A detailed portrait of quantum many-body dynamics

Zlatko K. Minev
IBM Quantum

Oles Shtanko*, Derek Wang*, Haimeng Zhang, Nikhil Harle, Alireza Seif, Ramis Movassagh, Zlatko K. Minev
arXiv:2307.07552

Acknowledgements: A. Deshpande, O. Dial, A. Eddins, D. Egger, B. Fuller, J. Garrison, D. Hahn, A. Kandala, W. Kirby, D. Layden, H. Liao, D. Luitz, S. Majumder, A. Mezzacapo, T. Prosen, J. Raftery, D. Sels, K. Temme, M. Tepaske, K. Wei, the IBM Quantum team, and many friends and colleagues

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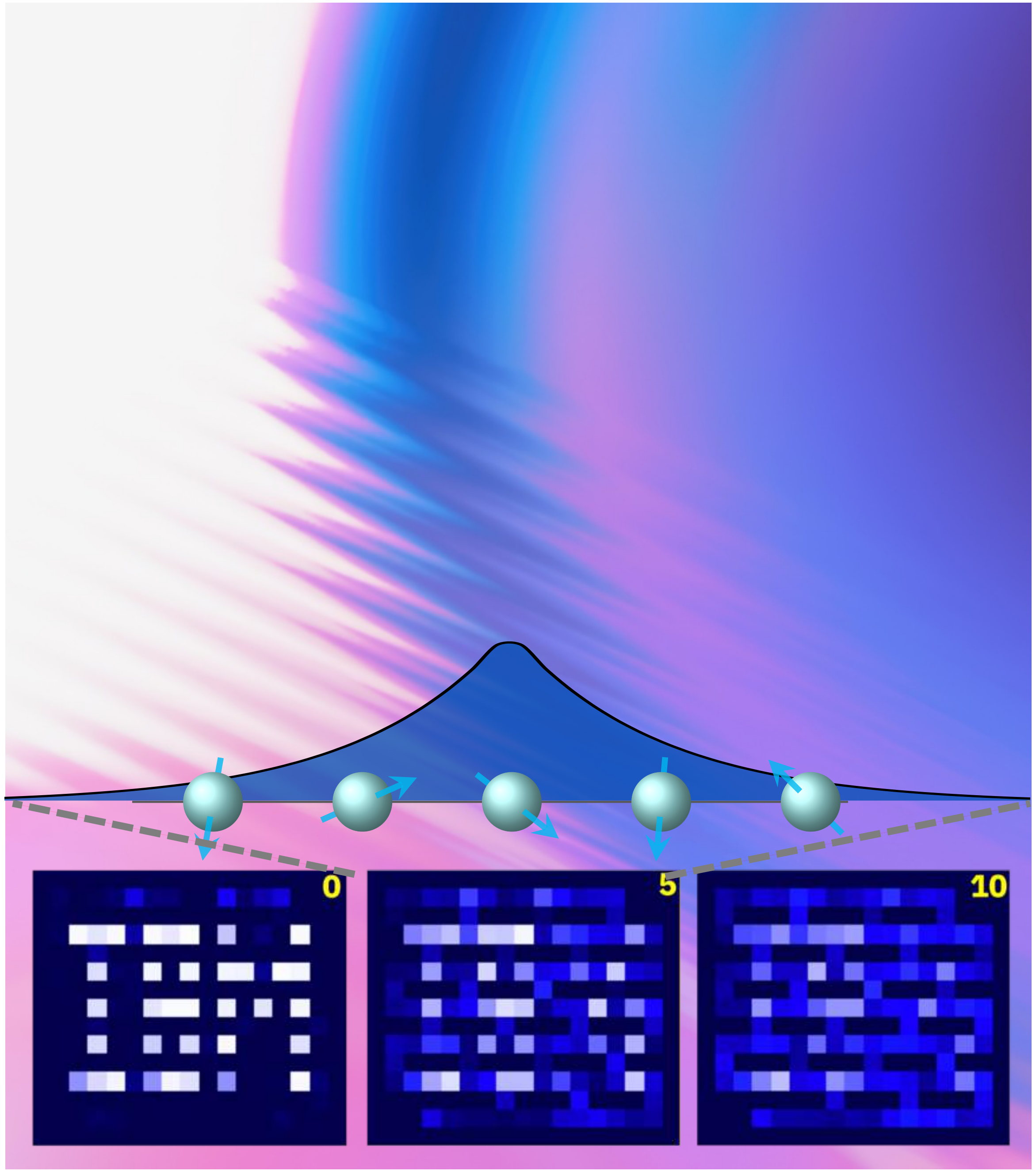

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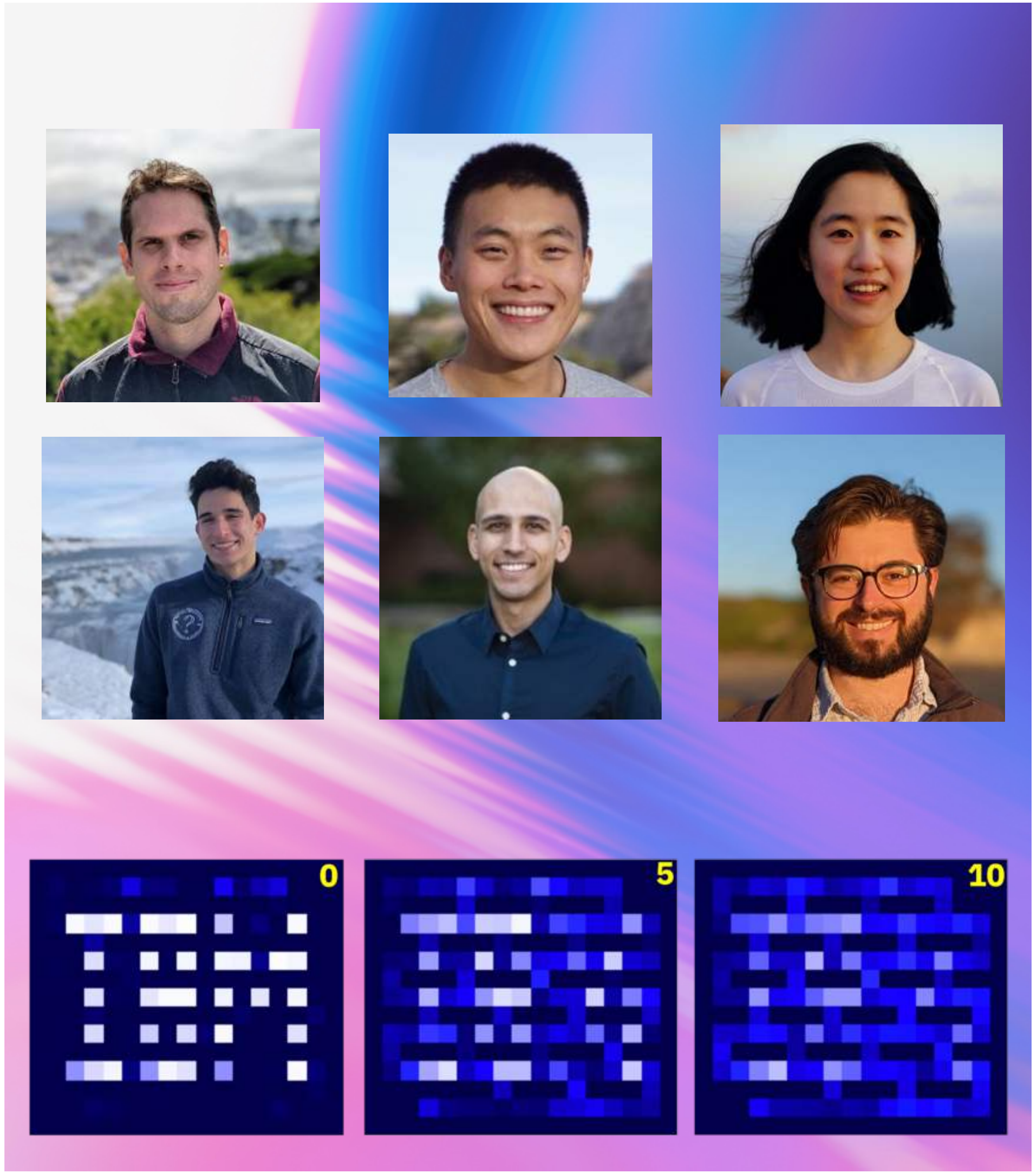
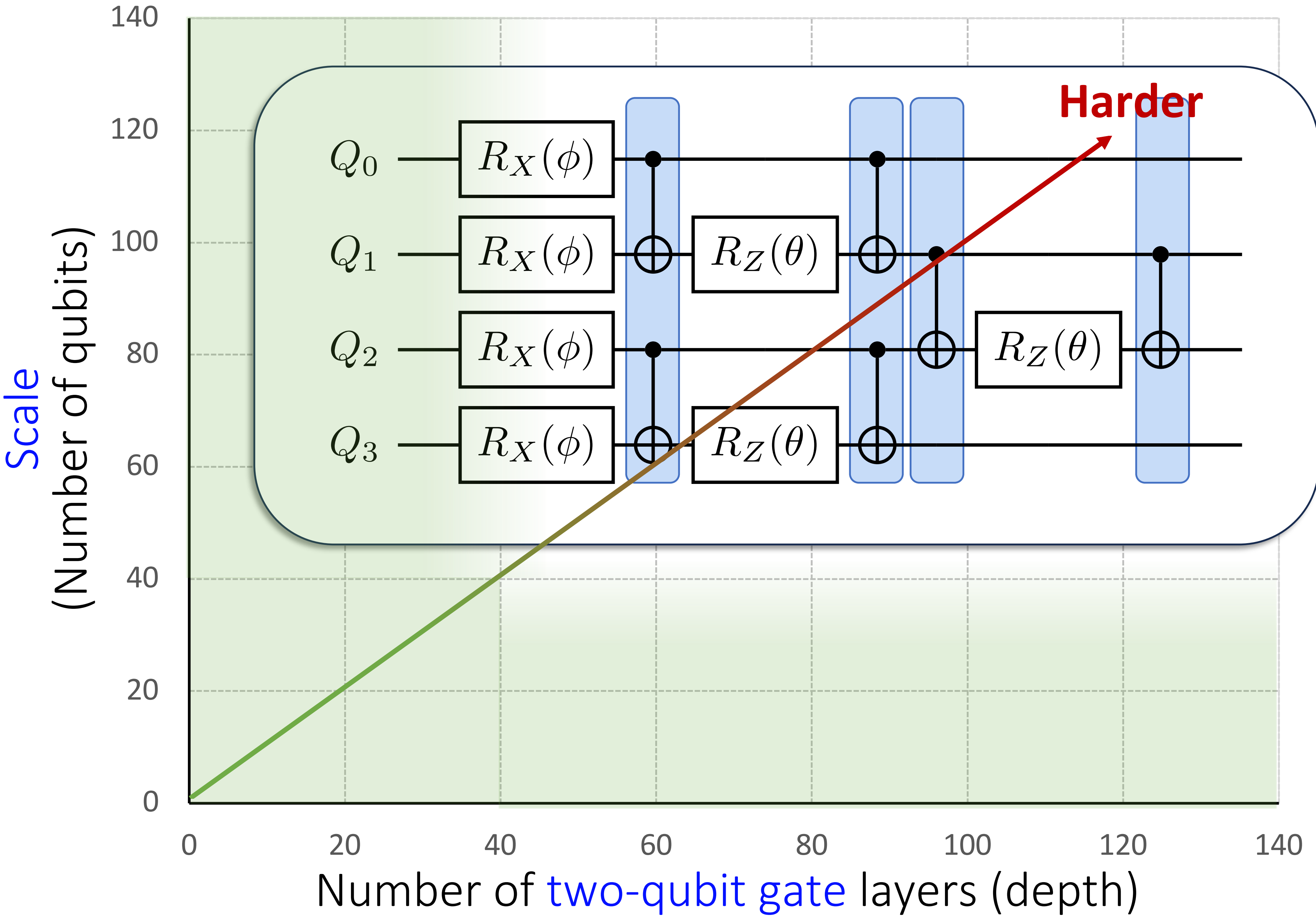


Quantum dynamics with large-scale superconducting quantum computers



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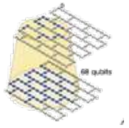
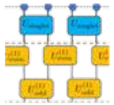
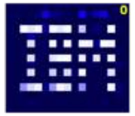
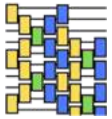
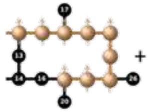
Some early utility-scale experiments


[0] Kim, Eddins, ..., Temme, Kandala.
Nature 618, 500–505 (2023)

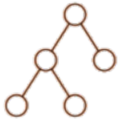

[1] Yu, Zhao, Wei.
arXiv: 2207.09994 (2022)


[2] Shtanko, Wang, Zhang, Harle, Seif,
Movassagh, Minev.
arXiv: 2307.07552 (2023)

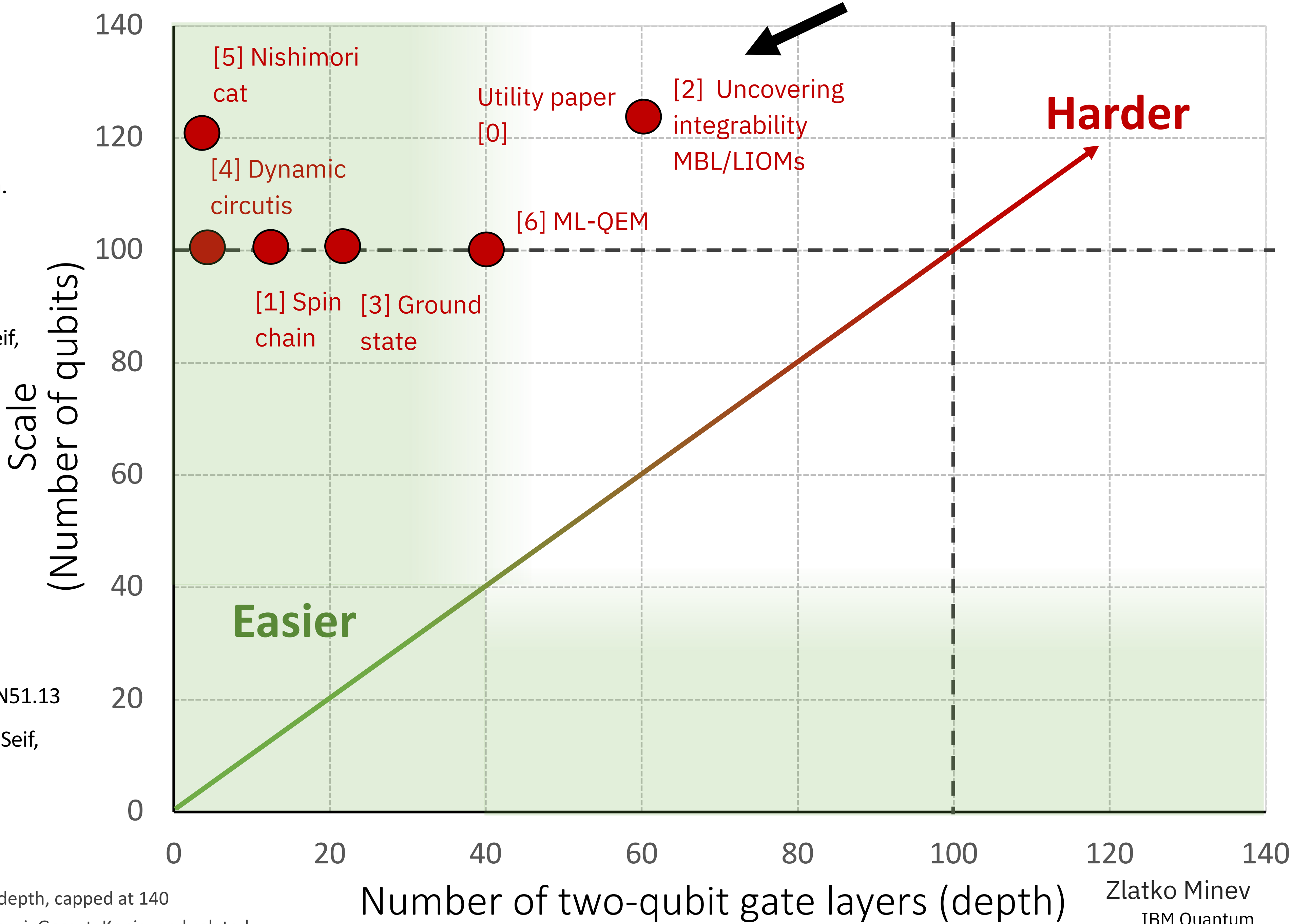

[3] Farrell, Illa, Ciavarella, Savage.
arXiv: 2308.04481 (2023)


[4] Bäumer, Tripathi, ... Seif,
Minev. APS Y45.4
arXiv: 2308.13065 (2023)


[5] Chen, Zhu, Verresen, Seif,
Baümer, ... Trebst, Kandala.
arXiv: 2309.02863 (2023) APS N51.13


[6] Liao, Wang, Sitdikov, Salcedo, Seif,
Minev.
arXiv: 2308.13065 (2023)

...



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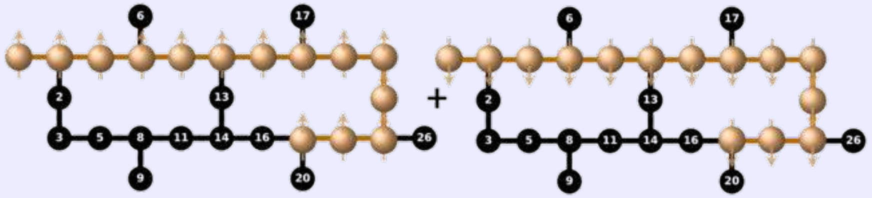
* signal stops or decays more than 50% beyond this depth, capped at 140
* note: quantum advantage with shallow circuits, Bravyi, Gosset, Konig, and related

Check out APS24

Y45.4: Efficient Long-Range Entanglement using Dynamic Circuits (invited)

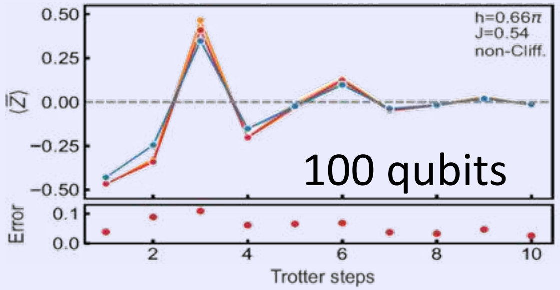


Gate teleportation over 100+ qubits

arXiv:2308.13065 (2023)

Bäumer, Tripathi, Wang, Rall, Chen, Majumder, Seif, Minev

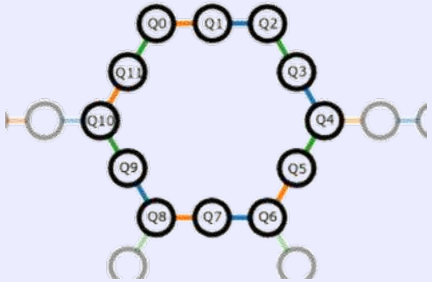
D52.3: Machine Learning for Practical Quantum Error Mitigation (ML-QEM)



arXiv:2308.13065 (2023)

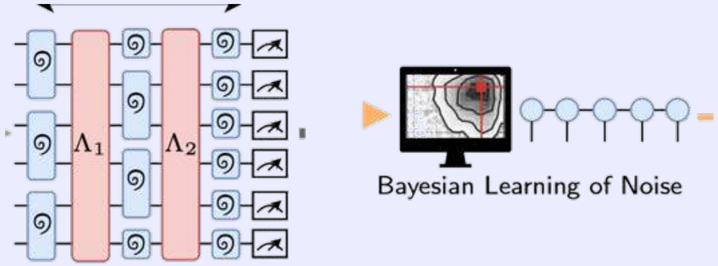
Liao, Wang, Sitdikov, Salcedo, Seif, Minev

Y51.5: Learning about quantum noise at scale



Seif, Liao, Majumder, Chen, Wang, Bäumer, Malekakhlagh, Javadi-Abhari, Jiang, Minev

D50.9 Demonstration of Robust and Efficient Quantum Property Learning with Shallow Shadows



arXiv:2402.17911 (2024)

Hu, Gu, Majumder, Ren, Zhang, Wang, Minev, You, Seif, Yelin

Can quantum computers be useful for many-body physics in the next 3-5 years?

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Uncovering the dynamics of many-body systems

Many-body quantum systems and their dynamics

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

Symmetries, conservation laws, and integrability

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

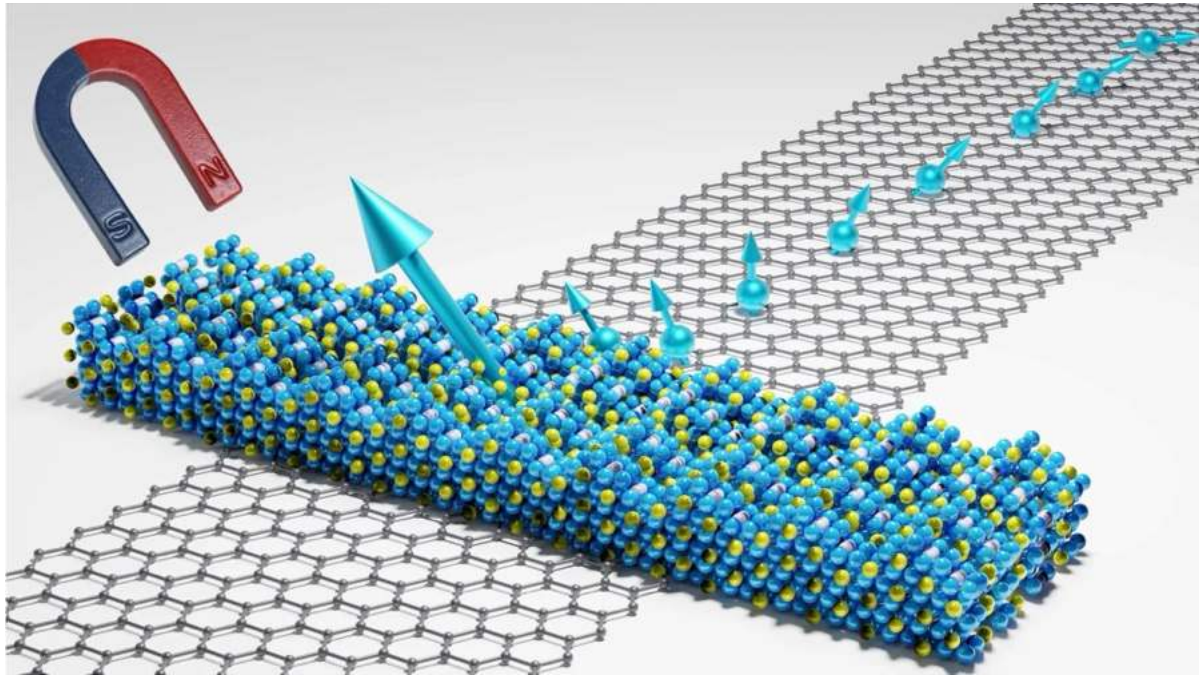

Image: Chalmers

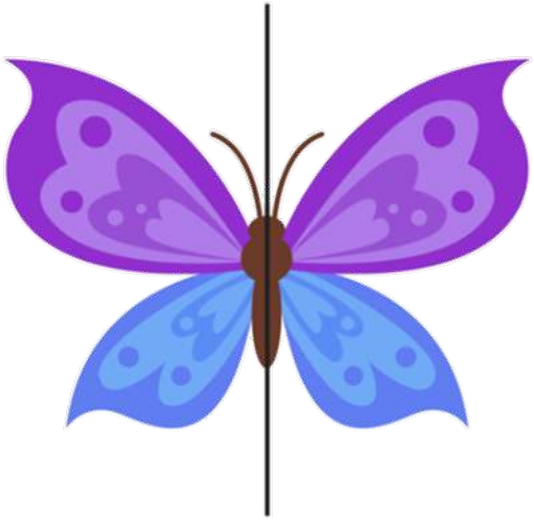

Image: SuperSimple

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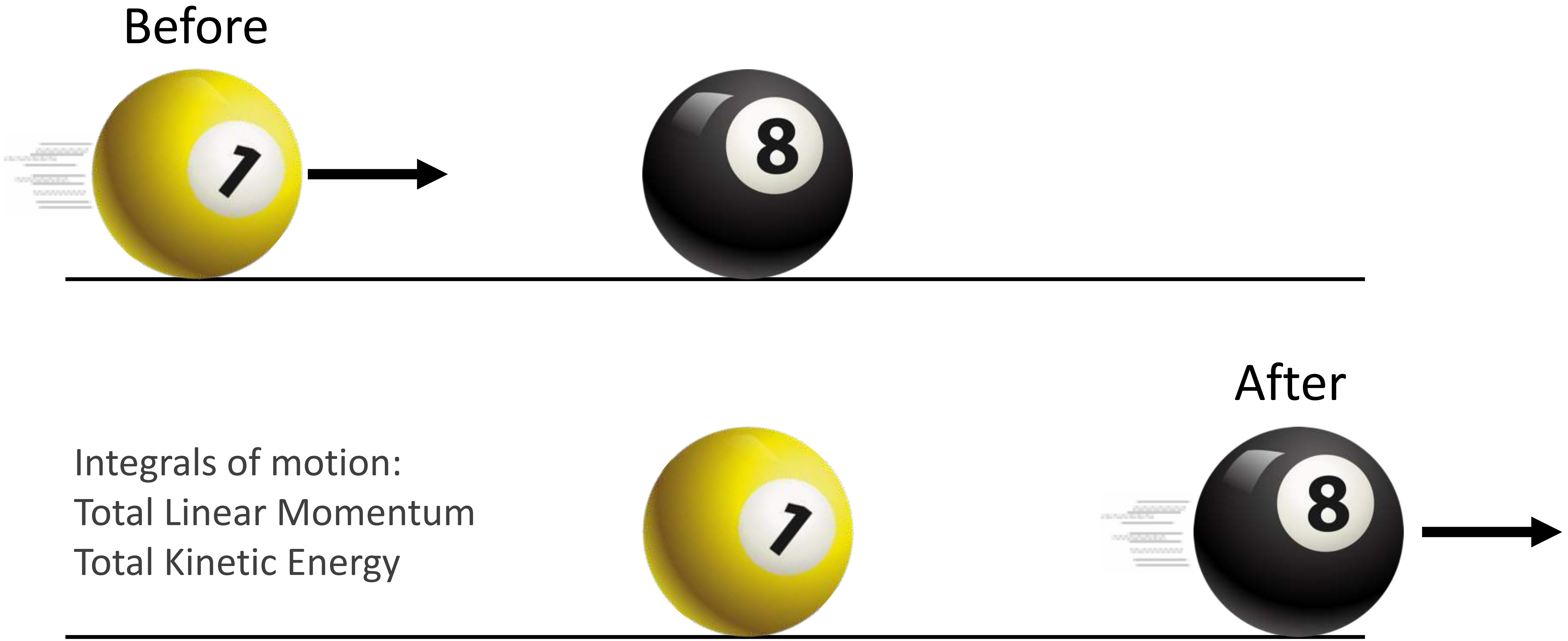
Classical Physics: Integrals of Motion



Integrals of motion:
Total Linear Momentum
Total Kinetic Energy

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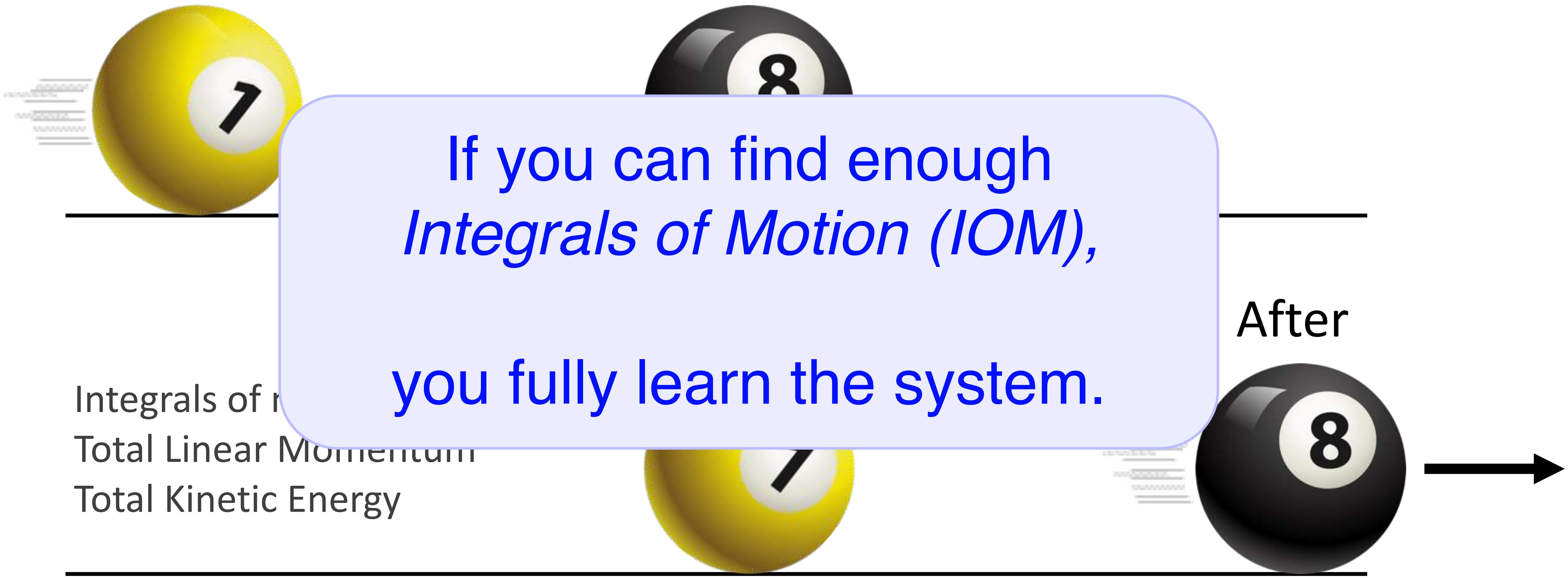
Balls: boris-farias

Classical Physics: Integrals of Motion

Before



If you can find enough *Integrals of Motion (IOM)*,

you fully learn the system.

