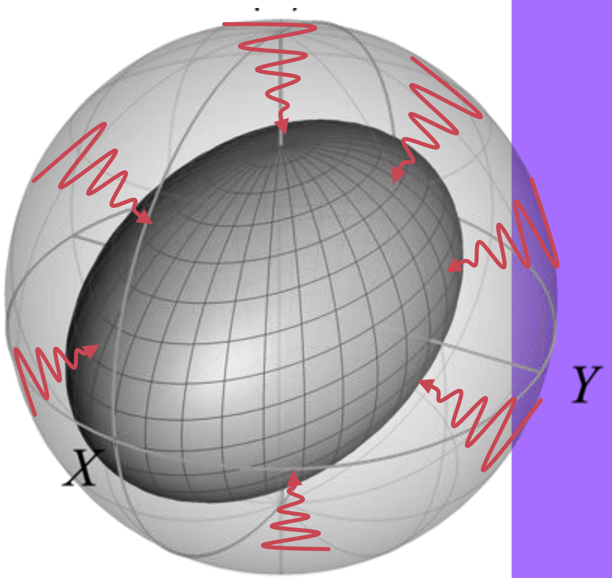
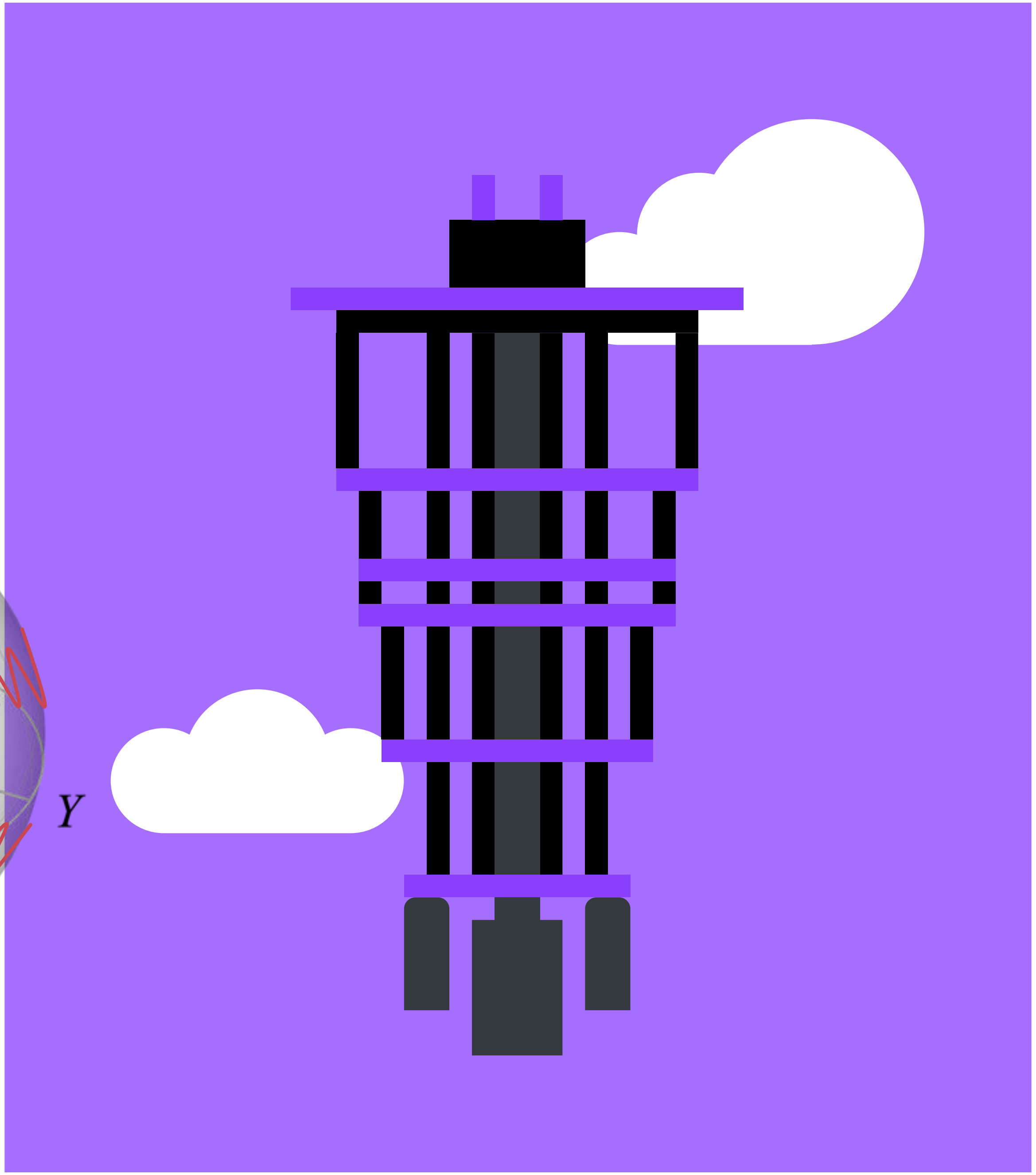
- IBM Quantum Summer Learning Session

Introduction to real quantum computers (and noise)

Zlatko K. Minev

IBM Quantum





@zlatko_minev

zlatko-minev.com/blog

IBM

Have you used a quantum computer?

Image: Freepik

Quantum Noise and Error Mitigation

Lecture 1

Big picture

Quantum computers status

Why error mitigation?

Noise in quantum computers

Overview of error mitigation

Mitigation fundamentals

Probabilistic error cancelation (PEC)

Introduction

One qubit example

Next lecture

Learning noise

State-of-art mitigation experiments

Hardware

Outlook

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

Where?

Slides from lecture

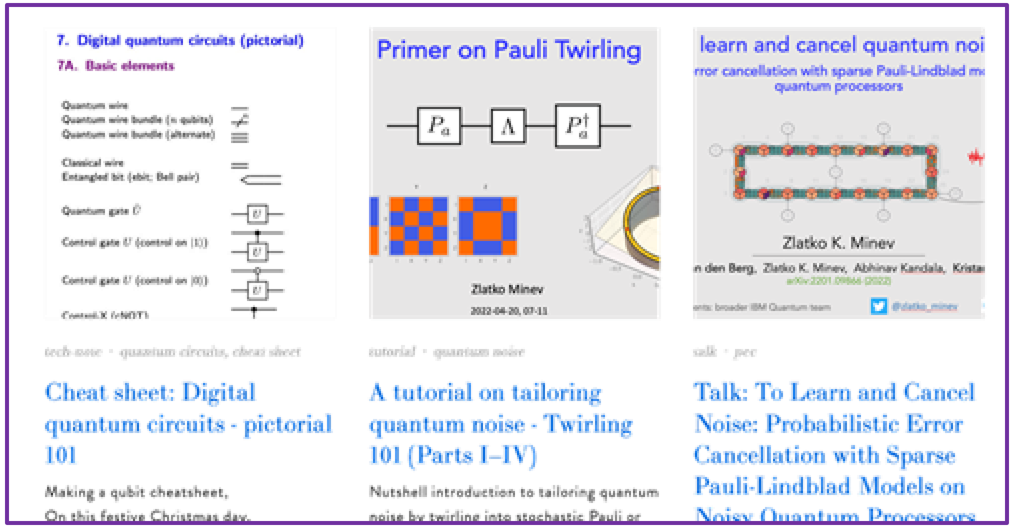
Posted here [zlatko-minev.com/education]
Tutorials [/blog]

See

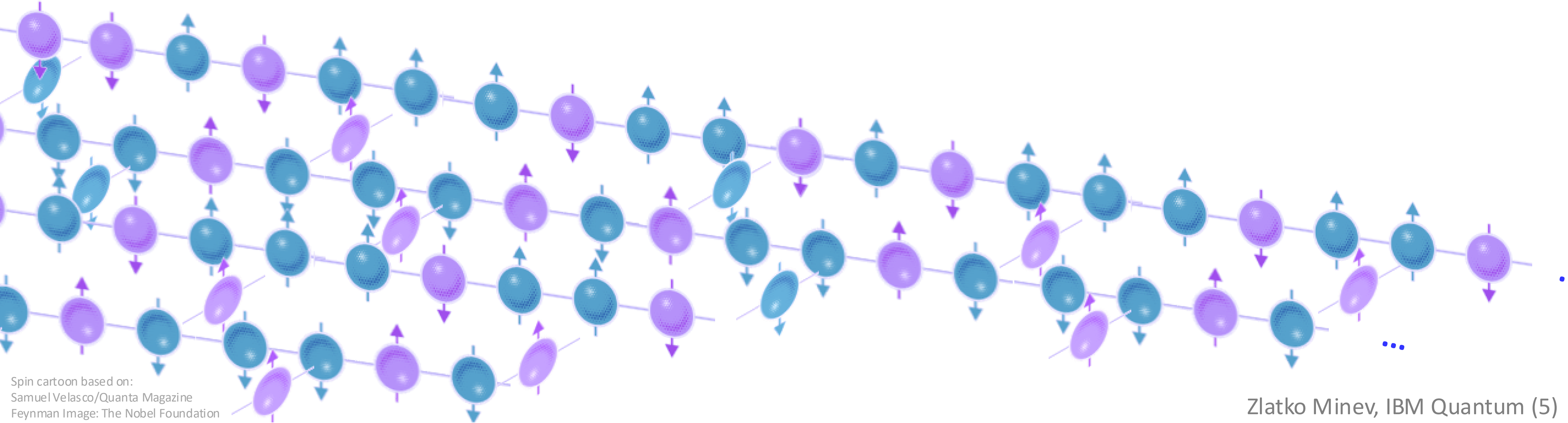
IBM Learning
[learning.quantum.ibm.com]

Weekly seminars

[qiskit YouTube]



How is it going for quantum computers?



Spin cartoon based on:
Samuel Velasco/Quanta Magazine
Feynman Image: The Nobel Foundation

This year 2023

A 127-qubit quantum computer installed in the the lobby cafeteria of a research building dutifully executing jobs almost all the time.

at Cleveland Clinic

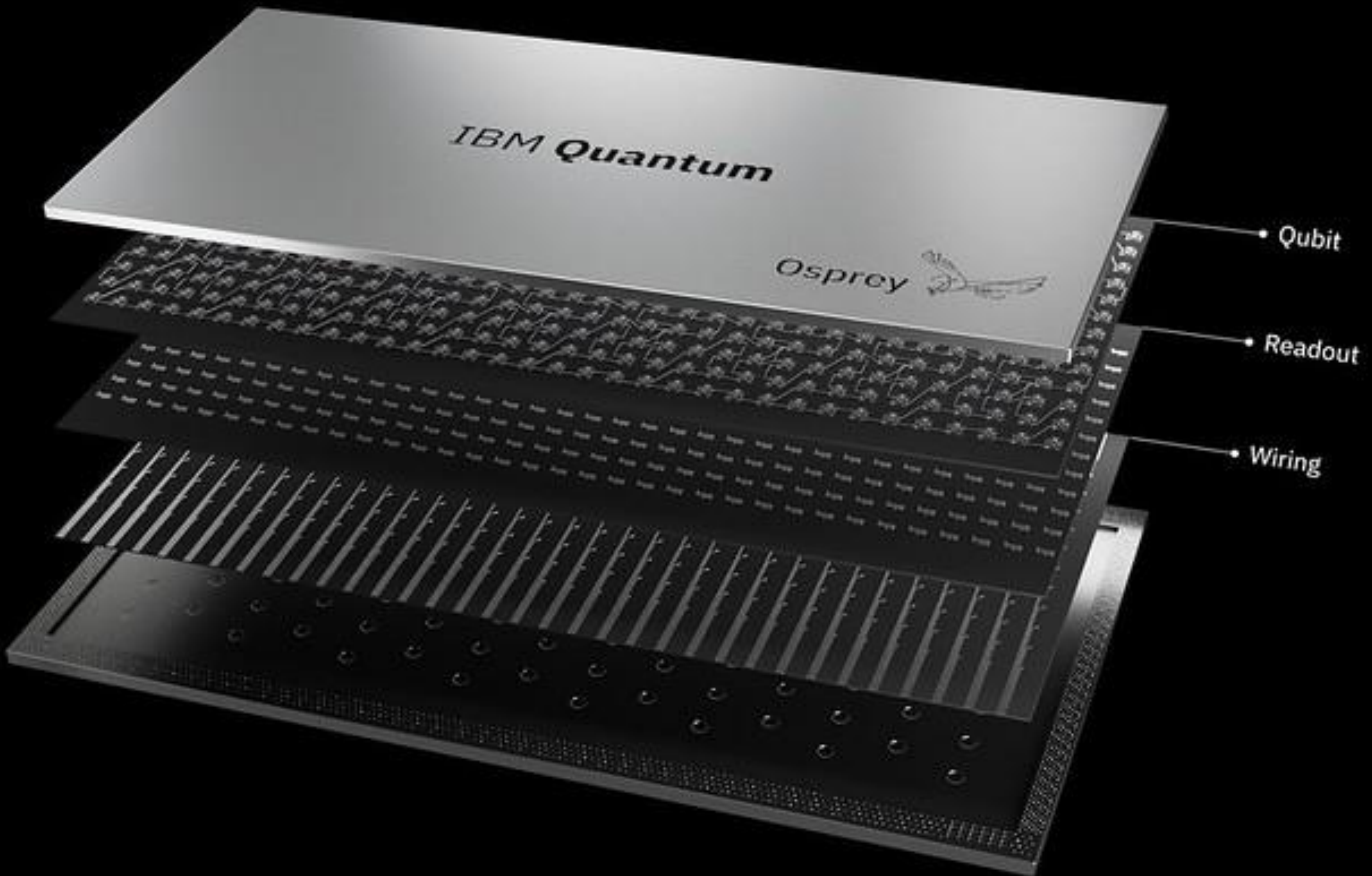
Credit: Connie Zhou for IBM

2019
Falcon
27 Qubits

2020
Hummingbird
65 Qubits

2021
Eagle
127 Qubits

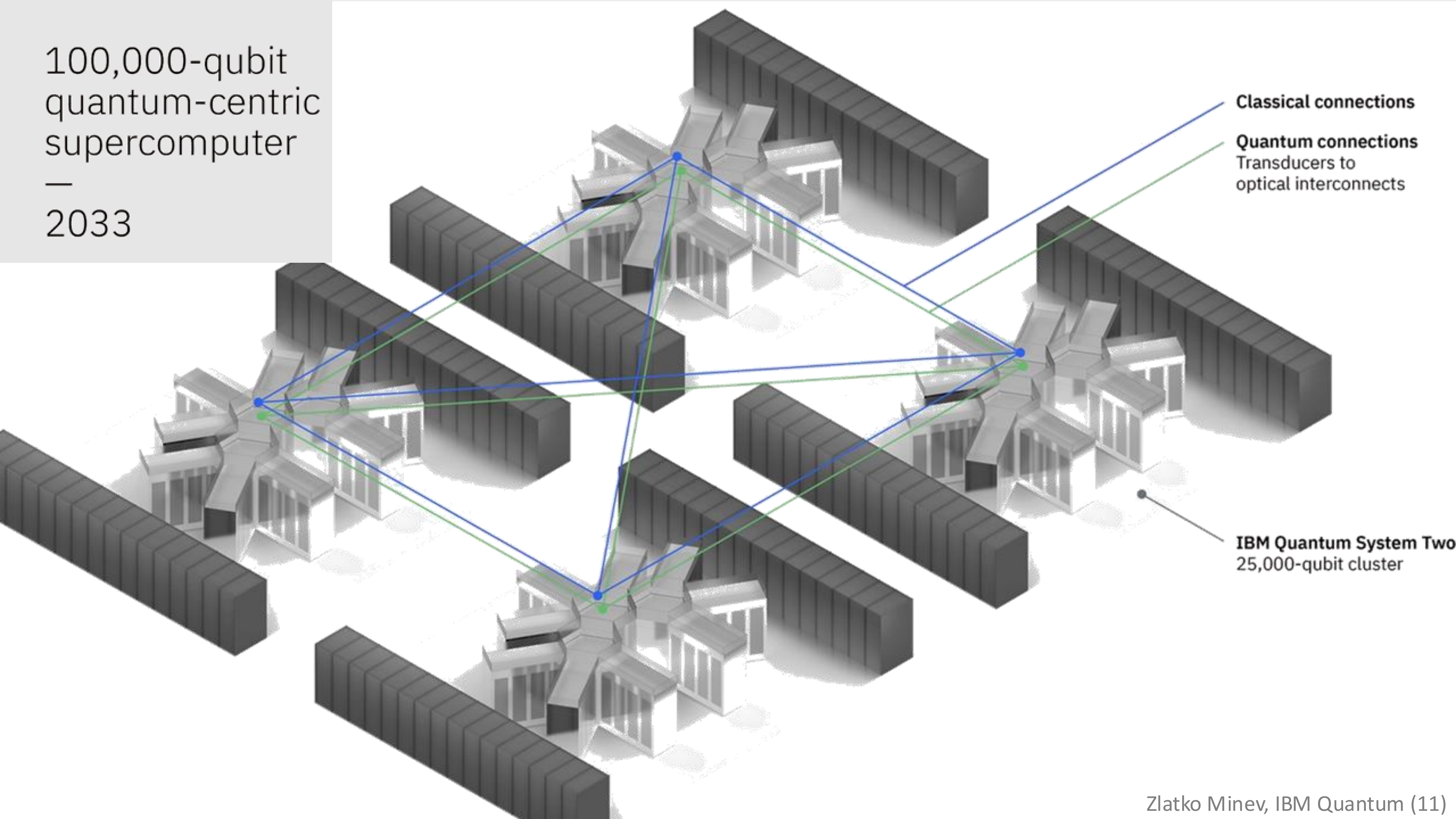
2022
Osprey
433 Qubits



IBM Quantum
Osprey
Qubit
Readout
Wiring

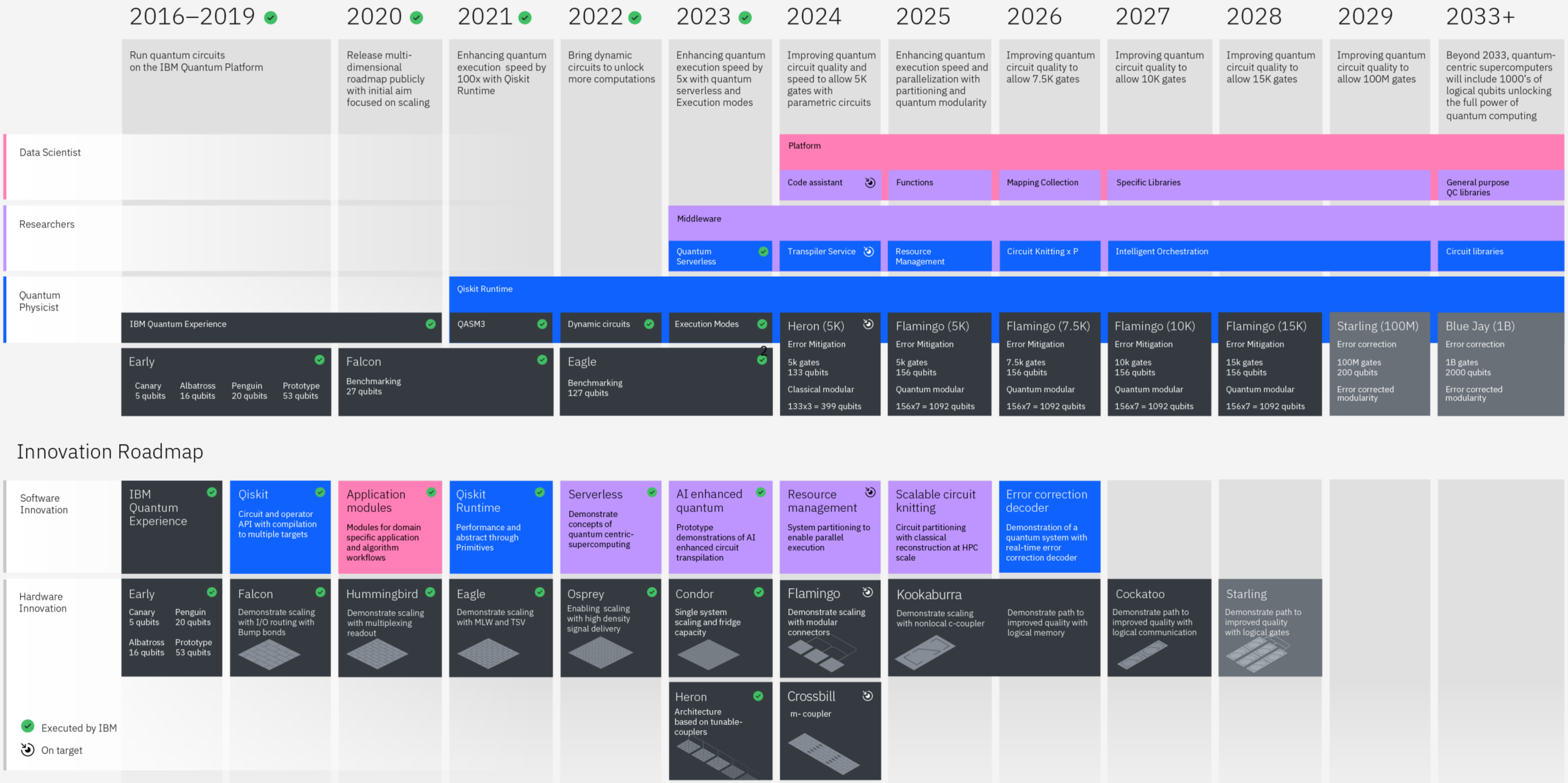
Image: Freepik

100,000-qubit quantum-centric supercomputer
—
2033



Development Roadmap

IBM **Quantum**



Back to today …

Example: Quantum simulation

Example task:

Simulate the out-of-equilibrium quantum dynamics of a 2D spin chain lattice to find the evolution of the global and local magnetization.

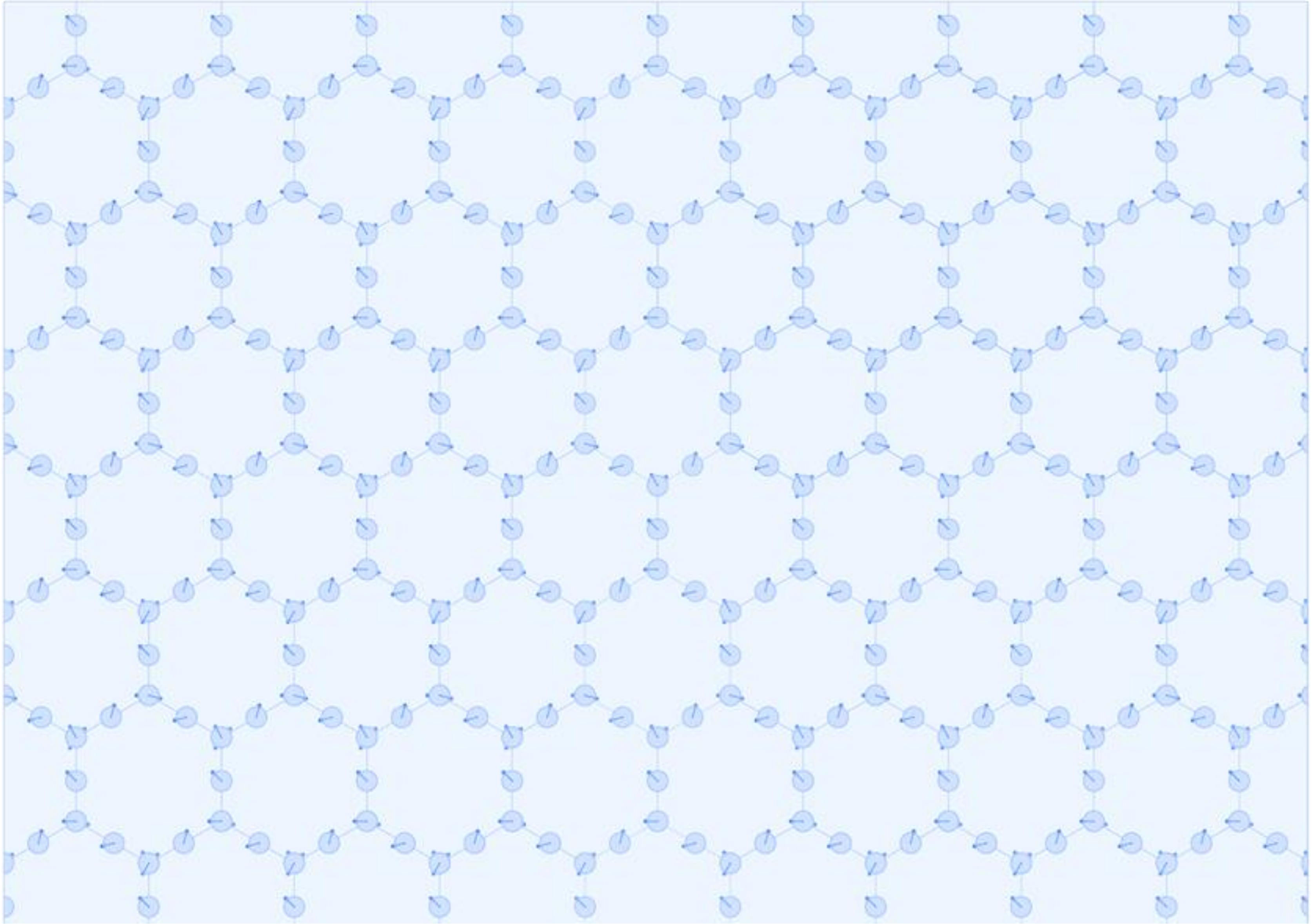


Image: IBM Quantum

Quantum simulation on a quantum computer

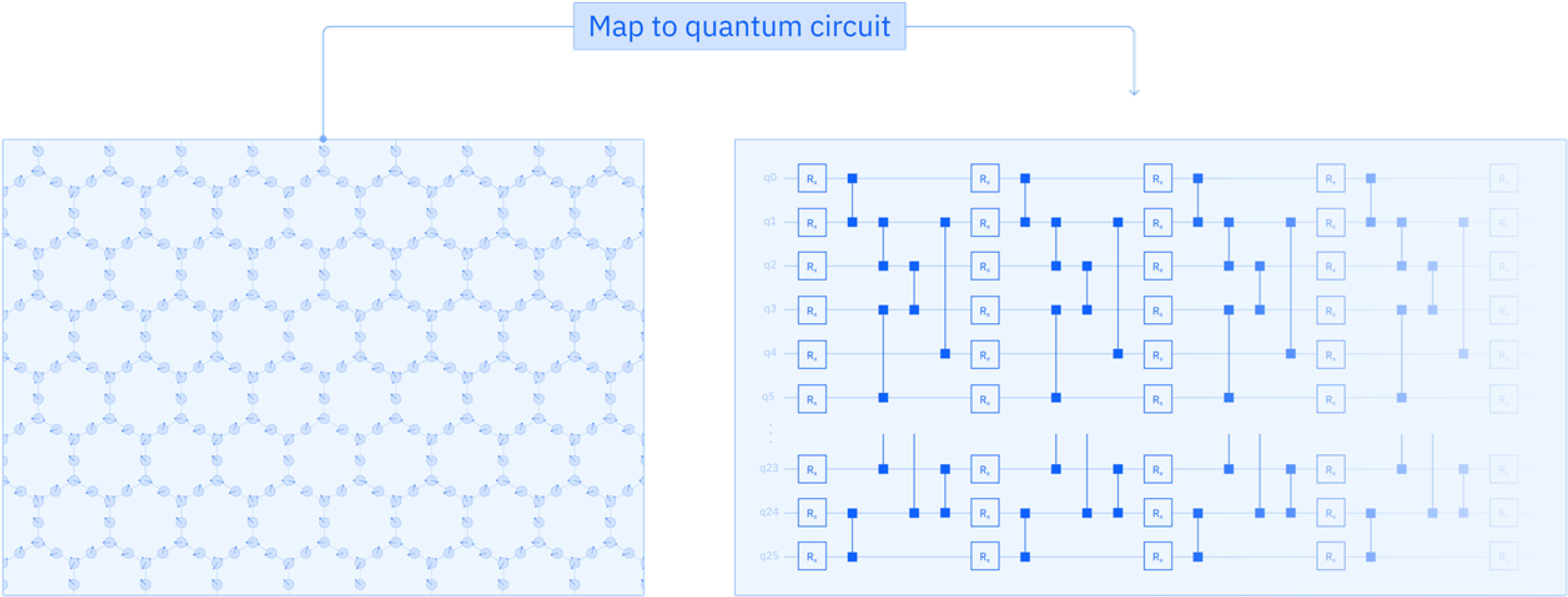


Image: IBM Quantum

Quantum simulation on a quantum computer

Execute on a real quantum computer device and obtain results as classical data

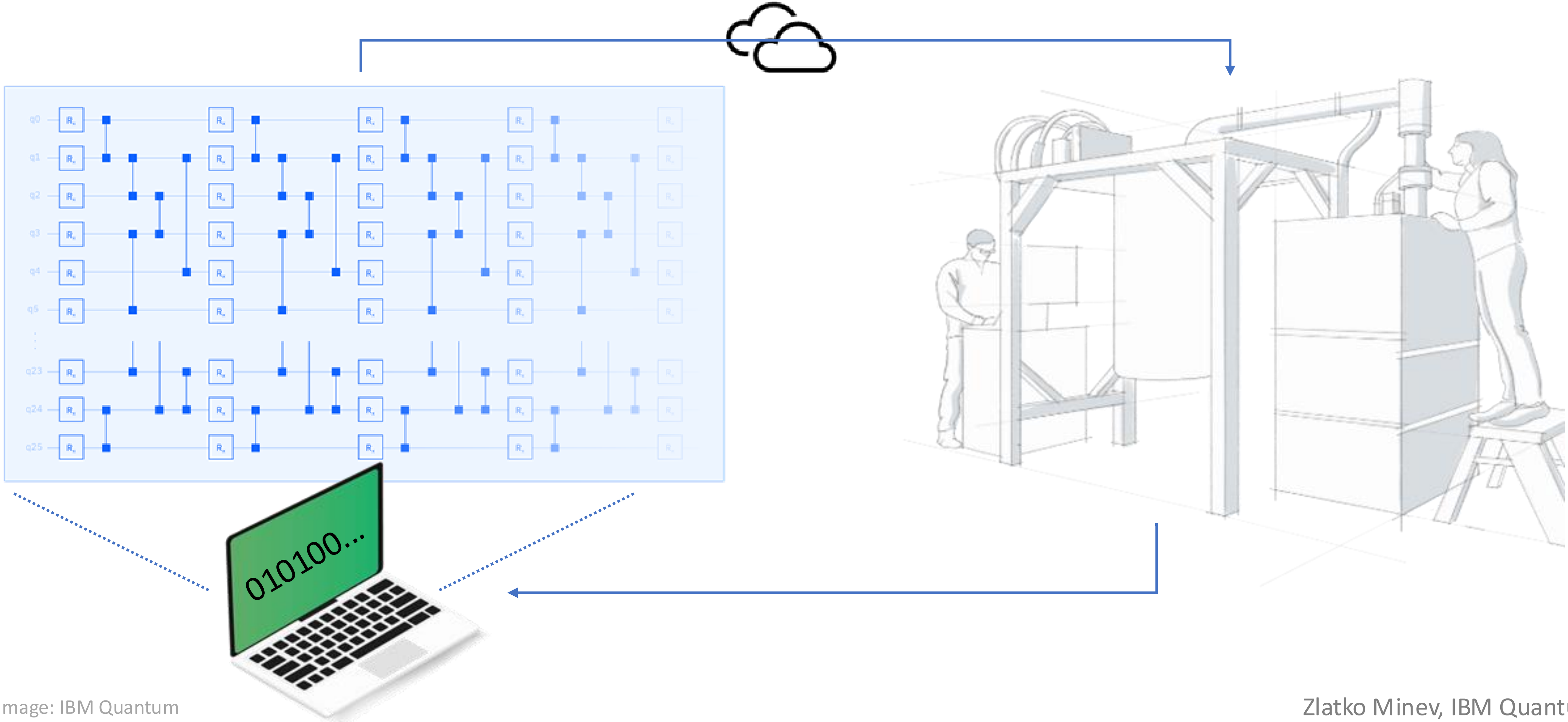


Image: IBM Quantum

Biggest challenge?

