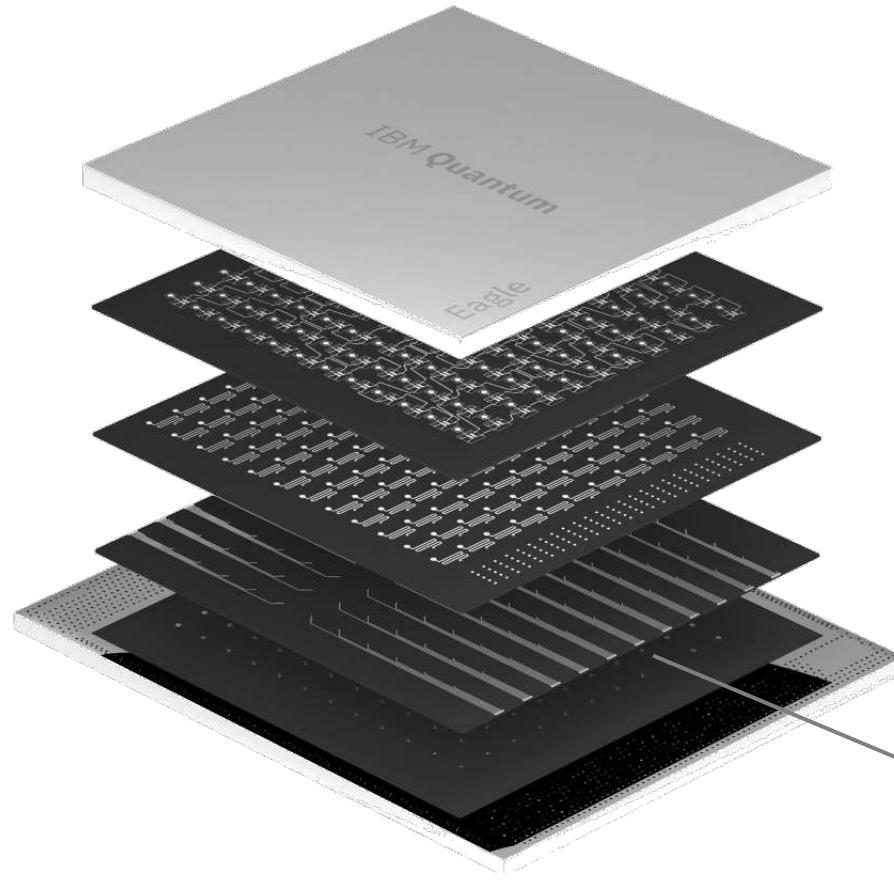


Hello Quantum World!



Zlatko K. Minev, Ph.D.

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



@zlatko_minev

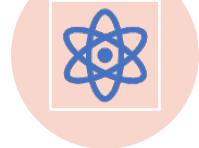


zlatko-minev.com

Hello Quantum World!



About me: Career overview



Lessons along the way



Quantum Computers
and IBM Quantum



Experiments on large
devices / making
quantum chips / ...

Avoid firehose of information



Thanks to Fred Moxley for gif reference.

Overview of career in brief

at time $t \approx 0$

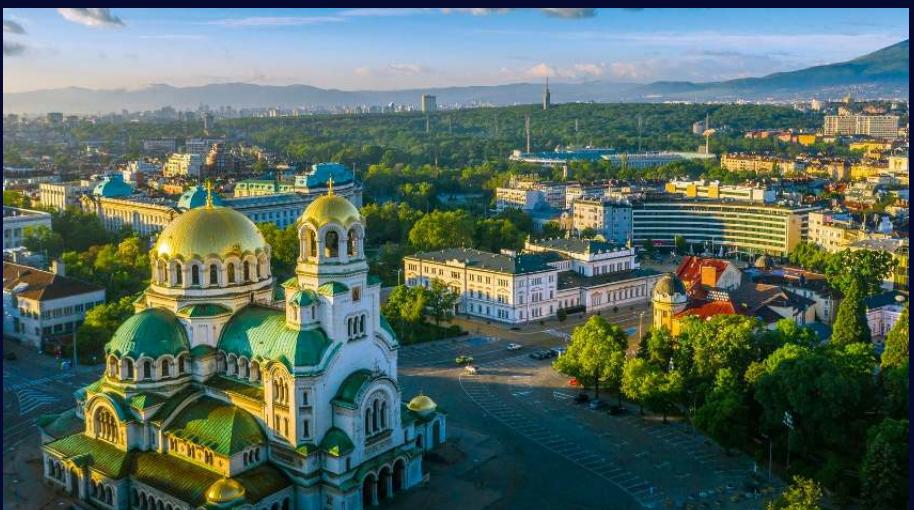
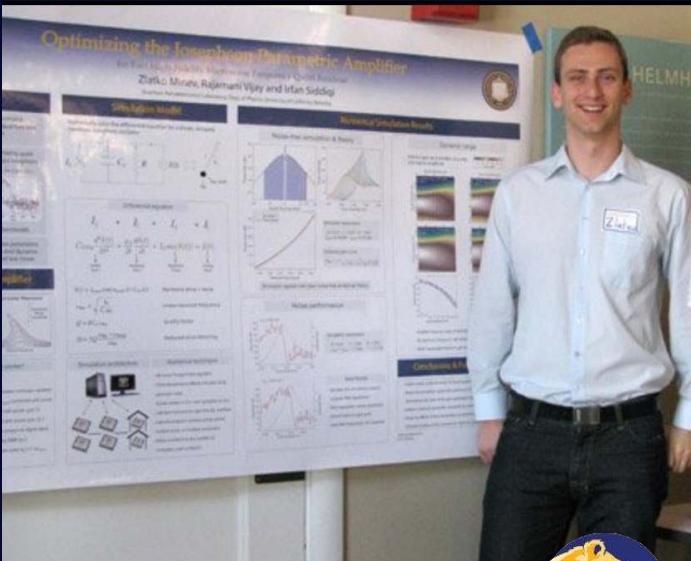
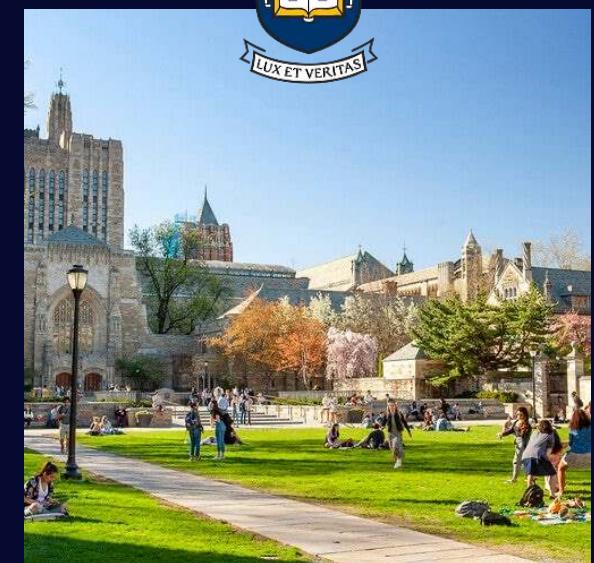


Image: National Geographic

Sofia, Bulgaria



UC Berkeley, CA



Yale University, CT

Roles since then

IBM Quantum



- **Technical Lead and Manager**
for 2 teams and missions I founded:
 - **Qiskit Leap Research**
advanced collaborative quantum computing research
 - **Qiskit Metal**
quantum processor design and analysis

ADDITIONAL ROLES



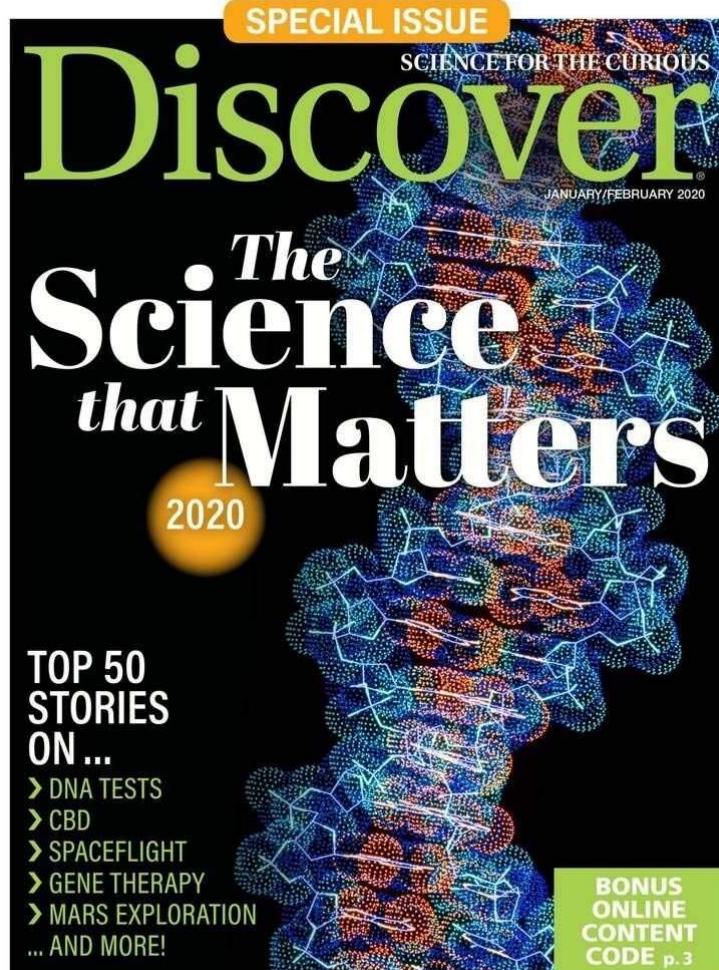
Quantum
Information Science
Seminar Series

- **Associate Fellow,**
Canadian Institute for Advanced Research (**CIFAR**)
- **Member of the Board,**
Yale University, Graduate School Alumni Association
- **Board of Governors,**
Yale Alumni Association
- **Lead and Host,**
IBM Quantum, YouTube Seminar
- **Chairman,**
Open Labs Science Outreach



Zlatko Minev

Some highlights



INNOVATORS UNDER 35

MIT
Technology
Review

In chaotic times it can be reassuring to see so many people working toward a better world. That's true for medical professionals fighting a pandemic and for ordinary citizens fighting for social justice. And it's true for those among us striving to employ technology to address those problems and many others.



Zlatko Minev

AGE: 30

AFFILIATION: IBM QUANTUM RESEARCH, TJ WATSON

COUNTRY OF BIRTH: BULGARIA

His discovery could reduce errors in quantum computing.

Zlatko Minev overturned a mainstay of quantum physics that had troubled Niels Bohr and Albert Einstein alike. For most of the 20th century, it was assumed that atoms change from one energy level to another in abrupt, unpredictable, discrete quantum jumps. Minev proved otherwise.

nature
International journal of science

Letter | Published: 03 June 2019

To catch and reverse a quantum jump mid-flight



Yale-Jefferson Award for
Public Service

Forbes
You Don't Have To Be A Rocket (Or Quantum) Scientist To Design A Quantum Computer Chip Using IBM's New Tool Called Qiskit Metal

Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Gruen G.
Cloud
Anchored in technology, driven by innovation.

Zlatko Minev — Shapes of Success 2020 (7)

Quantum Jumps



H.J. Carmichael



Letter | Published: 03 June 2019

To catch and reverse a quantum jump mid-flight

Z. K. Minev , S. O. Mundhada, S. Shankar, P. Reinhold, R. Gutiérrez-Jáuregui, R. J. Schoelkopf, M. Mirrahimi, H. J. Carmichael & M. H. Devoret 

Nature **570**, 200–204 (2019) | Download Citation 

Le Monde

the guardian

npr

RT SEPA MÁS

The CHRISTIAN SCIENCE
MONITOR

GIZMODO



WIRED

physicsworld

Популярная Механика

SCIENCE FOR THE CURIOUS
Discover

Quanta magazine

Economy.bg

Бизнесът в България

b tv



THE QUANTUM DAILY
QUANTUM COMPUTING AND BEYOND

MIT
Technology
Review

...

Zlatko Minev, IBM Quantum

Catching and Reversing a Quantum Jump
Mid-Flight

A Dissertation
Presented to the Faculty of the Graduate School
of

Yale University
in Candidacy for the Degree of
Doctor of Philosophy



by
Zlatko Kristev Minev

Dissertation Director: Michel H. Devoret
May 2018

Quantum

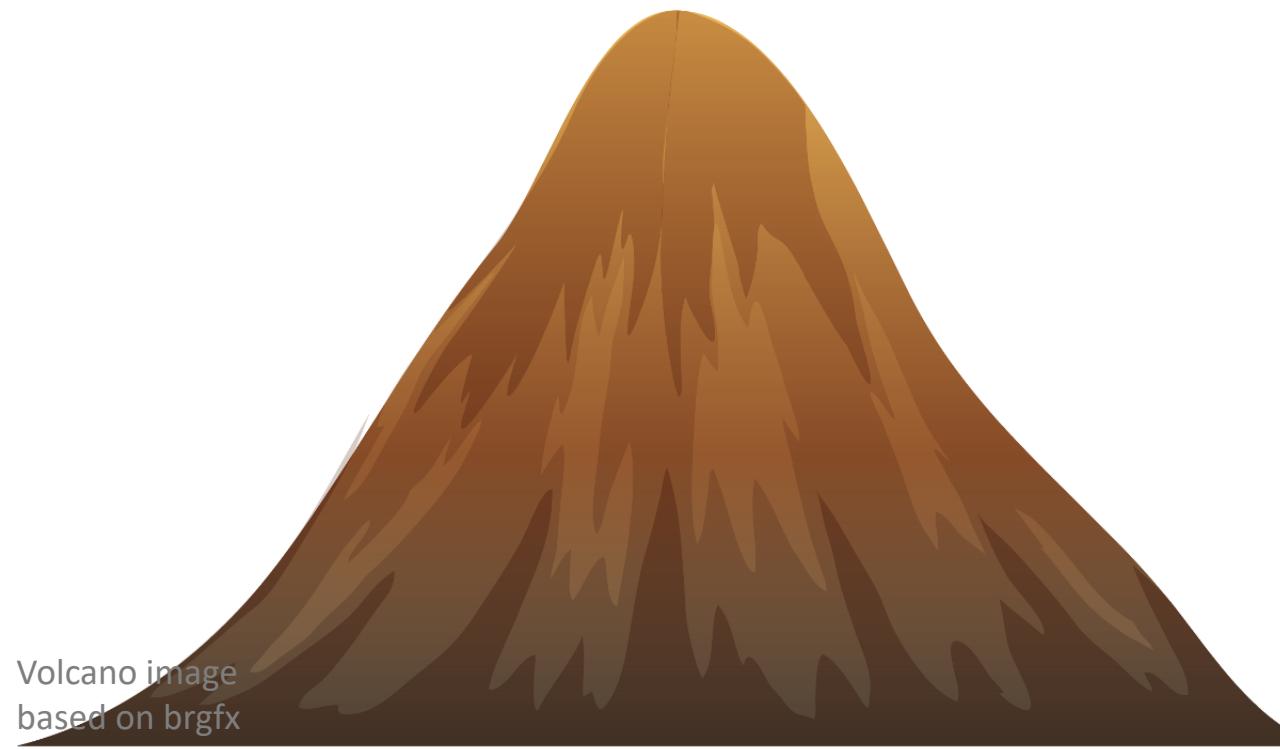
Discreteness



Unpredictability



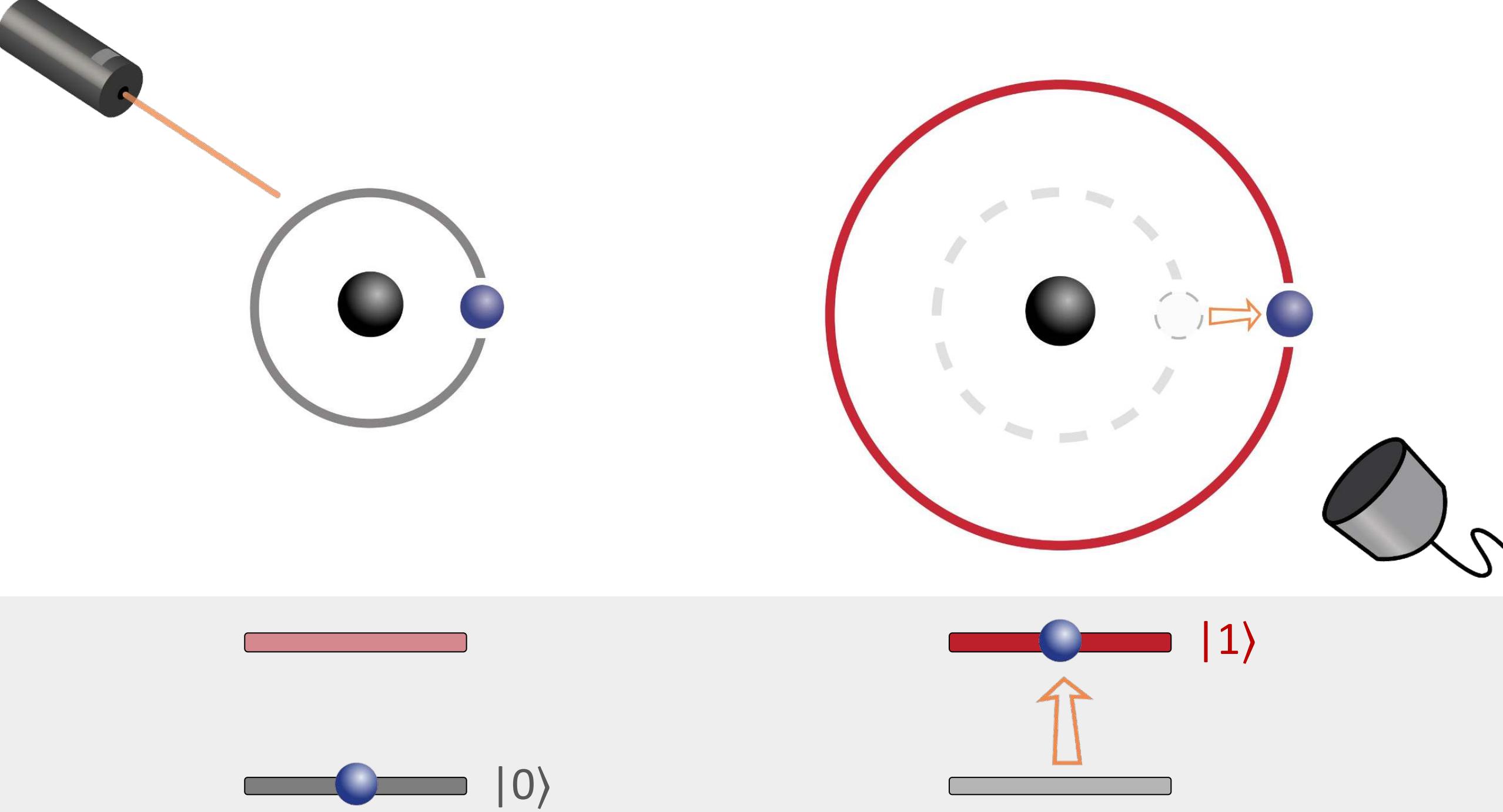
Predict?



Volcano image
based on brgfx



Zlatko Minev, MIT TR35



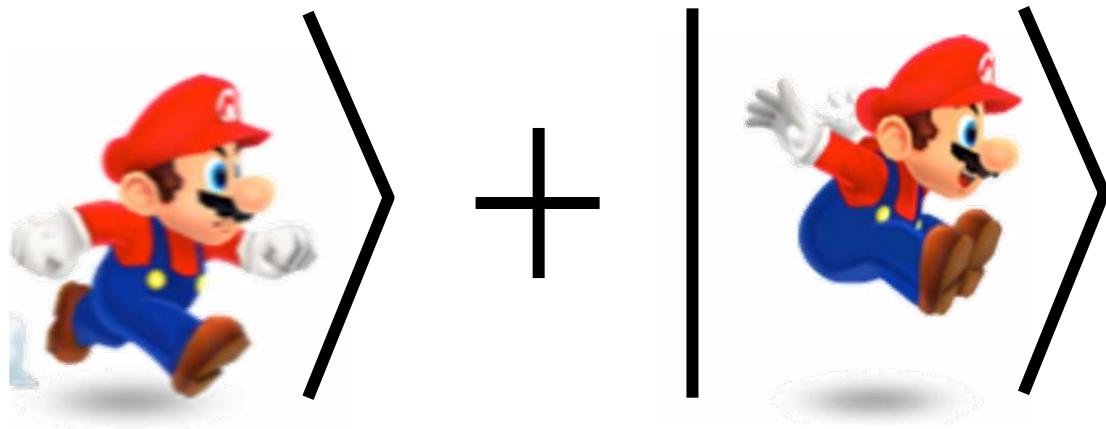
Quantum Jump: Until Now



↑ - ? - -

Discrete?
Instantaneous?
Unpredictable?

The Real Quantum Jump



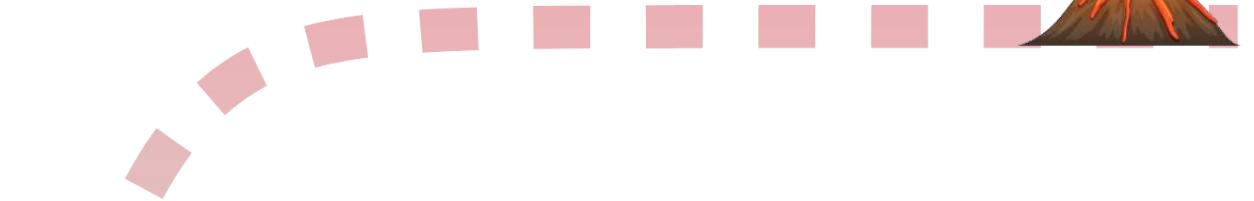
**Coherent
superposition!**

*Continuous
Coherent
Degree of predictability*

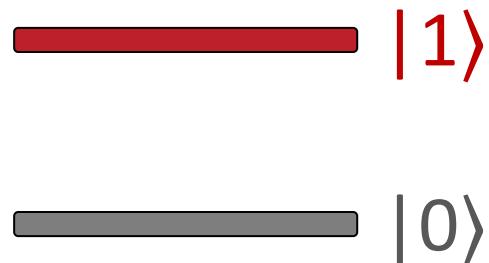
Predict & Control: Catch and reverse jump mid-flight



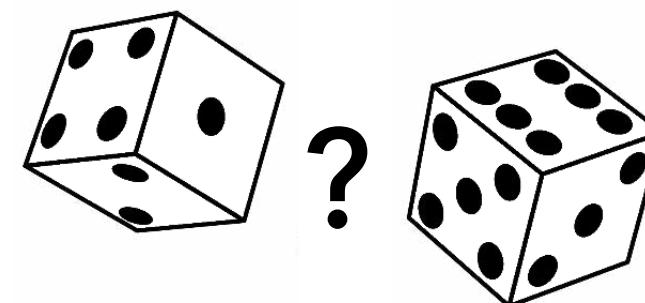
$|0\rangle$



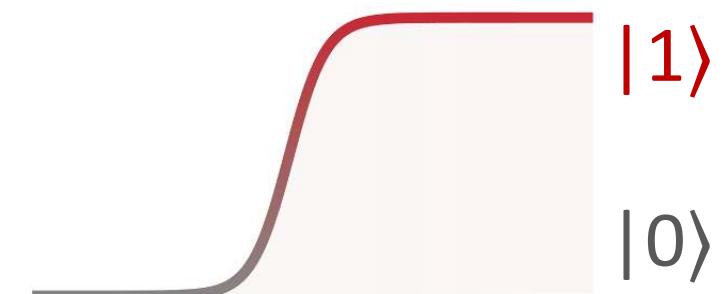
Bohr



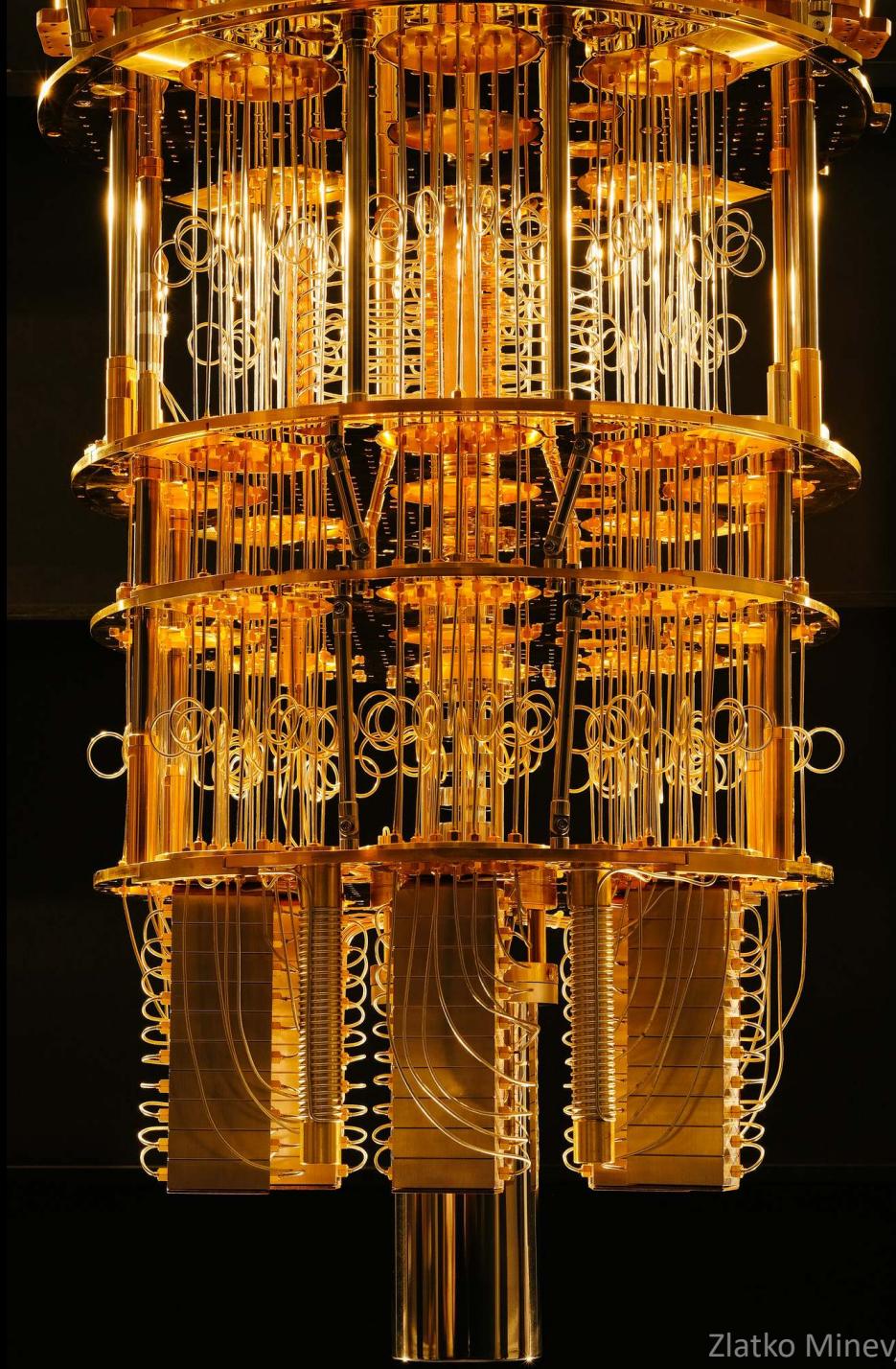
Einstein



Schrödinger



Quantum Computing: Error correction Quantum Sensing



There is more to the story of quantum physics ...

