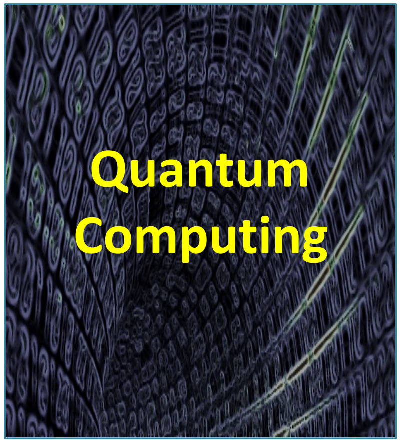
Quantum Advantage & Robust Quantum Information Processing

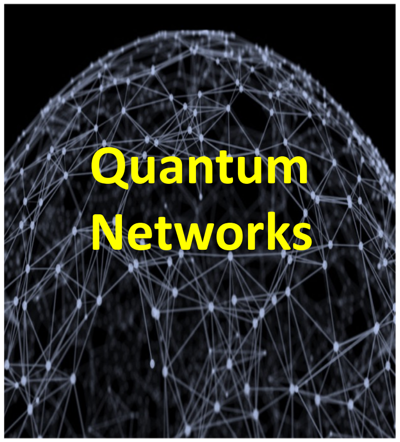
Liang Jiang
Pritzker School of Molecular Engineering (PME)
The University of Chicago

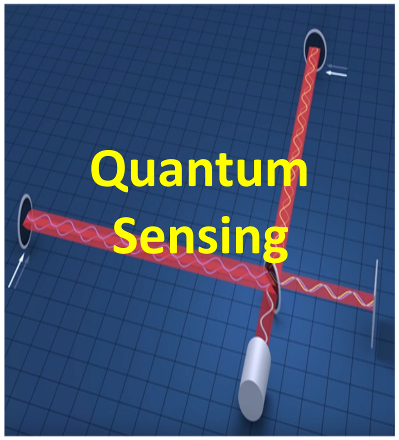
ASPIRE Quantum Kock-off Workshop
UTokyo-UChicago
7/25/2024

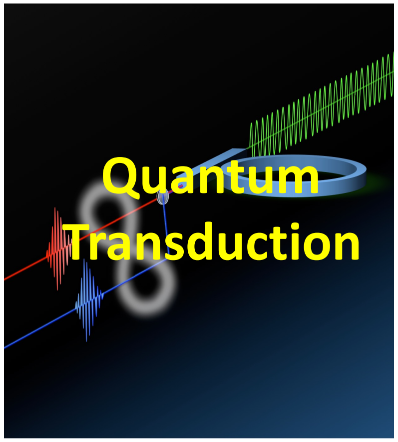
PRITZKER SCHOOL OF MOLECULAR ENGINEERING