Please do share

Biggest challenge?

Noise
(Errors)

hardware development

decoherence

loss

stability

heat

algo development

error correction overheads

high error rates

scalability

engineering

modularization

importance of N in NISQ

hype

need CS/EE talent

material quality

gravity

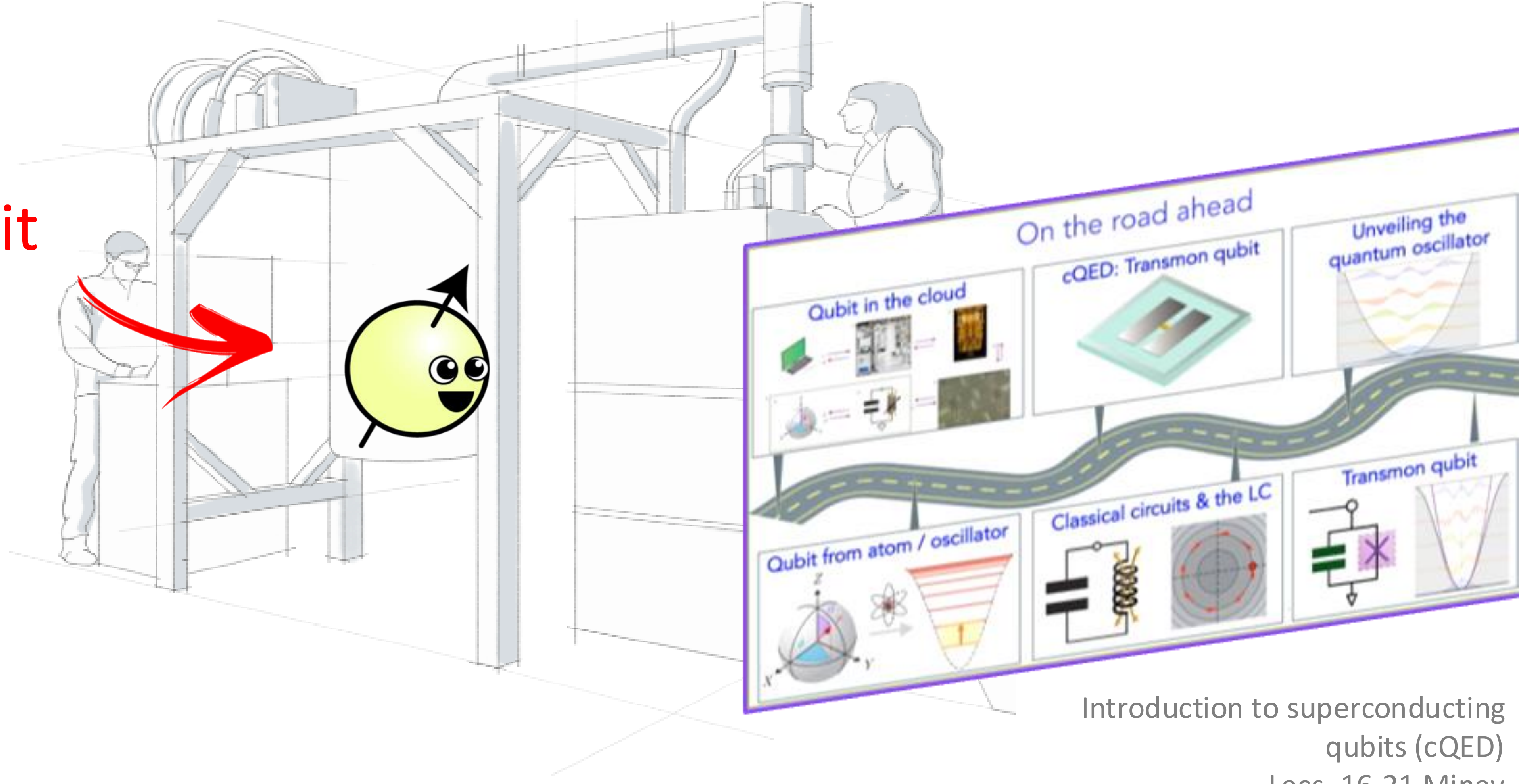
expectations

Biggest challenge

Noise
(Errors)

Hello World with a real experiment!

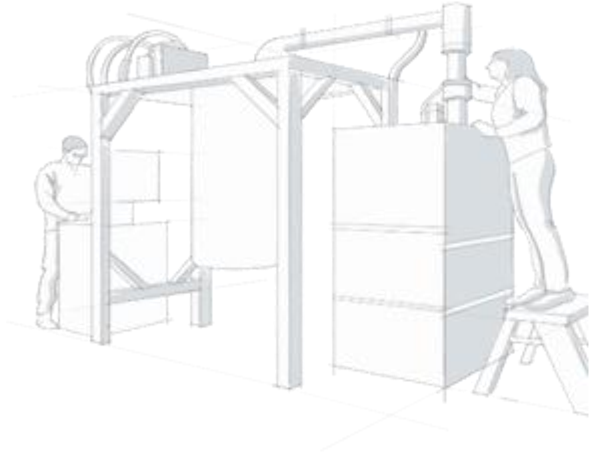
A qubit



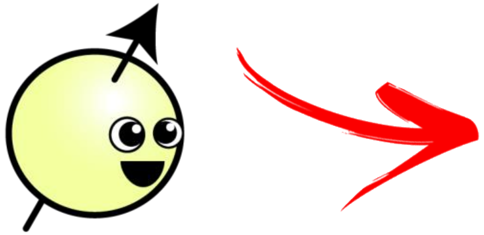
Introduction to superconducting qubits (cQED)
Lecs. 16-21 Minev
QGSS 2020 at **qiskit.org/learn**

image: qiskit

Hello World! building blocks



A qubit



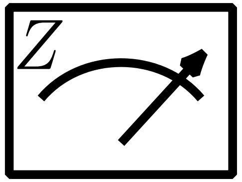
$$|1\rangle$$
$$|0\rangle$$

Computational basis states

Operations: qubit gate

$$\boxed{X}$$

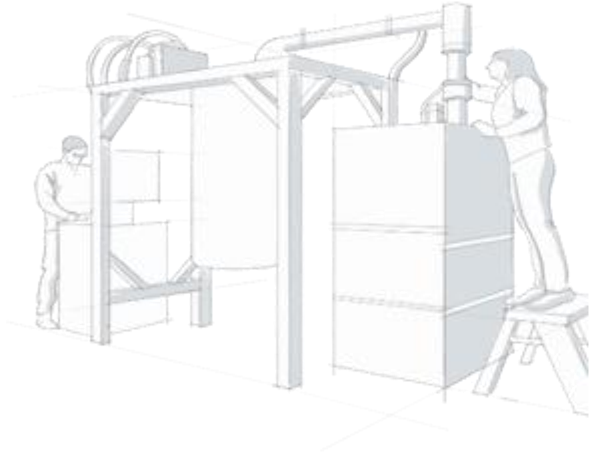
Measurements: qubit observable



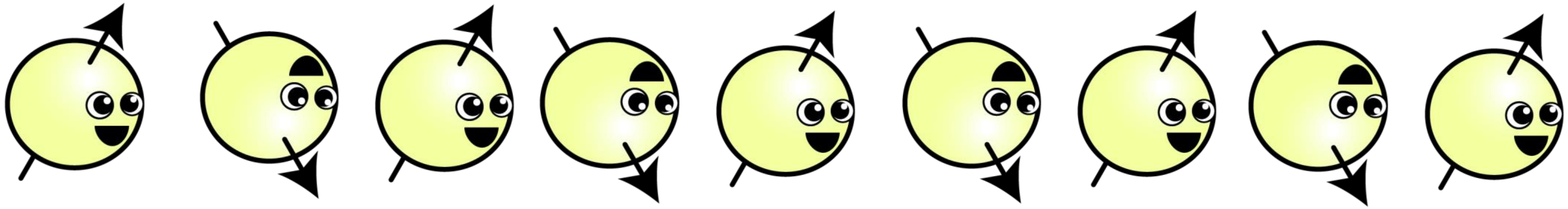
refresher:

$$X\,|0\rangle = |1\rangle \qquad Z\,|0\rangle = +1\,|0\rangle$$
$$X\,|1\rangle = |0\rangle \qquad Z\,|1\rangle = -1\,|1\rangle$$

Hello World! Even-odd algo: qubit flipper



Task: Classify or report if a classical positive integer *d* is even or odd.



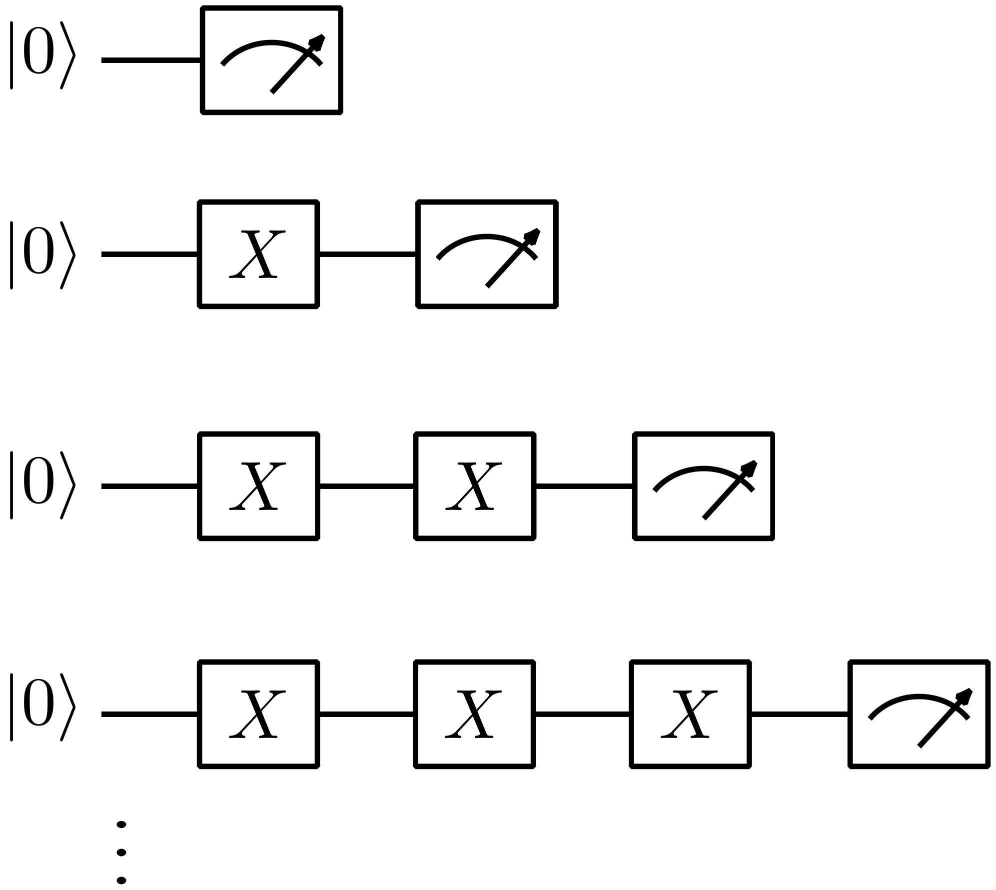
flip spin *d* times, measure polarization

refresher:

$$X|0\rangle = |1\rangle \qquad Z|0\rangle = +1|0\rangle$$
$$X|1\rangle = |0\rangle \qquad Z|1\rangle = -1|1\rangle$$

Hello World! qubit flipper quantum circuits

depth

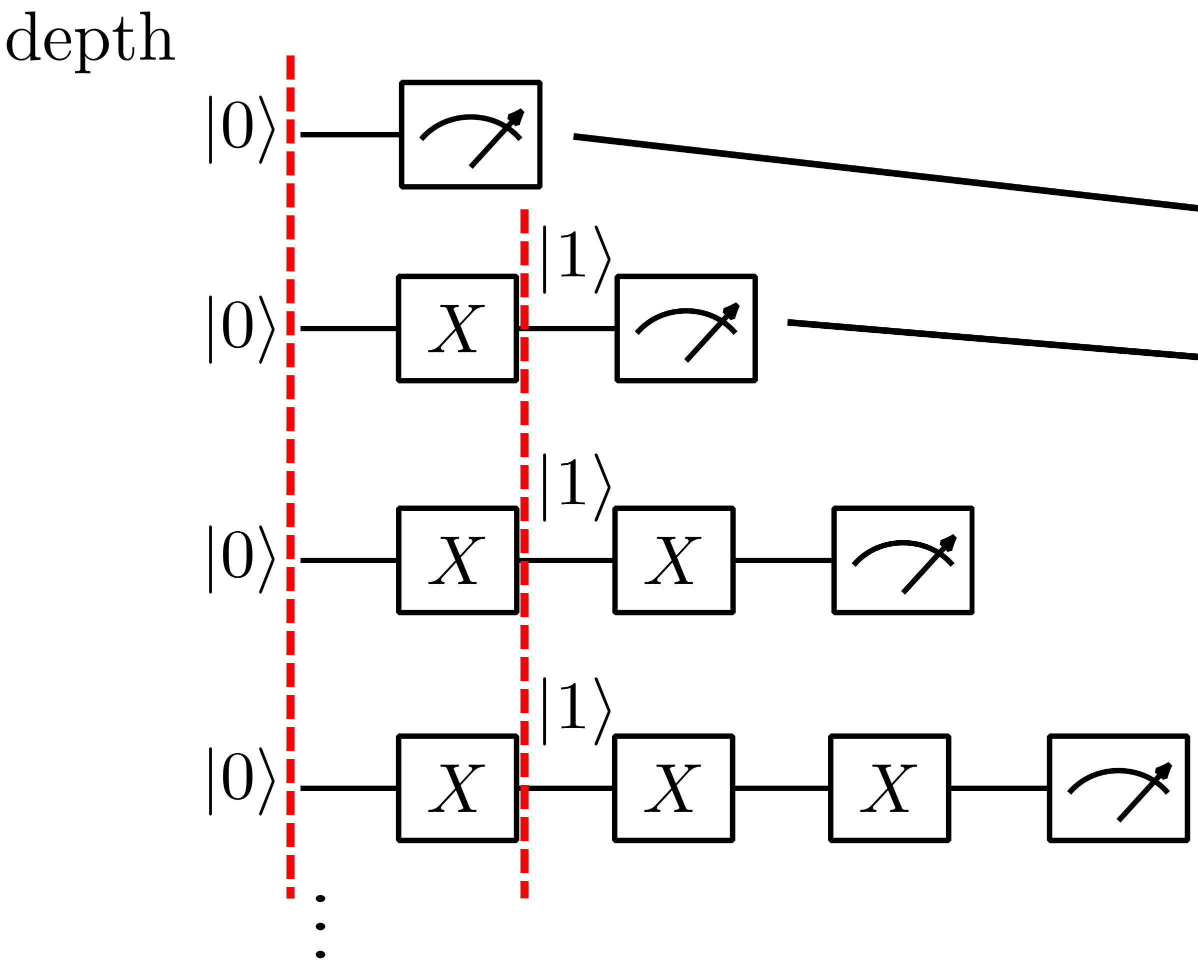


refresher:

$$X|0\rangle = |1\rangle \qquad Z|0\rangle = +1|0\rangle$$

$$X|1\rangle = |0\rangle \qquad Z|1\rangle = -1|1\rangle$$

Hello World! “debugger” step through



Measurement

$$\langle 0|Z|0\rangle = +1$$

$$\langle 1|Z|1\rangle = -1$$

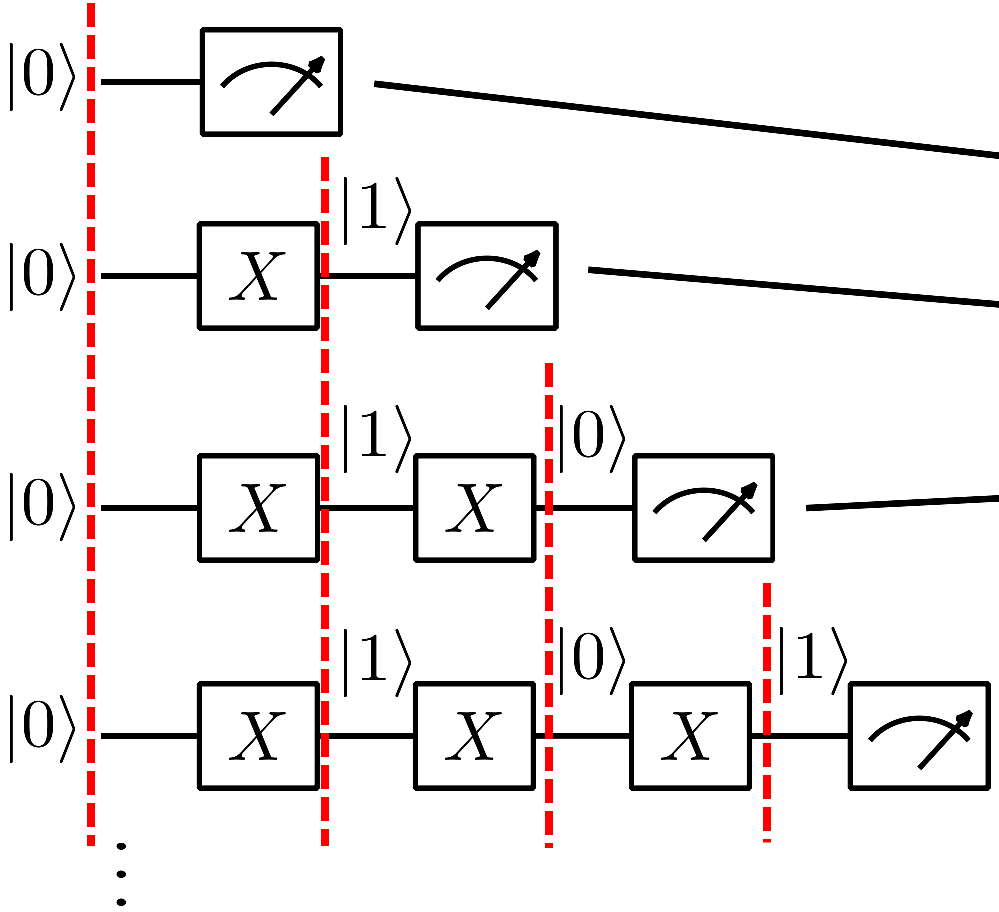
refresher:

$$X\,|0\rangle = |1\rangle \qquad Z\,|0\rangle = +1\,|0\rangle$$

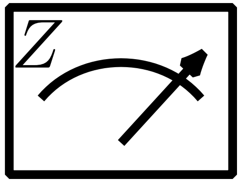
$$X\,|1\rangle = |0\rangle \qquad Z\,|1\rangle = -1\,|1\rangle$$

Hello World! “debugger” step through

depth



Measurement



$$\langle 0|Z|0\rangle = +1$$

$$\langle 1|Z|1\rangle = -1$$

$$\langle 0|Z|0\rangle = +1$$

$$\langle Z\rangle = (-1)^d$$

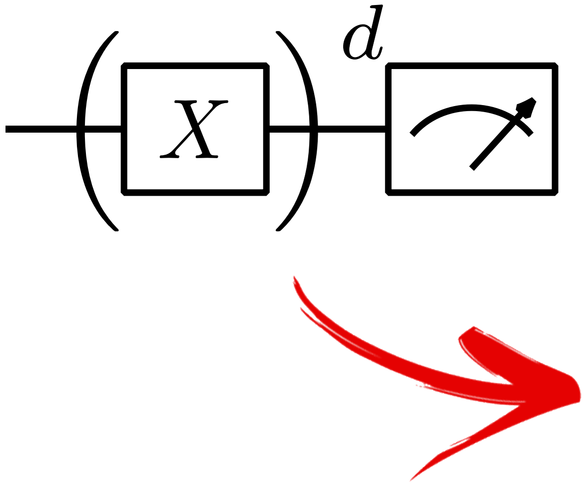
where d is the circuit depth

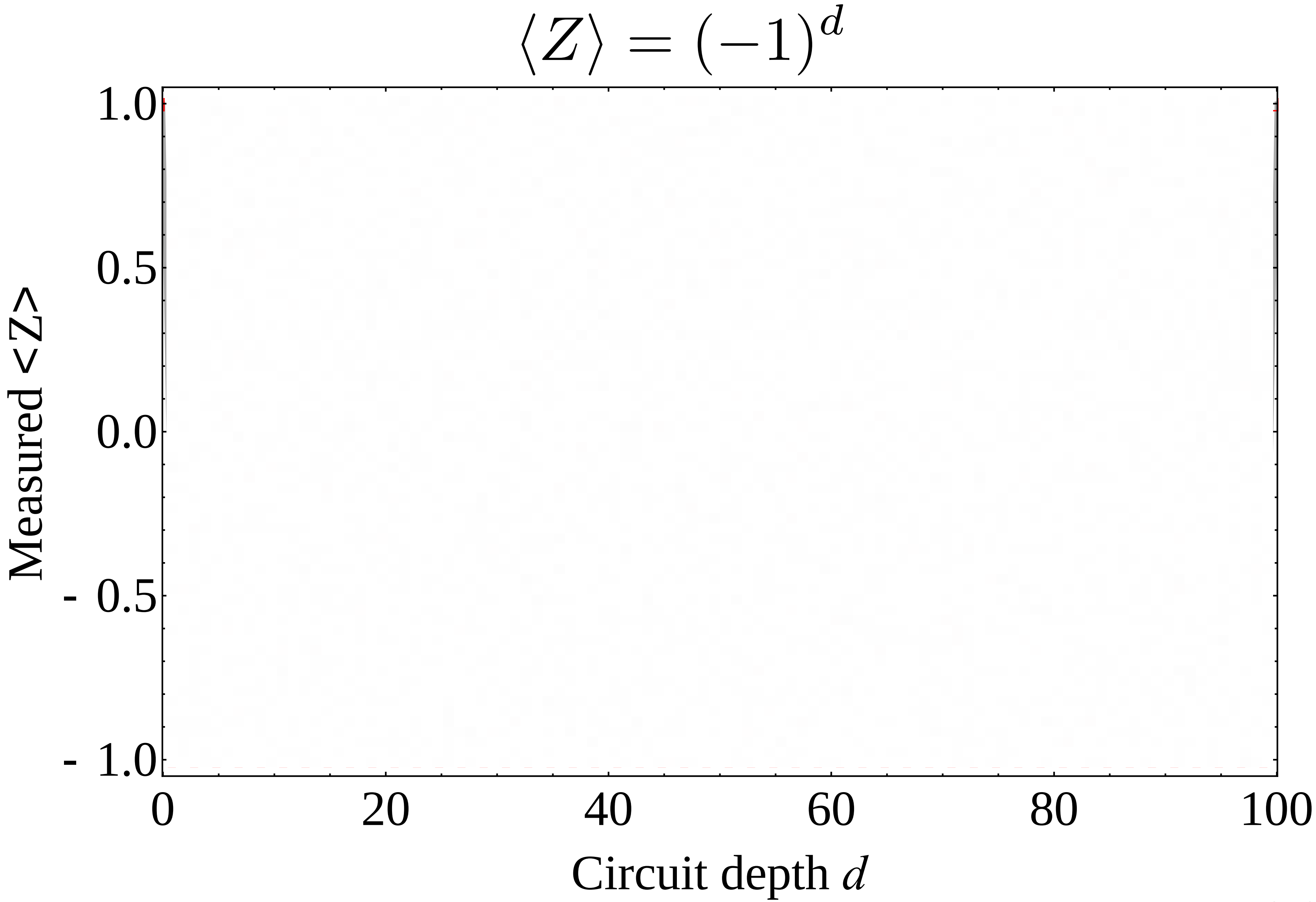
refresher:

$$X\,|0\rangle = |1\rangle \qquad Z\,|0\rangle = +1\,|0\rangle$$

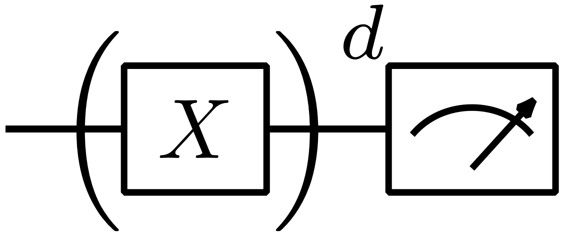
$$X\,|1\rangle = |0\rangle \qquad Z\,|1\rangle = -1\,|1\rangle$$

Hello World! Ideal expectation results

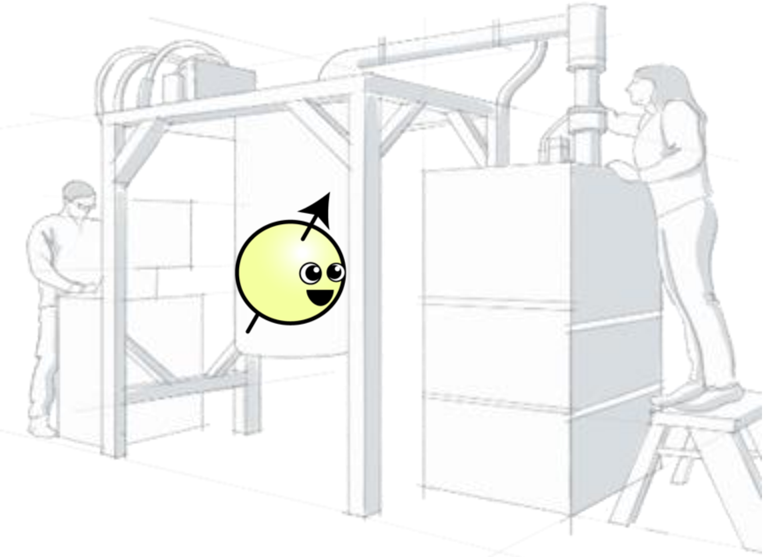


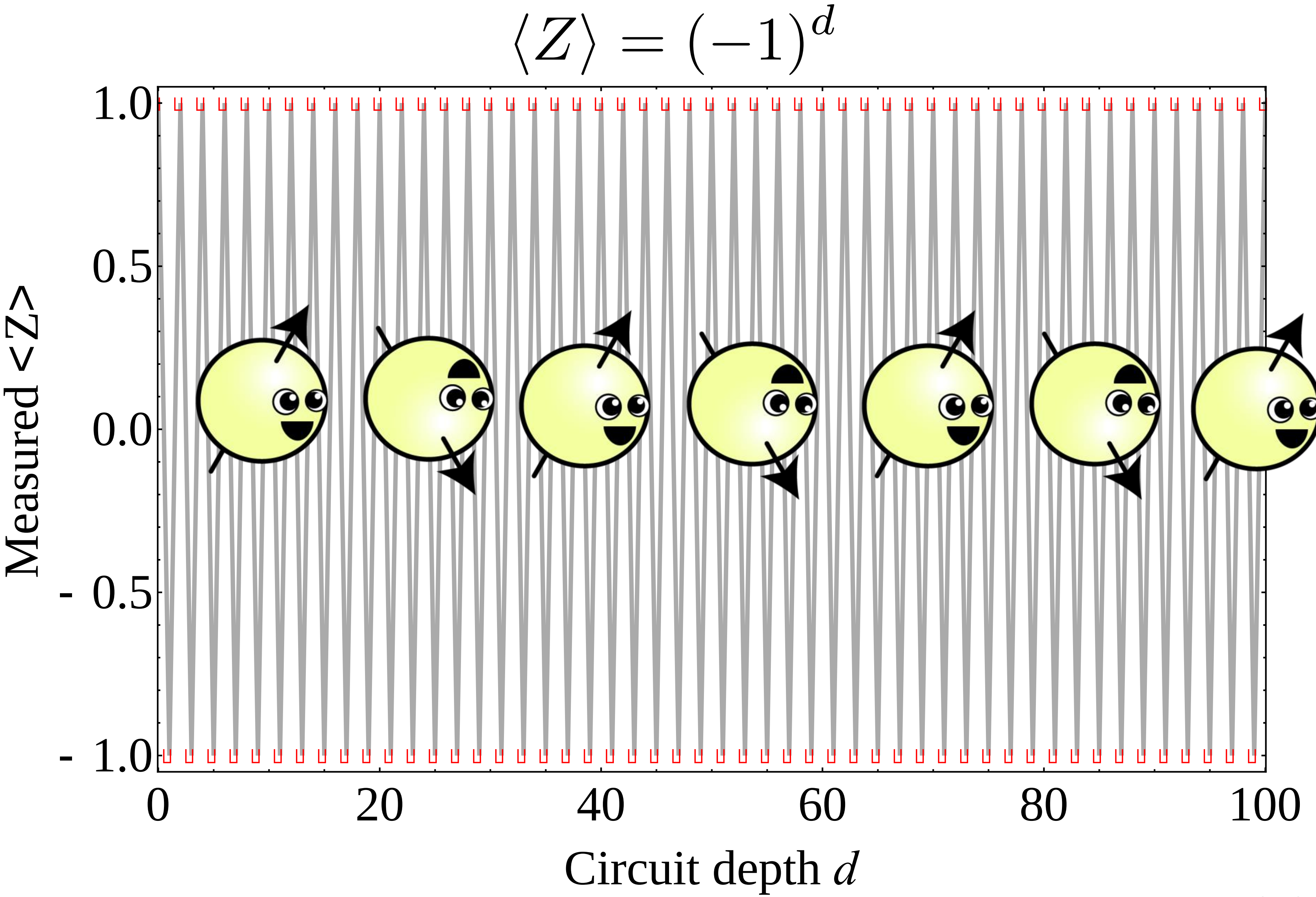


Hello World! Ideal expectation results

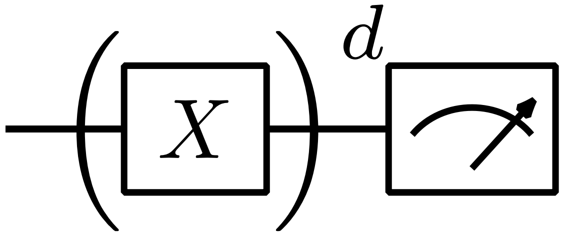


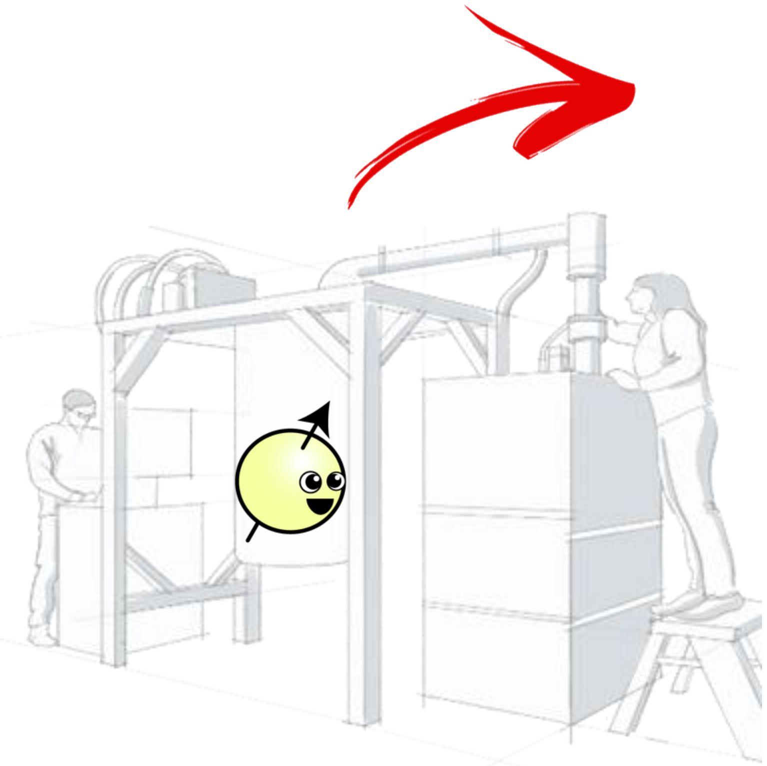
Let’s run on a real device!

