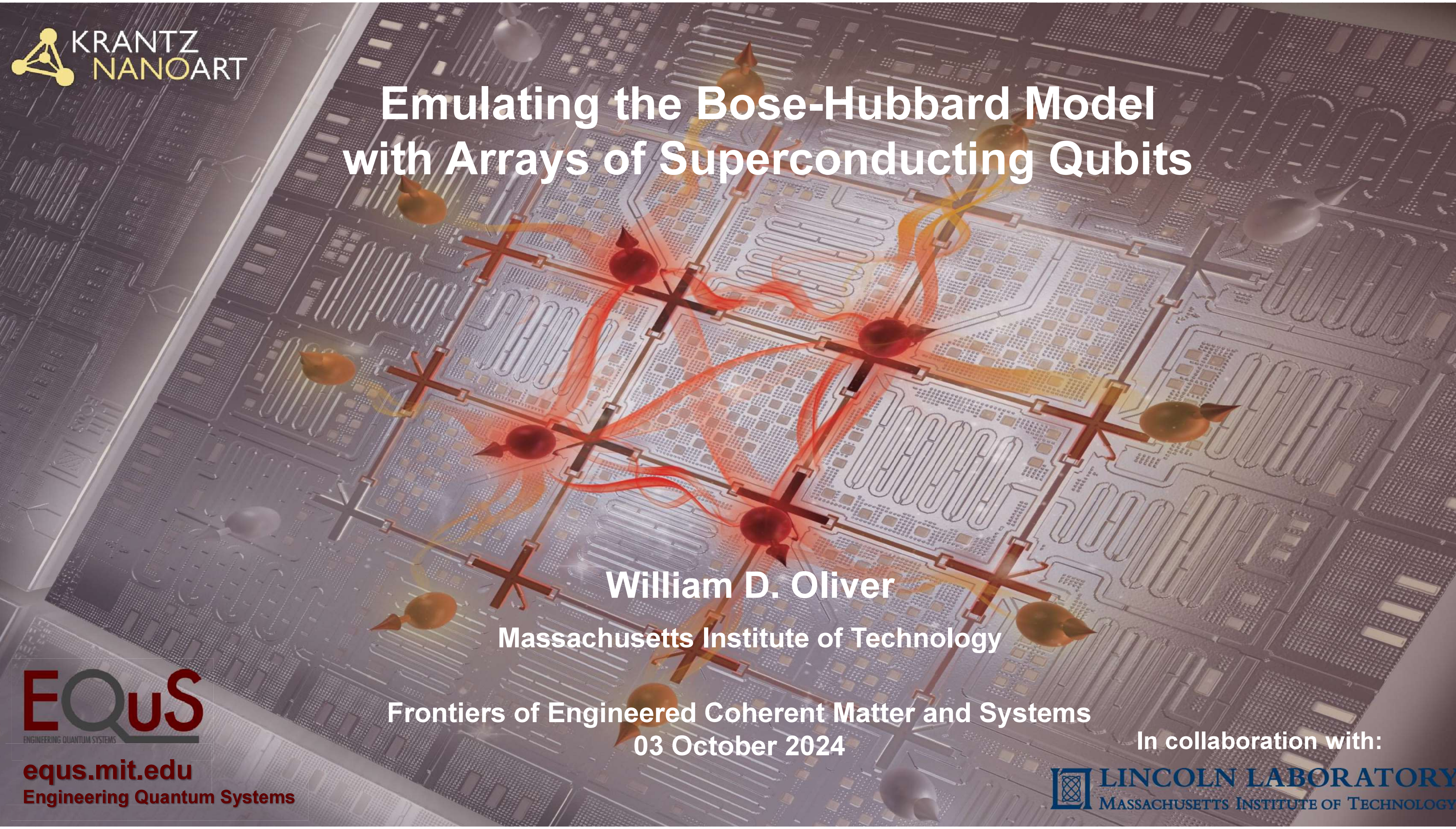


Emulating the Bose-Hubbard Model with Arrays of Superconducting Qubits

William D. Oliver

Massachusetts Institute of Technology

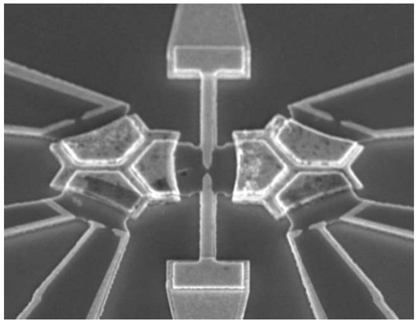
Frontiers of Engineered Coherent Matter and Systems
03 October 2024

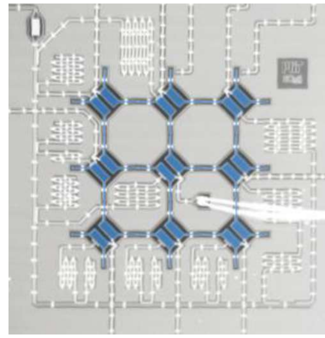
EQuS
ENGINEERING QUANTUM SYSTEMS
equs.mit.edu
Engineering Quantum Systems

In collaboration with:
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

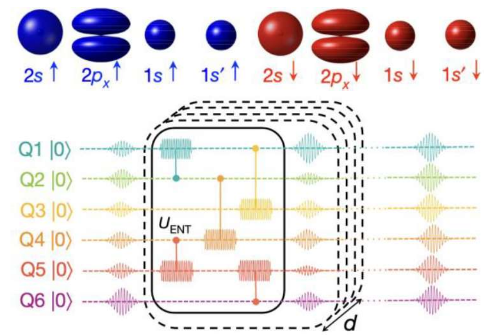
Flavors of Quantum Simulation

Pouse *et al.* *Nat. Phys.* **19** (2022)





Karamlou *et al.* *npj Q. I.* **8** (2022)



Kandala *et al.* *Nature* **549** (2017)

Natural materials
- Large lattices
- Less control
- Extensive measurements

Quantum dot model systems

Qubit arrays

Quantum chemistry

Simulators
- Small lattices
- Precision control
- Site-resolved measurements

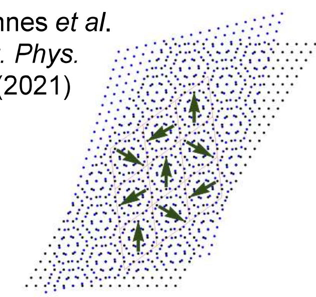
Moire lattices

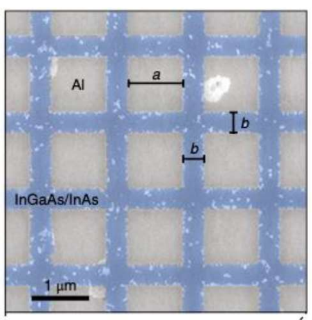
Metamaterials

Trotterized interactions

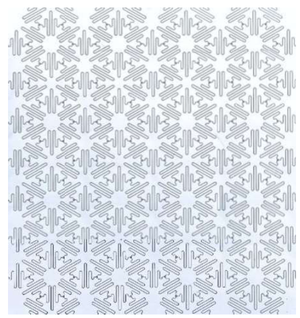
Algorithms (fault tolerant hardware)

Kennes *et al.* *Nat. Phys.* **17** (2021)

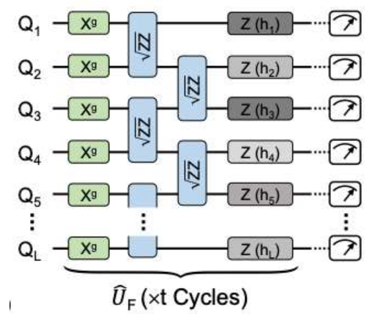




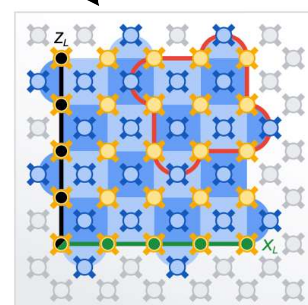
Bøttcher et al. *arXiv* (2022)



Kollár, Fitzpatrick, and Houck. *Nature* **571** (2019)



Mi *et al.* *Science* **378** (2022)



Google Quantum AI, *Nature* **614** (2023)

Flavors of Quantum Simulation

Hardware

Superconducting qubits

Trapped ions

Neutral atoms

Quantum dots, …

Approach

Analog/Hybrid

Set/sweep H parameters
Digital gates for initialization, benchmarking, ….

Digital

Sequence of digital gates

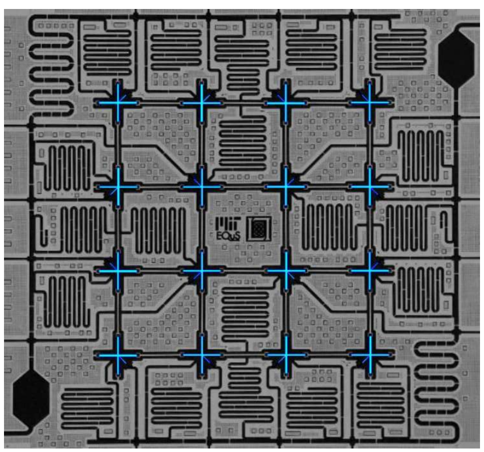
System Evolution

Emulation

System evolution mimics the Hamiltonian of interest

Simulation

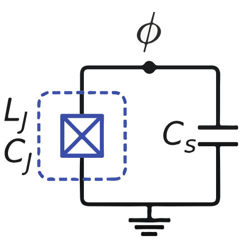
System evolution is encoded and inferred from an algorithm

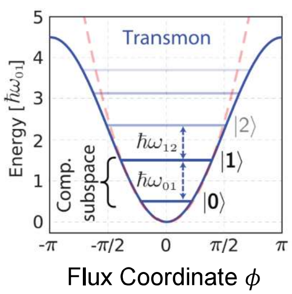


- **9-qubit and 16-qubit artificial lattices**
- **XYZ control for each site, simultaneous and distinct**
- **Always-on and parametrically driven coupling**
- **Site-resolved readout, simultaneous and unique**
- **Bose-Hubbard Hamiltonian**

