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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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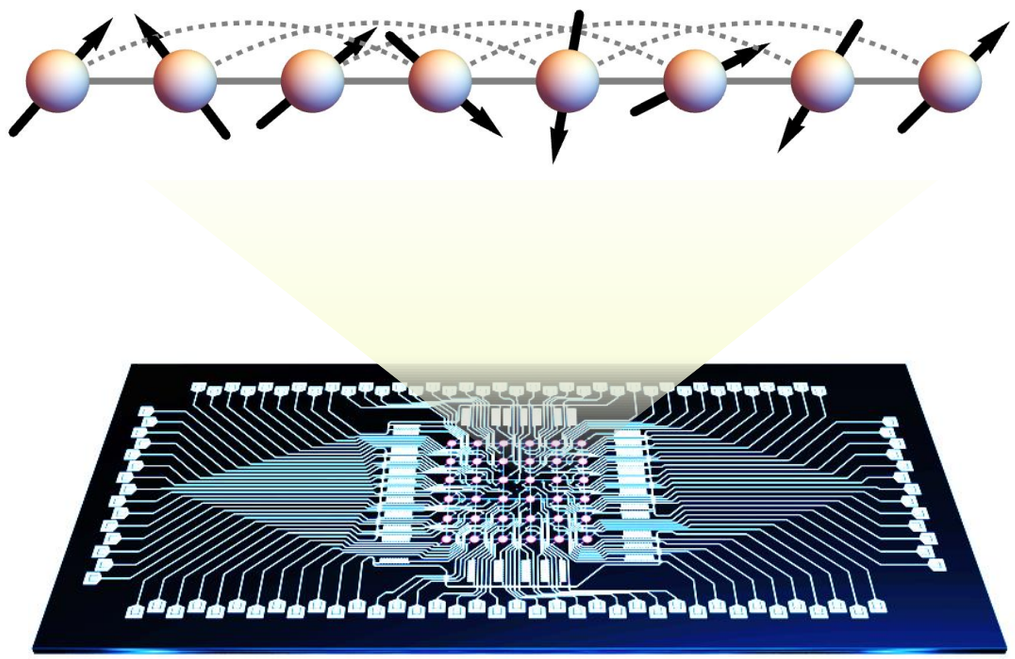