Overview of Research Topics



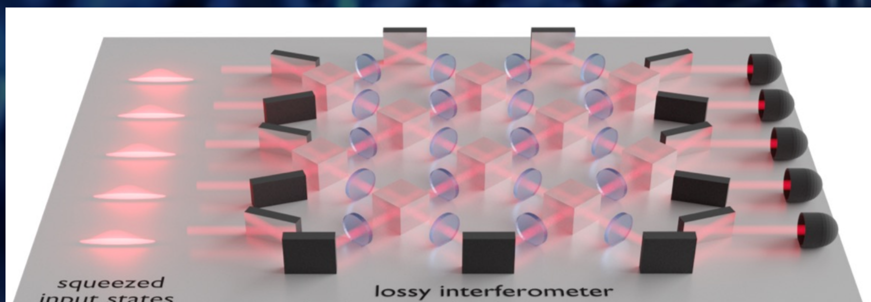




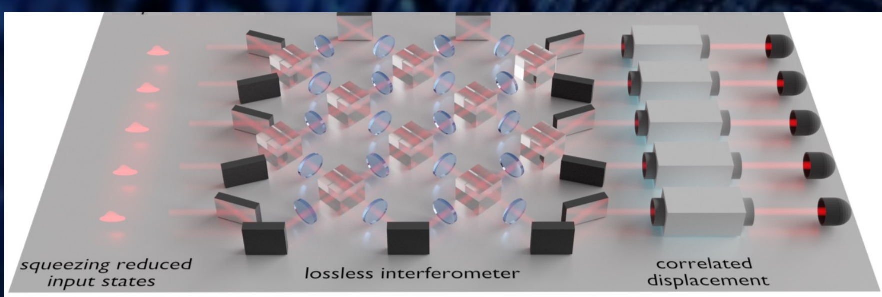


NISQ Quantum Advantage

Lossy Gaussian boson sampling circuit

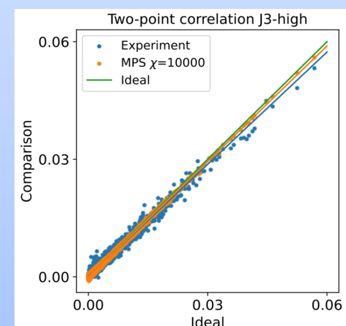


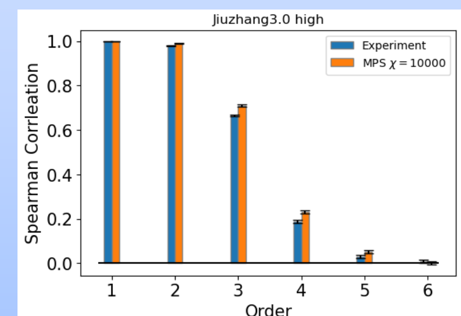
Effective Gaussian boson sampling circuit



New **classical tensor network algorithm** can simulate state-of-the-art Gaussian boson sampling experiments.

- Obtain effective circuit with **reduced squeezing (entanglement)**
- Use **MPS tensor and GPUs** to construct 1M samples in less than 10 mins
- **Excellent agreement** in various correlations.

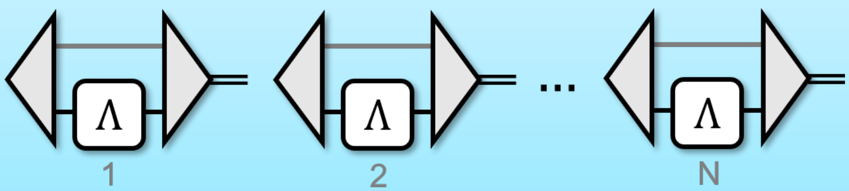




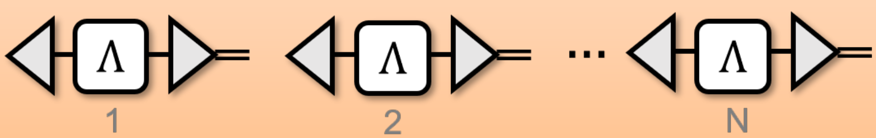
- Oh, Liu, Alexeev, Fefferman, L.J., arXiv:2306.03709 (Nature Physics, 2024)

Entanglement Enhanced Learning (EEL)

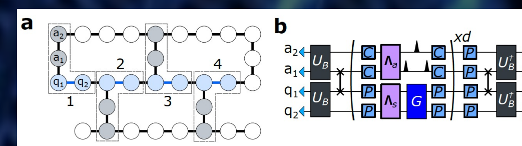
THM 1. There exists an n-qubit **entanglement-enhanced learning (EEL) protocol** achieving ϵ-close estimate of Pauli channel fidelity with probability $1 - \delta$ using $N = \mathcal{O}(n\epsilon^{-2} \log \delta^{-1})$ copies of Λ.