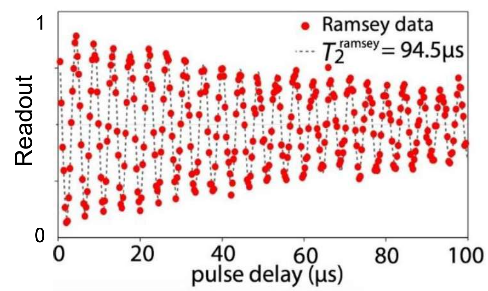
Superconducting Qubit Arrays

SC Qubit – Nonlinear Oscillators



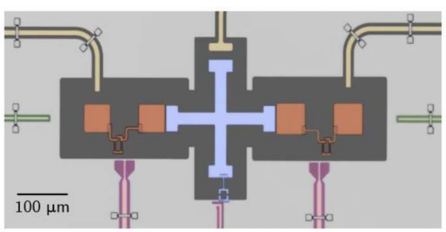


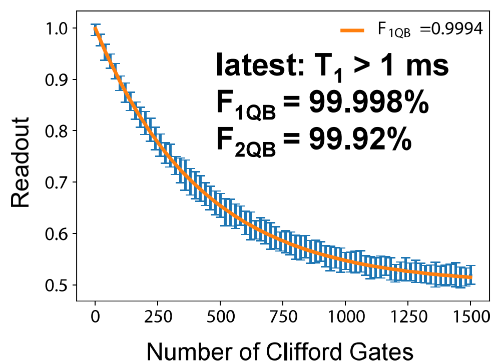
Quantum Coherence



F. Yan, PR Applied (2018); Y. Sung, PRX (2021); M. Kjaergaard, et al., PRX (2022)

Gate-Model Fluxonium & Tunable Couplers

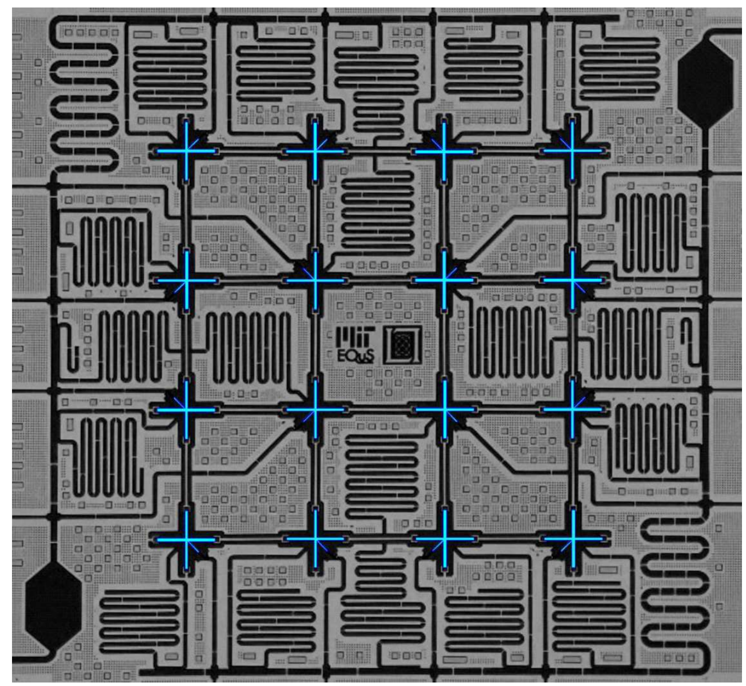




L. Ding, et al., PRX (2023); D. Rower, et al., arXiv:2406.08295

2D Arrays of Qubits

Lattices, Error Propagation, Coherent Errors, …

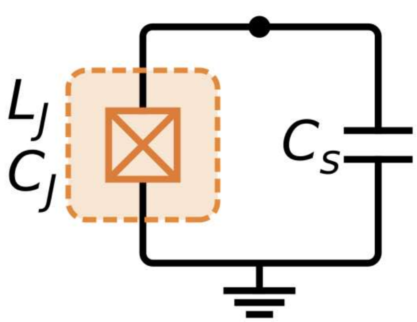


Y. Yanay, et al., npj Quantum Information 6, 58 (2020)
A. Karamlou, et al., Nature (2024)

Qubit Array Elements

Transmon qubit

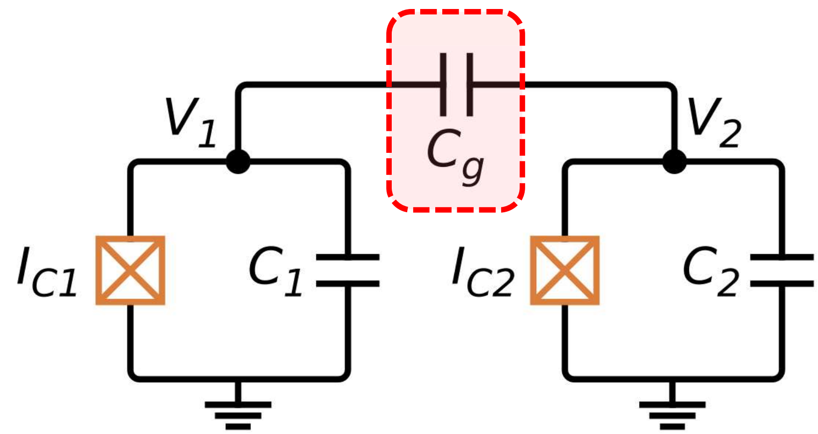
"Artificial atom"



$$H = \omega a^\dagger a + \alpha a^\dagger a(a^\dagger a - 1)$$

Capacitively coupled transmons

"Artificial molecule"



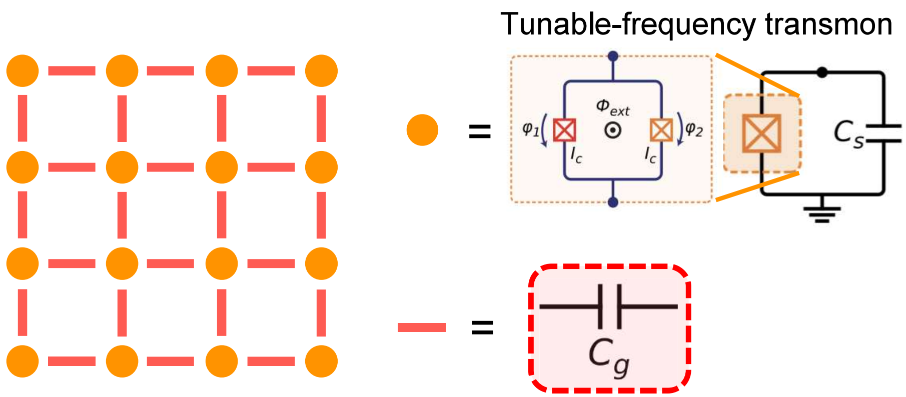
$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + J(a^\dagger b + a b^\dagger) + \alpha[\ldots]$$

Krantz et al., App. Phys. Rev. 6 (2019); arXiv:1904.06560

Qubit Array Elements

Coupled transmon lattice

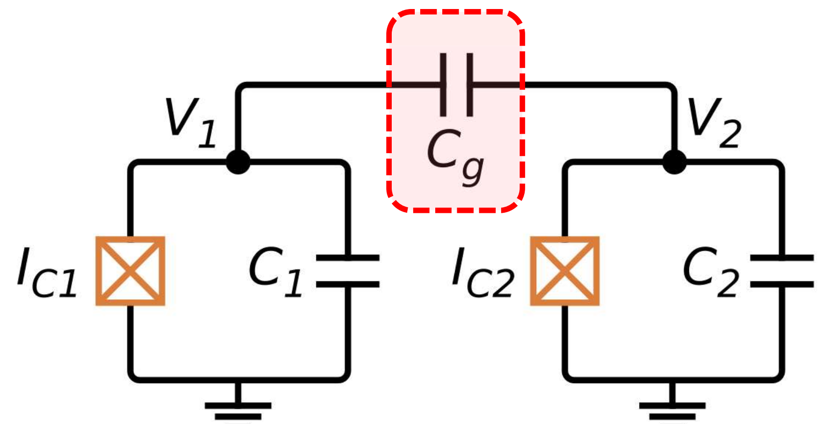
Artificial material



$$\hat{H}_{\mathrm{BH}}/\hbar = \sum_i \epsilon_i \hat{n}_i + \sum_i \frac{U_i}{2}\hat{n}_i(\hat{n}_i - 1) + \sum_{\langle i,j \rangle} J_{ij}\hat{a}_i^\dagger \hat{a}_j$$

Capacitively coupled transmons

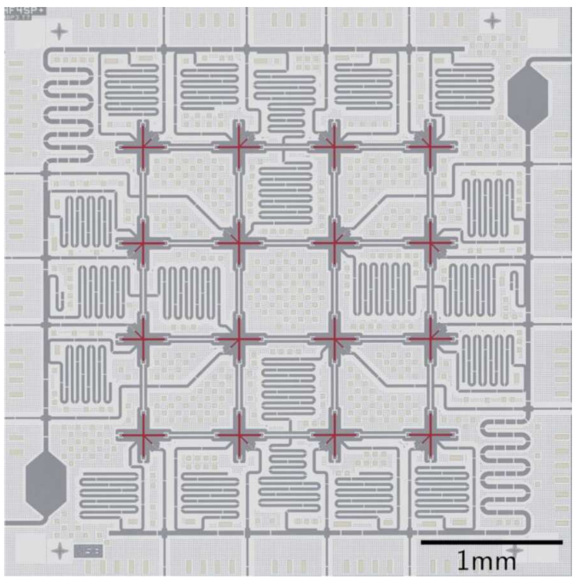
"Artificial molecule"



$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + J(a^\dagger b + a b^\dagger) + \alpha[\ldots]$$

Krantz et al., App. Phys. Rev. 6 (2019); arXiv:1904.06560

Qubit Array → Bose-Hubbard Model



4x4 transmon array
Flux tunable
Capacitive coupling

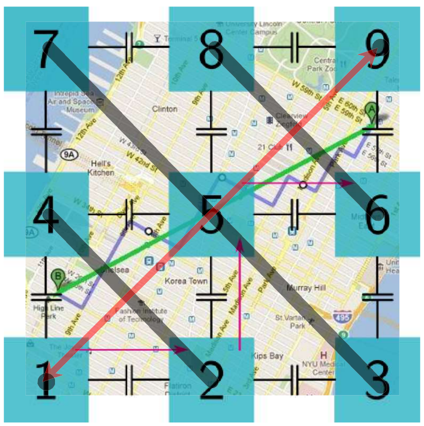
$$\hat{H}_{\mathrm{BH}}/\hbar = \sum_i \epsilon_i \hat{n}_i + \sum_i \frac{U_i}{2}\hat{n}_i(\hat{n}_i - 1) + \sum_{\langle i,j \rangle} J_{ij}\hat{a}_i^\dagger \hat{a}_j$$

