Using chaos to characterize a programmable analog quantum simulator

Adam Shaw
Endres Lab

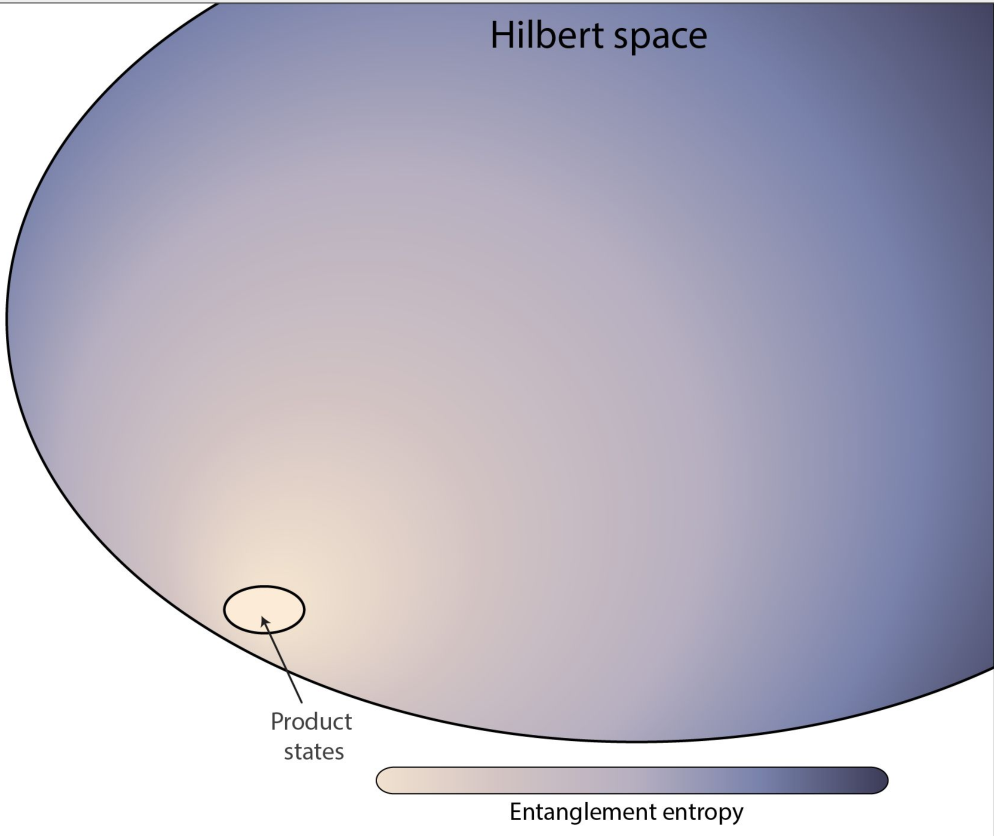
Mostly following:

Shaw*, Chen*, Choi*, Mark*, *et al*, Nature 628 (2024), arXiv:2308.07914
Shaw*, Mark*, *et al*, arXiv:2403.11971

Caltech

The entanglement challenge

Start with some simple **initial** state...



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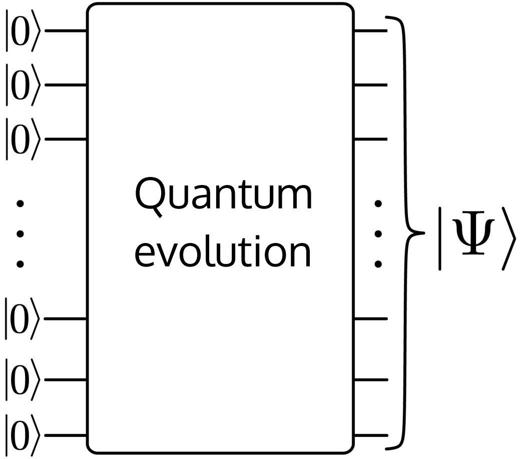
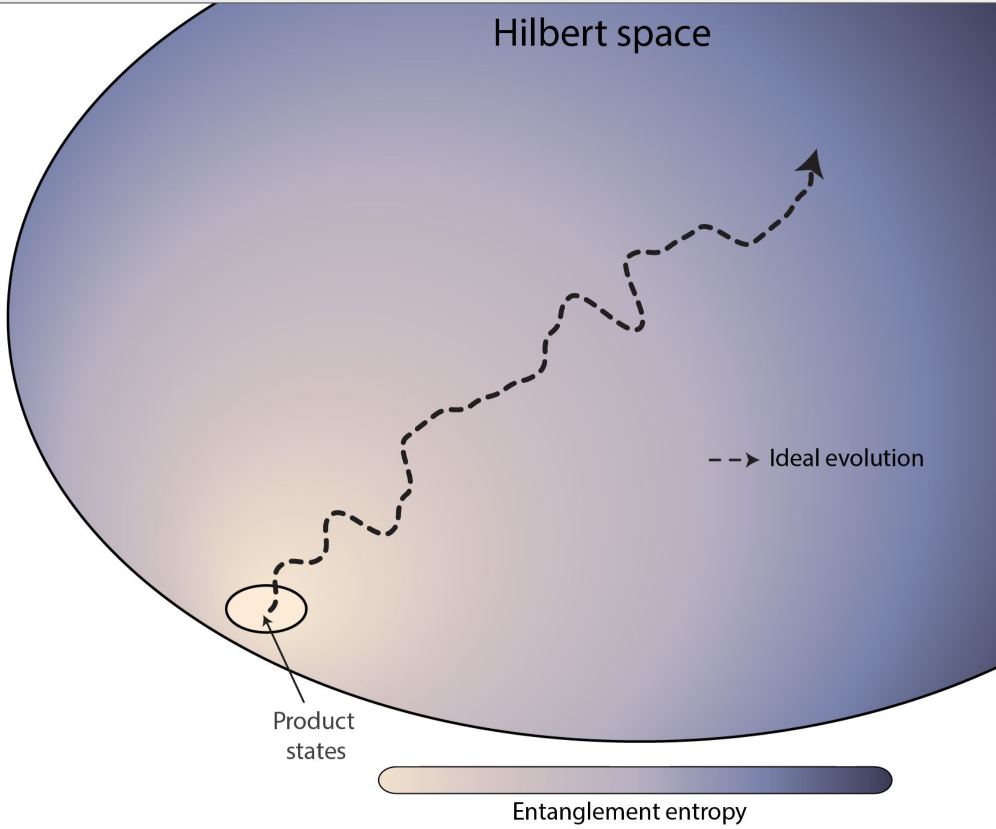


... create a useful **entangled** state

(as a resource for computation, simulation, metrology, etc...)



The entanglement challenge

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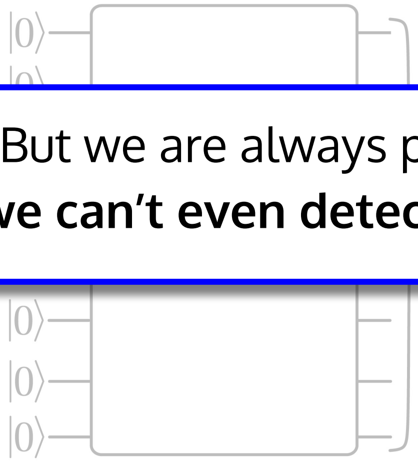
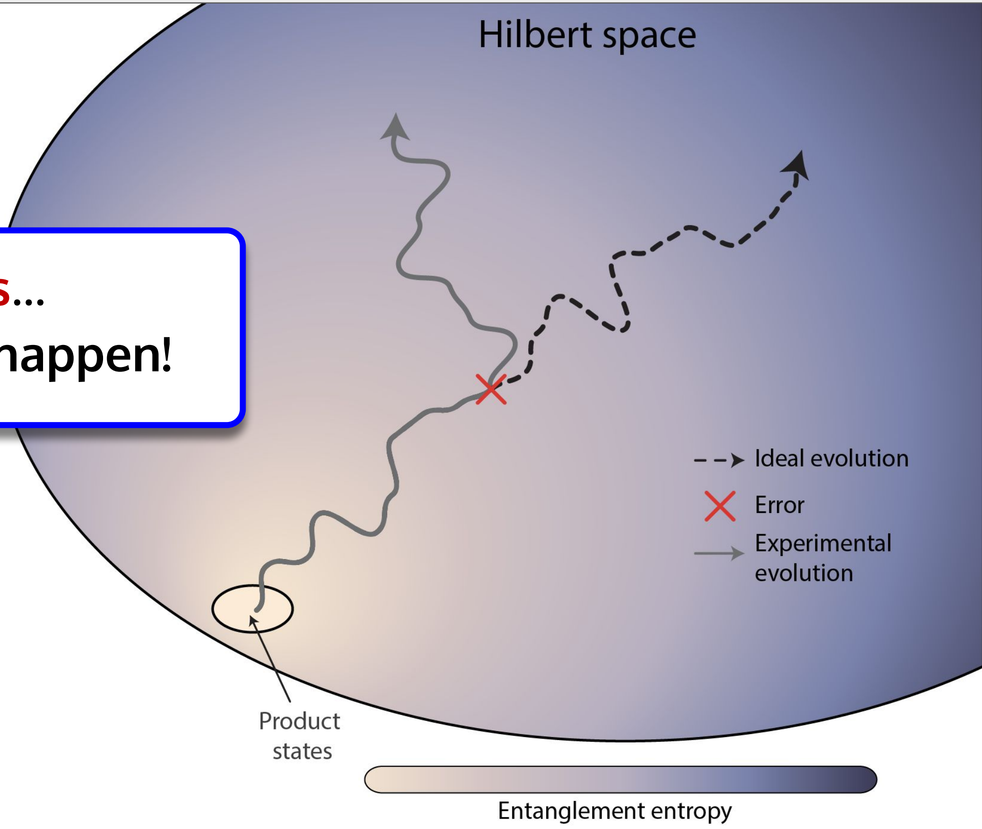


But we are always prone to **errors**...

And we can't even detect when they happen!

... create a useful entangled state
(as a resource for computation,
simulation, metrology, etc...)



The entanglement challenge

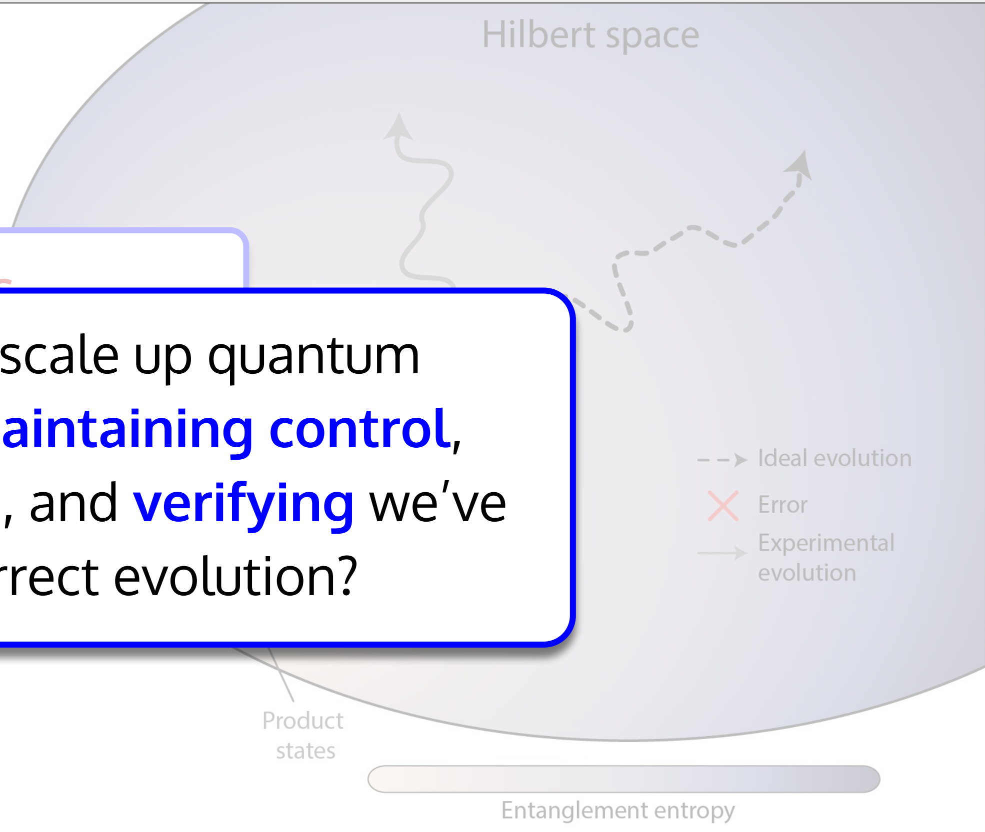
Start with some simple initial state...

But we are always prone to errors

And we can't ev

So how do we scale up quantum systems while maintaining control, minimizing errors, and verifying we've done the correct evolution?

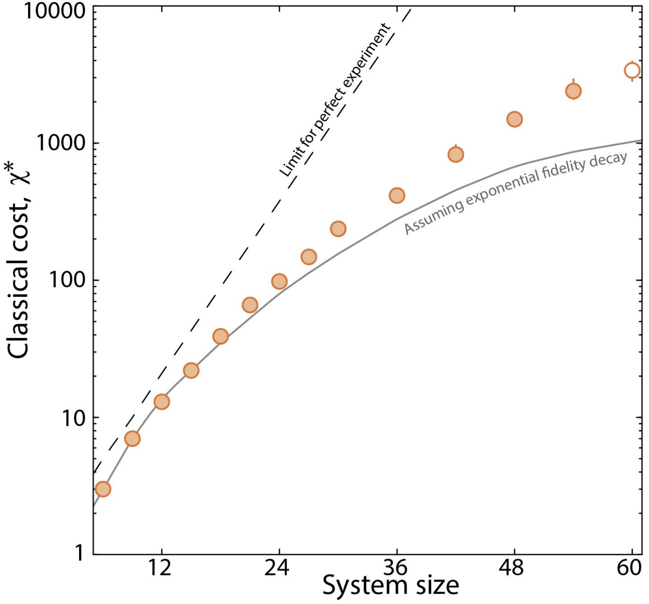
... create a useful entangled state
(as a resource for computation,
simulation, metrology, etc...)



Outlook

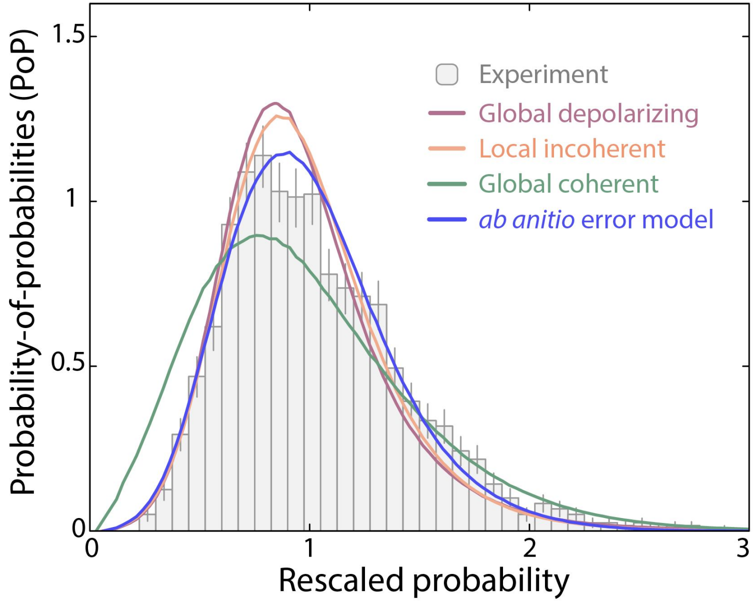
Benchmarking

For a large scale analog quantum simulator



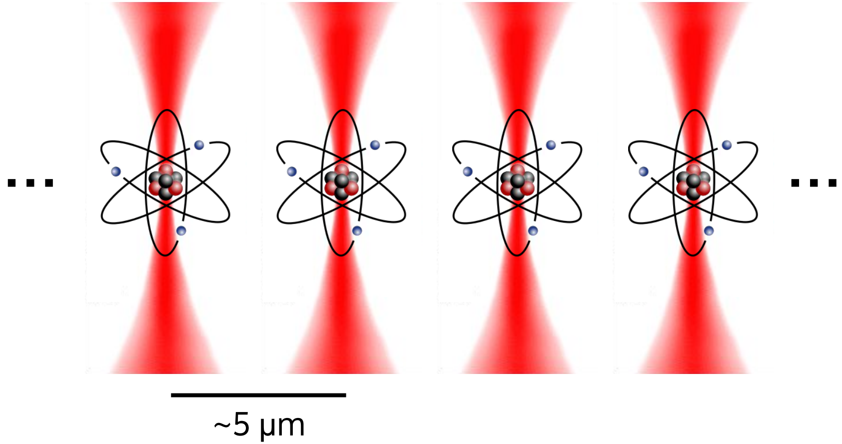
Applications

Entanglement estimation, noise learning, etc

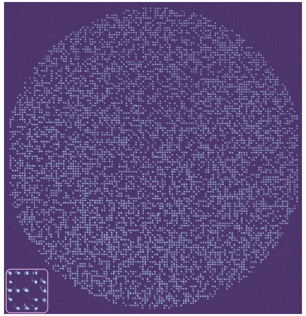


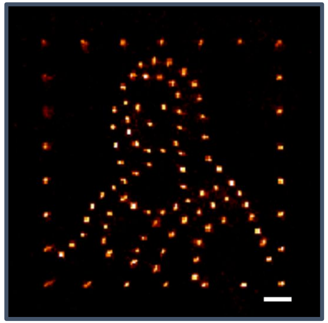
Rydberg atom arrays

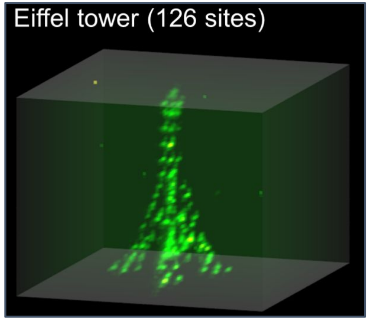
Optical tweezers:
focused laser beams which can trap single atoms



Can create large arrays in multiple dimensions with full positional control ("rearrangement")







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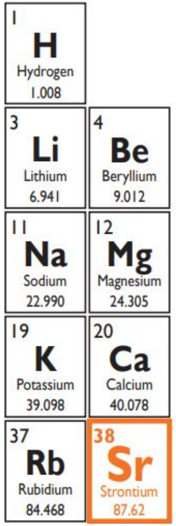
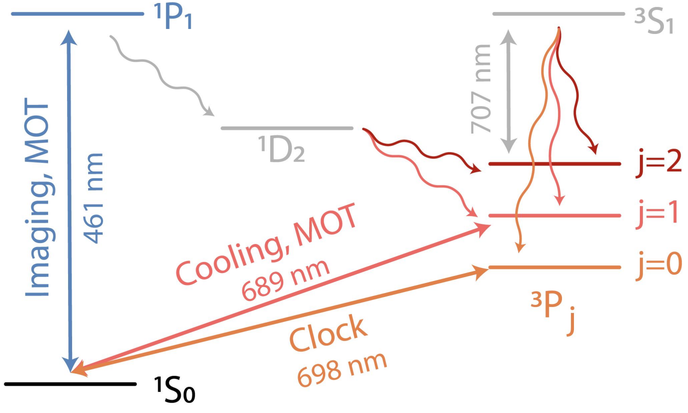
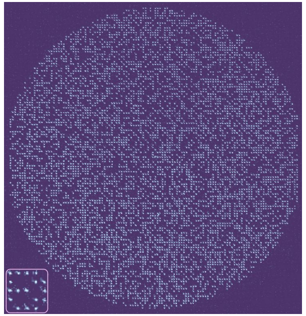


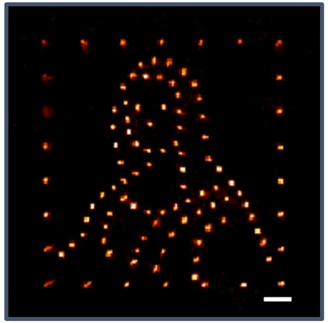


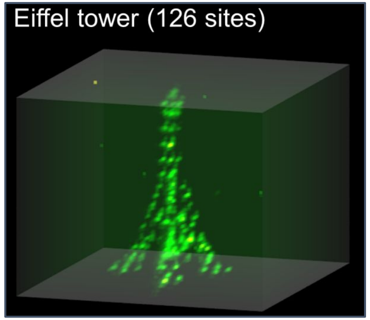
In our experiment we work with arrays of strontium atoms

Lots of interesting atomic physics to discuss…

Can create large arrays in multiple dimensions with full positional control (“rearrangement”)







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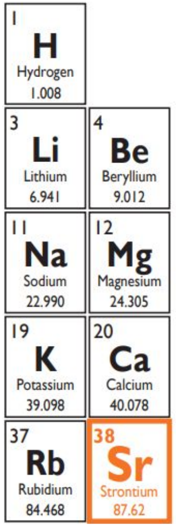
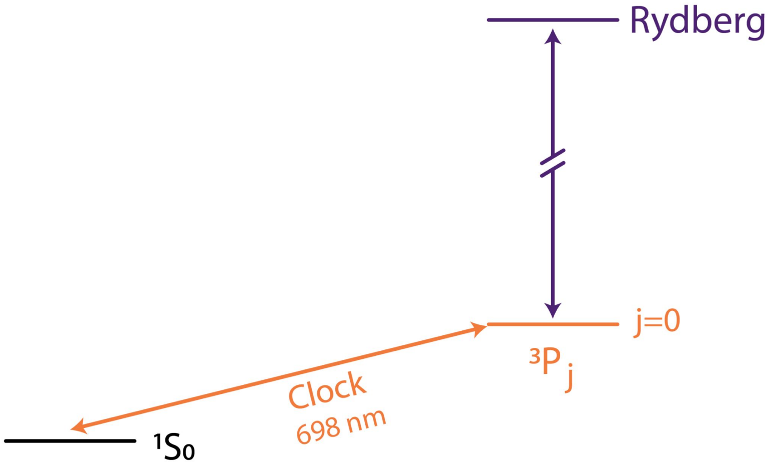


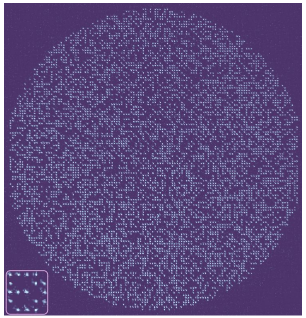


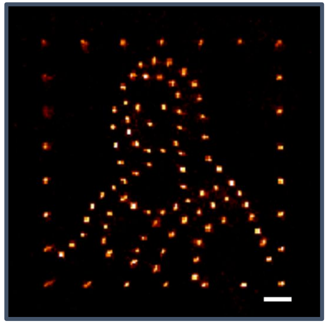
In our experiment we work with arrays of strontium atoms

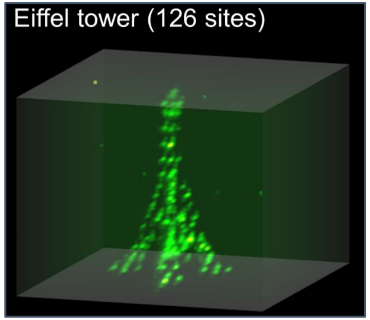
Lots of interesting atomic physics to discuss…

But not for this talk!

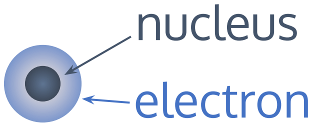
Can create large arrays in multiple dimensions with full positional control (“rearrangement”)







Making atoms interact

$|g\rangle =$ 

Atom in the ground state

Review: Browaeys *et al*, Nature Physics **16**, 132 (2020)

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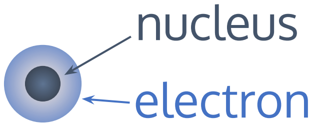
$|g\rangle =$ 

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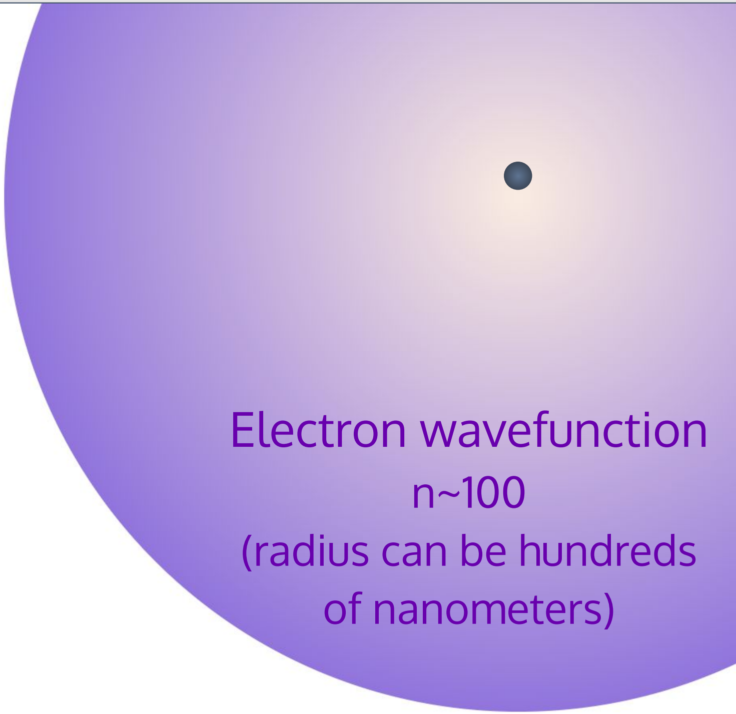
$|r\rangle =$ 

Rydberg atom

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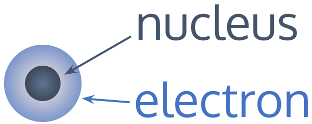

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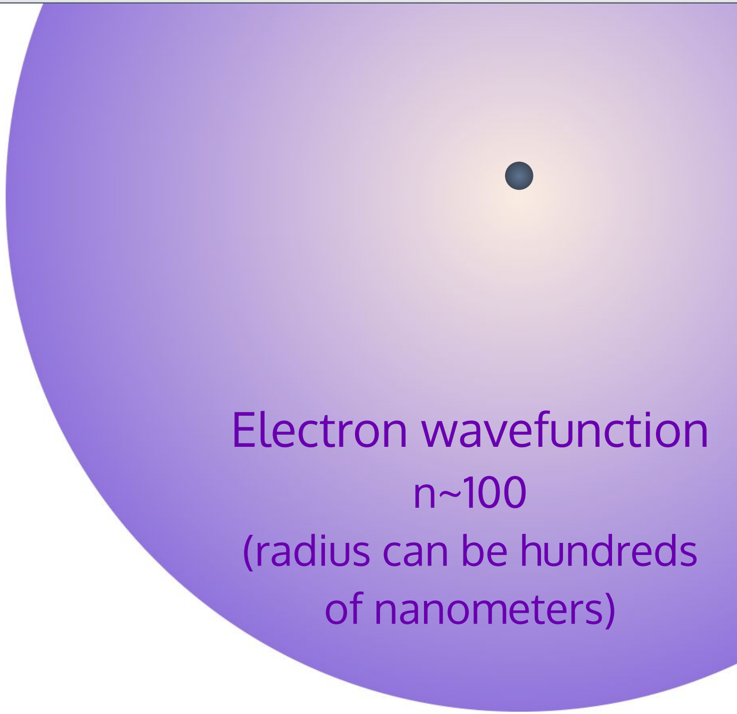

Rydberg atom

Try exciting two atoms...

Review: Browaeys *et al*, Nature Physics **16**, 132 (2020)

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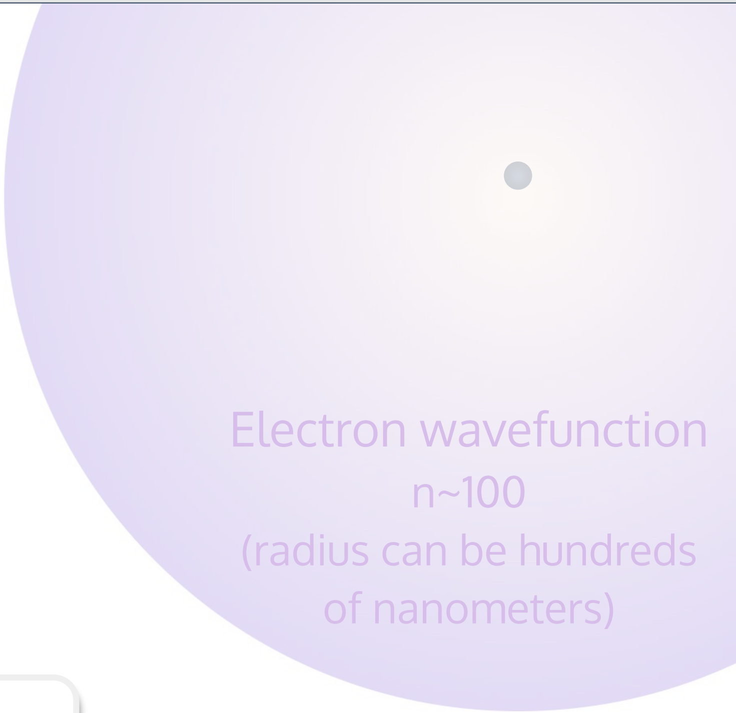
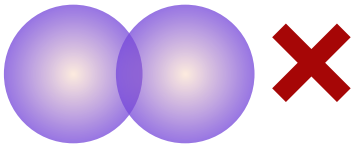
$|r\rangle =$ 

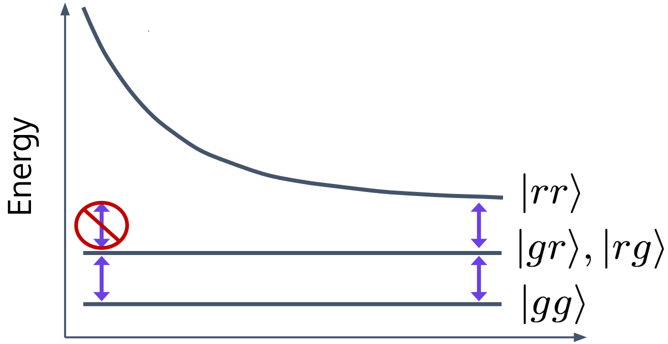
Rydberg atom

Small separations*:
Double excitation is **blocked**

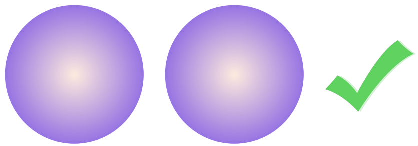


*Visual is exaggerated

Try exciting two atoms...



