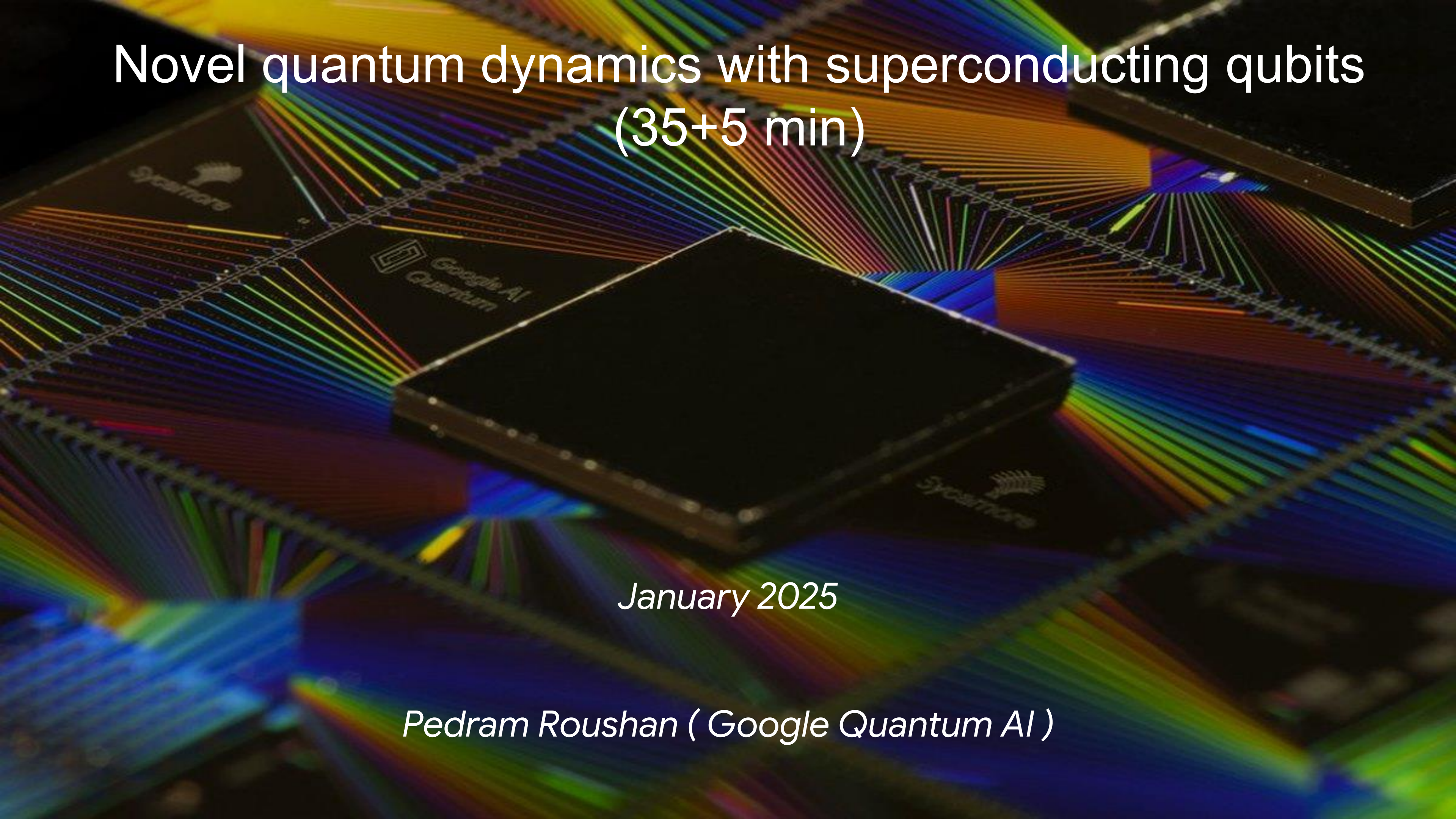
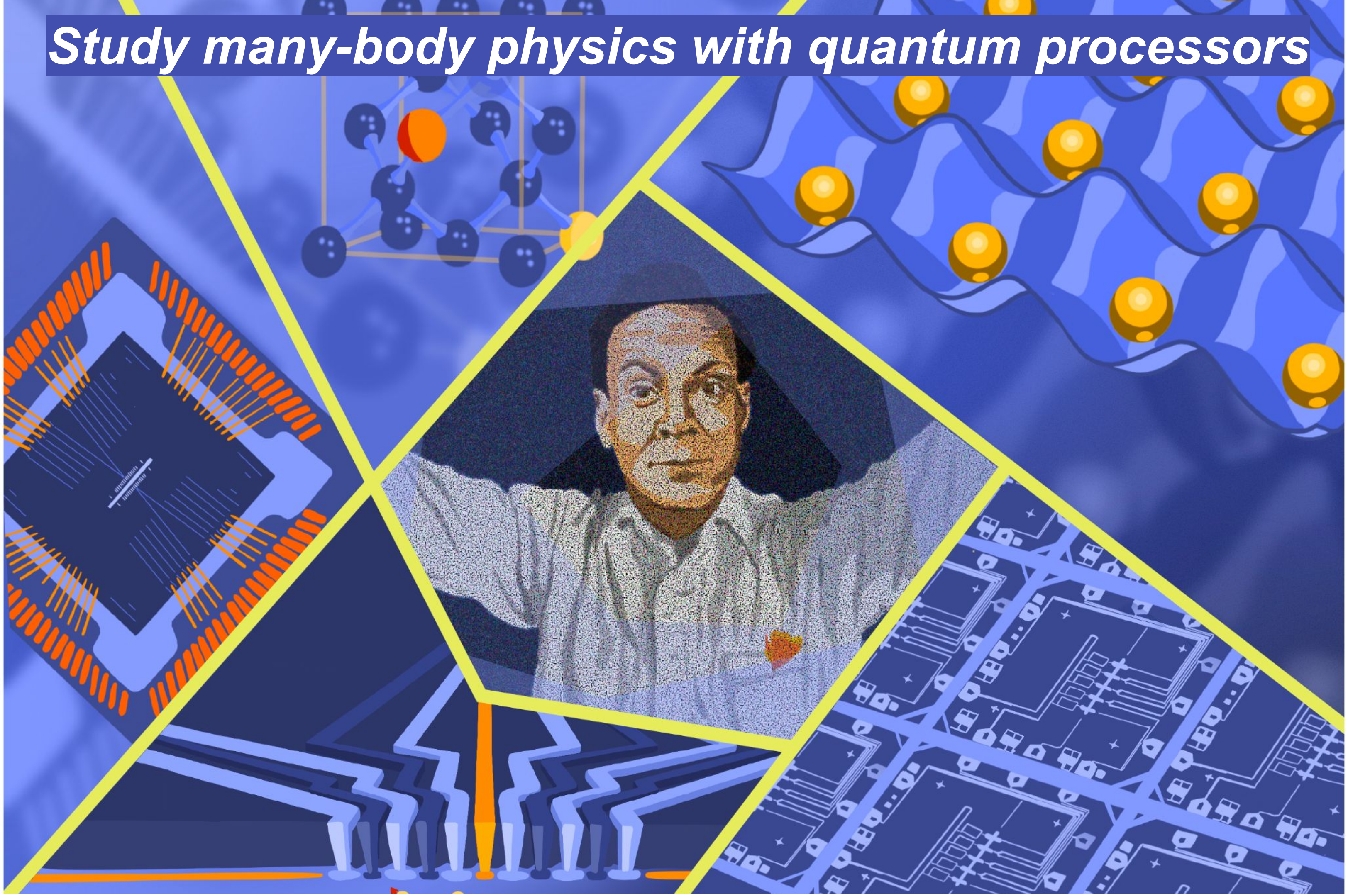
Novel quantum dynamics with superconducting qubits
(35+5 min)

January 2025

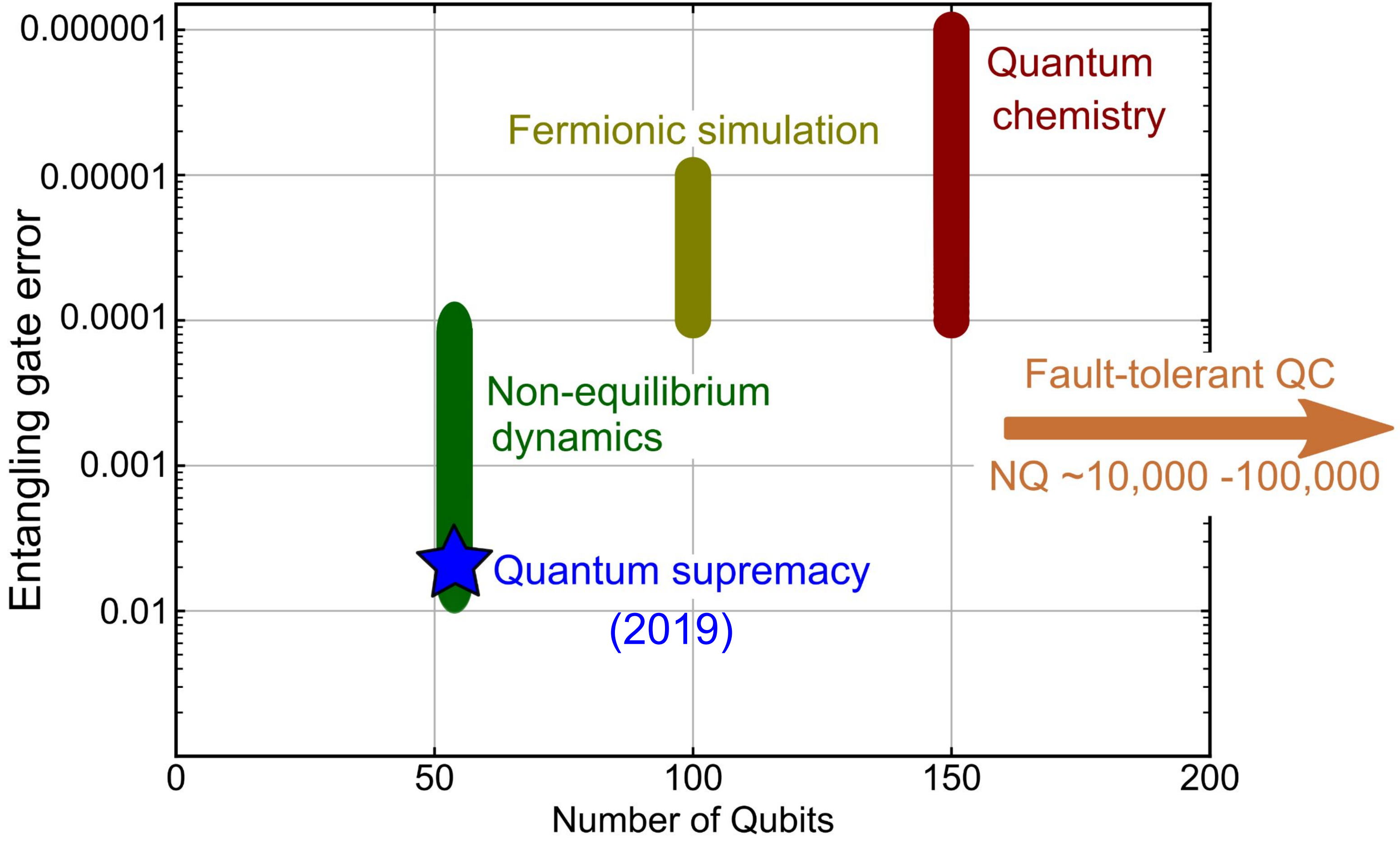
Pedram Roushan (Google Quantum AI)

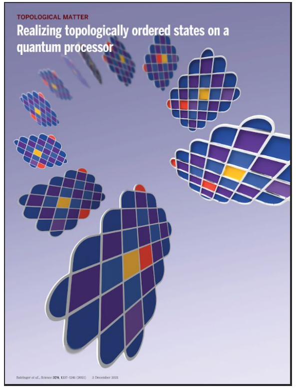


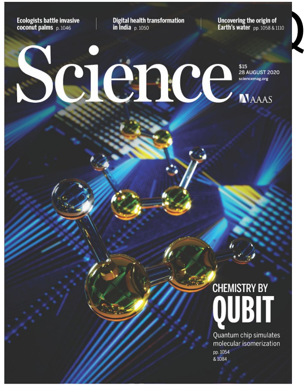
Study many-body physics with quantum processors

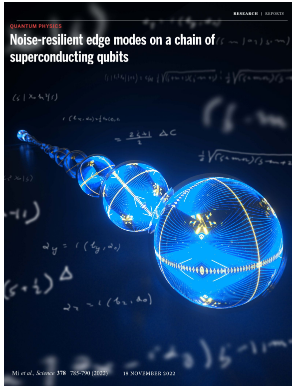


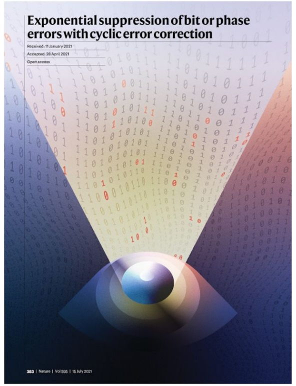
Two Paradigms: Erorr correction and NISQ

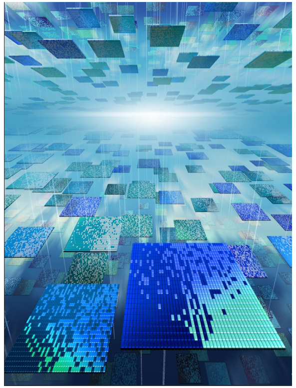


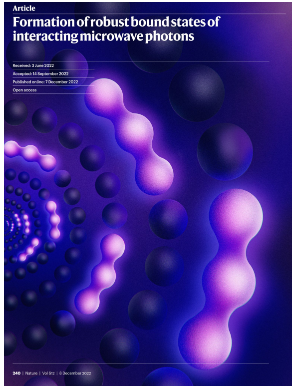


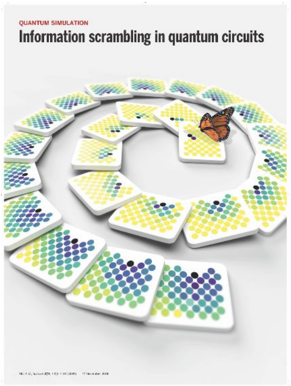












“ Tell me something I didn’t know before ”

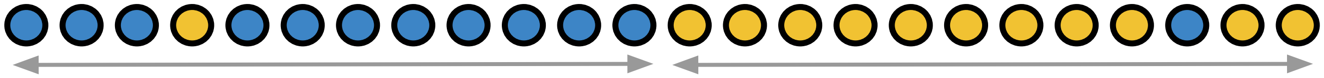
-a theoretical physicist

Discoverino

Discoveries made by NISQ processors, which could also been made in theory or by using classical computing resources.

