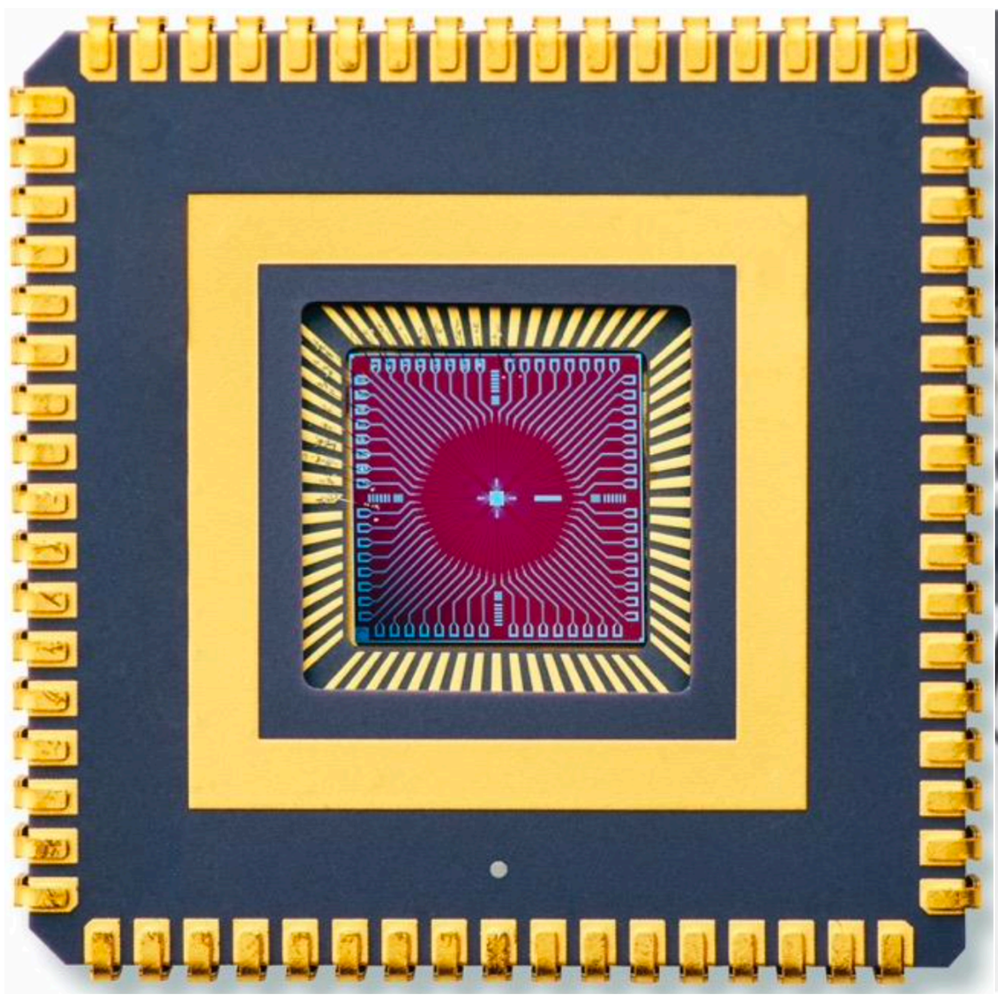
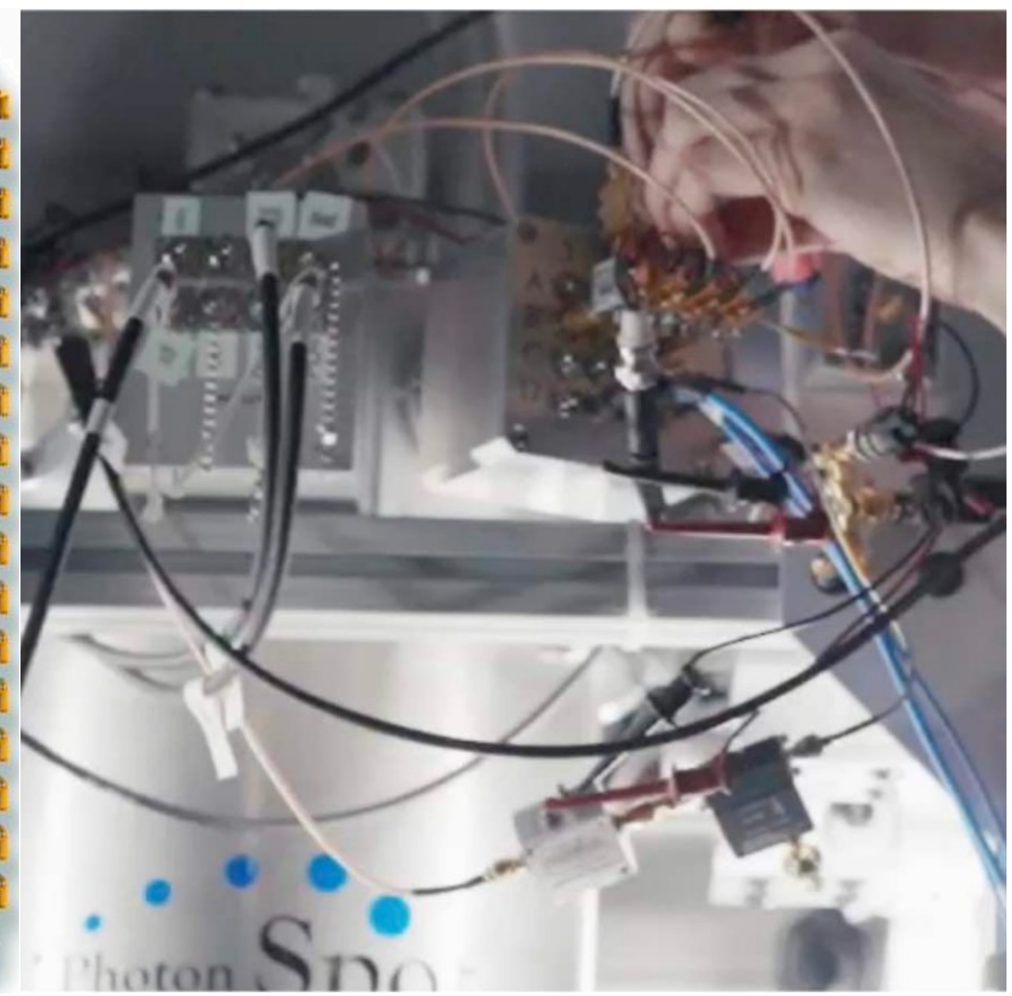
Fermilab Core HEP Competences: from Detectors, to Quantum Networks, to Dark Matter



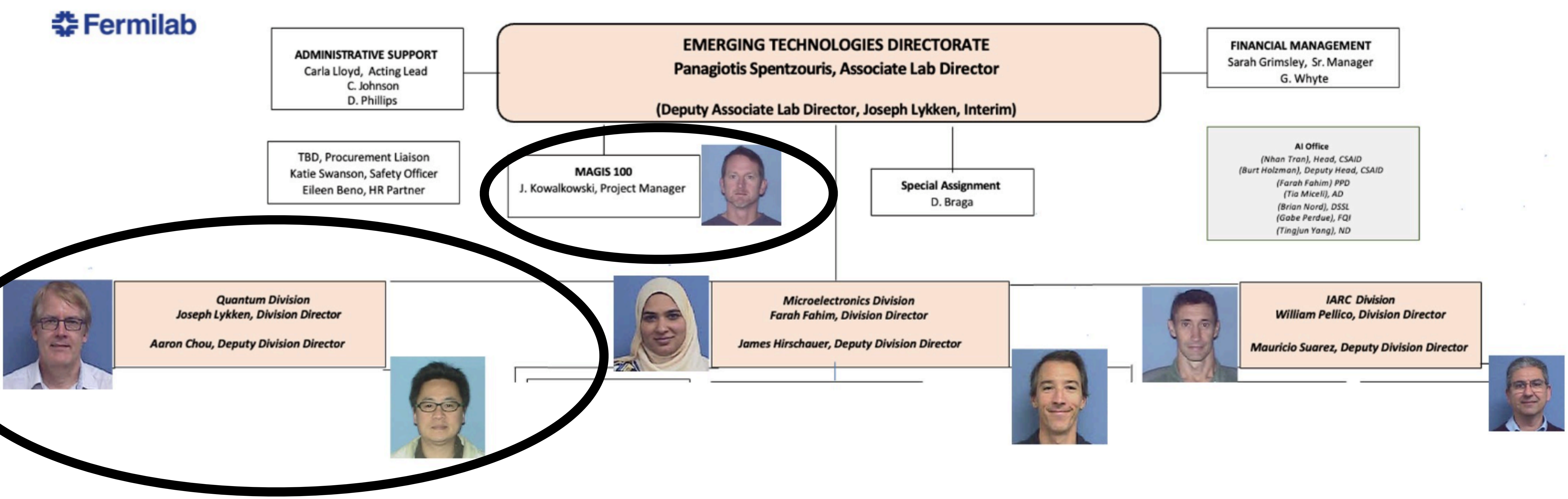


Cristián H. Peña

Fermilab

January 10, 2024

Emerging Technologies Directorate (ETD)

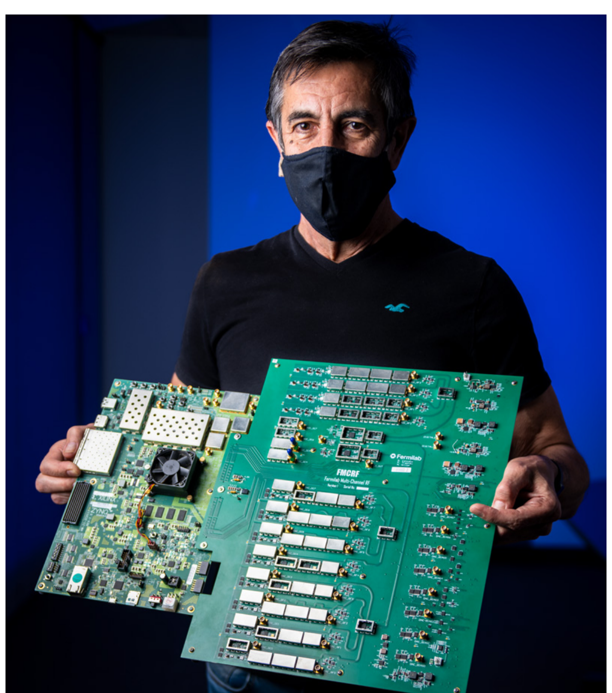
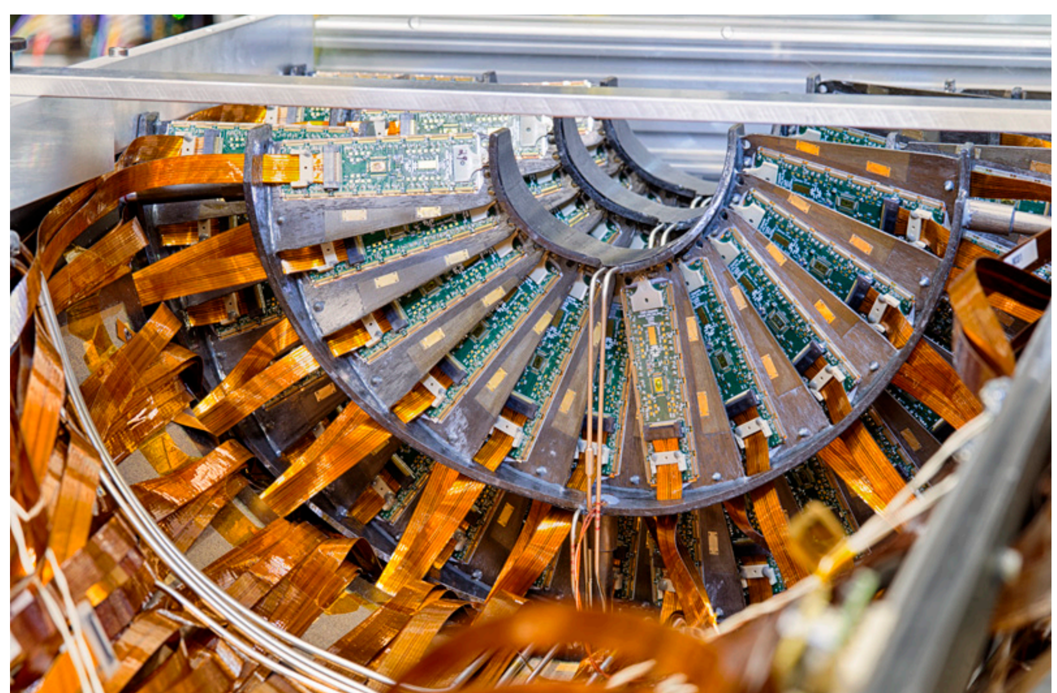
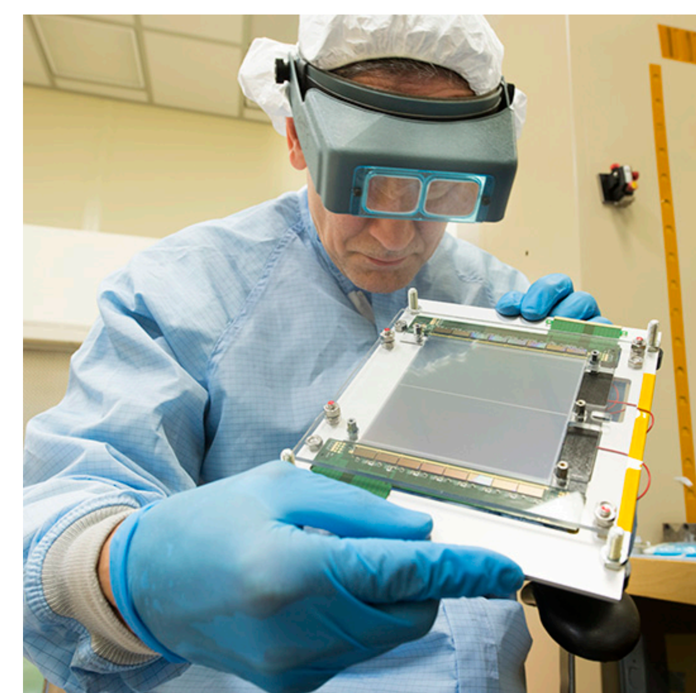


- The Quantum S&T program effort, outside of SQMS scope, resides in the Quantum Division (formerly known as FQI) within the new Emerging Technologies Directorate (ETD), and the Theory Division within the Particle Physics Directorate (PPD). Both ETD and PPD organizations provide effort towards SQMS activities

- The Quantum Division houses the Quantum S&T “base” program, supported by competitive awards from DOE/HEP (QuantISED), DOE/ASCR, and private foundations, as well as Fermilab’s QSC scope

Fermilab Core HEP Competences

- Advancing HEP science requires unprecedented sensitivities which goes beyond conventional HEP approaches
    - Quantum S&T has the potential to deliver such sensitivity
    - System engineering, detectors, electronics, fast timing, controls, etc.

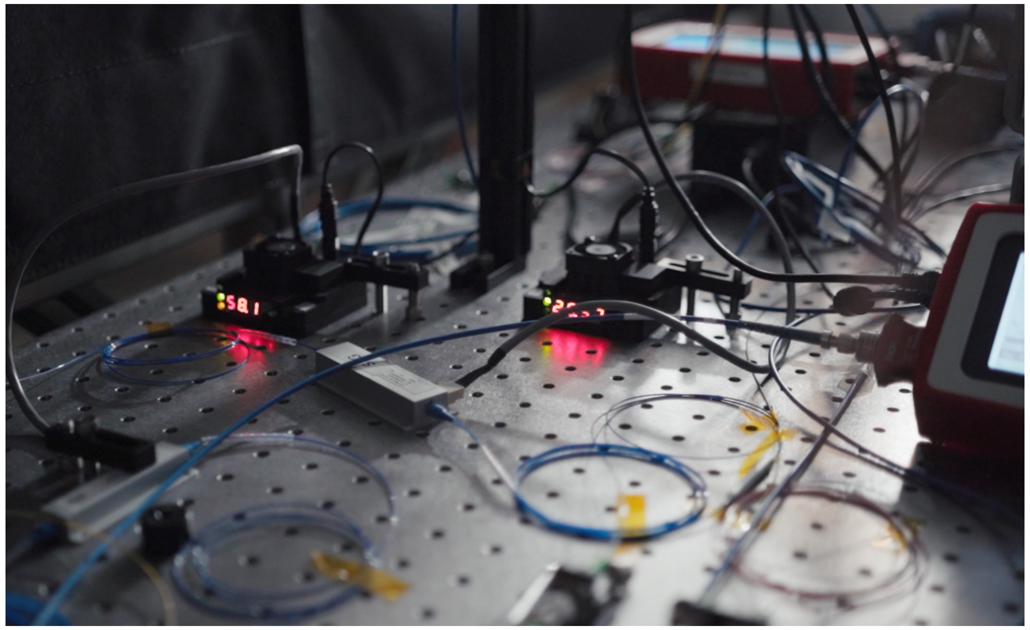
Fermilab Core HEP Competences

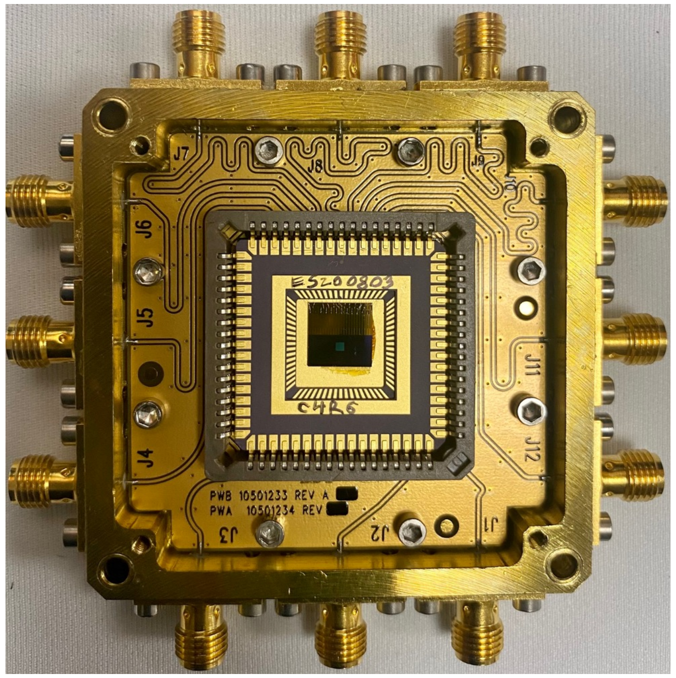
- In addition our research might enable applications beyond HEP & new sensor capabilities

- Overarching goal is to realize distributed quantum sensors

  - When realized quantum networks (QNETs) will enable impactful applications outside HEP

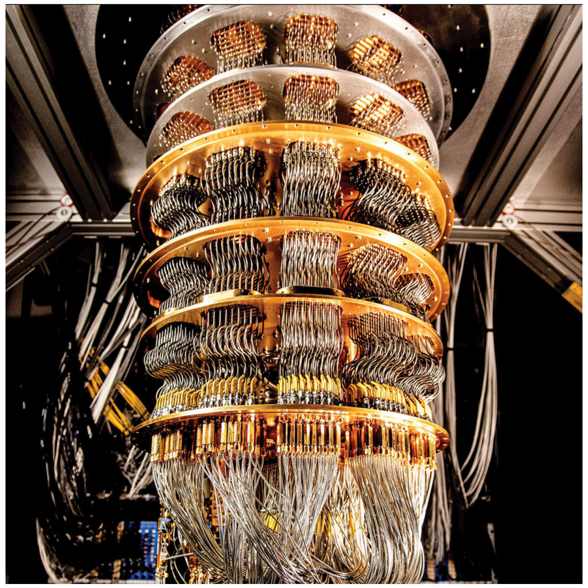
  - SNSPD (QNETs sensor) is a powerful tools for discovery

