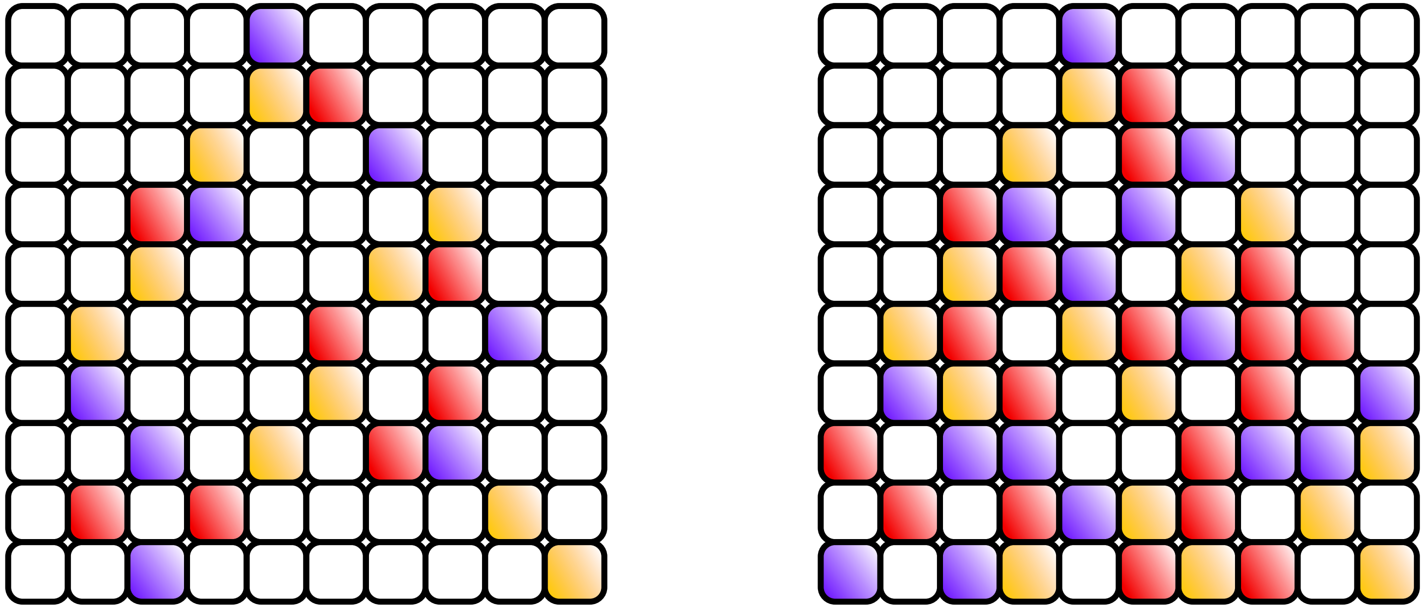
Noise, complexity, and information dynamics in quantum circuits

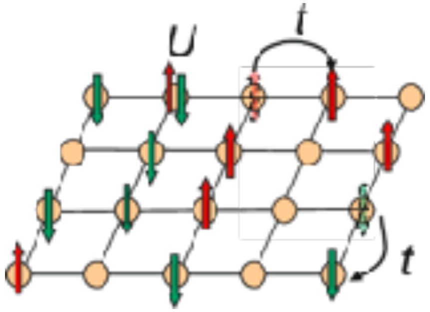


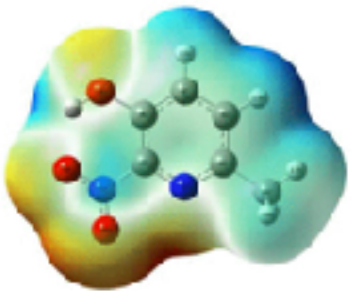
TS, Yao PRL 131, 160402 (2023)
TS, Yao forthcoming (2023)

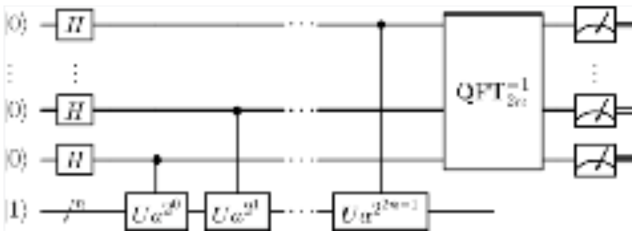
Thomas Schuster
IPAM, November 2023

Many-body quantum science

Coherent large-scale quantum systems may achieve large advantages in computation, physics, chemistry, sensing, cryptography, …







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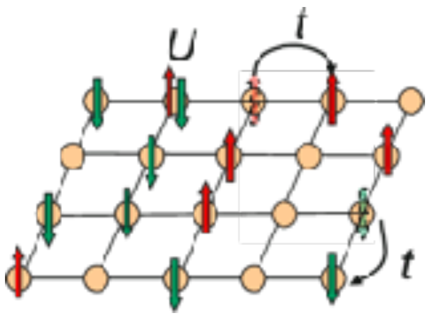

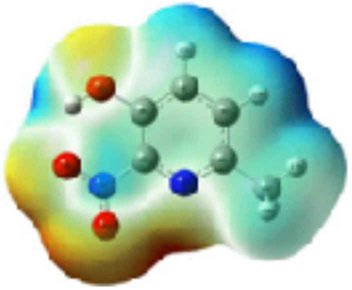

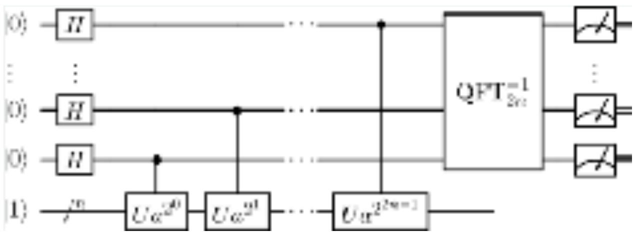

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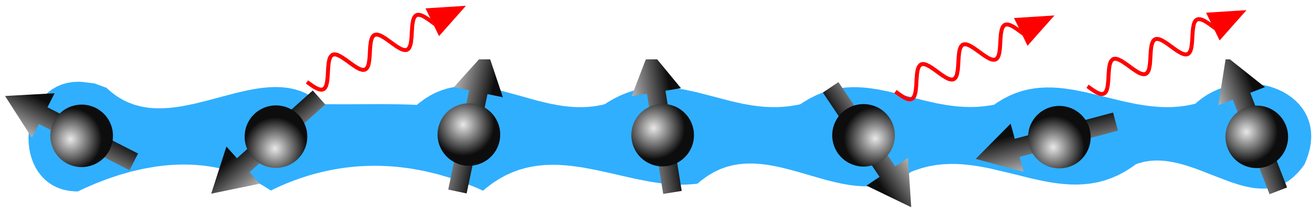
However, near-term quantum devices are impacted by noise



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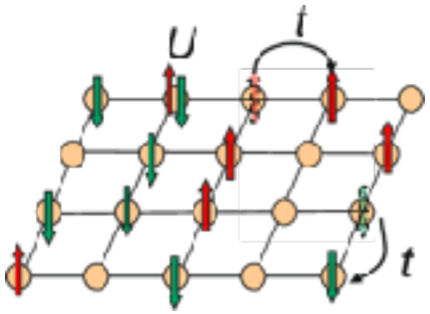

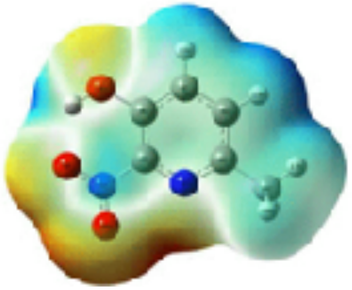

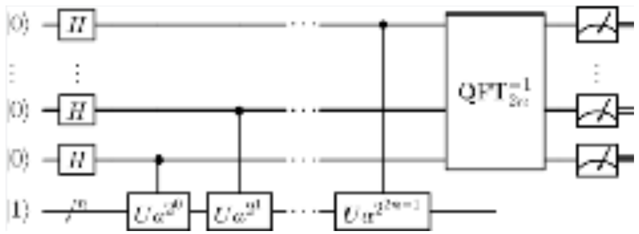

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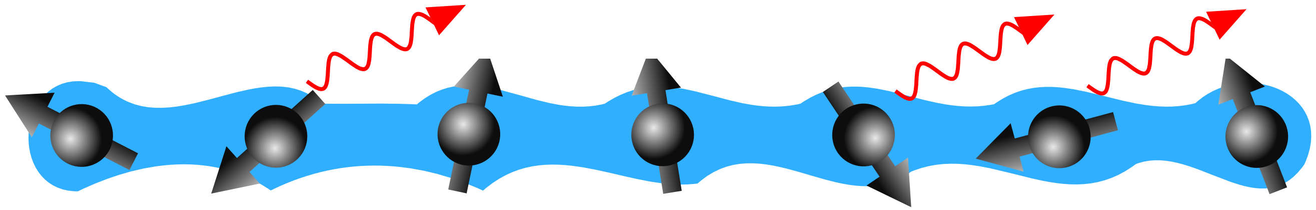

Quantum error correction can address this, but requires additional capabilities/overhead

Noisy many-body quantum science

What can we do with noisy quantum devices?

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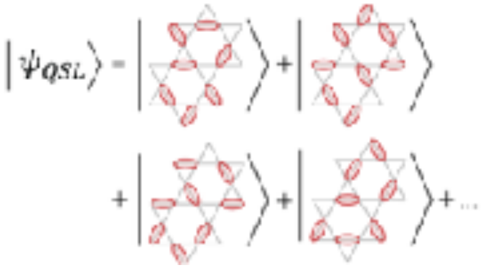
Physics experiments



Harvard/MIT (2022)

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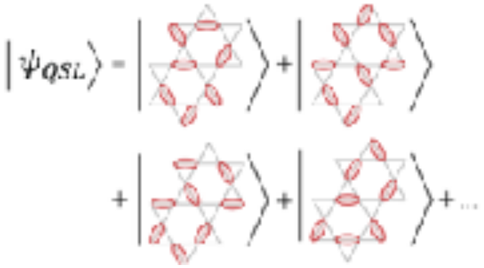

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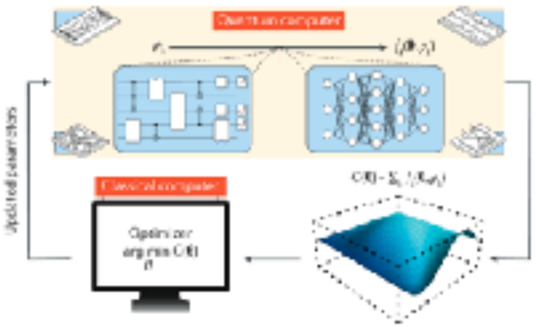
NISQ algorithms



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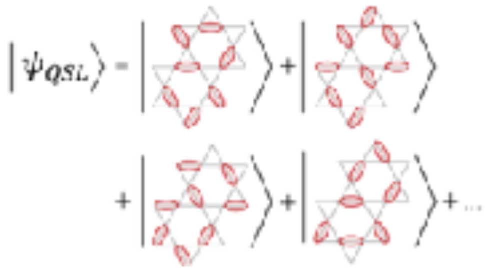

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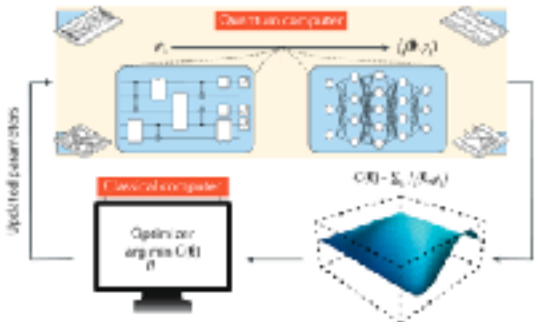
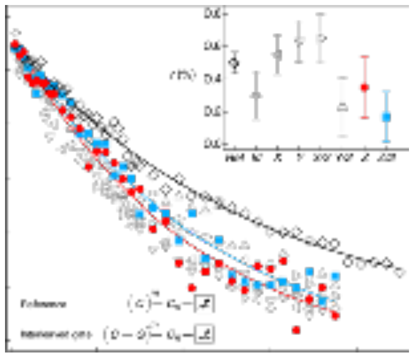


Cerezo et al (2021)

Benchmarking noise



Marcus group (2015)

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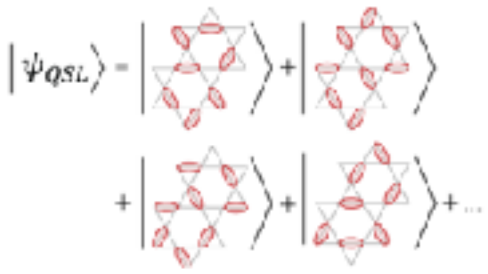

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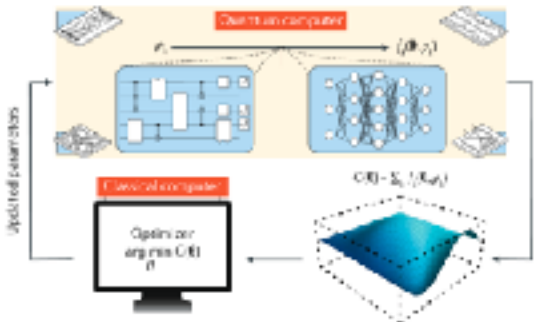

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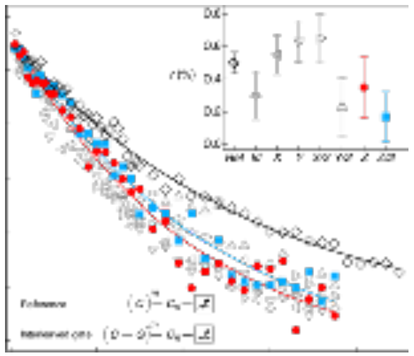

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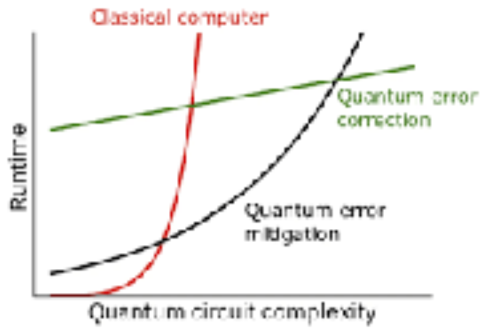
Error mitigation



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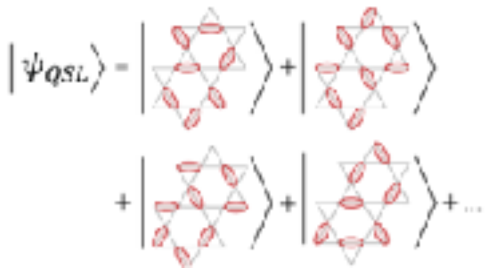

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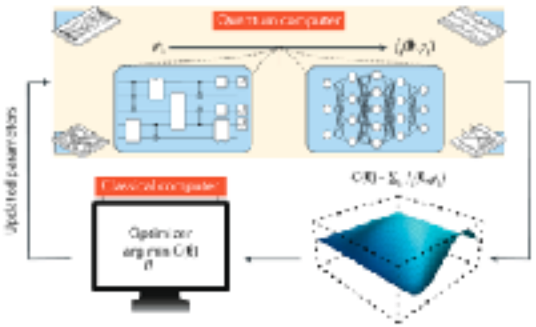

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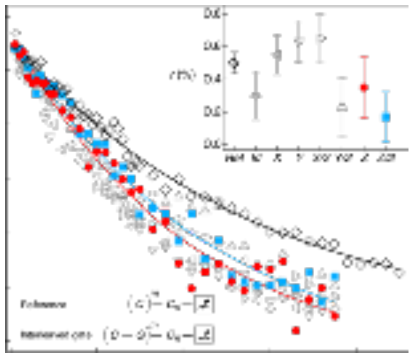

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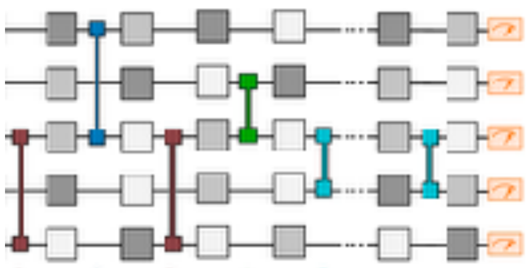
Complexity



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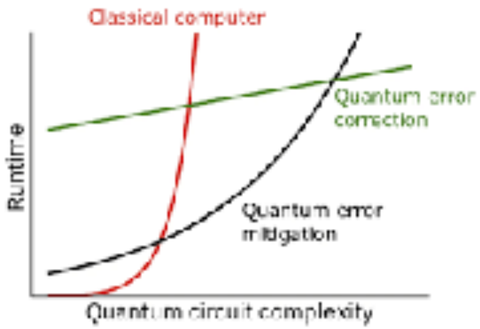

