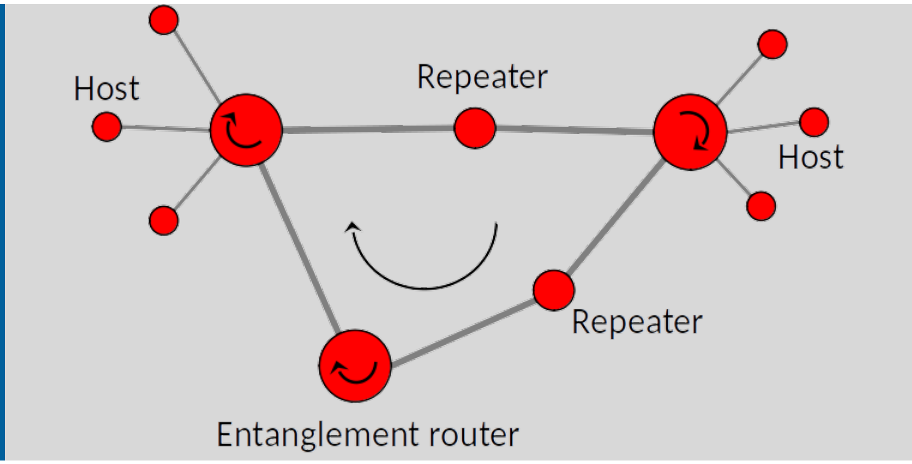
5GRP Workshop 2024

Argonne Quantum Network (ArQNet)



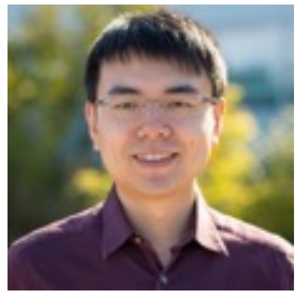
Rajkumar Kettimuthu

Argonne National Laboratory and The University of Chicago

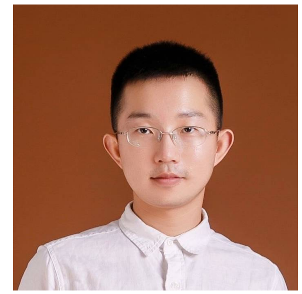
Sep. 17, 2024

Team


Joaquin Chung


Xu Han

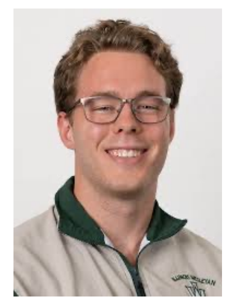

Md Shariful Islam


Caitao Zhan


Anirudh Ramesh


Ansh Singhal


Sagar Patange

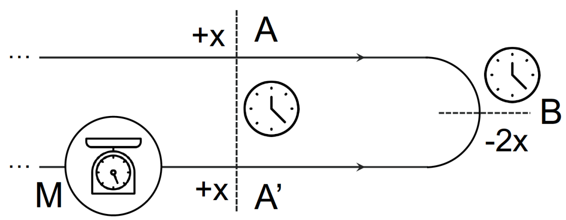

Ethan Lowder

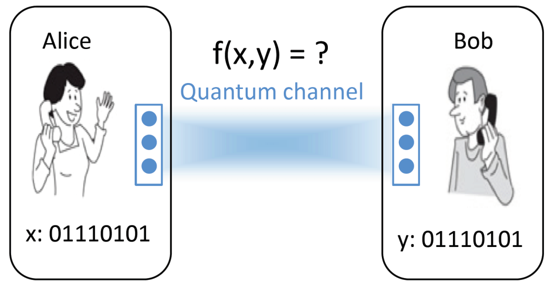
Outline

- Quantum network applications
- State of the art
- Challenges
- Argonne Quantum Network (ArQNet)
- Projects that use ArQNet
  - InterQnet
  - SeQUeNCe
- Metropolitan Scale Network
- Summary

Quantum Network Applications

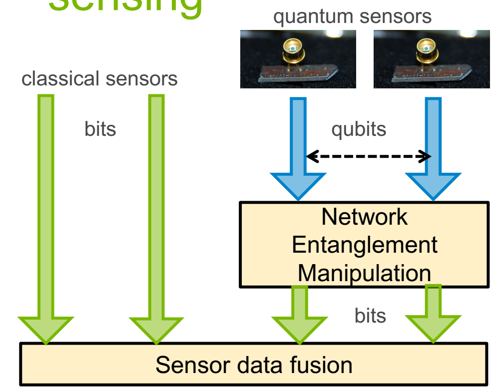
Clock synchronization



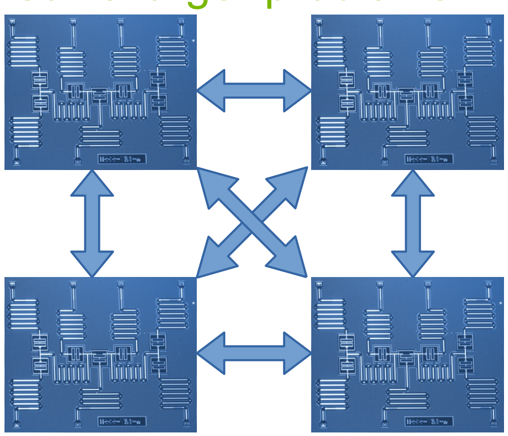


Distributed computing with less communication

Distributed quantum sensing



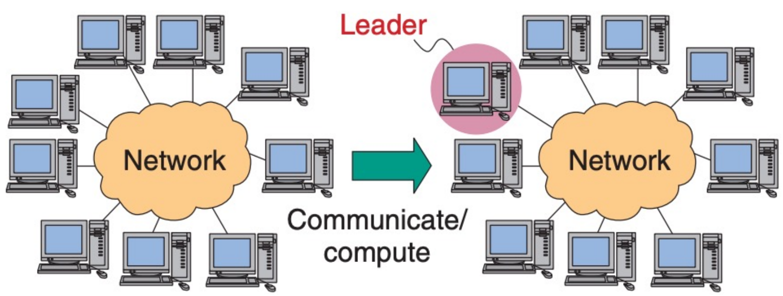
Connect multiple QPs to solve larger problems