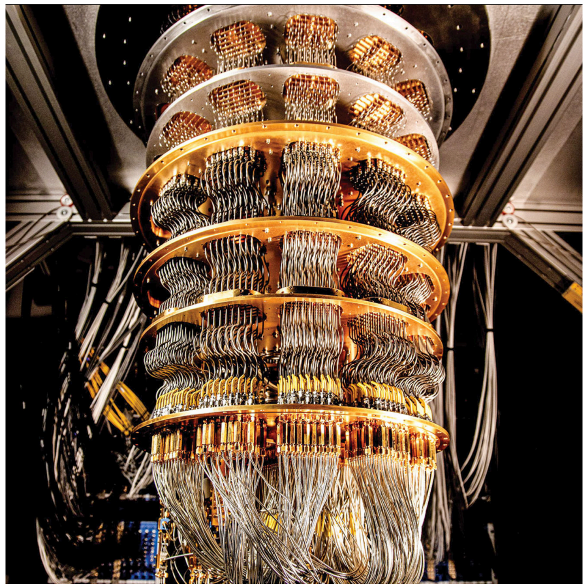




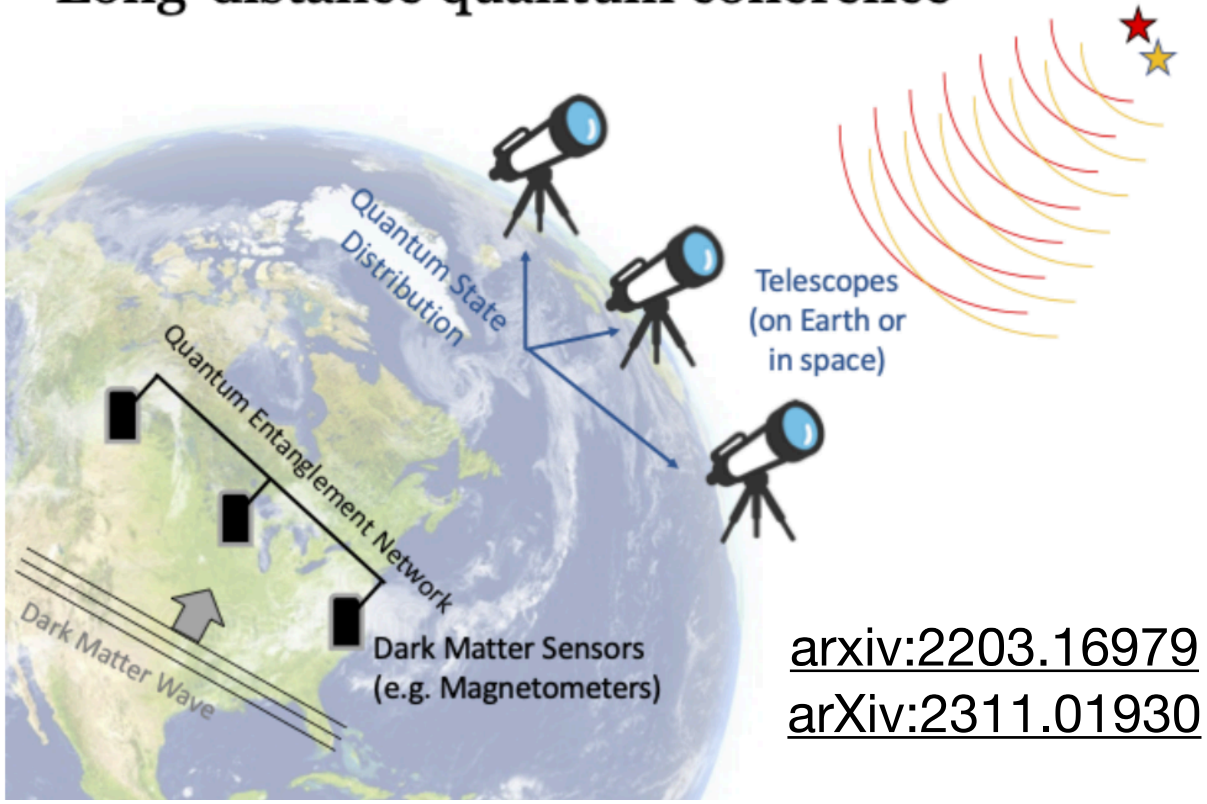
Quantum Internet Vision

Quantum Computer Networking





Long-distance quantum coherence

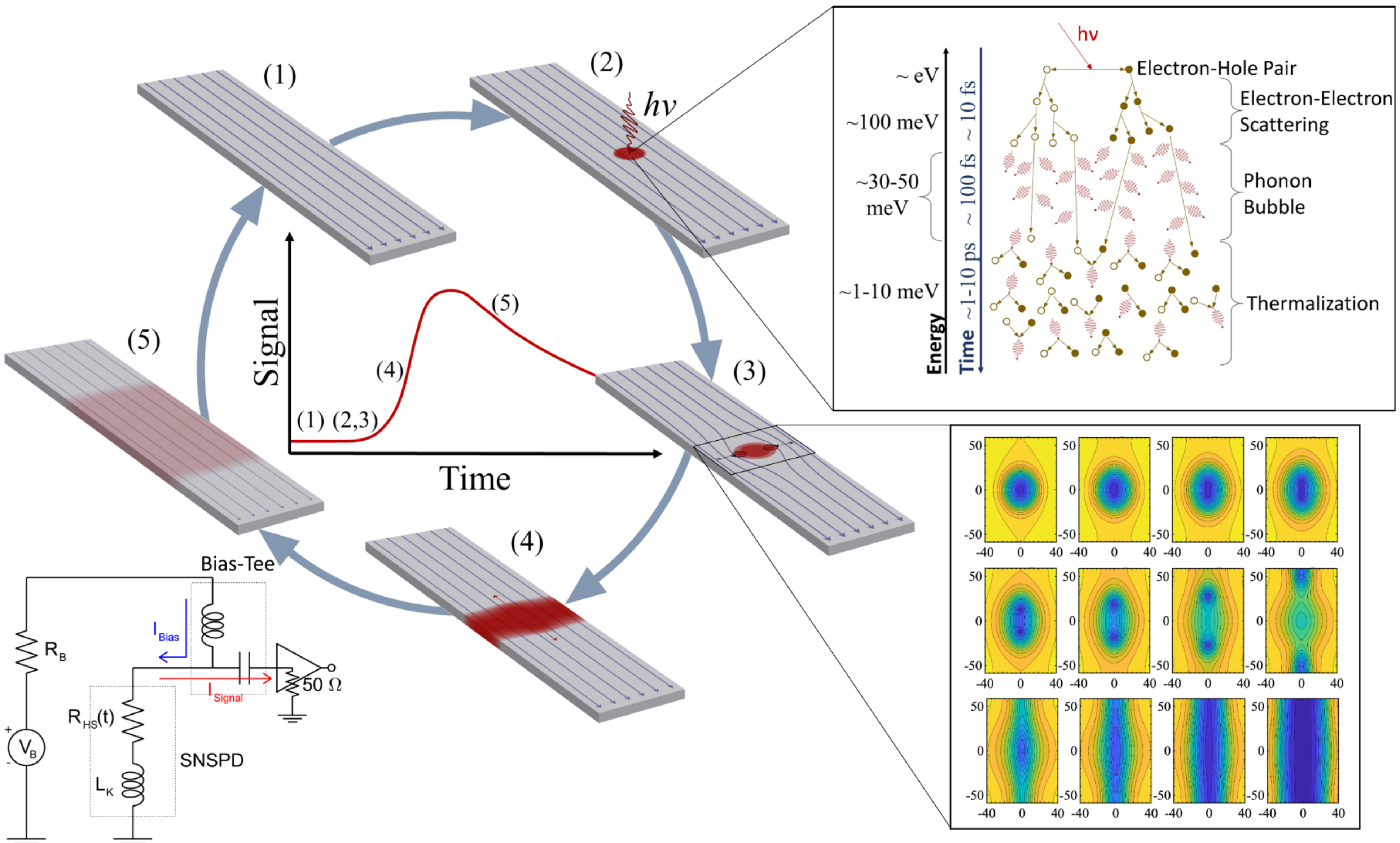


arxiv:2203.16979
arXiv:2311.01930

Quantum-enhanced security

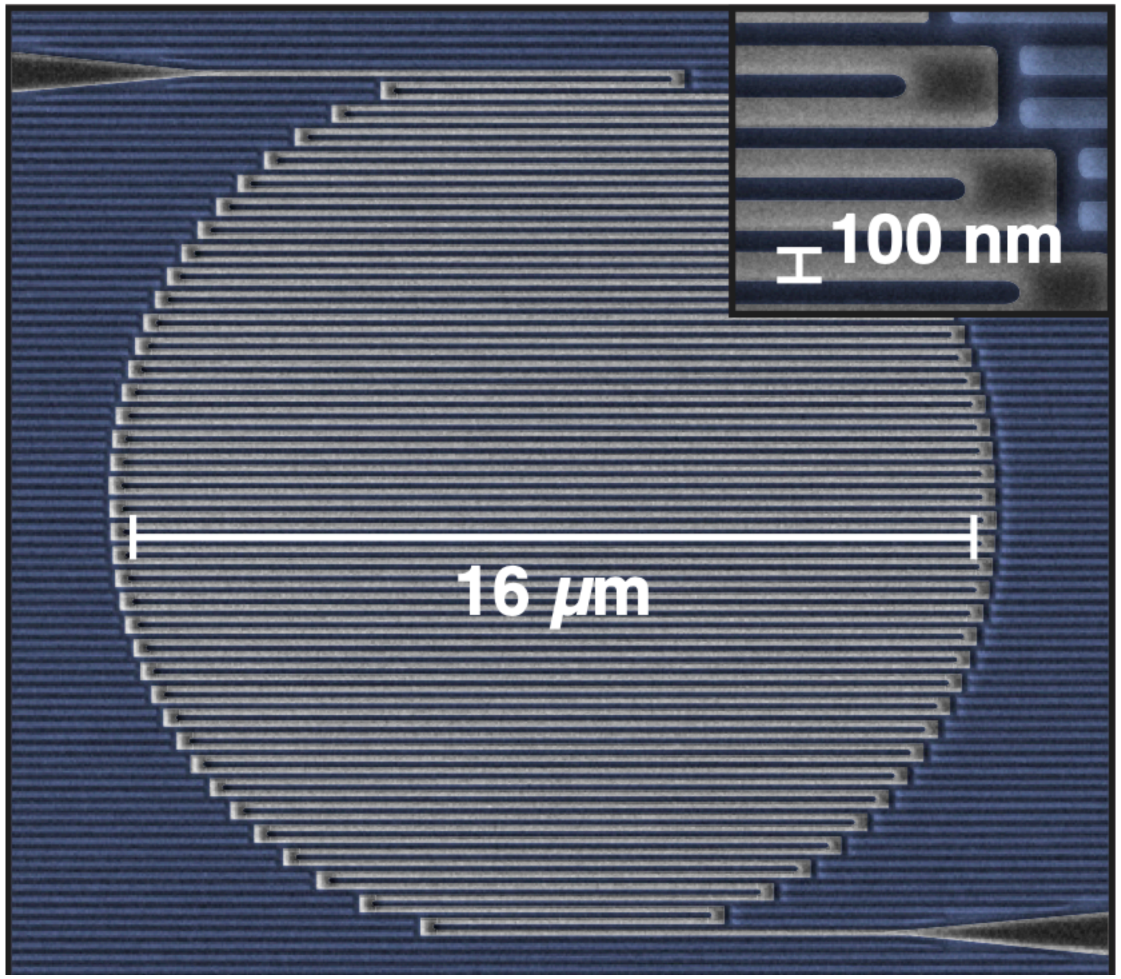
Quantum Sensors (SNSPD)

- Single photon (heat) triggers detector out of superconductor state
- Resistance quickly (ps) jumps to few kΩ → detector current into readout
- Highest performance single-photon detector, from UV to mid-infrared
- Operating temperature : 1-4 Kelvin



more on quantum sensors in A. Chou's presentation

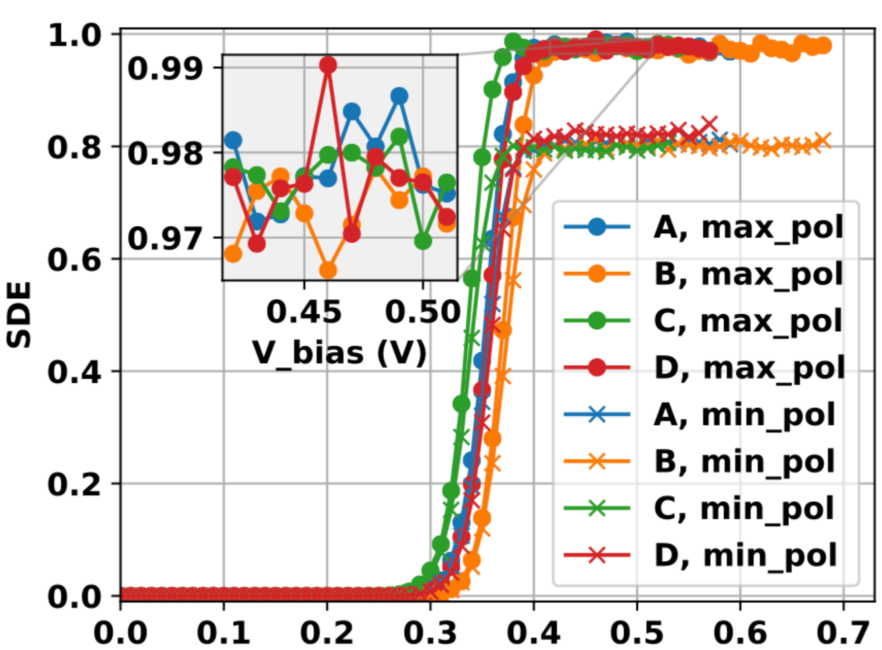
Quantum Communication Enabler: SNSPDs



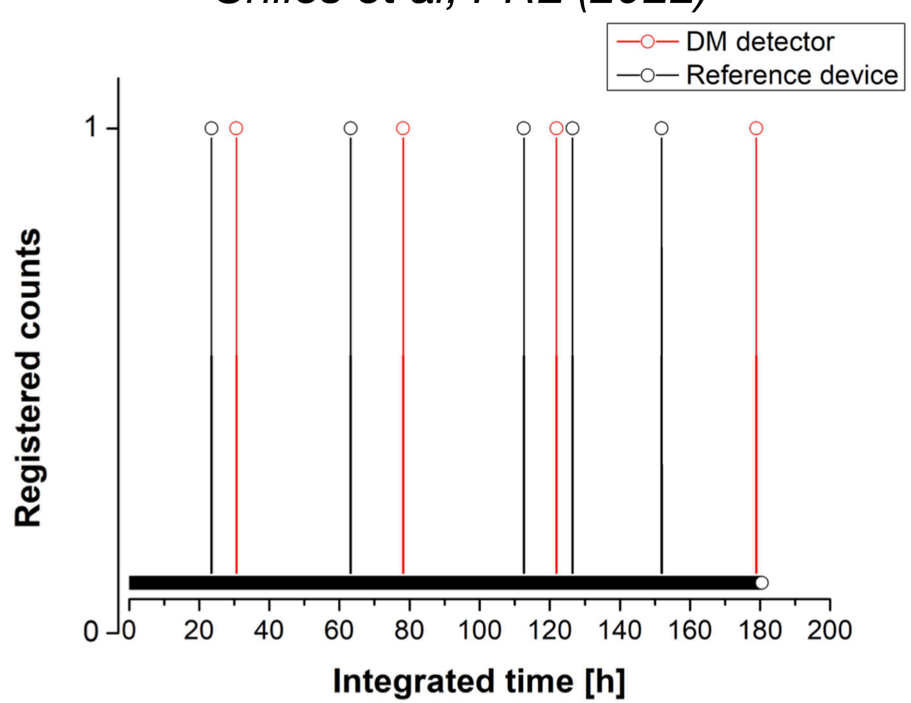
SNSPD Has Achieved:

- **> 90% system efficiency** ✓
- Low **dark count** rate **1e-5Hz** ✓
- Record **time resolution ~3ps** ✓

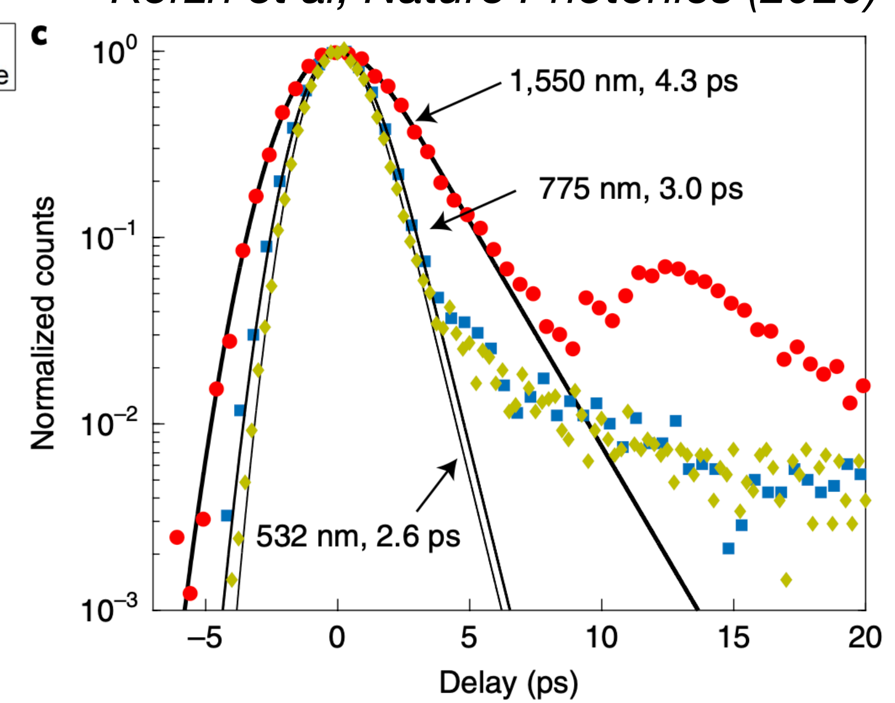
Reddy et al, Optica (2018)



Chiles et al, PRL (2022)



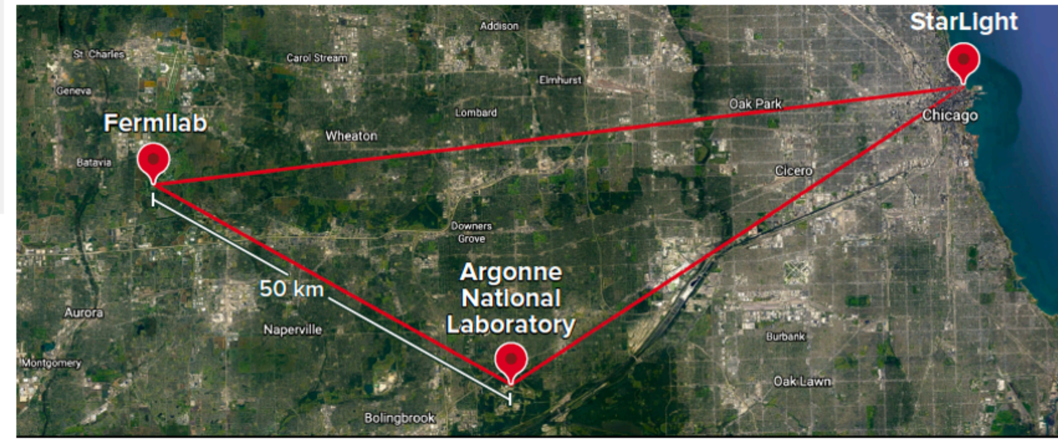
Korzh et al, Nature Photonics (2020)



Quantum Networks Overview

Quantum Networks: towards a Quantum Internet

Current focus: deploy a **multi-node, multi-user metropolitan scale quantum network** in the greater Chicago area.