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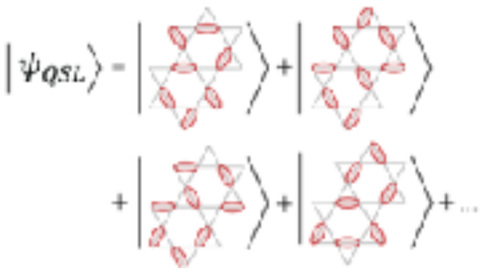

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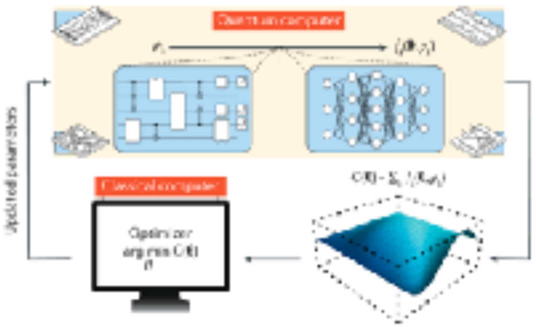

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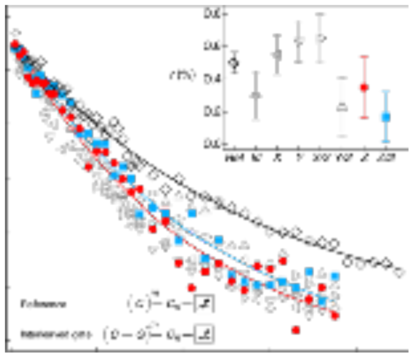

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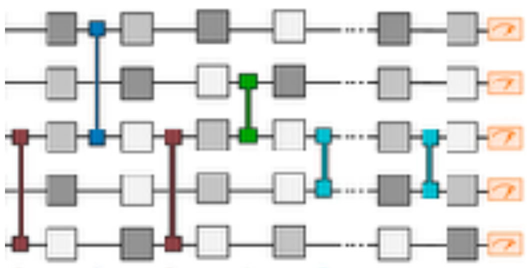

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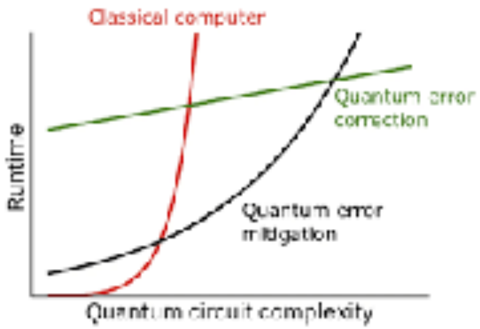

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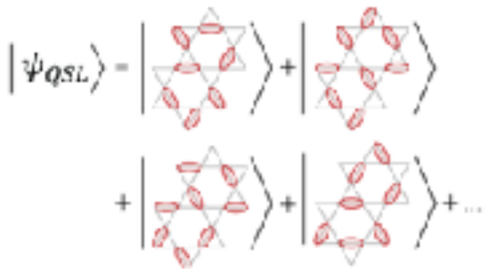

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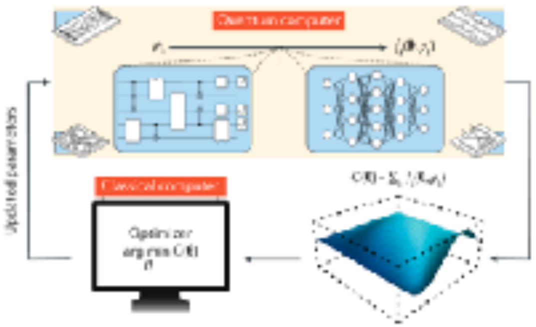

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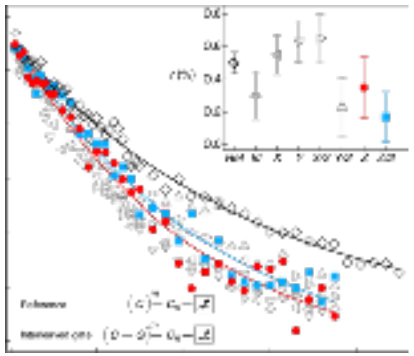

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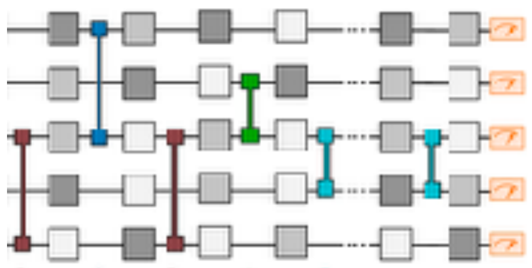

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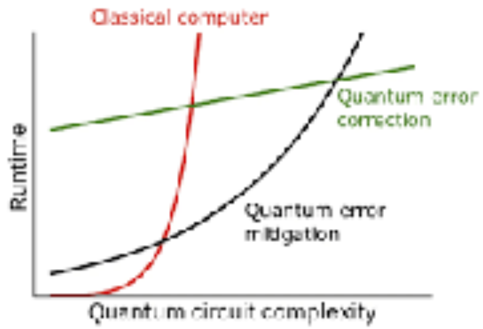

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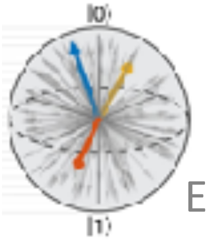

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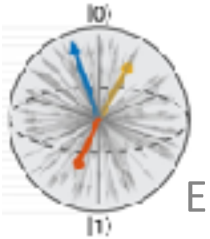

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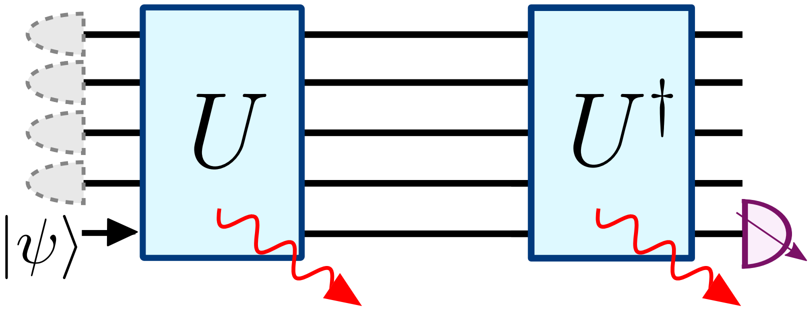
Loschmidt echo: thought expt ~1870's, NMR ~1980's, single-particle theory ~2000's, NISQ expts ~2010s Pines, Pastawski, Peres, Jalabert, Zurek, Cappellaro, Sanchez,...



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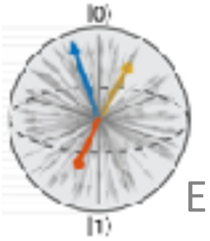

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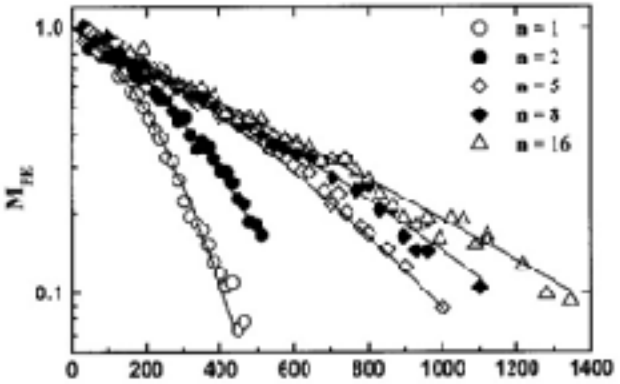
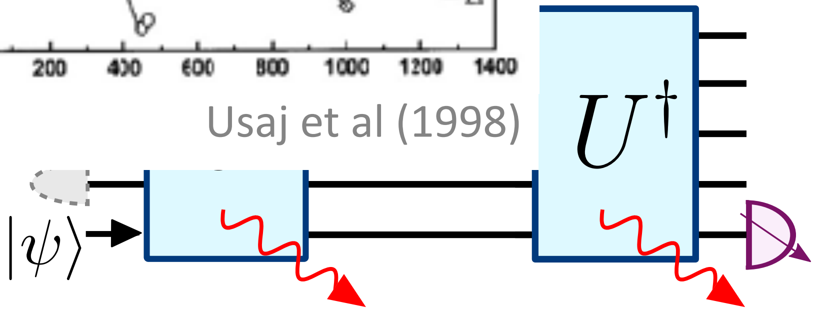


Usaj et al (1998)



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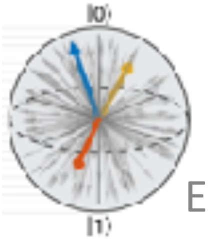

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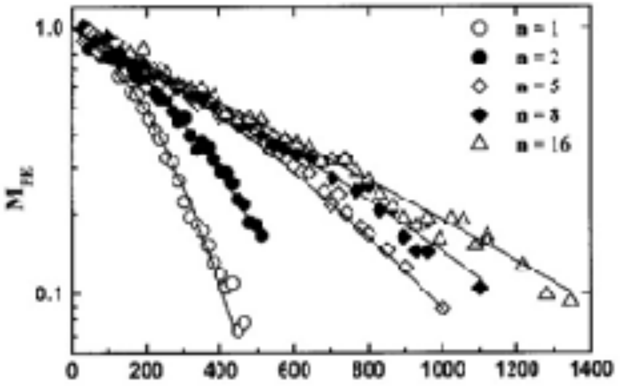

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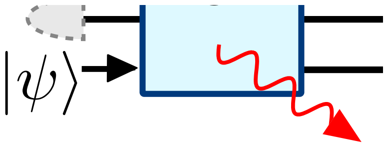

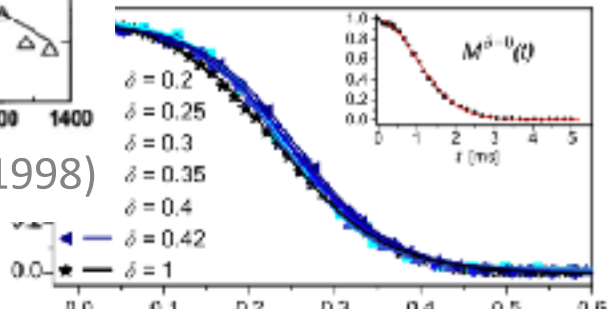

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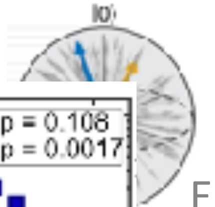

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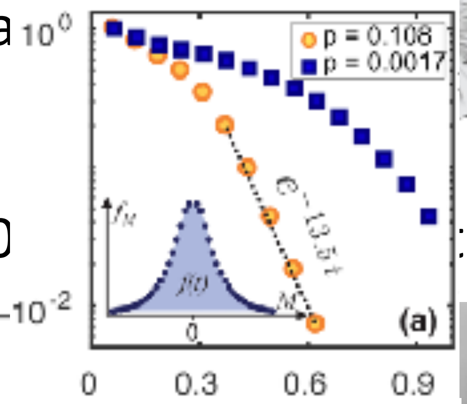

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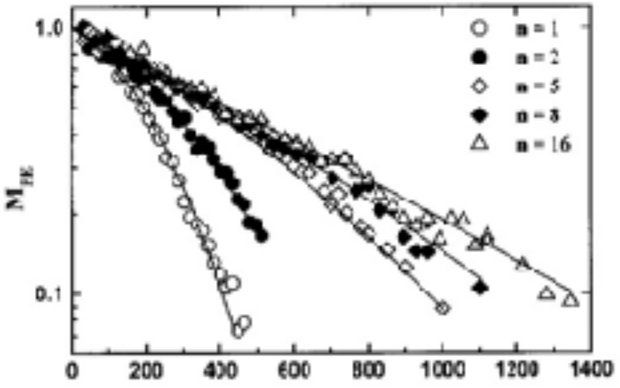

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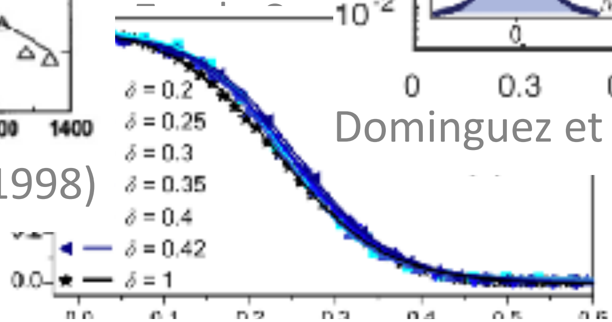

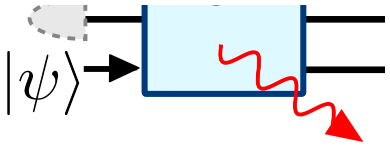

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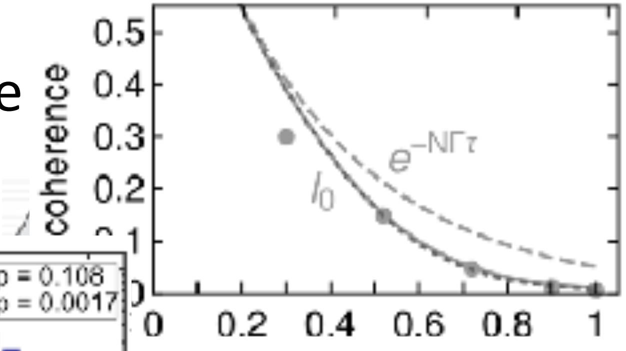

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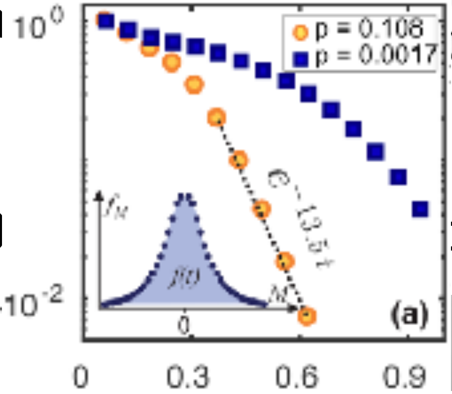

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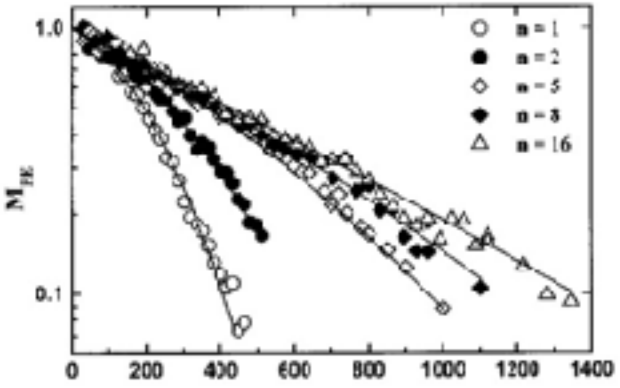

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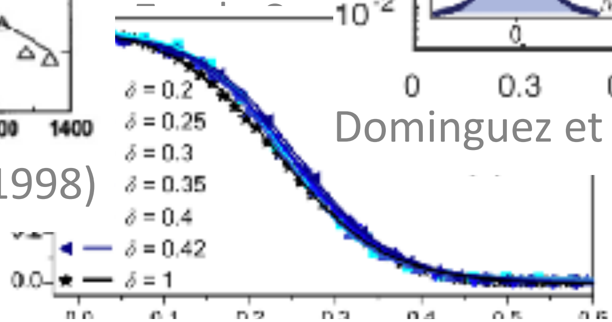

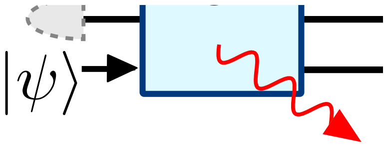

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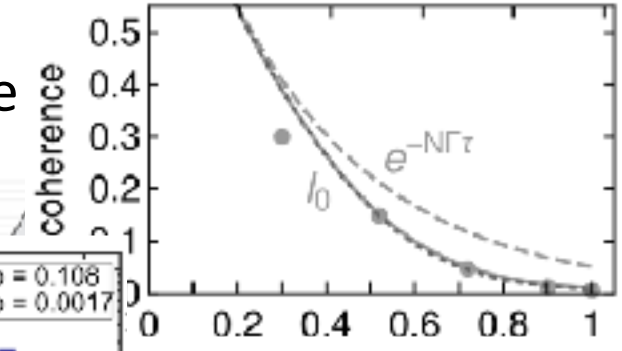

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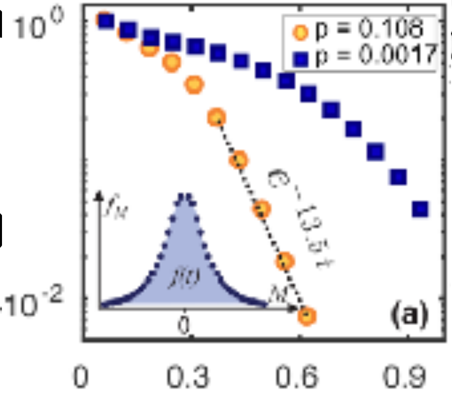