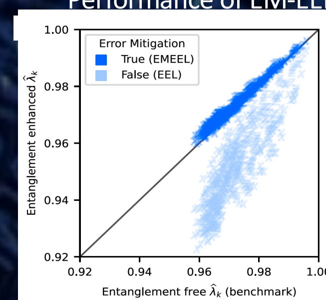
THM 2. Any **entanglement free learning (EFL) protocol** would require at least $N = \Omega(2^n/\epsilon^2)$ rounds of measurement to complete the same task (with $\epsilon \leq 1/3$).



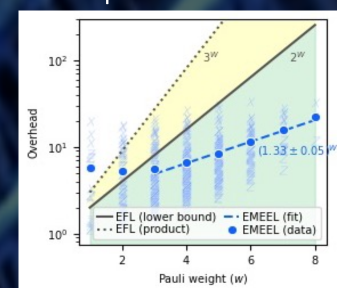
Discrete Variable



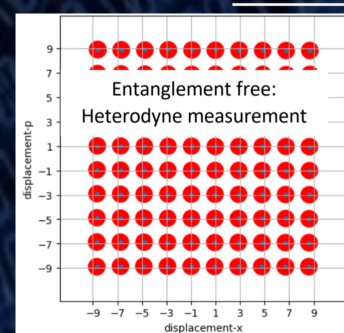
Performance of EM-EEL

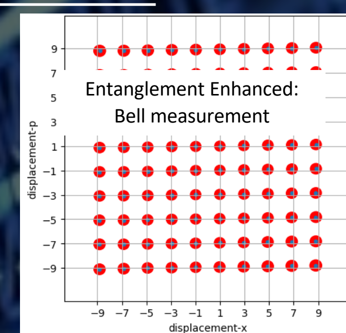


Sample overhead of EM-EEL



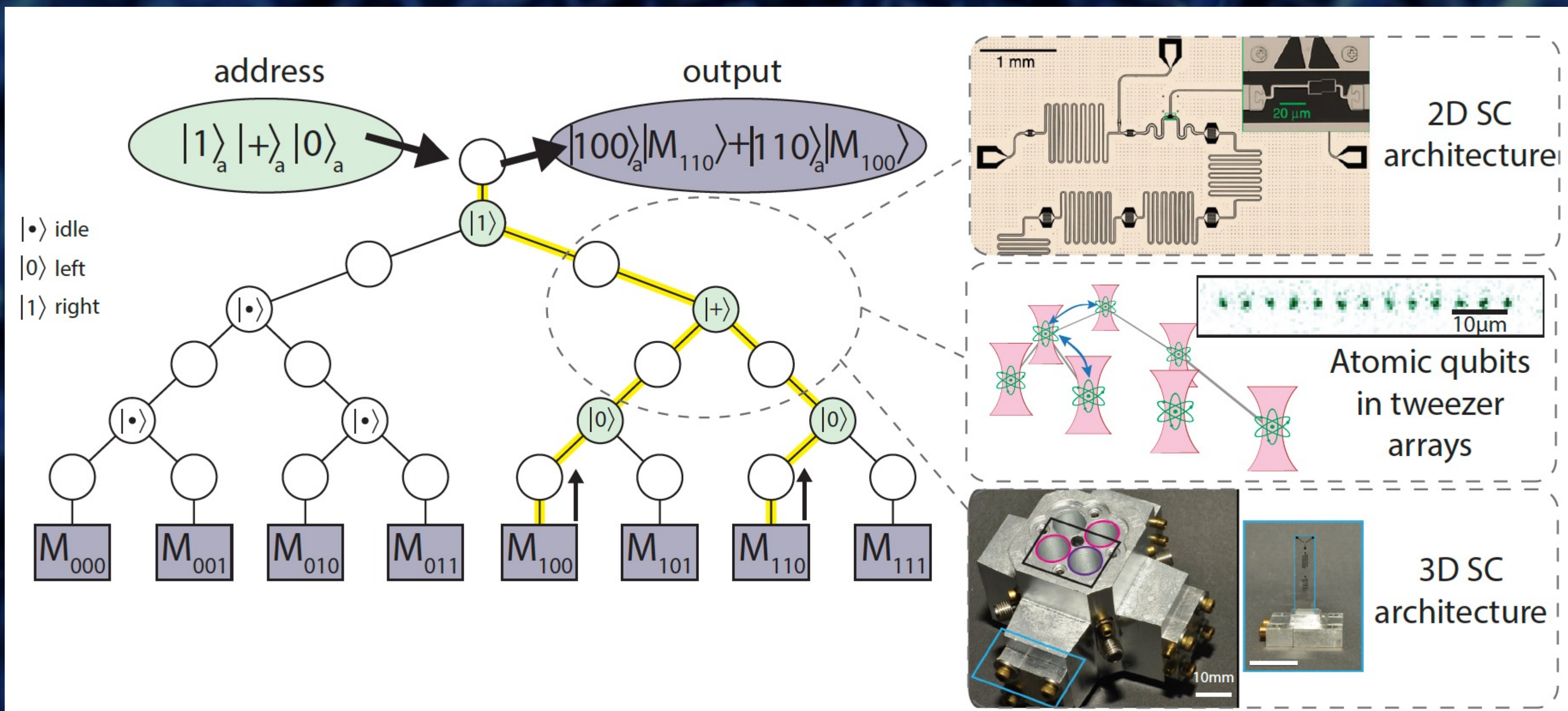
Continuous Variable





Phys. Rev. Letts. 132, 180805 (2024); arXiv:2402.18809

Quantum Computation - qRAM



PRX Quantum 2, 020311 (2021)

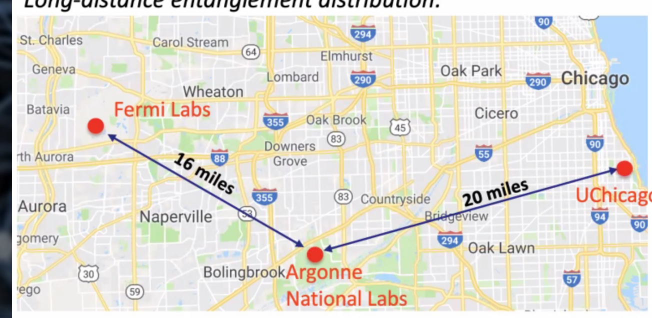
Quantum Networks

Exp: Awschalom, Zhong

Potential Applications:

