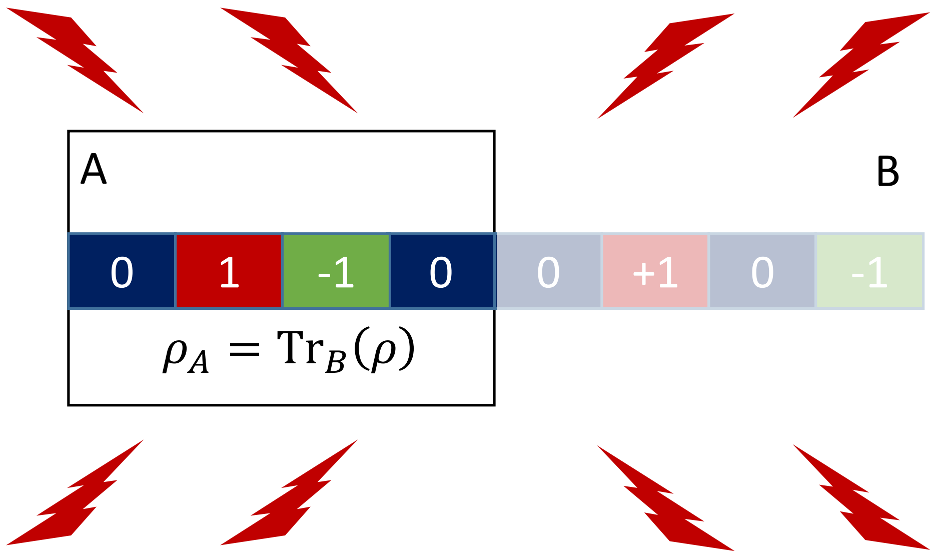
Quantum simulations:

topological phases on noisy quantum computers



Azses, Haenel, Naveh, Raussendorf, Sela, and Dalla Torre (PRL, 2020)

Many-body quantum dynamics group

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Robert Raussendorf

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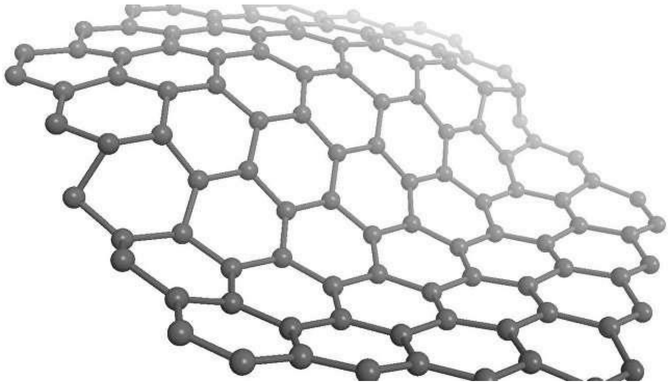
Quantum simulations: motivation I

