Taking a LEAP with superconducting quantum processors

Nordita program on Entanglement Dynamics:

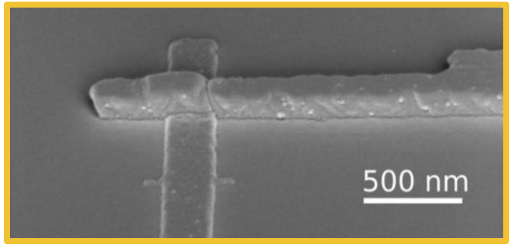
Open Quantum Systems, Monitored Circuits, and Topological Order

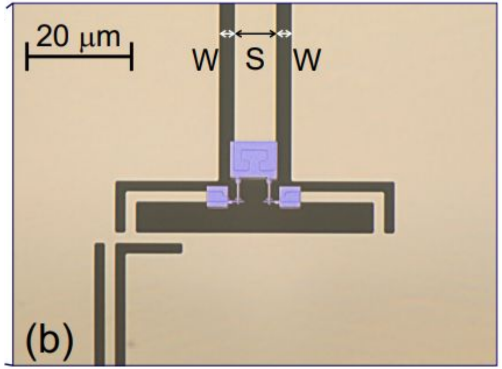
Stockholm, June 2026

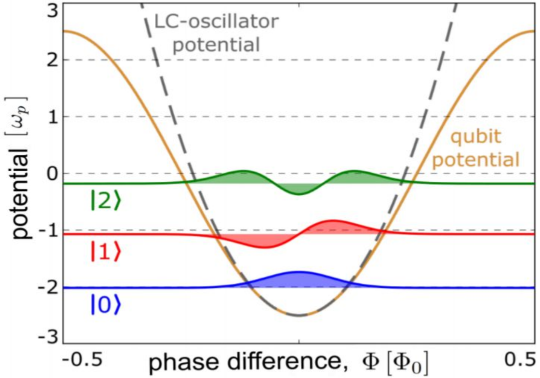
Pedram Roushan, Google Quantum AI

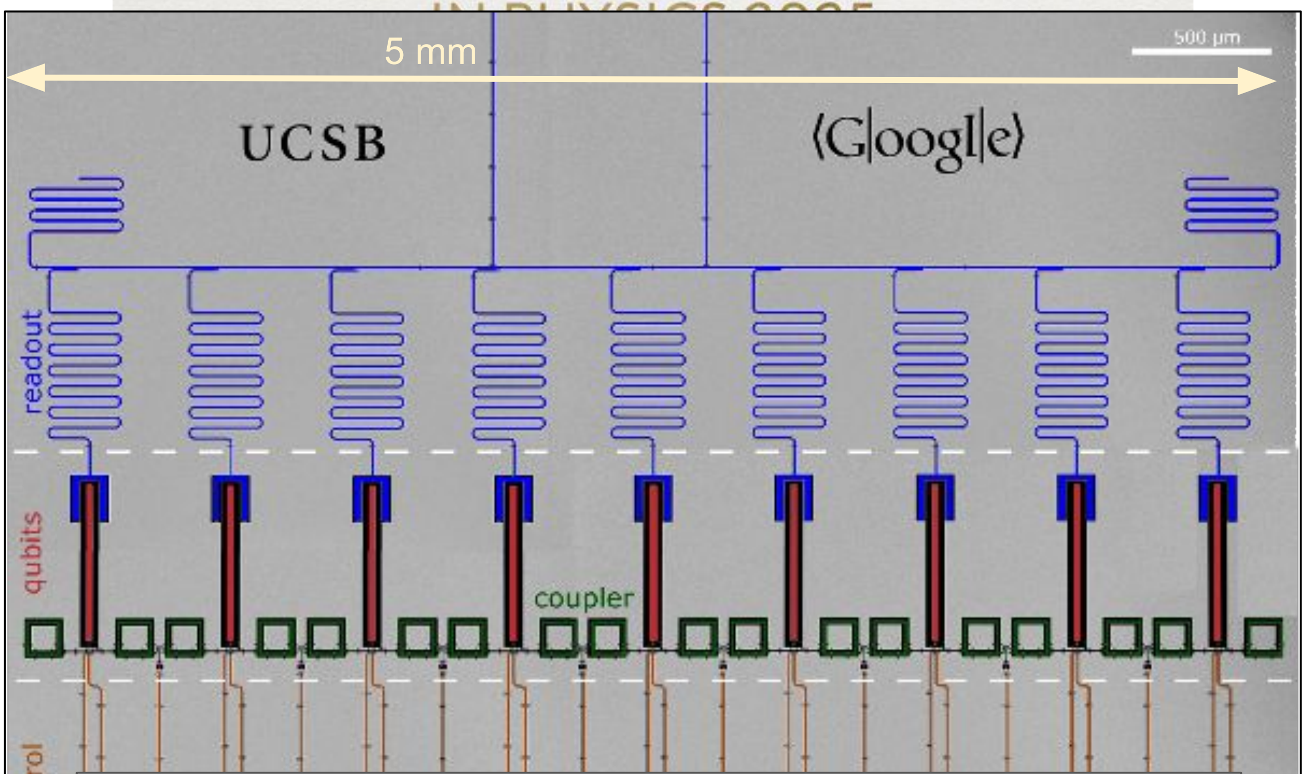
pedramr@google.com

Array of coupled non-linear resonators





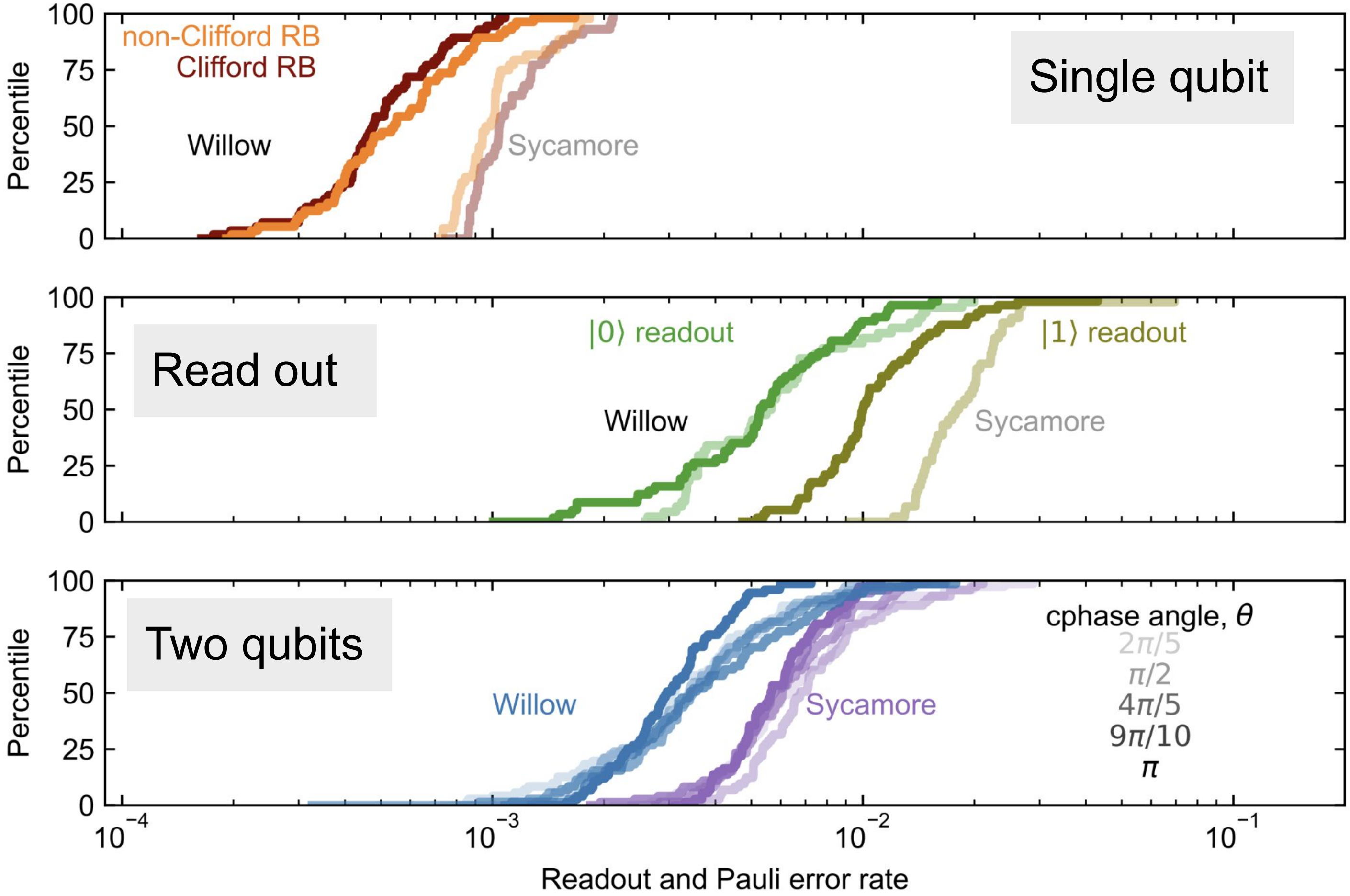




$$\hat{H}_{BH} = \sum_i h_i a_i\, a_i^\dagger + \sum_{<i,j>} J_{i,j}(a_i\, a_j^\dagger + a_i^\dagger\, a_j) + \frac{U}{2}\sum_i a_i\, a_i^\dagger(a_i\, a_i^\dagger - 1) + h.o.t$$

$h_i \in$ [-500, 500]MHz , $J_{i,j} \in$ [-50, +2] MHz, $U \sim$ -200MHz

Improvement in fidelities from Sycamore to Willow



Taking a LEAP with the next generation of quantum processors

L: Large-scale

~ 100-200 qubits real-space → 10^{30} (nonillion) in Hilbert-space

arXiv: 2601.01309: *Hilbert space signatures of non-ergodic glassy dynamics*

E: Error-resilience

Single-qubit ~ 10^{-4}, 2-Qubit ~ 10^{-3}, Readout ~10^{-2}

(in prep.): *Decodability phase transition in error correction surface codes*

A: Adaptive

Integrating mid-circuit measurements with non-local classical processing

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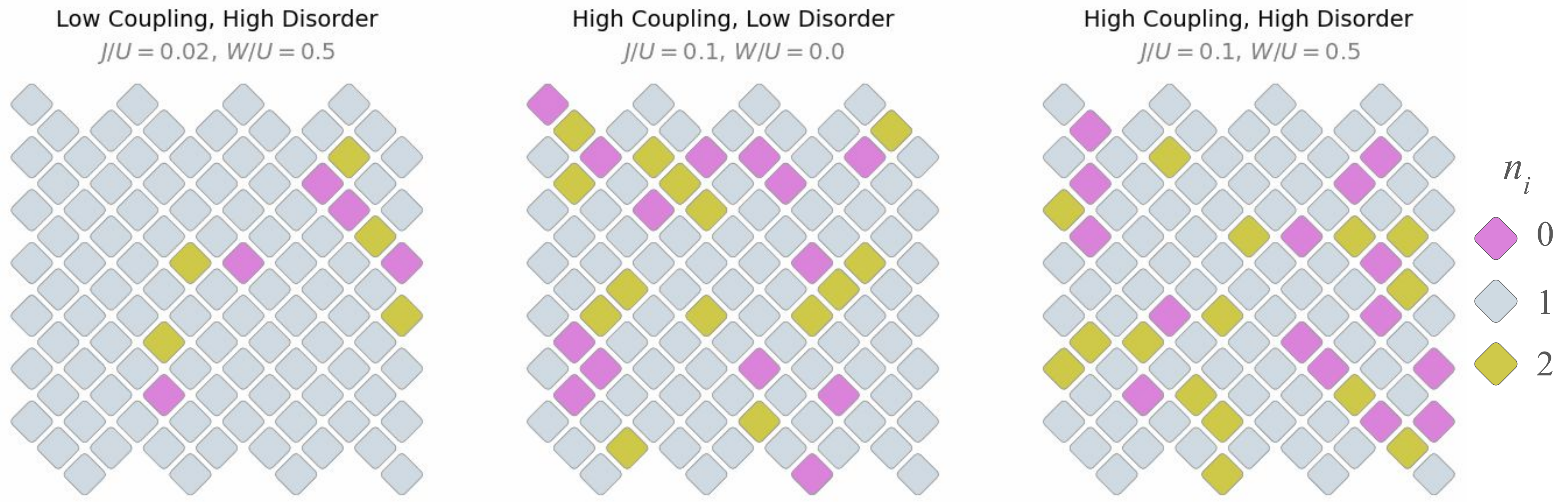
P: Programable

Novel gates, addressing higher transmon level

arXiv: 2512.21416 : *Observation of disorder-induced superfluidity*

Emergence of macroscopic properties from microscopic mechanism

$$H = -J \sum_{\langle i,j \rangle} \left(a_i^\dagger a_j + a_j^\dagger a_i \right) + \frac{U}{2} \sum_i n_i (n_i - 1) - \sum_i \mu_i n_i$$

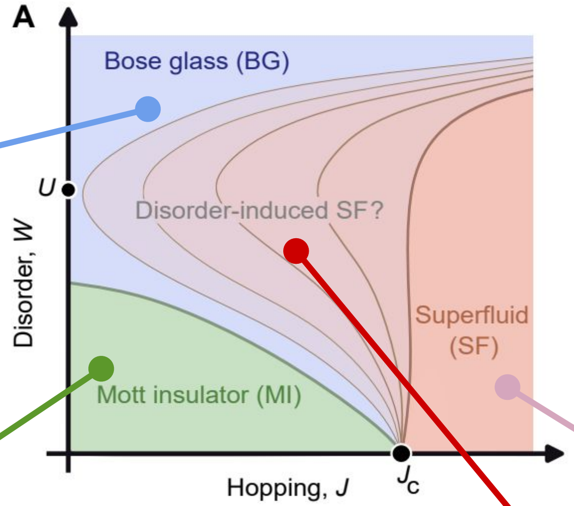


→ Mott insulator

→ Superfluid

Superfluid ?

