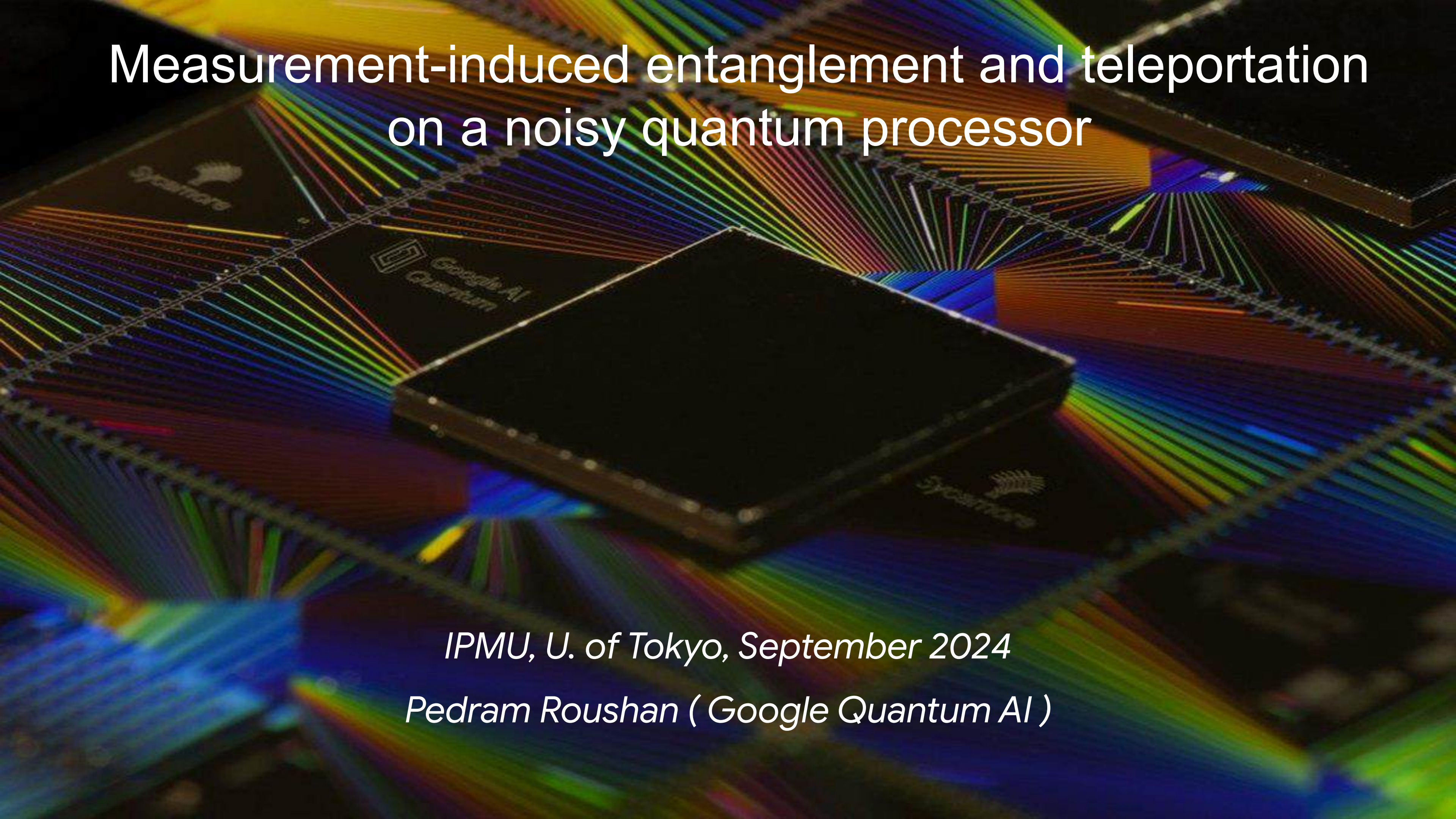
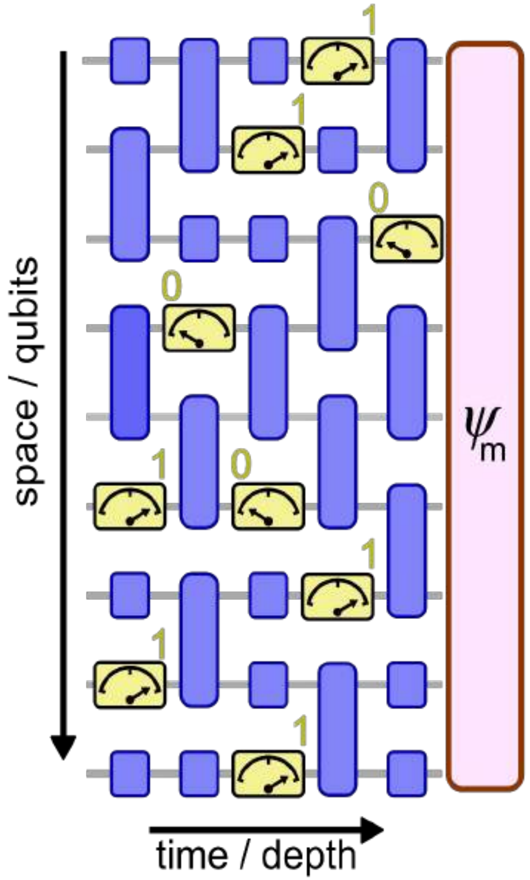
Measurement-induced entanglement and teleportation on a noisy quantum processor



IPMU, U. of Tokyo, September 2024

Pedram Roushan (Google Quantum AI)

Measurement-induced entanglement and teleportation
→ Quantum information phases in space-time



Measurement is key in many protocols

A genuine NISQ problem
Can noise destabilize phases

Jesse Hoke
(Stanford)

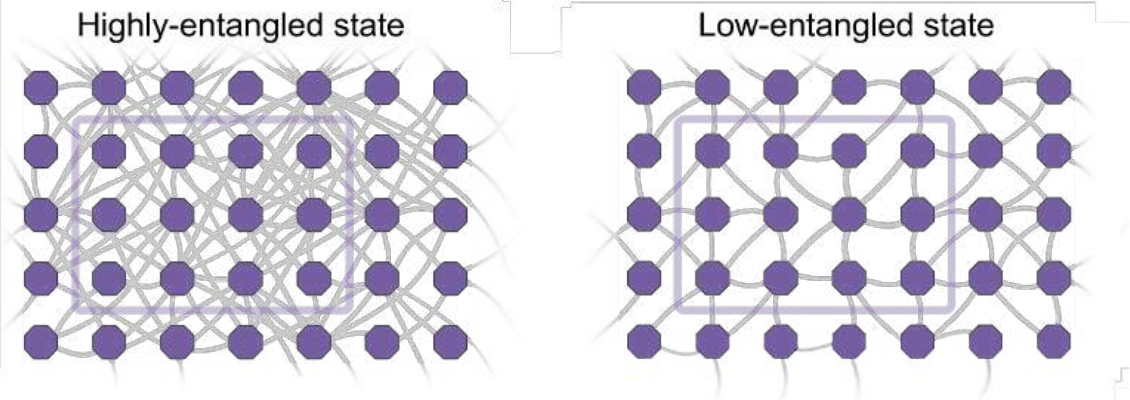
Eliott Rosenberg
(Cornell U)

Vedika Khemani
Stanford

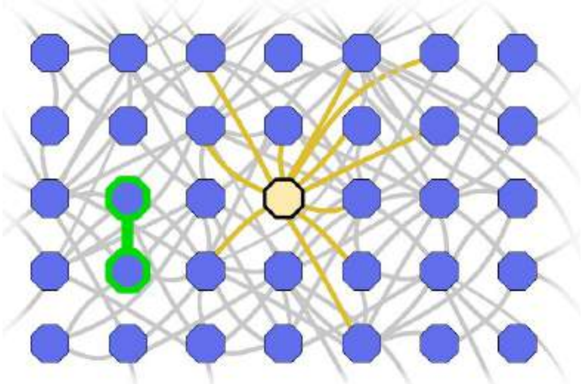
Matteo Ippoliti
Stanford

Nature **622** (2023) (arXiv:2303.04792)

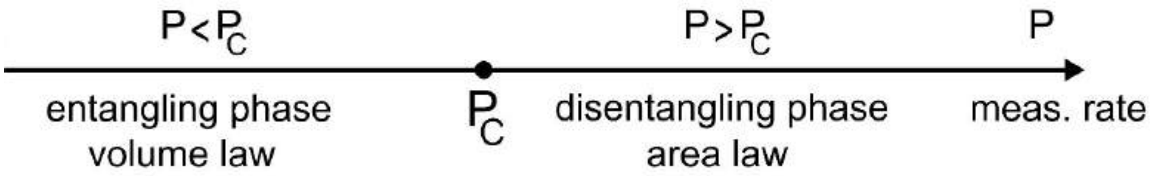
Common entanglement structures



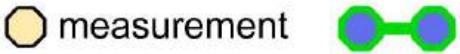
e.g. thermalizing state, $S \sim l^{d}$ e.g. MBL, $S \sim l^{d-1}$



"Vandalized resistor grid"



phase transition in quantum information

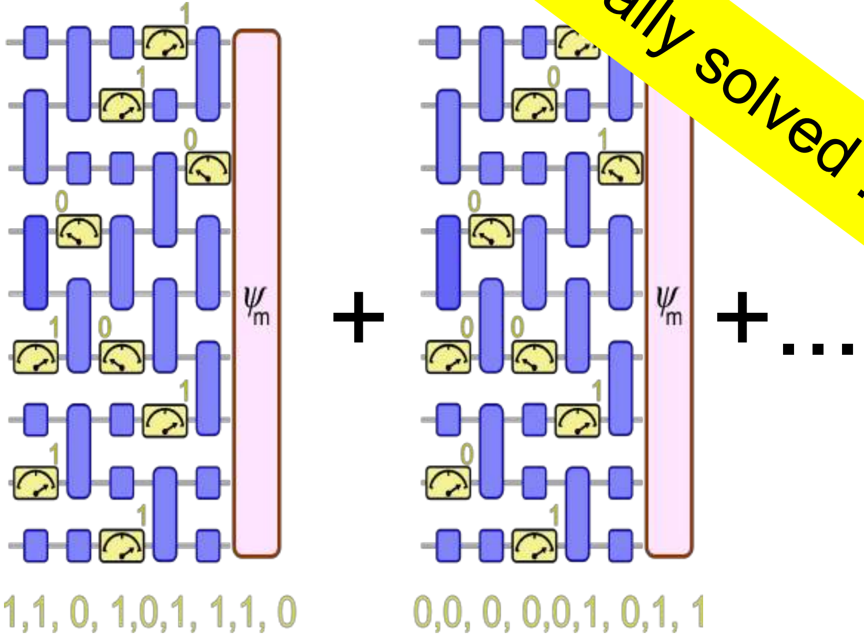


Cao, Tilloy, De Luca, SciPost Physics (2019)
Skinner, Ruhman, Nahum, PRX (2019), Li, Chen, Fisher, PRB (2018), Chan, Nandkishore, Pretko, Smith, PRB (2019)

Challenges in studying monitored circuits

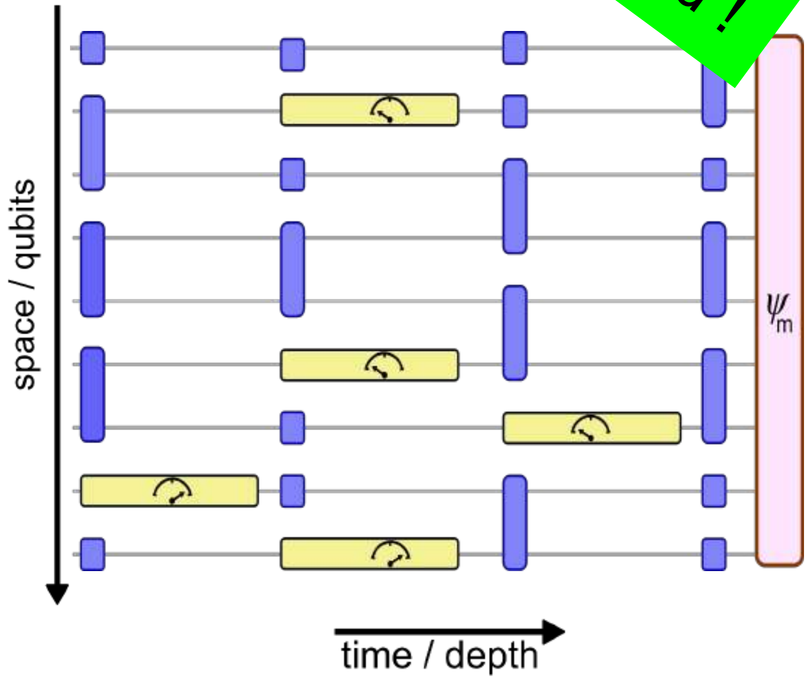
1. Post -selection: staying o m trajectory

Partially solved !

