Overview: Quantum Information Dynamics

Matteo Ippoliti (UT Austin)

CMMRC Workshop on Frontiers of Engineered Coherent Matter and Systems | Washington, DC | 2024/10/03

Synthetic Quantum Matter

Superconducting qubits

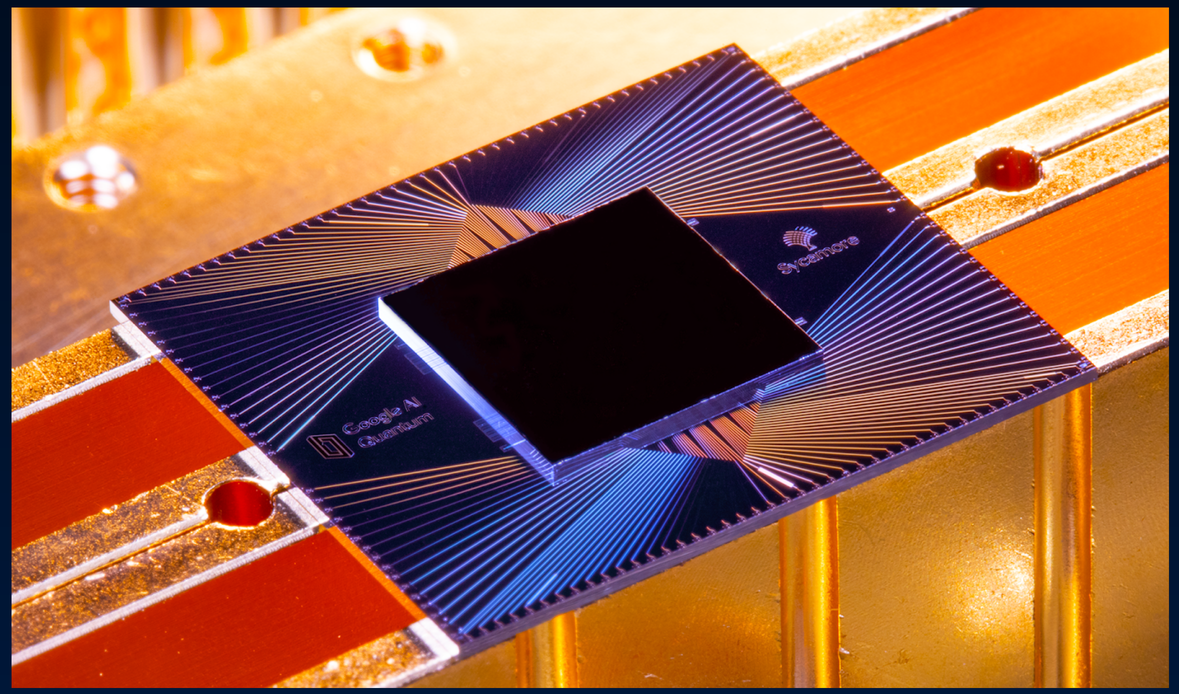


image: Google Quantum AI

Trapped ions

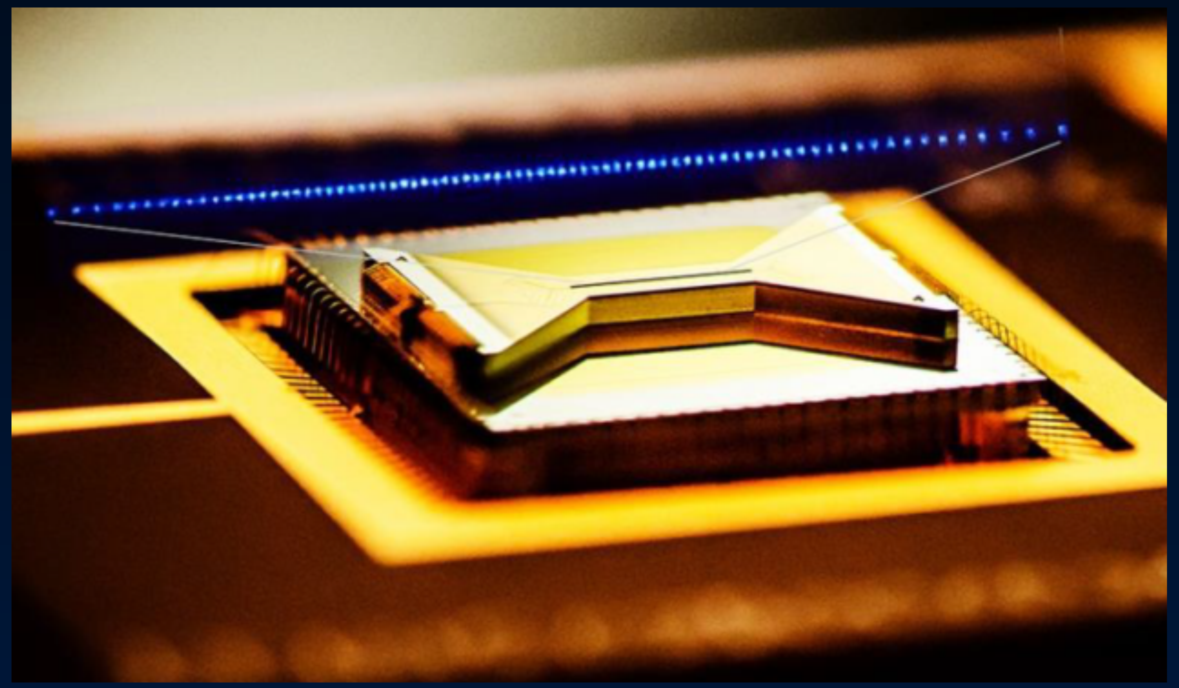


image: IonQ

Ultracold atoms

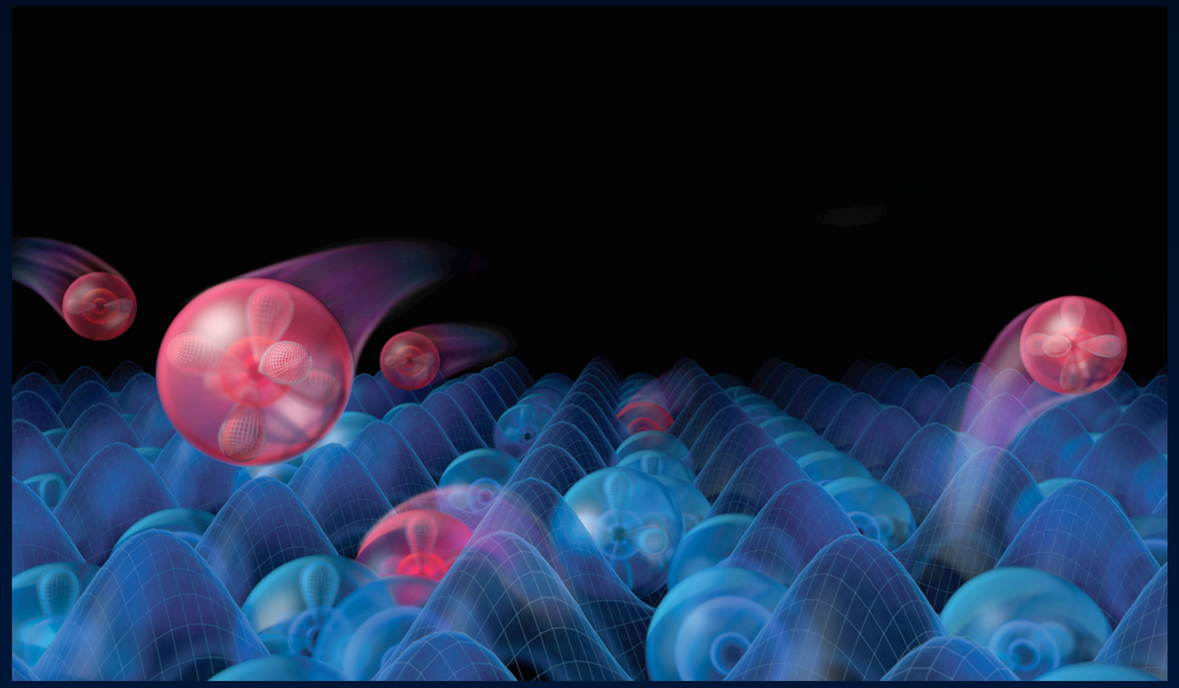


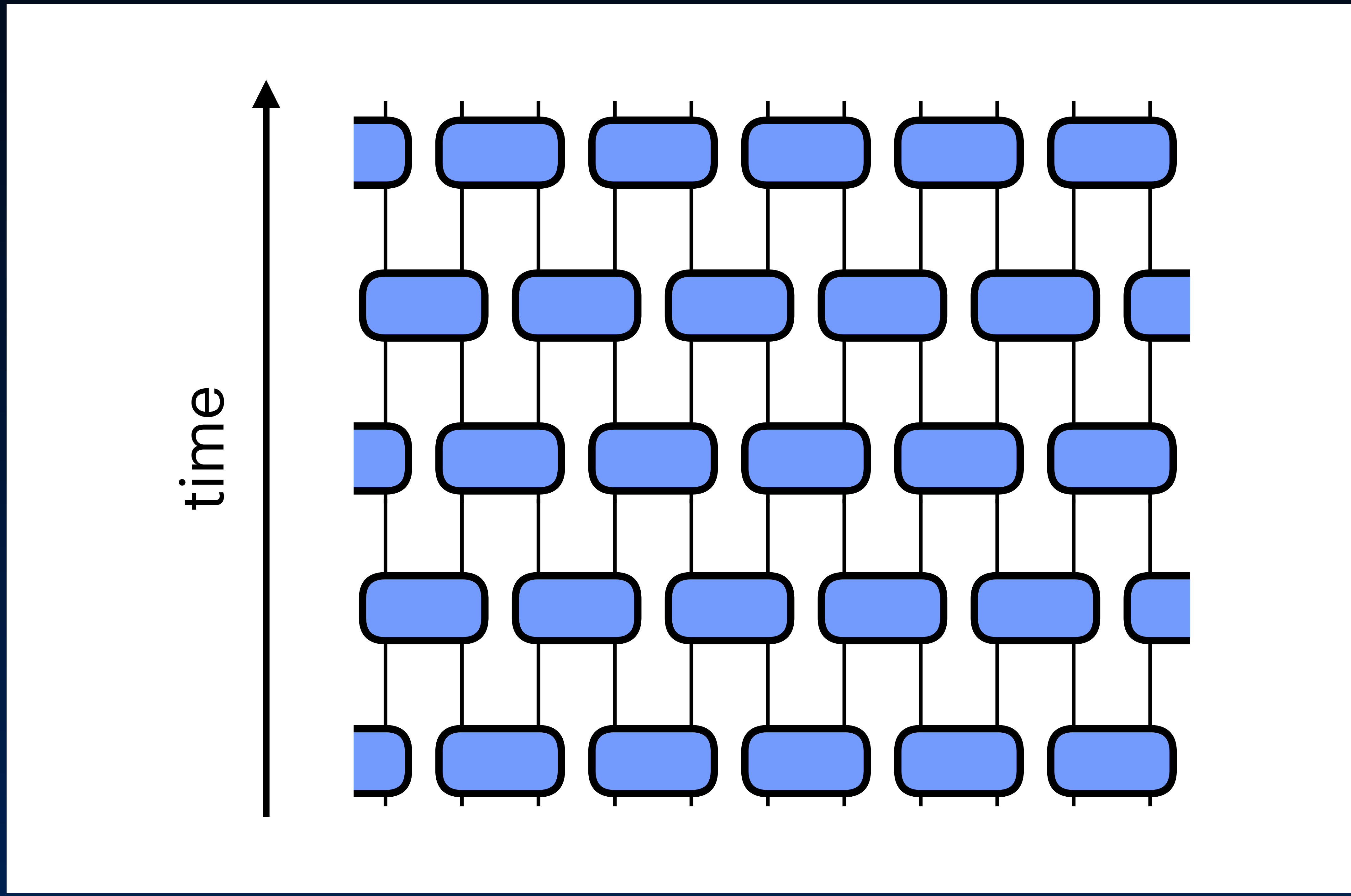
image: Science **357**, 984 (2017)

- Unprecedented **control** and **measurement** of many-body systems, more **interactive** role for the observer
- New opportunities for many-body physics, in and out of equilibrium

The Non-Equilibrium Frontier

Quantum computing as a **non-equilibrium** process:

- drive (unitary operations)



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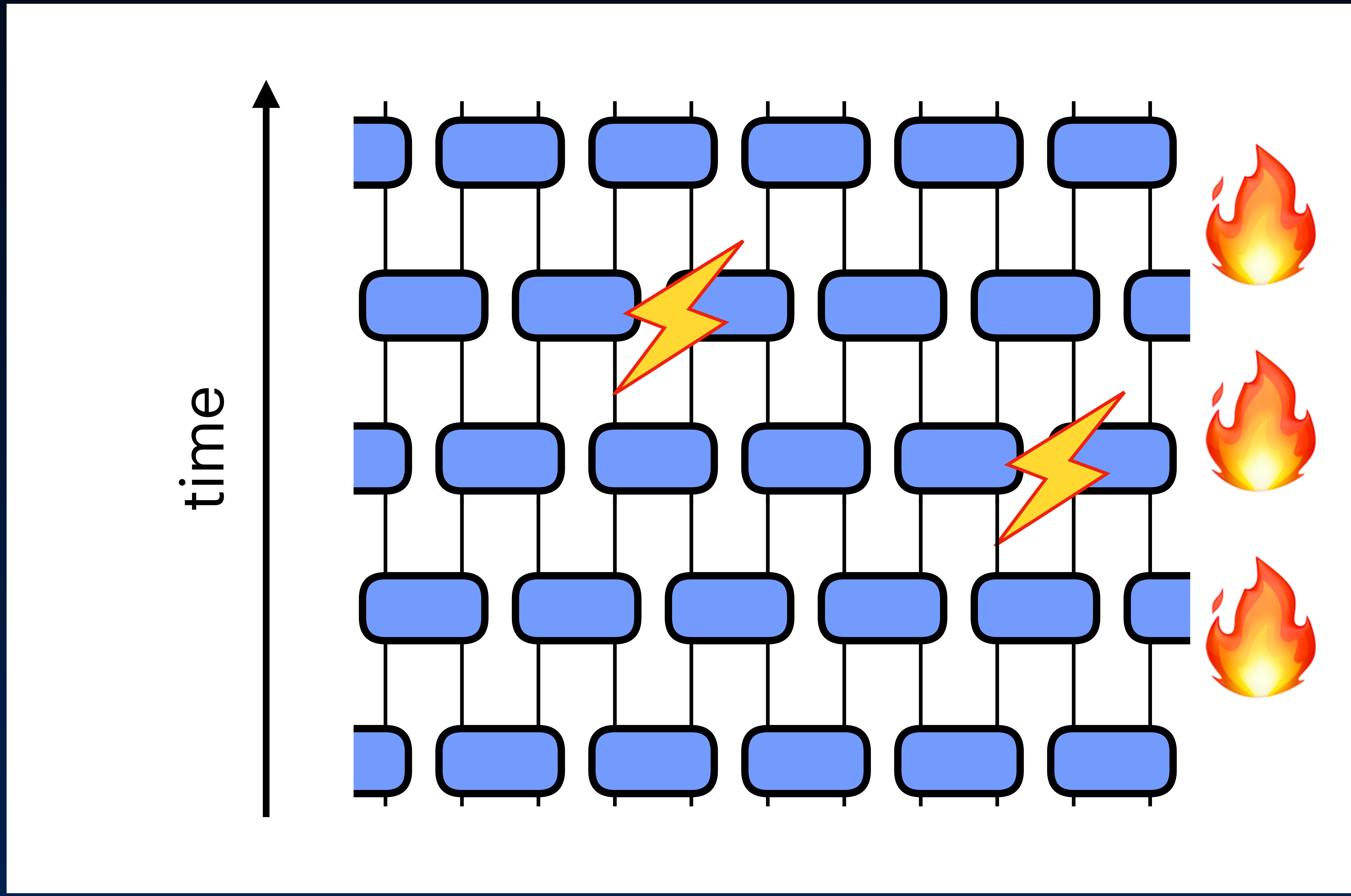

