Quantum Energy Teleportation

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Demonstration of Quantum Energy Teleportation on Superconducting Quantum Hardware

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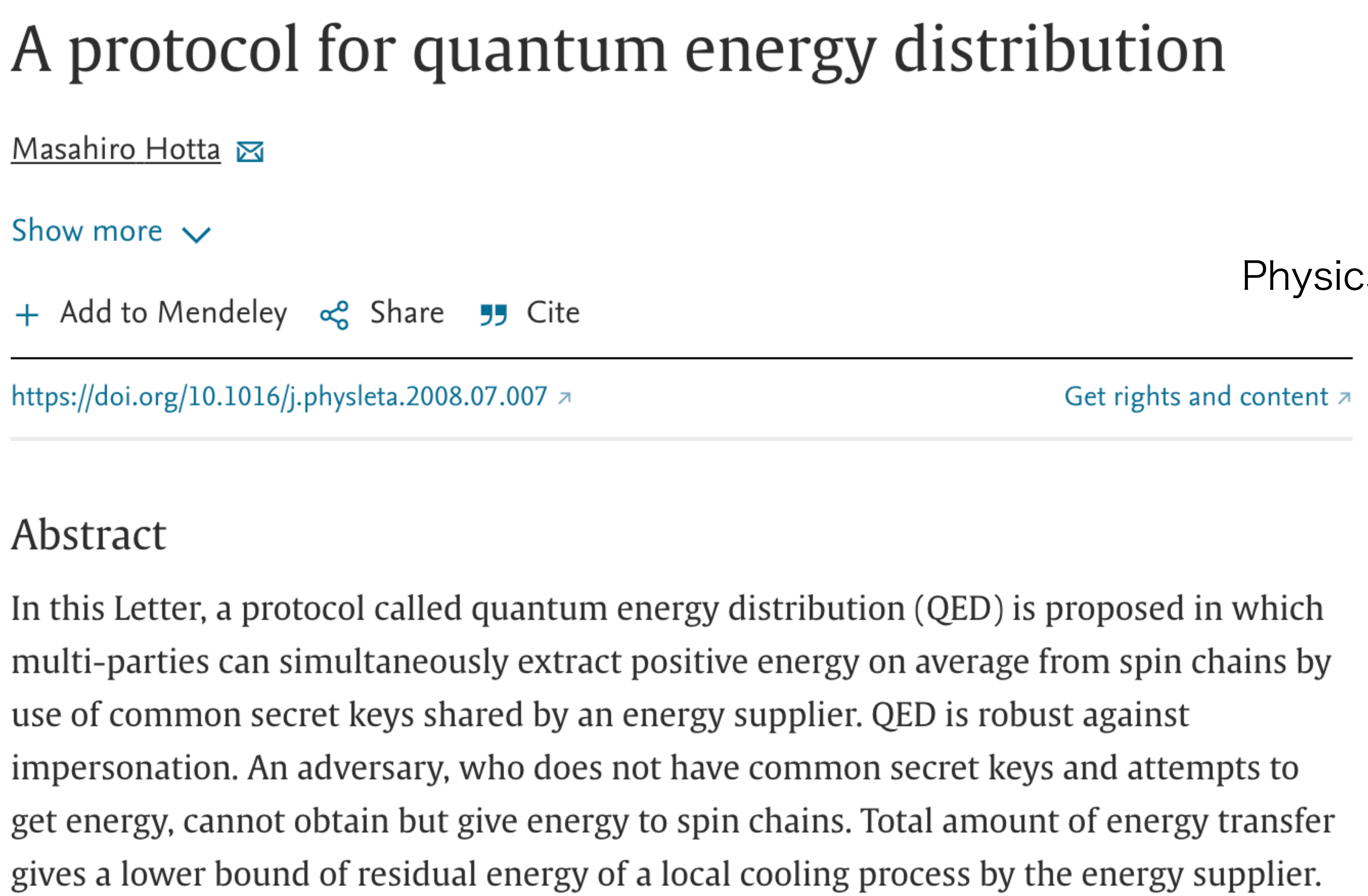
- Highest-scoring outputs from Physical Review Applied (#3 out of all publications)
- Featured Media Outlets Worldwide (Quanta Magazine, WIRED, NIKKEI)

The First Demonstration of Zero Temperature QET

Background of energy teleportation

Theory was proposed in 2008 by Dr. Hotta at Tohoku U



Physics Letters A (2008)

Three Steps for QET

(1) Alice injects energy $\langle E_A \rangle$ into system by projective measurement $P_A(\mu) = \frac{1}{2}(1 + \mu \sigma_A)$

$$H = \sum_n H_n \qquad \langle g | H | g \rangle = \langle g | H_n | g \rangle = 0$$

$$\langle E_A \rangle = \sum_{\mu = \pm 1} \frac{1}{p_A(\mu)} \langle g | P_A(\mu) H_A P_A(\mu) | g \rangle > 0$$

(2) Alice observes $\mu \in \{-1, +1\}$ & tells μ to Bob by classical channel

Alice's operations do not affect Bob's system

$$[H - H_A, P_A(\mu)] = 0$$

(3) Bob applies $U_B(\mu)$ & measures his local Hamiltonian to receive energy

$$\langle E_B \rangle = \sum_{\mu = \pm 1} \frac{1}{p_A(\mu)} \langle g | P_A(\mu) U_B^\dagger(\mu) H_B U_B(\mu) P_A(\mu) | g \rangle < 0$$

Due to energy conservation, he will get $-\langle E_B \rangle > 0$

Setup and model of QET

Hamiltonian

$$H = H_A + H_B + V_{int} \qquad H_n = hZ_n + \frac{h^2}{\sqrt{h^2+k^2}}, \quad (n = A, B) \quad V_{int} = 2kX_AX_B + \frac{2k^2}{\sqrt{h^2+k^2}}$$

Ground state

$$|g\rangle = \frac{1}{\sqrt{2}}\sqrt{1 - \frac{h}{\sqrt{h^2+k^2}}}\,|00\rangle - \frac{1}{\sqrt{2}}\sqrt{1 + \frac{h}{\sqrt{h^2+k^2}}}\,|11\rangle$$