Not quite as discrete and random as we thought ...

Opens doors to otherwise inaccessible technology ...

Lessons

“It is by *logic* that we prove,
but by *intuition* that we discover.”

Henri Poincaré

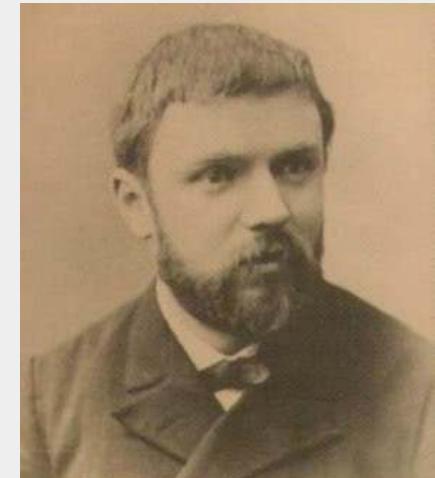


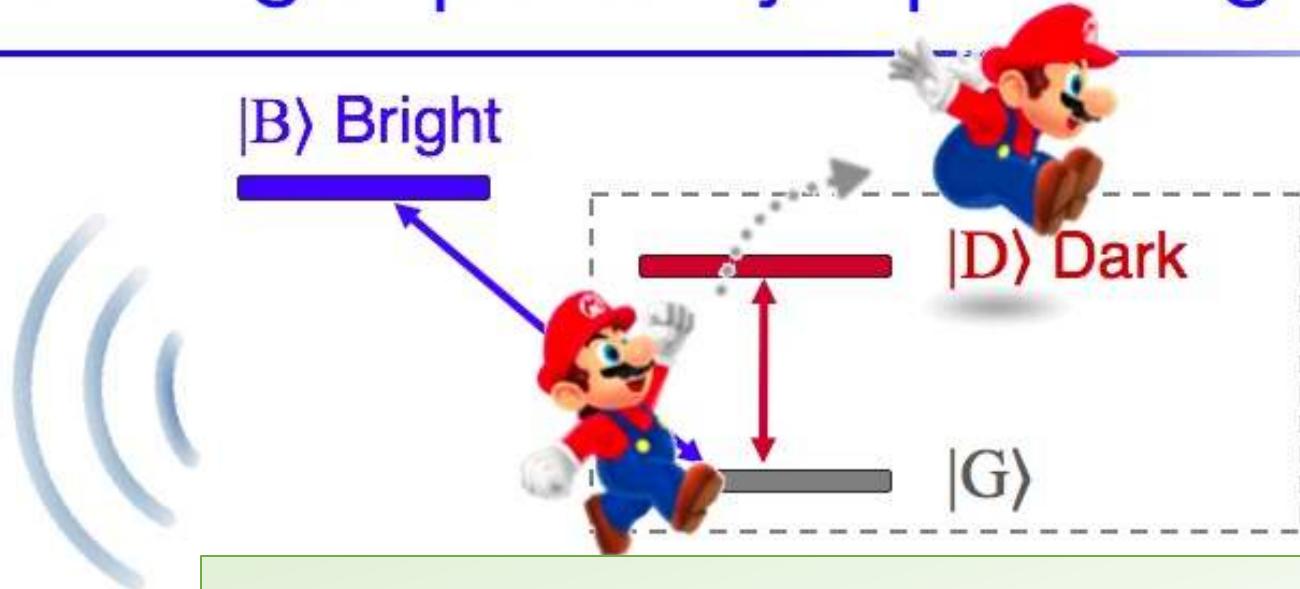
Photo by Eugène Pirou

Believe in your ideas

Hear criticism,
then make a quantum leap



Catching a quantum jump mid-flight



Have fun & misbehave a bit

(John Cohn)

If I knew what I was doing, it
wouldn't be called research.

Albert Einstein
See Hawken *et al.* (2010)

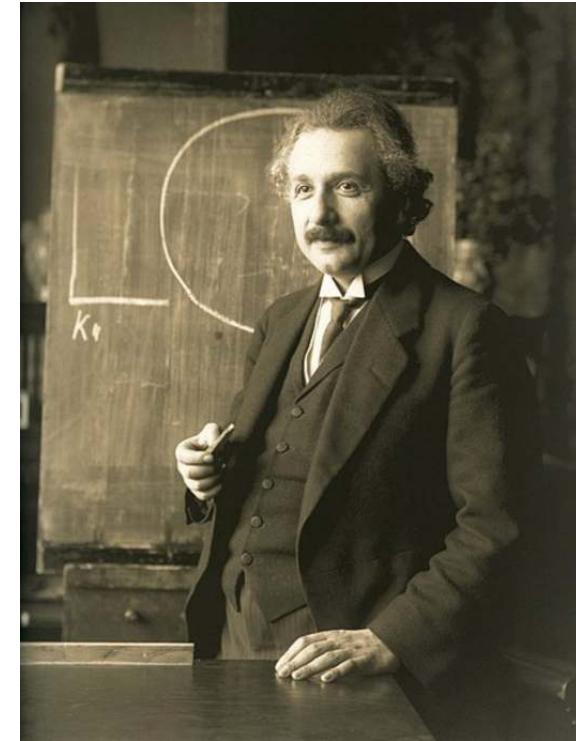


Photo: F. Schmutz

Learn beyond apparent boundaries

“We are not students of some subject matter, but students of problems. And problems may cut right across the borders of any subject matter or discipline.”

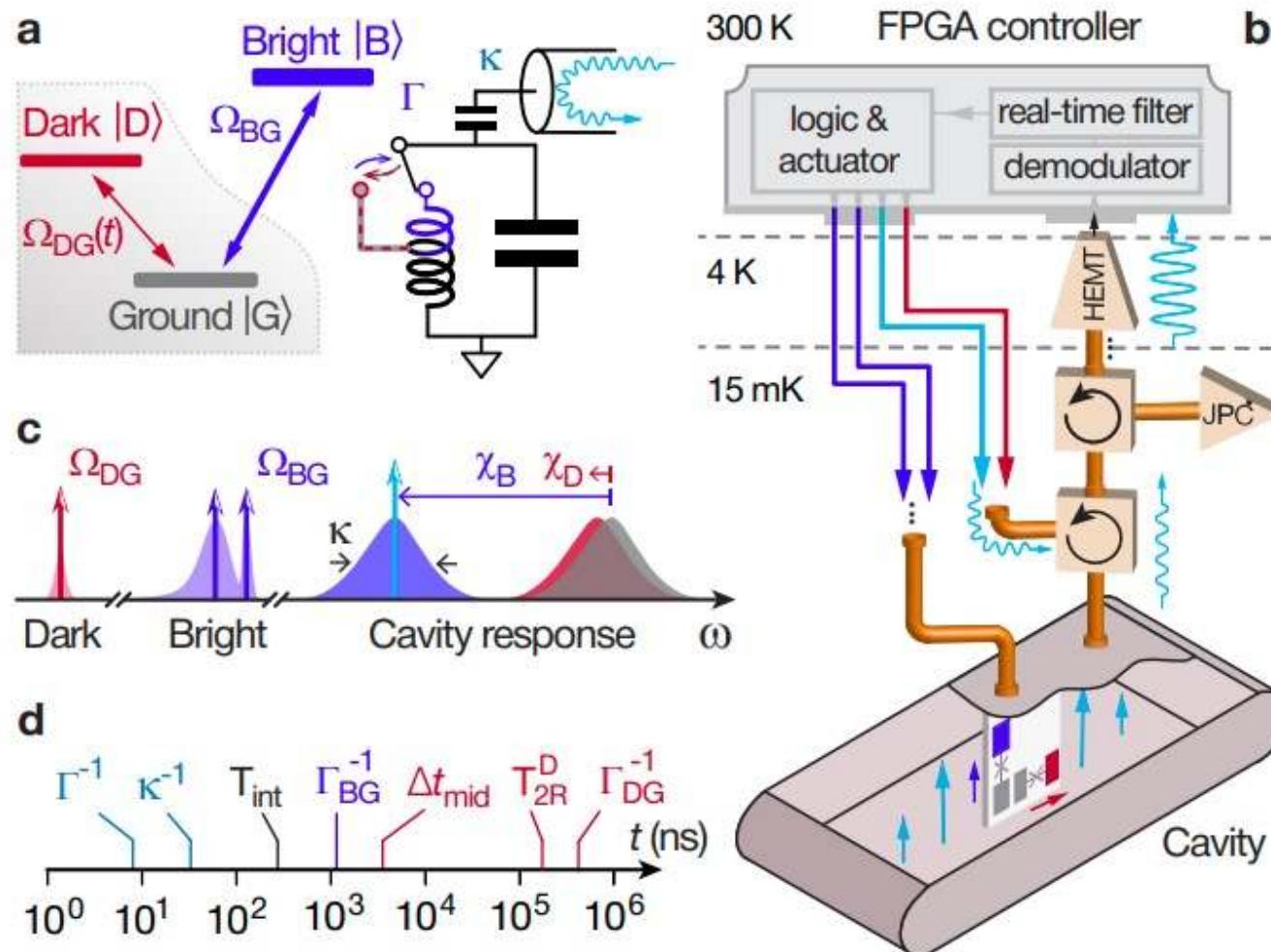
Karl Popper



“I'M ON THE VERGE OF A MAJOR BREAKTHROUGH, BUT I'M ALSO AT THAT POINT WHERE CHEMISTRY LEAVES OFF AND PHYSICS BEGINS, SO I'LL HAVE TO DROP THE WHOLE THING!”

We're in the business of challenging

There are no unsolvable problems, only paths which do not lead to their solution



"Having fun can smooth the ride" (John Cohn, IBM Fellow)



Lessons from the quantum jumps story

Question-driven research

You can only have great answers if you start with great questions

Believe in your ideas

Hear criticism, then make a quantum leap

We're in the business of challenging

There are no unsolvable problems, only paths which do not lead to their solution

Learn, learn, learn

Learn widely; learn always; do not limit self; Can't just keep doing what you've been doing

Periods of intense single-minded focus

Alternate with learning widely

Have fun & misbehave a bit

(John Cohn)

The science of success & the art of fulfillment



Teach to learn

**Find the way,
Go the way,
Show the way**
i.e., give back

Extra broader work

Broader work
adjacent to research and tech



Educational, enablement, advocacy



140 years in 115 seminars: Quantum research community connects on YouTube



Results.

So how is it going?

115+ seminar

244,461+ hours of total viewer watch time

1 million + viewers (people who watched the video)

Nearly 26 million impressions
(people who saw the video in their feed)

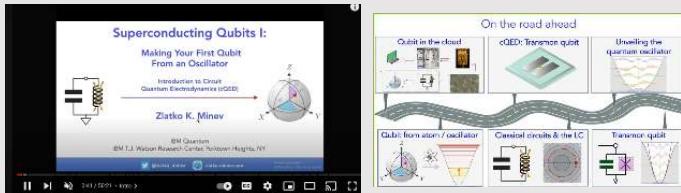
Equivalent to 140 years of a person's work life [i.e., full-time equivalent (FTE)]

Global Summer Schools

4 years x 5,000+ students MOOC

cQED book
WIP

Introduction to Quantum Computing and Quantum Hardware Superconducting circuits



- 5,000+ live attendees

Contents

1 Qubit in the Cloud	1
1.1 Road Ahead	1
1.2 Quantum and Computing: A Brief History	2
1.3 Qubit: A bigger picture	3
1.4 Build the cloud	4

4 The Electromagnetic Harmonic Oscillator

As we discussed in the previous chapter, Circuit Quantum Electrodynamics (cQED) plays a vital role in both classical and quantum electromagnetic theory. This is because it paints a picture of all of the "variables" that describe the components present in a standard electrical circuit as shown in Fig. 4.1. The voltage across the inductor L is $v_L = i_L L$, the current through the inductor L is i_L , and the magnetic flux and charge associated with the capacitor C (Φ_C and Q_C), respectively. All of these variables that define the system are correlated with each other. In this chapter we will be discussing about some missing pieces that we can use to define relations among these variables so that we can define our electromagnetic system in a proper way.

4-1 Beginning from the basics: Kirchoff's Network Laws

Any electrical circuit follows the Kirchoff's Network laws for current and voltage. These laws are effectively the reduced versions of the Maxwell's electromagnetic equations and conservation of current.

Kirchoff's Current Law (KCL) This law takes into consideration the conservation of charge (and thus, conservation of current), and states that the total sum of currents (or the rate of change of charge) for each node of a closed system should always equal to zero. This can be succinctly written using Eq. (4.1) below. In simple words, the charge leaving a capacitor, should decrease the net charge Q_C on the capacitor, whereas the charge associated with the inductor Q_L should increase.

$$\sum_{\text{nodes}} \dot{Q}_i(t) = 0 \quad (4.1)$$

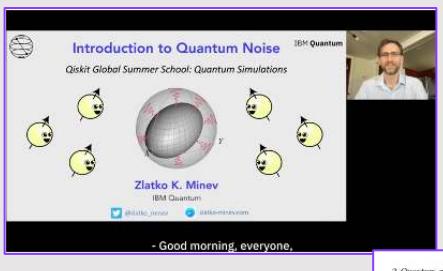
where, $\dot{Q}_i(t)$ is the current passing through a node 'i' within the system, and the $+$ / $-$ signs is determined by the relative direction of the current flow. Therefore, for a node n_1 in the Fig. 4.2, we can write the KCL equation as follows,

$$n_1 : \dot{Q}_C + \dot{Q}_L = 0 \quad (4.2)$$

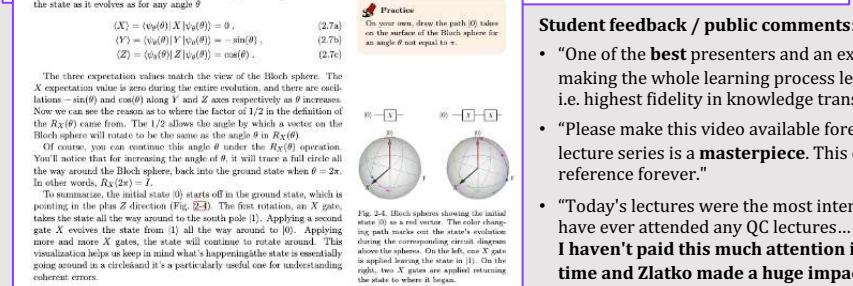
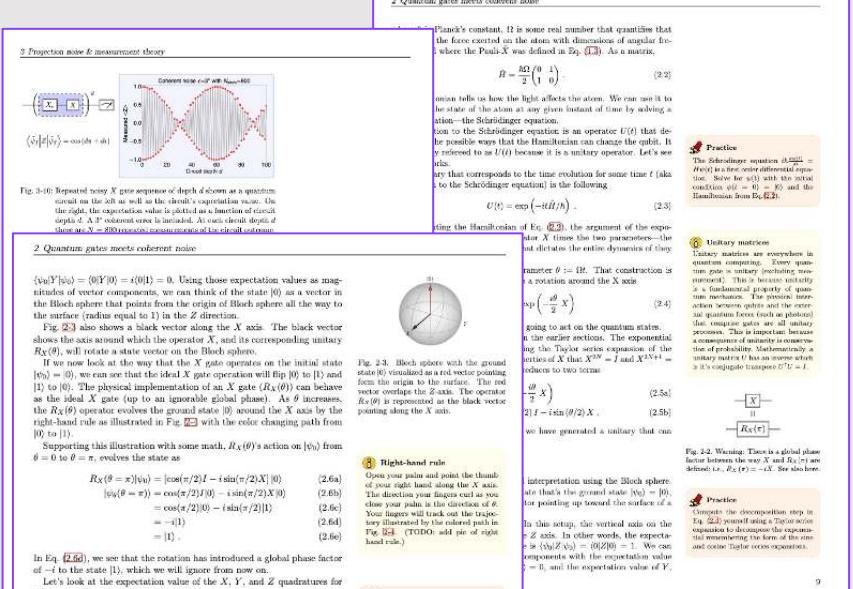
The above Eq. (4.2) represents the upward direction to be positive, the change in charge with respect to time (or the current) of the capacitor is positive, whereas for the inductor it is negative.

12

Introduction to noise in quantum computers



- 5,000 live attendees
- 111 countries
- 27% active industry professionals
- 73% students



10

Introduction to quantum circuits: artificial atoms and microwave photons

Book WIP: Zlatko, Jens Koch, Michel Devoret

1. Your first qubit: from a classical circuit to a transmon (a rapid tour)

1.1 The simplest resonant circuit

1.2 Hubs on Earth Quantum

1.3 From oscillator to qubit

1.4 Qubit control and measurement

1.5 All is not so simple: spherical wave

Quantum information can be stored, manipulated, and processed with the right flavor of electrical circuit. These circuits contain innumerable electric charges, yet they can cause them to behave collectively—to act as if they had just one global degree of freedom. Entanglement properties of these systems can make them useful circuits as if they were individual atoms—artificial atoms. These form the fabric of quantum information processing. Paradoxically, the laws governing artificial circuits can be expressed by a relatively simple mathematical formalism that students can easily learn.

Now, let's see how the behavior of an artificial atom? How do we engineer it to do what things? In this chapter, we begin our journey to find answers. We won't go deep yet, but we will go far—taking a bird's-eye view. We will meet the abstractions and models used to simplify circuit analysis. We will introduce general ideas by studying the simplest classical circuit that oscillates, and will then bridge its description to a quantum one. By understanding how a circuit deals with non-linearity, we will ready for artificial atom and full-programmable qubit. Details and formalities will be relegated to the rest of the book. For now, have fun on your first foray into the world of quantum circuits.

1.1.1. The simplest resonant circuit

(1.1)

(1.2)

(1.3)

Written in the more compact $\partial_t \Phi(t) + \dot{\Phi}(t) = 0$.

(1.4)

Fig. 1.1: Analog between the LC circuit circuit in the classical regime and the mechanical spring whose displacement position x is analogous to the magnetic flux Φ .

1.1.2. Your first qubit: from a classical circuit to a transmon (a rapid tour)

combination with the current bias (KCL) equations,

(1.5)

(1.6)

(1.7)

Fig. 1.1: Graphical representation (circuit diagram) of the LC electrical circuit. The inductance L and capacitance C are connected by this series.

1.1.3. Position, Velocity, Momentum, Force, Mass, and Energy

1.1.4. Practice

The Schrödinger equation $i\hbar\frac{d}{dt}\psi(t) = H\psi(t)$ is a first order differential equation. Solve for $\psi(t)$ with the initial condition $\psi(0) = |\psi\rangle$ and the Hamiltonian from Eq.(2.2).

1.1.5. Unitary matrices

Unitary matrices are everywhere in quantum mechanics. They are often called a unitary (because they are normalized). This is because unitary operations are the only ones that preserve probabilities and energy. The generic interaction between spin and environment is not unitary and does not conserve energy or momentum. A consequence of unitarity is conservation of probability. Mathematically, a unitary operator U satisfies $U^\dagger U = I$ and $U^{\dagger -1} = U$. It is its conjugate transpose $U^\dagger = U$.

1.1.6. Right-hand rule

Open your hand and point the thumb (your right hand) along the X axis. The direction your fingers curl as you close your palm is the direction of $\partial/\partial X$. This is illustrated by the path in Fig. 2.1. (TODD: add pic of right hand rule.)

1.1.7. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.8. Practice

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1.1.9. Practice

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1.1.10. Practice

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1.1.11. Practice

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1.1.12. Practice

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1.1.13. Practice

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1.1.14. Practice

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1.1.15. Practice

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1.1.16. Practice

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1.1.17. Practice

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1.1.19. Practice

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1.1.20. Practice

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1.1.21. Practice

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1.1.22. Practice

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1.1.23. Practice

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1.1.24. Practice

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1.1.25. Practice

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1.1.26. Practice

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1.1.27. Practice

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1.1.28. Practice

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1.1.29. Practice

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1.1.30. Practice

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1.1.31. Practice

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1.1.32. Practice

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1.1.34. Practice

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1.1.35. Practice

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1.1.36. Practice

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1.1.37. Practice

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1.1.38. Practice

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1.1.39. Practice

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1.1.40. Practice

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1.1.41. Practice

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1.1.42. Practice

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1.1.43. Practice

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1.1.44. Practice

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1.1.45. Practice

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1.1.46. Practice

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1.1.47. Practice

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1.1.48. Practice

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1.1.49. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.50. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.51. Practice

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1.1.53. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.54. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.55. Practice

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1.1.56. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.57. Practice

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1.1.58. Practice

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1.1.59. Practice

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1.1.60. Practice

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1.1.61. Practice

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1.1.62. Practice

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1.1.64. Practice

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1.1.67. Practice

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1.1.68. Practice

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1.1.69. Practice

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1.1.70. Practice

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1.1.71. Practice

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1.1.72. Practice

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1.1.73. Practice

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1.1.77. Practice

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1.1.79. Practice

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1.1.80. Practice

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1.1.81. Practice

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1.1.82. Practice

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1.1.83. Practice

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1.1.84. Practice

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1.1.85. Practice

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1.1.86. Practice

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1.1.87. Practice

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1.1.88. Practice

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1.1.89. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.90. Practice

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1.1.91. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.92. Practice

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1.1.93. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.94. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.95. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.96. Practice

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1.1.97. Practice

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1.1.98. Practice

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1.1.99. Practice

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1.1.100. Practice

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1.1.101. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.102. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.103. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.104. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.105. Practice

Comments the decomposition step in Eq. (2.2) using a Taylor series expansion. Then, decompose the angle θ into two parts: $\theta = \theta_x + \theta_y$. Then, remember the form of the sine and cosine Taylor series expansion.

1.1.106. Practice

Comments the decomposition step in Eq. (2.2) using

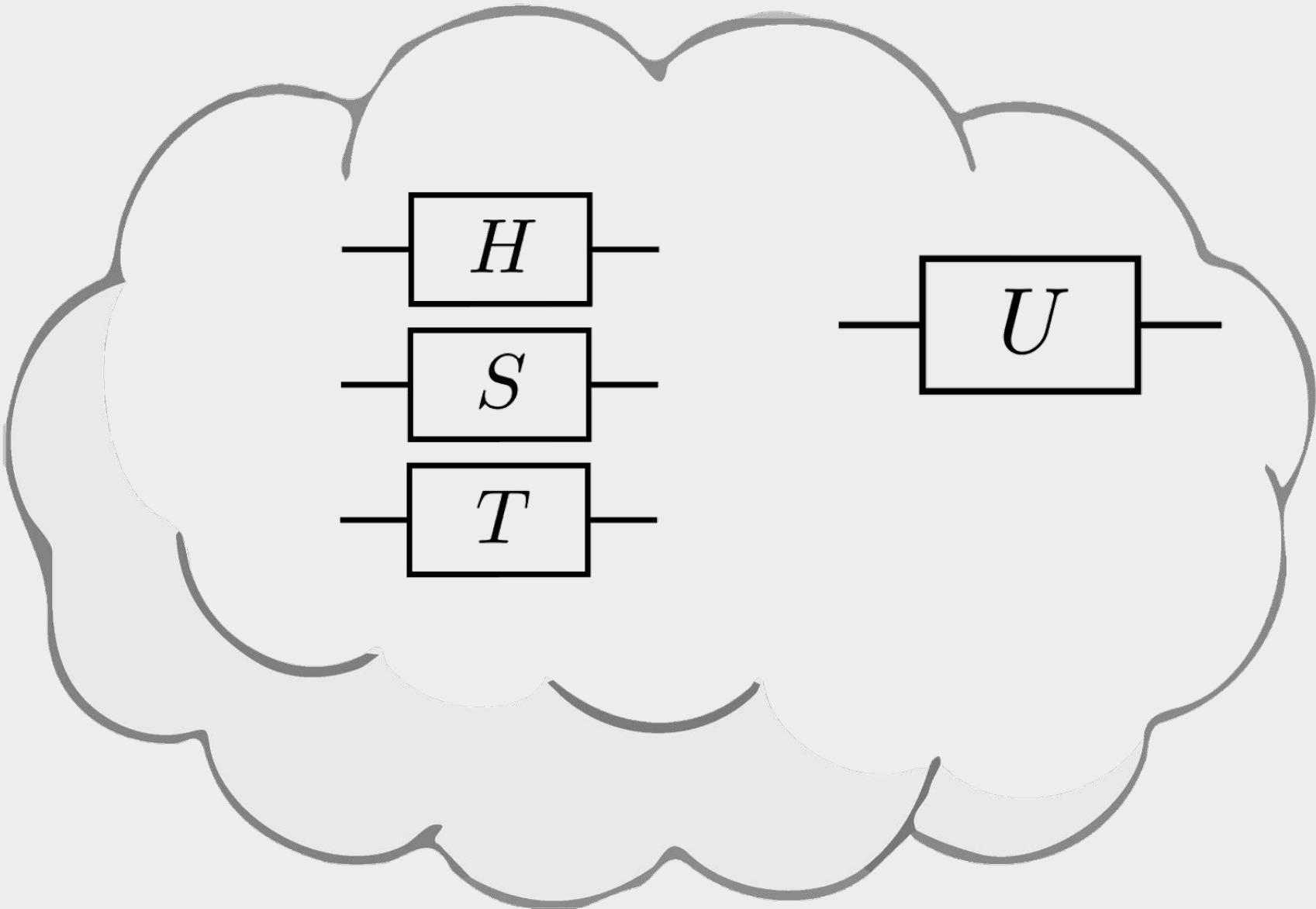


Open Labs

Est. 2012

Quantum Computer and IBM Quantum

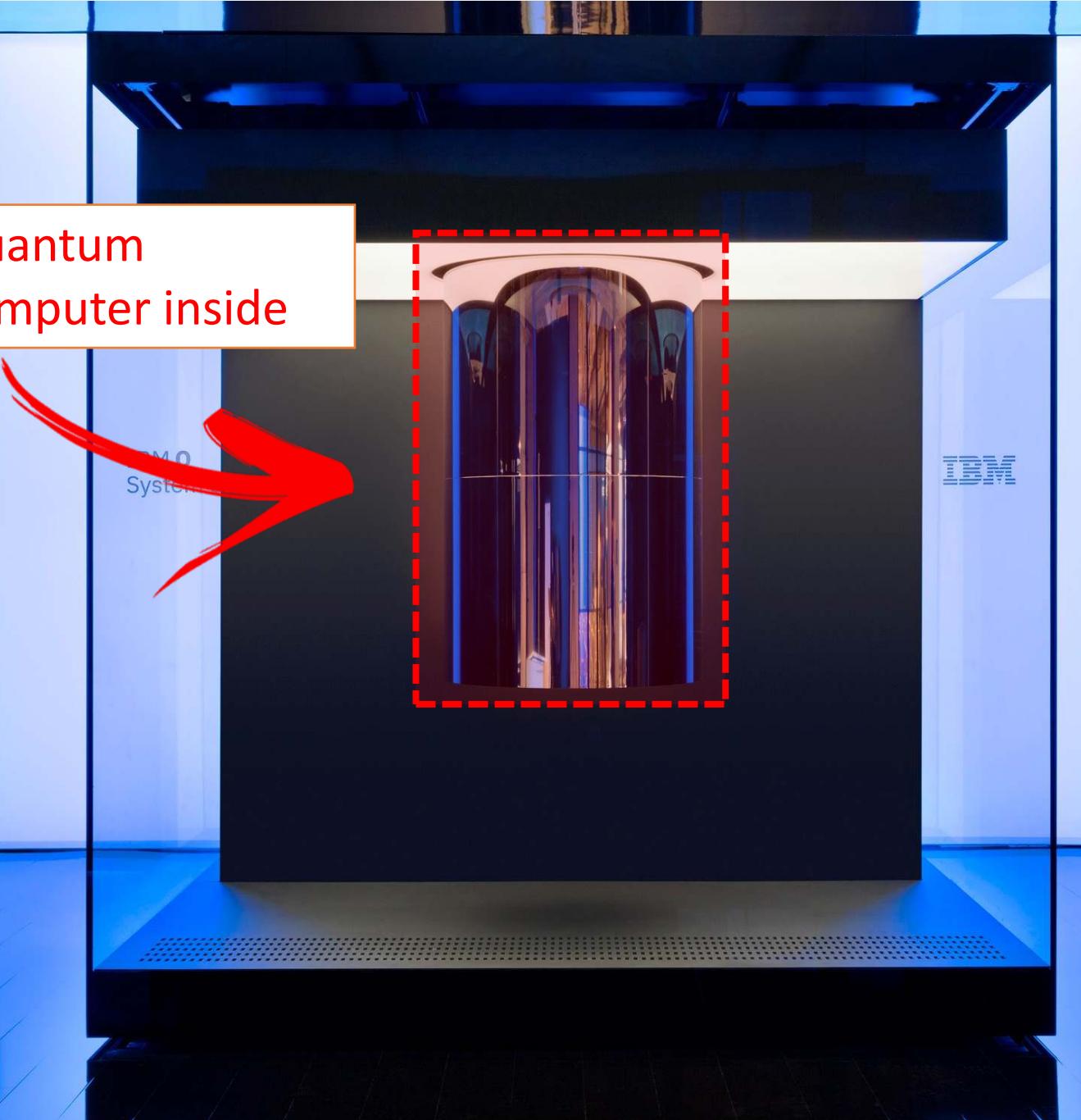
“Quantum cloud”