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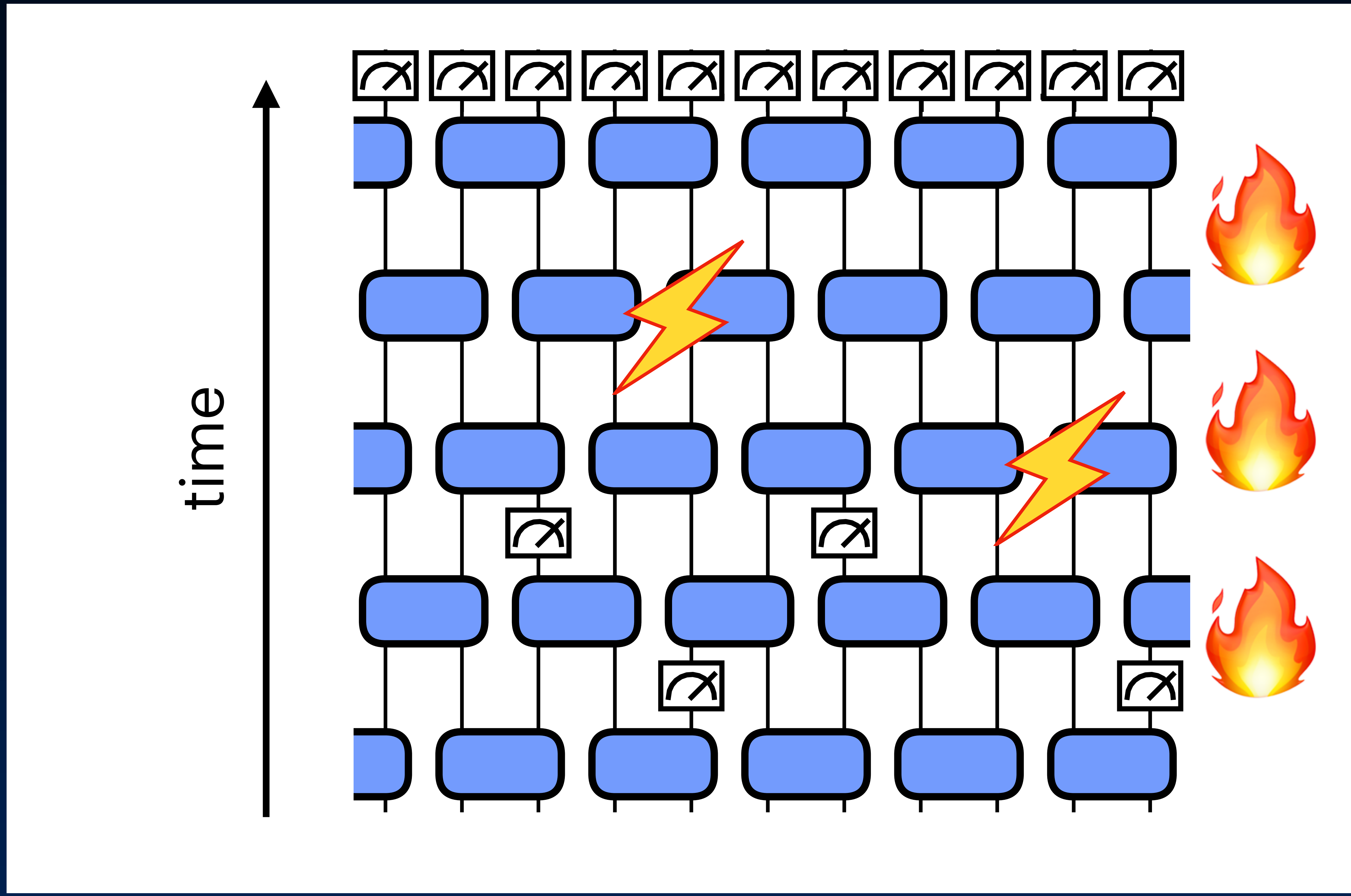

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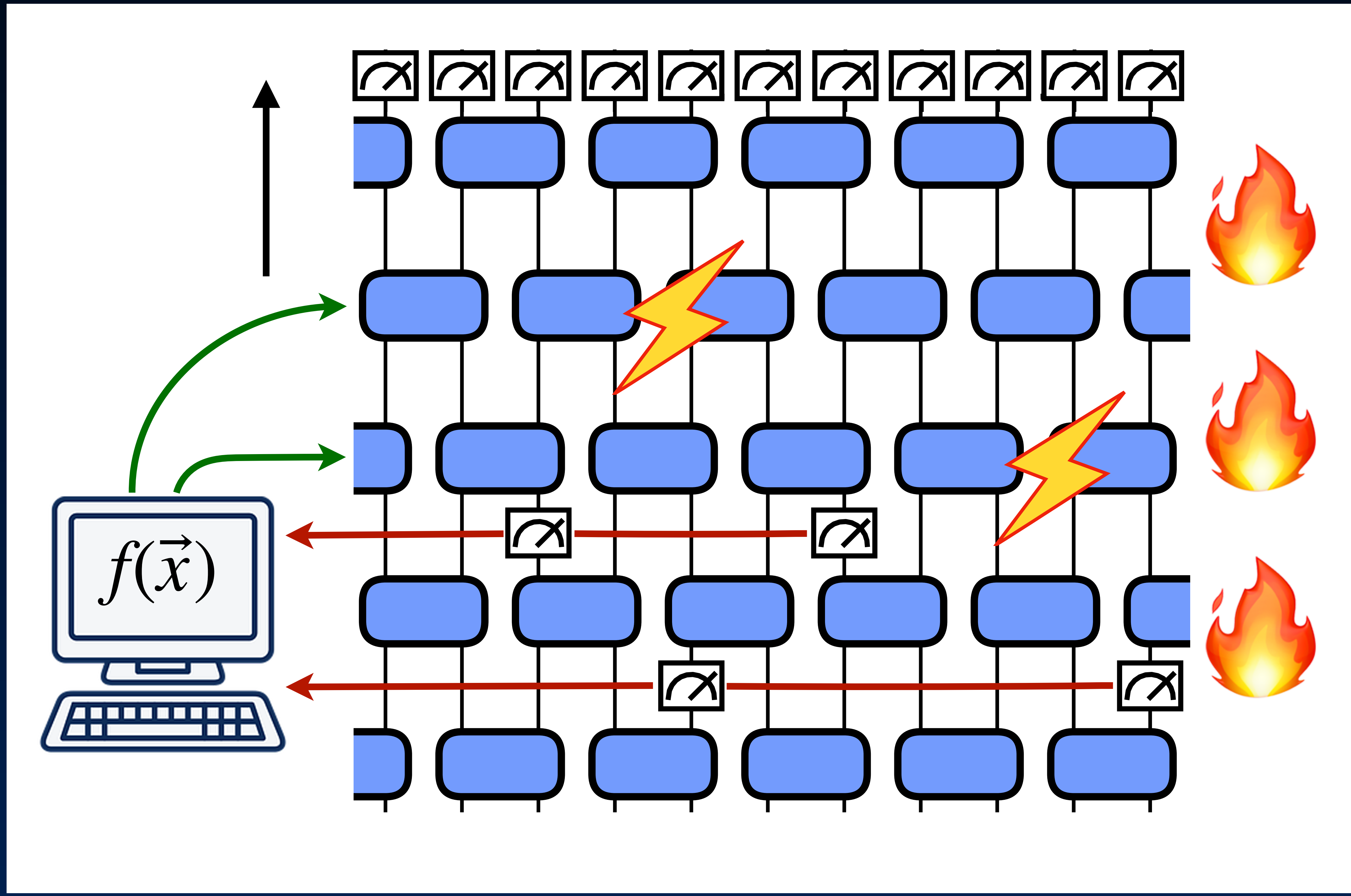
- feedback (error correction)
- ....



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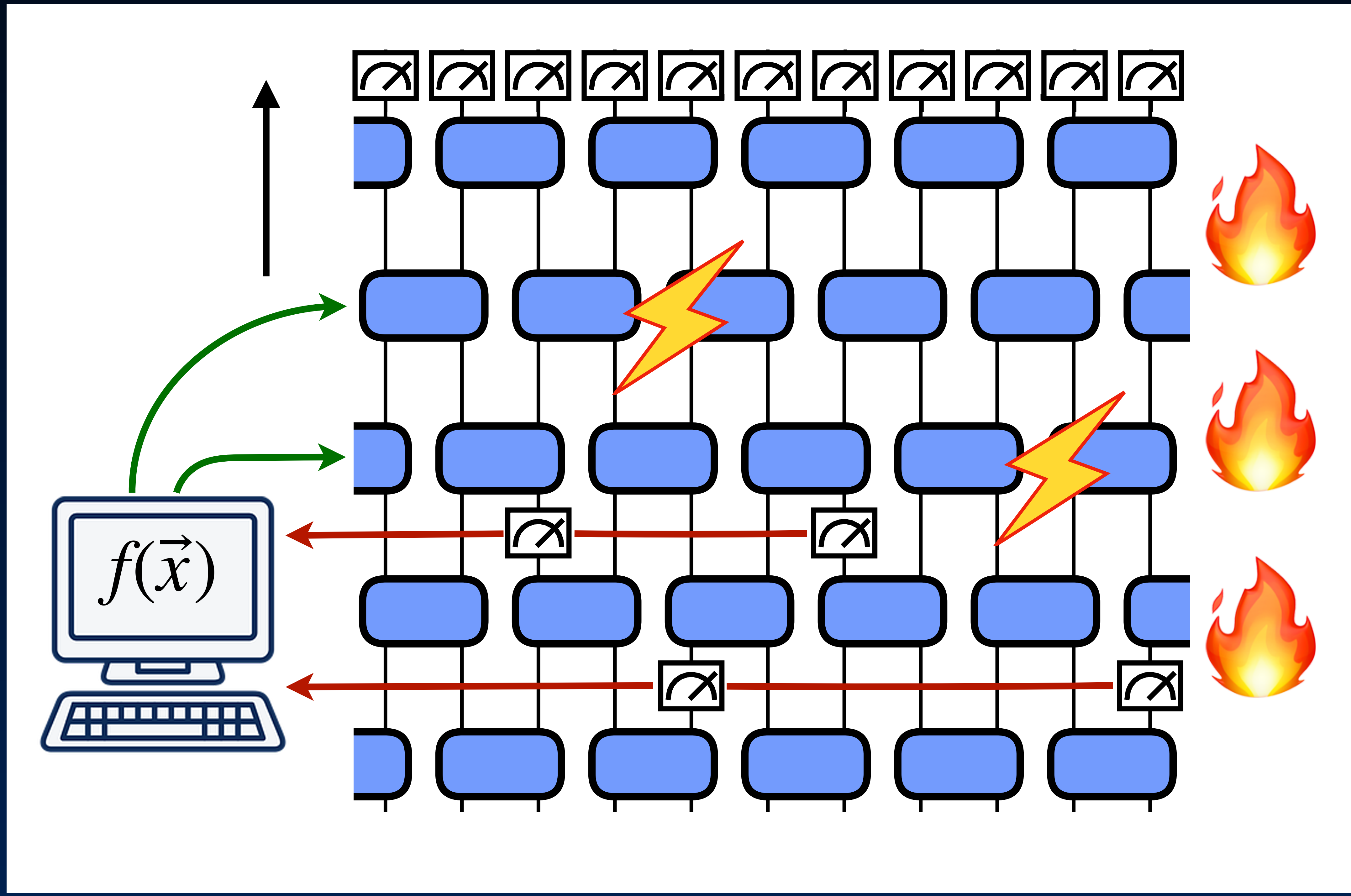


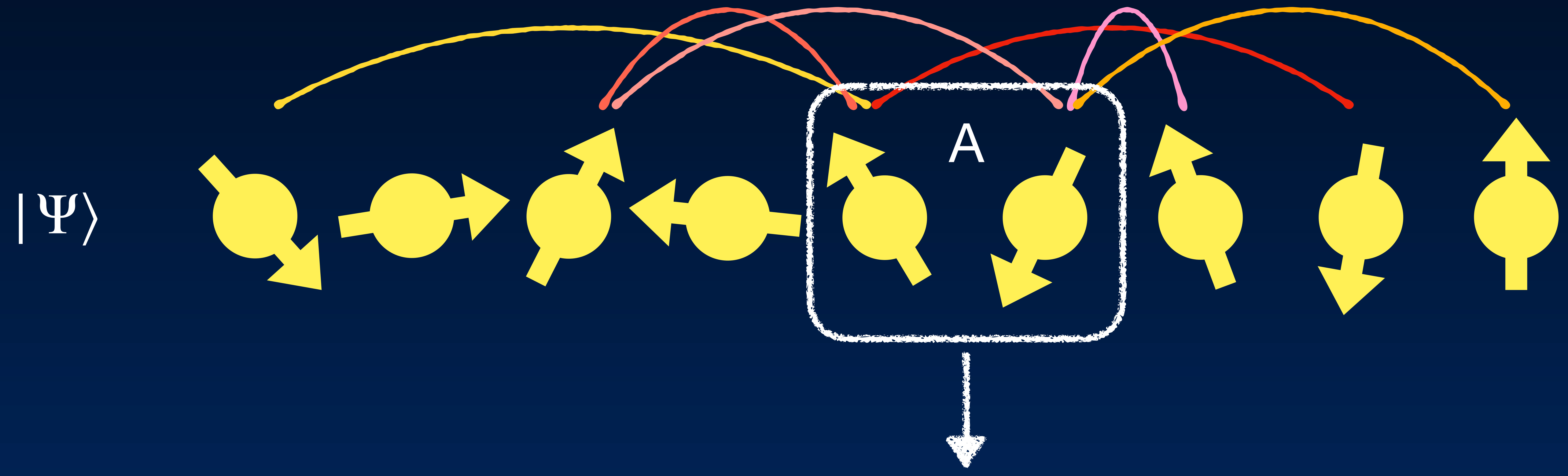
A vast new domain for many-body physics far from equilibrium

Thermalization

Thermal equilibrium in the quantum world

Entanglement: information can be shared among quantum particles and become **inaccessible** to local measurements

Allows the system to serve as its own "heat bath"