- ➢ Secure communication
- ➢ Secure quantum computing in the cloud
- ➢ Clock synchronization & quantum sensors
- ➢ Quantum games, …

Long-distance entanglement distribution:

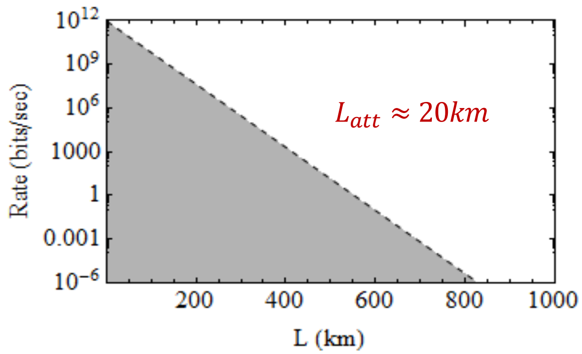


Jiang Group @ UChicago

Quantum Repeaters

Major Challenges:

- **[Loss Error]** Attenuation in quantum channel
- **[Operation Error]** Imperfect quantum gates

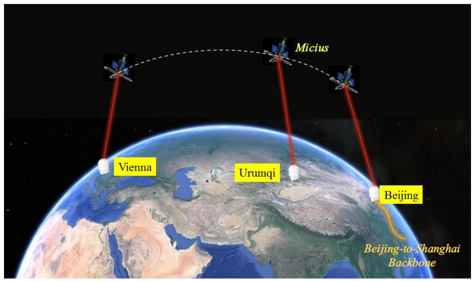


Challenges	Approaches	1G-QR	2G-QR	3G-QR
Loss Error	Quantum Error **Detection** [two-way signaling]	✓	✓	
	Quantum Error **Correction** [one-way signaling]			✓
Operation Error	Quantum Error **Detection** [two-way signaling]	✓		
	Quantum Error **Correction** [one-way signaling]		✓	✓

