Quantum simulations with superconducting qubits

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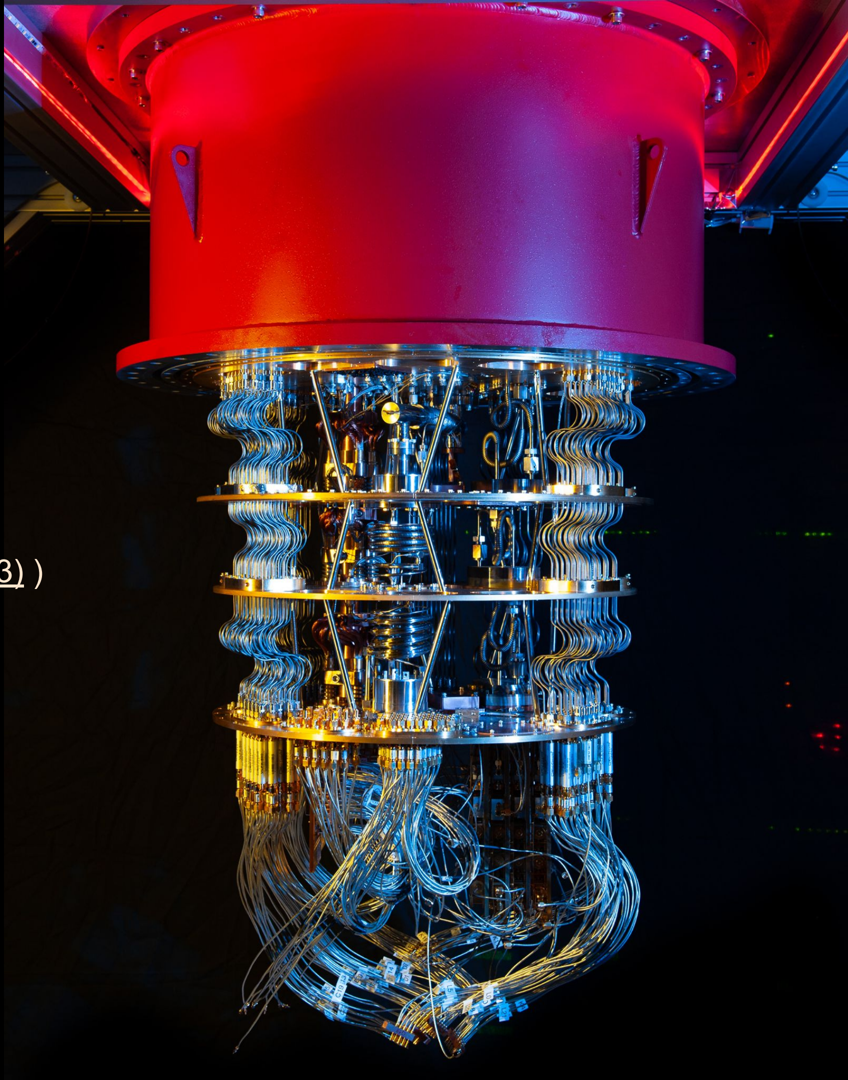
Google Quantum AI,

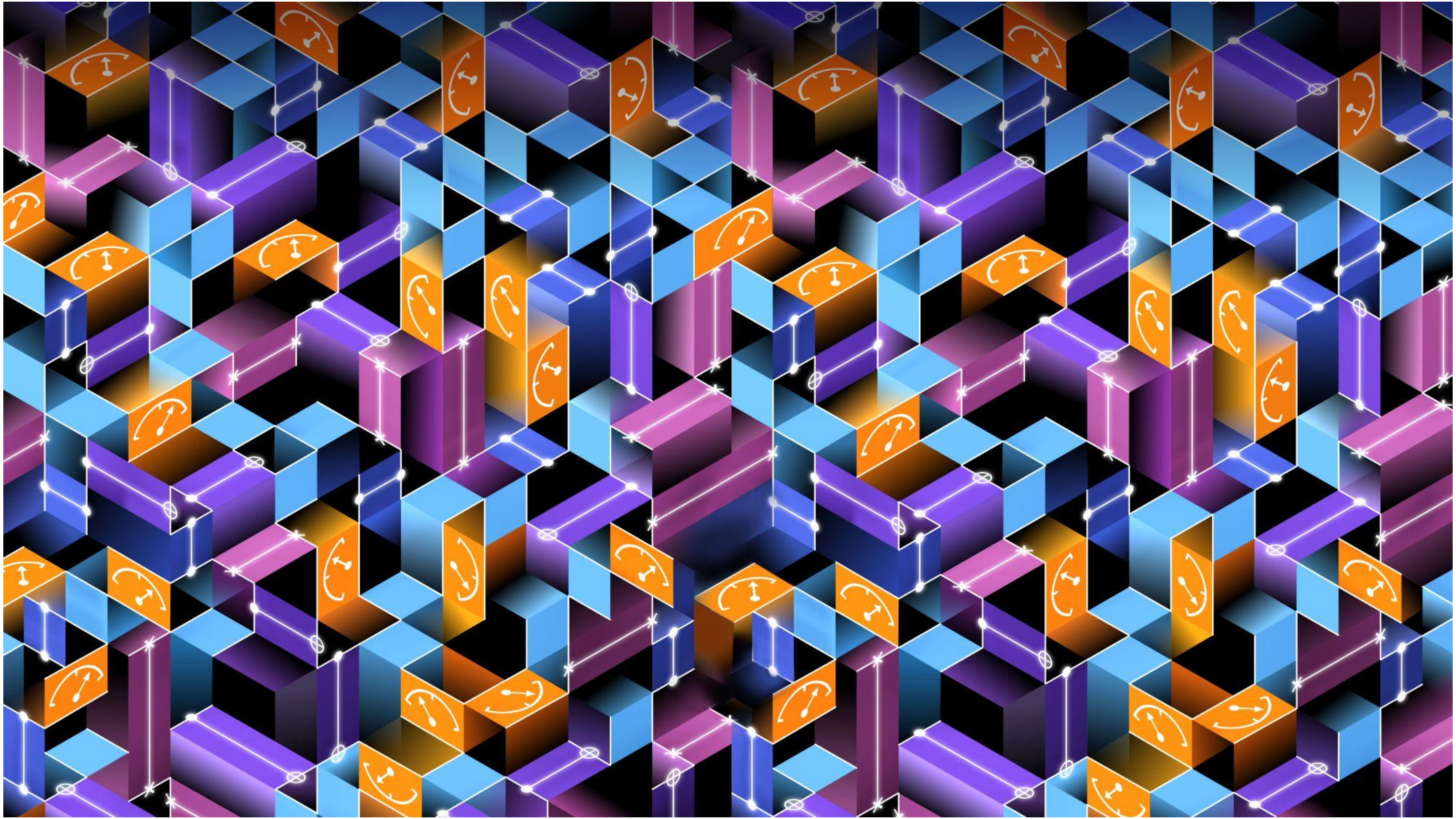


Measurement-induced Phases of quantum matter

Measurement-induced entanglement and teleportation (Nature **622** (2023))

