



## Towards long-distance phase coherence for large-area quantum sensors.

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Michael Bregar, Si Xie, and Cristián Peña

CPAD - RDC 8 Quantum & Superconducting Sensors

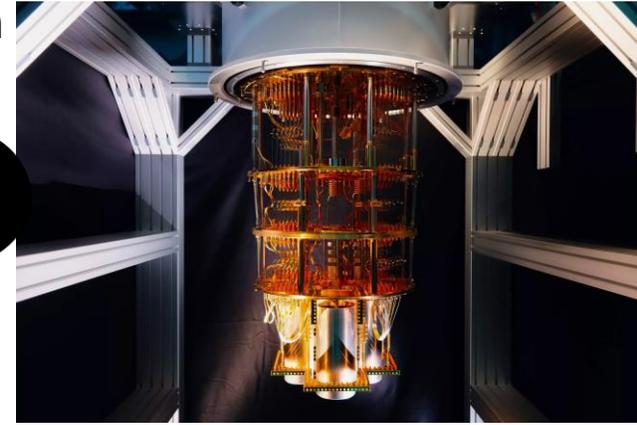
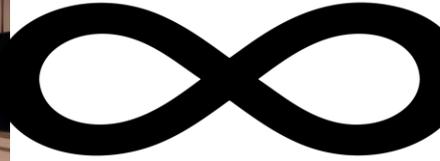
9th October 2025



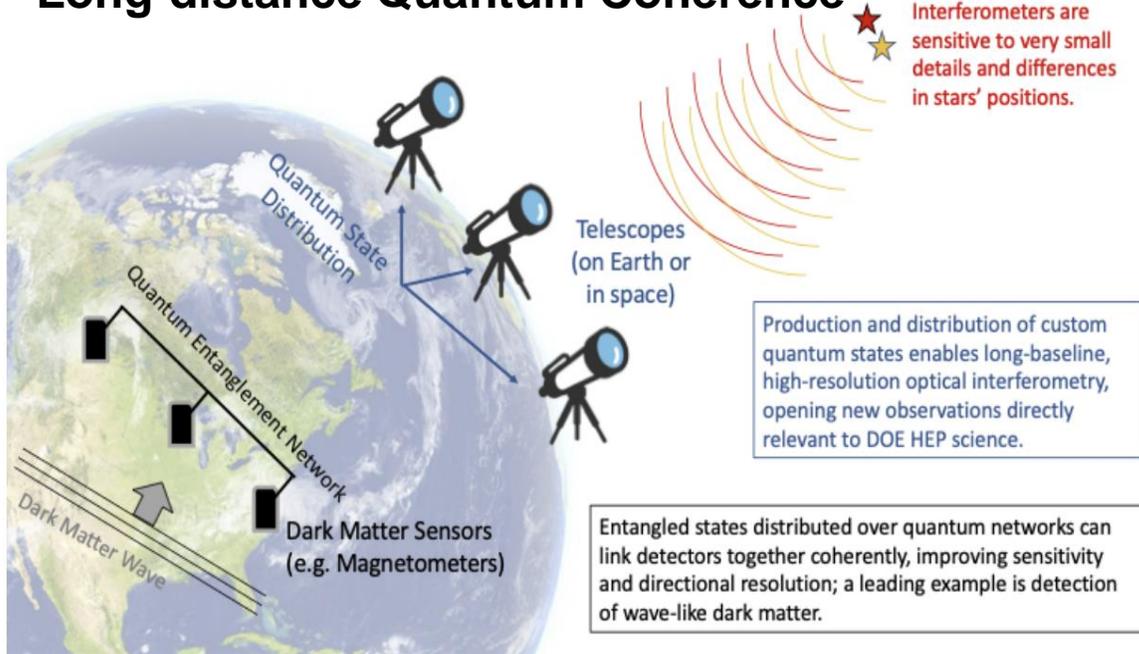
# Why build a quantum network?



Connect Quantum Devices



## Long-distance Quantum Coherence



## Quantum-Enhanced Security



# The quantum internet



Long-baseline  
quantum telescope

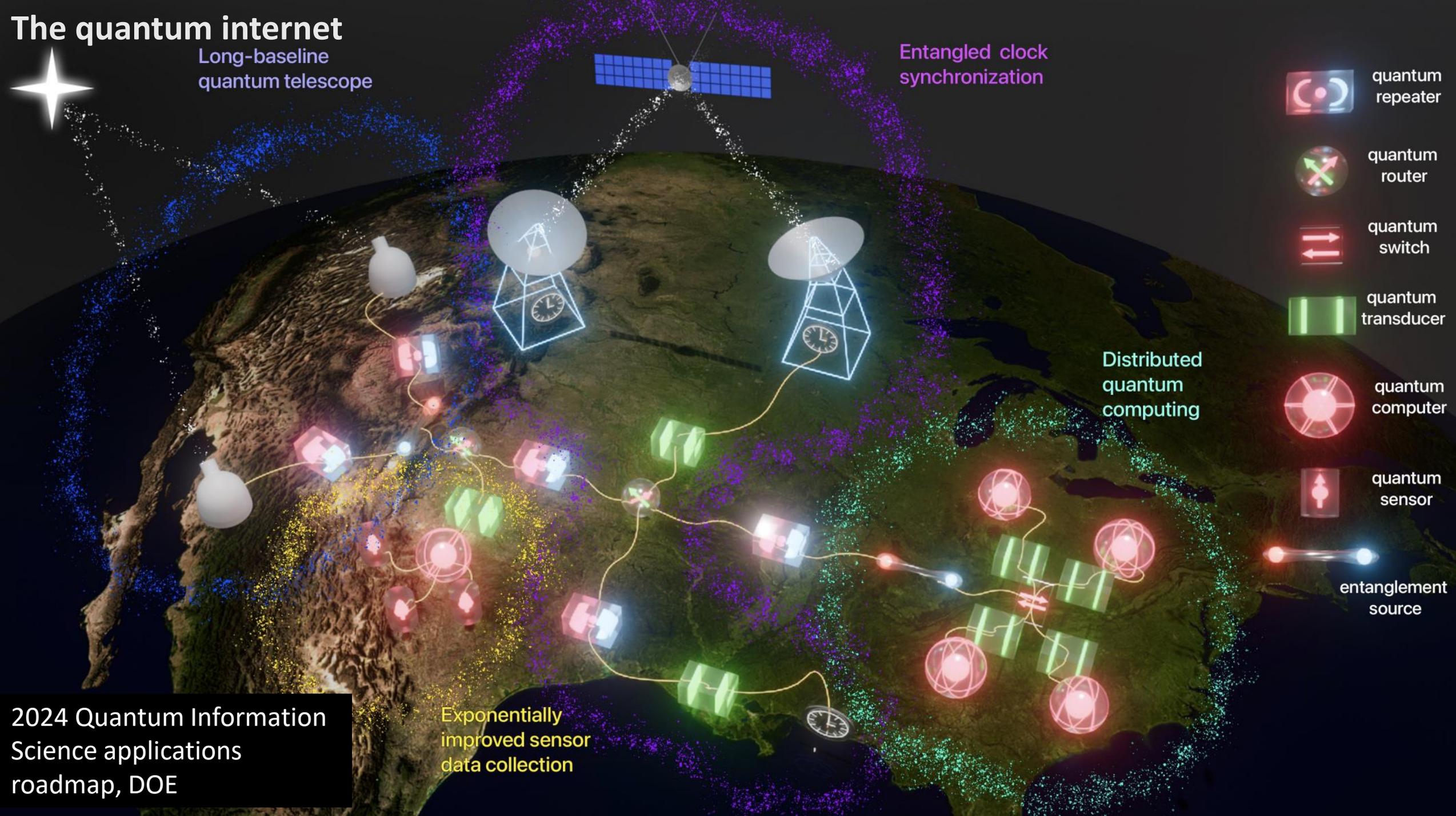
Entangled clock  
synchronization

-  quantum repeater
-  quantum router
-  quantum switch
-  quantum transducer
-  quantum computer
-  quantum sensor
-  entanglement source

