

A Prelude to Practical Quantum Computing

A brief overview

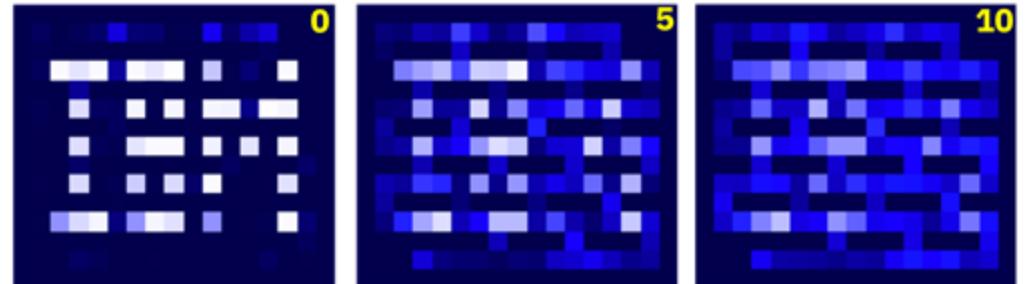
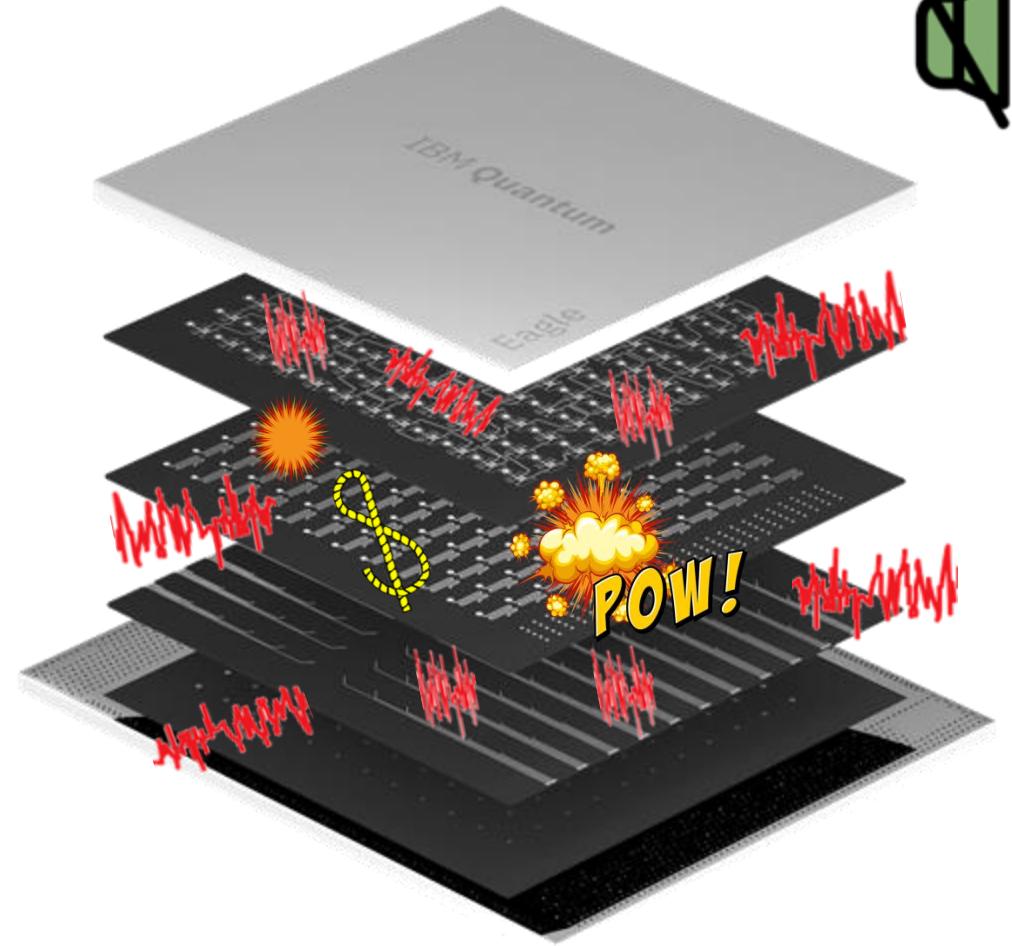
Zlatko Minev

Got Slides?

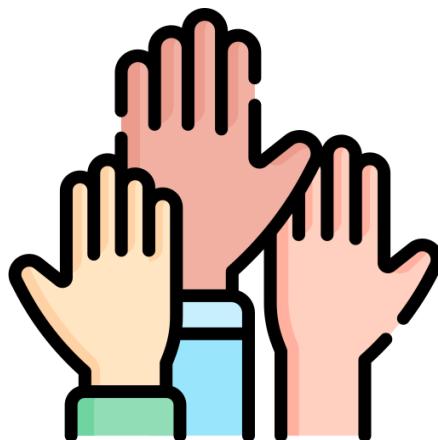
zlatko-minev.com/blog



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Have you used
a quantum computer?



A Prelude to Practical Quantum Computing

I. Big picture today?

Quantum Computing Status

II. What is a qubit?

Physics & Hardware

III. Let's run a real quantum algorithm

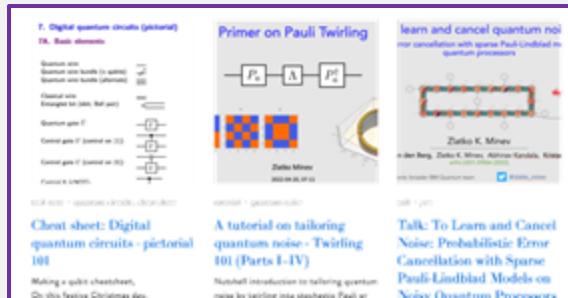
Design, Noise & Mitigation

Slides from lecture

Posted here

Tutorials

IBM Weekly Seminar



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zlatko-minev.com/blog

Qiskit YouTube



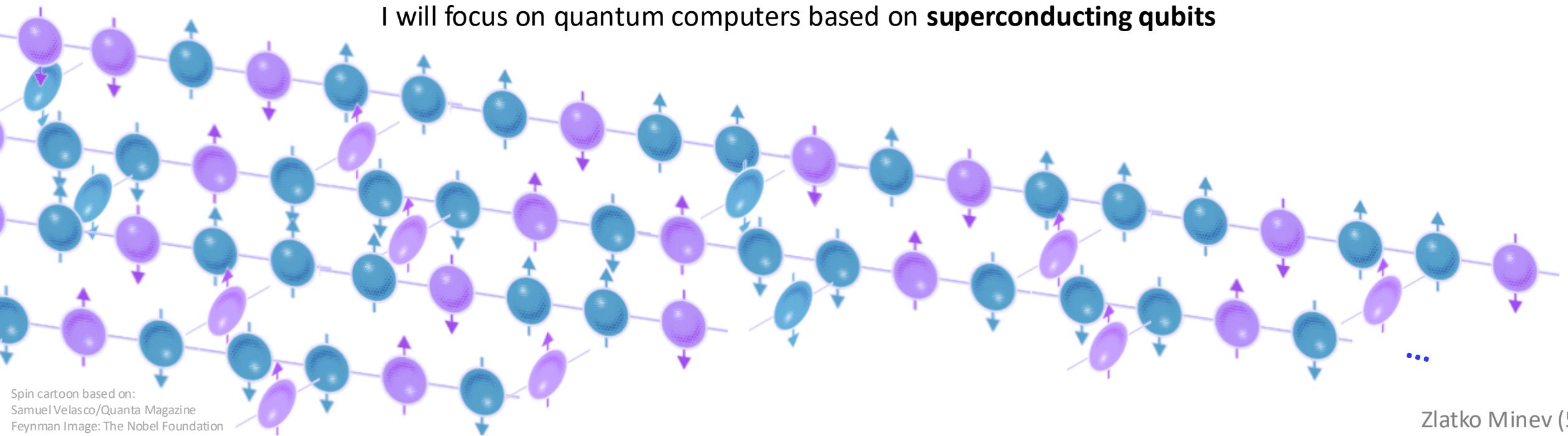
Part I

What is the big picture today?

How is it going for quantum computers?

The last 40 years and looking ahead to 10 more
1980 – . . . – 2010 – 2020 – 2023 in 60 seconds

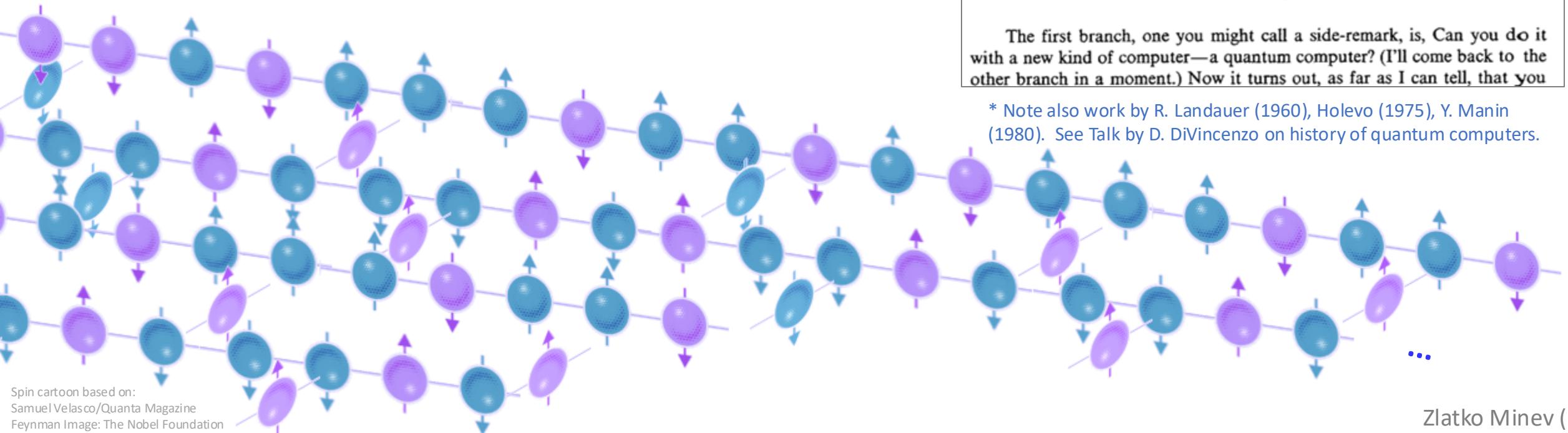
I will focus on quantum computers based on **superconducting qubits**





“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

- R.P. Feynman 1981



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

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

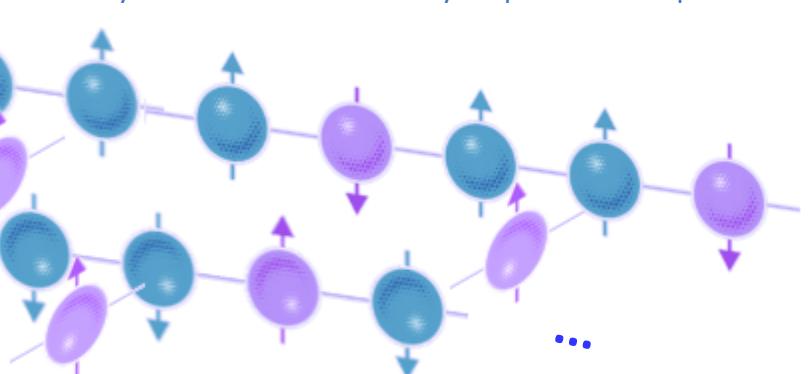
1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what we thought of before a logical, universal automation, can we imagine this situation? And I'm going to separate my talk here, for it branches into two parts.

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM * SIMULATORS

The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you

* Note also work by R. Landauer (1960), Holevo (1975), Y. Manin (1980). See Talk by D. DiVincenzo on history of quantum computers.



My experience circa 2010

Maybe **1 or 2** qubits
working some small
fraction of the time
in select labs

Photo with dilution fridge called Sunshine from Michel Devoret's lab at Yale during my Ph.D.



Hopes for a
working
qubit in
here

Today

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





Credit: Connie Zhou for IBM



2019

Falcon

27 Qubits

2020

Hummingbird

65 Qubits

2021

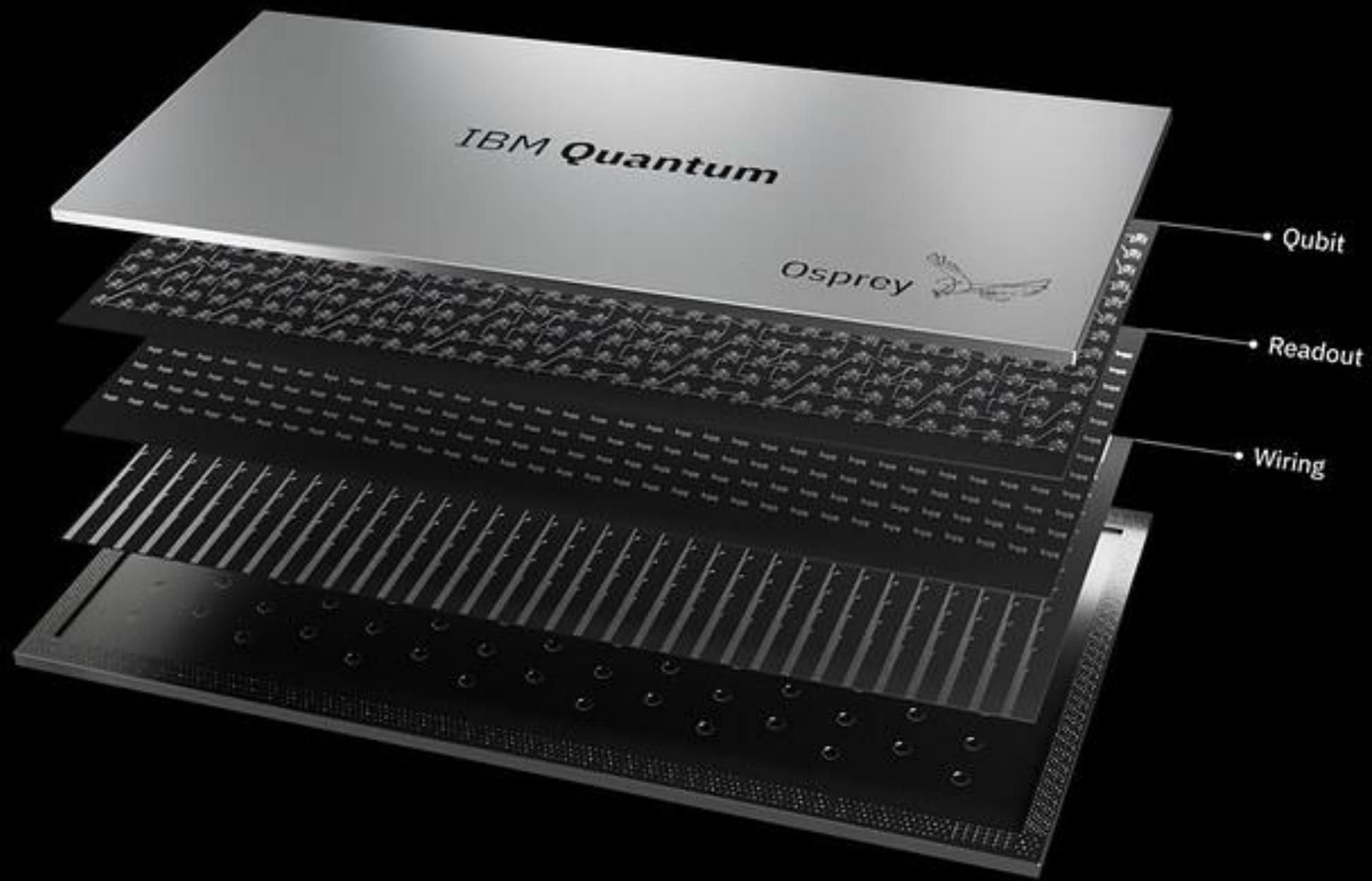
Eagle

127 Qubits

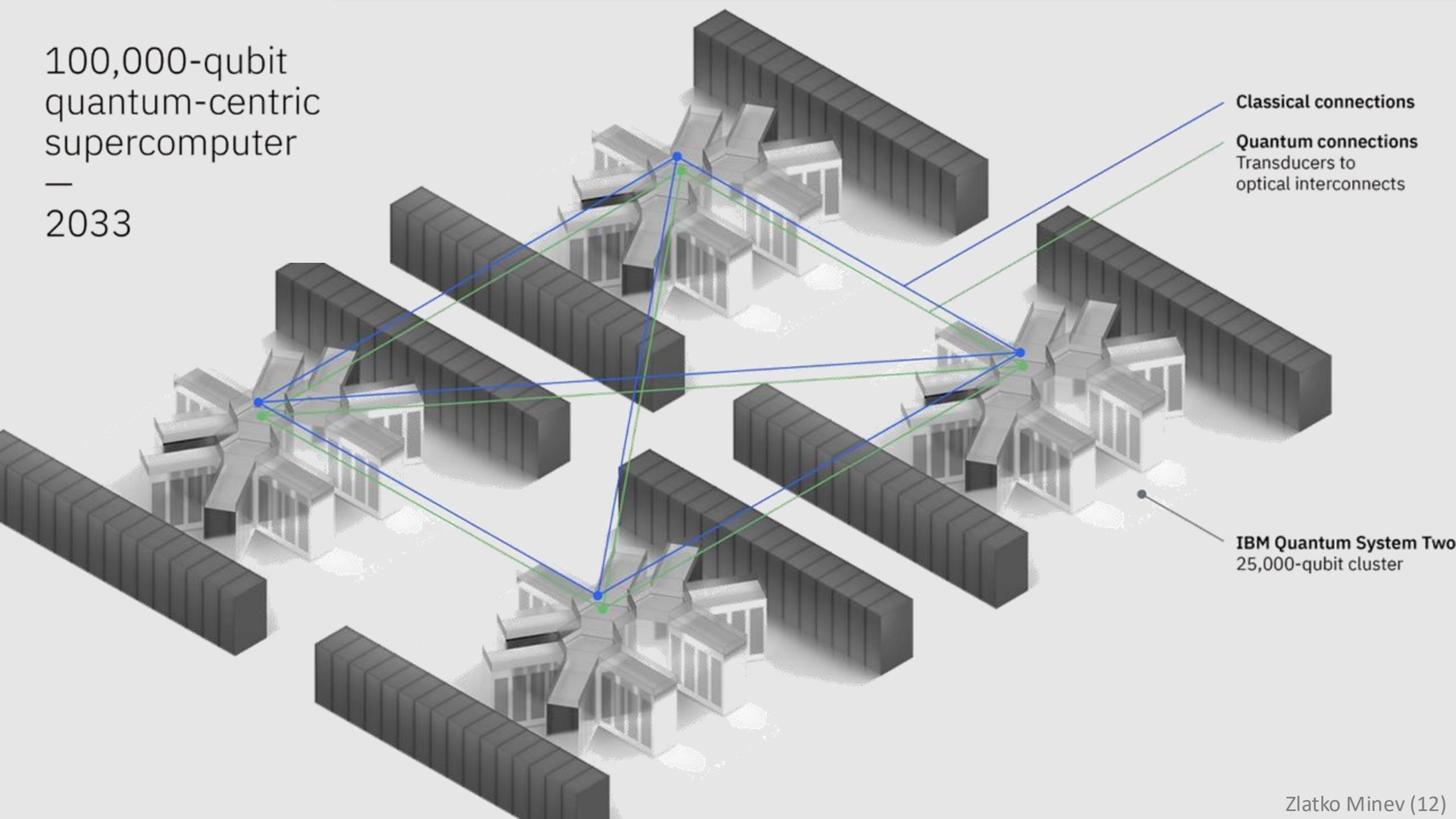
2022

Osprey

433 Qubits



100,000-qubit
quantum-centric
supercomputer
—
2033

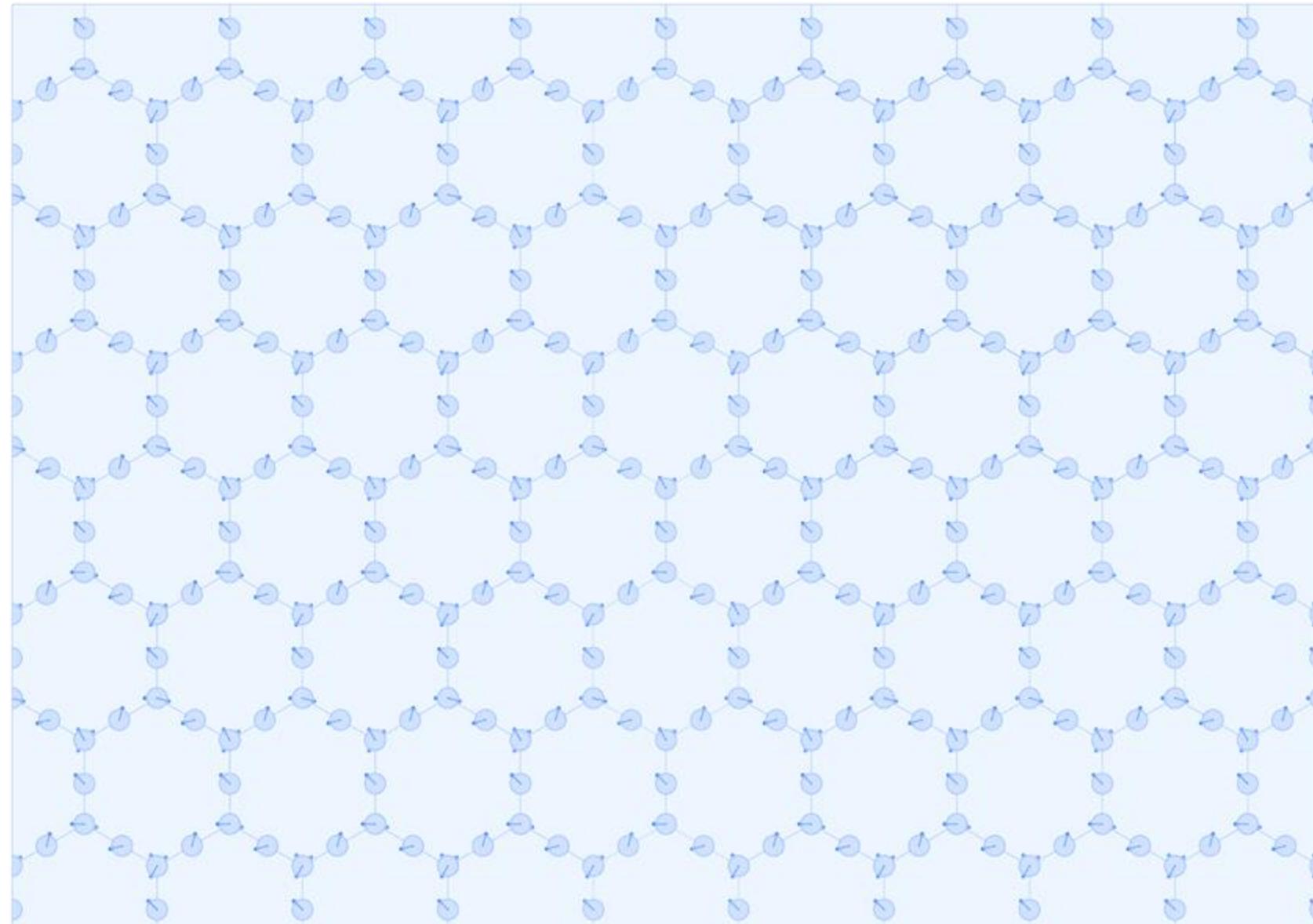


Back to today ...

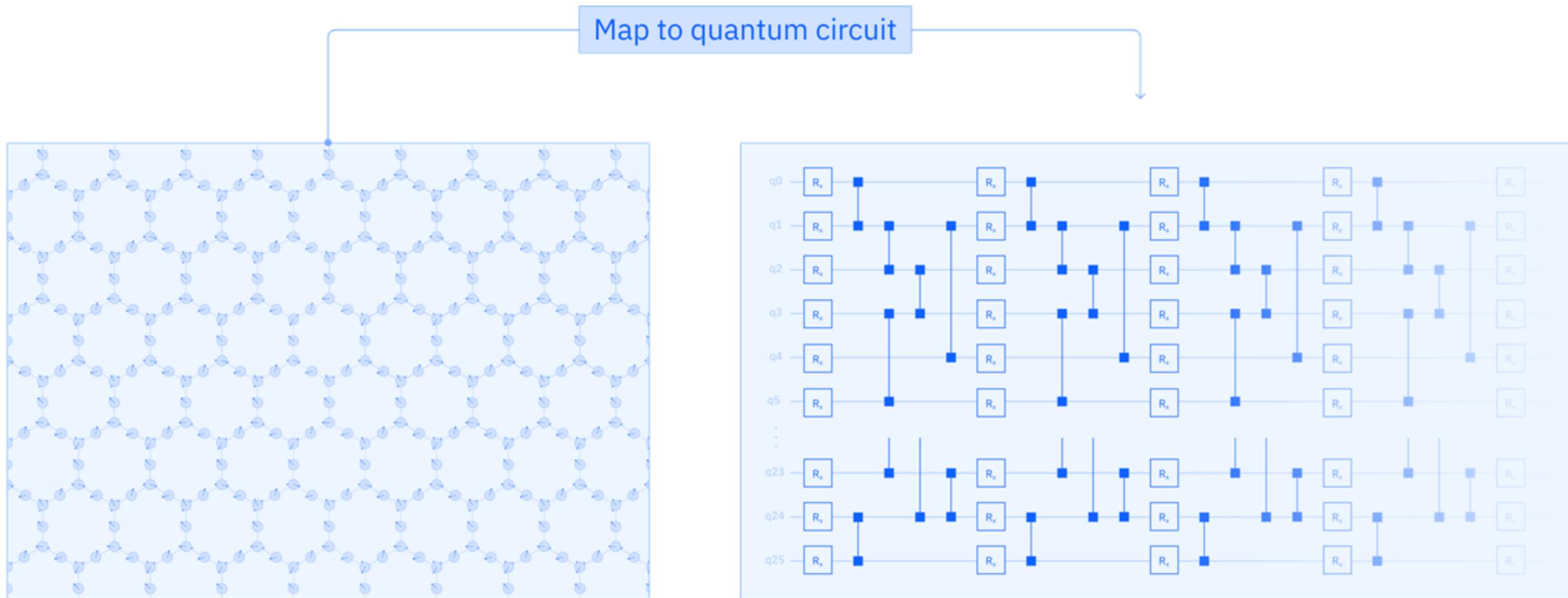
Example: Quantum simulation

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.