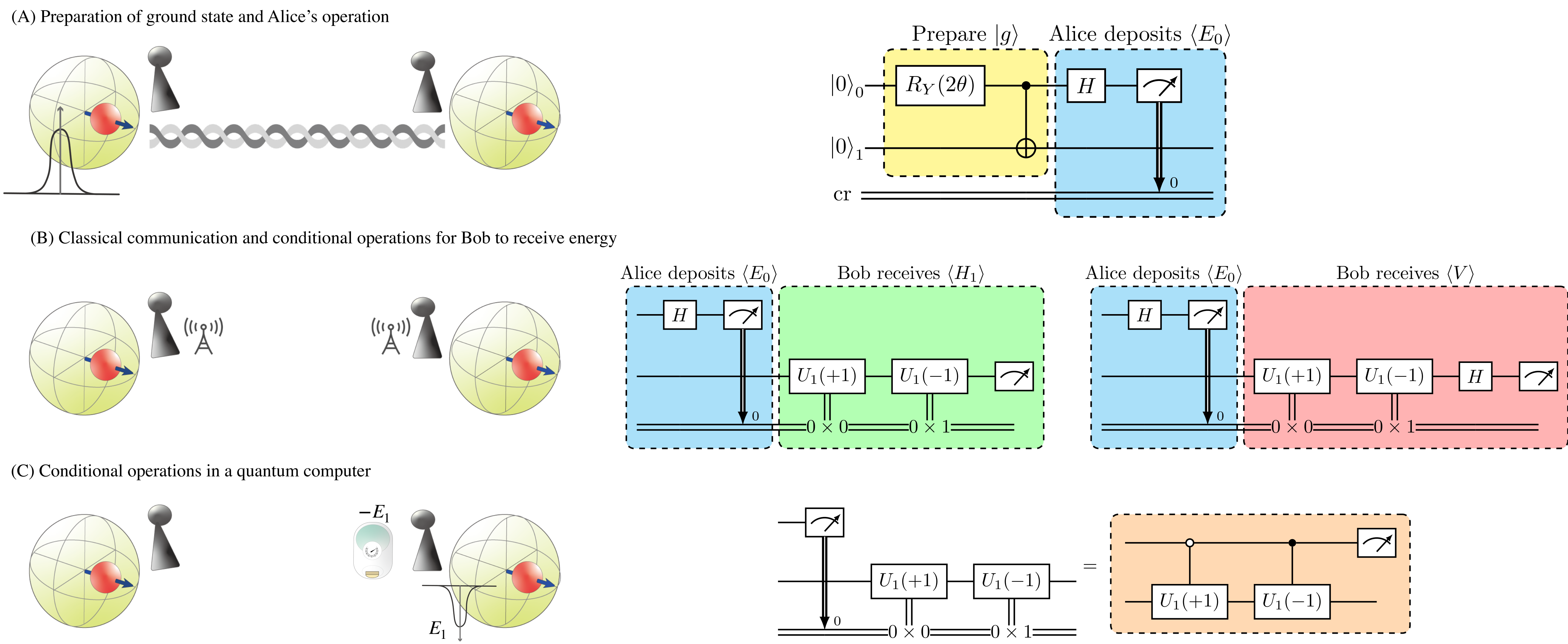
Alice's projective measurement

$$P_A(\mu) = \frac{1}{2}(1 + \mu X_A)$$

Bob's conditional operation

$$U_B(\mu) = R_Y(2\phi\mu)$$

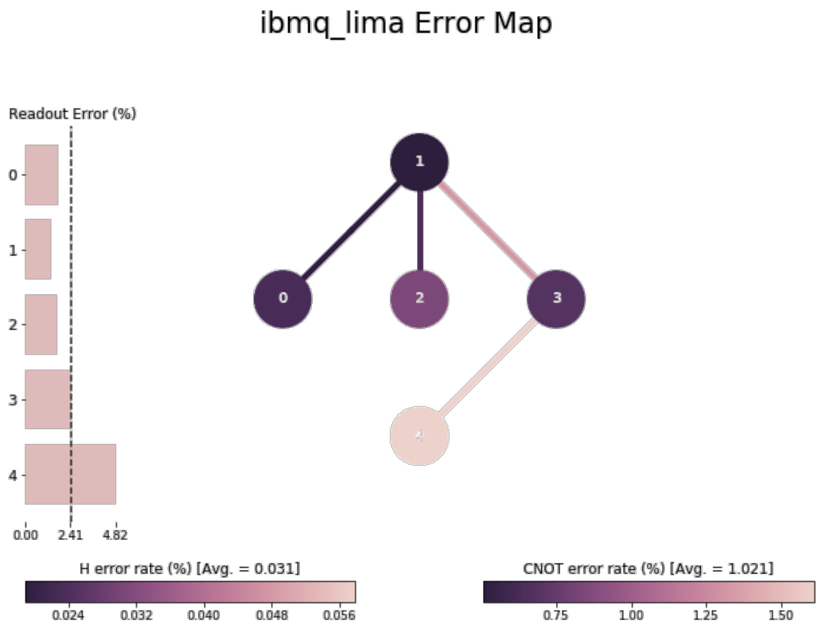
Quantum Circuit for QET



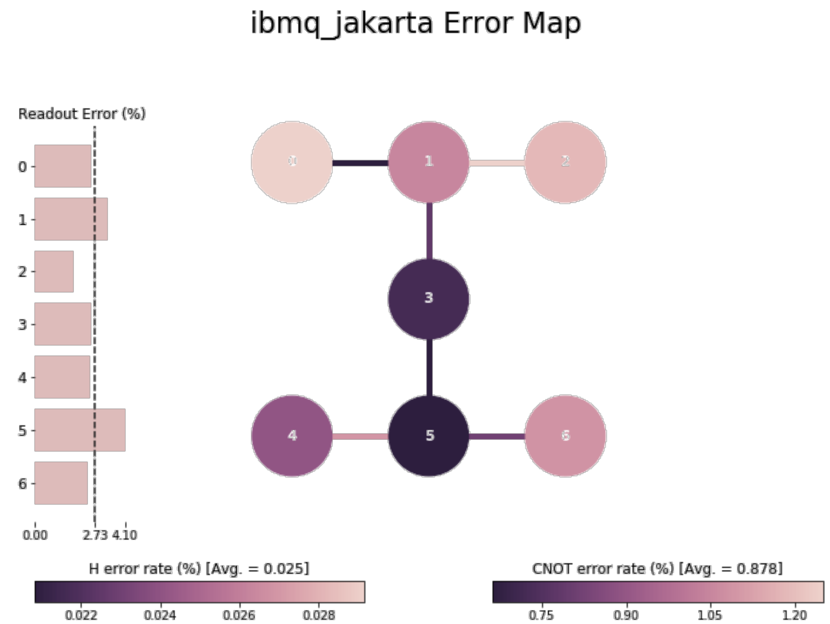
K. Ikeda, "Demonstration of quantum energy teleportation on superconducting quantum hardware"
Physical Review Applied (2023)