Phases of interacting bosons in a disordered landscape



Gapless insulator

Strongly-correlated,
Finite excitation gap

$$H = -J\sum_{\langle i,j\rangle}\left(a_i^\dagger a_j + a_j^\dagger a_i\right) + \frac{U}{2}\sum_i n_i(n_i-1) - \sum_i \mu_i n_i$$

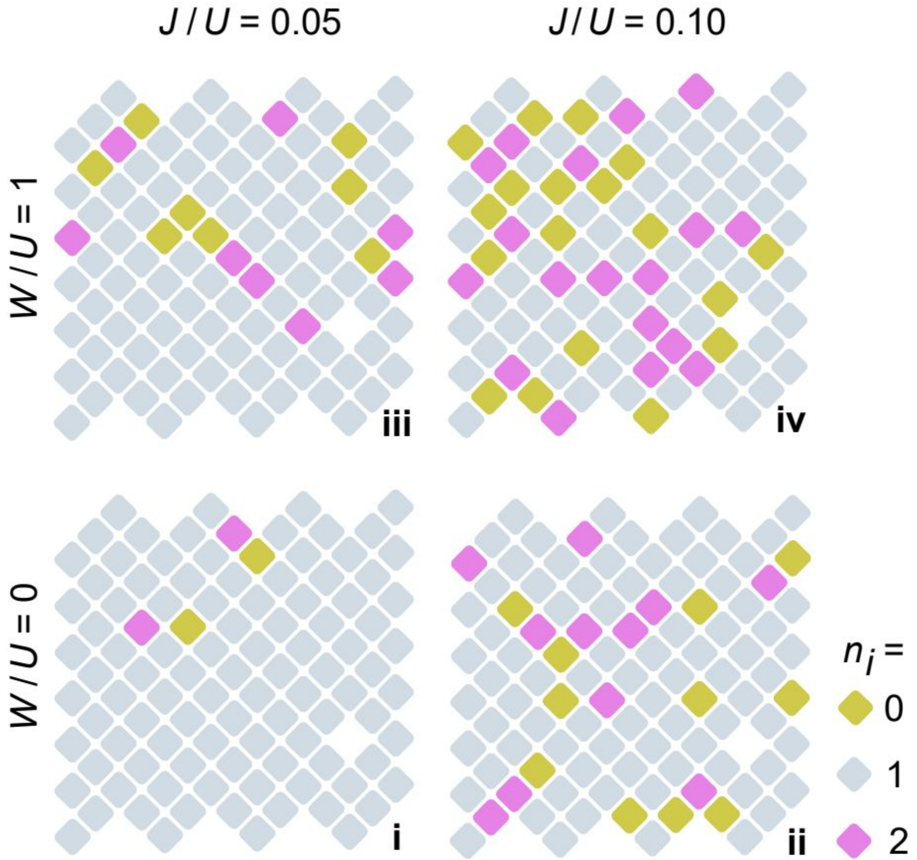
Condensate formation,
bosons freely move

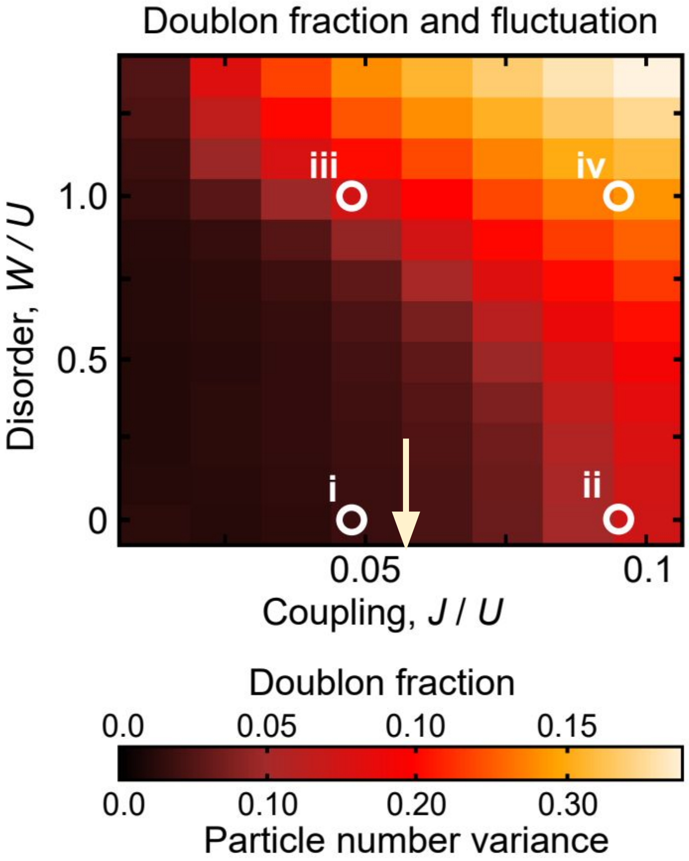
Local tunneling →
Long-range coherence ?

M. P. A. Fisher *et al.*, PRB (1989), L. Pollet *et al.*, PRL (2009), N. Elstner and H. Monien, PRB (1999), B. Capogrosso-Sansone *et al.*, PRA (2008), V. Gurarie *et al.*, PRB (2009), L. Dang *et al.*, PRB (2009).

Arxiv 2512.21416

Doublon fraction and fluctuations

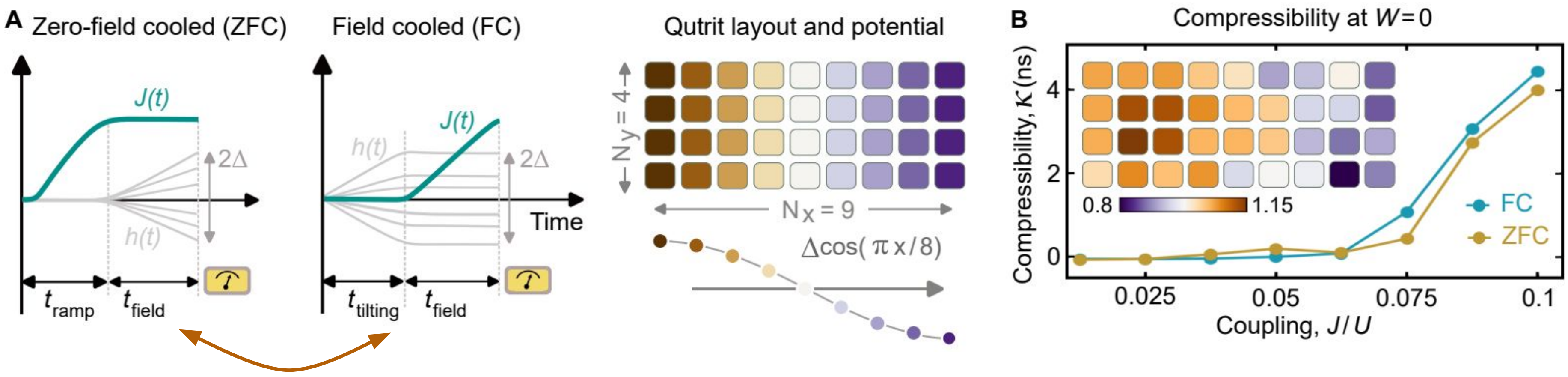




Arxiv 2512.21416

Mapping the compressibility in the J − W plane

$$\kappa = \frac{2}{N\Delta}\sum_i \langle n_i \rangle \cos(\pi \boldsymbol{x}_i / L)$$



phase-space path-dependency

$\kappa \equiv (\partial n / \partial \mu)$: System compressibility.

$\langle \delta n_i \rangle$: The system's response.

$\delta \mu$: The applied potential gradient.

→ finite density of excitations

distinction: gapped Mott Insulator and compressible phases.

t_{ramp} = 100 ns, t_{field} = 250 ns, Δ = 30 MHz

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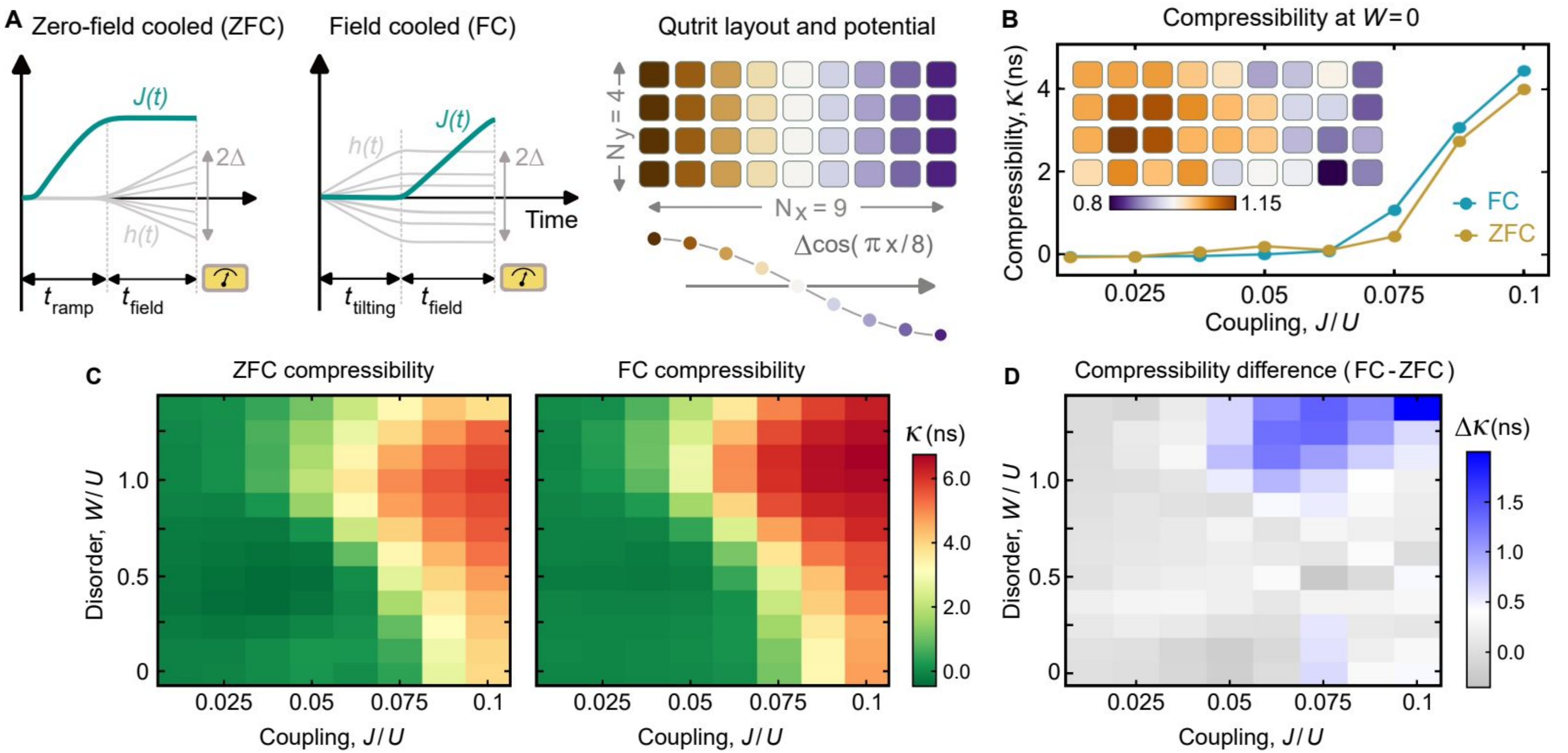
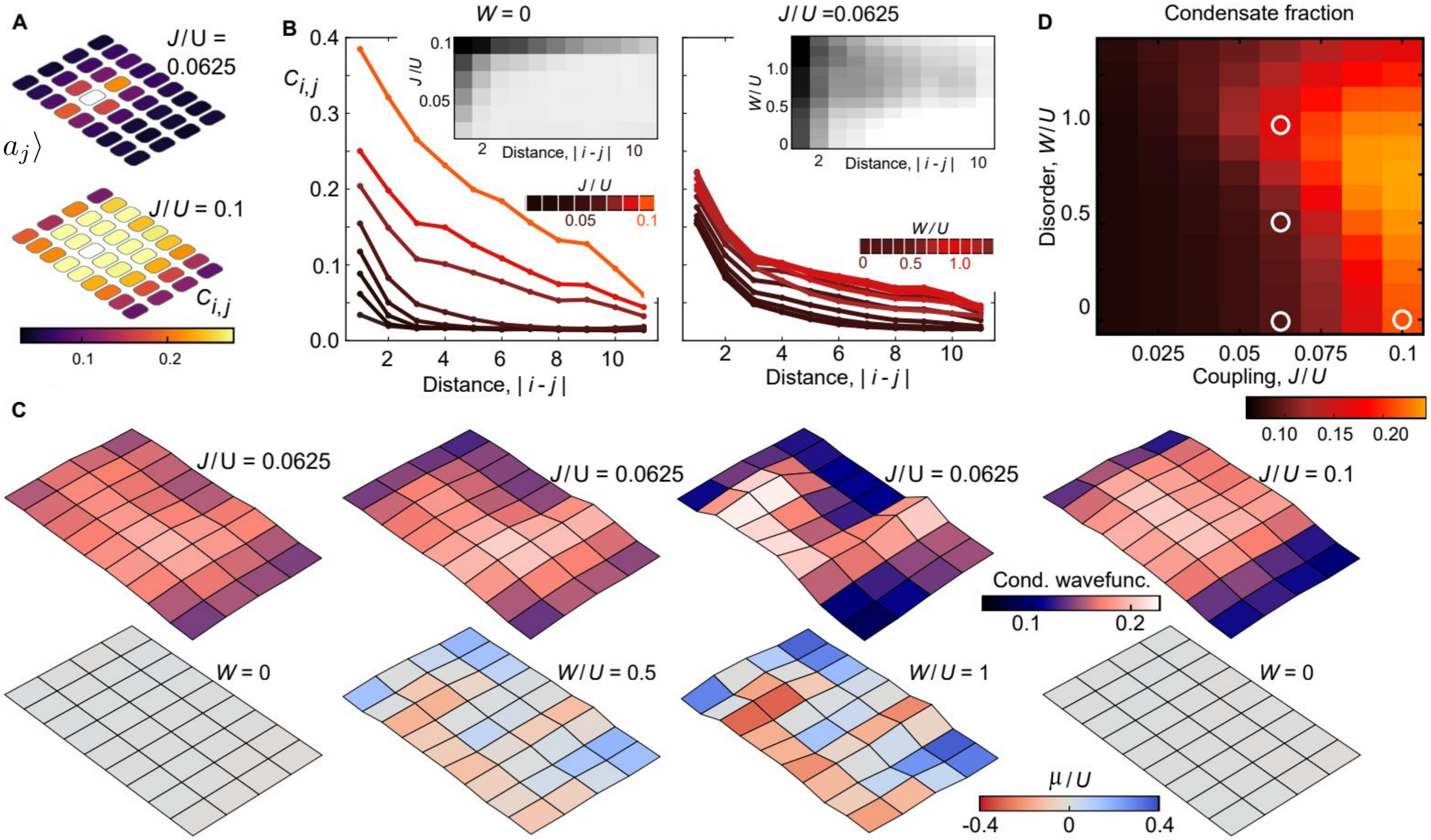