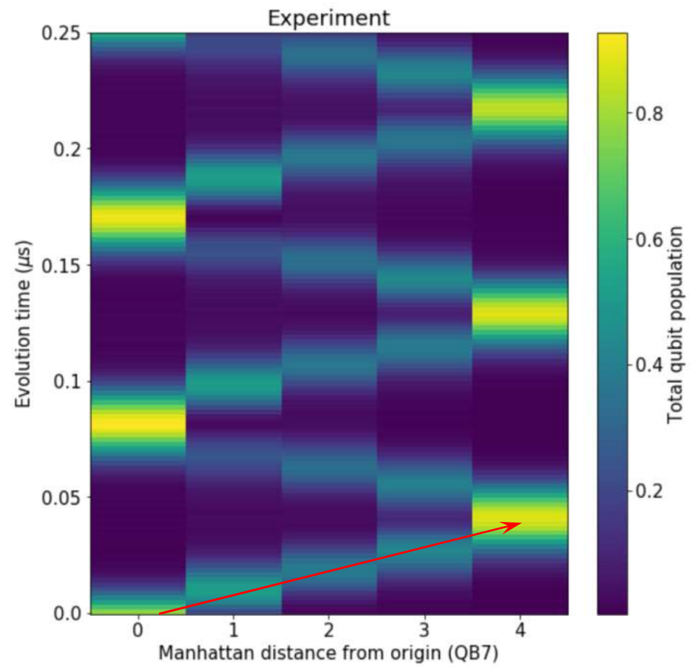
local site energy (qubit frequency)	on-site interaction (qubit anharmonicity α)	nearest-neighbor interaction (capacitance)
Tunable 3-5 GHz	**200 MHz**	**6 MHz**

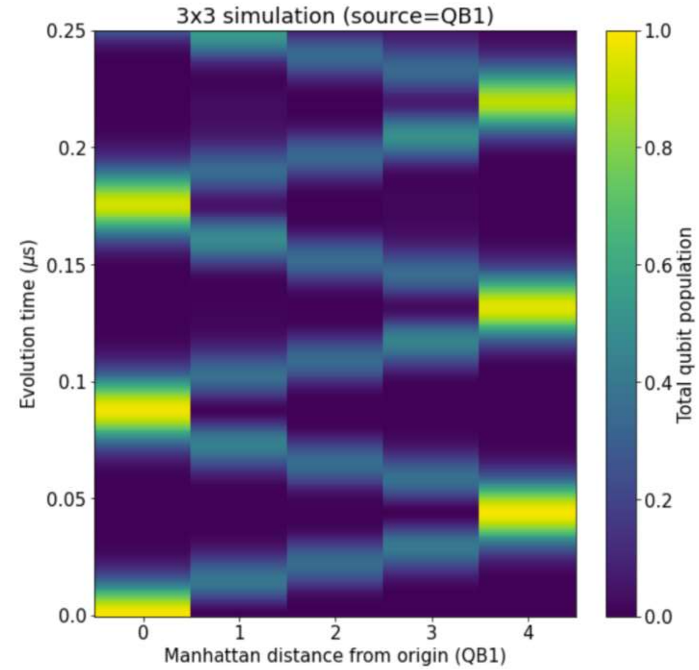
Transmon array emulates the Bose-Hubbard Model
U >> J → hard-core limit

Quantum Random Walks in 2D

Manhattan distance





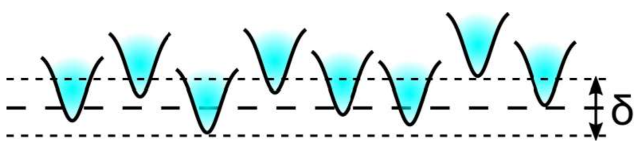


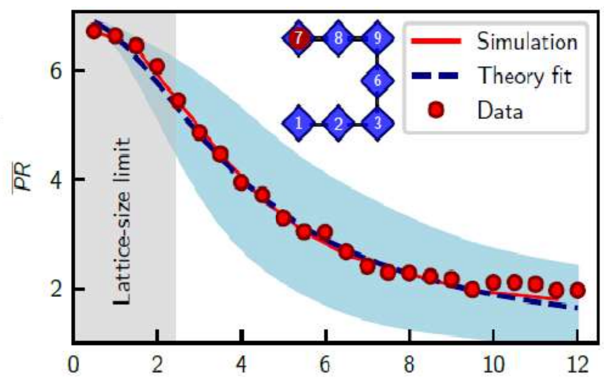
Recent work on 9-qubit and 16-qubit chips:

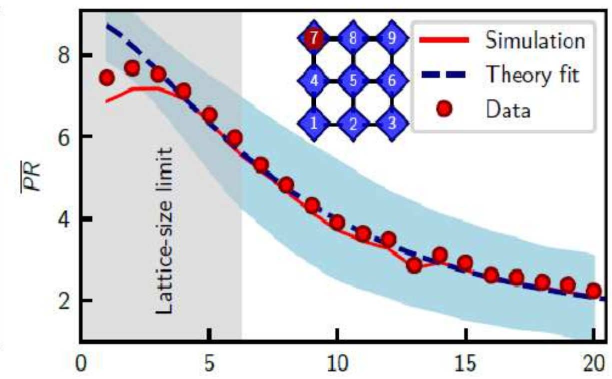
- **Out-of-time-ordered correlation (OTOC) functions – Nature Physics 2022**
- **Anderson & Stark localization, Bloch oscillations – npj Quantum 2022**
- **Area versus volume law entanglement – Nature 2024**
- **Synthetic magnetic vector potential – arXiv:2405.00873 | accepted Nature Physics 2024**
- **Quantum attention network – with Prof. Eun-Ah Kim, et al., arXiv:2405.11632**

Localization Experiments

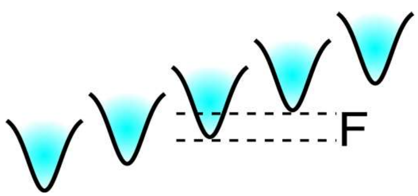
Disordered Lattice

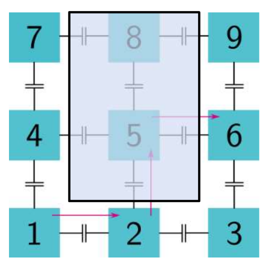


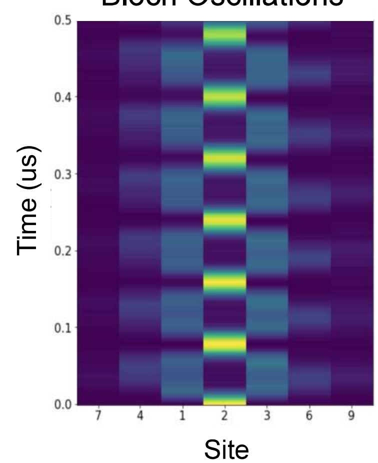


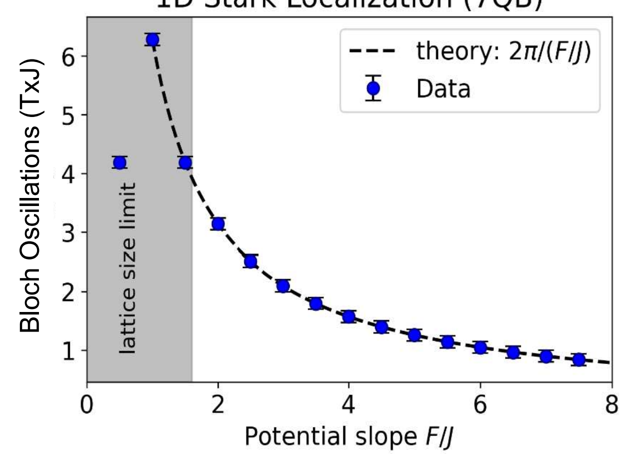


Wannier-Stark Ladder





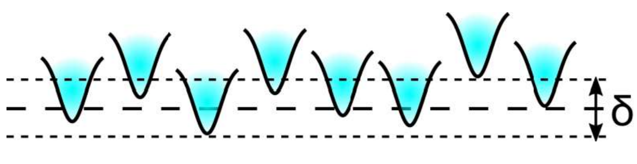


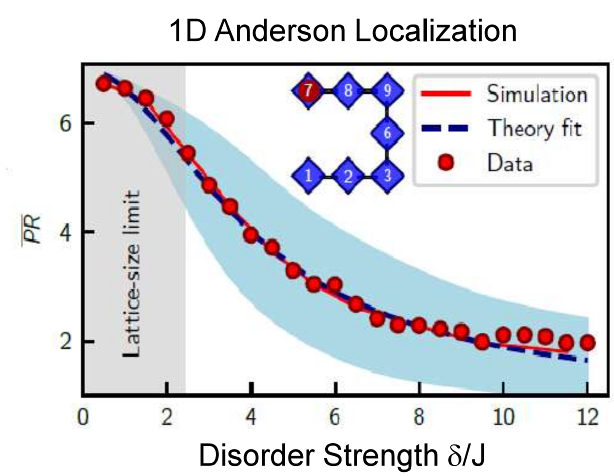


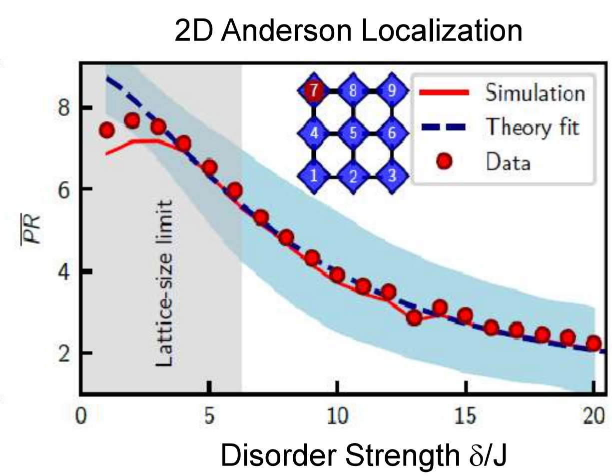
J. Braumueller, A. Karamlou, Y. Yanay, et al., Nat. Phys. 18, 172 (2022)
A. Karamlou, J. Braumueller, Y. Yanay, et al., npj Quantum Inf. 8, 35 (2022)

