Phonon-qubit and Phonon-qubit Hybrid Quantum Systems in Trapped Ions

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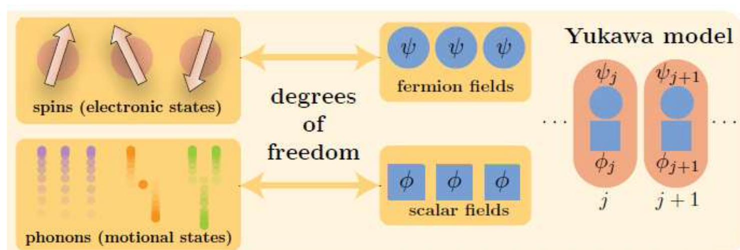
U.S.-Korea Forum on Nanotechnology, Raleigh NC
Sept 14, 2026



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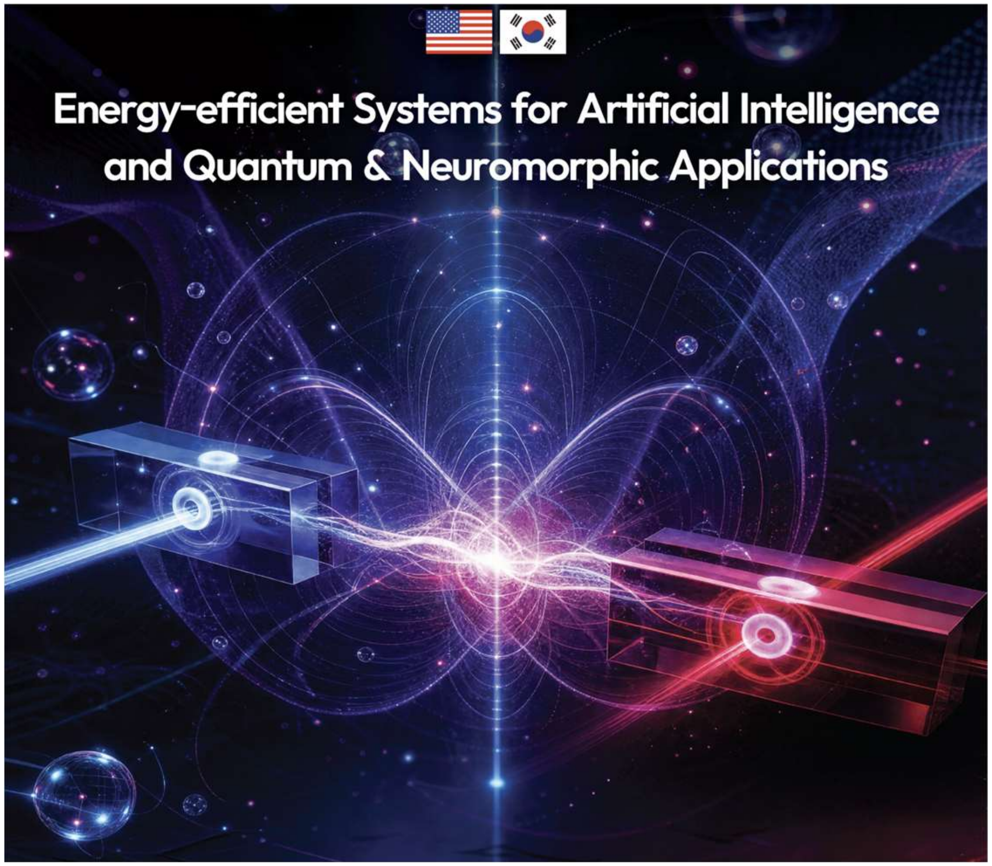
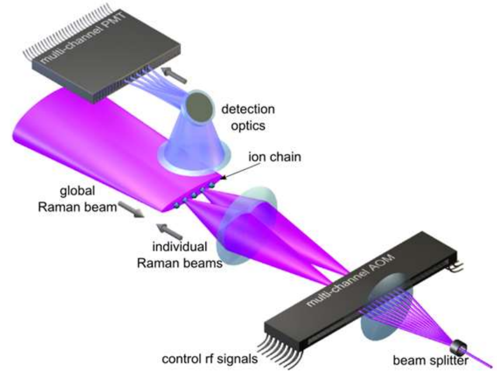
How to scale quantum systems

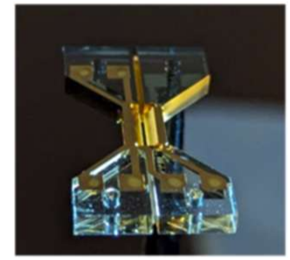


Path 1: Top-Down
Modularize (photonic interconnects)

Path 2: Bottom-up
Expand control (phononic modes)

Overview



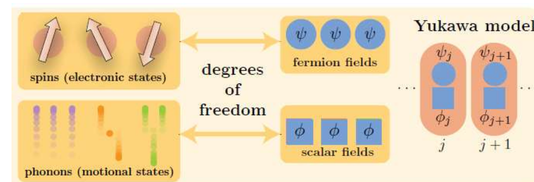


Trapped ions

Experimental system

Hybrid analog-digital quantum simulations

Spin-phonon simulation of the Yukawa model



A. Than et al., arXiv:2509.1147 (Nat. Phys. in print)

A city-scale quantum network

Qubit-photon entanglement distribution with Sr ions

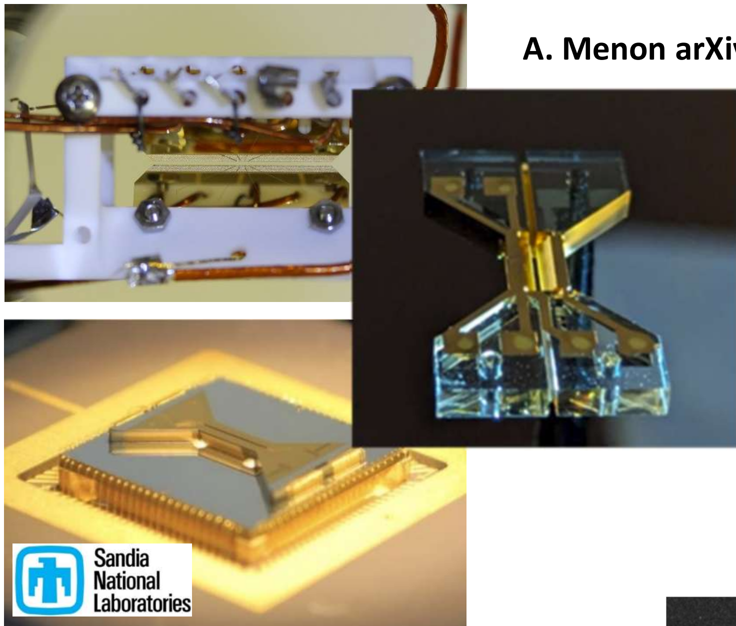
M. A. Zalewski et al., Phys. Rev. A 113, 012615 (2026)