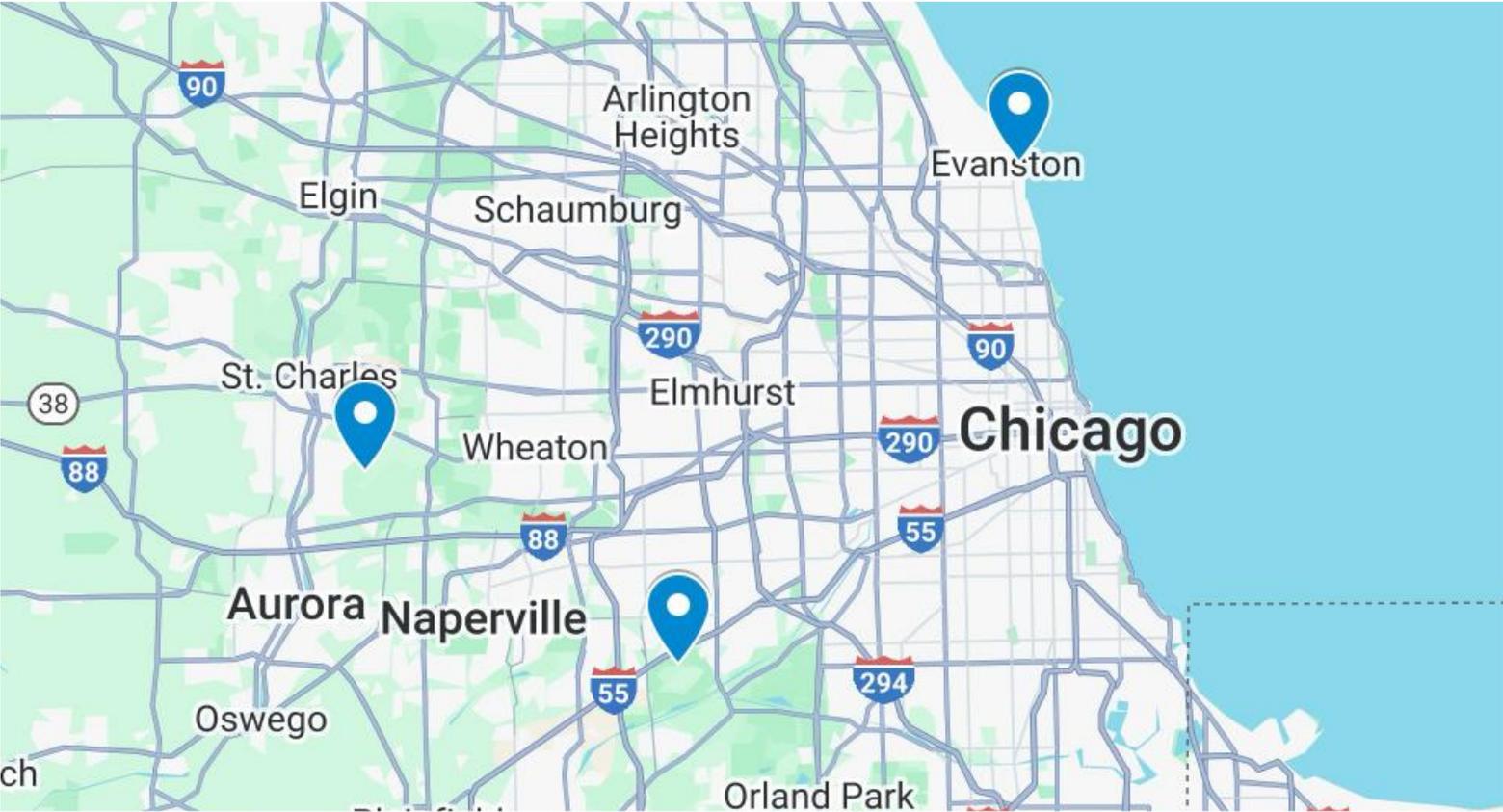
Distributed  
quantum  
computing

Exponentially  
improved sensor  
data collection

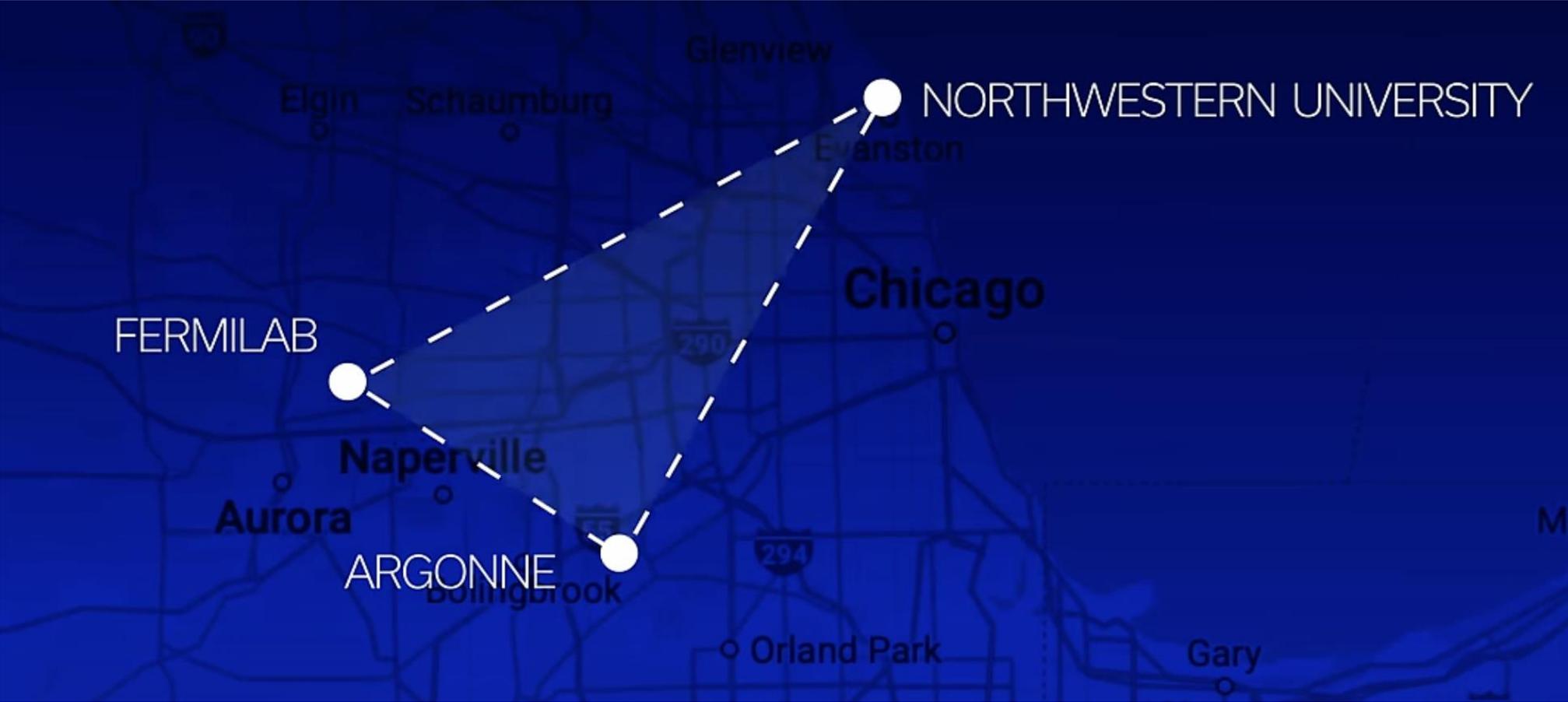
2024 Quantum Information  
Science applications  
roadmap, DOE



# Advanced Quantum Network (AQNET)



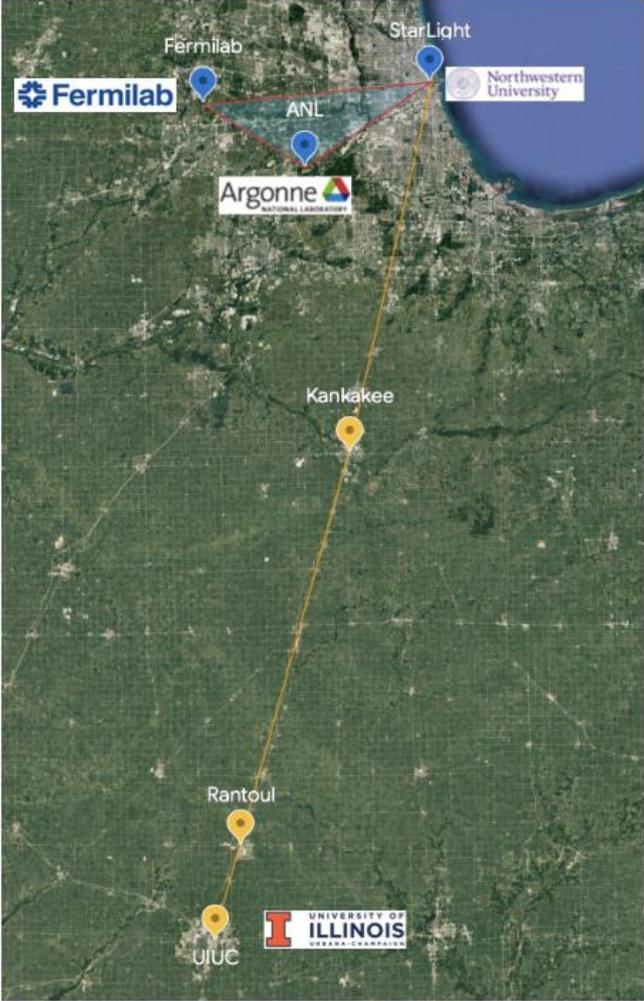
# Advanced Quantum Network (AQNET)



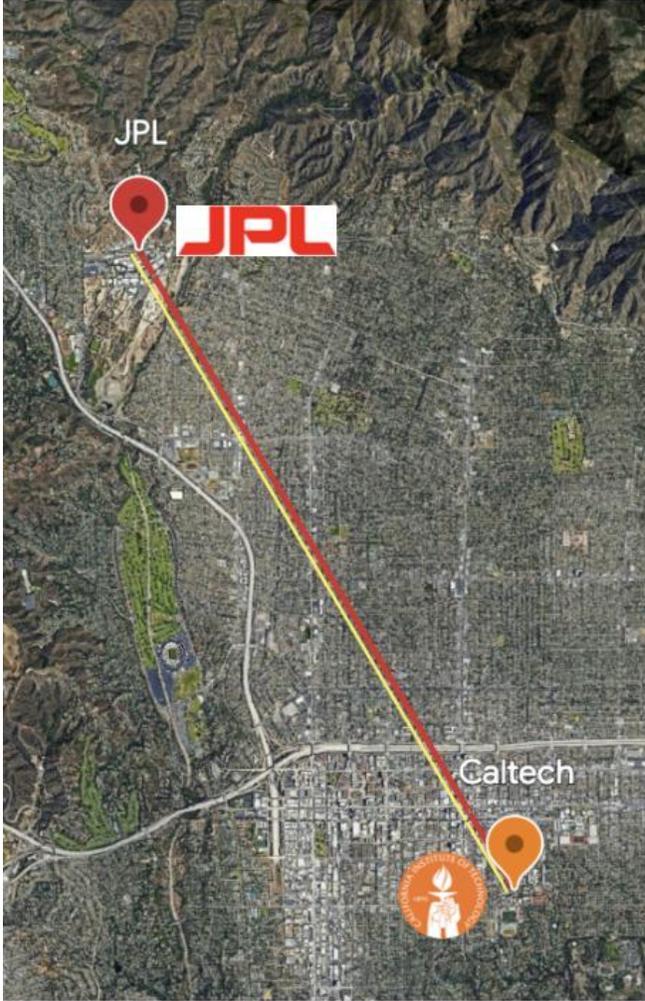
# Advanced Quantum Network (AQNET)