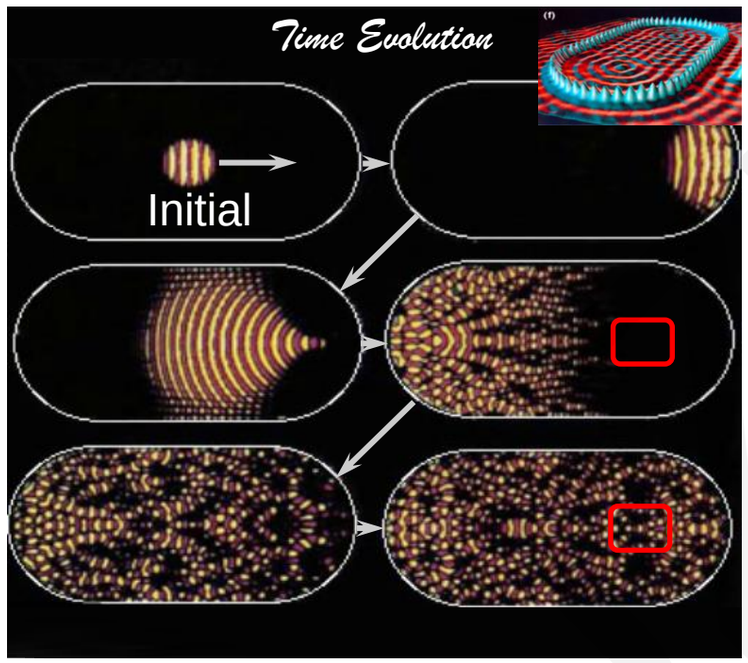
Equillibrium in isolated systems

Classical

Thermal Equilibrium

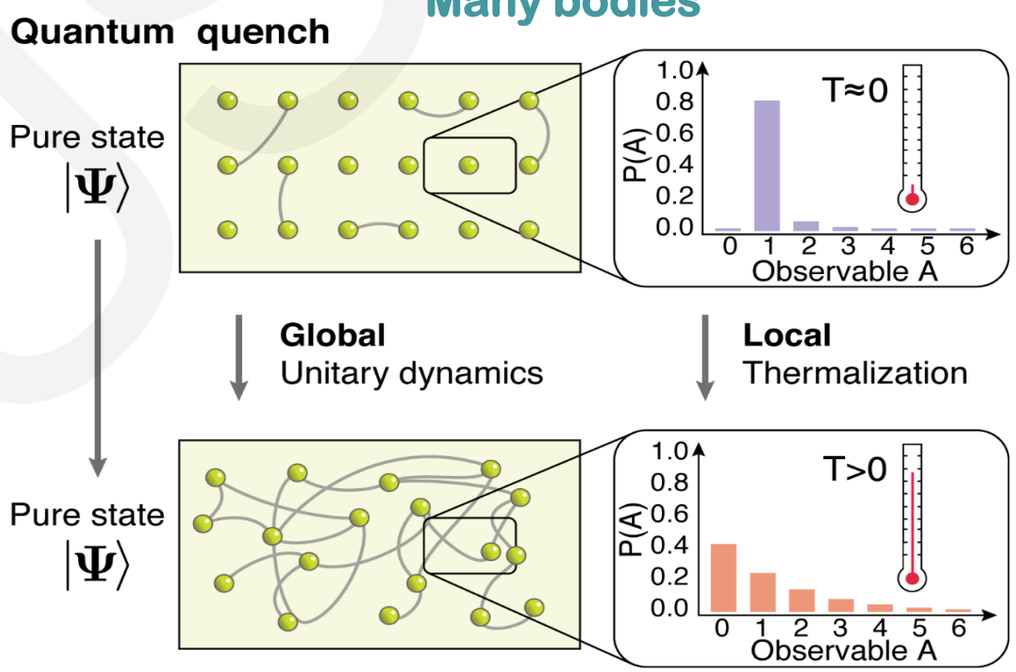
Quantum

Single particle



ergodic≈chaotic

Many bodies

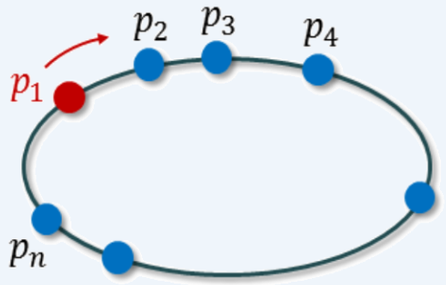


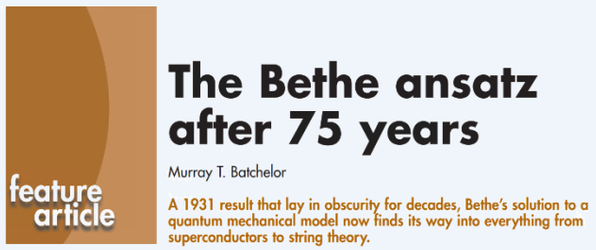
-*Science* **353**, 794

Equilibrium State

Counter examples

Quantum integrability



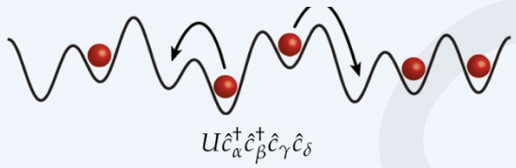

feature article

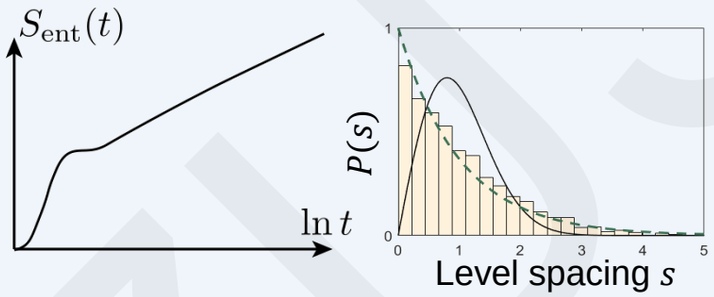
The Bethe ansatz after 75 years

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.