Outlook

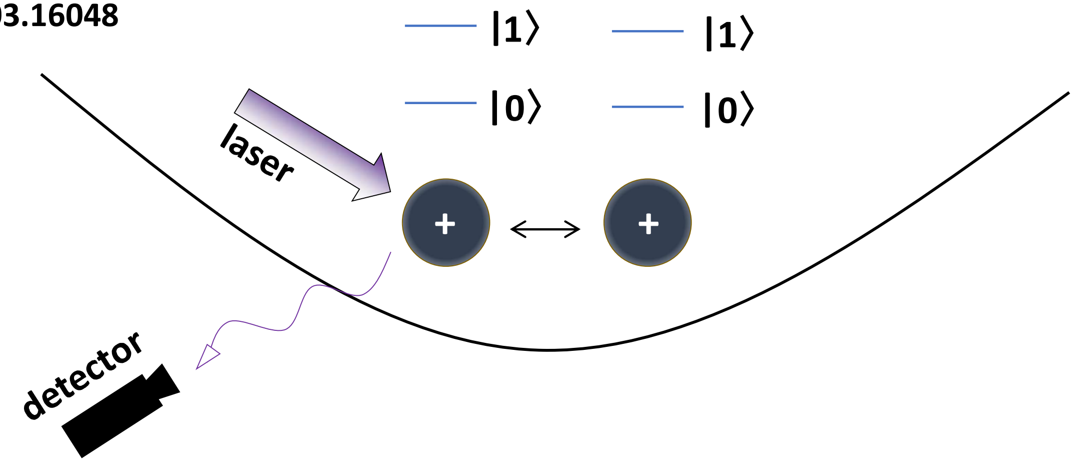
QLab – Quantum For All

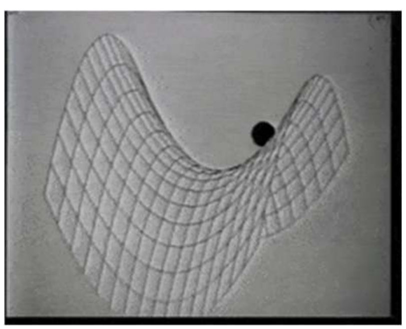
Experimental system

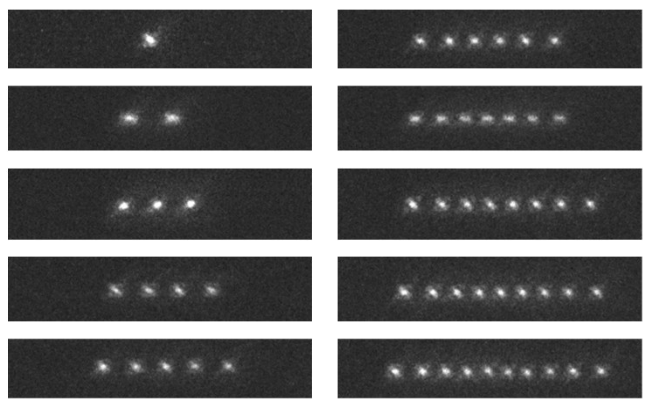
Ion trap quantum processor



A. Menon arXiv:2603.16048

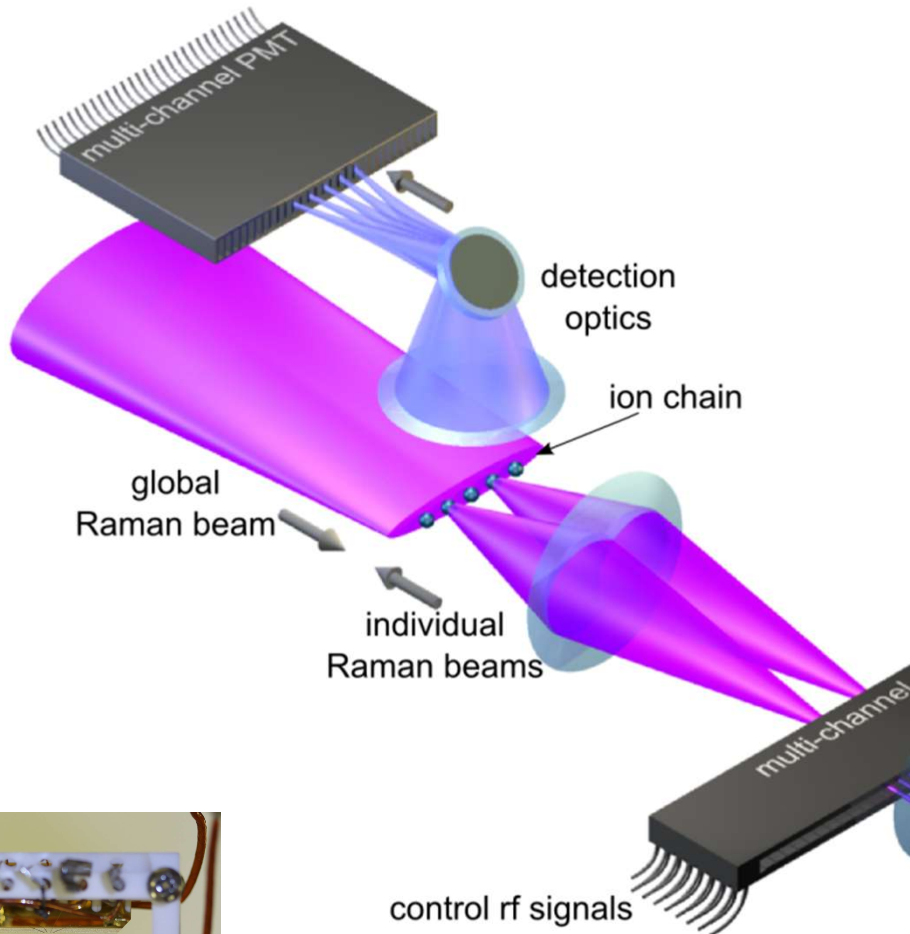


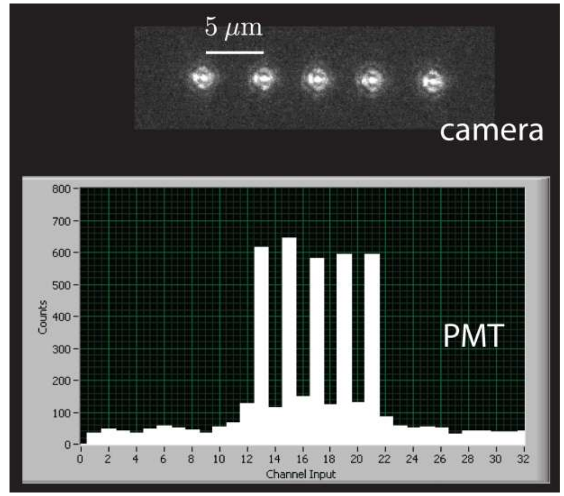


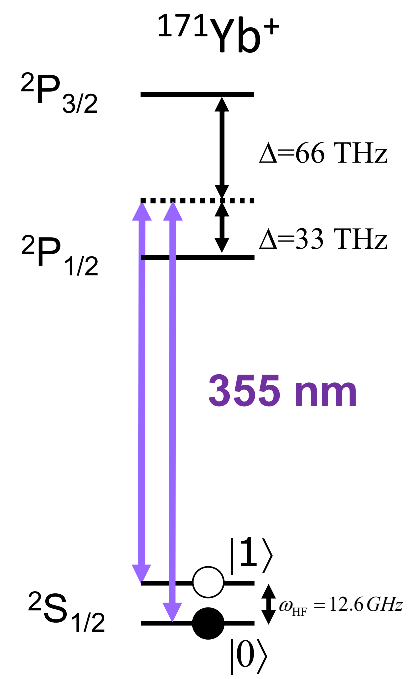


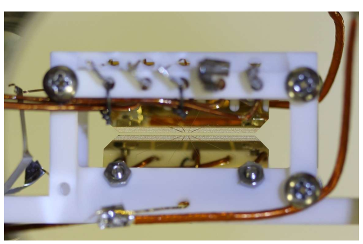
trapped ion Coulomb crystals: $^{171}Yb^{+}$

Experimental system: Hardware

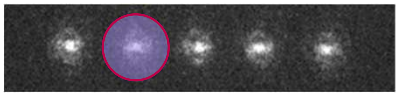


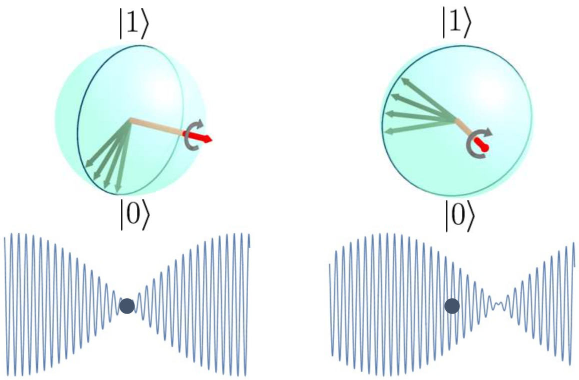




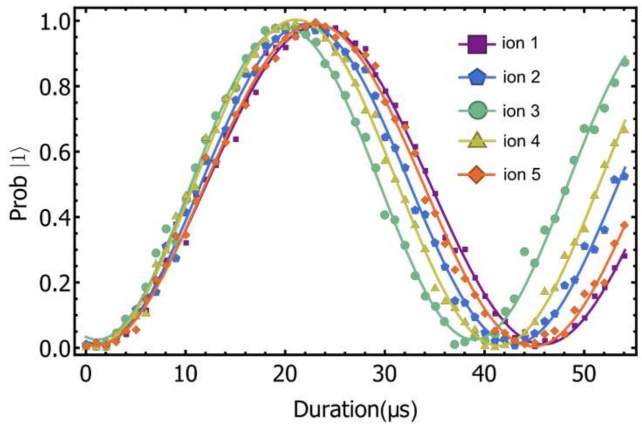


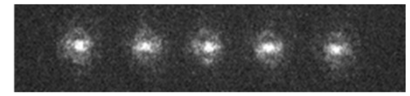
Experimental system: Single qubit gates

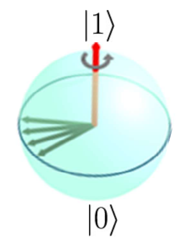




Raman beat note







Classical phase shifts

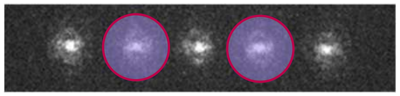
R-gate (*x*/*y* rotations)

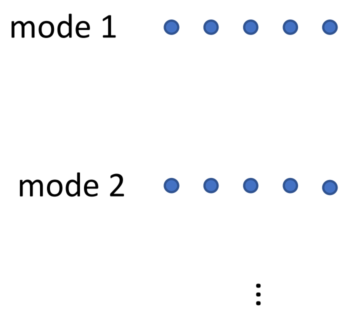
$$R_\phi(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -i\sin(\frac{\theta}{2})e^{-i\phi} \\ -i\sin(\frac{\theta}{2})e^{i\phi} & \cos(\frac{\theta}{2}) \end{bmatrix}$$