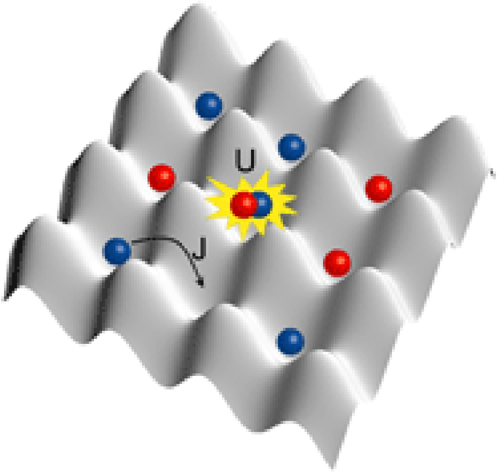
Quantum molecules/material

Size of Hilbert space = 2^{N_A}

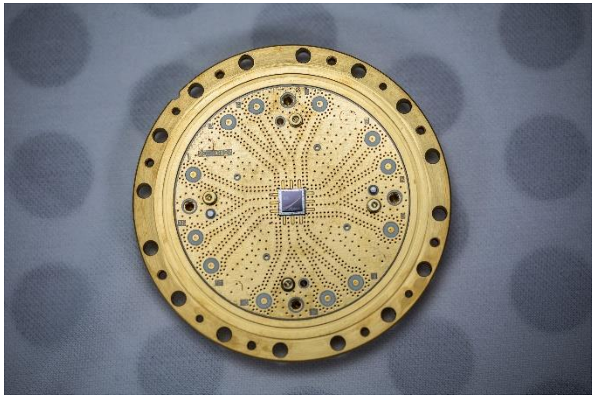


Classical supercomputers

Ultracold atoms

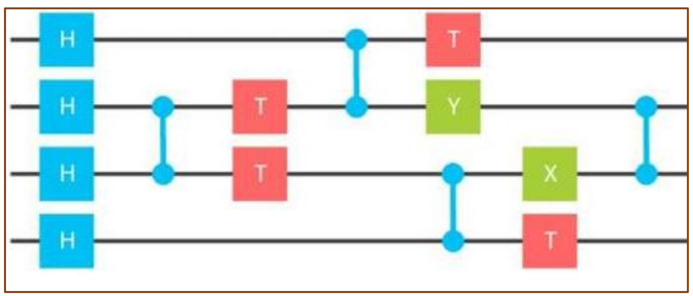


Quantum computer



Quantum simulations: motivation II

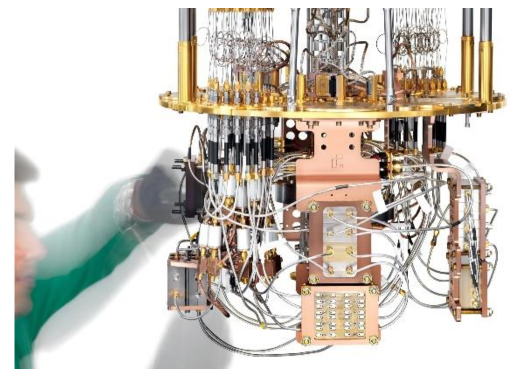
Model : Unitary
quantum computer



quantum error correction

open quantum systems

Reality : Noisy
Josephson junctions



Introduction : phases of matter

Ordered

0	1	0	1	0	1	0	1

Disordered

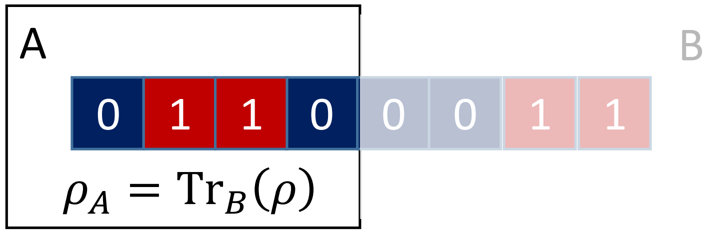
0	1	1	0	0	1	0	1

Topological

0	1	1	0	0	0	1	1

Haldane (1982), AKLT (1987), den Nijs&Rommelse (1989), ….

Symmetry protected topological phases



Subsystem probabilities:

Eigs(ρ_A) = 0.3, 0.3, 0.15, 0.15, 0.05, 0.05, …

Degeneracy is “protected” by the symmetry

Pollmann, Turner, Berg, & Oshikawa (2010) Chen, Gu & Wen (2011)

Identification of symmetry-protected topological states on noisy quantum computers

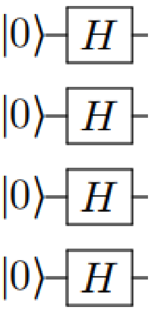
1. **Symmetry resolved entanglement entropy**

2. **Measurement based quantum computing**

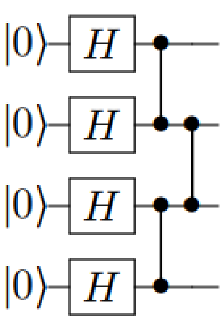
Topological phase with **qubits**

Ordered: Ising coupling

Disordered: Magnetic field



Topological: cluster model



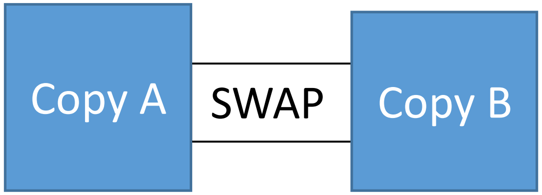
Friedman, Raj… and ref. therein

How to measure the density matrix?