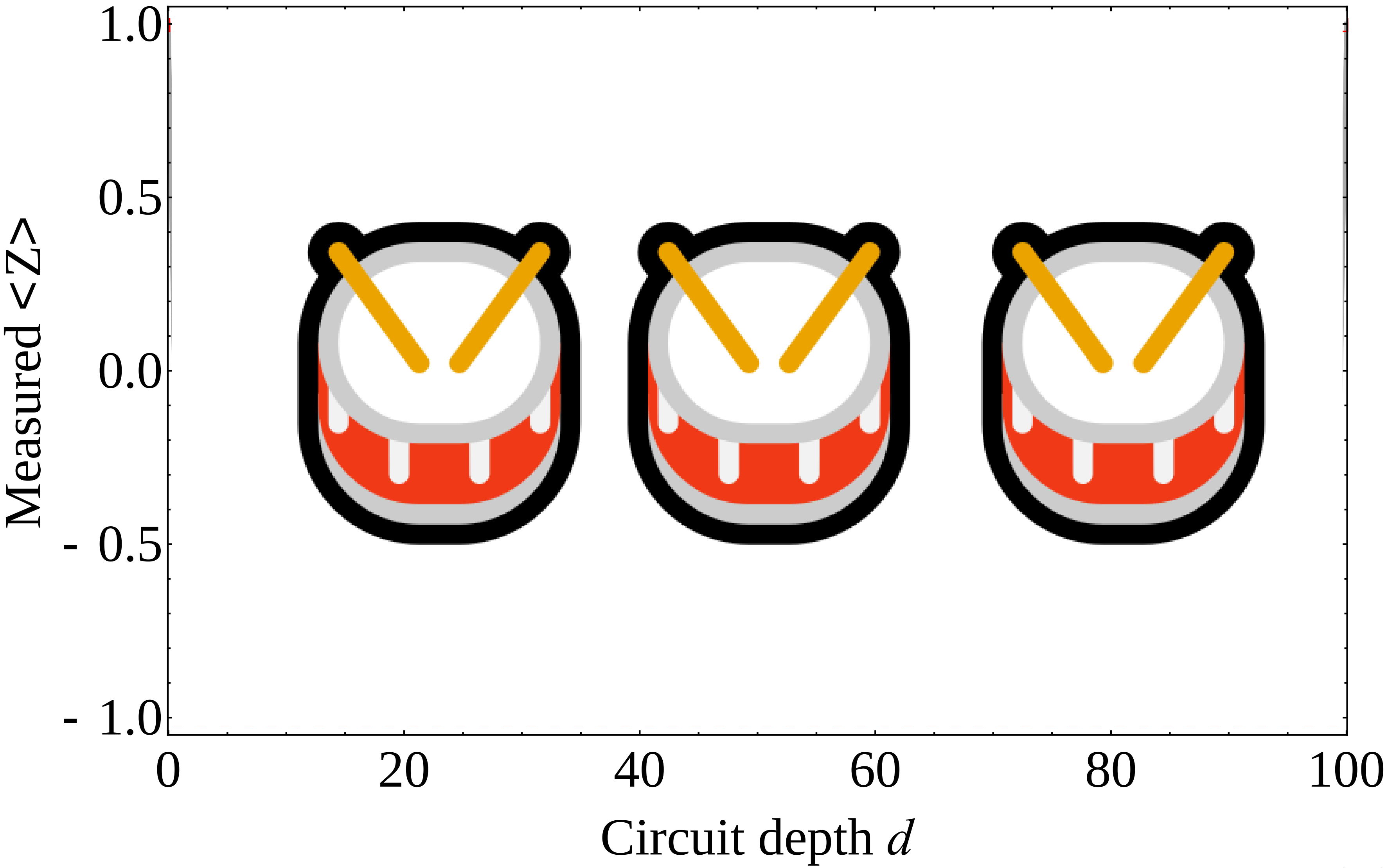




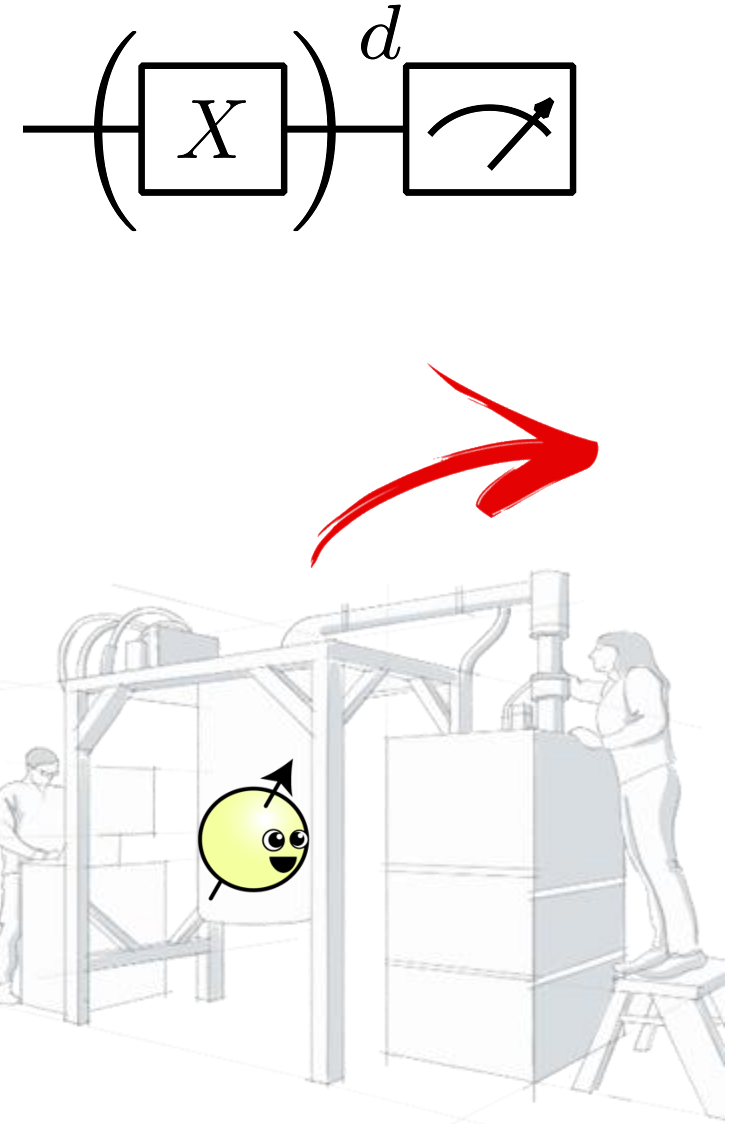
Hello World! Running ….

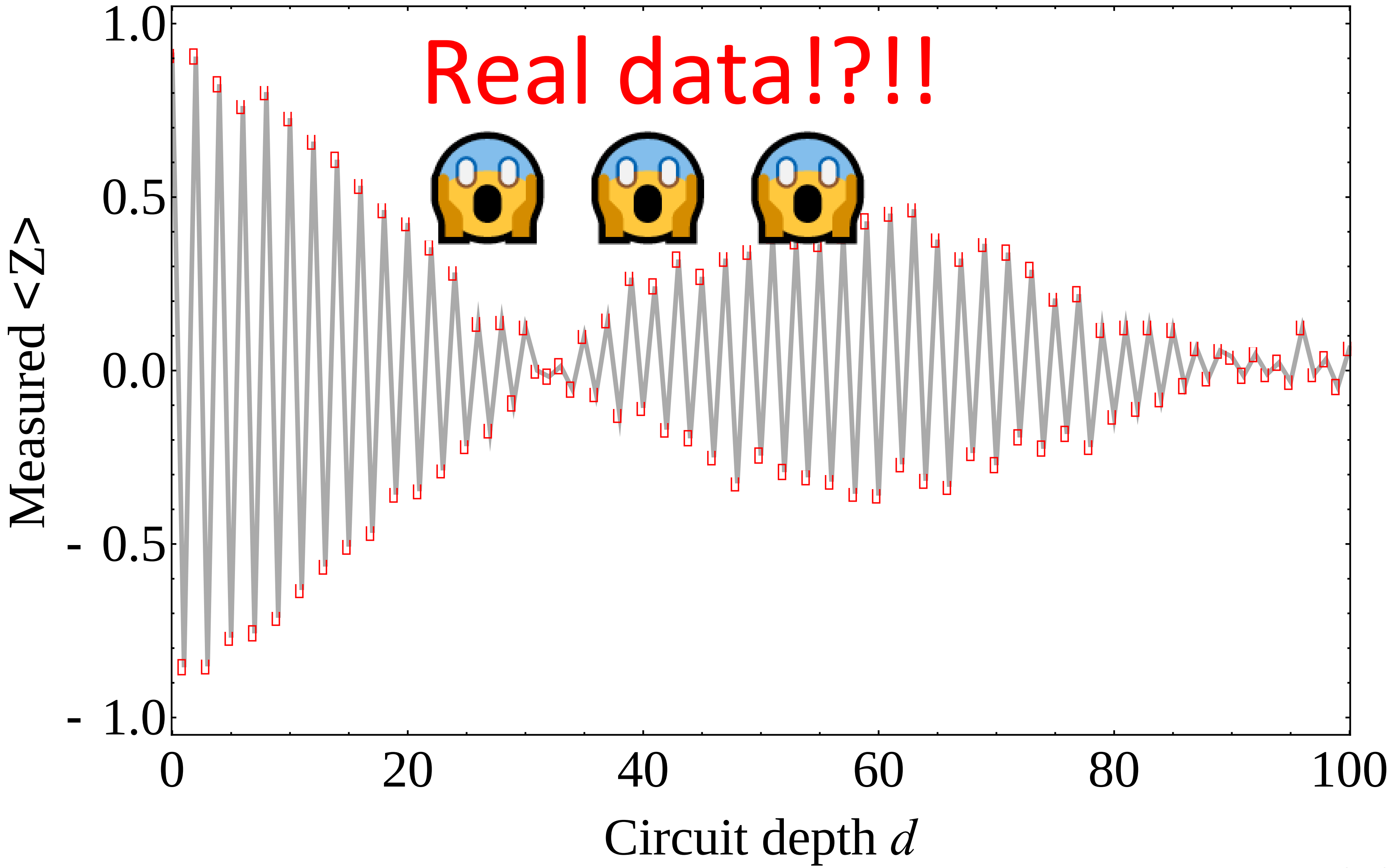




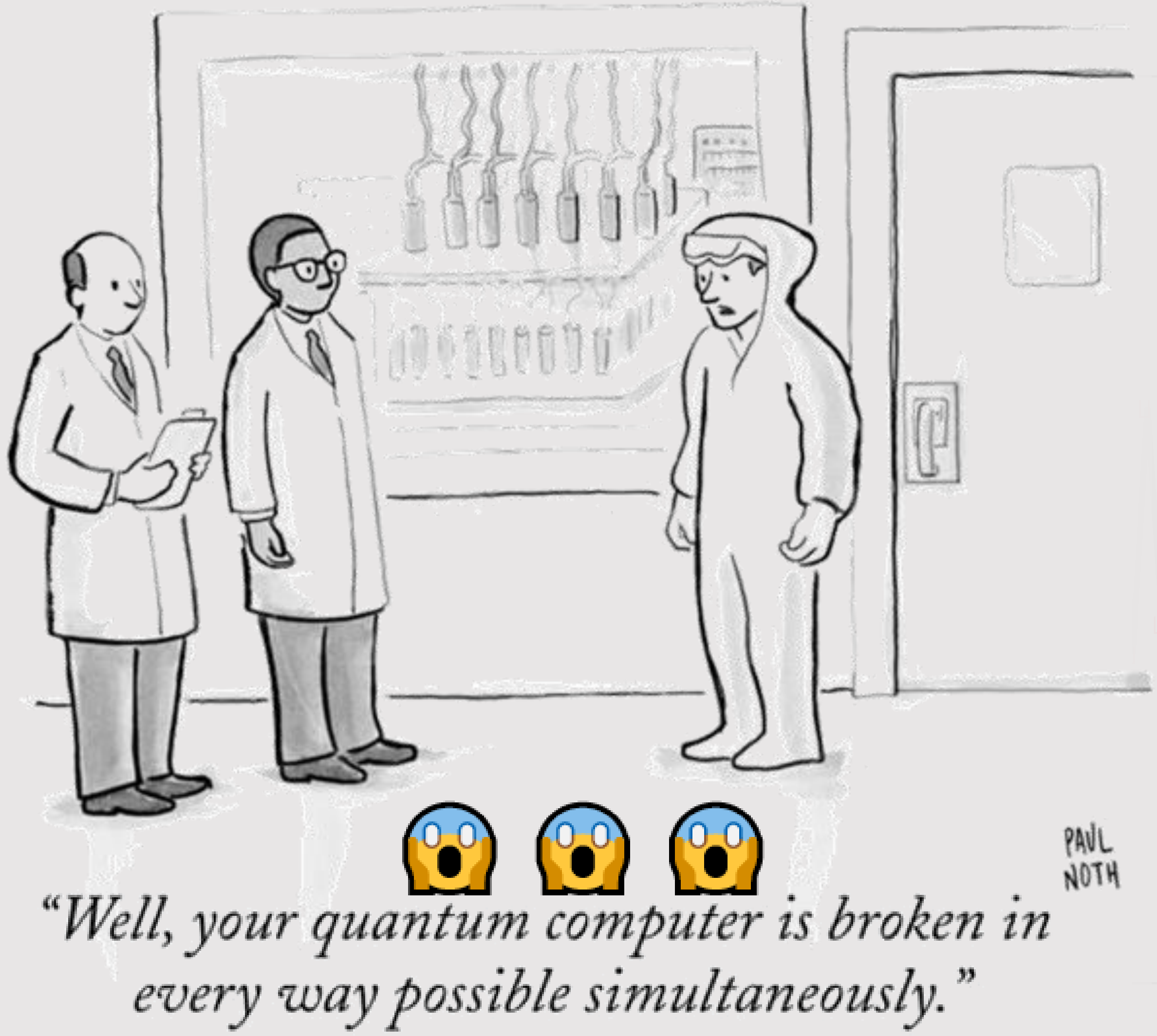


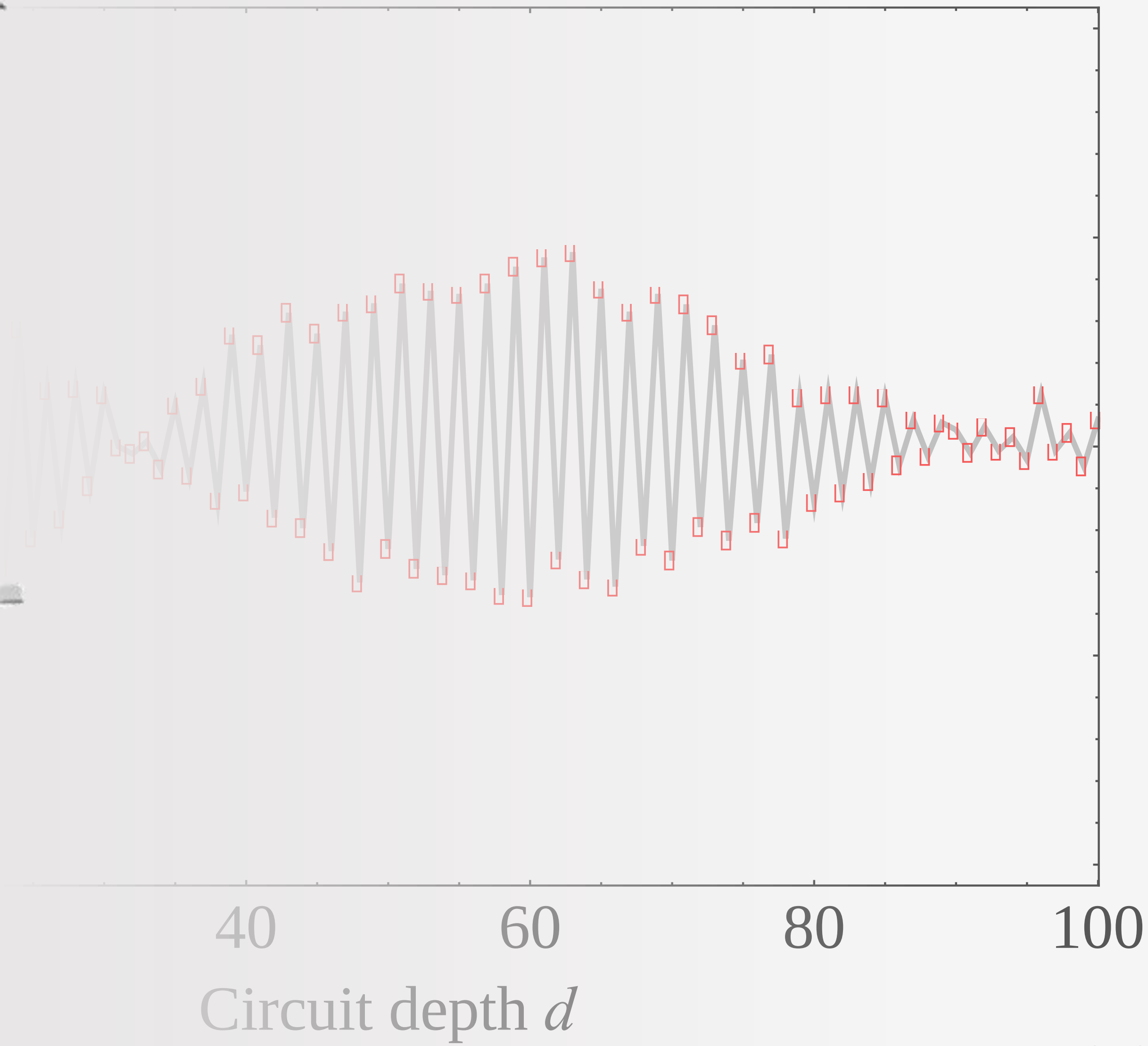
Hello World! Real expectation results



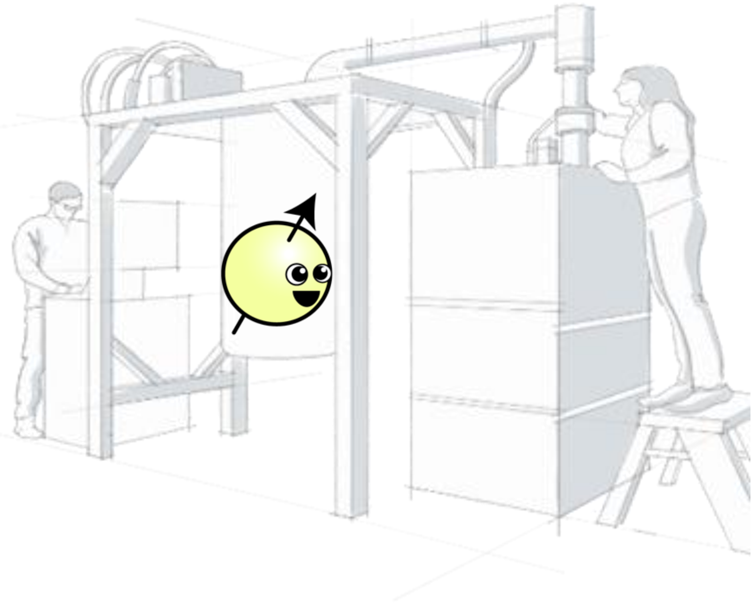


Real & noisy quantum processors: Why study noise?





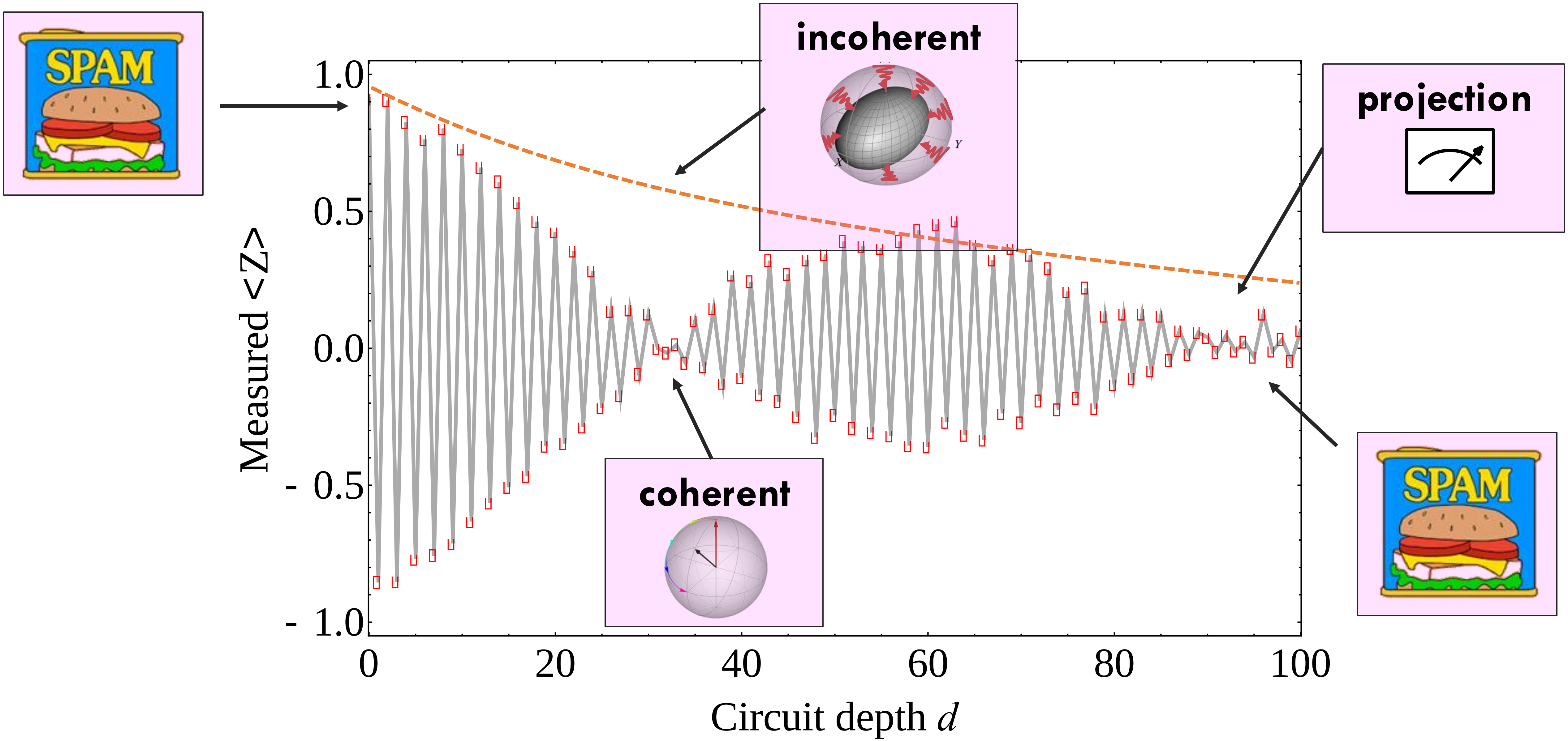
Cartoon: Paul Noth



"Quantum phenomena
do *not* occur in a Hilbert space,
they occur in a laboratory."

Asher Peres

Elements of 😱 noise



How to deal with errors due to noise?

Monitor
Error occurs
Error detect

Quantum error correction

Shor, PRA (1995), ...

Monitor
Error anticipated
Tell signal detected

Catch and reverse

Minev, Nature (2019), ...

No monitor
Error occurs
Error undetected

Error mitigation

... subject of today

Quantum simulation on a noisy quantum computer

Execute on a real quantum computer device and obtain results as classical data

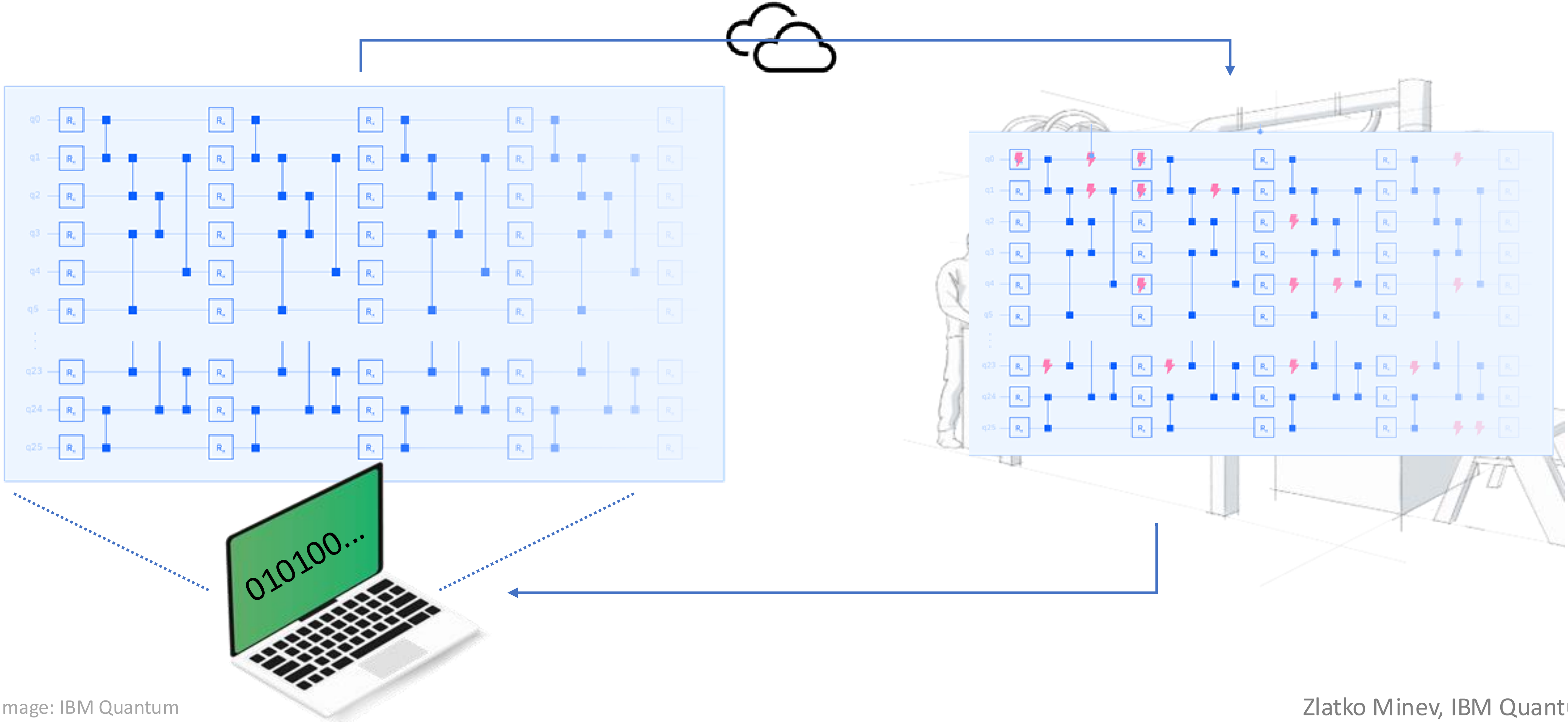


Image: IBM Quantum

Quantum error mitigation overview

Execute on a real quantum computer device and obtain results as classical data

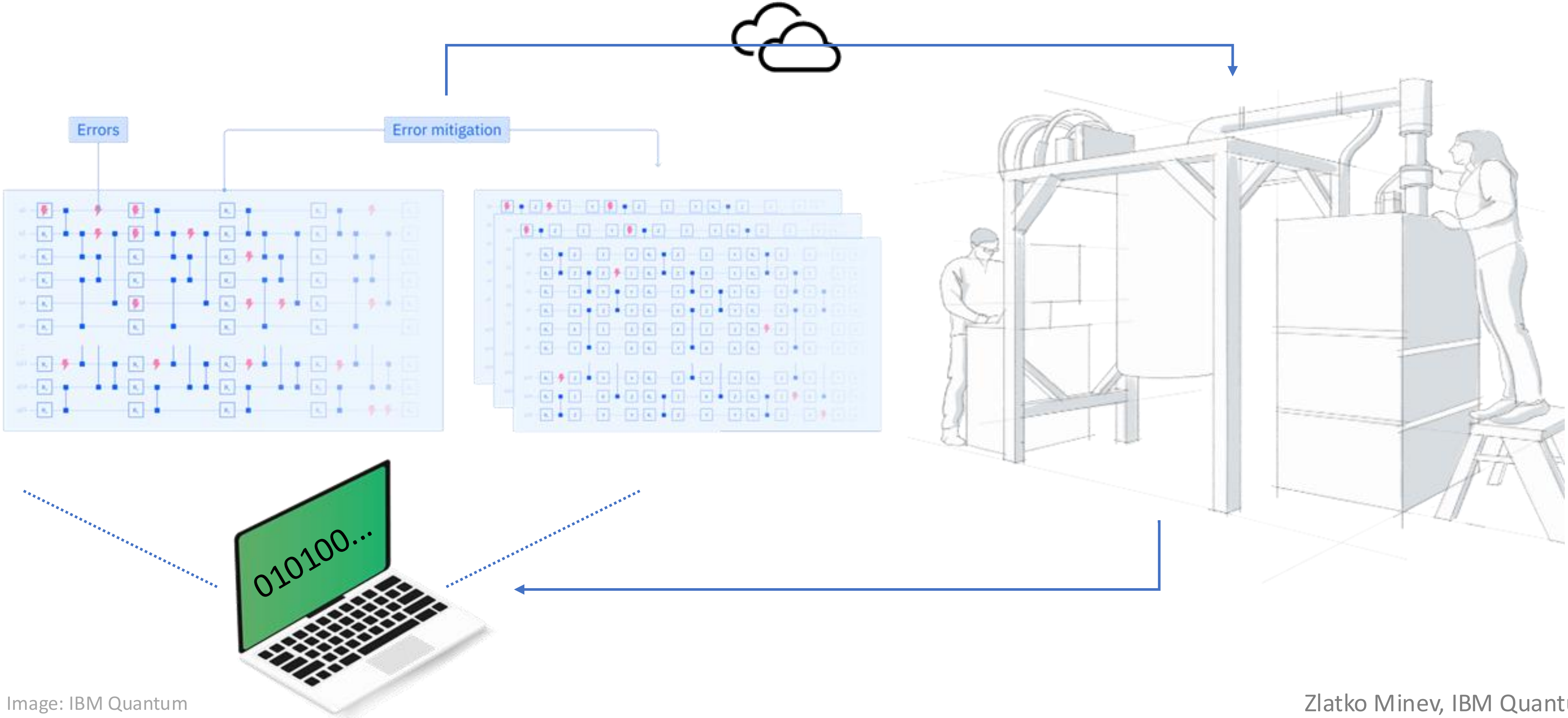
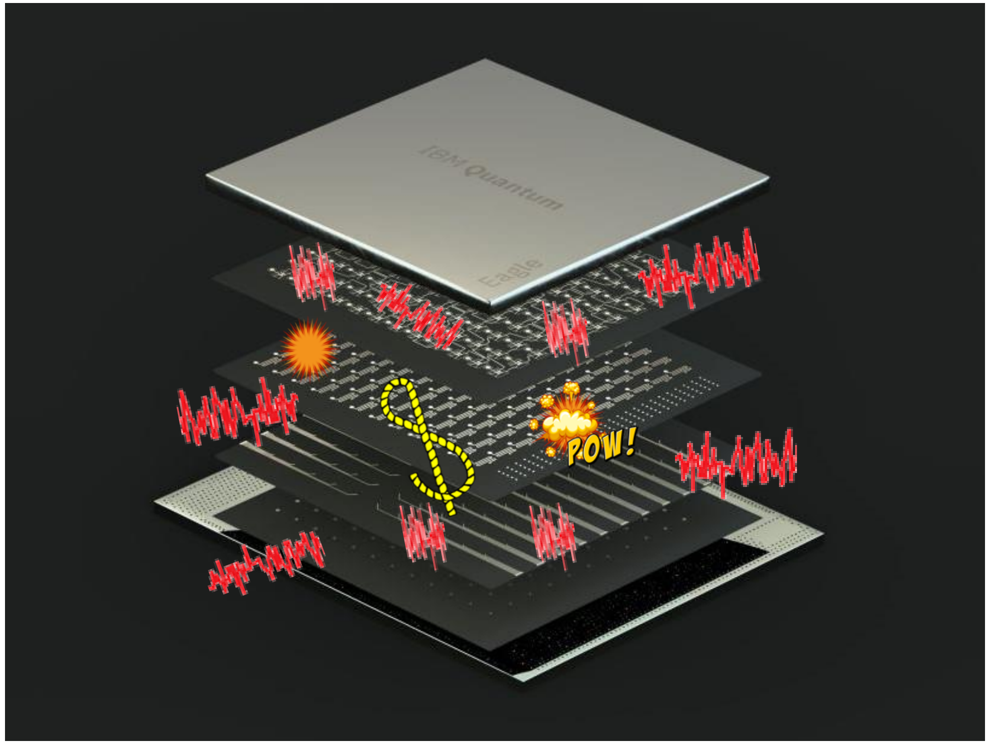