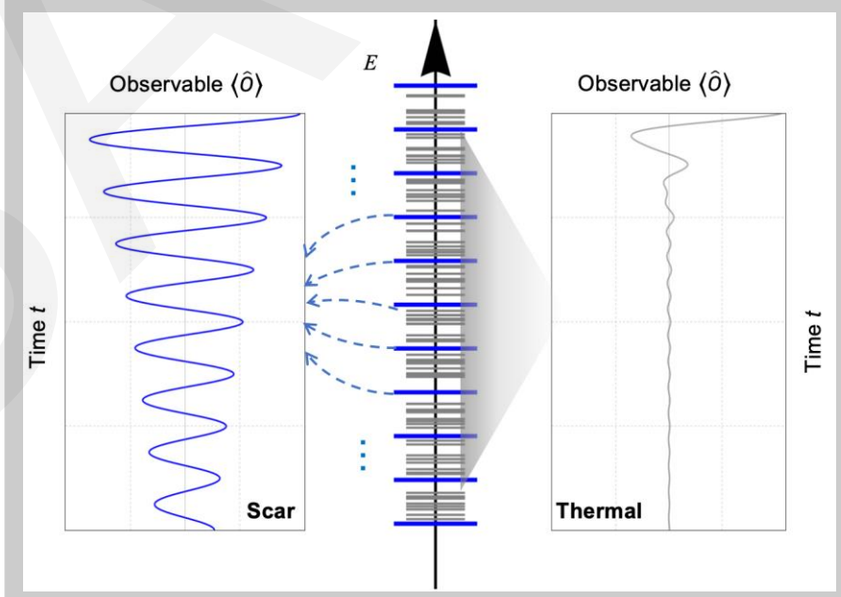
Many-body localization





-Rev. Mod. Phys. **91**, 021001

Many-body scars

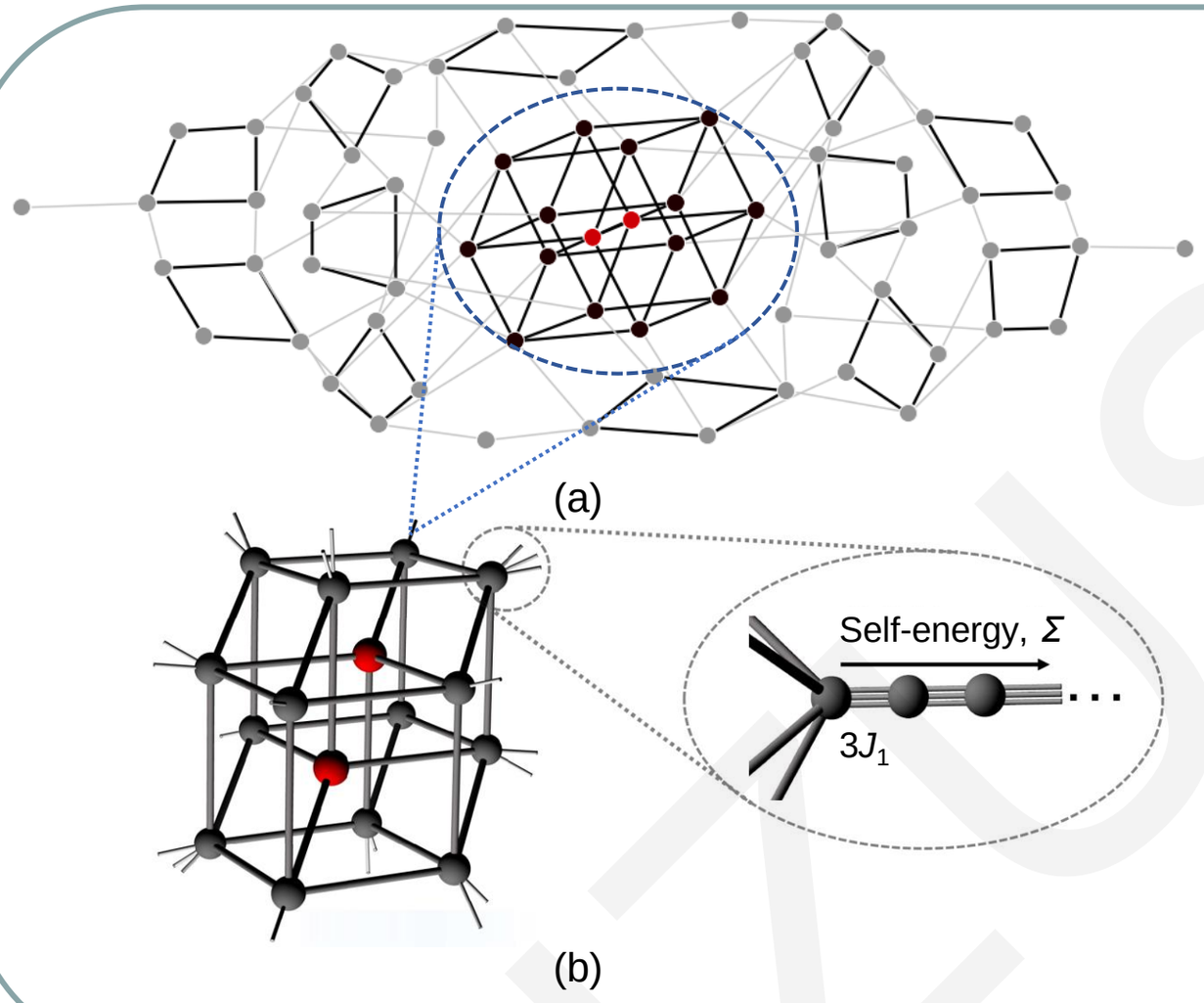


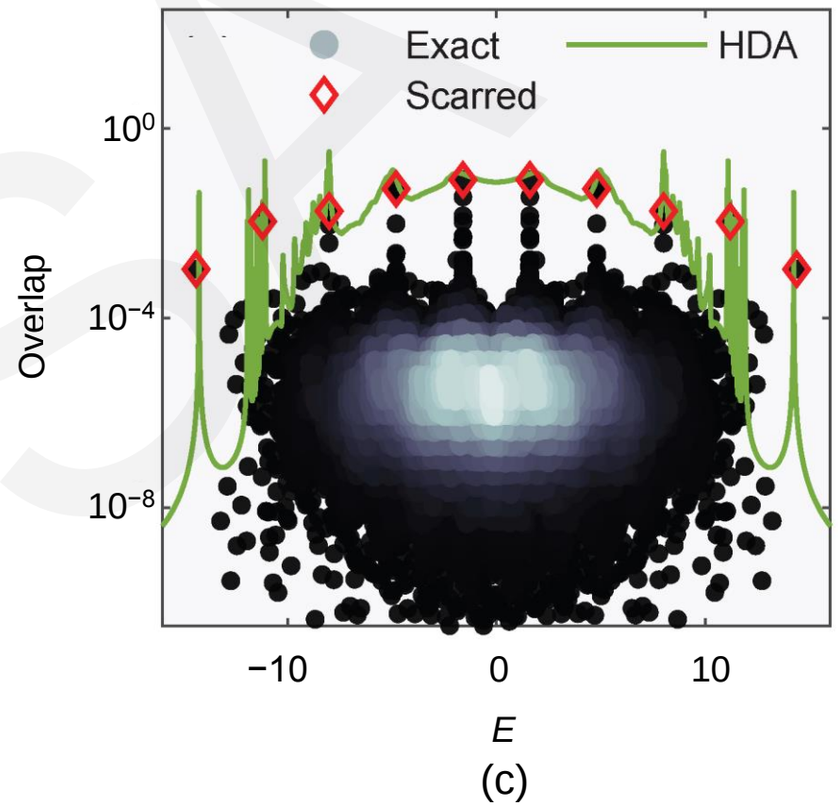
Strong ergodicity breaking

Weak ergodicity breaking

- **Enough conserved quantiles to analytically solve the problem.**
- **Inter-particle interactions do not destroy localization.**
- **Approximately equally spaced tower in the energy spectrum.**
- **Coherent quantum dynamics and revivals.**

Theoretical Framework