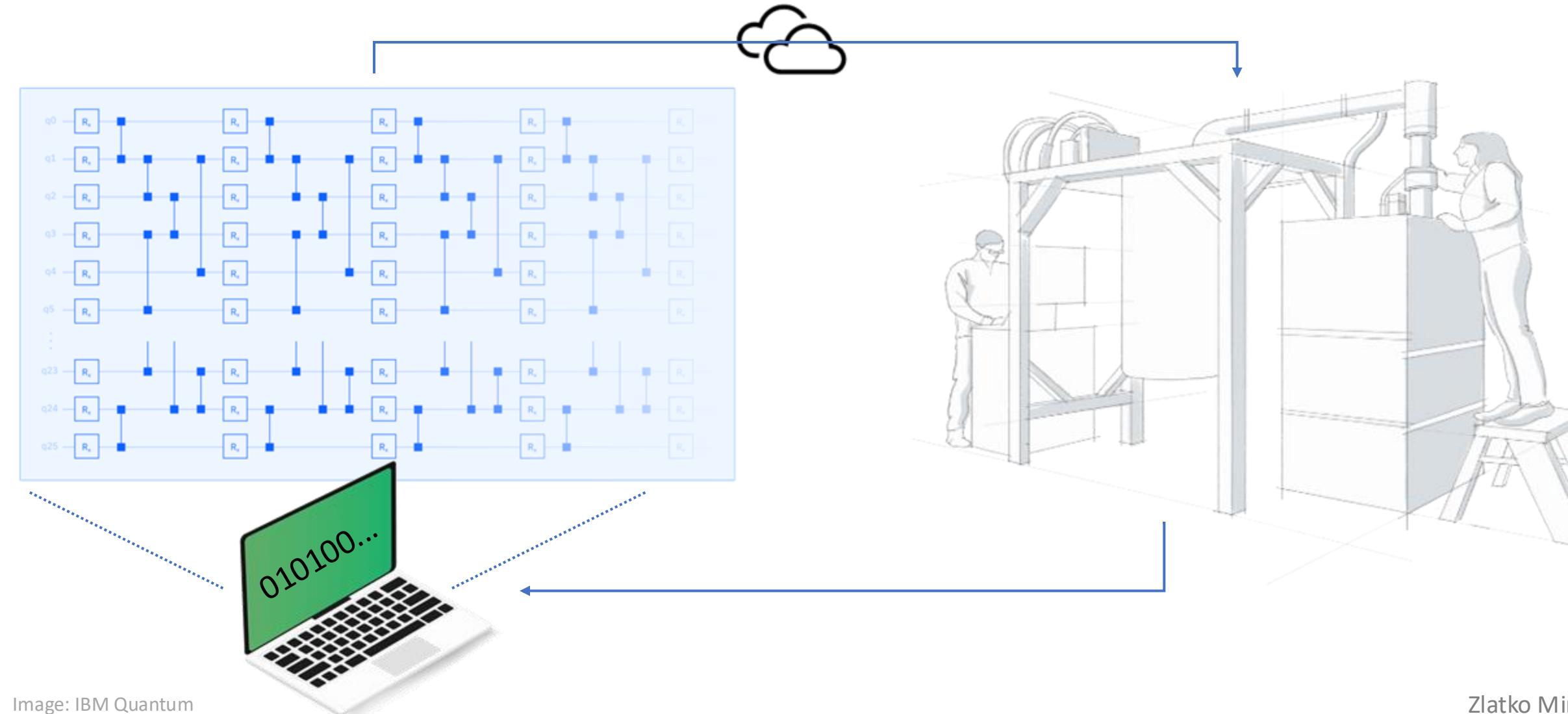


Quantum simulation on a quantum computer



Quantum simulation on a quantum computer

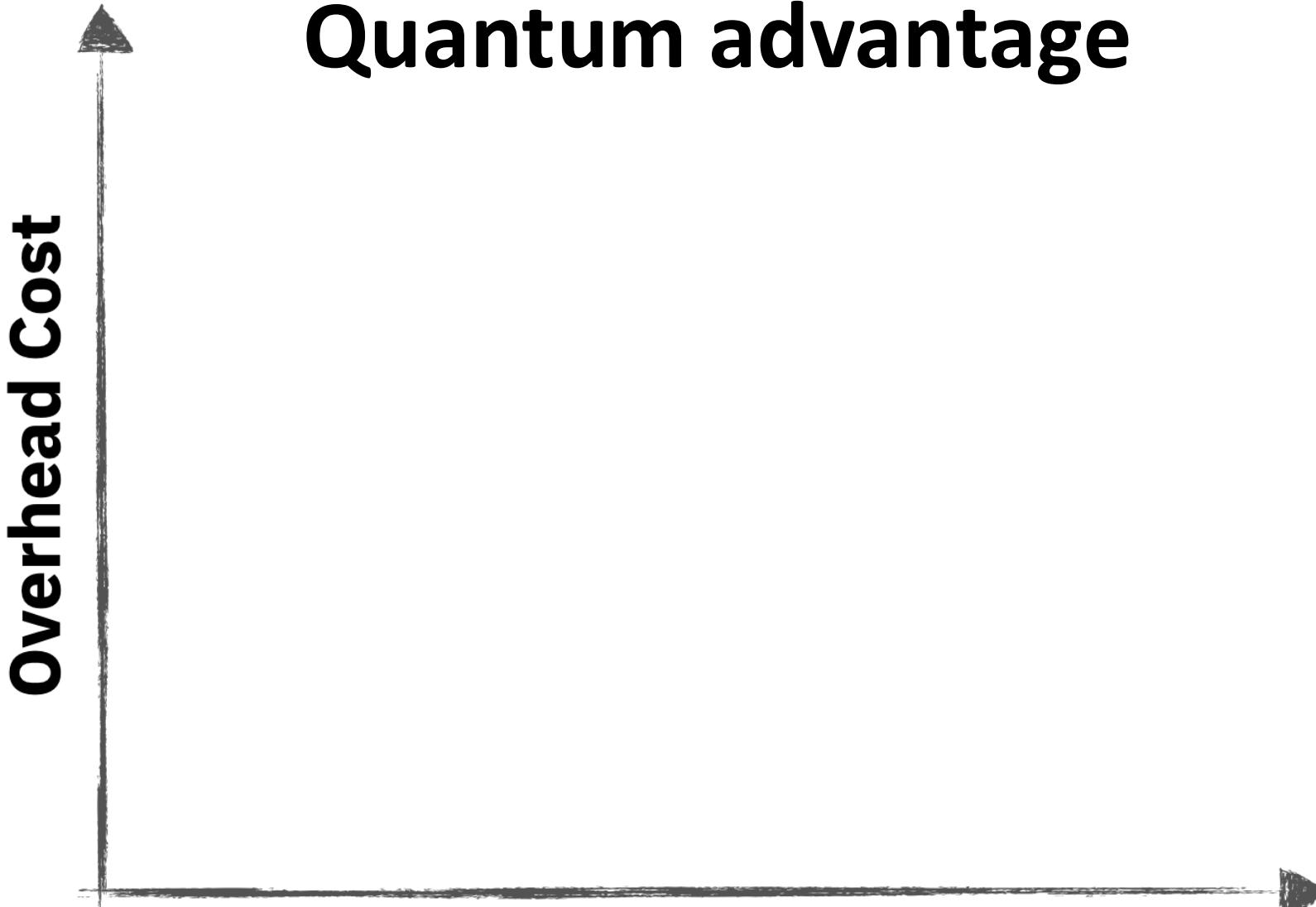
Execute on a real quantum computer device and obtain results as classical data



Quantum advantage

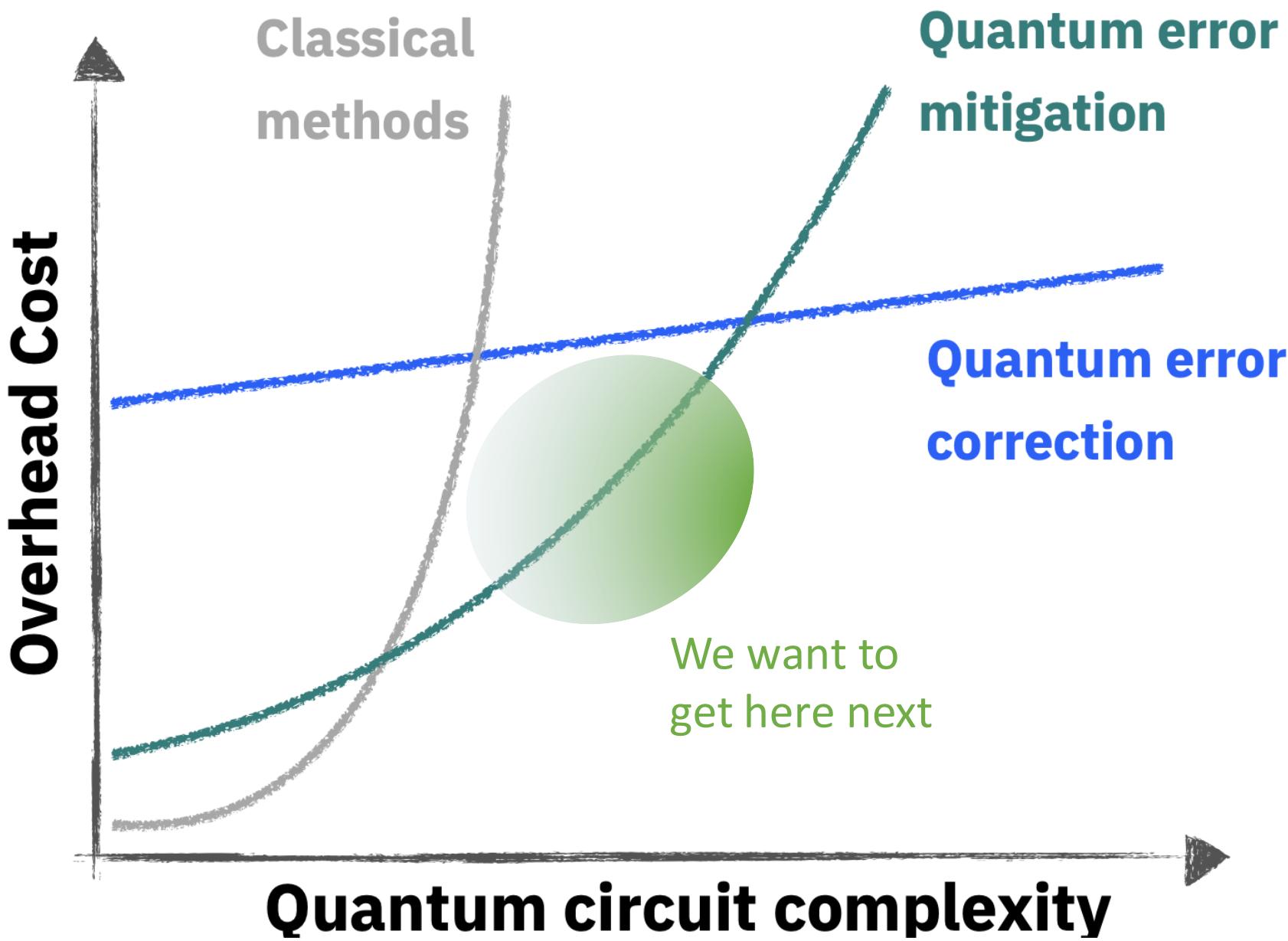


Quantum advantage

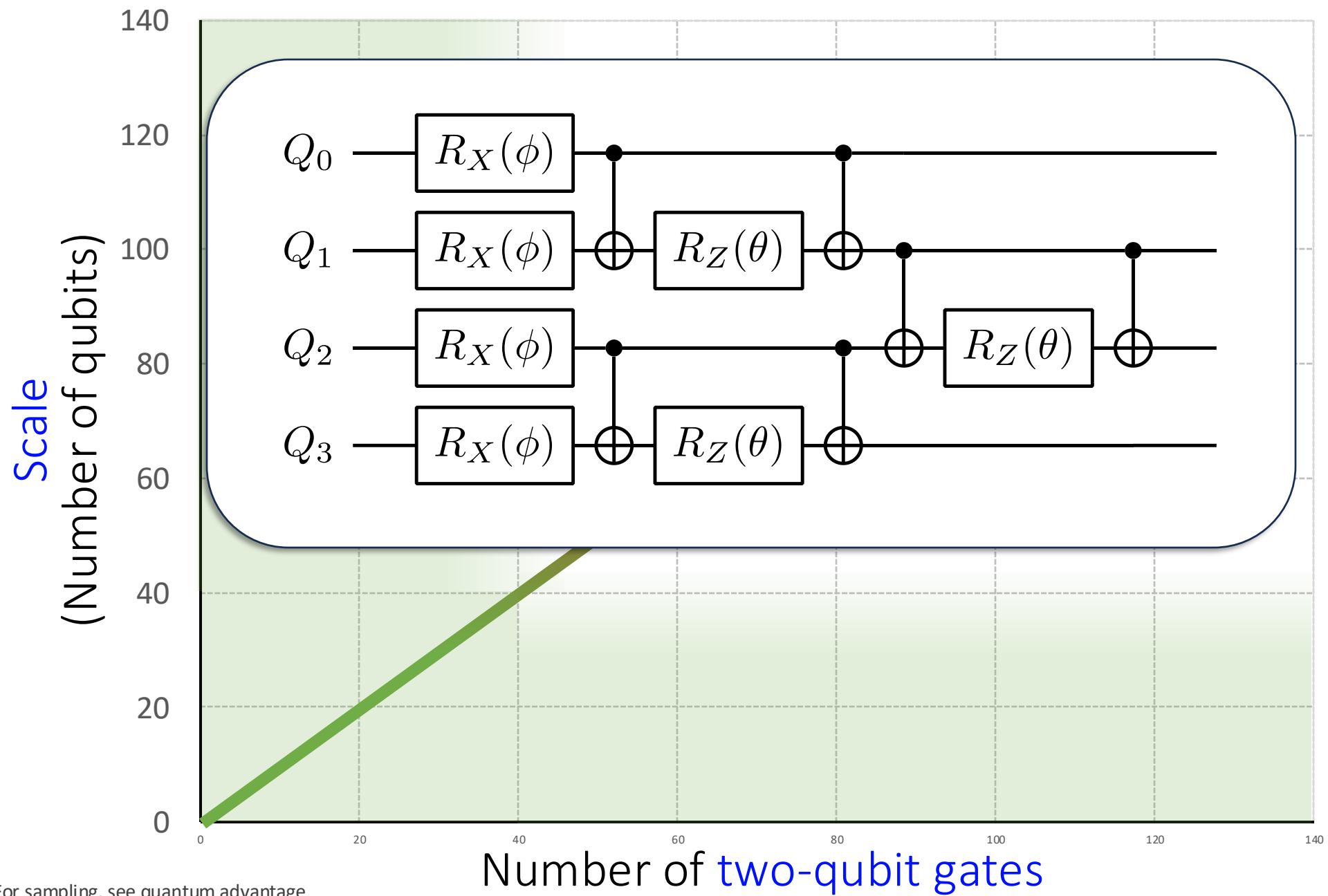


Quantum circuit complexity

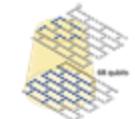
Quantum advantage: Quantum computation that delivers a significant, practical benefit beyond either brute force or approximate classical computing methods, calculating solutions in a way that is cheaper, faster or more accurate than all known classical alternatives.”
ibm.com/quantum/blog/gammabar-for-quantum-advantage



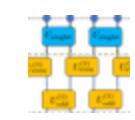
Landscape of quantum circuits



Some early utility-scale experiments



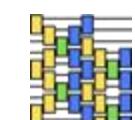
[0] Kim, Eddins, ..., Temme, Kandala.
Nature 618, 500–505 (2023)



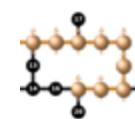
[1] Yu, Zhao, Wei.
arXiv: 2207.09994 (2022)



[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.
arXiv: 2308.13065 (2023)

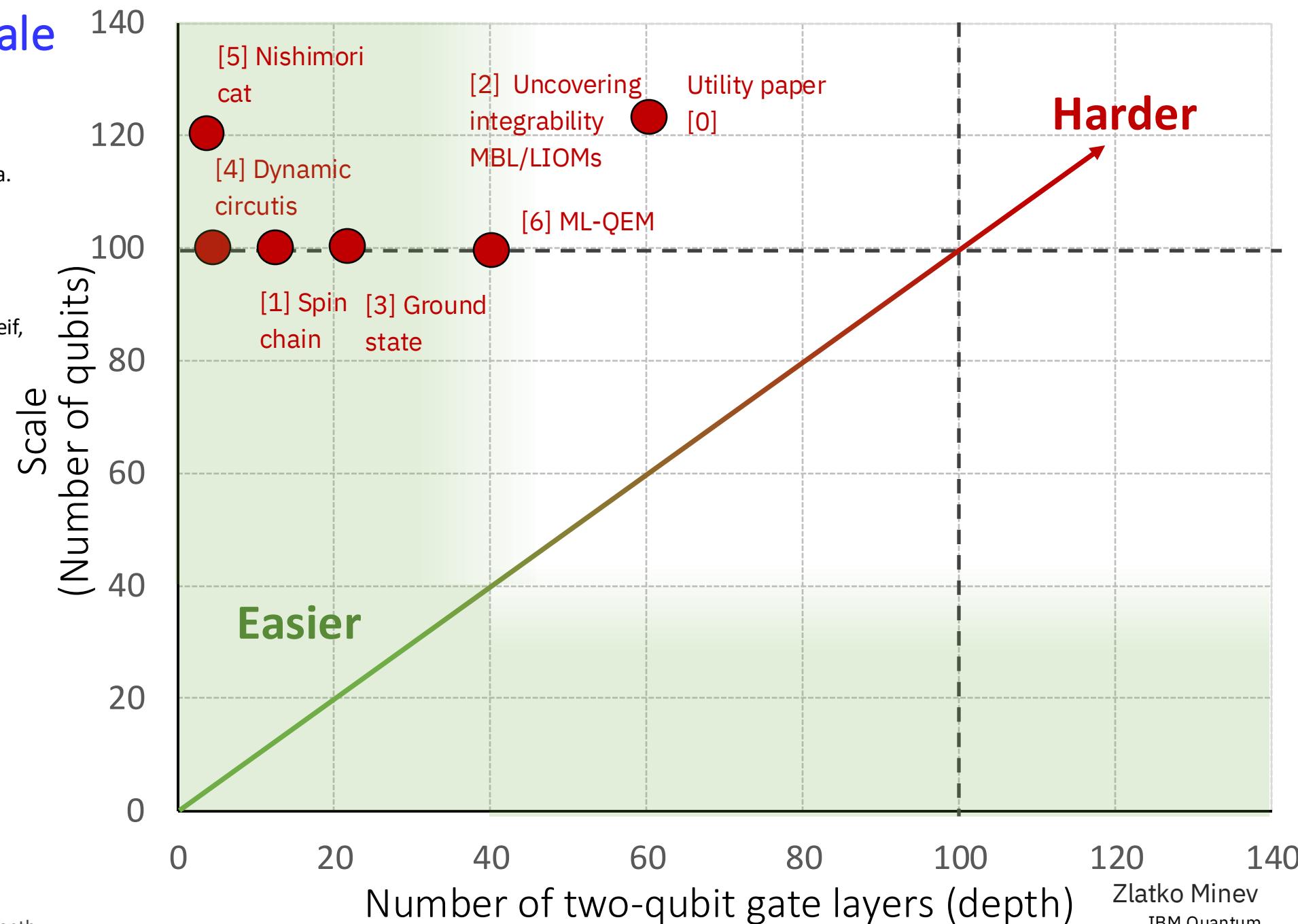


[5] Chen, Zhu, Verresen, Seif,
Bäumer, ... Trebst, Kandala.
arXiv: 2309.02863 (2023)



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

... see next slide

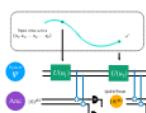


Utility-scale demos: More recent examples



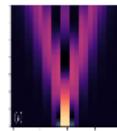
Evidence for the utility of quantum computing before fault tolerance
Nature, 618, 500 (2023)
127 qubits / 2880 CX gates

simulation



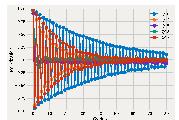
Quantum reservoir computing with repeated Measurements on superconducting devices
arXiv:2310.06706
120 qubits / 49470 ECR gates + meas.

QML



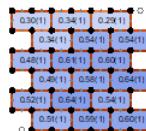
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits
arXiv:2401.08044
112 qubits / 13,858 CZ gates

simulation



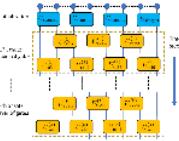
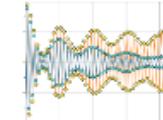
Characterizing quantum processors using discrete time crystals
arXiv:2301.07625
80 qubits / 7900 CX gates

simulation



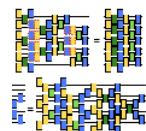
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
arXiv:2309.02863
125 qubits / 429 gates + meas.

simulation



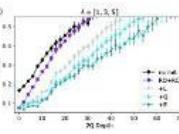
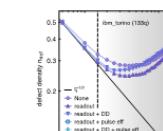
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
Phys. Rev. Research 5, 013183 (2023)
102 qubits / 3186 CX gates

simulation



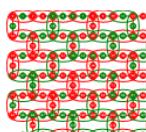
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
PRX Quantum 5, 020315 (2024)
100 qubits / 788 CX gates

simulation



Best practices for quantum error mitigation with digital zero-noise extrapolation
arXiv:2307.05203
104 qubits / 3605 ECR gates

tools



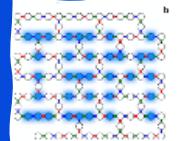
Scaling Whole-Chip QAOA for Higher-Order Ising Spin Glass Models on Heavy-Hex Graphs
arXiv:2312.00997
127 qubits / 420 CX gates

optimization

A diagram showing a complex molecular structure with atoms and bonds.

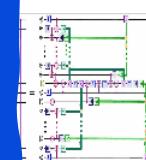
Chemistry Beyond Exact Solutions on a Quantum-Centric Supercomputer
arXiv:2405.05068
77 qubits / 3590 CZ gates

simulation



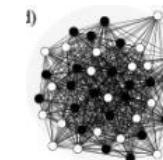
Uncovering Local Integrability in Quantum Many-Body Dynamics
arXiv:2307.07552
124 qubits / 2641 CX gates

simulation



Efficient Long-Range Entanglement using Dynamic Circuits
arXiv:2308.13065
101 qubits / 504 ECR gates + meas.

tools

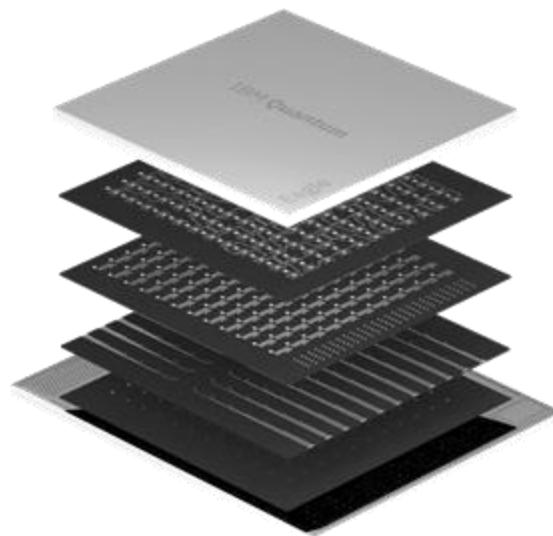


Towards a universal QAOA protocol: Evidence of quantum advantage in solving combinatorial optimization problems
arXiv:2405.09169
109 qubits / 21,200 ECR gates

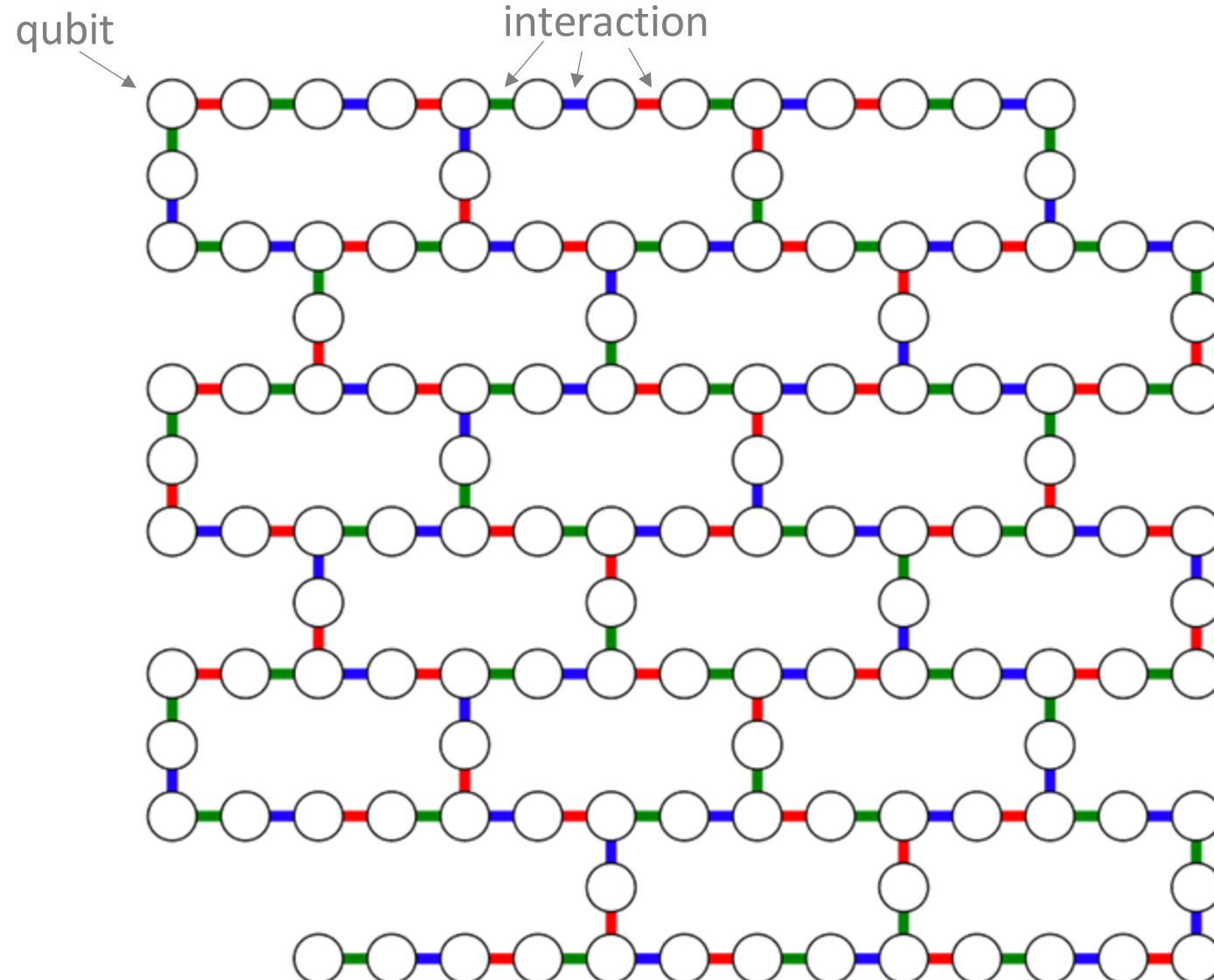
optimization

....