Localization Experiments

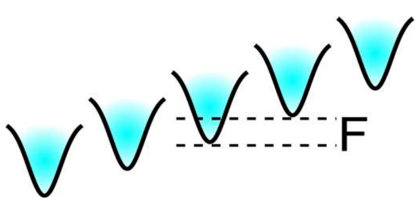
Disordered Lattice

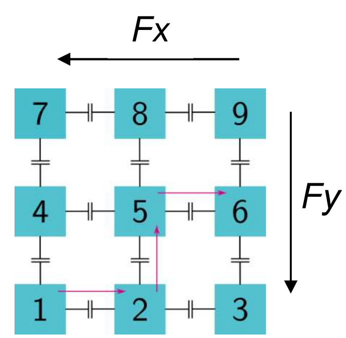


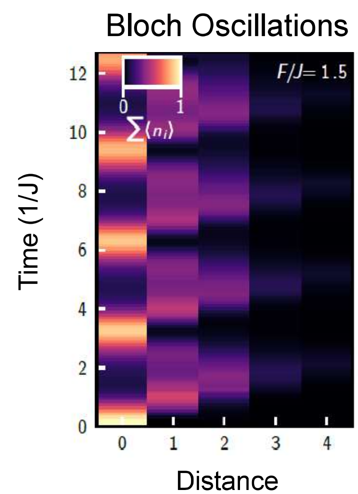


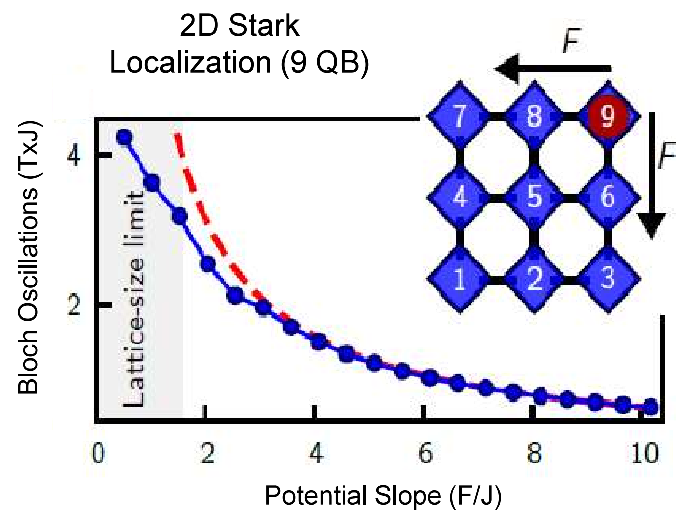


Wannier-Stark Ladder





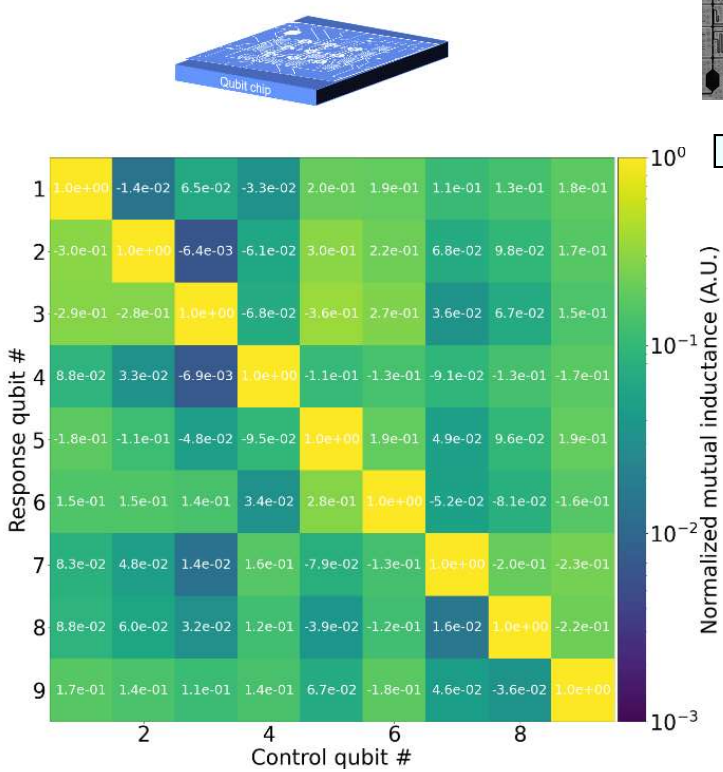


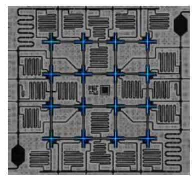


J. Braumueller, A. Karamlou, Y. Yanay, et al., Nat. Phys. 18, 172 (2022)
A. Karamlou, J. Braumueller, Y. Yanay, et al., npj Quantum Inf. 8, 35 (2022)

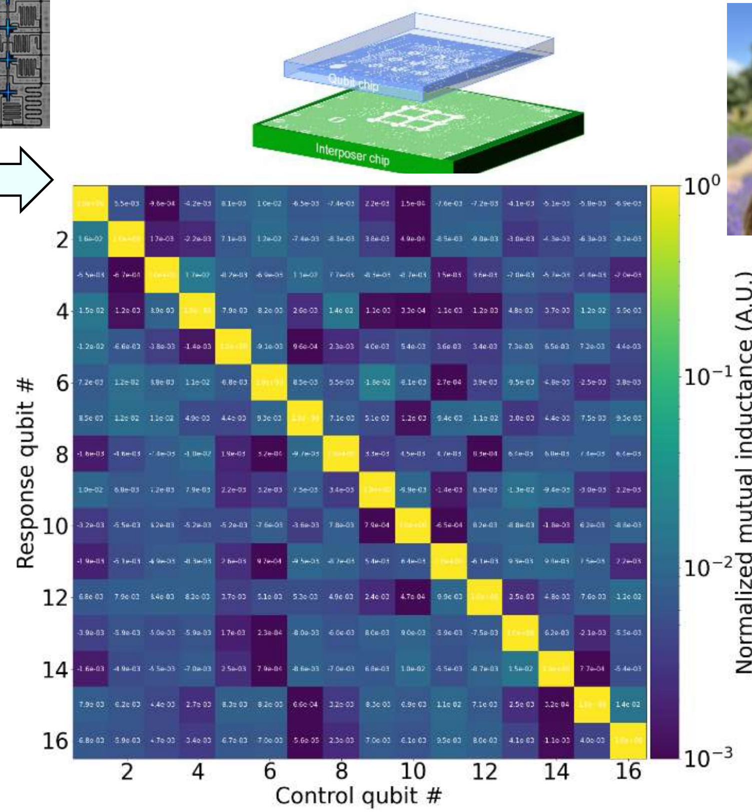
3D Integration Improves Calibration

Planar chip (9 qubits)

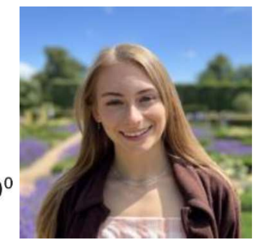




Flip chip (16 qubits)



Cora Barrett



Amir Karamlou

Sarah Muschinske

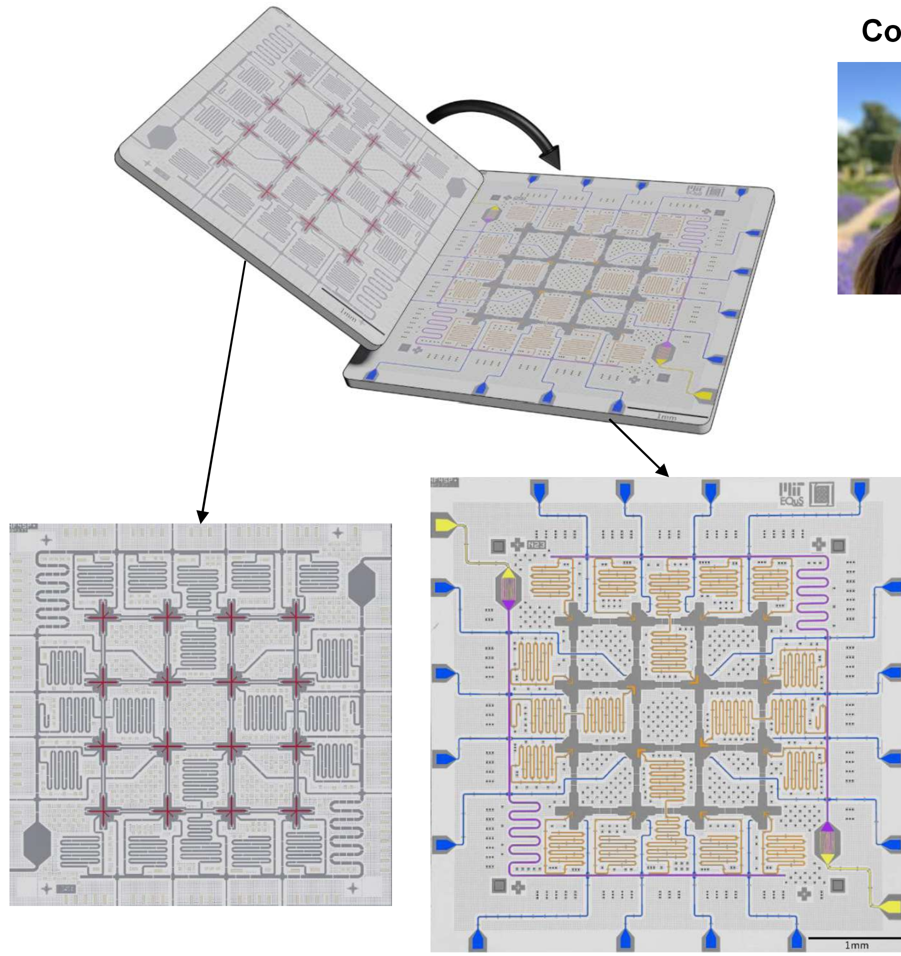
Ilan Rosen (PD)

