Center for
Quantum Networks
NSF Engineering Research Center

Center for Quantum Networks

NSF Site Visit

October 21-24, 2025

University of Maryland, College Park MD

Funded by National Science Foundation Award #1941583

Center for
Quantum Networks
NSF Engineering Research Center



Welcome and Introductions

Samuel Graham, Jr.

Dean, *A. James Clark School of Engineering*

University of Maryland, College Park

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Land Acknowledgement

Every community owes its existence and strength to the generations before them, around the world, who contributed their hopes, dreams, and energy into making the history that led to this moment.

Truth and acknowledgement are critical in building mutual respect and connections across all barriers of heritage and difference.

So, we acknowledge the truth that is often buried: We are on the ancestral lands of the Piscataway People, who are the ancestral stewards of this sacred land. It is their historical responsibility to advocate for the four-legged, the winged, those that crawl and those that swim. They remind us that clean air and pristine waterways are essential to all life.

This Land Acknowledgement is a vocal reminder for each of us as two-leggeds to ensure our physical environment is in better condition than what we inherited, for the health and prosperity of future generations.

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University of Maryland Welcome

Dr. Gretchen Campbell

***Associate Vice President**, Quantum Research and Education*

University of Maryland

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University of Arizona Welcome

David Hahn

Dean of Engineering

University of Arizona

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NSF Welcome Address

Kemi Ladeji-Osias

Acting Deputy Division Director, *Engineering Education and Centers (EEC)*

Directorate for Engineering, National Science Foundation (NSF)

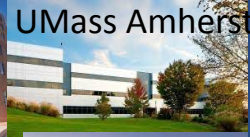
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Directors' Overview

Saikat Guha

Co-Director CQN & Co-PI

A. James Clark Endowed Chair Professor, ECE, University of Maryland, College Park MD

Adjunct Professor, Wyant College of Optical Sciences, University of Arizona, Tucson AZ

Affiliate Faculty, EECS, MIT, Cambridge MA

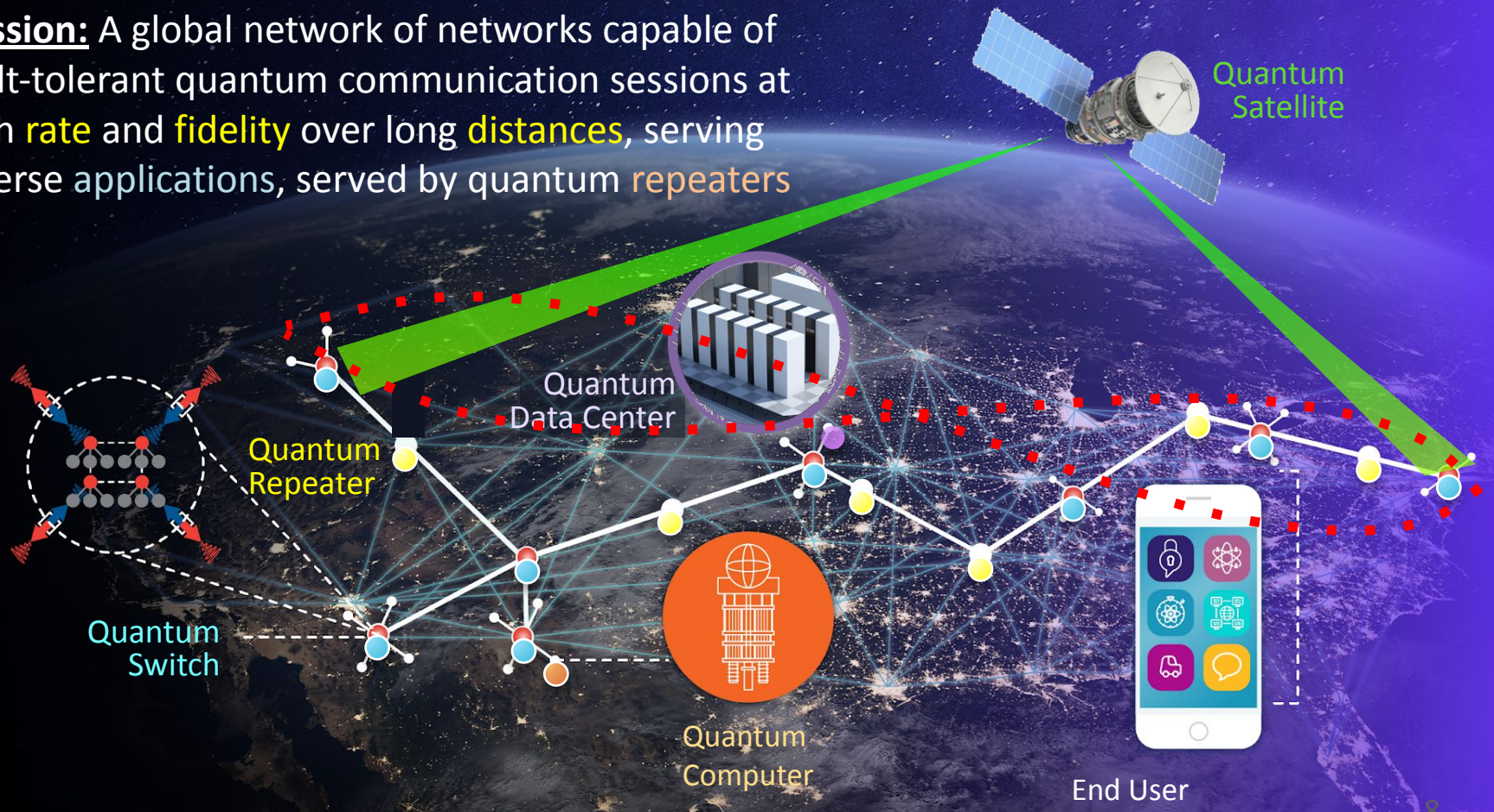


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The Quantum Internet

Mission: A global network of networks capable of fault-tolerant quantum communication sessions at high rate and fidelity over long distances, serving diverse applications, served by quantum repeaters

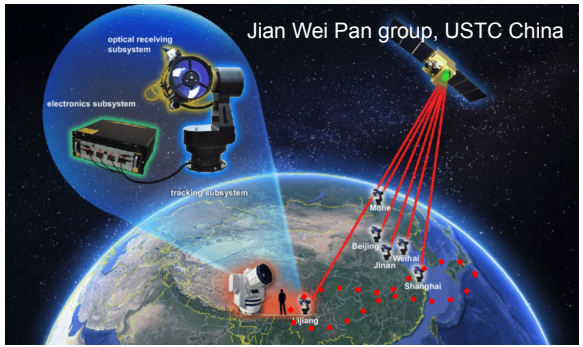


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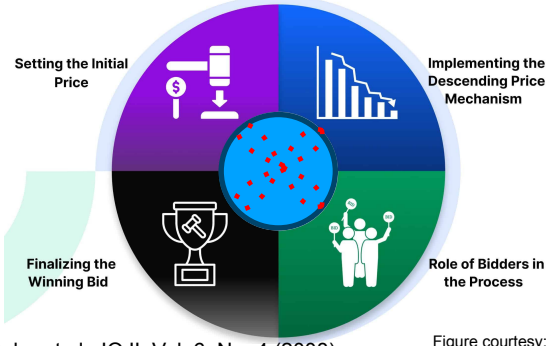
Why quantum networking?

(1) Privacy and security

Secure communications



Auctions; and other multiparty privacy-preserving computations

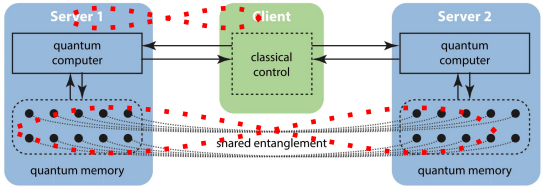


Guha et al., IQJI, Vol. 6, No. 4 (2008)

Figure courtesy: ProQsmart

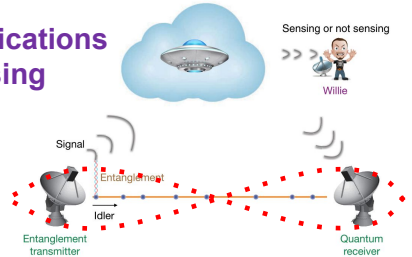
(2) Private and distributed quantum computing

Blind quantum computing



Fitzsimons, Nature npj Quantum Information, Vol. 3, No. 23 (2017)

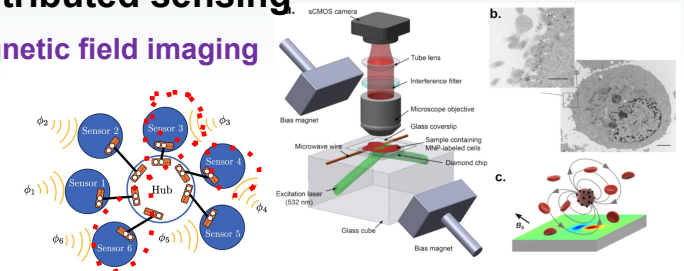
Covert communications and sensing



Hao, Shi, Gagatsos, Mishra, Bash, Djordjevic, Guha, Zhuang, Zhang, Phys. Rev. Lett. 129, 010501 (2022)
Gagatsos, Bullock, Bash, IEEE Journal on Selected Areas in Information Theory, Vol: 1 , Issue: 2, (2020)

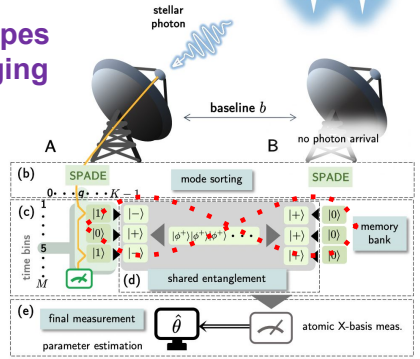
(3) Distributed sensing

Magnetic field imaging



Boretti et al., Beilstein J. Nanotechnol., 10, 2128–2151 (2019)
Van Milligen, Gagatsos, Kaur, Towsley, Guha, Phys. Rev. Applied 22, 064085 (2024)

Long baseline telescopes and gravitational imaging (LIGO clusters)



Khabiboulline, Borregaard, De Greve, and Lukin, Phys. Rev. Lett. 123, 070504 (2019)
Brown, … Raymer, Smith, Phys. Rev. Lett. 131, 210801 (2023)
Padilla, Sajjad, Saif, Guha, arXiv:2504.03117 (2025)
Stas, …, Lukin, arXiv:2509.09464 (2025)
Liu et al., arXiv:2510.07898 (2025)

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Highlights from the past year

- **Convergent research**
  - City-scale entanglement of quantum memories, demonstrations of blind quantum computing and distributed telescope primitives
  - High-fidelity hyperfine-mediated quantum logic in SiV and SnV color centers
  - All-optical strain engineering based tuning of ZPLs of an array of color center qubits
  - High-efficiency quantum frequency conversion from SiV frequency to telecommunications band
  - Capacity-approaching quantum link architectures for generating spin-spin entanglement, with and without classical feedback control
  - ZALM architectures with “island based” joint spectral amplitudes for optimized rate-fidelity operation
  - Measurement based entanglement distillation and fault-tolerant constant-overhead repeater architecture
  - Application-aware entanglement routing algorithms for serving entanglement-assisted distributed sensors in a network
  - Full network protocol stack replete with a versatile link-layer and connectionless transport, borrowing principles from the Internet
  - The quantum index report: a data-driven assessment of quantum technologies
- **Innovation ecosystem**
  - Applications Roadmap now a QED-C led national-scale QNAR2.0 effort: hosted first workshop in summer 2025
  - Virtual testbed development: a full time engineer supported by IPP, and center-wide integration via weekly open office hours
  - 99 provisional or full patents, a 23.75% YoY increase in 2025, shared with industry partners for licensing interest
  - Two diamond members, Cisco and L3Harris, conducted customized research projects with CQN PIs
  - Our PIs spun out two new companies: Diffraqtion (UMD) & Blanqet (UChicago), bringing new total to 6 active CQN-led startups
  - Ciena – telecommunications company joined CQN’s IPP, and has been interacting with Virtual Testbed group
- **Engineering Workforce Development**
  - Another year of successful Winter School, SPARCQS events, and REU
  - Graduate certificate program–drawing courses from the MS-in-QISE: in final approvals at UArizona
  - Co-hosted NSF Quantum Que webinar on professional development in between community college attendees and CQN institutions
- **Expanding participation**
  - GLEAM program to engage high school students at Maryland
  - Cross-campus student exchanges (multiple)
  - Community outreach via SPARQCS
  - Community of practice: CQN co-organized / co-sponsored multiple workshops, including ERVA report
  - SPLC organized the Q^3 initiative (https://q3initiative.org/) - engaged with experts in art, policy, economics

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Research strategic plan: 3-plane chart



Don Towsley,
UMass Amherst



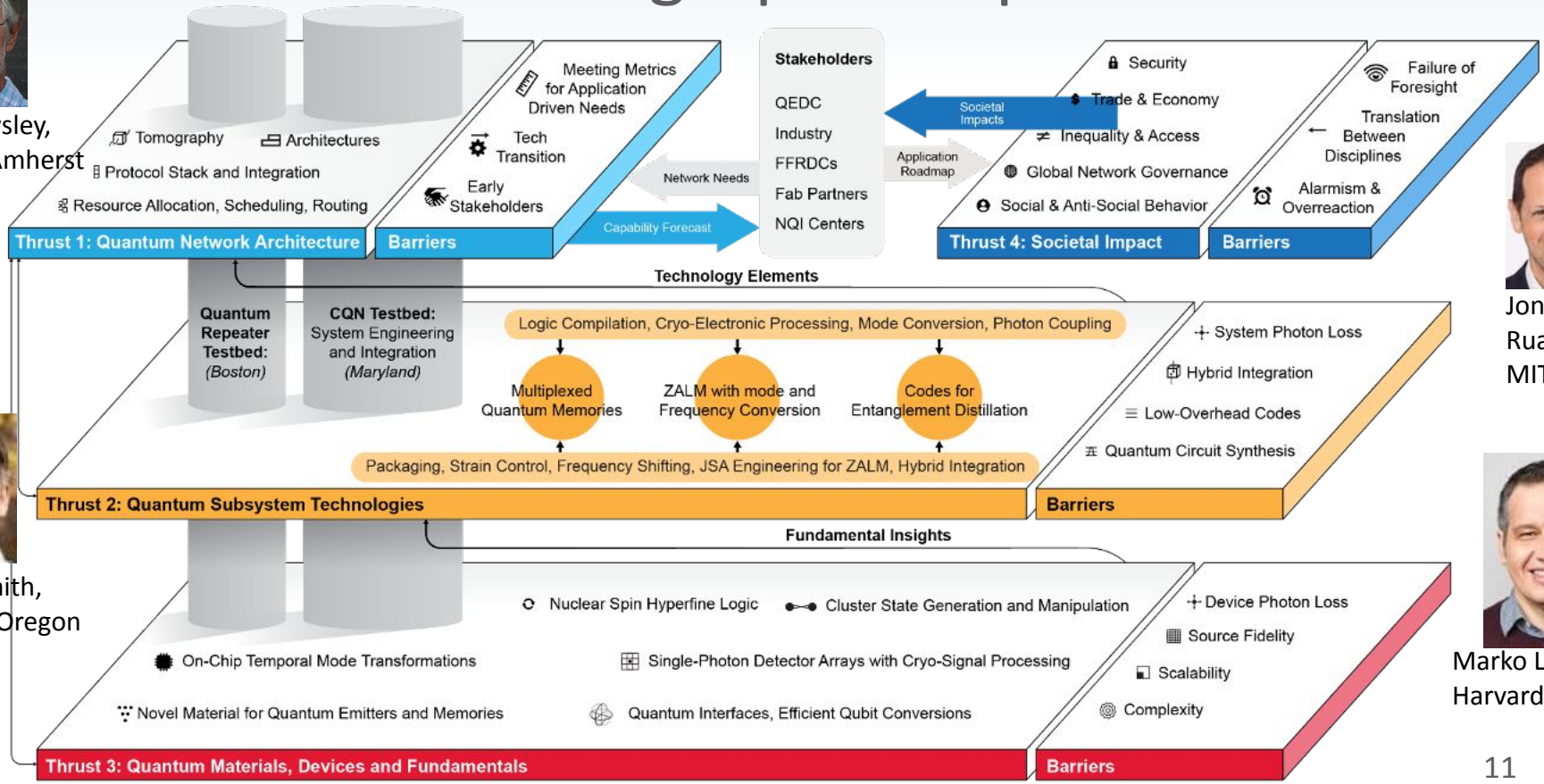
Brian Smith,
Univ. of Oregon



Jonathan
Ruane,
MIT

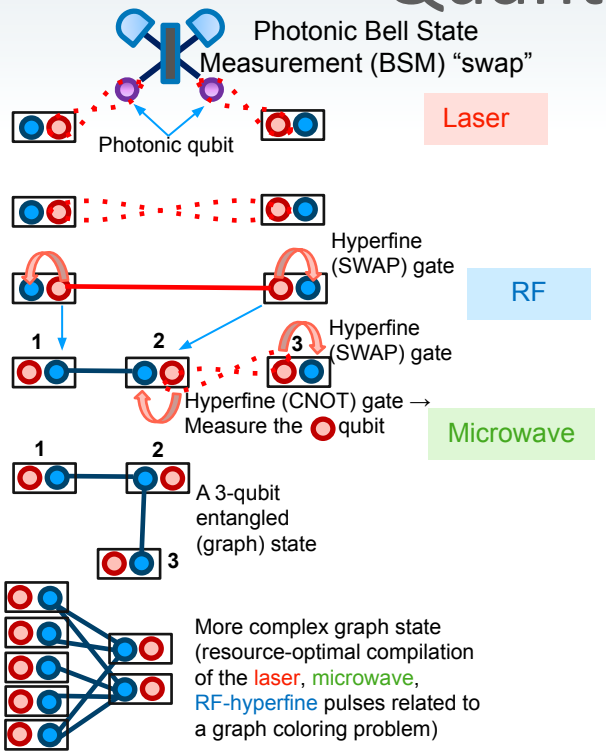


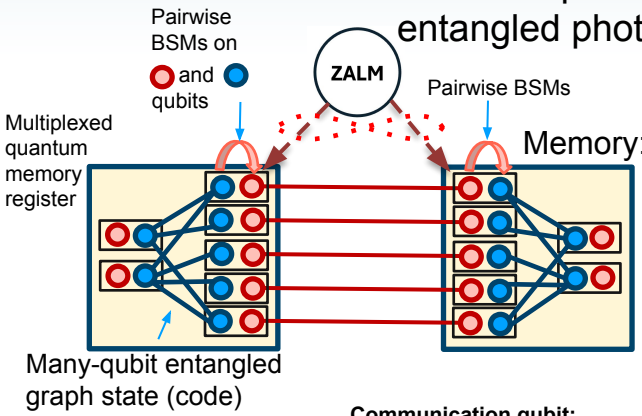
Marko Loncar,
Harvard



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Quantum Network Architecture





Communication qubit: shorter lived, high-efficiency coupling to optical photon

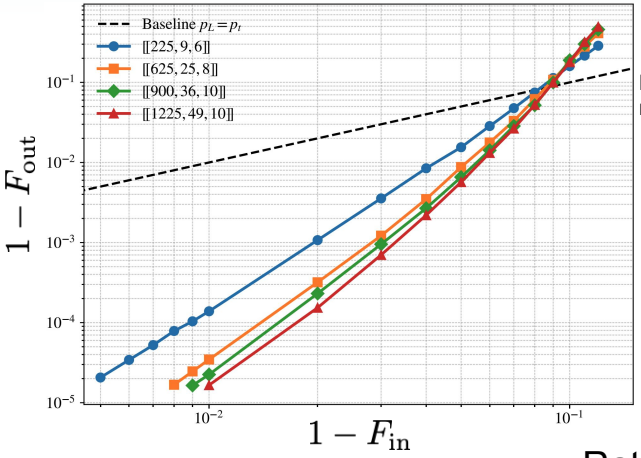
Memory qubit: longer lived, high-Fidelity two-qubit gate allowed to the communications qubit

	Color center SiV or SnV	**Dual species trapped ion**
	Silicon or Tin electron spin	$^{138}Ba^{+}$ $^{9}Be^{+}$
	^{29}Si or ^{117}Sn nuclear spin	$^{171}Yb^{+}$ $^{25}Mg^{+}$

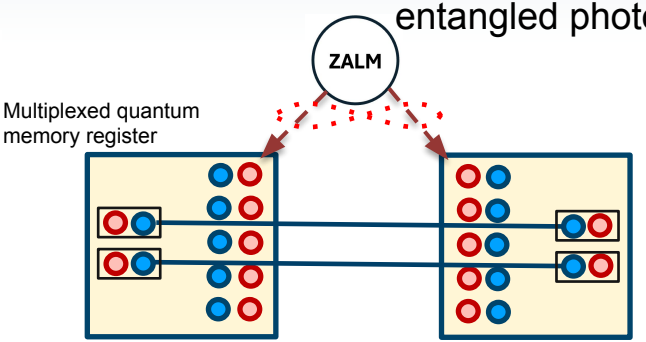
Lukin and Loncar groups, Science, Vol 378, Issue 6619, pp. 557-560 (2022)
Chen, Dhara, Heuck, Lee, Dai, Guha, Englund, *Zero-Added-Loss Entangled-Photon Multiplexing for Ground- and Space-Based Quantum Networks*, Phys. Rev. Applied 19, 054029 (2023)
Englund group, *Large-scale integration of artificial atoms in hybrid photonic circuits*, Nature volume 583, pages 226–231 (2020)

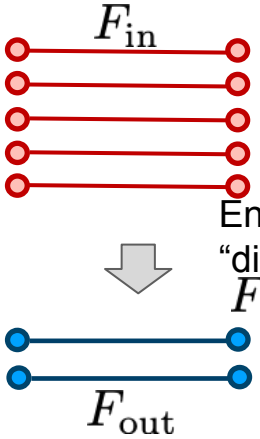
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Quantum Network Architecture



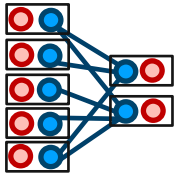
ZALM: A quasi-deterministic entangled photon pair source





Rate 2/5 quantum (Stabilizer) code →

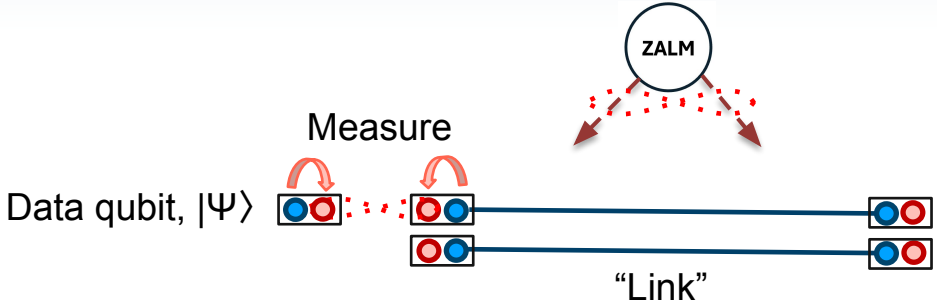
5 + 2 qubit graph state



Shi, Patil, Guha, *Measurement-Based Entanglement Distillation and Constant-Rate Quantum Repeaters over Arbitrary Distances*, Phys. Rev. Lett. 135, 130803 (2025)
Lukin and Loncar groups, Science, Vol 378, Issue 6619, pp. 557-560 (2022)
Chen, Dhara, Heuck, Lee, Dai, Guha, Englund, *Zero-Added-Loss Entangled-Photon Multiplexing for Ground- and Space-Based Quantum Networks*, Phys. Rev. Applied 19, 054029 (2023)
Englund group, *Large-scale integration of artificial atoms in hybrid photonic circuits*, Nature volume 583, pages 226–231 (2020)

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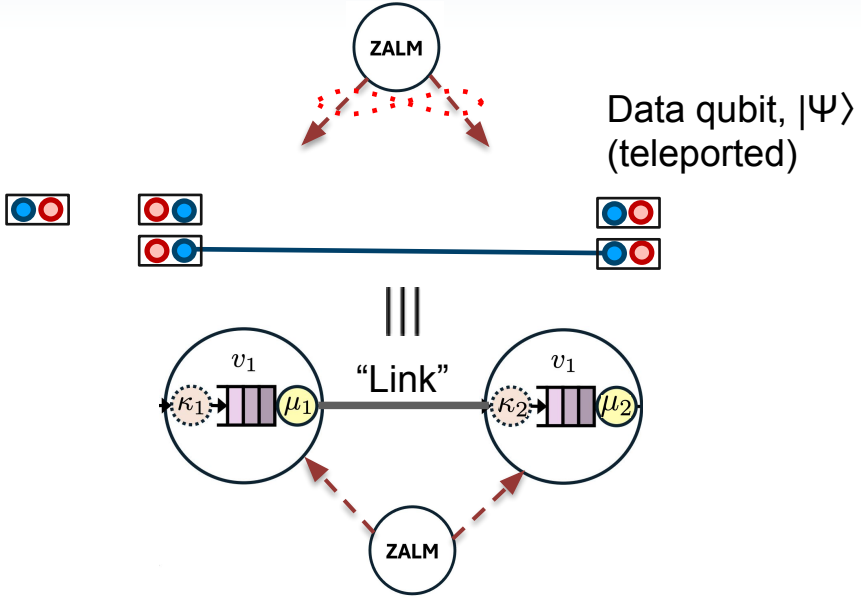
Quantum Network Architecture



Shi, Patil, Guha, *Measurement-Based Entanglement Distillation and Constant-Rate Quantum Repeaters over Arbitrary Distances*, Phys. Rev. Lett. 135, 130803 (2025)
Lukin and Loncar groups, Science, Vol 378, Issue 6619, pp. 557-560 (2022)
Chen, Dhara, Heuck, Lee, Dai, Guha, Englund, *Zero-Added-Loss Entangled-Photon Multiplexing for Ground- and Space-Based Quantum Networks*, Phys. Rev. Applied 19, 054029 (2023)
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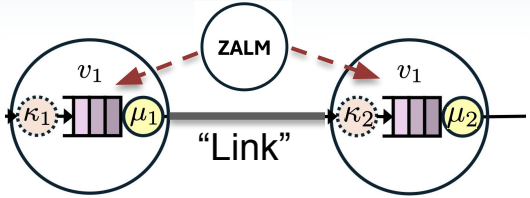
Quantum Network Architecture



Shi, Patil, Guha, *Measurement-Based Entanglement Distillation and Constant-Rate Quantum Repeaters over Arbitrary Distances*, Phys. Rev. Lett. 135, 130803 (2025)
Lukin and Loncar groups, Science, Vol 378, Issue 6619, pp. 557-560 (2022)
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Quantum Network Architecture

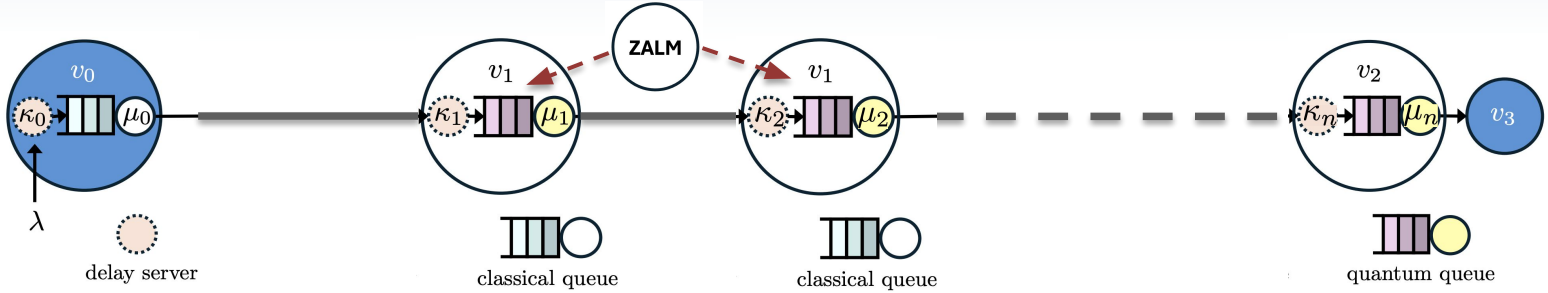


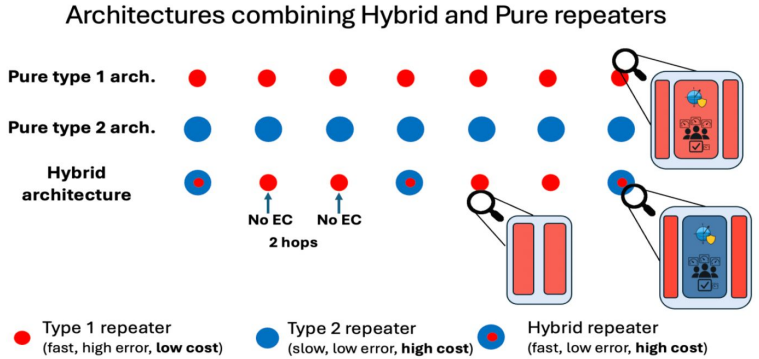
"Leveraging Internet Principles to Build a Quantum Network", Leonardo Bacciottini, Matheus Guedes De Andrade, Shahrooz Pouryousef, Emily A. Van Milligen, Aparimit Chandra, Nitish K. Panigrahy, Nageswara S. V. Rao, Gayane Vardoyan, **Don Towsley**, IEEE Network, May 12, 2025

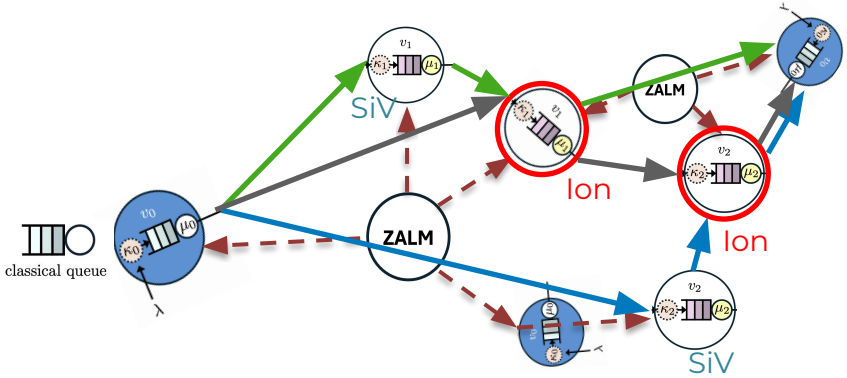
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Quantum Network Architecture







"Leveraging Internet Principles to Build a Quantum Network", Leonardo Bacciottini, Matheus Guedes De Andrade, Shahrooz Pouryousef, Emily A. Van Milligen, Aparimit Chandra, Nitish K. Panigrahy, Nageswara S. V. Rao, Gayane Vardoyan, **Don Towsley**, IEEE Network, May 12, 2025

"Hybrid repeaters with encoding for long distance entanglement distribution", Haldar, Guha, Towsley, Rozpedek; IEEE QCE 2025

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Work packages

T2 T3

WP1

Near-deterministic high-rate photonic entanglement source (bulk-optic/ integrated)

T1 T2 T3

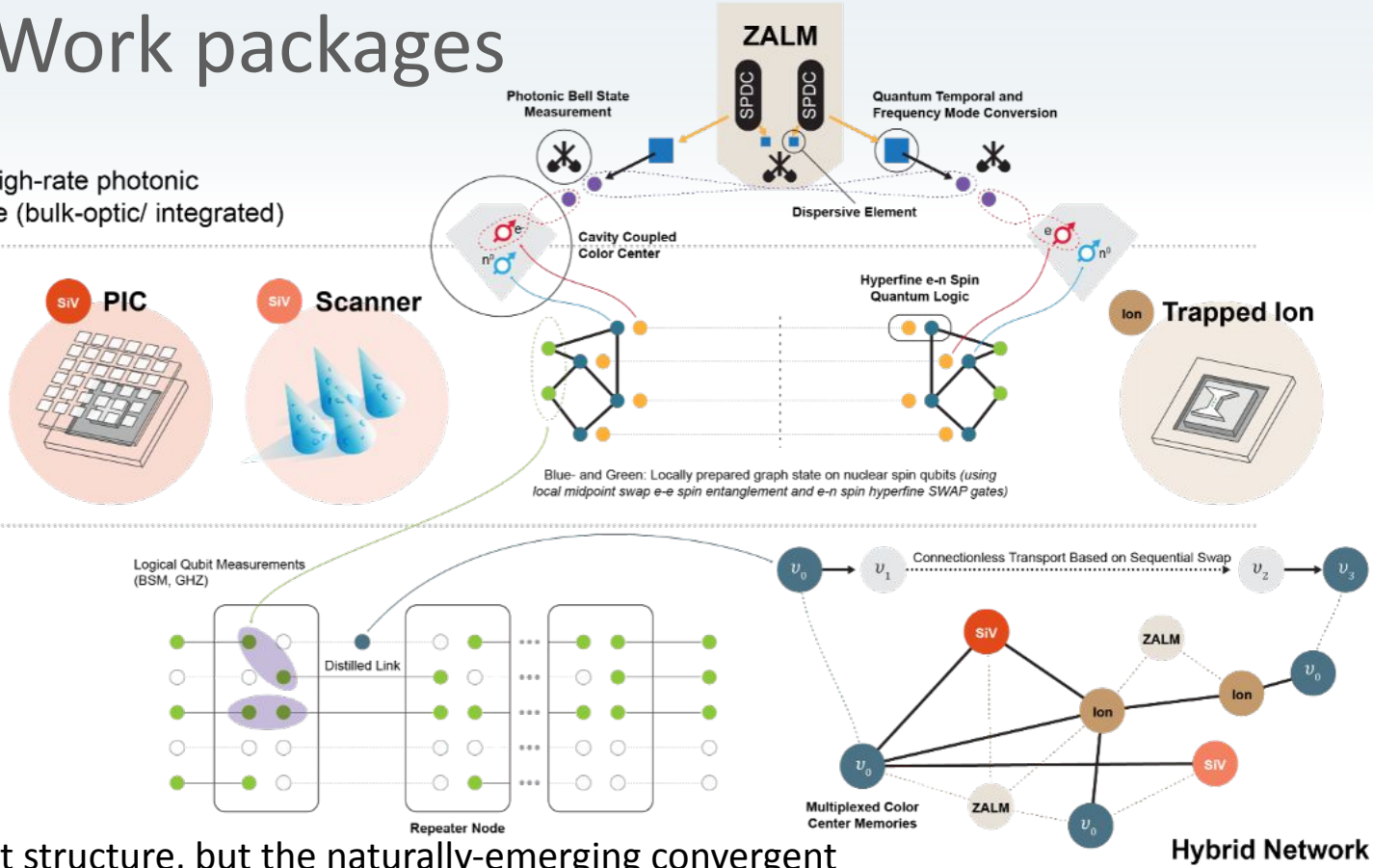
WP2

Multiplexed quantum memories

T1 T2

WP3

System integration and performance evaluation



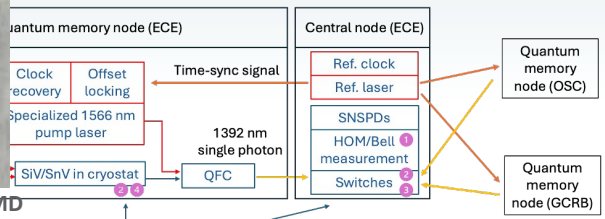
CQN retains its Thrust structure, but the naturally-emerging convergent research is best described in terms of these interconnected work packages: each straddling all Thrusts, with their regular working group meetings.

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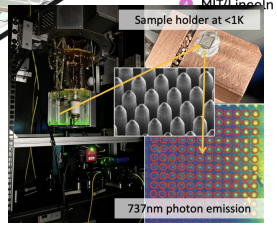
CQN Testbeds


Chaohan Cui, UMD



Tucson testbed






Matt Eichenfield


Linran Fan


Zheshen Zhang

Boston testbed


Dirk Englund


Mikhail Lukin

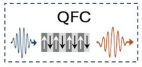

Chao Li, MIT


Julia Mundy


Marko Loncar


Danna Freedman





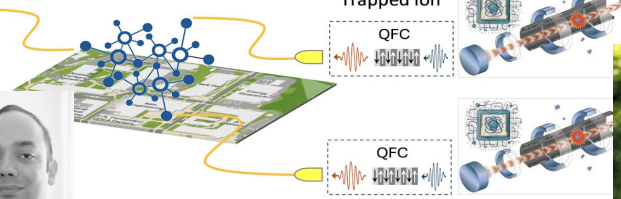
Solid-state spin

NSF C-Accel Program: Waks (PI), Guha, Englund

Trapped ion

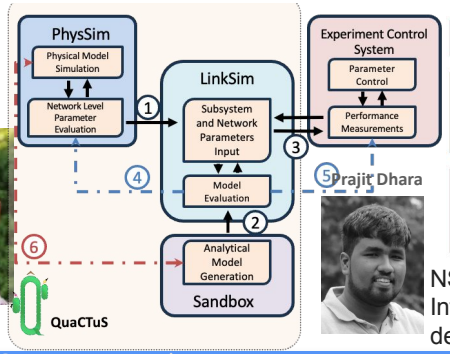

Qudsia Quraishi


Saikat Guha

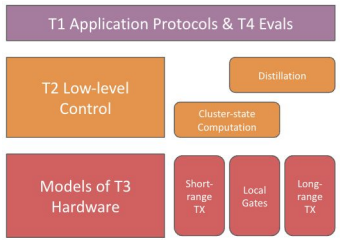


UMD (MARQI) Testbed


Edo Waks



Prajit Dhara



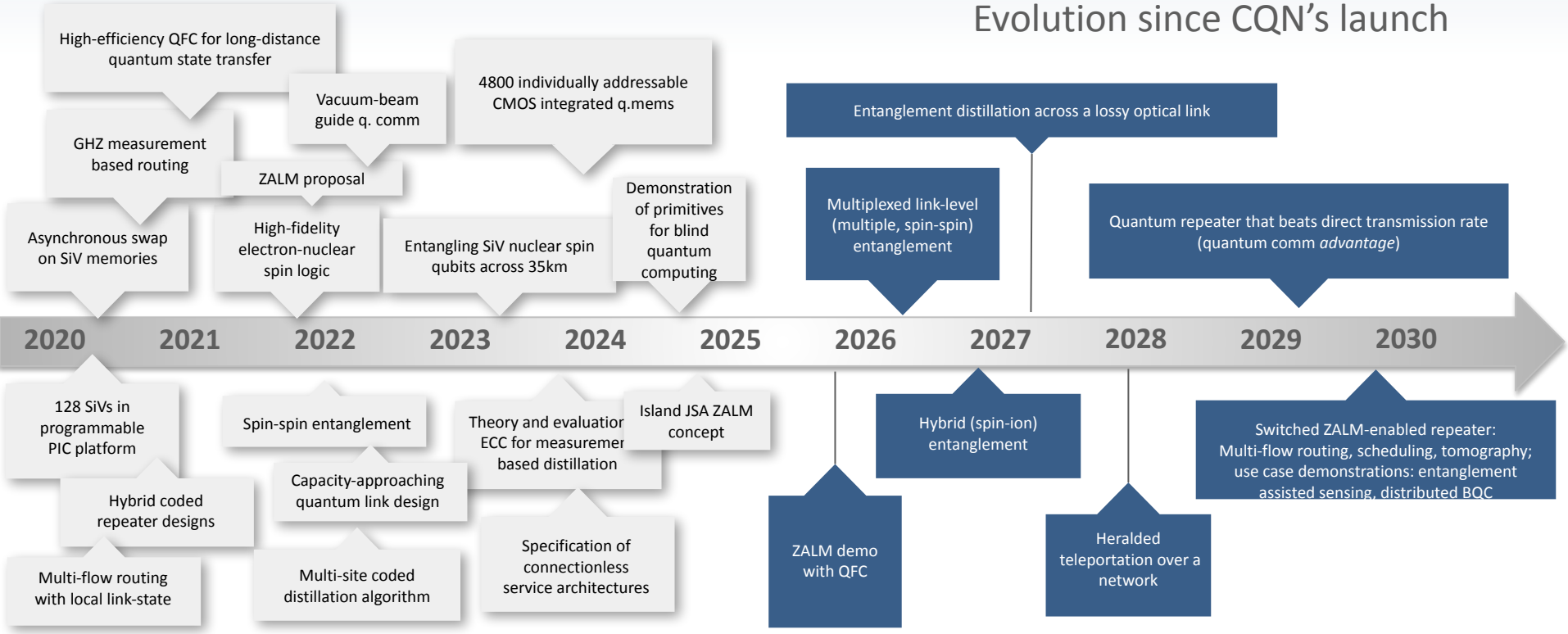

Stefan Krastanov

Virtual testbed

NSF Award # 2346089 "Research Infrastructure: CIRC: Full-stack Co-design Tools for Quantum Hardware"

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Research Strategic Plan:
Evolution since CQN's launch



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Societal impacts and stakeholders

Satellite-assisted remote entanglement distribution, for long-baseline sensing and imaging

Quantum-Augmented Networks for physical and network layer security

DARPA

Quantum enhanced receivers for deep-space laser-communications

Entanglement assisted magnetic field sensing

NASA

Entanglement. Enhanced Quantum Secure Covert Comms. and Sensing

MURI on Quantum Network Science

Federal Government

Raytheon Technologies

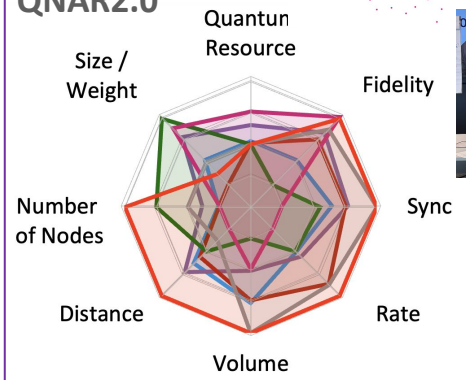
L3HARRIS

Defense

Associated Project Ecosystem, Applications Development

Applications Roadmap QNAR2.0

QED·C





QIA

QUANTUM INTERNET ALLIANCE

CoQREATE
Convergent Quantum Research Alliance in Telecommunications

NATIONAL QUANTUM MISSION OF INDIA

International

Startup

Qunett

LIGHTSYNQ



Laura B. Andre · 1st
CEO @ Qunett

Techyawn (UMass), **Hydroteck** (BYU)

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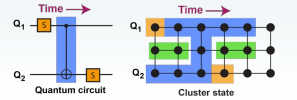
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Engineering Workforce Development



Dr. Noel Hennessey, UA, EWD Director

EWD Fellowship





ChatCQN

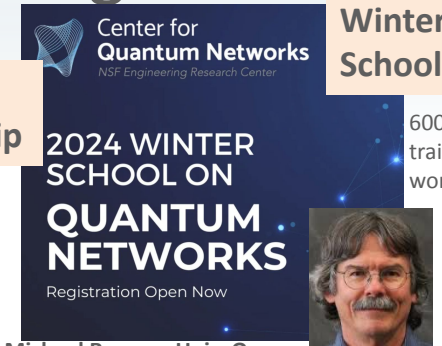
Ashlesha Patil, CQN student UA

Quantum computing as a Tangram Puzzle

Student Innovator of the Year Award 2023, UA

Patil, Jacobson, Towsley, SG, arXiv:2210.11465, IEEE QCE 2022

Winter School

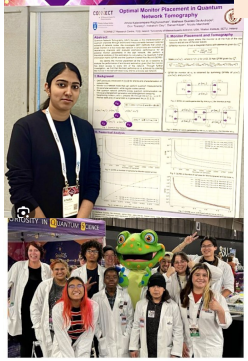


600+ people trained worldwide

Michael Raymer, Univ. Oregon

Conferences















Ines Montano, NAU









Sparking Curiosity in Quantum Science (SPARCQS)



REU 2025

MS in QISE

WYANT COLLEGE OF OPTICAL SCIENCES
QISE EMPHASIS REQUIREMENTS (version 2024.06.05)

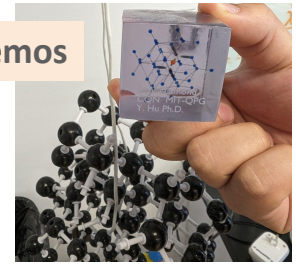
MS Thesis option: 26 units of coursework + 6 units of OPTI 910: Thesis = 32 total units
MS Report option: 29 units of coursework + 3 units of OPTI 909: Report = 32 total units

* Total coursework units include Core and Approved Elective units (below) + 3 additional units of any graded OPTI coursework not listed below.
* With advisor and Associate Dean approval, up to 3 units of OPTI 599: Independent Study may be taken in place of the same number of units of Approved Electives.
* Courses listed as available online may require a minimum online enrollment to be offered as a distance course in any given semester.

CORE COURSES - COMPLETE AT LEAST 4 COURSES, ONE PER GROUP: 12 UNITS TOTAL	Units	Term	Online?	Prereq
OPTI 570 Quantum Mechanics *(or other graduate-level Quantum Mechanics course)*	3	F	yes	OPTI 511R or undergraduate quantum mechanics, or proficiency with linear algebra
OPTI 544 Foundations of Quantum Optics	3	S	yes	OPTI 570 or equiv
OPTI 646 Introduction to Quantum Information and Computation	3	F	yes	OPTI 570 or equiv. OPTI 544 recommended
or				
OPTI 647B Photonic Quantum Information Processing	3	S	yes	OPTI 570 or equiv, or OPTI 647A
OPTI 560 Quantum Nanophotonics	3	S	yes	E&M (OPTI 501 or equiv), intro. QM (OPTI 511R)
or				
OPTI 572 Quantum Photonic Integrated Circuits *(may not be offered every year). This course also counts as a lab class.*	3	S	yes	E&M (OPTI 501 or equiv), intro. QM (OPTI 511R)

APPROVED ELECTIVES - 11 UNITS FOR MS THESIS OPTION *OR* 14 UNITS FOR MS REPORT OPTION (includes minimum 2 units of lab courses)				
** Thesis and Report options allow for 3 units outside of the approved elective list to satisfy total coursework units requirements.*				
** With Faculty Advisor and Associate Dean approval, a student may use a suitable course in place of one of the approved electives in this list.*				
** Any units beyond 12 from courses in the Core Course list will count towards elective units*				
Elective lab courses - AT LEAST TWO LAB COURSES	**Units**	**Term**	**Online?**	**Prereq**
One lab may be waived for relevant industry experience (with Assoc. Dean approval)				
OPTI 511L Lasers and Solid-State Devices	1	F		OPTI 511R or other QM course; or 507 co-req
OPTI 571L Optical Physics Computational Laboratory	1	F	yes	OPTI 570 or equiv
OPTI 587L Photonics Communications	1	S		
OPTI 572 Quantum Photonic Integrated Circuits	3	S	yes	E&M (OPTI 501 or equiv), intro. QM (OPTI 511R)

Demos



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Center for
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Expanding Participation

Powered by QuEST teams



Brianna Moreno,
Administrative Director

Mentorship Program

- Inaugurated in April 2024
- Mentors from 3 NSF entities: CQN, NoirLab, CUA–faculty, senior researchers postdocs, and grad students
- Mentees from Quantum Que and REU, undergraduates and graduates

Outreach



Arizona Quantum Boot Camp

Community of Practice



EP Council

- Inaugural meeting 04/12/24 to discuss EP programming and equity in CQN [UG, G, faculty, IPP, REU]

Seven Falls trail, Annual Retreat 2024



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Innovation Ecosystem


Alireza Shabani,
UA, ILO co-officer


John Sawyer
UMD, ILO co-officer

Joint research

Cisco: Towsley (design of quantum data center networks)

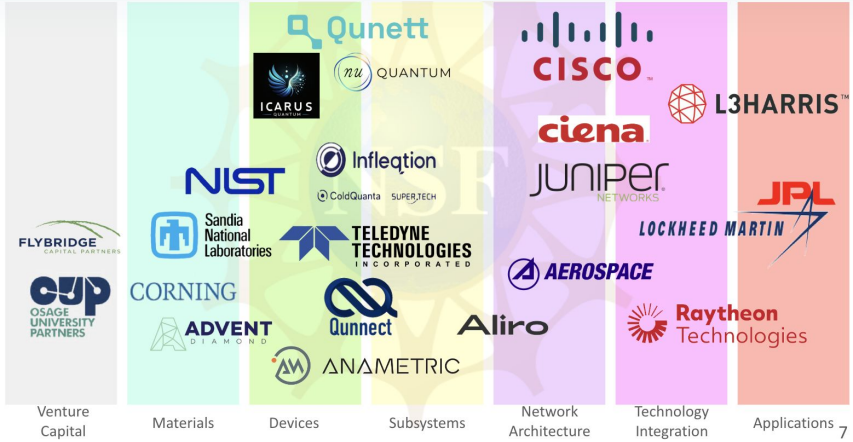
L3Harris: Bash and Guha (secure comms theory and demo)

Advent: Eichenfield (SBIR new quantum sensor architecture)

RTX: Zhang and Guha (covert comms and sensing)

Juniper: Jiang (quantum repeaters and network routing)

GDMS: Zhang and Guha (RF photonic sensors, squeezed)





CQN's Industry Partnership Plan (IPP): An "IUCRC like" tiered membership plan

Total financial support > +2M

Testbed integration

1. L3Harris [demonstrating quantum clock synchronization],
2. Qunett [fiber connection to LL and MIT, incorporating confocal scanner into CQN testbeds],
3. Qunnect [exploring integration of room temp memories into testbed via synergistic QFC]

Xia, Li, Clark, Hart, Zhuang, Zhang, Phys. Rev. Lett. 124, (2020)
Rozpędek, Seshadreesan, Polakos, Jiang, Guha, Phys. Rev. Research 5, 043056 (2023)
Van Milligen, Gagatsos, Kaur, Towsley, Guha, arXiv:2407.15652, to appear: Phys. Rev. App. (2024)
Webb, Bullock, Knarr, Burt, Drakes, Guha, Bash, Bucklew, MILCOM 2023

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NIST
Leader, Quantum Optics Group



Ananthram Swami
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Ben Sussman
National Research Council Canada
Program Director



Chip Elliott
Raytheon BBN
Retired CTO



Christopher Yoo
University of Pennsylvania
Professor of Law, Communication, and Computer & Information Science



Derya Cansever
US Army Research Office
Program Officer



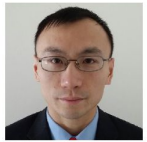
Fredrik Fatemi
U.S. Army Research Laboratory
Senior Research Scientist for Quantum Science



Ian Walmsley
Imperial College London
Provost & Chair of Experimental Physics



Jeff Lundeen
University of Ottawa
Associate Professor, Physics



John Zhang
City of Chicago
Division Chief, Smart Cities



Konrad Banaszek
University of Warsaw
Professor; Director, Centre of Quantum Optical Technologies



Nicolas Treps
Sorbonne Université
Professor, Multimode Quantum Optics



Norbert Lutkenhaus
University of Waterloo
Professor, Physics and Astronomy
(Chair of CQN EAB)



Sara Chavarria
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Assistant Director, STEM Learning Center



Stephanie Wehner
Delft University of Technology
Professor, Quantum Information
Director, European Quantum Internet Alliance

Industry Advisory Board (IAB)



Alex Tingle
Infleqtion
Technical Product Manager



Bryan Spann
Lockheed Martin Space
Staff Research Scientist



Domenico di Mola
Juniper Networks
Group Vice President



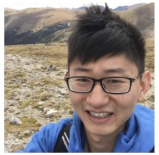
Gert Grammel
Juniper Networks
Optics Networks and Solutions



Mark Meisner
Raytheon Technologies
Technology Area Lead



Mehdi Namazi
Qunnect
Founder and CSO



Peng Zhao
Cisco Systems
Quantum Research Scientist



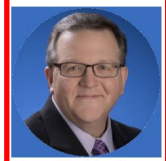
Reza Nejabati
Cisco Systems
Head of Quantum Research



Samuel Knarr
L3Harris
Optical Engineer, Quantum Solutions



Siamak Dadras
Toptica Photonics
Quantum Application Scientist



Timothy Burt
L3Harris
Scientist, Quantum Solutions



William Clark
Infleqtion
VP Quantum Development



Zac Dutton
Raytheon BBN
Lead Scientist, Physical Sciences & Systems

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Questions?

CQN Annual Retreat, Tucson 2024



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CQN Integration

Dirk Englund and Matt Eichenfield

Deputy Director & Co-PI / Co-Director & PI

Professor of EECS MIT

Professor, SPIE Endowed Chair, Optical Sciences, University of Arizona

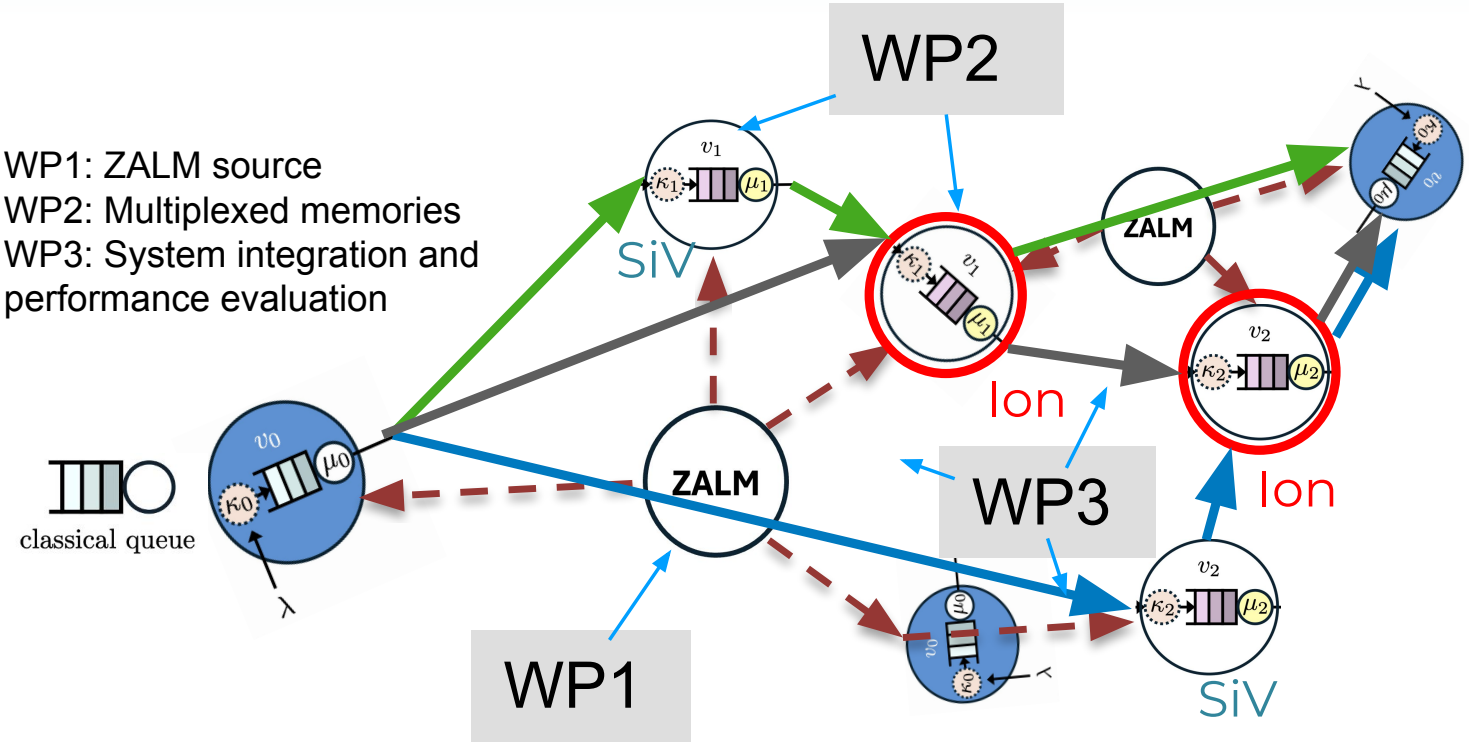
Funded by National Science Foundation Award #1941583

ARIZONA · MIT · HARVARD · UNIVERSITY OF MARYLAND · University of Massachusetts Amherst · BYU · THE UNIVERSITY OF CHICAGO 1890 · HOWARD UNIVERSITY · NAU NORTHERN ARIZONA UNIVERSITY · UNIVERSITY OF OREGON

CQN Architecture

Work packages serve as integration tools

WP1: ZALM source
WP2: Multiplexed memories
WP3: System integration and performance evaluation



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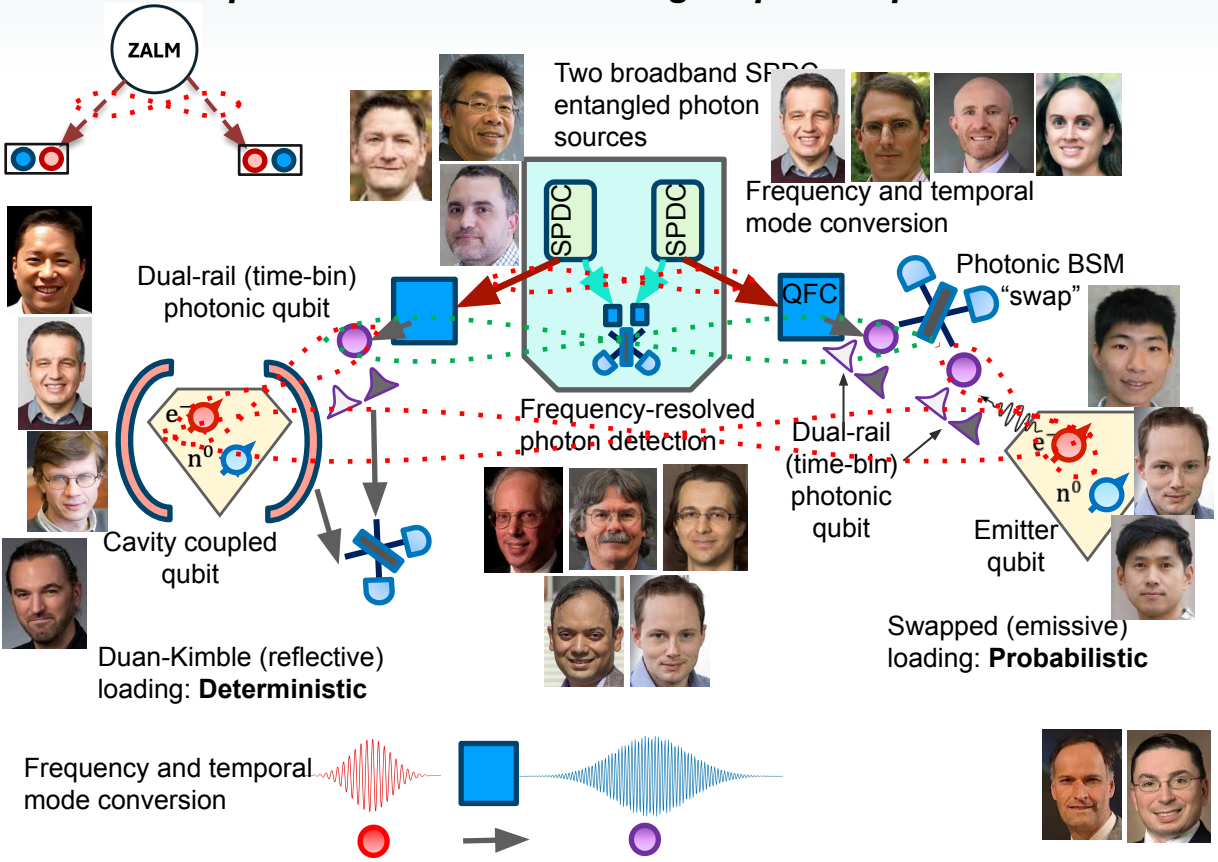
Center for Quantum Networks
NSF Engineering Research Center

Working Group coordinator:
Clark Embleton, UOregon



Zero-Added-Loss Multiplexing (ZALM): WP1

A quasi-deterministic entangled photon pair source



Original Proposal (theory and experiment):

- [NASA] Dhara et al., Heralded Multiplexed High-Efficiency Cascaded Source of Dual-Rail Entangled Photon Pairs Using Spontaneous Parametric Down-Conversion, Phys. Rev. Applied 17, 034071 (2022)
- Mercouche et al., Phys. Rev. Lett. 128, 063602 (2022)
- Chen et al., Zero-Added-Loss Entangled-Photon Multiplexing for Ground- and Space-Based Quantum Networks, Phys. Rev. Applied 19, 054029 (2023)

Improved architectures and memory-loading:

- Shapiro et al., Entanglement source and quantum memory analysis for zero-added-loss multiplexing, Phys. Rev. Applied 22, 044014 (2024); arXiv:2507.14427
- Raymer et al., Phys. Rev. Applied 22, 044013 (2024)
- [NASA] Chahine et al., Heralded entanglement source analysis for cascaded parametric down-conversion, QW3A.17 Quantum 2.0 (QUANTUM) 2025

Analysis within network architectures:

- [C2C] Campbell et al., Entanglement distribution through separable states via a zero-added-loss photon multiplexing inspired protocol, Phys. Rev. Research 6, 033317 (2024)
- [C2C/IPP] Bali et al., ICC 2024 - IEEE International Conference on Communications, Denver CO (2024)

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Working Group coordinator:
Joohyung Song, UMD



Multiplexed Quantum Memories: WP2

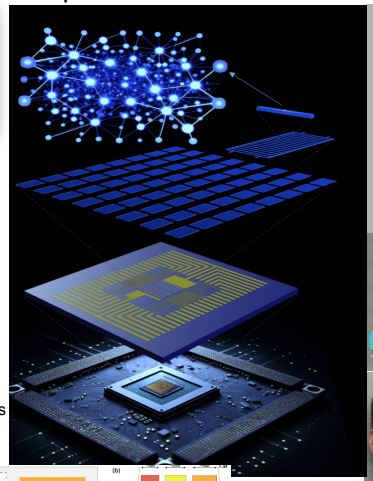
Scalable platforms: 1. thousands (ions) to **millions** (SiVs) individually addressable qubits, 2. **efficient qubit-photon interface**, 3. high-fidelity **quantum logic**

Reconfigurable photonic integrated waveguides coupled to color centers

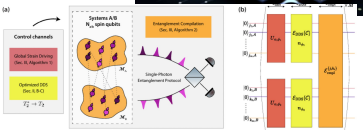






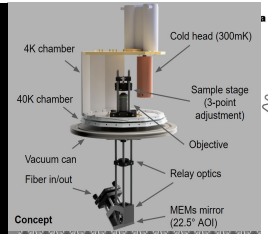


Superconducting electronics, Nature Electronics volume 8, 375 (2025)



Programmable quantum matter, arXiv:2509.02992 (2025)
Chip integrated photonic control, Optica Vol. 10, Issue 5, pp. 634-641 (2023)
Optical strain tuning, Xue, …, Cui, Guha, Eichenfield, Fan, Nature Communications 16 (1), 6275 (2025)
Spectral tuning, Nature Communications volume 16, Article number: 8829 (2025)

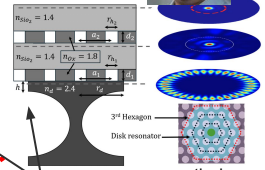
Color centers in diamond nanopillars and a MEMS scanner with fiber tip



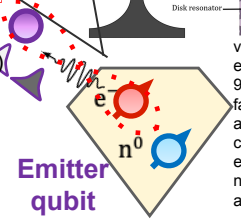




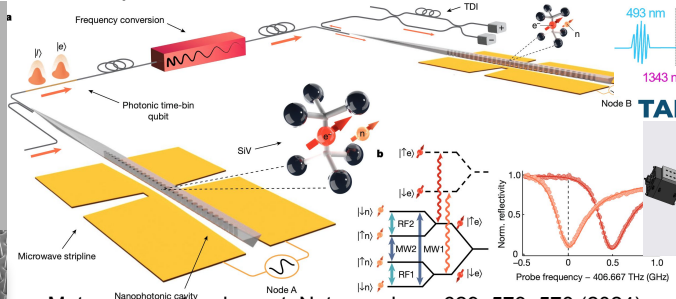




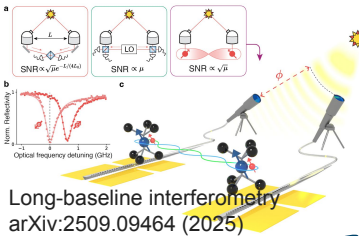
vertical emissions with 95% Gaussian far-field overlap and 97% collection efficiency at the numerical aperture of 0.7



Color centers in nanophotonic diamond cavities integrated with telecom fiber

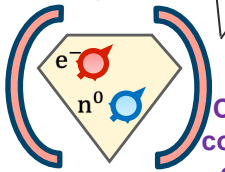


Metro-area entanglement, Nature volume 629, 573–578 (2024)

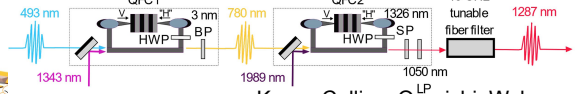


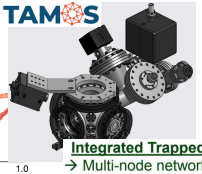
Long-baseline interferometry arXiv:2509.09464 (2025)





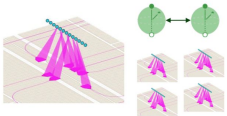
Trapped ion qubits strongly coupled to a cavity with efficient optical interface



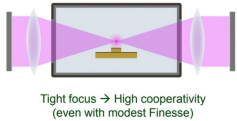


Kwan, Collins, Quraishi, Waks, "Telecom Quantum Frequency Conversion of Ba+ Trapped Ions for Quantum Networking", CLEO 2025

Integrated Trapped Ion Platform
→ Multi-node network + multiplexing

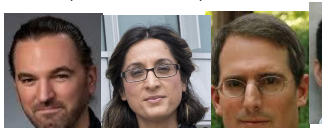


Integrated Platform + Cavities
→ **Quantum Repeaters**



Tight focus → High cooperativity (even with modest Finesse)

Niffenegger et al., Nature 2020, arXiv:2402.16742





Optically addressable molecular-spin qubit diluted in a host matrix; US Patent Application #18845790 (2025)



"Low-dimensional solid-state single-photon emitters", Nanophotonics, 14(11):1687-1713, (2025)

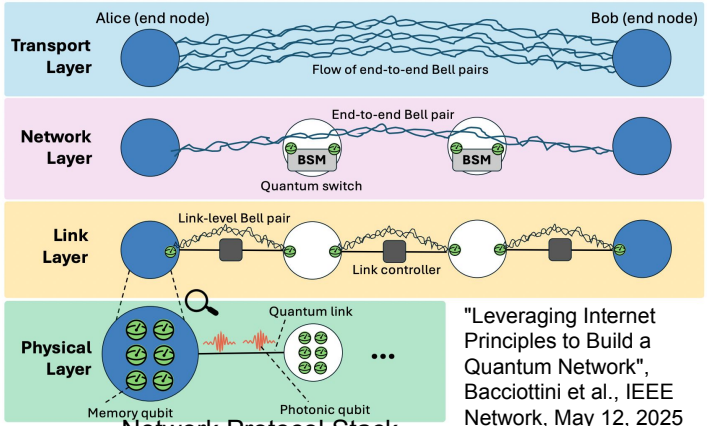
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Working Group coordinator:
Dr. Stav Haldar, UMass



System integration and performance evaluation: WP3



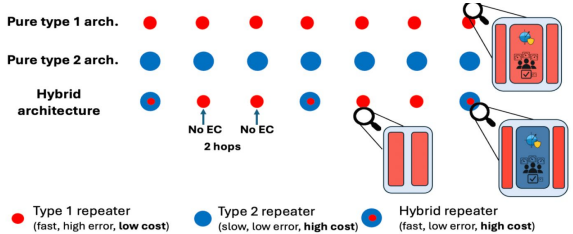
"Leveraging Internet Principles to Build a Quantum Network", Bacciottini et al., IEEE Network, May 12, 2025

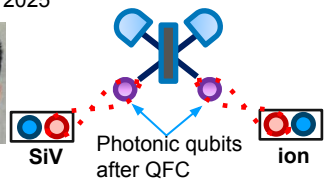
Network Protocol Stack



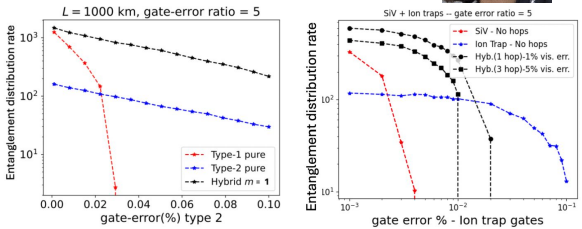


Hybrid quantum repeater architectures

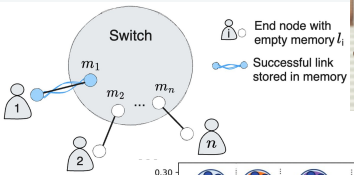




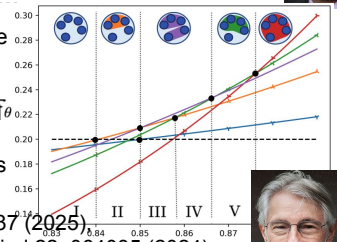




"Hybrid repeaters with encoding for long distance entanglement distribution", Haldar, Guha, Towsley, Rozpedek; IEEE QCE 2025

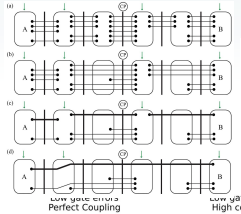


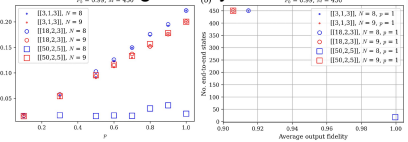
Resource-aware multiparty entanglement distribution, and applications to sensor networks

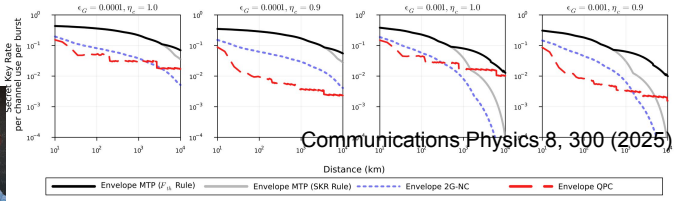


arXiv:2508.14737 (2025)
Phys. Rev. Applied 22, 064085 (2024)

One-way and two-way coded quantum repeaters
Patil, Pacenti, Vasić, Guha, Rengaswamy, arXiv:2405.00849

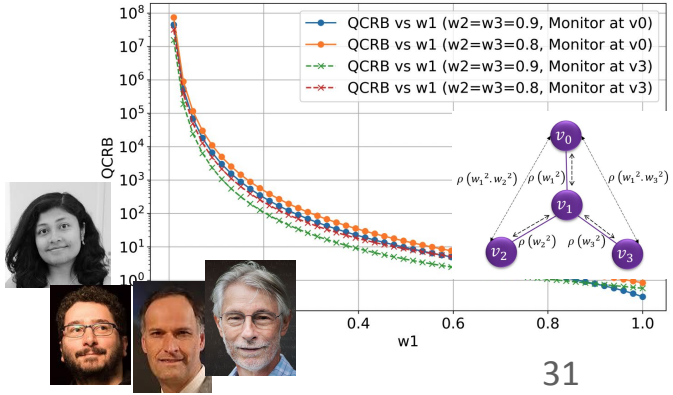






Communications Physics 8, 300 (2025)

Optimal monitor placement in quantum network tomography, Raghunadhan, De Andrade, Towsley, Dey, Kilper, Marchetti, IEEE QCE2024



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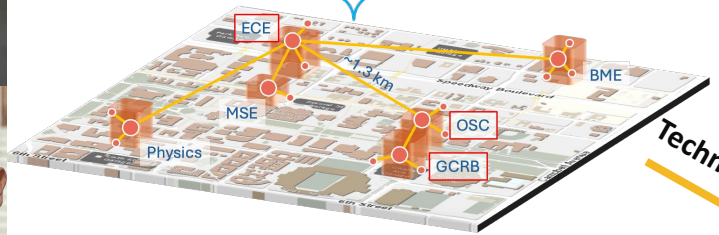
Tucson ⟶ Maryland testbed



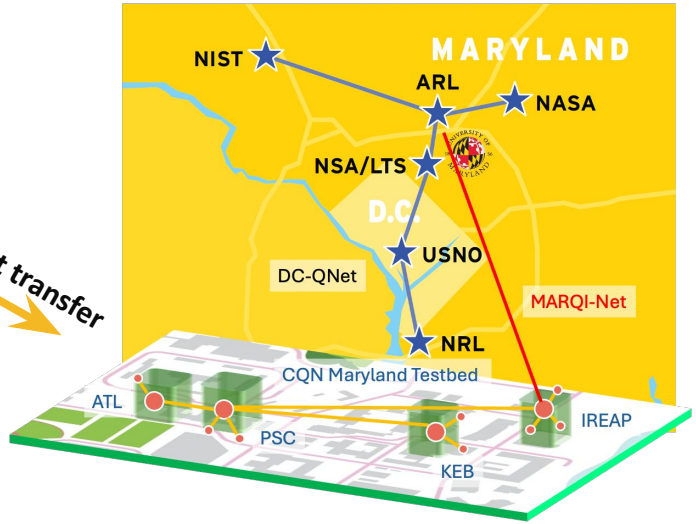
Birth of the Tucson Testbed: NSF INQUIRE
Remote programmable AI-powered QREAL receiver
Characterizing SiC-4H SiV quantum memory
QuaCTUS - Tucson Testbed Simulator
Superadditive capacity using Green Machine
Characterizing SiV color center quantum memory
Quantum frequency conversion
Integrated quantum memory devices

2020
2025
2030

Establishing the central quantum hub
First entanglement distribution in Tucson
New space and cryostat
Time domain interferometer
Cryostat-compatible confocal scanning microscope
Supporting systems for quantum network



Technology/equipment transfer



- Including trapped-ion technology and workforce
- Testbed connected to broad end-users, programs and technologies



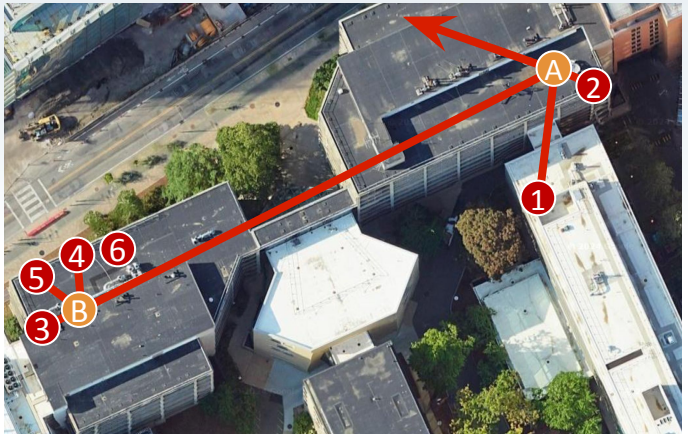
Dr. Chaohan Cui, UMD Research Faculty

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Boston Testbed



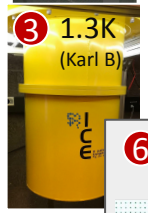


Dr. Chao Li, Research Faculty, MIT EECS

https://github.com/dirkenglund/quantum-network-code/tree/main

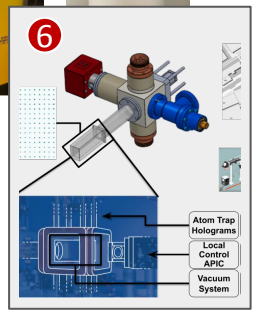










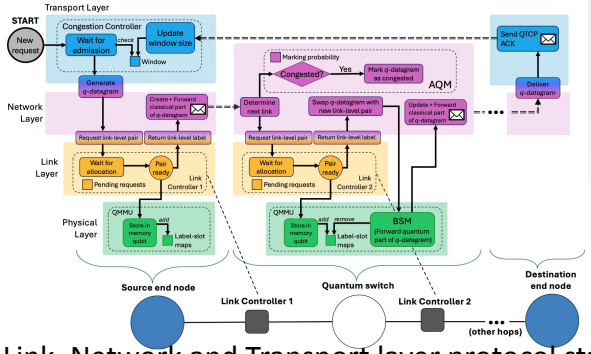






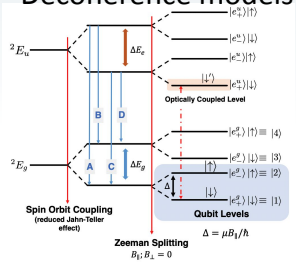
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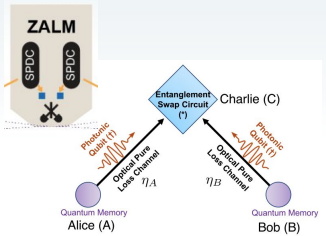
Virtual Testbed



Link, Network and Transport layer protocol stack

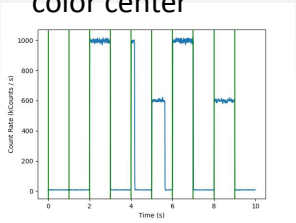
Decoherence models





Physical layer link models

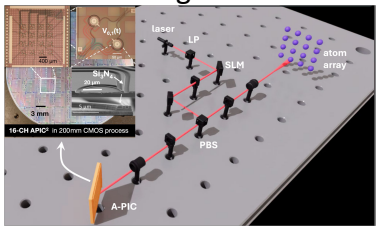
FPGA Controlled color center

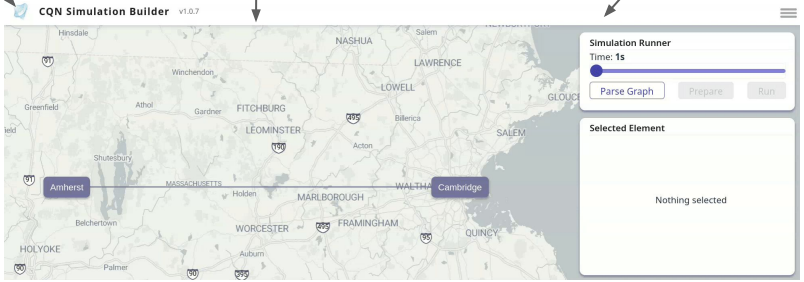




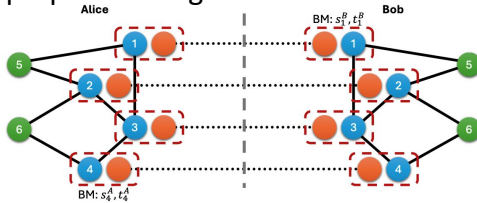
Dr. Stefan Krastanov, UMass Amherst

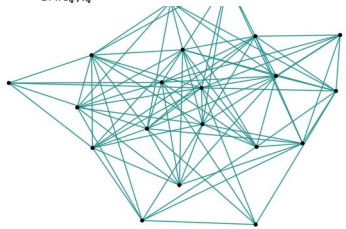
Hardware Co-designed Quantum Optimal Control with Digital Twin Model of Programmable PIC



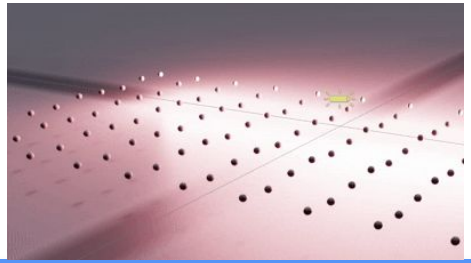


Measurement based entanglement distillation and resource state preparation algorithm



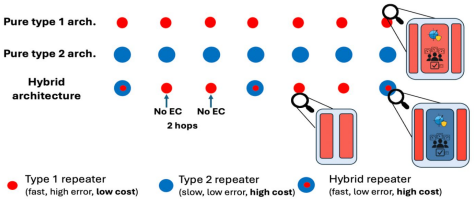


Physics informed digital twin with NVIDIA Omniverse & Zemax Ansys team



Hybrid quantum repeater architecture

Architectures combining Hybrid and Pure repeaters

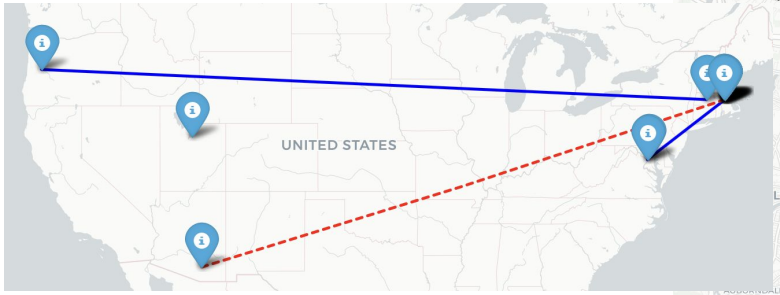


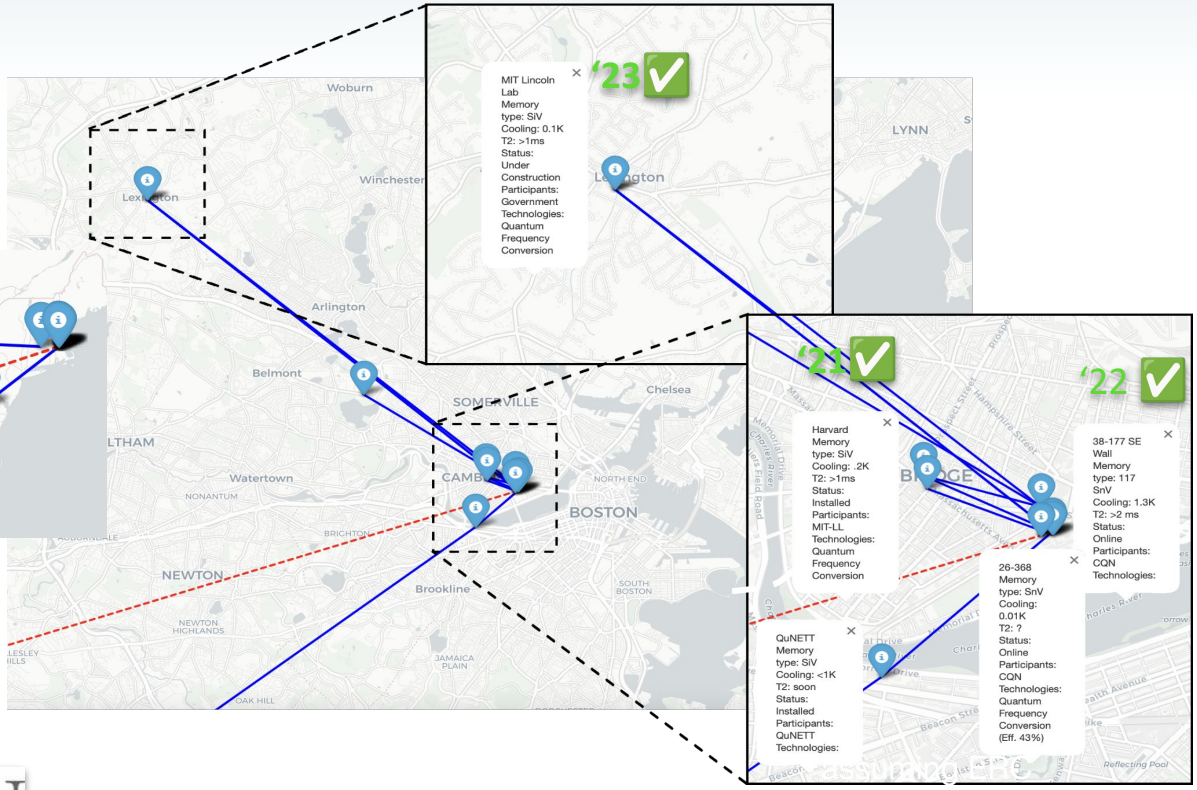
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CQN Boston Testbed

Information on network nodes, existing and planned edges:
`https://github.com/dirkenglund/quantum-network-code/tree/main`





- Existing Edge
- Planned Link
- Fiber Connection

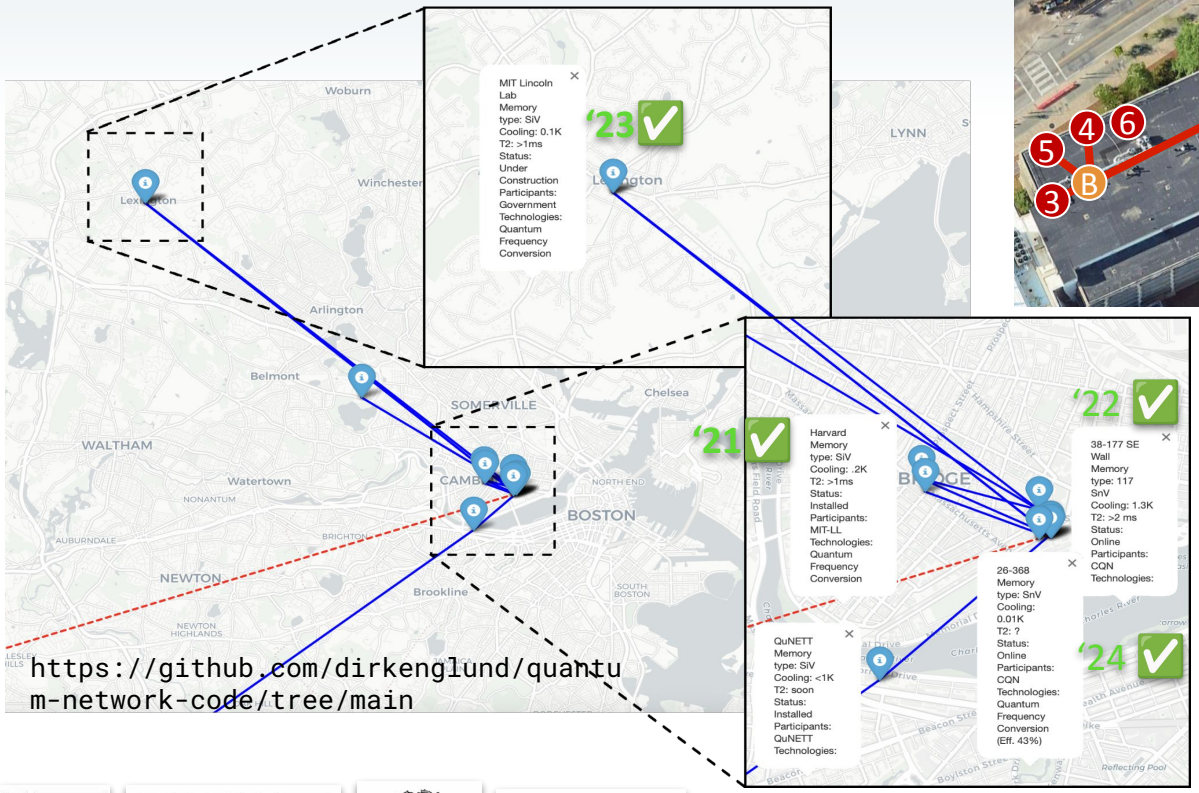
BBN TECHNOLOGIES

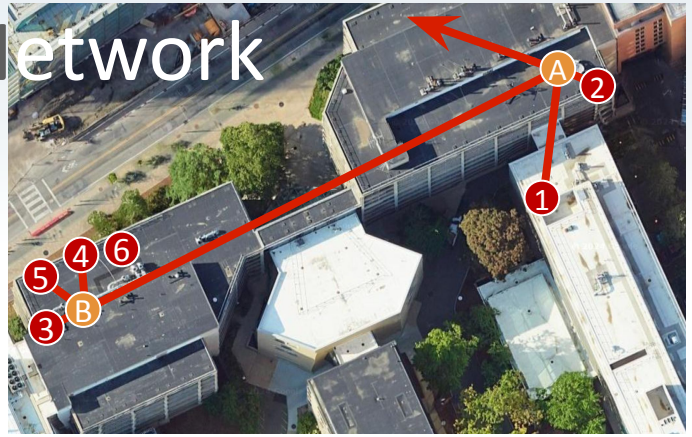
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MIT Local Network









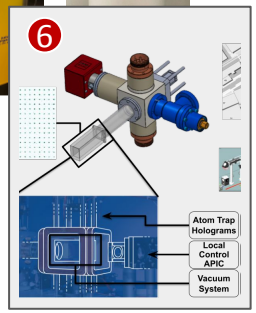










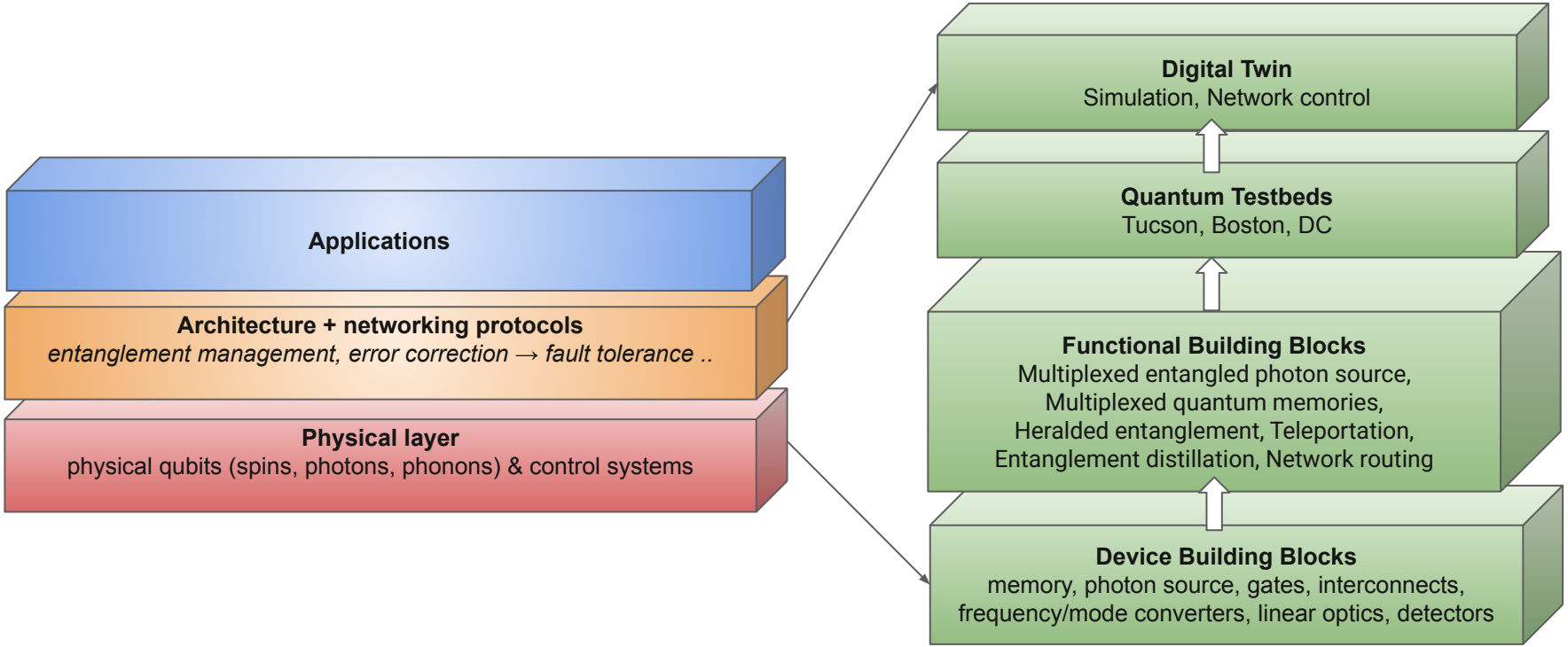


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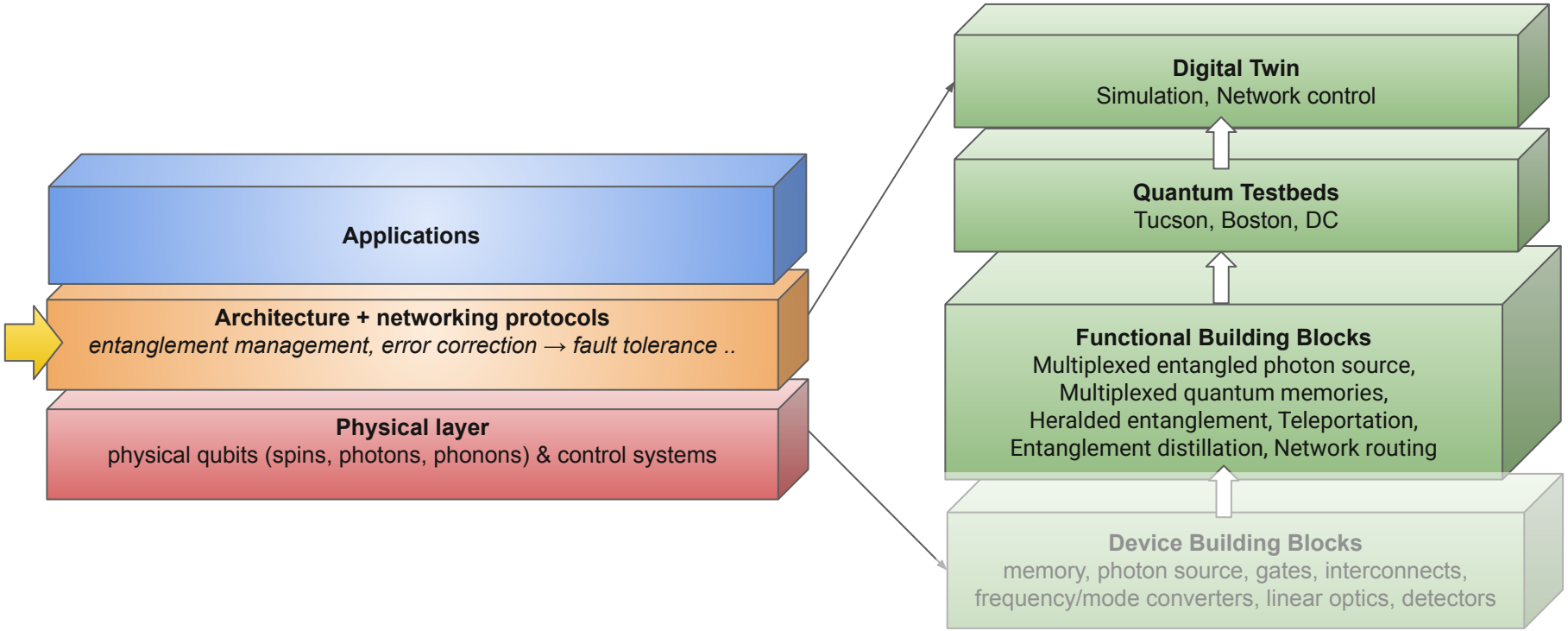
CQN Technical Stack



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CQN Technical Stack



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Major results from last 12 months

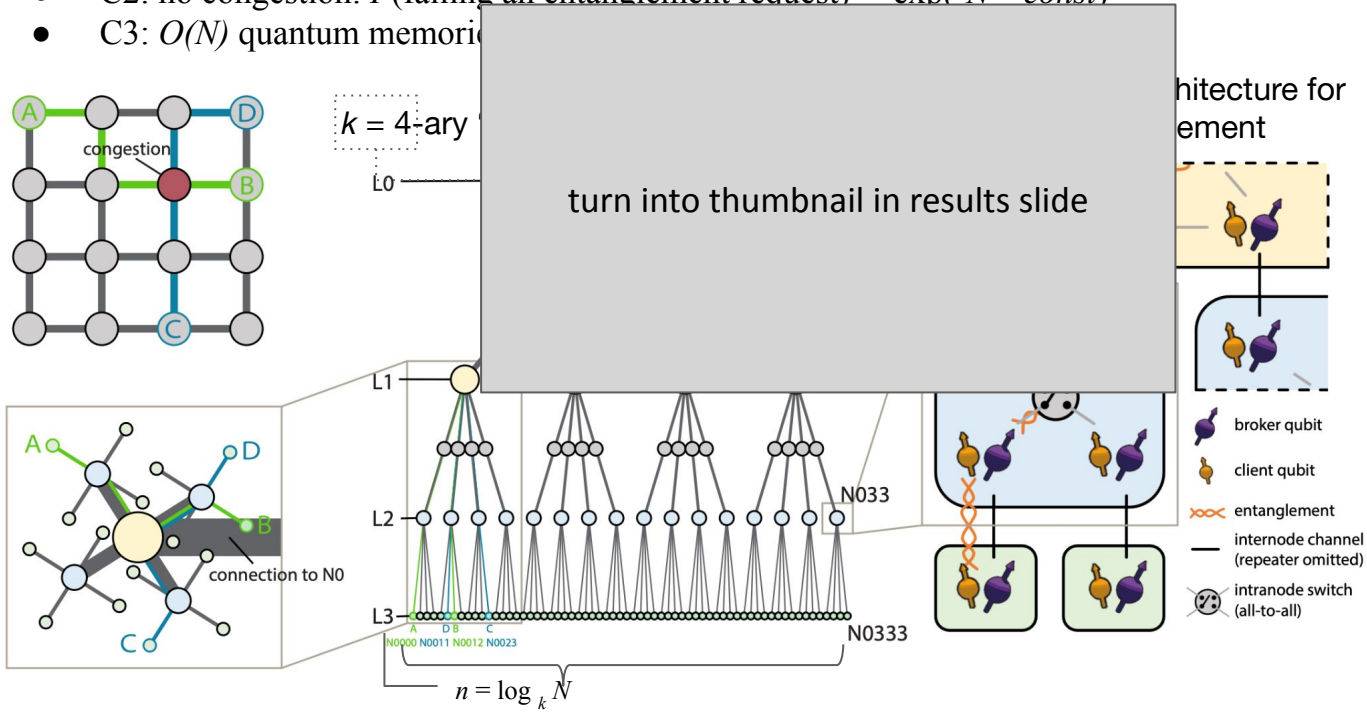
List papers and other results

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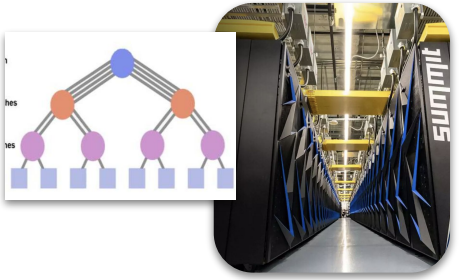
A Hierarchical Network Topology for *Scalable** Quantum Networks: Globe(?)-covering congestion-free entanglement routing with error correction

*Requirements: An N-user quantum network is "scalable" under uniform random under these Conditions:

- C1: supports *O(N)* error-corrected simultaneous entanglement flow across large distance (like global)
- C2: no congestion: *P*(failing an entanglement request) $\propto \exp(-N \cdot const)$
- C3: *O(N)* quantum memori



Similar to "Fat Tree" Topology:
C. E. Leiserson, IEEE Trans.Comp. 100 (1985)
M. Al-Fares et al, ACM SIGCOMM 38 (2008)



H Choi*, M G. Davis*, Álvaro G. Iñesta, Dirk R. Englund, ArXiv: 45092 (2023). *equal contributors

see also "Quantum Routing with Teleportation" arXiv:2204.04185 - Gershkov group

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Heterogeneous integration of spin–photon interfaces with a CMOS platform

Linsen Li ✉, Lorenzo De Santis, Isaac B. W. Harris, Kevin C. Chen, Yihuai Gao, Ian Christen, Hyeongrak Choi, Matthew Trusheim, Yixuan Song, Carlos Errando-Herranz, Jiahui Du, Yong Hu, Genevieve Clark, Mohamed I. Ibrahim, Gerald Gilbert, Ruonan Han & Dirk Englund ✉

Nature **630**, 70–



Linsen Li

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Architecture: Quantum System-on-Chip

SnVs on **microchiplets** (16-waveguide stru
integrated onto a cryogenic CMOS ASIC via
printing (lock and release).