Renyi entropy: $S_n = Tr[\rho_A^n]$

$$S_n = 0.3^n + 0.3^n + 0.15^n + 0.15^n + 0.05^n + 0.05^n$$

Replica trick $n = 2$

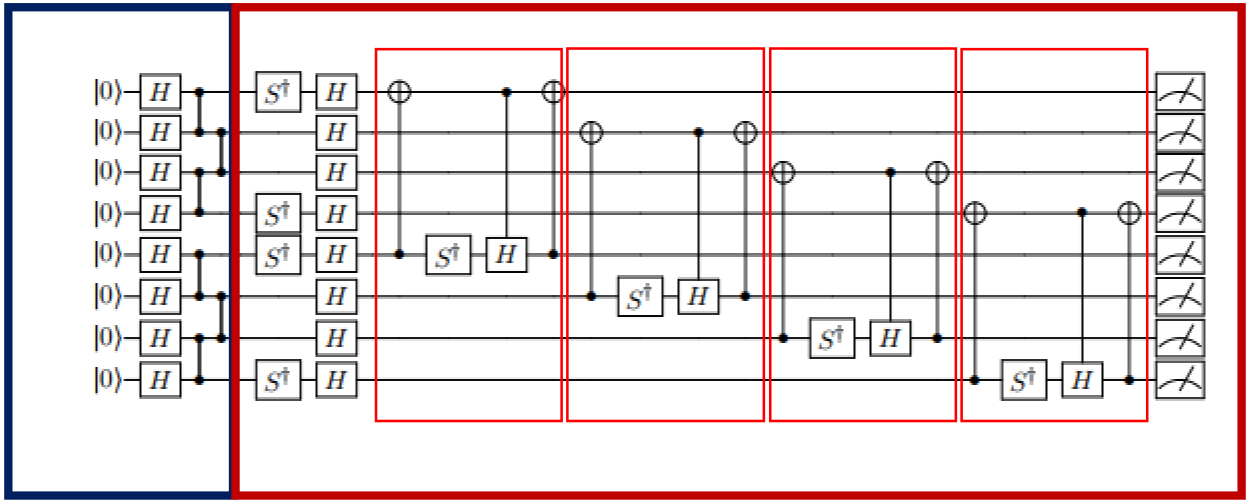


Daley, Pichler, Schachenmayer, Zoller, PRL (2012)

PROOF: $\langle SWAP_{AB}\rangle = Tr[\rho^A\rho^B\, SWAP_{AB}] = \sum_{i,j}\langle i_A j_B|\rho^A\rho^B SWAP_{AB}|i_A j_B\rangle$

$$= \sum_{i,j}\langle i_A j_B|\rho^A\rho^B|j_A i_B\rangle = \sum_{i,j}\langle i_A|\rho^A|j_A\rangle\langle j_B|\rho^B|i_B\rangle = Tr[\rho^A\rho^B] = Tr[\rho^2]$$