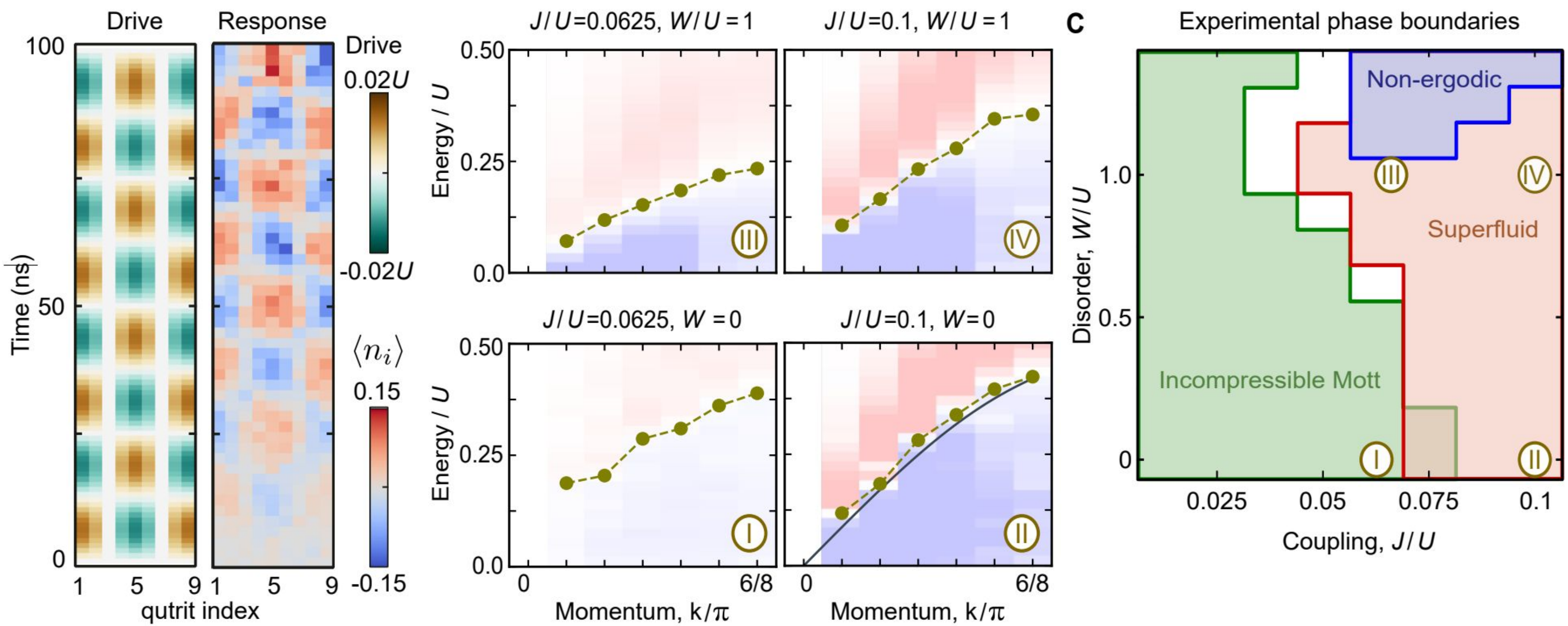
Condensate wavefunction and fraction

where C_{ij} is the single-particle density matrix (SPDM) whose largest eigenvalue, λ_0, gives the condensate frac-

$$C_{ij} \equiv \langle a_i^\dagger a_j \rangle$$



Direct measurement of dynamical structure factor



slope in II, III, IV

→ c_s speed of sound ~ sqrt(n_s / κappa)

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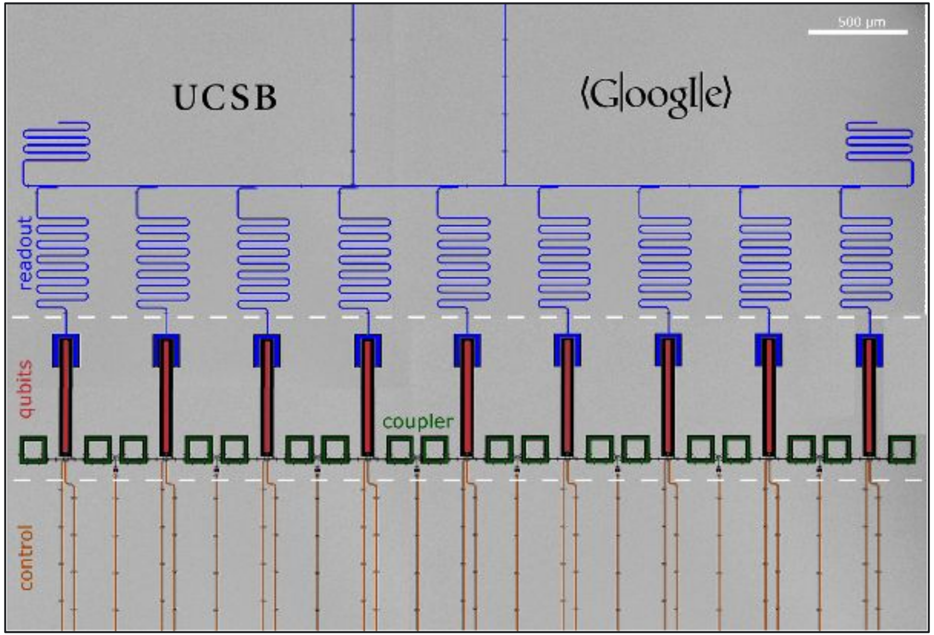
Multifractal and Glassy Signatures of Non-Ergodic 2D Quantum Dynamics



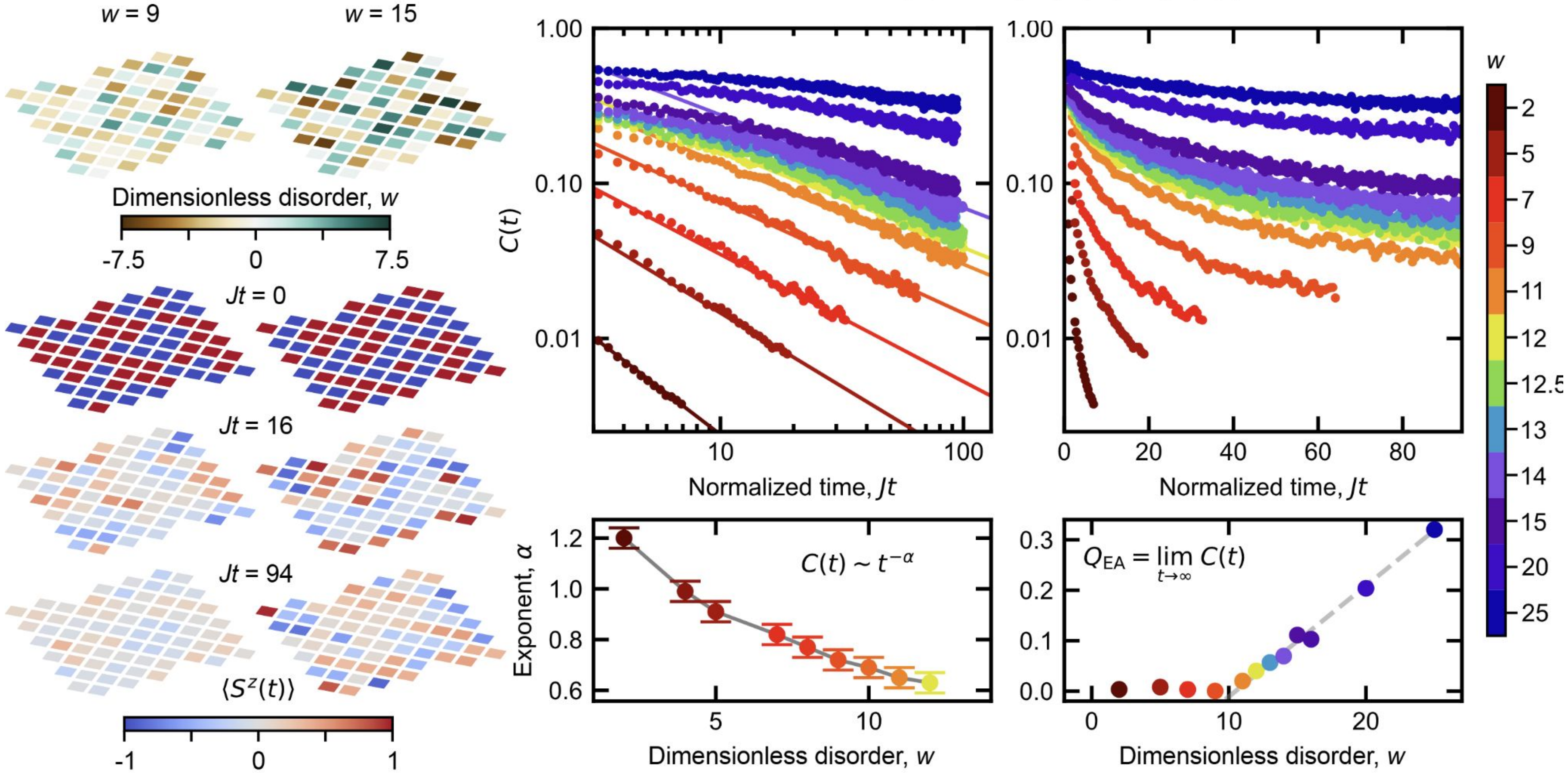
$$H = -J \sum_{\langle i,j \rangle} (S_i^+ S_j^- + S_i^- S_j^+) + \sum_i h_i S_i^z$$

