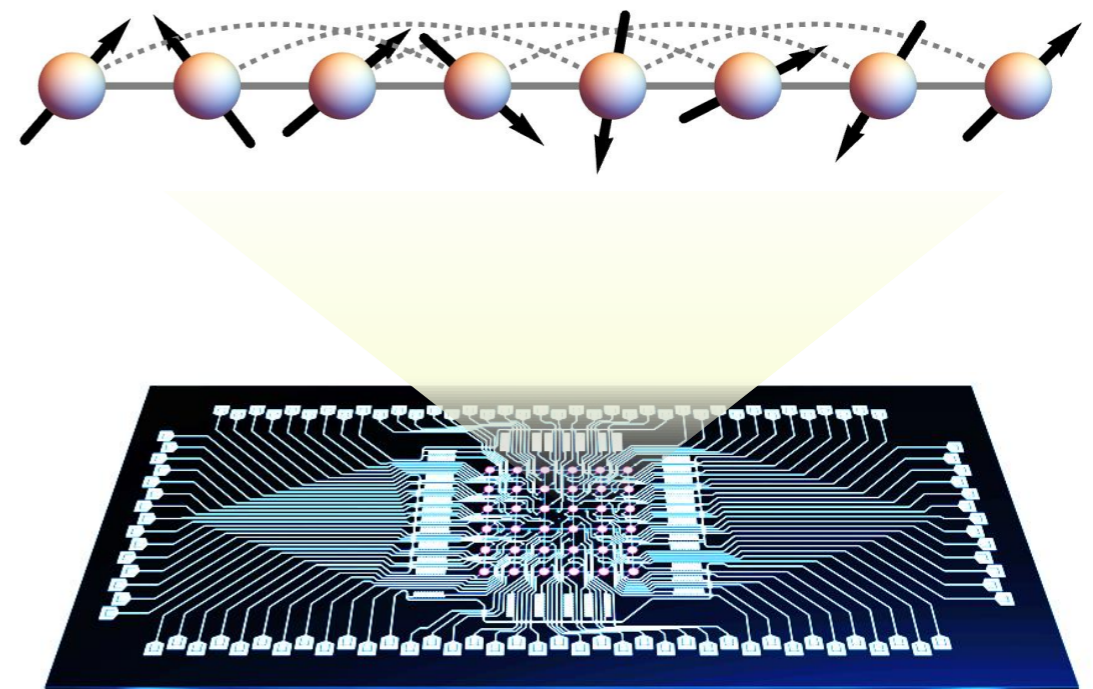


Many-body scars in quantum Heisenberg XY models and analog simulations on superconducting circuits

Zexian Guo, Jinlou Ma, Yu Gao, Lei Ying

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<https://doi.org/10.1631/jzus.A2500059>