Calibration: C. Barrett, A. Karamlou, et al., Phys. Rev. Applied (2023)
Many-Body Engtanglement: A. Karamlou, I. Rosen, et al., Nature (2024)

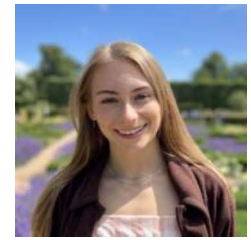
Crosstalk improved >10x using flip-chip "screening"

4x4 Transmon Array

- Excitation frequency: 4.5 GHz
- Avg. anharmonicity: −218 MHz
- Avg. coupling rate: 5.9 MHz
- Avg. T1: 22.8 μs
- Avg. readout fidelity: 93%
- Avg. single-qubit RB:
  - 99.8% (individual),
  - 99.6% (simultaneous)
- U (200 MHz) >> J (6 MHz)



Cora Barrett



Amir Karamlou

Sarah Muschinske

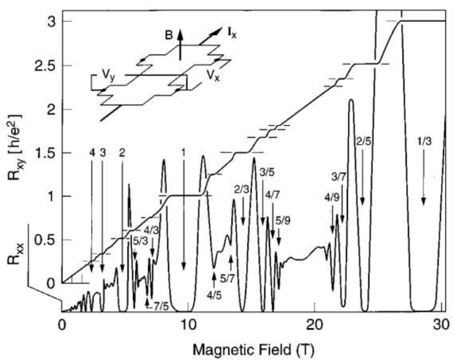
Ilan Rosen (PD)

Design: Sarah Muschinske; Rosenberg et al. *npj Quantum Inf* **3**, 42 (2017)

Quantum Simulation with Magnetism

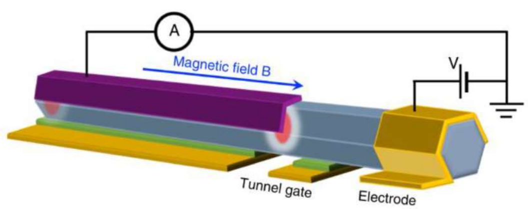
States with broken time-reversal symmetry

Quantized Hall effects

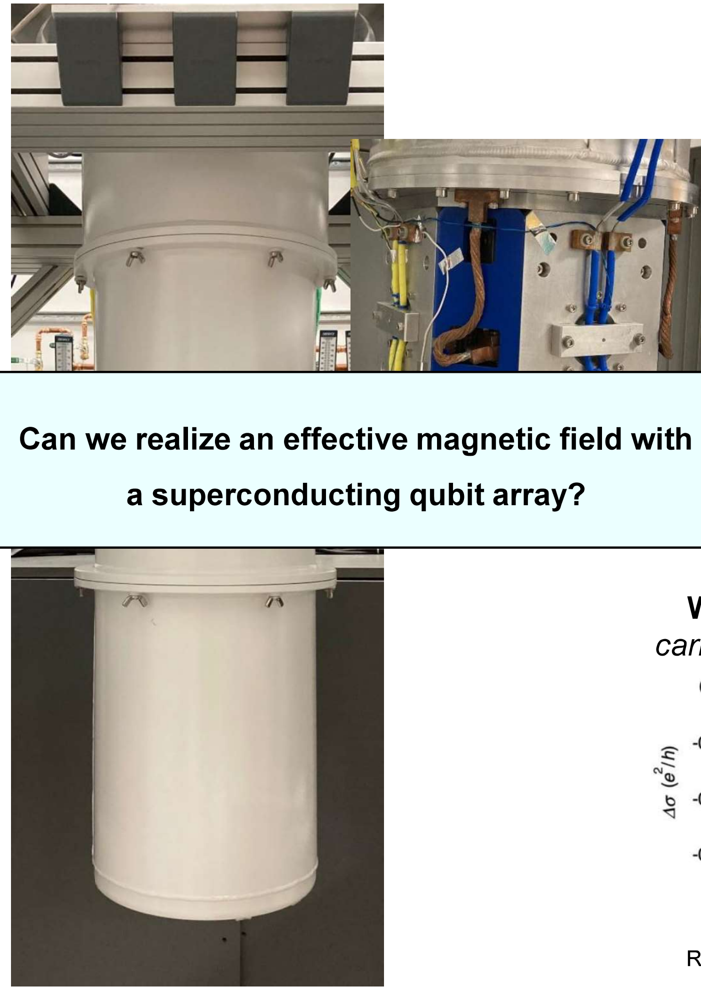


Eisenstein and Stormer, Science 248 (1990)

Topological superconductivity



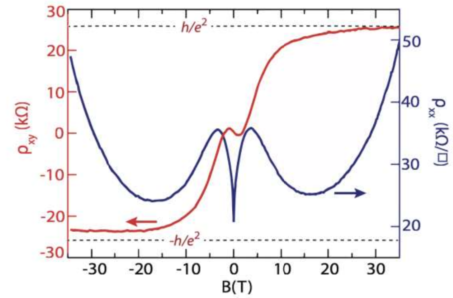
Zhang et al. Nat. Comm. 10 (2019)



Can we realize an effective magnetic field with a superconducting qubit array?

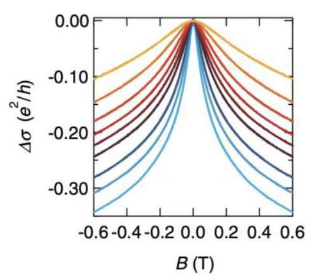
Material characterization with magnetic fields

Hall effect: *carrier density, mobility, multi-band fluids*



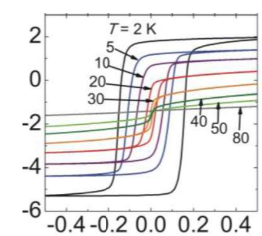
Salehi et al. Adv. Mater. 31 (2019)

Weak localization: *carrier coherence length*



Rosen et al. PRB 99 (2019)

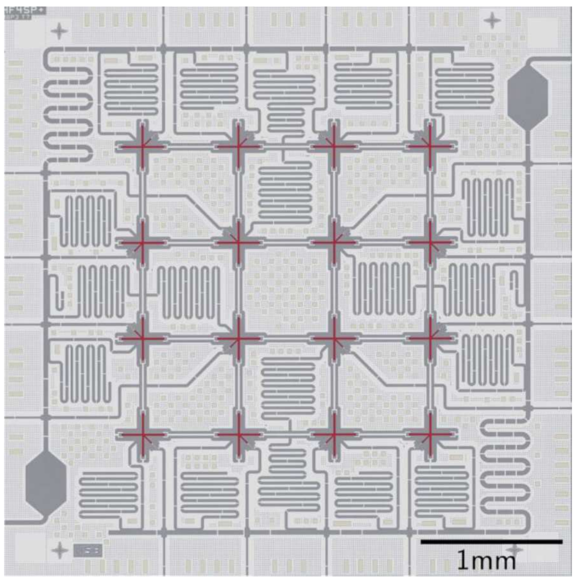
Anomalous Hall: *magnetic coercivity*



Checkelsky et al. Nat. Phys. 10 (2014)

Emulating a Magnetic Vector Potential

Superconducting processor



Bose-Hubbard model

$$\hat{H}_{\mathrm{BH}}/\hbar = \sum_i \epsilon_i \hat{n}_i + \sum_i \frac{U_i}{2} \hat{n}_i(\hat{n}_i - 1) + \sum_{\langle i,j \rangle} J_{ij} \hat{a}_i^\dagger \hat{a}_j$$