Many-body quantum dynamics at utility scale

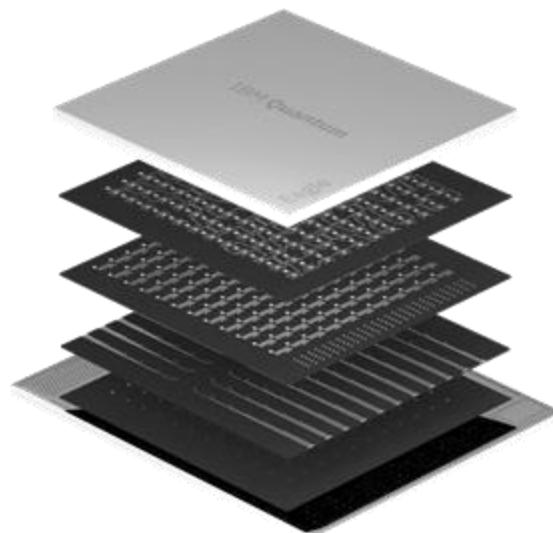


Number of qubits	124Q
Connectivity	2D h-hex
Depth in cX gates	60
Floquet steps	20
Total number of cXs	2,641

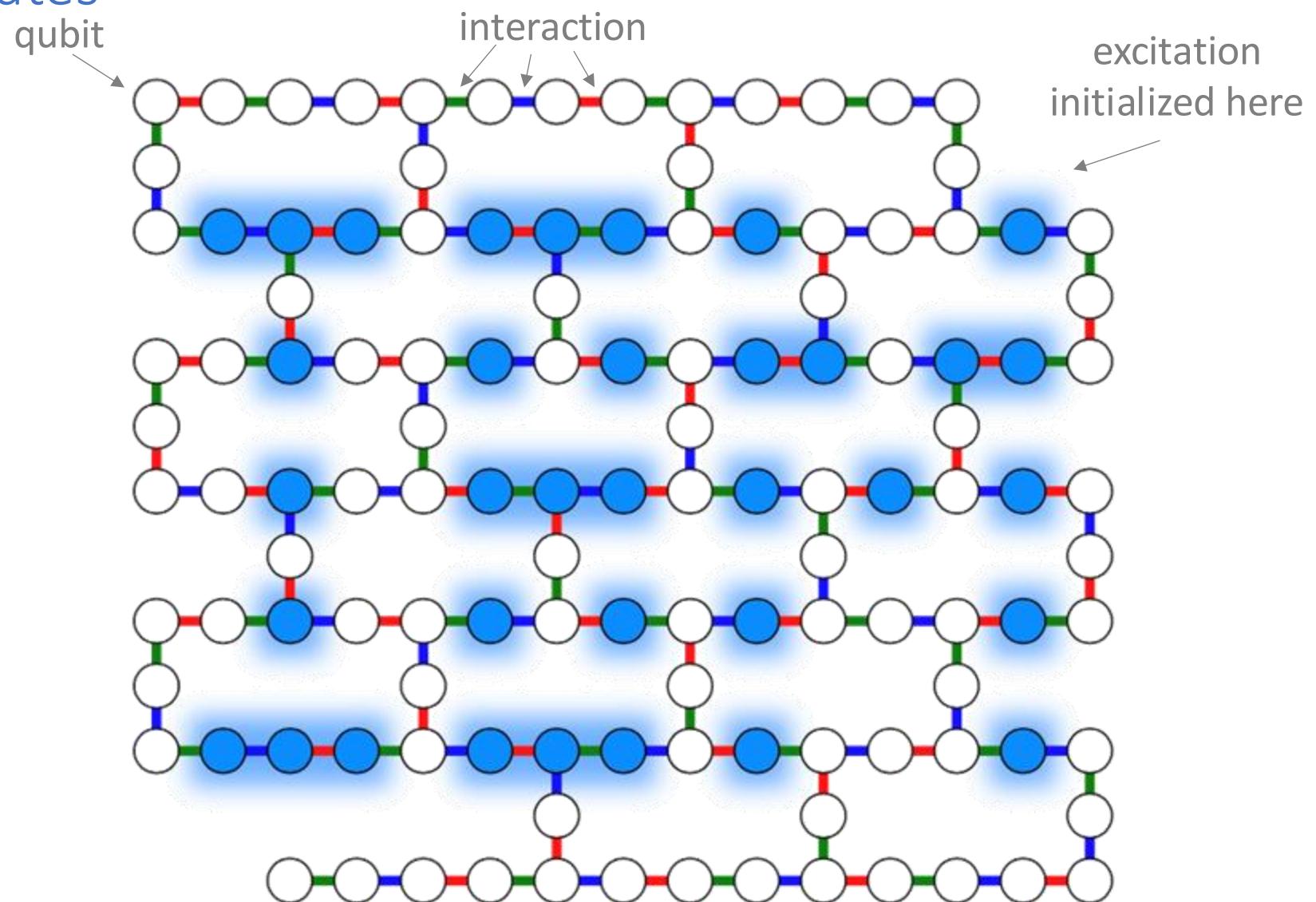


Uncovering Local Integrability in Quantum Many-Body Dynamics

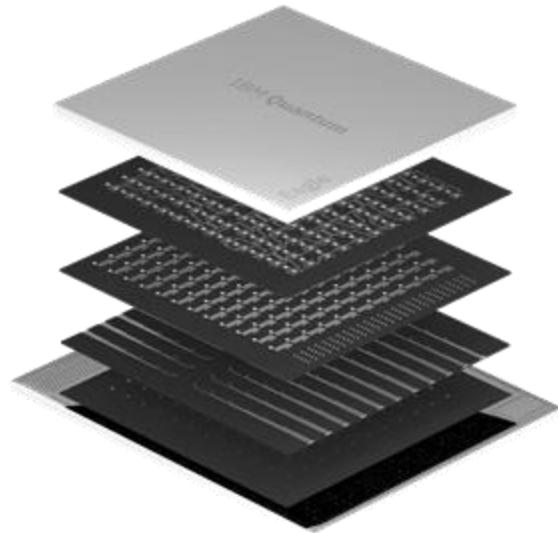
Initialize lattice in fun states



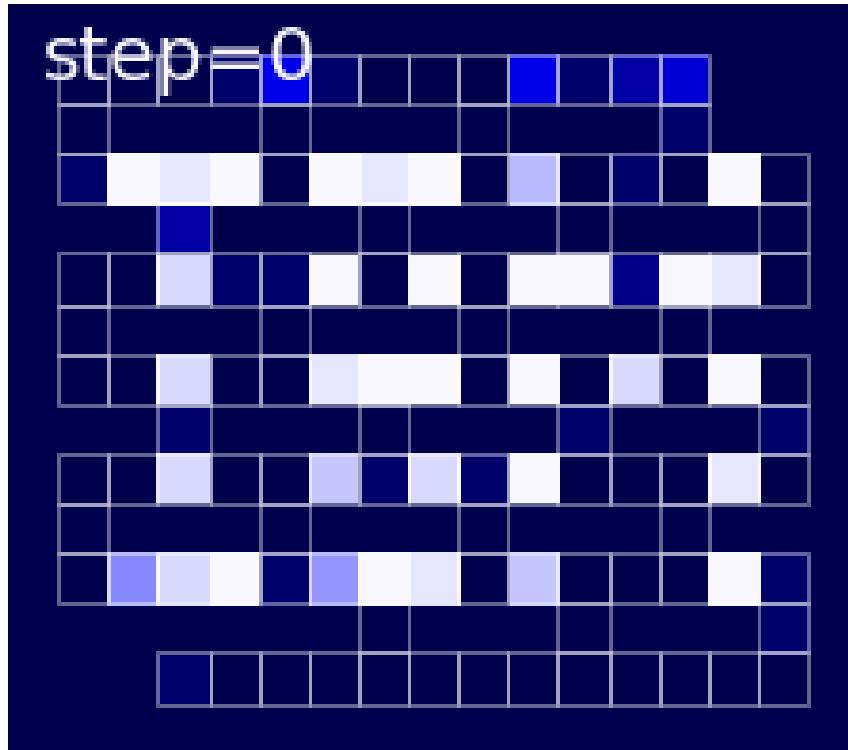
Number of qubits	124Q
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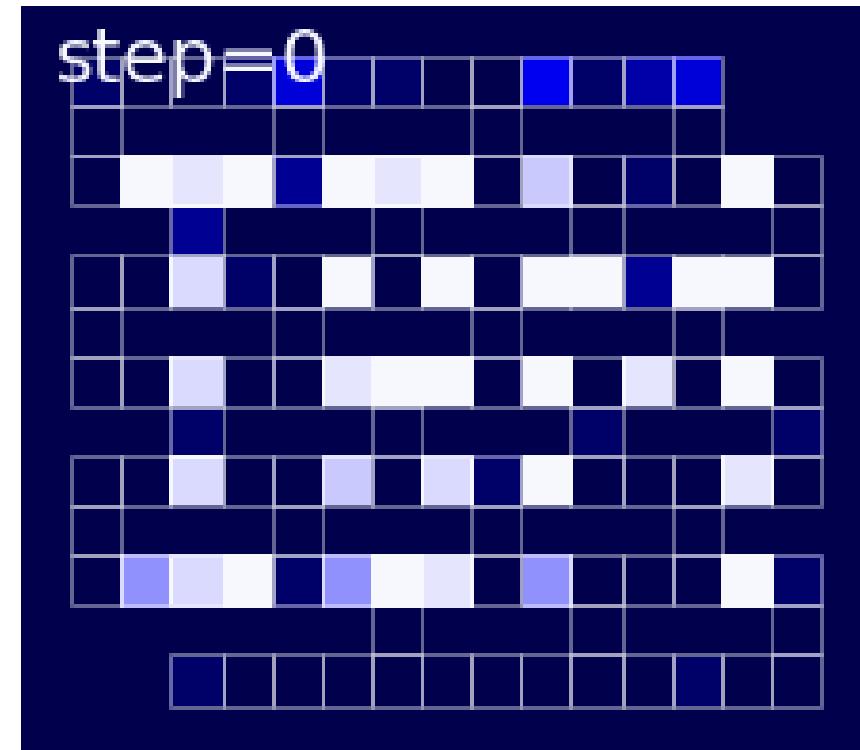
Quantum dynamics in different regimes



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

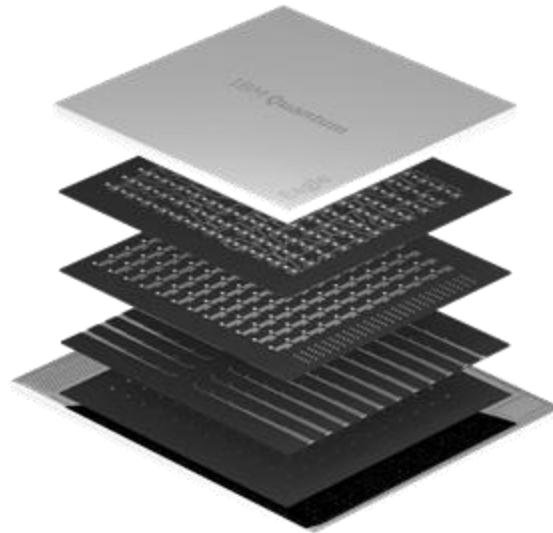


Thermalizing regime

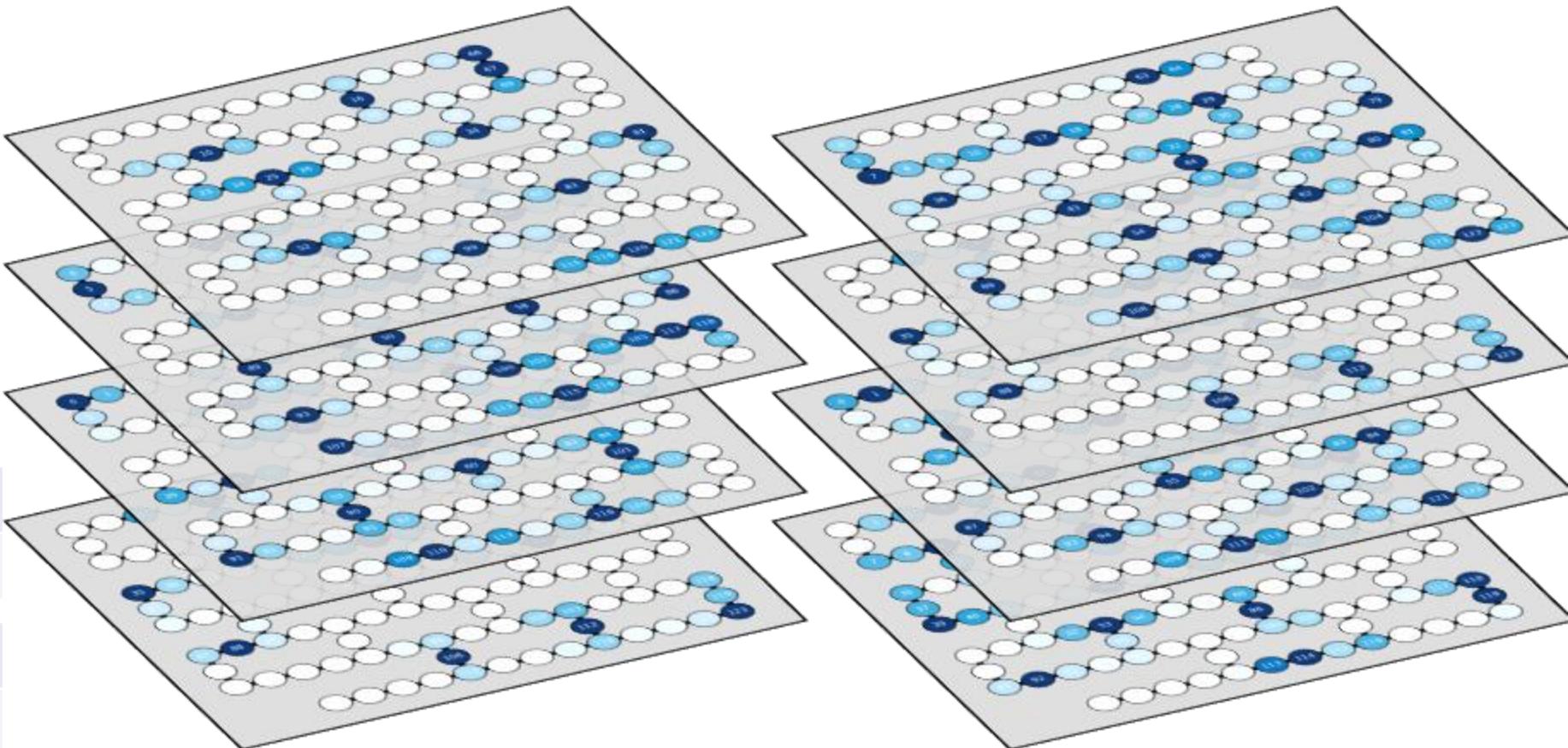


Prethermal regime

All 124 local integrals of motion (LIOMs) extracted



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

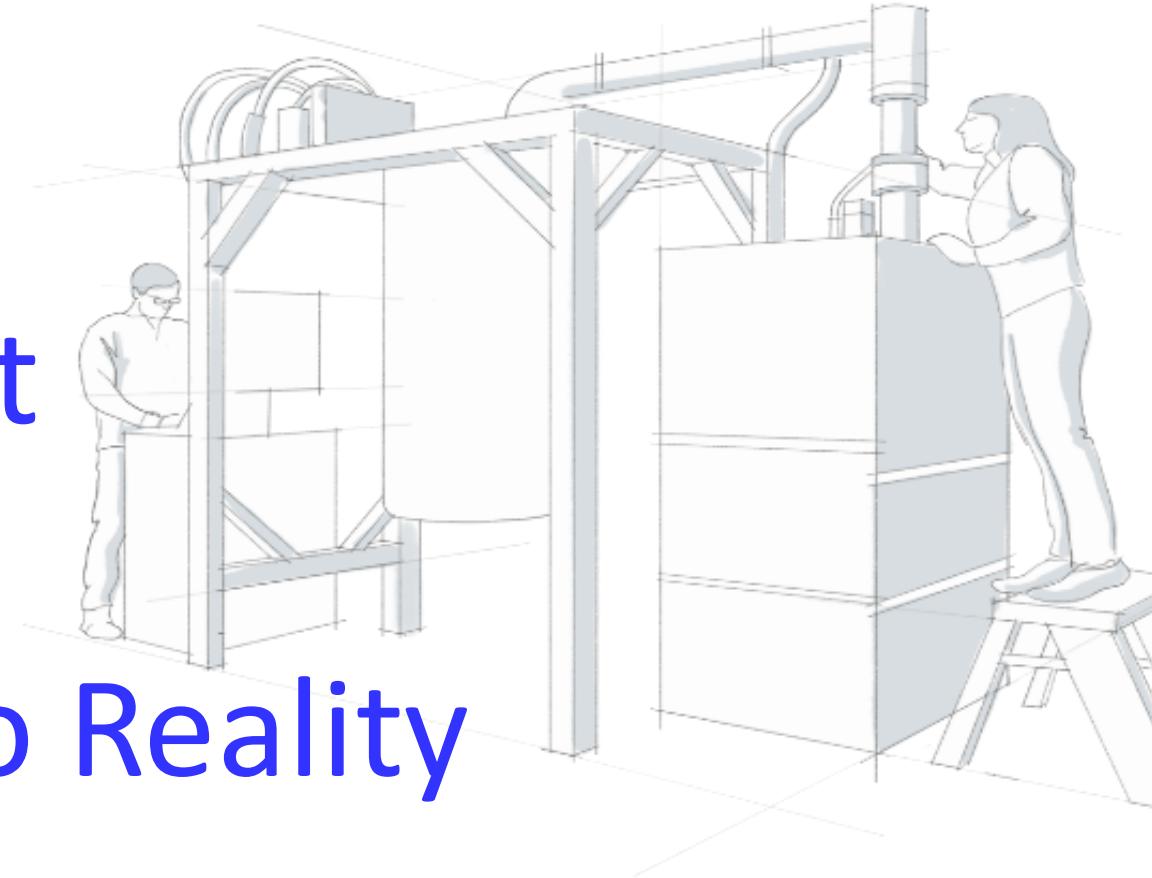


Part II

What is a qubit?

Qubit

From Idea to Reality



THE BIG PICTURE
before calculations

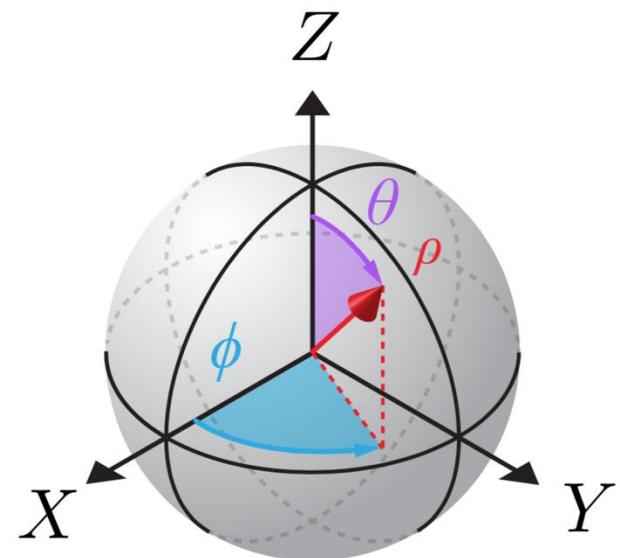
Qubit: idea

Energy levels

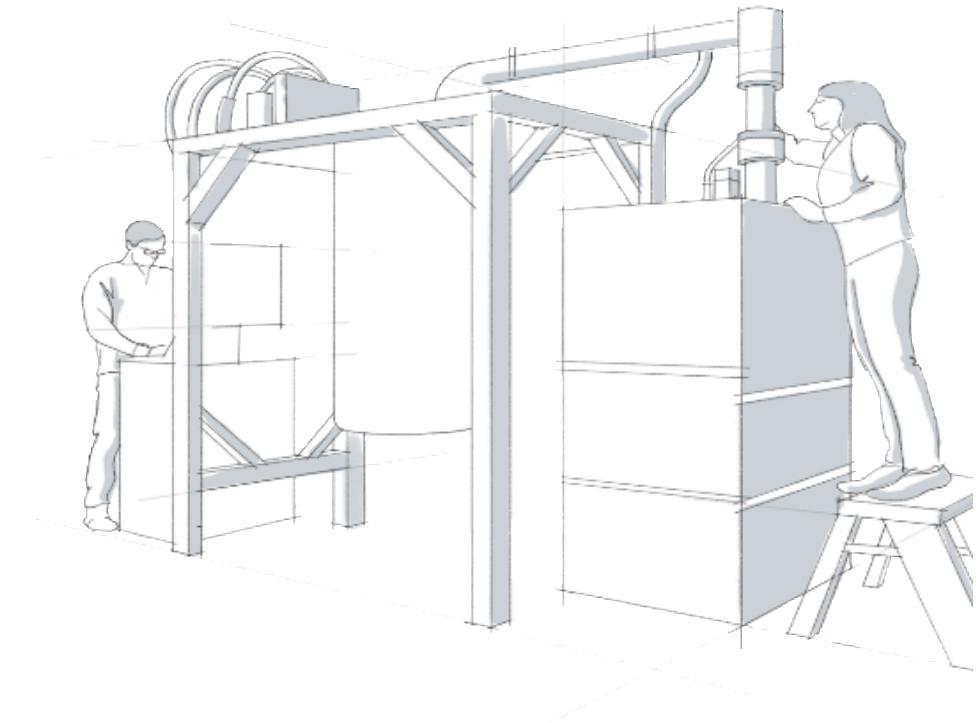
 $|1\rangle$

 $|0\rangle$

Hilbert space



Quantum cloud?



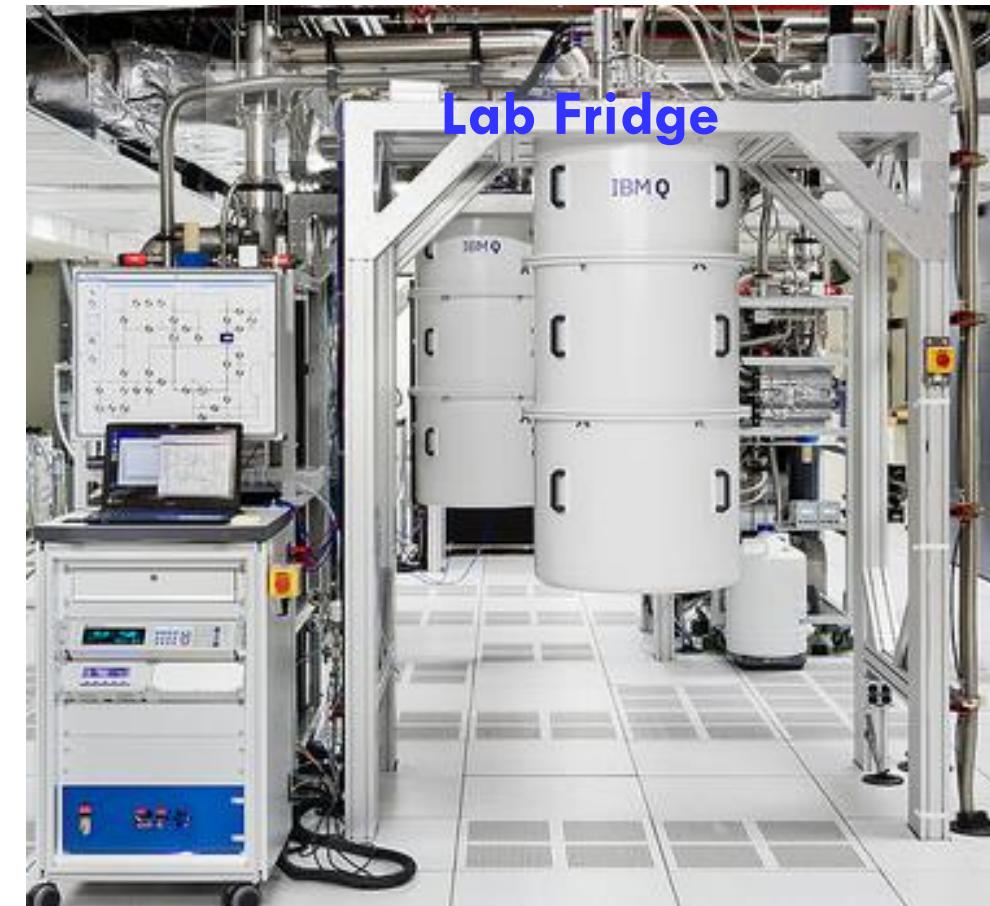
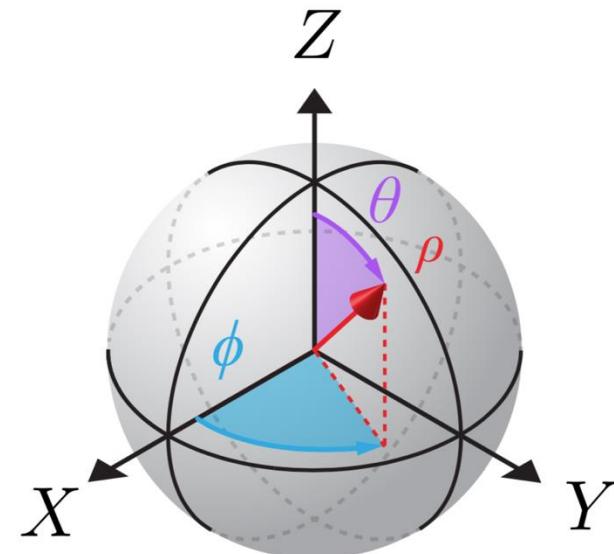
Qubit: idea and reality

Energy levels

 $|1\rangle$

 $|0\rangle$

Hilbert space



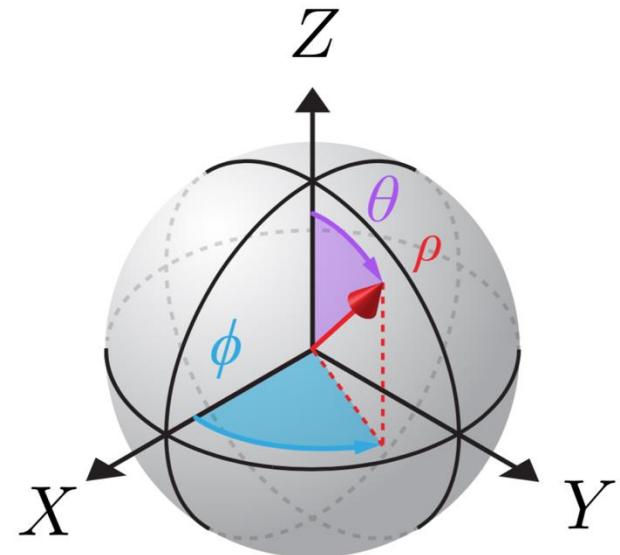
Qubit: idea and reality

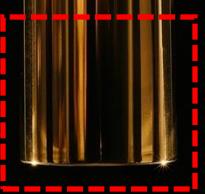
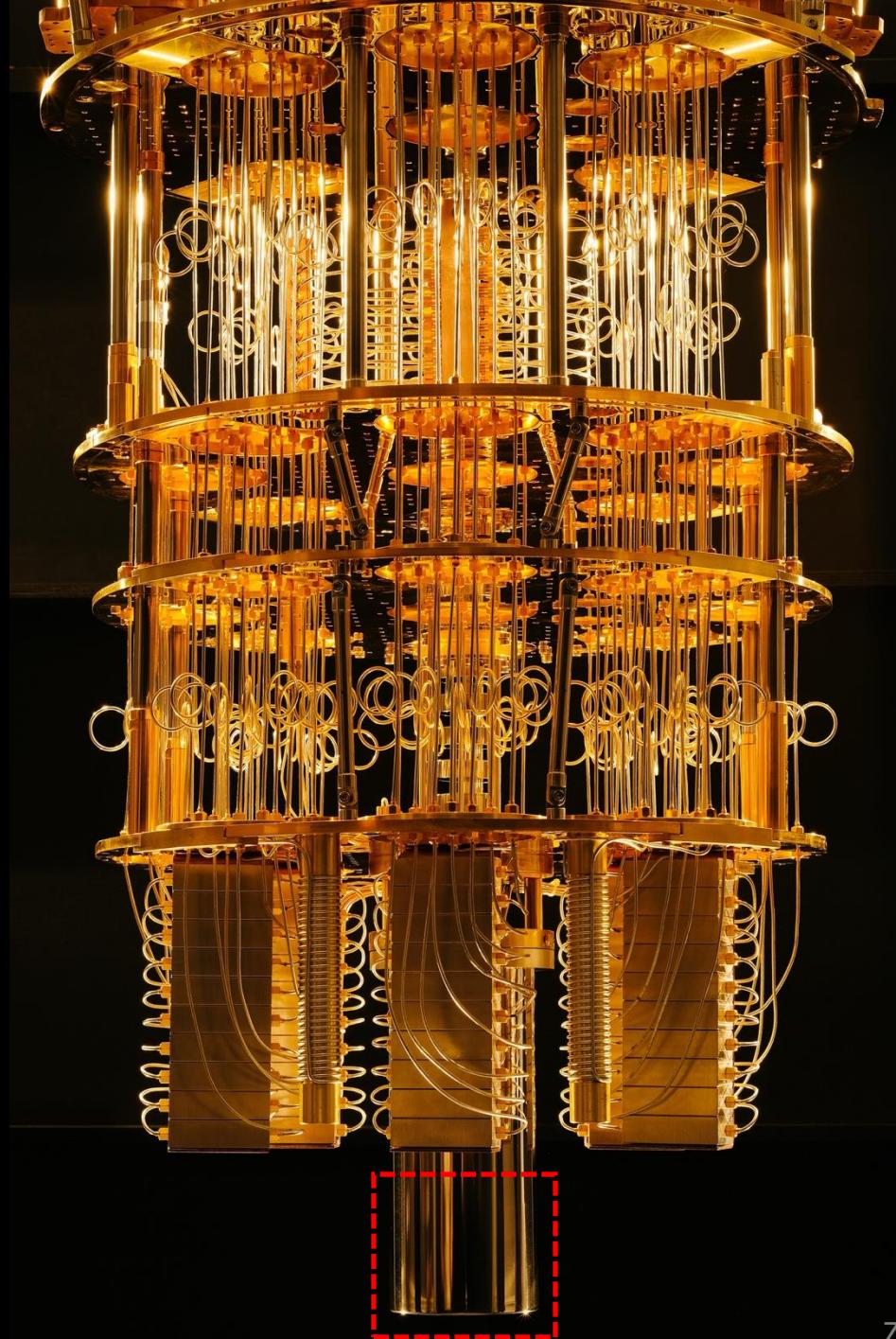
Energy levels