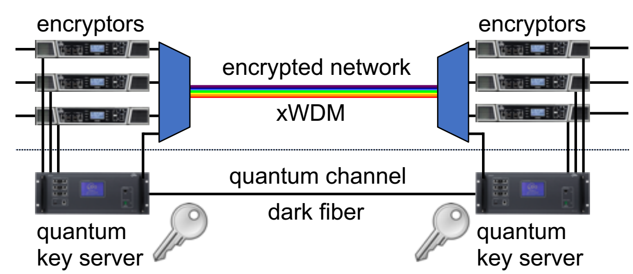


Distributed decision making

Leader election problem

Autonomous election of a leader by several computers



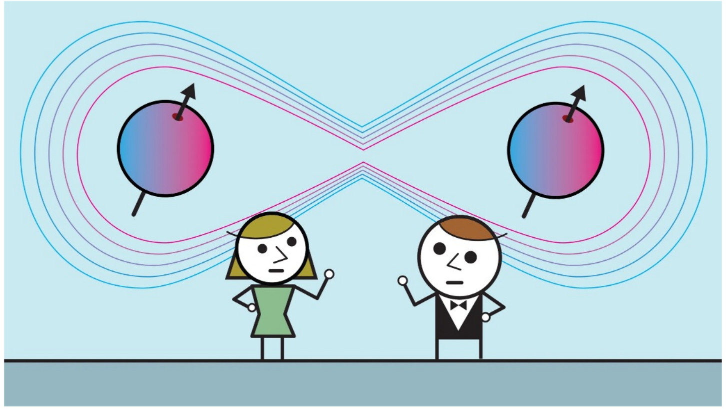


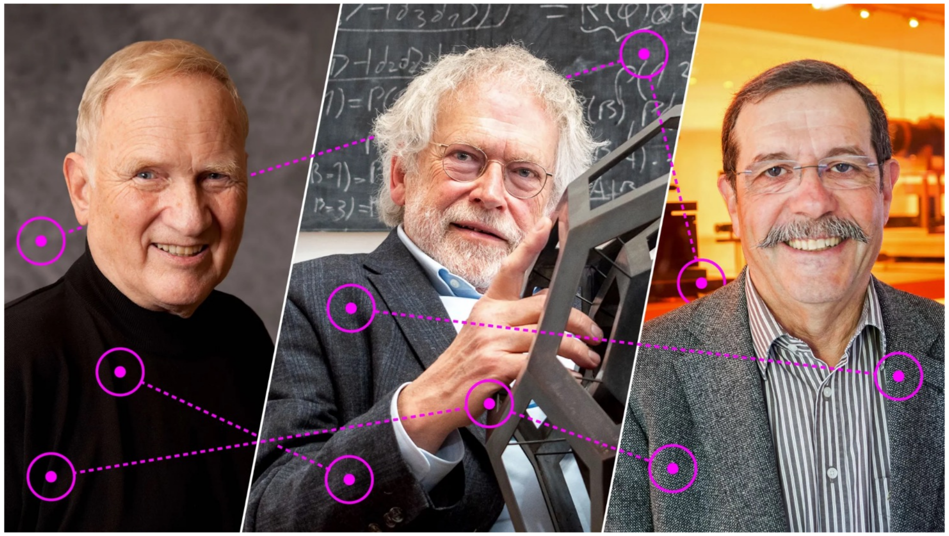
Quantum key distribution

Quantum Entanglement

Foundation for near-term quantum networks

Phenomenon in which two or more particles are connected in such a way that they cannot be described independently. Moreover, they will remain connected despite distance.

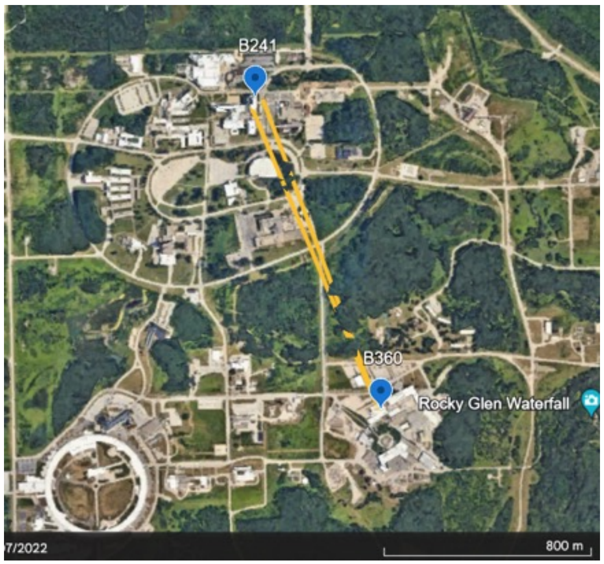




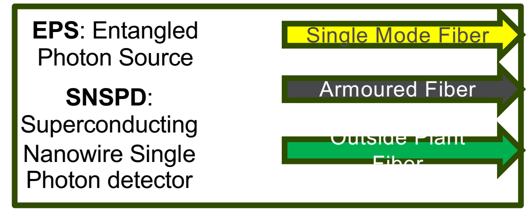
John Clauser, Anton Zeilinger and Alain Aspect, winners of the Nobel prize in Physics for their work in quantum entanglement

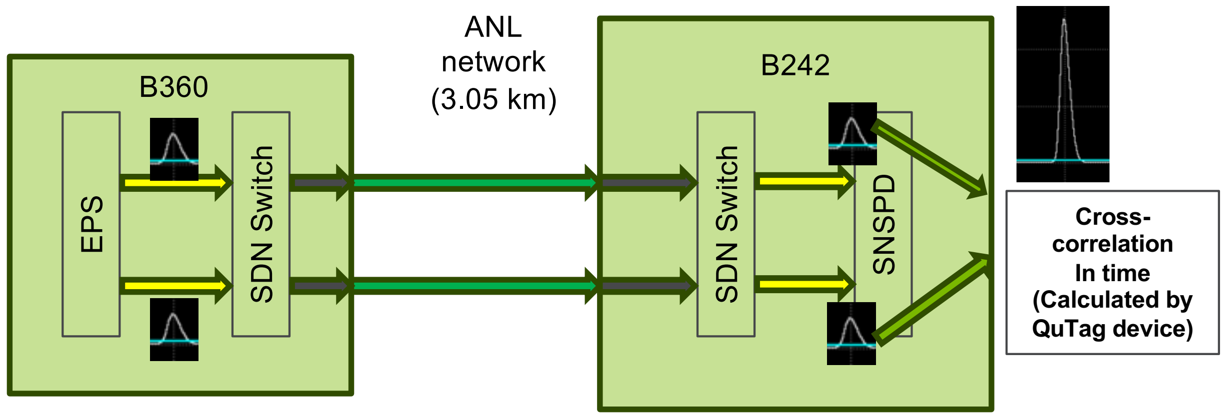
Remote Entanglement distribution at Argonne