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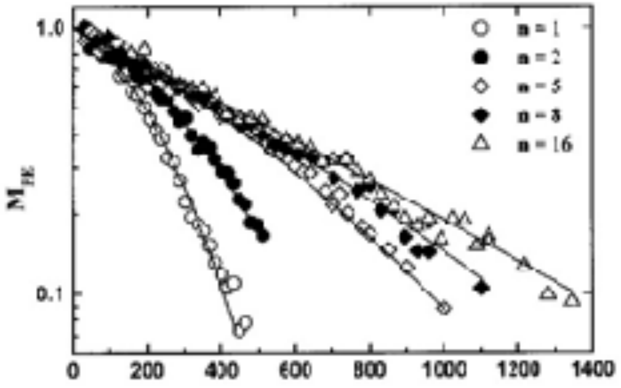

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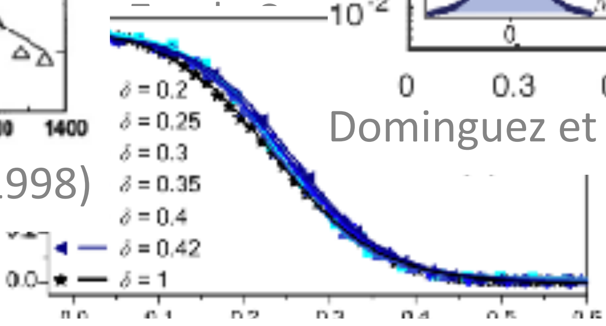

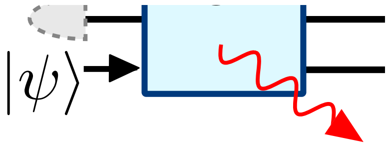

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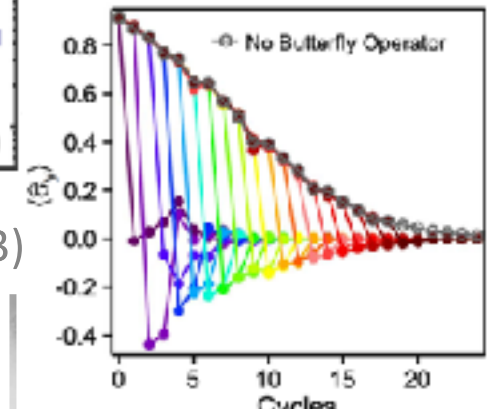

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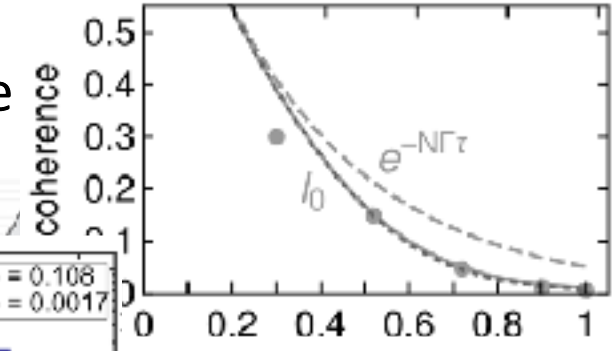
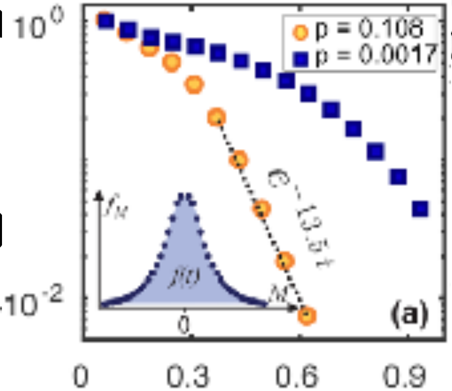


Garttner et al (2016)

Sampling: measure bitstrings, compare with classica

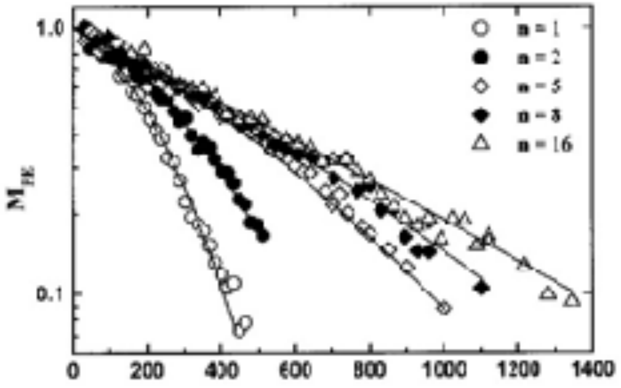


Dominguez et al (2023)

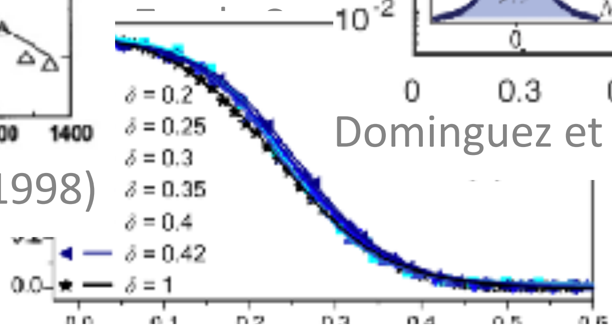
Loschmidt echo:

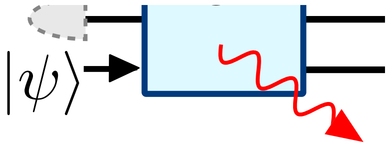
R ∼1980

NISQ expts ∼201

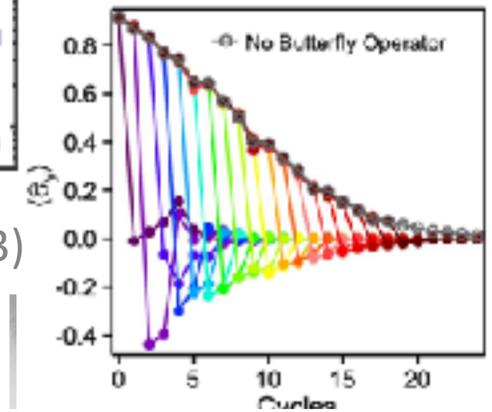


Usaj et al (1998)





Sanchez et al (2020)

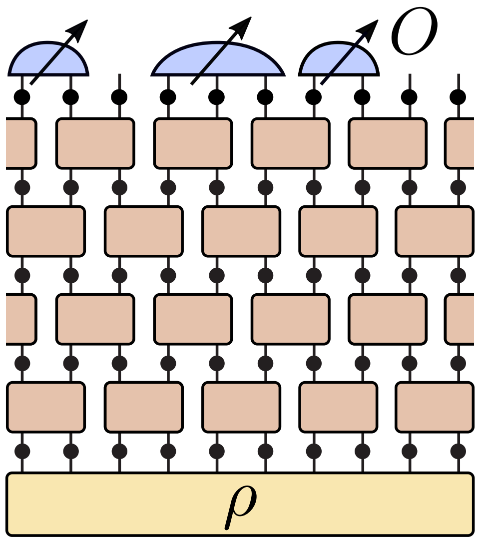


Google Quantum AI (2021)

Experiments show the Loschmidt echo decay ***depends on U itself***

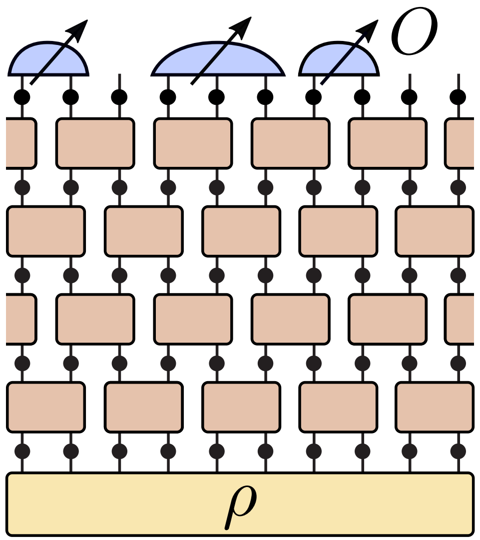
How can we understand this in many-body quantum systems?

How does noise impact complexity?



How does noise impact complexity?

- **Intuition:** Noise limits entanglement, so easy to classically simulate



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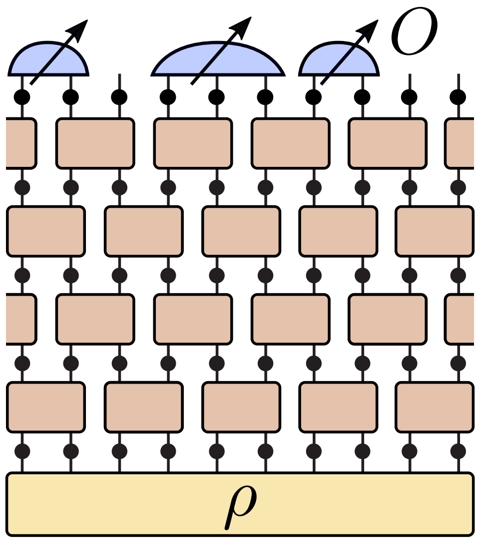
Aharonov, Ben-Or, Impagliazzo, Nisan (1996)



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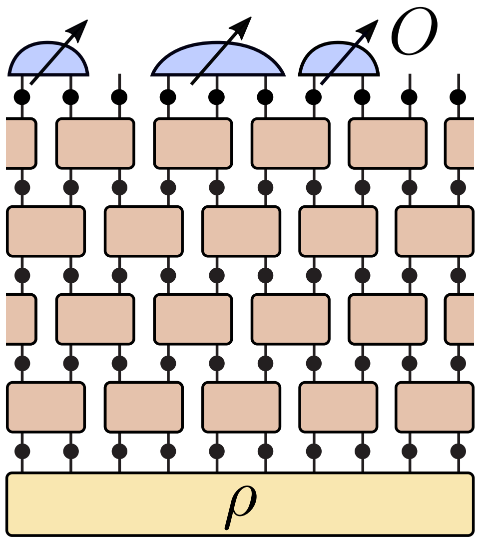
  - Perform lots of noisy circuits in parallel, take quantum majority votes



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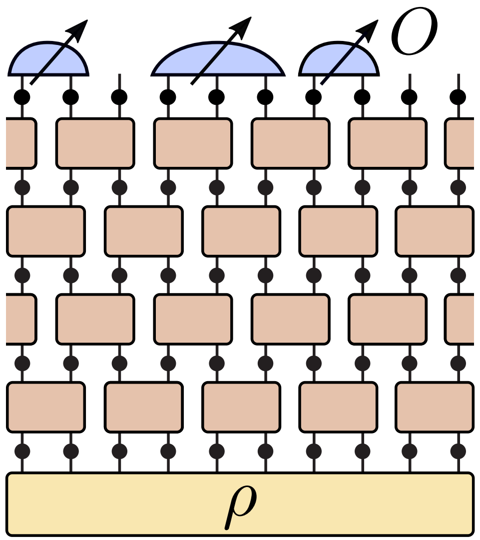

How does noise impact the circuits ***that we are actually performing***?

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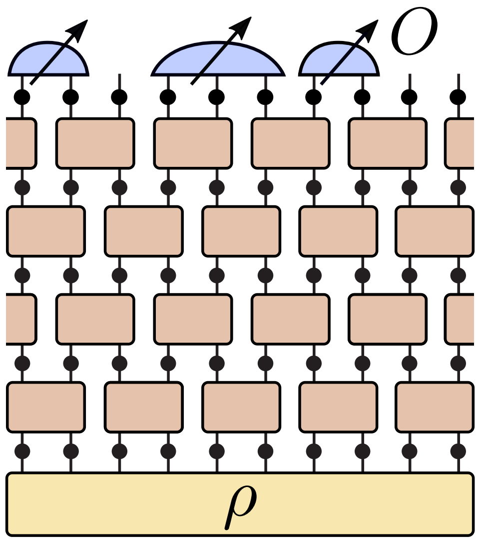

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- Recent results show that **random noisy circuits** are classically simulable (in scaling with n)

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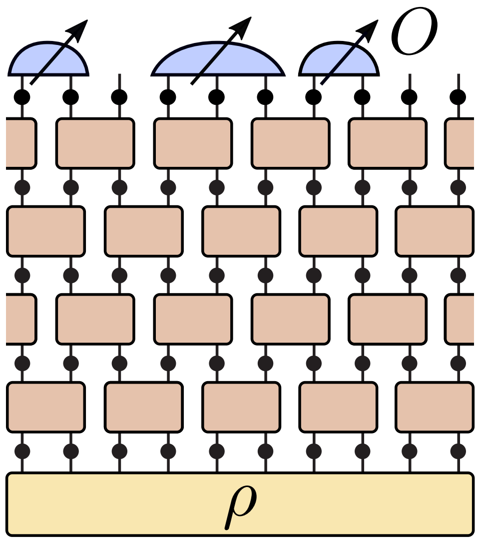

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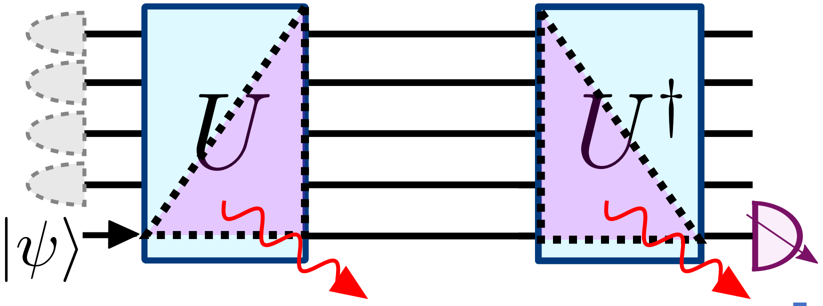
Does this extend to more general classes of quantum circuits?

This talk:

Noise ⇔ Information dynamics ⇔ Complexity

Operator growth in open quantum systems

TS, Yao PRL 131, 160402 (2023)



Noise ⇔ **Information dynamics** ⇔ **Complexity**

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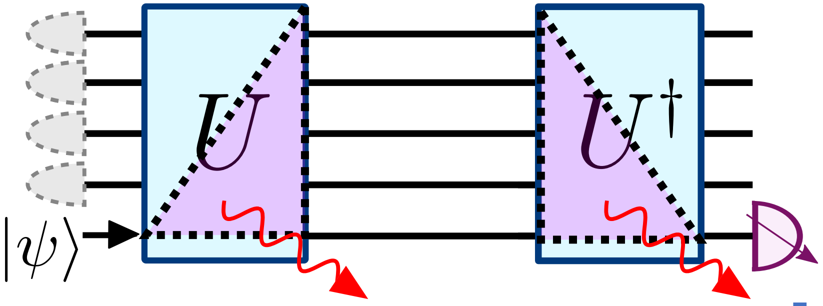

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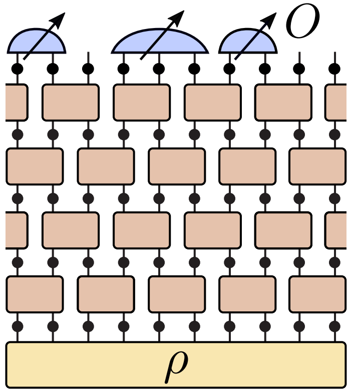

TS, Yao forthcoming (2023)

A polynomial-time classical algorithm for almost any noisy quantum circuit

Operator growth in open quantum systems

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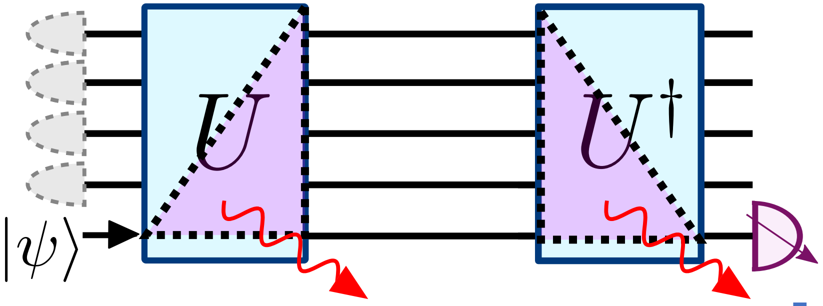

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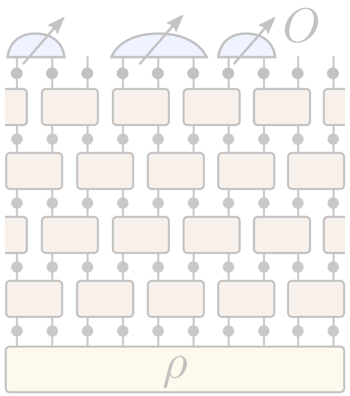