 $|1\rangle$

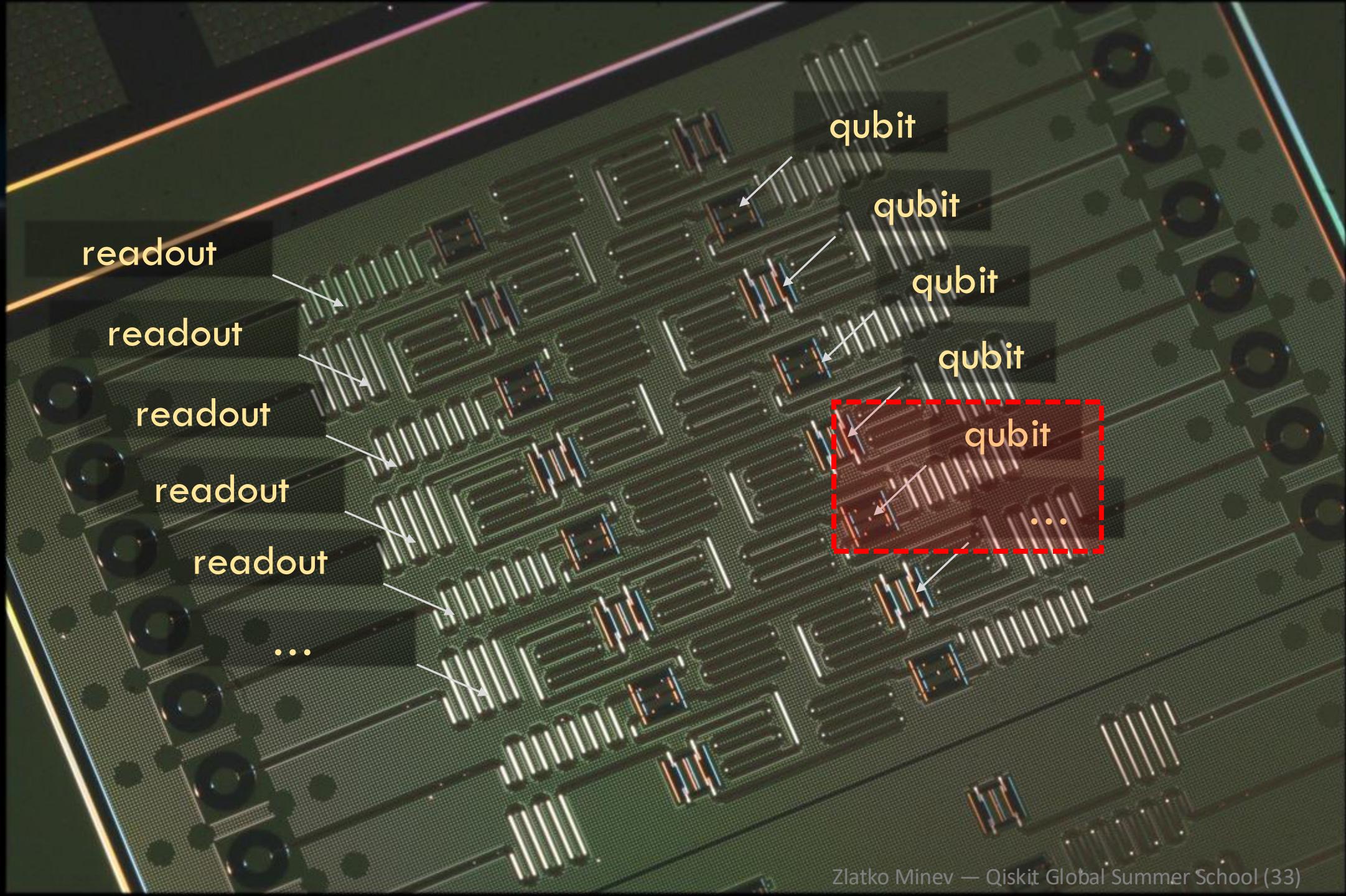
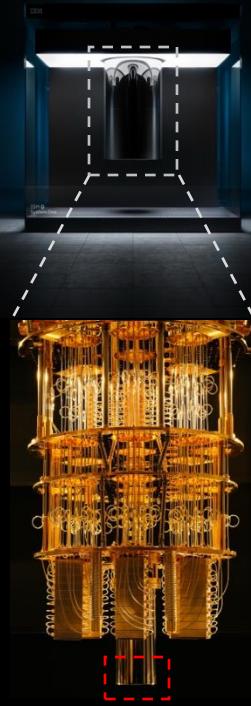
 $|0\rangle$

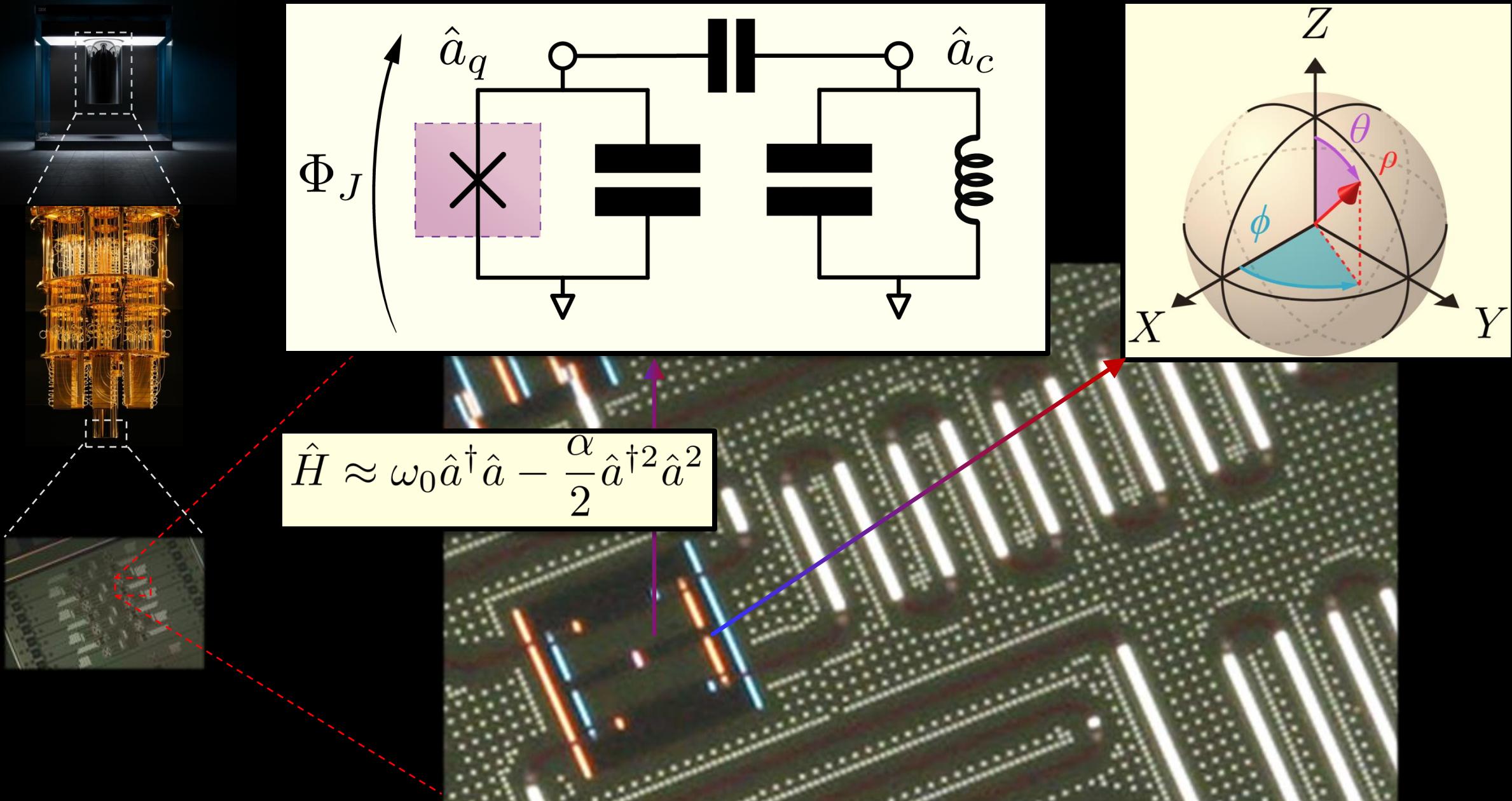
Hilbert space



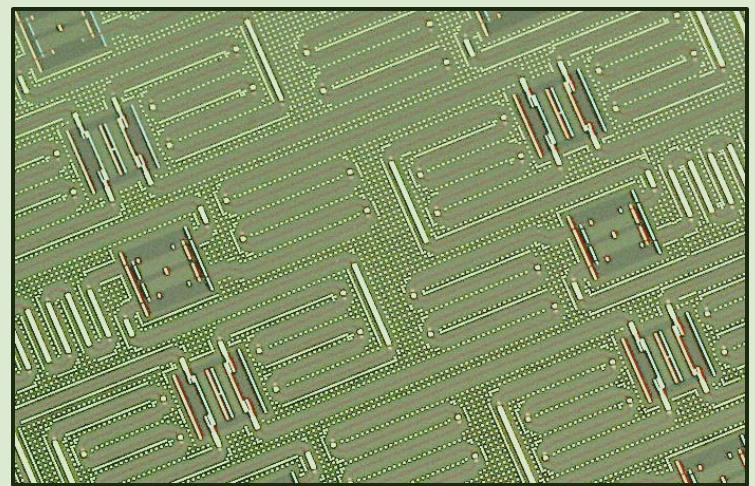
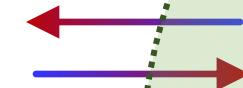
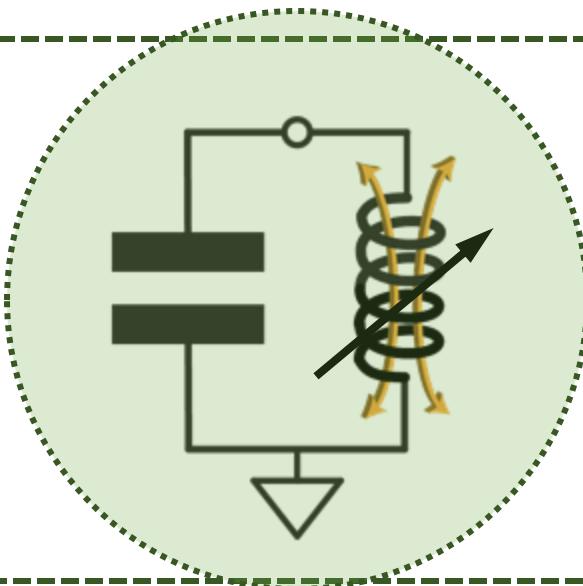
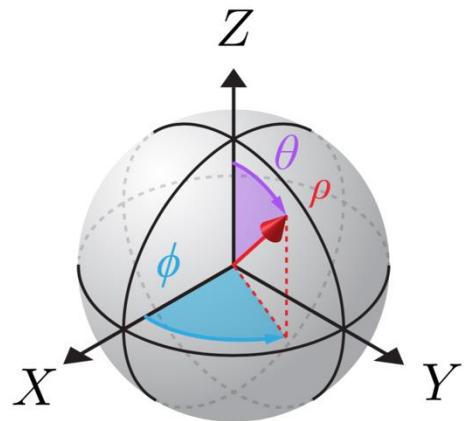
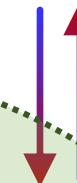
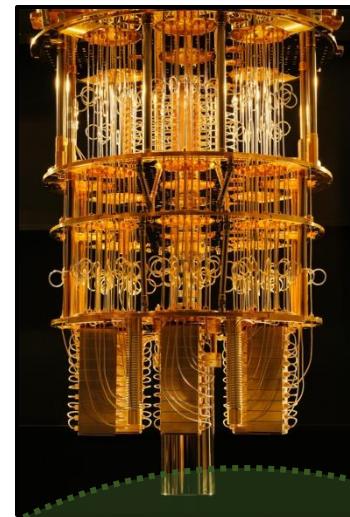


Operation at
15 mK (-273.13 °C)





cQED qubit in the cloud: Summary of flow



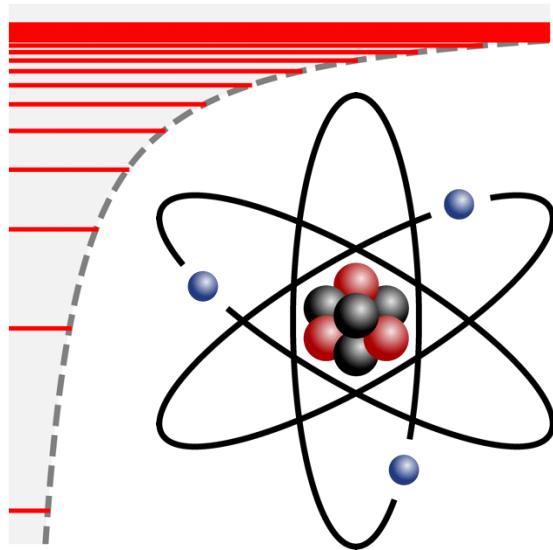
Qubit

From Idea to Reality

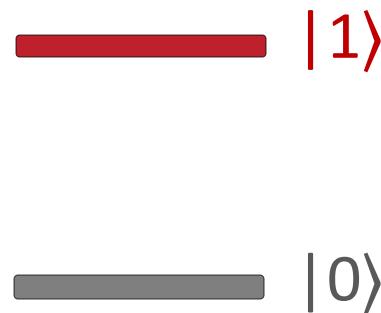
Concepts

From qubit representation to reality

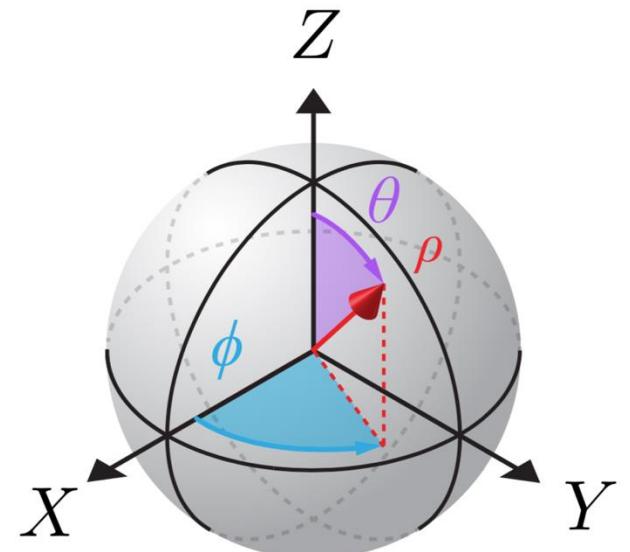
Realization



Energy levels



Hilbert space*



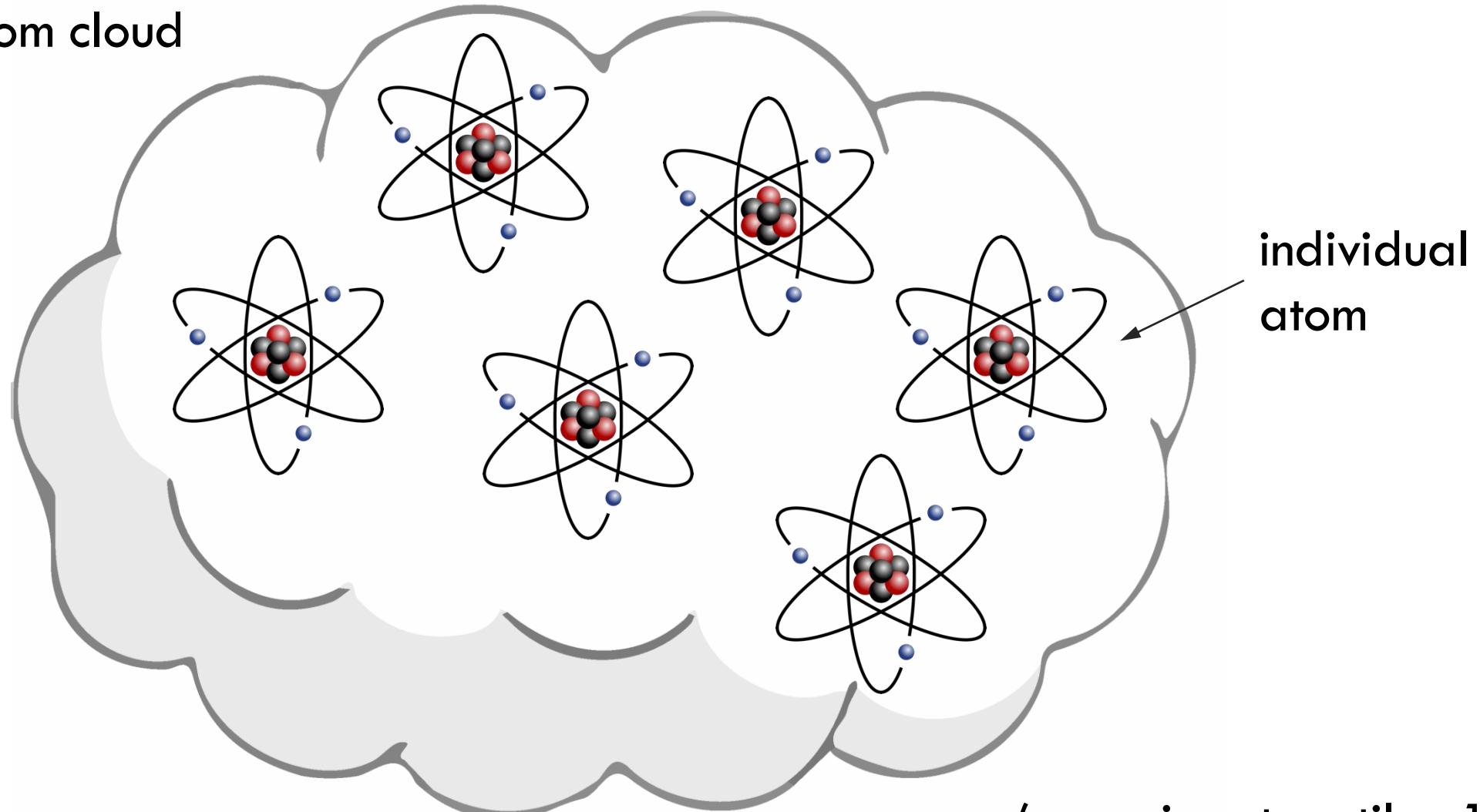
* Bloch sphere is a mere geometrical representation of $SO(3)$, but the density matrix ρ is in $SU(2)$, a double cover of $SO(3)$.

* A density matrix operator lives not in the Hilbert space H but in the Liouville space $H \otimes H$.

Images: Minev, arXiv:1902.10355; atom art: Indoleces.

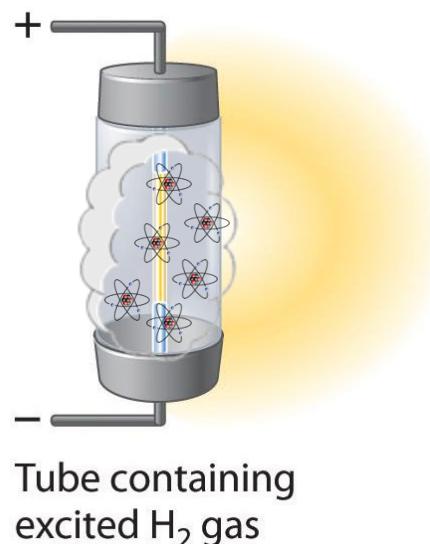
Origins of quantum

e.g., atom cloud

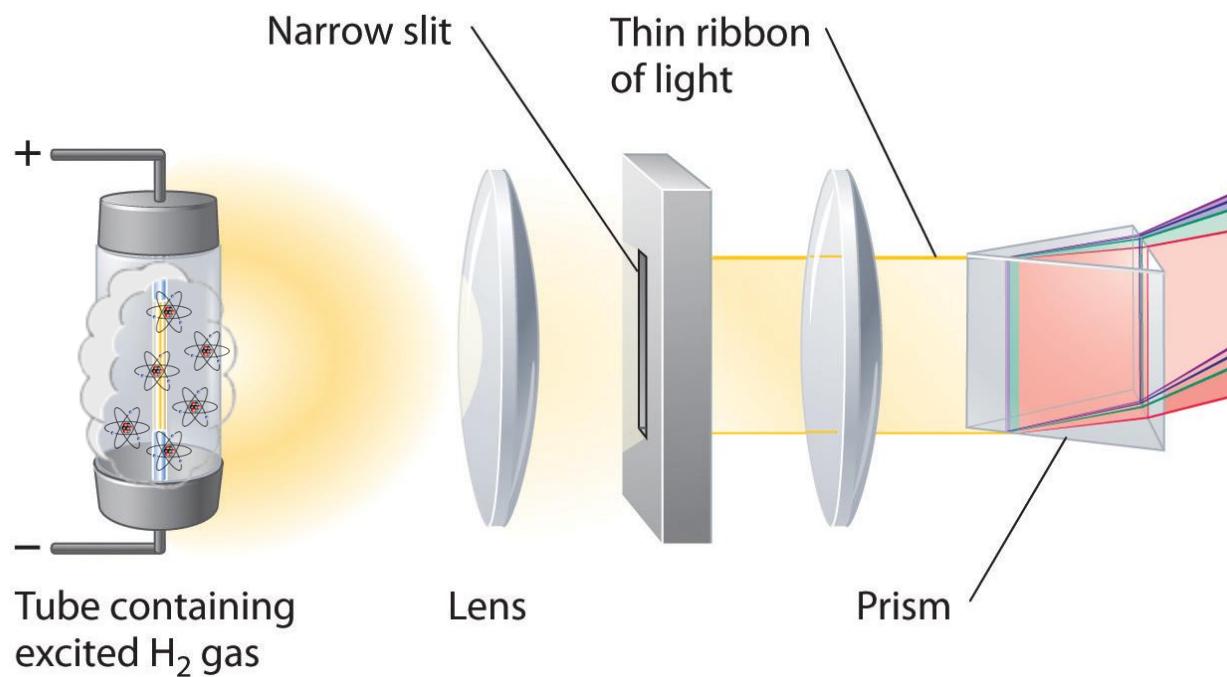


(experiments until c. 1980)