# Chicago-based Networks developed in parallel with Pasadena-based Networks



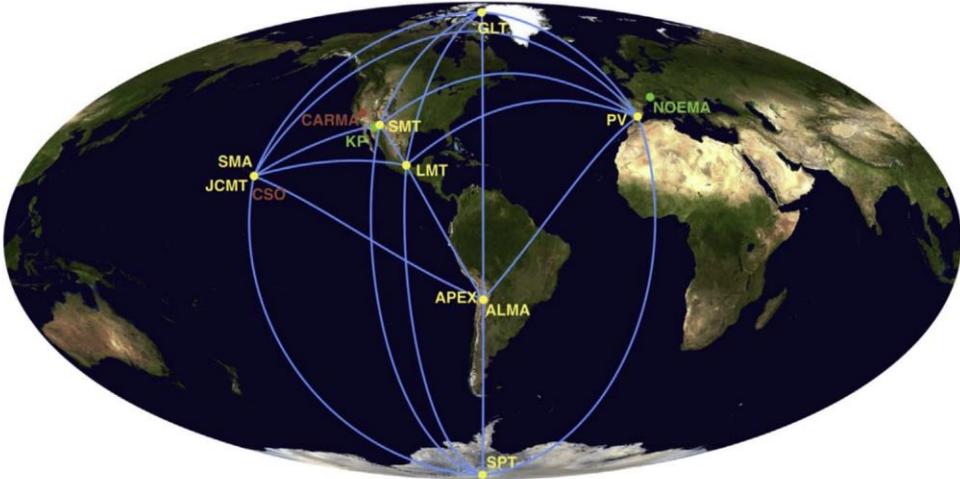
AQNET



# Turning a quantum network into a quantum sensor – telescope arrays

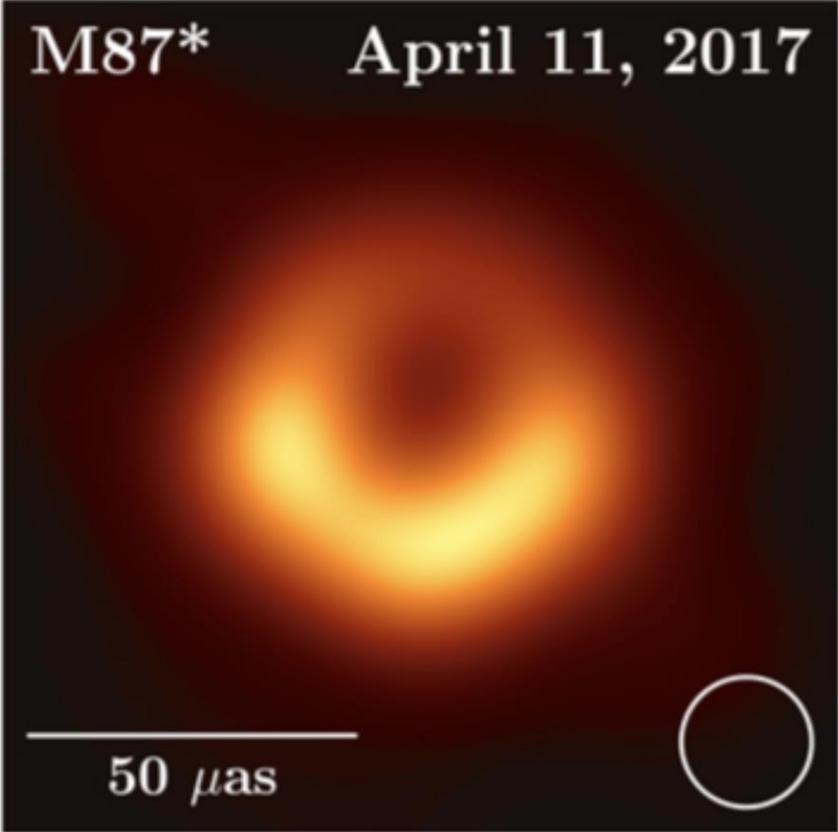
THE ASTROPHYSICAL JOURNAL LETTERS, 875:L2 (28pp), 2019 April 10

The EHT Collaboration et al.



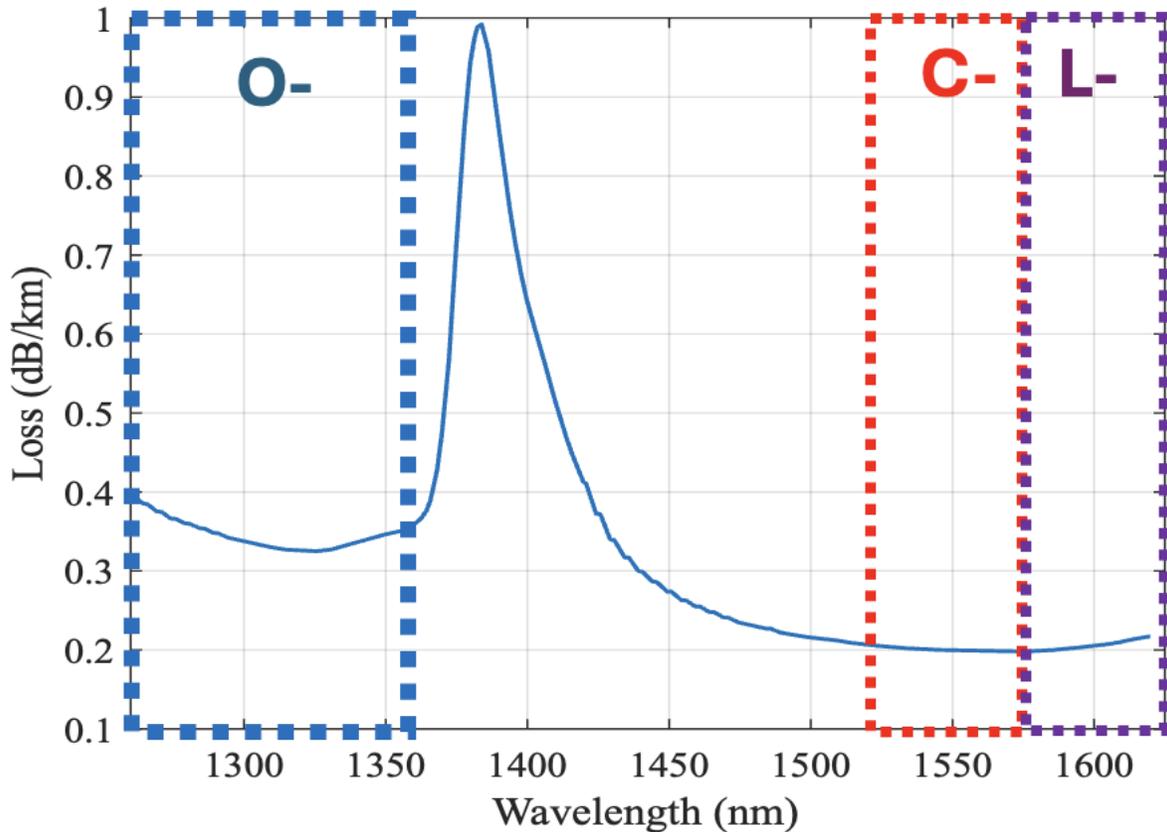
**Figure 1.** Map of the EHT. Stations active in 2017 and 2018 are shown with connecting lines and labeled in yellow, sites in commission are labeled in red. Legacy sites are labeled in green. Nearly redundant baselines are overlapping each other, i.e., to ALMA/APEX and SMA/JCMT. Such redundancy allows in determining the amplitude calibration of the array (Paper III).

Radio Telescope array  
1.3 mm wavelength (4.35ps)



