Center for **Quantum Networks**
National Science Foundation Engineering Research Center

Full-stack Physics-level model of cascaded entanglement links

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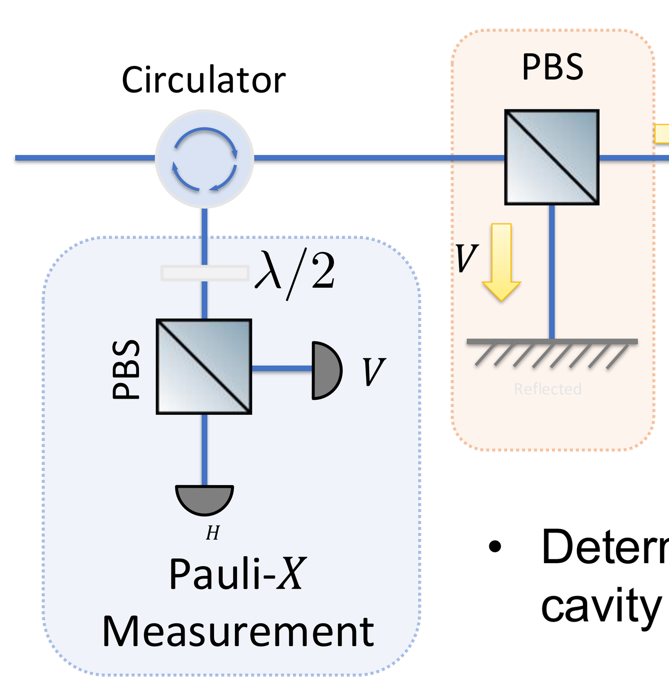
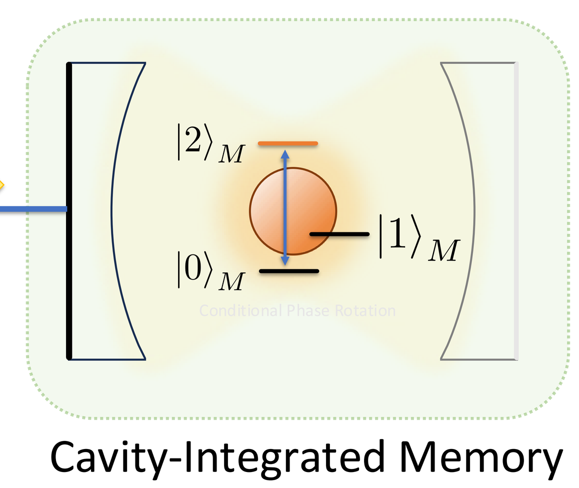
Motivation

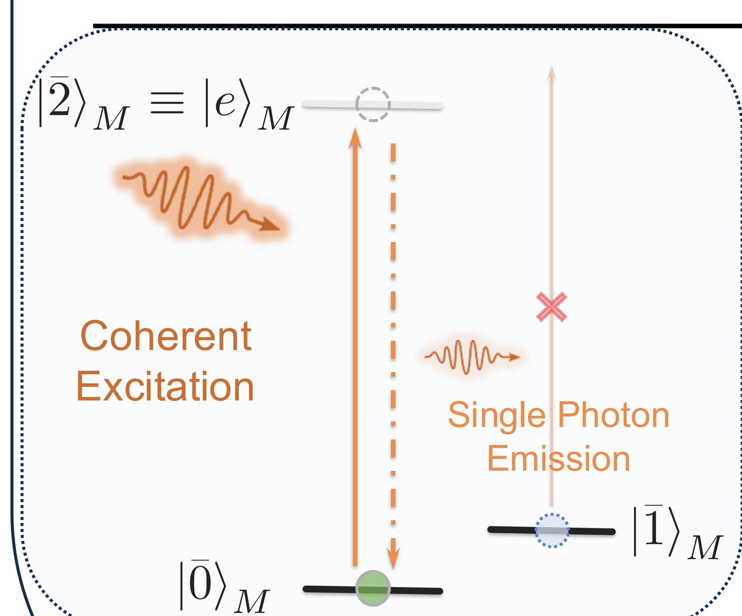
- An approximation free physics accurate model of ZALM is very difficult
- Current models of ZALM are limited by assumptions
- Models are not easily available for integration with other works