Large separations:
Both atoms can be excited



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Making atoms interact

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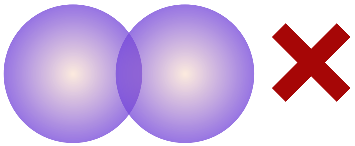
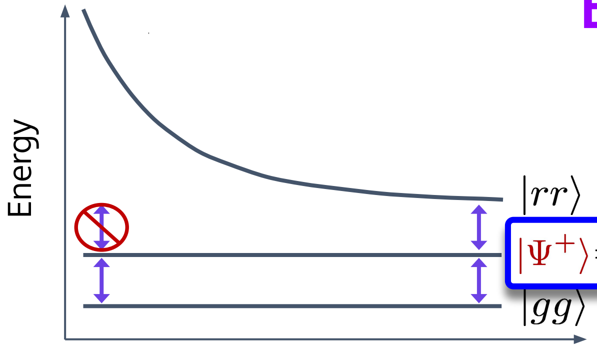


*Visual is exaggerated

Try exciting two atoms...

One excitation becomes **shared** across both atoms...

Entanglement!



$$|\Psi^+\rangle = (|gr\rangle + |rg\rangle)/\sqrt{2}$$

Large separations:
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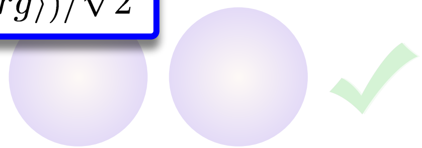
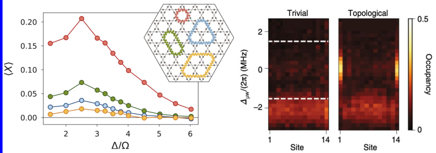


Review: Browaeys *et al*, Nature Physics **16**, 132 (2020)

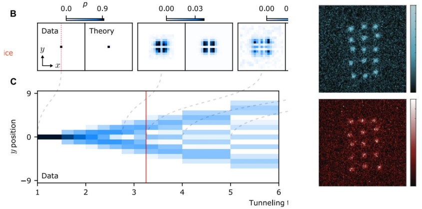
Physics with atom arrays, a small selection (pre 2024)

New phases of matter



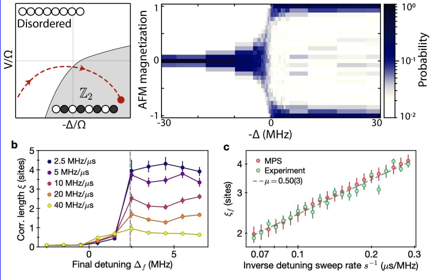
Semeghini, Science (2021)   de Leseleuc, Science (2019)

Hubbard physics



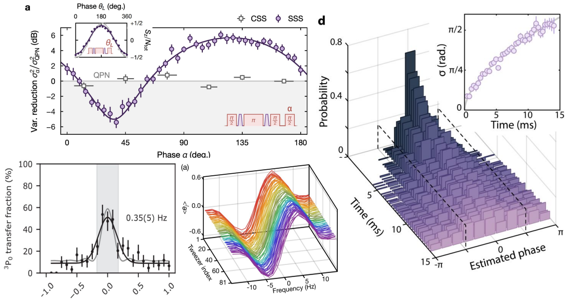
Young, Science (2022)   Yan*, Spar*, PRL (2022)

Quantum phase transitions



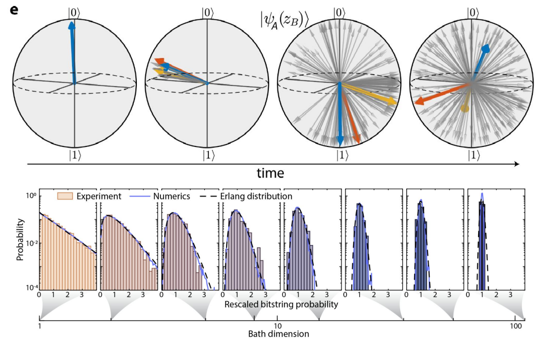
Scholl*, **Shaw***, Nature (2023)   Keesling, Nature (2019)

Metrology



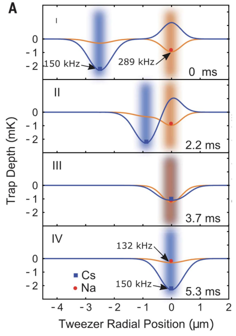
Norcia, Science (2019)
Madjarov, PRX (2019)
Shaw*, Finkelstein*, Nat Phys (2023)
Eckner, Nature (2023)

Quantum randomness



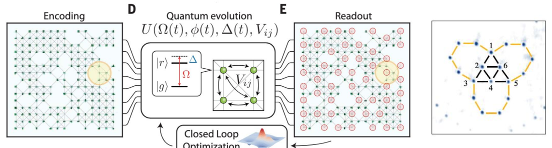
Choi*, **Shaw***, Nature (2023)

Making molecules



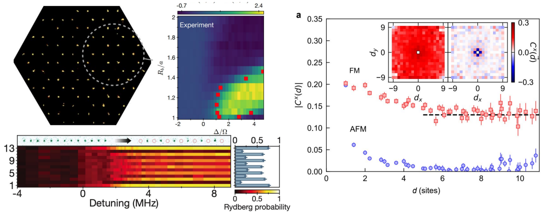
Liu, Science (2018)

Optimization problems



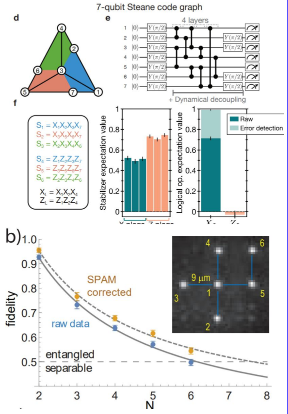
Ebadi, Science (2022)   Byun*, Kim*, PRXQ (2022)

Quantum magnetism



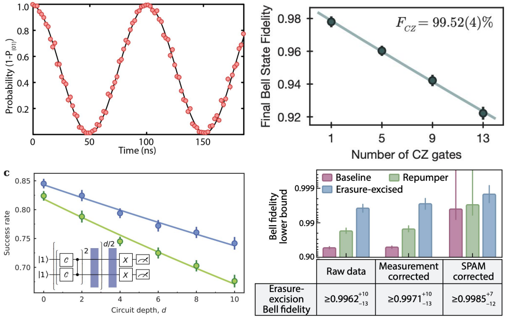
Bernien, Nature (2017)
Ebadi, Nature (2022)
Scholl, Nature (2021)
Chen, Nature (2023)

Quantum algorithms



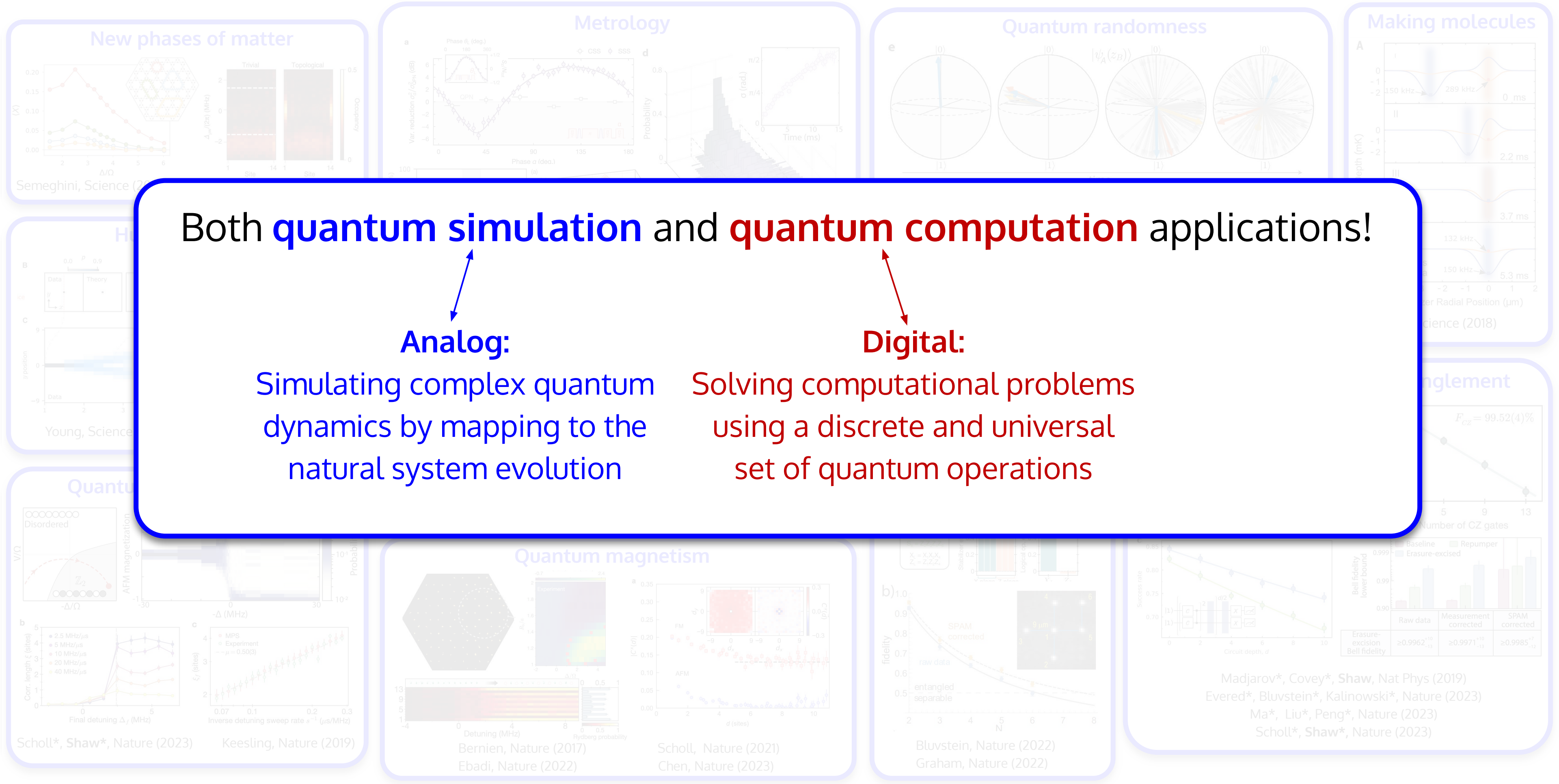
Bluvstein, Nature (2022)
Graham, Nature (2022)

High-fidelity two-qubit entanglement



Madjarov*, Covey*, **Shaw**, Nat Phys (2019)
Evered*, Bluvstein*, Kalinowski*, Nature (2023)
Ma*, Liu*, Peng*, Nature (2023)
Scholl*, **Shaw***, Nature (2023)

Physics with atom arrays, a small selection (pre 2024)



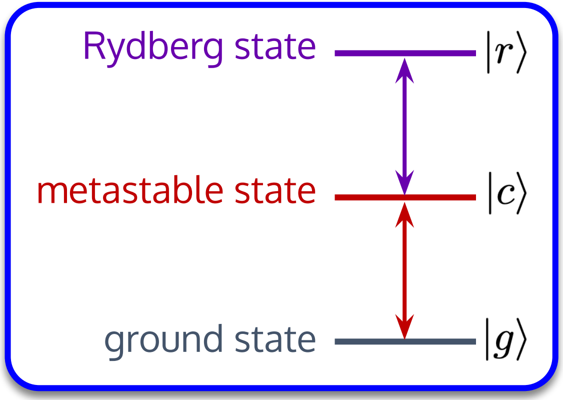
Both **quantum simulation** and **quantum computation** applications!

Analog:
Simulating complex quantum dynamics by mapping to the natural system evolution

Digital:
Solving computational problems using a discrete and universal set of quantum operations

A tale of two qubits

Two different choices of qubit...



Approximate energy levels of strontium, the atom we use

A tale of two qubits

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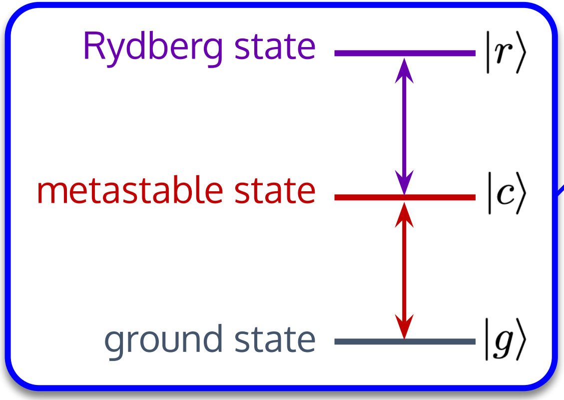

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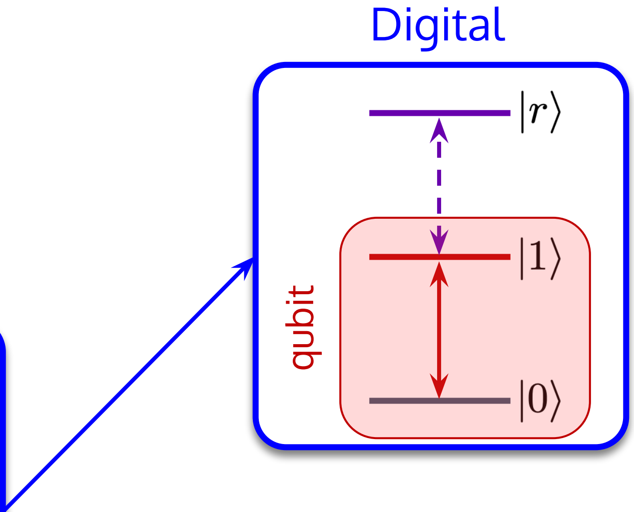

Digital:
Long-lived qubit, amenable to gate-based operation, Rydberg state is only excited transiently

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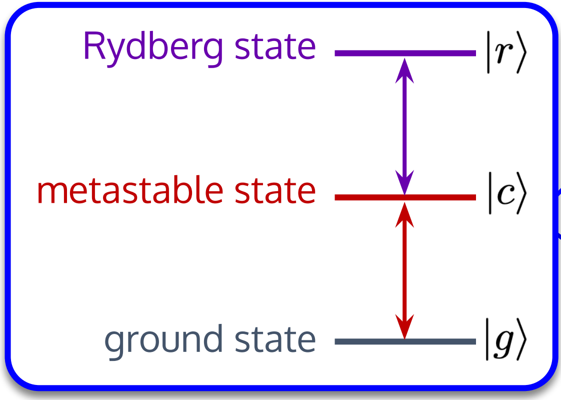

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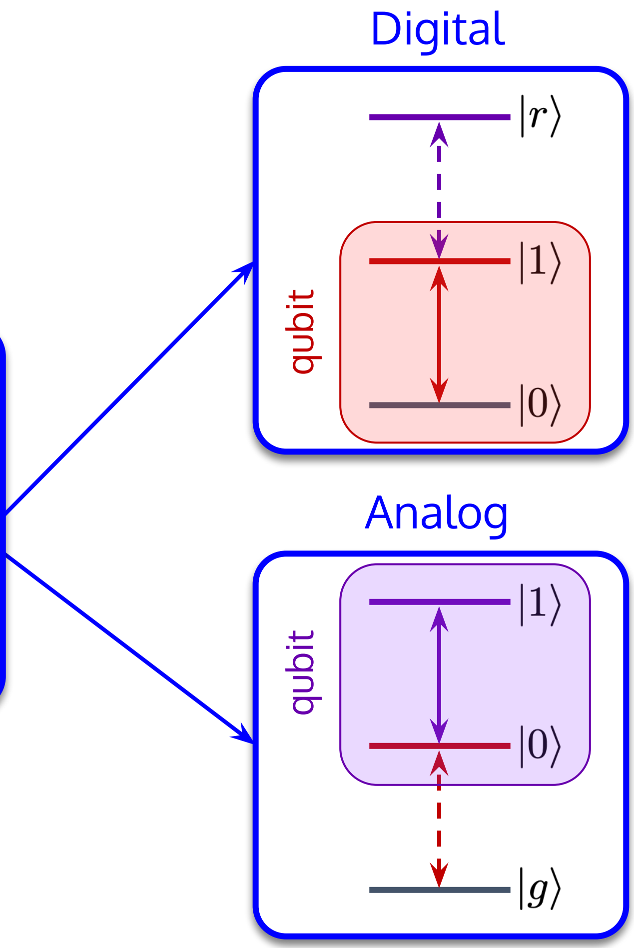

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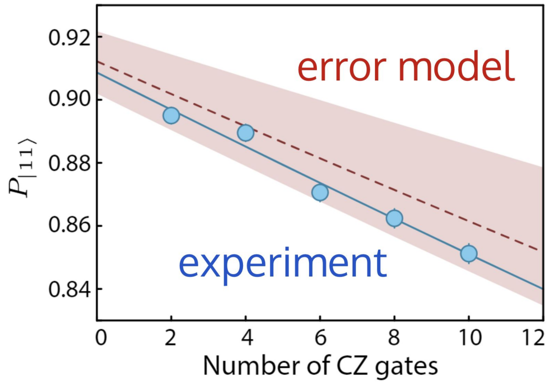
Long-lived qubit, amenable to gate-based operation, Rydberg state is only excited transiently

Analog:
Strongly interacting spin system with an Ising-like Hamiltonian which exhibits critical and high-entanglement behavior

A tale of two qubits

Digital qubit: CZ gate fidelity (measured with RB) of **0.9973(4)***

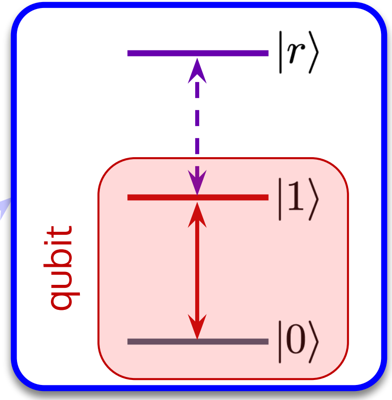
*unpublished, published value is 0.9935



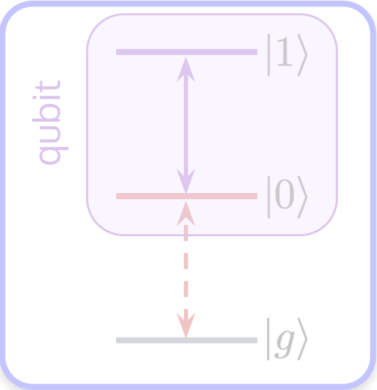
Finkelstein*, Tsai*,..., **Shaw**, Endres, arXiv:2402.16220 (2024)

Other gate results from: Saffman, Lukin, Thompson, Kaufman, Bernien, Zhan, and more

Digital



Analog



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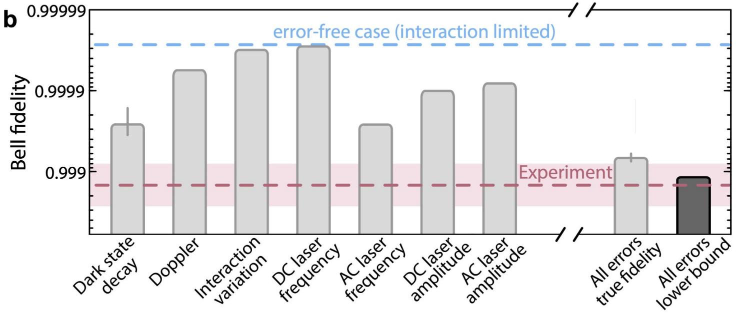
A tale of two qubits

Analog qubit: Bell state fidelity of **~0.9992** (with erasure conversion*)

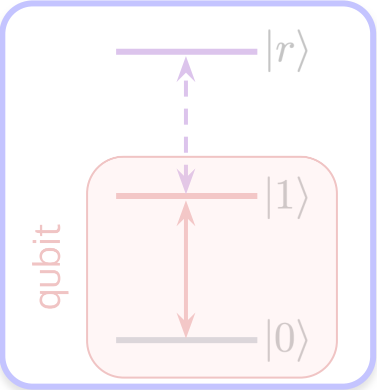


Detailed error modeling shows that **~0.9999** is experimentally realistic

Scholl*, **Shaw***, et al., Nature 622 (2023)

*for erasure conversion, see also
theory: Wu,..., Thompson, Nat Comm (2022)
experiment: Ma,...,Thompson, Nature 622 (2023)

Digital



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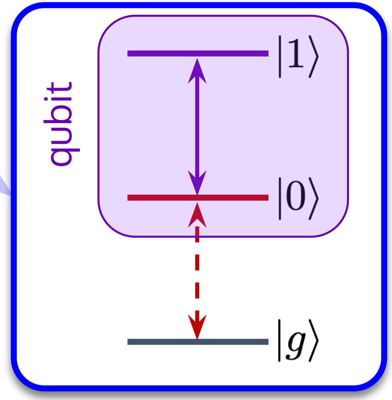

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A tale of two qubits

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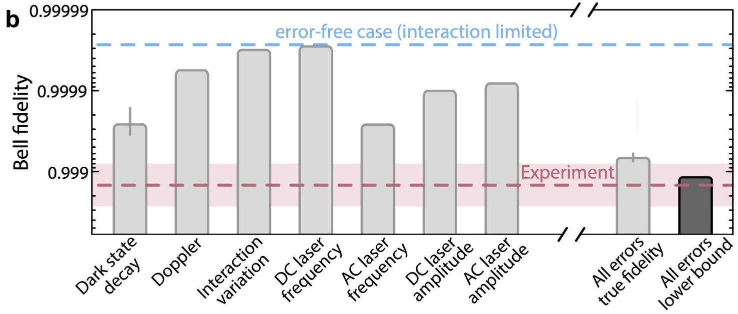

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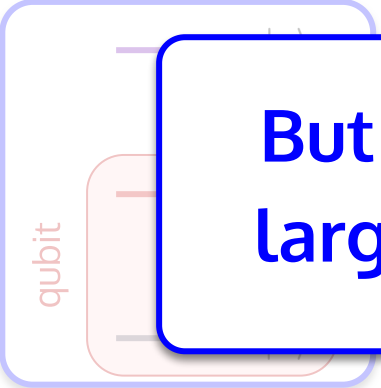
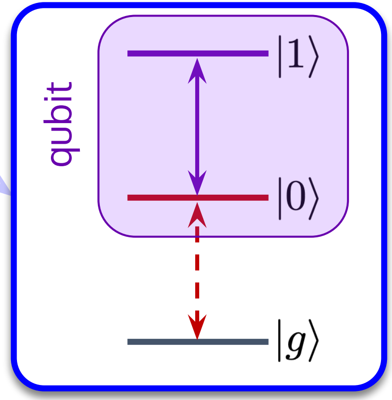


But what about larger systems?

Analog



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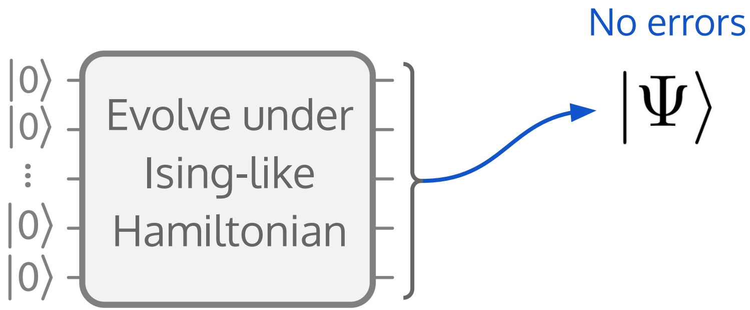
Fidelity benchmarking

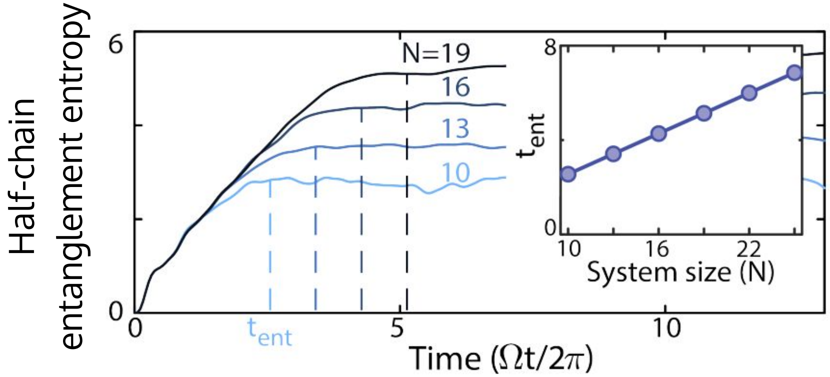
One-dimensional array of up to 60 atoms

Fidelity benchmarking

One-dimensional array of up to 60 atoms



$$\hat{H}/\hbar = \Omega \sum_i \hat{S}_i^x - \Delta \sum_i \hat{n}_i + \frac{C_6}{a^6} \sum_{i>j} \frac{\hat{n}_i \hat{n}_j}{|i-j|^6}$$



Entanglement entropy grows linearly with a system-size independent rate, but saturates at system size dependent time/level

Fidelity benchmarking

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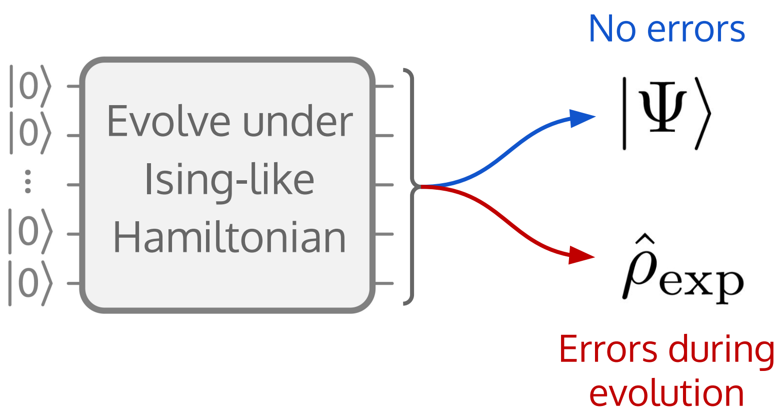

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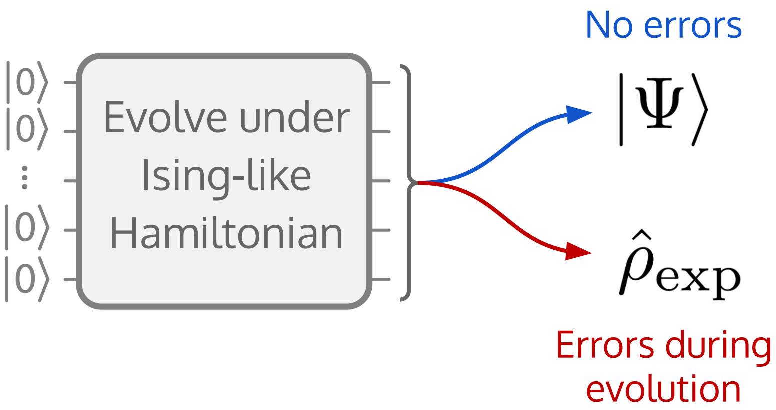
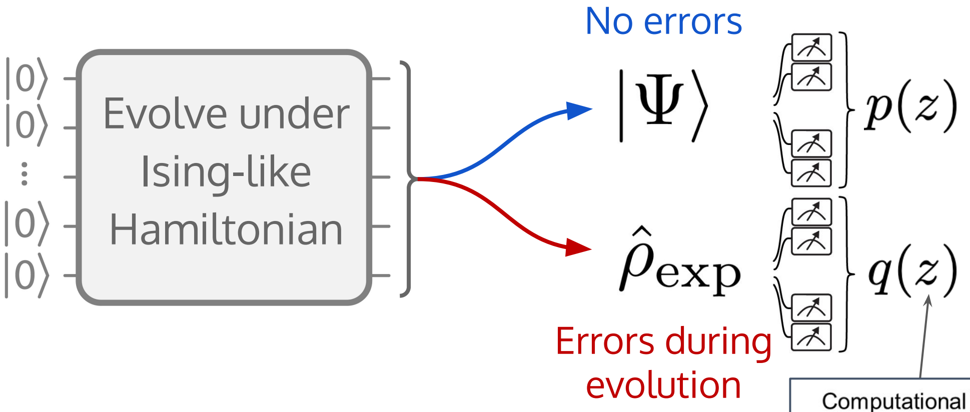


Fidelity: $F = \langle\Psi|\hat{\rho}_{\text{exp}}|\Psi\rangle$

Fidelity is the probability that we don't make an error → Exponentially difficult to measure for large systems!