PR and Leigh Martin, under review (2025)

Dynamics of magnetization at infinite temperture in a Heisenberg spin chain



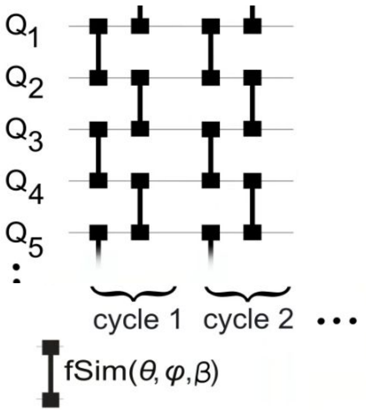
prob. of $e^{\mu} / (e^{\mu} + e^{-\mu})$ prob. of $e^{\mu} / (e^{\mu} + e^{-\mu})$

1D XXZ Hamiltonian:

$$\mathcal{H} = \sum_i (X_i X_{i+1} + Y_i Y_{i+1}) + \Delta Z_i Z_{i+1}$$

kinetic (hopping) interaction

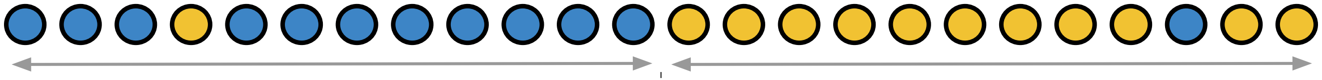
1D XXZ Floquet :



$$\mathrm{fSim}(\theta, \phi, \beta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & ie^{i\beta}\sin\theta & 0 \\ 0 & ie^{-i\beta}\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{i\phi} \end{pmatrix}$$

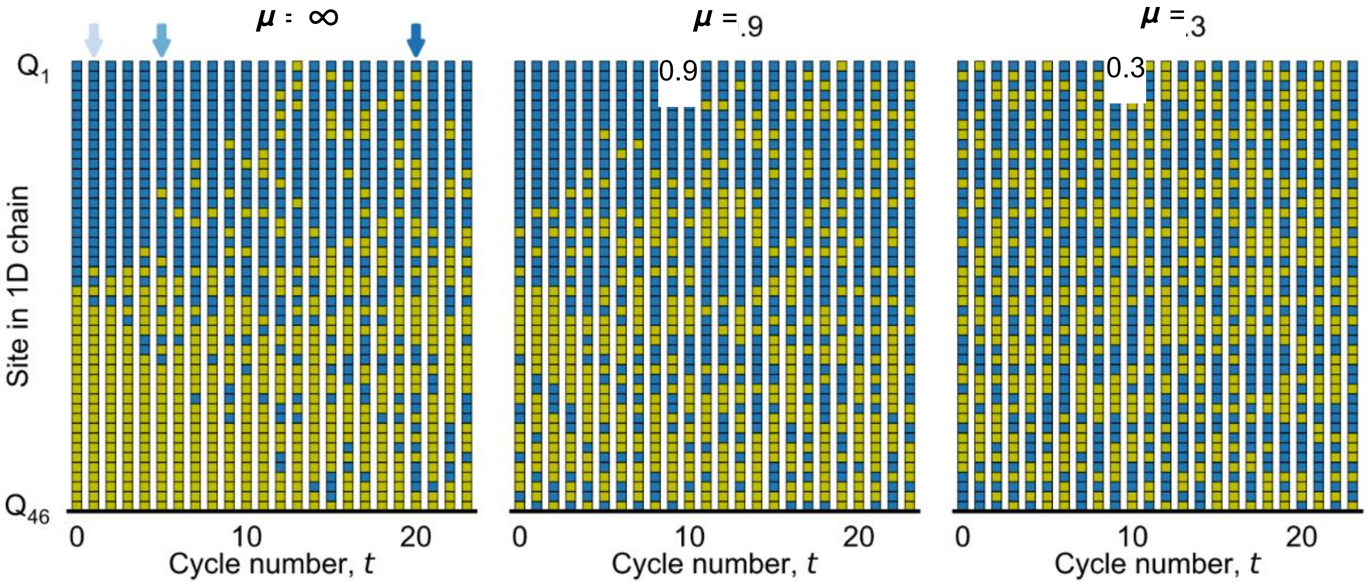
Rosenberg *et al.*, Science **384**, (2024)

Domain wall dynamics in a Heisenberg spin chain of 46 qubits



prob. of (blue) $e^{\mu} / (e^{\mu} + e^{-\mu})$ prob. of (yellow) $e^{\mu} / (e^{\mu} + e^{-\mu})$

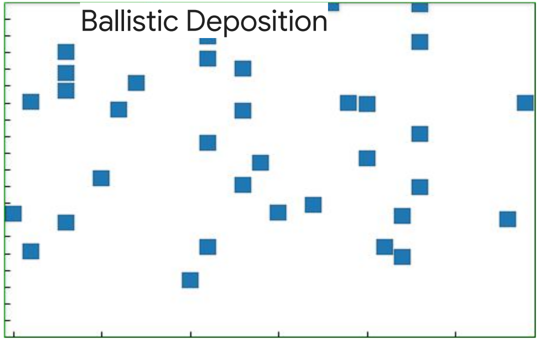
Transferred magnetization $\mathcal{M}(t)/2 = N_{R,1}(b_t) - N_{R,1}(b_i)$

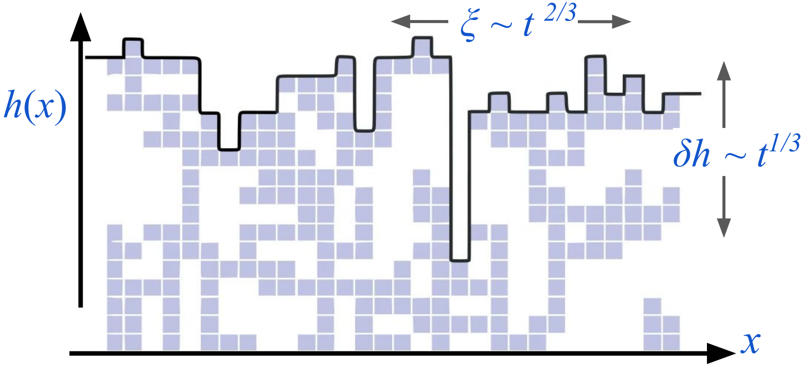


Kardar-Parisi-Zhang (KPZ) Universality Class

$$\frac{\partial h}{\partial t} = \nu \nabla^2 h + \frac{\lambda}{2} (\nabla h)^2 + \eta(x,t)$$

diffusion growth noise



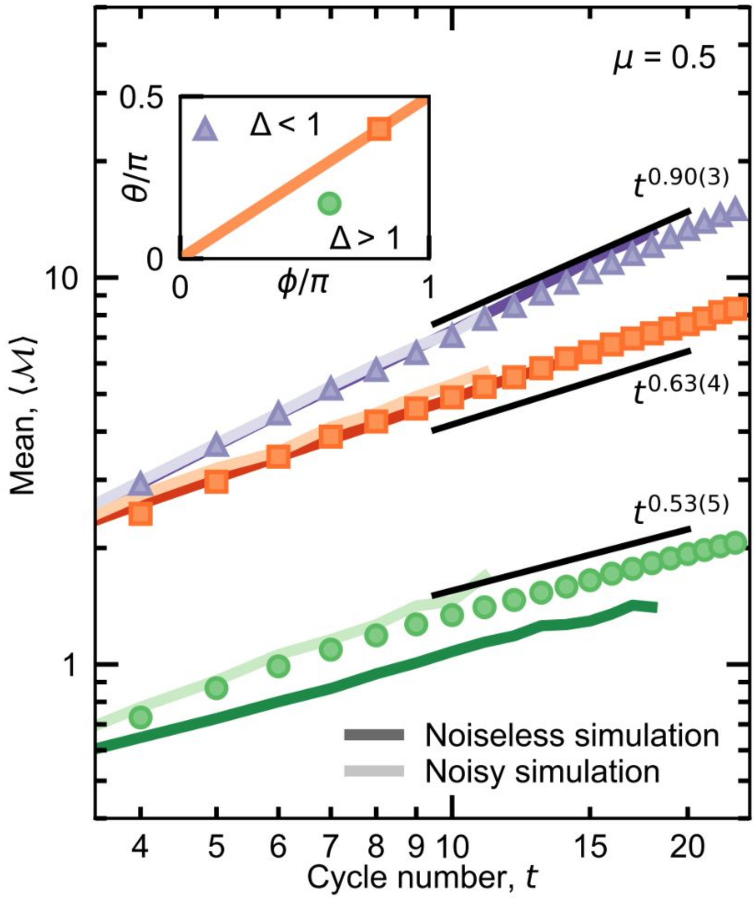


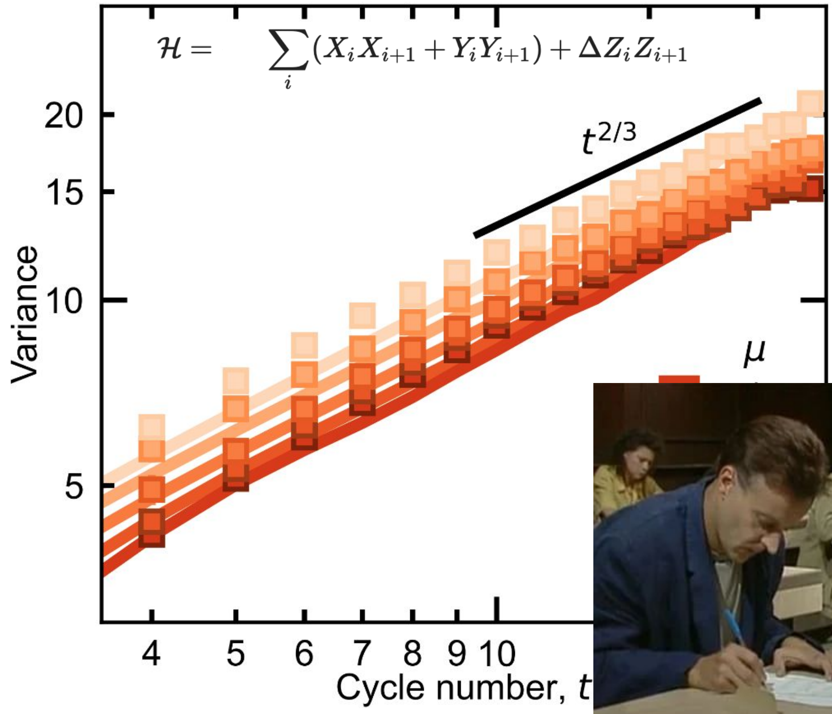
The KPZ conjecture :

KPZ		Heisenberg spin chains
$\partial h/\partial x$	$\rightarrow$	$S^z(x,t)$ Magnetization profile
$2h(0,t) - h(-L/2,t) - h(L/2,t)$	$\rightarrow$	$\mathcal{M}(t)/2 = N_{R,1}(b_t) - N_{R,1}(b_i)$
Relative height at the center		Transferred magnetization

Baik-Rains $\boldsymbol{\mu} = 0$ TW-GUE $\boldsymbol{\mu} \neq 0$

Mean and Variance of M → consistent with KPZ

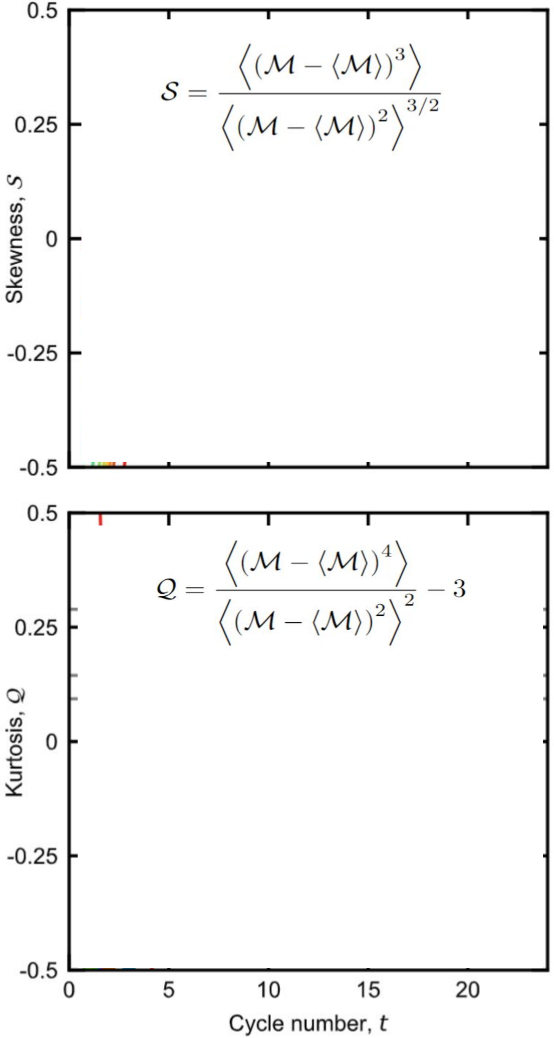


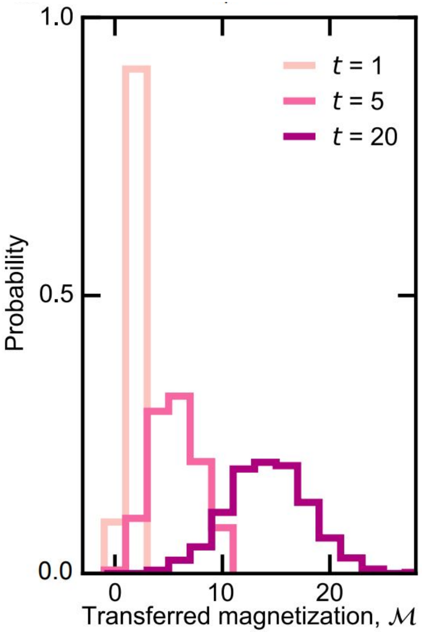


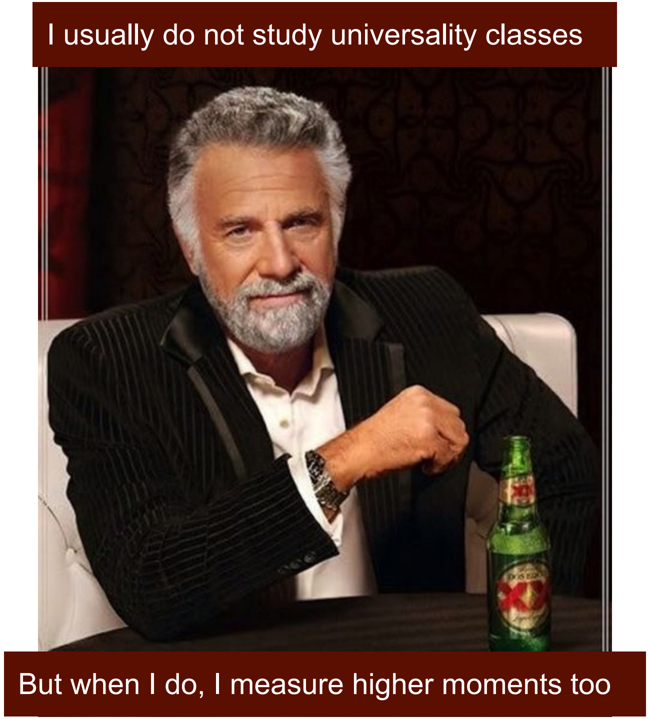
agreement with
cold atom experiments: Wei *et al.*, Science 376, 2022