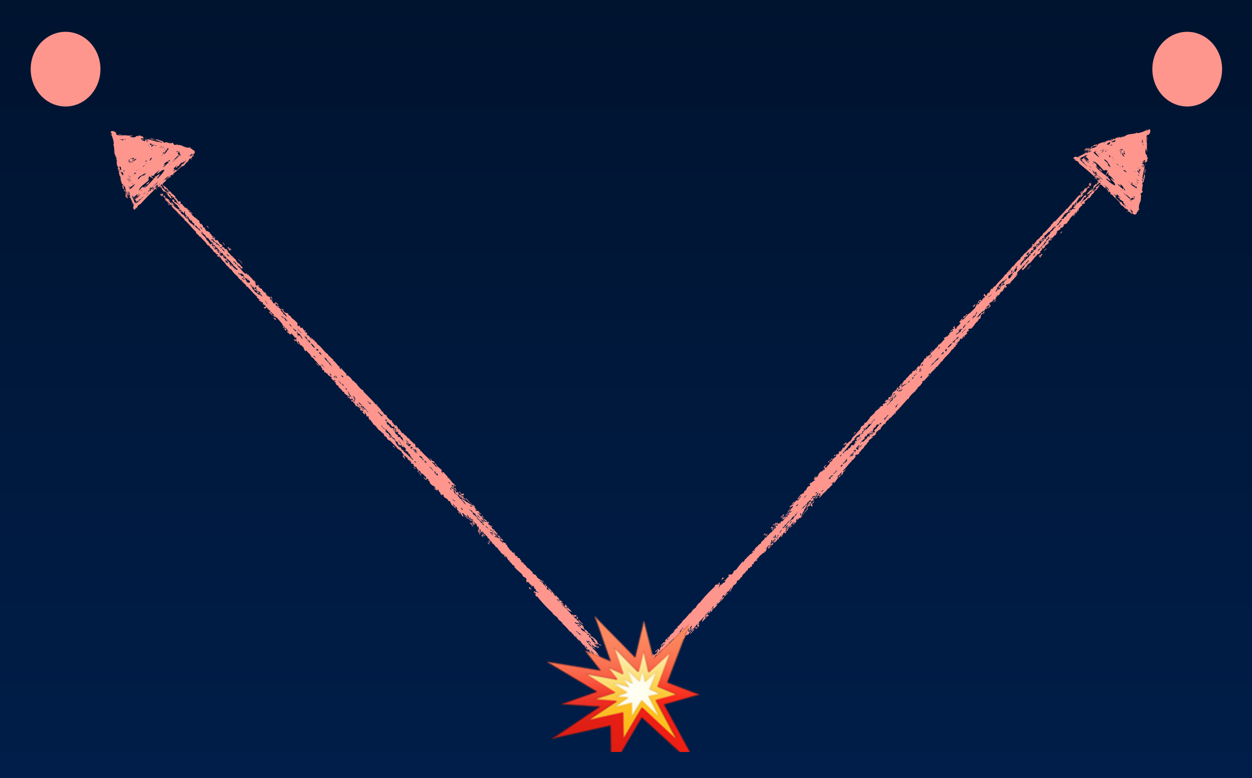


thermal equilibrium state

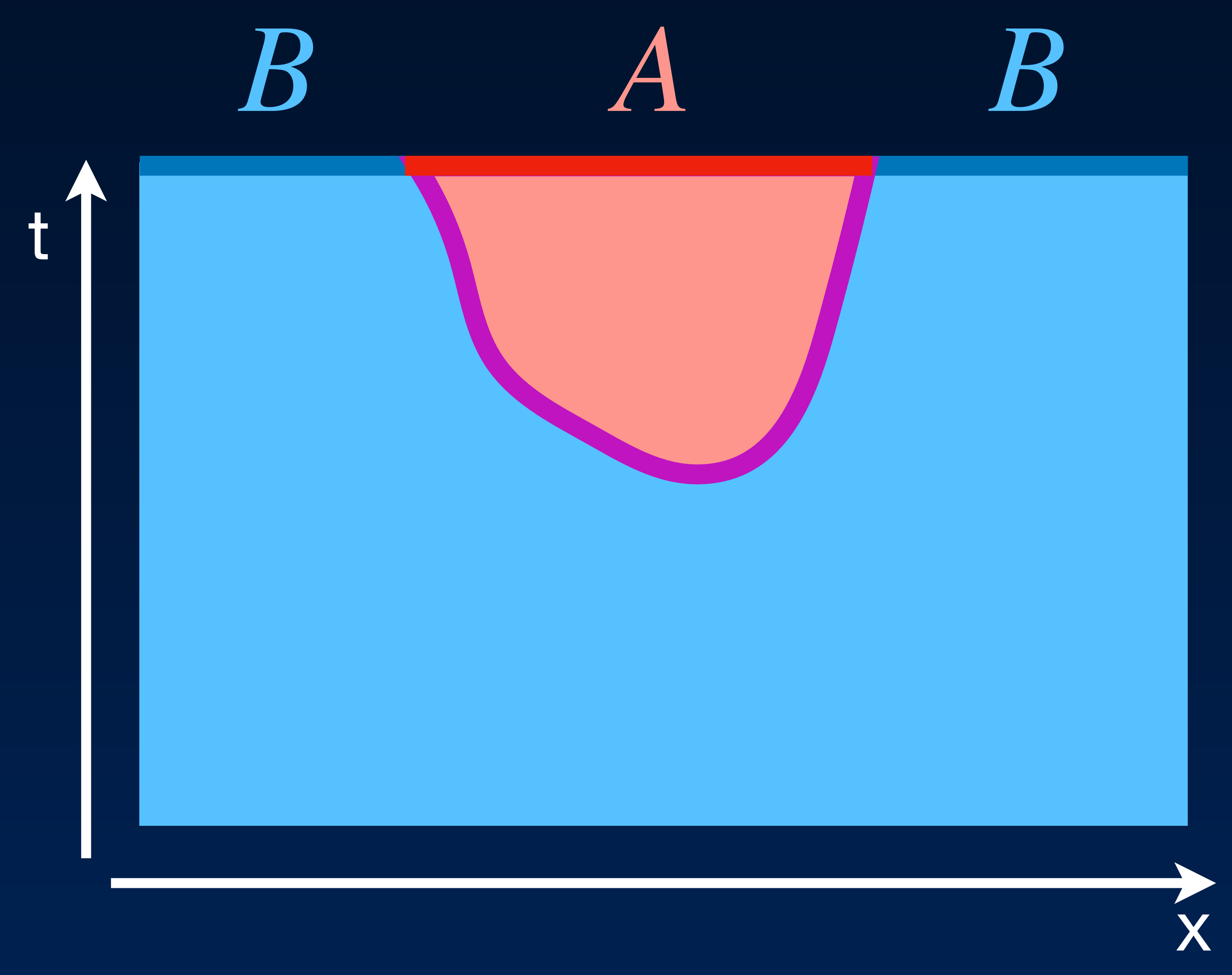
[Srednicki, PRE 50, 888 (1994)]

Dynamics of entanglement

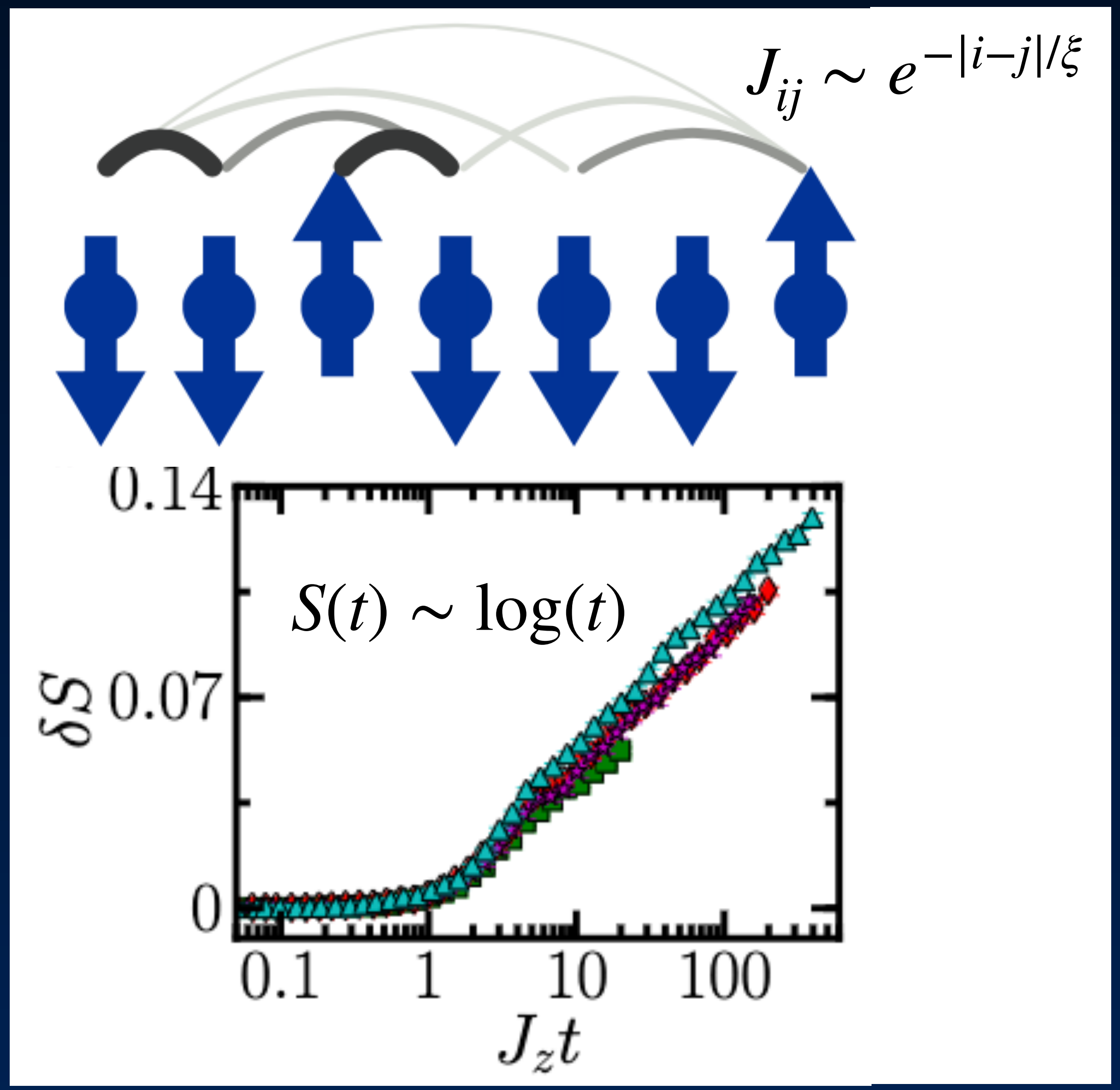
Understanding the build-up of entanglement in many-body dynamics can shed light on the process of **thermalization** — or its exceptions



Quasiparticle picture
[Calabrese, Cardy 2005]



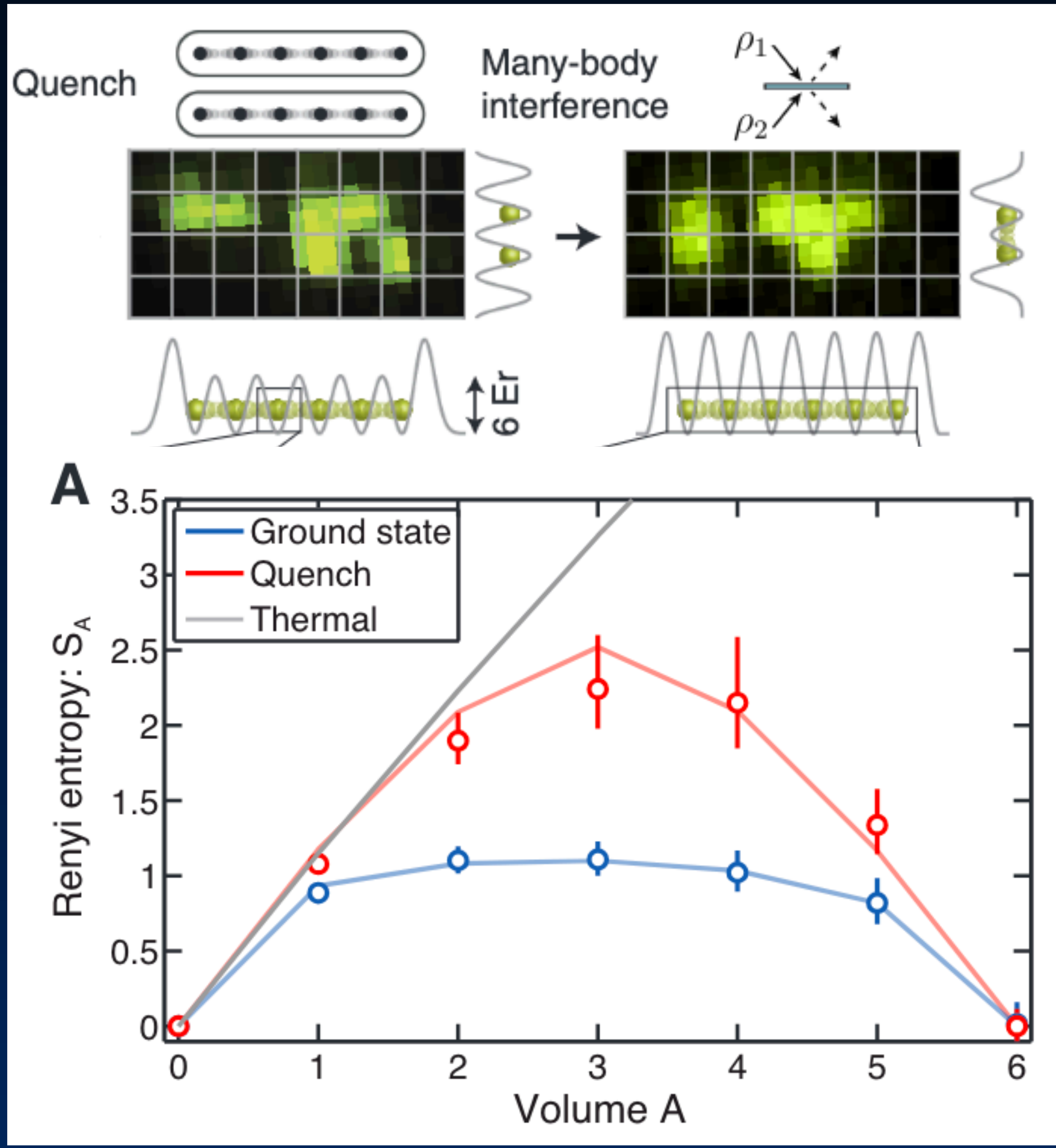
Minimal cut picture
[Ryu, Takayanagi 2006; Nahum et al 2016+]