arXiv:2601.01309

Evidence of glassy behaviour

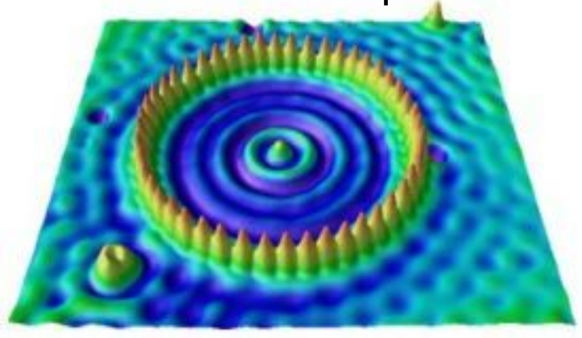
Spin-glass correlation

$$C(t) = \overline{\langle S_i^z(0) S_i^z(t) \rangle^2}$$

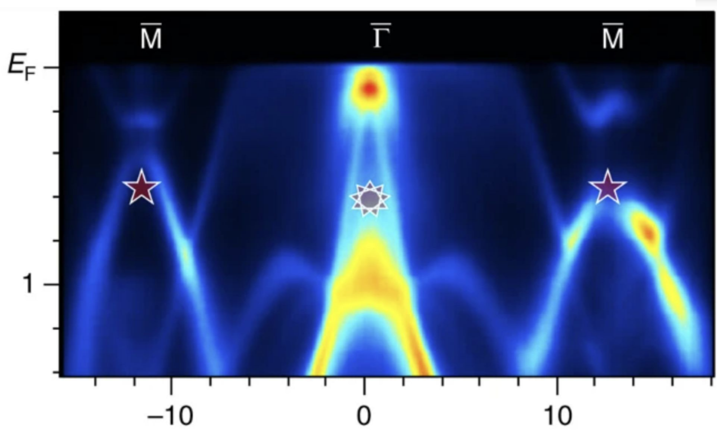


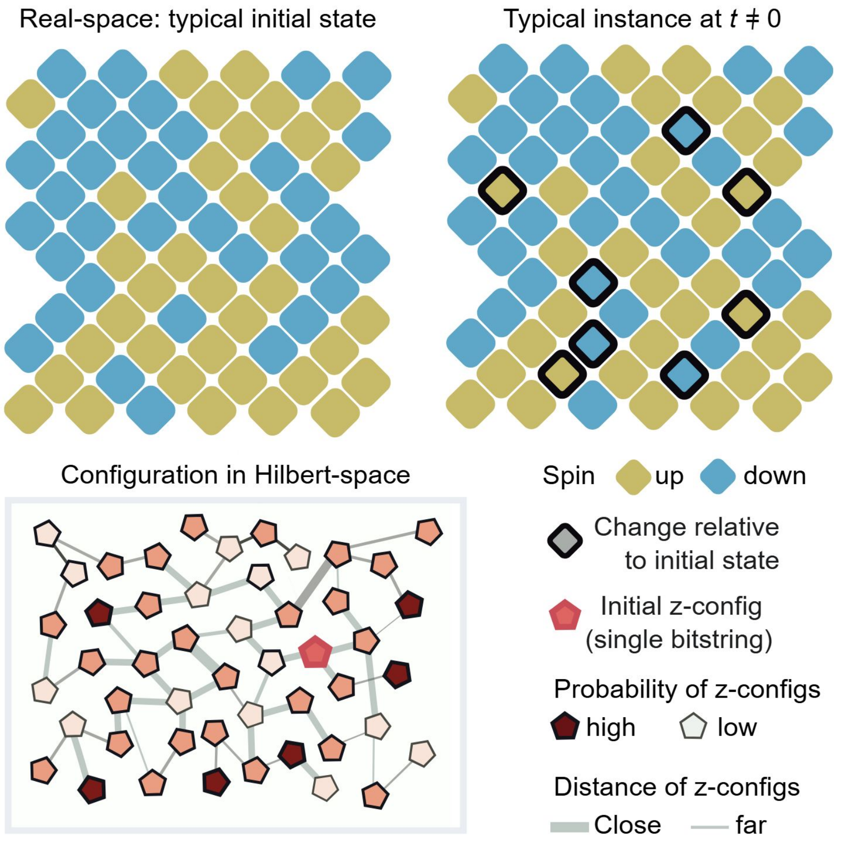
Visualizing Dynamics in Hilbert-space

STM: Real-space



ARPES: Momentum-space





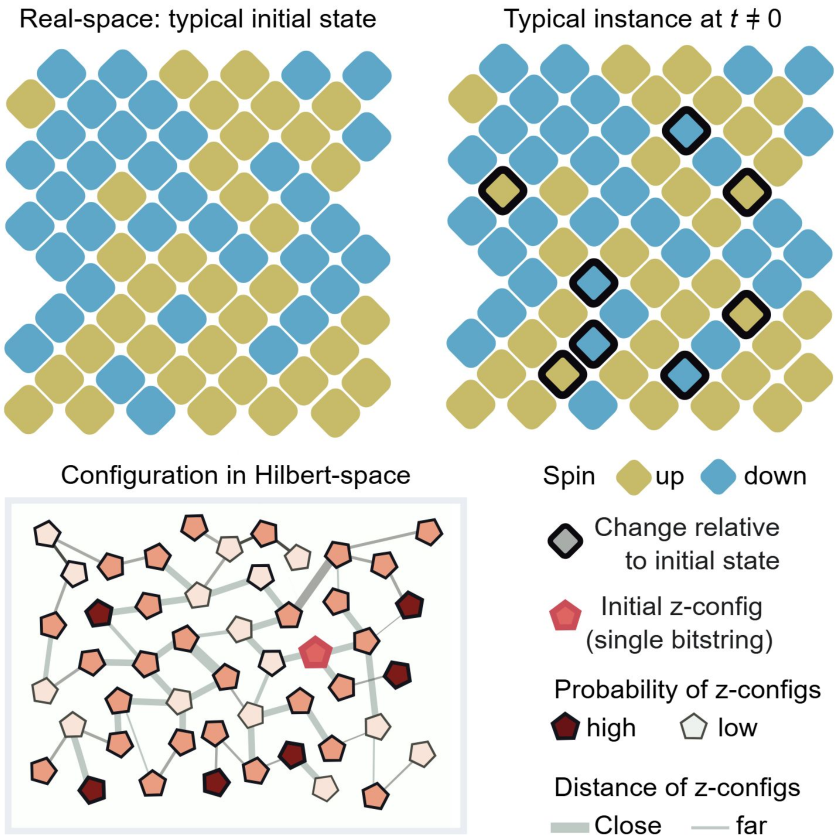
Sampling rate: 100kHz to 1MHz

Visualizing Dynamics in Hilbert-space

Real space:
limited by the system's linear dimension, ~ $\sqrt{n}$

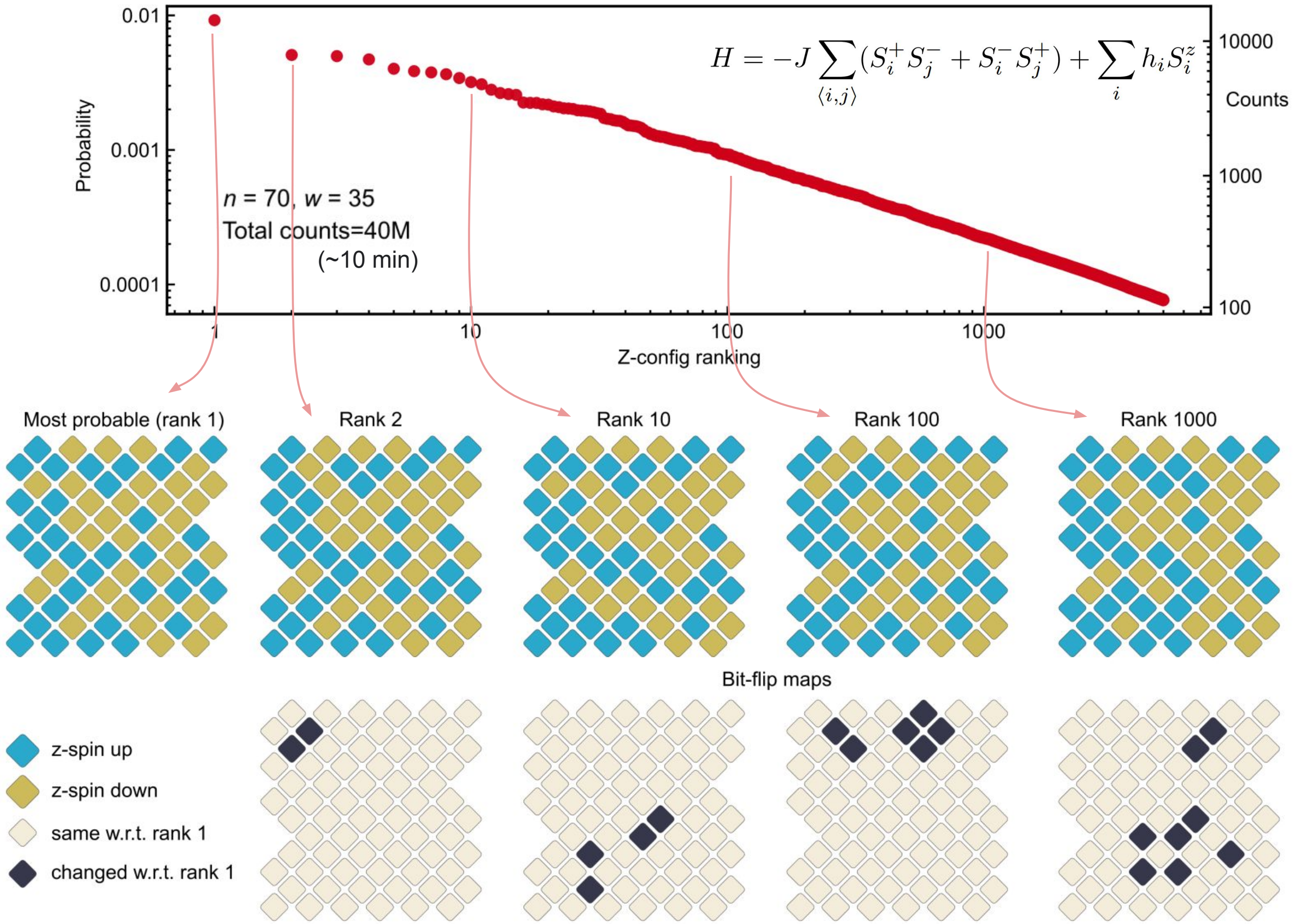
Time domain:
e.g. population imbalance suffers from a poor signal-to-noise ratio.

A fundamental experimental advantage:
Questions asked are focused on the shape or dimensionality of wavefunctions.



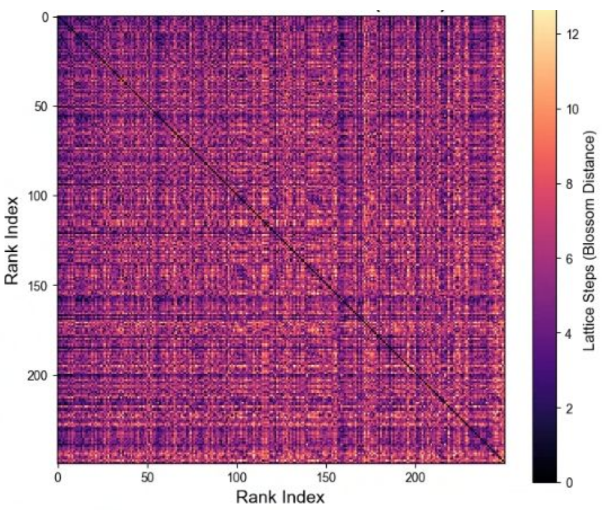
Sampling rate: 100kHz to 1MHz

Probability distribution of z-config (bitstrings)