M. Znidaric PRL (2011), M. Ljubotina *et al.* Nat. Commun. (2017), J.-M. Stephan, J. Stat. Mech. (2017), R. J. Sanchez *et al.* PRL (2018), E. Ilievski *et al.* PRL (2018), S. Gopalakrishnan *et al.* PRL (2019), J. De Nardis et al. PRL (2019), S. Gopalakrishnan *et al.* Proc. Natl. Acad. Sci. (2019), J. De Nardis *et al.* PRL (2020), M. Dupont *et al.* PRB (2020), M. Dupont *et al.* PRL (2021), E. Ilievski *et al.* PRX (2021), A. Scheie *et al.* Nat. Phys. (2021)

Higher moments of the transferred magnetization

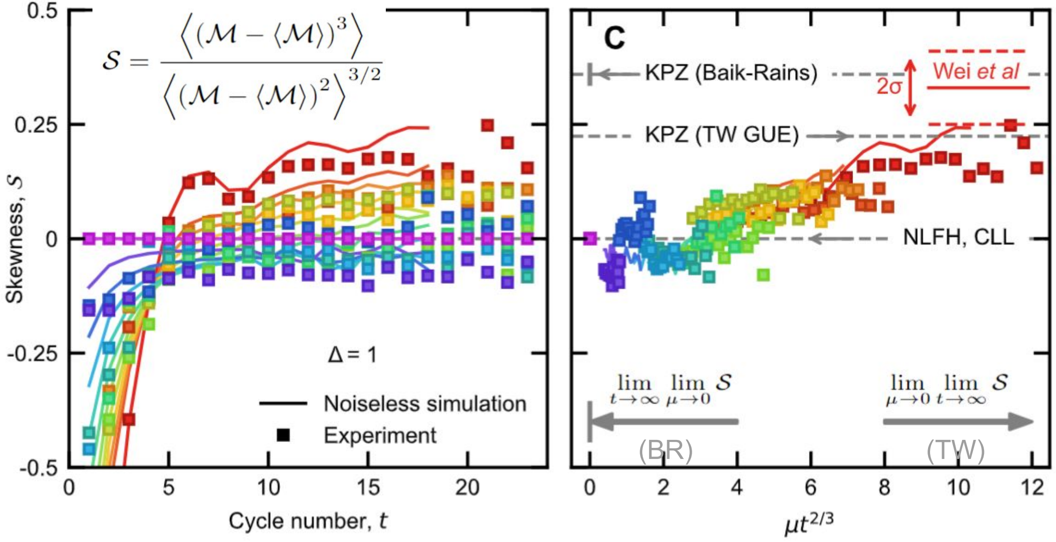


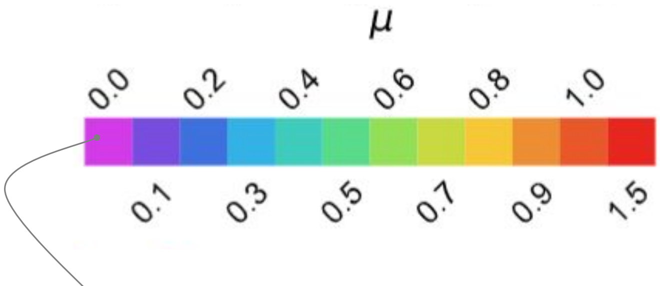




Significance of studying higher moments in determining dynamic universality classes ?

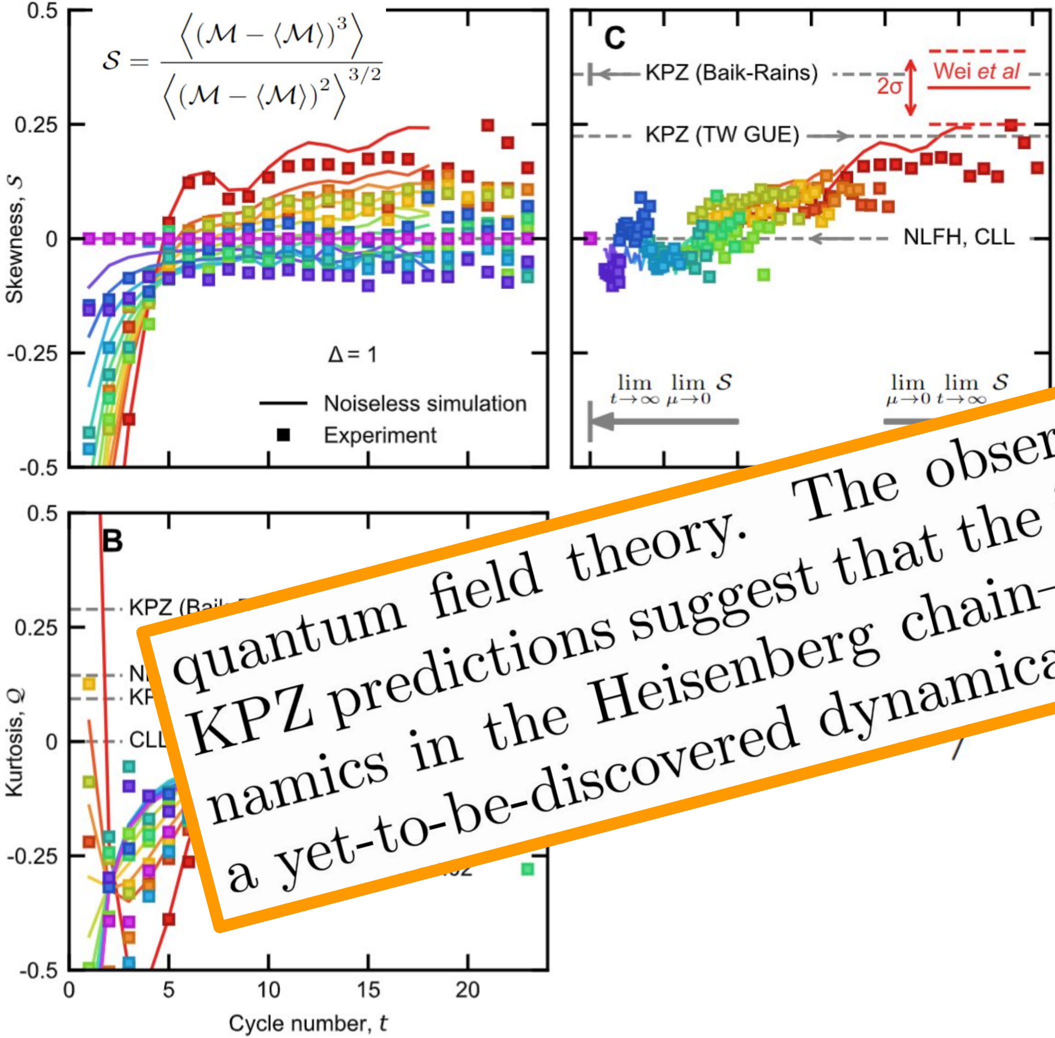
Skewness of transferred magnetization





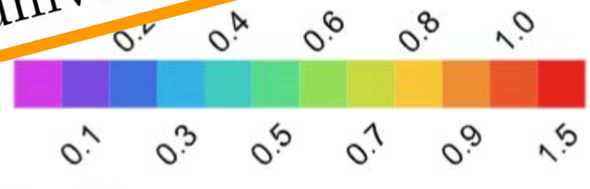
SU(2) symm initial state

Higher moments of the transferred magnetization



quantum field theory. The observed discrepancies with KPZ predictions suggest that the infinite-temperature dynamics in the Heisenberg chain—if universal—belong to a yet-to-be-discovered dynamical universality class.

	$\langle \mathcal{M} \rangle$	σ^2	$\mathcal{S}$	$\mathcal{Q}$
Experiment	$t^{2/3}$	$t^{2/3}$	0 *	[illegible]05 ± 0.02
KPZ (Baik-Rains)	$t^{2/3}$	[illegible]	[illegible]	[illegible]0.29
NLFH	[illegible]	[illegible]	[illegible]	[illegible].14
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]03, 0.03]

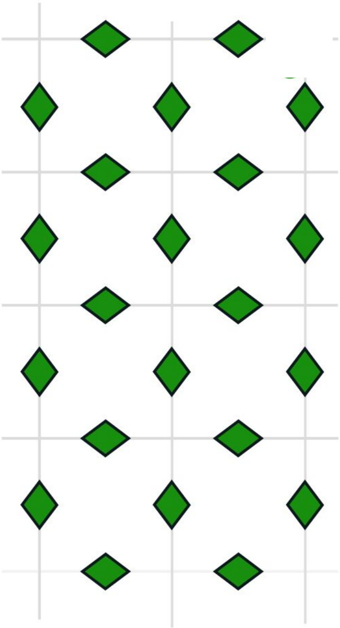


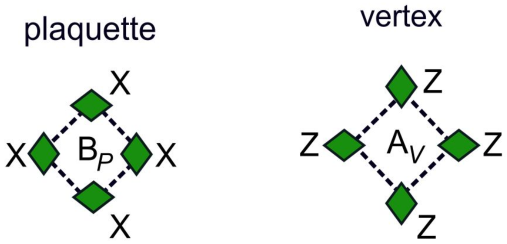
NLFH = non-linear fluctuating hydrodynamics
(De Nardis, **Gopalakrishnan**, and Vasseur, 2023)

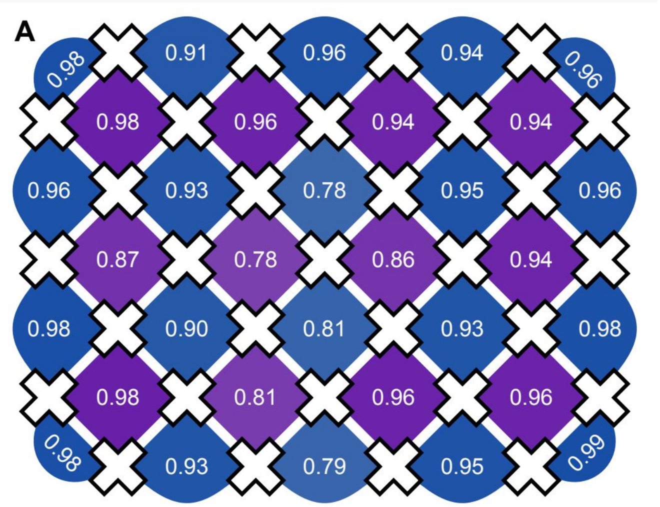
CLL = classical Landau-Lifshitz
(Krajnik, Ilievski, and **Prosen**, 2022)

Realizing topologically ordered states on a quantum processor

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







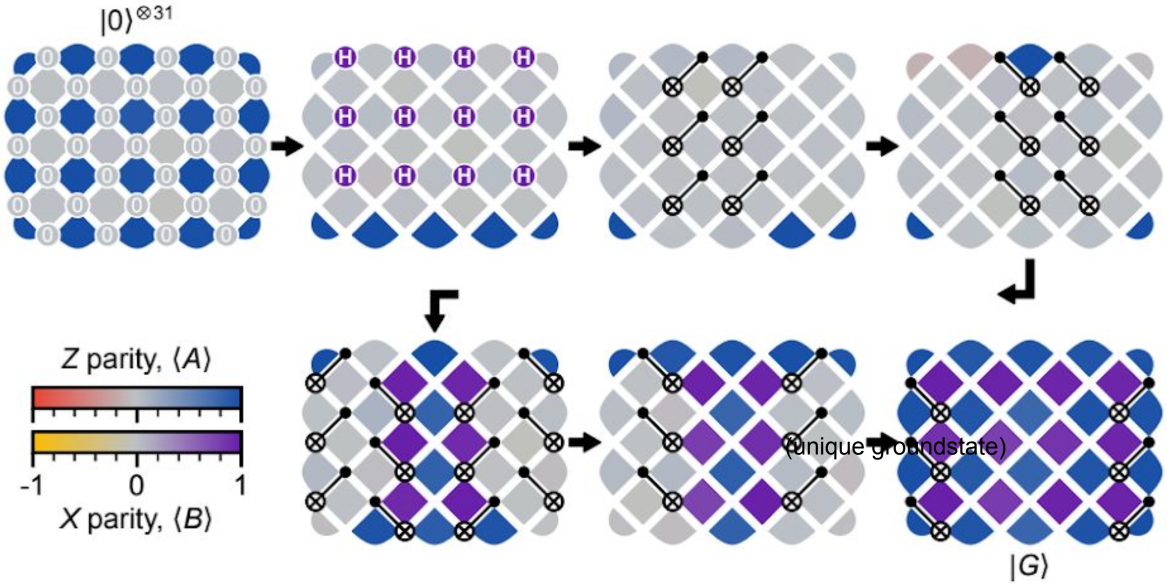
A. Y. Kitaev, Ann. Phys. (N. Y). 303, 2 (2003).