Detection@ 241: Alan Dibos

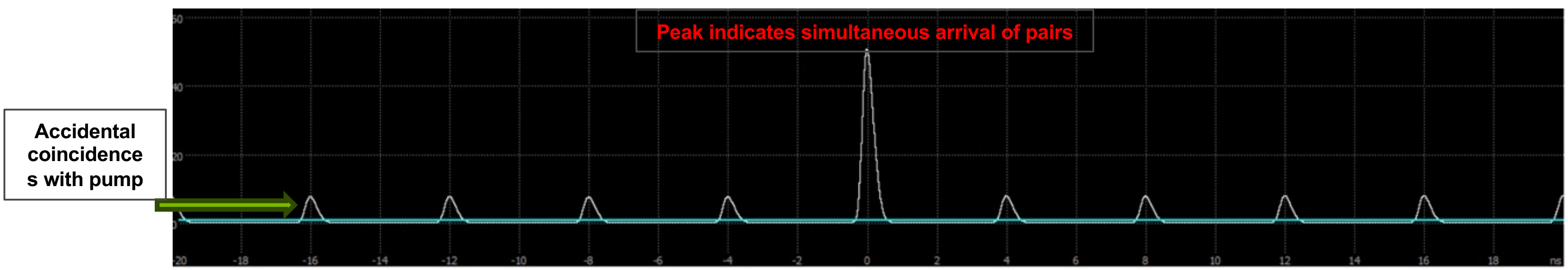


Source: B360
Detectors: B242
Total pair distance: 6.1 km
Total pair loss: 7.1 dB





Distribution@ 360: Anirudh Ramesh, Shariful Islam, Joaquin Chung

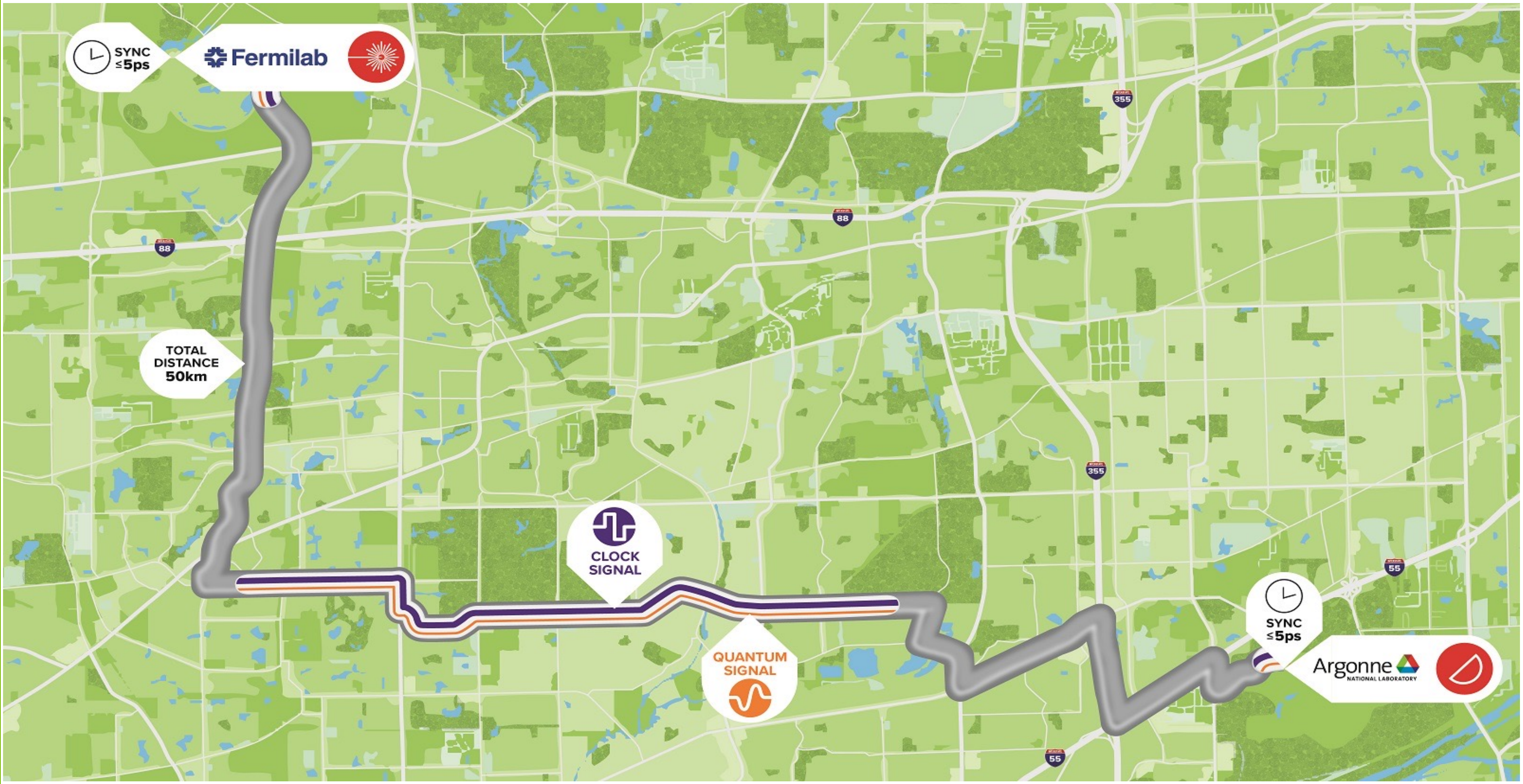


Cross-correlation $g^2(t)$ (Y-axis) vs time (ns, X-axis)

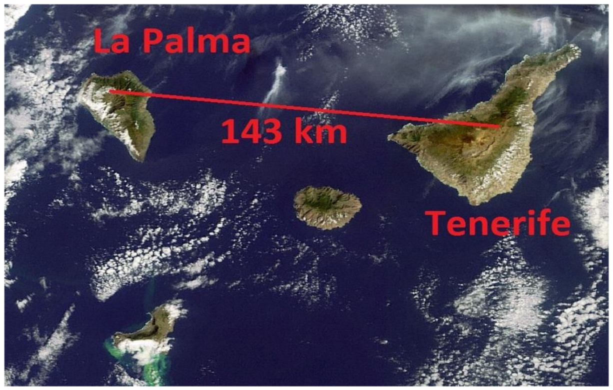
Entanglement Distribution Over a 26 Mile Loop

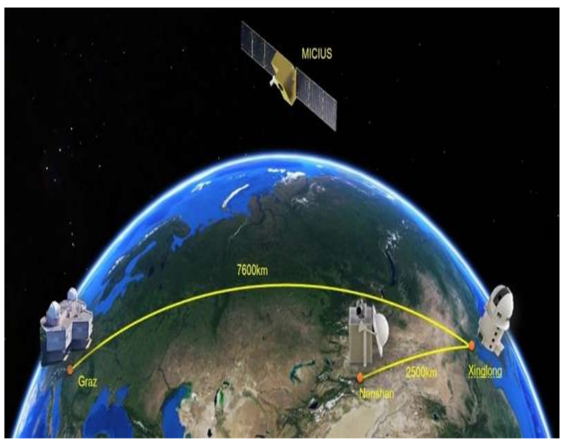
Awschalom, Dibos, Heremans et. al

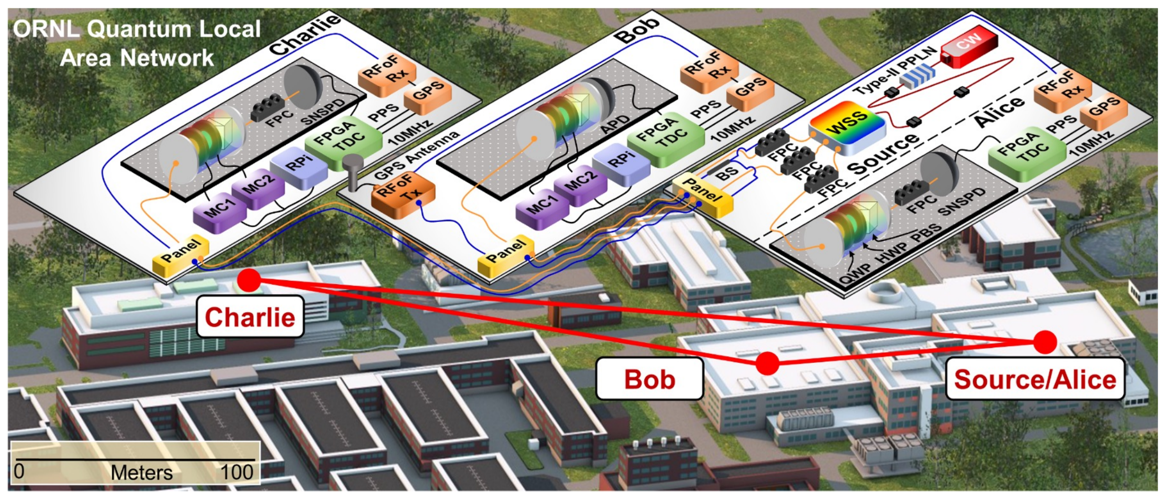
Remote Entanglement between Argonne and Fermi