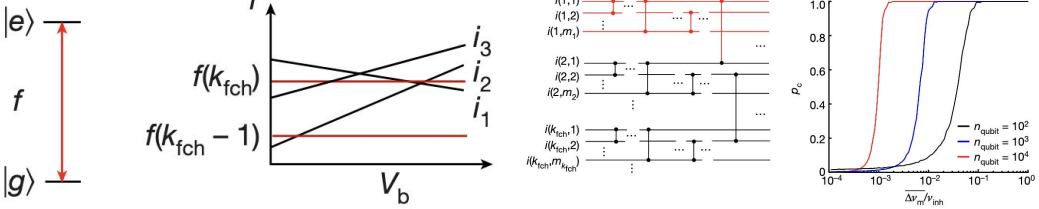
8x8 = **64** microchiplet sockets, i.e. **1024** add
waveguides (~2.3 emitters/waveguide).

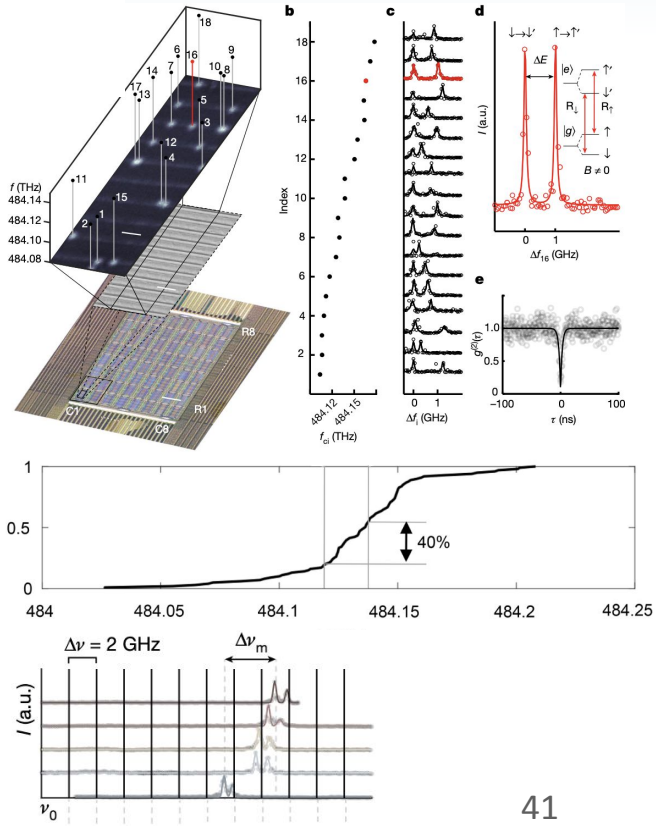
Results towards a spin-Photon Interface

• Frequency tuning via local voltage, leading
all-to-all connectivity if all emitters tune to at
channels.

• Enhanced photon collection (antennas) of 2.4×10^{-3}, verification of single-photon emission ($g^2(0) < 0.5$).

• Improved spin-state preparation (SPAM error ~3% with heralded initialization).

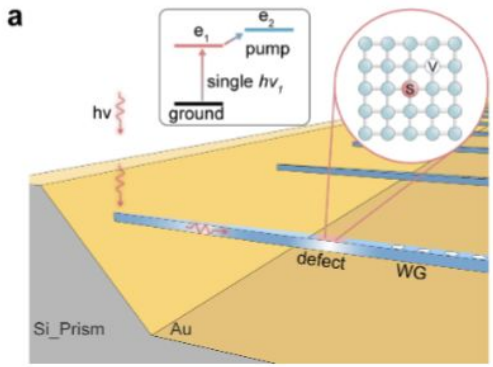




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Programmable Quantum Matter: Heralding Large Cluster States in Driven Inhomogeneous Spin Ensembles

Quantum Networks
NSF Engineering Research Center

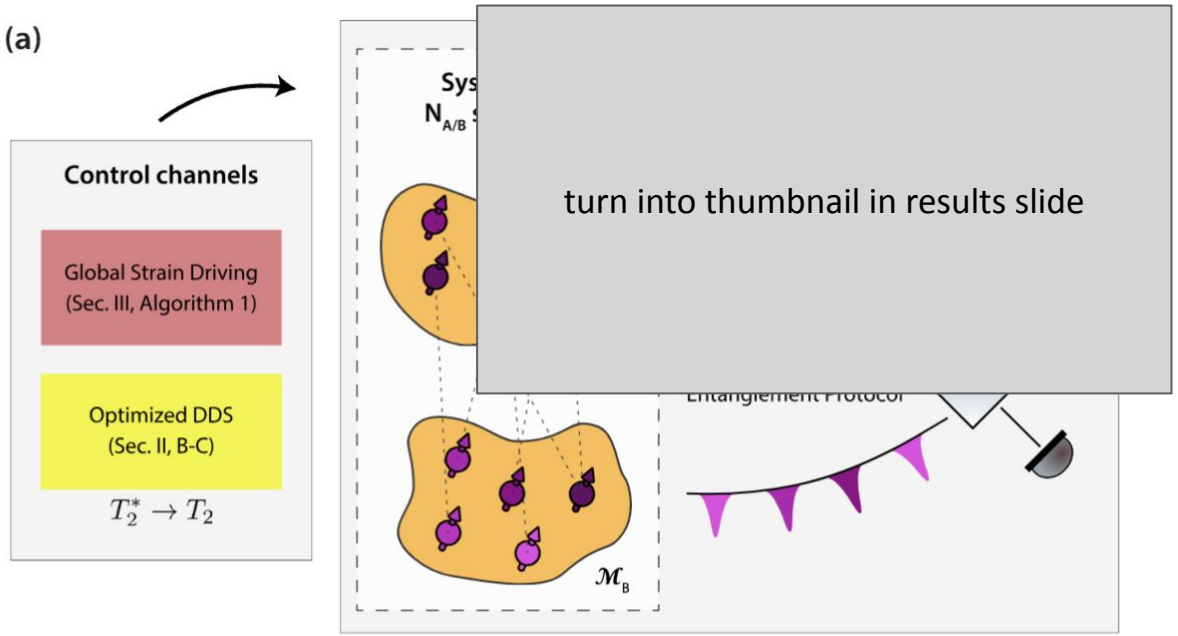


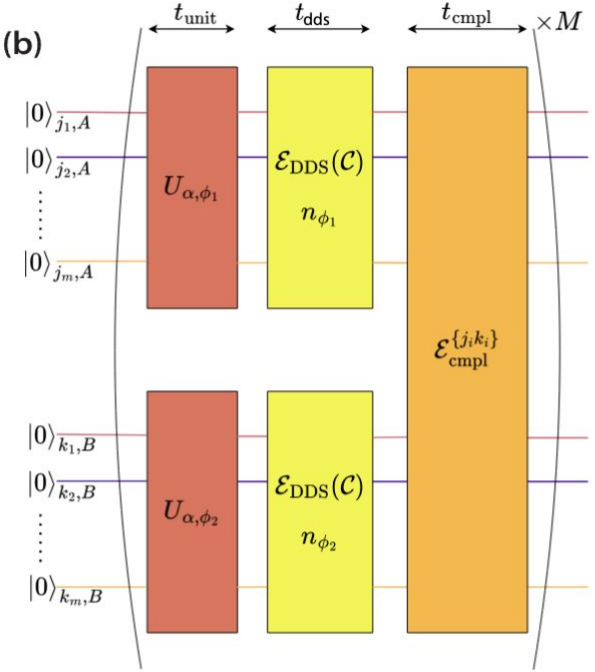
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Pratyush Anand, Louis Follet, Odiel Hooybergs, Dirk R. Englund ,

arXiv:2509.02992

Driven qubit ensemble





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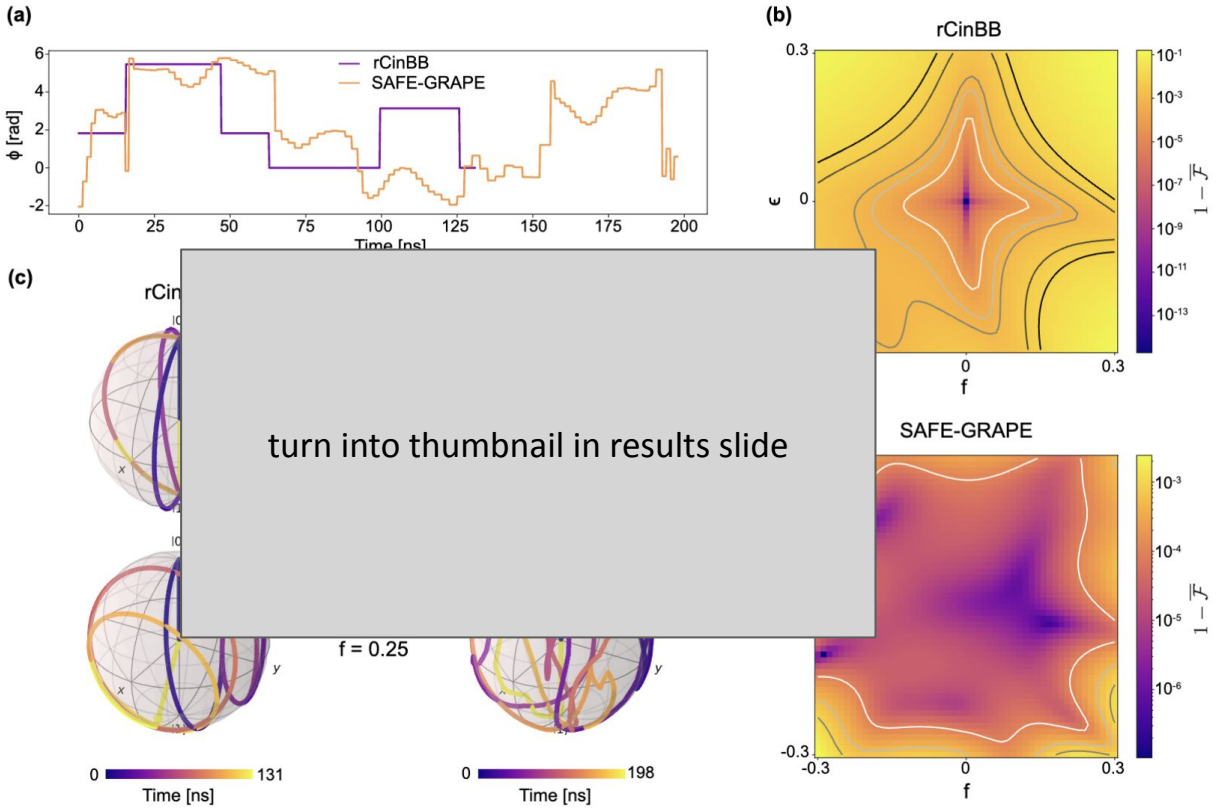


FIG. 2. **SAFE-GRAPE optimal control pulse sequence for implementing $\hat{\mathcal{U}}^{\text{ideal}}(\theta = \pi, \phi = 0)$.** **(a)** Control pulse sequence before (rCinBB) and after (SAFE-GRAPE) optimization for a Rabi drive strength $\Omega = 200$ Mrad/s. **(b)** Action of rCinBB (left) and SAFE-GRAPE (right) pulse sequence on the Bloch sphere for initial state $|0\rangle$ in case of $\epsilon = f = 0$ (top) and $\epsilon = f = 0.25$ (bottom). **(c)** Average gate infidelity heatmap for rCinBB (top) and SAFE-GRAPE (bottom) pulse sequence. Contours denote infidelities of $10^{-4}, 5 \times 10^{-4}, 10^{-3}, 5 \times 10^{-3}$ and 10^{-2}, increasing from white to black. Note that both plots have their own color bar.

Expected sample temperature

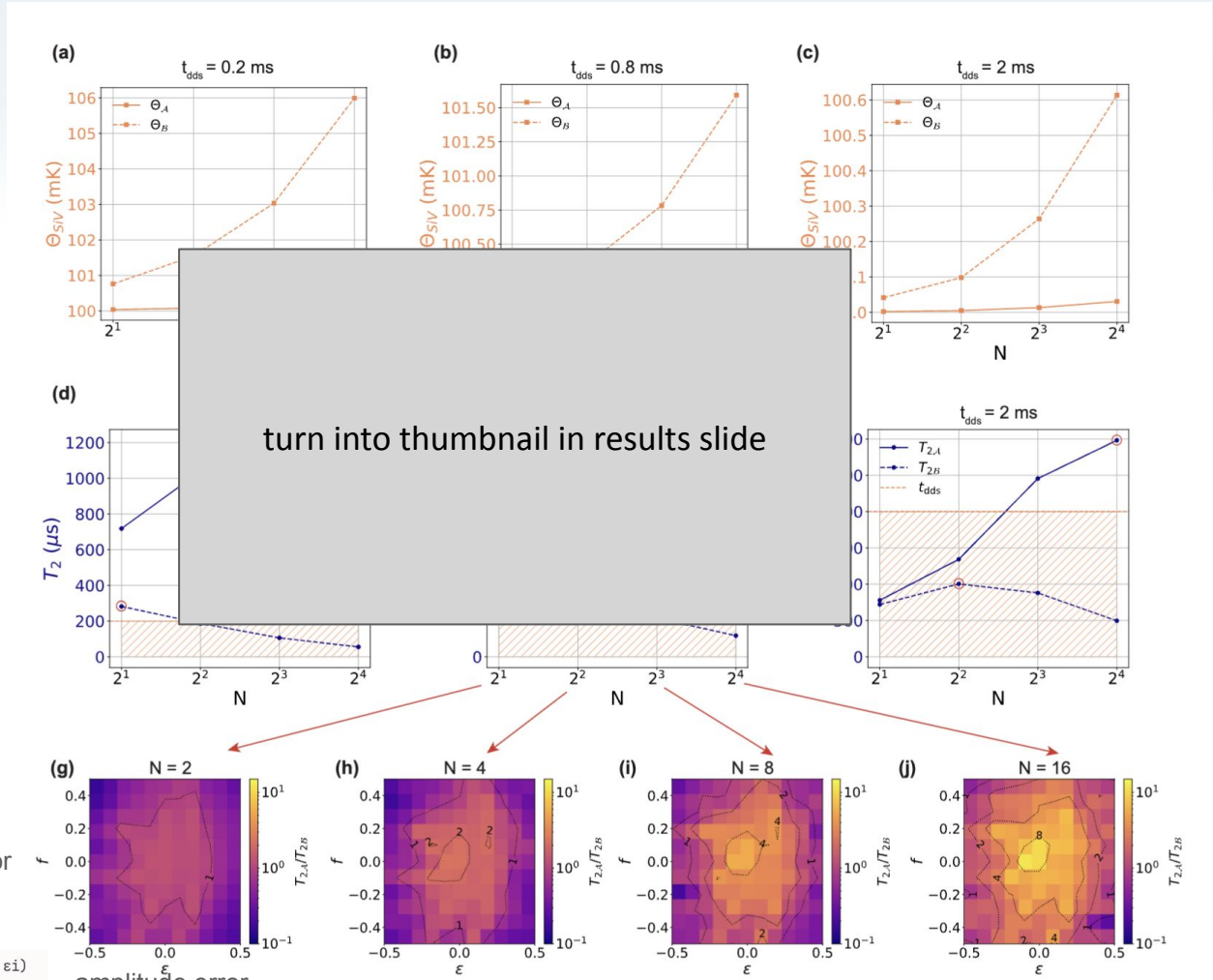
Expected T2

coherence ratio

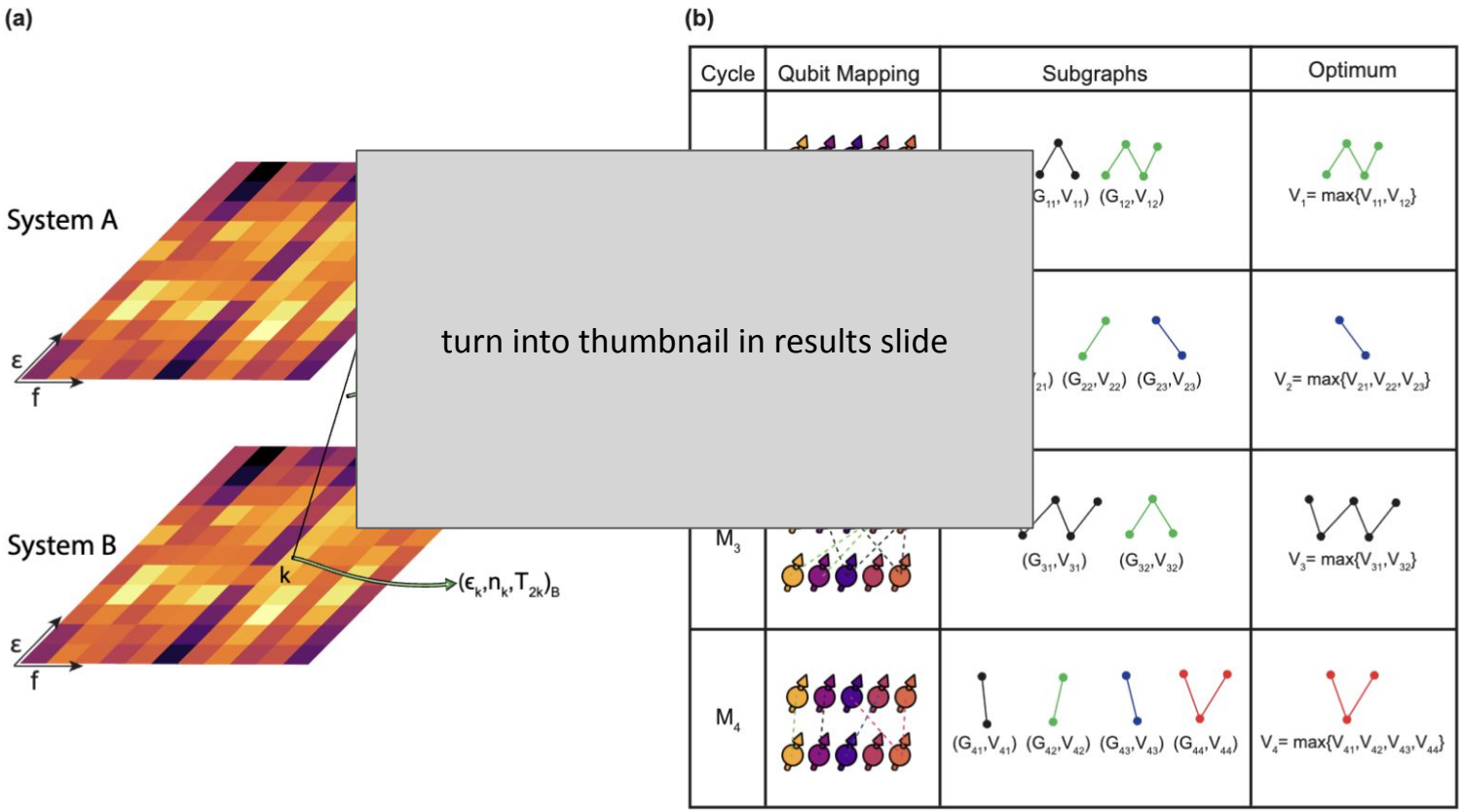
frequency error

$\Omega i = \Omega(1 + \varepsilon i)$

amplitude error



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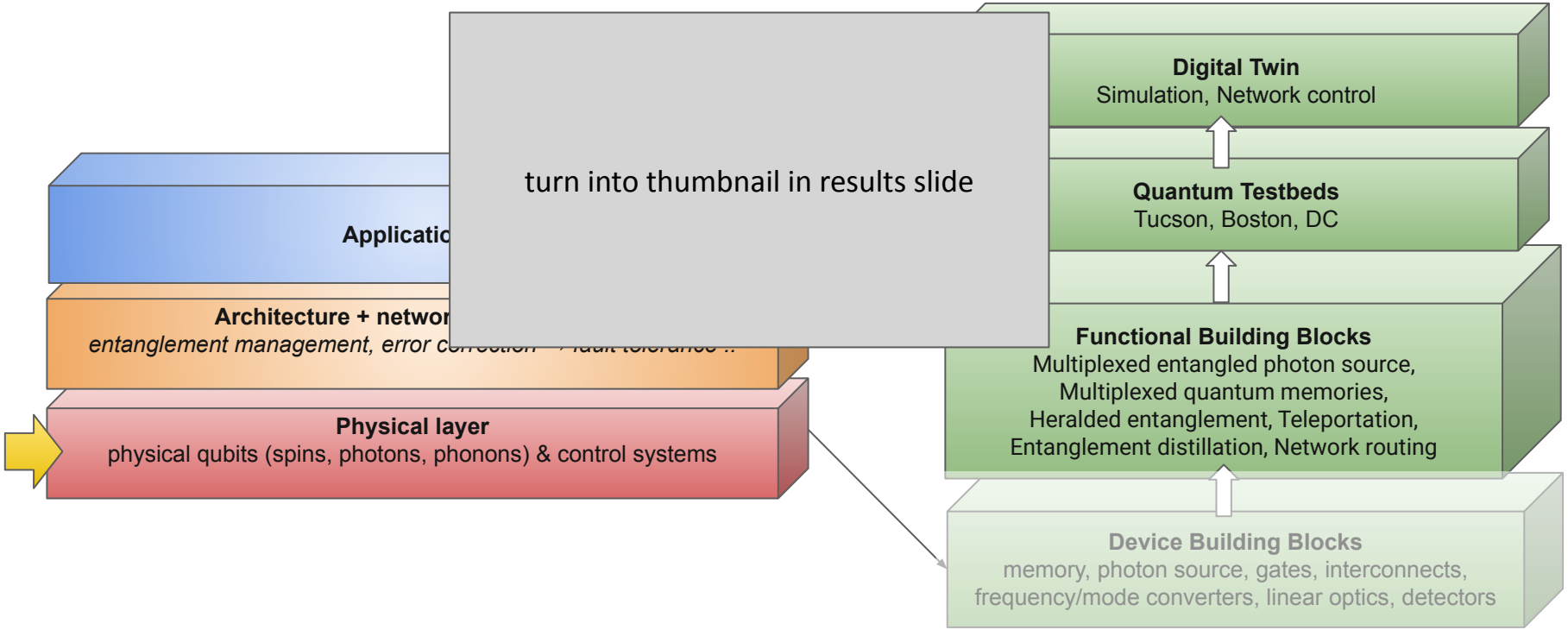


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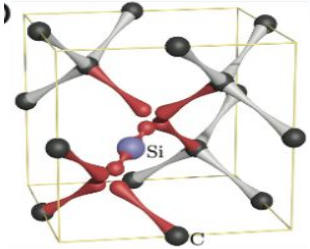
CQN Technical Stack



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Silicon Vacancy (SiV^-)

Frequency-stable artificial atoms in diamond



Group IV-vacancy centers don't have permanent electric dipole moment →
Stable, narrow zero phonon line (ZPL) with branching ratio~80%. Internal quantum ef

Lo , Becher (Saarbrücken)

SiV J. Cambridge (Atature), Harvard (Loncar, Lukin), MIT (DE), Stanford (Vu
.. a

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G ucture; Stable, narrow ZPL, DWF~0.8. IQE > 50%



GeV: Nonlinear optics : M. K. Bhaskar et al (Harvard), PRL 118 (2017)
SnV: T. Iwasaki et al, Phys. Rev. Lett. 119, 253601 (2017); see also Vuckovic group, Stanford
T_2 > 0.3 ms at "warm" temp of ~2 K (**R Debroux, PRX 11, 041041**), expect > 10 ms for T<1 K
Indistinguishable emission

PbV: M Trusheim et al, PRB 99 (2019); D Tchernij et al, ACS Photonics (2019)

Flerovium-289: τ ~ 1.9 seconds

Pioneering work: Wrachtrup, Jelezko, Lukin, Awschalom, ..

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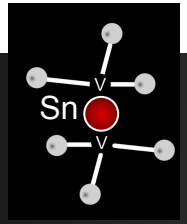
Applications
Architectures
Physical layer

Robotic quantum spectroscopy → big data → high-yield qubits

Large-scale optical characterization of solid-state quantum emitters

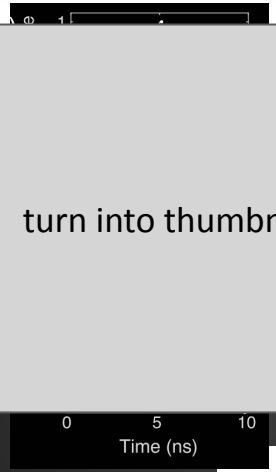
Madison Sutula[1],* Ian Christen[1], Eric Bersin[1,2], Michael P. Walsh[1], Kevin C. Chen[1], Justin Mallek[2], Alexander Melville[2], Michael Titze[3], Edward S. Bielejec[3], Scott Hamilton[2], Danielle Braje[2], P. Benjamin Dixon[2], and Dirk R. Englund[1]

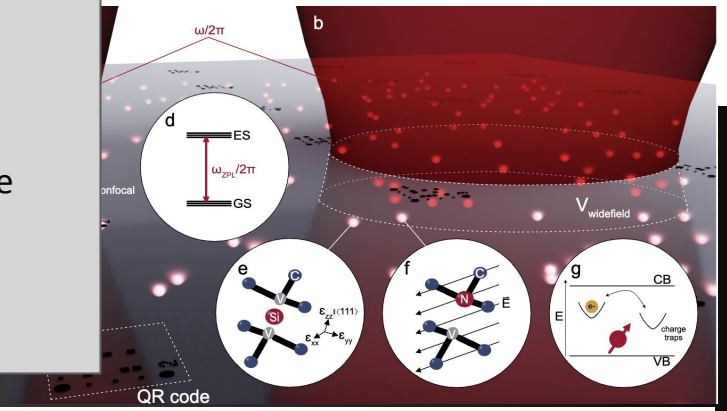
Diamond crystal "symmetry-protected" spin-photon interfaces: SiV, GeV, SnV, ..



Trusheim et al, PRL **124** (2020)

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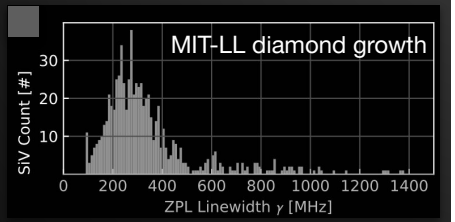


An integrated photonic engine for programmable atomic control

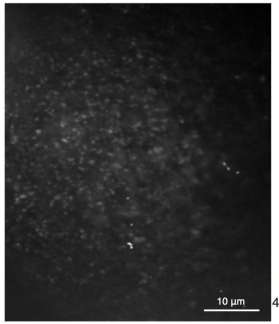
Ian Christen[1,*], Madison Sutula[1], Thomas Propson[1], Hamed Sattari[2], Gregory Choong[2], Christopher Panuski[1], Alexander Melville[3], Justin Mallek[3], Scott Hamilton[3], P. Ben Dixon[3], Adrian J. Menssen[1], Danielle Braje[3], Amir Ghadimi[2,*], and Dirk Englund[1,*]

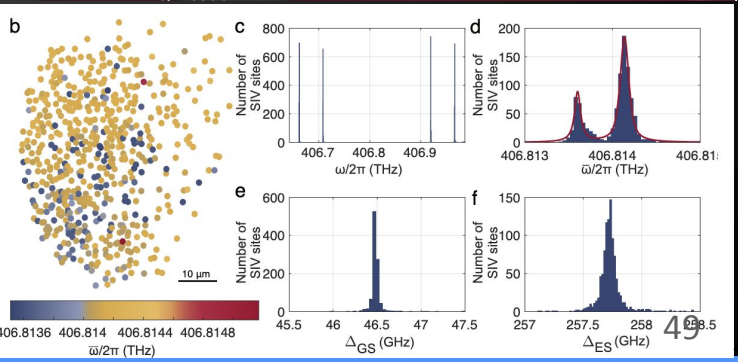
A statistical comparison of diamond tin-vacancy centers in diamond nanostructures by robotic spectroscopy on over 10,000 quantum emitters

Yihuai Gao[1,2,4], Linsen Li[2,4,*], Kevin Chen[2], Ian Christen[2], Matthew Trusheim[2], Prajit Dhara[3], and Dirk Englund[2,*]



Early work: Lukin, Park, Becher, Jeleczko, ..





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Atomic Localization Fluorescent Microscopy

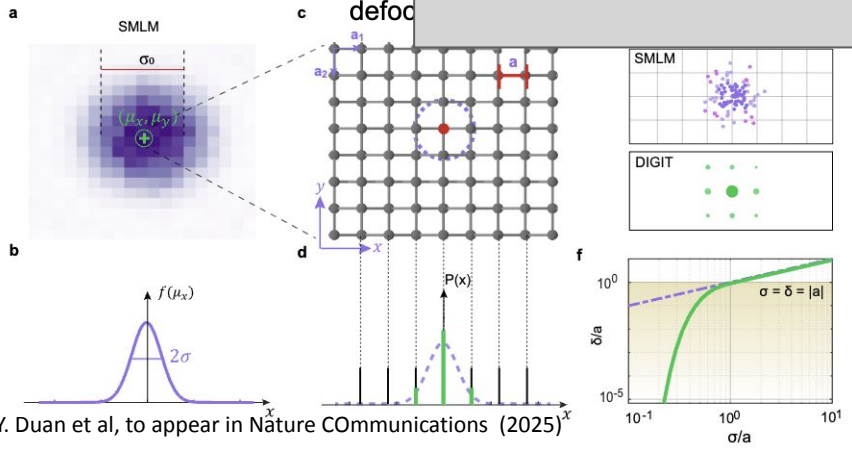
Yuqin Duan[1,2],* Qiushi Gu[1,2], Yong Hu[1,2], Kevin C. Chen[1,2], Matthew E. Trusheim[3], and Dirk R. Englund[1,2]†

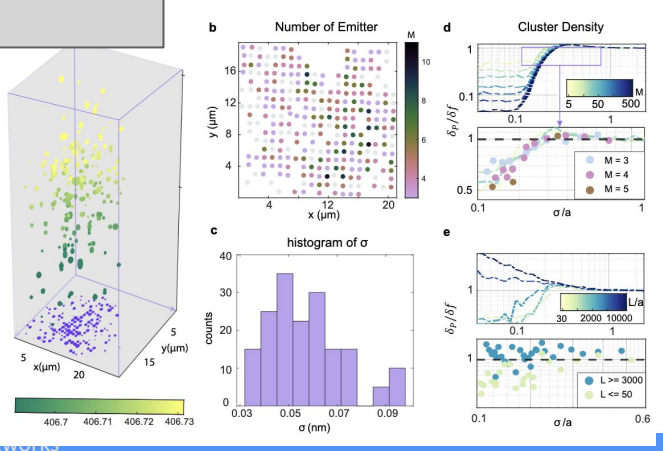


Yuqin Sophia Duan

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Motiv s for super-
resolu well-defined
locati
Chall emands a hundred-
fold ir
Appr ere the position of
each on of lattice vectors:
μ_i =
Resu $\mathbf{0.178 \pm 0.107}\boldsymbol{A}$
Digit se nonuniformity,
defoc





Y. Duan et al, to appear in Nature COmmunications (2025)

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High Fidelity Control of a Strongly Coupled Electro-Nuclear Spin-Photon Interface

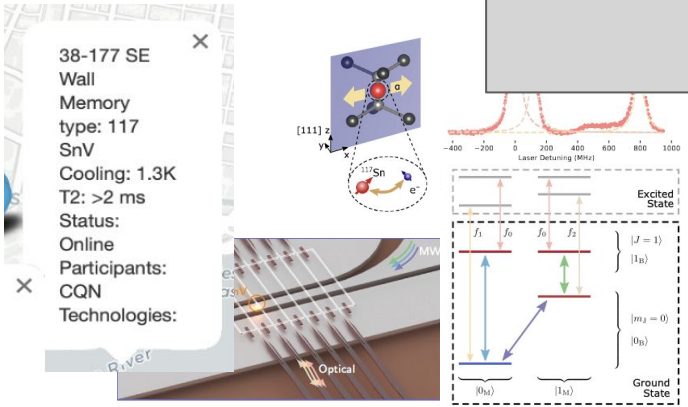


Isaac Harris

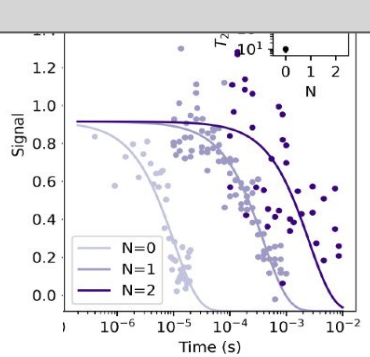
Isaac B. W. Harris*, Jan Christen*, Sofia M. Patomäki, Hamza Raniwala, Maxim Sirotin, Ke… …irk R. Englund

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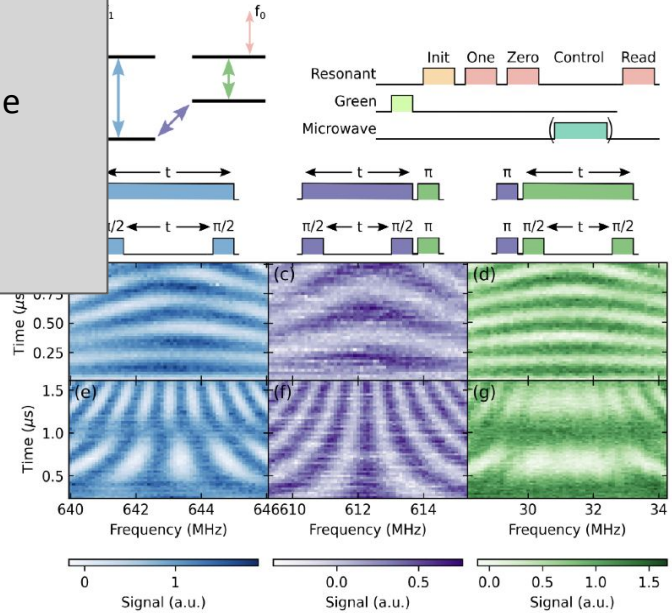
Motivation: Quantum networks need ar…
a long-lived nuclear spin (*"memory"*) for…
System: $^{117}SnV^-$ in diamond at zero ma…
linewidth, enabling independent electron…
Results: 98.4% optical ground-state po…
Memory qubit coherence up to 2.5 ms (…



Microchiplet-integrated SnV memory



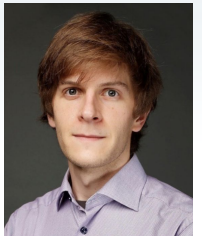
Coherence time results



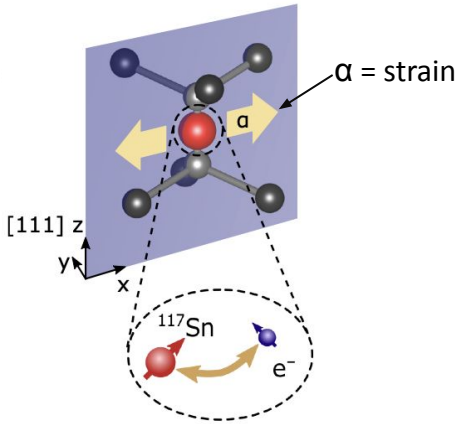
Coherent control results

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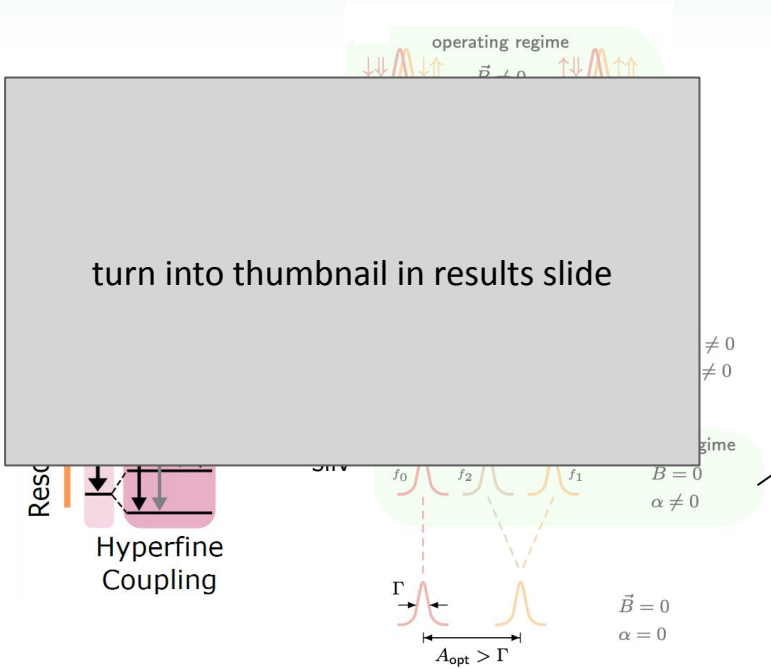
117 Tin vacancy (SnV) electro-nuclear spin system

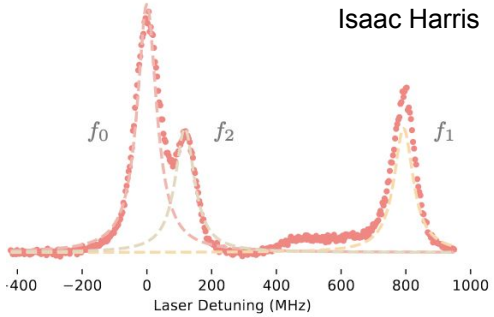


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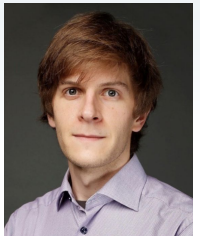
Resonant photoluminescence excitation data at zero magnetic field
(x-axis is offset by 484.375 THz)

- The tin vacancy (SnV) center is a group-IV color center (like SiV, GeV)
- Can be operated > 1 K
- The 117-isotope is a I=½, S=½ spin system

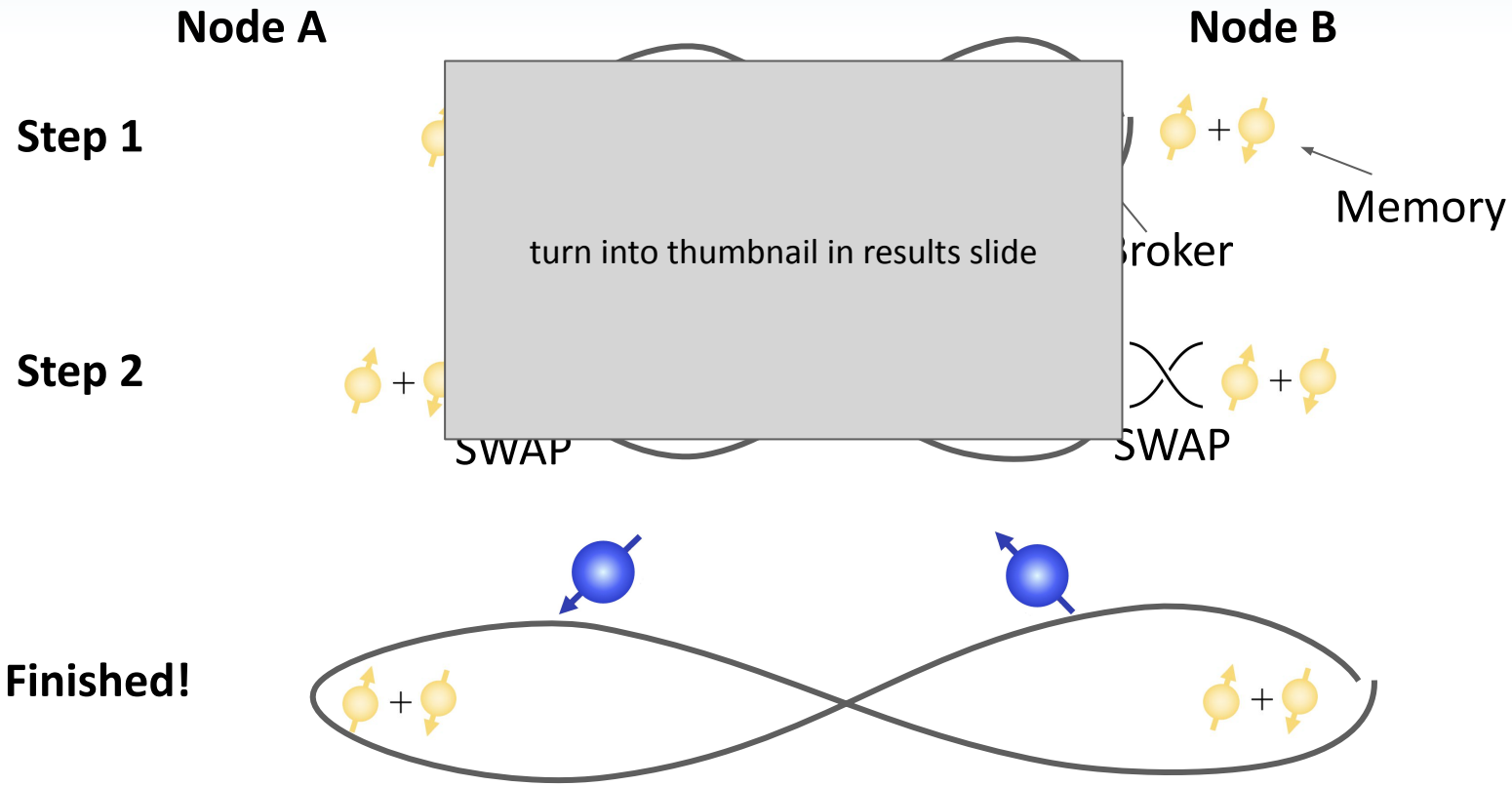
Unlike for SiVs (top), hyperfine interaction and strain splits the optical states in the absence of a magnetic field.

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Broker-memory qubits for heralded entanglement

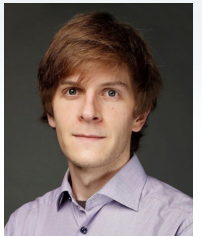


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Electro-nuclear spins as a broker-memory two-qubit system



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I=½, S=½ broker-memories dephase under hyperfine:

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

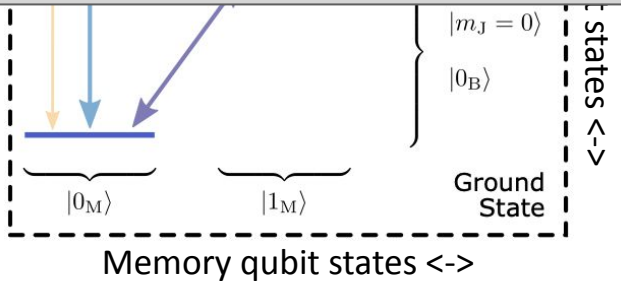
$$\rightarrow \alpha\,|0\rangle + e^{i(\omega_{\mathrm{M}}^{\mathrm{exc}} - \omega_{\mathrm{M}}^{\mathrm{gnd}})t_{\mathrm{exc}}}\beta\,|1\rangle$$

Example memory state

Fidelity after *n* attempts

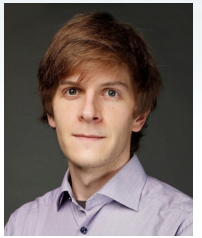
$$F = \frac{1}{2}\left(1 + (1 + \Delta\omega_{\mathrm{M}}^2\tau^2)^{-n/2}\right)$$

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Electro-nuclear spins as a broker-memory two-qubit system



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I=½, S=½ broker-memories dephase under hyperfine:

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

$$\rightarrow \alpha\,|0\rangle + e^{i(\omega_{\mathrm{M}}^{\mathrm{exc}} - \omega_{\mathrm{M}}^{\mathrm{gnd}})t_{\mathrm{exc}}}\beta\,|1\rangle$$

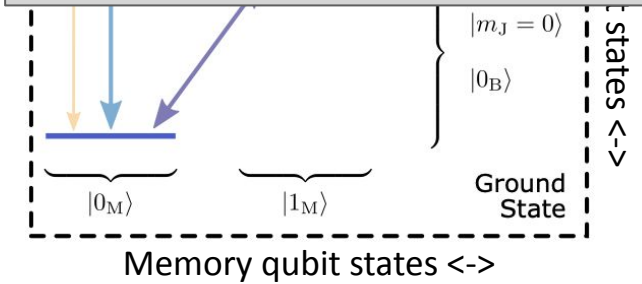
Example memory state

Fidelity after *n* attempts

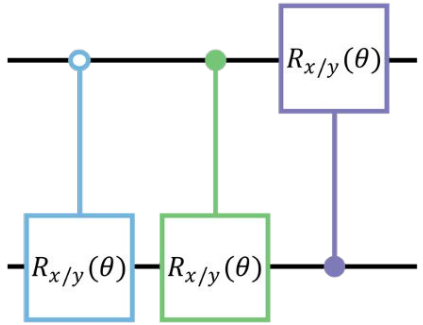
$$F = \frac{1}{2}\left(1 + (1 + \Delta\omega_{\mathrm{M}}^2\tau^2)^{-n/2}\right)$$

Optically excite f0 to avoid phase shift

turn into thumbnail in results slide

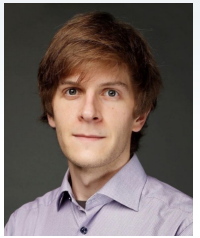


Driving microwave transitions corresponds to ROT gates:



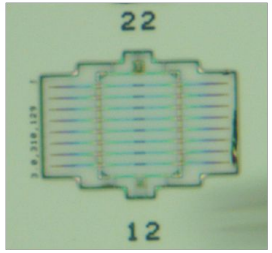
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Photonic-Integrated Circuit Integration



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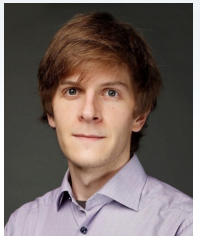
Microchiplet



turn into thumbnail in results slide

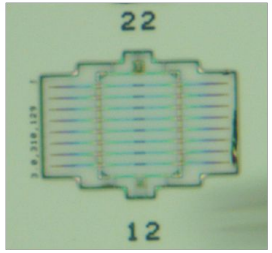
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Photonic-Integrated Circuit Integration



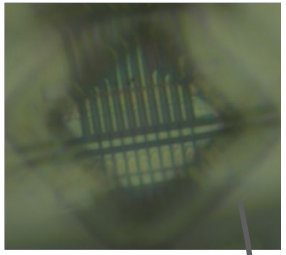
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is **transfer printed** onto a photonic-integrated circuit (PIC) "socket":

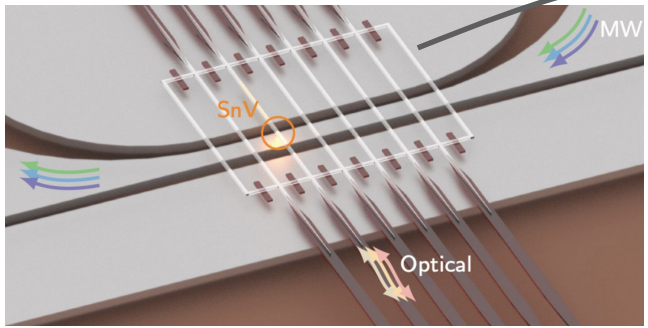


Diamond nanostructure

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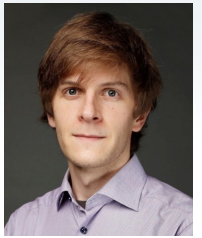


Stamp onto PIC socket



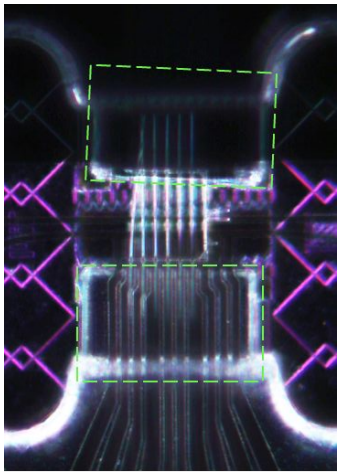
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Photonic-Integrated Circuit Integration



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Microchiplet is secured with printed polymer

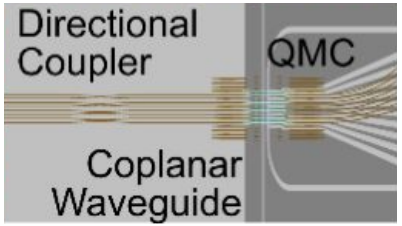


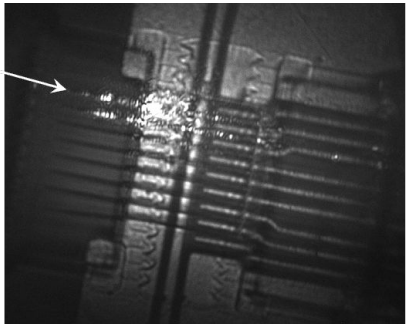
PIC is aligned to a fiber array (in this case, without epoxy)

turn into thumbnail in results slide



Emitter is excited via fiber, and light is collected in reflection.

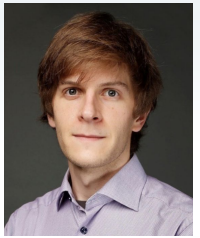




Collection efficiency in full experimental setup: 1.4×10^{-4}

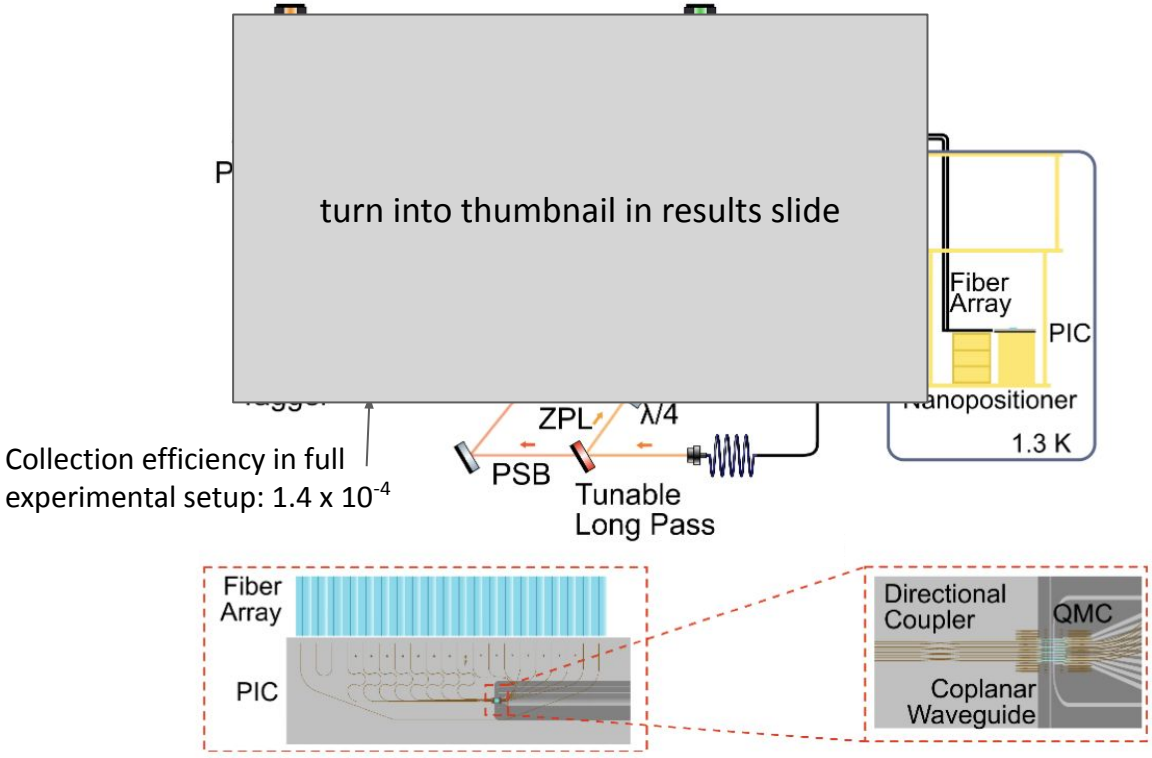
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Photonic-Integrated Circuit Integration



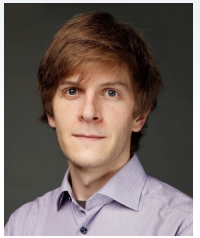
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Quantum memory demonstration



Isaac Harris

Summary of quantum memory parameters
(measured in this work)

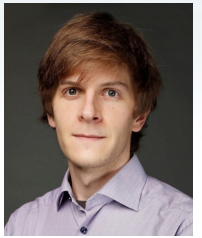
Parameter	Optical FWHM	Optic	y)	Spin coherence time (CPMG)
Value	f0: 79 MHz f1: 71 MHz f2: 89 MHz	6 ns (27 M		0.4 ms (N=1, memory, broker=0) **2.5 ms** (N=2, memory, broker=0)

@1.3 K

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Quantum memory demonstration

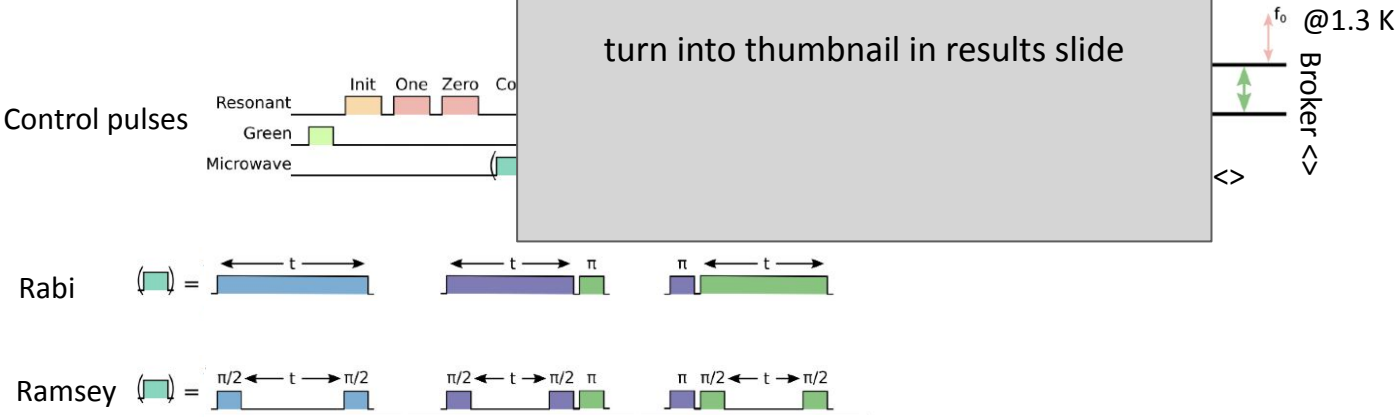


Isaac Harris

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turn into thumbnail in results slide



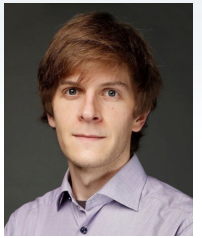
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Quantum memory demonstration

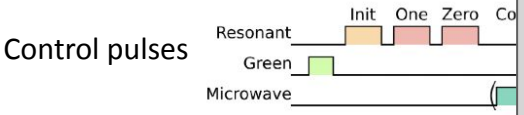
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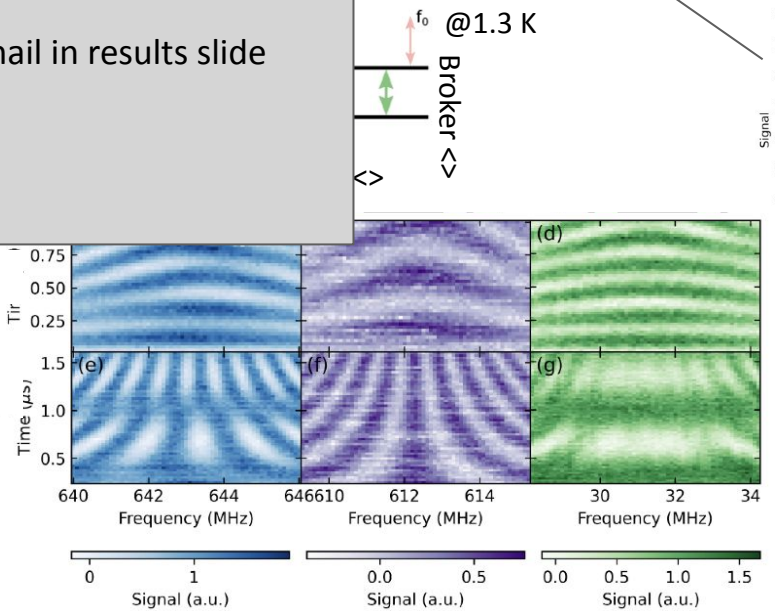
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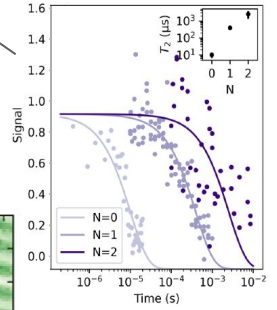
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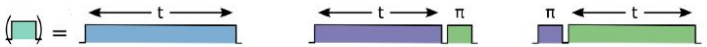




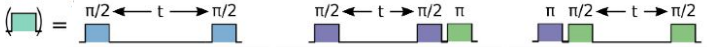


Data with XY decoupling pulse sequence

Rabi



Ramsey



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Digital twin of the 117 tin vacancy

Hamiltonian model

$$\hat{H} = \hat{H}_{\mathrm{SOC}} + \hat{H}_{\mathrm{Egx}} + \hat{H}_{\mathrm{Egy}} + \hat{H}_{\mathrm{HF}} + \hat{H}_{\mathrm{IOC}} + \hat{H}_{\mathrm{Z}} + \hat{H}_{\mathrm{I}} + \hat{H}_{\mathrm{L}}$$

$$\hat{H}_{\mathrm{SOC}} = \frac{1}{2}\lambda\,\hat{\sigma}_z^{\mathrm{L}}\hat{\sigma}_z^{\mathrm{S}}$$

$$\hat{H}_{\mathrm{IOC}} = \frac{1}{2}\upsilon\,\hat{\sigma}_z^{\mathrm{L}}\hat{\sigma}_z^{\mathrm{I}}$$

$$\hat{H}_{\mathrm{Egx/y}} = -\alpha_{\mathrm{Egx/y}}\hat{\sigma}_{x/y}^{\mathrm{L}}$$

$$\hat{H}_{\mathrm{HF}} = \frac{1}{4}A_{\perp}\left(\hat{\sigma}_x^{\mathrm{S}}\hat{\sigma}_x^{\mathrm{I}} + \hat{\sigma}_y^{\mathrm{S}}\hat{\sigma}_y^{\mathrm{I}}\right) + \frac{1}{4}A_{\parallel}\hat{\sigma}_z^{\mathrm{S}}\hat{\sigma}_z^{\mathrm{I}}$$

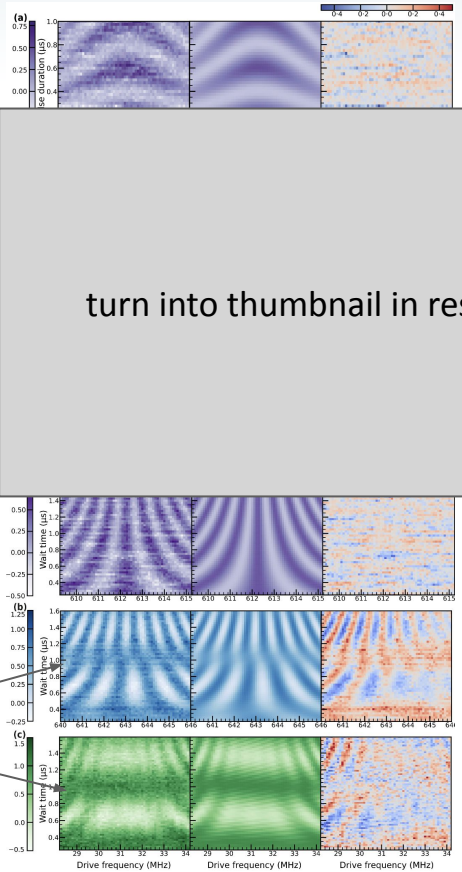
$$\hat{H}_{\mathrm{Z}} = g_{\mathrm{e}}\mu_{\mathrm{B}}\boldsymbol{B}\cdot\hat{\boldsymbol{S}} = \frac{1}{2}g_{\mathrm{e}}\mu_{\mathrm{B}}\left(B_x\sigma_x^{\mathrm{S}} + B_y\sigma_y^{\mathrm{S}} + B_z\sigma_z^{\mathrm{S}}\right)$$

$$\hat{H}_{\mathrm{I}} = g_{\mathrm{I}}\mu_{\mathrm{N}}\boldsymbol{B}\cdot\hat{\boldsymbol{I}} = \frac{1}{2}g_I\mu_N\left(B_x\sigma_x^{\mathrm{I}} + B_y\sigma_y^{\mathrm{I}} + B_z\sigma_z^{\mathrm{I}}\right)$$

$$\hat{H}_{\mathrm{L}} = \frac{1}{2}q g_{\mathrm{e}}\mu_{\mathrm{B}}B_z\sigma_z^{\mathrm{L}}$$

Explained by
- external dc magnetic field (O(200 uT))
- Jann-Teller distortion

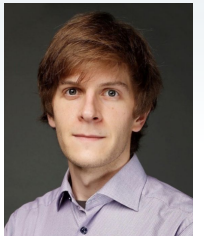
Rabi data Data fit Error



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Fitted parameters

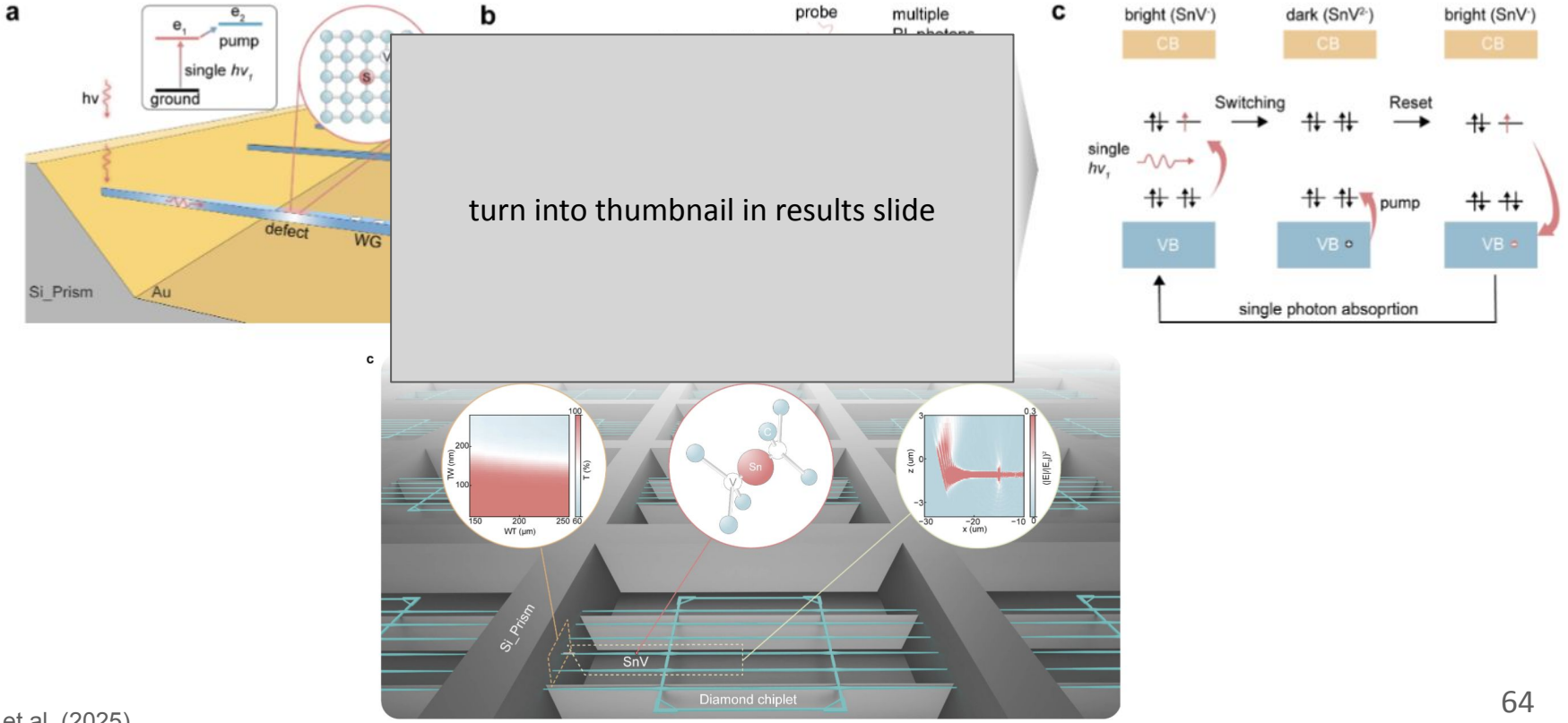
Parameter	Symbol	Fixed values (GHz)	Best fit values (GHz)
ic field	bx_dc, bz_dc		0.006030 0.001547
field	bx_ac, bz_ac		0.008912 0.004997
ity”	q	0.171	
strength	L	830	
, “parallel”	Apar		0.67389
Hyperfine coupling, “perpendicular”	Aperp		0.67095
Strain component	alpha		928.52
Strain component	beta	0	
Strain component	upsilon	0	



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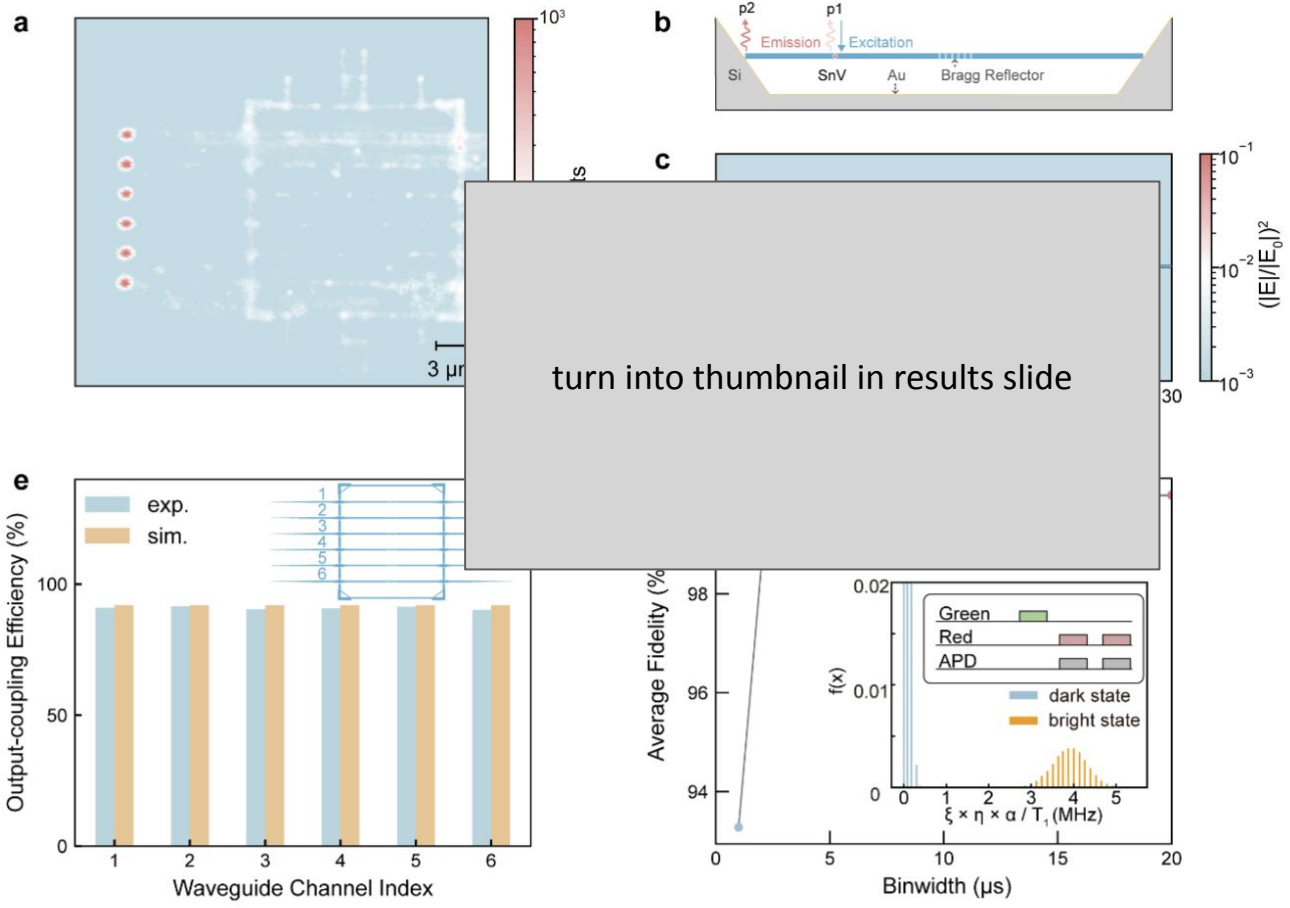
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Single photon sensitivity switching in artificial atoms



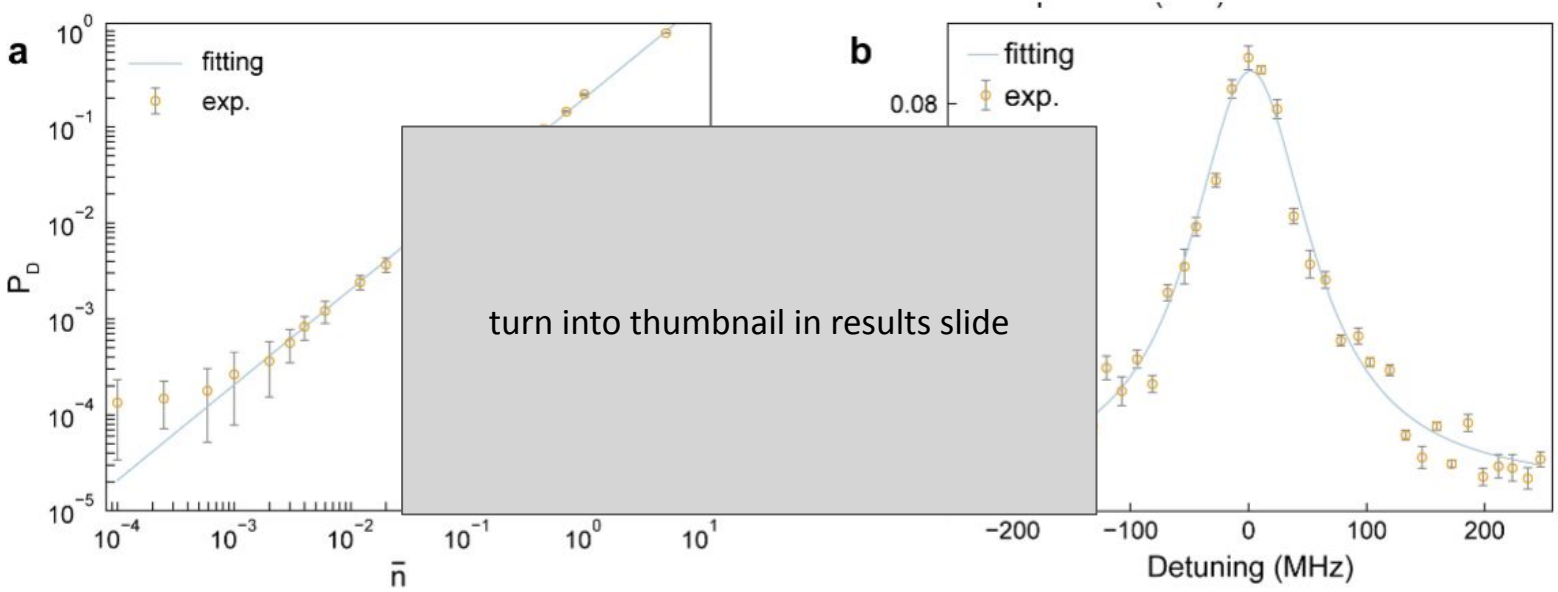
Y. Hu et al, (2025)

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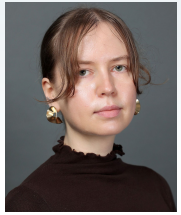
Y. Hu et al, to be submitted (2025)

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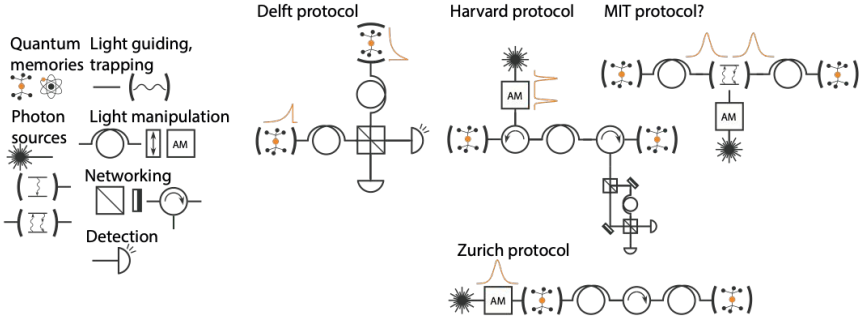
Quantum input-output description of entanglement generation protocols

S. Patomäki, K. Jacobs, D. Englund



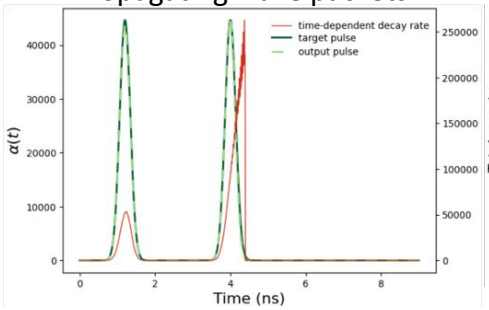
Sofia Patomäki

Motivation: Optimization of entanglement generation protocols given resources.
Challenge: Comparison of protocol tradeoffs is slow (and inaccurate) without a digital twin.
Approach: Quantum input-output theoretic "SLH" formalism: Open system description of interconnected nodes (localised systems).
Results: Python implementation time domain simulation inc. pulse shaping.
Outlook: optimization, automatic generation of experiment topologies.