Quantum computer



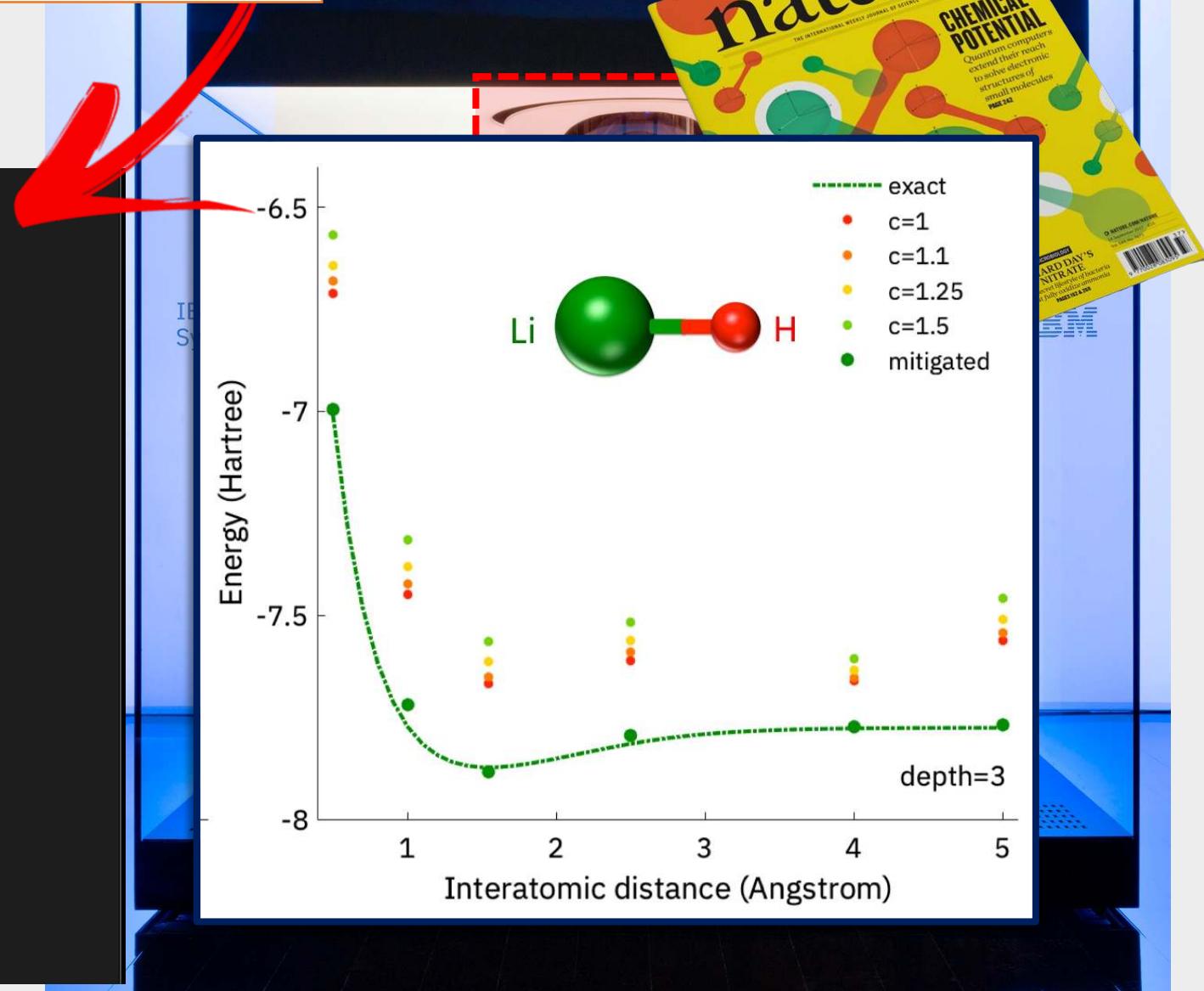
Quantum
computer inside



Programming quantum

execute program
in Python

```
(Qiskit) → qprogram_examples git:(master) ✘
```



Biggest challenge?

Please do share

Biggest challenge?

Noise
(Errors)

hardware
development

decoherence

loss

stability

error correction
overheads

high error rates

heat

algo
development

scalability

engineering

need CS/EE
talent

importance of
N in NISQ

modularization

material
quality

gravity

hype

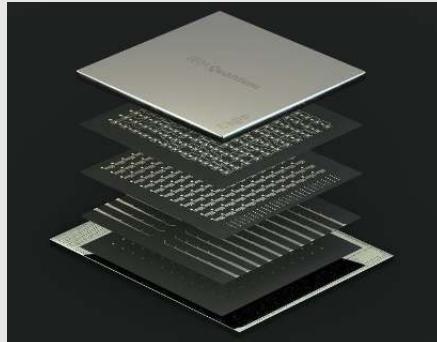
expectations

Biggest challenge

Noise
(Errors)



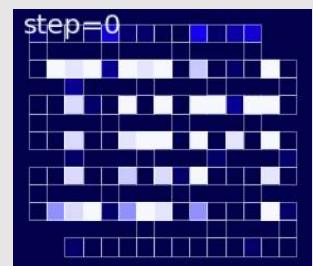
Quantum computational science on quantum hardware



What should I know about using today's quantum hardware?



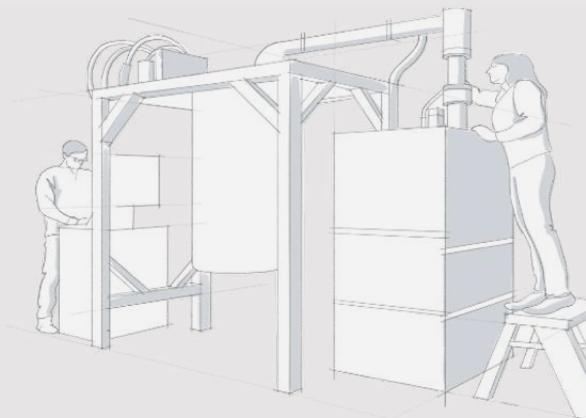
Quantum and Noise Introduction in a nutshell



1 qubit (Hello World!)
to
100+ qubits (state of art)



Hello World: Is it even or odd?

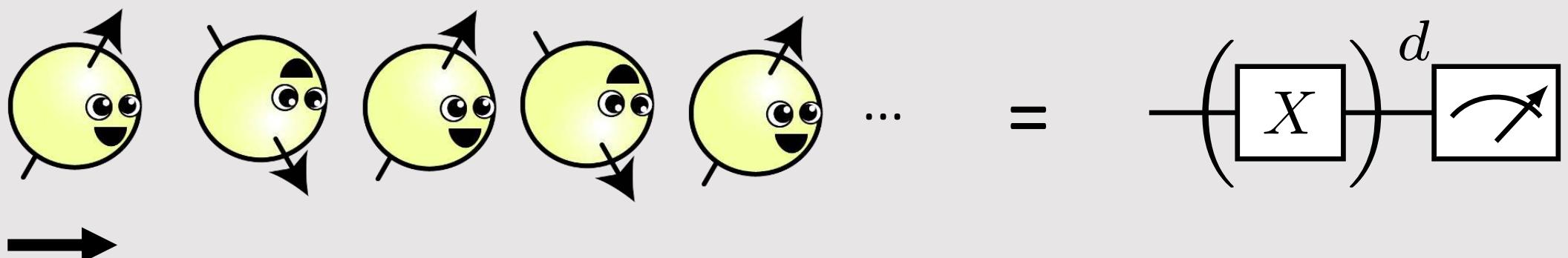


Compute resources
Algorithm input
Task

1 qubit
an integer $d > 0$
even or odd?

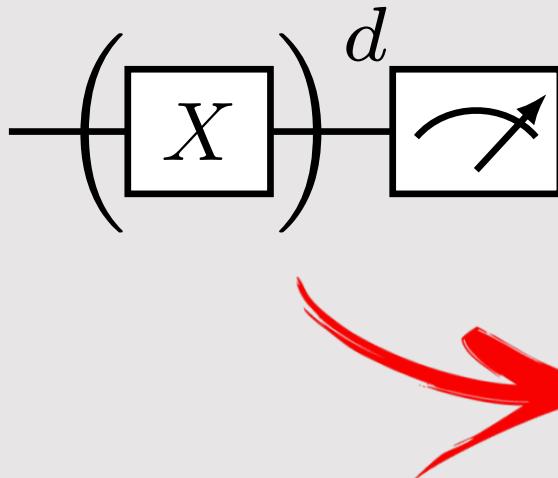
A toy algorithm

Start in 0, flip d times, measure

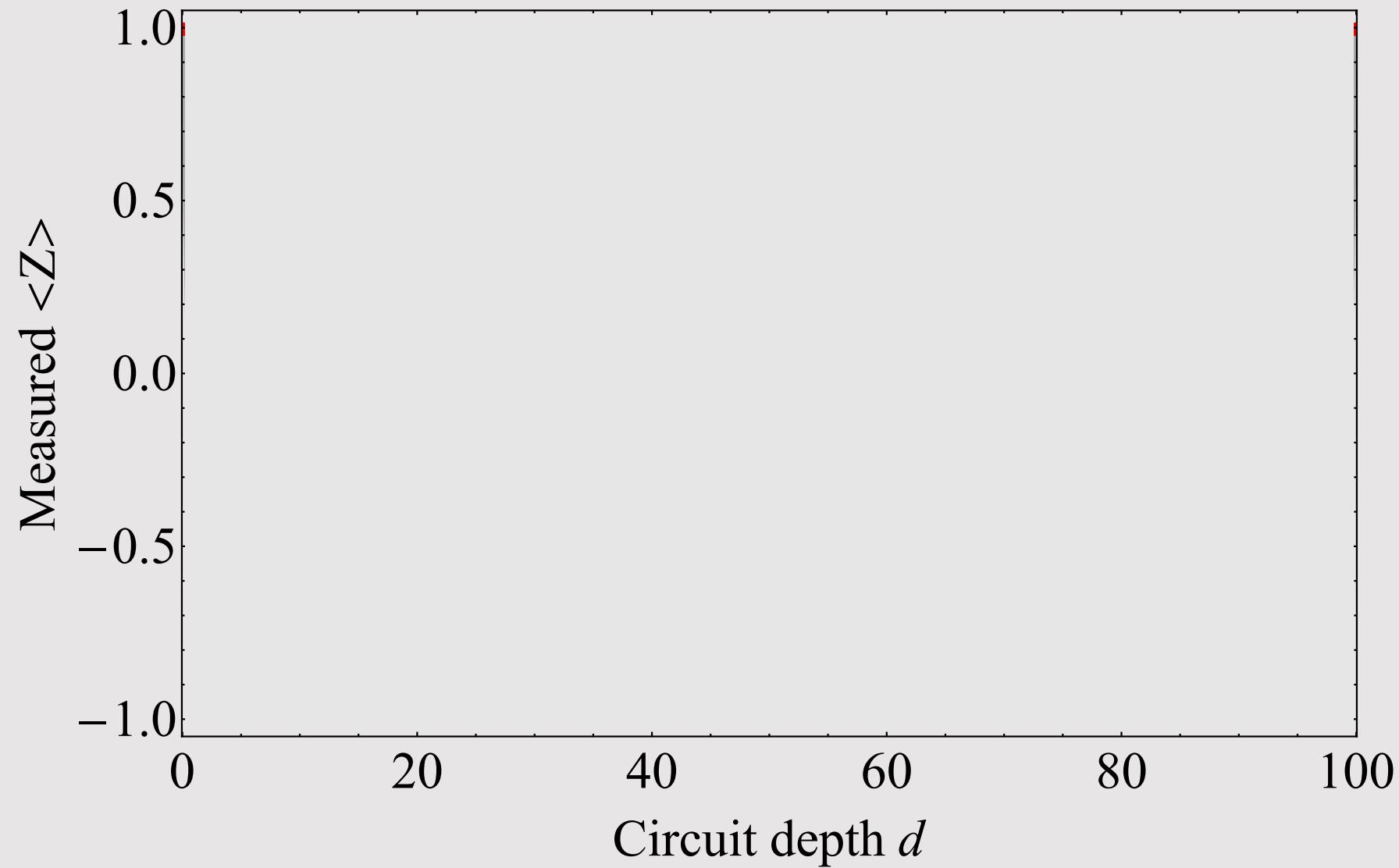




Hello World! Ideal expectation results

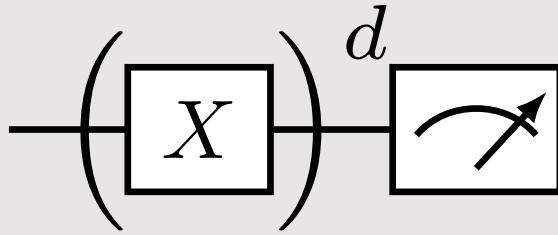


$$\langle Z \rangle = (-1)^d$$

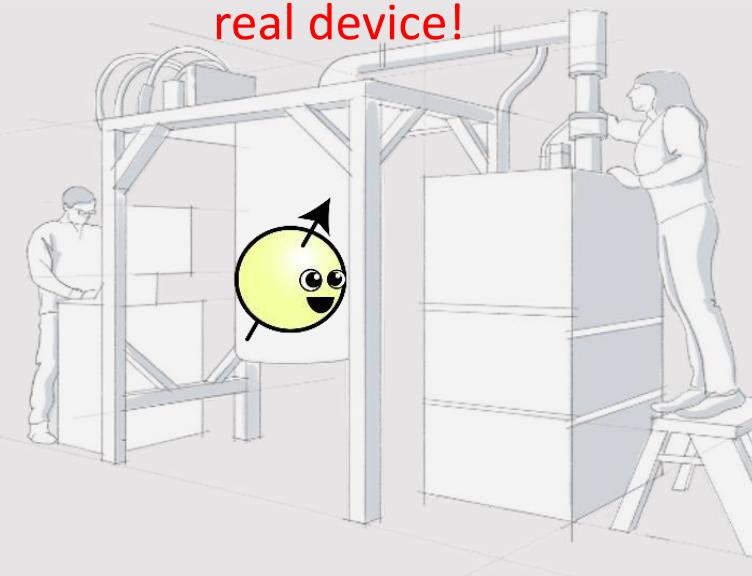




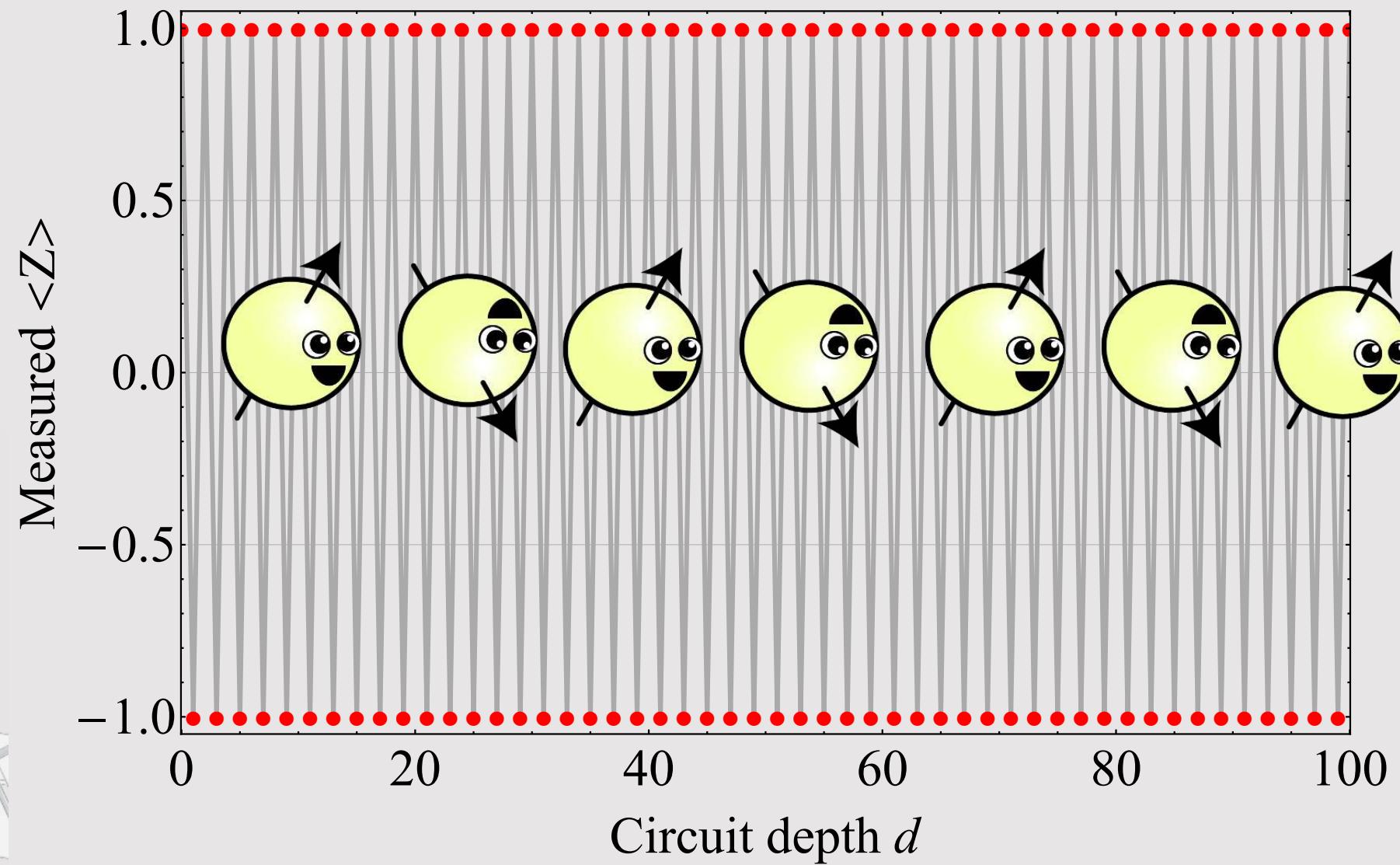
Hello World! Ideal expectation results



Let's run on an (old)
real device!

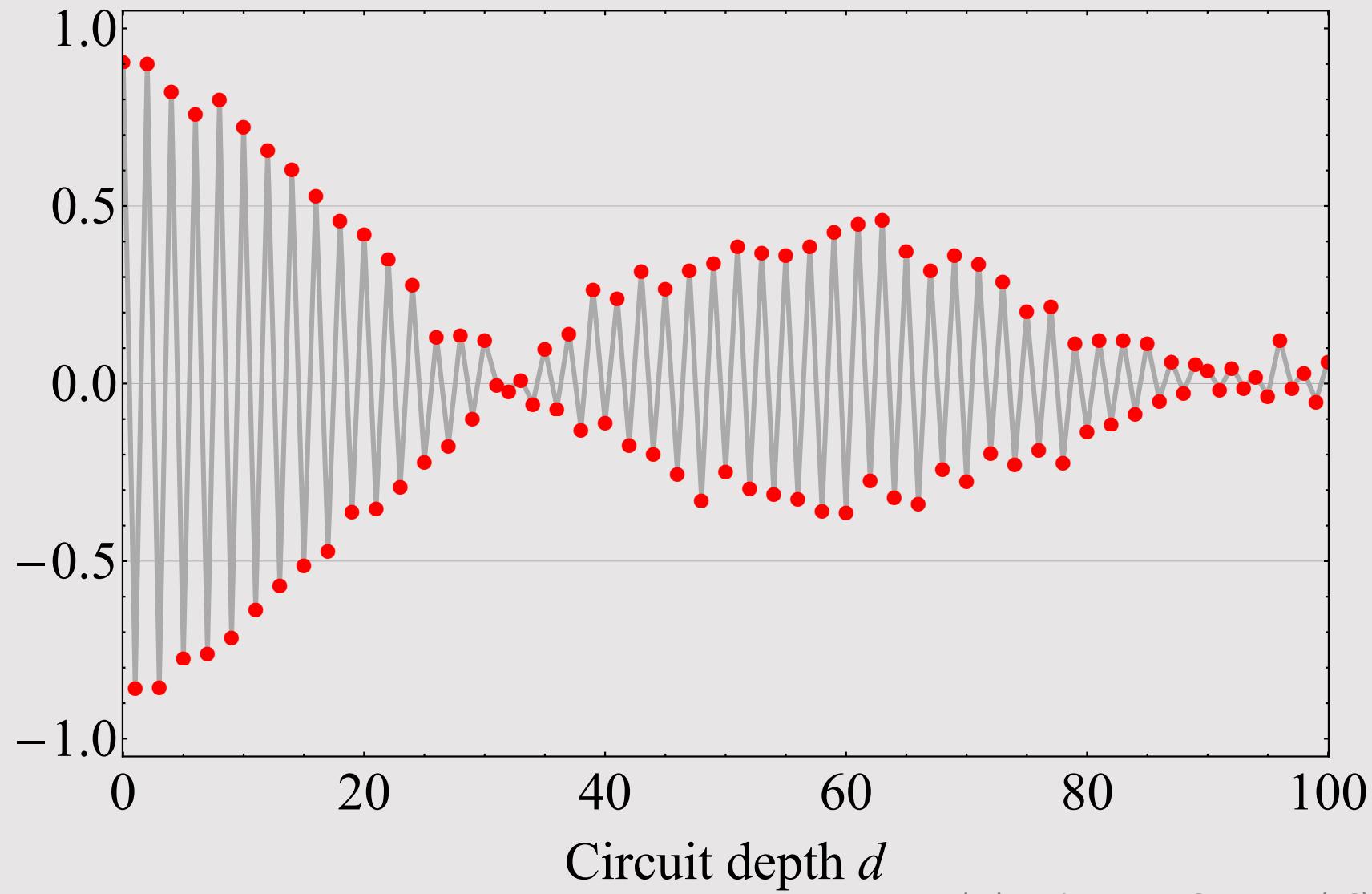
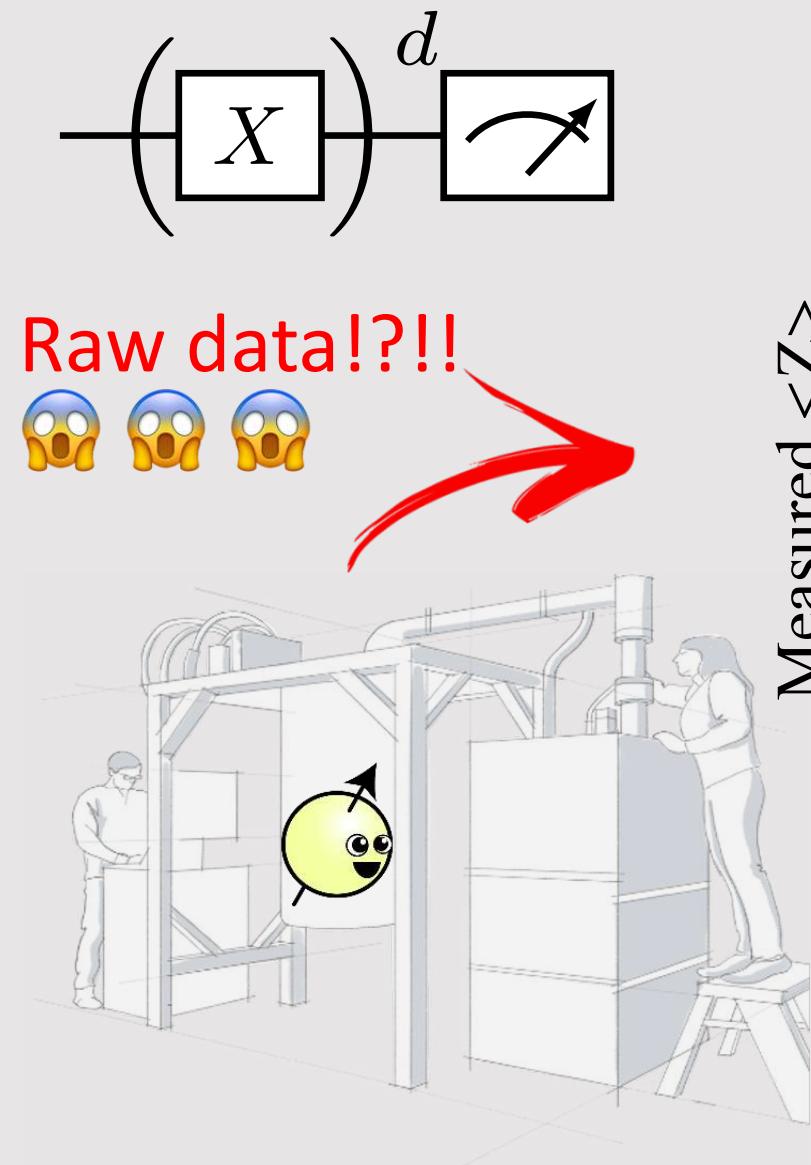