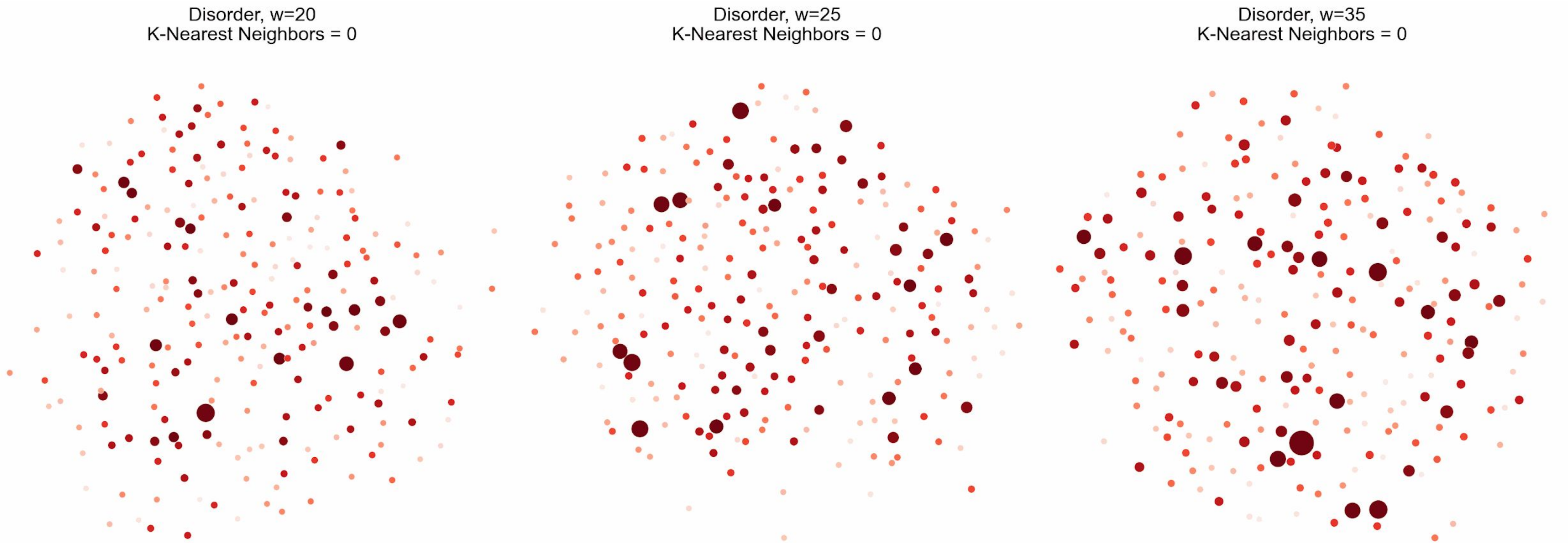


Hamming and bit-flip distances

Adjacency matrix



Many-body wavefunction as a network



Nodes = 200 most probable z-configs

Links = 10 closest distance to each node

Return probability of the initial states

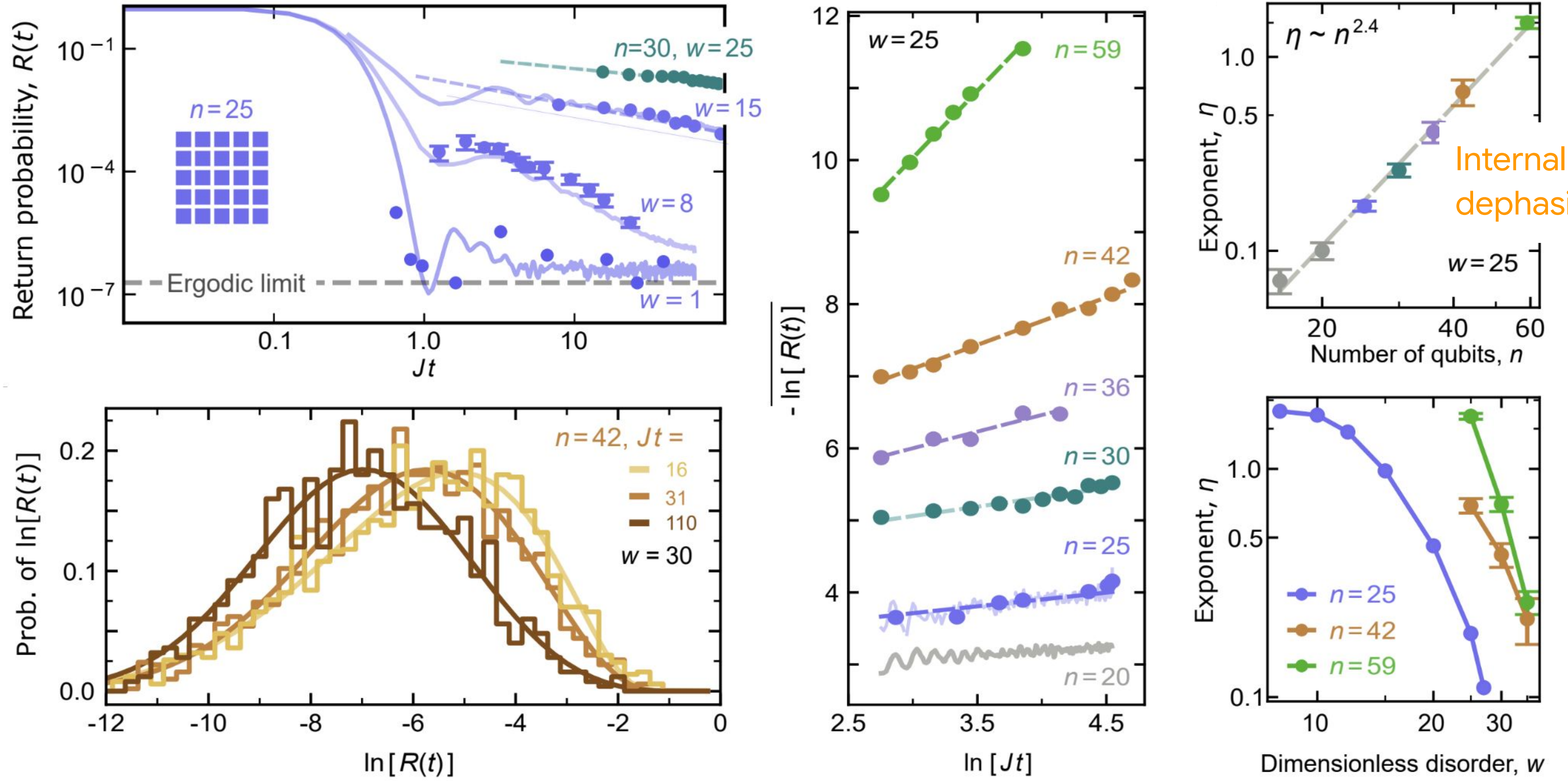
Distribution of observed configurations

Structure of wavefunction as a graph in Hilbert-space.

arXiv:2601.01309

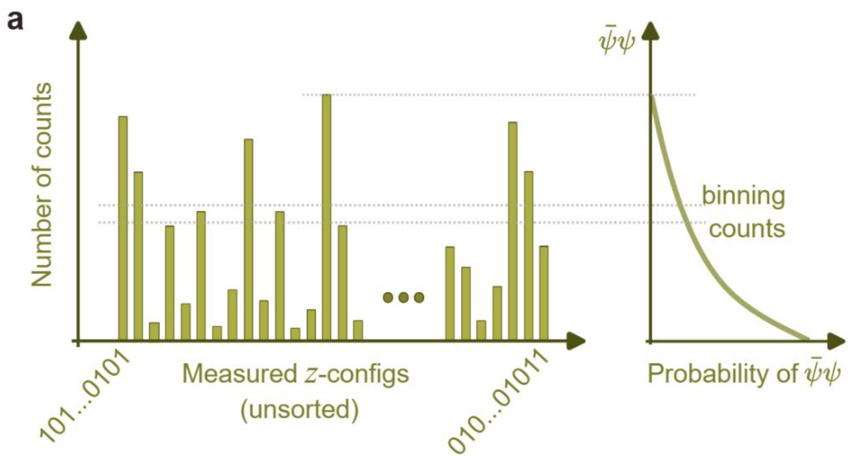
Signatures of glassy behaviour in R(t)

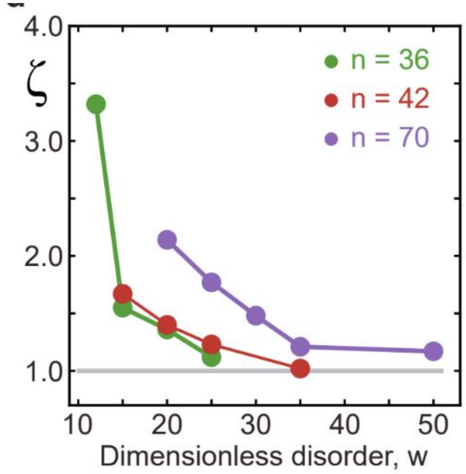
$$R_{\mathrm{typ}}(t) \sim (Jt)^{-\eta}$$

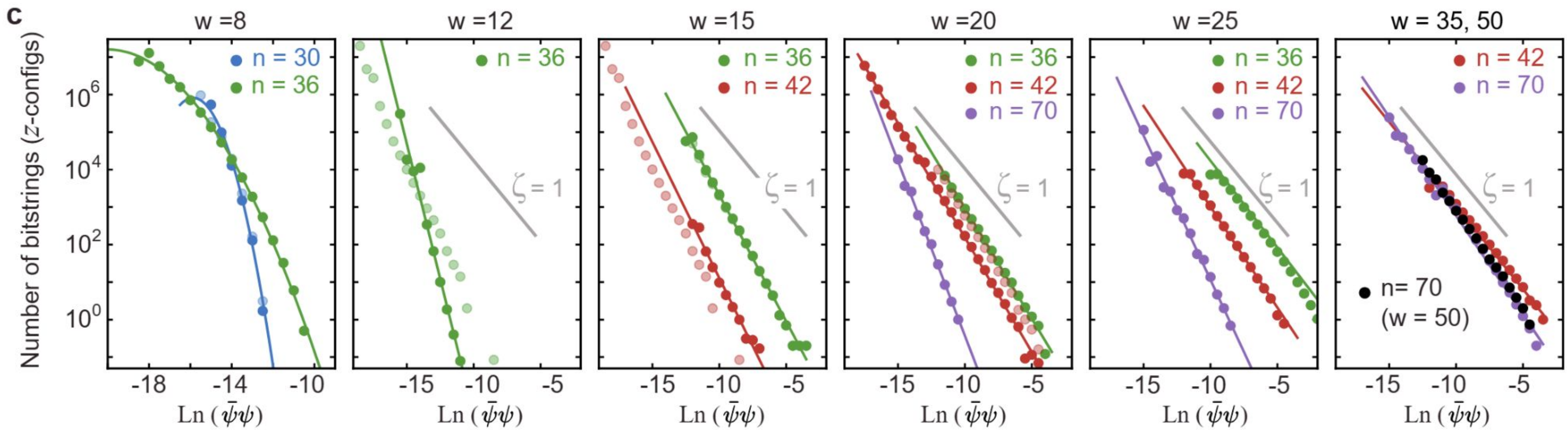


Internal spin dephasing

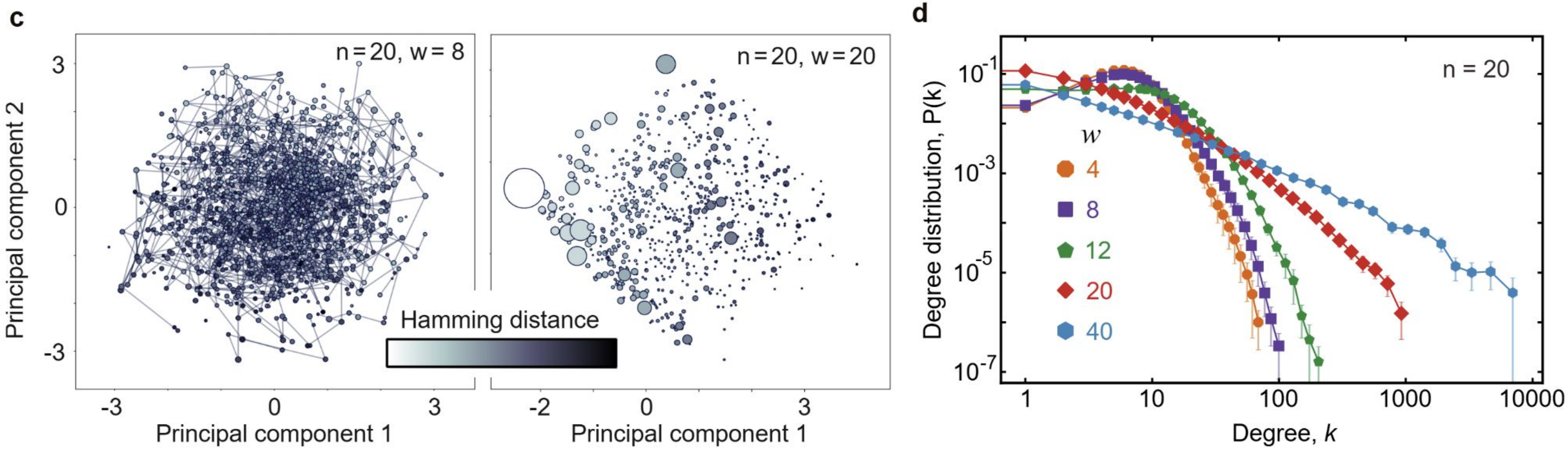
Wavefunction statistics







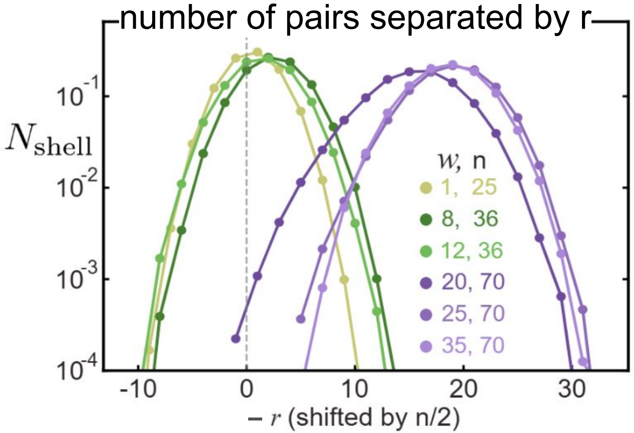
Representing z-configs as a Graph

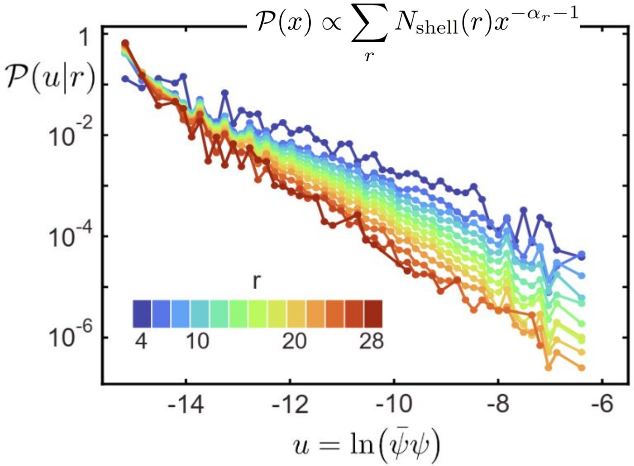


Degree, k : the number of direct network connections per z-config.
(computed with 10,000 representative sample)

small w: random geometric network large w : scale-free behavior

Non-ergodicity and multifractality





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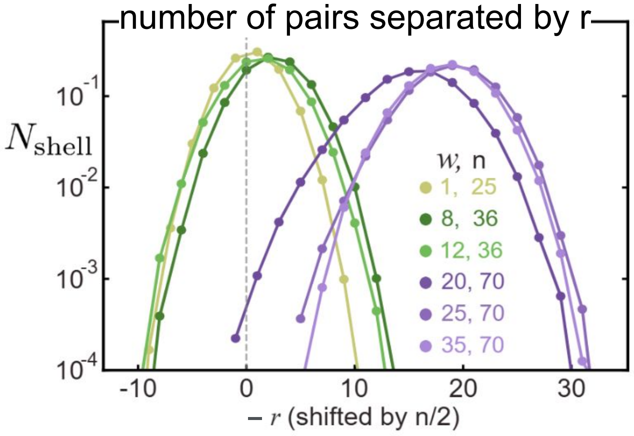

