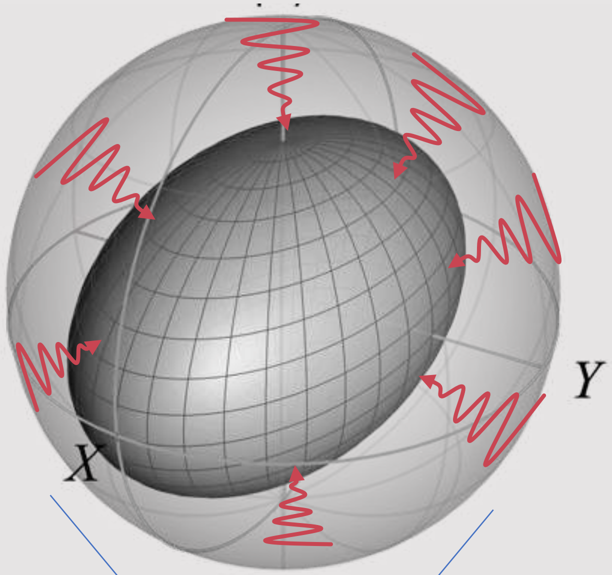
Boulder School for Condensed Matter and Materials Physics: Non-Equilibrium Quantum Dynamics

Quantum Error Mitigation for Non-Equilibrium Quantum Dynamics on Quantum Computers

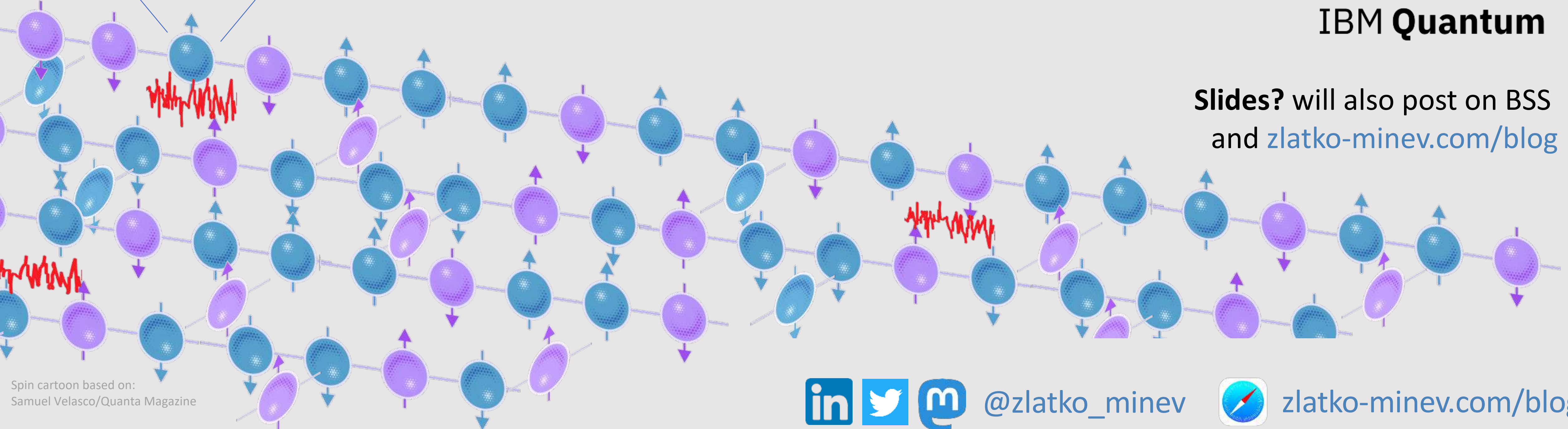
Lecture 3



Zlatko K. Minev

IBM **Quantum**

Slides? will also post on BSS and zlatko-minev.com/blog



Spin cartoon based on: Samuel Velasco/Quanta Magazine

@zlatko_minev zlatko-minev.com/blog

Quantum Error Mitigation for Non-Equilibrium Quantum Dynamics

Lecture 2

Probabilistic error cancelation (PEC)

Summarize one qubit example

Analogy to random walks

Error bars & confidence

Generalize (optional)

Show unbiased estimator

Learning quantum noise

Challenge

Overcoming: sparse model

Lecture 3

Putting it together

Simulate Ising time evolution

Experiments with PEC

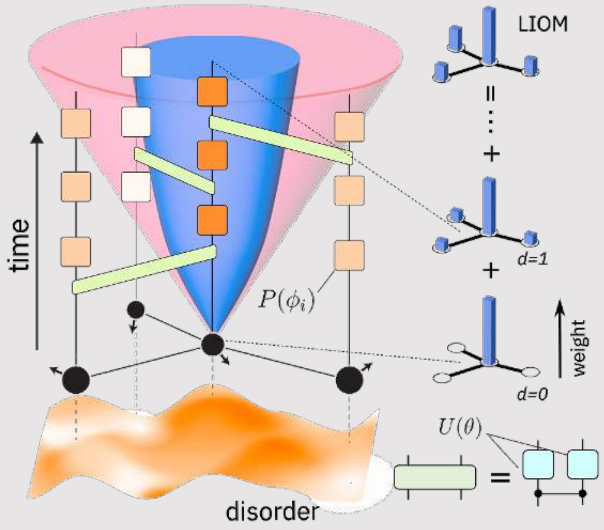
Big picture consequences

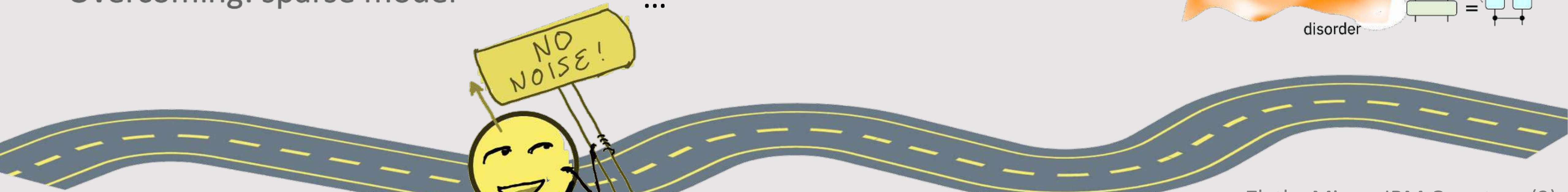
Many body experiment example

State-of-art experiments at the 120Q+, depth 50+: uncovering local integrals of motion

…

Outlook and hardware progress





road based on: freepik; Monster image by jcomp on Freepik

Simulating transverse-field Ising model time evolution with PEC

Spins

$$H = -J \sum_j Z_j Z_{j+1} + h \sum_j X_j$$

J: exchange coupling between neighbouring spins
h: transverse magnetic field

Average magnetization density?

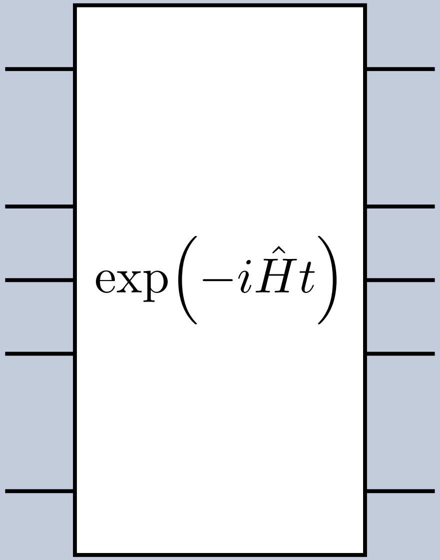
$$\vec{M} := \sum_n \left(\langle X \rangle_n , \langle Y \rangle_n , \langle Z \rangle_n \right) / N$$

Top image: Samuel Velasco/Quanta Magazine

Step 1: Map to quantum circuit

$$H = -J \sum_j Z_j Z_{j+1} + h \sum_j X_j$$

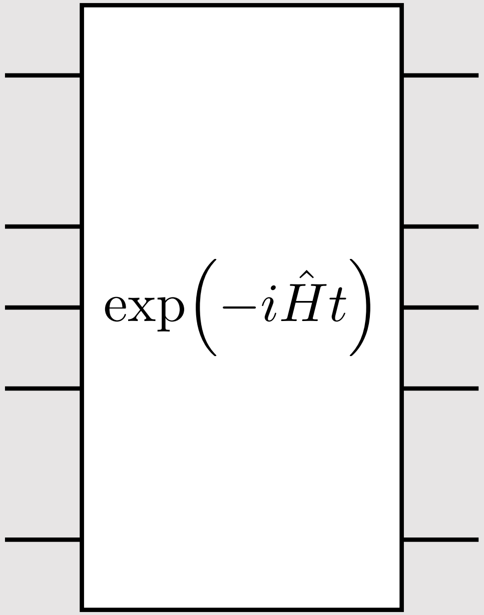
Time evolution



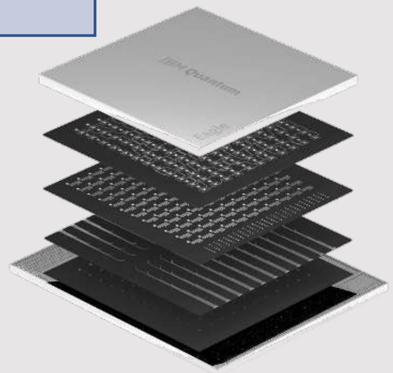
See lecture by Frank Pollmann

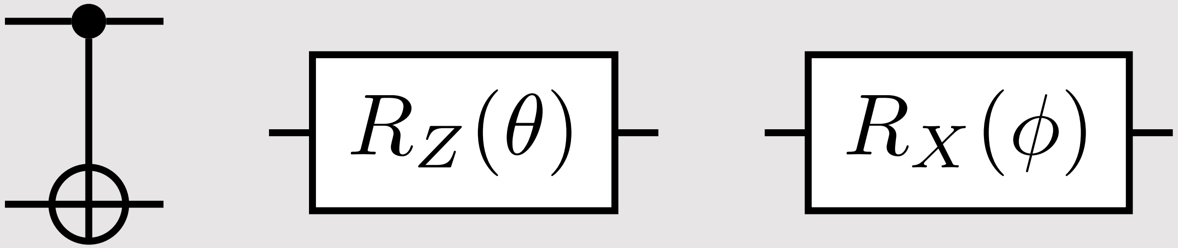
Step 1: Map to quantum circuit

$$H = -J \sum_j Z_j Z_{j+1} + h \sum_j X_j$$



Decompose into native gates that
we can actually implement on the QPU

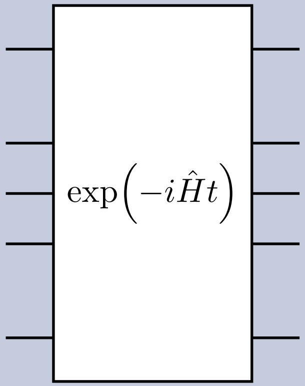




Step 1: Trotter circuit (30 sec)

The product formula describing the time evolution of a quantum system over time *t* is

See lecture by Frank



$$\exp\left(-i\hat{H}t\right) \approx \prod_{d=1}^{D} \hat{U}_k\left(\Delta t\right) \; ,$$

U_k: Unitary time evolution over a finite Trotter time-step delta t for k-th order Trotter-Suzuki product formula

$$\hat{U}_1(\Delta t) = \prod_{j=1}^{N} e^{-i\hat{H}_j \Delta t} \; ,$$

First order expansion

$$\hat{H} = -J\sum_j Z_j Z_{j+1} + h\sum_j X_j = -J\hat{H}_{ZZ} + h\hat{H}_X$$

$$\hat{H}_{ZZ} = \sum_j Z_j Z_{j+1}$$

$$\hat{H}_X = \sum_j \hat{X}_j$$

$$\exp\left(-i\hat{H}t\right) \approx \left[\exp\left(iJ\hat{H}_{ZZ}t/d\right)\exp\left(-ih\hat{H}_X t/d\right)\right]^d$$

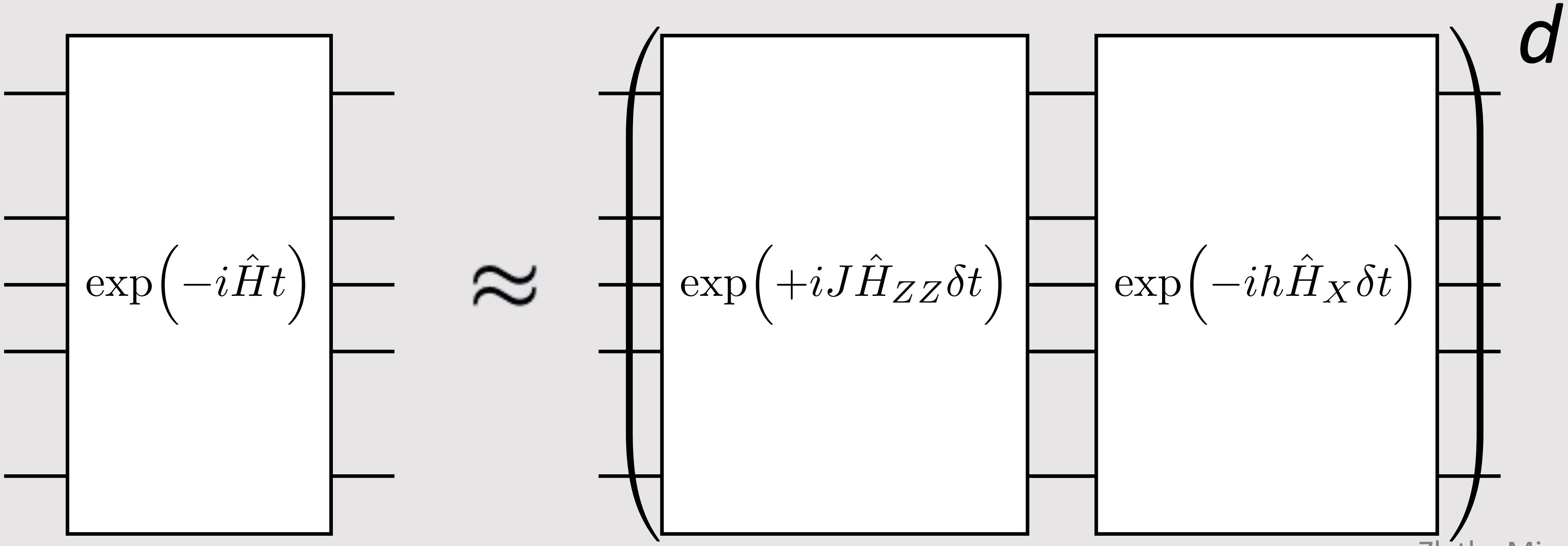
$$\delta t := t/d$$

First order Trotter

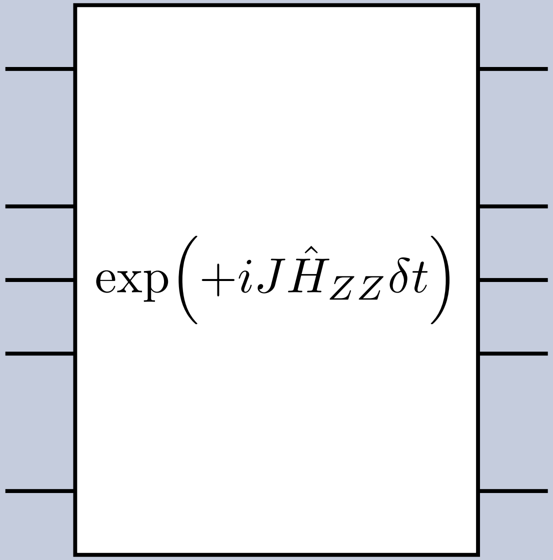
For error bounds, see arxiv:2302.14592

Step 1: Map to quantum circuit

$$H = -J\sum_j Z_j Z_{j+1} + h\sum_j X_j$$



Step 1: Trotter circuit (30 s)

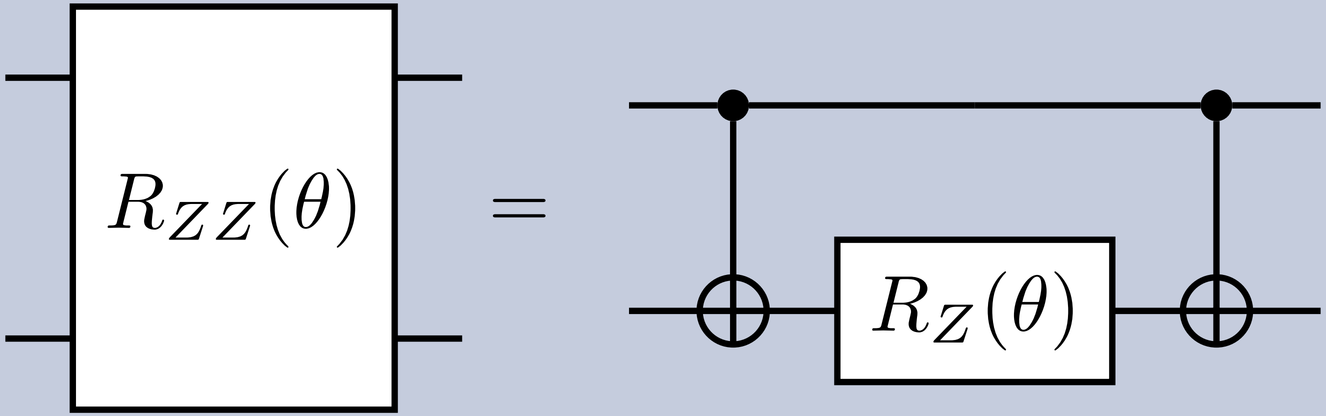


$$\exp\left(-i\frac{\theta}{2}\sum_{j=0}^{n-1} Z_j Z_{j+1}\right) = \quad (\text{use } [Z_j Z_{j+1}, Z_{j'} Z_{j'+1}] = 0)$$

$$\theta := -2J\delta t$$

$$= \prod_{j=0}^{n-1} \exp\left(-i\frac{\theta}{2} Z_j Z_{j+1}\right)$$

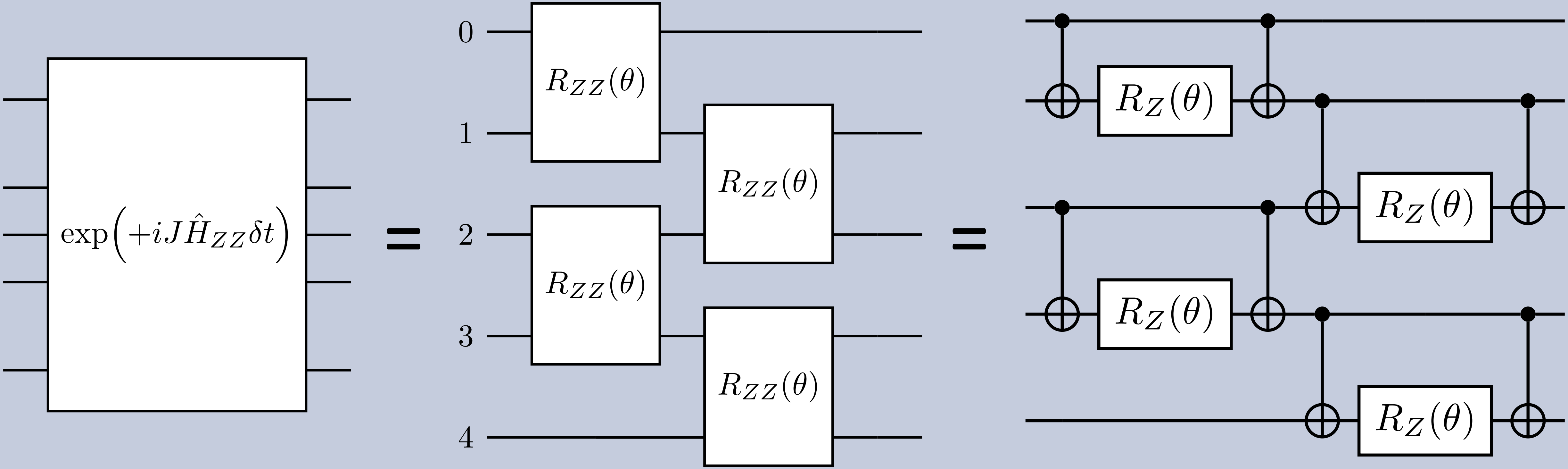
$$= \prod_{j=0}^{n-1} R_{ZZ}\left(\theta\right)$$



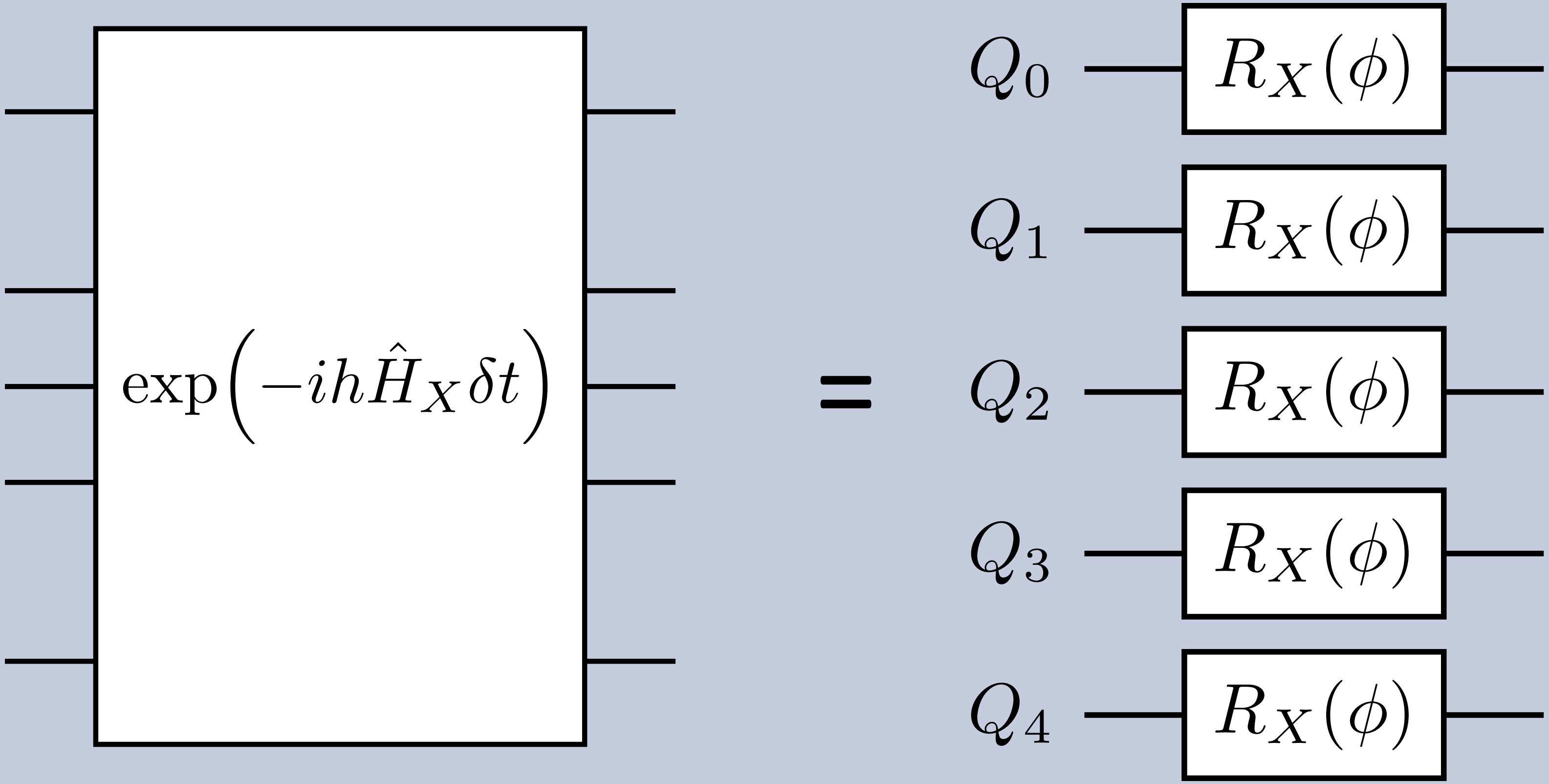
$$R_{ZZ}\left(\theta\right) = \exp\left(-i\frac{\theta}{2} ZZ\right)$$

$$= \mathrm{cXRz}\left(\theta\right)\mathrm{cX}$$

Step 1: Decompose into native gates



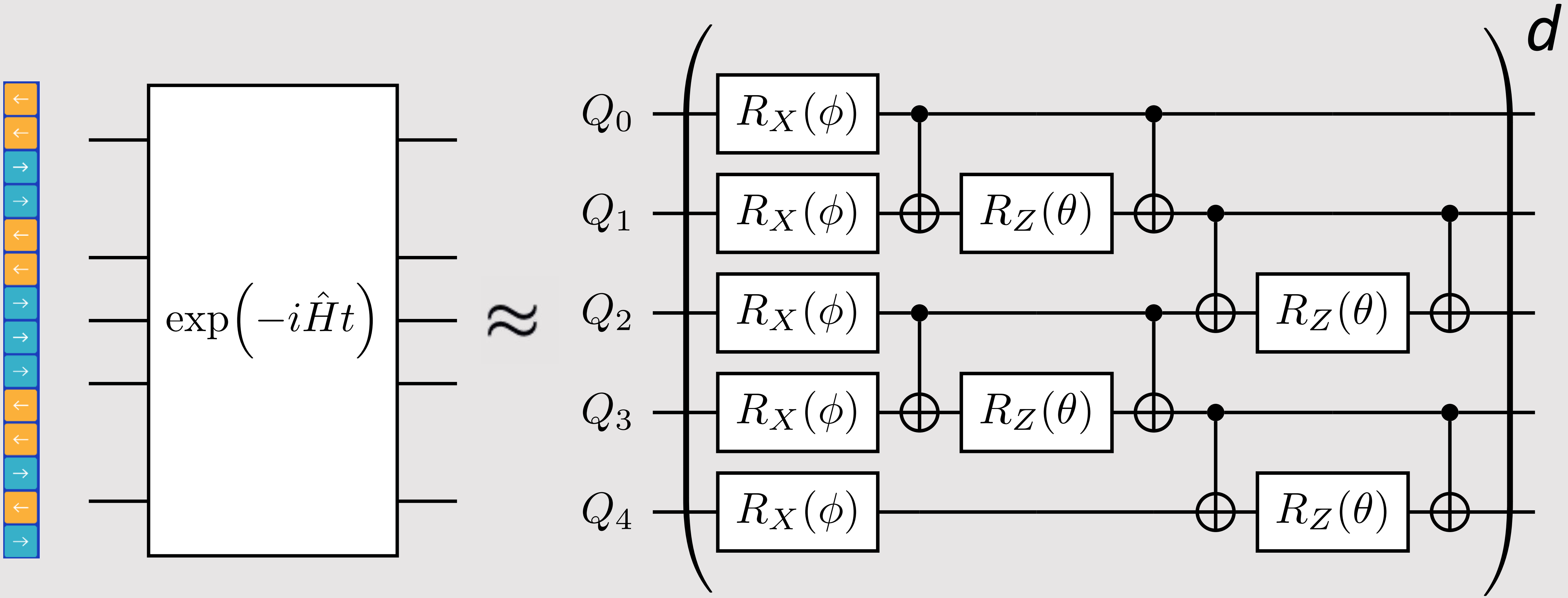
Step 1: Decompose into native gates



$$R_X(\phi) \coloneqq \exp\left(-\frac{1}{2}\phi X\right)$$

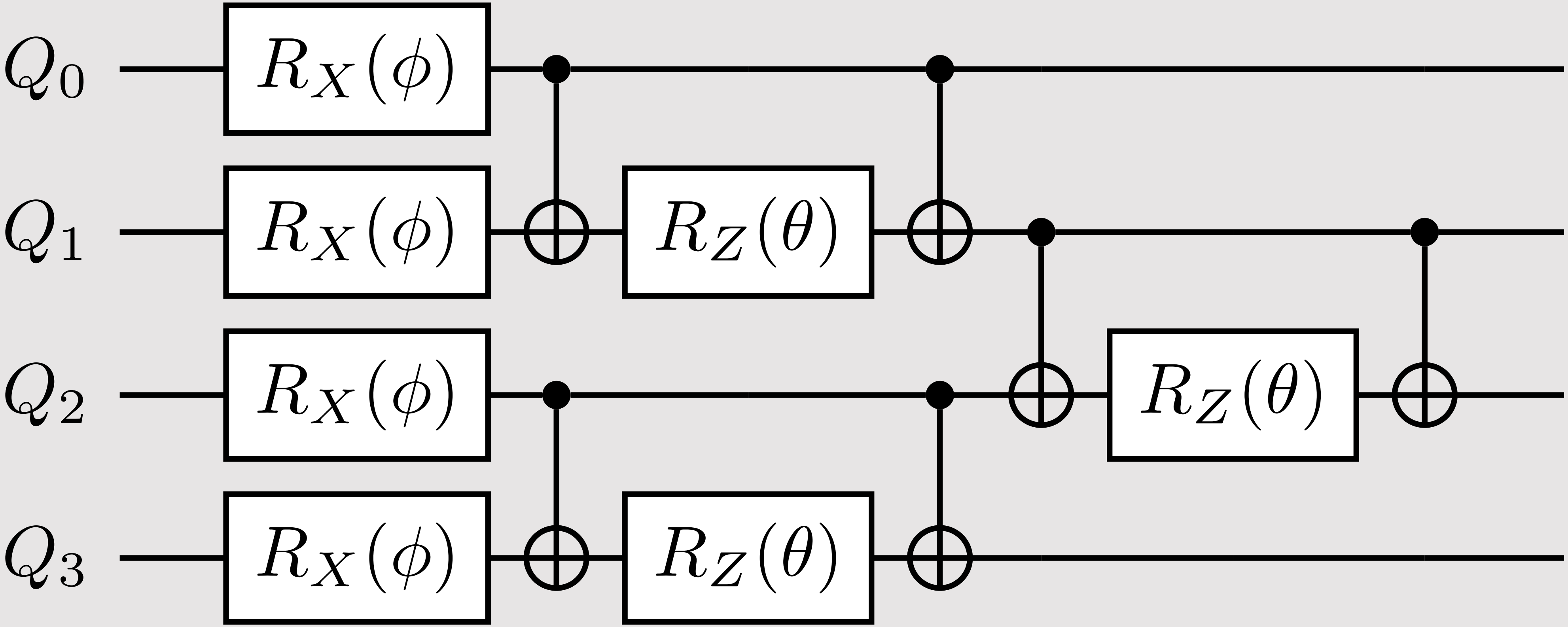
$$\phi \coloneqq +2h\delta t$$

Step 1: Quantum Hamiltonian time evolution

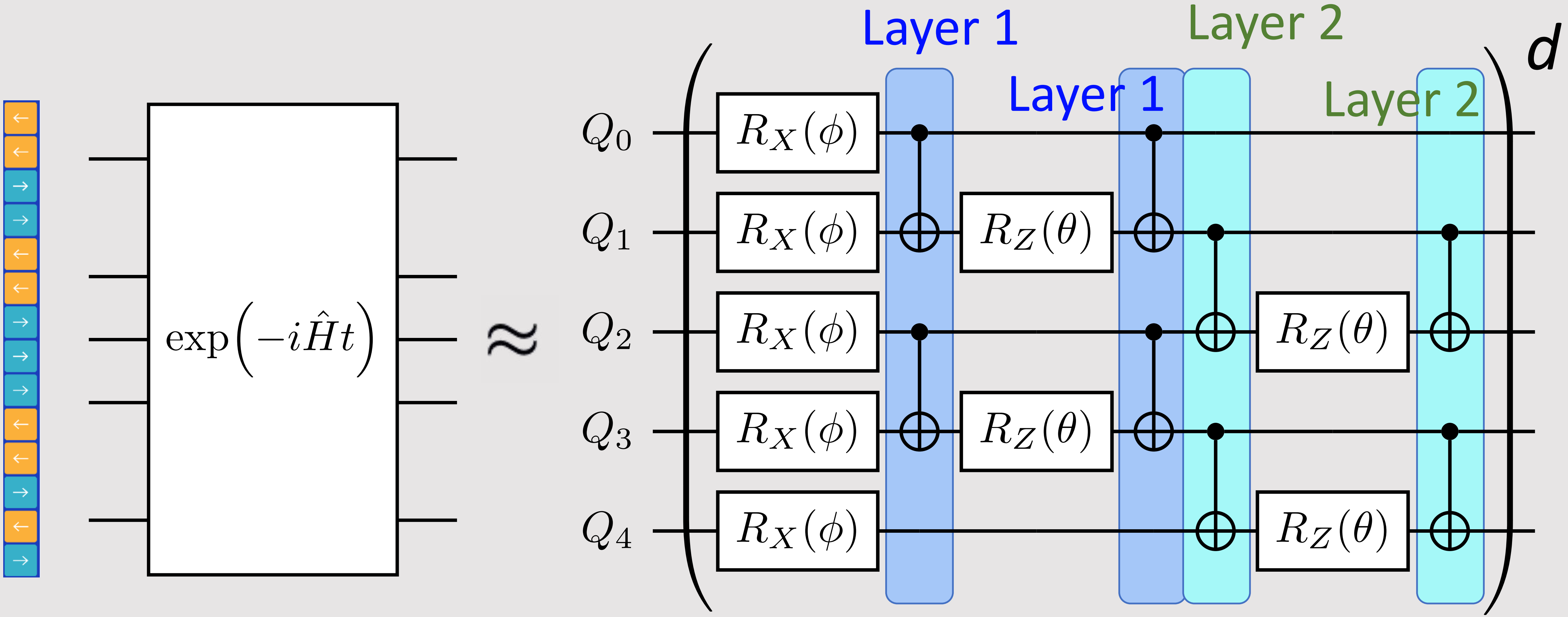


Decomposed into quantum computer native gates

Make things even simpler



Step 2: Decompose into layers

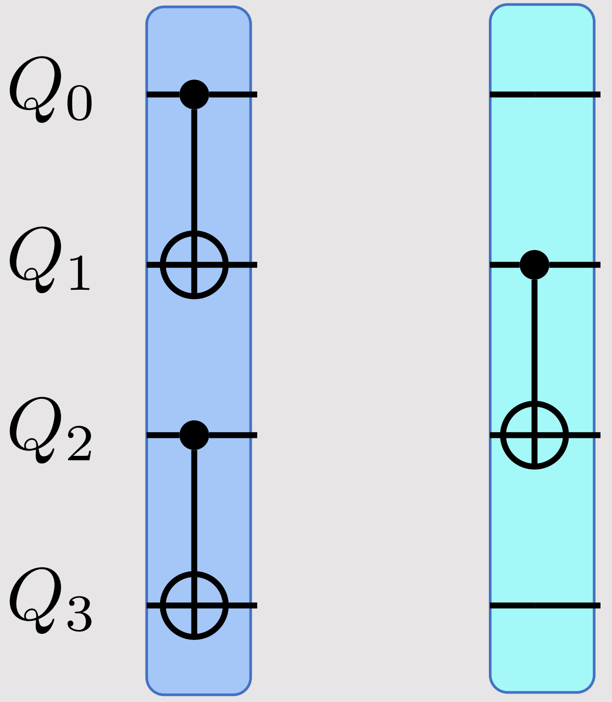


Decomposed into 2Q gate layers

Step 2: Learn the noise on each layer

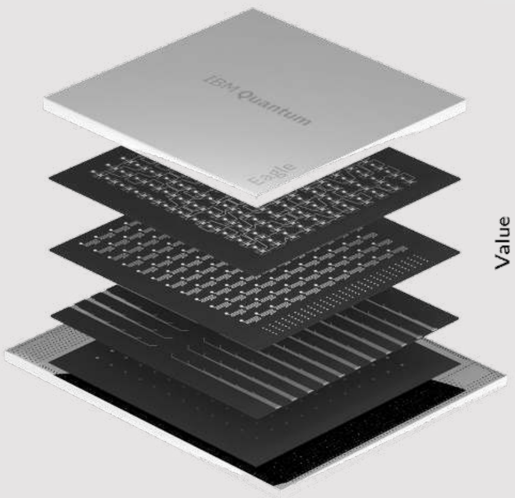
Let’s make even simpler, and make it 4 qubits (instead of 5 for our first example)

