

Overview of US Quantum Networking Efforts

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BROOKHAVEN
NATIONAL LABORATORY

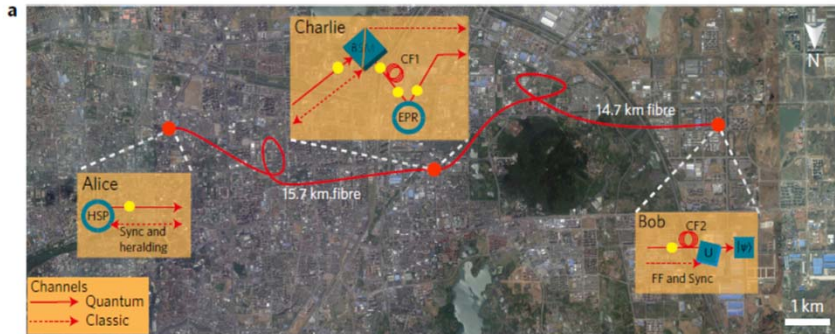
The logo for Brookhaven National Laboratory, featuring the word "BROOKHAVEN" in a bold, black, sans-serif font above "NATIONAL LABORATORY" in a smaller, black, sans-serif font. A stylized grey orbital path with a red dot at its center is positioned behind the text.

Quantum communication

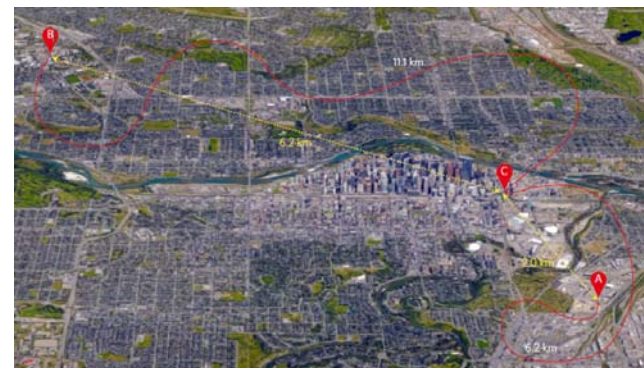
Quantum communication:

Is the ability to transmit qubits or entanglement between two distant locations.

Hefei-QN



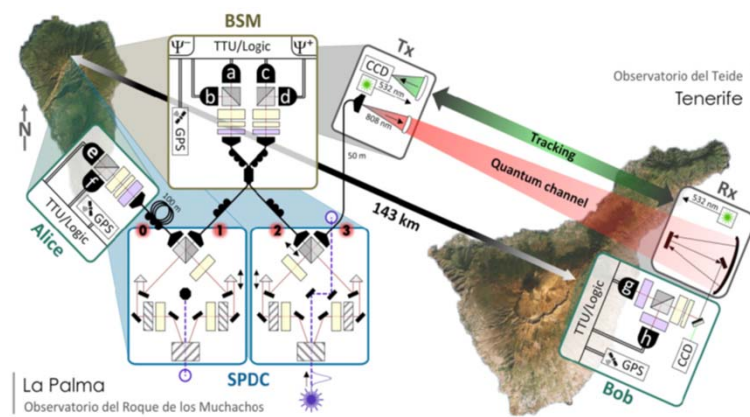
Calgary QN



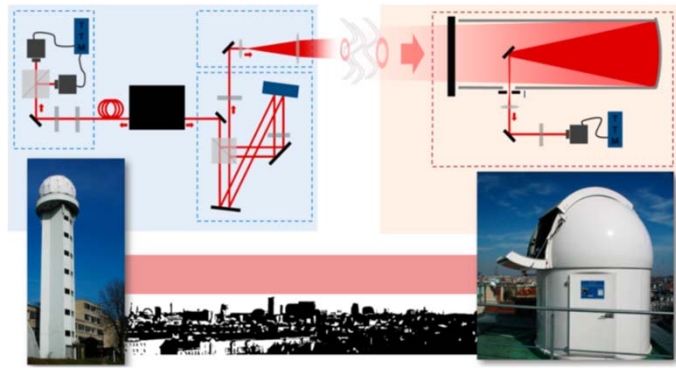
Chinese Space QN



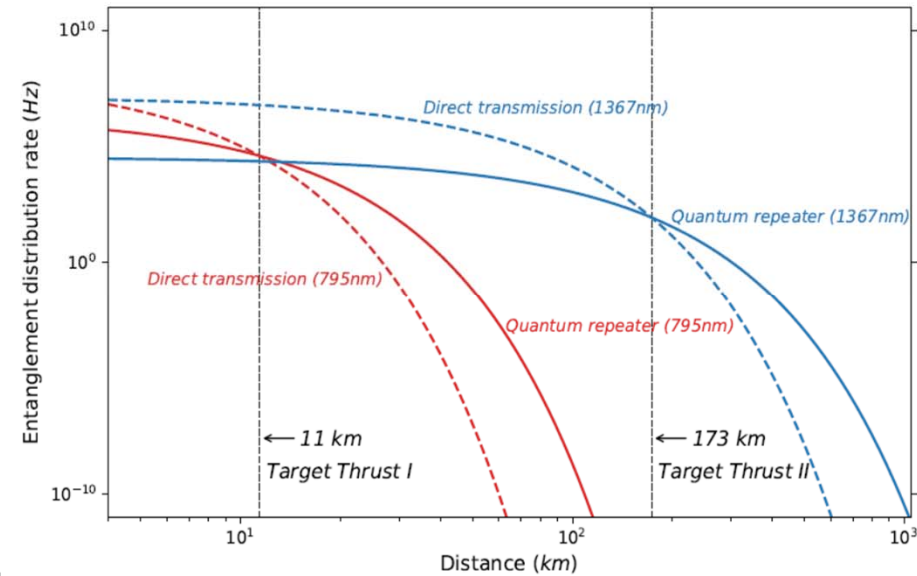
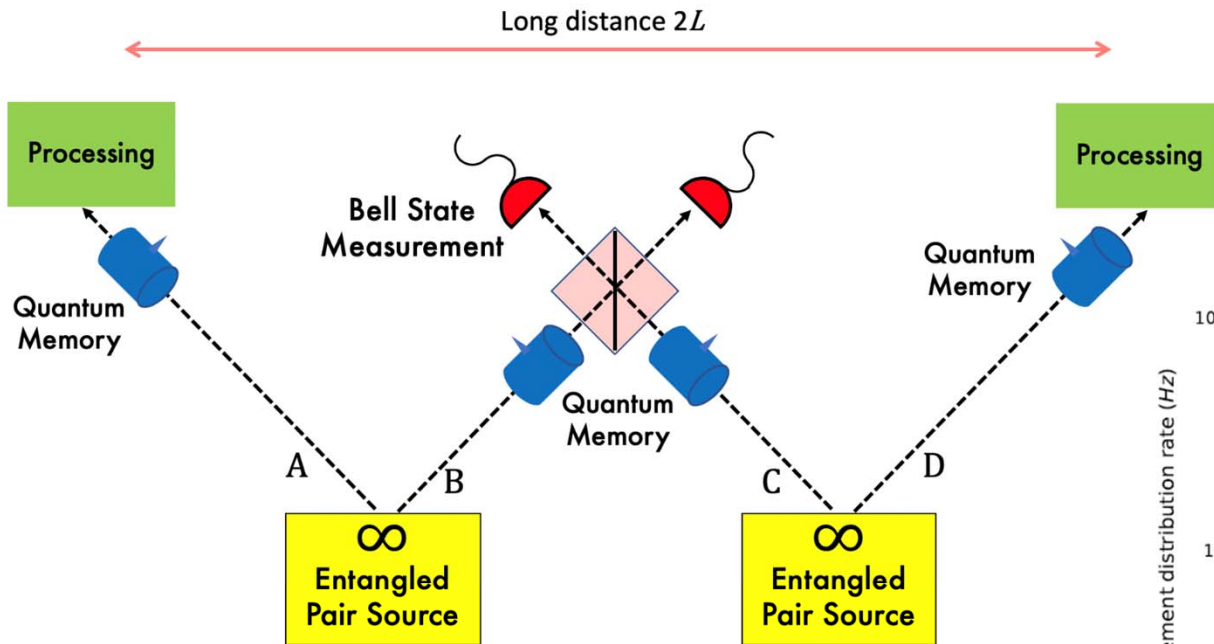
Tenerife QN



Vienna QN



Quantum Repeaters

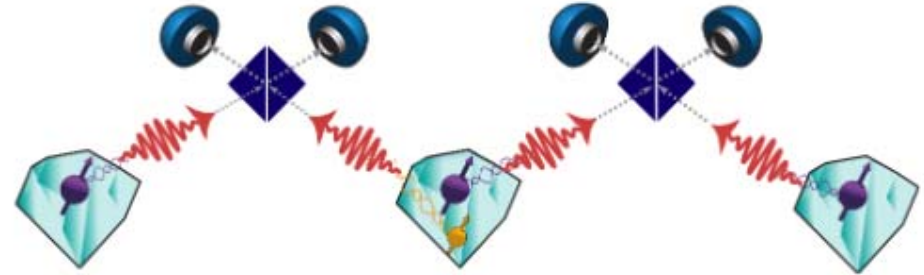


- Good entanglement sources compatible with QMs.
- Quantum Memories with good efficiency, fidelity and storage time.
- Entanglement distribution using optical fibers.
- All connections must preserve entanglement with high fidelity