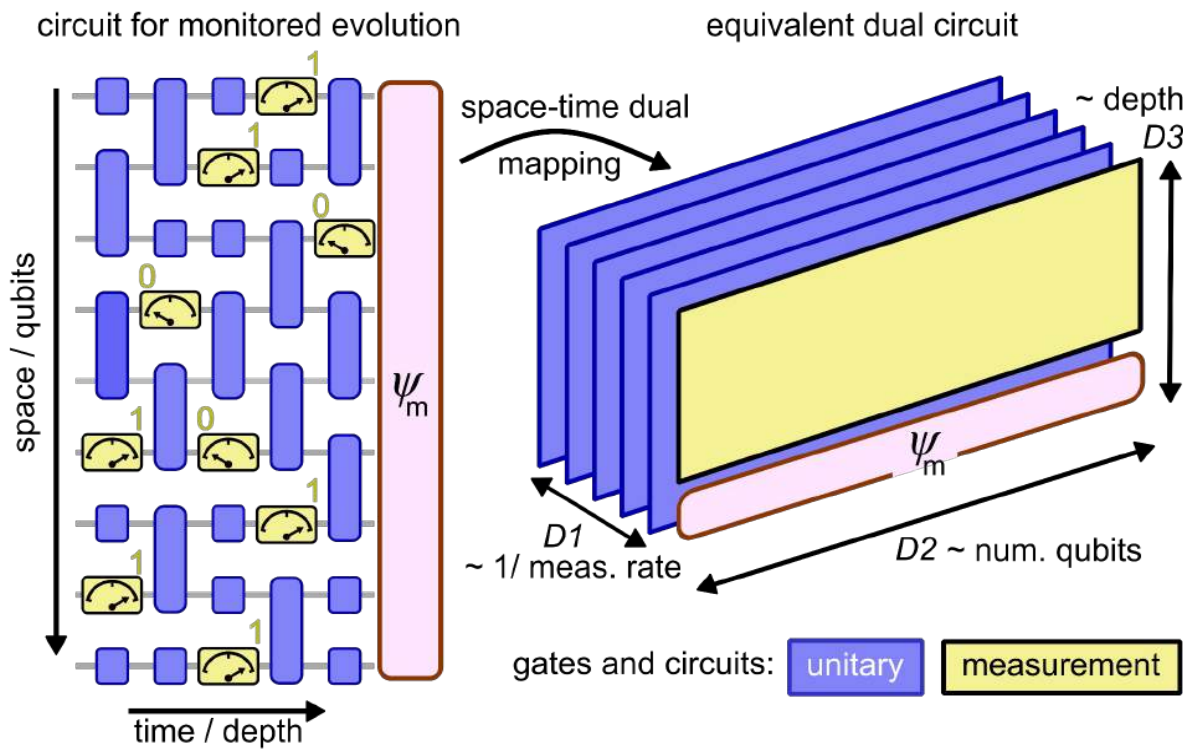


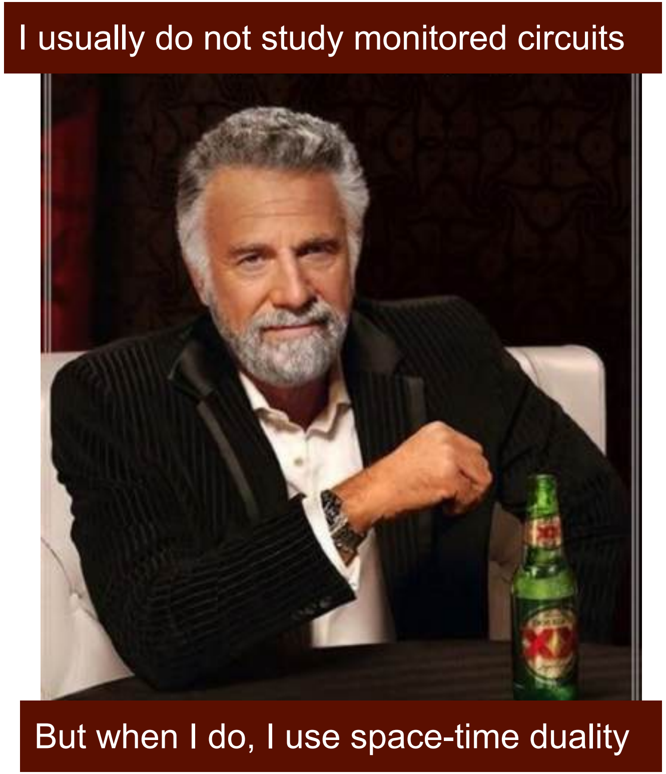
2. Mid-circuit measureme

solved !



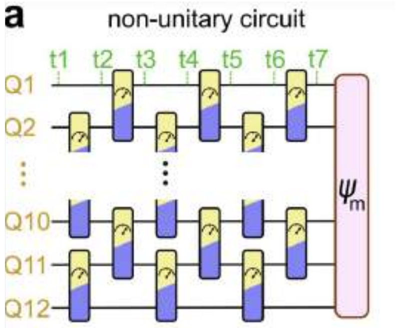
$$\sum_m \langle\psi_{\mathbf{m}}|\,\hat{C}\,|\psi_{\mathbf{m}}\rangle = \sum_m \mathrm{Tr}\Big(|\psi_{\mathbf{m}}\rangle\langle\psi_{\mathbf{m}}|\,\hat{C}\Big) = \mathrm{Tr}\sum_m |\psi_{\mathbf{m}}\rangle\langle\psi_{\mathbf{m}}|\,\hat{C} = \mathrm{Tr}(\rho_{\text{ave}}\hat{C})$$

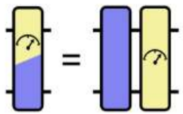


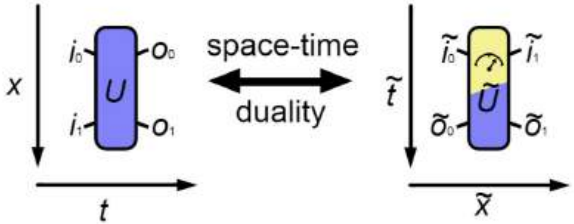


Absence of causality : “arrow of time” loses its unique role
→ network of quantum information in space-time

Implementation of space-time duality in 1D







$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -i\sin\theta & 0 \\ 0 & -i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{-2i\theta} \end{pmatrix} \mapsto \tilde{U} = \begin{pmatrix} 1 & 0 & 0 & \cos\theta \\ 0 & 0 & -i\sin\theta & 0 \\ 0 & -i\sin\theta & 0 & 0 \\ \cos\theta & 0 & 0 & e^{-2i\theta} \end{pmatrix}$$

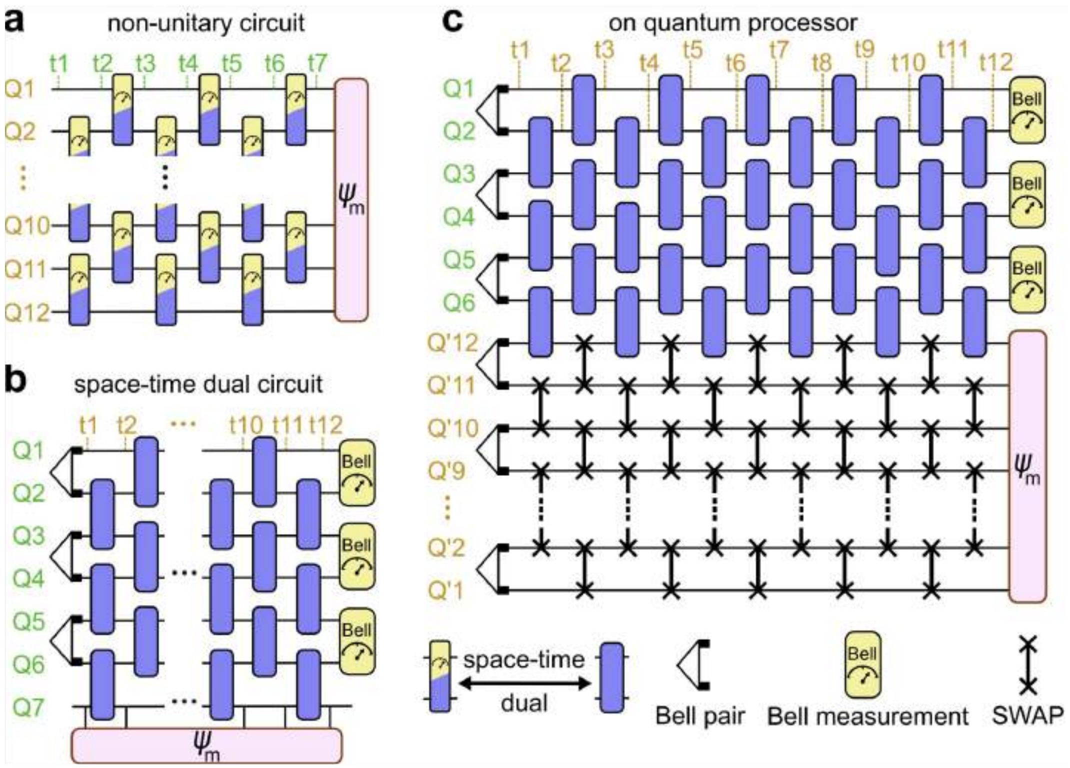
$\tilde{U} = 2VH$ where V is unitary and H is Hermitian

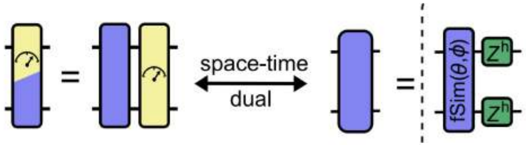
$$H = \frac{1}{2}\sqrt{1 + 3\cos^2(\theta)}\, |\psi_\theta\rangle\langle\psi_\theta| + \frac{1}{2}|\sin(\theta)|(I - |\psi_\theta\rangle\langle\psi_\theta|)$$

$$|\psi_\theta\rangle \equiv \frac{1}{\sqrt{2}}(e^{-i\theta}|00\rangle + e^{i\theta}|11\rangle)$$

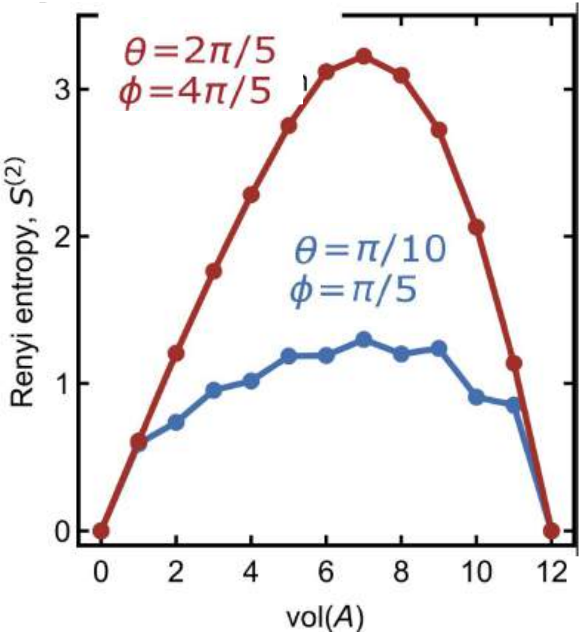
$$V' = \begin{pmatrix} 0.6487 - 0.3993i & 0.4935 + 0.4198i \\ 0.4935 + 0.4198i & 0.2901 - 0.7043i \end{pmatrix} \qquad (\theta = \pi/10)$$