Fidelity benchmarking

One-dimensional array of up to 60 atoms



If the dynamics are explicitly randomized, **you can estimate fidelity by measuring q(z)**, the experimental bitstring probability distribution in a fixed basis

Arute *et al*, Nature (2019)

Computational basis
(Bitstring of length N)

$z_1 = |000\cdots000\rangle$

$z_2 = |000\cdots001\rangle$

$\vdots$

$z_D = |111\cdots111\rangle$

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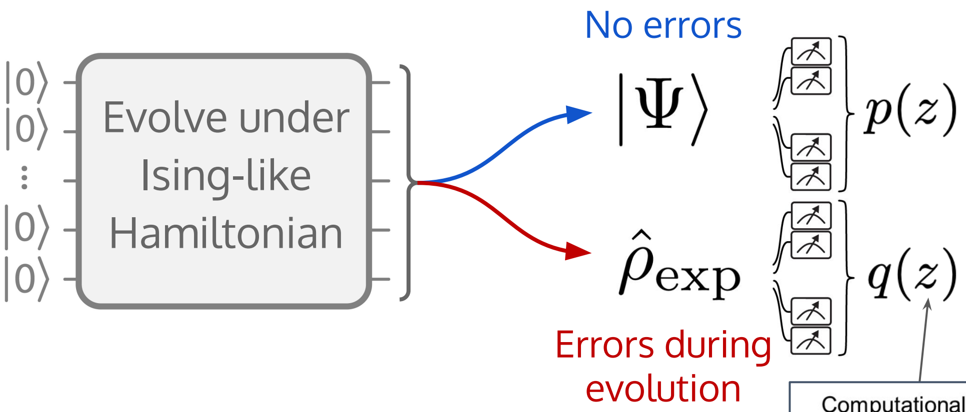

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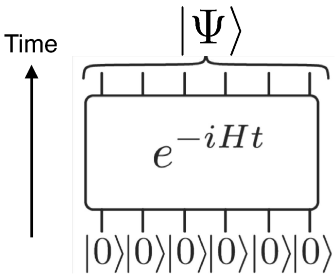
Arute *et al*, Nature (2019)

We showed this also holds for time-independent Hamiltonian systems!

Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, PRL (2023)
Cotler,...**Shaw**, *et al*, PRXQ (2023)

Fidelities from bitstrings



Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, Phys Rev Lett (2023)

Also see: Arute *et al*, Nature (2019)

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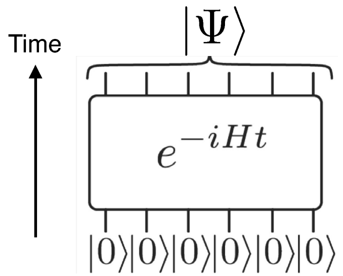


Quantum dynamics maps to near-random distribution...

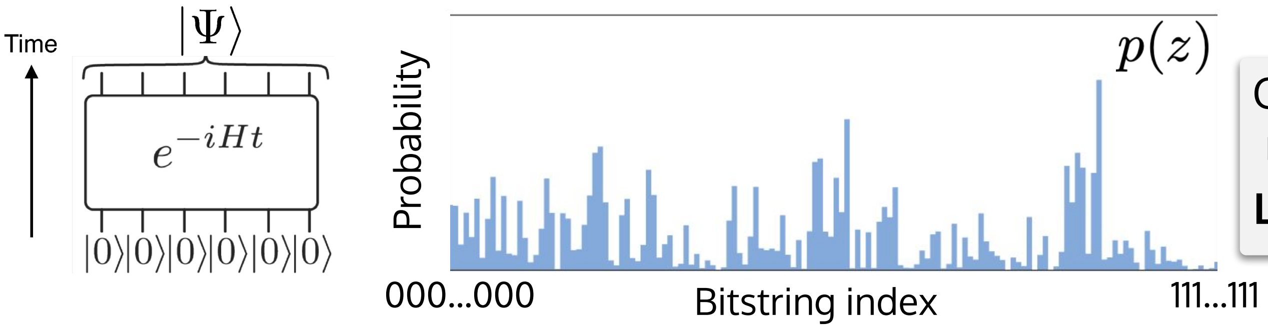
Like a quantum fingerprint

Very sensitive to the exact initial state and dynamics!

Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, Phys Rev Lett (2023)

Also see: Arute *et al*, Nature (2019)

Fidelities from bitstrings



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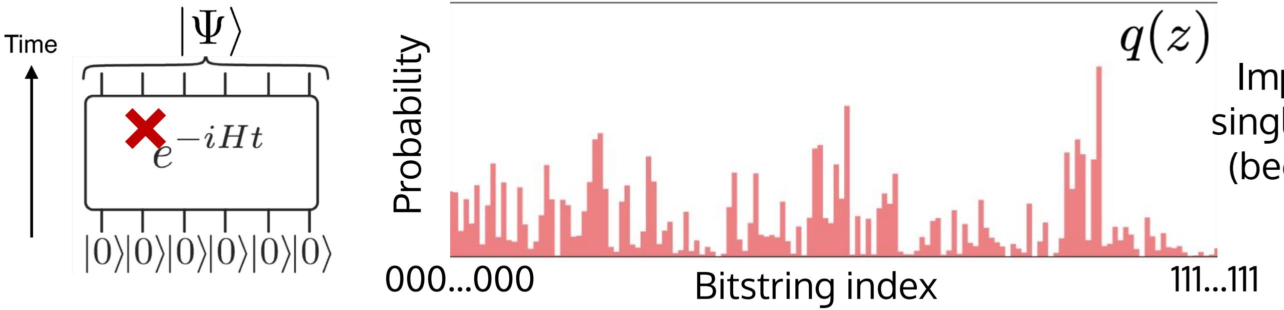
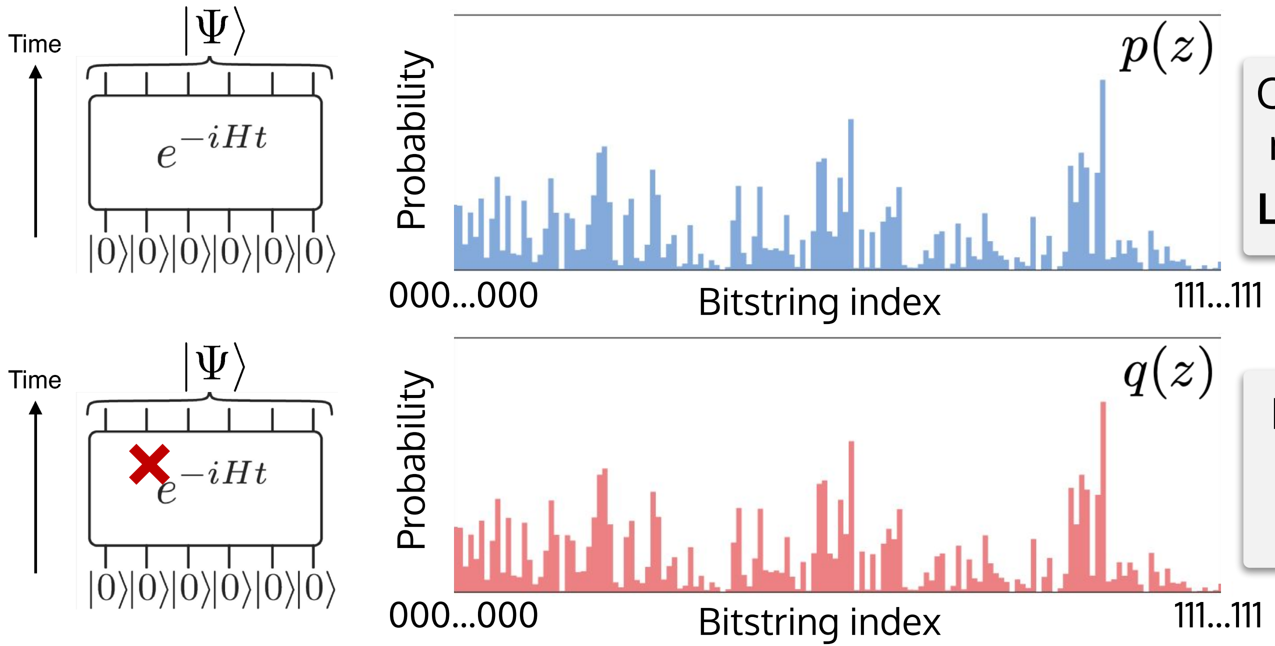


Impose a phase flip error on a single qubit: **initially not visible!** (because error is orthogonal to measurement basis)

Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, Phys Rev Lett (2023)

Also see: Arute *et al*, Nature (2019)

Fidelities from bitstrings



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But error soon **scrambles**, changing the distribution! "**Butterfly effect**"

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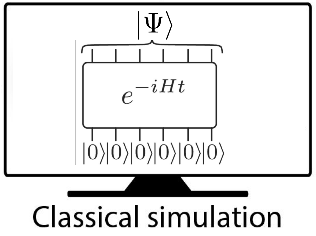
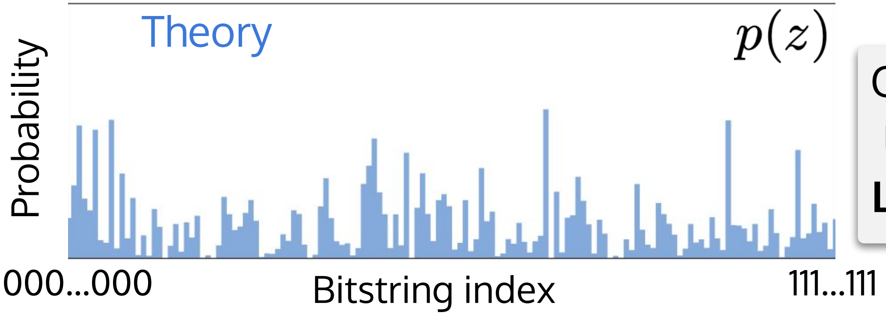
Fidelities from bitstrings





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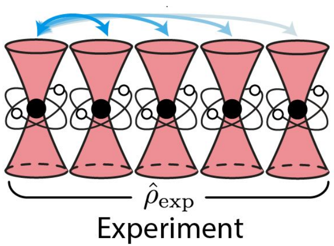
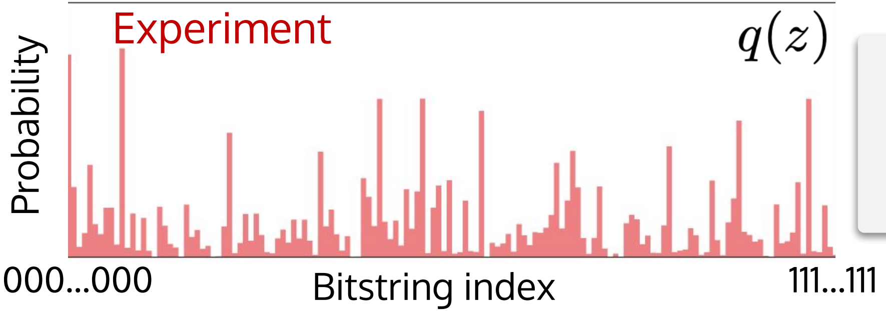




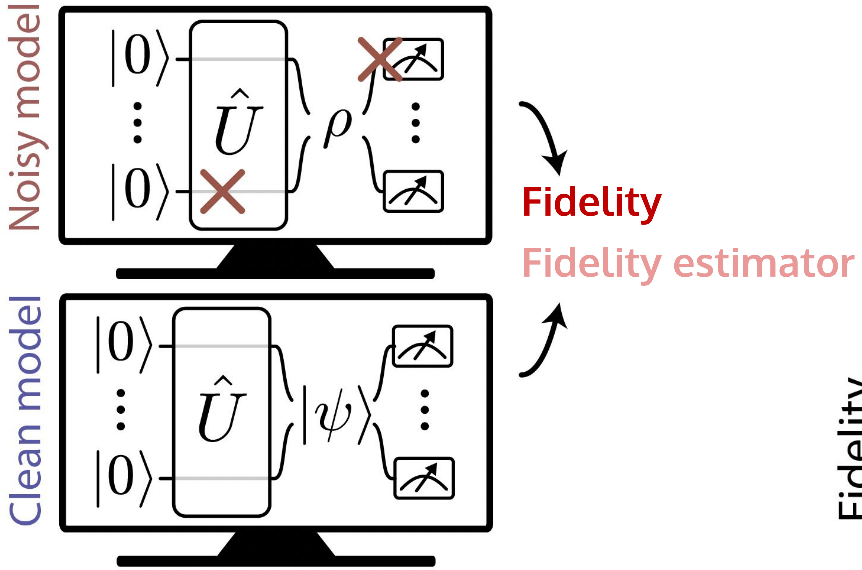
But error soon **scrambles**, changing the distribution! "**Butterfly effect**"

Fidelity estimator proportional to **Theory**-**Experiment** correlation!

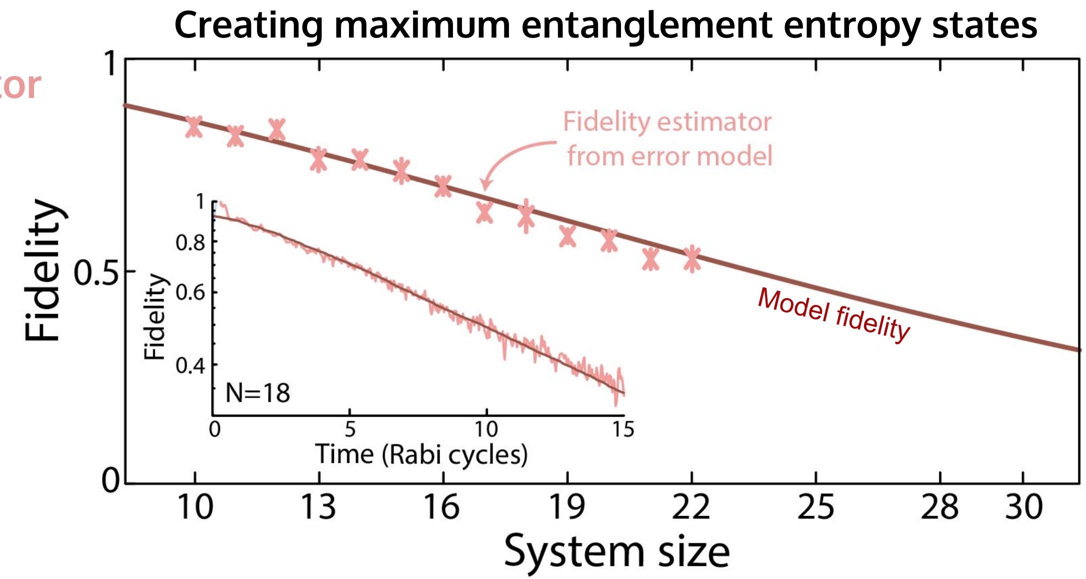
Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, Phys Rev Lett (2023)

Also see: Arute *et al*, Nature (2019)

Demonstration of benchmarking with experiment



First, use noisy simulation to verify fidelity estimator is accurate to the model fidelity



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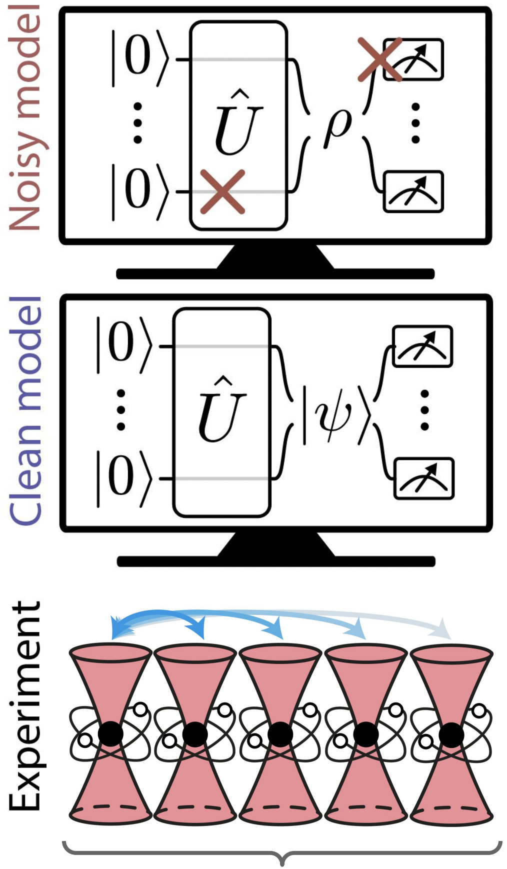
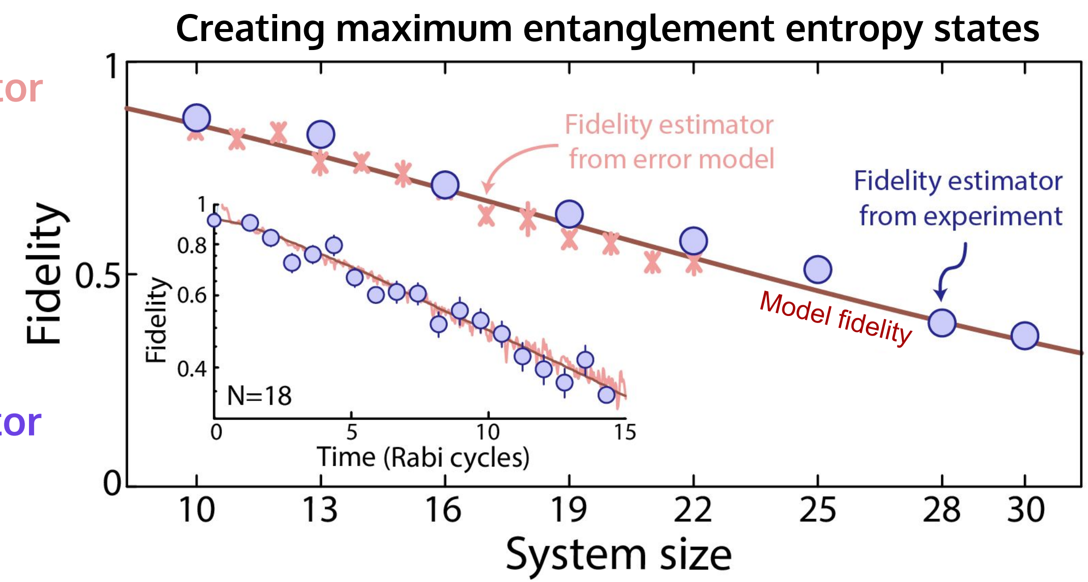


Fidelity

Fidelity estimator

Experimental fidelity estimator

First, use noisy simulation to verify fidelity estimator is accurate to the model fidelity



Can accurately benchmark the experiment!

Choi*, **Shaw*** *et al*, Nature (2023)
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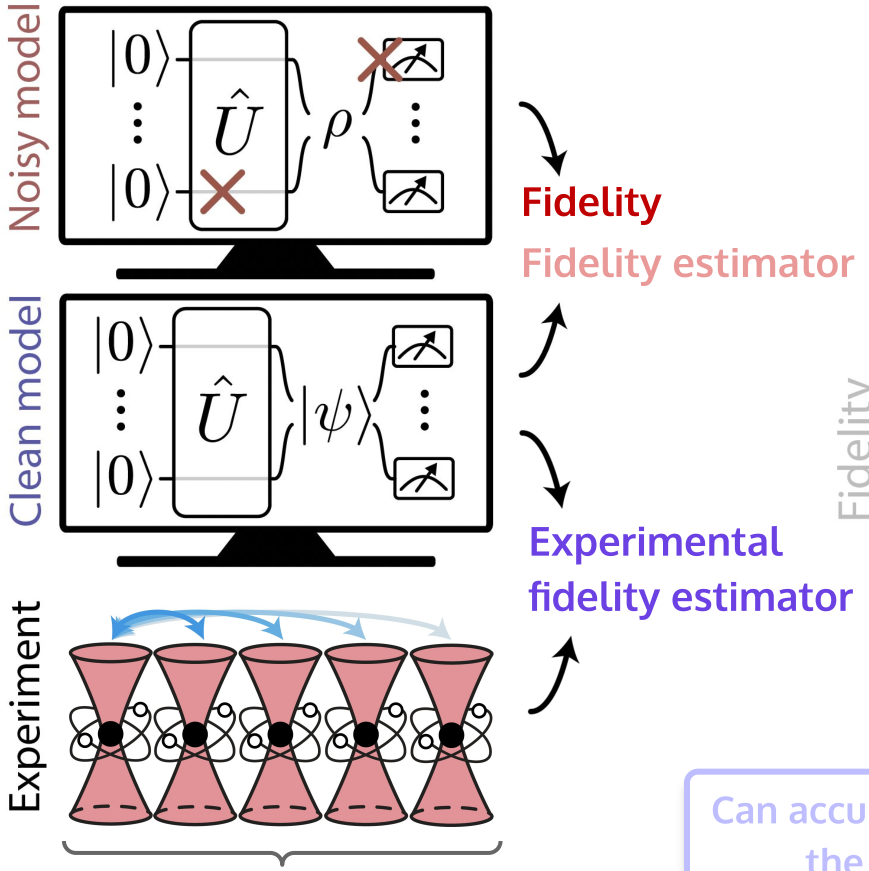

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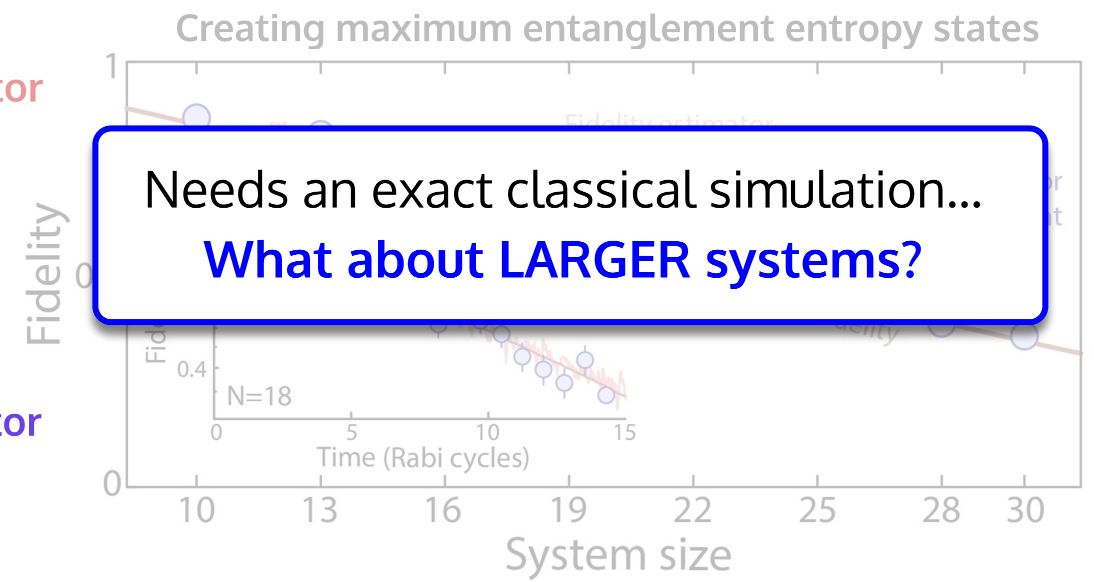


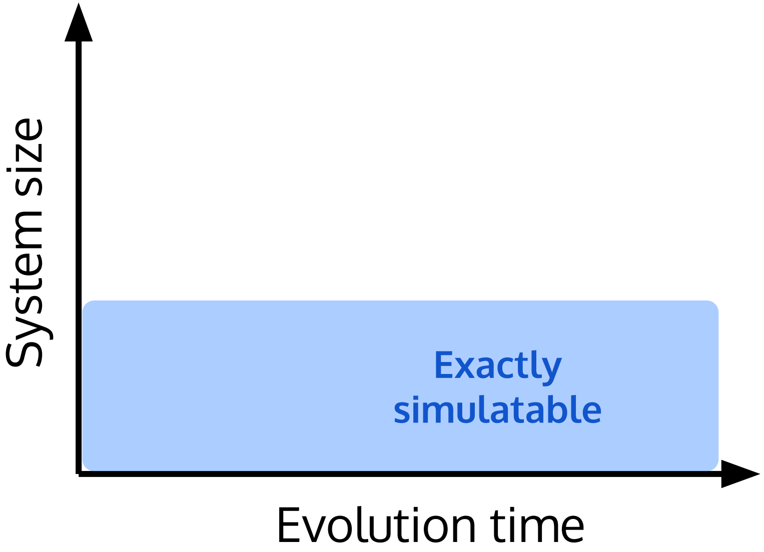
Needs an exact classical simulation…

What about LARGER systems?

Can accurately benchmark the experiment!

Choi*, **Shaw*** *et al*, Nature (2023)
Mark, Choi, **Shaw** *et al*, PRL (2023)

What makes classical simulation hard?



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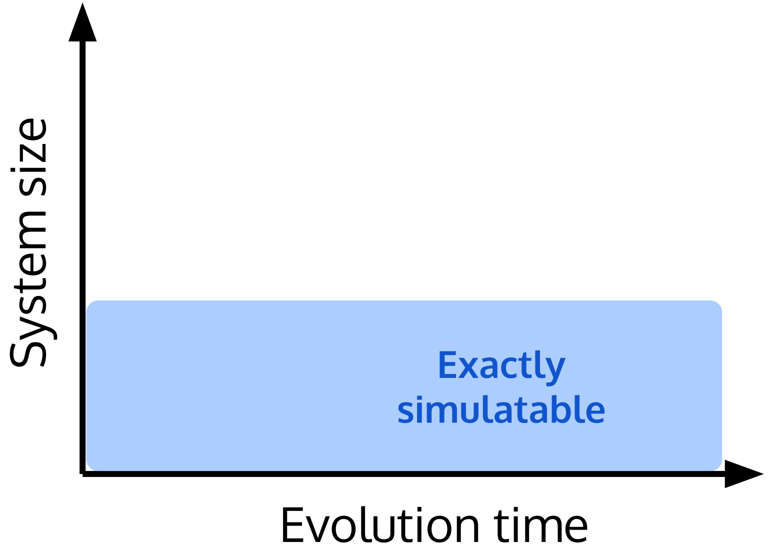

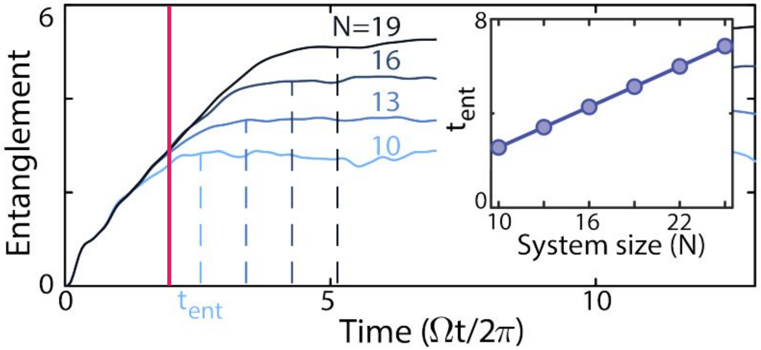

At early times the system hasn't built up much entanglement

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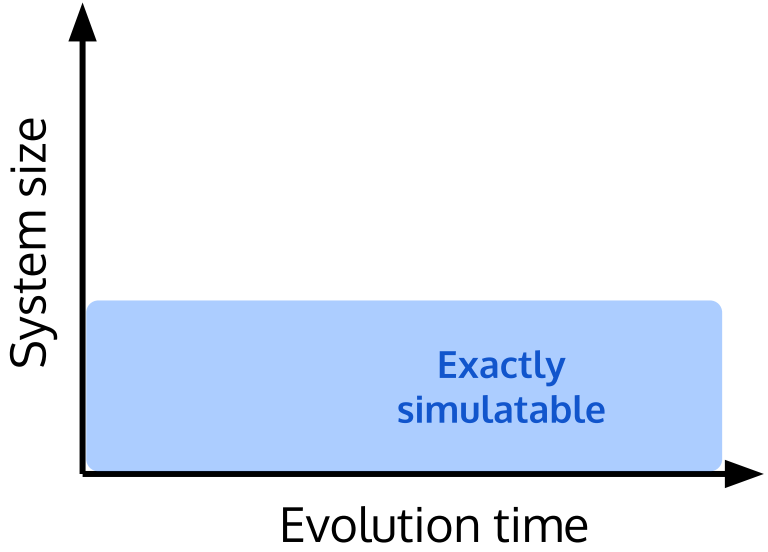

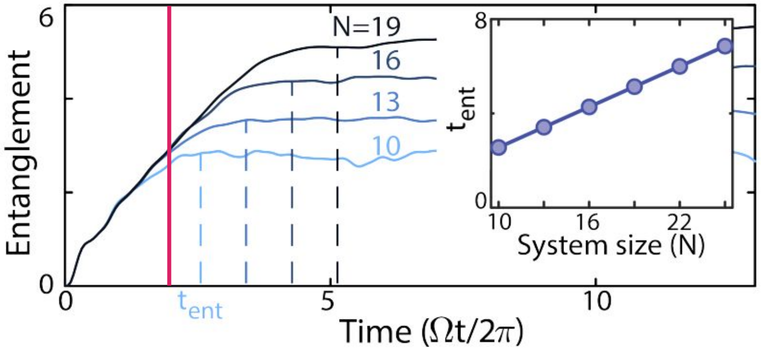

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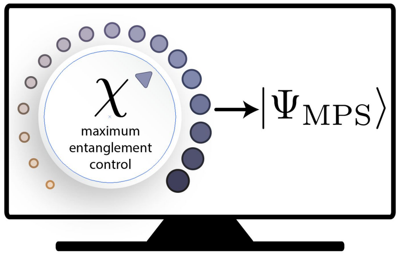
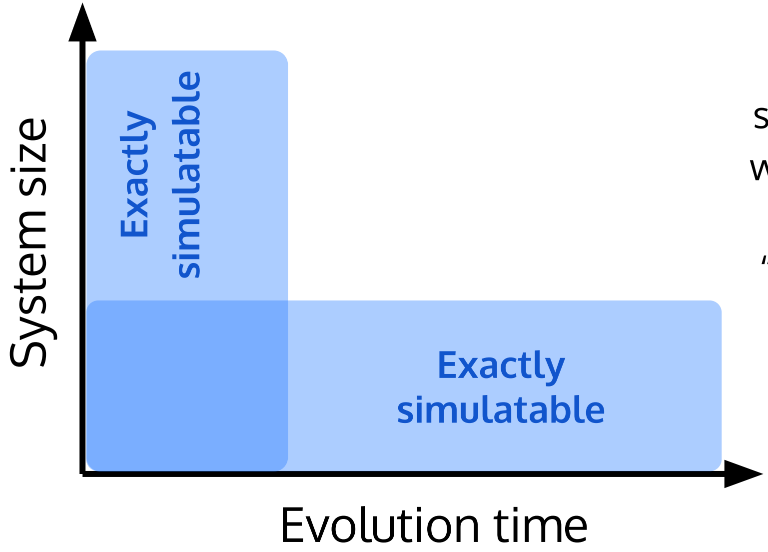
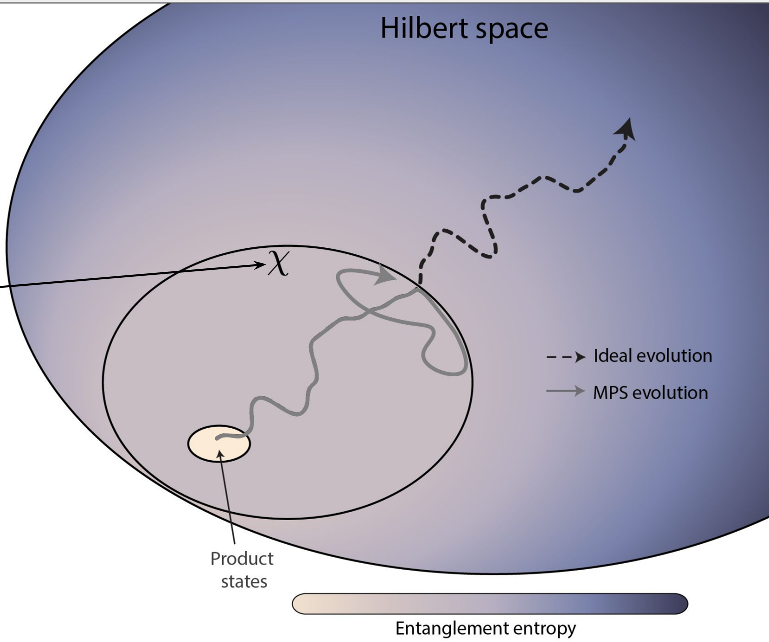


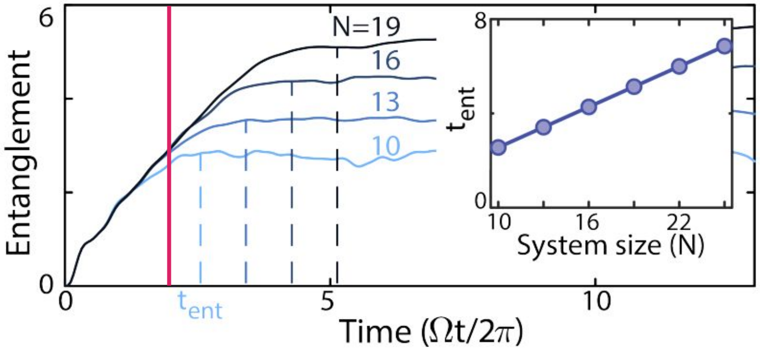
We can simulate by using **Matrix product states (MPS)!**

What makes classical simulation hard?