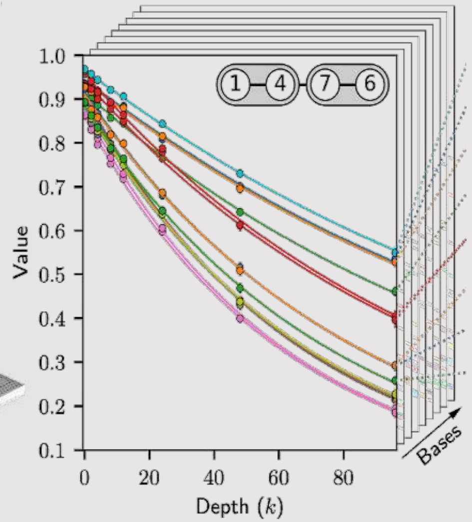
Layer 1 Layer 2

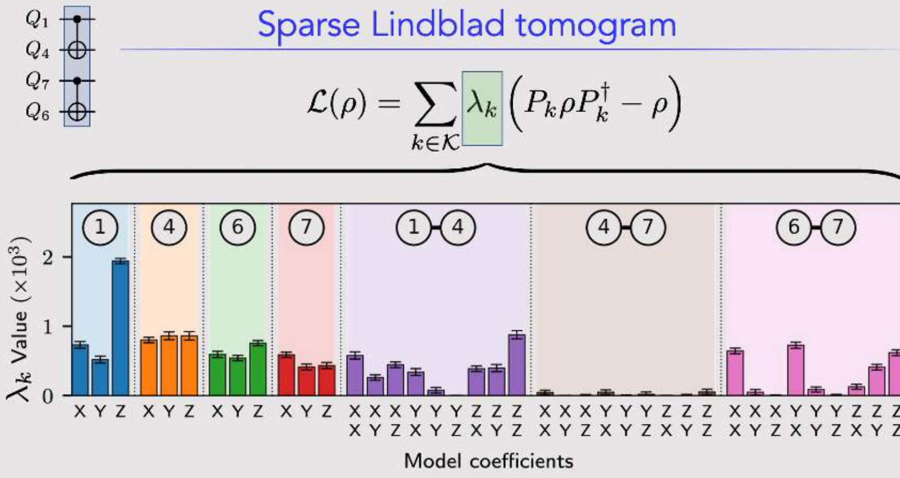


Λ_1 Λ_2

See lecture 2 for learning the noise



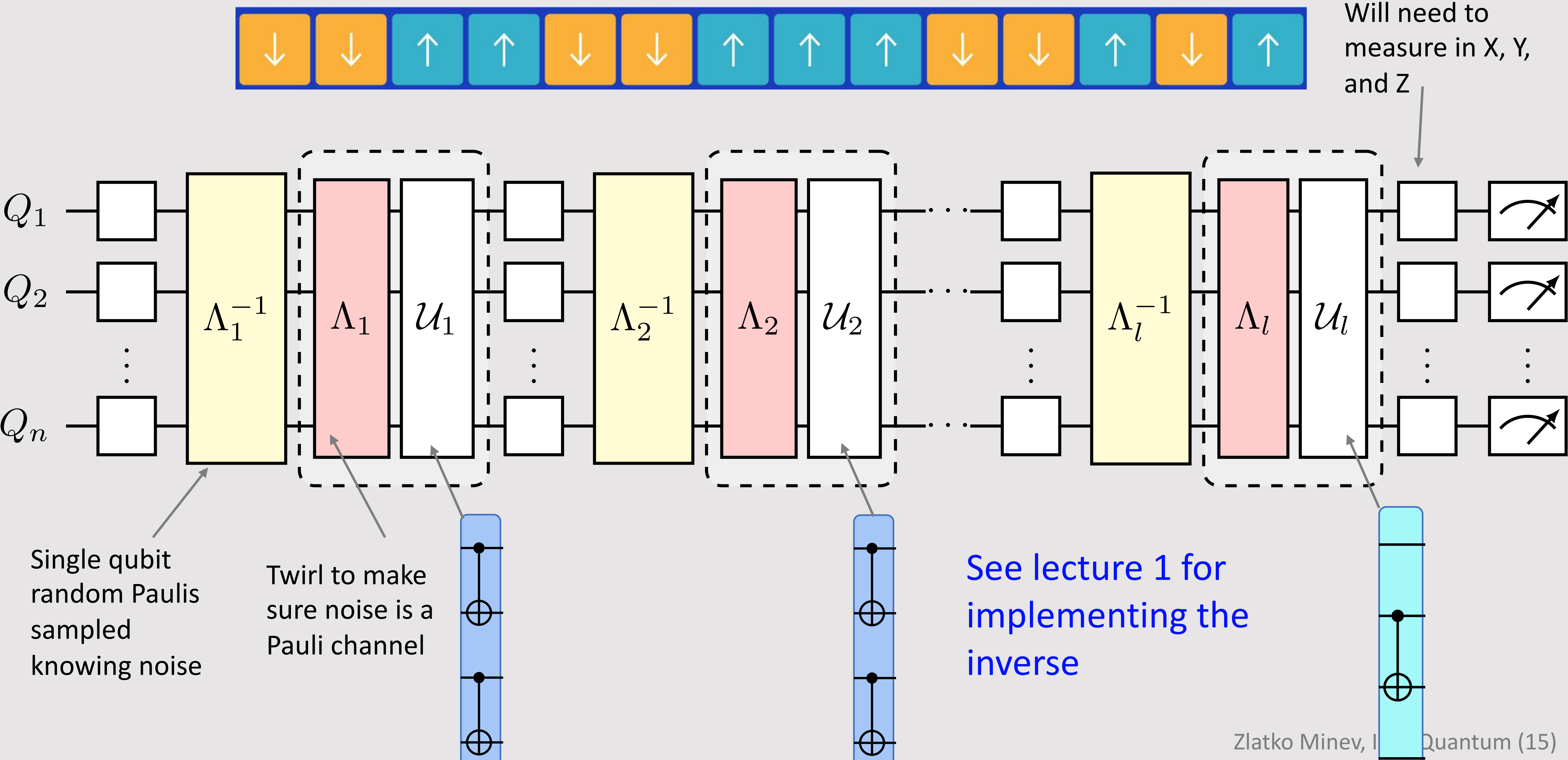




$$\gamma_1 = 1.0309 \pm 8.40 \cdot 10^{-5}$$

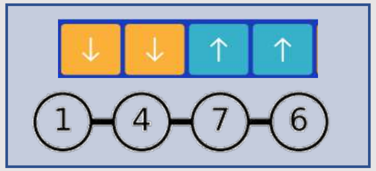
$$\gamma_2 = 1.0384 \pm 2.20 \cdot 10^{-4}$$

Step 3: Cancel the noise

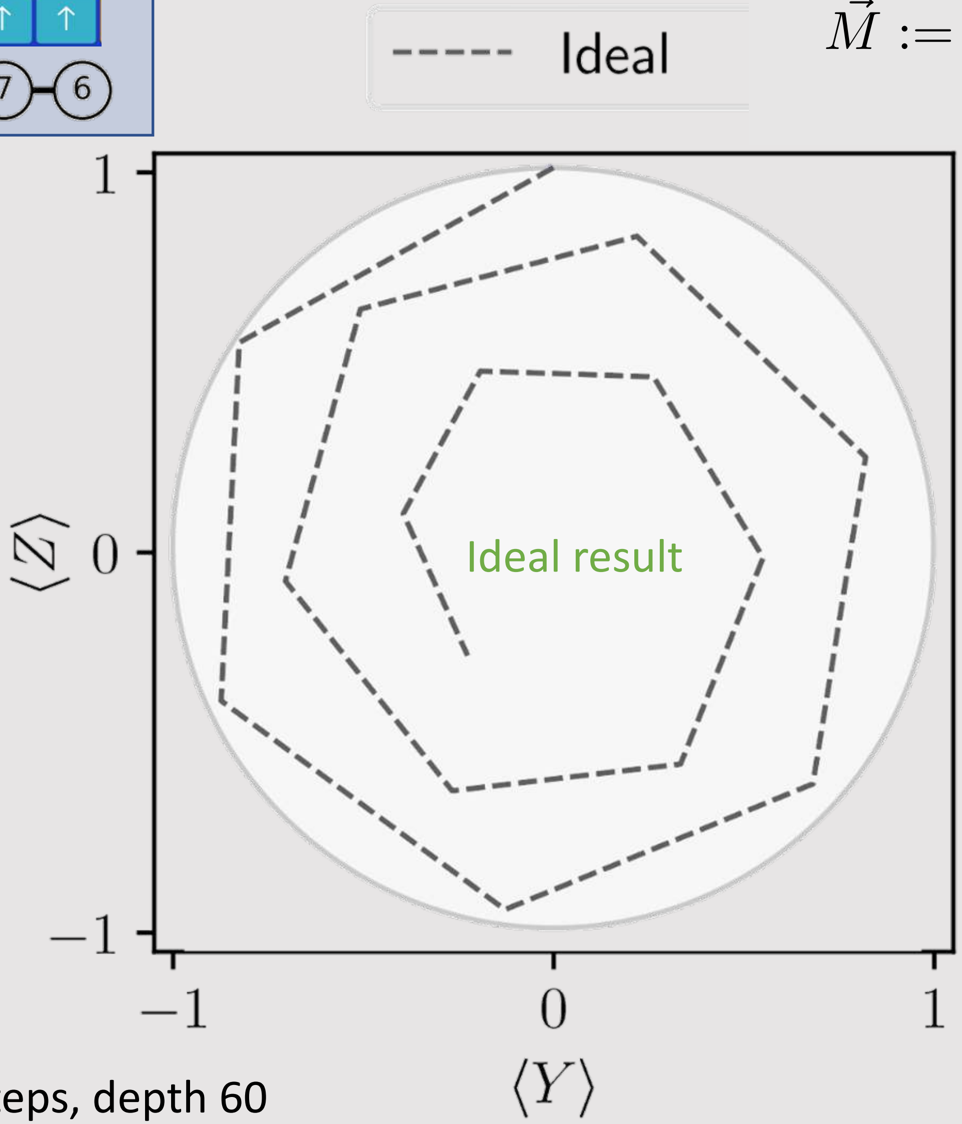


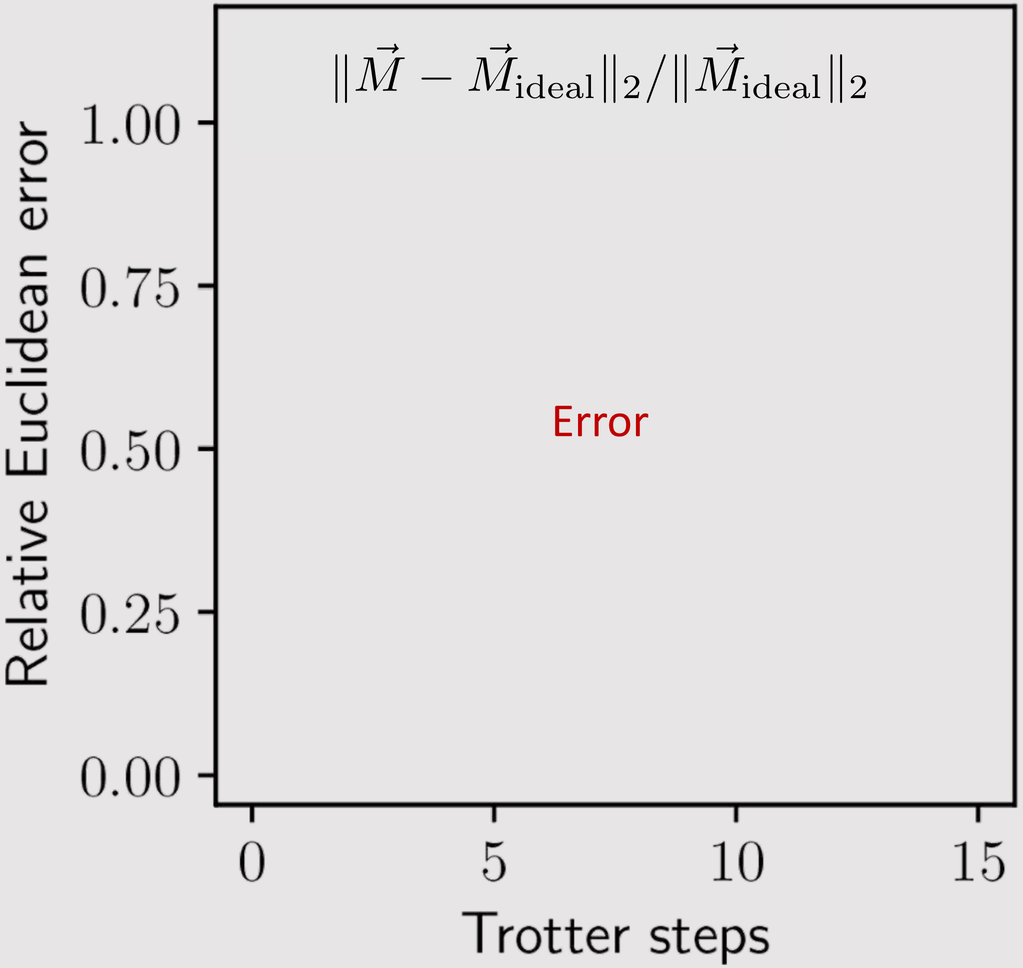
See lecture 1 for implementing the inverse

Ideal Ising model evolution



$$\vec{M} := \sum_n \left(\langle X \rangle_n , \langle Y \rangle_n , \langle Z \rangle_n \right) / N$$

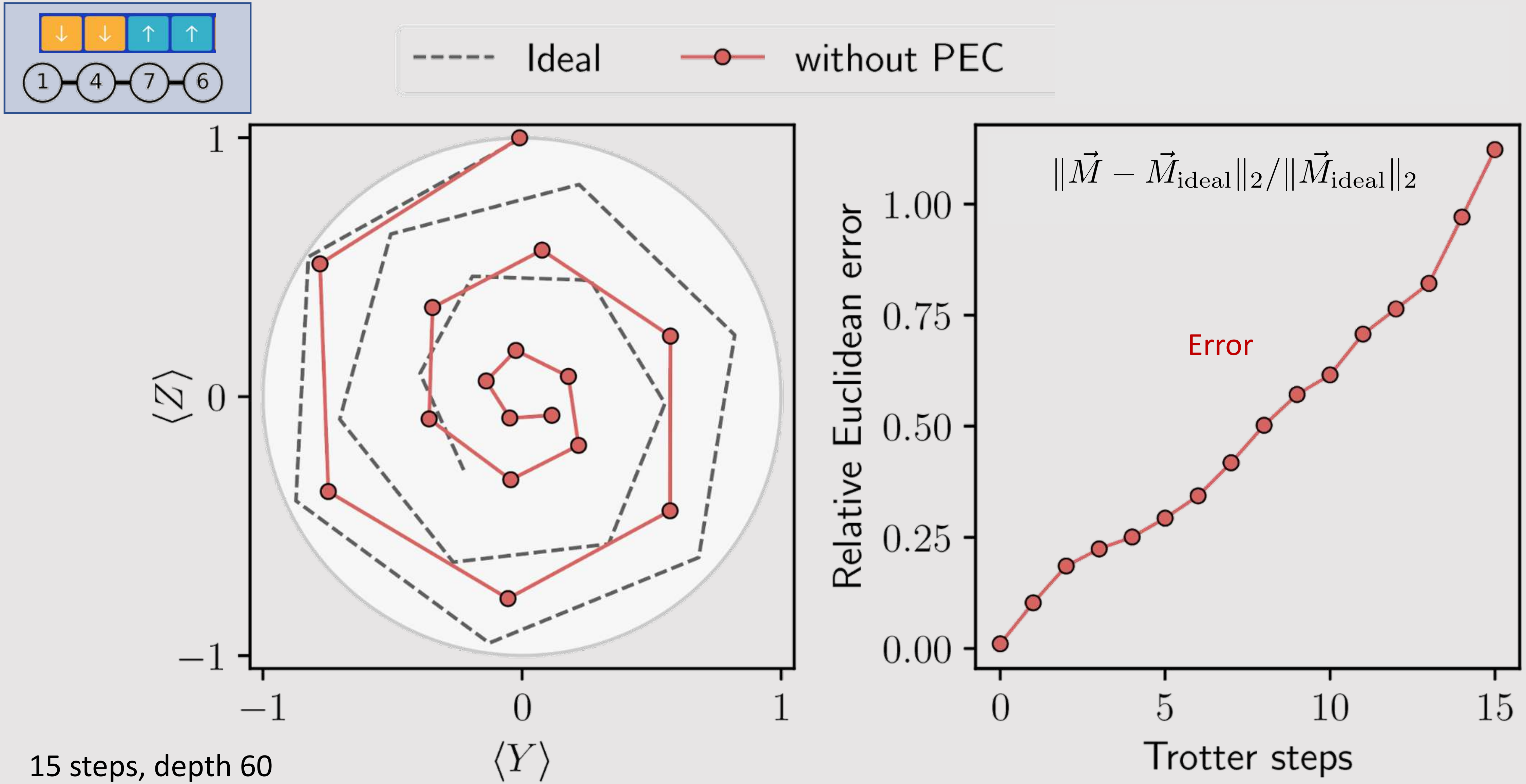




4Q, 15 steps, depth 60

$h = 1, J = -0.15, \delta t = 1/4$

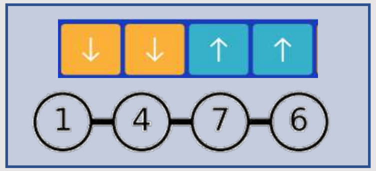
Without PEC: but with DD & twirl readout mitigation

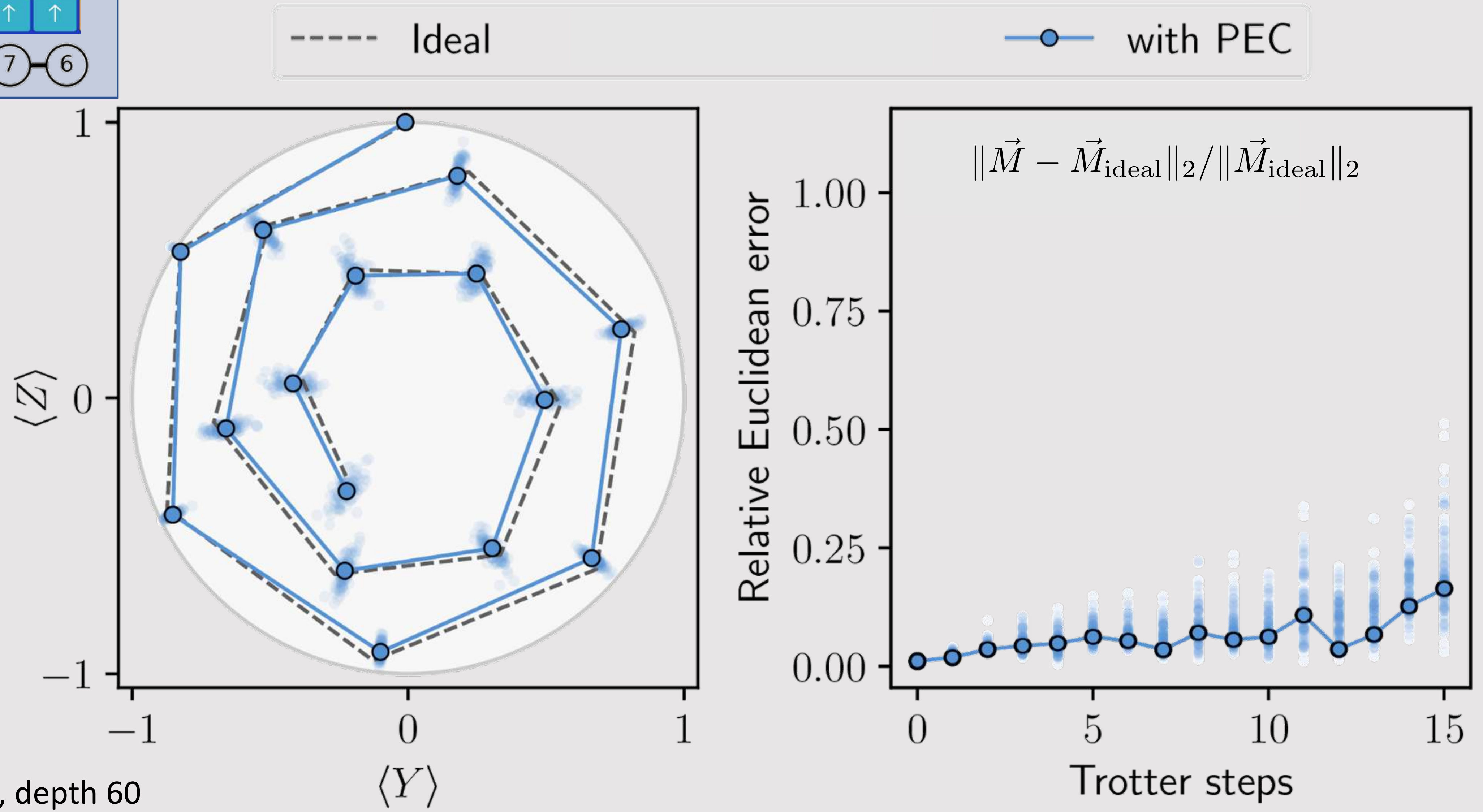


15 steps, depth 60

$h = 1, J = -0.15, \delta t = 1/4$

With PEC

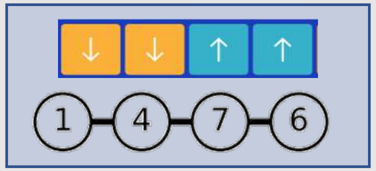


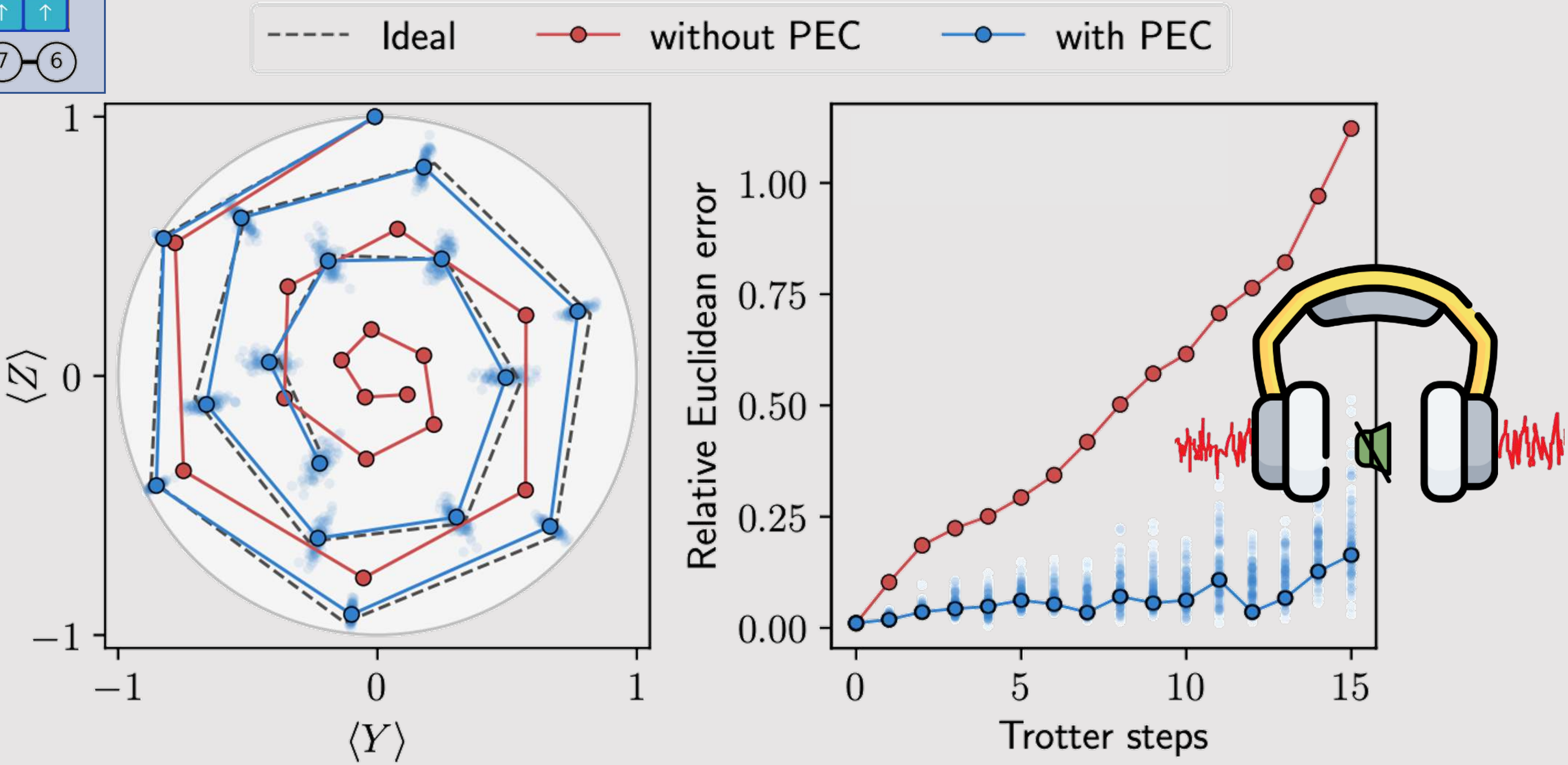


15 steps, depth 60

$h = 1, J = -0.15, \delta t = 1/4$

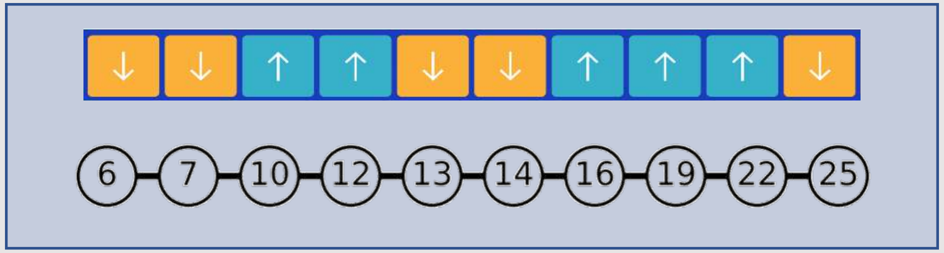
With vs. without PEC

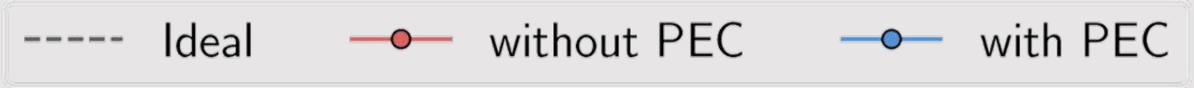


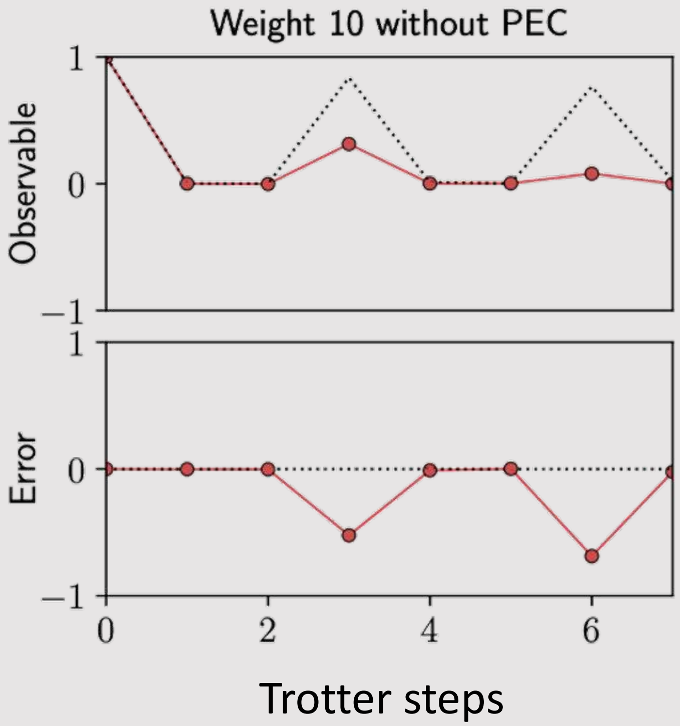


$h = 1, J = -0.15, \delta t = 1/4$

With vs without PEC: 10 qubit high-weight observables



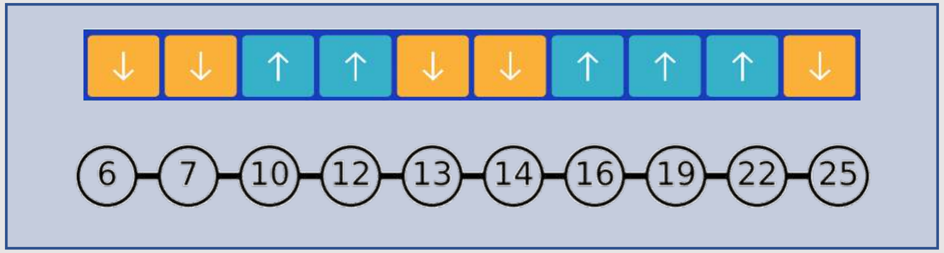


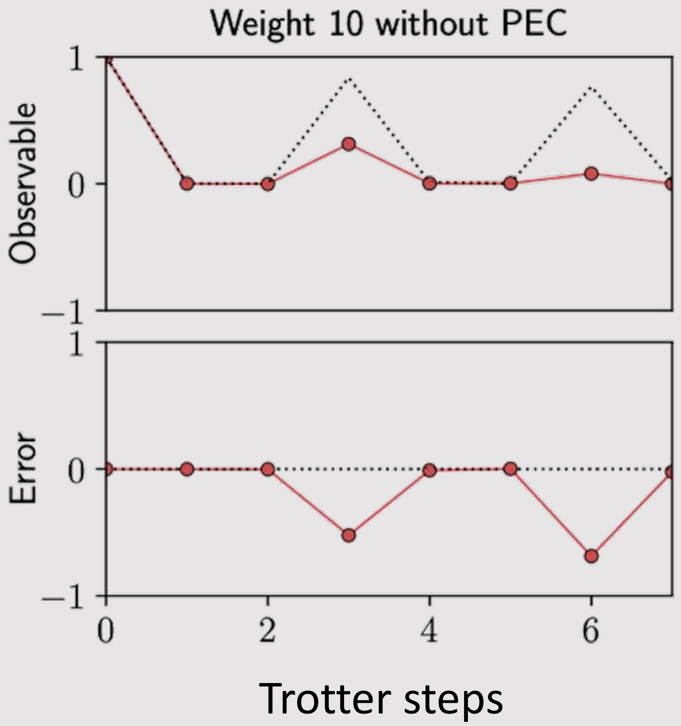


ZZZZZZZZZZ

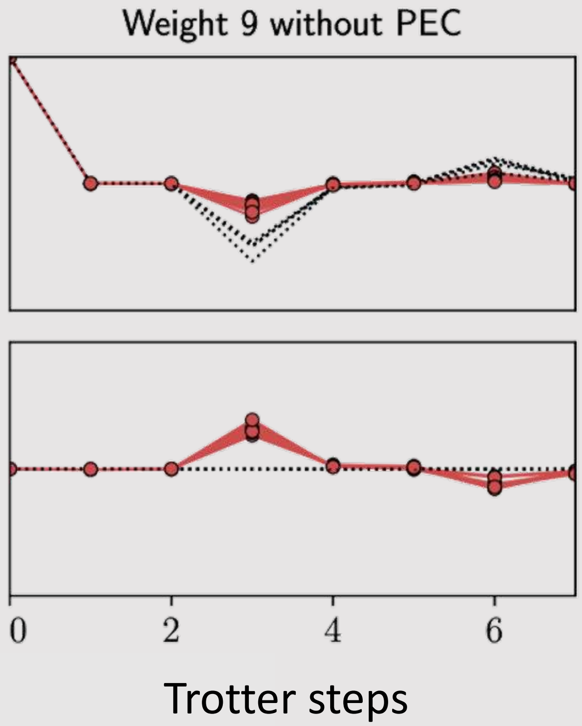
$h = 1, J = -0.5236, \delta t = 1/4$

With vs without PEC: 10 qubit high-weight observables





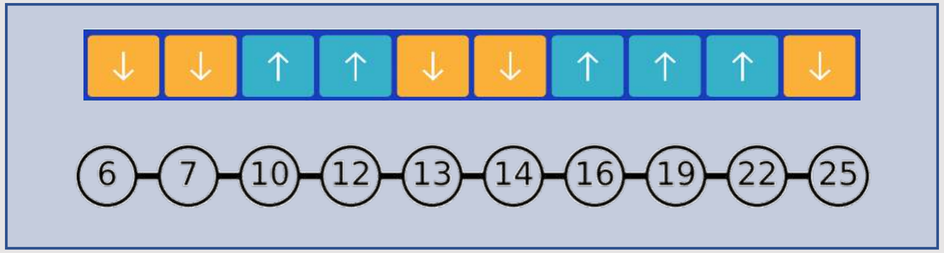
ZZZZZZZZZZ

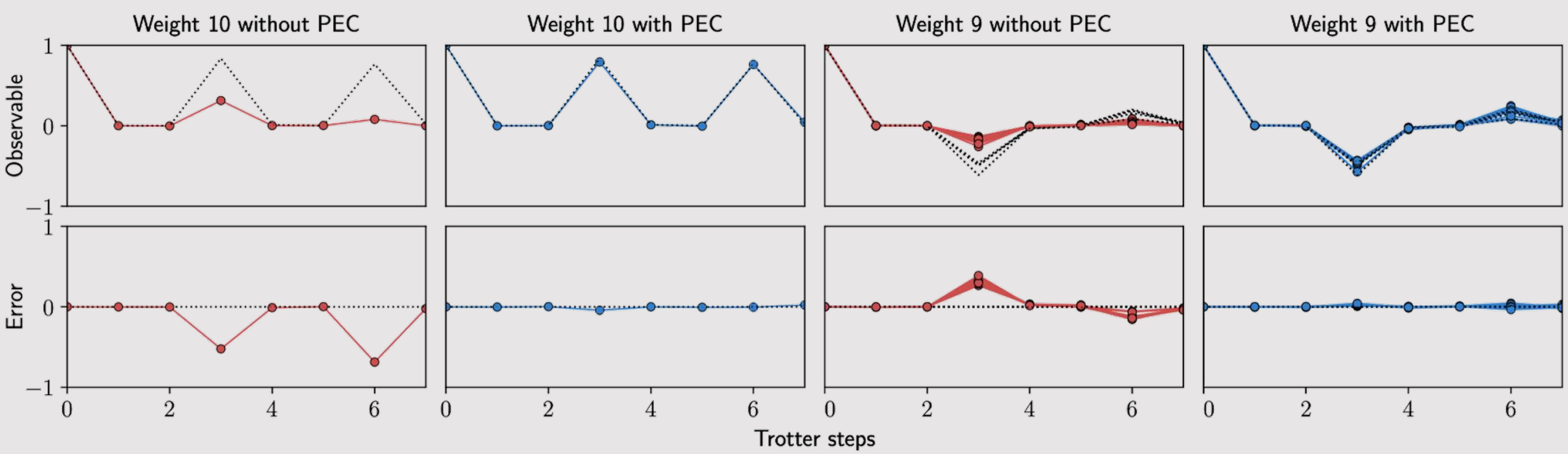


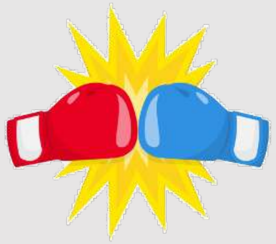
IZZZZZZZZZ
ZIZZZZZZZZ
ZZIZZZZZZZ
…
ZZZZZZZZZI