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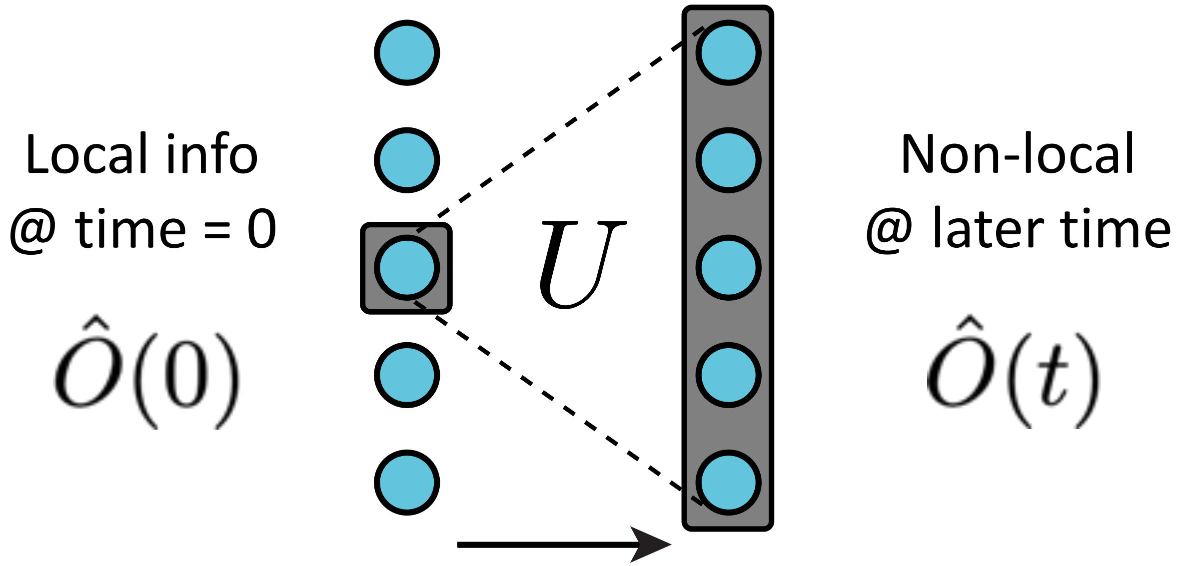
Quantum information dynamics

Operator growth: How does local information evolve in time?

e.g. $U = e^{-iHt}$



Linked to recent developments in quantum gravity, quantum chaos, quantum state transfer, tensor network algorithms, quantum thermalization…

Zooming in... Operator size distributions

Roberts et al. (2018), Streicher, Qi (2019)

Zooming in… Operator size distributions

Define the **size** (a.k.a. "weight") of a Pauli string = its number of non-identity elements

$$\hat{R} = \mathbb{1} \otimes \mathbb{1} \otimes X \otimes \mathbb{1} \otimes Y \otimes Z \otimes X \otimes X \otimes \mathbb{1} \otimes Y$$

Size = 6

Roberts et al. (2018), Streicher, Qi (2019)

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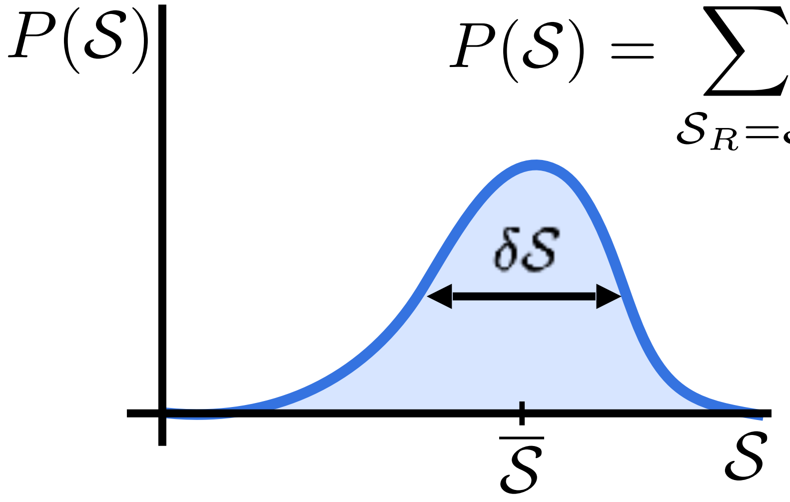
Size = 6

Time-evolved operators have a **size distribution**:

$$\hat{Q}(t) = \sum_R c_R \hat{R}$$

$$P(\mathcal{S}) = \sum_{\mathcal{S}_R = \mathcal{S}} |c_R|^2$$



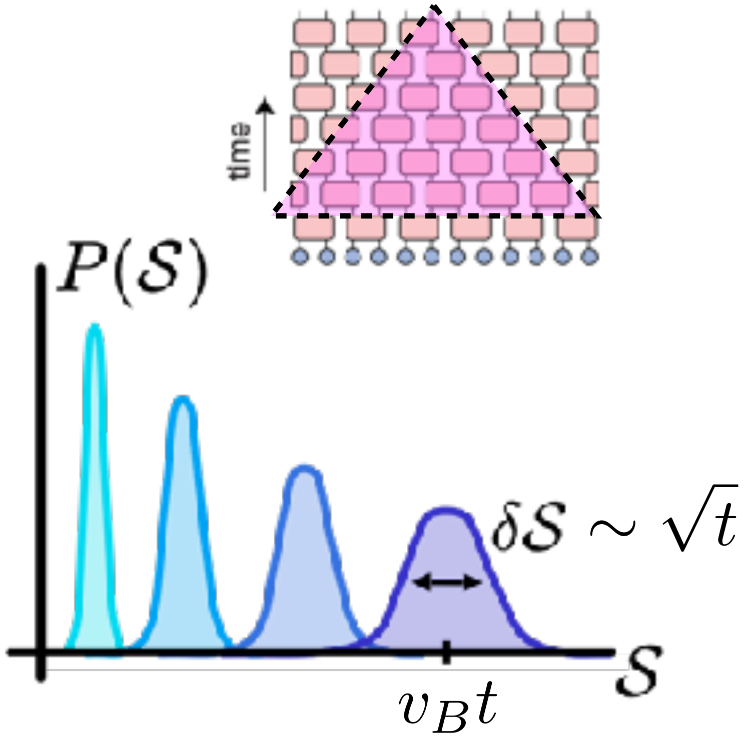
Roberts et al. (2018), Streicher, Qi (2019)

Universal classes of quantum information dynamics

Nahum (2018), Roberts (2015), Streicher (2018), Khemani (2018), von Keyserlink (2018), Rakovszky (2021)…

Universal classes of quantum information dynamics

1D circuits



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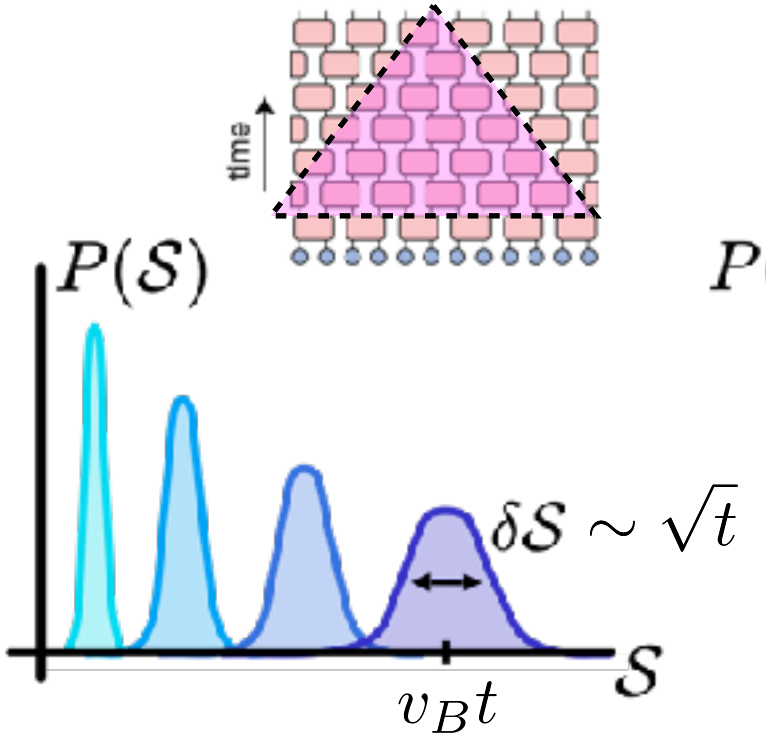
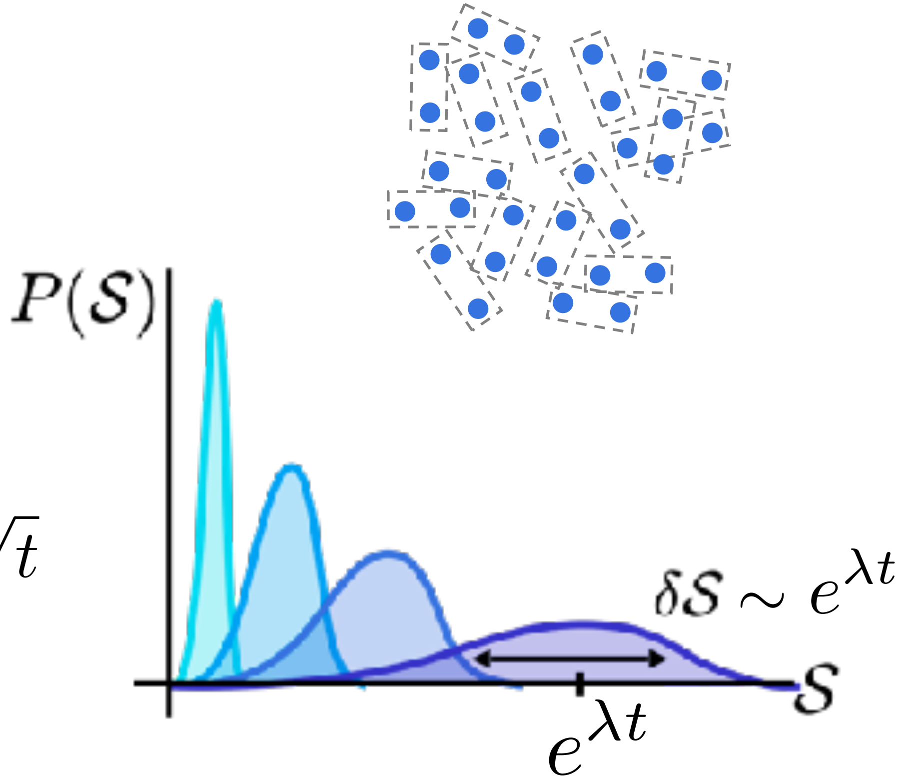


All-to-all systems



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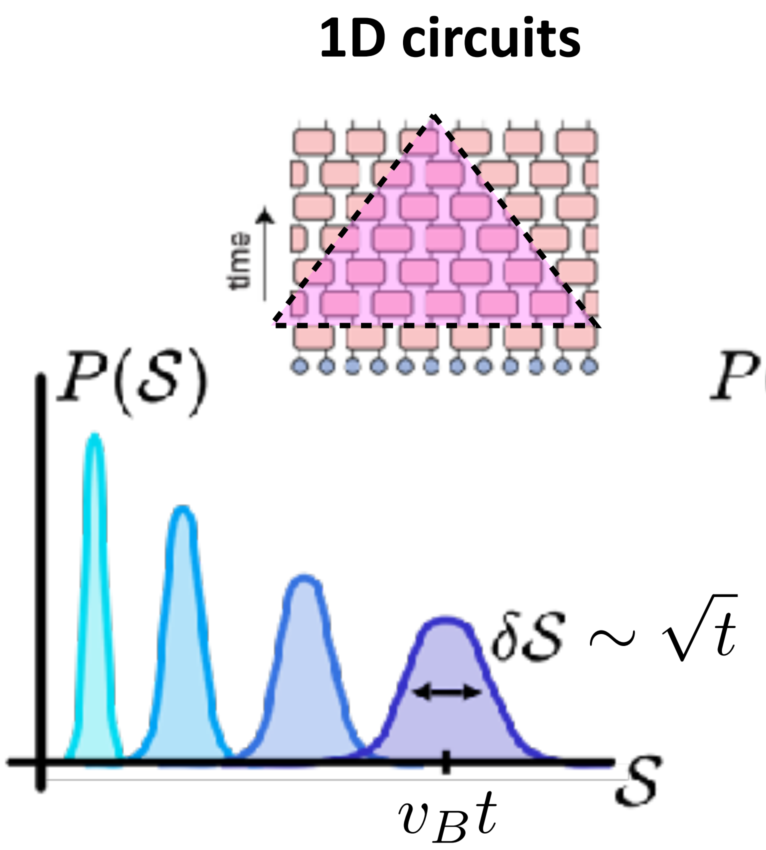