QET on IBM's superconducting hardware

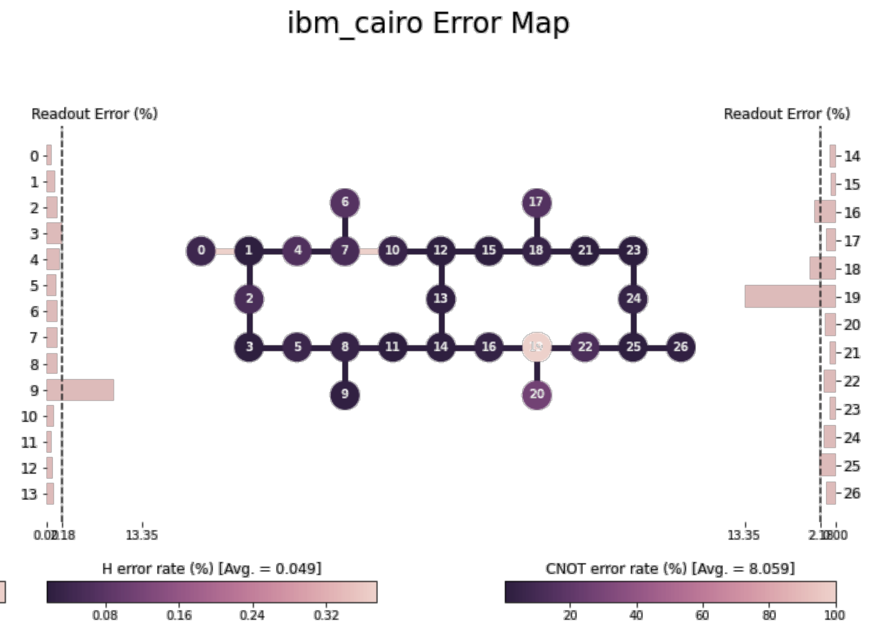
5 qubits

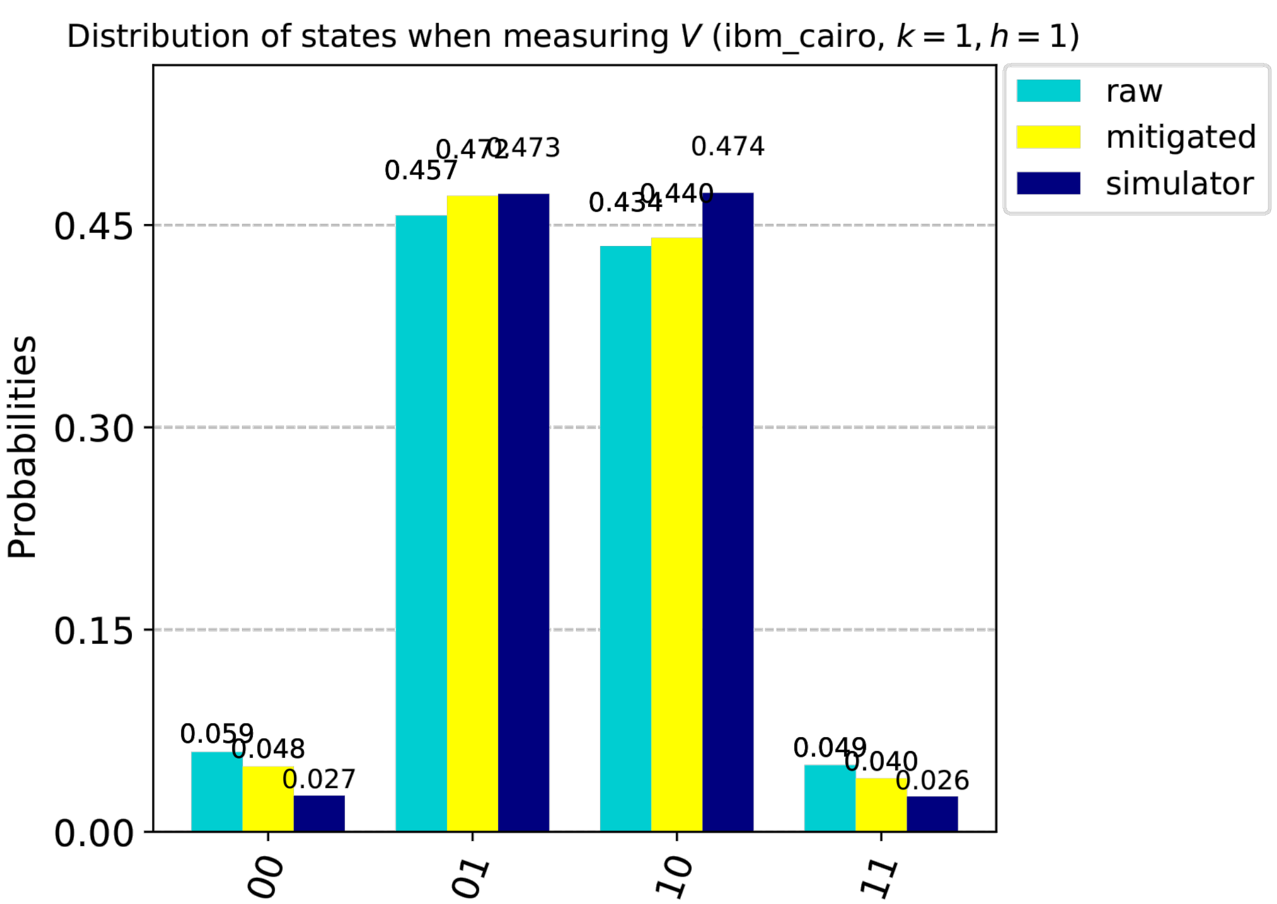


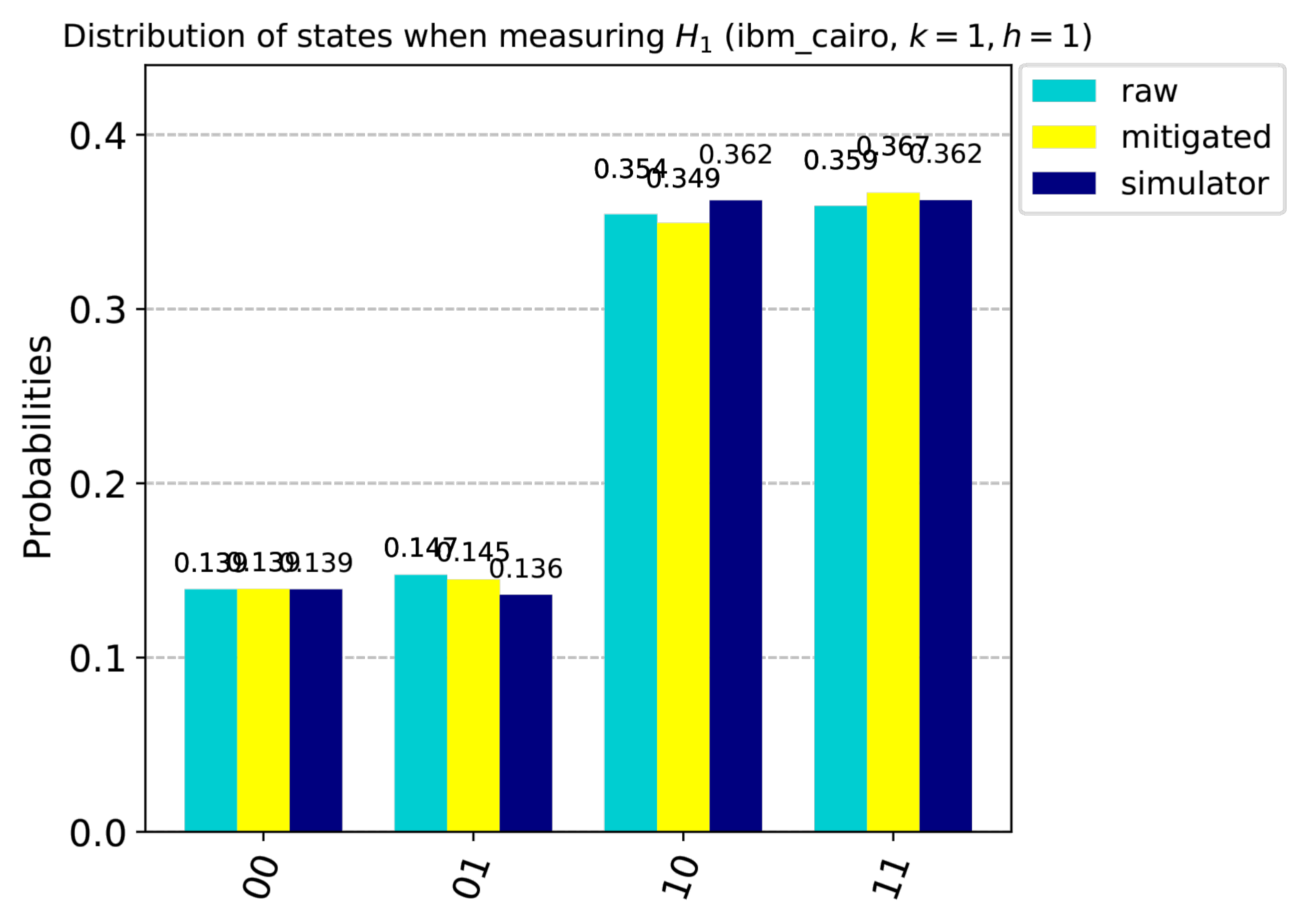
7 qubits



27 qubits







Backend		$(h,k)=(1,0.2)$	$(h,k)=(1,0.5)$	$(h,k)=(1,1)$	$(h,k)=(1.5,1)$
Analytical value	$\langle E_0 \rangle$	0.9806	0.8944	0.7071	1.2481
qasm_simulator		0.9827 ± 0.0031	0.8941 ± 0.0001	0.7088 ± 0.0001	1.2437 ± 0.0047
ibmq_lima	error mitigated	0.9423 ± 0.0032	0.8169 ± 0.0032	0.6560 ± 0.0031	1.2480 ± 0.0047
	unmitigated	0.9049 ± 0.0017	0.8550 ± 0.0032	0.6874 ± 0.0031	1.4066 ± 0.0047
ibmq_jakarta	error mitigated	0.9299 ± 0.0056	0.8888 ± 0.0056	0.7039 ± 0.0056	1.2318 ± 0.0084
	unmitigated	0.9542 ± 0.0056	0.9089 ± 0.0056	0.7232 ± 0.0056	1.2624 ± 0.0083
ibm_cairo	error mitigated	0.9571 ± 0.0032	0.8626 ± 0.0031	0.7277 ± 0.0031	1.2072 ± 0.0047
	unmitigated	0.9578 ± 0.0031	0.8735 ± 0.0031	0.7362 ± 0.0031	1.2236 ± 0.0047
Analytical value	$\langle H_1 \rangle$	0.0521	0.1873	0.2598	0.3480
qasm_simulator		0.0547 ± 0.0012	0.1857 ± 0.0022	0.2550 ± 0.0028	0.3487 ± 0.0038
ibmq_lima	error mitigated	0.0733 ± 0.0032	0.1934 ± 0.0032	0.2526 ± 0.0032	0.3590 ± 0.0047
	unmitigated	0.1295 ± 0.0053	0.2422 ± 0.0024	0.2949 ± 0.0028	0.4302 ± 0.0039
ibmq_jakarta	error mitigated	0.0736 ± 0.0055	0.2018 ± 0.0056	0.2491 ± 0.0056	0.3390 ± 0.0084
	unmitigated	0.0852 ± 0.0022	0.2975 ± 0.0045	0.3365 ± 0.0052	0.4871 ± 0.0073
ibm_cairo	error mitigated	0.0674 ± 0.0032	0.1653 ± 0.0031	0.2579 ± 0.0031	0.3559 ± 0.0047
	unmitigated	0.0905 ± 0.0014	0.1825 ± 0.0022	0.2630 ± 0.0027	0.3737 ± 0.0037
Analytical value	$\langle V \rangle$	-0.0701	-0.2598	-0.3746	-0.4905
qasm_simulator		-0.0708 ± 0.0012	-0.2608 ± 0.0032	-0.3729 ± 0.0063	-0.4921 ± 0.0038
ibmq_lima	error mitigated	-0.0655 ± 0.0012	-0.2041 ± 0.0031	-0.2744 ± 0.0063	-0.4091 ± 0.0063
	unmitigated	-0.0538 ± 0.0011	-0.1471 ± 0.0025	-0.1233 ± 0.0041	-0.2737 ± 0.0046