$h = 1, J = -0.5236, \delta t = 1/4$

With vs without PEC: 10 qubit high-weight observables







$h = 1, J = -0.5236, \delta t = 1/4$

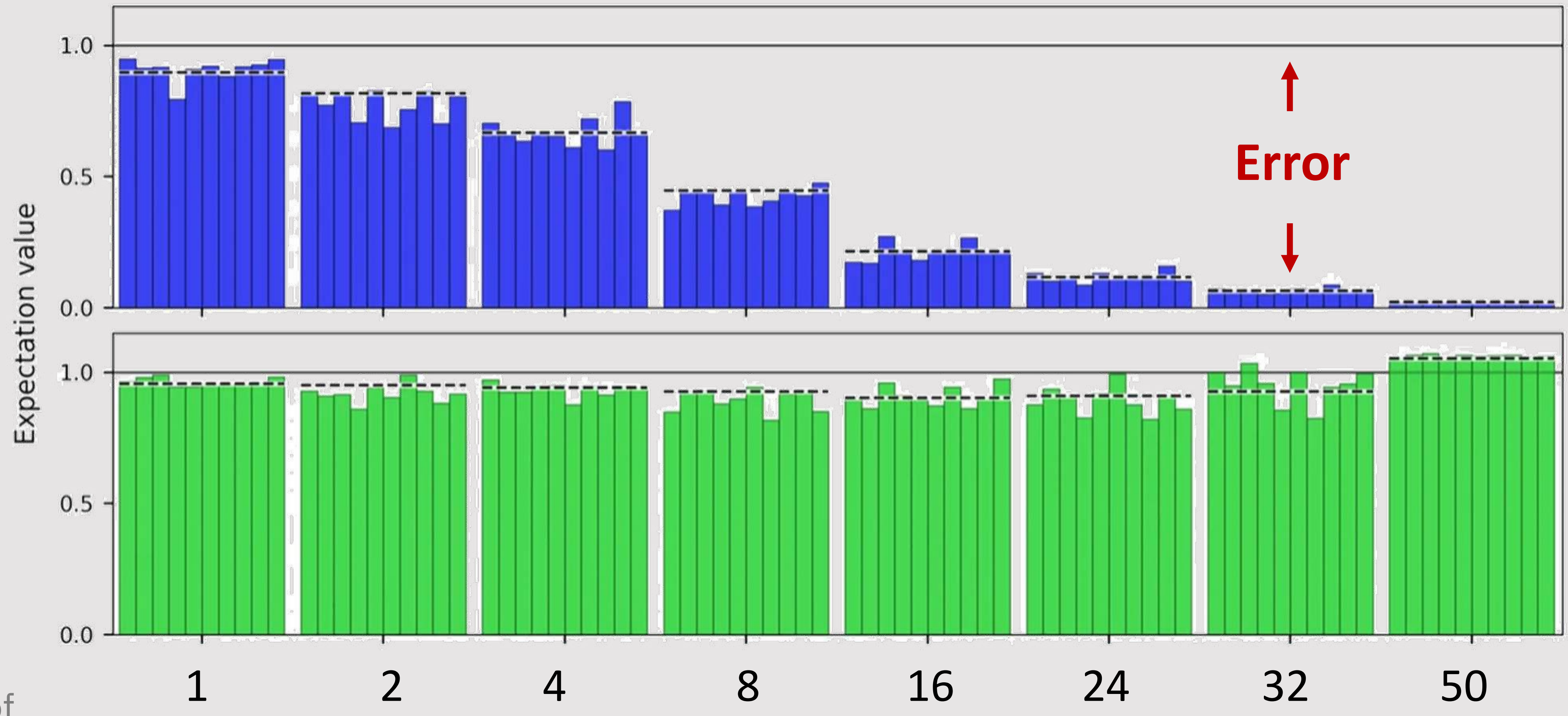
Scaling and error budget

PEC on 50 qubit observables

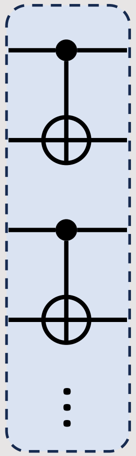
Z stabilizers of increasing weight

Without PEC

With PEC



Weight of mitigated observable

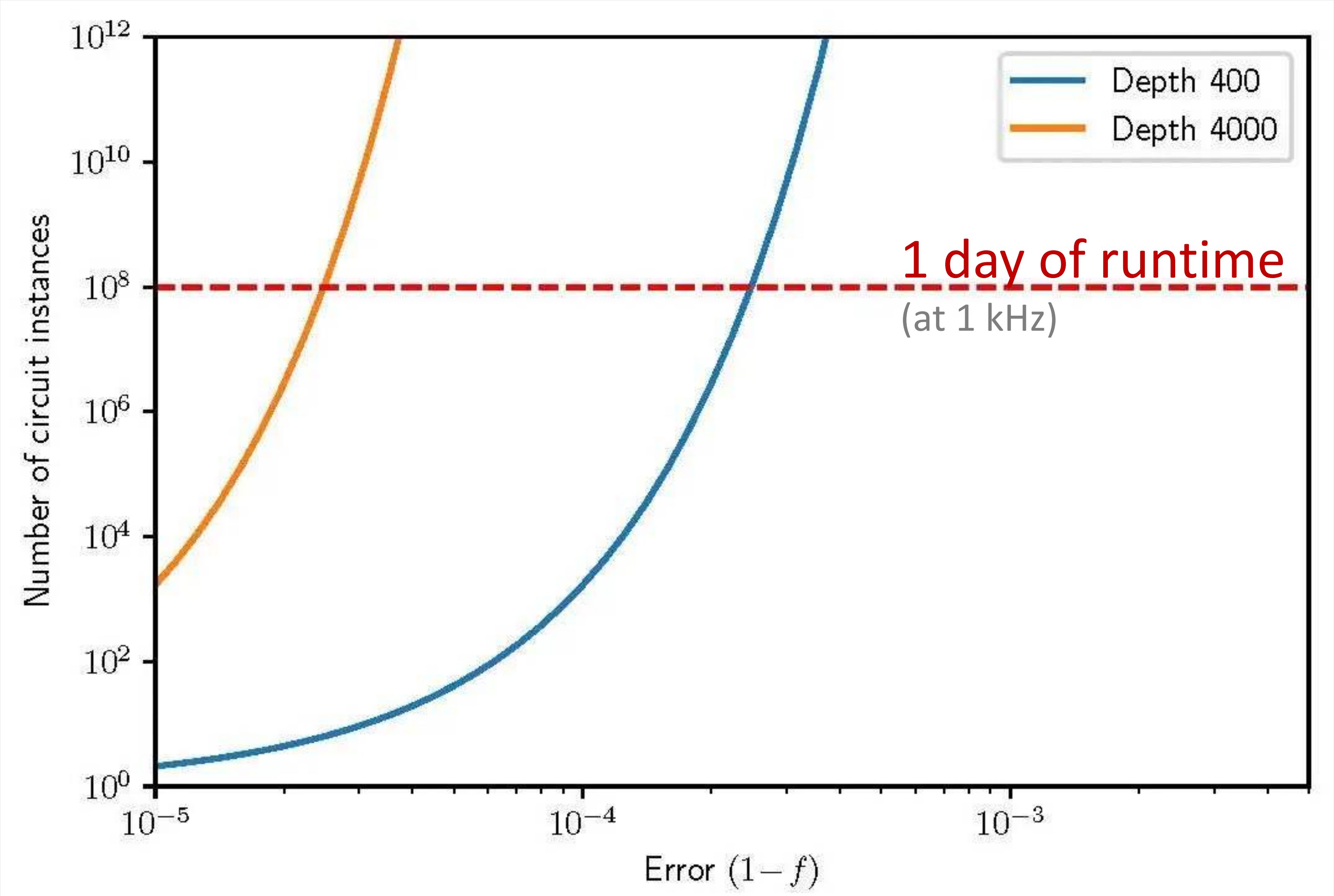


50Q
2 layers of
cNOT gates

See research.ibm.com/blog/gammabar-for-quantum-advantage

Path to 100+ qubits?

Estimating PEC overhead for Trotter circuits comprising 100 qubits



See also on speed: A. Wack, et al., Quality, speed, and scale: three key attributes to measure the performance of near-term quantum computers (2021).

Path to quantum computing

Noise-free estimators can be obtained from noisy quantum computers TODAY, at a runtime cost that is exponential in number of qubits *n* and circuit depth *d*

$$\text{Runtime} = \beta\, d\ (\bar{\gamma})^{n\,d}\ \text{seconds}$$

You can further reduce runtime using light cones and other strategies.

d is the depth of the quantum circuit

β is a measure of the time per circuit layer operation (CLOPS) (increase by pushing speed)

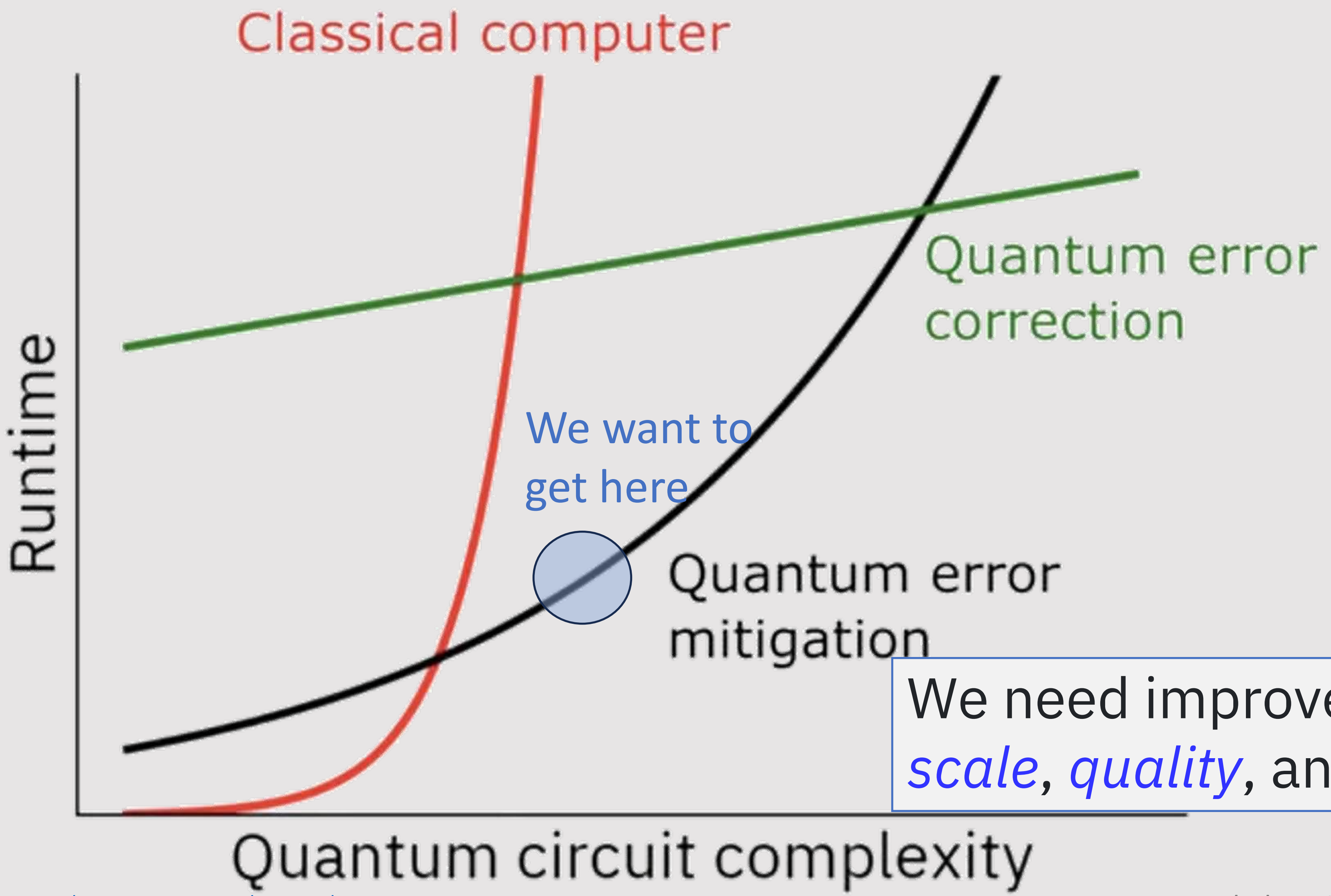
$\bar{\gamma}$ is a measure of the collective quantum noise (increasing quality brings it closer to 1)

n is the number of operational qubits (increase by pushing scale)

	Improvements	$\bar{\gamma}$
Hummingbird r2 (Brooklyn, 65Q)		1.038
Hummingbird r3 (Ithaca, 65Q)	2-3x coherence improvements over r2	1.024
Falcon r10 (Prague, 32Q)	State-of-the-art two-qubit gates, reduced crosstalk	1.012

https://research.ibm.com/blog/gammabar-for-quantum-advantage

Path to utility of quantum computers before error correction



We need improvements in *scale*, *quality*, and *speed*.

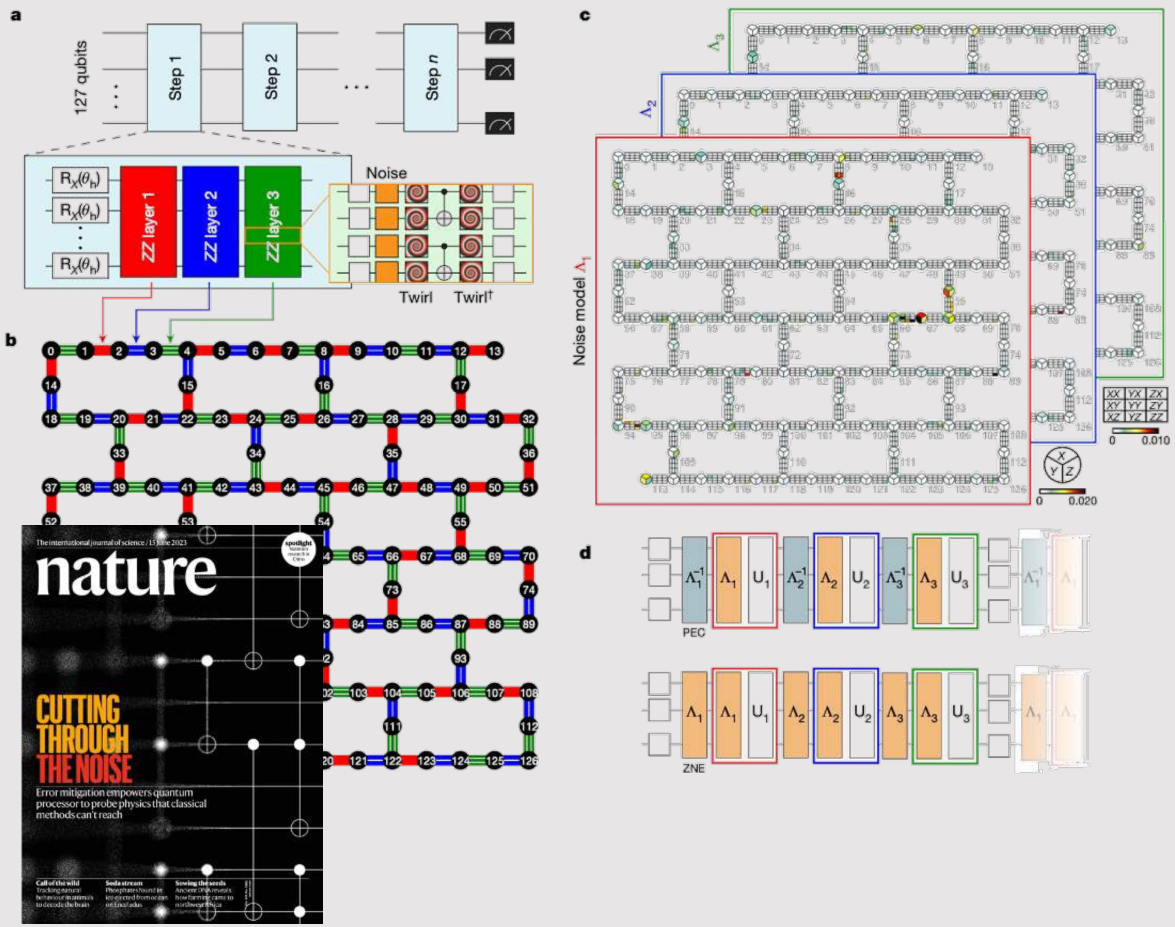
https://qiskit.org/documentation/partners/qiskit_ibm_runtime/tutorials/Error-Suppression-and-Error-Mitigation.html

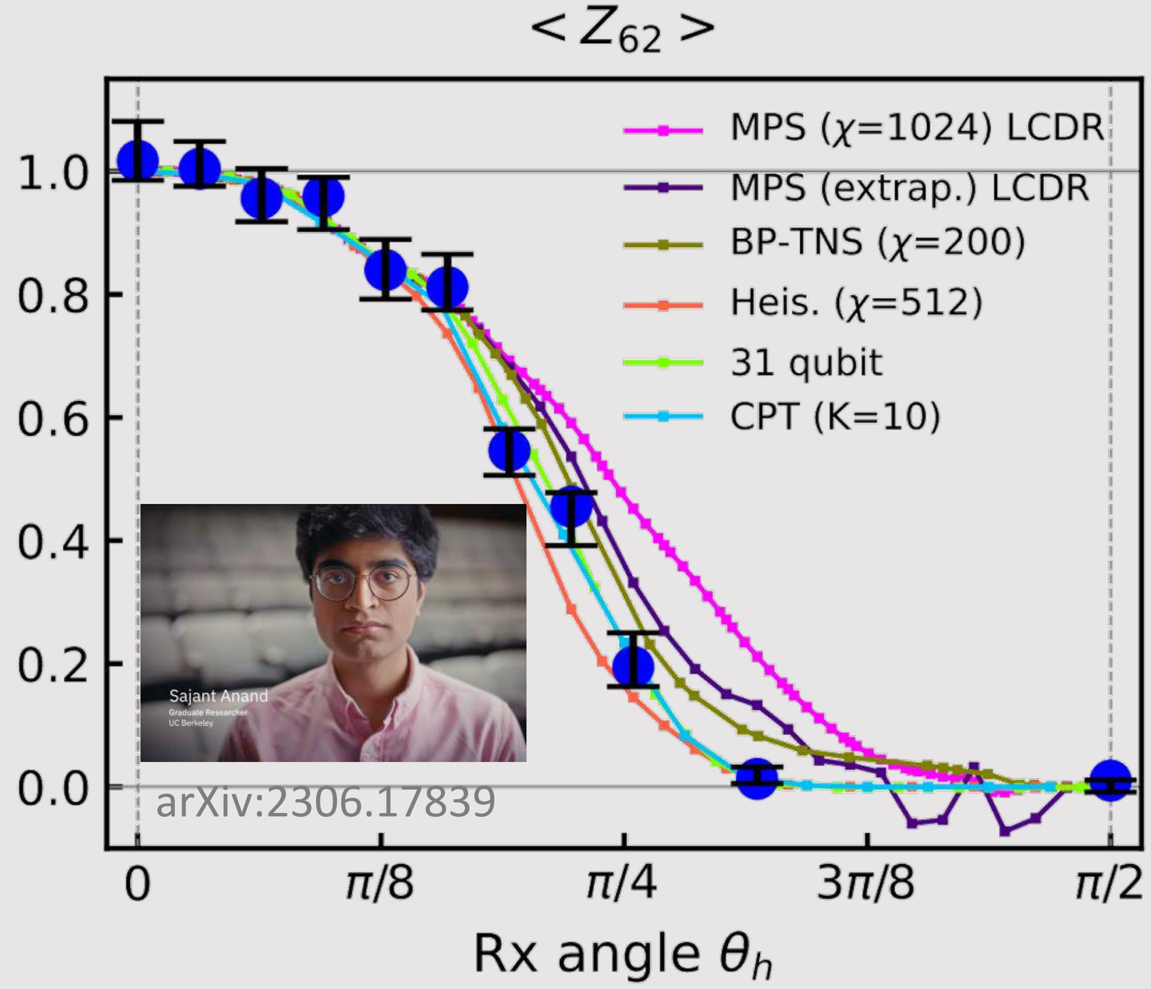
PEC + ZNE for 127 qubits

Article

Evidence for the utility of quantum computing before fault tolerance

Youngseok Kim[1,6]✉, Andrew Eddins[2,6]✉, Sajant Anand[3], Ken Xuan Wei[1], Ewout van den Berg[1], Sami Rosenblatt[1], Hasan Nayfeh[1], Yantao Wu[3,4], Michael Zaletel[3,5], Kristan Temme[1] & Abhinav Kandala[1]✉





Kim, Eddins, Anand, et al. Nature (2023)

How to think about experiments from the point of view of error mitigation?

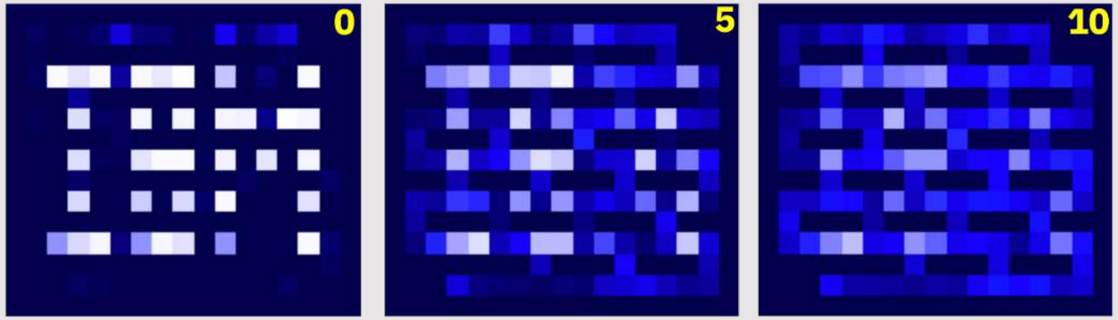
Uncovering Local Integrability in Quantum Many-Body Dynamics

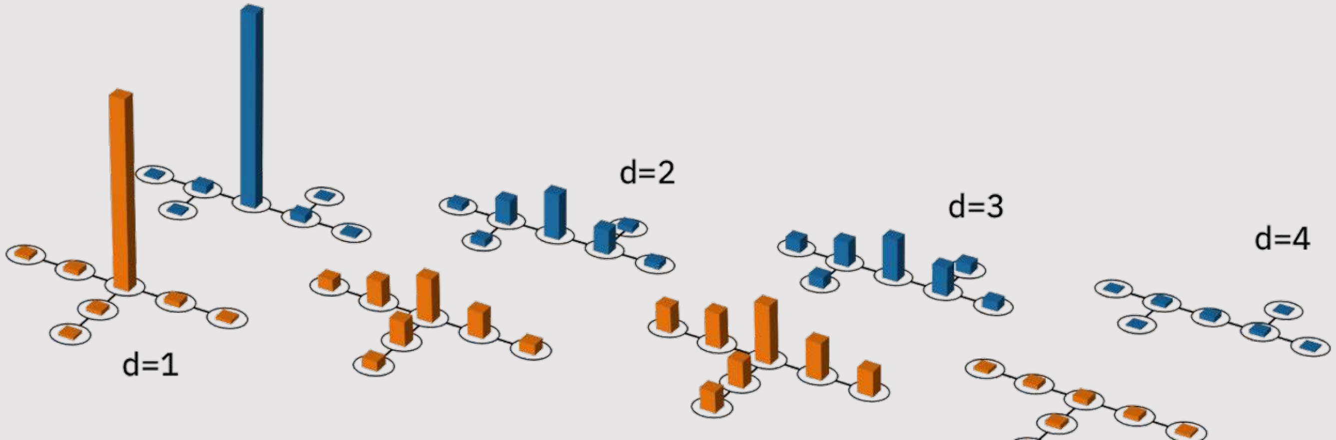
A detailed portrait

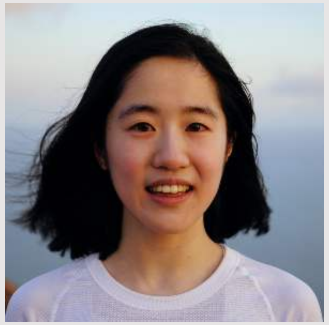
arXiv:2307.07552

Oles Shtanko*†,[1] Derek S. Wang*,[2] Haimeng Zhang,[2] Nikhil Harle,[2,3]
Alireza Seif,[2] Ramis Movassagh,[4] and Zlatko Minev&[2]

IBM Quantum







Acknowledgements: IBM Quantum team

Uncovering the dynamics of many-body systems

Many-body quantum systems and their dynamics

- fundamental and technological
- but generically difficult to simulate and understand

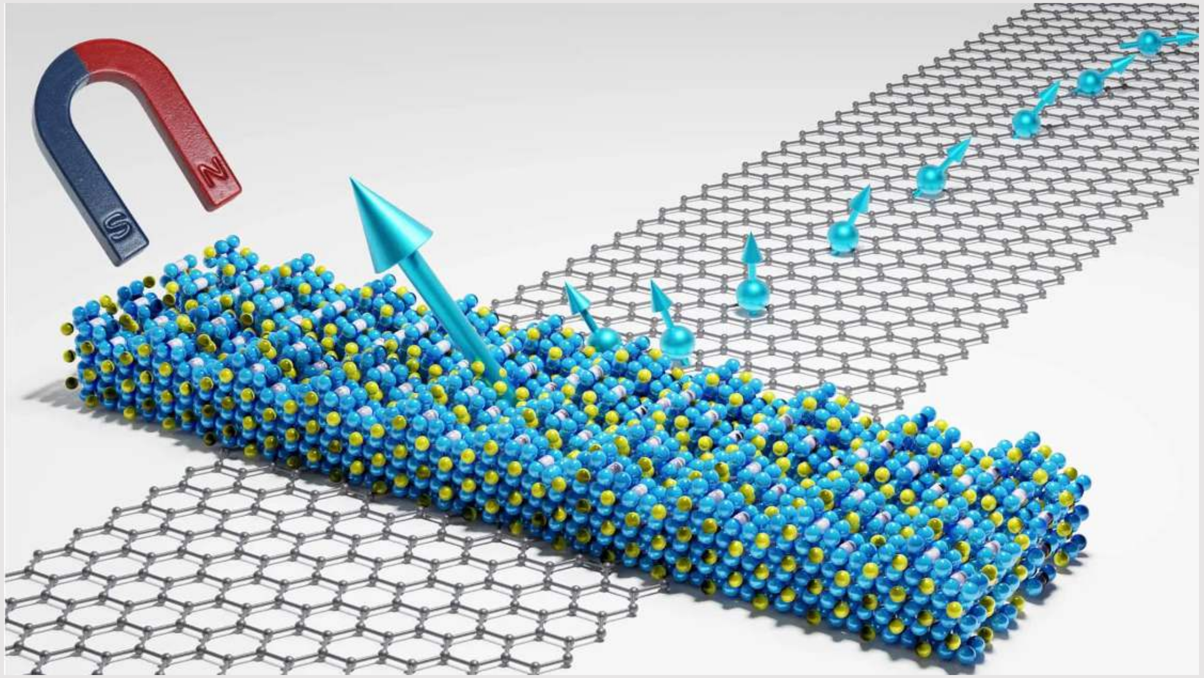


Image: Chalmers

Symmetries, conservation laws, and integrability

- can unravel intricacies of these complex systems
- but generically difficult to discover

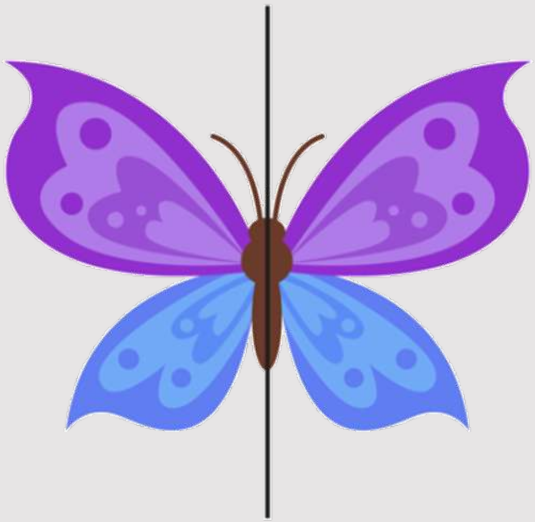


Image: SuperSimple

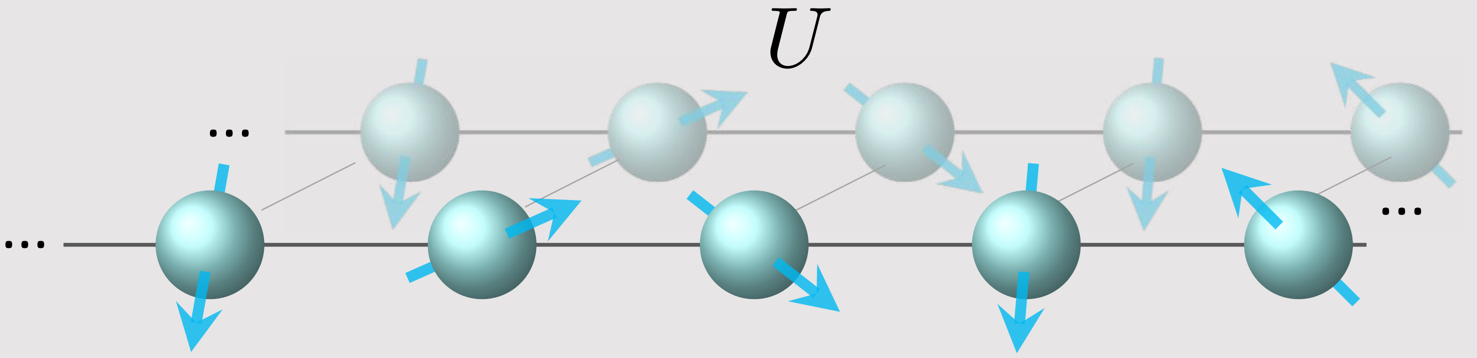
Integrals of motion

Integral of motion L

$$[U, L] = 0 \qquad [H, L] = 0$$

$$\langle L \rangle = \text{const}$$

$$L = \sum_{\mu=1}^{4^n-1} a_\mu P_\mu$$



Integrals of motion (IOM): toy example

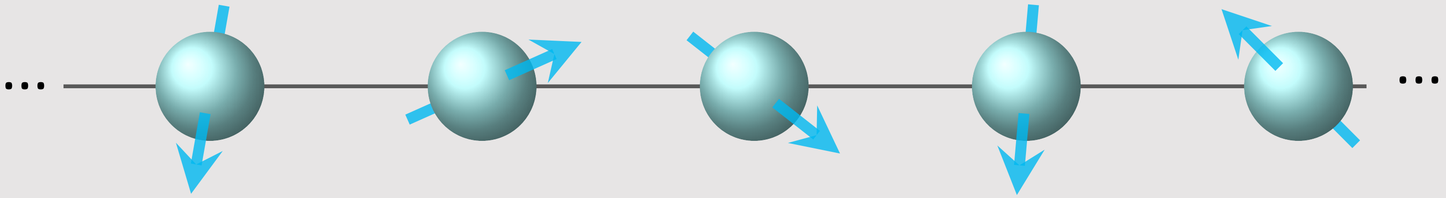
Integral of motion L

$$[U, L] = 0 \qquad [H, L] = 0$$

$$\langle L \rangle = \text{const}$$

$$L = \sum_{\mu=1}^{4^n-1} a_\mu P_\mu$$

$$H = \sum_{i=0}^{n-1} c_i Z_i + \sum_{i \neq j} c_{ij} Z_i Z_j$$



$$[H, Z_0] = 0 \qquad \dots \qquad [H, Z_{n-2}] = 0$$

$$[H, Z_1] = 0 \qquad \qquad [H, Z_{n-1}] = 0$$

n integrals of motion (IOM) $\qquad L_0 = Z_0, L_1 = Z_1, \cdots$

can label eigenstates* $\qquad |l_0 l_1 \cdots l_{n-1}\rangle = |l_0\rangle_{L0} \otimes |l_1\rangle_{L1} \otimes \cdots \otimes |l_{n-1}\rangle_{n-1}$

For this trivial toy model easy, but generically very hard!

* Say if we construct *n* orthogonal IOMs with eigenvalues +-1.

Energy is the only constant of motion in a non-integrable system (time independent).
In general, an **integrable system** has constants of motion other than the energy.