Quantum Network Demonstrators







Scalability has emerged as a key challenge

Most quantum networking demonstrators focus on point-to-point or linear topologies

Great need to develop scalable architectures

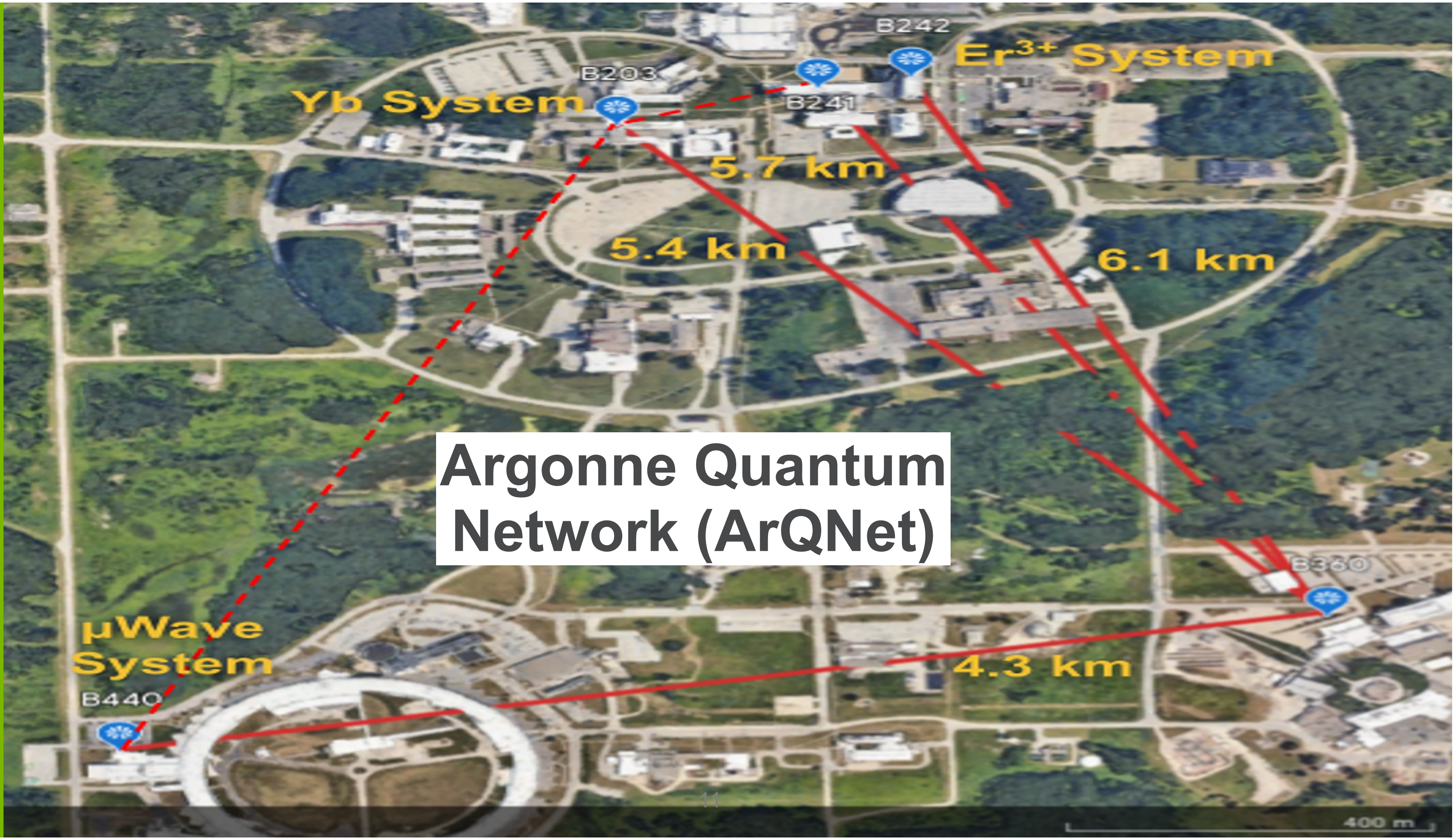
Campus-scale to metropolitan and regional scales

Go beyond linear topologies

Demonstrate multi-user, multi-node

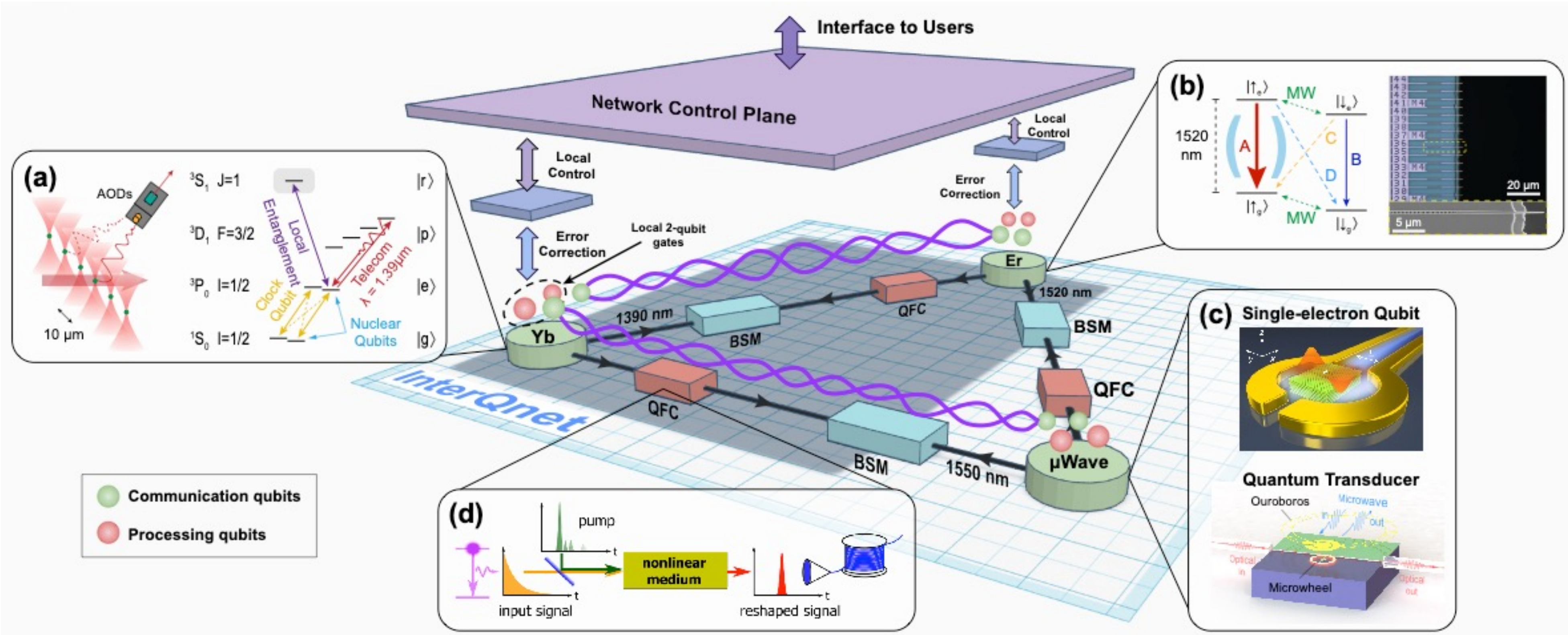
Hardware heterogeneity, number of devices, applications and concurrent users