2nd Renyi entropy of the cluster state



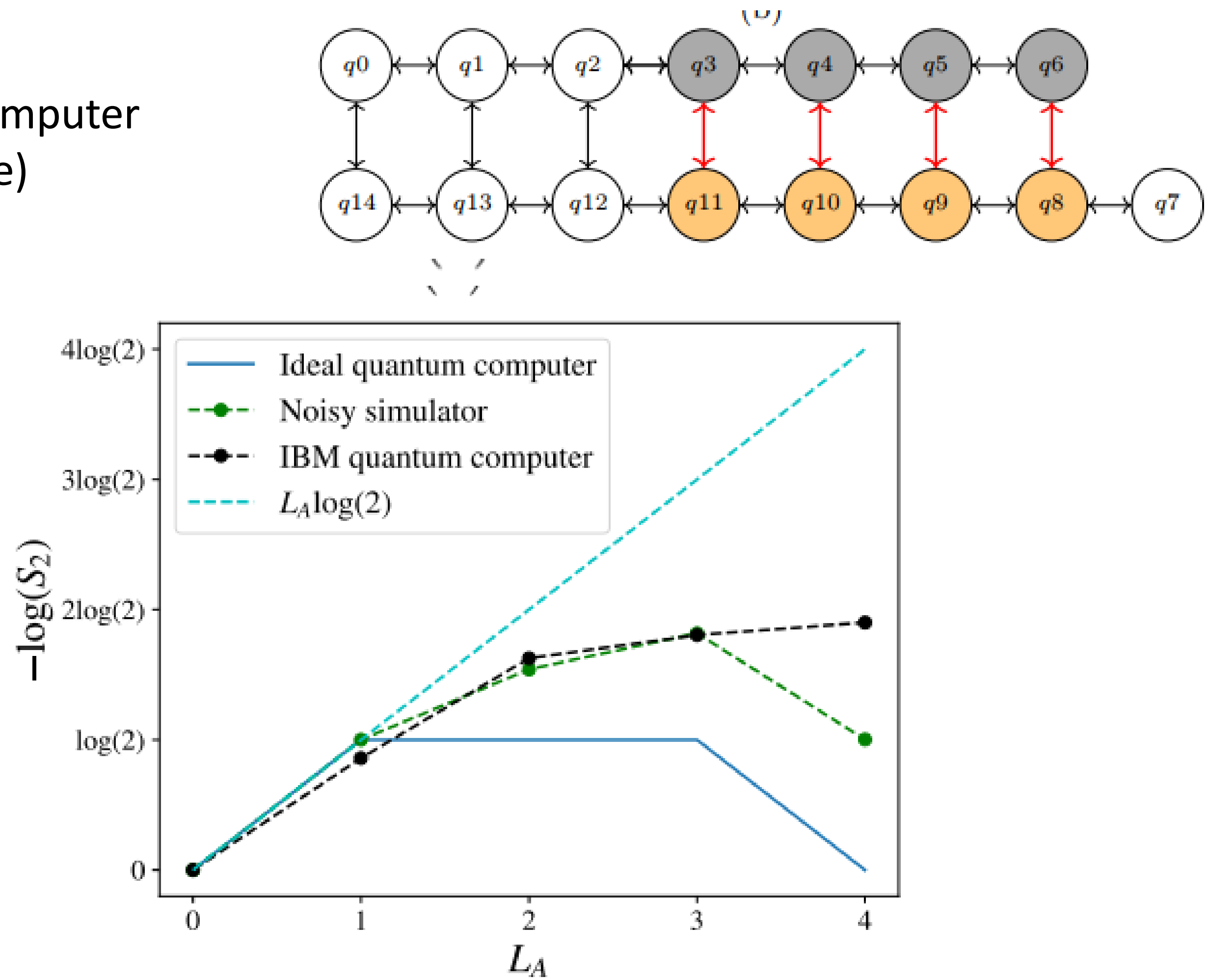
Step 1 : create two copies of the cluster state

Step 2 : entangle each pair of the two copies (SWAP)

Step 3 : compute Renyi entropy

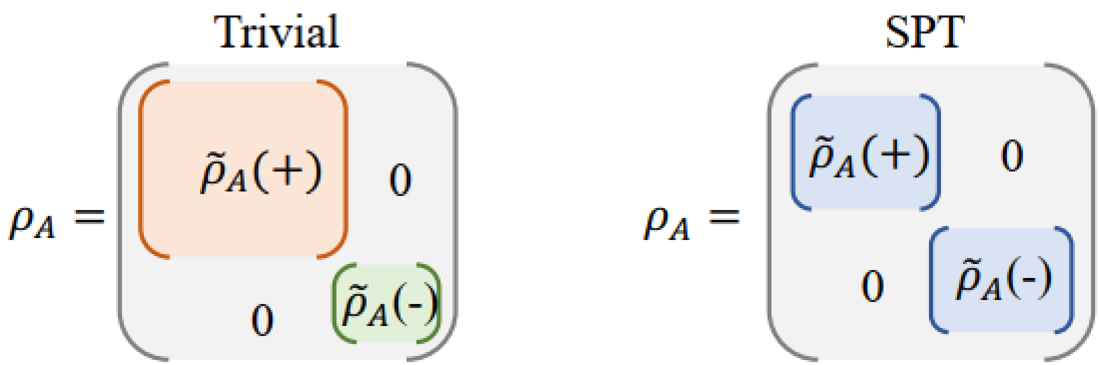
2^{nd} Renyi entropy of the cluster state