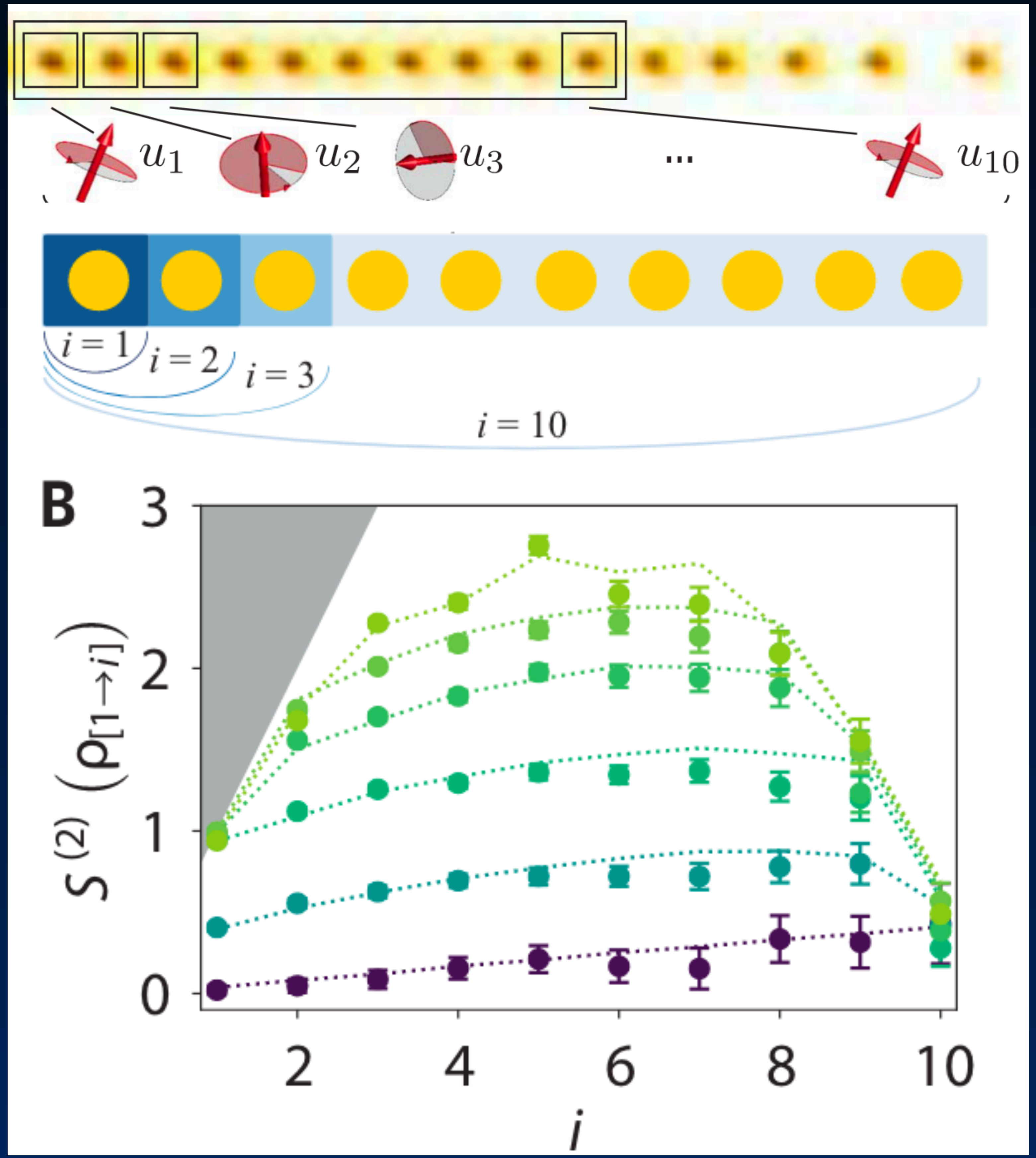
Many-body localization
[Bardarson, Pollmann, Moore 2012; Huse, Nandkishore, Oganesyan 2014]

Not just theory

Direct measurement of entanglement in quantum simulators sheds light on the microscopic mechanism of thermalization



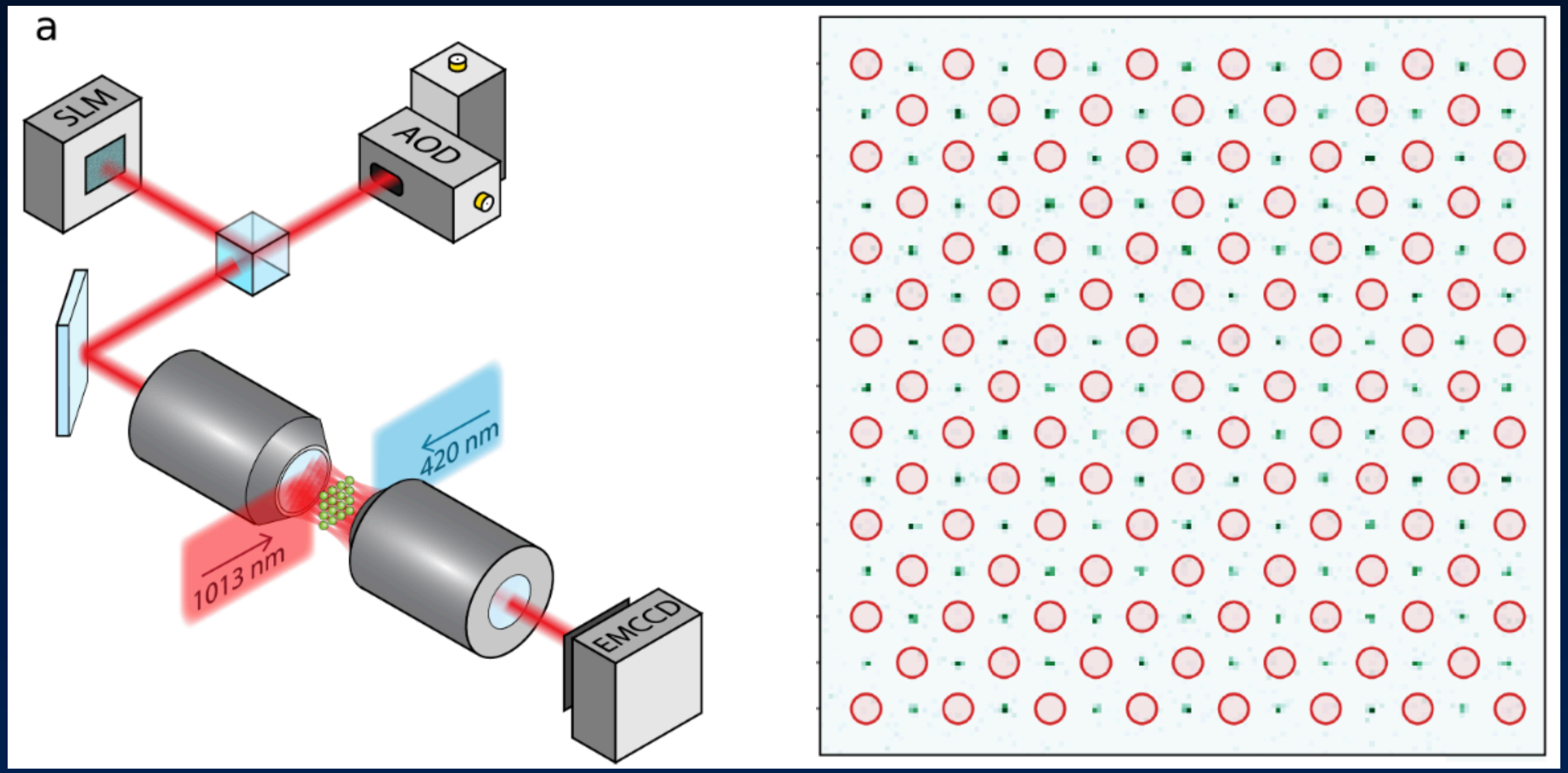
[Kaufman et al, Science 353, 794 (2016)]



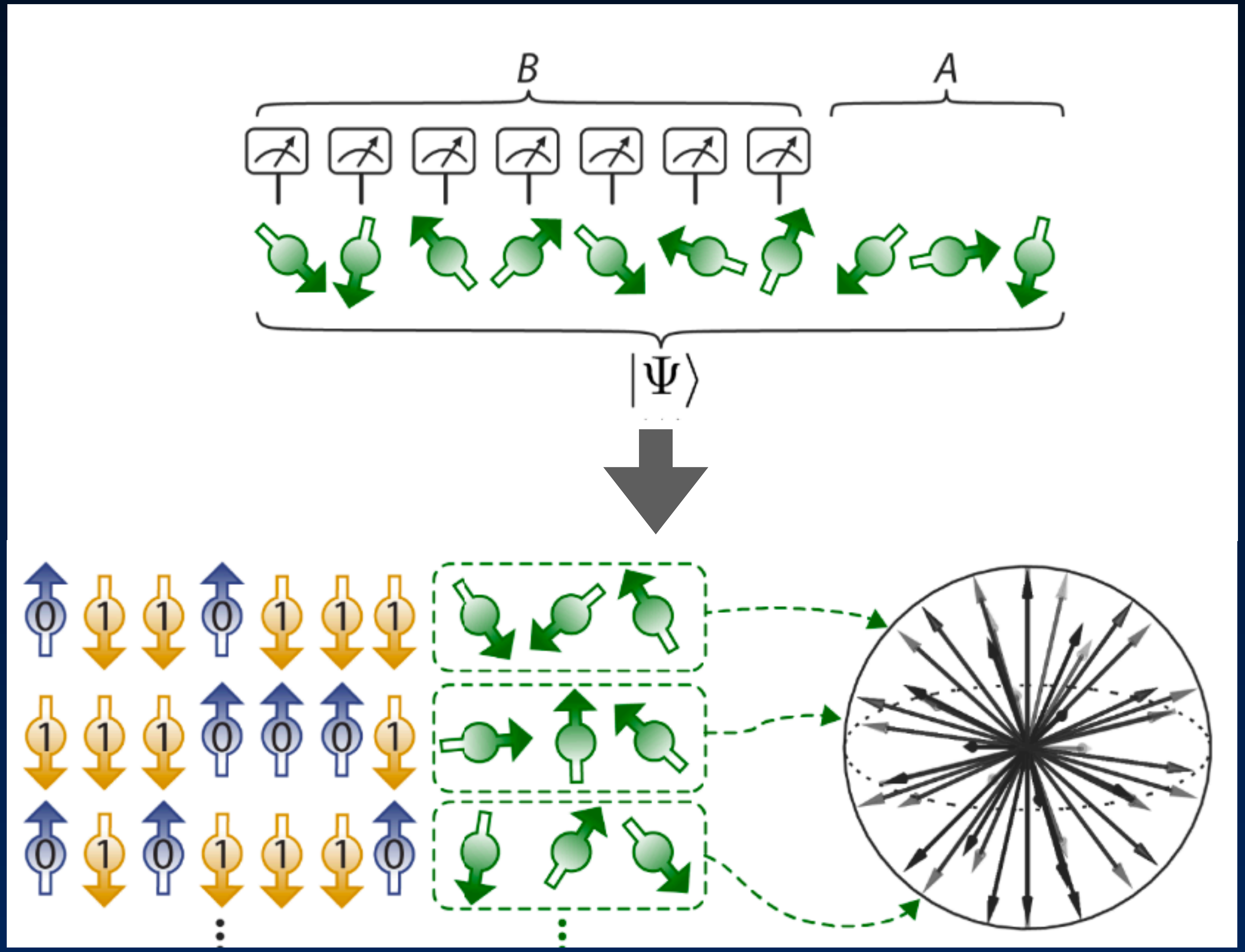
[Brydges et al, Science 364, 260 (2019)]

Snapshots of dynamics

- Microscopically-resolved measurements on entire system: classical "snapshots" of quantum state
- Need not discard "bath" B: can probe **conditional, post-measurement** states

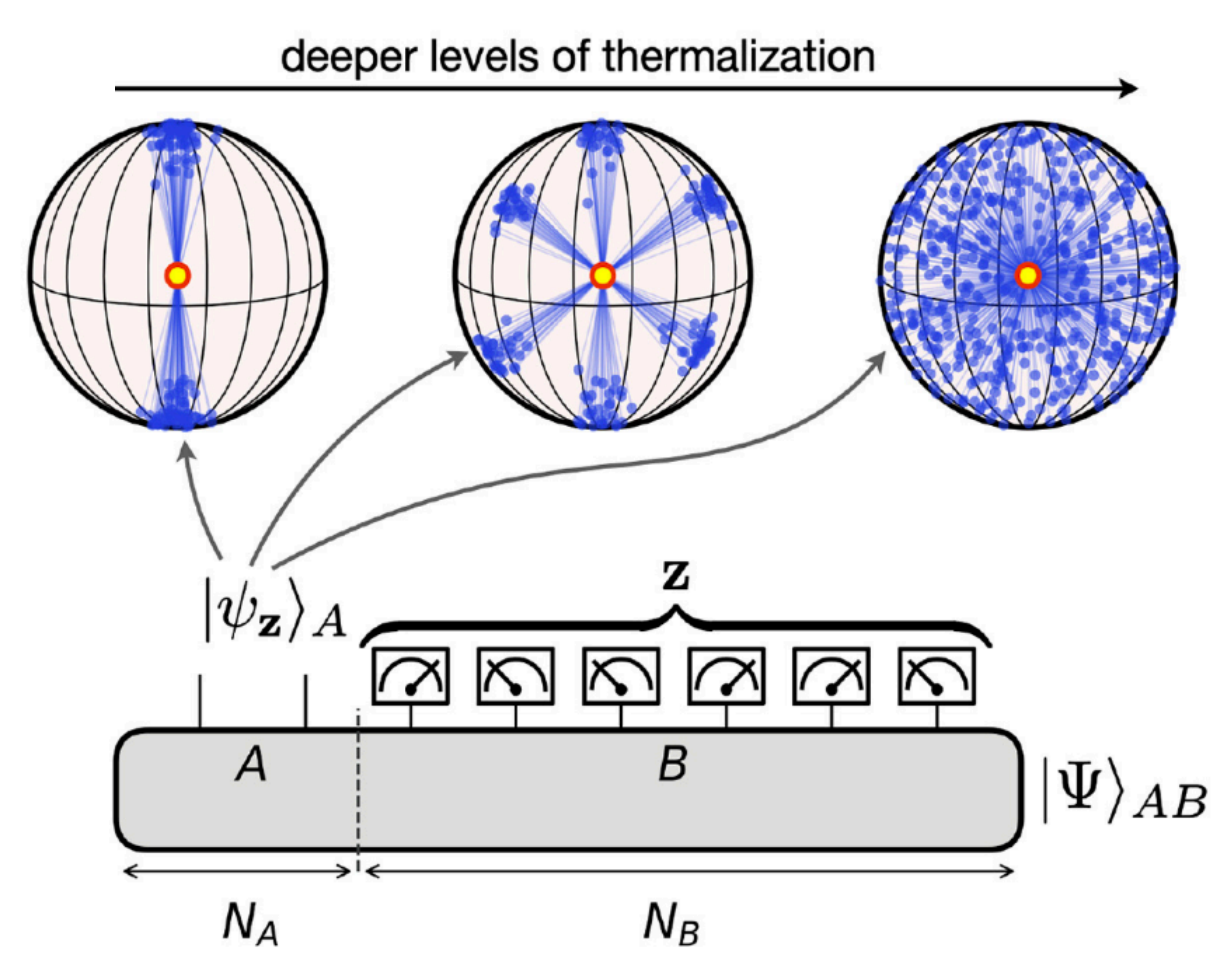


[Ebadi et al, Nature 595, 227 (2021)]



[Cotler et al, PRX Quantum 4,010311 (2023)]

Deep thermalization



- Universal distributions of post-measurement wavefunctions at late time in dynamics
- Strong version of thermodynamic equilibrium
- Depends not just on entanglement but also on its **spatial structure**

[MI, Wen Wei Ho, PRX Quantum 4, 030322 (2023)]