Fully dynamic and automated quantum networks


B242
Er^{3+} System
B203
Yb System
B241
5.7 km
5.4 km
6.1 km
Argonne Quantum Network (ArQNet)
B360
μWave System
B440
4.3 km
400 m

InterQnet

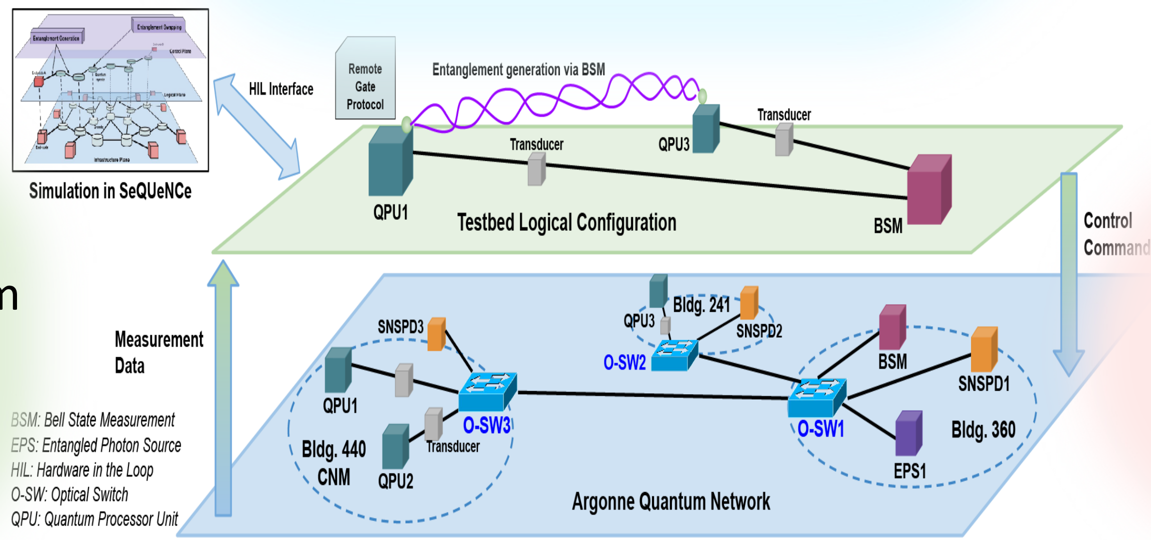
Integrating heterogeneous qubit platforms developed at Argonne



Connected Superconducting Quantum Processor Units

Thrust 1: Develop transmon qubit-based quantum processor units (QPUs) and electro-optic (EO) quantum transducers

Thrust 3: Develop quantum network services for DQC

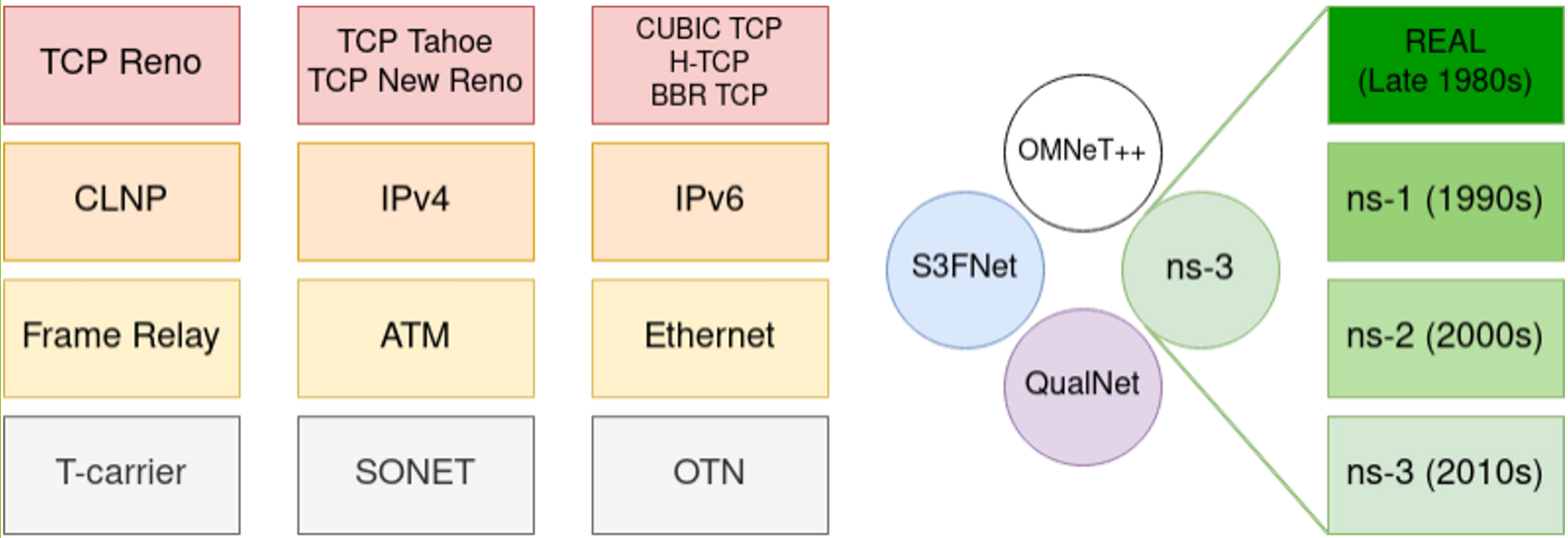


Thrust 2: Demonstrate remote qubit gates

Evolution of classical network

Simulators played a major role

L. Kleinrock, **Analytic and simulation methods in computer network design**, Proceedings of the spring joint computer conference, May **1970** Pages 569–579 https://doi.org/10.1145/1476936.1477022



Technologies for Quantum Networks

Many alternatives for various functionalities

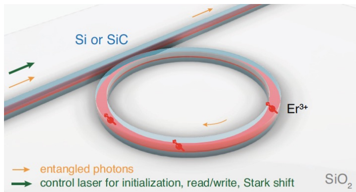
Different memory and repeater types

EIT	GEM	Raman
Cold Atom	Atomic Vapor	Solid State
QR - 1G	QR - 2G	QR - 3G
HEG	HEP	QEC

Different qubit representations, entanglement generation and purification protocols

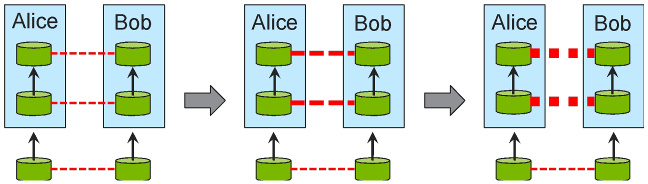
Time-bin	Polarization	Energy-time
Barrett-kok	Duan-Kimble	Cabrillo
BBPSSW	DEJMPS	Entanglement Pumping

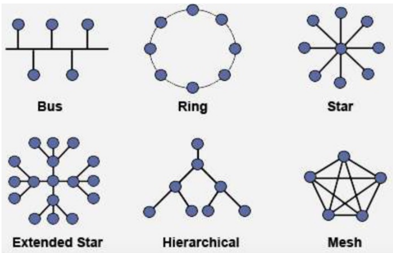
Quantum Network Simulations



Evaluate alternatives and motivate experimental advances – Detectors, memories, repeaters, light sources

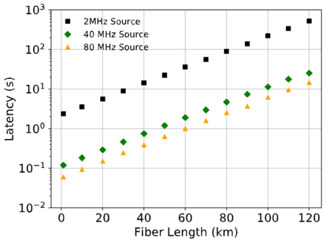
New protocol and control plane design – evaluate performance, scalability etc.