ibmq_jakarta	error mitigated	-0.0515 ± 0.0022	-0.2348 ± 0.0056	-0.3255 ± 0.0112	-0.4469 ± 0.0112
	unmitigated	-0.0338 ± 0.0021	-0.1371 ± 0.0046	-0.0750 ± 0.0075	-0.2229 ± 0.0083
ibm_cairo	error mitigated	-0.0497 ± 0.0013	-0.1968 ± 0.0031	-0.2569 ± 0.0063	-0.3804 ± 0.0063
	unmitigated	-0.0471 ± 0.0012	-0.1682 ± 0.0026	-0.1733 ± 0.0038	-0.3089 ± 0.0045
Analytical value	$\langle E_1 \rangle$	-0.0180	-0.0726	-0.1147	-0.1425
qasm_simulator		-0.0161 ± 0.0017	-0.0751 ± 0.00398	-0.1179 ± 0.0069	-0.1433 ± 0.0054
ibmq_lima	error mitigated	0.0078 ± 0.0034	-0.0107 ± 0.0045	-0.0217 ± 0.0071	-0.0501 ± 0.0079
	unmitigated	0.0757 ± 0.0054	0.0950 ± 0.0035	0.1715 ± 0.0050	0.1565 ± 0.0060
ibmq_jakarta	error mitigated	0.0221 ± 0.0059	-0.0330 ± 0.0079	-0.0764 ± 0.0125	-0.1079 ± 0.0140
	unmitigated	0.0514 ± 0.0030	0.1604 ± 0.0064	0.2615 ± 0.0091	0.2642 ± 0.00111
ibm_cairo	error mitigated	0.0177 ± 0.0035	-0.0315 ± 0.0044	0.0010 ± 0.0070	-0.0245 ± 0.0079
	unmitigated	0.0433 ± 0.0018	0.0143 ± 0.0034	0.0897 ± 0.0047	0.0648 ± 0.0058

Very close to exact solutions

Simulations perfectly agree with theory

Negative values (Succeeded in QET)

Summary of my contributions

Link to paper

What I did in Phys. Rev. Applied (2023)

- Created quantum circuits and tested with IBM Q
- Confirmed negative $\langle E_B \rangle$ on real superconducting quantum hardware
- All simulated results completely agreed with analytical prediction
- Extended the protocol for long-range and large-scale quantum network
- Reproduced phase diagrams with the QET protocol

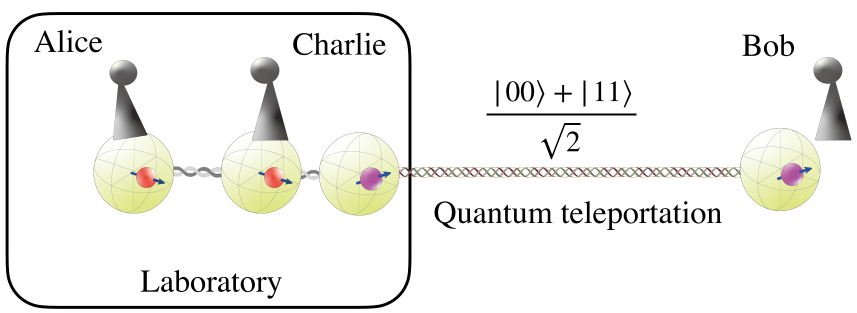
Milestone

The First QET Demonstration at Zero Temperature

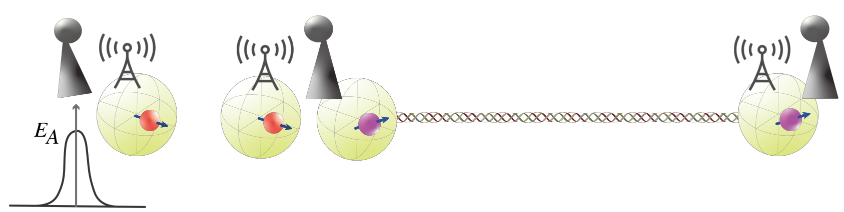
Applications of QET

Protocol for long-range quantum network

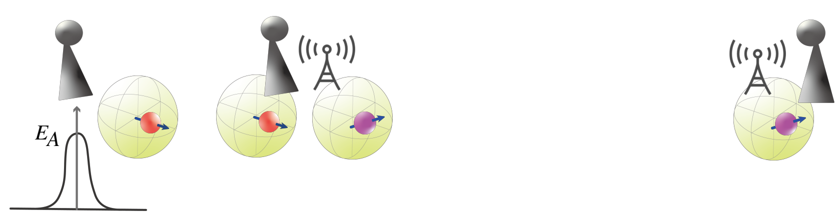
(1) Alice and Charlie share the same ground state in a laboratory and Charlie and Bob share a Bell state