Local integral of motion (LIOM)

Integral of motion L

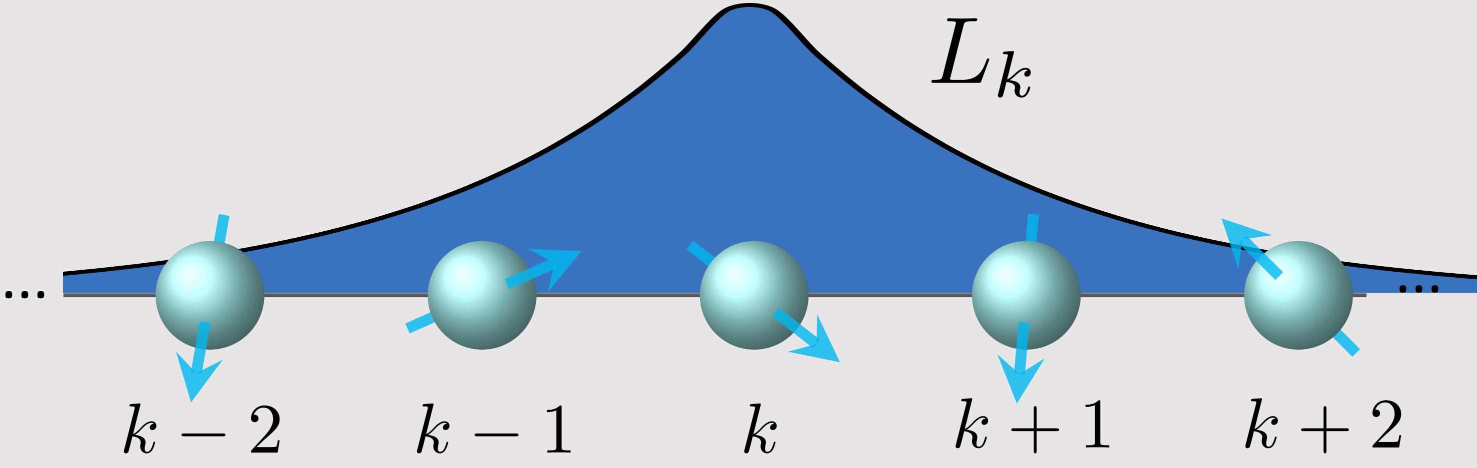
$$[U, L] = 0 \qquad [H, L] = 0$$

$$\langle L \rangle = \text{const}$$

Local integral of motion (LIOM) L

$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$

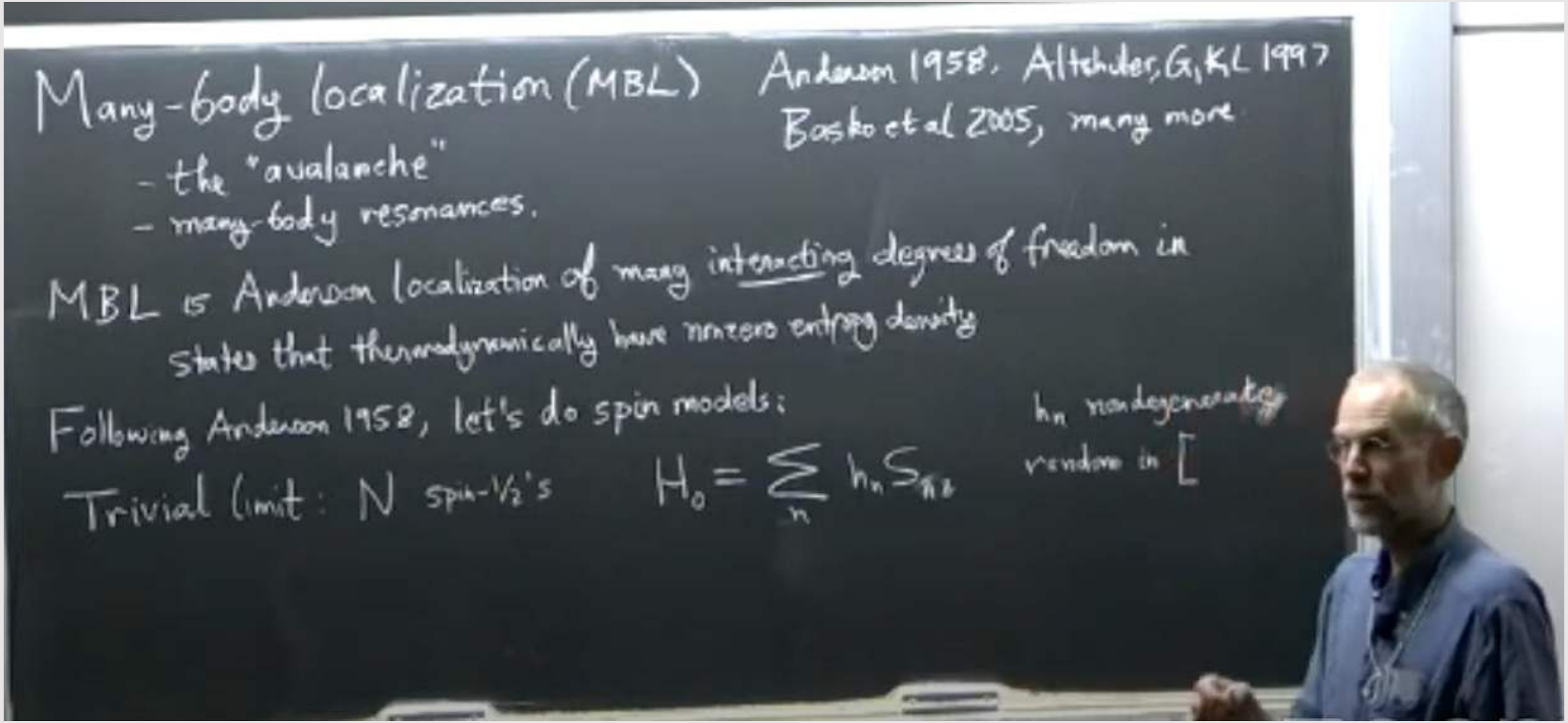
local neighborhood



Tricky

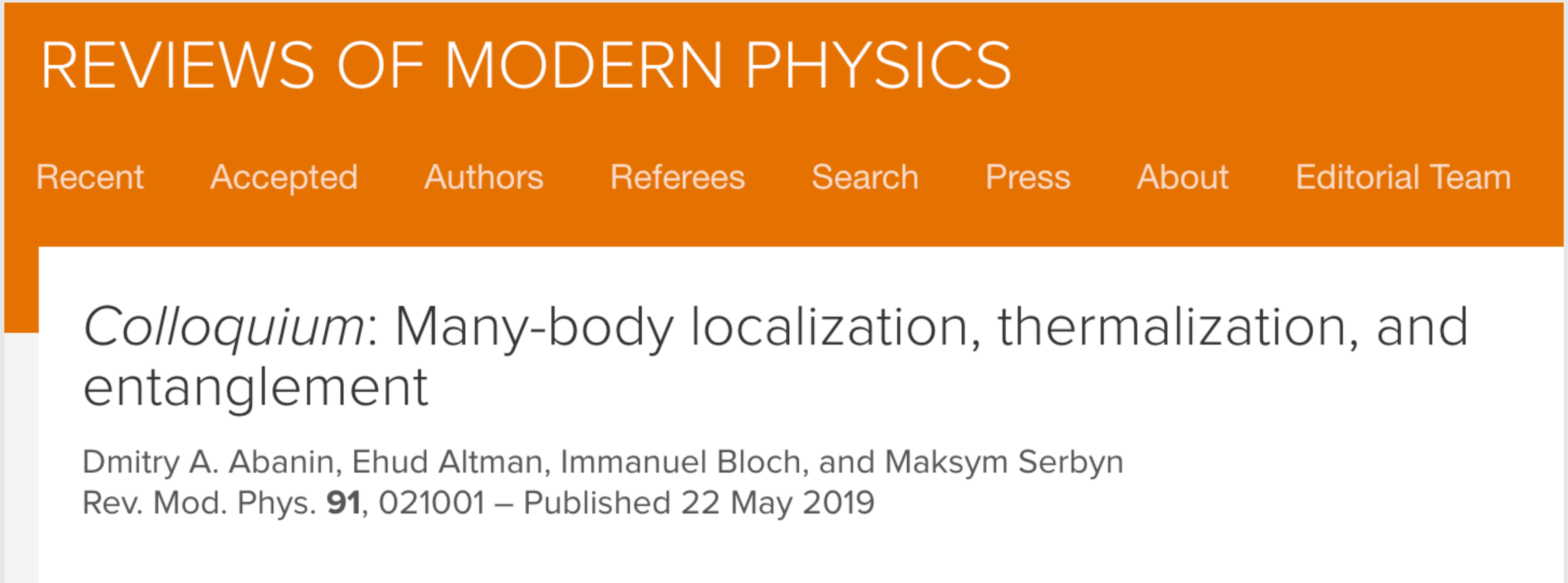
- Beyond finding ground states
- We will be interested in dynamics and the full Hilbert space and spectrum
- Harder, can't use most methods like subspaces

Connection to pre-thermalization and many-body localization



See earlier lectures by David Huse, Vedika, …

Many-body localization, thermalization, and entanglement



REVIEWS OF MODERN PHYSICS

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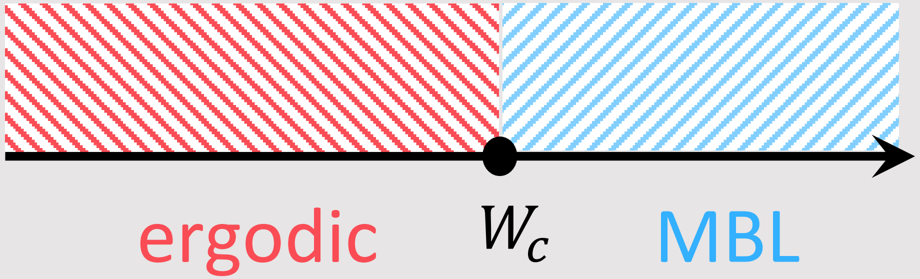
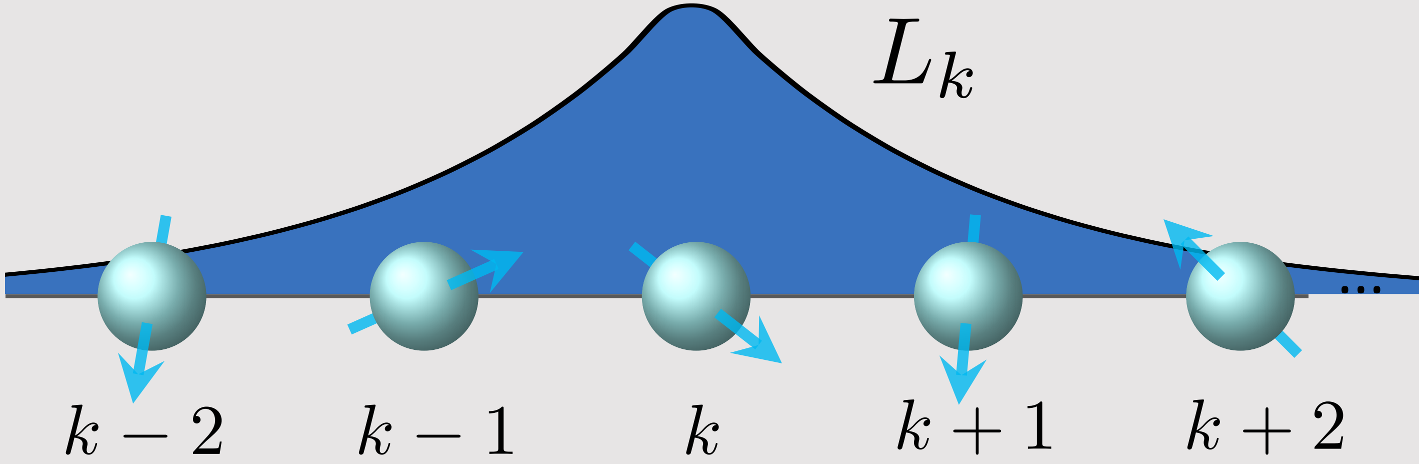
Colloquium: Many-body localization, thermalization, and entanglement

Dmitry A. Abanin, Ehud Altman, Immanuel Bloch, and Maksym Serbyn

Rev. Mod. Phys. **91**, 021001 – Published 22 May 2019

Connection to pre-thermalization and many-body localization





Hypothesis: In the MBL regime, the original Hamiltonian

$$H = \sum_k \epsilon_k L_k + \sum_{k<j} J^{(2)}_{kj} L_k L_j + \sum_{i<j<k} J^{(3)}_{ijk} L_i L_j L_k + \cdots$$

Basko, Aleiner, Altshuler, Ann Phys (2006)
Pal and Huse, RRB (2010)
Serbyn, Papic, Abanin, PRL (2013)
Huse, Nandkishore, Oganesyan PRB (2014)
...

See earlier lectures by David Huse, Vedika, …

Local integrals of motion (LIOM): Ergodicity breaking and many-body localization

Prototypical phenomenon:
prethermalization and **many-body localization (MBL)**

Goes back to Anderson and **disordered** systems,
but this was single non-interacting particles

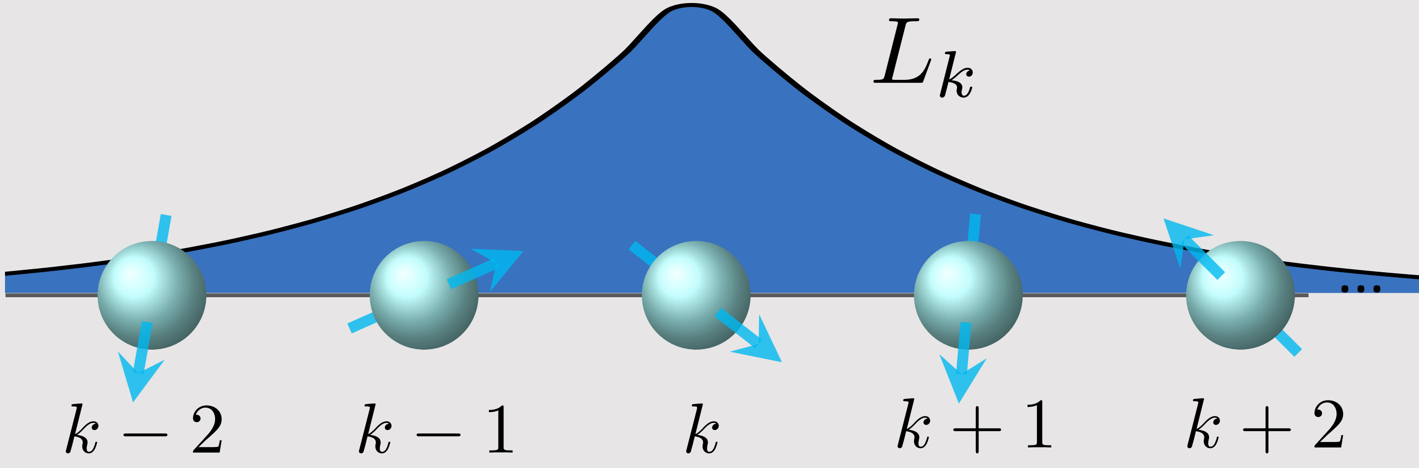
"for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems"

Existence of MBL phase is under debate.
Most of community agree that MBL exists in 1D.

- **MBL systems** have extensive set of local integrals of motion (LIOMs).
- **Prethermal systems (non-MBL)** can have approximate LIOMs

$$\left[e^{-iHt}, L_k\right] \approx 0$$

- We uncover LIOMs in 1D and approximate LIOMs in 2D in 104 and 124 qubit lattices using a digital quantum computer



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Pal and Huse, RRB (2010)
Serbyn, Papic, Abanin, PRL (2013)
Huse, Nandkishore, Oganesyan PRB (2014)
...

Experiments related to MBL

- M. Schreiber, S. S. Hodgman, P. Bordia, H. P. Lu¨schen, M. H. Fischer, R. Vosk, E. Altman, U. Schneider, and I. Bloch, Observation of many-body localization of inter- acting fermions in a quasirandom optical lattice, Science 349, 842 (2015).
- J.-y. Choi, S. Hild, J. Zeiher, P. Schauß, A. Rubio- Abadal, T. Yefsah, V. Khemani, D. A. Huse, I. Bloch, and C. Gross, Exploring the many-body localization transition in two dimensions, Science 352, 1547 (2016).
- J. Smith, A. Lee, P. Richerme, B. Neyenhuis, P. W. Hess, P. Hauke, M. Heyl, D. A. Huse, and C. Monroe, Many-body localization in a quantum simulator with pro- grammable random disorder, Nat. Phys. 12, 907 (2016).
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- M. Rispoli, A. Lukin, R. Schittko, S. Kim, M. E. Tai, J. L´eonard, and M. Greiner, Quantum critical behaviour at the many-body localization transition, Nature 573, 385 (2019).
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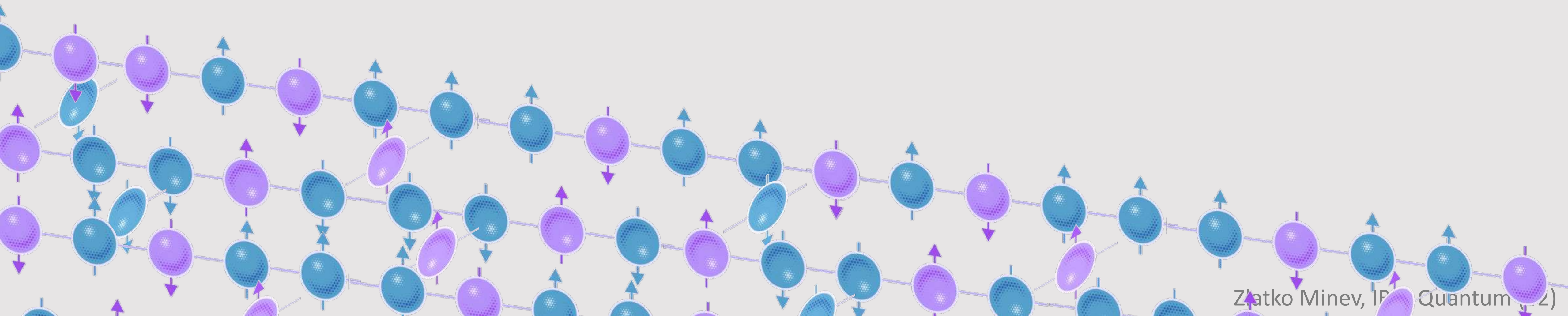
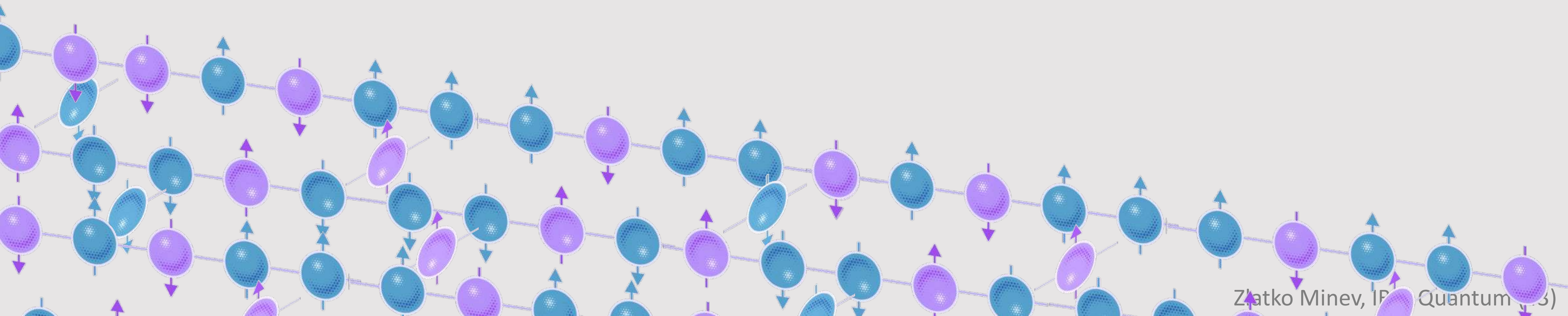
- ……

Can we uncover the integrals of motion $\{L\}$
of a large, disordered many-body system
using a digital quantum computer?



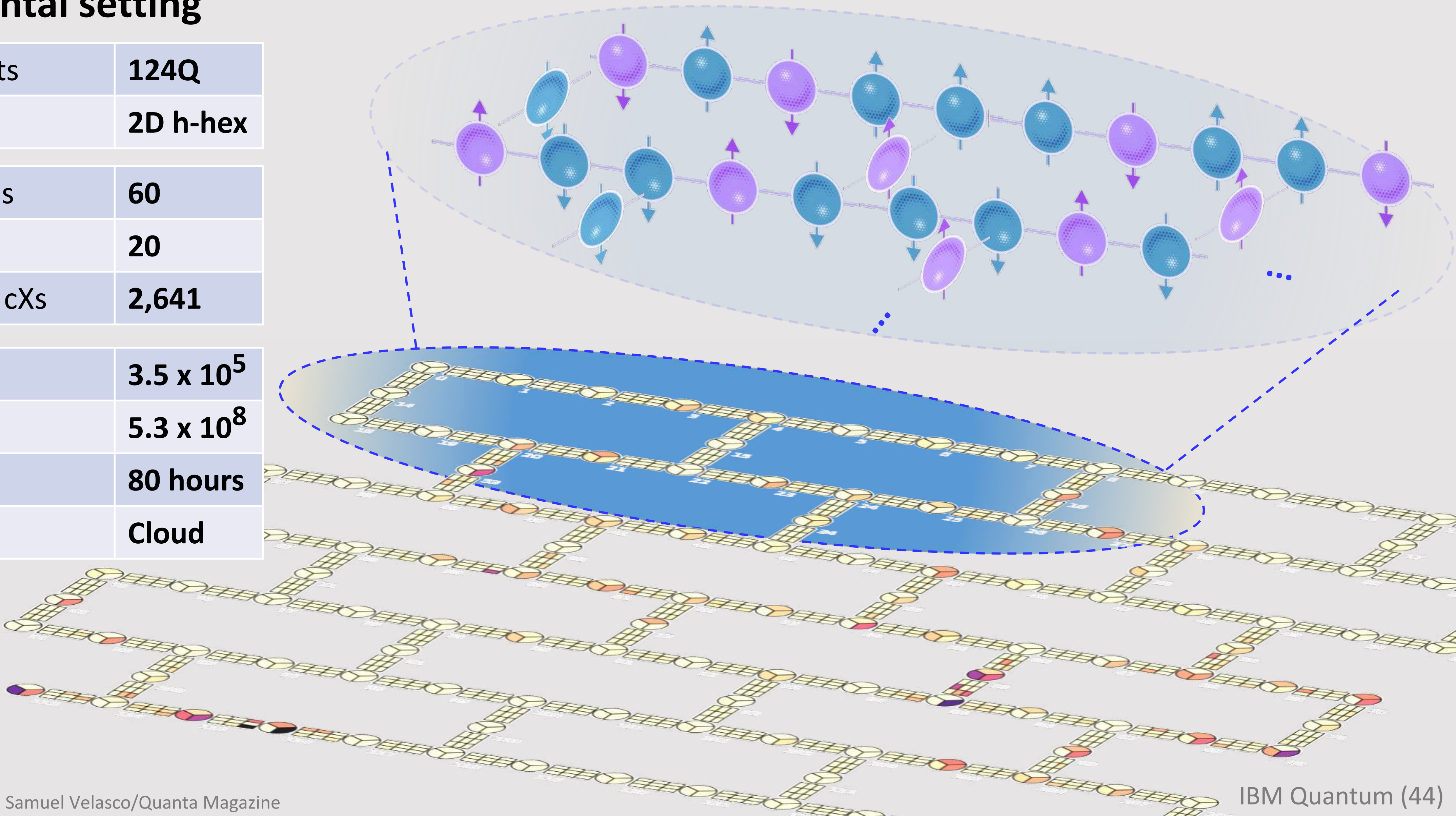
Preview



QSim on 100Q+: 2D interacting many-body Floquet system

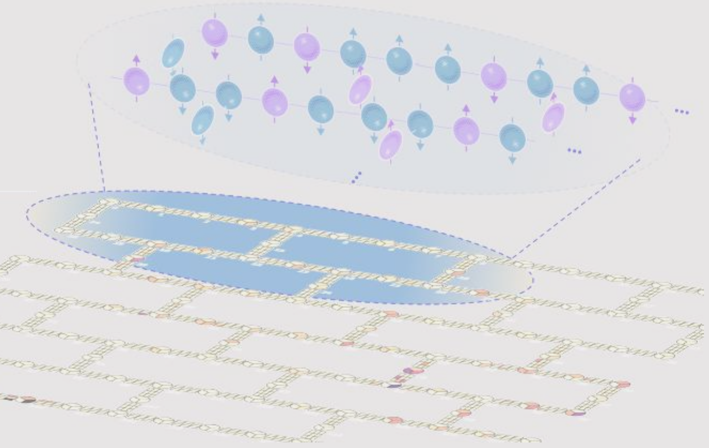
Experimental setting

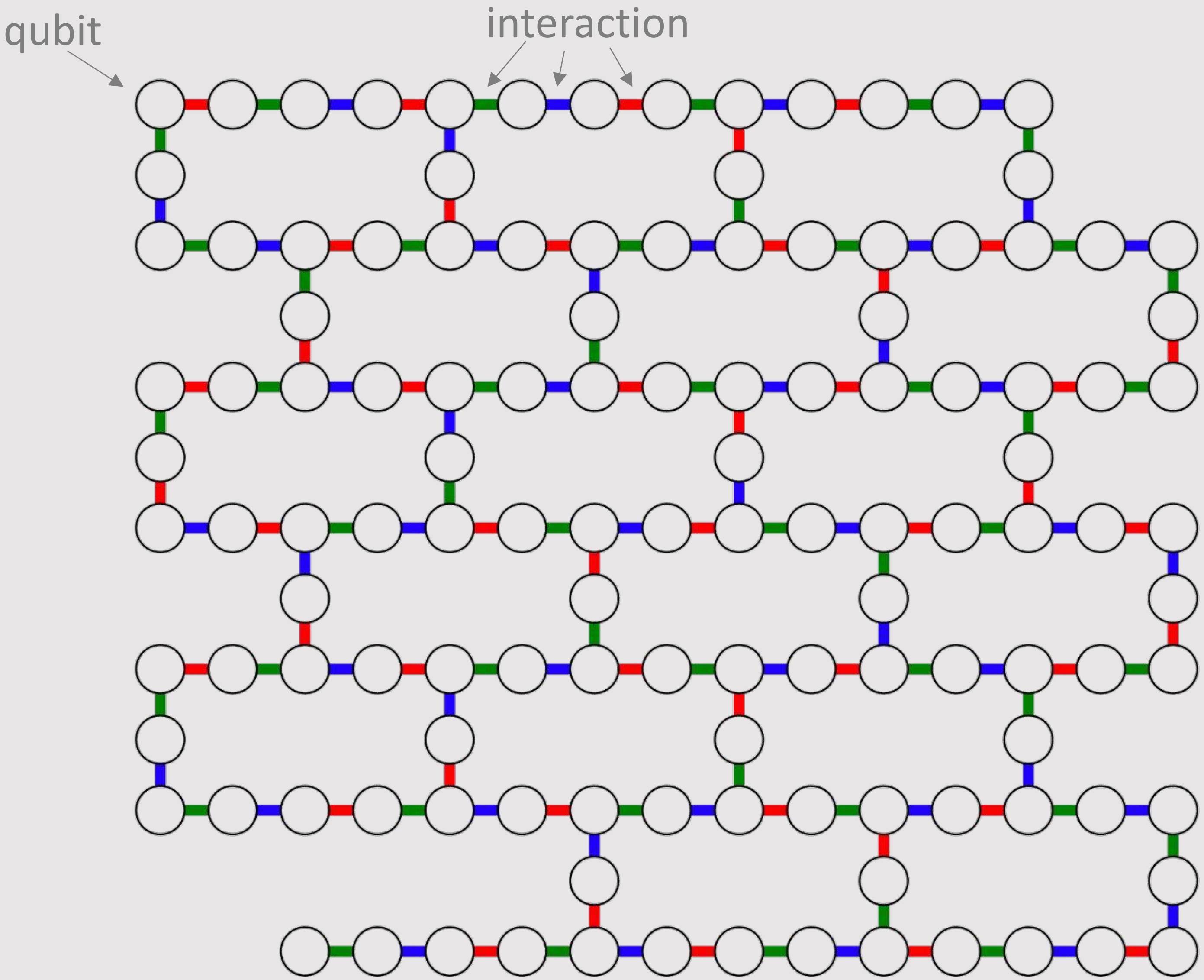
Number of qubits	**124Q**
Connectivity	**2D h-hex**
Depth in cX gates	**60**
Floquet steps	**20**
Total number of cXs	**2,641**
Circuits	**3.5×10^5**
Shots	**5.3×10^8**
QPU runtime	**80 hours**
Environment	**Cloud**



Spin image cartoon based on: Samuel Velasco/Quanta Magazine

Interaction map and device layers





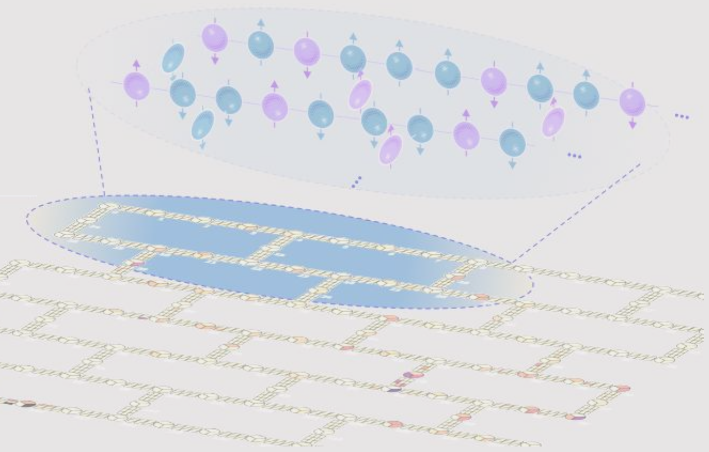
Experimental setting

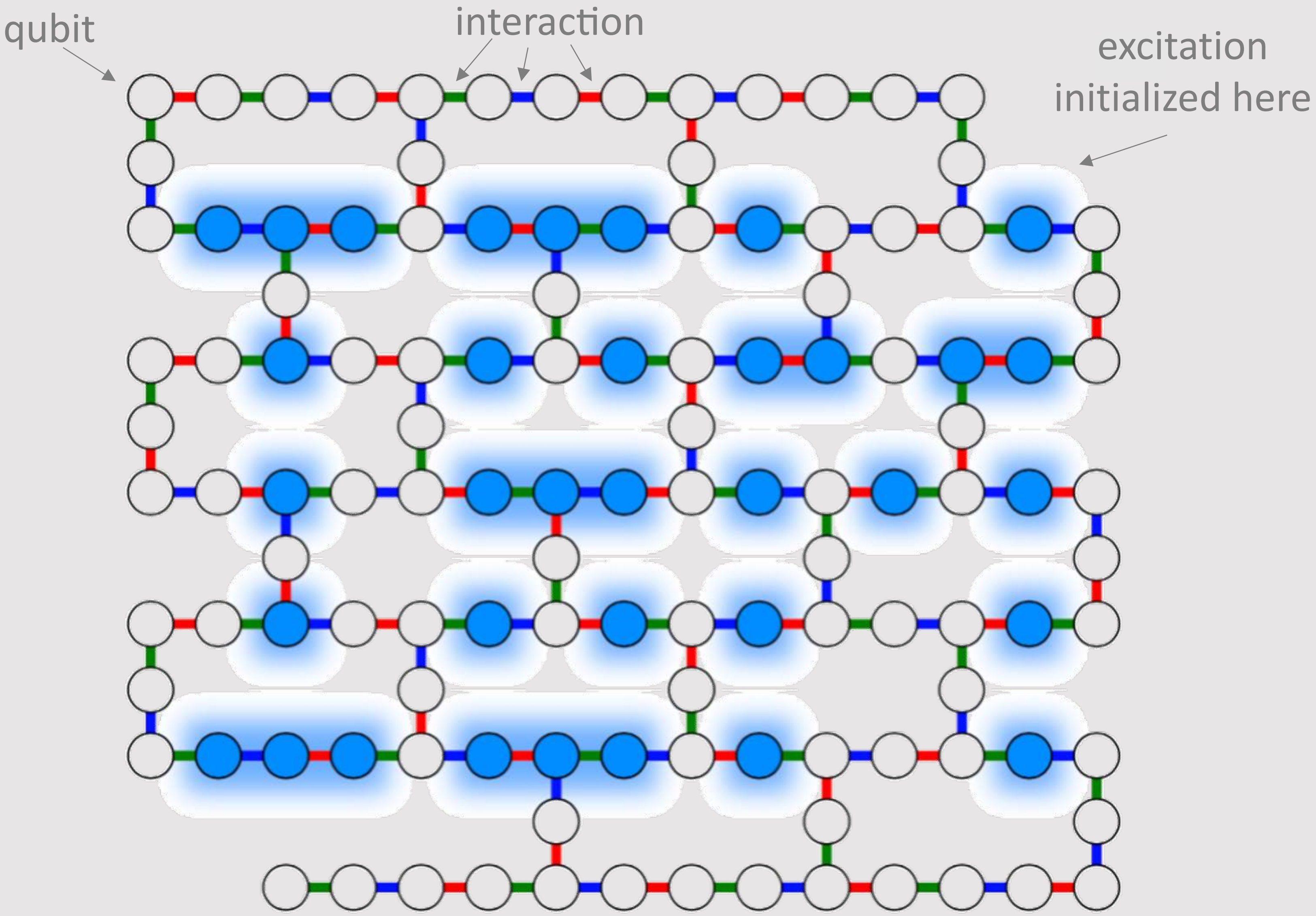
Number of qubits	124Q
Connectivity	2D h-hex
Depth in cNOTs	60
Total number of cNOTS	2,641
Floquet steps	20

Shtanko, Wang, ..., Minev (2023)

Color represent charge/spin polarization

Initialize lattice in fun states





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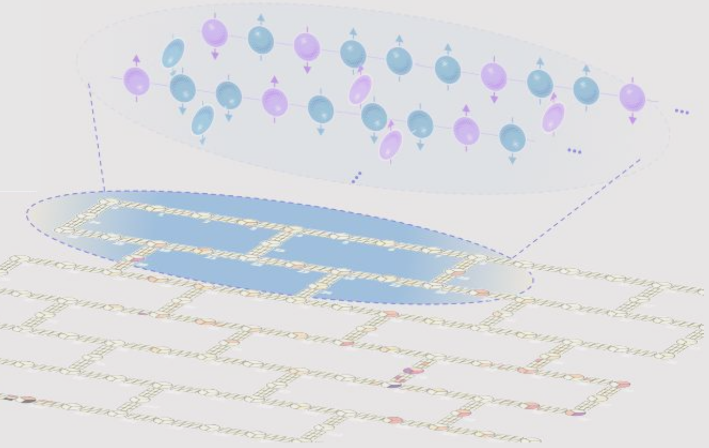
Shtanko, Wang, …, Minev (2023)

Color represent spin polarization

Quantum dynamics in different regimes



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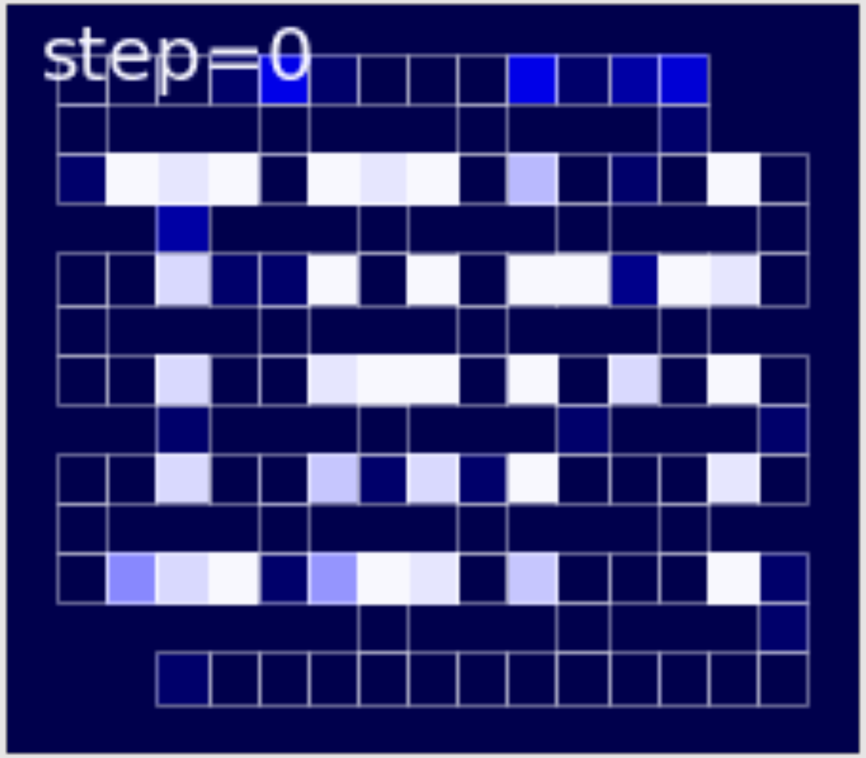
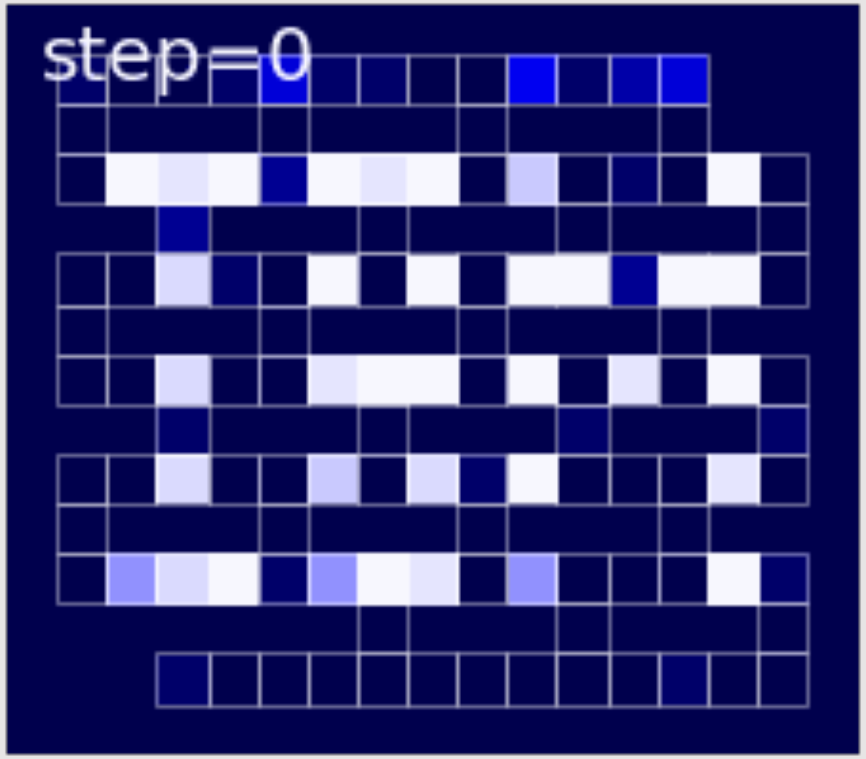
Shtanko, Wang, ..., Minev (2023)