Types of quantum light-matter interfaces (QLMI)

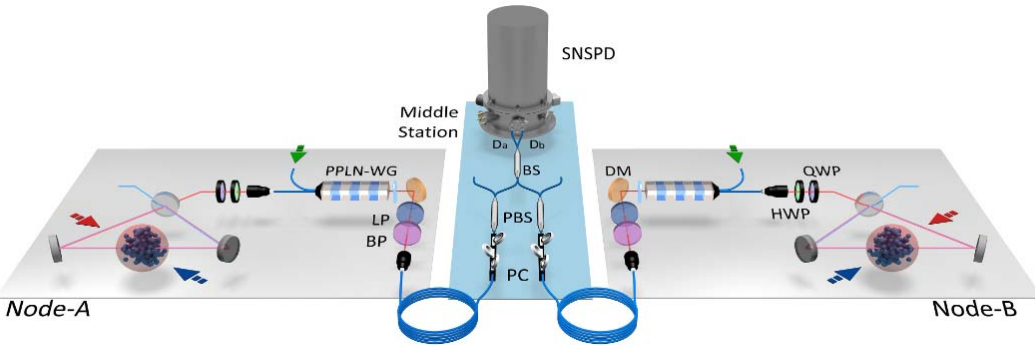
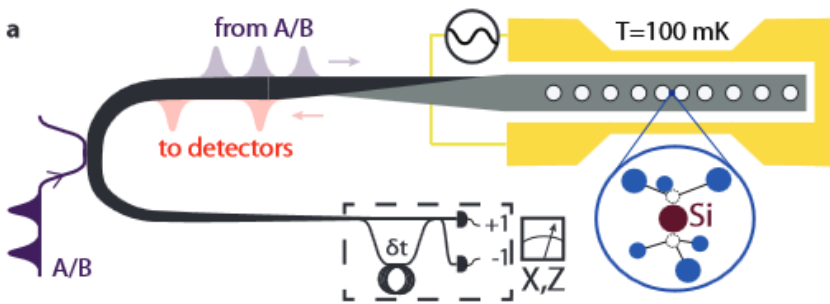
Type I Read-out QLMI (Q-registers)

(Atomic ensembles: USTC China, Barcelona, Caltech)



(SiV centers: MIT, Harvard, USA)

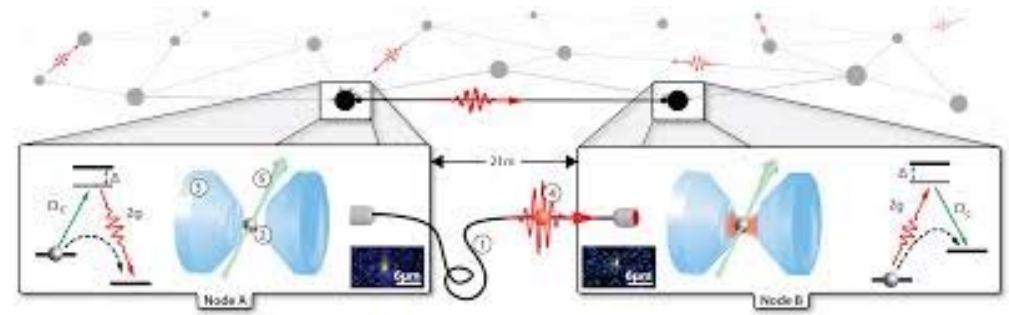
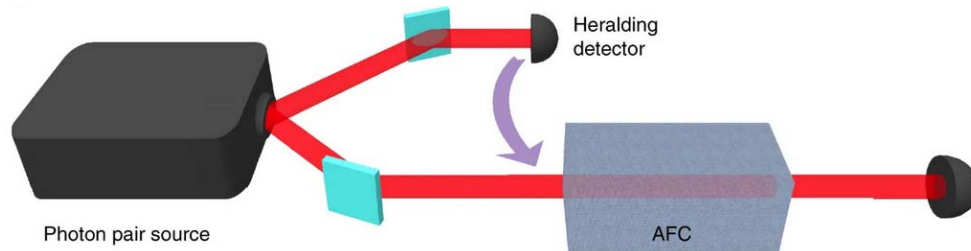
(NV Diamond centers: TU Delft, Chicago/Argonne)



Types of quantum light-matter interfaces (QLMI)

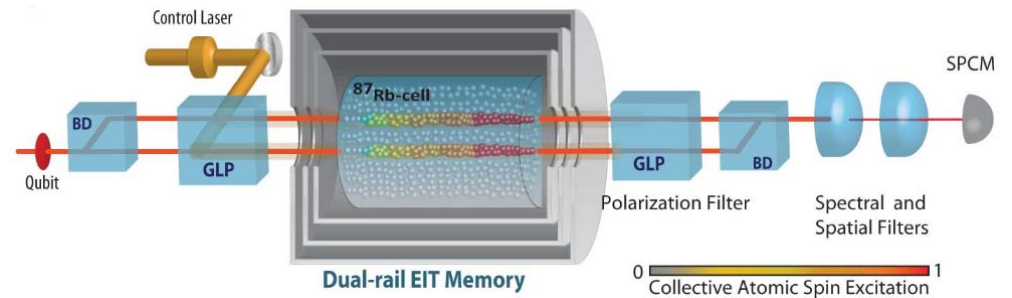
Type II In-out QLMI (Q-memory buffer)

(Single-atoms: MPQ, Munich)



(Rare-earth doped crystals: MPQ, Munich)

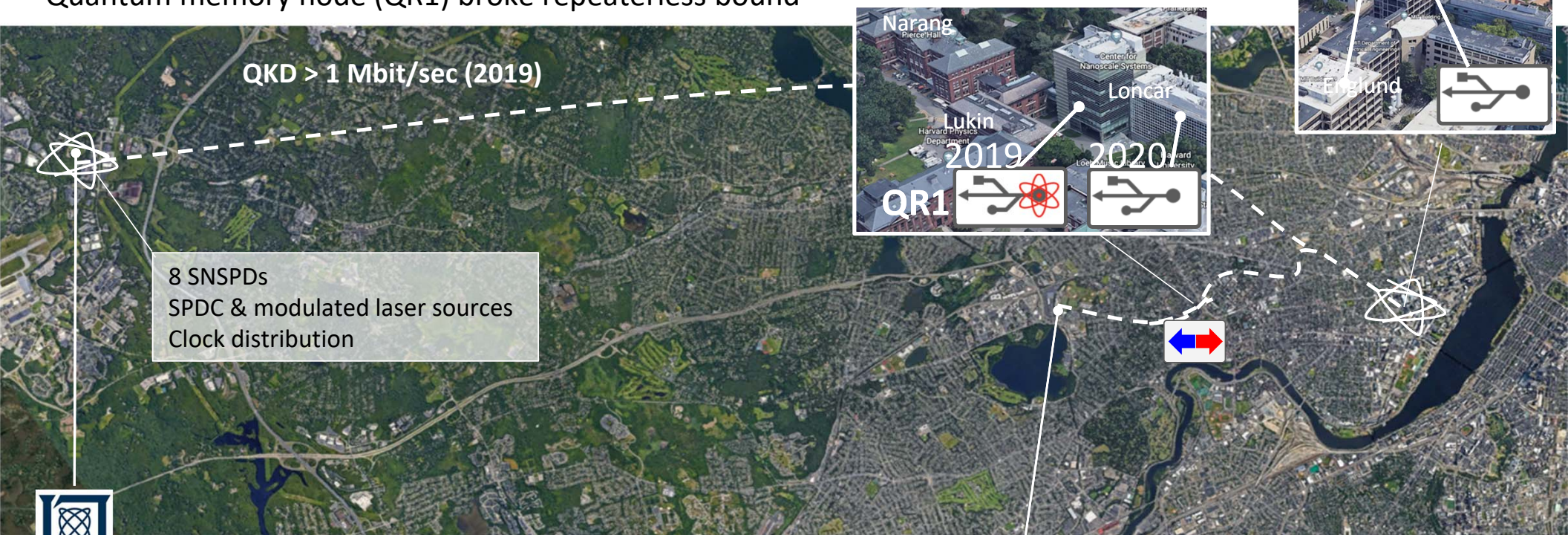
(Room temperature ensembles: Stony Brook, Oxford)



Boston-Area Quantum Testbed



Validated for state-of-art quantum secure comm* [>1 Mbit/sec @16 dB, > 20 Mbits/s local]
Quantum memory node (QR1) broke repeaterless bound