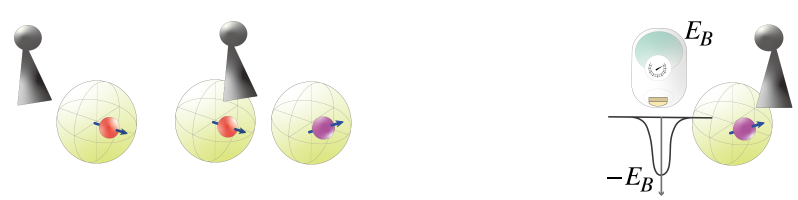
(2) Alice performs operations and announces results to Bob and Charlie



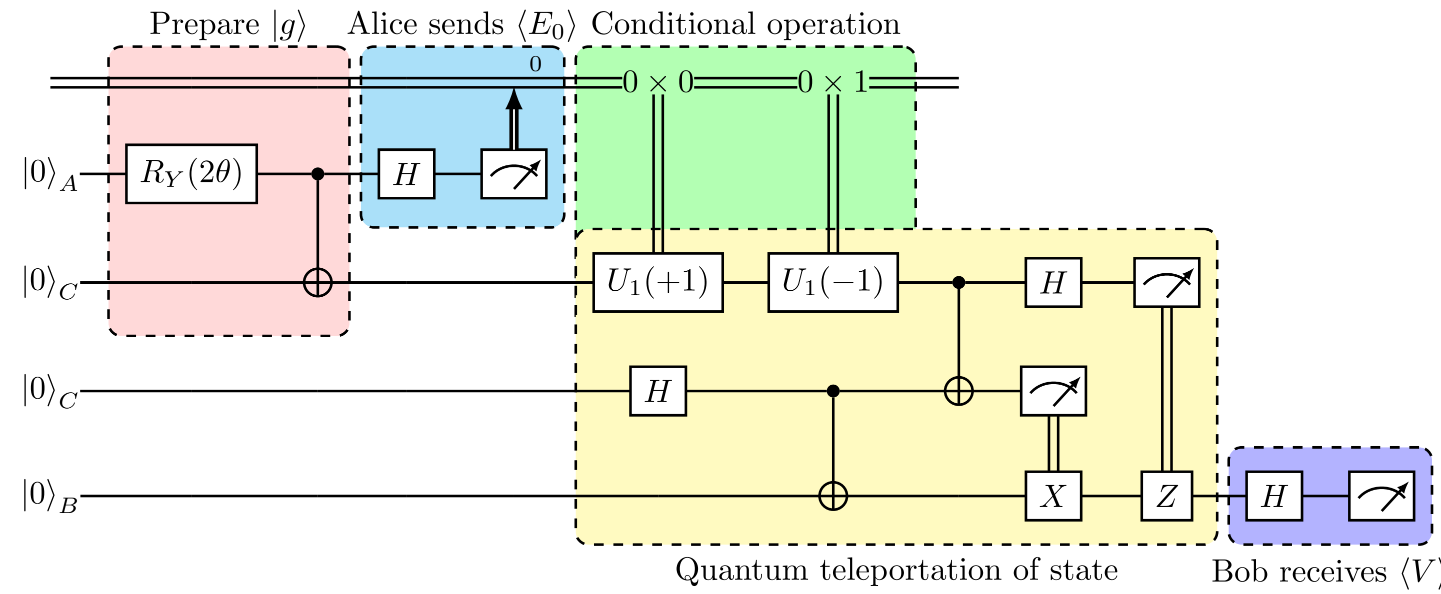
(3) Charlie sends the state to Bob by quantum teleportation



(4) Bob receives energy by performing conditional operations and measurement



K. Ikeda, IET Quantum Communication (2024)

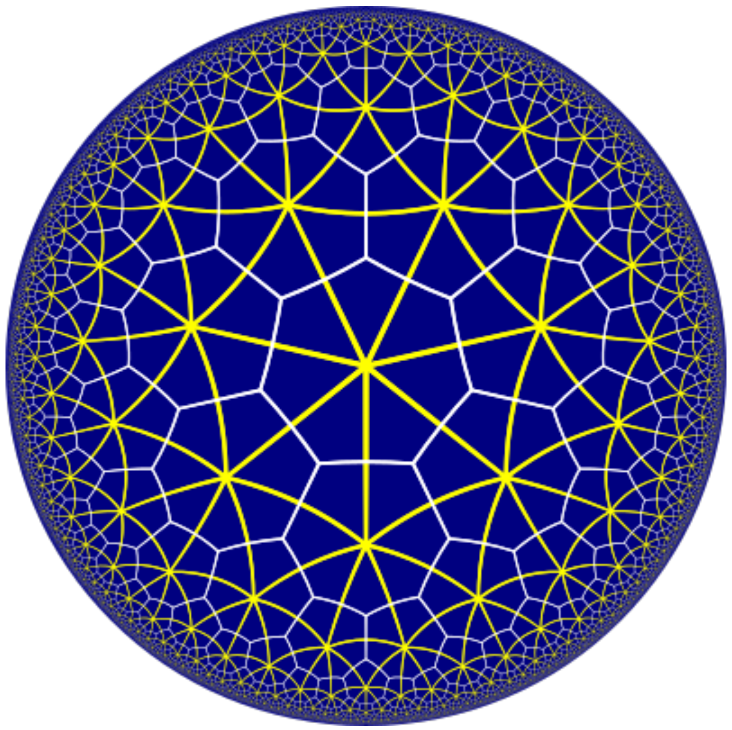


Testable with SBU/BNL quantum network

Image: The Long Island Quantum Ring (LIQR)

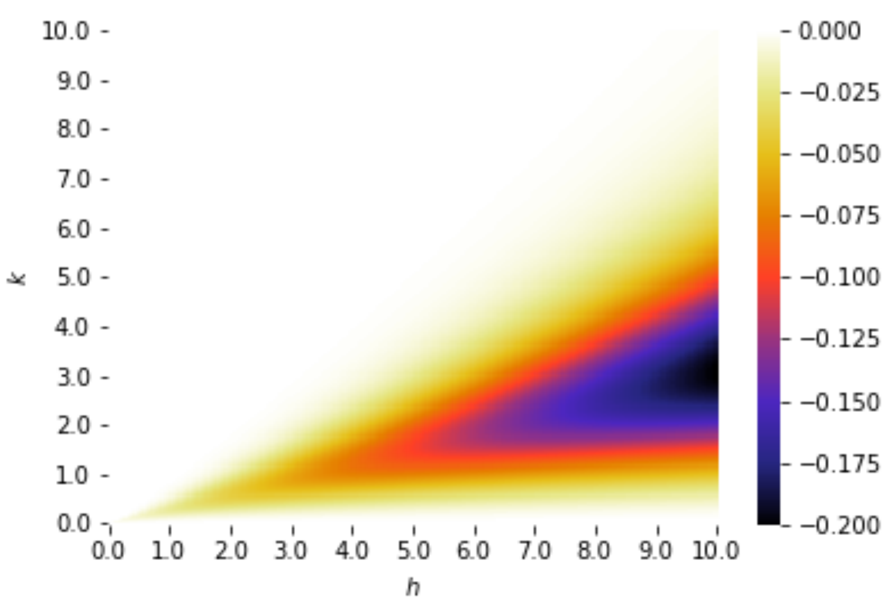
https://www.bnl.gov/instrumentation/quantum/research.php