Phys. Rev. B 108, 075124 (2023).

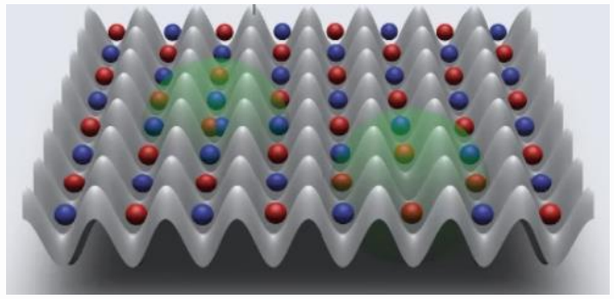
- **A new type of QMBS based on the Heisenberg XY model, which is beyond constraint model.**
- **It originate from a special subspace with a hypercube or hypergrid geometry.**
- **It can be visualized by the overlap between the eigenstates and the special collective state.**

Experiment and Application of QMBS

- High-precision control
- Rapid operation
- Scalability

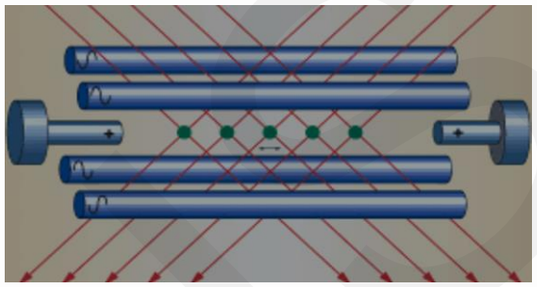
Quantum Simulators

BSS Lecture, 02 (2023).