Equilibrium in isolated systems

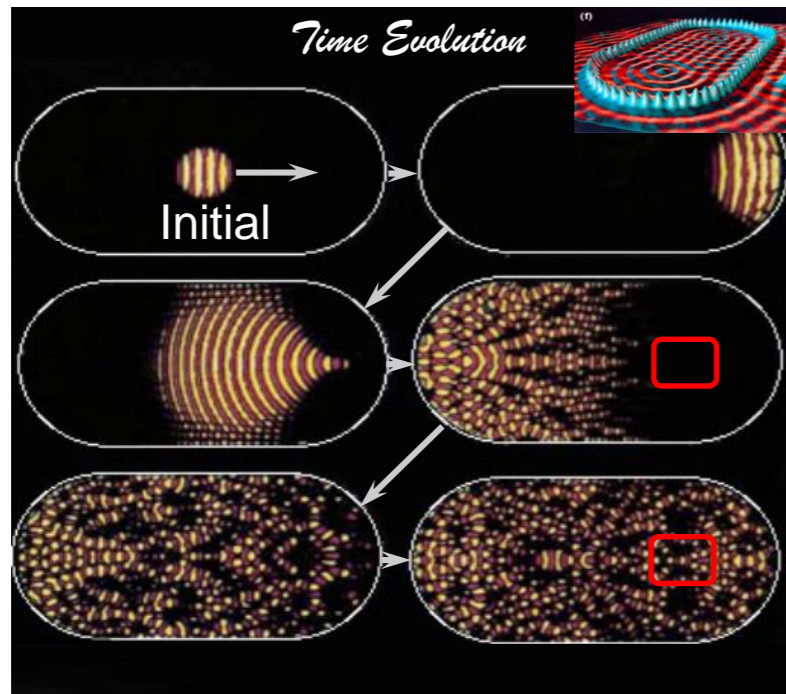
Classical



Thermal Equilibrium

Quantum

Single particle

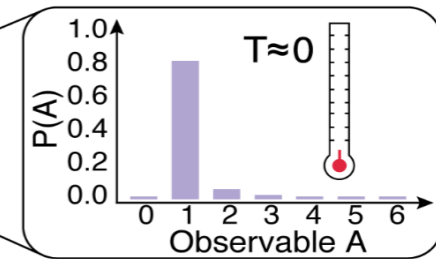
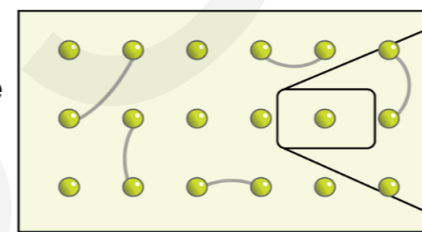


ergodic \approx chaotic

Many bodies

Quantum quench

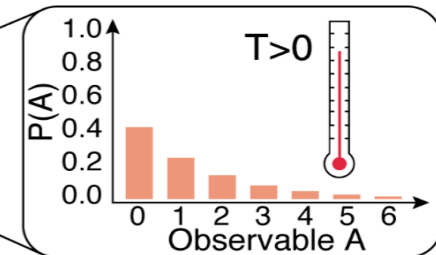
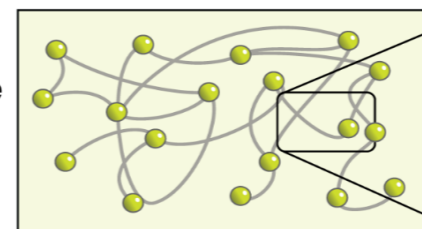
Pure state $|\Psi\rangle$



Global Unitary dynamics

Local Thermalization

Pure state $|\Psi\rangle$

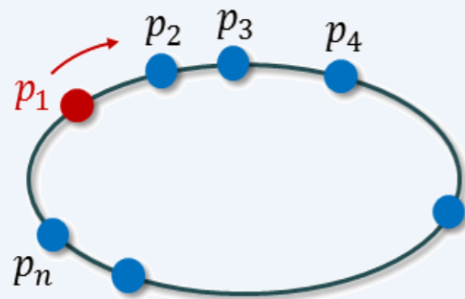


-Science 353, 794

Equilibrium State

Counter examples

Quantum integrability

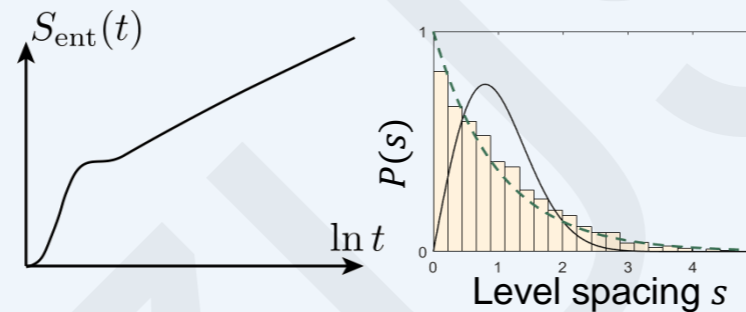
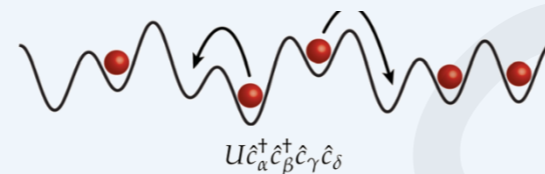


The Bethe ansatz after 75 years

Murray T. Batchelor

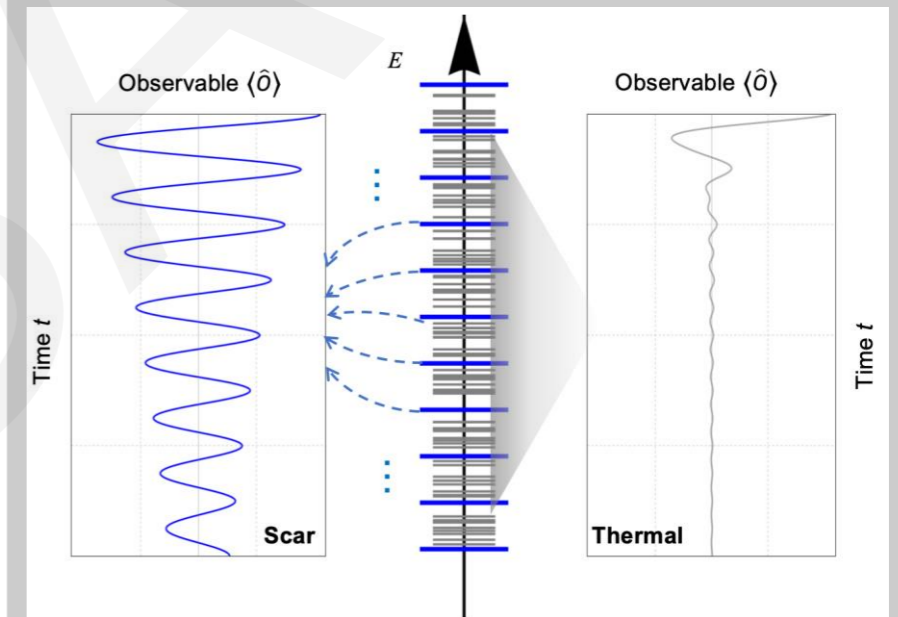
A 1931 result that lay in obscurity for decades, Bethe's solution to a quantum mechanical model now finds its way into everything from superconductors to string theory.