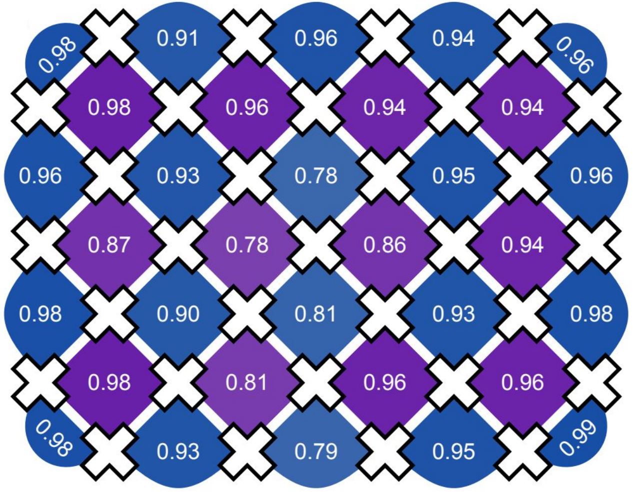
Satzinger *et al.* Science 374, 1237-1241 (2021)

Gate sequence to create ground-states

$$[B_p, A_v] = 0,\ \forall p, v \longrightarrow |G\rangle = \frac{1}{\sqrt{2^{12}}} \prod_p (\mathbb{I} + B_p)\, |0\rangle^{\otimes 31}$$

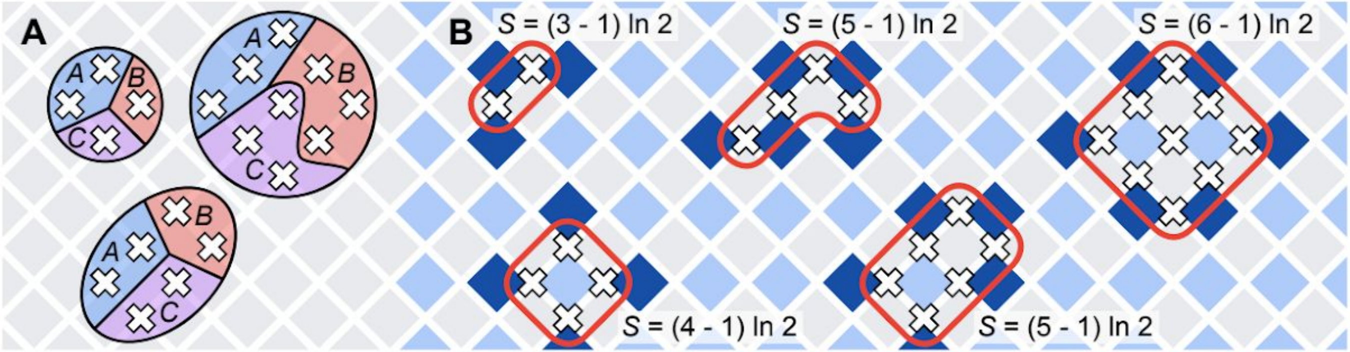
superposition of all plaquette configurations





Topological entanglement entropy

$$S_{\text{topo}} = S_A + S_B + S_C - S_{AB} - S_{BC} - S_{AC} + S_{ABC}$$



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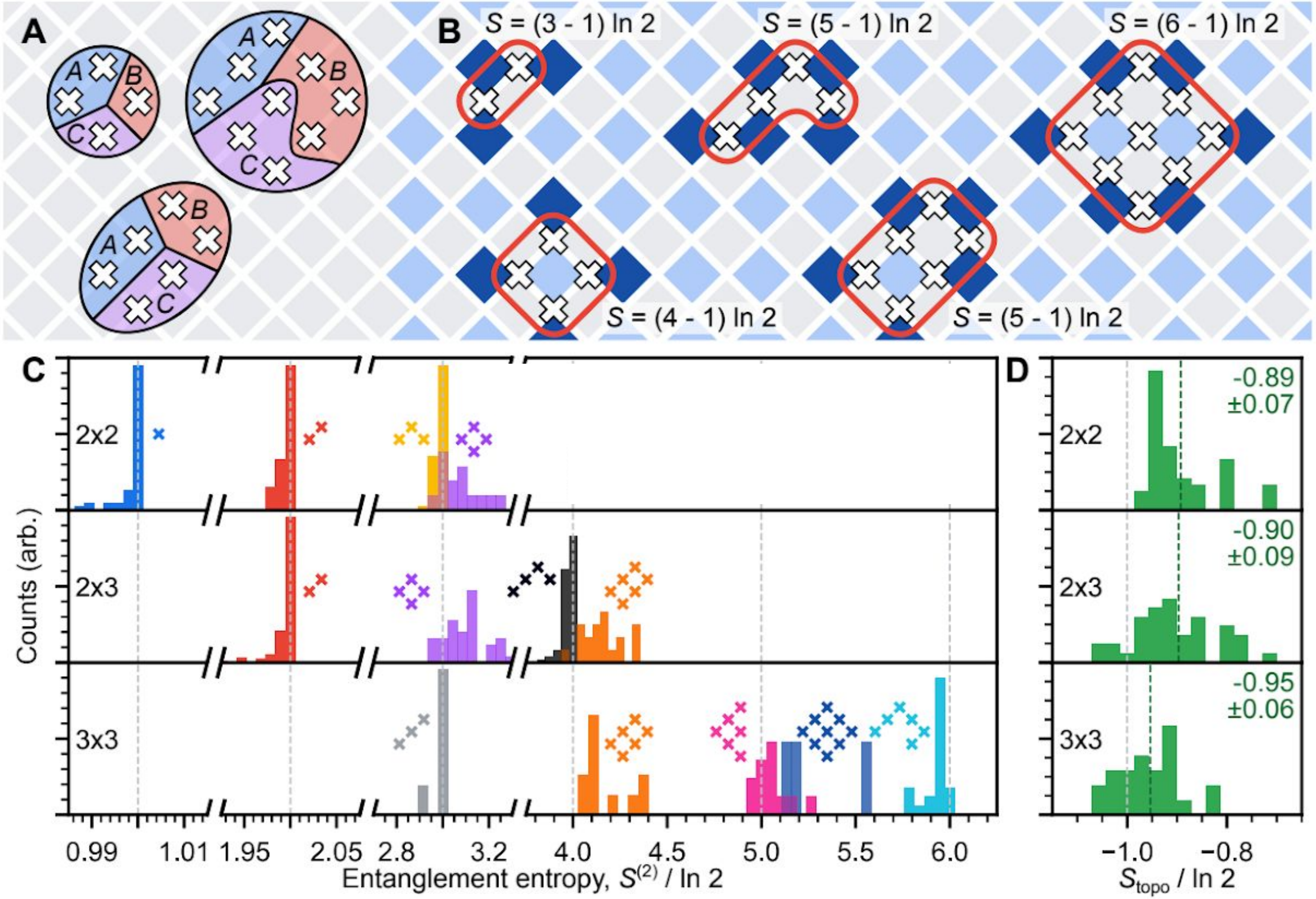
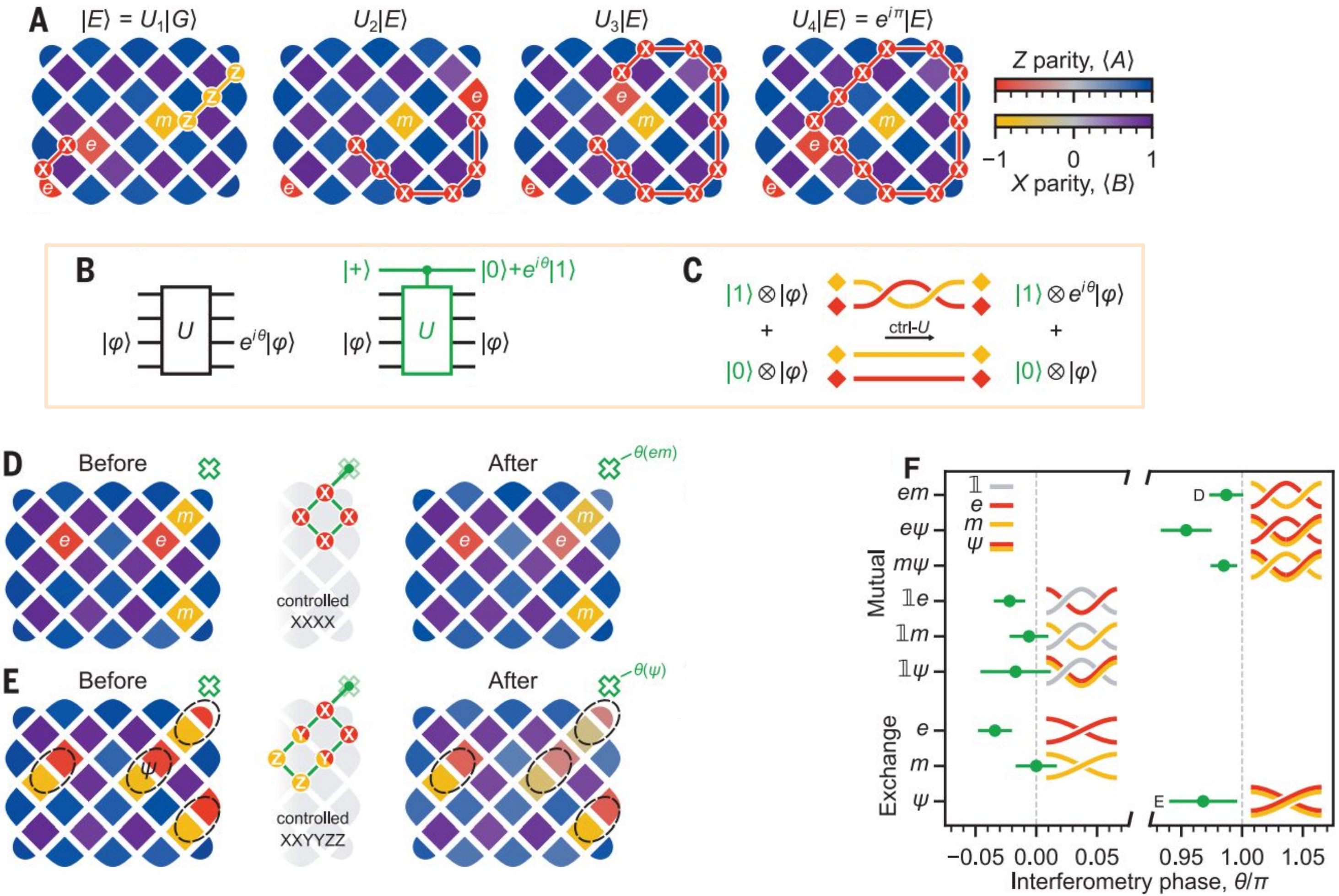


Randomized measurement:
Tiff *et al.*, Science (2019),
Vermersch *et al.*, PRA (2018)

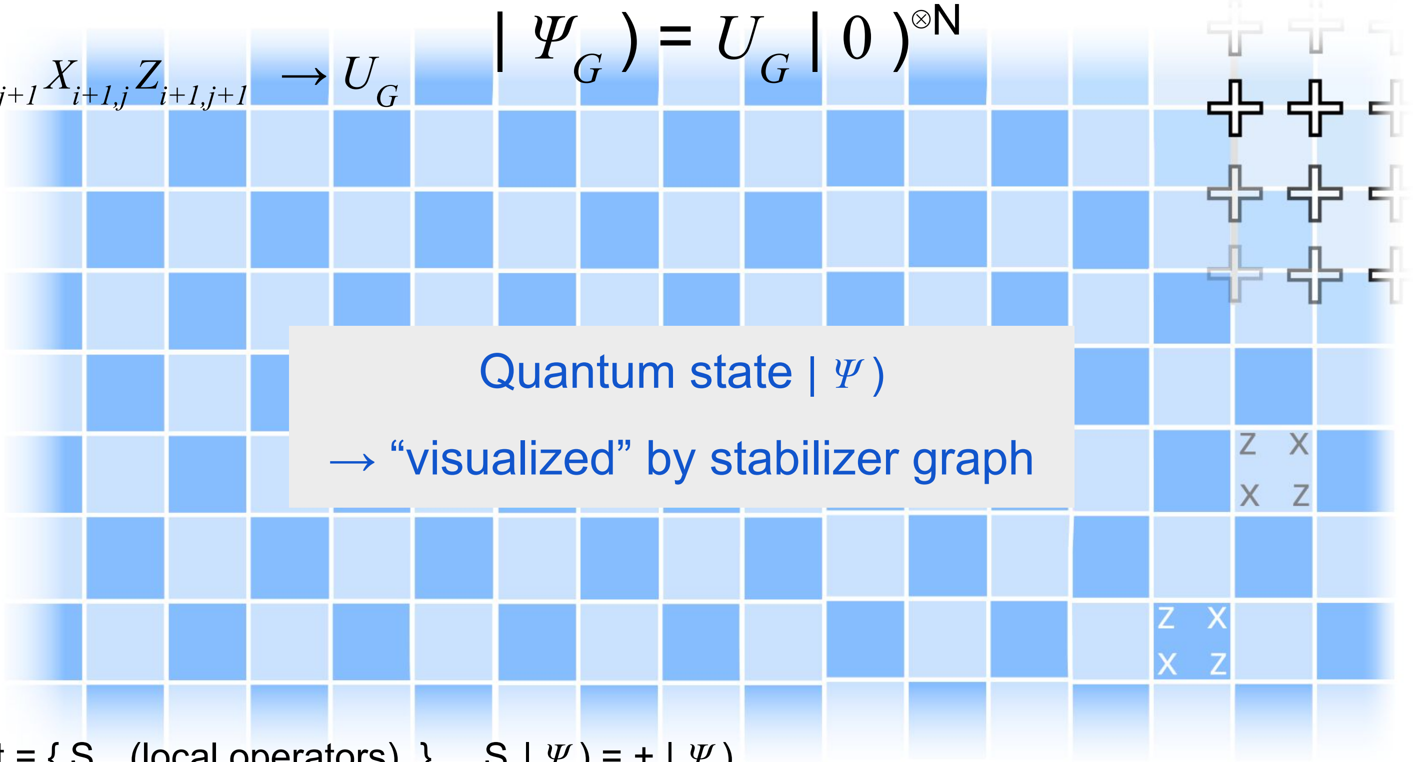
Abelian braiding statistics by Ramsey interferometry



Non-Abelian braiding of graph vertices in a superconducting processor

$$H = \sum Z_{i,j} X_{i,j+1} X_{i+1,j} Z_{i+1,j+1} \rightarrow U_G$$

$$| \Psi_G) = U_G \,| 0)^{\otimes N}$$



Quantum state $| \Psi)$

→ "visualized" by stabilizer graph

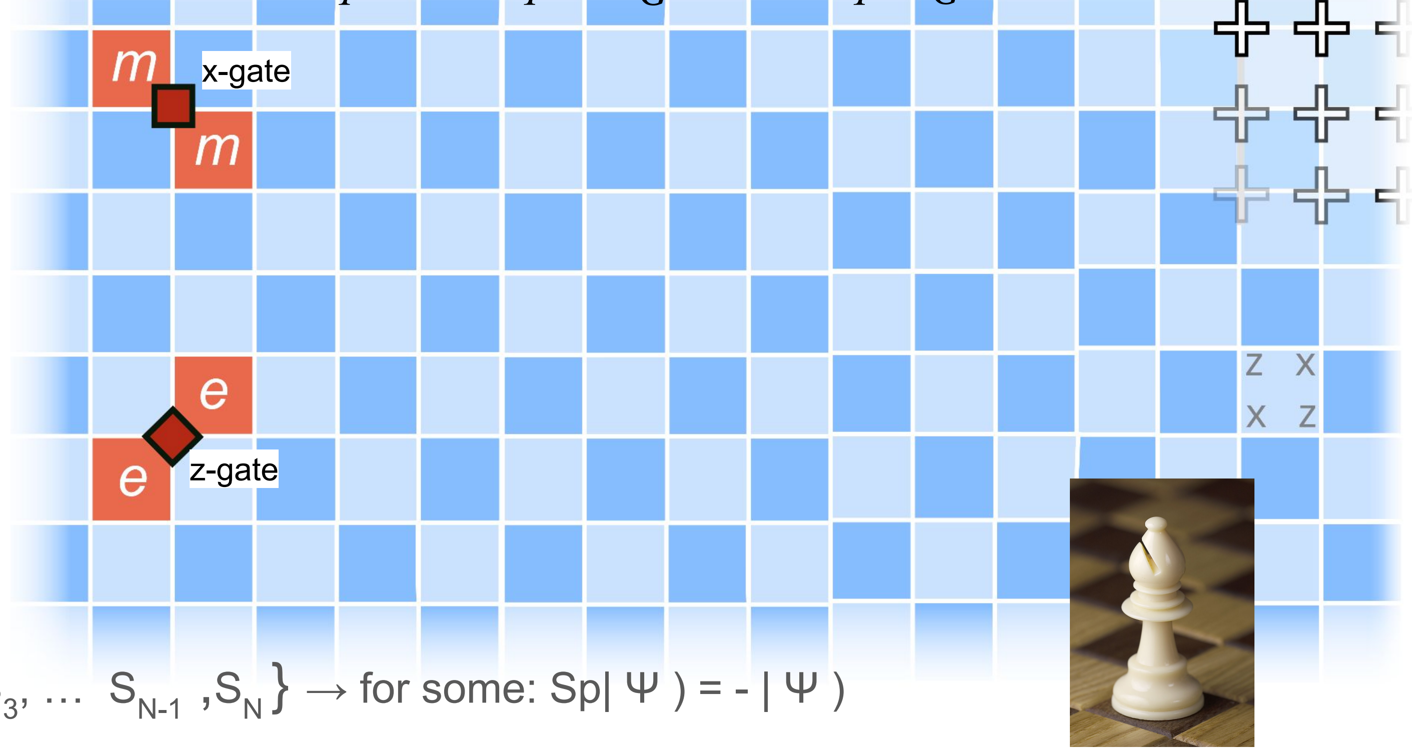
Stabilizer set = { S_p (local operators) }, $S_p | \Psi) = + | \Psi)$