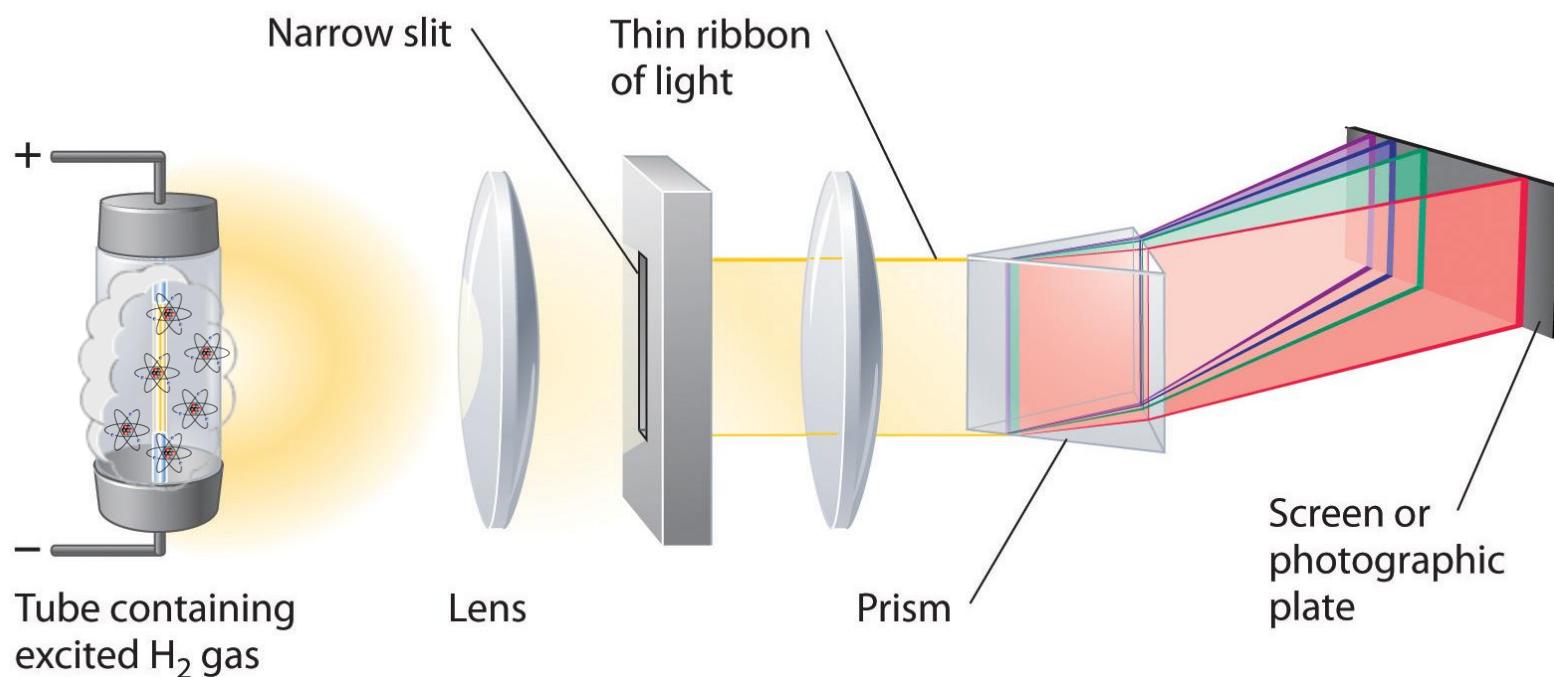
Atomic emission of light



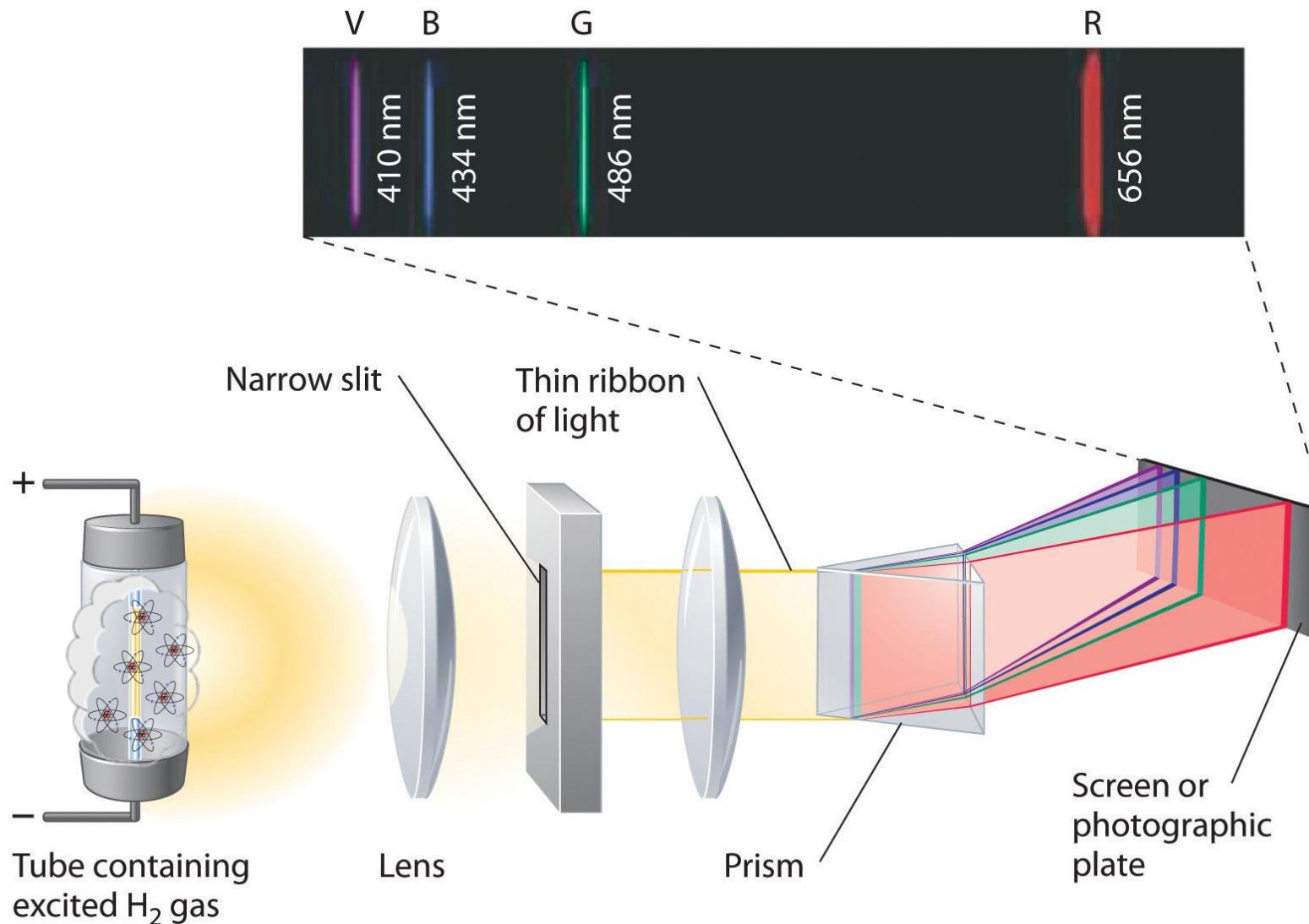
Atomic emission of light



Atomic emission of light



Atomic emission of light



Quantized levels

Atomic emission spectra

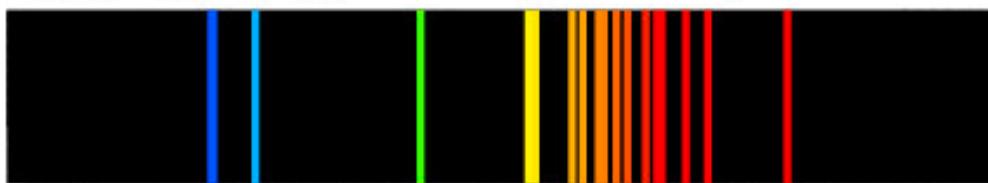
Hydrogen



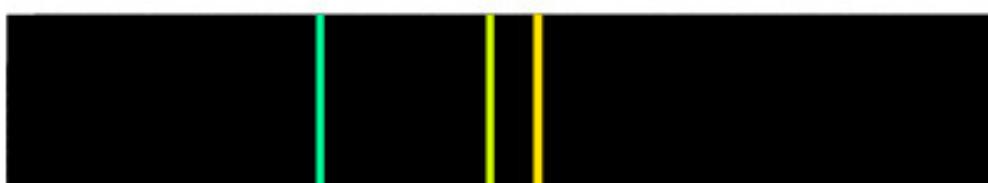
Helium



Neon



Sodium



Mercury

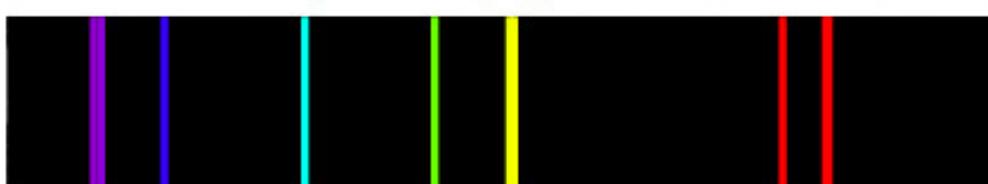
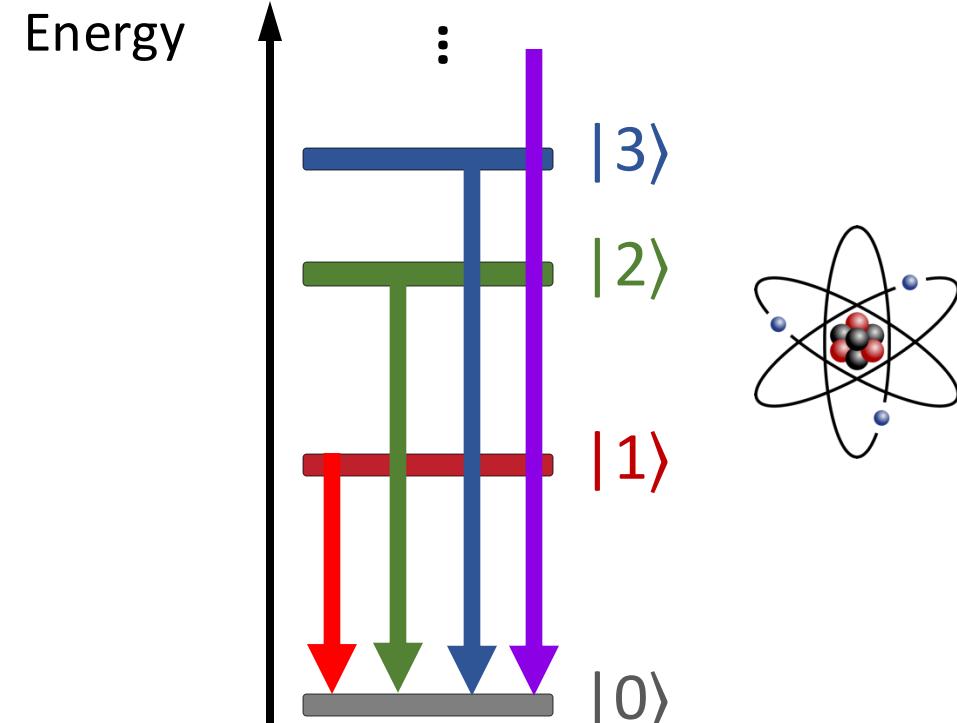


Image credit: NMSU, N. Vogt

**Atoms are quantum:
discrete intrinsic energy levels***



Quantization of energy

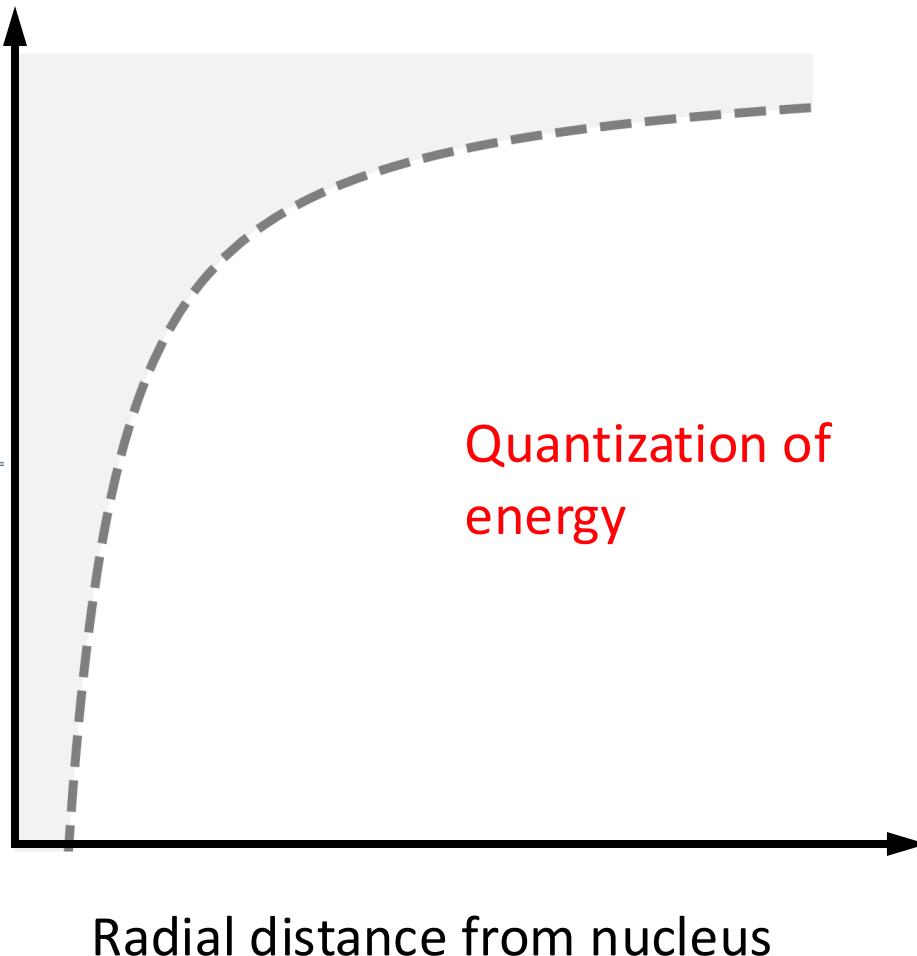
* The notion of an energy level was proposed by Bohr in 1913.
Zlatko Minev — Qiskit Global Summer School 2020 (43)

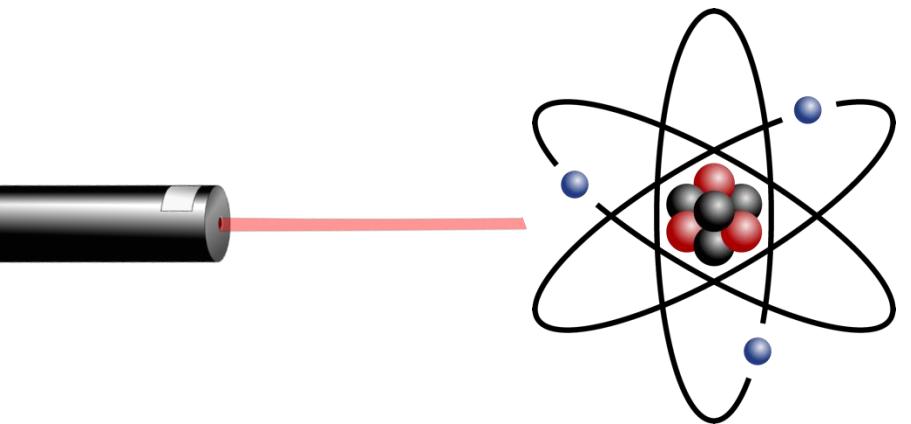
The light of atoms



Atomic energy levels and transitions

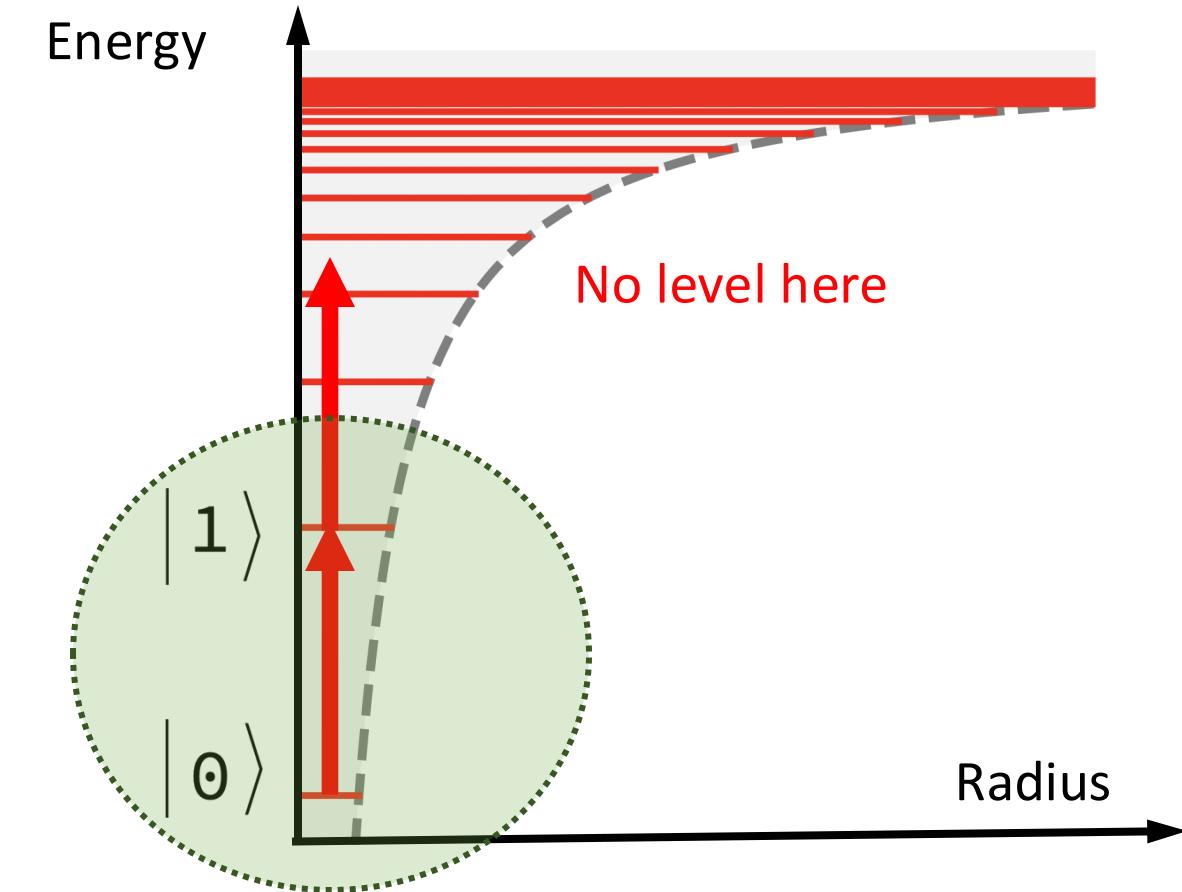
Electron potential-energy landscape





Qubit from Atom

Anharmonic degree of freedom and spin



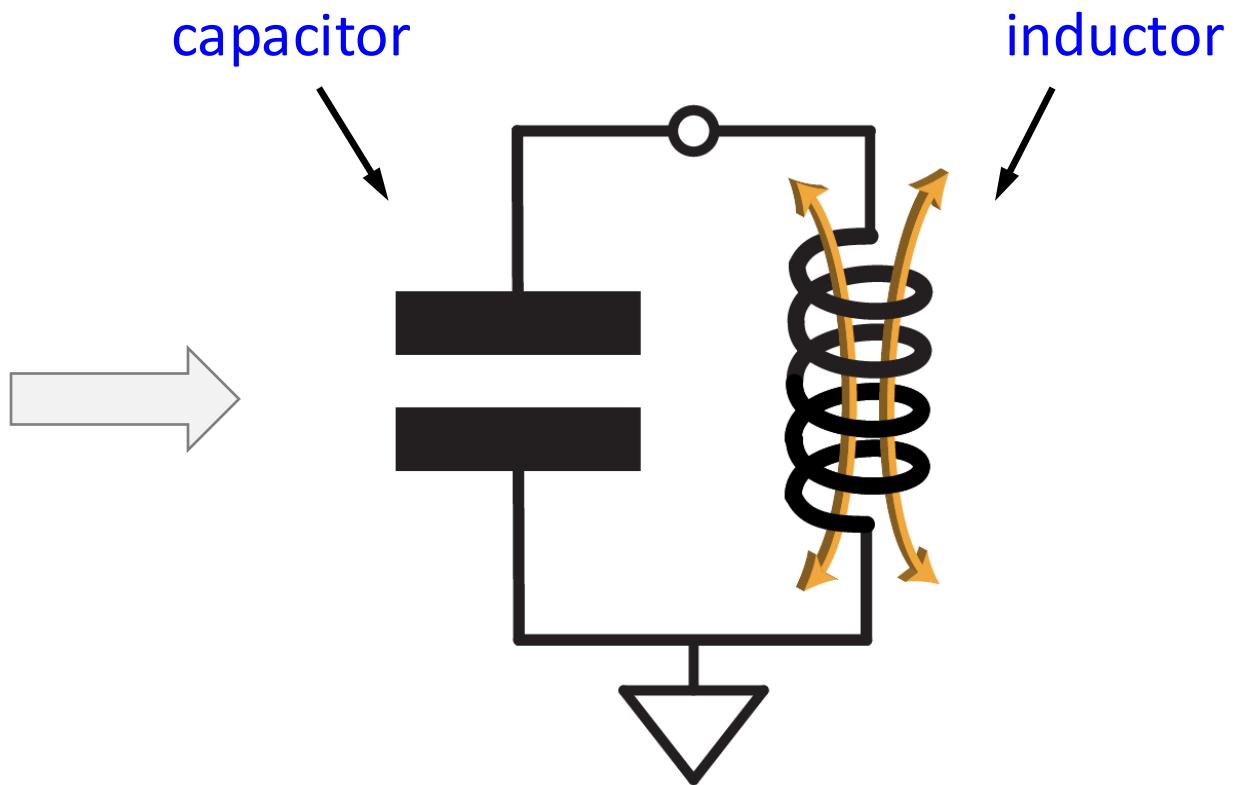
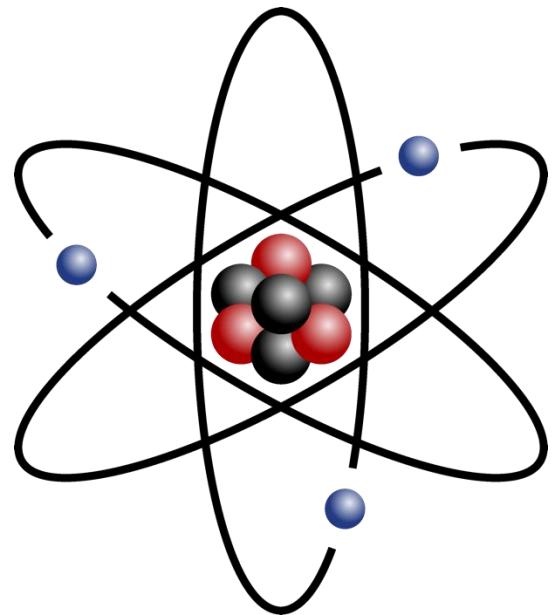
Isolated from environment and thermal bath

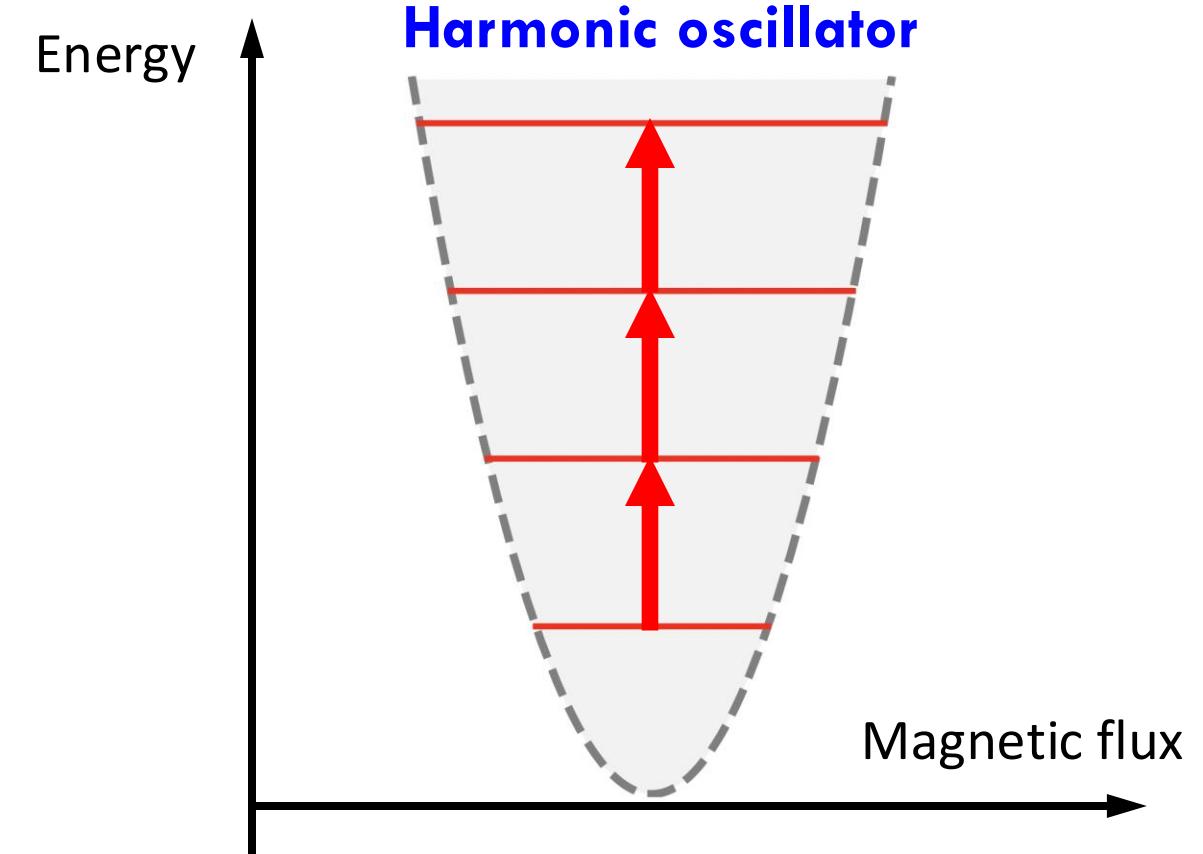
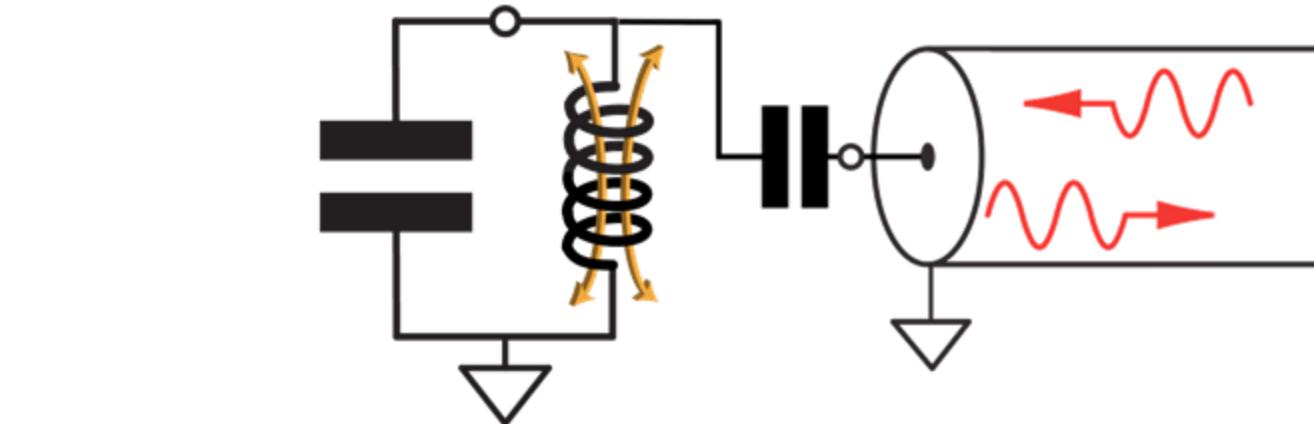
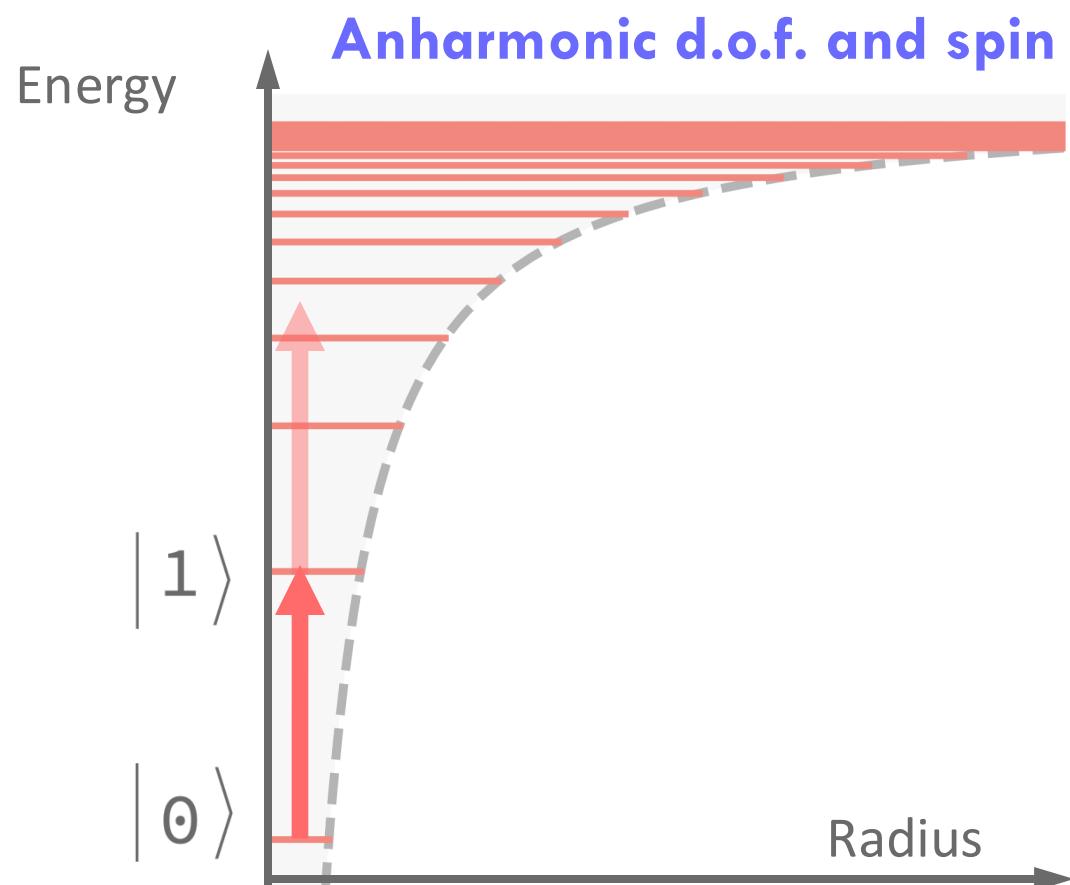
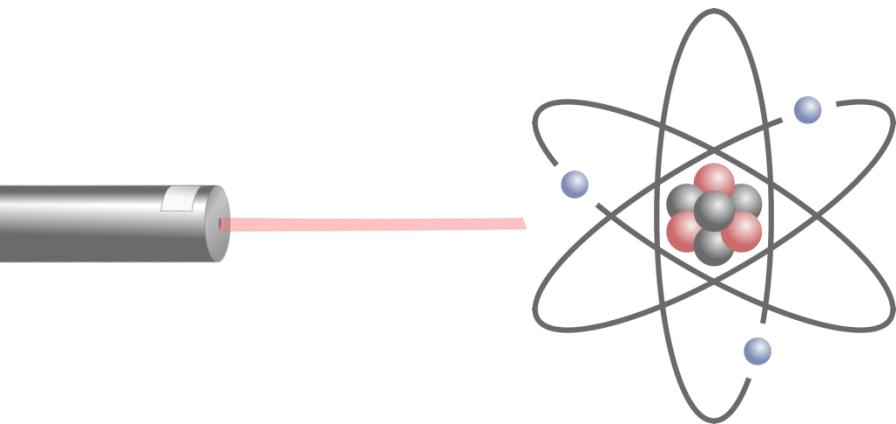
Low-loss