# Optical or NIR Telescope arrays are much more challenging

Corning SMF-28 loss spectrum



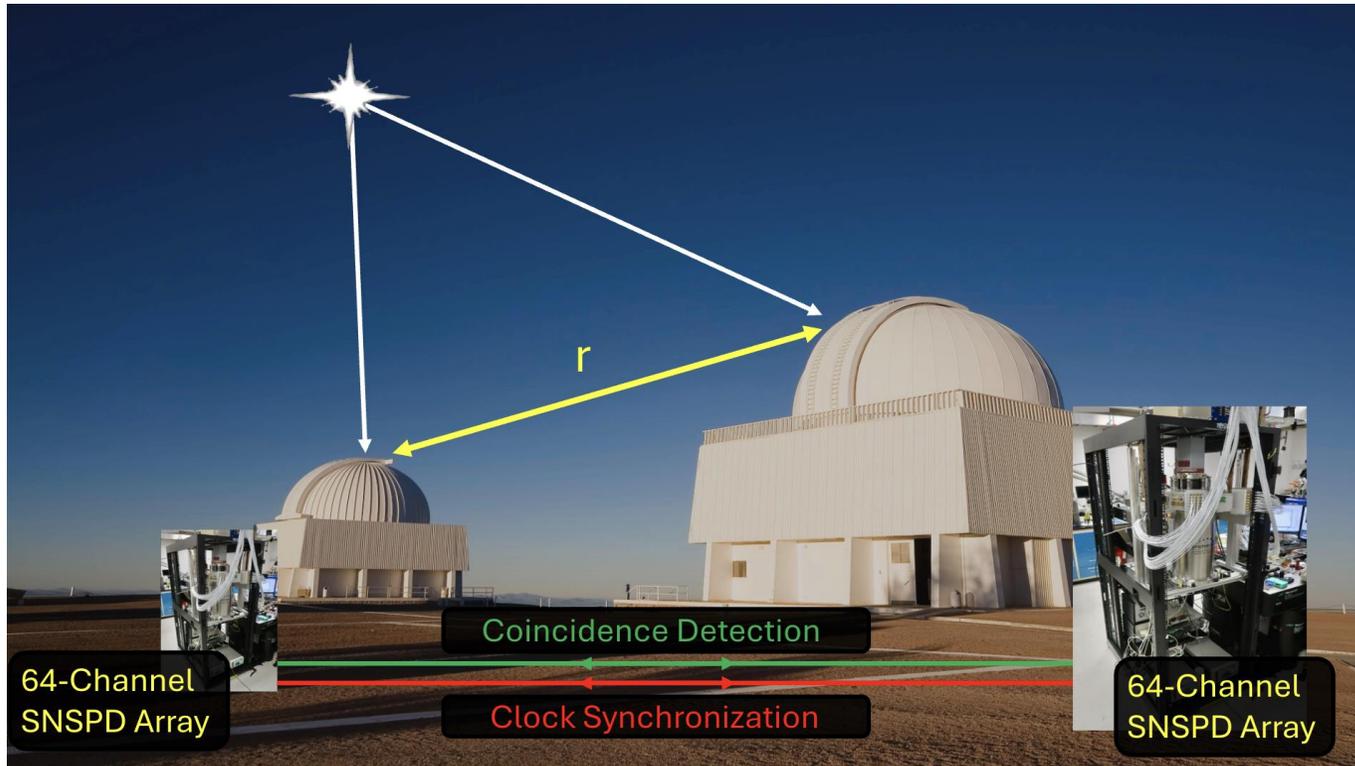
Quantum networks typically operate in telecom fiber compatible frequency bands.

Take the C-band as an example. With a wavelength of **1550nm**, that corresponds to a optical period of **5fs**.

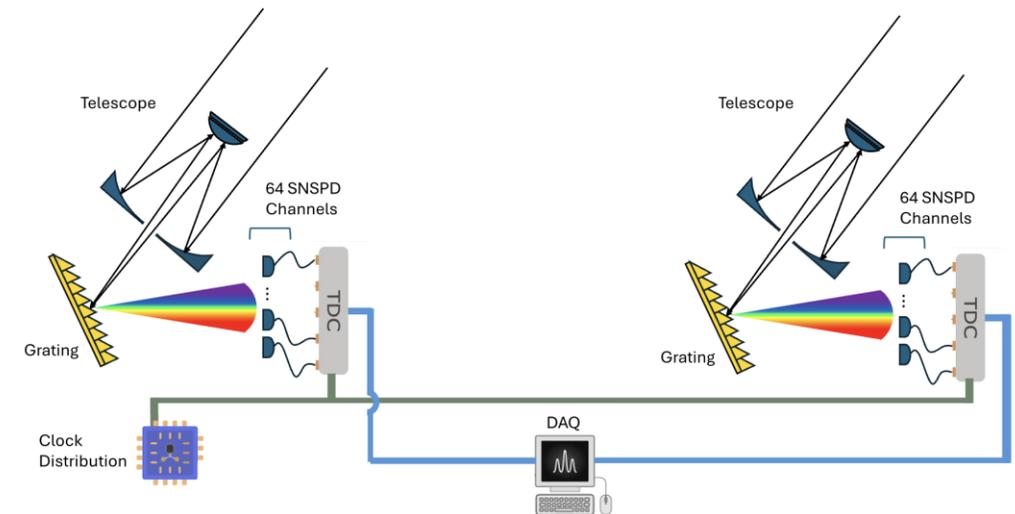
While that's much more experimentally demanding, it also provides better angular resolution!

$$\theta_{resolution} \sim \frac{\lambda}{D}$$

# Optical telescope array step 1: Intensity interferometry



HBT intensity interferometry for optical telescope arrays



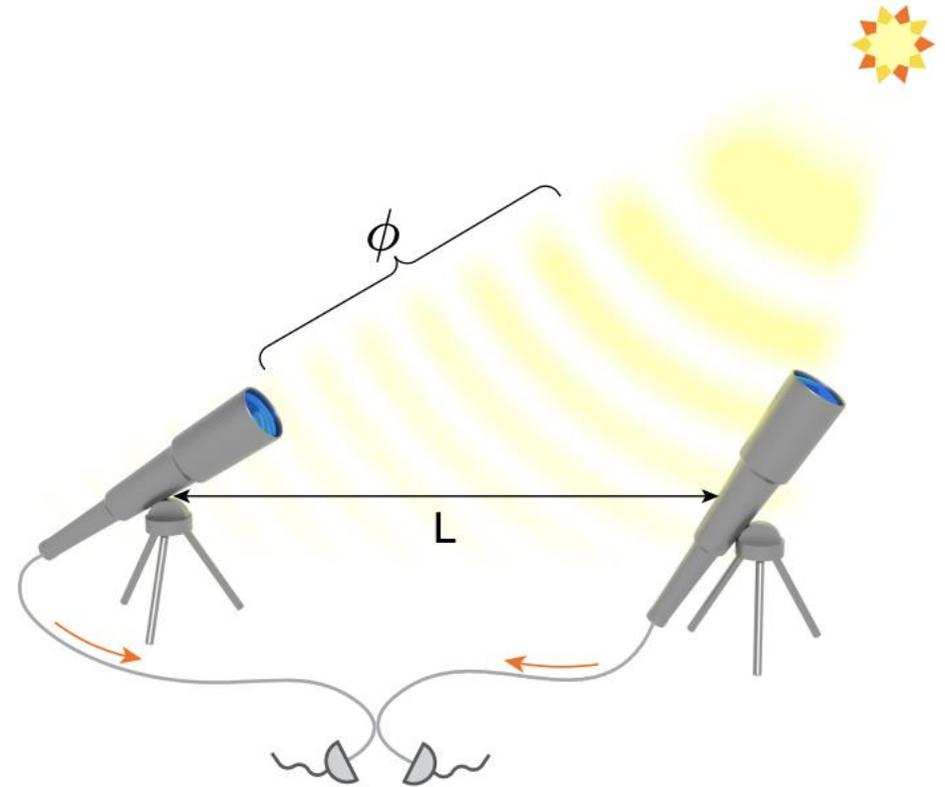
Cristián Peña's 2024 CPAD talk first introduced this our group's intensity measurement concept

[https://indico.phy.ornl.gov/event/510/contributions/2156/attachments/1638/3846/CPAD\\_2024\\_Networks\\_CPENA.pdf](https://indico.phy.ornl.gov/event/510/contributions/2156/attachments/1638/3846/CPAD_2024_Networks_CPENA.pdf)

# Towards phase coherence

- Intensity interferometry relied only on time synchronization and fast detectors
- To fully explore the potential of a quantum network, consider protocols that require phase coherence.
- In contrast to intensity interferometry, amplitude interferometry, or direct detection, interferes light from two telescopes.

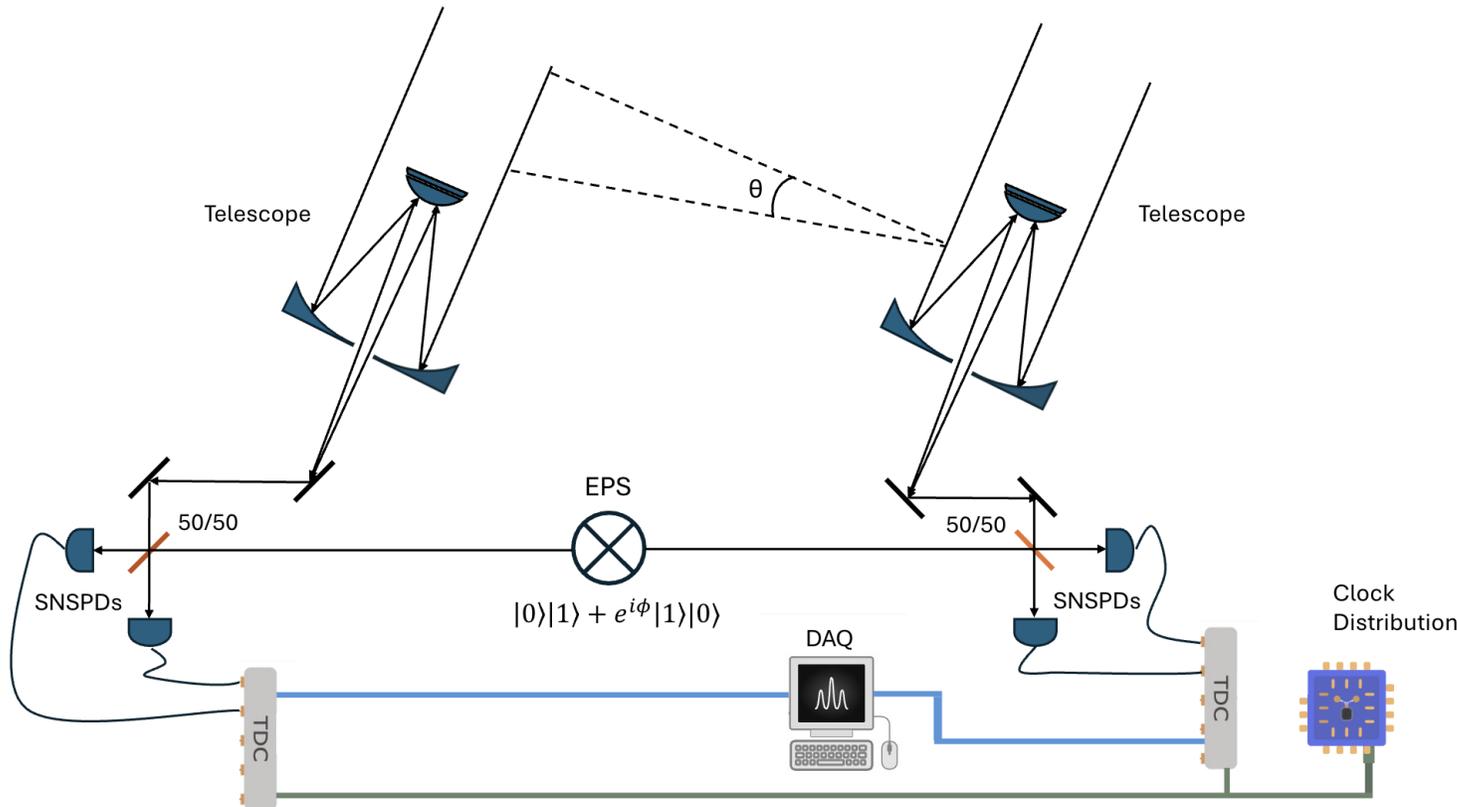
## Conventional amplitude interferometry