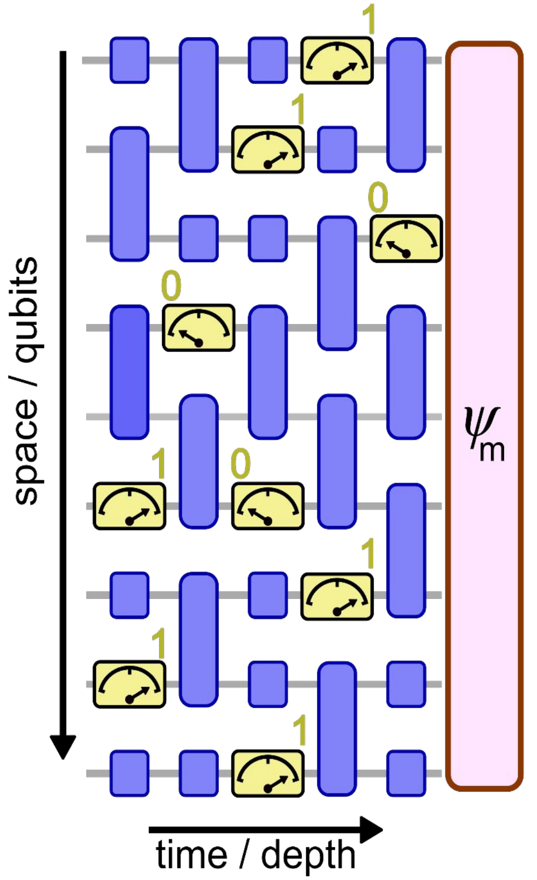
Quantum connection , Stockholm 2025

Quantum information phases in space-time



Measurement-induced entanglement and teleportation

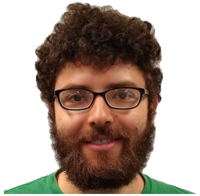
→



Measurement is key in many protocols

A genuine NISQ problem
Can noise destabilize phases

Jesse Hoke
(Stanford)



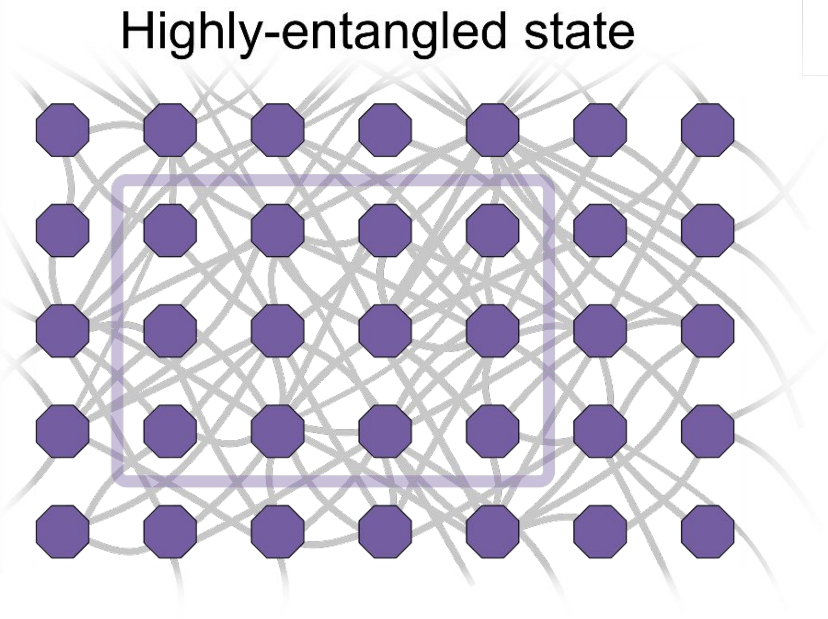
Eliott Rosenberg
(Cornell U)