Leveraging Fermilab competencies in precision timing, controls, network architecture, and systems integration

The FQNET/CQNET collaboration

The IEQNET collaboration

Fermilab

Argonne National Laboratory

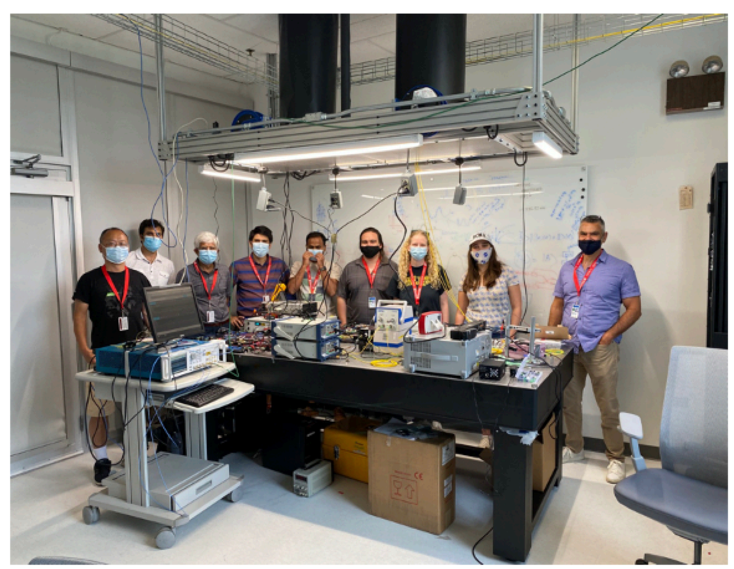
Caltech

Northwestern University

HYPERLIGHT

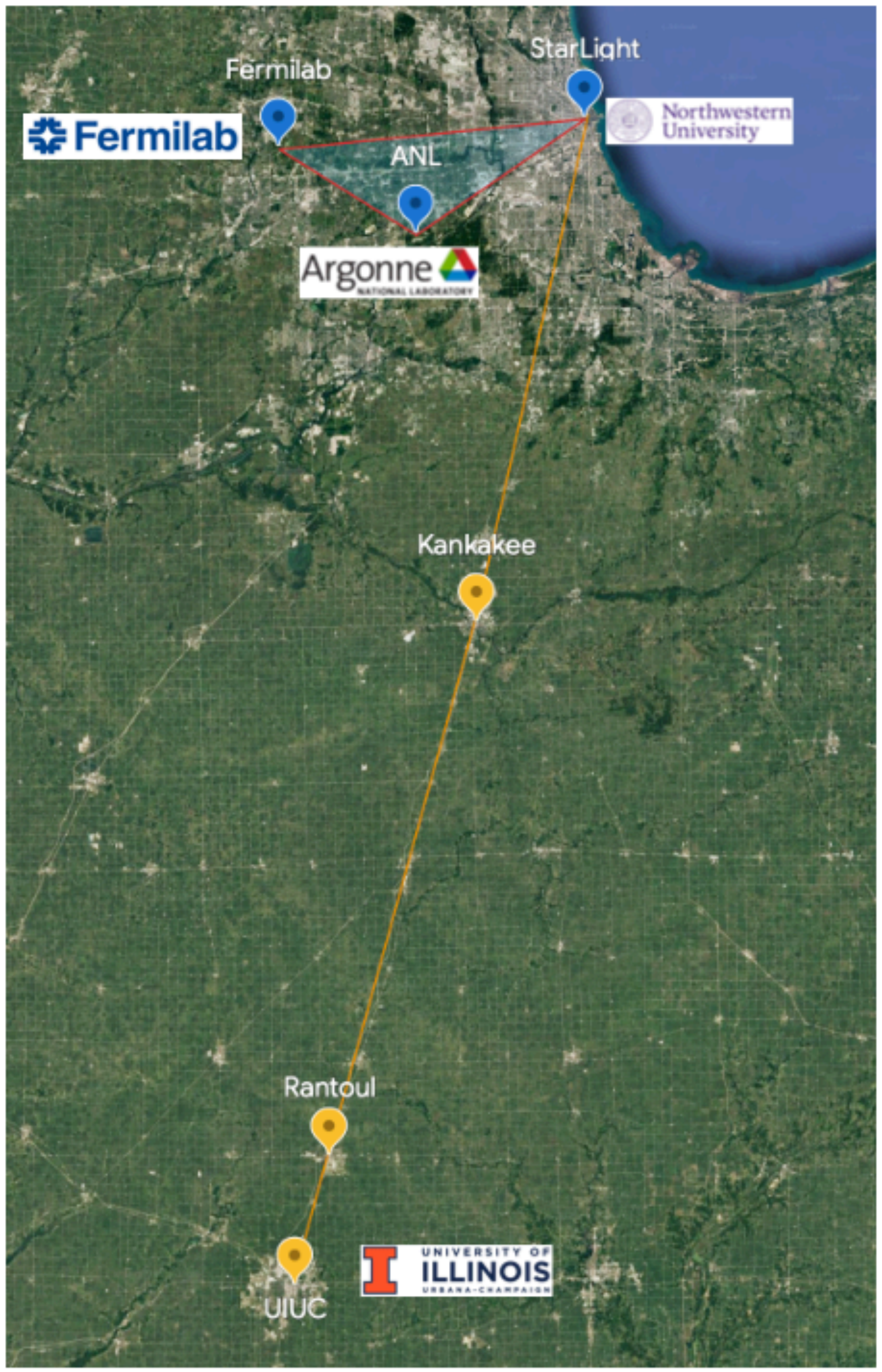
NuCrypt

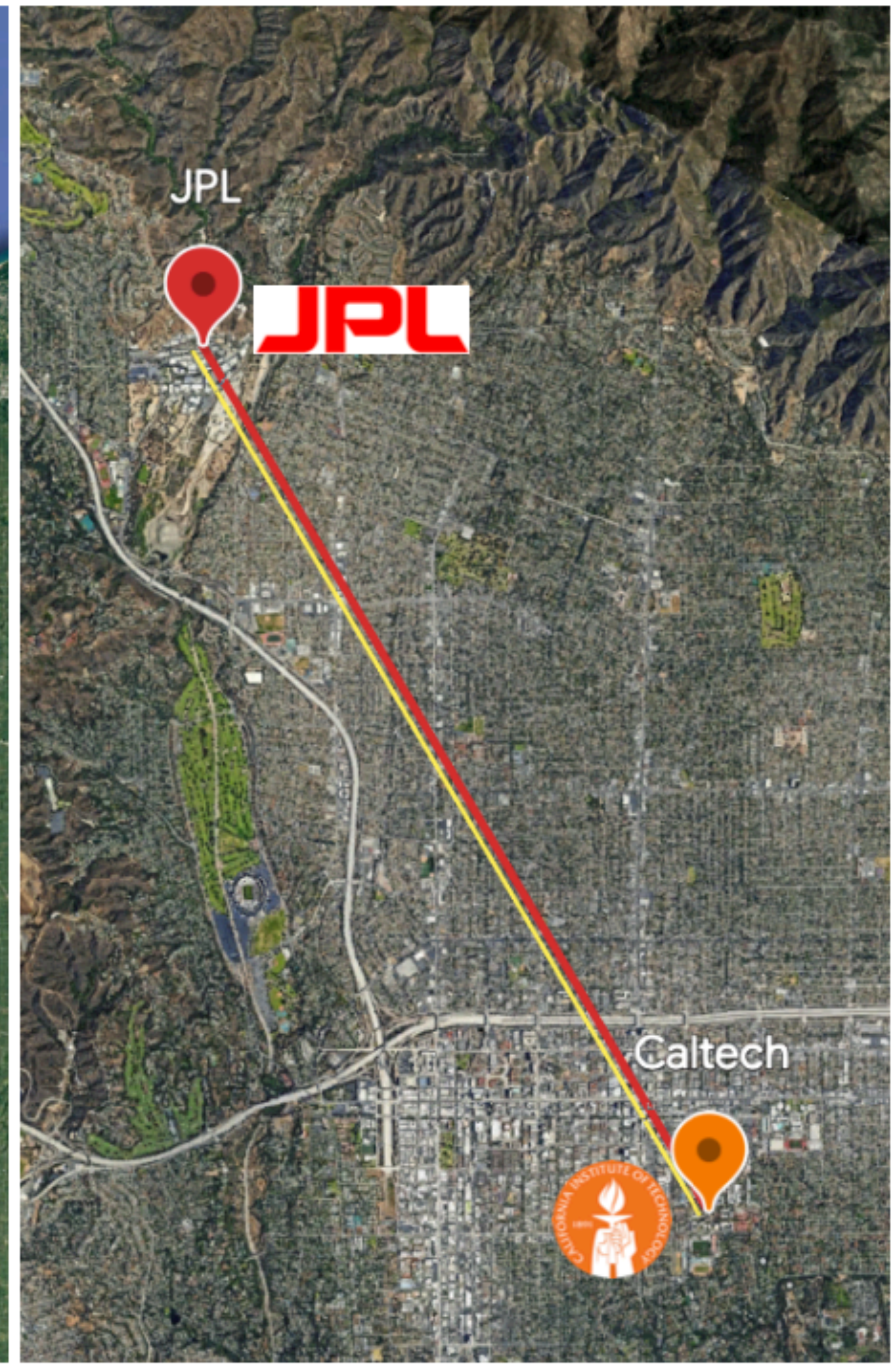
Long-term vision: enable security, sensor, and computing applications, following the **DOE Quantum Internet Blueprint**



Next Quantum Network Initiative

New DOE Project: Advanced Quantum Networks (A-QNET)





More Nodes; Longer distances; Higher Rates; Hybrid free-space to fiber

Large Collaborative Effort

Andrew Cameron
Fermilab quantum optics
Postdoctoral scholar

Maria Spiropulu
FQNET Co-Spokesperson
FQNET PI
CALTECH

Cristián Peña
Fermilab
AQNET PI

Eric Chitambar
UIUC
A-QNET co-PI

Panagiotis Spentzouris
Emerging Technologies Head
IEQNET PI

Leandro Stefanazzi
Fermilab senior electrical
engineer

Raju Valivarthi
INQNET Postdoctoral Scholar
CALTECH

Matt Shaw
Microdevices Engineer
JET PROPULSION LABORATORY

Silvia Zorzetti
Fermilab Senior Engineer
AQNET co-PI

Gustavo Cancelo
Fermilab senior electrical
engineer

Prem Kumar
Northwestern University
AQNET & IEQNET co-PI

Boris Korzh
Microdevices Engineer
JET PROPULSION LABORATORY

Rajkumar Kettimuthu
ANL
IEQNET co-PI

Si Xie
Physics and Technical Coordinator
CALTECH

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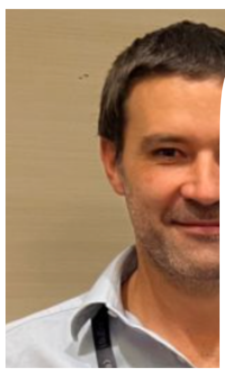
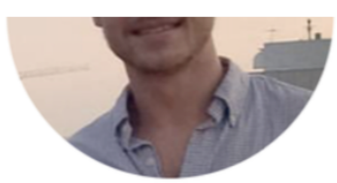


Leandro Stef
Fermilab senior
enginee

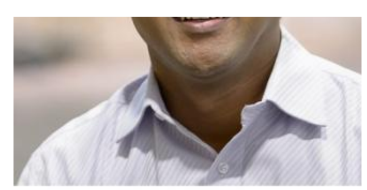
More than 30 active members: students (grad&undergrad), postdocs, engineers

iustavo Cancelo
nilab senior electrical
engineer

Prem Kumar
Northwestern University
AQNET & IEQNET co-PI



Boris Korzh
Microdevices Engineer
JET PROPULSION LABORATORY

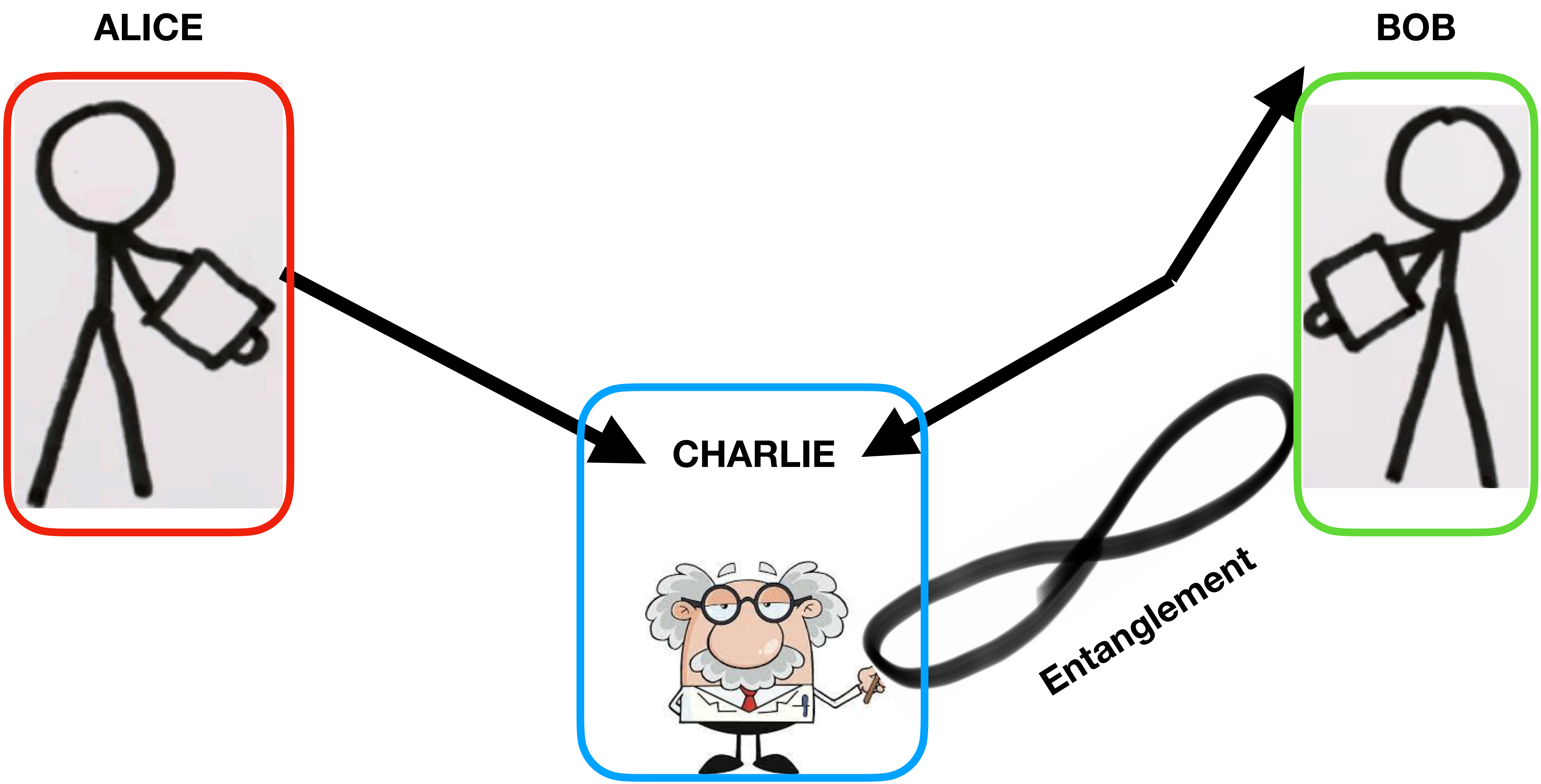


Rajkumar Kettimuthu
ANL
IEQNET co-PI

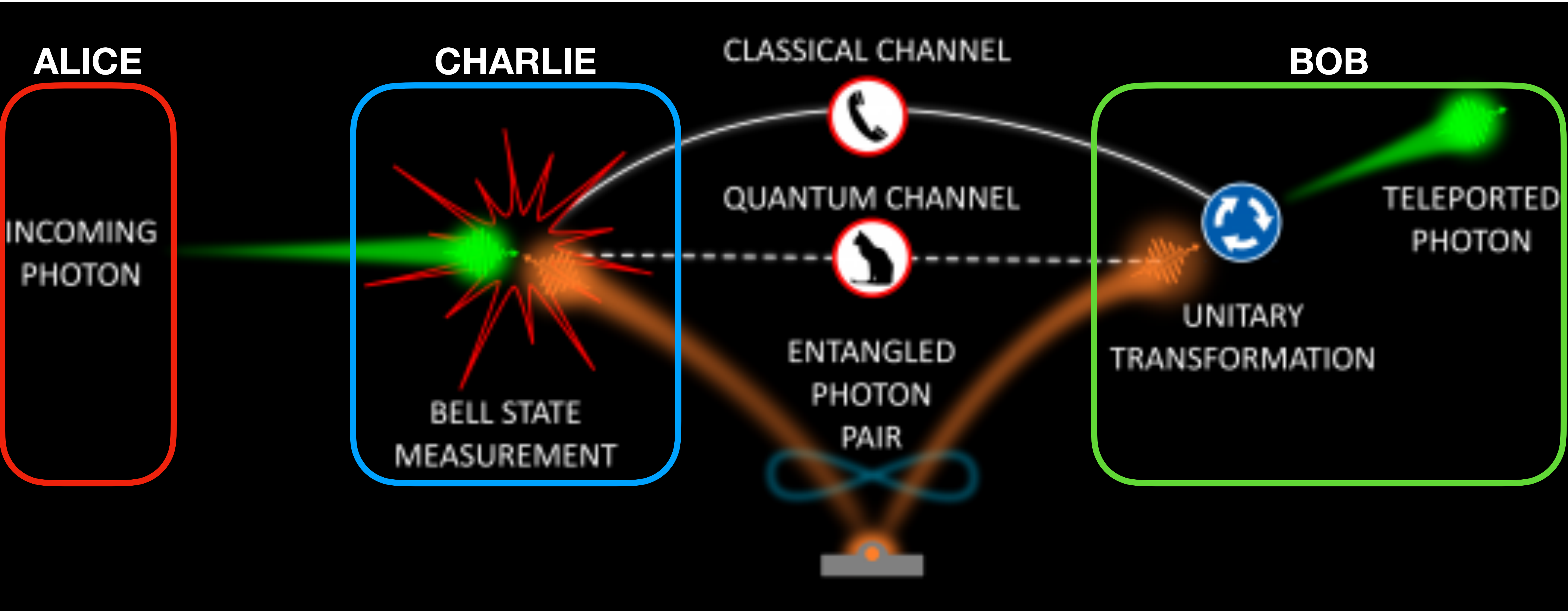
Si Xie
Physics and Technical Coordinator
CALTECH