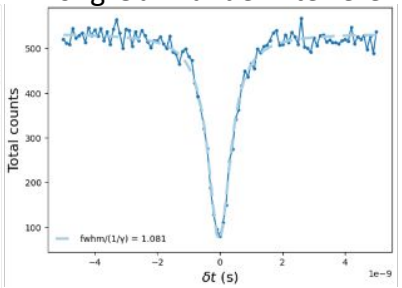


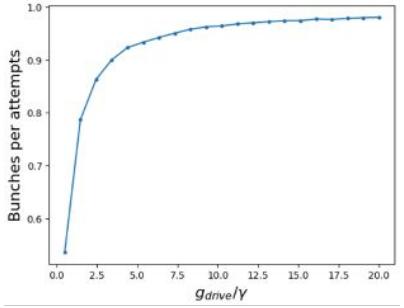
Concept: represent entanglement generation protocols as connected components described by (Scattering, Lindblad, Hamiltonian).

Propagating wave packets

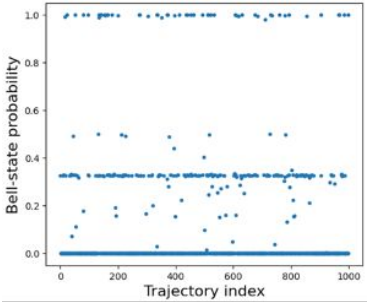


Hong-Ou-Mandel interference





HOM dependence on drive



Bell state prep. probability

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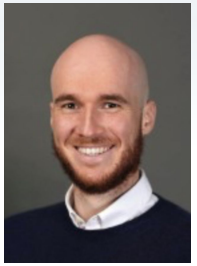
Spectral tuning and nanoscale localization of single color centers in silicon via controllable strain

Alessandro Buzzi, Camille Papon, Matteo Pirro, Odiel Hooybergs, Hamza Raniwala, Valeria Saggio, Carlos Errando-Herranz, Dirk Englund

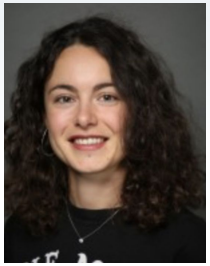
arXiv:2501.17290 [physics.optics]

Motivation: G-centers in silicon can serve as CMOS-compatible telecom quantum emitters.
Challenge: Control over each emitter's wavelength is crucial for generating indistinguishable photo
Appr nded silicon wave
Resu -phonon line.
Singl
Digit ement simulation of strain

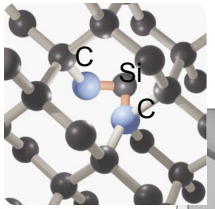
turn into thumbnail in results slide



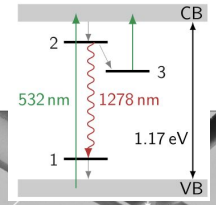
Alessandro Buzzi

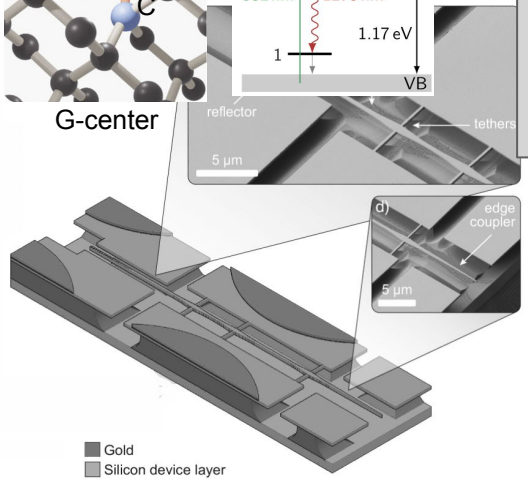


Camille Papon

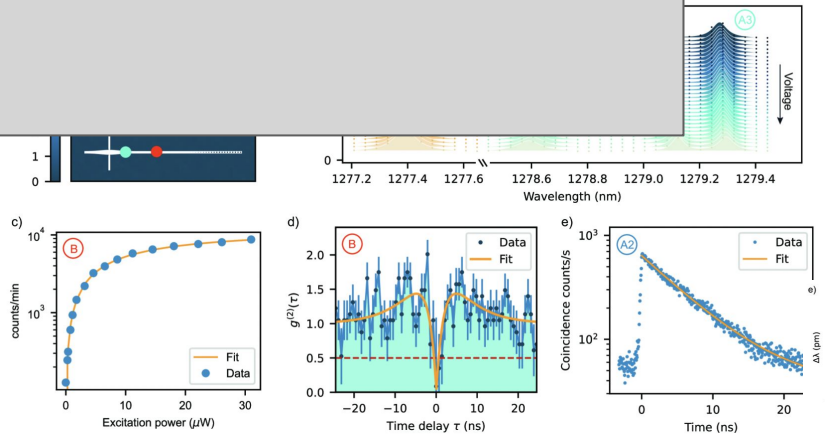


G-center

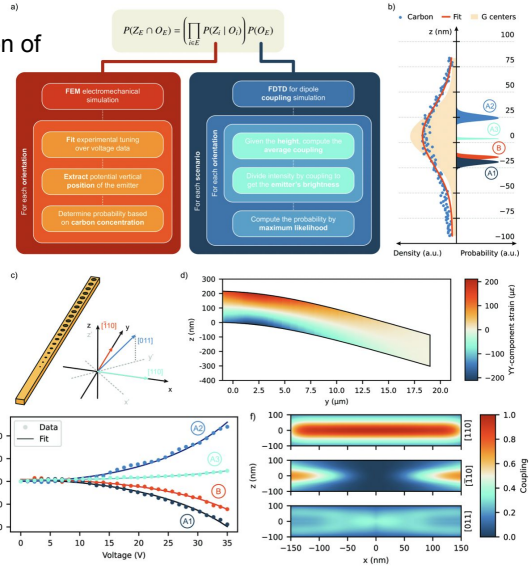




Device architecture



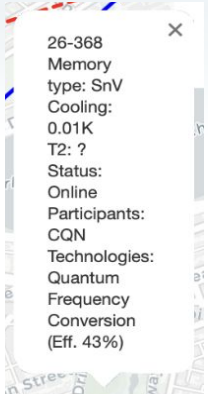
Experimental results



Digital twin

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Quantum frequency conversion @MIT



Experiment: sum-frequency generation at 737 nm (SiV λ)

Previous work :

1350 (net) + 1623 (pump) -> 737

- PRX Quantum **5,** 01
  - 12% external effic
- Nature **629,** 573 (20
  - 30% efficiency, 32

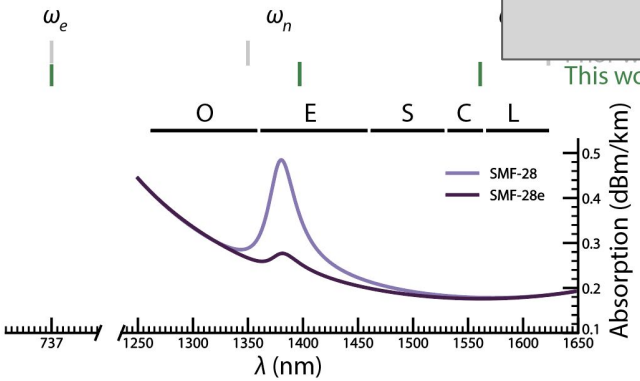
Current work (Universal Quantum Bus) :

1397 (net) + 1561 (pump) -> 737

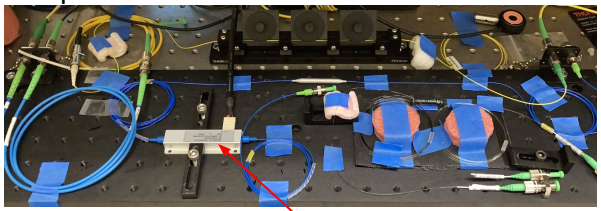
iciency, 1.5 W pump

5% ext. eff., 150 mW

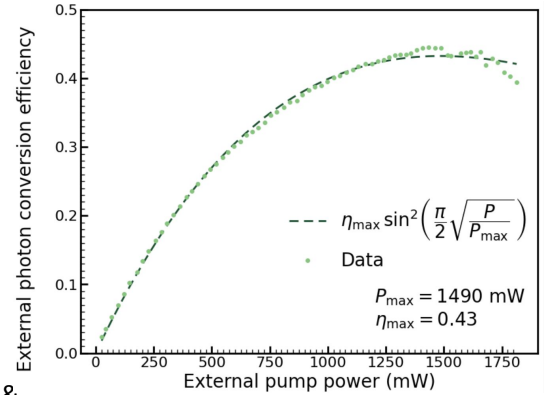
turn into thumbnail in results slide

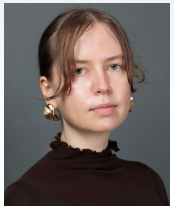


Setup



1.5-cm-long HC Photonics PPLN WG





Sofia Patomäki



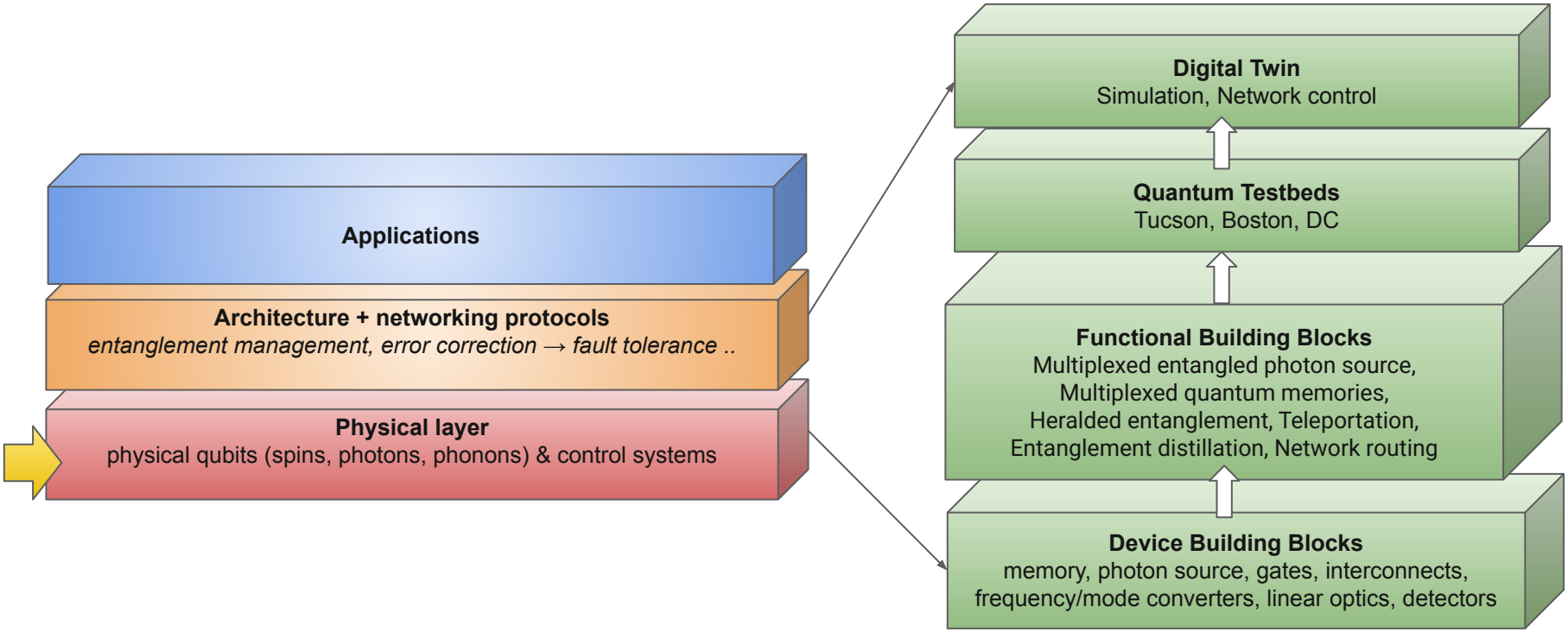
Franco Wong

Contributions from M. Sirotin, B. Dixon, D. Starling, E. Bersin

Close coupling with Mehmet [SC laser] & Matt [4wm] & Chaohan & Saikat of UA team, U-Oregon team

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Architecture + networking protocols



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let me focus on 1 major topic: digital twin modeling of physical layer [yong, marc d, ian berkman, qian ding, pratyush anand]

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Modeling of an FPGA-Controlled NV Color Center

Python Code

- Send a program to the T-Processor (DSL)
- Read FPGA RAM for output
- Process output (e.g. plotting)

FPGA

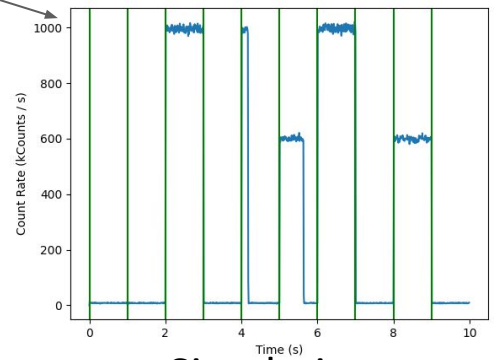
- Specialized CPU (“T-Processor”) controls other components
- 4 AWGs
- 2 Click Counters
- RAM can be read from Python

Color Center

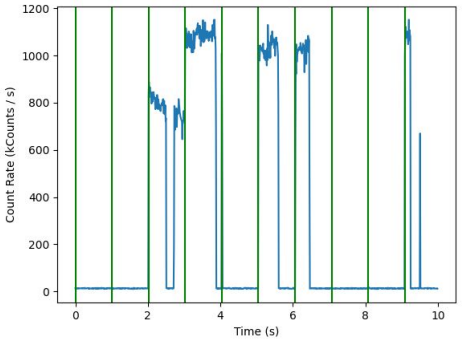
- Optics are connected to FPGA-controlled components
- Laser controlled by AWG
- Photon detector connected to click counter

Our digital twin of this system:

- Emulated versions of FPGA-implemented components
- Physics-based color center simulation
- Nanosecond-level detail
- Faster than real-time simulation
- Identical Python code works in both environments
- Next Steps: Reinforcement learning
  - Improve simulation with real data
  - Improve algorithm sent to the “T-Processor” by training in simulation



Simulation



Experiment



Marc Davis



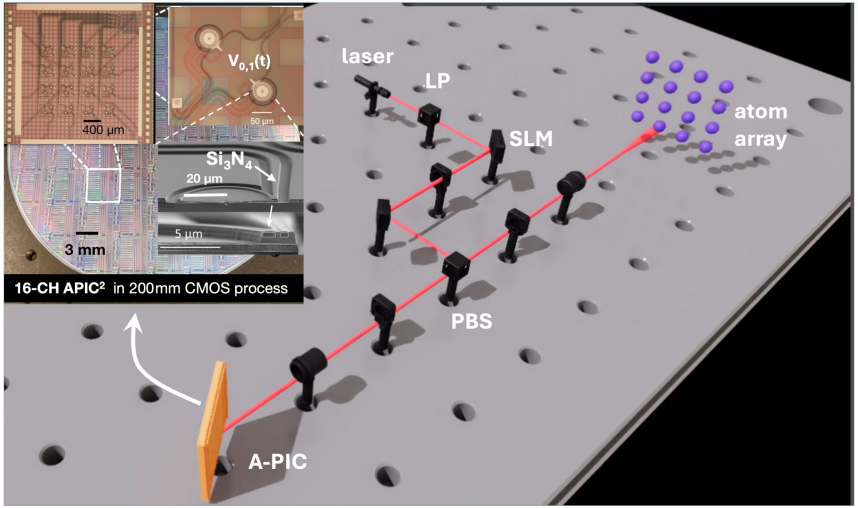
Yong Hu

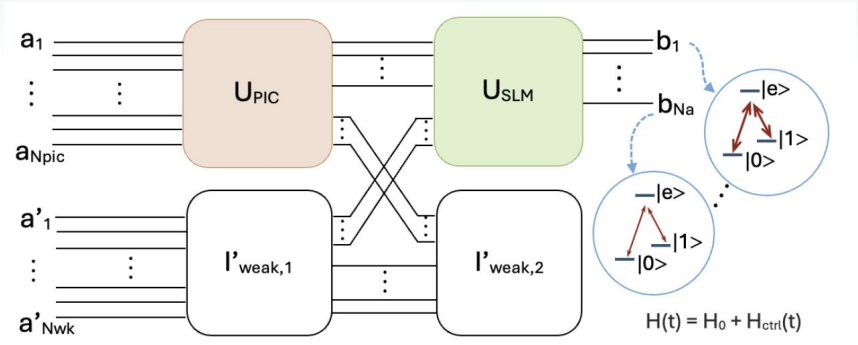


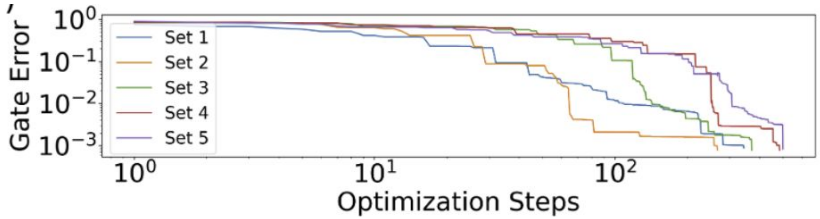
Ian Berkman

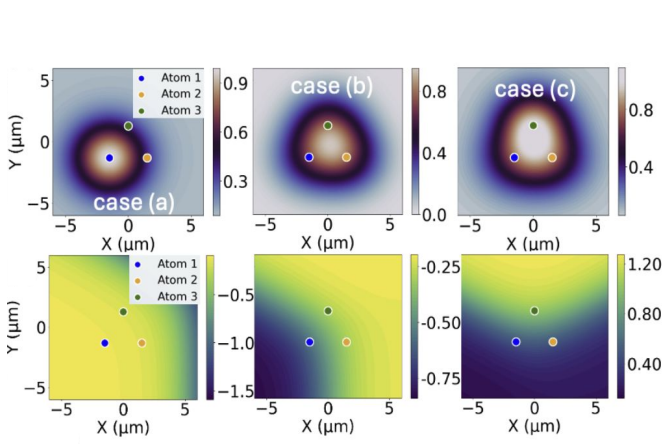
© 2024 Center for Quantum Networks

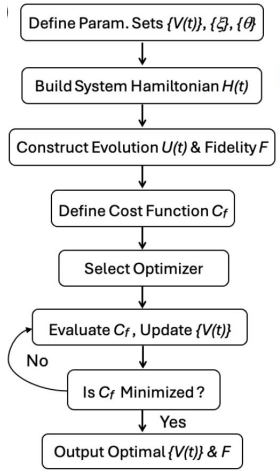
Hardware Co-designed Quantum Optimal Control with Digital Twin Model of Programmable PIC











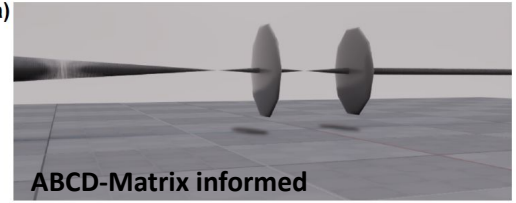
Q. Ding and D.E., arXiv:2504.11737v1

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Physics informed digital twin with NVIDIA Omniverse & Zemax Ansys team

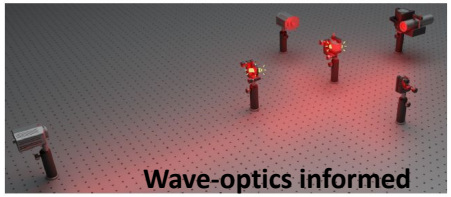
MIT: Pratyush Anand, Mahdi Mazaheri, Armando Martinez de la Villa, Adrian Menssen, Dirk R. Englund
NVIDIA: John Stone, Jeffrey Lancaster

(a)

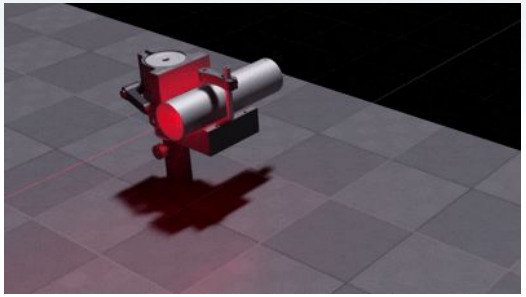


ABCD-Matrix informed

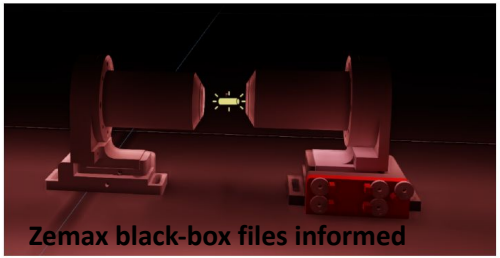
(b)



Wave-optics informed

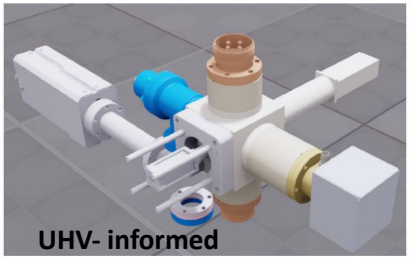


(c)

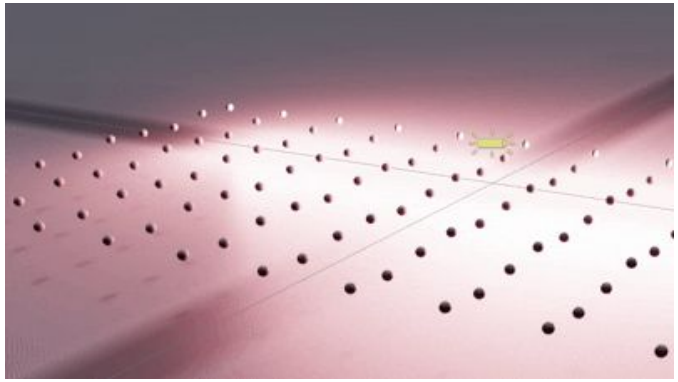


Zemax black-box files informed

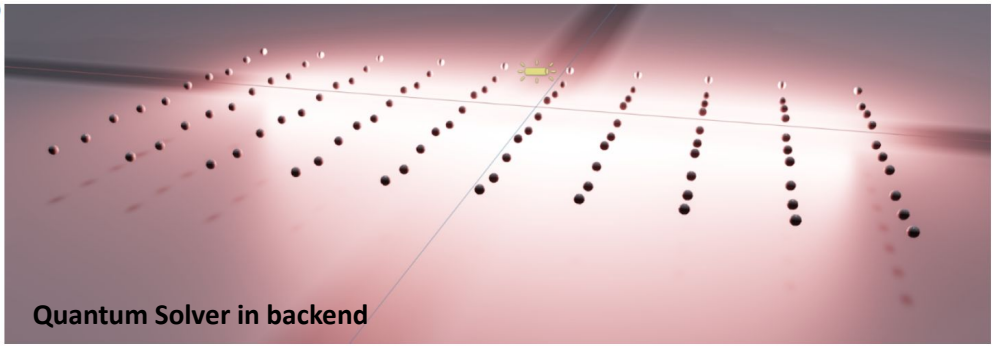
(d)



UHV- informed

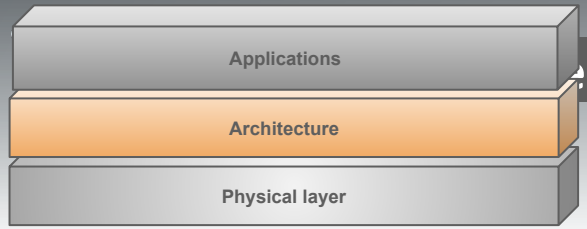


(e)



Quantum Solver in backend

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...d > 1k *logical* qubits/node for useful applications

Qu. factoring (Shor):
> 10^3 logical qubits
> 10^6 physical qubits

Article | Open Access | Published: 22 November 2019

Percolation-based architecture for cluster state creation using photon-mediated entanglement between atomic memories

Hyeongrak Choi, Mihir Pant, Saikat Guha & Dirk Englund

Quantum repeaters with 2-way communication: need > 1 M physical qubits for practical utility

ARTICLE OPEN

A quantum router architecture for high-fidelity entanglement flows in quantum networks

Yuan Lee, Eric Bersin, Axel Dahlberg, Stephanie Wehner and Dirk Englund

Zero-Added-Loss Entangled Photon Multiplexing for Ground- and Space-Based Quantum Networks arXiv:2206.03670v1

Kevin C. Chen, Prajit Dhara, Mikkel Heuck, Yuan Lee, Wenhan Dai, Saikat Guha, Dirk Englund

ARTICLE OPEN

A polarization encoded photon-to-spin interface

K. C. Chen, E. Bersin and D. Englund

qRAM: useful at ~> 10^9 logical qubits, > 10M physical qubits

PRX QUANTUM **2,** 030319 (2021)

Scalable and High-Fidelity Quantum Random Access Memory in Spin-Photon Networks

K. C. Chen, W. Dai, C. Errando-Herranz, S. Lloyd, and D. Englund

Efficient simulation of noisy quantum circuits applied to network-based quantum random access memory

L Bugalho, E Cruzeiro, W Dai, KC. Chen, DE, Y Omar, to appear (2022).
Upshot: matrix product states + NetSquid → more realistic simulations at > 1000 qubits & refined protocol using mixture of deterministic & heralded probabilistic entangling gates

→ The "Quantum Datacenter" , see Liu, Hann, Liang, arXiv:2207.14336v2 (2022)

PHYSICAL REVIEW LETTERS **123,** 070504 (2019)

Optical Interferometry with Quantum Networks

E. T. Khabiboulline, J. Borregaard, K. De Greve, and M. D. Lukin

N_q > 10M

One-way quantum comm: 100s of qubits every km or so: ~ M qubits at 1000 km

ARTICLE OPEN

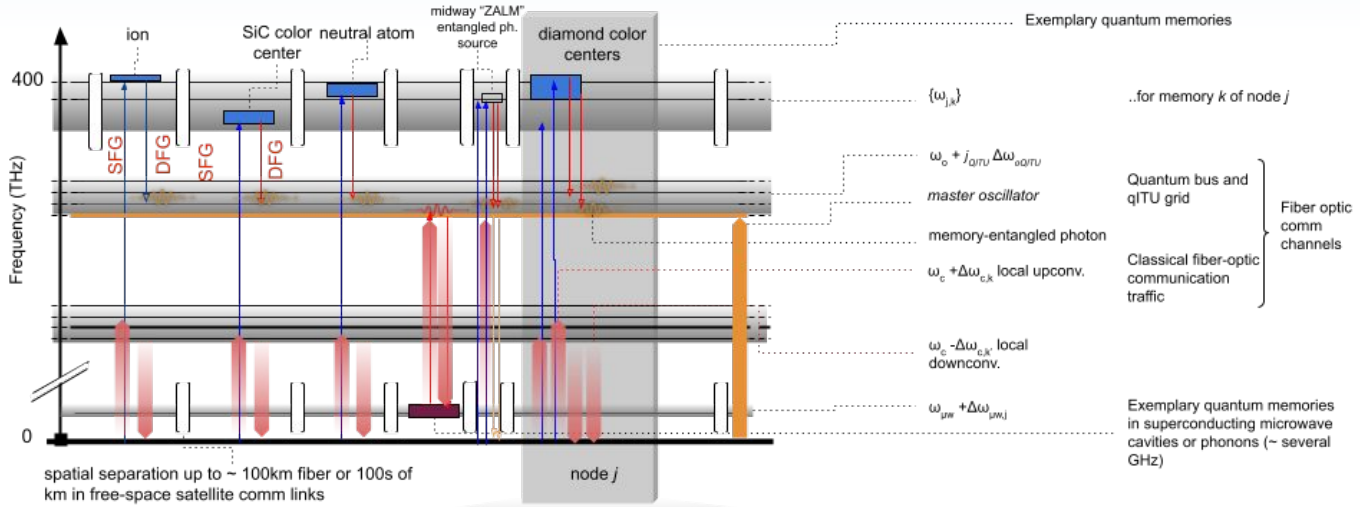
Quantum optical neural networks

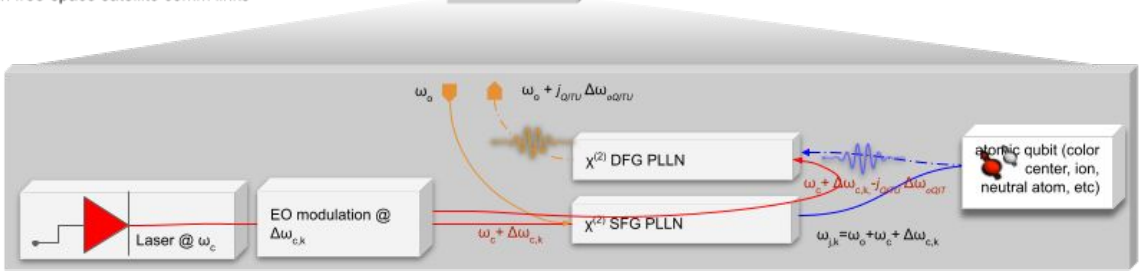
Gregory R. Steinbrecher, Jonathan P. Olson, Dirk Englund and Jacques Carolan

Chuck

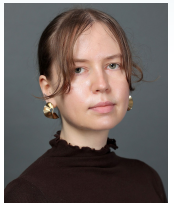
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Universal Quantum Bus





E. Bersin, B. Dixon, D.Englund, to be published; TLO filed (2023)


Sofia Patomäki


Franco Wong


Ben Dixon


Eric Bersin

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Year 5-10 Major Milestones (Boston Testbed)

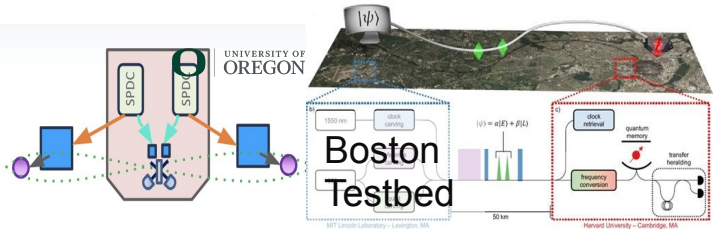
Both Testbeds

2025 — Bring number of quantum memory nodes: $N_{node} > 4$; demonstrate # qubits switched to telecom fiber $N_{mem} > 10^2$ with local entanglement demonstration; UQB demonstration

2026 — $N_{node}>6$, $N_{mem} > 10^3$ in at least one node; entanglement distribution across all nodes across metro network; ZALM and UQB demos. (Funded externally:) entanglement to Rb cold atom qu. computer

2027 — **High-brightness ZALM** source operating at star-hub $N_{node}>9$ between Boston and U.A. Online access and in-person access programs. At least $N_{ext}=10$ external R&D programs supported. Qubit logic for net-useful EC.

2028 — $N_{node}>10$. Upgrade to $N_{mem} > 10^5$ QBs with full connectivity. $N_{ext}> 20$.



2029 — Full connectivity across all nodes within regional networks. $N_{ext} > 50$. Distributed quantum computing demonstrations.

2030 — Full Integration in both testbeds and test/verification
Gradually grant access to IAB members and community partners

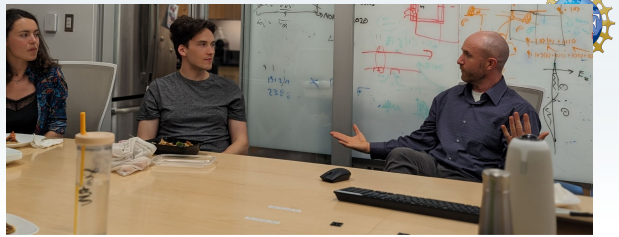
77
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Cross-netWork

Camille Papon: Si (--> Microsoft Quantum)

Thomas Propson (Rb arrays)

Prof Matt E.





Helaman Flores

Research Assistant

Alumni



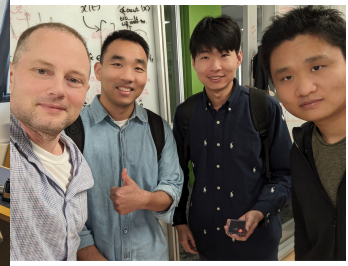
MIT Department: Electrical Engineering & C
Faculty Mentor: Prof. Dirkk Englund
Research Supervisor: Charles Hsu
Undergraduate Institution: North Carolina Central University
Hometown: Barisal, Bangladesh
Website: LinkedIn

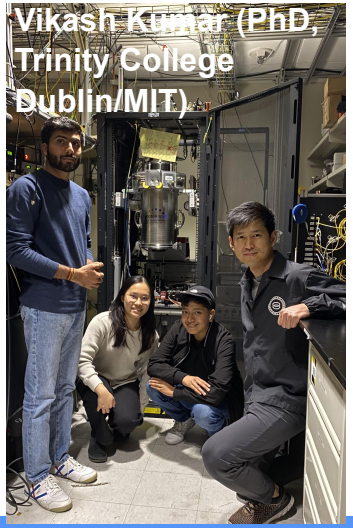
- **Prajit Dhara (PhD, MIT): U.A. → MIT in 2022, 2023**
- **Helaman Flores (PhD, MIT)**: Former BYU undergrad with Ryan Camacho, now at MIT with Dirk Englund, focused on quantum networking and photonic switches.

Vikash Kumar: Formerly with Dan Kilper, now working on Tucson testbed quantum memory and network protocols with Dirk Englund.

Arizona Team (Chaohan Cui): Leads Tucson testbed efforts on SiV quantum memory and entanglement technologies.

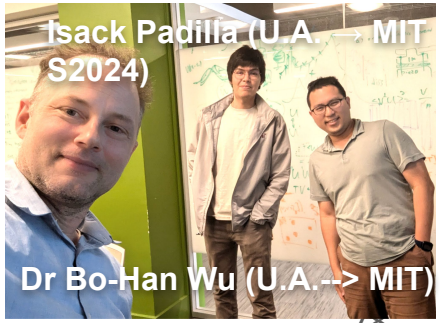








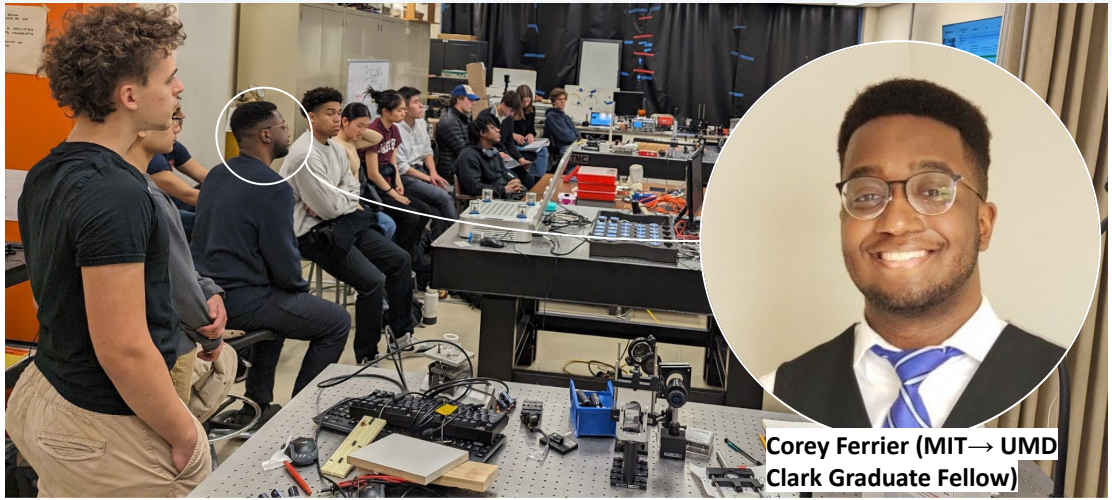




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Networked learning

- **Graduate Students**: Collaborate with Stefan Krastanov (UMass) on **QuantumSavory** testbed and entanglement simulations.
- **Undergrad. & visiting grad students** → to testbed simulations
- **Courses (MIT 6.2410 & 6.2400)**: Hands-on labs and quantum network theory

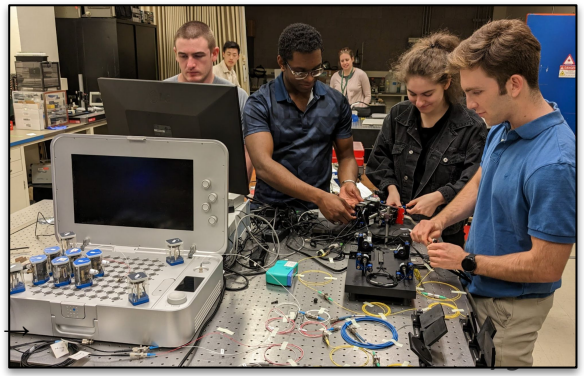


CQN Winter School on Quantum Networks


Michael Raymer

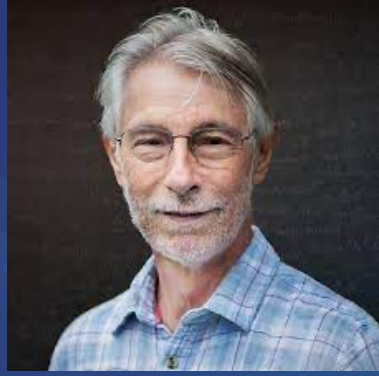

Brianna Moreno


Vaishnavi Addala: MIT UROP → DoE Graduate Fellow



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Quantum Networks
NSF Engineering Research Center



Thrust 1- Quantum Network Architecture

Don Towsley

Thrust 1 Lead

University of Massachusetts- Amherst

towsley@cs.umass.edu

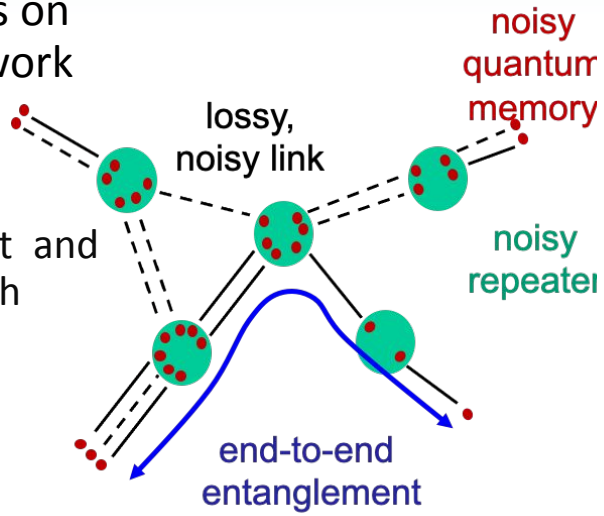
Funded by National Science Foundation Award #1941583

ARIZONA · MIT · HARVARD · UNIVERSITY OF MARYLAND · University of Massachusetts Amherst · BYU · THE UNIVERSITY OF CHICAGO 1890 · HOWARD UNIVERSITY · NAU NORTHERN ARIZONA UNIVERSITY · UNIVERSITY OF OREGON

Thrust 1 Architecture - Overview

Goal: Design quantum network (Q-net) architecture that builds on subsystems developed in Thrust 2. This includes design of network protocols, resource allocation algorithms and network management tools that support entanglement distribution.

Challenges: Understanding performance limits in a noisy environment and the development of an architecture, algorithms, and tools to deal with noise.



Projects:

- Project A: Network architecture for entanglement distribution (Towsley, Guha, Englund)
- Project B: Hybrid network architectures (Rozpedek, Towsley, Guha)
- Project C: Routing in entanglement generation networks (Towsley, Guha)
- Project D: Quantum network tomography (Towsley, Bash, Montano)

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Thrust 1 Summary

Main accomplishments:

- Development of a ZALM-based connectionless Q-network architecture
  - Simple to manage & understand
  - Allows access to rich set of classical network algorithms and protocols
- Design and evaluation of a hybrid (trapped ion-vacancy center) network architecture
- Routing in quantum networks
- Efficient characterization of quantum networks composed of Pauli channels

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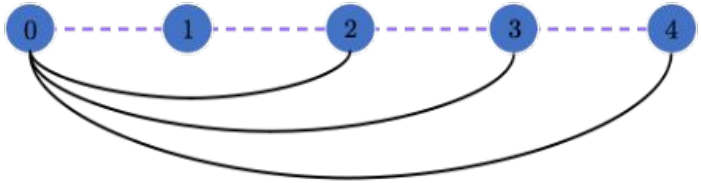
Connectionless two-way Q-net architecture

Question: Can we achieve same ease of management as classical networks for two-way qnet architectures while keeping high rates?

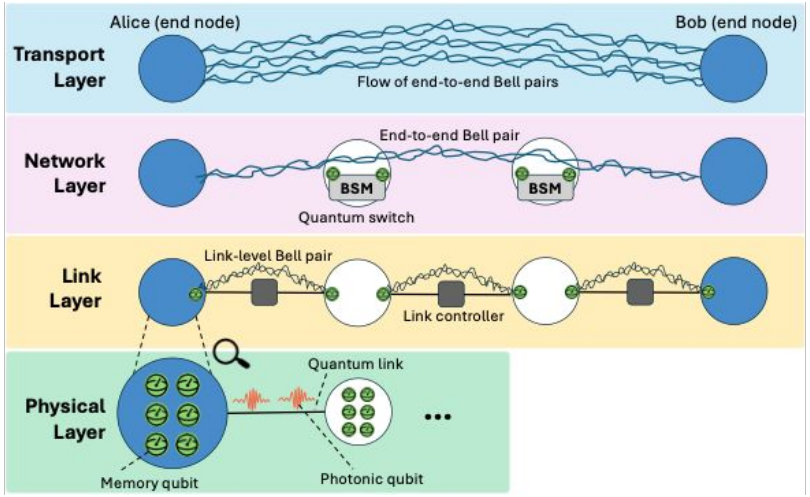
Approach: ZALM enabled sequential swapping

- Give link resources to flow only when request arrives to it
- Analogous to datagram service in classical Internet

No need for path reservation



Two-way Sequential Swapping



- Quantum TCP
- Routing and sequential swapping with store and forward
- Heralded Bell pair generation (link-controller)
- Quantum operations

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ZALM enabled 2-way Sequential Q-net architecture

Numerical experiments:

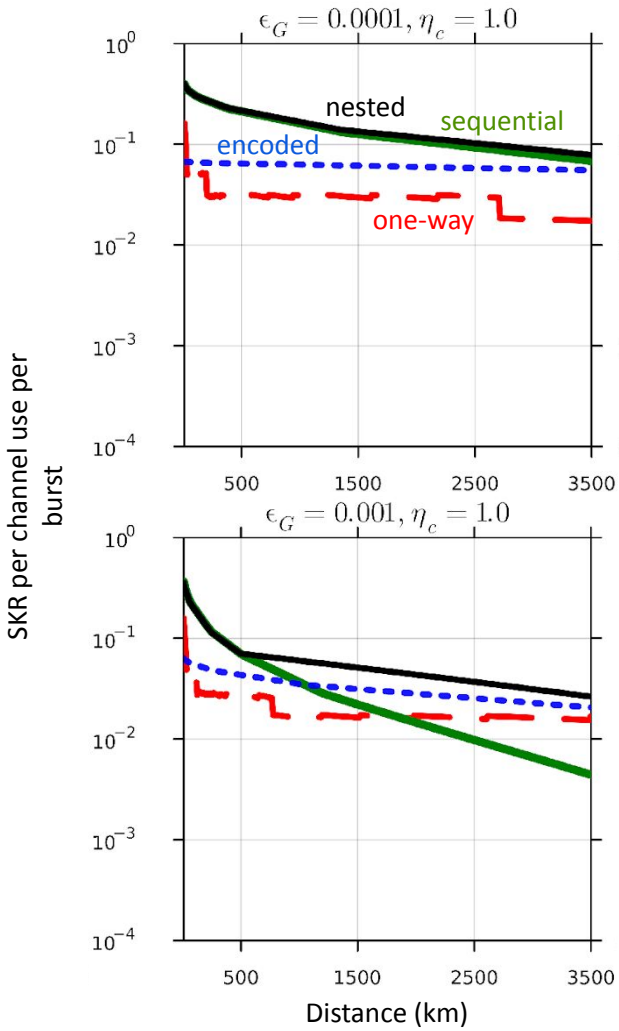
- 1 sec coherence time; gate infidelity 0.001, 0.0001; coupling efficiency 0.9, 1.0

Results:

- Sequential swapping performs as well as nested and outperforms one-way for high-quality hardware setting, and for short distances for moderate quality hardware
- Two-way schemes incurs lower costs

Future directions:

- Performance analysis for networks under load; Label switching
- Evaluation using Oregon ZALM traces
- Optimal distillation and swapping scheduling
- Integration with hybrid satellite–terrestrial backbones



Manuscript under preparation

ZALM enabled 2-way Sequential Q-net architecture

Goals:

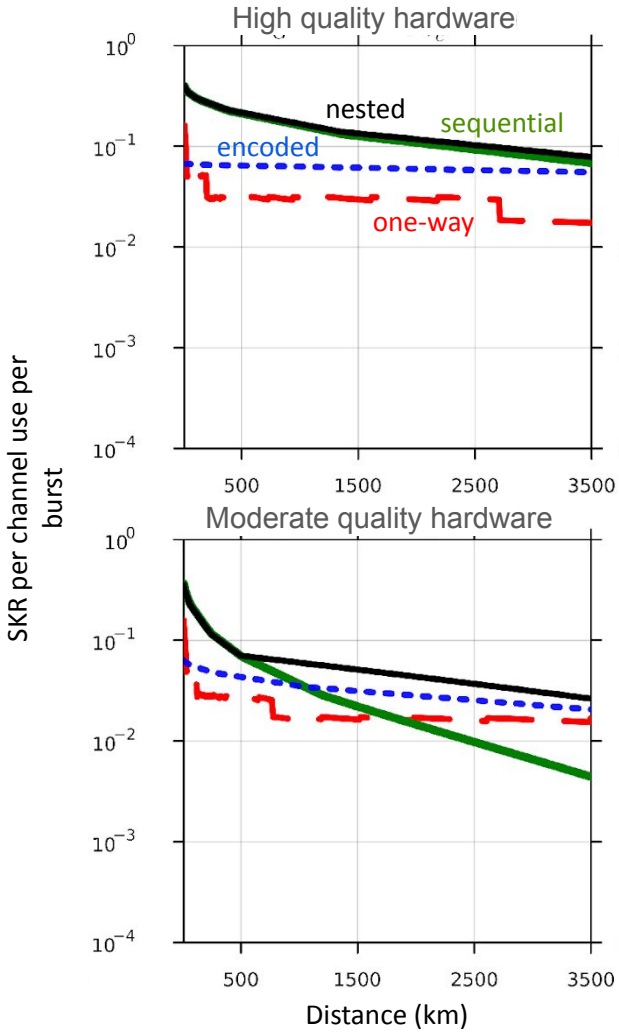
- Performance of ZALM based sequential 2-way architecture.
- Comparison to nested swap, one-way architectures

Results:

- Sequential swapping performs as well as nested and outperforms one-way for high-quality hardware setting, and for short distances for moderate quality hardware
- Two-way schemes incurs lower costs

Future directions:

- Performance analysis for networks under load; Label switching
- Evaluation using Oregon ZALM traces
- Optimal distillation and swapping scheduling
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Manuscript under preparation

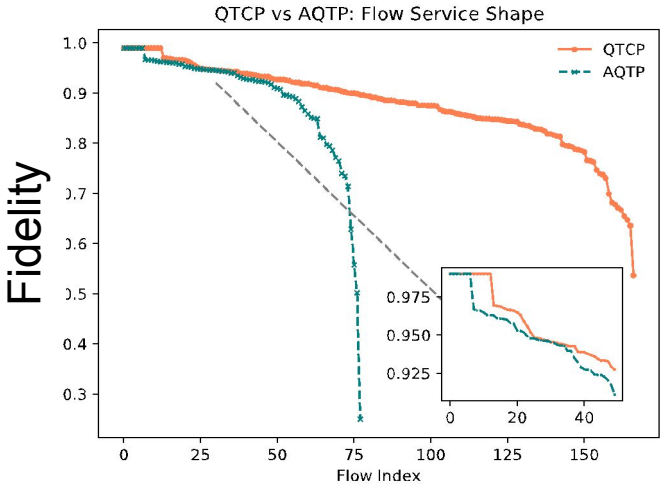
Connectionless Q-net architecture

Quantum TCP (proof of concept):

- Rate controller at end node
- Memory decoherence at link
- Memory decoherence management control

Future directions:

- Resource allocation, routing - borrow & adapt from classical Internet
- Incorporate distillation, error correction
- Evaluation using Oregon ZALM traces



arXiv:2405.18252 , arXiv:2410.08980

Quantum Network Utility Maximization

Goal: Develop approach for providing fair, application specific performance to multiple applications.

Challenge: Mathematical tools developed for classical networks not well suited given presence of noise.

Results:

- Developed otpmization-based framework for allocating resources to diverse set of applications that trade off rate with fidelity.
- Developed distributed QPrimalDual, QPD-approx

Future directions:

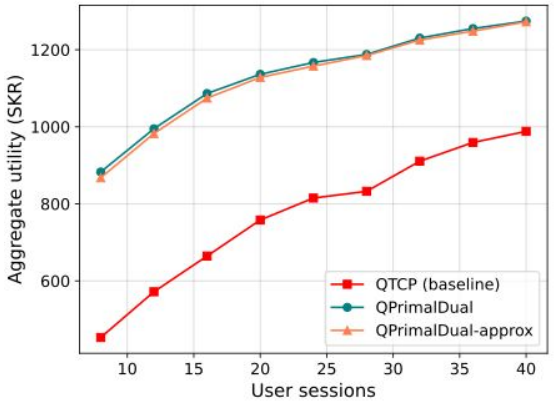
- Evaluate using Oregon ZALM traces with goal of evaluation on UMd testbed.

IEEE JSAC 2024, arXiv:2404.18818, arXiv:2404.17077

Goal: $\max \sum \log U_r(R_r, F_r)$

s.t. $\sum_{r:l \in r} R_r \leq d\alpha_l$ link capacity constraints

$F_r > F_r^*$ E2E fidelity constraints

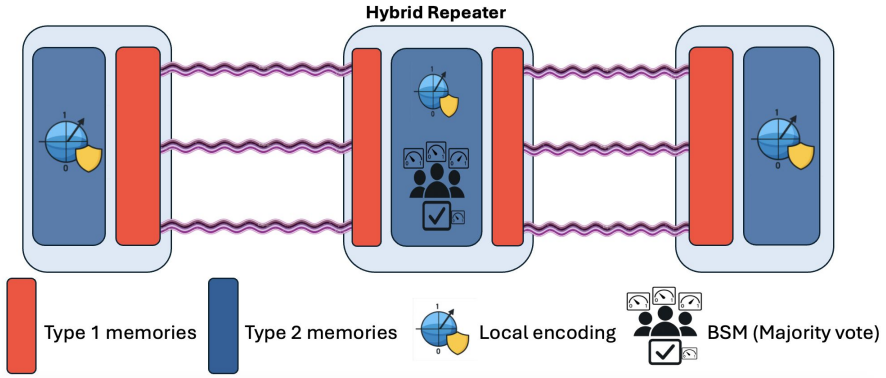


Encoded hybrid repeater chain architectures

Project Goals:

- Improve performance through hybrid architectures.
- Design, optimize hybrid architectures combining non-hybrid and hybrid repeaters.
- Develop new entanglement distribution policies.

Challenges: Matter-based memories support fast or high-fidelity two-qubit gates, presenting unique optimization challenges.



Hybrid repeater combines type 1 – "Fast" and type 2 – "high fidelity ops." platforms

Encoded hybrid repeater chain architectures

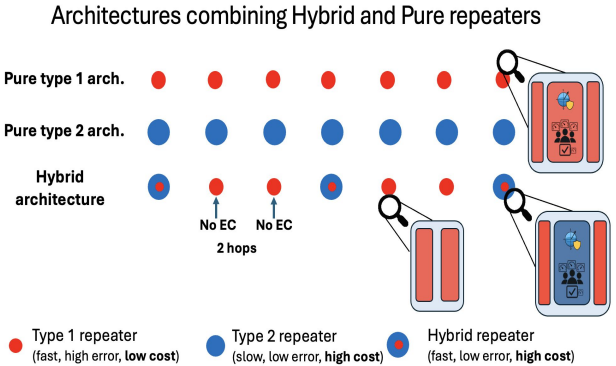
Project Goals:

- Improve performance through hybrid architectures.
- Design, optimize hybrid architectures combining non-hybrid and hybrid repeaters.
- Develop new entanglement distribution policies.

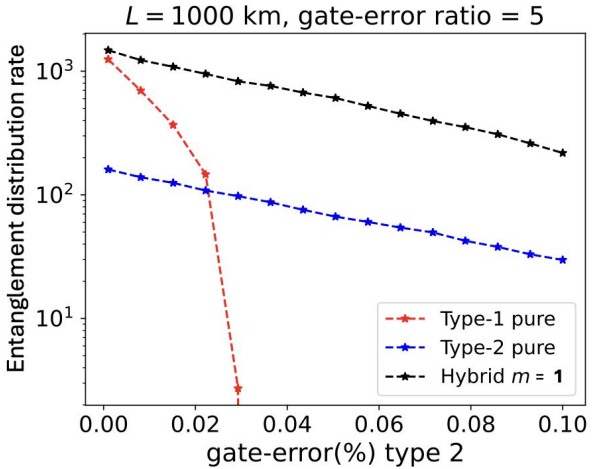
Challenges: Matter-based memories support fast or high-fidelity two-qubit gates, presenting unique optimization challenges.

Results:

- Hybrid schemes outperform monolithic schemes. Non-hybrid and hybrid repeater combinations outperform pure hybrid, monolithic architectures.
- “ASAP”(multiplexed version using distance-based ranking of links) scheduling of operations improves performance compared to nested/swap-all-at-once.
- Optimal number hops for each architecture; depends on hardware parameters.



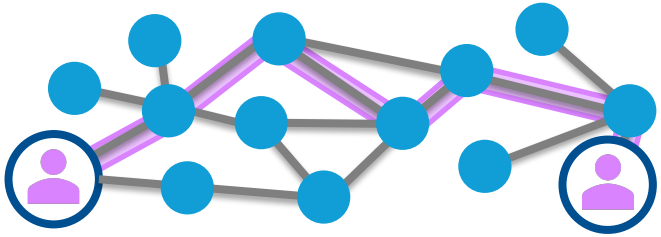
Hybrid architectures cost-effective. (fewer error correction enabled nodes)



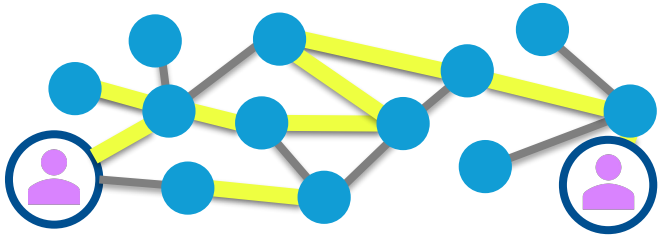
Entanglement Routing over Networks with Time Multiplexed Repeaters

Question: How do dynamic local link state knowledge routing protocols compare to path-based routing? Does time multiplexing or graph topology affect relative performances?

Fixed Path Based Routing

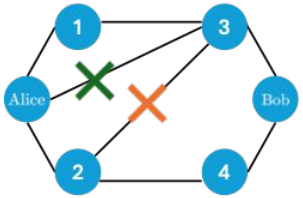


Dynamic Local Link State Based Routing



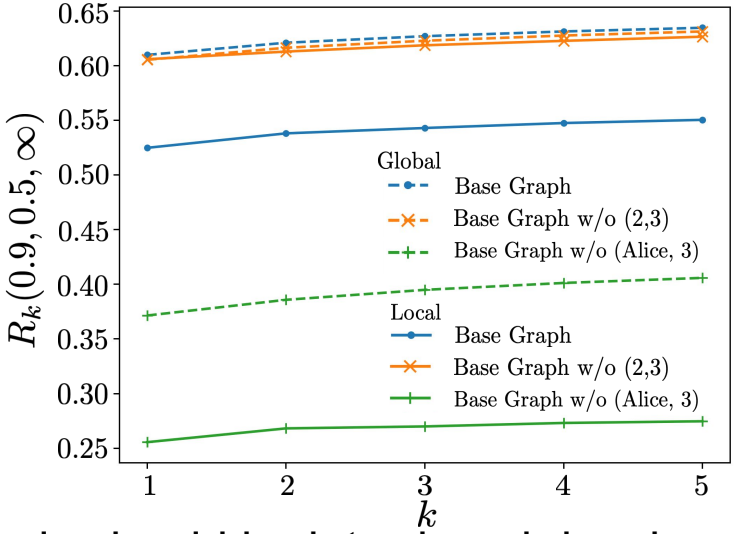
Setting: Link level entanglement generation (LLEG) attempted k times.
Enough quantum memories to accommodate multiple successes.
Each link succeeds with probability p.
BSMs succeed with probability q.
Knowledge of nodes limited to network topology and outcomes of local LLEGs

Entanglement Routing over Networks with Time Multiplexed Repeaters



Outcomes:

- *Dynamic* routing protocols are useful to handle probabilistic link generation.
- *Path-based* routing can prove more reliable, especially when paired with *time multiplexing*.



Future directions:

- Improved local link state knowledge protocols should be introduced drawing on topology aware routing protocols
- Incorporate imperfect Bell pairs and refined decoherence models for realism
- Multi-user networks with competing demands
- Investigate smart GHZ distribution techniques

arXiv:2308.15028

Quantum network tomography (QNT)

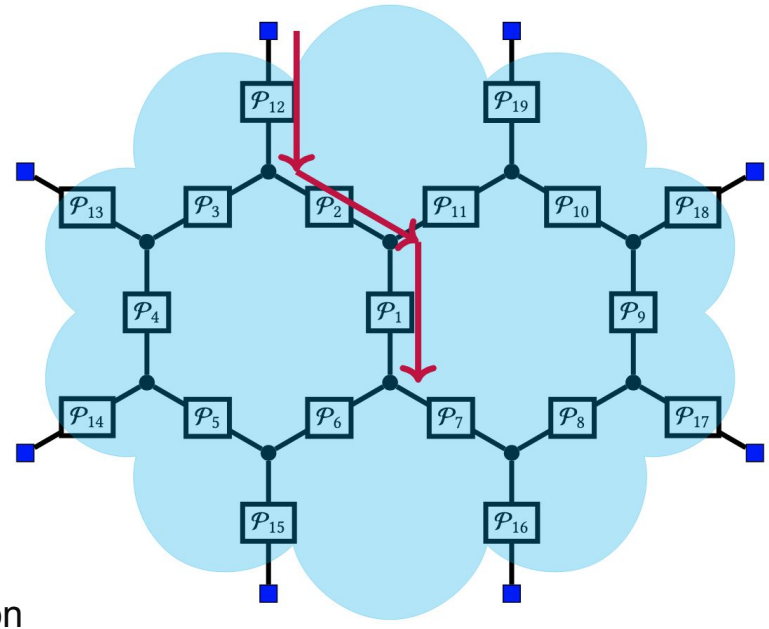
Goal: end-to-end link characterization in quantum networks

System

- Quantum network with Pauli + loss channels (links)
- State Preparation and Measurement (SPAM) errors

Approaches:

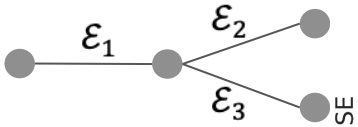
- Distribute bipartite/multipartite entanglement across network
- Perform different measurements at the end-nodes
- Combine statistics to identify parameters
- Select monitoring nodes for end-to-end measurements
- Quantify estimation error with Quantum Fisher Information



QNT results and future directions

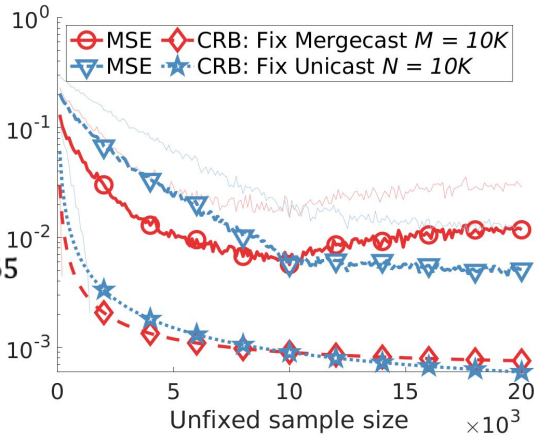
Multipartite estimation

- Mergecast algorithm
- Arbitrary topology
- SPAM errors



Depolarizing
$p_1 = 0.5, p_2 = 0.75, p_3 = 0.65$
SPAM errors $s, m = 0.95$
MSE for $\mathcal{E}_1$

CRB - Cramer Rao Bound
MSE - Mean squared error



Manuscripts under review for all tasks

QNT results and future directions

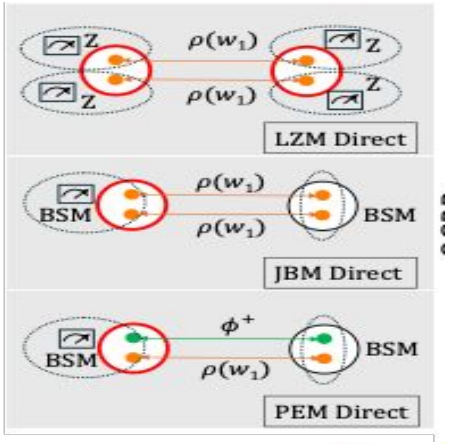
Multipartite estimation

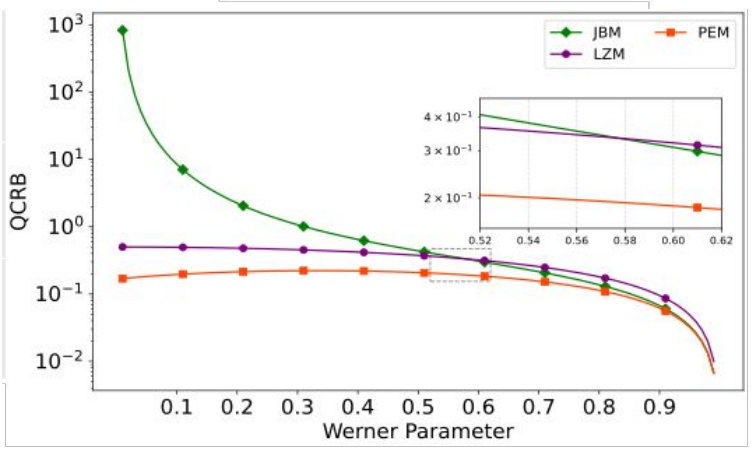
- Mergecast algorithm
- Arbitrary topology
- SPAM errors

Monitor placement (CoQREATE)

- Measurement evaluation (QFIM)
  - Entanglement based vs. non-entanglement based
  - Perfect vs imperfect entanglement
- ILP formulation
  -

Manuscripts under review for all tasks





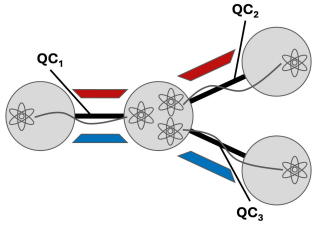
QNT results and future directions

Multipartite estimation
- Mergecast algorithm
- Arbitrary topology
- SPAM errors

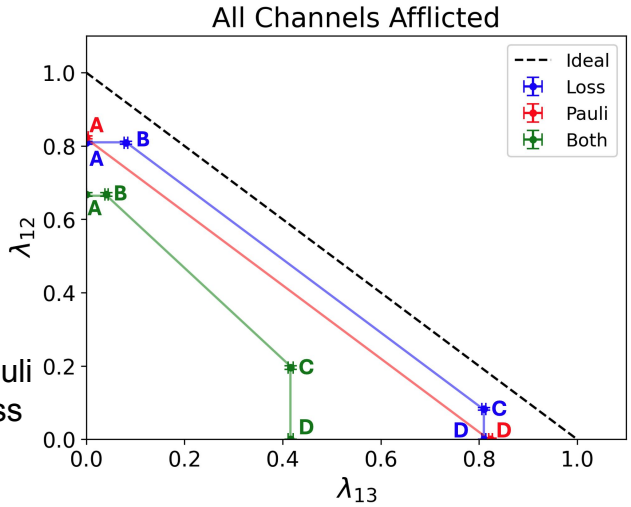
Monitor placement (CoQREATE)
- Measurement evaluation (QFIM)
- ILP formulation

Tomography with capacity region
- Estimate loss with capacity region
- Detect existence of Pauli errors

Manuscripts under review for all tasks



Blue: 15% loss
Red:10% loss + 10% Pauli
Green: 10% loss + 10% Pauli (QC 1 and 2), QC3 30% loss + 30% Pauli



Future directions:
- Test on UMd testbed, Oregon lab
- Adapt to support sensing on connectionless networks
- Consider impact of gate noise

Thrust 1 Integration Across Center

EWD: Participation in CQN Winter School; Towsley introduced seminar on distributed quantum computing.

DCI: Student rotations through UMass ACQuIRE Lab (Arizona, Northern Arizona University, Trinity College). One REU & one undergraduate honors thesis.

Thrust 2: Collaboration on hybrid networks that include ZALM sources, trapped ion and vacancy center repeaters, and on Q-network tomography.

Thrust 4: Collaboration on quantum security

IE: Customized Research w/ Diamond Members:

- Cisco w D. Towsley on quantum data center networks
- L3Harris w B. Bash on secure communications

Close interactions with ARO MURI on quantum network science, DOE on development of quantum TCP.

Participation in IETF

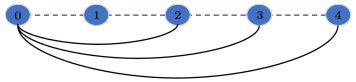
Thrust 1 Summary

Main accomplishments:

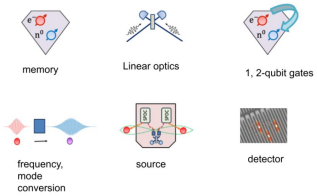
- Development of a ZALM-based connectionless Q-network architecture
  - Simple to manage & understand
  - Allows access to rich set of classical network algorithms and protocols
- Development of hybrid quantum network architectures
- Routing in quantum networks
- Efficient characterization of quantum networks composed of Pauli channels

Year 5-10 Major Milestones

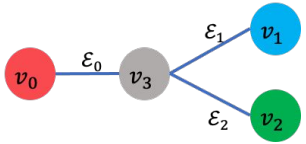
2025 Specification of connectionless service architectures (incl. routing algorithms)



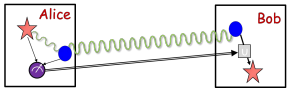
2026 Evaluation of connectionless architectures on virtual testbed



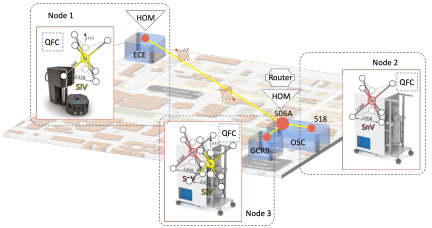
2027 Development of tomographic techniques for arbitrary channel models; incorporation into protocols, e.g.,distillation selection
Evaluation in Oregon Lab



2028 Develop network protocols for quantum teleportation enabled by connectionless quantum networks.



2029 Evaluation of tomographic techniques on UMd/Boston testbeds with distillation optimized for CQN target rates



2030 Evaluation of connectionless architecture on UMd/Boston testbeds (incl. MBQC distillation)

Center for
Quantum Networks
NSF Engineering Research Center



Thrust 2 - Quantum Subsystem Technologies

Brian Smith

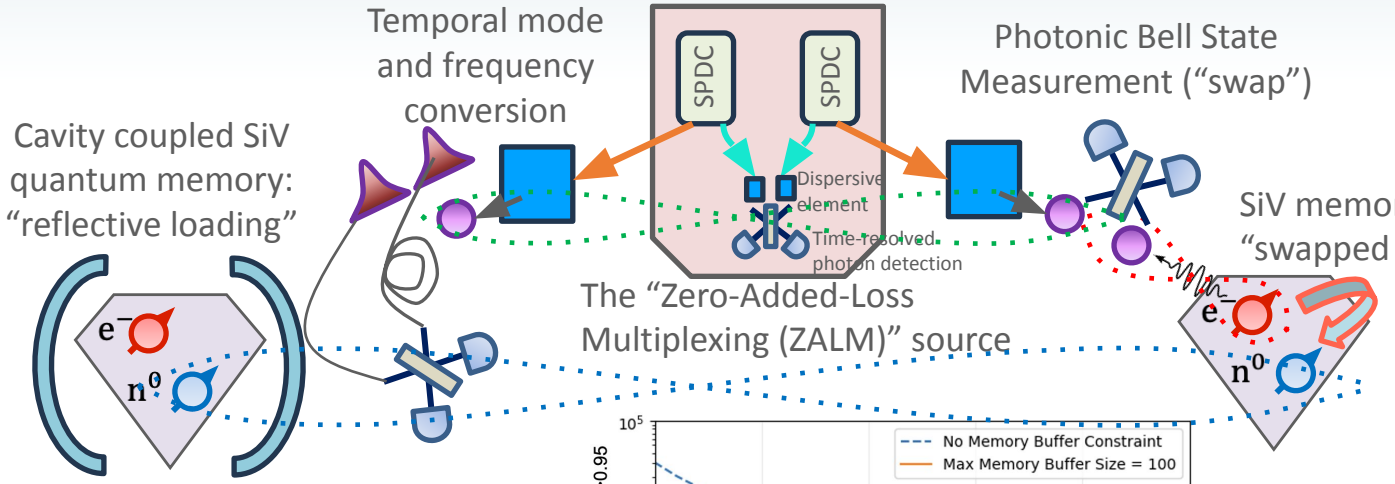
Thrust 2 Lead

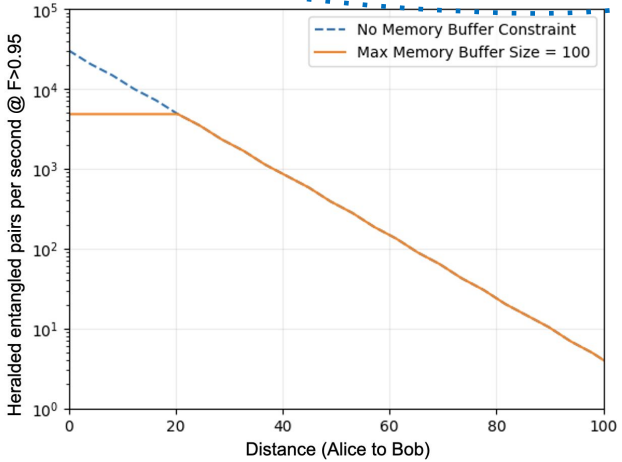
University of Oregon

bjsmith@uoregon.edu

Funded by National Science Foundation Award #1941583

Subsystem 1: The ZALM





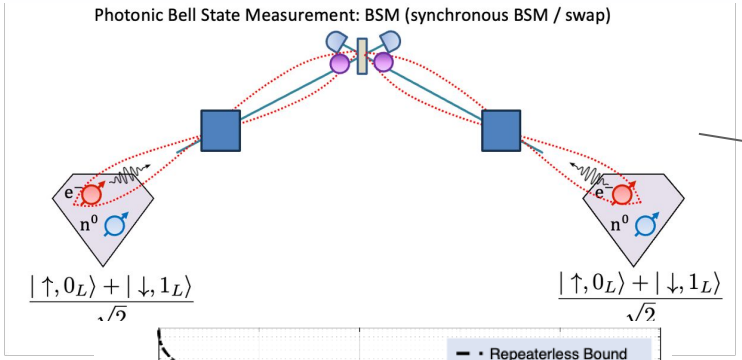
Phys. Rev. Applied 17, 034071 (2022)
Phys. Rev. Lett. 128, 063602 (2022)
Phys. Rev. Applied 19, 054029 (2023)
Phys. Rev. Applied 22, 044014 (2024)
Phys. Rev. Applied 22, 044013 (2024)

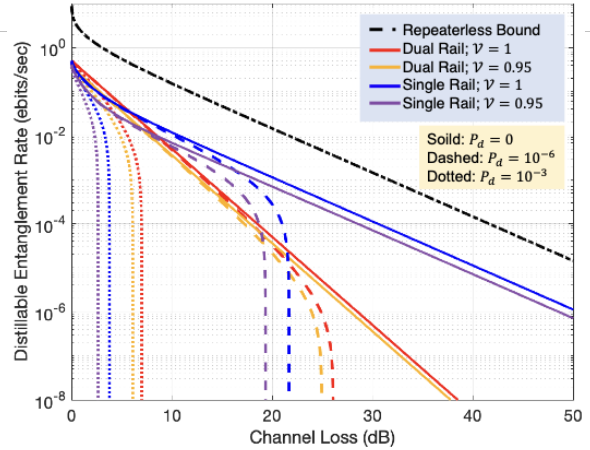
C2C paper: Phys. Rev. Research 6, 033317 (2024)
New Award: # 2427047 ExpandQISE: Track 1

Evaluated detailed extensive models for 6+ different quantum link-architecture alternatives

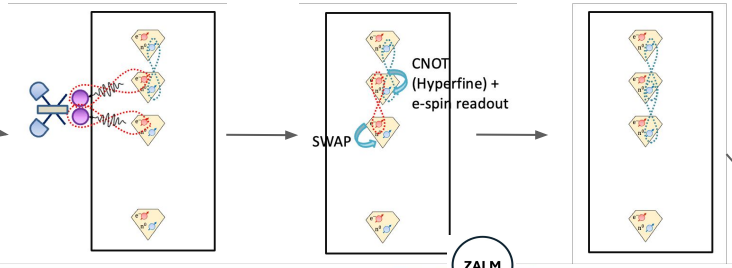
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Subsystem 2: Multiplexed entangled SiV module
Subsystem 3: Measurement based ent. distillation

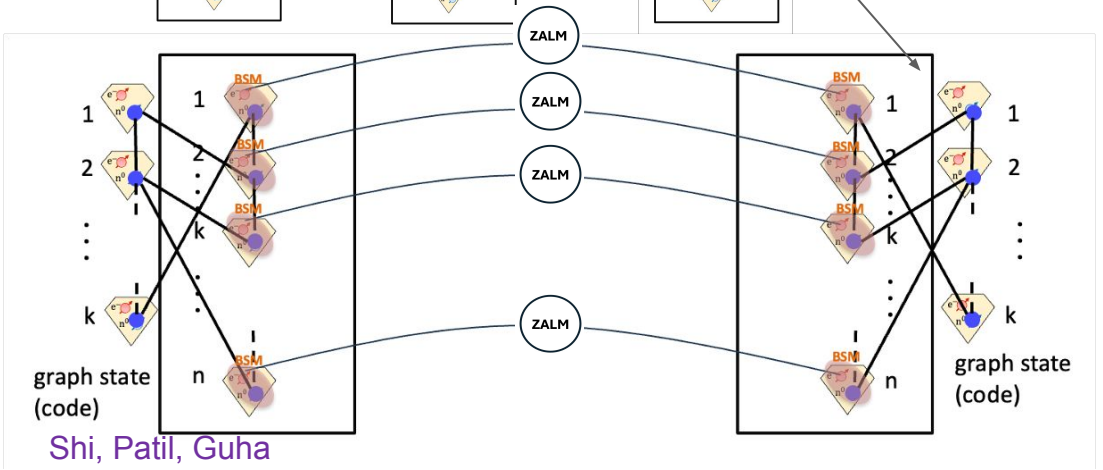




Dhara, Englund, Guha, PRR 5, 033149 (2023)



Loncar and Lukin Groups, Harvard, Science, Vol 378, Issue 6619 (2022)

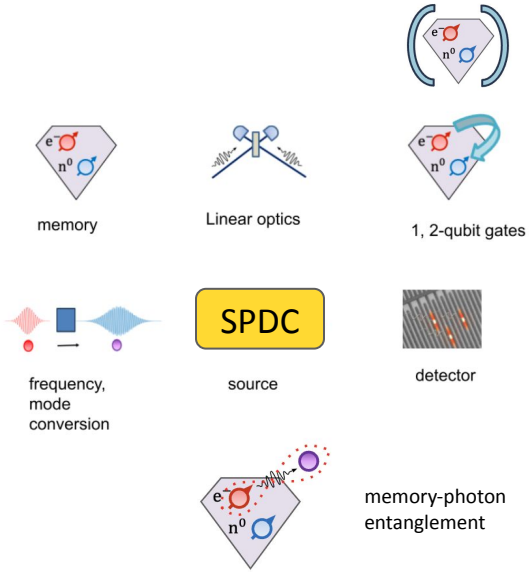


Shi, Patil, Guha
PRX Quantum 6, 010339 (2025)
Physical Review Letters 135, 130803 (2025)

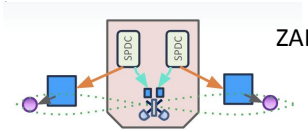
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Development Timeline

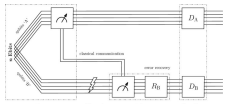
Device blocks



Functional blocks



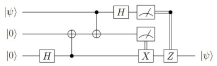
ZALM source



Entanglement distillation

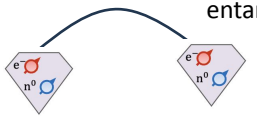


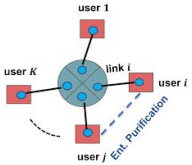
Multiplexed Qubit Array



teleportation

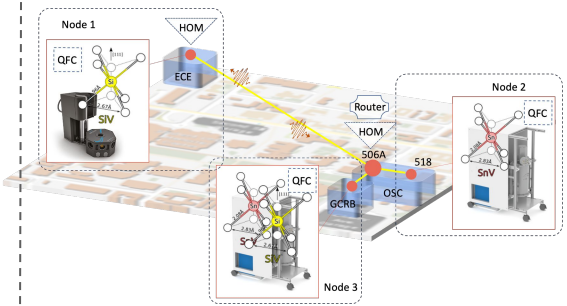
Heralded entanglement





routing

testbeds



Year 1-4

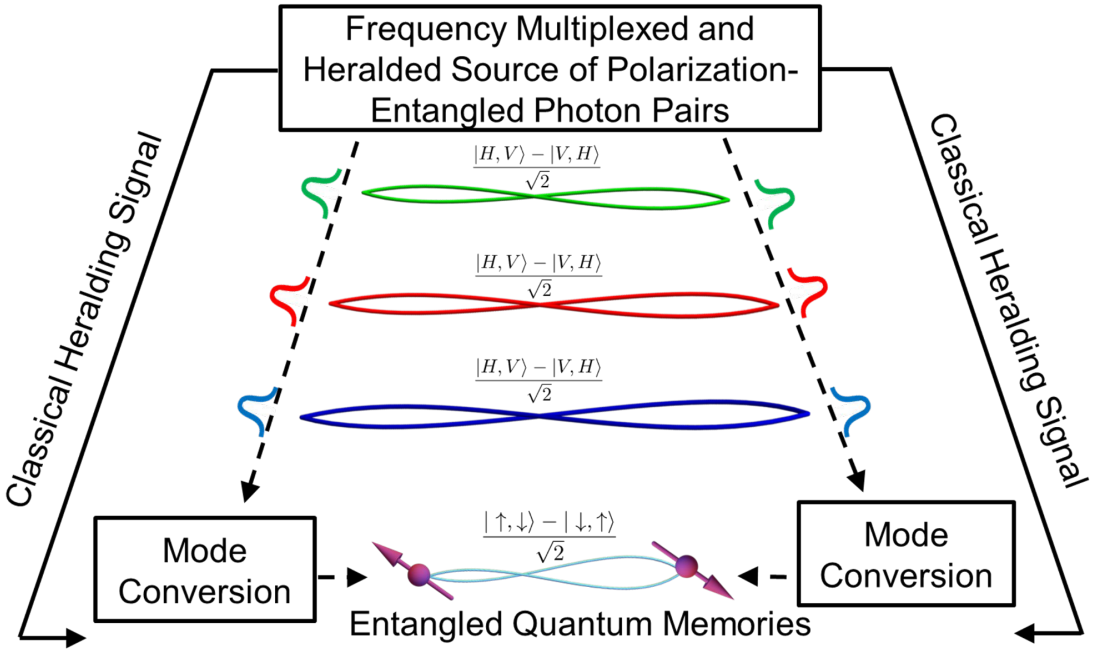
Year 5-7

Year 8-10

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Zero-added-loss multiplexing (ZALM) scheme

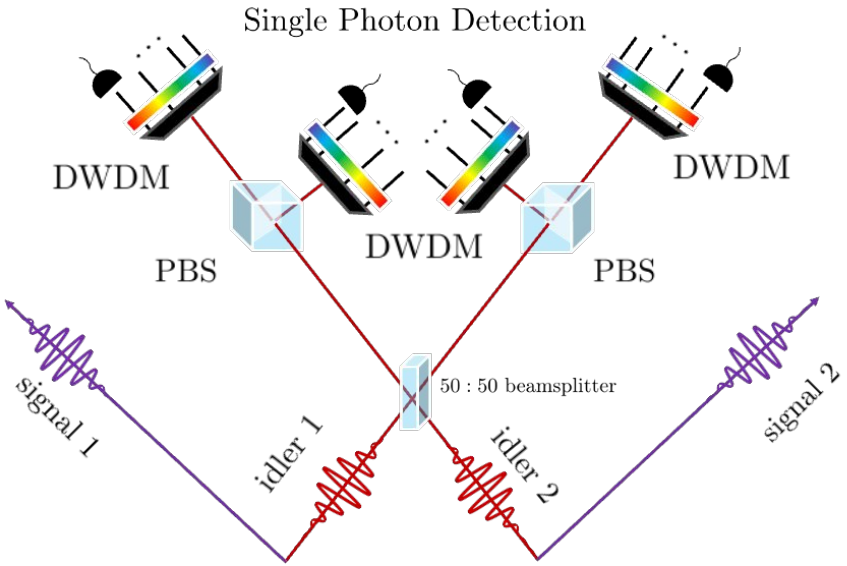
Saikat Guha (UMd) and Dirk Englund (MIT)

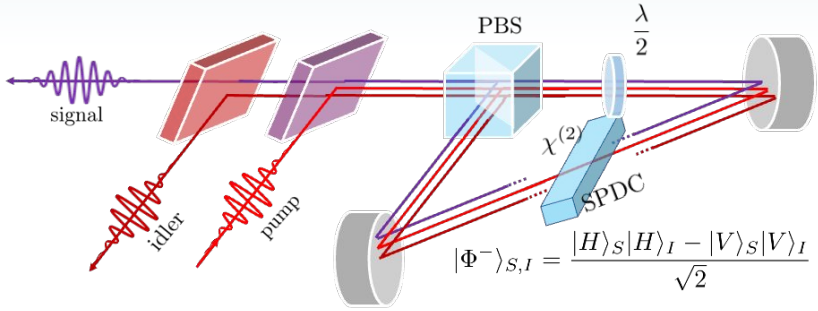


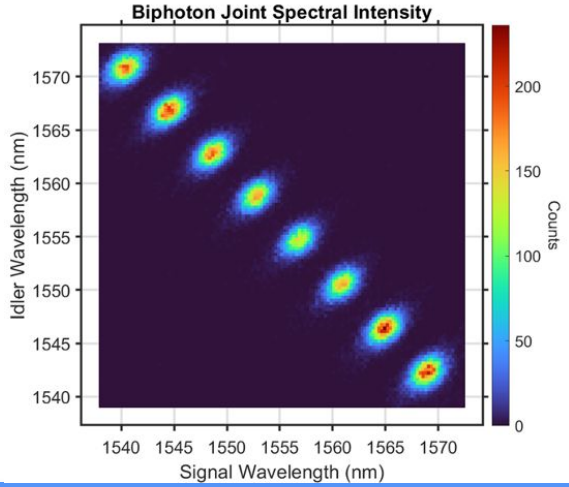
Chen, Dhara, Heuck, Lee, Dai, Guha, and Englund, Physical Review Applied 19, 054029 (2023)

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ZALM source: Engineered frequency islands







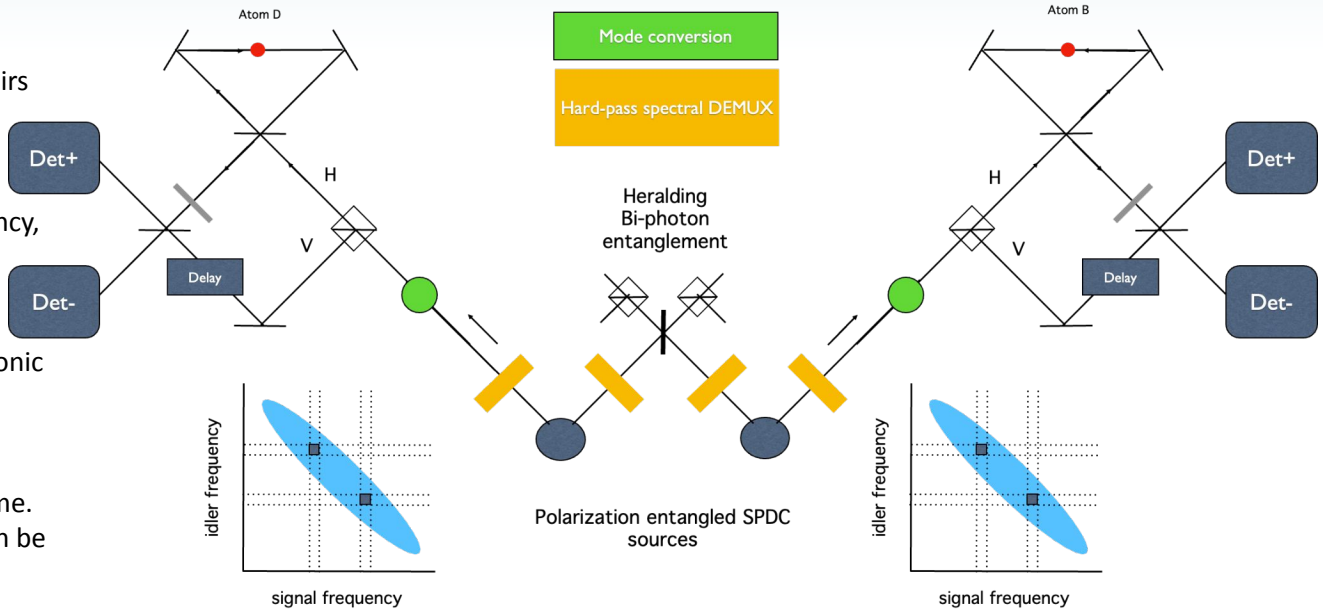
Merkouche, Thiel, Davis, and Smith, Phys. Rev. Lett. 128, 063602 (2022)

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ZALM source: Filtered frequency islands

Analyzed:

1. ZALM's heralded source of entangled photon pairs
2. loading of the entangled states into pairs of intra-cavity color-center quantum memories,
3. Tradeoffs between distribution rate, heralding probability, heralding efficiency, and entangled-state fidelity.



Findings:

1. Perfect transfer of the entangled photonic state to the quantum memories is possible when the photonic state is bandwidth compressed to reach the memory's narrowband operating regime.
2. Multichannel broadband operation can be analyzed quantitatively.