Vedika Khemani
Stanford

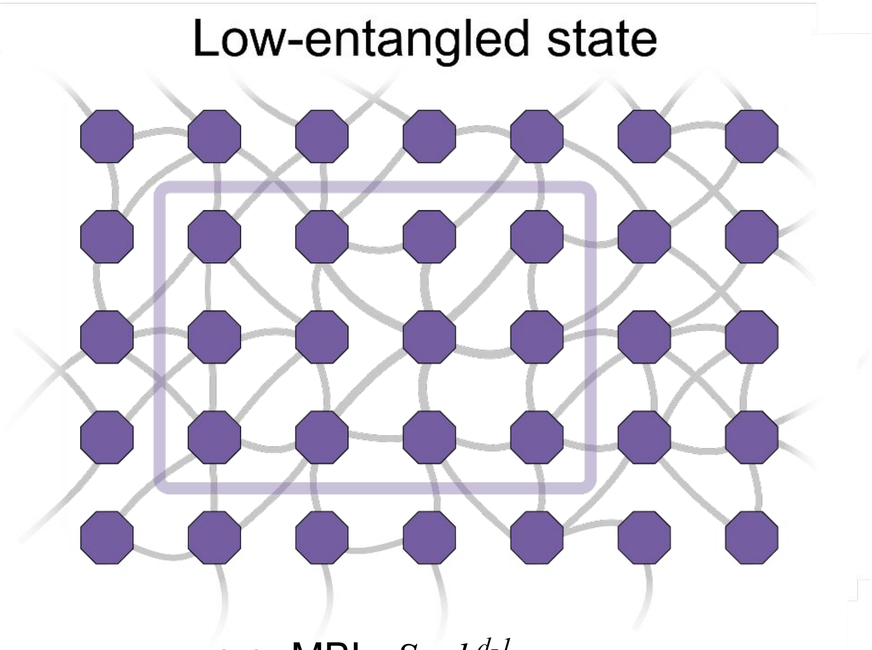
Matteo Ippoliti
Stanford

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

Common entanglement structures



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

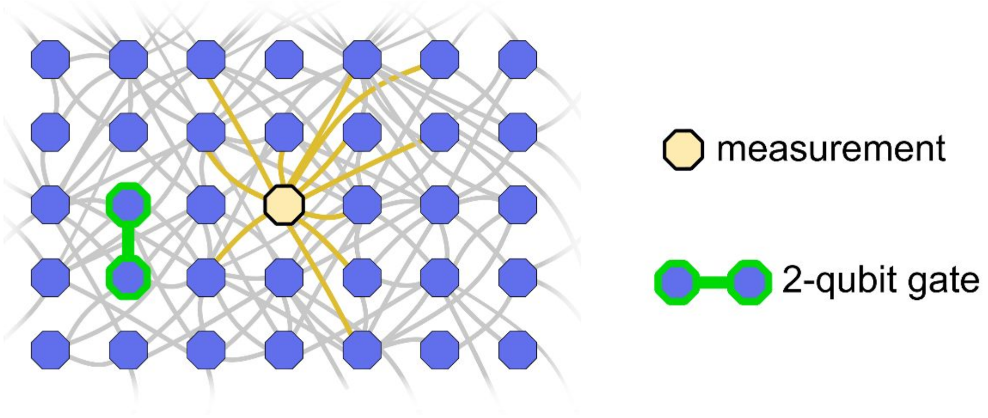


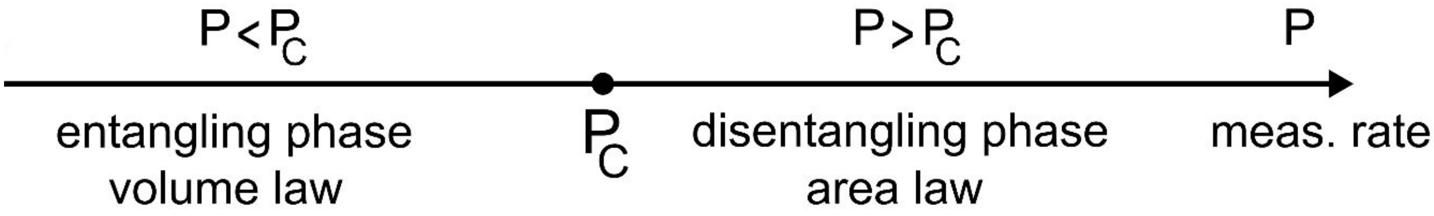
e.g. MBL, $S \sim l^{d-1}$

What happens if we add mid-circuit measurements ?

Physics folklore of circa 2017: Entangled states are very fragile, entanglement would be no match for measurement.

Phase transition in quantum information





"Vandalized resistor grid"

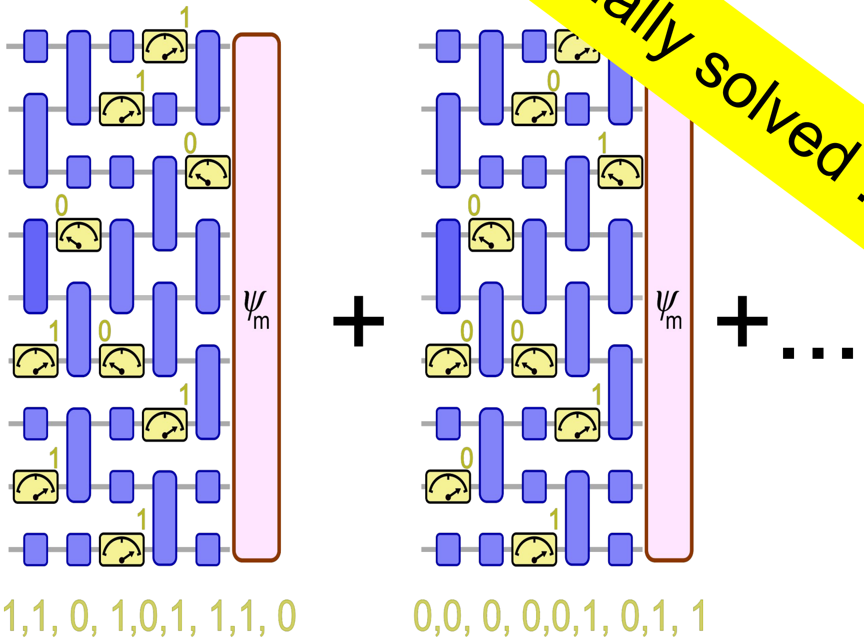
Cao, Tilloy, De Luca, SciPost Physics (2019)

Skinner, Ruhman, Nahum, PRX (2019), Li, Chen, Fisher, PRB (2018), Chan, Nandkishore, Pretko, Smith, PRB (2019)

Challenges in studying monitored circuits

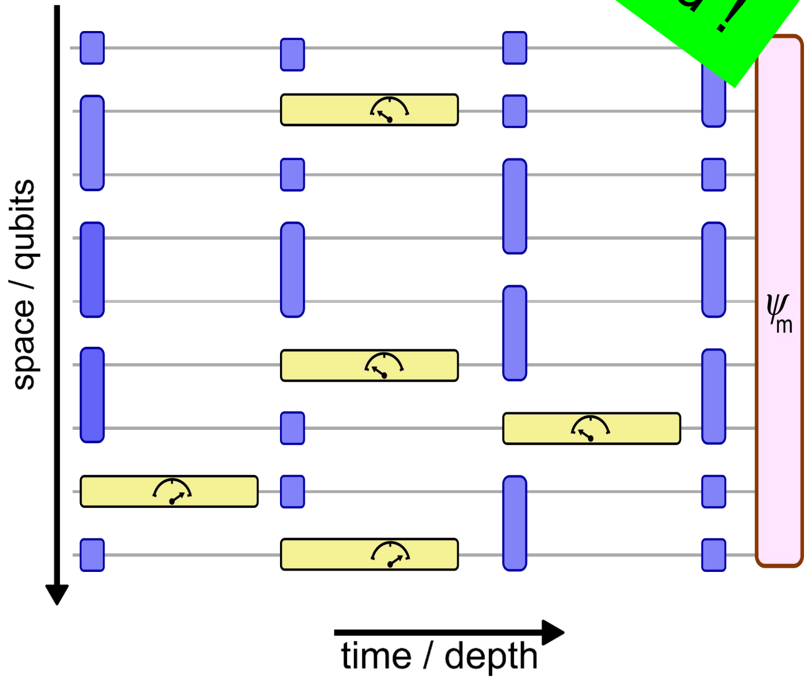
Partially solved !