Protocol for large-scale quantum network

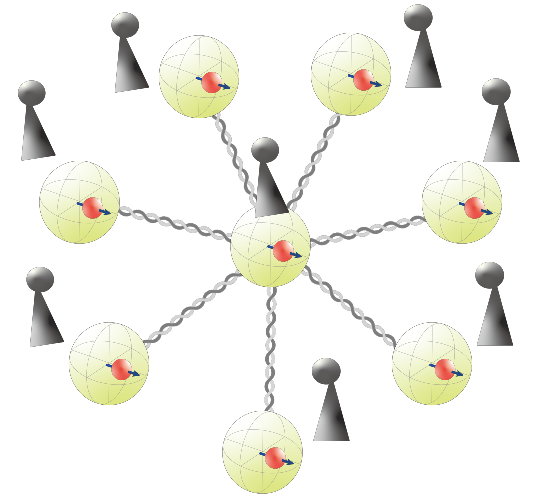


$\{3,7\}$ tiling and dual $\{7,3\}$ tiling

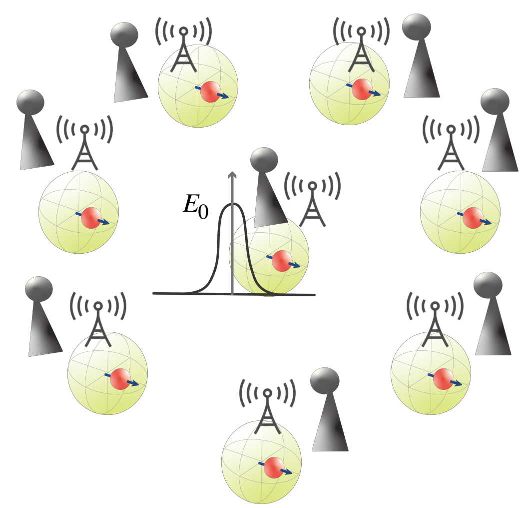
Teleported energy



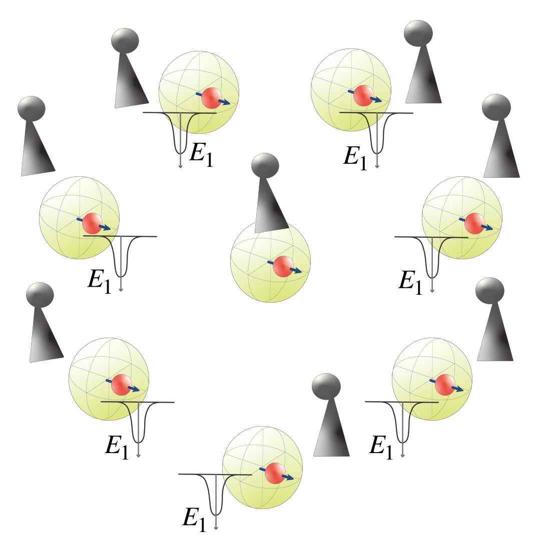
(1) Step 1: generate entanglement

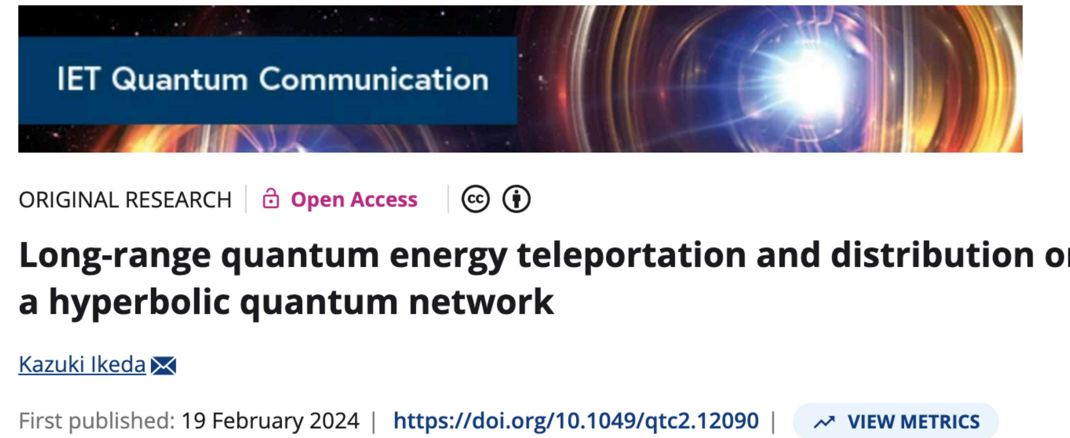


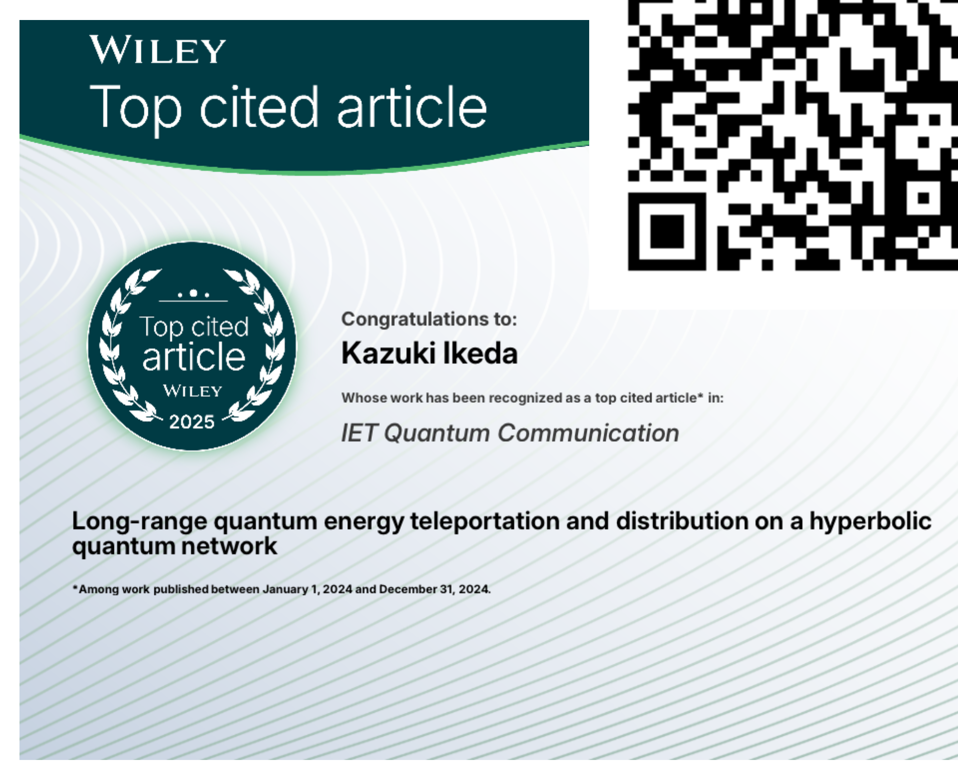
(2) Step 2: energy injection



(3) Step 3: energy reception





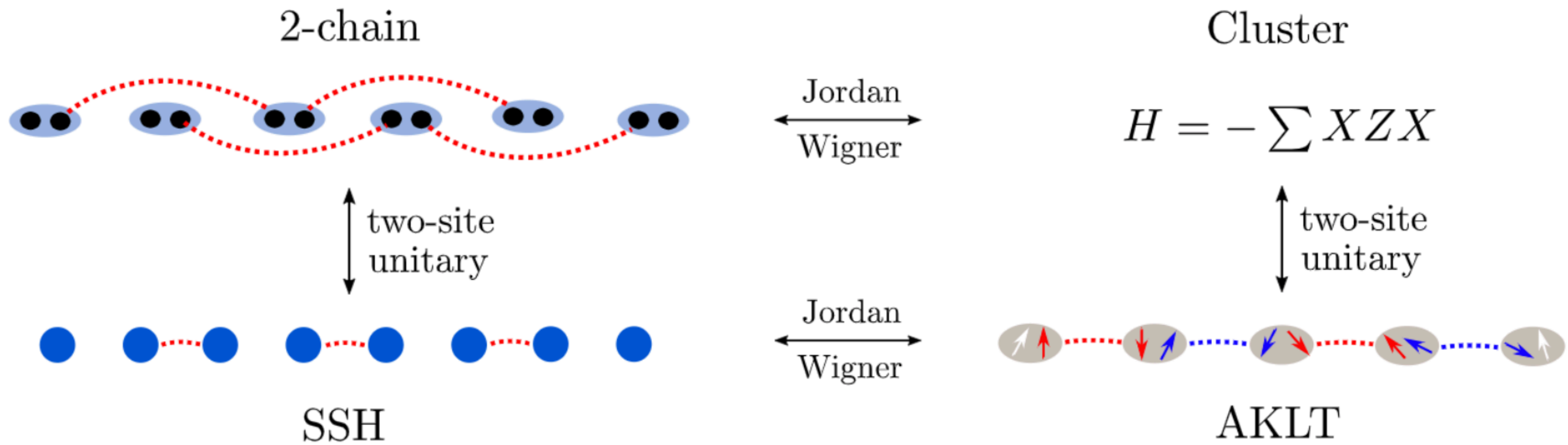