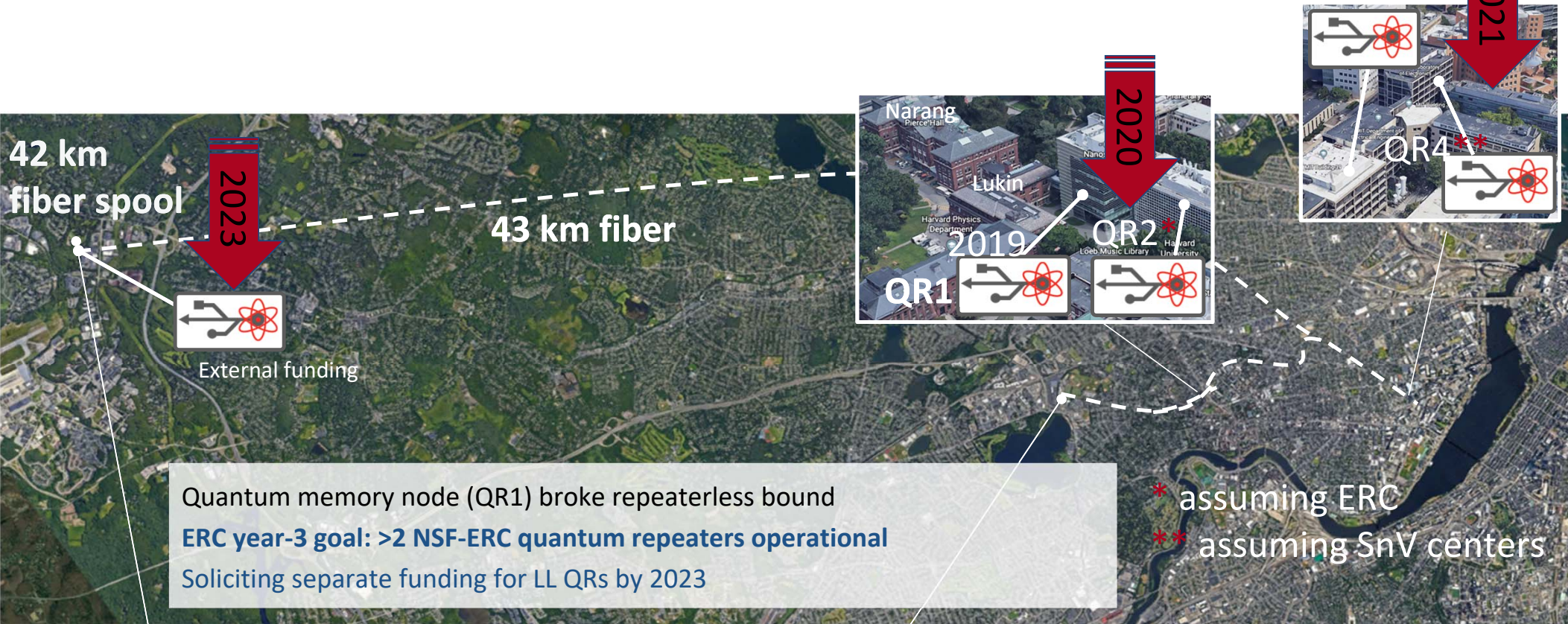


*C. Lee et al, Opt. Express **27** (2019); D. Bunandar et al, PRX **8**, 021009 (2018)

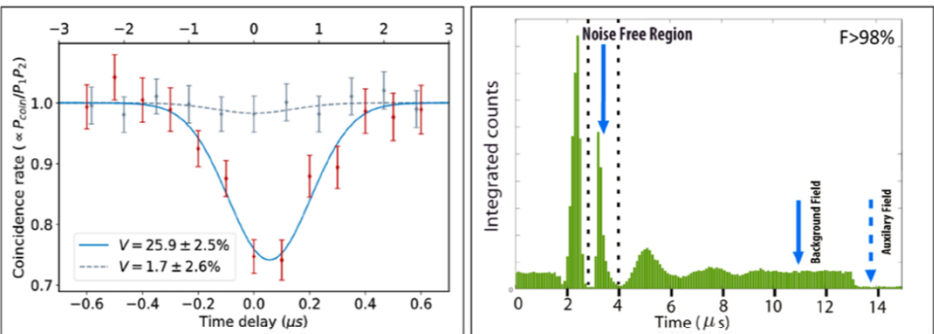
Courtesy Dirk Englund



Quantum Repeaters Upgrade

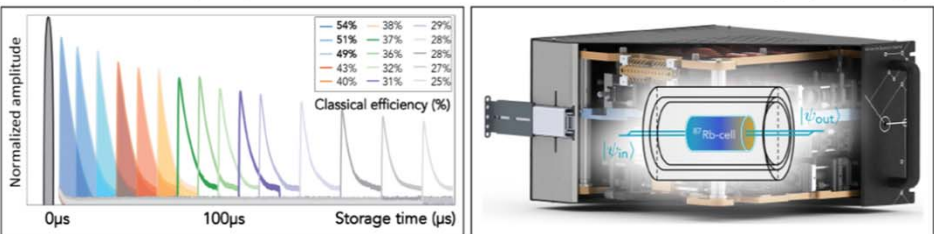


Available quantum technology in SBU quantum network



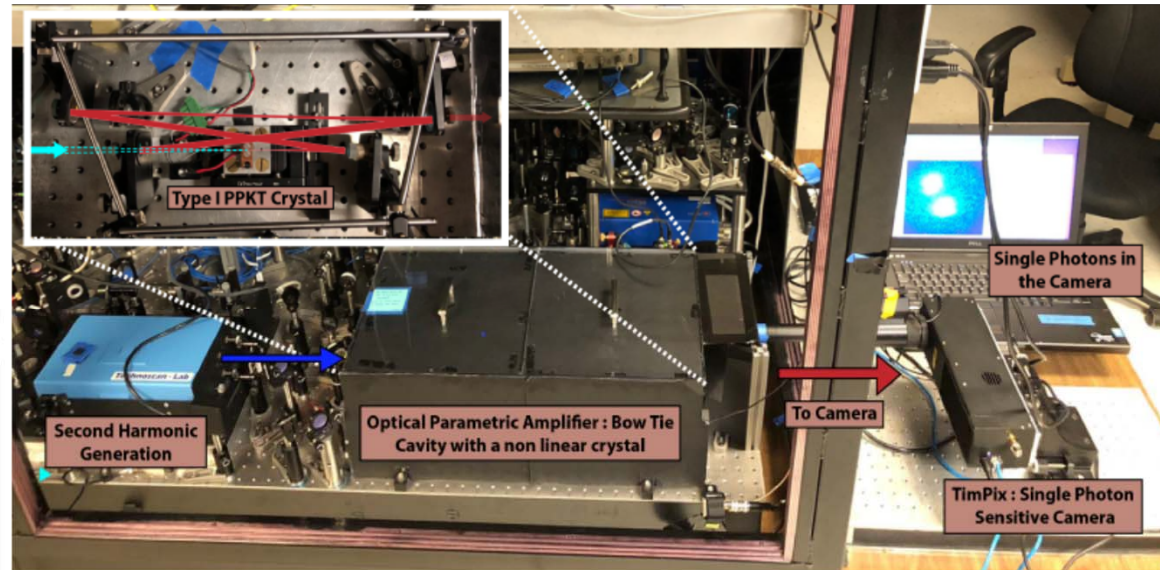
Two-memory Hong-Ou-Mandel interference

Ultra-low noise single-photon regime



Long coherence times

Room-temperature deployable quantum memory



Quantum memory buffers:

- High-Fidelity ($\sim 99\%$)
- Storage efficiency ($\sim 50\%$)
- Storage time ($\sim 100\mu\text{s}$)
- Room-Temperature

- Resonant to ^{87}Rb absorption line
- Single photons with a 2 MHz bandwidth
- Entanglement production at $10^4/\text{sec}$ ratios.