Image: IBM Quantum

Error mitigation and error correction



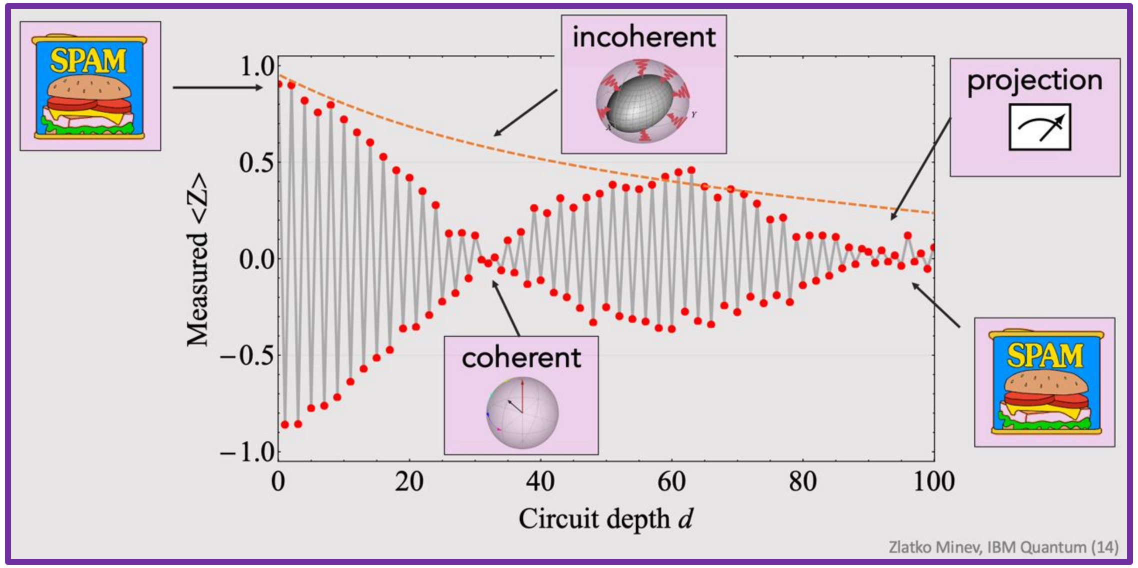
Error mitigation: working with what you have

- **benefit** suppress errors on classical results (expectation values)
- **q-cost** no extra qubits or hardware resources needed
- **c-cost** trades classical resources (post-processing) for lower error
- **limitation** bad asymptotic scaling: high number of samples & circuits

Error correction: protecting quantum information

- **benefit** suppress & correct errors to arbitrarily small level
- **q-cost** very large qubit and hardware overhead
- **c-cost** decoding and encoding can be classically costly
- **challenge** requires fault-tolerant operations and readout

Error mitigation landscape



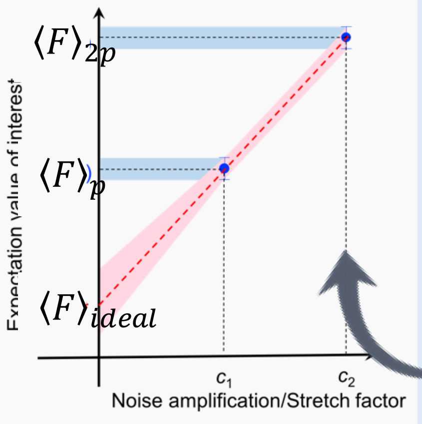
more speed

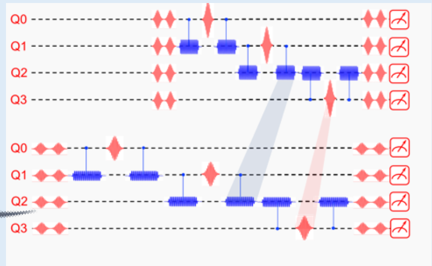
more information, accuracy

Photos courtesy of Y. Liu

Error mitigation landscape

Zero-noise extrapolation (ZNE)

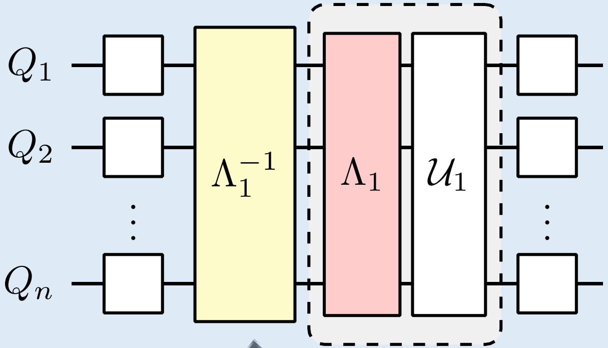


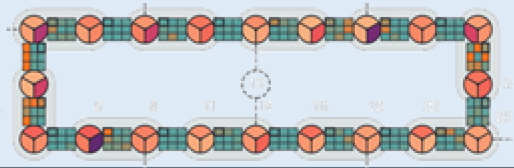


Nature 567, 491 (2019)

…

Probabilistic error cancelation (PEC)



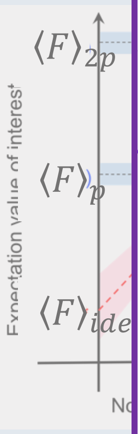


This talk

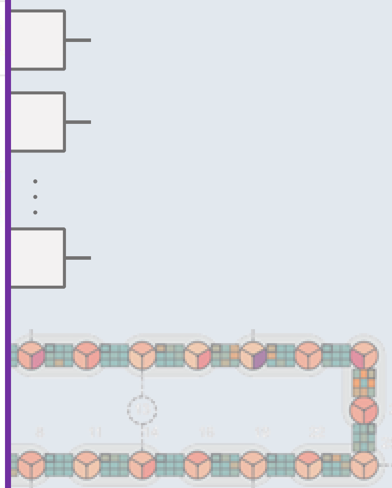
more speed → **more information, accuracy**

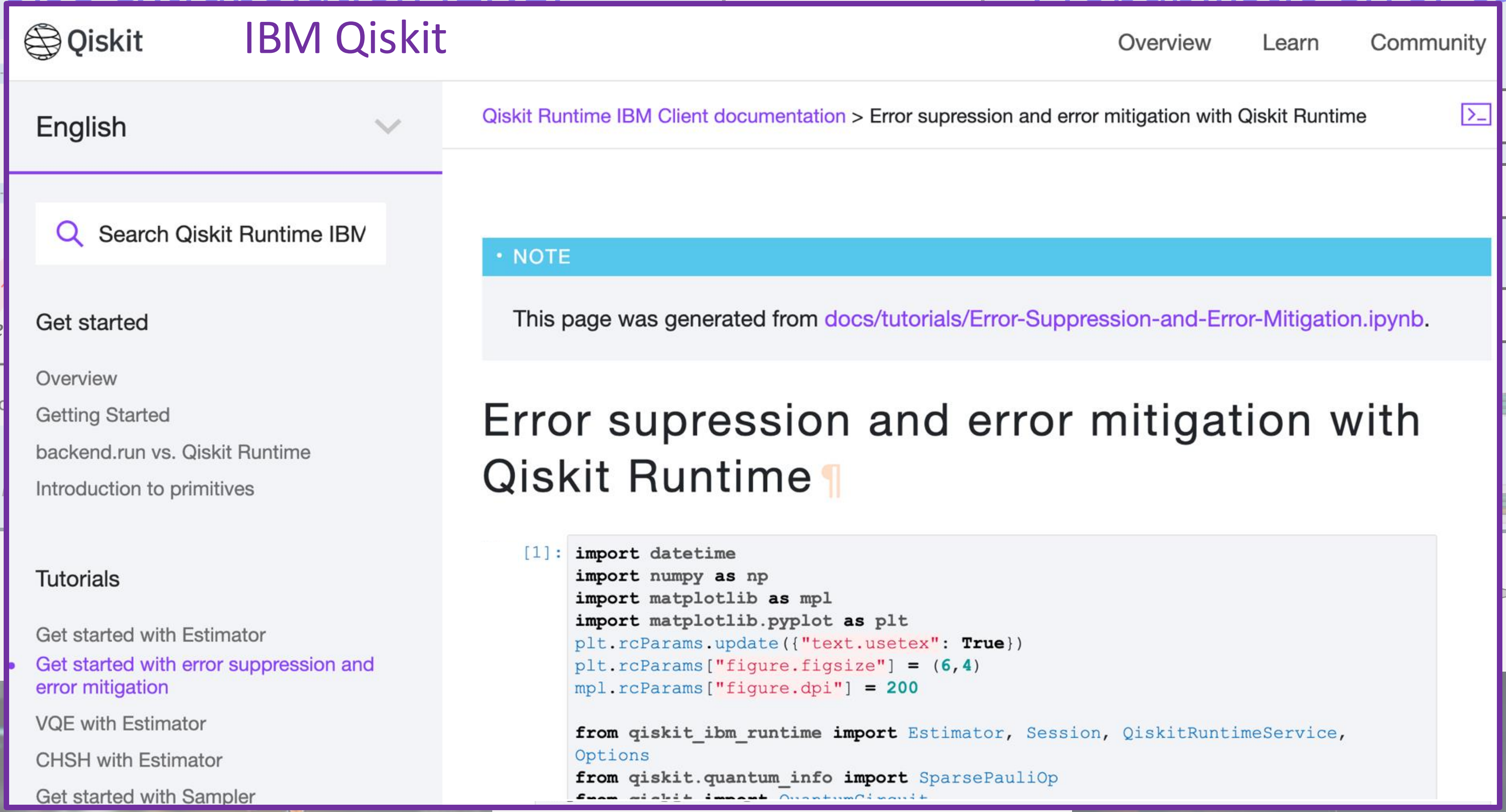
Error mitigation landscape

Zero-noise extrapolation (ZNE)



Probabilistic error cancelation (PEC)

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English

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Get started

Overview
Getting Started
backend.run vs. Qiskit Runtime
Introduction to primitives

Tutorials

Get started with Estimator
Get started with error suppression and error mitigation
VQE with Estimator
CHSH with Estimator
Get started with Sampler

Qiskit Runtime IBM Client documentation > Error supression and error mitigation with Qiskit Runtime

NOTE

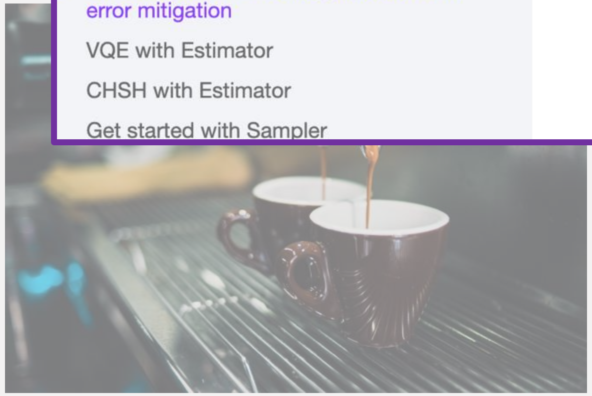
This page was generated from docs/tutorials/Error-Suppression-and-Error-Mitigation.ipynb.

Error supression and error mitigation with Qiskit Runtime

[1]:
```
import datetime
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.rcParams.update({"text.usetex": True})
plt.rcParams["figure.figsize"] = (6,4)
mpl.rcParams["figure.dpi"] = 200

from qiskit_ibm_runtime import Estimator, Session, QiskitRuntimeService,
Options
from qiskit.quantum_info import SparsePauliOp
```

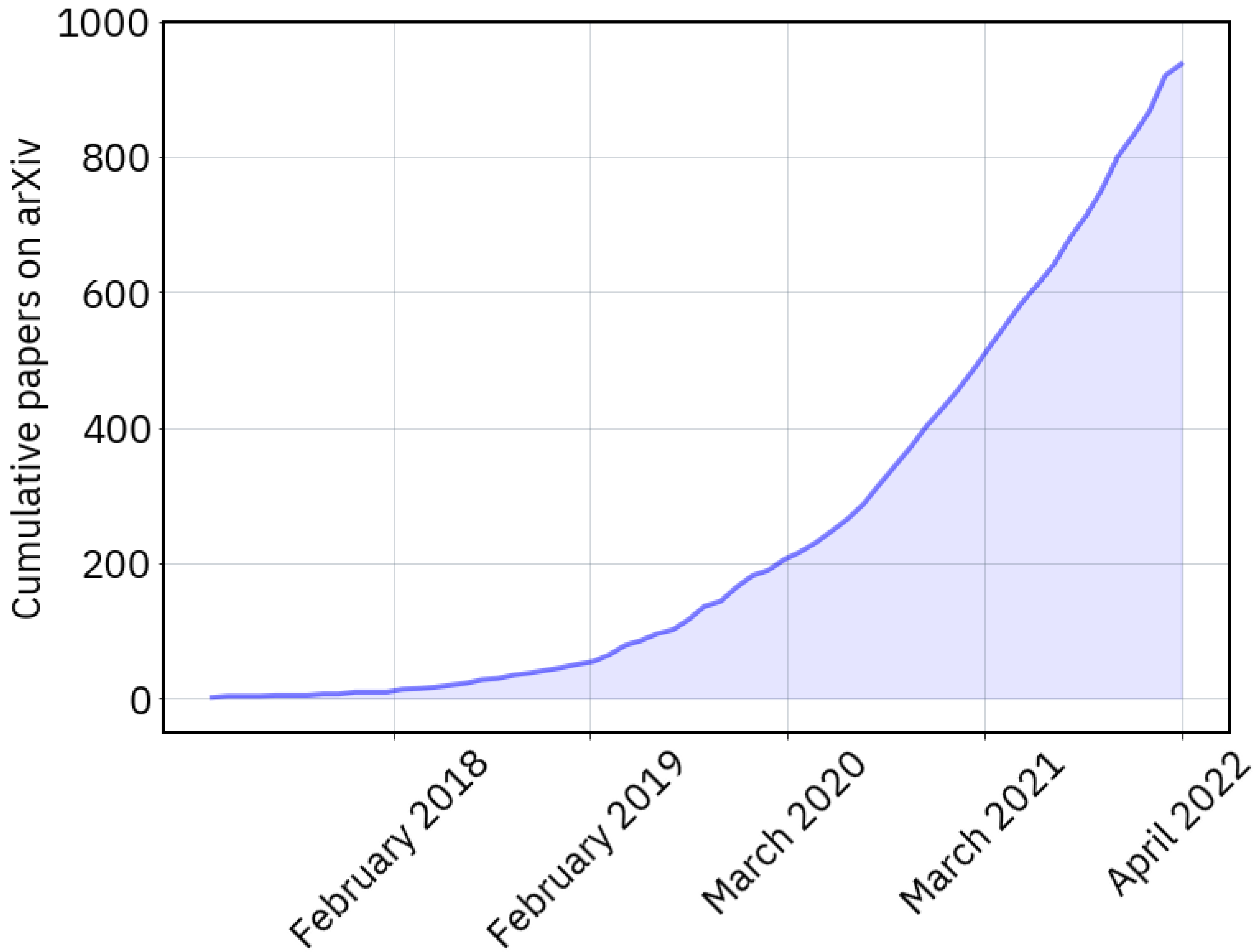
more speed



more information, accuracy

Adoption of error mitigation

Papers involving error mitigation over time



Examples

ARTICLE
https://doi.org/10.1038/s41467-020-14376-z OPEN
Error-mitigated quantum gates exceeding physical fidelities in a trapped-ion system
Shuaining Zhang[1], Yao Lu[1], Kuan Zhang[1,2], Wentao Chen[1], Ying Li[3*], Jing-Ning Zhang[1,4*] & Kihwan Kim[1*]

Matrix product channel: Variation
to mitigate noise and reduce errors
Sergey Filippov,* Boris Sokolov, Ma
Borrelli, Daniel Cavalcanti, Sabrina
Algorithmiq Ltd, Kanavakat

Article | Published: 08 May 2023
Probabilistic error cancellation with sparse Pauli–Lindblad models on noisy quantum processors
Ewout van den Berg, Zlatko K. Minev, Abhinav Kandala & Kristan Temme
Nature Physics (2023) | Cite this article

Quantum Error Mitigation
Zhenyu Cai,[1,2,*] Ryan Babbush,[3]
McClean,[3] and Thomas E. O'Brie
[1] *Department of Materials, Universit*
[2] *Quantum Motion, 9 Sterling Way,*
[3] *Google Quantum AI, Venice, Calif*
[4] *NTT Computer and Data Science*
[5] *Graduate School of China Academ*
(Dated: July 3, 2023)

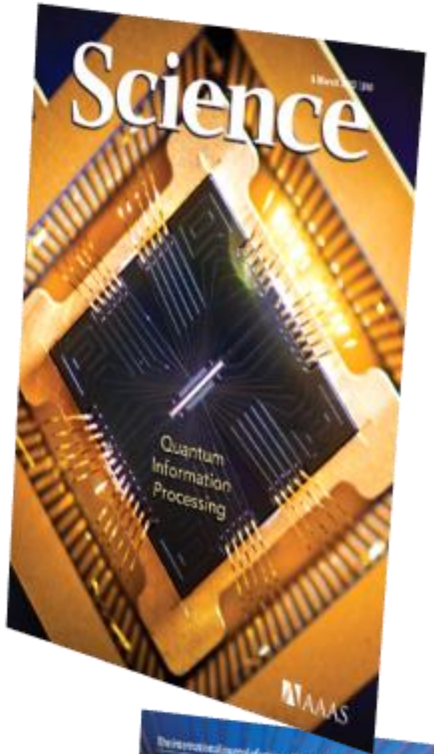
npj | quantum information
ARTICLE OPEN
Fundamental limits of quantum error mitigation
Ryuji Takagi[1], Suguru Endo[2], Shintaro Minagawa[3] and Mile Gu[1,4]

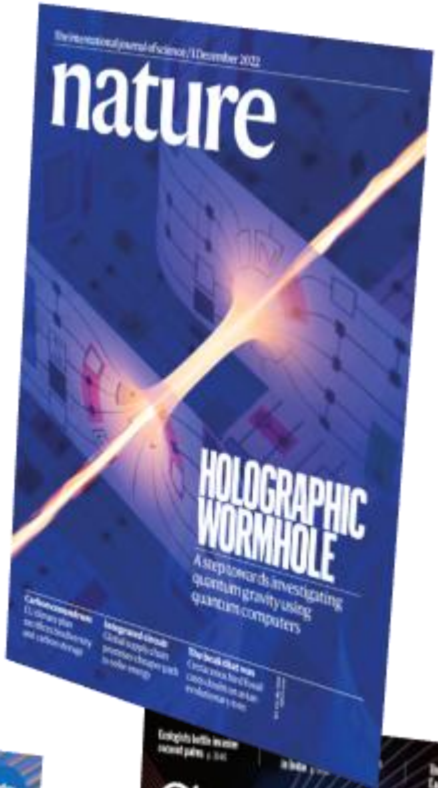
Single-shot error mitiga
Ewout van den Berg, Sergey B
Dmitri Maslo
ntum, IBM T.J. Watson Resea
Dece

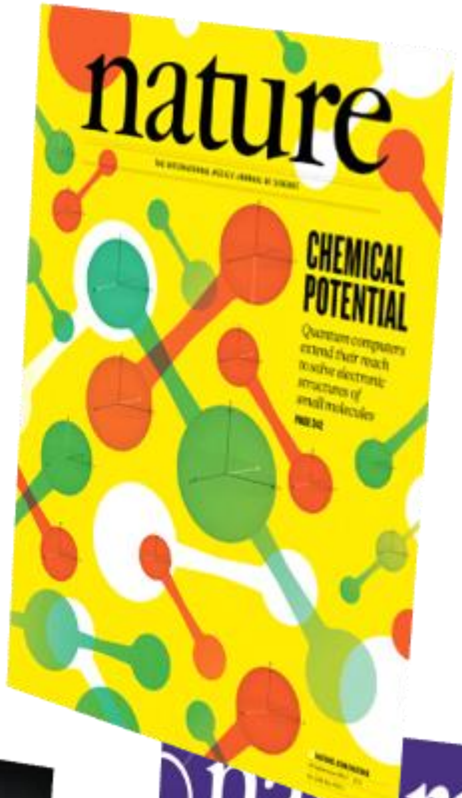
PHYSICAL REVIEW LETTERS **127**, 200505 (2021)
Error Mitigation for Universal Gates on Encoded Qubits
Christophe Piveteau
IBM Quantum, IBM Research—Zurich, 8803 Rüschlikon, Switzerland

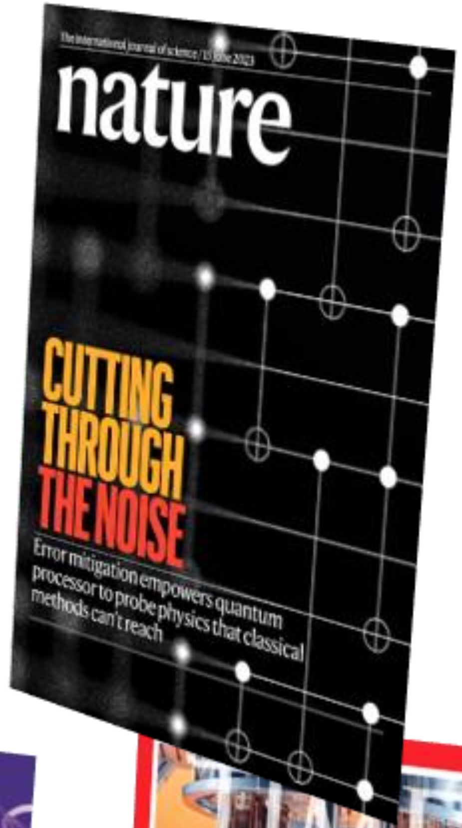
Model-free readout-error mitigation for quantum expectation values
Ewout van den Berg, Zlatko K. Minev, and Kristan Temme
Phys. Rev. A **105**, 032620 – Published 30 March 2022

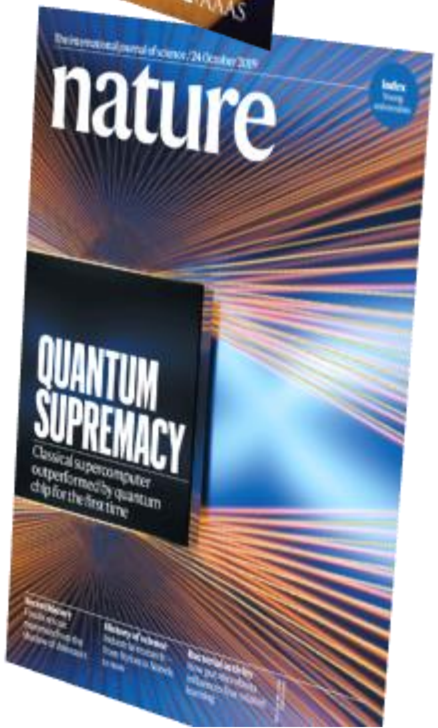
Is science with noisy devices of broad interest today?











Some of these ideas covered in other lectures at the school

Deep dive:

Probabilistic error cancellation (PEC)

To learn and cancel quantum noise

Got Slides?

SCAN ME

Ewout van den Berg, Zlatko K. Minev, Abhinav Kandala, Kristan Temme

Nature Physics (2023)

Cancel quantum noise

Icon: Flaticon

High-level message

Learn

accurate, efficient, scalable

Cancel

noise with noise, practical

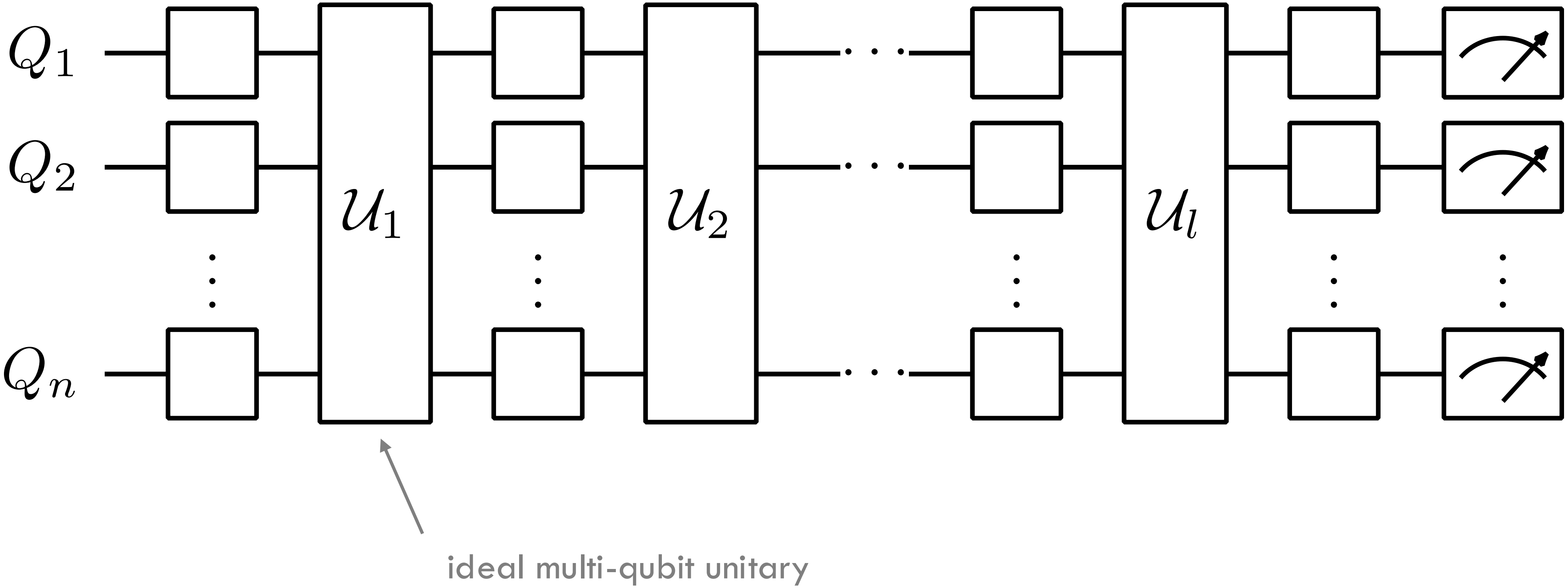
Cost

more noise more cost

Idea

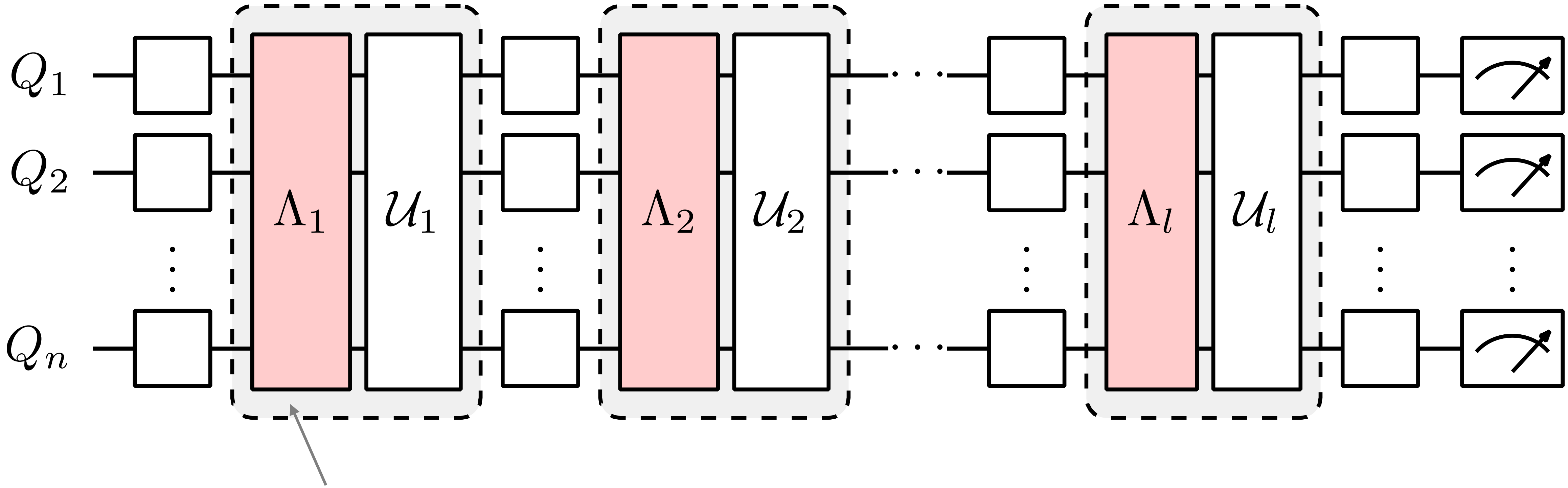
Icon: Flaticon

Ideal (noise-free) quantum circuit



A circuit can be decomposed into a layer construction
Example: Trotterization of Ising model simulation

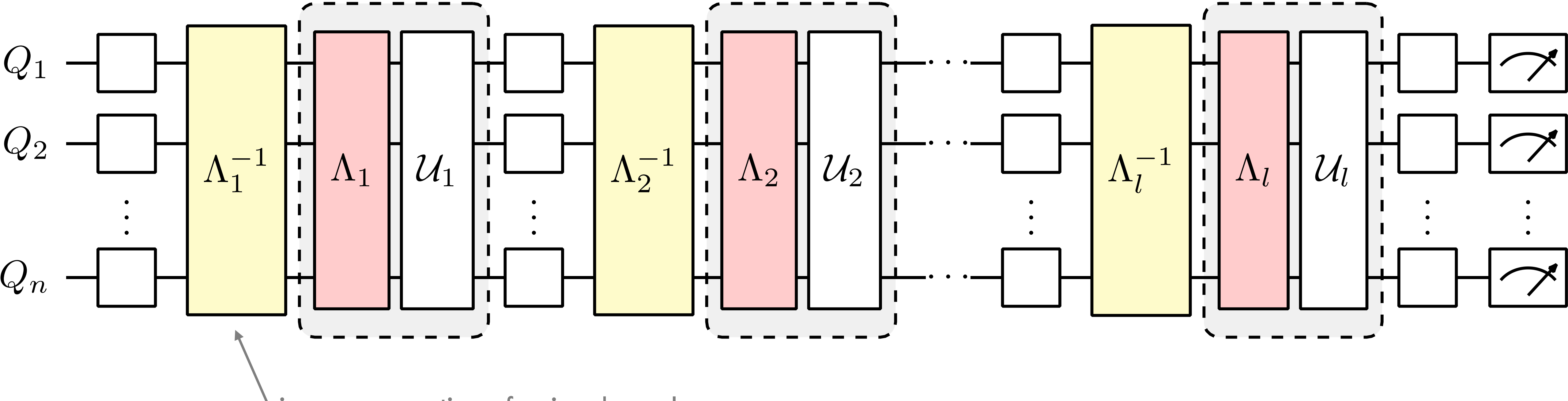
Real (noisy) quantum circuit



multi-qubit noise channel
inseparable from gate

completely positive and trace preserving (CPTP)
representable by a 4^n x 4^n matrix

Why not invert noise?



inverse operation of noise channel

unphysical

would need to know lost information due to noise

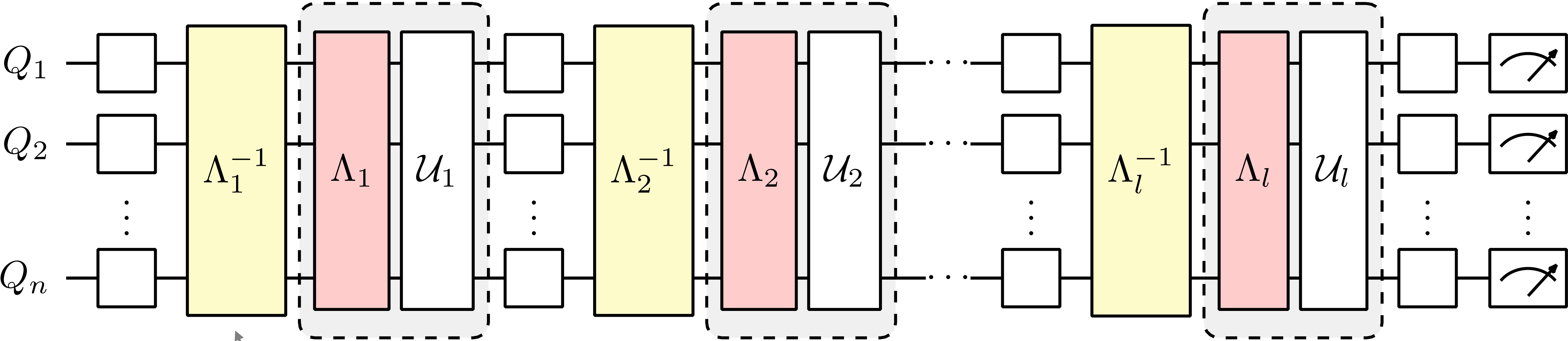
non CPTP map

has negative eigenvalues

…

Not possible?