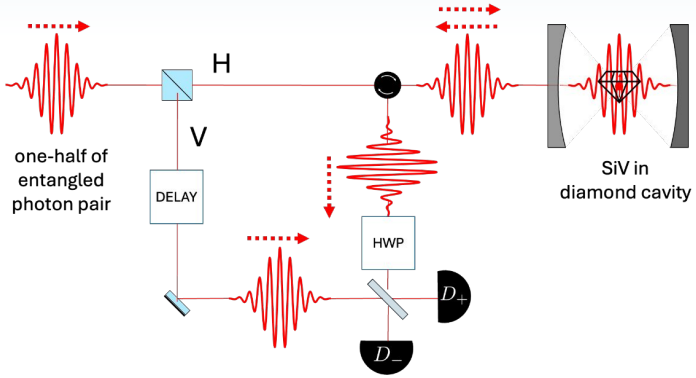
Ongoing work:

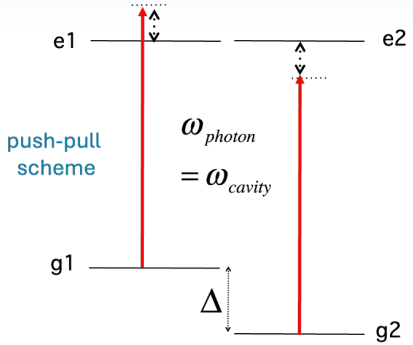
1. Multi-frequency heralding
2. Spectral-temporal pump engineering
3. Optimizing the Frequency-conversion / bandwidth compression trade
4. Joint optimization of source + conversion

Shapiro, Raymer, Embleton, Wong, Smith, Phys. Rev. Appl. **22**, 044014 (2024)
Shapiro, Embleton, Raymer, Smith, arXiv:2507.14427 (2025).

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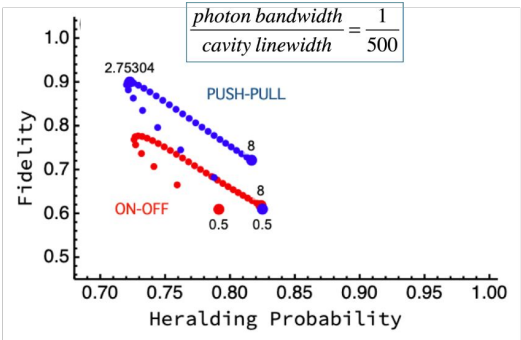
Improved Duan-Kimble scheme for loading cavity-Based Quantum Memories

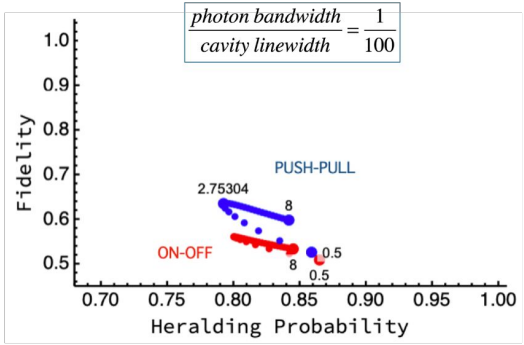




Main findings: Narrowband photons of less than 1 GHz are needed for high-fidelity operation with a SiV color center type quantum memory

Ongoing research: Source + conversion requirements vis-a-vis Emissive versus reflective loading





Raymer, Embleton, Shapiro, Phys. Rev. Appl. **22**, 044013 (2024)

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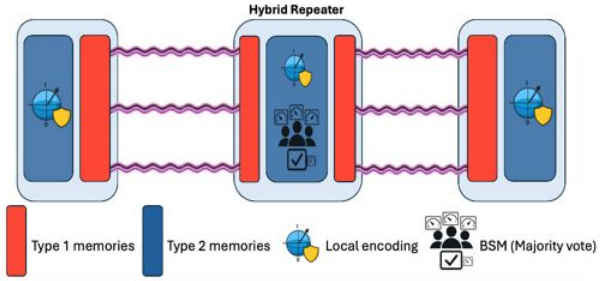
SiV + Ion trap-based hybrid repeaters for encoded entanglement distribution

Goals:

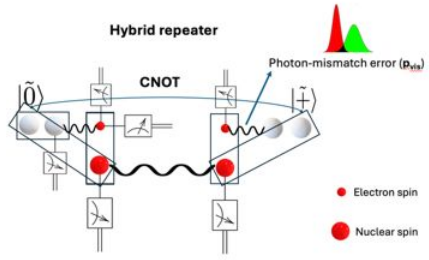
1) Improve performance error correction-based entanglement distribution by combing two physical platforms that perform distinct functions.
2) Design and optimize hybrid architectures based on SiV and Ion trap qubits.
3) Find new optimal pulse level protocols for implementation of such a hybrid encoded repeater architecture.

Challenges:

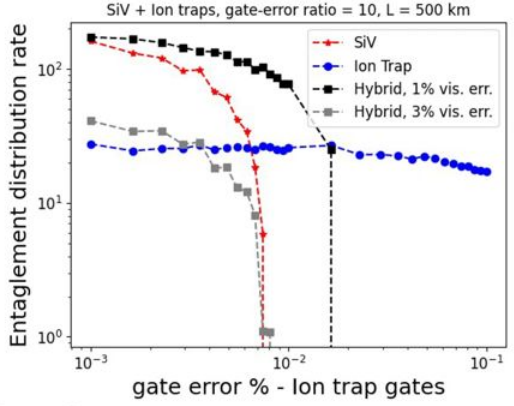
1) A tailored model with gate-count level details for color-center and ion-trap based implementation needed to assess real-world performance.
2) Important factors like loss and noise from transduction, pulse-shaping challenges need to be included in sims.

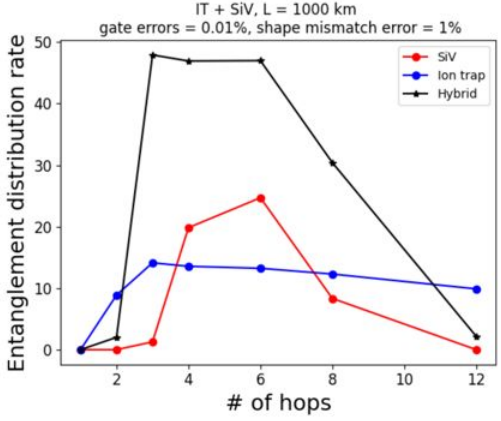


Hybrid repeater combines type 1 – "Fast" and type 2 – "high fidelity ops." platforms



Gate-counts, transduction errors based on physical platform constraints included.

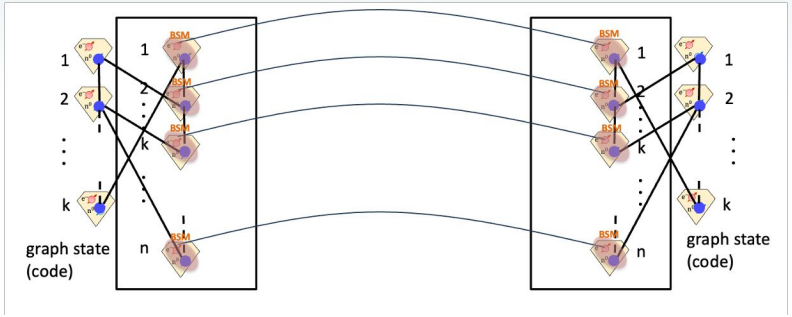


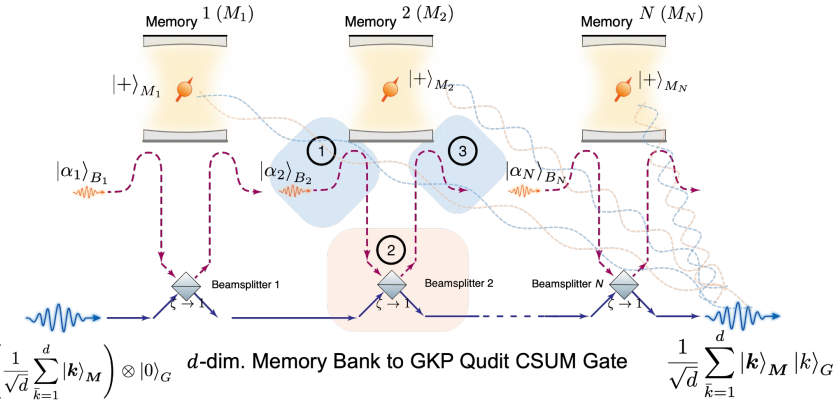


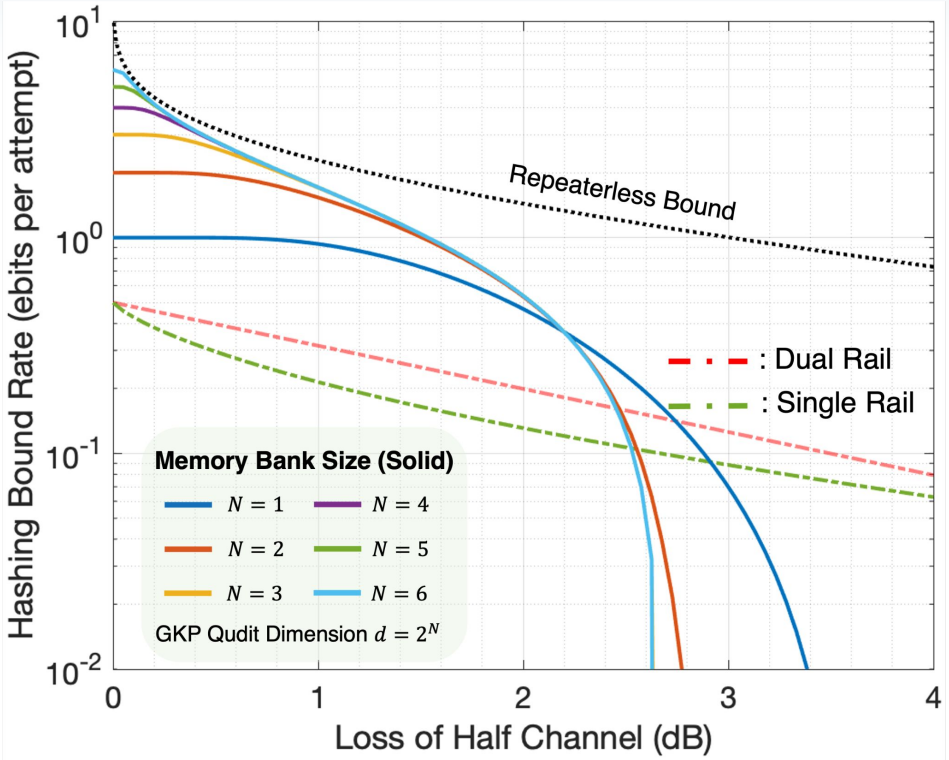
Results:

1) Hybrid architecture (SiV+Ion trap-based repeaters) outperforms pure (SiV or Ion-based) architectures.
2) Optimal choice of # of hops between two error-corrected nodes exists.
3) Photon shape mismatch/visibility error plays a deciding role in performance.

High rate entanglement at low loss



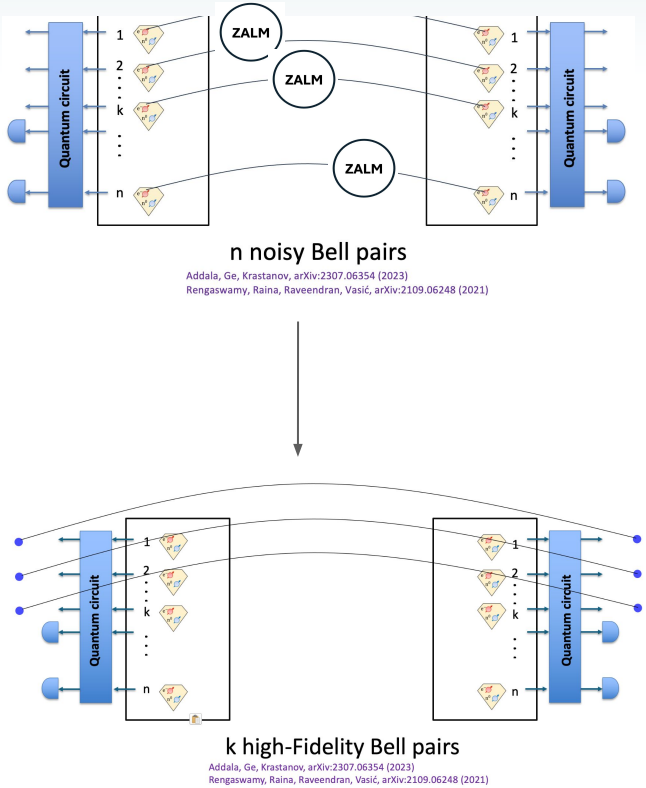




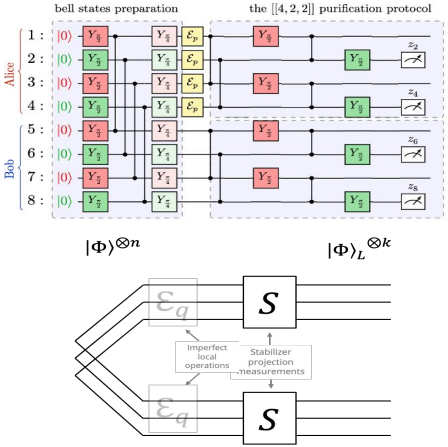
Dhara, Jiang, Guha,
arXiv:2406.04272 (to appear in Optica Quantum 2025)
Phys. Rev. A 112, 012401 (2025)

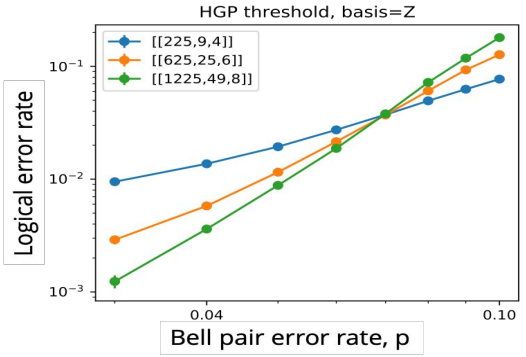
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Code based entanglement distillation



- Translate QECC to block and convolutional entanglement distillation protocols – PRL 135 (13), 130804 (2025)
  - Bikun Li (Chicago), Qian Xu (Chicago/Caltech), Gefan Baranes (Harvard/MIT), Pablo Ataides (Harvard), Mikhail Lukin, (Harvard), Liang



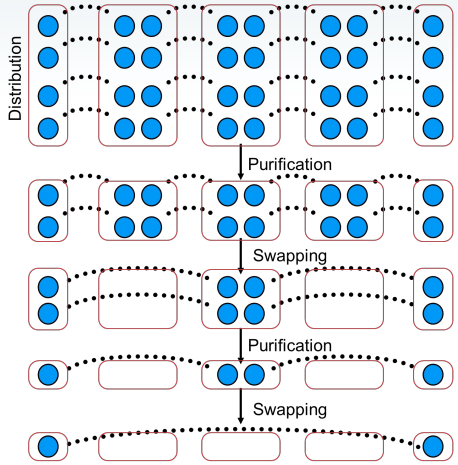


Circuit level noise simulation (with gate error q=0.1%), HGP QLDPC code has threshold p_{th}≈7%

- Extended the above protocol to the measurement based model of quantum computing (for compliance with SiV logic)
  - Y. Shi, A. Patil, S. Guha, 2408.06299, PRX Quantum 6, 010339 (2025)
  - Y. Shi, A. Patil, S. Guha, 2502.11174 (2025)

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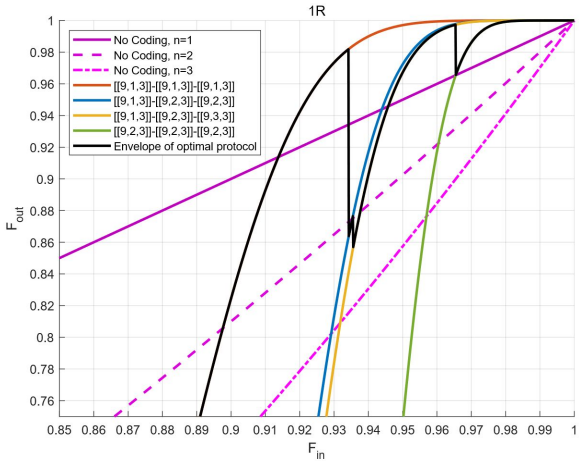
Code based entanglement distillation

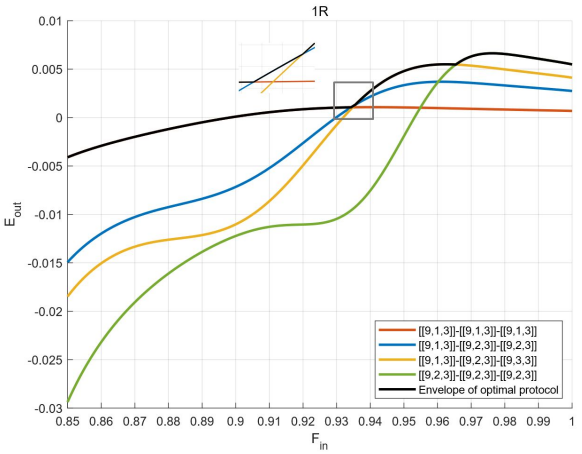


- Adaptive error correction for entanglement distillation
  - Adaptively change the code in the sequence of distillation rounds for a chain of repeaters — gradually increase the rate while limiting error correction capability as fidelity monotonically increases with rounds.
  - This approach jointly optimizes both rate and fidelity (“efficiency” metric).
  - S. Cheng and N. Rengaswamy, 2504.11670

Example of adaptive protocol using [[9,1,3]], [[9,2,3]] and [[9,3,3]] codes

The black line shows the envelope of optimal code sequence as a function of input fidelity





Efficiency:

$$E(F_{in}) = \frac{n_{out} D(F_{out})}{n_{in} D(F_{in})}$$

F – Fidelity
n_{in} – The total number of input Bell States
n_{out} – The total number of output Bell States
D – Distillable Entanglement

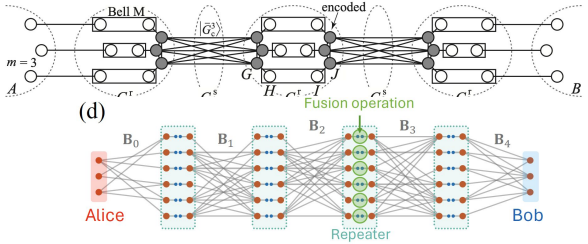
$$D(F) = 1 + F \log_2 F + (1 - F) \log_2 \left(\frac{1 - F}{3} \right)$$

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Using spin qubits as a source of photonic graph states for all-photonic repeaters

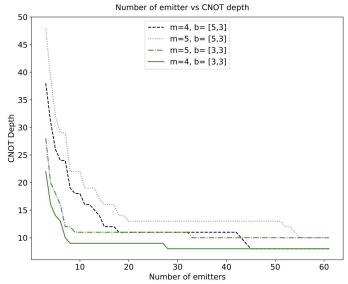
Improved Quantum Repeater Graph States:

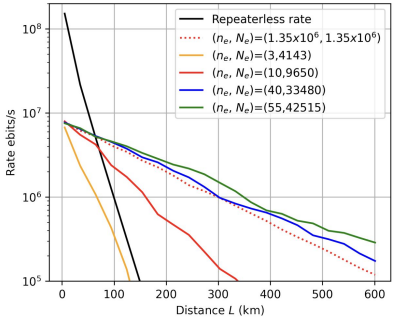
Simultaneously entanglement swapping even for probabilistic (optical) Bell measurement.

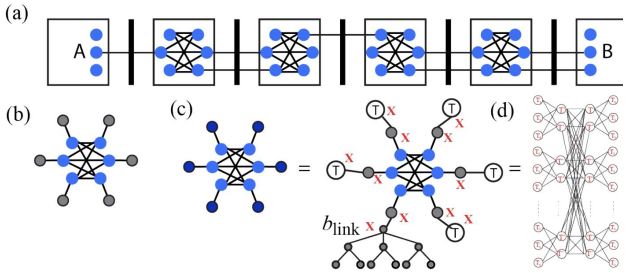


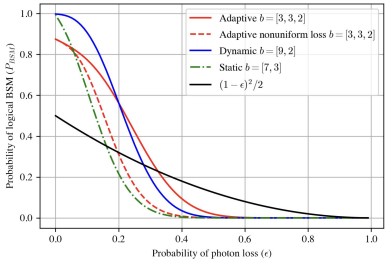
[CQN Collaboration UChicago + UMass] Li,Googenough, Pozpedek, Jiang, arXiv:2407.01429

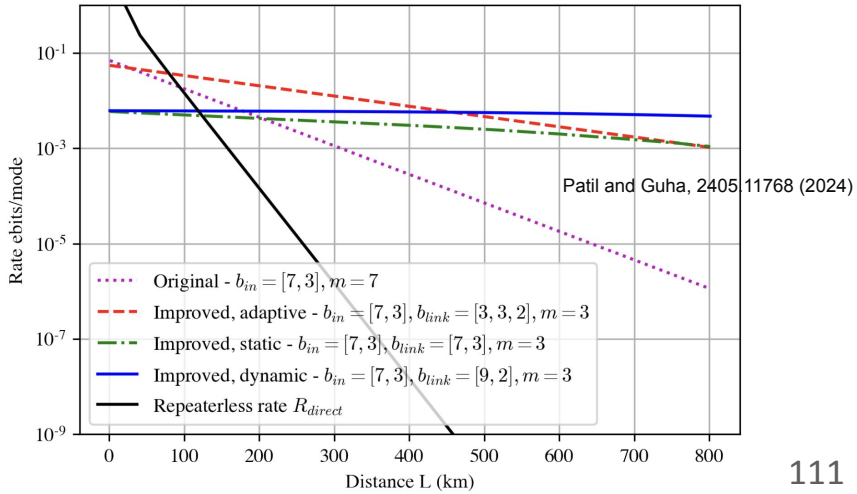
Preparation of the graph state using emitters











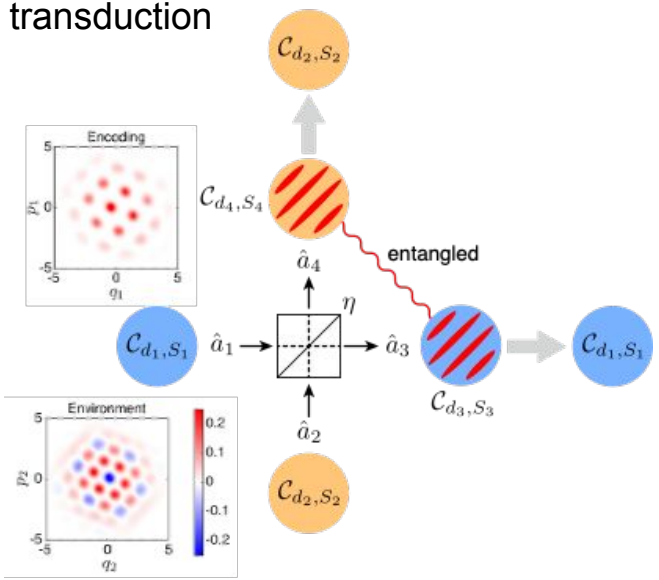
Patil and Guha, 2405.11768 (2024)

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Theoretical Investigation of Quantum Transducers

Invent novel quantum transduction protocols enhanced through co-designed QEC

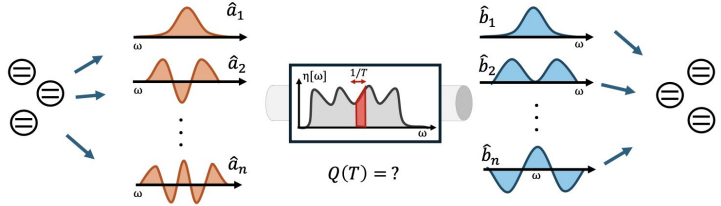
- Inject non-Gaussian (e.g., GKP) state into environmental mode to enhance quantum transduction

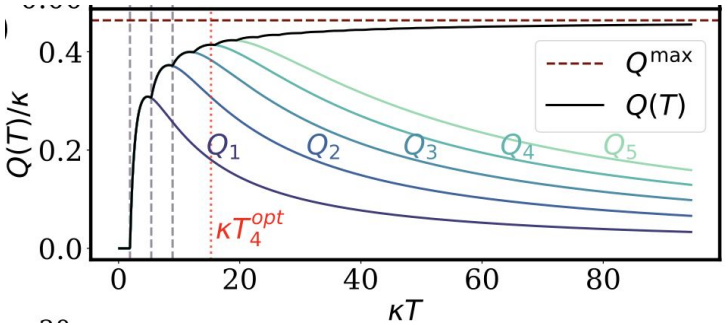


Wang, Jiang, Phys. Rev. X 15, 021003 (2025)

Quantify the fundamental limits of practical quantum transduction channels

- Accounting for constraints such as limited bandwidth (B) and finite signal pulse duration (T)





Gandotra, Wang, Clerk, Jiang, arXiv:2502.08831

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Thrust 2 Integration Across Center

EWD: Raymer organizing Winter school, Smith developed Quantum Masters Internship program at UO, Jiang and Rozpedek organized Quantum Networks Workshop at UChicago, Rengaswamy and Vasic organized Quantum Information Knowledge (QuIK) workshop at IEEE International Symposium on Information Theory in Athens, Greece, involvement of undergrads in research. EWD Fellowship: Quantum Tangram (efficient mapping of quantum circuit to MBQC, https://arxiv.org/pdf/2210.11465)

DCI: Recruitment of underrepresented groups at undergrad, grad and postdoc levels to engage in research, high-school student involved in research at UO. Student and faculty involvement in DCI Council, Winter School, the Global Quantum Discussion Group, the SLC Annual Retreat, and other QuESTs and integrated DCI activities

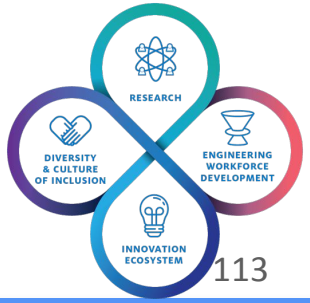
Thrust 1: Collaboration on hybrid networks that include ZALM sources, quantum network tomography; combining error correction based distillation with scheduling policies that can be used for routing

Thrust 3: Collaboration between UO, BYU, MIT and Harvard to address mode conversion; discussions between the groups of Rengaswamy and Berggren about SNSPDs for measurement-based implementation of distillation

Thrust 4: Smith organized panel discussion on Societal impacts of Quantum Tech at Quantum 2.0 in San Francisco 2025; Smith organized workshop on Societal impacts of Quantum Tech in Spring 2025

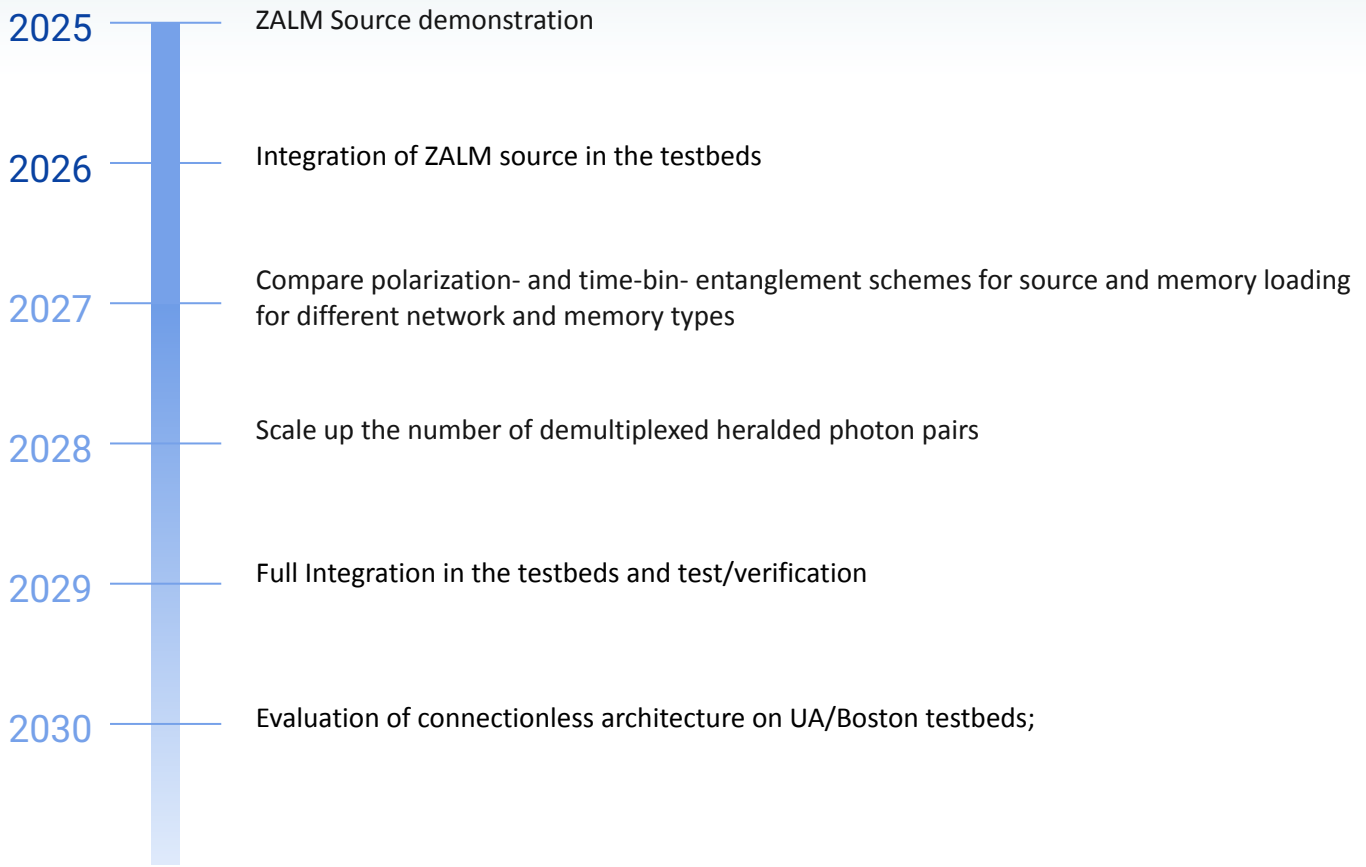
IE: Rengaswamy building partnerships with Photonic, Xanadu, and Quantinuum with the help of Jill Allen,

UA Director of Industry Engagement



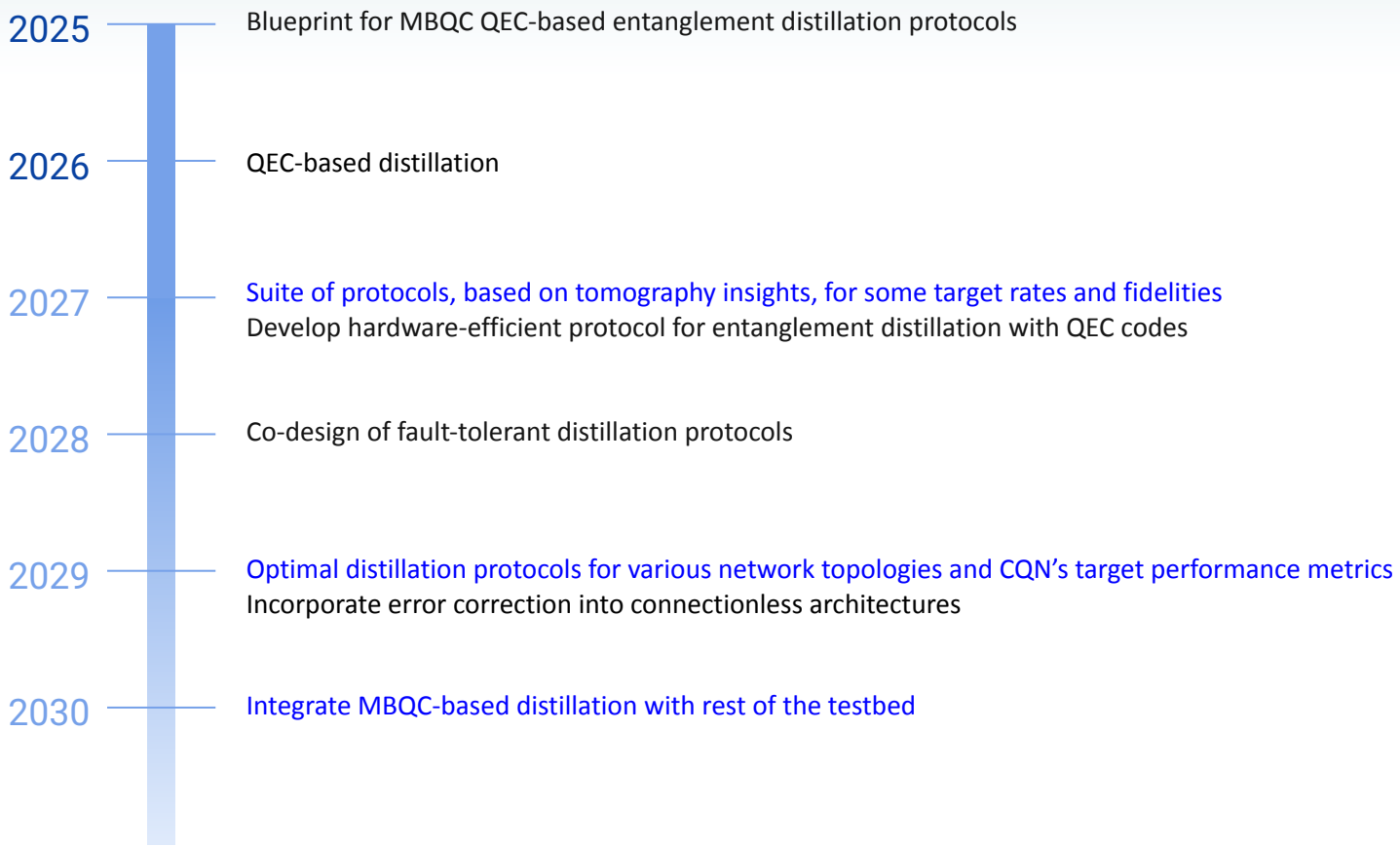
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Year 5-10 Major Milestones
(Source and mode conversion subsystems)



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Year 5-10 Major Milestones
(Error Correction and distillation Protocols)



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Year 5-10 Major Milestones
(Physical Layer Repeater Protocols)

2025 — High-level analysis of combining multiplexing platforms with processing node platforms.

2026 — Investigation of quantum codes/decoherence free subspaces for the SiV-trapped ion repeater architecture.

2027 — Designing proof-of-principle experiment of the SiV-trapped ion repeater and evaluating parameter thresholds for this setup.

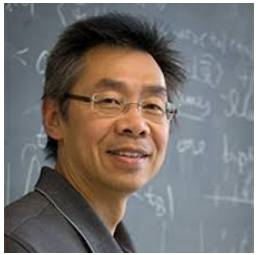
2028 — Overall performance of the hybrid SiV-trapped ion repeater scheme on a line.

2029 — Overall performance of the hybrid SiV-trapped ion repeater scheme in a 2D network.

2030 — Integration of proof-of-principle experiment design into the network schemes.

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Thrust 2 Team














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Center for
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NSF Engineering Research Center



Thrust 3 - Quantum Materials, Devices, and Fundamentals

Marko Loncar

Thrust 3 Lead

Harvard University

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Funded by National Science Foundation Award #1941583

ARIZONA · MIT · HARVARD · UNIVERSITY OF MARYLAND · University of Massachusetts Amherst · BYU · THE UNIVERSITY OF CHICAGO · HOWARD UNIVERSITY · NAU NORTHERN ARIZONA UNIVERSITY · UNIVERSITY OF OREGON

Thrust 3 - Materials, Devices -Overview

Goal: Materials, devices and chip-scale systems that enable more efficient and "friendly" quantum repeater nodes.

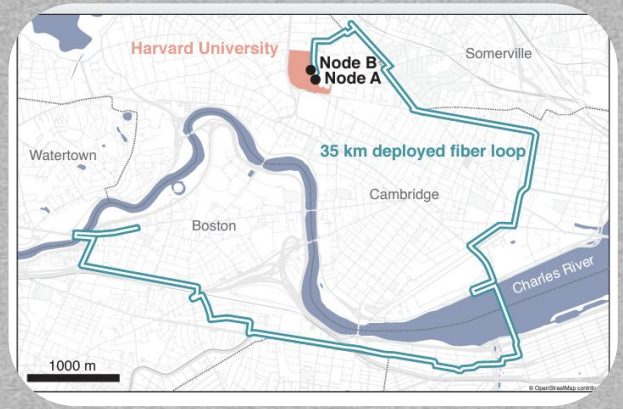
Challenges:

- **Quantum memory limitations**: operating temperature, inhomogeneous broadening, emission wavelength, speed…
- **Quantum frequency conversion** and photon **collection efficiency** limitations?
- Performance limits of **superconducting single photon detectors**?
- **Electronics**, both cryo and room temperature, needed to control thousands of memories?
- **Integrated photonics based ZALM source**?

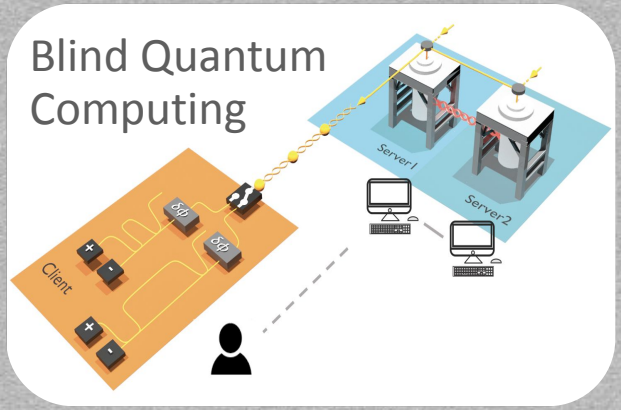
Project A: Quantum Memories Beyond SiV (**Freedman, Englund, Eichenfield**)
Project B: Superconducting Electronics (**Berggren**, **Mundy**)
Project C: Qubit Conversion Technologies (**Loncar, Mundy, Eichenfield**)
Project D: Quantum Logic on Spin Qubits (**Lukin**)
Project E: Qubit Control (**Eichenfield, Loncar, Englund**)
Project F: Integrated Multiplexed Swaps (**Eichenfield**)
Project G: Efficient Photon Coupling (**Camacho**, **Loncar**, **Englund, Eichenfeld**)

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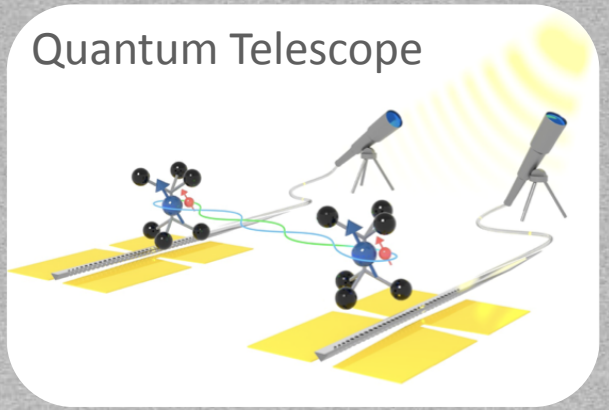
Y1-Y4: City-scale quantum-memory-based quantum-comms! Y5: Applications!



Can M Knaut et al, "Entanglement of Nanophotonic Quantum Memory Nodes in a Telecommunication Network". *Nature*, **629**, 573 (2024)



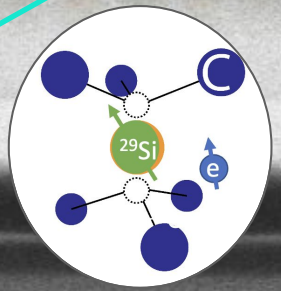
Wei, Stas, Suleymanzade, Baranes et al., *Universal distributed blind quantum computing with solid-state qubits*, Science **388**, 509-513 (2025)



Stas, Wei, Sirotin et al., *Entanglement Assisted Non-local Optical Interferometry in a Quantum Network*, arXiv:2509.09464 (2025)

Diamond nanocavity enables strong spin-photon interactions

Silicon Vacancy Centers deterministically incorporated into device



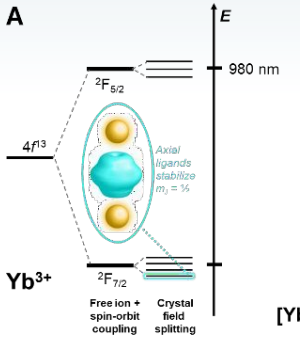
Efficient fiber coupling of photons

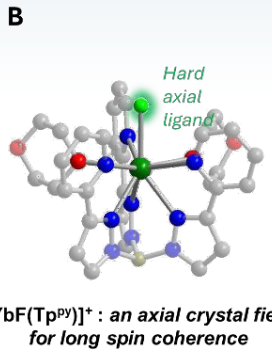
Memory enhanced quantum communication M. Bhaskar, et al, *Nature*, **580**, 60 (2020)

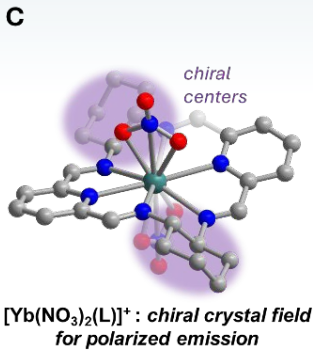
Project 3A: Quantum Memories Beyond SiV

Project Goals:

- Synthesize and design a series of Yb^{3+} molecules to correlate spin coherence times to crystal field symmetry
- Investigate chiral antenna ligands for spin polarized emission
- Perform resonant optical experiments including measurements of optical storage lifetimes and optical coherence times (Englund Lab)
- Attempt optical initialization of the Yb^{3+} electron spin and ODMR experiments







Barriers:

- Fast spin decoherence due to magnetic anisotropy
- Parity forbidden optical transitions lower quantum yield

Methodologies to Overcome Barriers:

- Synthetic manipulation of the Yb^{3+} electronic structure to minimize anisotropy
- Ligand induced mixing of optical transitions to relax optical selection rules and increase quantum yield

Recent achievements:

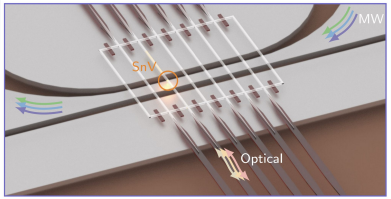
- Designed and synthesized several Yb^{3+} molecules as well as diamagnetic Y^{3+} analogues
- Grew magnetically dilute single crystals for characterization of the spin and optical properties
- Began optical measurements at 4K in the Englund lab cryostat

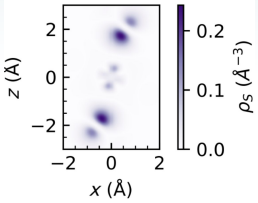
Freedman & Englund

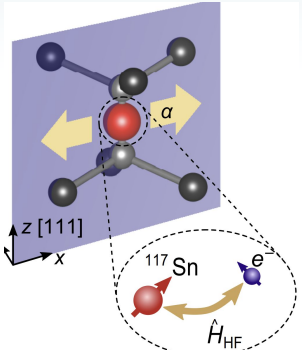
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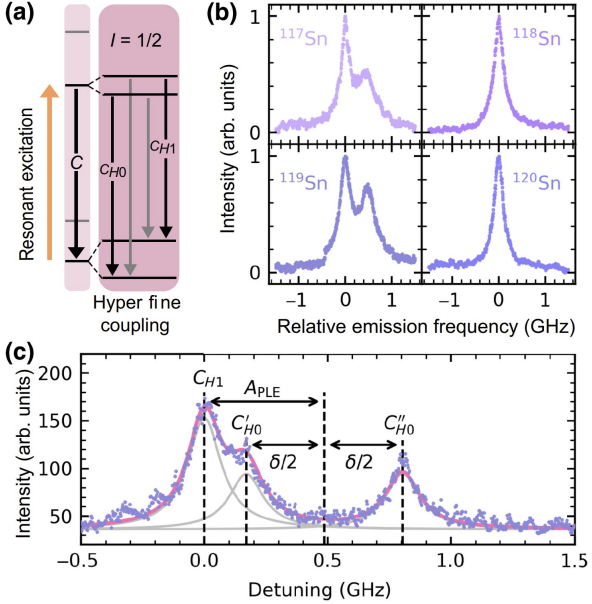
Project 3A: Quantum Memories Beyond SiV

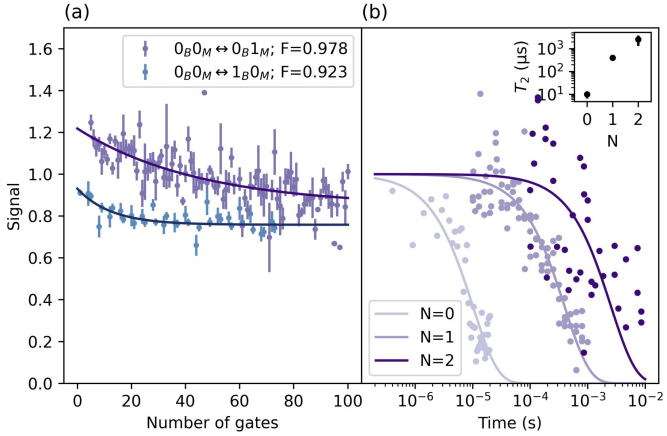
Hyperfine Electro-Nuclear Spin-Photon Interface







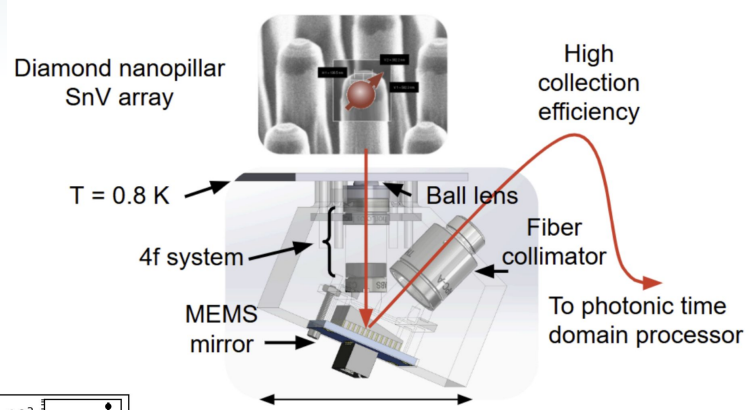


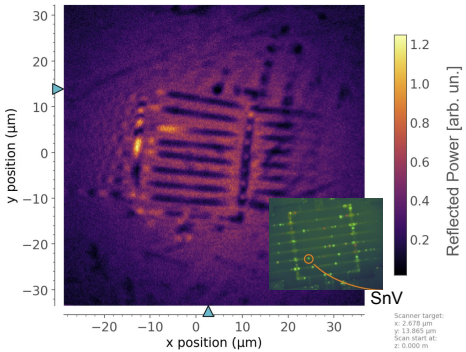


IBW Harris, et al PRX Quantum (2023) & Manuscript Under Review (2025)

Englund

Cryo-vacuo MEMS Scanner QuMemory Module

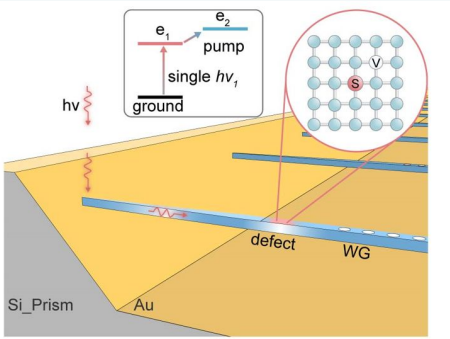


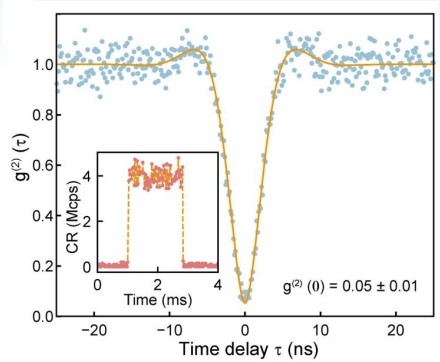


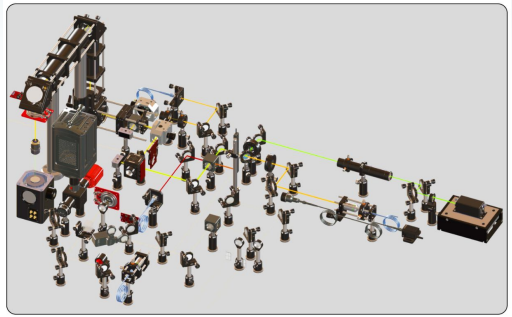
Chao Li, Vikash Kumar, et al, to be submitted (2025)

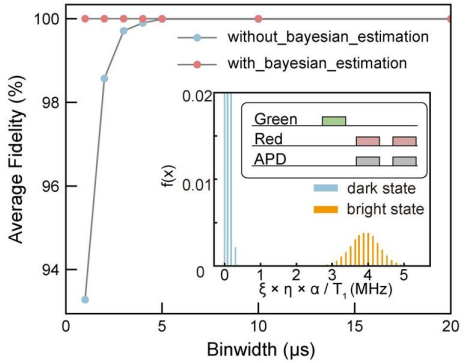
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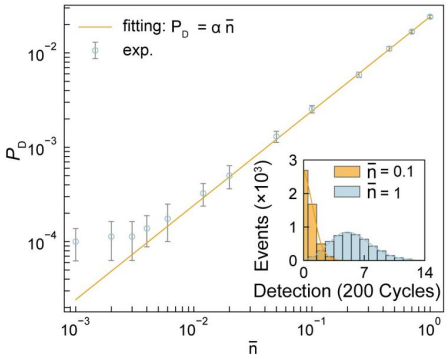
Project 3A: Diamond-Color-Center Single-Photon Detector

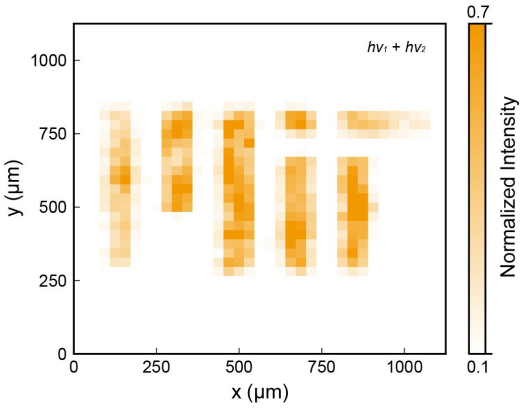












Yong Hu, to be submitted (2025)

Englund

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Project 3B: Superconducting Electronics

Project Goals:

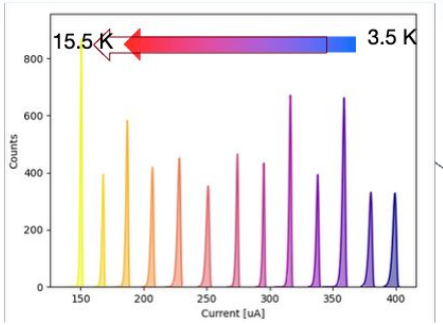
- Detecting photons for quantum communication in a scalable, cost-effective manner
- Develop integrated nanowire detectors and electronics for photonic feedforward control
- Study high temperature materials for electronics applications

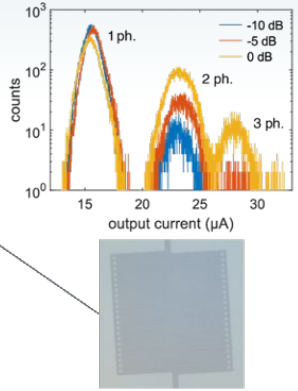
Barriers:

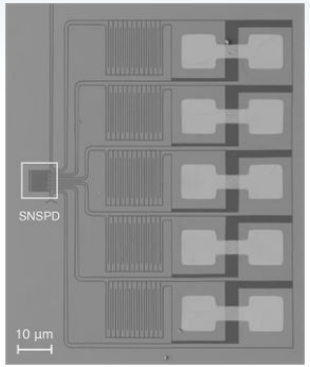
- High bit error rate in photon number resolving circuit
- Difficult to etch and protect sensitive high temperature materials

Methodologies to Overcome Barriers:

- Explore different circuit architectures
- Develop new fabrication techniques







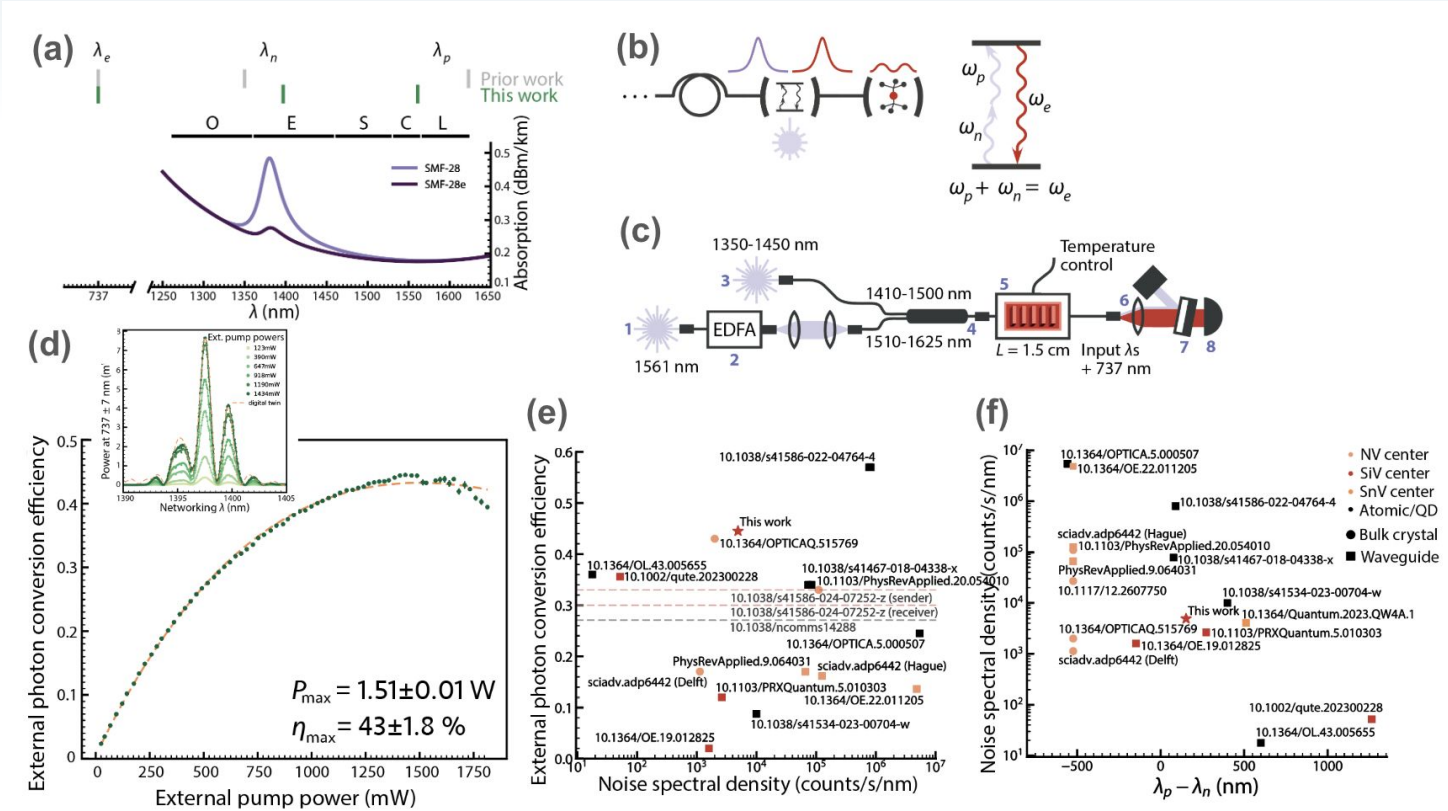
Recent achievements:

- SNSPD coupled to an integrated nanowire circuit to distinguish between photon-number states
- Nanowire logic gates for SNSPDs in Bell measurements
- Fabrication process for narrow-wire magnesium diboride electronics down to 200 nm and studied fluctuations in epitaxial film
- Hysteretic switching in YBCO nanowires at 72 K, which shows the possibility of YBCO-based nanocryotron electronics operating as high as 72 K

Berggren & Englund

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Project 3C: Qubit Conversion Technologies



S. Patomaki, to be submitted (2025)

Englund & Wong

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Project 3C: Qubit Conversion Technologies

Project Goals:

- Efficient frequency conversion for photons emitted by quantum memories (e.g. 737 nm wavelength) to telecom wavelength range (1,300 nm or 1,500 nm) using thin film lithium niobate (TFLN) photonics.
- Overcome inhomogeneous broadening of quantum emitters using electro-optic frequency shifting
- Multiplexed entangled photon pair sources for ZALM protocols

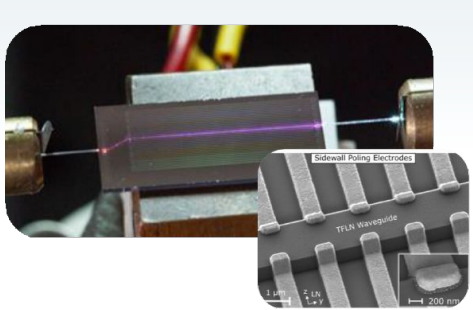
Barriers:

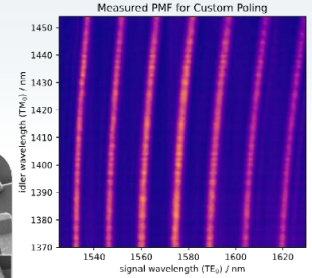
- Variations in strain environment result in different memories operating at different wavelengths
- Thickness variations in TFLN wafers as well as material etching nonuniformities make nonlinear frequency conversion less efficient and difficult/ impossible to target wavelengths of interest;

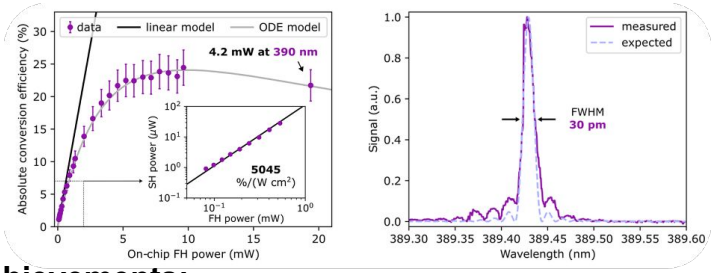
Methodologies to Overcome Barriers:

- Pole-after etch process developed and can take all imperfections into account
- TFLT pursued in addition to TFLN

Loncar







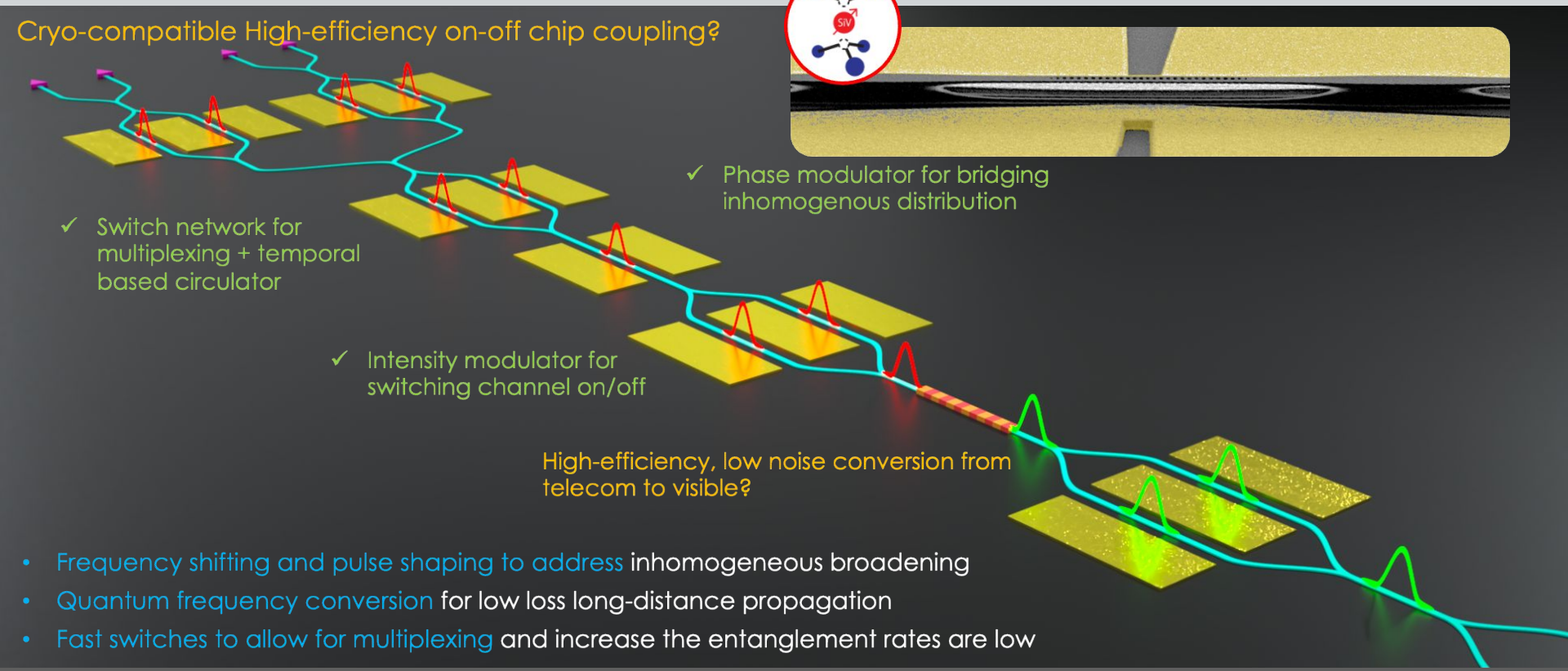
Recent achievements:

- Pole-after etch process for efficient and wavelength specific frequency conversion [Comm. Physics, **8**, 136 (2025)]
- Side-wall poling for efficient and short wavelength frequency conversion [arXiv:2503.16785 (2025)]
- Multiplexed photon pair source [in preparation]
- Frequency shifting and shearing using TFLN phase modulators and photonic molecules [Nat. Comm, **15**, 1 (2024)]
- Cascaded frequency shifters and shearing [in review in *Nature*]

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NSF Engineering Research Center

Project 3C: Qubit Conversion Technologies



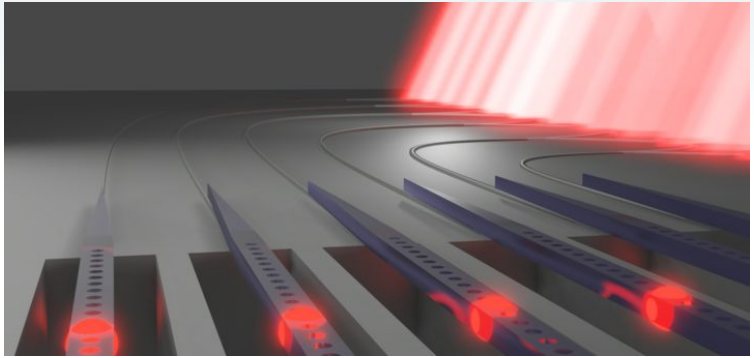
- Frequency shifting and pulse shaping to address inhomogeneous broadening
- Quantum frequency conversion for low loss long-distance propagation
- Fast switches to allow for multiplexing and increase the entanglement rates are low

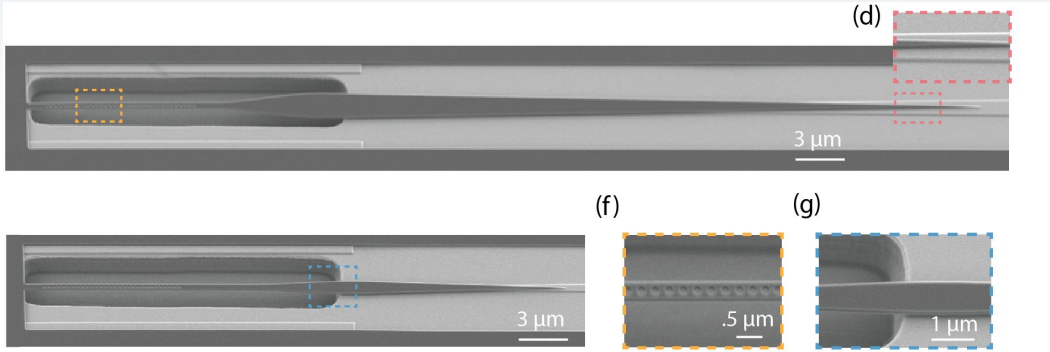
D. Assumpcao*, D. Renaud*, et al, *Nature Comm.*, **15**, 1 (2024)

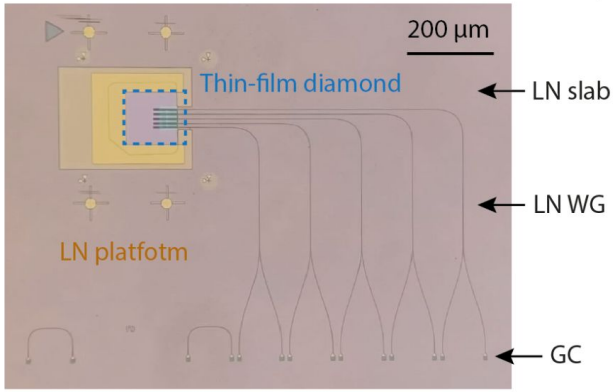
C. Xin, S. Lu, J. Yang, A. Shams-Ansari, *et. al. Comm. Physics,* **8**, 136 (2025)

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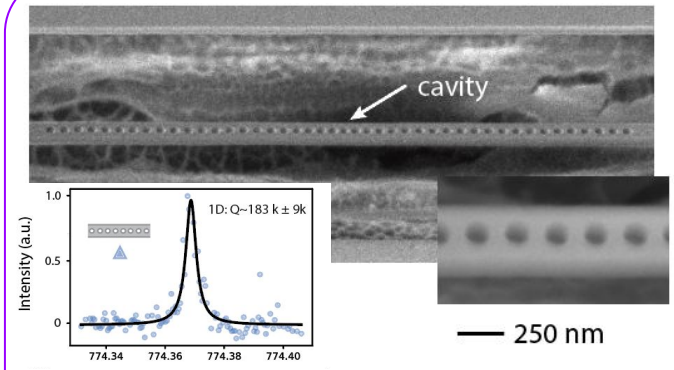
Project 3C: Diamond on LN Photonics

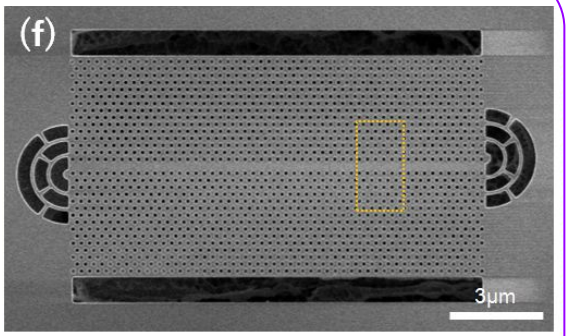






Sophie Ding, *in preparation*

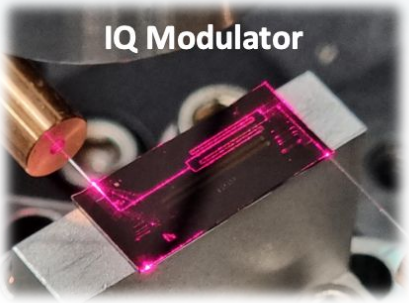




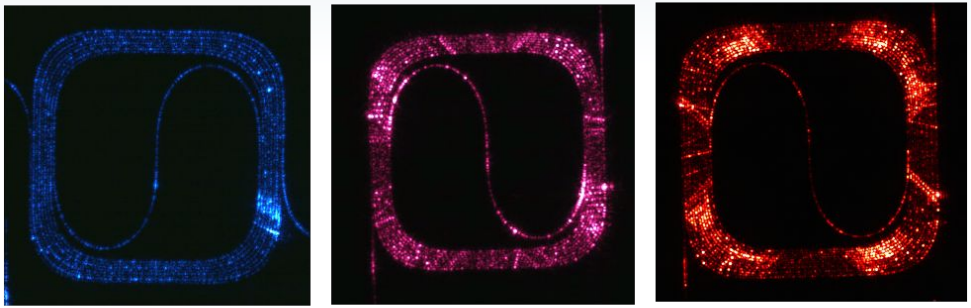
Thin film diamond cavities: Ding et al, *Nature. Comm.*, **15**, 6358 (2024)
Thin film diamond PhC waveguideS: Ding et al, *Nano Letters*, **25**, 32 (2025)

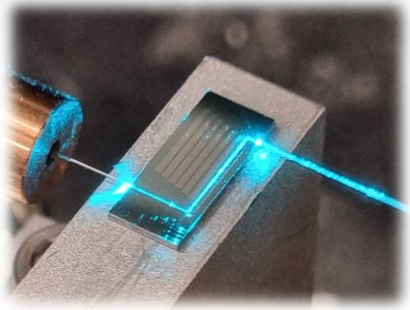
© 2024 Center for Quantum Networks

Project 3C: TFLT Development

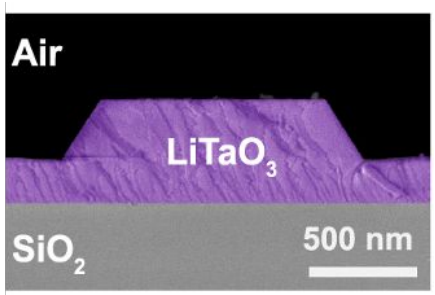


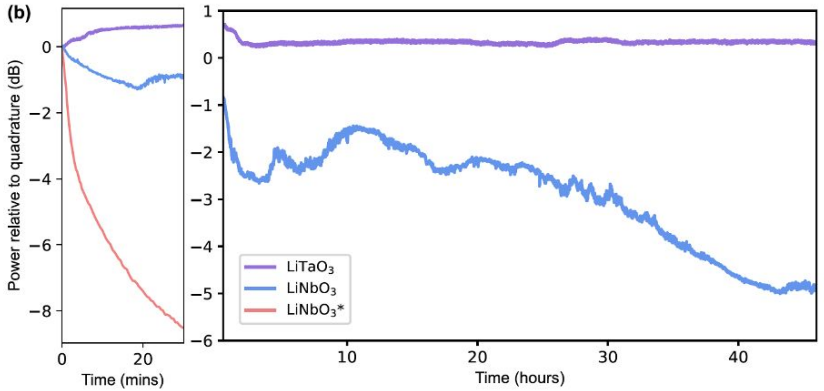
493 nm 630 nm 780 nm

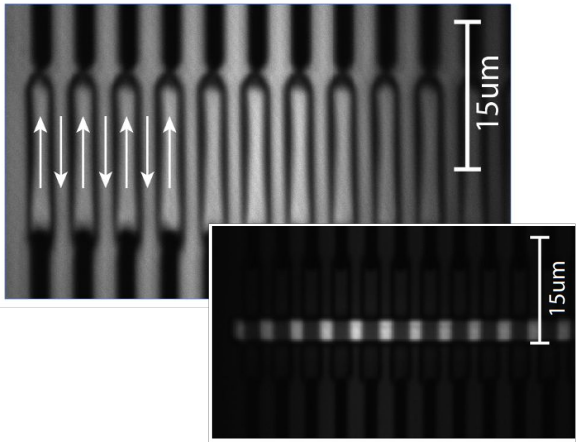




1.1 dB/cm 0.5 dB/cm 0.4 dB/cm





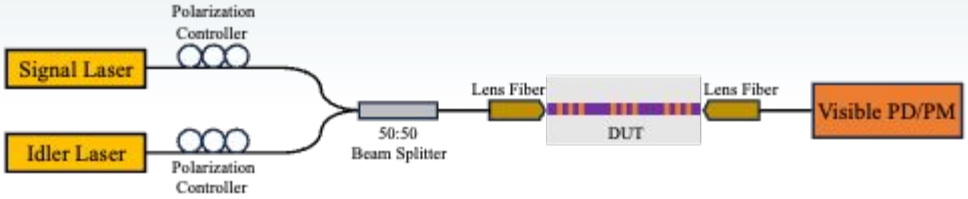


K. Powell, et al *Optics Express*, **32** ,44117 (2024)
K. Powell, et al *APL Photonics*, **10** , 9 (2025)
A. Shelton et al, *APL Photonics*, **10** ,091302 (2025)

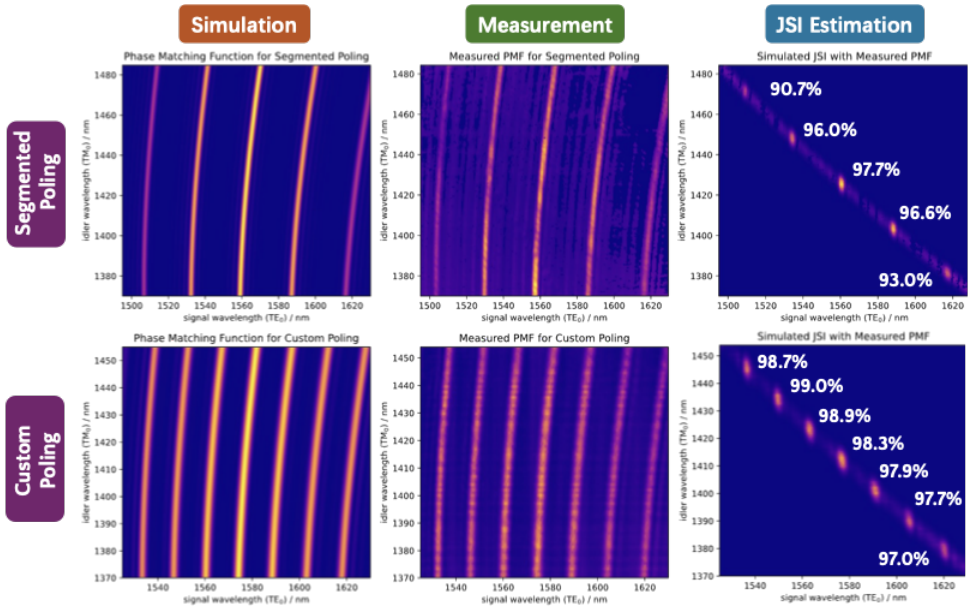
Loncar

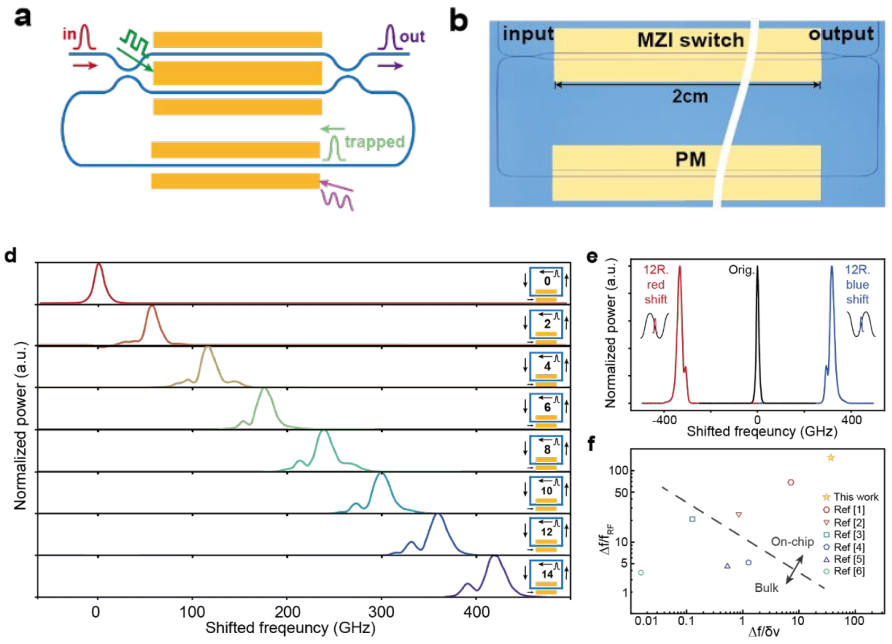
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Project 3C: ZALM source & Frequency Shifting



Cascaded frequency shifting developed for spectral control of generated photons





J. Yang et al, *in preparation*

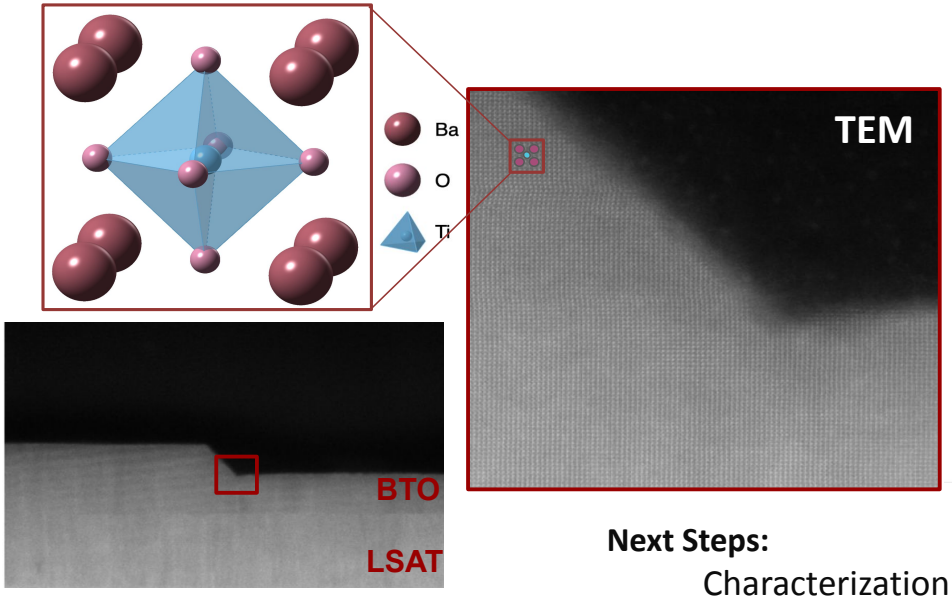
Loncar

X. Li et al, arXiv:2509.25102 *in review in Nature*

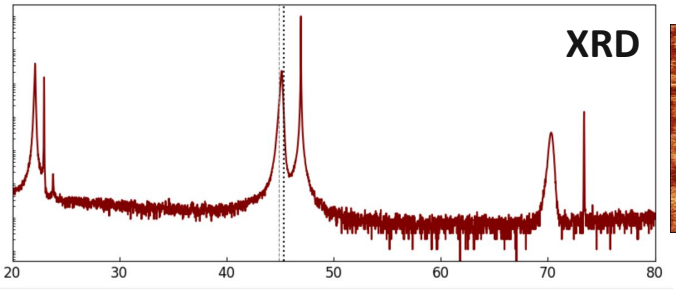
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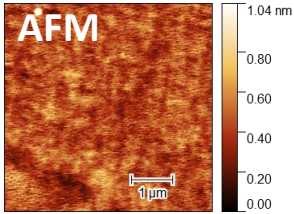
Project 3C: BTO Development

- **Idea:** Barium Titanate (BTO) integrated photonics to leverage large (>1000pm/V) pockels coefficient
- **Requires:** development of high-quality crystalline thin-films with device-compatible thickness
- **Our approach:**
  1. Hybrid molecular beam epitaxy (hMBE) for stoichiometric self-regulated growth of >200nm films



TEM, XRD, and AFM reveal high-quality BTO films grown via hMBE robust to nanofabrication





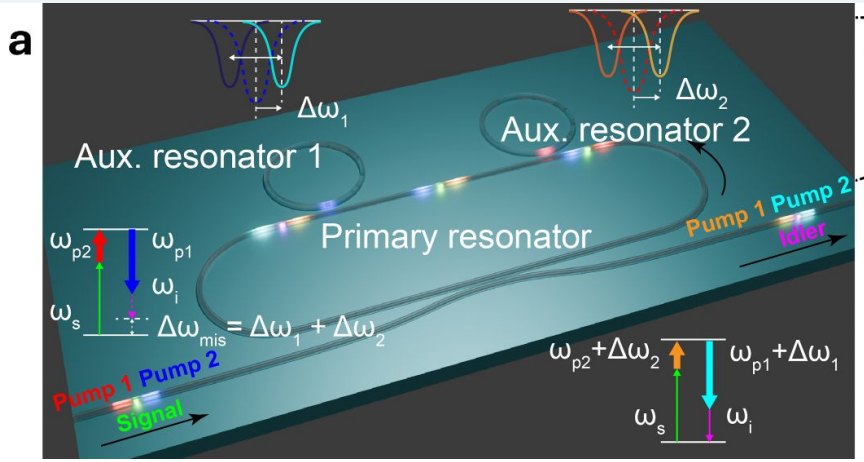
Next Steps:

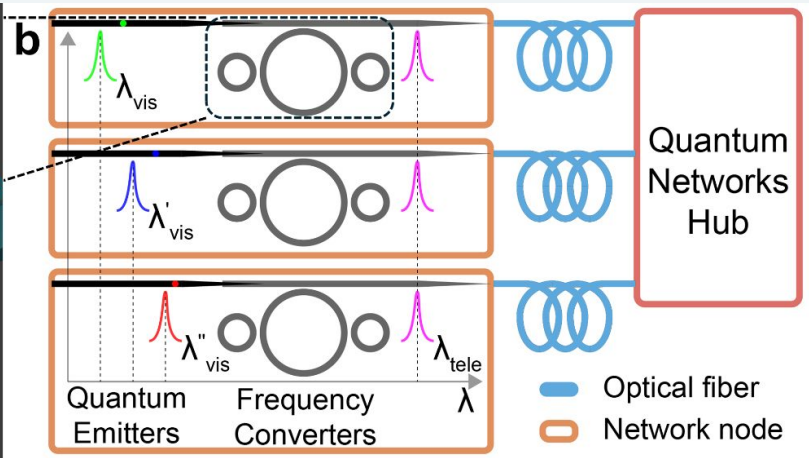
Characterization of material optical losses and modulator performance

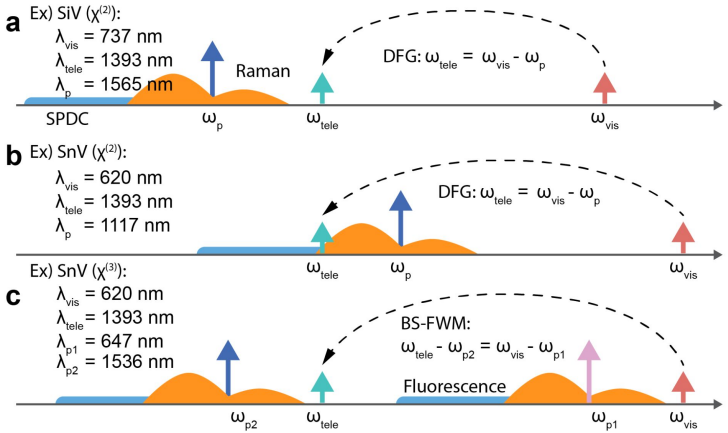
T. Zulu, et al. In Preparation
A. Cavanagh, et al. Advanced Optical Materials 2025

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3C: Low-noise QFC via SiN PIC







Challenge:

- In $\chi^{(2)}$-based quantum frequency conversion between SnV photon and telecom photon, Raman-Stokes processes scattering from the pump into the idler mode become a significant noise process degrading entanglement fidelity

Approach:

- Low-noise $\chi^{(3)}$-based quantum frequency conversion allows for pump frequency arrangement that puts Raman-Stokes processes far from idler mode, vastly improving entanglement fidelity. Ultra-low loss silicon nitride also allows for low pump powers and we have devised methods for active phase matching.