Many-body localization



-Rev. Mod. Phys. 91, 021001

Many-body scars



Strong ergodicity breaking

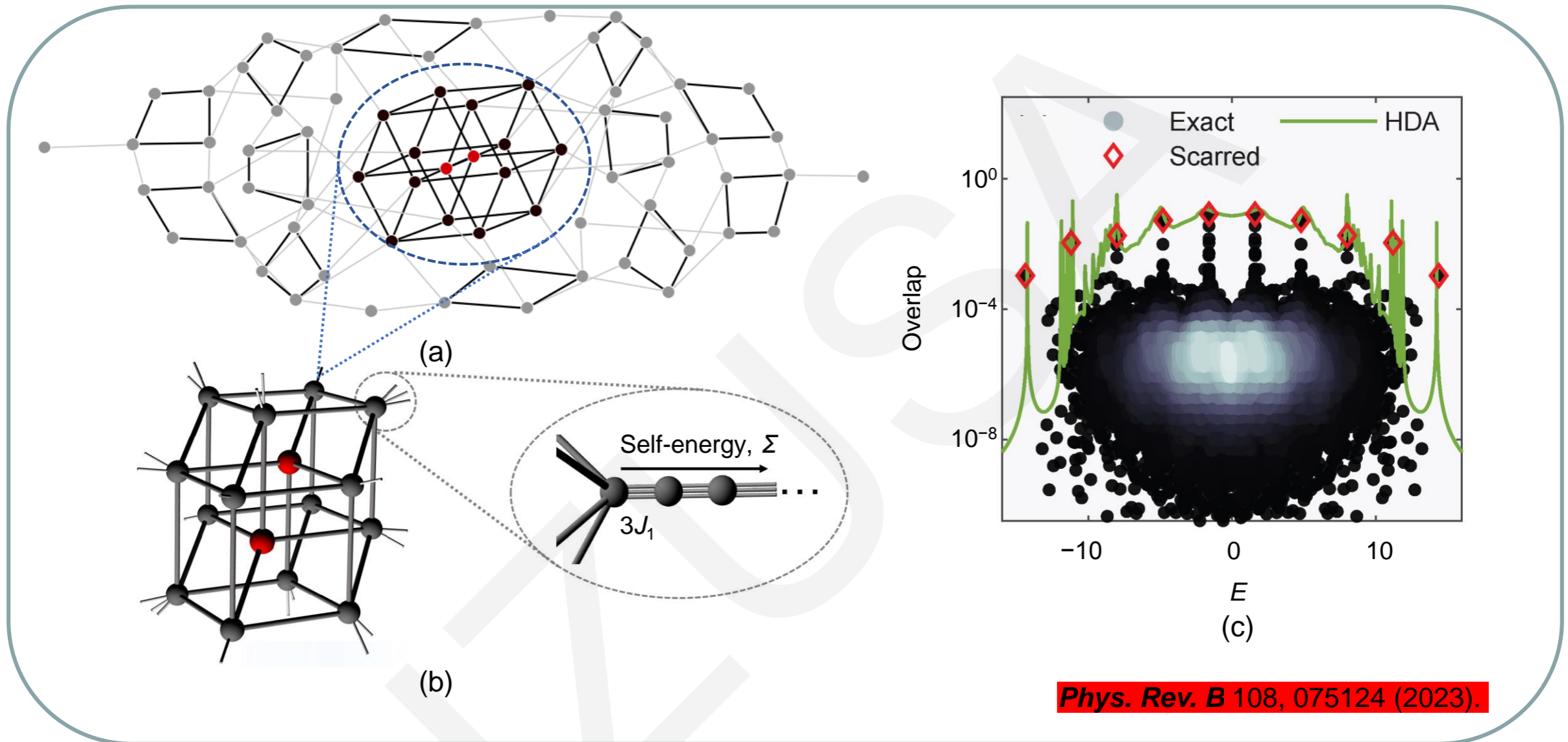
- Enough conserved quantiles to analytically solve the problem.