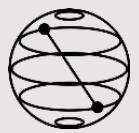
$$\langle Z \rangle = (-1)^d$$





Hello World! Real expectation results

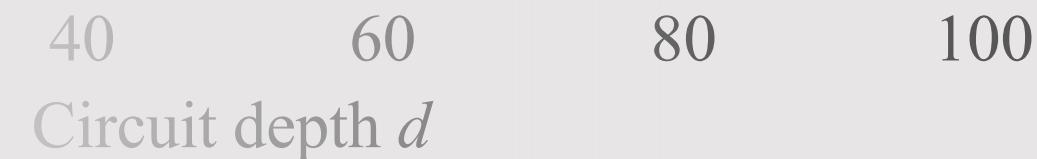


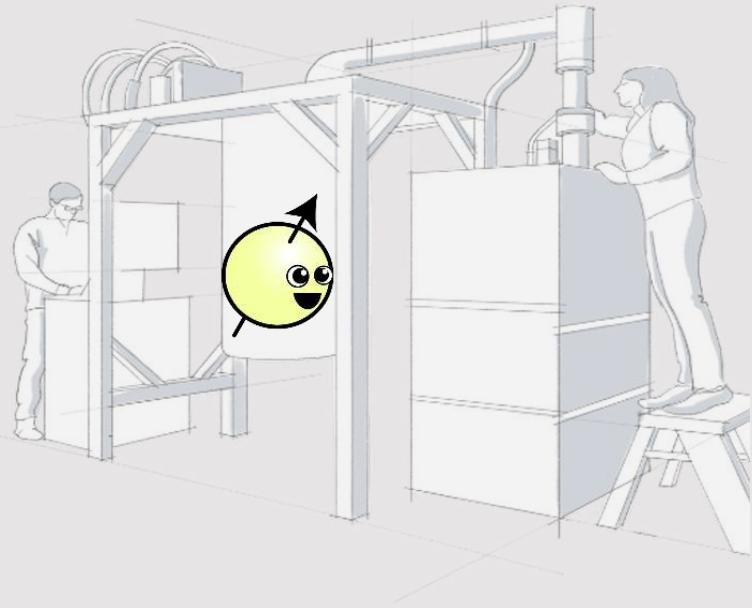


Real & noisy quantum processors: Why study noise?



“Well, your quantum computer is broken in every way possible simultaneously.”



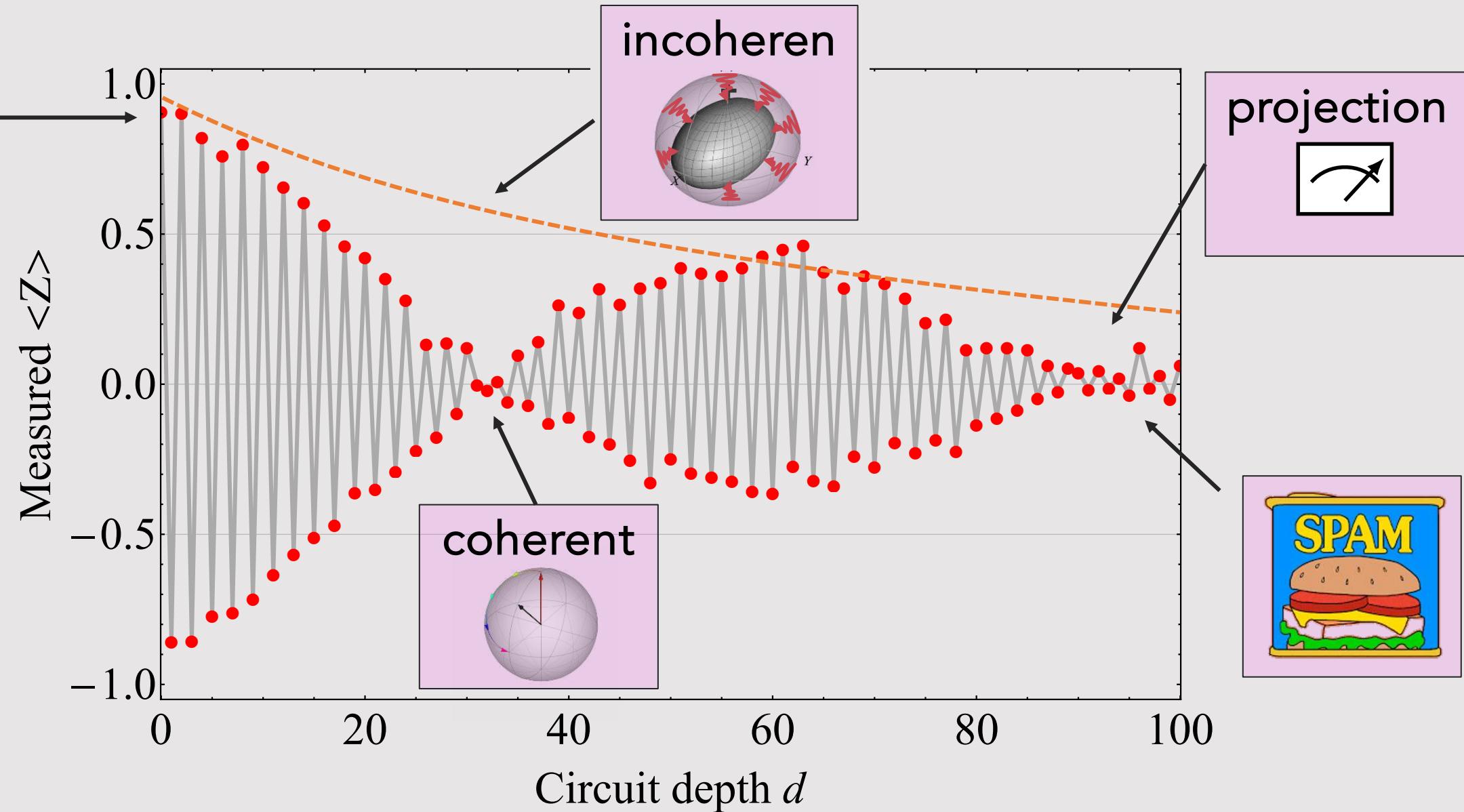


“Quantum phenomena
do not occur in a Hilbert space,
they occur in a laboratory.”

Asher Peres



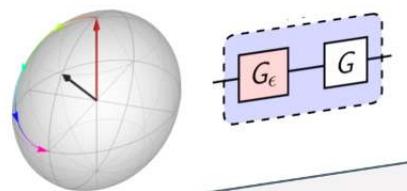
Elements of 😱 noise



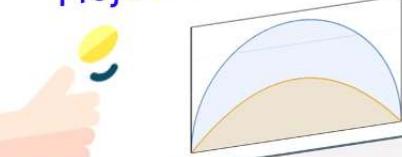
Learn the basics?

The road ahead

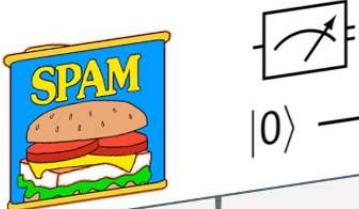
Coherent noise



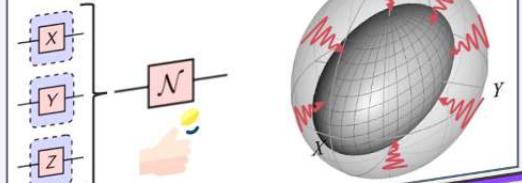
Measurement in a nutshell
Projection noise



SPAM: Noisy meters



Incoherent noise



NO NOISE!



Bonus content
Coherent ZZ
State preparation

coin toss: flatiron; spam: make it move;
road based on: freepik
Zlatko Minev, IBM Quantum (17)

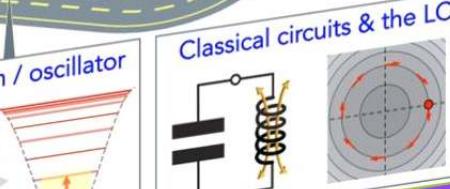
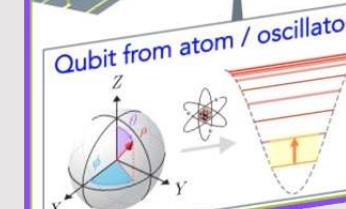
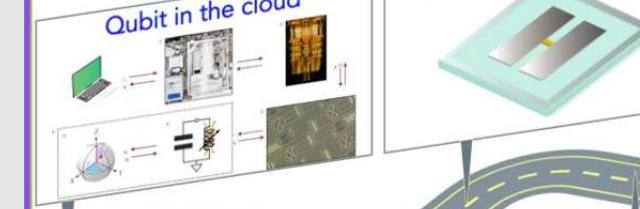
2021, 2022, 2023
Intro to Quantum Noise
Z. Minev

qiskit.org/learn

Qiskit Global Summer School 2023 coming up soon!
5,000+ students

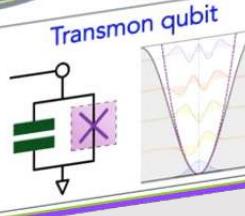
On the road ahead

cQED: Transmon qubit



Unveiling the
quantum oscillator

Quantum oscillator



Introduction to superconducting
qubits (cQED)
Lecs. 16-21 Minev
QGSS 2020

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

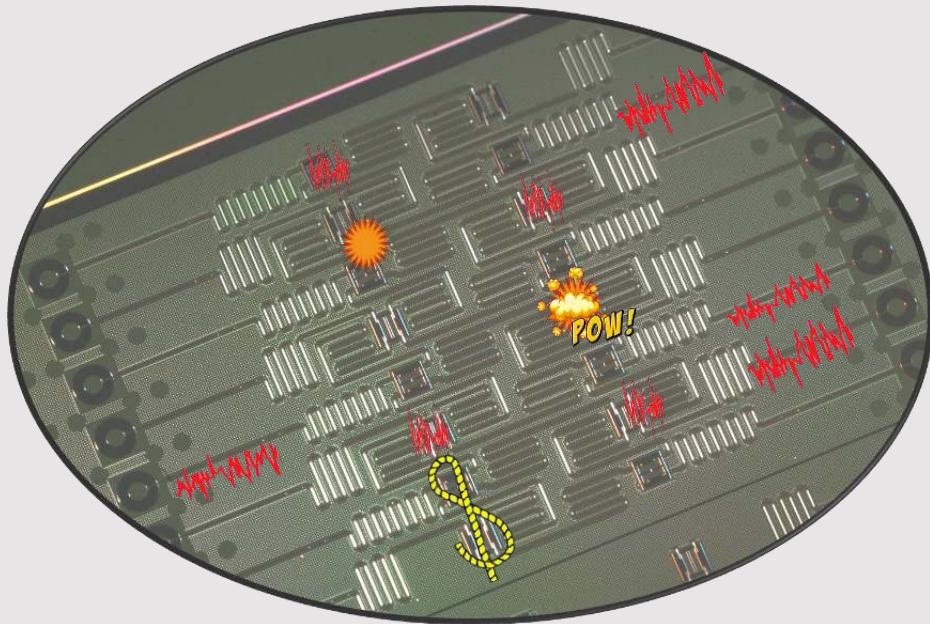
Error occurs
Error undetected



Error mitigation

... subject of today

Error mitigation and error correction at a glance



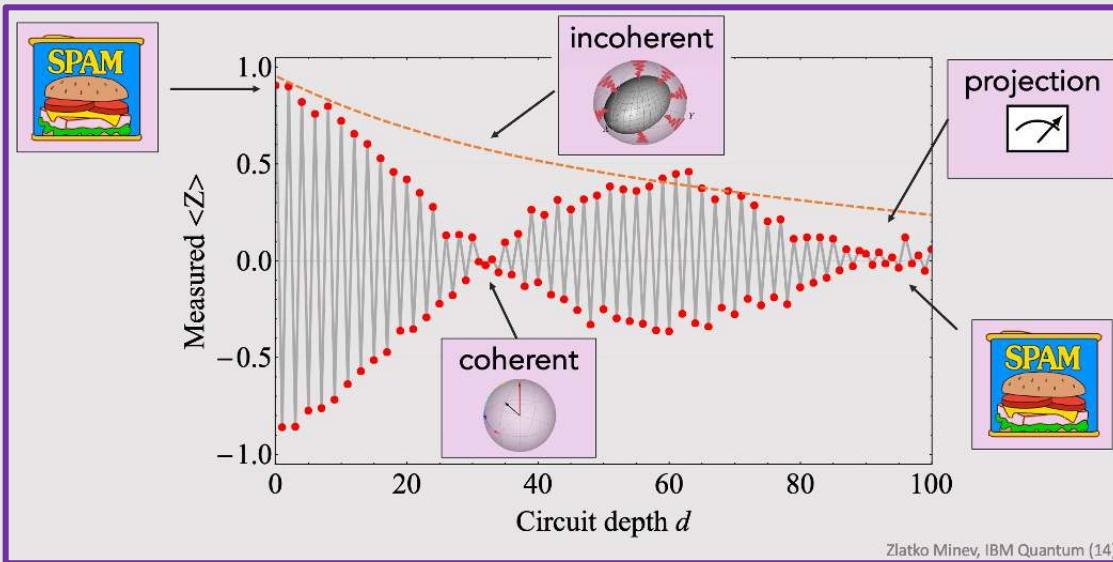
Error mitigation Working with what you have

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

Error correction Protecting your 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

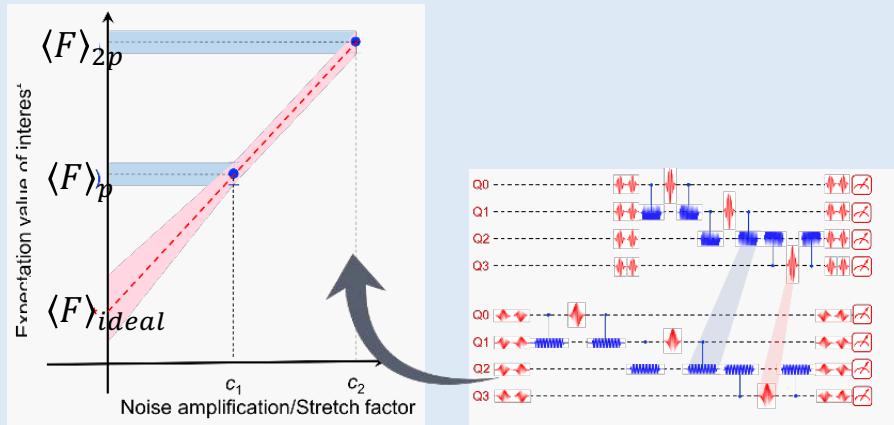


more information, accuracy



Error mitigation landscape

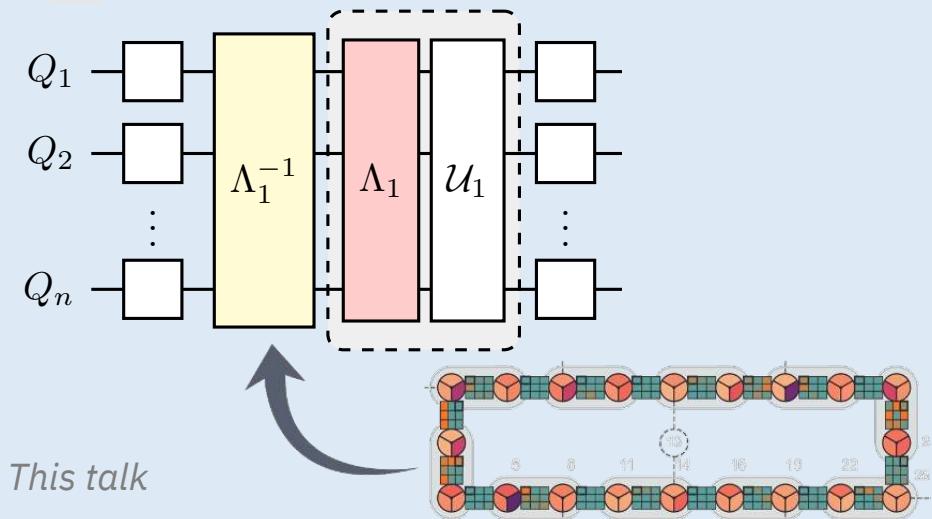
Zero-noise extrapolation (ZNE)



Nature 567, 491 (2019)

...

Probabilistic error cancellation (PEC)



more speed

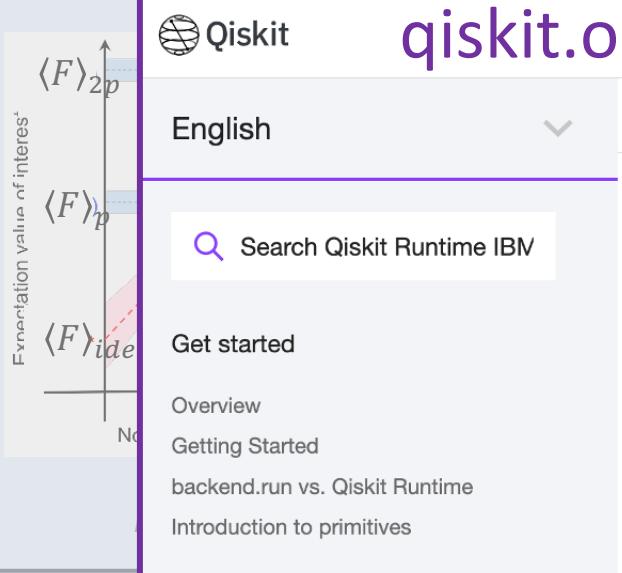


more information, accuracy

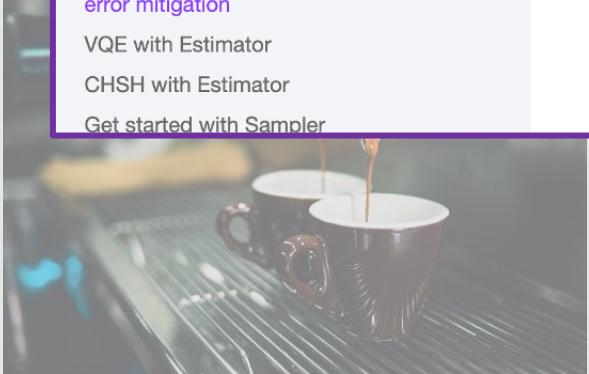


Error mitigation landscape

Zero-noise extrapolation (ZNE)



more speed

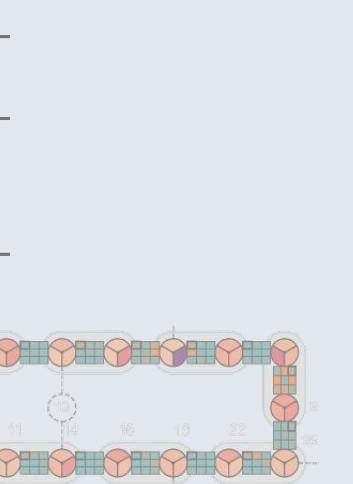


Probabilistic error cancellation (PEC)

The screenshot shows a documentation page from qiskit.org titled "Error suppression and error mitigation with Qiskit Runtime". It includes a note that the page was generated from `docs/tutorials/Error-Suppression-and-Error-Mitigation.ipynb`. Below the note, there is a quantum circuit diagram and a code snippet:

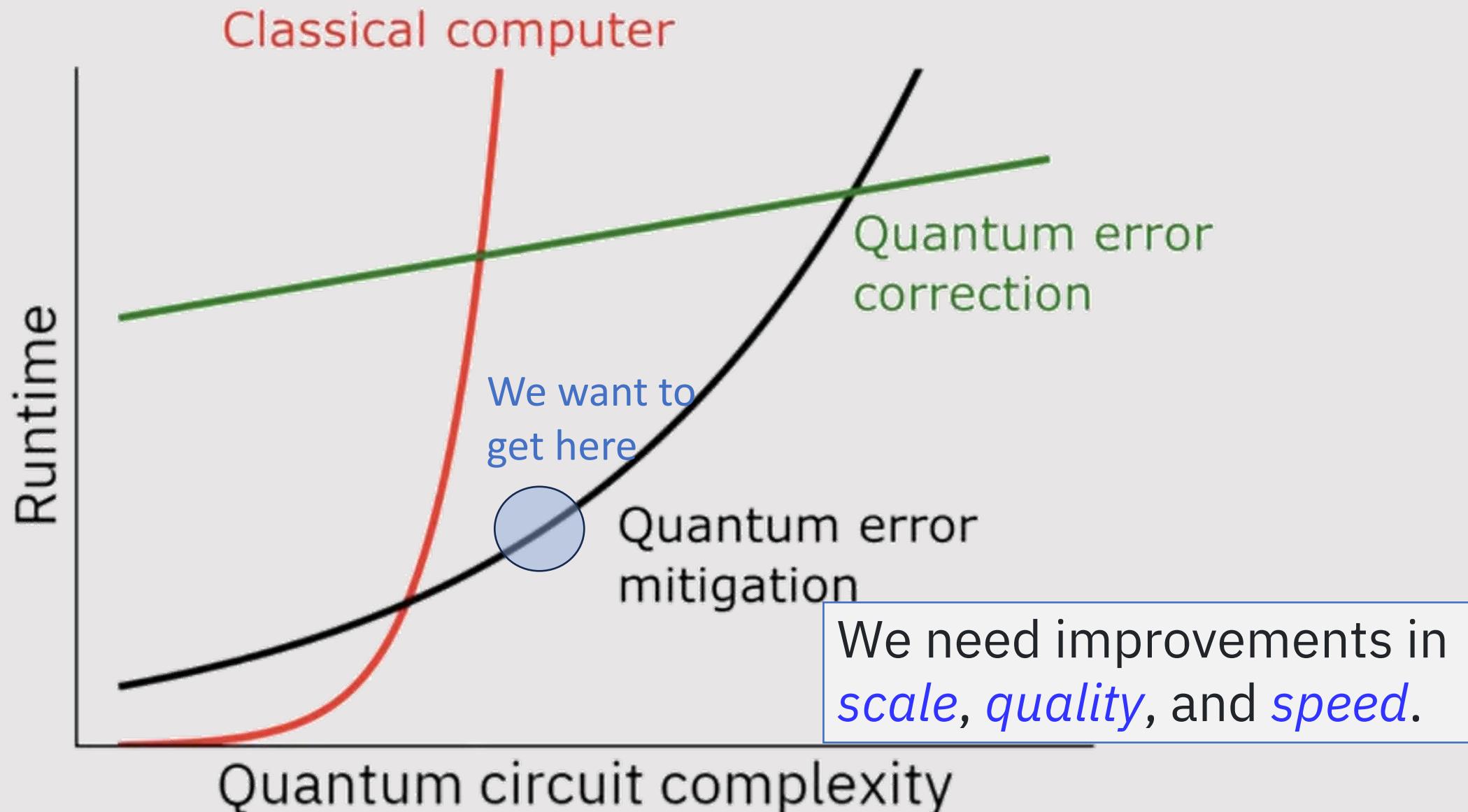
```
[1]: import datetime
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.rcParams.update({"text.usetex": True})
plt.rcParams["figure.figsize"] = (6,4)
mpl.rcParams["figure.dpi"] = 200

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



more information, accuracy

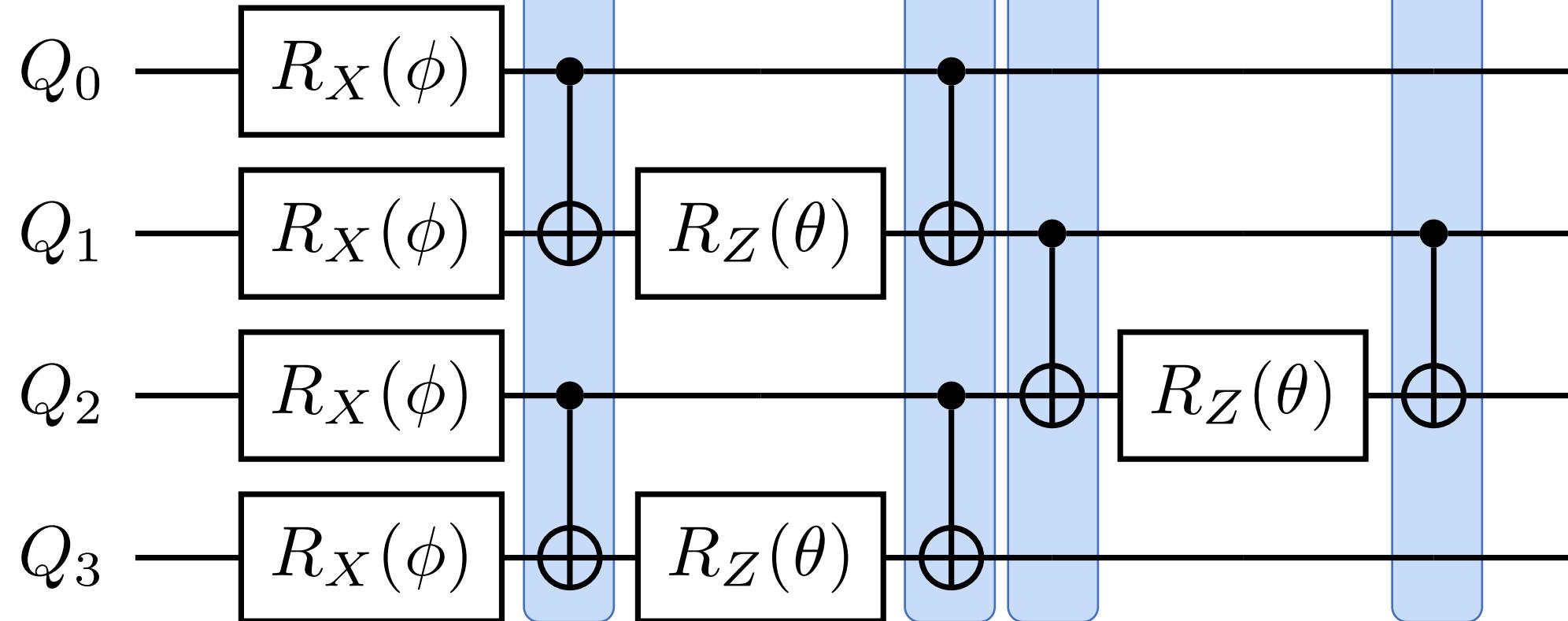
Path to utility of quantum computers before error correction



Bring useful quantum computing

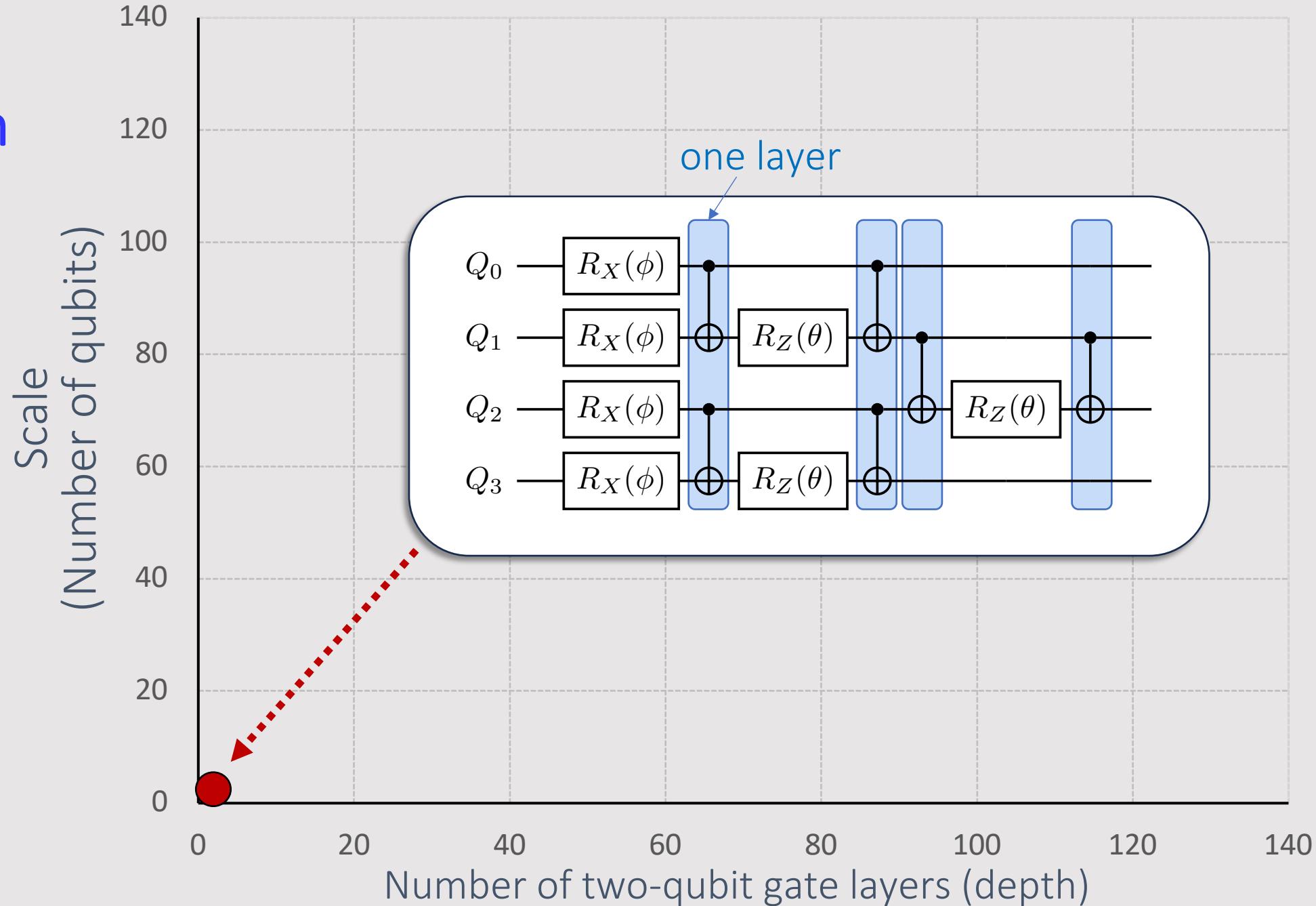
A prequel to the panel

one gate layer



4 qubits x 4 gate layers

Circuit width × depth



Many-body physics on superconducting quantum computers

A representative subset of many-body physics experiments on superconducting quantum computers until 2023, depths approximate*

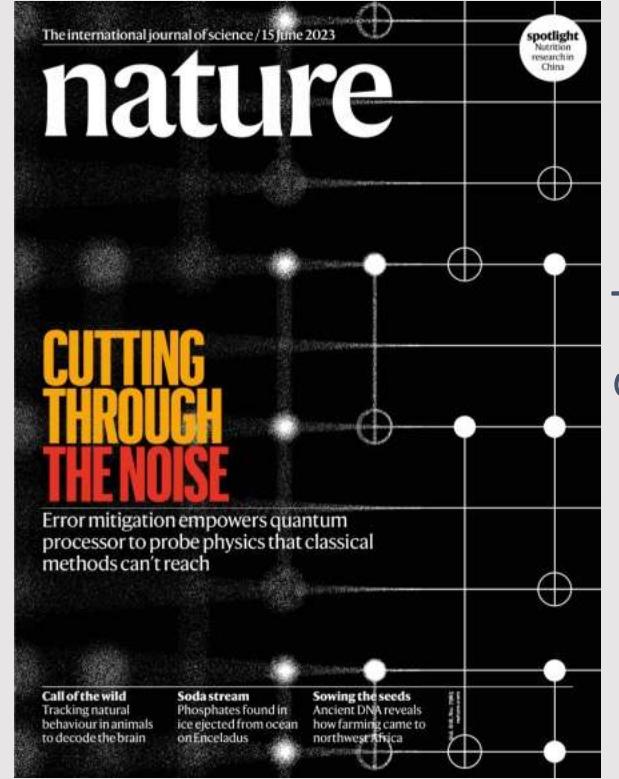
- [1] Science 369, 1084 (2021)
- [2] Nature 594, 508 (2021)
- [3] Science 374, 1479 (2021)
- [4] Nature 601, 531 (2022)
- [5] Science 378, 785 (2022)
- [6] Nature 612, 240 (2022)
- [7] Nature 618, 264 (2023)

...

* signal stops or decays more than 50% beyond this depth, capped at 140



Some experiments in last 3 months



Evidence for the utility of quantum computing before fault tolerance

Youngseok Kim, Andrew Eddins, Sajant Anand, Ken Xuan Wei, Ewout van den Berg,

Sami Rosenblatt, Hasan Nayfeh, Yantao Wu, Michael Zaletel, Kristan Temme & Abhinav

Kandala

Nature 618, 500–505 (2023) | Cite this article



Some recent experiments

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

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

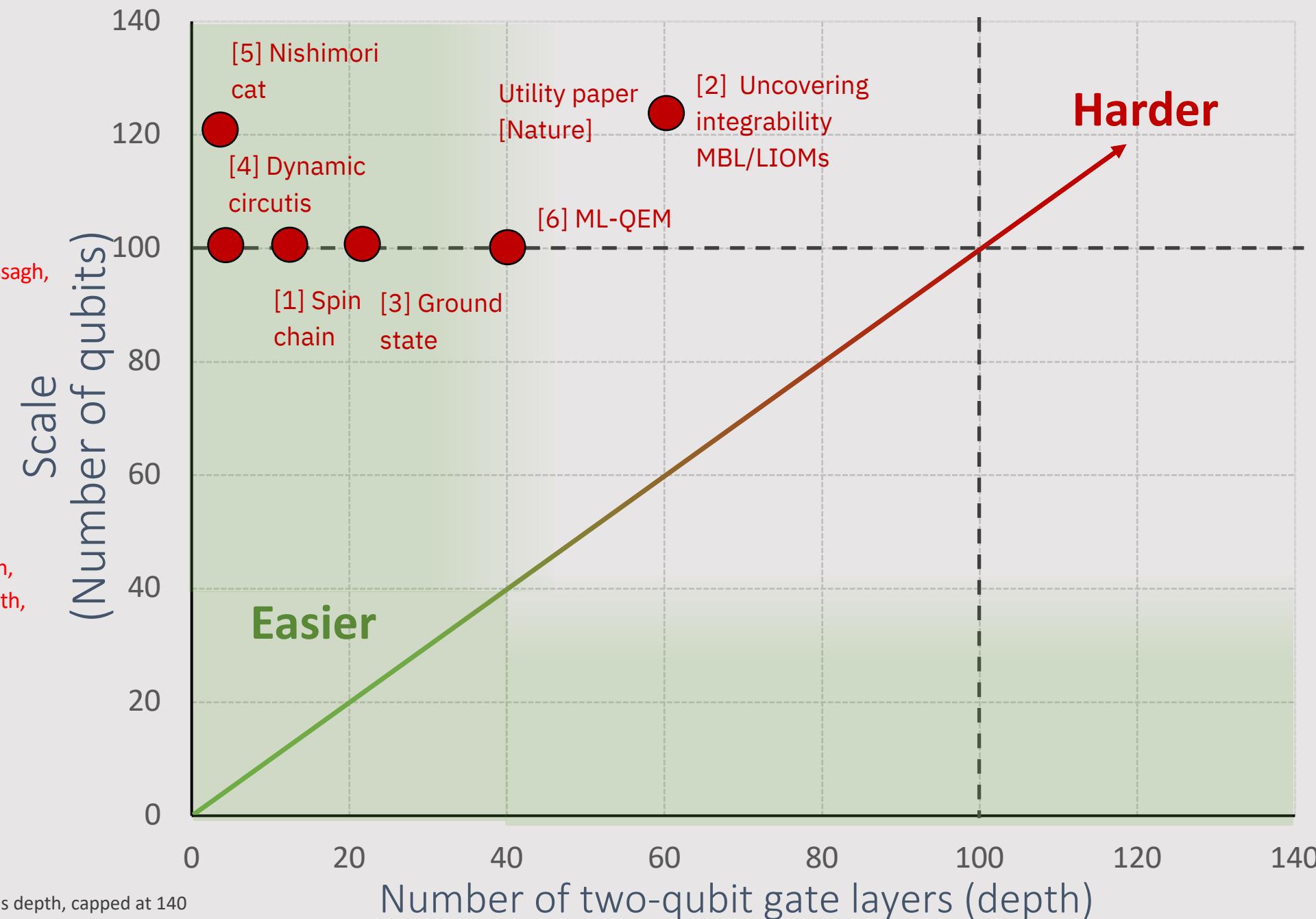
[3] Farrell, Illa, Ciavarella, Savage.
arXiv: 2308.04481 (2023)

[4] Bäumer, Tripathi, Wang, Rall, Chen,
Majumder, Seif, Minev.
arXiv: 2308.13065 (2023)

[5] Chen, Zhu, Verresen, Seif, Baümer, Layden,
Tantivasadakarn, Zhu, Sheldon, Vishwanath,
Trebst, Kandala.
arXiv: 2309.02863 (2023)

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

...



* signal stops or decays more than 50% beyond this depth, capped at 140

* note: quantum advantage with shallow circuits, Bravyi, Gosset, Konig, and related



2019

Falcon

27 Qubits

2020

Hummingbird

65 Qubits

2021

Eagle

127 Qubits

2022

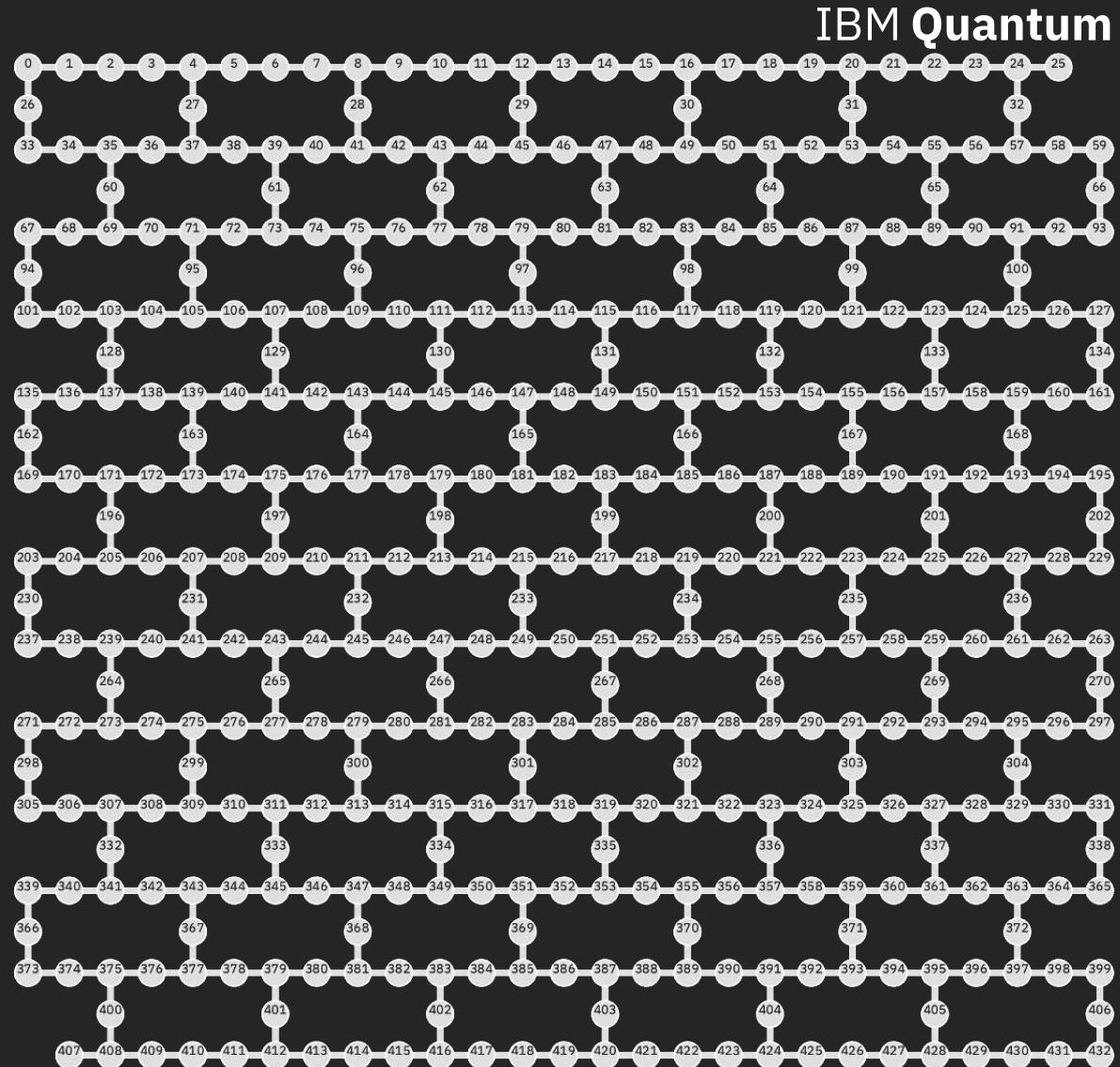
Osprey

433 Qubits

IBM Quantum



Osprey – 433 Qubits



Performance =

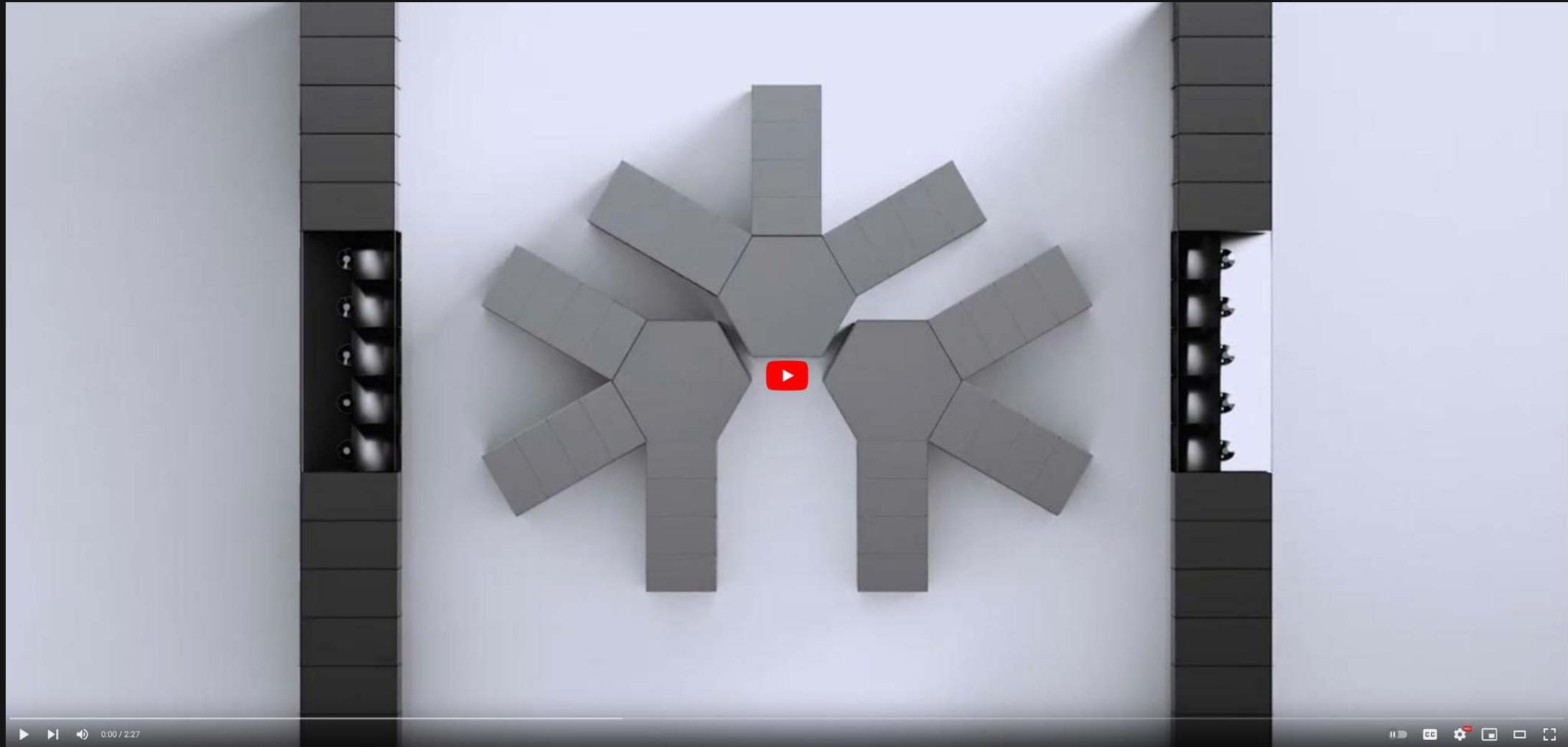
Scale ————— Number of qubits

+ Quality ————— Circuit fidelity

+ Speed ————— Circuit execution speed

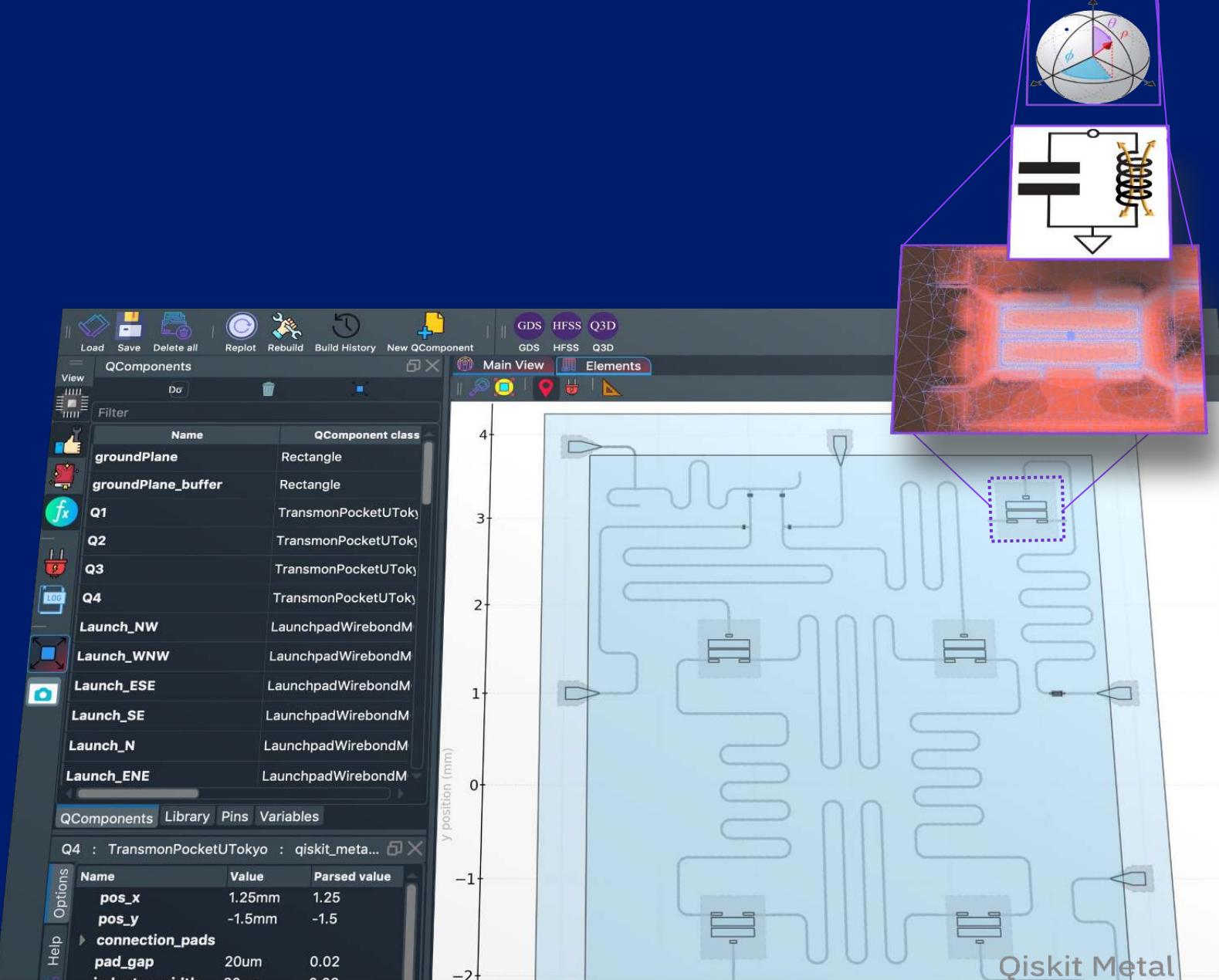
100K-qubit Quantum-Centric Supercomputer

IBM **Quantum**



https://www.youtube.com/watch?v=7aa_ik_UYTw

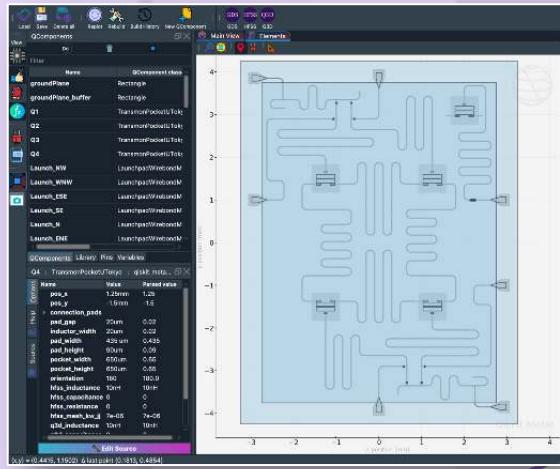
Qiskit Metal



IBM Quantum

Technology stack

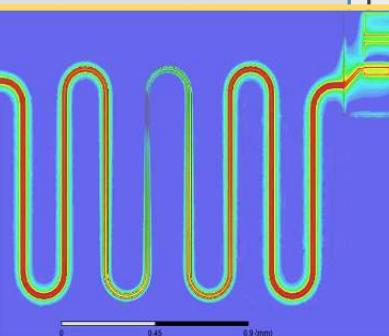
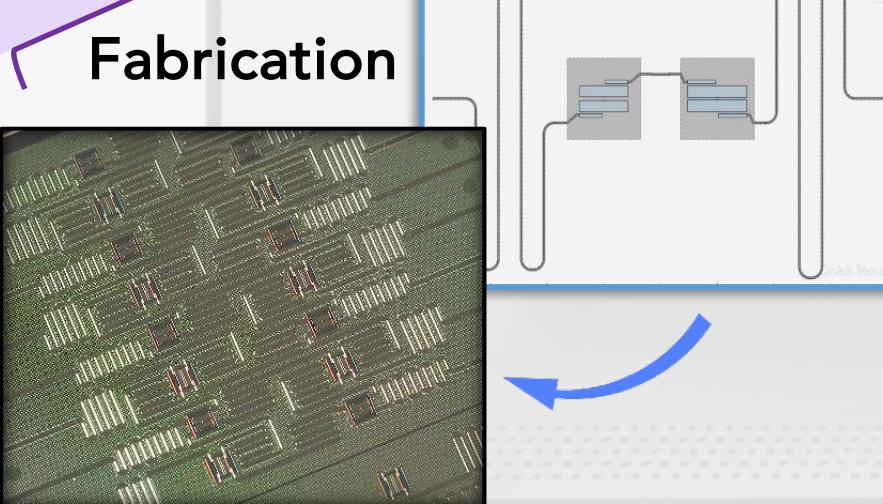
Gates & time-
evolution analysis



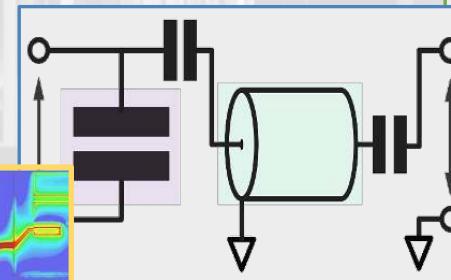
Layout

E&M
Simulation

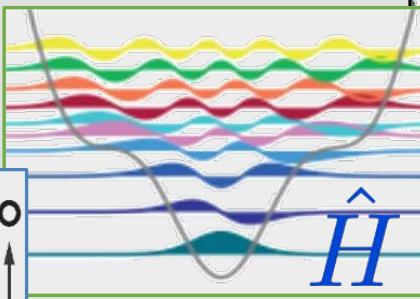
Fabrication



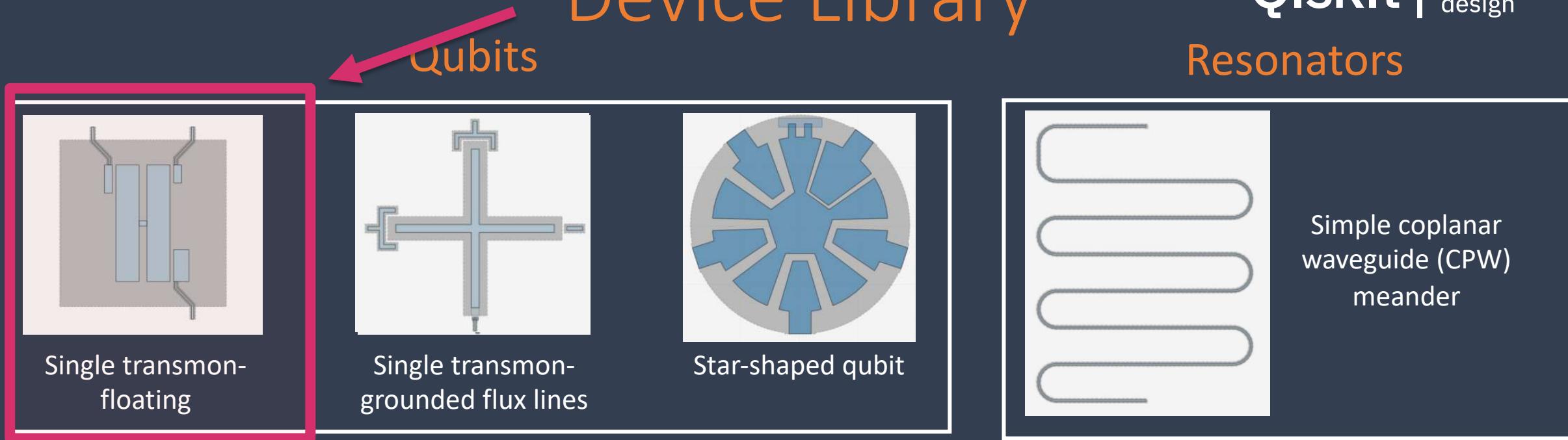
Quantization
Methods



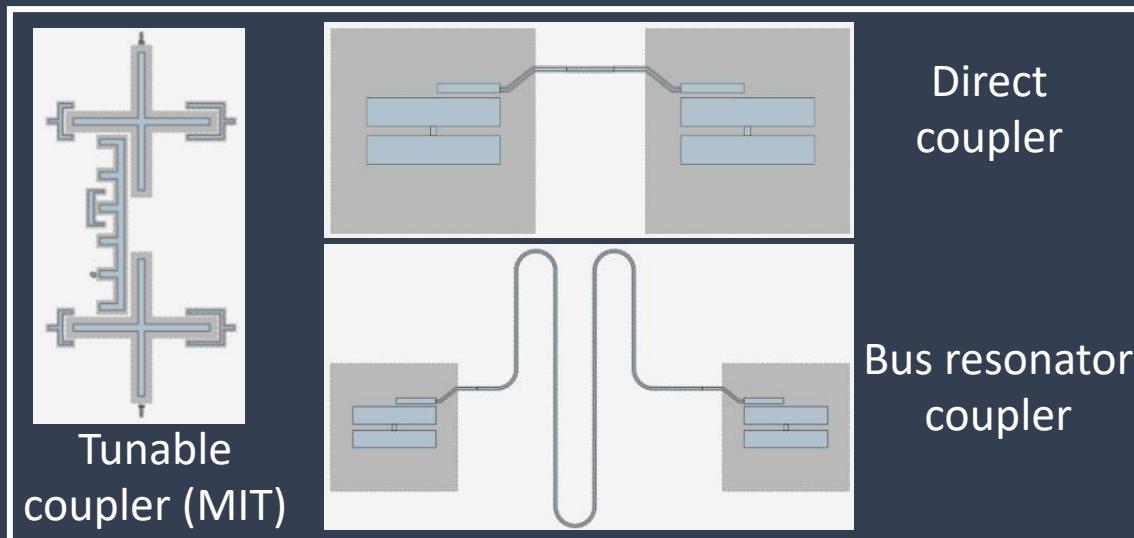
Quantum
Hamiltonian



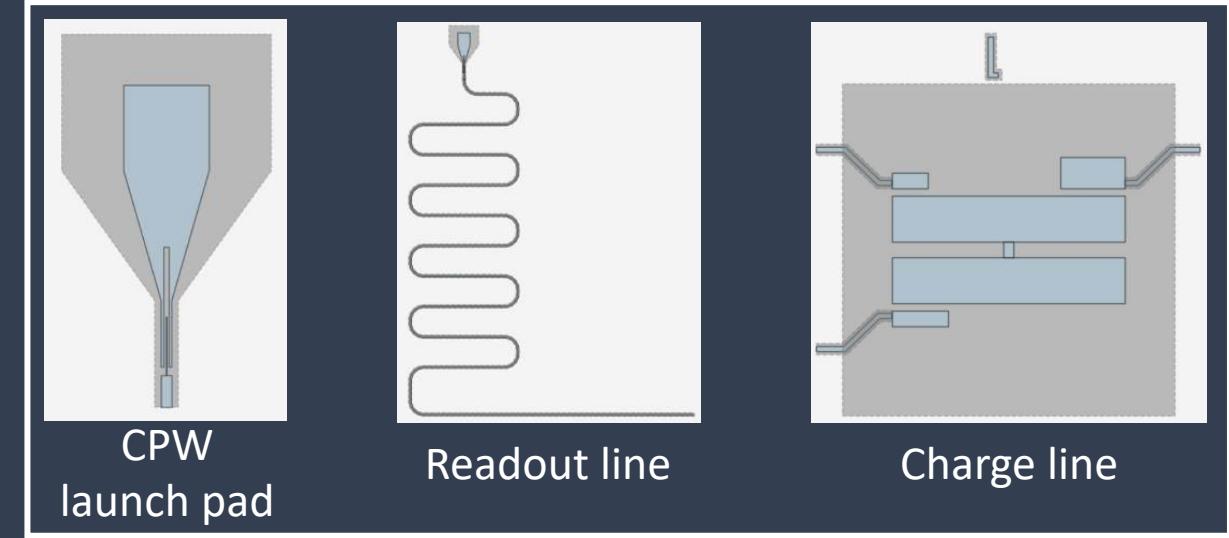
Device Library



Qubit Couplers



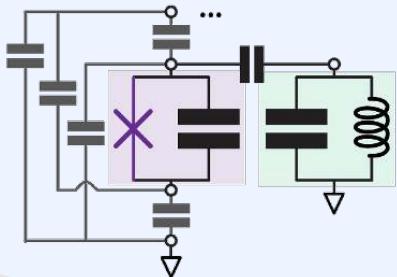
Input – Output Coupling



Landscape of quantization methods

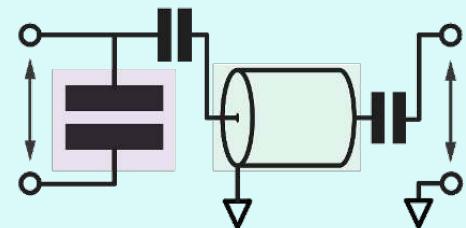
quasi-static

lumped



Yurke & Denker (1984), Devoret (1997), Burkard et al. (2004), Koch et al...

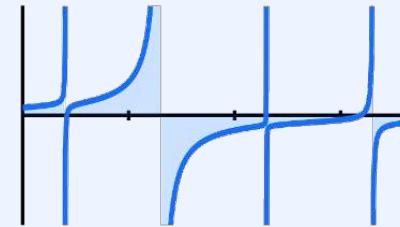
quasi-lumped



Malekakhlagh et al. (2017, 2019), Gely et al. (2019), Parra-Rodriguez et al. (2019), Minev et al. (2021), ...

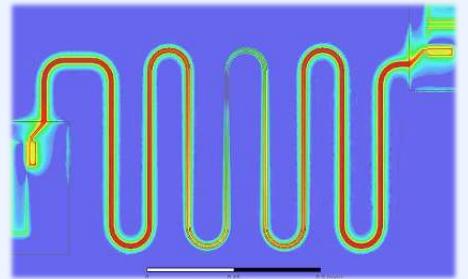
full-wave

impedance



Nigg et al. (2012), Bourassa et al. (2012), Solgun et al. (2014, 2015, 2017)
...

energy



Minev (2018)
Minev et al. (2020)

more speed



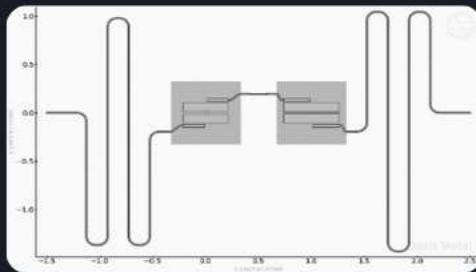
more information, accuracy



Qiskit Metal lumped model framework

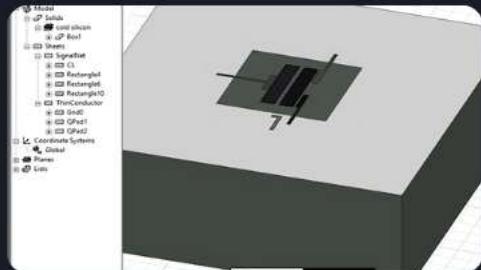
From layout to gates simulation in one notebook

Qiskit | quantum device design



Layout

Layout with Qiskit Metal's built-in EDA with either GUI or jupyter lab programmatically



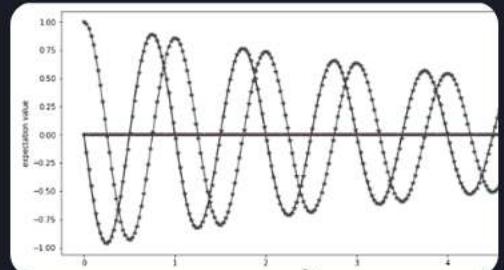
Electromagnetic simulation

Convenient interface with third-party EM simulation suites

$$\hat{H}_{\text{full}} = \hat{H}_0 + \sum_{n=1}^K \hat{H}_n + \sum_{n=0}^K \sum_{m=n+1}^K \hat{H}_{nm}$$

Quantum analysis

Lumped model analysis and Hamiltonian analysis



Pulse simulation

Convenient Hamiltonian interface with Qutip, Qiskit Dynamics, seQuencing for time evolution simulation

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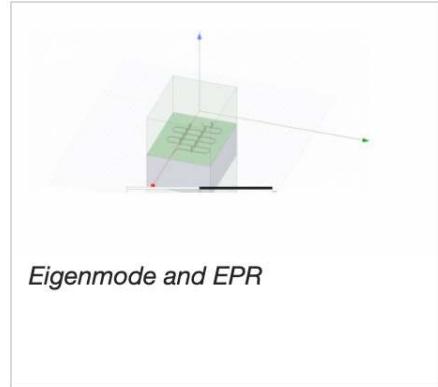