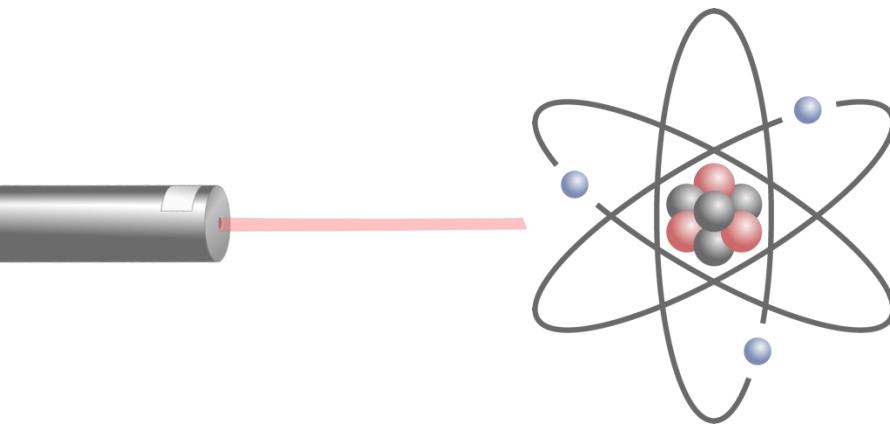
Level diagram allows for qubit-specific control and readout

There are always more than two levels

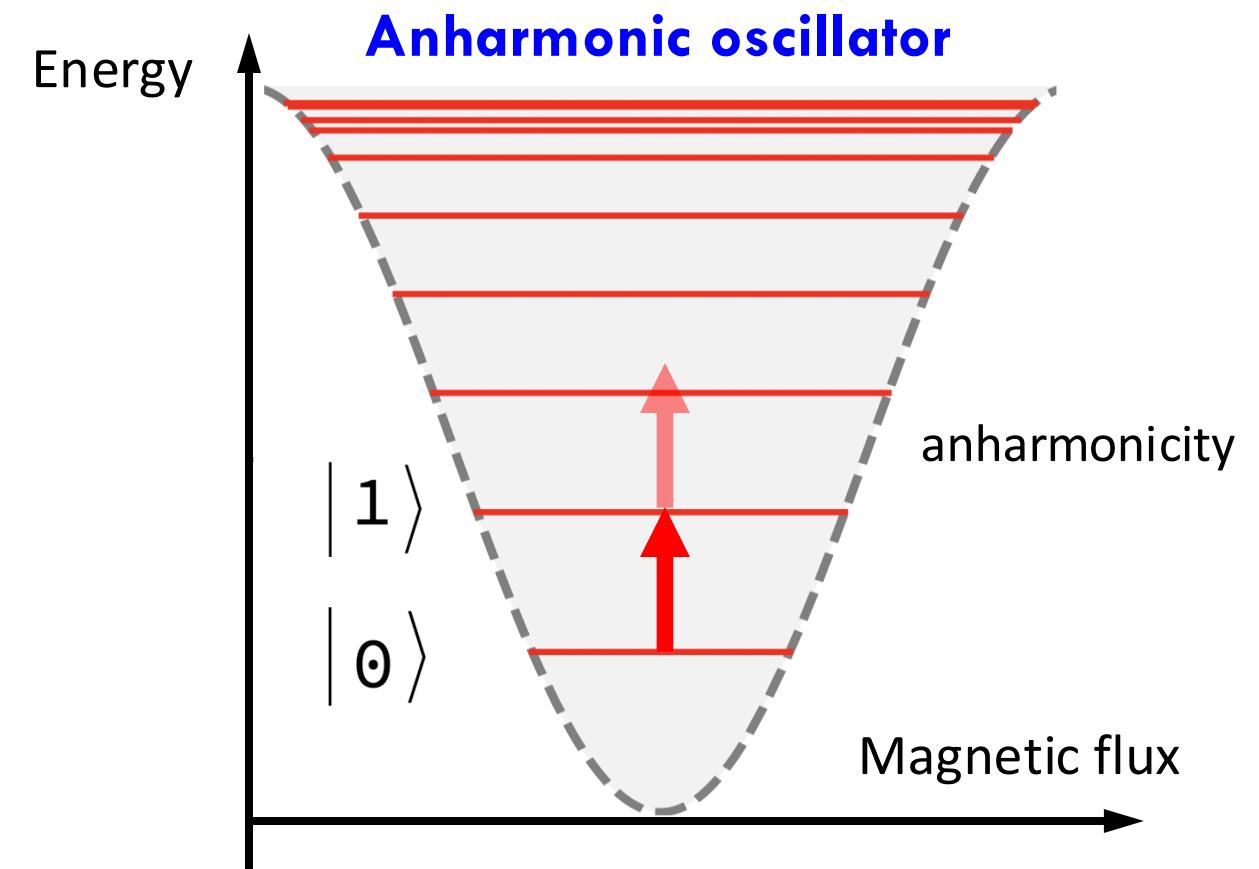
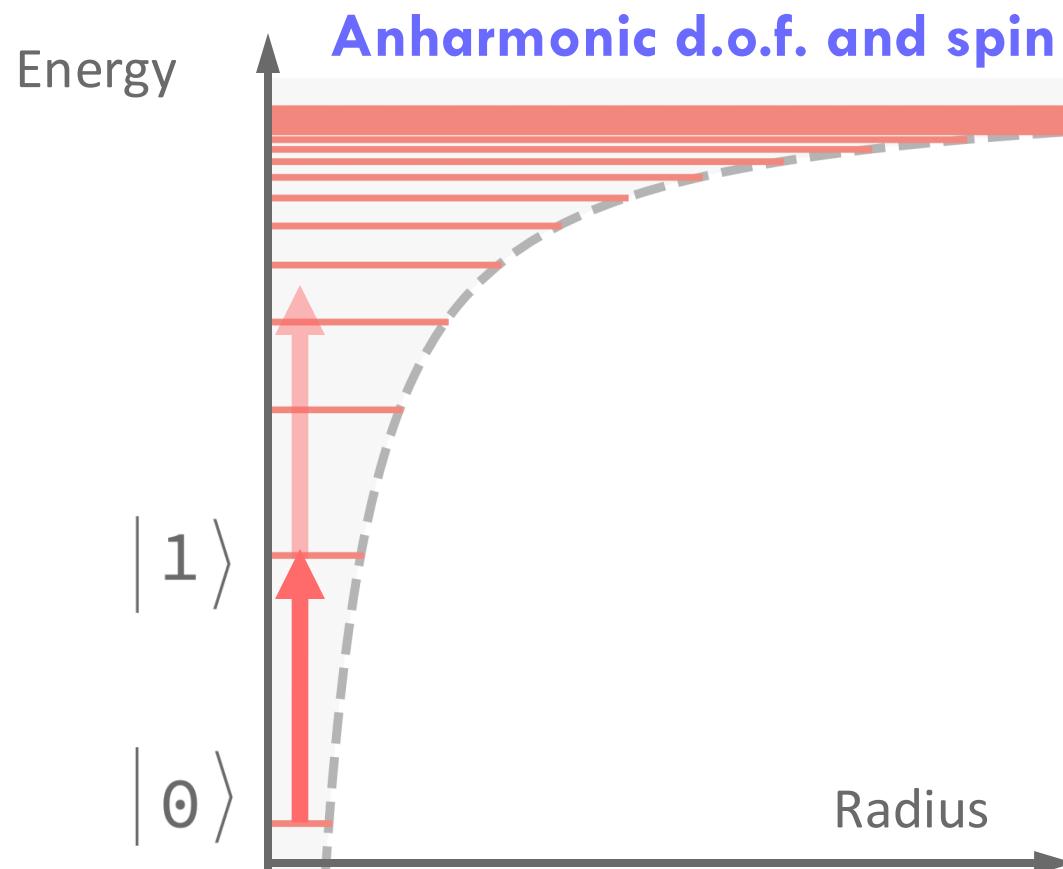
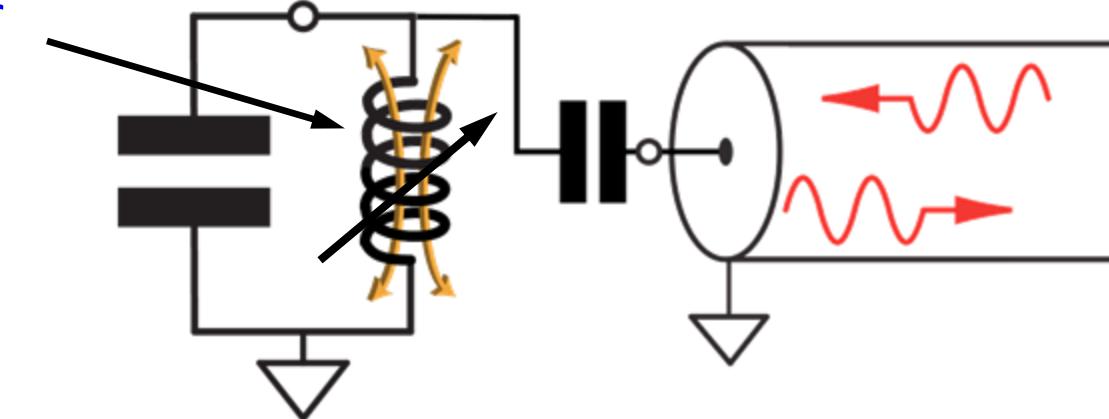
Artificial atoms







non-linear
inductor



Big-picture connections

Idealization of
qubit

$|1\rangle$

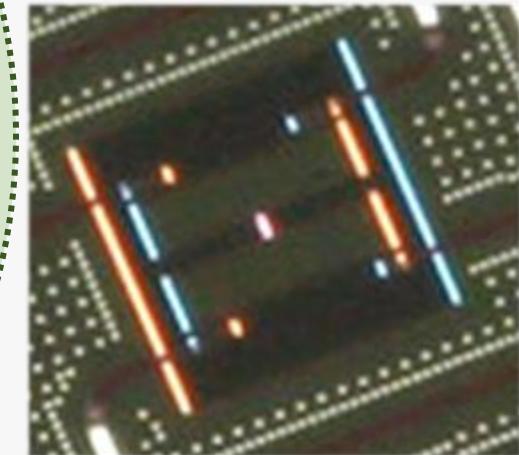
$|0\rangle$

Anharmonic
oscillator

Physical circuit
model

Circuit Quantum
Electrodynamics
(cQED)

Physical layout



Idealization

Physical reality

There are two kinds of physicists:

Those who believe all of physics is *spins*.

Those who believe all of physics is *oscillators*.

A few introductory reviews

And many more... check online or ask us for specific topic

Qiskit Textbook (2020; more chapters coming)

Blais, A., Grimsmo, A. L., Girvin, S. M., & Wallraff, A. (2020)
Circuit Quantum Electrodynamics (*arXiv:2005.12667*)

Kjaergaard, M., Schwartz, ... Oliver, W. D. (2020)
Superconducting Qubits: Current State of Play
Annual Reviews of Condensed Matter Physics 11, 369-395

Krantz, P., Kjaergaard, M., Yan, F., ... & Oliver, W. D. (2019)
A quantum engineer's guide to superconducting qubits
Applied Physics Reviews, 6(2), 021318

Corcoles, A. D., Kandala, A., ... Gambetta, J. M. (2019)
Challenges and Opportunities of Near-Term Quantum Computing Systems. *Proceedings of the IEEE*, 1–15.

Wendin, G. (2017)
Quantum information processing with superconducting circuits. *Reports on Progress in Physics*, 80(10), 106001

Gambetta, J. M., Chow, J. M., & Steffen, M. (2017)

Building logical qubits in a superconducting quantum computing system. *Npj Quantum Information*, 3(1), 2

Girvin, S. M. (2011) Circuit QED: superconducting qubits coupled to microwave photons. *Quantum machines: measurement and control of engineered quantum systems*, 113, 2.

Clerk, A. A., Girvin, S. M., Marquardt, F., & Schoelkopf, R. J. (2010)
Introduction to quantum noise, measurement, and amplification
Reviews of Modern Physics, 82(2), 1155–1208

Clarke, J., & Wilhelm, F. K. (2008)
Superconducting quantum bits. *Nature*, 453(7198), 1031–1042

Devoret, M. H. (1997)
Quantum Fluctuations in Electrical Circuits.
In *Fluctuations Quantiques/Quantum Fluctuations* (p. 351)

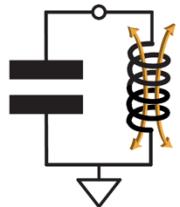
...

Qiskit Global Summer School – Minev lectures on cQED

Superconducting Qubits I:

Making Your First Qubit From an Oscillator

Introduction to Circuit
Quantum Electrodynamics (cQED)



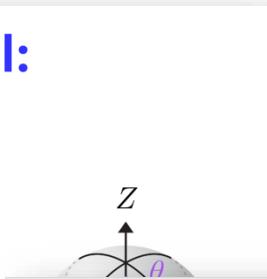
Zlatko K. Minev

IBM Quantum
IBM T.J. Watson Research Center, Yorktown Heights, NY

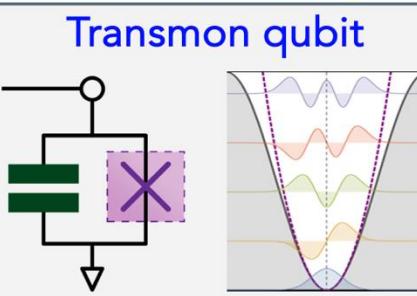
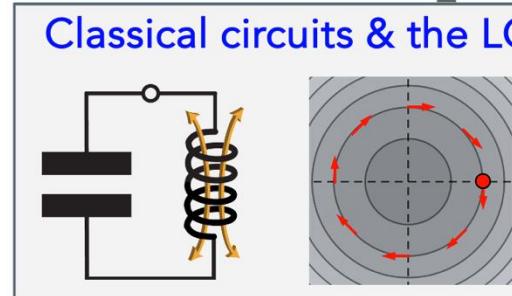
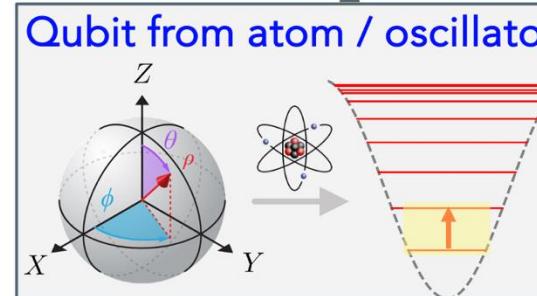
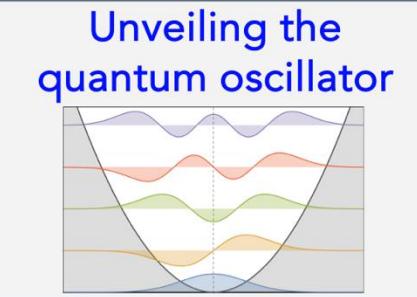
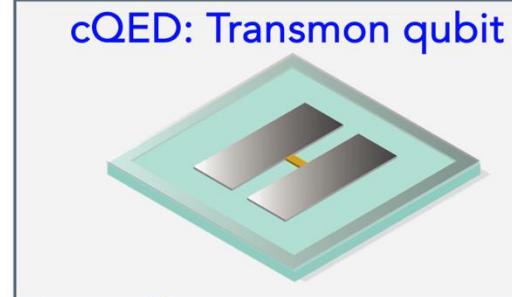
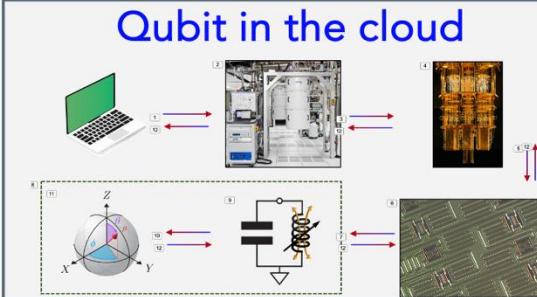
@zlatko_minev

zlatko-minev.com

Find on the internet



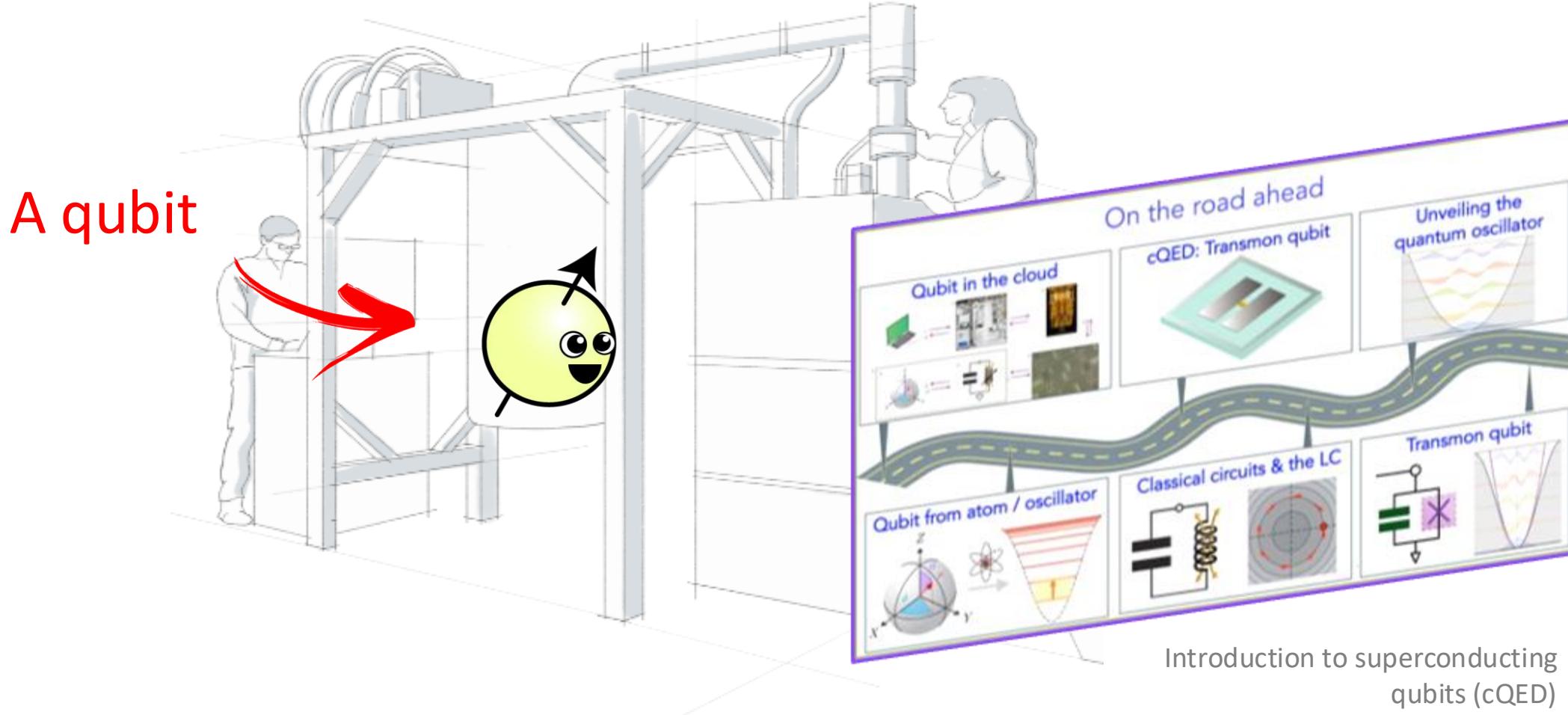
On the road ahead



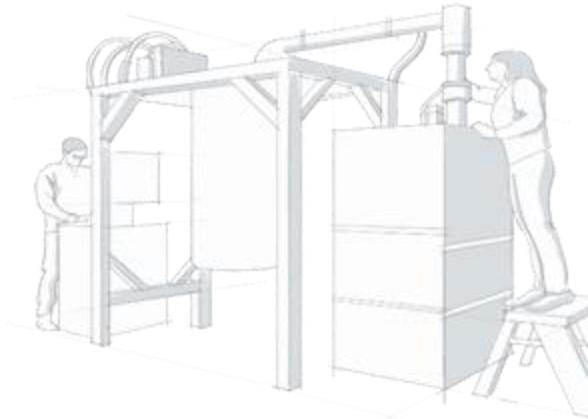
Part III

Let's design and run a real quantum circuit

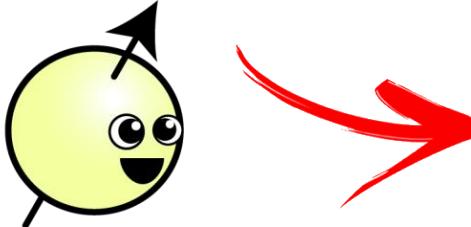
Hello World with a real experiment!



Hello World! building blocks



A qubit

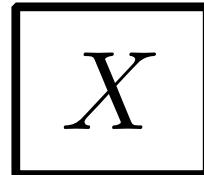


$|1\rangle$

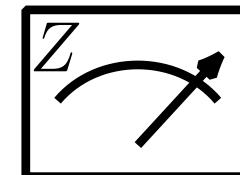
$|0\rangle$

Computational
basis states

Operations: qubit gate



Measurements: qubit observable



refresher:

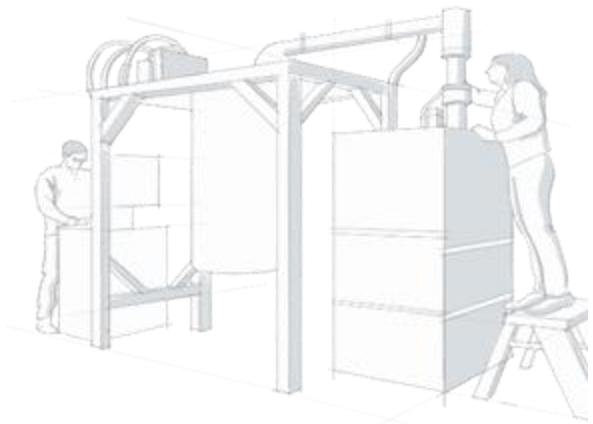
$$X |0\rangle = |1\rangle$$

$$X |1\rangle = |0\rangle$$

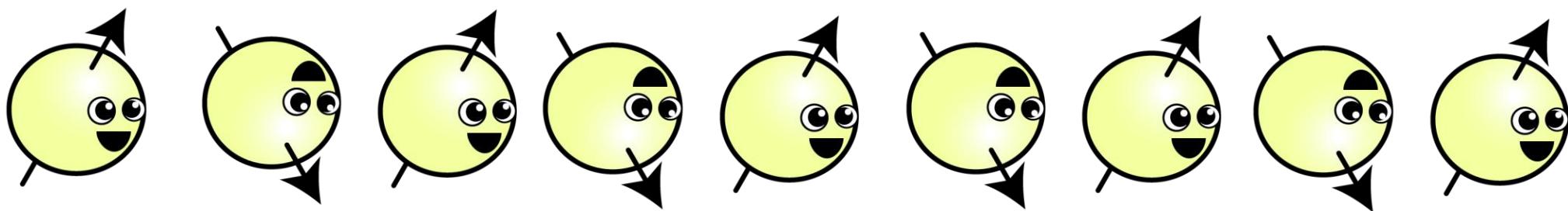
$$Z |0\rangle = +1 |0\rangle$$

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

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:

$$X |0\rangle = |1\rangle$$

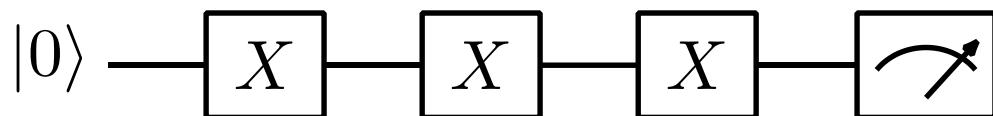
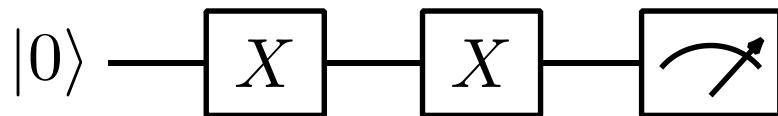
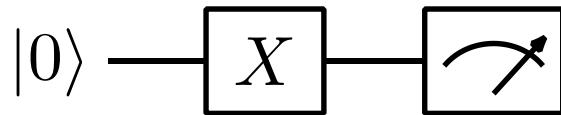
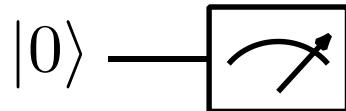
$$X |1\rangle = |0\rangle$$

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

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

Hello World! qubit flipper quantum circuits

depth



:

refresher:

$$X |0\rangle = |1\rangle$$

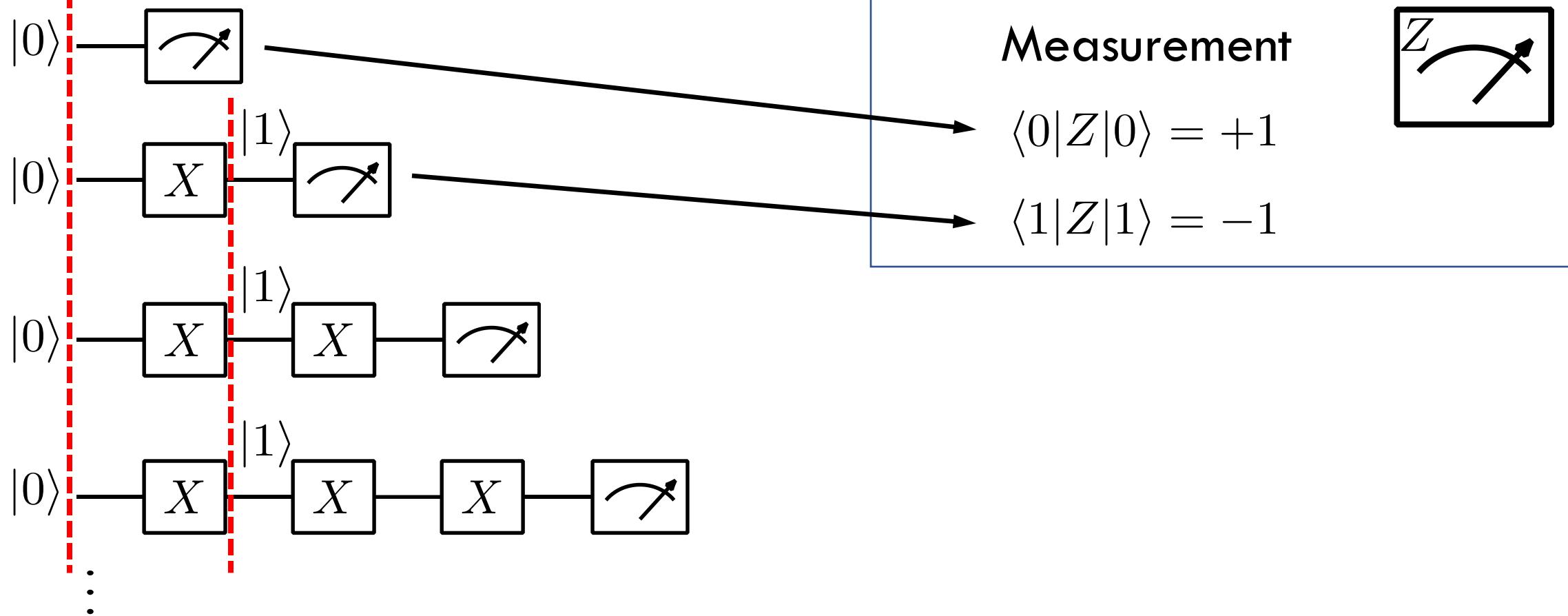
$$X |1\rangle = |0\rangle$$

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

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

Hello World! “debugger” step through

depth



refresher:

$$X |0\rangle = |1\rangle$$

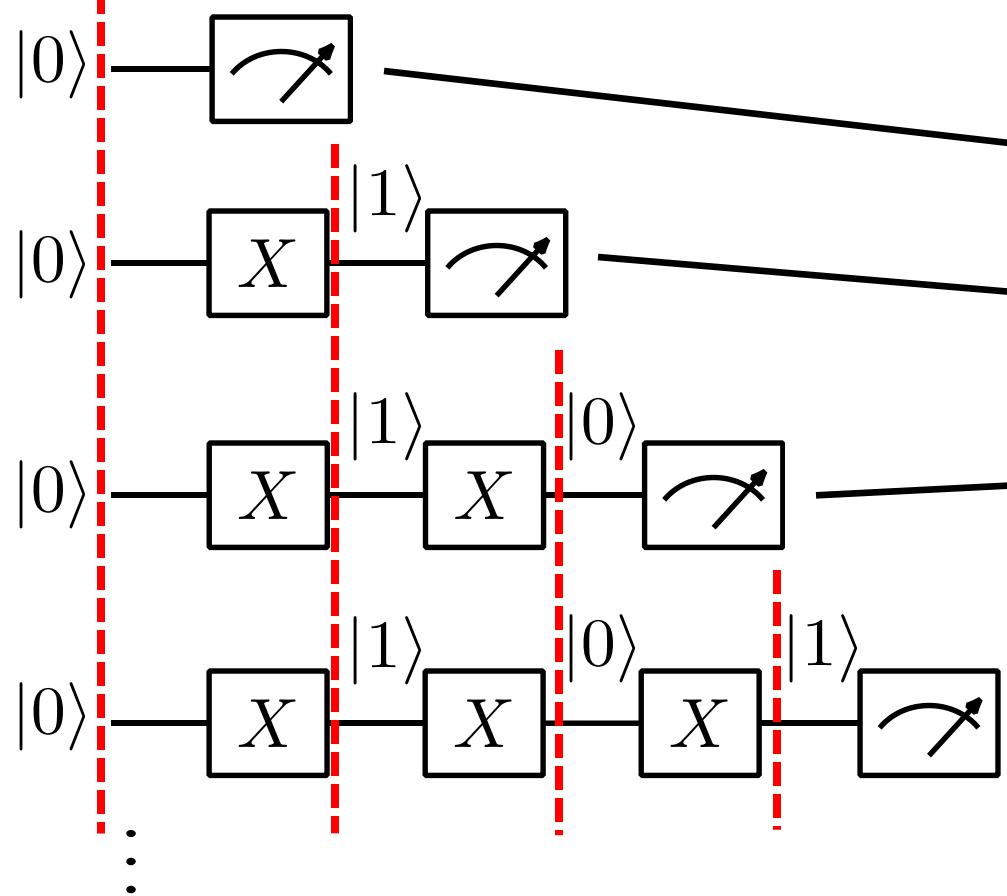
$$X |1\rangle = |0\rangle$$

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

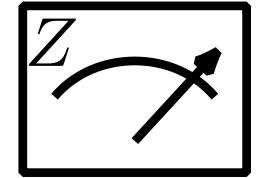
$$Z |1\rangle = -1 |1\rangle$$

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:

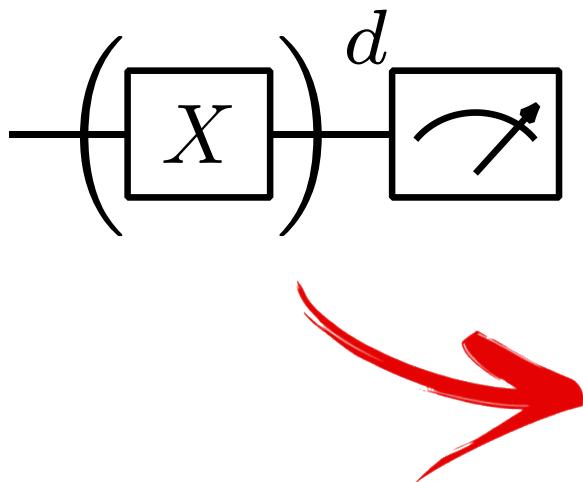
$$X |0\rangle = |1\rangle$$

$$X |1\rangle = |0\rangle$$

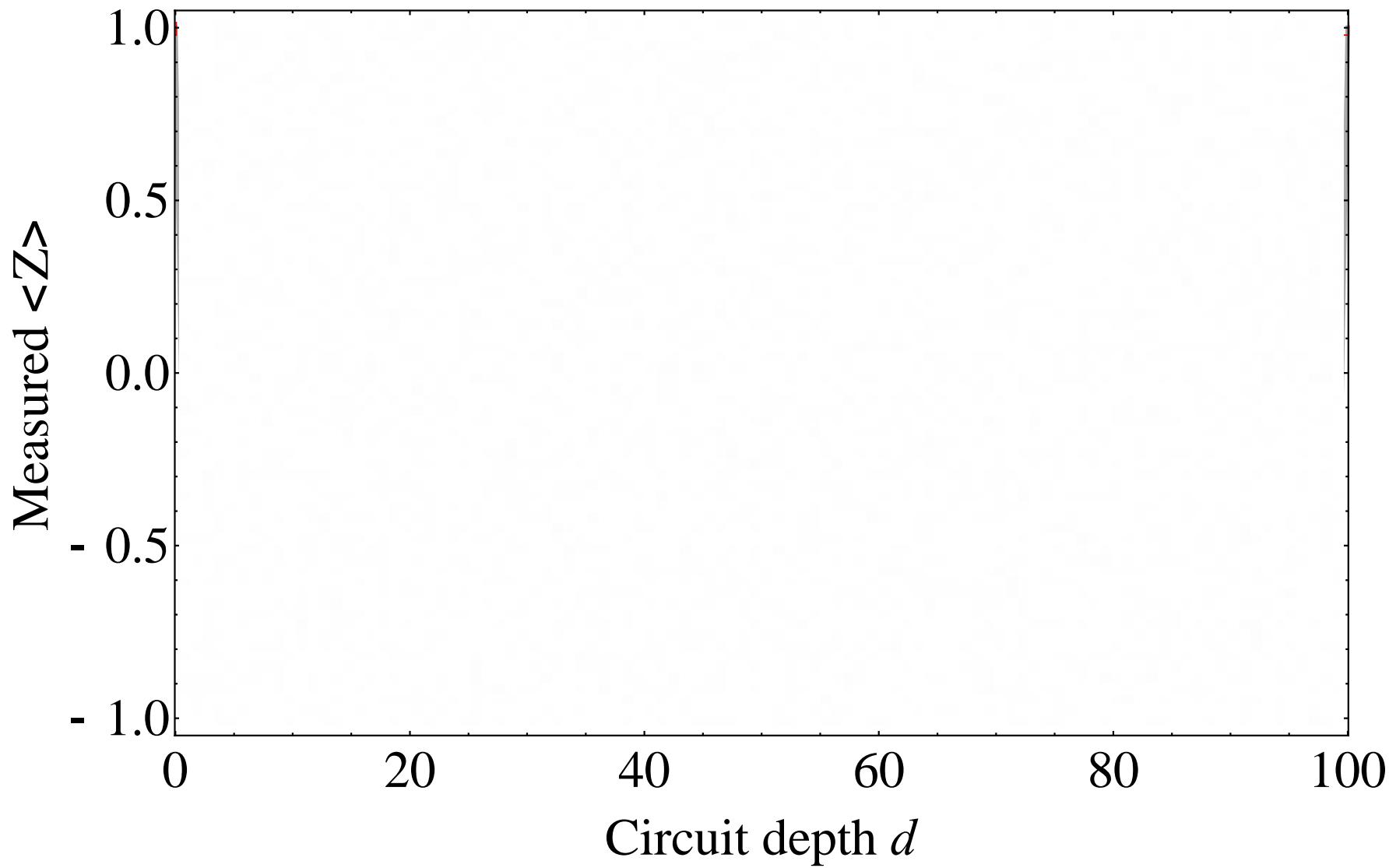
$$Z |0\rangle = +1 |0\rangle$$

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

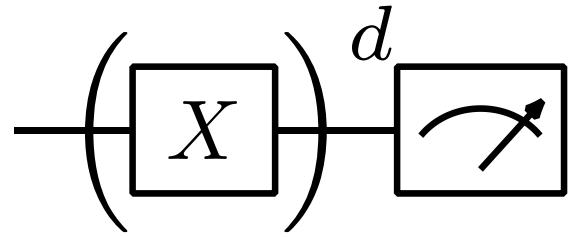
Hello World! Ideal expectation results



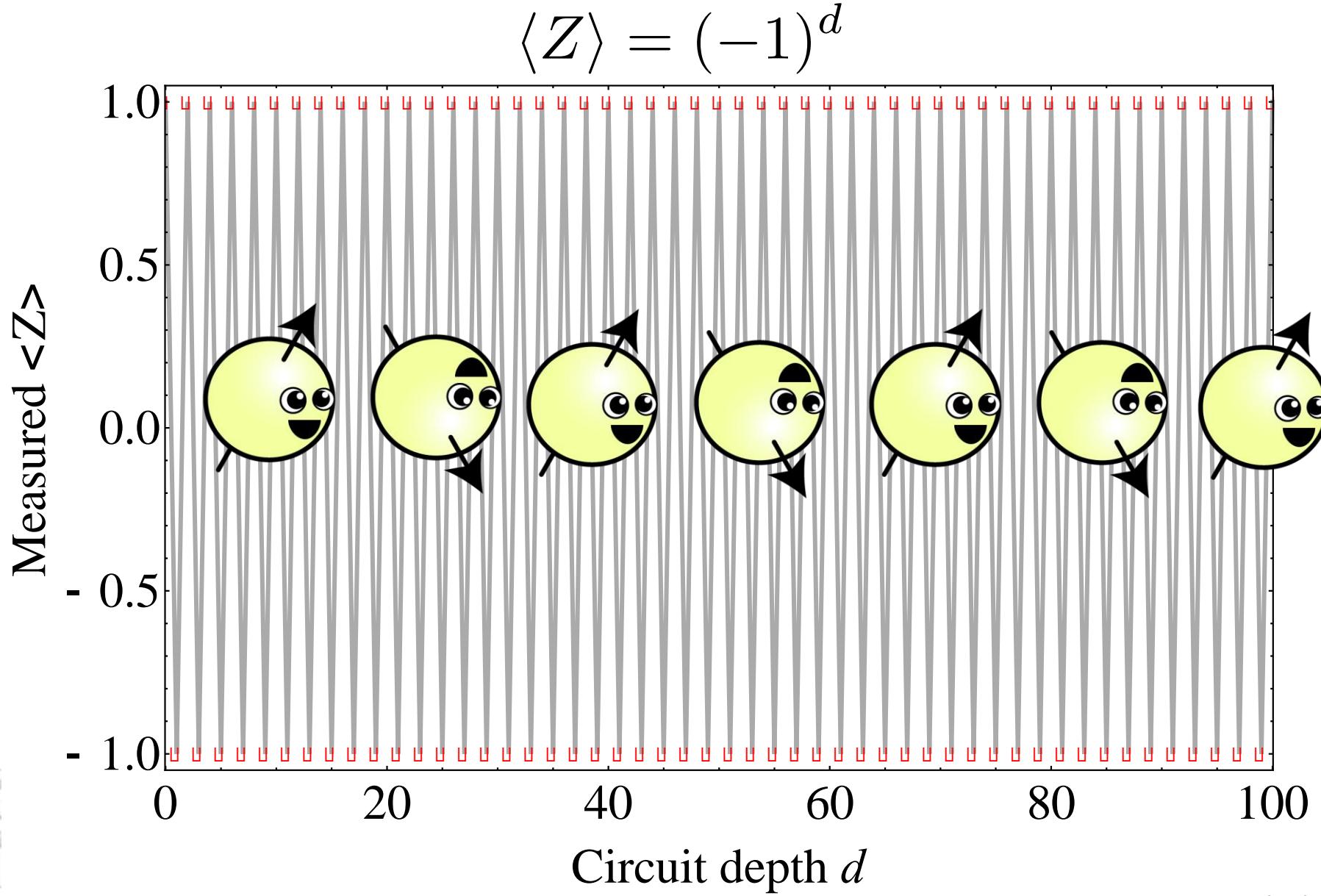
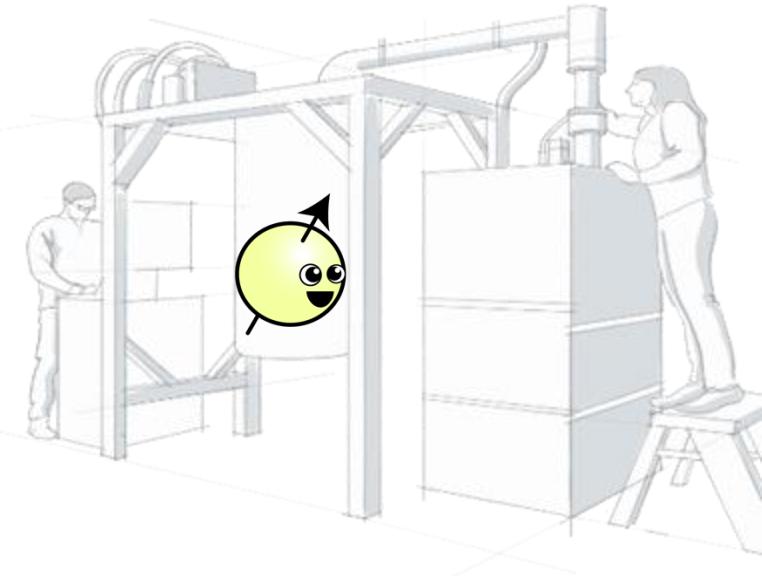
$$\langle Z \rangle = (-1)^d$$



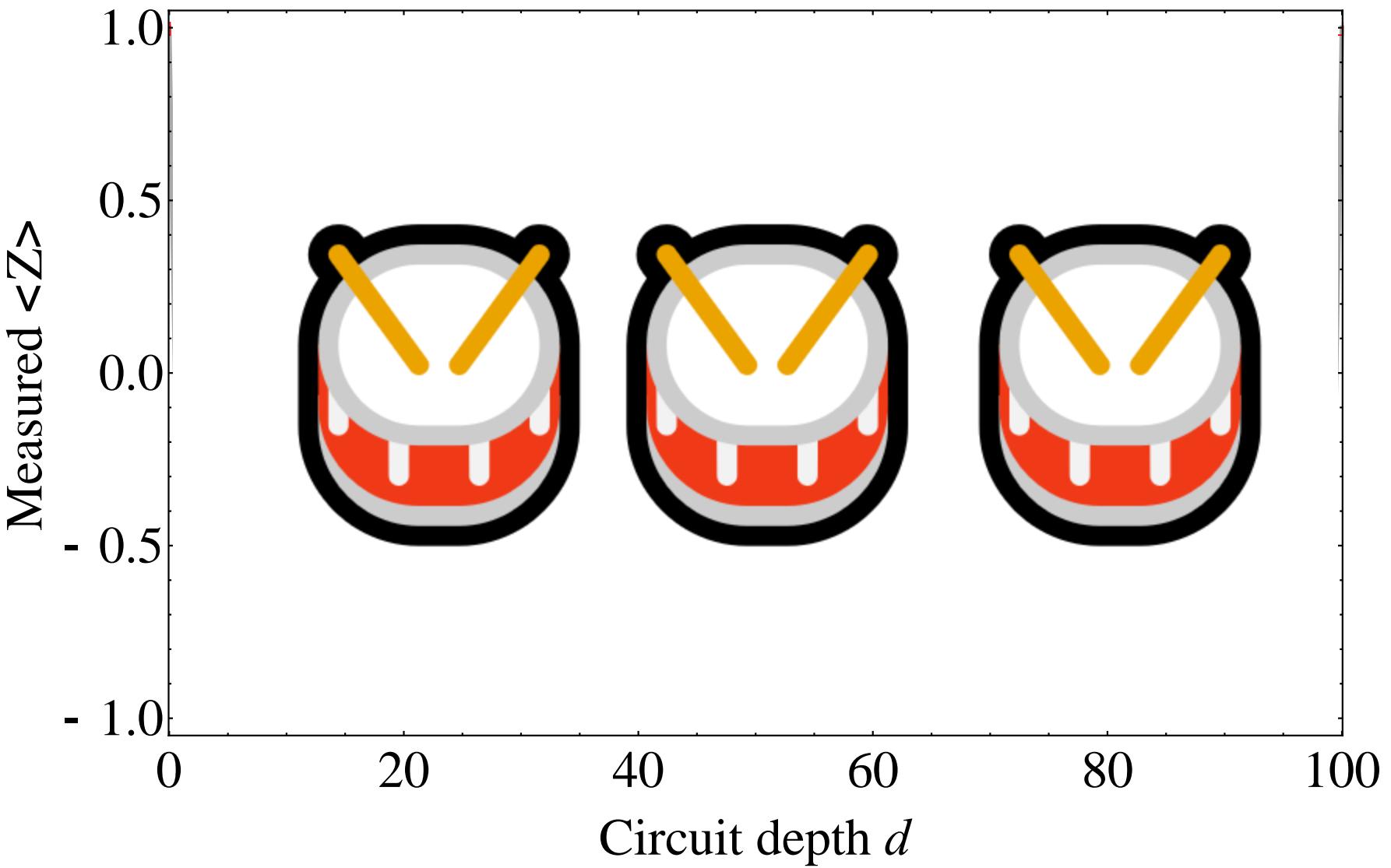
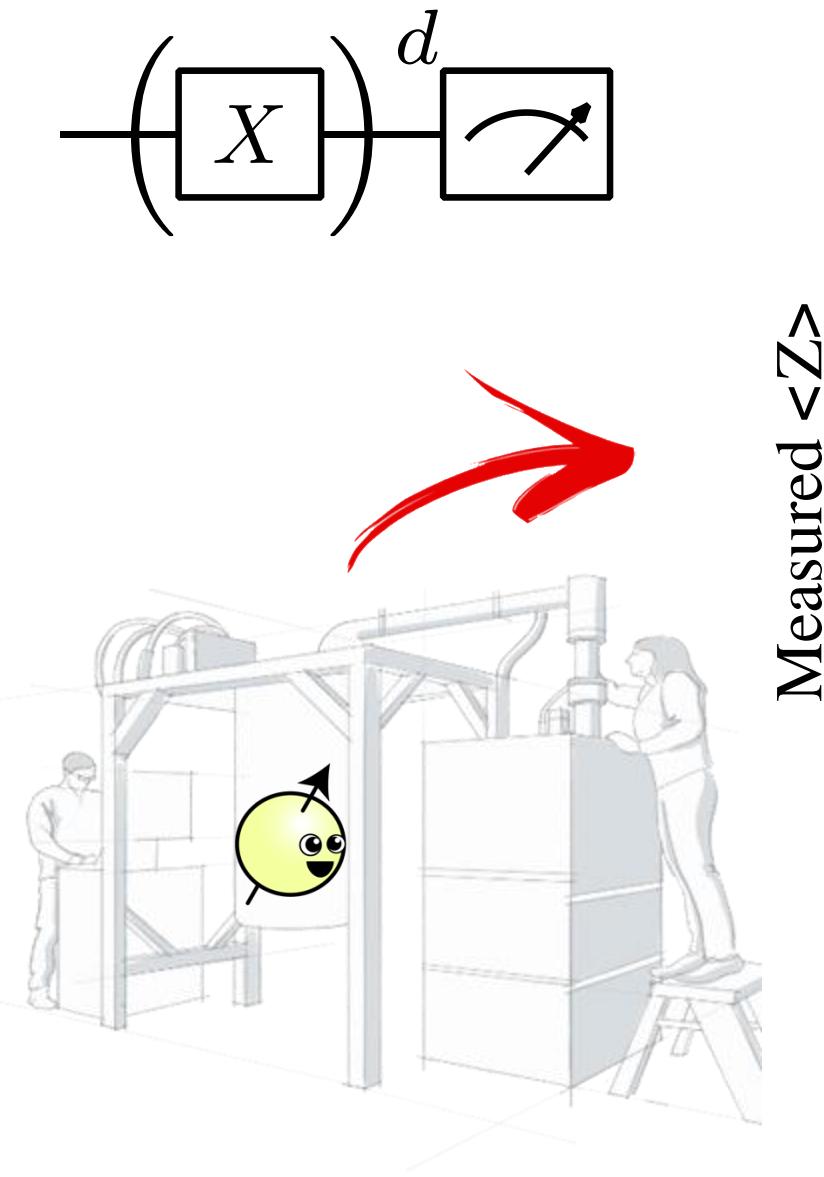
Hello World! Ideal expectation results



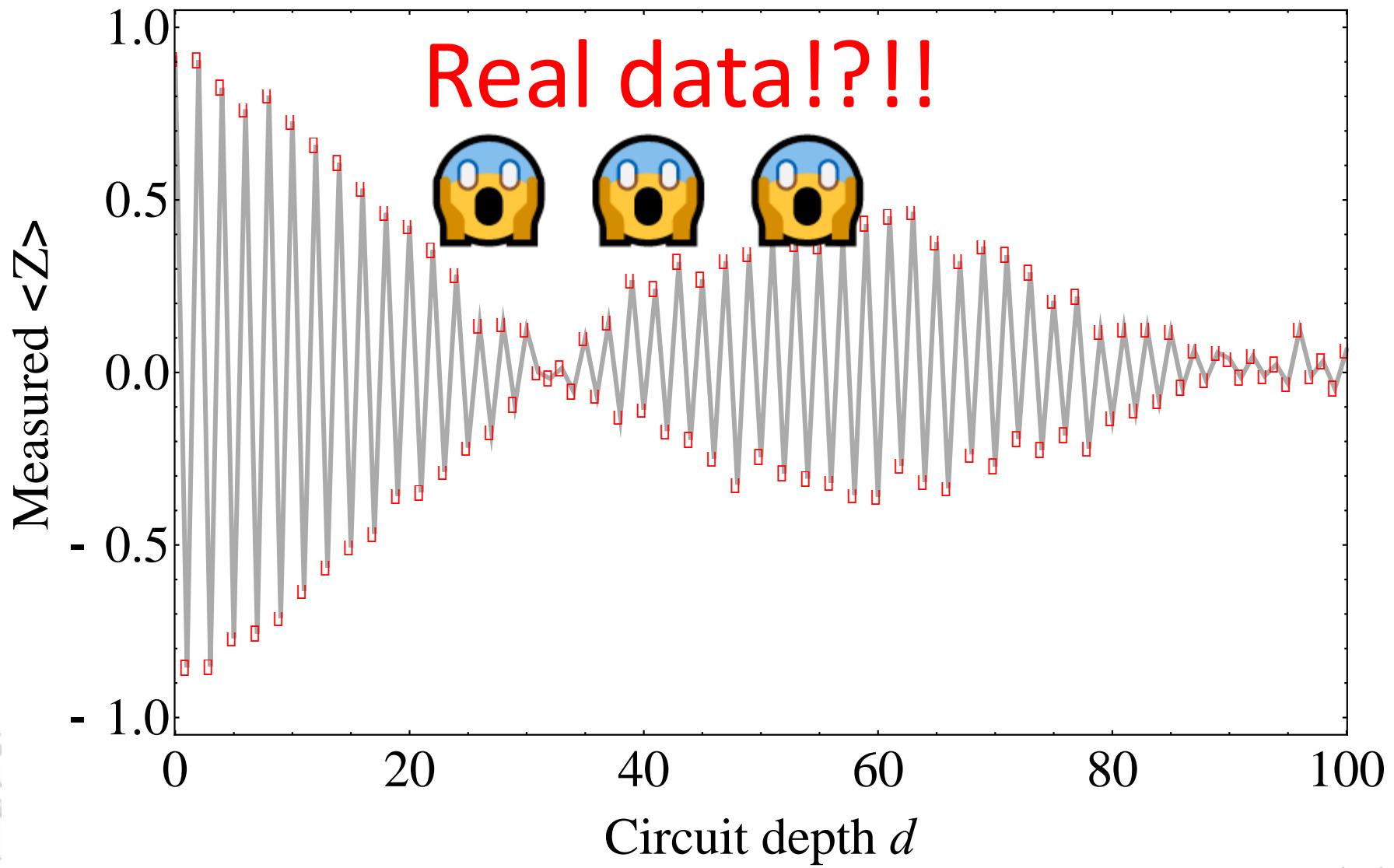
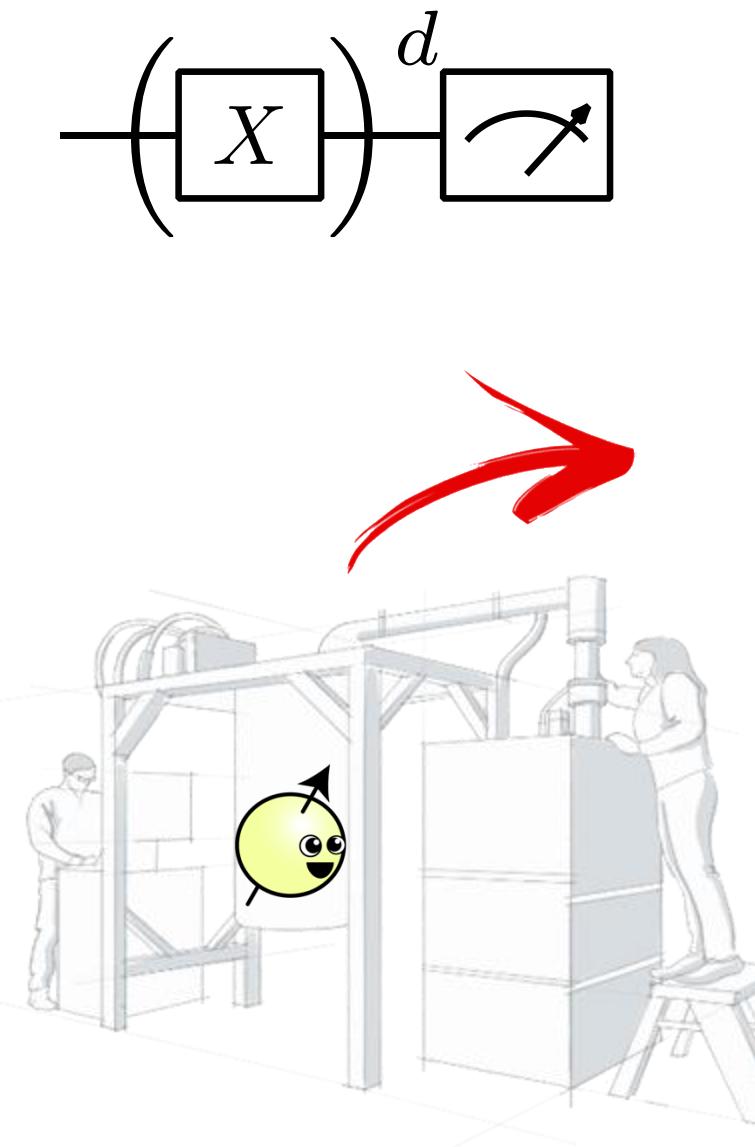
Let's run on a real device!



