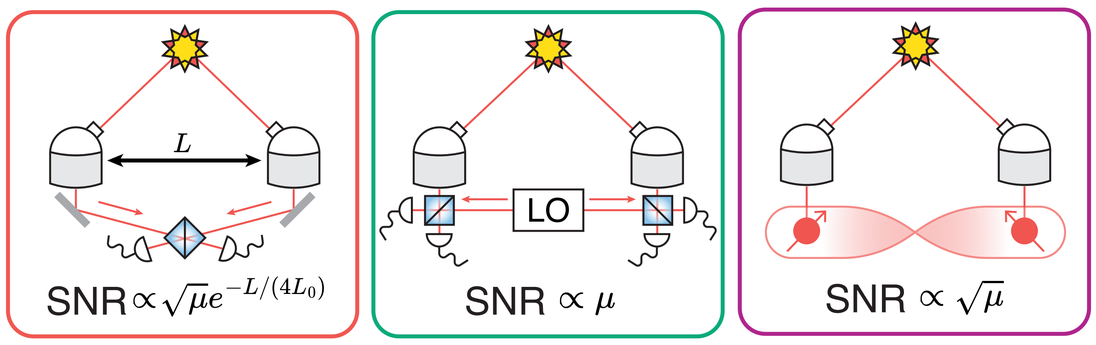
Entanglement Assisted Non-Local Optical Interferometry in a Quantum Network

P.-J. Stas[1*], Y.-C. Wei[1*], M. Sirotin[1,2*], Y. Q. Huan[1], U. Yazlar[1,3], F. Abdo Arias[1], E. Knyazev[1], G. Baranes[1,2], B. Machielse[4,5], S. Grandi[6], D. Riedel[5], J. Borregaard[1], H. Park[1,7], M. Loncar[4], A. Suleymanzade[1,8] and M. D. Lukin[1]

[1]Dept. of Physics, Harvard University, [2]Dept. of Physics and Research Laboratory of Electronics, MIT, [3]Division of Materials Science & Engineering, BU, [4]John A. Paulson School of Engineering and Applied Sciences, Harvard University, [5]IonQ Inc., [6]ICFO, Spain, [7]Dept. of Chemistry and Chemical Biology, Harvard University., [8]Dept. of Physics, University of California
*These authors contributed equally

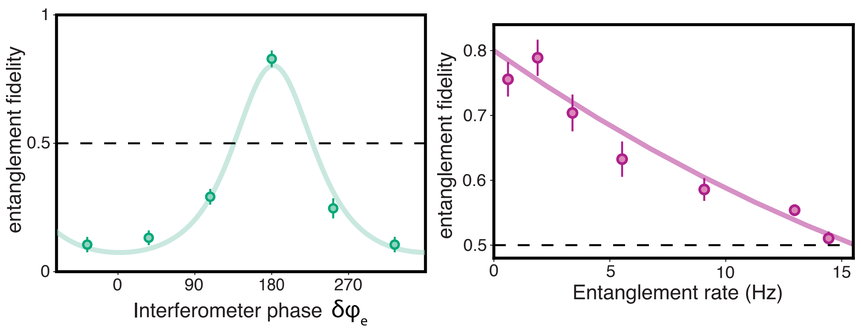
Comparing Measurement Methods



Direct measurement | Local measurements | Entanglement Assisted

For weak thermal optical incident light, three different measurement methods exist with different signal-to-noise (SNR) ratio scalings: direct measurement SNR scales optimally with signal strength but incurs exponential photon loss due to routing, local measurements cannot distinguish signal from vacuum and thus SNR scales worse with signal strength, and entanglement assisted SNR scales optimally with signal strength without exponential photon loss, enabled by remote entanglement.