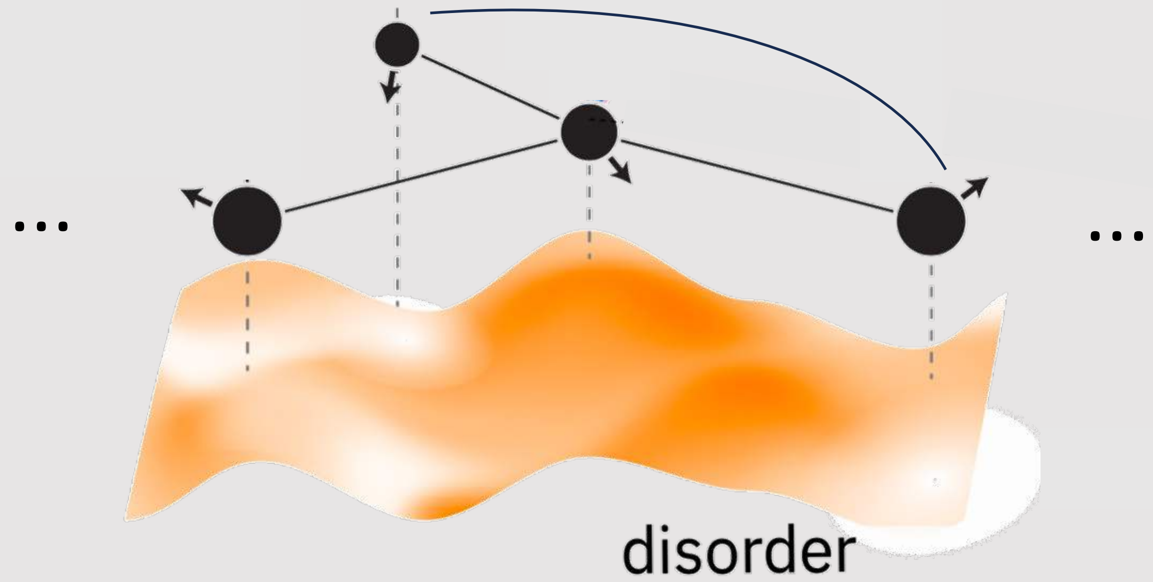
Thermalizing regime



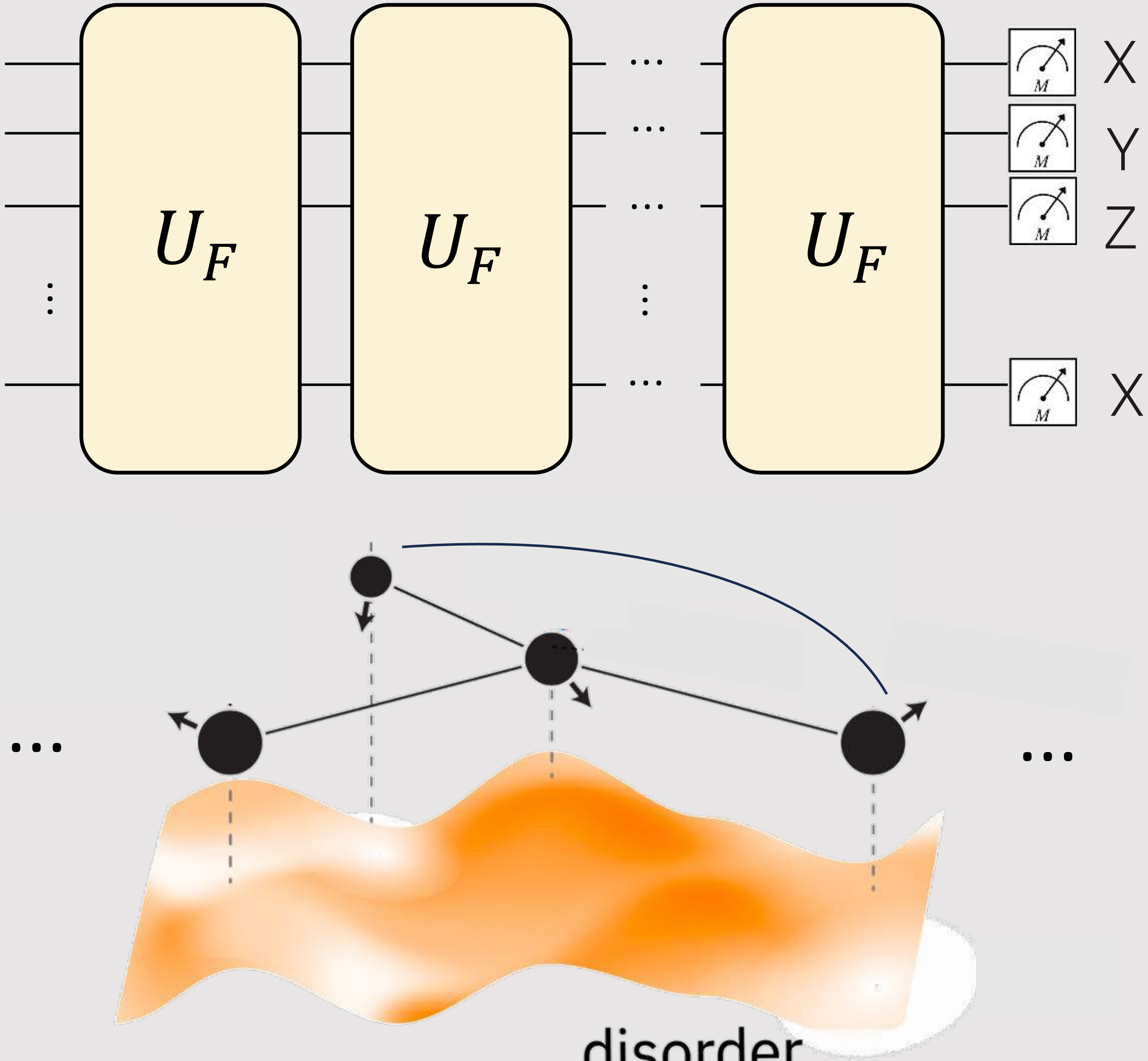
Prethermal regime

Color represent spin polarization

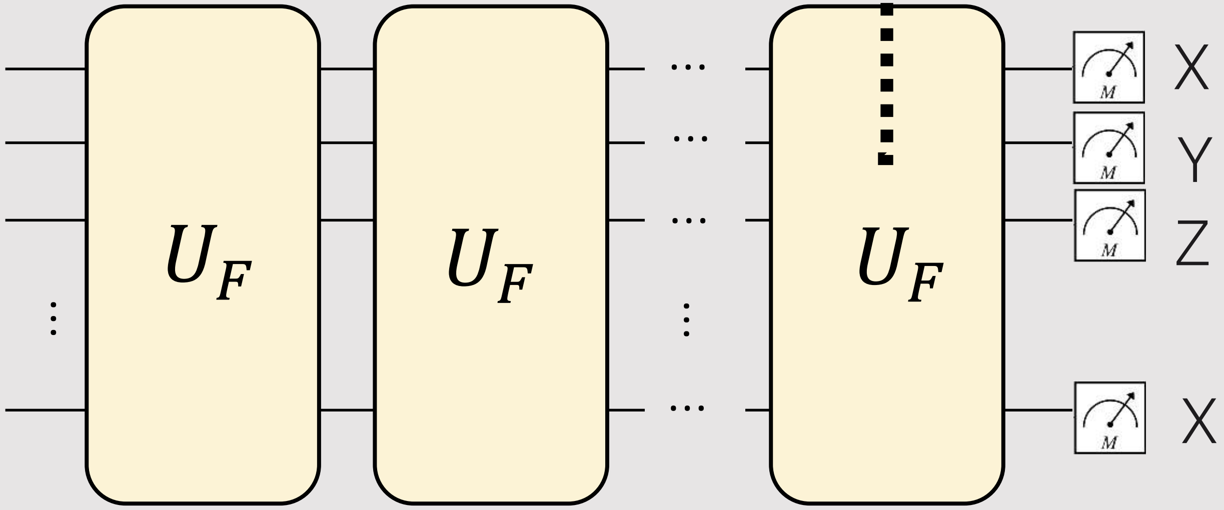
Spin lattice system over some potential

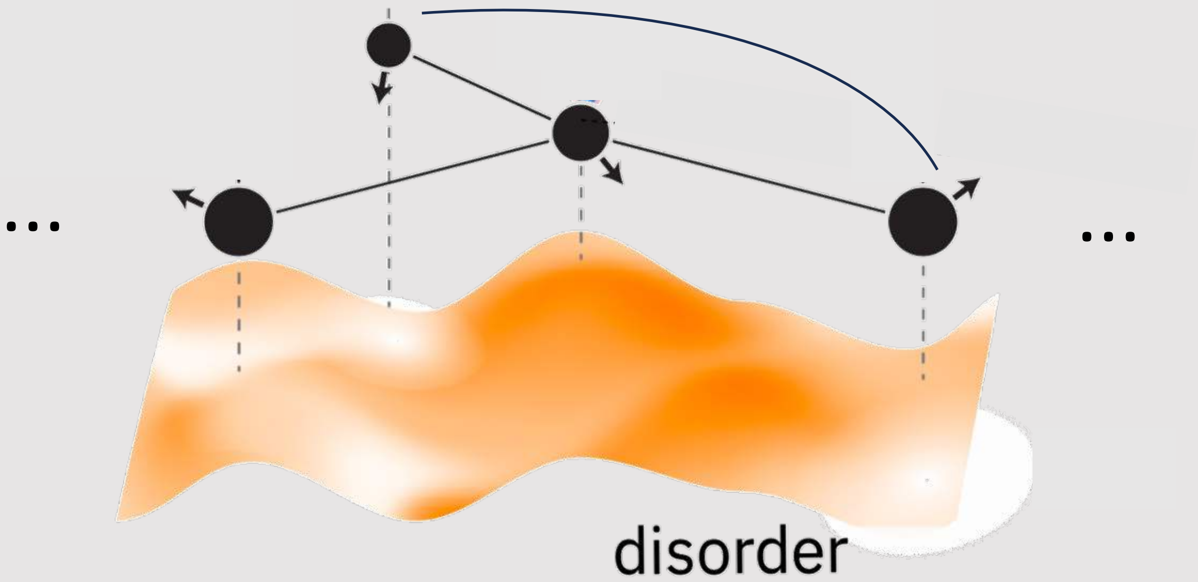


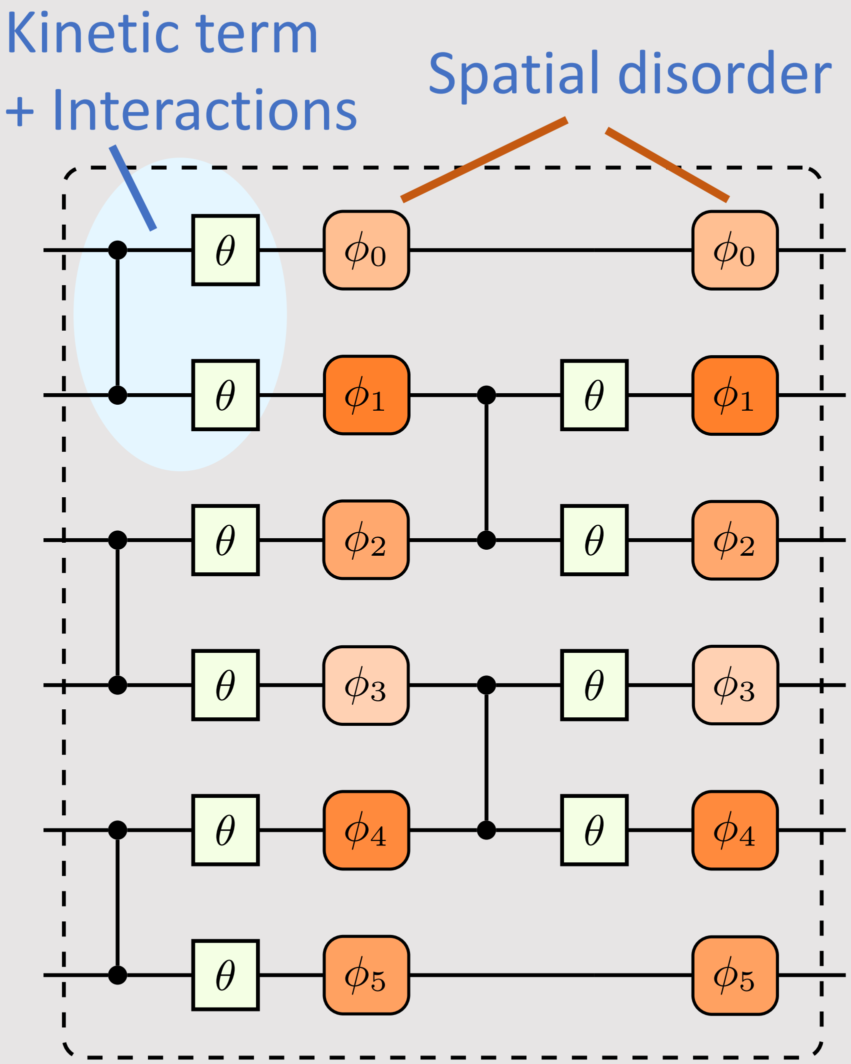
Floquet circuit evolution



Circuit model





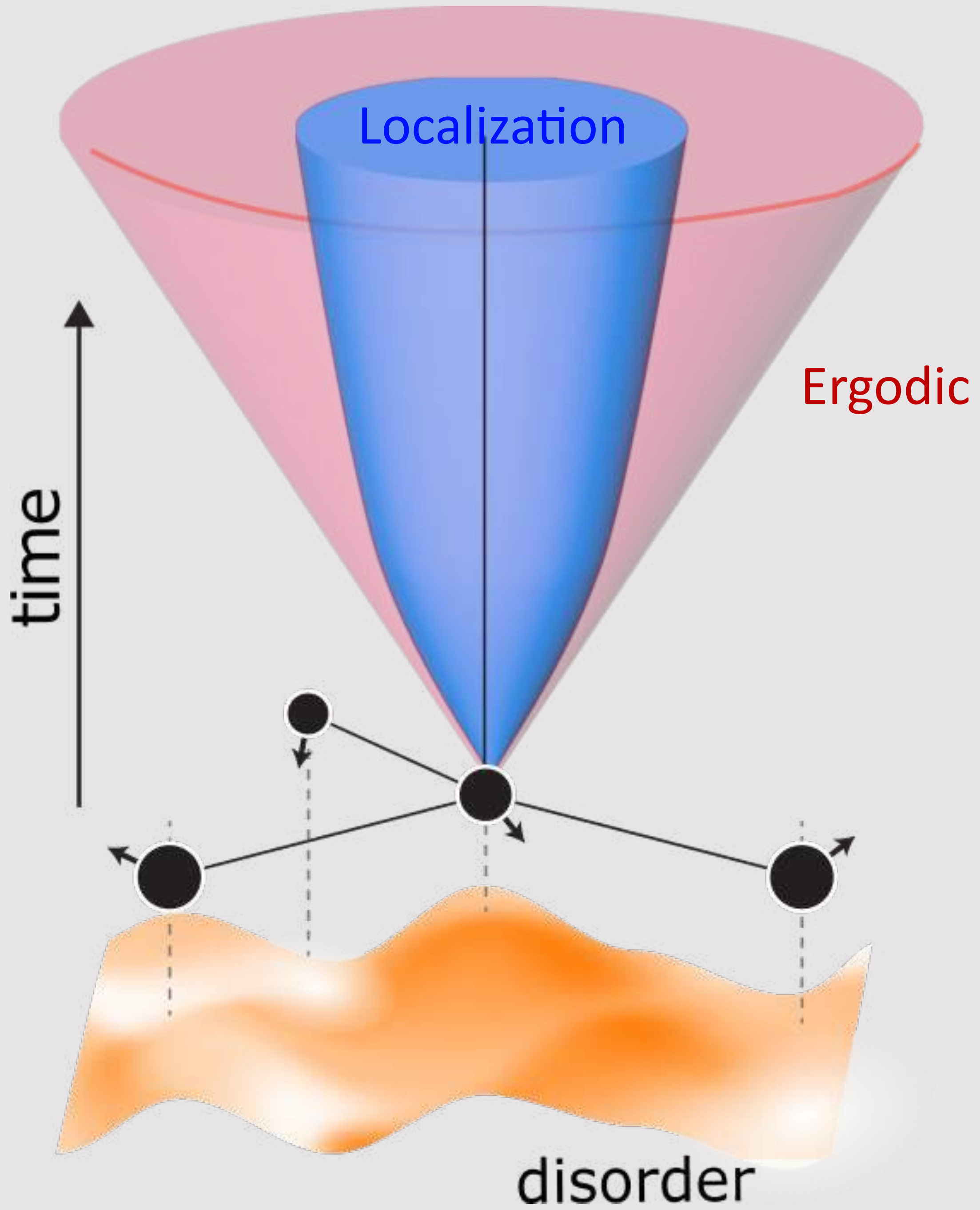


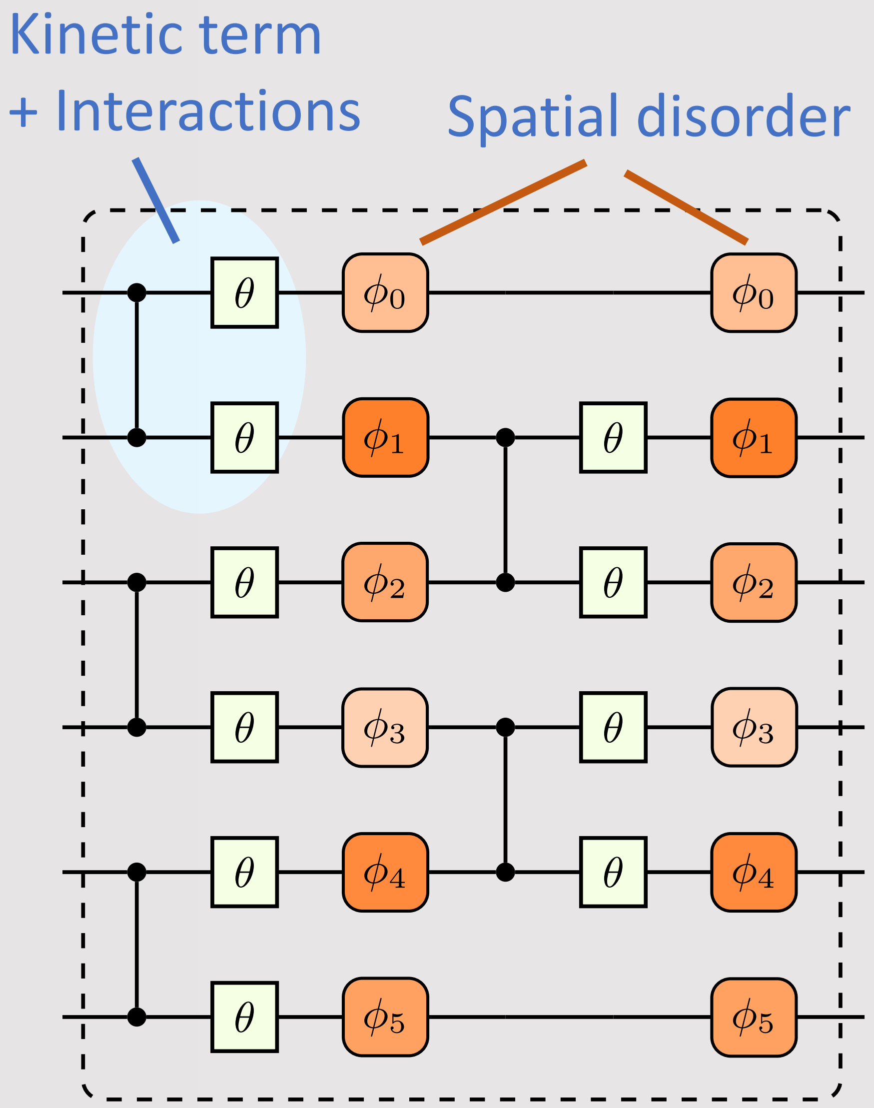
$$P(\phi_k) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi_k} \end{pmatrix}$$

$$\phi_k \in [-\pi, \pi]$$

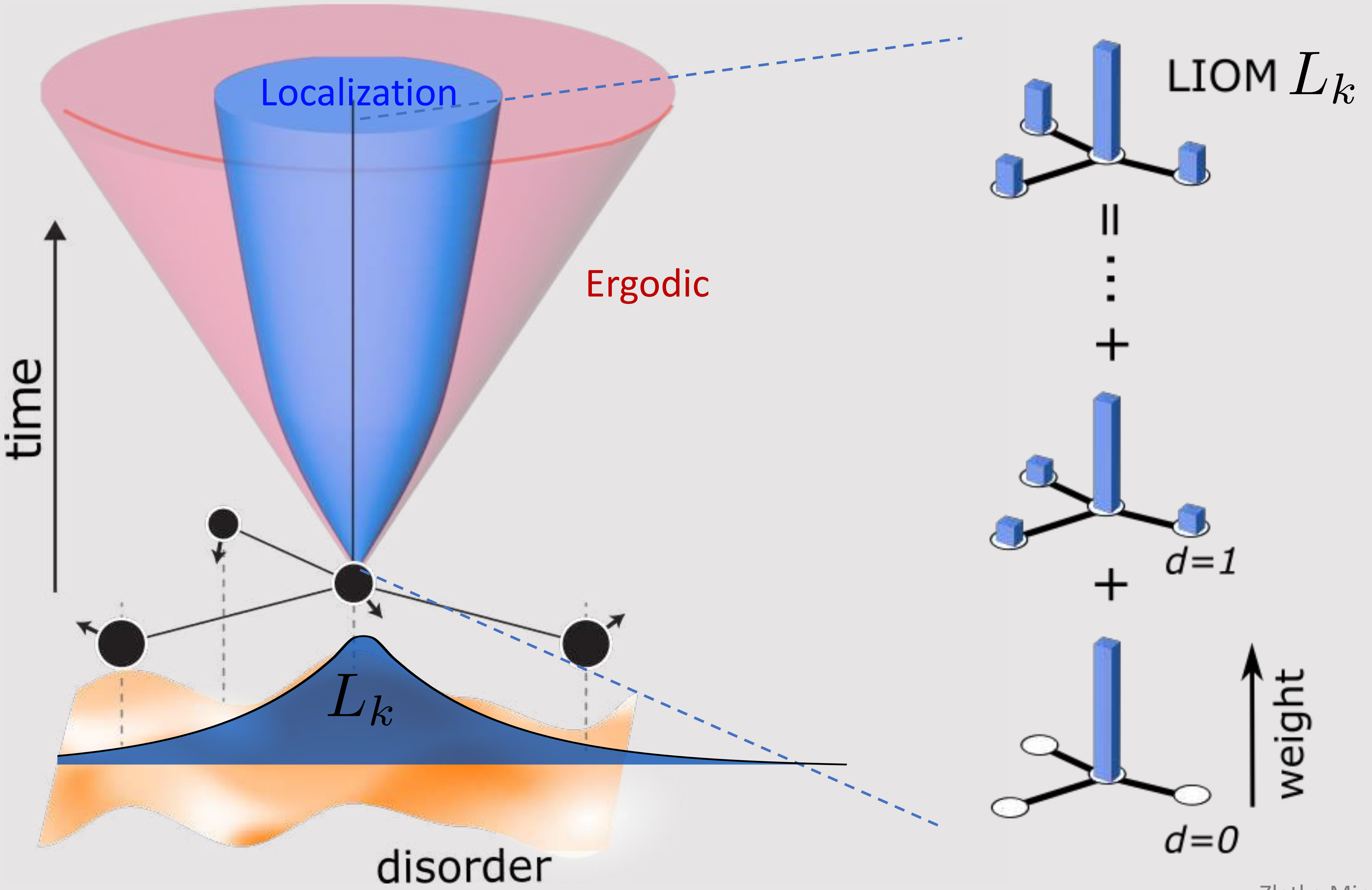
Uniformly sample disorder

$$U(\theta) = \begin{pmatrix} \cos\theta/2 & \sin\theta/2 \\ \sin\theta/2 & -\cos\theta/2 \end{pmatrix}$$



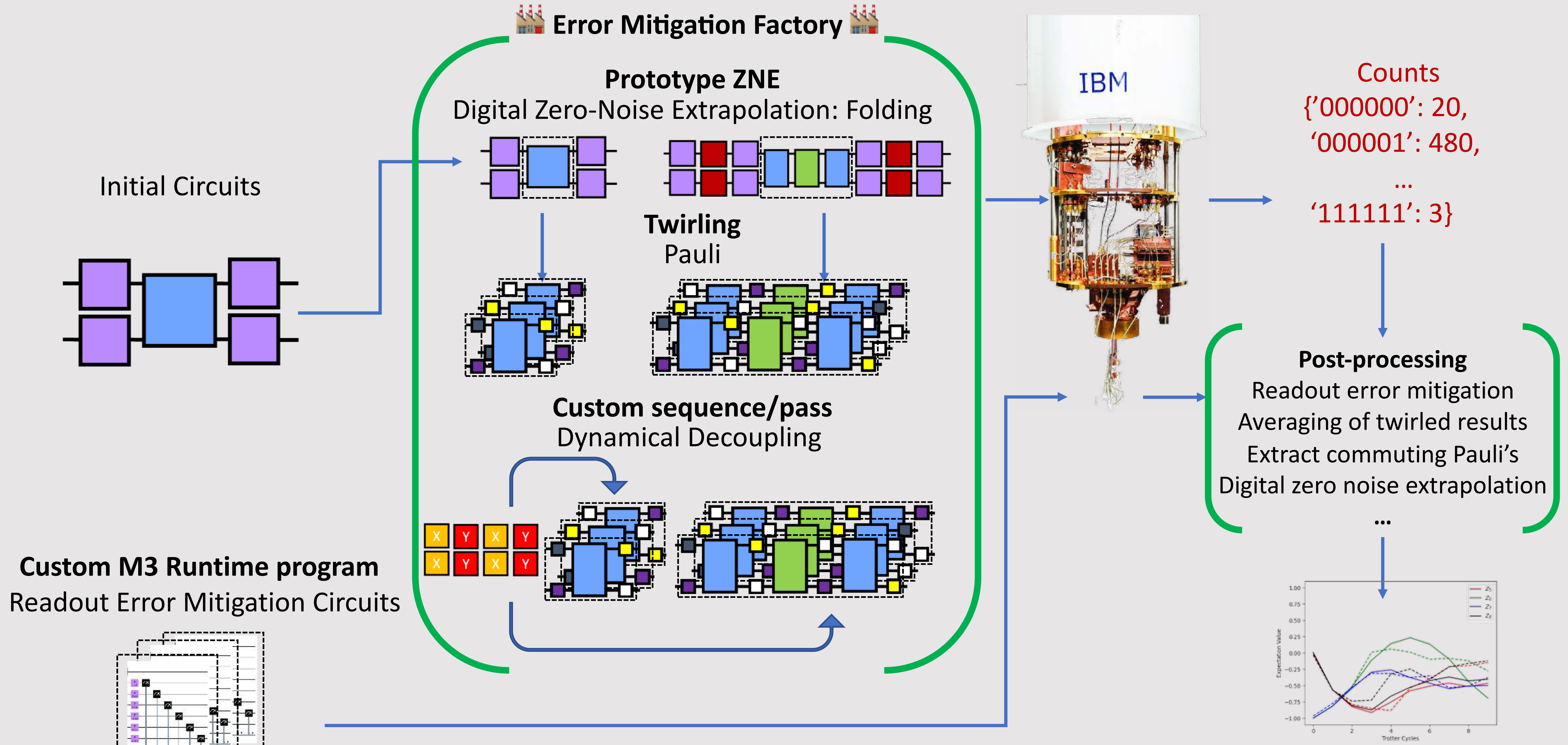


Depends on parameters



Localization
Ergodic
time
L_k
disorder
LIOM L_k
=
⋮
+
+
$d=1$
$d=0$
weight

A composite error mitigation strategy

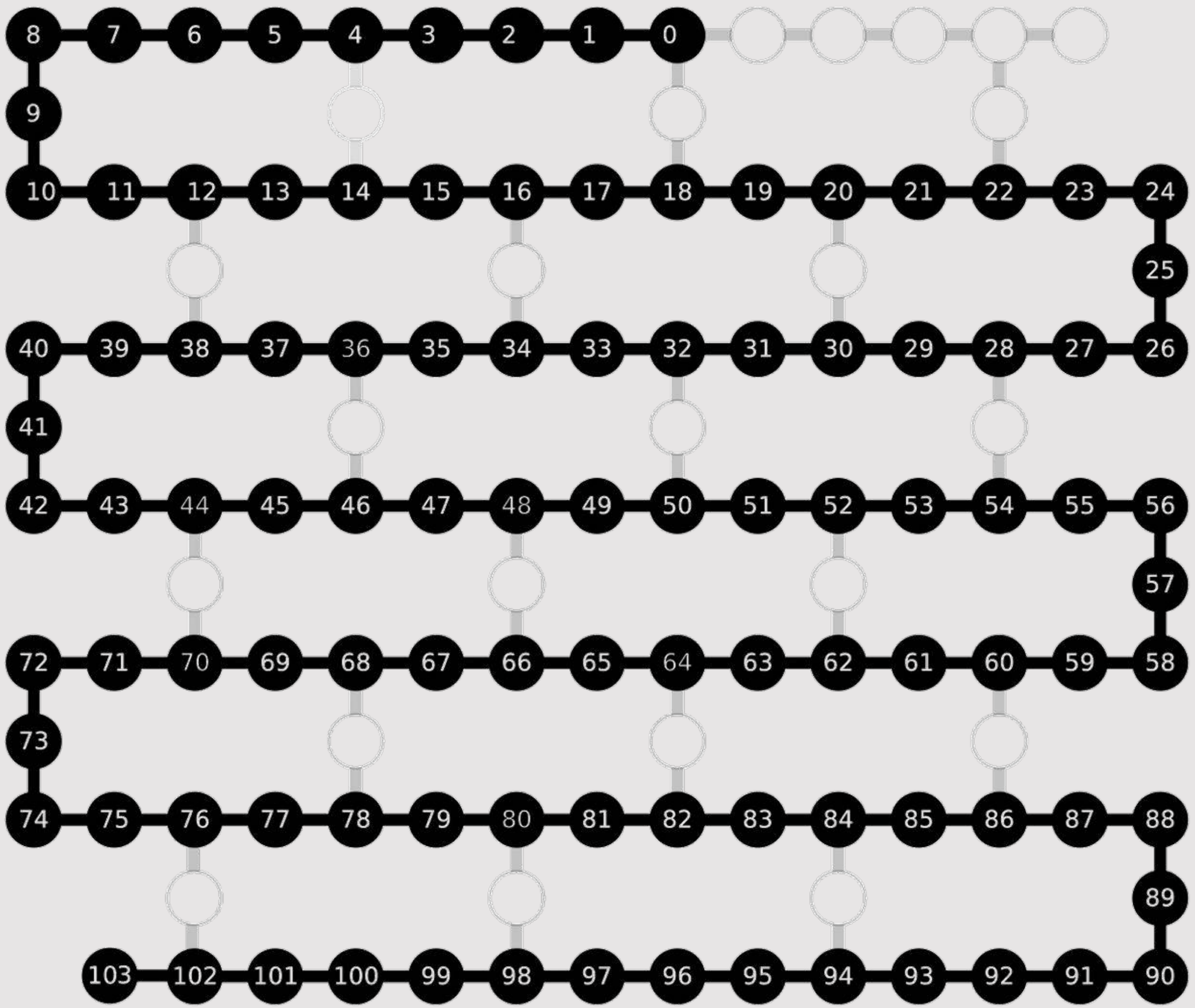


Benchmark quantum hardware and model

Start with 1D

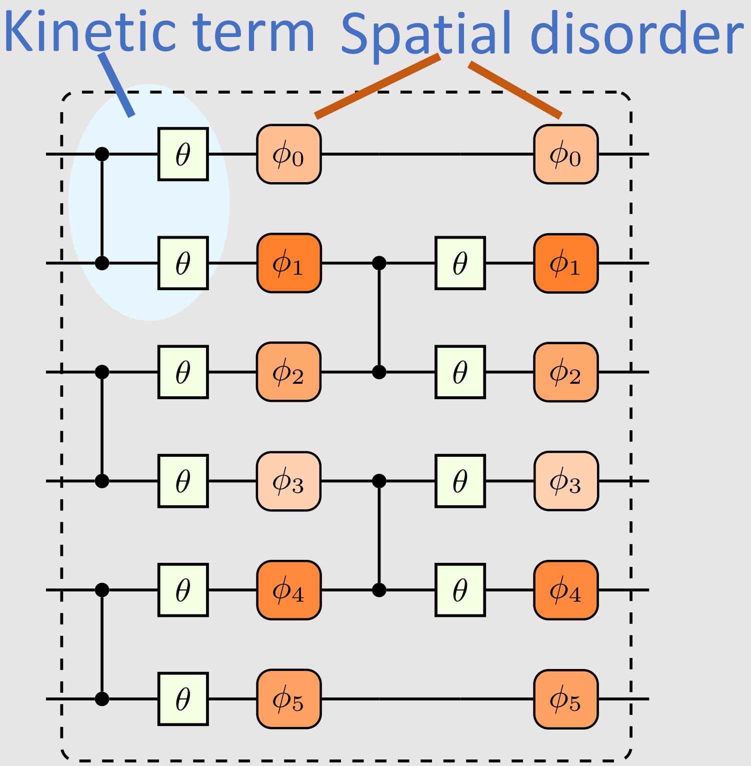
1D spin chain

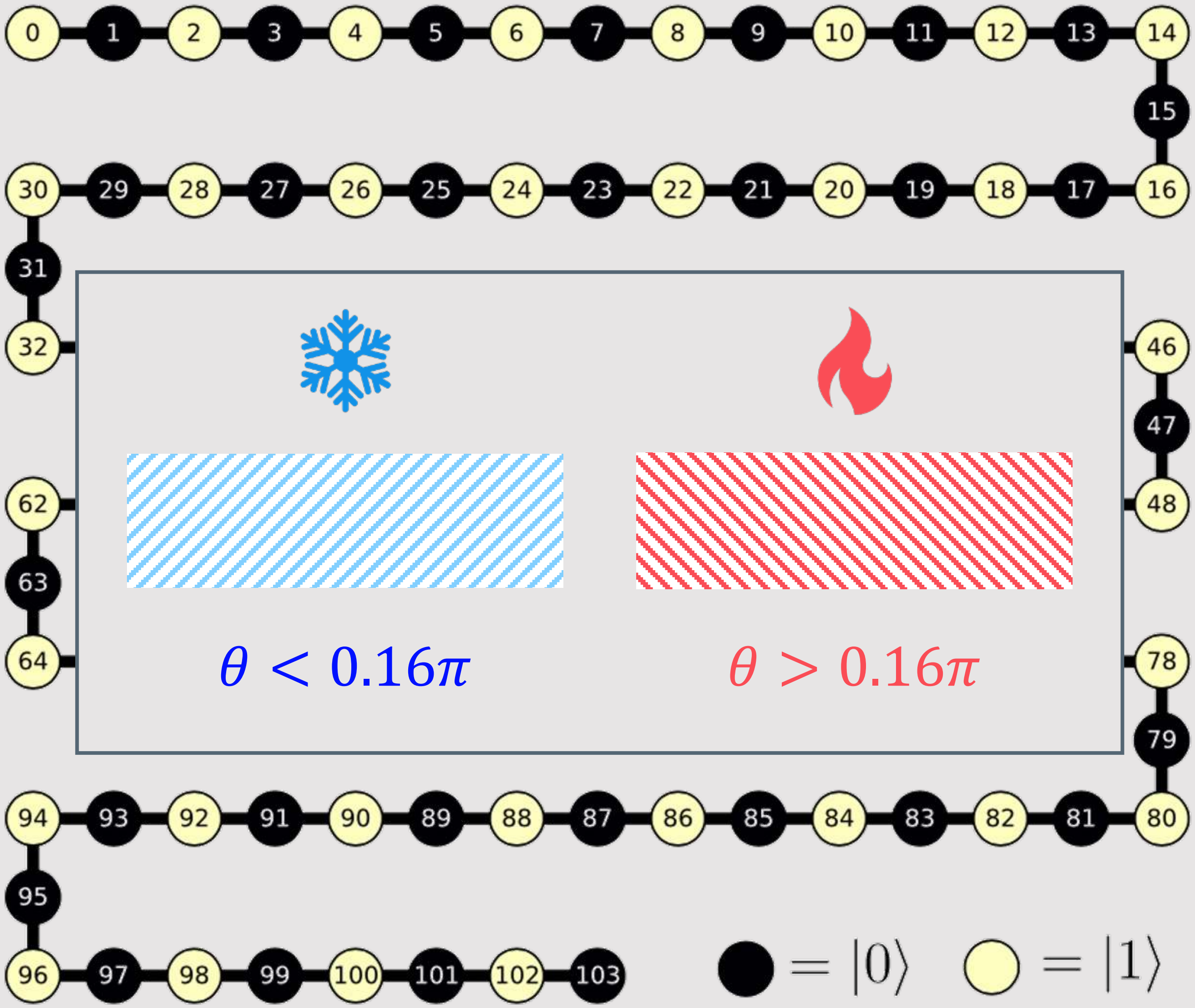
ibmq kolkata
ibm washington



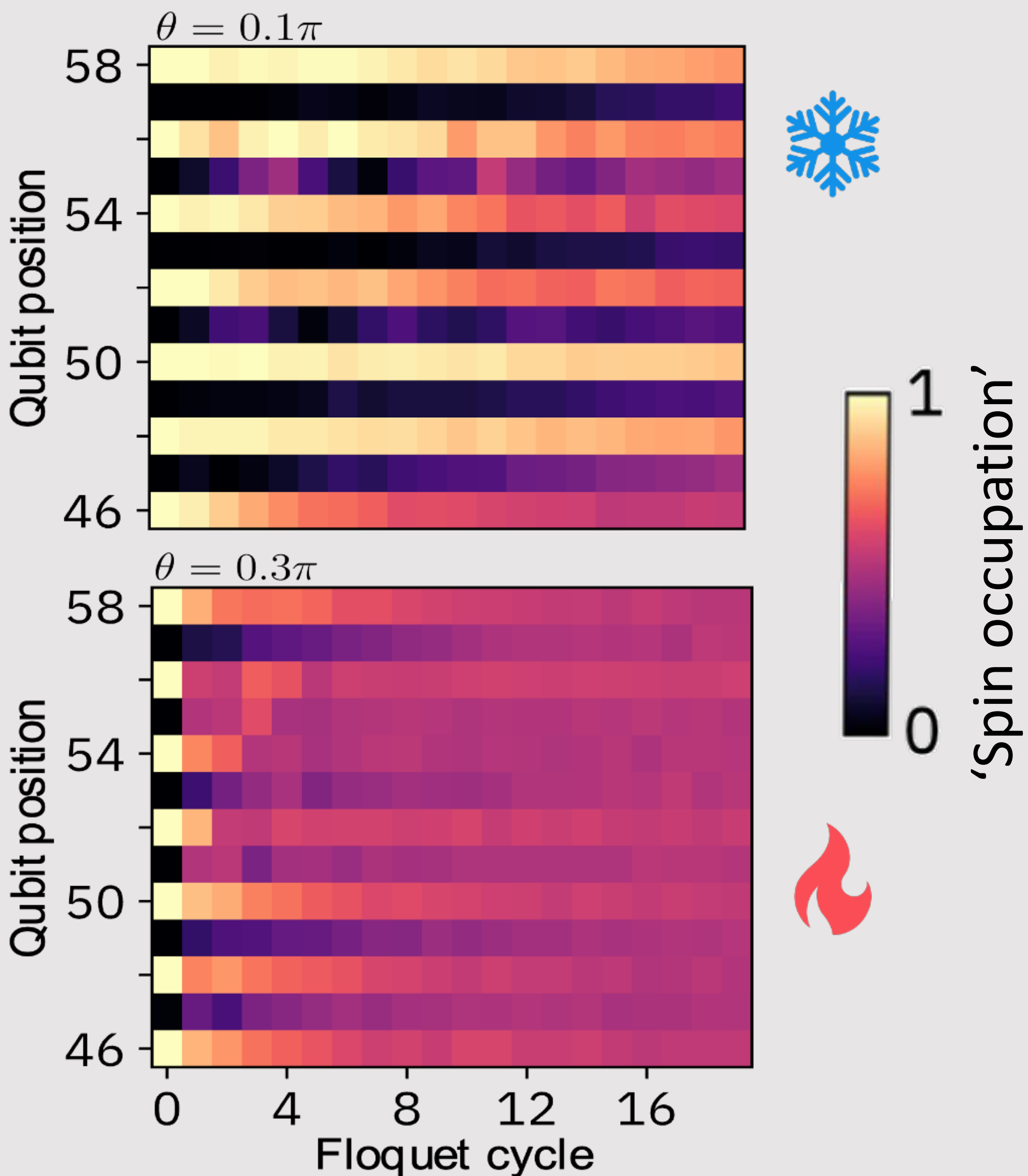
Initial antiferromagnetic state with spin imbalance