G. Choi et al., "Nonlinear Quantum Frequency Conversion for Quantum Networks based on Bragg Scattering Four-Wave Mixing", CLEO 2025
G. Choi et al., "Resonator-Assisted dispersion engineering for efficient frequency conversion using Bragg Scattering Four-Wave Mixing", *in-preparation*

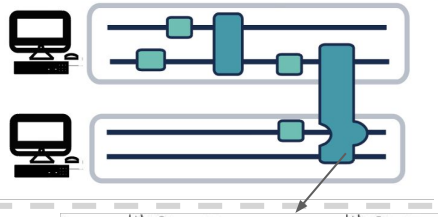
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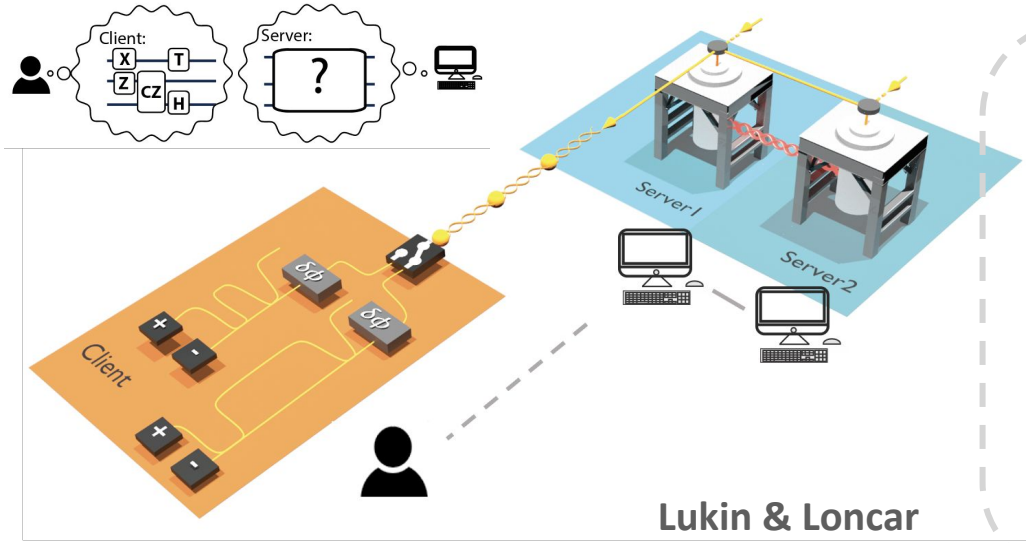
Project 3D: Blind Quantum Computing

- **Idea:** quantum computation + quantum-enabled privacy
- **Requires:** exchange quantum info between clients and servers, naturally using photons
- **Our approach:**
  1. Efficient light-matter interface using the cavity-QED system
  2. Integrated multi-qubit control for quantum logics

Universal blind logics

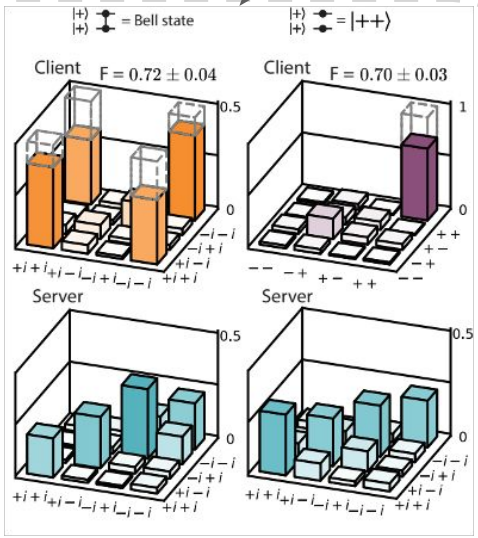
1. Controlled by clients
2. Hidden from servers





Lukin & Loncar

e.g. 2Q blind gate between servers:



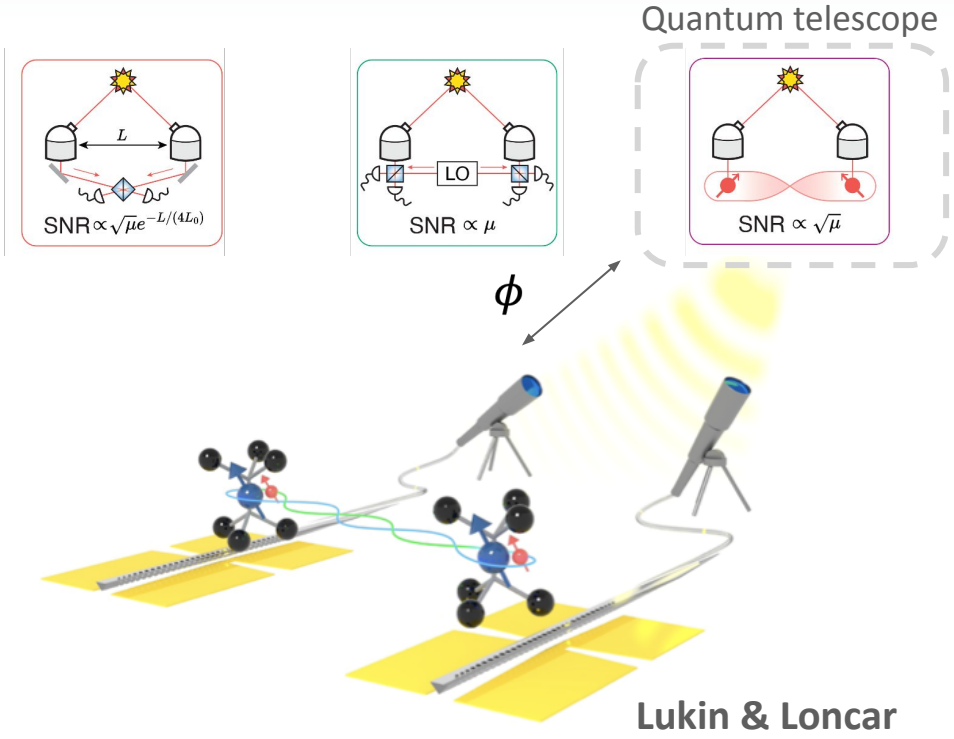
Info. leakage to servers < 0.12 bits (full info: 1 bit)

Wei, Stas, Suleymanzade, Baranes et al., *Universal distributed blind quantum computing with solid-state qubits*, Science **388**, 509-513 (2025)

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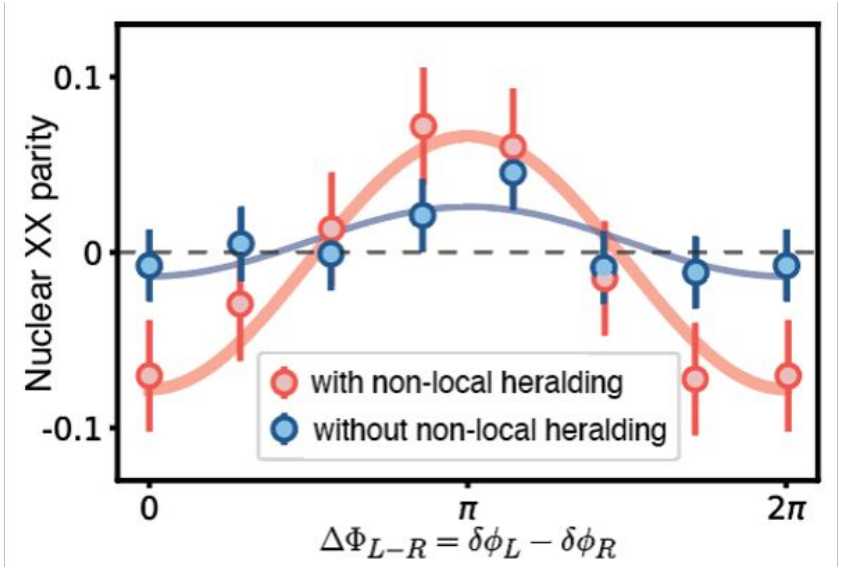
Project 3D: Quantum Telescopes

- **Idea:** remote entanglement to enable non-local phase sensing, with the sensitivity better than classical approaches



Key: Using entanglement to perform non-local heralding

1. Knowing arrival of a photon without destroying nonlocal phase info ϕ
2. Effectively enhance signal-noise ratio (SNR)



Stas, Wei, Sirotin et al., *Entanglement Assisted Non-local Optical Interferometry in a Quantum Network*, arXiv:2509.09464 (2025)

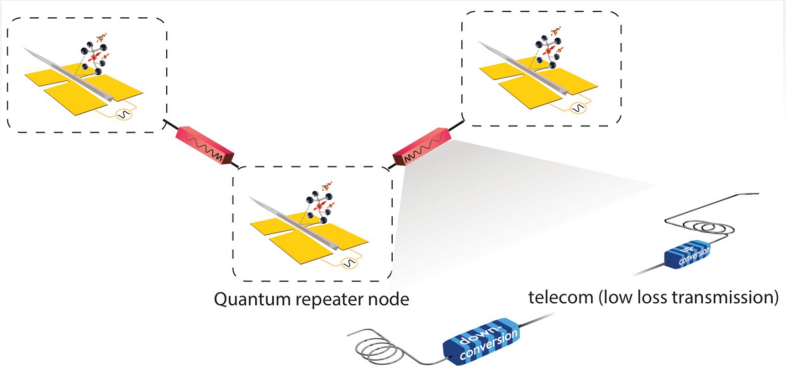
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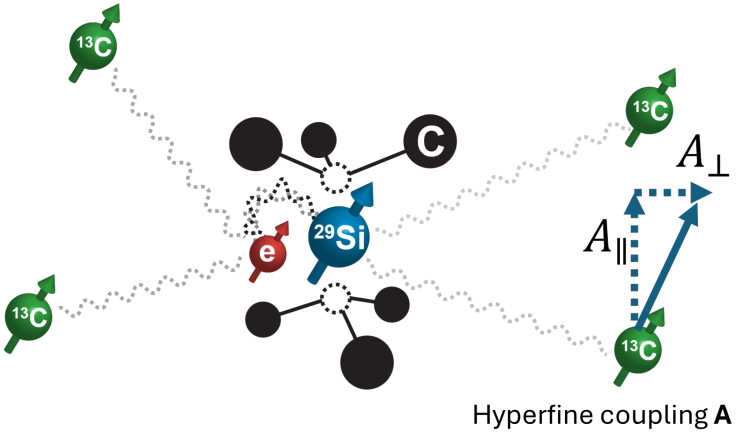
Project 3D: Nuclear Spin Memories for Multinode Network

Challenge: Photon loss over long distances for large scale quantum networks

Solutions:

1. Conversion from SiV 737 nm to low-loss 1350 nm telecom wavelength[1]
2. Integration of a quantum repeater node using an additional memory robust against repeated entanglement attempts





Hyperfine coupling **A**

Future directions:

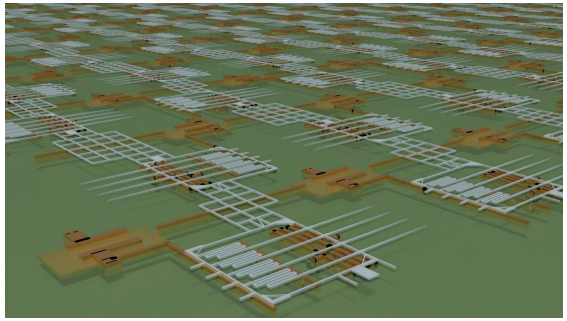
1. Develop ^{13}C nuclear spins as memories that remain coherent over hundreds to thousands of entanglement attempts
2. Demonstrate memory-enhanced generation of two concurrent spin-photon entangled pairs, followed by quantum repeater functionality with entanglement swapping in a three-node SiV quantum network

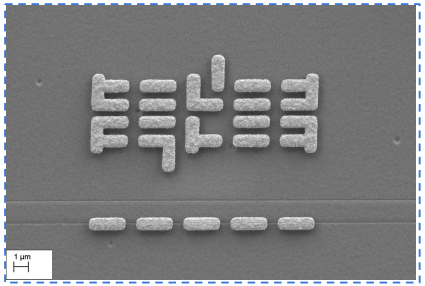
[1]Knaut et al., *Entanglement of Nanophotonic Quantum Memory Nodes in a Telecom Network*, Nature **629**, 573–578 (2024).

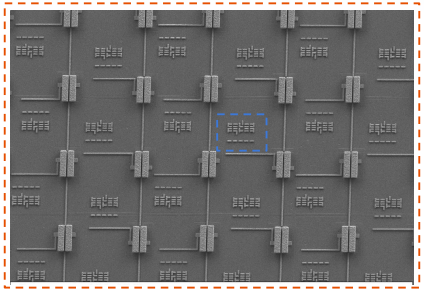
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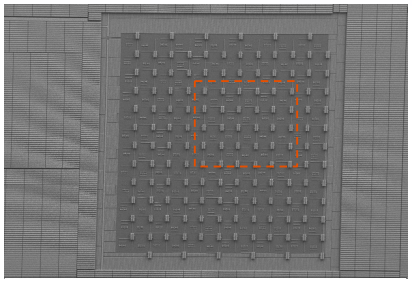
Project 3E: Qubit Control

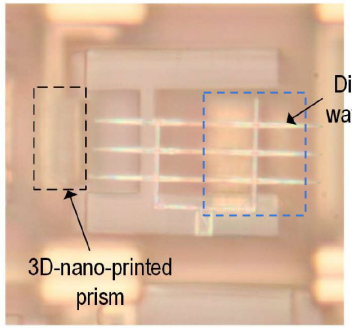
CMOS Platform for Scalable Heterogeneous Integration

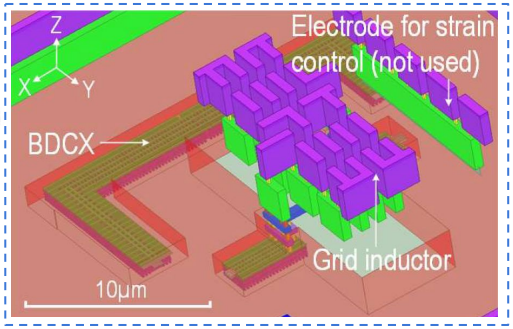


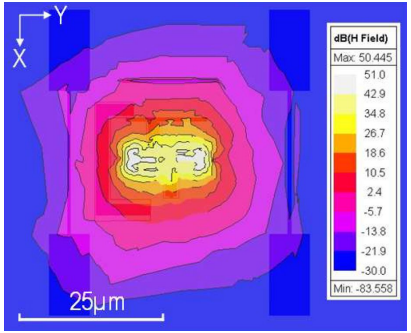


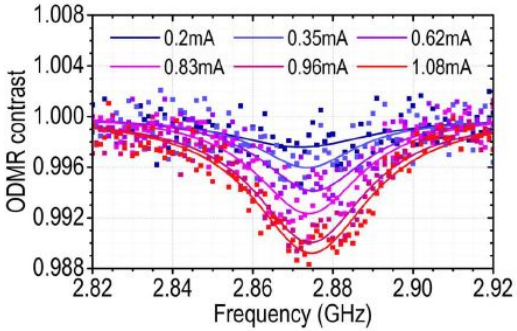












Team: Yuyang (Asher) Han, Jinchen Wang, Ruonan Han, Dirk Englund, et al.
Publication: ISSCC (2026) under review

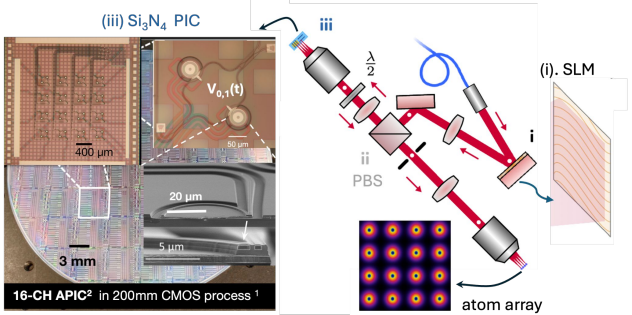
Englund

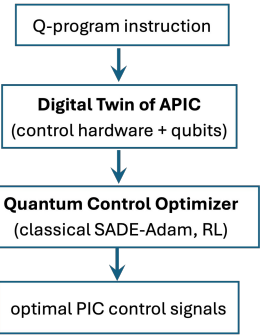
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Project 3E: Qubit Control

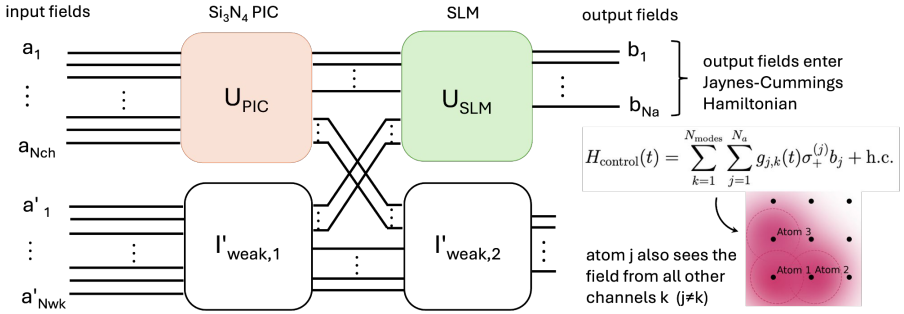
Hardware Co-Designed Optimal Control via Reinforcement Learning

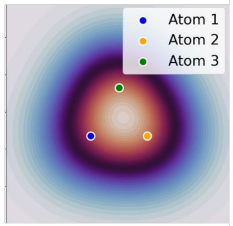
Physical System of APIC



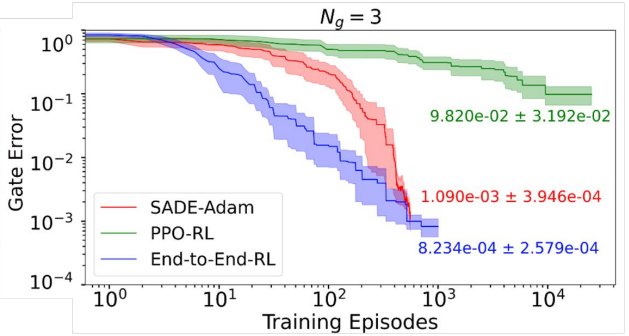


Digital Twin of APIC





- beam waist 2.0 um
- atom spacing 3.0 um
- $T_{1q\text{-}gate}$ set to 100 ns



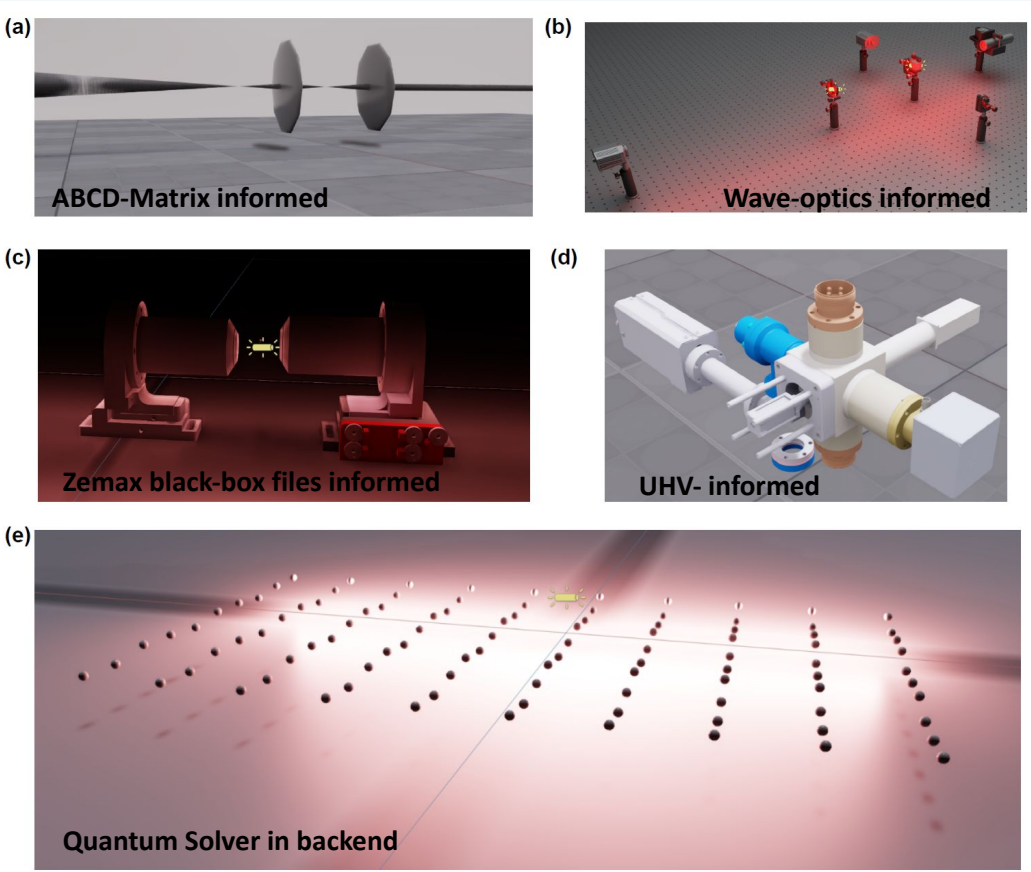
- DT model serves as env. for RL
- $U_{target} = R_1 \otimes R_2 \otimes R_3$
- R_i: single-qubit gate, random Clifford
- each curve shows the average over 5 random sets (shaded region shows std. deviation)

Q. Ding and D.E., arXiv:2504.11737v1

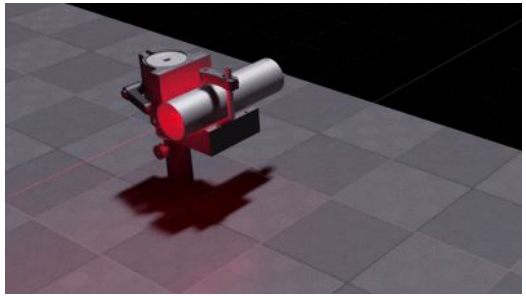
Englund

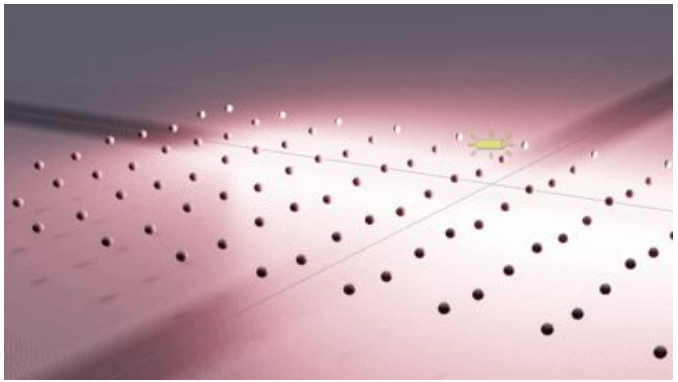
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Project 3E: Qubit Control



Physics informed digital twin with NVIDIA Omniverse & Zemax Ansys team





Englund

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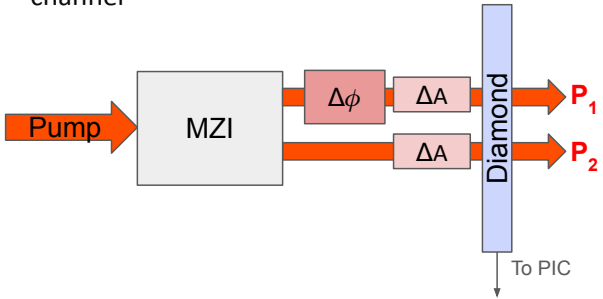
3F: Resonant pump suppression for high-fidelity emissive mode HOM interference

Motivation:

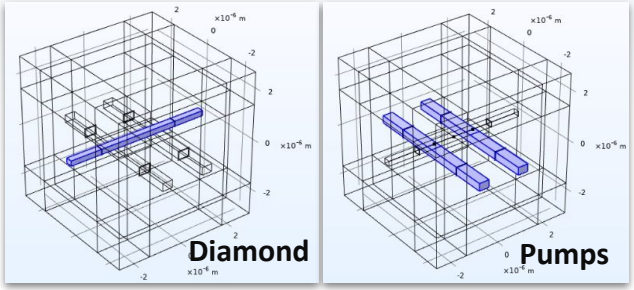
- Pump scattering into mode collecting SnV-emitted photons prevents high-fidelity heralded entanglement from false-detection events.
- Resonant excitation overlaps spectrally with emitted photons, pump scattering dominates collected signal, reducing entanglement fidelity from false-heralds

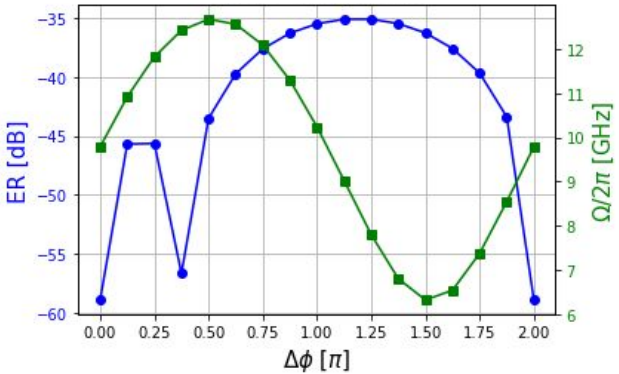
Goal: Efficient suppression of resonant pump photons ⟶ isolate **single-photon** from emitter

Concept: Evanescently excite emitter with one pump waveguide, control relative phase and amplitude of second pump waveguide to cancel scattering into diamond collection channel



Simulation:

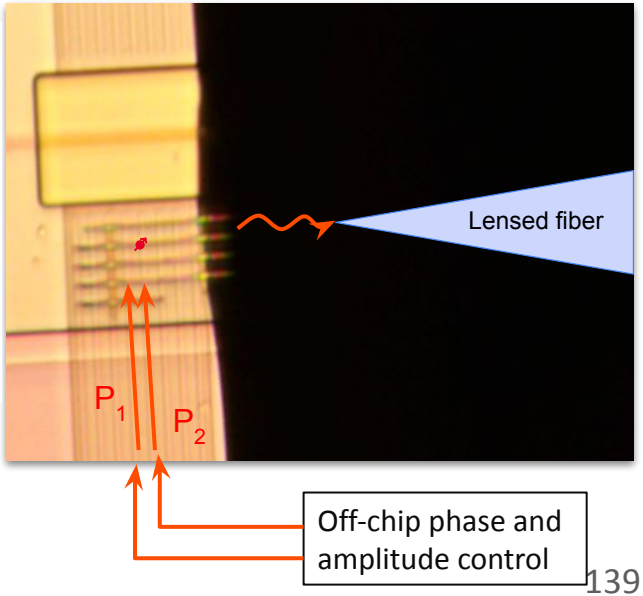




Simulations yield nearly 60dB pump extinction with high Rabi rate, but difficult to accurately model due to non-identical mesh points in scattering regions.

Experiments currently underway!

Proof-of-concept device:

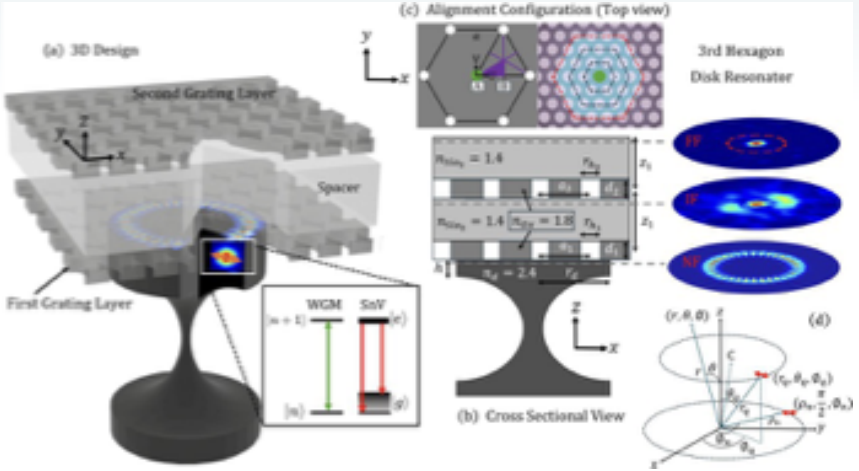


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Project 3G: Efficient Photon Counting

Project Goals:

- Designing efficient, scalable interfaces for spin-photon entanglement of color centers
- Efficiency Enhancement: Improve the efficiency, scalability, and reliability of quantum networks by enhancing spin-photon interfaces and quantum memory systems.
- Scalability: Develop multi-emitter spin-light interfaces within a single system to scale quantum networks effectively.
- Digital Twin Creation: Develop a digital twin for quantum networks to simulate and optimize spin-photon interfaces and quantum memory systems.



Barriers:

- Purcell enhancement and coupling efficiency are often inversely correlated
- Manufacturing variations reduce efficiency

Methodologies to Overcome Barriers:

- Further Enhanced Quantum Efficiency
- Optimization of Spin-Photon Interfaces
- Alignment-Free Coupling

Camacho & Englund

Future work

- Improving Entanglement generation
- Combine frequency conversion + spatial conversion
- Digital Twin Creation

S. Mirzaei-Ghormish, et al, "High-efficiency vertical emission spin-photon interface for scalable quantum memories," arXiv:2503.20111 (2025)

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Thrust 3 Summary

3A: *Lanthanide-based molecular color centers with engineered Yb^{3+} fields for tunable spin–optical coherence.*

3A: *Antenna and chiral ligands enhance yield and enable spin-selective processes.*

3B: *SNSPD-based logic circuits for scalable quantum communication.*

3B: *High-Tc MgB_2/YBCO devices operate up to 72 K with CMOS compatibility.*

3C: *Wafer-scale thin-film ferroelectrics (TFLN, TFLT) for nonlinear frequency conversion and wavelength trimming; UV generation demonstrated; Strategies for on-chip ZALM developed;*

3C: *Thin film diamond cavities and waveguides demonstrated and integrated with TFLN.*

3D: *SiV-based repeater nodes with asynchronous Bell-state measurements and ^{13}C memories.*

3D: *Metro-area network developed and used for blind quantum computing and astronomy;*

3E: *Piezo-actuated and strain-engineered photonics for tunable emitters.*

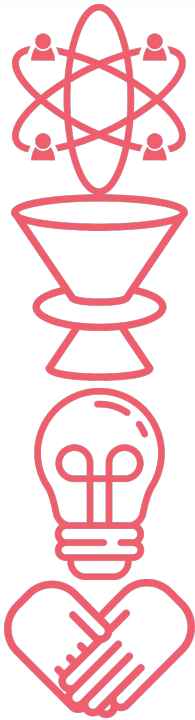
3E: *Diamond spin–phonon systems (LiNDa, phononic crystals) with long coherence and high-Q coupling.*

3F: *Architectures for multiplexed entanglement swaps.*

3F: *Reduced loss and improved throughput for scalable quantum networks.*

3G: *Cavity-QED and dual-layer photonic interfaces with >95% fiber mode overlap.*

3G: *>90% modeled coupling for SiV/SnV centers for scalable repeater nodes.*



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Year 5-10 Major Milestones

2025
ZALM Generation of high-purity, heralded and demultiplzed polarization-entangled photon pairs
SiV and SnV system improvements
Downselection of various frequency / mode conversion strategies

2026
Early Integration in the testbeds
Loading of heralded single photon in a single cavity-SiV memory
Frequency down-conversion of entangled photon pairs (1405 nm -> 737 nm)

2027
ZALM: Compare polarization- and time-bin- entanglement schemes
Loading of heralded photons into a pair of cavity-SiV memories
Integration into Testbeds

2028
Scale up number of photon pairs
On-chip ZALM source demonstrated
Integration into Testbed

2029
Full Integration in the testbeds and test/verification
Proof-of-principle integration for the ZALM Source.

2030
Quantum memory modules with 100 qubits, integrated into testbeds
Final integration into the testbeds

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CONNECT
Centre for Future Networks

NSF

Center for Quantum Networks

A World Leading SFI Research Centre

Science Foundation Ireland sfi For what's next



CoQREATE
US-Ireland Collaboration

Dan Kilper, TCD
Ryan Camacho, BYU

CoQREATE
Convergent Quantum Research Alliance in Telecommunications



HOST INSTITUTION

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

PARTNER INSTITUTIONS

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DCU
Maynooth University National University of Ireland Maynooth
DUBLIN
Tyndall National Institute
UCC University College Cork, Ireland
UCD University College Dublin An Coláiste Ollscoile, Baile Átha Cliath
University of Limerick Ollscoil Luimnigh
Waterford Institute of Technology

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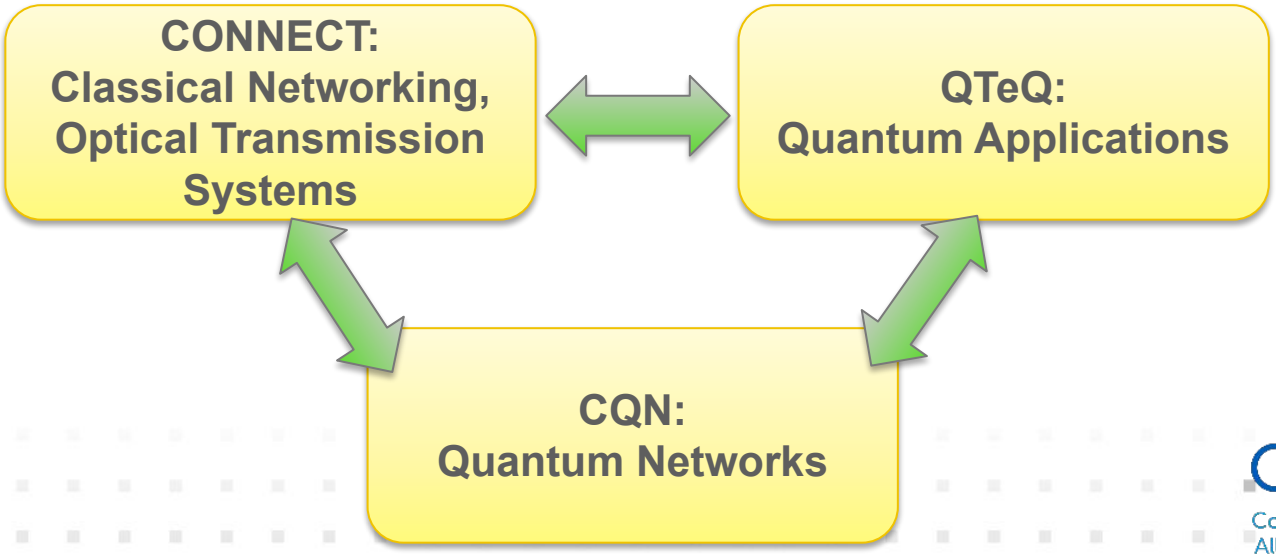
Ireland's European Structural and Investment Funds Programmes 2014-2020
European Union European Regional Development Fund
Science Foundation Ireland sfi For what's next

Convergent Quantum REsearch Alliance in Telecommunications: CoQREATE

SFI+DFE+NSF US-Ireland Centre to Centre Program

Northern Ireland: QTeQ @ Queens U. Belfast;

Republic of Ireland: CONNECT: 12 Universities and Institutes



CoQREATE

Convergent Quantum Research Alliance in Telecommunications

C2C Projects

Monitor placement problem for quantum network tomography
Student: Matheus Guedes de Andrade
CQN Faculty Advisor: Don Towsley
Ireland/NI Collaborator: Athira Raghunadhan / Indrakshi Dey / Nicola Marchetti / Daniel Kilper

Conference Key Agreement with Integrated Green Machine
Student: Benjamin Fisher, Sequoia Ploeg and Gabe Richardson
CQN Faculty Advisor: Ryan Camacho
Ireland/NI Collaborator: Peter O'Brien

Efficient decoding algorithms for quantum LDPC codes
Student: Michele Pacenti, Dimitris Chytas
CQN Faculty Advisor: Bane Vasic
Ireland/NI Collaborator: Mark Flanagan, Dan Kilper, Mauro Paternostro

Noise protection in Quantum Networks
Student: Debayan Bandyopadhyay
CQN Faculty Advisor: Liang Jiang
Ireland/NI Collaborator: Mauro Paternostro, Liam Barry, John Donegan, and Mark Flanagan

Quantum Internet Standards and Governance: Transatlantic privacy due diligence framework
Leads: Elif Kiesow Cortez & Robert Heverly





Student Exchanges



Matheus Guedes de Andrade
University of Massachusetts Amherst



Sequoia Ploeg
Brigham Young University



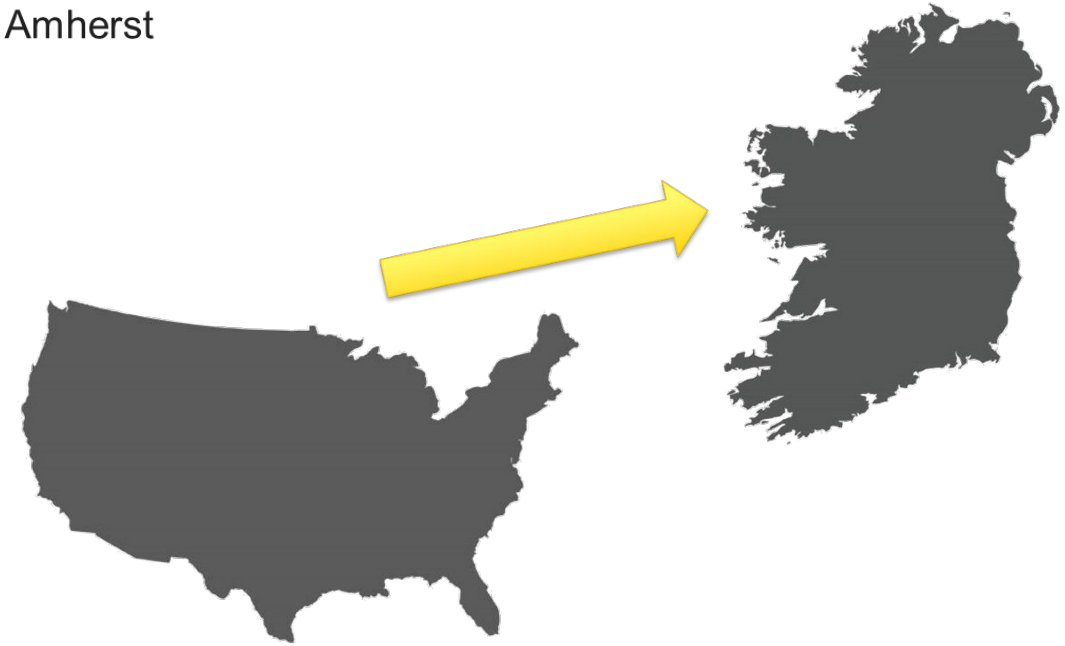
Gabe Richardson
University of Arizona



Debayan Bandyopadhyay
University of Chicago



Michele Pacenti
University of Arizona



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Student Exchanges



Vivek Vasan
Trinity College Dublin



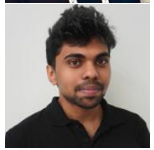
Sana Javed
University College Dublin



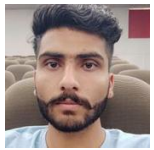
Conall Campbell
Queens Univ. Belfast



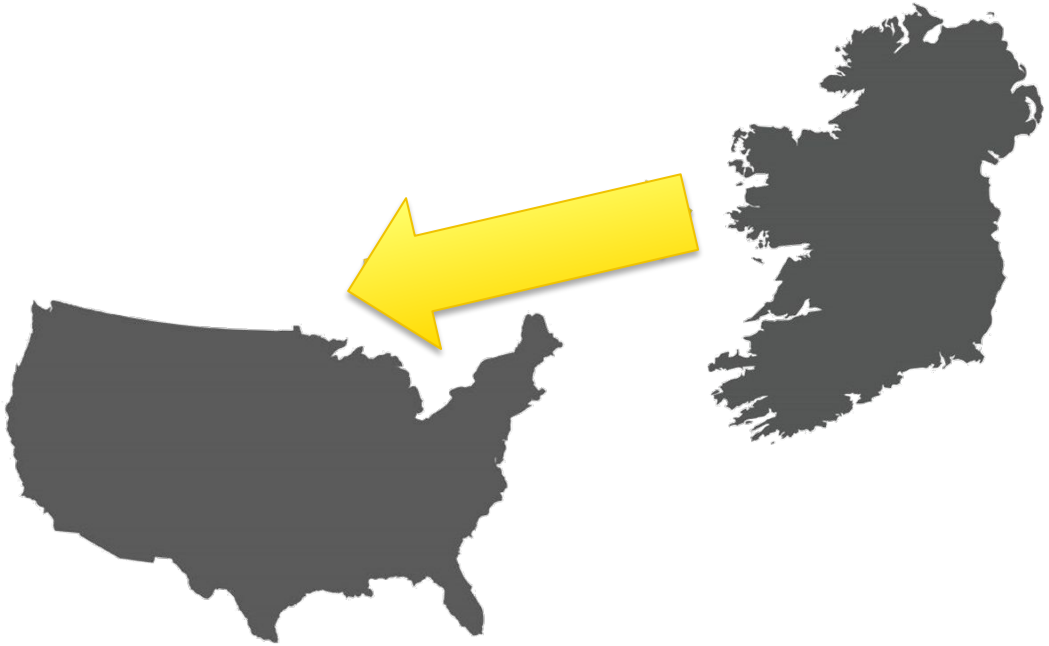
Athira Raghunda
Trinity College Dublin



Kavindu Sellahewa
Southeast Technological Univ.



Vikash Kumar
Trinity College Dublin



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Broader Impacts

Student Experiences

“I am truly happy to have had the opportunity to take part to this project; I feel enriched both academically and as a human.”

“Staying at CONNECT was a great opportunity considering the vast number of students working on quantum networks and the workshops that occurred in Dublin and Belfast throughout my stay.”

“Overall, I had a splendid time in Ireland—the country was beautiful and welcoming, and I learned a lot from the communications experts at Trinity College.”



BYU Undergrad
→ PhD TCD



Brandt Bashaw

PhD Student

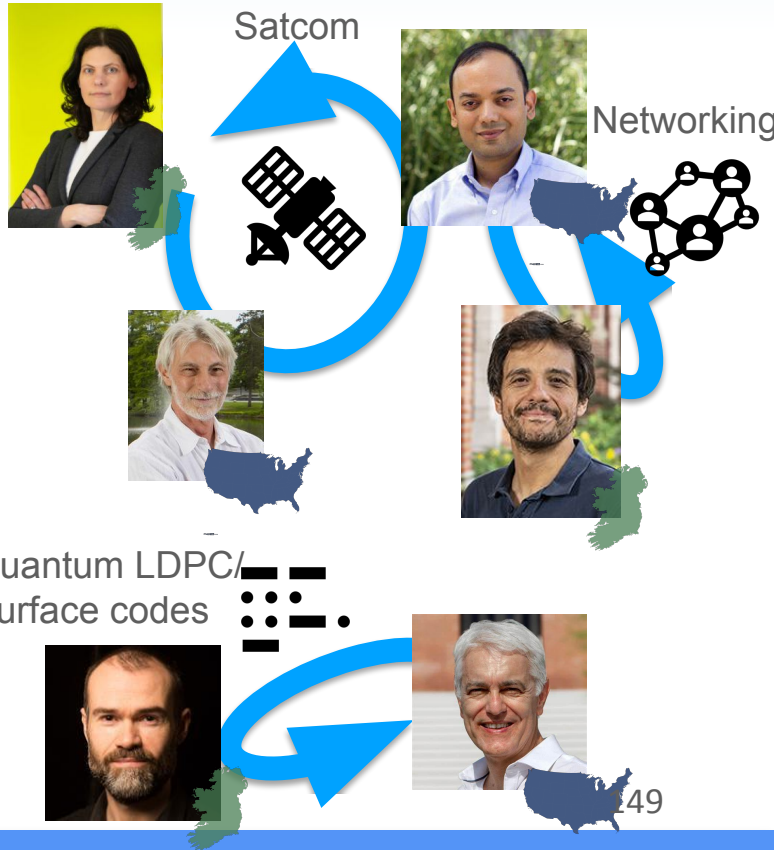
bashawb@tcd.ie

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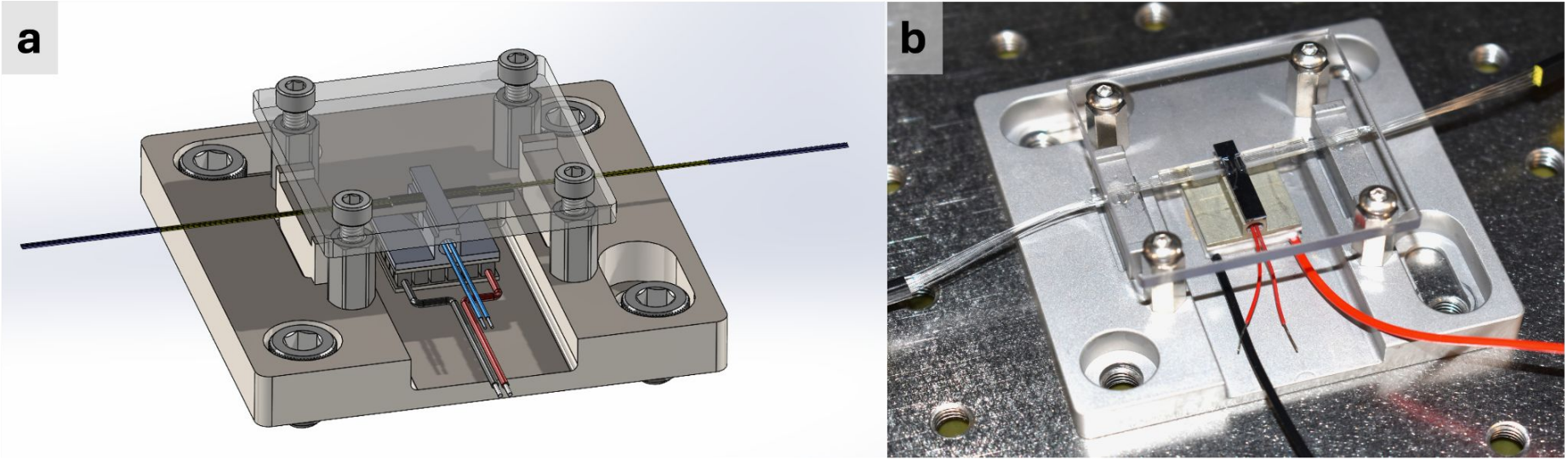
Collaboration



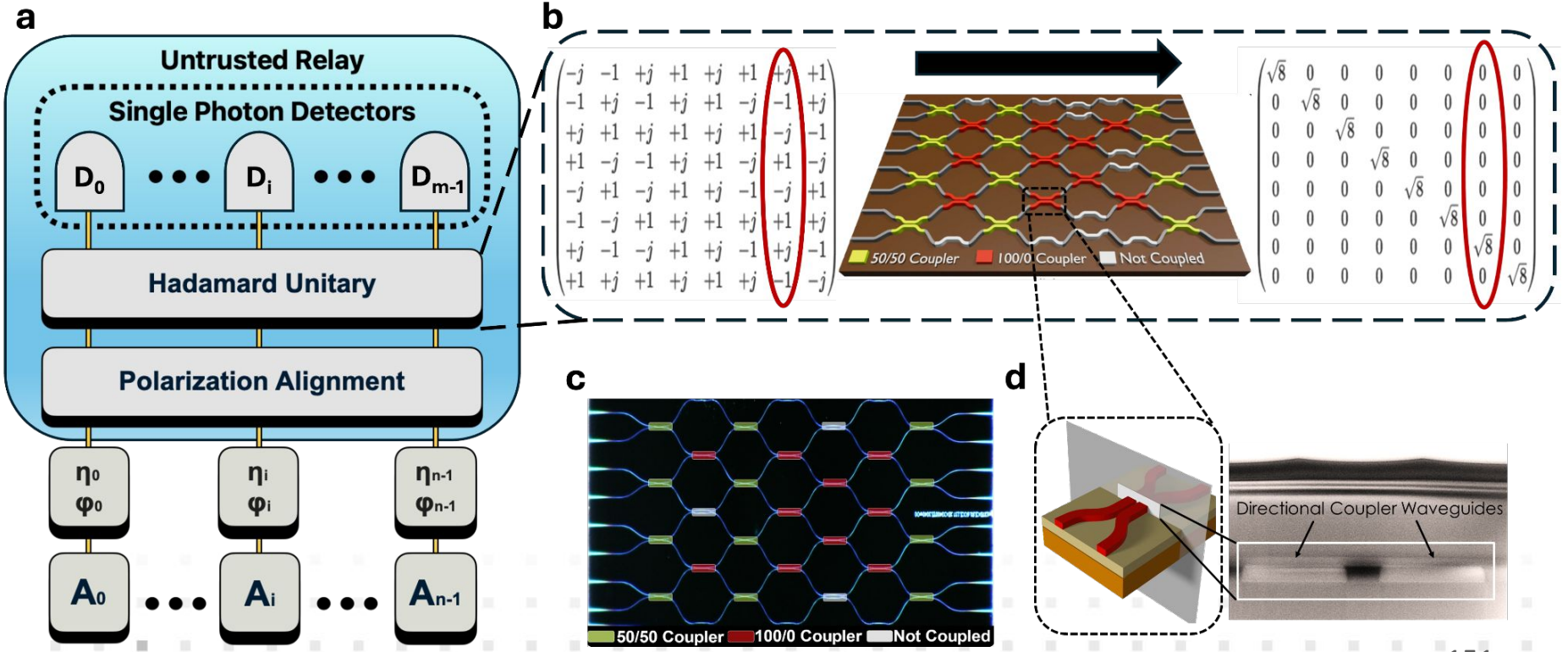


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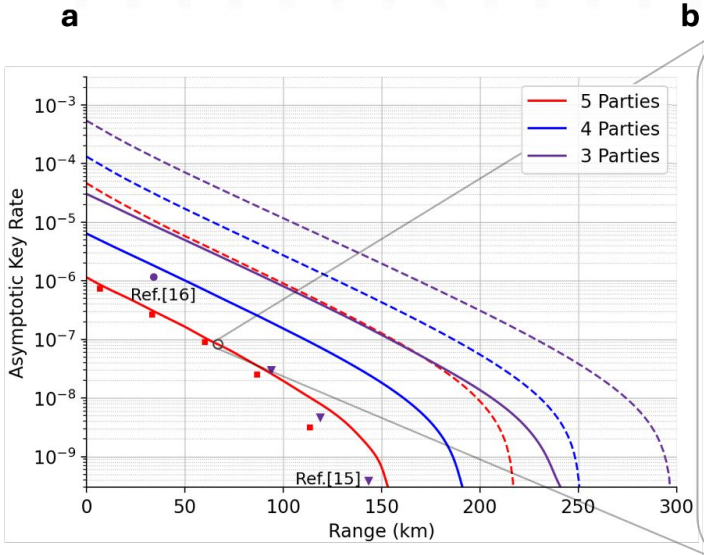
Integrated Photonic Green Machine

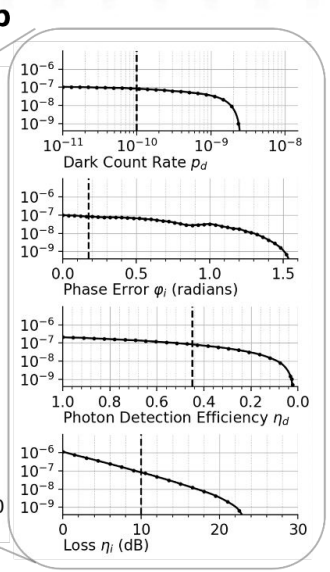


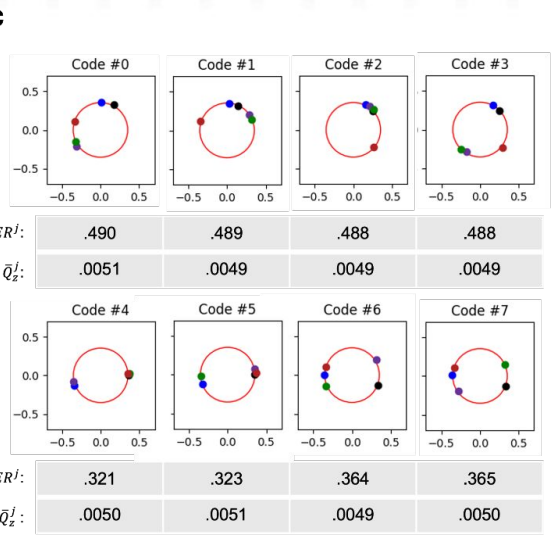
Integrated Photonics Green Machine



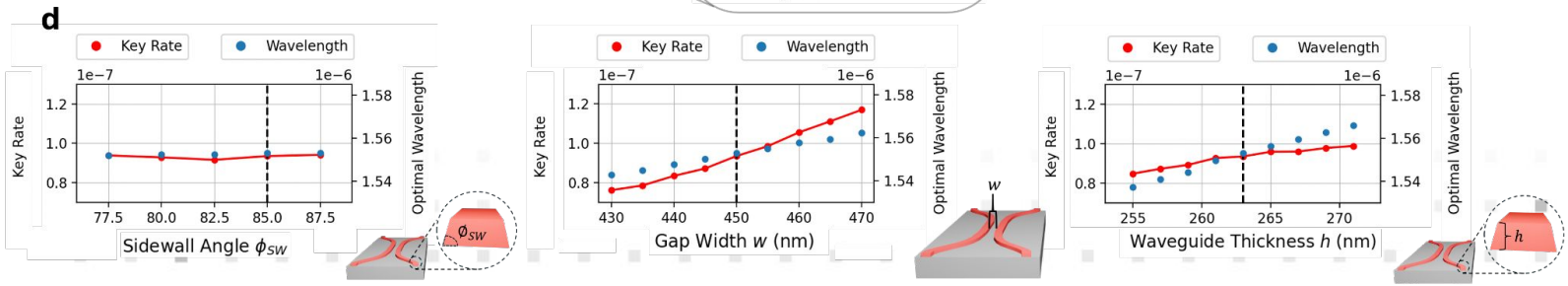
Conference Key Agreement







$QBER^j$:	.490	.489	.488	.488
$\bar{Q}_z^j$:	.0051	.0049	.0049	.0049
$QBER^j$:	.321	.323	.364	.365
$\bar{Q}_z^j$:	.0050	.0051	.0049	.0050



Publications

D. Chytas, M. Pacenti, N. Raveendran, M. F. Flanagan and B. Vasić, "Enhanced Message-Passing Decoding of Degenerate Quantum Codes Utilizing Trapping Set Dynamics," in IEEE Communications Letters, vol. 28, no. 3, pp. 444-448, March 2024, doi: 10.1109/LCOMM.2024.3356312.

M. Pacenti, M. F. Flanagan, D. Chytas and B. Vasić, "Progressive-Proximity Bit-Flipping for Decoding Surface Codes," in IEEE Transactions on Communications, doi: 10.1109/TCOMM.2024.3454029.

S. Javed, F. Garcia-Herrero, B. Vasić and M. F. Flanagan, "Low-Complexity Linear Programming Based Decoding of Quantum LDPC Codes," ICC 2024 - IEEE International Conference on Communications, Denver, CO, USA, 2024, pp. 1782-1787, doi: 10.1109/ICC51166.2024.10622622.

R. Bali et al., "Routing and Spectrum Allocation in Broadband Degenerate EPR-Pair Distribution," ICC 2024 - IEEE International Conference on Communications, Denver, CO, USA, 2024, pp. 4954-4960, doi: 10.1109/ICC51166.2024.10622453.

R. Bali, et. al. “Routing and Spectrum Allocation in Broadband Quantum Entanglement Distribution”

arXiv 2404.08744

C. J. Campbell, et. al. “Entanglement distribution through separable states via a zero-added-loss photon multiplexing inspired protocol” Phys. Rev. Research 6, 03331

A. Raghunda, M. G. de Andrade, D. Towsley, D. Kilper, N. Marchetti, “Optimal Monitor Placement in Quantum Network Tomography” QCE 2024

R Maule, et. al. “Fair and Efficient Scheduling Strategies for Satellite Assisted QKD Systems” QCE 2024

K. Sellahawa, et al. “Airborne reflectors for satellite-based quantum entanglement and key distribution,” Scientific Reports, 15, 36323 (2025). https://doi.org/10.1038/s41598-025-20273-6

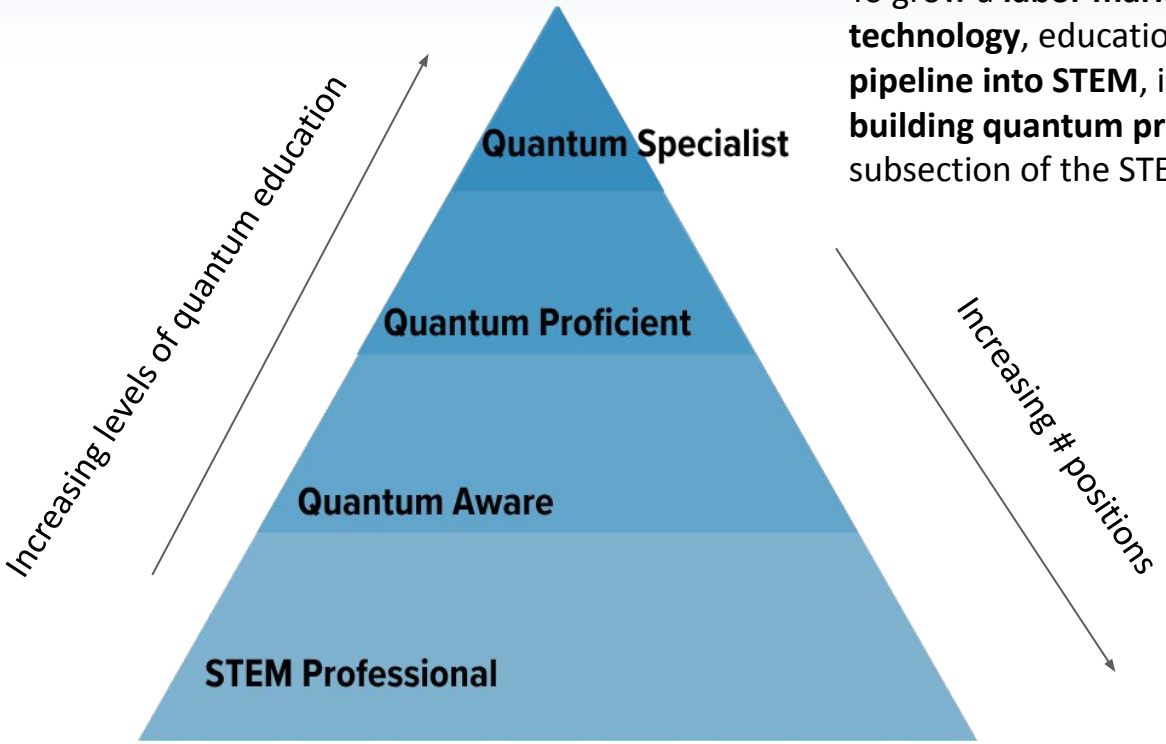
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Engineering Workforce Development

Noel Hennessey, PhD
Director, Engineering Workforce Development
University of Arizona
nhennessey@arizona.edu

Funded by National Science Foundation Award #1941583



To grow a **labor market supportive of quantum science and technology**, education initiatives should focus on a **broad pipeline into STEM**, introducing learners to QSE and **building quantum proficiency** and expertise with a smaller subsection of the STEM workforce.

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STRATEGY

INSPIRE

Engage learners in **new exploration** of quantum science and engineering

- Community and K12 outreach
- Online short courses
- Undergraduate bootcamps

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STRATEGY

INSPIRE **EDUCATE**

Provide **coursework, workshops,** and **formalized learning** to enhance knowledge and credentials of STEM/QSE professionals

- Graduate degree programs and certificates
- Undergraduate coursework and QSE minors
- Innovative collaborative course offerings

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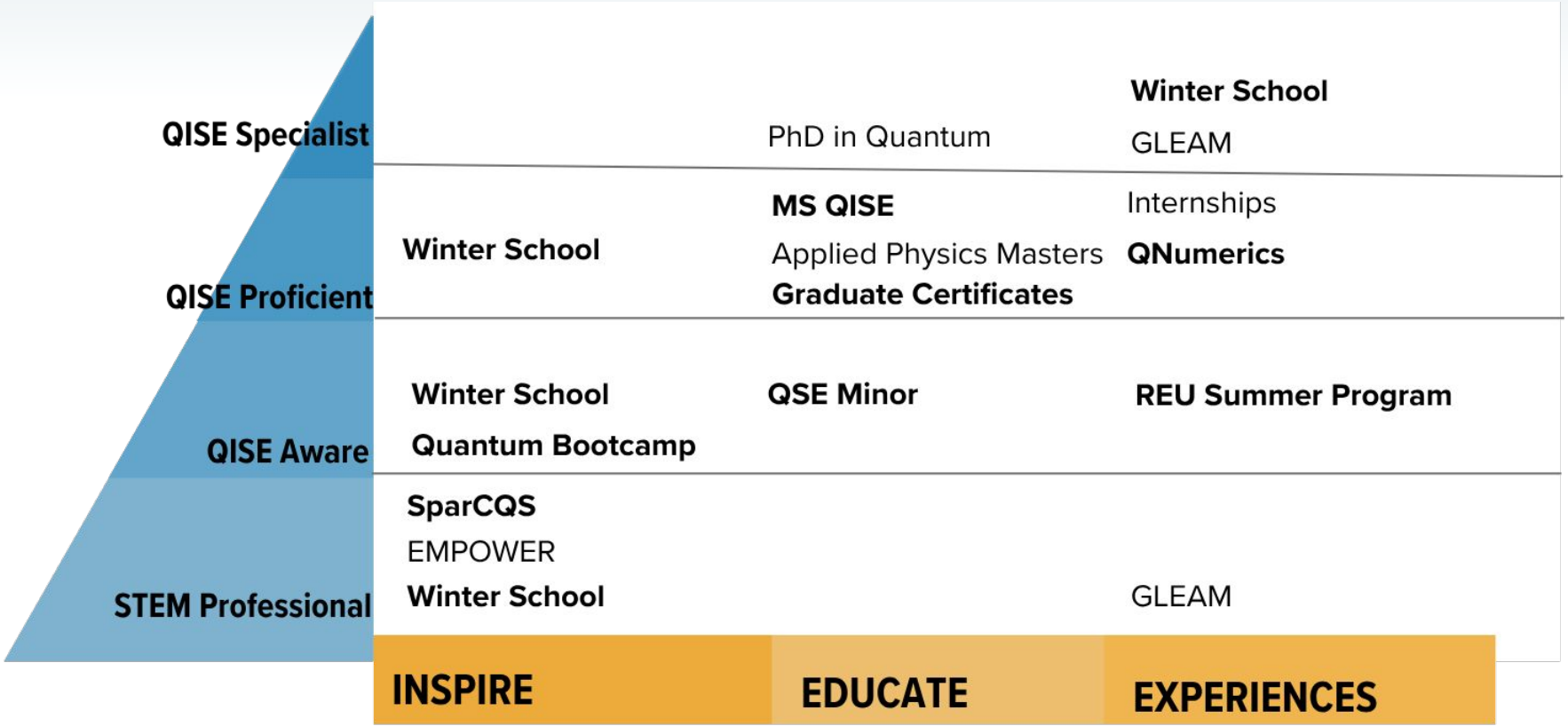
STRATEGY

INSPIRE | **EDUCATE** | **EXPERIENCES**

Cultivate **experiential learning opportunities** with industry and academic partners

- Research Experiences for Undergraduates
- Industry internship opportunities/partnerships with our IAB
- Young Scholars mentored research

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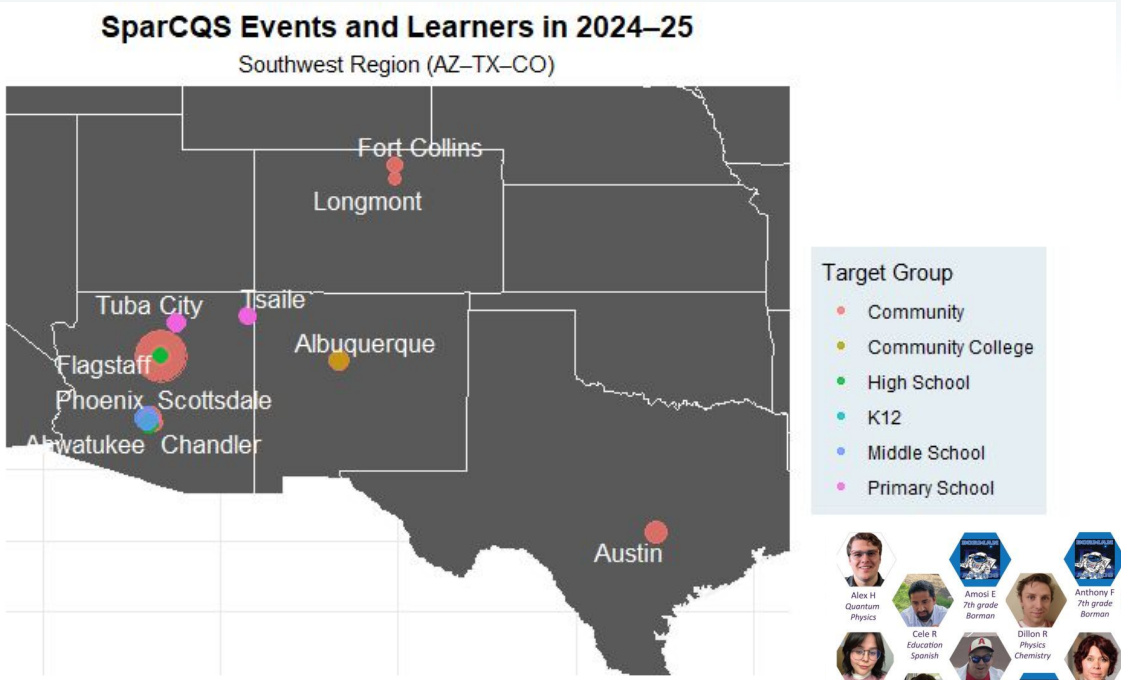
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INSPIRE | EDUCATE | EXPERIENCES

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Winter School

- **January 6th - 10th**
- Cultivates graduate student teaching and curriculum development skills
  - Based on the Science Literacy Program established at UOregon
- **7,001** registrations in 2025

****Winter School 2026****
January 5-9

	Mon.	Tues.	Wed.	Thurs.	Fri.
MORNING	The Physics Behind the Quantum Internet	Information in a Photon	Principles of Quantum Networks	Exploring & Designing Quantum Networks via Digital Twin Simulations	Quantum Network Integrated Devices & Systems
AFTERNOON	Getting Up to Speed on Quantum Networks	Theory of Quantum Channels	Error Correction for Quantum Networks	Integrated Photonics Platforms for Quantum Networks	Molecular Design with Relevance to Quantum Networks

LEVEL 1 no experience
LEVEL 2 some quantum + undergradate math
LEVEL 3 upper division undergraduate math
LEVEL 4 graduate quantum





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Community College Webinar

February 24th-28th | 15 participants

October 13th-18th | 25 participants

Mon	Student Panel
Tue	Advisor Q & A
Wed	Industry Storytelling
Thur	Career Development



Objective:

- Introduce community college students to quantum science and engineering majors and career opportunities
- Bring community college students into REU opportunities

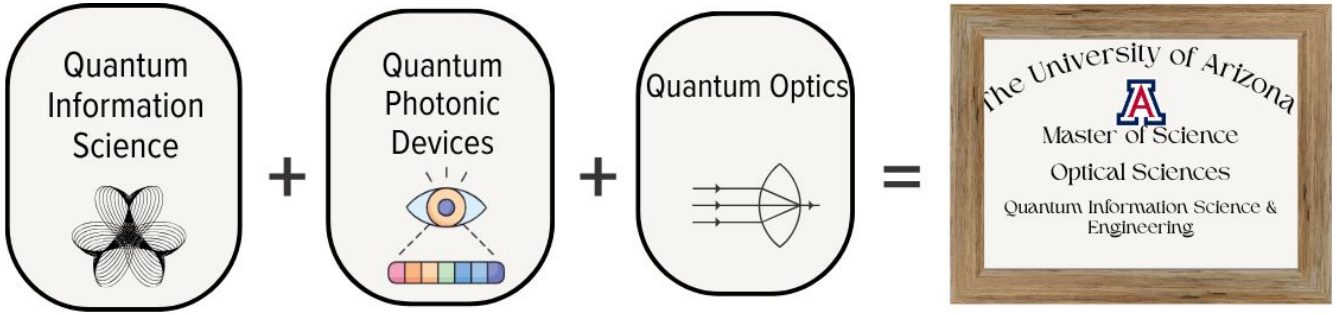
Future Goals:

- Develop programming for community colleges across the country
- Incorporate other Center institutions

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CQN Graduate Certificates



Three online, stackable certificates developed for professional re-training in response to industry

- **Quantum Optics**
- **Quantum Information Science**
- **Quantum Photonic Devices**

Three certificates contain the coursework for a **full Masters in Optical Sciences QISE subplan**

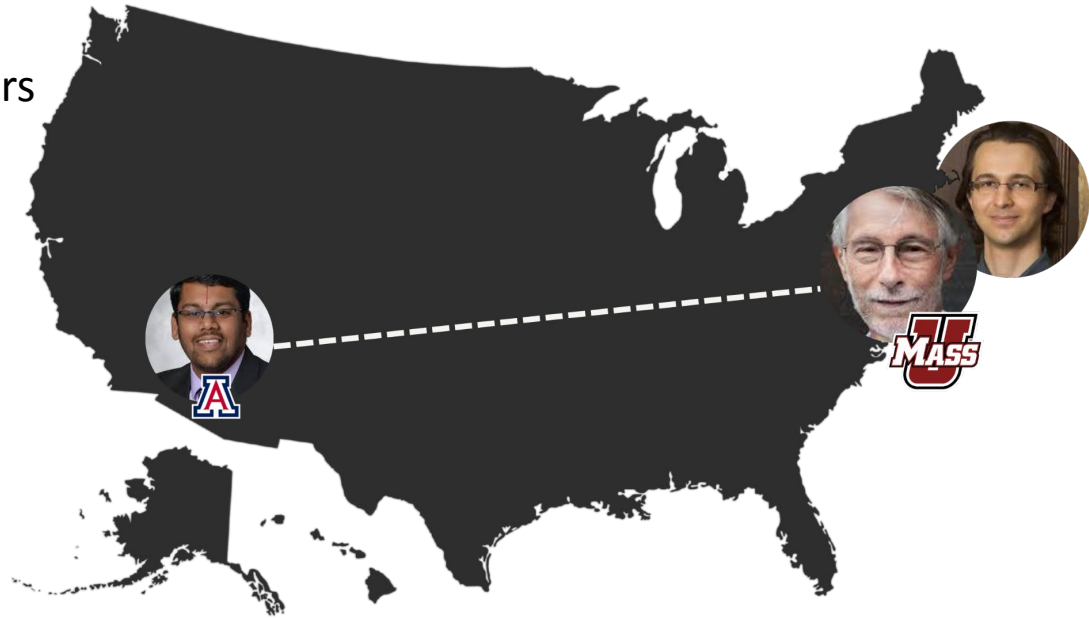
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Synergistic Graduate Coursework

Two CQN Institutions**; Three** professors

One course in Error Correction for Quantum Computing

Students from each institution take the same course together



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QNumerics
Virtual Testbed Coding School

July 14th - 18th | 80 learners (30 UMass, 50 external)

Daily Schedule from **9am to 10:30pm** with long breaks between sessions

	Mon.	Tues.	Wed.	Thurs.	Fri.
MORNING	introduction	state-vector simulation	optimal control of quantum systems	efficiently simulating large circuits	discrete-event simulation
AFTERNOON	high-performance programming	simulating quantum dynamics: pt I	GPU acceleration	tensor networks	simulating quantum networks
EVENING	linear algebra	simulating quantum dynamics: pt II	**hack-a-thon: GPU + Piccolo**	**hack-a-thon: tensor networks**	**hack-a-thon: HPC + quantum networks**





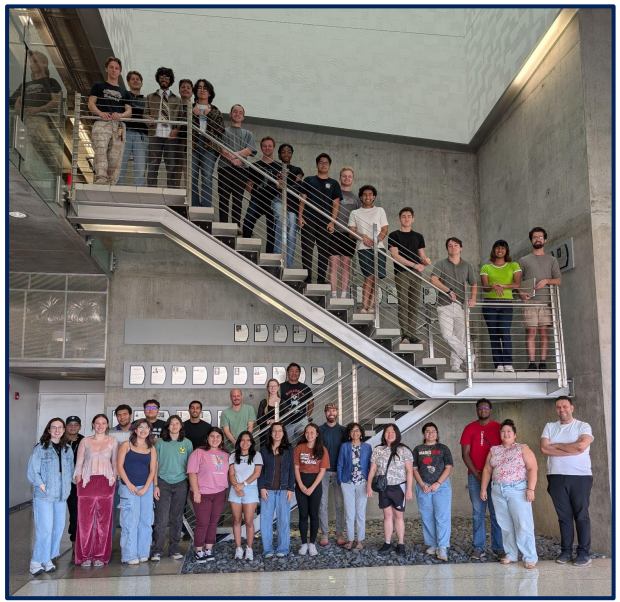
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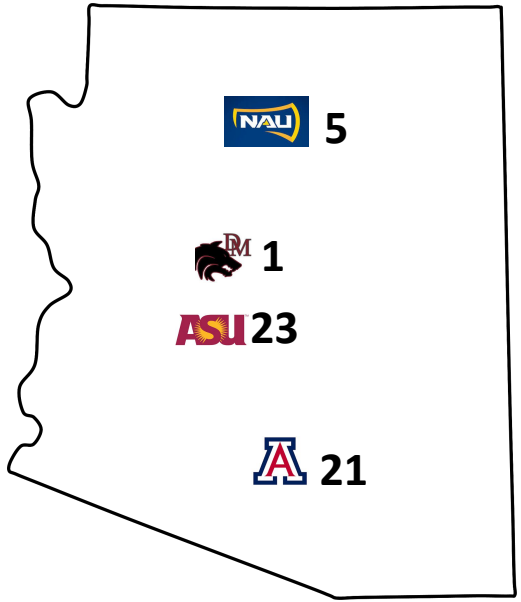
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Arizona Quantum Initiative

Quantum Bootcamp

August 17th - 22nd | 50 participants from across Arizona









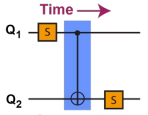
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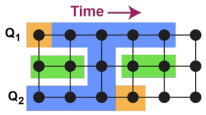
EWD Challenges

Tangram



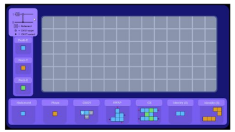


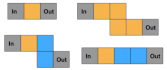
Quantum circuit



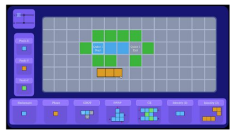
Cluster state


Tangram puzzle





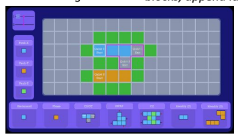
Equivalent measurement blocks are created by appending identity operations or shape deformation



The game interface at the start – minimal blocks for the Clifford gates, CZ, SWAP, identity, and Pauli measurements are given.

Intermediate stage – player can drag and drop fundamental blocks, append identity gates and rotate the selected block.





Two equivalent solutions of a quantum circuit challenge



Final screen – Correct solution that minimizes filled area ranks higher.

Q3 Initiative









Future Fellowships



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Research Experiences for Undergraduates



- **17** participants across **7** academic and industry sites
- Team building kickoff at the University of Arizona campus before students
- Weekly professional development workshops throughout the summer
- *Next Steps Week* during final week focused on graduate school opportunities and continuing undergraduate research
- **~135** applicants
  - New integration with the NSF ETAP system
- **4** community college transfer students
- **13** students from low-income backgrounds
- **2** students returning from prior years
  - Brizia Chavez (UOregon)
  - Aaron Bordeaux (Harvard)

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Research Experiences for Undergraduates

Leo Herrera

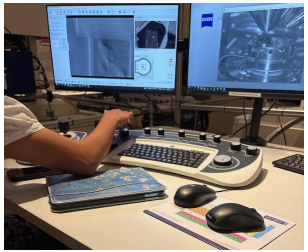
First in his family to attend college

Pell recipient

Community College transfer

(South Mountain CC to Arizona State)

Cultivated interested in graduate school at REU









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Research Experiences for Undergraduates

Nano-electromechanical actuation device made for diamond defect applications

Leonardo Herrera[1], Katie Barajas[2], Marko Lončar[2]
[1]South Mountain Community College, Phoenix, Arizona
[2]Harvard John A. Paulson School of Engineering & Applied Sciences, Cambridge, MA
NSF Engineering Research for Quantum Networks, NSF EEC-1941583

Harvard John A. Paulson School of Engineering and Applied Sciences
Center for Quantum Network
NSF Engineering Research Center

Abstract

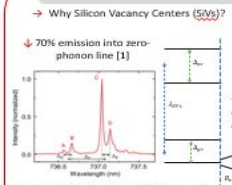
The silicon vacancy center in diamond (SiV^-) has proven to be an ideal platform for quantum systems due to long coherence time for spin states, bright emission into the zero-phonon line, and stability in nanostructures. While nanostructures enhance properties of the SiV^-, recent work has demonstrated the ability to tune SiV^- properties through engineering electromechanical devices in diamond. By introducing electromechanically actuated structures, we open up the possibility to develop mechanisms for photon routing and tuning, enabling the progression of quantum node efficiency and scalability. Inspired by work done in other material platforms, we present progress toward a tunable directional coupler consisting of two coupled waveguides whose distance is adjusted by an external voltage. This design is tailored for SiV^- platform applications including photon routing via directional coupling, tunable gaps for cavity coupling, and related quantum photonic operations.

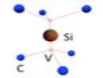
Background

SiV for Quantum Networks

→ Why Silicon Vacancy Centers (SiVs)?

↓ 70% emission into zero-phonon line [1]



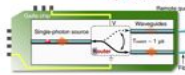


↑ SiV Crystal Lattice

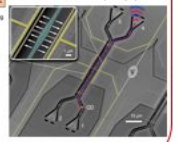
→ **Motivation**: Introduce a versatile and energy efficient electromechanically actuated directional coupler to SiV platforms to enable the progression of quantum node efficiency and scalability.[1]

Previous Application of a Directional Coupler

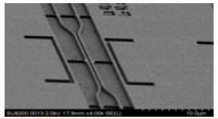
→ Previous work done in Gallium Arsenide [2]



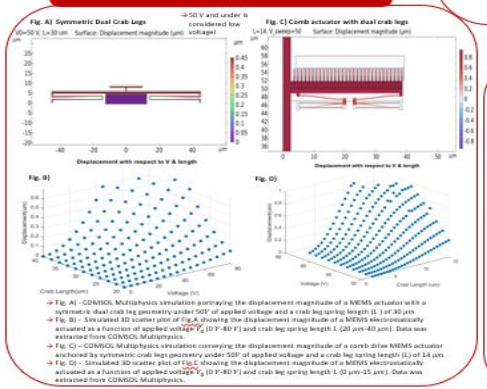
→ Visual representation of single photon routing via a directional coupler[2]



↓ Previous fabrication of a tunable directional coupler in diamond



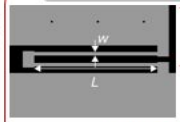
Micro-electromechanical structure (MEMS) actuation in SiV Platforms



→ Fig. A) - COMSOL Multiphysics simulation portraying the displacement magnitude of a MEMS actuator with a symmetric dual crab leg geometry under 50V of applied voltage and a crab leg spring length (L) of 30 μm
→ Fig. B) - Simulated 3D scatter plot of Fig A showing the displacement magnitude of a MEMS electrostatically actuated as a function of applied voltage (V_a [0 V-80 V]) and crab leg spring length L (20 μm-40 μm). Data was extracted from COMSOL Multiphysics.
→ Fig. C) – COMSOL Multiphysics simulation conveying the displacement magnitude of a comb drive MEMS actuator anchored by symmetric crab legs geometry under 50V of applied voltage and a crab leg spring length (L) of 14 μm
→ Fig. D) - Simulated 3D scatter plot of Fig C showing the displacement magnitude of a MEMS electrostatically actuated as a function of applied voltage (V_a [0 V-80 V]) and crab leg spring length L (0 μm-15 μm). Data was extracted from COMSOL Multiphysics.

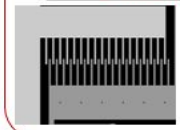
MEMS Structures

Crab Leg



→Flexible & compliant mechanical structure used in MEMS actuators to enable displacement[3]
→Beam dimensions (L, W, H) affect the spring constant which can be manipulated for displacement tuning[3]

Comb Drive



→Consists of fixed interdigitated fingers that generate a later electrostatic force when voltage is applied
→The force scales linearly enabling precise and repeatable displacement at low power consumption

Outlook

→Demonstrate single-photon routing in SiV center platforms
→Long Term:
→ Further enhance directional coupler to enable on-chip photon entanglement and other fully integrated photonic applications

References

[1] T. Schröder et al., "Optical signatures of silicon-vacancy spins in diamond," Nat Commun, vol. 5, no. 1, p. 3328, Feb. 2014, doi: 10.1038/ncomms4328.
[2] Y. Fujiwara et al., "Nanoelectromechanical single-photon routing," Optica, OPTICA, vol. 8, no. 4, pp. 526–530, Apr. 2018, doi: 10.1364/OPTICA.8.000526.
[3] T. A. J. Wiss, B. V. Laliguen, K. Tsaturyan, M. Albrechtsen, and S. Stobbe, "Design, fabrication, and characterization of electrostatic comb-drive actuators for nanoelectromechanical silicon photonics," Jul. 03, 2023, arXiv: arXiv:2307.01123. doi: 10.48550/arXiv.2307.01123.

Acknowledgements

Thank you to my funding sources, NSF & CQN, for giving me this once in a lifetime experience of conducting research at Harvard University. Also, thank you to Marko Lončar and his research group for welcoming me into the group for the summer. Thank you, Katie Barajas, for mentoring me throughout my journey, I couldn't have done it without you!

Contact Information

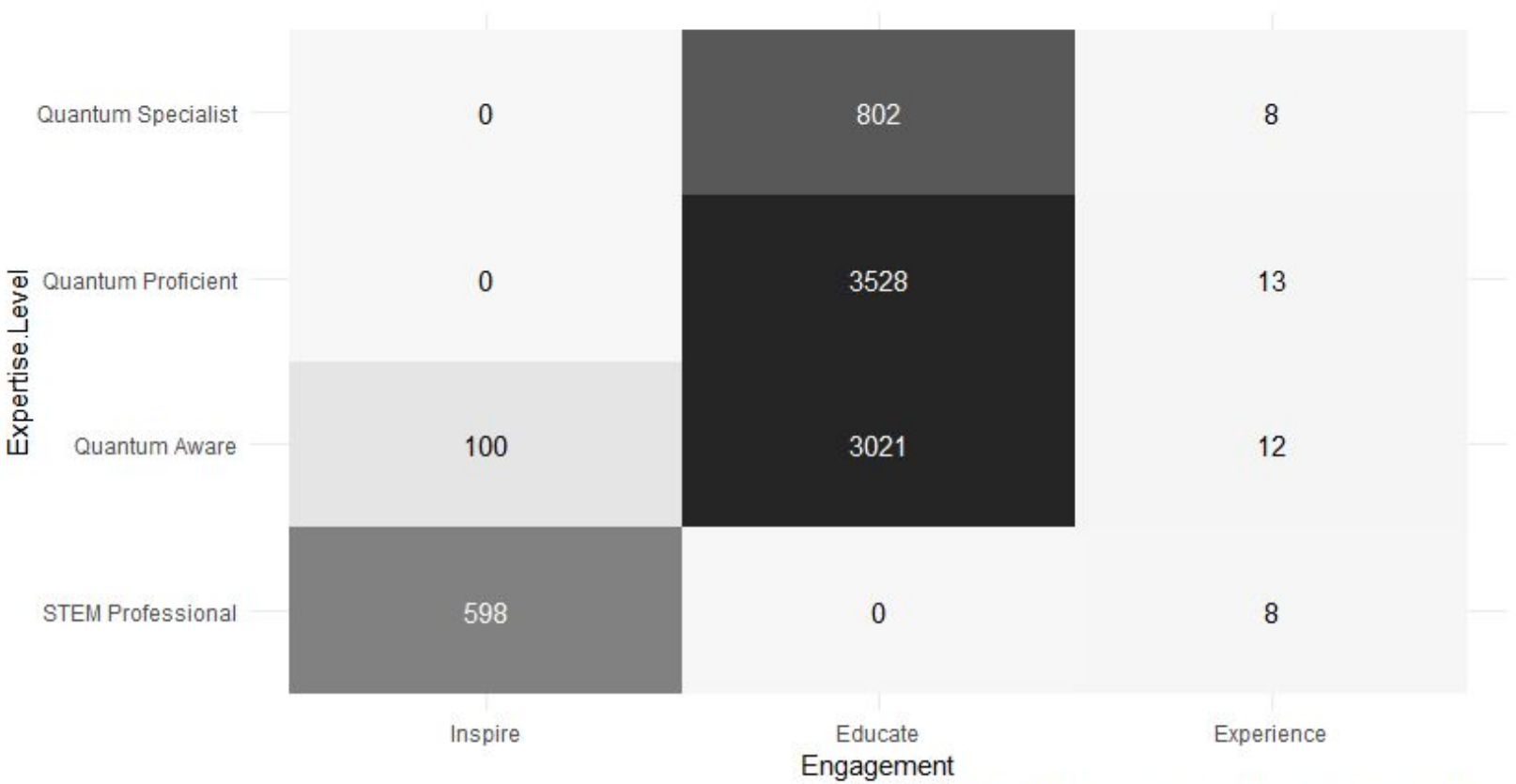
Phone(602)-626-0785
Email:ldherre1@asu.edu

LinkedIn Profile



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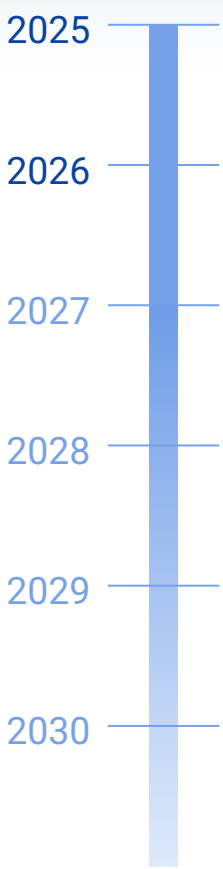


Note: Color intensity scaled to reduce effect of outliers

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Years 5-10 Goals (EWD)



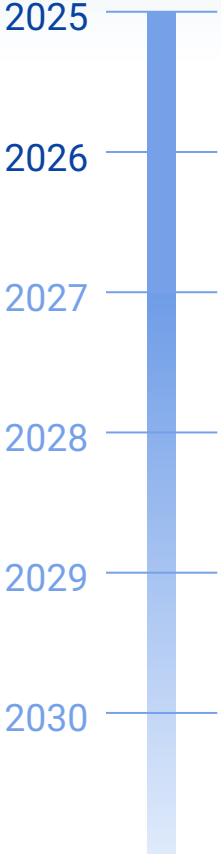
***New* REU processes** (professional development series, asset-based goal coaching, partnership with UA's New Frontiers of Sound NSF-STC)

EWD Director led a team to apply for NSF Innovation in Graduate Education (mentoring training and support)

New partnerships with Quantum Que and Quantum Quest camps (expanding high school and community college access)

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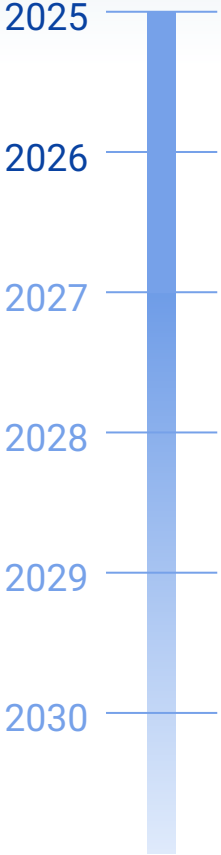


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Winter School will be used to promote graduate **certificates**, **master's** programs, and **PhD** programs across the Center
REU Mentors will benefit from ***new*** mentor training and support framework
***New* graduate certificate** programs at UA (Quantum Photonic Devices, Quantum Optics, Quantum Information Science)
EWD Challenges provide critical leadership opportunities (outreach demonstration development, REU retention)

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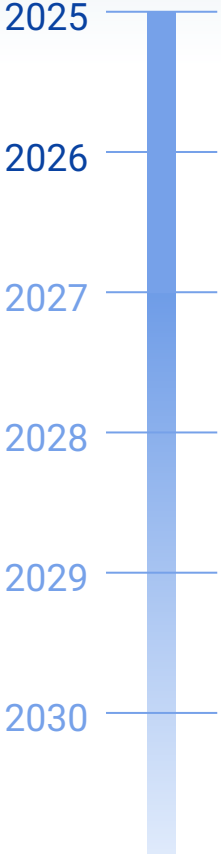
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Graduate certificates enrollments increase from **Winter School** connection
Quantum Que webinar series expands access to community college students to multiple CQN institutions
Launch **MentorLink Resource Hub** (online resource first developed in NSF-IGE proposal)

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CQN **PhD graduates** from each institution hired into academic/industry quantum specialist roles
Winter School acts as a labor market builder (using ***sustainable*** fee-for-service model)

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Years 5-10 Goals (EWD)

2025

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2026

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2027

Graduate certificates enrollments increase from **Winter School** connection
Quantum Que webinar series expands access to community college students to multiple CQN institutions
***Launch* MentorLink Resource Hub** (online resource first developed in NSF-IGE proposal)

2028

2029

CQN **PhD graduates** from each institution hired into academic/industry quantum specialist roles
Winter School acts as a labor market builder (using ***sustainable*** fee-for-service model)

2030

Sustainable library of outreach materials (from **EWD Challenges**) used in community programs across the Center
Converging network of undergraduate **coursework**, graduate **certificates**, and terminal **degrees** across the Center

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Expanding Participation

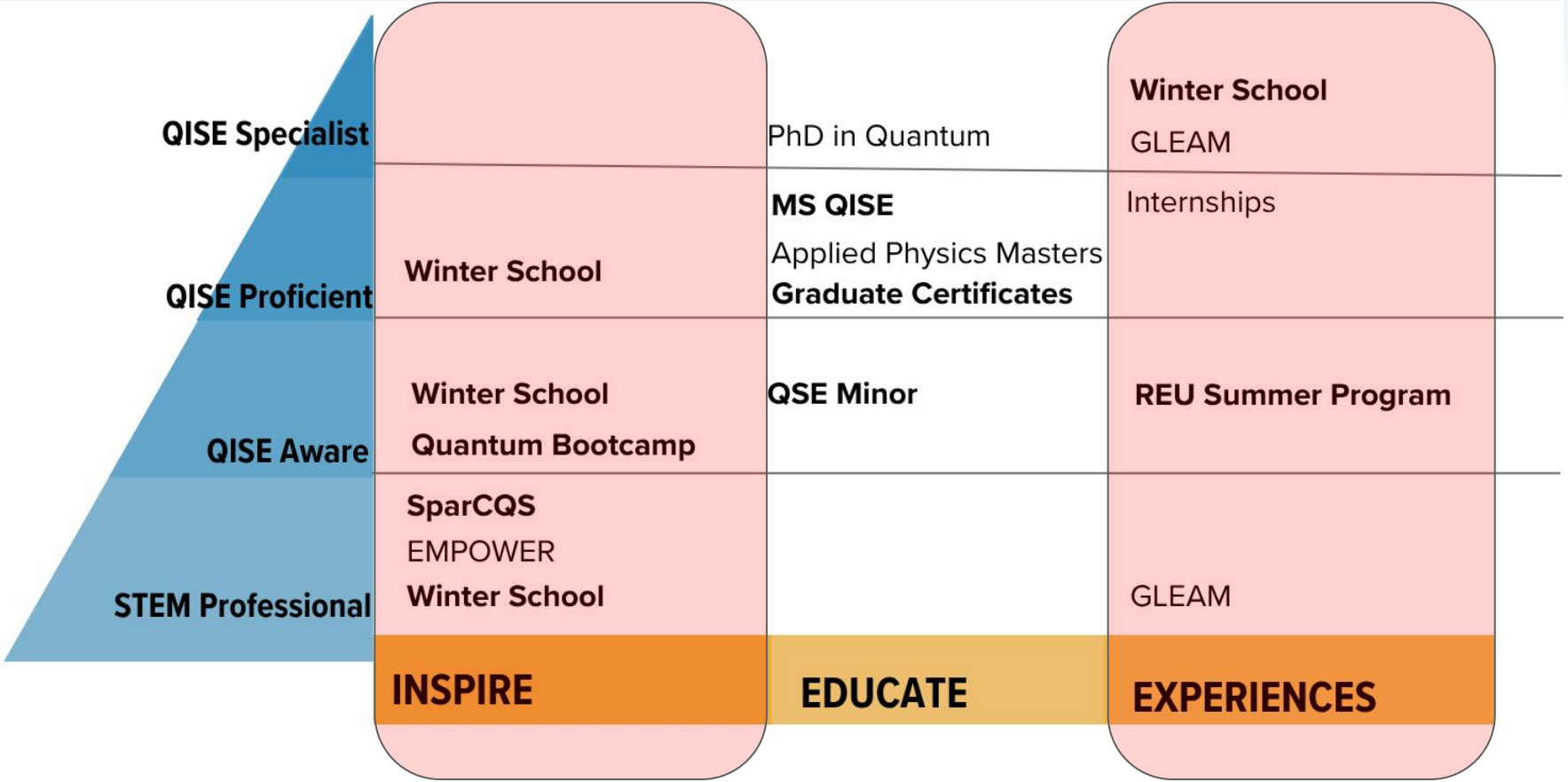
Brianna Moreno

Administrative Director

University of Arizona

Funded by National Science Foundation Award #1941583

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Core Activities

Powered by **QuESTs** - Quantum Engineering and Science Teams

1. Retreats
2. Graduate Leaders in Engineering Advising and Mentoring (GLEAM) Program
3. Cross-campus student exchange program
4. Community Outreach via SPARCQS
5. Quantum Community of Practice

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QuESTs

Quantum **E**ngineering and **S**cience **T**eams are intended to create a sense of inclusion and belonging among CQN members by:

- Having a focus on culture and development in CQN, not on research.
- Creating teams of CQN members who would not have opportunities to work together otherwise.
- Teaming up students with staff, PIs, senior researchers, and industry partners.
- Bringing together CQN members across campuses, industries, and labs.