Quantum Memories

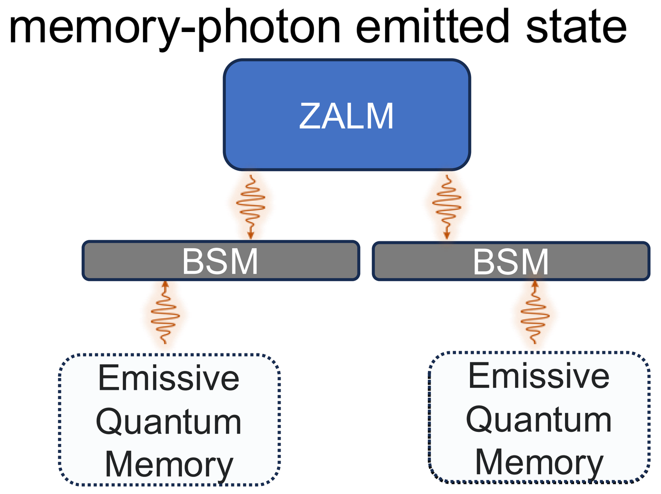




- Deterministic heralded loading with a cavity assisted memory-photon CZ gate



- Probabilistic heralded loading with a memory-photon emitted state



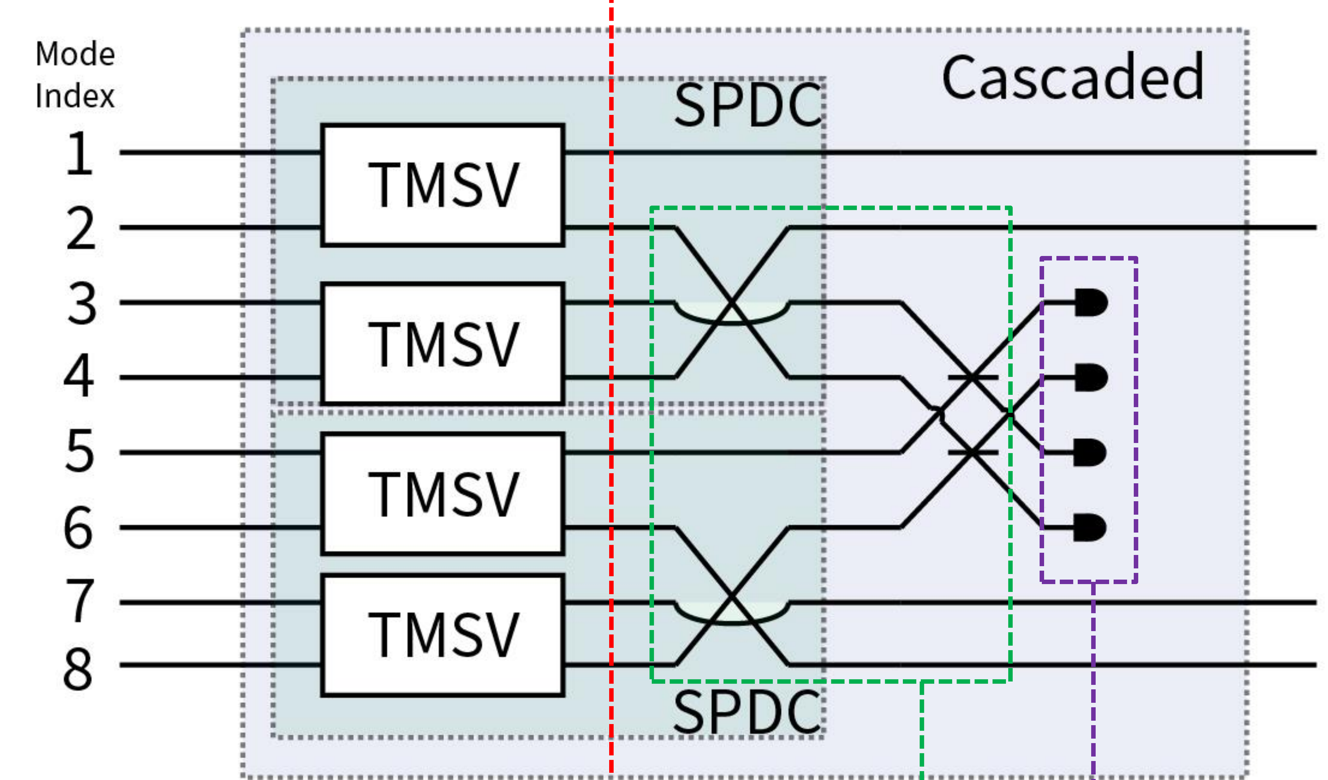
$$(\sqrt{\gamma}|\bar{0}\rangle_M + \sqrt{1-\gamma}|\bar{1}\rangle_M)\otimes|0\rangle_P \xrightarrow{\text{Coherent Excitation}} \sqrt{\gamma}|\bar{0}\rangle_M|1\rangle_P + \sqrt{1-\gamma}|\bar{1}\rangle_M|0\rangle_P$$