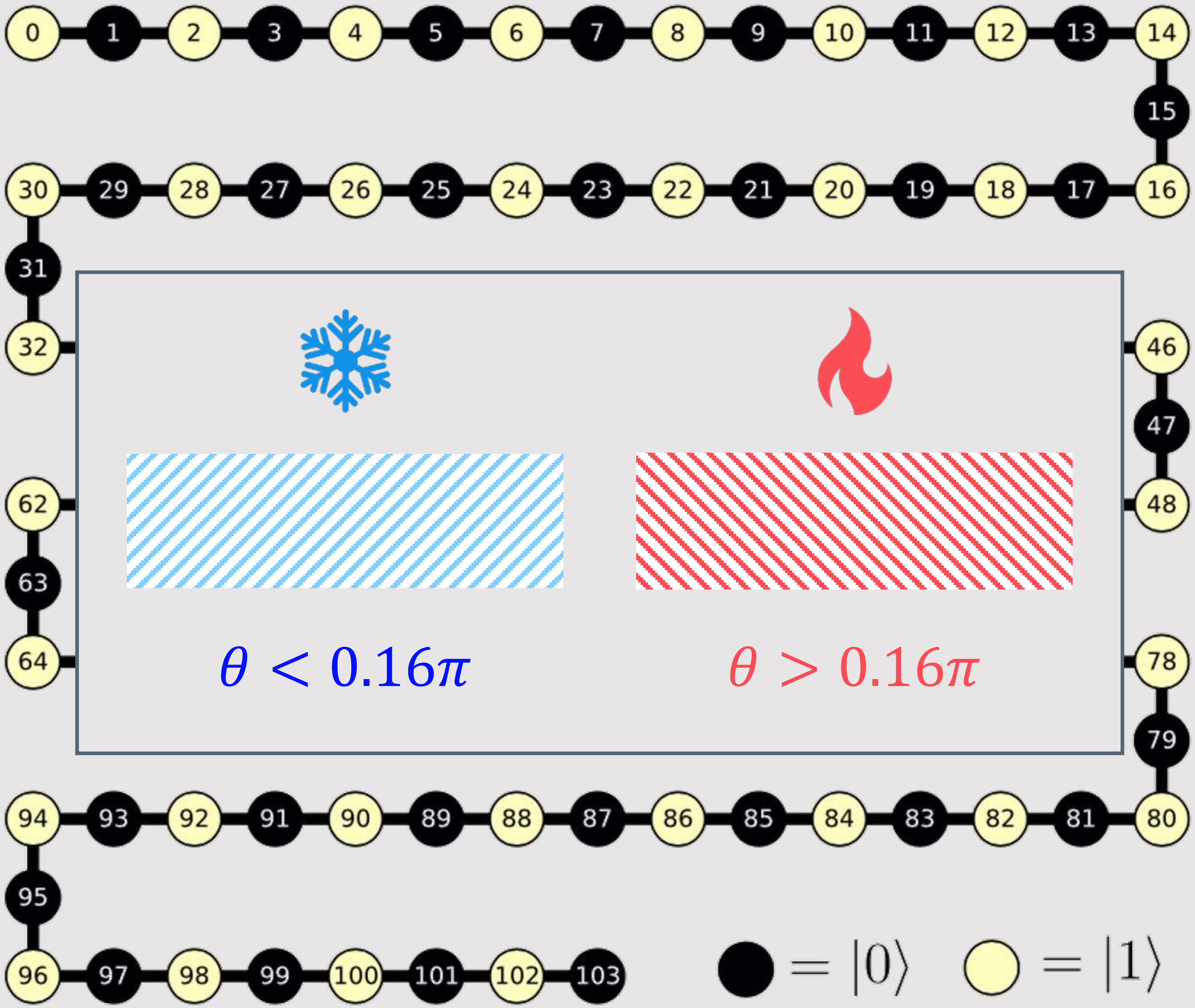
$$|\psi_0\rangle = |1\rangle|0\rangle|1\rangle|0\rangle|1\rangle|0\rangle \dots |1\rangle|0\rangle|1\rangle|0\rangle|1\rangle$$



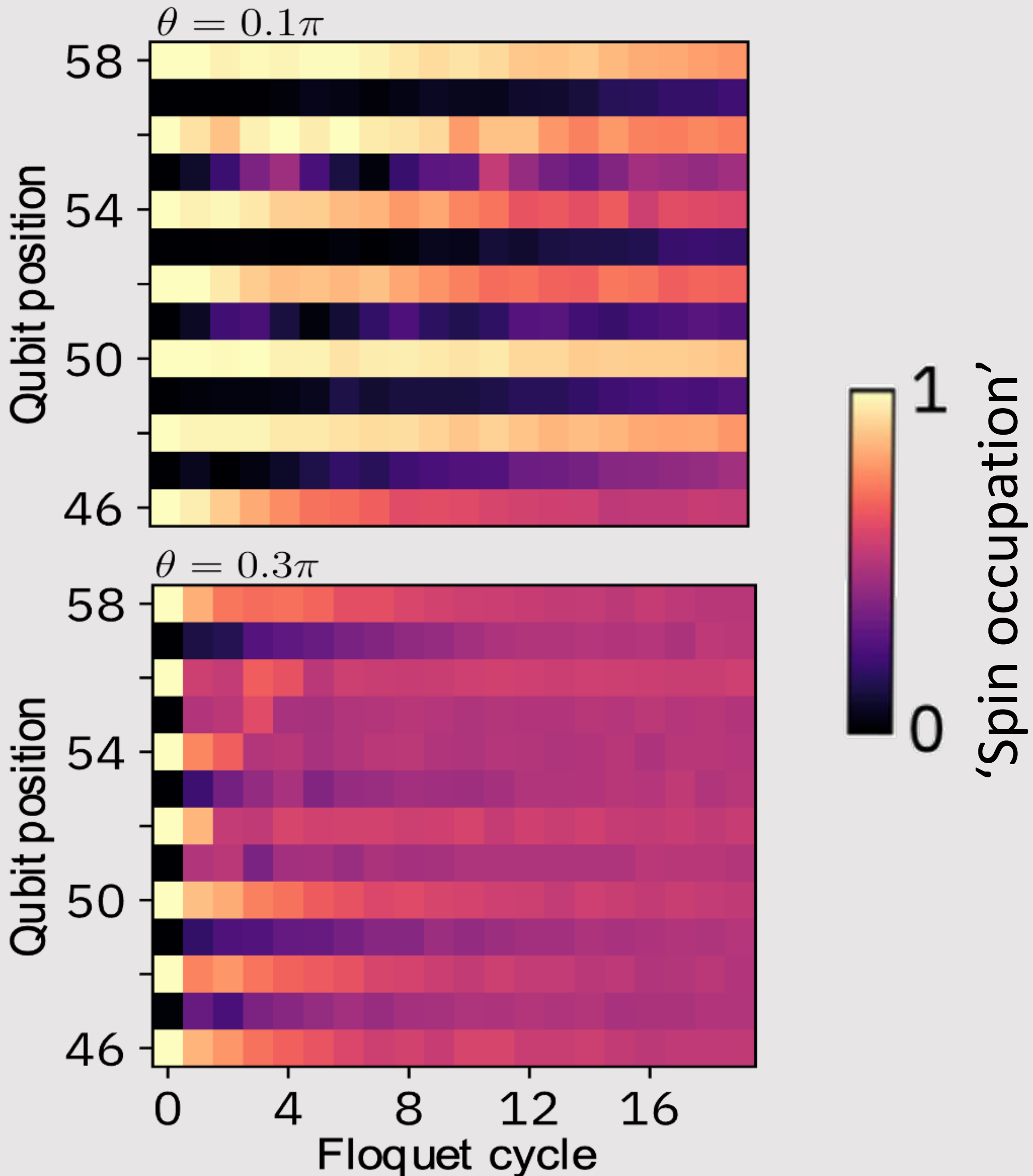


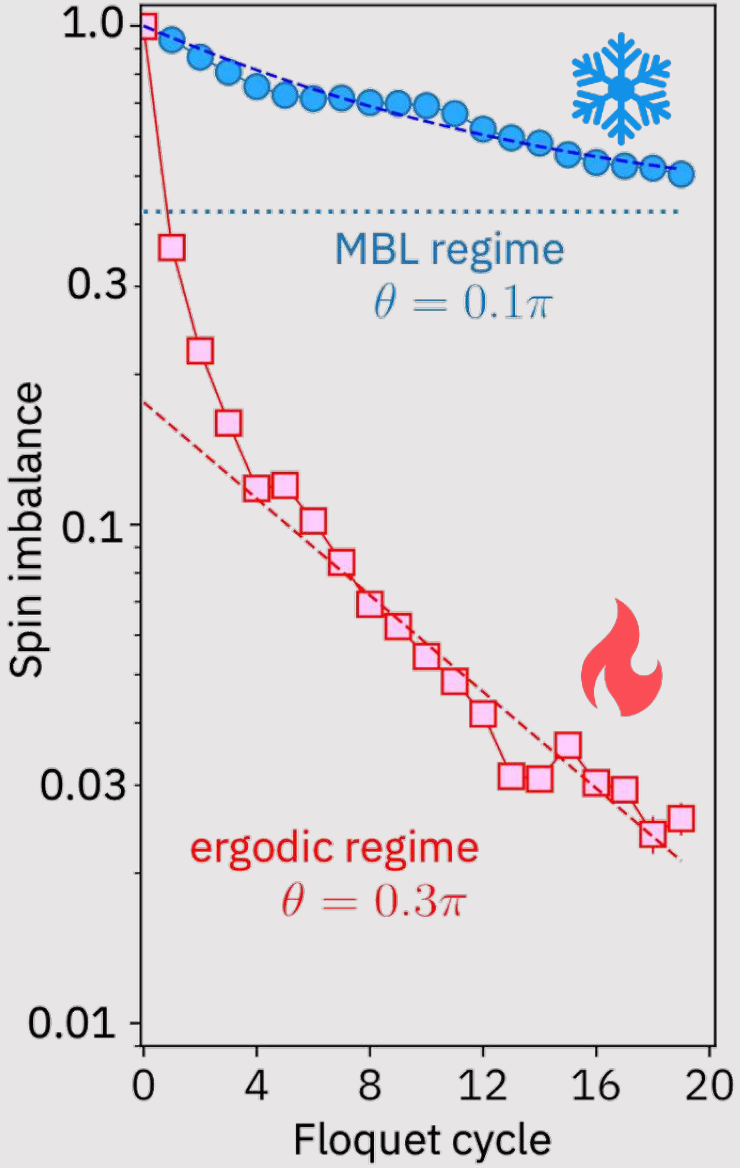
Time evolution of the antiferromagnetic state





Memory of the initial state





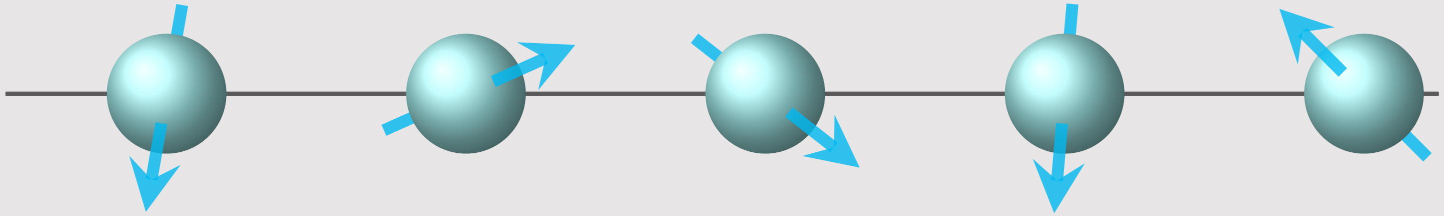
$$\mathcal{J} = \frac{n_1 - n_0}{n_1 + n_0}$$

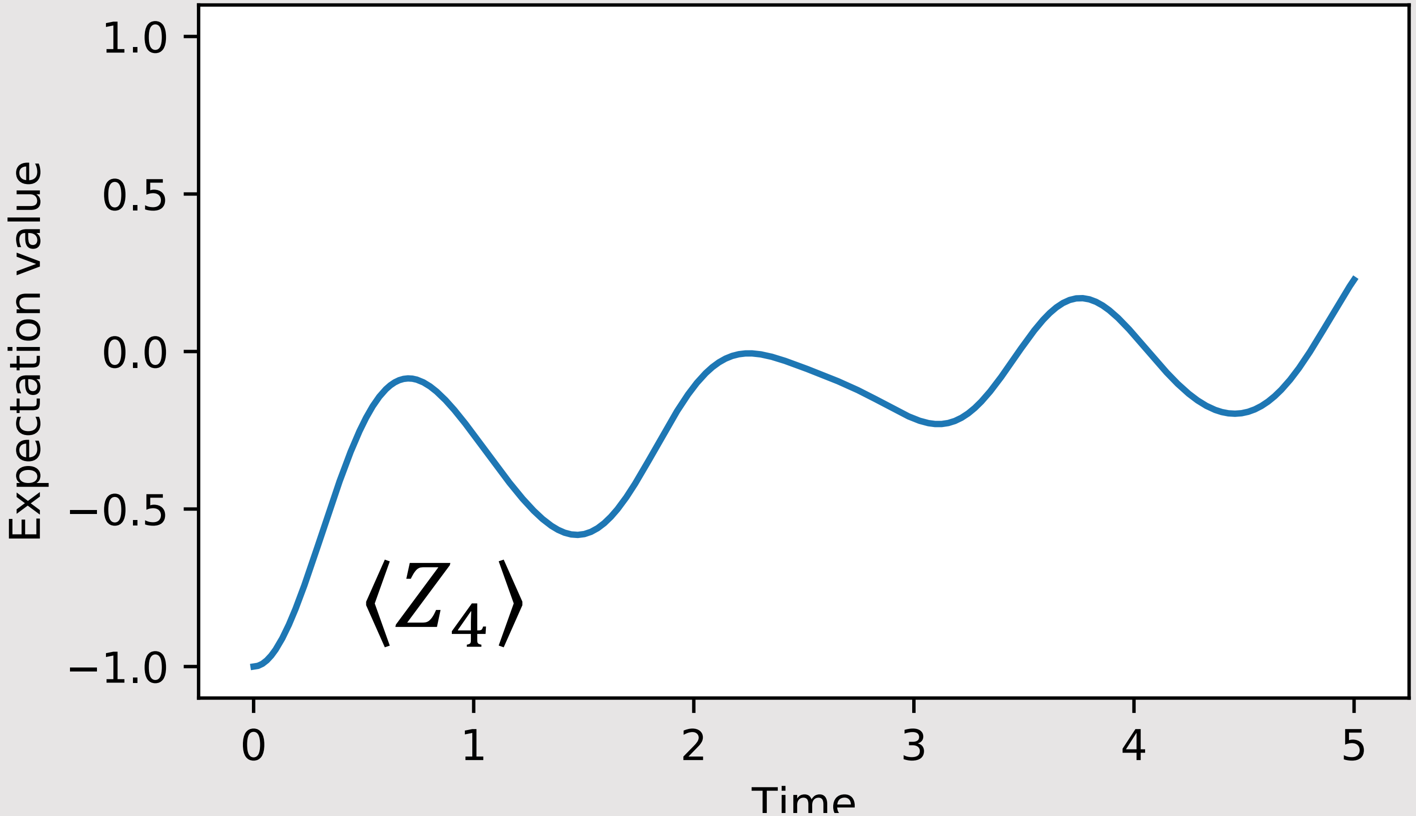
$$n_k = \frac{1}{2}\mathbb{E}(1 - \langle Z_i \rangle)$$

With error mitigation

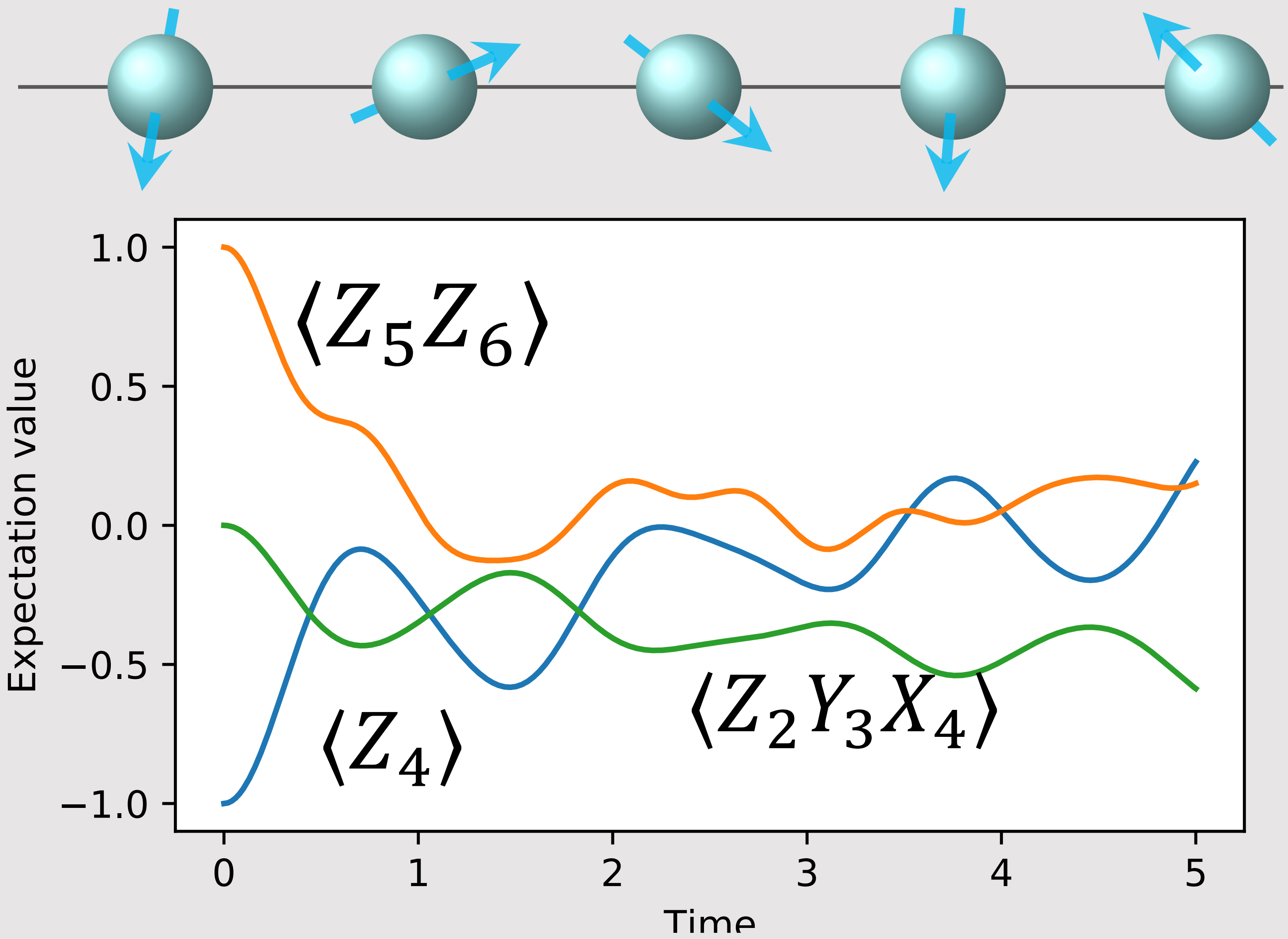
Local integrals of motion (LIOMs)

Consider some spin chain

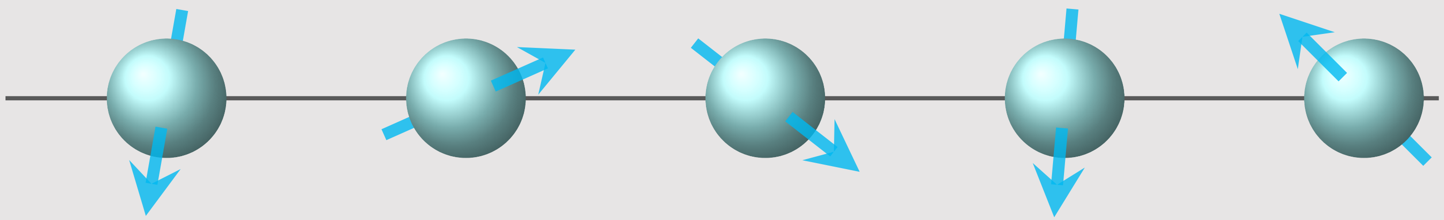


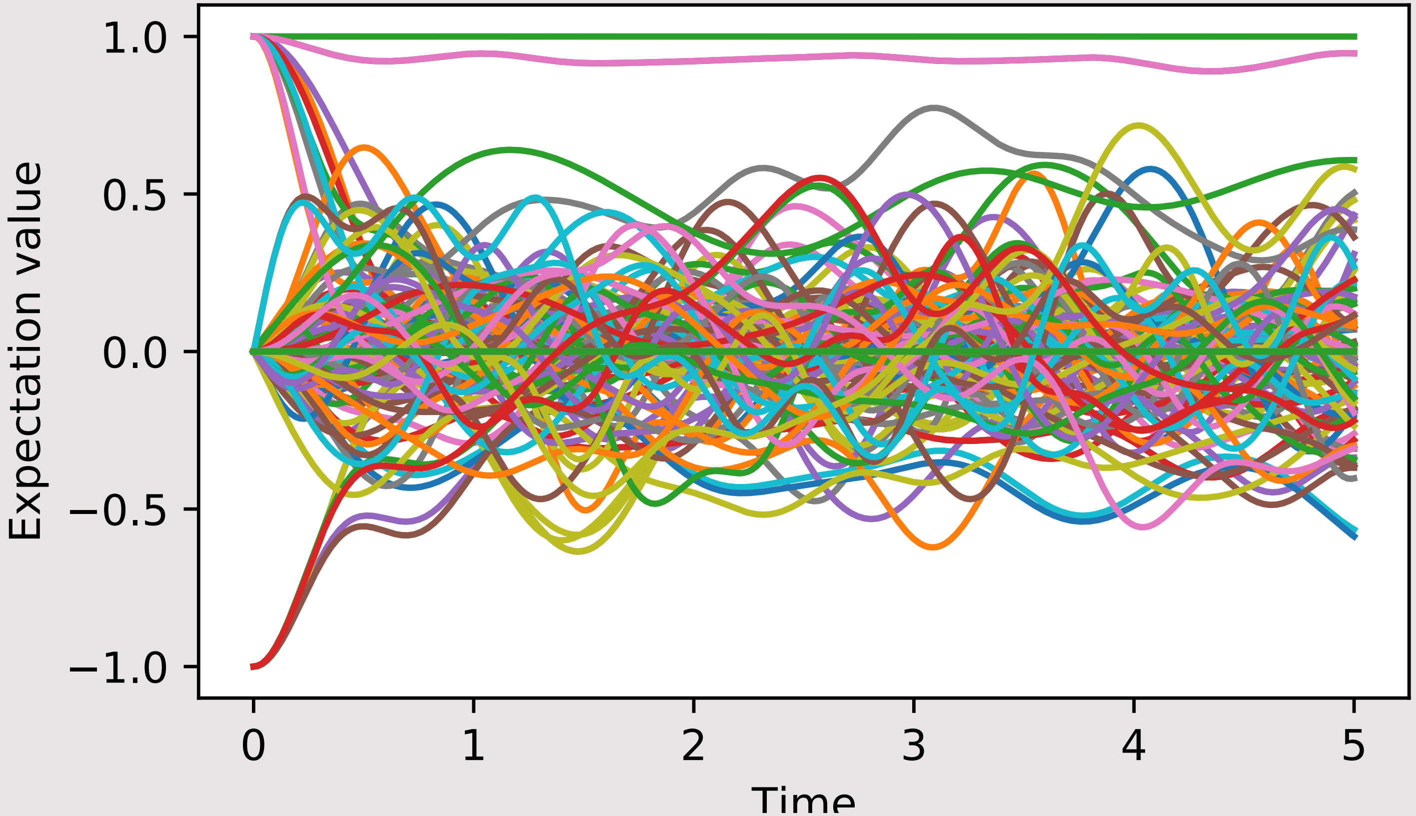


Measure time observables over time

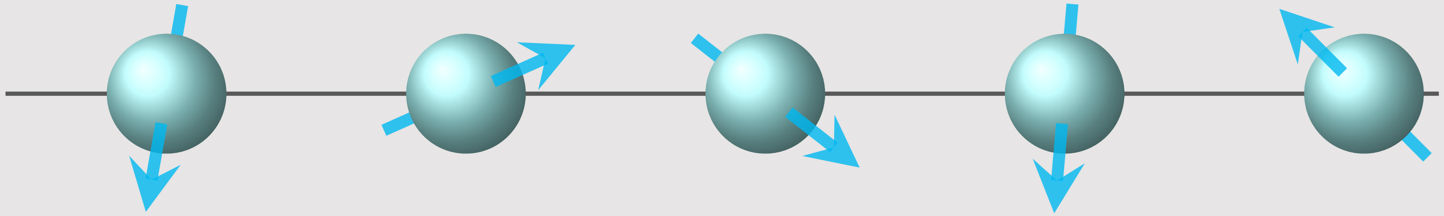


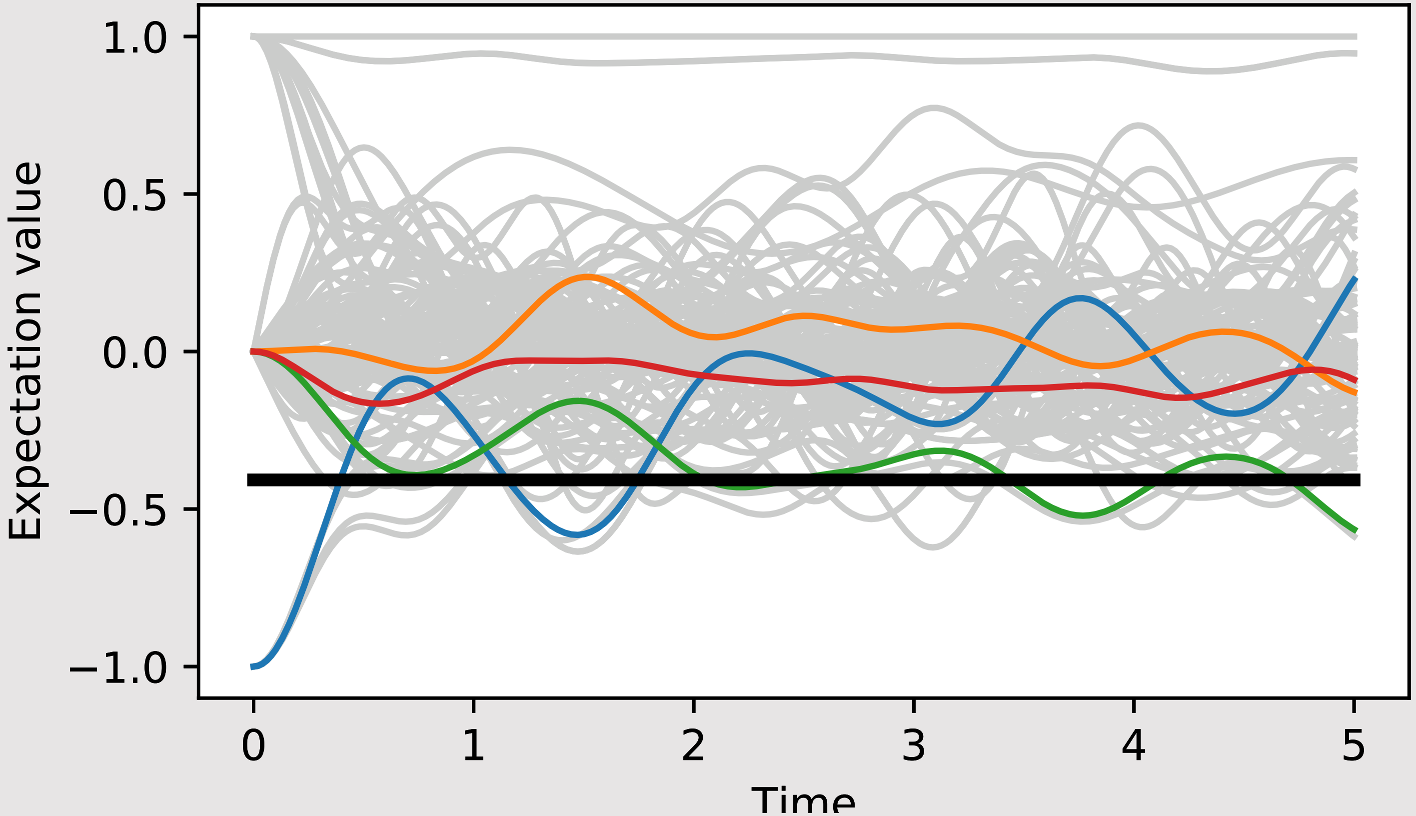
Measure many of them





Find a constant of motion over the observation timescale





Repeat for different initial states and find constant of motion over entire data set

$$a\langle Z_2\rangle + b\langle X_1 Y_2\rangle + c\langle Y_2 X_3\rangle + d\langle X_1 Z_2 X_3\rangle = \text{const}$$

Basis of protocol for measuring LIOMs

Given: Unitary operator U_F

Goal: Find an operator that commutes with the unitary $[U_F, L] = 0$

Pauli decomposition of LIOM:

$$L = \sum_{\mu=1}^{4^n-1} a_\mu P_\mu$$

Coefficients are

$$a_\mu = \frac{1}{2^n}\frac{1}{D+1}\sum_{d=0}^{D} \mathrm{Tr}(L_0 U^{d\dagger} P_\mu U^d)$$

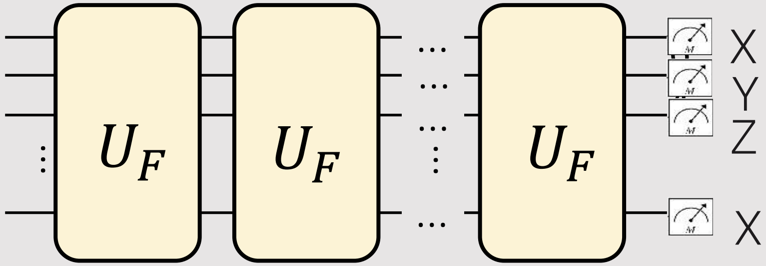
Solution. Follow the steps:

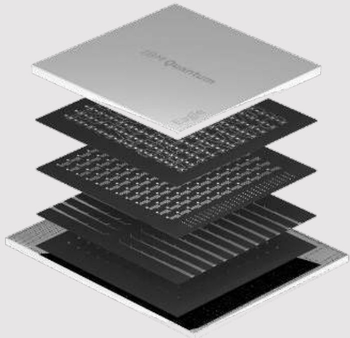
1. Start with a suitable local operator L_0
2. Evaluate the operator

$$L \propto L_0 + U_F L_0 U_F^\dagger + U_F^2 L_0 U_F^{2\dagger} + \cdots + U_F^D L_0 U_F^{D\dagger}$$

In the limit $D \gg 1$,

$$[U_F, L] \sim O(D^{-1})$$





Chandran, Kim, Vidal, Abanin, PRB (2015).