After

Integrals of r
Total Linear Momentum
Total Kinetic Energy

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Balls: boris-farias

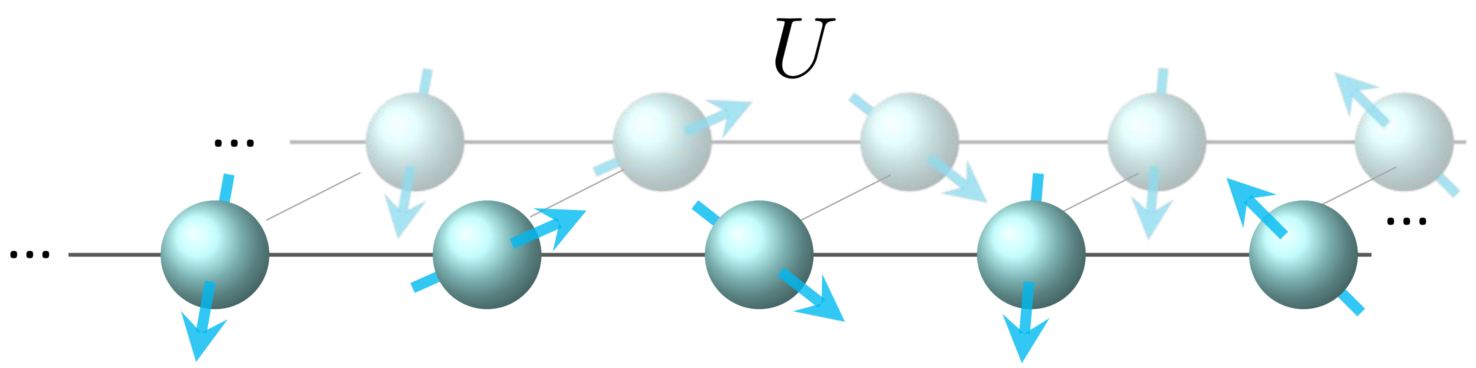
Quantum Physics: Integral of motion

Integral of motion L

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

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

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



J.-S. Caux and J. Mossel, Remarks on the notion of quantum integrability, J. Stat. Mech.-Theory E. 2011, P02023 (2011)
B. Sutherland, Beautiful models: 70 years of exactly solved quantum many-body problems (World Scientific, 2004)

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Integrals of motion (IOM): toy example

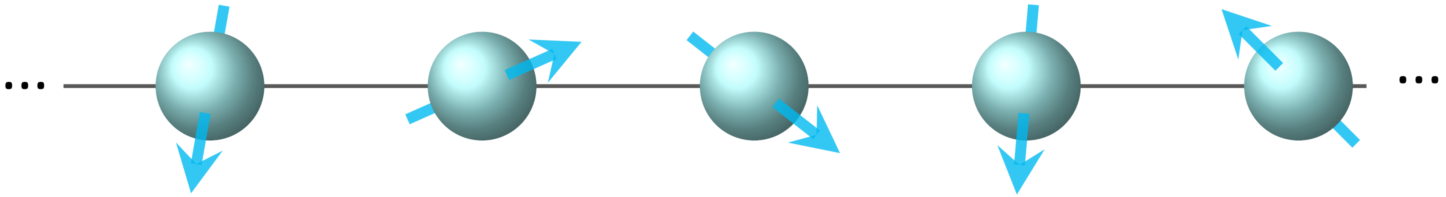
Integral of motion L

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

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

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

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



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

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

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

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

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

† N. Shiraishi and K. Matsumoto, Undecidability in quantum thermalization, Nature Comm. 12, 5084 (2021).

* 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.

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Local integral of motion (LIOM)

Integral of motion L

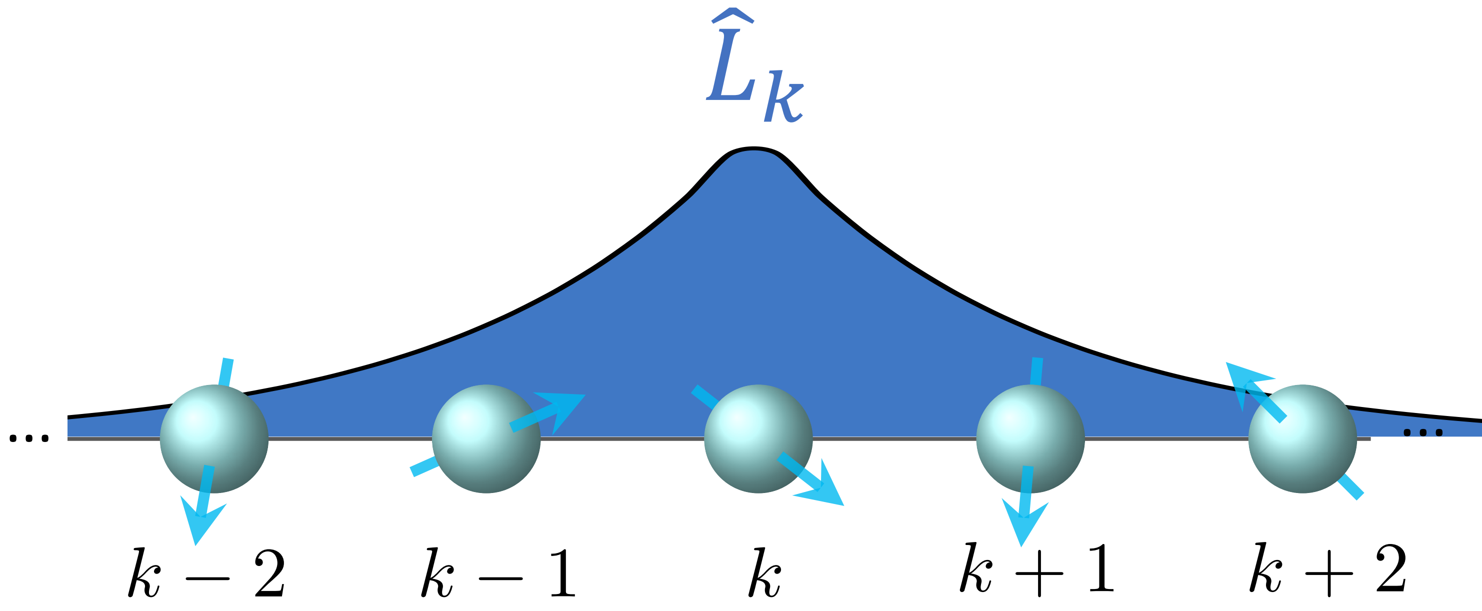
$$[U, L] = 0 \qquad [H, L] = 0$$

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

Local integral of motion (LIOM) L

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

local neighborhood



Proceed with caution regarding exponential tails

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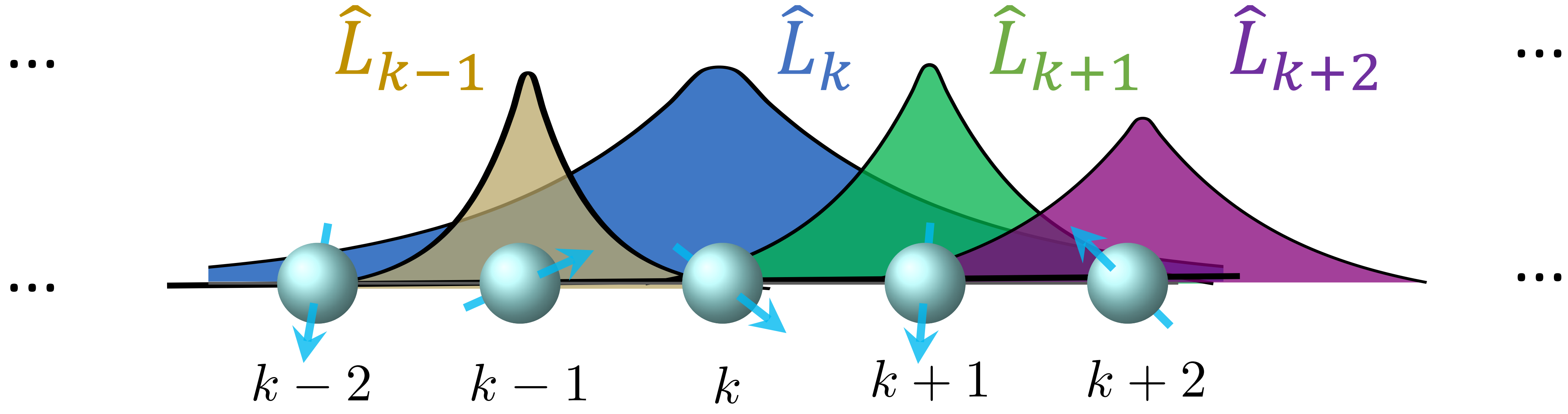
Local integrals of motion (LIOM) & Integrability



Quantum integrable

if a system is described by an extensive set of local integrals of motion (LIOMs).

S. Caux and J. Mossel, J. Stat. Mech.-Theory E. (2011).

Quantum integrability is tricky to define formally, see Caux and Mossel, for relationship to Yang-Baxter.

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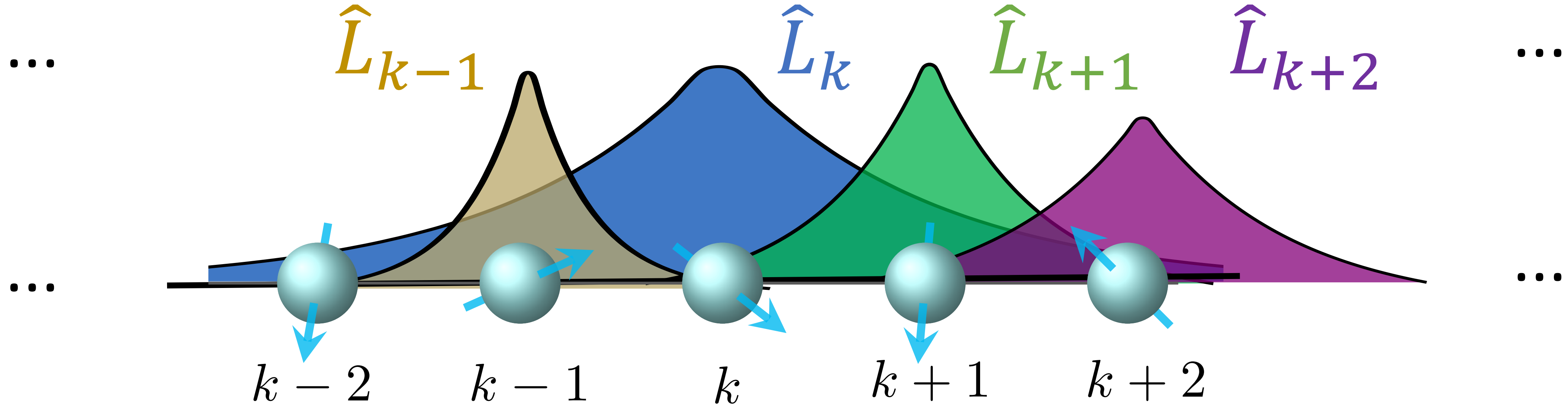
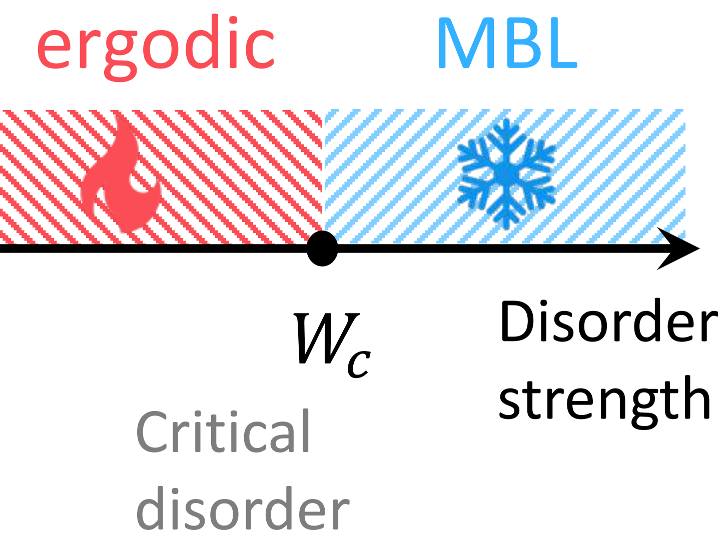
Example connection to disorder and many-body localization (MBL)





Many-body localized (MBL) systems suspected to have an extensive set of local integrals of motion (LIOMs) $\{ L_k \}$. Hypothesis: In the MBL regime, the original Hamiltonian can be understood as

$$\hat{H} = \sum_k \epsilon_k \hat{L}_k + \sum_{k<j} J_{kj}^{(2)} \hat{L}_k \hat{L}_j + \sum_{i<j<k} J_{ijk}^{(3)} \hat{L}_i \hat{L}_j \hat{L}_k + \cdots$$

MBL: Basko, Aleiner, Altshuler, Ann Phys (2006), Pal and Huse, RRB (2010), Serbyn, Papic, Abanin, PRL (2013), Huse, Nandkishore, Oganesyan PRB (2014) … See also recent work by Dries Sels

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New to LIOMs and many-body localization?

A. Chandran, M. Fisher, V. Khemani, S. Vijay, L. Radzihovsky (Organizers)

www.boulderschool.yale.edu/2023/boulder-school-2023

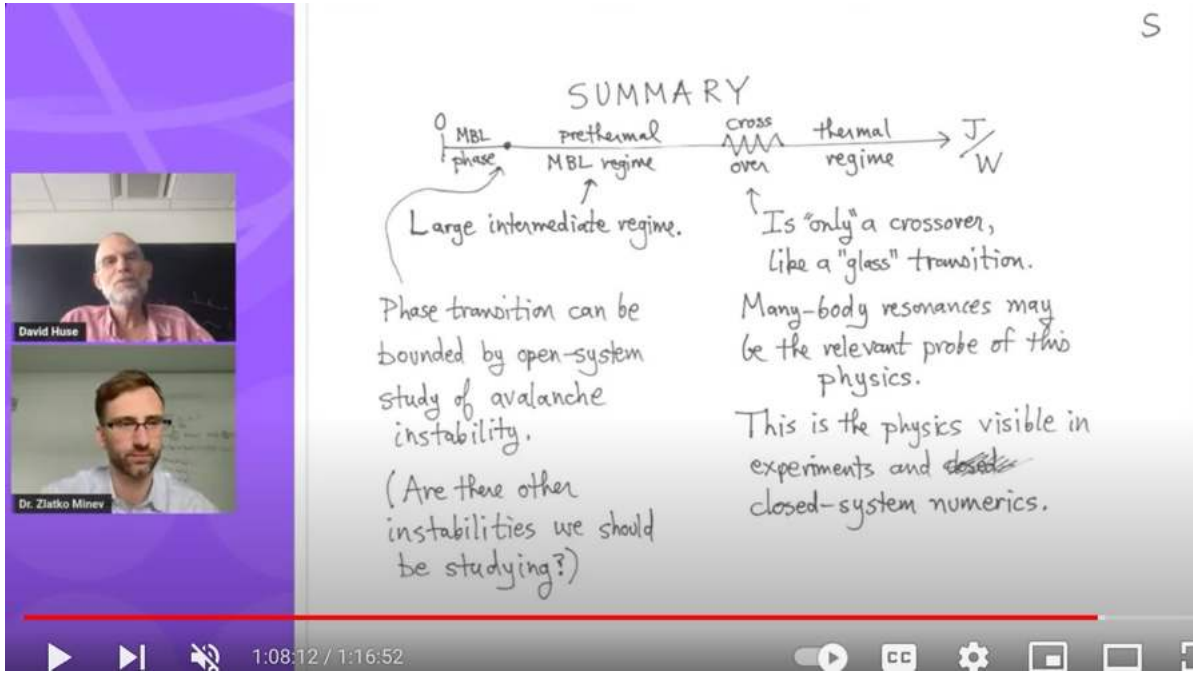
Lots of video lectures here on YouTube.
Also here lectures on quantum error mitigation by Z. Minev.

Reviews

Many-body localization, thermalization, and entanglement
Dmitry A. Abanin, Ehud Altman, Immanuel Bloch, and Maksym Serbyn Rev. Mod. Phys. 91, 021001

…

Qiskit Quantum Seminar (YouTube)



"Many-Body Localization" talk by David Huse
https://qiskit.org/events/seminar-series

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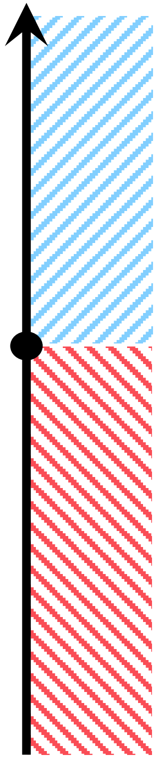
Experiments related to many-body localization



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- M. Rispoli, A. Lukin, R. Schittko, S. Kim, M. E. Tai, J. Leonard, and M. Greiner, Quantum critical behaviour at the many-body localization transition, Nature 573, 385 (2019).
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- J. Leonard, S. Kim, M. Rispoli, A. Lukin, R. Schittko, J. Kwan, E. Demler, D. Sels, and M. Greiner, Probing the onset of quantum avalanches in a many-body localized system, Nat. Phys. 19, 481 (2023).
- … … …

Pedram Roushan

Peter Schauß

Zlatko Minev

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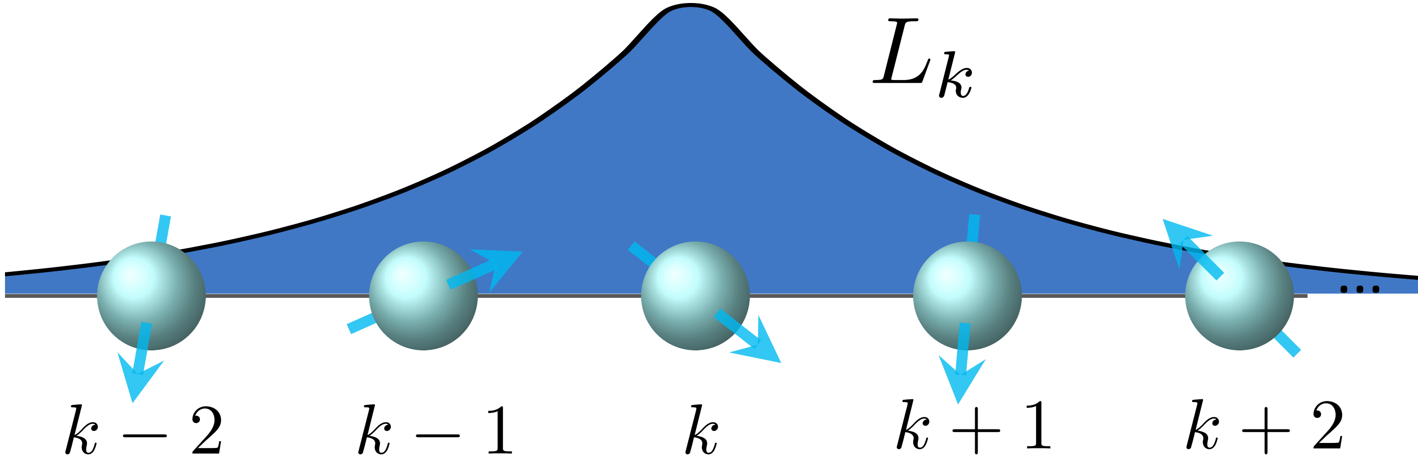
Local integrals of motion (LIOMs): Example connection to ergodicity breaking and many-body localization

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

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

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

Tricky to find

- Beyond finding ground states
- We will be interested in dynamics and the full Hilbert space and spectrum

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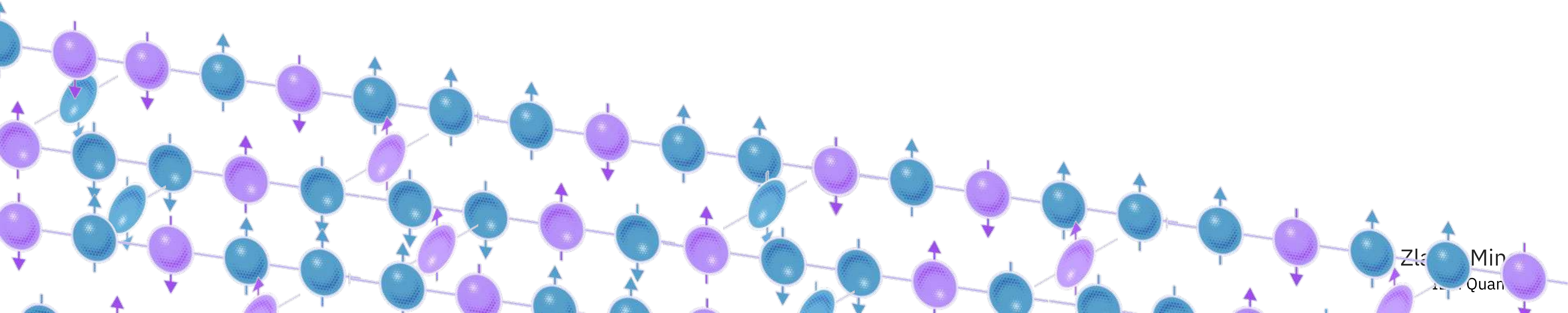
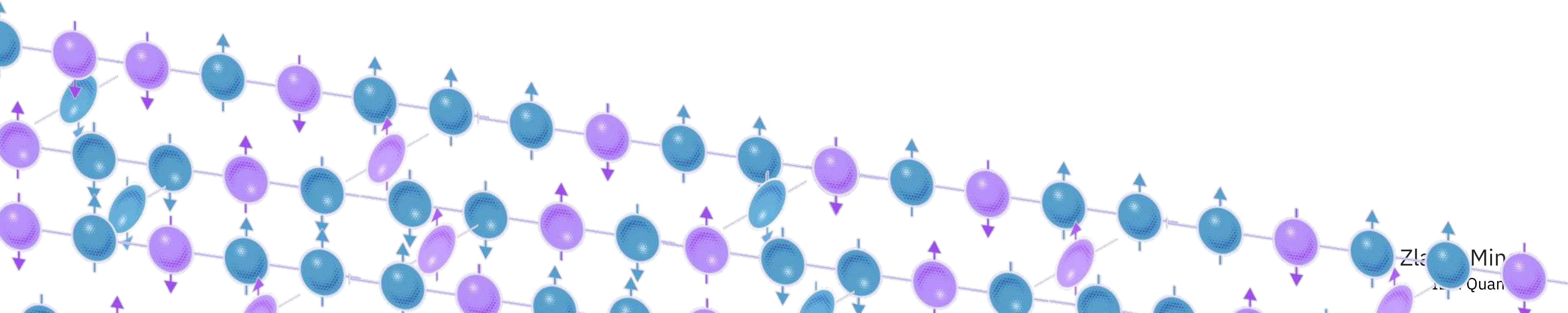
Can we uncover all integrals of motion $\{L\}$ of a large, disordered many-body system using a quantum computer?



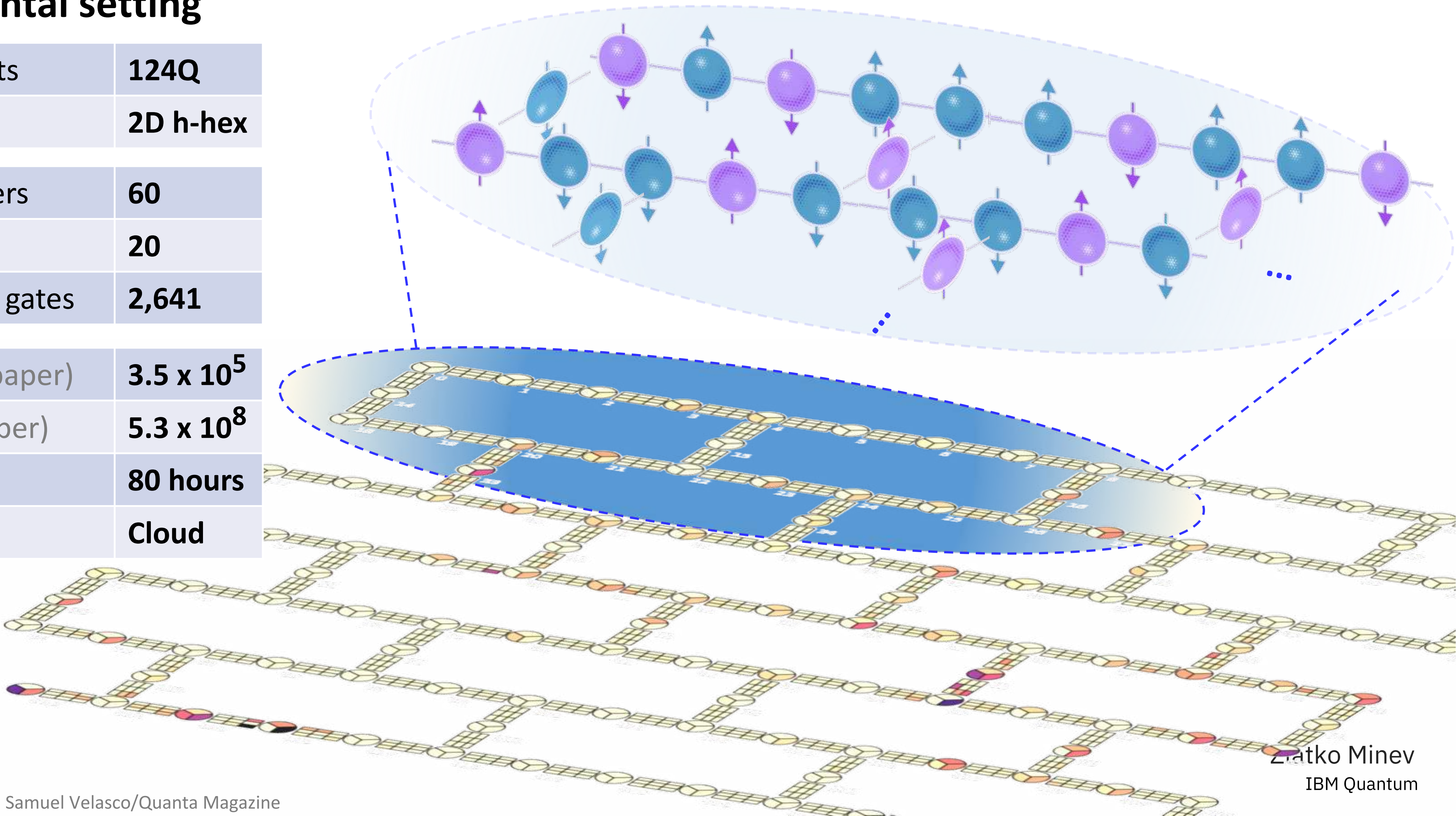
Preview



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

Experimental setting

Number of qubits	**124Q**
Connectivity	**2D h-hex**
Depth in 2Q layers	**60**
Floquet steps	**20**
Total num. of cX gates	**2,641**
Circuits (entire paper)	**3.5 x 10^5**
Shots (entire paper)	**5.3 x 10^8**
QPU runtime	**80 hours**
Environment	**Cloud**



arXiv:2307.07552

Spin image cartoon based on: Samuel Velasco/Quanta Magazine

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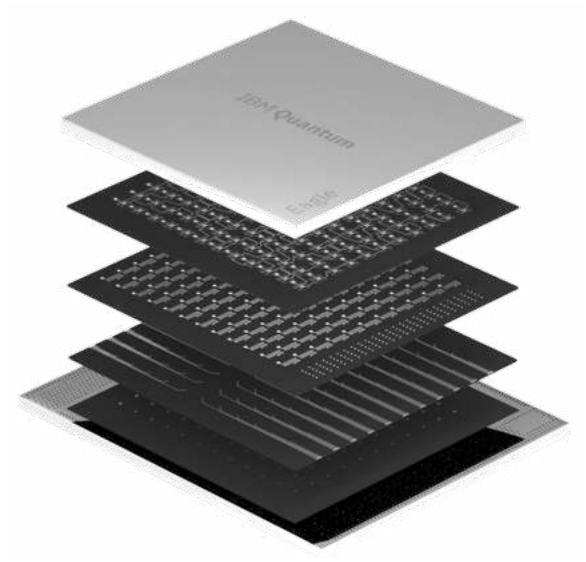
Interaction map and device layers