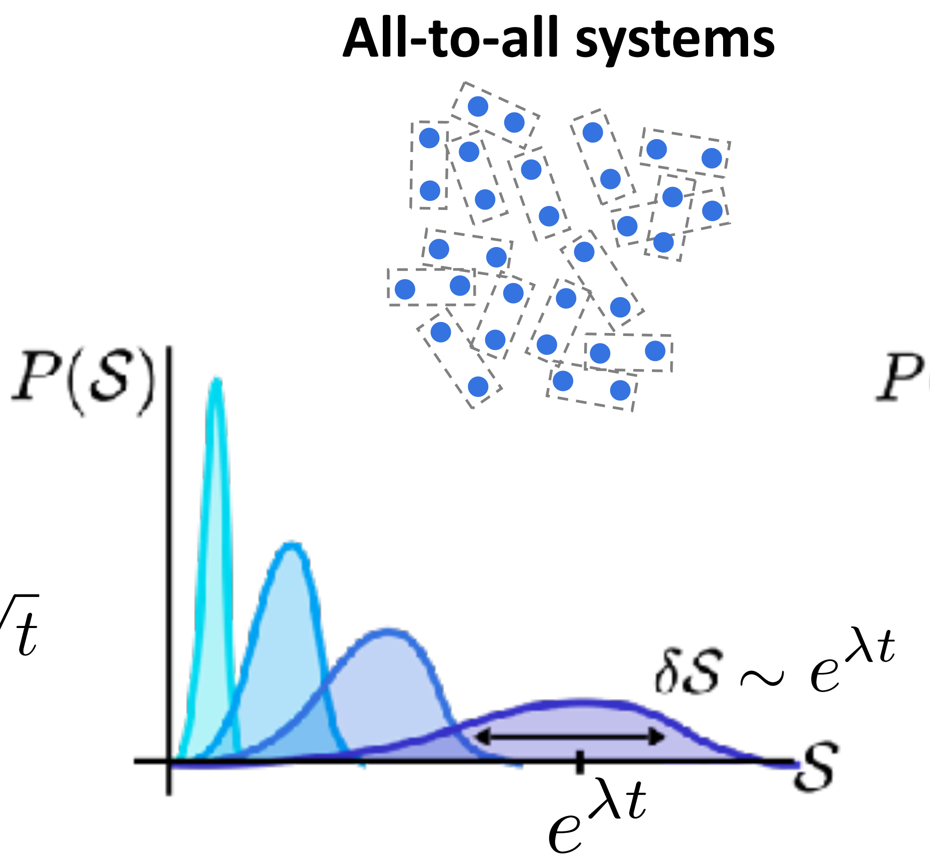

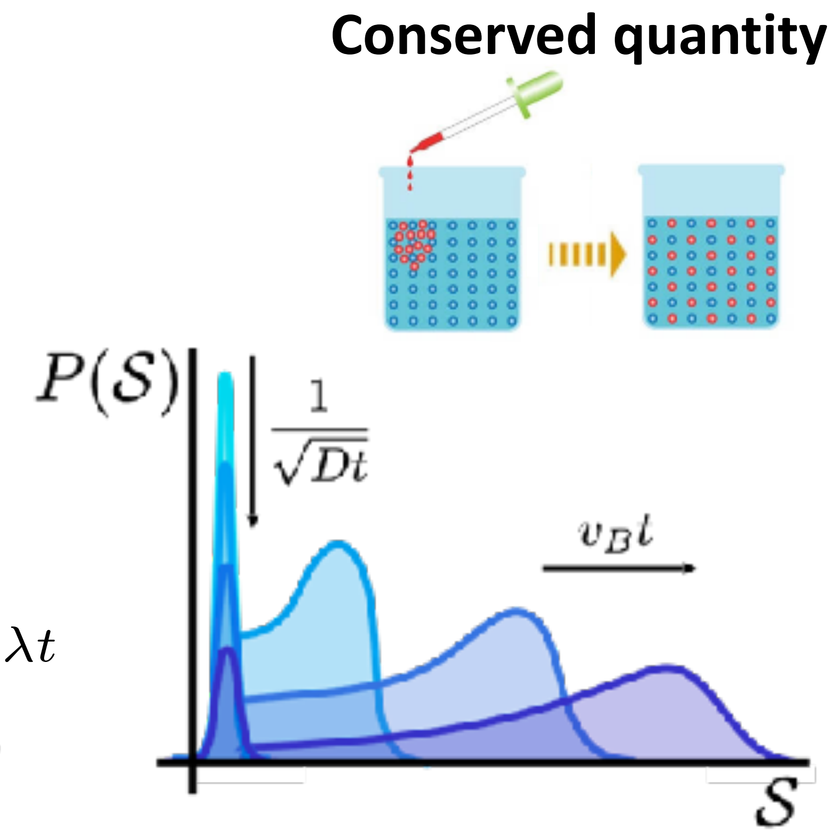

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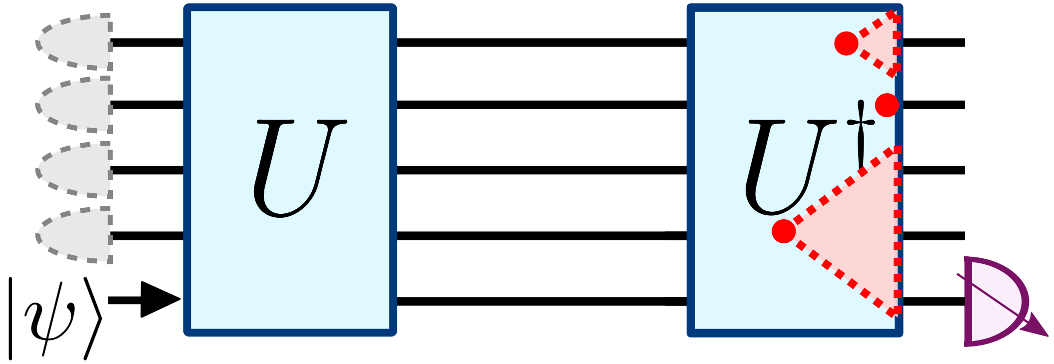
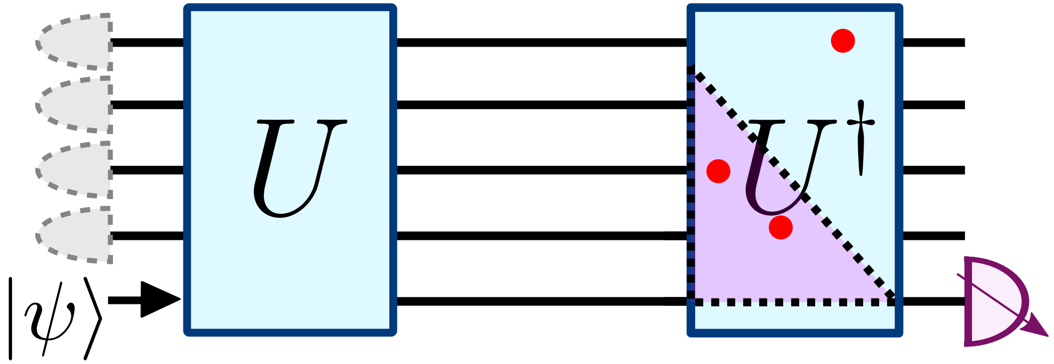
How does noise propagate in many-body quantum systems?

Intuition: noise propagates according to the circuit's operator growth dynamics



How does noise propagate in many-body quantum systems?

Intuition: highly non-local operators are more sensitive to noise



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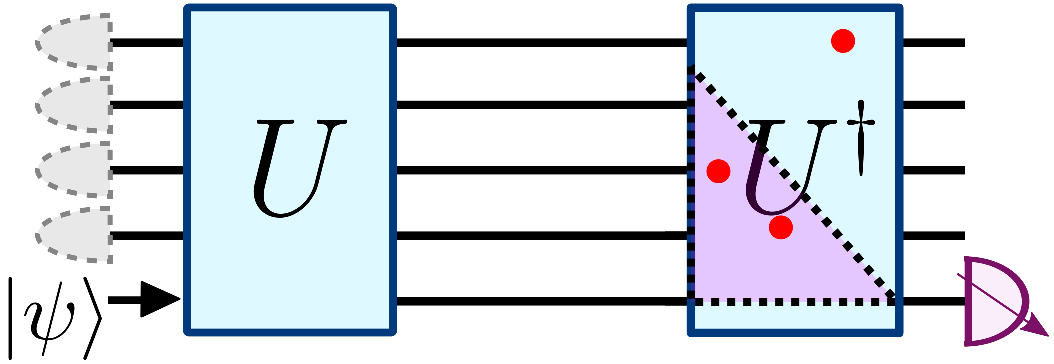

$$\hat{M}_t = X + Y \otimes \mathbb{1} \otimes Z + \ldots + Y \otimes Z \otimes \mathbb{1} \otimes X \otimes Z$$

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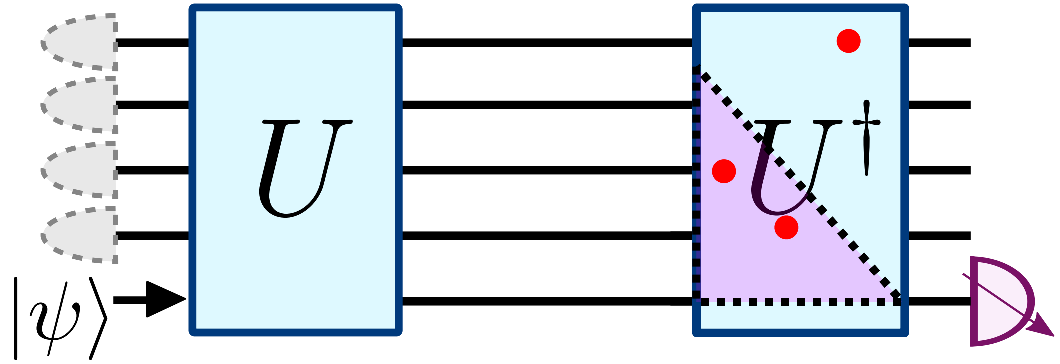

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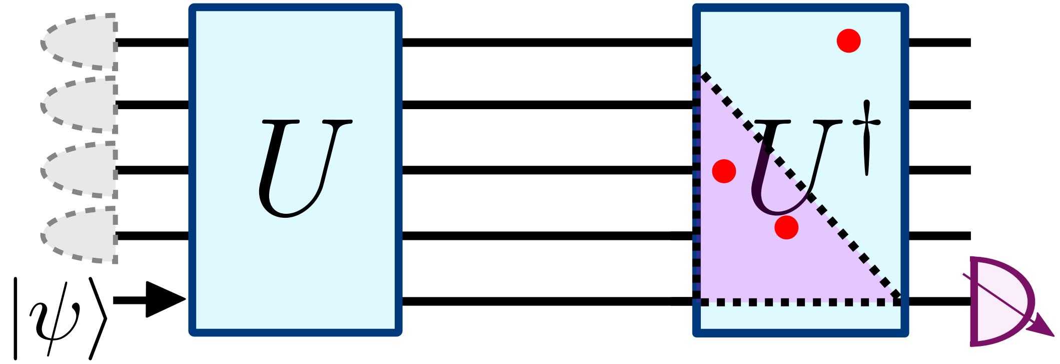
How does noise propagate in many-body quantum systems?

More precise: Noise decays Pauli strings at a rate proportional to their size $\sim \gamma \mathcal{S}$

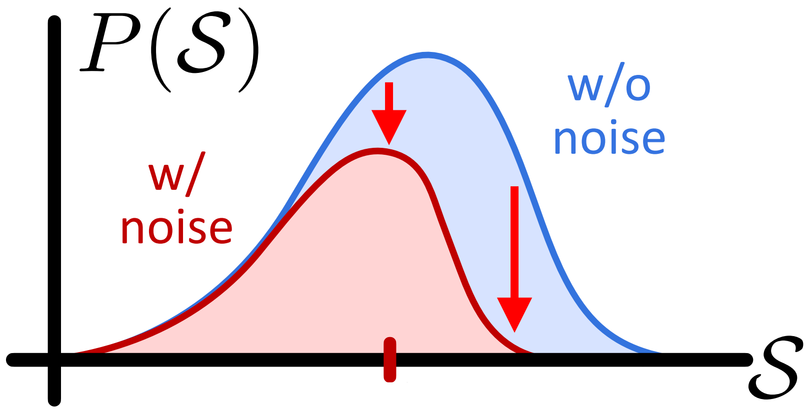


$$\hat{M}_t = X + Y \otimes \mathbb{1} \otimes Z + \ldots + Y \otimes Z \otimes \mathbb{1} \otimes X \otimes Z$$

(exact for single-qubit decoherence;
otherwise, approximation for *high-size components* under *ergodic dynamics*)

Noise ~ Size

Two effects of noise on size distribution:



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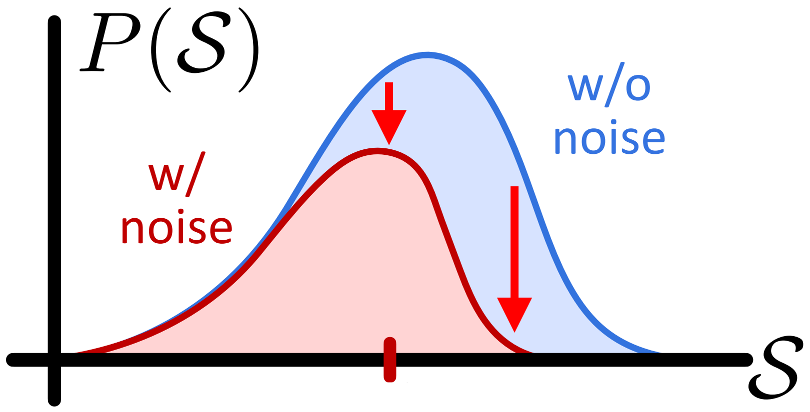
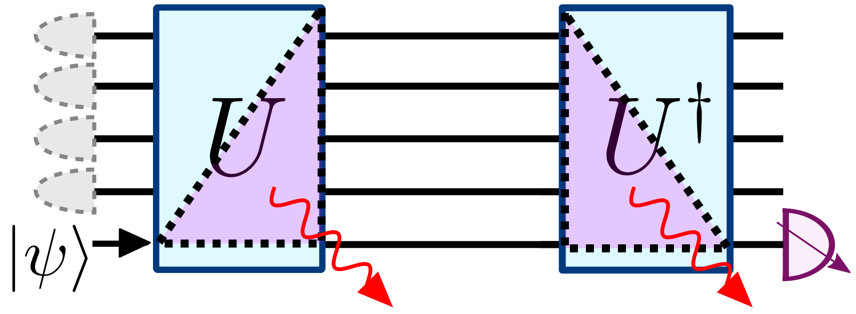


Two effects of noise on size distribution:

(1) Decrease normalization

$$\partial_t \mathcal{N} = -\gamma \overline{\mathcal{S}} \mathcal{N}$$



equal to Loschmidt echo!

Noise $\sim$ Size

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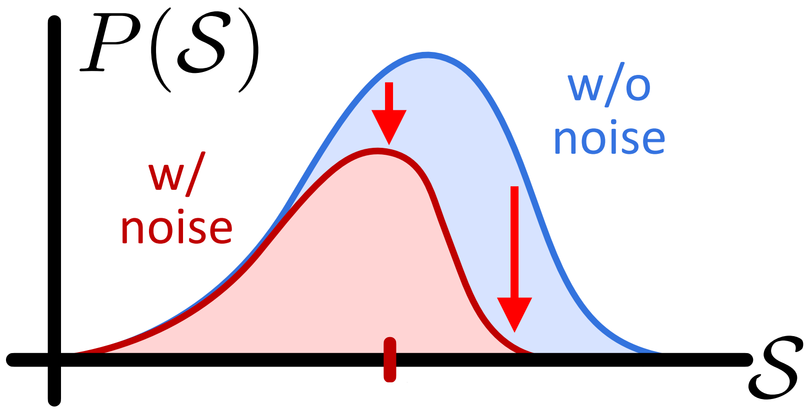

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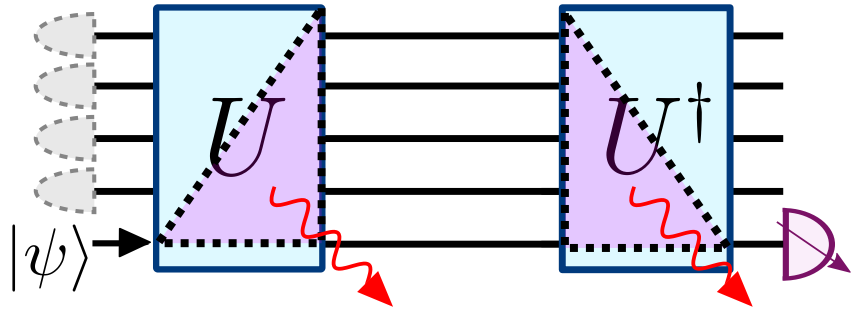

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(2) Shift "shape" towards small sizes

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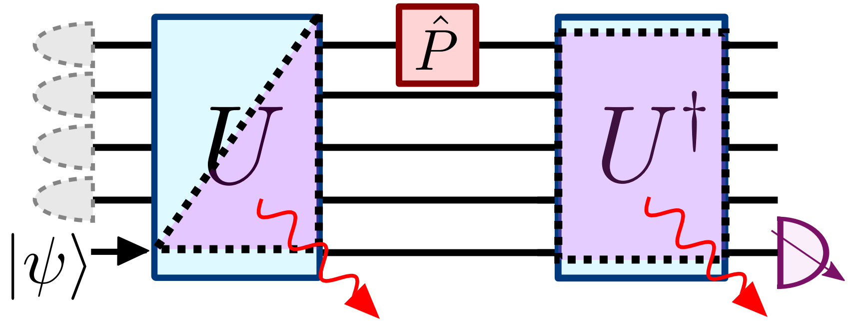

equal to average OTOCs!

Noise $\sim$ Size

<u>Interplay</u> between operator growth and noise determines the Loschmidt echo

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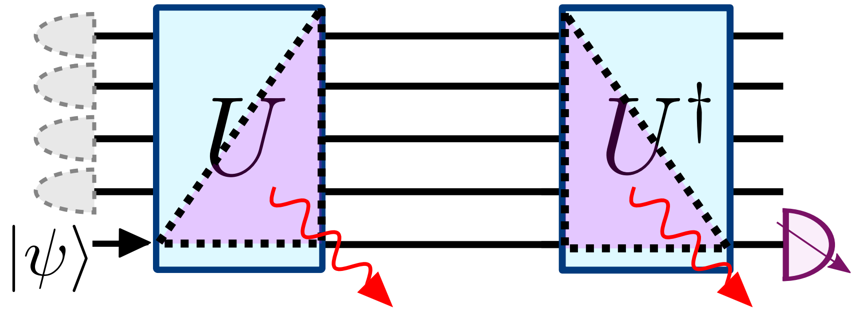

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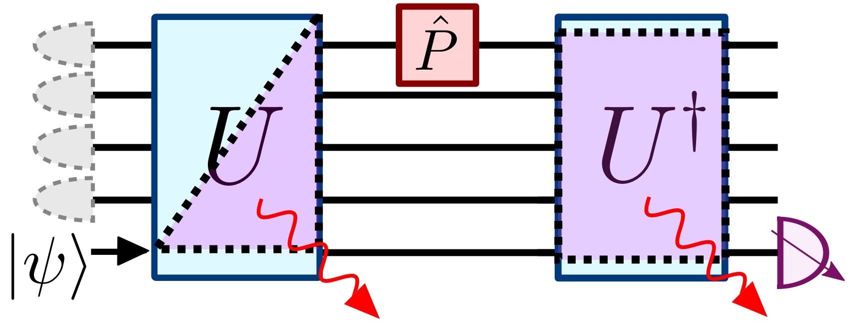