- Inter-particle interactions do not destroy localization.

Weak ergodicity breaking

- Approximately equally spaced tower in the energy spectrum.
- Coherent quantum dynamics and revivals.

Theoretical Framework

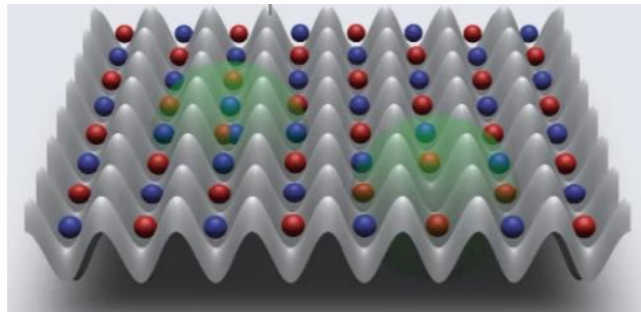


- A new type of QMBS based on the Heisenberg XY model, which is beyond constraint model.
- It originates from a special subspace with a hypercube or hypergrid geometry.
- It can be visualized by the overlap between the eigenstates and the special collective state.

Experiment and Application of QMBS

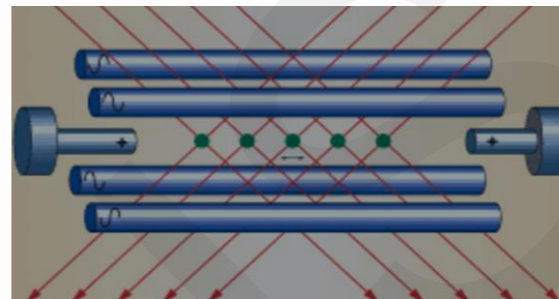
Quantum Simulators

BSS Lecture, 02 (2023).



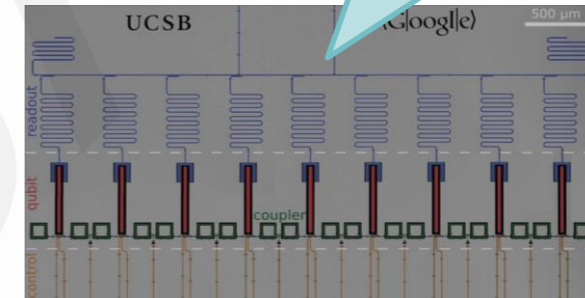
Cold Atom

Computer, 33(1), 38-45 (2000).



Ion Trap

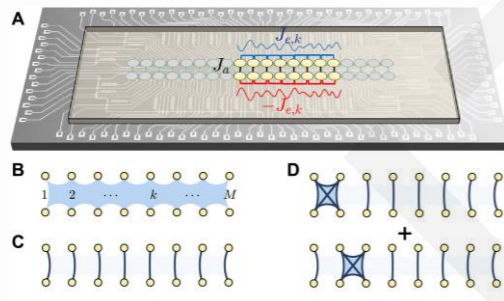
Science, 360, 6385 (2017).



Superconducting Quantum Processor

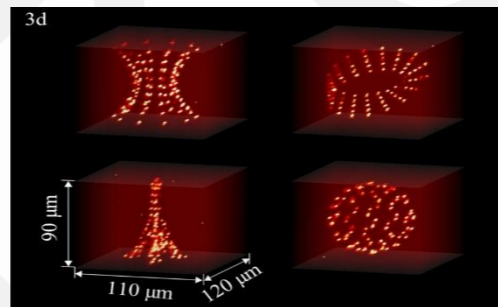
- High-precision control
- Rapid operation
- Scalability

Application



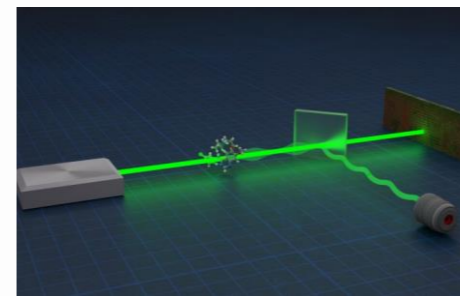
Sci. Adv. 9, eadj3822 (2023).

Entanglement Controlling



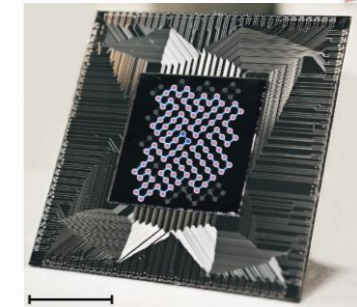
J. Phys. B 49, 152001 (2016).

Chemistry and Biology



Nat. Commun, 11, 3775 (2020).