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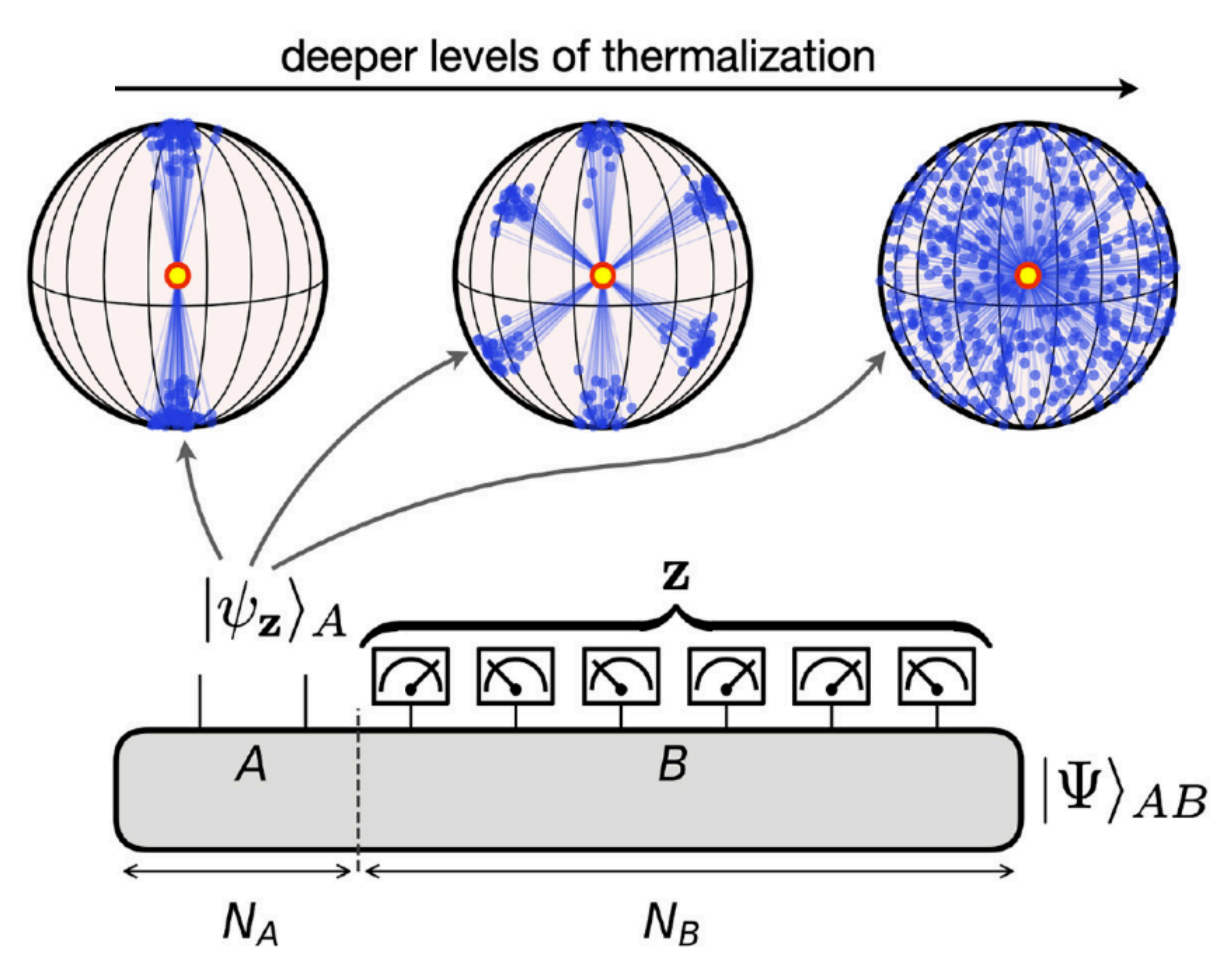

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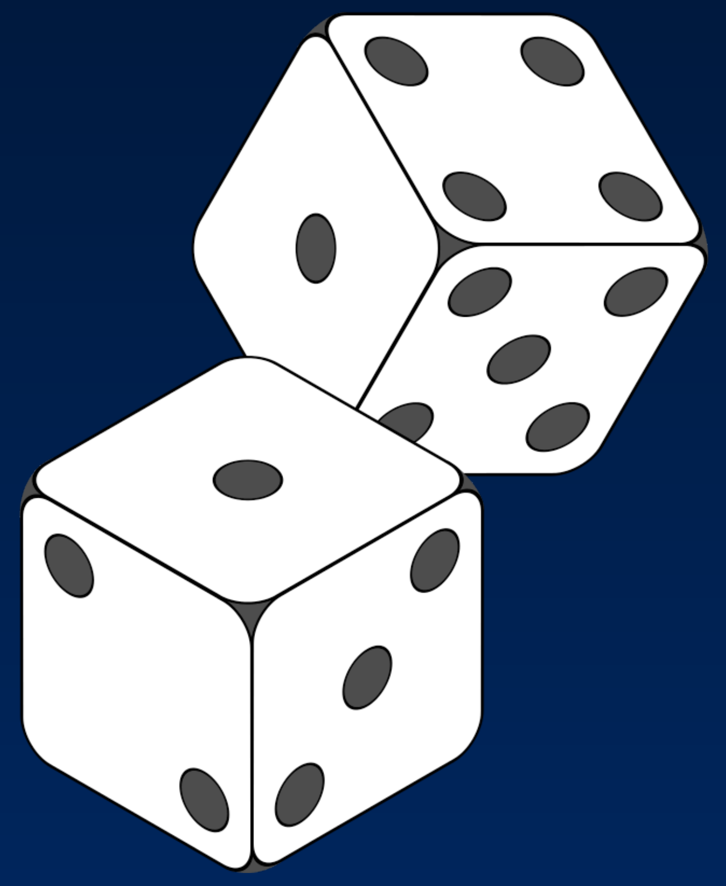


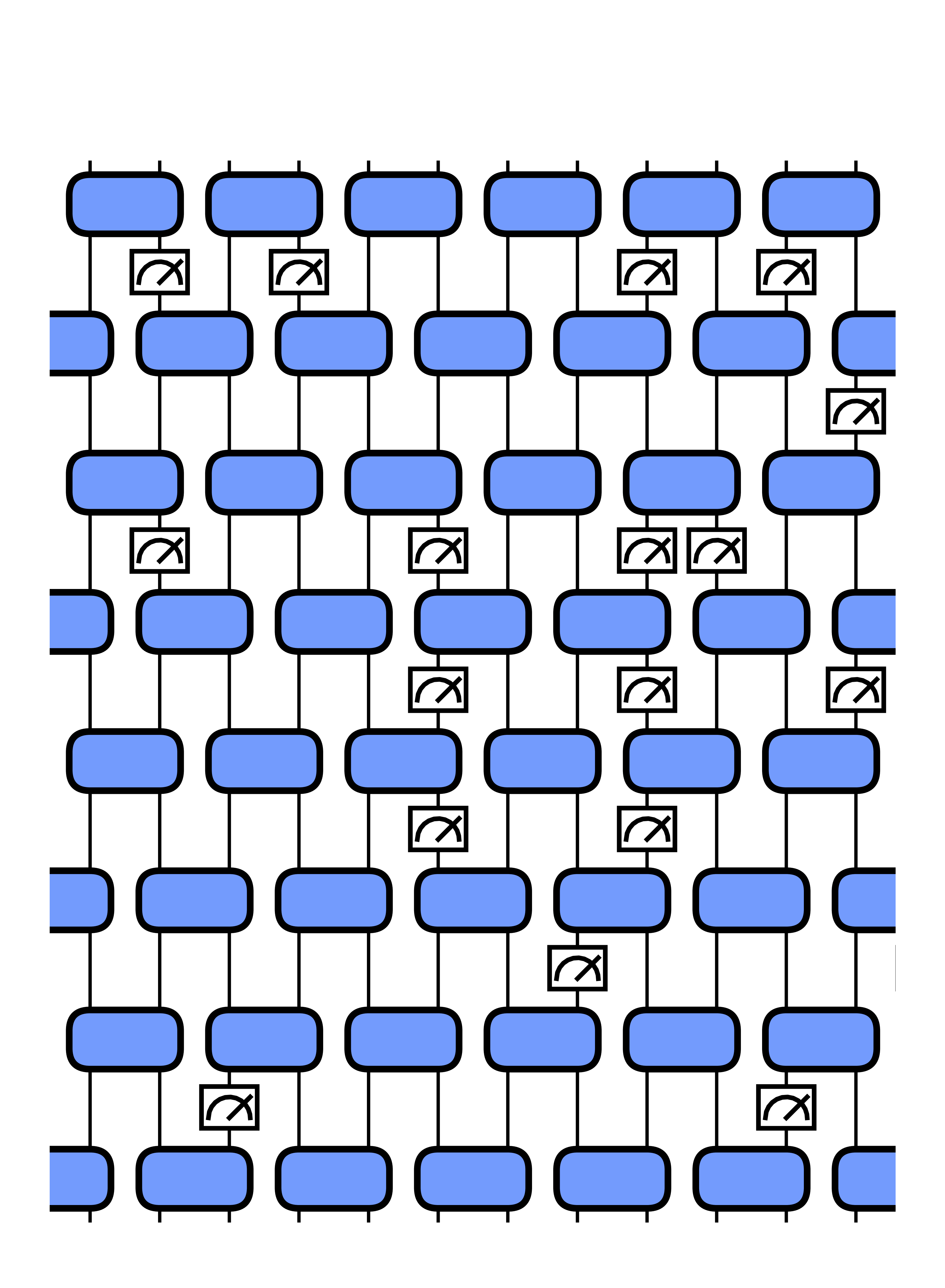
- Applications in **quantum computing**
  - "Random number generator", but for quantum algorithms
  - Useful for randomized benchmarking, state learning, quantum simulation…

[MI, Wen Wei Ho, PRX Quantum 4, 030322 (2023)]

Monitored dynamics

Measurement as a protagonist in the dynamics of many-body systems

New types of **non-equilibrium phases** defined by **structure of quantum information**



[Skinner, Ruhman, Nahum PRX 2018; Li, Chen, Fisher PRB 2018; Choi, Bao, Qi, Altman PRL 2019; Gullans, Huse PRX 2019; ...]

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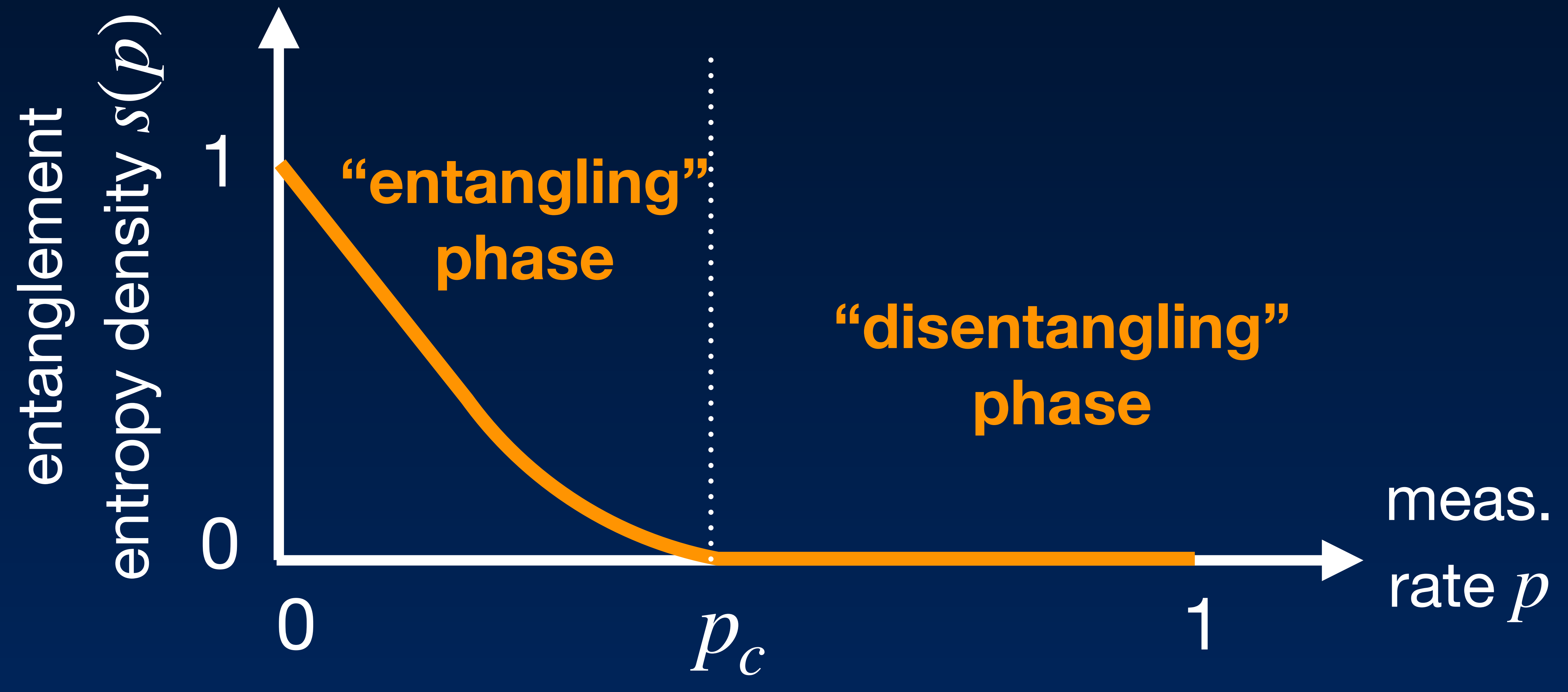