1. Post -selection: staying o… m trajectory

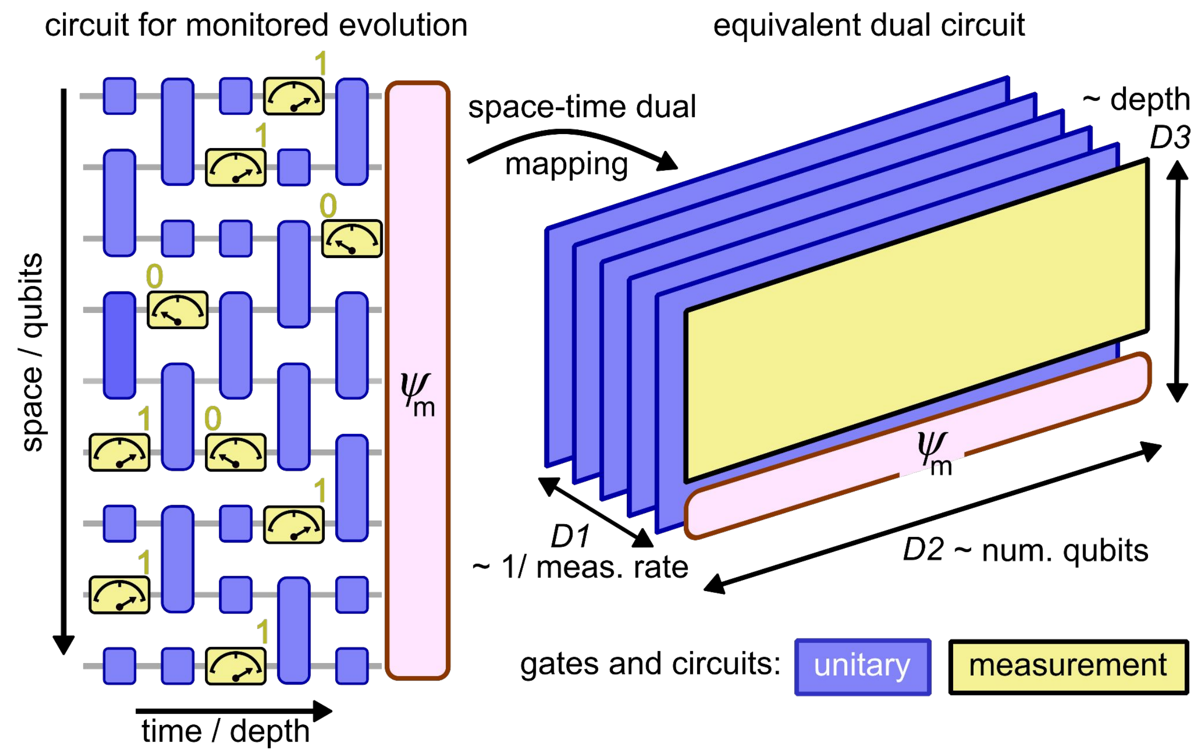


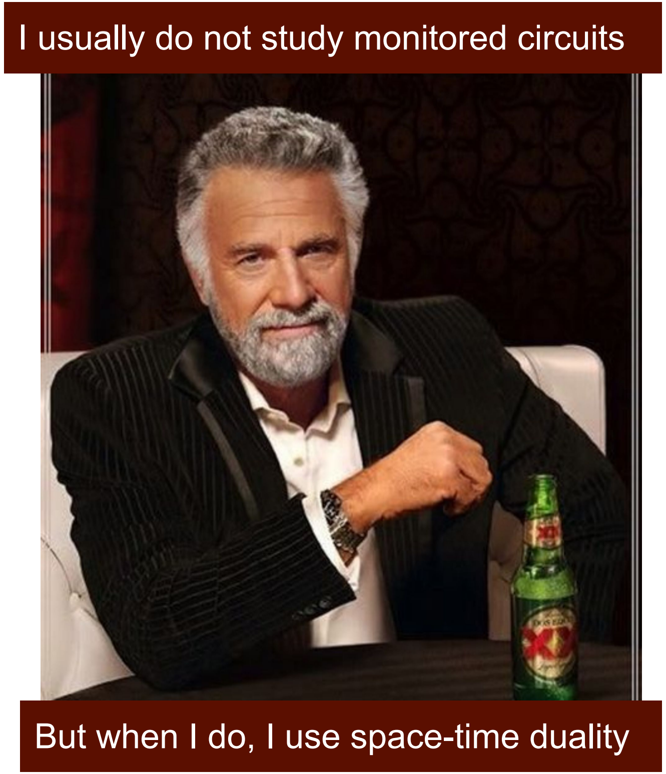
solved !

2. Mid-circuit measuremen…



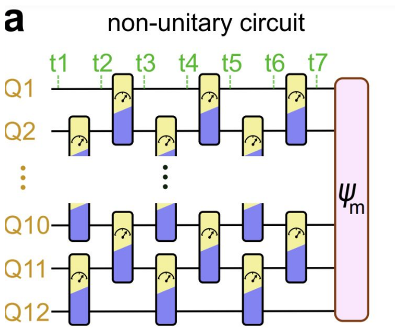
$$\sum_m \langle\psi_\mathbf{m}|\,\hat{C}\,|\psi_\mathbf{m}\rangle = \sum_m \mathrm{Tr}\Big(|\psi_\mathbf{m}\rangle\langle\psi_\mathbf{m}|\,\hat{C}\Big) = \mathrm{Tr}\sum_m |\psi_\mathbf{m}\rangle\langle\psi_\mathbf{m}|\,\hat{C} = \mathrm{Tr}(\rho_{\mathrm{ave}}\hat{C})$$

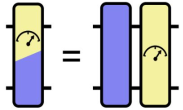


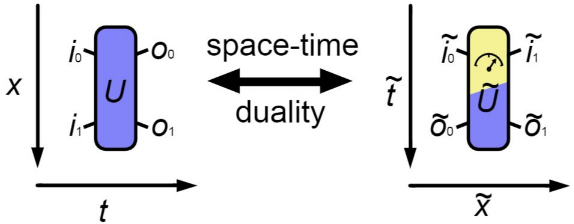


Absence of causality : “arrow of time” loses its unique role
→ network of quantum information in space-time

Implementation of space-time duality in 1D







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

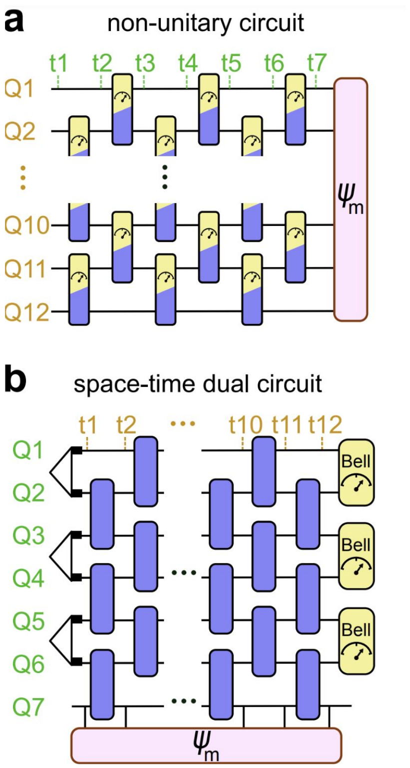
$\tilde{U} = 2VH$ where V is unitary and H is Hermitian

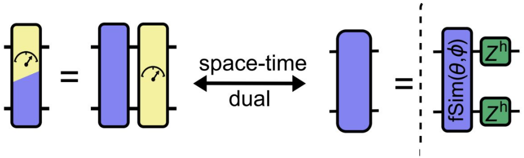
$$H = \frac{1}{2}\sqrt{1 + 3\cos^2(\theta)}\, |\psi_\theta\rangle\langle\psi_\theta| + \frac{1}{2}|\sin(\theta)|(I - |\psi_\theta\rangle\langle\psi_\theta|)$$