Probabilistic error cancelation

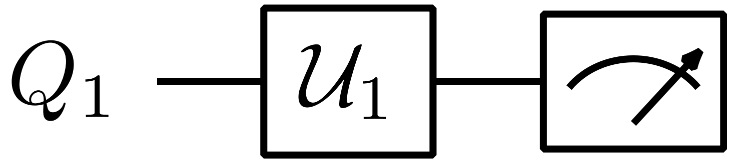


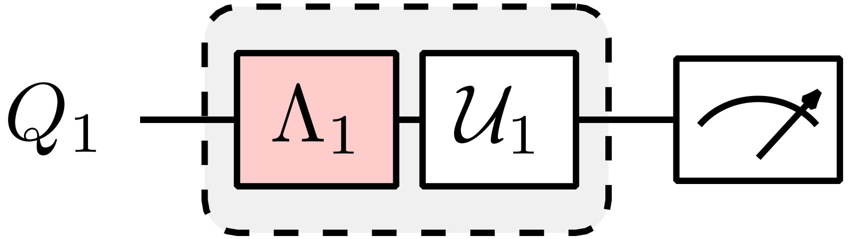
inverse operation of noise channel
implement on average

K. Temme, S. Bravyi, and J. M. Gambetta
PRL 119, 180509 (2017)

See also S. Endo, S. Benjamin, and Y. Li
Phys. Rev. X 8, 031027 (2018)

Toy model





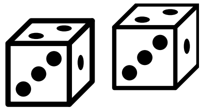
Toy model: noise unraveling into quantum trajectories

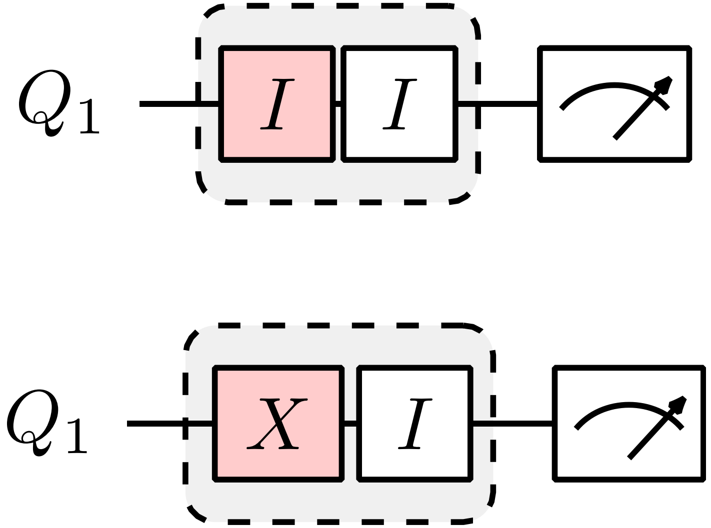
bit-flip noise

=

unraveling
(quantum trajectories)

probability 1-*p*



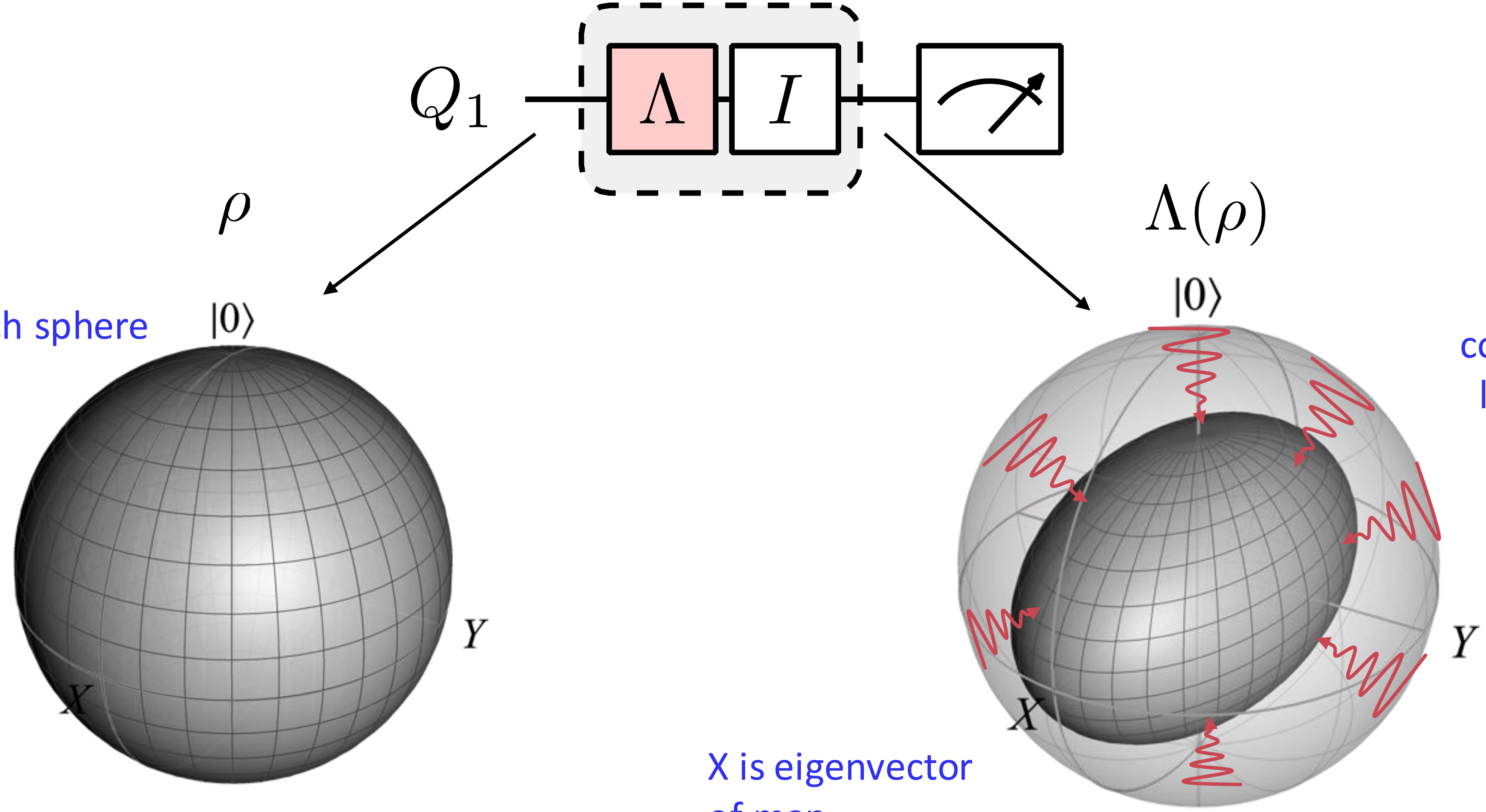


probability *p*

$$\Lambda(\rho) = (1-p)I\rho I + pX\rho X$$

Toy model: noise unraveling into quantum trajectories

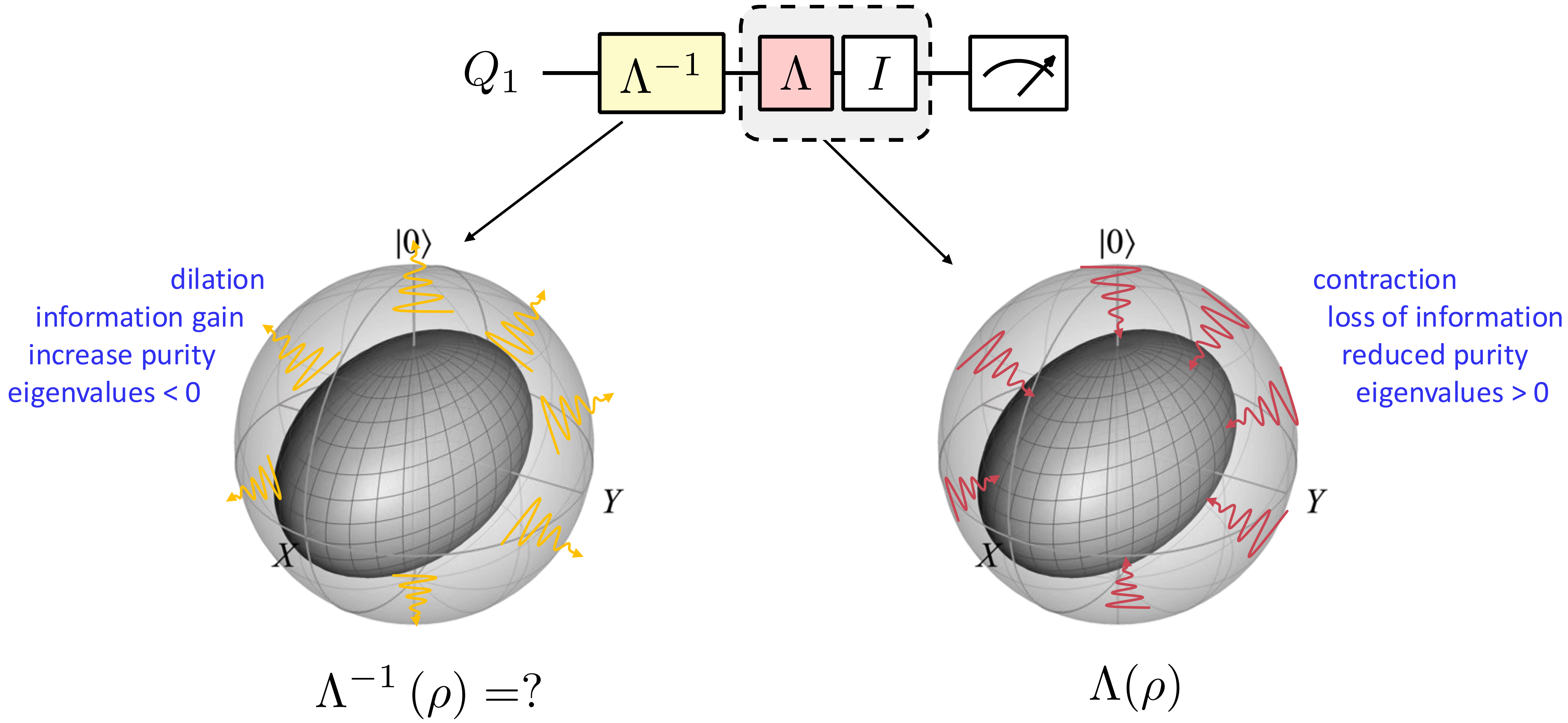
Bloch sphere



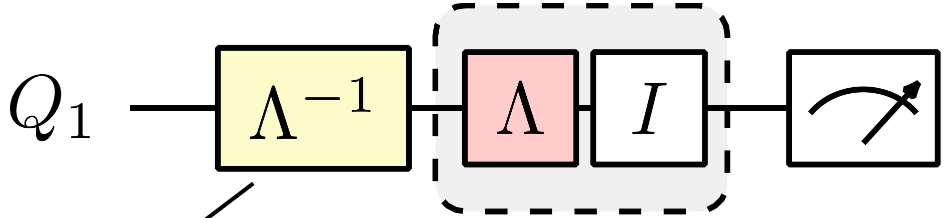
contraction
loss of information
reduced purity
eigenvalues > 0

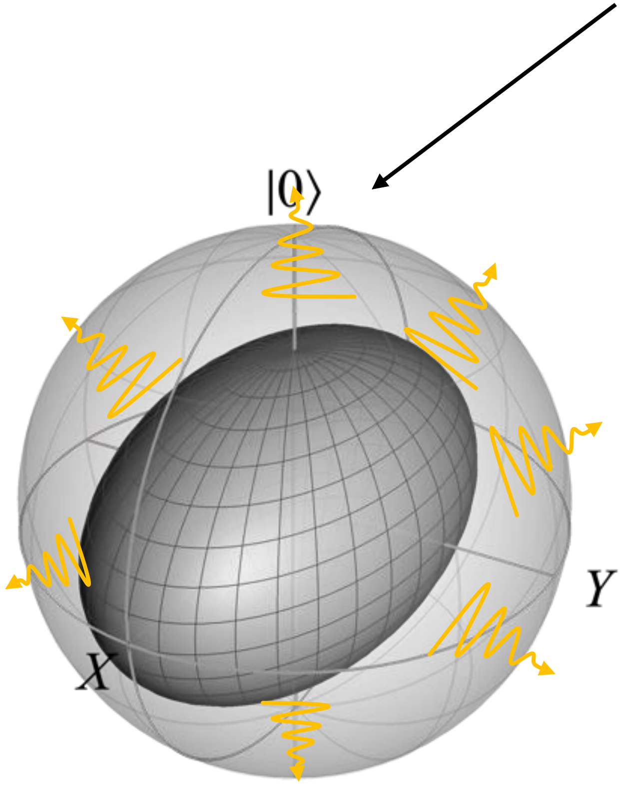
X is eigenvector
of map

Inverse of noise map is not physical

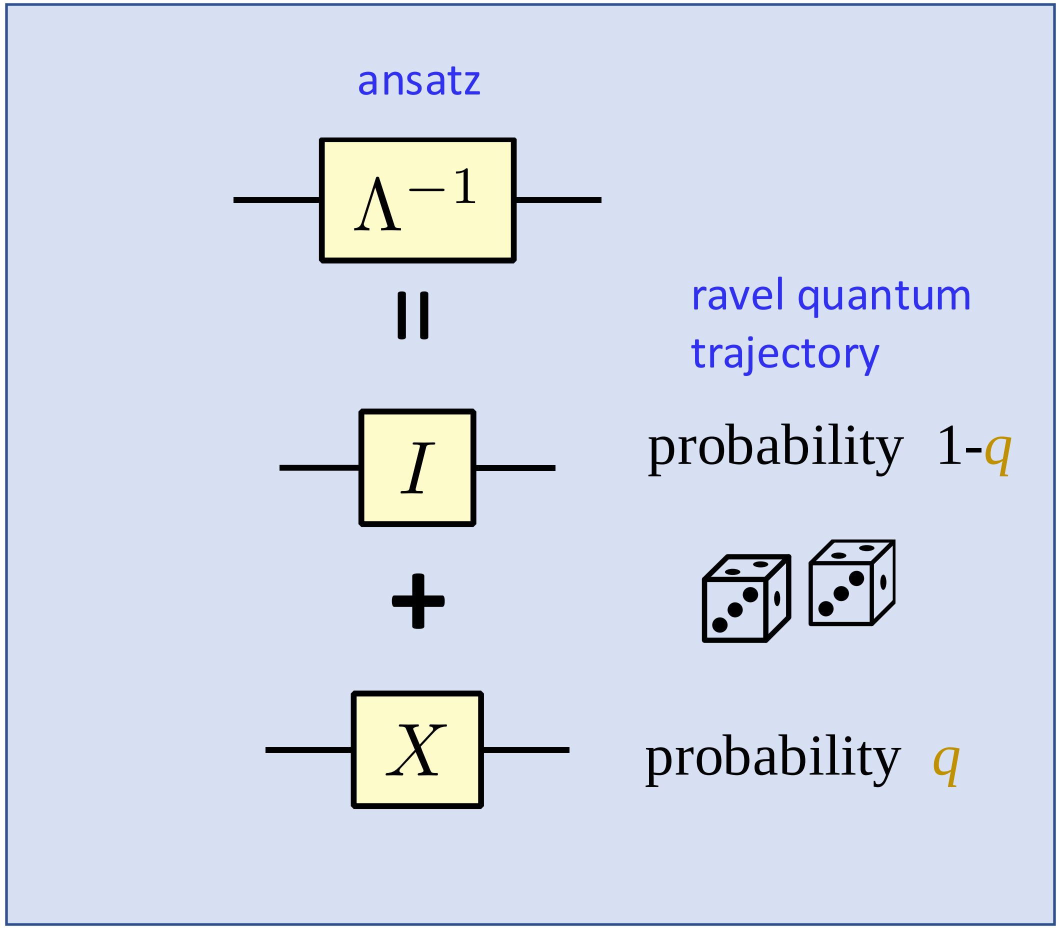


Inverse of noise map is not physical





$$\Lambda^{-1}(\rho) = ?$$

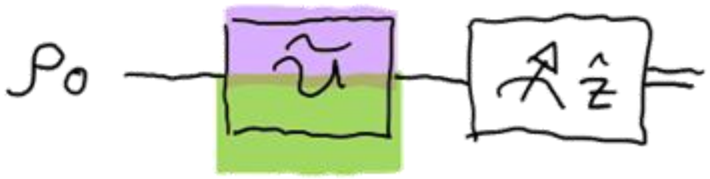


Blackboard derivation

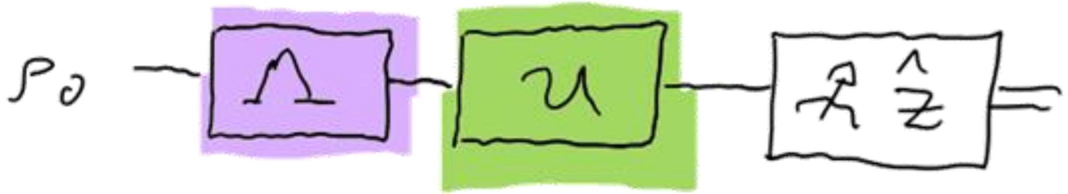
Setup

Details on notation:

Quantum register alphabet $\Sigma = \{0,1\}$
Hilbert space $\mathcal{H} = \mathbb{C}^{\Sigma}$
Initial state $\rho_0 \in D(\mathcal{H}) \subset L(\mathcal{H})$
Ideal unitary $U \in U(\mathcal{H}) \subset L(\mathcal{H})$
Ideal u-channel $\mathcal{U}(\rho) = U \rho U^{\dagger}$
$\mathcal{U} \in C(\mathcal{H}) \subset L(L(\mathcal{H}))$



Noisy gate/circuit $\tilde{\mathcal{U}} \in L(L(\mathcal{H}))$



Decompose noisy gate $\tilde{\mathcal{U}} = \mathcal{U}\Lambda$

Blackboard derivation

Simple Example

Keeping it simple and illustrative, let's do a simple case

Let $U = I$

$\mathcal{U} \cdot = I \cdot I$

For the noise, let's play with the simplest bit-flip channel

$$n(\rho) = \underbrace{(1-p)}_{\text{prob of no error}} I \rho I + \underbrace{p}_{\text{prob of a bit flip error}} X \rho X$$

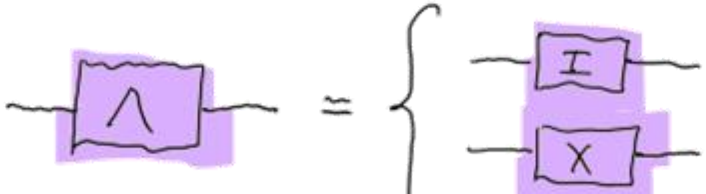
$$\Lambda_\rho = (1-p)\mathcal{I}_\rho + p\,\mathcal{X}_\rho$$

Equivalent superoperator channel representation

$$\mathcal{X}_\rho = X \rho X$$

$$\mathcal{I}_\rho = I \rho I = \rho$$

Equivalent trajectory unraveling



: Prob $1-p$

: Prob p

Blackboard derivation

Simple Example

Keeping it simple and illustrative, let's do a simple case

Let $U = I$

$\mathcal{U} = I \cdot I$

For the noise, let's play with the simplest bit-flip channel

$$\Lambda(\rho) = \underbrace{(1-p)}_{\text{prob of no error}} I \rho I + \underbrace{p}_{\text{prob of a bit flip error}} X \rho X$$

$$\Lambda_p = (1-p)\mathcal{I}_p + p\mathcal{X}_p$$

Equivalent superoperator channel representation

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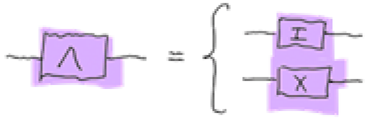
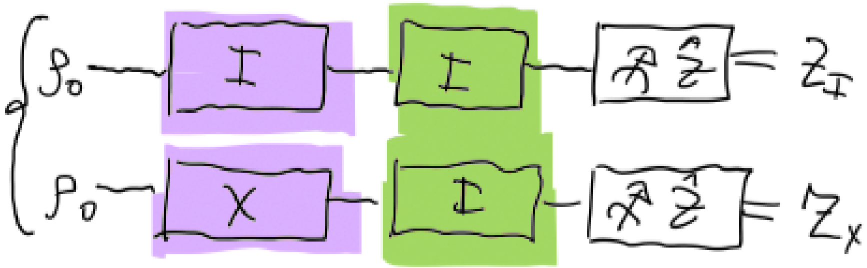
Equivalent trajectory unraveling



: Prob $1-p$

: Prob p

Our circuit then is equivalent to either



with prob $1-p$

with prob p

The ideal expectation value is

$$Z_{\text{ideal}} = \langle \hat{Z} \rangle = \mathrm{Tr}(Z \mathcal{I} \rho_0) = \mathrm{Tr}(Z \rho_0) = \rho_Z$$

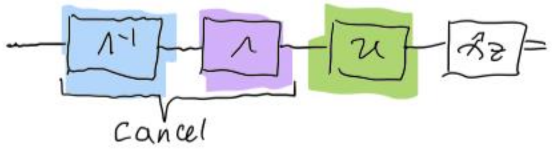
When the channel introduces an error however,

$$\mathbb{E}[Z_X] = \mathrm{Tr}(Z X \rho X) = \mathrm{Tr}(X Z X \rho) = \mathrm{Tr}(-Z \rho) = -\rho_Z$$

Blackboard derivation

Noise Inverse

To undo the noise, we'd like to introduce the inverse noise



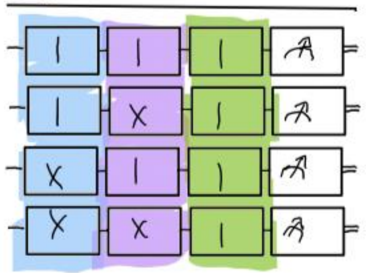
$$\Lambda^{-1}\Lambda = \Lambda\Lambda^{-1} = I$$

Taking the ansatz $\Lambda^{-1}(p) = (1-r)\, I \cdot I + r (X \cdot X)$

we see 4 cases of unraveling

inverse	noise	no error	prob
I	I	✓	$(1-r)(1-p)$
I	X	x	$(1-r)p$
X	I	x	$r(1-p)$
X	X	✓	rp

Circuit



ideally, we what to interfere trajectories so that the no-error on will coherently add to unity probably, and the ones with an error will cancel.

$\therefore$ (A) $(1-r)(1-p) + r \cdot p = 1$ $\wedge$ (B) $(1-r)p + r(1-p) = 0$

$1 - r - p + 2rp = 1$ $\quad$ $p + r - 2rp = 0$

$r + p - 2rp = 0$ $\quad$ same condition

$\Rightarrow \quad r(1-2p) = -p$

$\therefore \quad \boxed{r = \dfrac{-p}{1-2p}}$

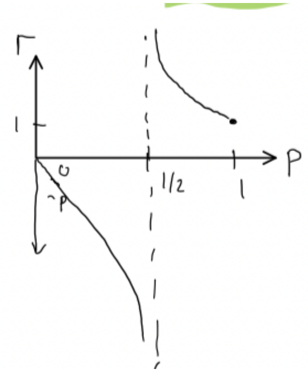
Recall p is a probability $0 \le p \le 1$,

$p = 0 \Rightarrow r = 0$ no noise, no need to do anything

$p = 1 \Rightarrow r = 1$ deterministic bit-flip, requires deterministic bit flip as well for Λ^{-1}

$p = 1/2 \Rightarrow r = \infty$ singular value, since at $p = 1/2$, we fully scramble the state

$p \ll 1 \Rightarrow r \simeq -p$



Blackboard derivation

Note that we could equivalently have used the algebraic condition and solved for r

$$\Lambda\left(\Lambda^{-1}(\rho)\right) = \mathcal{I}(\rho) = \rho \qquad \text{solve for } r$$

$$= \Lambda\left[(1-r)\rho + r X \rho X\right]$$

$$= \underbrace{(1-p)(1-r)\rho + p r \cancel{XX}\rho \cancel{XX}}_{} + \underbrace{(1-p) r X\rho X + (1-r) p X\rho X}_{}$$

no error $\qquad\qquad$ error

$$= \overbrace{\left[(1-p)(1-r) + pr\right]}^{}\rho + \overbrace{\left[(1-p)r + (1-r)p\right]}^{} X\rho X$$

same conditions as above! solution $\quad r = \frac{-p}{1-2p}$

Blackboard derivation

How to implement? Quasi-Probability

$$\Lambda^{-1} = (1-r) I \rho I + r X \rho X \qquad r = \frac{-p}{1-2p}$$

$$= \left[\frac{|1-r|}{|1-r| + |r|} \mathrm{sgn}(1-r) I \rho I + \frac{|r|}{|1-r|+|r|} \mathrm{sgn}(r) X \rho X \right] (|1-r| + |r|)$$

$$= \gamma \left[s_I p_I I \rho I + s_X p_X X \rho X \right]$$

with

$$\gamma = |1-r| + |r|$$

$$p_I = \frac{|1-r|}{\gamma} \qquad s_I = \mathrm{sgn}(1-r)$$

$$p_X = \frac{|r|}{\gamma} \qquad s_X = \mathrm{sgn}(r)$$

valid prob distribution

$$0 \le p_I, p_X \le 1 \quad \text{and} \quad |p_I| + |p_X| = 1$$

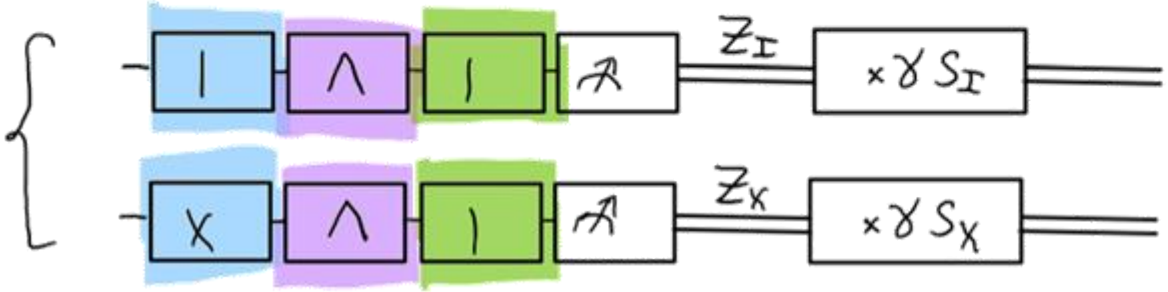
Blackboard

How to sample?

$$\langle Z \rangle = \mathrm{Tr}(Z \tilde{I} \Lambda \Lambda^{-1} \rho_0)$$
$$= \mathrm{Tr}(Z \tilde{I} [\gamma s_I p_I \rho_0 + \gamma s_X p_X X \rho_0 X])$$
$$= \gamma s_I p_I \mathrm{Tr}(Z \tilde{I} \rho_0) + \gamma s_X p_X \mathrm{Tr}(Z \tilde{I} X \rho_0 X)$$
$$= \gamma [s_I p_I \underbrace{\langle Z \rangle_I} + s_X p_X \underbrace{\langle Z \rangle_X}]$$

quantum circuit exp. val we can find

Equivallent interportation : sample prob



$\gamma s_I Z_I$: p_I

$\gamma s_X Z_X$: p_X

Blackboard

Estimator $\quad E_{mitg} = \gamma s_I Z_I + \gamma s_X Z_X$

$$\mathbb{E}[E_{mitg}] = \langle \hat{Z} \rangle_{ideal}$$

$$\mathbb{V}[E_{mitg}] = \mathbb{V}[\gamma s_I Z_I] + \mathbb{V}[\gamma s_X Z_X]$$

$$= \gamma^2 \mathbb{V}[Z_I] + \gamma^2 \mathbb{V}[Z_X]$$

$$= \gamma^2 (2 \sigma_{ideal}^2)$$

$$\sigma_{ideal}^2 = \mathbb{V}[Z_I] = 4q(1-q)$$

$$q = 1 - 2p_Z = \langle \tfrac{1-\hat{Z}}{2} \rangle$$

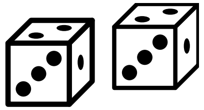
Since the X just flip $Z \to -Z$ of ρ, it follows that the variance is the same, since symmetric

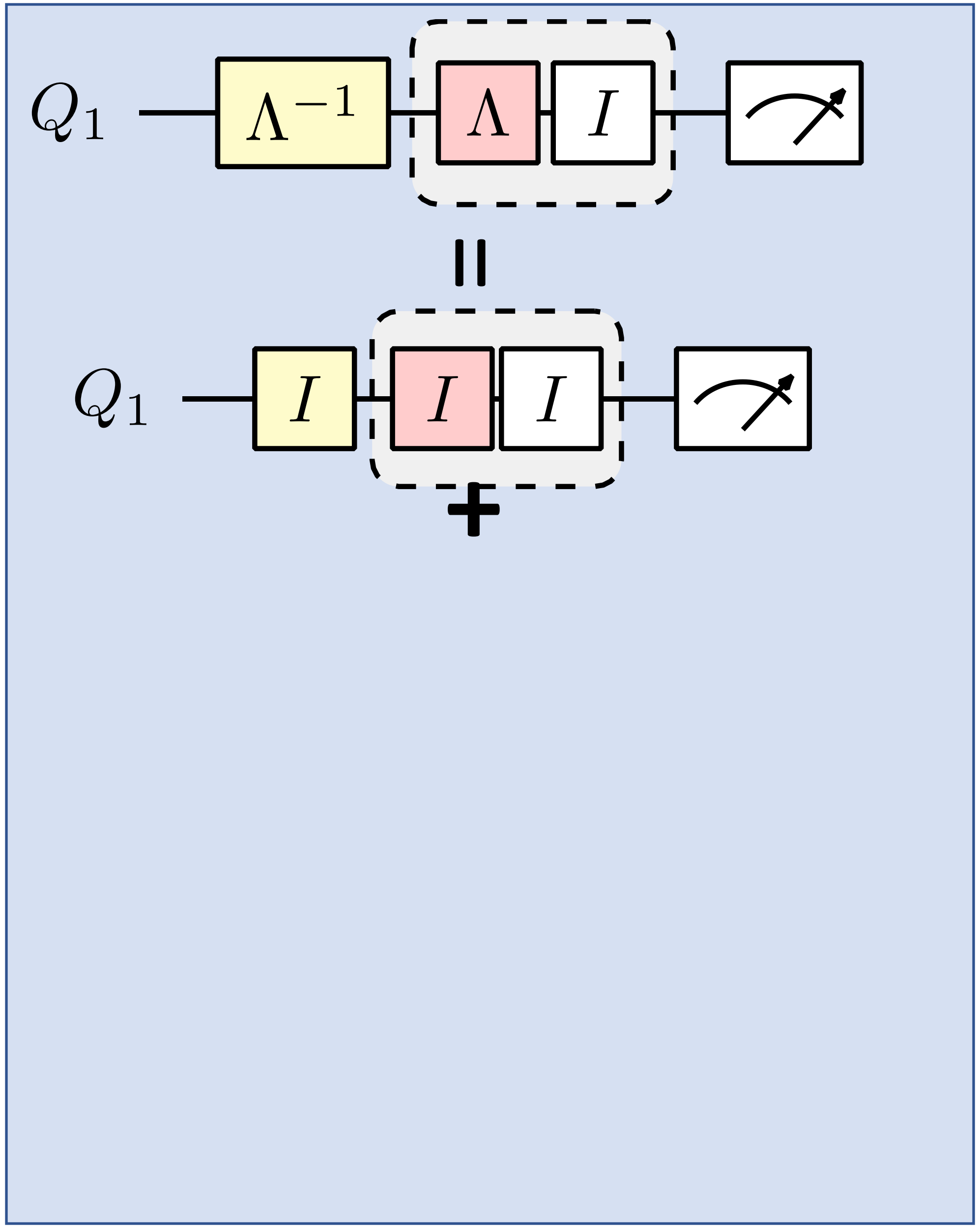
Raveling quantum trajectories to undo noise