Network architecture design – topology and architecture that allows scalability and long-distance communication

Experiment planning and validation – facilitate system integration with hundreds of optical components, allow easy parameter tuning, predict and validate results



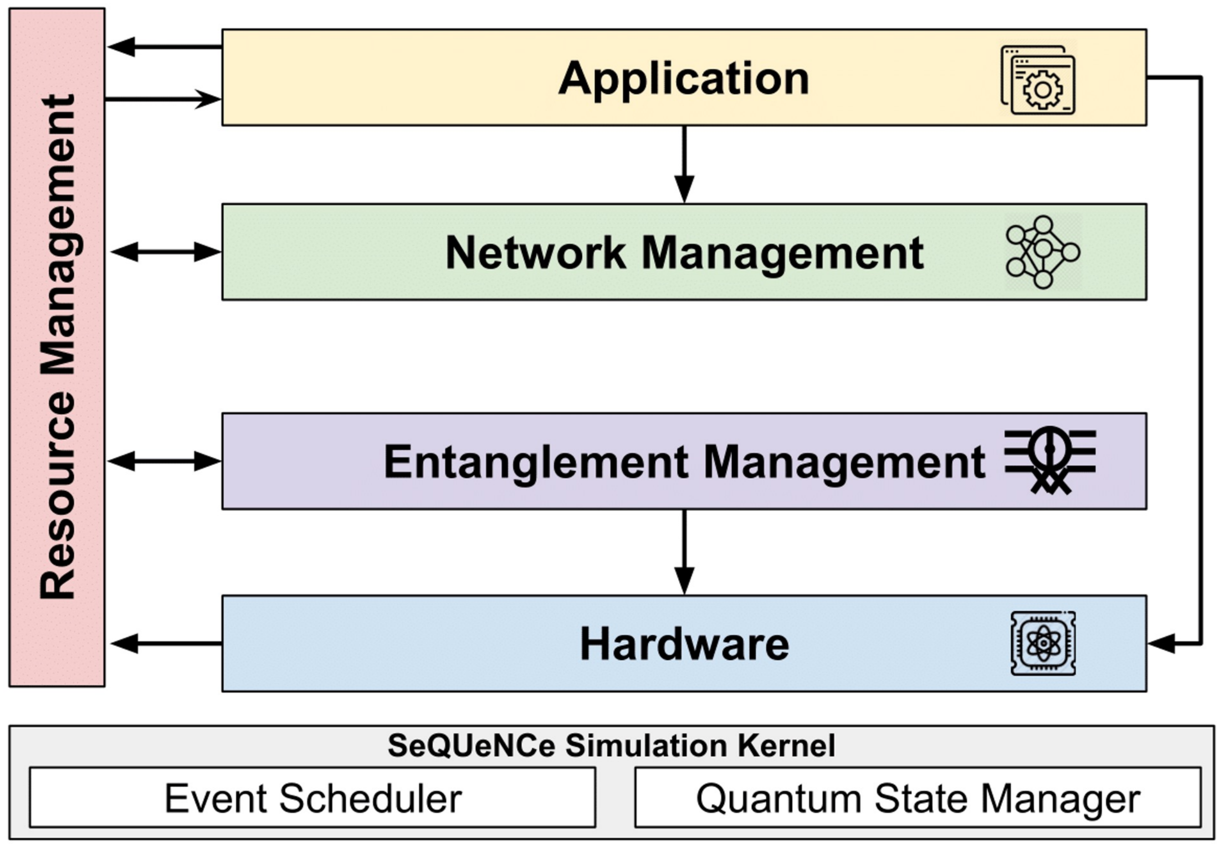
SeQUeNCe Simulator Overview

Modularized discrete event simulator with a clear separation of functionality

Simulates quantum communication at photon-level with picosecond accuracy

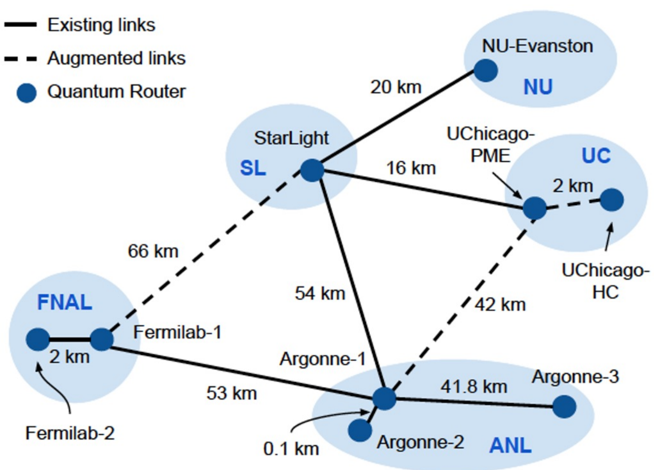
Allows simulations with different parameters, protocols, topologies, and network architectures

Hardware models of single-atom memories, entanglement generation, swapping, and purification protocols



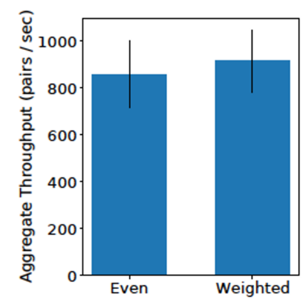
Evaluate Alternatives for Devices and Design

Chicago Metropolitan Quantum Network [QST'21]

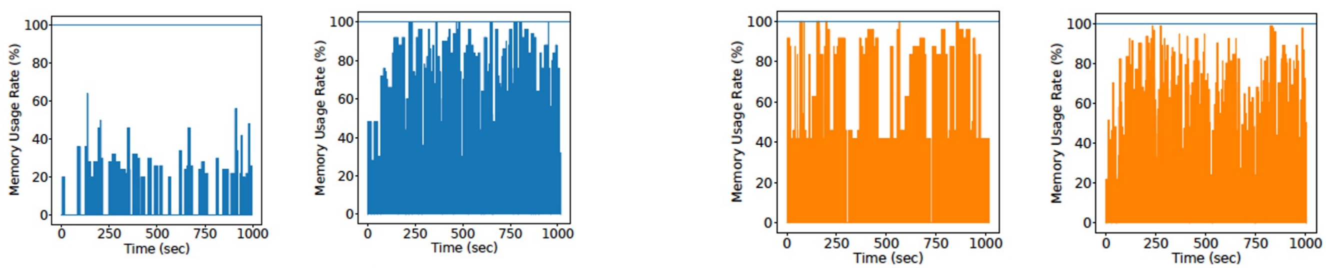


Parameter	Value
Memory efficiency §4.1.3	$e = 0.75$
Memory frequency §4.1.3	$f_m = 20$ kHz
Memory coherence time §4.1.3	$t_c = 1.3$ s
Atom-cavity cooperativity §4.1.3	$C = 500$
Memory array size	$a = 50$
Detector efficiency §4.1.2	$\eta = 0.8$
Detector count rate §4.1.2	$r = 50$ MHz
Detector dark count §4.1.2	$d \approx 0$ /s
Detector resolution §4.1.2	$s = 100$ ps
Attenuation §4.1.1	$\alpha_o = 0.2$ dB/km
Speed of light §4.1.1	$c^* = 2 \times 10^8$ m/s
Channel TDM time frame §4.1.1	$t_f = 20$ ns
Gate fidelity §4.2.3	$F_{gate} = 0.99$
Swap success probability §4.2.3	$p_{swap} = 0.64$