Hello World! Running



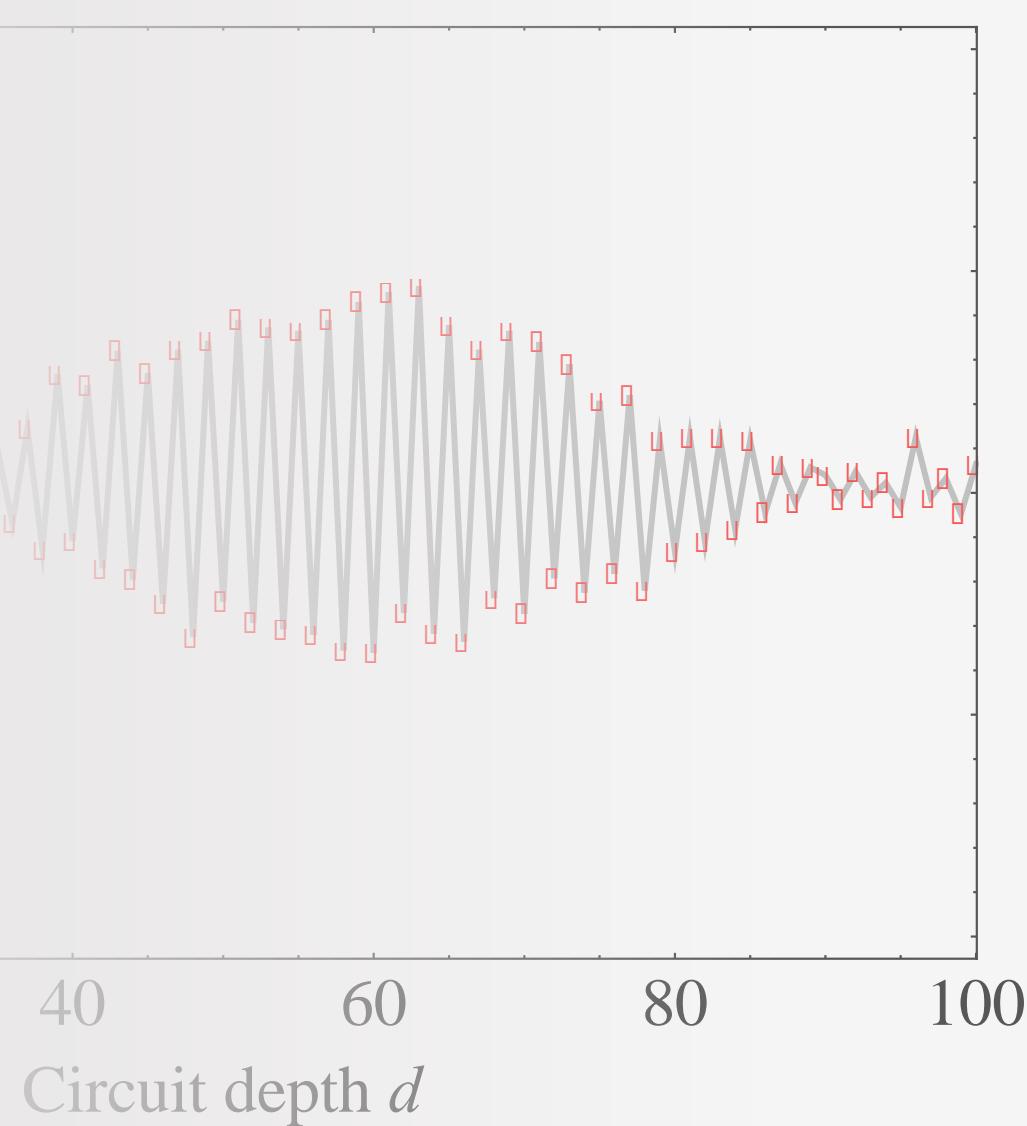
Hello World! Real expectation results

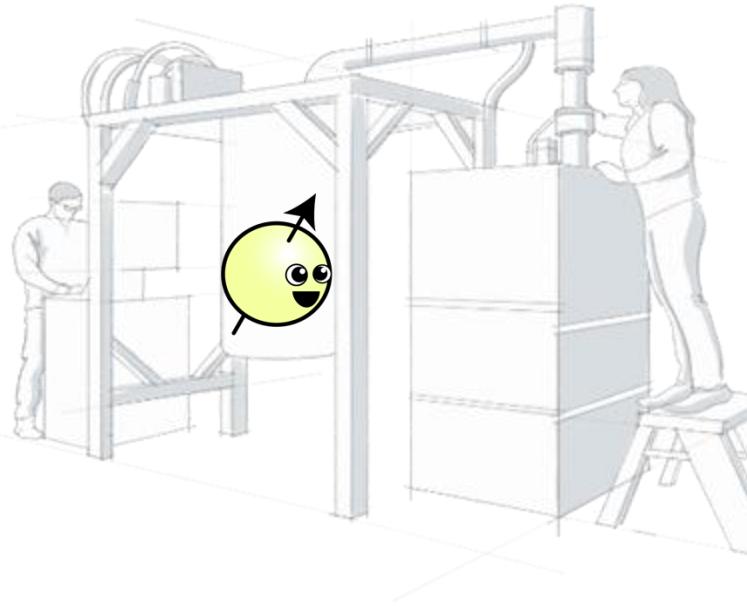


Real & noisy quantum processors: Why study noise?



*"Well, your quantum computer is broken in
every way possible simultaneously."*

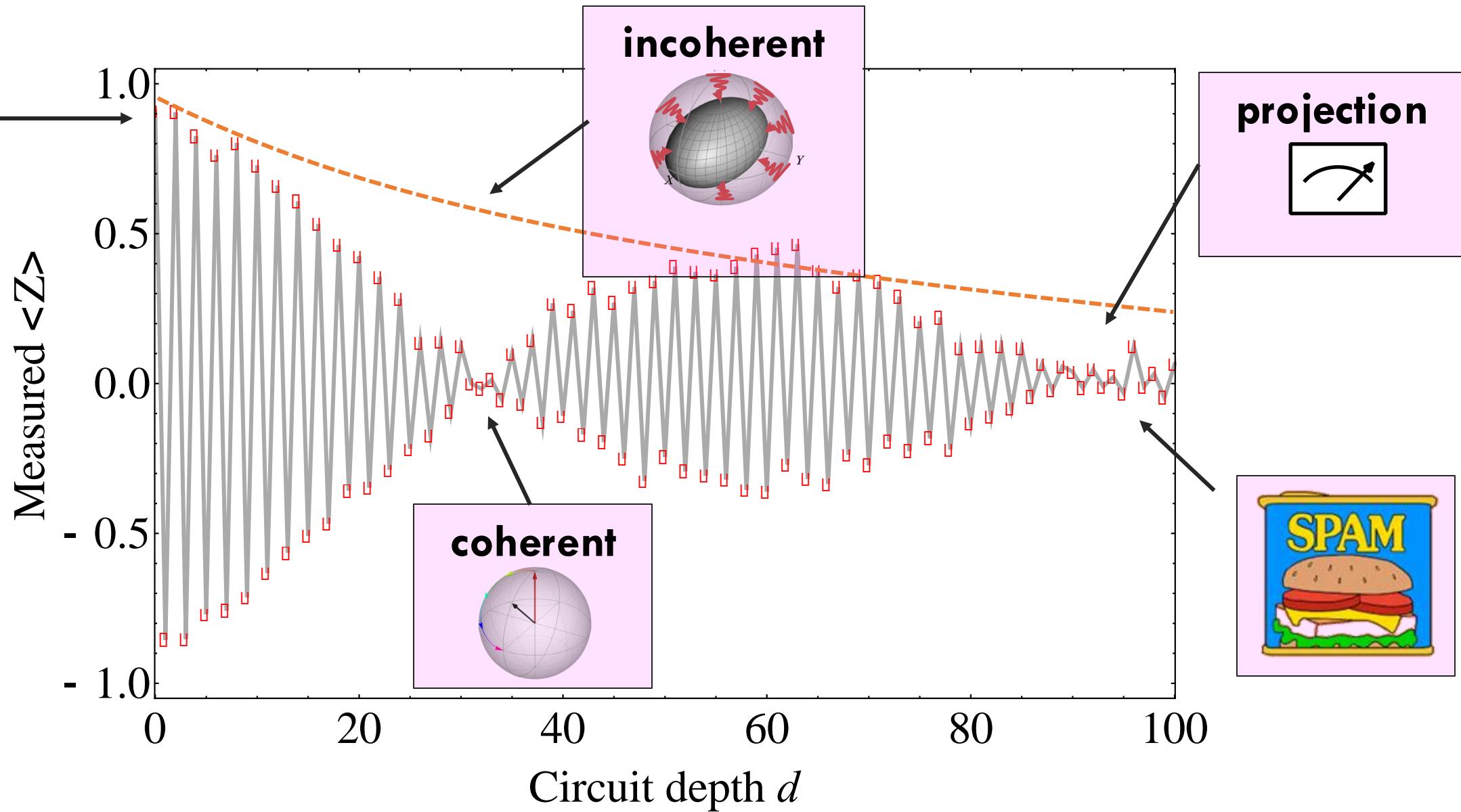




“Quantum phenomena
do *not* occur in a Hilbert space,
they occur in a laboratory.”

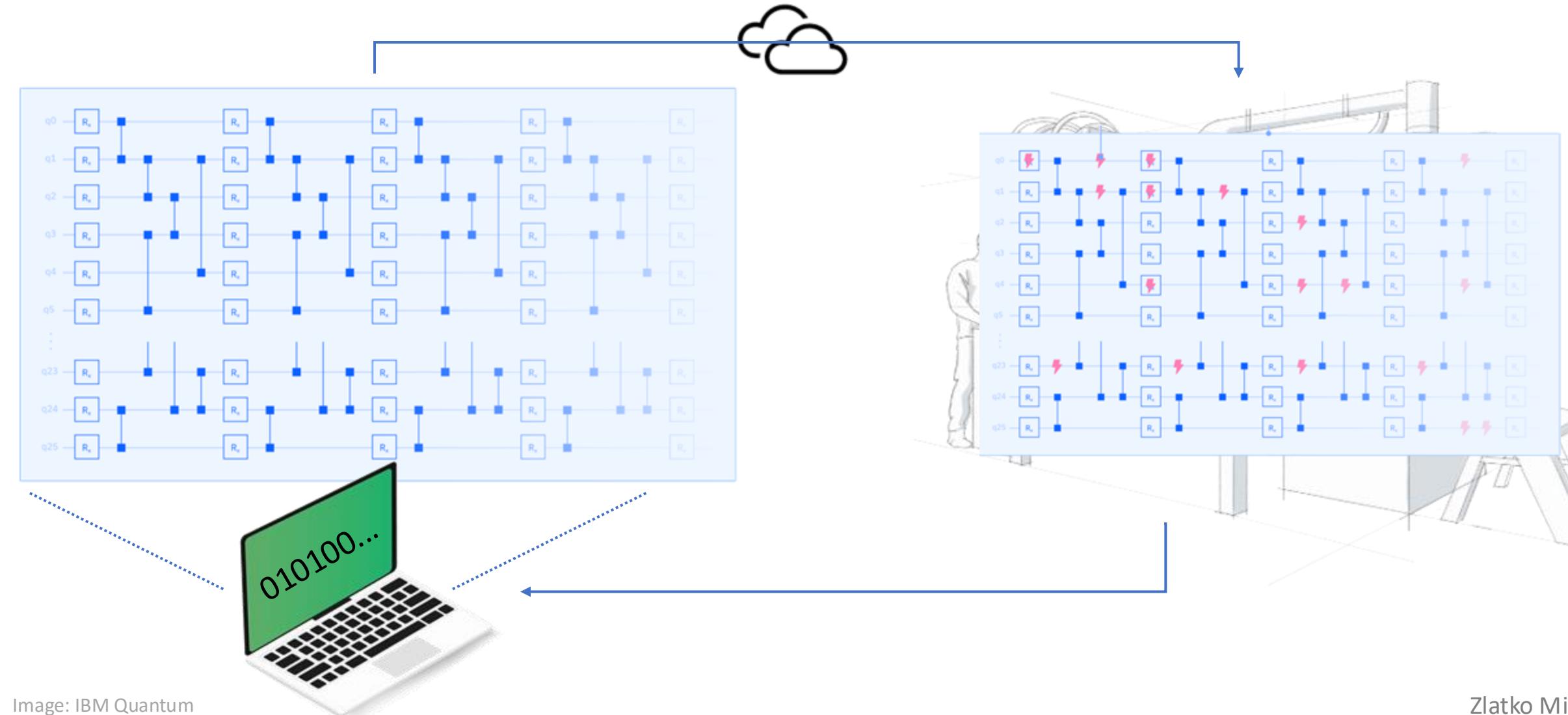
Asher Peres

Elements of noise



Quantum simulation on a noisy quantum computer

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



Biggest challenge?

Please do share

hardware
development

error correction
overheads

scalability

engineering

need CS/EE
talent

decoherence

high error rates

material
quality

Noise (Errors)

Biggest challenge?

loss

heat

stability

algo
development

modularization

importance of N
in NISQ

gravity

hype

expectations

Biggest challenge

Noise
(Errors)



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

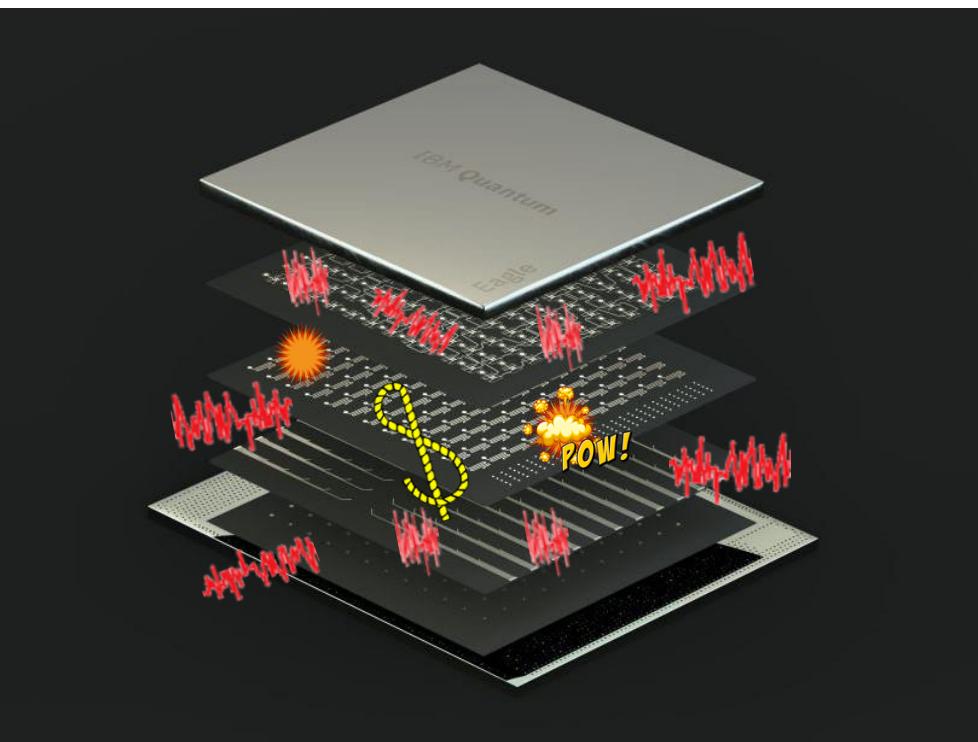
Error undetected



Error mitigation

... subject of today

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

Cancel quantum noise



High-level message

Learn

accurate, efficient, scalable



Cancel

noise with noise,
practical



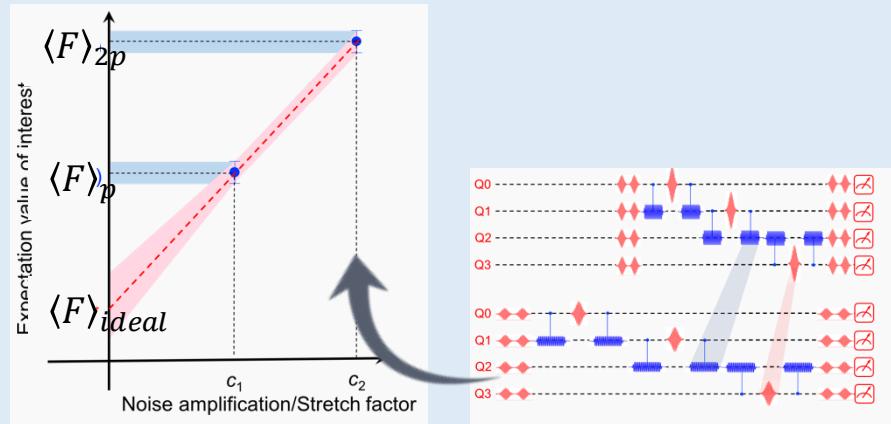
Cost

more noise more cost



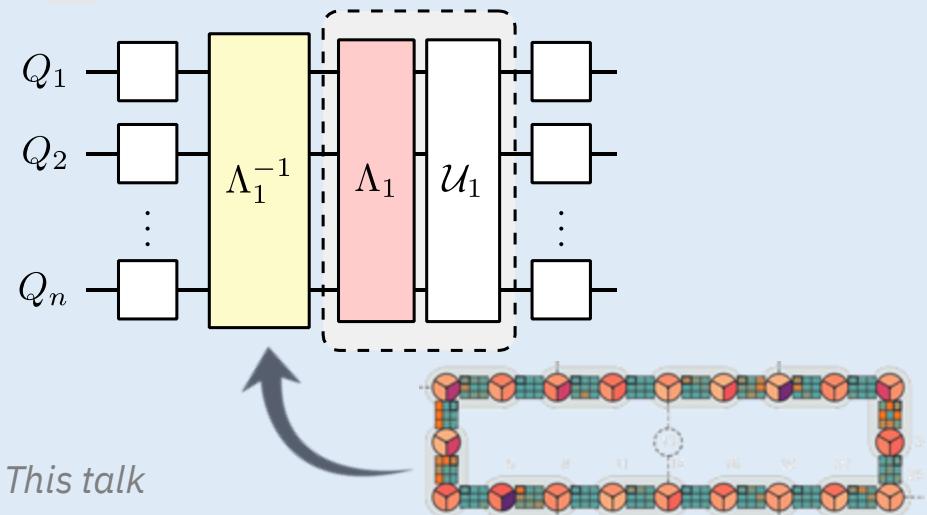
Error mitigation landscape

Zero-noise extrapolation (ZNE)



Nature 567, 491 (2019)

Probabilistic error cancellation (PEC)



This talk

more speed

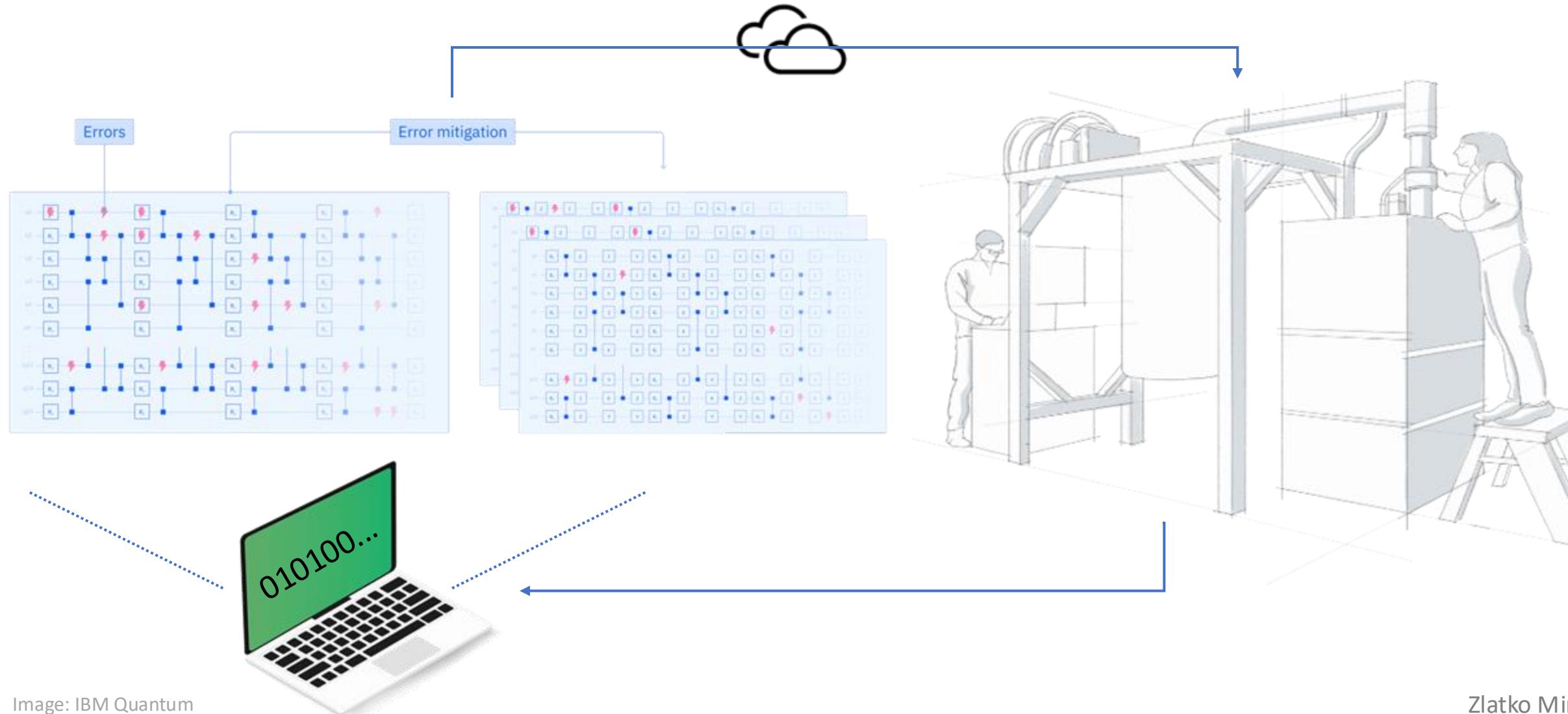


more information, accuracy



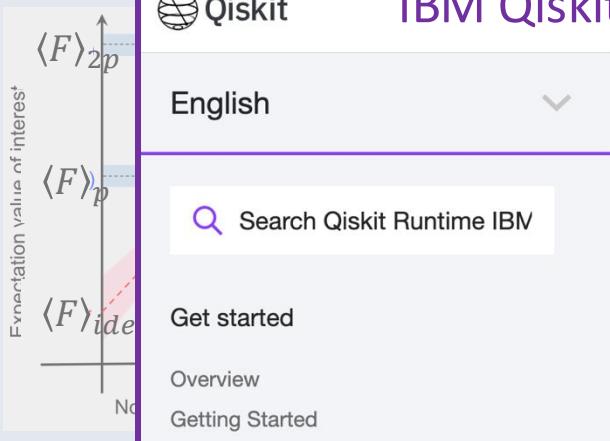
Quantum error mitigation overview

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

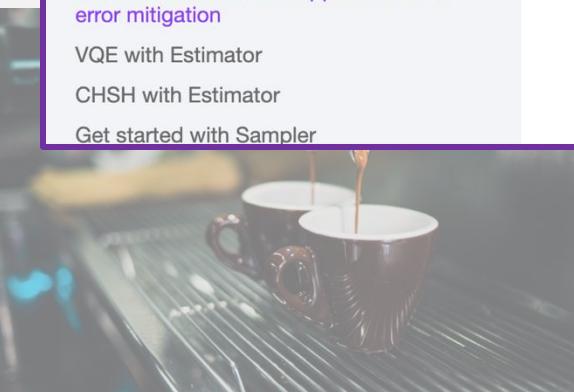


Error mitigation landscape

Zero-noise extrapolation (ZNE)



more speed



Probabilistic error cancelation (PEC)

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

Overview Learn Community

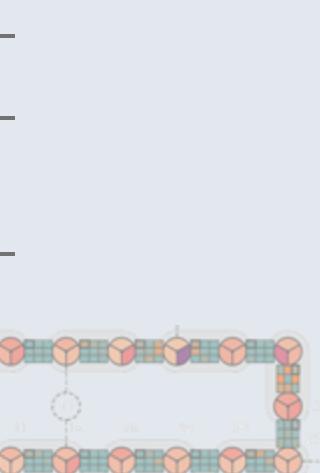
• NOTE

This page was generated from [docs/tutorials/Error-Suppression-and-Error-Mitigation.ipynb](#).

Error suppression 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
```

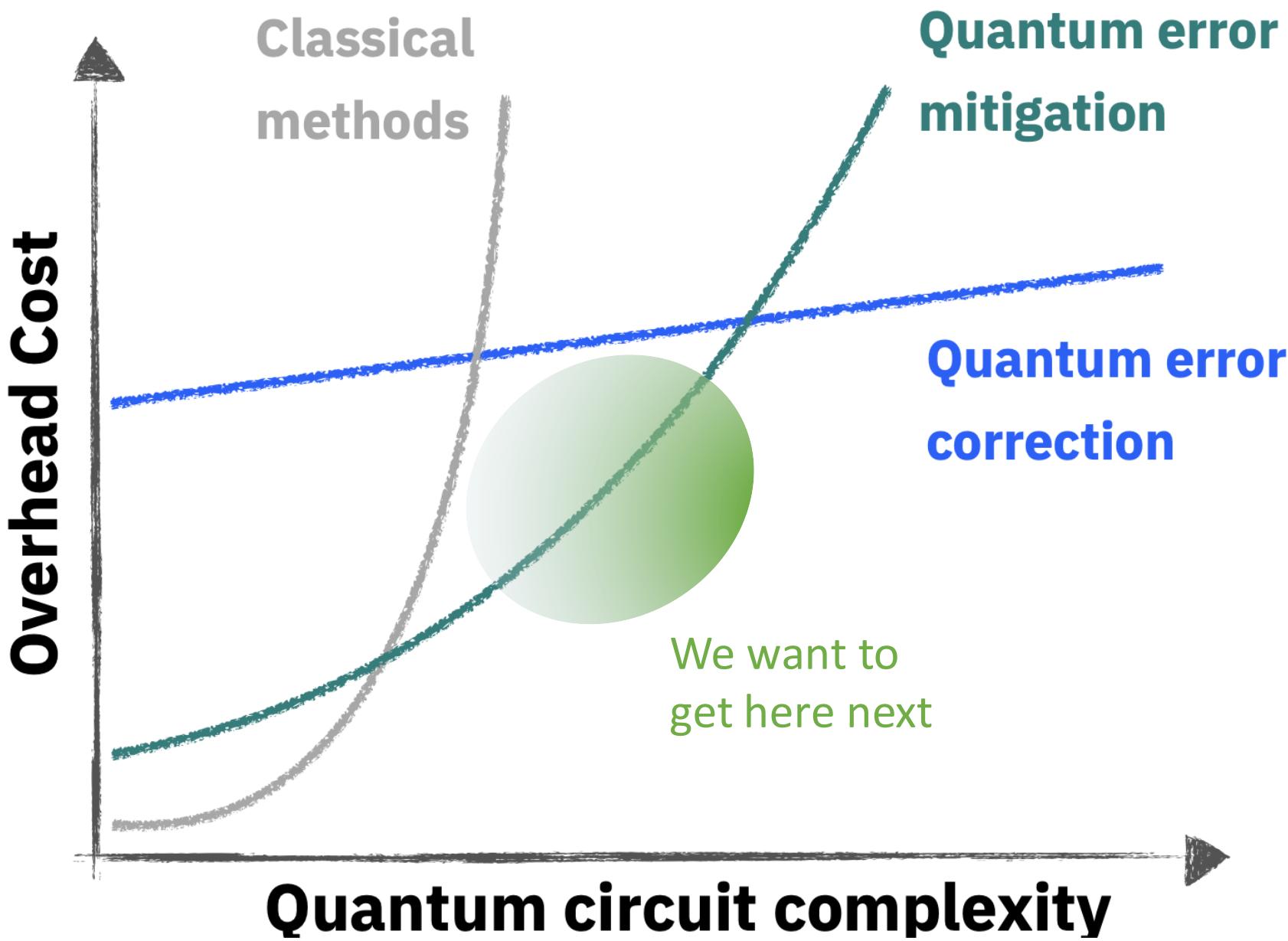


more information, accuracy



Quantum advantage





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

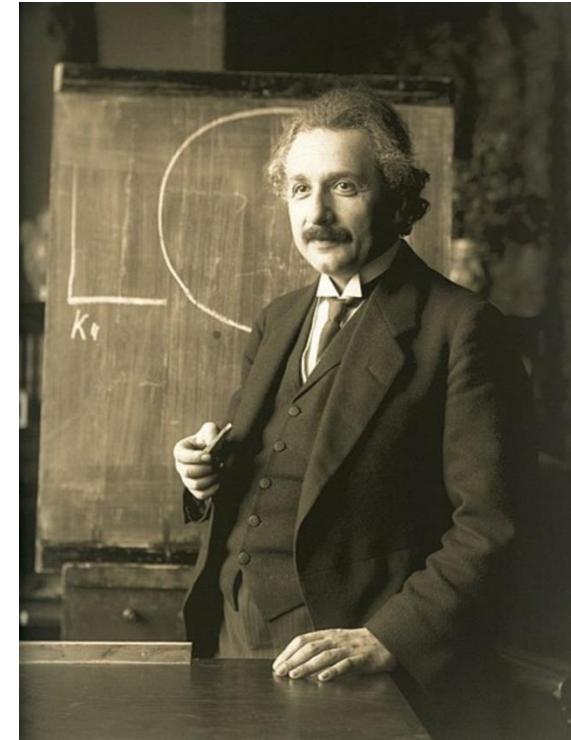


Photo: F. Schmutzler



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IBM Quantum

A Prelude to Practical Quantum Computing

A brief overview

Zlatko Minev

Got Slides?

zlatko-minev.com/blog



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