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

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

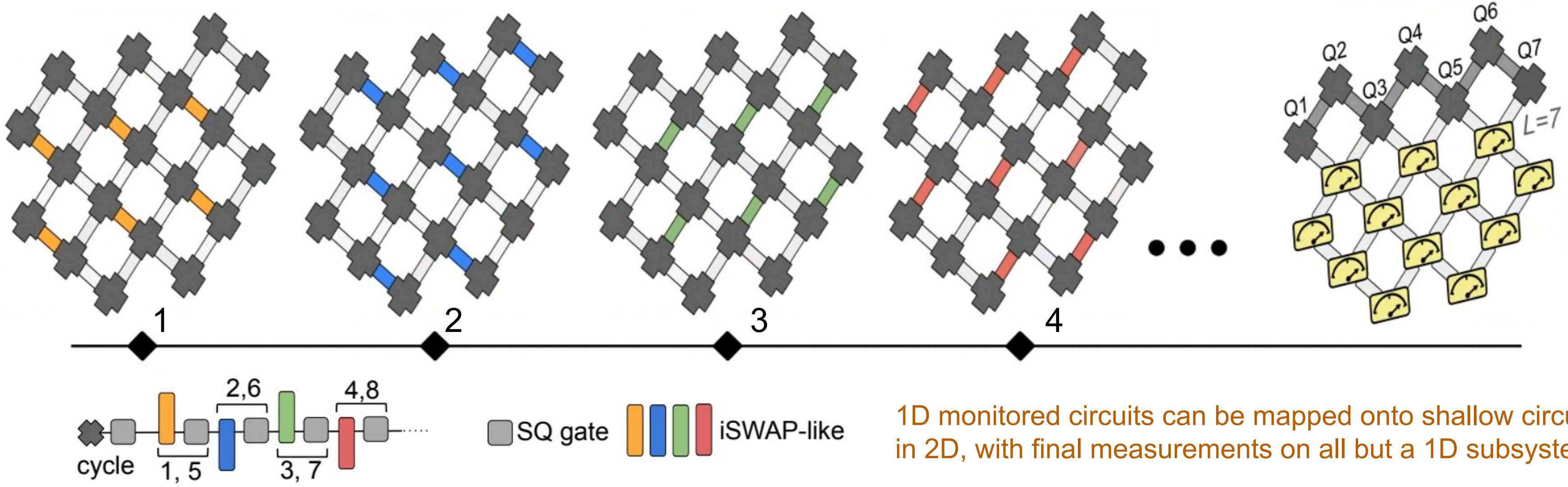
Implementation of space-time duality in 1D



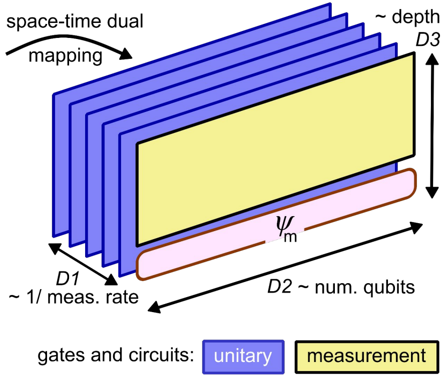


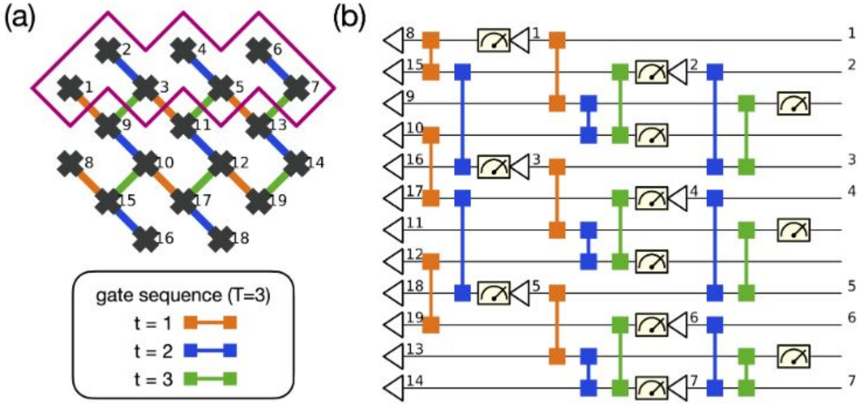
$$\mathrm{fSim}(\theta,\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & i\sin\theta & 0 \\ 0 & i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{i\phi} \end{pmatrix}$$

1D entanglement phases from 2D shallow quantum circuits

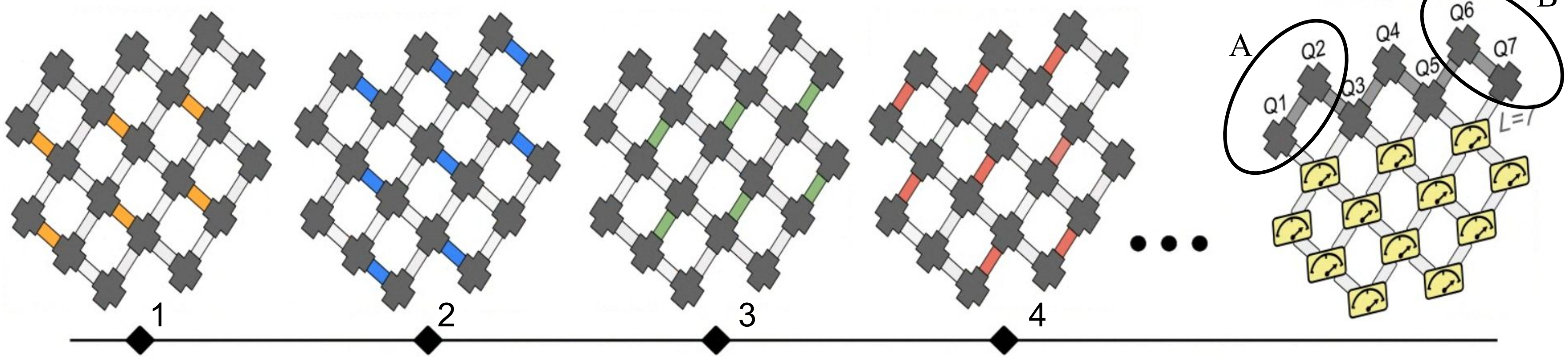


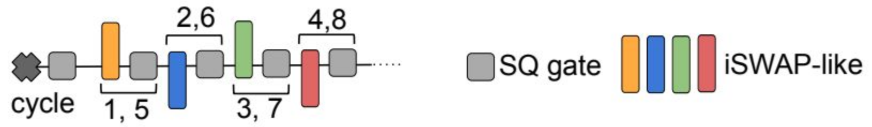
1D monitored circuits can be mapped onto shallow circuits in 2D, with final measurements on all but a 1D subsystem