On-site energy — Anharmonicity — Exchange interaction

Peierls substitution

Continuum model

$$H = (p - A)^2$$

Vector potential

$\longrightarrow$

Lattice model

$$H = \sum_m J e^{i\phi} |m\rangle\langle m+1| + H.C.$$

Peierls phase

Direct transverse coupling

$$J(a^\dagger b + a b^\dagger)$$

Transverse parametric coupling

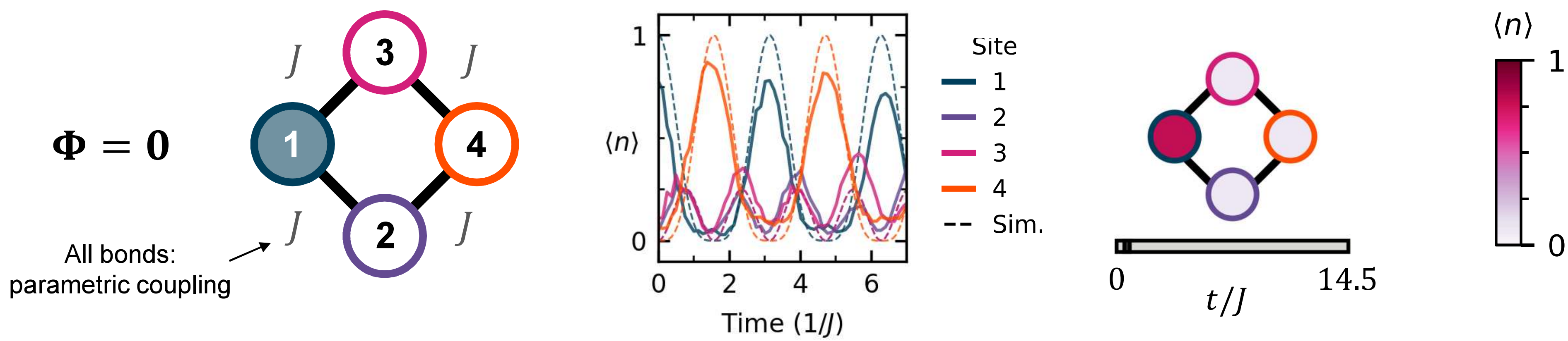
$$\Omega \sin(\delta t + \phi)$$

$$J(\Omega)(e^{i\phi} a^\dagger b + e^{-i\phi} a b^\dagger)$$

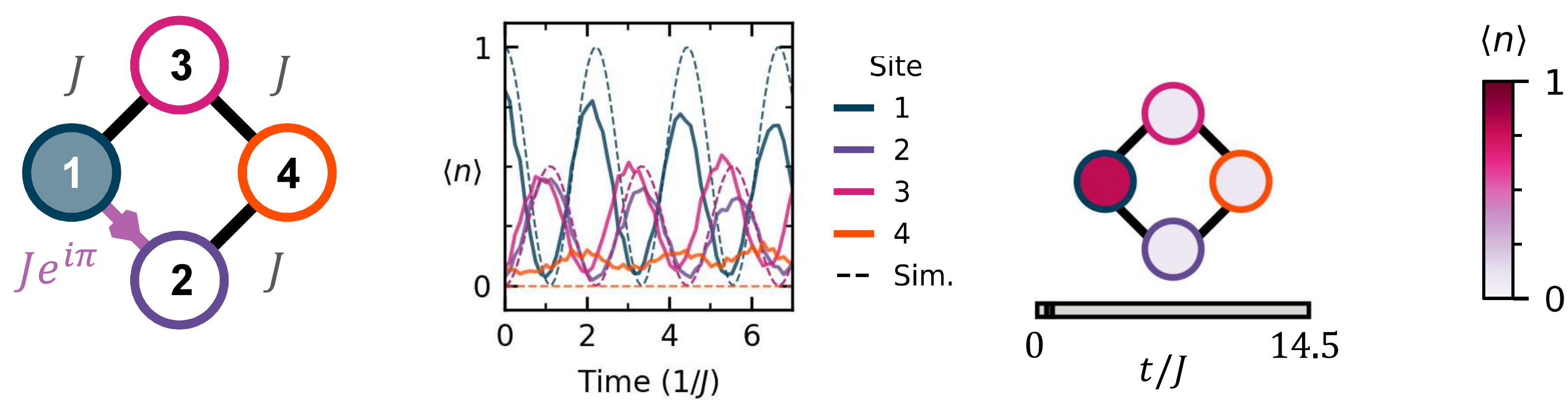
We can set Peierls phases in our lattice by parametrically driving pairs of superconducting qubits and thereby emulate the magnetic vector potential