Quantum Metrology



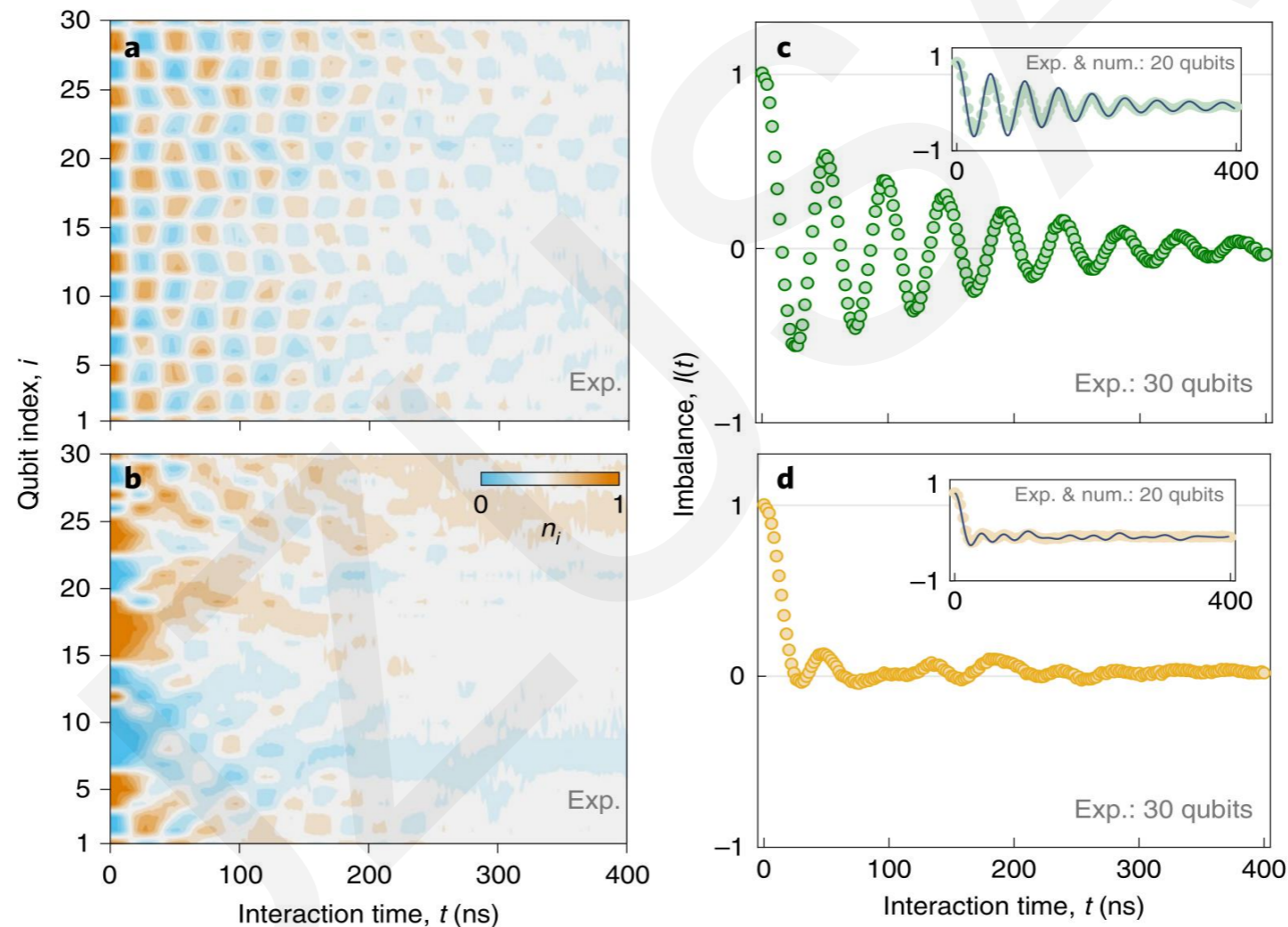
Nature, 09476 (2025).