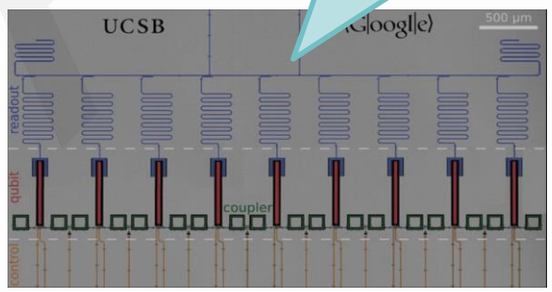
Cold Atom

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



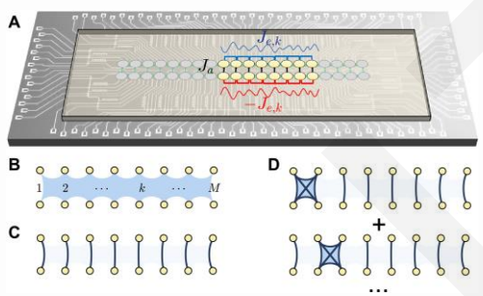
Ion Trap

Science, 360, 6385 (2017).



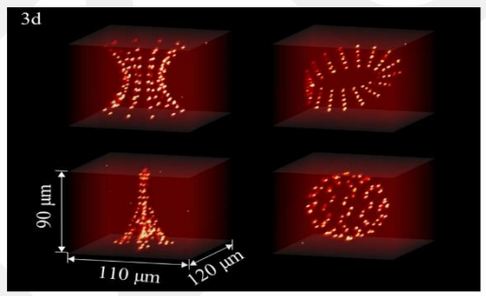
Superconducting Quantum Processor

Application



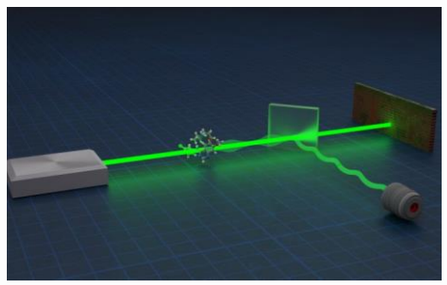
Sci. Adv. 9, eadj3822 (2023).

Entanglement Controlling



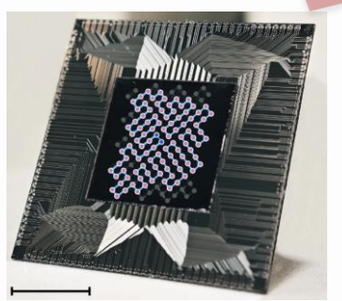
J. Phys. B 49, 152001 (2016).

Chemistry and Biology



Nat. Commun, 11, 3775 (2020).