Aharonov-Bohm Caging

$\Phi = 0$

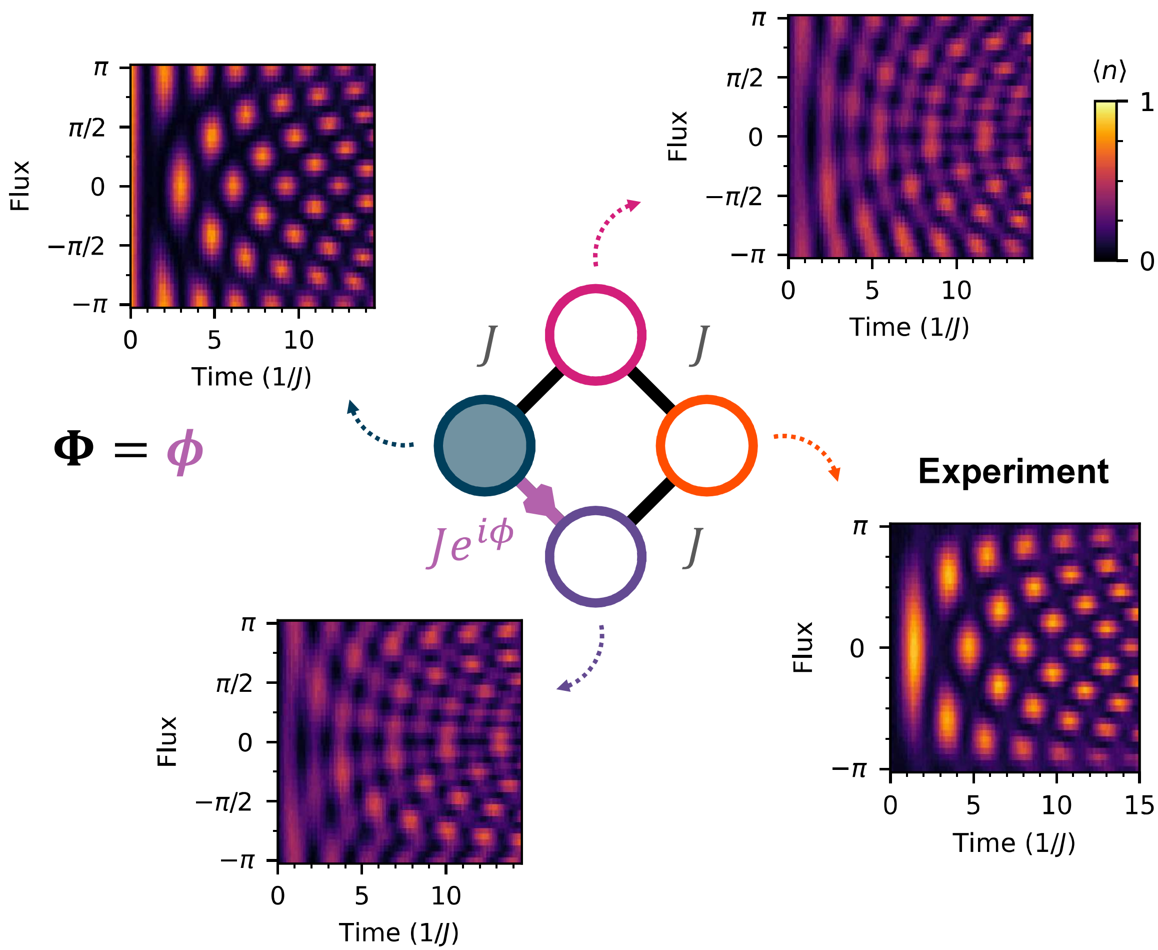


$\Phi = \pi$



I. T. Rosen, S. Muschinske, et al., arXiv:2405.00873; *Also see:* Martinez et al. Sci. Adv. 9 (2023)

Aharonov-Bohm Effect



We can read out the qubits simultaneously on each trial

Experiment

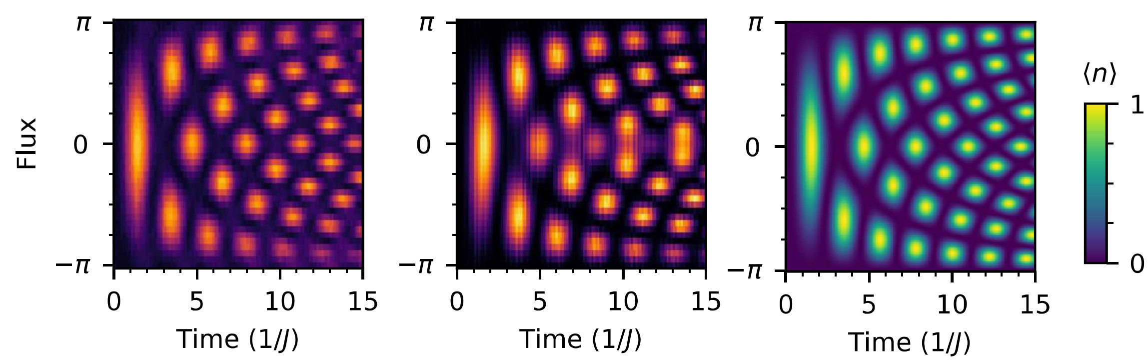
Simulation

Full simulation of experiment

Model

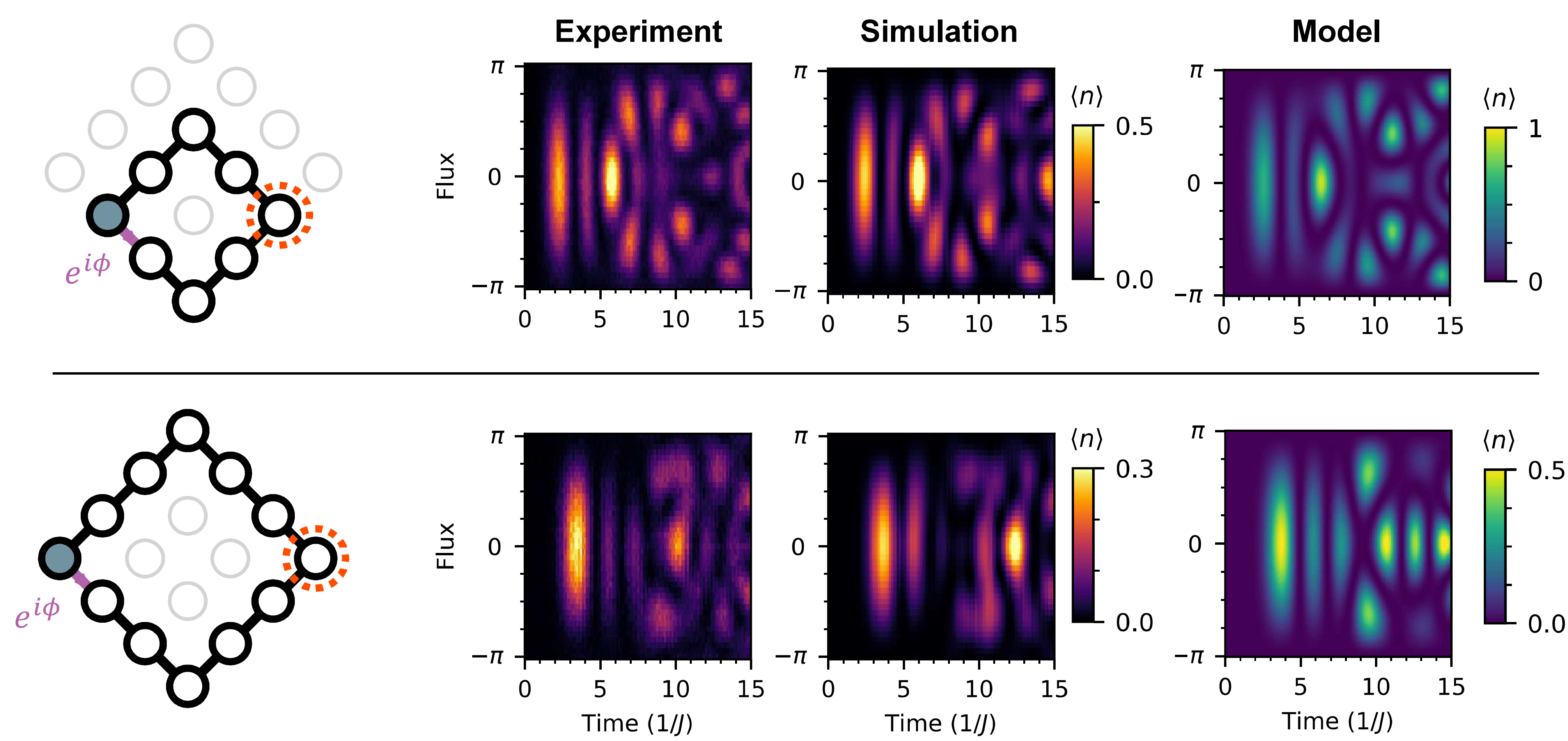
Harper-Hofstadter

$H = J \sum e^{i\phi_{ij}} a_i^\dagger a_j + \text{H.C.}$



I. T. Rosen, S. Muschinske, et al., arXiv:2405.00873

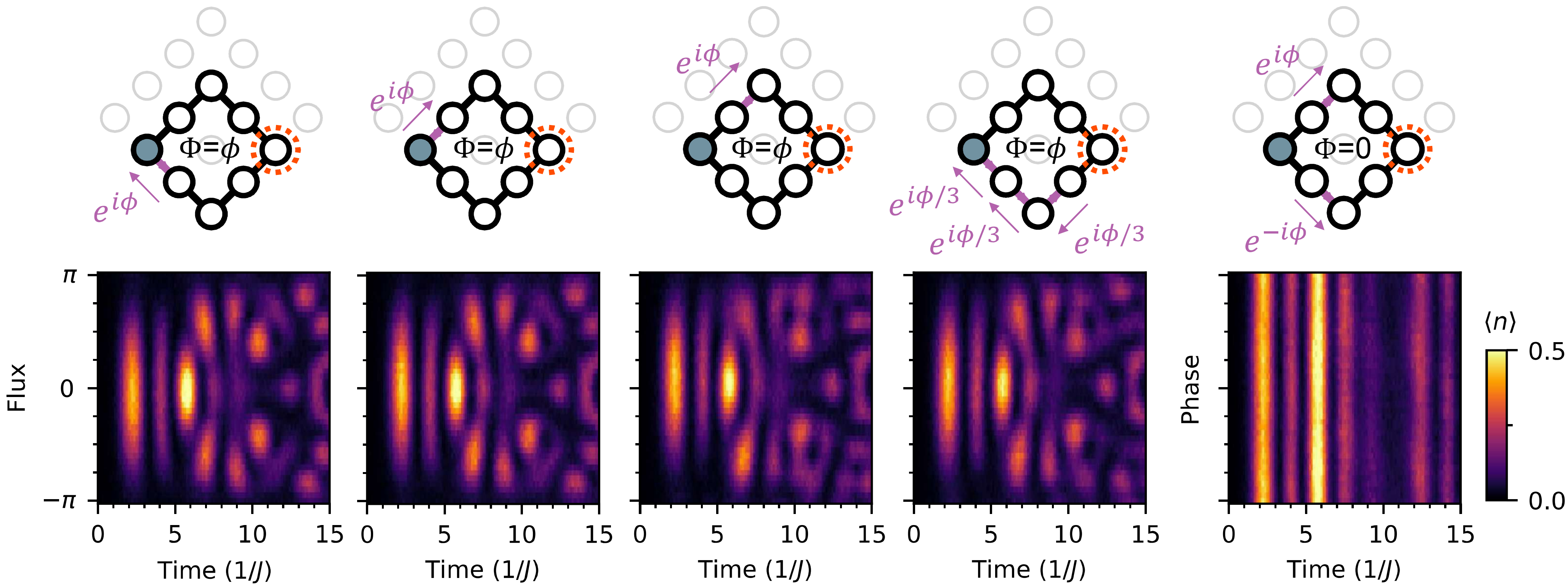
Aharonov-Bohm Effect in Larger Rings



I. T. Rosen, S. Muschinske, et al., arXiv:2405.00873

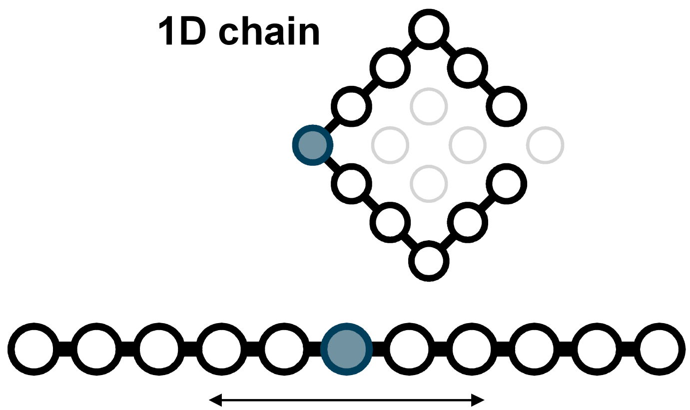
Gauge Invariance

Synthetic magnetic flux: $\Phi = \sum_{m,\ \text{oriented}} \phi_m$ (sum around loop)



I. T. Rosen, S. Muschinske, et al., arXiv:2405.00873

Electromagnetic Duality – Faraday's Law



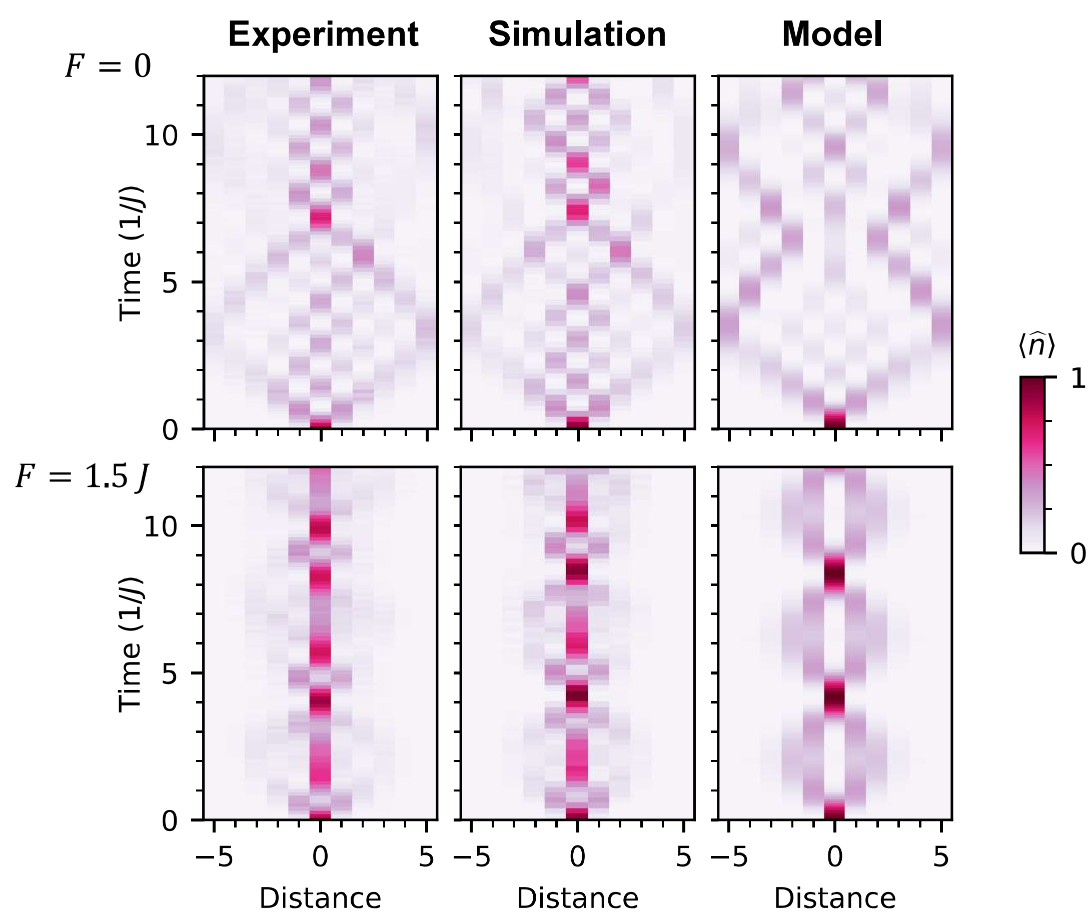
Continuum model → *Lattice model*

$$\boldsymbol{A} \rightarrow \phi$$

$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t} \rightarrow F = -\frac{\partial \phi}{\partial t}$$

Synthetic *E*-field → Bloch Oscillations

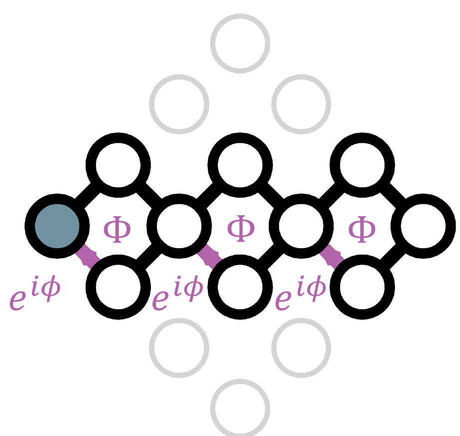
Bloch, Z. Phys. 52 (1929)
Guo et al. npj Quant. Inf. 7 (2021)
Karamlou et al. npj Quant. Inf. 8 (2022)



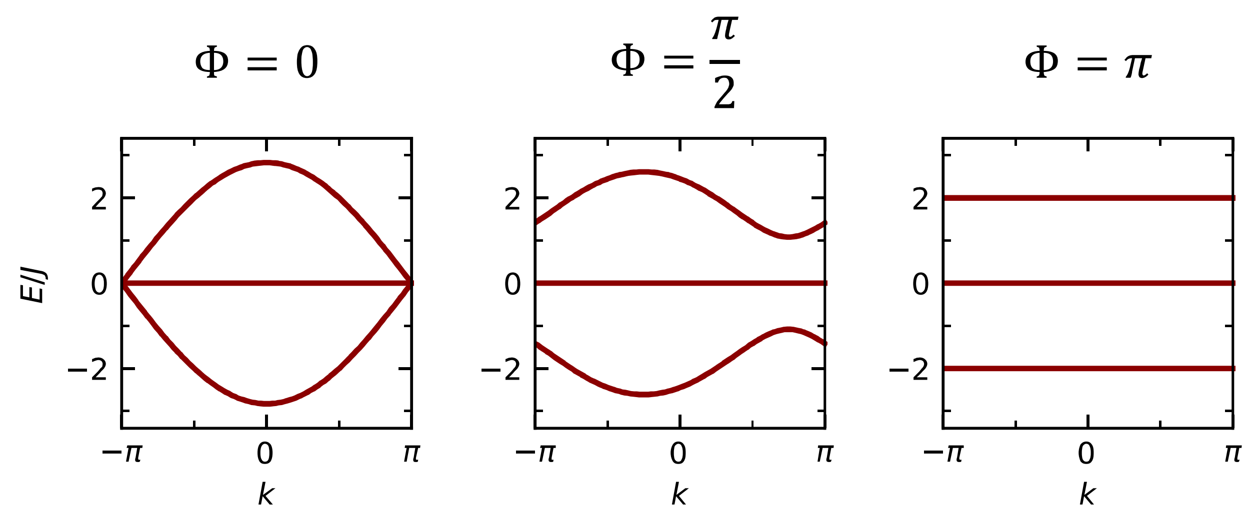
I. T. Rosen, S. Muschinske, et al., arXiv:2405.00873