Stas, P.-J. C., Wei, Y.-C., Sirotin, M. et al. (2025). *Entanglement Assisted Non-local Optical Interferometry in a Quantum Network*. arXiv. <https://doi.org/10.48550/arXiv.2509.09464>

# Entanglement assisted amplitude interferometry

## Gottesman-Jennewein-Croke Protocol [1]



- Instead of interfering two stellar photons, an entangled photon pair source (EPS) transmits photons to each telescope for interference with stellar photons.
- Detector coincidence counts between sites results in a measurement of  $\theta$ .
- Can extend the baseline of telescope arrays.

[1] D. Gottesman, T. Jennewein, and S. Croke, Longer baseline telescopes using quantum repeaters, Phys. Rev. Lett. 109, 070503 (2012).

## Time bin vs Fock state encoding



$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|EE\rangle + e^{i\phi}|LL\rangle)$$

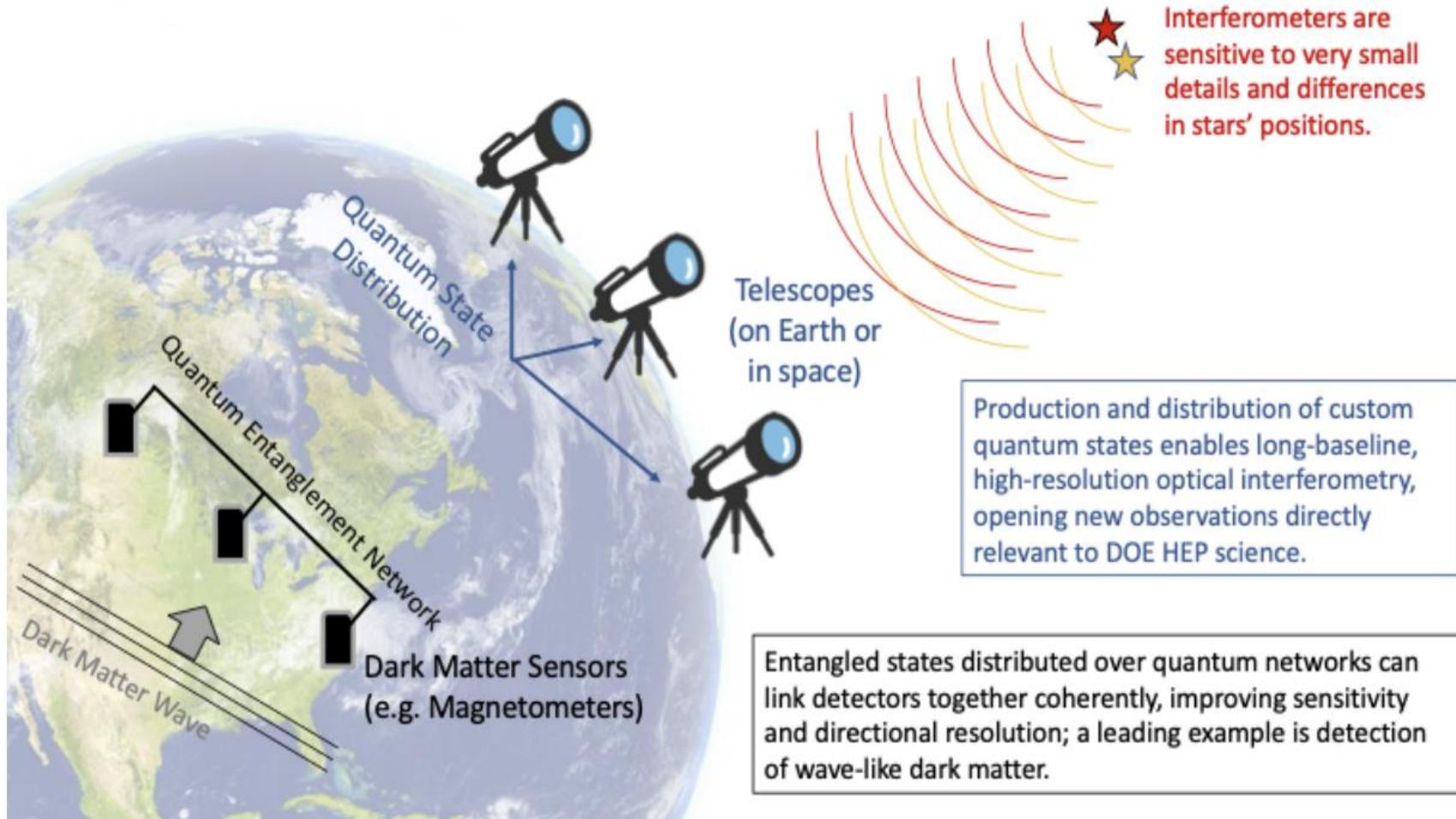


$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|01\rangle + e^{i\phi}|10\rangle)$$

- The experimental price you pay – phase stabilization .