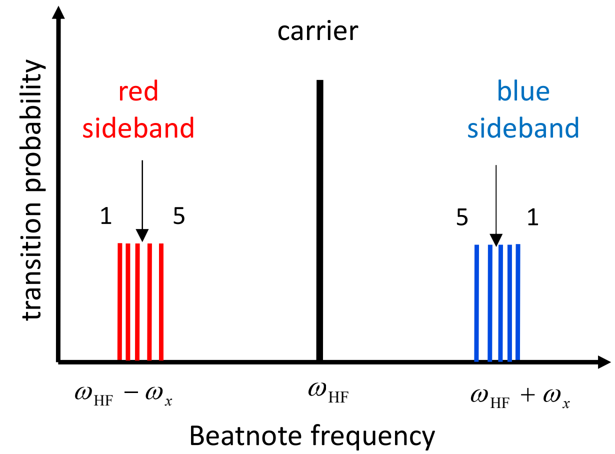
***z*-gates**

$$R_z(\theta) = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$

Experimental system: Two-qubit gates







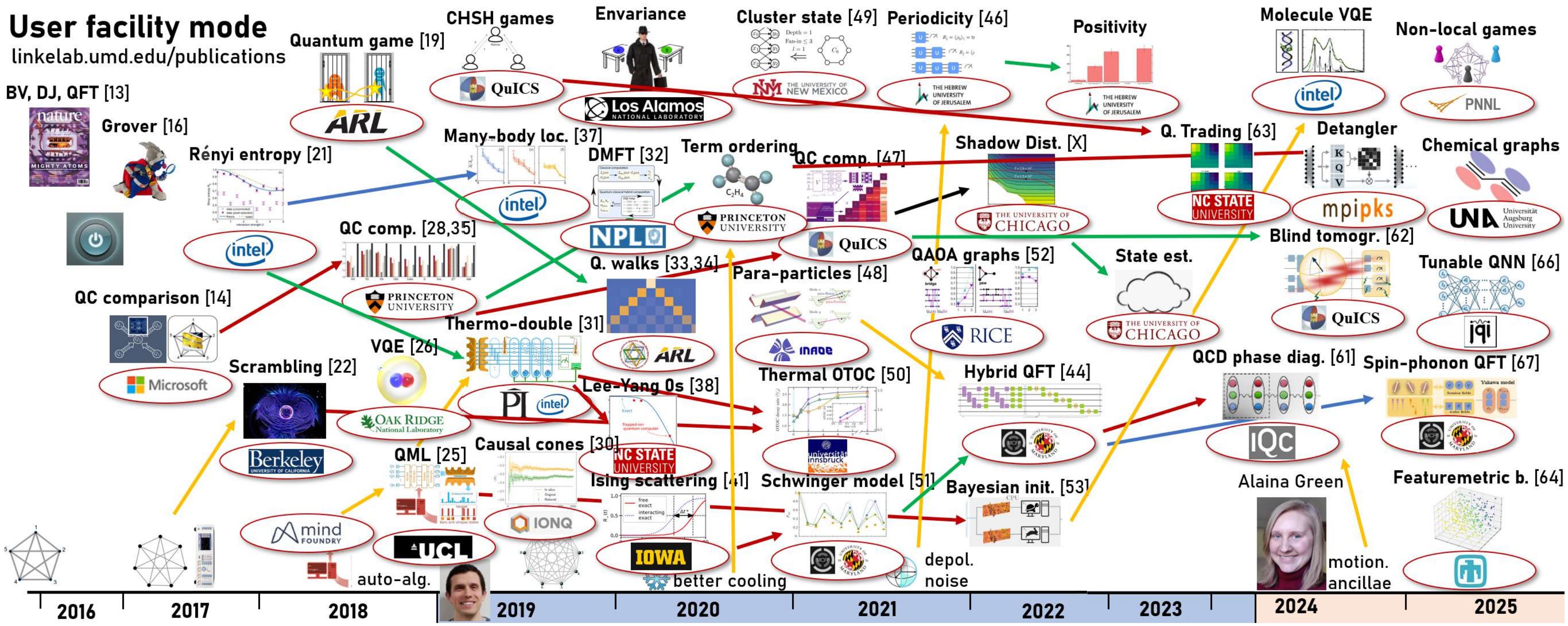
$$U(t) = \exp[-i \sum_{n,k} \hat{D}(\cancel{\alpha_n^k(t)})\sigma_x^n - i \sum_{i,j} \chi_{ij}(t)\sigma_x^i \sigma_x^j]$$

$$XX(\chi_{i,j}) = \begin{bmatrix} \cos(\chi_{i,j}) & 0 & 0 & -i\sin(\chi_{i,j}) \\ 0 & \cos(\chi_{i,j}) & -i\sin(\chi_{i,j}) & 0 \\ 0 & -i\sin(\chi_{i,j}) & \cos(\chi_{i,j}) & 0 \\ -i\sin(\chi_{i,j}) & 0 & 0 & \cos(\chi_{i,j}) \end{bmatrix}$$

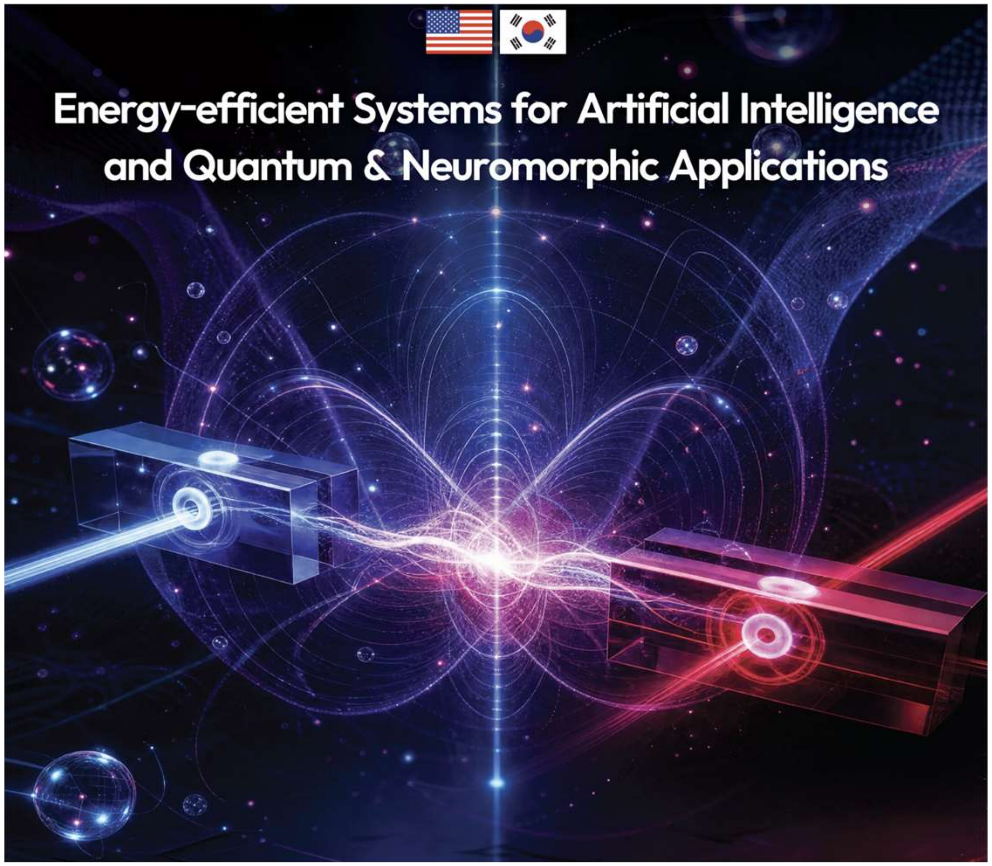
$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle - i|11\rangle)$$

MS gate: PRL **82** (1999)
T. Choi et al. PRL **112**, 19502 (2014)
T. J. Green et al., PRL **114**, 120502 (2015)
P. H. Leung et al. PRL **120**, 020501 (2018)
Y. Shapira et al., PRL **121**, 180502 (2018)

A Quantum computer in User Facility mode



linkelab.umd.edu

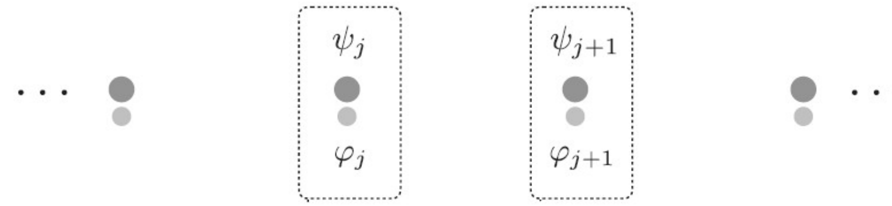


Path 2: Bottom-up
Expand control (phononic modes)

Hybrid Quantum Simulation: The Yukawa model

Hybrid Quantum Simulation: The Yukawa model

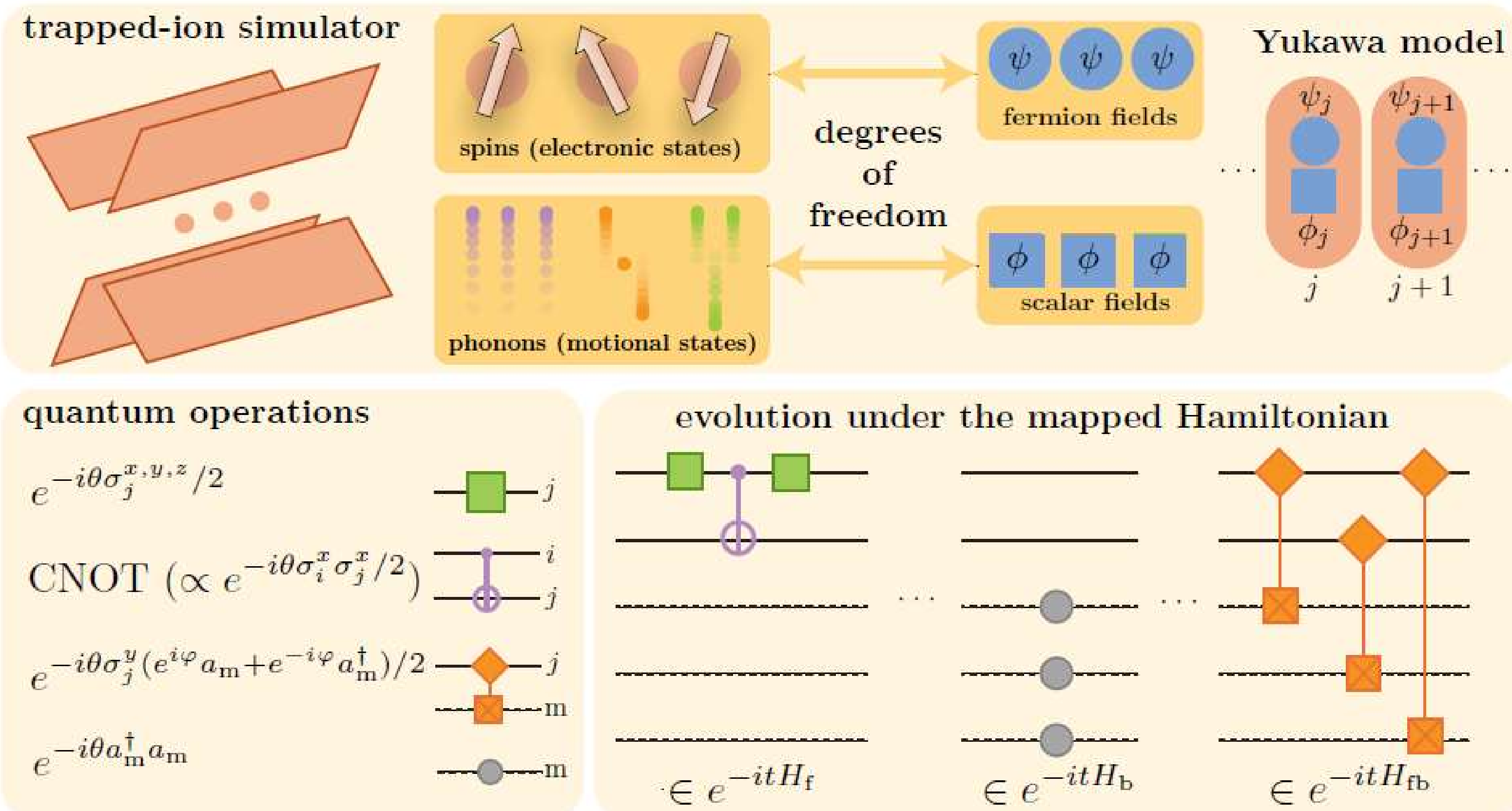
$$V(r) = -\frac{g^2}{4\pi}\,\frac{1}{r}\,e^{-\mu r}$$



- Scalar field theory: scalar bosons (field) interact with fermions (matter)
- Describes the Higgs field interacting with the leptons and quarks
- Explains mass generation
- Difficult to simulate classically and for a QC (bosonic mode cutoff).