Our Solution

- Evaluate quantum state with a hybrid CV-DV modelling, considering Gaussian state nature of ZALM source.
- Incorporating frequency dependence starts from the single-mode model.
- Make these models available open-source, via the "genqo" python toolbox, integrated with QuantumSavory and QuantumSymbolics

Hybrid Model Approach

Initial state can be represented as a covariance matrix



Gaussian operations performed via matrix operations

Non-gaussian operations performed by basis change via the K-function formalism

$$|\psi\rangle = \frac{1}{(2\pi)^N}\int d^{2N}\vec{x}_\alpha\,|\vec{\alpha}\rangle\langle\vec{\alpha}|\psi\rangle = \int d^{2N}\vec{x}_\alpha K(\vec{x}_\alpha)\,|\vec{\alpha}\rangle$$

K-function formalism $\quad K(\vec{x}_\alpha) = (2\pi)^{-N}\langle\vec{\alpha}|\psi\rangle$

Gagastos and Guha, Phys. Rev. A **99**, 053816 (2019)

Pre-detection state (with photon loss) in coherent basis

$$\rho_{zl} = \int d^{16}\vec{x}_\alpha d^{16}\vec{x}_\beta K(\vec{x}_\alpha)K(\vec{x}_\beta)^*\mathcal{G}(\vec{\alpha},\vec{\beta},\vec{\eta})\,|\vec{\alpha}_L\rangle\langle\vec{\beta}_L|$$

Dhara et al, Phys. Rev. Applied **17**, 034071 (2022)

Post-detection state in Fock basis

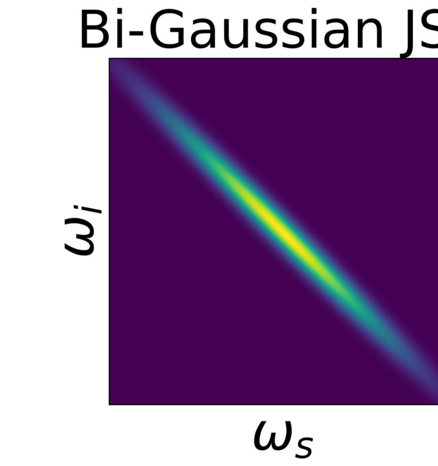
$$\langle n_1,\ldots,n_8|\,\rho_{zl}\,|n_1',\ldots,n_8'\rangle = \int d^{16}\vec{x}_\alpha d^{16}\vec{x}_\beta \left(\prod_{i=1}^{8}\alpha_i^{n_i}\beta_i^{n_i'}\right)e^{-\frac{1}{2}\vec{x}A\vec{x}^T}$$

Simplification via the Hafnian (Wick's Theorem)

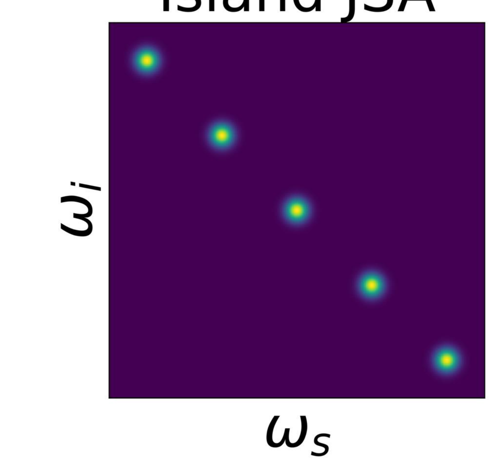
Incorporating Frequency

- Frequency characteristics of source represented by the joint spectral amplitude (JSA) function
- Use Schmidt decomposition of JSA for orthogonalization
- TMS Hamiltonian is separable under JSA Schmidt decomp.
- Broadband ZALM source can be decomposed into multiple single-mode cascaded sources whose mean photon numbers are modulated according to the Schmidt coefficients.

Bi-Gaussian JSA



Island JSA



Results