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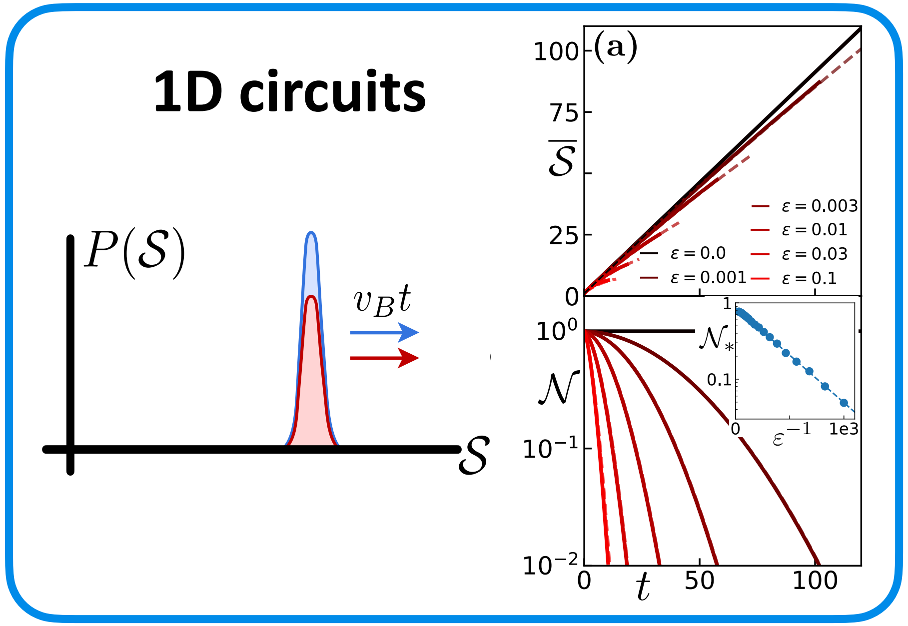
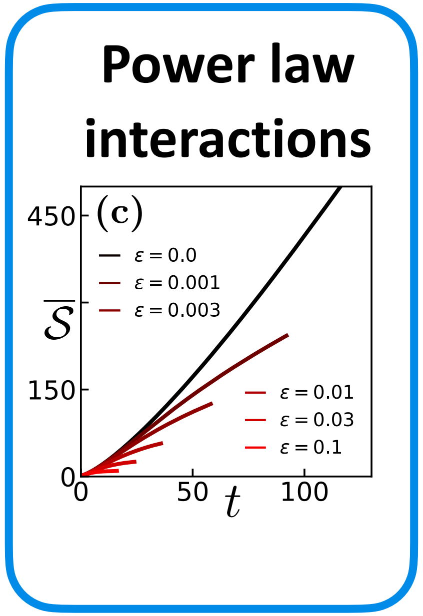
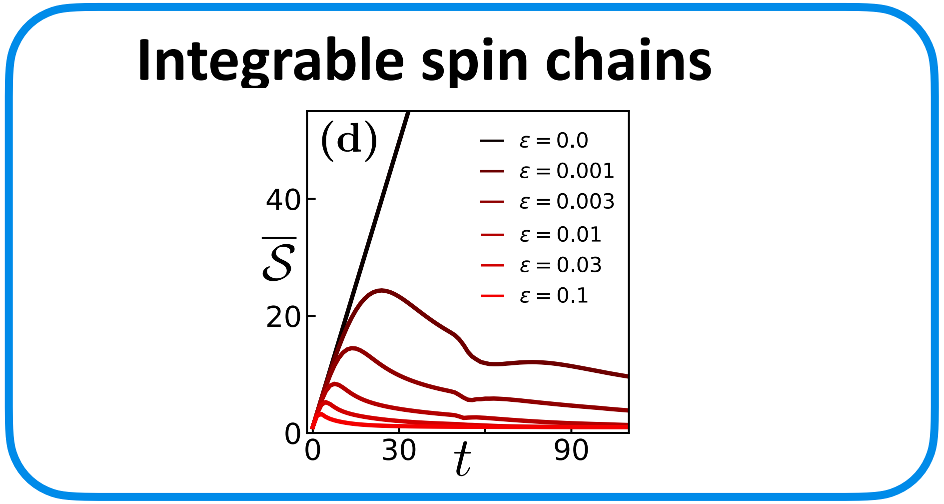
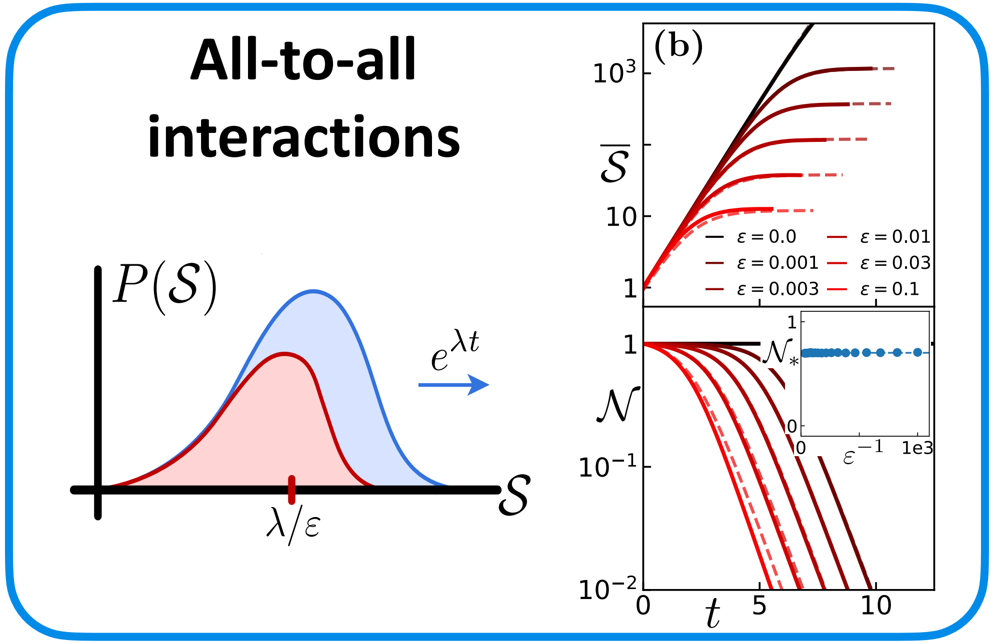
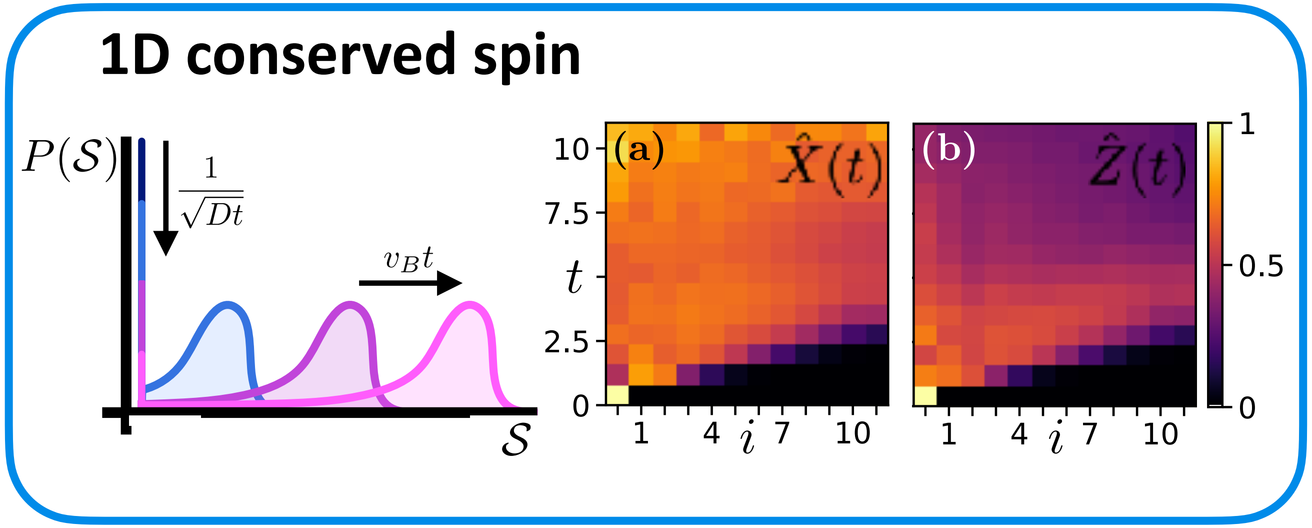
Universal classes of noisy quantum information dynamics











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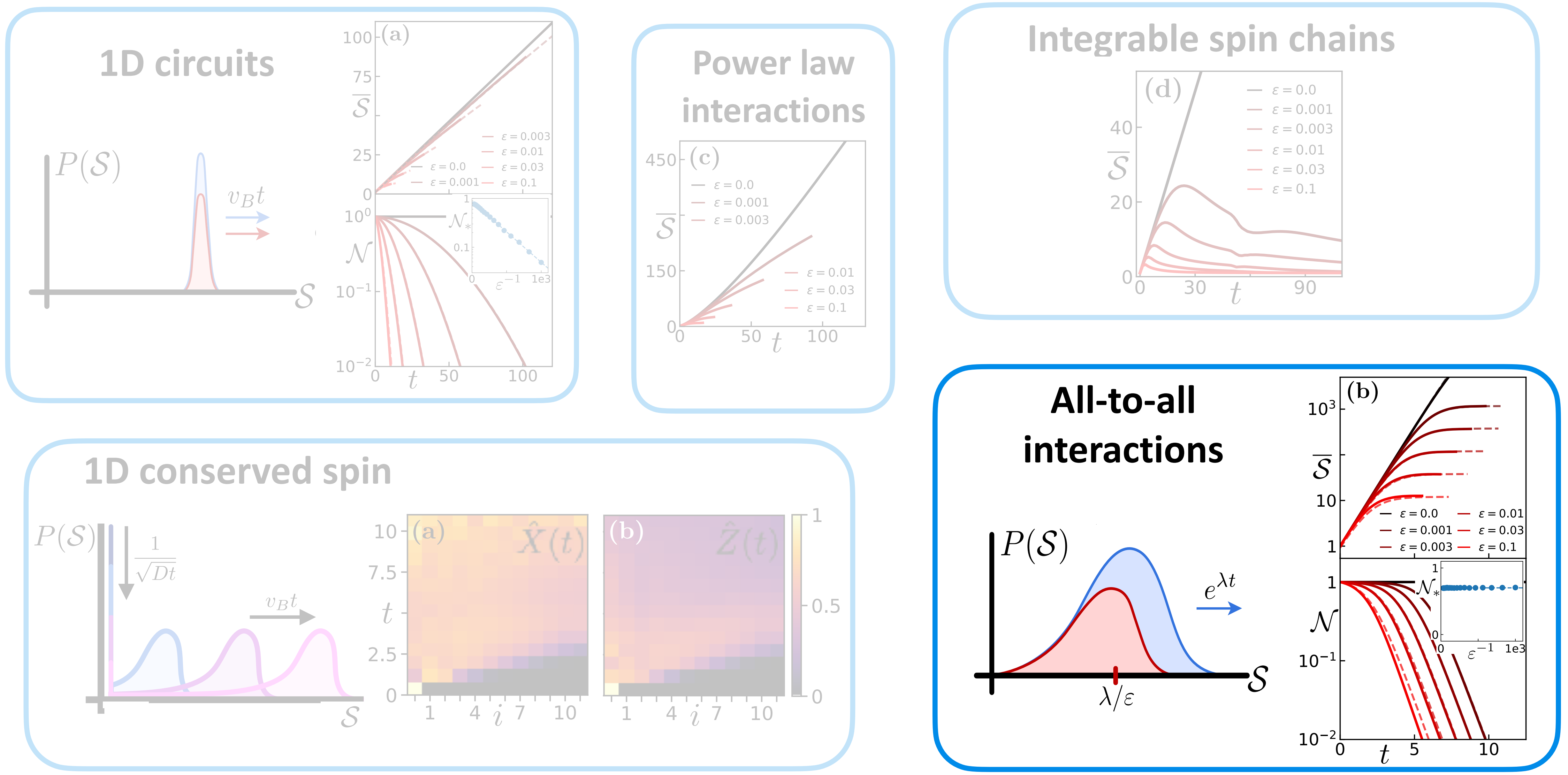
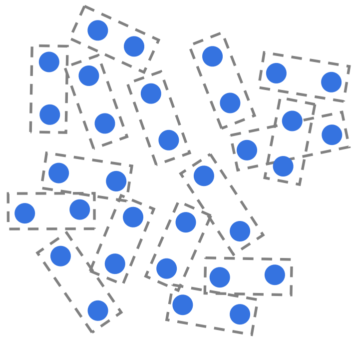


Example: All-to-all dynamics

Unitary: Size grows exponentially in time. Distribution is broad.



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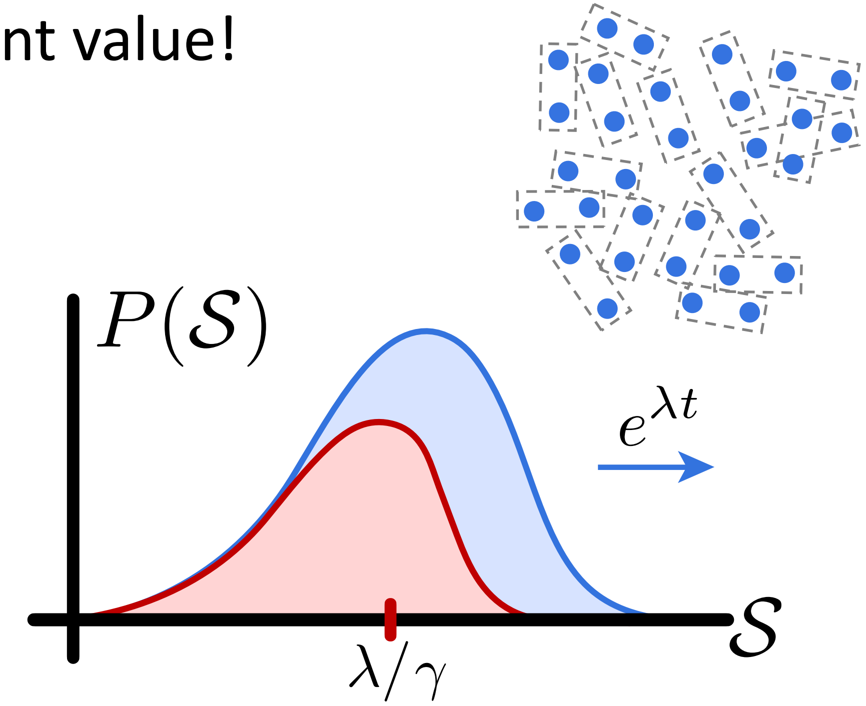
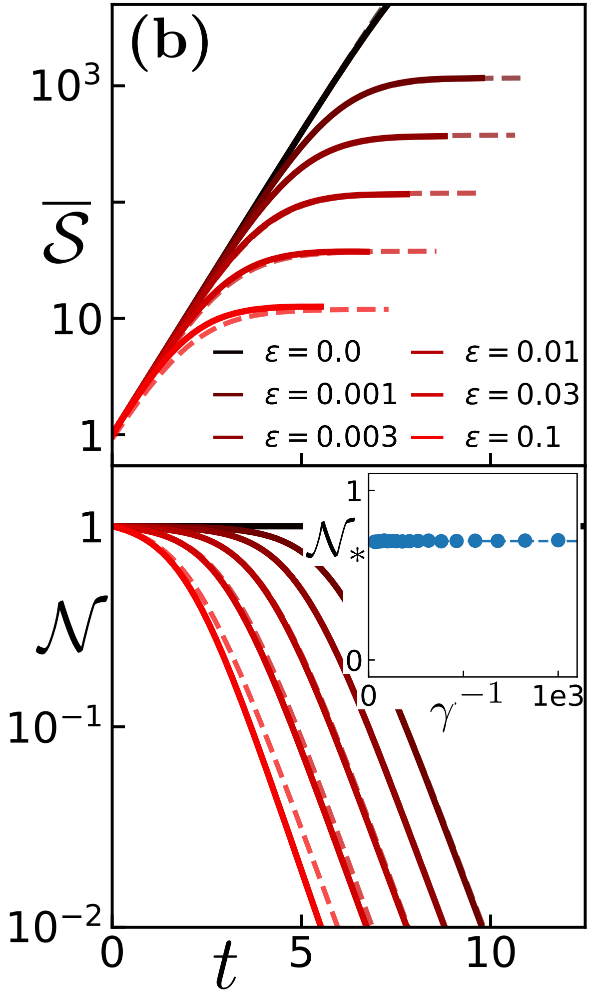
Noisy: Size *plateaus* to constant value!

$$\partial_t \overline{\mathcal{S}} \approx \lambda \overline{\mathcal{S}} - \gamma \delta \mathcal{S}^2$$

$\downarrow$ $\delta\mathcal{S} \sim \mathcal{S}$

$$\mathcal{S}_{\text{sat}} = \frac{\lambda}{\gamma}$$





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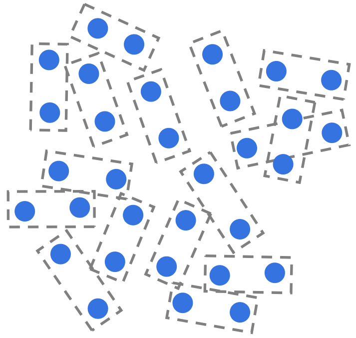