Conserved quantity: LIOM

Integral of motion L

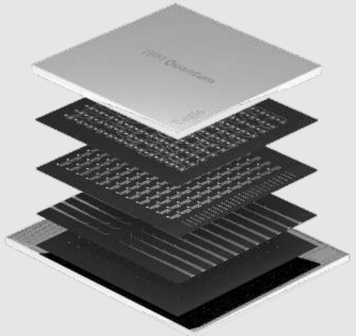
$$[U, L] = 0 \qquad [H, L] = 0$$

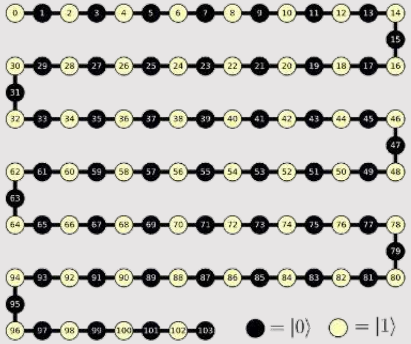
$$\langle L \rangle = \text{const}$$

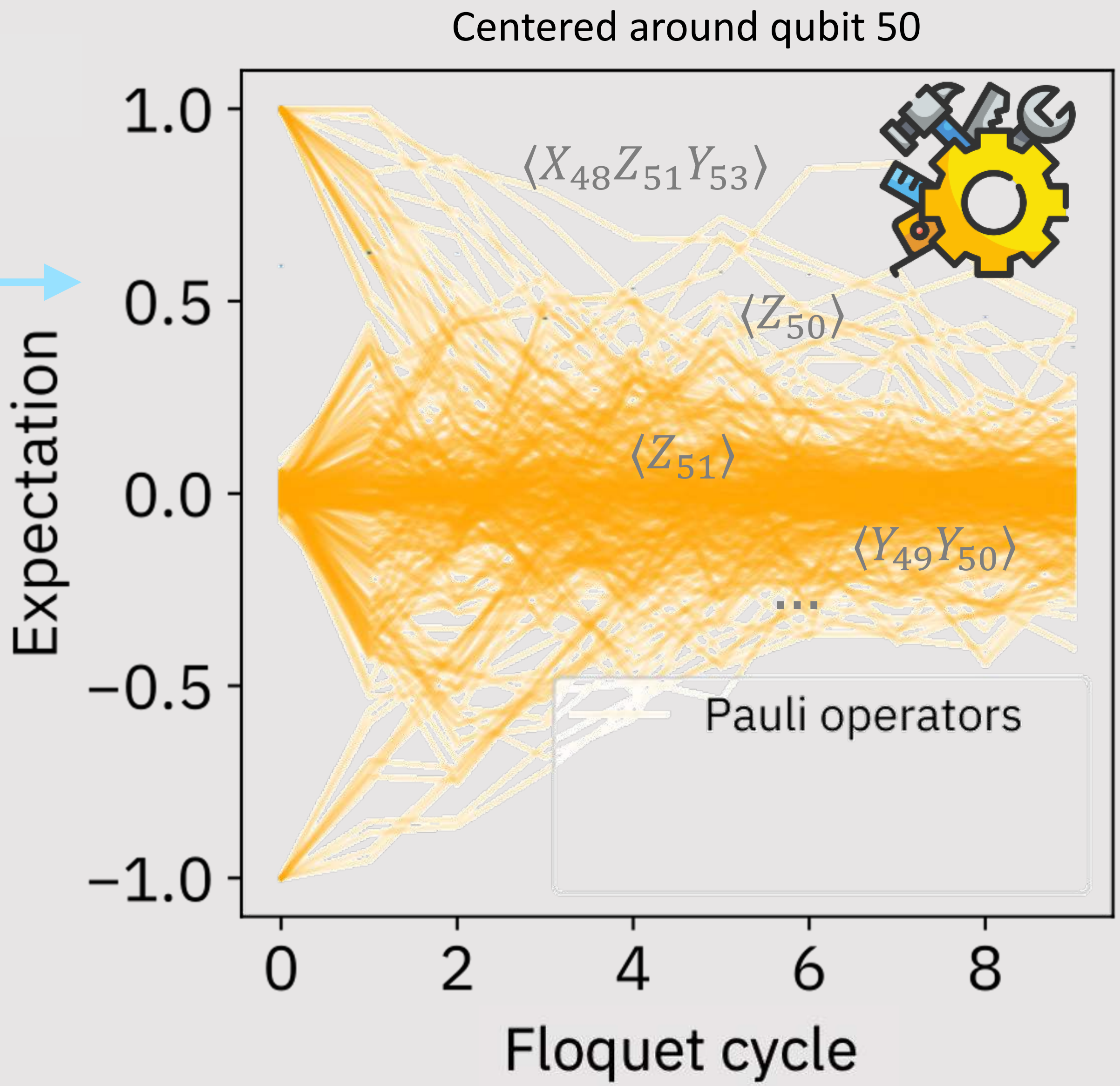
Local integral of motion (LIOM) L

$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$

local neighborhood







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Conserved quantity: LIOM

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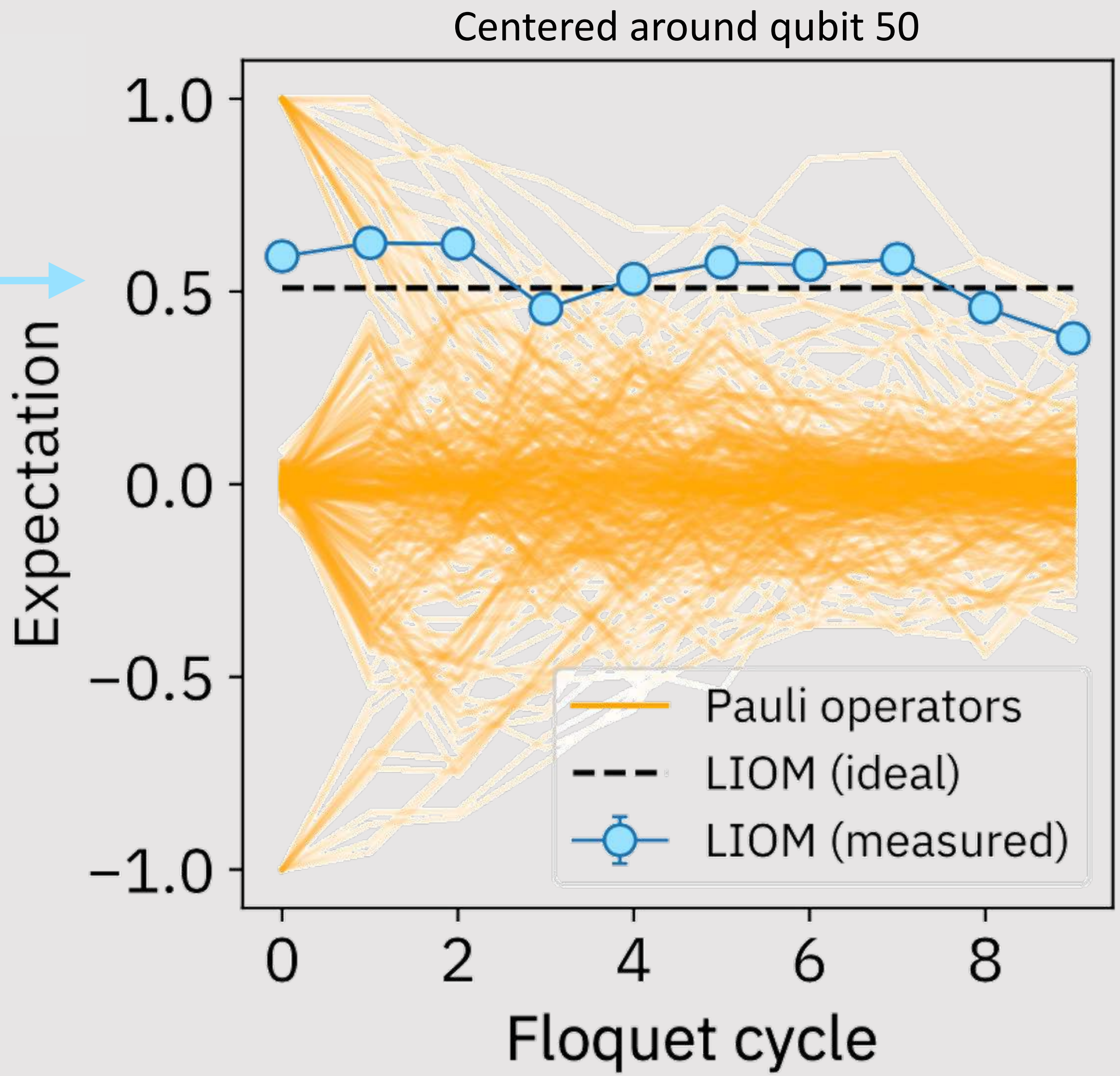
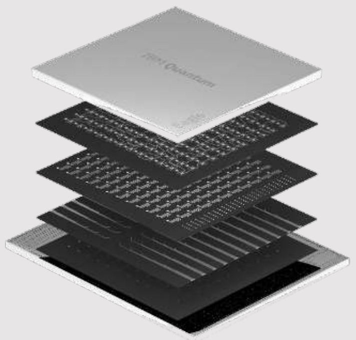
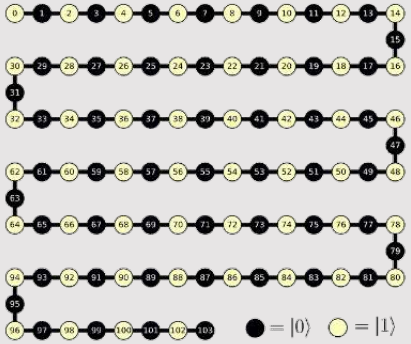
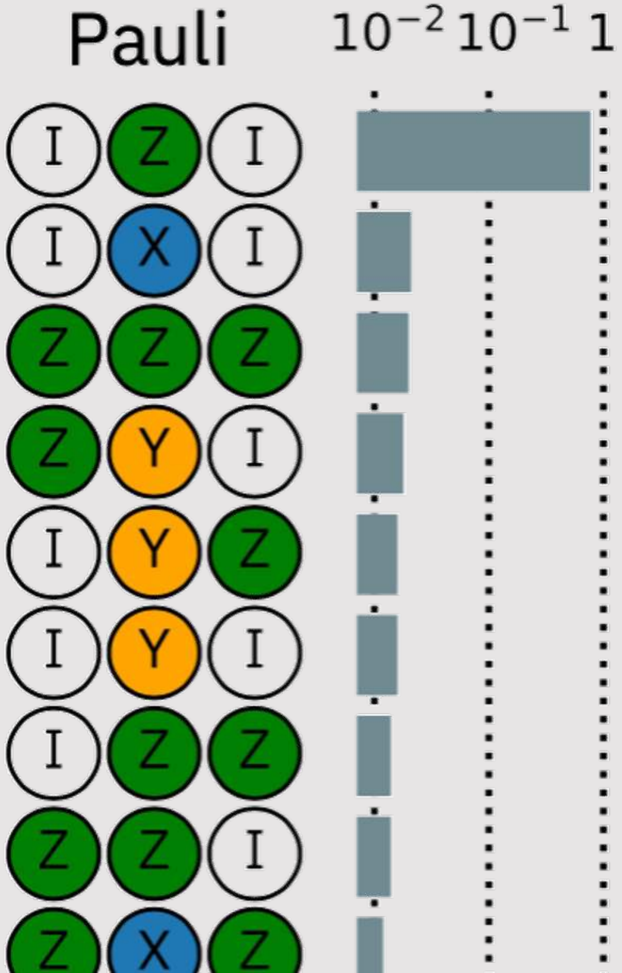




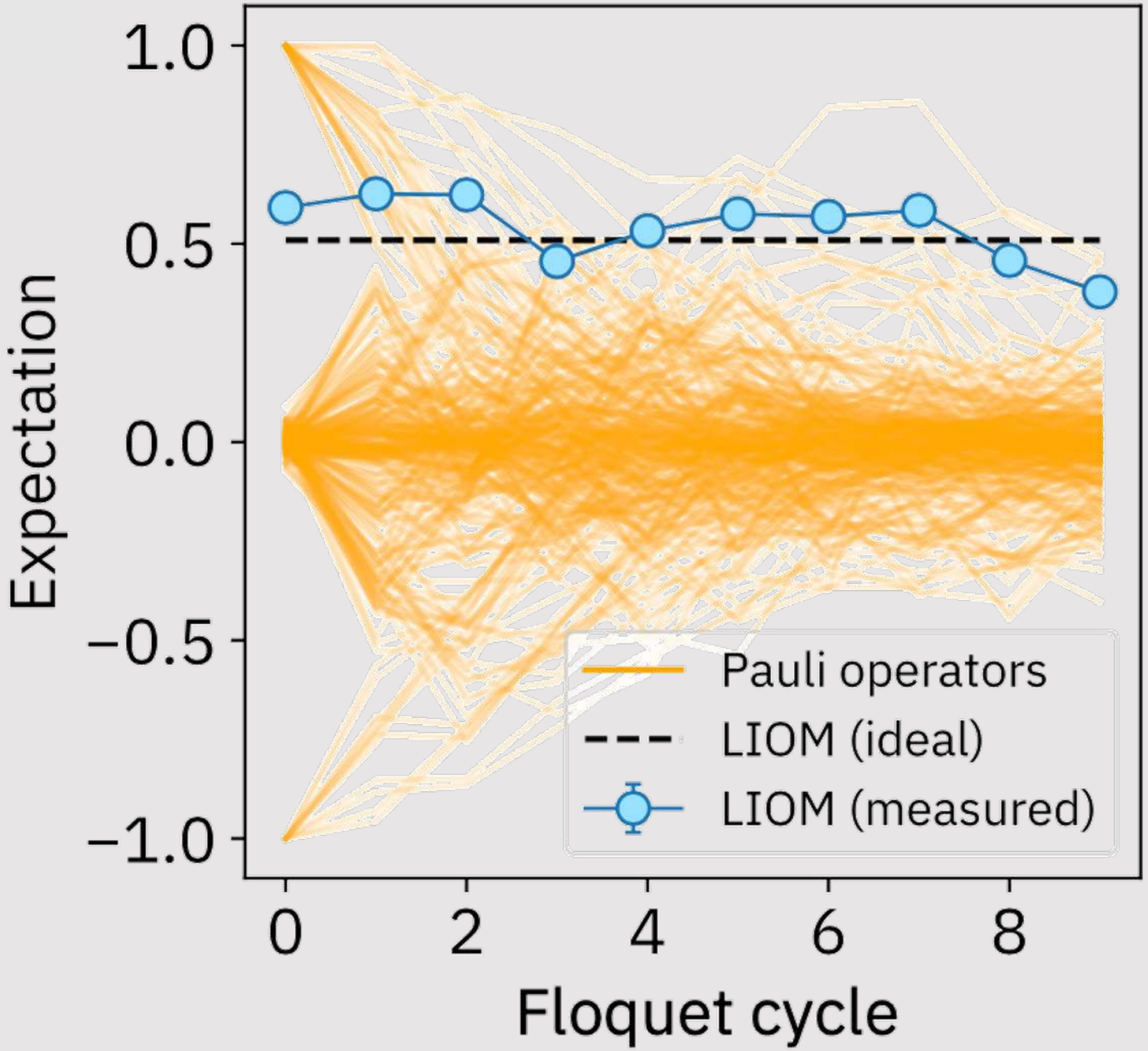


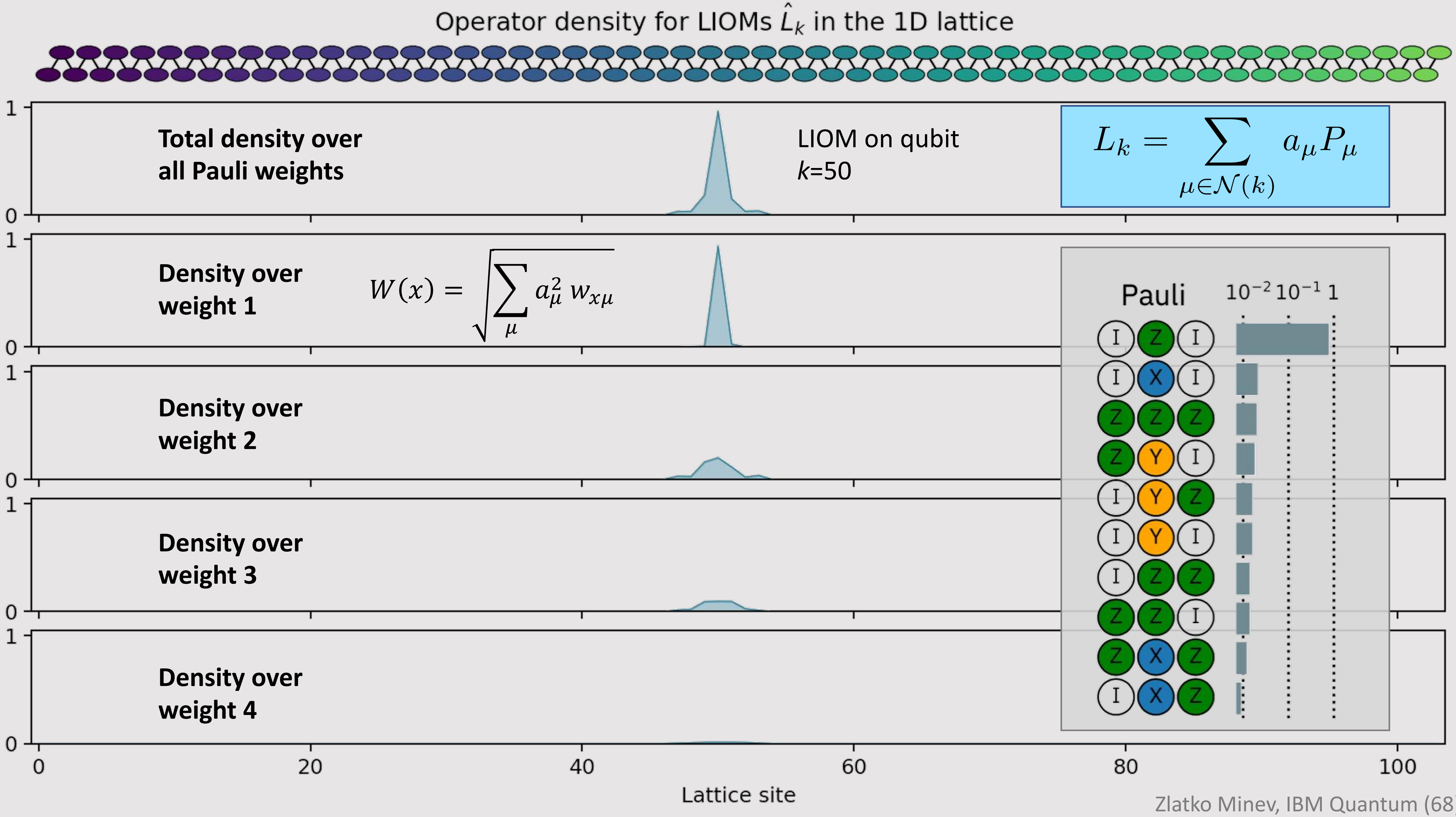
Conserved quantity: LIOM

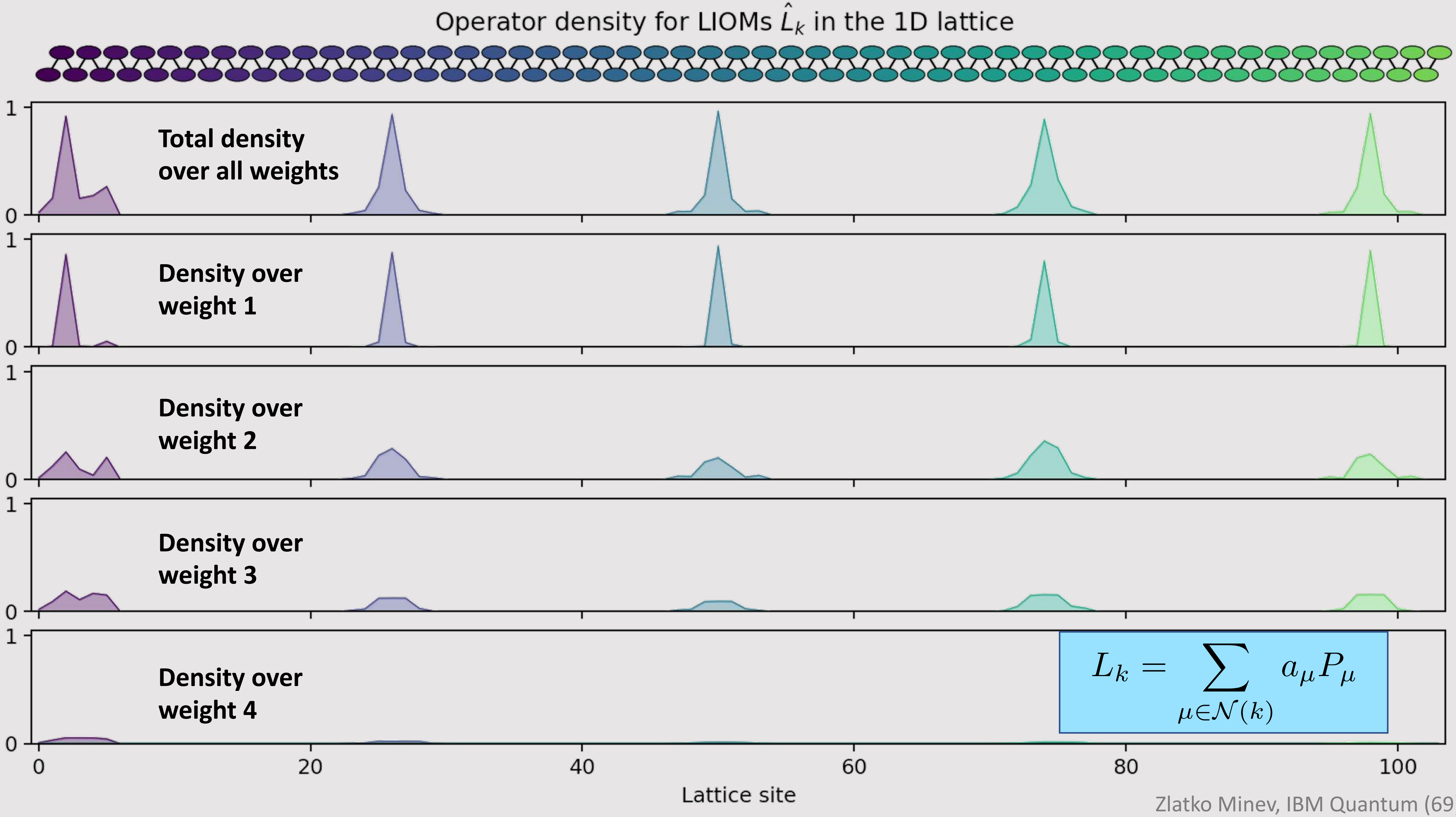
$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$



For qubit 50

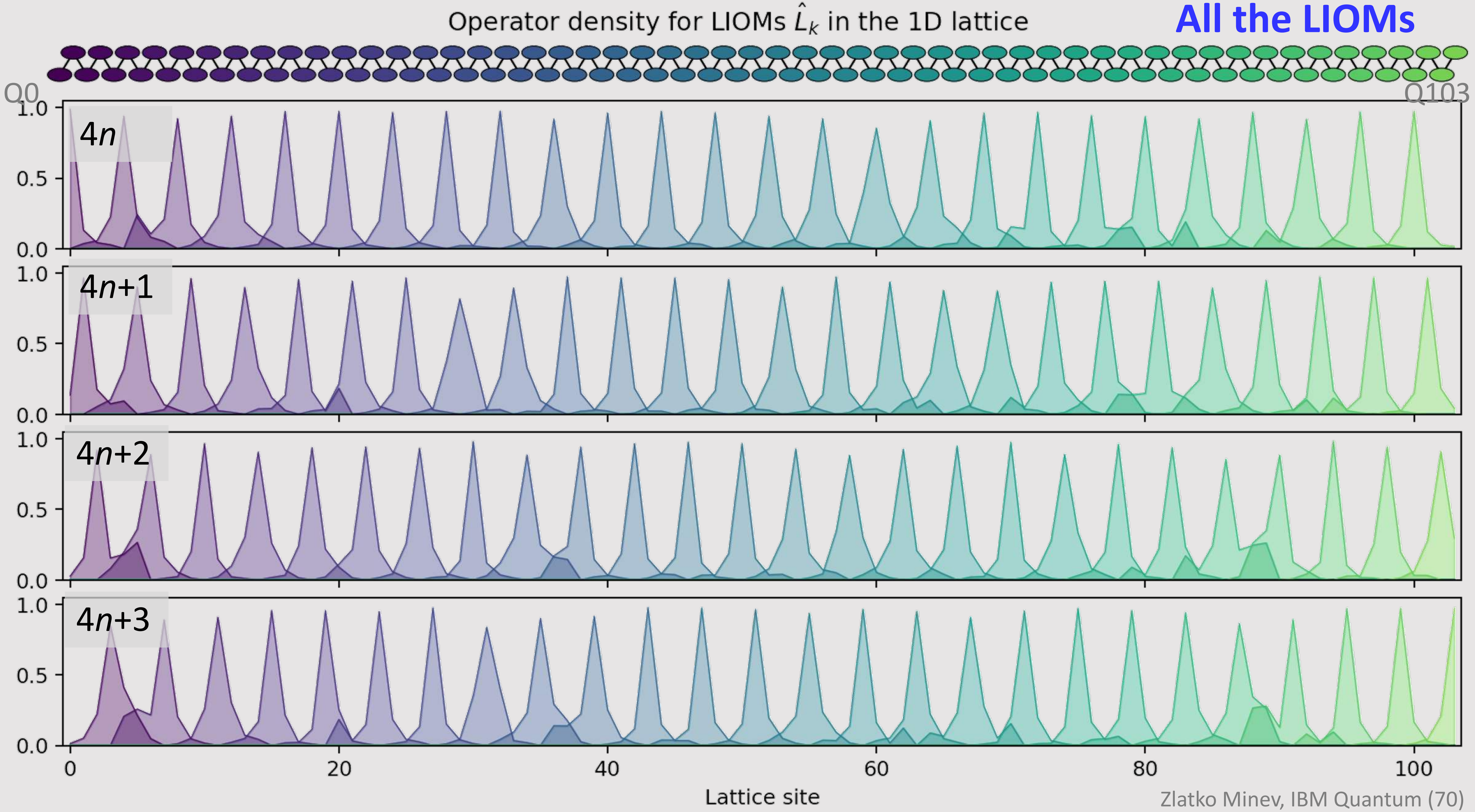



Operator density for LIOMs $\hat{L}_k$ in the 1D lattice
Total density over all Pauli weights
LIOM on qubit k=50
$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$
Density over weight 1
$W(x) = \sqrt{\sum_\mu a_\mu^2 \, w_{x\mu}}$
Density over weight 2
Density over weight 3
Density over weight 4
Pauli
10^{-2} 10^{-1} 1
I Z I
I X I
Z Z Z
Z Y I
I Y Z
I Y I
I Z Z
Z Z I
Z X Z
I X Z
0
1
0
20
40
60
80
100
Lattice site



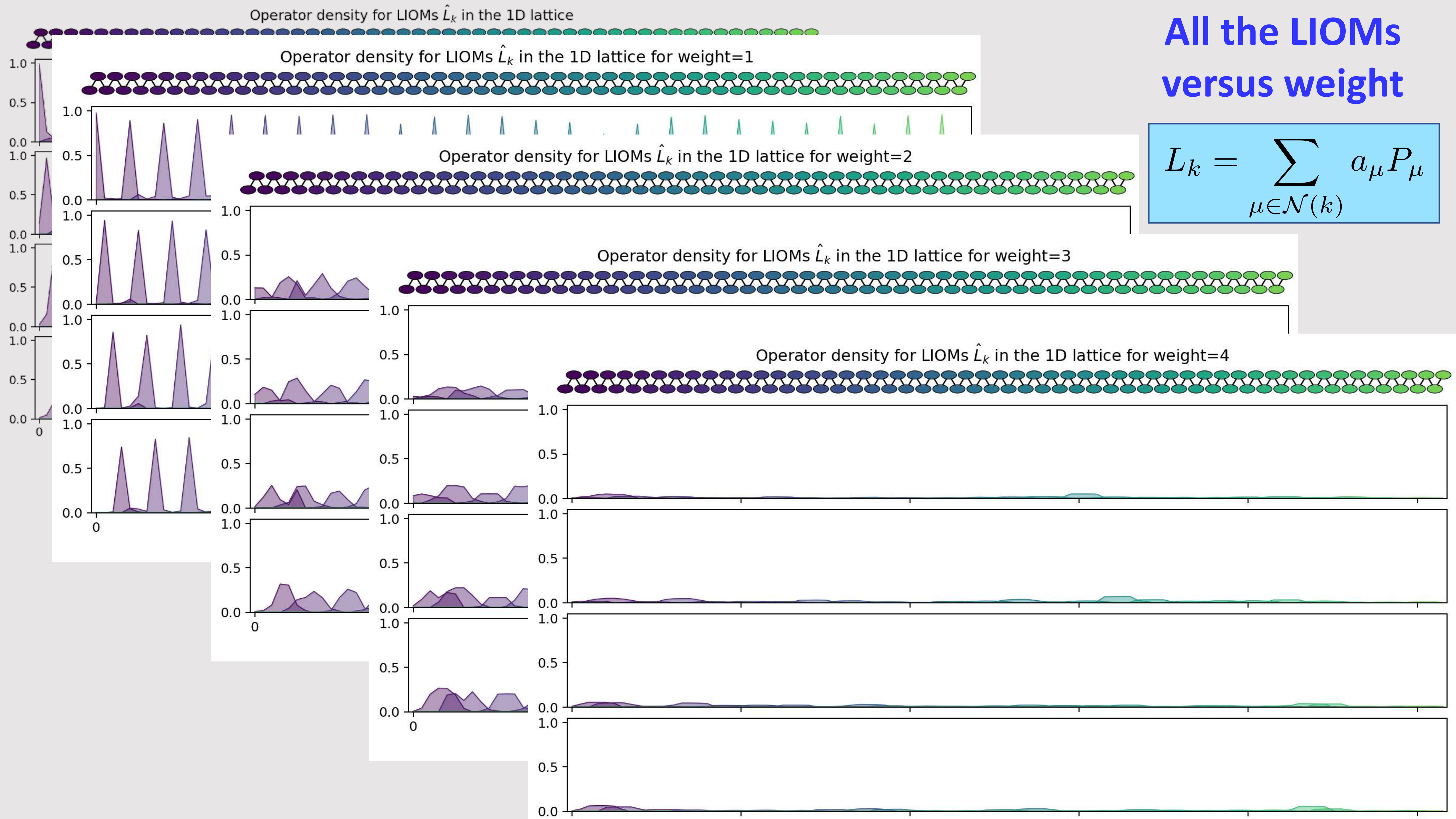
Operator density for LIOMs $\hat{L}_k$ in the 1D lattice
Total density over all weights
Density over weight 1
Density over weight 2
Density over weight 3
Density over weight 4
$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$
0
1
0
20
40
60
80
100
Lattice site