Hybrid Quantum Simulation: The Yukawa model

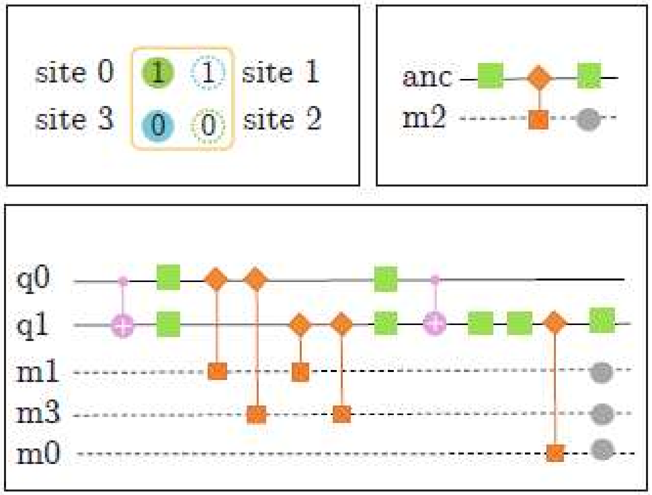
Map fermions to spins and bosons to phonons



based on Z. Davoudi, NML, G. Pagano, Phys. Rev. Research 3, 043072 (2021)

Hybrid Quantum Simulation: The Yukawa model

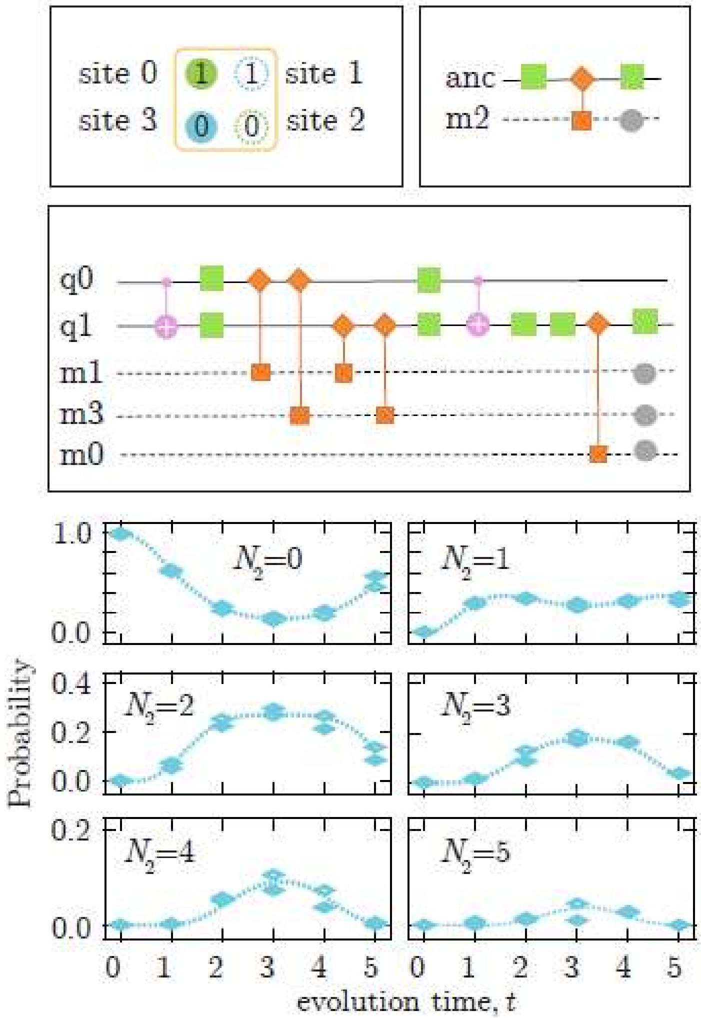
N=4

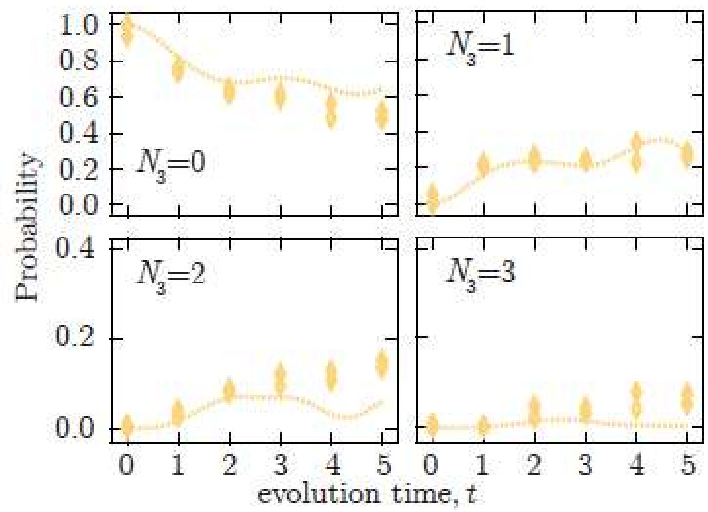


A. Than et al., arXiv:2509.1147 (Nat. Phys. in print)

Hybrid Quantum Simulation: The Yukawa model

N=4





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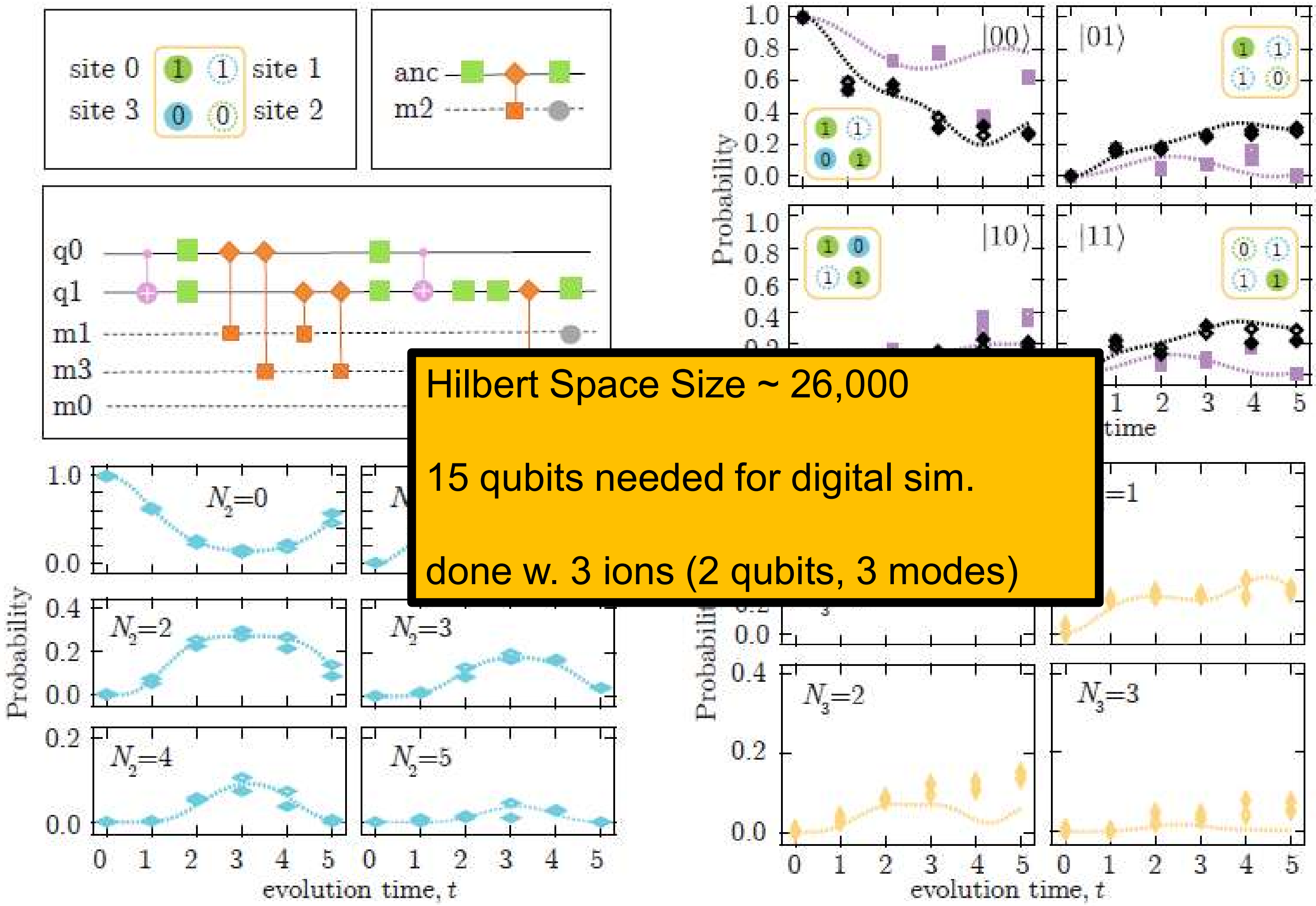
Hybrid Quantum Simulation: The Yukawa model

N=4



Hilbert Space Size ~ 26,000

15 qubits needed for digital sim.

done w. 3 ions (2 qubits, 3 modes)

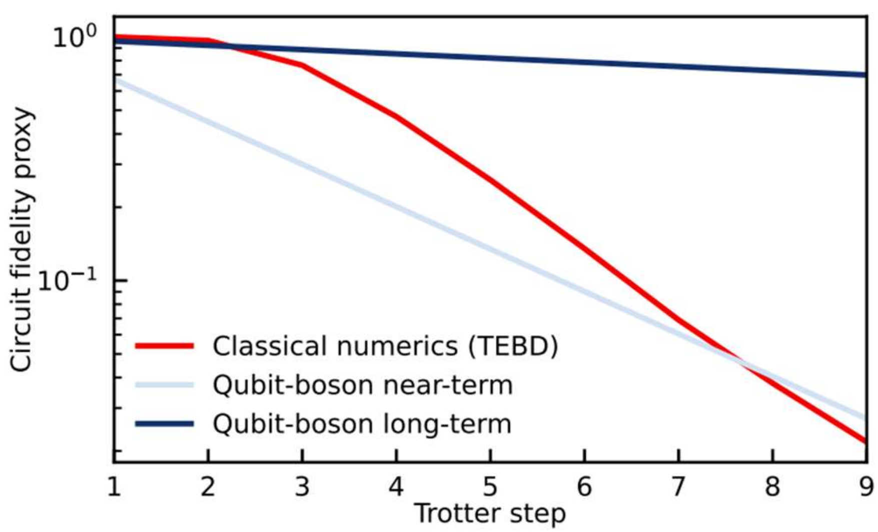
A. Than et al., arXiv:2509.1147 (Nat. Phys. in print)

Hybrid Quantum Simulation: Why it matters!