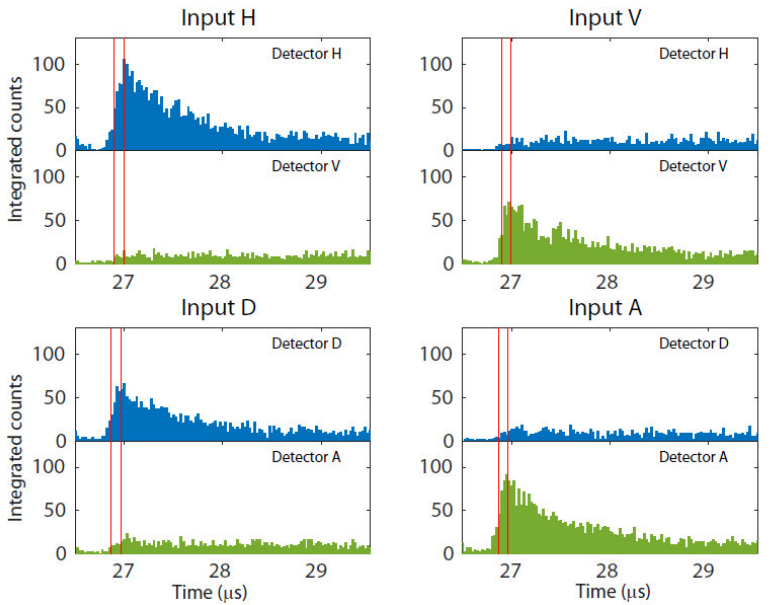
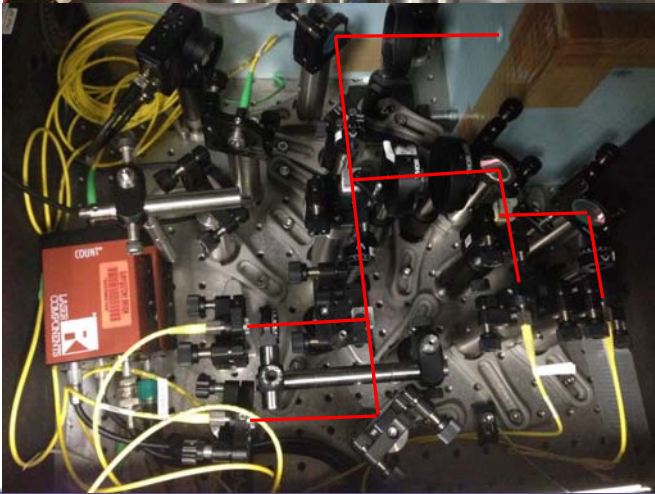
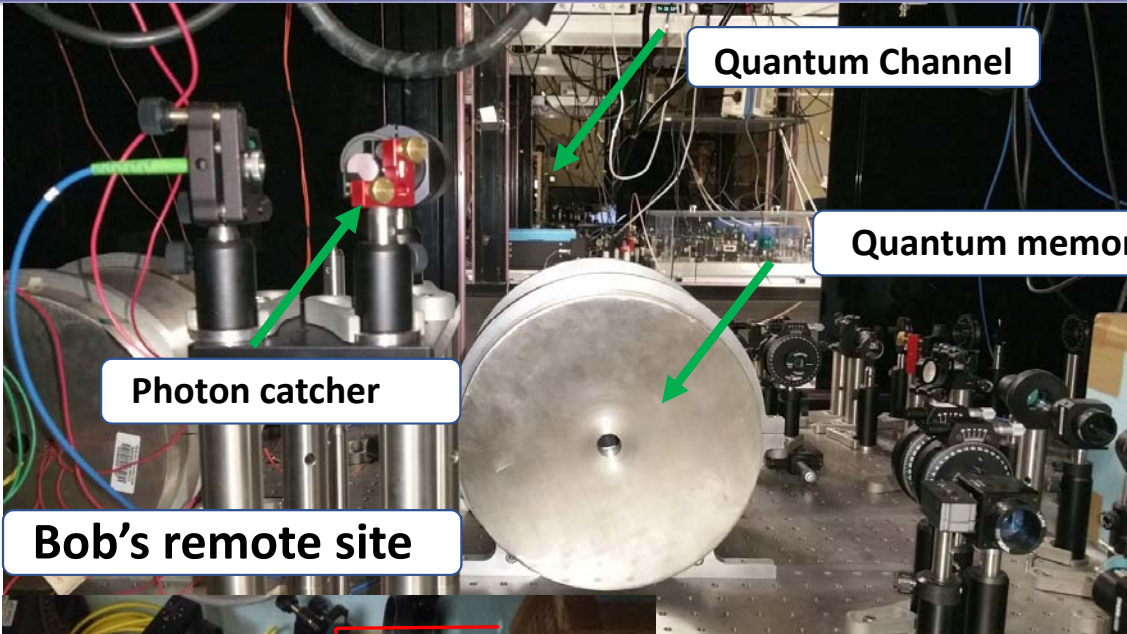
Scientific Reports 5, 7658 (2015).

Phys. Rev. Applied 8, 034023 (2017).

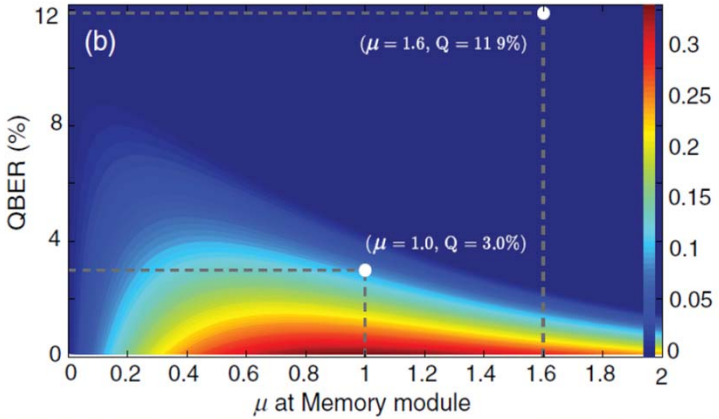
Phys. Rev. Applied 8, 064013 (2017).

Patent pending: PCT/US19/24601 (2019)

Quantum Network SBU: random polarization qubits and quantum cryptography



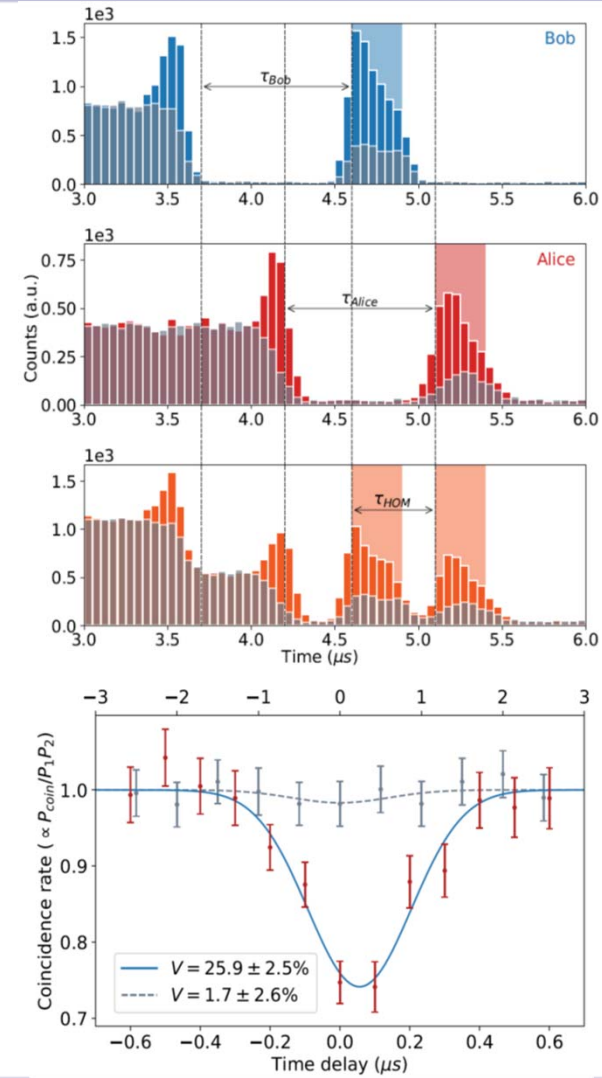
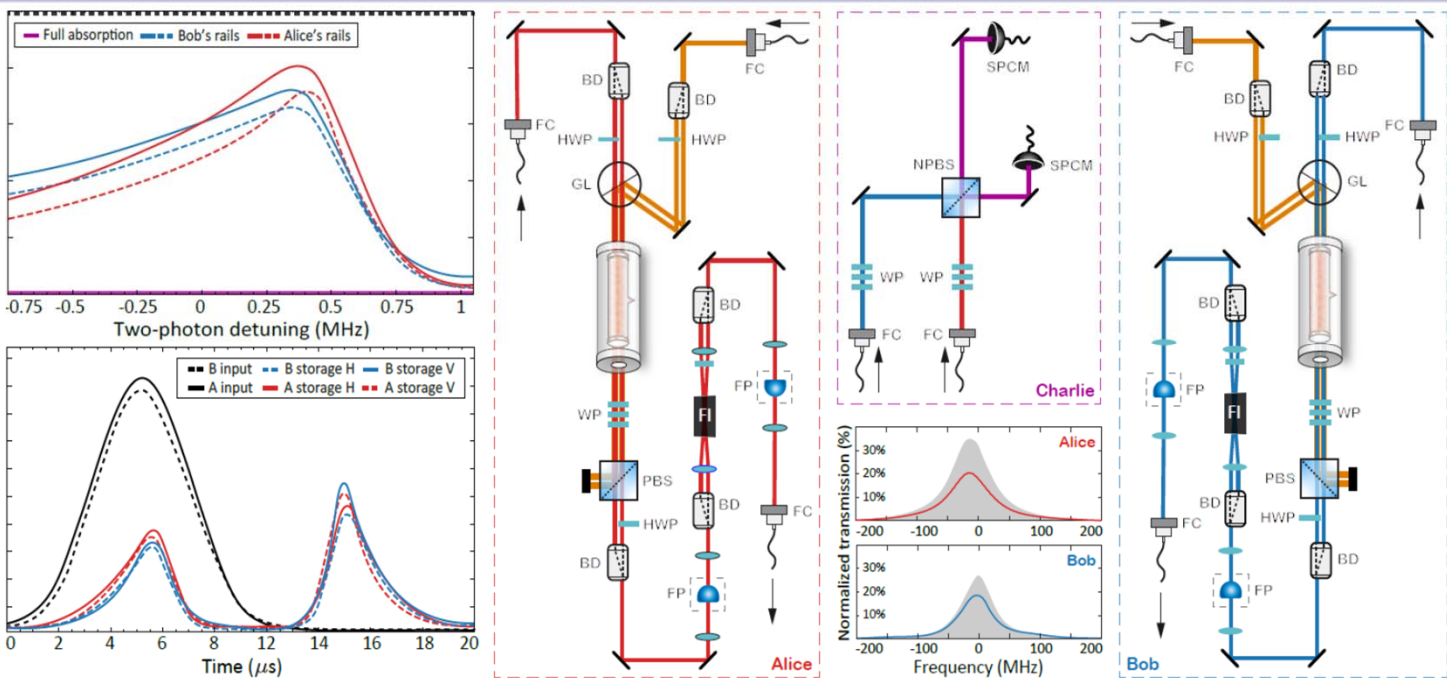
$$R = \mu(e^{-\mu}(1 - H(Q_X)) - H(Q_Z)f(Q_Z))$$