Implementation of space-time duality in 1D

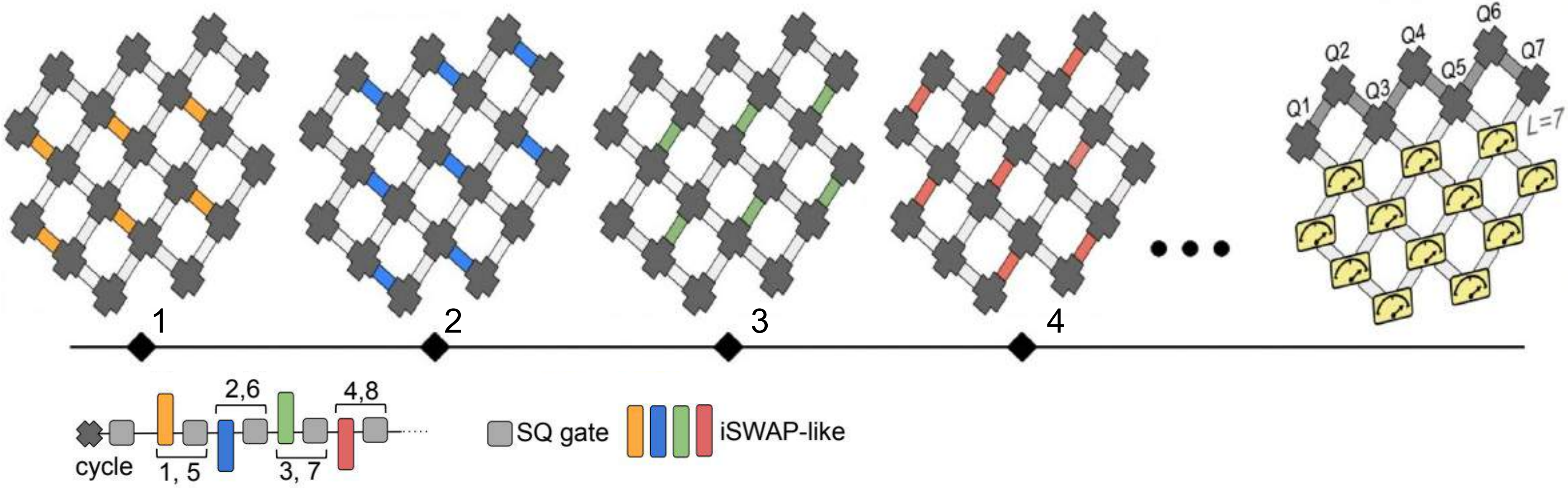


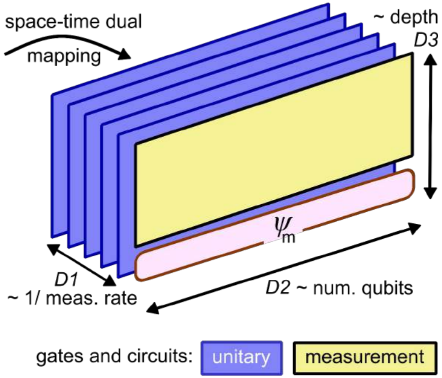


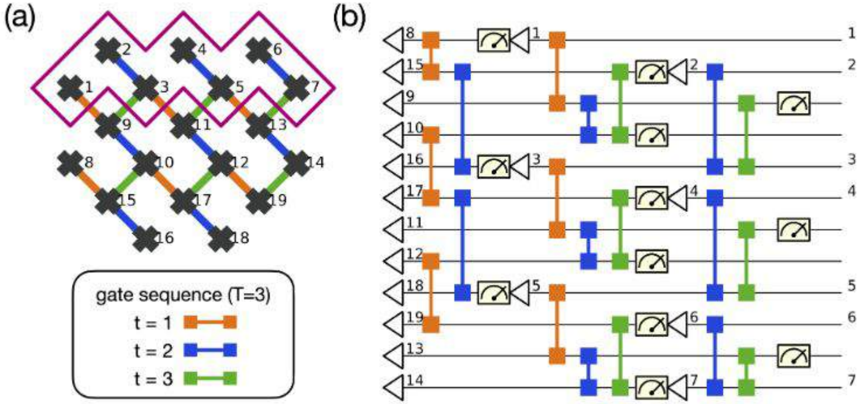
$$\mathrm{fSim}(\theta,\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & i\sin\theta & 0 \\ 0 & i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{i\phi} \end{pmatrix}$$



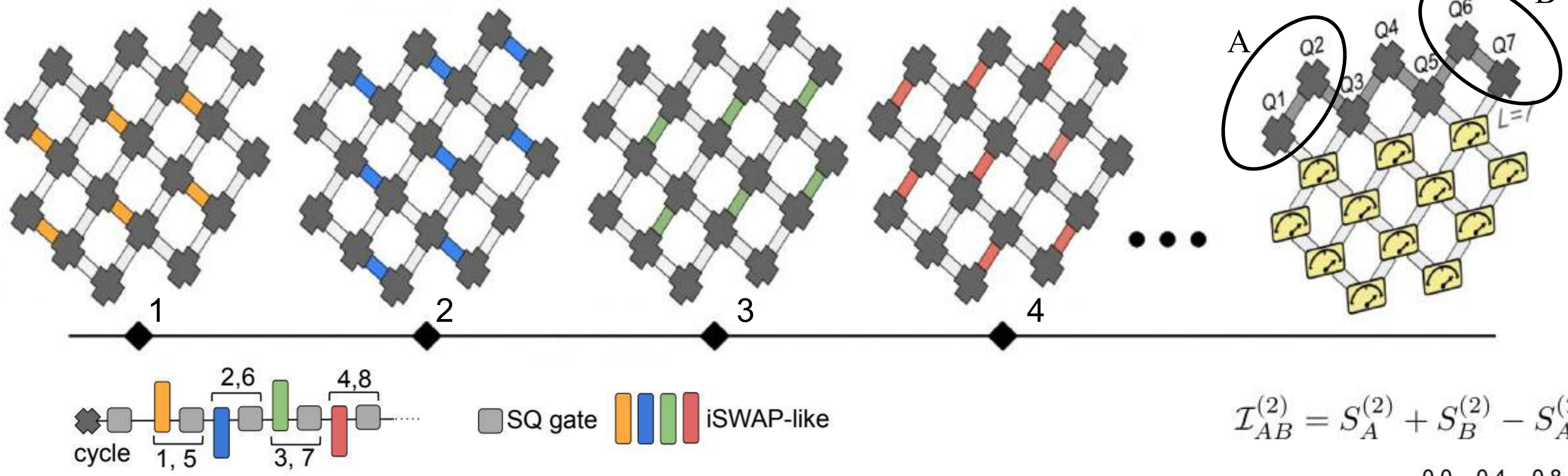
1D entanglement phases from 2D shallow quantum circuits



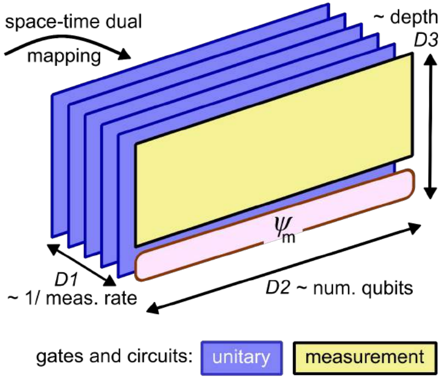




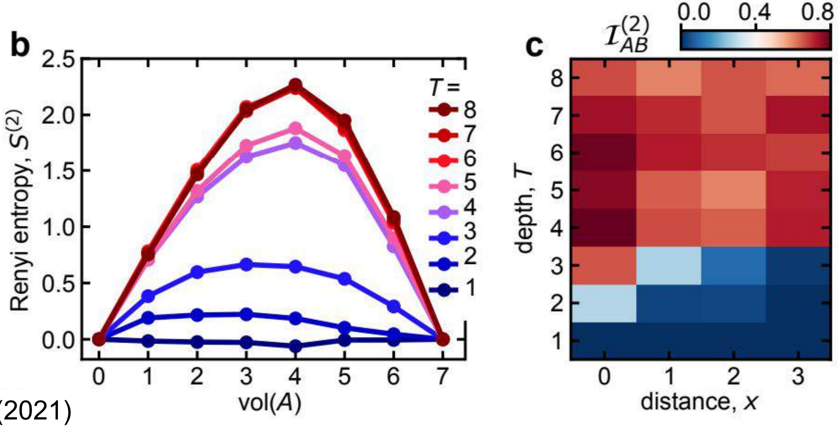
1D entanglement phases from 2D shallow quantum circuits



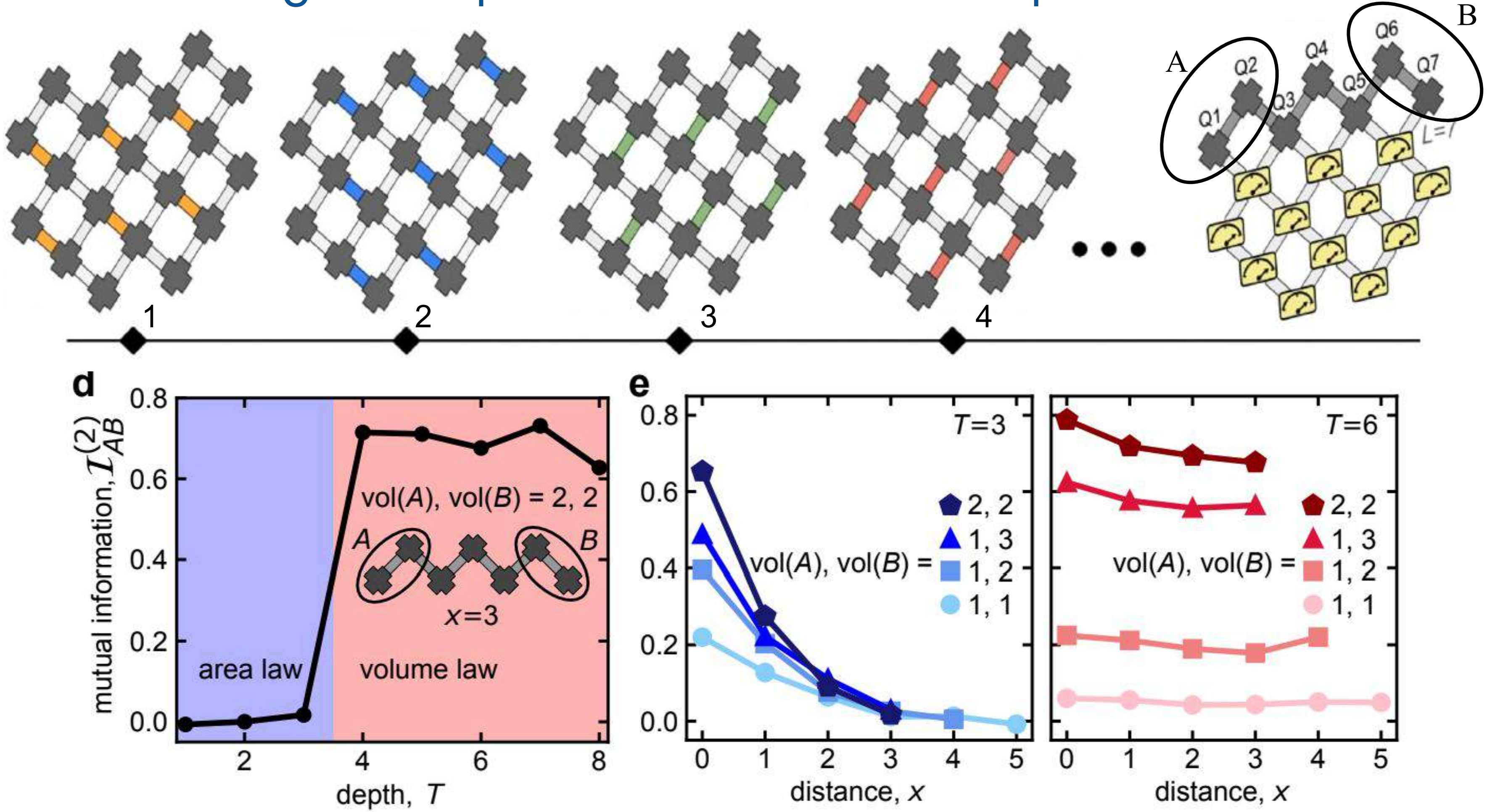
$$\mathcal{I}_{AB}^{(2)} = S_A^{(2)} + S_B^{(2)} - S_{AB}^{(2)}$$