Paul Kwiat
UIUC
AQNET co-PI

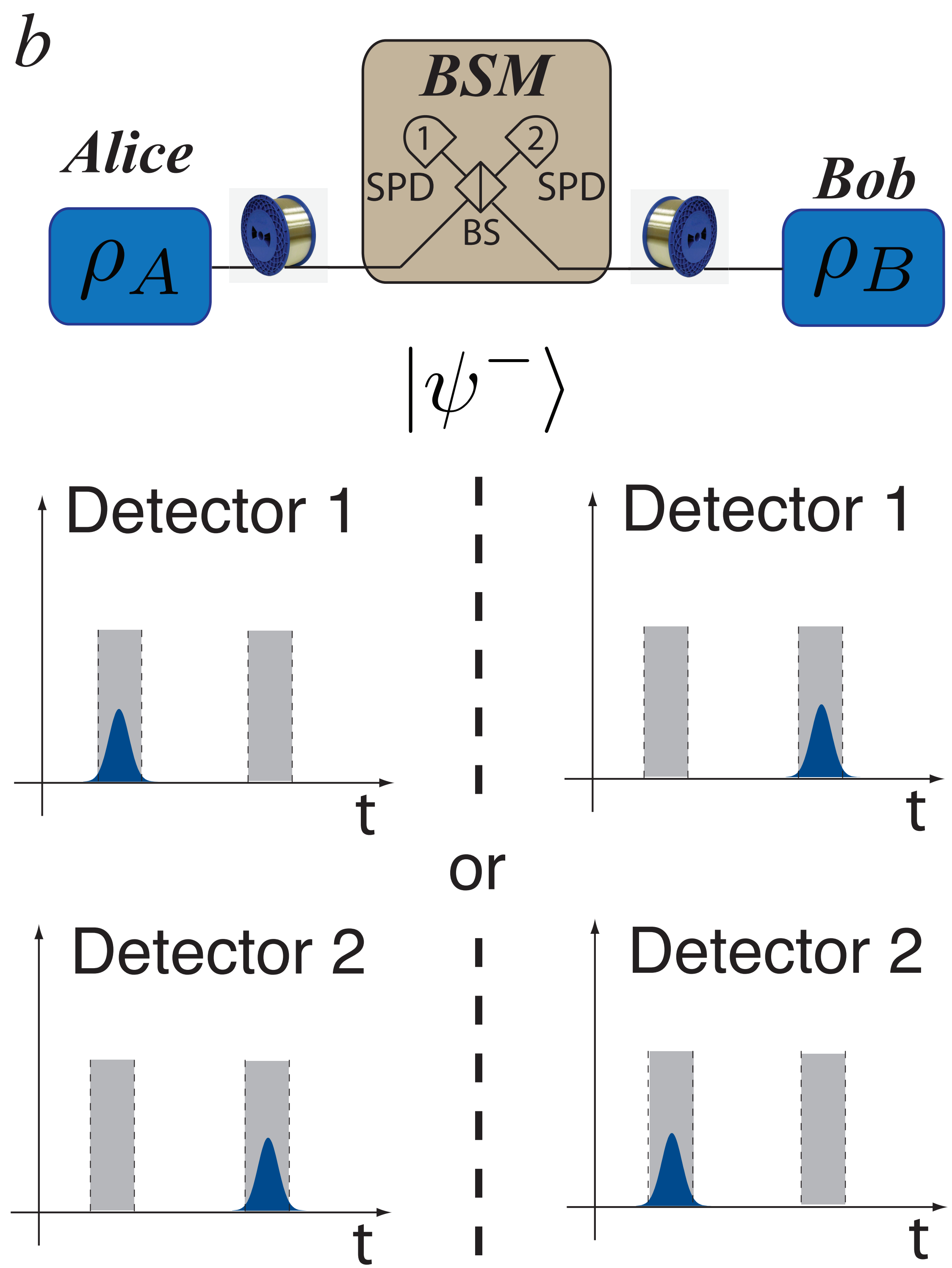
Entanglement-enabled Communication



Entanglement enabled Communication



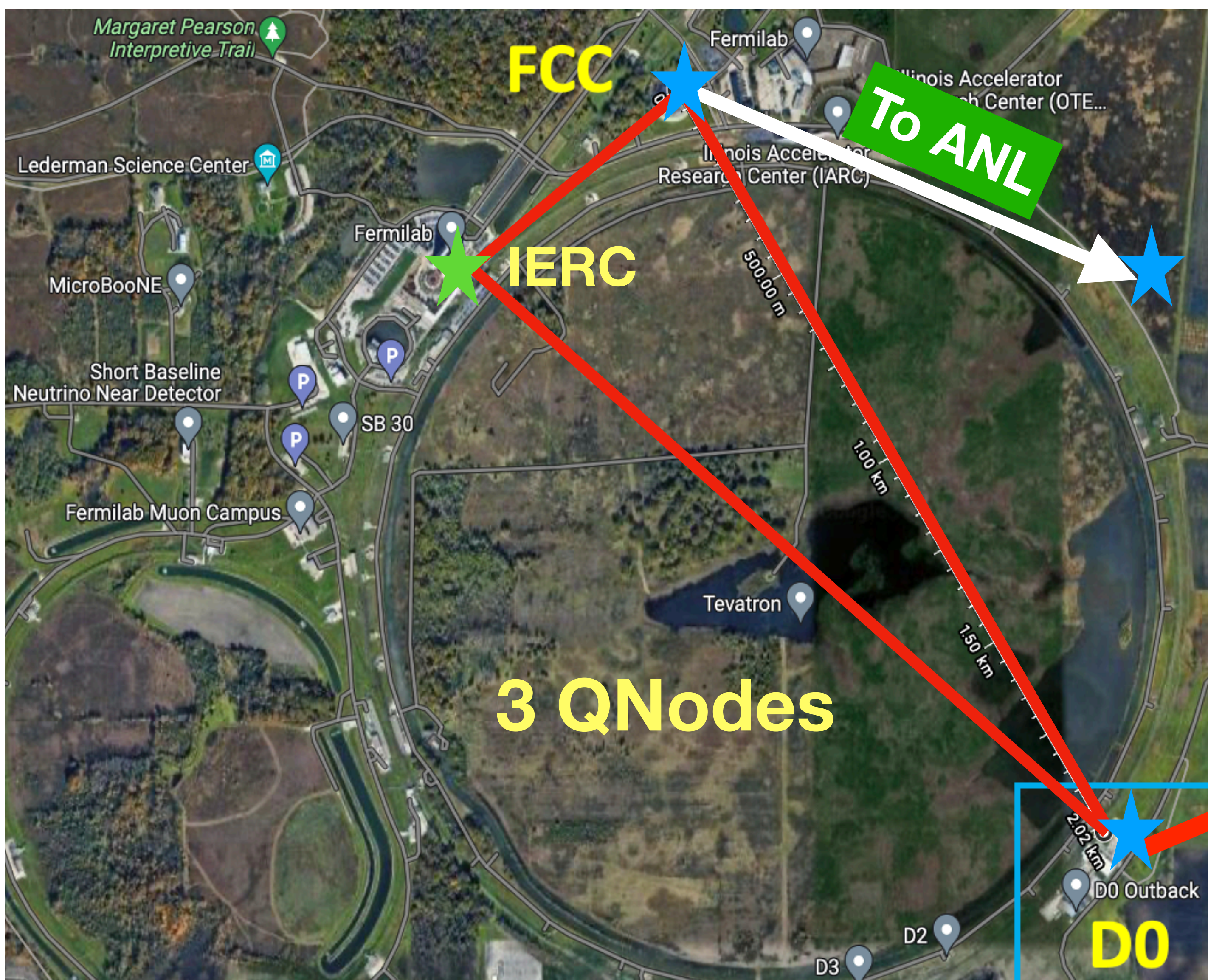
Time-bin Qubit System



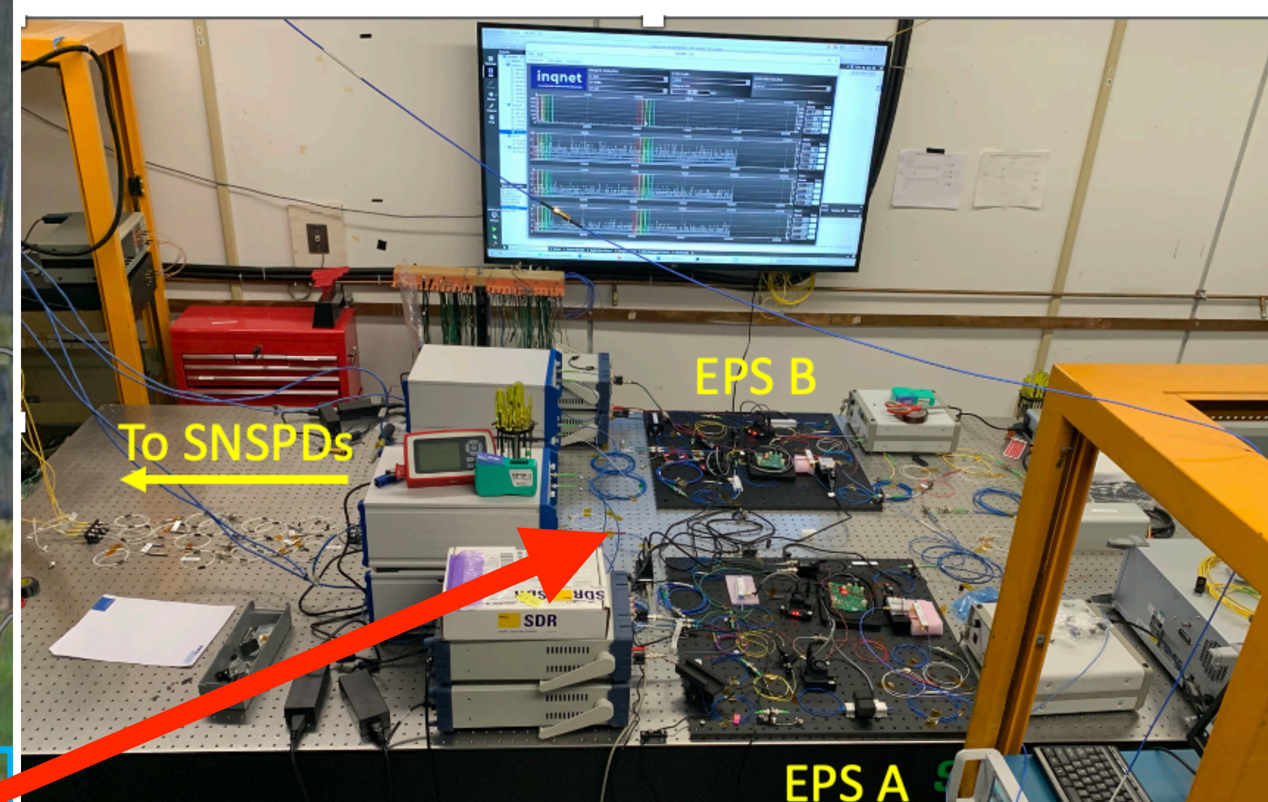
Challenge: Increase detector efficiency with negligible dark count rate and excellent time resolution

Fermilab Quantum Network (FQNET)

- Multiple deployed QNodes at Fermilab (D0, FCC, IERC*) and at ANL
- Demonstrated **Quantum Teleportation and Swapping** with **record high fidelities**



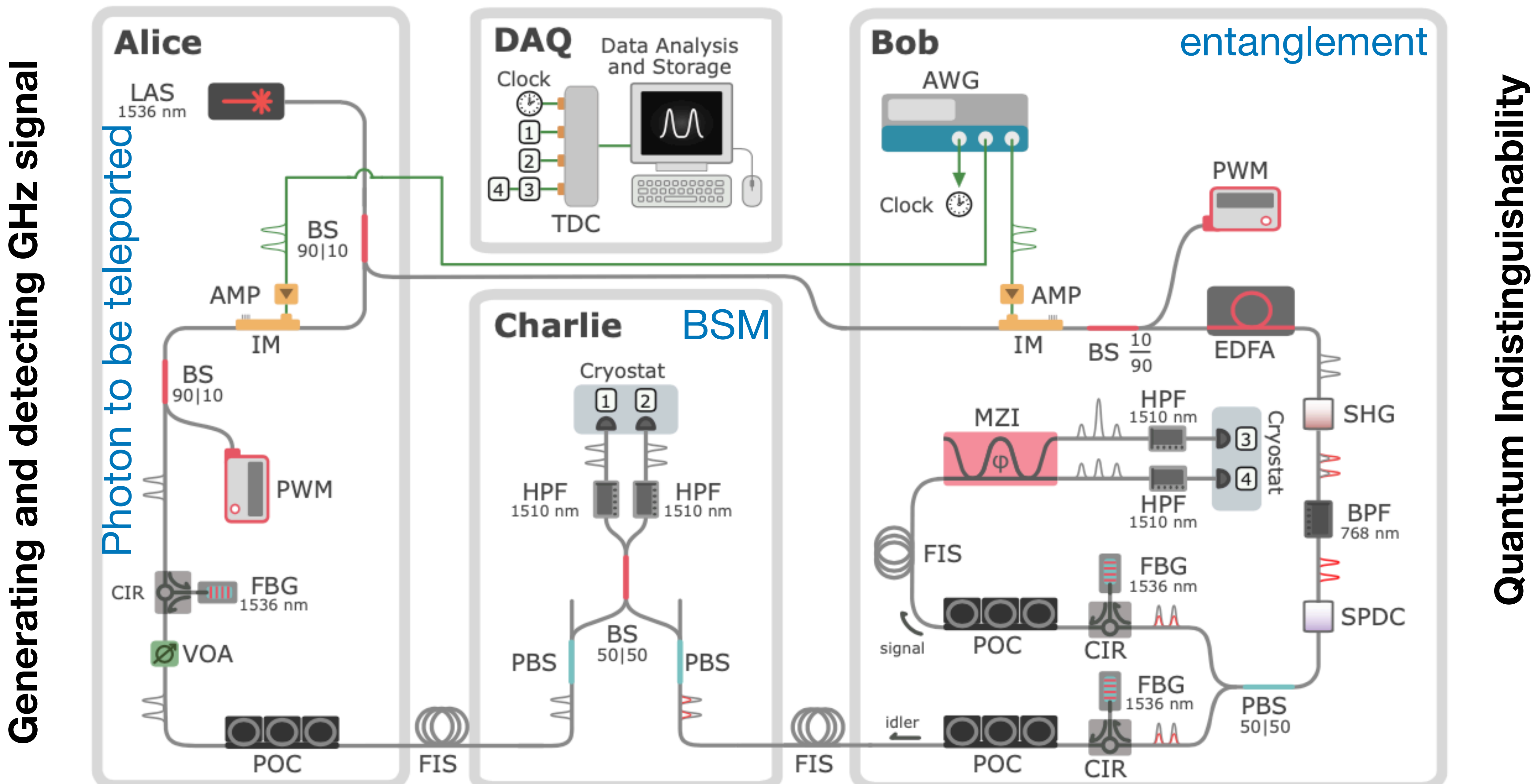
Deployed infrastructure at D0-QNode



Including multiple EPS, SNSPDS, high-speed electronics and dedicated DAQ

FNAL/Caltech Quantum Networks

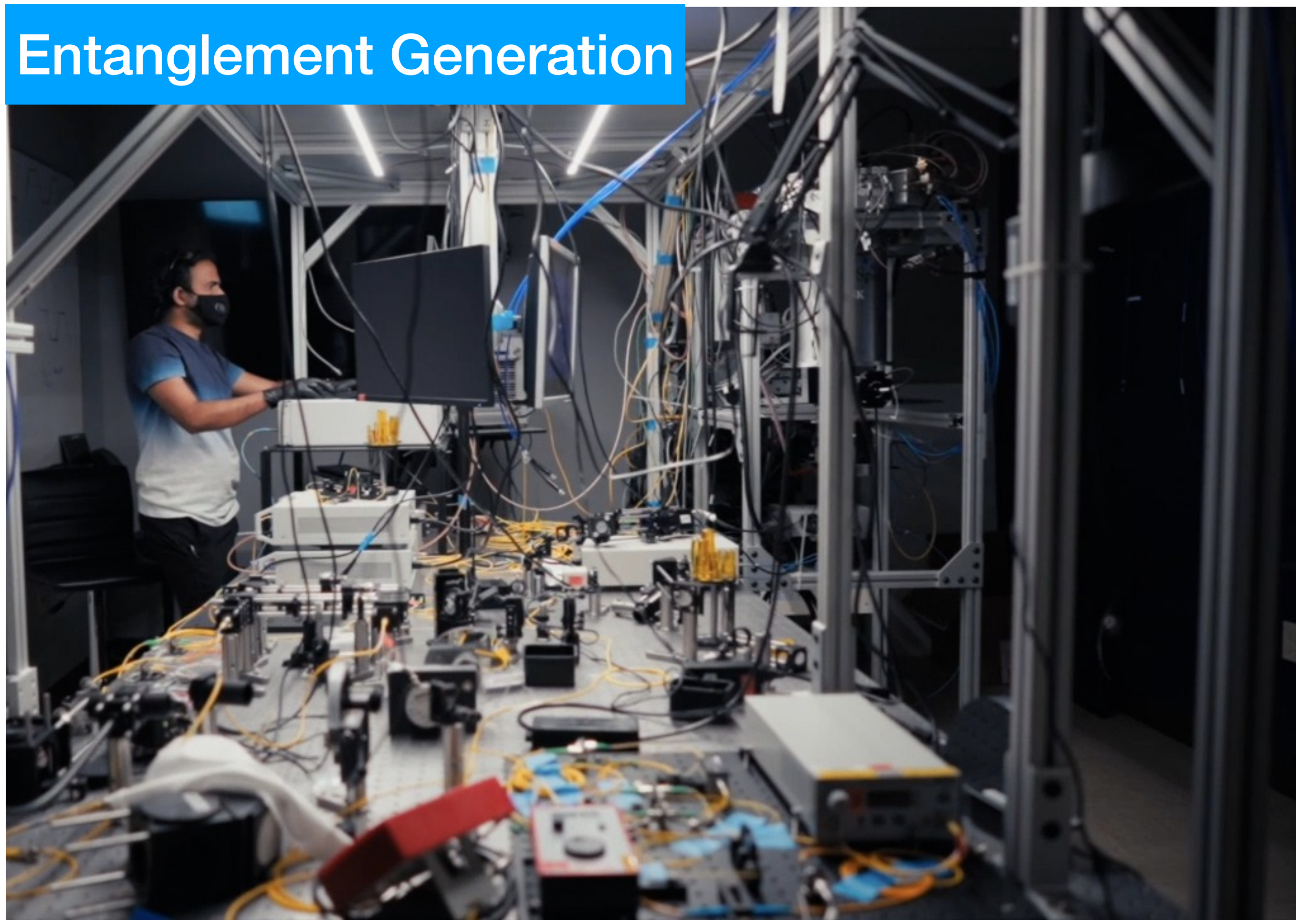
Use telecom (1536 nm) photon qubits



Cutting-edge optics, high-speed electronics and **quantum sensors**

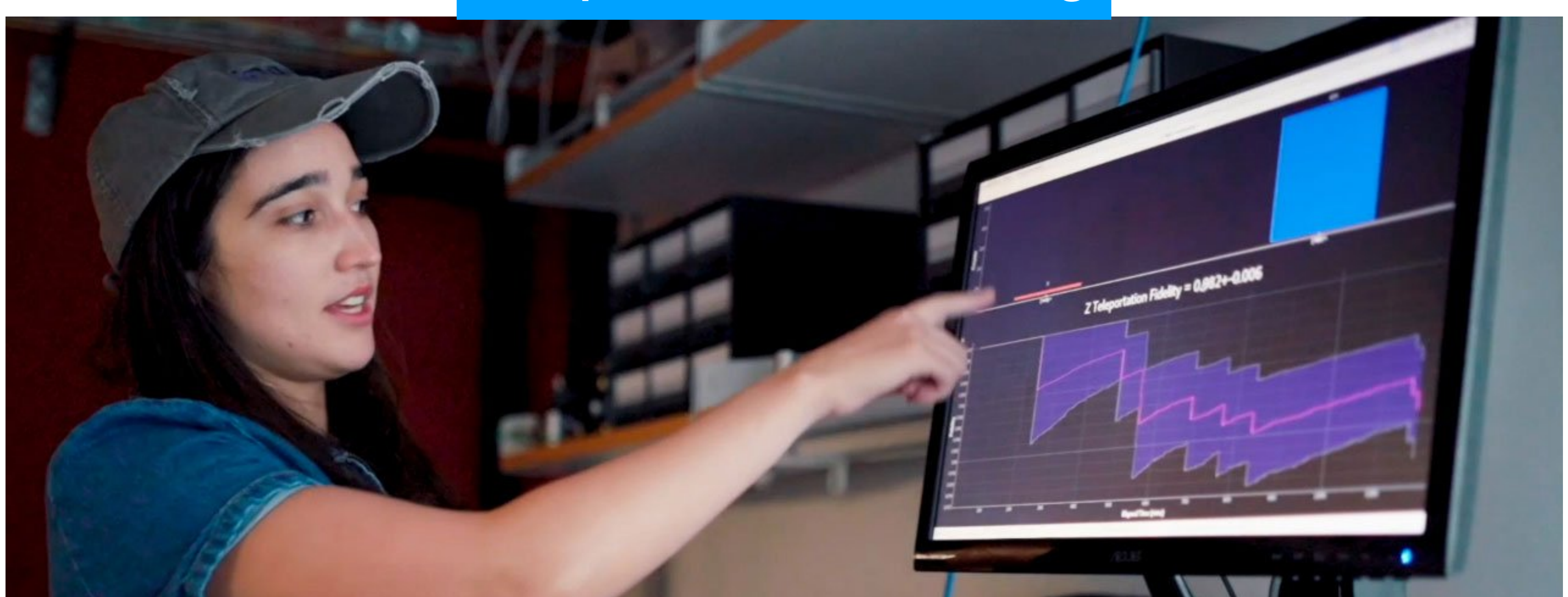
FNAL/Caltech Quantum Networks

Entanglement Generation



Quantum Sensor: SNSPDs

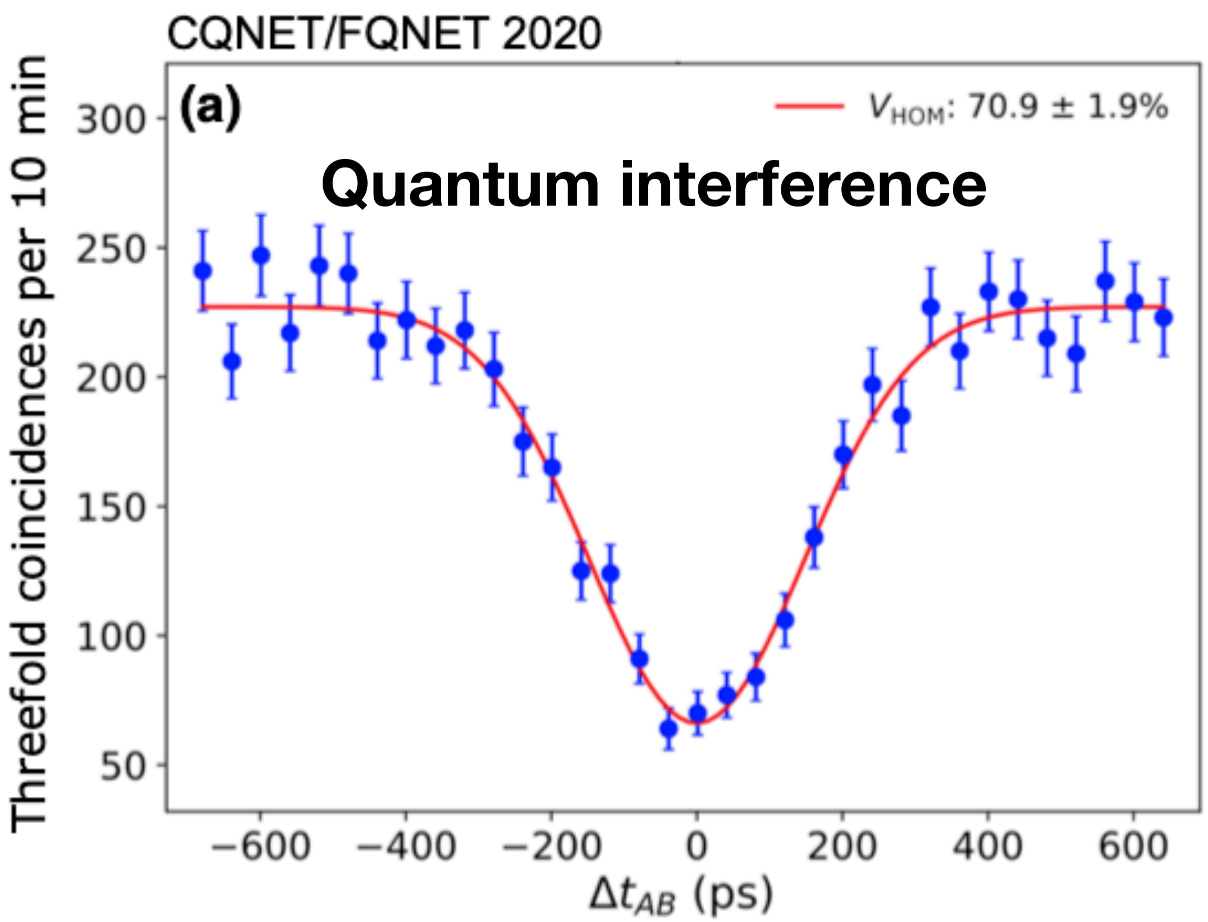
Teleportation Monitoring



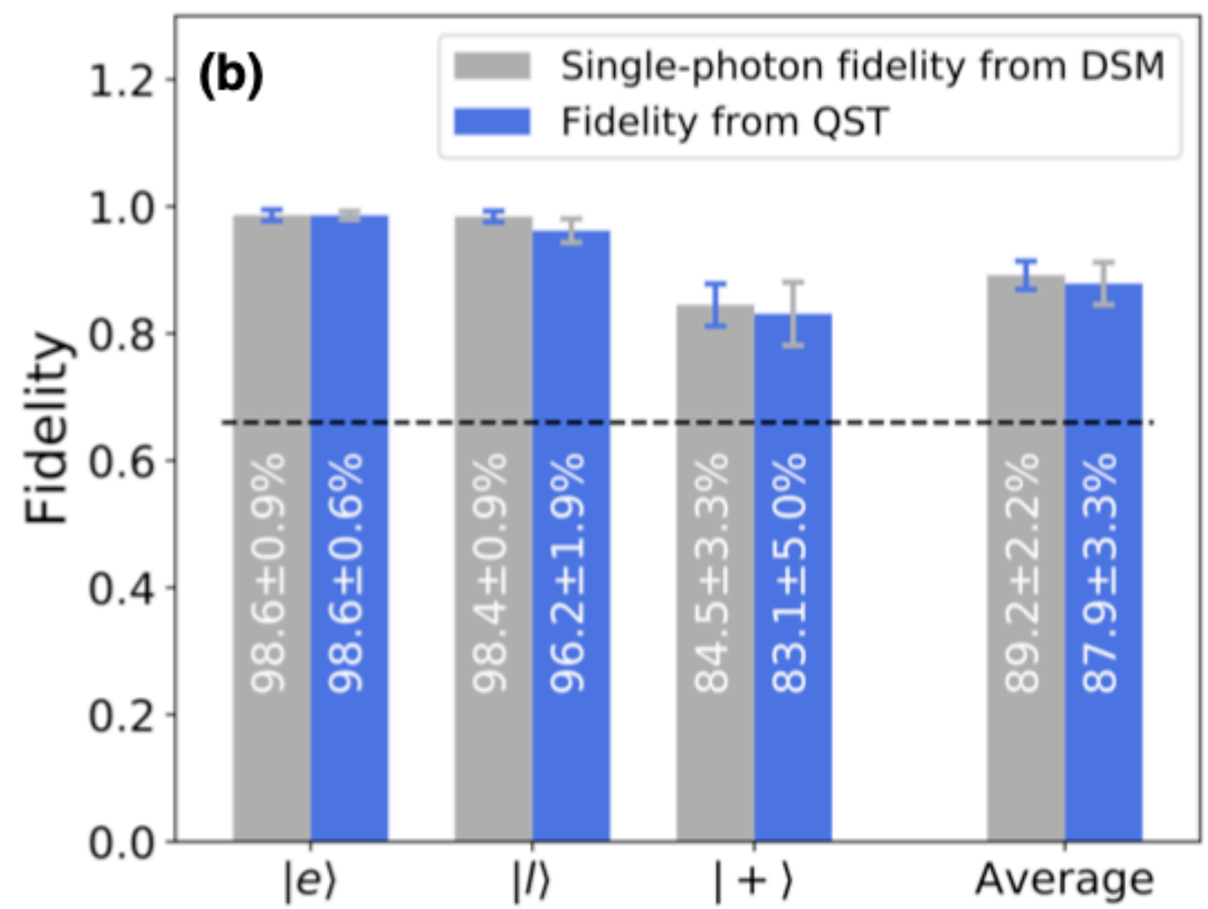
FNAL/Caltech Quantum Networks

The results: PRX QUANTUM **1,** 020317 (2020)