IBM Quantum computer
(publicly available)



How to measure topological properties?

G: Symmetry $\rightarrow G\,|\psi\rangle = g|\psi\rangle$ $\rightarrow [G, \rho_A] = 0$



Goldstein & Sela (PRL, 2018)

Symmetry resolved reduced density matrix

$$\rho_A^{\pm} = P^{\pm}\rho_A \quad \Rightarrow \quad S_n^{\pm} = Tr\left[\left(\rho_A^{\pm}\right)^n\right] = \sum_i \left(\lambda_i^{\pm}\right)^n$$

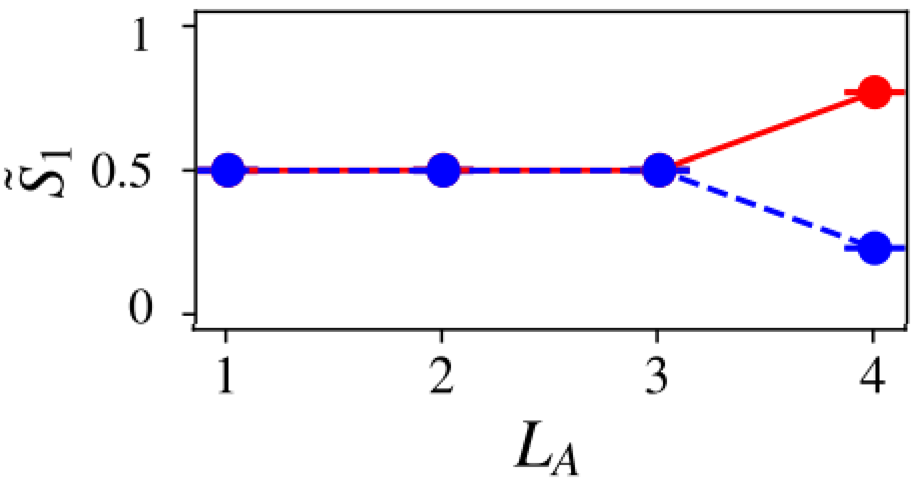
$$S_2^{+} = 0.3^2 + 0.15^2 + 0.05^2$$

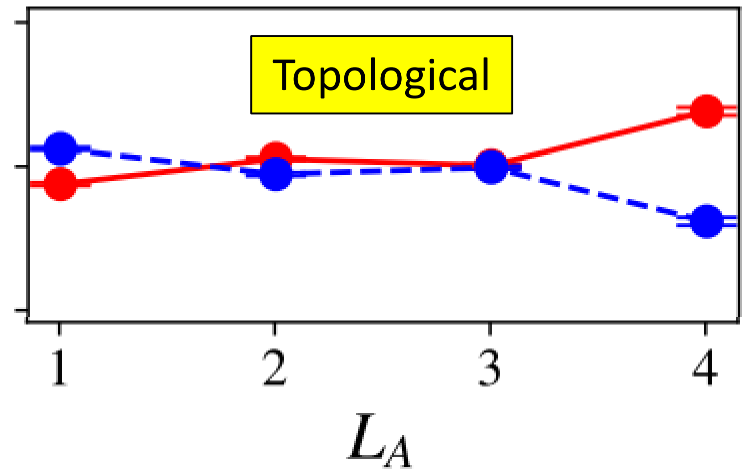
$$S_2^{-} = 0.3^2 + 0.15^2 + 0.05^2$$

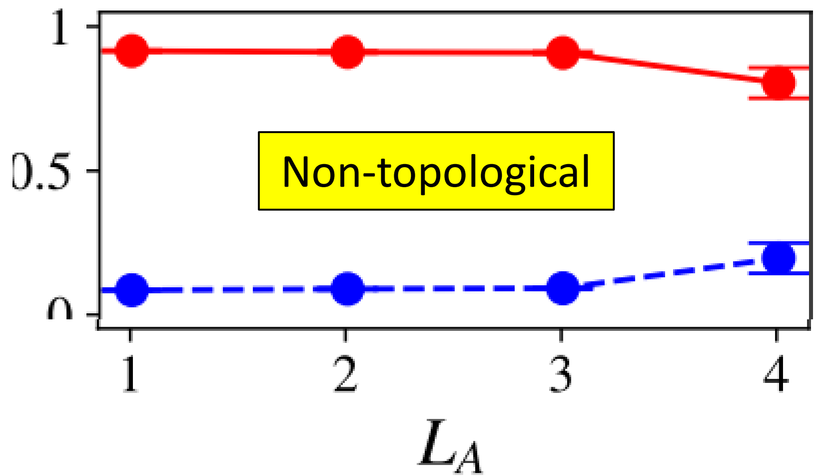