Slide Credit: Alexander Schukert (ENS Paris)

1-dimensional Z_2 Higgs-LGT with 20 sites (large Trotter step):

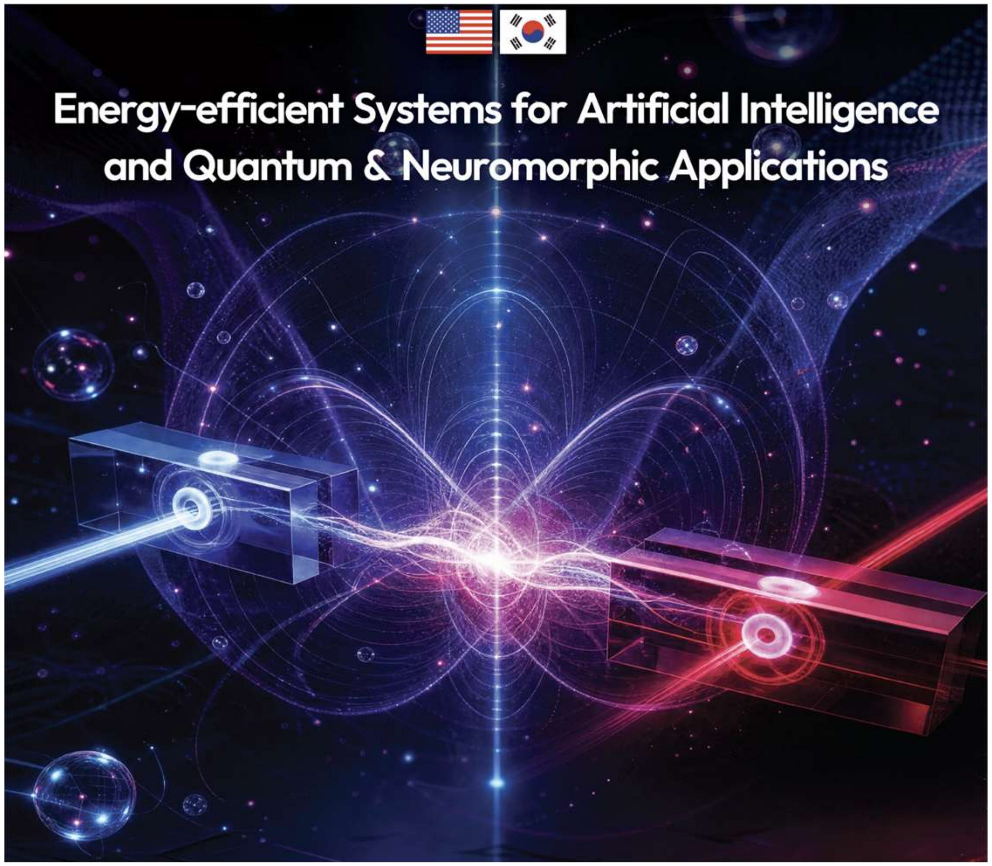
$$H= -g\sum_i Z_i - J\sum_i X_i\left(a_{i+1}^\dagger a_i + a_i^\dagger a_{i+1}\right)$$



- Initial state (bunching phase)
  $|0{+}0{+}\ldots 0{+}\,16{+}\,16{+}\,0{+}0{+}0\rangle$
  (20 bosonic modes & 19 qubits)
- Large Trotter step of Z_2 LGT model
- Qubit-only circuits:
  20*9*1000~10^5 CNOT gates
- Includes loss and dephasing of qubit-boson gates

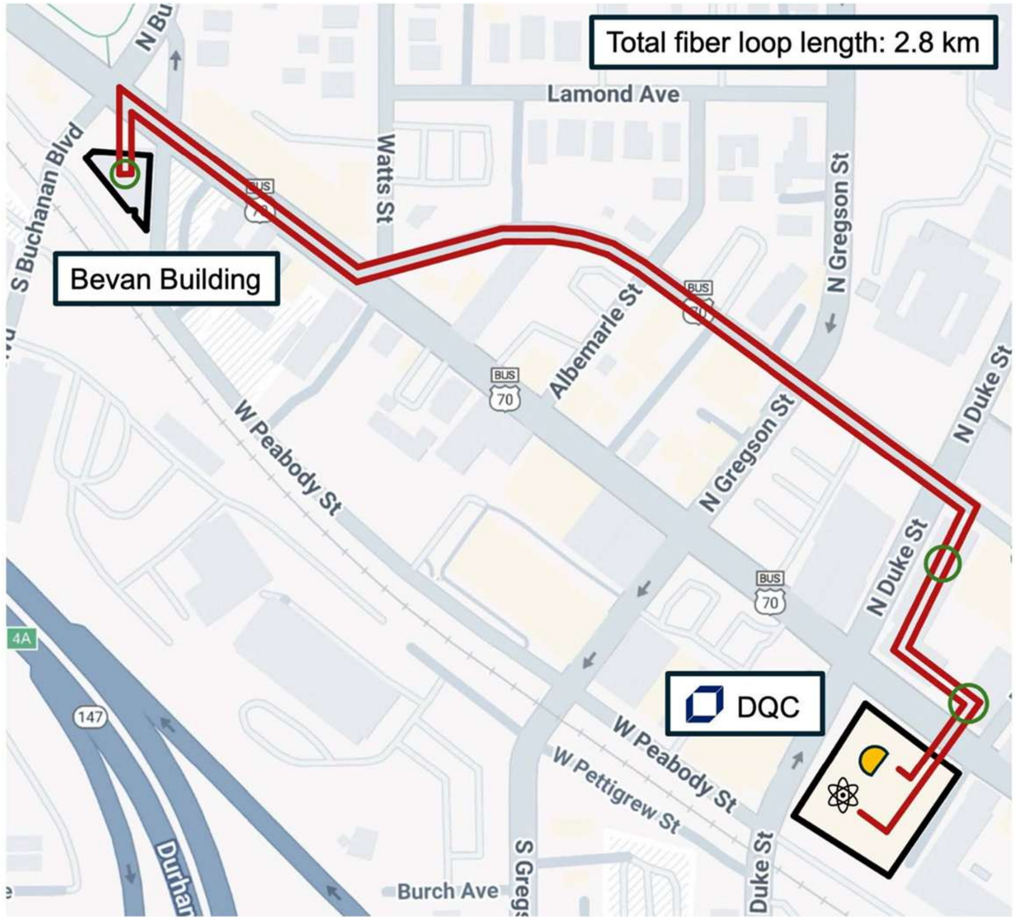
NISQ quantum advantage for a problem which (using current methods) would require a MegaQuop qubit machine!

Crane et al.; arXiv:2409.03747v2 (2024); Schuckert et al; arXiv:2503.03828 (2025)



Path 1: Top-Down
Modularize (photonic interconnects)

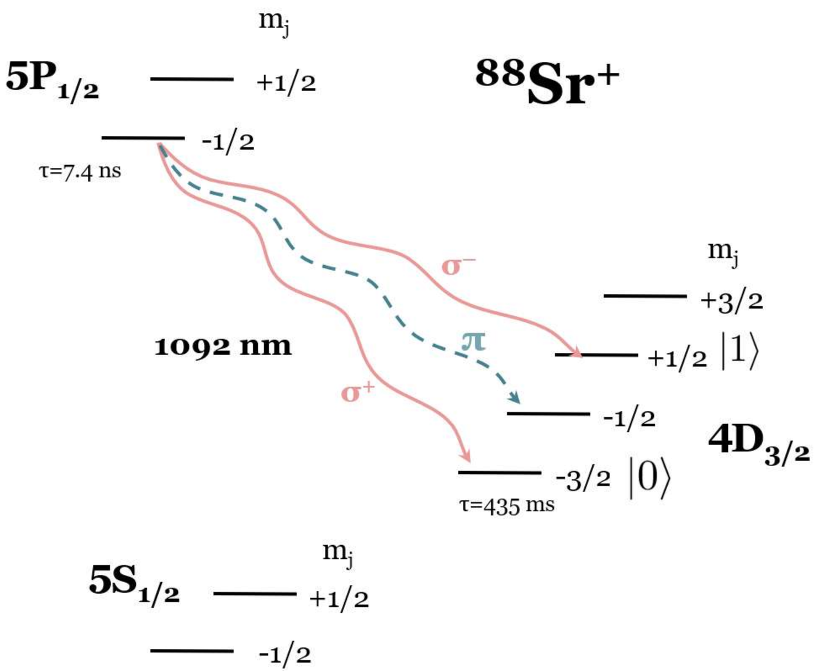
Photon transmission through a municipal dark fiber