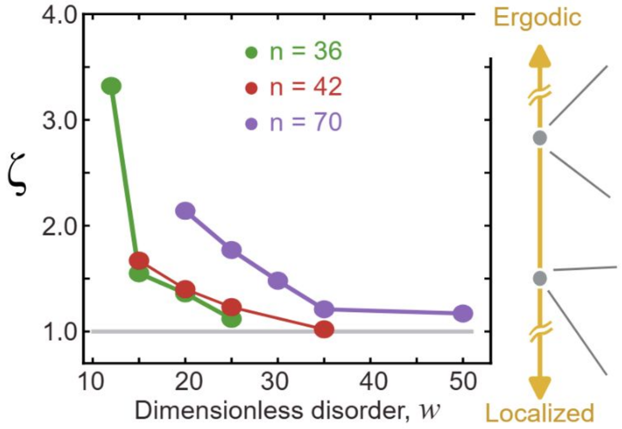

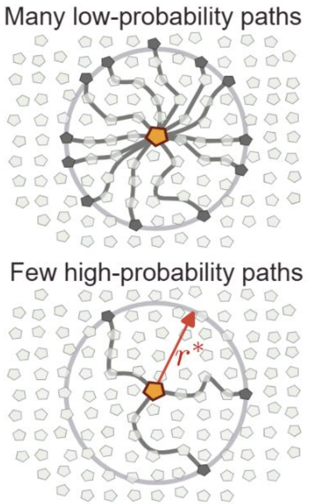

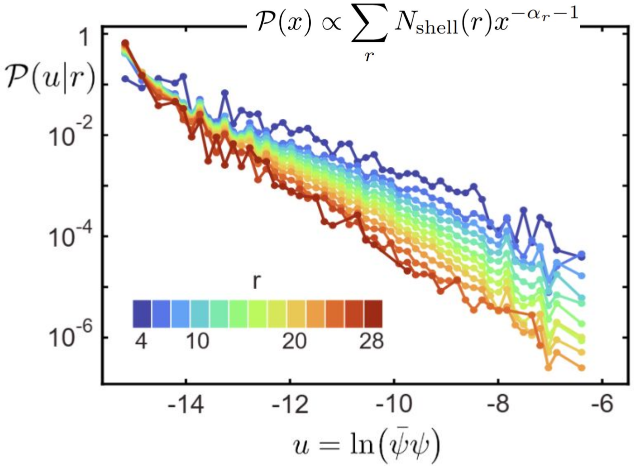

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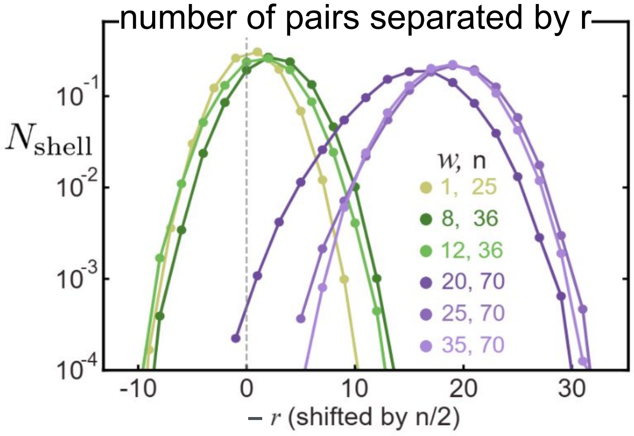

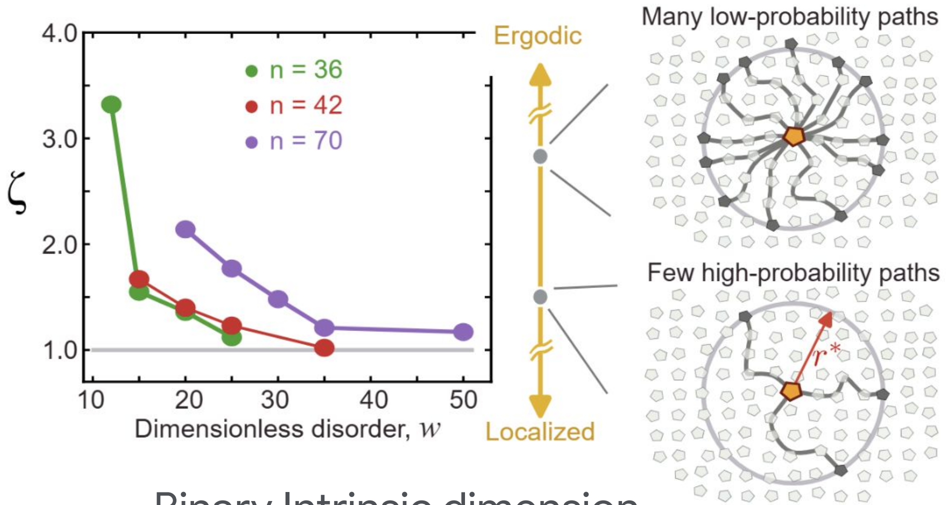

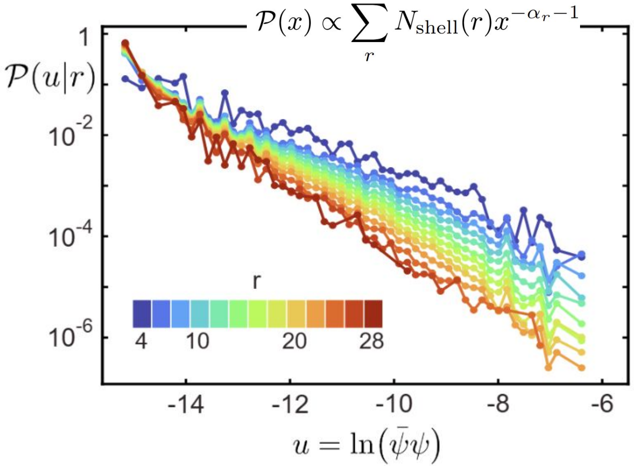

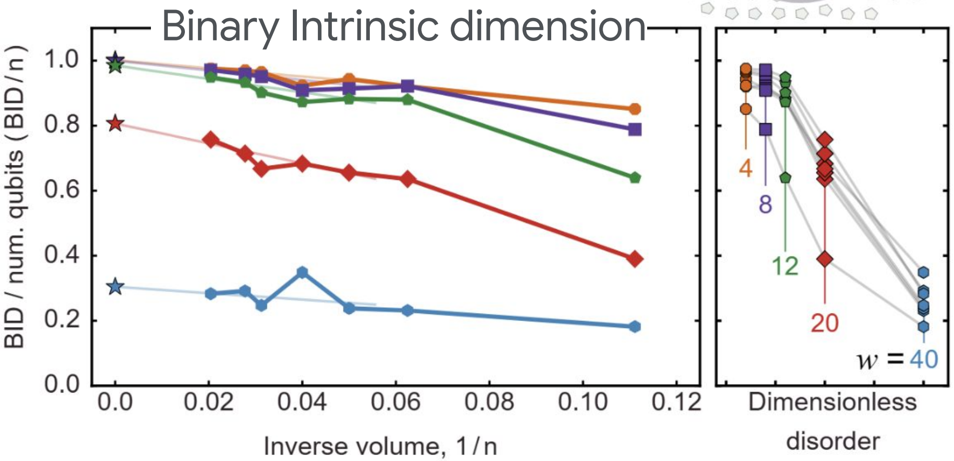

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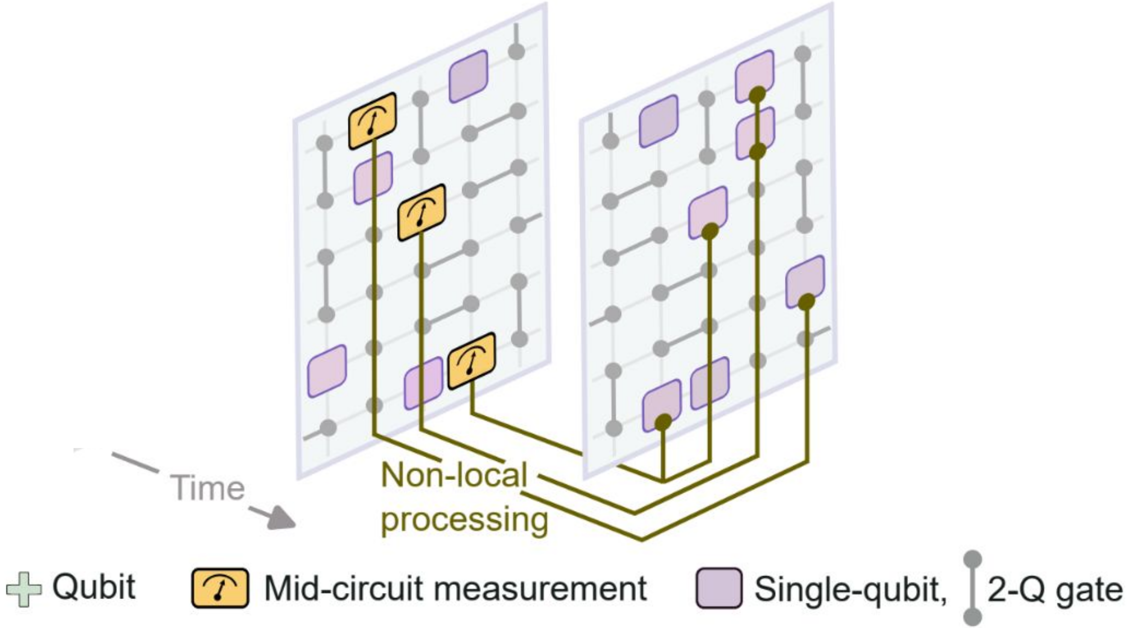
Realizing Long-range entangled quantum states

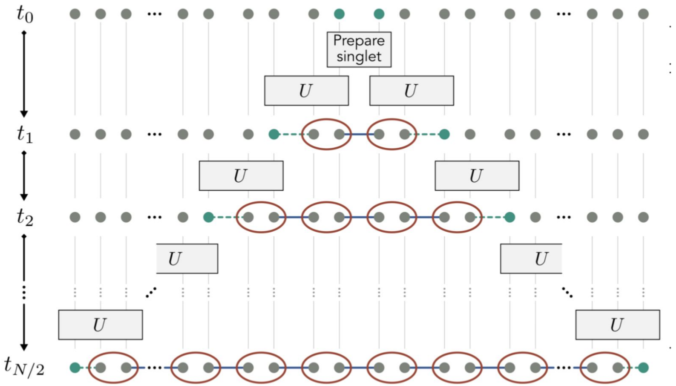


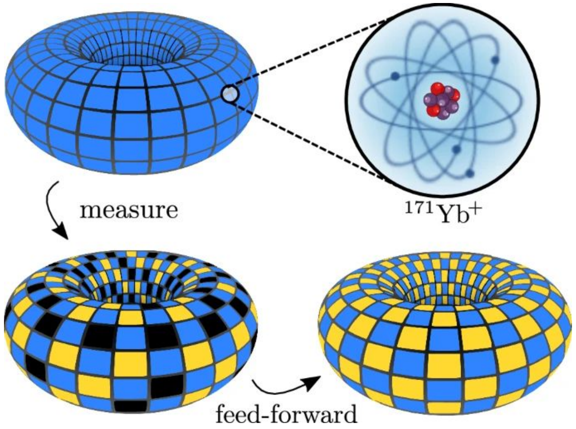
[1] Bravyi et al., PRL 97, 050401 (2006)
[2] Hastings, Q. Theory Small to Large 95 (2010)
[3] Dennis et al., J. Math. Phys. 43, 4452 (2002)
[4] Wen, Quantum Field Theory (Oxford, 2010)
[5] Moessner & Moore, Topological Phases (CUP, 2021)
[6] Aguado et al., PRL 101, 260501 (2008)
[7] Setia et al., Phys. Rev. Res. 1, 033033 (2019)
[8] Derby et al., Phys. Rev. B 104, 035118 (2021)
[9] Hastings & Wen, Phys. Rev. B 72, 045141 (2005)
[10] Wen, Quantum Field Theory (Oxford, 2004)
[11] Lieb & Robinson, Comm. Math. Phys. 28 (1972)
[12] Briegel & Raussendorf, PRL 86, 910 (2001)
[13] Raussendorf et al., Phys. Rev. A 71 (2005)
[14] Bolt et al., PRL 117, 070501 (2016)
[15] Piroli et al., PRL 127, 220503 (2021)

Adaptive Quantum Circuits

IBM

- Deterministic Constant-Depth Preparation of the AKLT State on a Quantum Processor Using Fusion Measurements. Kevin Smith *et al.*, PRX Quantum (2023)
- Efficient Long-Range Entanglement Using Dynamic Circuits. Elisa Bäumer *et al.*, PRX Quantum (2024)