$$S_2^{+} = S_2^{-}\ ?$$

Note: need algorithm to measure SWAP and P at the same time

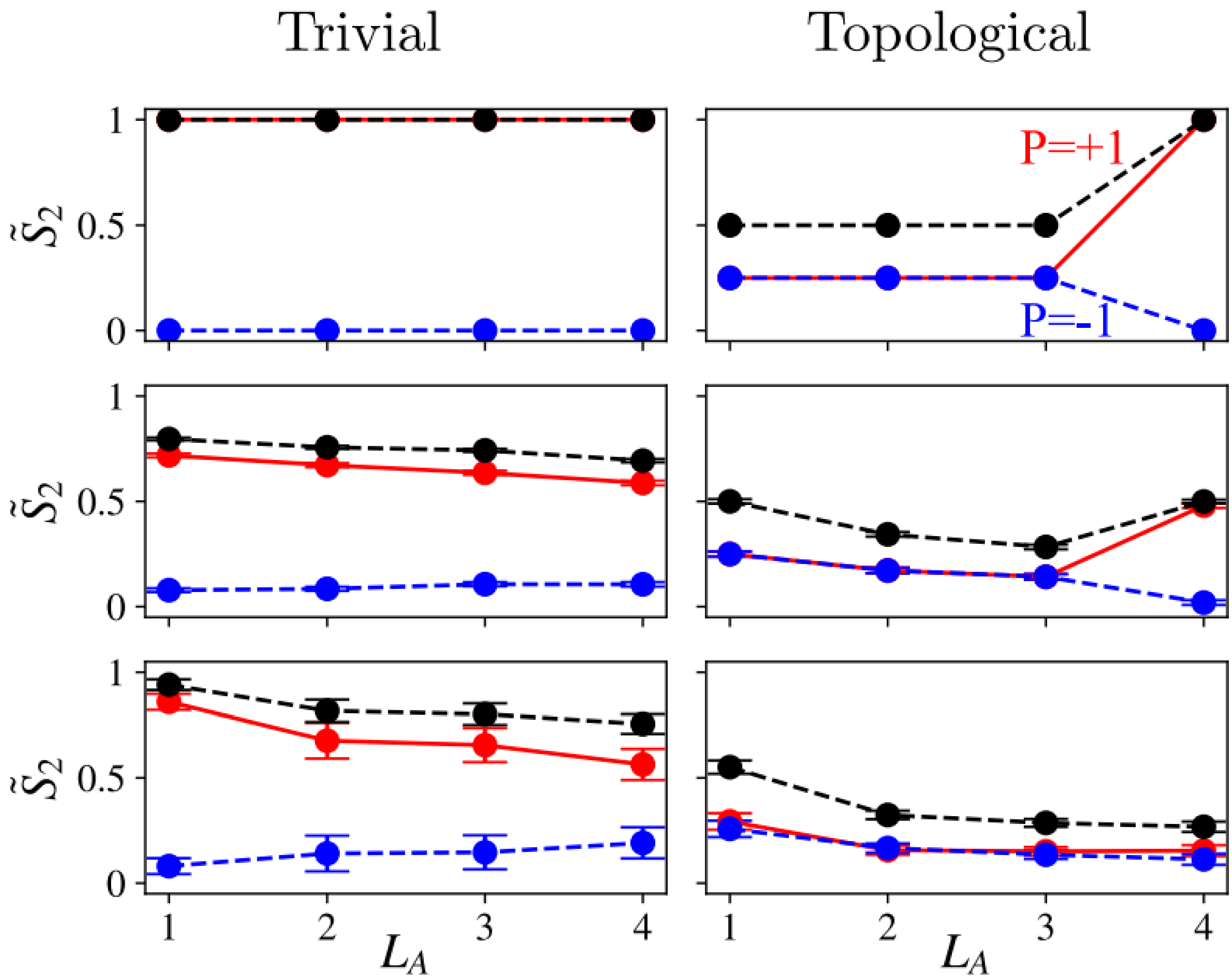
Simulation vs. Experiment



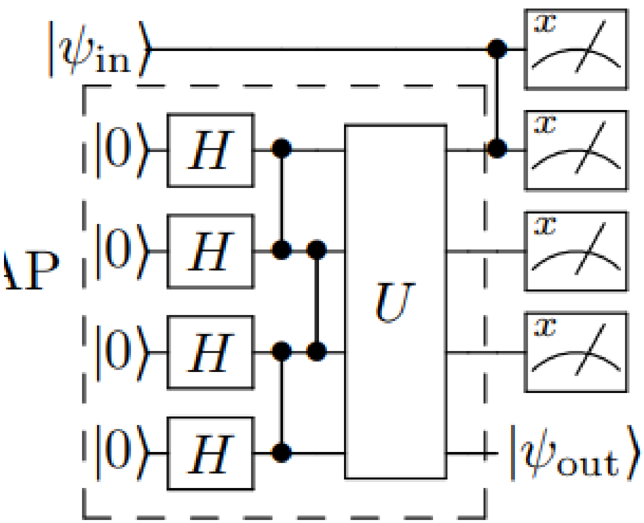




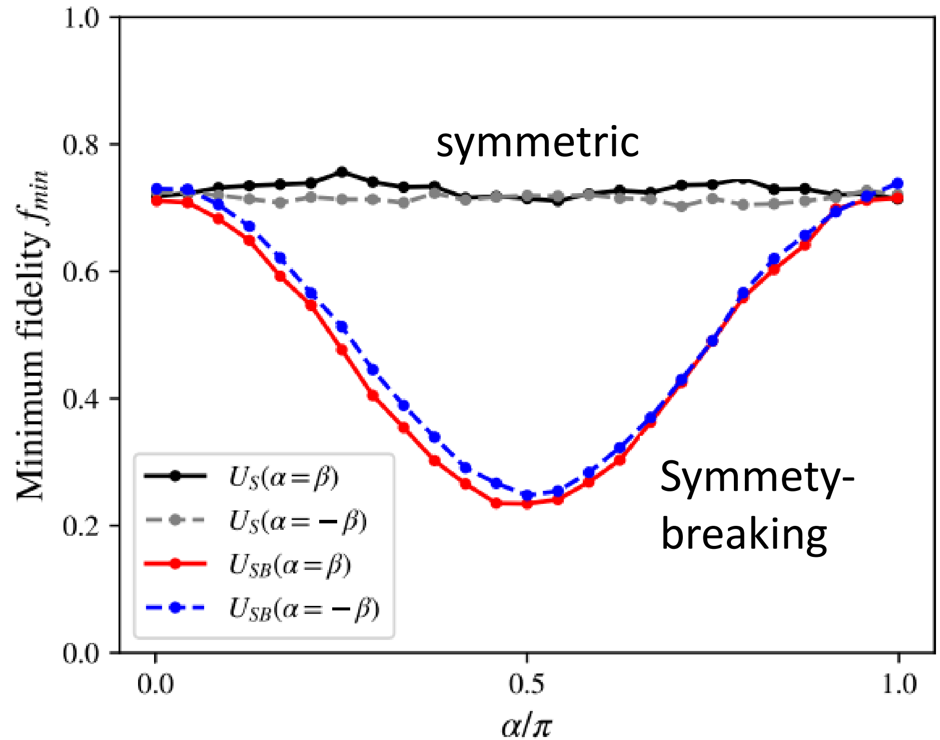
(b) Purity $\tilde{S}_2 = \mathrm{Tr}[\tilde{\rho}_A^2]$