MPS perfectly simulates dynamics while entanglement is below the "**bond dimension**"





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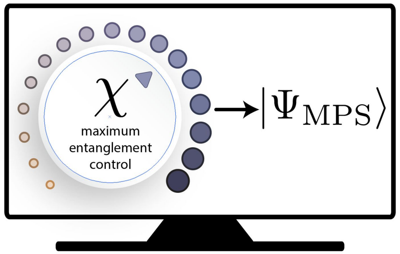

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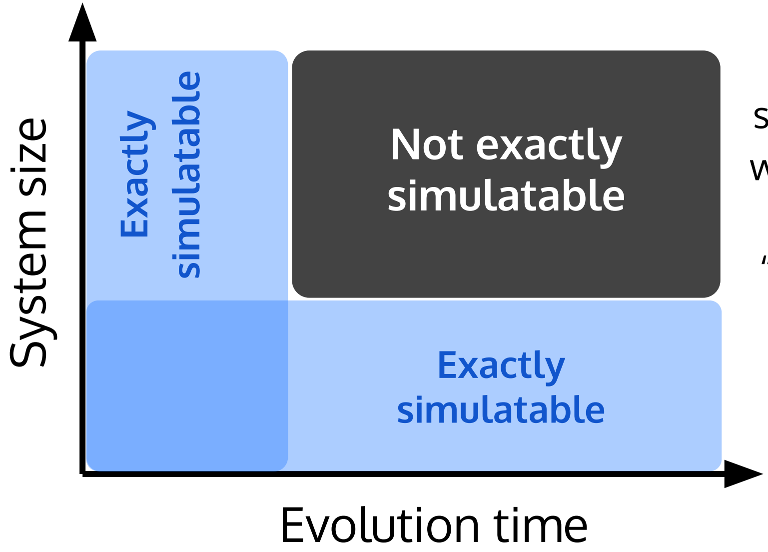

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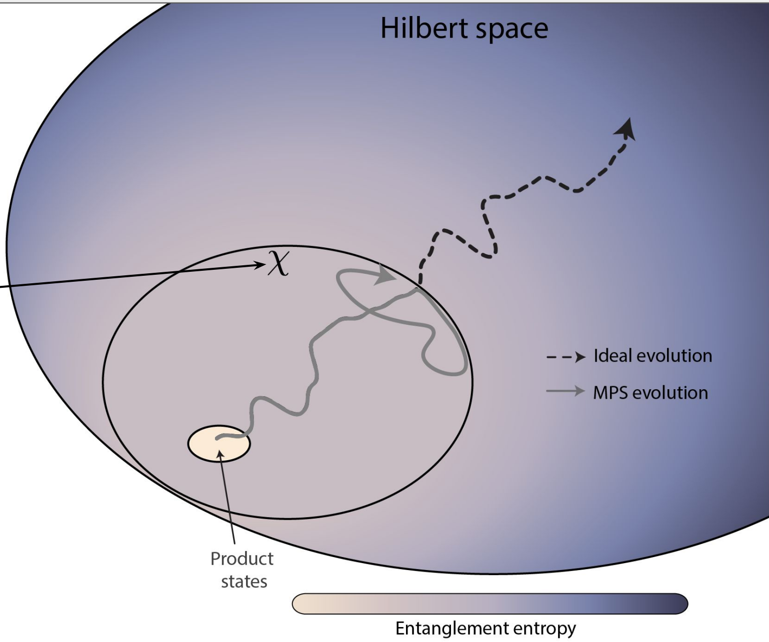

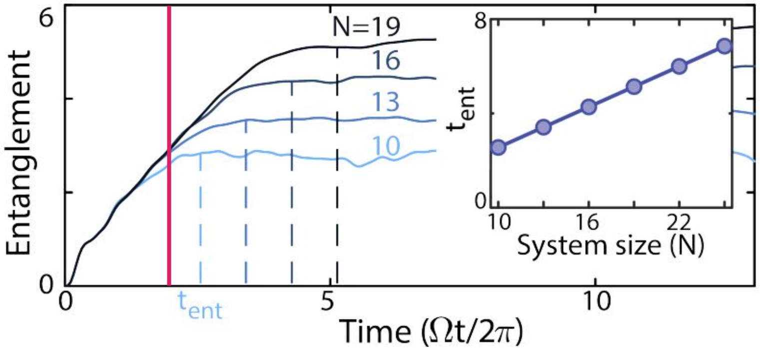

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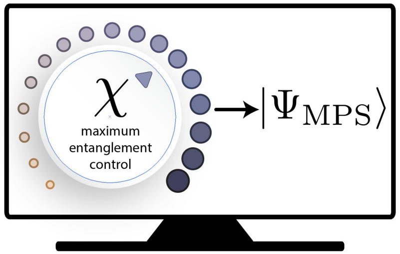

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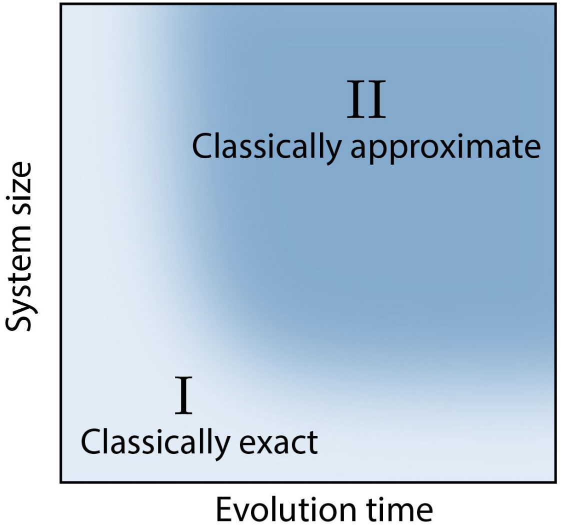
Fidelity benchmarking breakdown



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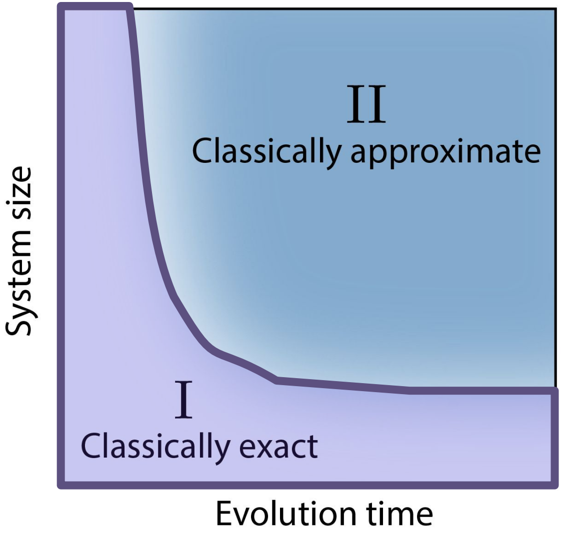
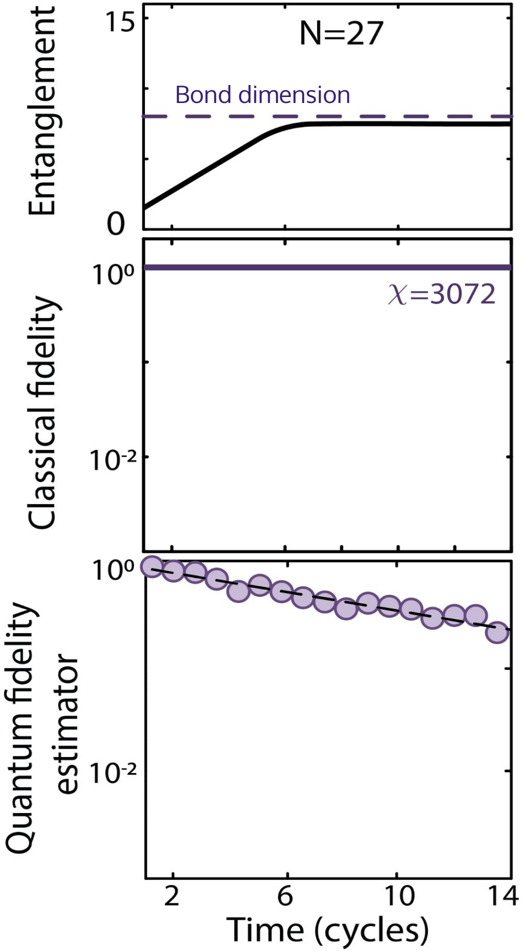
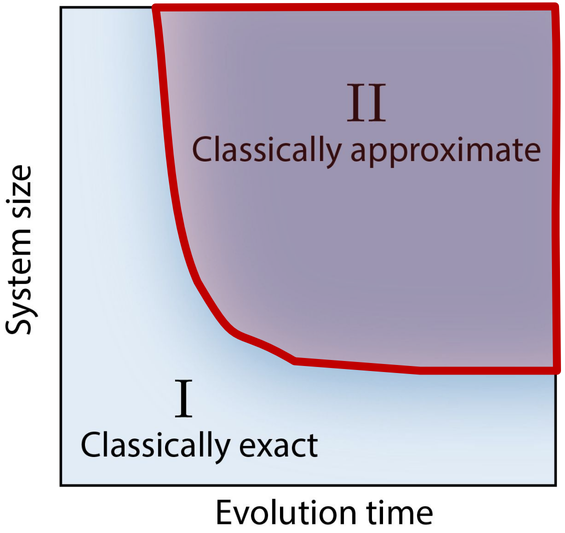




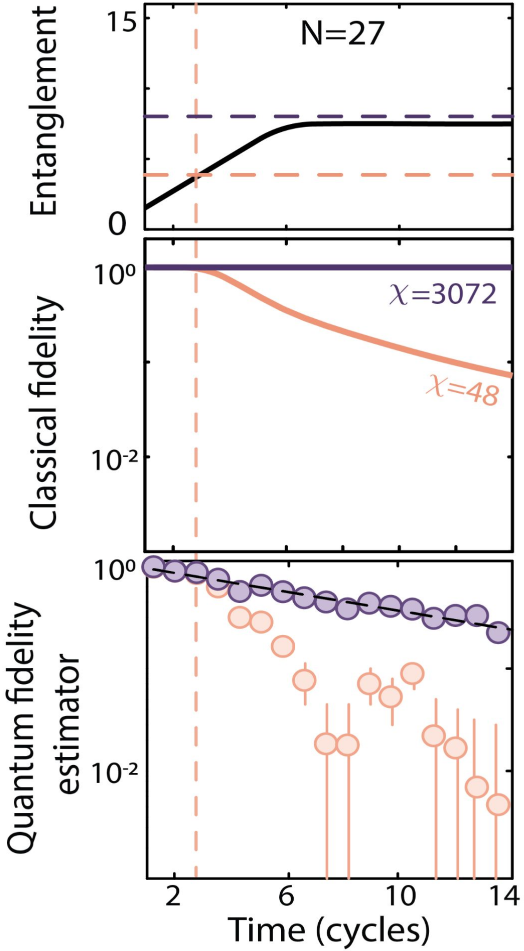
For large enough bond dimension, we exactly benchmark the system

Fidelity benchmarking breakdown



Fidelity estimate ≈ **Experimental true fidelity** × **Simulation fidelity**

(Not exactly, but qualitatively)

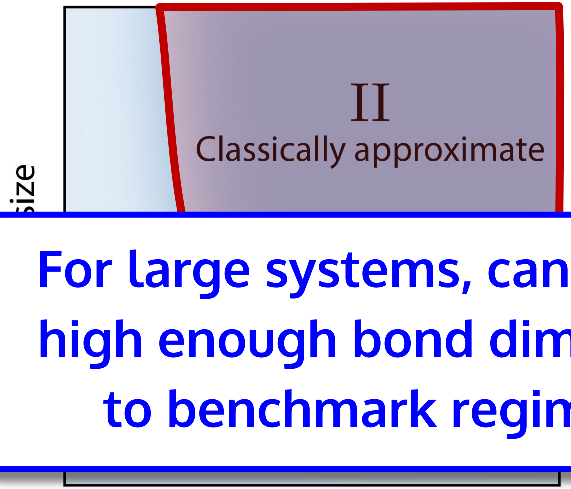


For large enough bond dimension, we exactly benchmark the system

When bond dimension is too small, classical accuracy drops

And so does the benchmarked quantum fidelity!

Fidelity benchmarking breakdown



For large systems, can't go to high enough bond dimension to benchmark regime II!

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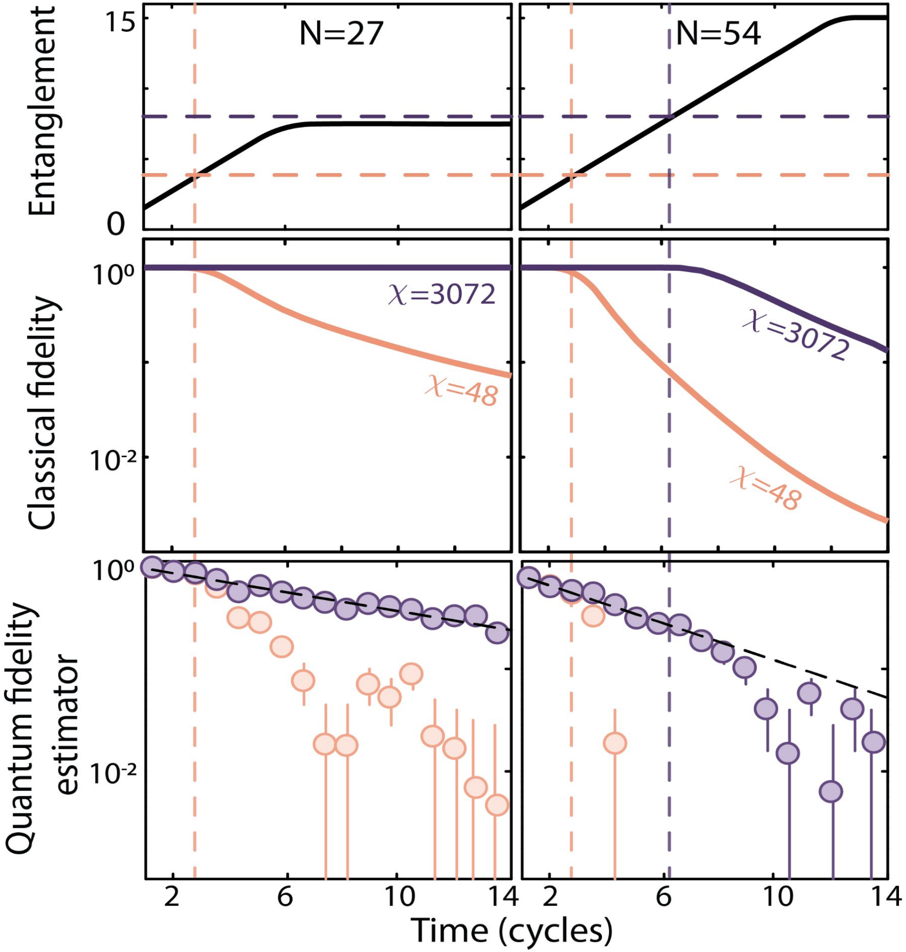
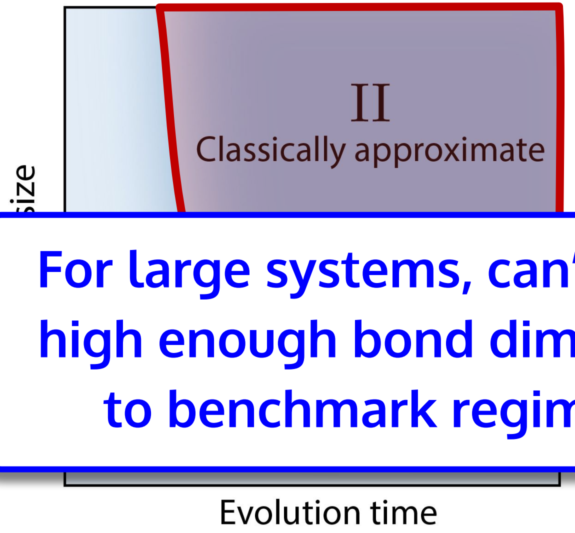


Fidelity benchmarking breakdown



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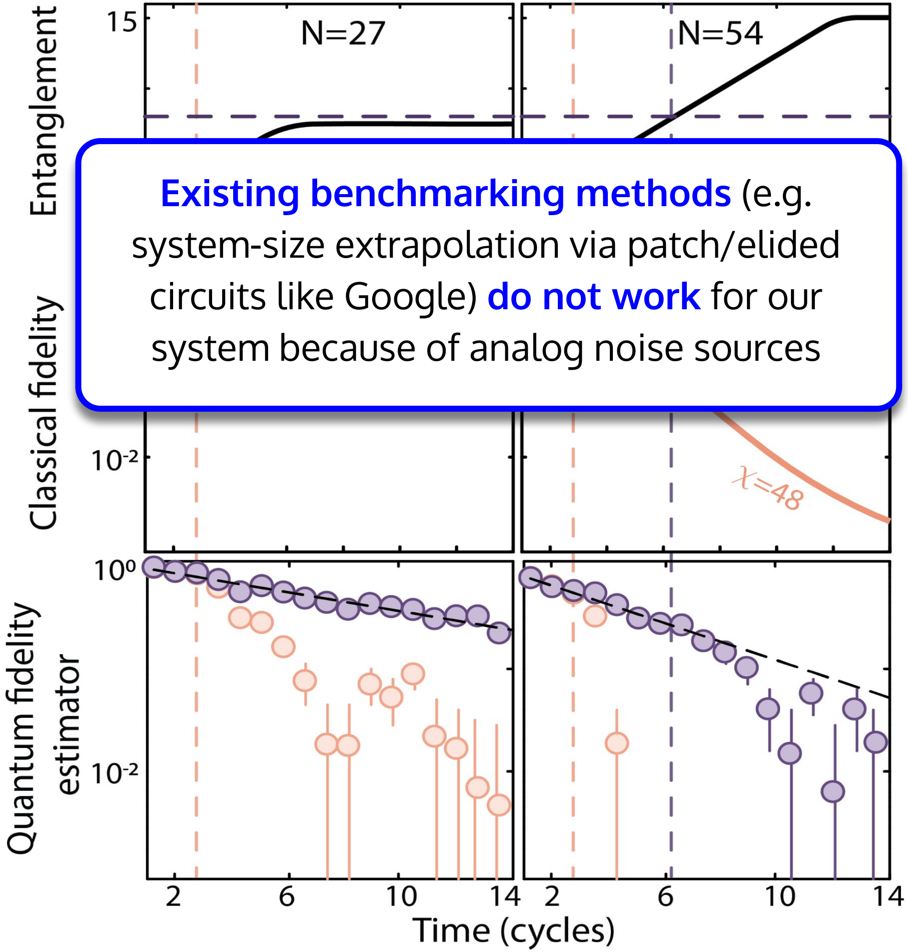
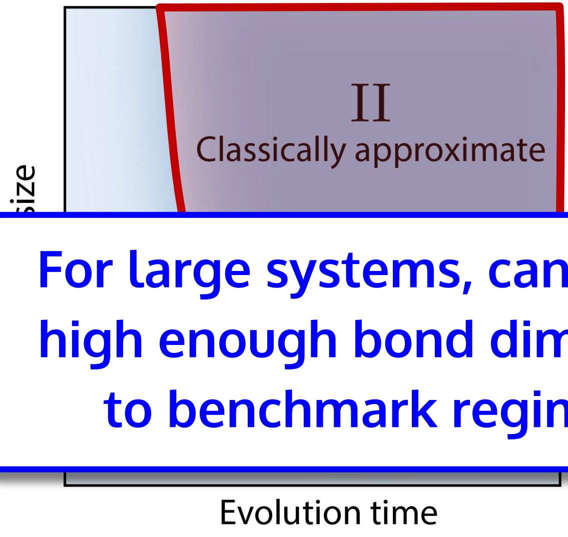


Existing benchmarking methods (e.g. system-size extrapolation via patch/elided circuits like Google) **do not work** for our system because of analog noise sources

Fidelity estimate ≈ **Experimental true fidelity** × **Simulation fidelity**

(Not exactly, but qualitatively)

Fidelity benchmarking breakdown

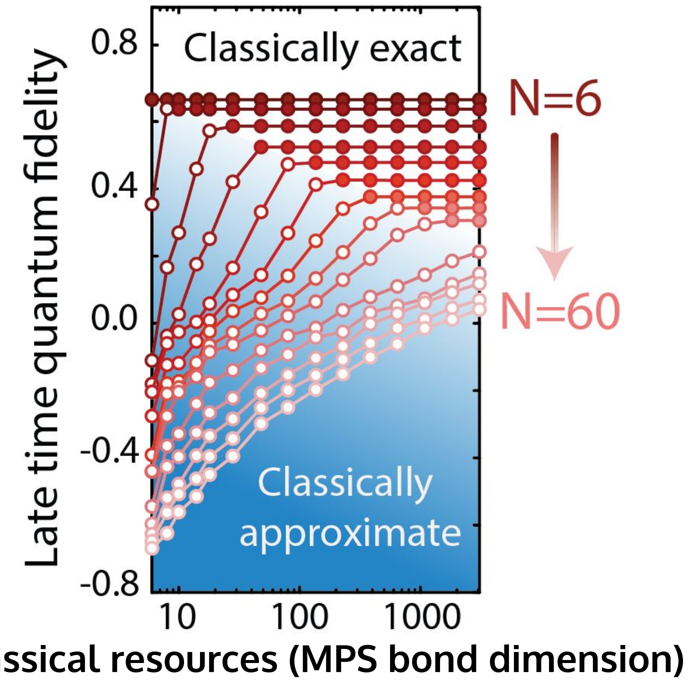


For large systems, can't go to high enough bond dimension to benchmark regime II!

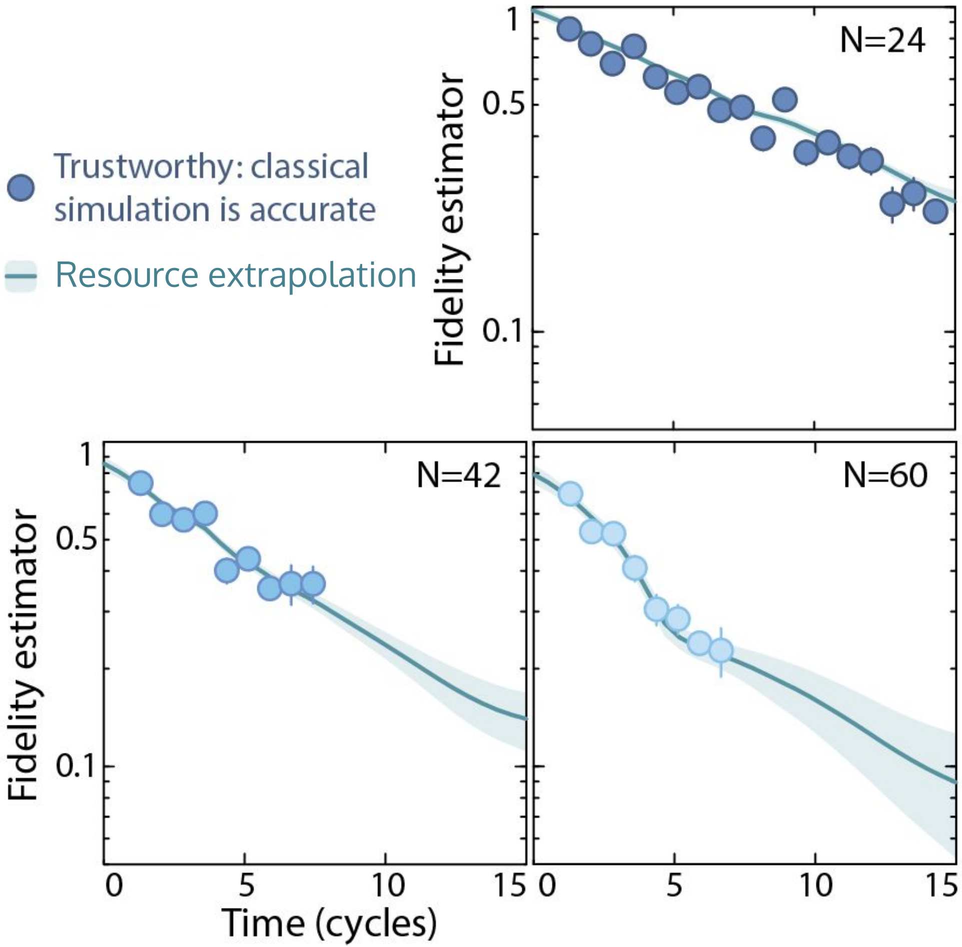
Fidelity estimate	$\approx$	**Experimental true fidelity**	$\times$	**Simulation fidelity**

(Not exactly, but qualitatively)

But we can extrapolate as a function of bond dimension!