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Summer Student + Postdoc Retreat





- Annual summer retreat hosted by SPLC
  - Cross-thrust technical interchanges via talks/posters/sidebars
  - Rotates through CQN campuses (MIT: 2022, UArizona: 2023)
  - LT/faculty involvement only for coordination and overview talks as needed

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All Member Winter Retreat

Annual all member retreat

- Hosted at various CQN institutions
  - Invite local collaborators to join
- Updates from all pillars and thrusts
- Host external and industry advisory boards
- Formal and informal idea exchange



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Graduate Leaders in Engineering and Academic Mentoring (GLEAM)

- High-school research experience program
  - Funded by UMD College of Engineering
  - Call for project proposals sent out to UMD Engineering (G) students
  - MD high school students rank order projects in available list
  - GLEAM coordinator maps high school students to grad students
- Outcomes
  - HS students work 10-15 hours a week, write thesis+poster, earn grade
  - Grad students get mentorship experience, earn $500 award
  - Monthly professional development events
  - 25-26 Cohort: 23 students



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Cross Organization Student Exchanges

- Academic cross-campus research exchanges
  - Helaman Flores (Summer 2023): BYU → MIT [resonator design for photon coupling]
  - Yongzhou Xue (Sept 2023): UA → MIT [SiV-PIC memory devices]
  - Jake Navas (Summer 2023): NAU → UMass [QN tomography]
  - Emily Van Milligen (Fall 2024, Spring 2025): UA → UMass
  - C2C Exchanges
- University ←→ Industry research exchanges
  - Michael Bullock [internship]: UA → L3Harris
  - Miles Ackerman [industry collaboration]: UA → Qunett
  - Panos Prampanos [internship]: Yale → Cisco

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SparCQS

Sparking **C**uriosity in **Q**uantum **S**cience

- Brings the world of quantum science to the community
  - Interacted with thousands of individuals
  - Across the southwest
  - Hands on demos



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Community of Practice

- Workshops
  - SIPQNP
  - ERVA
  - QNAR2.0
  - Quantum and Astronomy
- Hack a thons + Schools
  - **Q^3 Initiative**
  - QNumerics Summer School
  - **Arizona Quantum Boot Camp**
  - Winter School



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Community of Practice

- Quantum Quest in partnership with Girl Scouts of Arizona
- Community College webinar
- Project scoping workshops
  - ARO MURI topic exploration: for Quantum Network Science [2019] and Quantum Control [2020]
  - NQVL [December 2020]
  - Quantum Photonics Workshop [UMD, November 2025]

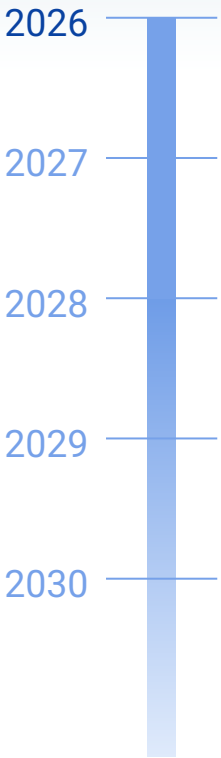
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Impact

- SparCQS inspired **IrelandQCI Quantum & Answers Trailer**
- Career progressions within CQN lifetime
  - Narayanan (postdoc -> faculty)
  - Stefan (student w Liang, Postdoc w Dirk, faculty at UMass)
  - Anjolie (REU w Ines+Matt, UG student w Saikat)
- Careers post CQN
  - Danny Watkins (Pima community college ⟶ CQN REU with Karl B. ⟶ Flatrock Wealth Partners)
  - Sandra (REU with Ines+Matt ⟶ UG at USC)
  - Ashlesha (UA⟶PsiQuantum), Prajit (UMD⟶ RTX-BBN), Eneet (UA⟶ Cisco), Brandt (CONNECT), Connall (Belfast⟶UMD)
- Increased quantum and quantum adjacent resources

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Years 6-10 Goals



Winter School will be used to promote graduate **certificates**, **master's** programs, and **PhD** programs across the Center

GLEAM at UMD high school students transition to university
Quantum Que webinar series expands access to community college students to multiple CQN institutions

Quantum Quest camps connected to multiple institutions (through partnership with Qbit-by-Qbit)

CQN **PhD graduates** from each institution hired into academic/industry quantum specialist roles
Winter School acts as a labor market builder (using ***sustainable*** fee-for-service model)

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Evaluation

Emily Goff, PhD

CQN Evaluator

Goff Group — emily@goffgroupllc.com

Funded by National Science Foundation Award #1941583

Y6 Evaluation Context and Purpose

Context: The Year 6 evaluation builds on five years of CQN infrastructure and learning documented under prior evaluation efforts, using those assets as a foundation for continuous improvement.

Focus: Align with Gen-4 ERC performance criteria while shifting from compliance-based reporting to learning-oriented evaluation using a developmental evaluation framework.

Purpose: Strengthen CQN's capacity as a learning organization that uses data for decision-making, sustainability, and societal impact.

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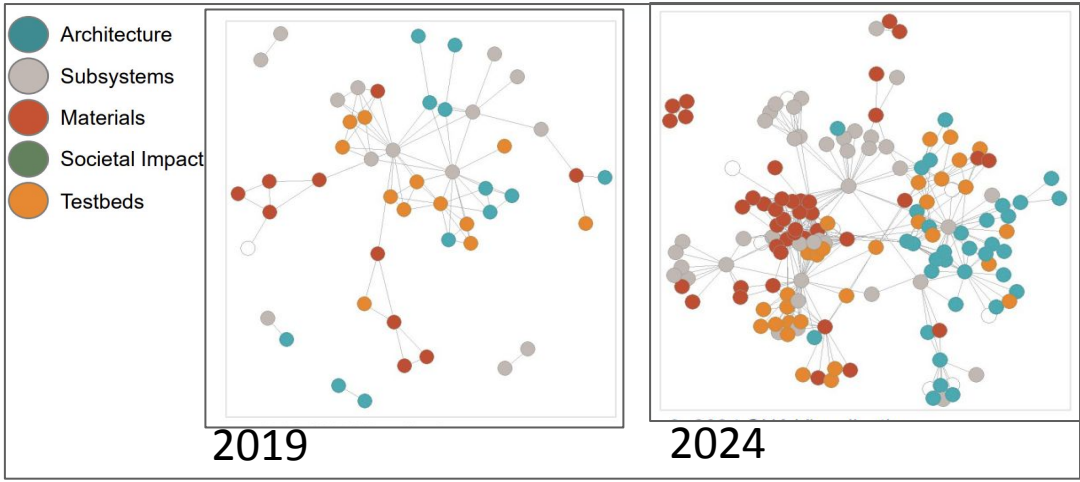
Findings: Integration and Vision (Y5)

Integration

- 154 members co-authored 239 publications across CQN
- 61% of projects involved three or more institutions
- ZALM working group a best practice for cross-thrust collaboration (Thrust 2 + 3)
- Integration between Thrusts 1–3 strong; Thrust 4 integration still developing

Vision and Leadership

- Clear and ambitious vision for the quantum internet recognized nationally
- 70–77% of members report receiving needed information from CQN
- All foundational components met or partially met objectives



"The Center achieves interdisciplinary collaboration as part of its foundation– that's what makes it effective." (Spring 2025 CQN member survey)

Opportunity: Enhance use of evaluation and feedback loops to connect strategic goals with real-time decision-making

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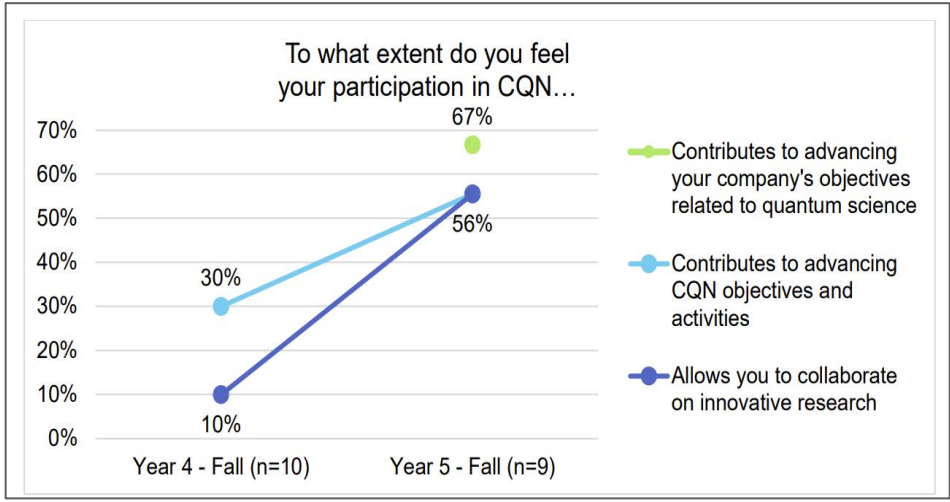
Findings: Workforce & Partnerships (Y5)

Engineering Workforce Development

- 55% improved professional skills, 57% improved research skills
- 86% rated mentoring as high quality
- 70% participated in ≥1 EWD activity
- 81% of Winter School participants sustained or increased interest in quantum
- SparCQS: 70% repeat visits; 100% teachers reported high student engagement

Innovation Ecosystem

- 19 industry partners retained (+1 new) | 13 patent applications filed
- 2 customized industry research projects completed
- Translational publications still emerging (*lagging indicator*)



Increase in perception of benefits from partners from 2024-2025

Opportunities: Strengthen industry integration in research and expand tracking of alumni and workforce outcomes.

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Developmental Evaluation to Support Sustainability

Strategy

Developmental Evaluation

Informs and supports innovative and adaptive program development in complex environments or within interconnected and changing systems--exemplified by the interdisciplinary ERC model.

Patton, M. Q. (2011). Developmental Evaluation: Applying Complexity Concepts to Enhance Innovation and Use. Guilford Press.

Traditional Evaluation Process



Developmental Evaluation Process



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Framework for Year 6-10

- Fully aligned with NSF Gen-4 Performance Criteria.
- Uses Developmental Evaluation to provide real-time learning and iterative feedback.
- Incorporates mixed-method data collection (surveys, interviews, bibliometrics, and network analysis).
- Emphasizes utilization, reflection, and continuous improvement across all foundational components.

Vision	Vision	Vision	Vision
Performance Criteria Section	**Evaluation Question**	**Outcome Measures**	**Data Sources**	**Success Criteria**
Performance Criteria Section	**Evaluation Question**	**Outcome Measures**	**Data Sources**	**Success Criteria**
Transformational	To what extent is CQN's vision transforming the engineering community, scientific enterprise, and society?	Evidence of influence on the field (citations, recognition in national/global forums, policy engagement). Documented societal use cases (e.g., secure quantum communications, entanglement-enhanced sensing).	Renewal proposal milestones, publication metrics, external advisory board (EAB) input, industry/government stakeholder interviews.	CQN is recognized as enabling transformative applications and shaping the emerging field of quantum networks.
Leading Edge	How is CQN recognized as a leader in the field due to its cross-disciplinary, systems-level vision?	Leadership roles in national/international collaborations; visibility in high-impact journals; partnerships across academia, industry, and government.	Bibliometric analysis, NSF/ERC reports, industry advisory board (IAB) feedback, participant surveys.	CQN is acknowledged as a global leader in transdisciplinary quantum networking research and education.
Integration	How well does CQN integrate its four foundational components (CR, EWD, IE, EP) into a coherent vision?	Evidence of cross-pillar collaboration; shared goals across thrusts/testbeds; activities refined based on feedback.	Leadership interviews, annual reports, meeting notes, evaluation focus groups.	Demonstrated interdependencies between pillars; leaders articulate a clear, integrated strategy.
Societal Impact	How is CQN beginning to demonstrate societal impact (resilience, productivity, safety)?	Early technology translation outcomes (patents, startups, licensing, testbed partnerships). Evidence of workforce outcomes.	NSF reports, innovation ecosystem data, stakeholder workshops, REU/EWD/EP program tracking.	Demonstrated early societal impact, such as technology demonstrations with partners, impactful workforce development, and visible pathways to broader adoption.
Strategic plan	Strategic plan	Strategic plan	Strategic plan
Performance Criteria Section	**Evaluation Question**	**Outcome Measures**	**Data Sources**	**Success Criteria**
Integrated Strategic Plan	How effectively does CQN integrate its four foundational components (CR, EWD, IE, EP) into a coherent and adaptive plan?	Evidence of refinement of goals across pillars; cross-pillar initiatives documented; alignment with NSF ERC requirements.	Annual reports, logic model, leadership interviews, EXCOM/leadership team meeting notes.	Strategic plan demonstrates evolving integration; feedback from NSF Site Visit Team (SVT) and advisory boards is incorporated.
Convergence	To what extent does the strategic plan foster deep, transdisciplinary collaboration toward societal impact?	Evidence of cross-disciplinary publications, collaborative projects, new frameworks or paradigms.	Bibliometric analysis, project milestone tracking, thrust leader interviews, publication networks.	Clear evidence of transdisciplinary collaboration leading to novel results that could not be achieved within disciplines alone.
Stakeholder Engagement	How effectively does CQN engage stakeholders in shaping its direction and activities?	Documented engagement of industry, government, and community partners; evidence of co-development of initiatives; evolving stakeholder relationships.	IAB meeting notes, stakeholder surveys, partnership agreements, workshop records.	Stakeholders are active participants in CQN's planning and decision-making; feedback loops shape center priorities.
Team Formation	How intentional and effective is CQN in forming a diverse, cross-institutional, interdisciplinary team?	Evidence of onboarding and integration of new team members; diversity in disciplines, institutions, and demographics; faculty/student perceptions of team effectiveness.	Demographic tracking, collaboration surveys, interviews with thrust and pillar leads, leadership retreat observations.	Team is cohesive, diverse, and well-integrated across partner institutions, with effective onboarding processes in place.

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Learning Organization in Action

- Evaluation insights will inform leadership meetings, retreats, and advisory board discussions.
- Data will be used to identify **patterns, not just outcomes** in order to clarify the ways that CQN's systems enable or constrain progress.
- Evaluation findings will directly feed into:
  - Annual goal-setting and pillar plans
  - Cross-site integration efforts
  - Sustainability planning (post-NSF transition)

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Next Steps: Evaluation Priorities (Y6)

- Embed evaluation within leadership decision-making (Evaluator as *Ex Officio* member of leadership team).
- Implement streamlined Workplace Excellence survey to broadly assess culture, communication, and collaboration.
- Launch CQN Alumni Tracking System to measure long-term workforce and translational outcomes.
- Map all data collection to Gen-4 criteria to ensure comparability and reduce reporting burden.
- Build evaluation capacity within CQN teams using existing tools where effective, refining and discarding others as needed

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Closing Takeaways

- CQN is well positioned for its second phase: The foundation is strong, and learning systems are being built and will be used and strengthened through evaluation work.
- Year 6 evaluation will bridge assessment and action, supporting CQN's maturation as a learning, adaptive, and sustainable organization.
- CQN's evaluation approach will now prioritize using results to inform action in addition to documenting outcomes.

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CQN Testbed - Boston

Chao Li

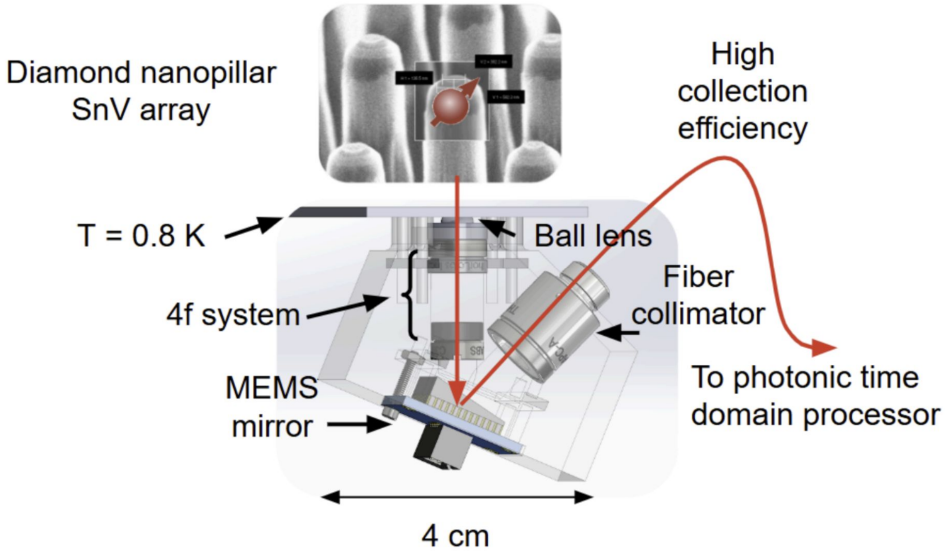
Boston Testbed Lead

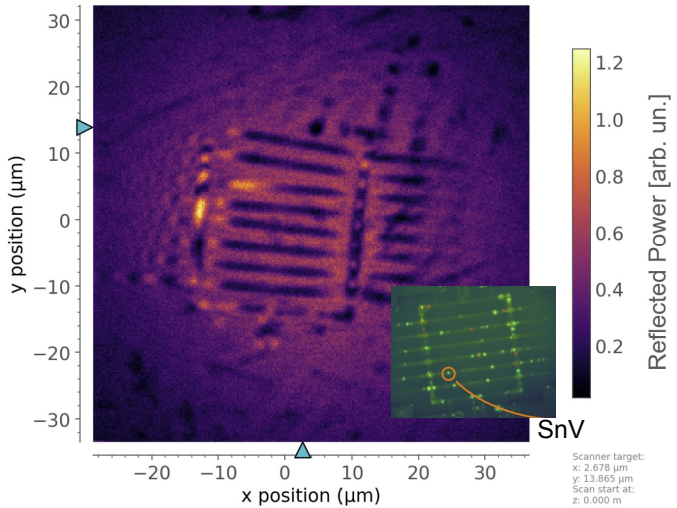
Massachusetts Institute of Technology

Funded by National Science Foundation Award #1941583

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Cryo-vacuo MEMS Scanner QuMemory Module

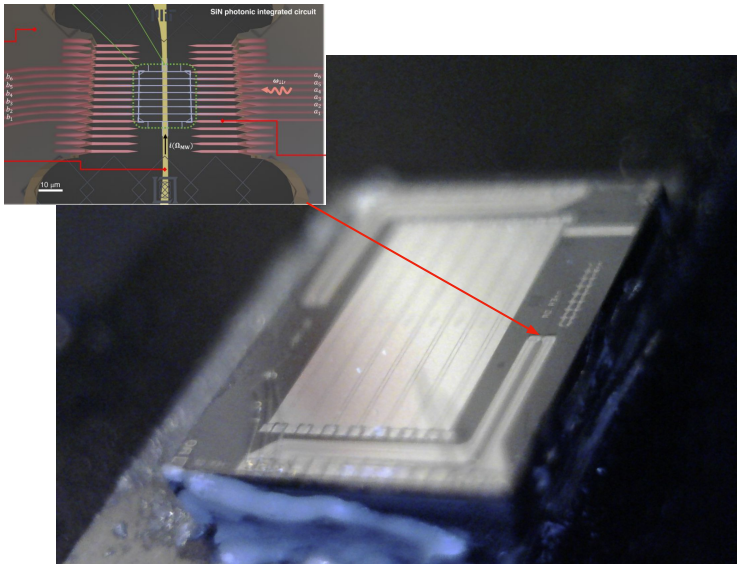


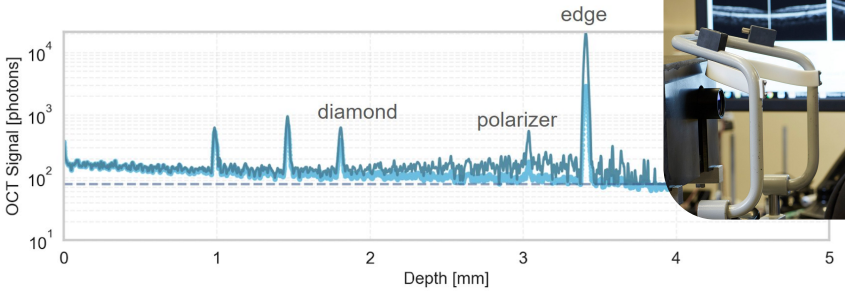


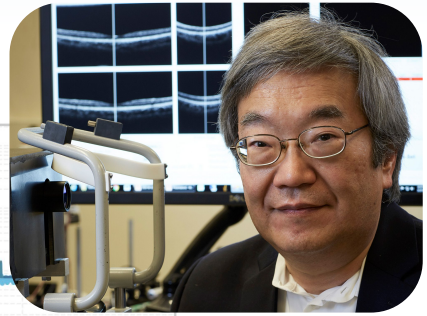
Team: Chao Li, Vikash Kumar, Yin Min Goh, Dan Kilper, John Donegan, Dirk Englund et al.
Publication: to be submitted (2025)

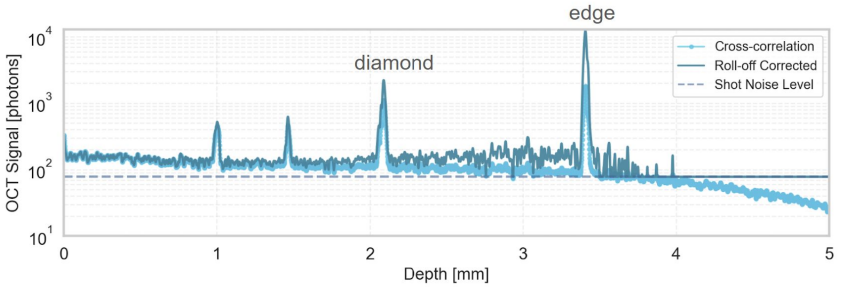
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OCT for PIC – Towards Single Photon and Single Emitter Regime





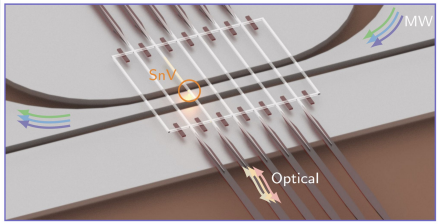


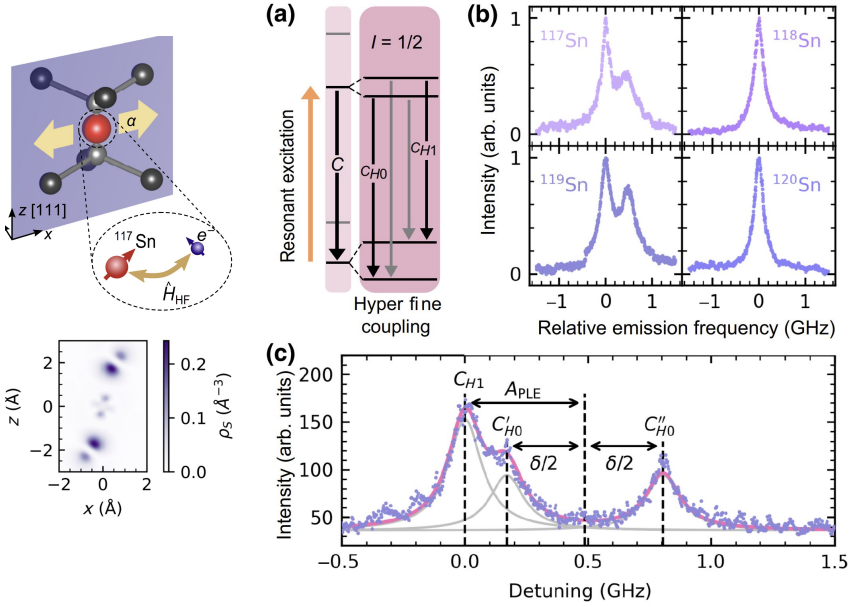


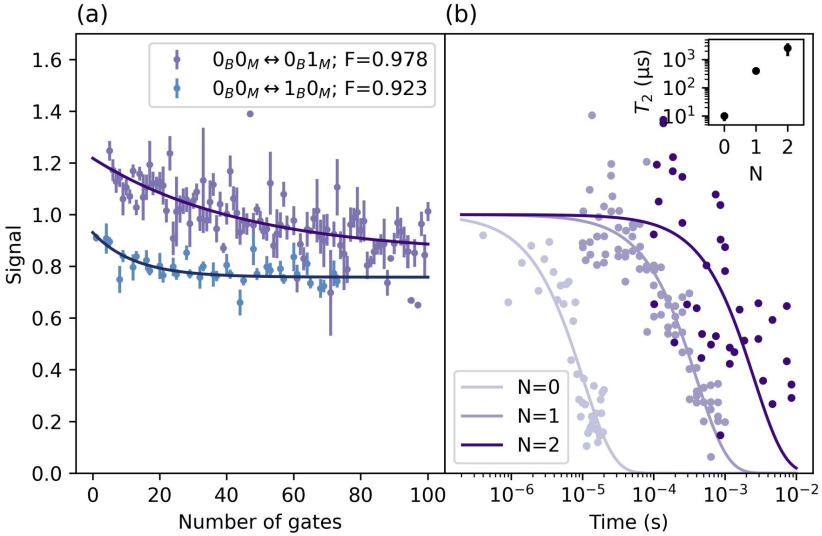
Team: Yin Min Goh, Chao Li, Yunchan Hwang, James Fujimoto, Dirk Englund et al.
Publication: to be submitted (2025)

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Hyperfine Electro-Nuclear Spin-Photon Interface



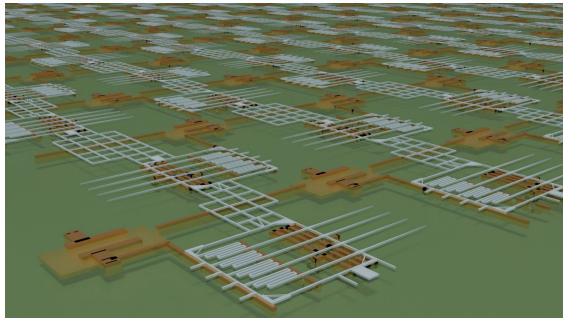


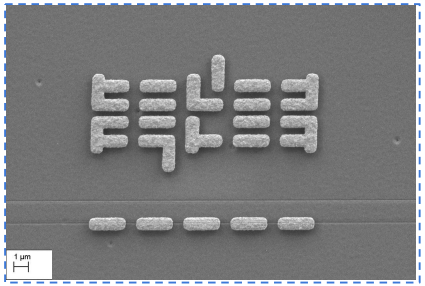


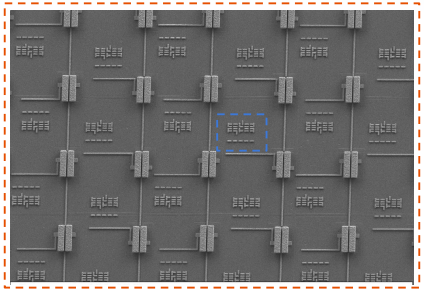
Team: IBW Harris, I Christen, SM Patomäki, H Raniwala, P. Benjamin Dixon, Mete Atatüre, Karl Berggren, Dirk Englund, et al.
Publication: PRX Quantum (2023) & Manuscript Under Review (2025)

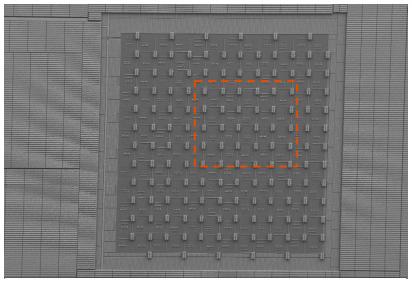
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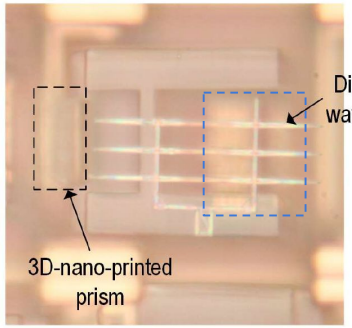
CMOS Platform for Scalable Heterogeneous Integration

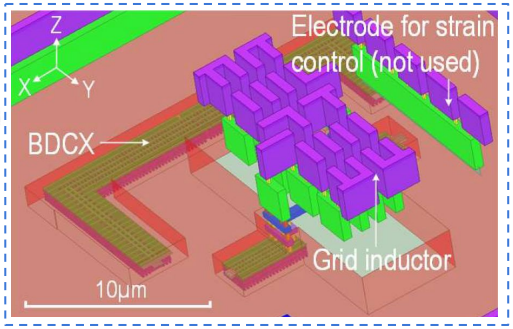


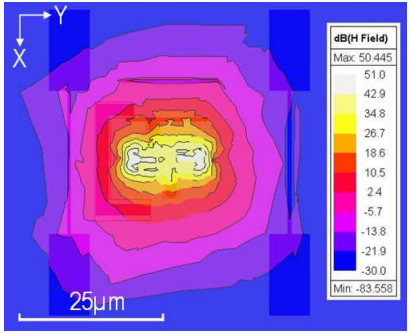


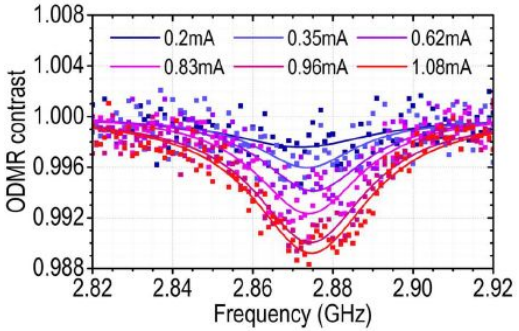








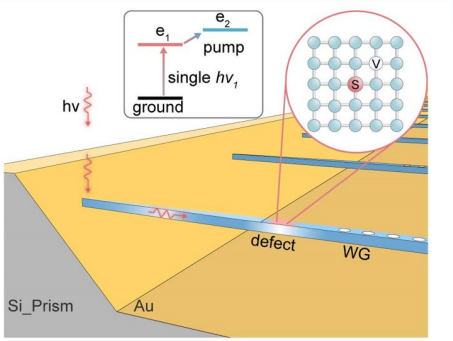


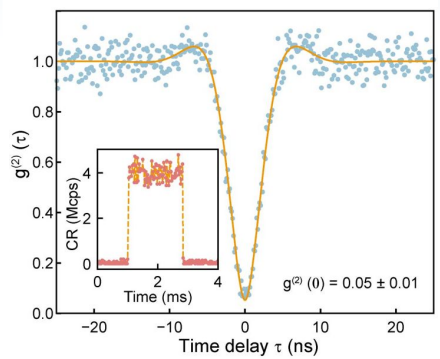


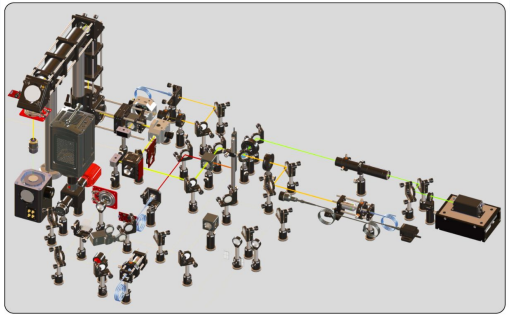
Team: Yuyang (Asher) Han, Jinchen Wang, Ruonan Han, Dirk Englund, et al.
Publication: ISSCC (2026), Accepted

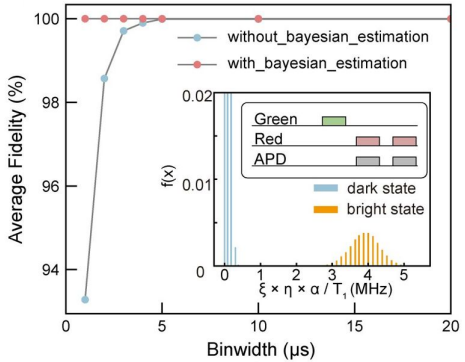
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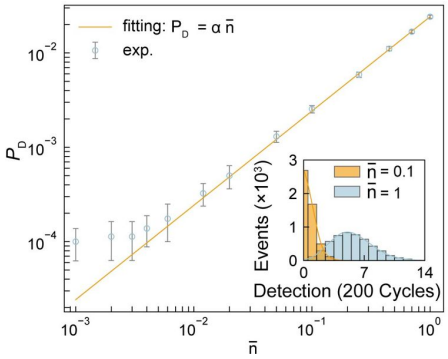
Quantum Imager: Diamond-Color-Center Single-Photon Detector

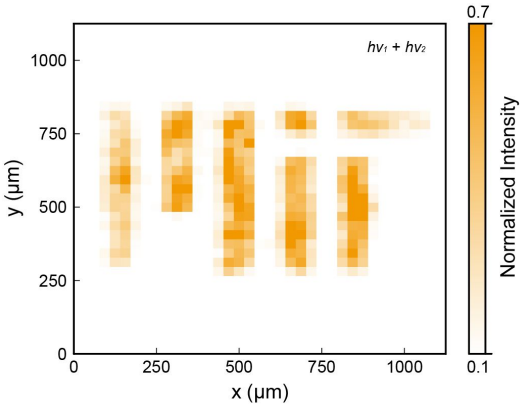










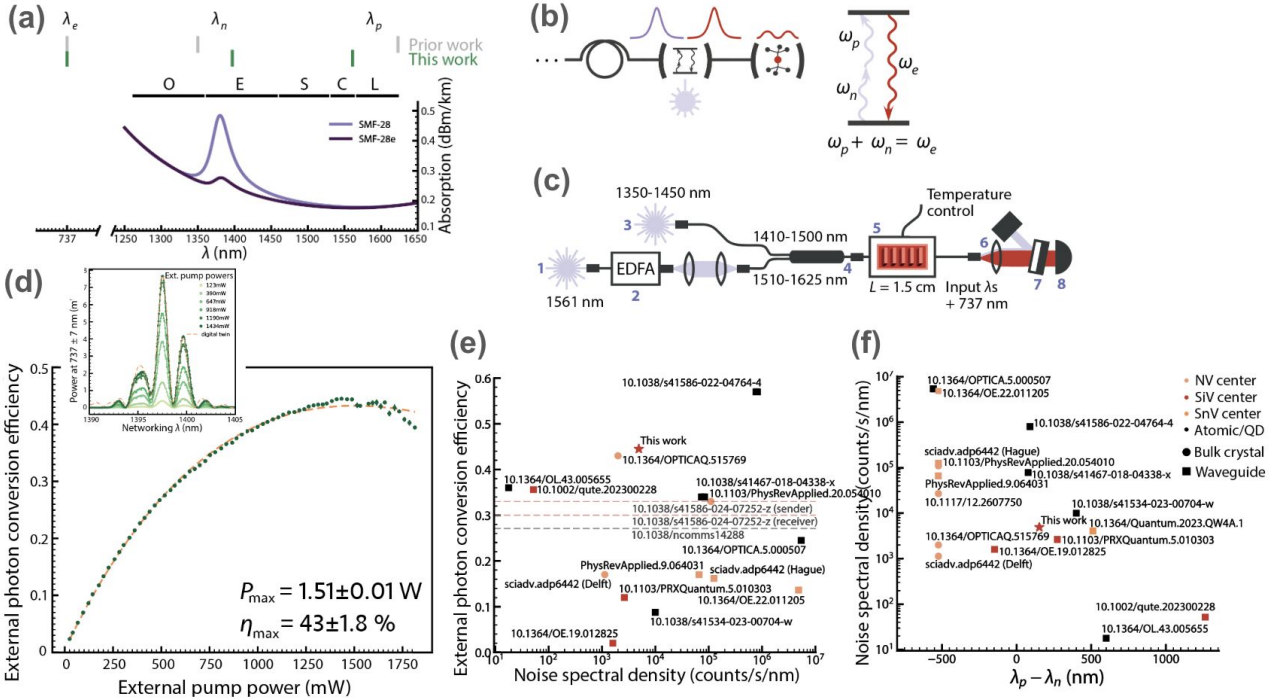


Team: Yong Hu, Ian Berkman, Dirk Englund, et al.

Publication: to be submitted (2025)

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Quantum Frequency Conversion

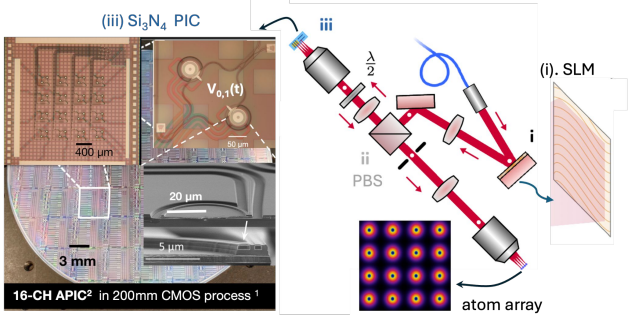


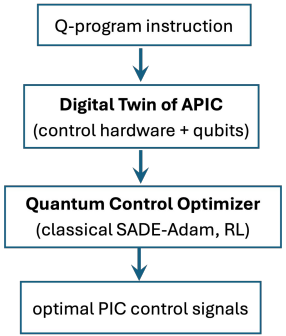
Team: Sofia Patomaki, Dirk Englund, Franco Wong et al.
Publication: to be submitted (2025)

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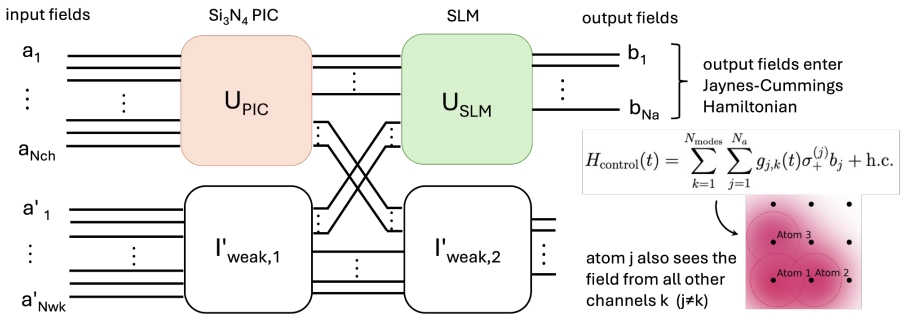
Hardware Co-Designed Optimal Control via Reinforcement Learning

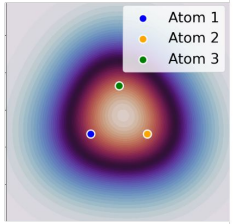
Physical System of APIC



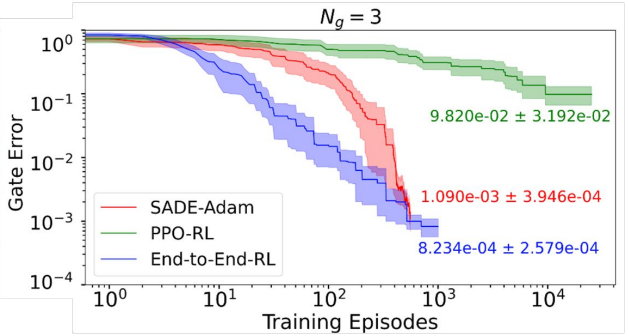


Digital Twin of APIC





- beam waist 2.0 um
- atom spacing 3.0 um
- $T_{1q\text{-}gate}$ set to 100 ns

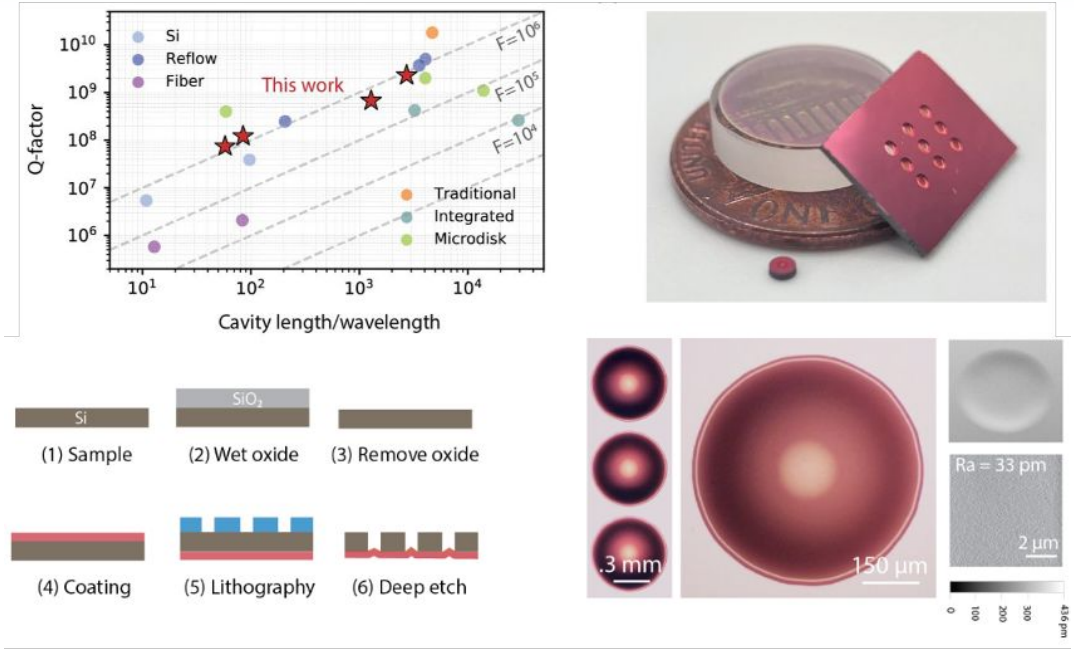


- DT model serves as env. for RL
- $U_{target} = R_1 \otimes R_2 \otimes R_3$
- R_i: single-qubit gate, random Clifford
- each curve shows the average over 5 random sets (shaded region shows std. deviation)

Team: Qian Ding and Dirk Englund
Publication: under review (2025)

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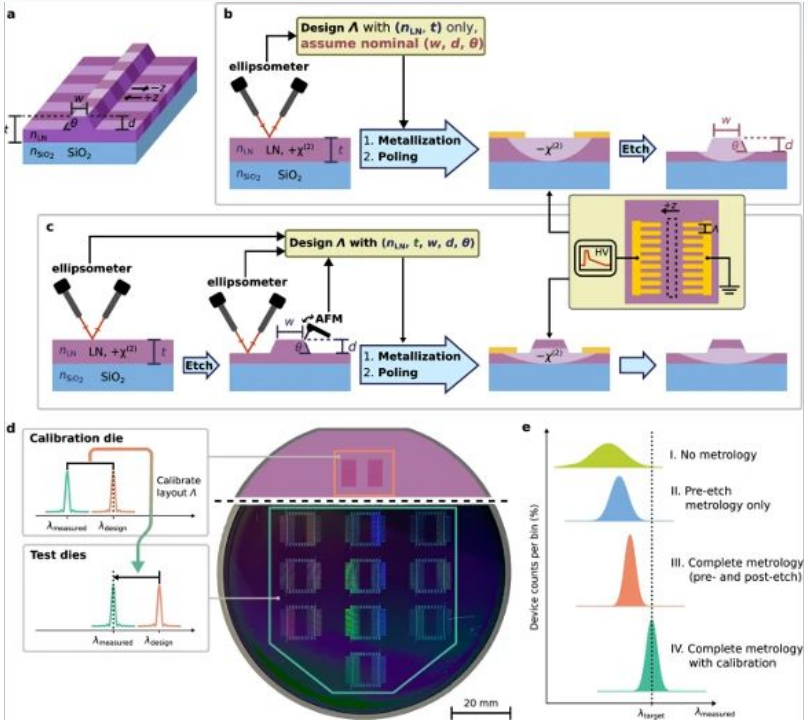
Scalable high-finesse microcavities for neutral atom network links

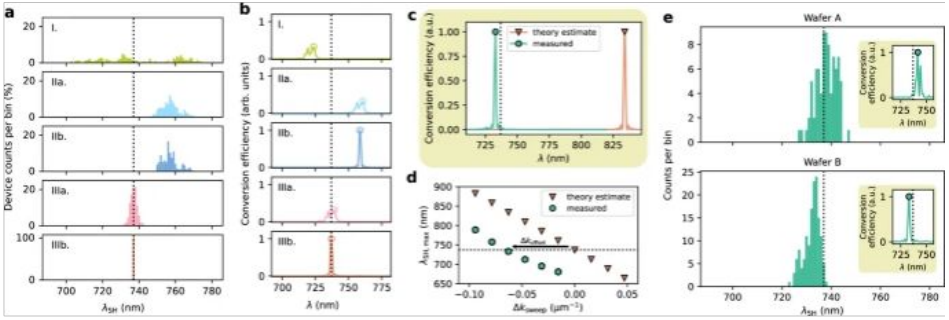


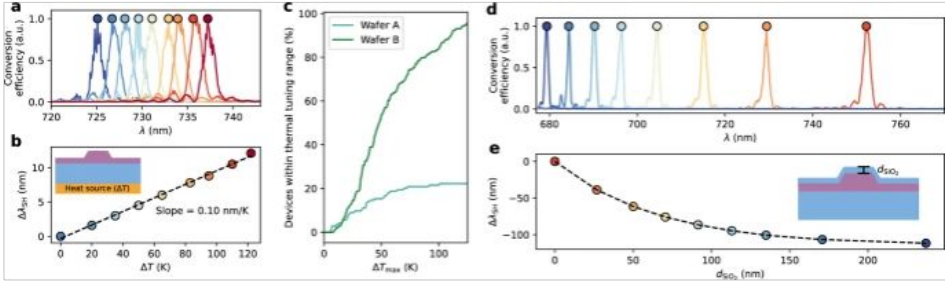
Team: S. Ding, B. Grinkemeyer, M.D. Lukin, M. Lončar, et al.
Publication: Manuscript under review (2025)

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Wafer-scale wavelength-accurate fabrication of PPLN for SiV frequency conversion





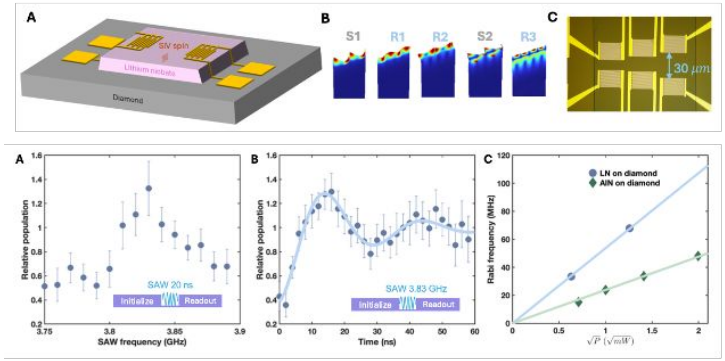


Team: C.J. Xin, N. Sinclair, M. Lončar, et al.
Publication: Communications Physics (2025)

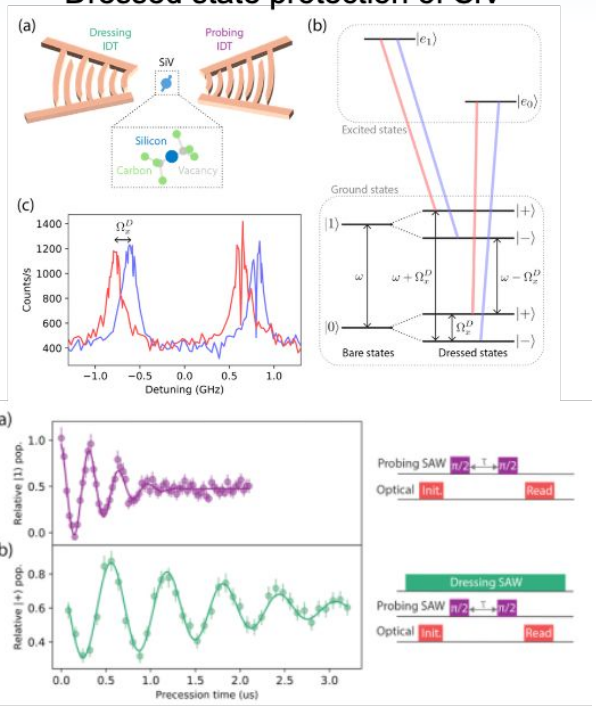
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Dressed state protection of SiV and LN-diamond integration

LN on diamond for fast SiV acoustic control



Dressed state protection of SiV



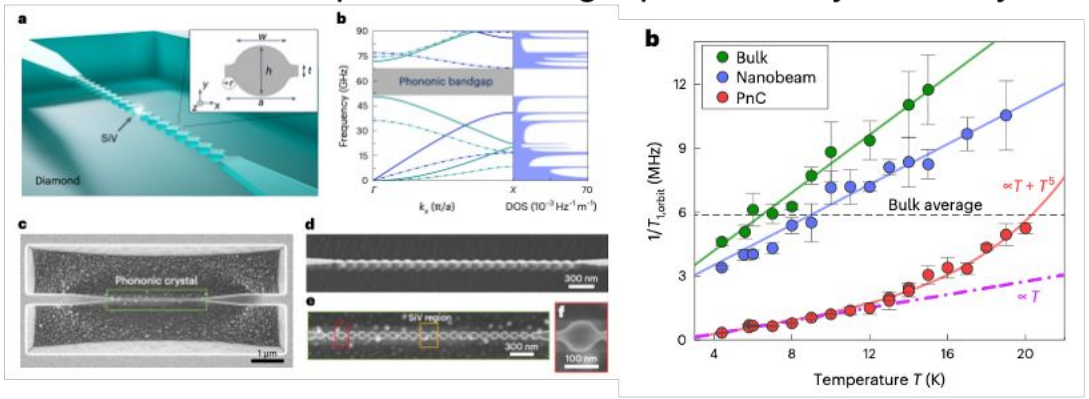
Team: E. Cornell, Z. Xu, B. Pingault, M. Lončar, et al.

Publication: Manuscript under review (2025); Manuscript under review (2025)

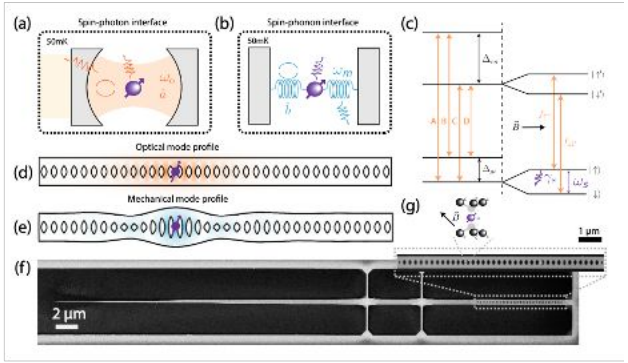
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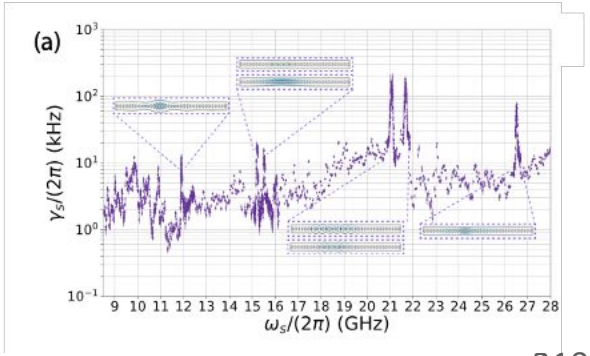
Spin-phonon interaction using phononic crystal cavities

SiV orbital state protection using a phononic crystal cavity



Acoustic Purcell effect using SiV

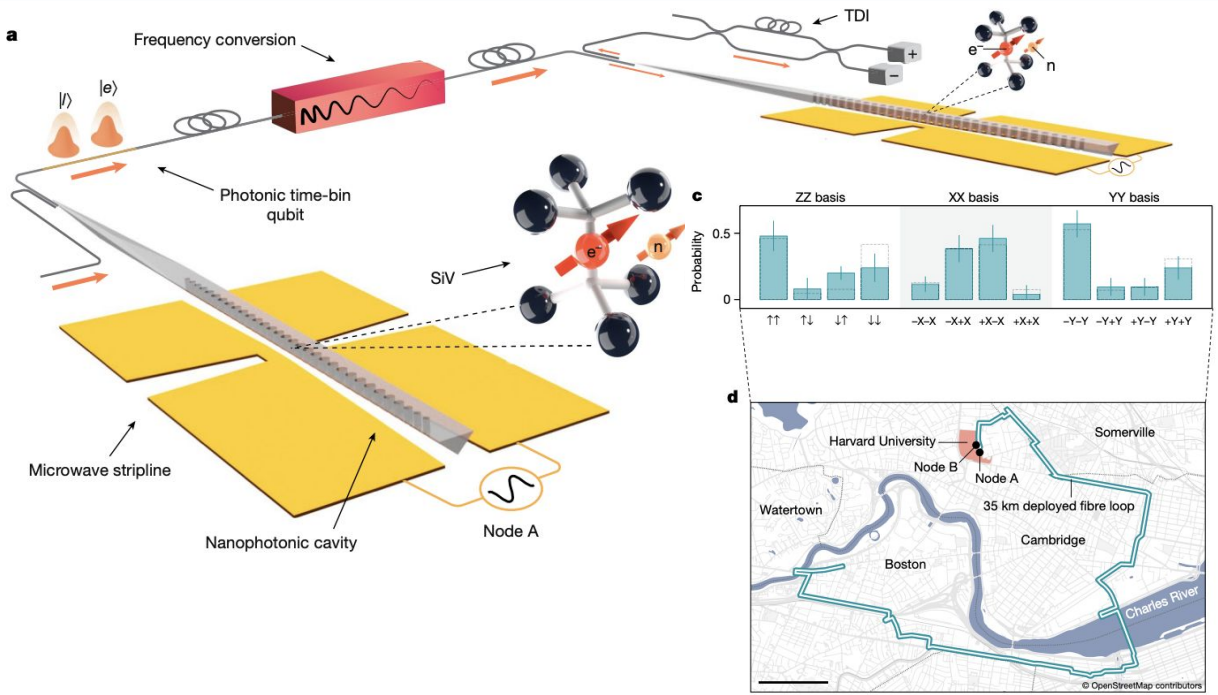




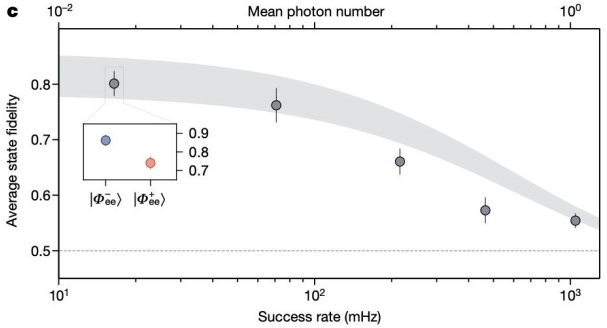
Team: K. Kuruma, G. Joe, M. Haas, B. Pingault, M. Lončar, et al.
Publication: Nature Physics (2025); Manuscript under review (2025)

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SiV-SiV entanglement over a 35 km metropolitan fiber



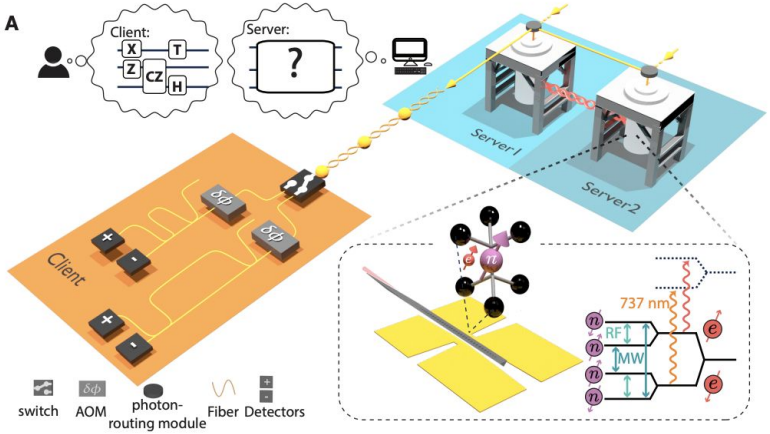
1 Hz entanglement rate



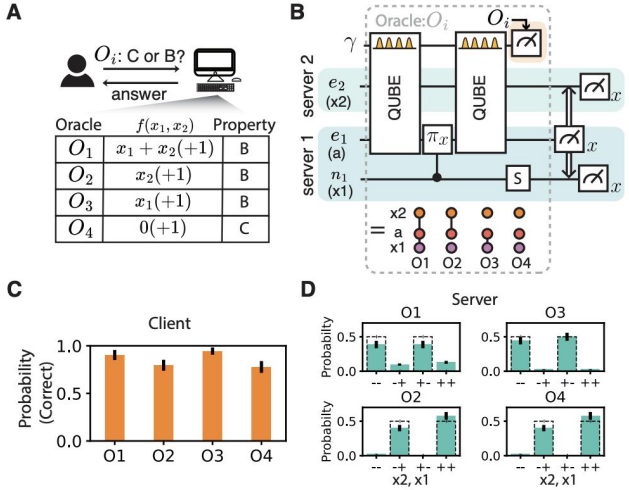
Team: C. Knaut, A. Suleymanzade, Y.-C. Wei, D. Assumpcao, P.-J. Stas, M. Lukin et al.
Publication: Nature (2024)

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Distributed Blind Quantum Computing with an SiV Quantum Network



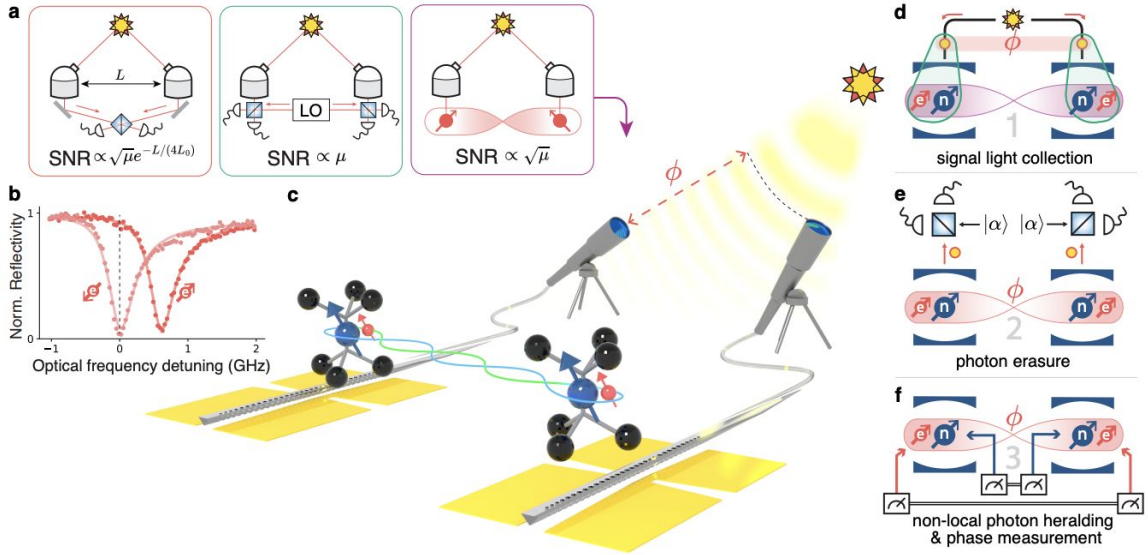
Distributed Deutsch-Jozsa type algorithm with blind oracles

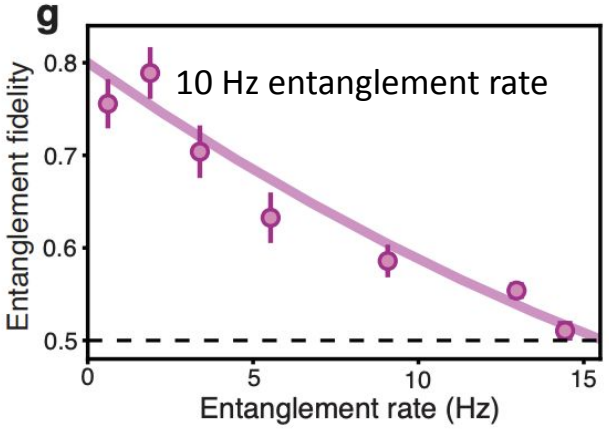


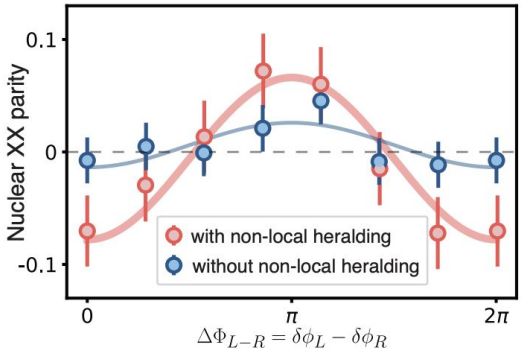
Team: Y.-C. Wei, P.-J. Stas, A. Suleymanzade, G. Baranes, M. Lukin et al.
Publication: Science (2025)

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Entanglement Assisted Non-Local Optical Interferometry







Team: P.-J. Stas, Y.-C. Wei, M. Sirotin, M. Lukin et al.
Publication: Under Review (2025)

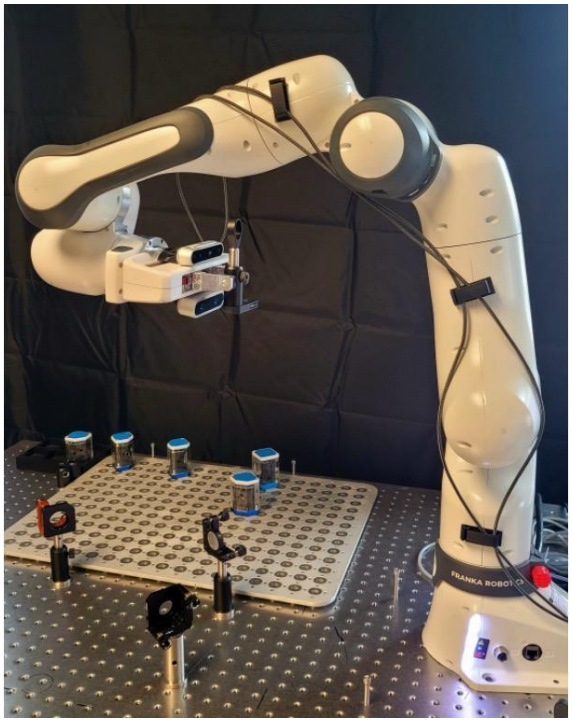
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AI-Driven Robotics for Quantum Optics

- Plan in twin→ simulate → act → measure → infer

Action rule: $a^* = \arg\max_{a \in A} V_\theta(a)$

(cost, design, safety, time,..)



- Design and search: $V_\theta(a) = \mathrm{E}_y\,[\text{information gain on } \theta]$

  Compute in the twin
  (integrates over y and posterior updates).
  selected action **can be non-obvious/under-explored**
  if that maximizes expected information about θ.

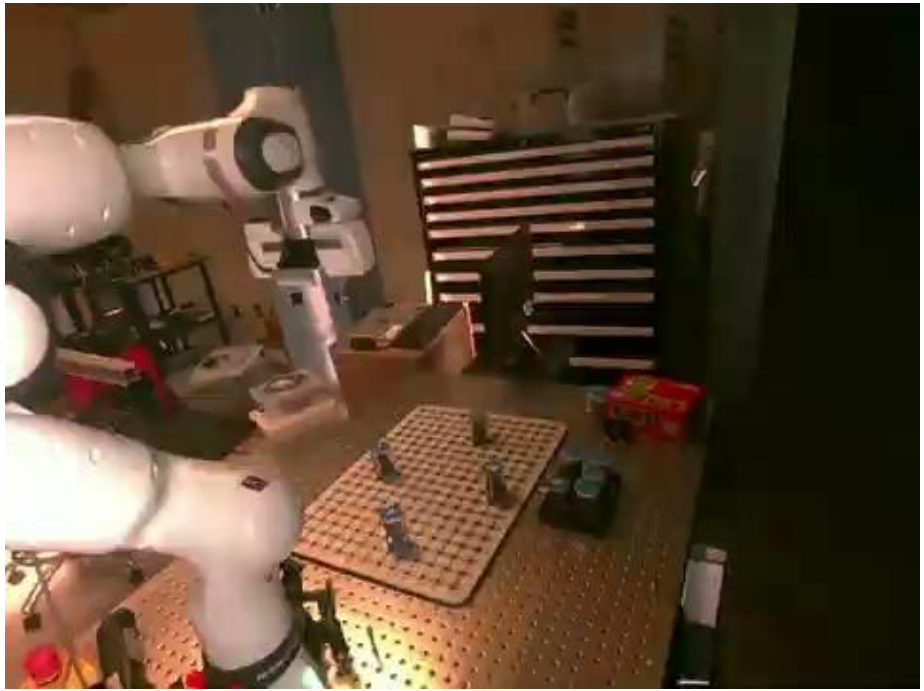
- Reduce Sim→Real Gap

  Calibrate twin parameters (actuators, sensors, noise,etc) with real data;
  iterate plan→execute→fit until action rankings agree and task-level
  Δmetrics are within tolerance (e.g., ≤10% or MAE ≤ 50 μm / 0.2°).

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Robot in action: pick and place of optical elements

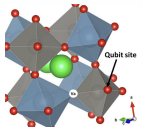


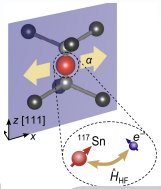


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CQN Boston Testbed Synergy Cycle



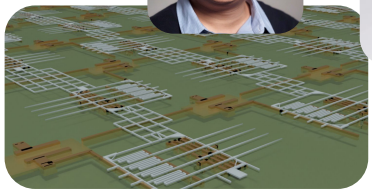




Material/Qubits

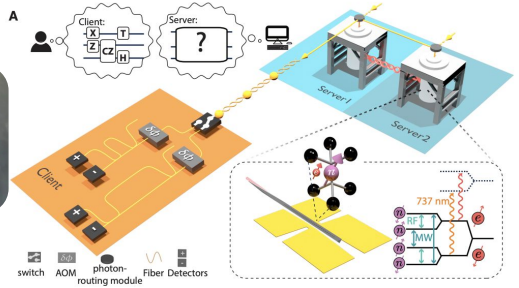






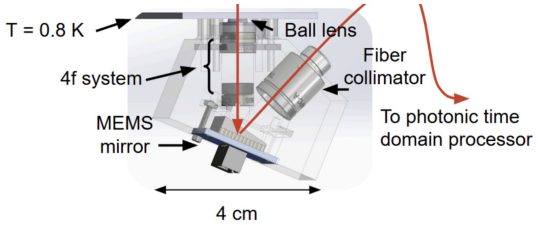
Architecture



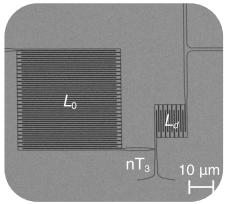


NSF ERC CQN Boston Testbed

System

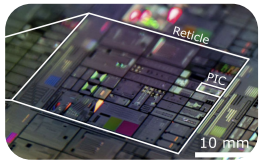


Device

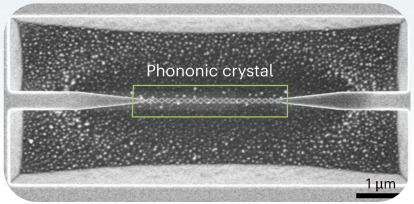




Fabrication







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Year 6-10 Boston Testbed

2026 Develop the MEMS-scanner QuMemory module and integrate the ZALM entanglement source

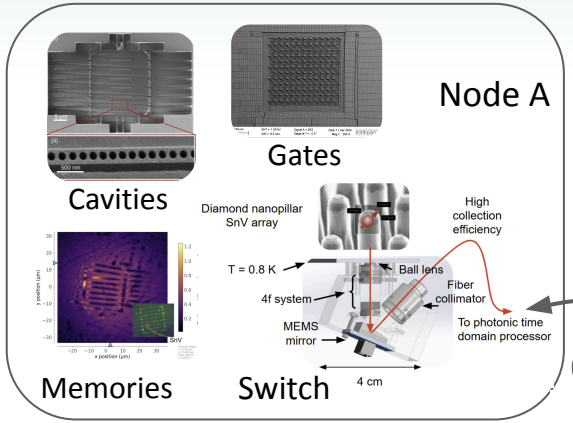
2027 Integrate with other subsystems (nanopillar arrays, cavity arrays, CMOS backplanes) and deploy new nodes at BBN and QuNett

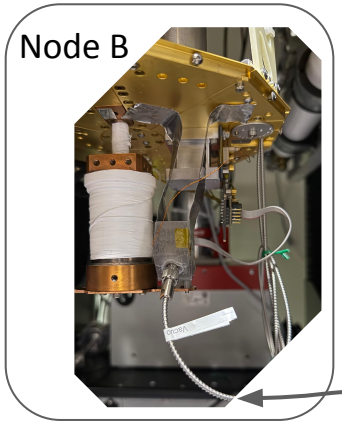
2028 Demonstrate heralded teleportation across newly added BBN, QuNett links

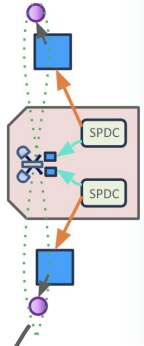
2029 Benchmark ZALM entanglement-generation scaling and optimize toward the target rate

2030 Provide open-access tooling/APIs for system tomography and benchmarking

Create deployable modules that expand geographic distribution and lower barriers to co-development.







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Quantum Networks
NSF Engineering Research Center



CQN Testbed: Tucson ⟶ Maryland

Chaohan Cui

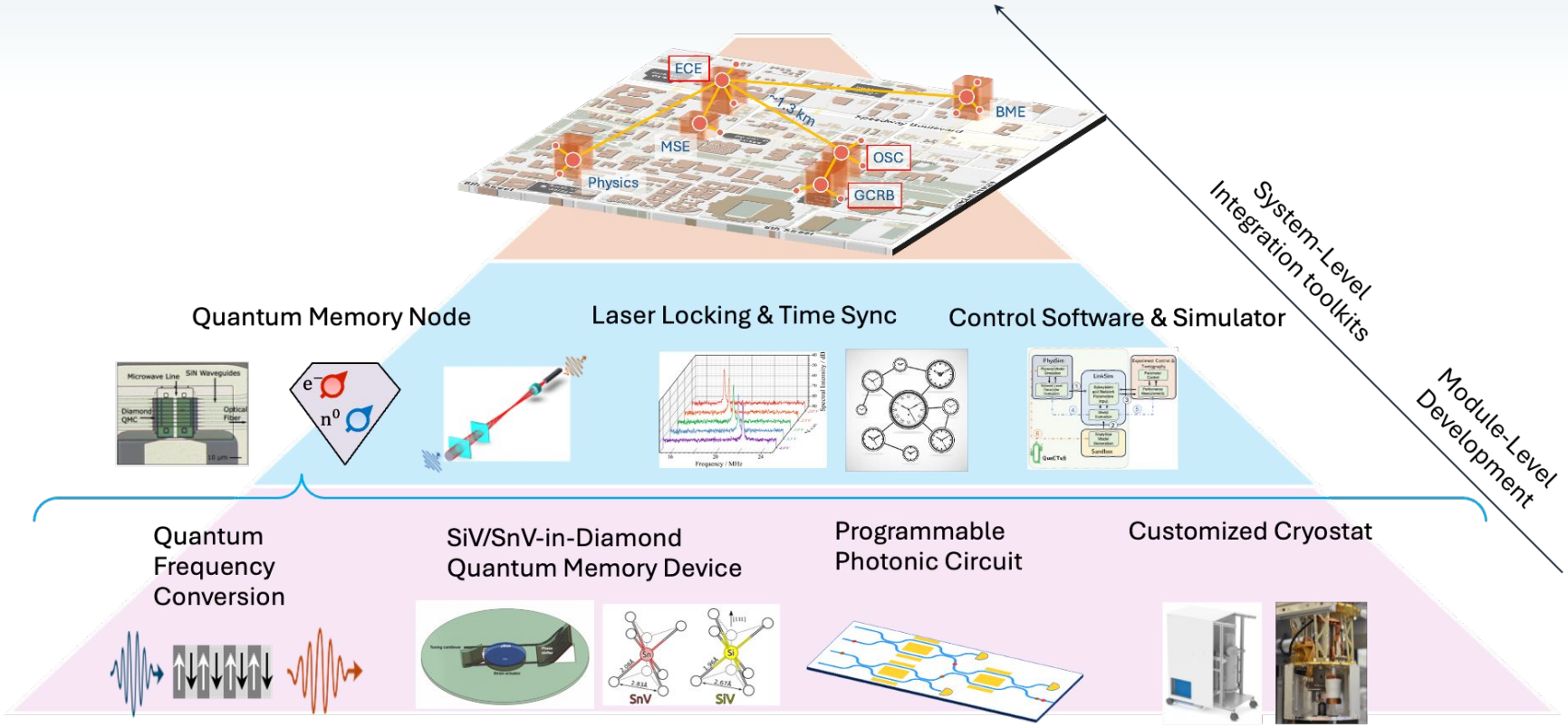
Maryland Testbed Lead

University of Maryland College Park

Funded by National Science Foundation Award #1941583

ARIZONA · MIT · HARVARD · UNIVERSITY OF MARYLAND · University of Massachusetts Amherst · BYU · THE UNIVERSITY OF CHICAGO 1890 · HOWARD UNIVERSITY · NAU NORTHERN ARIZONA UNIVERSITY · UNIVERSITY OF OREGON

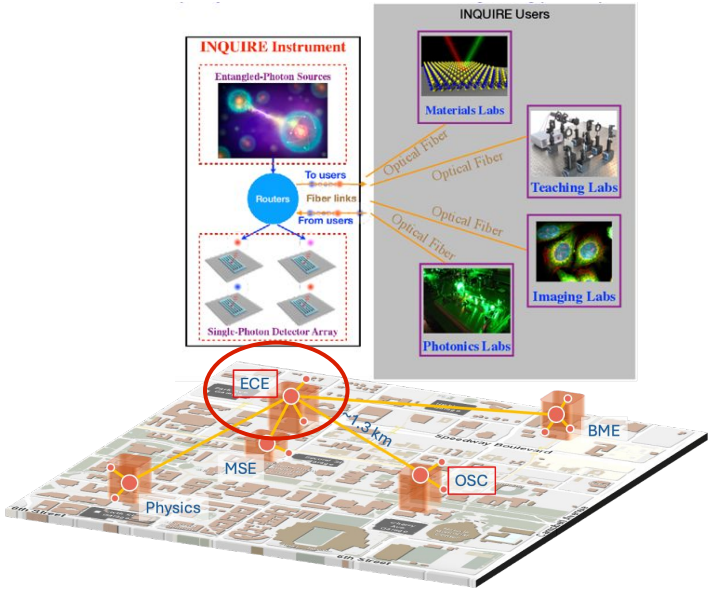
Tucson Testbed Y1-Y5 overview



© 2024 Center for Quantum Networks

Tucson Testbed Y1-Y5 overview

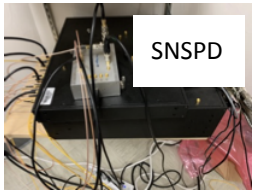
Birth of the Tucson Testbed: NSF INQUIRE project funds the new fiber network between five U. Arizona buildings for QIS education and research.

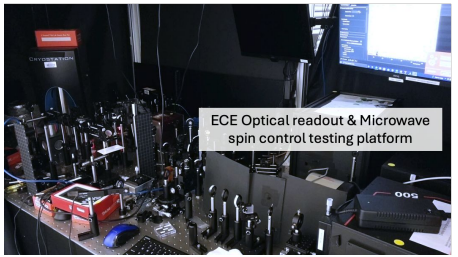


2020
2021
2022
2023
2024
2025

Establishing the central quantum hub: Recovering from COVID, we gradually established a central quantum network hub at ECE basement, equipped with SNSPDs, optical switches, one cryogenic platform for testing quantum memory.







Seed fund: NSF INQUIRE, led by Prof. Zheshen Zhang (now at UMich)

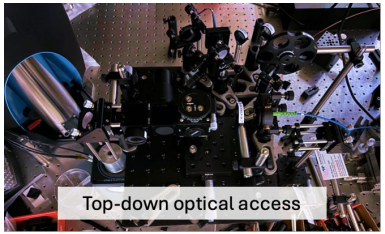
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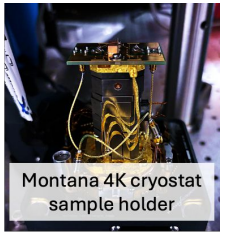
Tucson Testbed Y1-Y5 overview

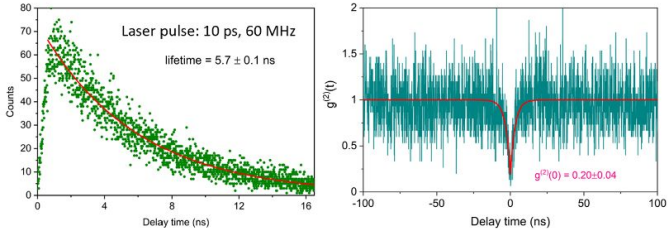
2020
2021
2022
2023
2024
2025

Birth of the Tucson Testbed

Characterizing SiC-4H SiV quantum memory: We characterized a single SiC-4H SiV color center as a potential candidate of quantum memory



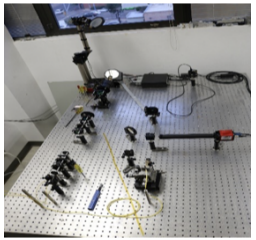




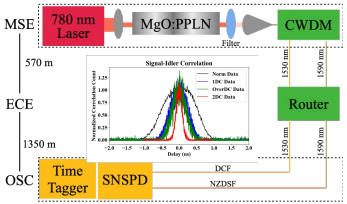
Y. Xue, M. Titze, J. Mack, Z. Yang, L. Zhang, S.S. Su, Z. Zhang, L. Fan
Nano Letters 24 (7), 2369-2375, (2024)

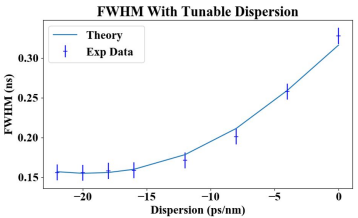
Establishing the central quantum hub

First entanglement distribution in Tucson: We established a free-space optical channel from ECE to the roof of OSC. We generated entangled photon pairs, distributed them through both fiber and free-space channels, and characterized the time-frequency entanglement.









C. Cui, W. Horrocks, L. McCaffrey, V. Nafria, I.B. Djordjevic, Z. Zhang
2021 CLEO, 1-2

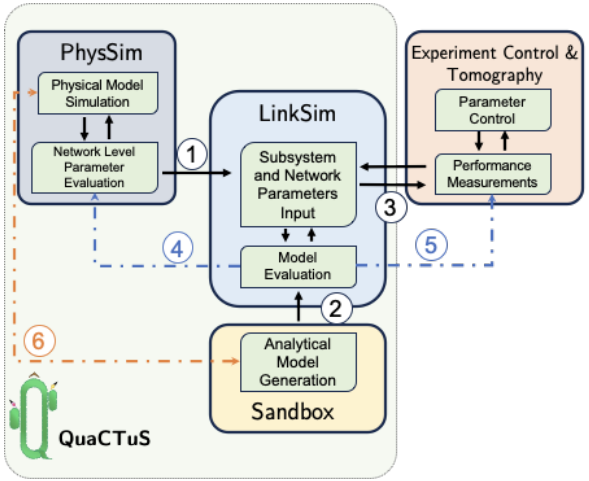
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Tucson Testbed Y1-Y5 overview

2020

Birth of the Tucson Testbed
Characterizing SiC-4H SiV quantum memory

QuaCTUS - Tucson Testbed Simulator: We launch the development of a physical-layer digital twin of the quantum network as a complimentary interface between the Tucson Testbed and Virtual Tested.



P. Dhara, S. Guha, Python code 2023

2021

2022

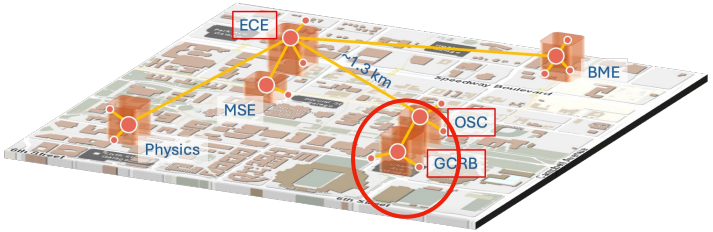
2023

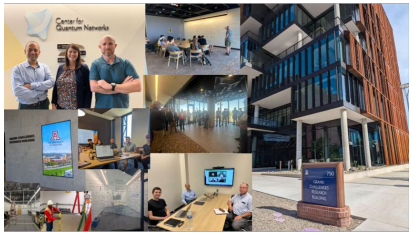
2024

2025

Establishing the central quantum hub
First entanglement distribution in Tucson

New space and cryostat: The New GCRB building added another node to the Tucson Testbed. We received the co-designed low-cost cryostat that accommodates our quantum memory at sub-1K temperature with scalability.







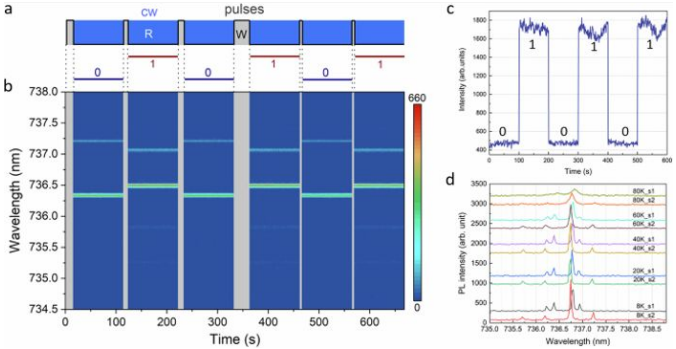
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Tucson Testbed Y1-Y5 overview

2020

Birth of the Tucson Testbed
Characterizing SiC-4H SiV quantum memory
QuaCTUS - Tucson Testbed Simulator

Characterizing SiV color center quantum memory: We found that a second pulsed IR laser can thermalize the lattice structure of SiV defect in diamond, which changes the ground state splitting drastically. It may make SiV a good quantum memory at >1K temperature.



Y. Xue, X. Ni, M. Titze, S.S. Su, B. Wu, L. Zhang, C. Cui, S. Guha, M. Eichenfield, L. Fan, Nat. Commun. 16 (1), 6275, (2025)
J. Chen, C. Cui, B. Lawrie, Y. Xue, S. Guha, M. Eichenfield, H. Zhao, X. Yan, Nanophotonics 14 (11), 1687-1713, (2025)

2021

2022

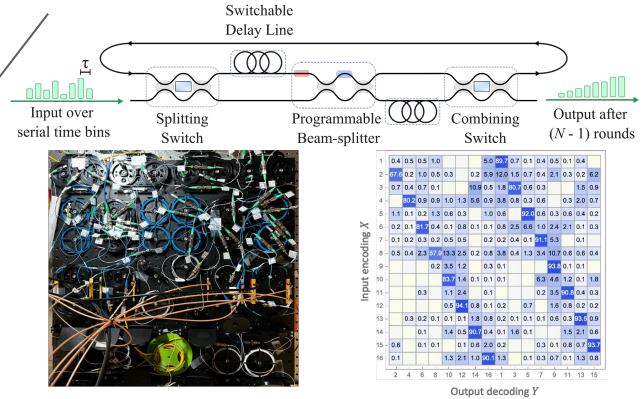
2023

2024

2025

Establishing the central quantum hub
First entanglement distribution in Tucson
New space and cryostat

Time domain interferometer: We developed the first scalable time-domain optical joint receiver - G*reen Machine* with > 0.9 fidelity. This architecture is now being adapted for generating entanglement among many quantum memory.