Scientific Reports 6, 20463 (2016)

Vacuum Beam Guide

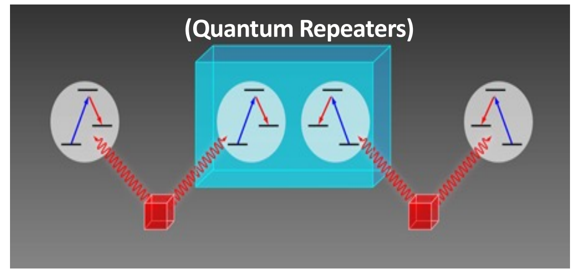
Solution 1: Satellite based Quantum Links



Quantum satellites:

- *Advantage: Long distance*
- *Challenges: limited bandwidth, weather dependent, expensive to launch, …*

Solution 2: Ground based Quantum Links



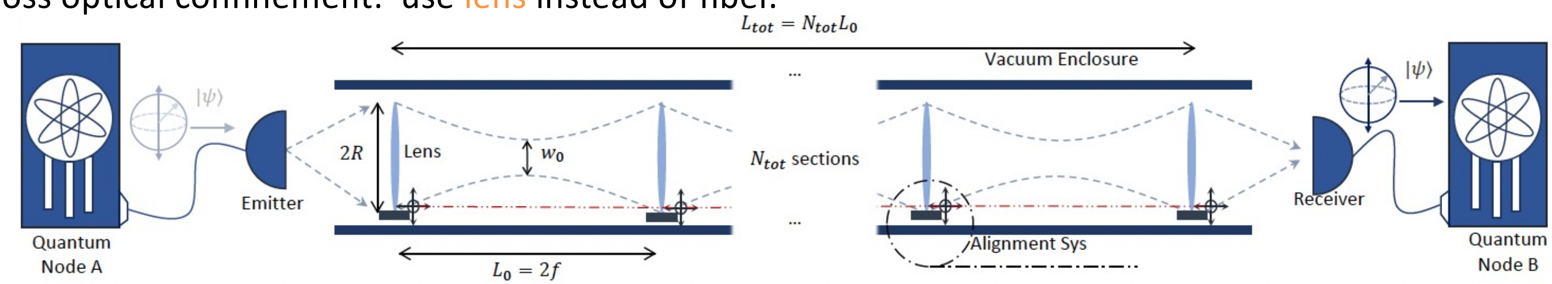
Quantum repeaters:

- *Advantages: Compatible with fiber network, more reliable, high bandwidth,*
- *Challenges: Entanglement swapping, quantum mem, operation errors, …*

Solution 3: Vacuum Beam Guide (VBG)

- **Inspired by LIGO**
- **Ground-based vacuum enclosure** and insulated from outer environment:
- Reduced air or medium absorption: use vacuum (~ 1 Pa)
- Low loss optical confinement: use lens instead of fiber.

> ➢ **Attenuation length ~ 10^4 km**
> ➢ **Channel capacity ~10^{13} qubit/sec**



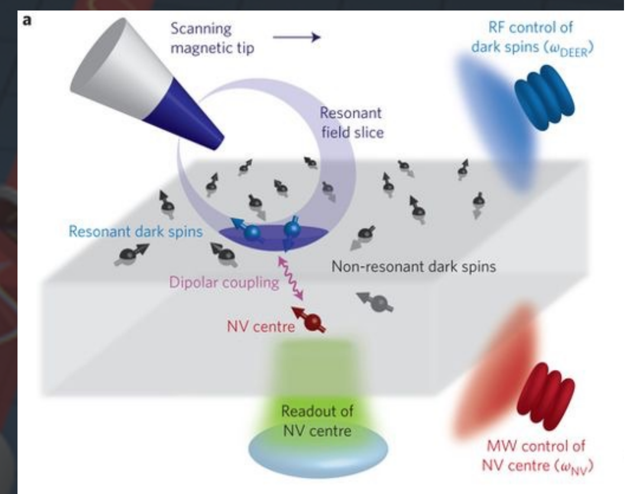
Phys. Rev. Lett. 133, 020801 (2024)