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All Quantum Devices

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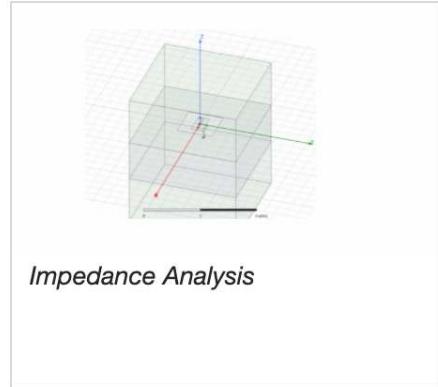
Code of Conduct



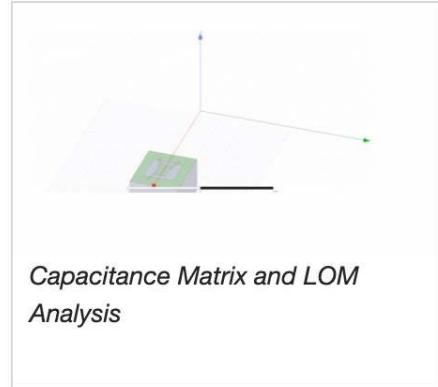
Tutorials: Quantum analysis library



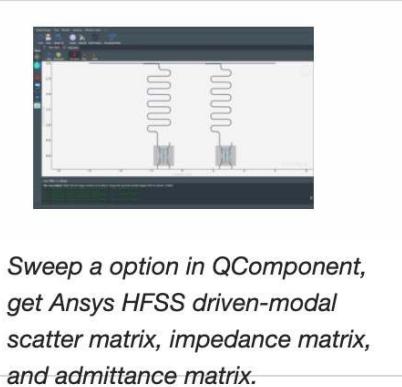
Eigenmode and EPR



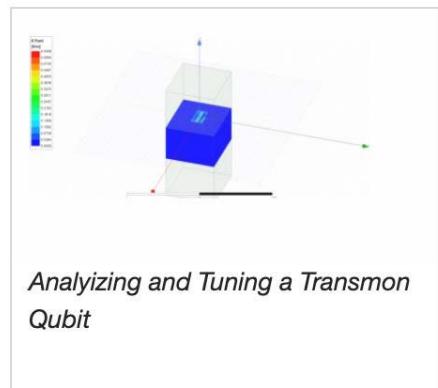
Impedance Analysis



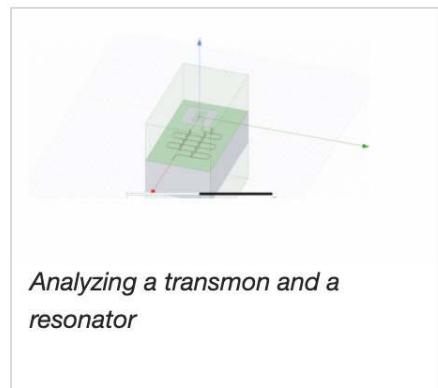
Capacitance Matrix and LOM Analysis



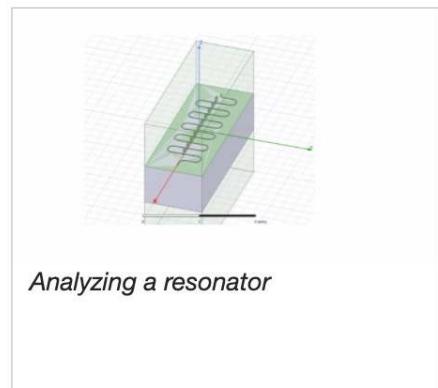
Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.



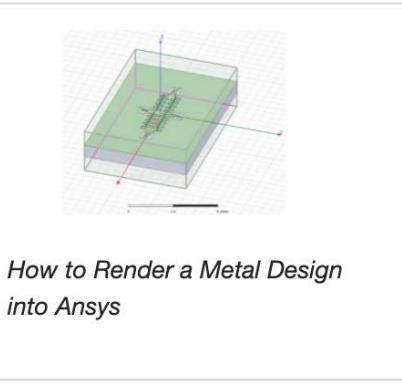
Analyzing and Tuning a Transmon Qubit



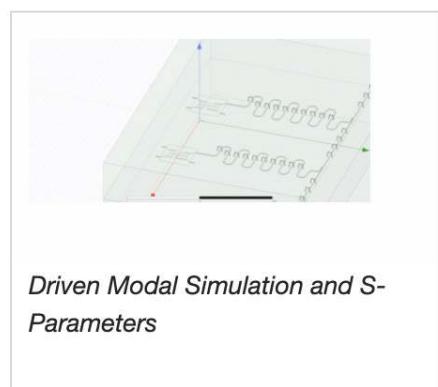
Analyzing a transmon and a resonator



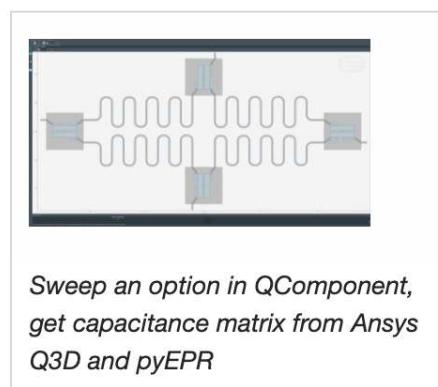
Analyzing a resonator



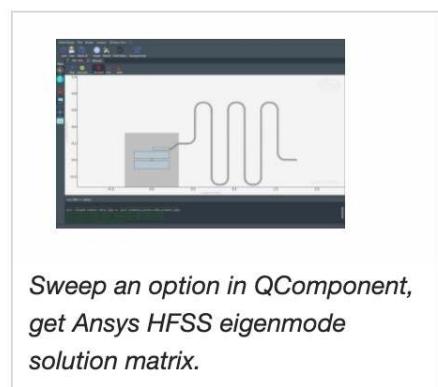
How to Render a Metal Design into Ansys



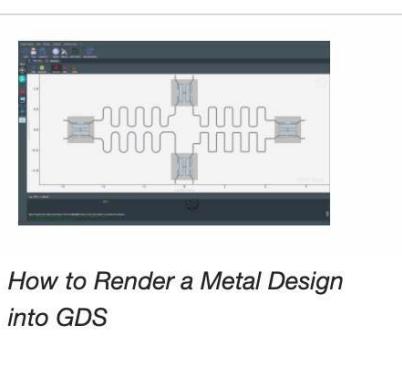
Driven Modal Simulation and S-Parameters



Sweep an option in QComponent, get capacitance matrix from Ansys Q3D and pyEPR



Sweep an option in QComponent, get Ansys HFSS eigenmode solution matrix.



How to Render a Metal Design into GDS

Resonators
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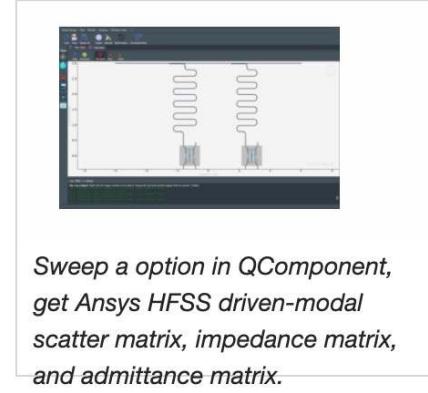
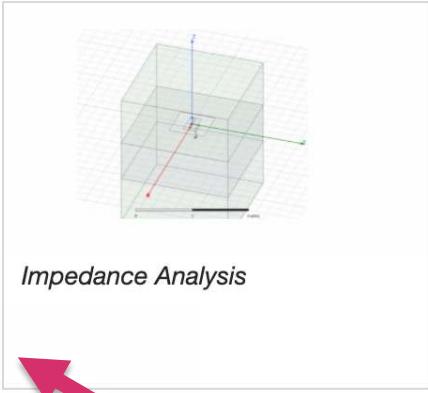
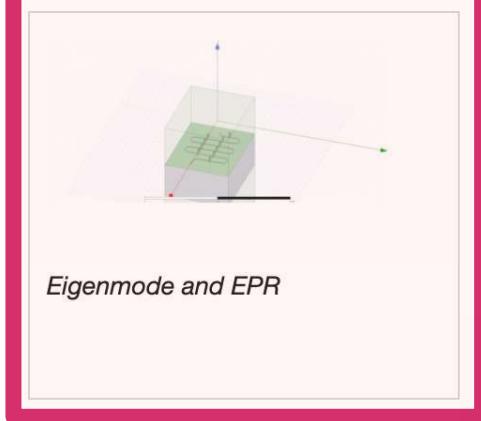
API References

Overview

QDF

C

Tutorials: Quantum analysis library



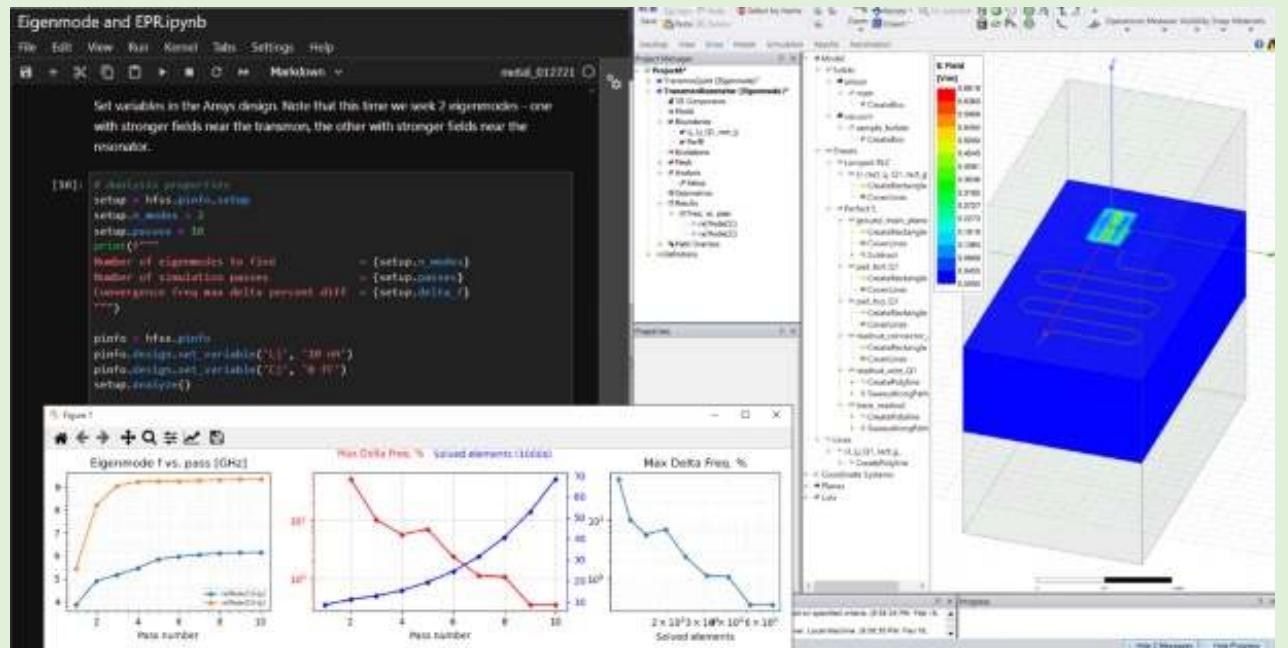
Eigenmode

Energy-participation quantization of Josephson circuits

Zlatko K. Minev [✉](#), Zaki Leghtas, Shantanu O. Mundhada, Lysander Christakis, Ioan M. Pop & Michel H. Devoret

npj Quantum Information 7, Article number: 131 (2021) | [Cite this article](#)

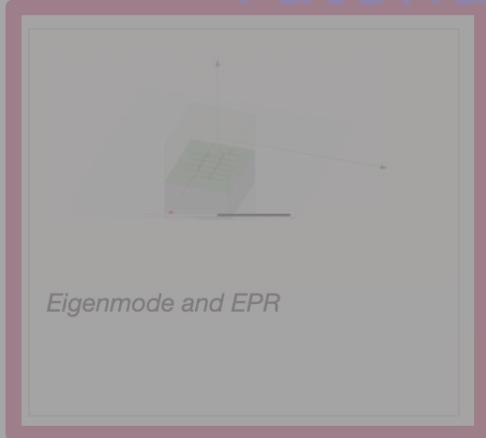
Minev arXiv: 1902.10355
Minev arXiv: 2010.00620



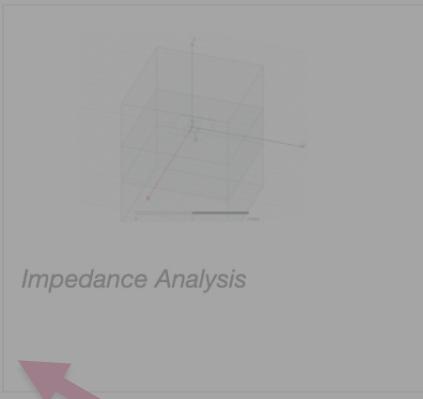
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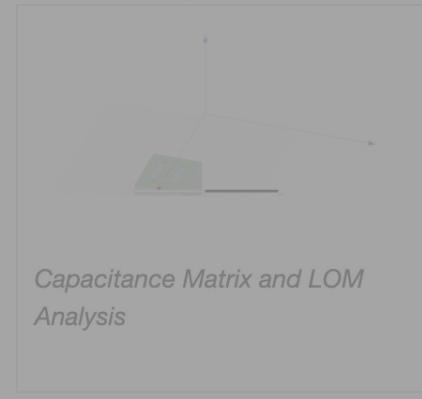
Tutorials: Quantum analysis library



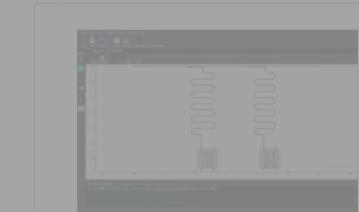
Eigenmode and EPR



Impedance Analysis



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Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.

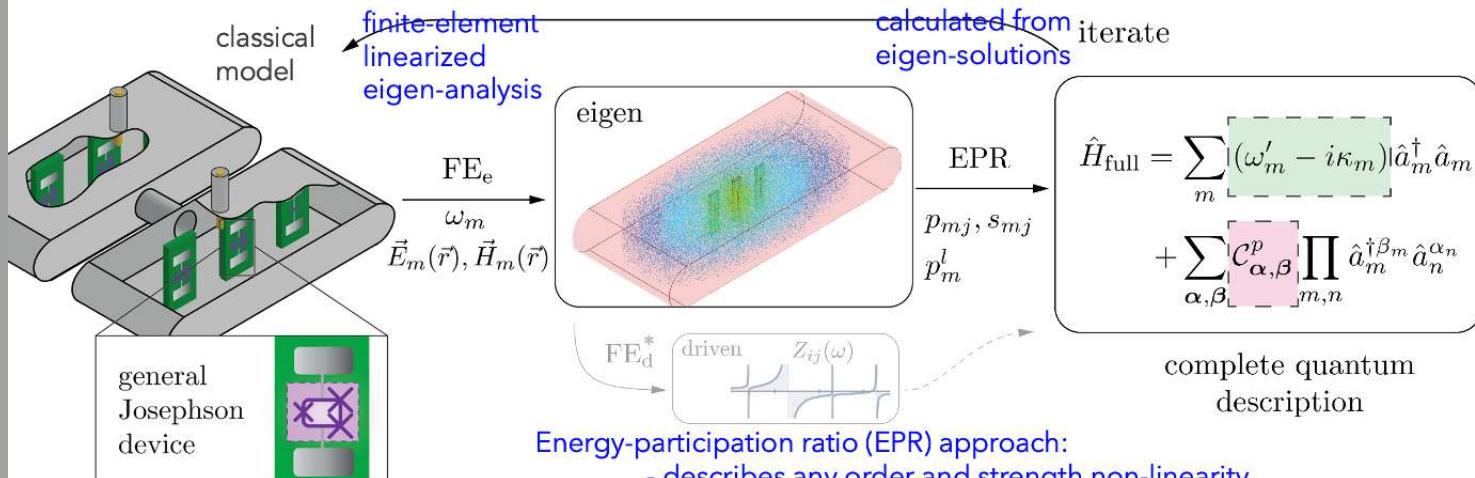
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npj Quantum Information 7, Article number: 131 (2021) | [Cite this article](#)

Minev arXiv: 1902.10355
Minev arXiv: 2010.00620

Overview of energy-participation approach



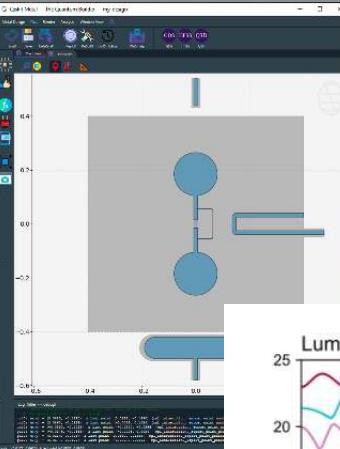
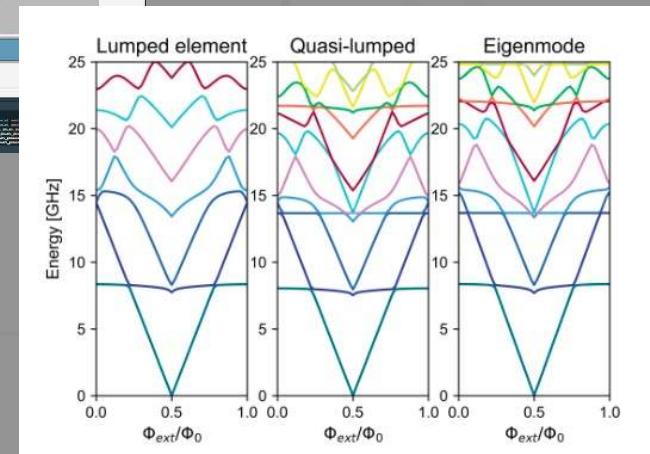
Energy-participation ratio (EPR) approach:

- describes any order and strength non-linearity
- describes arbitrary (composite) non-linear inductive devices
- first-principle derivation
- zero approximations (aside from truncation of modes)
- fully automated in python (github.com/zlatko-minev)

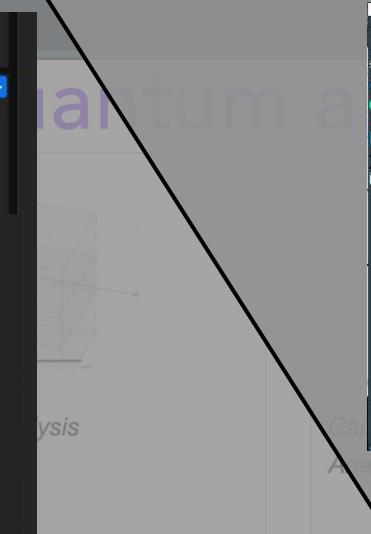
Practical limits: Fock and mode basis truncation due to computing power

* Nigg, Paik, et al., PRL (2012),
Bourassa et al. (2012),
Solgun et al. (2014, 2015, 2017), ...

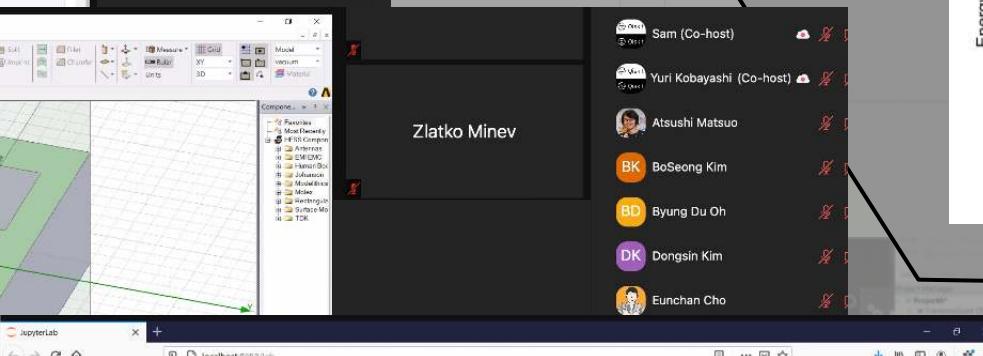
Example: fluxonium (Delft)



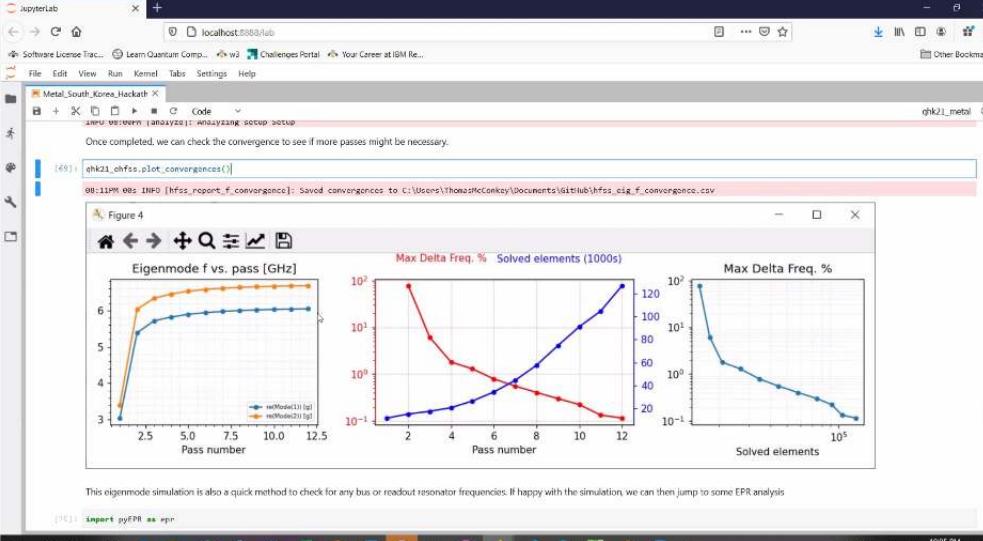
Example:
transmons



Zlatko Minev

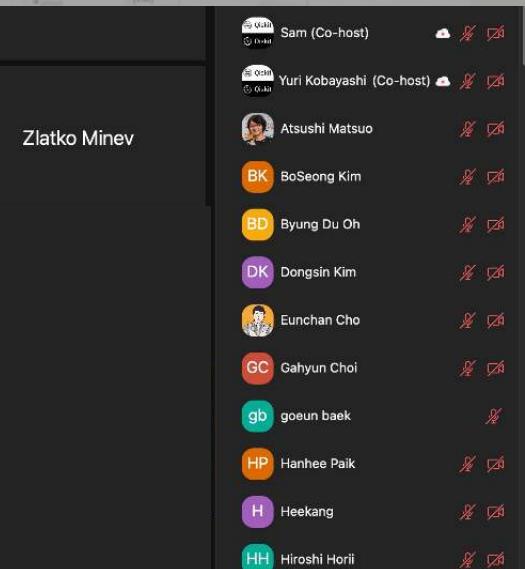


Zlatko Minev

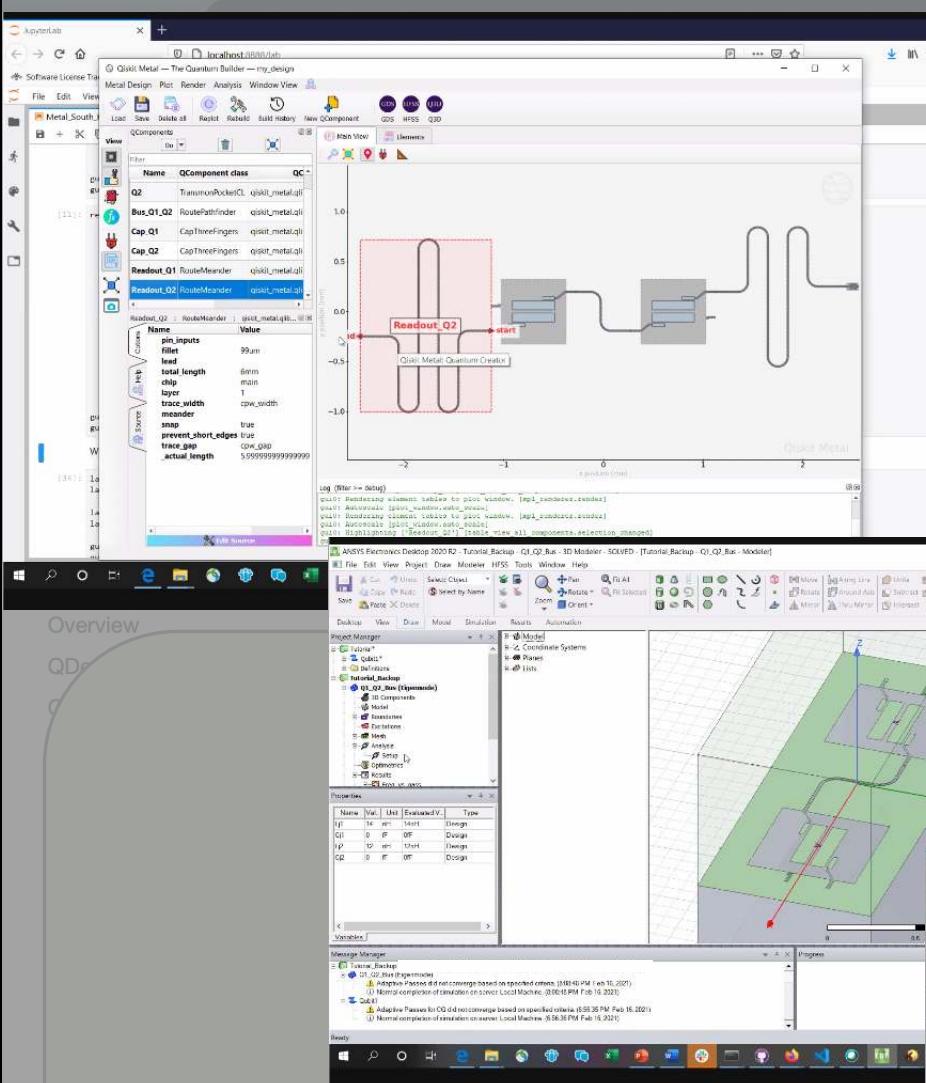


This eigenmode simulation is also a quick method to check for any bus or readout resonator frequencies. If happy with the simulation, we can then jump to some EPR analysis

In [69]: `import pyEPR as epr`



Minev arXiv: 1902.10355
Minev arXiv: 2010.00620



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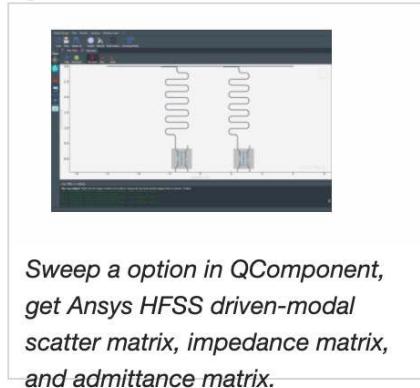
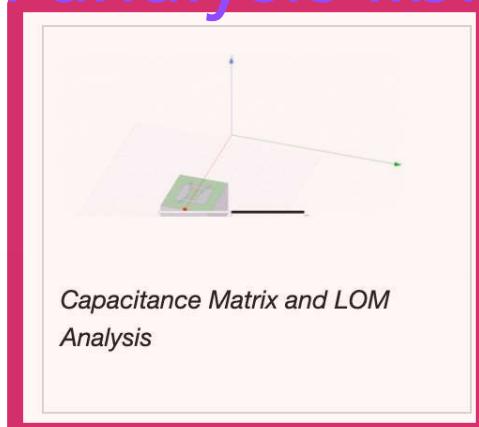
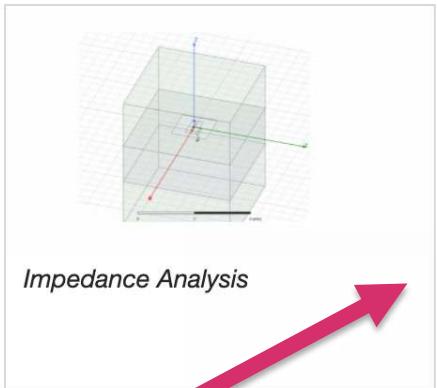
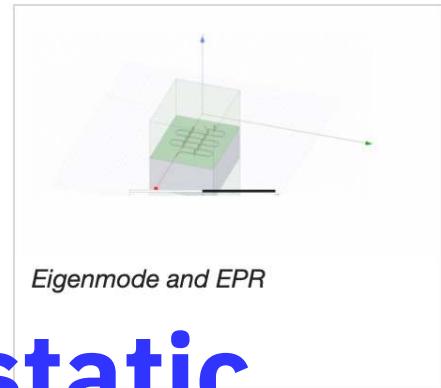
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Quasi-static



Cornell University

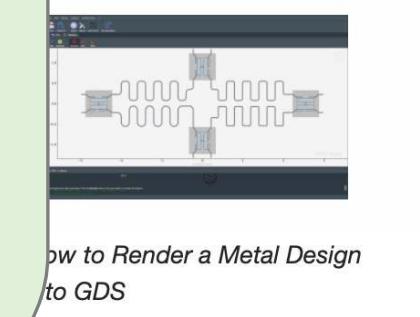
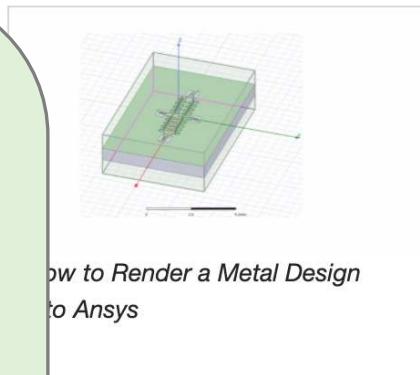
arXiv.org > quant-ph > arXiv:2103.10344

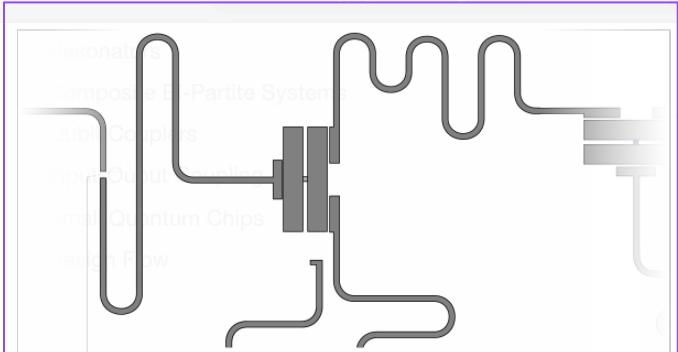
Quantum Physics

Circuit quantum electrodynamics (cQED) with modular quasi-lumped models

Zlatko K. Minev,^{*} Thomas G. McConkey, Maika Takita, Antonio Corcoles, and Jay M. Gambetta
IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, US

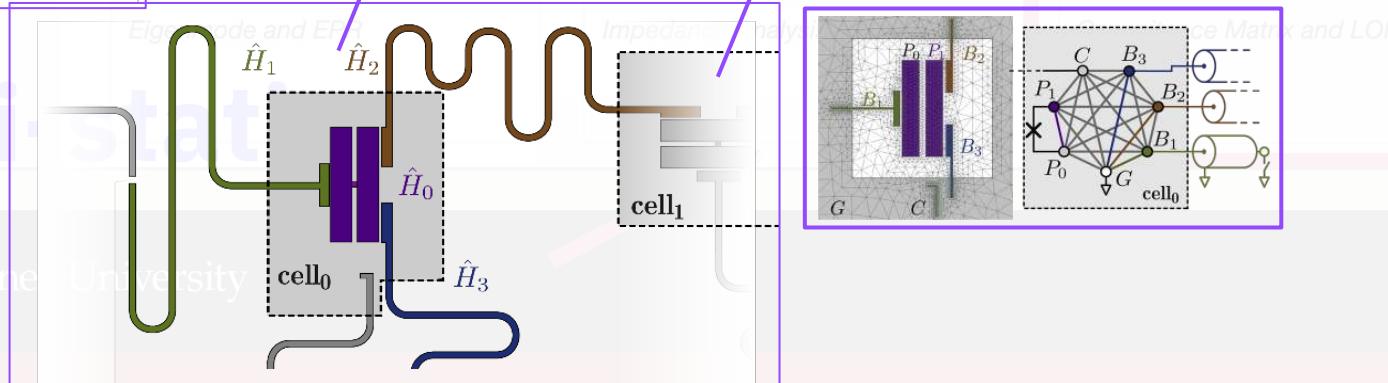
General capacitive analysis code
map to known building blocks: e.g.,
transmon, fluxonium, zero-pi, etc.



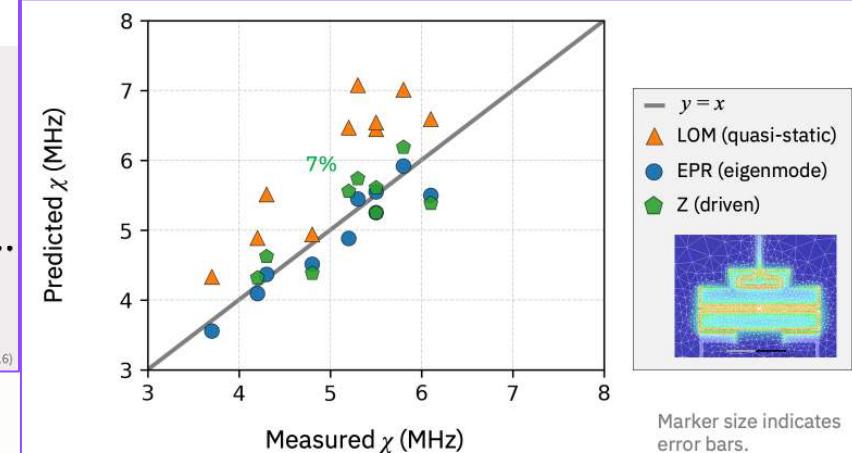
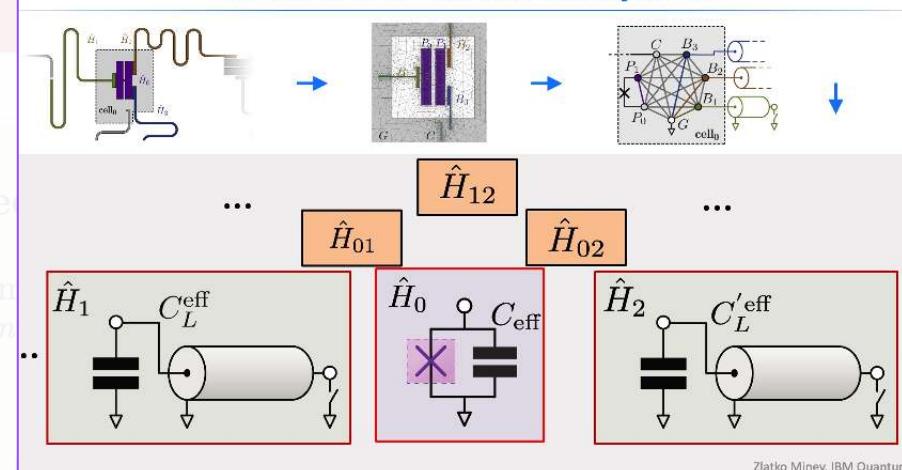


Simple example

Quasi-Static



Reduction to dressed subsystems



load transmon cell Q3d simulation results ¶