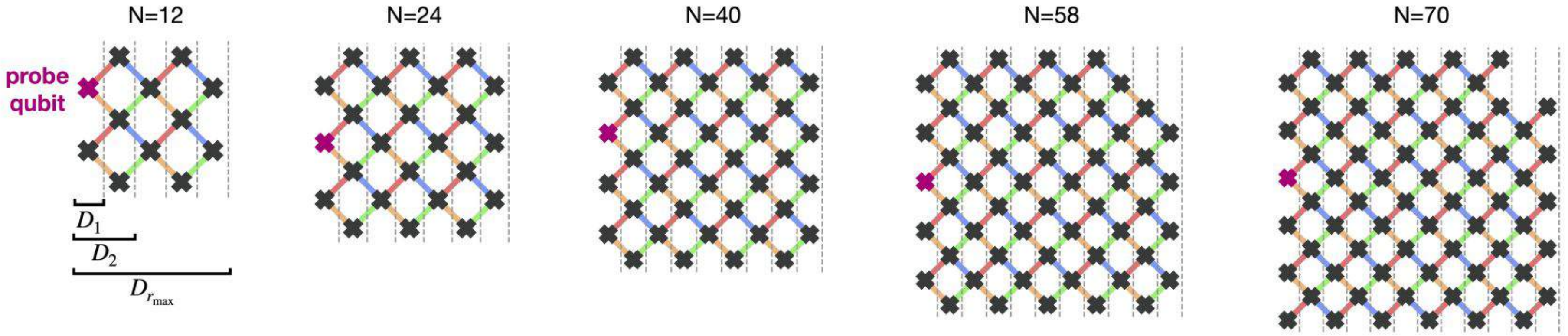
Theory work: Bao *et al.*, arXiv:2110.06963 (2021)



1D entanglement phases from 2D shallow quantum circuits



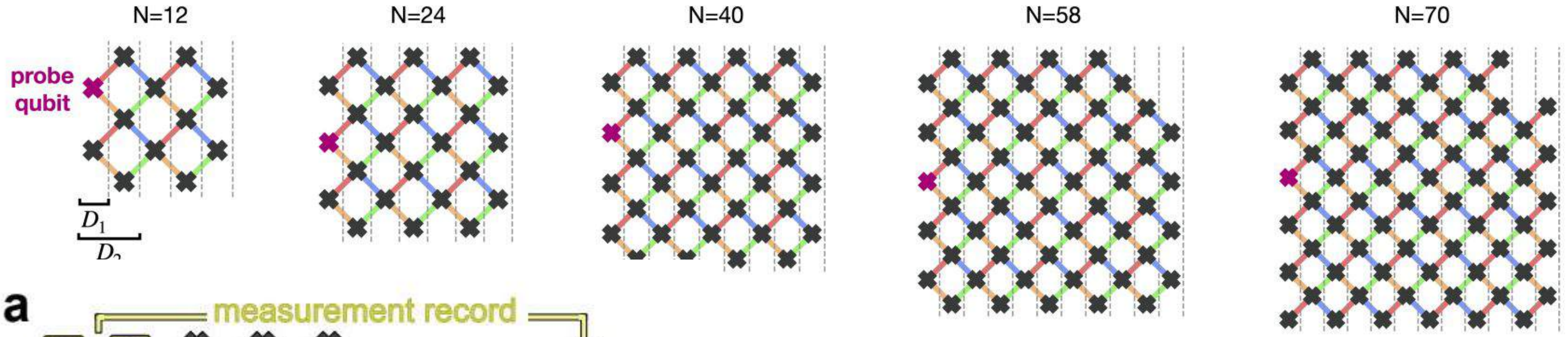
Decoding to overcome the post-selection challenge

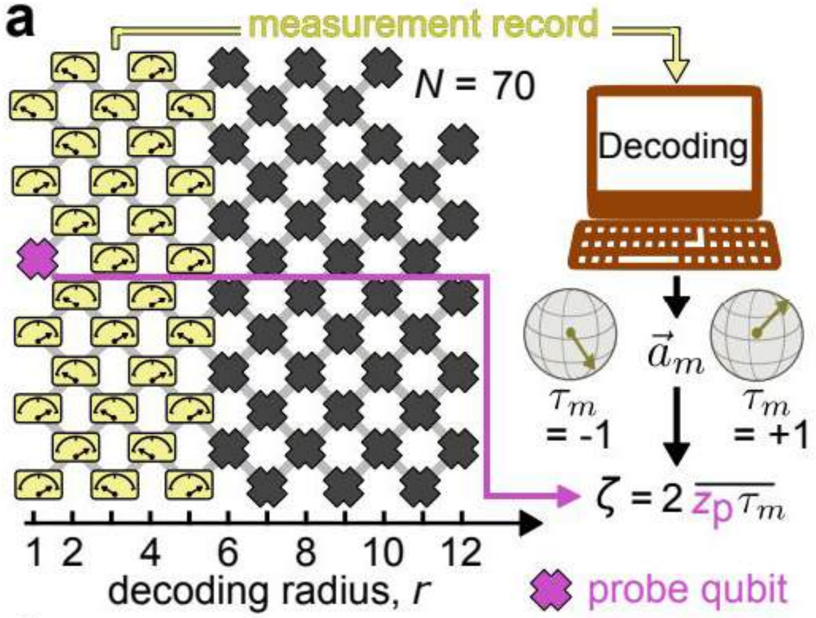


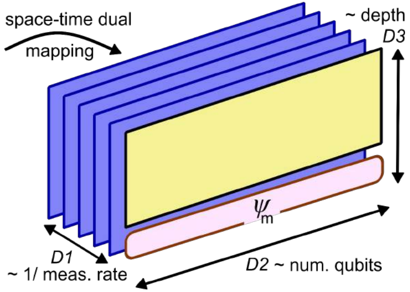
In the entangling phase, an initially mixed state (exponential in the system size) purified.
In the disentangling phase, initially mixed states are easily purified.

Gullans and Huse, PRX (2020)

Decoding to overcome the post-selection challenge

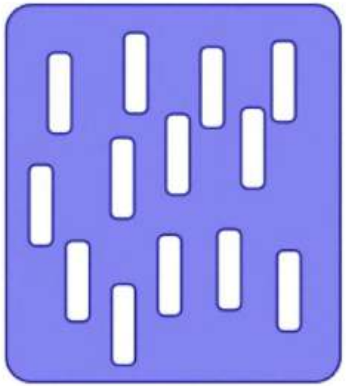




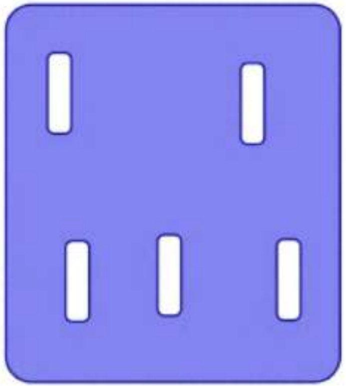


Decoding of local order parameter

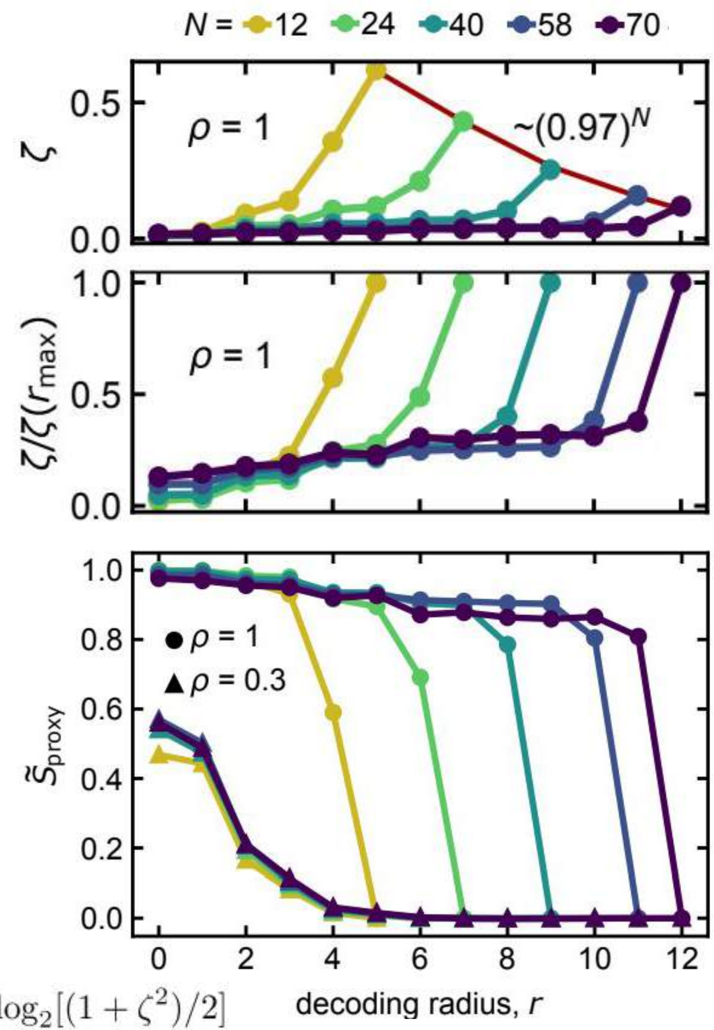
Cross-correlator →
“probe” qubit entanglement →
proxy for the system entanglement