# HEP Applications – switch out telescopes for axion detectors

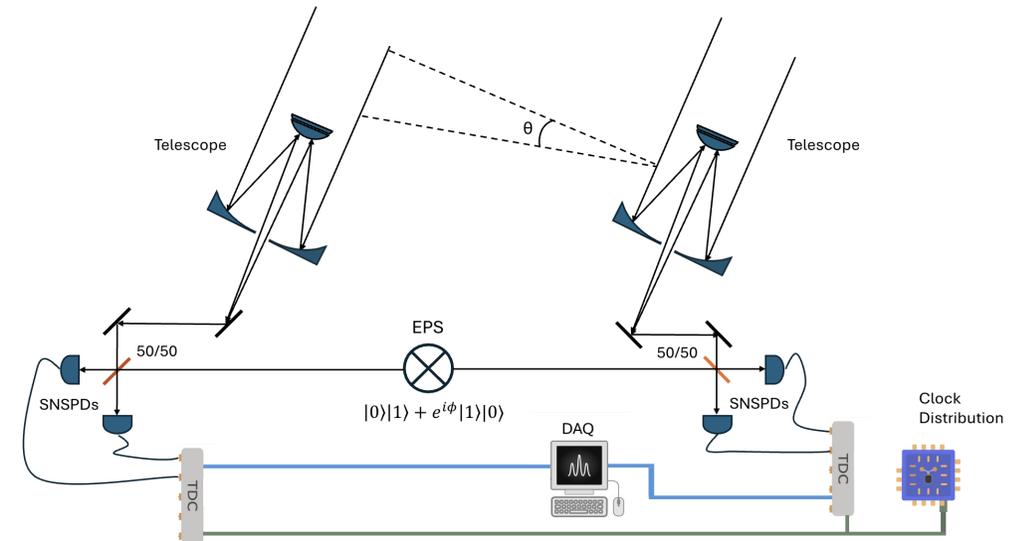
## Long-distance Quantum Coherence



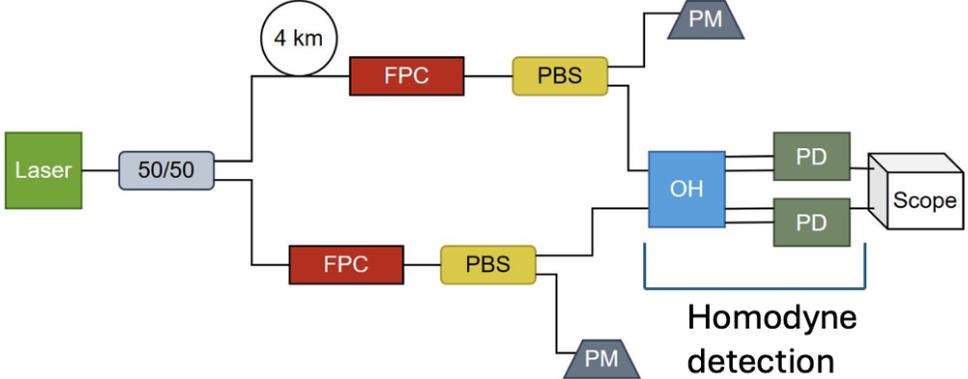
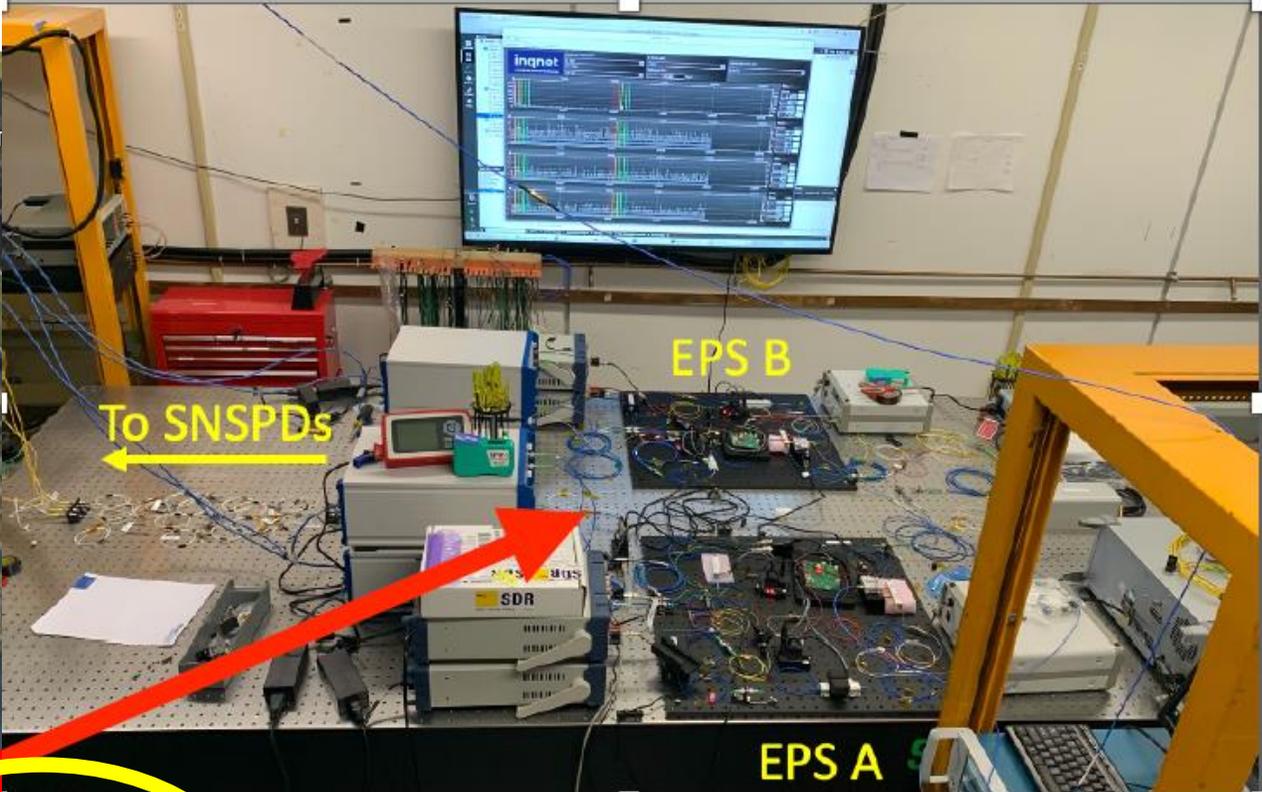
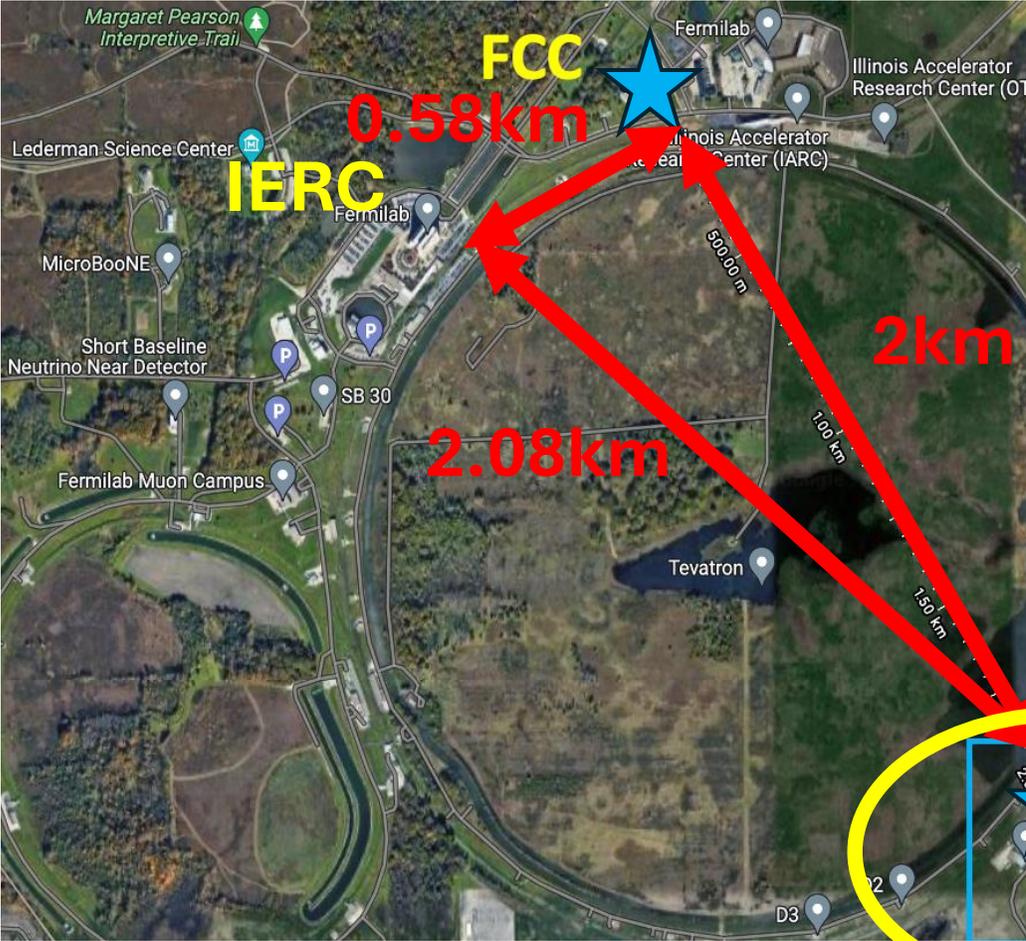
A very exciting emerging field as highlighted by Snowmass White Paper (arxiv:2203.16979) and Quantum Sensor for HEP DOE Workshop Report (arXiv:2311.01930)

# Optical phase stabilization is challenging over long distances

- That's our vision, but we need to work on the technology required for these measurements
- Our group works on each of the experimental challenges
  - Timing resolution of single photon detectors
  - Quantum networking protocol deployment
  - Generation and distribution of entanglement
  - **Phase stability of fiber networks (this talk)**

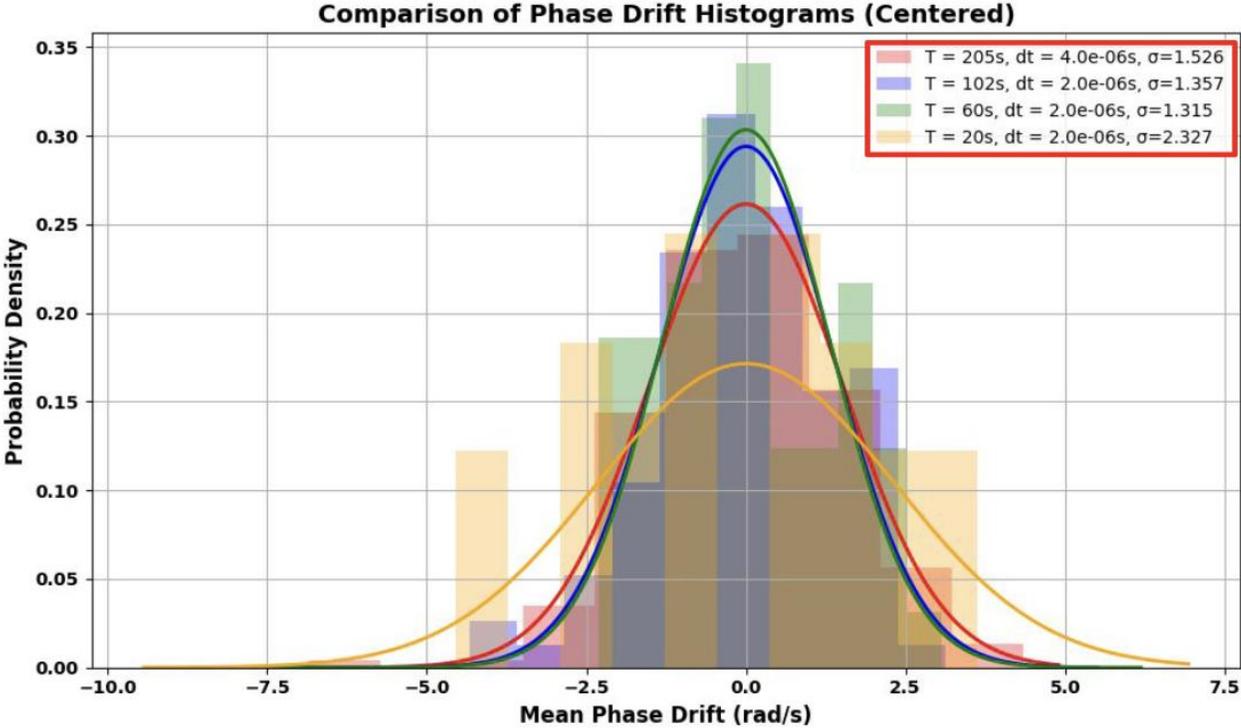
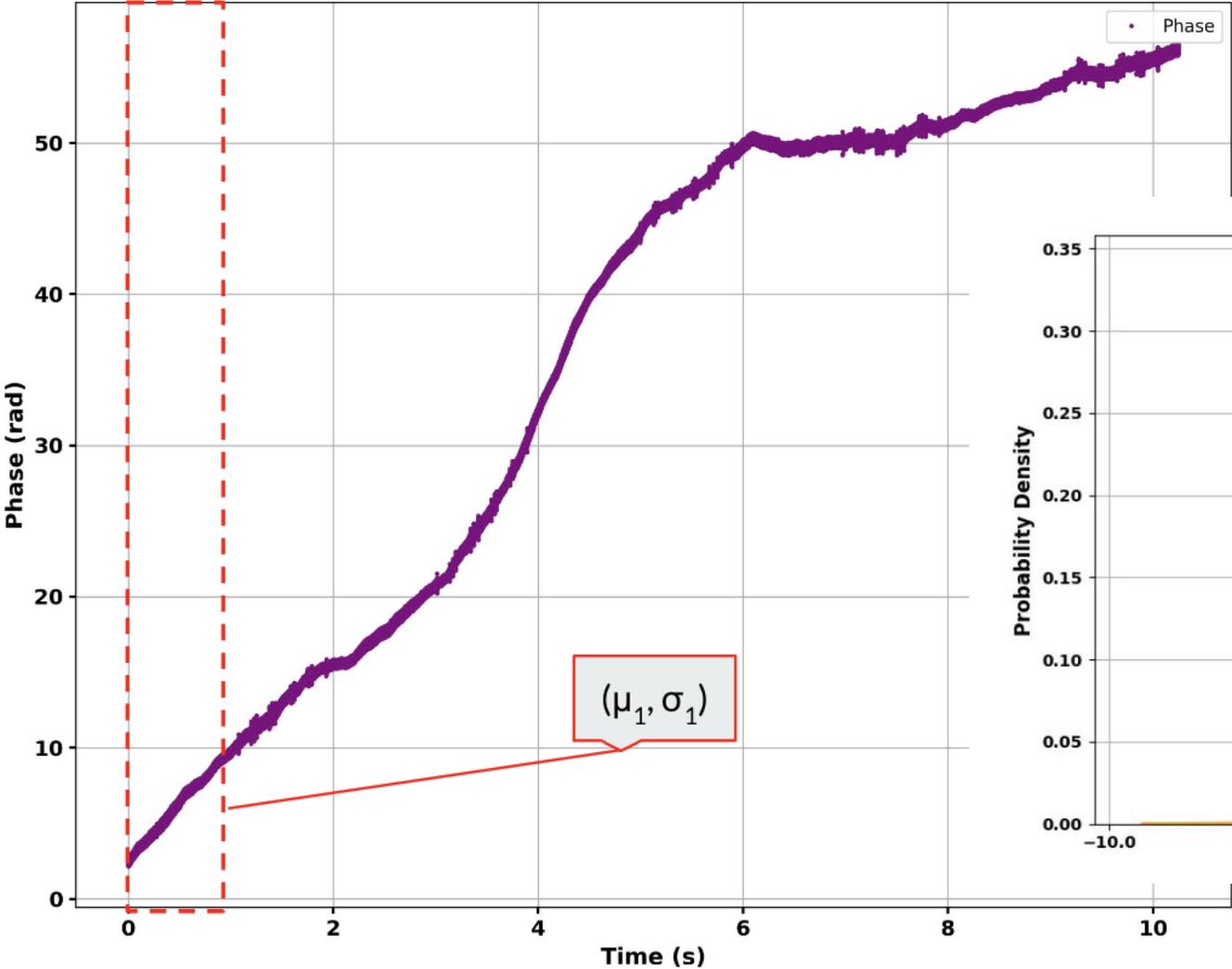