Hong-Ou-Mandel Effect



Teleportation Fidelity

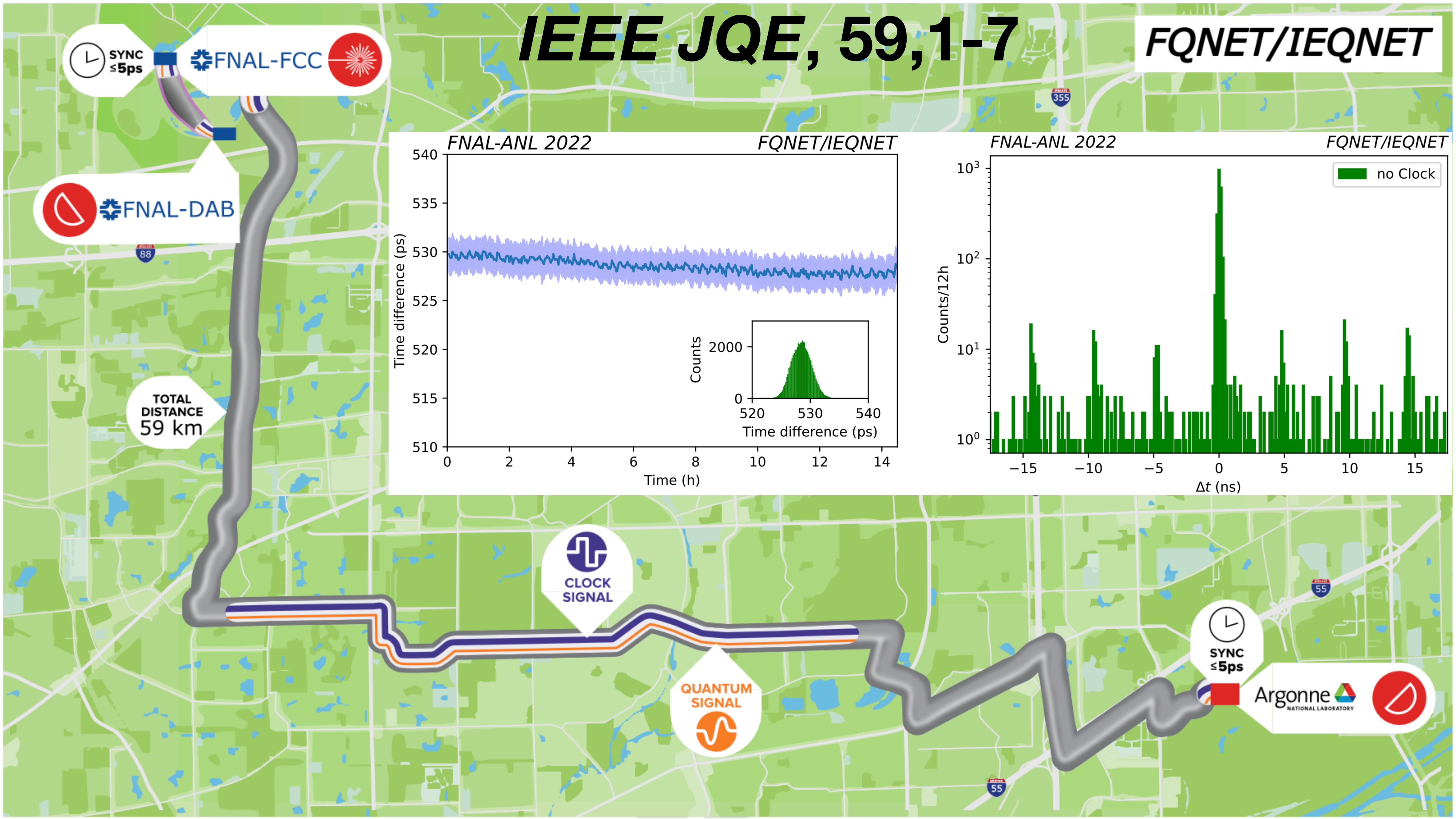


Record-high teleportation fidelity over 44 km of fiber

https://www.caltech.edu/about/news/quantum-internet-tested-caltech-and-fermilab

High precision timing (3 ps) synchronization

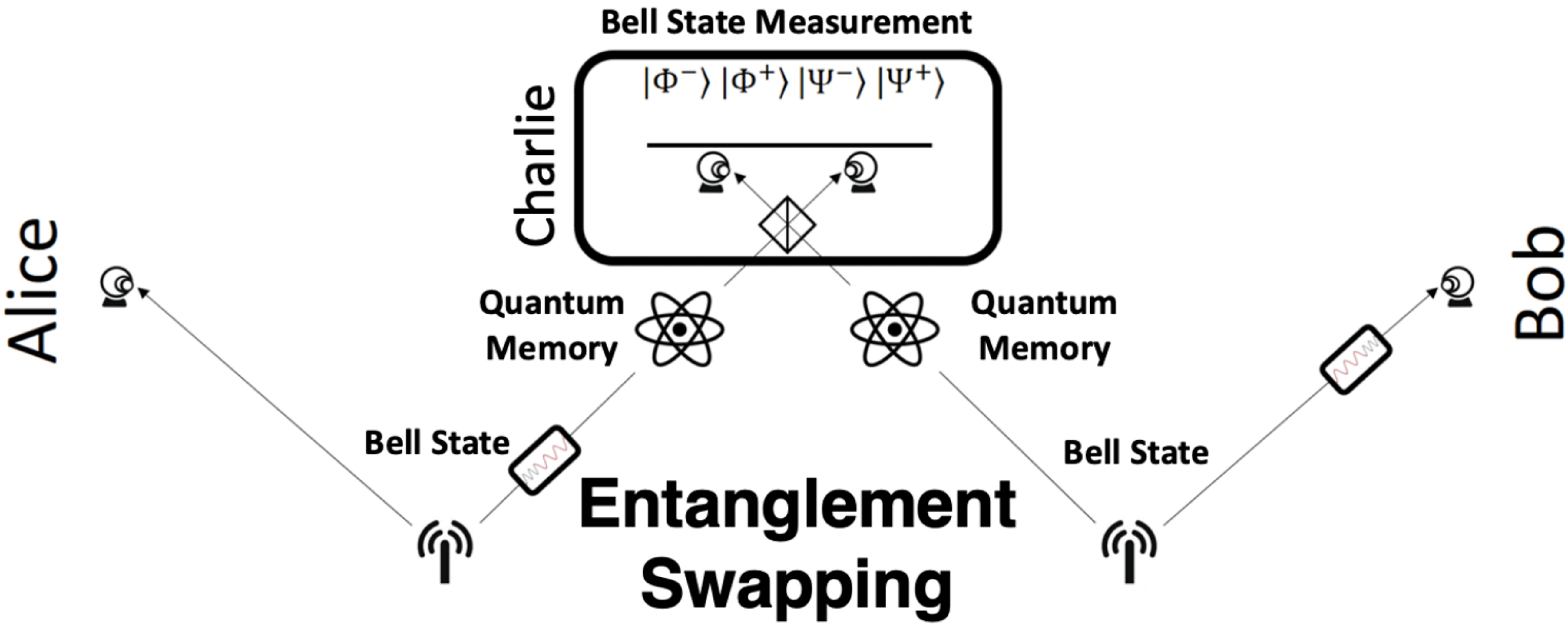
Classical resources needed for network operation



Coexistence of quantum and classical signal achieved

Fermilab Quantum Network

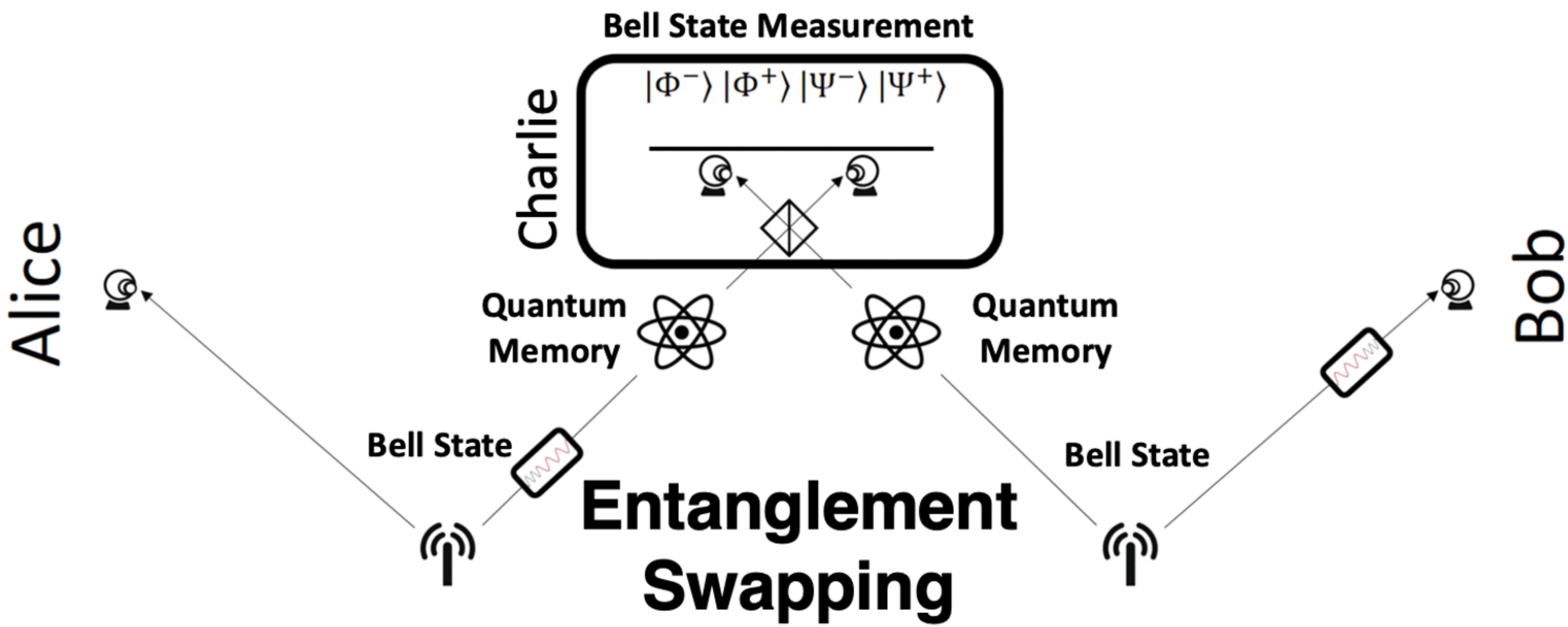
Complex protocols: **Entanglement Swapping**



Underpins long-distance quantum communication

Fermilab Quantum Network

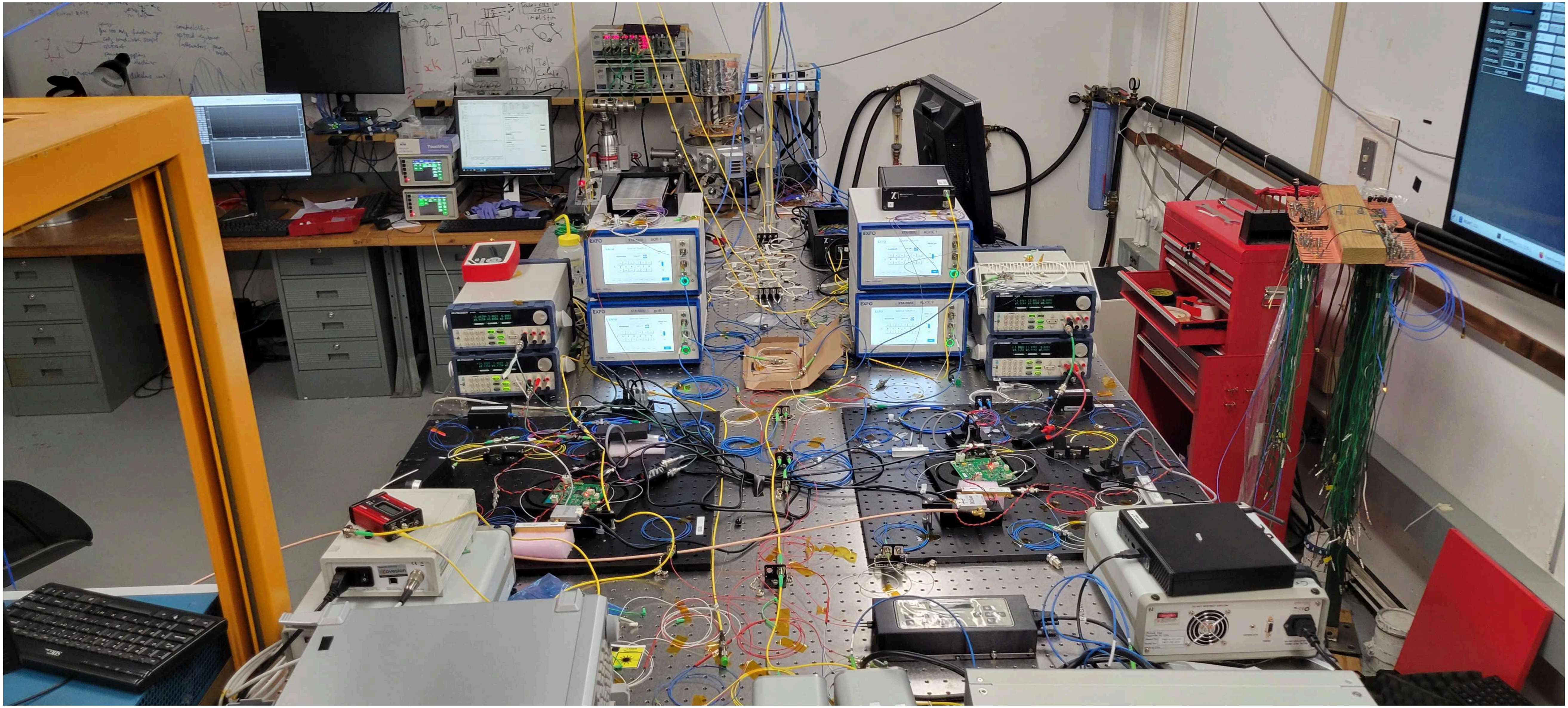
Teleportation of entanglement!