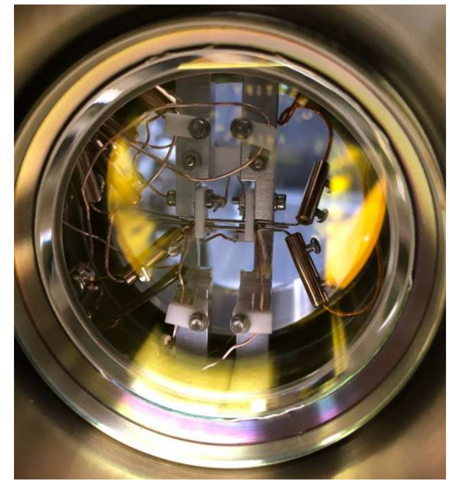


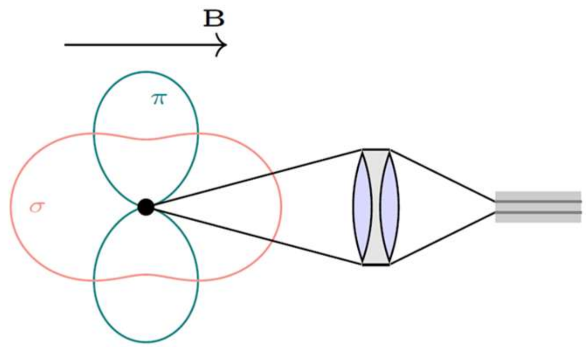
continous telecom fiber, no active stabilization

Zalewski et al. PRA 113 (2026)

Quantum networking: A fiber-ready quantum network node



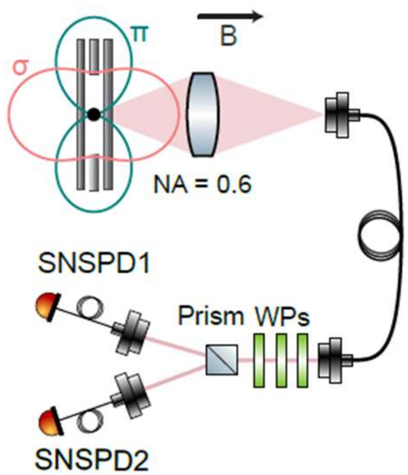


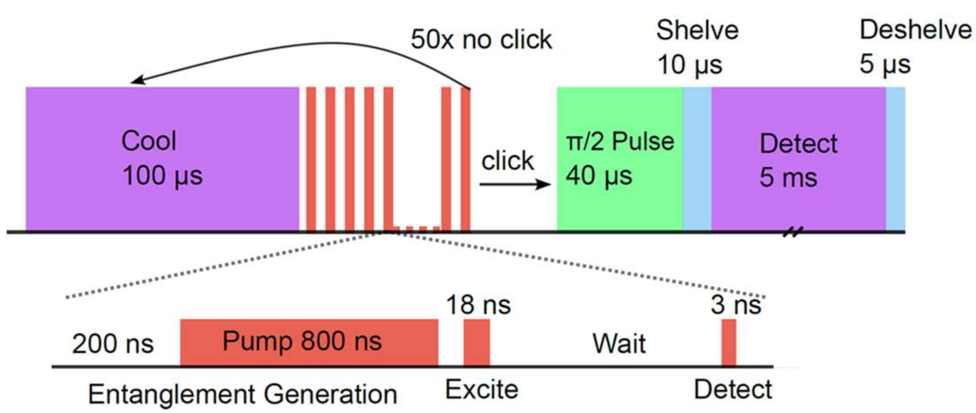


$$|\psi\rangle = \frac{\sqrt{3}}{2}|0\rangle|\sigma^+\rangle + \frac{1}{2}|1\rangle|\sigma^-\rangle$$

Zalewski et al. PRA 113 (2026)

Quantum networking: A fiber-ready quantum network node





Zalewski et al. PRA 113 (2026)

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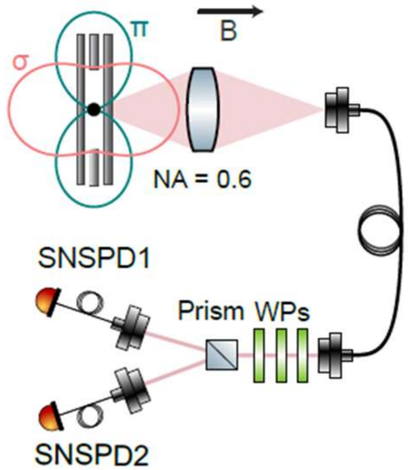
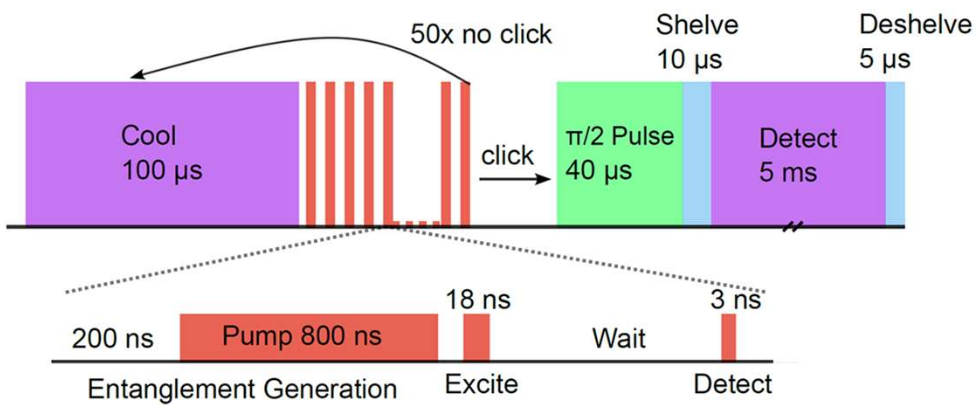
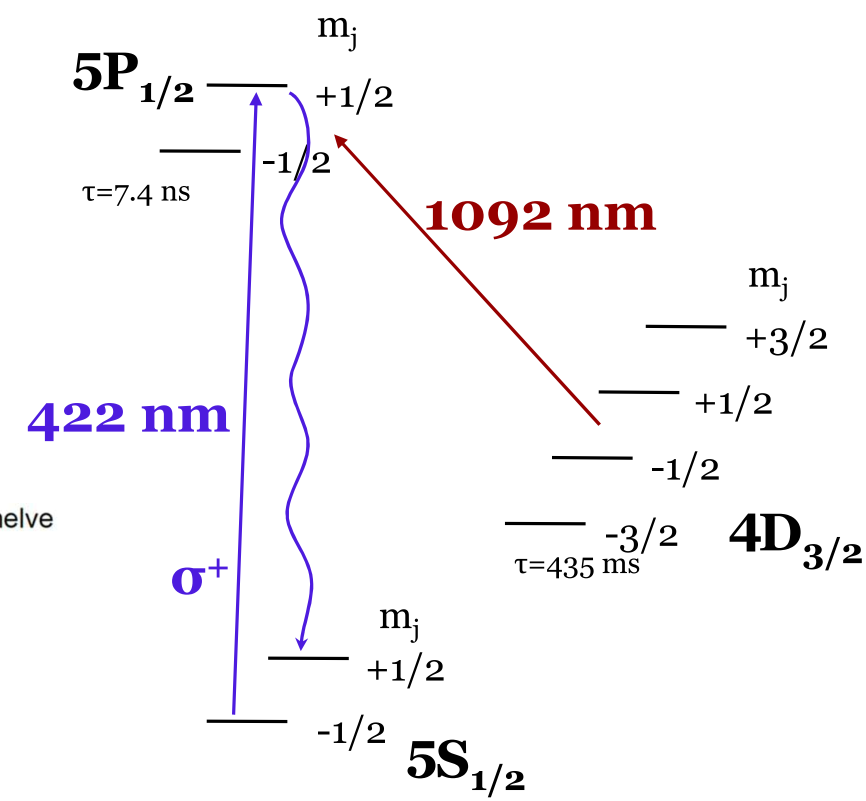
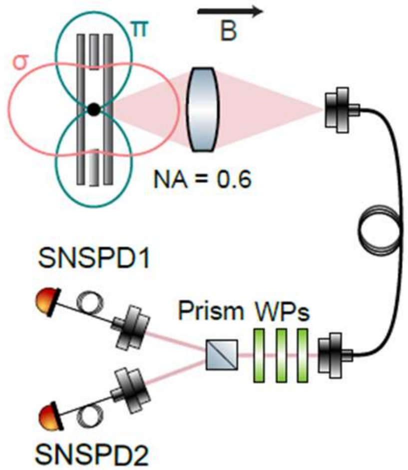