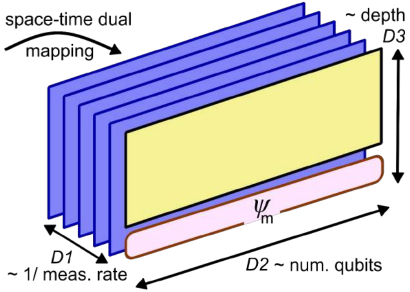
(weak unitary)
ρ → 0



(strong unitary)
ρ → 1

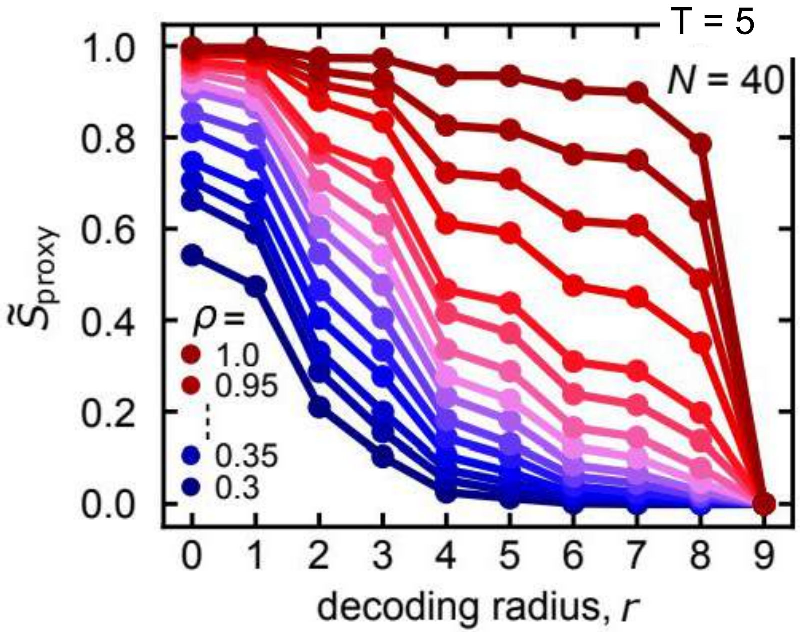


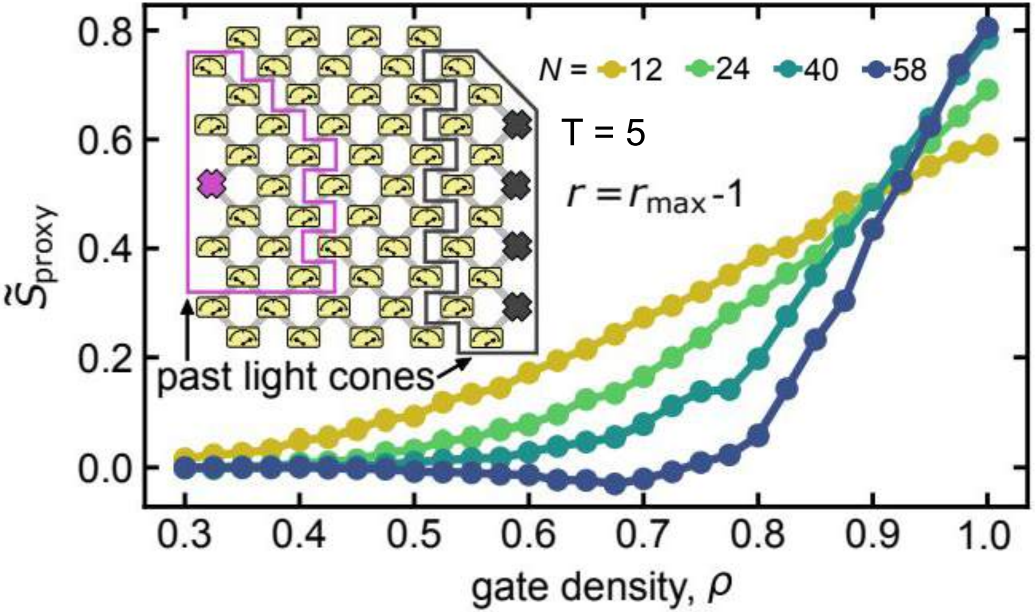
$S_{\mathrm{proxy}} = -\log_2[(1+\zeta^2)/2]$



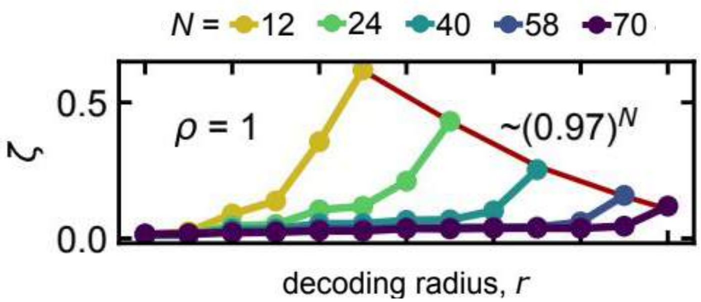
Crossover between entanglement structures

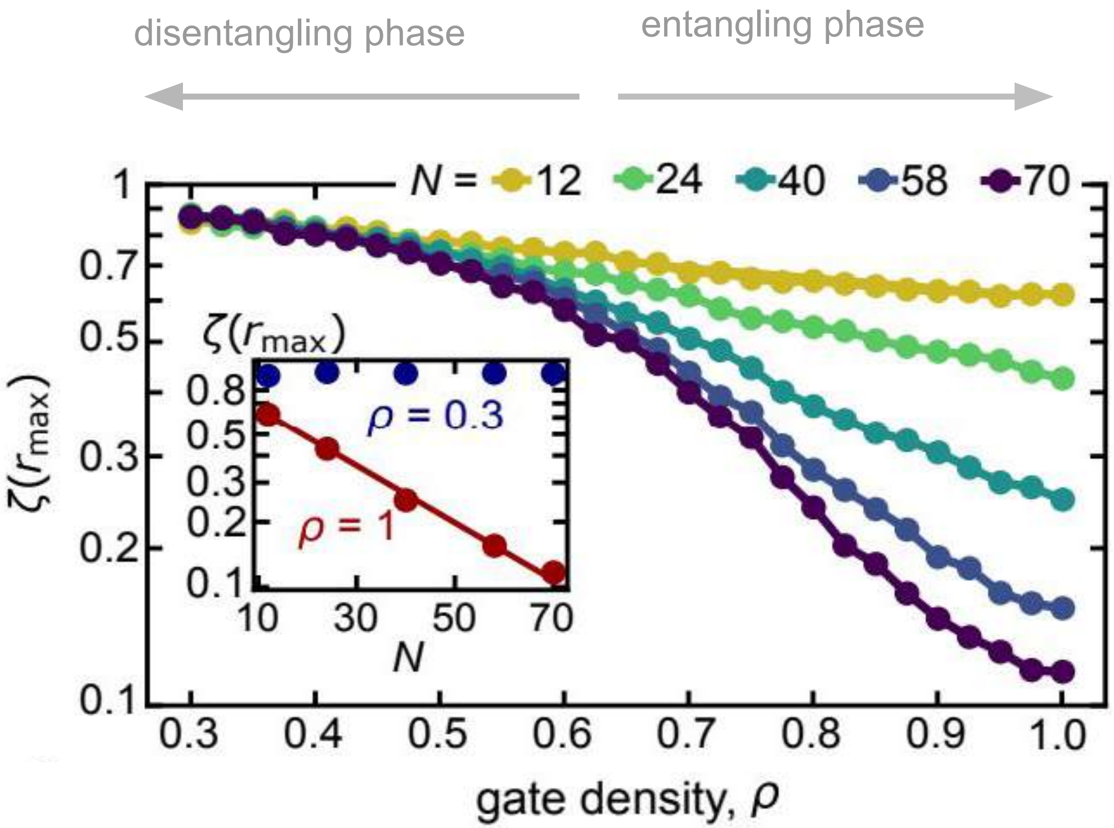
$$S_{\text{proxy}} = -\log_2[(1+\zeta^2)/2]$$





Noise as a probe of the entanglement structure





Coherence → upper limit on qubit array sizes of about 12 × 12

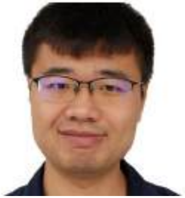
TOPOLOGICAL MATTER

Realizing topologically ordered states on a quantum processor

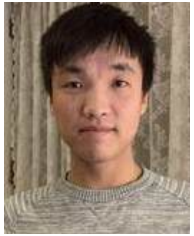

Kevin Satzinger


Michael Newman


Chris Quintana


Xiao Mi


Jimmy Chen


Yujie Liu
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Adam Smith
TU Munich □ Nottingham


Chrstina Knapp
Caltech □ Station-Q


Andrew Dunsworth


Cody Jones


Craig Gidney

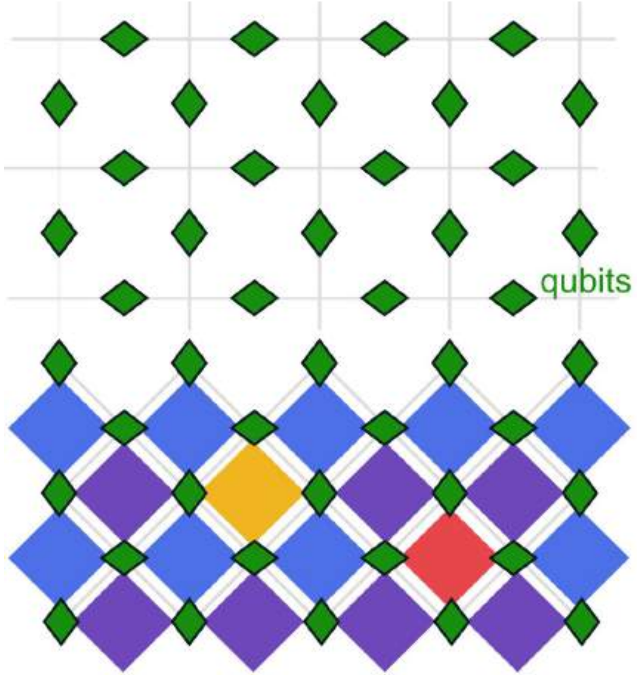

Michael Knap
TU Munich

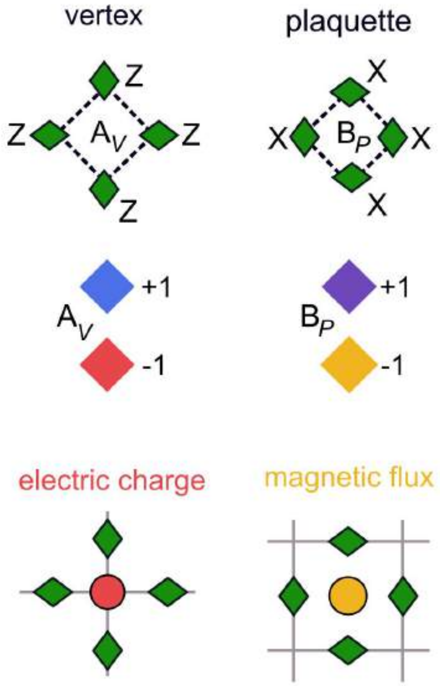

Frank Pollman
TU Munich

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

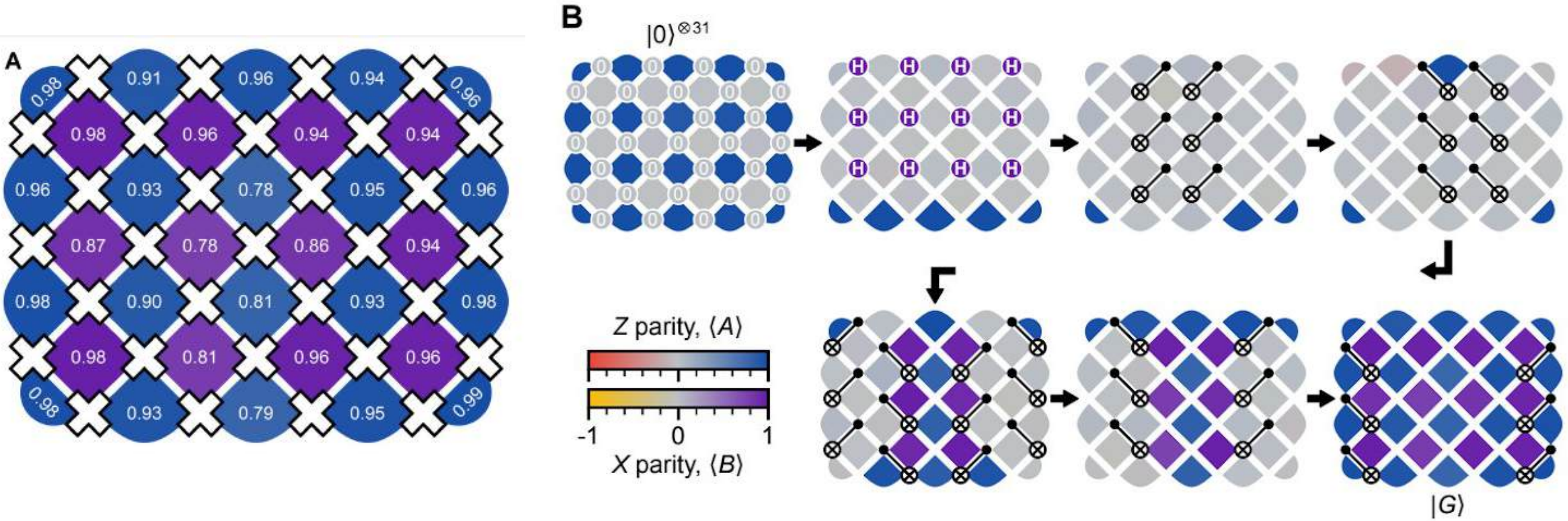
Realizing topologically ordered states on a quantum processor