Quantum Metrology

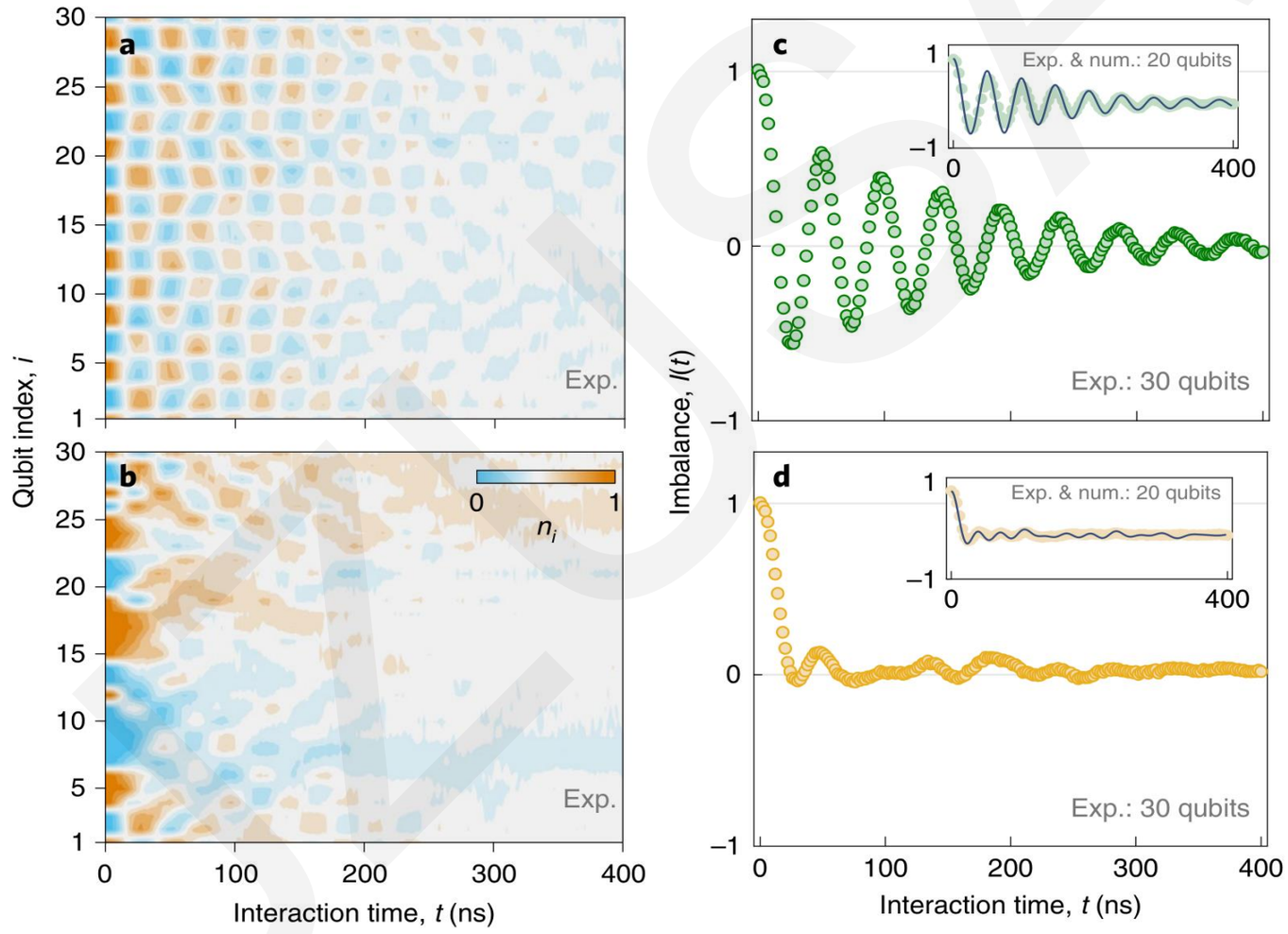


Nature, 09476 (2025).

Quantum Computing

Frontier of QMBS experiment on superconducting circuit

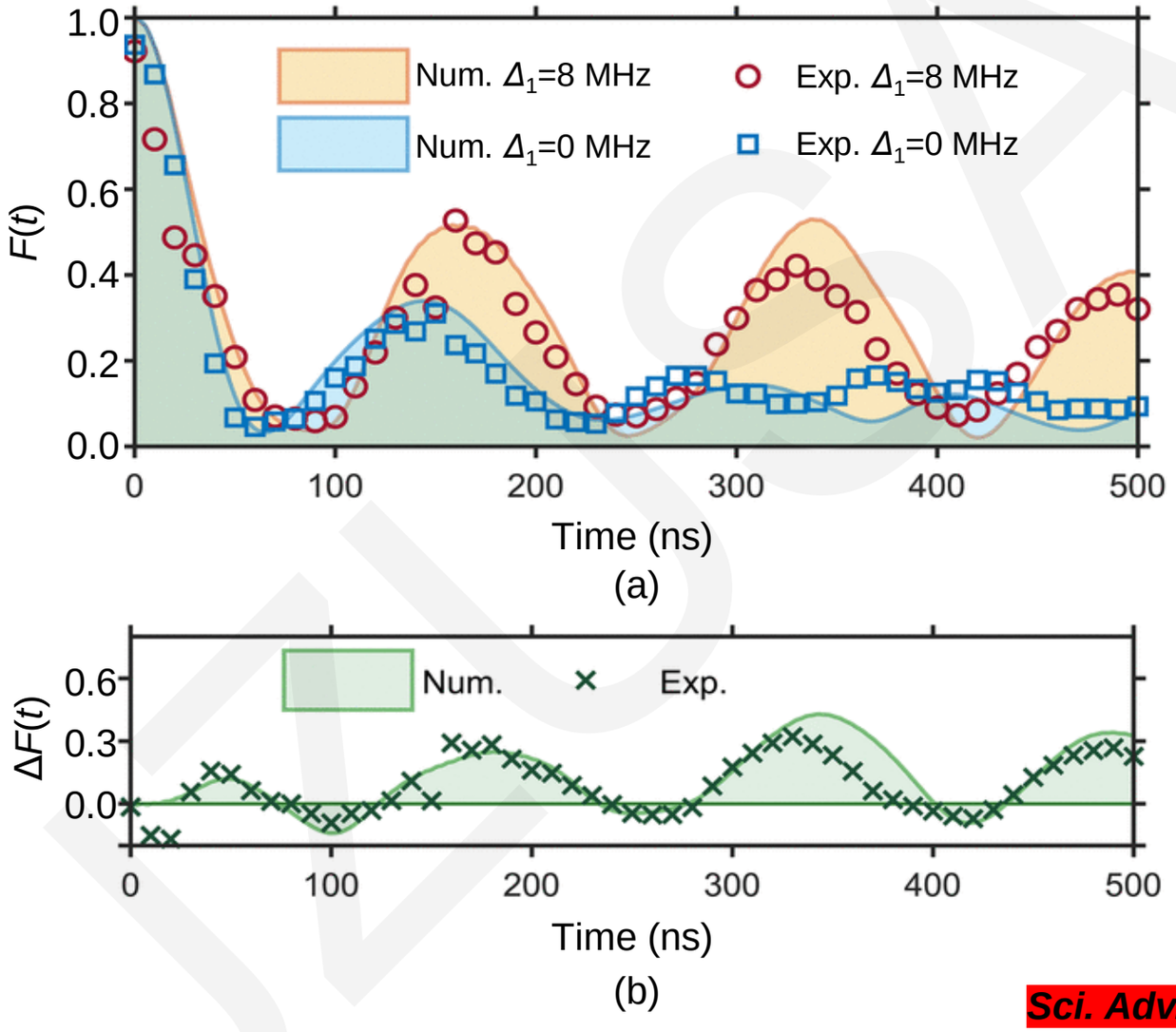
$$\langle S_i^z(t)\rangle = \langle\psi(t)|S_i^z|\psi(t)\rangle \Rightarrow I(t) = \frac{1}{L}\sum_{i=1}^{L}\langle \mathcal{S}_i^z(0)\rangle\langle \mathcal{S}_i^z(t)\rangle$$