Jiang Group @ UChicago

Quantum Sensing

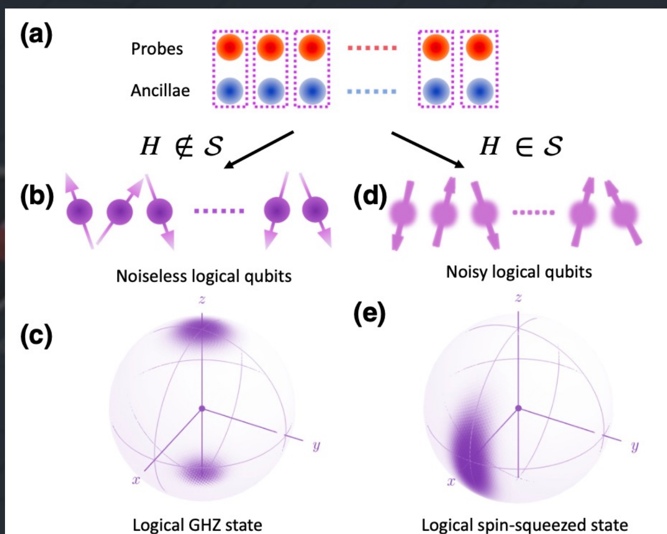
Key Idea: Use *quantum properties to boost sensitivity*

- Fundamental limits of quantum sensors
  - Quantum metrology enhanced by QEC
  - Quantum sensing at exceptional points
- Protocols for efficient quantum sensors
  - Nano magnetic sensors (e.g, NV diamond)
  - Atomic clocks, atom interferometers
  - Dark matter search



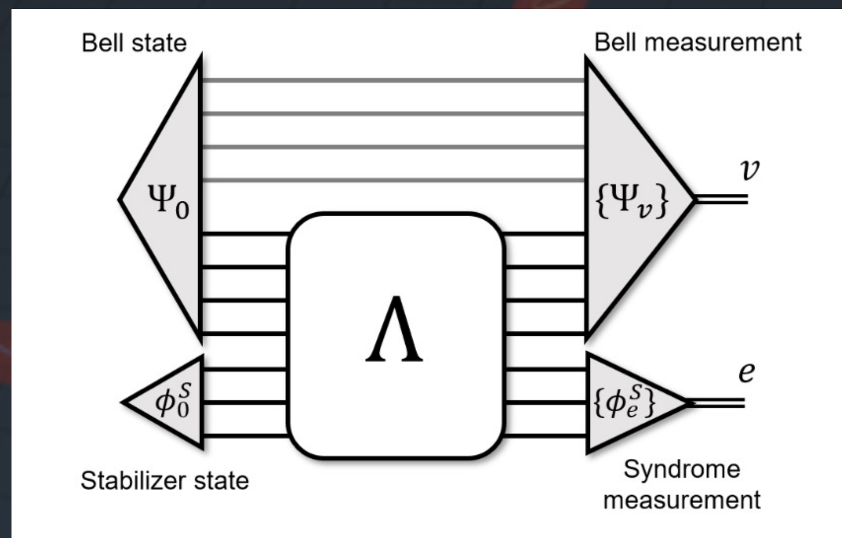
Quantum Sensing

QEC Sensing (Heisenberg Scaling)



PRX Quantum, 010343 (2021);
Nat Comm 9, 78 (2018)