Underpins long-distance quantum communication

Swapping Experimental Setup

Real world implementation

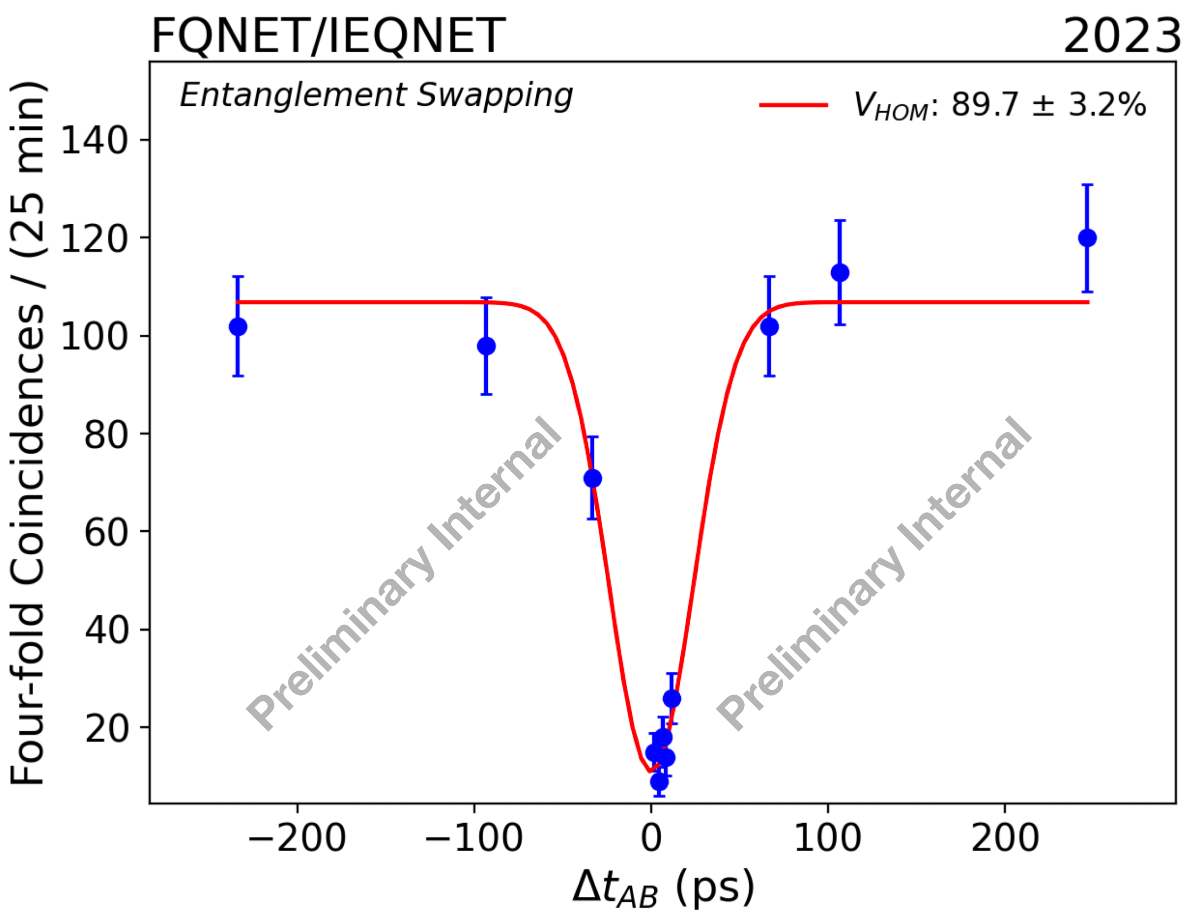


Challenging experiment with several cutting edge technologies

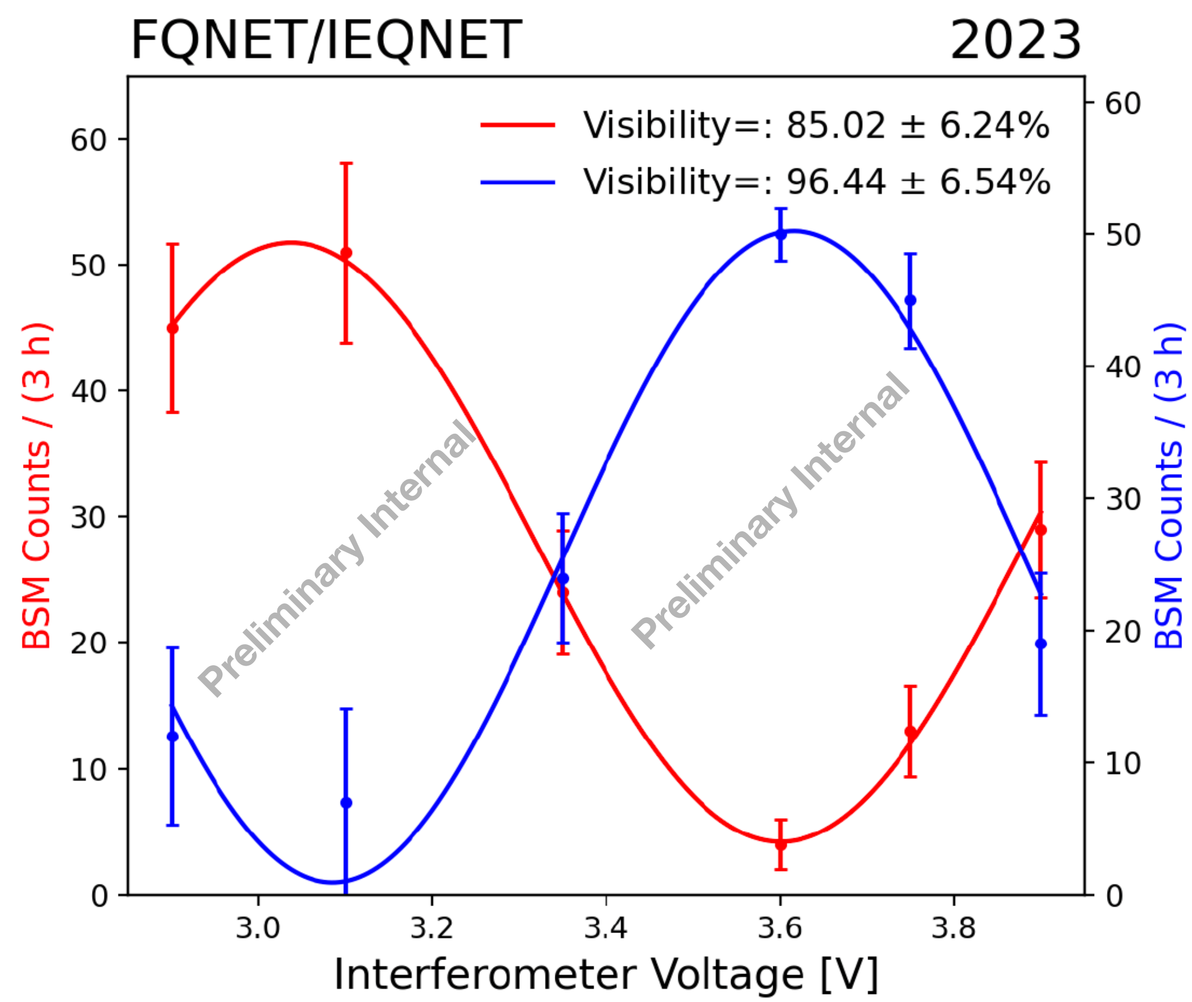
Entanglement Swapping

Preliminary experimental results

Hong-Ou-Mandel Effect



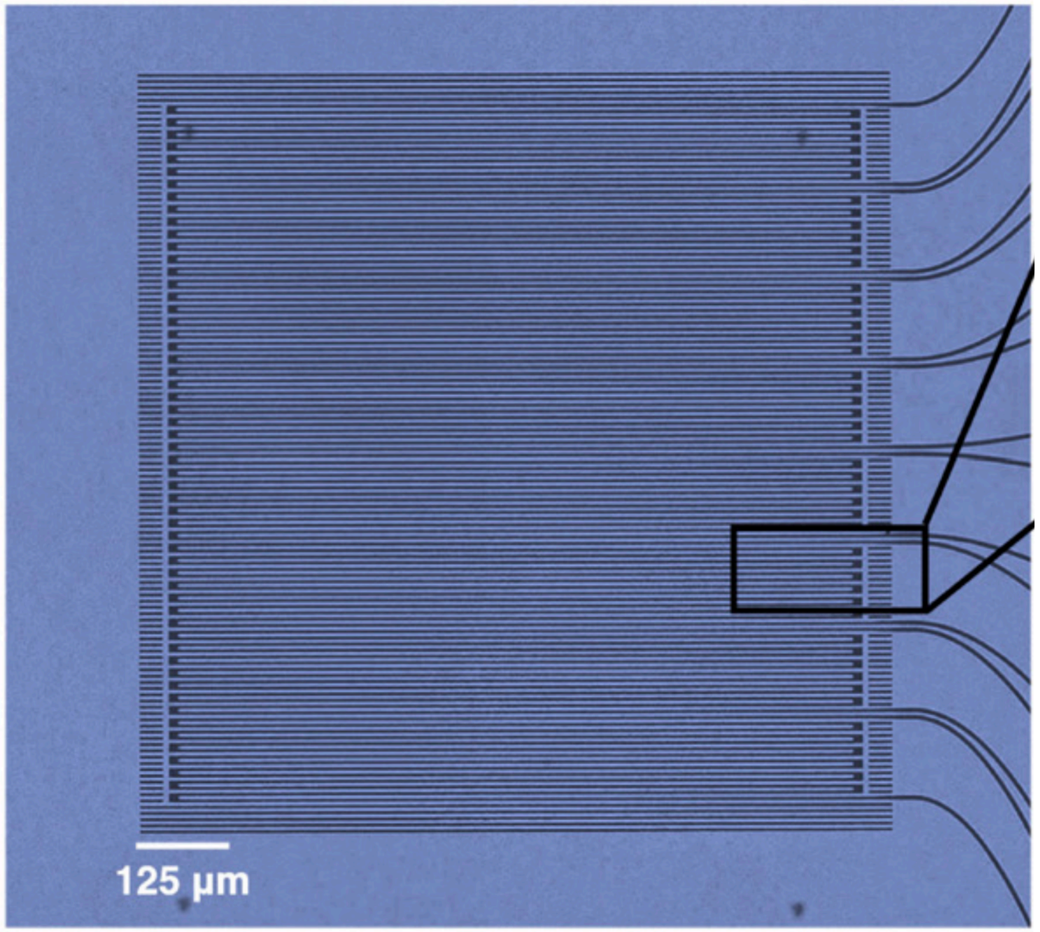
Swapping Visibility



4-fold HOM dip with high visibility → **High swapping visibility (x-basis)**

HEP Dark Matter Enabler

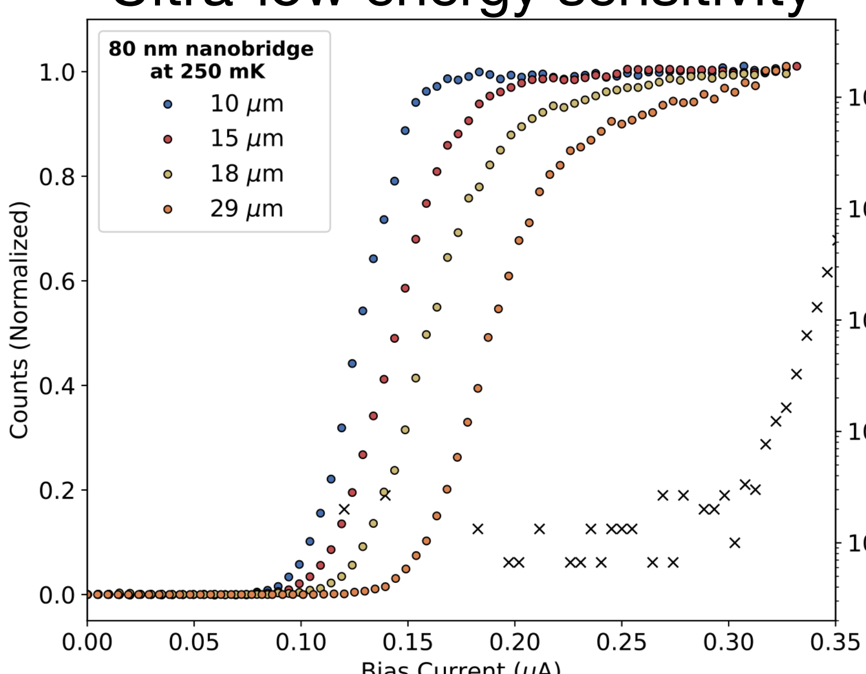
Appl. Phys. Lett. 122, 243506 (2023)



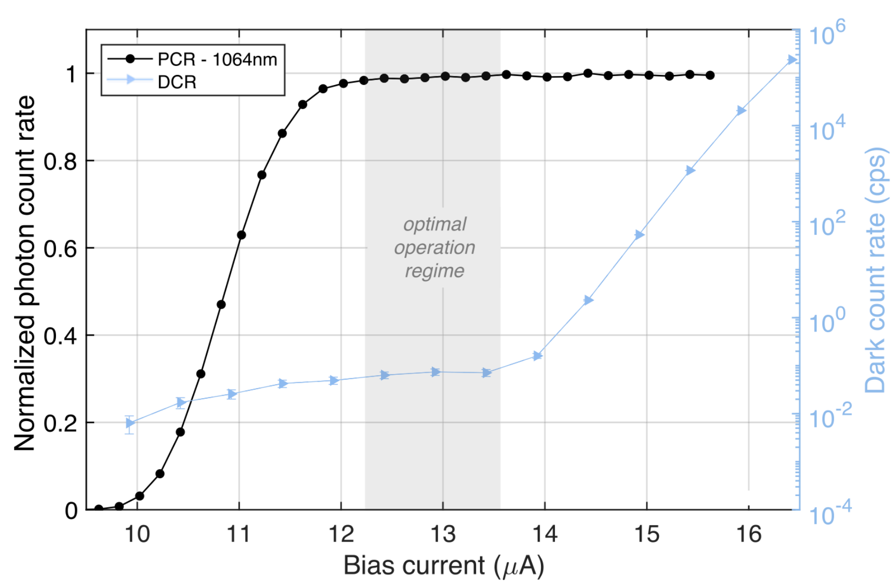
SNSPD R&D **recently achieved:**

- **Ultra-low energy sensitivity (40 meV)** ✓
  - Opens up unexplored DM regions
- **Large area single device (> mm²)** ✓
  - Compatible with HEP needs
- **Ultra-low dark counts rate** ✓
  - Critical for HEP applications

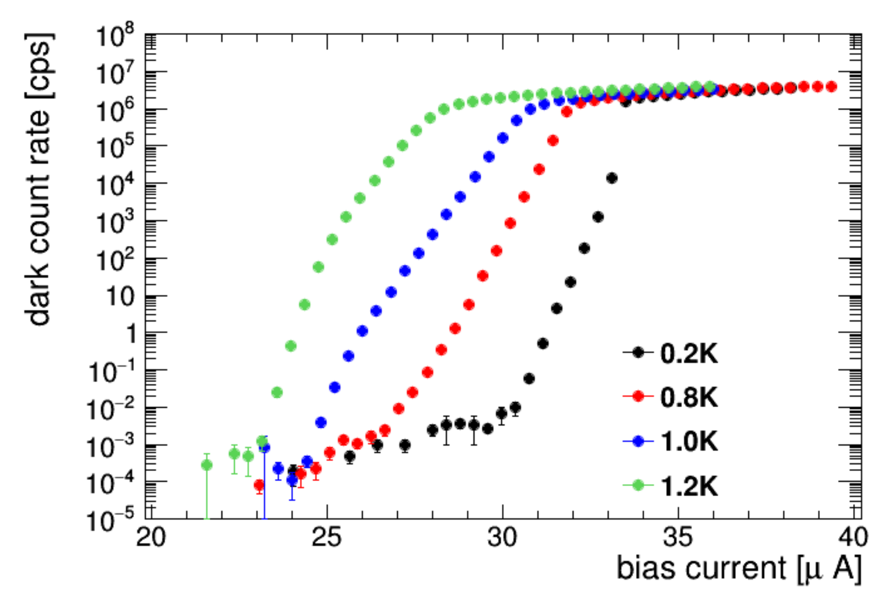
Ultra-low energy sensitivity



First large area SNSPD operation

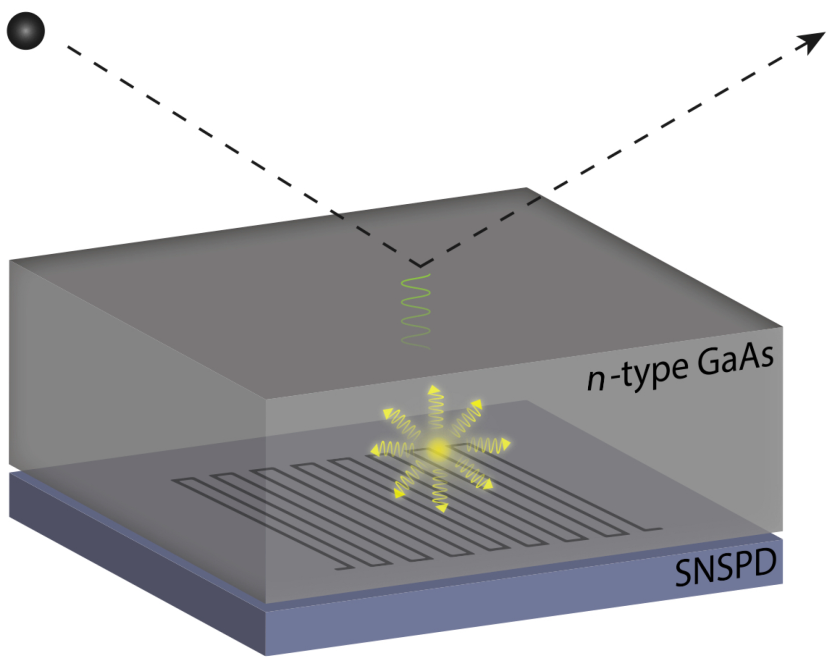


Dark count characterization



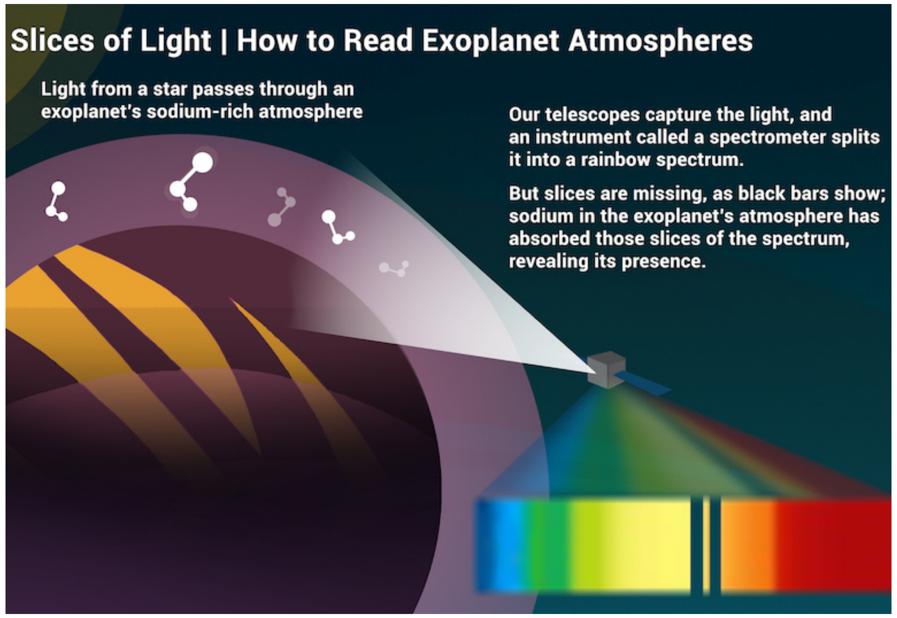
Deeper into the IR:
New probes for fundamental physics

sub-MeV DM



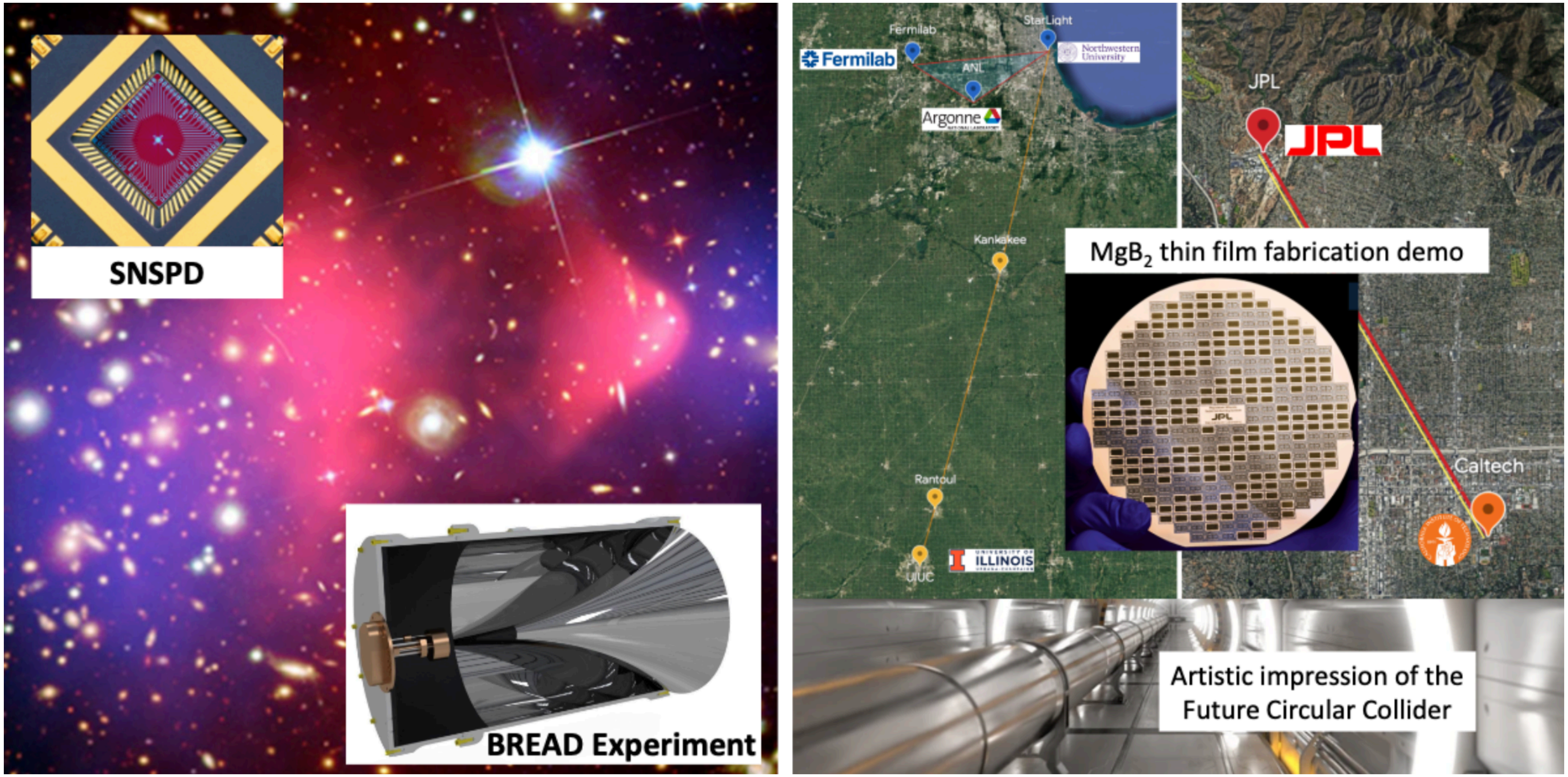
sub-eV axions
&
dark photons

Exoplanet transit spectroscopy



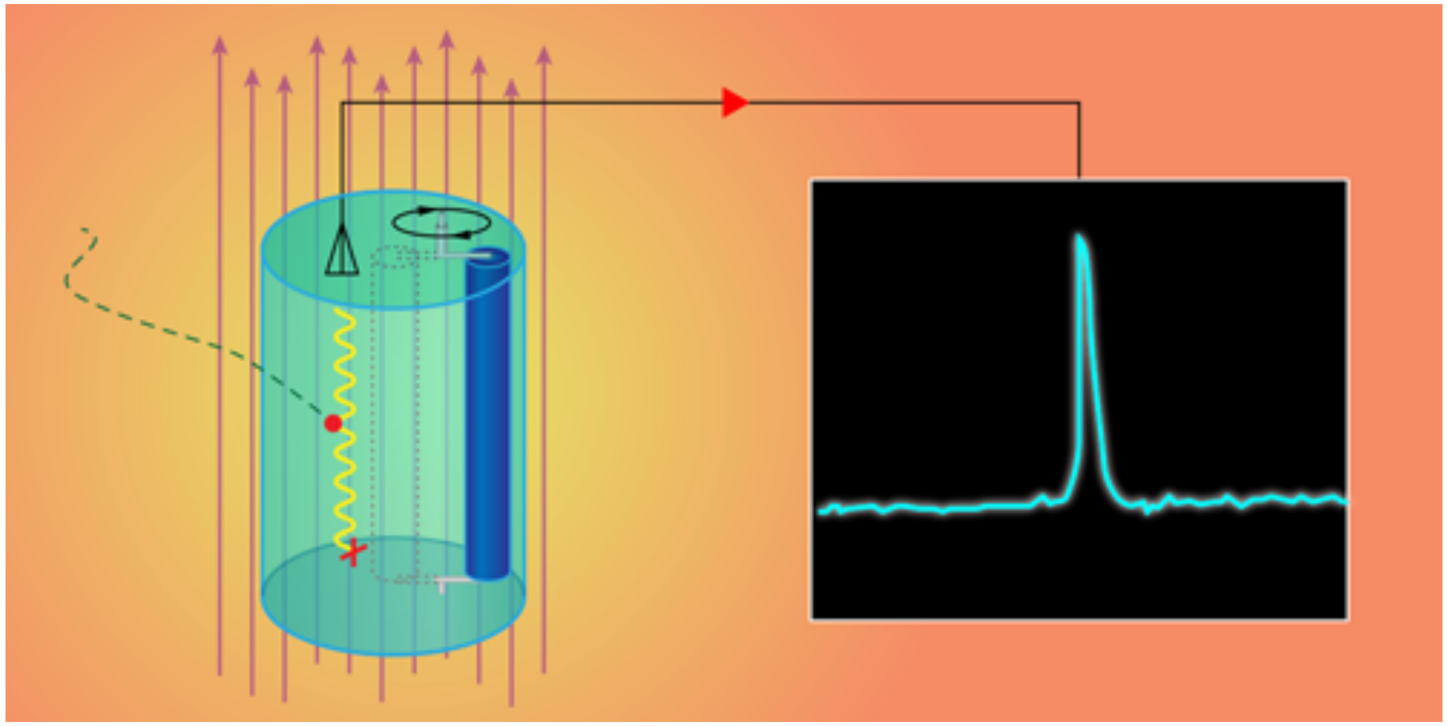
Accelerate SNSPD R&D

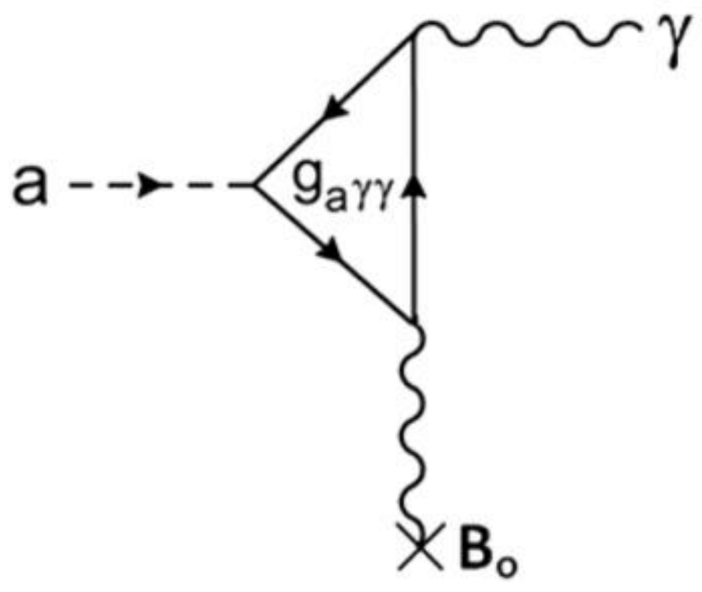
DOE project for R&D towards large area, ultra-low energy sensitivity, and ultra-low dark count rate