No error

probability

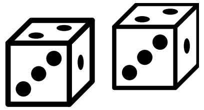
(1-q) (1-p)

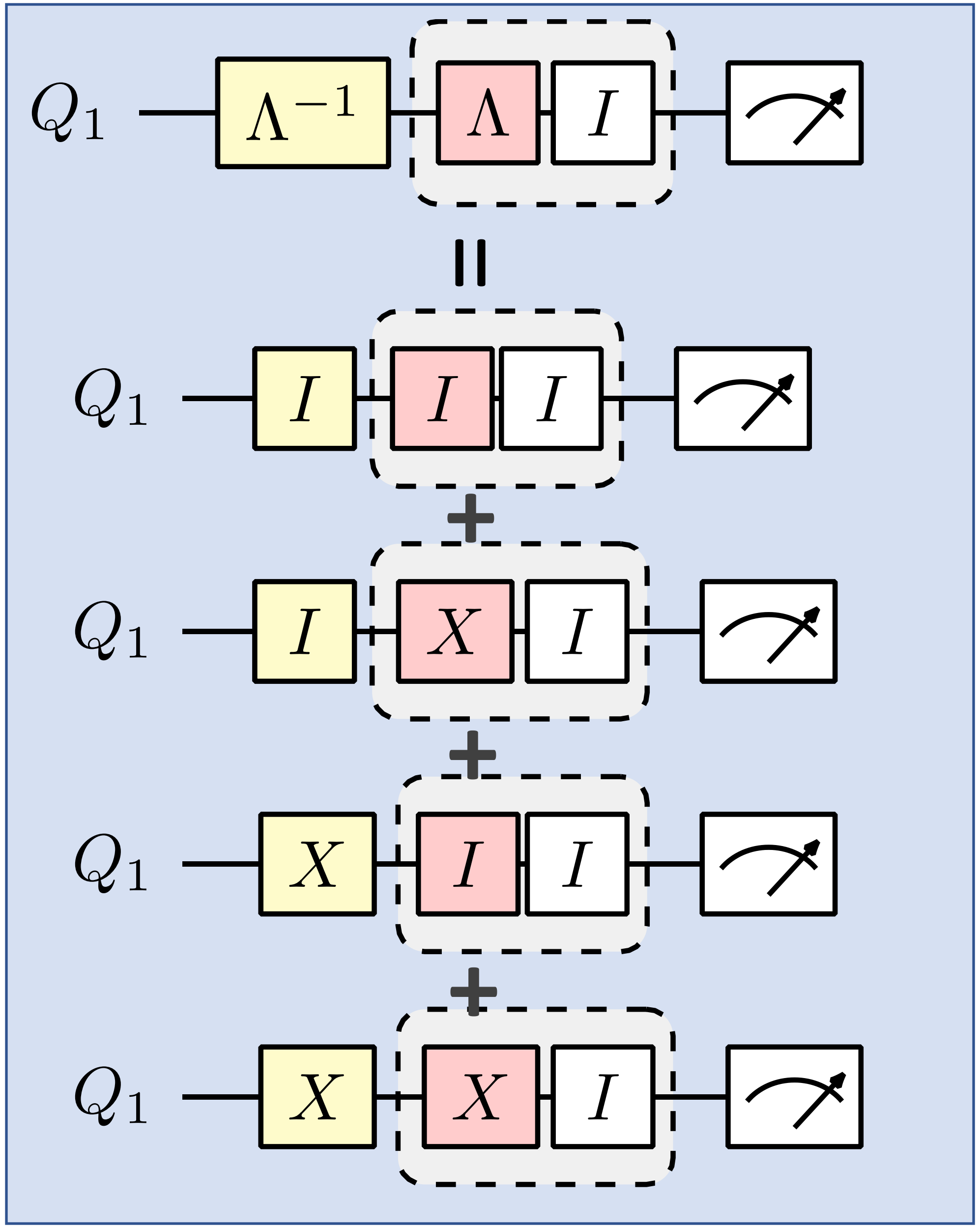




Raveling quantum trajectories to undo noise

	probability
No error	$(1\text{-}q)\ (1\text{-}p)$
ERROR!	$(1\text{-}q)\ p$
ERROR!	$q\ (1\text{-}p)$
Error CANCELED!	$q\ p$

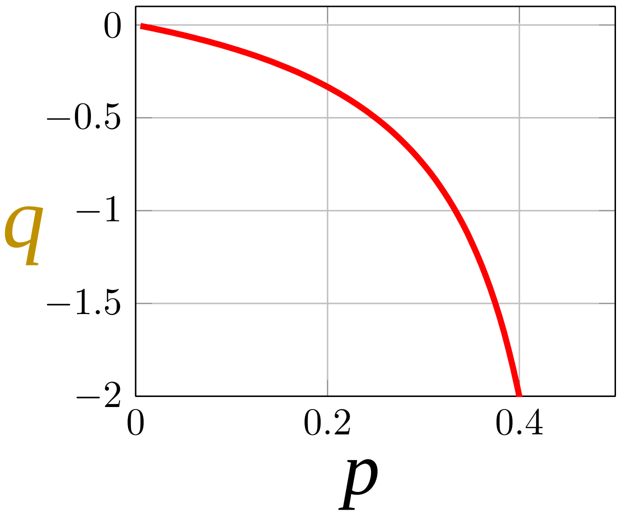




Solution to noise free!

$$q = \frac{-p}{1-2p}$$

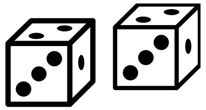
Sign & scale:
quasi-probability



How to implement?

probability

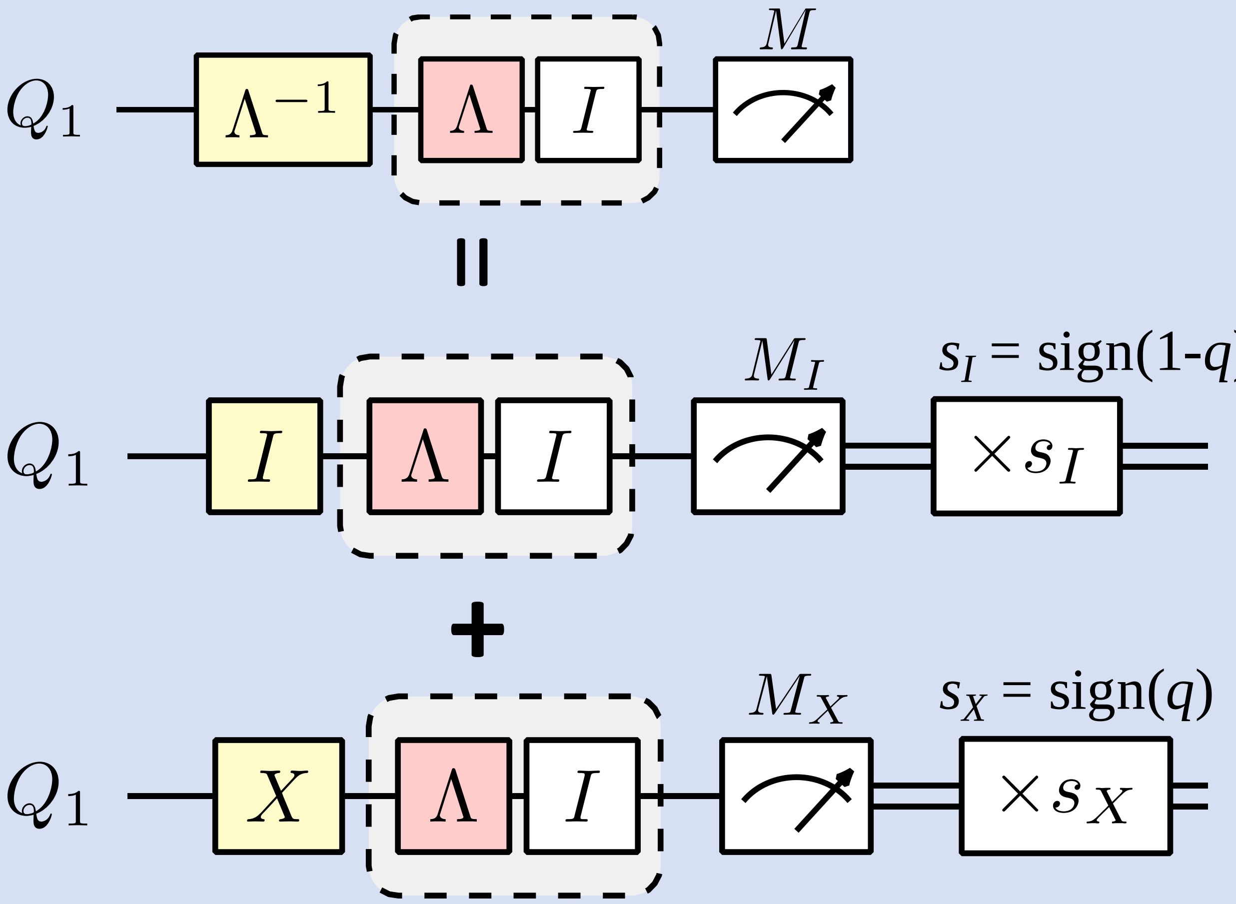
$P_I = |1\text{-}q|/\gamma$



$P_X = |q|/\gamma$

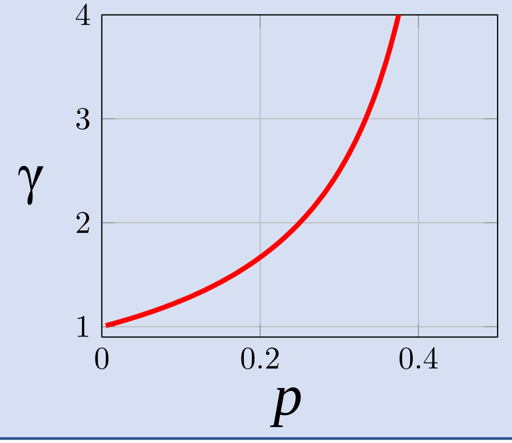
$P_I + P_X = 1$

random circuits
(quantum trajectories)



sampling overhead

$\gamma = |1\text{-}q| + |q|$



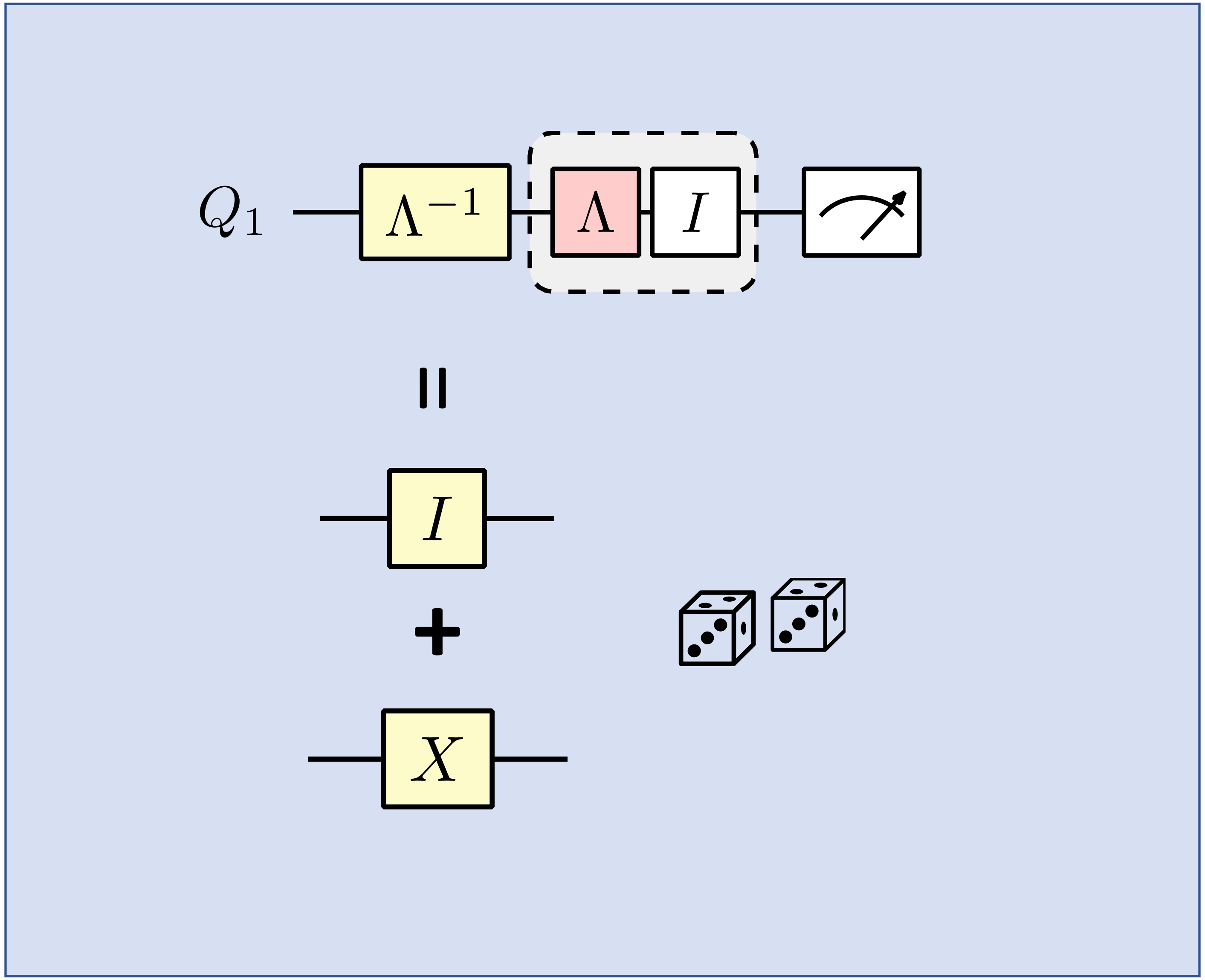
mitigated expectation

$$\langle M \rangle = \gamma\big(s_I P_I M_I + s_X P_X M_X\big)$$

Gain: Bias-free estimate!

Cost: Variance

Canceling noise with noise



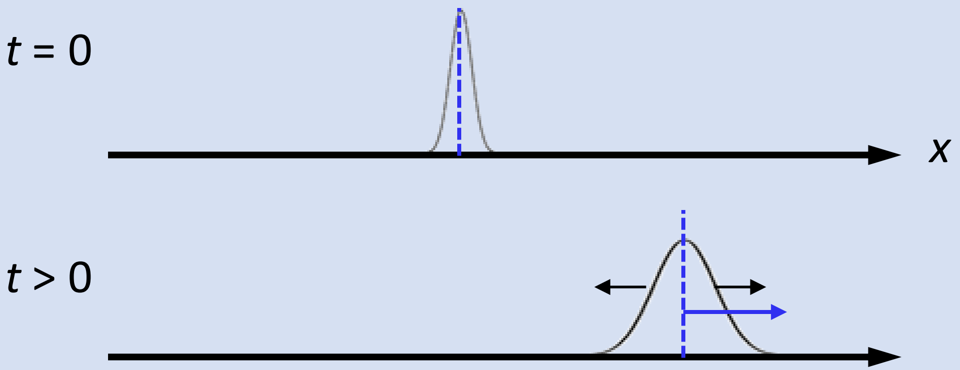
Canceling noise with noise: Drunkard's classical random walk analogy

Random step

P(1 step left) = ½-p

P(1 step right) = ½+p

Distribution of random walk



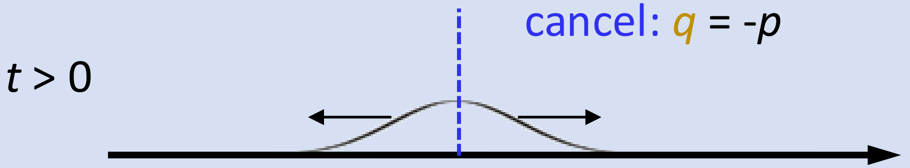
add 2nd random process
wind blows

P(1 step left) = ½+q

P(1 step right) = ½-q

Distribution of random walk with wind

cancel: q = $-p$



Gain: Bias-free estimate!

Cost: Variance

Image: A. Brand

Quantum Noise and Error Mitigation

Lecture 1

Big picture

Quantum computers status

Why error mitigation?
- Noise in quantum computers
- Overview of error mitigation

Mitigation fundamentals

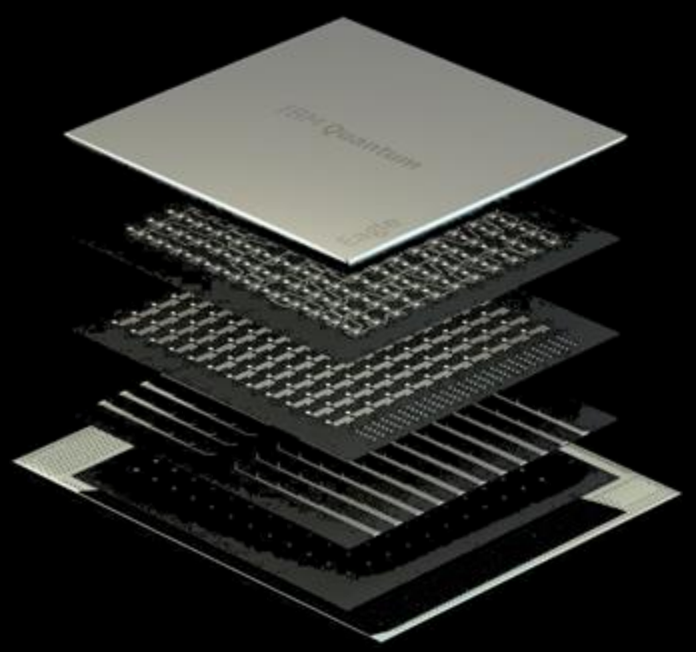
Probabilistic error cancelation (PEC)
- Introduction
- One qubit example

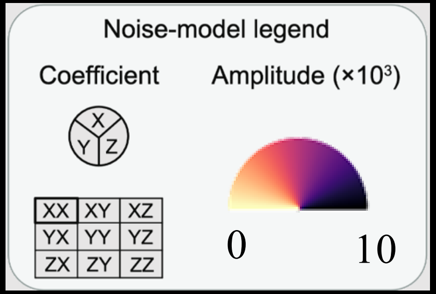
Next lecture

- Learning noise
- State-of-art mitigation experiments
- Hardware
- Outlook

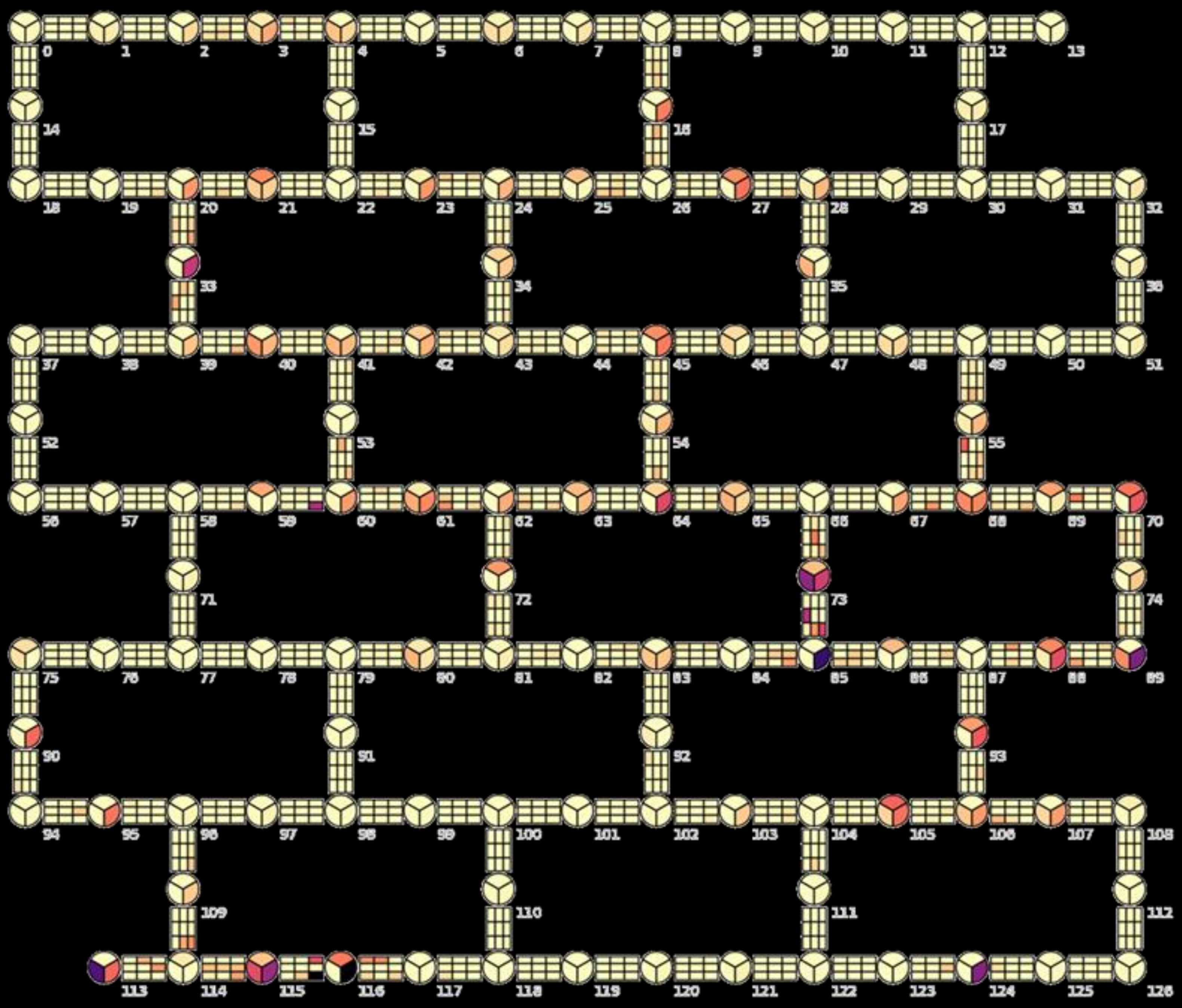
road based on: freepik; Monster image by jcomp on Freepik

Noise tomogram for 127Q Trotter layer



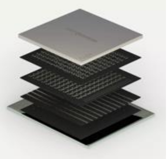


Same number of learning circuits as for 4Q



Zlatko Minev, IBM Quantum

Scaling and error budget

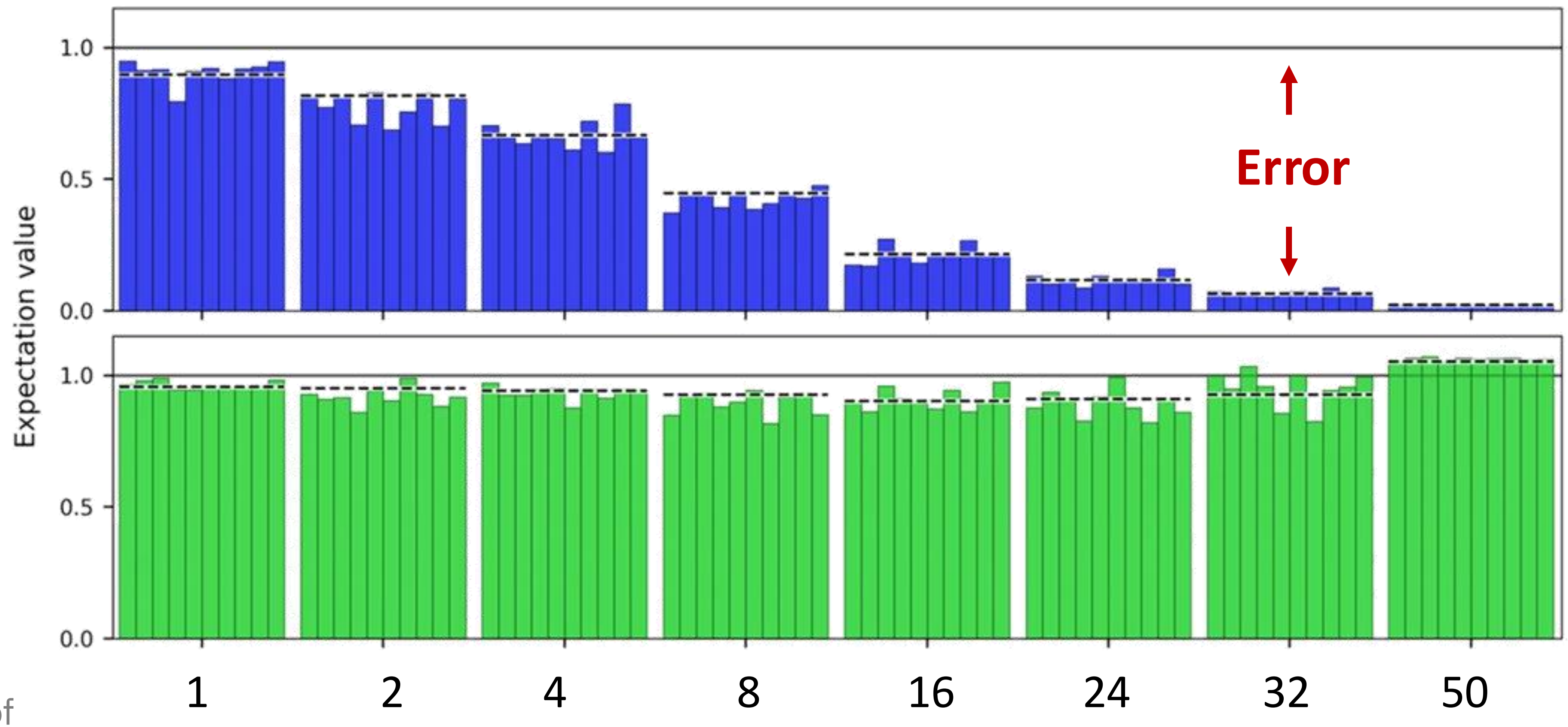


PEC on 50 qubit observables

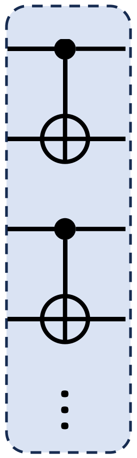
Z stabilizers of increasing weight

Without PEC

With PEC



Weight of mitigated observable

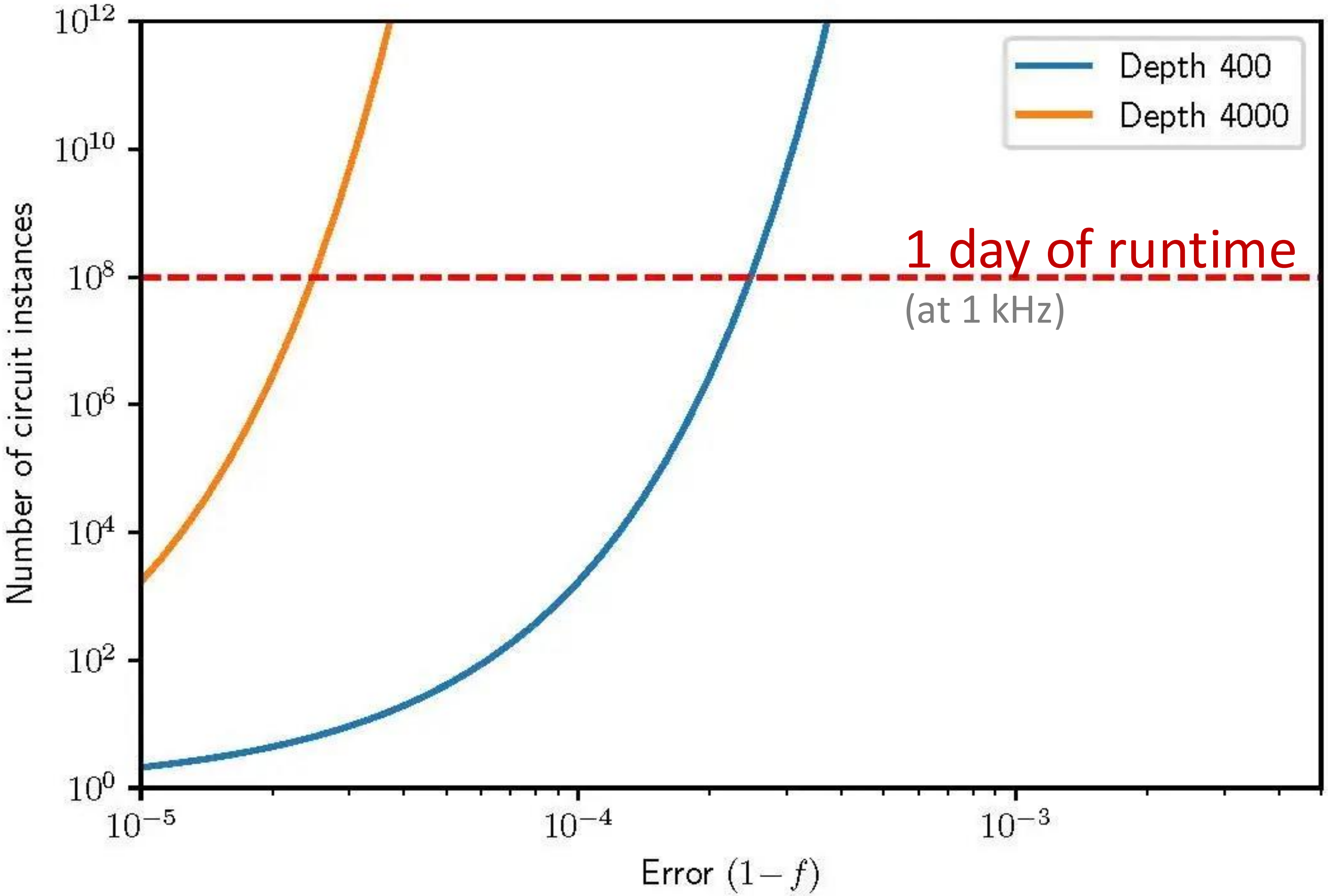


50Q
2 layers of
cNOT gates

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

<u>Noise-free</u> 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

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

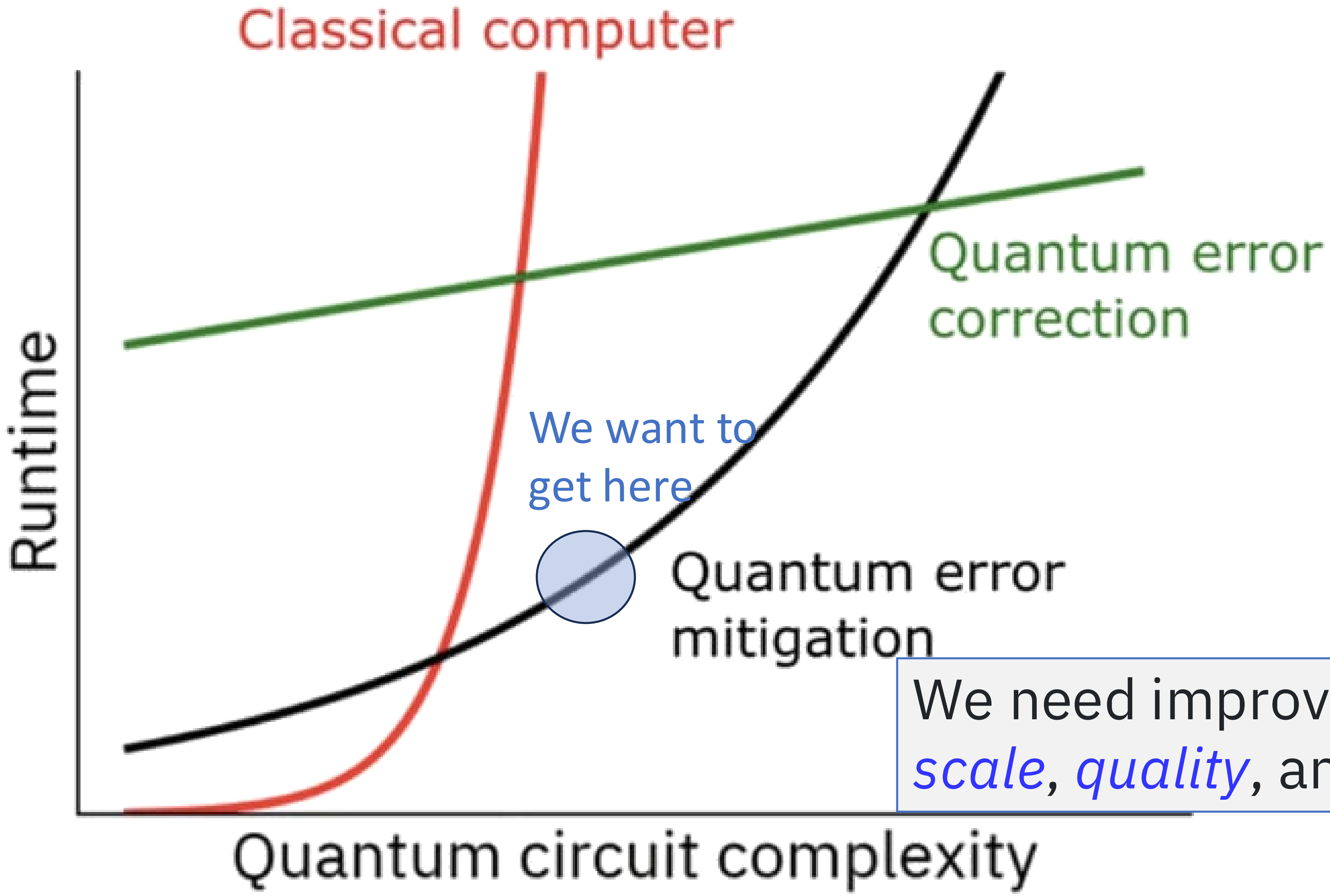
$\bar{\gamma}$ is a measure of the collective quantum noise (increasing quality brings it closer to 1)

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*.