Multi-parameter sensing & learning

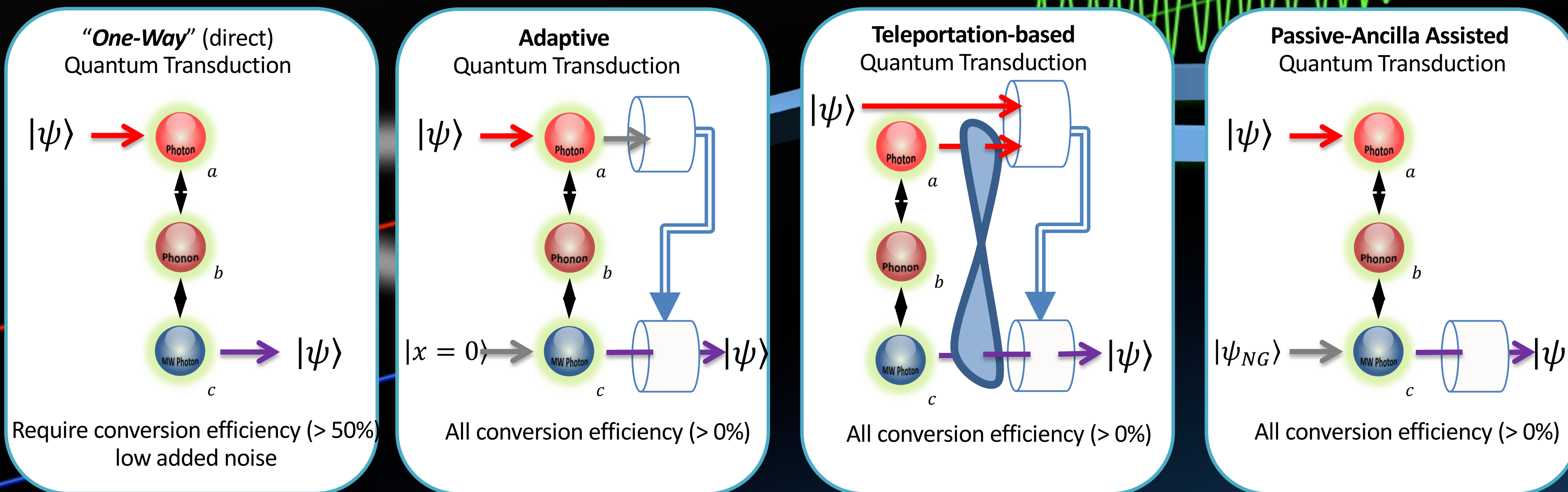


Phys. Rev. Lett. 132, 180805 (2024);
arXiv:2402.18809

Jiang Group @ UChicago

Quantum Transduction

Question: How to relax the strigent requirement for quantum transduction?



NJP 13, 013017 (20211)

PRL 120, 020502 (2018)

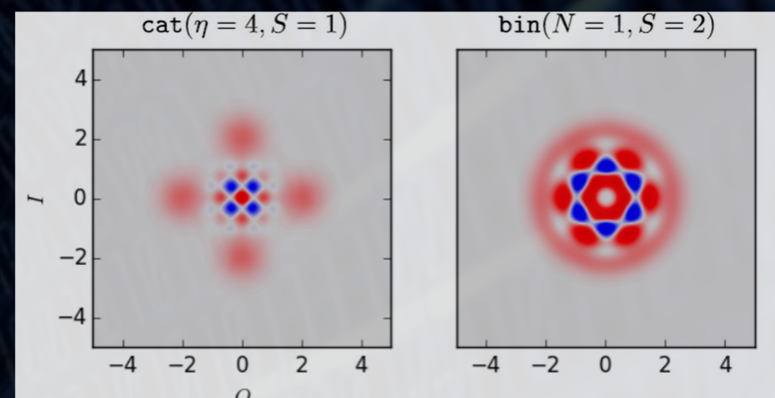
npj Quant Info 5, 1 (2019)
PRL 124, 010511 (2020)
PRA 101, 032345 (2020)