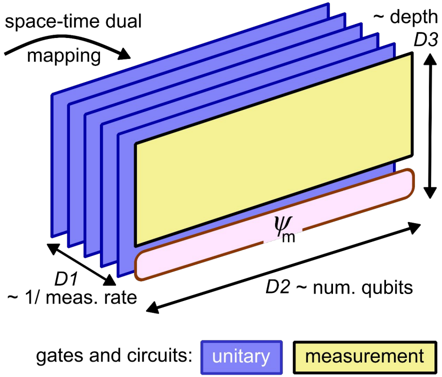


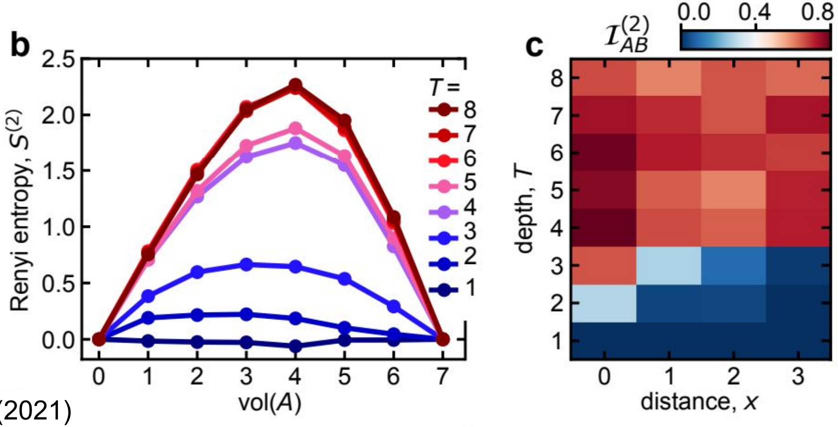
1D entanglement phases from 2D shallow quantum circuits





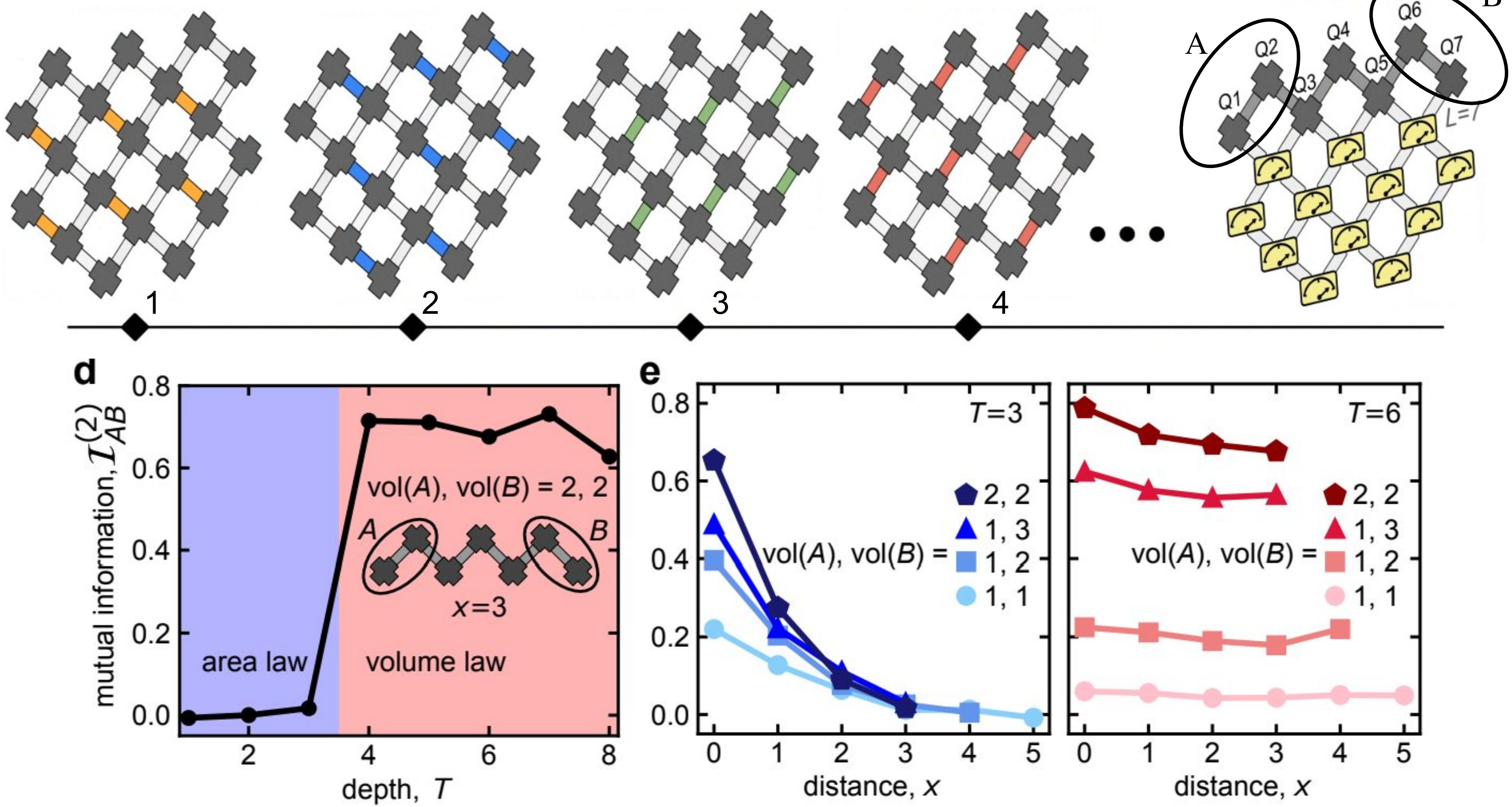
$$\mathcal{I}_{AB}^{(2)} = S_A^{(2)} + S_B^{(2)} - S_{AB}^{(2)}$$



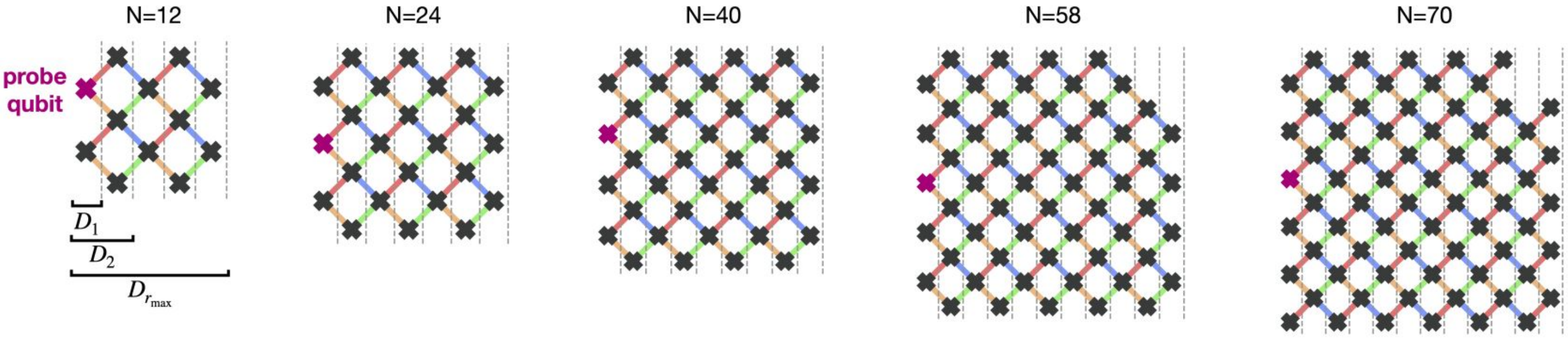


Theory work: Bao *et al.*, arXiv:2110.06963 (2021)