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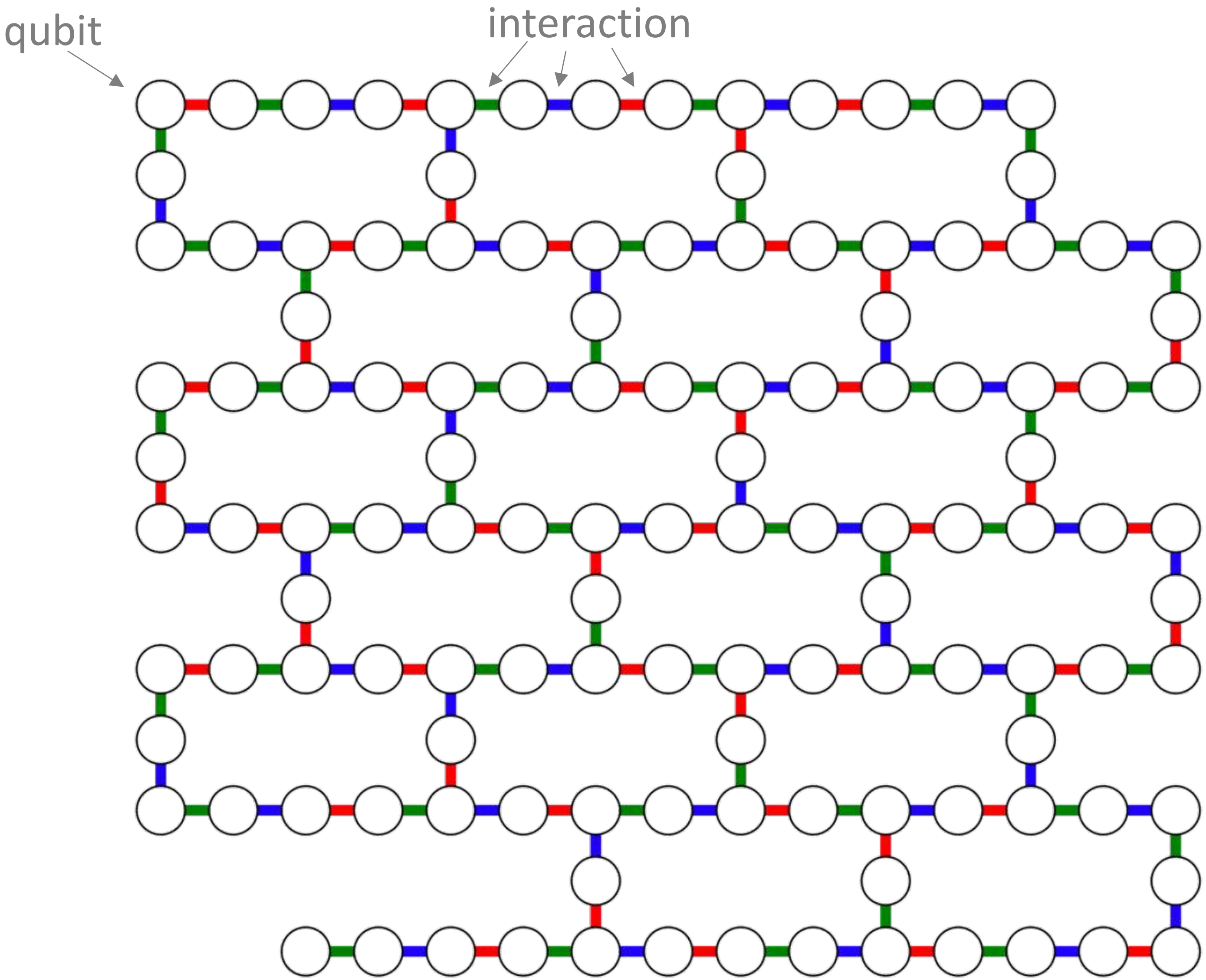
arXiv:2307.07552



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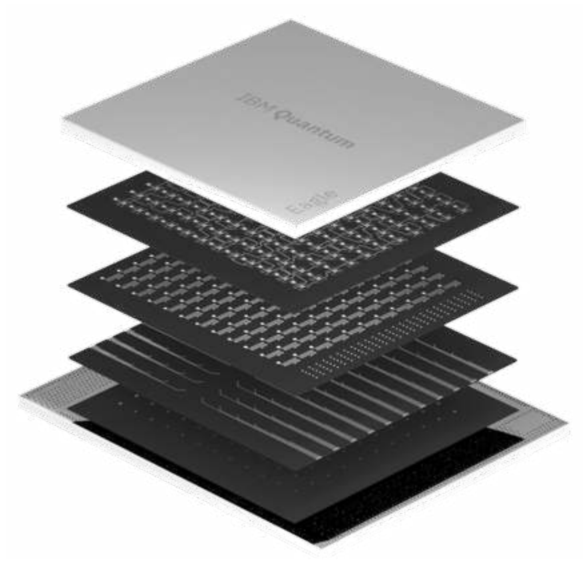
Initialize lattice in fun states



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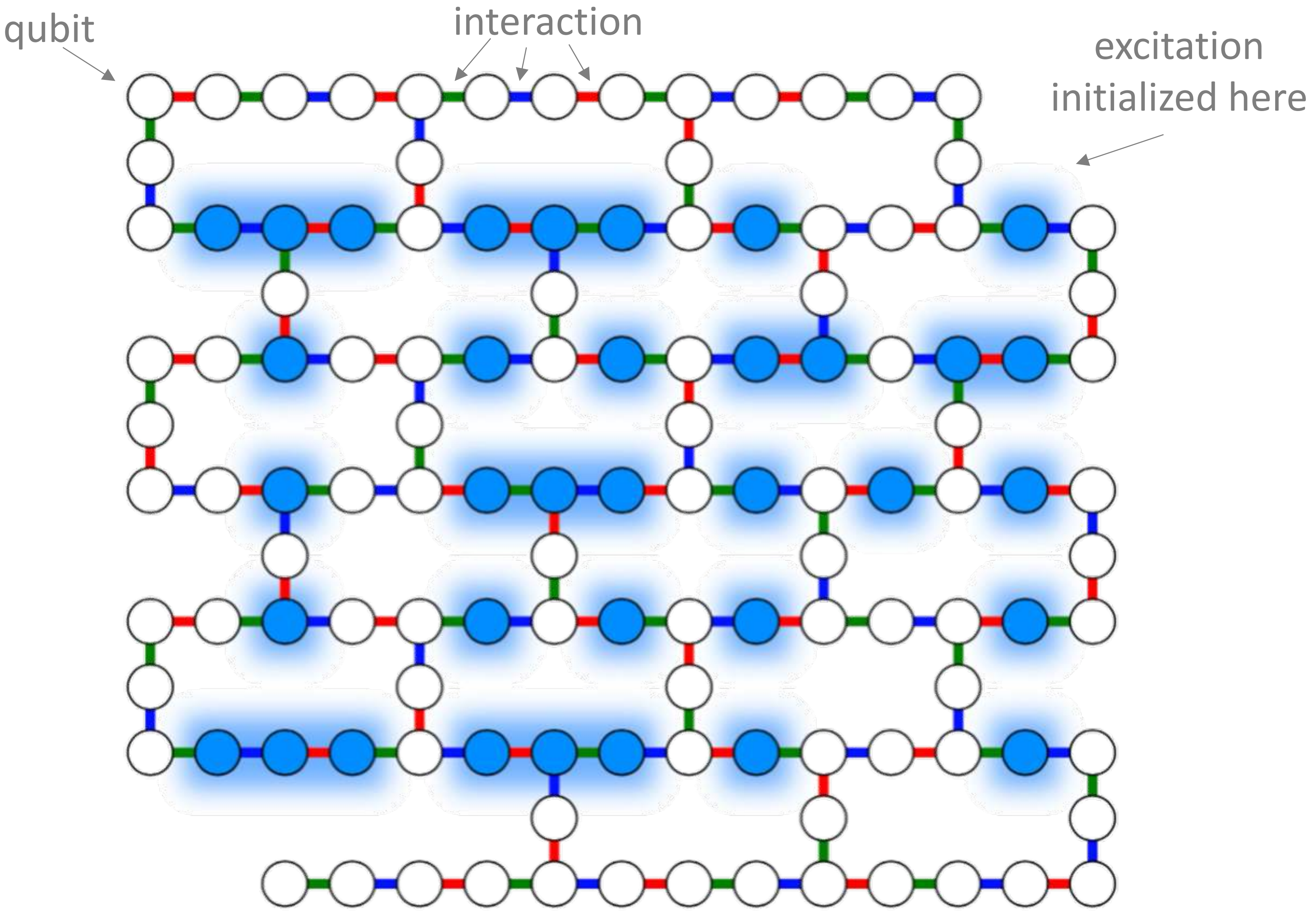
arXiv:2307.07552



Color represent spin polarization

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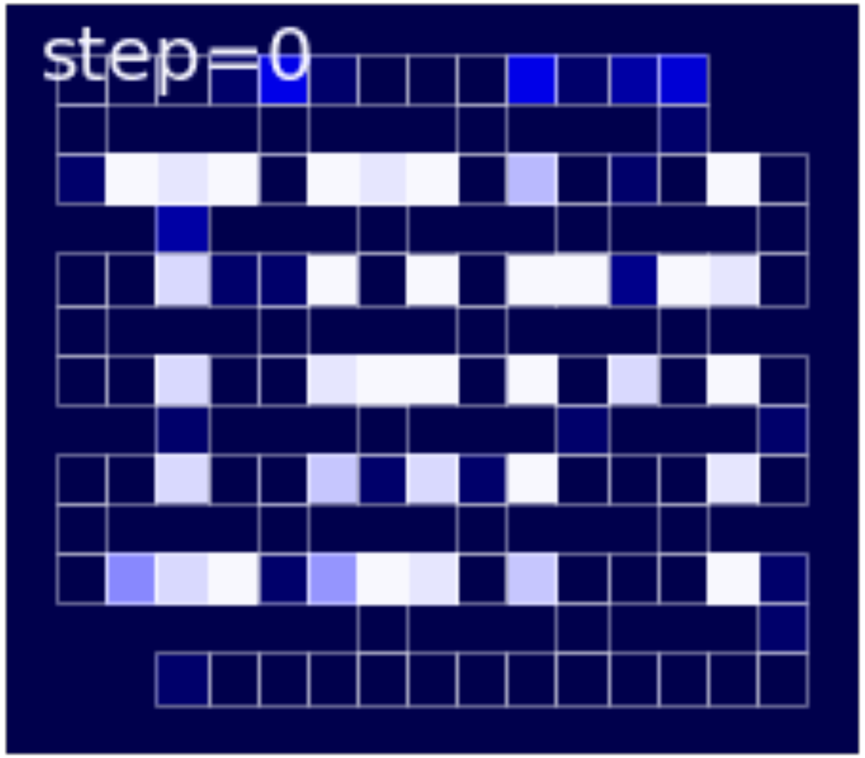
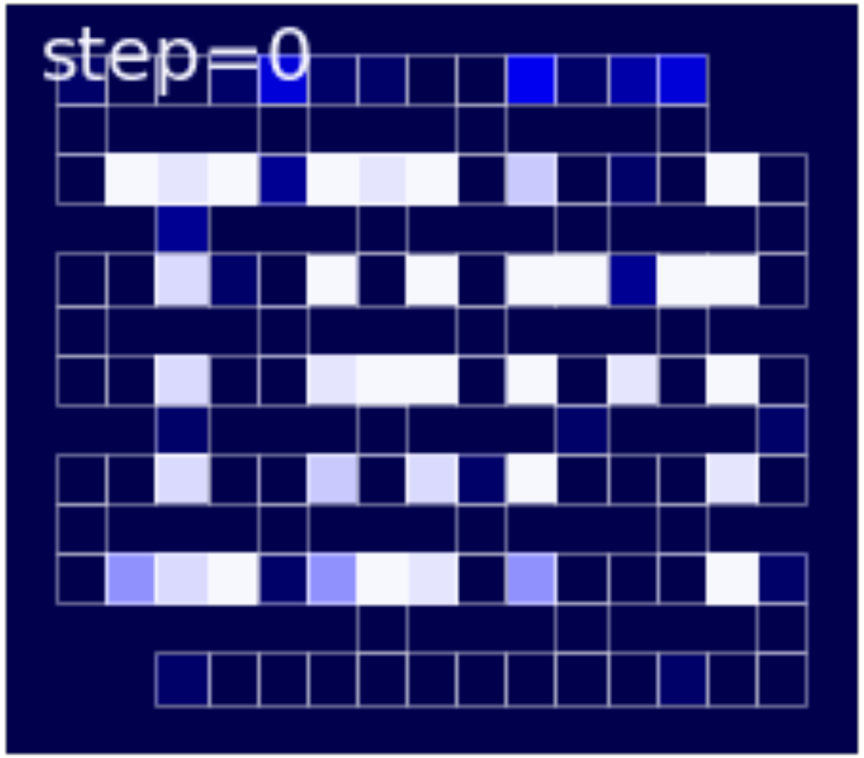
Quantum dynamics in different regimes

Number of qubits	**124Q**
Connectivity	**2D h-hex**

Depth in cX gates	**60**
Floquet steps	**20**
Total number of cXs	**2,641**





Thermalizing regime

Prethermal regime

arXiv:2307.07552

Color represent spin polarization

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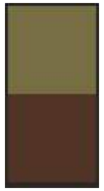
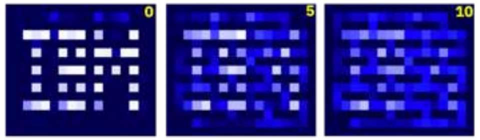
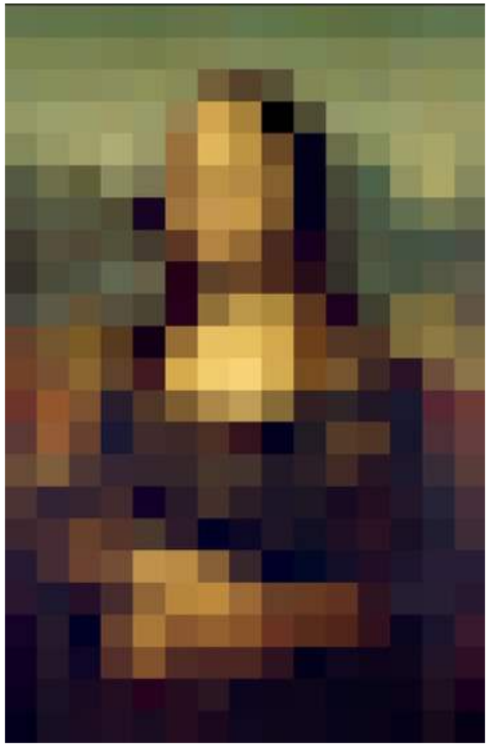
A more detailed portrait





Spin
imbalance



One-particle density
matrix (OPDM)

Local integrals of motion
(LIOMs)

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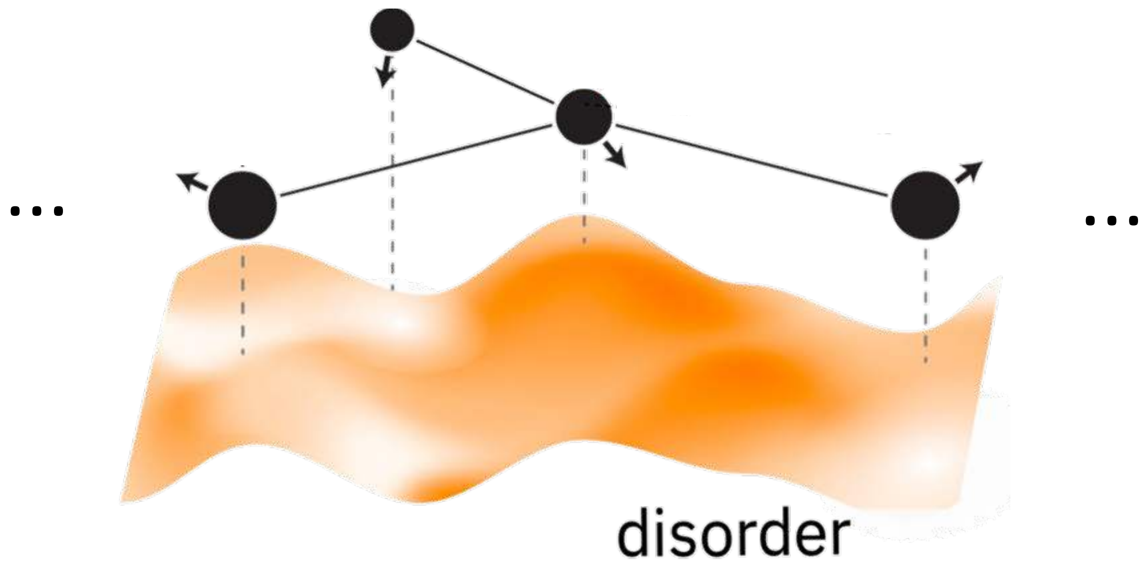
Spin lattice system over some potential



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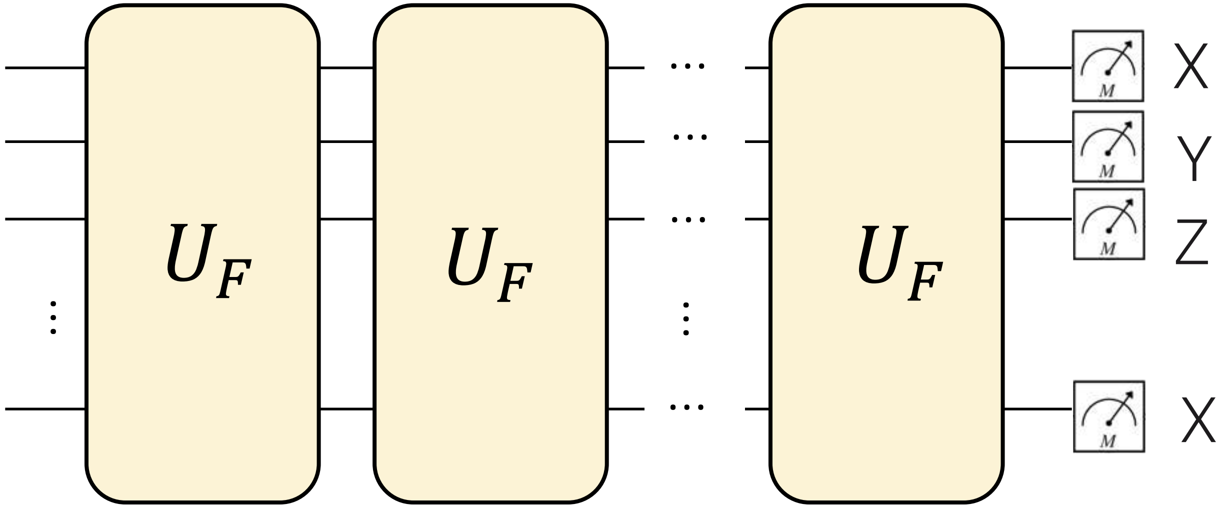
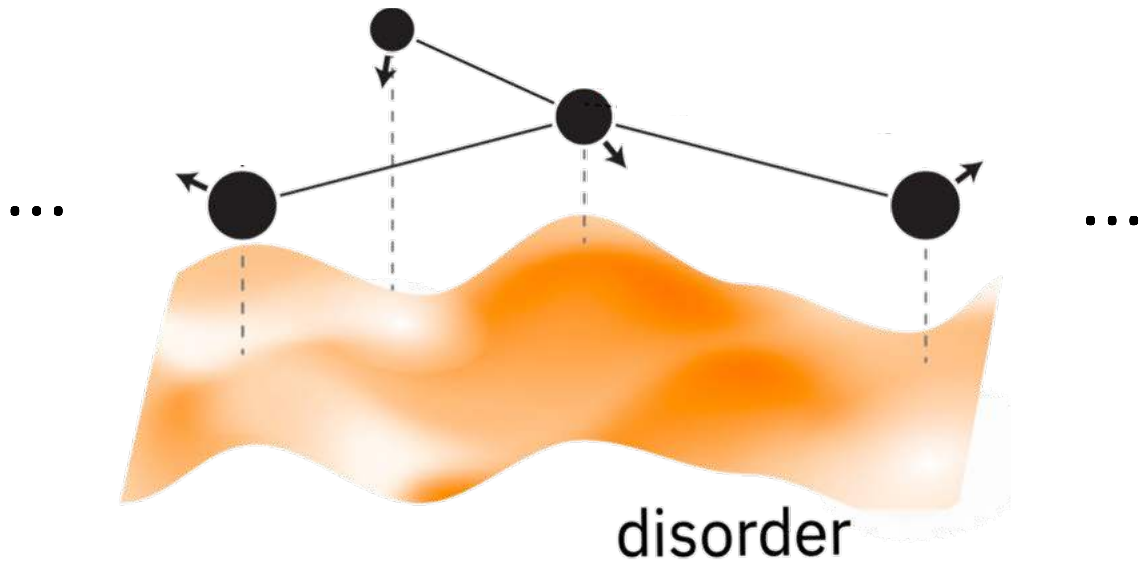
Floquet circuit evolution





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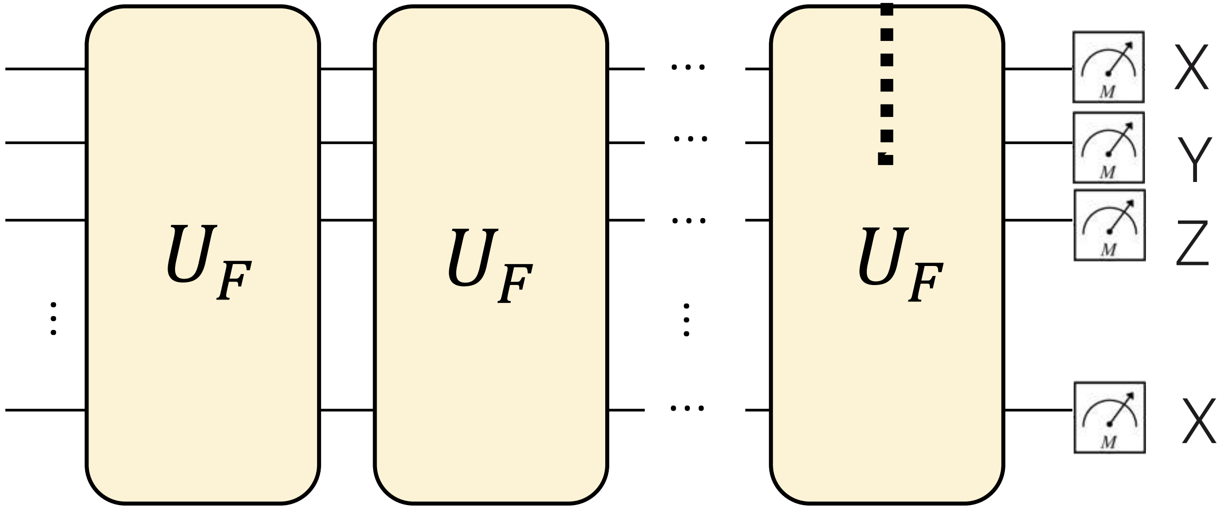
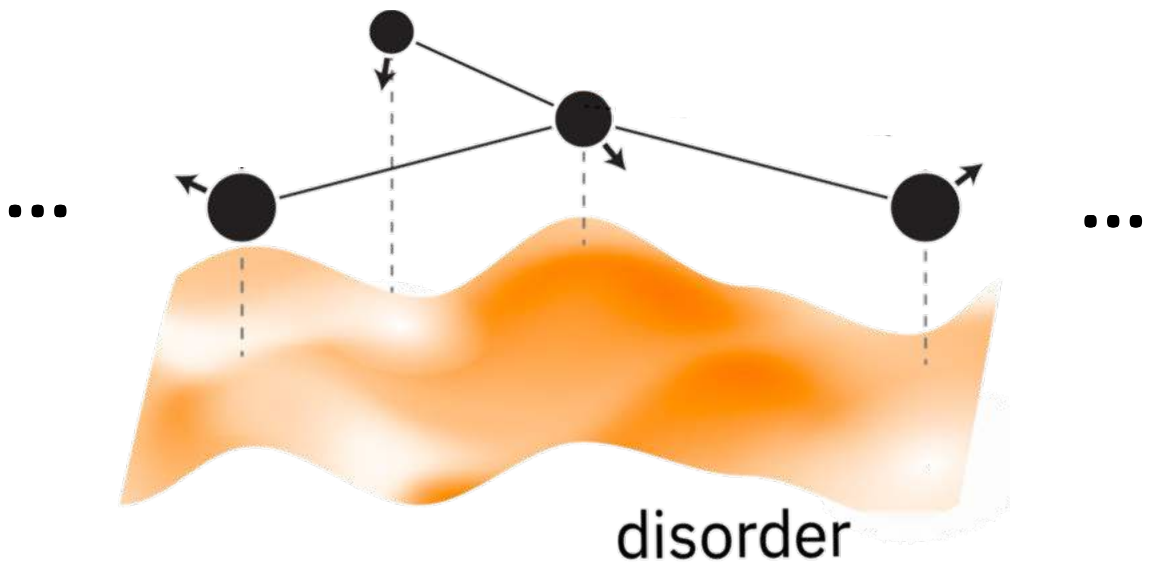
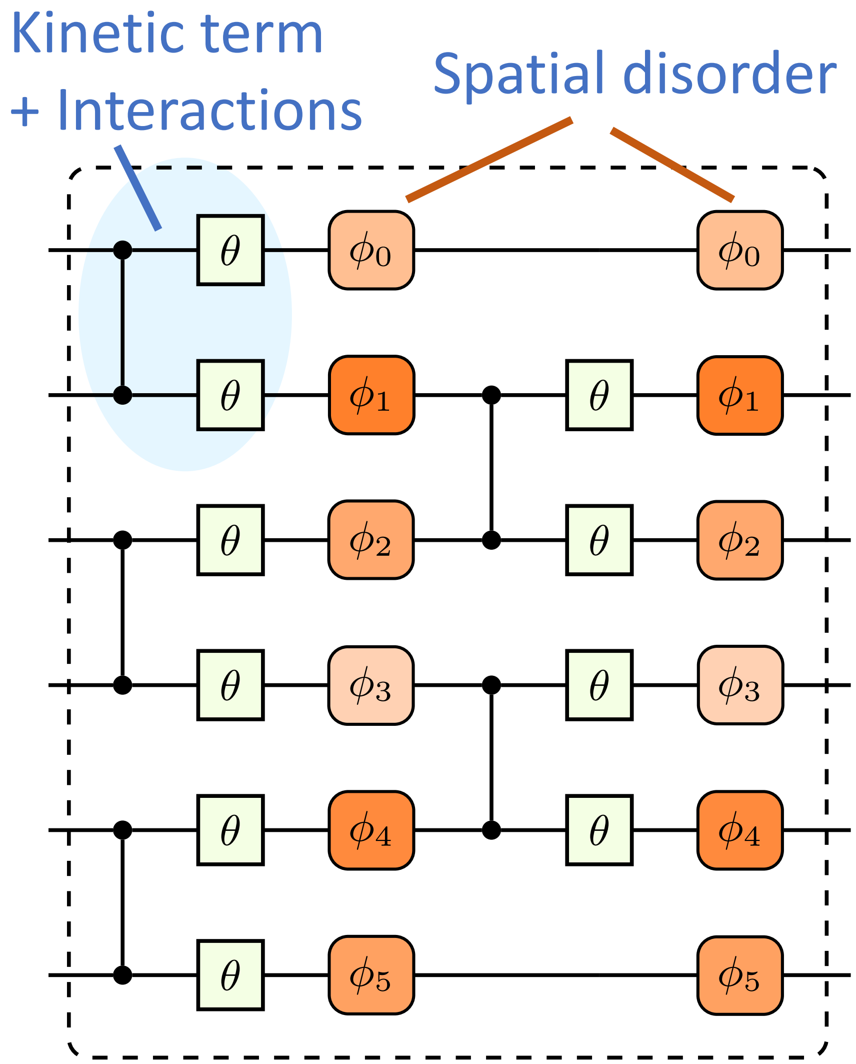
Circuit model







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

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

Uniformly sample disorder

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

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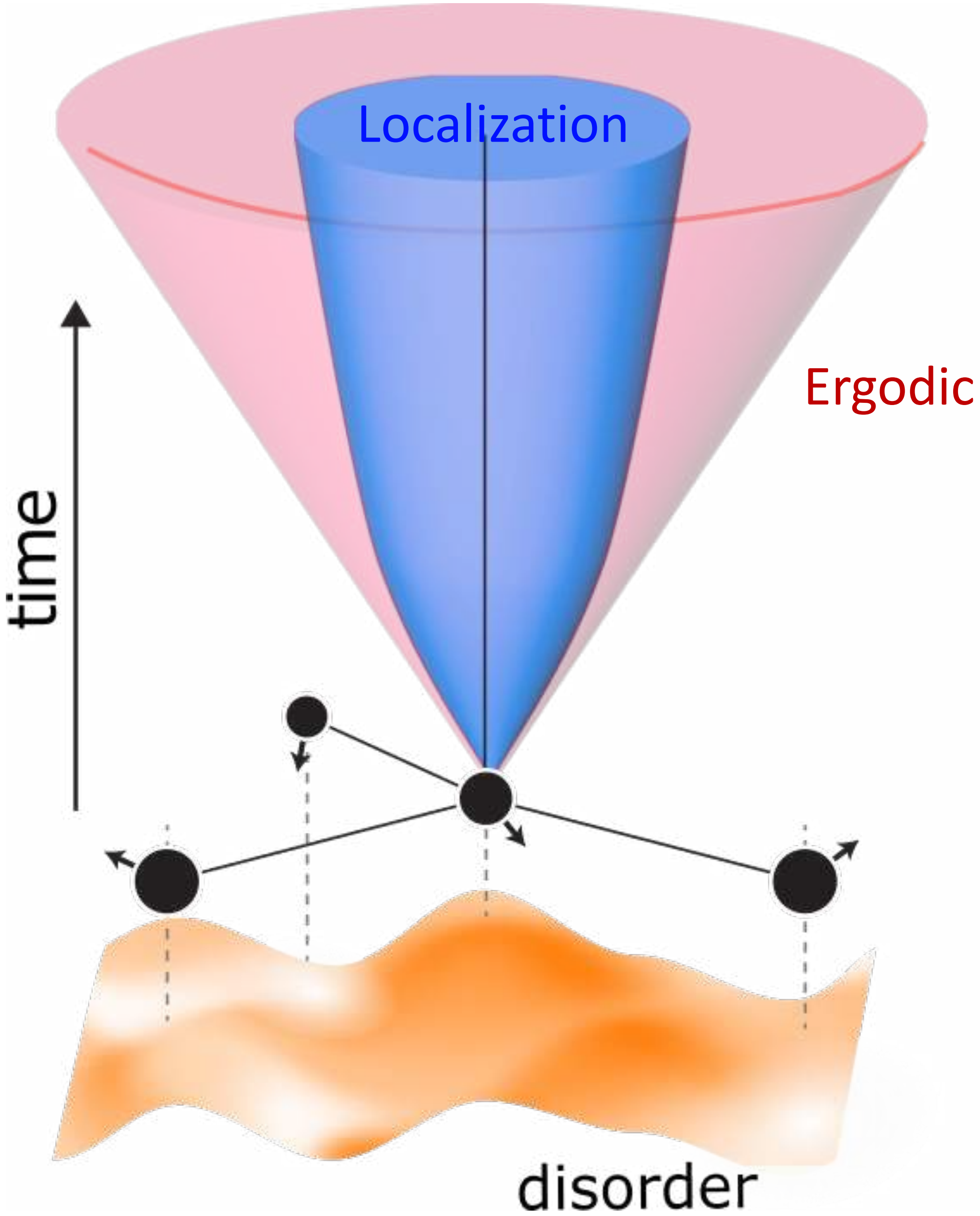