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





Realizing topologically ordered states on a quantum processor

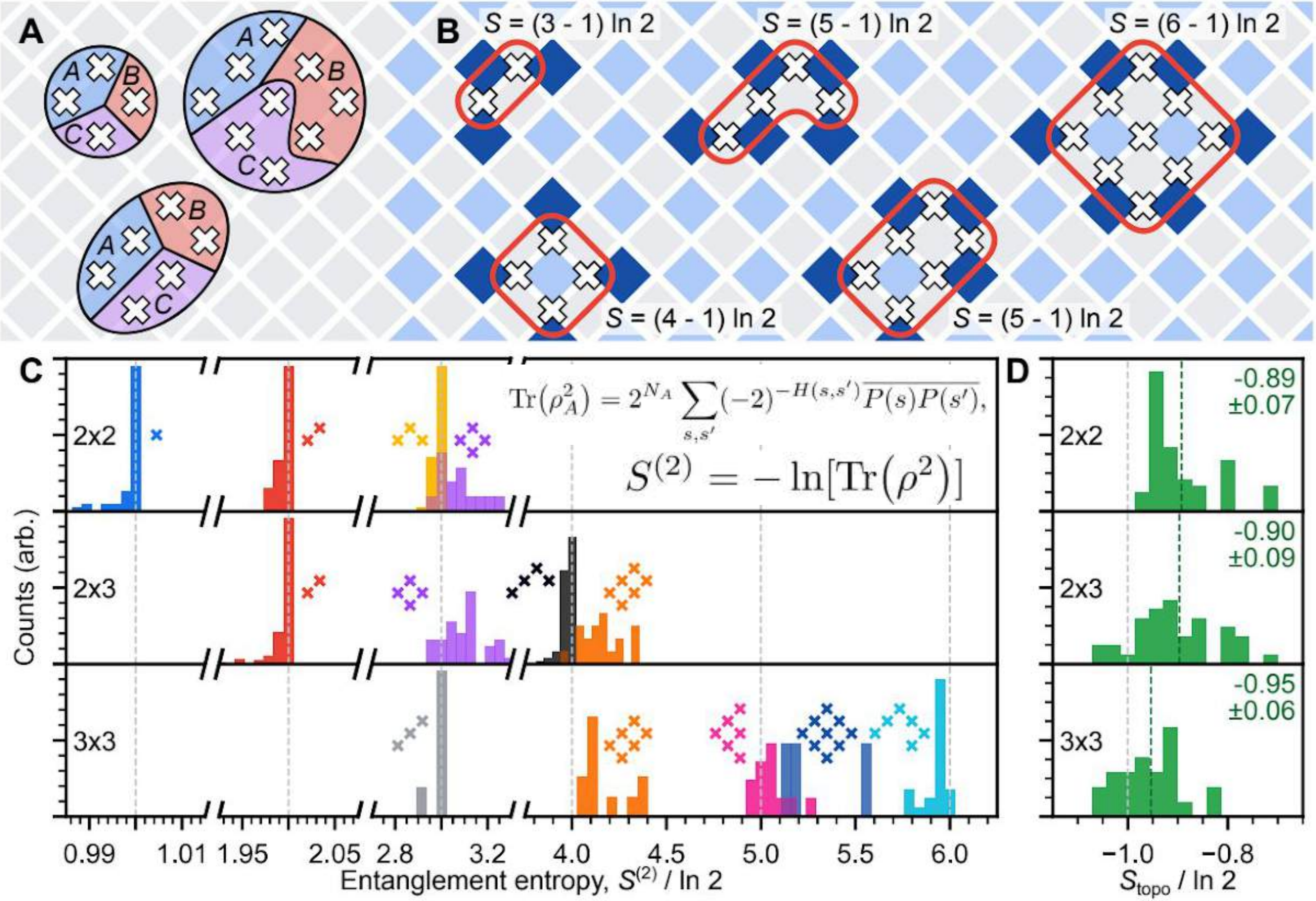


(unique groundstate)

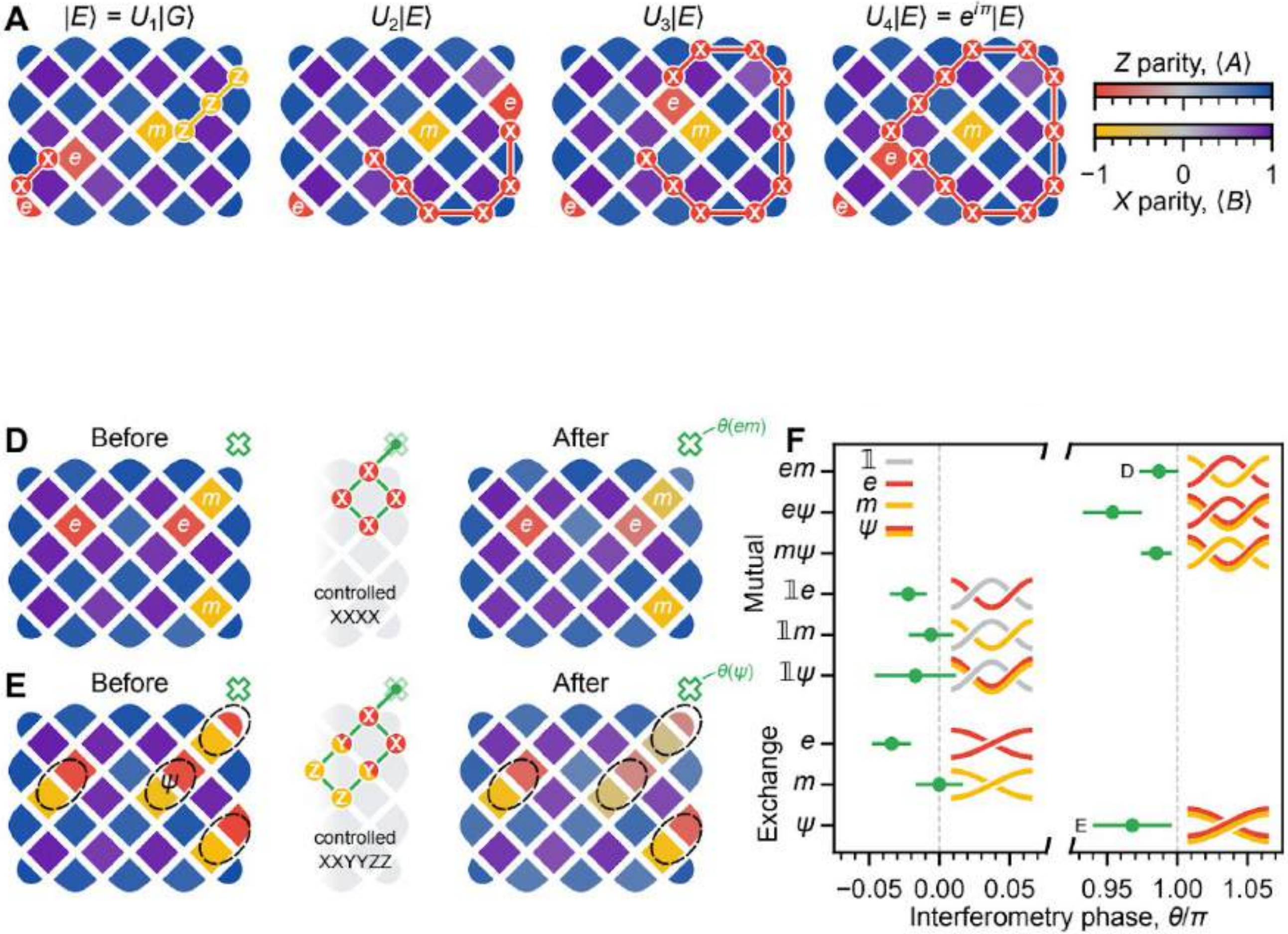
$$[B_p, A_v] = 0, \;\forall p, v \longrightarrow |G\rangle = \frac{1}{\sqrt{2^{12}}} \prod_p (\mathbb{I} + B_p) \, |0\rangle^{\otimes 31}$$

superposition of all plaquette configurations

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



Extracting braiding statistics



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

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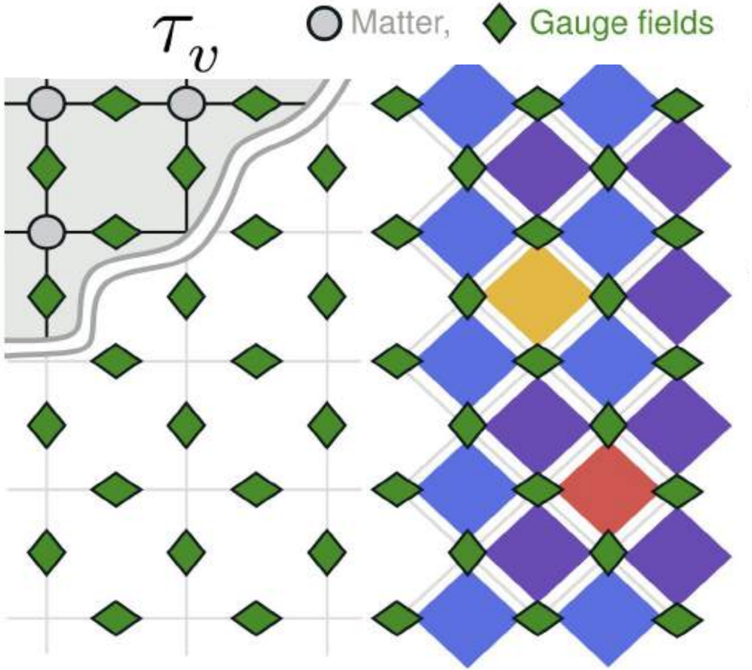
arXiv:2409.17142

A (2+1)D Lattice Gauge model

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

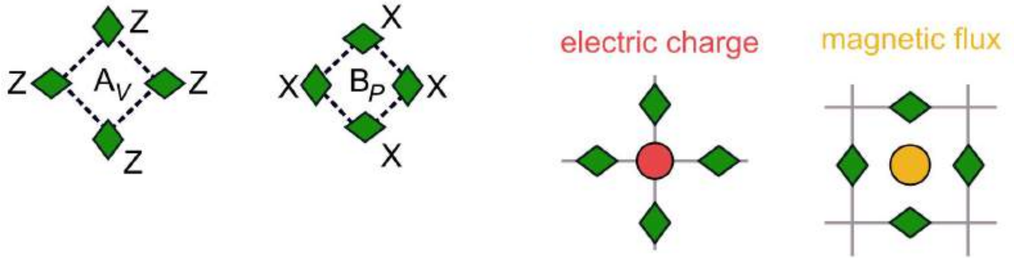
$$B_p = \prod_{i \in p} X_i$$

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



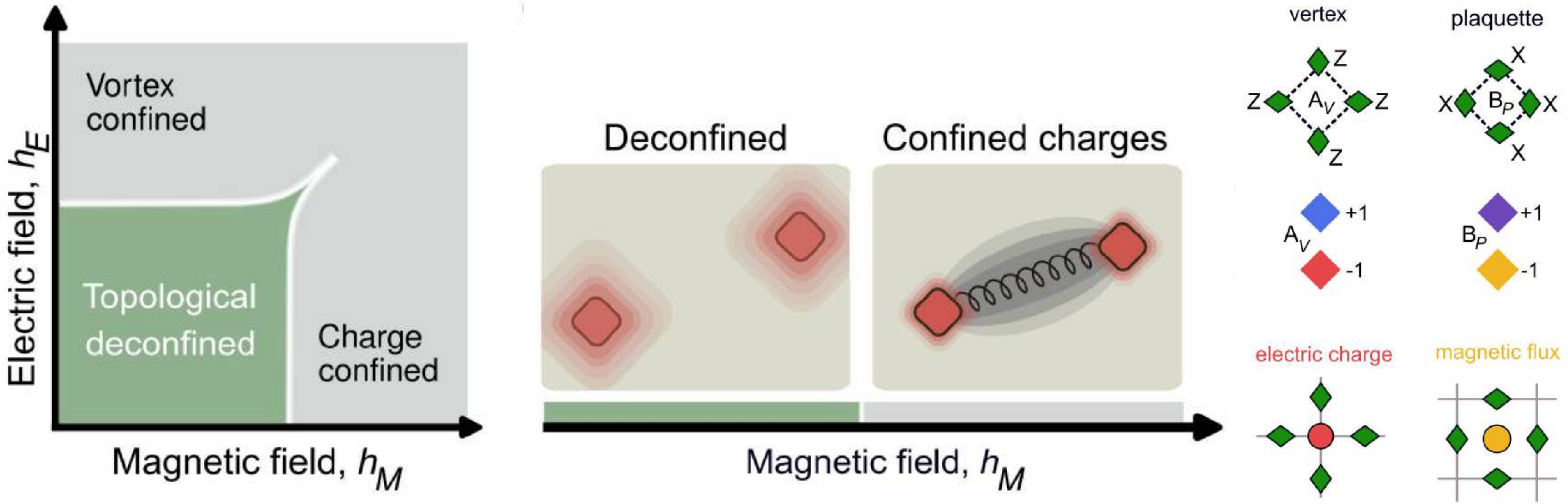
$$G_v = A_v \tau_v^X \;\rightarrow [\mathcal{H}_{\mathsf{LGT}}, G_v] = 0, \forall v$$