Quantum Computing

Frontier of QMBS experiment on superconducting circuit

$$\langle S_i^z(t) \rangle = \langle \psi(t) | S_i^z | \psi(t) \rangle$$

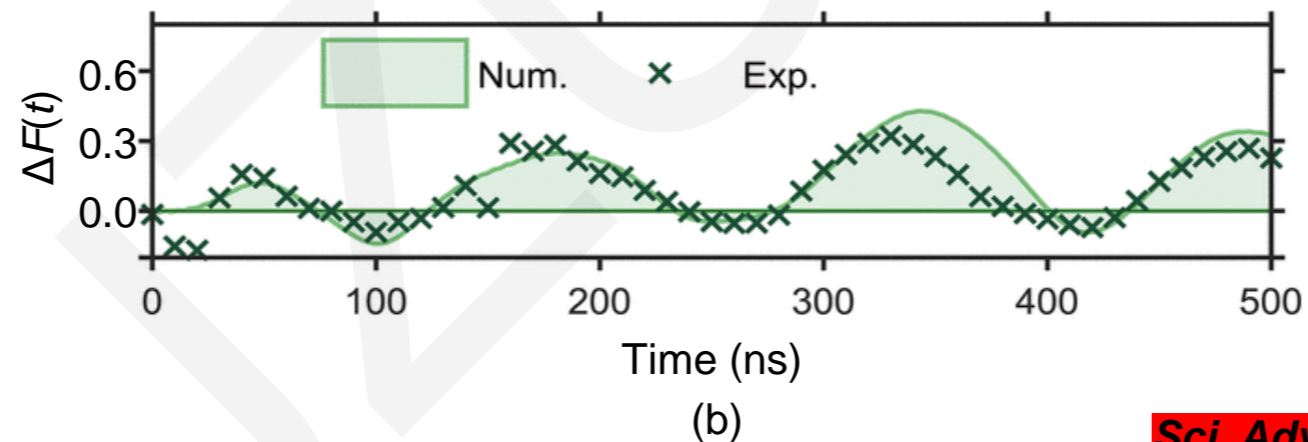
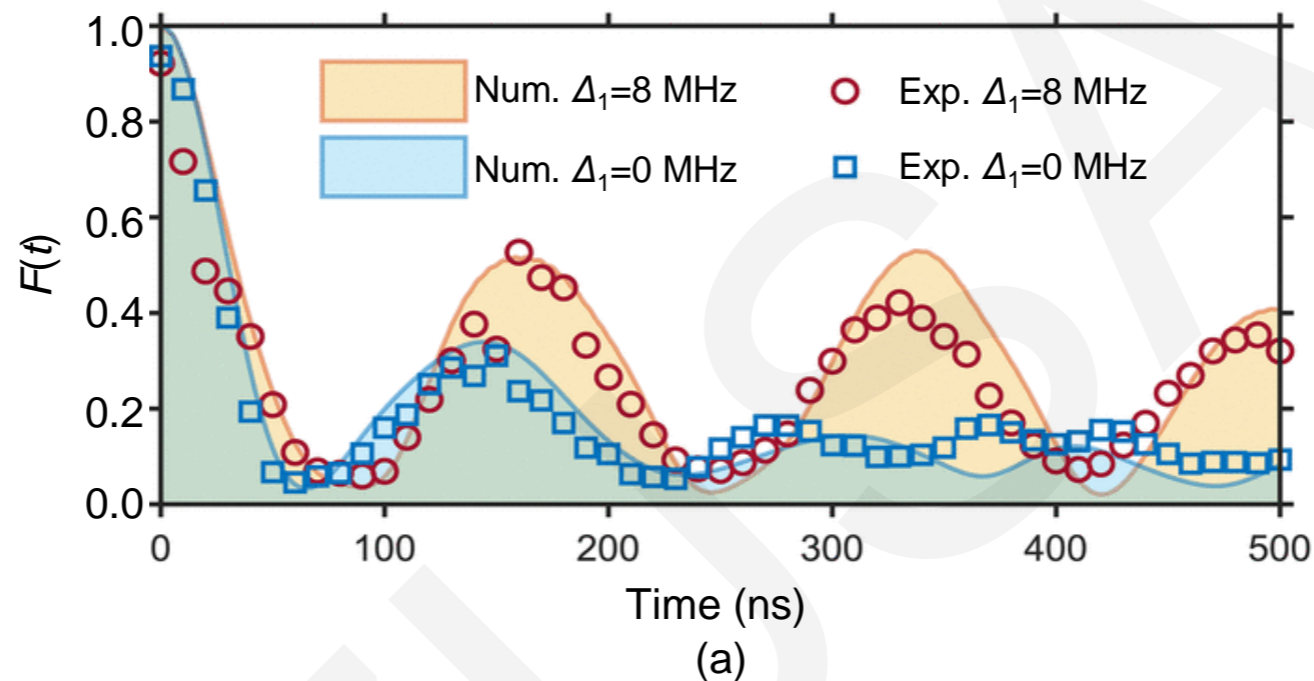
$$I(t) = \frac{1}{L} \sum_{i=1}^L \langle S_i^z(0) \rangle \langle S_i^z(t) \rangle$$



Nat. Phys. 19, 120 (2023).

- The evidence of QMBS can be directly observed by the evolution of **population**, **imbalance** and their **Fourier transformation**.