- On average 1.6 photons per pulses before the memory
- QBER of ~3.0% for Z and X bases

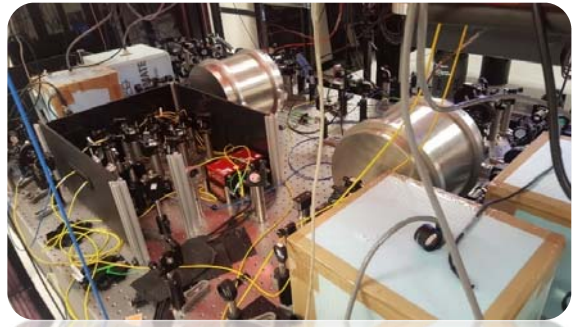
Phys. Rev. Applied 8, 064013 (2017)

SBU room temperature quantum network



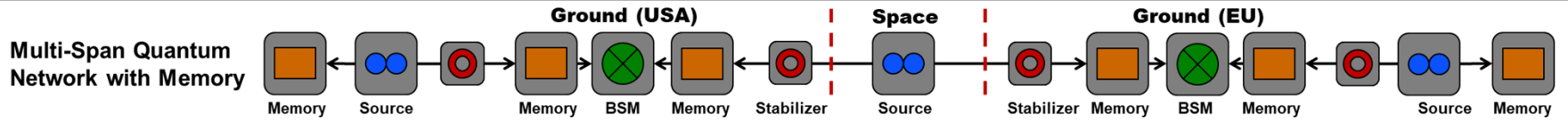
- Four matched EIT resonances.
- Four simultaneous storage experiments.
- Two polarization independent single photon level filters

arXiv:1808.07015v2 (2019)





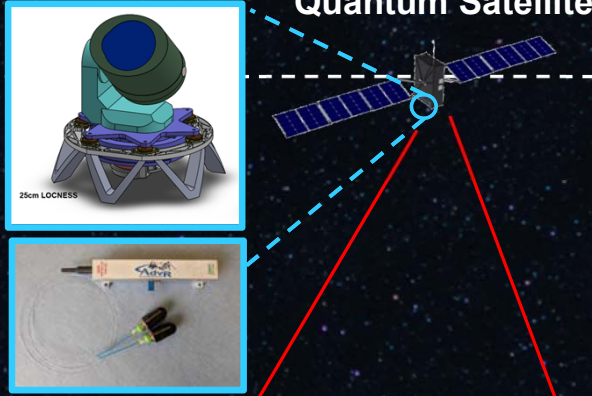
Marconi 2.0 – US-European MEO Dual-Span Ground-to-Ground Entanglement Swap Demonstration



Medium-Earth Orbit (MEO)

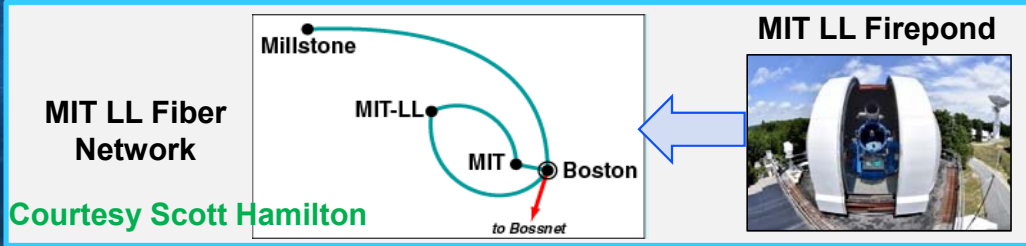
Large-Aperture Terminal

10-GHz Entanglement Source



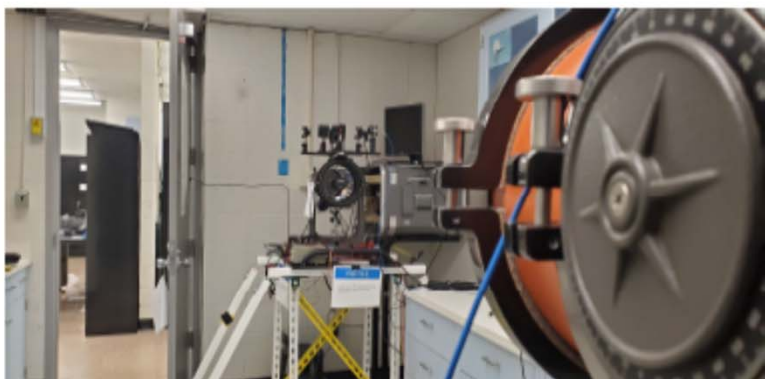
- MEO satellite with two quantum terminals provides trans-Atlantic ground-to-ground entanglement swap
- Pathfinder Goals:
 - Multi-span scalable quantum network demonstration
 - Facilitates ground terminal and quantum technology partnering
- Multiple passes per day with trans-Atlantic ground terminal line-of-sight
 - ~10-min session per pass, ground elevation angle $>20^\circ$
 - ~4K entanglement distribution and ~400 swap events per pass

Ground Stations





Laser equipment and experimental enclosures installed



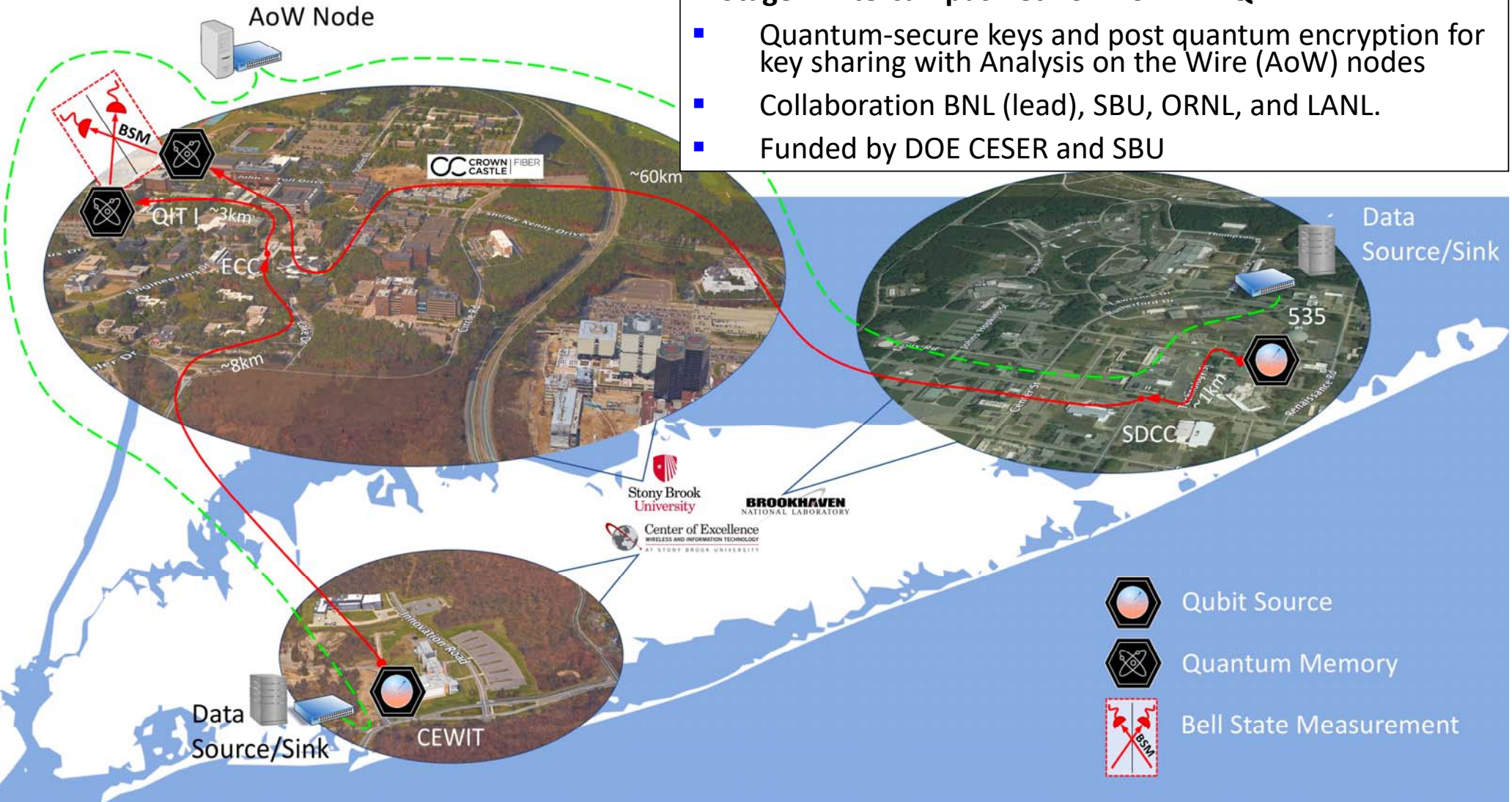
Free-space long distance quantum link in development