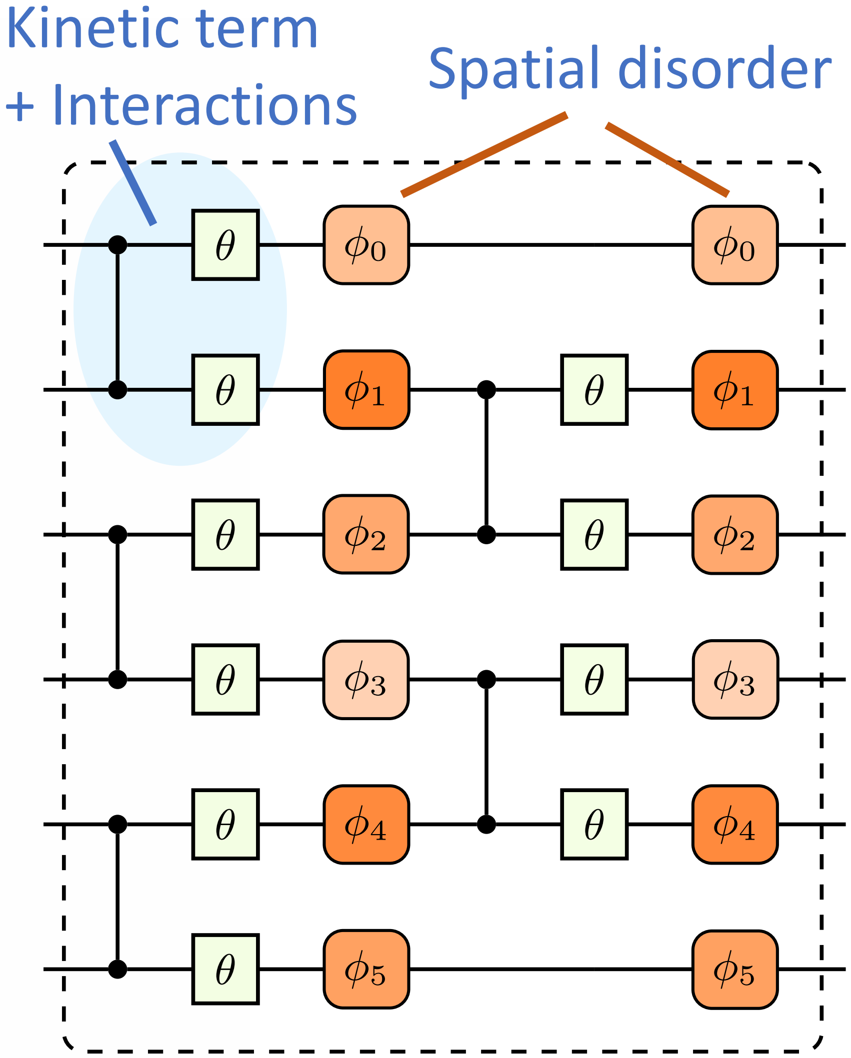

Depends on parameters

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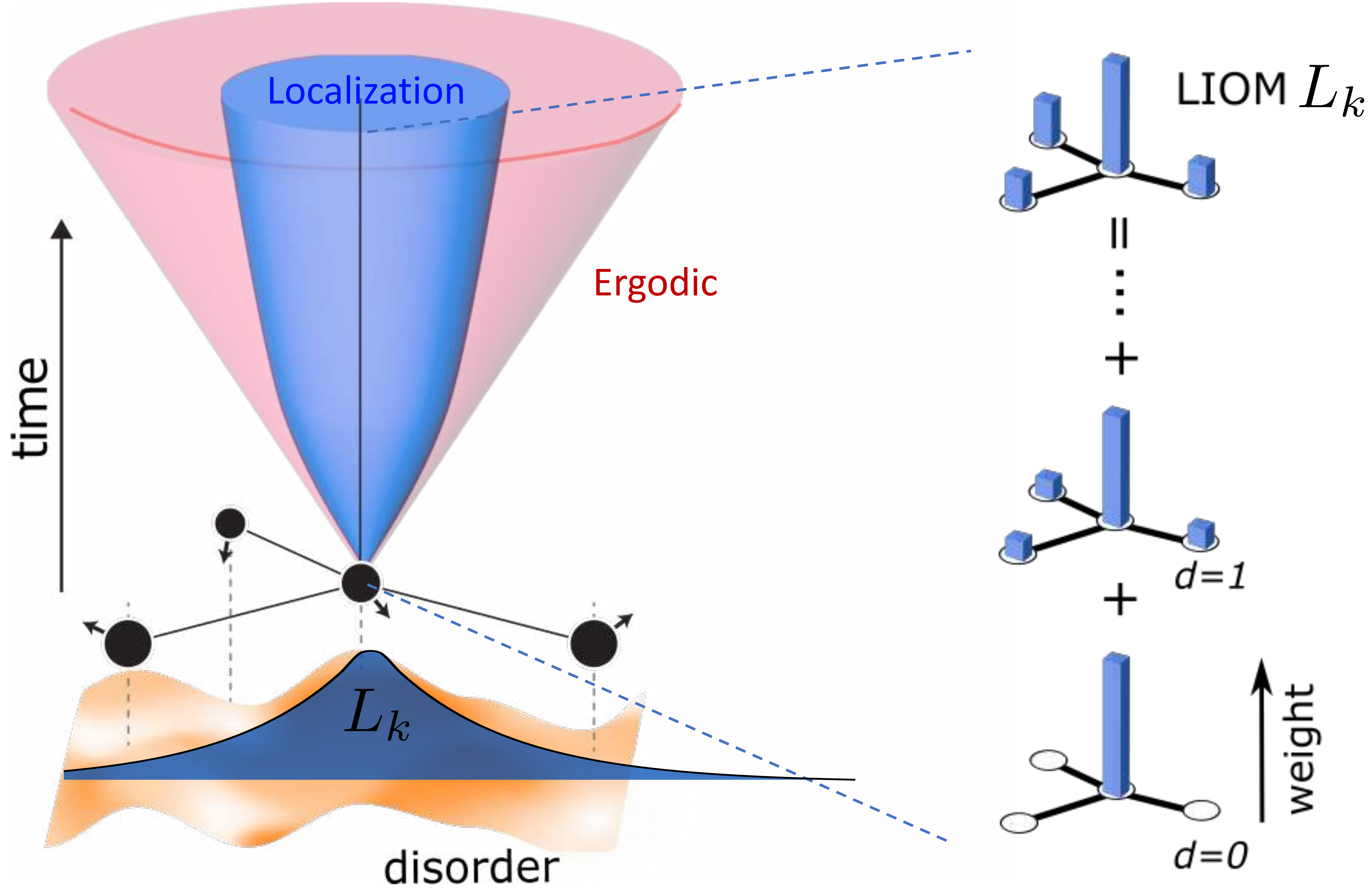

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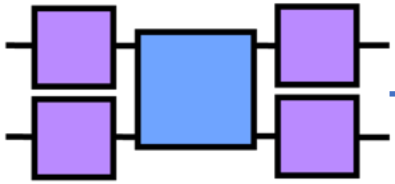
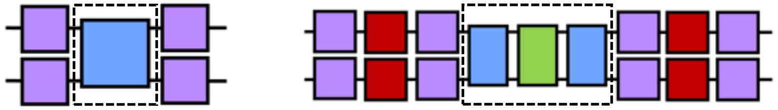
A composite error mitigation strategy

Initial Circuits

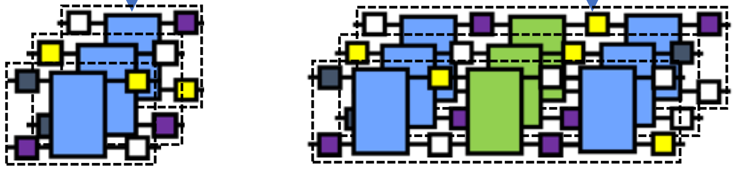


Error Mitigation Factory

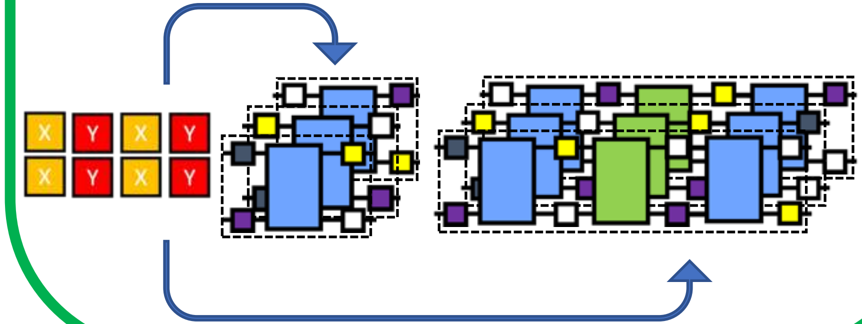
Prototype ZNE
Digital Zero-Noise Extrapolation: Folding

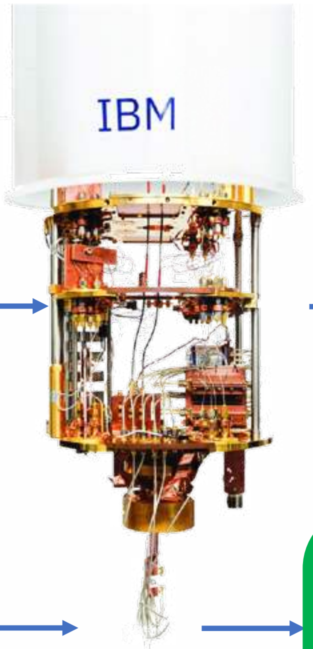


Twirling
Pauli



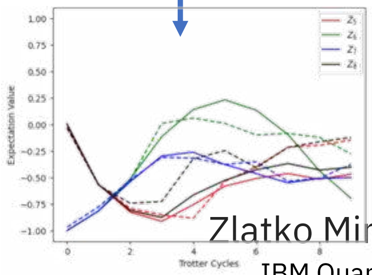
Custom sequence/pass
Dynamical Decoupling





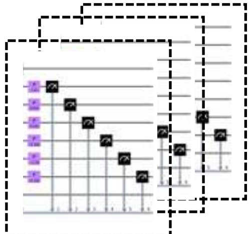
Counts
{'000000': 20,
'000001': 480,
...
'111111': 3}

Post-processing
Readout error mitigation
Averaging of twirled results
Extract commuting Pauli's
Digital zero noise extrapolation
...



Twirling references
1. C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, W. K. Wootters, et al., Phys. Rev. Lett. 76, 722 (1996).
2. Tutorial: zlatko-minev.com/blog/twirling (2022)
3. ...

Custom M3 Runtime program
Readout Error Mitigation Circuits



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Benchmarks of quantum hardware and model

Benchmarks	1D	2D
LIOMs	1D	2D

Spin imbalance experiments
Memory of initial state

Classical numerics in 1D
Spectral and time analysis

One-particle density matrices (OPDM) experiments
Natural orbitals and occupations
Scaling with system size: cross-overs
…

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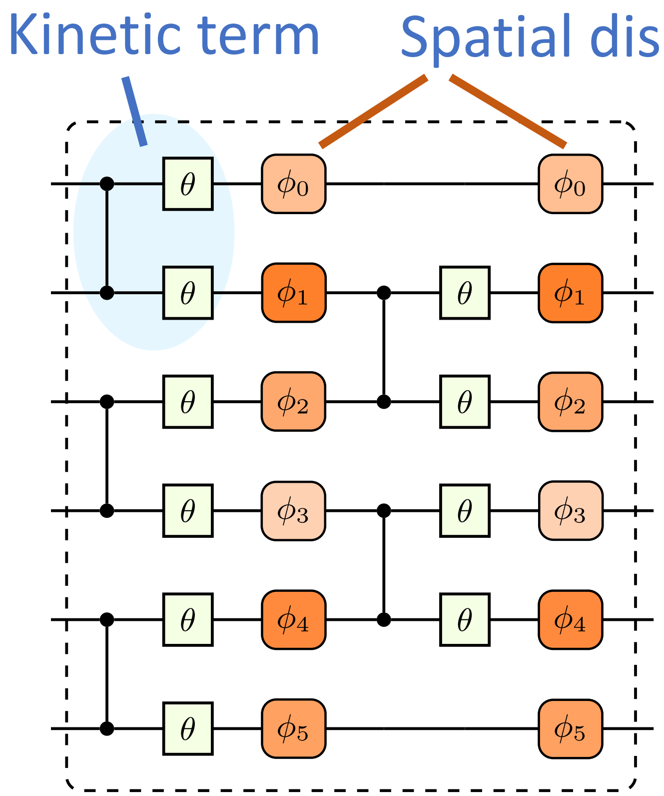
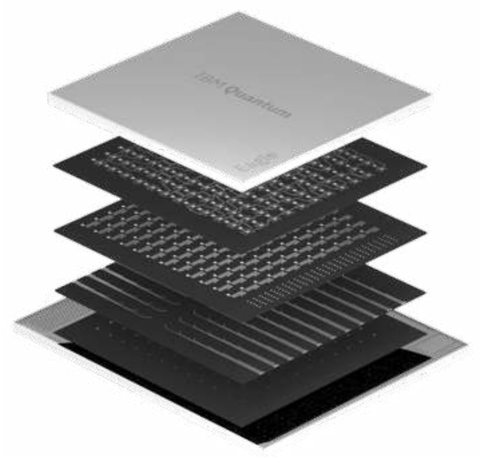
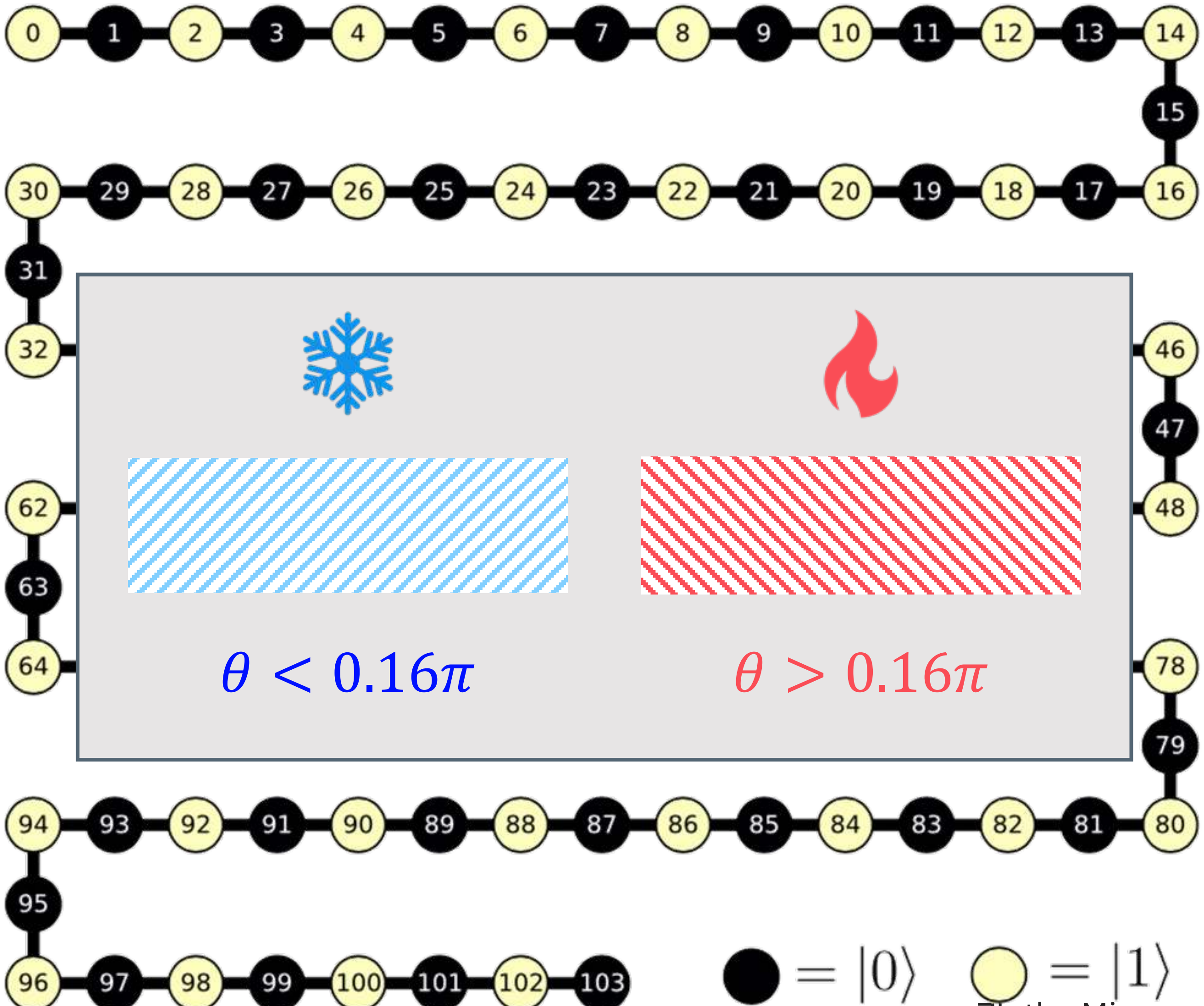
Initial antiferromagnetic state with spin imbalance

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







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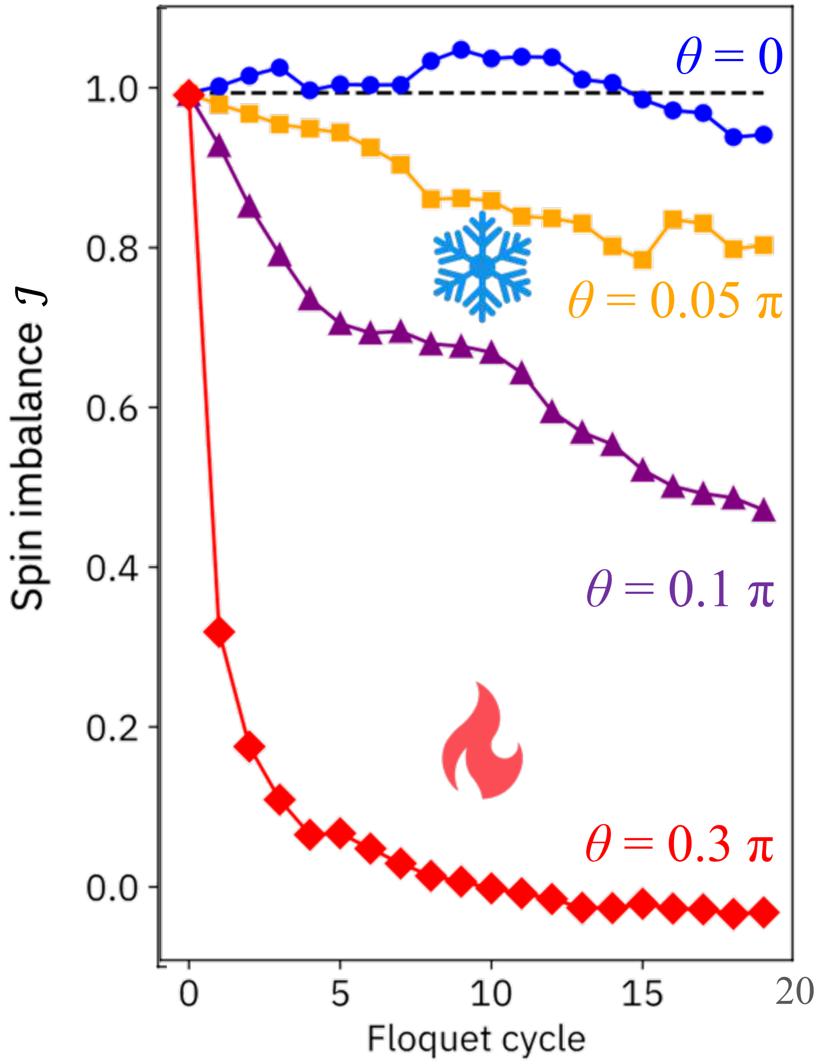
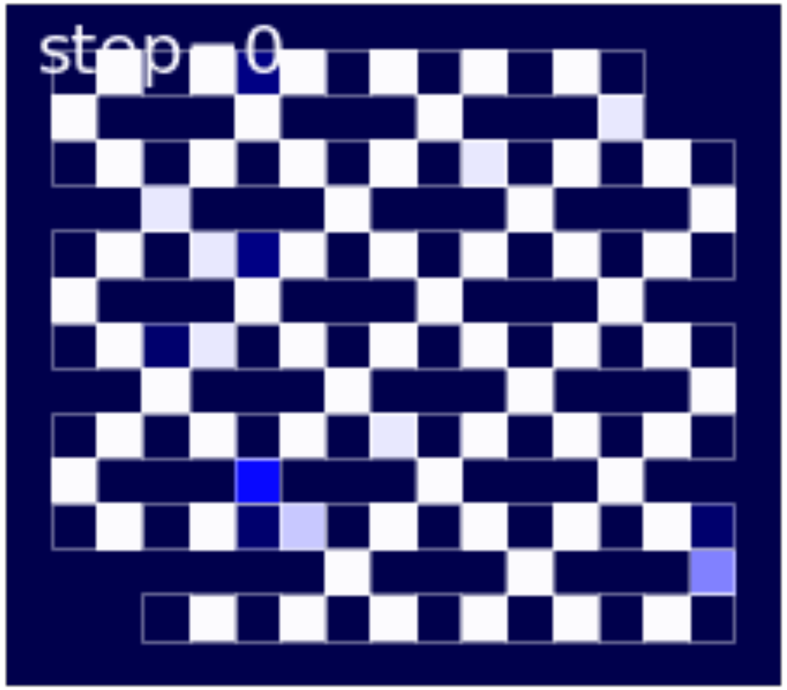
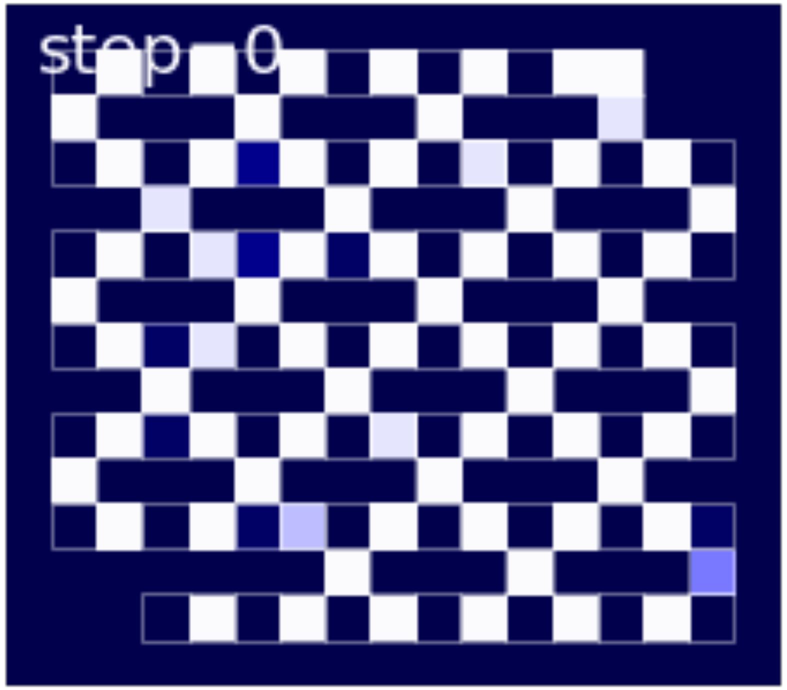
Spin imbalance for antiferromagnetic ordering



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



Thermalizing regime
$\theta = 0.3\pi$



Prethermal regime
$\theta = 0.1\pi$

Color represent spin polarization

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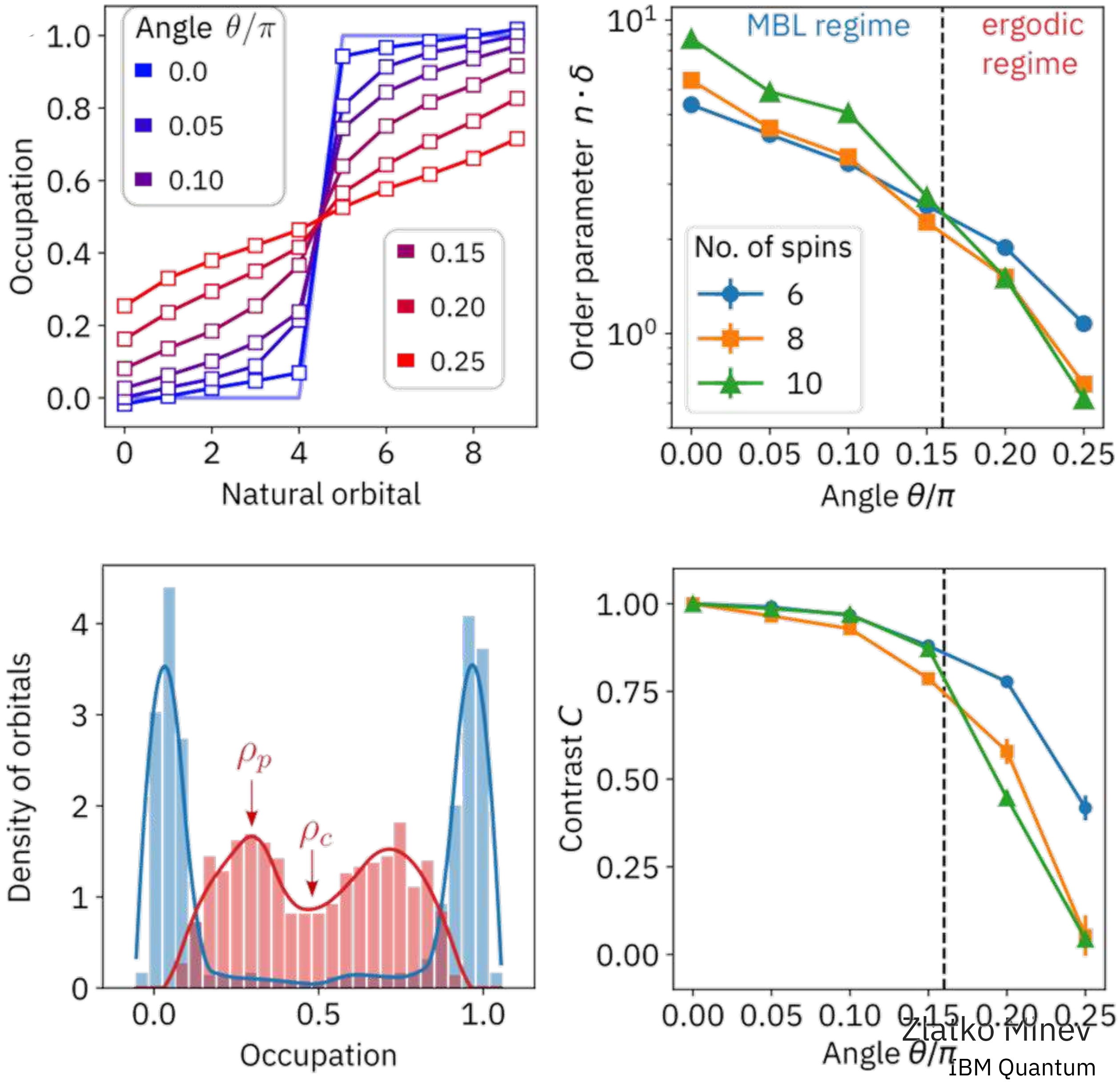
More benchmarks …

One-particle density matrices (OPDM) experiments

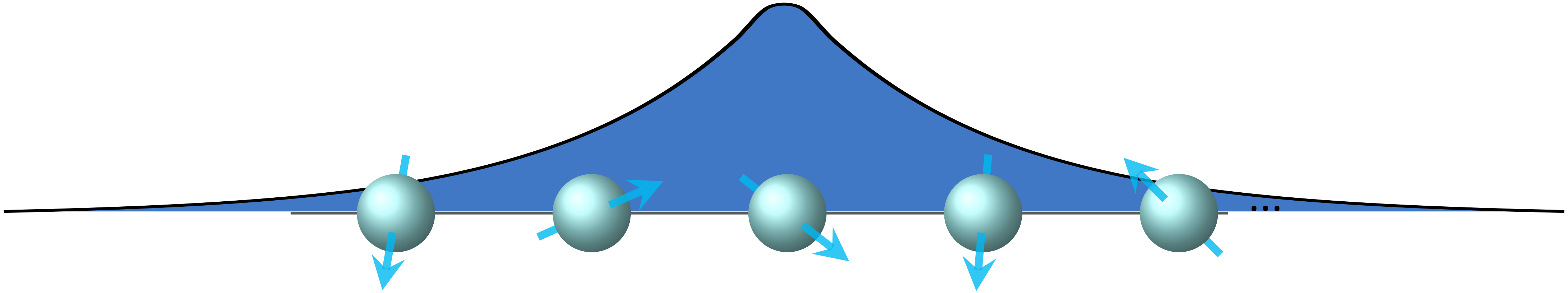
- Natural orbitals and occupations
- Scaling with system size: cross-overs
- …

Classical numerics in 1D

- Spectral and time analysis
- …



Local integrals of motion (LIOMs)