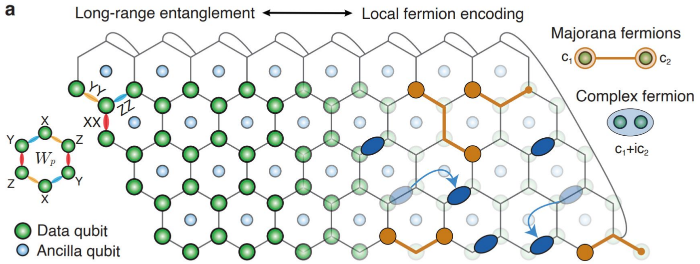


Quantinuum

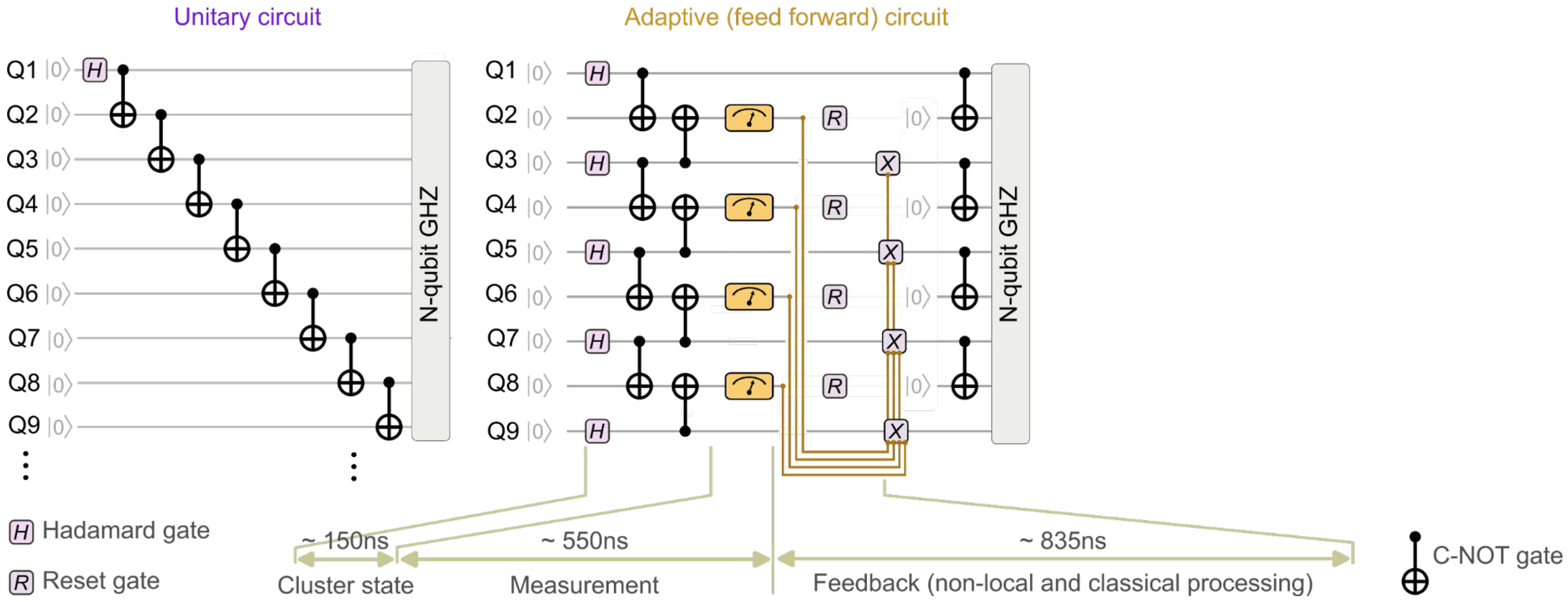
- Experimental demonstration of the advantage of adaptive quantum circuits. Foss-Feig *et al.*, arXiv:2302.03029 (2023)
- Topological order from measurements and feed-forward on a trapped ion quantum computer. Iqbal *et al.*, Commun. Phys. (2024)

QuEra

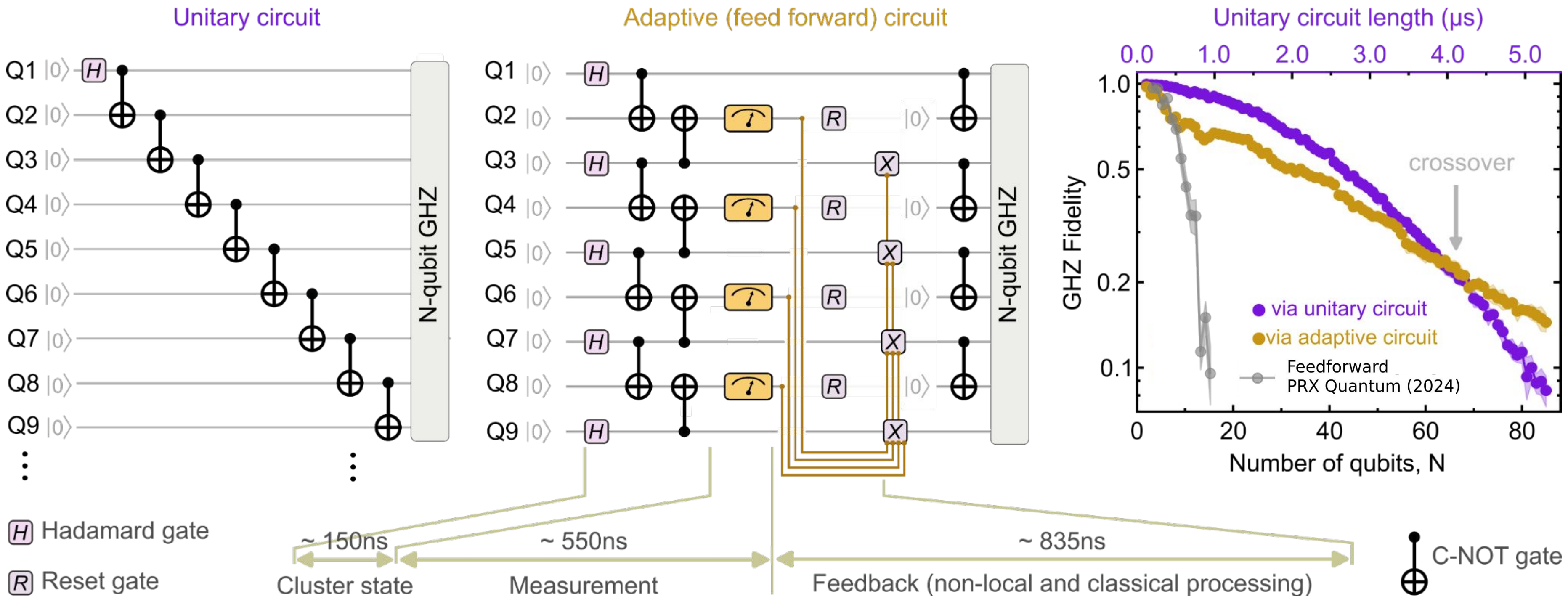
- Probing the Kitaev honeycomb model on a neutral-atom quantum computer.
Evered *et al.*, Nature (2025)



Making GHZ states



Benchmarking with GHZ states



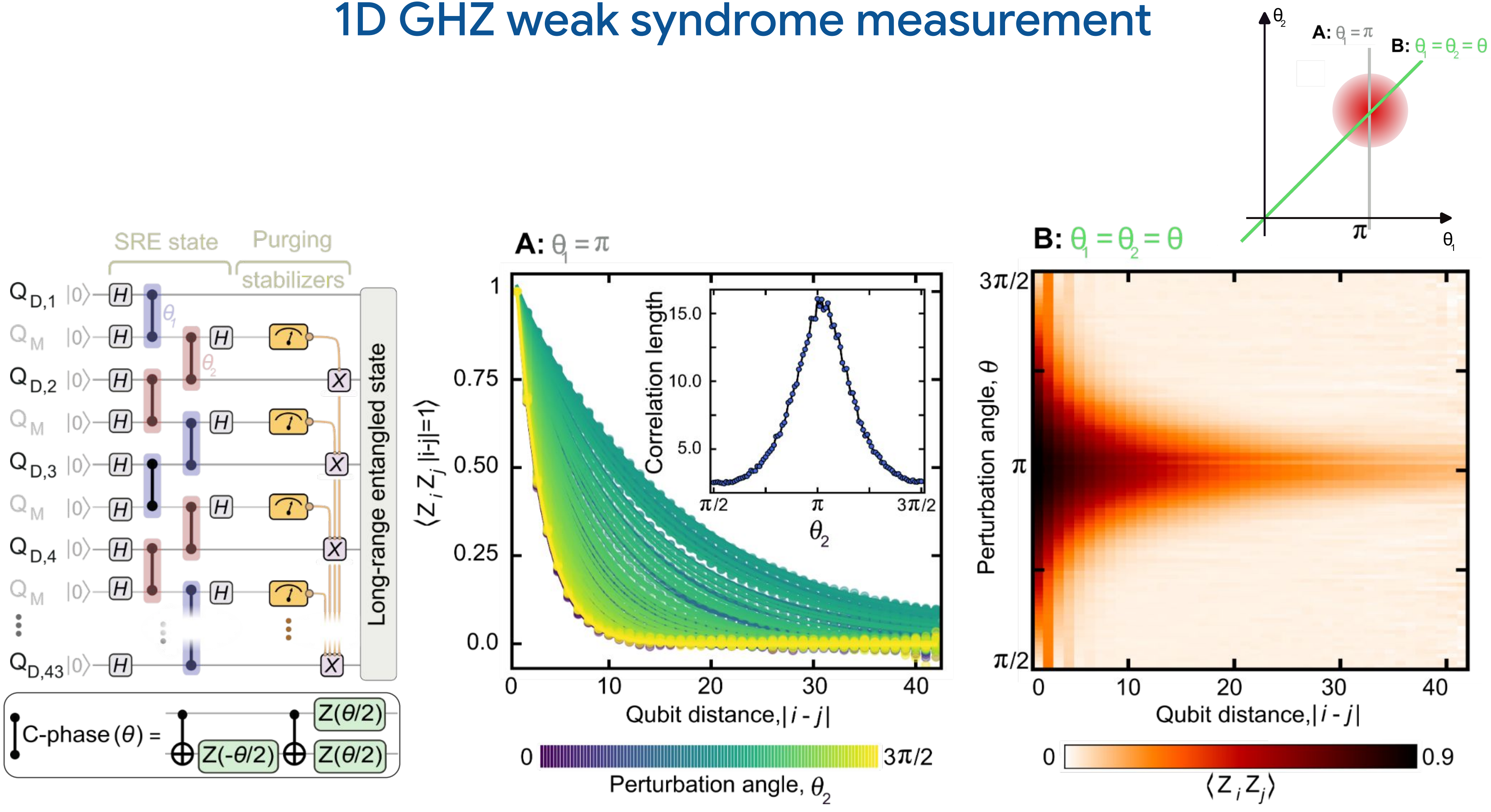
Sample random GHZ stabilizer

$$\mathcal{S}_k|GHZ\rangle = |GHZ\rangle \quad \forall k,$$

$$\hat{\mathcal{F}} = \frac{1}{n}\sum_{\mathcal{S}_j\in\Omega_{\mathcal{S}}} \langle S_j\rangle_\rho \quad \mathcal{S}_k \in \{XX...X, ZZI...I, IZZI...I, ...\}$$

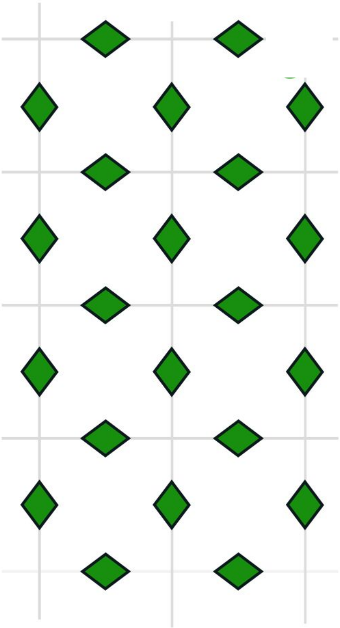
(N independent, 2^N total)

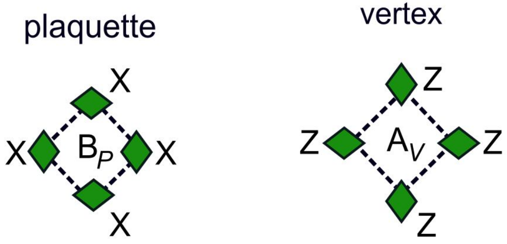
1D GHZ weak syndrome measurement

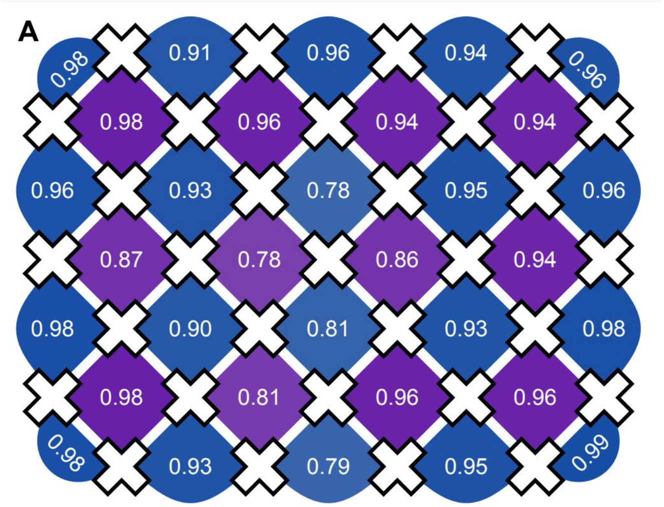


Realizing topologically ordered states on a quantum processor

$$\mathcal{H}_{\text{Kitaev}} = -\sum_{p}\prod_{i\in p} X_i - \sum_{v}\prod_{i\in v} Z_i = -\sum_{\text{plaquettes}} B_p - \sum_{\text{vertices}} A_v$$







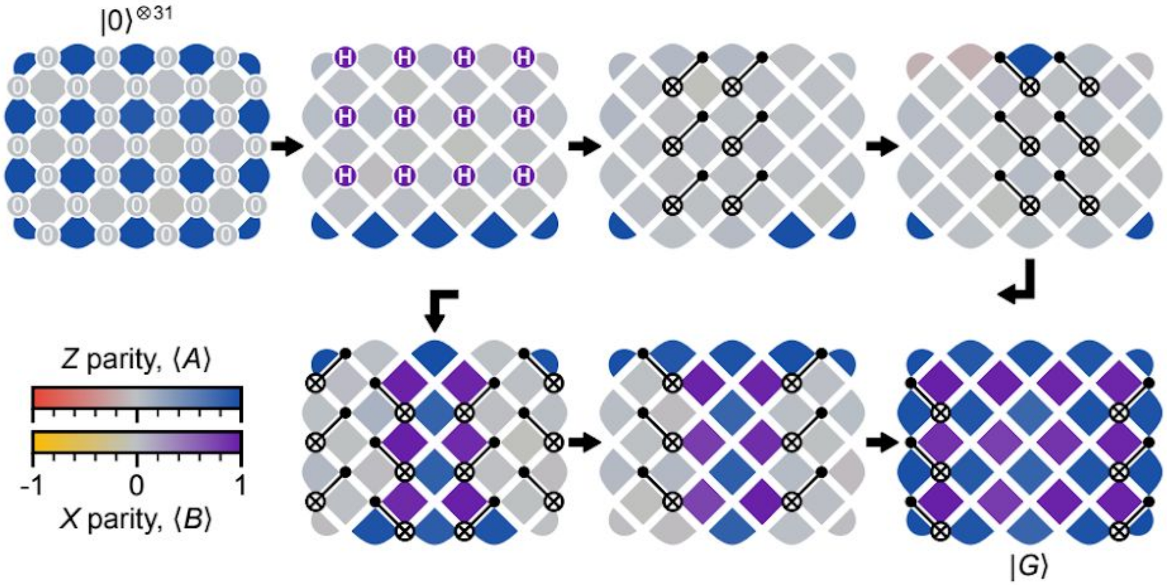
A. Y. Kitaev, Ann. Phys. (N. Y). 303, 2 (2003).