Parallel Entanglement



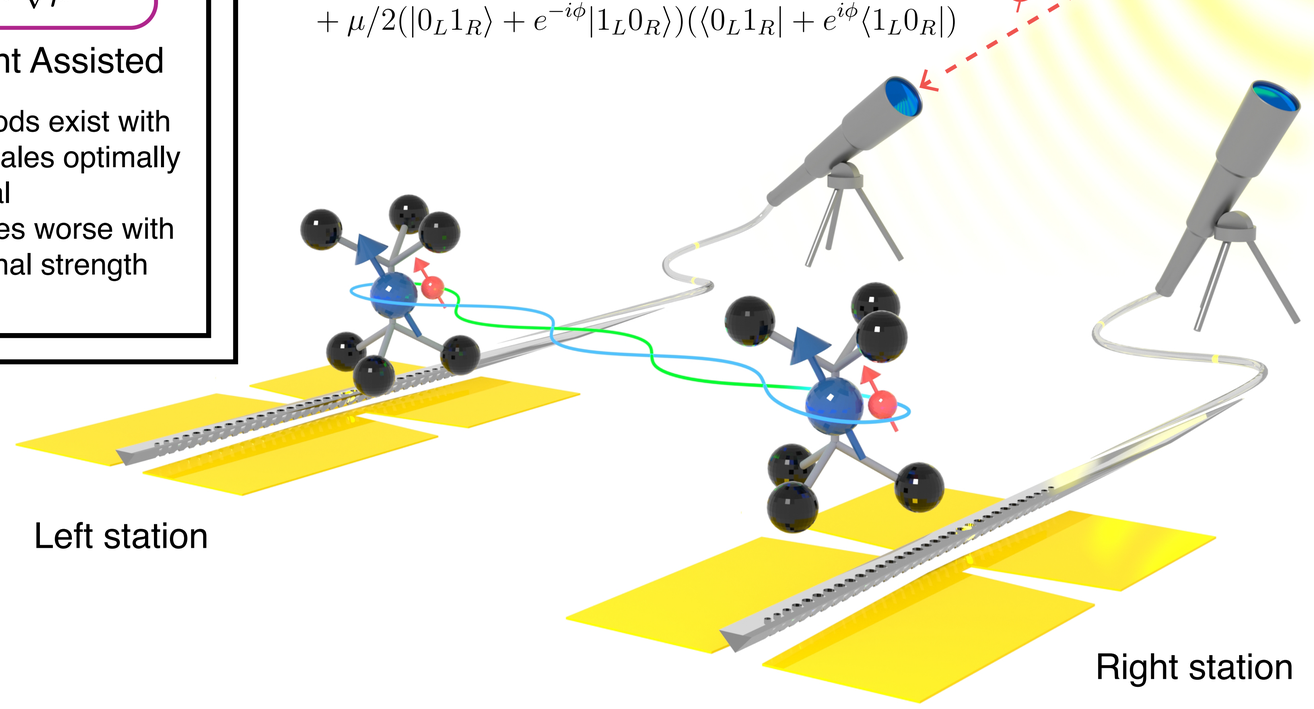
10x rate improvement over previous serial entanglement scheme

Non-Local Optical interferometry

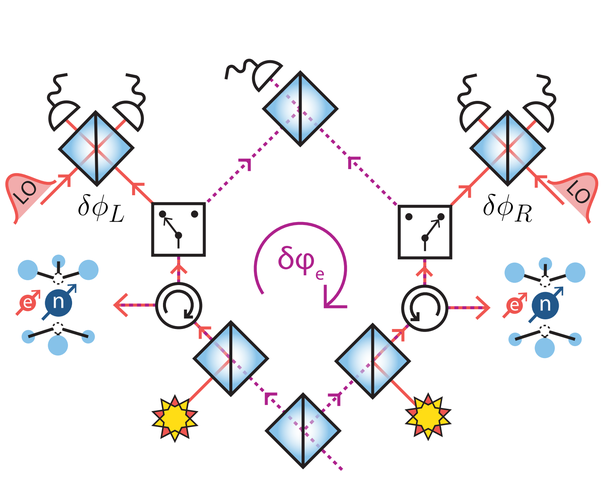
In non-local optical interferometry, we want to measure the differential phase ϕ of light arriving at two locations separated by distance L to precisely determine the position of the object from which the light came.