Link: IET Quantum Communication

QET with Topological Materials

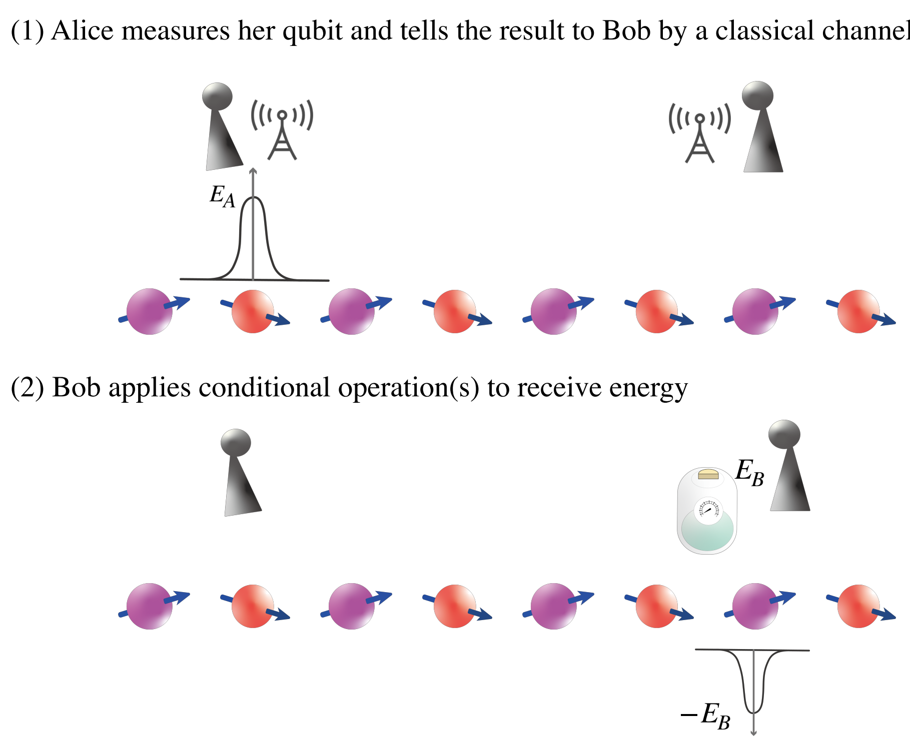
Symmetry protected topological phases

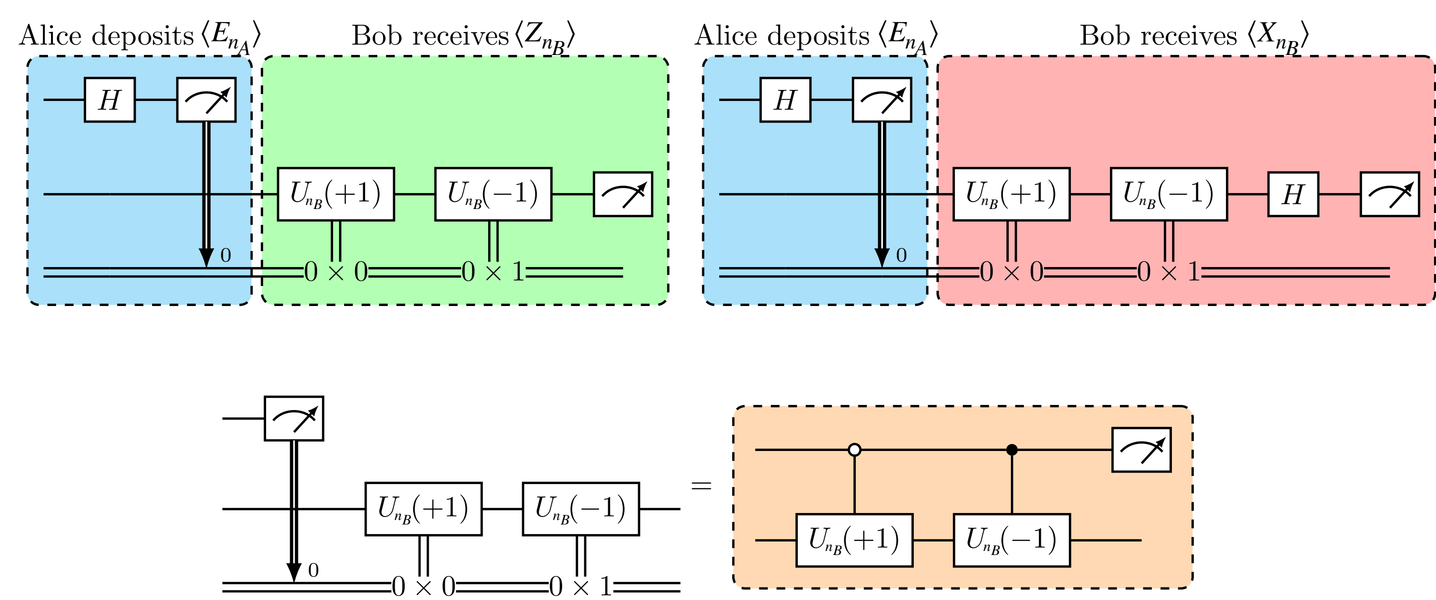
Verresen, Moessner & Pollmann, PRB (2017)



Quantum teleportation protocol

K. Ikeda, AVS Quantum Science (2023)





K. Ikeda, AVS Quantum Science (2023)

Models of SPT states

$$H = \sum_n (Z_n - J_1 X_n X_{n+1} - J_2 X_{n-1} Z_n X_{n+1} + \frac{1}{2} Z_n Z_{n+1})$$