```
path1 = './Q1_TwoTransmon_CapMatrix.txt'
ta_mat, _, _ = load_q3d_capacitance_matrix(path1, _disp=False)
path2 = './Q2_TwoTransmon_CapMatrix.txt'
tb_mat, _, _ = load_q3d_capacitance_matrix(path2, _disp=False)
```

Create LOM cells from capacitance matrices

```
# cell 1: transmon Alice cell
opt1 = dict(
    node_rename = {'coupler_connector_pad_01': 'coupling', 'readout_connector_pad_01': 'readout_alice'},
    cap_mat = ta_mat,
    ind_dict = {('pad_top_01', 'pad_bot_01'):10, ('pad_top_02', 'pad_bot_02'):11, ('pad_top_03', 'pad_bot_03'):12},
    jj_dict = {('pad_top_01', 'pad_bot_01'):13, ('pad_top_02', 'pad_bot_02'):14, ('pad_top_03', 'pad_bot_03'):15},
    cj_dict = {('pad_top_01', 'pad_bot_01'):21, ('pad_top_02', 'pad_bot_02'):22, ('pad_top_03', 'pad_bot_03'):23}
)
cell_1 = Cell(opt1)

# cell 2: transmon Bob cell
opt2 = dict(
    node_rename = {'coupler_connector_pad_02': 'coupling', 'readout_connector_pad_02': 'readout_bob'},
    cap_mat = tb_mat,
    ind_dict = {('pad_top_02', 'pad_bot_02'):12, ('pad_top_03', 'pad_bot_03'):13, ('pad_top_01', 'pad_bot_01'):14},
    jj_dict = {('pad_top_02', 'pad_bot_02'):15, ('pad_top_03', 'pad_bot_03'):16, ('pad_top_01', 'pad_bot_01'):17},
    cj_dict = {('pad_top_02', 'pad_bot_02'):22, ('pad_top_03', 'pad_bot_03'):23, ('pad_top_01', 'pad_bot_01'):21}
)
cell_2 = Cell(opt2)

Make subsystems

# subsystem 1: transmon Alice
transmon_alice = Subsystem(name='transmon_alice', sys_type='TRANSMON', nodes=['j1'])

# subsystem 2: transmon Bob
transmon_bob = Subsystem(name='transmon_bob', sys_type='TRANSMON', nodes=['j2'])

# subsystem 3: Alice readout resonator
q_opts = dict(
    f_res = 8, # resonator dressed frequency in GHz
    Z0 = 50, # characteristic impedance in Ohm
    vp = 0.404314 * c_light # phase velocity
)
res_alice = Subsystem(name='readout_alice', sys_type='TL_RESONATOR', nodes=['readout_alice'], q_opts=q_opts)

# subsystem 4: Bob readout resonator
q_opts = dict(
    f_res = 7.6, # resonator dressed frequency in GHz
    Z0 = 50, # characteristic impedance in Ohm
    vp = 0.404314 * c_light # phase velocity
)
res_bob = Subsystem(name='readout_bob', sys_type='TL_RESONATOR', nodes=['readout_bob'], q_opts=q_opts)
```

Create the composite system from the cells and the subsystems

```
composite_sys = CompositeSystem(
    subsystems=[transmon_alice, transmon_bob, res_alice, res_bob],
    cells=[cell_1, cell_2],
    grid_node='ground_main_plane',
    nodes_force_keep=['readout_alice', 'readout_bob']
)
```

Generate the hilberspace from the composite system

```
hilbertspace = composite_sys.create_hilbertspace()
hilbertspace = composite_sys.add_interaction()
```

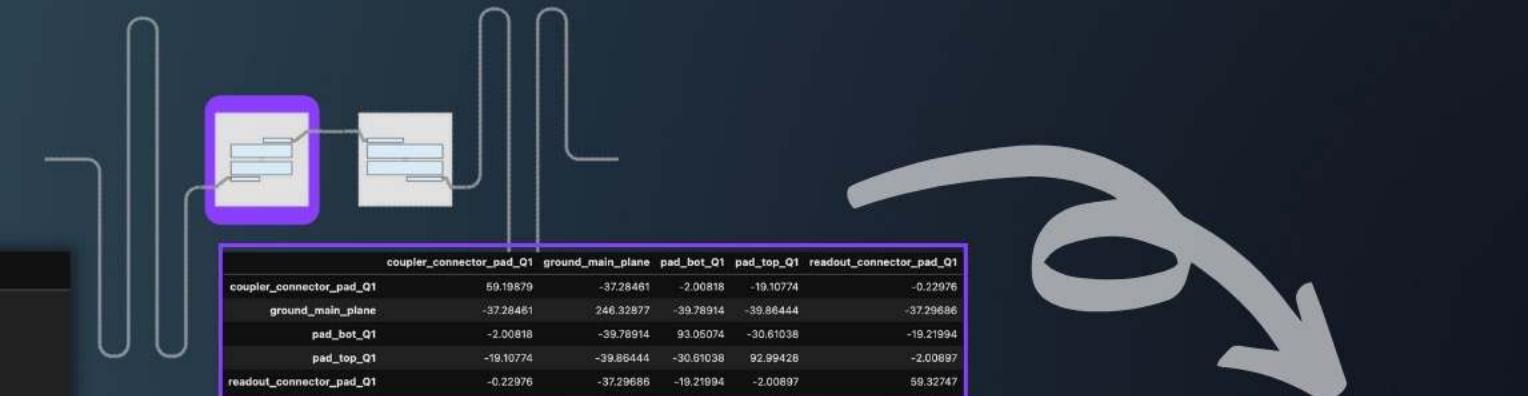
Print the results

```
hamiltonian_results = composite_sys.hamiltonian_results(hilbertspace, evals_count=30)
Finished eigensystem.