Flat Bands in 1D

Rhombus Lattice



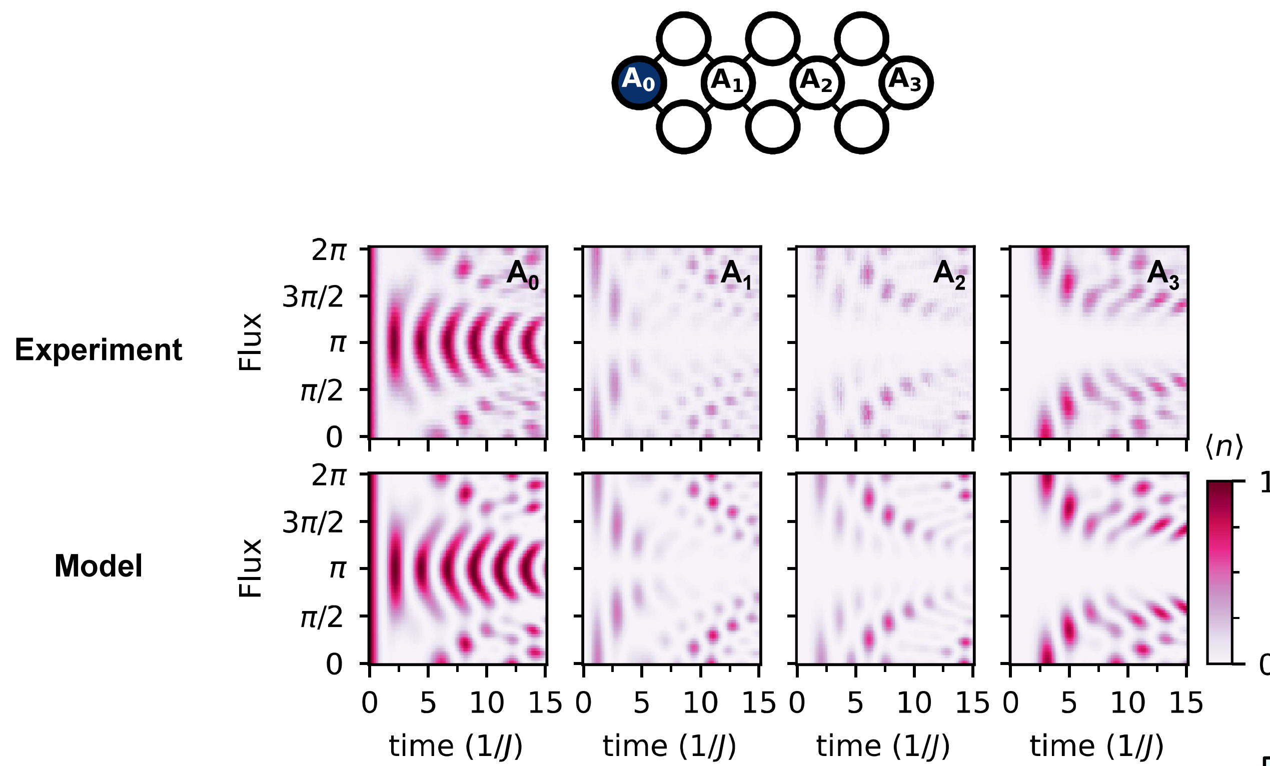
Band Structure (continuum)

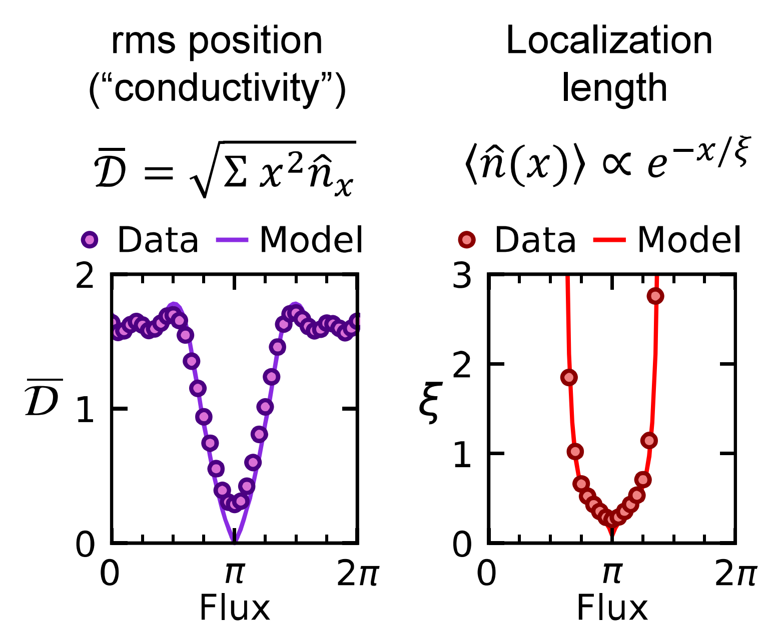


String together 2x2 plaquettes to emulate three unit cells of the rhombus lattice, which always features one flat band, and at Φ=π, all bands become flat.

I. T. Rosen, S. Muschinske, et al., in preparation; Carwright et al., PRB 98 (2018)

Flat-Band Localization

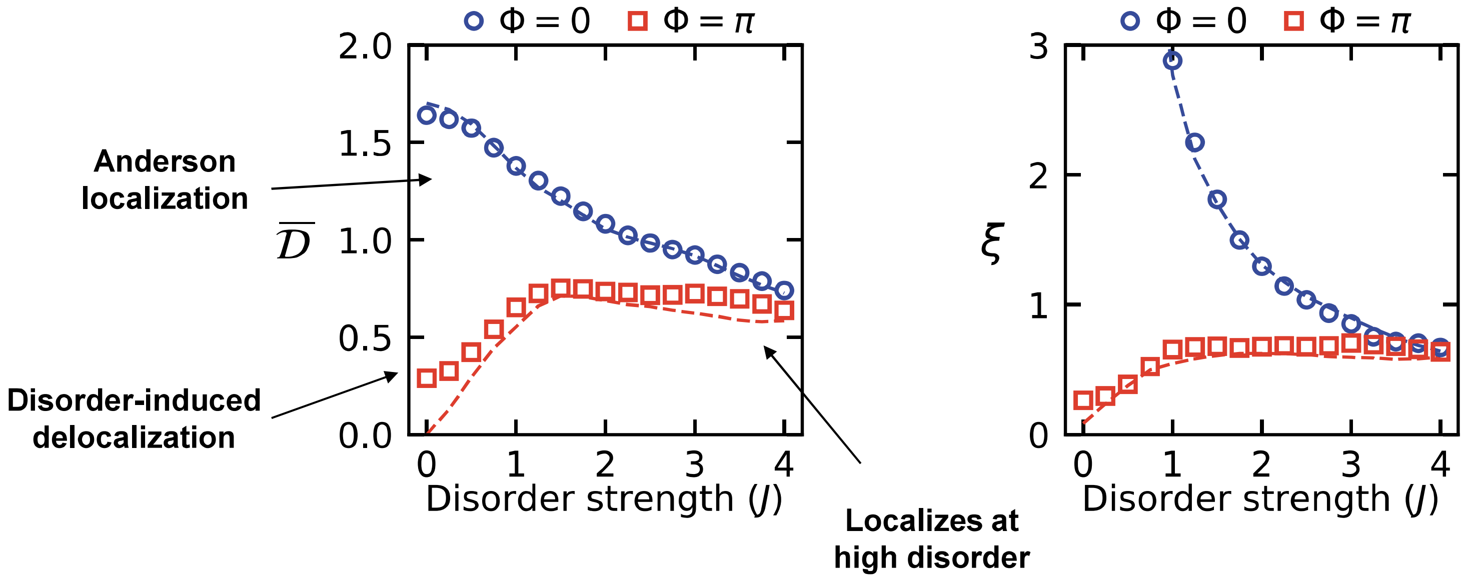




Particle motion is arrested near the flat-band condition at half-flux

Disorder-Induced Delocalization

Add Gaussian-distributed on-site disorder.
Average over 10 random instantiations



Anderson localization is reversed near the flat-band condition at half-flux

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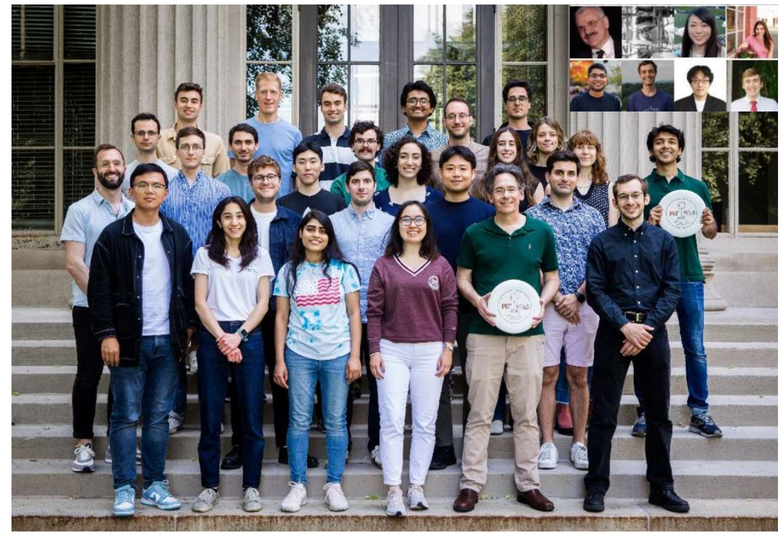
MIT Engineering Quantum Systems (EQuS)



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