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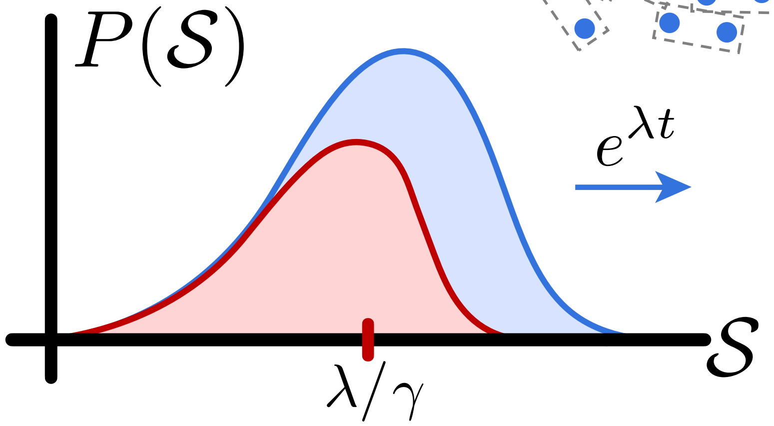
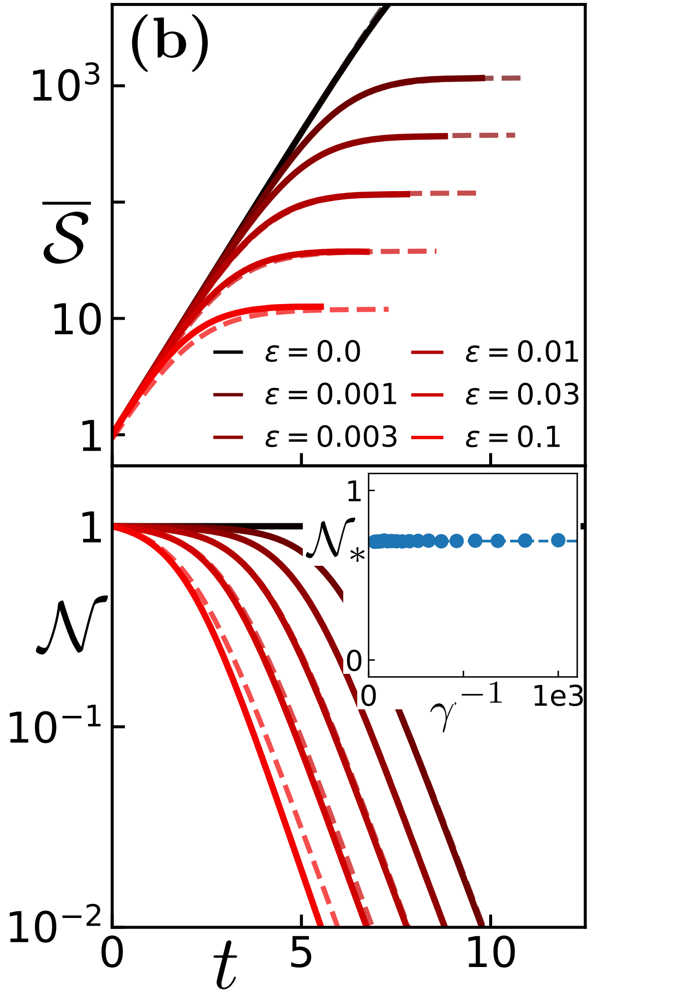




$$\mathcal{N}_t = e^{-\gamma \int dt\, \mathcal{S}_t}$$

⇒ Loschmidt echo decay is *independent* of noise rate!

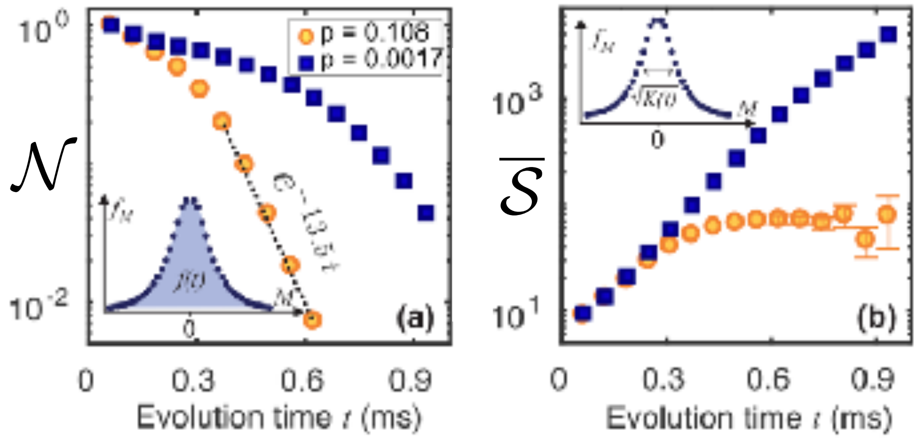
Echoes seminal results in single-particle quantum chaos

Jalabert, Pastawski (2001)

Recent NMR experiments

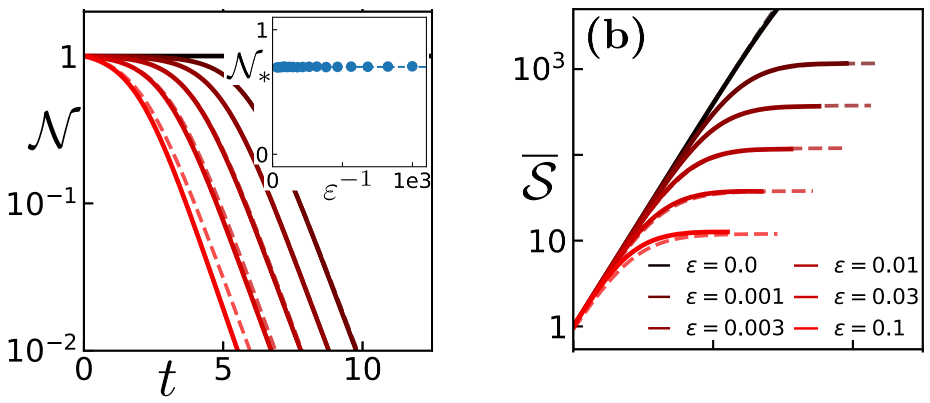
NMR expts w/ ~1000 spins

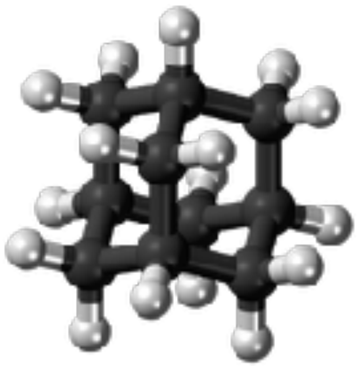
Domínguez et al. (2021)



All-to-all random circuits

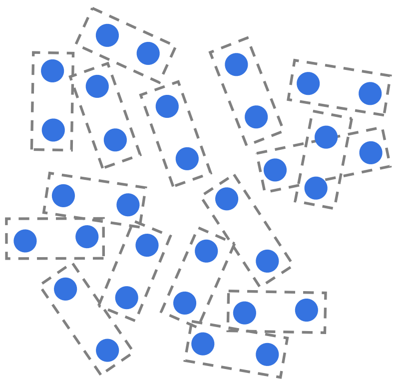
TS, Yao, arXiv:2208.12272 (2022)





Adamantane lattice

192 nearest neighbors

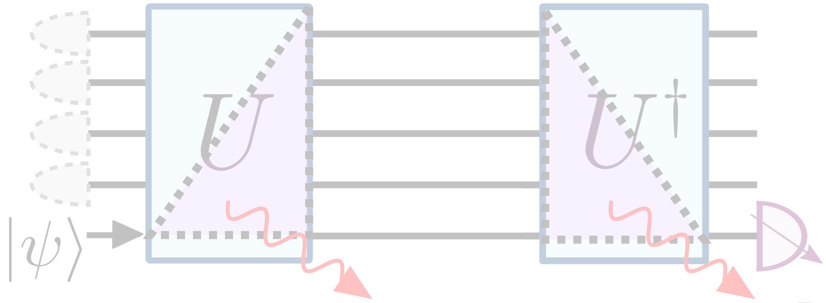


All-to-all

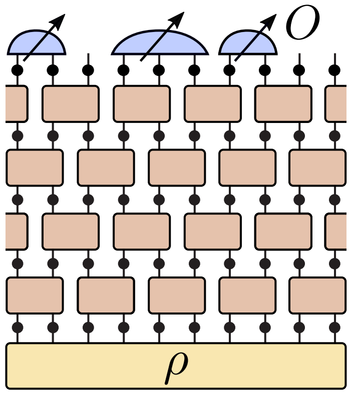
random circuit

Operator growth in open quantum systems

TS, Yao PRL 131, 160402 (2023)



Noise ⇔ Information dynamics ⇔ Complexity



TS, Yao forthcoming (2023)

A polynomial-time classical algorithm for almost any noisy quantum circuit

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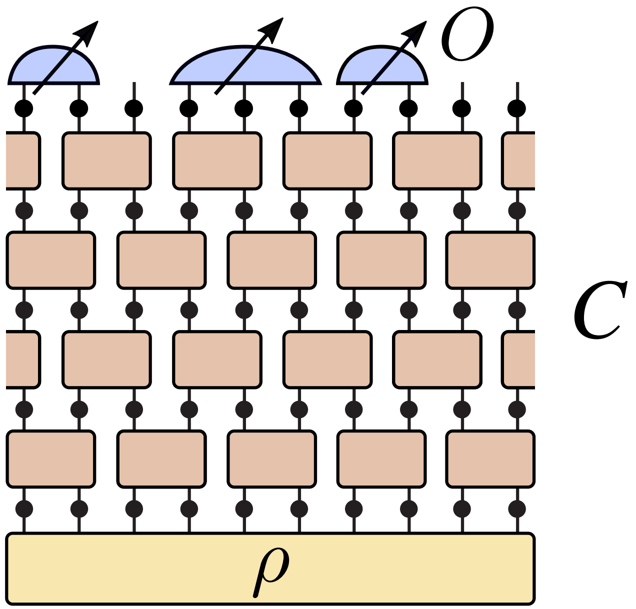
We provide an efficient classical algorithm for "almost any" noisy quantum circuit

Task: Compute expectation values $\mathrm{tr}(C\{\rho\}O)$



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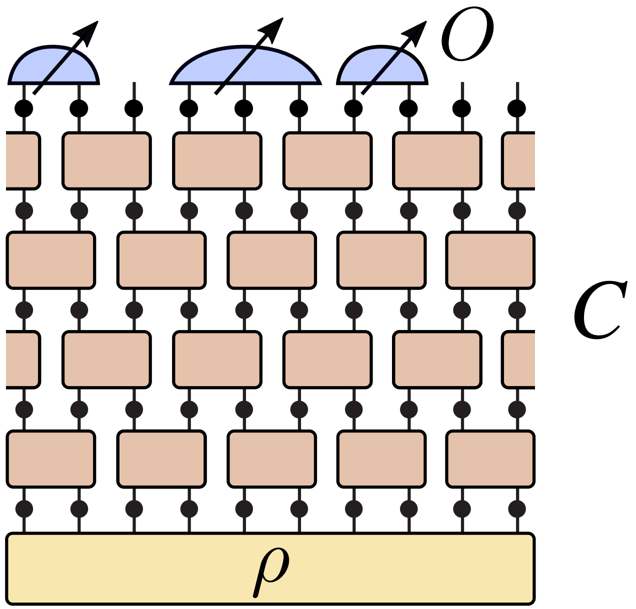

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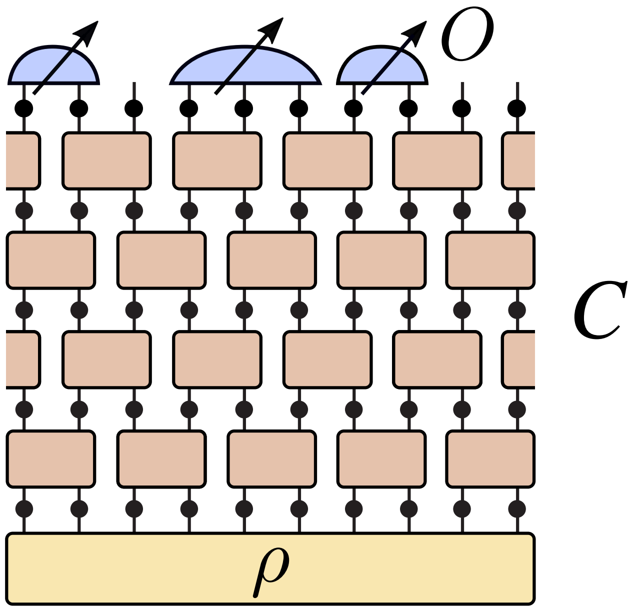

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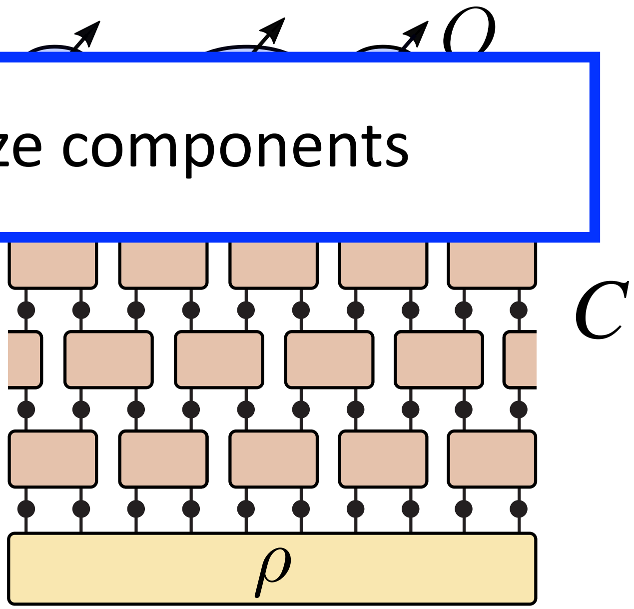
Idea: Simulate in Heisenberg picture, keep only low-size components



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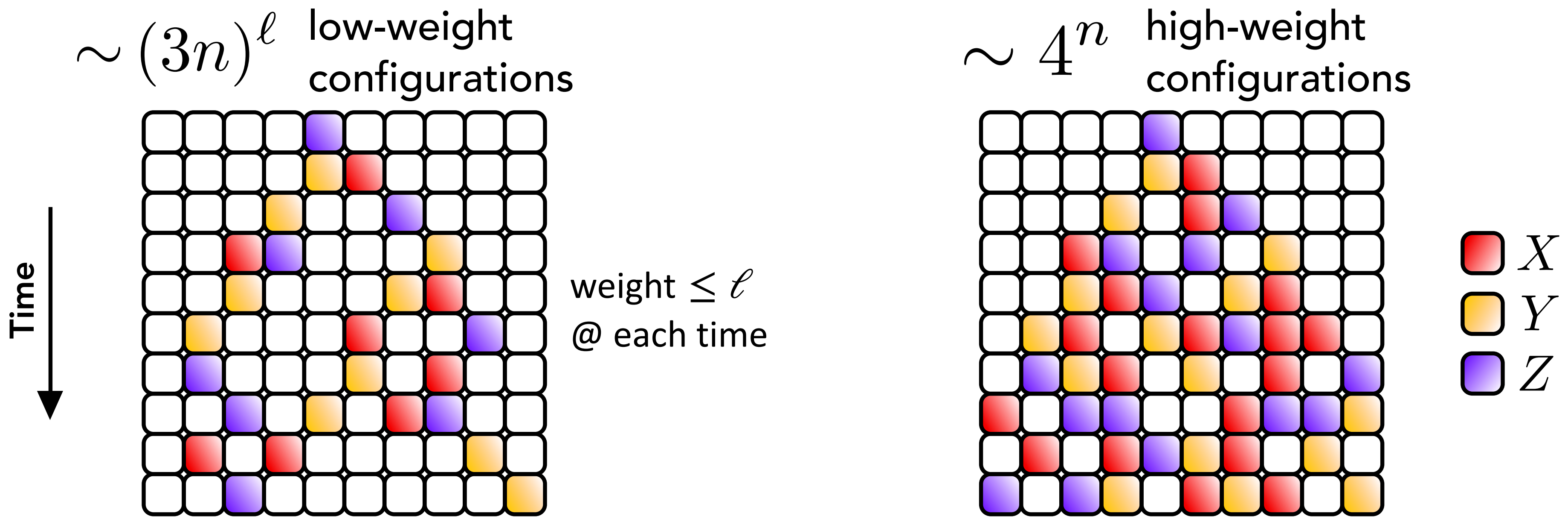
Sensitivity to noise ⇔ Complexity

Decompose operator in Pauli string basis at each time step

Close correlation between "paths" of Pauli strings that are hard to simulate, and those that are strongly damped by noise [Aharonov, Gao, Landau, Liu, Vazirani (2023)]