Portable entanglement source in construction

• **Stage I: Intercampus network for MDI QKD**

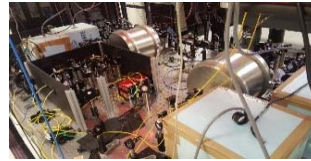
- Quantum-secure keys and post quantum encryption for key sharing with Analysis on the Wire (AoW) nodes
- Collaboration BNL (lead), SBU, ORNL, and LANL.
- Funded by DOE CESER and SBU



Quantum Memory



Quantum Memories and Bell measurement



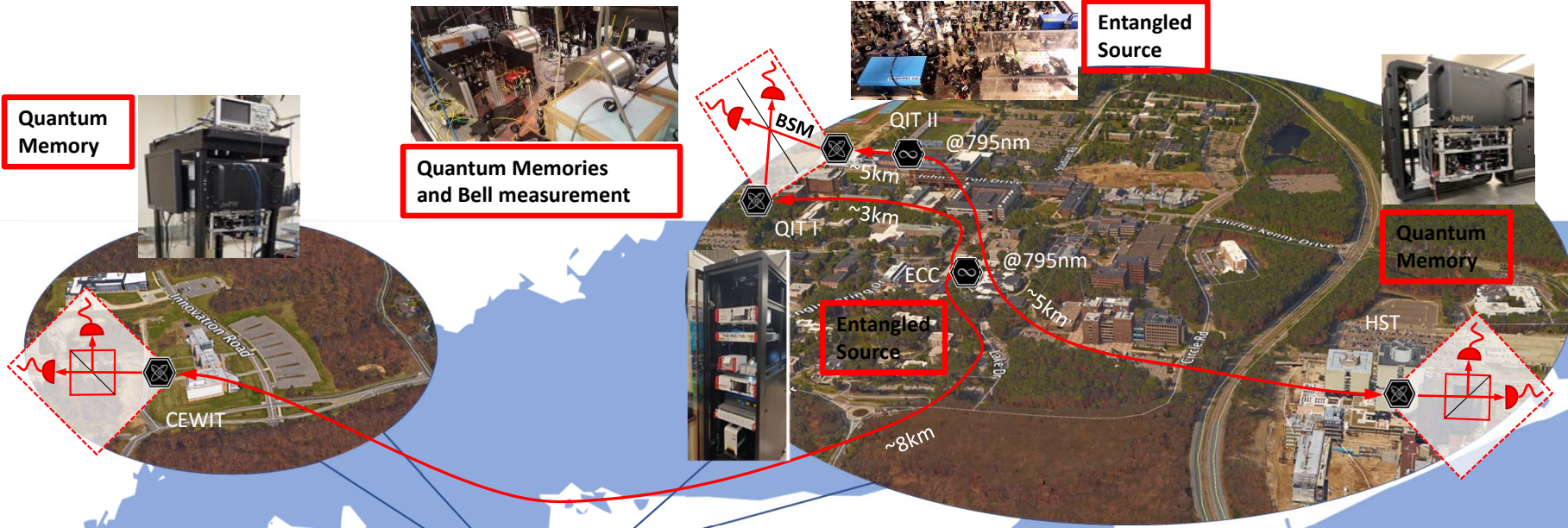
Entangled Source



Quantum Memory

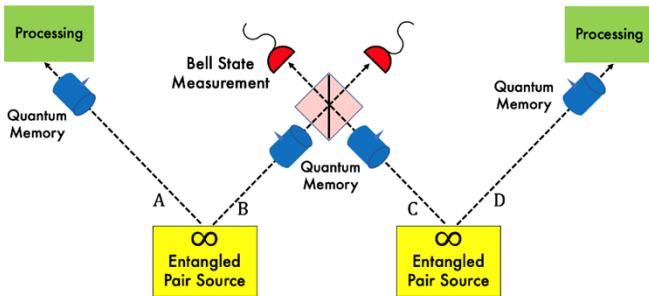


Entangled Source



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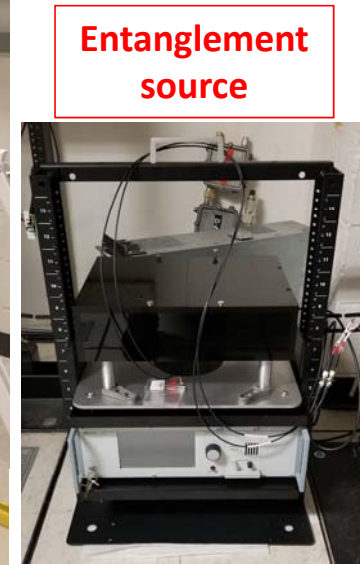
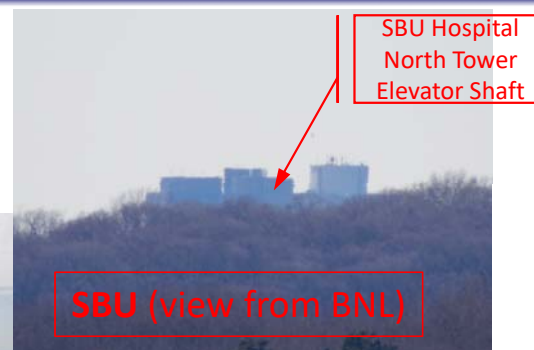
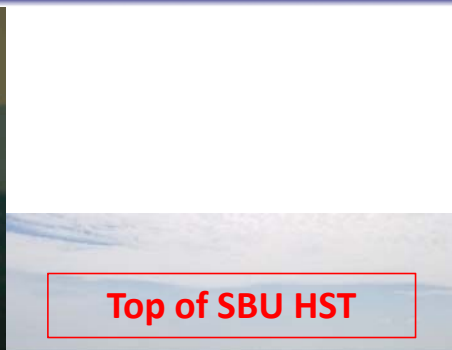
Long distance $2L$

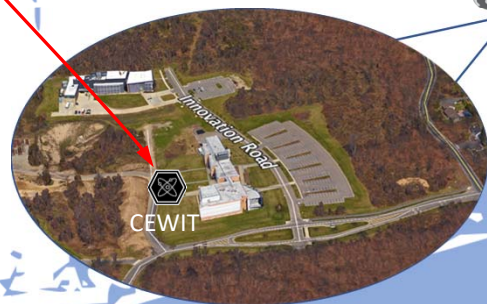
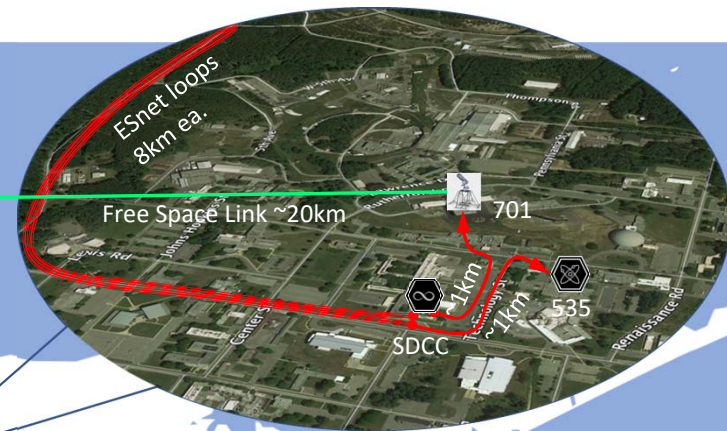
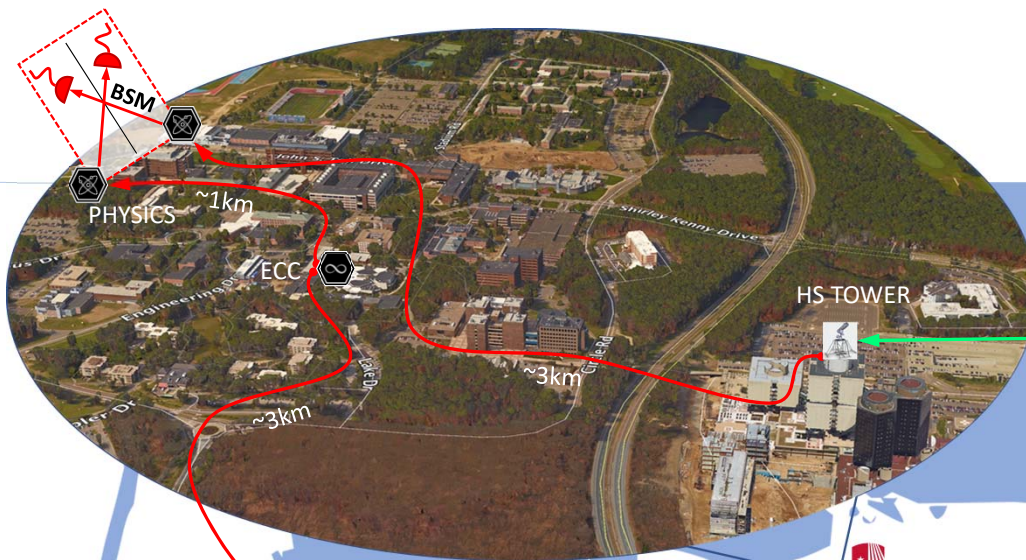