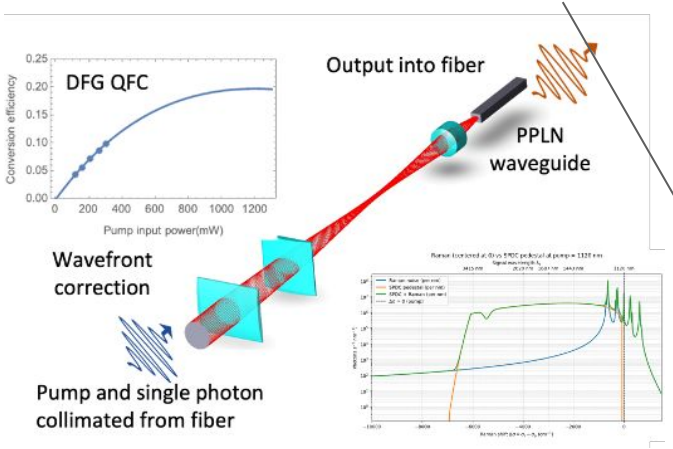
C. Cui, J. Postlewaite, B.N. Saif, L. Fan, S. Guha, Nat. Commun. 16 (1), 3760, (2025)
J.R. Basani, C. Cui, J. Postlewaite, E. Waks, S. Guha, arXiv:2505.00865 (2025)

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Tucson Testbed Y1-Y5 overview

2020
- Birth of the Tucson Testbed
- Characterizing SiC-4H SiV quantum memory
- QuaCTUS - Tucson Testbed Simulator
- Characterizing SiV color center quantum memory

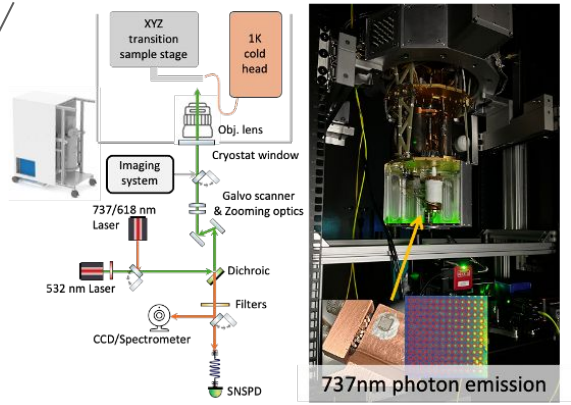
Quantum frequency conversion: We demonstrated 10% efficiency 737 nm single photon from SiV emitter -> 1392 nm single photon.



Team: M. Akbulut, C. Cui, Y. Wang, Y. Xue, M. Eichenfield

2021
- Establishing the central quantum hub
- First entanglement distribution in Tucson
- New space and cryostat
- Time domain interferometer

Cryostat-compatible confocal scanning microscope: We designed a confocal scanning microscope for PhotonSpot crystal we received in mid 2023 and tested for collecting emissions from SiV in diamond.



Team: M. D. Ackerman, C. Cui, Y. Xue, M. Akbulut, M. Eichenfield

2022
2023
2024
2025

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Tucson Testbed Y1-Y5 overview

2020
- Birth of the Tucson Testbed
- Characterizing SiC-4H SiV quantum memory
- QuaCTUS - Tucson Testbed Simulator

2021
- Characterizing SiV color center quantum memory
- Quantum frequency conversion

2022
- Establishing the central quantum hub
- First entanglement distribution in Tucson
- New space and cryostat

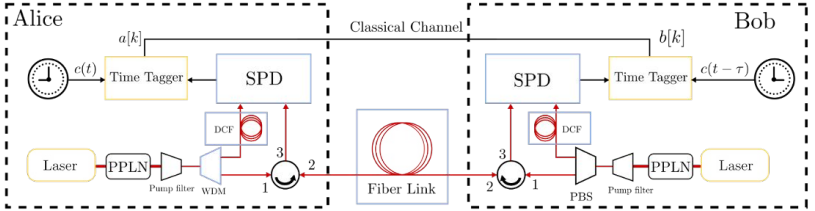
2023
- Time domain interferometer
- Cryostat-compatible confocal scanning microscope

2024
Granting access to industrial partners: We help L3Harris establish their experiments sharing the quantum networking facilities on U. of Arizona campus.

2025
Collaborations and technology sharing across testbeds: In 2023-2024, we visited Boston testbed to learn their techniques and brought back some SiV chips from MIT, MIT Lincoln Lab, and our industrial partner Qunett.



Team: C. Cui, Y. Xue, M. Eichenfield, C. Li, Y. Hu, I. Christen
H. Raniwala, D. Englund, L. Andre, B. Shields, MITLL …





Team: M. Bullock, B. Bash, L3Harris

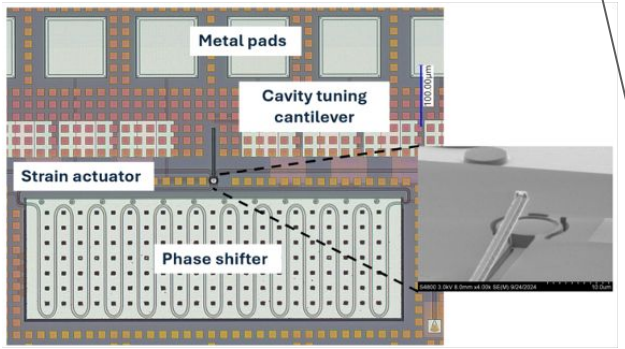
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Tucson Testbed Y1-Y5 overview

2020
- Birth of the Tucson Testbed
- Characterizing SiC-4H SiV quantum memory
- QuaCTUS - Tucson Testbed Simulator

2021
- Characterizing SiV color center quantum memory
- Quantum frequency conversion
- Collaborations and technology sharing across testbeds

2022
- Integrated quantum memory devices: We designed diamond micro-disk resonator for Purcell enhancement rate, scalability, and compatibleness to photonic integrated circuits

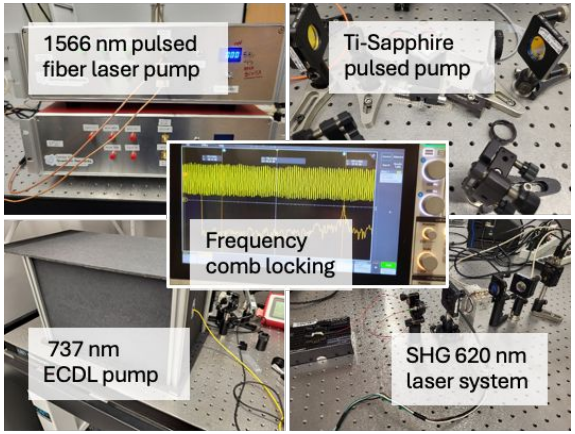


Team: A. Zhai, M. Eichenfield, Sandia National Lab

2023
- Establishing the central quantum hub
- First entanglement distribution in Tucson
- New space and cryostat

2024
- Time domain interferometer
- Cryostat-compatible confocal scanning microscope
- Granting access to industrial partners

2025
- Supporting systems for quantum network: remote laser locking and special pump laser systems



Team: M. Akbulut

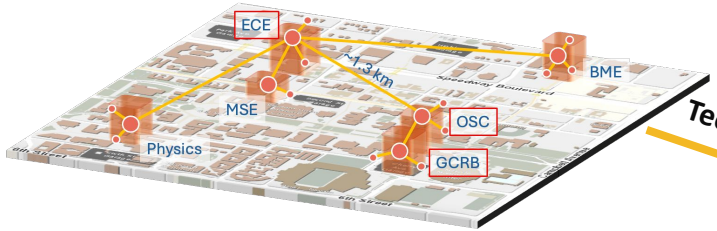
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Tucson Testbed → UMD Testbed

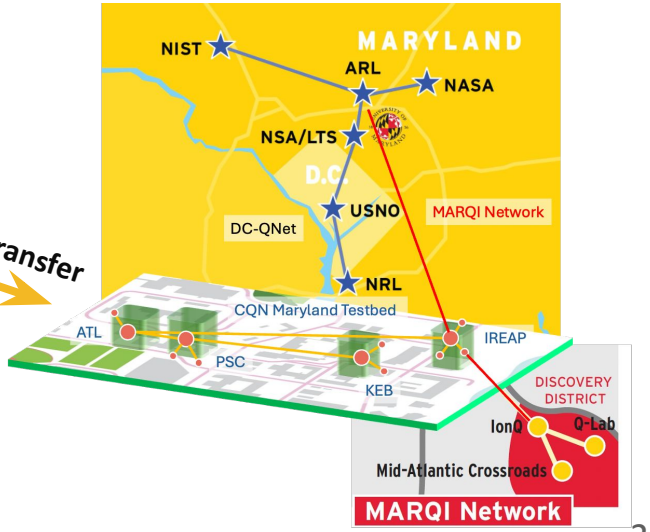
Birth of the Tucson Testbed
Characterizing SiC-4H SiV quantum memory
QuaCTUS - Tucson Testbed Simulator
Characterizing SiV color center quantum memory
Quantum frequency conversion
Collaborations and technology sharing across testbeds
Integrated quantum memory devices

2020
2025
2030

Establishing the central quantum hub
First entanglement distribution in Tucson
New space and cryostat
Time domain interferometer
Cryostat-compatible confocal scanning microscope
Granting access to industrial partners
Supporting systems for quantum network



Technology/equipment transfer



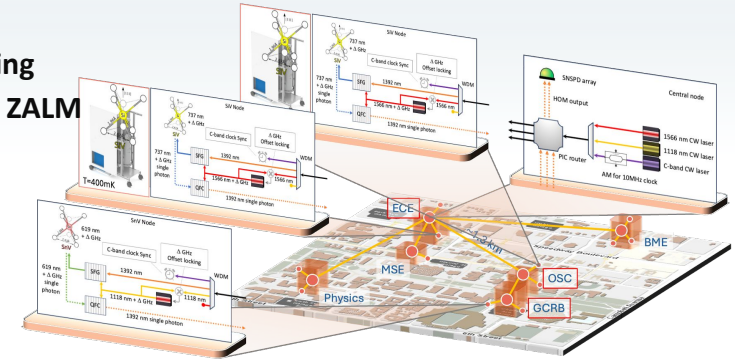
New features:

- Including trapped-ion workforce
- Trans-scale networks for more end-users
- Quantum communities and collaborations

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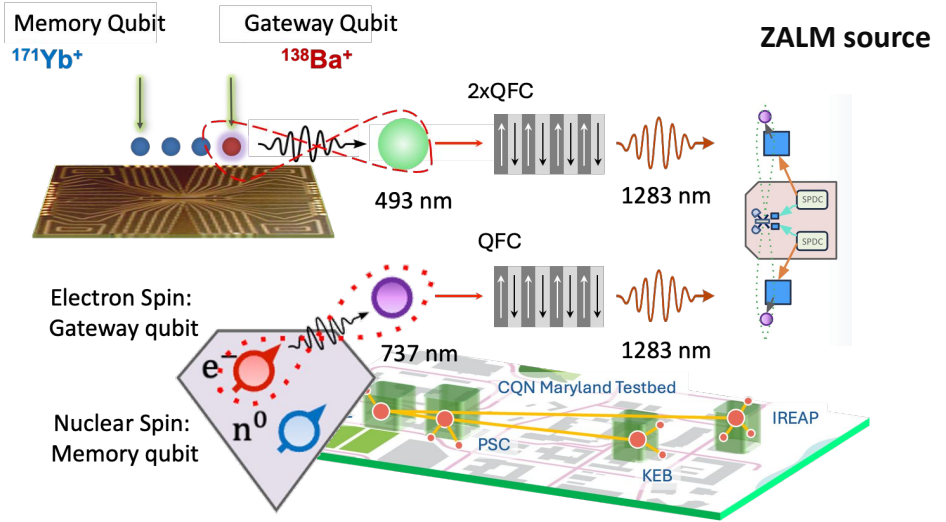
Tucson Testbed → UMD Testbed

Design change: Including Trapped-ion QPU, and ZALM source for practical quantum networking

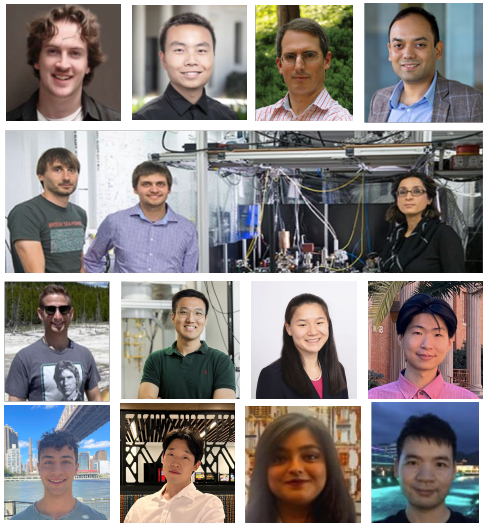




Team change: Adding specialties of trapped-ion systems

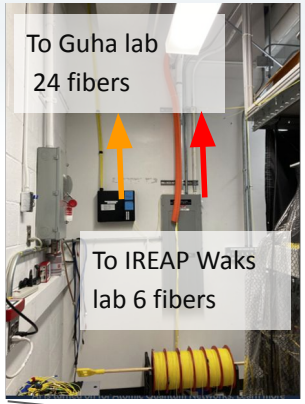


ZALM source

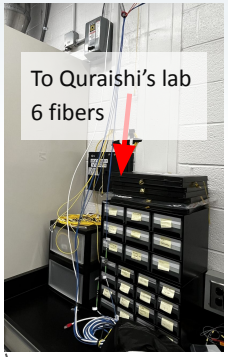


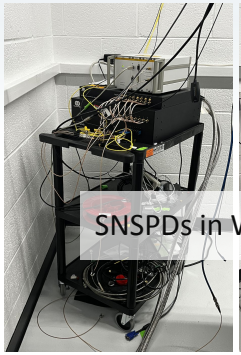
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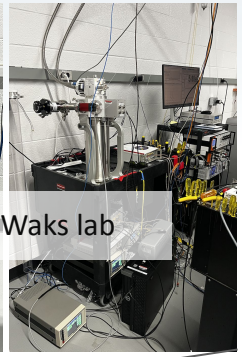
Maryland Testbed in Y5: Facilities



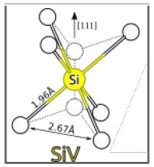


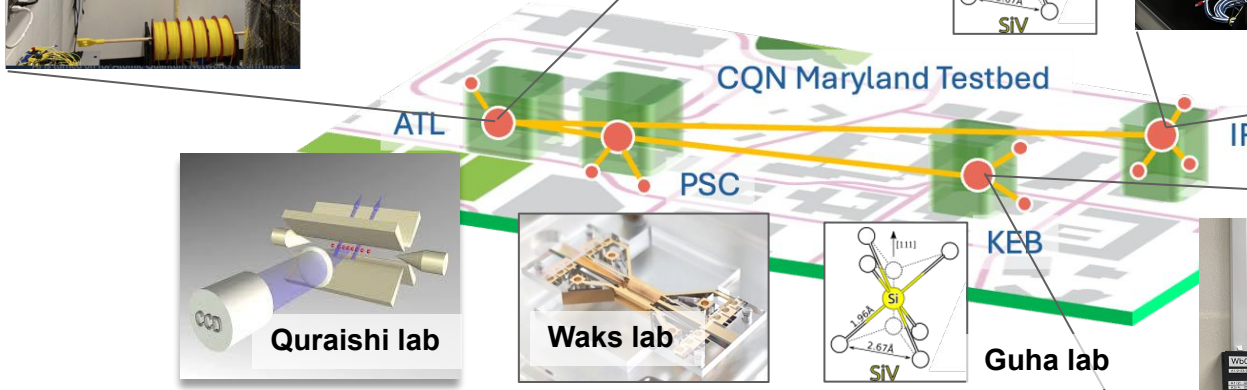




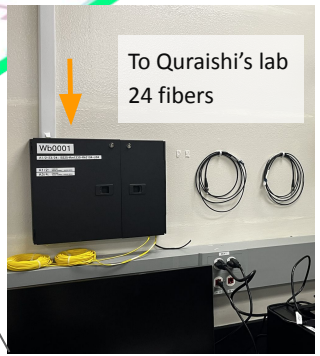


Waks lab









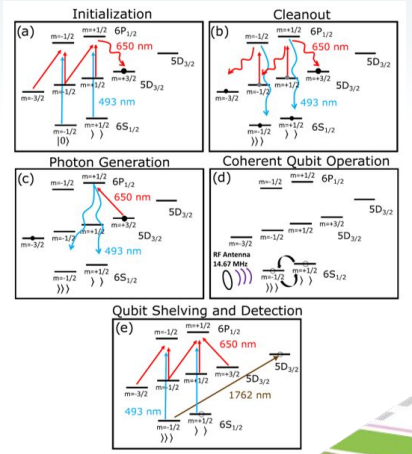


Full Network connectivity is underway

- (summer 2025) Fiber installed Guha to fiber hub/Quraishi lab.
- (upcoming) Fiber install Waks to fiber hub
- (upcoming) Characterization (loss, temporal variation,..)

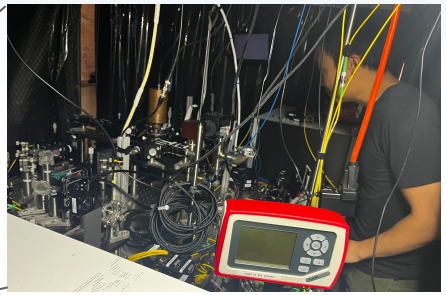
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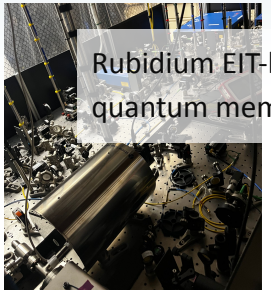
Maryland Testbed in Y5: Trapped Ion



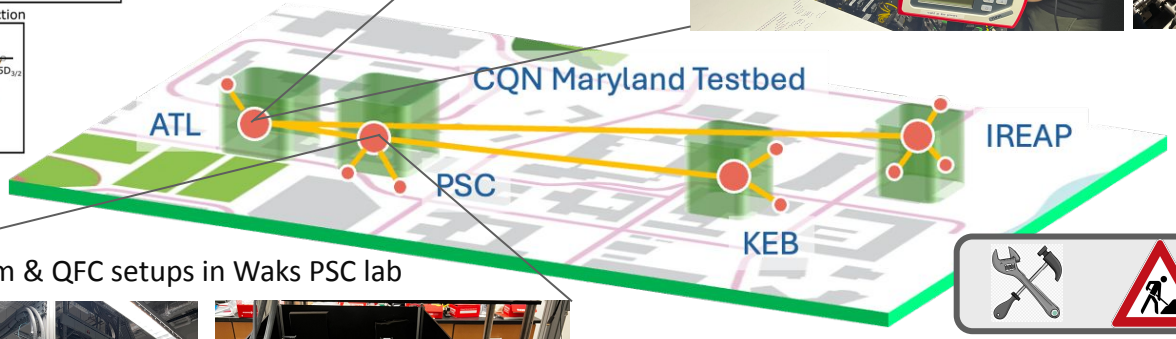
Barium ion entangled with photon polarization 50k/s

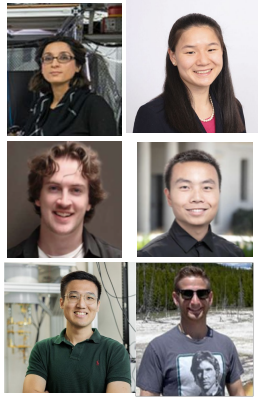
Trapped-ion system in Quraishi ATL lab



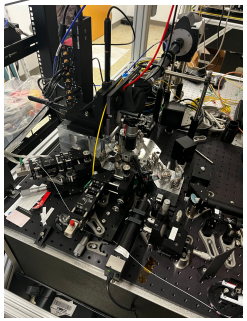


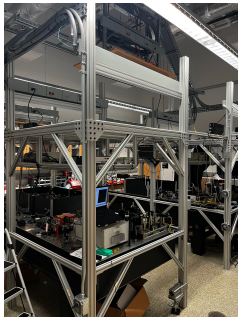
Rubidium EIT-based quantum memory

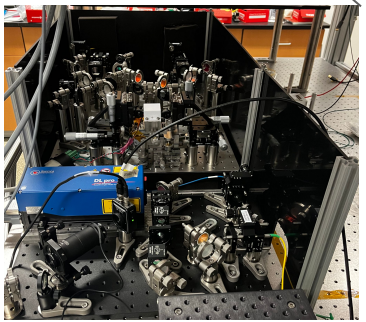




Trapped-ion system & QFC setups in Waks PSC lab







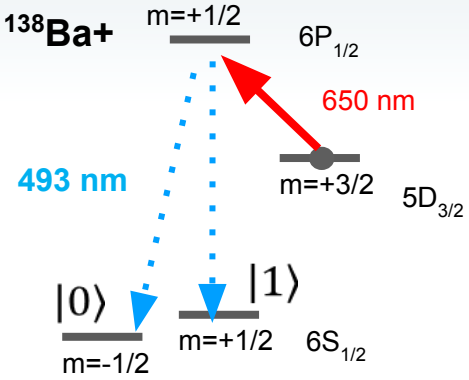
Upgrading the Trapped-Ion Systems

- (summer 2025) Polarization-independent QFC to 1283 nm
- (upcoming) Ion to telecom photon entanglement fidelity
- (upcoming) HOM with QFC-converted photon from SiVs

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Maryland Testbed in Y5: Trapped Ion



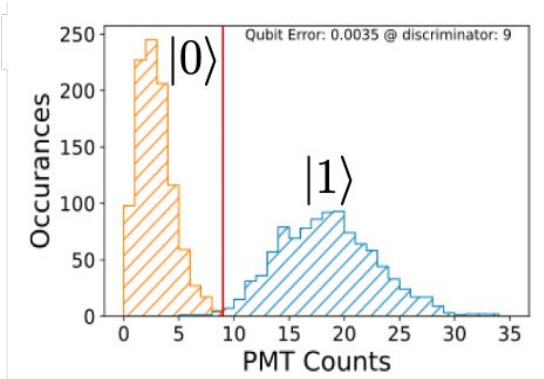
Overview trapped ion system + frequency conversion

telecom photon via two-stage frequency conversion *(newly completed)*



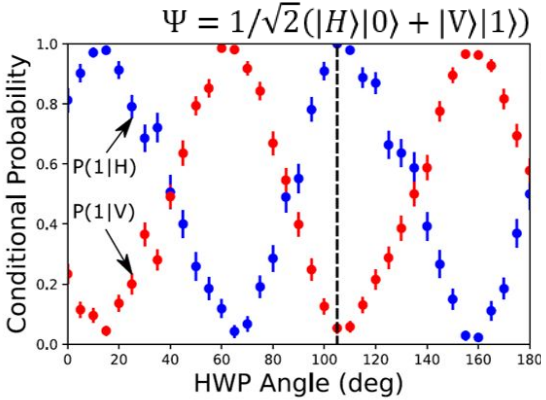
J. Hannegan, U. Saha, et al., ACS Photonics 10, 8, 2861 (2023) (o-band)
J. D. Siverns, J. Hannegan, Q. Quraishi, Appl. Phys. Lett. 119, 084001 (2021) (c-band)

Trapped Ba+ ion system



- Ba+ emits 493 nm photon.
- First-stage frequency conversion 493 nm (93% fidelity) → 780 nm (84%) (ion-visible-photon entanglement fidelity)
- ***(upcoming)*** Second-stage frequency conversion 780 nm → 1283 nm ion-telecom-photon entanglement fidelity.

Thermally *phase-matched ZnO-doped periodically poled lithium niobate (PPLN)*

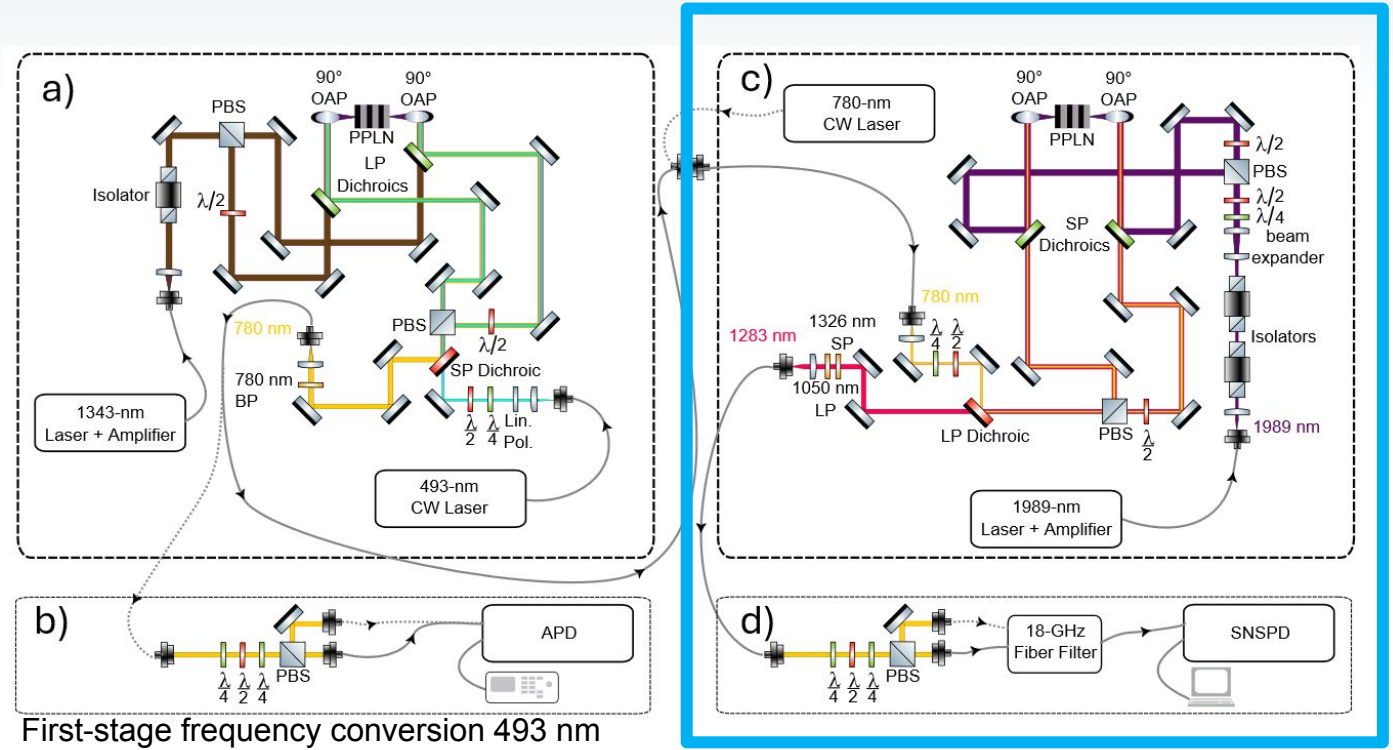


J. Hannegan, Doctoral thesis, Uni. of MD, (2022).

J. Hannegan, J.D. Siverns and Q. Quraishi, Phys. Rev. A 106, 042441 (2022).

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Maryland Testbed in Y5: Trapped Ion



First-stage frequency conversion 493 nm (93% fidelity) → 780 nm (84%)
(ion-visible-photon fidelity lower bound)

NEW QFC stage for telecom for connecting to converted photon from SiV side

Summer 2025: Characterized two-stage, polarization-preserving QFC to 1283 nm.

J. Hannegan, J.D. Siverns and Q. Quraishi, Phys. Rev. A 106, 042441 (2022).

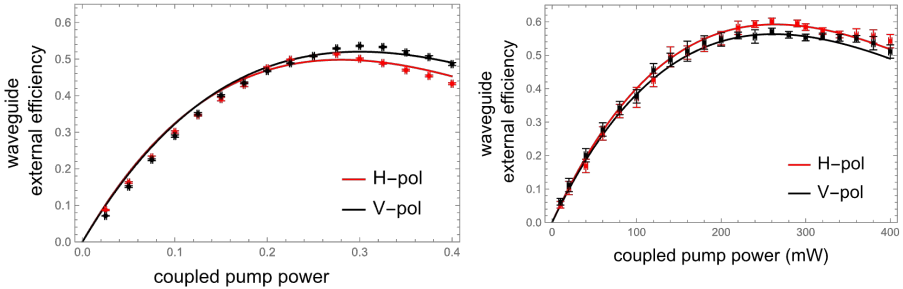
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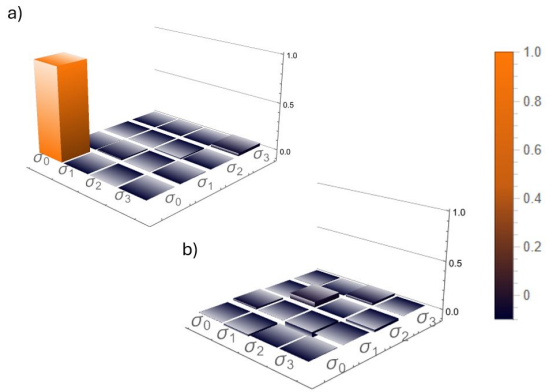
Maryland Testbed in Y5: QFCs

493 nm → 1283 nm two-stage QFC results

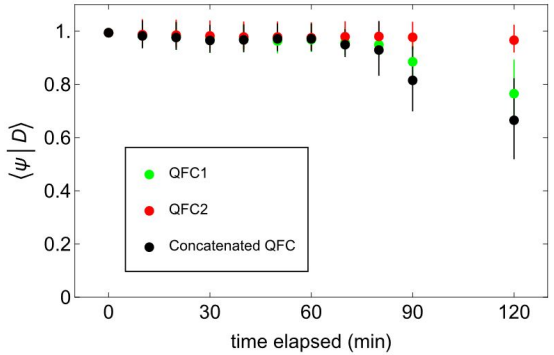
97.(0)% process fidelity (polarization-preserving)

>33% fiber-to-fiber conversion efficiency of each stage





> 60 min polarization stability



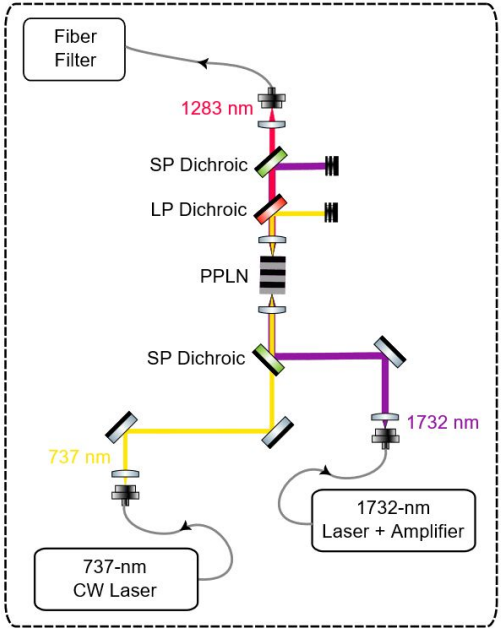
projected ion-photon entanglement rate and fidelity

	rates	fidelity
493 nm	137/s	> 0.93(2)
780 nm	45/s	> 0.84(2)
1283 nm (projected)	15/s	> 0.7(5)

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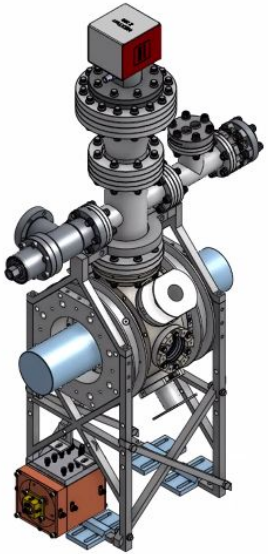
Maryland Testbed in Y5: Trapped Ion + QFC

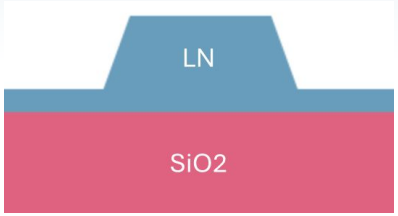
Upcoming:

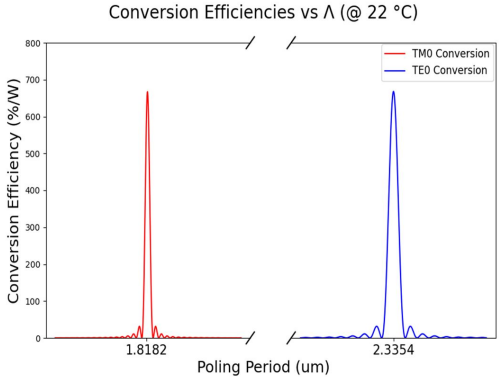


737 nm ⟶ 1283 nm QFC (Winter 2025)

Waks Lab and TAMOS: next-generation ion trap system (Winter-Spring 2026)





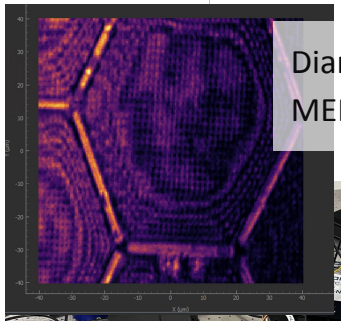


Waks Lab & Loncar Group: next-gen 493 nm⟶ 737 nm Pol-Res QFC on TFLN (Summer-Fall 2026)

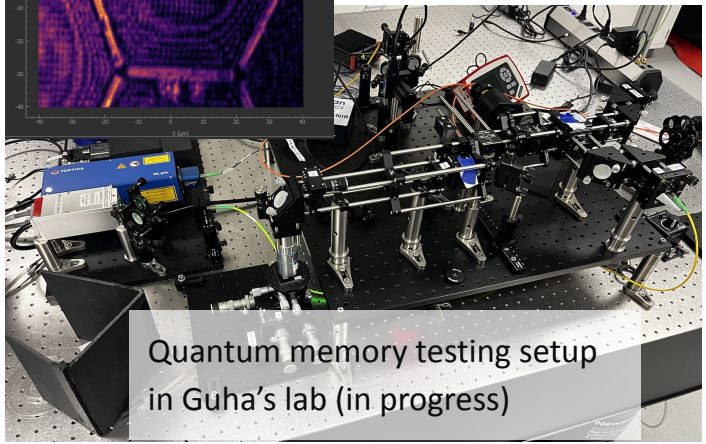
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Maryland Testbed in Y5: Diamond Color Center

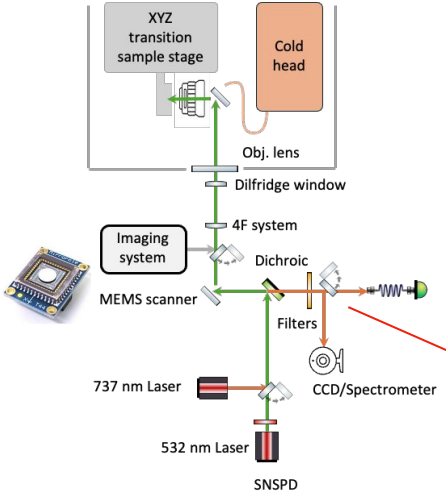
Building a dil-fridge compatible confocal MEMS-scanner microscopy

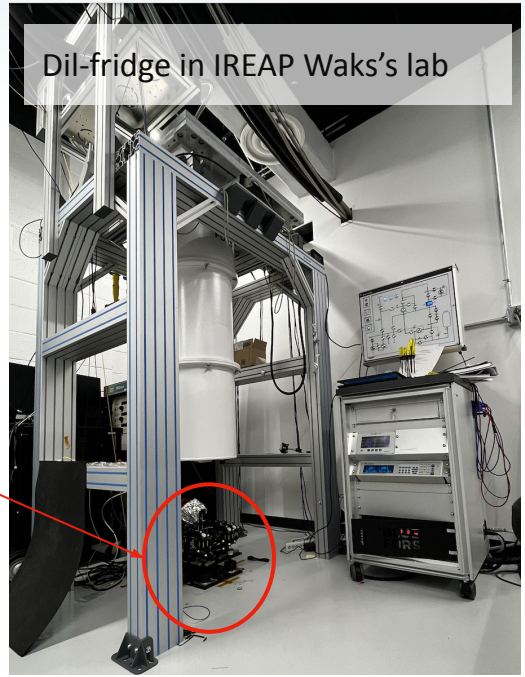


Diamond nanopillars under MEMS confocal scanner



Quantum memory testing setup in Guha's lab (in progress)





Dil-fridge in IREAP Waks's lab

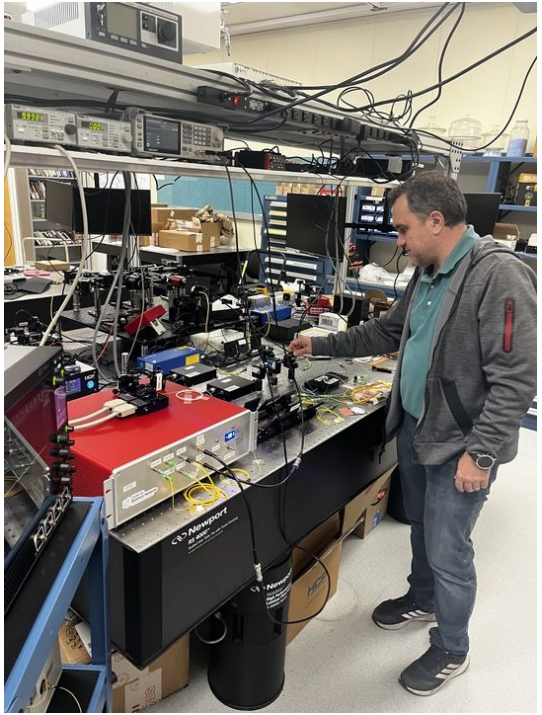




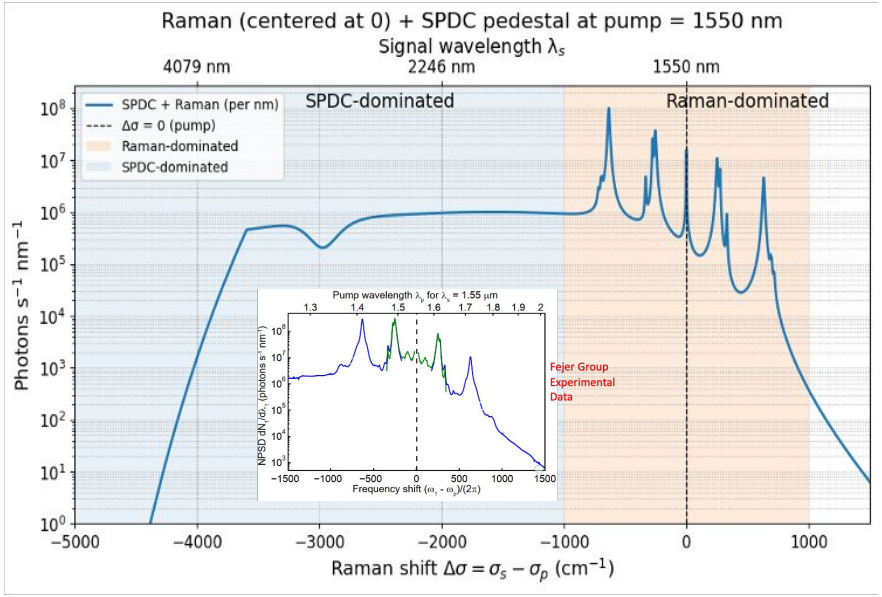

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Maryland Testbed in Y5: QFC & Noise (Tucson Testbed)

Transferring SiV QFC setup from UArizona to UMD



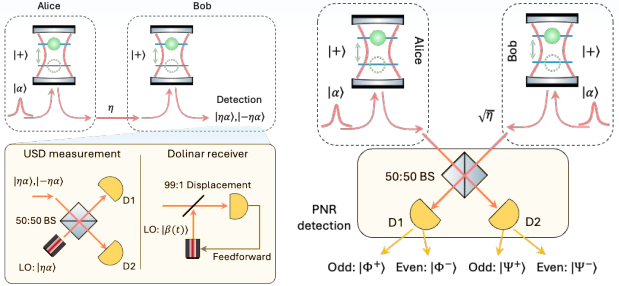
PPLN high-power pump noise photon simulations

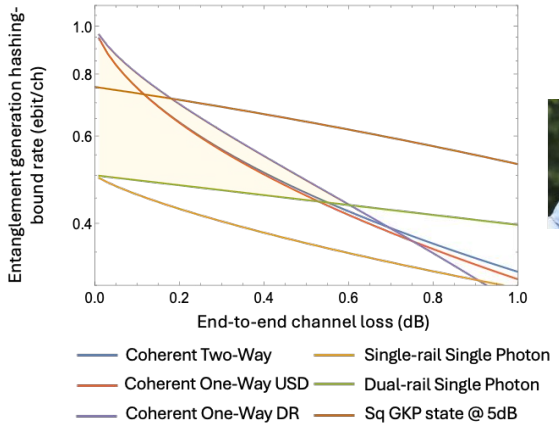


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Maryland Testbed in Y5: New Networking Protocols

Coherent-state-assisted entanglement distribution

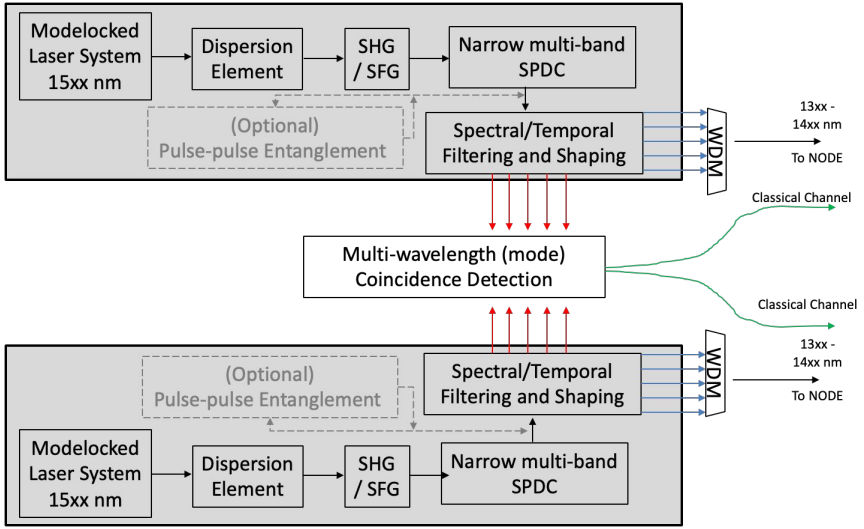






C. Cui, P. Dhara, S. Guha, arXiv:2504.20344 (2025)

ZALM-source based entanglement distribution, working with UArizona, UOregon, MIT



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Year 6-10 Maryland Testbed

2026
Develop the MEMS-scanner quantum memory module and ZALM source together with other CQN thrusts
Set up new TAMOS ion trap system in Waks lab & build QFC modules.
Testing next-gen QFC module in fiber networks throughout the testbed and MARQI network

2027
Integrate the network and classic control with quantum memory and the trapped ion system. (Together with MARQI)
Investigating temporal mode shaping and other potential bottlenecks.
Wrap up QFC noise characteristics of using PPLN together with U of A team

2028
Demonstrate basic quantum memory functions and HOM interference between SiVs and trapped ions. Open testbed access to industrial partner.

2029
Benchmark ZALM entanglement-generation scaling and optimize toward the target rate, implement it together with Boston testbed.

2030
Demonstrate high-rate entanglement distribution over multiple quantum memory nodes.
Demonstrate advanced quantum networking protocols

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The Virtual Testbed

Stefan Krastanov

Virtual Testbed Lead

University of Massachusetts Amherst

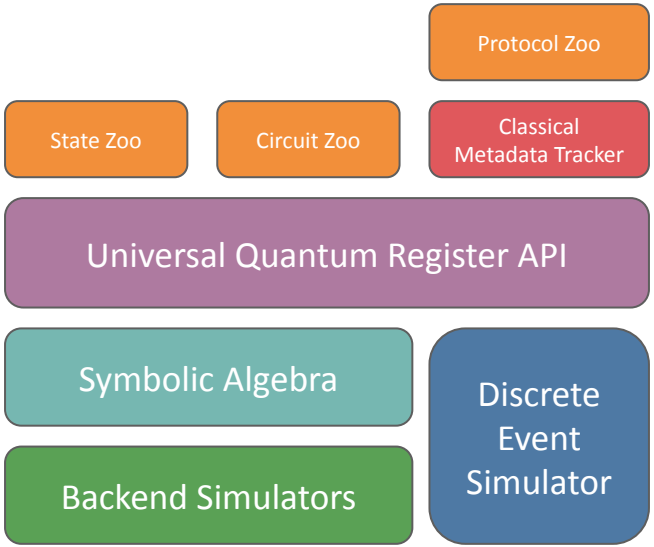
skrastanov@umass.edu

Funded by National Science Foundation Grant #1941583

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System Integration Stage
i.e.
The whole is greater than its parts

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User Story – Integration between Thrusts

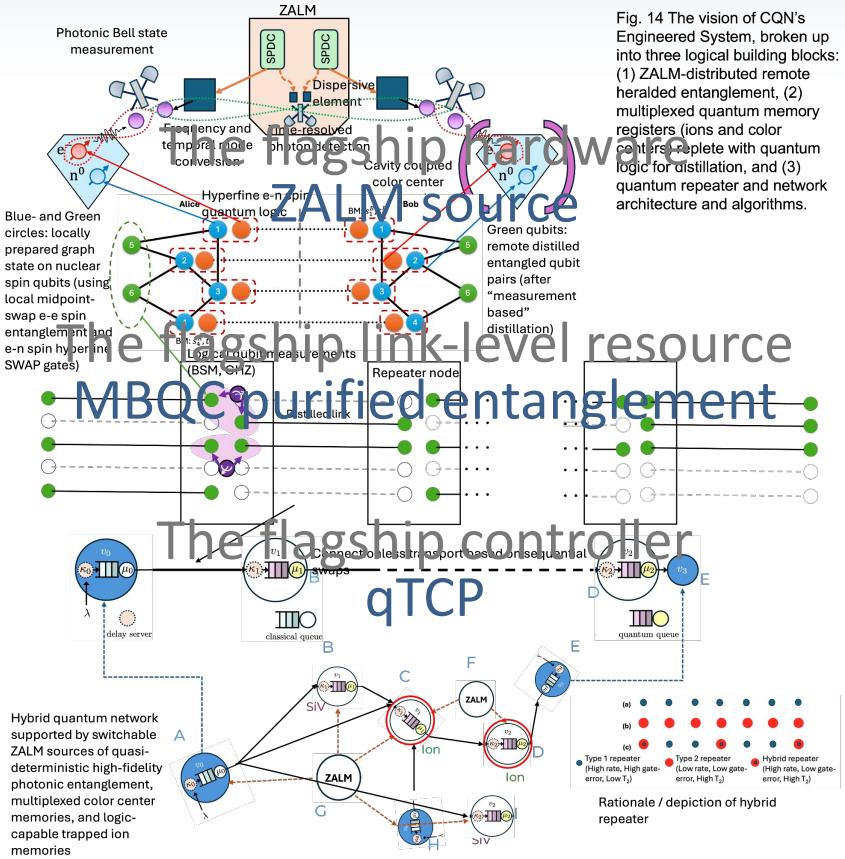


Fig. 14 The vision of CQN's Engineered System, broken up into three logical building blocks: (1) ZALM-distributed remote heralded entanglement, (2) multiplexed quantum memory registers (ions and color centers) replete with quantum logic for distillation, and (3) quantum repeater and network architecture and algorithms.

The flagship hardware

ZALM source

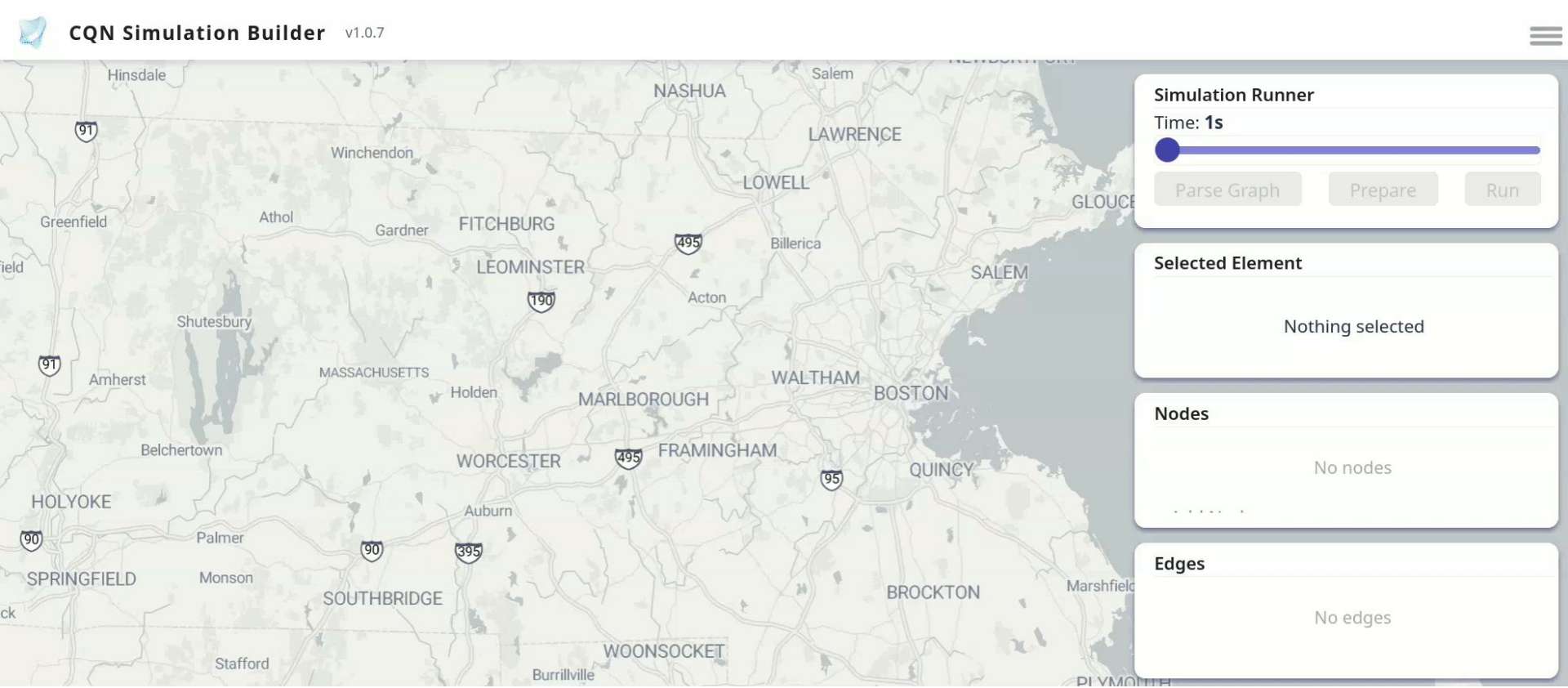
The flagship link-level resource

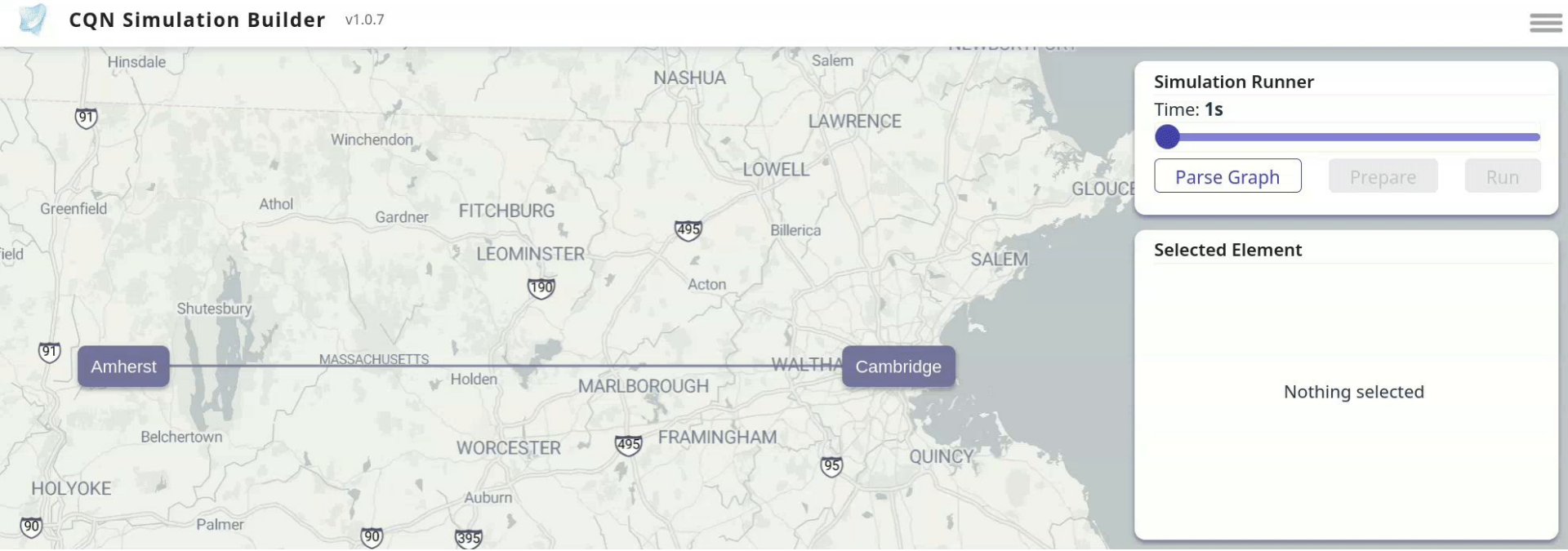
MBQC purified entanglement

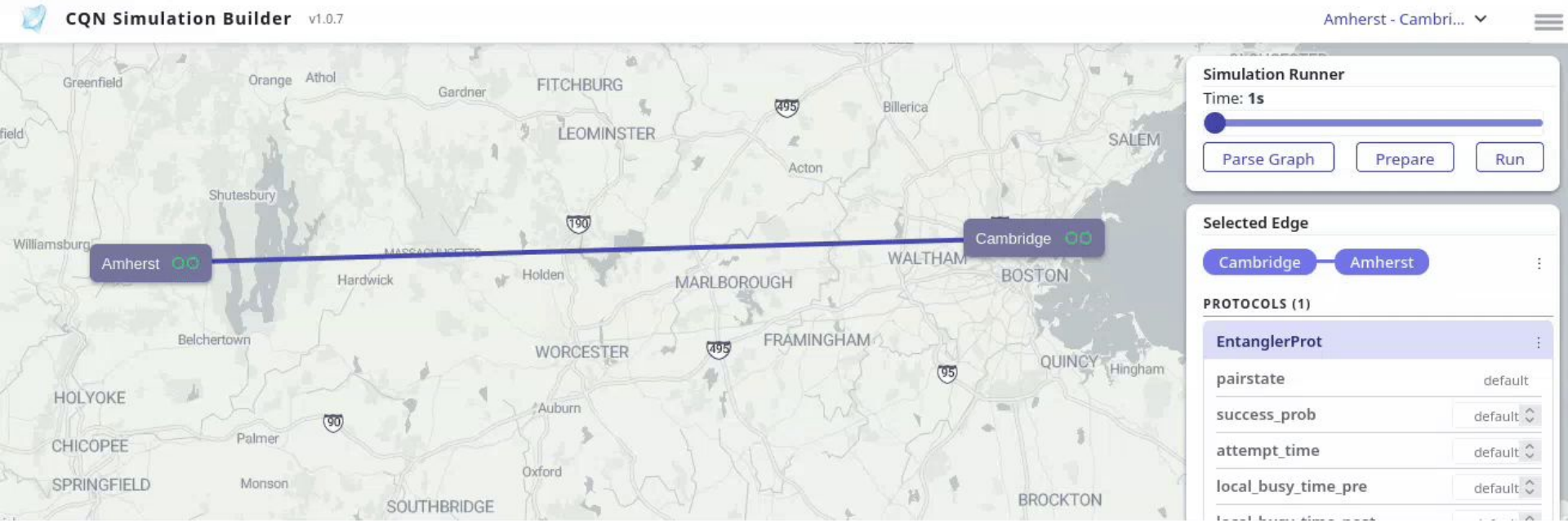
The flagship controller

qTCP

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CQN Simulation Builder
v1.0.7
Hinsdale
NASHUA
Salem
LAWRENCE
Winchendon
LOWELL
Greenfield
Athol
Gardner
FITCHBURG
Billerica
LEOMINSTER
SALEM
Acton
Shutesbury
Amherst
MASSACHUSETTS
Holden
MARLBOROUGH
WALTHAM
BOSTON
Belchertown
WORCESTER
FRAMINGHAM
QUINCY
HOLYOKE
Auburn
Palmer
SPRINGFIELD
Monson
SOUTHBRIDGE
BROCKTON
Stafford
WOONSOCKET
Burrillville
Simulation Runner
Time: 1s
Parse Graph
Prepare
Run
Selected Element
Nothing selected
Nodes
No nodes
Edges
No edges


CQN Simulation Builder
v1.0.7
Hinsdale
NASHUA
Salem
LAWRENCE
Winchendon
LOWELL
Greenfield
Athol
Gardner
FITCHBURG
Billerica
LEOMINSTER
SALEM
Acton
Shutesbury
Amherst
MASSACHUSETTS
Holden
MARLBOROUGH
Cambridge
Belchertown
WORCESTER
FRAMINGHAM
QUINCY
HOLYOKE
Auburn
Palmer
Simulation Runner
Time: 1s
Parse Graph
Prepare
Run
Selected Element
Nothing selected


CQN Simulation Builder
v1.0.7
Amherst - Cambri...
Greenfield
Orange
Athol
Gardner
FITCHBURG
LEOMINSTER
Billerica
SALEM
Acton
Shutesbury
Williamsburg
Amherst
Hardwick
Holden
MARLBOROUGH
Cambridge
WALTHAM
BOSTON
Belchertown
WORCESTER
FRAMINGHAM
QUINCY
Hingham
HOLYOKE
Auburn
CHICOPEE
Palmer
SPRINGFIELD
Monson
Oxford
SOUTHBRIDGE
BROCKTON
Simulation Runner
Time: 1s
Parse Graph
Prepare
Run
Selected Edge
Cambridge
Amherst
PROTOCOLS (1)
EntanglerProt
pairstate
default
success_prob
default
attempt_time
default
local_busy_time_pre
default

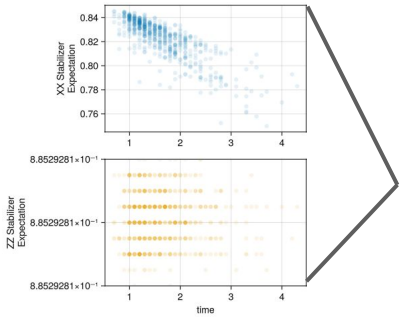
Friendly abstractions both in GUI and Scripting

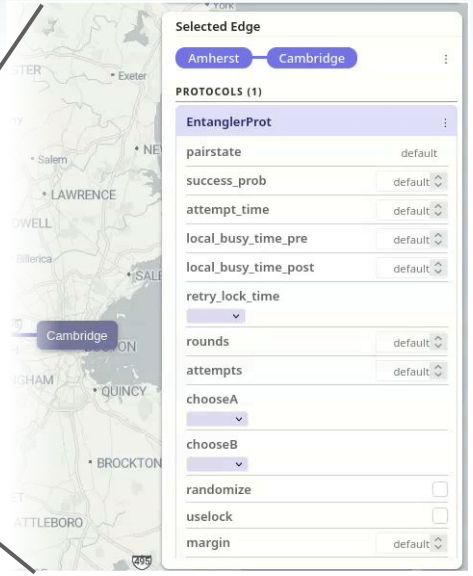
```
regA = Register(2)
regB = Register(2)
net = RegisterNet([regA, regB])
sim = get_time_tracker(net)

entangler = EntanglerProt(sim, net, 1, 2)
@process entangler()
consumer = EntanglementConsumer(sim, net, 1, 2)
@process consumer()

run(sim)

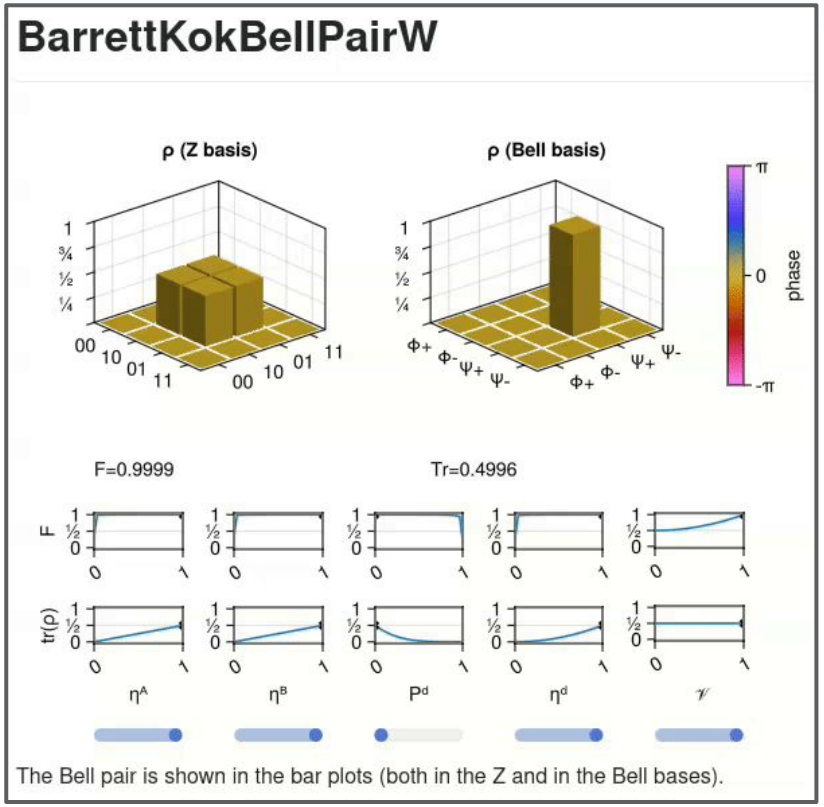
show(..., consumer)
```





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Common Entanglement Models



Arbitrary symbolic states

and

Highly Parameterized Intricate Models
Barret Kok
SPDC
ZALM
…

Integrating many
T2&T3 research results

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Available Protocols

Entangler / Swapper / Information Tracker / Purifier / Consumer

Simple Switch (Yale)

Graph Preparer (Arizona/Maryland)

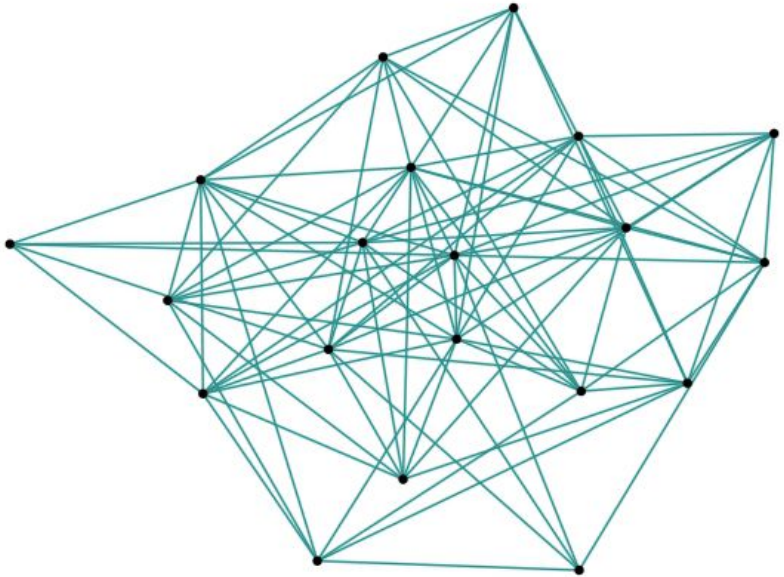
Piecemaker / GHZ distributer (Amherst)

qTCP: link controller, node controller, end node controller (Amherst)

Integrating many T1 research results

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Advanced Compilation Capabilities
e.g. Optimal MBQC resource preparation



Independent Edge “coloring” for maximizing network utilization

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Running MBQC

- Pick a code
- Convert to graph state
- Optimize graph state compilation
- Compile graph state
- Run MBQC purification protocol

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The Virtual Testbed

The flagship hardware
ZALM source

The flagship link-level resource
MBQC purified entanglement

The flagship controller
qTCP

Not Discussed:

State representation

QuantumSymbolics.jl
Gabs.jl
QuantumClifford.jl (non-Clifford too)
GPU acceleration

Simulation management

classical metadata management and queries
surrogates
stochastic autodifferentiation

Supplementary resources and databases

ECC database beyond the ECC Zoo
better entanglement distillation with optimizer UI

Community service

took over maintenance of Graphs software ecosystem
summer school
conference workshops
bounties program

Thrust 1 Protocols

optimal switches (Yale, UMass)
entanglement prep for sensor nets (Arizona)
projection based routing (Arizona)
qTCP (UMass)
MBQC resource prep (Arizona, UMass)

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Center for
Quantum Networks
NSF Engineering Research Center



Thrust 4: Quantum Society

Jonathan Ruane

Thrust 4 Lead

MIT

jruane@mit.edu

Funded by National Science Foundation Award #1941583

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Goals of a novel 4th Thrust

- Create, ***for the first time***, a **research community** and agenda for the study of the societal impact of quantum communications technologies.

- Foster and **produce research** that:
  - Carefully describes societal opportunities, risks, and trade-offs
  - Identifies the range of credible predictions and the reasons for differing accounts
  - Conscientiously includes research about the distributional effects of quantum technologies and the needs of underserved communities
  - Remains neutral on ultimate policy conclusions about how priorities and trade-offs should be made where there is legitimate debate

- **Integrate the insights** from the social science research into the technical research, education, and innovation ecosystem work of the Center, and into business practices and regulatory fabric outside the Centre

- Originally a Working Group - decision to **expand into full thrust**.

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T4 Research Project Areas

T4A. Internet Standards and Governance

T4B. The Quantum Technology Marketplace

T4C. Post-Quantum Privacy & Security

T4D. Equitable Access, Fairness & Accountability

ARIZONA SENATOR
MARK KELLY

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Major Accomplishments (Yrs 1-3)

Year 1: Quantum Technologies, Law, and Public Policy Conference (online)

Year 2: Trans-Atlantic Quantum Forum: Yale, UCLA, Technology Institute of Munich. Law & Policy focus.

Year 3: Quantum Policy and Ethics Roadmap, Quantum Economics Conference; Engagement with NIST, NTIA, FCC, Q-EDC

Focused on:

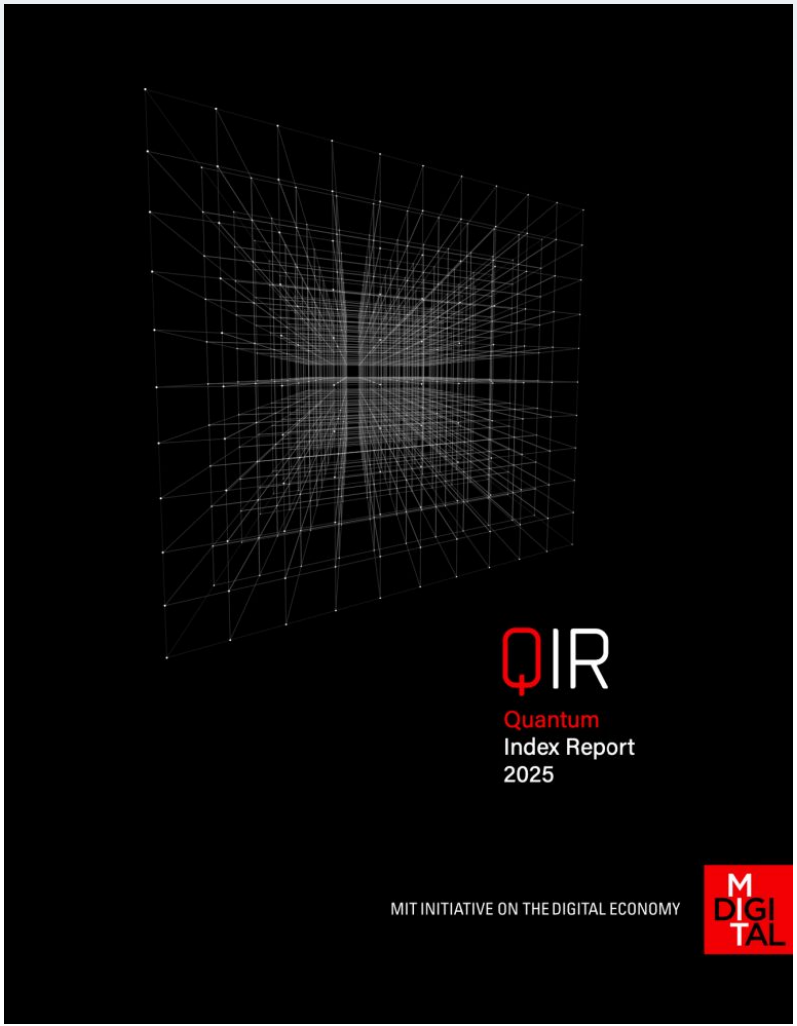
- Community building
- Interdisciplinarity
- Law was primary anchor (led by Jane Bambauer)

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Quantum Index Report

CQN Thrust 4

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Quantum Index Report

Jonathan Ruane, Elif Kiesow, Johannes Galatsanos, Carl Dukatz, Edward Blomquist, Prashant Shukla

Comprehensive, data-driven assessment of the state of quantum technologies.

Tracks, measures, and visualizes trends across research, development, education and public acceptance.

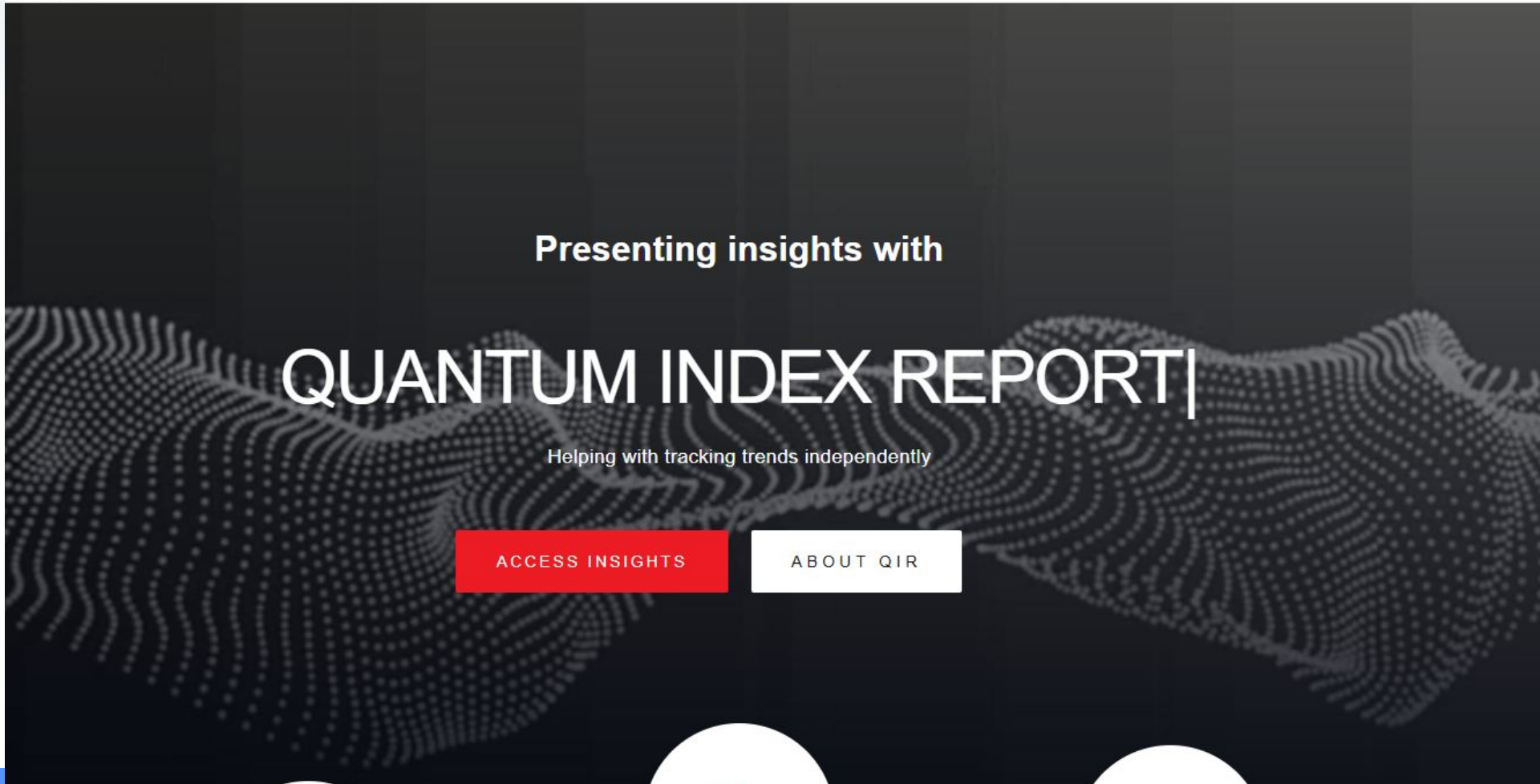
Aggregates data from academia, industry and policy sources.

10 Chapters, 132 pages

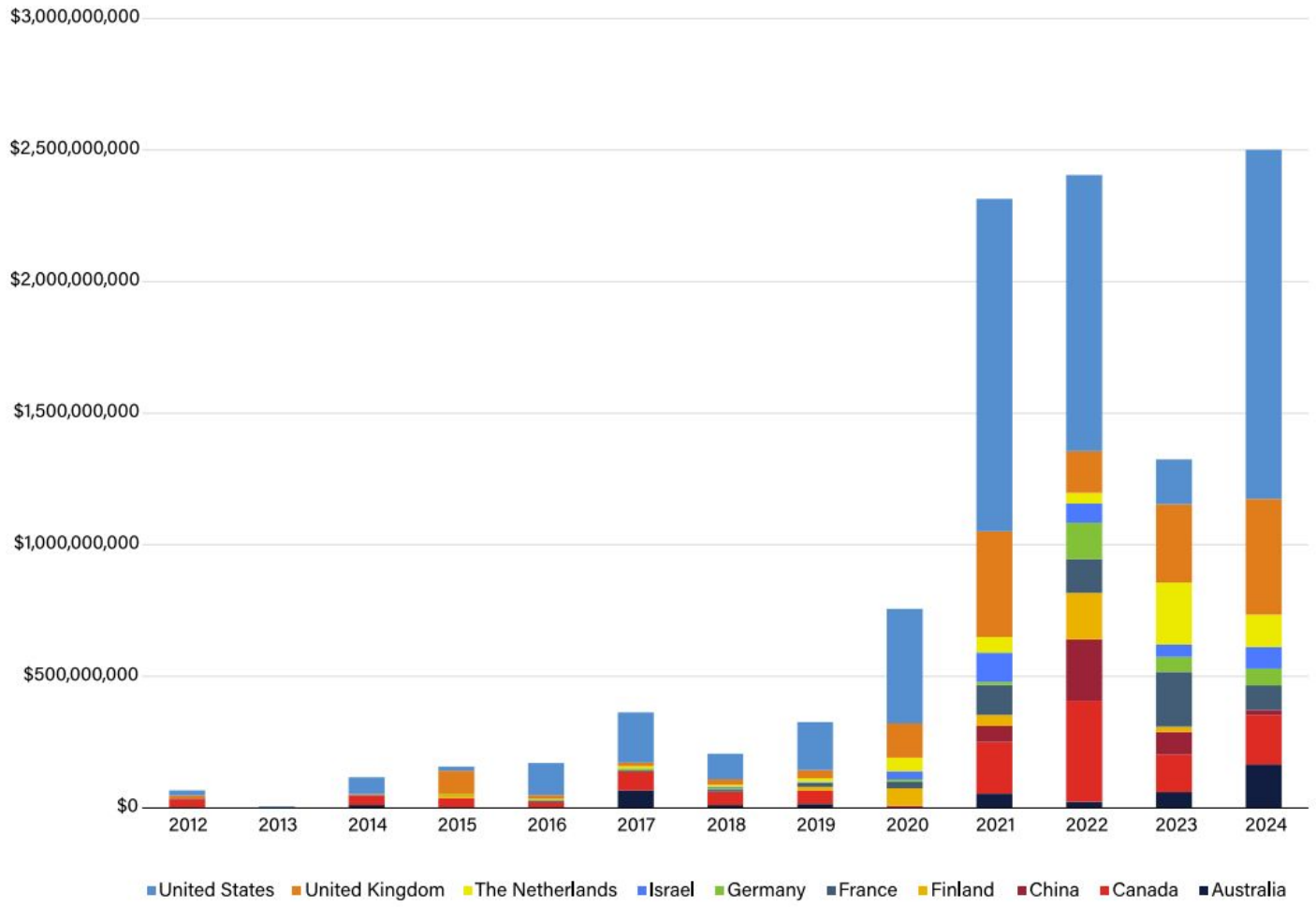
Accenture partnership

1. Patents
2. Academic Research
3. Venture Funding
4. Quantum in Corporate Communications
5. Policy
6. Workforce
7. Education
8. Public Opinion
9. Quantum Networking
10. Quantum Processor Benchmarking

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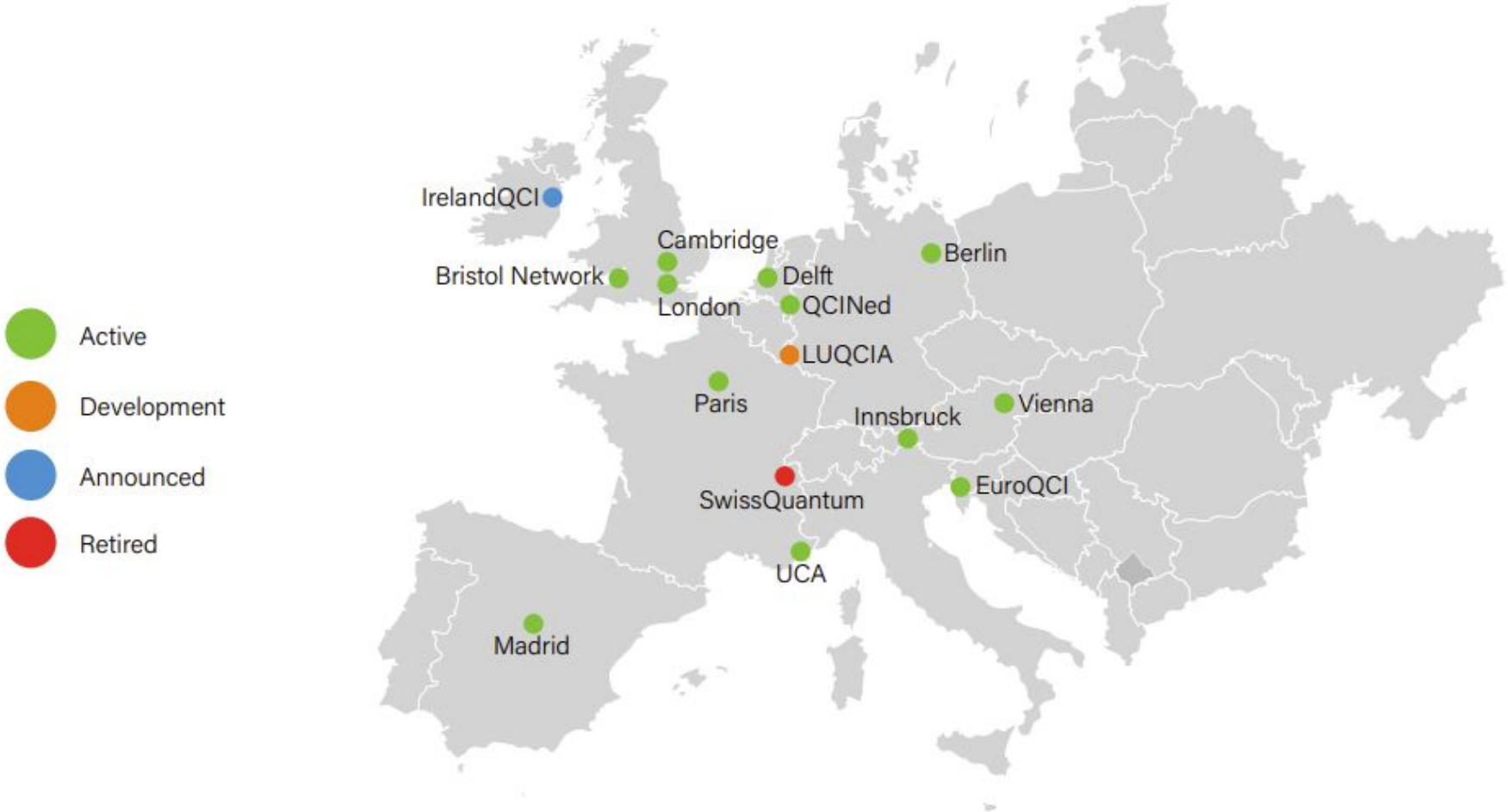

Presenting insights with
QUANTUM INDEX REPORT|
Helping with tracking trends independently
ACCESS INSIGHTS
ABOUT QIR

Quantum technology funding landscape by top 10 countries, 2012-2024

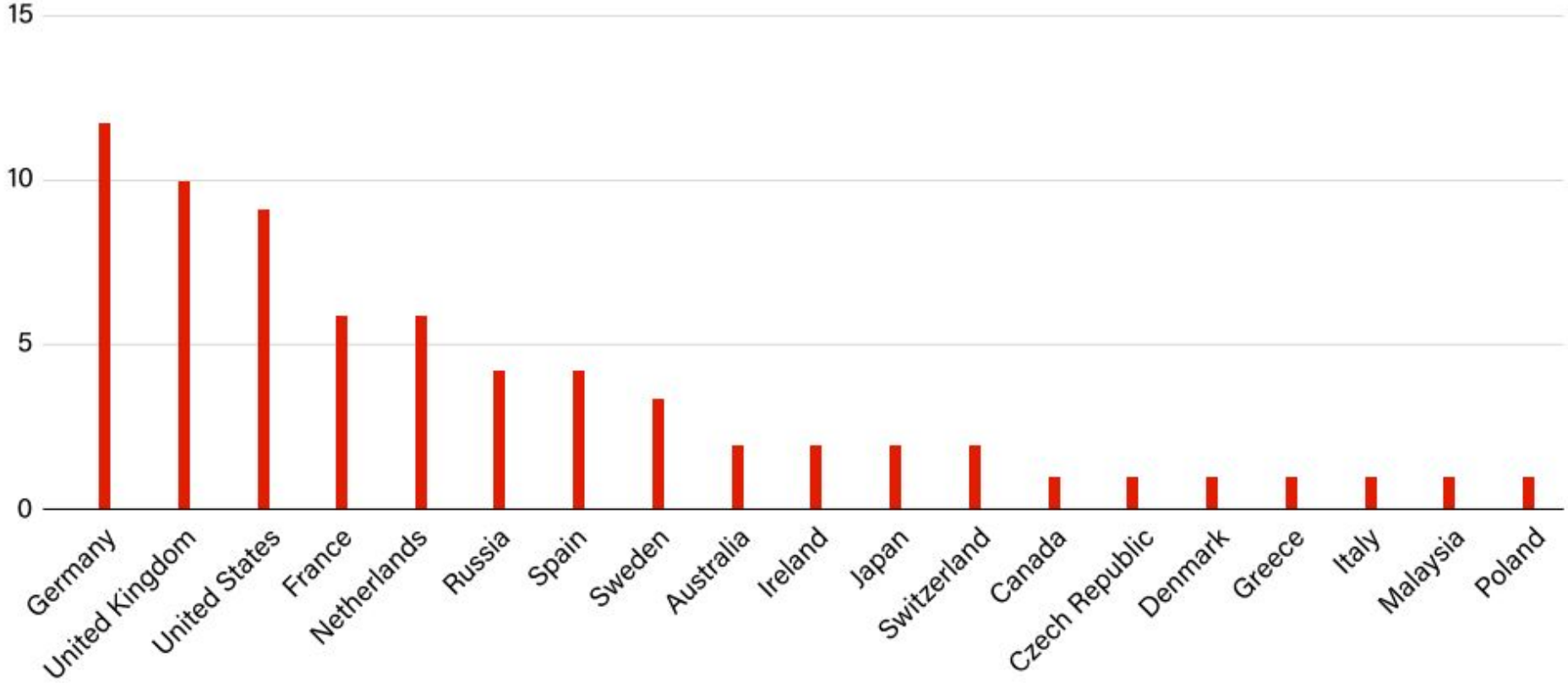


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Quantum network testbeds in Europe



Master degrees with a specific reference to 'quantum' in the degree name

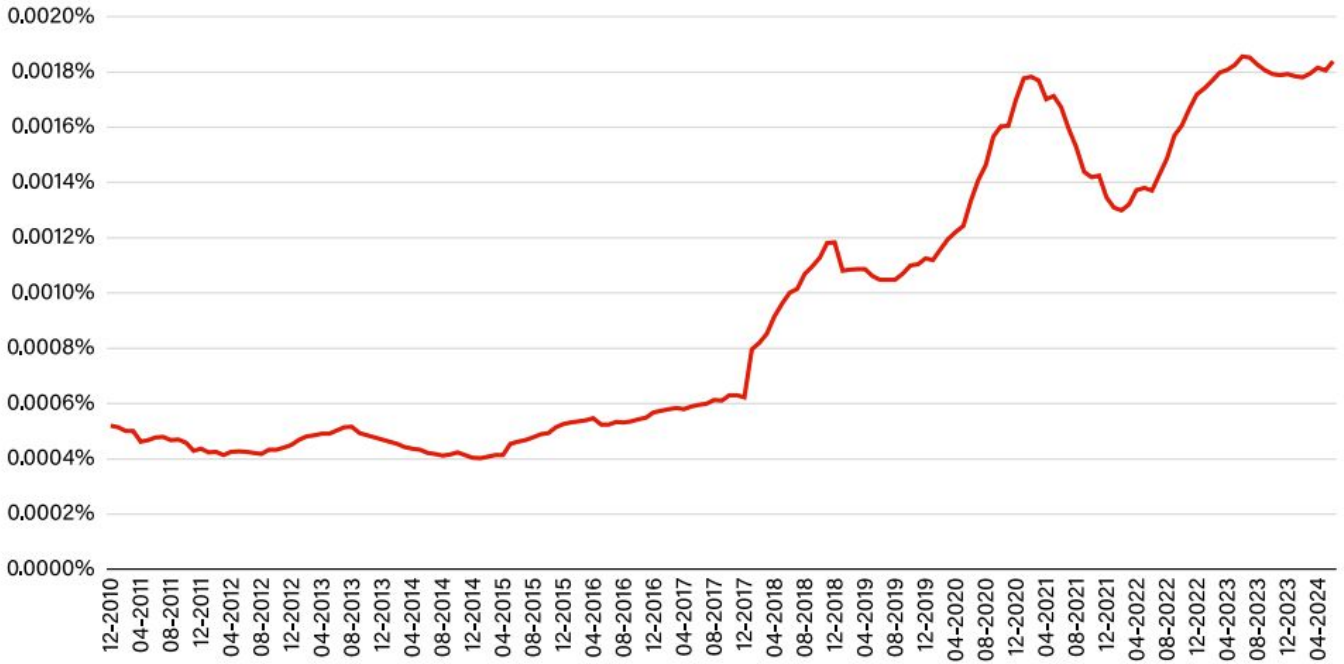


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6.1 | Quantum skills in job postings

- The US labor market has shown relatively steady growth in demand for quantum skills since 2018.