1D entanglement phases from 2D shallow quantum circuits



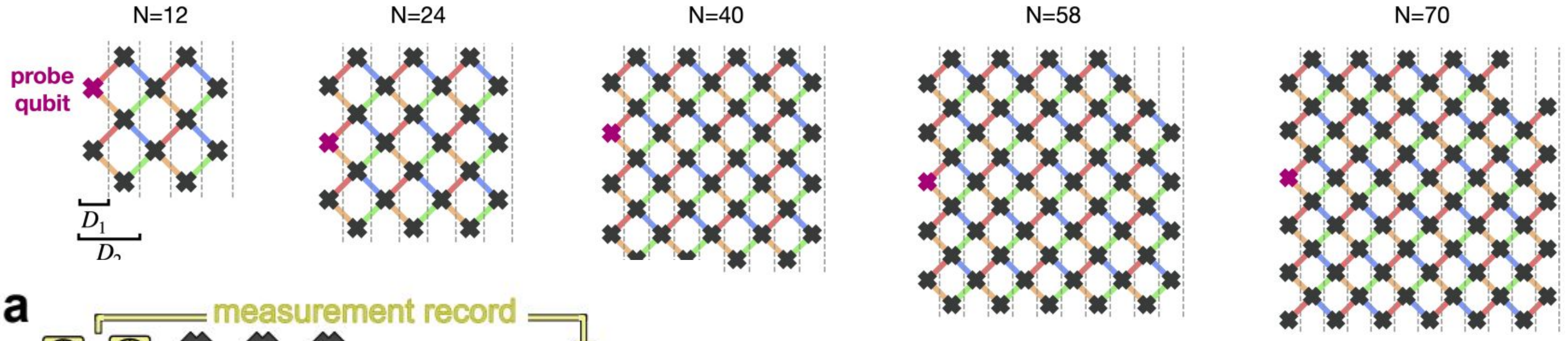
Decoding to overcome the post-selection challenge

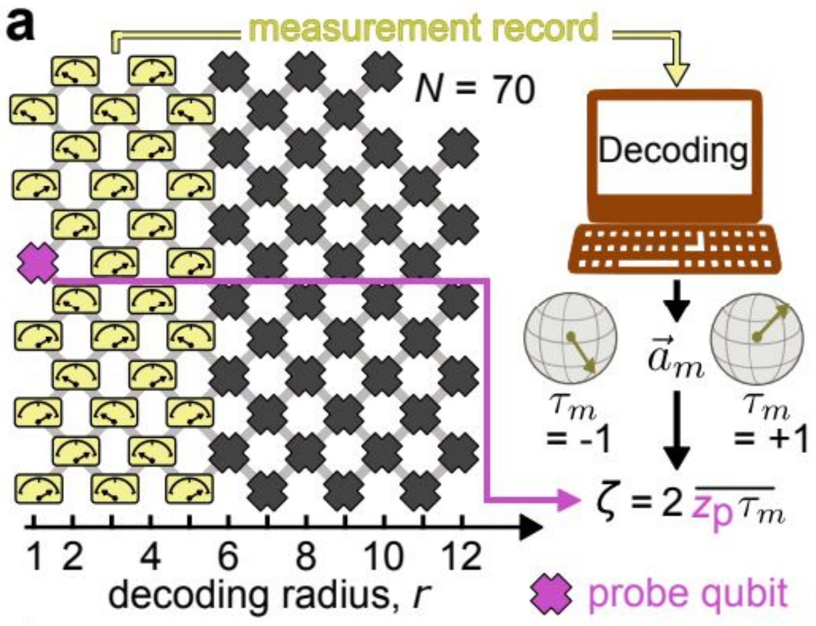


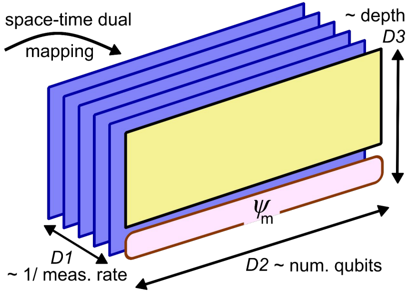
In the entangling phase, an initially mixed state (exponential in the system size) purified.
In the disentangling phase, initially mixed states are easily purified.

Gullans and Huse, PRX (2020)

Decoding to overcome the post-selection challenge

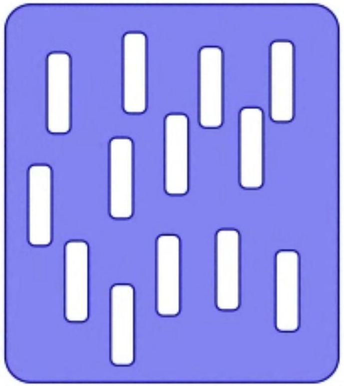




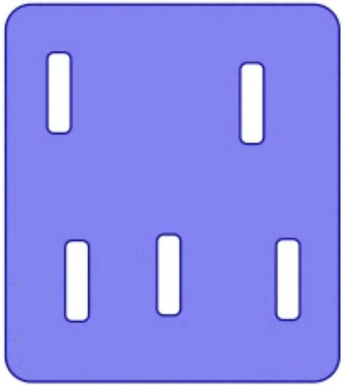


Decoding of local order parameter

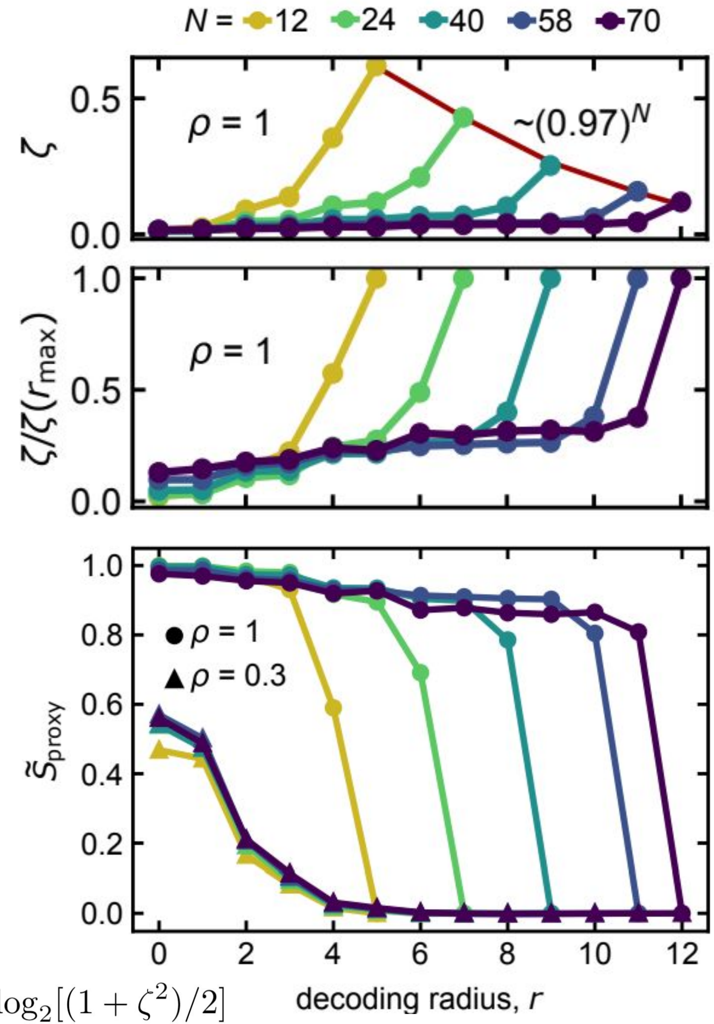
Cross-correlator →
“probe” qubit entanglement →
proxy for the system entanglement