Average throughput:



Memory usage:



(a) Argonne-3 even (b) StarLight even (c) Argonne-3 weighted (d) StarLight weighted

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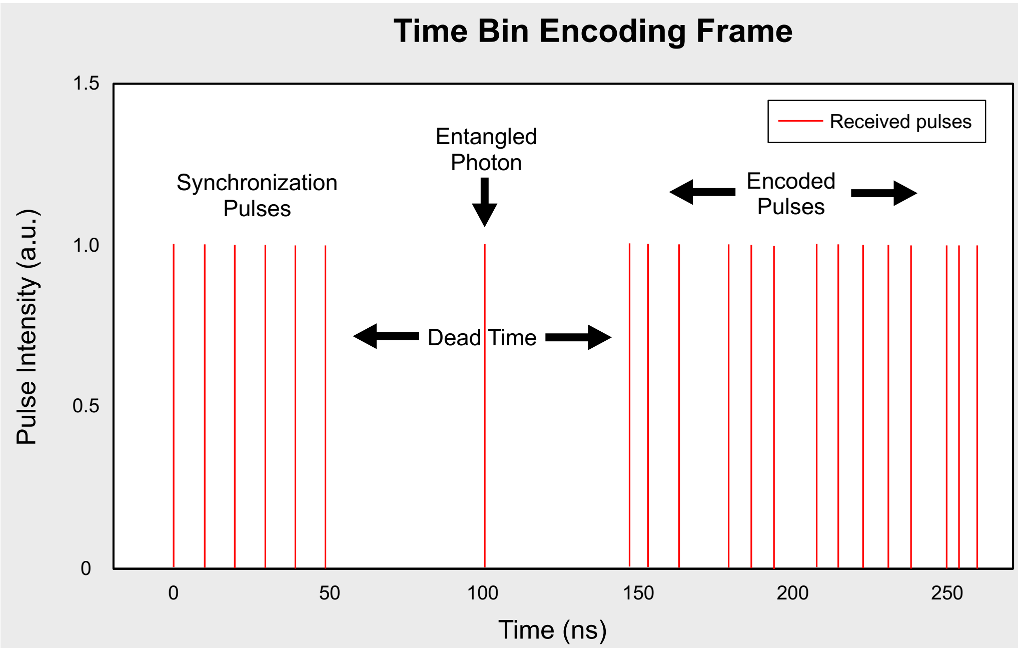
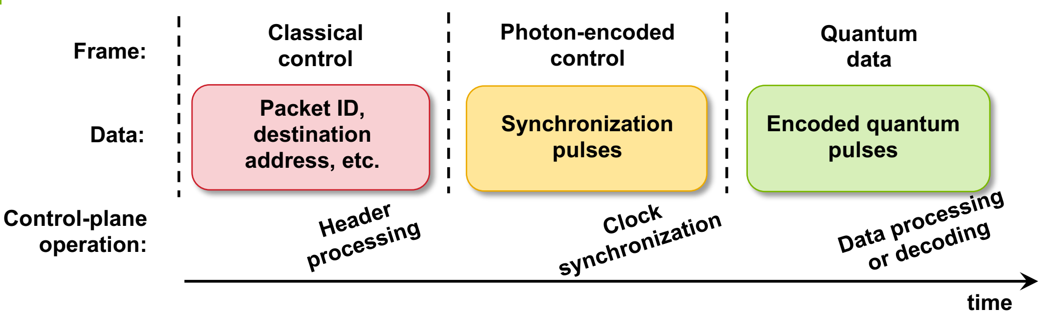
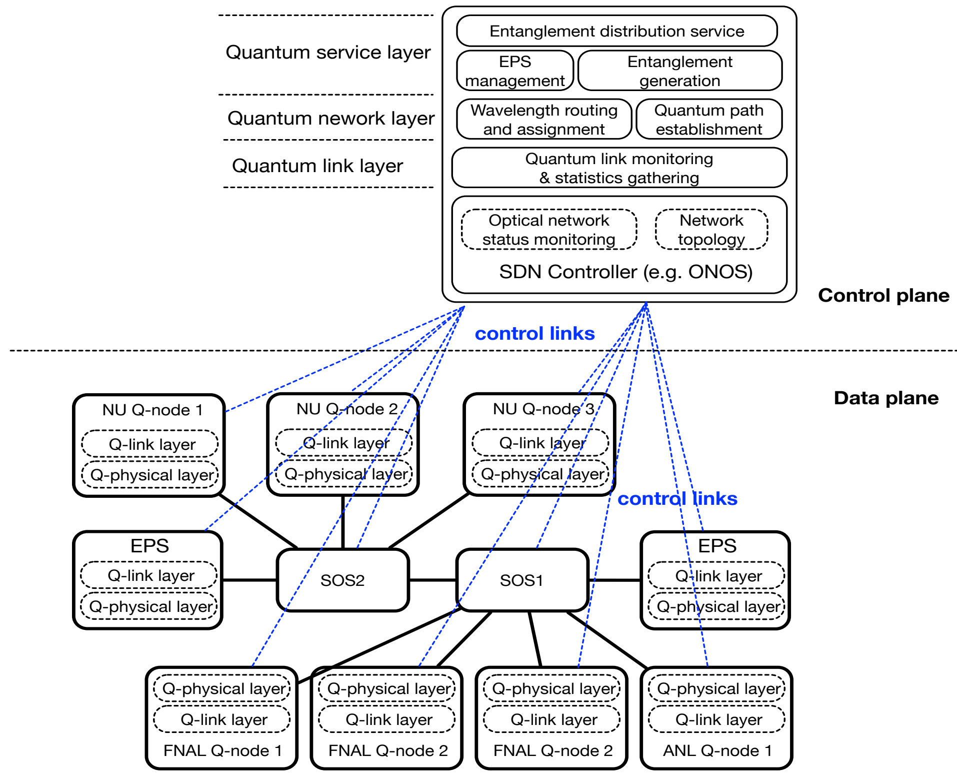
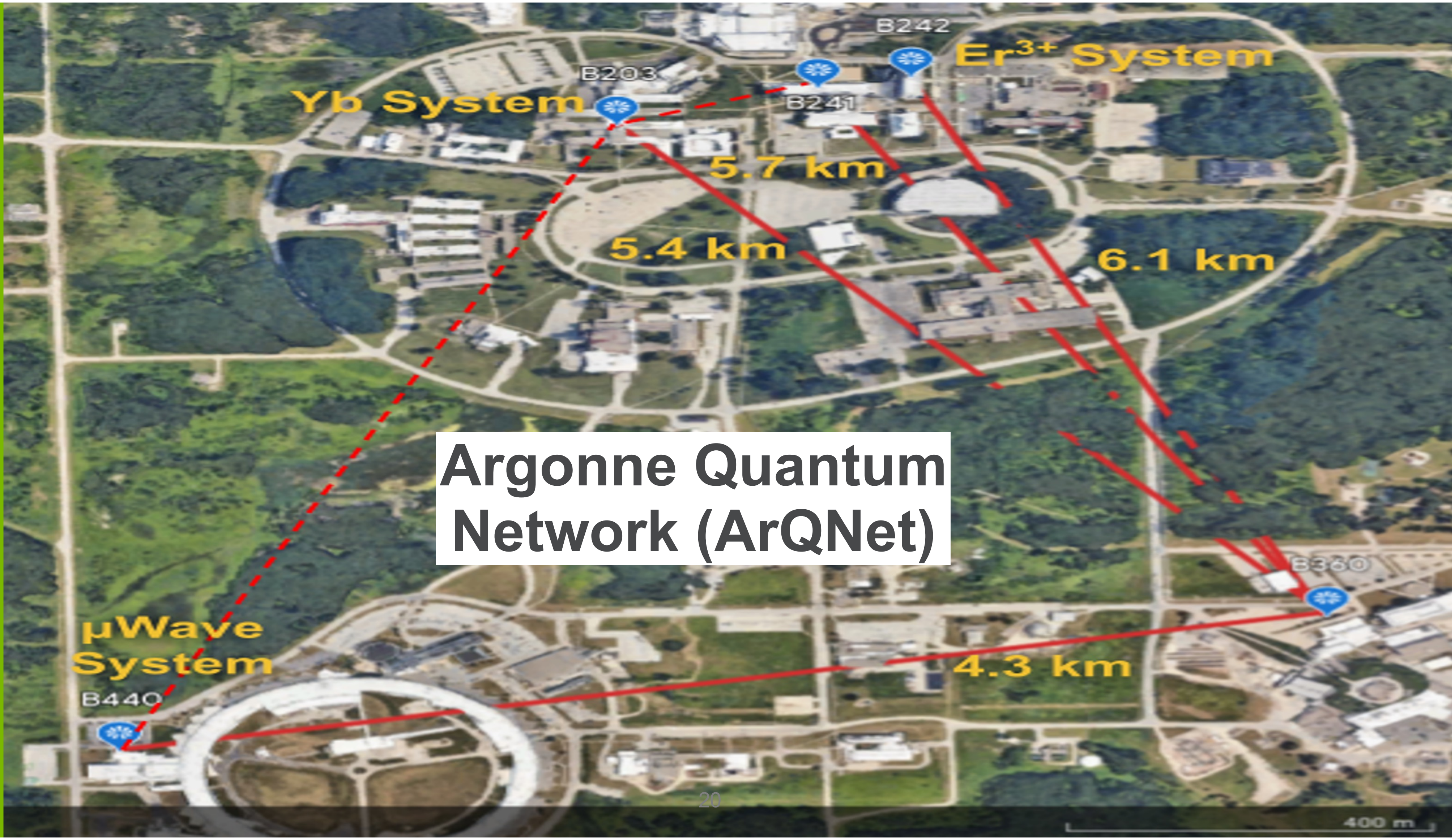
Architectural Choices for Quantum Networks