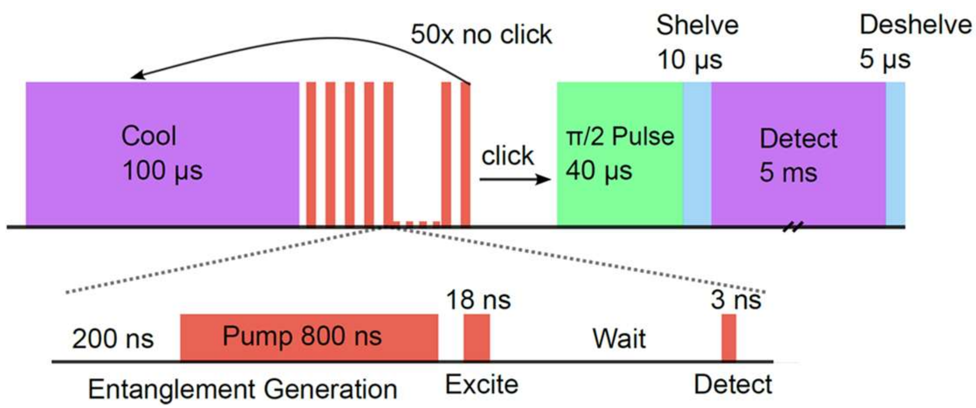


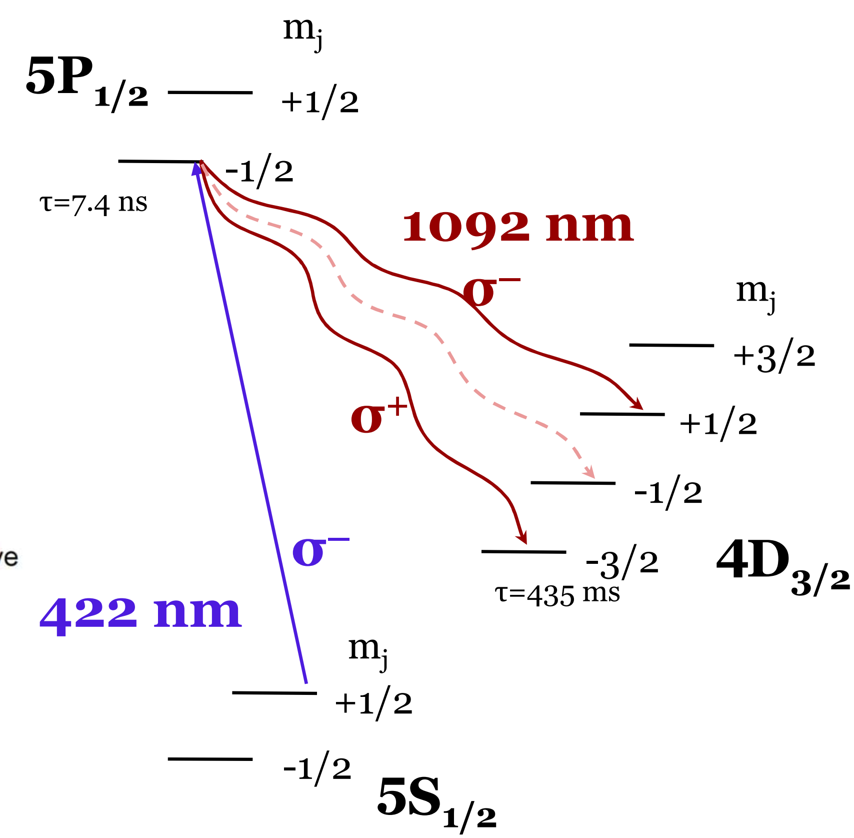


Zalewski et al arXiv:2506.11257

Quantum networking: A fiber-ready quantum network node







Zalewski et al. PRA 113 (2026)

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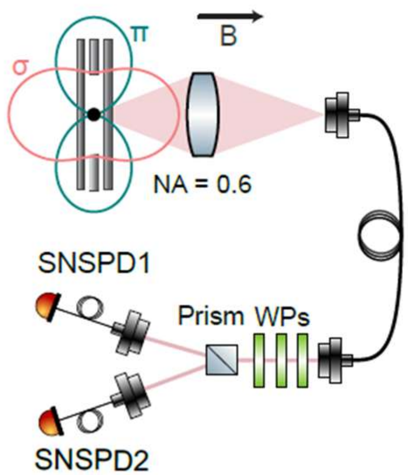
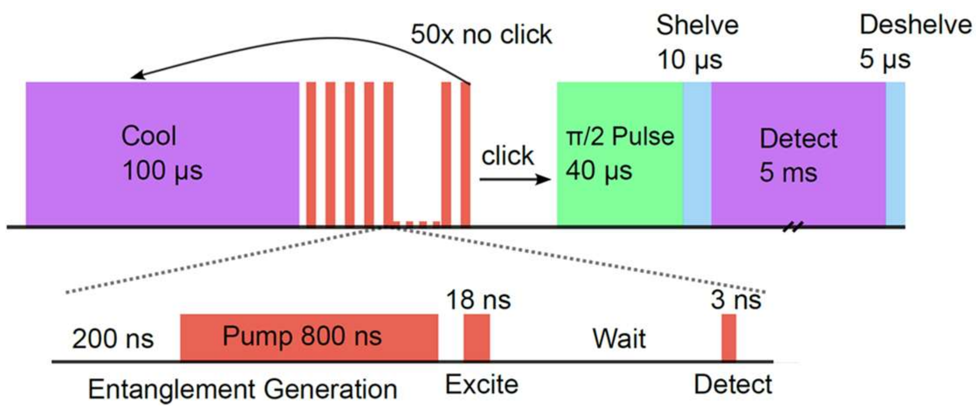


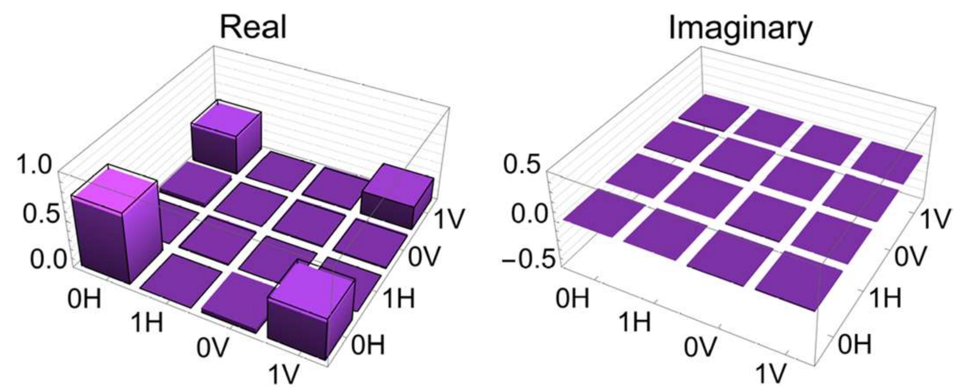


350(4)/s 2 m fiber
15.9(4)/s 2.8 km fiber

Zalewski et al. PRA 113 (2026)

Results: Ion-photon entangled state tomography

2m fiber



Fidelity: 94.9(4)%
Purity: 90.8(7)%
Rate: 96(1)/s

$$F = \langle\psi|\rho|\psi\rangle$$

$$|\psi\rangle = \frac{\sqrt{3}}{2}|0\rangle|\sigma^+\rangle + \frac{1}{2}|1\rangle|\sigma^-\rangle$$

$$P = \mathrm{Tr}(\rho^2)$$

Zalewski et al arXiv:2506.11257

Results: Ion-photon entangled state tomography

Fidelity: 94.9(4)%
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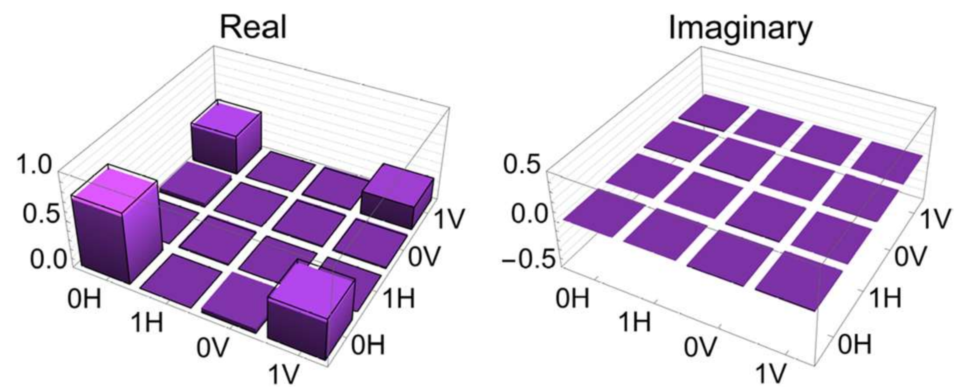
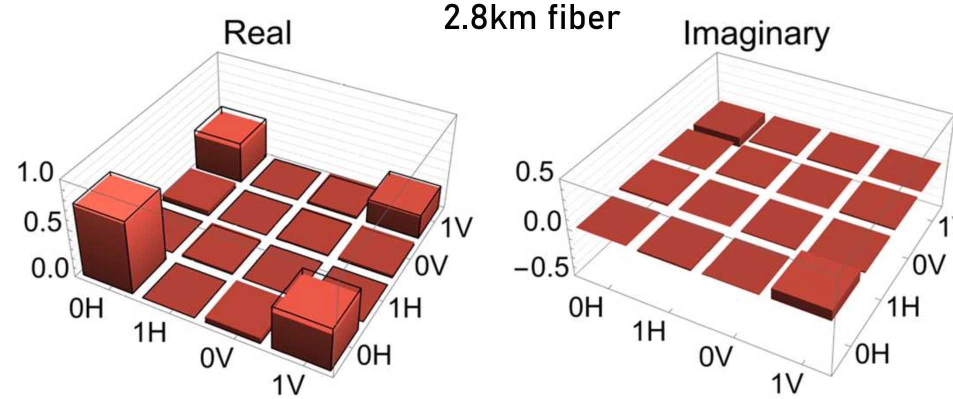
2m fiber



Fidelity: 92.9(5)%
Purity: 89.9(9)%
Rate: 3.5(1)/s

2.8km fiber



Zalewski et al arXiv:2506.11257

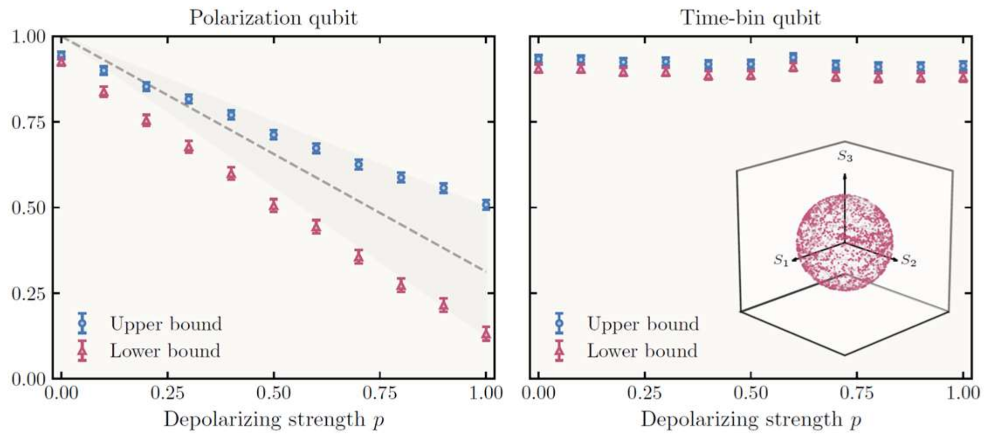
Error analysis: Ion-photon entangled state