Stage II: Quantum repeater prototype @ 795 nm

- Memory assisted entanglement swapping.
- Entanglement distribution beyond fibre losses.
- Funded by NSF, DOE ASCR, SBU and Simons Foundation

Quantum entanglement distribution between BNL and SBU





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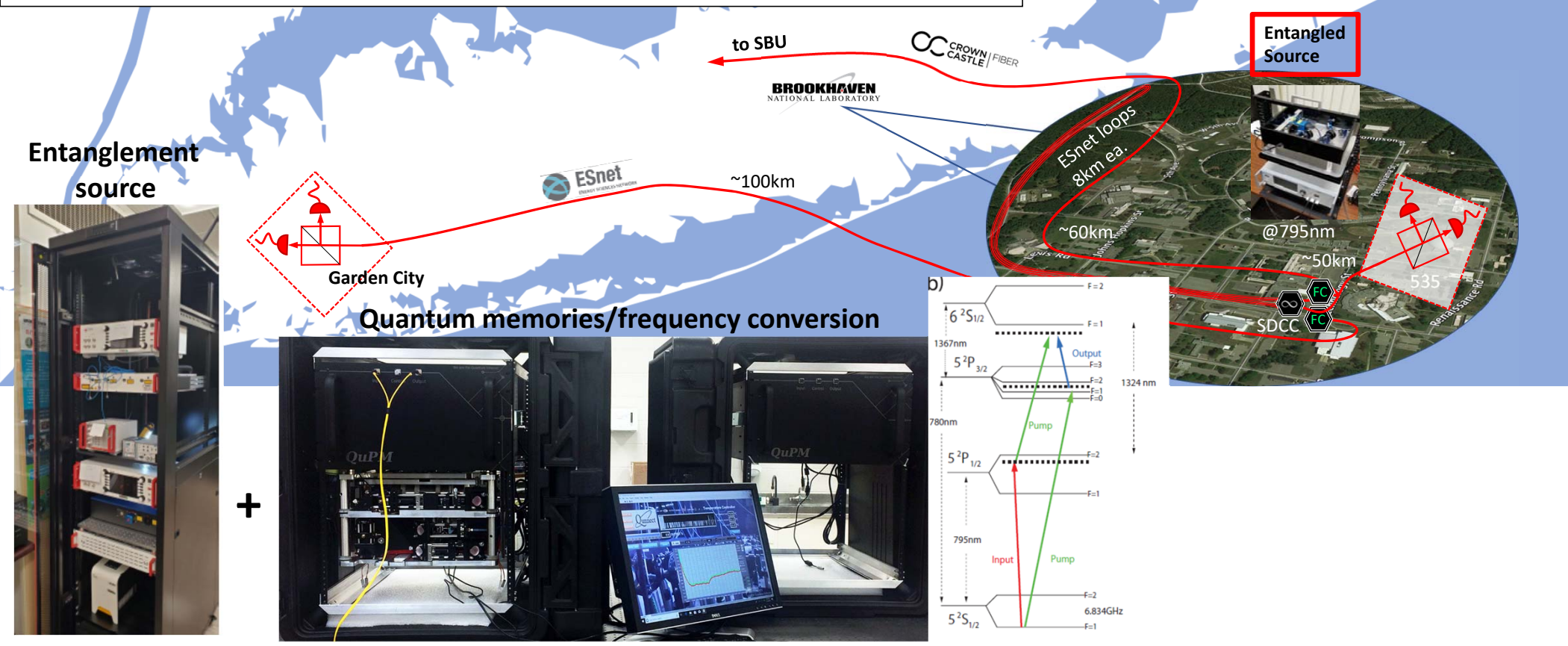
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AT STONY BROOK UNIVERSITY

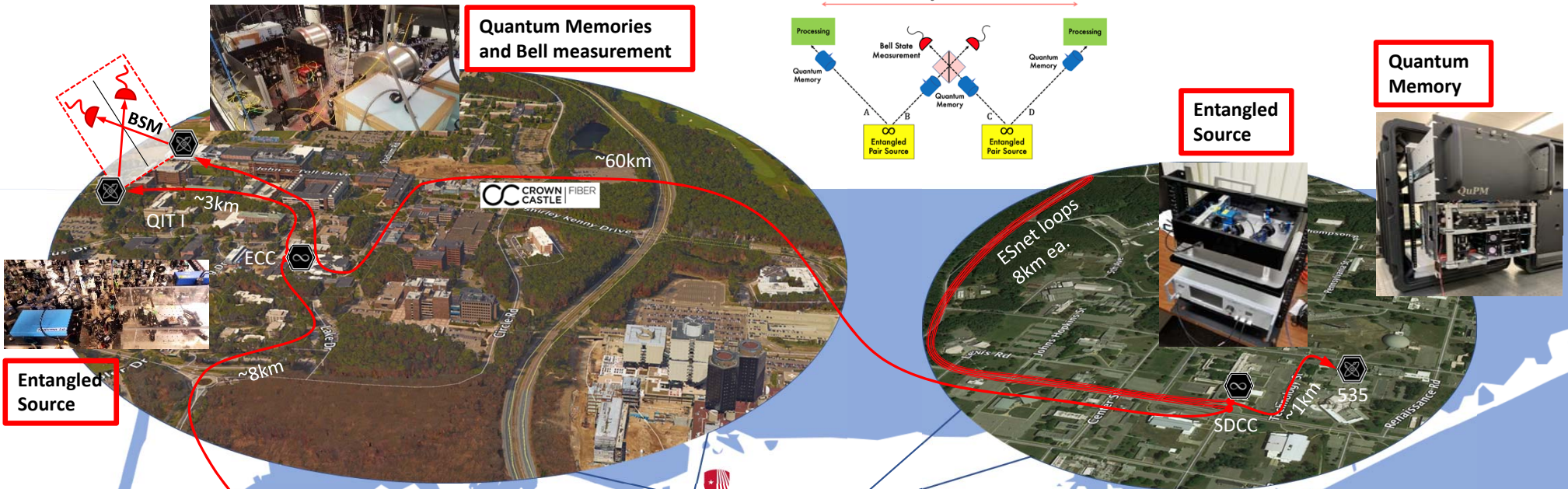
Stage III: Free space expansion to BNL

- Long distance operation at 795 nm.
- Entanglement distribution between SBU and BNL.
- Funded by SBU and BNL PDs

Stage IV: Entanglement distribution at telecom wavelengths.

- Memory-compatible telecom entanglement.
- Polarization compensation over long distances.
- Funded DOE ASCAR and BNL LDRD.





Quantum Memories and Bell measurement

Entangled Source

Quantum Memory

Entangled Source

Quantum Memory

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Stage V: Quantum repeater prototype @ 1324 nm

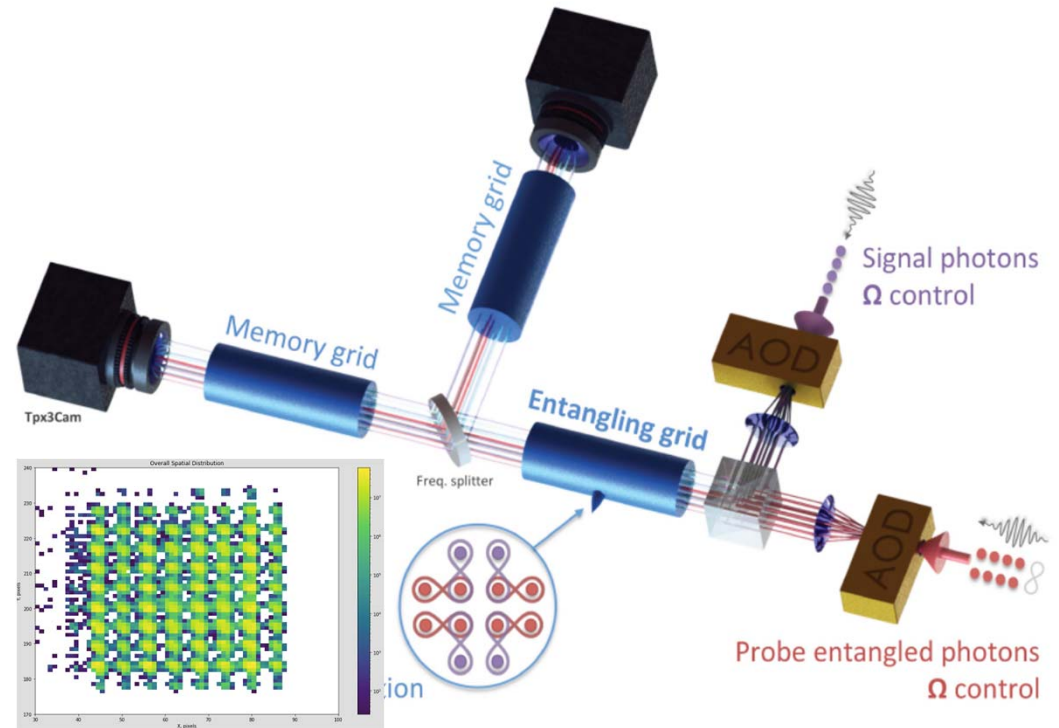
- Memory assisted entanglement distribution > 170 km.
- First prototype of a long-distance quantum repeater.
- Funded by DOE ASCR and DOE CESER.