$\{ S_1, S_2, S_3, \ldots, S_{N-1}, S_N \}$ → Stabilizer set

Andersen *et al.* nature 618, 264–269 (2023)

“quasi-particles” → Plaquette violations

$$|\,\Psi_1\,) = U_1\,|\,\Psi_G\,) \;=\; U_1\,U_G\,|\,0\,)^{\otimes N}$$

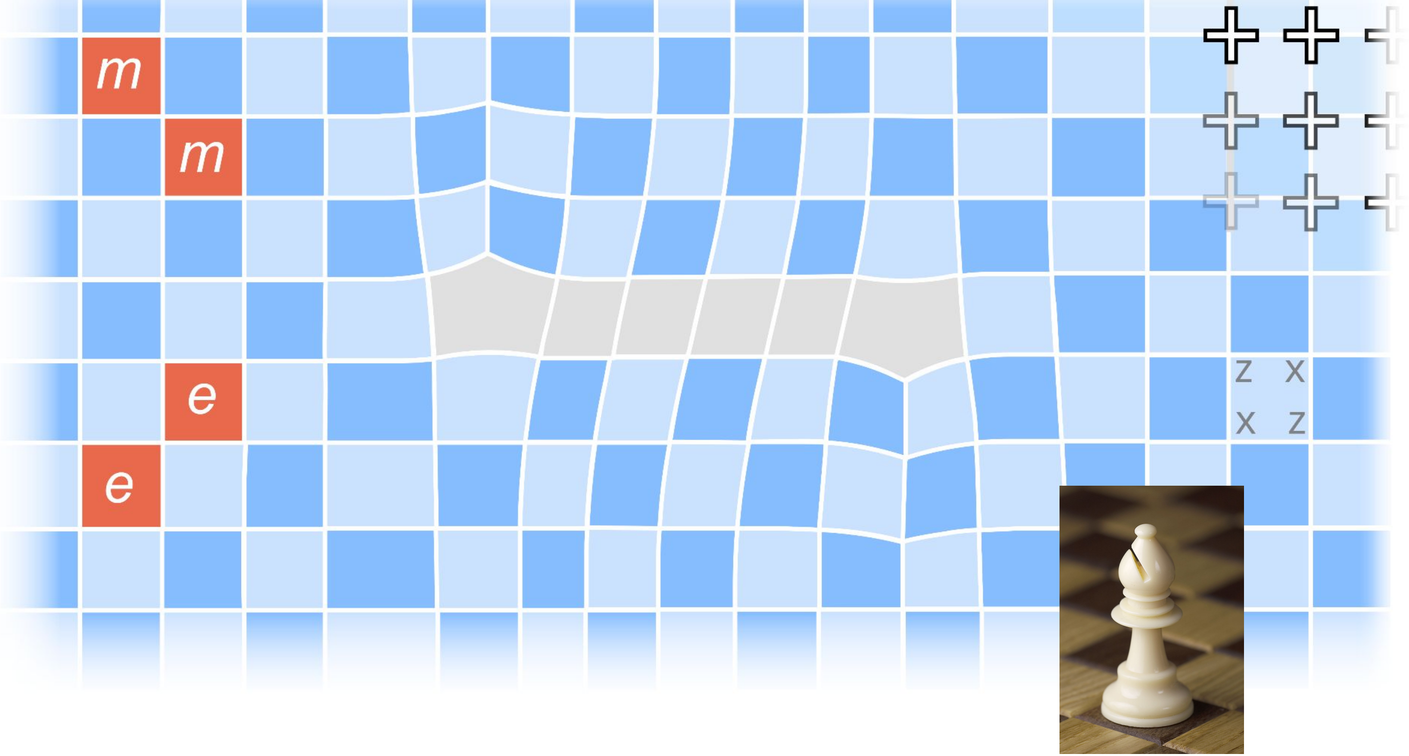


$\{\, S_1, S_2, S_3, \ldots\; S_{N-1}\;, S_N \,\}$ → for some: Sp| Ψ) = - | Ψ)

e and *m* on different sublattices→ can never “meet”

Unitarily modifying wavefunctions to have “defects”

$$|\Psi_2\rangle = U_2|\Psi_1\rangle = U_2 U_1 U_G |0\rangle^{\otimes N}$$



Unitarily modifying wavefunctions to have "defects"

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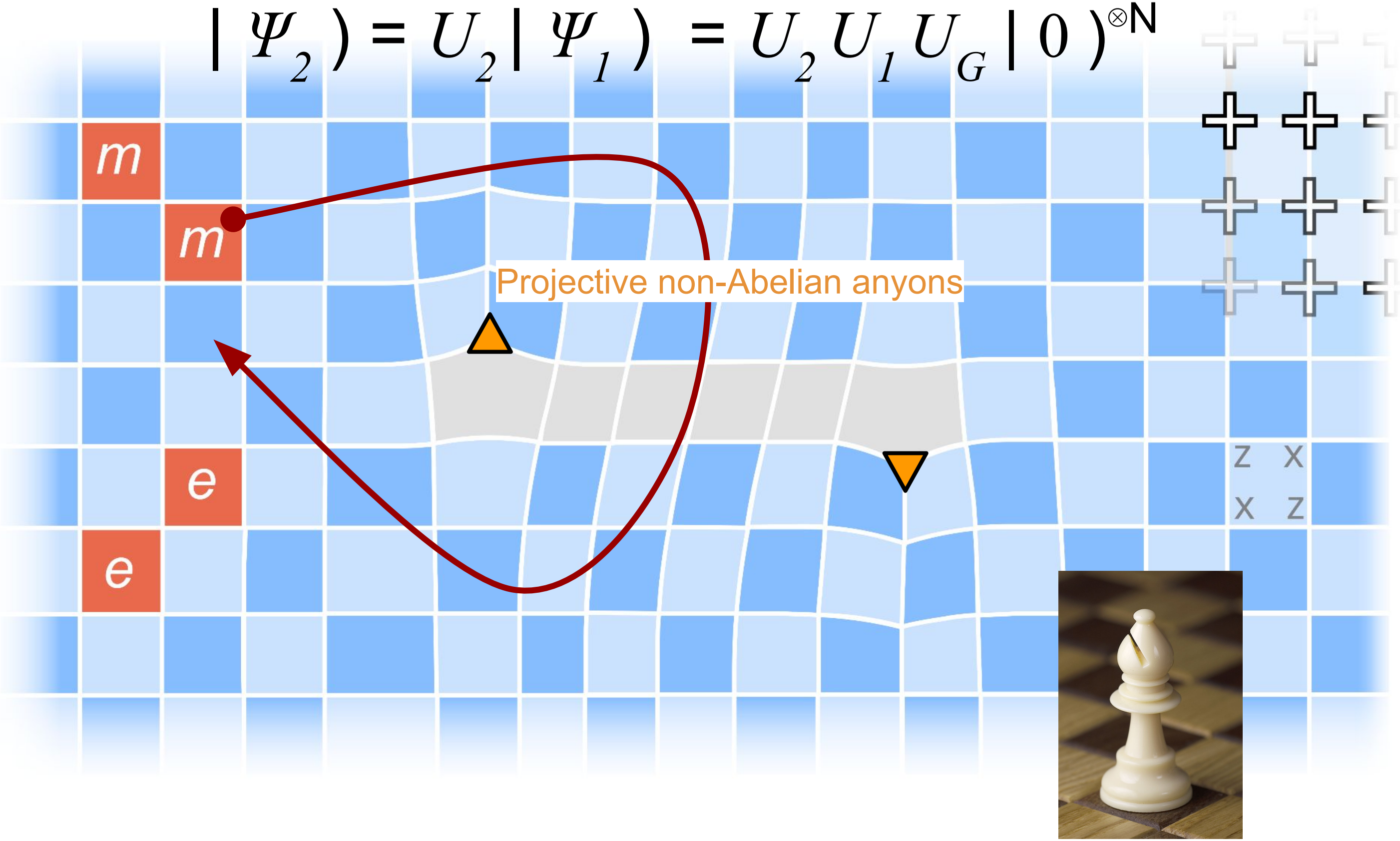
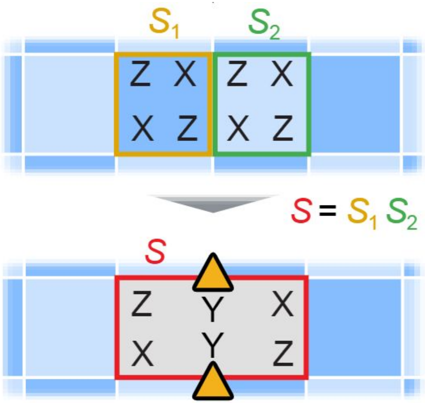
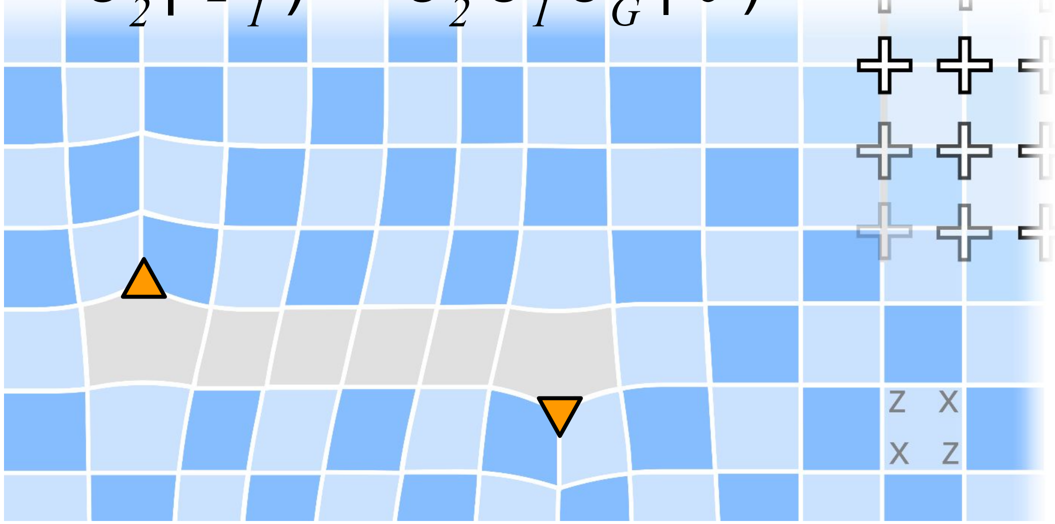


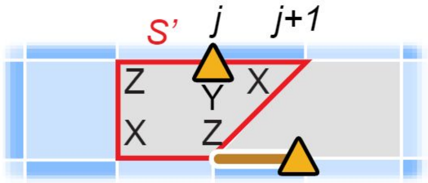
Recipe to modifying wavefunctions to have Degree-3 vertices

$$| \Psi_2 \rangle = U_2 | \Psi_1 \rangle = U_2 U_1 U_G | 0 \rangle^{\otimes N}$$





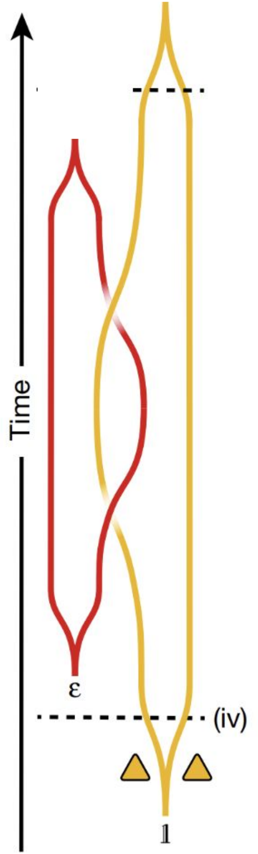
$U = \exp(\pi/8\ [S', S]) = \exp(i\ \pi/4\ X_{i,j} Z_{i,j+1})$

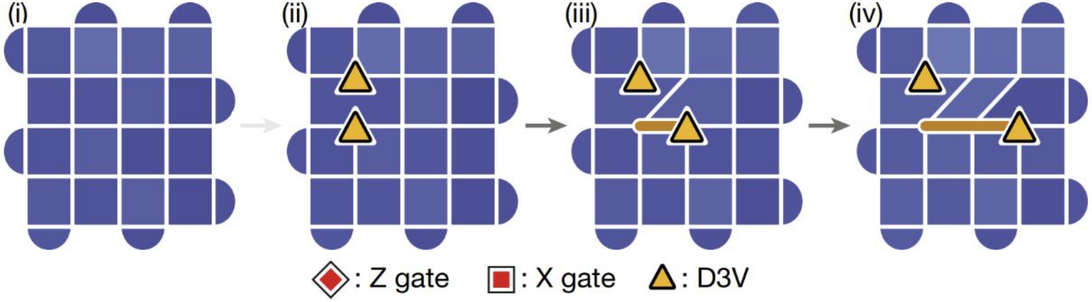


Move the D3Vs with 2-qubit gates
→ deform the stabilizer graph !