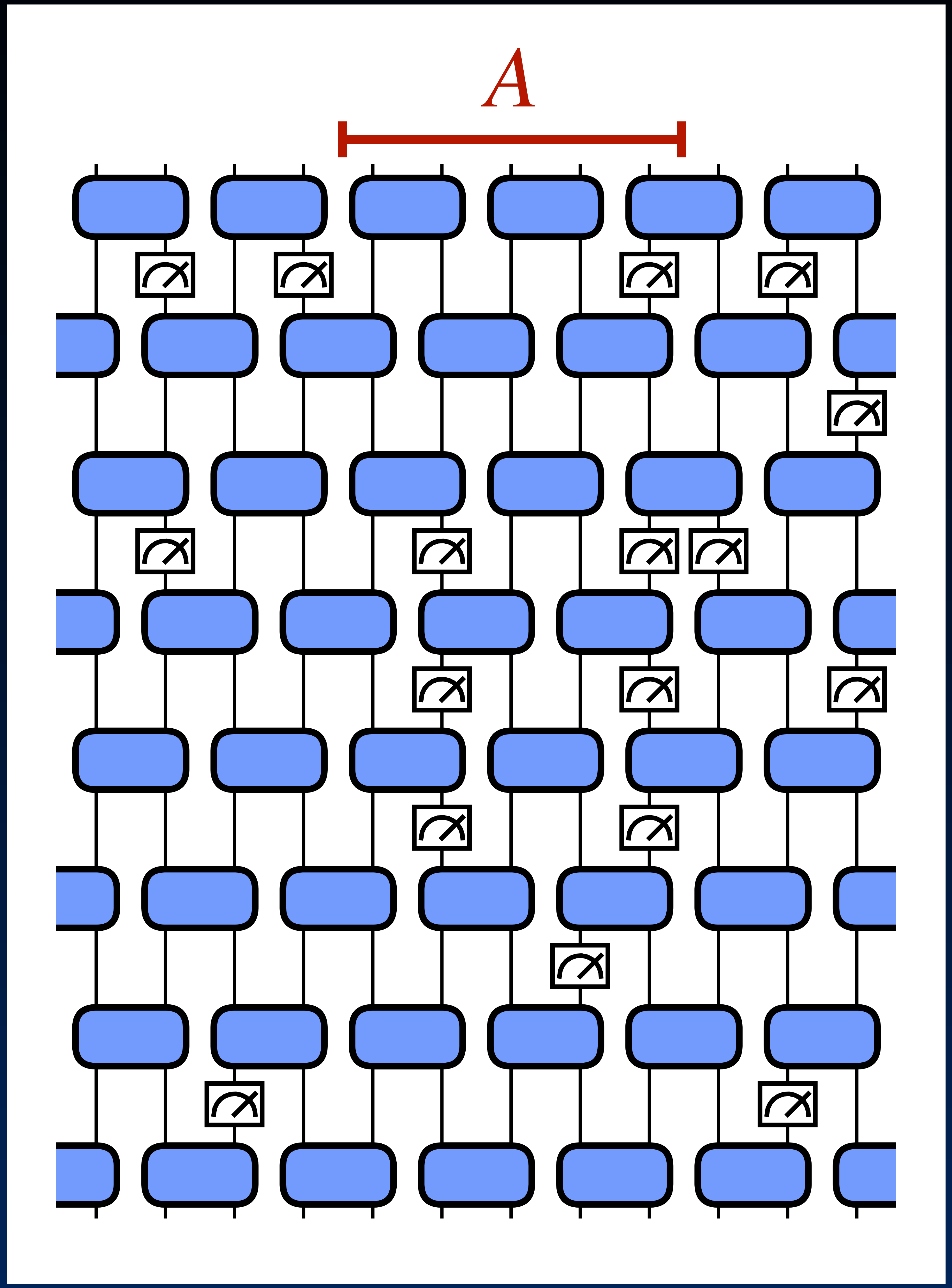

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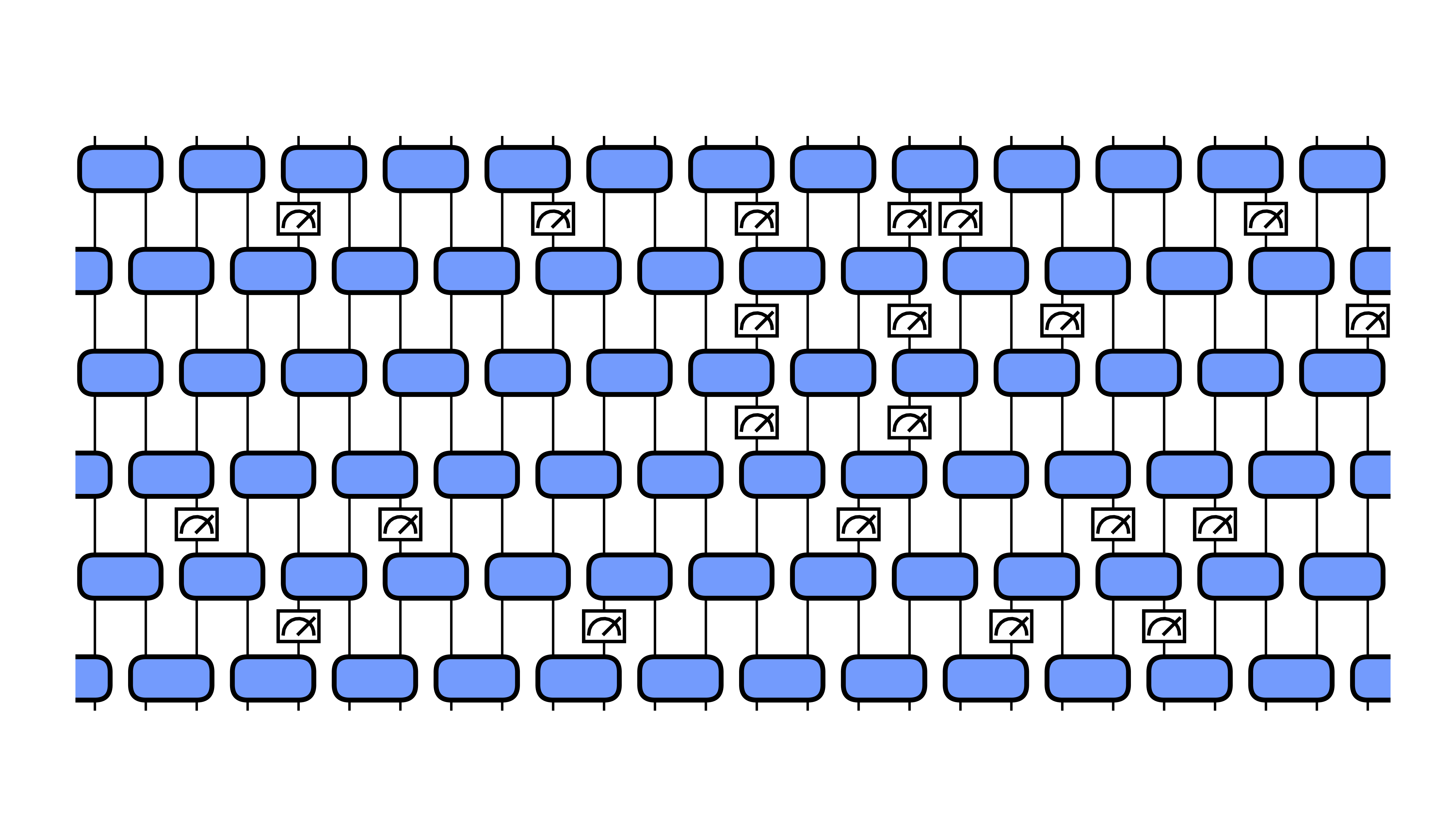
Phase Structure from Measurement

A **network of quantum information**

- Unitary gates (interactions between qubits) create connections
- Measurements may create or destroy them

“Entangling” vs “disentangling”: **phase transition** in network connectivity



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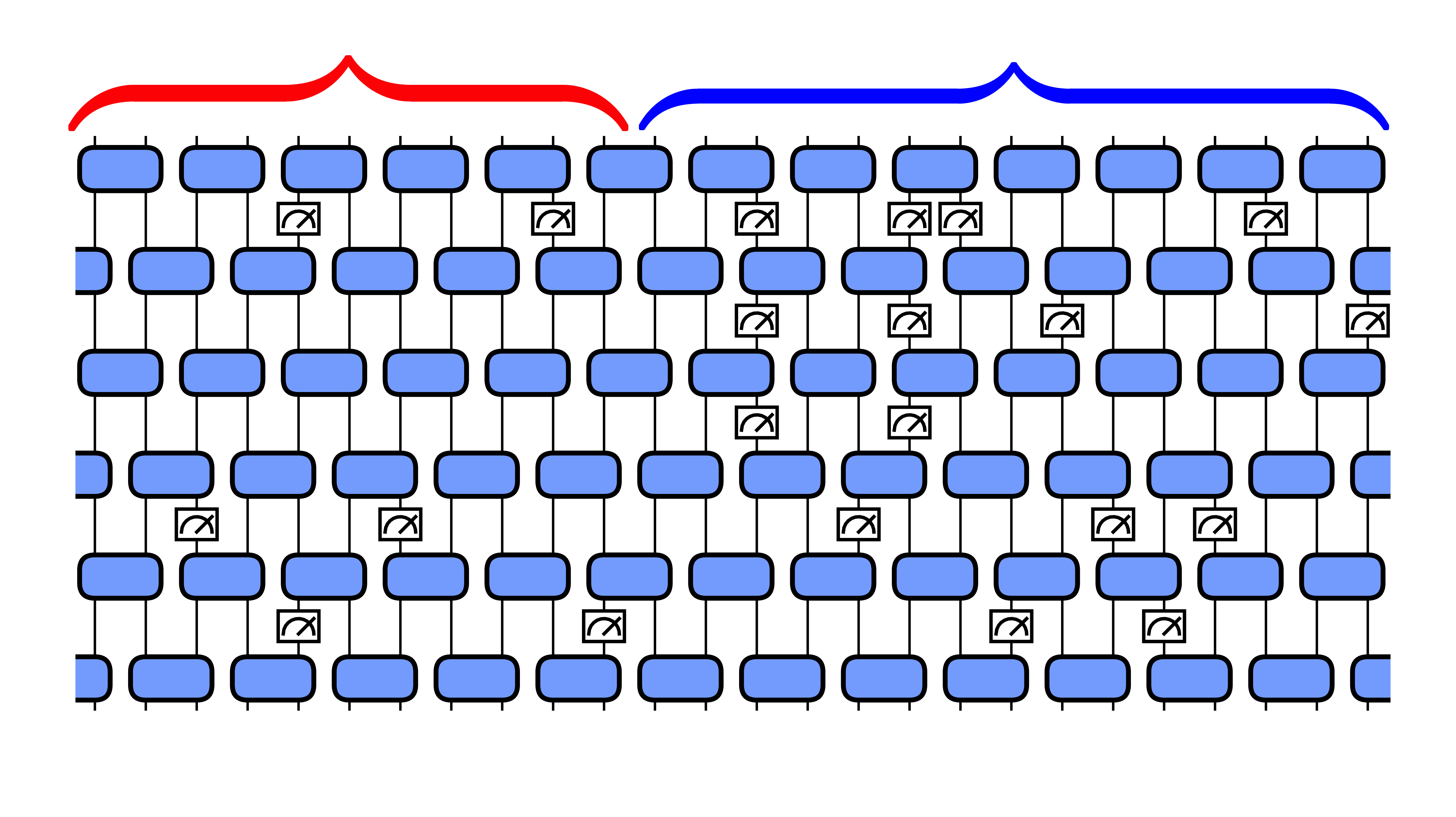

- **Entanglement** of local subsystems [Skinner, Ruhman, Nahum PRX 2018; Li Chen Fisher PRB 2018]

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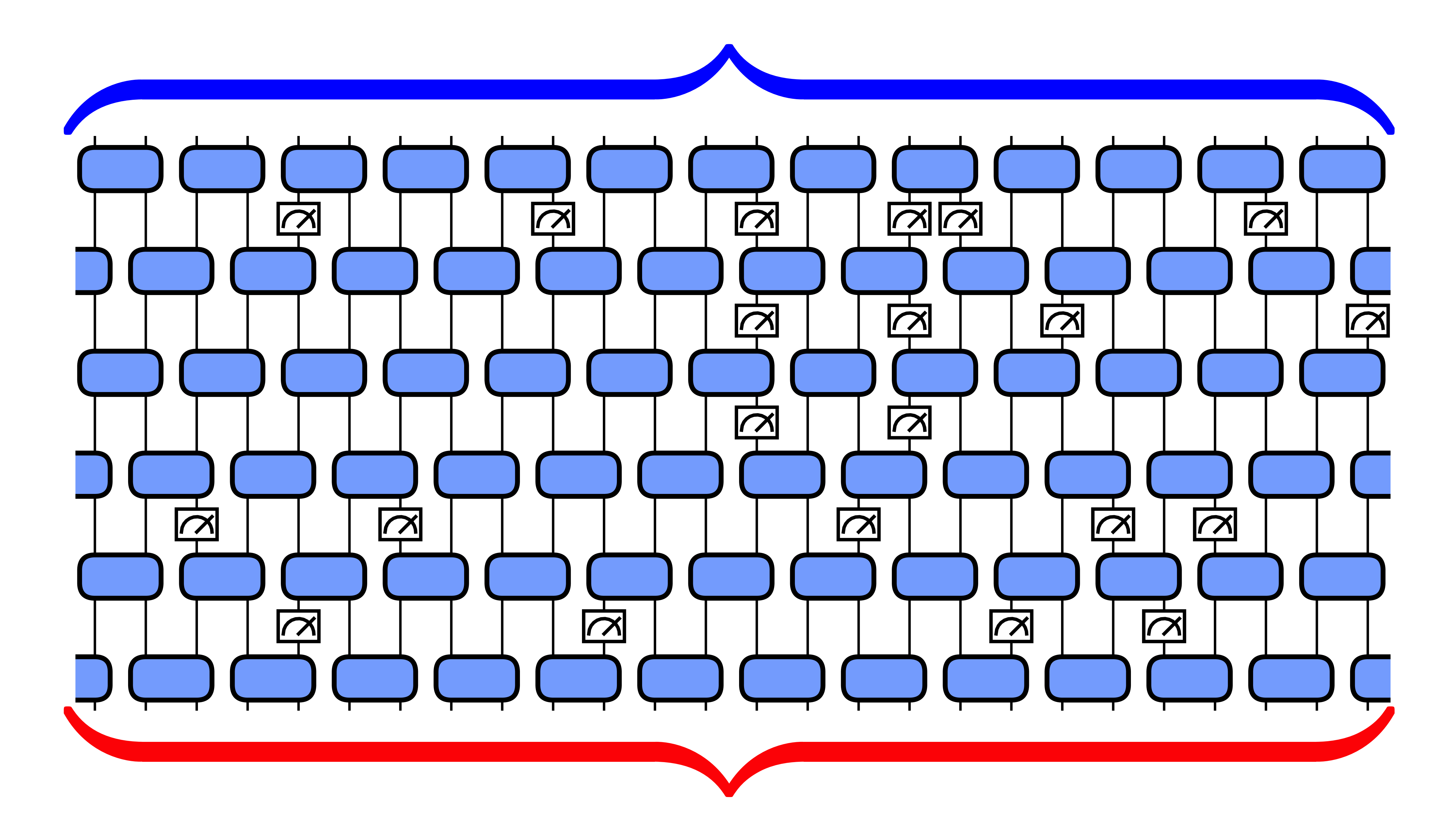

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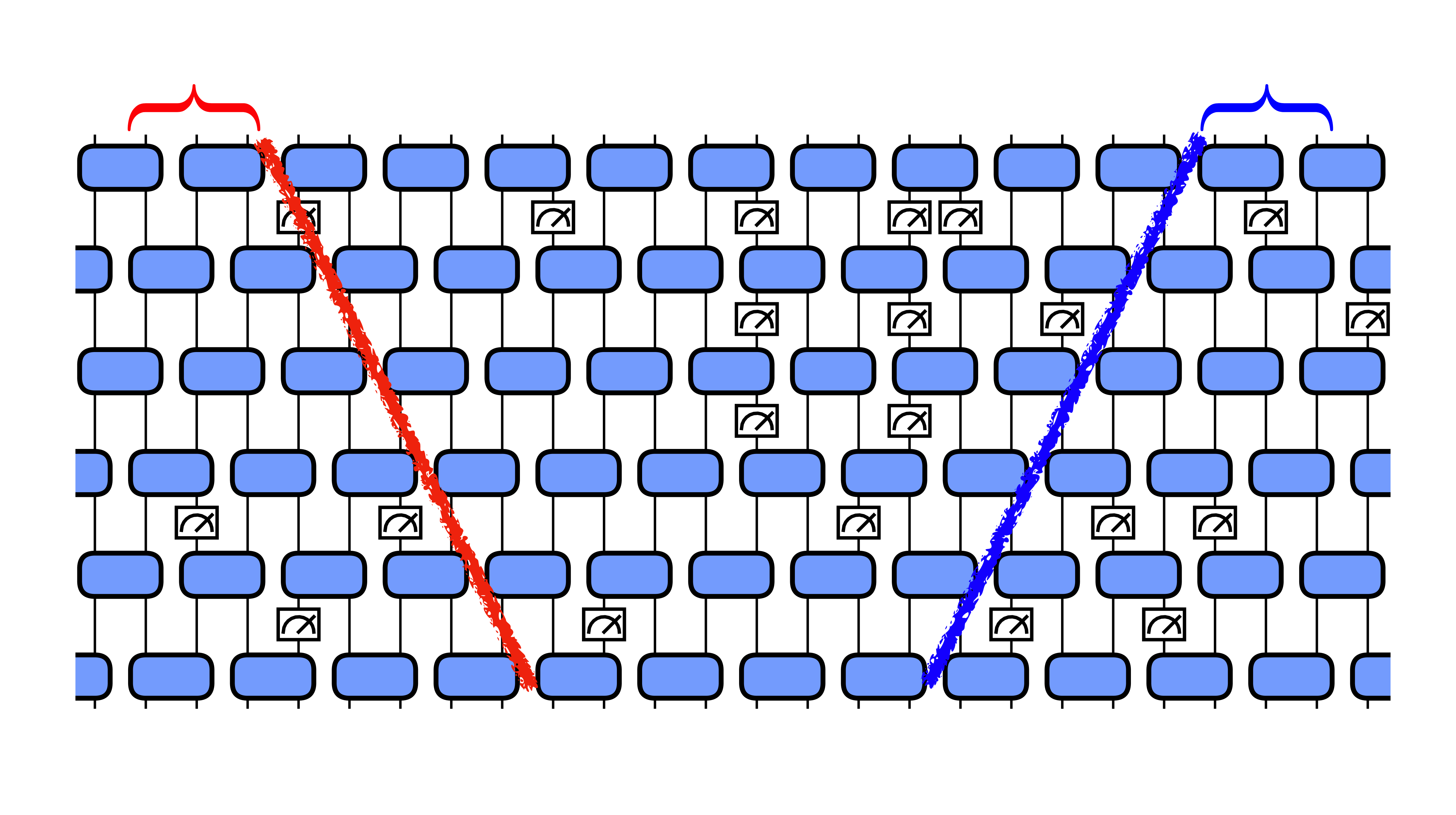