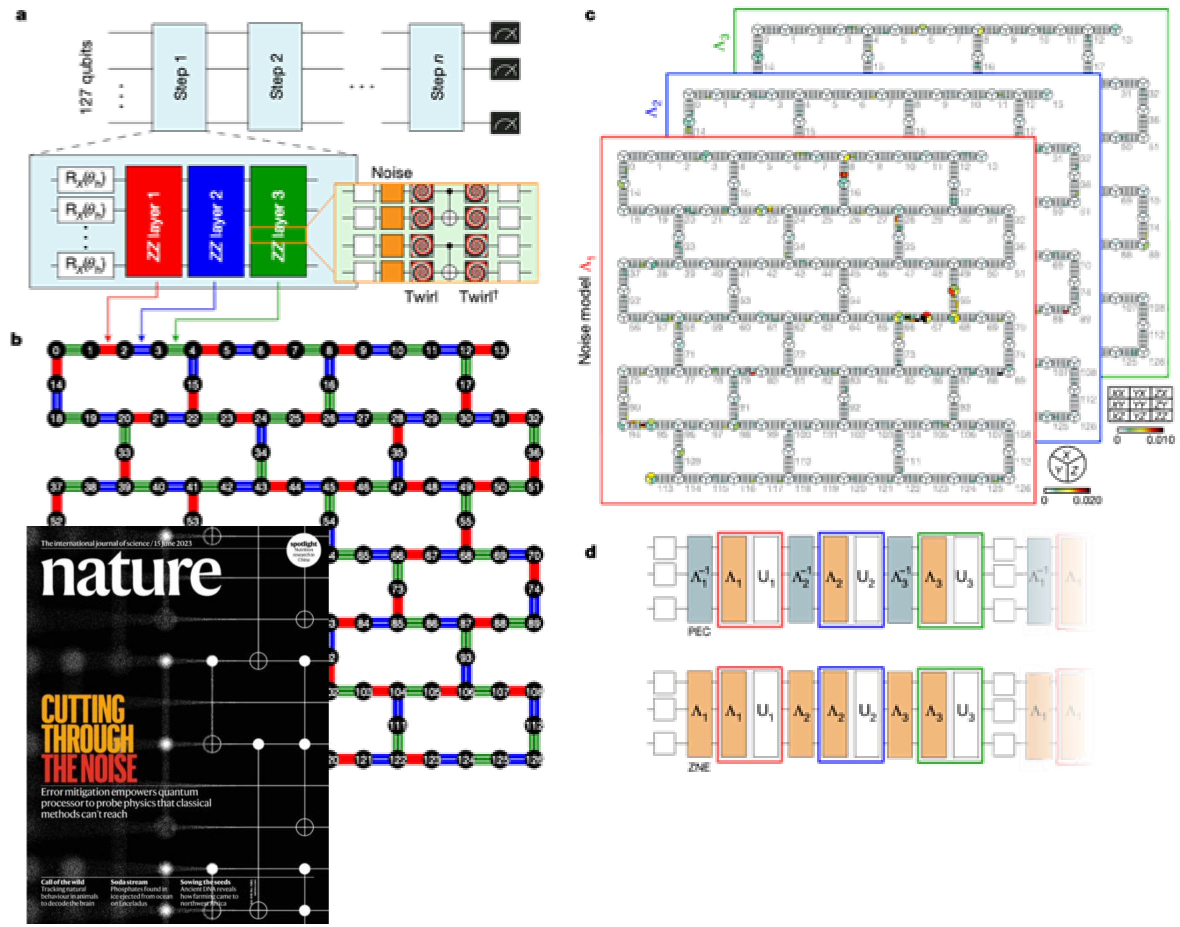
https://qiskit.org/documentation/partners/qiskit_ibm_runtime/tutorials/Error-Suppression-and-Error-Mitigation.html

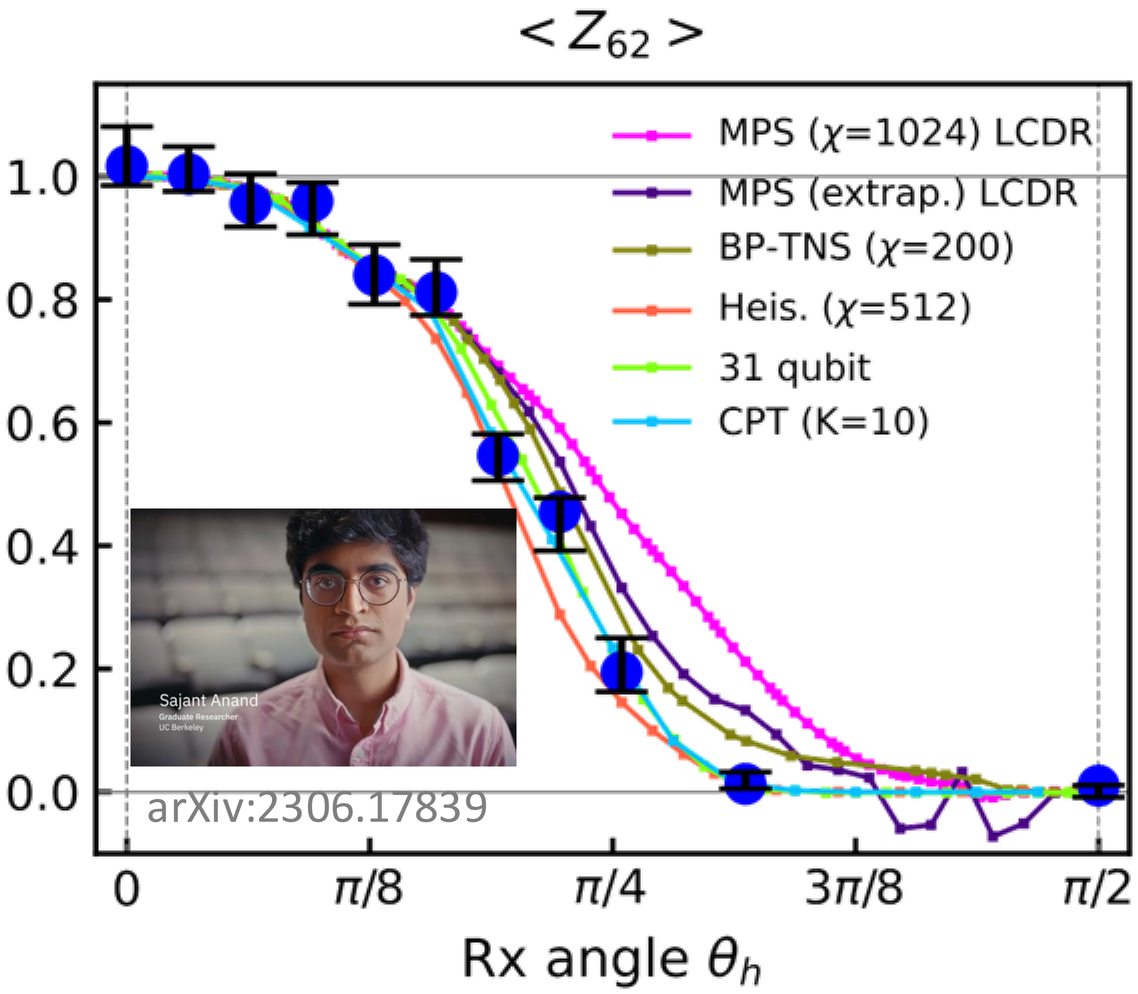
PEC + ZNE for 127 qubits

Article

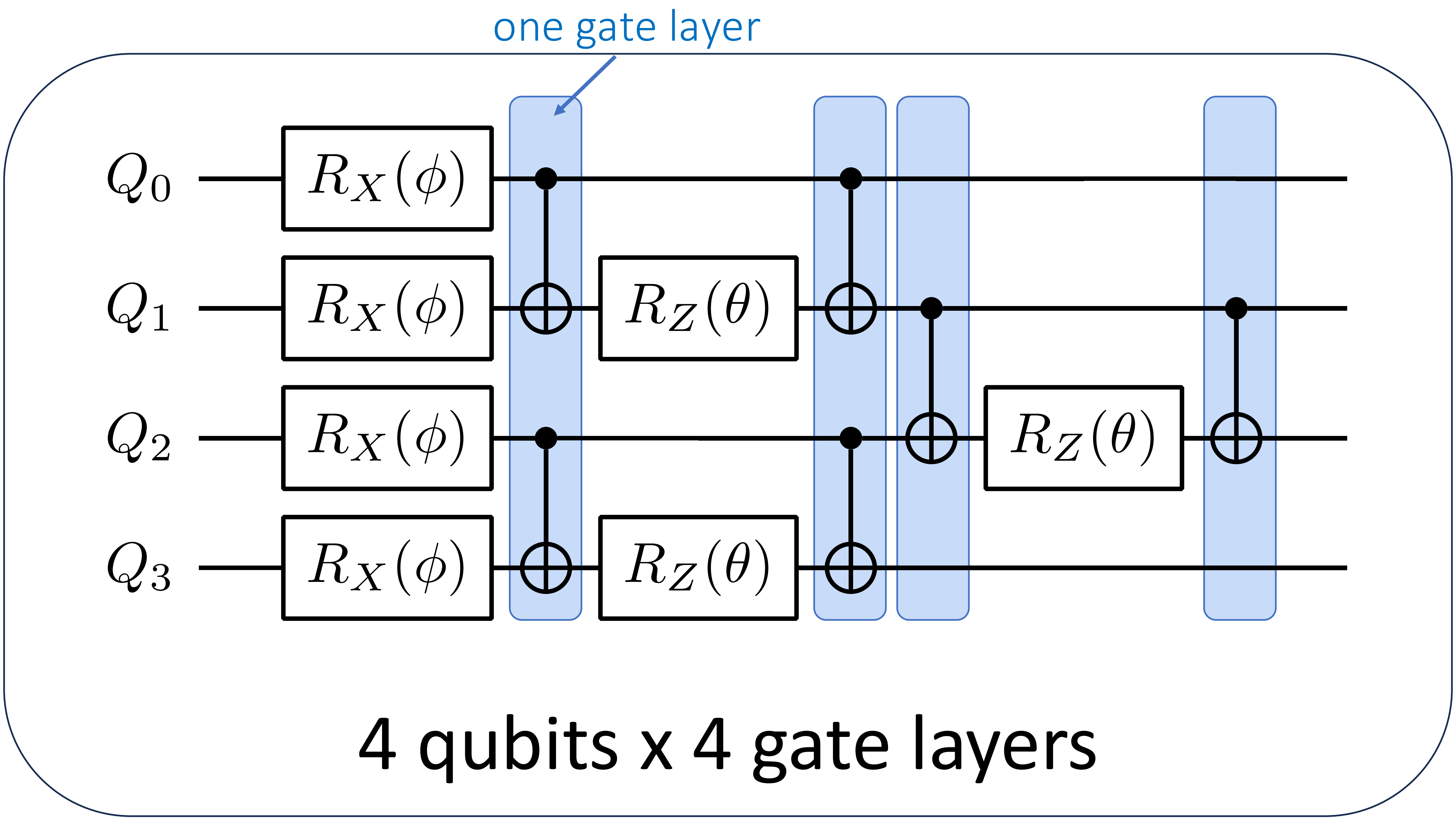
Evidence for the utility of quantum computing before fault tolerance

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]✉

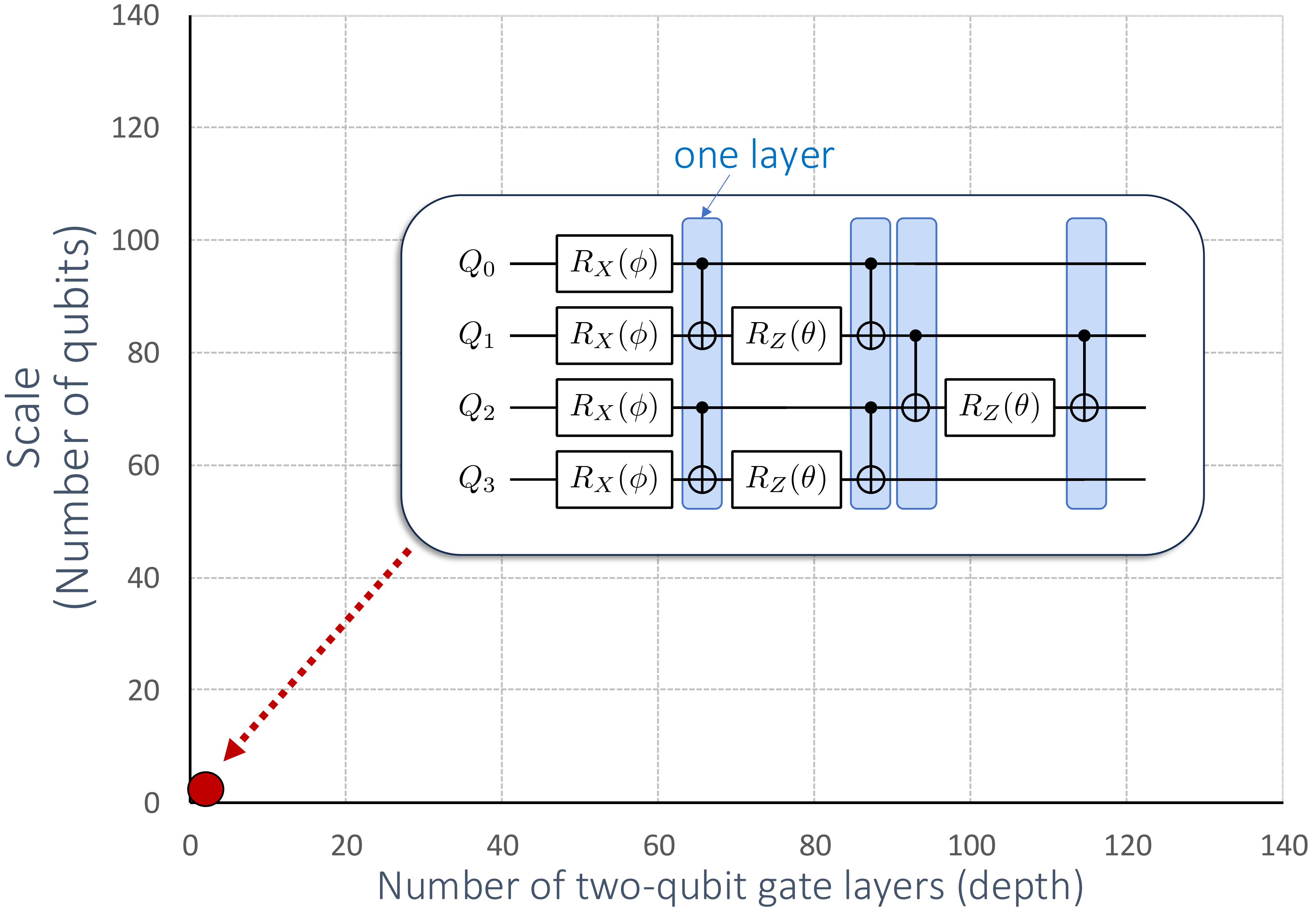




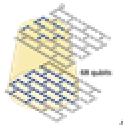
Kim, Eddins, Anand, et al. Nature (2023)


one gate layer
Q_0
Q_1
Q_2
Q_3
$R_X(\phi)$
$R_X(\phi)$
$R_X(\phi)$
$R_X(\phi)$
$R_Z(\theta)$
$R_Z(\theta)$
$R_Z(\theta)$
4 qubits x 4 gate layers

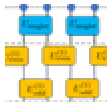
Circuit
width × depth



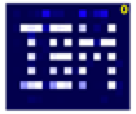
Some early utility-scale experiments



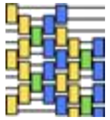
[0] Kim, Eddins, …, Temme, Kandala.
Nature 618, 500–505 (2023)



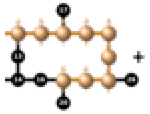
[1] Yu, Zhao, Wei.
arXiv: 2207.09994 (2022)



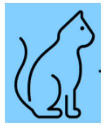
[2] Shtanko, Wang, Zhang, Harle, Seif, Movassagh, Minev.
arXiv: 2307.07552 (2023)



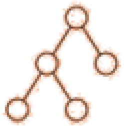
[3] Farrell, Illa, Ciavarella, Savage.
arXiv: 2308.04481 (2023)



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

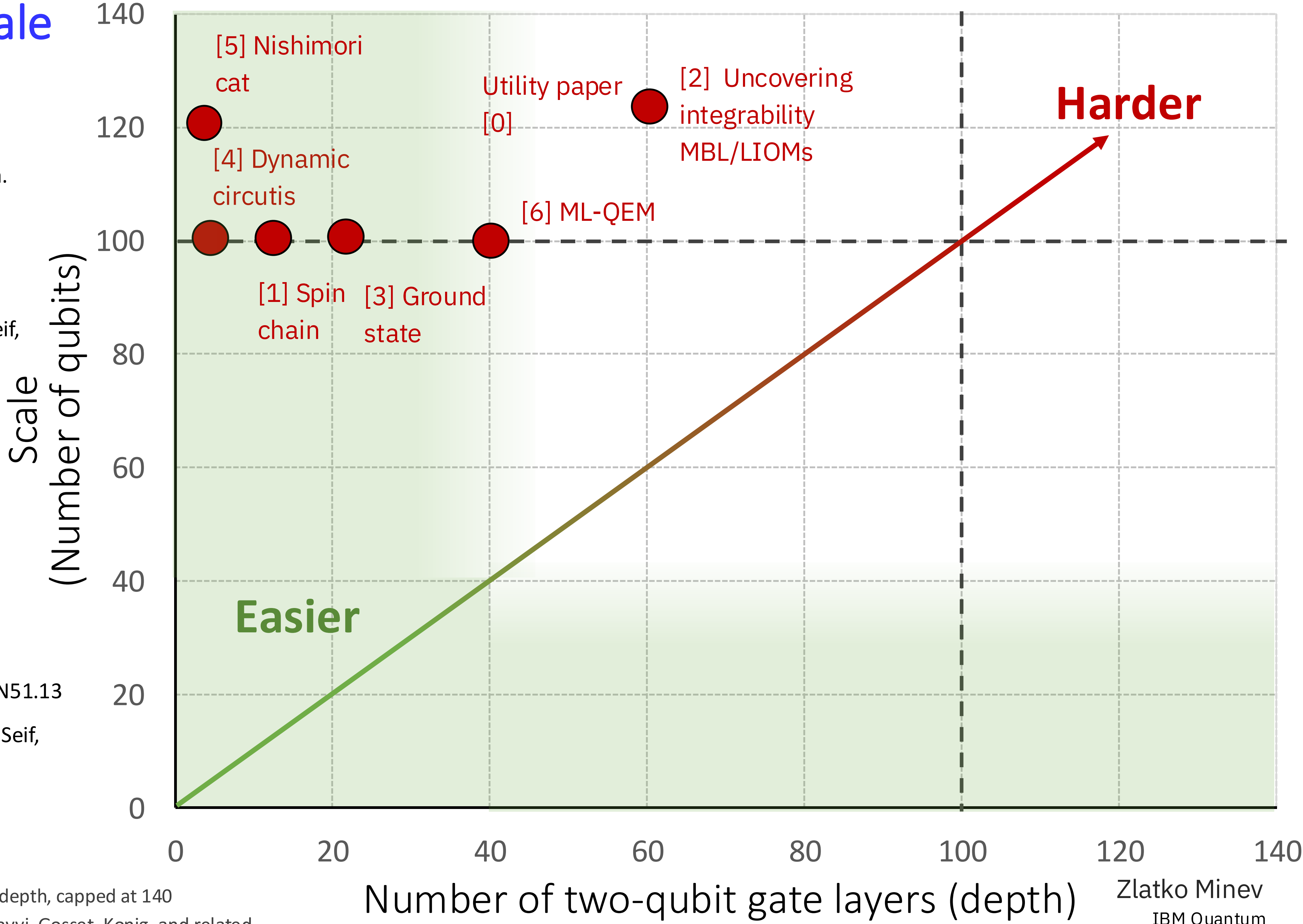


[5] Chen, Zhu, Verresen, Seif, Baümer, … Trebst, Kandala.
arXiv: 2309.02863 (2023) APS N51.13



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

…



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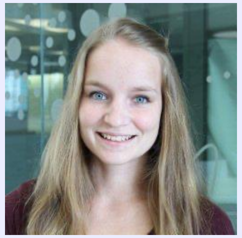
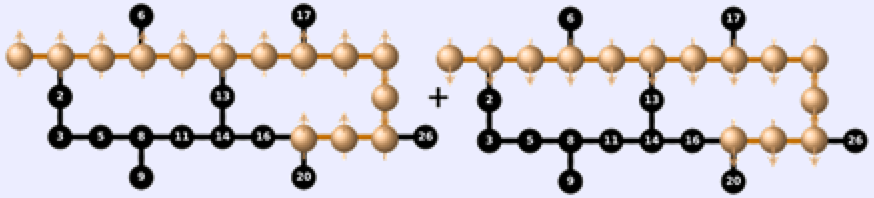
* signal stops or decays more than 50% beyond this depth, capped at 140
* note: quantum advantage with shallow circuits, Bravyi, Gosset, Konig, and related

Check out related utility-scale work

Efficient Long-Range Entanglement using Dynamic Circuits (invited)



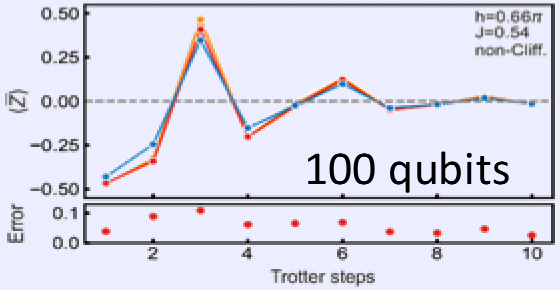


Gate teleportation over 100+ qubits

arXiv:2308.13065 (2023)

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

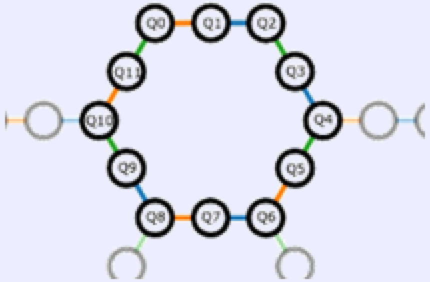
Machine Learning for Practical Quantum Error Mitigation (ML-QEM)



arXiv:2308.13065 (2023)

Liao, Wang, Sitdikov, Salcedo, Seif, Minev

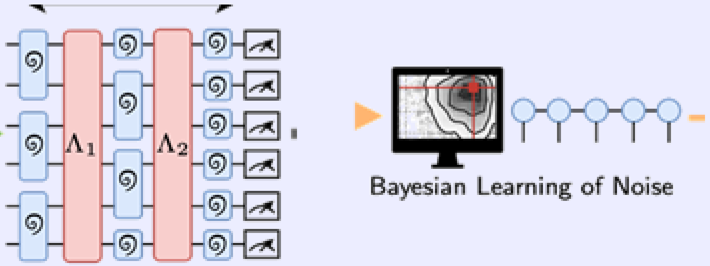
Learning about Quantum Noise at Scale



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

arXiv:2408.03376 (2024)

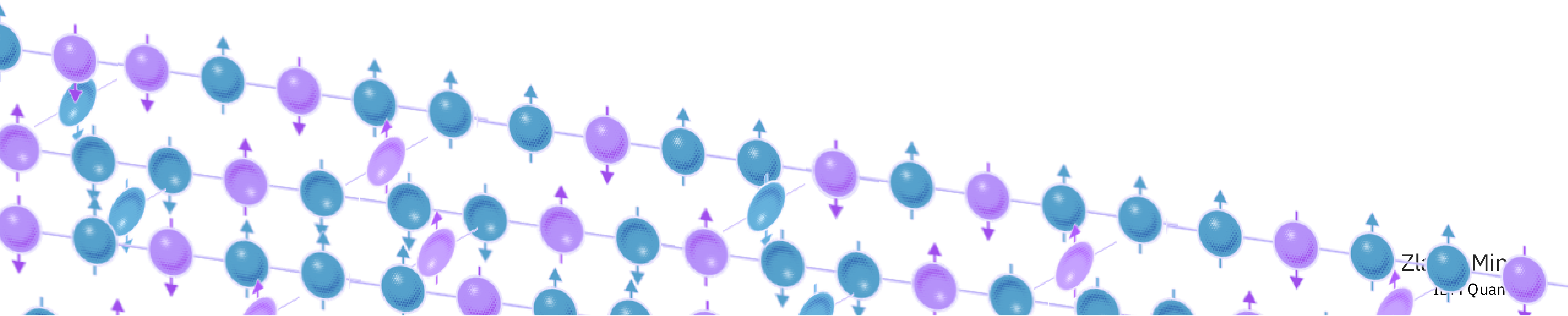
Demonstration of Robust and Efficient Quantum Property Learning with Shallow Shadows



arXiv:2402.17911 (2024)

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

Preview



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

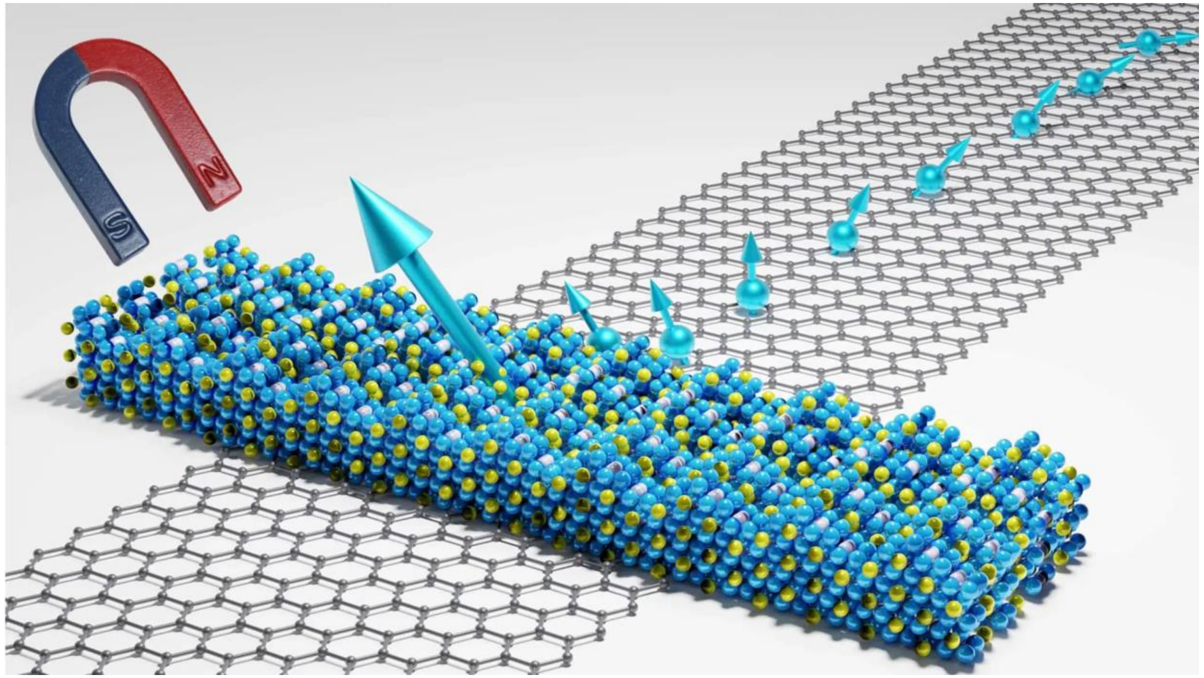

Image: Chalmers

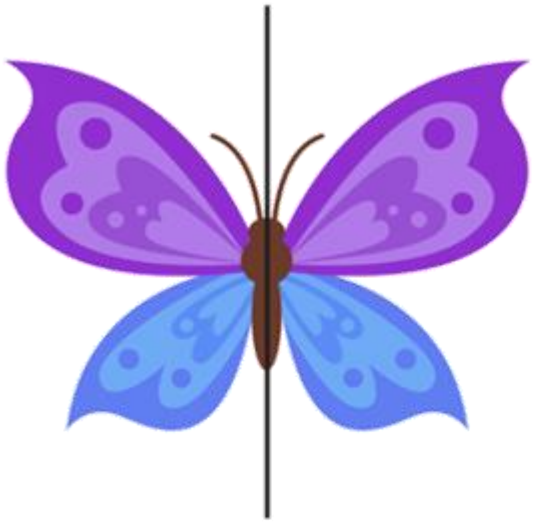

Image: SuperSimple

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Classical Physics: Integrals of Motion