All the LIOMs

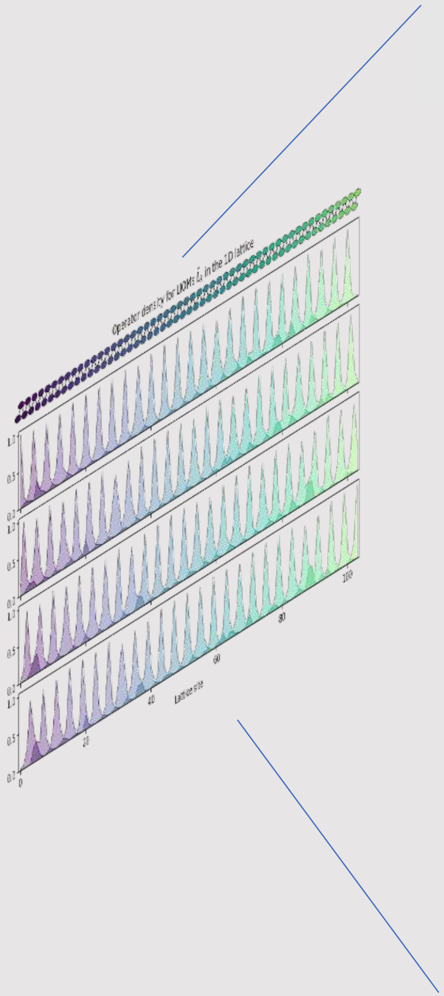


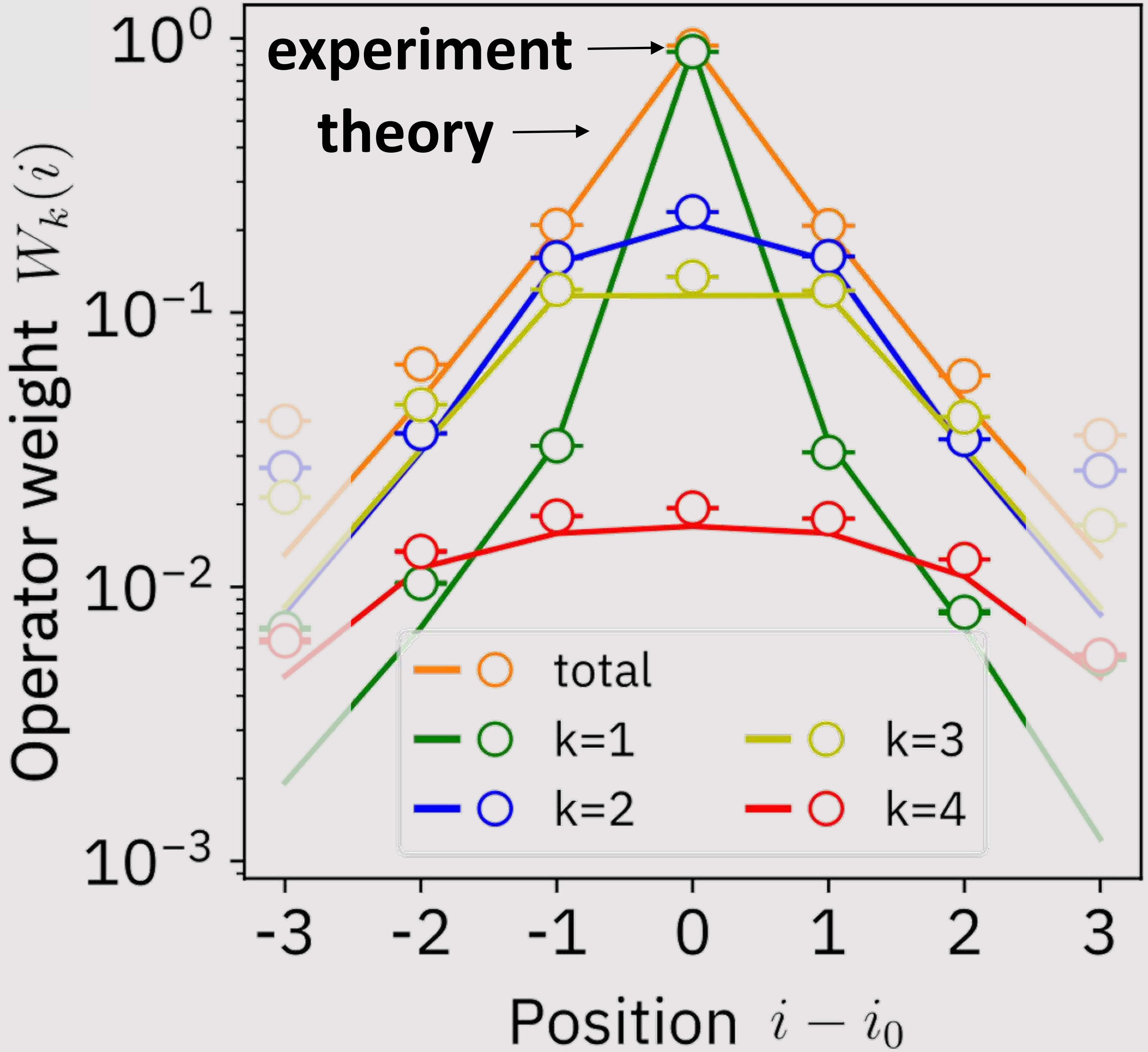
All the LIOMs versus weight

$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$



Average LIOM decomposed by weight: experiment vs. theory





$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$

total

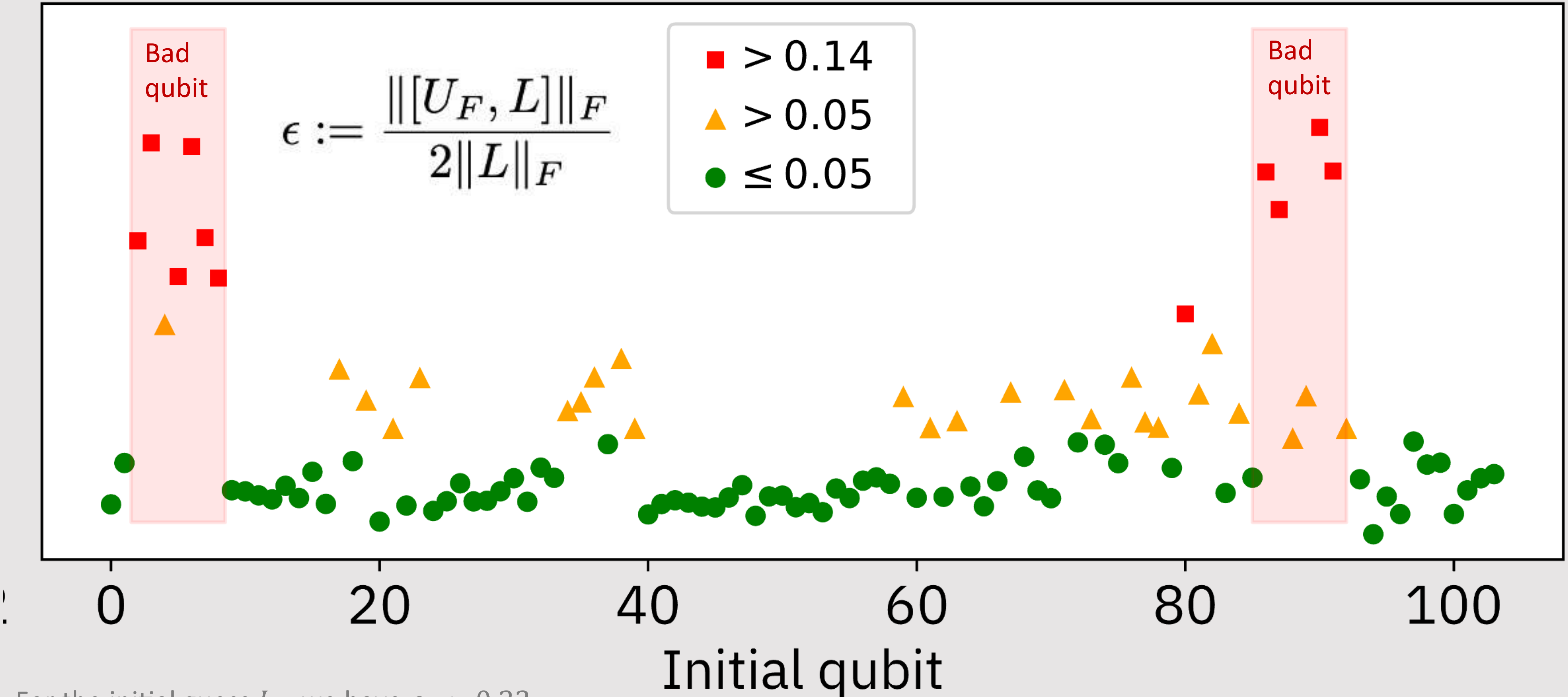
weight 1

weight 2

weight 3

weight 4

LIOMs error due to noise in device



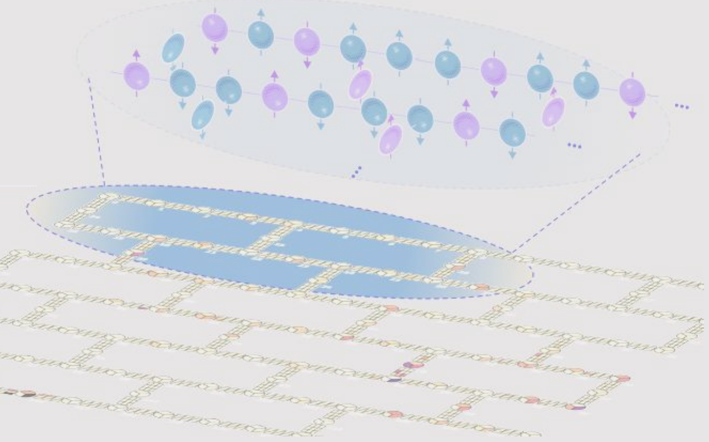
For the initial guess L_0, we have $\epsilon_0 \approx 0.23$

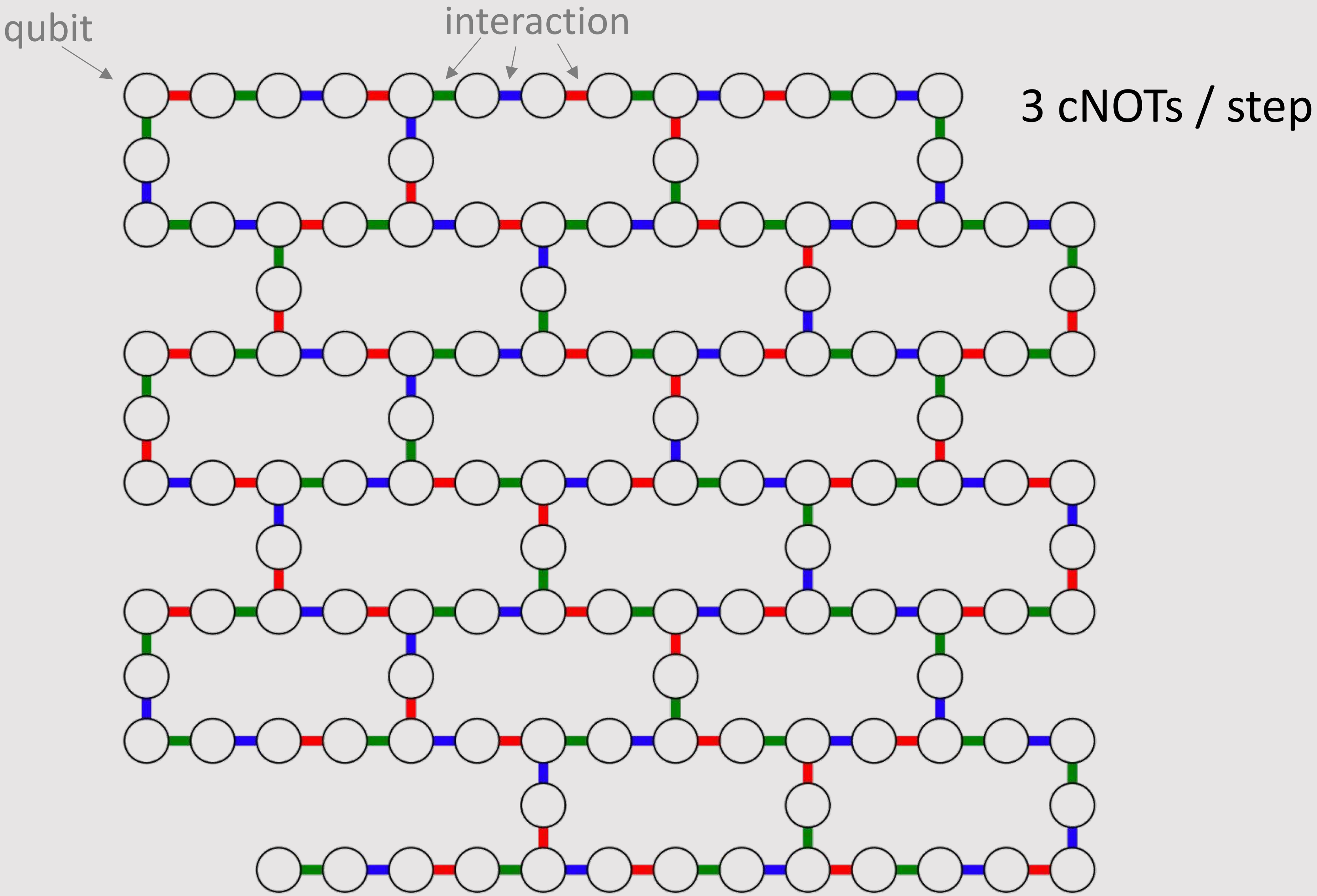
2D

We study

- Spin imbalance
- OPDMs
- Scaling with system size
- LIOMs
- …

Interaction map and device layers





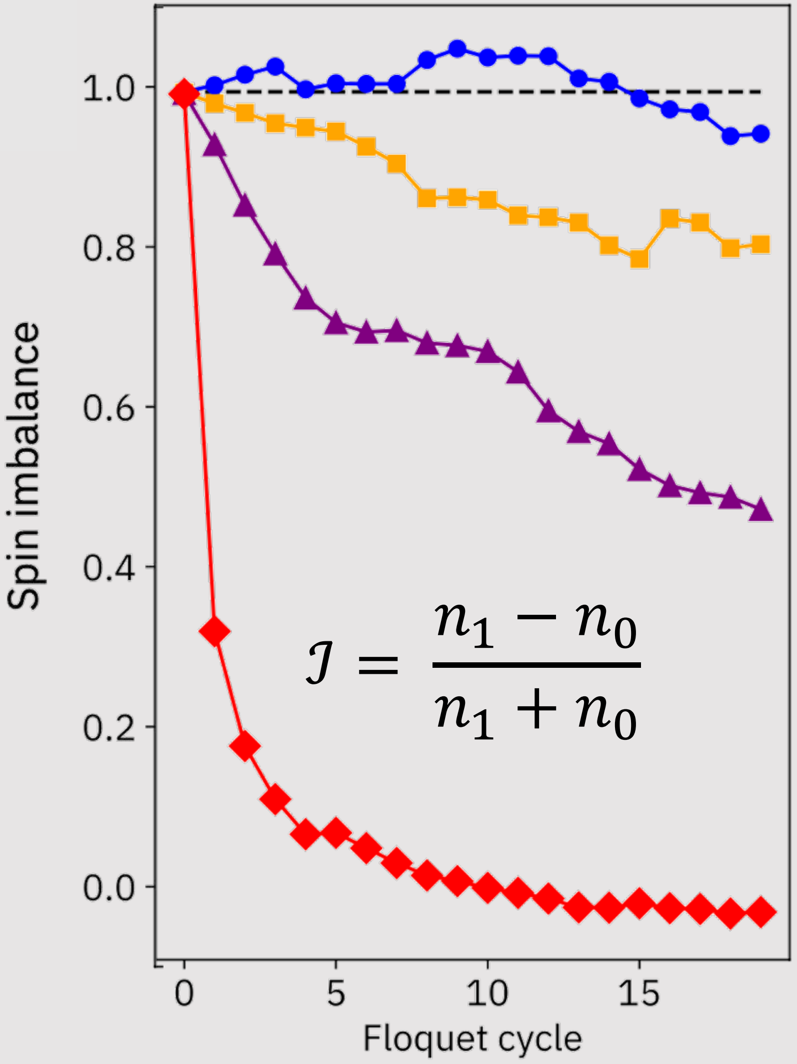
Experimental setting

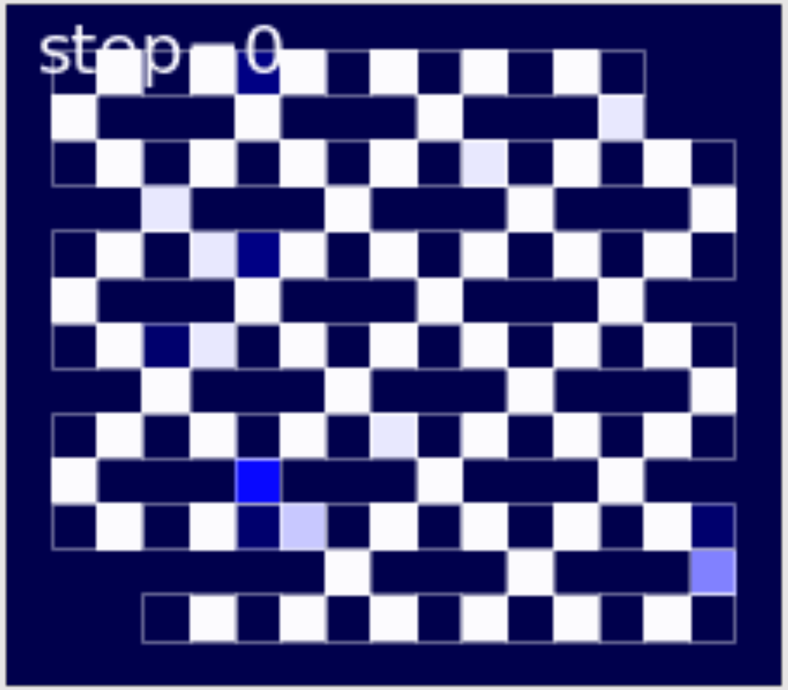
Number of qubits	124Q
Connectivity	2D h-hex
Depth in cNOTs	60
Total number of cNOTS	2,641
Floquet steps	20

Shtanko, Wang, ..., Minev in-prep (2023)

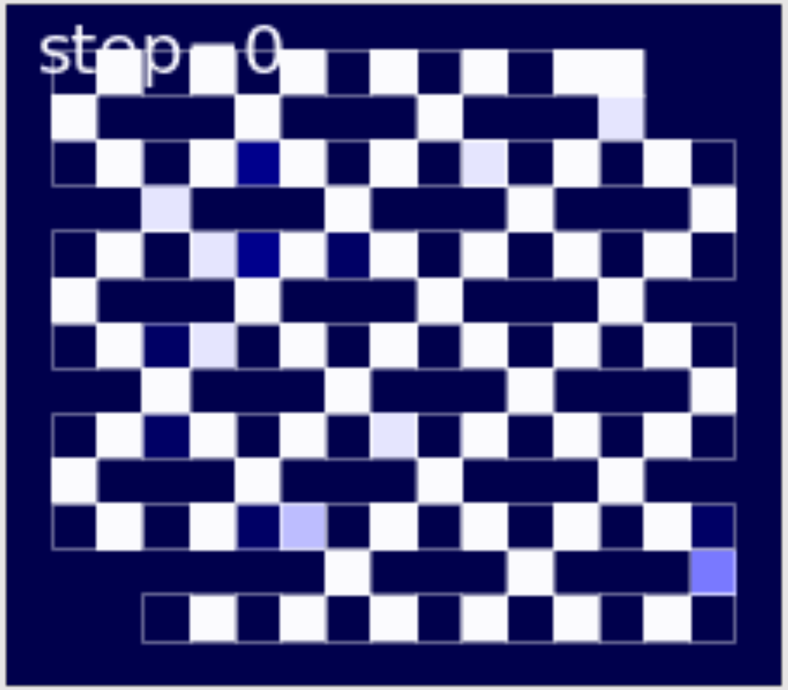
Color represent charge/spin polarization

Spin imbalance for antiferromagnetic ordering





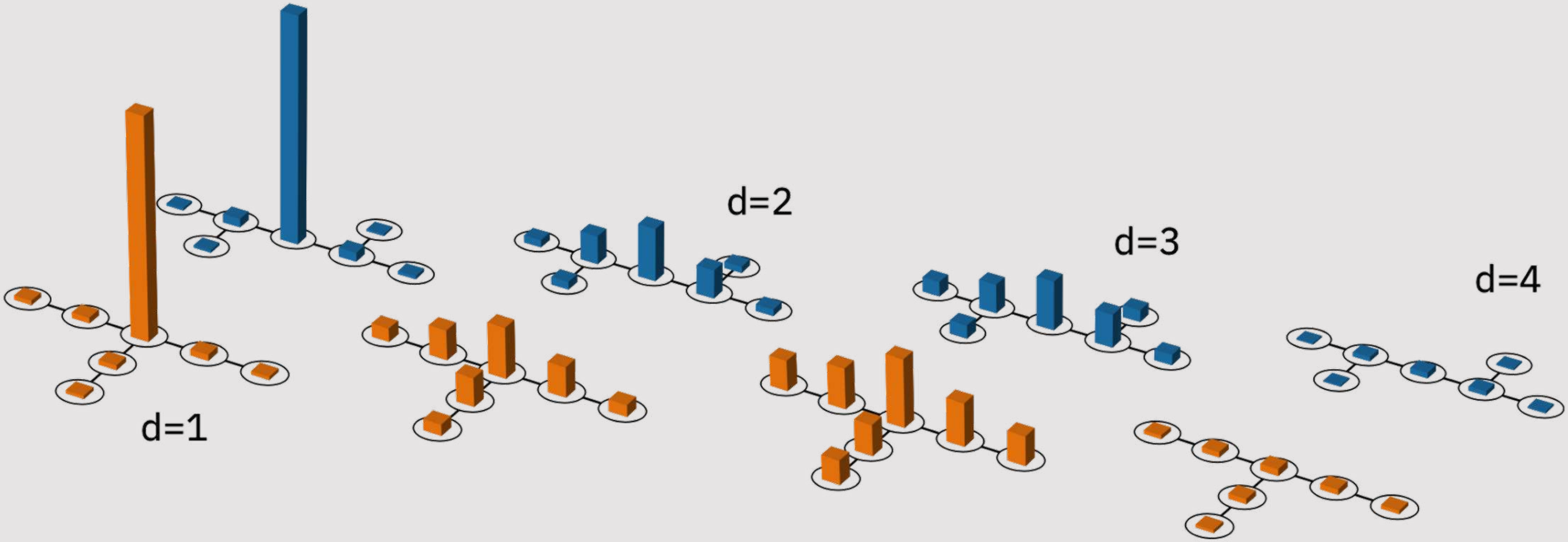
Thermalizing regime
$\theta = 0.3\pi$



Prethermal regime
$\theta = 0.1\pi$

Shtanko, Wang, ..., Minev in-prep (2023)

Color represent charge/spin polarization


d=2
d=3
d=4
d=1

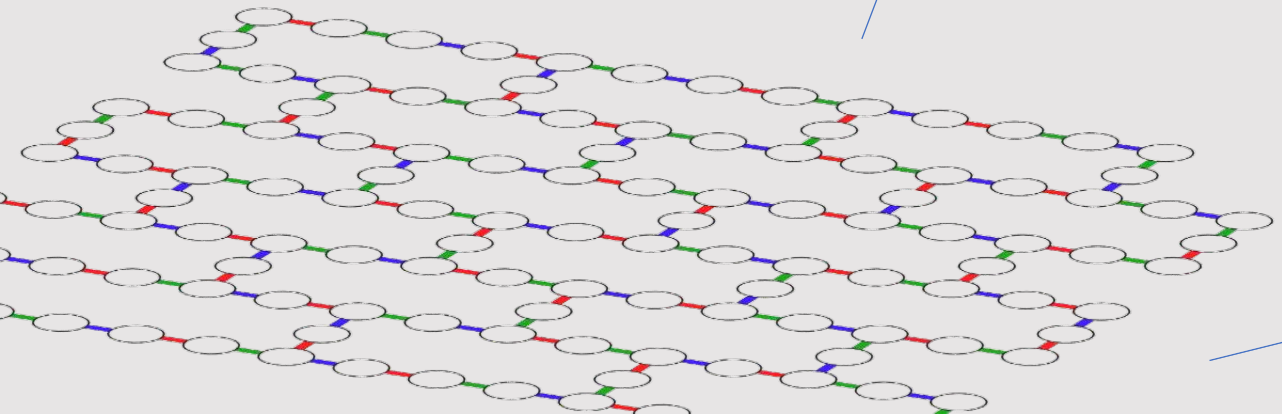
LIOM reconstruction in 2D

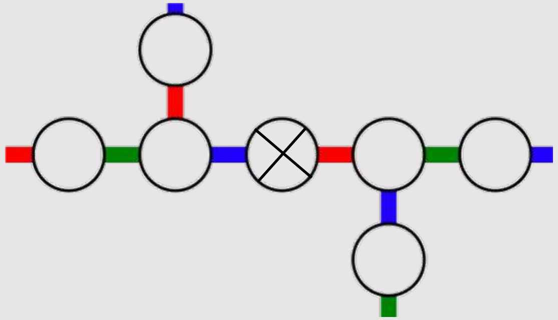
Prethermal LIOMS

$$\left[e^{-iHt}, L_k\right] \approx 0$$

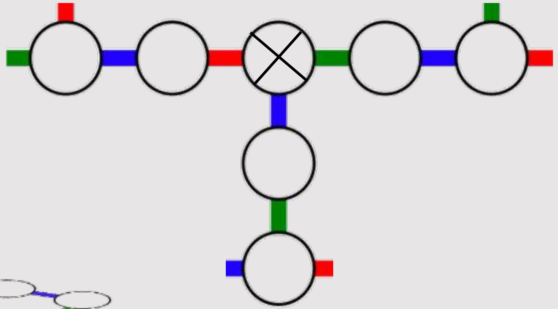
$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$

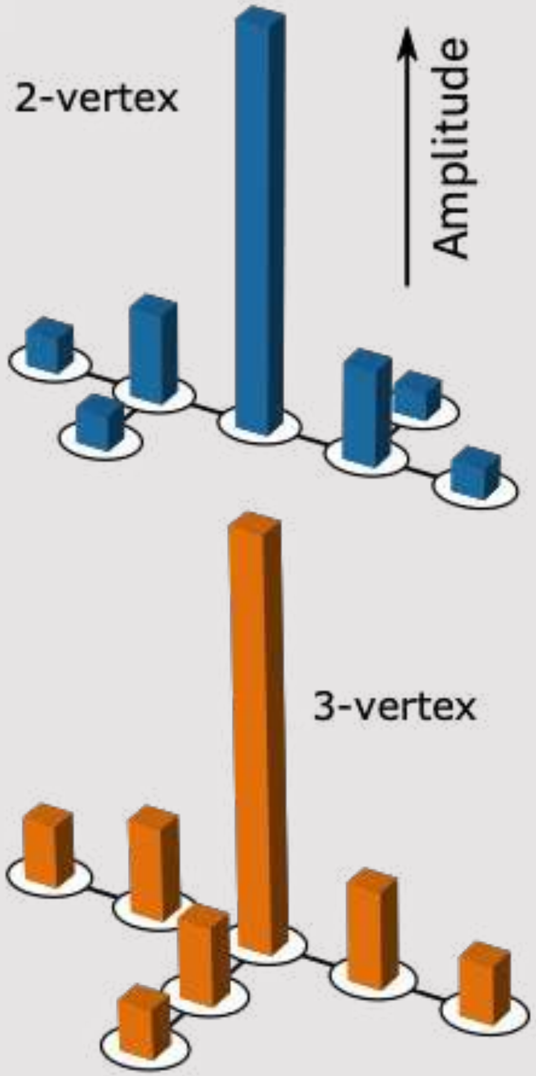
local neighborhood





⊗ LIOM center (position of the initial guess)



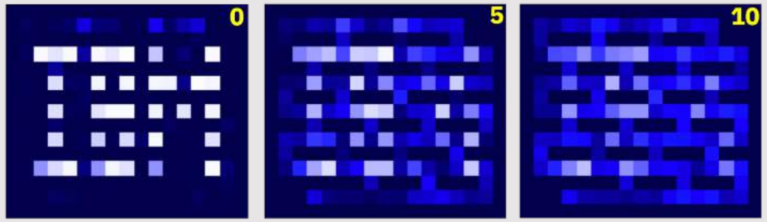


Discussion and future directions

Used 124Q, depth 60 circuits with error mitigation for many-body dynamics

Operationally restored a detailed portrait of a system's localized/prethermal dynamics in a new experimental regime

Explored a new model for MBL/ergodic phase transition



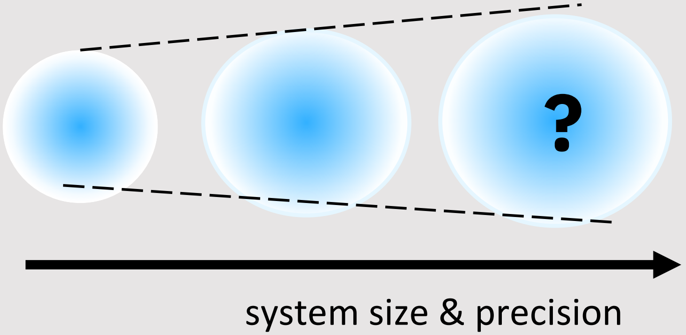
Use LIOMs for proper **calibration** of quantum hardware

Use these systems as playground for **competition** quantum vs. classical

Deciding the **fate of MBL** in two dimensions?

Study other initial states, such as thermal

Improved error mitigation, further explore existing data, …



…

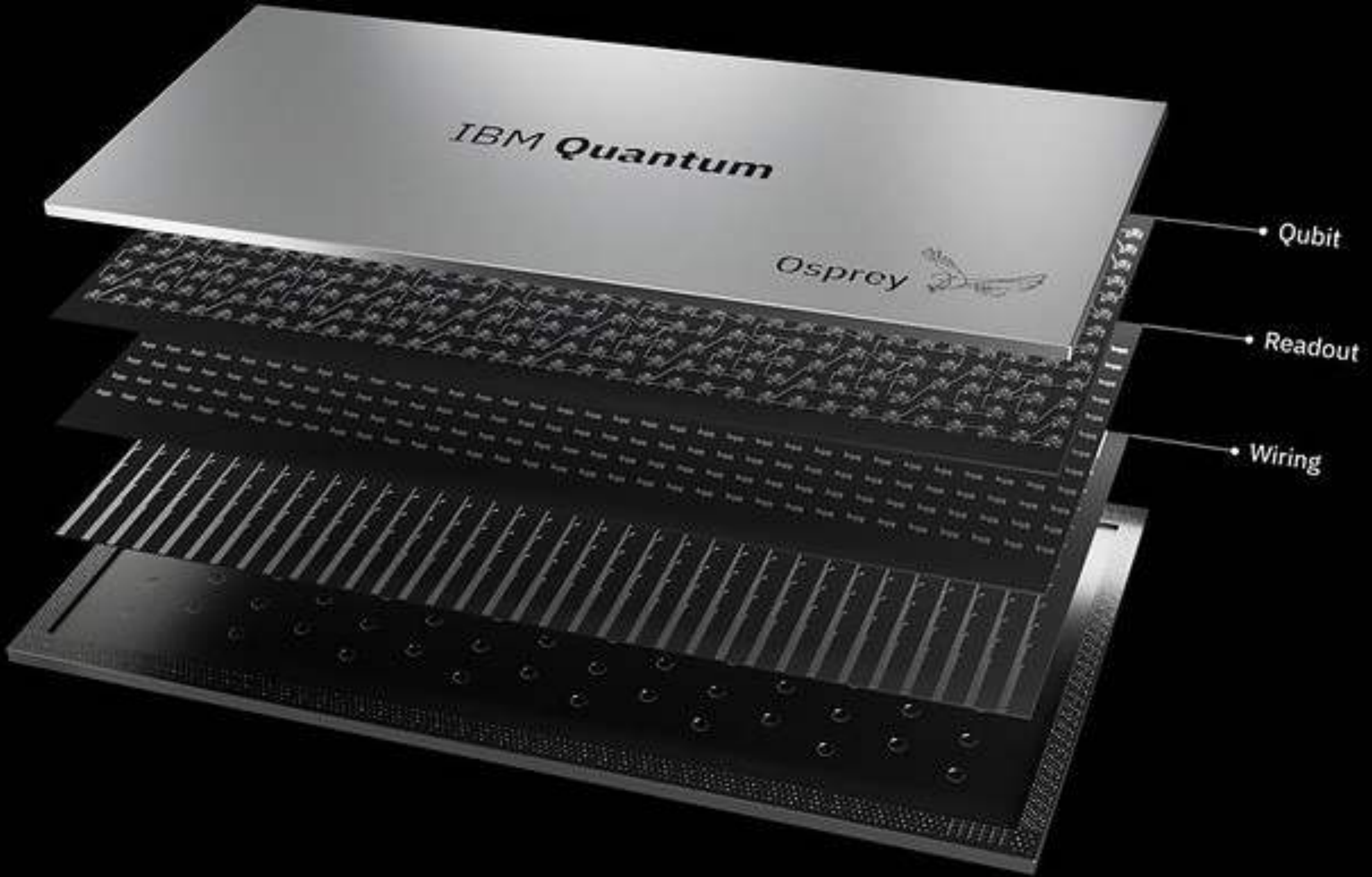
Scale and quality

2019
Falcon
27 Qubits

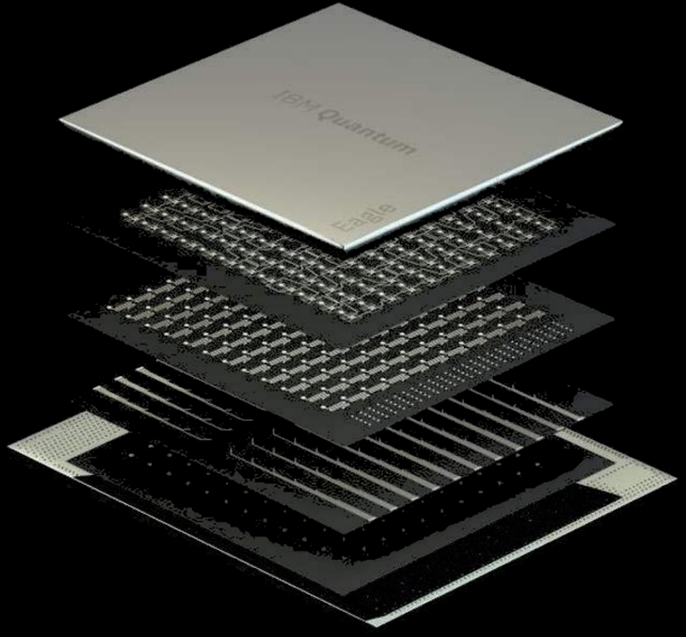
2020
Hummingbird
65 Qubits

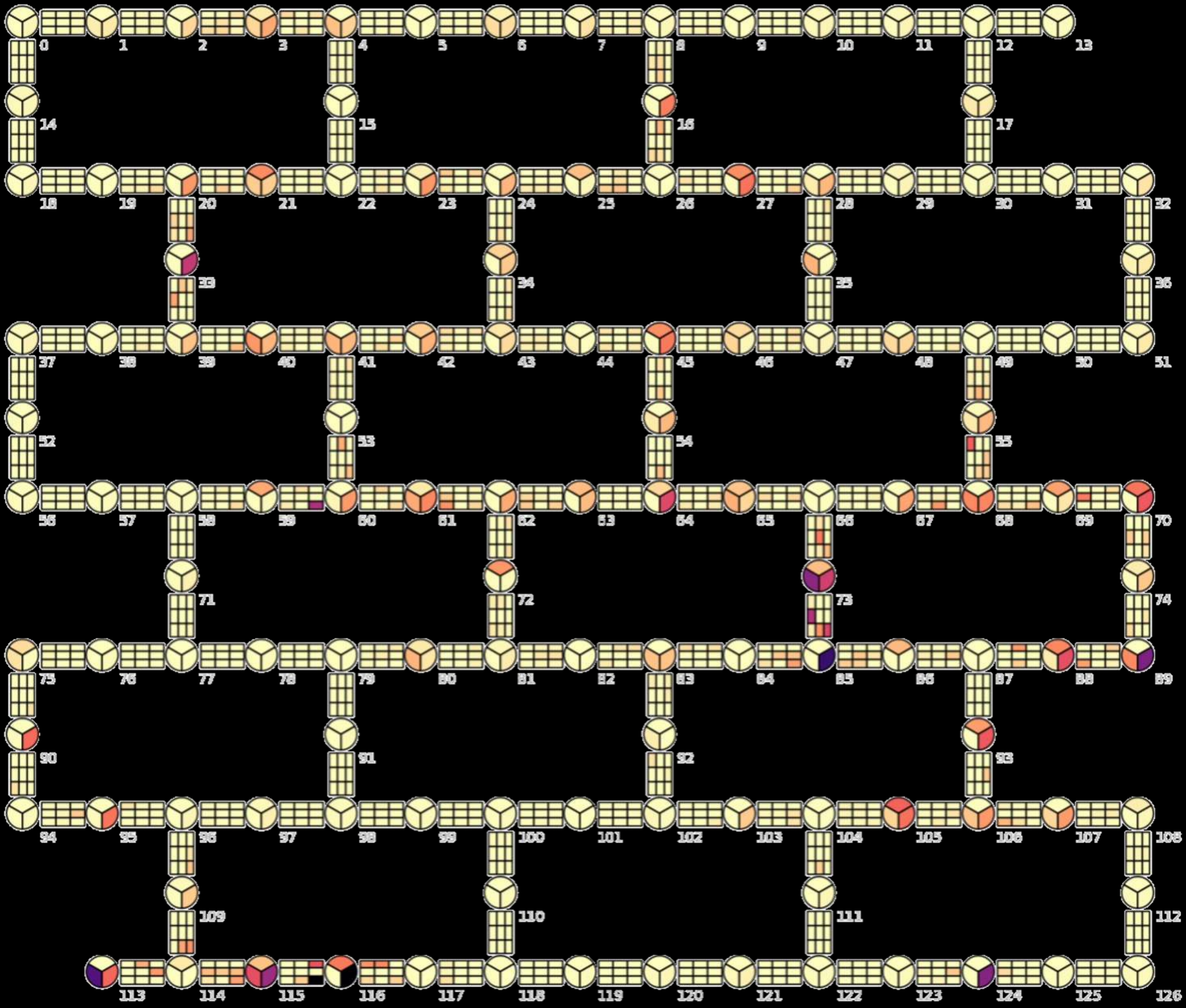
2021
Eagle
127 Qubits

2022
Osprey
433 Qubits


IBM Quantum
Osprey
Qubit
Readout
Wiring

Quantum simulation





The important thing is not to stop questioning. Curiosity has its own reason for existence.

One cannot help but be in awe when they contemplate the mysteries of eternity, of life, of the marvelous structure of reality.

It is enough if one tries merely to comprehend a little of this mystery each day.

Albert Einstein

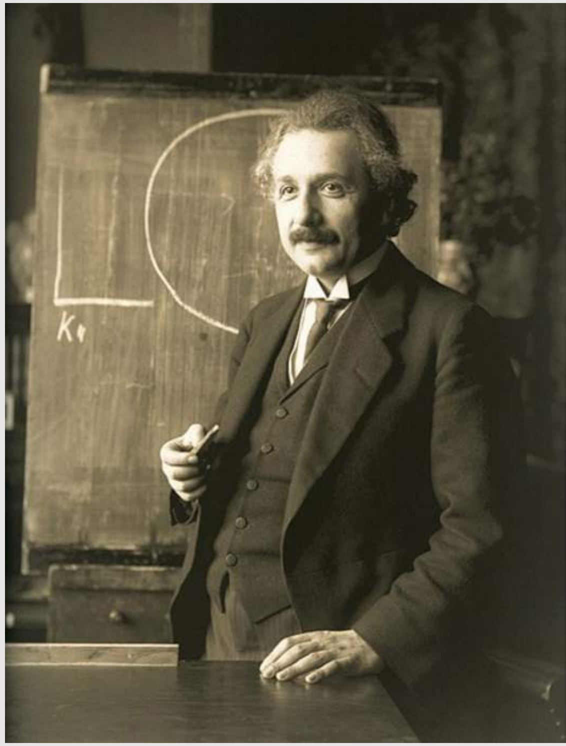


Photo: F. Schmutzer