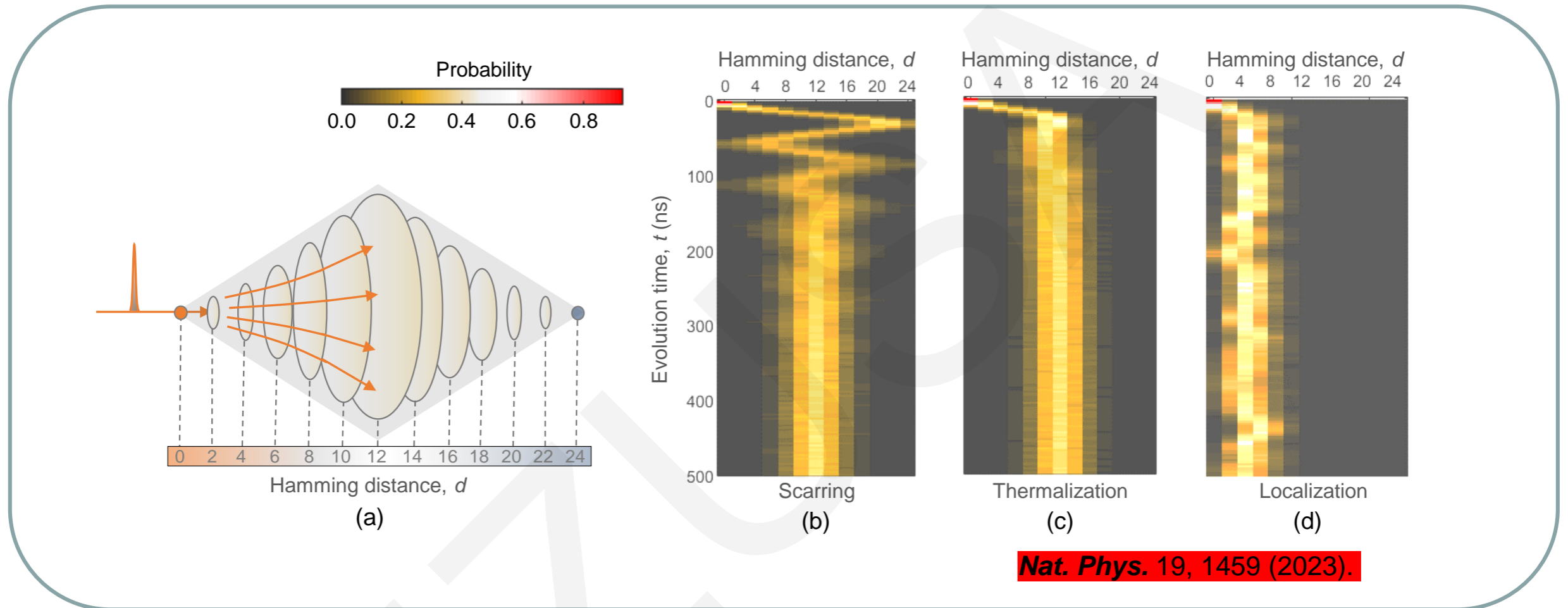
Frontier of QMBS experiment on superconducting circuit



Sci. Adv. 9, eadj3822 (2023).

- Dong et al. (2023) realized **disorder-tunable entanglement** at infinite temperature.
- They demonstrated **non-thermalizing states with rich entanglement structures**.
- They measured the fidelity, showing that the scar they found was **disorder-tunable**.

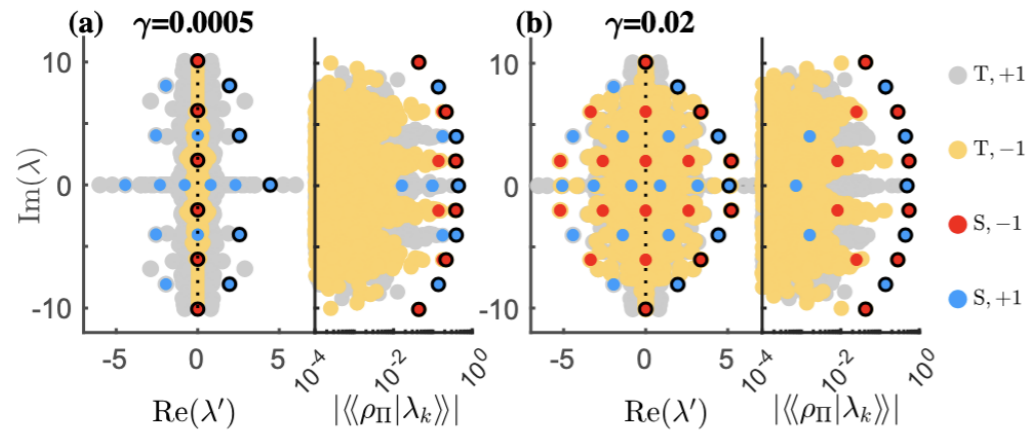
Frontier of QMBS experiment on superconducting circuit