Error Budget, Laboratory Fiber	
Error Source	Fidelity Error
Polarization Mixing	$2 - 2.5 \times 10^{-2}$
Atomic Qubit Decoherence	$1.25(6) \times 10^{-2}$
Atomic Qubit Readout	$6(2) \times 10^{-3}$
Photon Path Errors	$< 5 \times 10^{-3}$
$\pi/2$-pulse Errors	1×10^{-3}
Background Counts	$< 1 \times 10^{-3}$
Imaging Alignment	$< 1 \times 10^{-3}$
Raman Phase Noise	$< 1 \times 10^{-3}$
Additional Errors in Deployed Fiber	
Error Source	Fidelity Error
Polarization Instability	1.65×10^{-2}
Atomic Qubit Decoherence	3.5×10^{-3}

Zalewski et al. PRA 113 (2026)

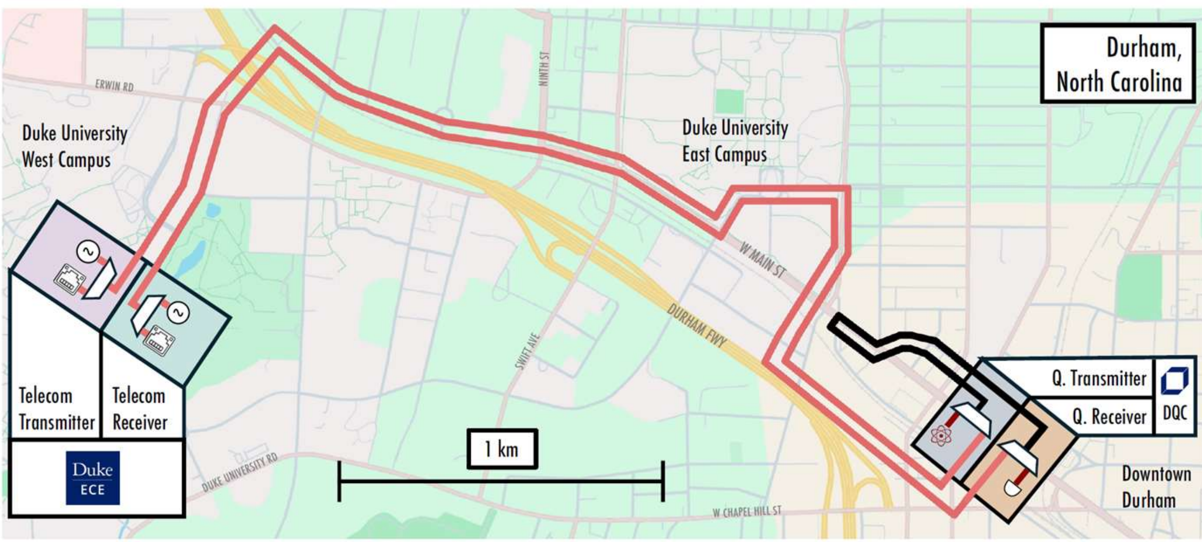
Recent results

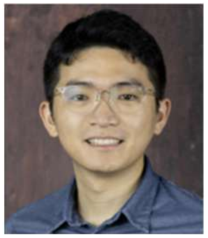
Time-bin encoding (robust):



A. Ferreira Ferrari et al., arXiv:2607.07805

Coexistence with classical 5G / Ethernet traffic:



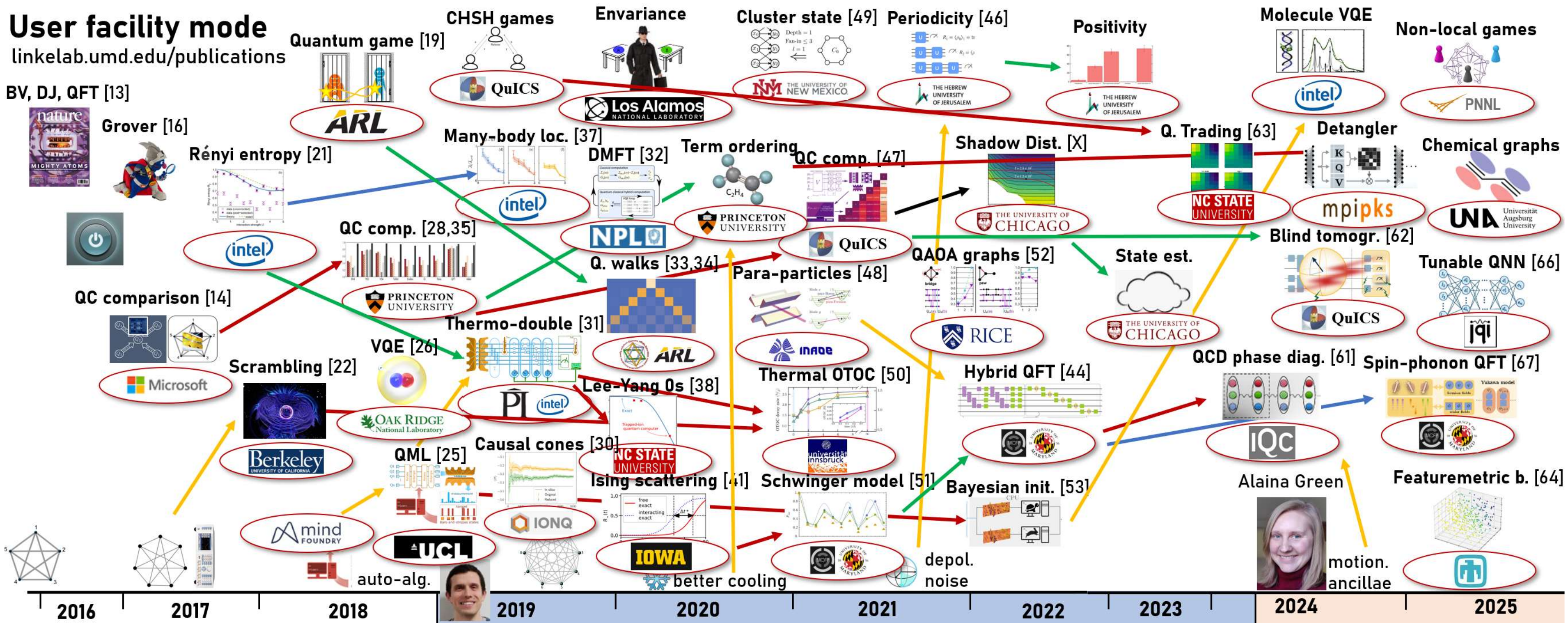


Prof Tingjun Chen, Duke ECE

D. Wu et al., arXiv:2609.06387

Outlook

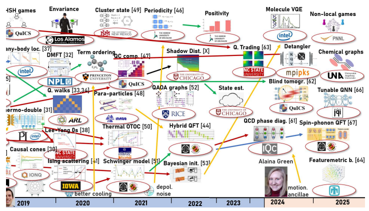
A Quantum computer in User Facility mode



QLab: user facility mode 2.0

QLab
National Quantum Laboratory

research systems



⋮

$ $ $ $

commercial systems

IONQ

Forte-1 (36 qubits)
Forte-1 Enterprise (36 qubits)

QuEra

Aquila (256 analog)
Gemini (digital, coming 2026)

other vendors

⋮

"Quantum For All"

users/collaborators

- research
- spin-offs

QUANTUM STARTUP FOUNDRY

- educators

Thomas Barthel

Franz Klein

NML

Anton Than

Matthew Diaz

Alaina Green (NIST)

Kalea Wen

Xingxin Liu

Free/cheap access to quantum computers available!
50+ active research users, 10 Fellows, 10+ start-up users

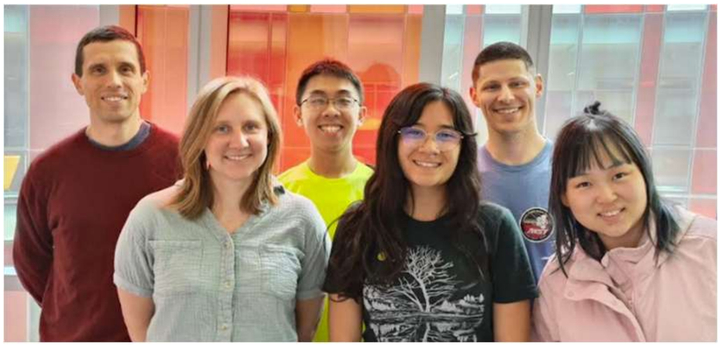
qlab.umd.edu

QLab
NATIONAL QUANTUM LABORATORY

NML

Anton Than

Matthew Diaz



Alaina Green (NIST)

Kalea Wen

Xingxin Liu

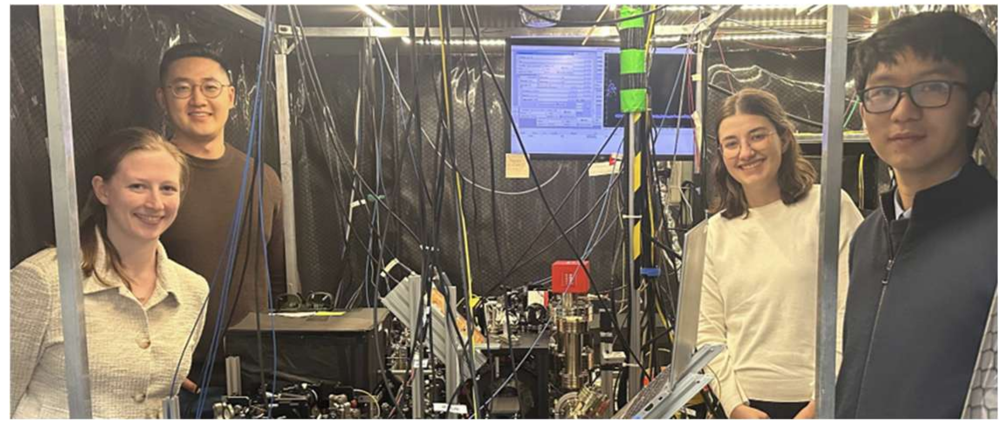
Zohreh Davoudi (UMD)

Guido Pagano (Rice)

Duke Quantum Center

Denton Wu

Ana Ferrari



Mika Zalewski

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QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

Institute for Robust Quantum Simulation