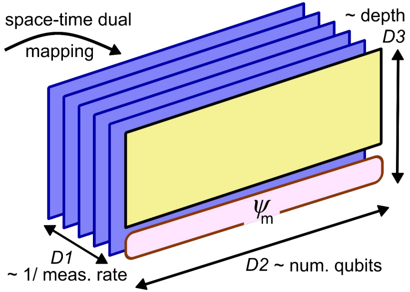
(weak unitary)
ρ → 0



(strong unitary)
ρ → 1

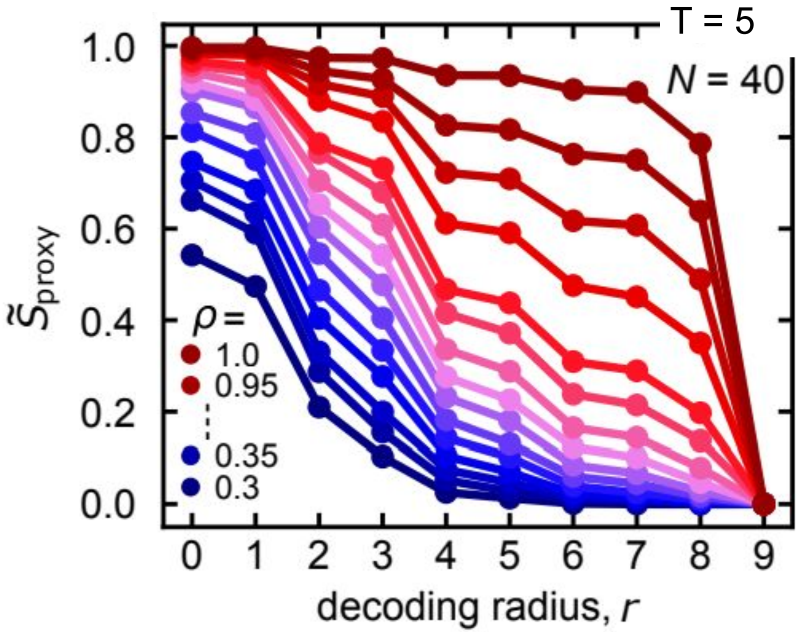


$$S_{\mathrm{proxy}} = -\log_2[(1+\zeta^2)/2]$$

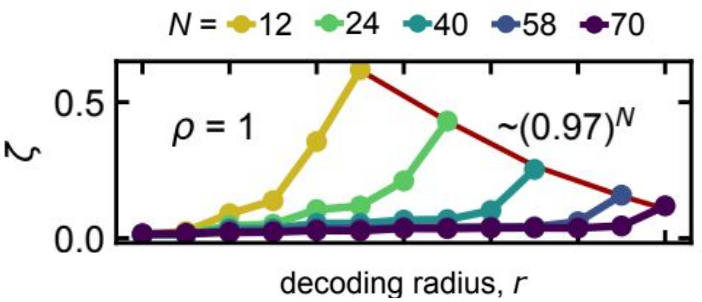


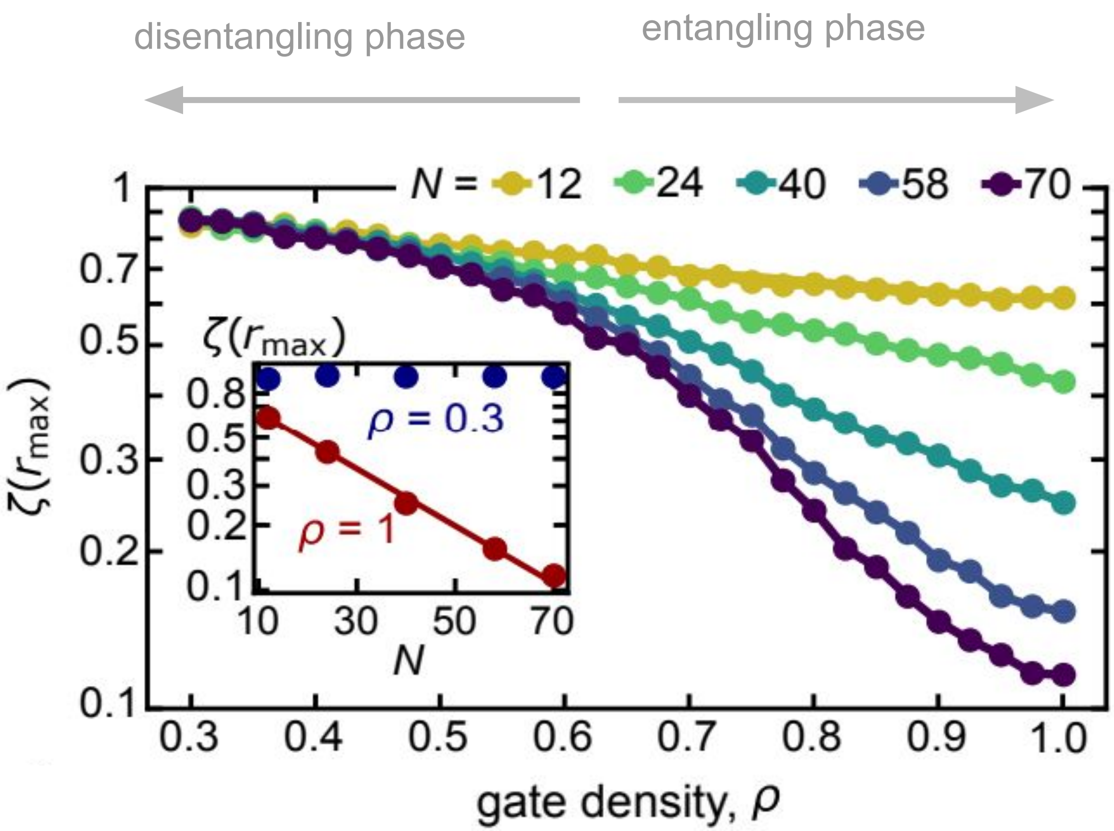
Crossover between entanglement structures

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



Noise as a probe of the entanglement structure





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