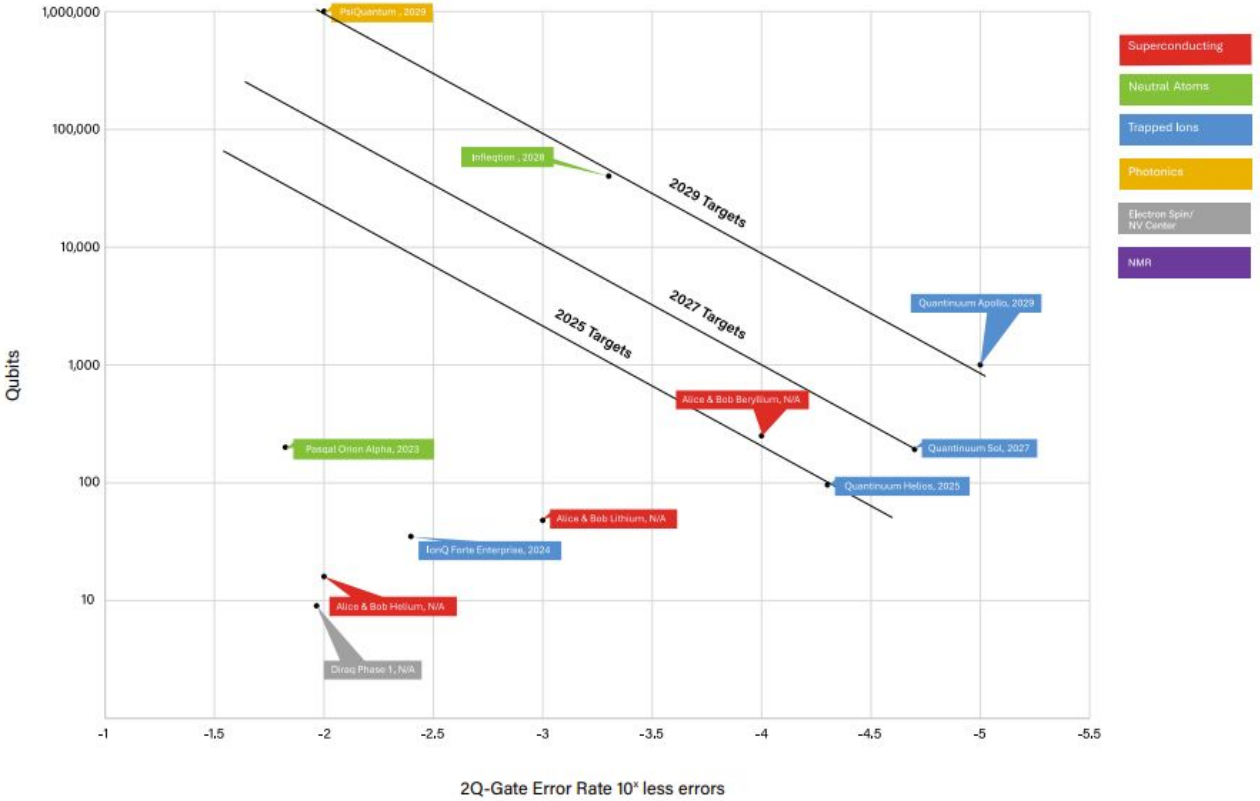
US job postings requiring "quantum" skills as share of total job postings, 2011 to mid-2024



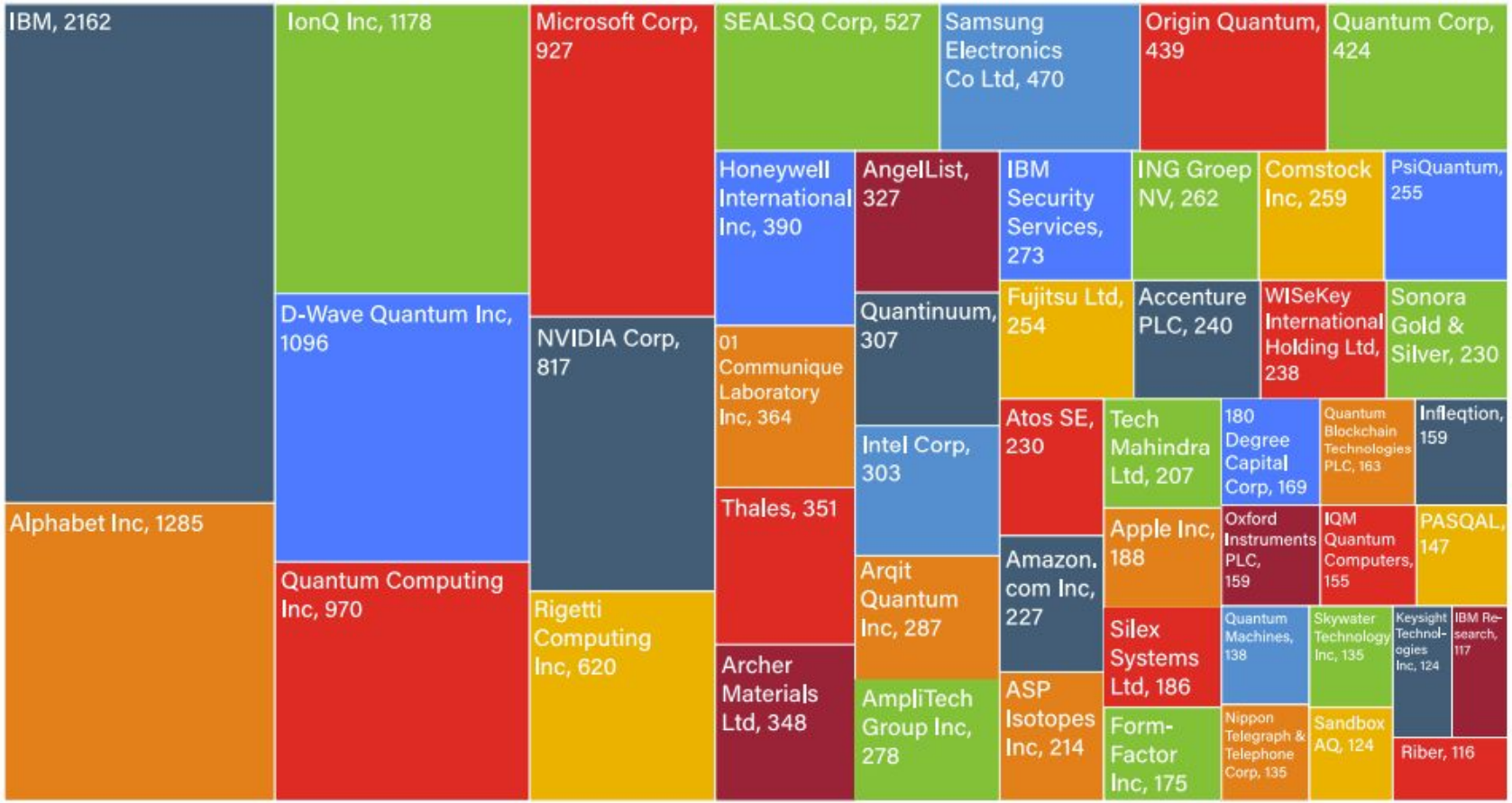
10.7.2 | A look into the future: qubit count and fidelity

QPUs vs 2Q gate fidelity

Announced QPUs



4.1.2. Quantum computing mentions by company





WIRED 9 DE JUNIO DE 2025

Quién lidera la computación cuántica a nivel mundial, según el MIT

China lidera e
computación
realizados en

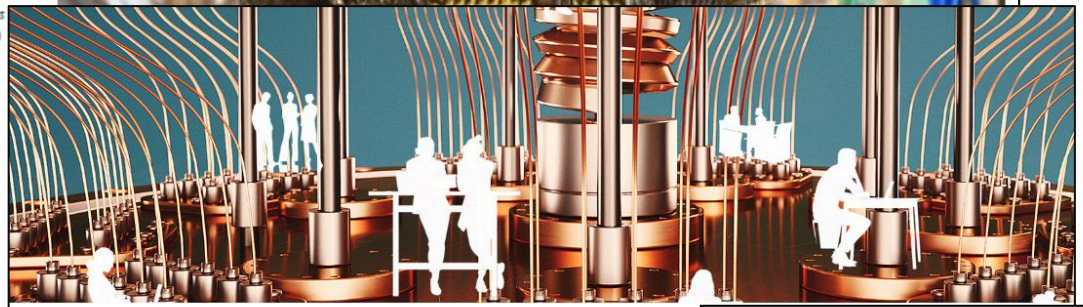
IDEAS MADE TO
New
quar
by Beth Stackp
Why It Matte
The "Qu
global
Share

HPC wire

Since 1987 - Covering the Fastest Computers in the World and the People Who Run Them

- Topics
- Sectors
- QCwire Home
- QCwire Subscribe
- Exascale
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- Resource Library
- Podcast
- Events
- Job Bank
- About





IDEAS MADE TO MATTER | FUTURE OF WORK

Building a quantum wor

by **Beth Stackpole** | Sep 15, 2025

What you'll learn:

- **Quantum skills are in demand.** Posts for jobs requiring
from 2011 to 2024

physicsworld

Forbes

Business of Quantum Summit

CQN Thrust 4

Apr 4th, 2025 at MIT

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Speakers Orgs include:

- Google, MIT, NVIDIA, NIST, BCG,Microsoft Research
- Qunett, Lightsynq, Alice & Bob

Dedicated Quantum Networks panel


M
DIGI
TAL

150 Attendees



Quantum Research and Public Policy Workshop

CQN Thrust 4

29 May 2025

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Dr. Sarah Young

Lecturer University of Arizona

Quantum Research and Public Policy Workshop

Legal, economic, and social implications of quantum communications technologies

Topic: **Policy questions** related to advances in quantum research, e.g. national security challenges, privacy challenges, equitable development challenges

Approach: **Interdisciplinary, international** panel of researchers, industry personnel, and government strategists.

Format: The five panels including dedicated ‘Quantum networks and the future of communication’

CQN Thrust collaborators: Brian Smith, University of Oregon

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Quantum Research and Public Policy Workshop

Legal, economic, and social implications of quantum communications technologies

55 Participants

20 Panelists (academia, industry, international:

- Edward Parker, RAND (Physics)
- Nikolas Guggenberger, University of Houston (Law)
- Lee Humphreys, Cornell University (Social Scientist)
- Brian Smith, University of Oregon (CQN T2)





Quantum Based Security Protocol For Cloud Computing & AI Applications

Research led by Dirk Englund

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Quantum-secure multiparty deep learning

Kfir Sulimany*[1], Sri Krishna Vadlamani[1], Ryan Hamerly[1,2], Prahlad Iyengar[1], and Dirk Englund[1]
[1]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Physics & Informatics Laboratories, NTT Research, Inc., Sunnyvale, CA, USA

Abstract

Secure multiparty computation enables the joint evaluation of multivariate functions across distributed users while ensuring the privacy of their local inputs. This field has become increasingly urgent due to the exploding demand for computationally intensive deep learning inference. These computations are typically offloaded to cloud computing servers, leading to vulnerabilities that can compromise the security of the clients' data. To solve this problem, we introduce a linear algebra engine that leverages the quantum nature of light for information-theoretically secure multiparty computation using only conventional telecommunication components. We apply this linear algebra engine to deep learning and derive rigorous upper bounds on the information leakage of both the deep neural network weights and the client's data via the Holevo and the Cramér-Rao bounds, respectively. Applied to the MNIST classification task, we obtain test accuracies exceeding 96% while leaking less than 0.1 bits per weight symbol and 0.01 bits per data symbol. This weight leakage is an order of magnitude below the minimum bit precision required for accurate deep learning using state-of-the-art quantization techniques. Our work lays the foundation for practical quantum-secure computation and unlocks secure cloud deep learning as a field.

Massachusetts Institute of Technology

Education Research Innovation Admissions + Aid

MIT News

ON CAMPUS AND AROUND THE WORLD

New security protocol shields data from attackers during cloud-based computation

The technique leverages quantum properties of light to guarantee security while preserving the accuracy of a deep-learning model.

Adam Zewe | MIT News
September 26, 2024



Leveraging quantum properties of light to guarantee security while preserving the accuracy of a deep-learning model.

A linear algebra engine that leverages the quantum nature of light for information theoretically secure multiparty computation using only conventional telecommunication components.

Near-term application addressing vulnerabilities that compromise data security, which is crucial in applications such as business, finance, nd healthcare

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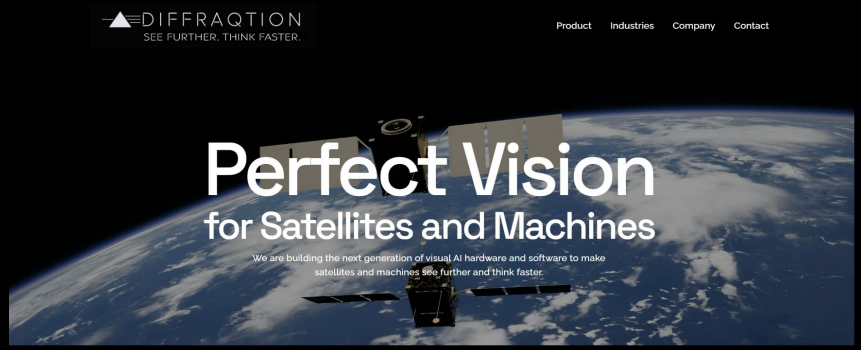
Commercial Spinout

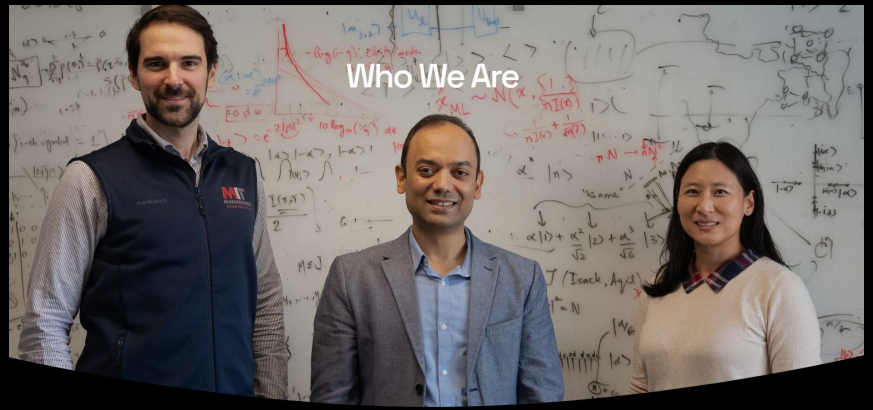
CQN Thrust 4

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DIFFRAQTION
SEE FURTHER. THINK FASTER.

Saikat Guha & Johannes Galatsanos







Other Notable Outcomes

CQN Thrust 4

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Other Notable Outcomes T4 Yr 5

- Sponsorship of 2nd **Economics of Quantum conference** at University of Southern California

- **Panel at Optica Frontiers in Optics:** Impacts of Quantum Technologies on Society'. Brian Smith (T2) and organized by Sarah Young (T4).

- Sponsored the **Quantum Workforce Challenge at MIT Policy Hackathon** (student led initiative)

- **Quantum Networking included as part of MIT's xPro online course** on Quantum Strategy and Impact. Jonathan Ruane & Will Oliver & MIT Colleagues.

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William Oliver



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Jonathan Ruane

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or $1,600 per course

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Isaac Chuang



William Oliver



Peter Shor

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Year 6-10 Major Milestones

2026
Expansion of Quantum Index Report
Longitudinal Study: Quantum Nascent Market. Establish Study.

2027
Longitudinal Study: Quantum Nascent Market Study. Data capture.
Business of Quantum Teaching Expansion (curriculum, cases, articles)

2028
Congressional Quantum Bootcamp
Longitudinal Study: Quantum Nascent Market. Publication.

2029
Publications Focus: Regulatory Frameworks, Data Privacy, Cross-Border Data Transfer & Sovereignty

2030
Long Term Funding for Quantum Networking Societal Impacts

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Innovation Ecosystem

Alireza Shabani

Director of Strategic Partnerships and Innovation, University of Arizona

John Sawyer

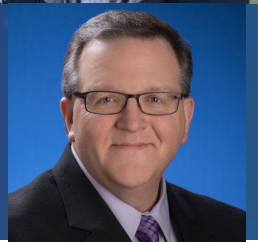
Director of Strategic Research Initiatives, University of Maryland

Timothy Burt

Chair of Industry Advisory Board, L3Harris







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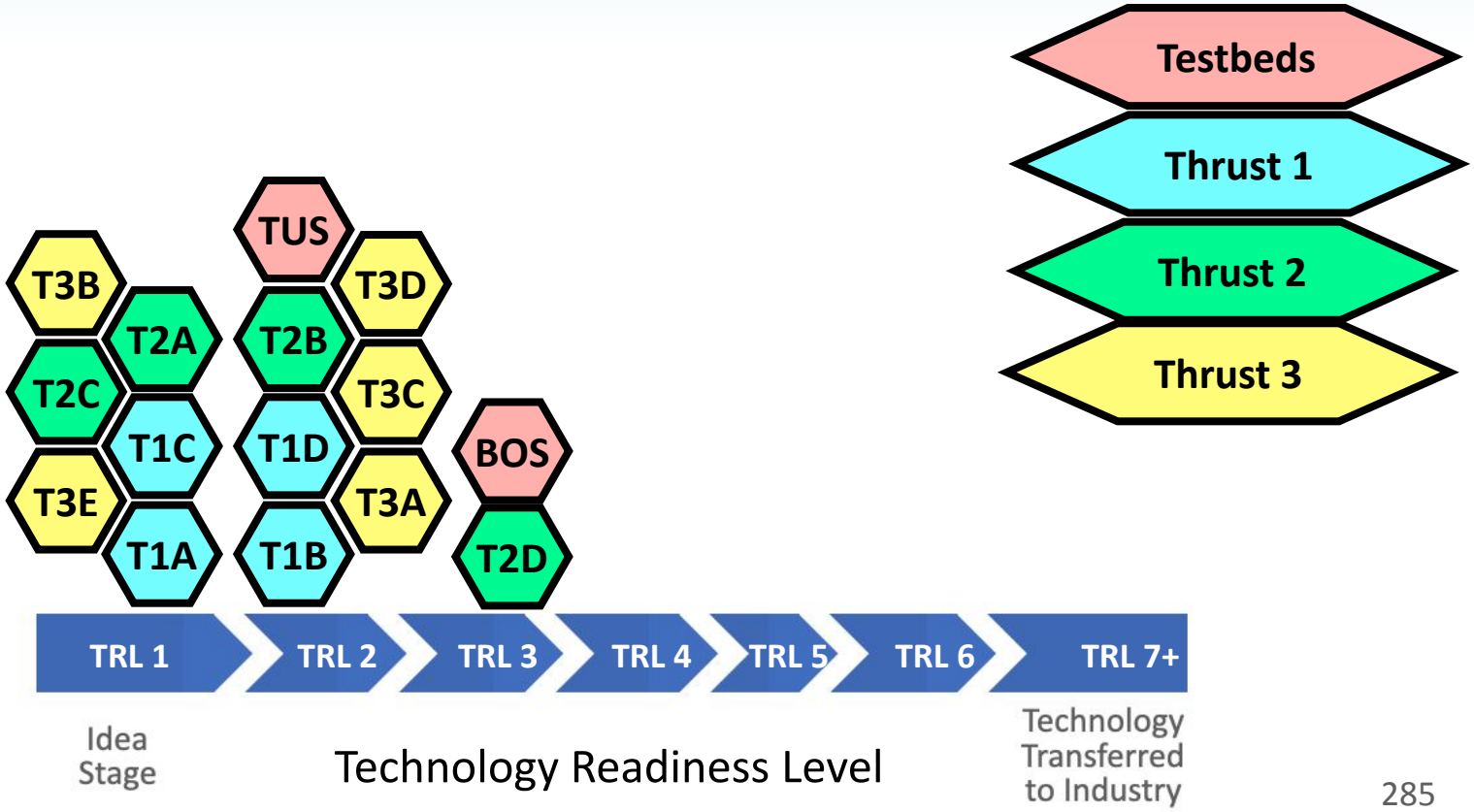
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IPP Membership — October 2025

Bronze	Silver	Gold	Diamond
AEROSPACE	ciena (New!)	LOCKHEED MARTIN	CISCO
FLYBRIDGE CAPITAL PARTNERS	JUNIPER NETWORKS	Raytheon An RTX Business	L3HARRIS
OSAGE UNIVERSITY PARTNERS	CORNING	Qunnect	Infleqtion
JPL	nu QUANTUM	Qunett	ColdQuanta
	ICARUS QUANTUM (New!)		SUPERTECH
	Aliro		
	ADVENT DIAMOND		
	ANAMETRIC		
	TELEDYNE TECHNOLOGIES INCORPORATED		

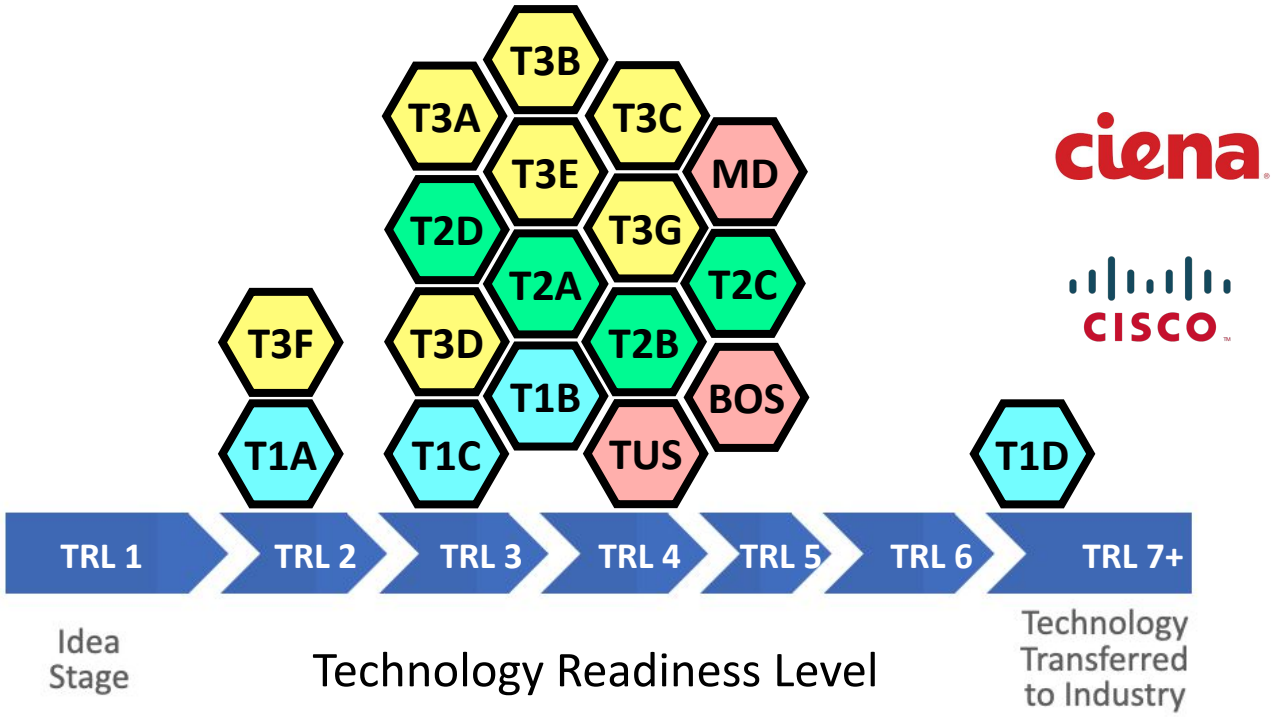
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2022 Technology Maturity Level



© 2024 Center for Quantum Networks

2025 Technology Maturity Level



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Major Accomplishments Y1-5

- Total 25 and current 20 **members**: Major telecom and defense corporates, and midsize and startup companies. 80% retention.
- 117 **Patents**: 29 Full + 88 Provisional
- 8 customized **research projects**, 10+ joint paper and patent publications with industry
- **Services:** Physical and Digital-Twin Testbeds
- **Entrepreneurship:** 6 spin-out companies
- **Education programs:** Masters programs, UArizona and UChicago

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Joint CQN-Industry Research

CISCO L3HARRIS™ JUNIPER NETWORKS GENERAL DYNAMICS Raytheon Technologies

All-photonic Gottesman-Kitaev-Preskill–qubit repeater using analog-information-assisted multiplexed entanglement ranking

Filip Rozpędek, Kaushik P. Seshadreesan, Paul Polakos, Liang Jiang, and Saikat Guha
Phys. Rev. Research **5**, 043056 – Published 18 October 2023

States, Modes, Fields, and Photons in Quantum Optics

Michael G. Raymer[1] and Paul Polakos[2]*

[1] Department of Physics, and Oregon Center for Optical, Molecular and Quantum Science, University of Oregon, Eugene, OR 97403, USA
[2] Cisco Systems, New York, NY 10119, USA

Resource Management in Quantum Virtual Private Networks

Publisher: IEEE Cite This PDF

Shahrooz Pouryousef ; Nitish K. Panigrahy ; Monimoy Deb Purkayastha ; Sabyasachi Mukhopadhyay ; Gert Grammel ; Domenico Di Mola

Spread Photon Transceiver for Quantum Secure Communications

Publisher: IEEE Cite This PDF

Wesley Webb ; Michael S. Bullock ; Samuel H. Knarr ; Timothy C. Burt ; Jim A. Drakes ; Saikat Guha All Authors

(12) **United States Patent**
Zhang et al.

(54) **ENTANGLED RADIOFREQUENCY-PHOTONIC SENSOR SYSTEMS AND SENSING METHODS**

(71) Applicants: **ARIZONA BOARD OF REGENTS OF THE UNIVERSITY OF ARIZONA**, Tucson, AZ (US); **GENERAL DYNAMICS MISSION SYSTEMS, INC.**, Fairfax, VA (US)

(72) Inventors: **Zheshen Zhang**, Tucson, AZ (US); **Quntao Zhuang**, Tucson, AZ (US); **William Clark**, Scottsdale, AZ (US)

Quantum Network Planning for Utility Maximization

Authors: Shahrooz Pouryousef, Hassan Shapourian, Alireza Shabani, Don Towsley

(19) **United States**
(12) **Patent Application Publication**
Bash et al.

(54) **COVERT SENSOR**

(71) Applicant: **RAYTHEON BBN TECHNOLOGIES CORP.**, Cambridge, MA (US)

(72) Inventors: **Boulat A. Bash**, Winchester, MA (US); **Saikat Guha**, Cambridge, MA (US)

Resource Placement for Rate and Fidelity Maximization in Quantum Networks

Publisher: IEEE Cite This PDF

Shahrooz Pouryousef ; Hassan Shapourian ; Alireza Shabani ; Ramana Kompella ; Don Towsley All Authors

Spread-photon architecture for quantum-secure c

Publisher: IEEE Cite This PDF

Michael S. Bullock ; Wesley Webb ; Samuel H. Knarr ; Timothy C. Burt ; James A. Drakes ; Victor G. Bucklew All Authors

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Entrepreneurial Culture & Impact





LightSynq Technologies, Inc. is a spin out of Mikhail Lukin's lab (Harvard), that was incubated at AWS before being founding in 2024 and acquired by IonQ in 2025. It specializes in photonic interconnects and quantum memory, essential technologies for quantum internet and scaling quantum computers.

Quantum Network Technologies, Inc. (Qunett), co-founded by Saikat Guha (UMD) and Dirk Englund (MIT) to develop scalable hardware for quantum device connectivity, integrate with existing infrastructure and enable deployable quantum networks ranging from data centers to metro fiber optic networks to satellite-based global communication.

5 other startups from CQN researchers:

- Diffraqtion: Advanced Imaging (Guha, UMD)
- Blanqet: Quantum Security (Jiang, UChicago)
- Techyawn: Quantum Security (Raza, UMass)
- Hydroteck: Optical Blood Measure Camacho, BYU)
- Axiomatic-AI: Reasoning in science and engineering (Englund, MIT)

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IPP Membership Trend Chart



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Major Y5 Efforts

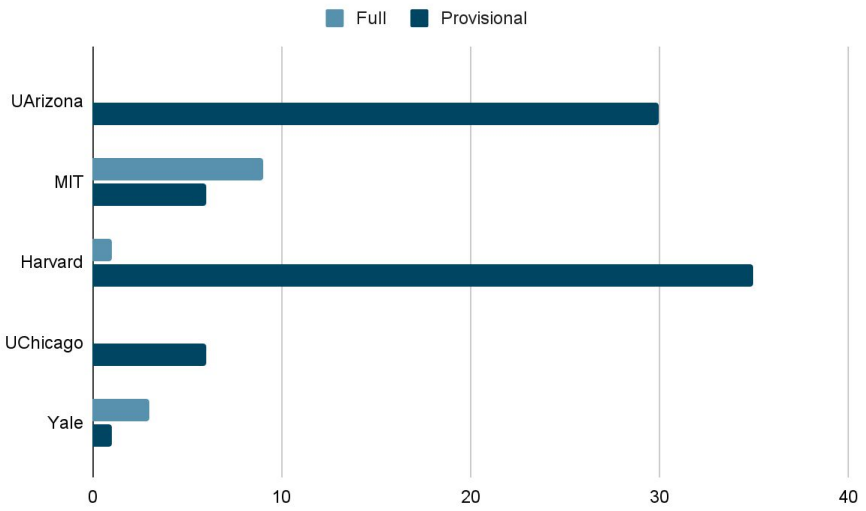
- **Churn rate reduced**: Y4 (%18) -> Y5(%5)
- **First technical IPP project launched**: Digital-Twin testbed (QuantumSavory)
- **Deeper member engagement**: Interaction among IAB members and CQN PIs
- **Broader community building**: Major collaboration with Quantum Economic Development Consortium (QED-C) on Quantum Network Application Roadmap (QNAR) project

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IP and Technology Transfer

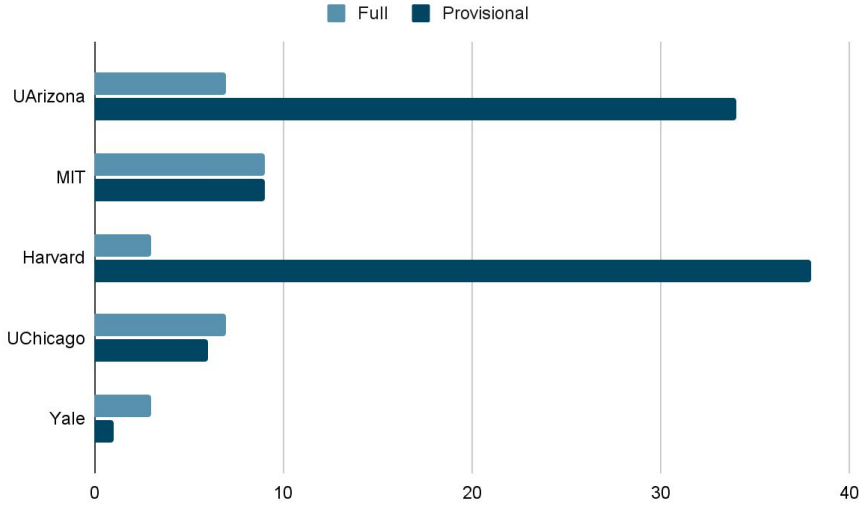
Y1-4

91 Patents: 13 Full + 78 Provisional



Y1-5

117 Patents: 29 Full + 88 Provisional



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QN Applications Roadmap 2.0

Organizing committee

September 2024



CQN-NSF-QEDC organized QNAR2.0 workshop, July 2025

Congress hearing

May 2025



Celia Merzbacher

Workshop

July 2025



Mark Mortensen
Telco Market Analyst

Surveys Ready

October 2025

Report Ready

December 2025

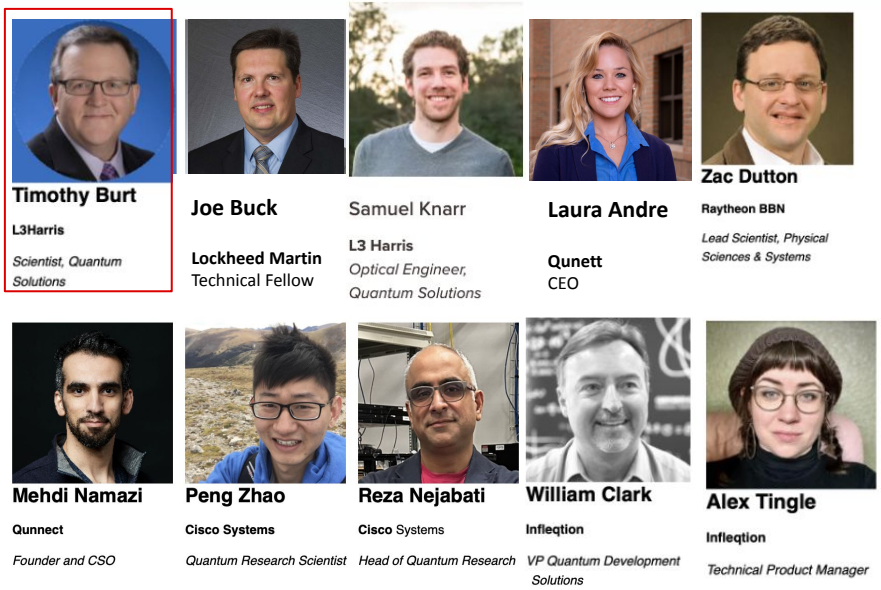
IPP fund use

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Industry Advisory Board

2 VPs
1 Fellow
1 CEO
1 CSO

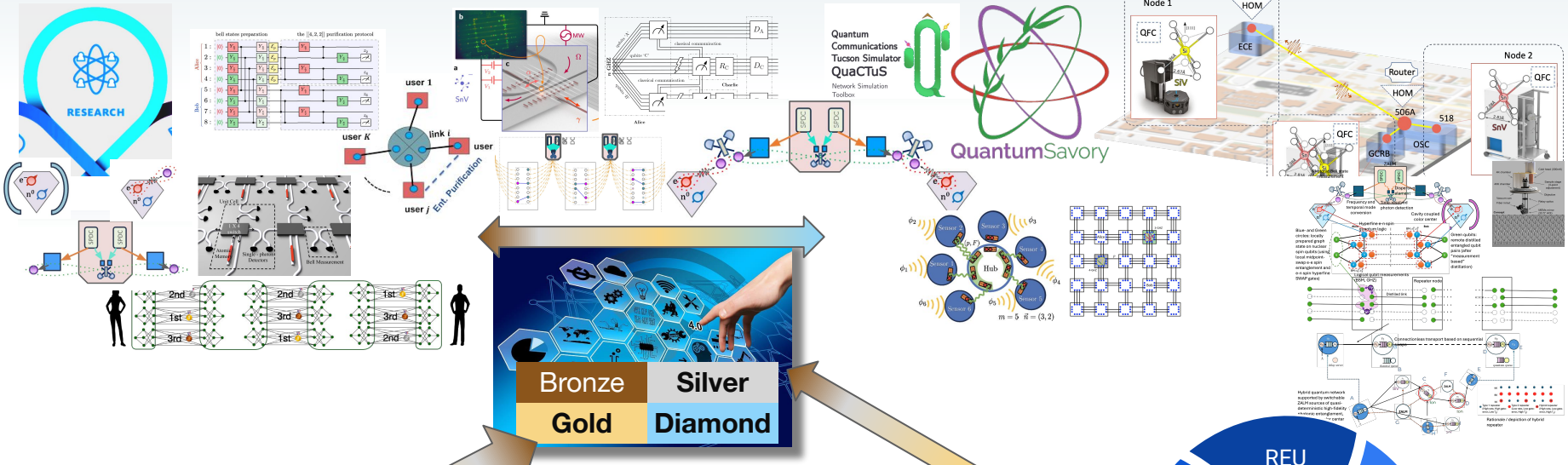
Chair



Quarterly Meetings

1-1 meetings

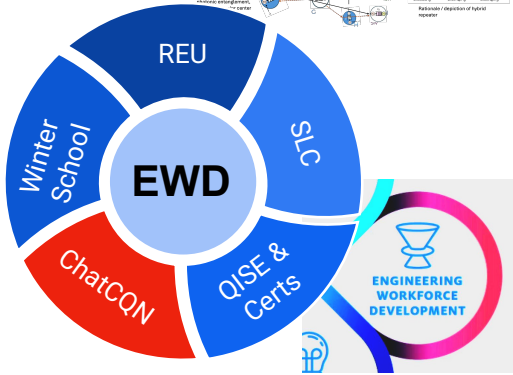
Overview from the IAB Chair



Intellectual Property



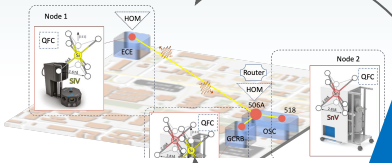
Research, talent, and internships



The Center and Industry have built broad interactions to be continued and expanded through deliberate effort and effective, timely communication.

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Example Interplays for Year 5



Industry ▾ News ▾ Ab

cqn-erc.org

- Industrial Partner Programs
- IPP Membership
- Industry Advisory Board
- Applications Roadmap
- IPP Member Portal

- CQN IPs List
- Annual Reports
- Presentations
- Applications Roadmap
- CQN Member Information
- Center Updates
- Templates/Logos

Posters

Papers

Patents



Devices

Internships & Research Opportunities

Research

Students & Researchers

Scientists & Engineers

QuantumSavory

Center

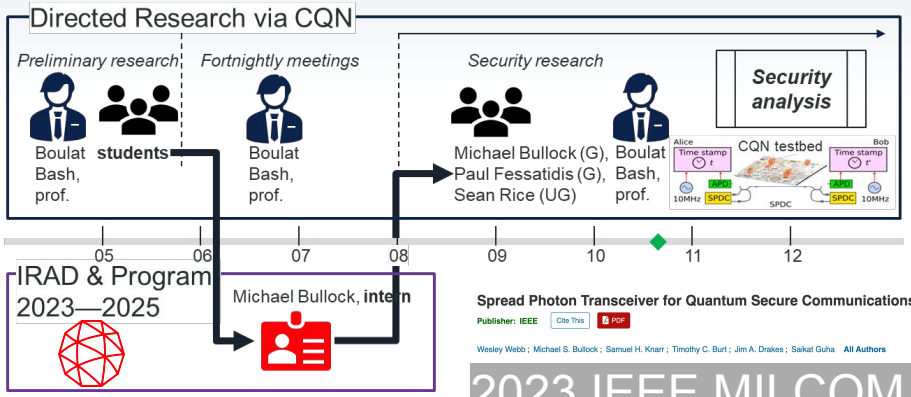
Industry

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Center for Quantum Networks
NSF Engineering Research Center

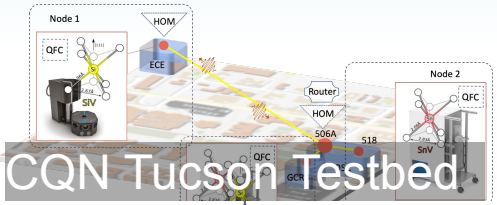
Illustrative Case Study

L3HARRIS™





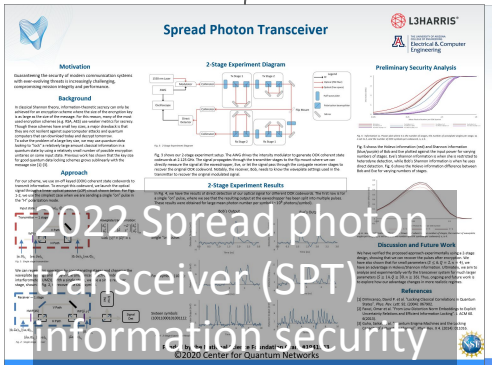




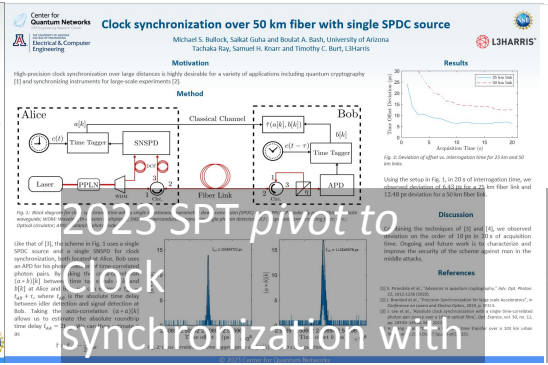
2025 patent 19/089,055

Spread Photon Transceiver for Quantum Secure Communications
Publisher: IEEE
Wesley Webb ; Michael S. Bullock ; Samuel H. Knarr ; Timothy C. Burt ; Jim A. Drakes ; Saikat Guha
All Authors

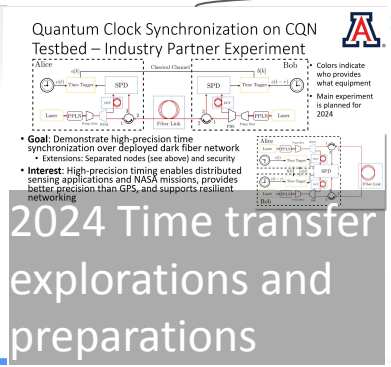
2023 IEEE MILCOM Conference paper



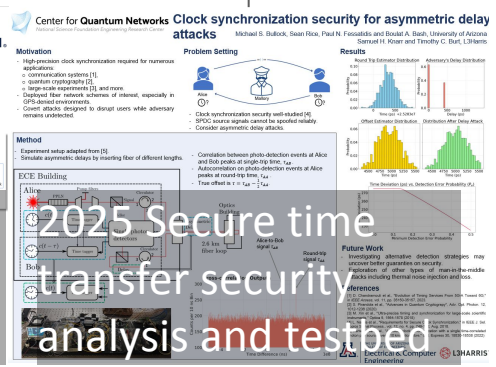
2022 Spread photon transceiver (SPT) information security



2023 SPT *pivot to* clock synchronization with experiment



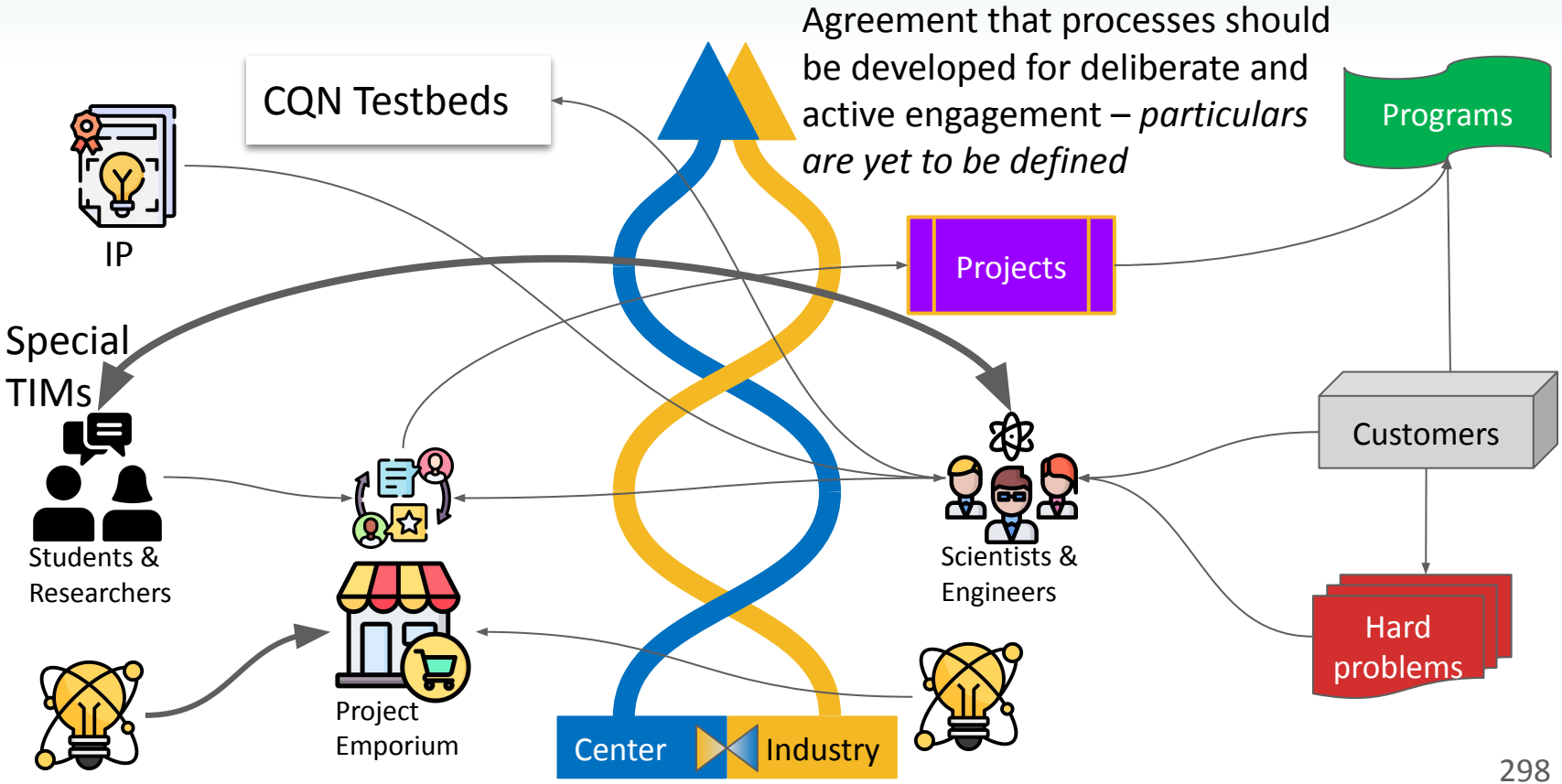
2024 Time transfer explorations and preparations



2025 Secure time transfer security analysis and testbed

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Cultivate Intertwining for Sustainability



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Building Toward Year 11 Transition

- Graduate into an IUCRC; keys to IUCRC success:
  - Strong & Active IAB & leadership that bridges cultural divide ☑️
  - Sizeable paying membership base (need ~50% growth)
  - High-Impact, Pre-Competitive Research (make more industry-led)
  - Robust Workforce Development Program (WFD transition metrics as industry grows)
- Phase 2 IPP Priorities:
  - Enhance relationship management & research development for retention, growth & impact
  - Expand programs to systematically build collaborative research, experiential learning & transition

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Leverage UMD's Ecosystem

MID-ATLANTIC QUANTUM ALLIANCE

- Quantum Leap Career Nexus
- Suppliers
- Co-Design Workshops
- DC-QNet
- Quantum World Congress
- Industry Challenges

QLab
NATIONAL QUANTUM LABORATORY

IONQ

UNIVERSITY OF MARYLAND

LIGHTSYNQ

IDQ

Qubitekk

Capella Space

Center for
Quantum Networks
NSF Engineering Research Center

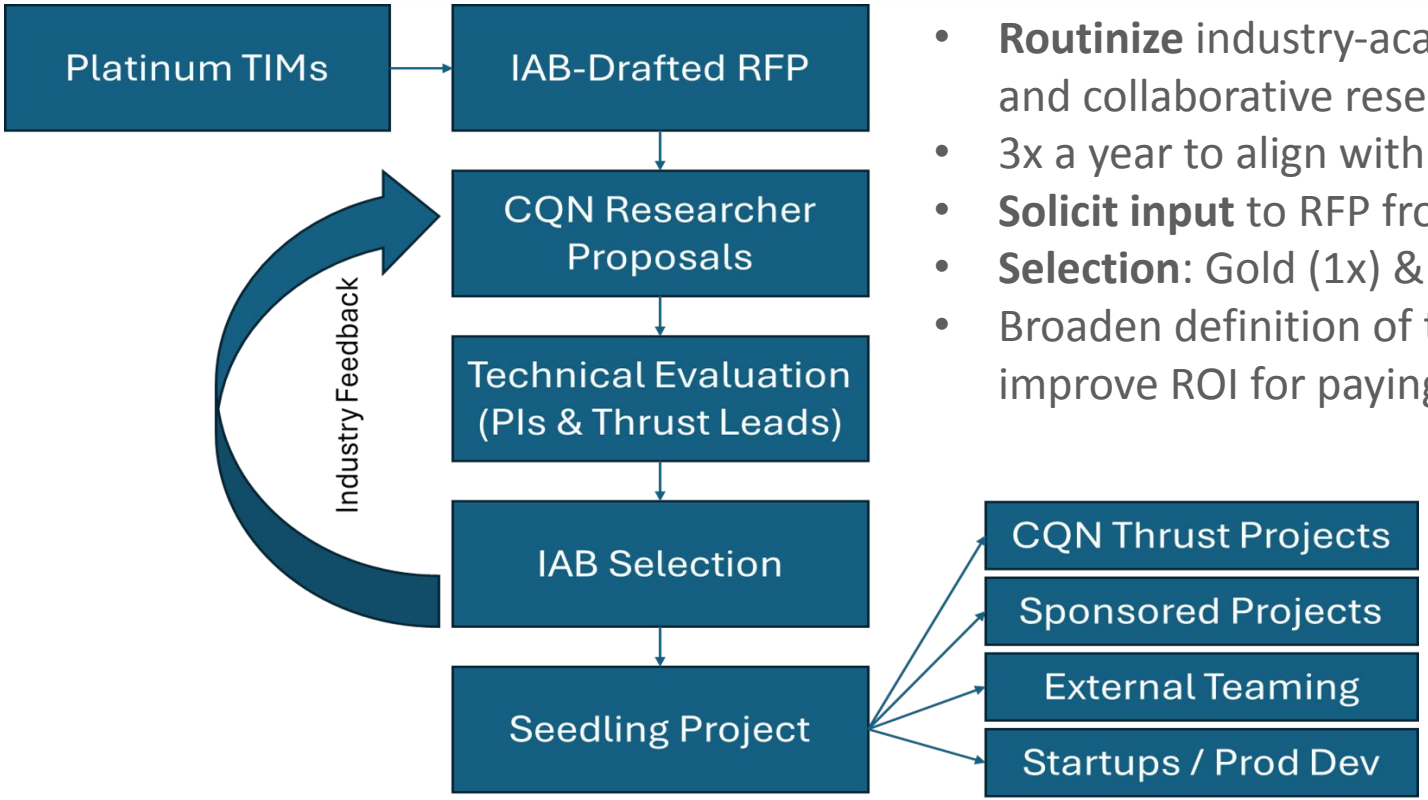
QUANTUM STARTUP FOUNDRY

DARPA

Capital Quantum Benchmarking Hub

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Updated Custom Research Program



- **Routinize** industry-academia interaction and collaborative research
- 3x a year to align with academic calendar
- **Solicit input** to RFP from all IAB members
- **Selection**: Gold (1x) & Platinum (2x) votes
- Broaden definition of transition **success** & improve ROI for paying members

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Enhancing Entrepreneurship

- Build on CQN's strong history of spin-outs
- Develop & aggressively recruit new Bronze "Investor" category
  - VCs & Incubators ($5k/in-kind)
- Joint programming with Investor members, I-Corps, etc.
  - Customer discovery
  - Pitch training & competitions
  - Business model development & coaching
- "Meet the Inventor" webinar series
  - Accelerate awareness of new IP & core inventor teams
  - Diamond can participate live; time-delays for release to Gold and beyond

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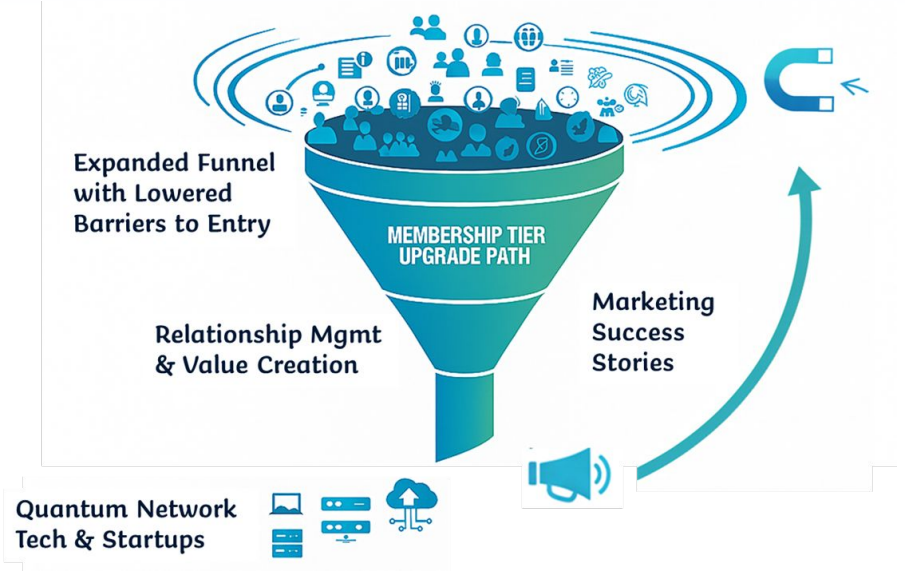
Growing an Engaged Community

Lower barriers to entry

- Software to expand virtual testbed
- Validation, beta-testing and co-design with hardware providers and enabling technology providers

Deliver value for all members, but make ROI of higher tier membership enticing

Market successes to retain & enhance recruitment of new members



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Center for
Quantum Networks
NSF Engineering Research Center



Center Organization, Management and Sustainability

Saikat Guha

Center Co-Director & Co-PI

Professor, Clark Chair, Electrical and Computer Engineering, University of Maryland; Adjunct Professor of Optical Sciences, Univ. of Arizona

saikat@umd.edu

Funded by National Science Foundation Award #1941583

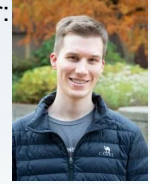
ARIZONA · MIT · HARVARD · UNIVERSITY OF MARYLAND · University of Massachusetts Amherst · BYU · THE UNIVERSITY OF CHICAGO 1890 · HOWARD UNIVERSITY · NAU NORTHERN ARIZONA UNIVERSITY · UNIVERSITY OF OREGON

Changes during Y5 and beyond

- CQN was awarded Y6, but was asked to rebid Y7-10
  - Chaohan Cui, Tucson testbed lead, now research faculty at UMD
  - Matt Eichenfield moving to CU Boulder, starting Jan 2026
  - MARQI a natural integration home given ion + color center work
  - Connecting with the vibrant MD Capital of Quantum Initiative
  - Tucson testbed: infrastructure to stay: L3 experiment, bulk ZALM with dispersion engineering and QFC for hybrid memory (Mehmet) to continue in Tucson. Quantum memory + QFC work transitioning to UMD
  - LT + EXCOM, in discussions with UArizona and UMD administration, decided to rebid Y7-10 proposal with UMD as lead
  - MIT, UArizona, Harvard, UMass Amherst to stay core partners
  - UMD signatory to current IPMP. UMD to lead new IPMP for Y7-10
  - New faculty: Daniel Soh and Xiaodong Yan, UArizona, Robert Niffenegger, UMass
  - Testbed Leads: Chaohan (UMD), Chao (Boston), Stefan (Virtual)
- Work packages versus Thrusts
  - Thrusts as a way to coin / track projects
  - Work packages as a way to organize ourselves day to day

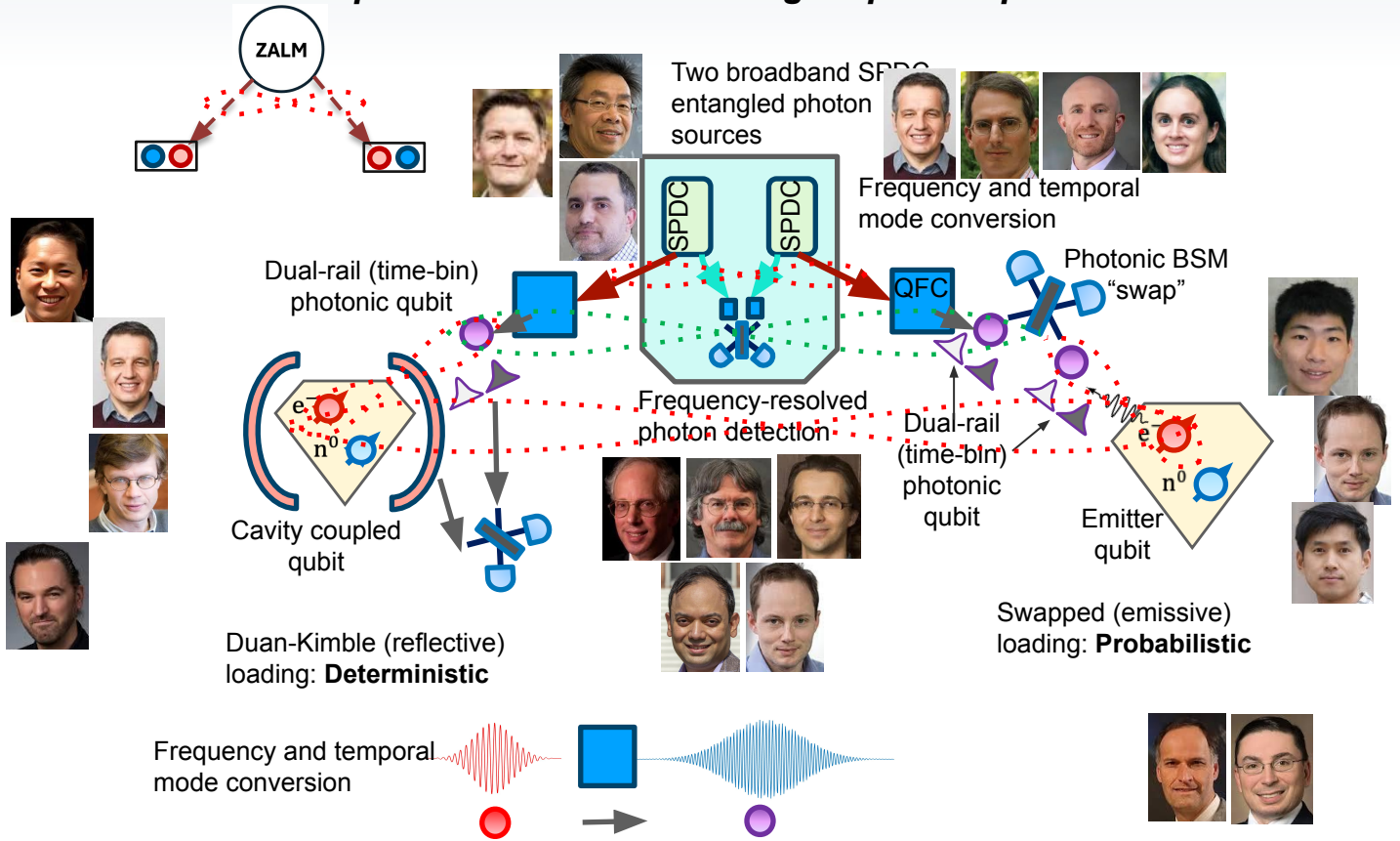
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Working Group coordinator:
Clark Embleton, UOregon



Zero-Added-Loss Multiplexing (ZALM): WP1

A quasi-deterministic entangled photon pair source



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NSF Engineering Research Center

Working Group coordinator:
Joohyung Song, UMD



Multiplexed Quantum Memories: WP2

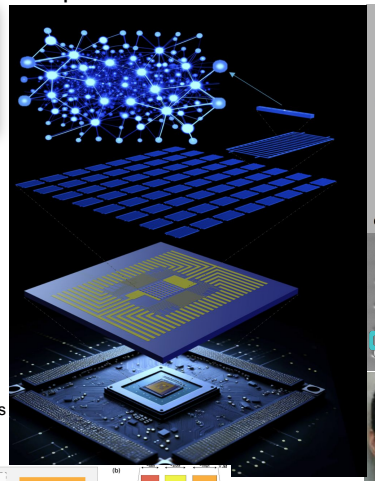
Scalable platforms: 1. thousands (ions) to **millions** (SiVs) individually addressable qubits, 2. **efficient qubit-photon interface**, 3. high-fidelity **quantum logic**

Reconfigurable photonic integrated waveguides coupled to color centers

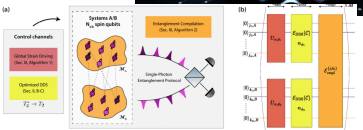






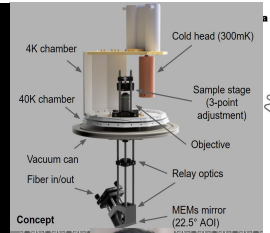


Superconducting electronics, Nature Electronics volume 8, 375 (2025)



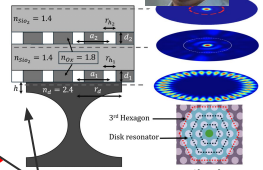
Programmable quantum matter, arXiv:2509.02992 (2025)
Chip integrated photonic control, Optica Vol. 10, Issue 5, pp. 634-641 (2023)
Optical strain tuning, Xue, …, Cui, Guha, Eichenfield, Fan, Nature Communications 16 (1), 6275 (2025)
Spectral tuning, Nature Communications volume 16, Article number: 8829 (2025)

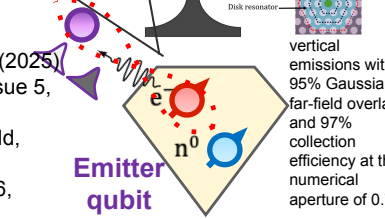
Color centers in diamond nanopillars and a MEMS scanner with fiber tip





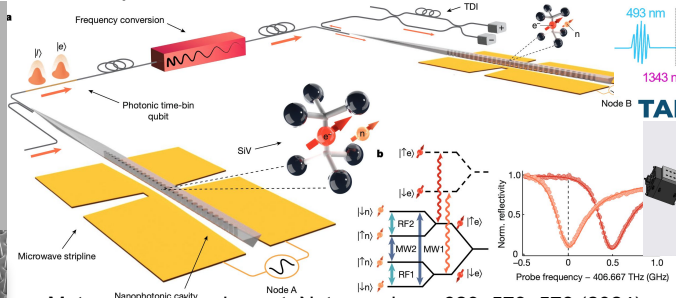




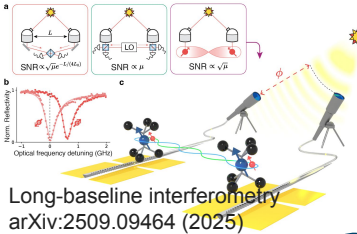


vertical emissions with 95% Gaussian far-field overlap and 97% collection efficiency at the numerical aperture of 0.7

Color centers in nanophotonic diamond cavities integrated with telecom fiber

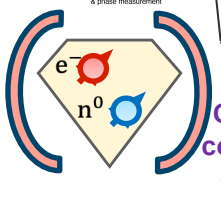


Metro-area entanglement, Nature volume 629, 573–578 (2024)

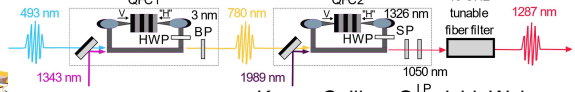


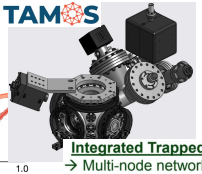
Long-baseline interferometry arXiv:2509.09464 (2025)





Trapped ion qubits strongly coupled to a cavity with efficient optical interface

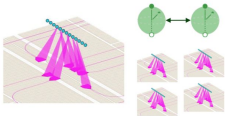


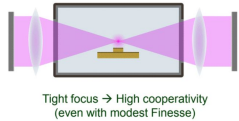


Kwan, Collins, Quraishi, Waks, "Telecom Quantum Frequency Conversion of Ba+ Trapped Ions for Quantum Networking", CLEO 2025

Integrated Trapped Ion Platform
→ Multi-node network + multiplexing

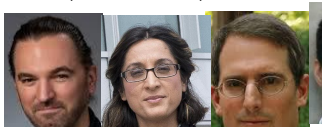
Integrated Platform + Cavities
→ **Quantum Repeaters**





Tight focus → High cooperativity (even with modest Finesse)

Niffenegger et al., Nature 2020, arXiv:2402.16742





Optically addressable molecular-spin qubit diluted in a host matrix; US Patent Application #18845790 (2025)



"Low-dimensional solid-state single-photon emitters", Nanophotonics, 14(11):1687-1713, (2025)

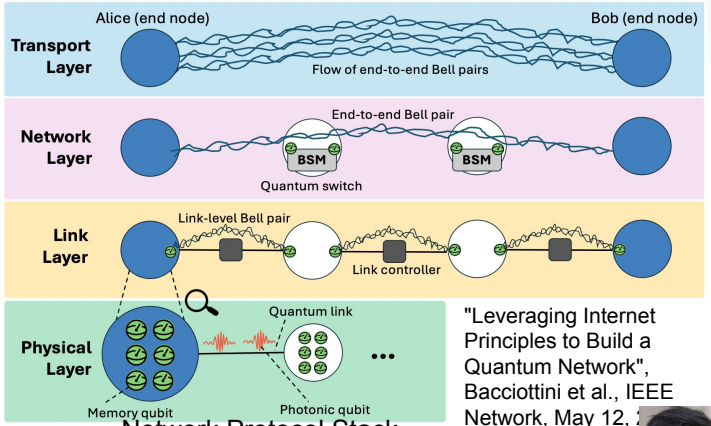
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Working Group coordinator:
Dr. Stav Haldar, UMass

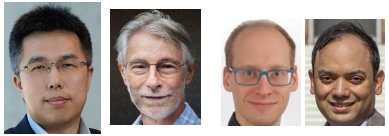


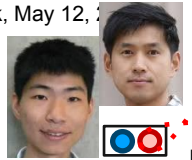
System integration and performance evaluation: WP3

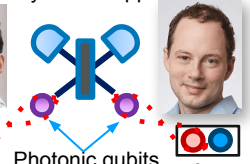


"Leveraging Internet Principles to Build a Quantum Network", Bacciottini et al., IEEE Network, May 12, 2

Network Protocol Stack

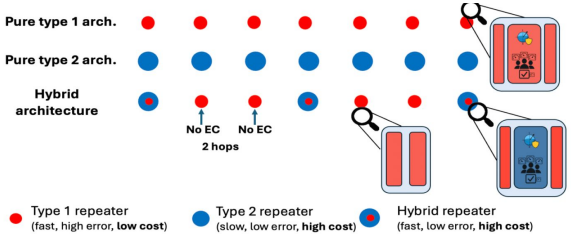


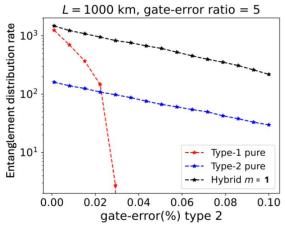


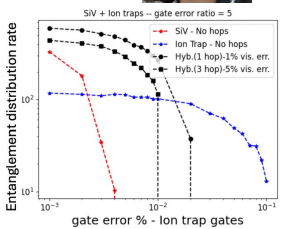




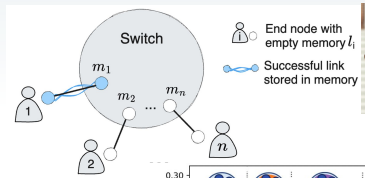
Hybrid quantum repeater architectures



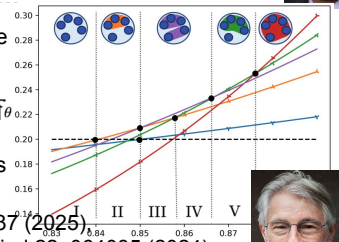




"Hybrid repeaters with encoding for long distance entanglement distribution", Haldar, Guha, Towsley, Rozpedek; IEEE QCE 2025

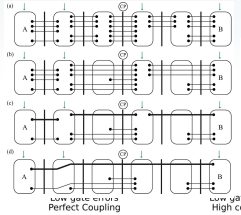


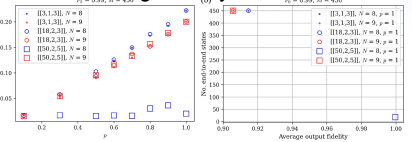
Resource-aware multiparty entanglement distribution, and applications to sensor networks

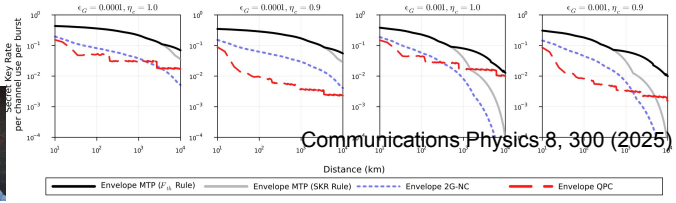


arXiv:2508.14737 (2025)
Phys. Rev. Applied 22, 064085 (2024)

One-way and two-way coded quantum repeaters
Patil, Pacenti, Vasić, Guha, Rengaswamy, arXiv:2405.00849

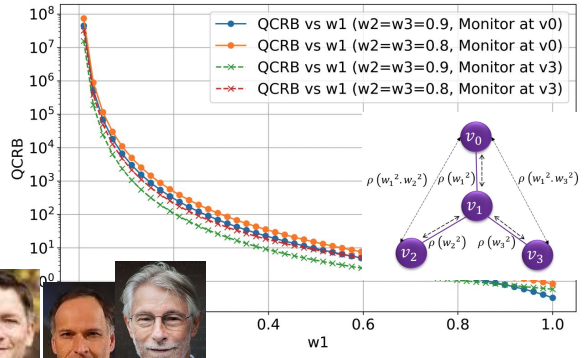






Communications Physics 8, 300 (2025)

Optimal monitor placement in quantum network tomography, Raghunadhan, De Andrade, Towsley, Dey, Kilper, Marchetti, IEEE QCE2024



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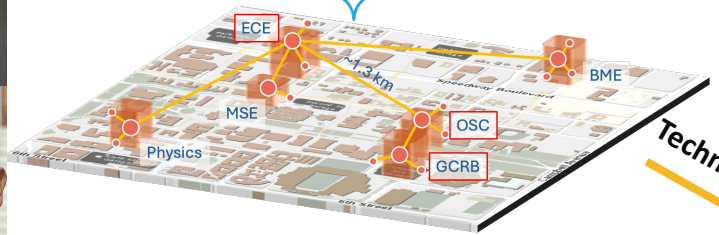
Tucson ⟶ Maryland testbed



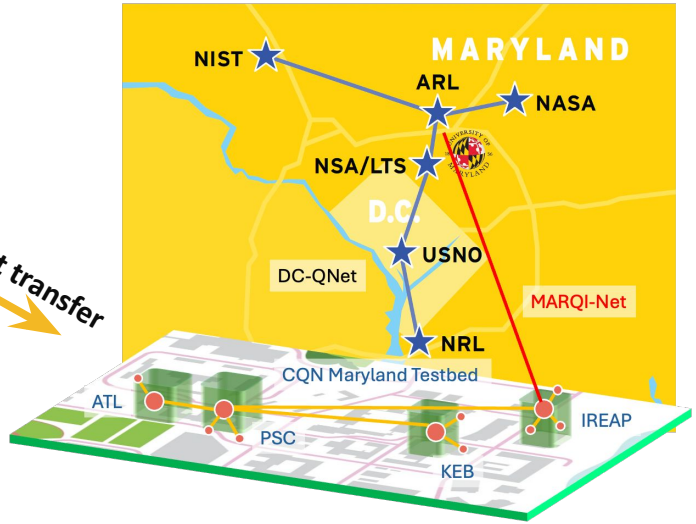
Birth of the Tucson Testbed: NSF INQUIRE
Remote programmable AI-powered QREAL receiver
Characterizing SiC-4H SiV quantum memory
QuaCTUS - Tucson Testbed Simulator
Superadditive capacity using Green Machine
Characterizing SiV color center quantum memory
Quantum frequency conversion
Integrated quantum memory devices

2020
2025
2030

Establishing the central quantum hub
First entanglement distribution in Tucson
New space and cryostat
Time domain interferometer
Cryostat-compatible confocal scanning microscope
Supporting systems for quantum network



Technology/equipment transfer



- Including trapped-ion technology and workforce
- Testbed connected to broad end-users, programs and technologies



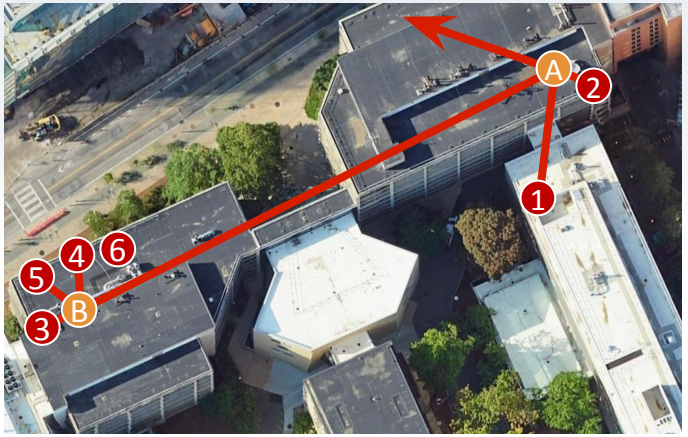
Dr. Chaohan Cui,
UMD Research Faculty

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Boston Testbed





Dr. Chao Li, Research Faculty, MIT EECS

https://github.com/dirkenglund/quantum-network-code/tree/main

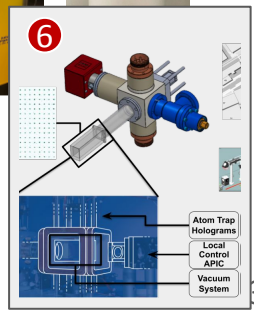












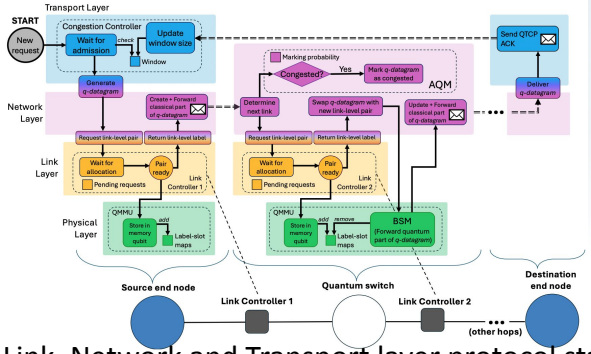




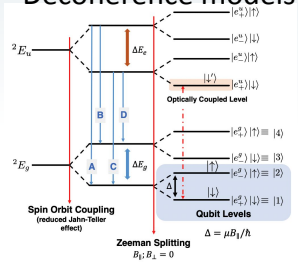
Sandia National Laboratories

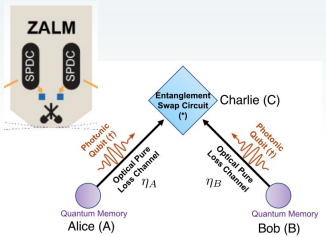
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Virtual Testbed

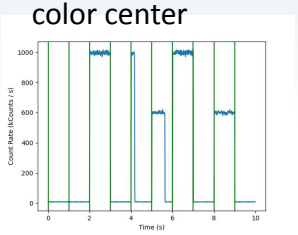


Link, Network and Transport layer protocol stack





Physical layer link models

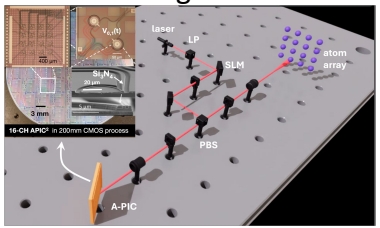


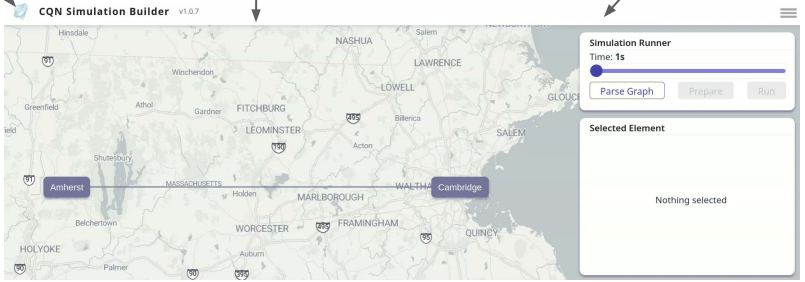
FPGA Controlled color center



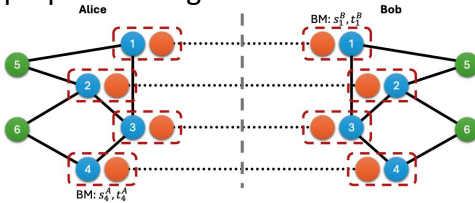
Dr. Stefan Krastanov, UMass Amherst

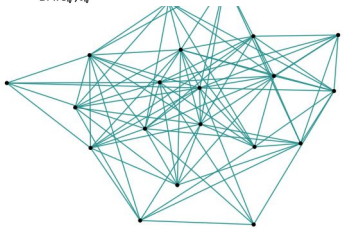
Hardware Co-designed Quantum Optimal Control with Digital Twin Model of Programmable PIC



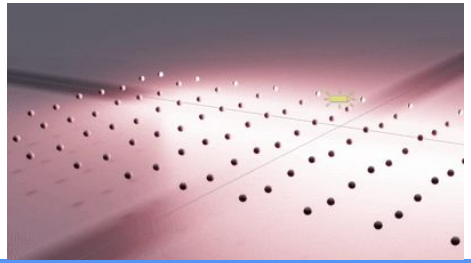


Measurement based entanglement distillation and resource state preparation algorithm

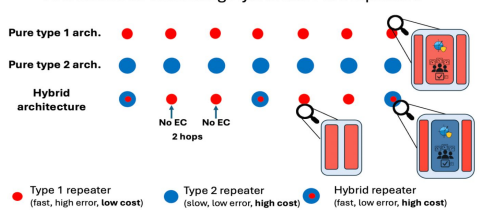




Physics informed digital twin with NVIDIA Omniverse & Zemax Ansys team



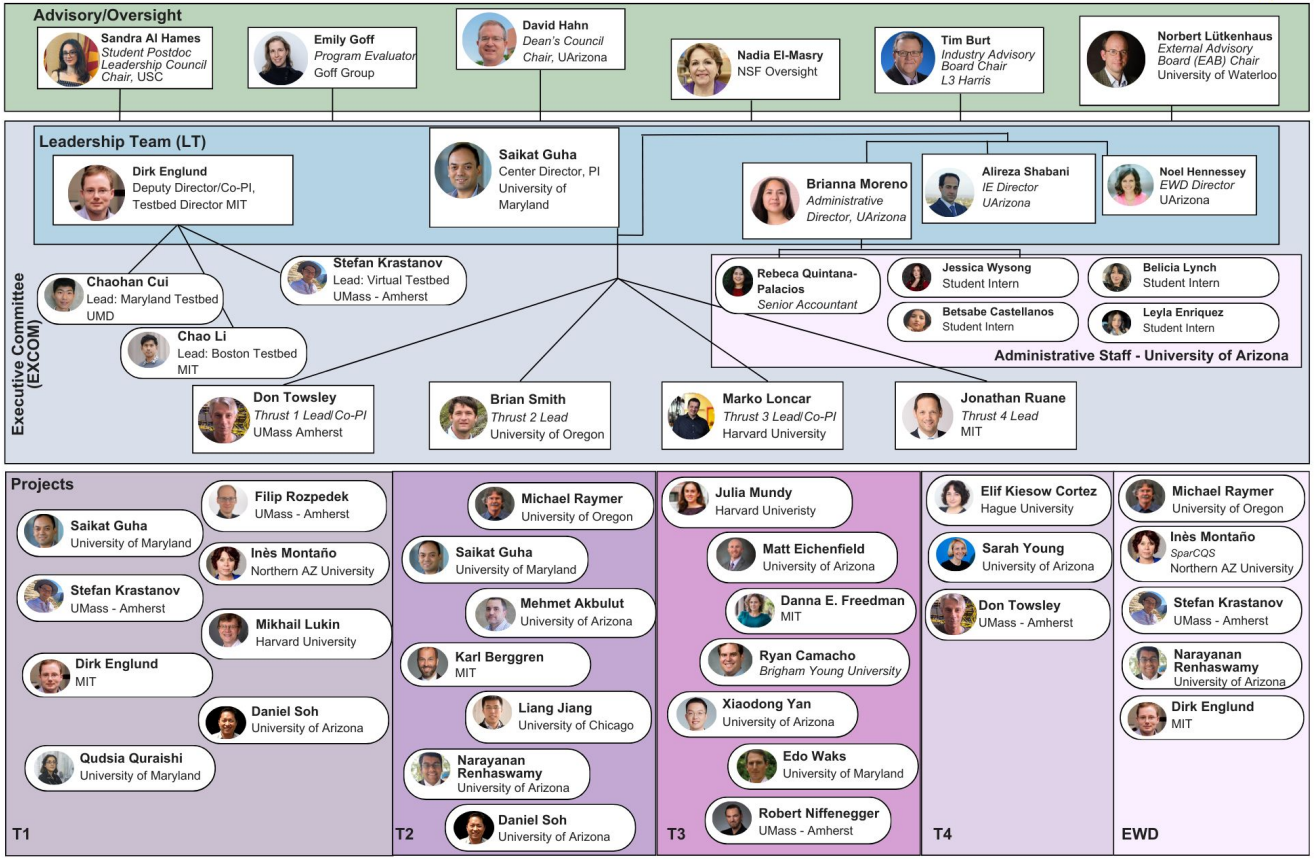
Hybrid quantum repeater architecture



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Center Organization Y7-10



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Center Sustainability

Space

1. New facility in Zupnik Hall (2026) will have laboratories dedicated to CQN, within a broader quantum-technology collaborative space.
2. In discussions with Brian Anderson, acting Dean Optical Sciences, UArizona to keep GCRB floor 4 as quantum collaborative space

Education

1. UArizona Certificate in for approvals. Dean Graham will facilitate the roll out of a certificate in QISE, available to DMV area industry, via UMD's well-established Maryland Applied Graduate Engineering (MAGE) that offers similar programs in AI and other topics.
2. CQN faculty to contribute to UArizona QISE MS, UMD QSE minor, UOregon QISE Minor, …, and cross-campus teaching
3. Winter School - a fee-bearing live quantum networking annual school

Industry

1. The CQN IPP maturing into a standalone "IUCRC-like" nationally-distributed academic-industry R&D consortium
2. More individual company <> university master research agreements
3. Joint CRAD opportunities, including DoD, SBIRs, and VC funded
4. More spin-outs on the horizon (3 that I am aware of!) building off of CQN IP and personnel

Testbeds

1. Fee-bearing access to virtual and physical testbeds (on contracted projects basis)
2. IP bearing subsystems: licensing revenue

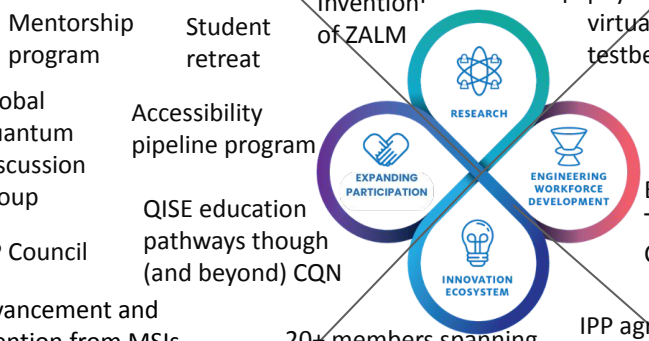
Federal opportunities (partial list) stringing groups of CQN faculty together

1. NQVL (efforts led by Brian Smith, Dirk Englund)
2. Space-assisted long range heralded entanglement MTSLT (planning stage)
3. DoE: PiQSci program on quantum network protocols, spatial entangled probes for bio-sensing (awarded)
4. ONR Entanglement assisted sensor networks MURI (selected)
5. NSF STC bringing together IoT, quantum, networking, control, and AI (going up for SV)
6. ARO MURI on Quantum Network Science (option awarded)
7. DARPA HARQ / Hybrid architectures (I am aware of at least 6 distinct full proposal submissions that CQN faculty are involved in. All the best!)
8. New NST-TIP effort on quantum photonics (planning stage)

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CQN: A Gen-4 ERC



Protocols, application-aware routing
ZALM-enabled memory entanglement: quantum repeater "advantage"
Switched-ZALM 5-node network, and protocol demonstrations
Heralded teleportation
Cross-institution grad and UG course exchanges
Expand High School (GLEAM like) programs to other communities
Site Visits
Massively multiplexed spin-spin entanglement
ion-SiV entanglement
Link-level distillation
Integrated system architecture
Student-driven conference talks
US-Ireland educational workshops, e.g., quantum network nomenclature workshop
Workshops: Allyship, unconscious bias, & more
Long-baseline demonstration
Efficient entanglement distillation algorithm
classical-internet inspired q. routing
network tomography
CQN Winter School trained 600+ worldwide
Integrate non-research programming with synergistic centers: NoirLab, CUA, QLCIs, JQI, …
Office Hours
A revamped REU program
city-scale entanglement
Millions of qubits in a chip
High-efficiency QFC
Quantum photonics lab
UMD QSE (UG) minor
Mentorship program
Student retreat
Invention of ZALM
physical and virtual testbeds
SPARCQS impacted 14,000+ K-12 and others across US
Proposal and BD training and mentoring for students and postdocs
Meet and exceed national bests–in STEM centers–in access for all
Global quantum discussion group
Accessibility pipeline program
MS-in-QISE at UArizona
Quantum information bootcamp
VR-compatible walkthrough of quantum networking: from the atom to the globe
QISE education pathways though (and beyond) CQN
EWD Fellowships: Tangram, ChatCQN, ChatTutor
Student exchanges across campuses
Rotate Q3, QNumerics, Bootcamp at other CQN campuses
EP Council
SPARCQS at all core campuses
Advancement and retention from MSIs
Generations of CQN REU students traversed academic journeys through CQN. Some spanning: community college -> UG -> G (R1)
Formal student/staff exchange program
20+ members spanning q. networking startup, telecom, defense, VC
IPP agreement with core partners with easy signup, made >$1.7M
Testbed(s) as an educational tool
10+ retention workshops, e.g., Women in Red STEM conference.
Mentoring REU at industry site
7 CQN startups
Perfect pitch
Integrate with other synergistic REU programs
Certificate program
Connect more with q. computing industry
Associated project revenue (federal, industry, FFRDC) to equal CQN's
Insightful demos of quantum network principles
More customized joint research
Testbed (incl. virtual) research participations
Triple 6 CQN-industry joint-authored papers in 5 years

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Thank you!

CQN Annual Retreat, Tucson 2024



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