arXiv:2401.16781

Quantum Error Correction

Key Idea: Use redundancy to protect encoded quantum information

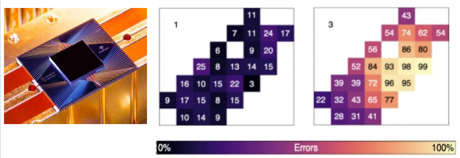
- **Good quantum codes**
  - **Error-aware quantum codes (e.g., bosonic codes, qLDPC codes)**
  - **Capacity achieving codes**
- **Fault-tolerant quantum architecture**
  - **Error-transparent gate**
  - **Hardware efficient FT QEC**
  - **Topological QC (Prof. Ruben Verresen)**

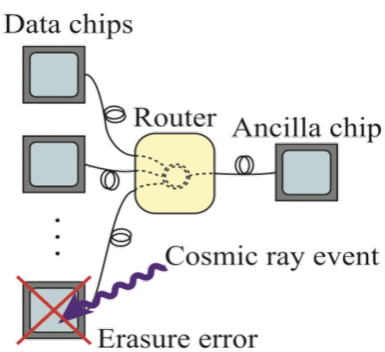


Co-Designed Quantum Error Correction

Error Model

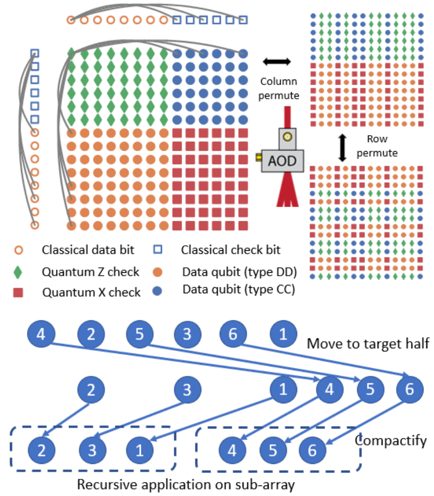
Distributed Quantum Error Correction





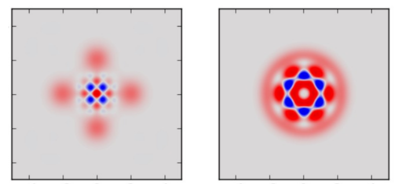
Control Capability

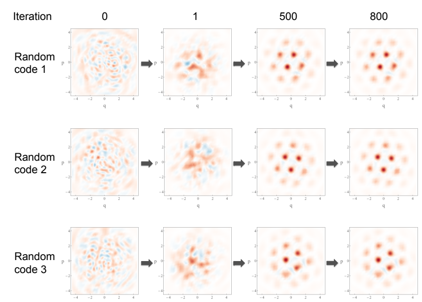
Atom Arrays Quantum LDPC Protection



Physical Platform

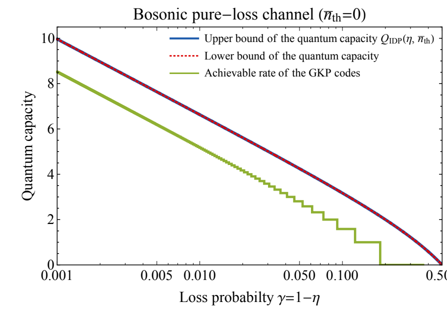
Bosonic Quantum Error Correction

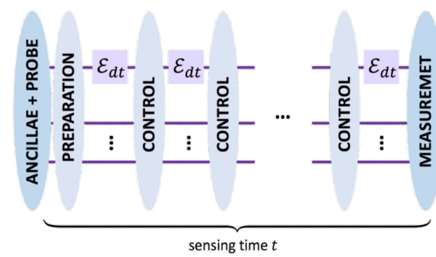




Applications

Quantum Communication, Transduction & Sensing





Physical Level → **Application Level**

Research Topics in Jiang Group at UChicago