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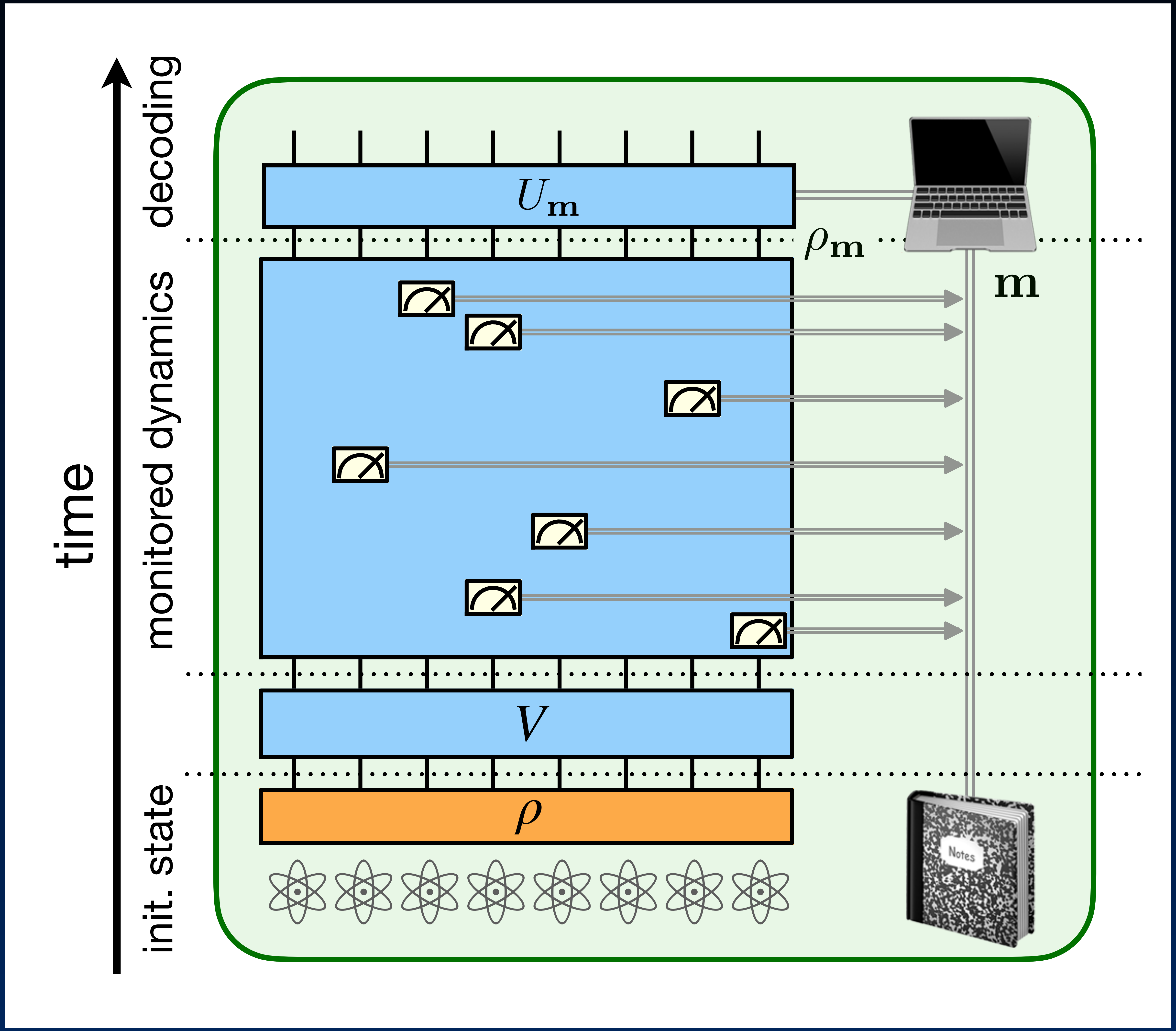
- **Memory of initial state** ("dynamical purification") [Gullans, Huse PRX 2019]
- Correlations between causally-disconnected subsystems (**teleportation**) [Bao, Block, Altman PRL 2024]

The Coding Perspective



[MI, V. Khemani, PRX Quantum 5, 020304 (2024)]

- Measurements are made & recorded by the experimentalist
- Information can be extracted via classical computation + feedback ("**decoding**") [Gullans, Huse PRL 2020]
  - Closely related to **quantum error correction**
- If quantum feedback control is unavailable: classical post-processing
  - "Hybrid" quantum-classical order parameters

[Garratt et al, PRX 2022; Li et al, PRL 2023; Hoke, MI et al, Nature 2023]

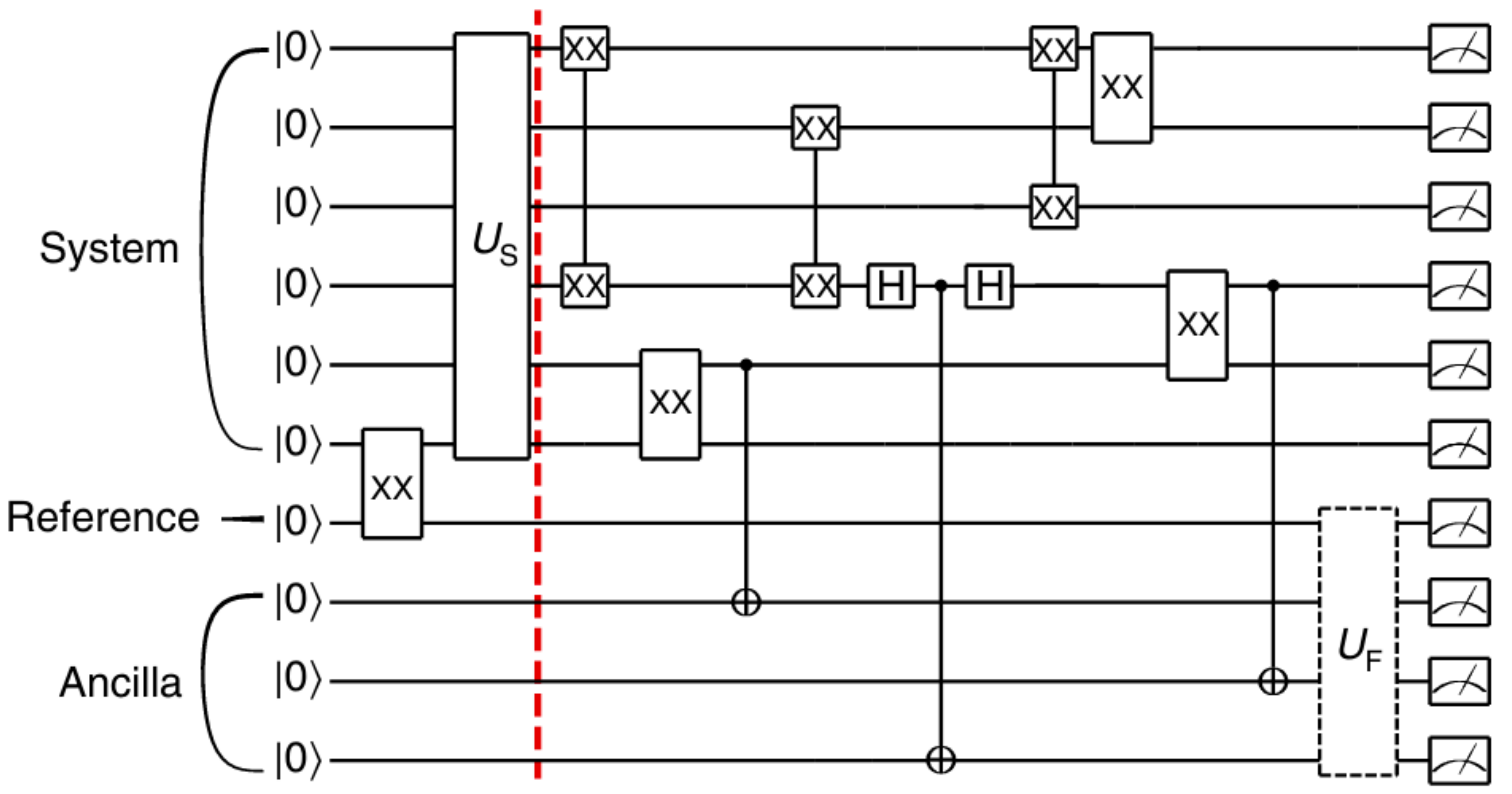
The Coding Perspective - Experiment

Letter | Published: 02 June 2022

Measurement-induced quantum phases realized in a trapped-ion quantum computer

Crystal Noel, Pradeep Niroula, Daiwei Zhu, Andrew Risinger, Laird Egan, Debopriyo Biswas, Marko Cetina, Alexey V. Gorshkov, Michael J. Gullans, David A. Huse & Christopher Monroe

Nature Physics **18**, 760–764 (2022) | Cite this article

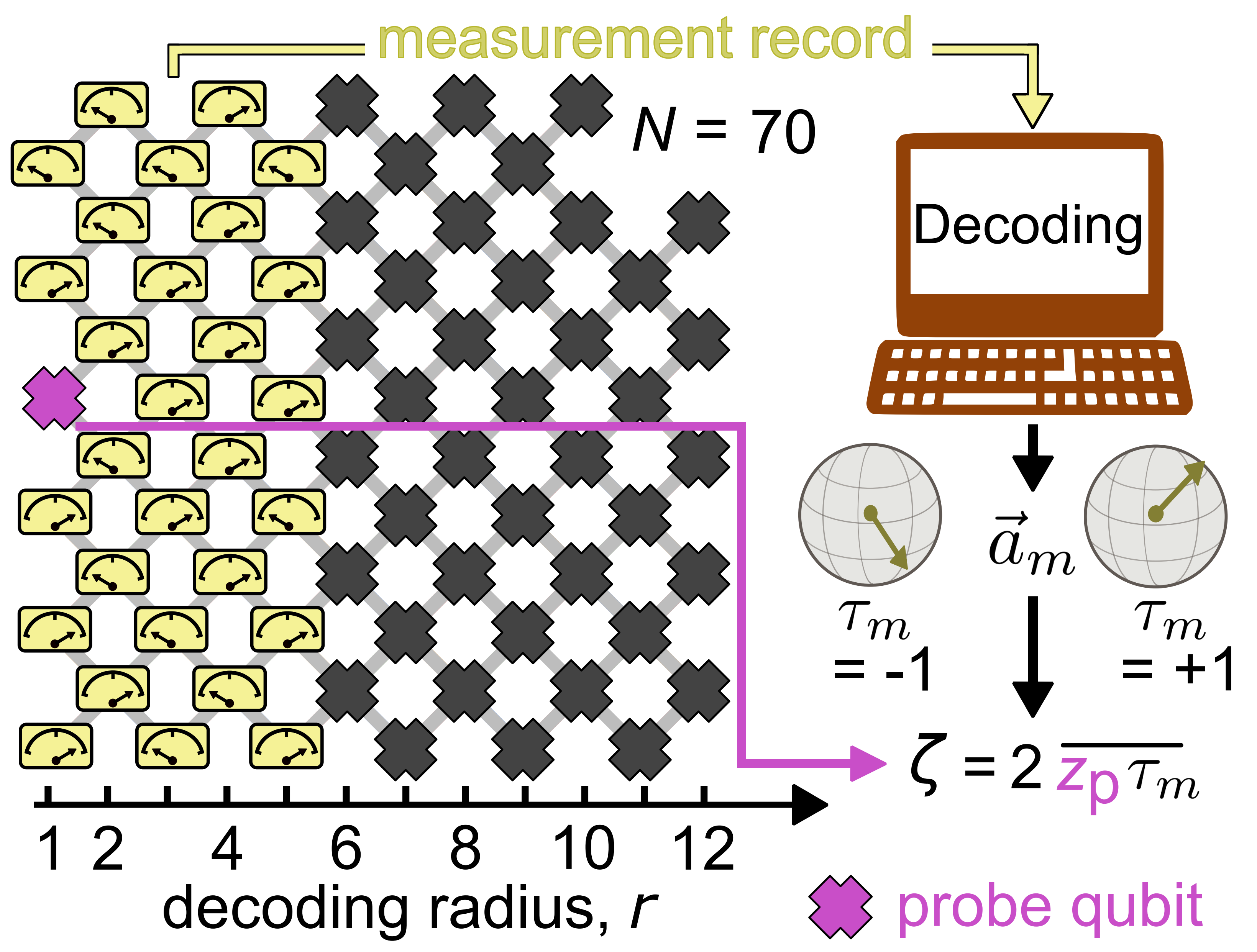


Article | Open access | Published: 18 October 2023

Measurement-induced entanglement and teleportation on a noisy quantum processor

Google Quantum AI and Collaborators

Nature **622**, 481–486 (2023) | Cite this article

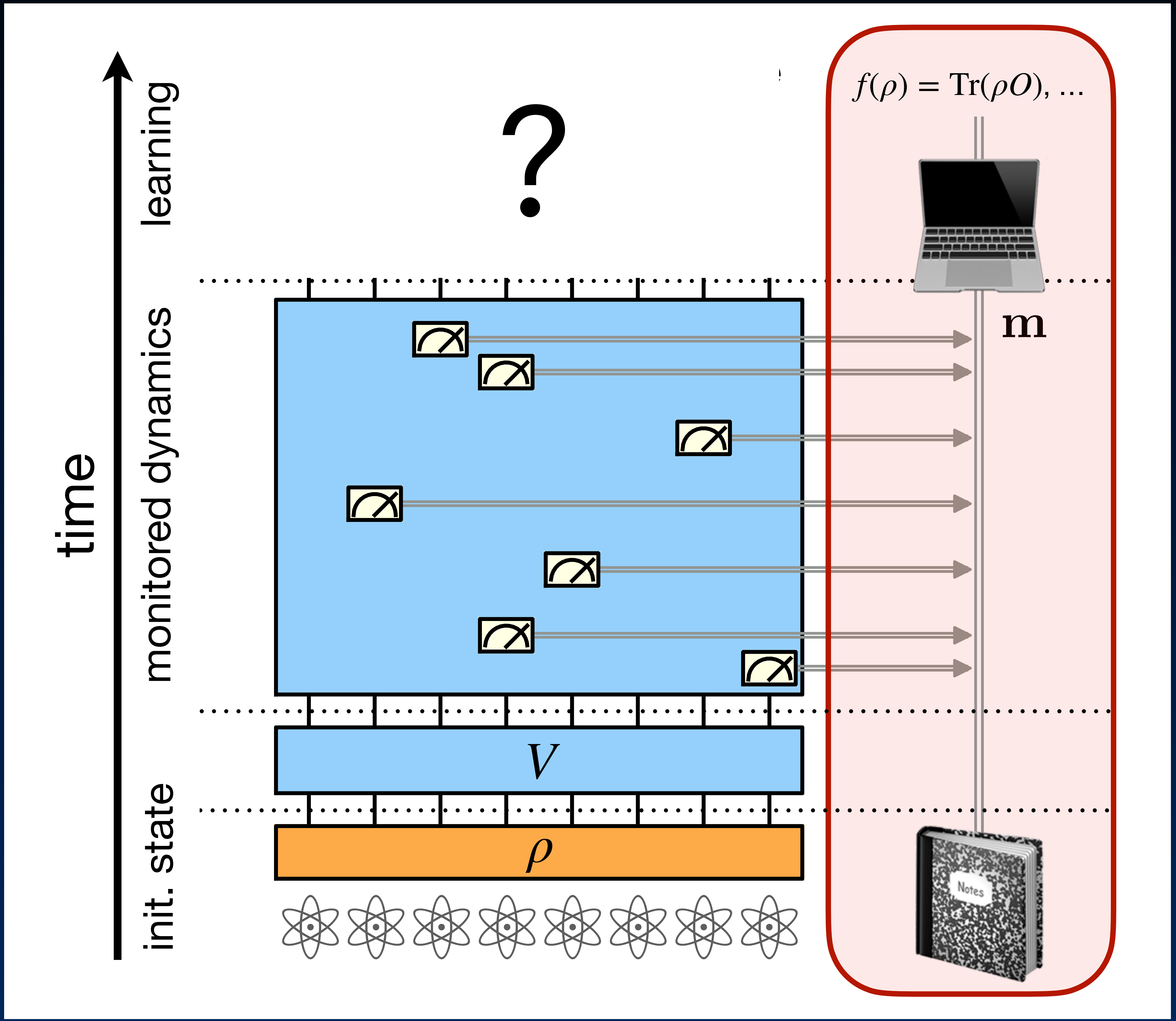


[Noel et al, Nat. Phys. 18, 760 (2022)]