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



Phase diagram of the LGT

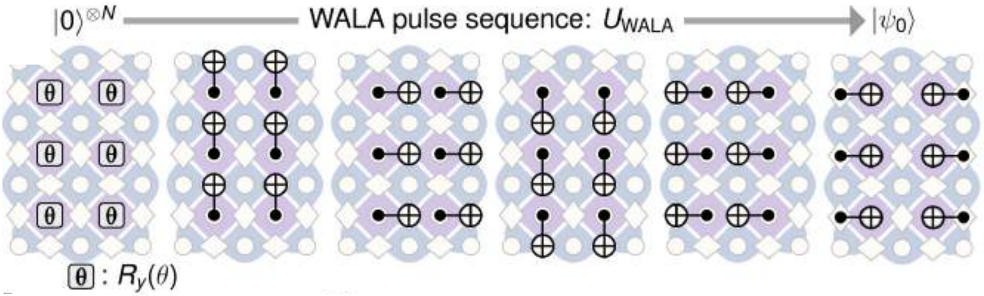
$$\mathcal{H} = -J_E \sum_{v} A_v - J_M \sum_{p} B_p - h_M \sum_{\text{links}} Z_l - h_E \sum_{\text{links}} X_l$$

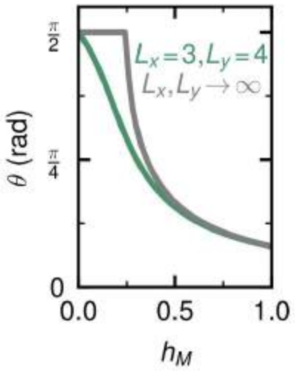


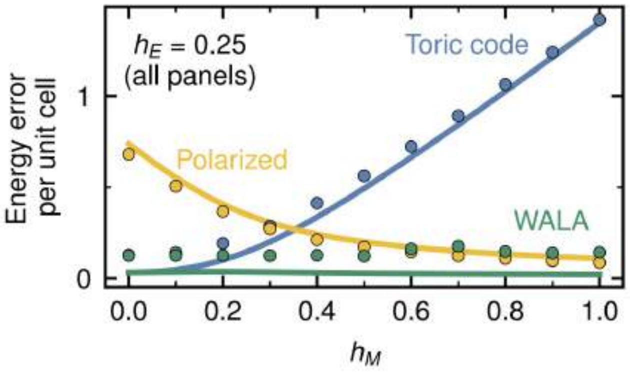
E. Fradkin and S. H. Shenker, PRD (1979), S. Trebst et al., PRL(2007), J. Vidal et al., PRB (2009).

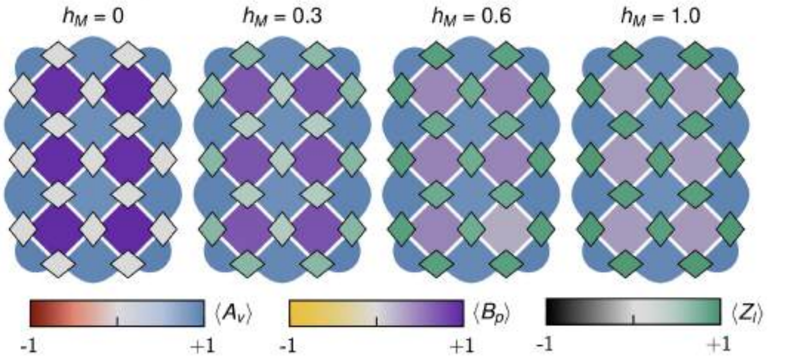
Weight Adjustable Loop Ansatz (WALA) ground state

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



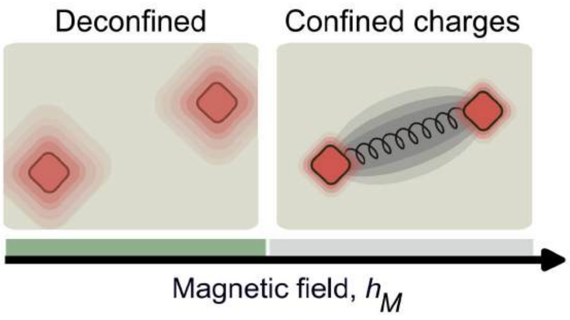




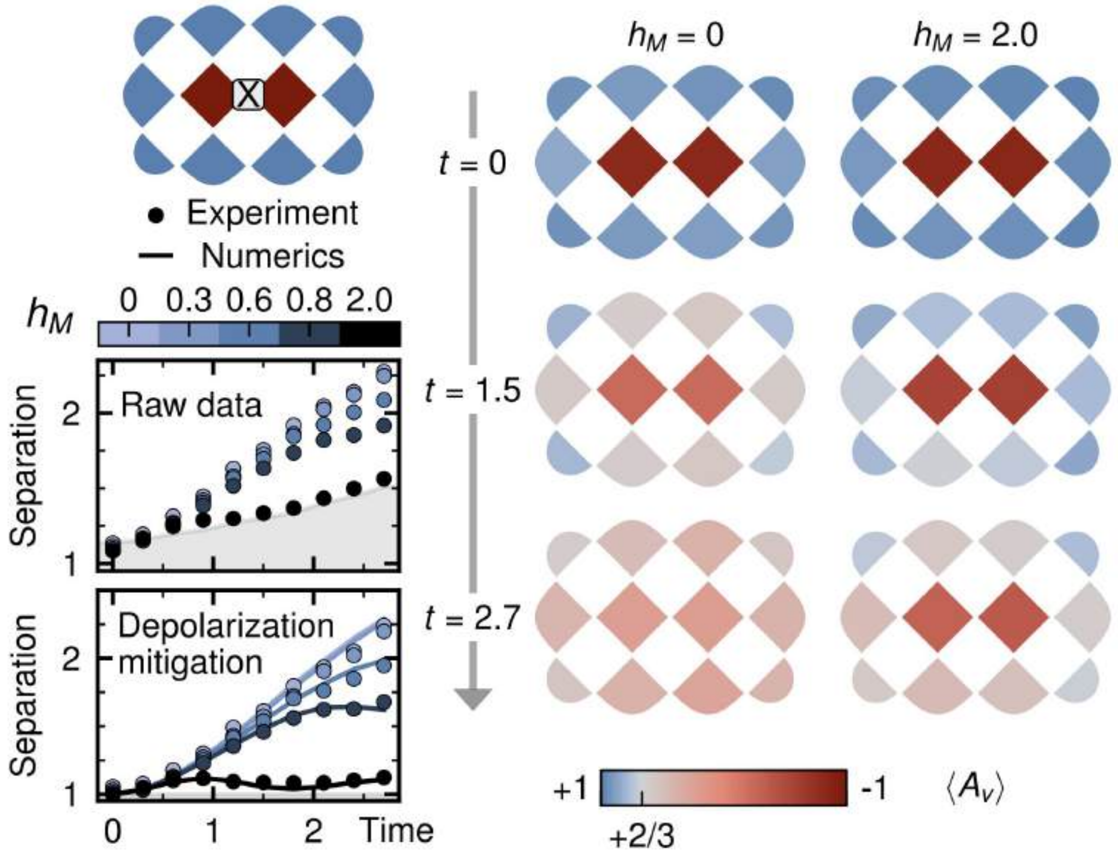


$$J_E = J_M = 1$$

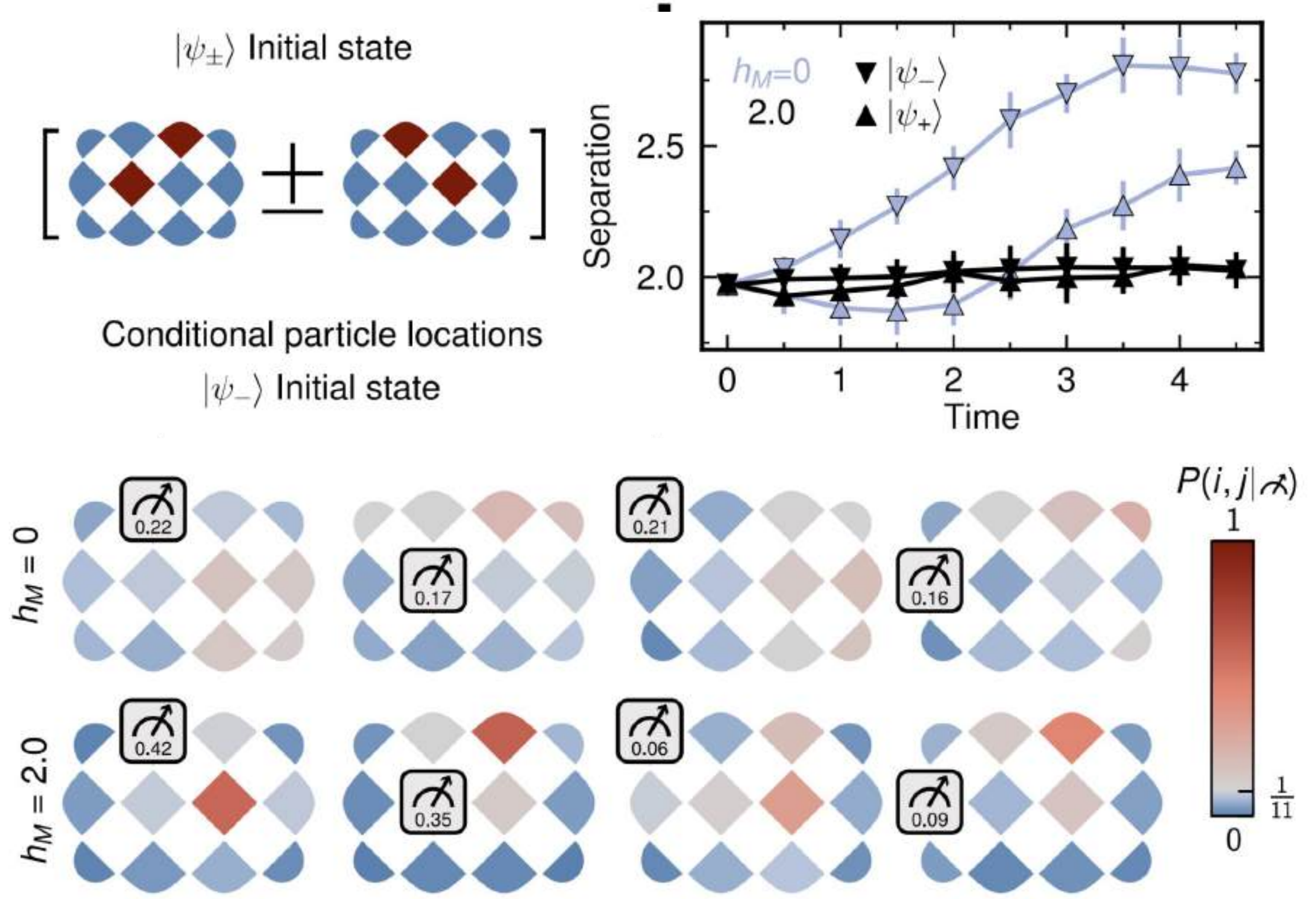
Confinement of electric excitations



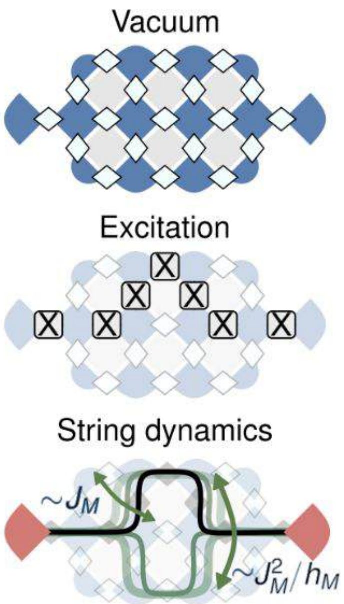
$$\mathcal{H} = -J_E \sum_v A_v - J_M \sum_p B_p - h_M \sum_{\text{links}} Z_l - h_E \sum_{\text{links}} X_l$$