Before

After

Integrals of motion:
Total Linear Momentum
Total Kinetic Energy

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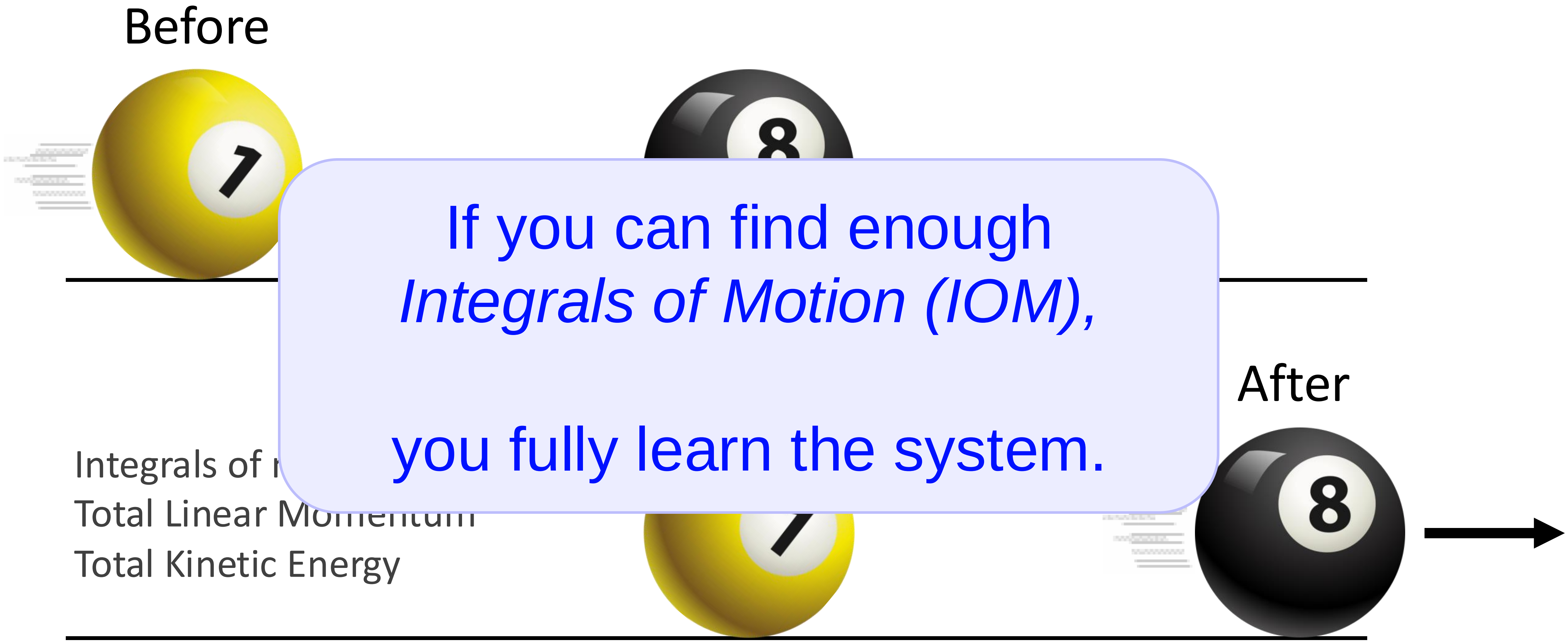
Balls: boris-farias

Classical Physics: Integrals of Motion



Balls: boris-farias

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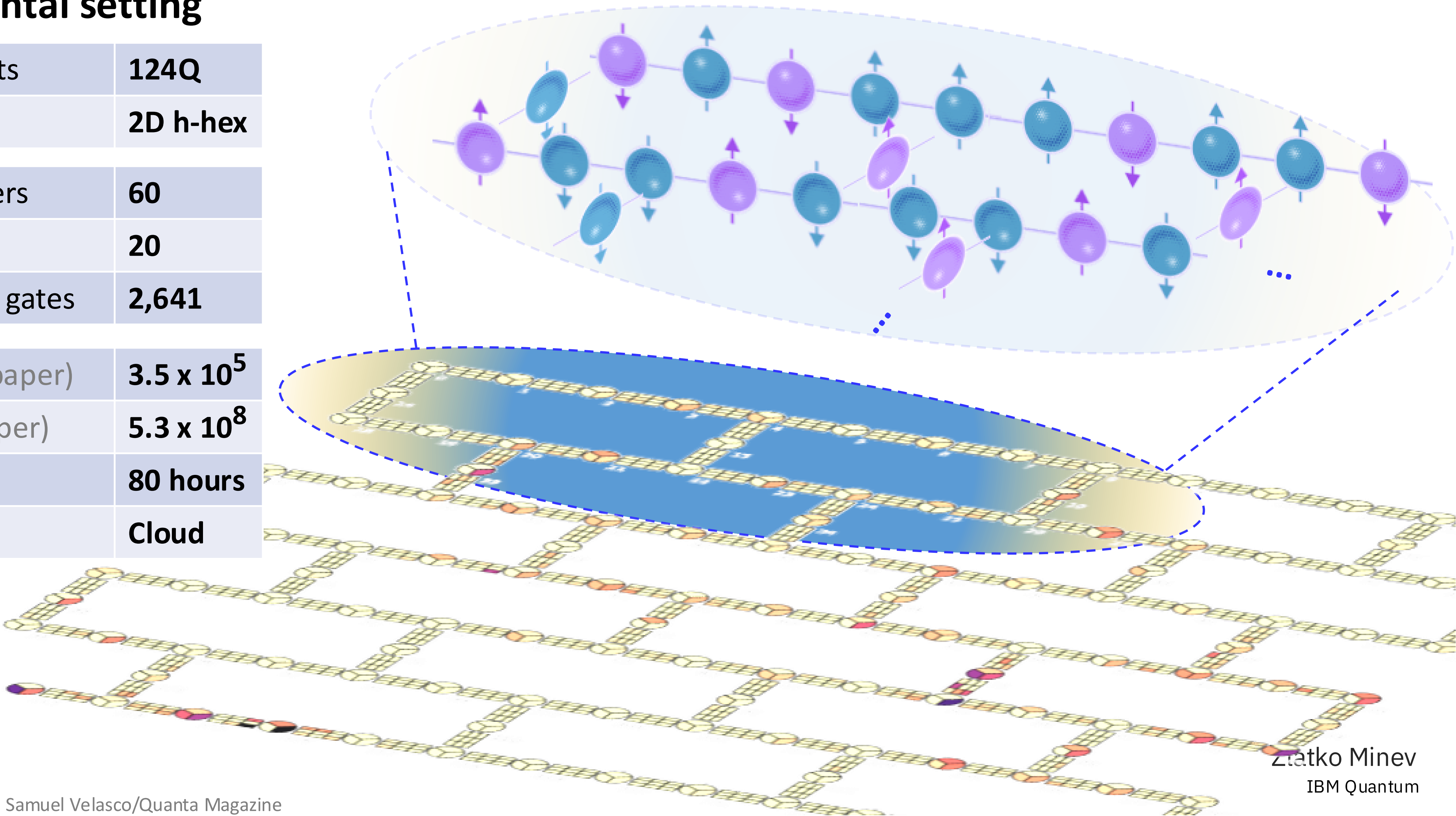
QSim on 100Q+: 2D interacting many-body Floquet system

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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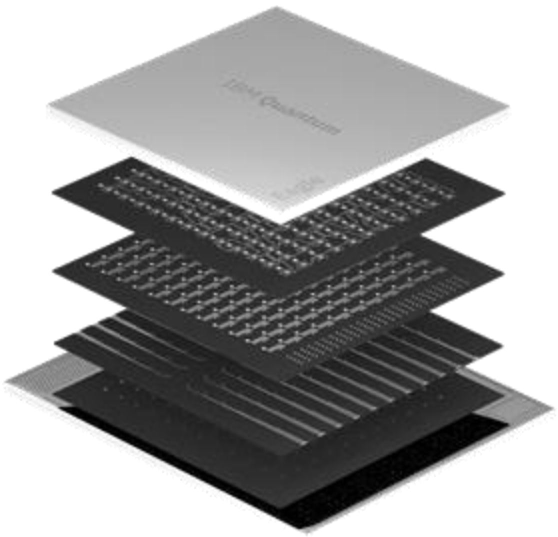
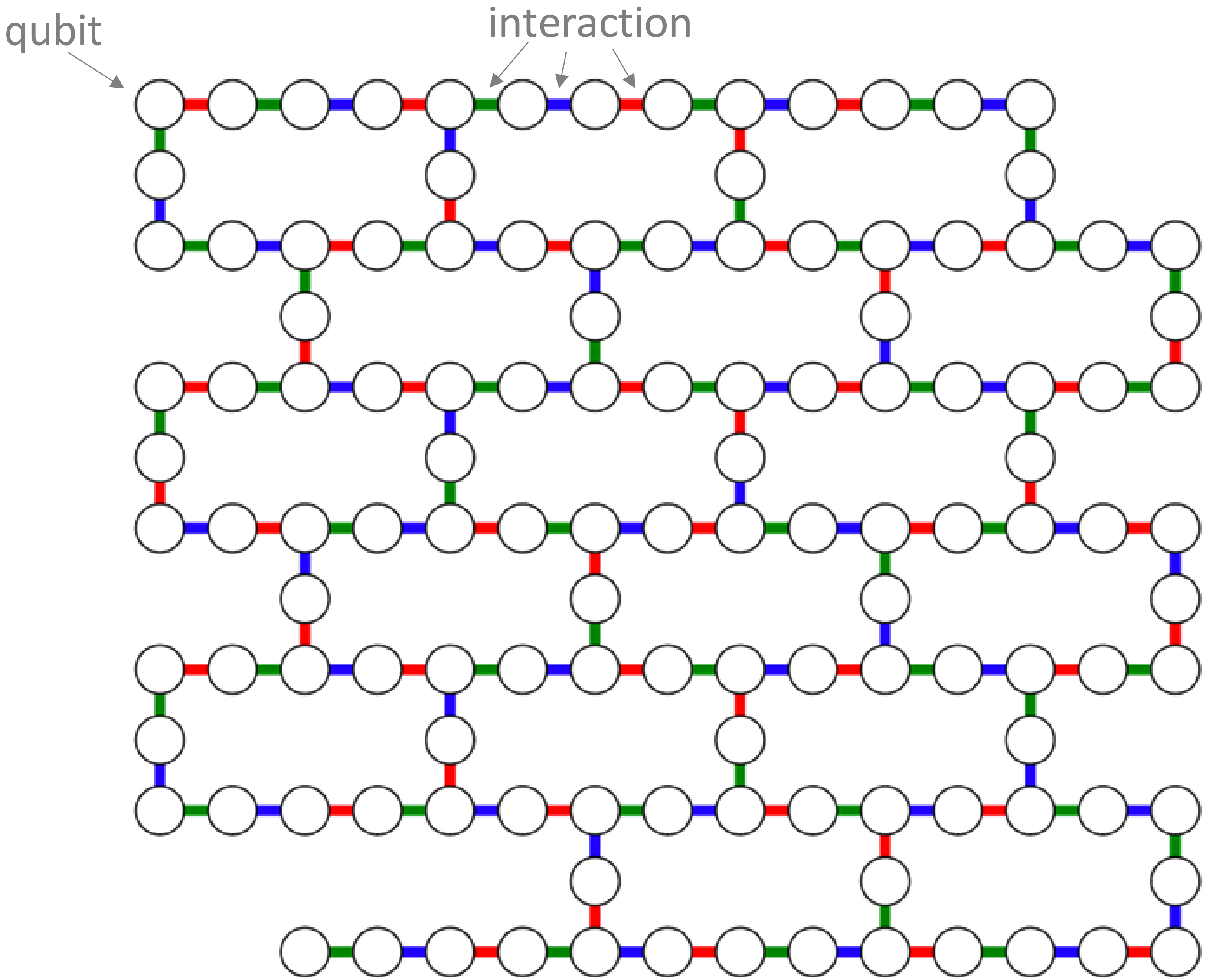
Interaction map and device layers



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

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

arXiv:2307.07552



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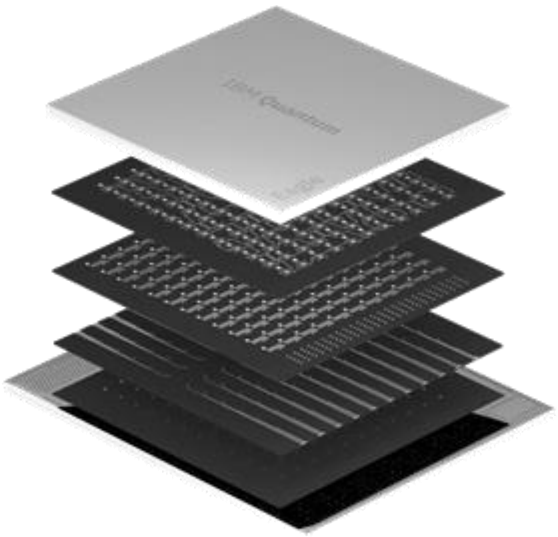
Initialize lattice in fun states



Number of qubits	**124Q**
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Floquet steps	**20**
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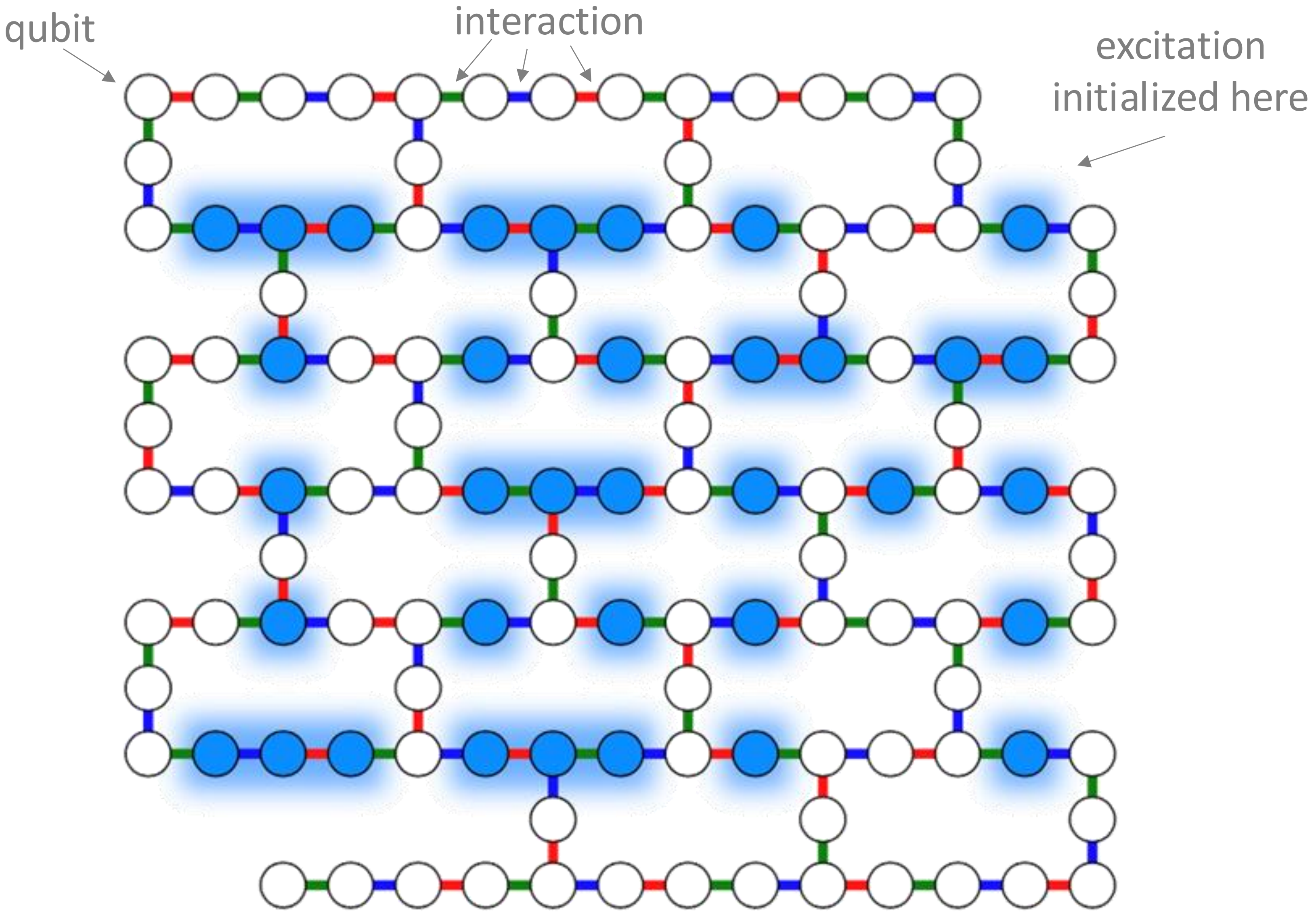
arXiv:2307.07552



Color represent spin polarization

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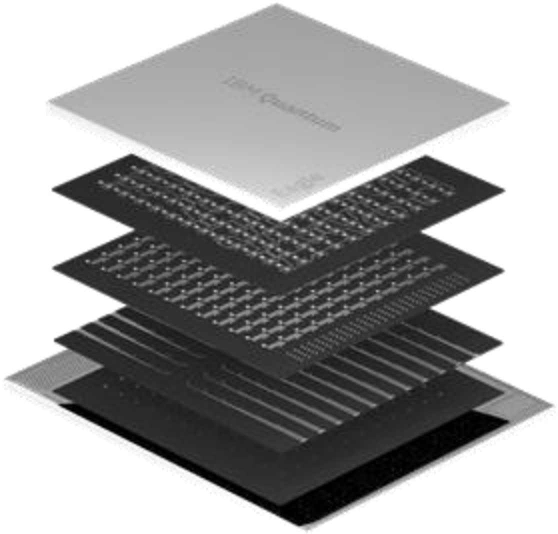
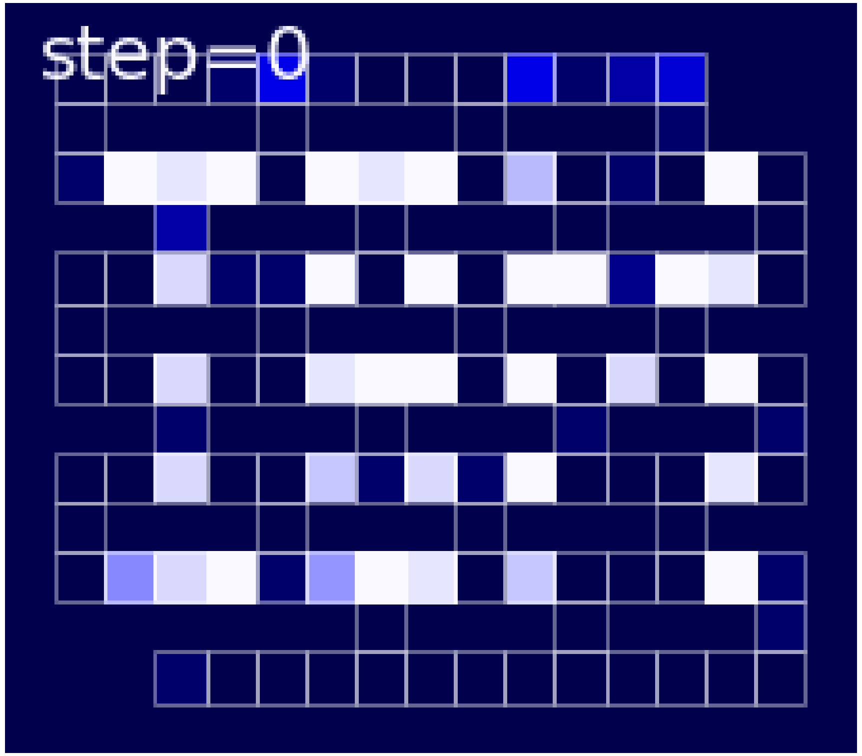
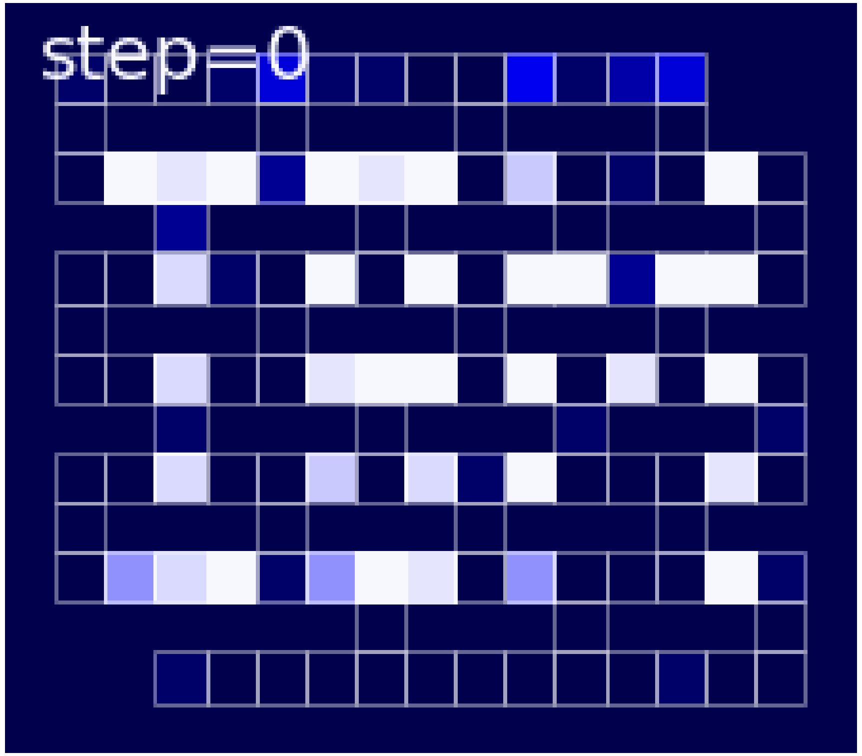
Quantum dynamics in different regimes



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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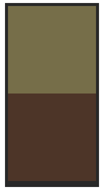
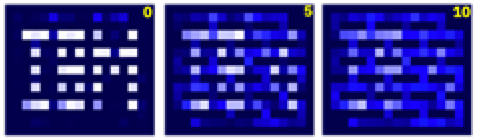
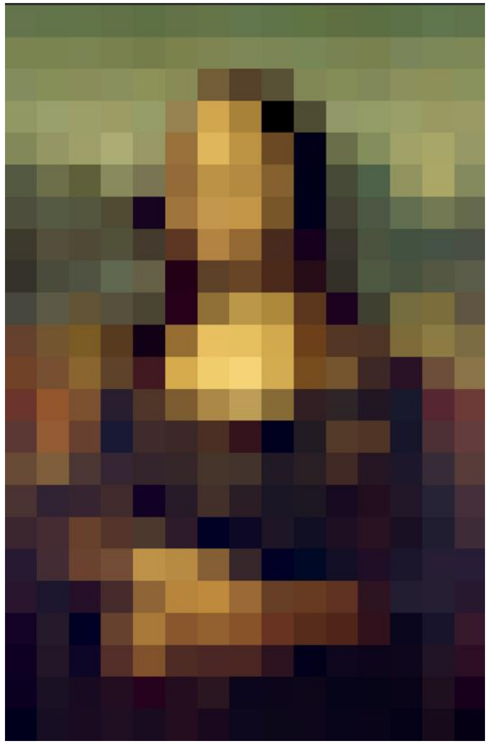
A more detailed portrait

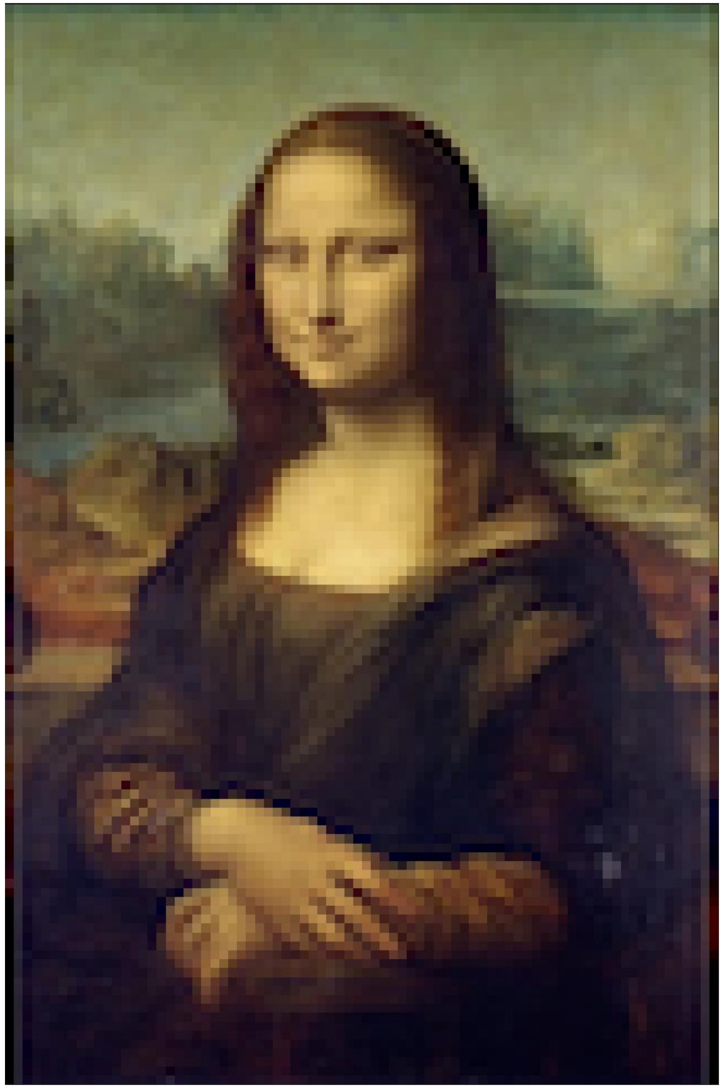




Spin
imbalance



One-particle density
matrix (OPDM)



Local integrals of motion
(LIOMs)

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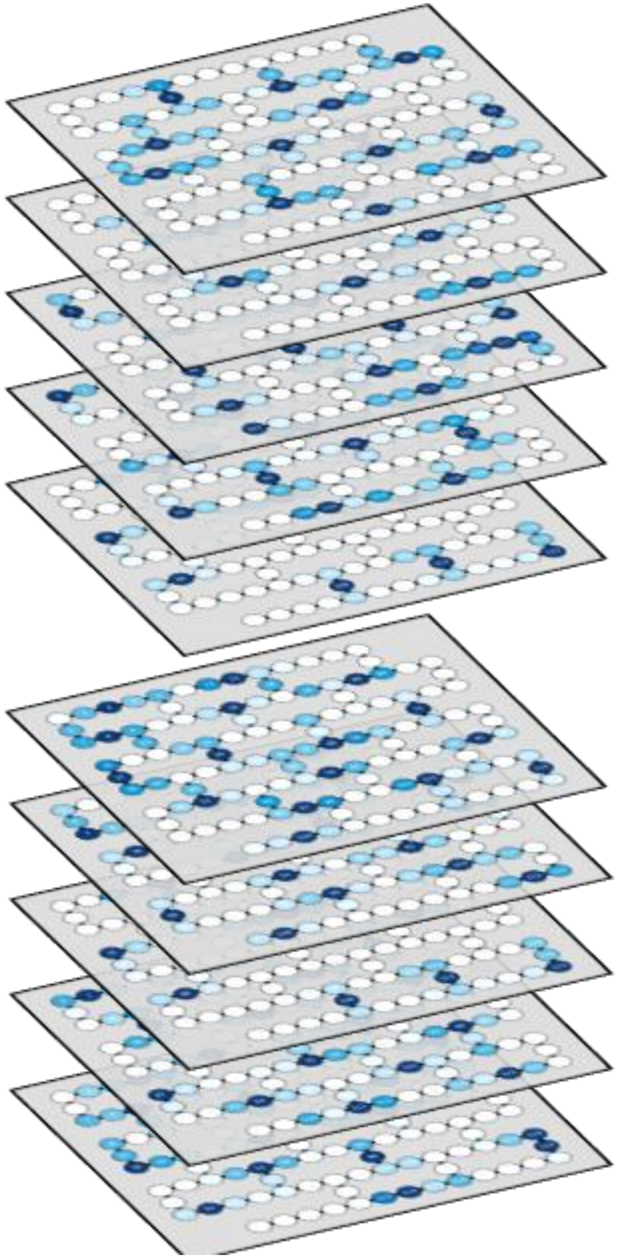
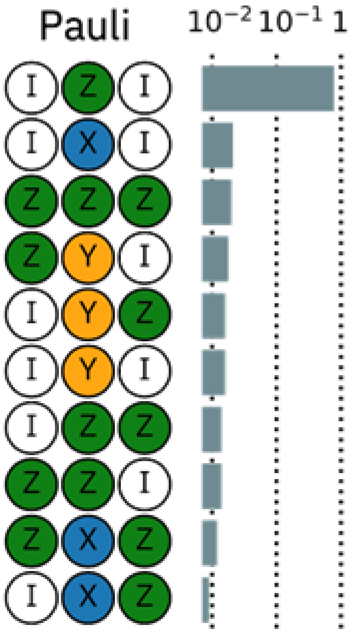
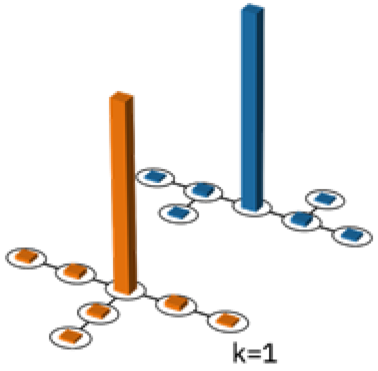
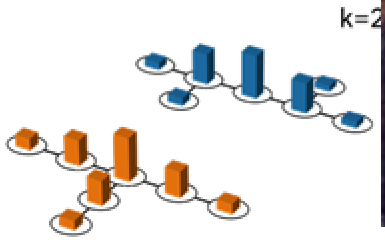
Operational LIOM description on observation timescales









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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

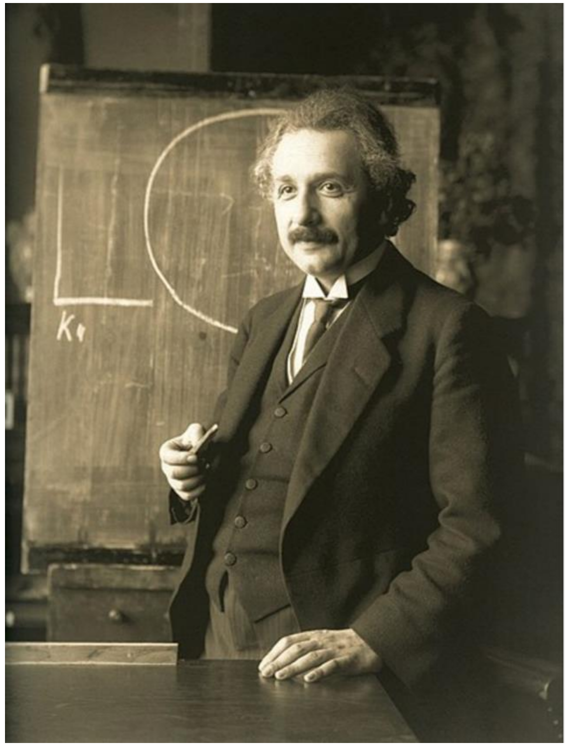

Photo: F. Schmutzer

Quantum Working Groups
From utility to advantage

IBM Quantum working groups bring together the best scientists in our field to accelerate our path to achieving Quantum Advantage by 2025, across domain areas:

Optimization

Quantum Optimization: Potential, Challenges, and the Path Forward

arXiv:2312.02279

Materials & HPC

Quantum-centric Supercomputing for Materials Science: A Perspective on Challenges and Future Directions

arXiv:2312.09733

High-Energy Physics

Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group

arXiv:2307.03236

Healthcare & Life Sciences

Towards quantum-enabled cell-centric therapeutics.

arXiv:2307.05734

Sustainability

Collaborative projects in the fields of Materials and Energy leveraging quantum computers.

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