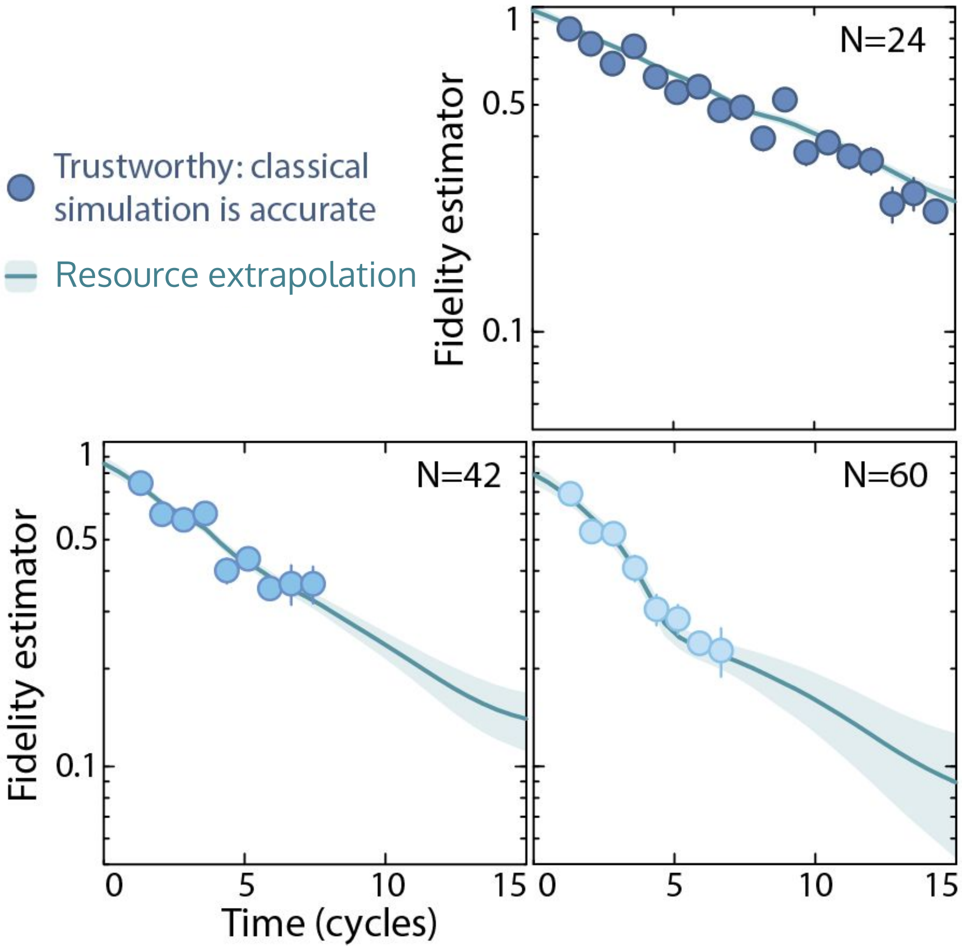


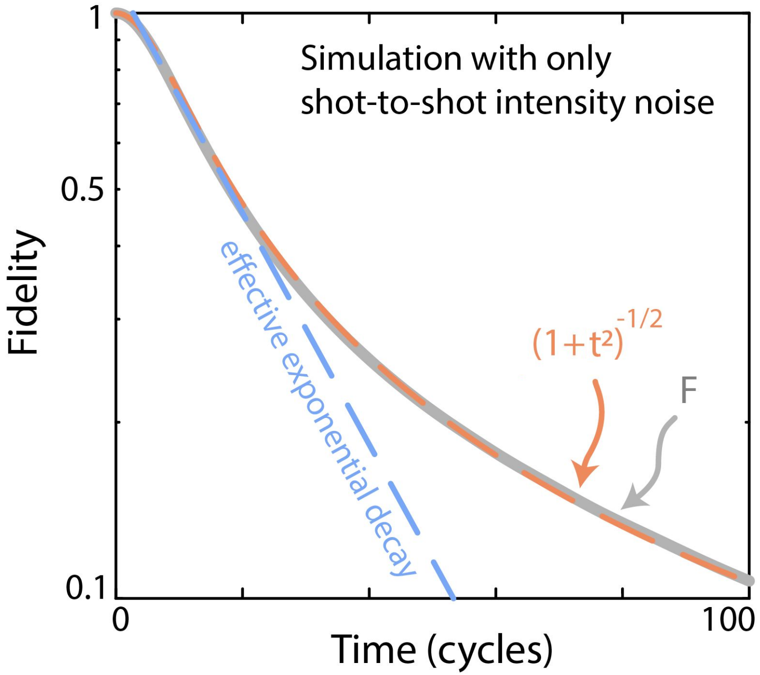
Large scale fidelity



Shaw*, Chen*, Choi*, Mark*, *et al*, Nature, 2024

Large scale fidelity

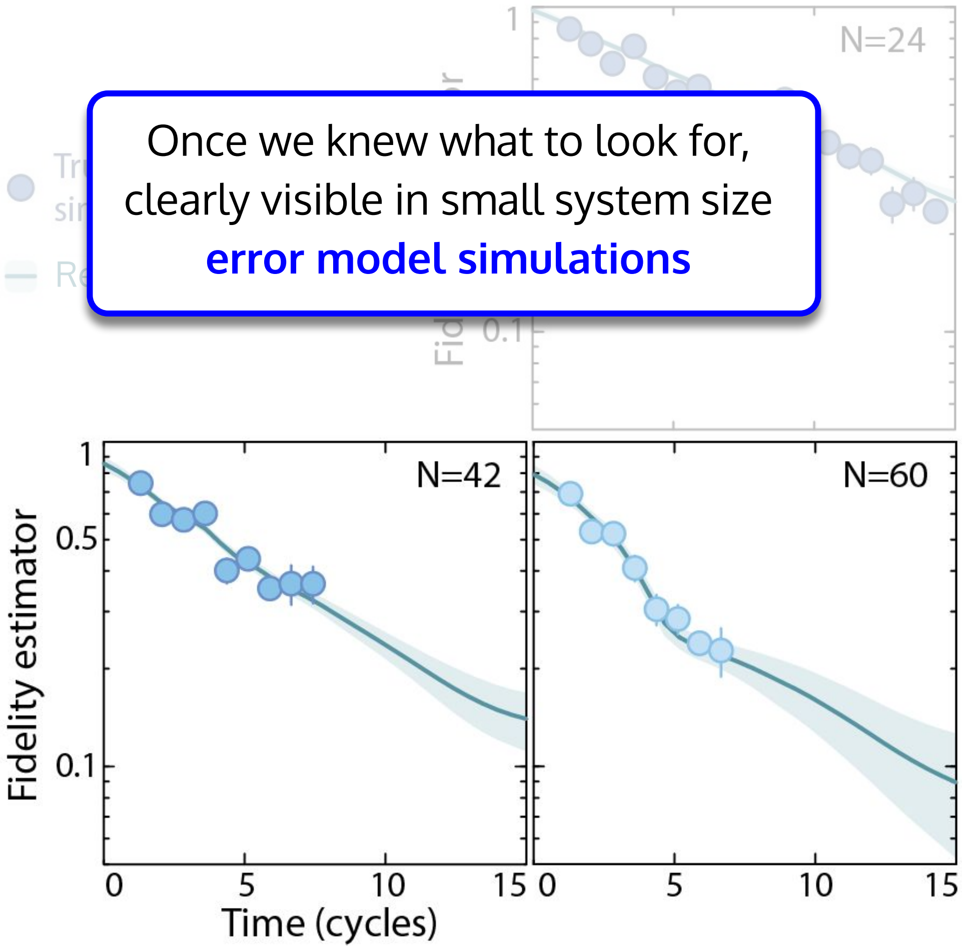




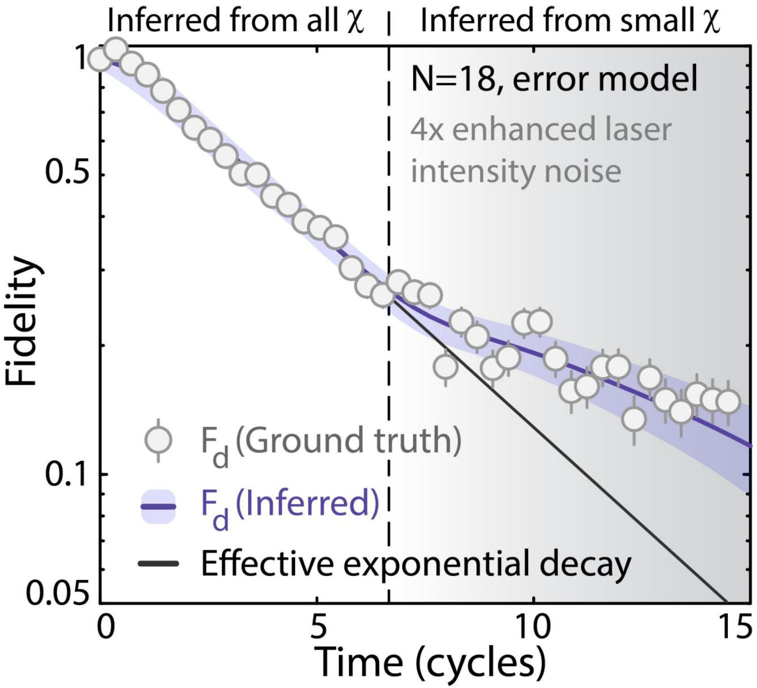
This led us to discover certain **non-Markovian** noise leads to power law fidelity decay!

Shaw*, Chen*, Choi*, Mark*, *et al*, Nature, 2024

Large scale fidelity



Once we knew what to look for, clearly visible in small system size **error model simulations**



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Shaw*, Chen*, Choi*, Mark*, *et al*, Nature, 2024

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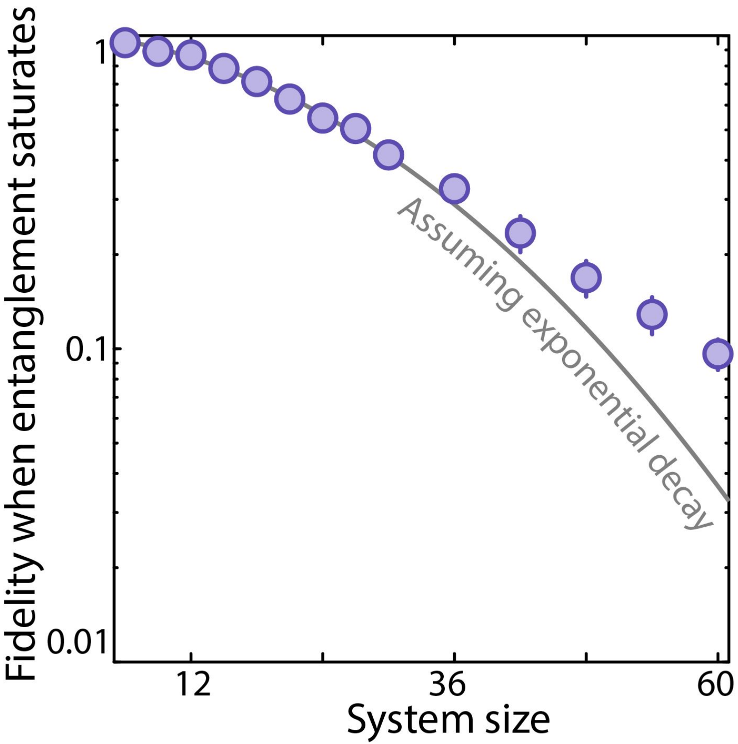


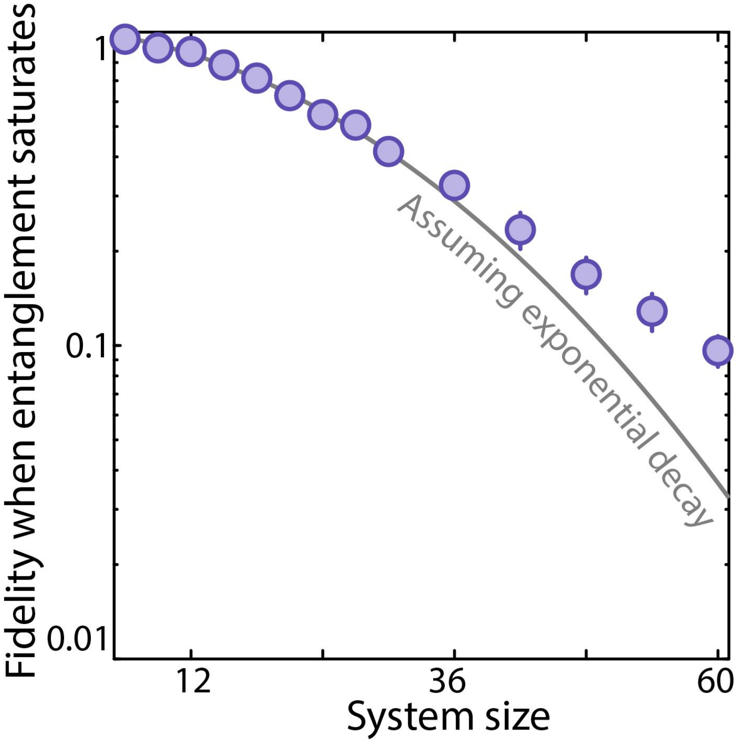
Fidelities

Our system - 0.095 @ N=60 in 1D*

***10% vs. 0.0000000000000001%**
17 orders-of-magnitude better
than random chance

Shaw*, Chen*, Choi*, Mark*, *et al*, Nature, 2024

Large scale fidelity



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These results are consistent with a two-qubit fidelity of ~0.999

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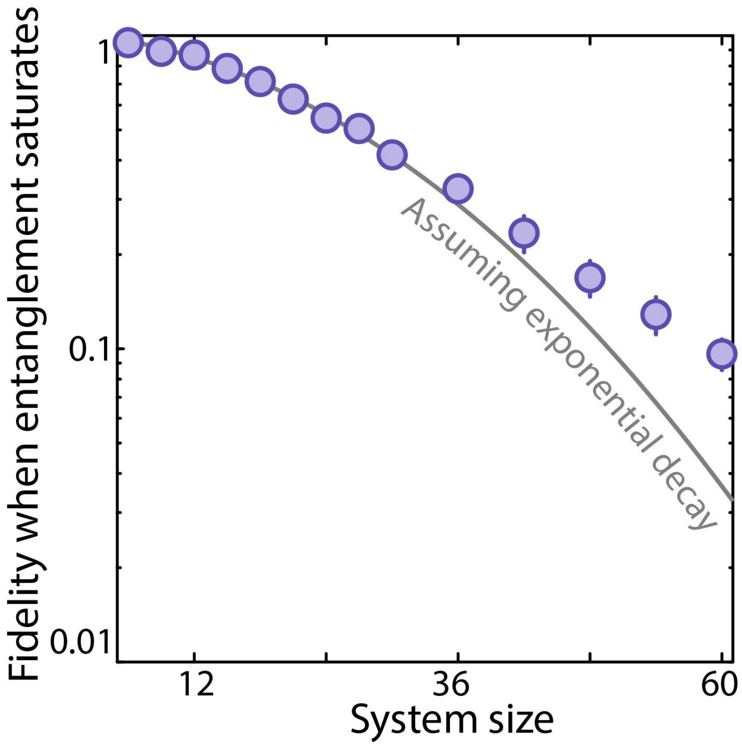


Fidelities

Our system - 0.095 @ N=60 in 1D*

Google** - 0.003 @ N=53 in 2D

These results are consistent with a two-qubit fidelity of ~0.999

***10% vs. 0.0000000000000001%**
17 orders-of-magnitude better than random chance

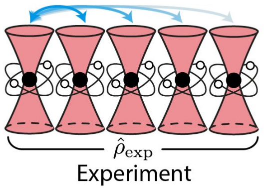
**Not a fair comparison because of different level of control, but gives a general sense of scale. Higher values in more recent papers (Morvan et al, 2023)

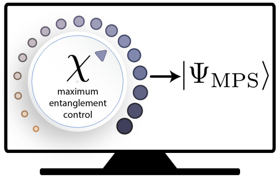
Shaw*, Chen*, Choi*, Mark*, *et al*, Nature, 2024

What is the actual classical cost?

Which better represents the quantum world?

Quantum experiment or classical computer?





Physical error vs approximation error

What is the actual classical cost?

Which better represents the quantum world?

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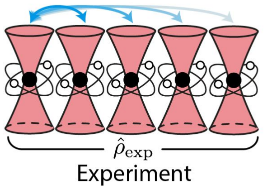
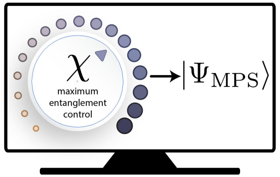
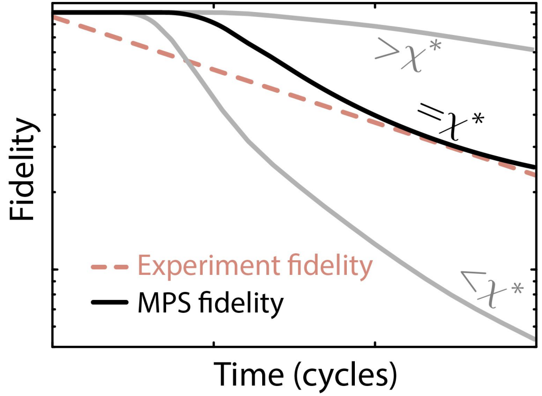




Physical error vs approximation error

Find minimum classical resources for classical computer to have higher fidelity than experiment



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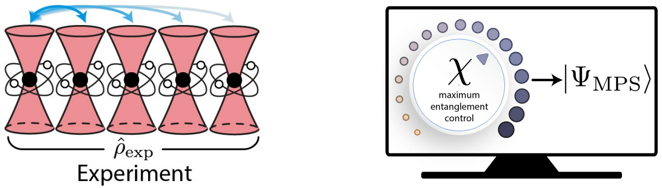

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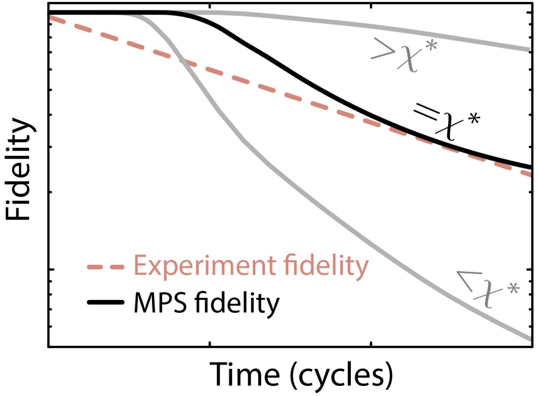

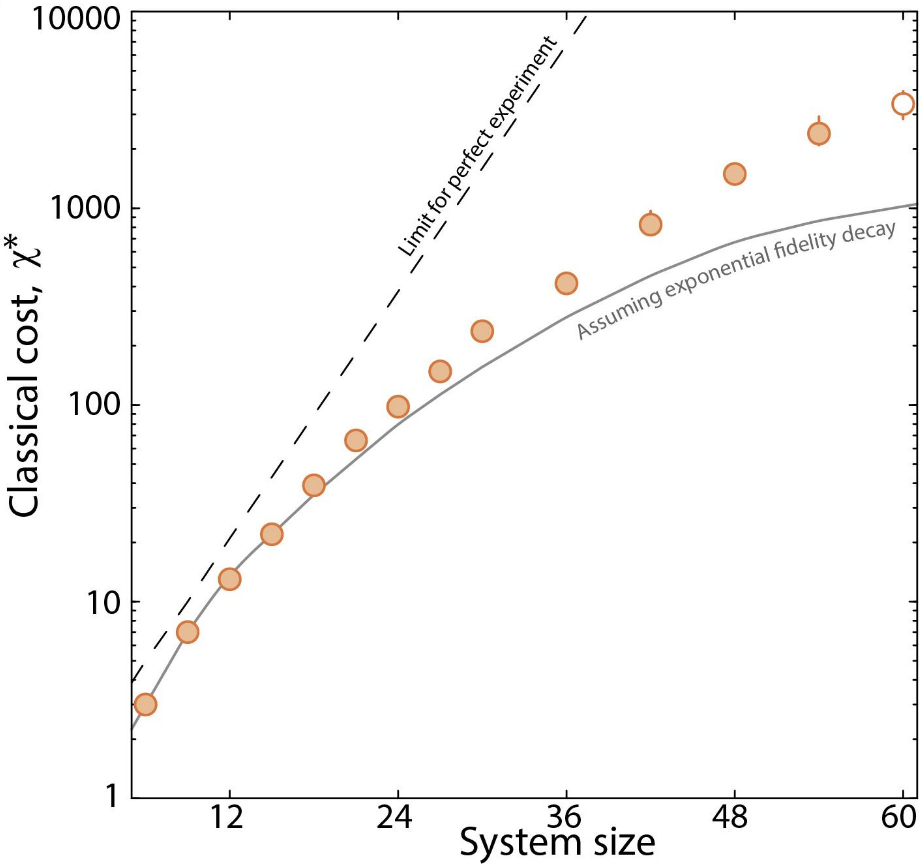

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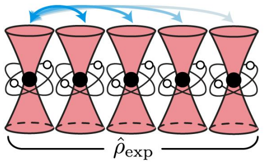

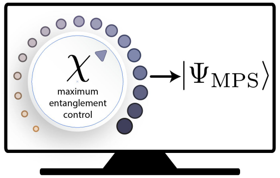

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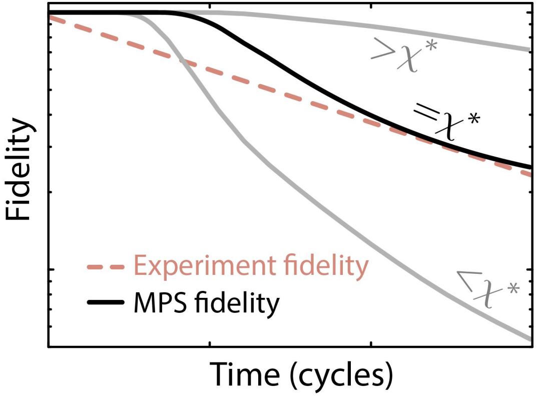
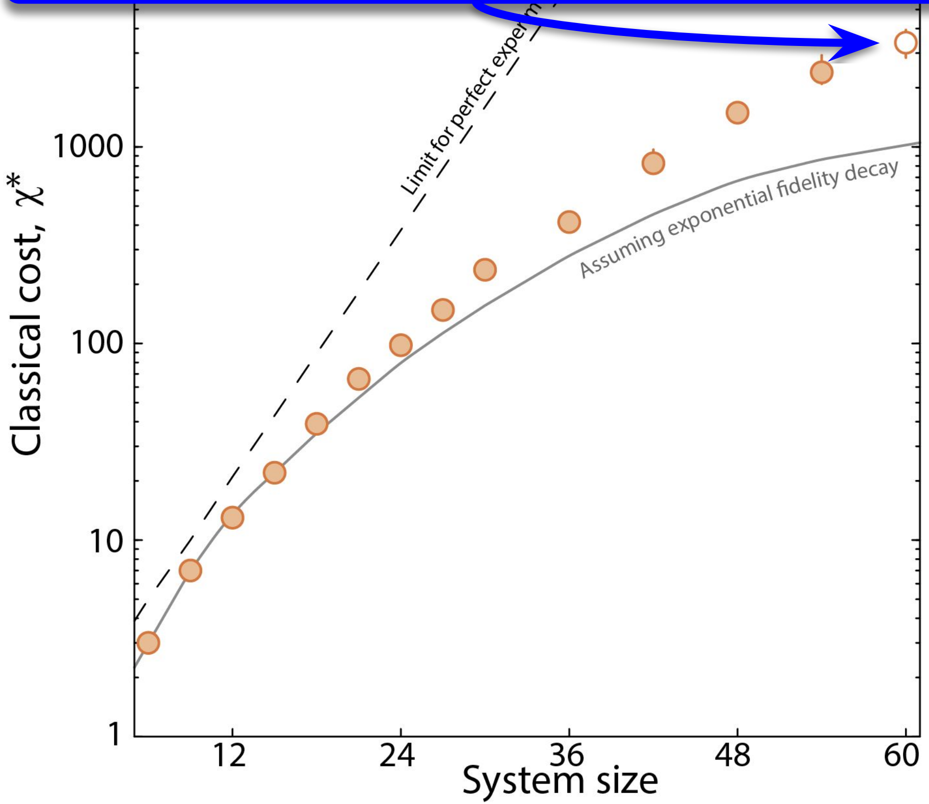


180 core-days on the Caltech supercomputer

(using a highly optimized algorithm)



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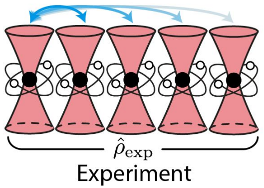

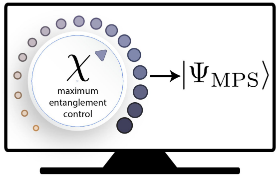

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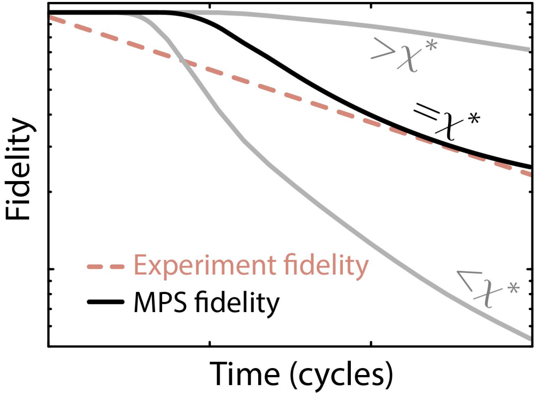
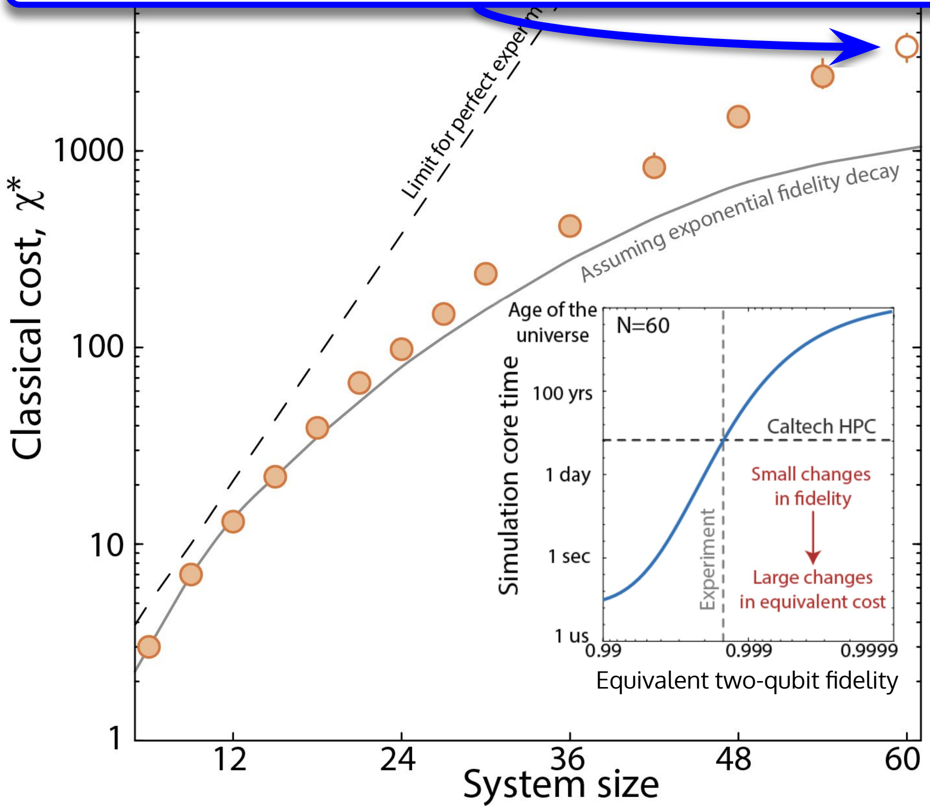
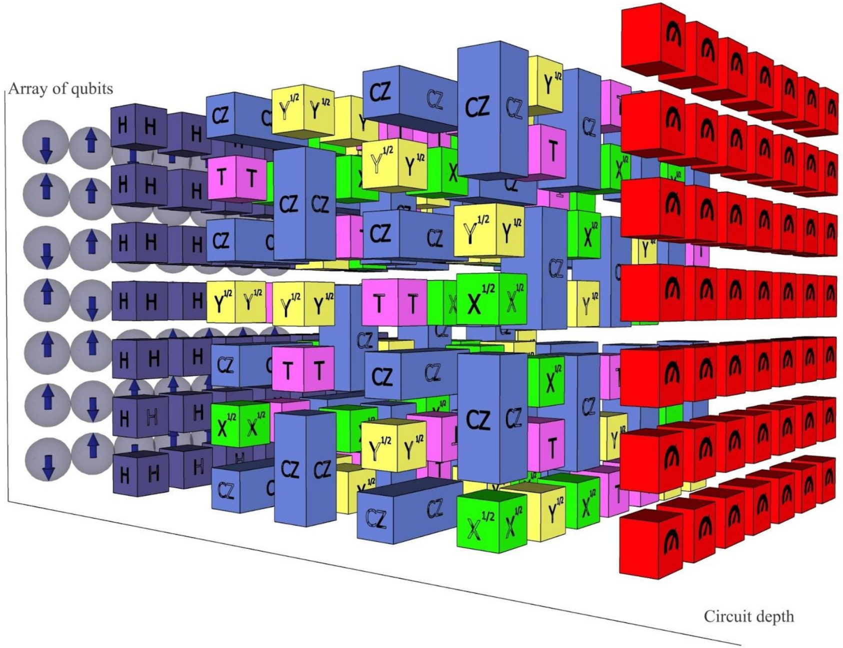