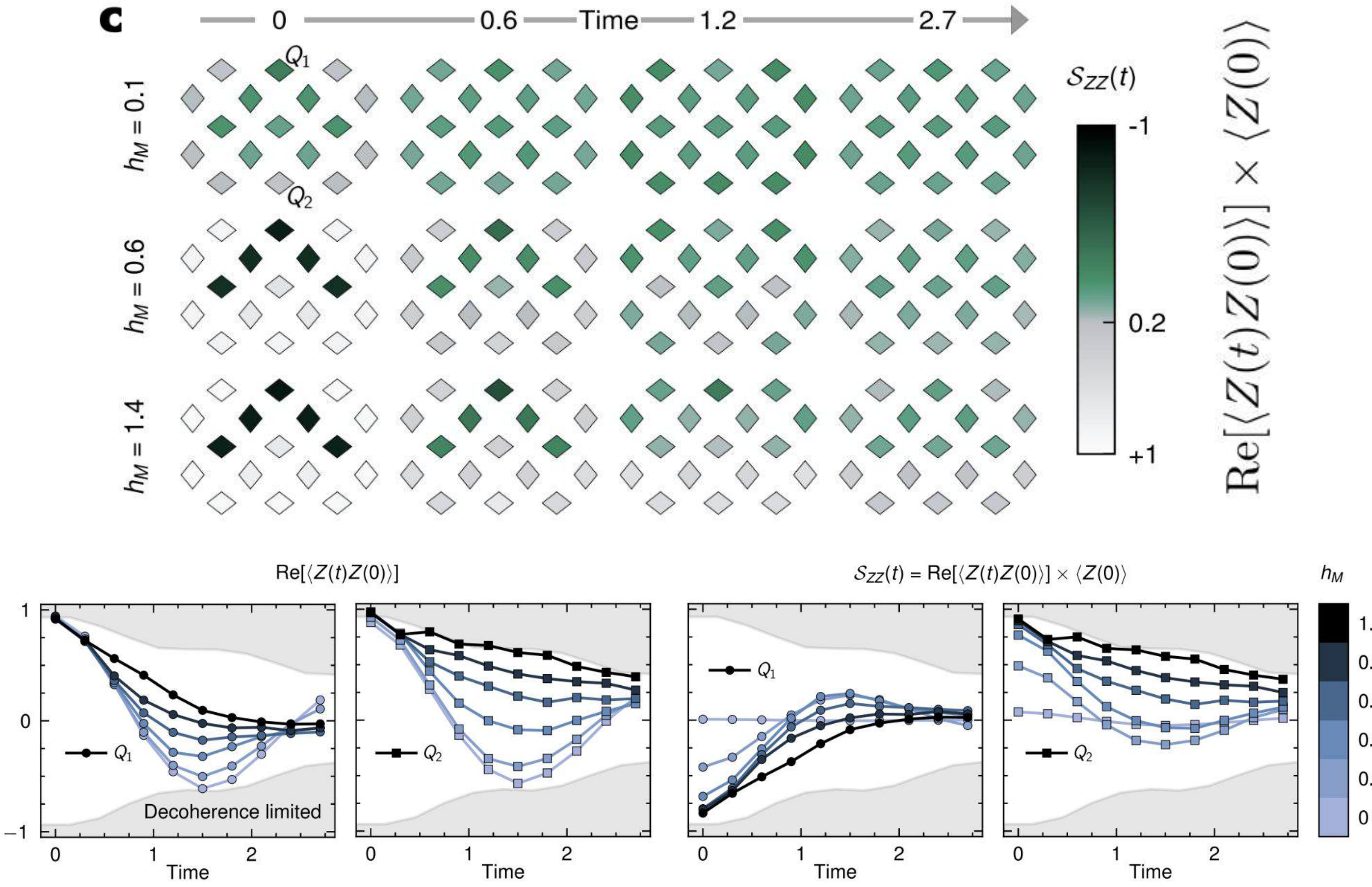


Confinement of electric excitations

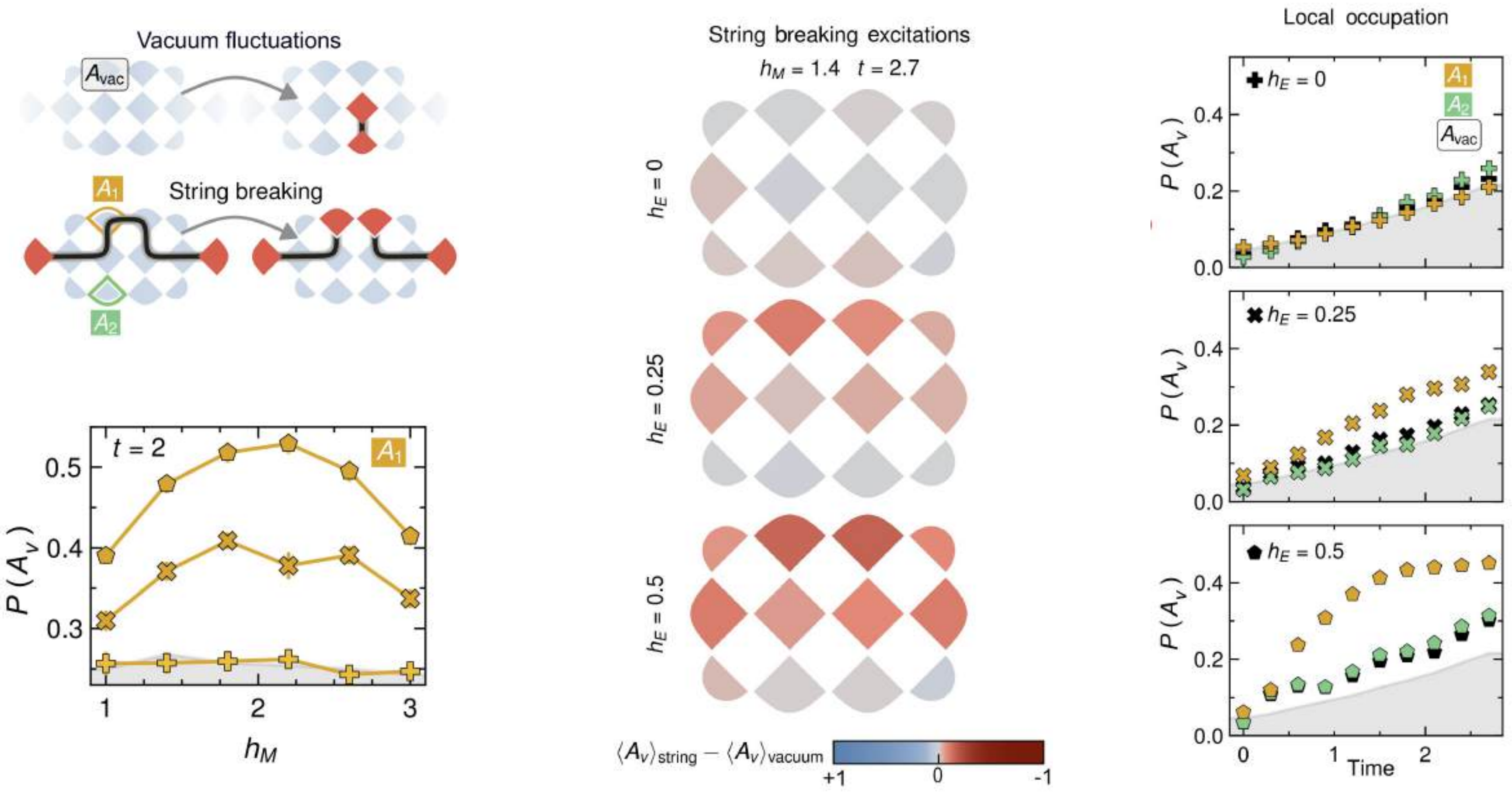


Dynamics of the string connecting two fixed electric particles

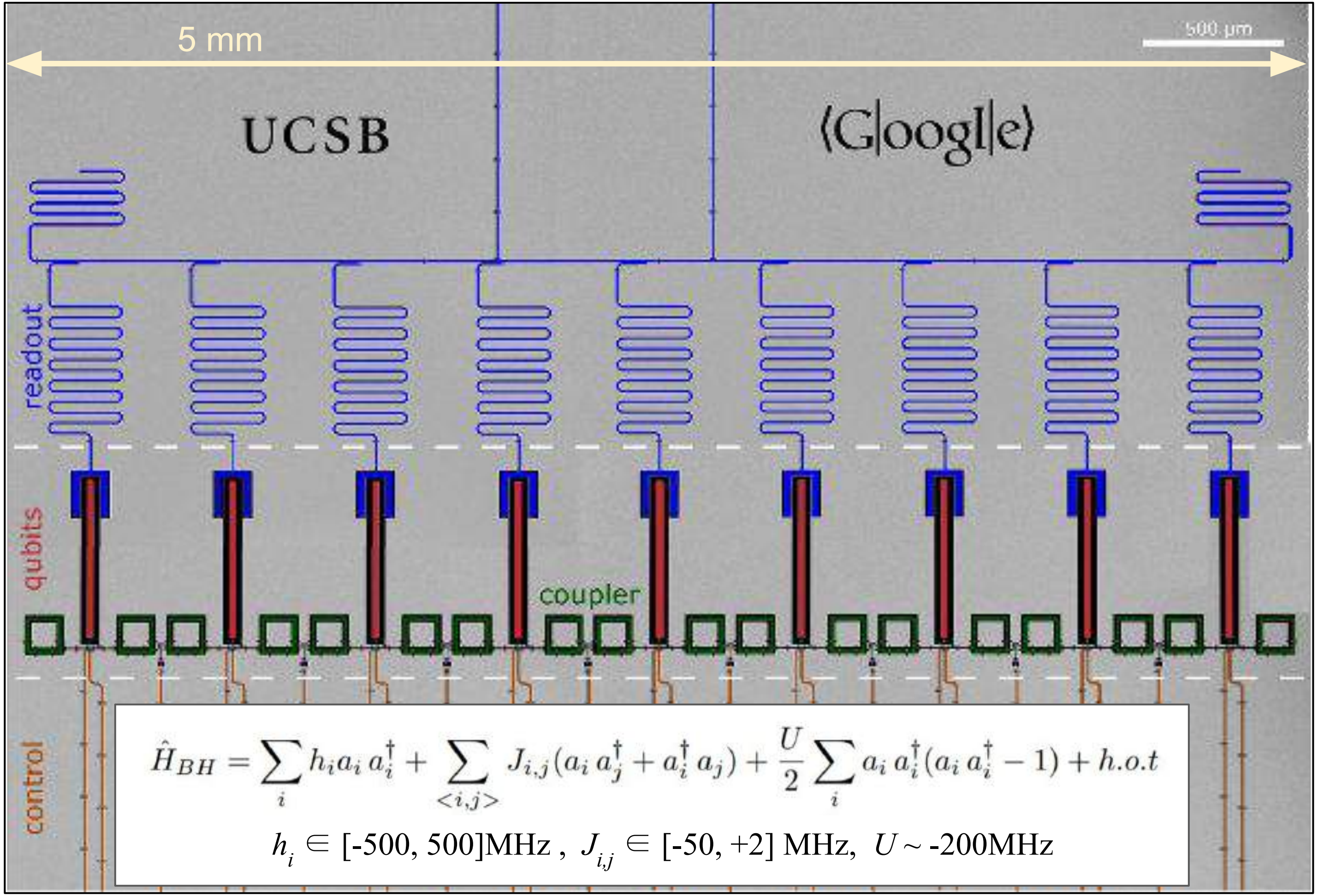




Dynamics of the string connecting two fixed electric particles



Array of coupled non-linear resonators (→ qubits)



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

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