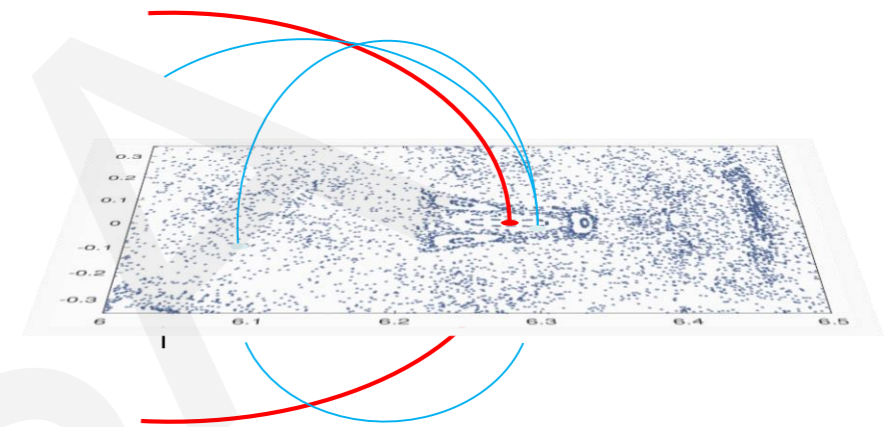
- Yao et al. (2023) showed signatures of 2D QMBS on a 4×6 superconducting qubit array.
- They directly visualized wave-packet propagation in the many-body state space, enabling observation of thermalization, localization, and scarring.

Future Work

arXiv:2504.12291

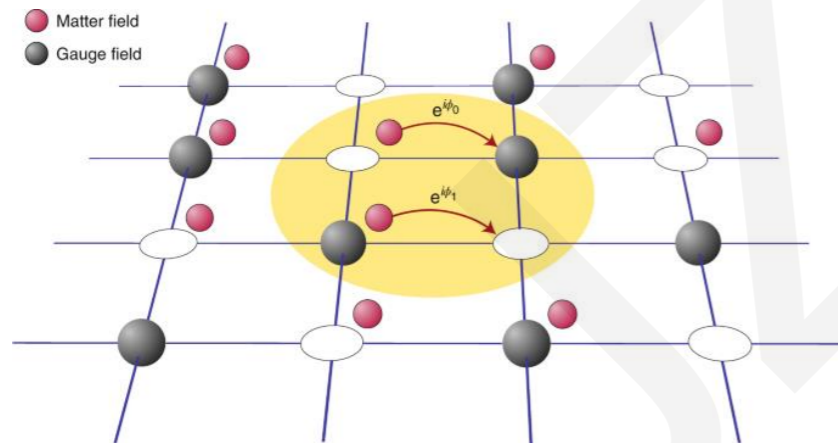


■ QMBS in Open System

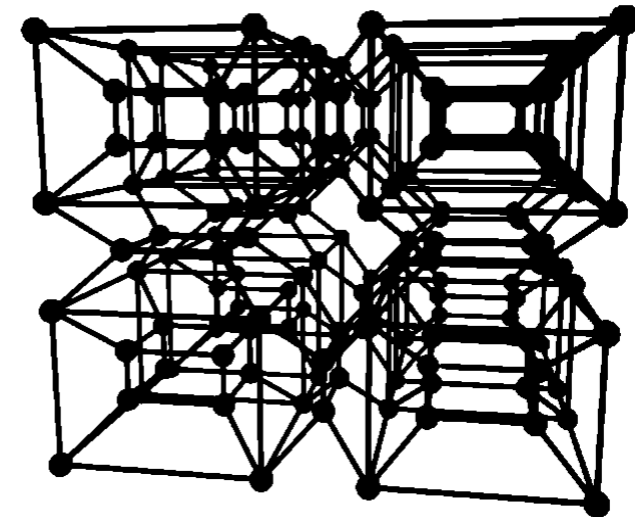


■ Semiclassical Correspondence

Nat. Phys., 15, 1106–1107 (2019)



■ QMBS using Lattice Gauge Theory



■ QMBS in Higher Dimension

Conclusions

■ Key Advances:

- QMBS is unexpectedly resilient to environmental noise.
- Beneficial for building functional quantum technologies.

■ Technological Potential:

- Quantum sensing, optimization, machine learning, and potentially faster quantum algorithms and fault-tolerant quantum memory.

■ Fundamental Physics Connections:

- Deep theoretical links with high-energy physics.
- Link with concepts like quantum gravity, holographic duality, and even traversable wormholes.

■ Future Directions:

- Topological protection, dissipation engineering.
- Hybrid quantum-classical algorithms specifically designed for scar-state dynamics.