Quantum is hard

Sycamore supremacy circuit

Complex 2D random unitary circuit



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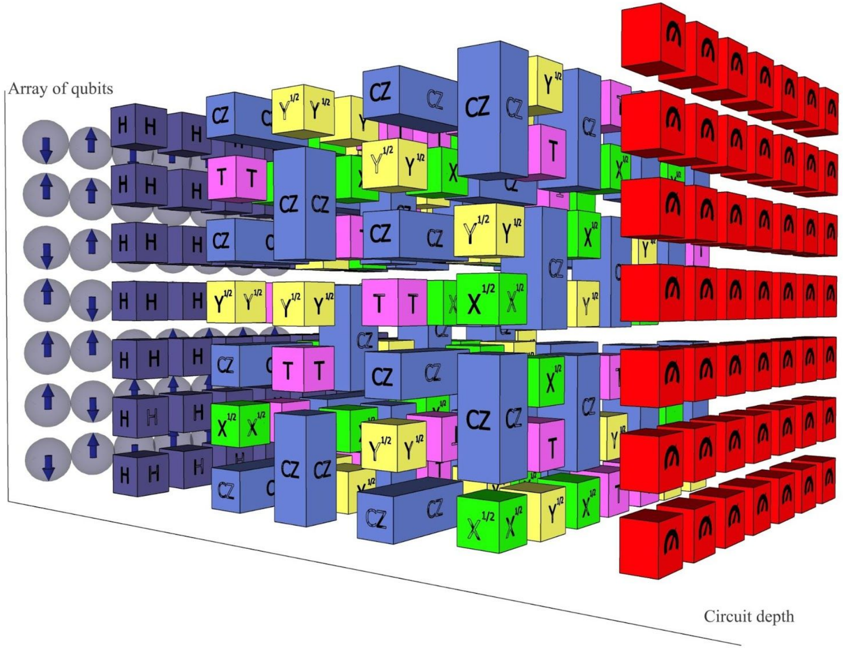
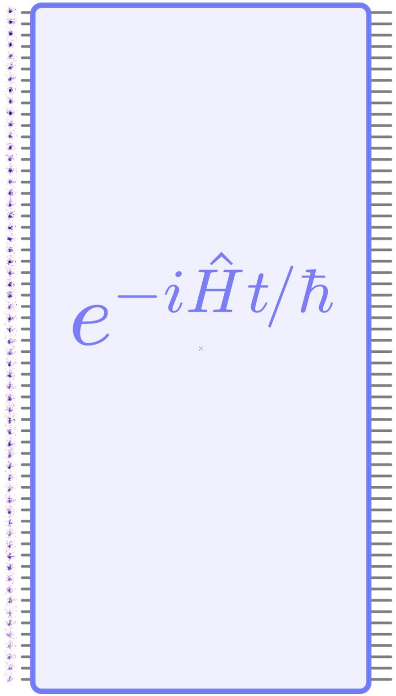


Our “circuit”

Time-independent, global, 1D evolution



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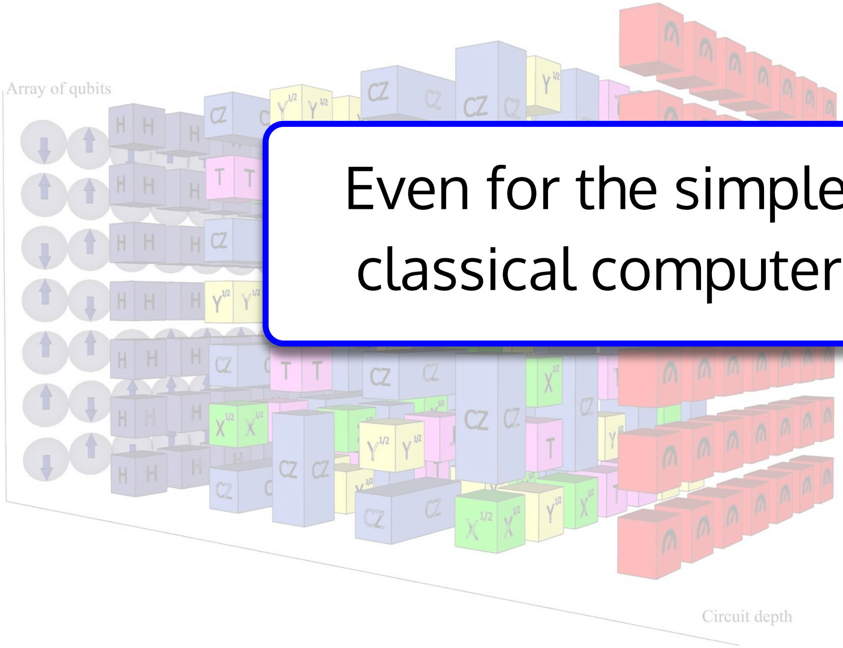

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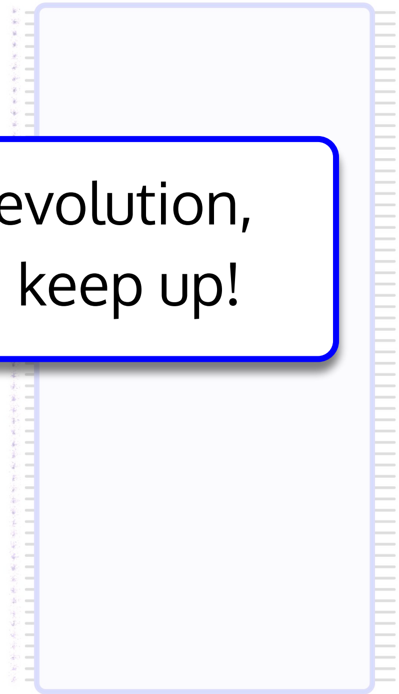
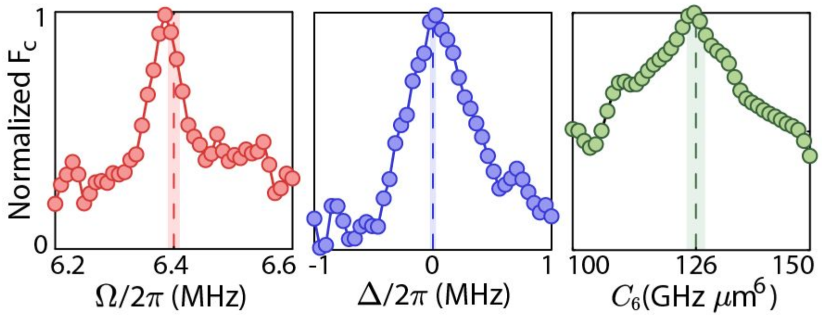


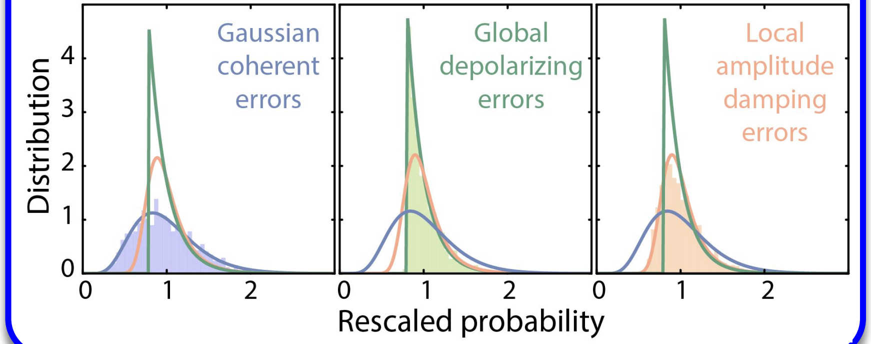
Even for the simplest quantum evolution, classical computers struggle to keep up!

Applications!

Hamiltonian estimation



Noise learning



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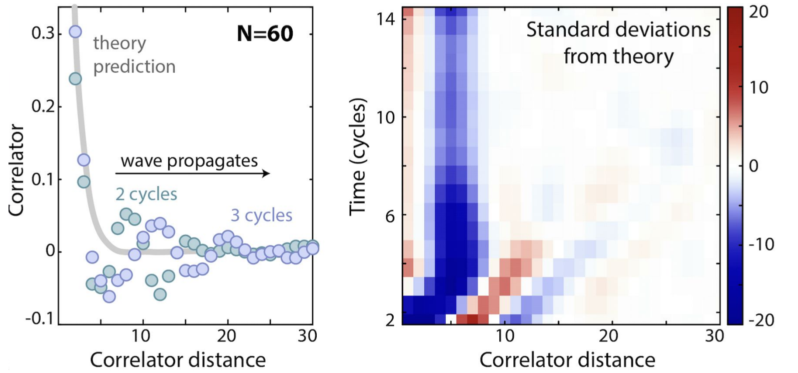
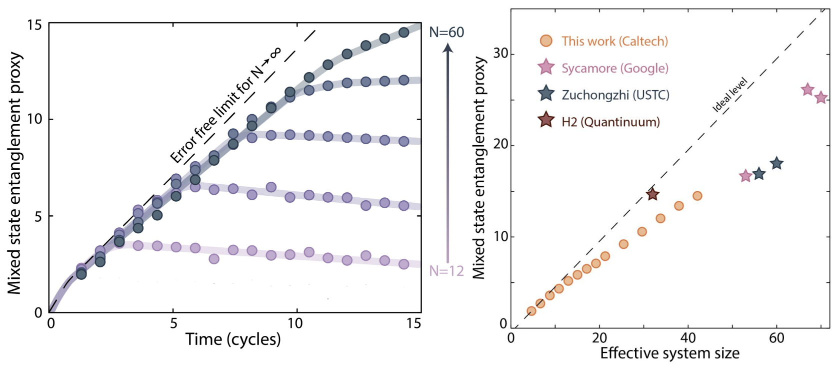


Entanglement estimation



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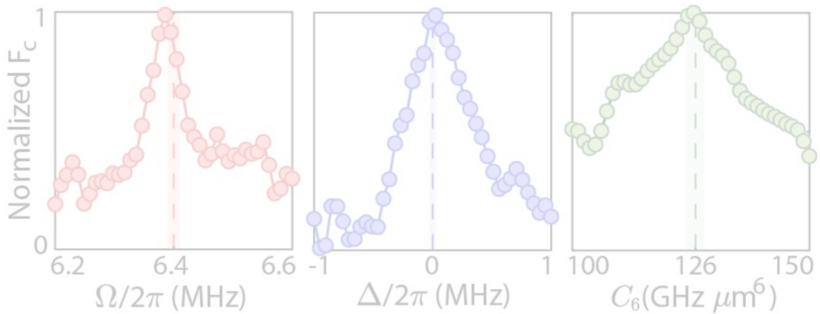

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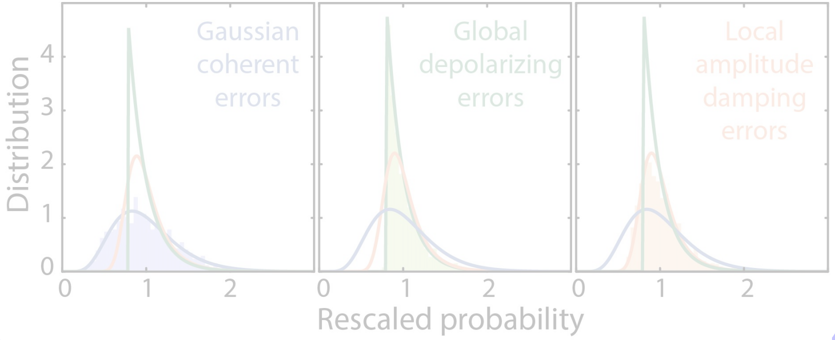

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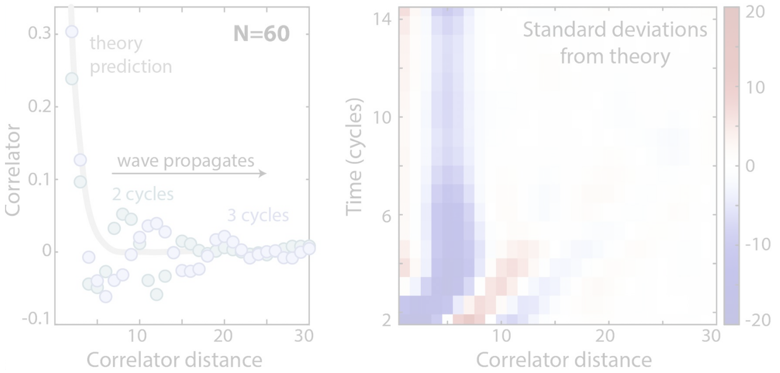

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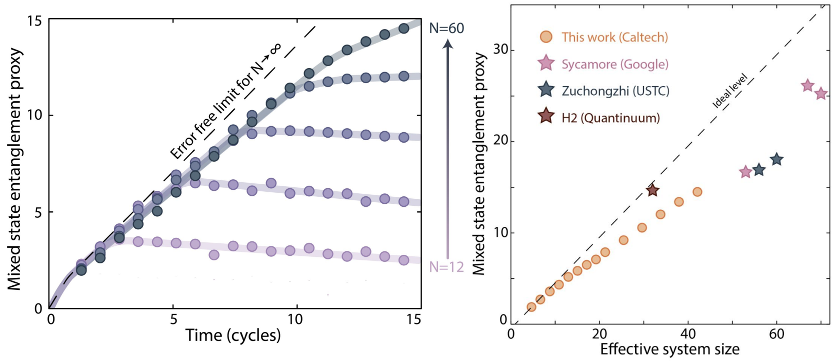
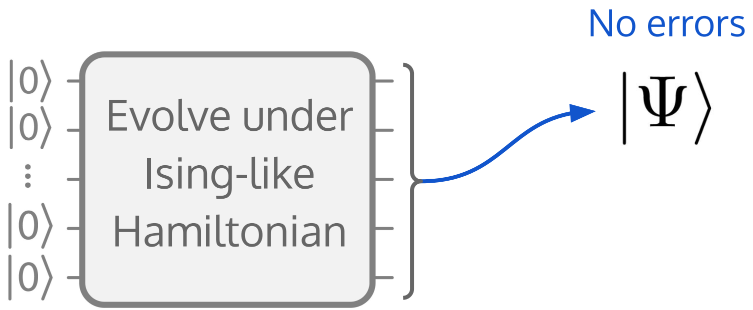


How entangled are we?

Whenever we've talked about entanglement, we've meant **pure state entanglement**



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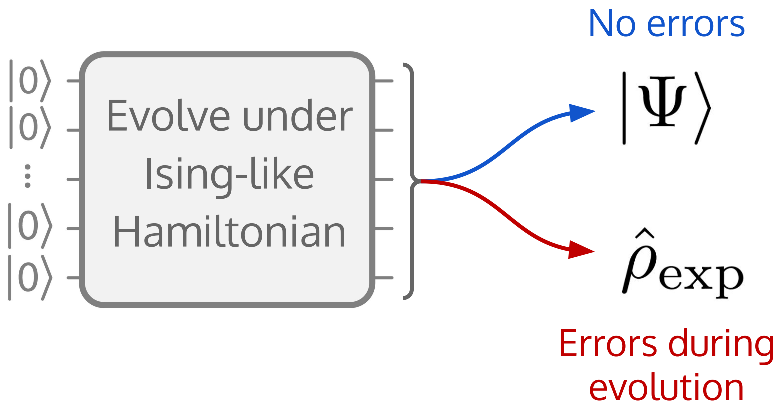

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Notoriously hard to measure, even theoretically!

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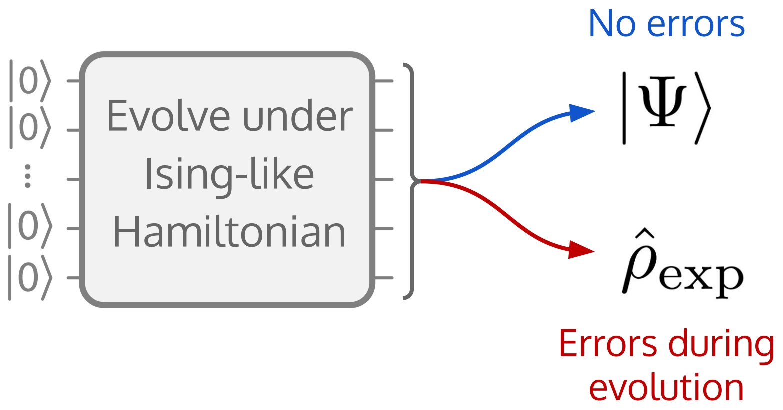

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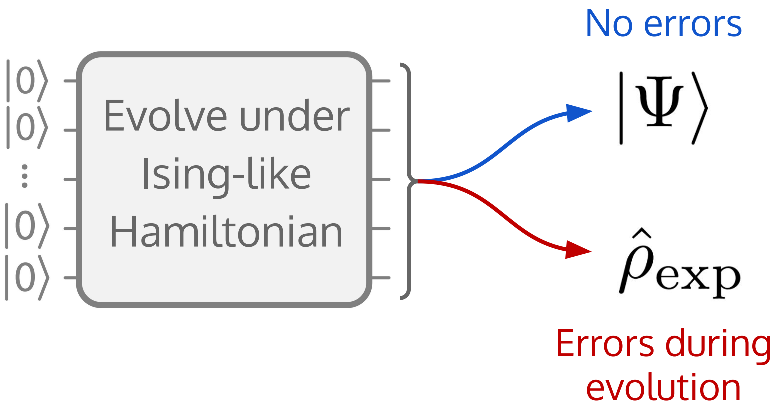

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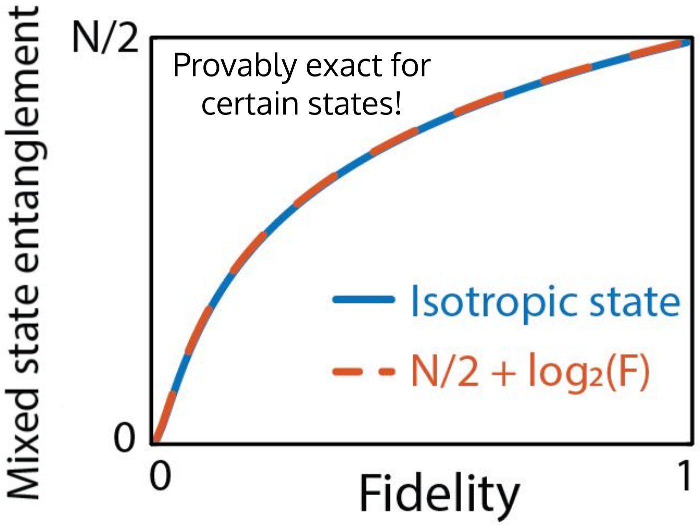

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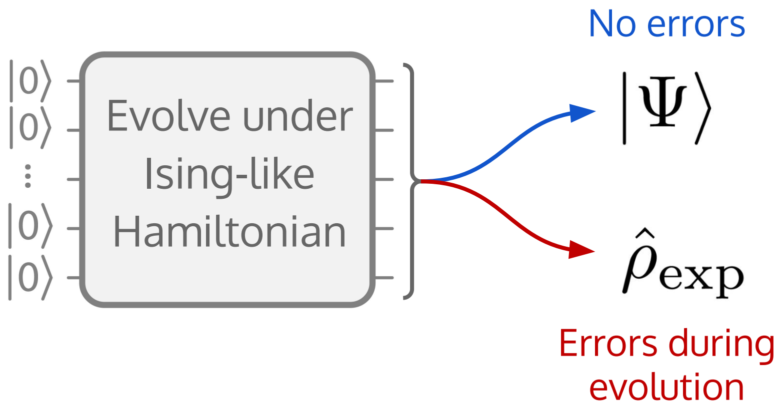

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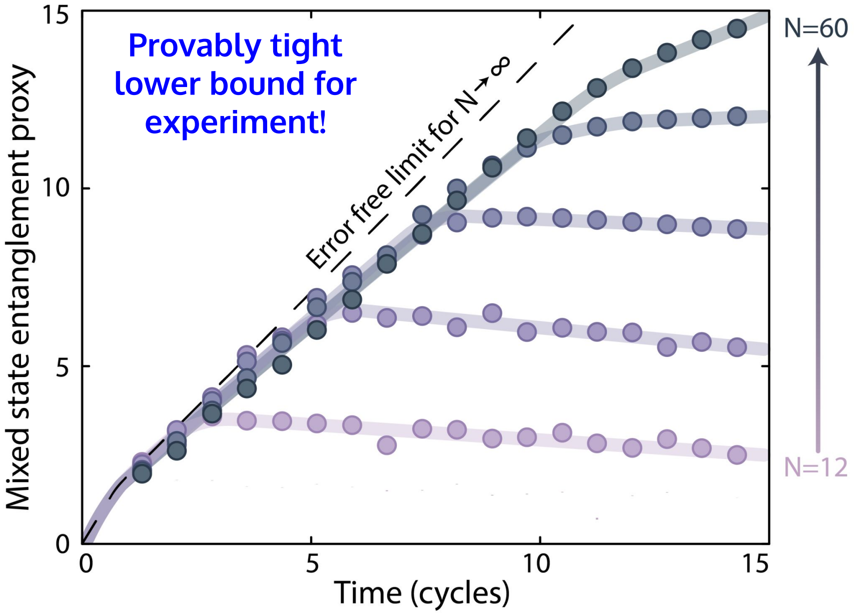

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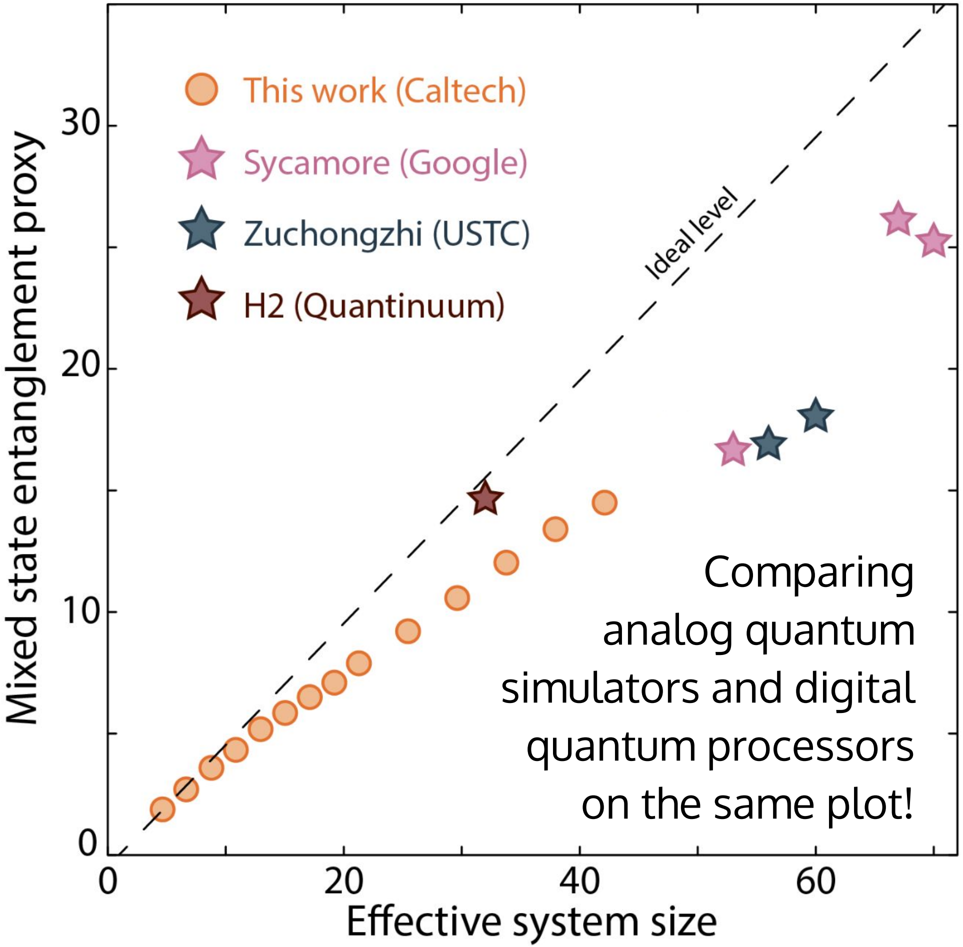

General purpose, cross-platform, evaluation metric including both qubit quantity and quality!

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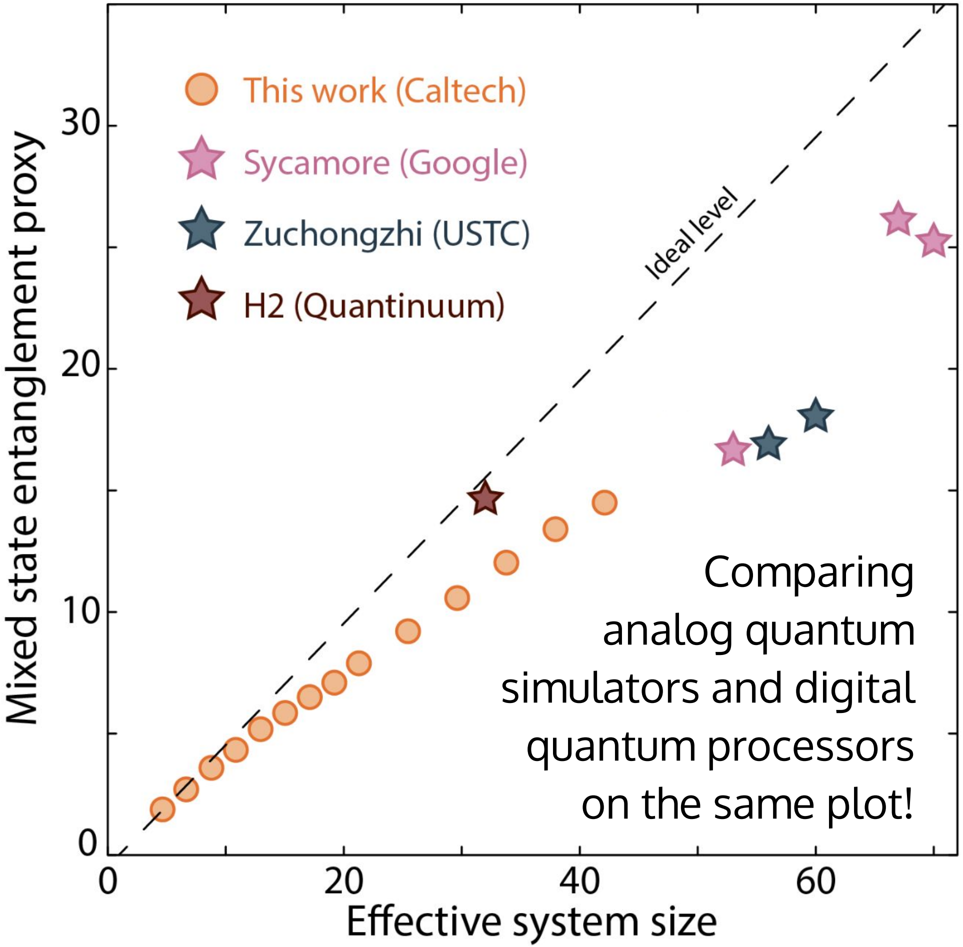


General purpose, cross-platform, evaluation metric including both qubit quantity and quality!

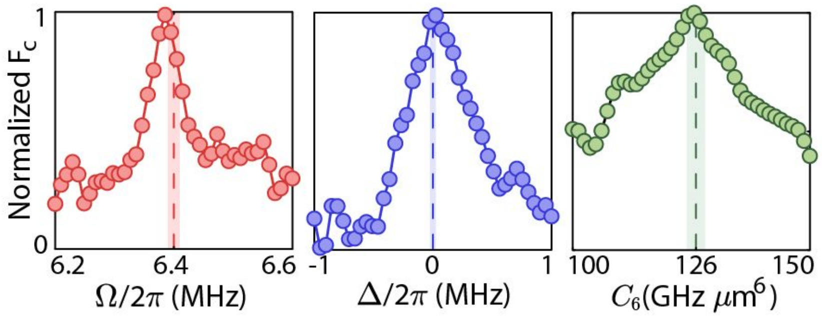
Closely related to questions of:

How many Bell pairs could we possibly extract?

What is the classical simulation complexity?

Applications!