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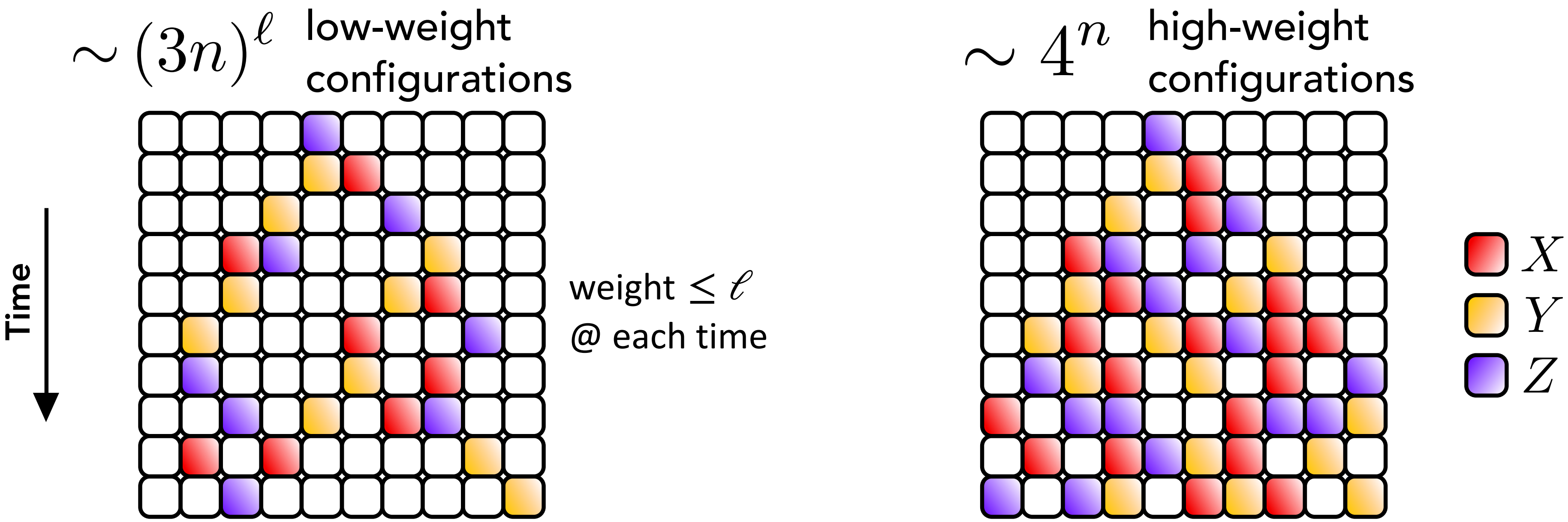
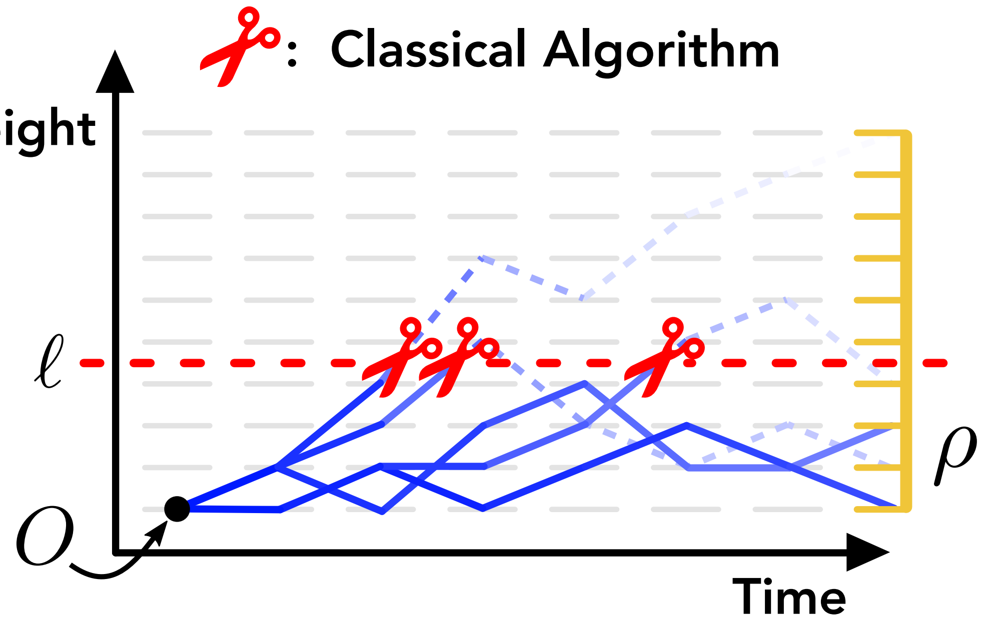


To bound contribution from high weights, previous works used that in random circuits, Pauli paths on average do not coherently interfere

A polynomial-time classical algorithm

Builds upon recent algorithms for noisy random circuit sampling, but with modifications in the algorithm + proof techniques [Aharonov, Gao, Landau, Liu, Vazirani (2023)]

Algorithm: At each time step, truncate any component of $O(t)$ with size above a threshold ℓ



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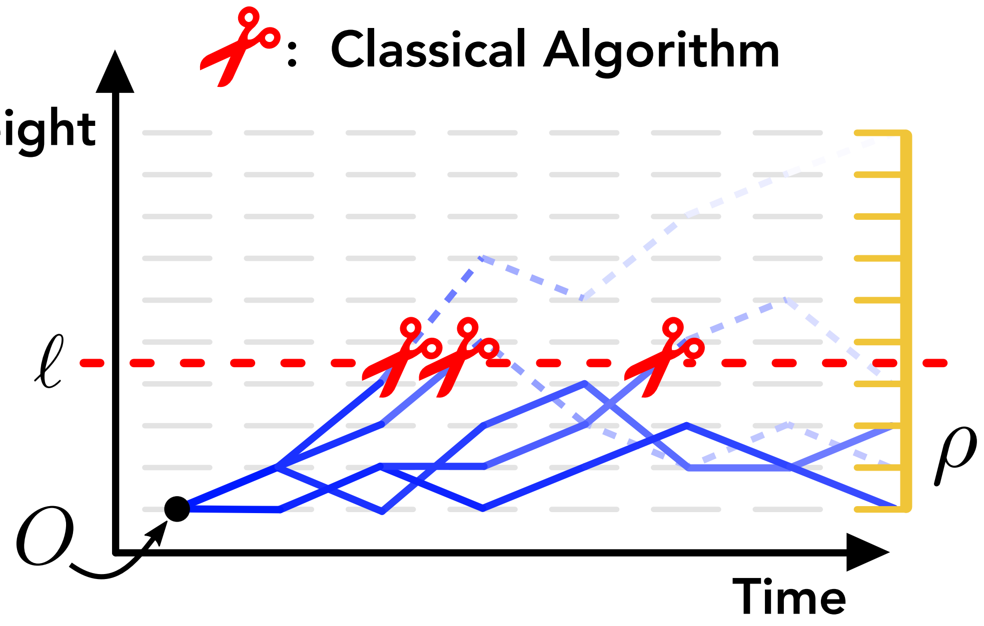

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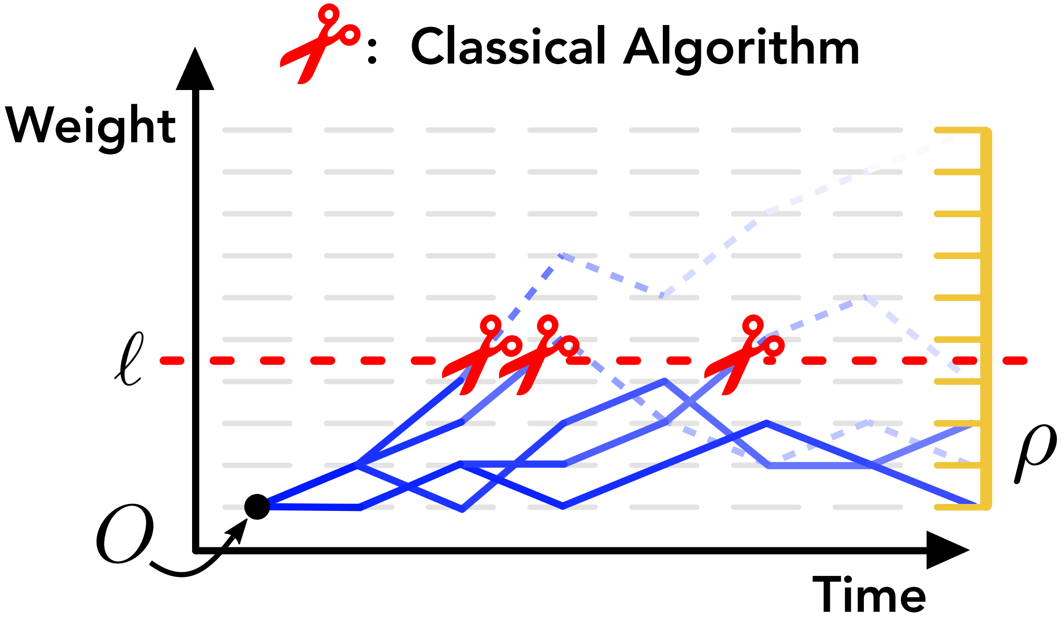

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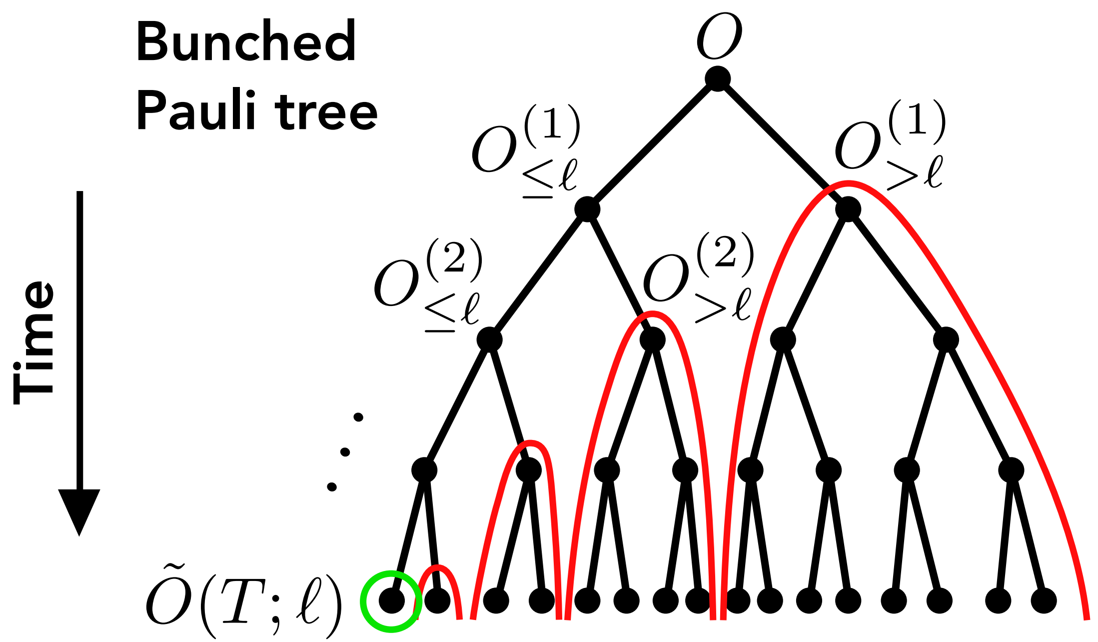

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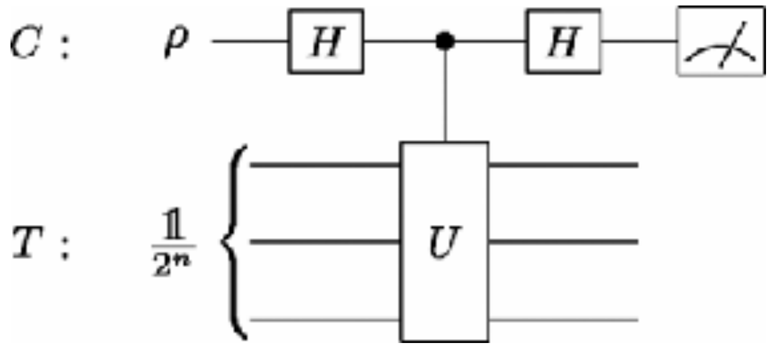
Simple extensions

Corollary 1: Can replace ensemble of input states with a single *highly mixed* state:

Noisy DQC1 ⊆ BPP



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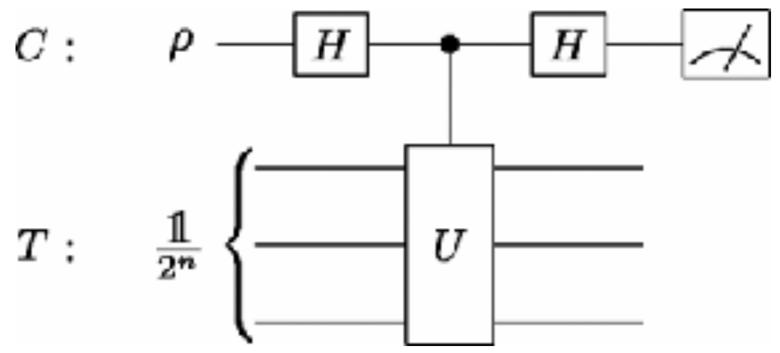

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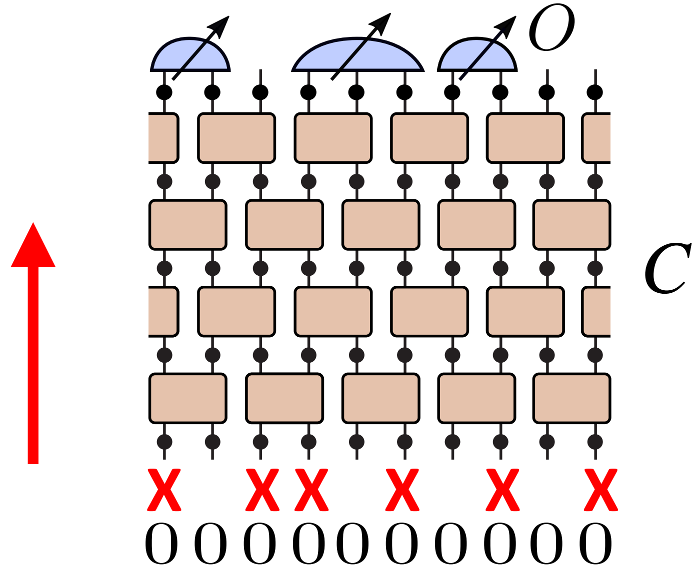
Corollary 2: Ensemble of input states → ensemble of circuits with *spatial disorder*



"Push" randomness from initial state into circuit

Encompasses quantum simulation of disordered spin models

Implications for NISQ experiments?

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But designing NISQ circuits that take advantage of these noise budgets is challenging!

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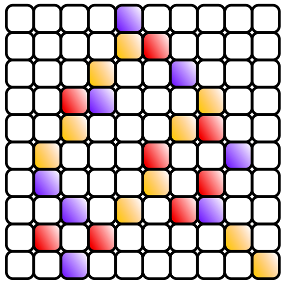
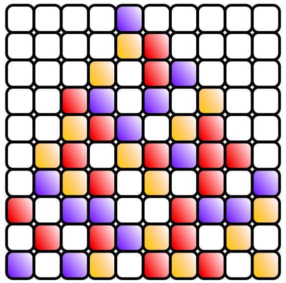


Classically simulable
Insensitive to noise



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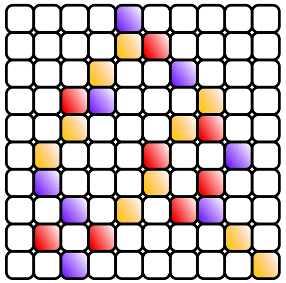

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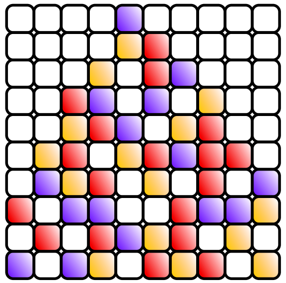

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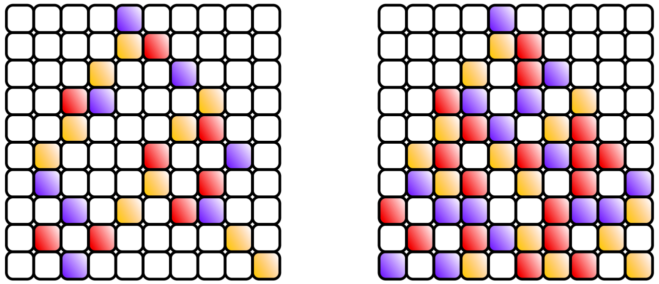
Corollary 3: Complex quantum circuits **must be** highly sensitive to noise:

Any quantum experiment* with classical complexity $\chi(n,\epsilon)$, *must only succeed* for

$$\gamma \leq \mathcal{O}\left(\frac{\log(n)\log\left(\sqrt{T^*}/\varepsilon\right)}{\log(\chi(n,\varepsilon))}\right)$$

e.g. if $\chi \sim \exp(n)$,
require $\gamma \lesssim 1/n$



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*For computing expectation values with small rms error

Quantum information dynamics provides a natural language for understanding noise and complexity in NISQ experiments

Future Directions

- Benchmarking Loschmidt echo predictions with NMR experiments; connection to noise-induced transitions Google Quantum AI (2023), Ware et al (2023)
- "Experimental tests" for efficient classical simulations
- Dephasing noise, related e.g. to Clifford + T gate simulations
- What is the sensitivity to noise of physical many-body dynamics? Can we identify classes of dynamics that are / are not sensitive? White, Refael, Pollman, Rakovsky, von Keyserlingk, Ye, Machado, Nahum, Zhou…

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Norman Yao