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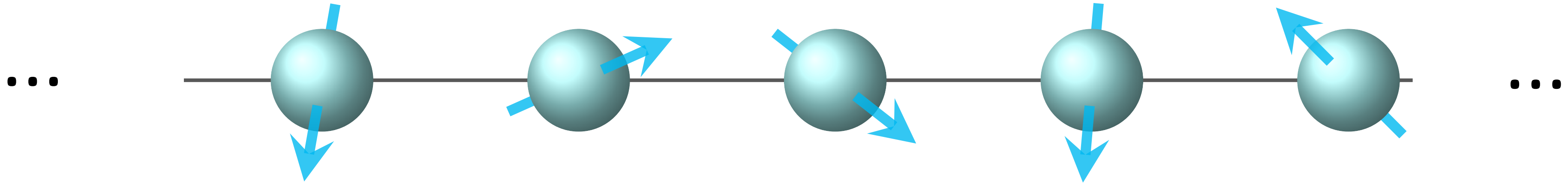
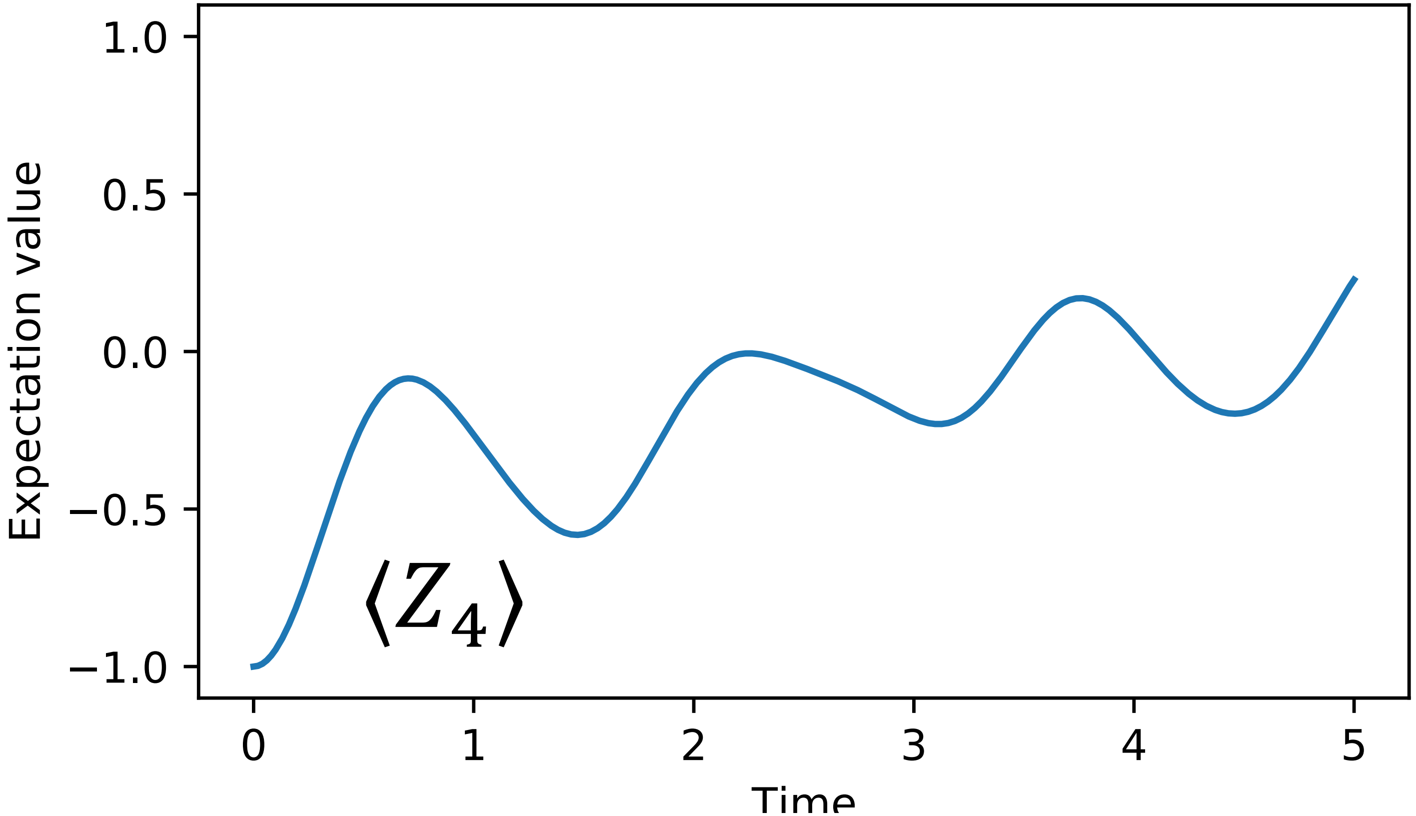
Concept: Consider some spin chain





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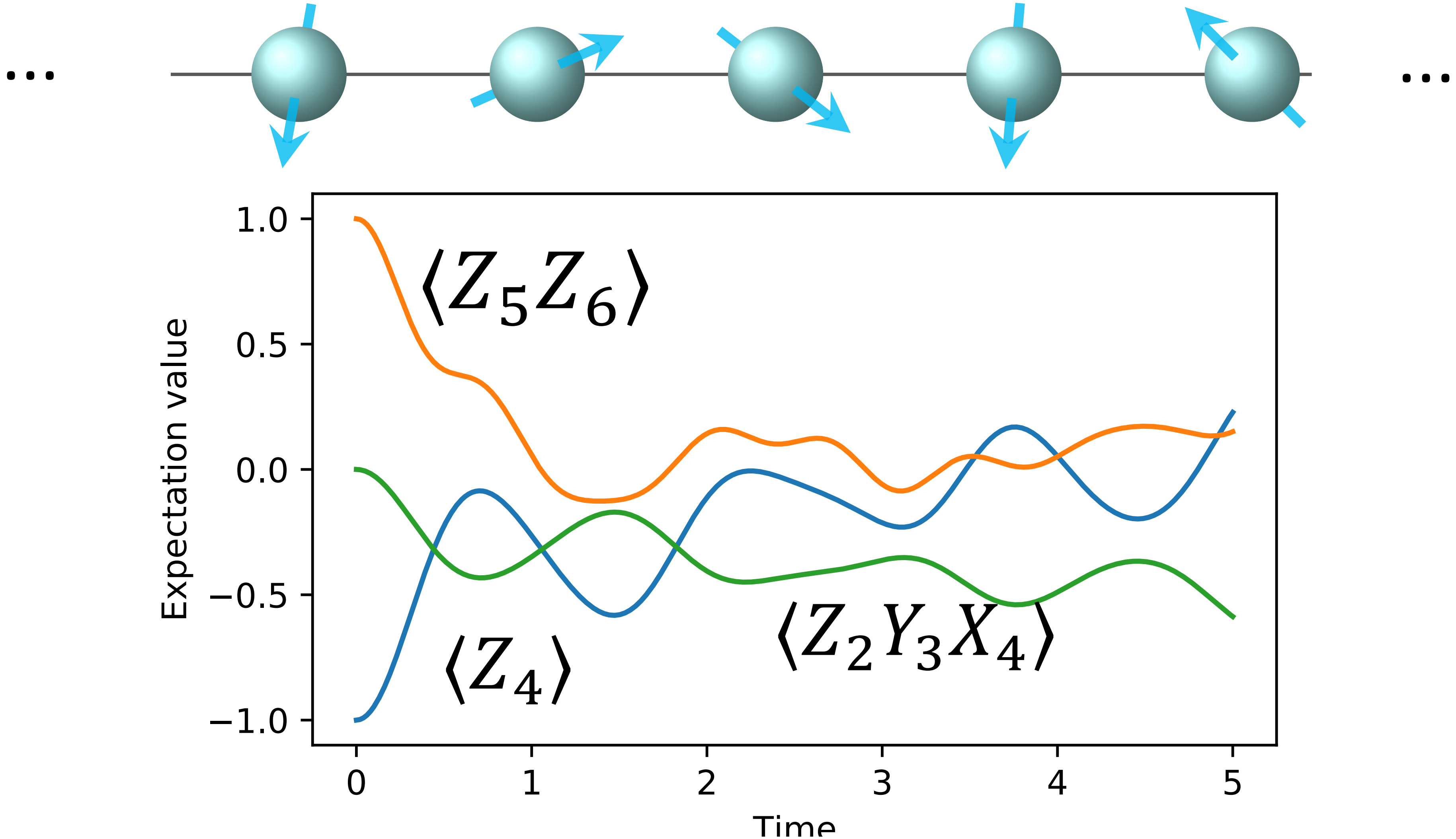
Measure Pauli observables over time



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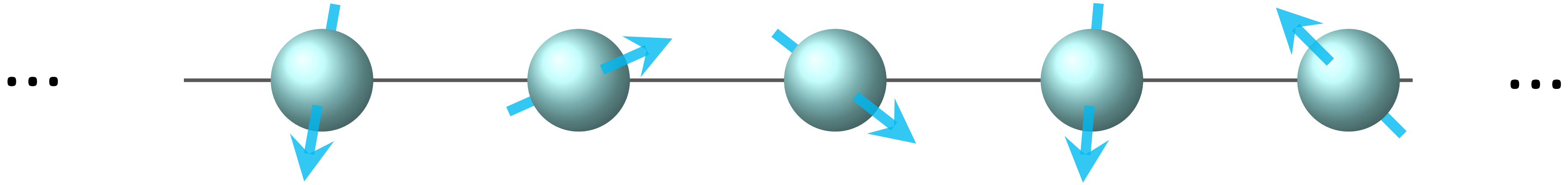
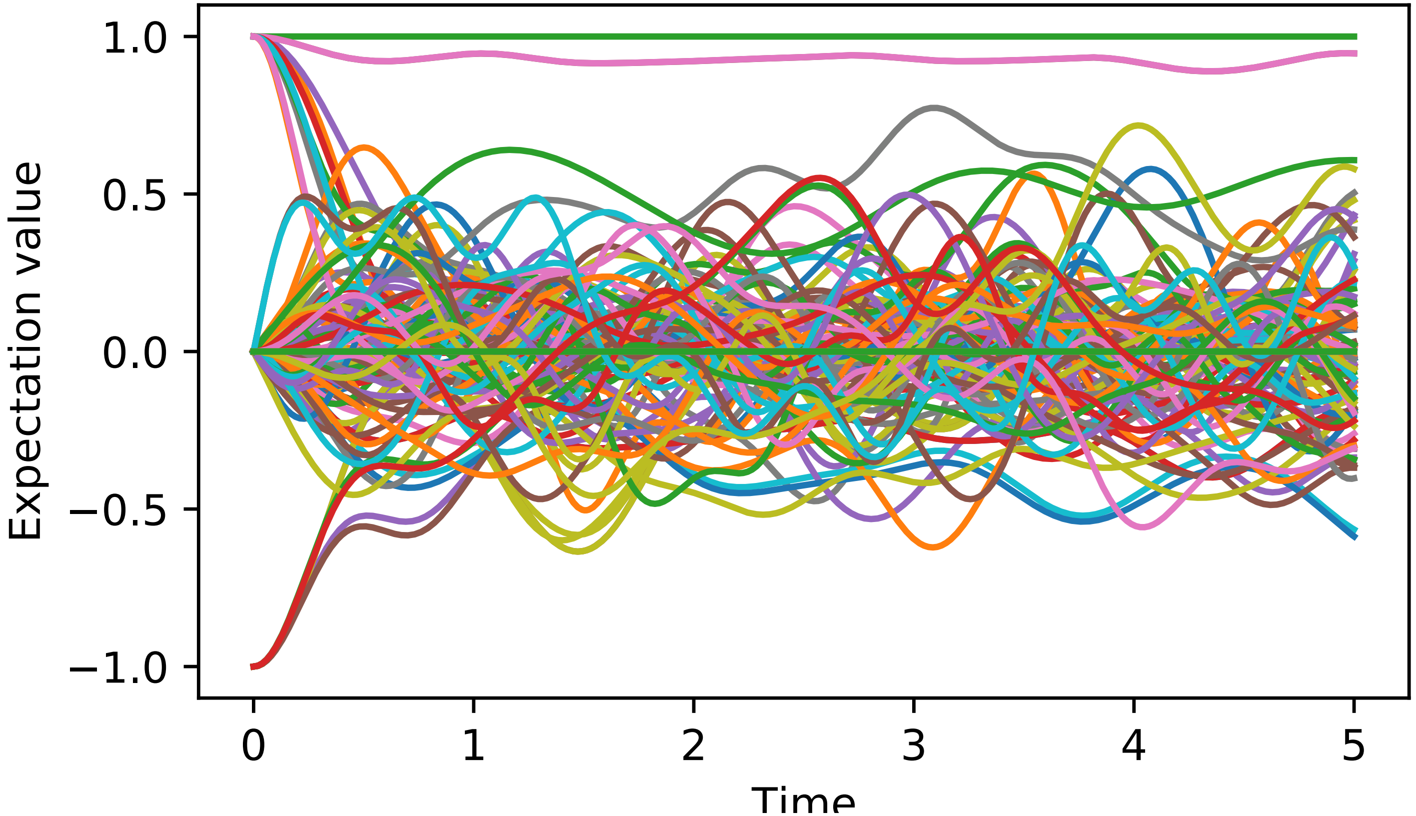
Measure many of them





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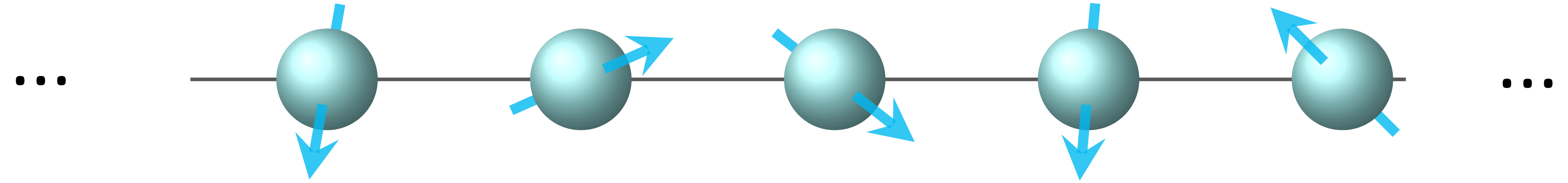
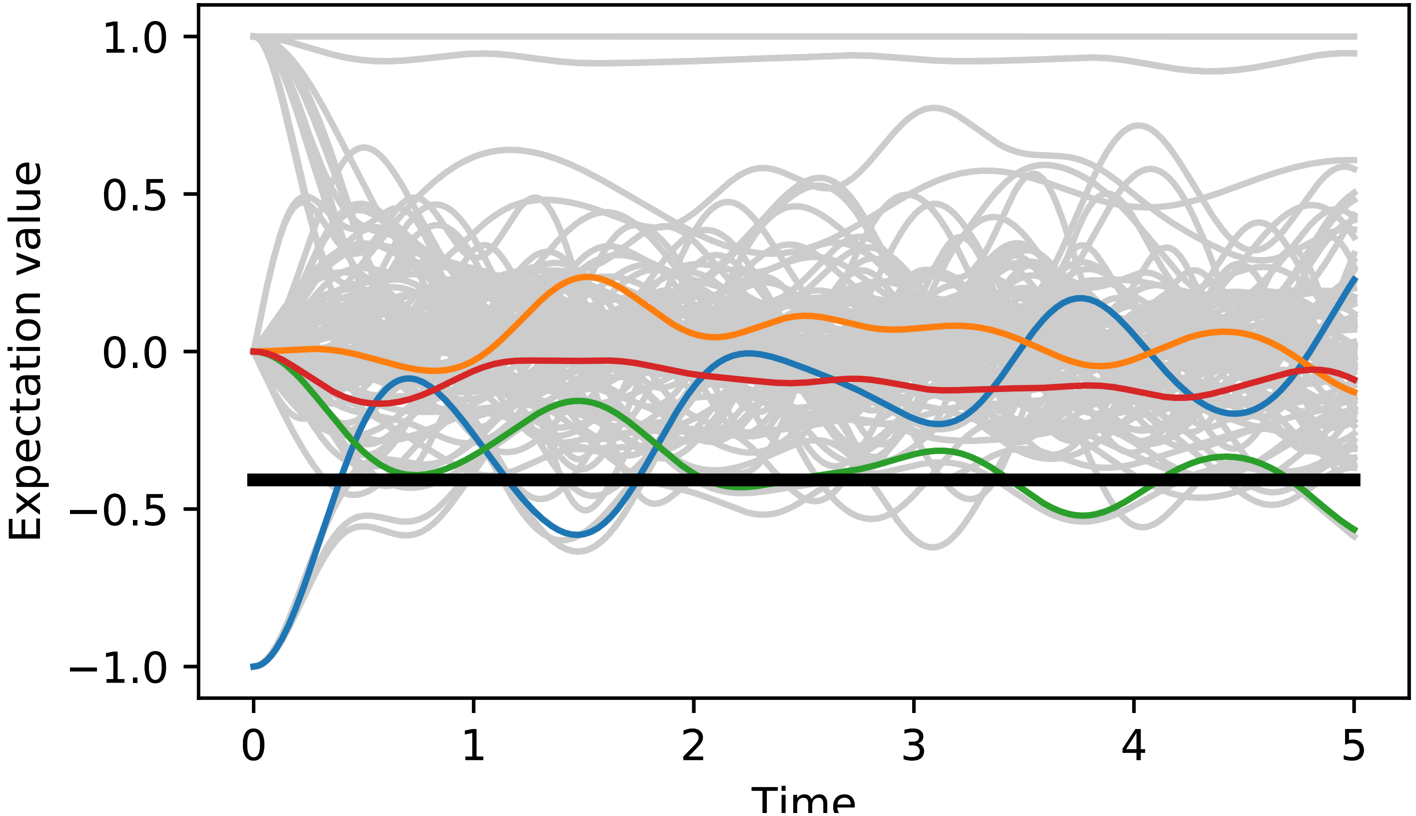
Find constant of motion over observation timescale





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

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

See closely related:

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

Mierzejewski, Prelovsek, Prosen, PRL (2015)

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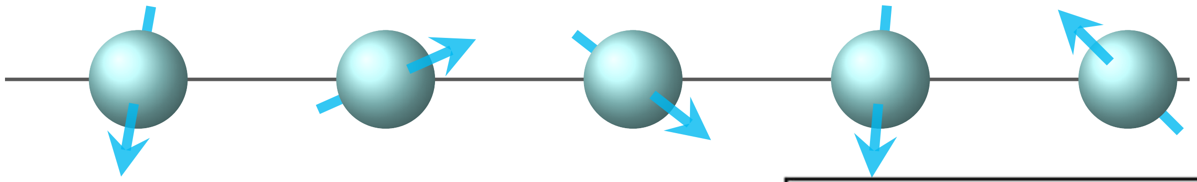
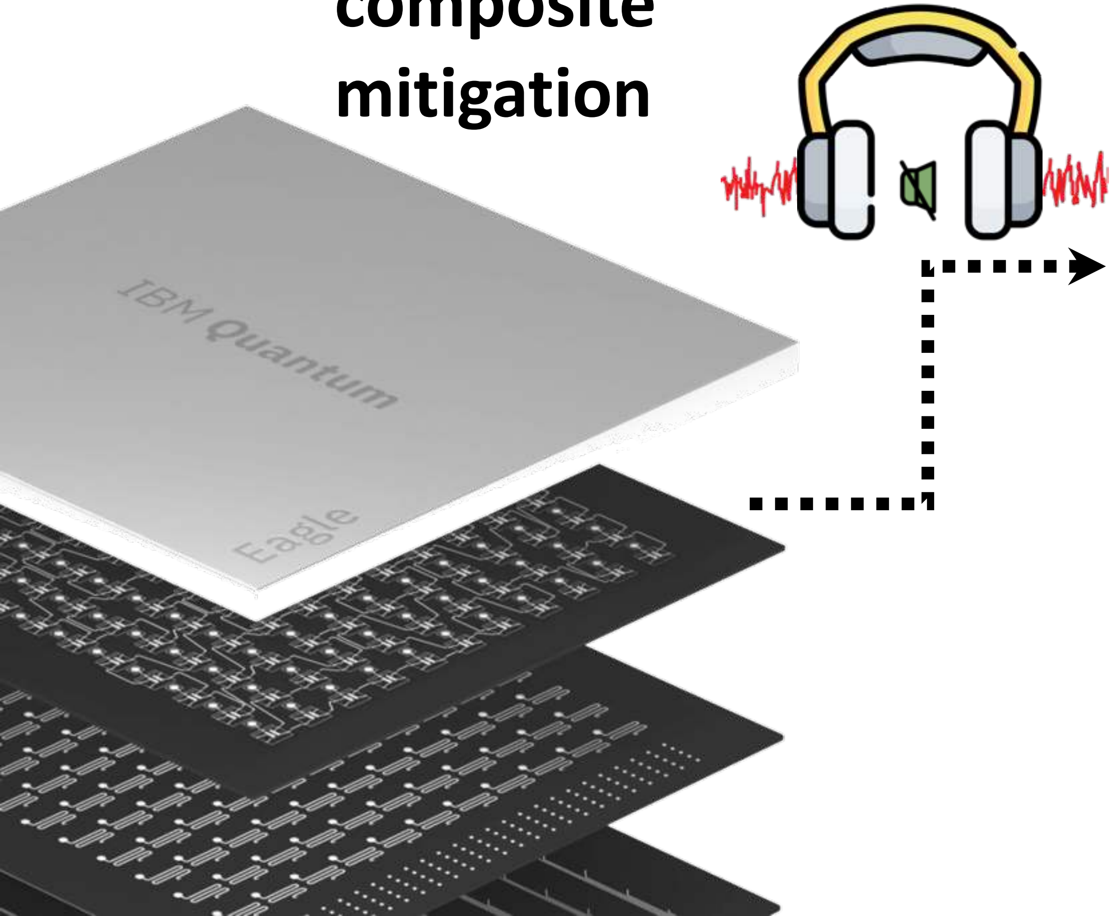
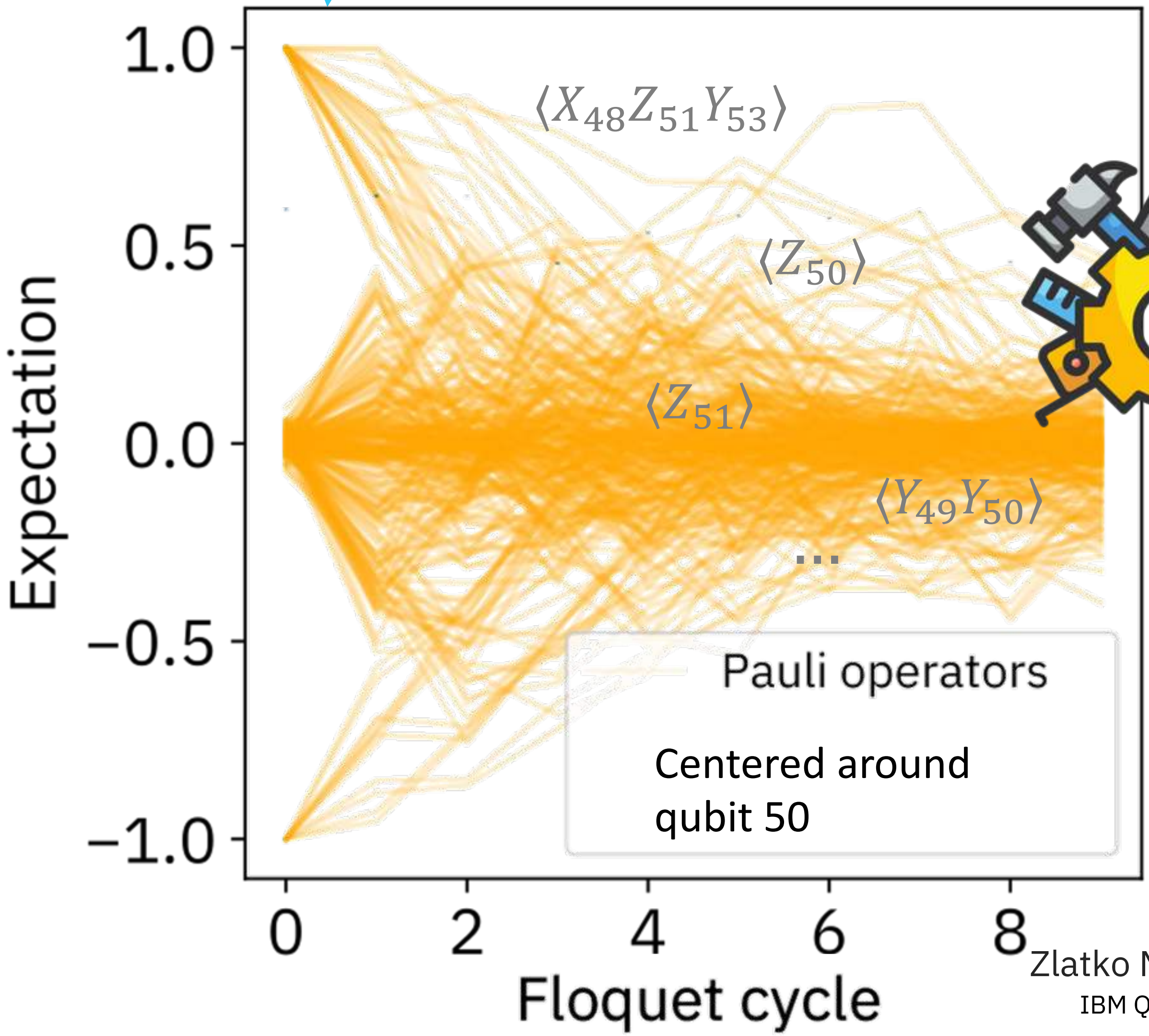
In hardware experiment: Example data

… **104 qubits**  …

composite mitigation





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Example uncovered LIOM from experiment

Integral of motion L

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

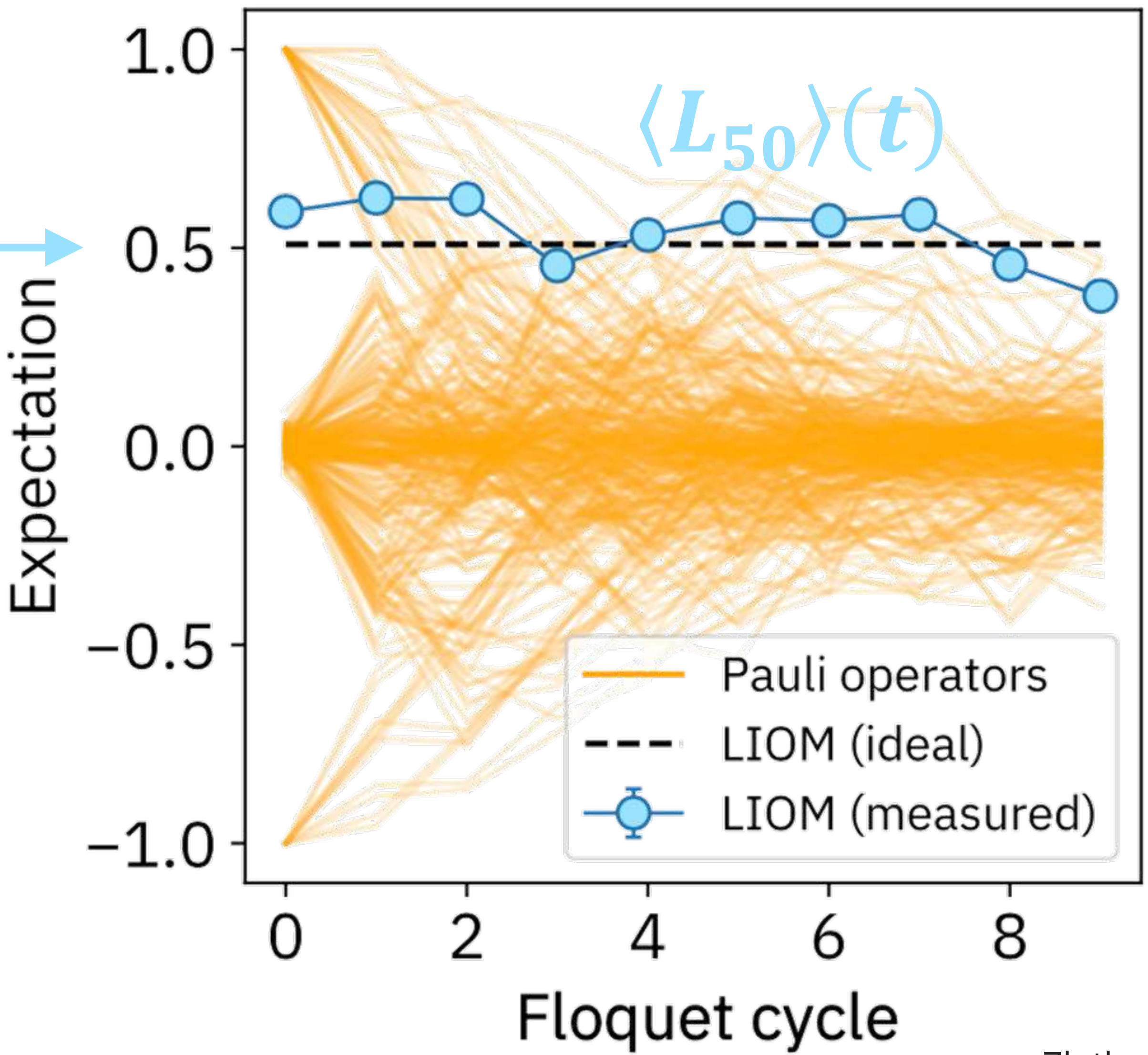
$$\langle L \rangle = \mathrm{const}$$

Local integral of motion (LIOM) L

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

local neighborhood

Centered around qubit 50



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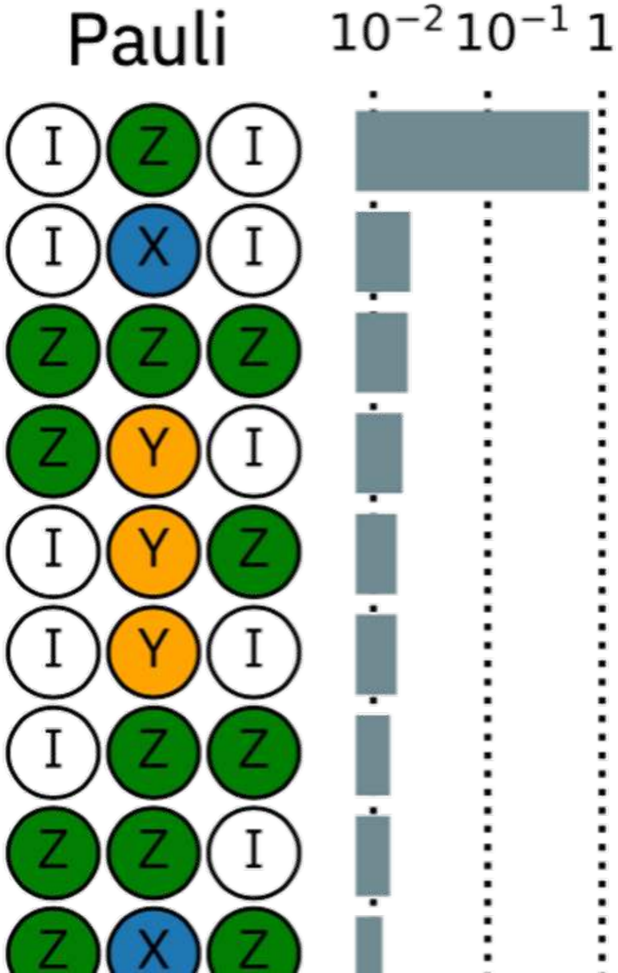
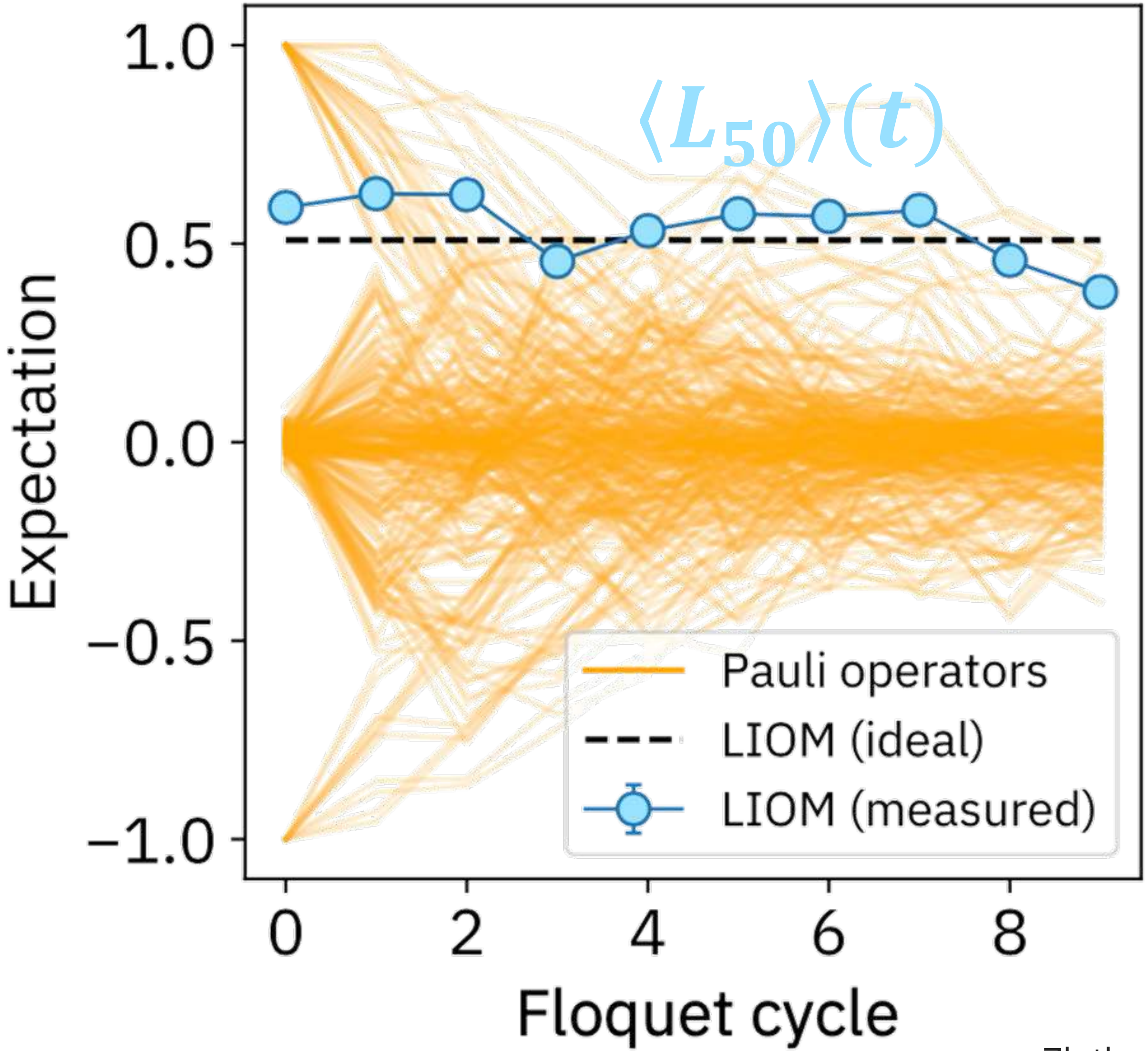
Operator decomposition of the LIOM