Experimentally verifying the fusion rules

Step	Gate
(ii)→(iii)	$U\_(X_{2,1}Z_{2,2})$
(iii)→(iv)	$U\_(X_{2,2}Z_{2,3})$





Experimentally verifying the fusion rules

Step	Gate
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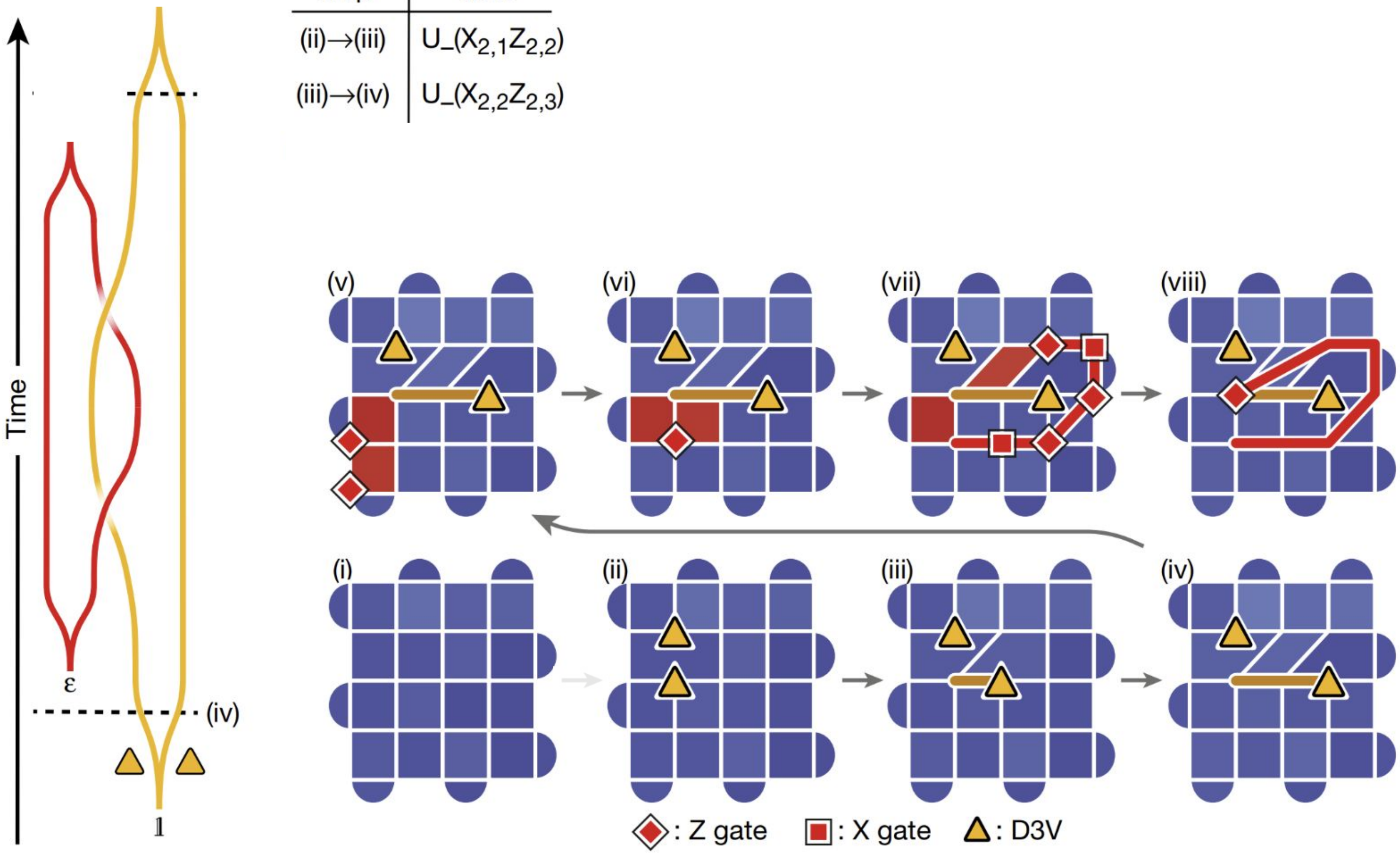
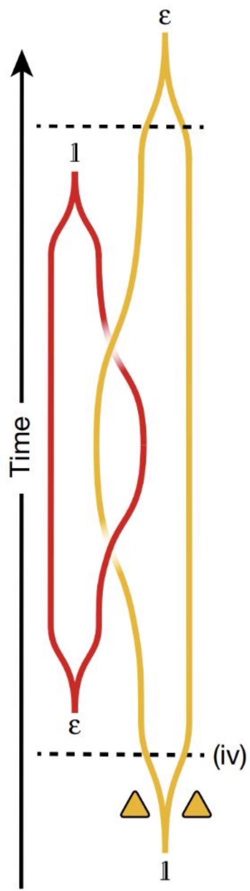
(iii)→(iv)	$U\_(X_{2,2}Z_{2,3})$



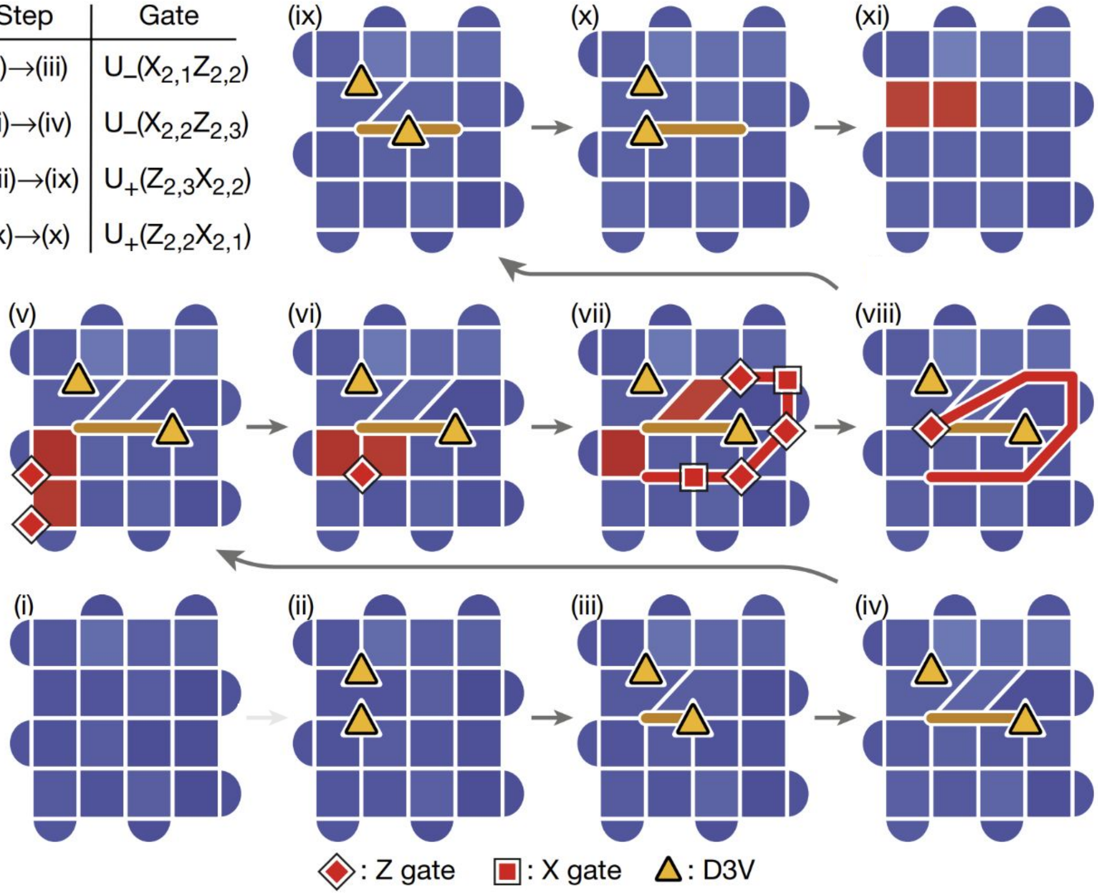
Experimentally verifying the fusion rules

Fermion can fuse into a D3V

$$\sigma \times \epsilon = \sigma$$



Step	Gate
(ii)→(iii)	$U_{-}(X_{2,1}Z_{2,2})$
(iii)→(iv)	$U_{-}(X_{2,2}Z_{2,3})$
(viii)→(ix)	$U_{+}(Z_{2,3}X_{2,2})$
(ix)→(x)	$U_{+}(Z_{2,2}X_{2,1})$



Experimentally verifying the fusion rules

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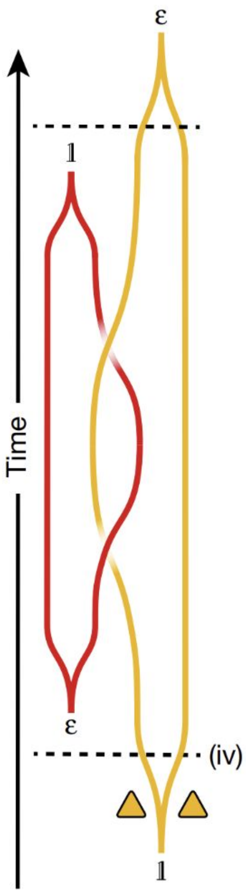
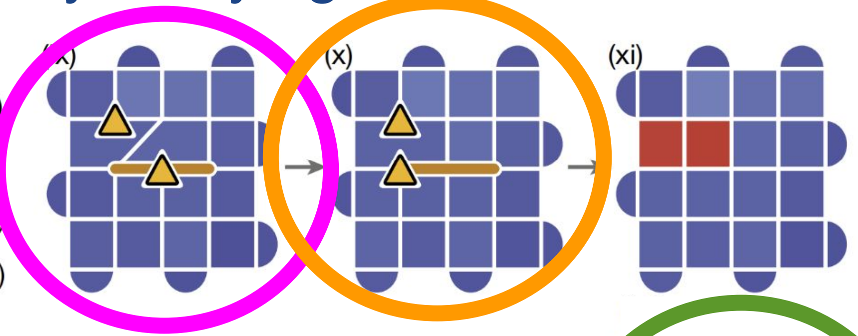
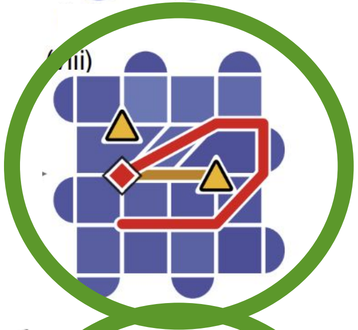


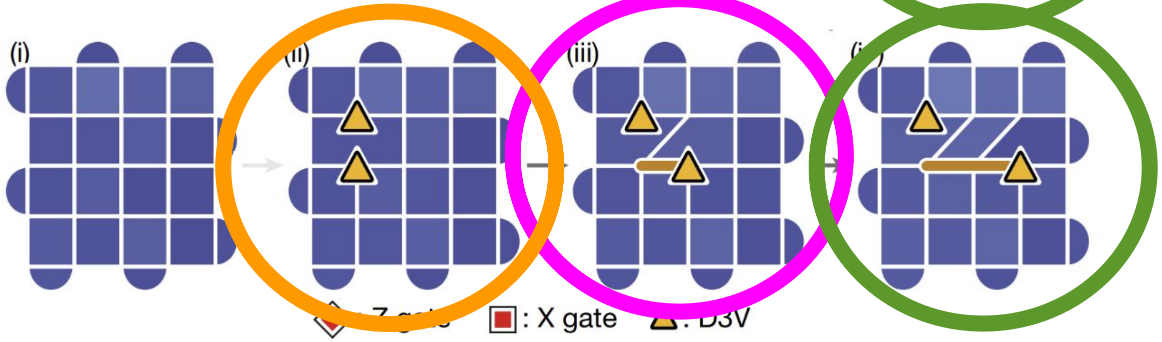
Step	Gate
(ii)→(iii)	$U_-(X_{2,1}Z_{2,2})$
(iii)→(iv)	$U_-(X_{2,2}Z_{2,3}$
(viii)→(ix)	$U_+(Z_{2,3}X_{2,2}$
(ix)→(x)	$U_+(Z_{2,2}X_{2,1})$



Two D3Vs can store (and later reveal through fusion) either zero or one fermion

$$\sigma \times \sigma = 1 + \varepsilon$$



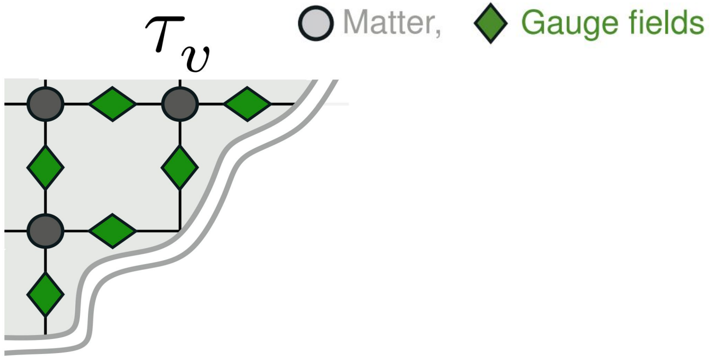


Visualizing Dynamics of Charges and Strings in (2+1)D Lattice Gauge Theories

$$\mathcal{H}_{\mathsf{LGT}} = -\underbrace{\sum_{plaq.} B_p}_{\text{magnetic flux}} - \underbrace{\sum_{\text{links}} Z_l}_{\text{electric field}} \underbrace{-\sum_{\text{links}} \tau_v^Z X_i \tau_{v'}^Z}_{\text{matter-field coupling}} \underbrace{-\sum_{\text{vert.}} \tau_v^X}_{\text{mass / charge}}$$

$$A_v = \prod_{i\in v} Z_i$$

$$B_p = \prod_{i\in p} X_i$$



$$G_v = A_v \tau_v^X \;\rightarrow [\mathcal{H}_{\mathsf{LGT}}, G_v] = 0, \forall v$$

arXiv:2409.17142

Visualizing Dynamics of Charges and Strings in (2+1)D Lattice Gauge Theories

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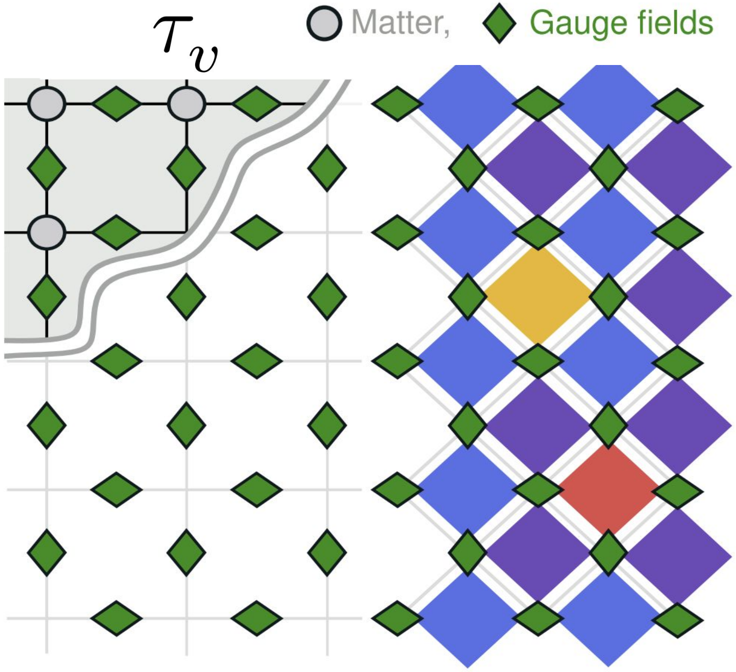
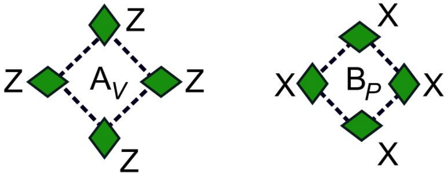
$$A_v = \prod_{i \in v} Z_i$$