Nat. Phys. 19, 120 (2023).

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

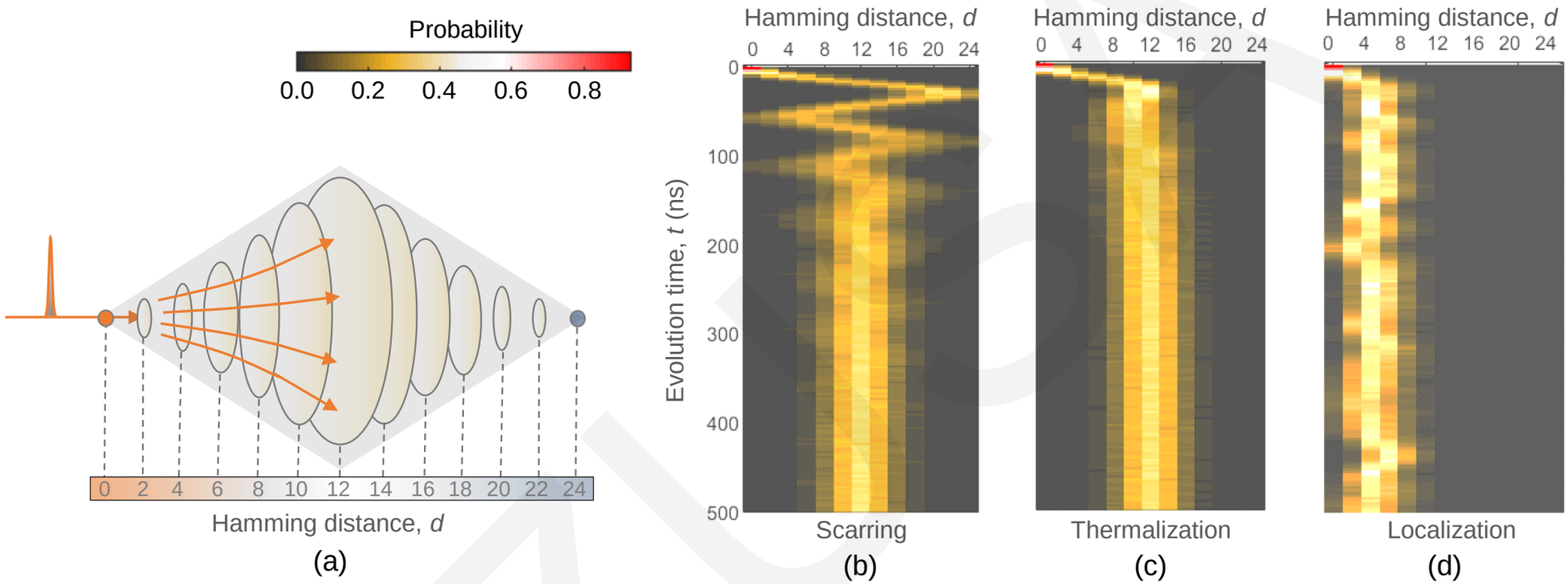
Frontier of QMBS experiment on superconducting circuit