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



LIOM for qubit 50



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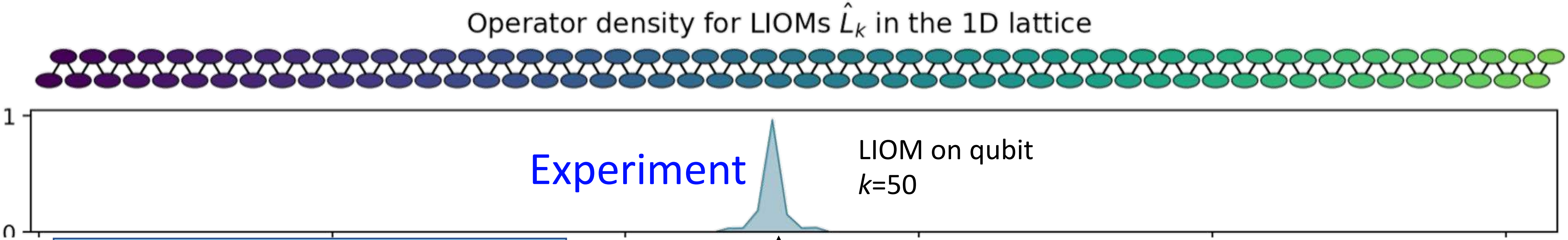
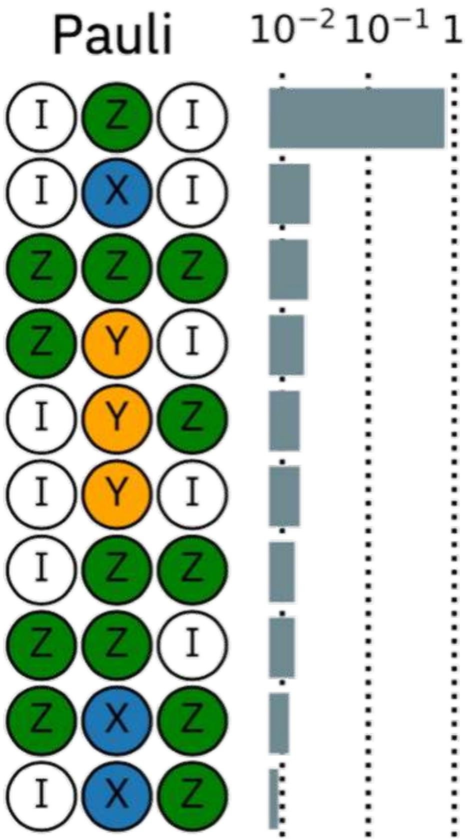
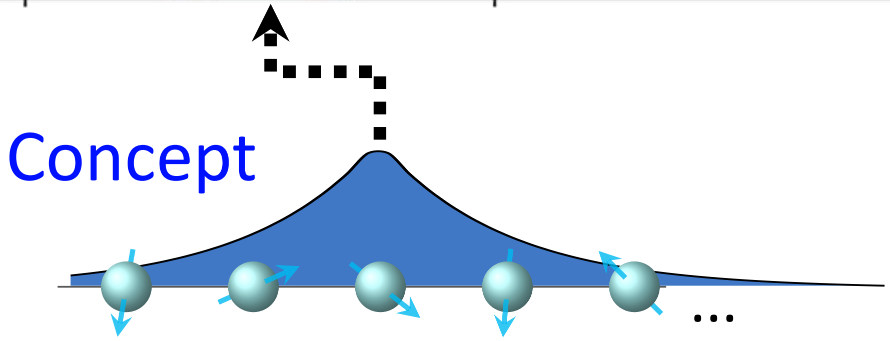


$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$





Total density over all Pauli weights $W(x)$

$$W(x) = \sqrt{\sum_p W(x,p)^2} \qquad W(x,p) = \sqrt{\sum_{\mu \sim N(k,p)} a_\mu^2 \, w_{x\mu}}$$

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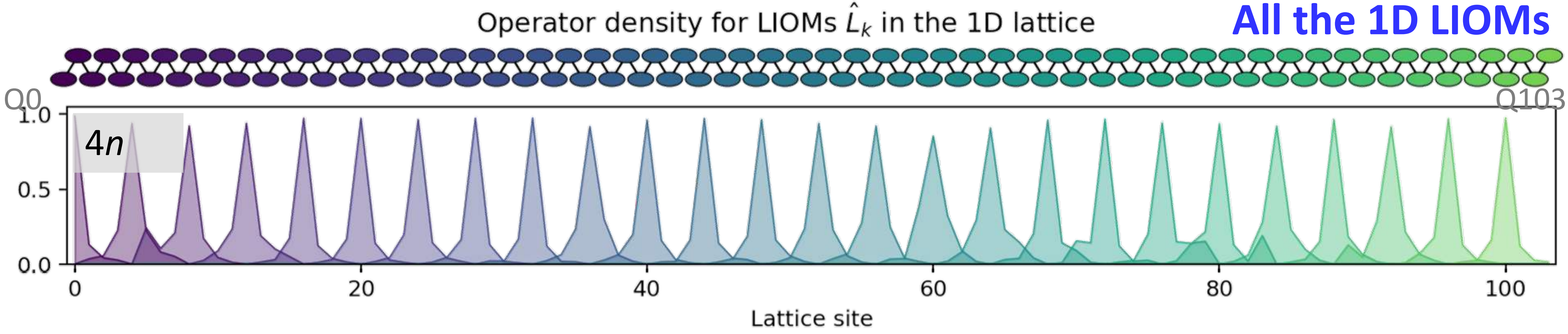
All the 1D LIOMs



Every 4th LIOM

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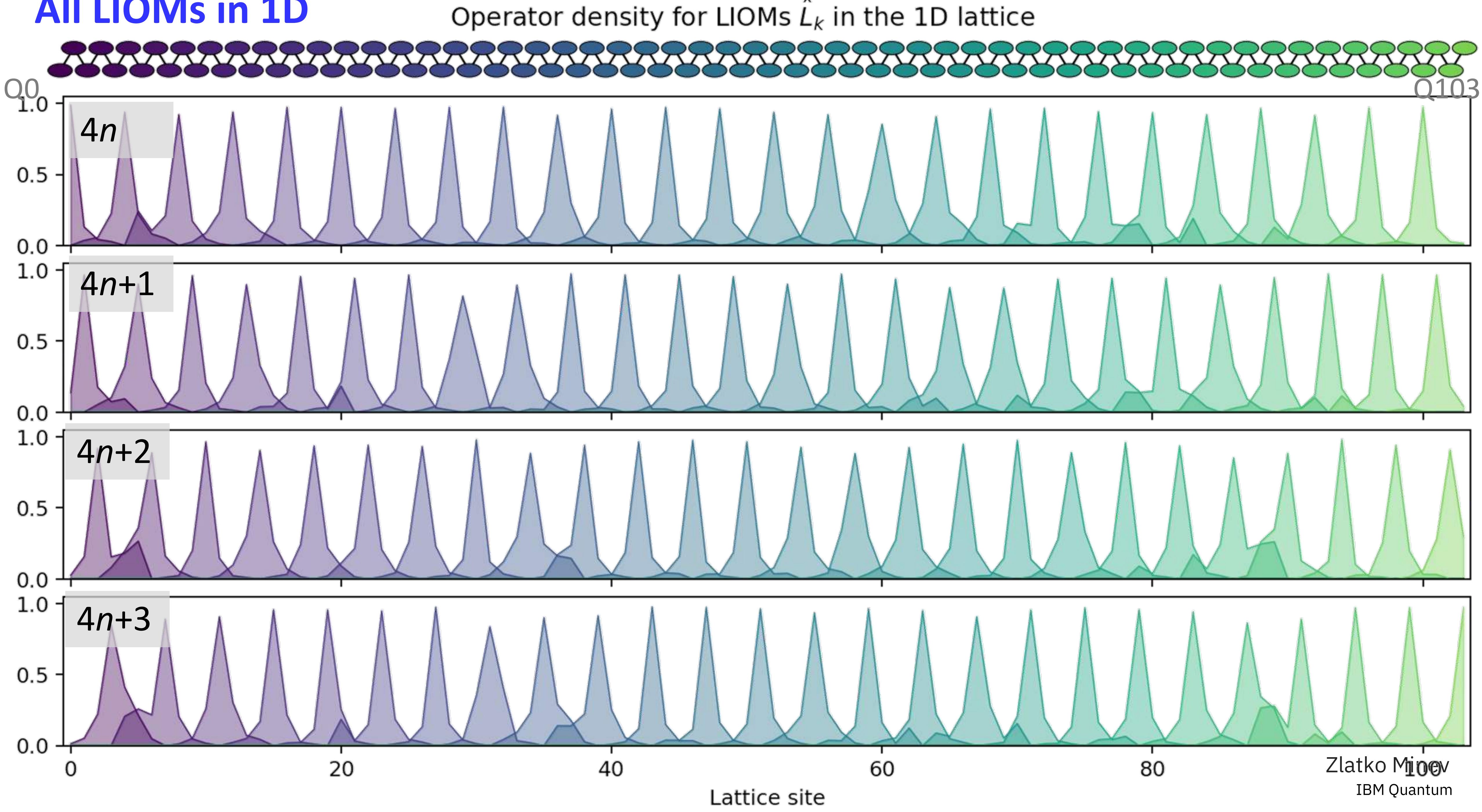
All LIOMs in 1D



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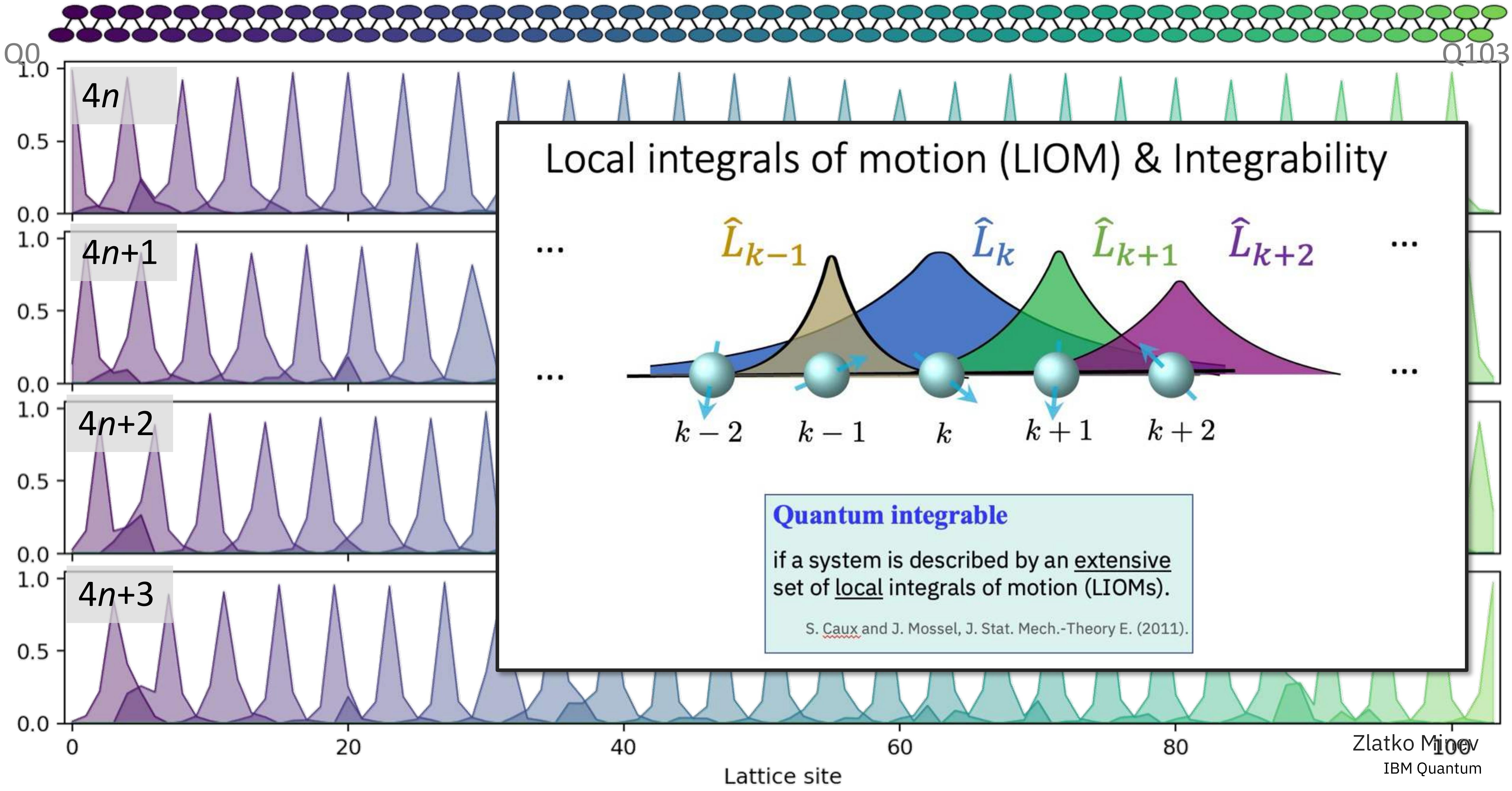
Integrable system on the observation timescale



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Caution: Ultimate integrability

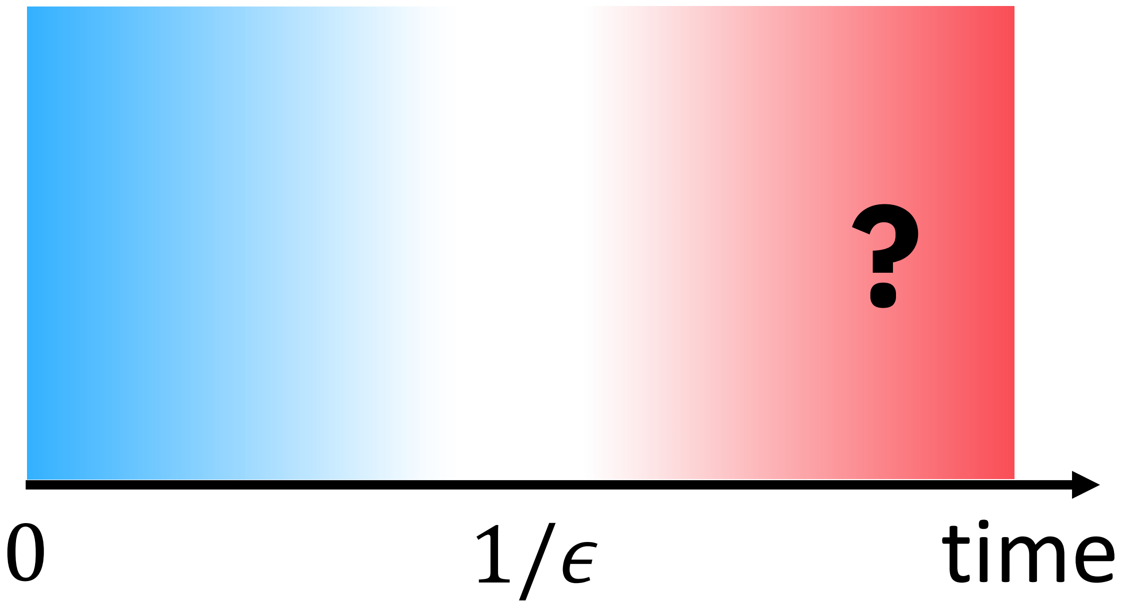
Derived LIOMs are conserved over the observation timescale.

In the long-time limit, they are always understood as approximate.

The ultimate integrability of a system is an undecidable problem in general.

Shiraishi, Matsumoto, *Nat Comm* (2021)

$$[U_F, L] = O(\epsilon)$$



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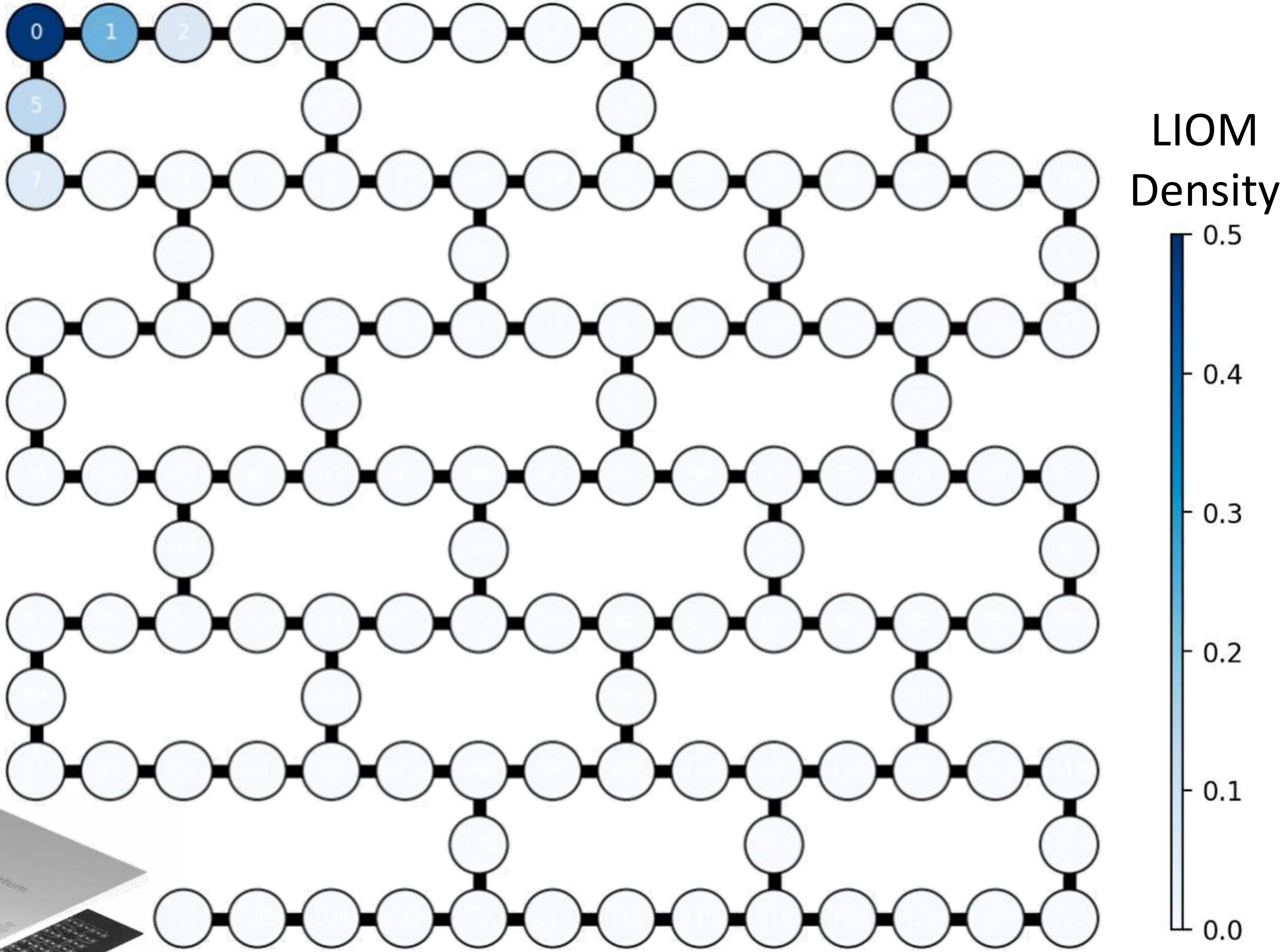
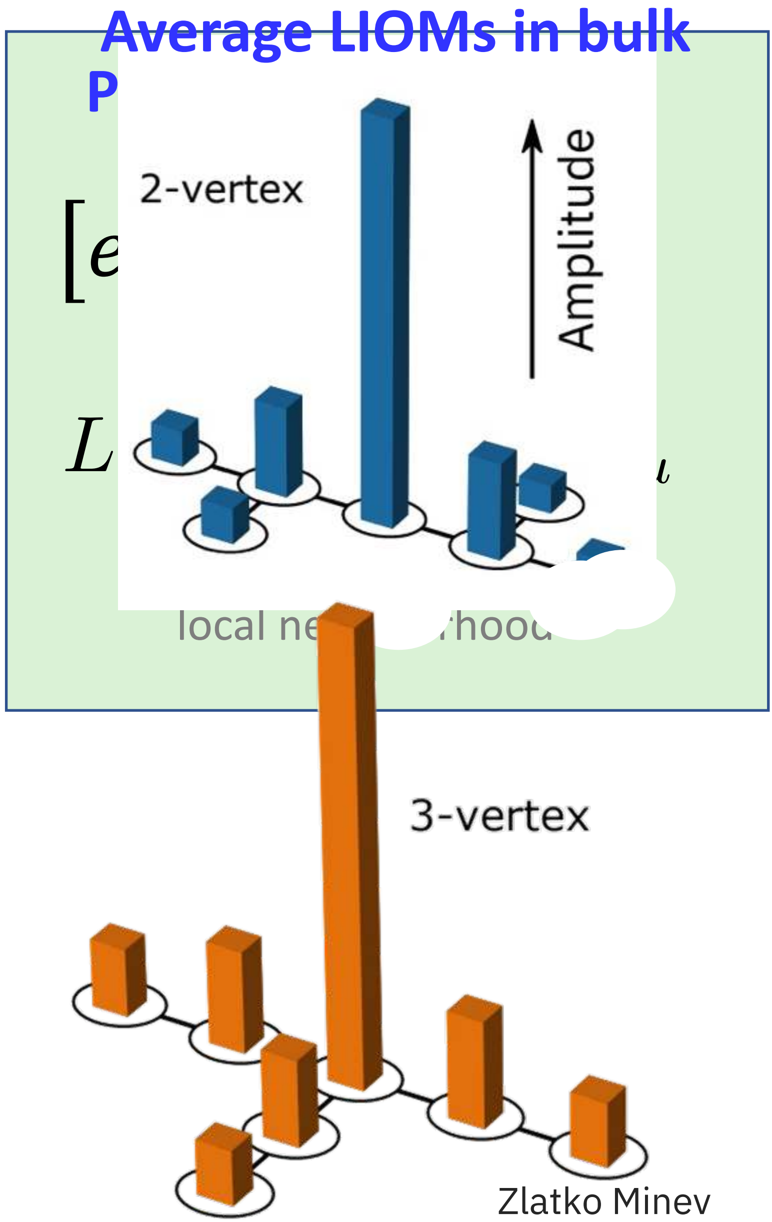
2D: All 124 pre-thermal LIOMs L_k





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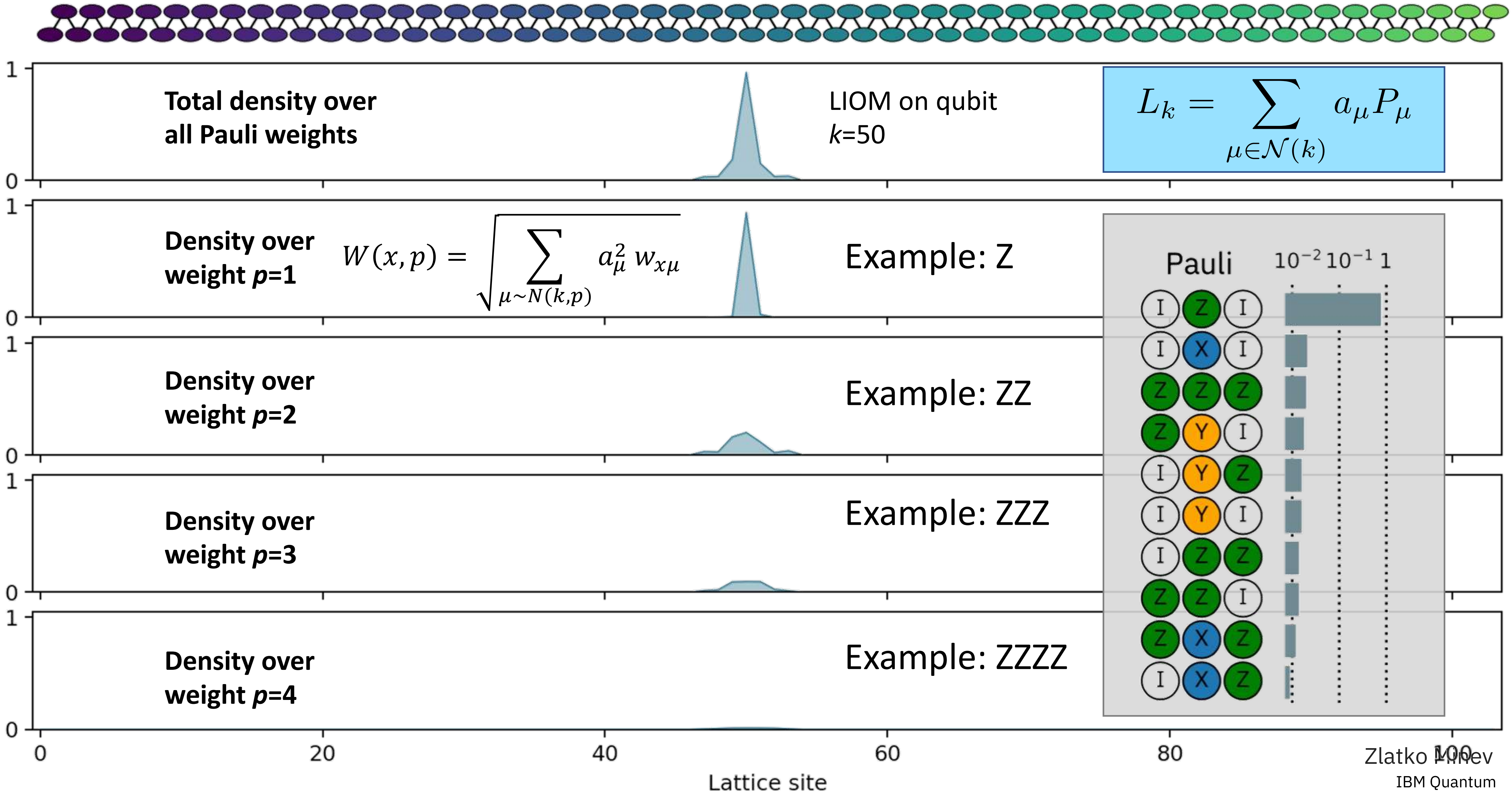
Operator density for LIOMs $\hat{L}_k$ in the 1D lattice