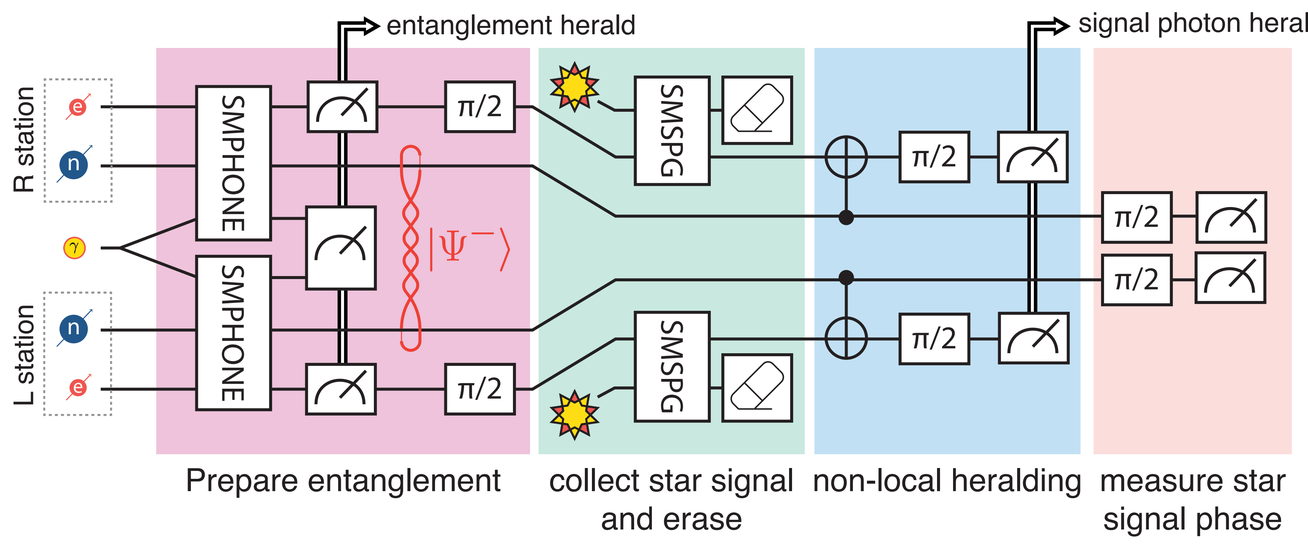
The weak thermal signal light state is:

$$\rho = |0_L 0_R\rangle\langle 0_L 0_R| + \mu/2(|0_L 1_R\rangle + e^{-i\phi}|1_L 0_R\rangle)(\langle 0_L 1_R| + e^{i\phi}\langle 1_L 0_R|)$$