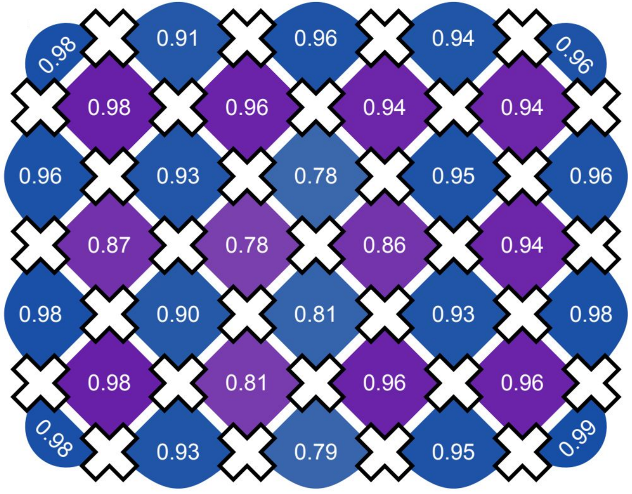
Satzinger *et al.,* Science 374, 1237-1241 (2021)

Gate sequence to create ground-states

$$[B_p, A_v] = 0 \longrightarrow |G\rangle \propto \prod_p \underbrace{(\mathbb{I} + B_p)}_{\text{projector}} |0\rangle^{\otimes 31}$$

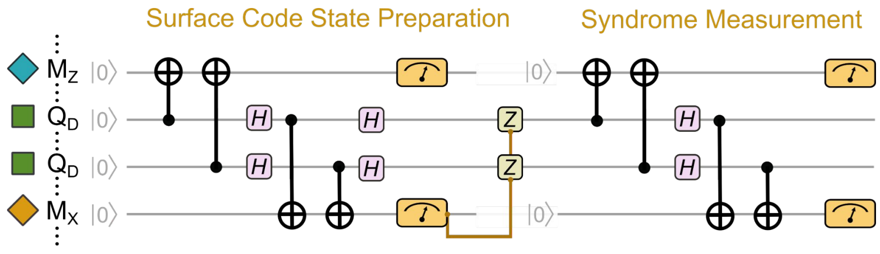
superposition of all plaquette configurations

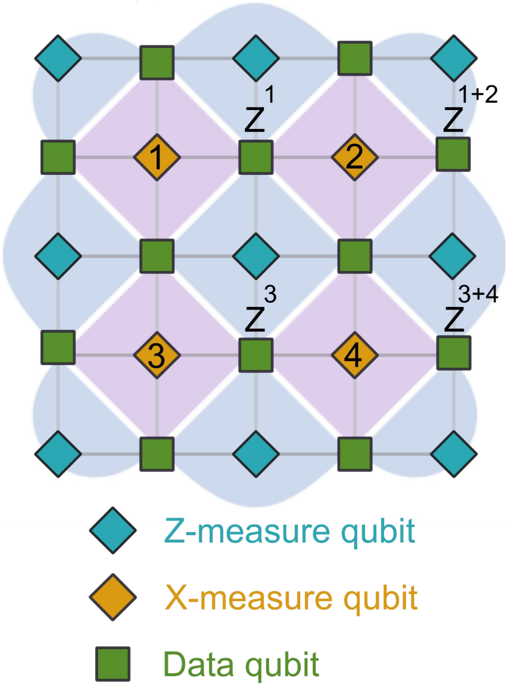


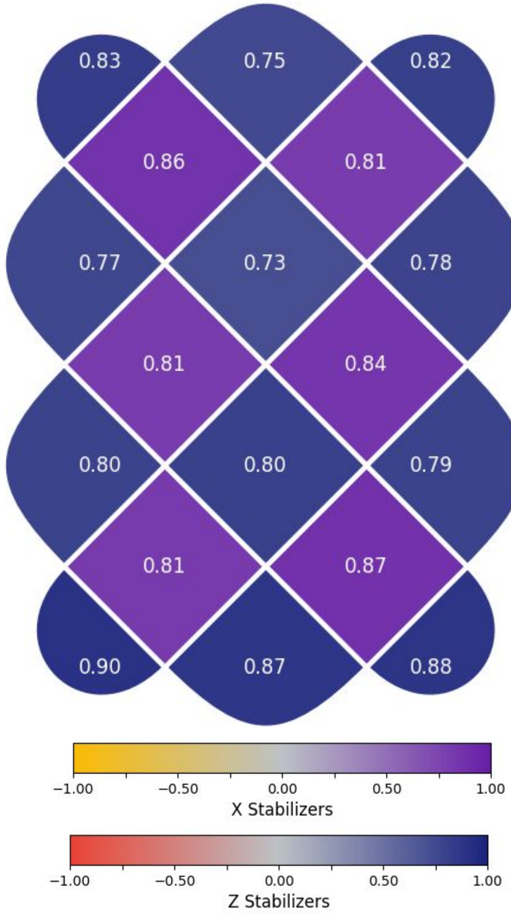


Satzinger *et al.*, Science 374, 1237-1241 (2021)

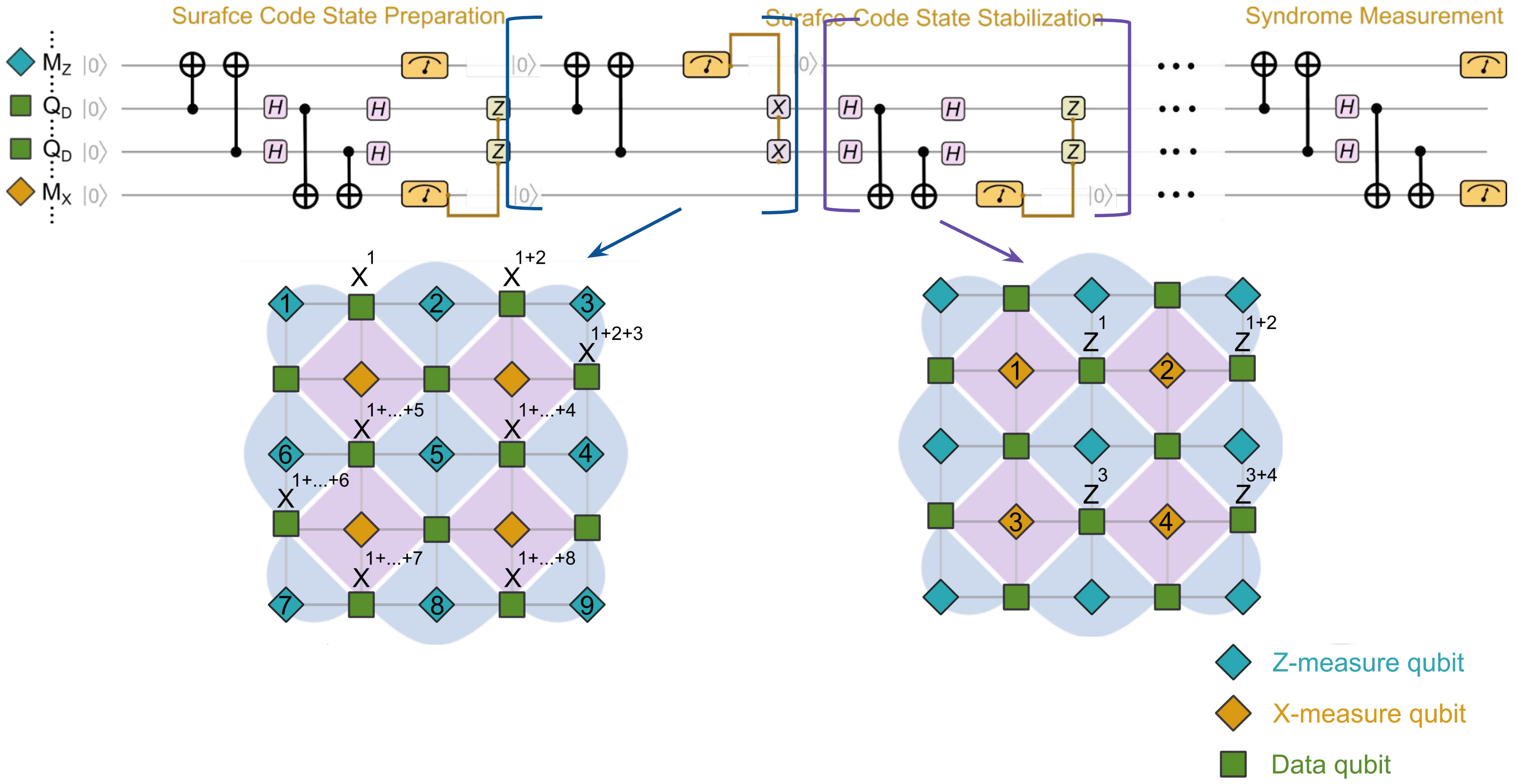
2D surface code preparation via feedforward



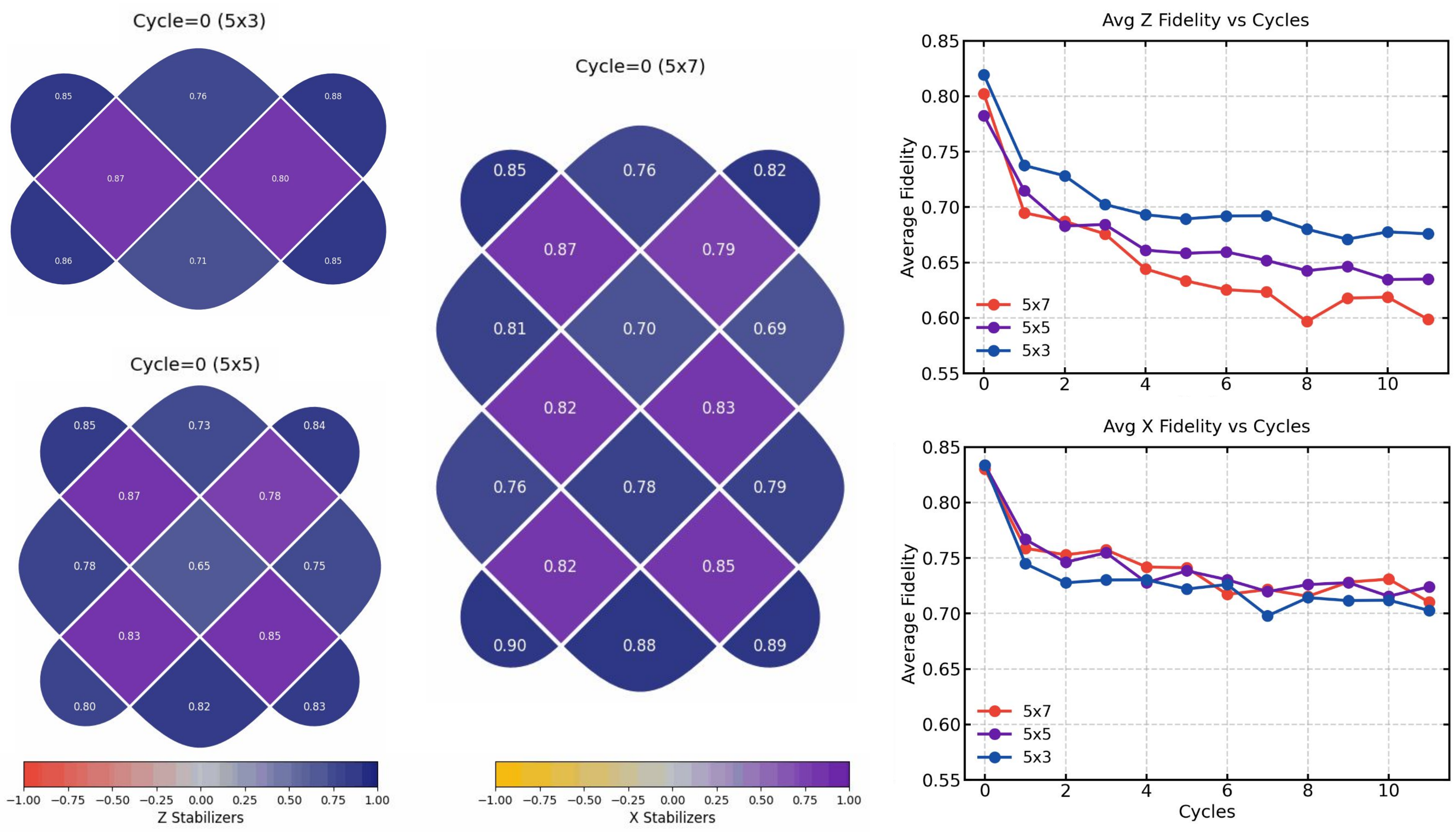




Stabilizing surface code via feedforward



Stabilizing surface code via feedforward



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