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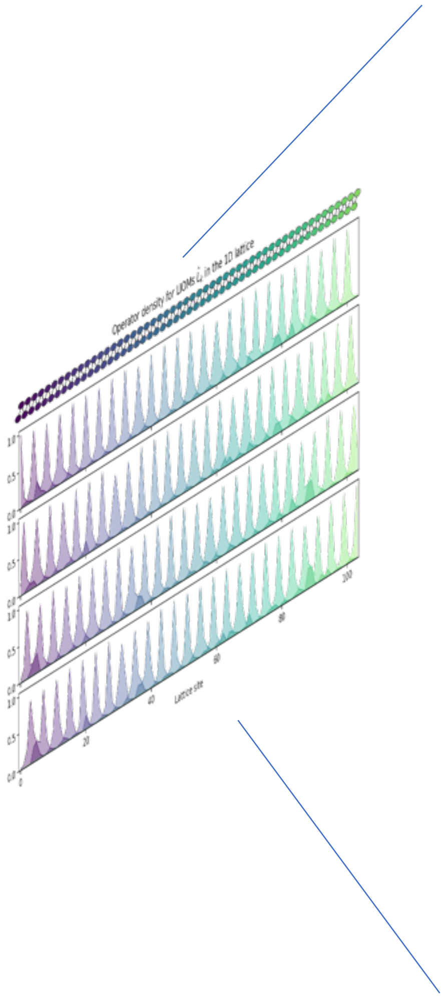
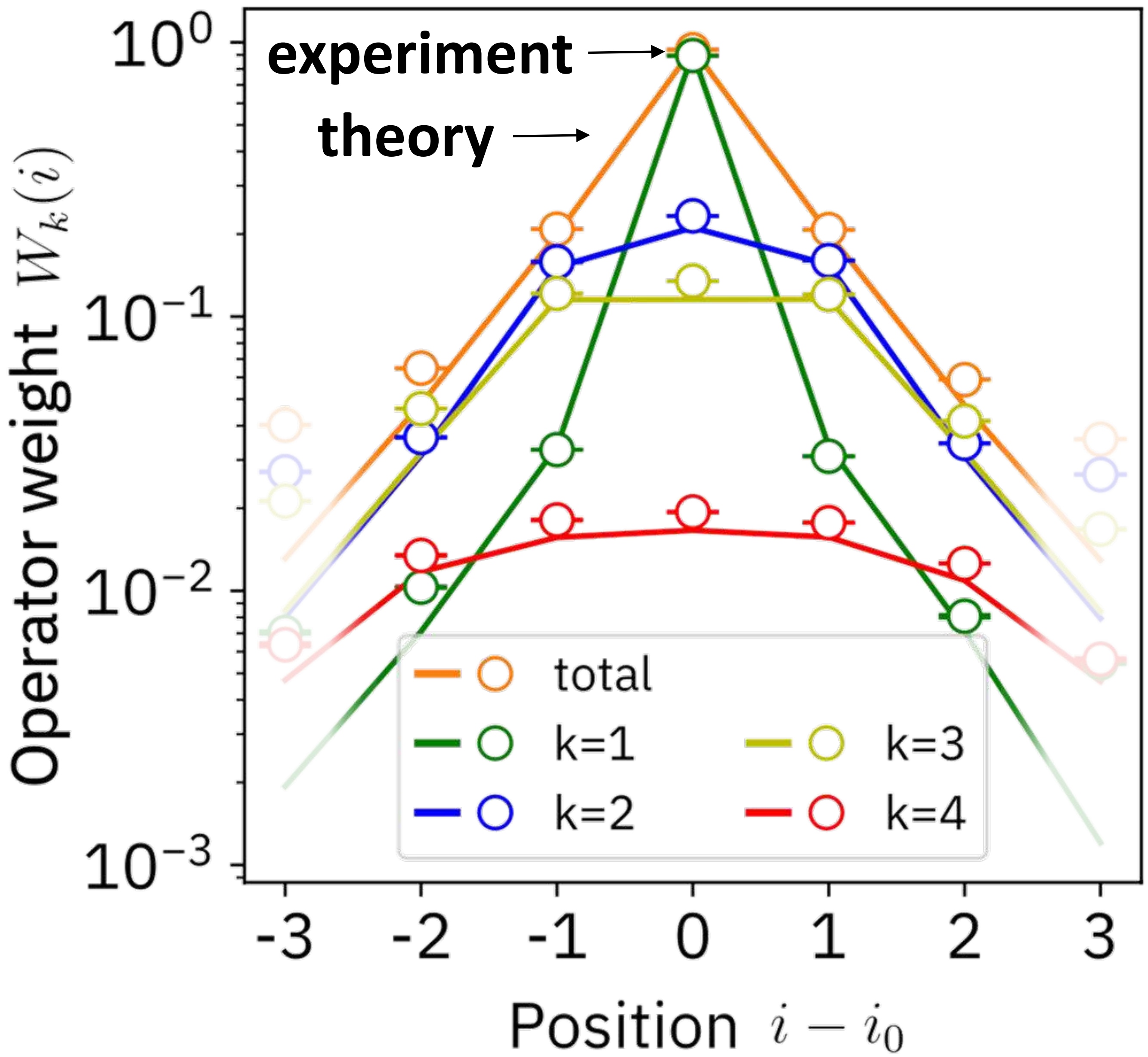
Average LIOM decomposed by weight: experiment vs. theory





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

total

weight 1

weight 2

weight 3

weight 4

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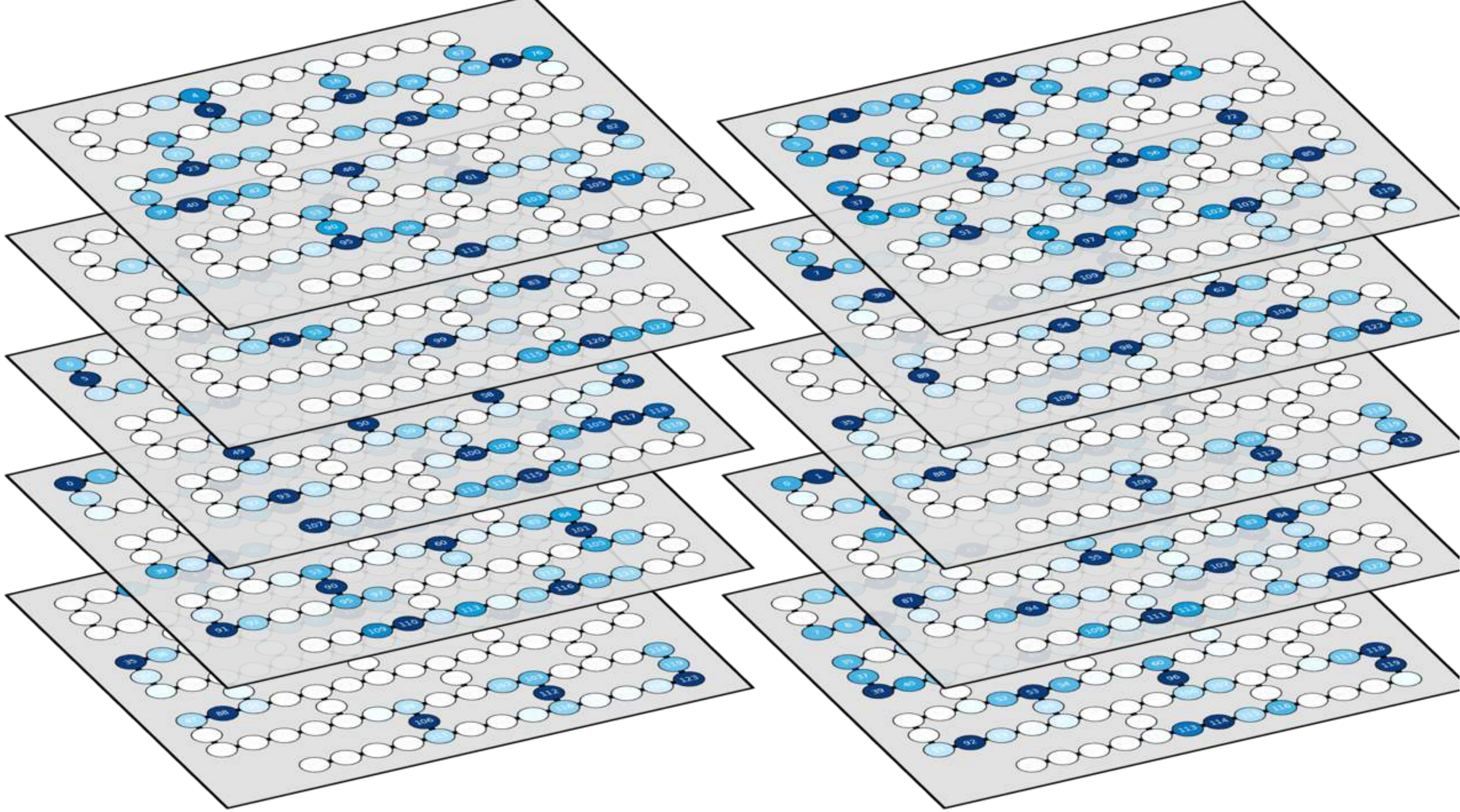
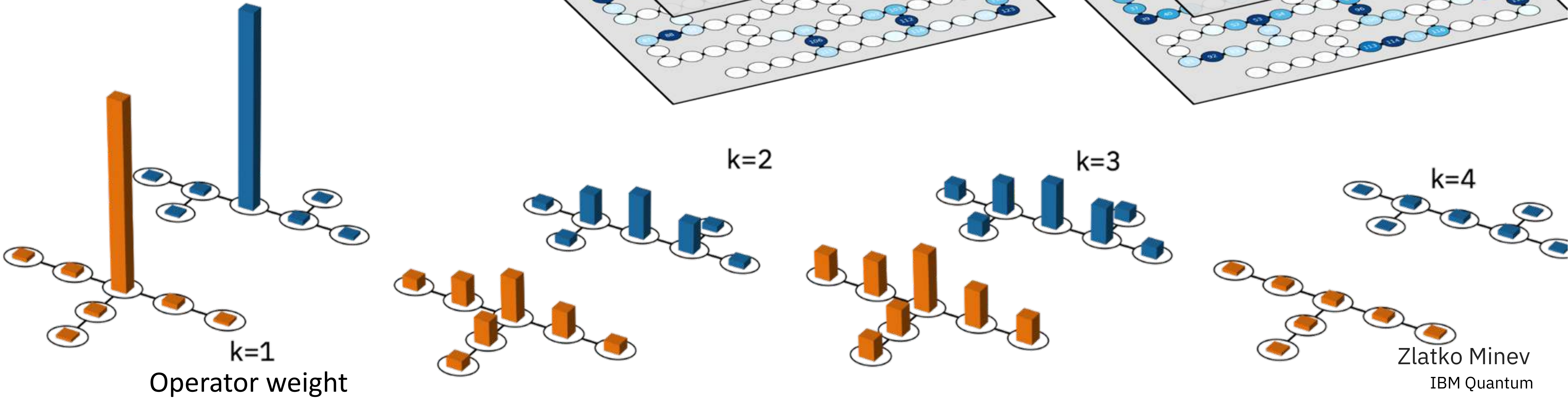
Decomposition by operator weight

Average LIOM density for a given operator weight





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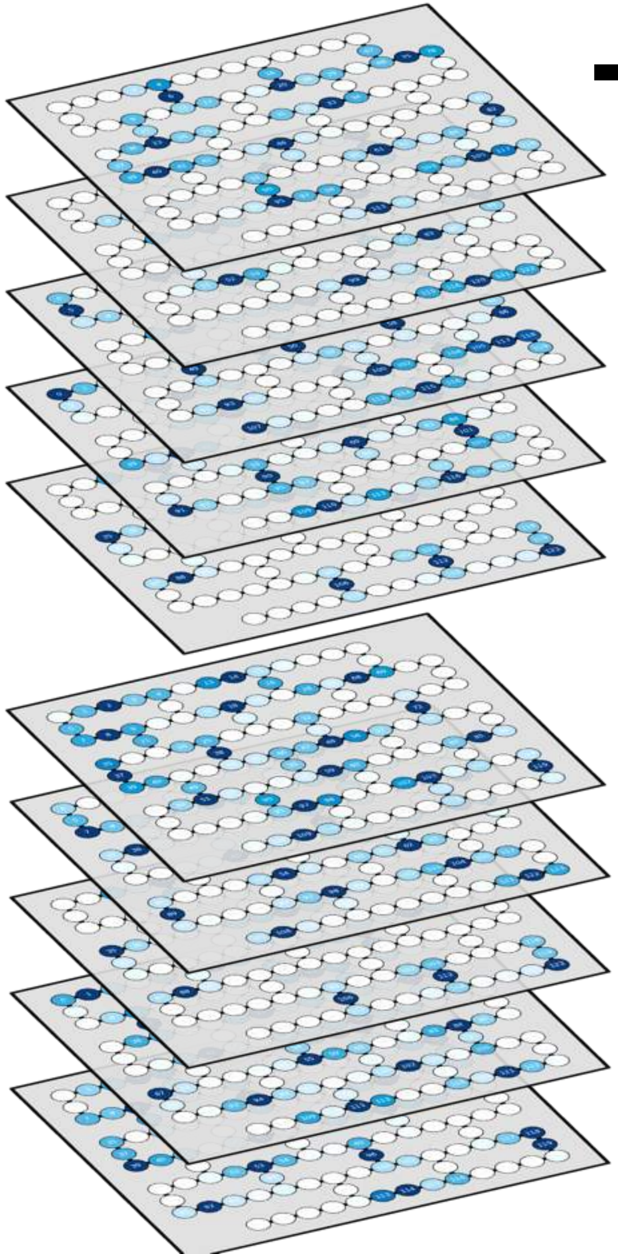
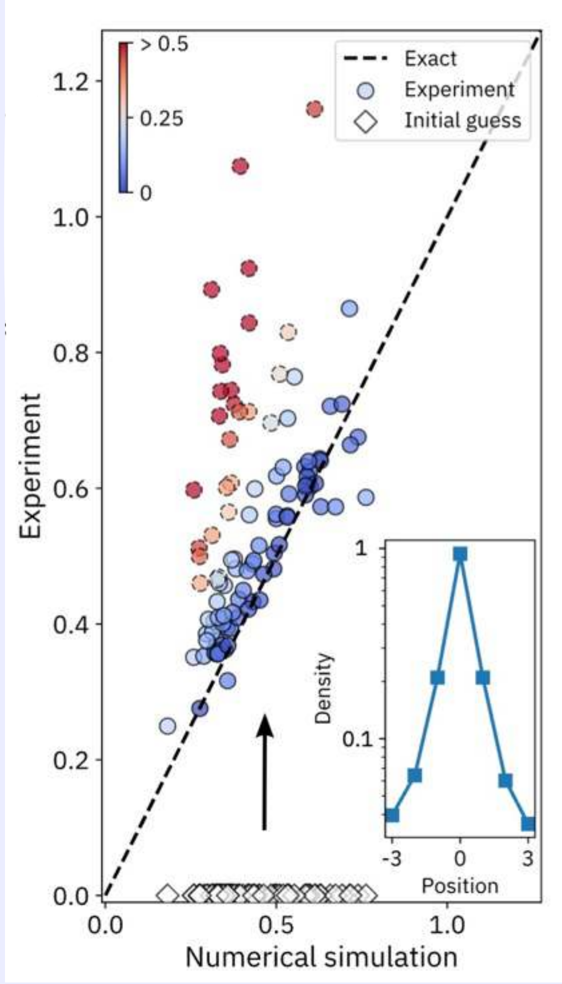
Example applications of the LIOMs and next steps



Site-based
localization lengths



Melting of the LIOMs across the phase / regime transition

Topological setting LIOMs and melting

Recover & track locally scrambled information

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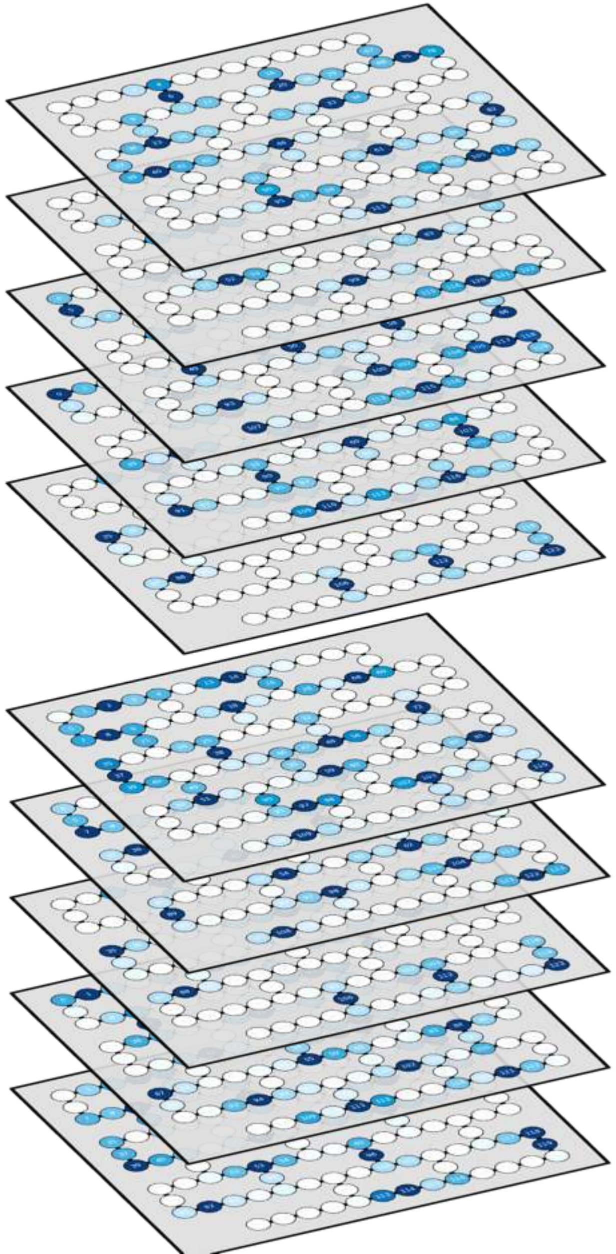
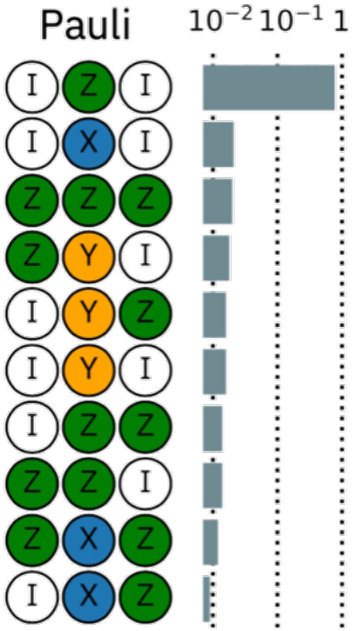
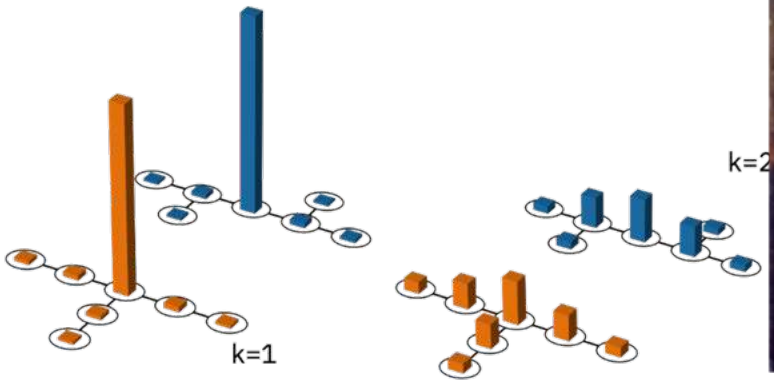
Icons: surang, nadiinko, Saepul Nahwan

Operational LIOM description on observation timescales







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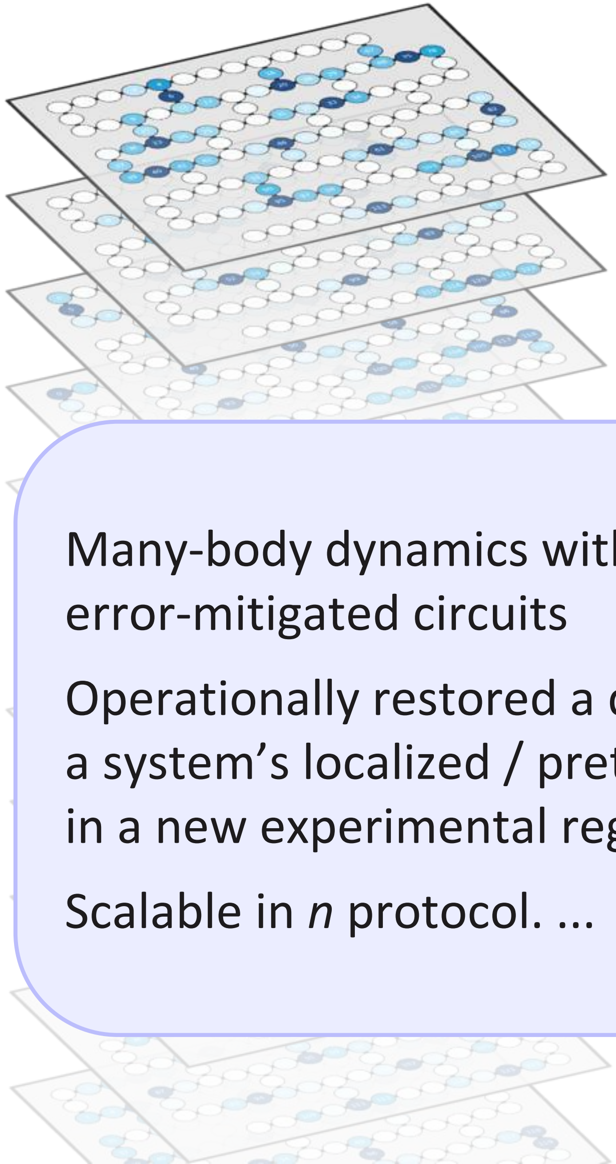
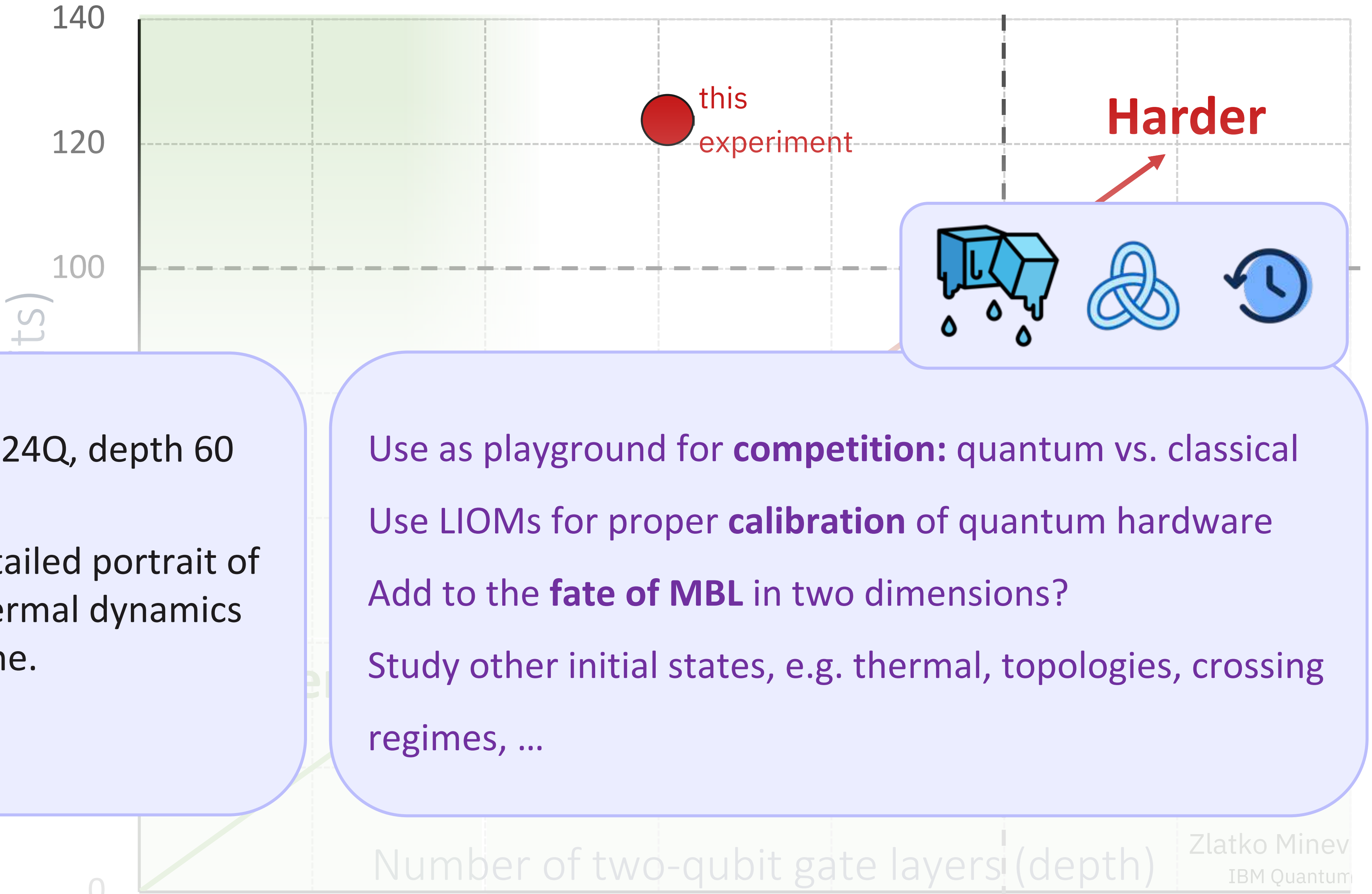
Conclusions and future





Many-body dynamics with 124Q, depth 60 error-mitigated circuits

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

Scalable in *n* protocol. ...

Use as playground for **competition:** quantum vs. classical

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

Add to the **fate of MBL** in two dimensions?

Study other initial states, e.g. thermal, topologies, crossing regimes, ...