Research questions I

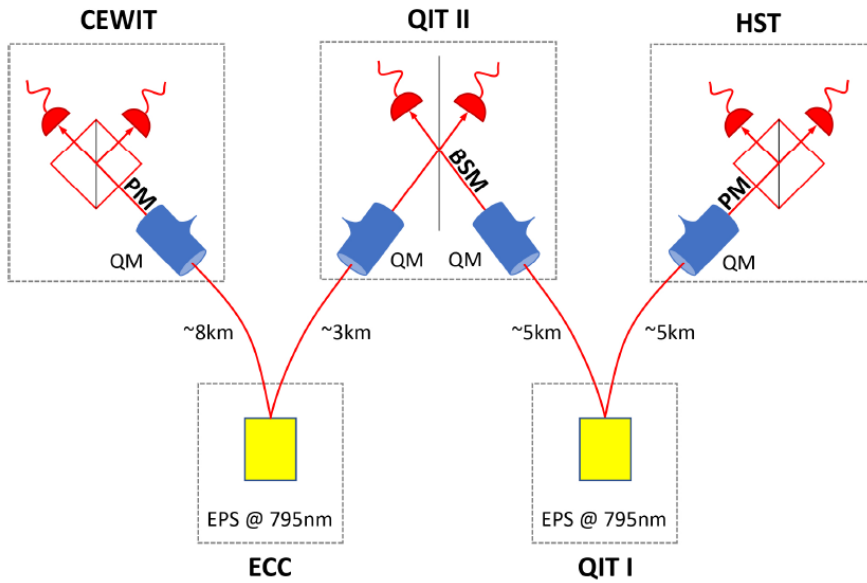


- Deployable “plug-tune & play” systems.
- Miniaturized for real-networks & outside of the laboratory storage.

- Increase the memory depth.
- Multiplexing and routing to enhance the network rates.



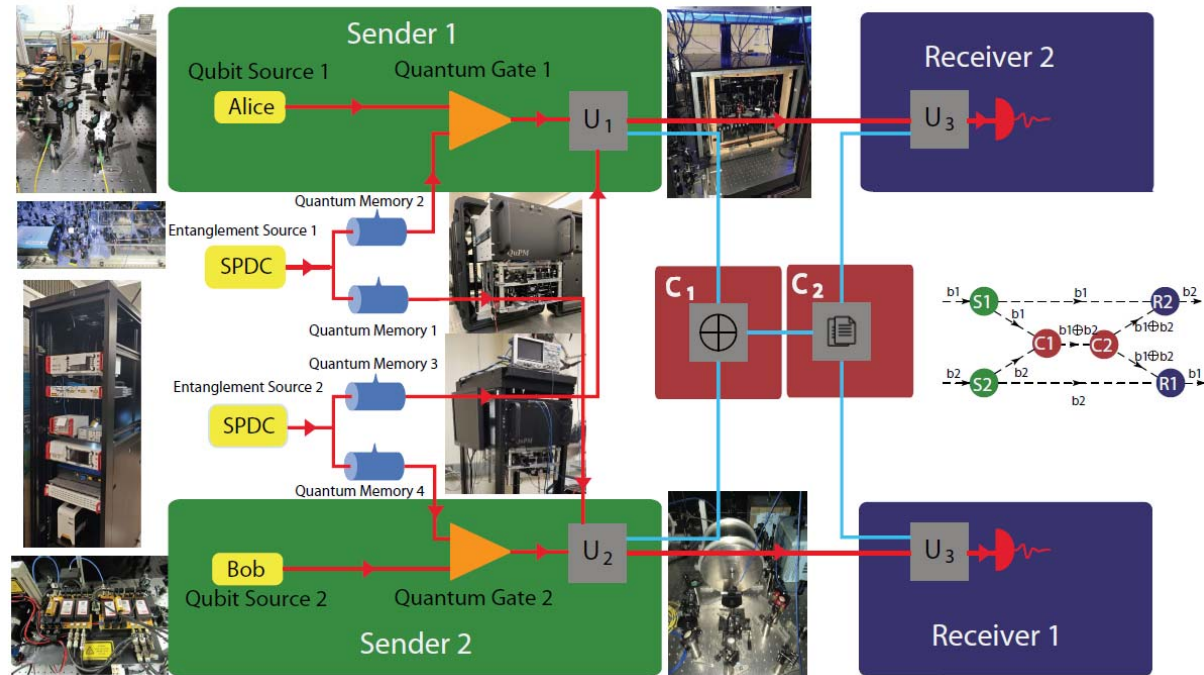
Research questions II



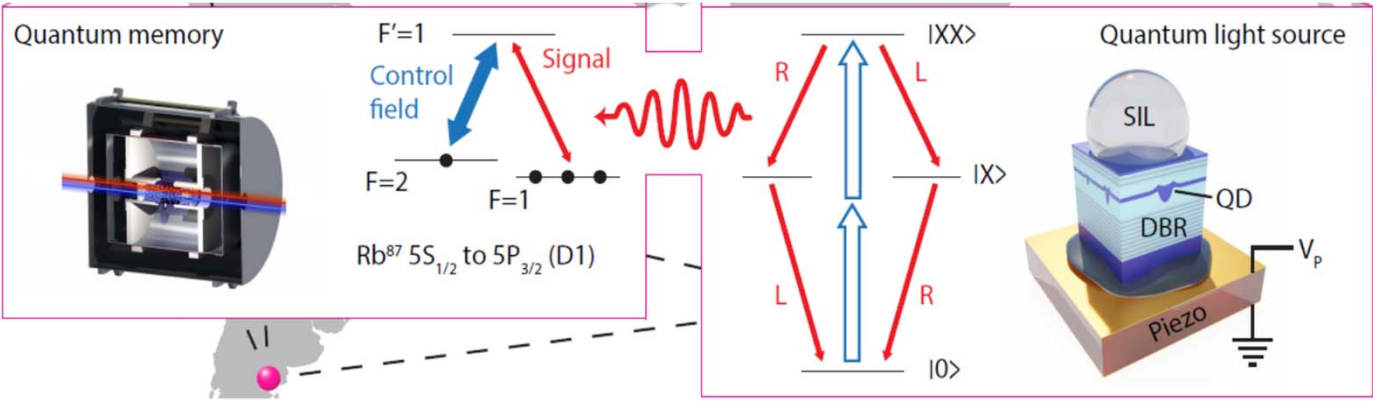
• Demonstrate quantum-memory-assisted entanglement swapping in a full quantum repeater network.

• Add quantum-gate capabilities to the entanglement distribution networks.

• Investigate error correction.

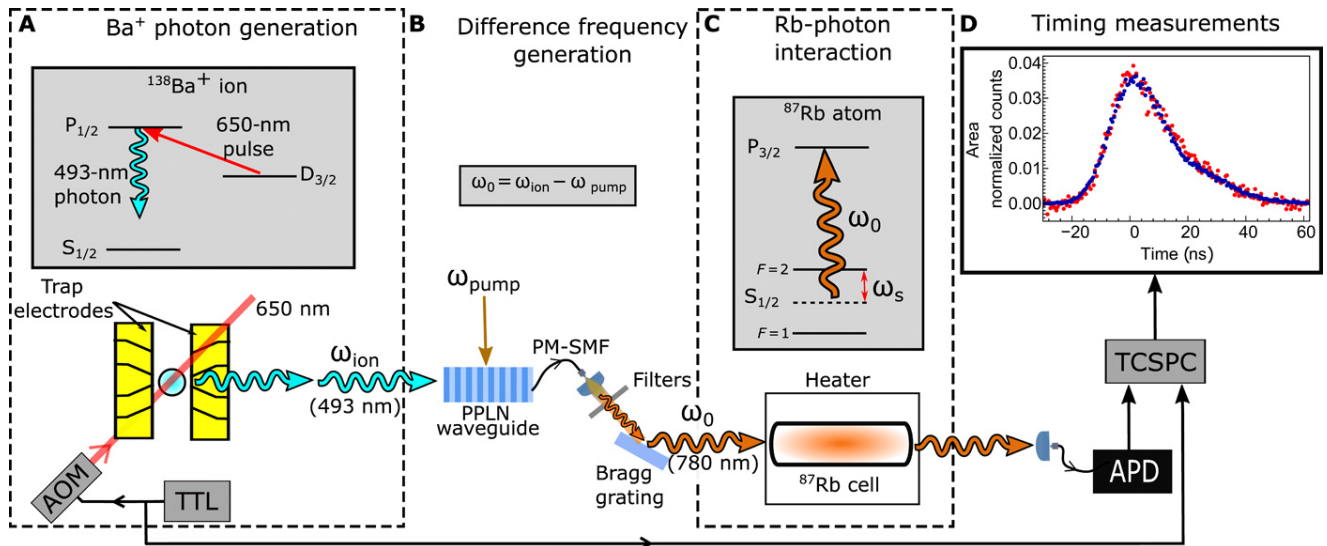


Research questions III



- Increase entanglement generation rates.
- Interface hybrid systems materials/light/atoms.

- Interface different quantum light-matter systems.



Science Advances 5, eaav4651(2019)