Second method : MBQC



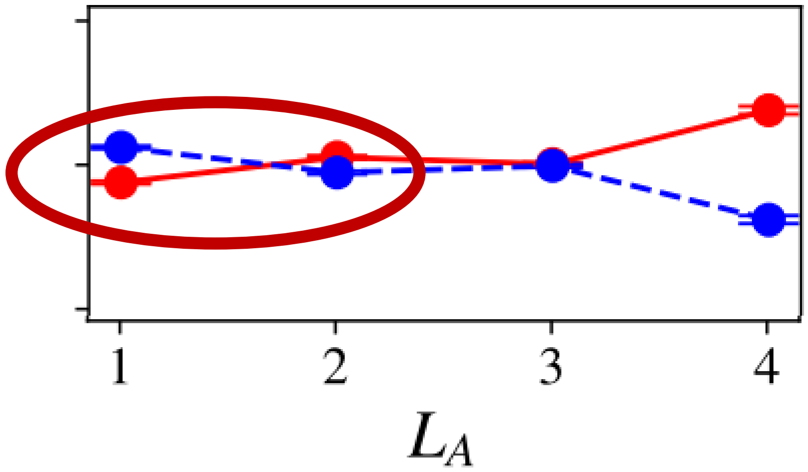
Else et al, PRL (2012)



Summary

Many-body physics with superconducting circuits

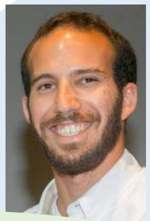
New phase of matter (?) : Noisy symmetry protected topological states



Azses, Haenel, Naveh, Raussendorf, Sela, and Dalla Torre (PRL, 2020)

Outlook

Periodic Drive



Mor Roses:
Simulation of long-range coupling
with Floquet dynamics (QISKIT Pulse)

Topological phases of matter

Meron Sheffer:
Solving nonlocal games
with SPT states

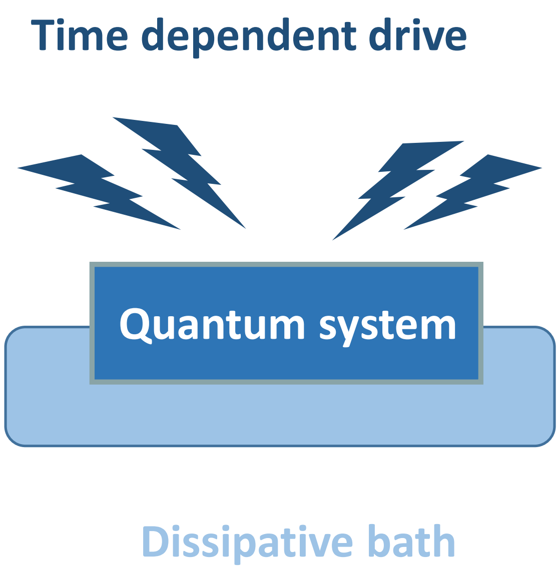
Measurement

Frima Kalyuzhner:
Neural networks for
measurement error mitigaton

Superconducting circuits

Inbar Shany:
Parametrically amplified
spin-cavity couplings

Many-body open quantum systems



Floquet engineering

Quantum bath engineering

Nonequilibrium universality

Topological phases