A detailed portrait of quantum many-body dynamics

Zlatko K. Minev
IBM Quantum

Oles Shtanko*, Derek Wang*, Haimeng Zhang, Nikhil Harle, Alireza Seif, Ramis Movassagh, Zlatko K. Minev
arXiv:2307.07552

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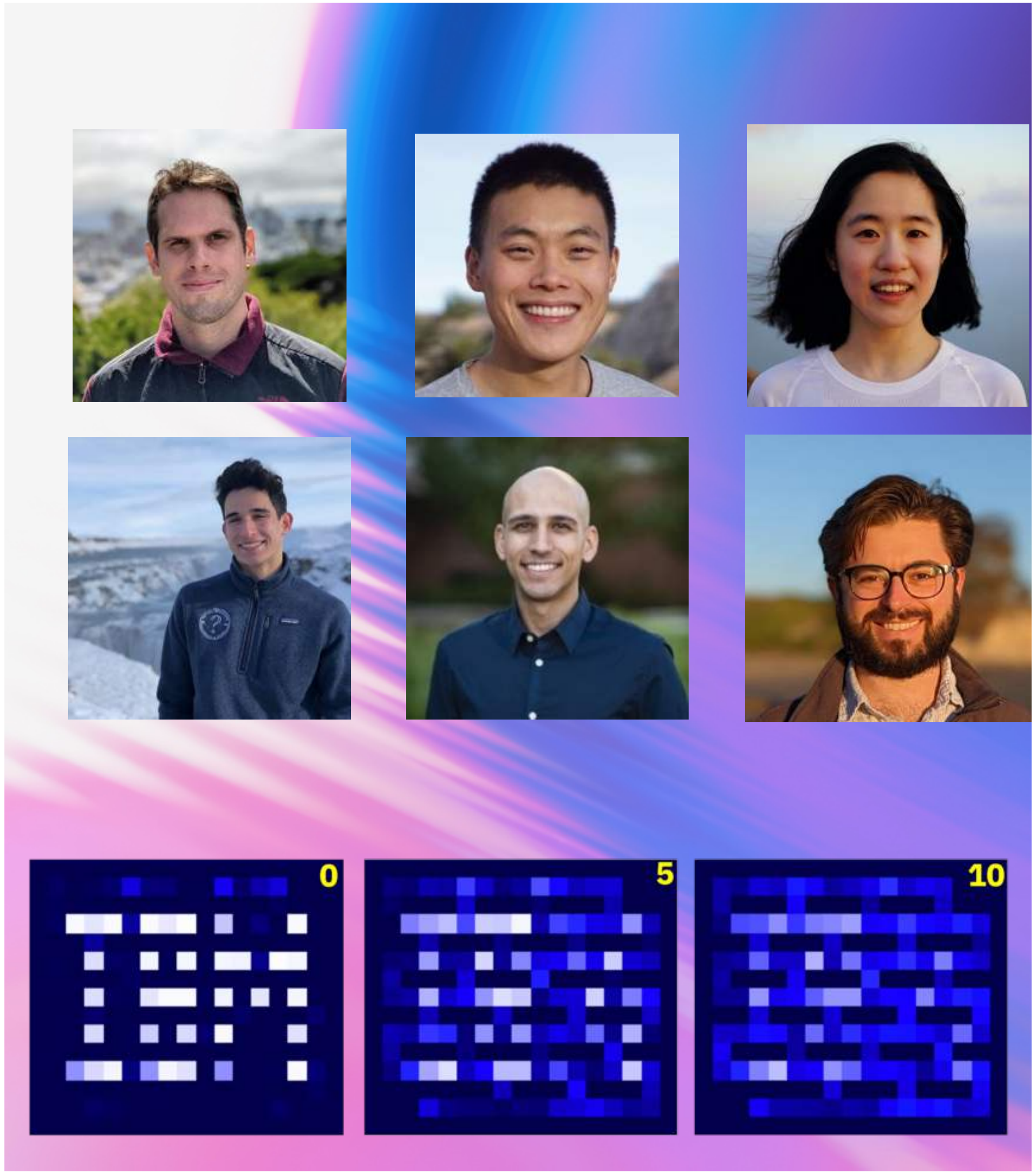

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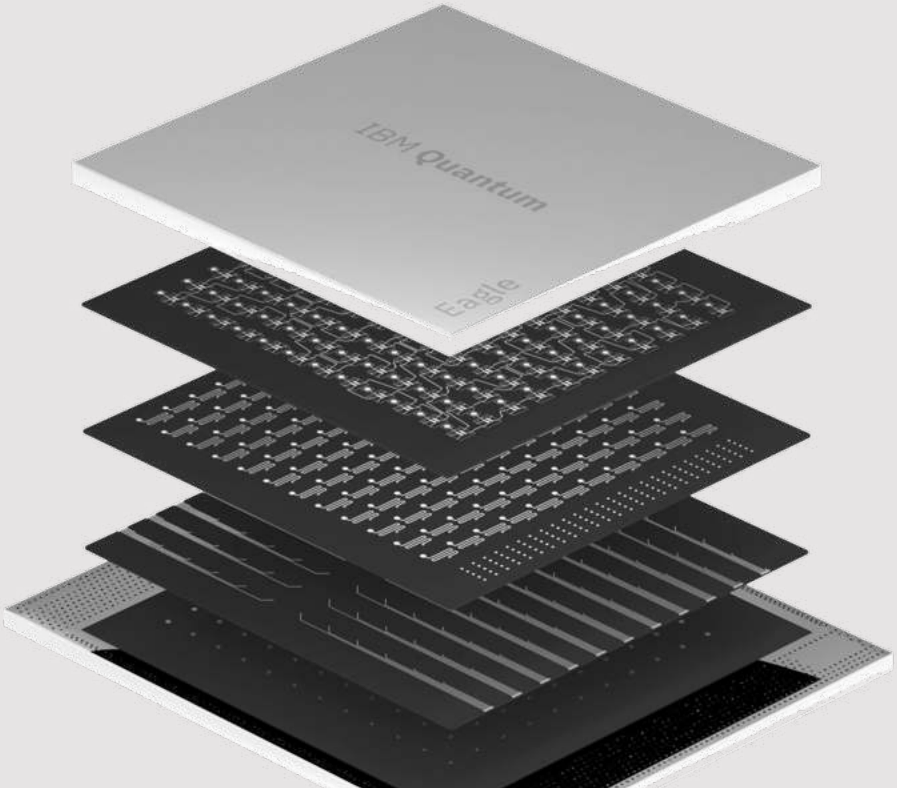
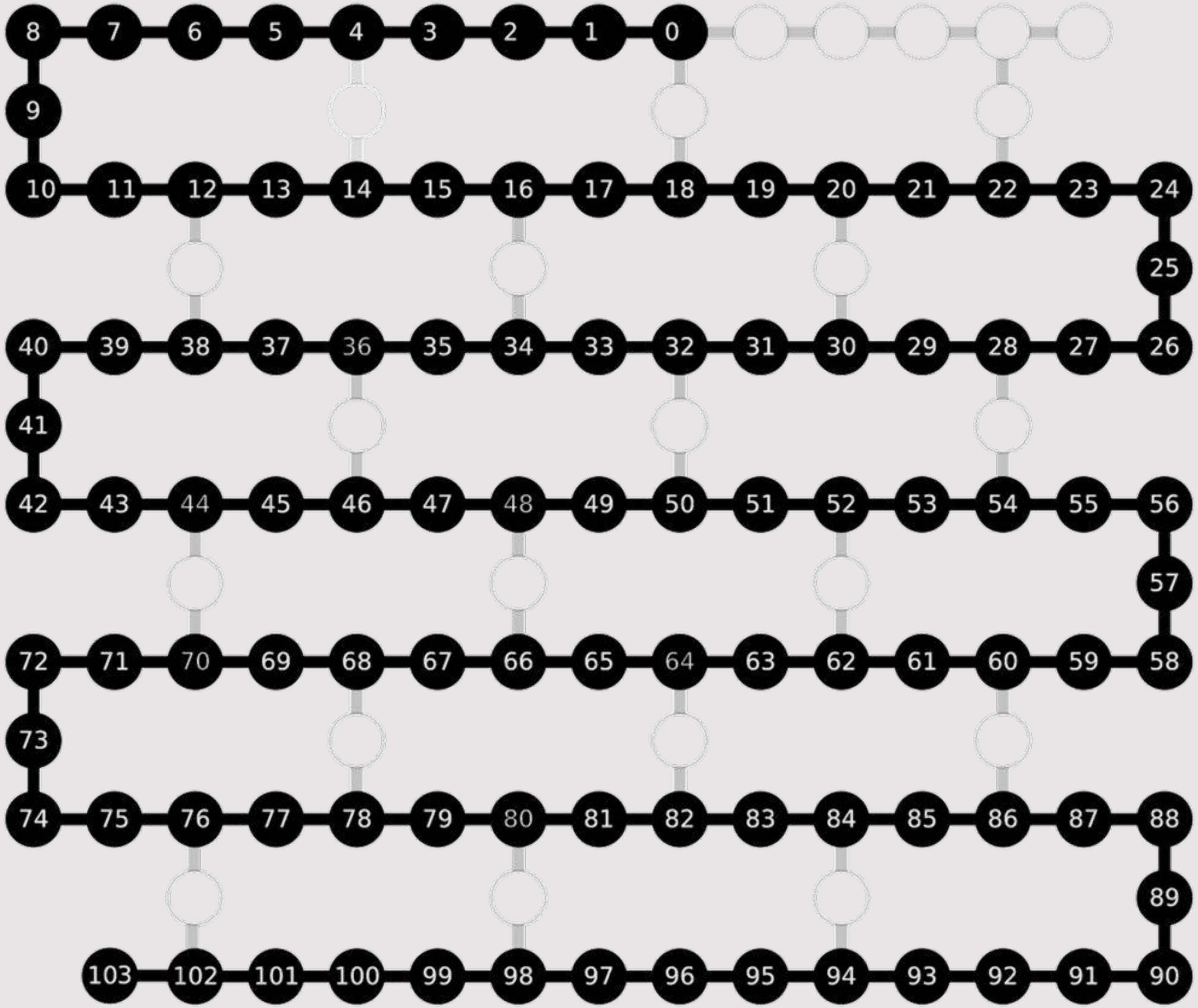
Bonus content:
Taken out from 60 min version

1D spin chain





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Basis of protocol for measuring LIOMs

Given: Unitary operator U_F

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

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 $\mathrm{D} \gg 1$,

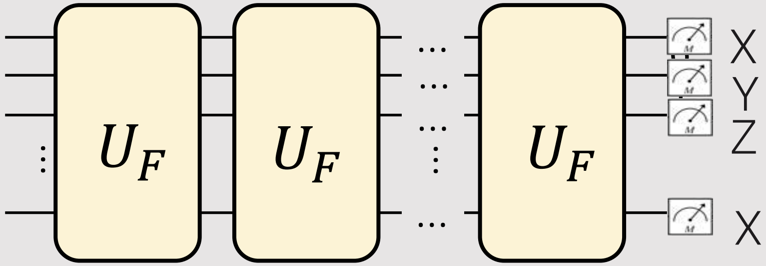
$$[U_F, L] \sim O(D^{-1})$$

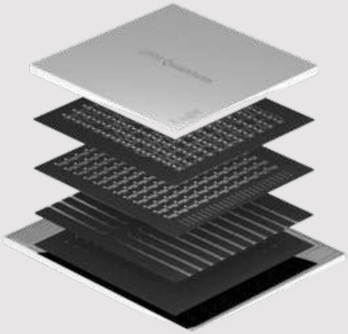
Pauli decomposition of LIOM:

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

Coefficients are

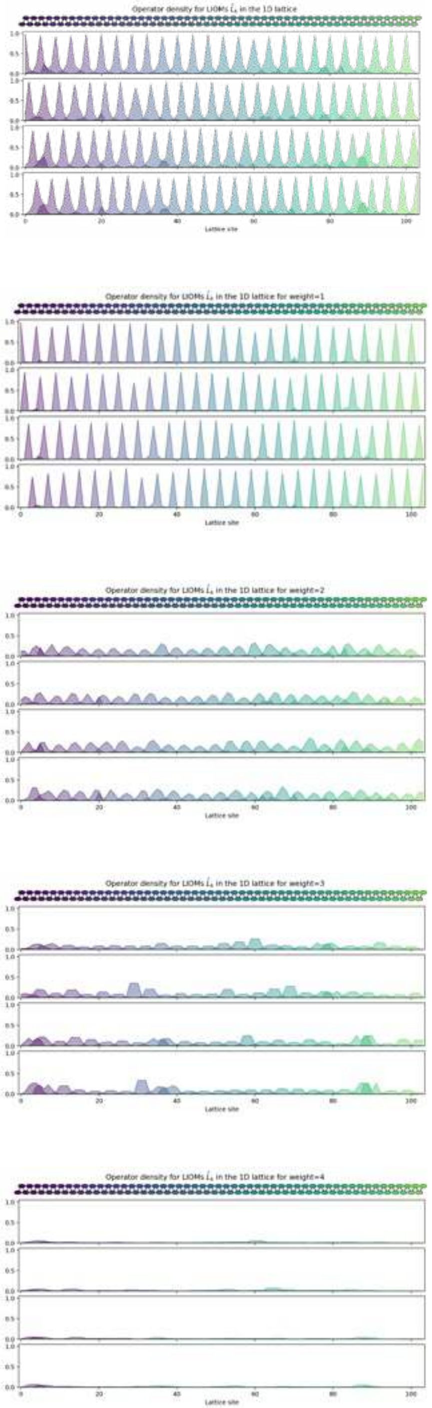
$$a_\mu = \frac{1}{2^n} \frac{1}{D+1} \sum_{d=0}^{D} \mathrm{Tr}(L_0 U^{d\dagger} P_\mu U^d)$$

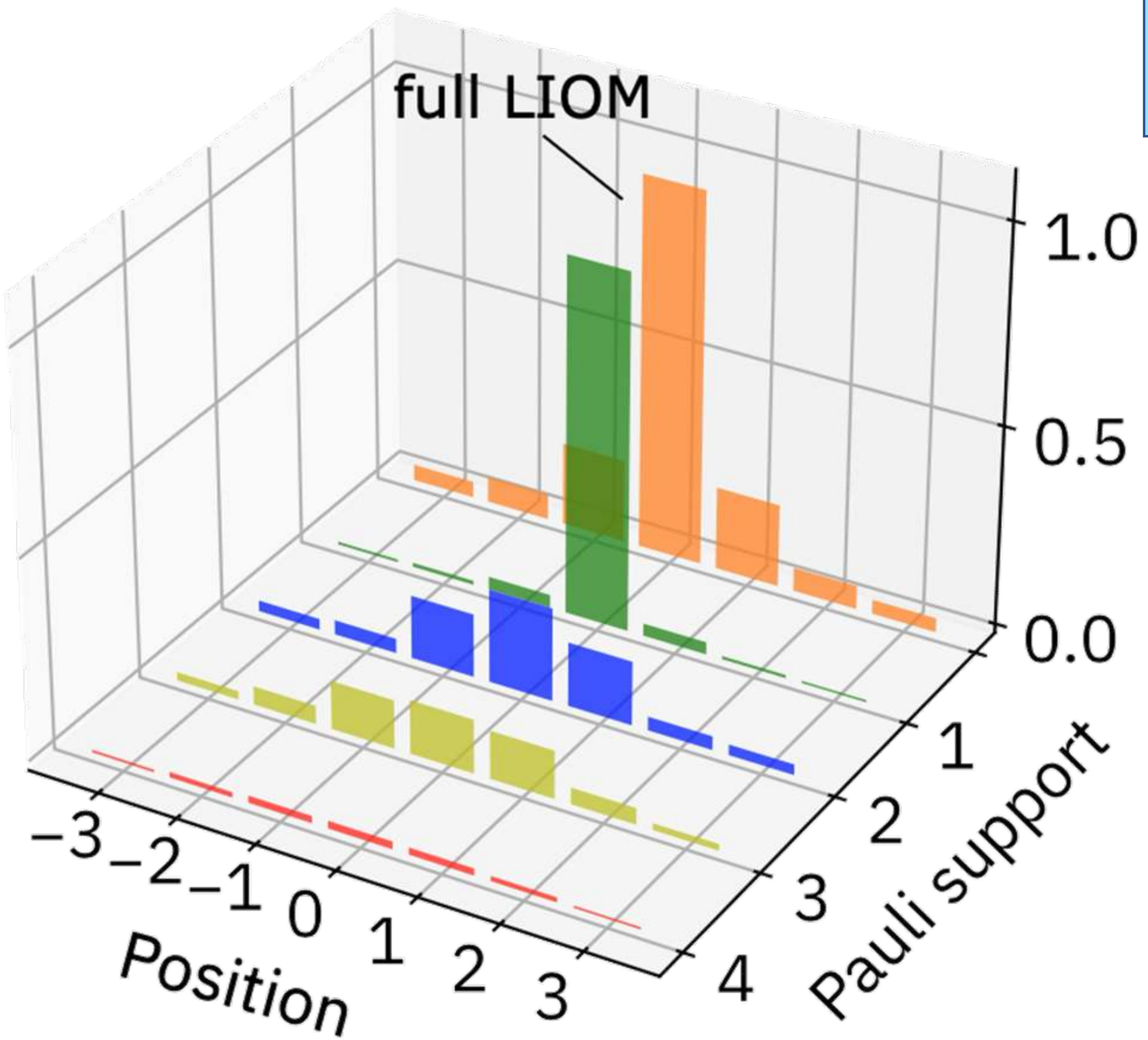




Chandran, Kim, Vidal, Abanin, PRB (2015)
Mierzejewski, Prelovsek, Prosen, PRL (2015)

Average LIOM decomposed by weight





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

total

weight 1

weight 2

weight 3

weight 4

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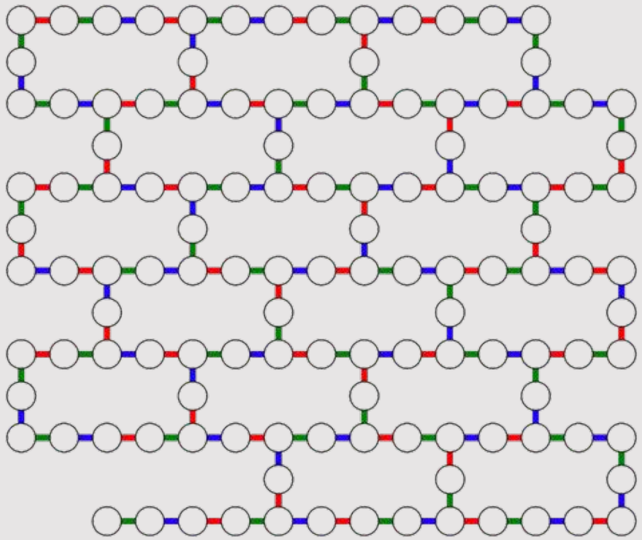
124 LIOMs in 2D

Prethermal LIOMS

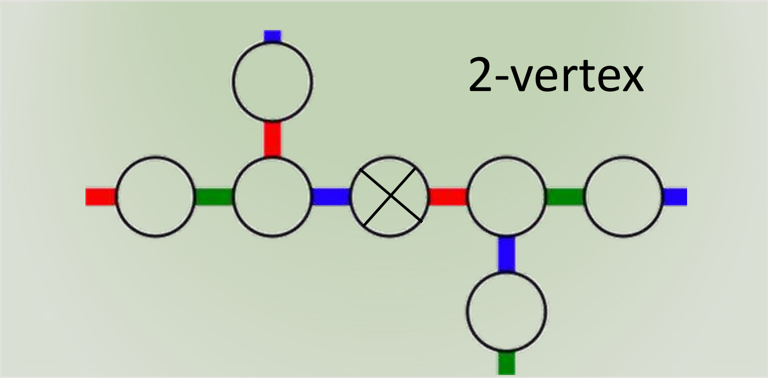
$$\left[e^{-iHt}, L_k\right] \approx 0$$

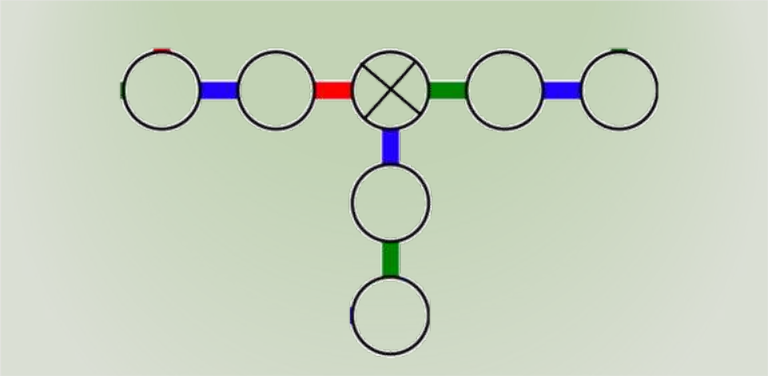
$$L_k = \sum_{\mu \in \mathcal{N}(k)} a_\mu P_\mu$$

local neighborhood



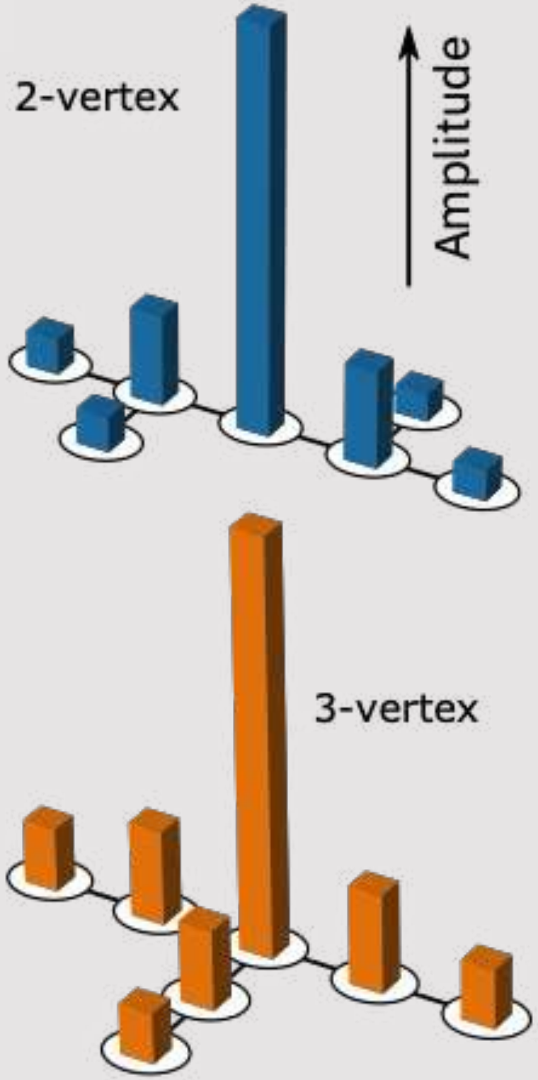
LIOM topologies



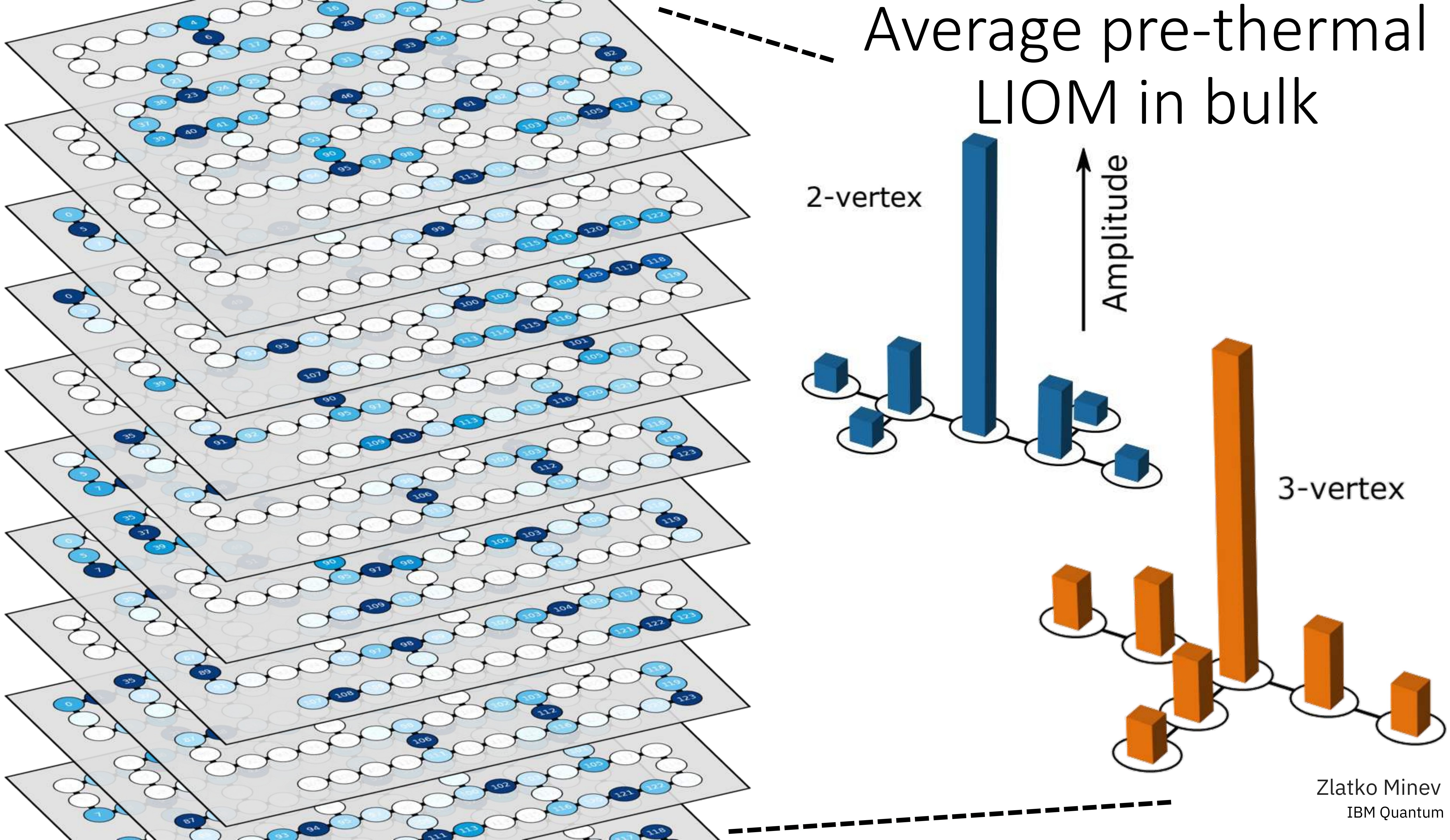


⊗ LIOM center
(position of initial guess)

Bulk LIOM average



Average pre-thermal LIOM in bulk



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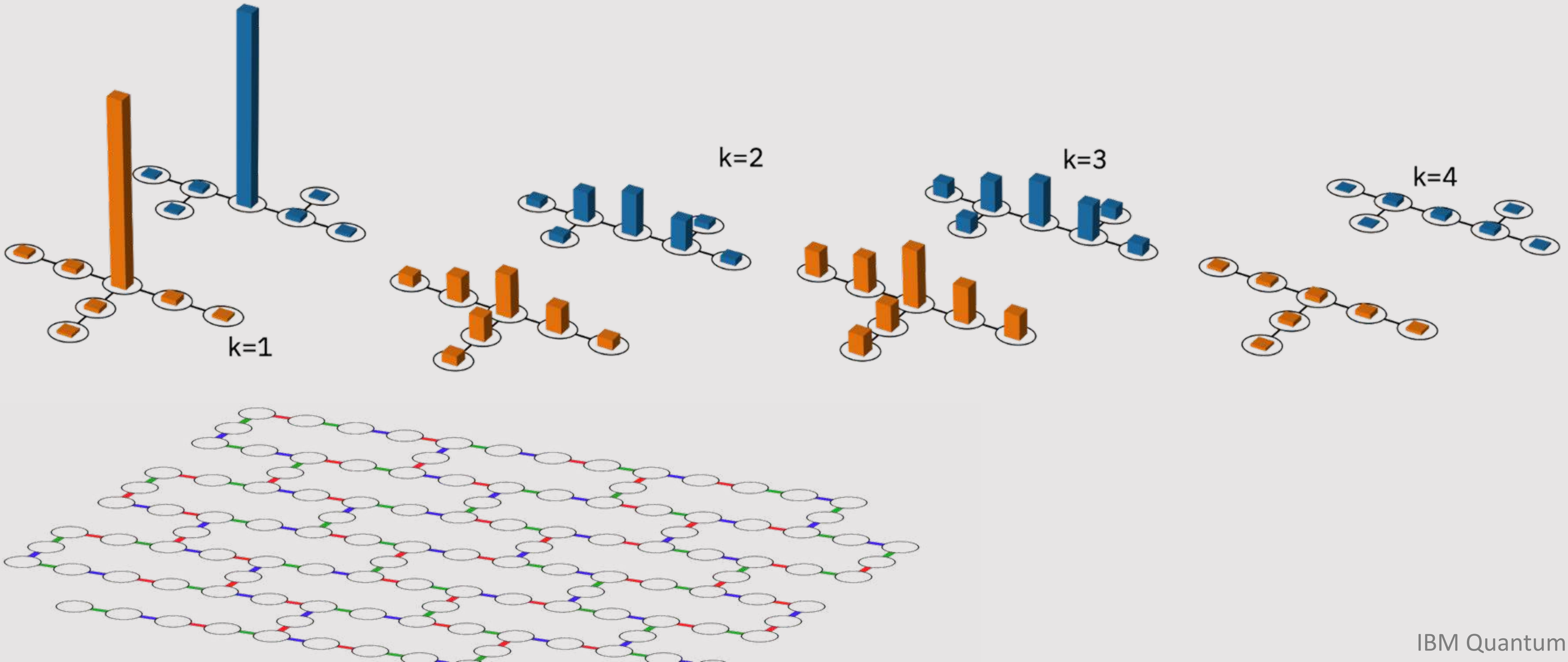
LIOMs in 2D

Decomposition of the average LIOM into contributions from *k*-local Pauli operators



Density definition

We visualize LIOMs using the density function

Position

$$W^2(x, p) = \sum_{\mu \in Q_p} a_\mu^2 \, w_{x\mu}$$

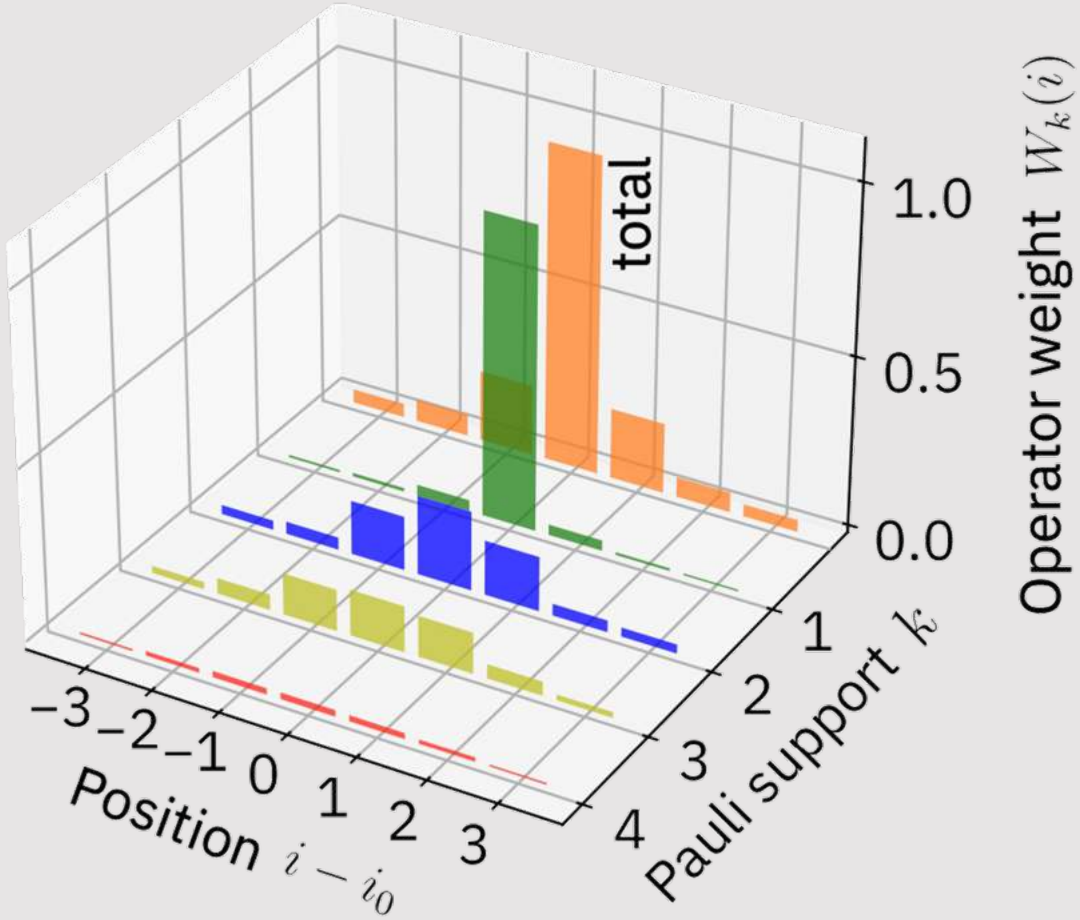
Operator weight

Locality

set of p-local Pauli operators

Weight of Pauli relative to site x

$$w_{x\mu} = \begin{cases} 0, \text{ if acts as identity} \\ 1/S, \text{ if acts as Pauli matrix, where S is the Pauli weight} \end{cases}$$



We compare to a unitary simulation of the experiment (truncated subsystem)