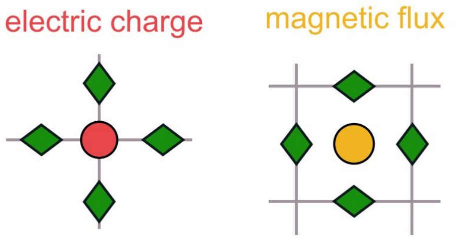
$$B_p = \prod_{i \in p} X_i$$



$$G_v = A_v \tau_v^X \rightarrow [\mathcal{H}_{\mathrm{LGT}}, G_v] = 0, \forall v$$

$$\mathcal{H} = -J_E \sum_v A_v - J_M \sum_p B_p - h_M \sum_{\text{links}} Z_l - h_E \sum_{\text{links}} X_l$$

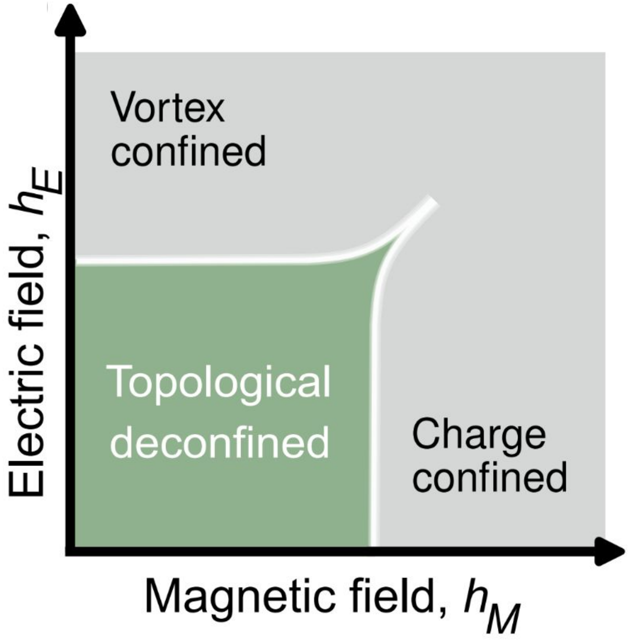


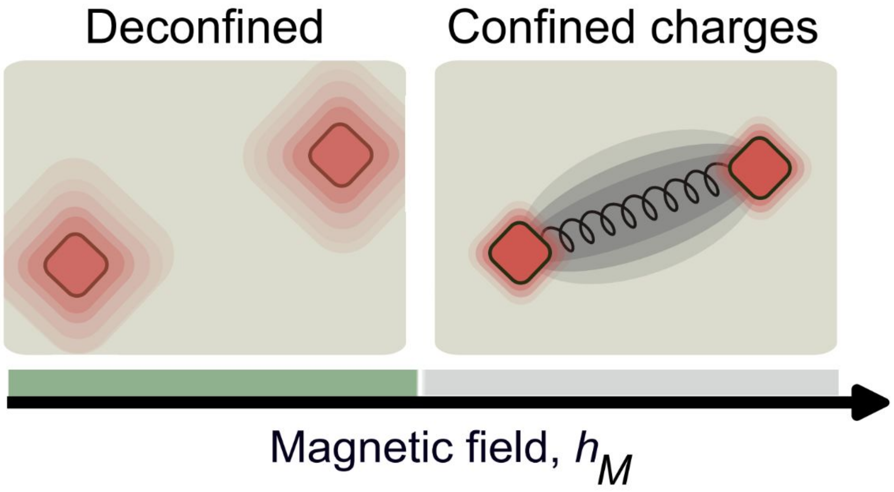


arXiv:2409.17142

Phase diagram of the LGT

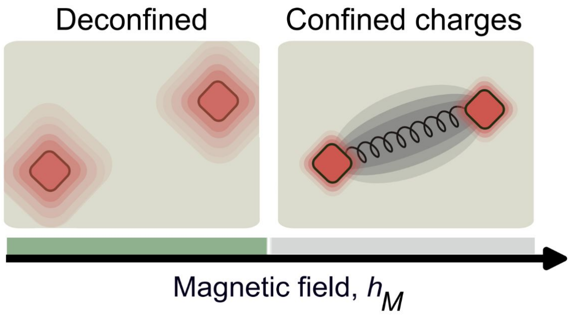
$$\mathcal{H} = -J_E \sum_v A_v - J_M \sum_p B_p - h_M \sum_{\text{links}} Z_l - h_E \sum_{\text{links}} X_l$$



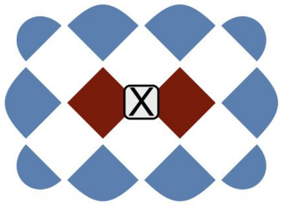


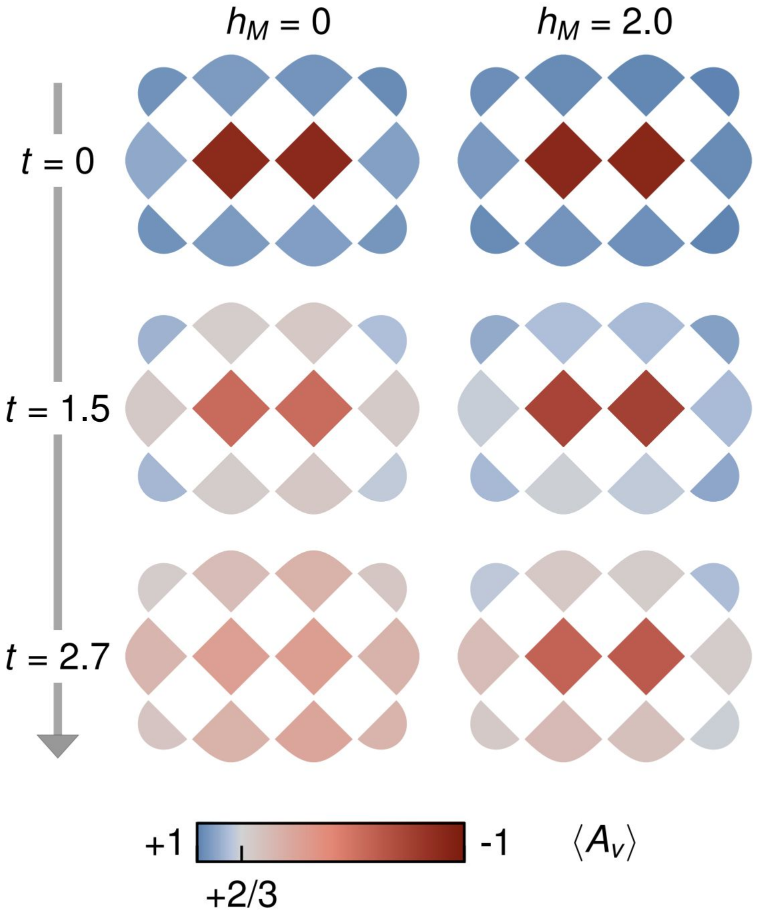
E. Fradkin and S. H. Shenker, PRD (1979), S. Trebst et al., PRL(2007), J. Vidal et al., PRB (2009).

Confinement of electric excitations

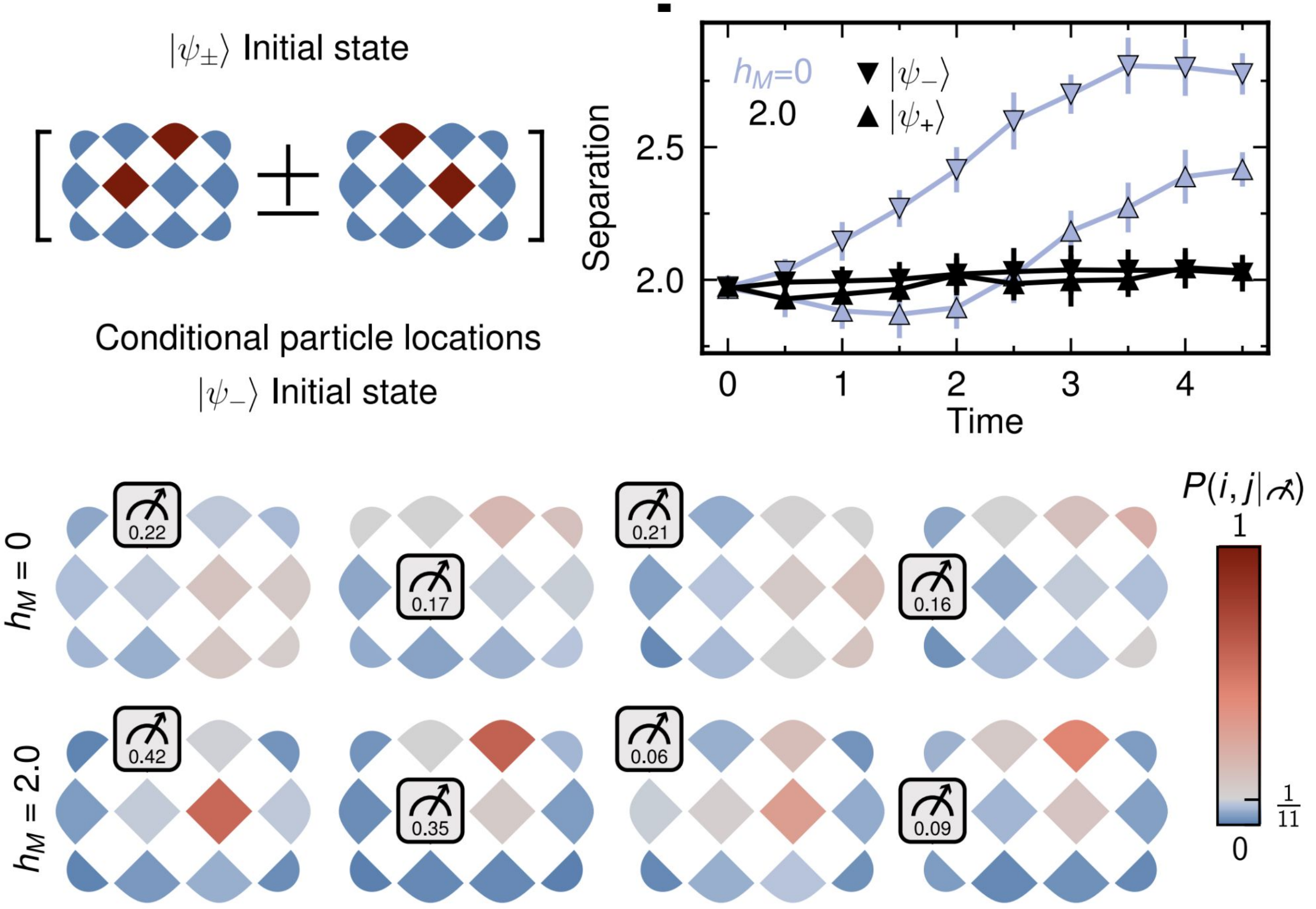


$$\mathcal{H} = -J_E \sum_v A_v - J_M \sum_p B_p - h_M \sum_{\text{links}} Z_l - h_E \sum_{\text{links}} X_l$$