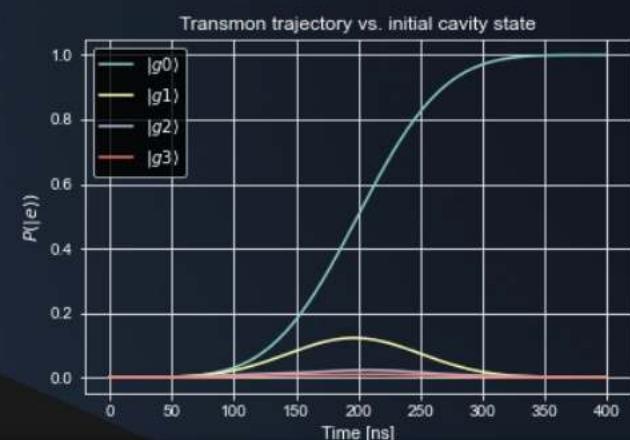
system frequencies in GHz:
{'transmon_alice': 6.053360688806868, 'transmon_bob': 4.7989883222888094, 'readout_alice': 8.0090548}

Chi matrices in MHz
-----
transmon_alice  transmon_bob  readout_alice  readout_bob
transmon_alice -353.239816 -0.542895 -4.132854 -0.003120
transmon_bob   -0.542895 -263.940098 -0.001154 -1.460416
readout_alice   -4.132854 -0.001154 4.283111 -0.000017
readout_bob    -0.003120 -1.460416 -0.000017 3.829744
```

From layout to time evolution simulation in one simple notebook



	coupler_connector_pad_Q1	ground_main_plane	pad_bot_Q1	pad_top_Q1	readout_connector_pad_Q1
coupler_connector_pad_Q1	59.19879	-37.28461	-2.00818	-19.10774	-0.22976
ground_main_plane	-37.28461	246.32877	-39.78914	-39.86444	-37.29686
pad_bot_Q1	-2.00818	-39.78914	93.05074	-30.61038	-19.1994
pad_top_Q1	-19.10774	-39.86444	-30.61038	92.99428	-2.00897
readout_connector_pad_Q1	-0.22976	-37.29686	-19.21994	-2.00897	59.32747



Time evolution simulation

```
system = lom_composite_sys_to_seq_sys(composite_sys, hilbertspace, levels=[3, 3, 10, 10])
alice = system.modes[1]

Finished eigensystem.

selective_sigma = 100 # ns

# tune selective qubit pulse using Rabi
with system.use_modes([alice]):
    with alice.temporarily_set(gaussian_pulse_sigma=selective_sigma):
        selective_qubit_amp = tune_rabi(
            system, system.fock(transmon_alice=0, transmon_bob=0, readout_alice=0, readout_bob=0)
        )

100% | 51/51 [00:01<00:00, 41.64it/s]

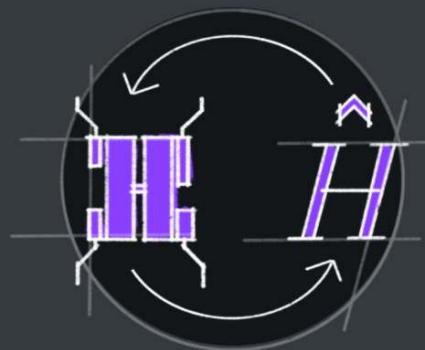
def selective_rotation(qubit, angle, phase=0, detune=0, sigma=selective_sigma):
    with qubit.gaussian_pulse.temporarily_set(sigma=sigma, amp=selective_qubit_amp):
        qubit.rotate(np.pi, phase, detune=detune)

Apply a selective pi pulse that is resonant with the qubit when the cavity is in |0>.

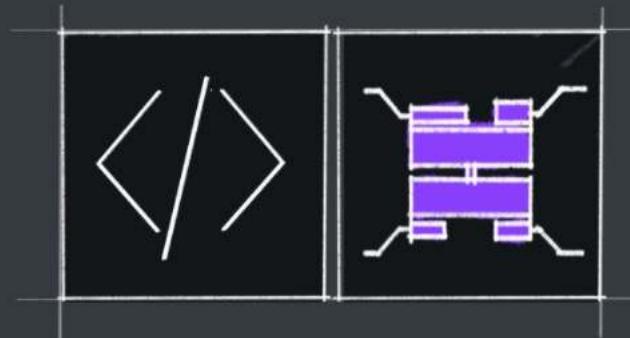
init_states = [
    (f'$|g{n}\rangle$\\range$', system.fock(transmon_alice=0, readout_alice=n)) for n in range(4)
```

Qiskit Metal: Key features and content

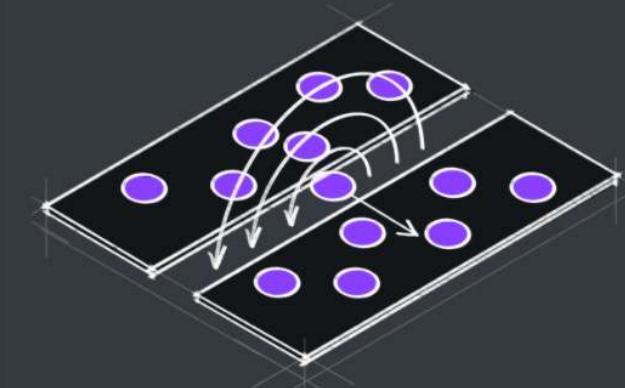
End-to-end automation



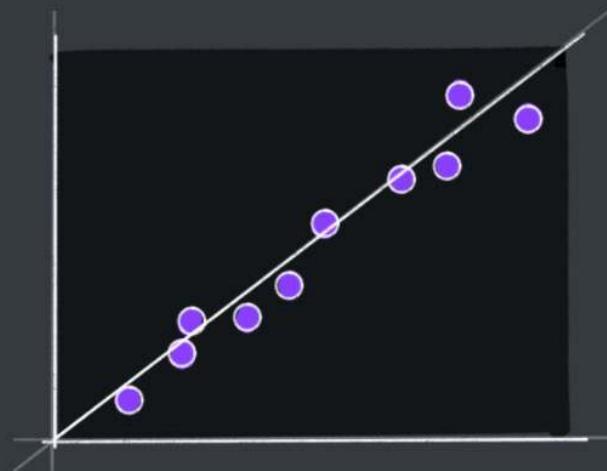
Flexible & extensible



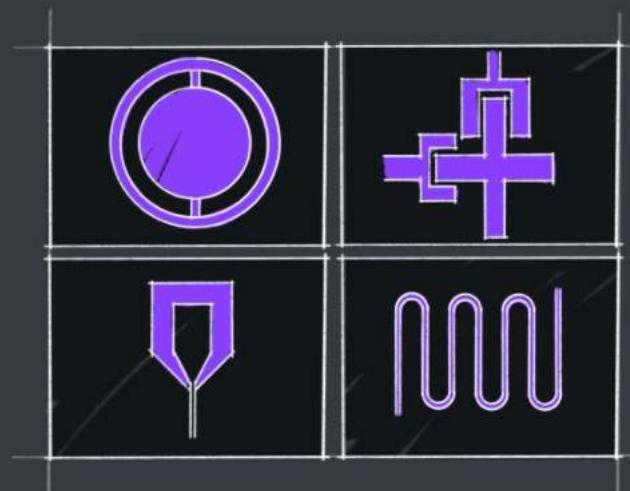
Light-weight interoperability



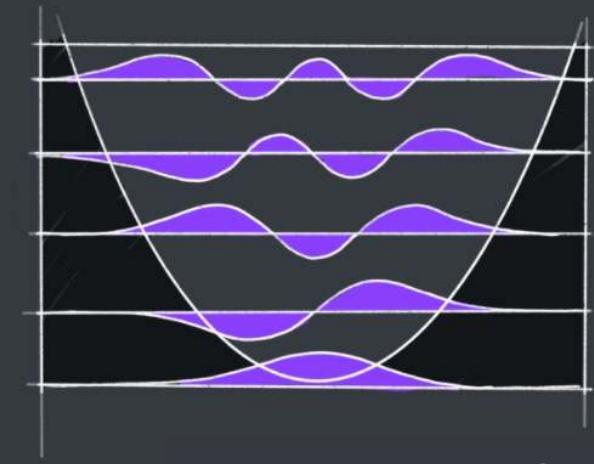
Experimentally tested



Library of components



Cutting edge resources

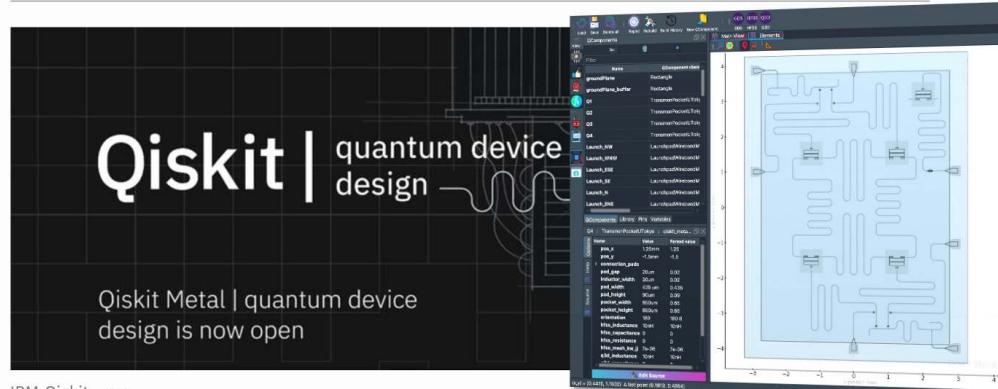


The buzz...

Forbes

You Don't Have To Be A Rocket (Or Quantum) Scientist To Design A Quantum Computer Chip Using IBM's New Tool Called Qiskit Metal

Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Group ©
Cloud
Analyst-in-residence, Quantum Computing



Qiskit | quantum device design

Qiskit Metal | quantum device design is now open

IBM Qiskit IBM

Intuitively, almost everyone can appreciate how difficult and knowledge-intensive it is to design, develop, analyze, and simulate a quantum computer chip. Without years

Public launch of Qiskit Metal (2021)

“Considering all its advantages, *Qiskit Metal* should be a clear long-term winner for IBM and the quantum community.”

- **Forbes**

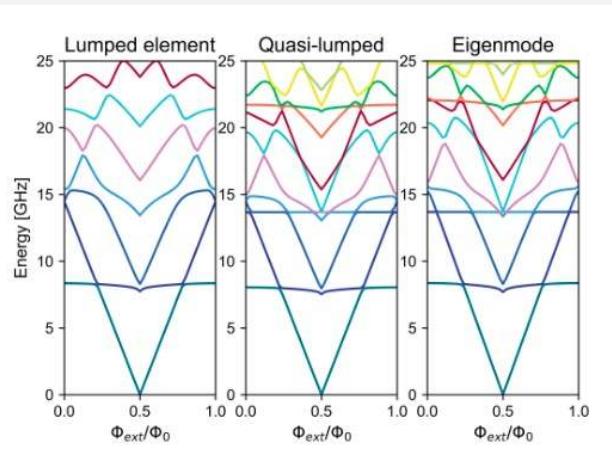
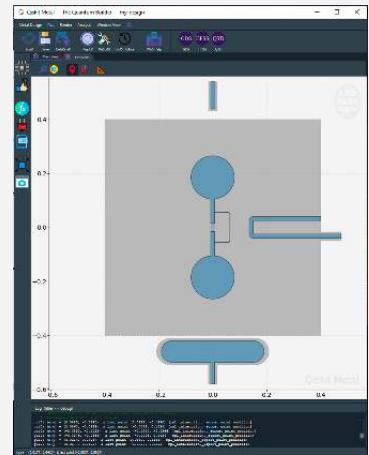
Use case example

QuTech / Technische Universiteit Delft

Figen Yilmaz-Andersen Lab: Fluxonium chip design

Roald van den Boogaart-Andersen Lab: Fluxonium spectrum (eigenmode = pyEPR) to show how they have extended the analysis methods to be able to handle fluxonium qubits

Sara Buhktari-Andersen Lab: Fabricated resonator design being measured



3.1. Final design

The final design consists of an S-shaped feedline routed between two launchpads. Eight resonators are capacitively coupled to this feedline. Every component on this 9×9 mm device is implemented by a coplanar waveguide transmission line. The schematic representations of the full device and single resonator geometry are depicted in Figure 6.

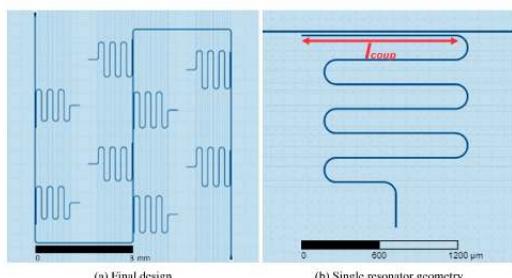


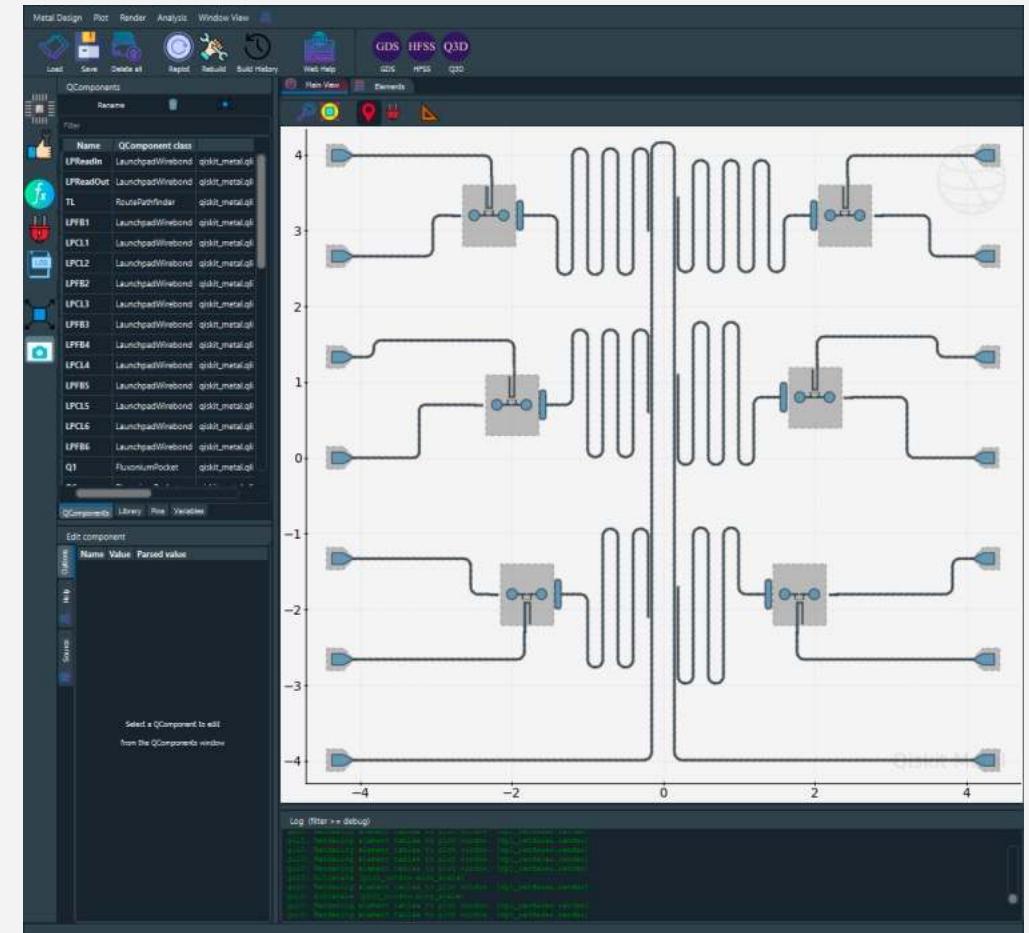
Figure 6: Schematic representations of the final design and single resonator geometry. Each resonator is capacitively coupled to the feedline. The resonator coupling length is denoted by l_{coupl} .

"Qiskit-Metal is the best tool if one studies superconducting qubits"

-- Figen Yilmaz

QuTech / Technische Universiteit Delft

Intermediate chip design. Quantum chip fabricated, cooled down, measured, reporting at APS MM23



Zlatko Minev, IBM Quantum

Ways to learn more

Qiskit Global Summer School

Qiskit 

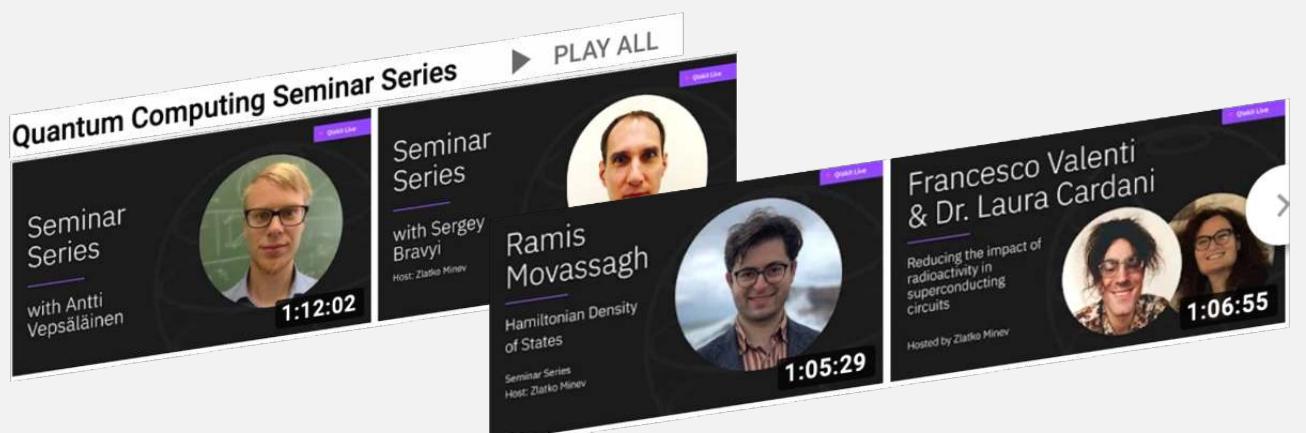
(Lec. 16-21 by Z. Minev)



Quantum Information Seminar Series

(Qiskit 

Host: Z. Minev)



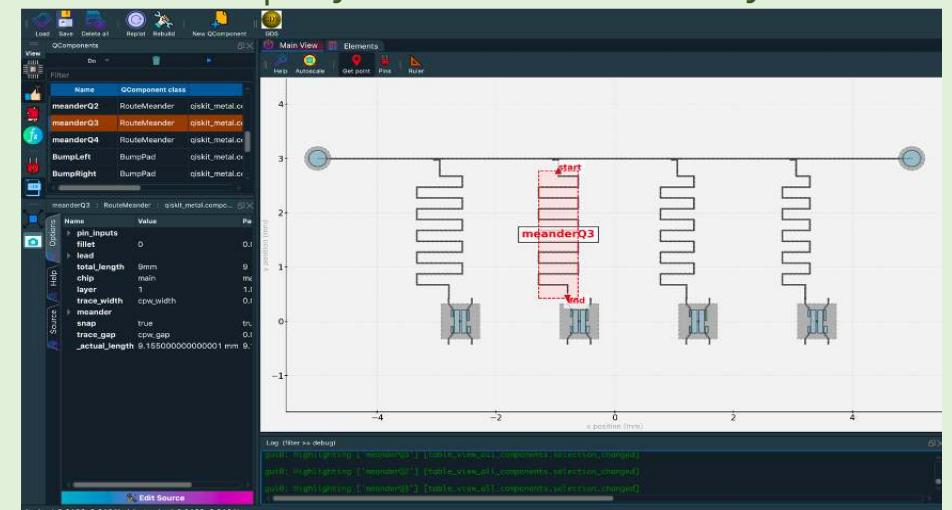
qiskit.org/textbook

Greetings from the Qiskit Community team! This textbook is a university quantum algorithms/computation course supplement based on Qiskit to help learn:

1. The mathematics behind quantum algorithms
2. Details about today's non-fault-tolerant quantum devices
3. Writing code in Qiskit to implement quantum algorithms on IBM's cloud quantum systems

Qiskit Metal — PowerUp

Python-based project started & led by Z. Minev



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

One cannot help but be in awe when he
contemplates 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

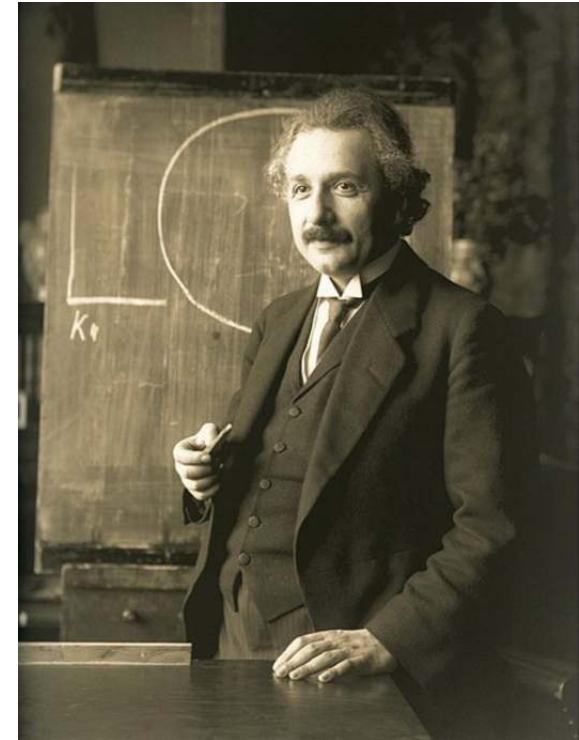


Photo: F. Schmutzler



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Open Questions in Quantum Computing v0.1

1. Where does the power of quantum computing come from?

useful to answer in order to design new quantum algorithms, compare to classical, and to find quantum advantages D/W: I. Deutsch, ...

2. What will quantum computers teach us about fundamental quantum physics?

predictability, collapse, tunneling time, many body scars, many worlds, ... D/W: A. Steinberg, I. Siddiqi, R. Gutierrez-Jauregui, P. Zoller, M. Lukin, ...

3. How can we efficiently extract information from quantum data (bridge quantum-to-classical boundary)?

E.g., learn many-body properties of large quantum systems, noise, channels. Challenges: Need to overcome fundamental no-go theorems in the bridge from quantum to classical interface, exponential scaling for quantum properties, validation, noise plague, ...

D/W: L. Jiang, J. Preskill, P. Zoller, M. Lukin, ...

4. Is it useful to build a quantum computer with 1% error?

What do we do with noisy pre-fault-tolerant quantum processors? D/W: J. Martinis

5. How to craft conventionally forbidden but useful quantum operations?

such as inverse of a large noise map; e.g., quasi-probability, ancilla-assisted, ... D/W: with K. Temme, S. Worner, D. Sutter, ...

6. How to overcome noise in real quantum processors?

Unmonitored systems, error mitigation, novel techniques, path to 100 qubits x 400 depth ...

7. What's beyond the thermodynamic limit and ETH in many-body physics?

Qs stimulated by quantum computers; e.g., MITP, MBL probes. D/W: M. Lukin, P. Zoller, V. Khemani, H. Pichler, S. Gopalakrishnan, M. Hafezi, A. Seif, D. Wang, ...

8. What tasks can quantum outperform classical in that we can demonstrate in the next 1-3 years?



Thank you!

Life & lessons as a scientist
in “real life”



Zlatko K. Minev, Ph.D.

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



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zlatko-minev.com

success noun

success | \ sək-'ses \

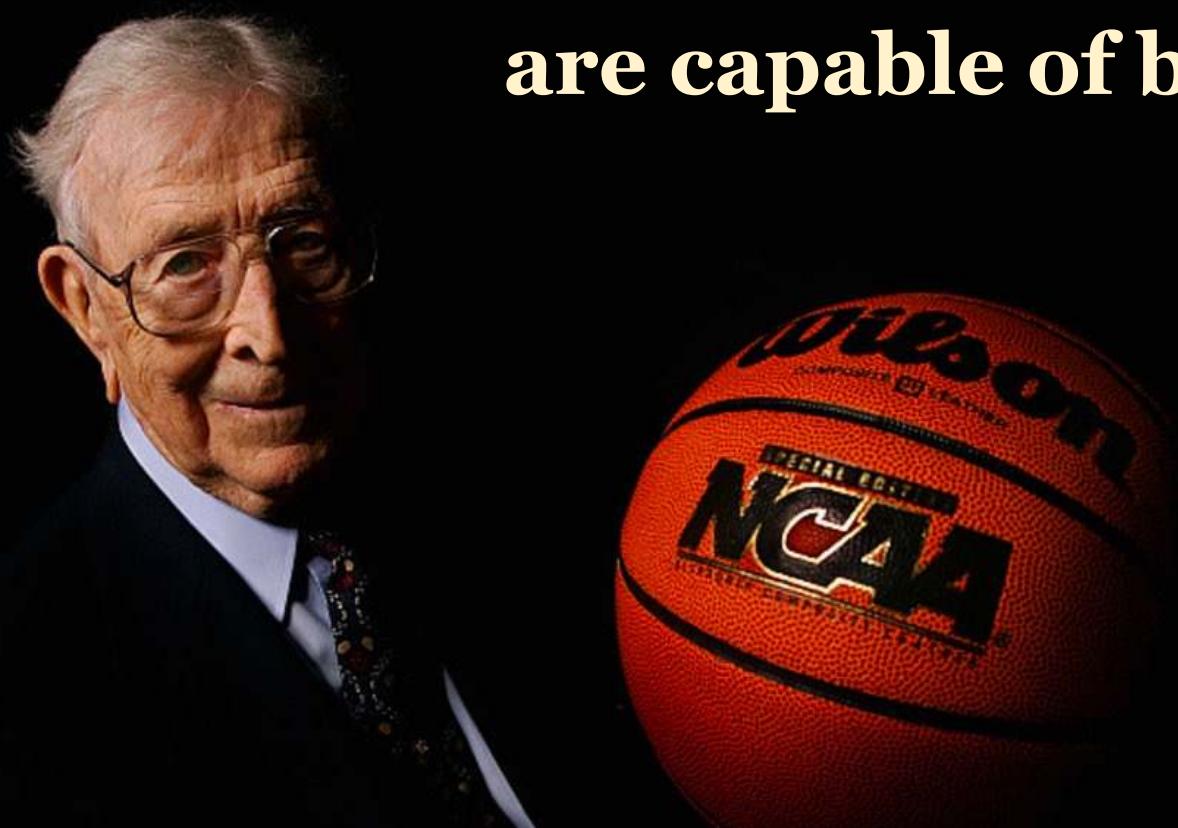
Definition of *success*



the attainment of wealth, favor, or eminence



“Success is peace of mind that is the direct result of self-satisfaction in knowing you did your best to become the best that you are capable of becoming.”



**Coach John Wooden
(1910–2010)**