Hamiltonian estimation



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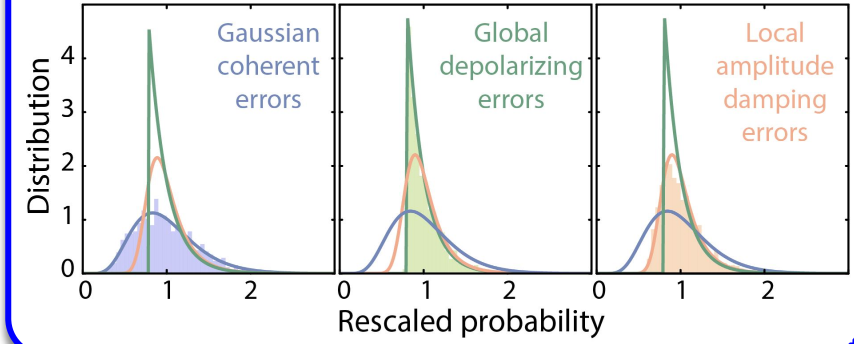

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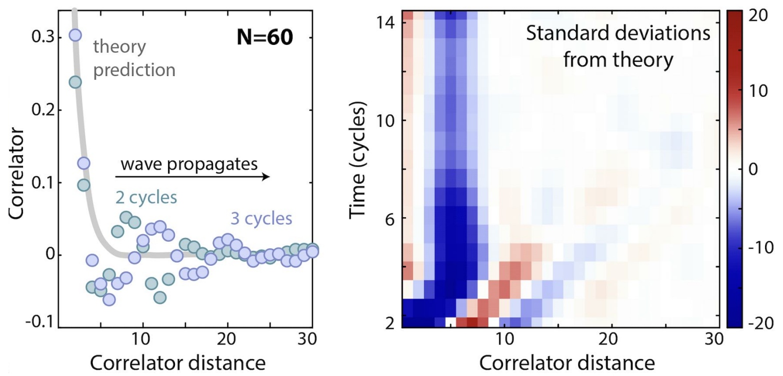

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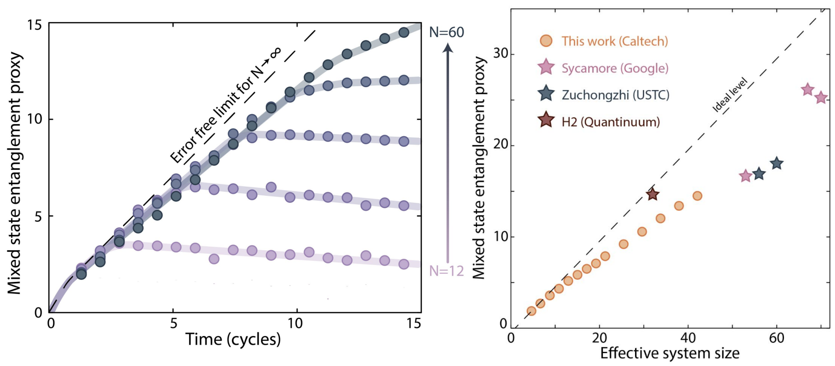

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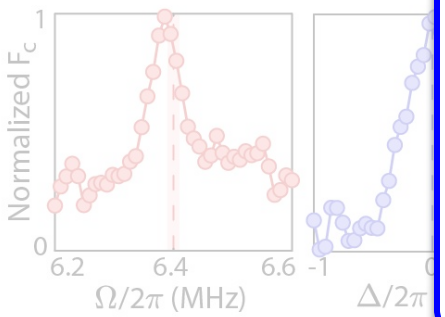
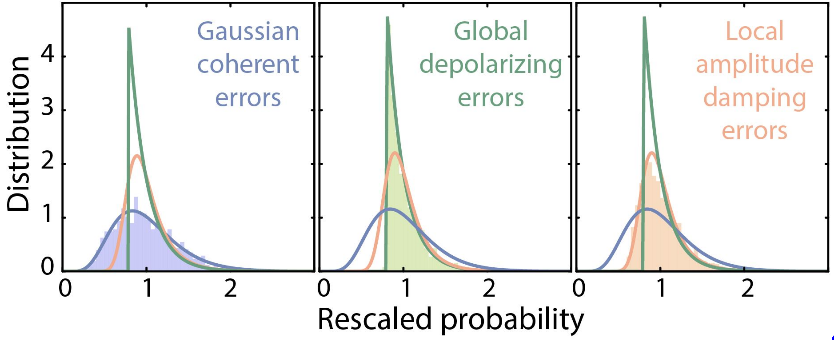


Noise learning

theory by Daniel Mark



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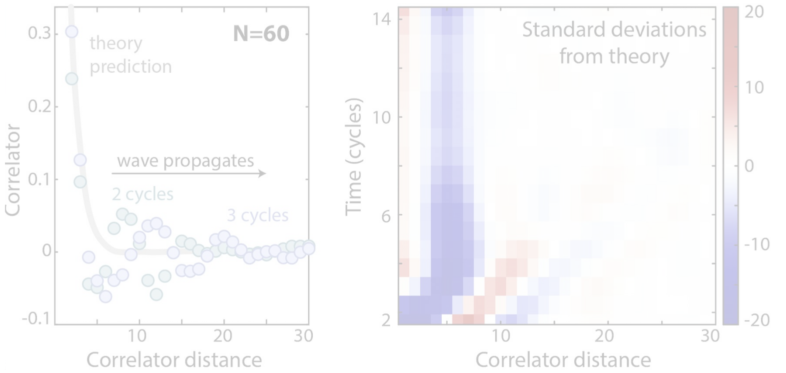

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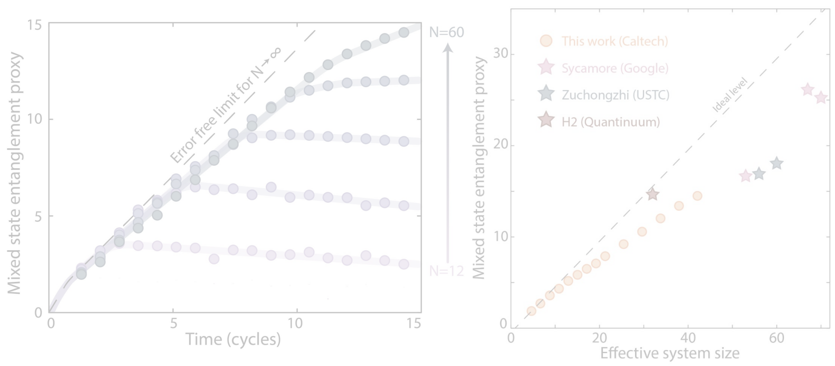
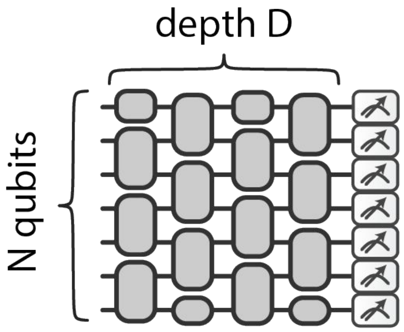


Learning noise from bitstring measurements

Consider random unitary circuit (RUC) evolution



Shaw*, Mark*, *et al*, arXiv:2403.11971

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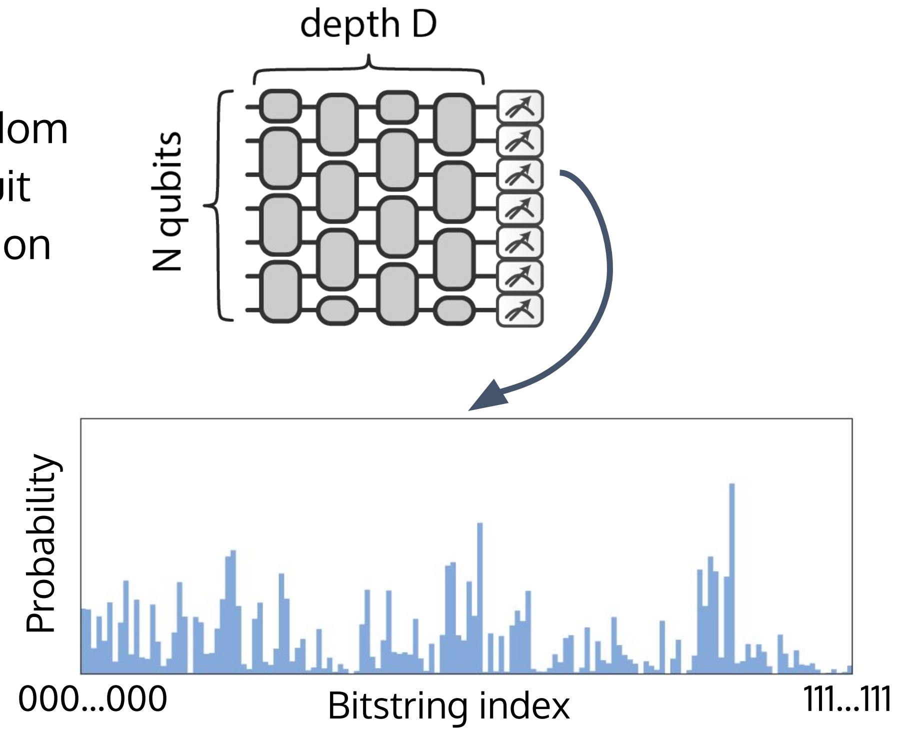

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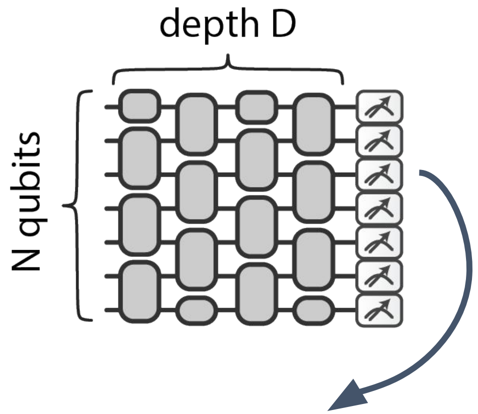
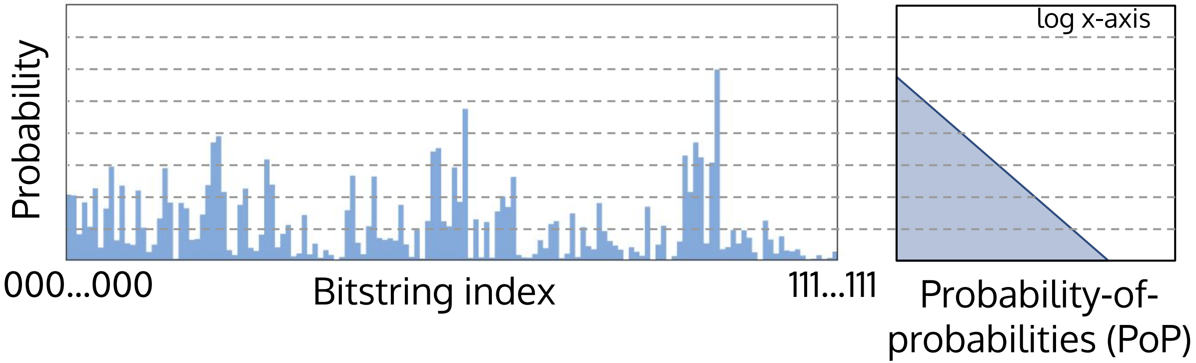


We will be studying the **probability-of-probabilities (PoP)** distribution… For RUCs, this is well known to be an **exponential distribution***



The PoP counts how many probabilities fall into each bin (gray lines)

*a Porter-Thomas distribution

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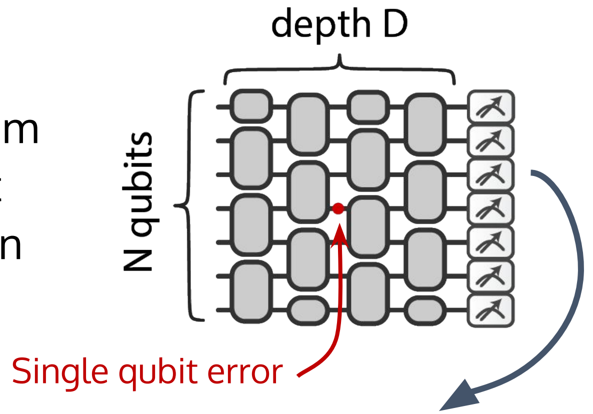
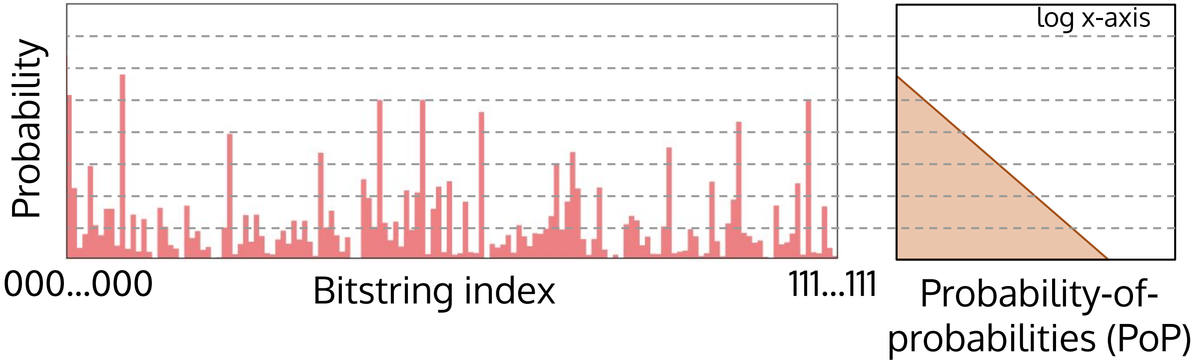


If **one** error occurs, the PoP distribution will still be an **independent**** exponential distribution*!



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**Assuming dynamics is sufficiently scrambling

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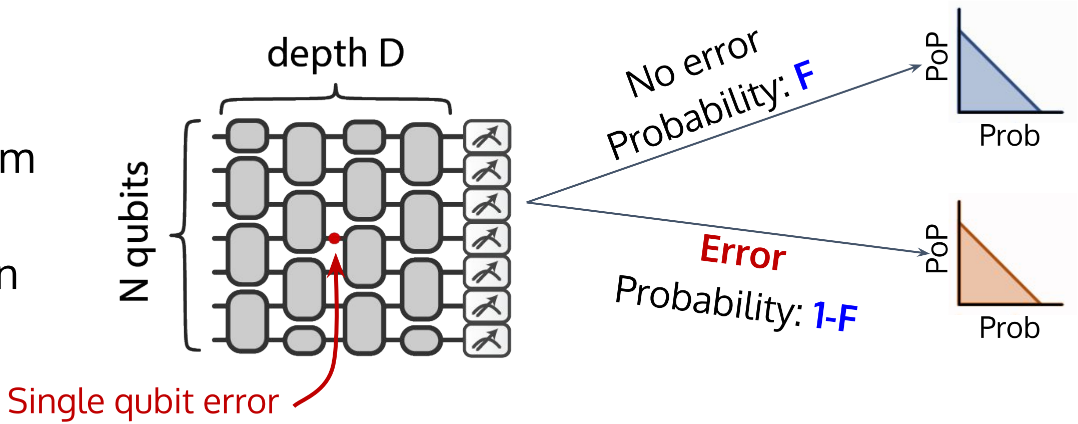

The probability of observing the different distributions is given by **the fidelity, F**

If **one** error occurs, the probability-of-probabilities (PoP) distribution will be an **independent**** exponential distribution*

Shaw*, Mark*, *et al*, arXiv:2403.11971

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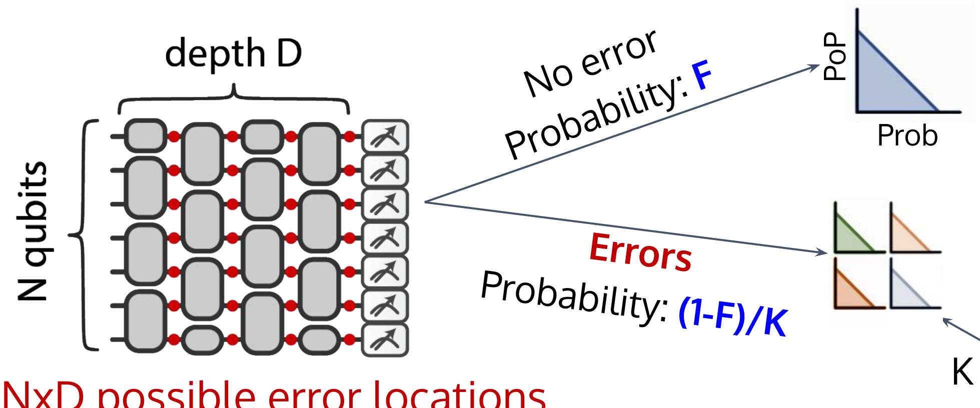

The probability of observing the different distributions is given by **the fidelity, F**

K = NxD possible error locations (spacetime volume of circuit)

If **many independent** errors occur, the probability-of-probabilities (PoP) distributions will be **many independent**** exponential distributions*

Shaw*, Mark*, *et al*, arXiv:2403.11971

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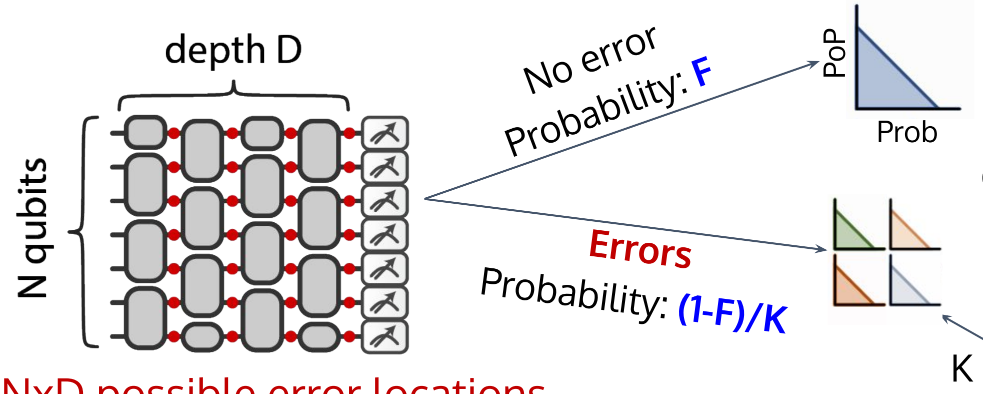

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probability-of-prob
distributions will be ma
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We can't keep track of all microscopic errors, so the aggregate PoP is an incoherent sum over all of them!

Shaw*, Mark*, *et al*, arXiv:2403.11971

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**Assuming dynamics is sufficiently scrambling

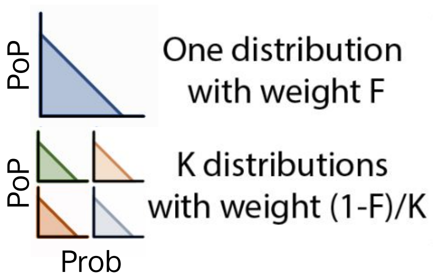
Learning noise from bitstring measurements

Conside... unitar... (RUC) e...

depth D ... error ... PoP

The probability of ... the ...butions is ...delity, F

Incoherent sum over



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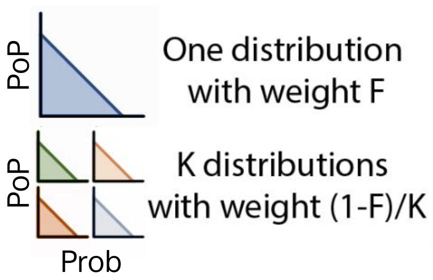
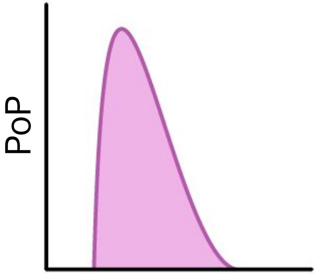


Hypoexponential distribution



$$P_{\mathrm{Hypo}}(x) = \underset{i}{\circledast} P_{\mathrm{Exp}}(x/\omega_i) = \sum_i \omega_i^{-1} \exp(-x/\omega_i) \prod_{j \neq i} \frac{\omega_i}{\omega_i - \omega_j}$$

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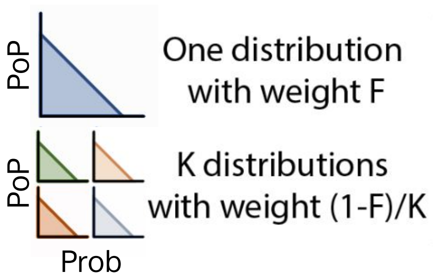

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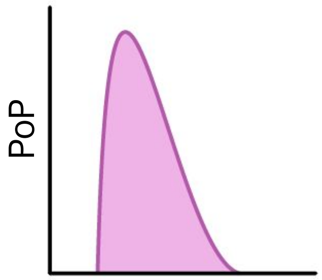
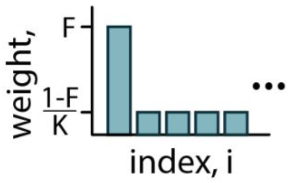


Parameterization is **defined by the noise channel**



$$P_{\text{Hypo}}(x) = \circledast_i P_{\text{Exp}}(x/\omega_i) = \sum_i \omega_i^{-1} \exp(-x/\omega_i) \prod_{j \neq i} \frac{\omega_i}{\omega_i - \omega_j}$$

distributions will be **many independent**** exponential distributions*

Shaw*, Mark*, *et al*, arXiv:2403.11971

*Assuming dynamics is sufficiently scrambling

Learning noise from bitstring measurements

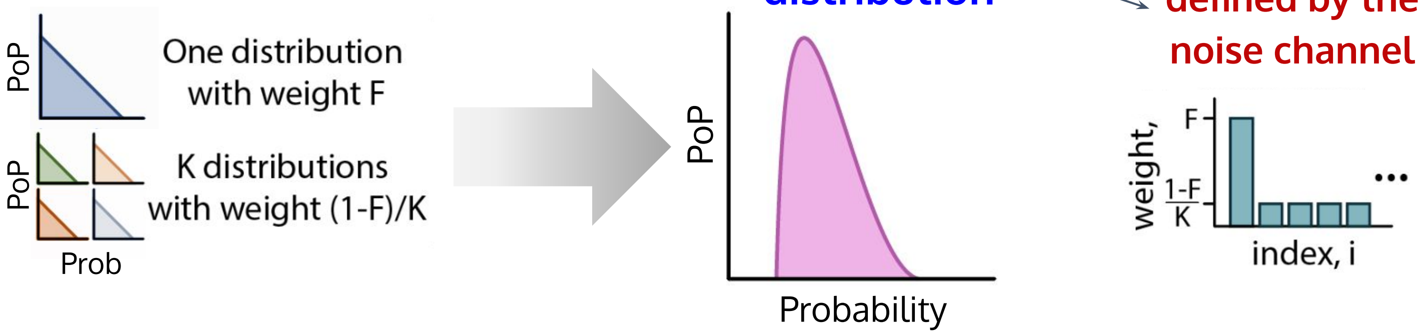
Conside… unitar… (RUC) e…

The probability of … the … butions is … delity, F

Incoherent sum over

Hypoexponential distribution

Parameterization is **defined by the noise channel**



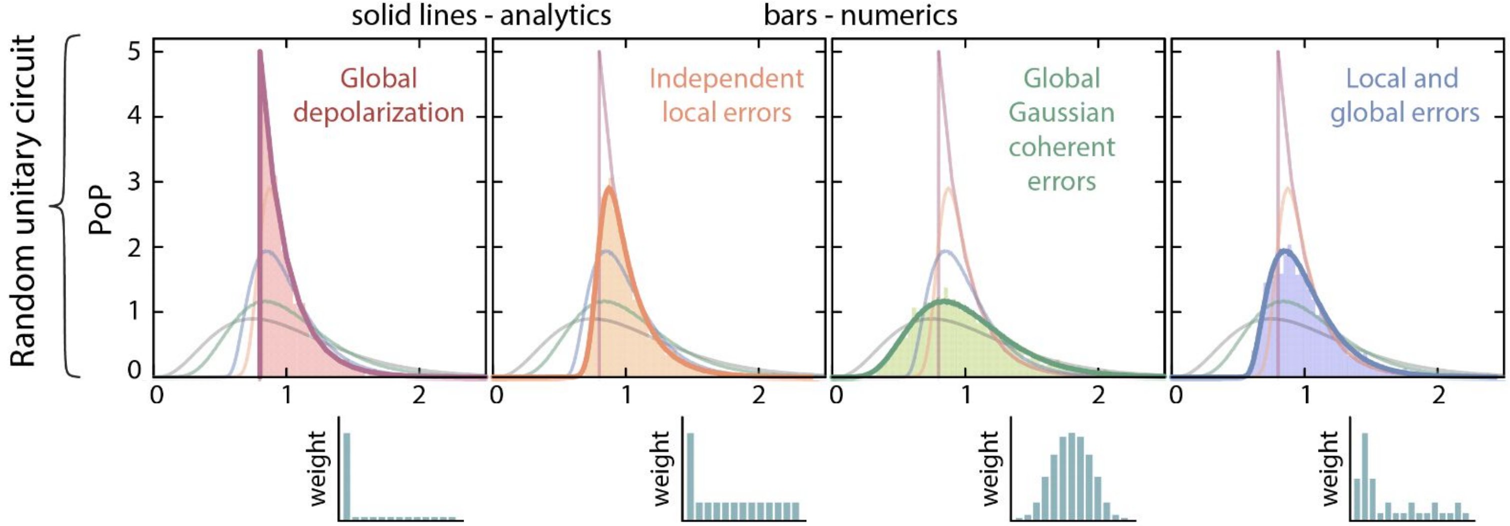
Technical details aside, the take-home message is:

Given a noise channel (and a measured fidelity) we can always write the corresponding hypoexponential weights and **analytically predict the PoP distribution**

Shaw*, Mark*, *et al*, arXiv:2403.11971

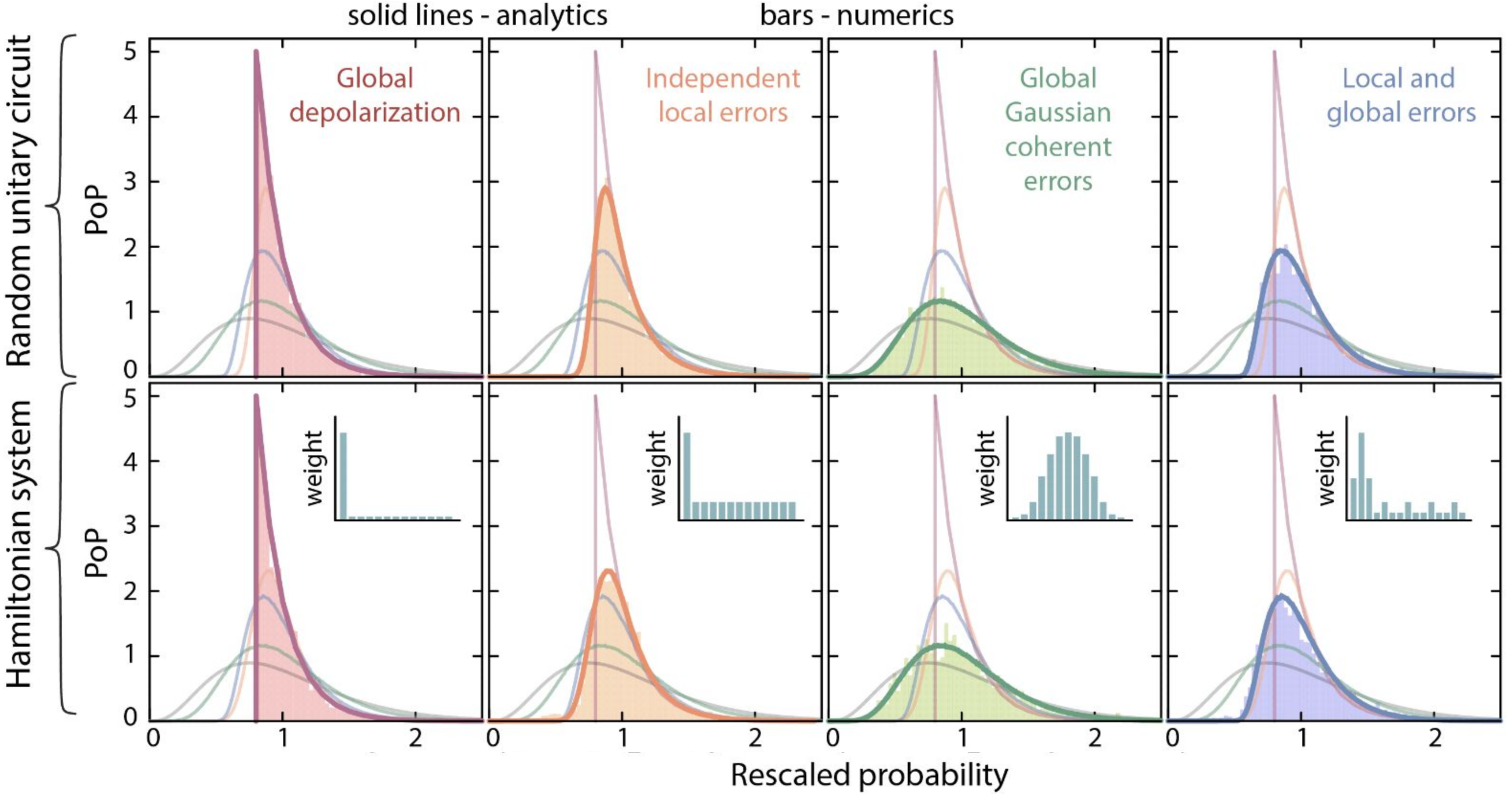
*Assuming dynamics is sufficiently scrambling

Learning noise from bitstring measurements



What to notice: results from **numerical simulations (bars)** agree very well with corresponding analytical predictions **(same color lines)**, while being clearly distinct from analytical predictions for other noise channels (faint lines)

Learning noise from bitstring measurements



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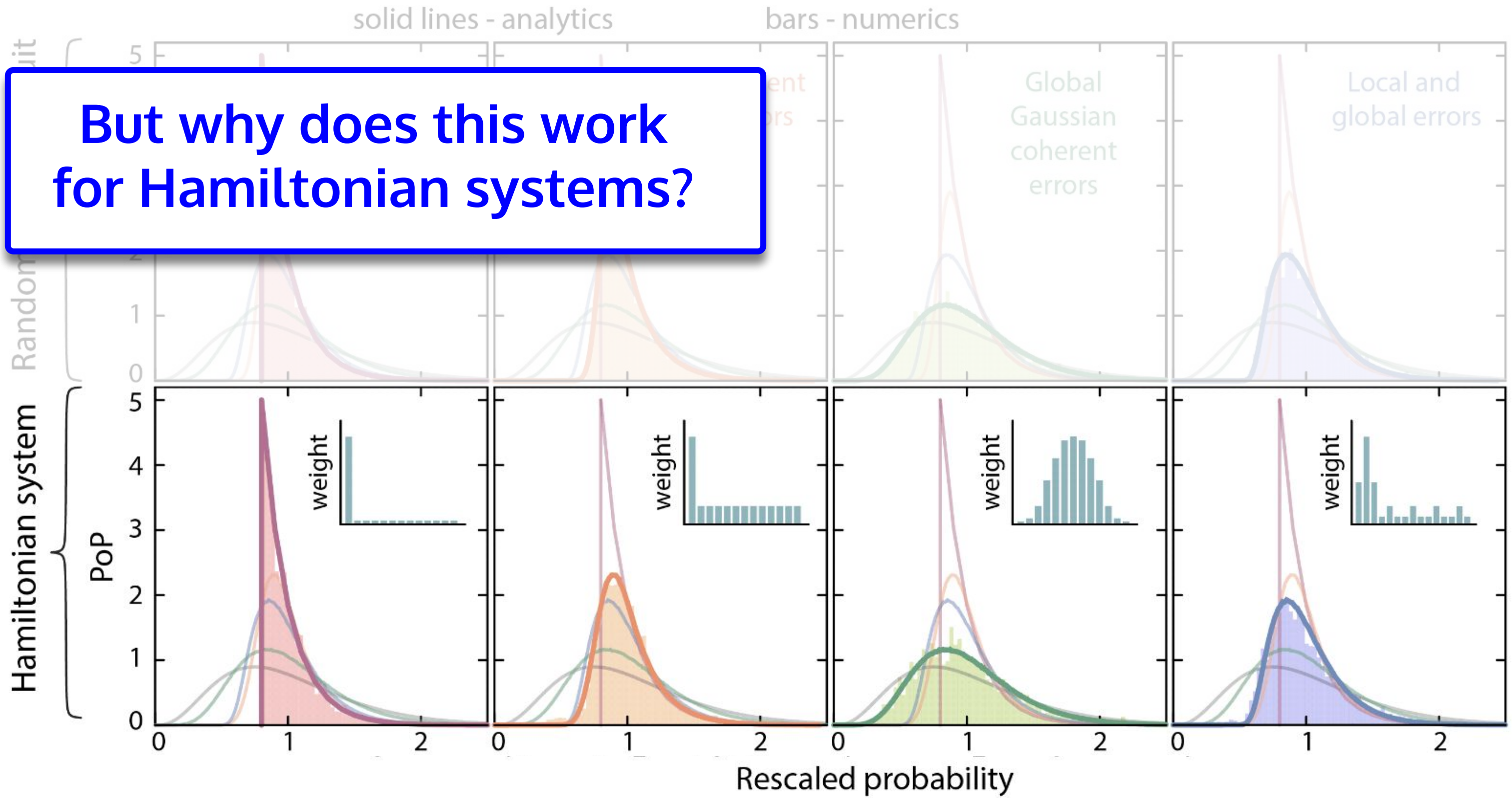
Learning noise from bitstring measurements