Axions

- Axions solve the strong CP problem and a dark matter candidate
- Axion-photon coupling under B-field converts axion to photon
- Past experiments use resonant cavities to detect ~μev axions, but:
  - The cavities need to scan for unknown axion mass
  - Technologically and practically difficult to reach higher axion masses

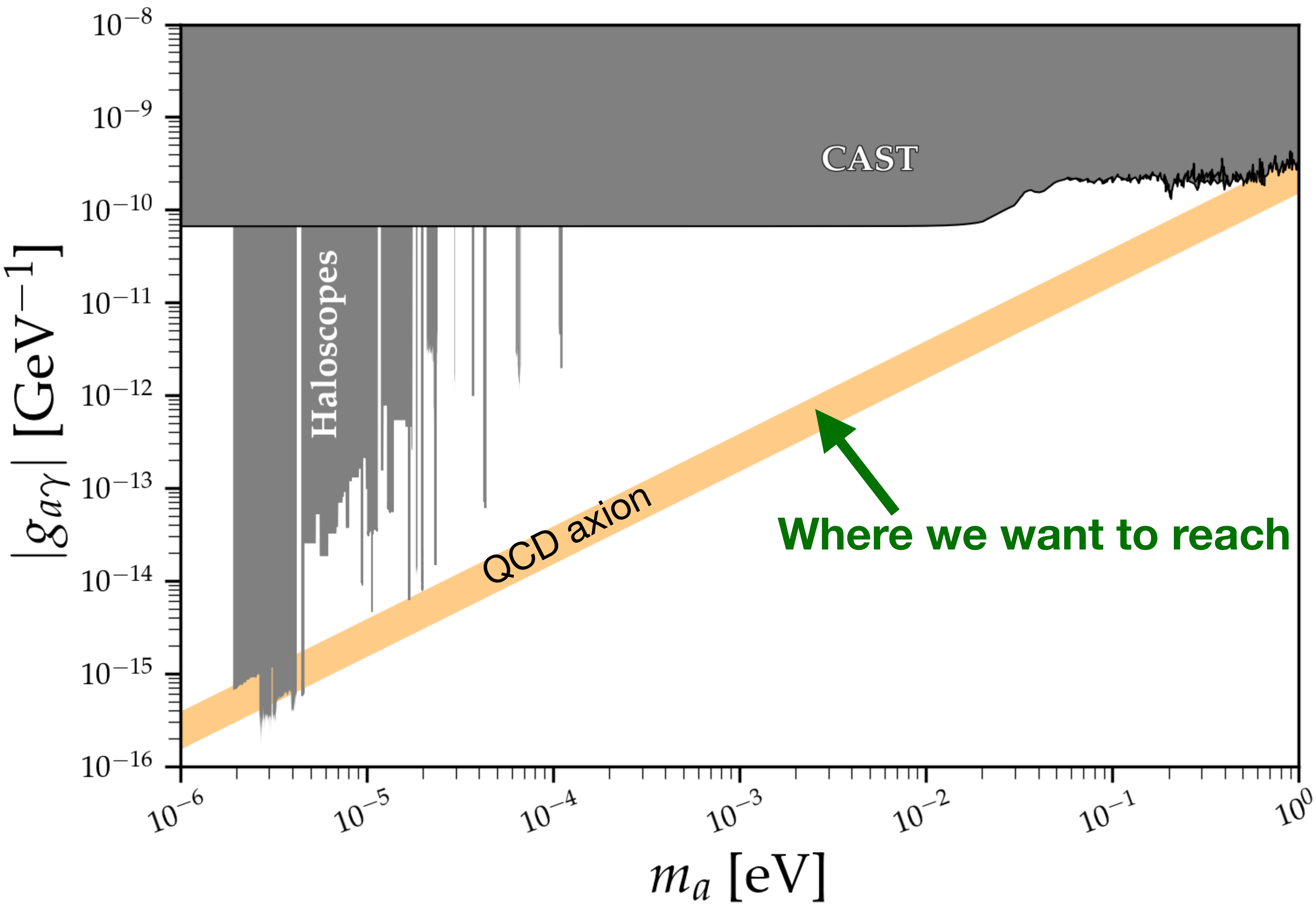




See more details in A. Chou's presentation

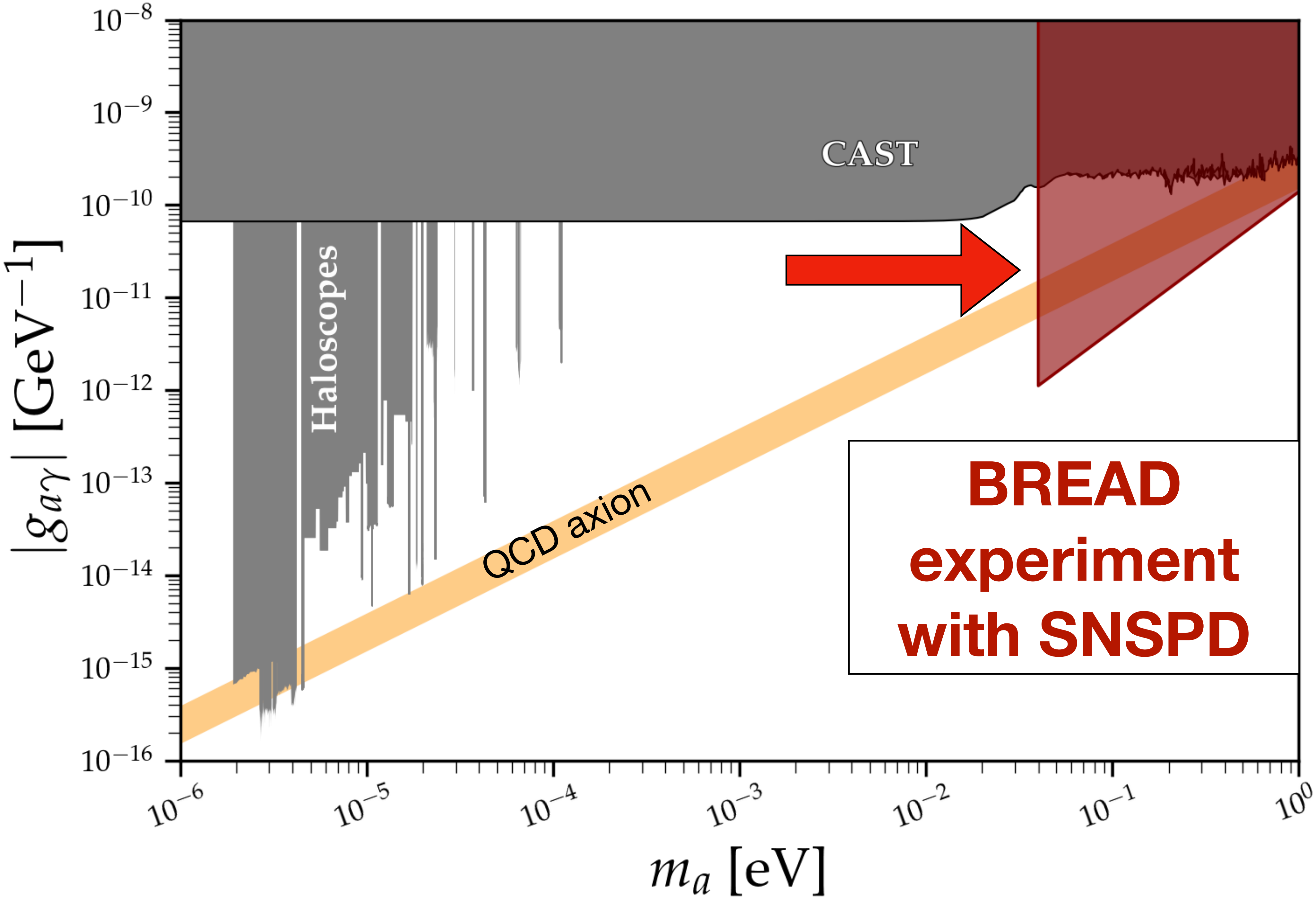
Axions Landscape

Large region of parameter space unexplored



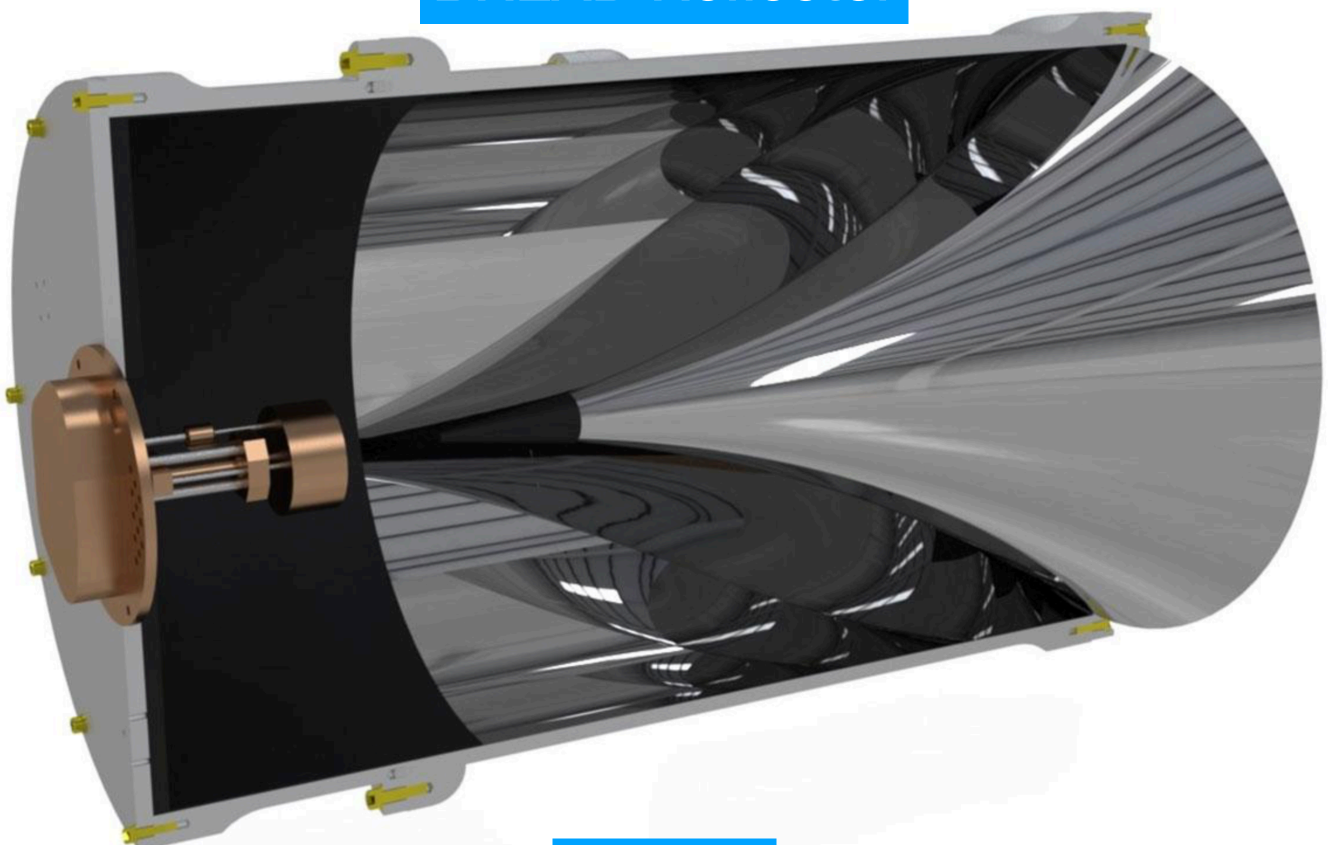
Axions Landscape

New SNSPDs can probe new parameter space

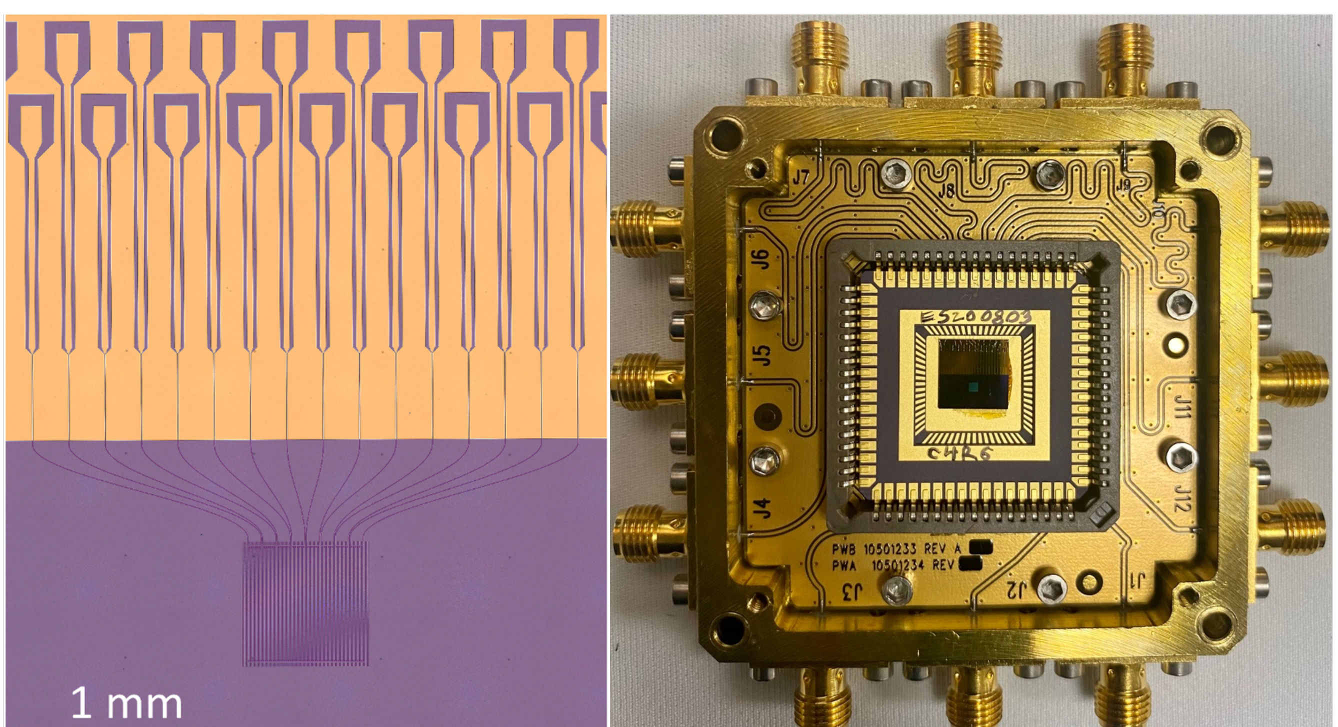


All Pieces in Place for Pilot Experiment

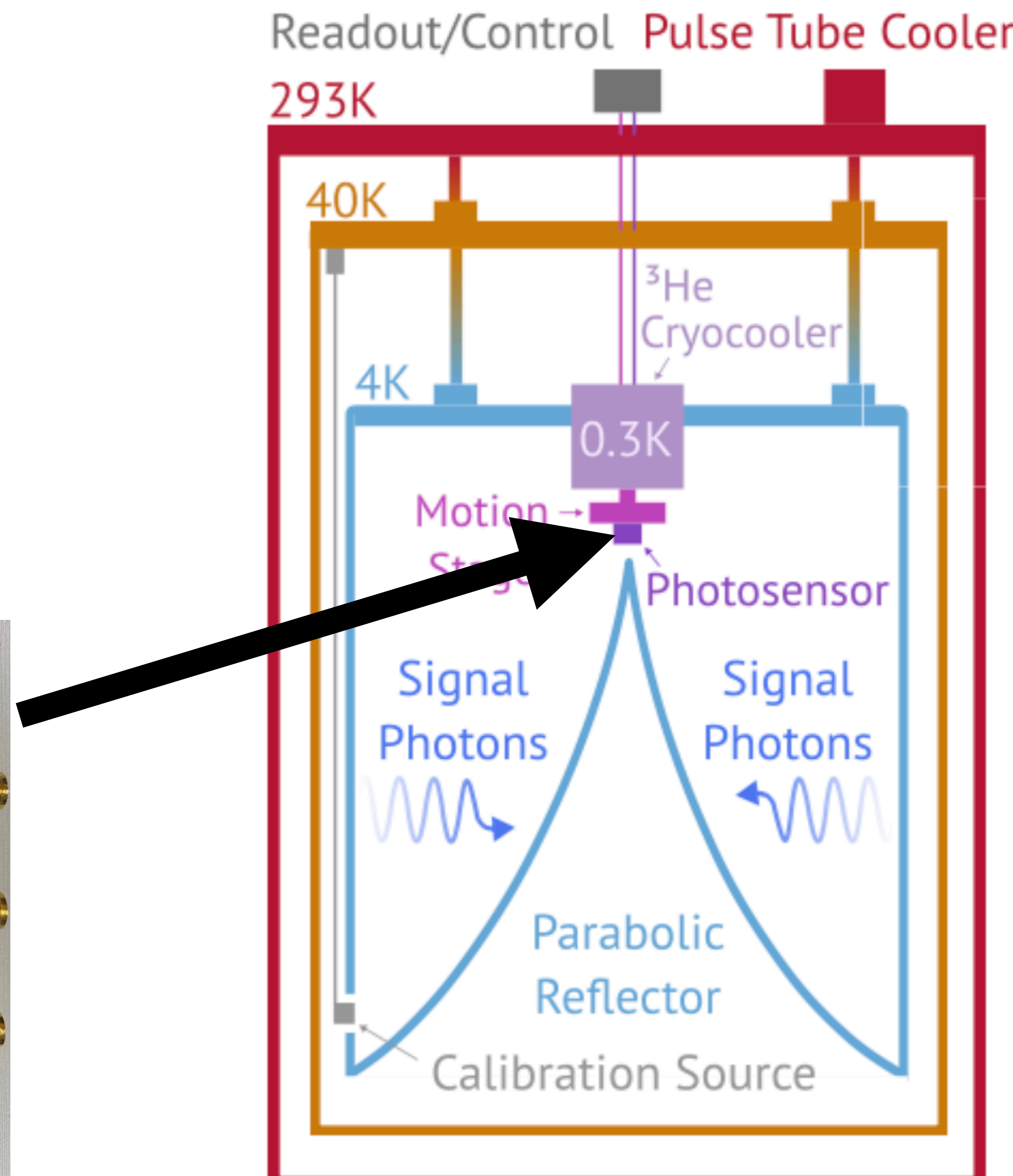
BREAD Reflector



SNSPD

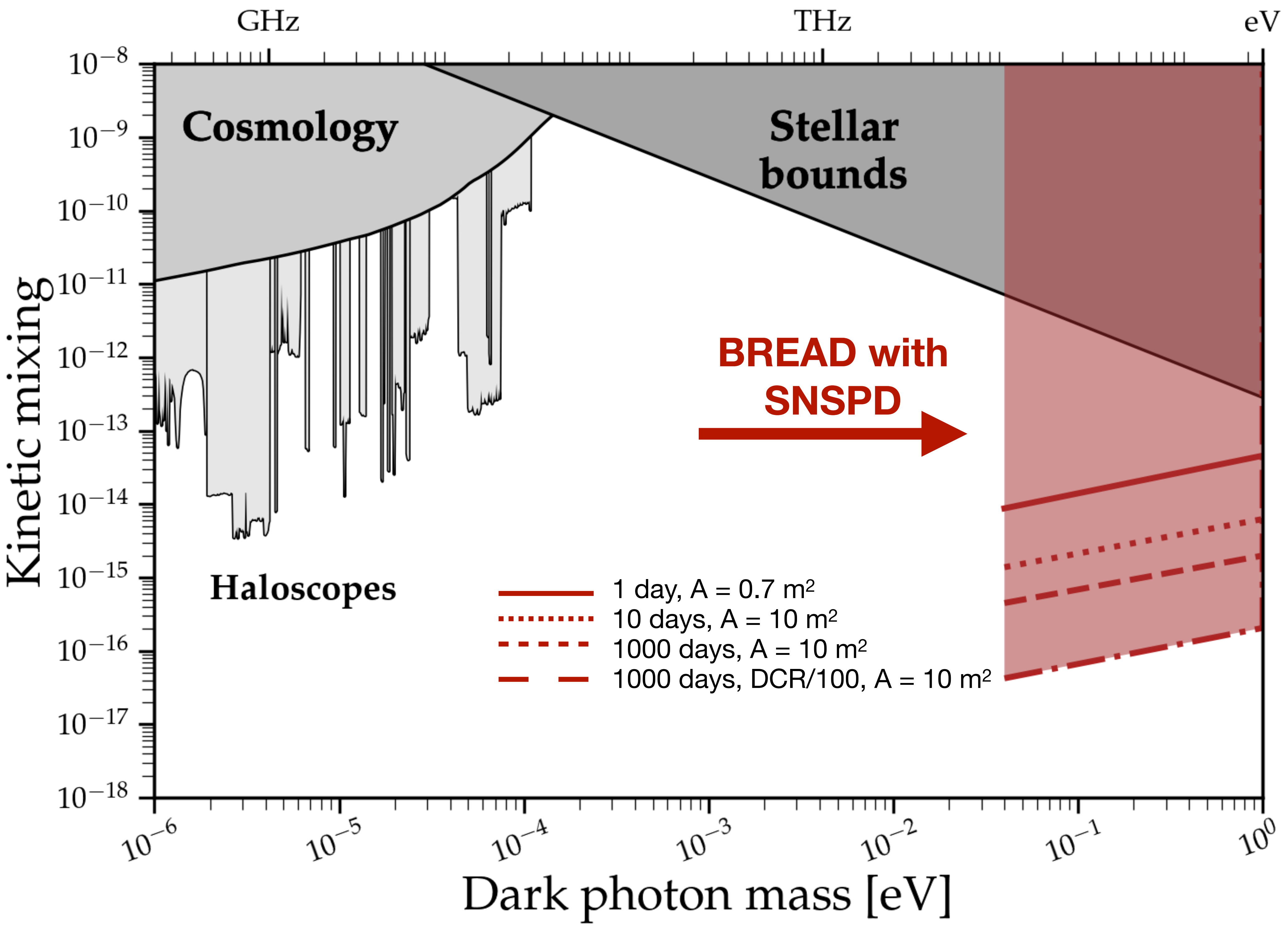


BREAD Experiment Concept



Dark Photon Pilot Experiment

New SNSPDs can probe new parameter space

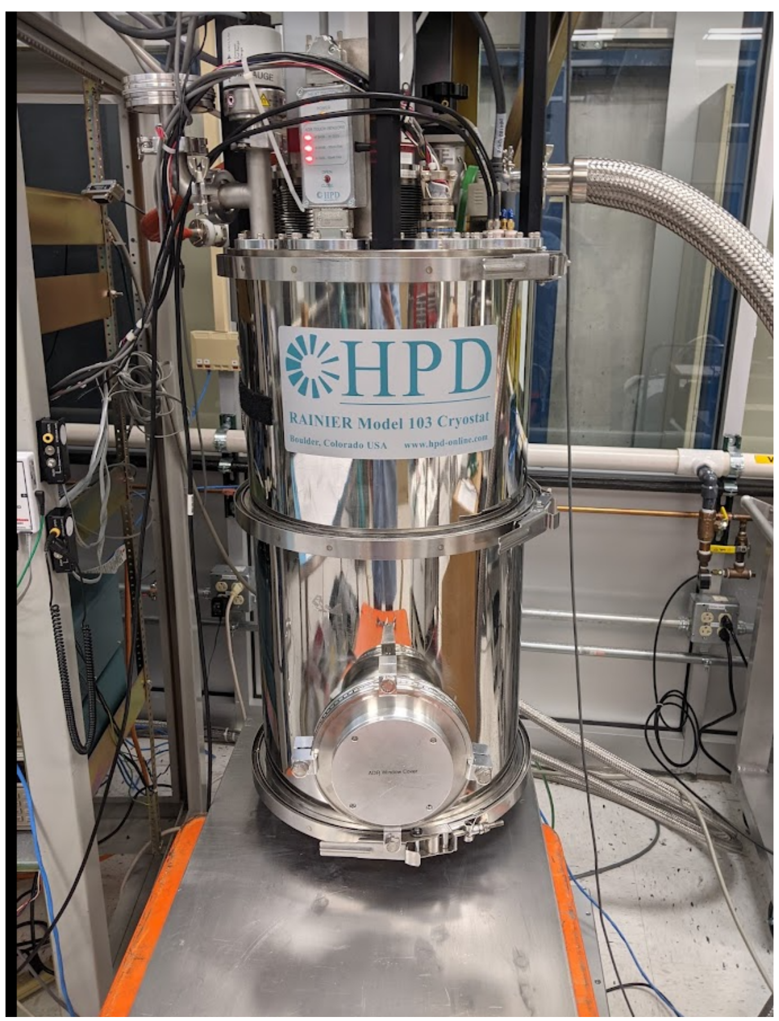


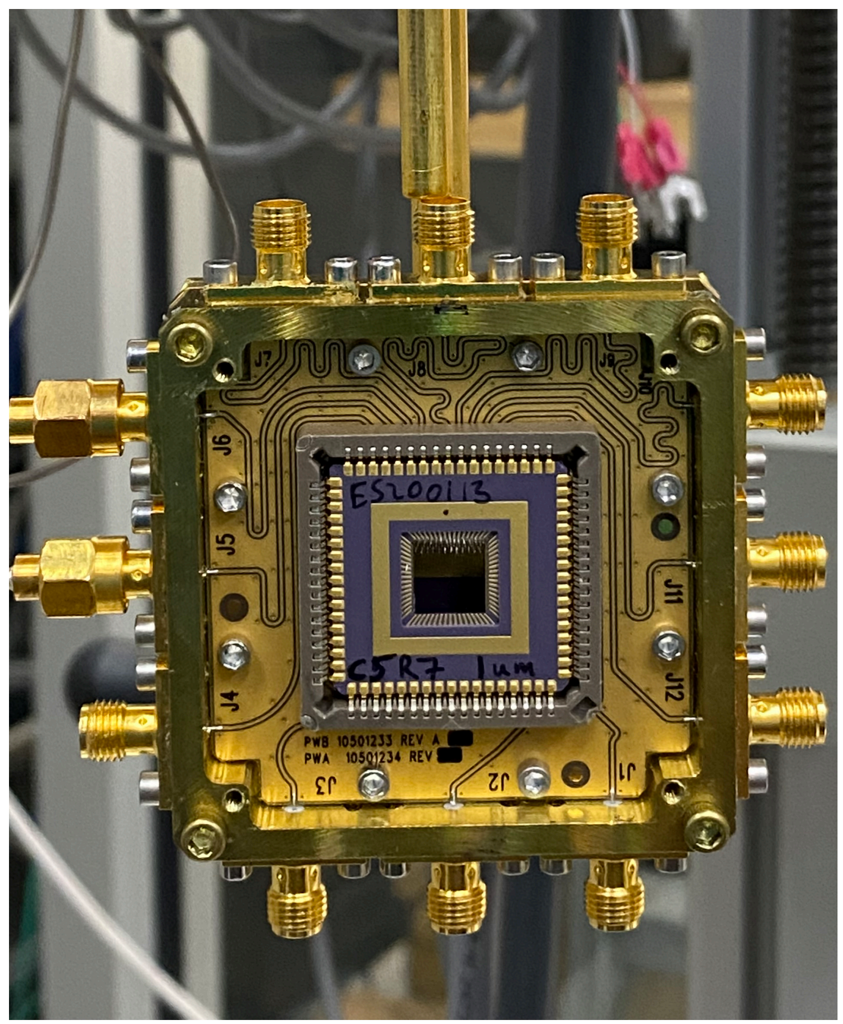
Unique Testing Capabilities at Fermilab

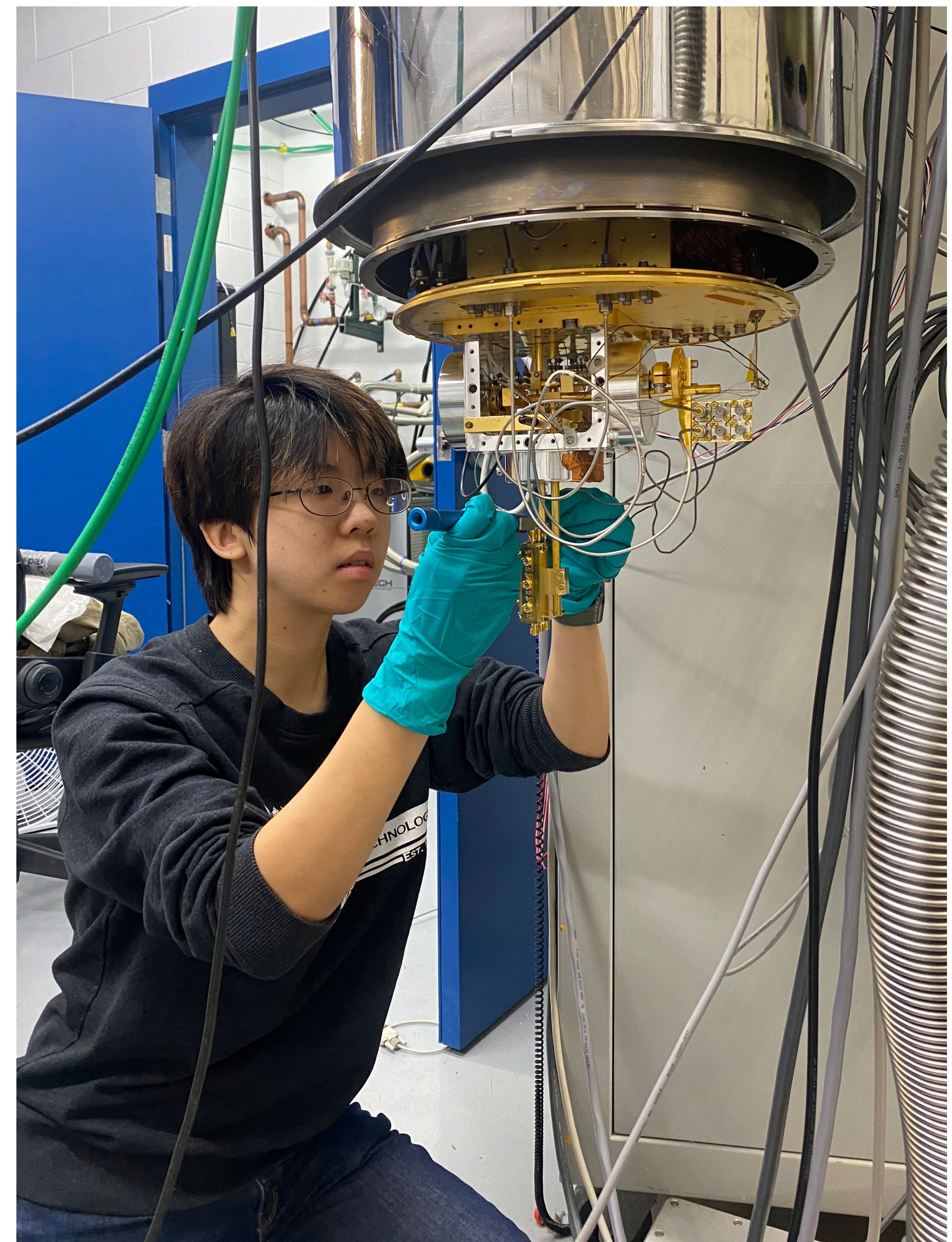
<u>Christina Wang</u>
New Lederman Fellow
SCGSR @ FNAL

Unique infrastructure to test new SNSPDs

- Absolute efficiency characterization
- Dark count rate dependence on T
- Cosmic ray response
- New underground facilities

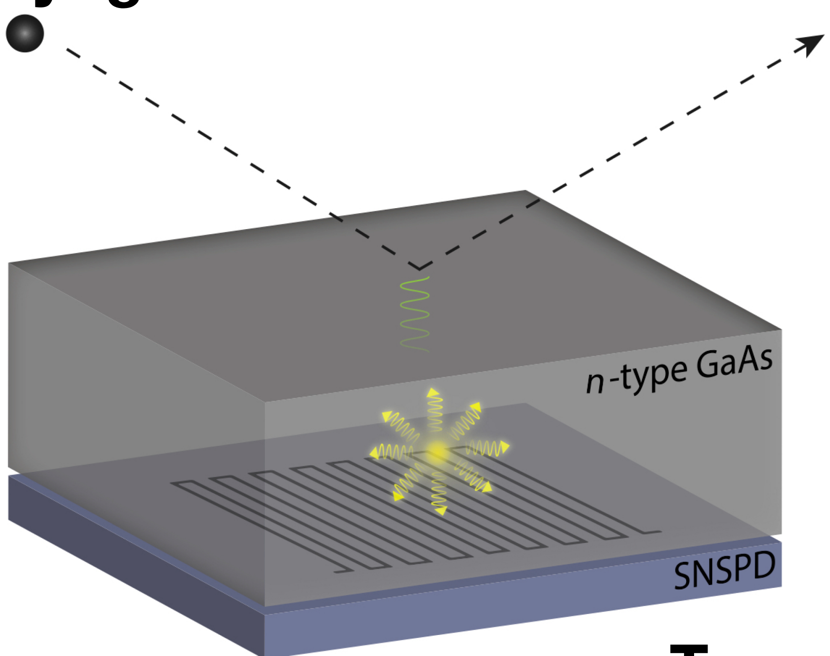




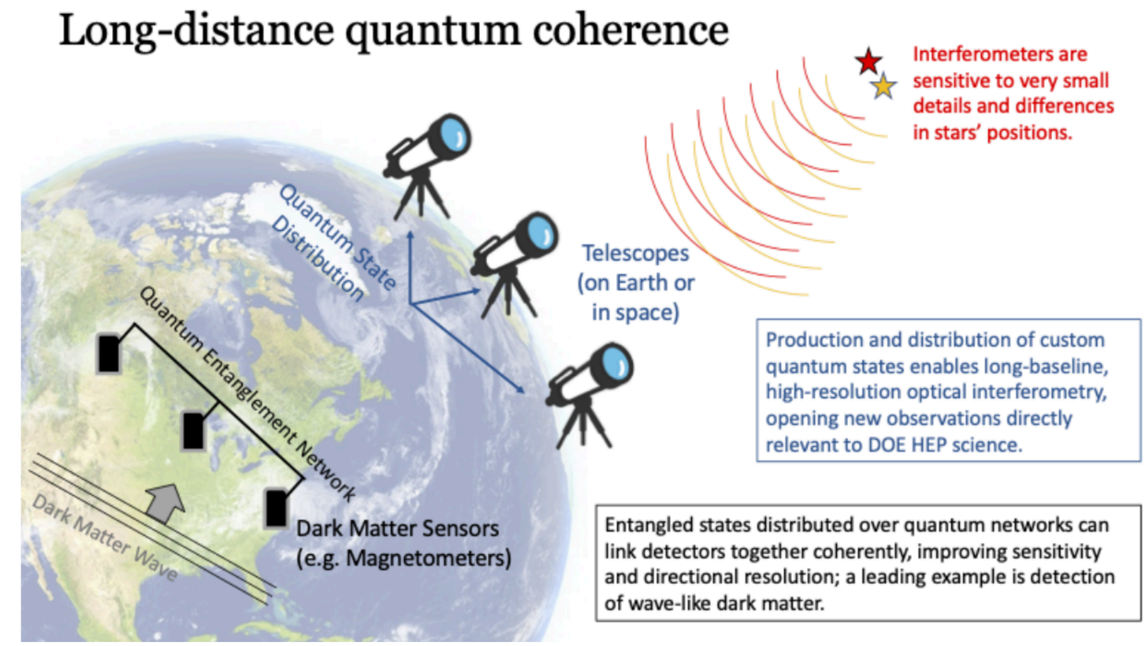


SNSPD Vision for HEP S&T Applications

sub-MeV DM (Cryogenic Scintillator readout)

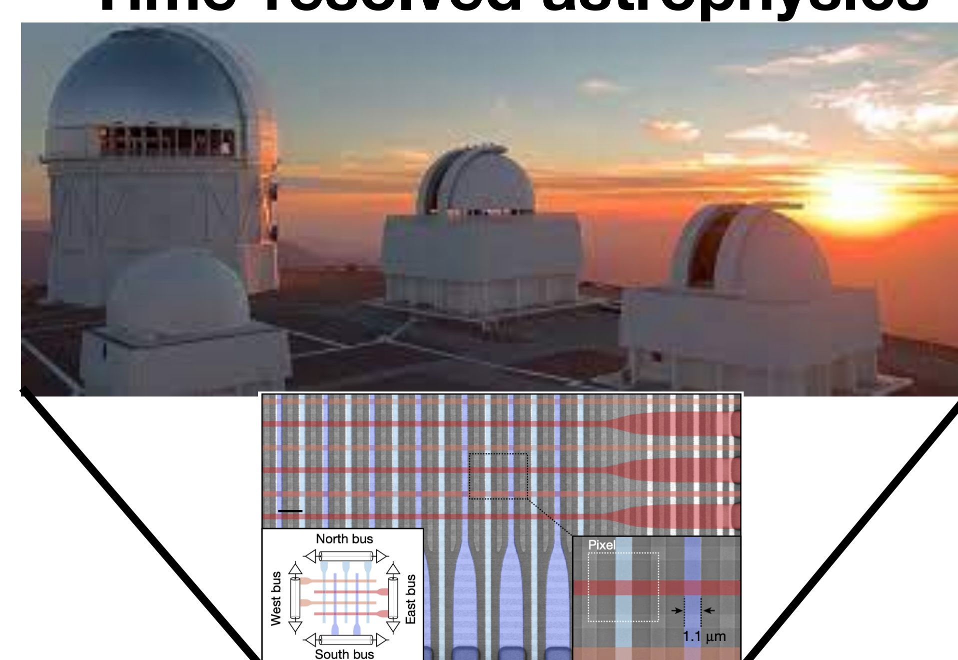


Distributed quantum sensors

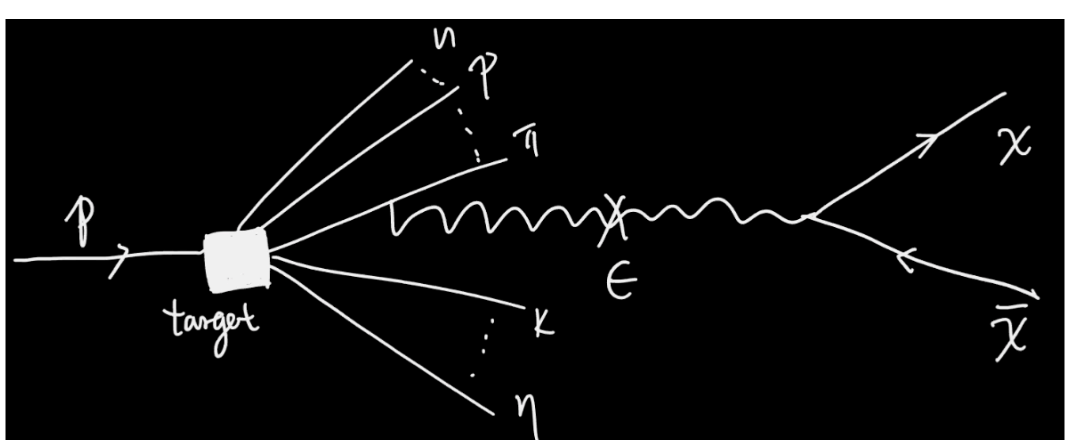


Towards the quantum internet