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

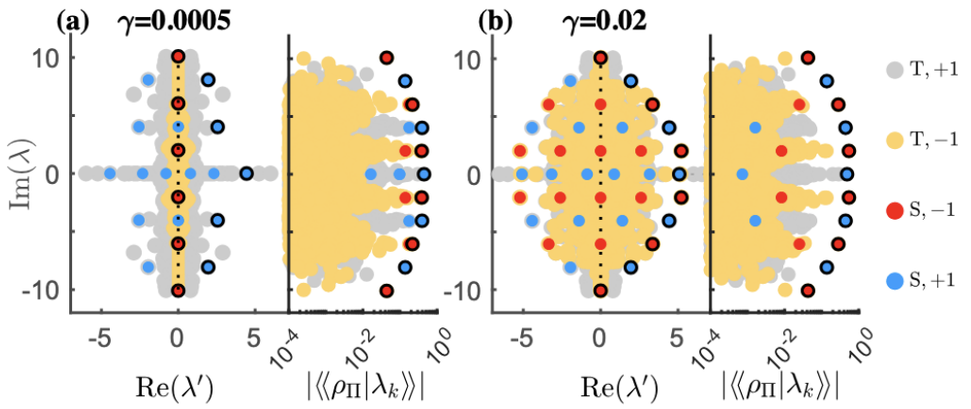


Nat. Phys. 19, 1459 (2023).

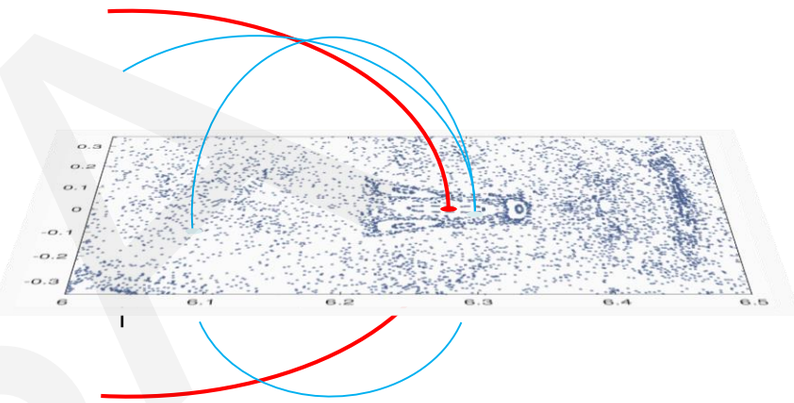
- **Yao et al. (2023) showed signatures of 2D QMBS on a 4×6 superconducting qubit array.**
- **They directly visualized wave-packet propagation in the many-body state space, enabling observation of thermalization, localization, and scarring.**

Future Work

arXiv:2504.12291

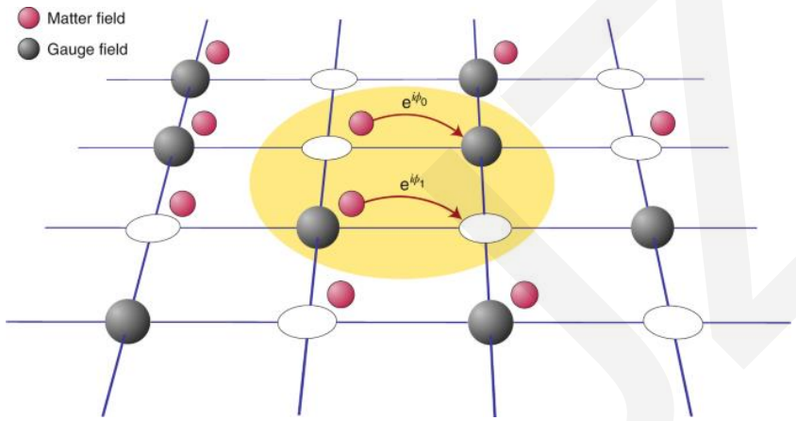


■ QMBS in Open System

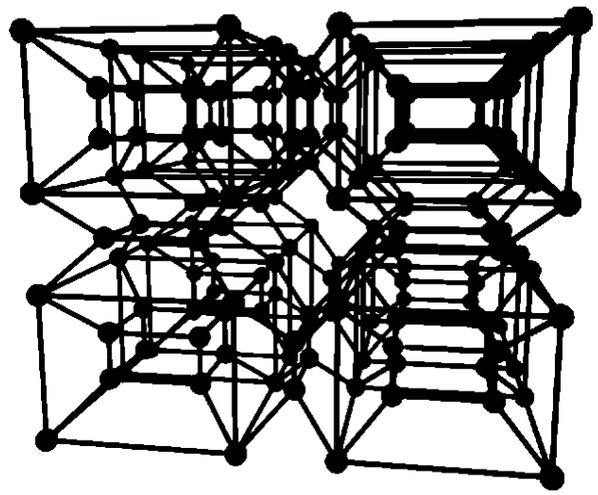


■ Semiclassical Correspondence

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.