# Phase Stability Testbed



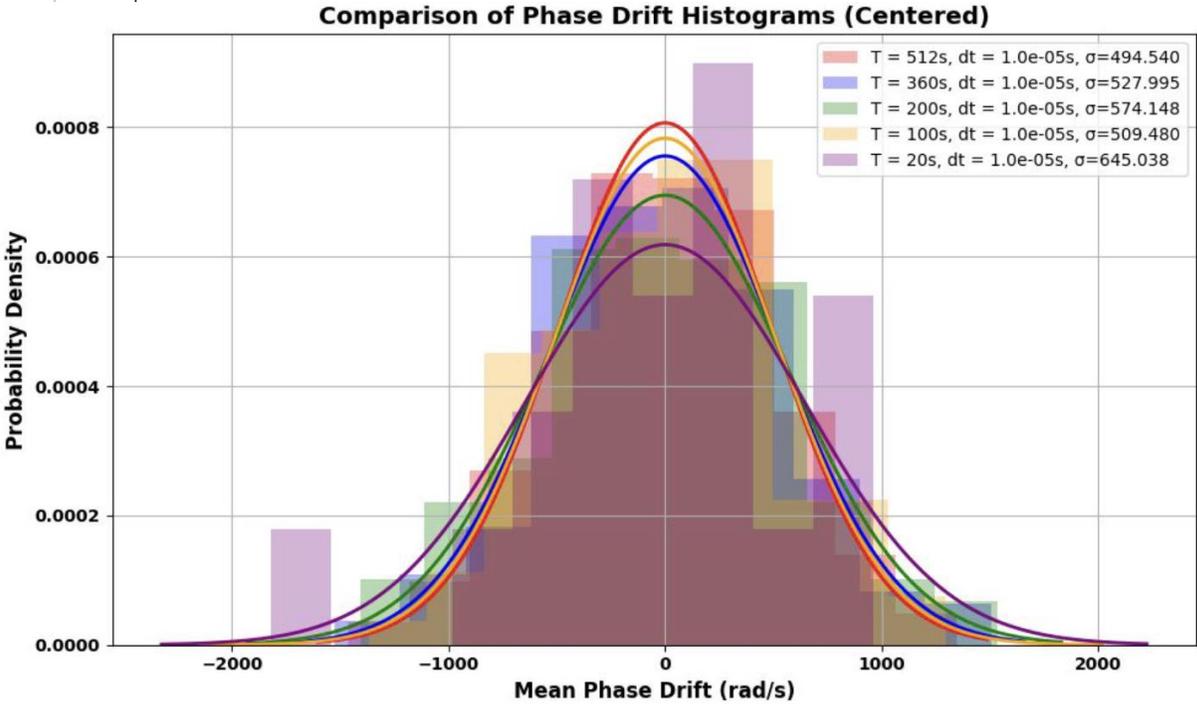
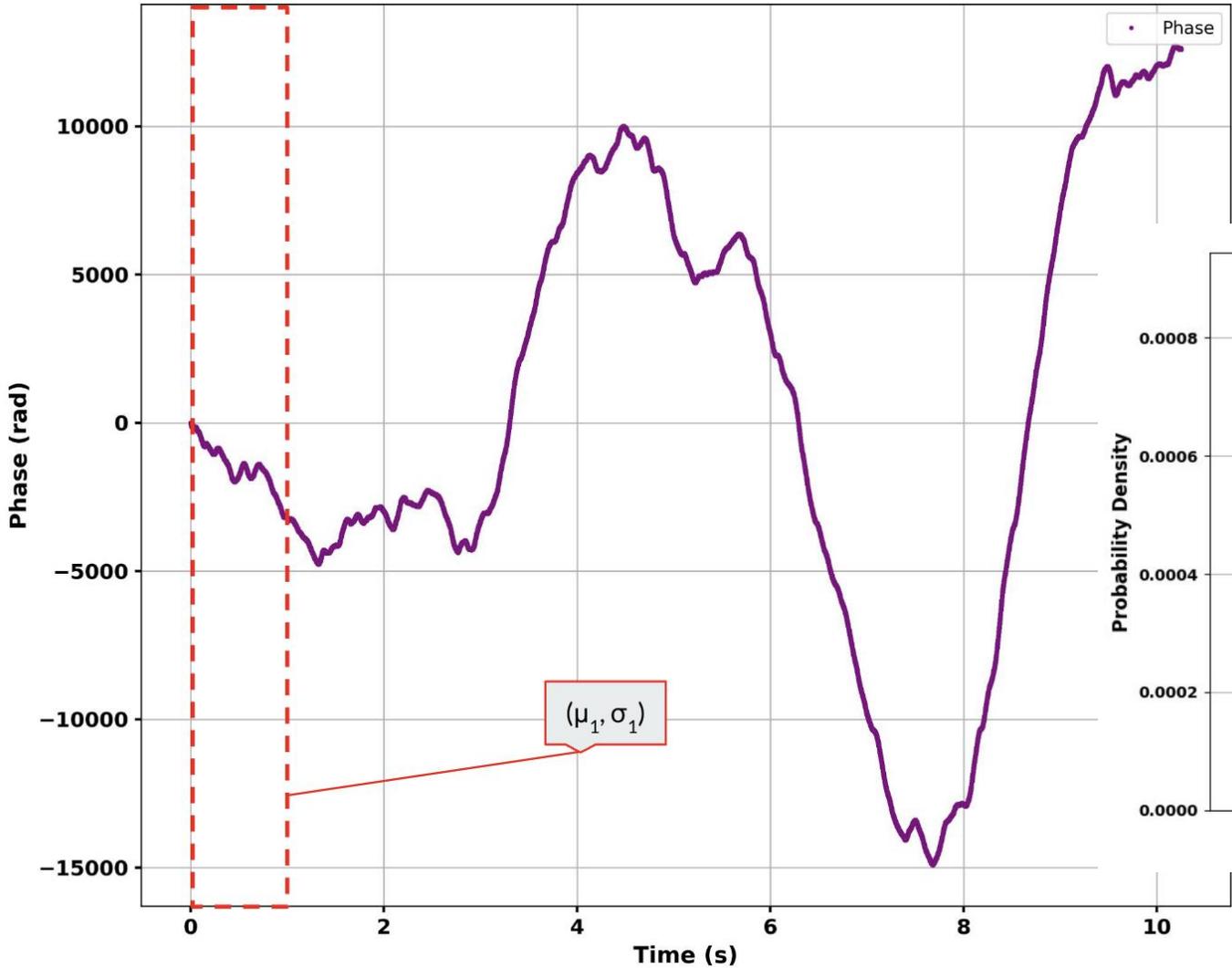
# Stability of interferometer (without 4km link)