Time-resolved astrophysics



Ultra low-threshold millicharged particles



List of Accomplishments (QNETs)

- Record high fidelity quantum teleportation. PRX Quantum **1**, 020317
- Entanglement distribution between Argonne and Femi National Labs. *IEEE JQE*, 59,1-7
- High precision clock synchronization between Argonne and Femi National Labs. *IEEE JQE*, 59,1-7
- Design and Implementation of the IEQNET, in *IEEE TQE*, 3, 1-20
- Entanglement Swapping at Fermilab. Samantha Davis at APS 2023
- Automated entanglement systems using QICK. *IEEE JQE*, 59, 1-7.
- High-rate multiplexed entanglement source based on time-bin qubits for advanced quantum networks. *arXiv:2310.01804*
- High fidelity entanglement swapping (teleportation of entanglement). *In preparation*
- The Illinois Express Quantum Network (IEQNET)*. DOE Award 2018-2023*
- Advanced Quantum Networks (AQNET) for Scientific Discovery*. DOE Award 2023-2026*

List of Accomplishments (SNSPD R&D)

- Demonstration of **sub-3 ps** temporal resolution with a SNSPD. *Nature Photonics, 14, 250–255 (2020)*
- Free-space coupled SNSPD with **low dark counts** (world-best). *Optica 8, 1586-1587 (2021)*
- **Large active-area** superconducting microwire detector array with single-photon sensitivity in the near-infrared. *Appl. Phys. Lett.* 122, 243506 (2023)
- **First** in depth characterization of SNSPD **dark count rate for HEP experiments**. To be submitted to *Appl. Phys. Lett.*.
- Impedance-matched differential superconducting nanowire detectors (first milestone towards ultra-low jitter). *arXiv:2108.07962*
- Accelerate SNSPD technology for HEP Discoveries. *DOE Award 2023-2026*