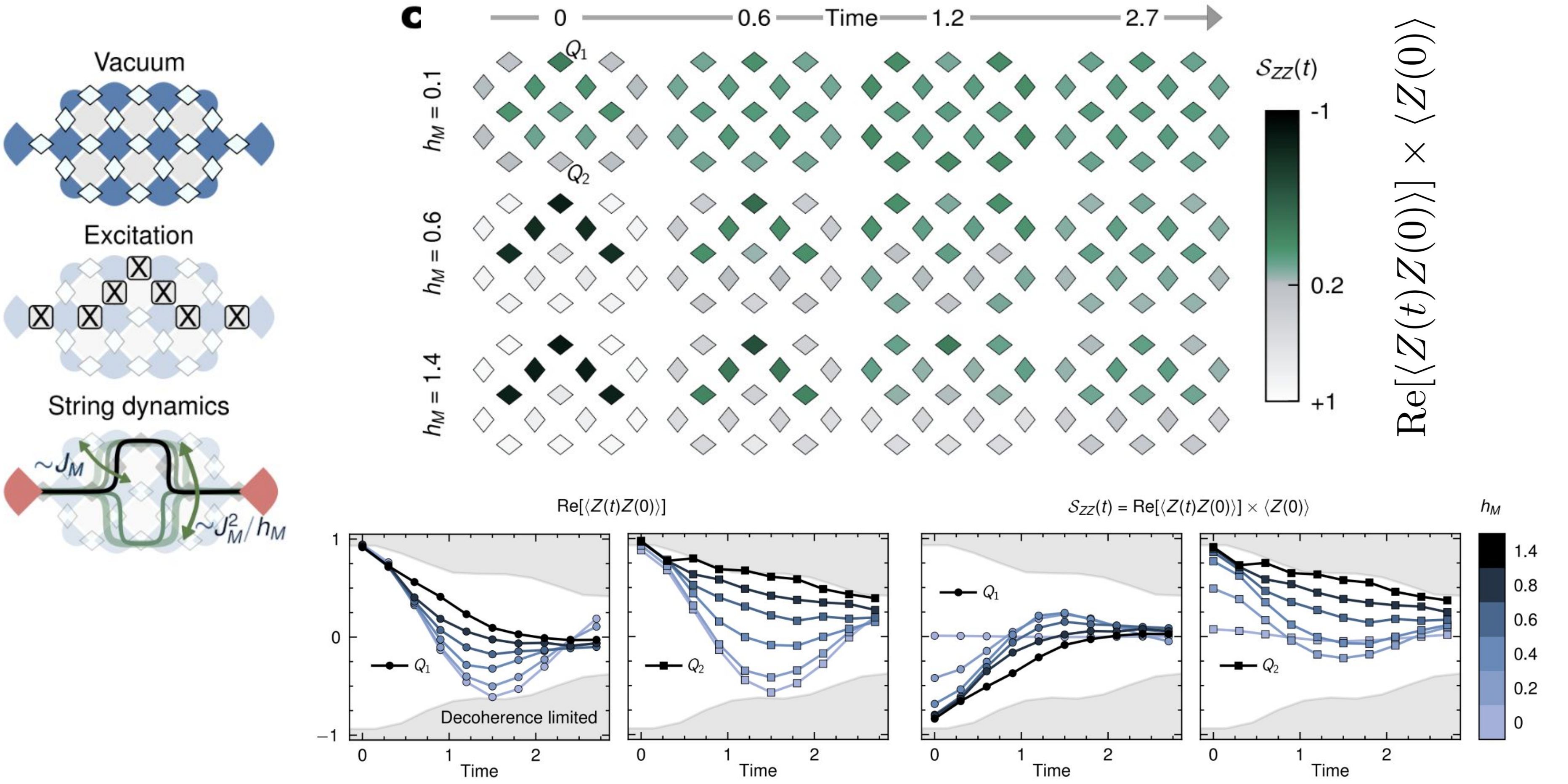




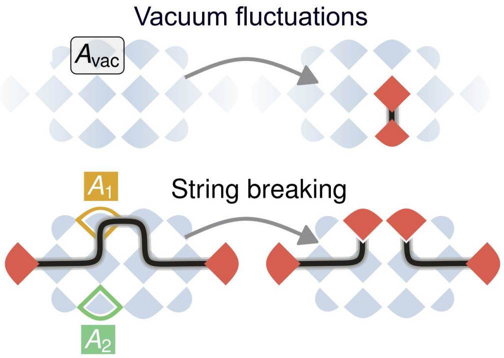
Confinement of electric excitations

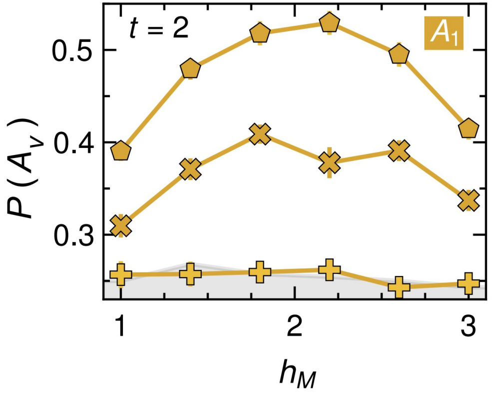


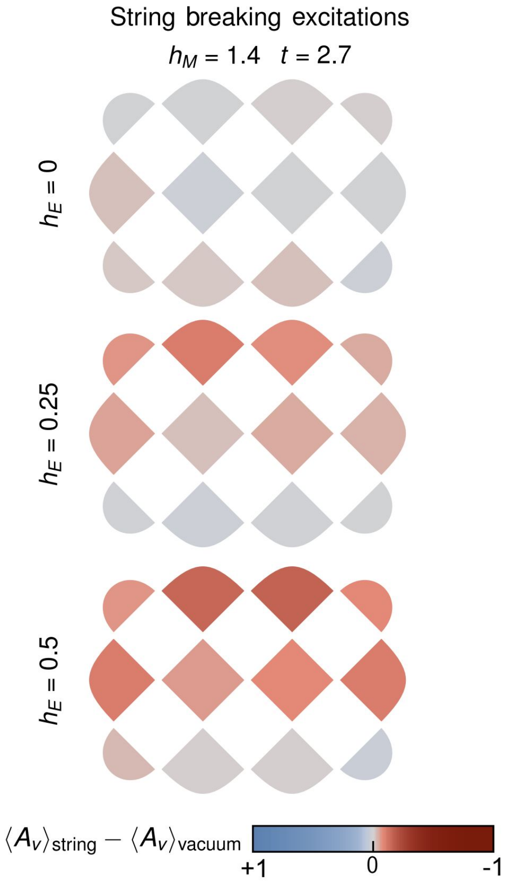
Dynamics of the string connecting two fixed electric particles

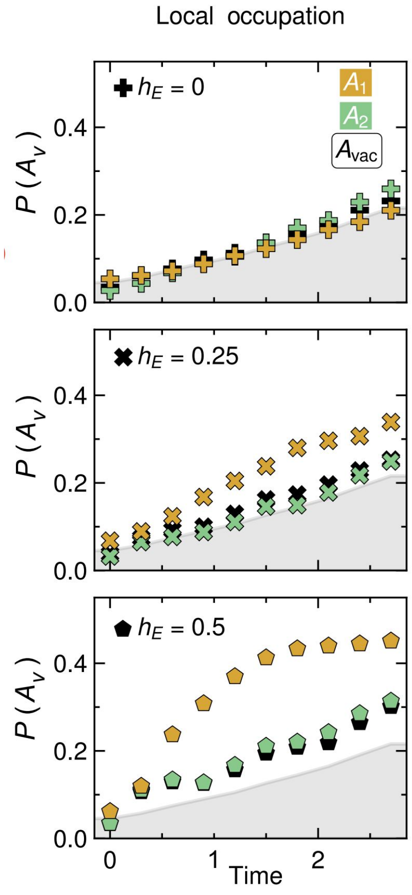


Dynamics of the string connecting two fixed electric particles









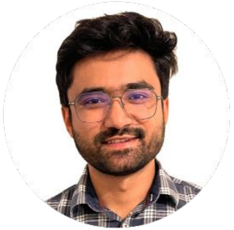
Google Quantum AI, Santa Barbara, California

Quantum residency program for PhD students

Jesse Hoke
(Stanford)

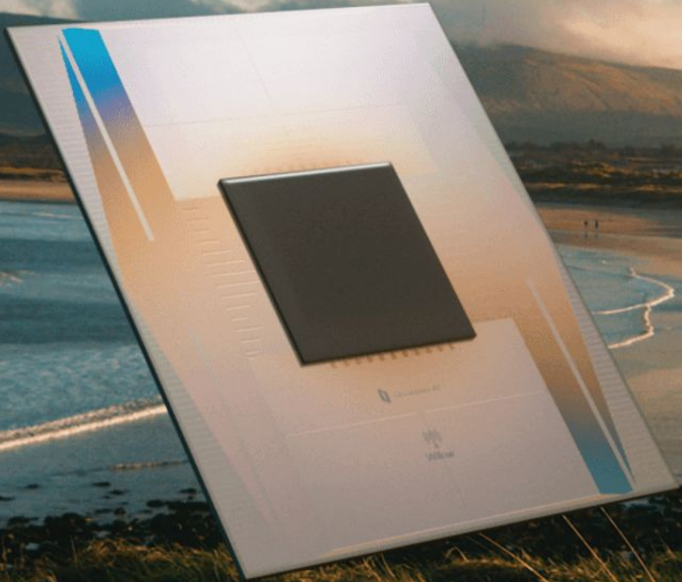
Eliott Rosenberg
(Cornell)

Tyler Cochran
(Princeton)



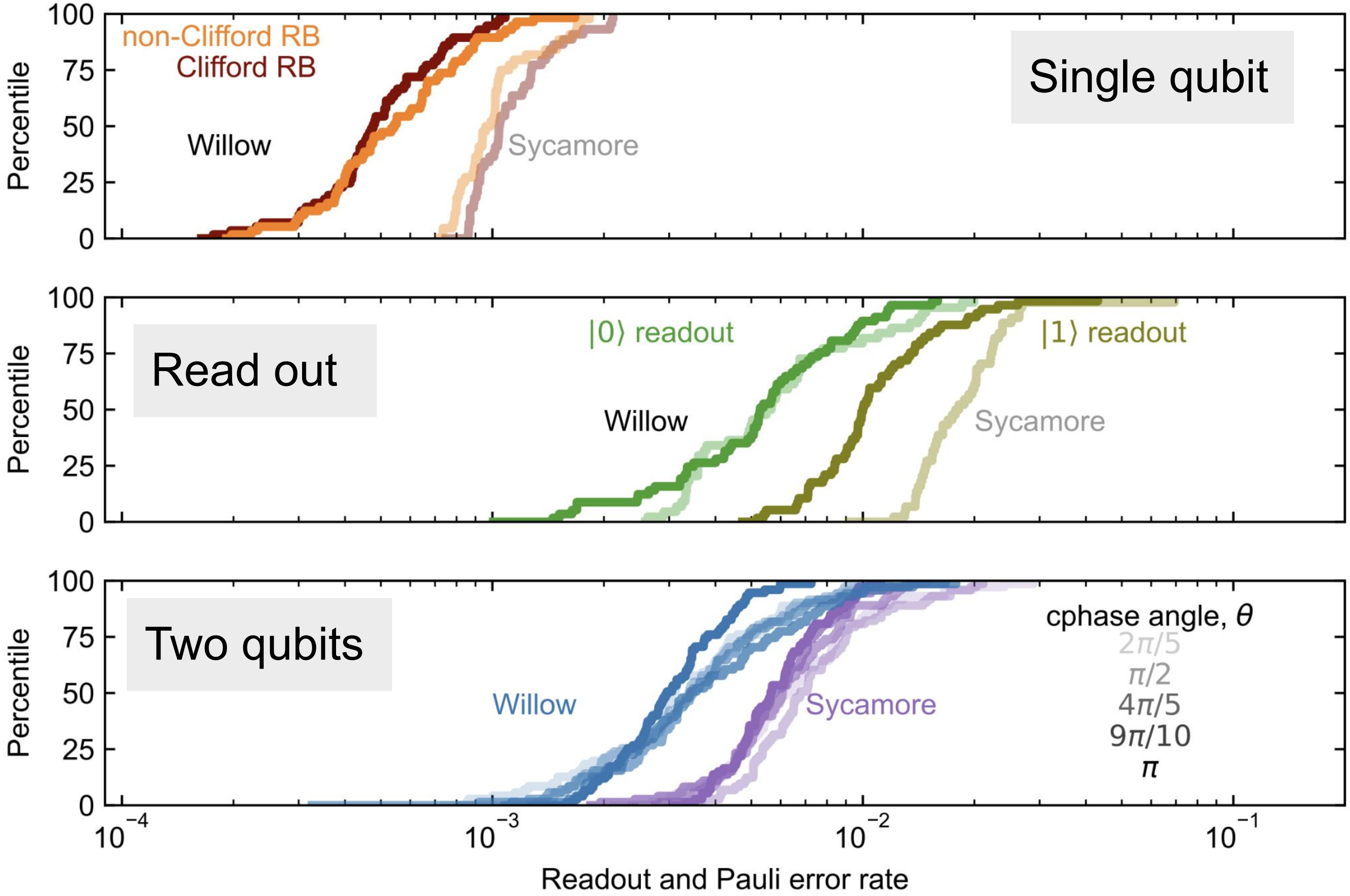
Gaurav Gyawali
(Cornell)

“ I have a feeling we are not in Kansas anymore ”



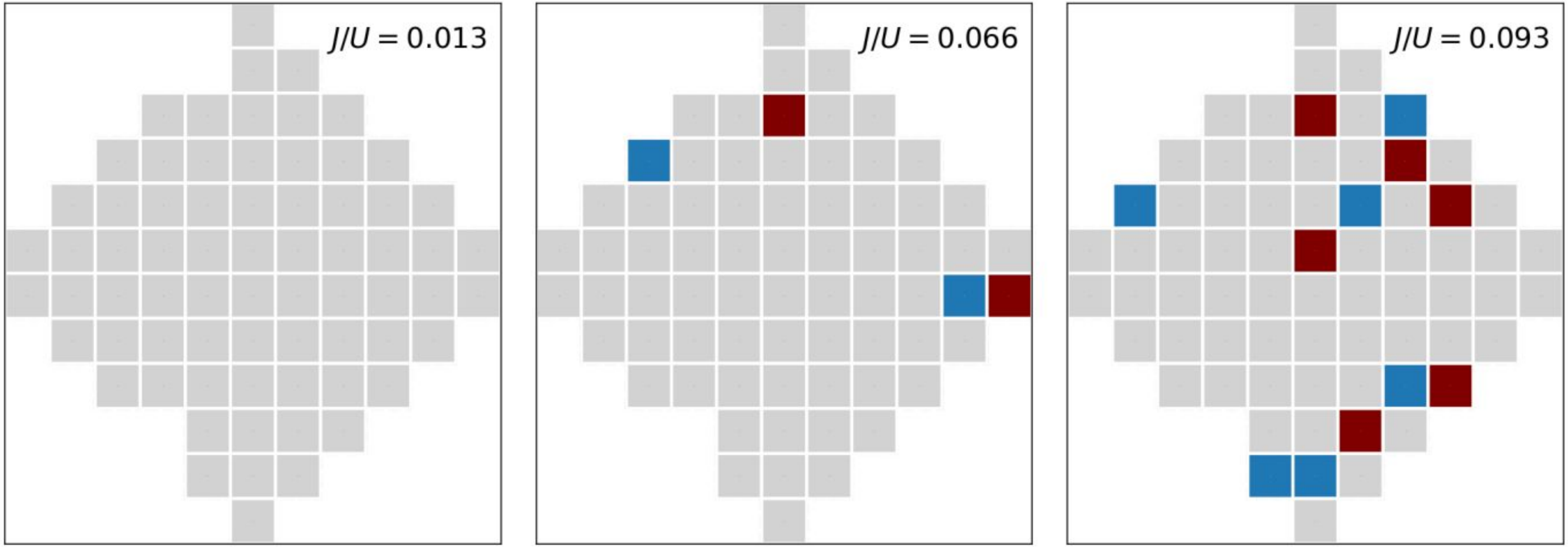
Willow

Improvement in fidelities from Sycamore to Willow



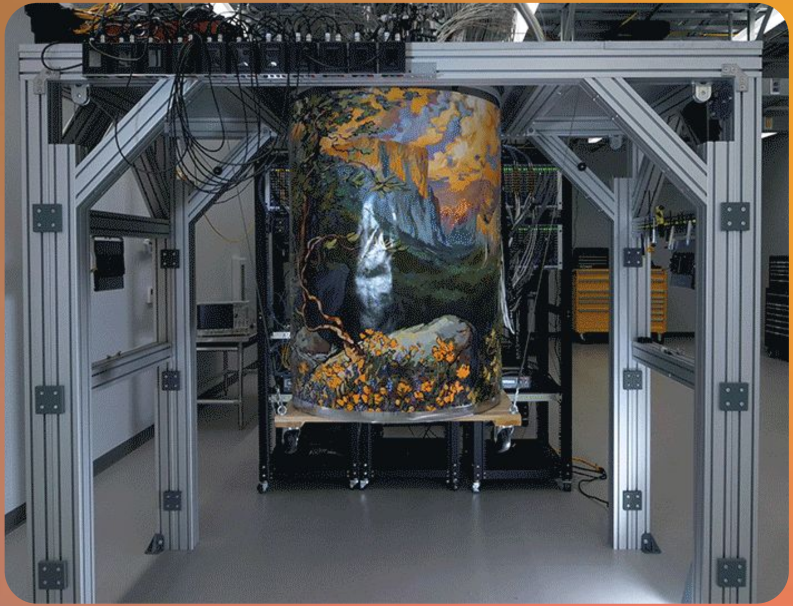
Theoretical properties vs. physical properties

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



Sycamore Quantum Computer

Subsystem	Number of parts
Quantum processor	**1**
Package + mount	1,000
Dilution refrigerator	1
Amplifiers & filters	1,000
Attenuators	1,000
Wiring	4,000
Control hardware	2,000



What are the possible phases of quantum information in space-time ?