[Hoke, MI, et al, Nature 481 (2023)]

Learning

The Learning Perspective



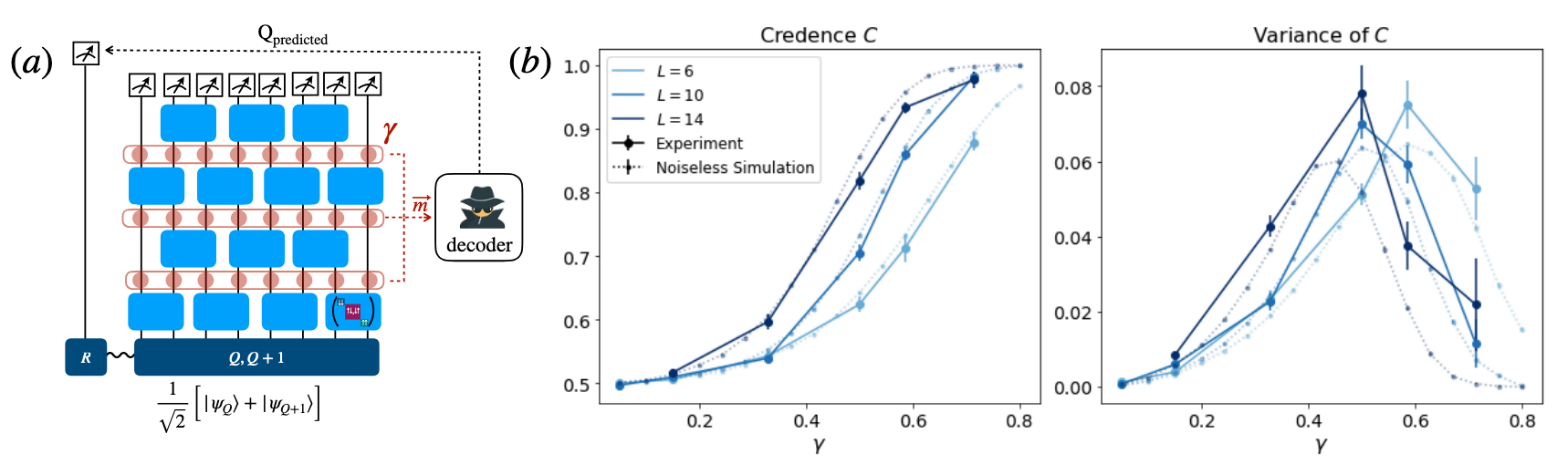
[MI, Khemani, PRX Quantum 5, 020304 (2024)]

- Quantum system is not directly accessible
- How much can be learned from the measurement record?
- Idea: information *either* in the system *or* in the measurement record — not both!
  - **Learnability phase transitions**

[Barratt et al, PRL 120, 200602 (2023); Agrawal et al, axiv:2311.00058 (2023)]

The Learning Perspective - Experiment

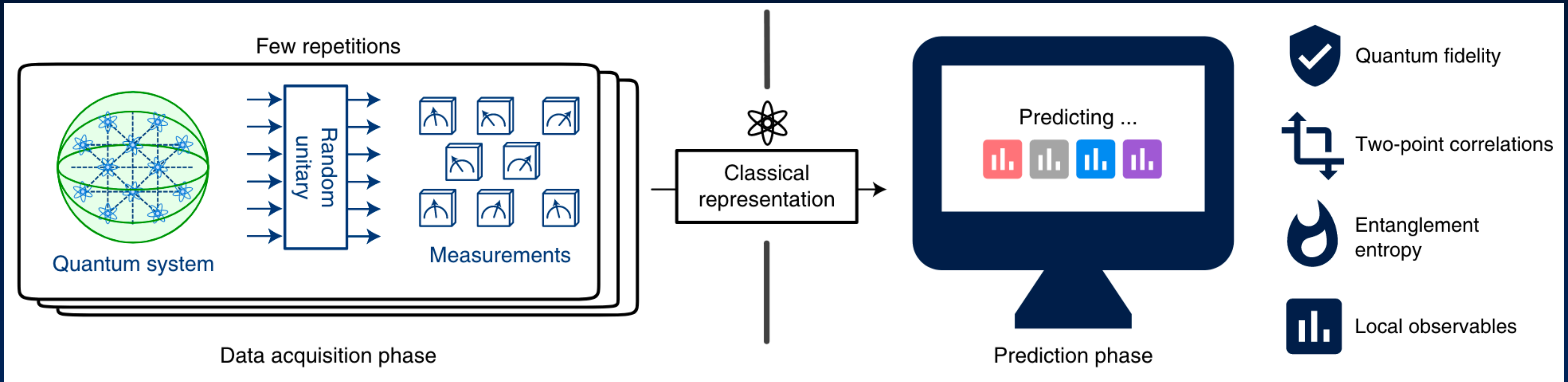
Recently implemented on Quantinuum trapped-ion hardware



[Agrawal, Lopez-Piqueres, Vasseur, Gopalakrishnan, Potter, arXiv:2311.00058 (2023)]

The randomized measurement toolbox

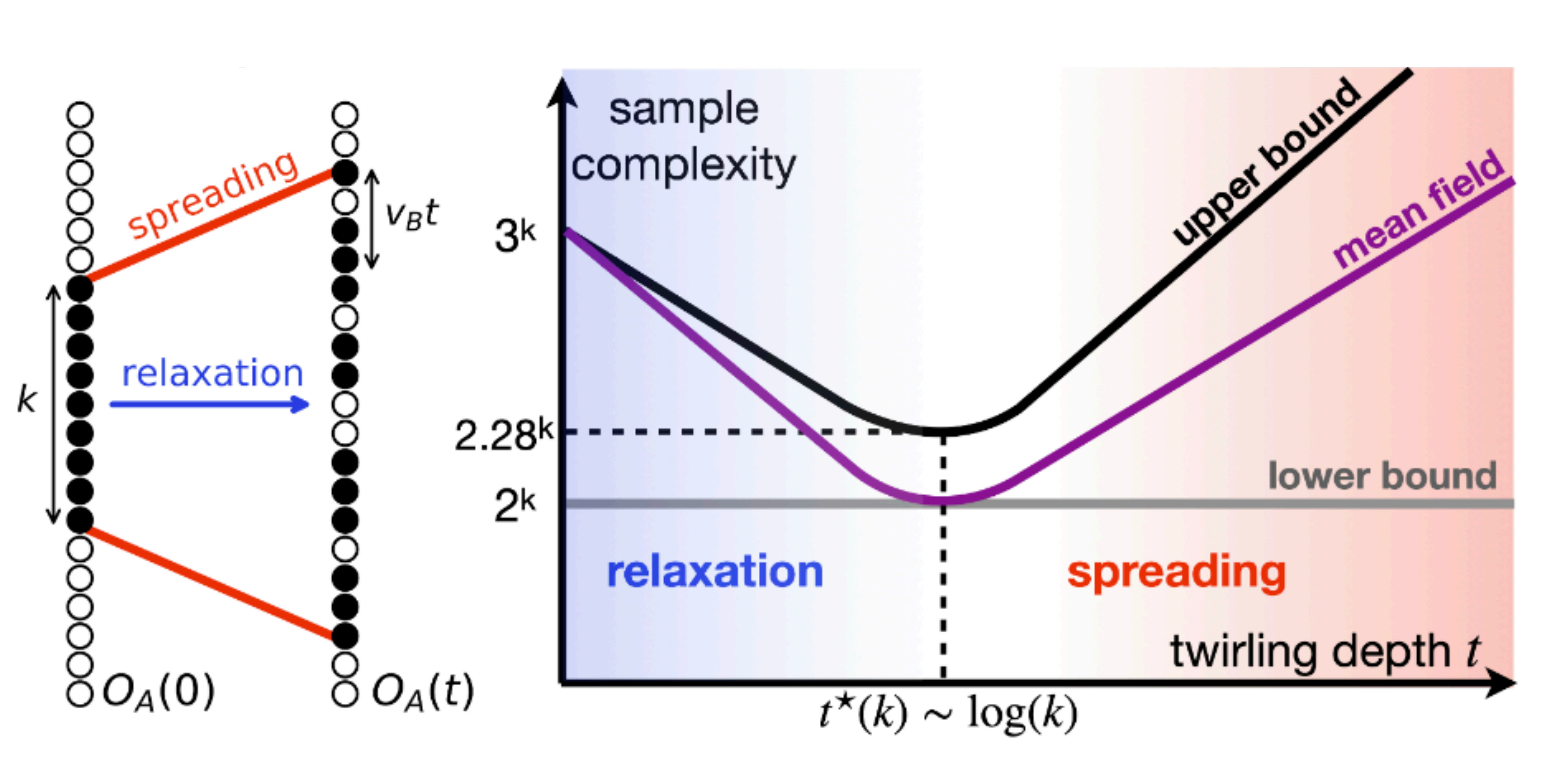
- Problem: **efficiently** characterizing complex quantum states and processes
- Approach: "*Measure first, ask questions later*"
  - Repeatedly measure system in **random bases**
  - Build compressed classical representation of the state
  - Predict many properties



[Huang, Küng, Preskill, Nat. Phys. 16, 1050 (2020); Elben et al, Nat. Rev. Phys. 5, 9 (2023)]

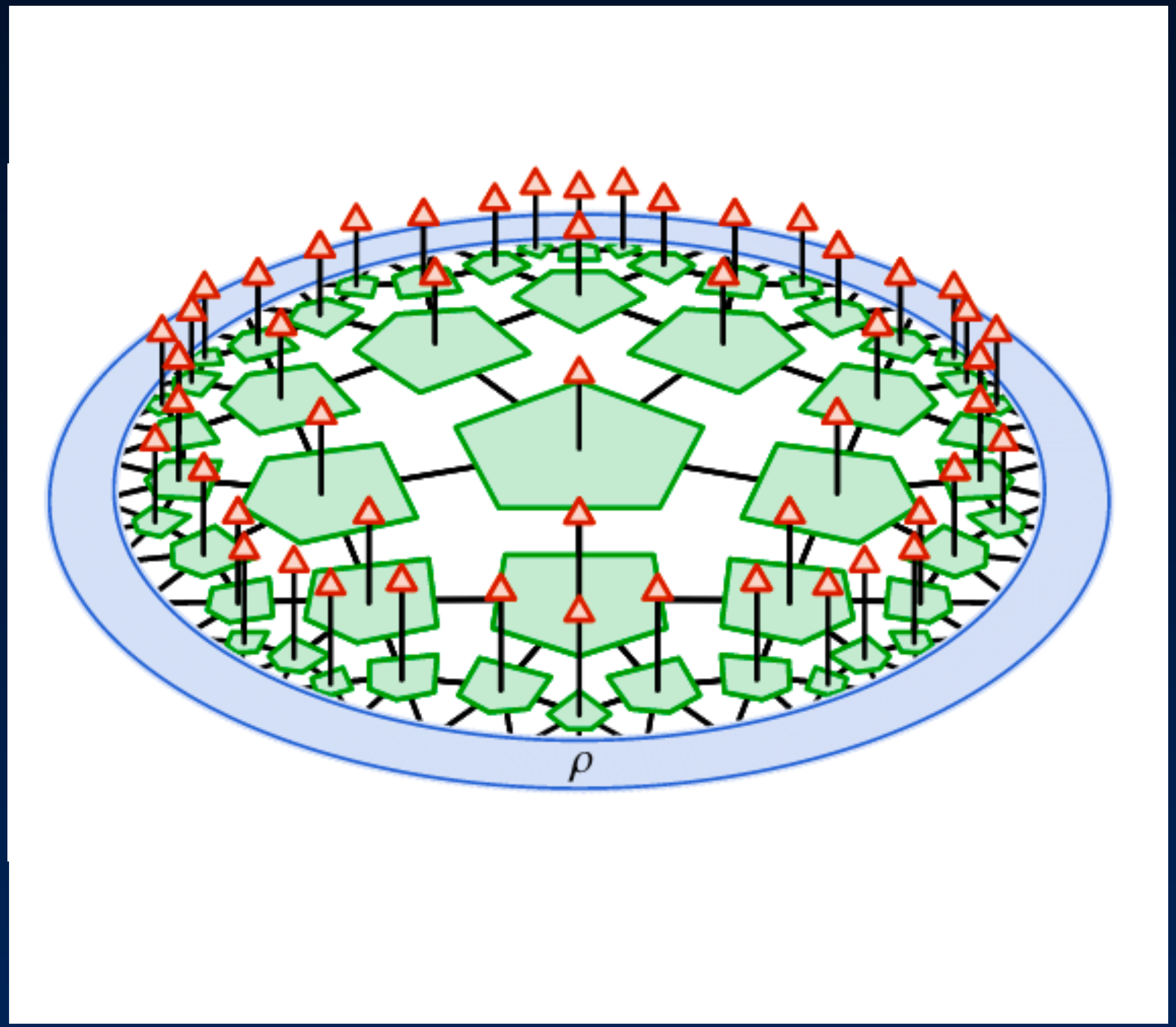
Insights on the dynamics of quantum information can guide the discovery of optimized learning protocols

Operator spreading / scrambling



[MI, Li, Rakovszky, Khemani, PRL 130, 230403 (2023)]

Holographic entanglement



[Zhang, Feng, MI, You, arXiv:2406.11788 (2024)]

Summary

- Programmable quantum matter: unprecedented access to the dynamics of quantum information
  - A new lens on long-standing, **foundational questions**
  - Possibility of entirely **new many-body phenomena**, especially far from equilibrium (QI phases in monitored dynamics)
  - New tools for **learning** complex quantum states and processes