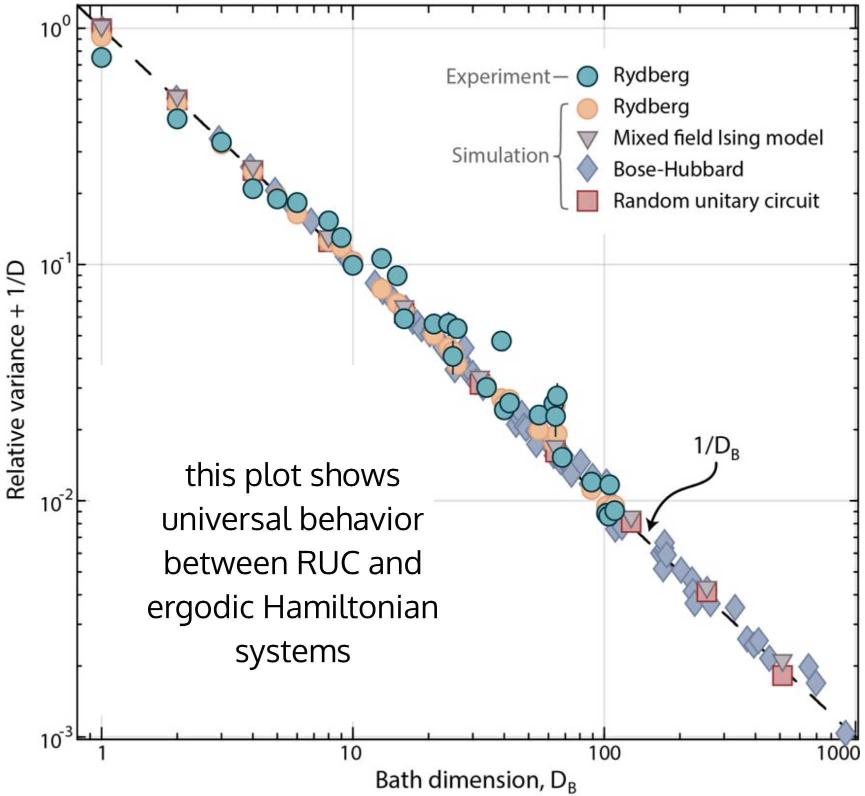


What to notice: results from **numerical simulations (bars)** agree very well with corresponding analytical predictions **(same color lines)**, while being clearly distinct from analytical predictions for other noise channels (faint lines)

Learning noise from bitstring measurements

solid lines - analytics bars - numerics

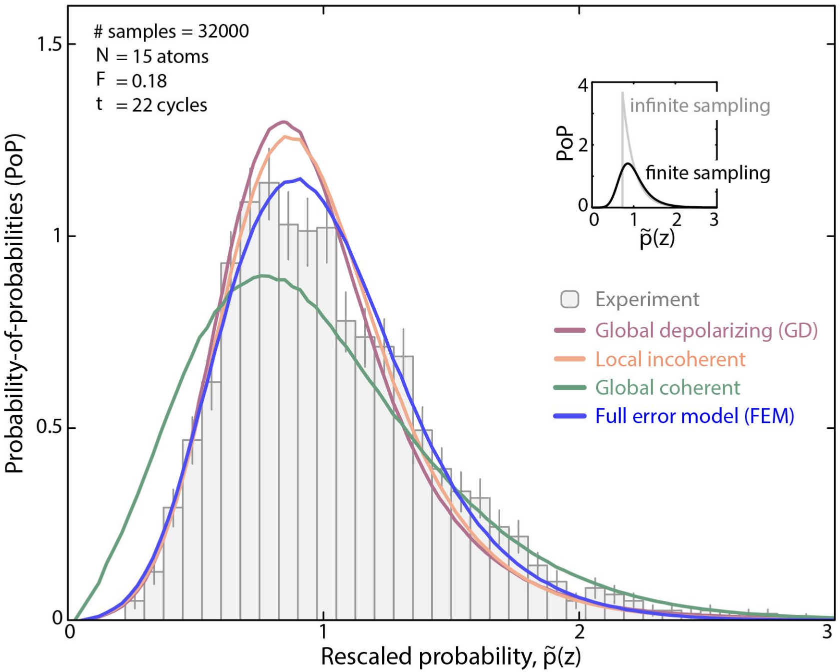
See Soonwon's talk just before mine about new theoretical discoveries (and experimental confirmations) that **ergodic Hamiltonian systems universally behave like random unitary circuits**...



Shaw*, Mark*, *et al*, arXiv:2403.11971
Mark, Elben, Surace, **Shaw** et al, arXiv:2403.11970

Learning noise from bitstring measurements

Can apply to experiment* using measured fidelity!



Shaw*, Mark*, *et al*, arXiv:2403.11971

*Because of finite-sampling costs, should actually compare low-order moments of the PoP, which are sample-efficient and still predictive

Learning noise from bitstring measurements

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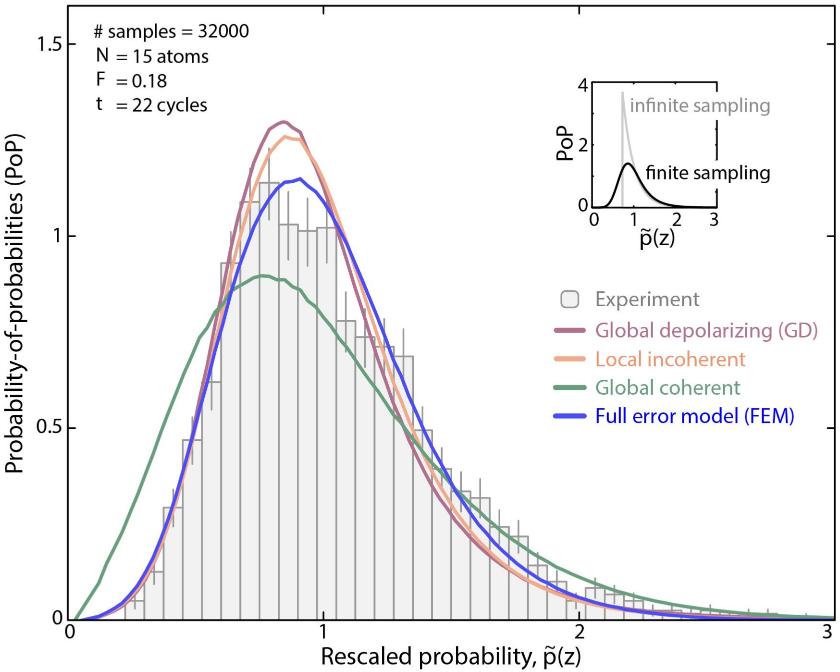
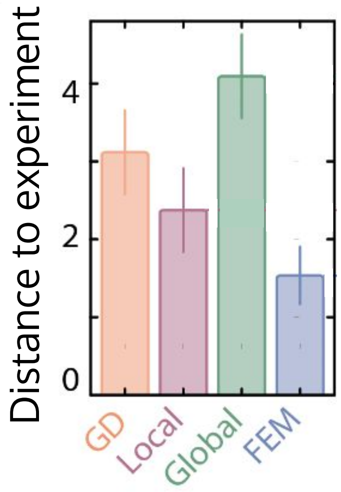


Can define a distance from experimental to predicted PoP



Shaw*, Mark*, *et al*, arXiv:2403.11971

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Learning noise from bitstring measurements

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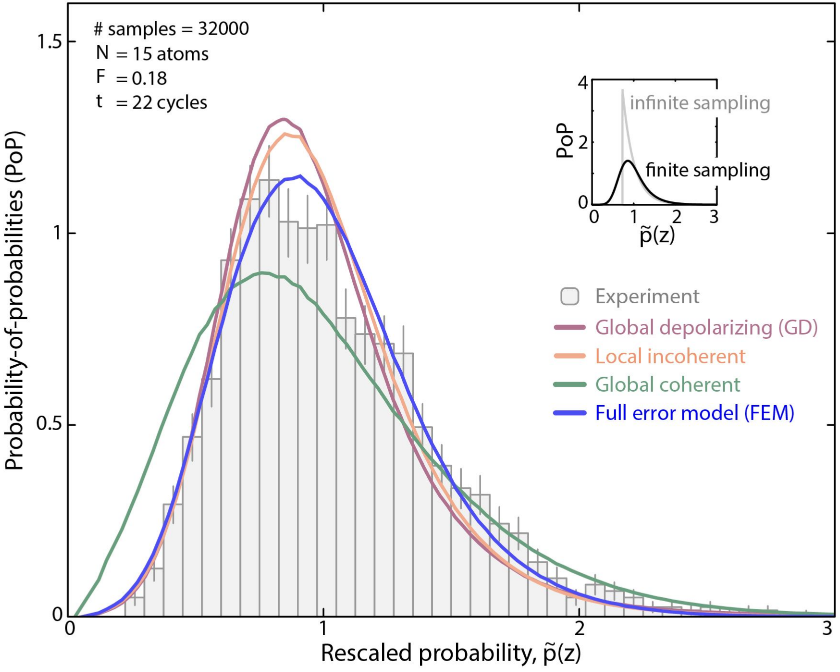
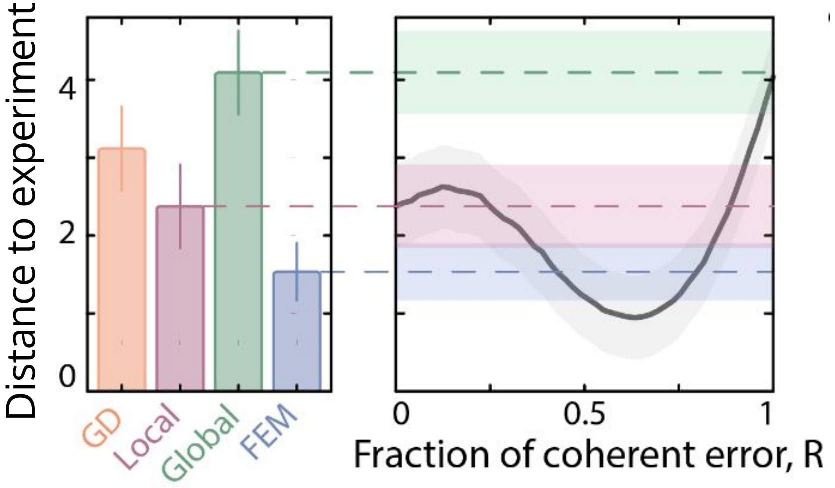


Can define a distance from experimental to predicted PoP → And learn experimentally consistent error models!



Shaw*, Mark*, *et al*, arXiv:2403.11971

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Learning noise from bitstring measurements

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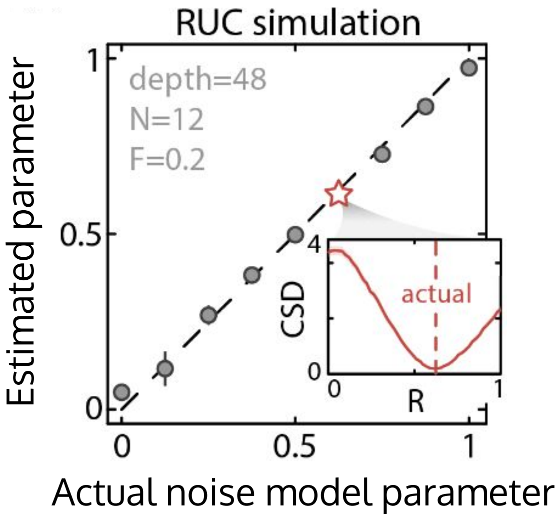
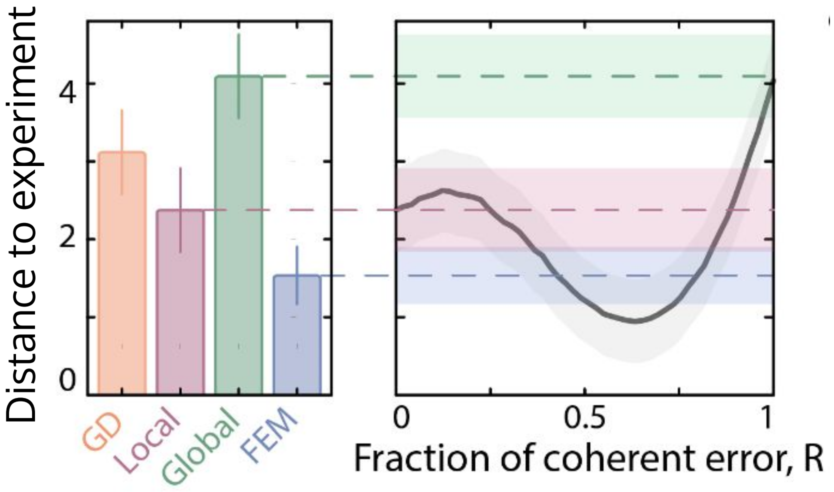


RUC simulation shows learning noise models in this way is accurate!

Can define a distance from experimental to predicted PoP → And learn experimentally consistent error models!



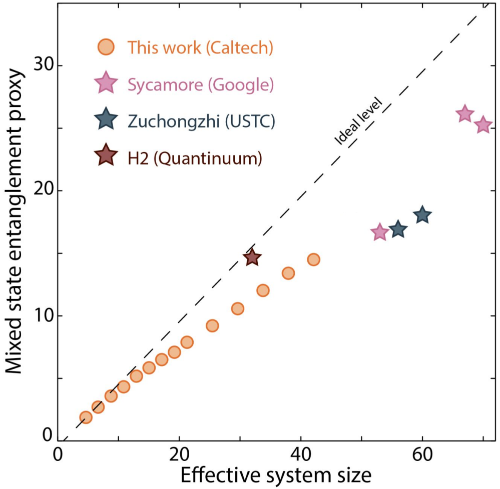
Shaw*, Mark*, *et al*, arXiv:2403.11971

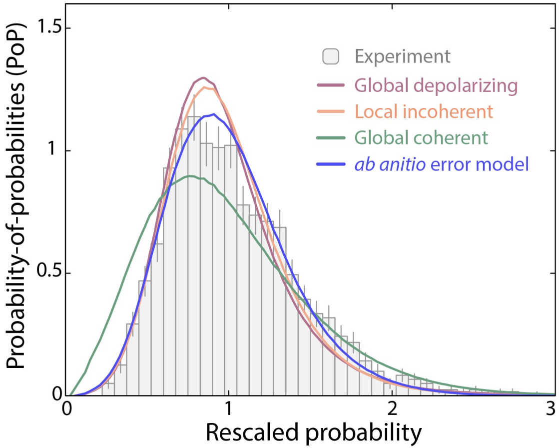
*Because of finite-sampling costs, should actually compare low-order moments of the PoP, which are sample-efficient and still predictive

Summary

Quantitative benchmarking enables both **improving quantum science**, and realizing **new science applications**

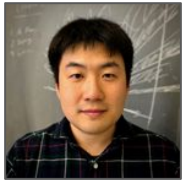
Shaw*, Chen*, Choi*, Mark*, *et al*, Nature 628 (2024), arXiv:2308.07914
Shaw*, Mark*, *et al*, arXiv:2403.11971





Thank you!


Manuel Endres


Soonwon Choi


Daniel Mark


Joonhee Choi


Zhuo Chen


Pascal Scholl

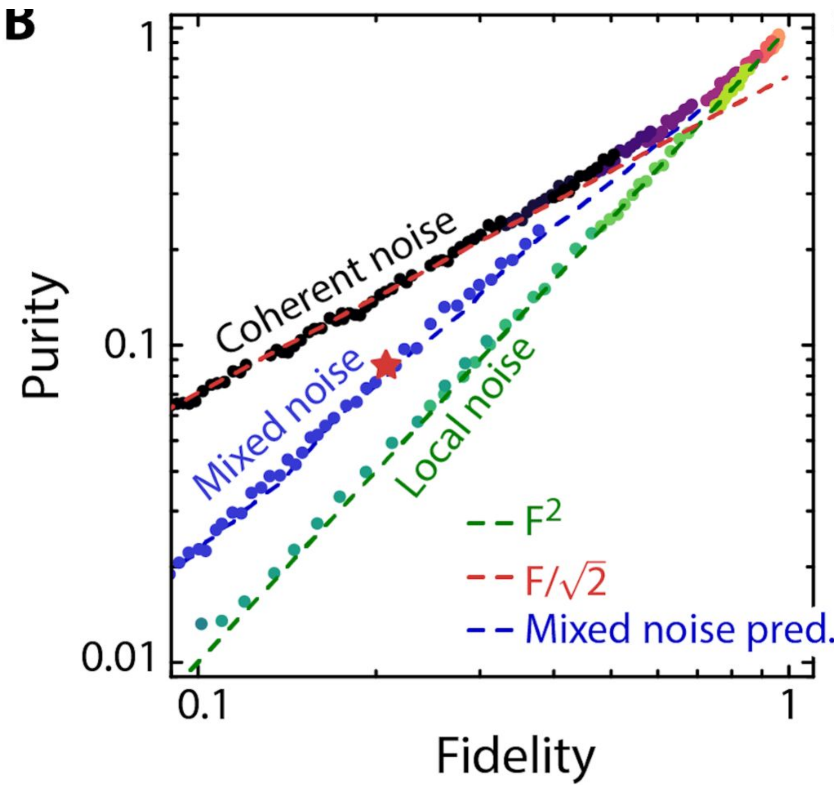

Ran Finkelstein


Andreas Elben

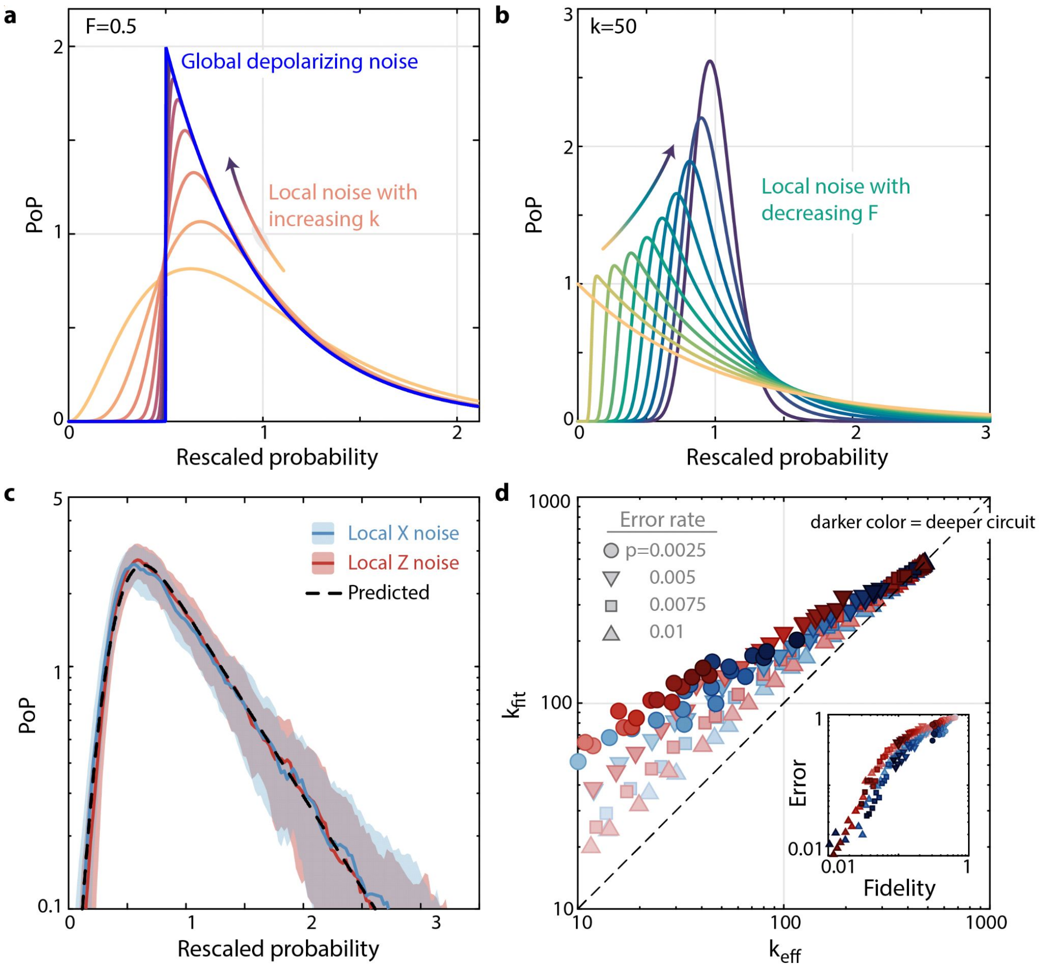
Moments analysis

Can more efficiently learn noises just from their effects on the **moments** of the PoP

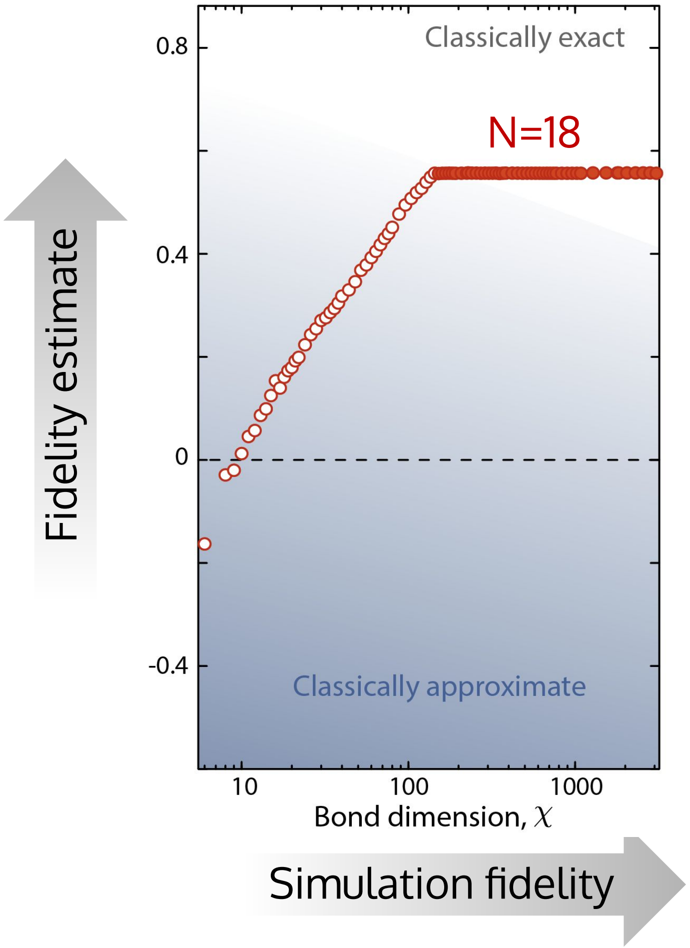
Noise channel	κ_2	κ_3
Global depolarization	F^2	$2F^3$
Local incoherent	$F^2 + (1-F)^2/k$	$2\left(F^3 + (1-F)^3/k^2\right)$
Global Gaussian coherent	$F/\sqrt{2}$	$2F^2/\sqrt{3}$



Local noise -> Global depolarizing

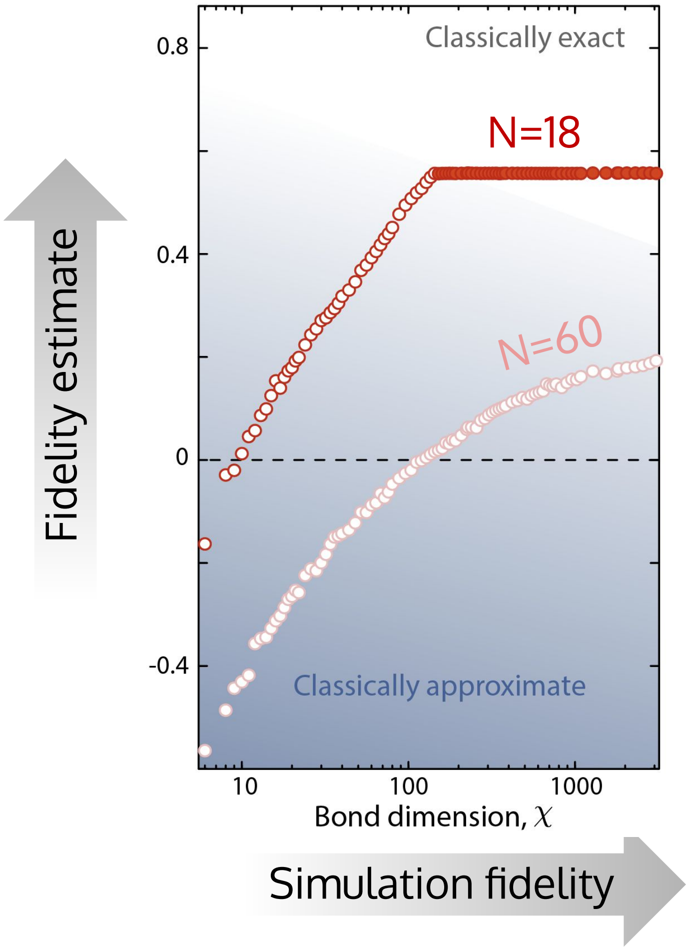


Identifying scaling behavior



As the bond dimension is increased, fidelity estimate **rises before saturating…**

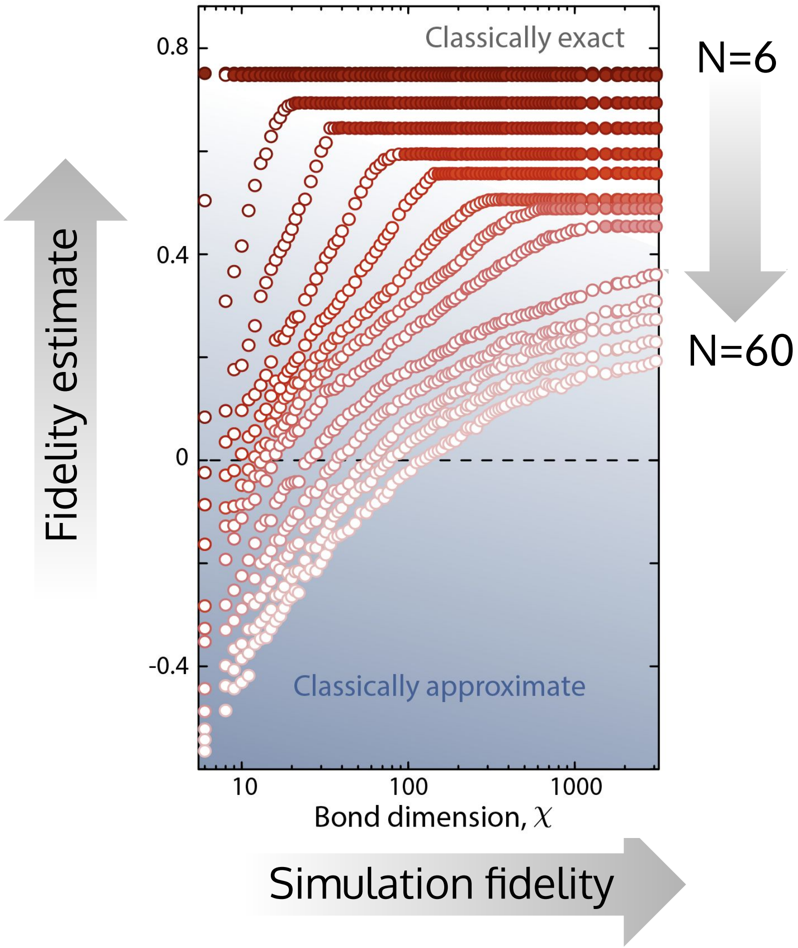
Identifying scaling behavior



As the bond dimension is increased, fidelity estimate **rises before saturating…**

For large systems, we can’t reach the “**saturation bond dimension**”

Identifying scaling behavior



As the bond dimension is increased, fidelity estimate **rises before saturating…**

For large systems, we can't reach the "**saturation bond dimension**"

But we can extrapolate as a function of the bond dimension!