Interferometer on optical table has a phase drift of  $\sim 1.3$  rad/s



# Stability of 4km link

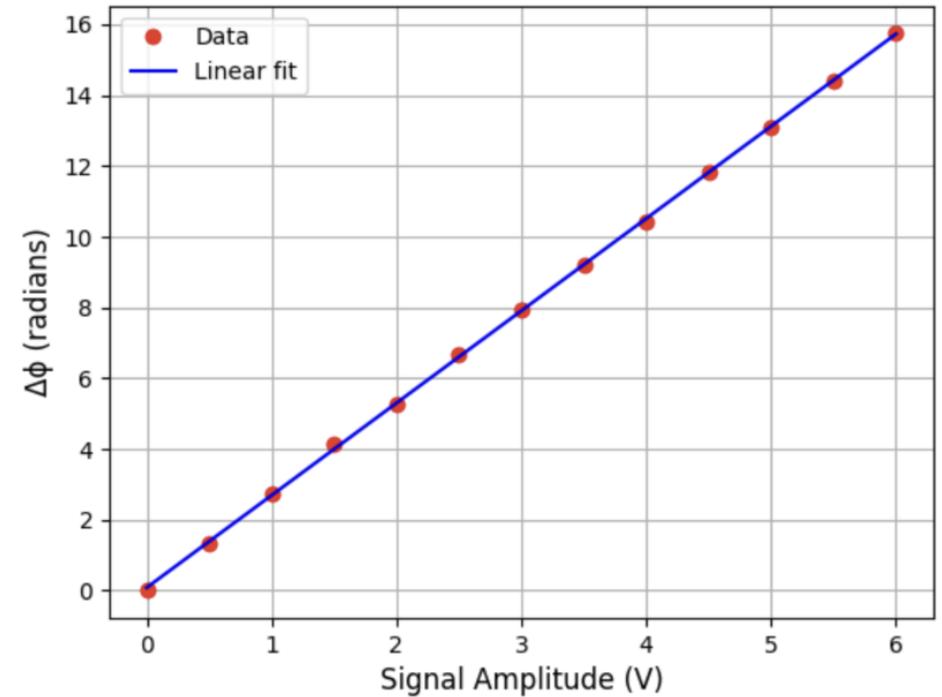
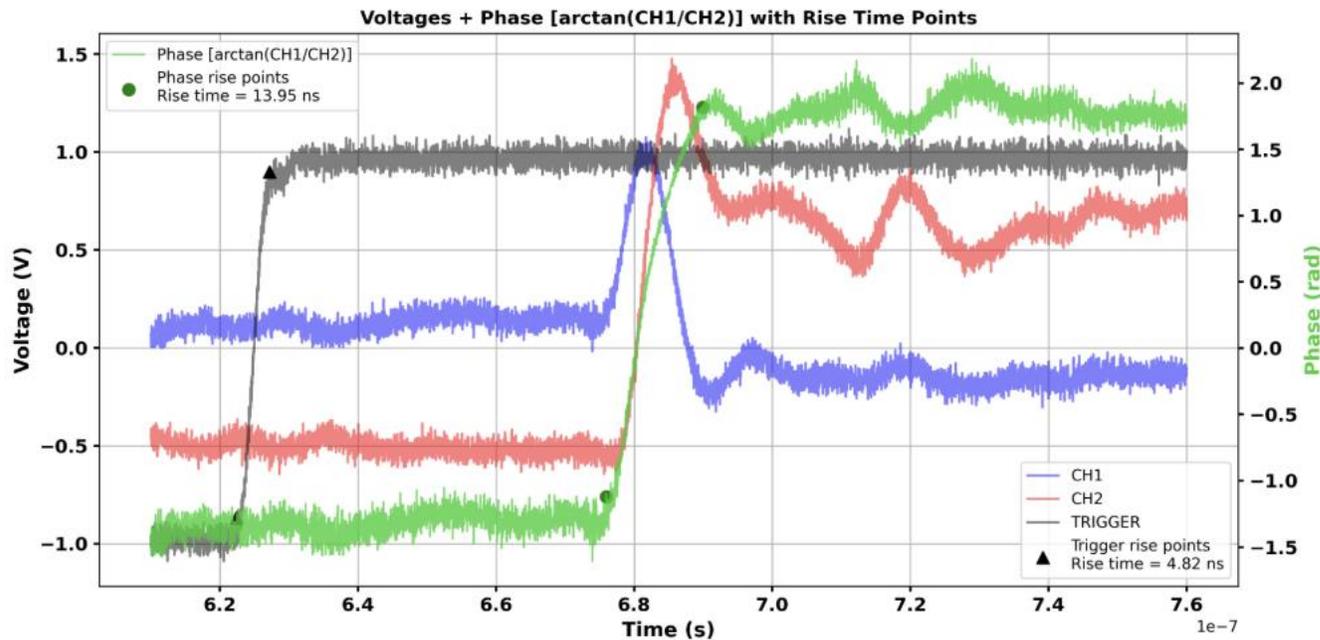
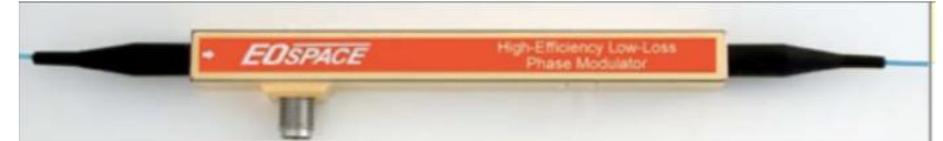
4km fiber link has a phase drift of ~500 rad/s



# Characterization of modulator

- Lithium Niobate Phase modulator will be used to apply fast phase changes that counteract link disturbances

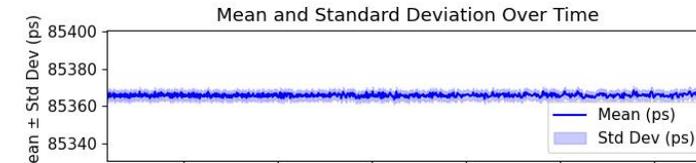
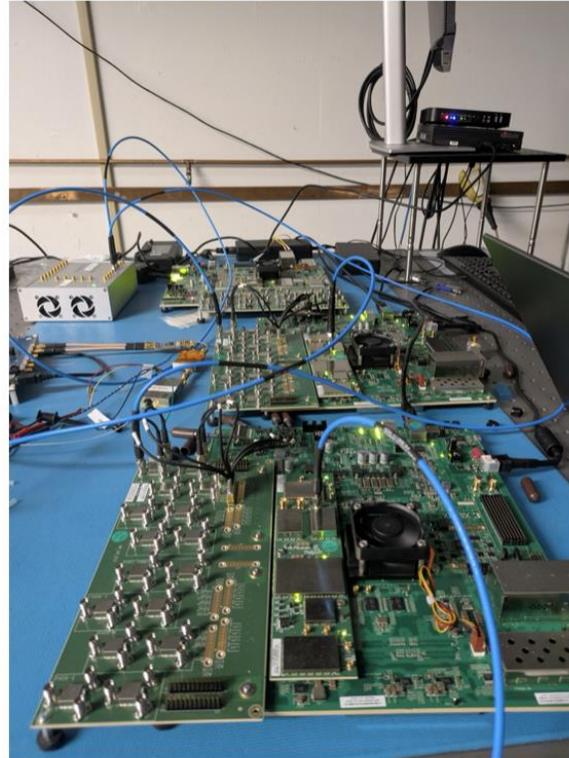
40GHz, low loss



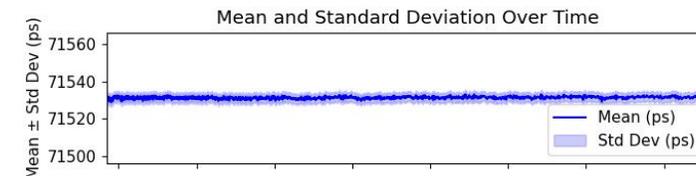
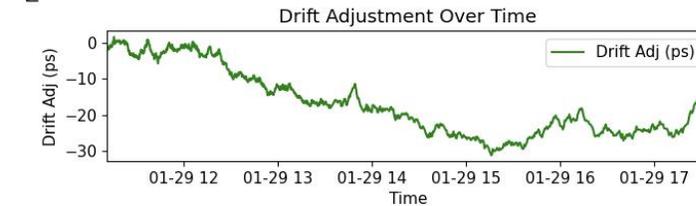
# Looking forward – feedback loop with FPGA

- The Quantum Instrumentation and Control Kit (QICK) team at Fermilab builds FPGAs for quantum information systems.
- Between the board's ADC and DAC, 100ns latency promises fast feedback for phase modulation

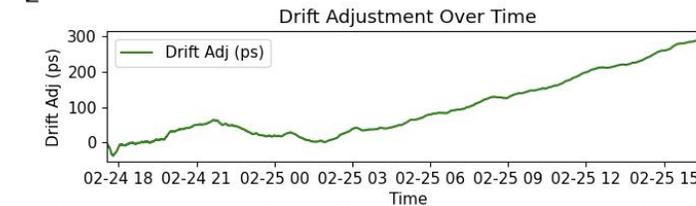
Tested capability for QICK board to synchronize clocks for different devices



Fermilab D0 to  
Fermilab FCC



Fermilab D0 to  
Argonne National  
Lab



Used Optical Delay-line Feedback Control to Maintain few ps level time synchronization

# Conclusion

- Quantum networks have the potential to connect distant quantum sensors to create a wide-area detector for astronomy and high energy physics measurements at optical and NIR wavelengths
- We have demonstrated high precision timing detection and synchronization over long distances connected by telecom fibers
- Our next step is long-distance phase stability:
  - We have measured phase changes in our fiber links ( $\sim 500\text{rad/s}$  over 4km)
  - Characterized phase modulators for active phase compensation
  - In the process of building fast feedback loops.



 **Fermilab**