Argonne NATIONAL LABORATORY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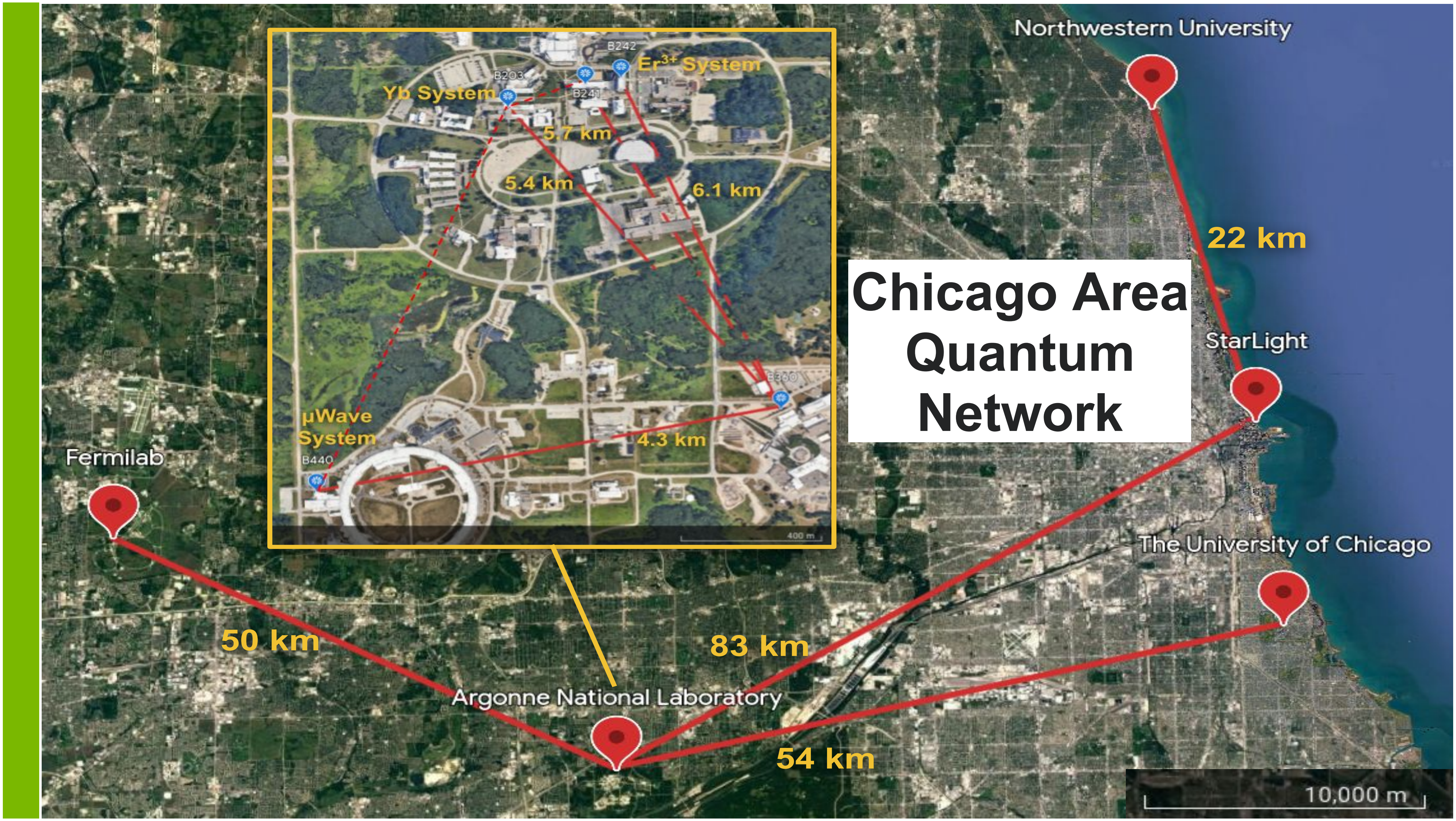
Chicago Area Quantum Network
Northwestern University
22 km
StarLight
The University of Chicago
Fermilab
50 km
83 km
54 km
Argonne National Laboratory
10,000 m
B242
Er^{3+} System
B203
B241
Yb System
5.7 km
5.4 km
6.1 km
B350
μWave System
B440
4.3 km
400 m

Summary

- Quantum networks hold a lot of promise
- Quantum network devices and protocols are under active development
- Several campus-scale and metropolitan-scale demonstrations
- Scalability has emerged as a key challenge
- Argonne Quantum Network (ArQNet) is being built to help address some of the scalability challenges
- Node heterogeneity, applications
- Validate simulation results

THANK YOU!

Contribute to the open-source project at https://github.com/sequence-toolbox/SeQUeNCe.

Student and postdoc positions in quantum networks are available. Contact Raj Kettimuthu at kettimuthu@anl.gov