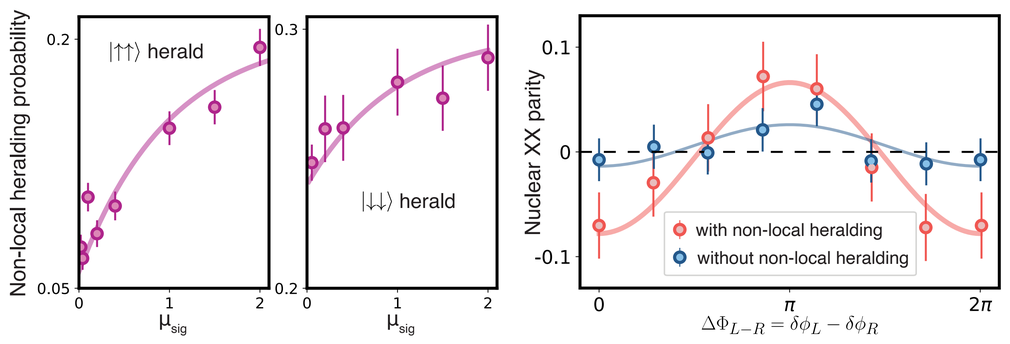


Non-Local Phase Sensing Protocol



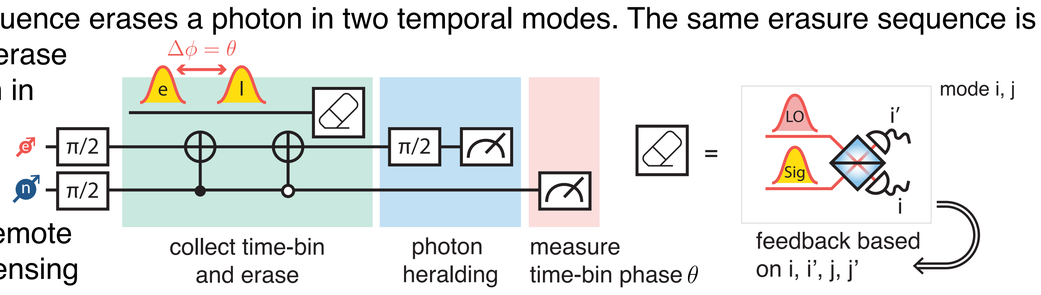


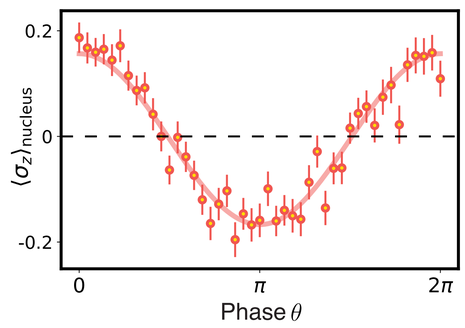
This sequence imprints the signal phase onto the entangled nuclear spin qubits, which we can then locally measure to determine the phase.
The non-local signal photon heralding step enabled by pre-generated entanglement heralds the presence of a photon without revealing the spatial location of the photon. This filters out the vacuum component of the signal light, which in turn enables optimal SNR scaling with signal strength.



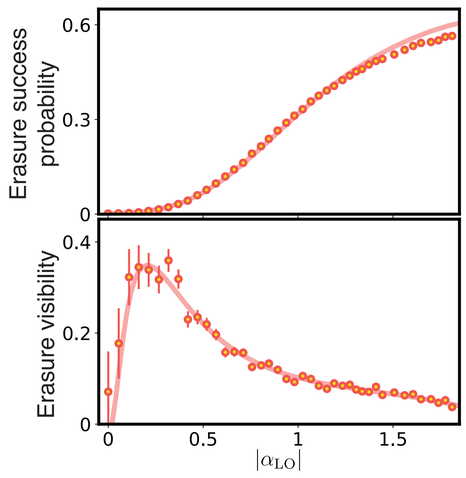
Photon Mode Erasure

This sequence erases a photon in two temporal modes. The same erasure sequence is used to erase a photon in two spatial modes for the remote phase sensing protocol.

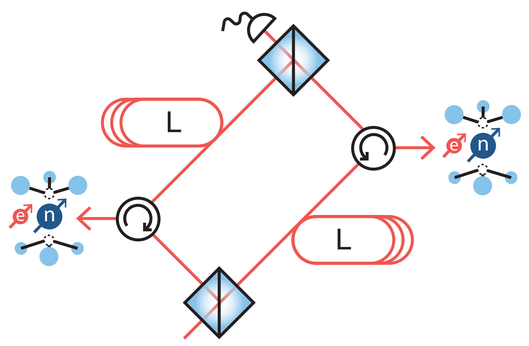


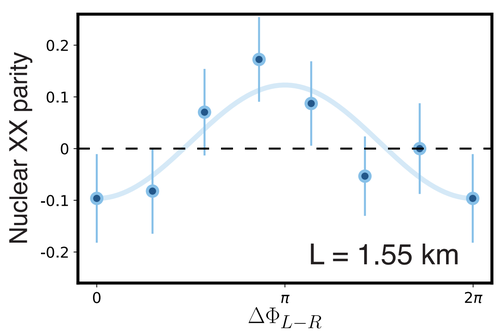


Photon mode erasure "erases" the presence in a given mode.
-> it hides the "which-mode" or "which-path" information.



1.55 km baseline





We extend the baseline of our non-local phase sensing protocol by placing fiber spools (L=1.55 km) in between the stations in the entanglement interferometer.

References

Theory: M. Tsang, PRL **107**, 270402 (2011), D. Gottesman et al., PRL **109**, 070503 (2012), E. Khabiboulline et al., PRL **123**, 070504 (2019)
SiV quantum network nodes: C. T. Nguyen, D. D. Sukachev, M. K. Bhaskar, B. Machielse et al., PRL **123**, 183602 (2019)
Si29 nuclear spin control: P.-J. Stas, Y. Q. Huan, B. Machielse et al., Science **378**, 557-560 (2022)
Remote SiV-SiV entanglement: C. Knaut, A. Suleymanzade, Y.-C. Wei, D. R. Assumcao, P.-J. Stas et al., Nature **629**, 573-578 (2024)