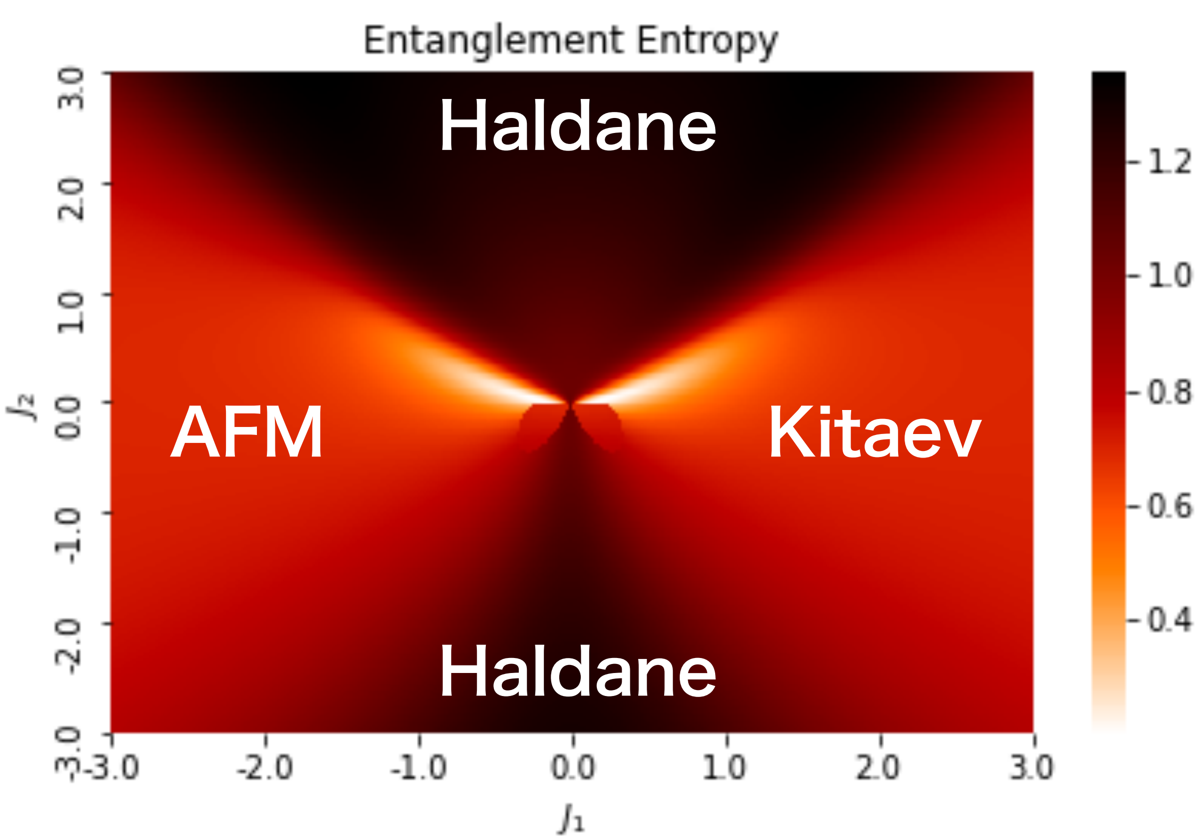
Bob's local energy

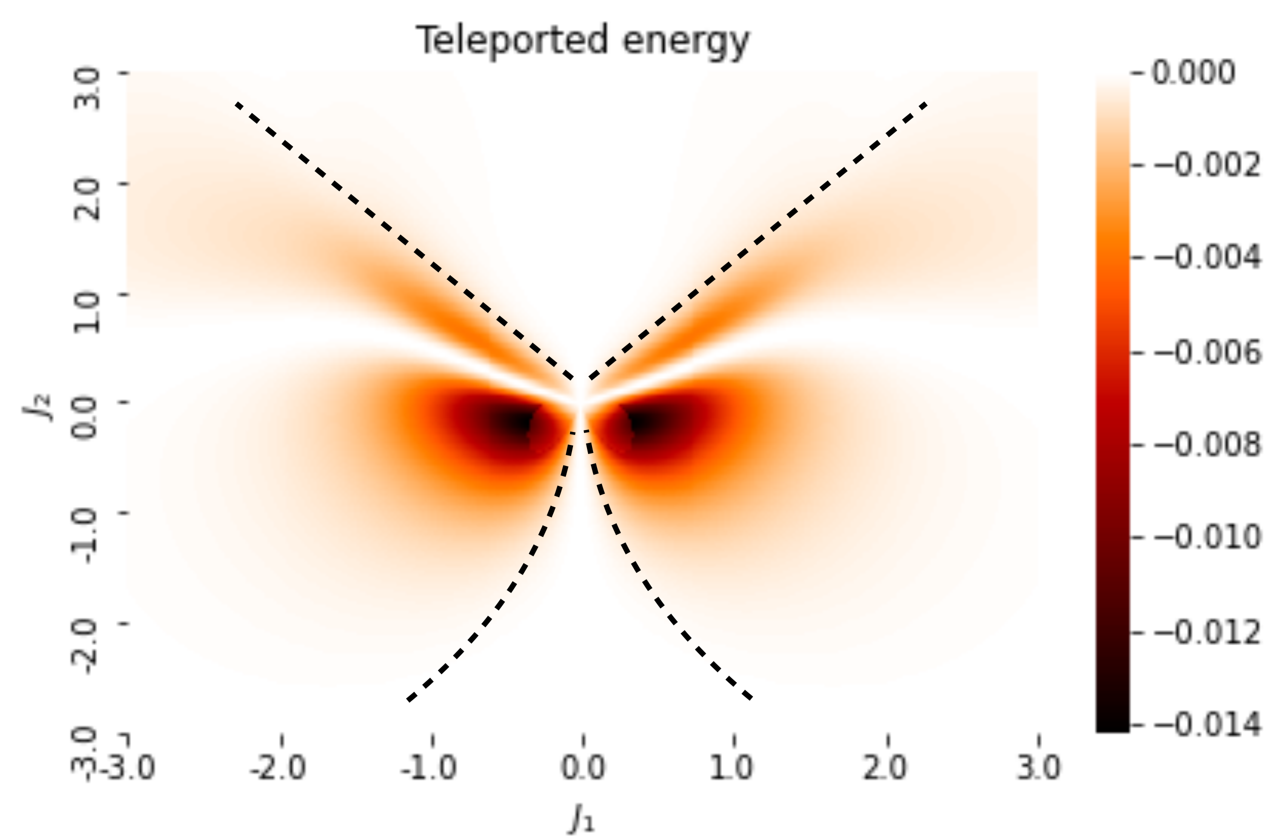
$$\langle E_{n_B} \rangle = \mathrm{Tr}[\rho_{\mathrm{QET}} H_{n_B}] = \frac{1}{2}\left[\xi - \sqrt{\xi^2 + \eta^2}\right]$$

$$\xi = \langle g | \sigma_{n_B} H \sigma_{n_B} | g \rangle$$

$$\eta = \langle g | \sigma_{n_A} \dot{\sigma}_{n_B} | g \rangle$$

$$\rho_{\mathrm{QET}} = \sum_{\mu \in \{-1,1\}} U_{n_B}(\mu) P_{n_A}(\mu) |g\rangle \langle g| P_{n_A}(\mu) U^{\dagger}_{n_B}(\mu)$$





Other Works of QET

- Long-distance QET on quantum network (K. Ikeda, IET Quantum Communication, 2023)
- Detecting topological phases (K. Ikeda, AVS Quantum Science, 2023)
- QET in Quantum Field Theory (K. Ikeda, PRD, 2023)
- Quantum Zero Knowledge Proofs by QET (K. Ikeda & A. Lowe, Quantum Information Processing, 2023)
- Quantum Discord and QET (K. Ikeda & A. Lowe, PRD, 2024)
- Quantum Batteries by QET (M. Hotta & K. Ikeda, Quantum Information Processing, 2025)
- Quantum Charge & Current Teleportation (K. Ikeda, PTEP, 2025)
- Review on QET (K. Ikeda, Canadian Journal of Physics, 2025)
- Quantum Games & Economics by QET (K. Ikeda, SSRN 5168193, 2025)
- Timelike QET (K. Ikeda, arXiv 2504.05353, 2025)
- Quantum Key Distribution by QET (S. Dolev, K. Ikeda, Y. Oz, PRA, 2026)
- QET across lattice and continuum (K. Ikeda, arXiv 2604.09973, 2026)