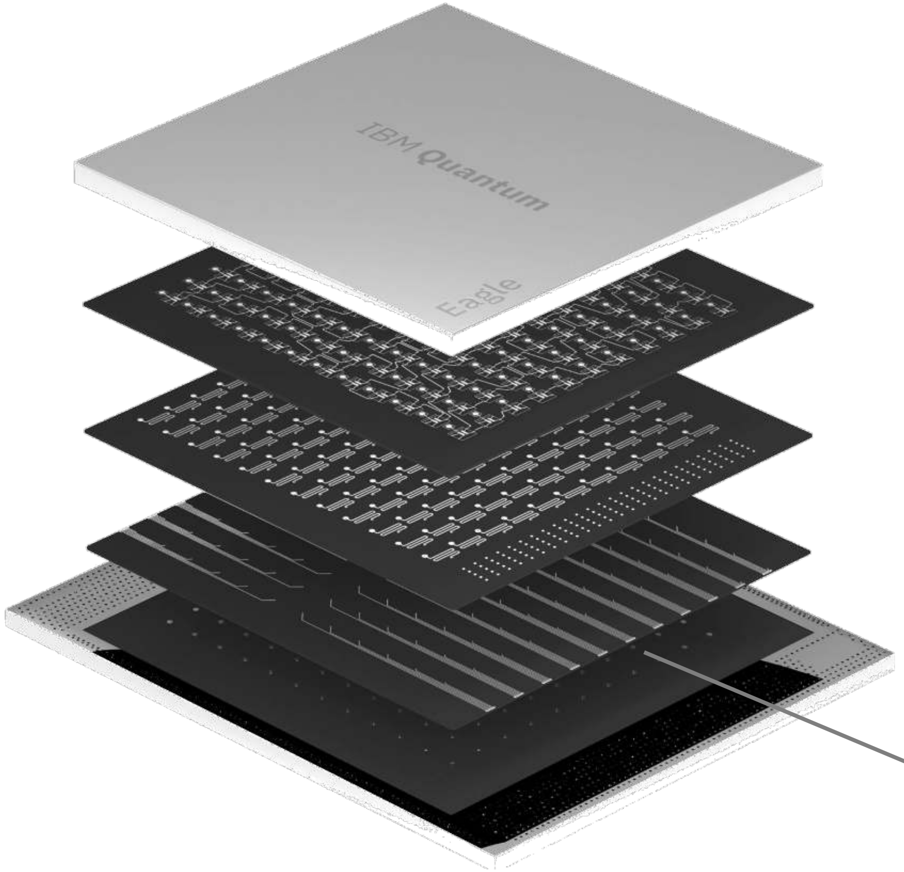
Hello Quantum World!



Zlatko K. Minev, Ph.D.

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

@zlatko_minev zlatko-minev.com

Hello Quantum World!

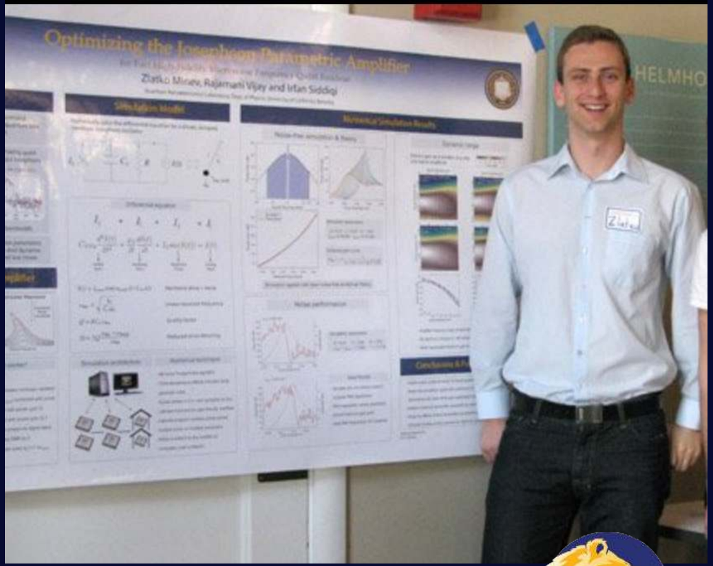
- About me: Career overview
- Lessons along the way
- Quantum Computers and IBM Quantum
- Experiments on large devices / making quantum chips / …

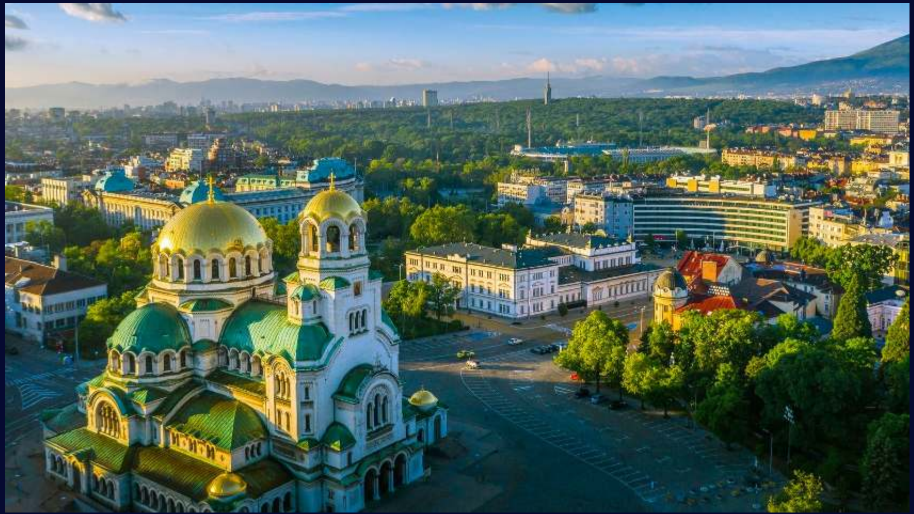
Avoid firehose of information

Thanks to Fred Moxley for gif reference.

Overview of career in brief

at time $t \approx 0$





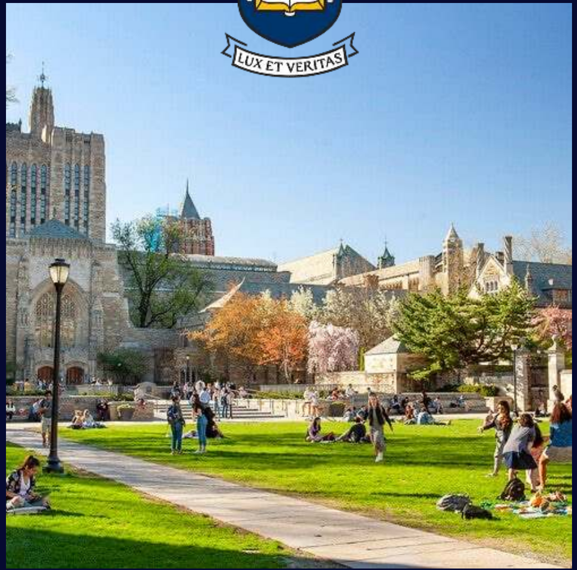


Image: National Geographic

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

Qiskit | quantum device design

ADDITIONAL ROLES

CIFAR 40 YEARS · ANS

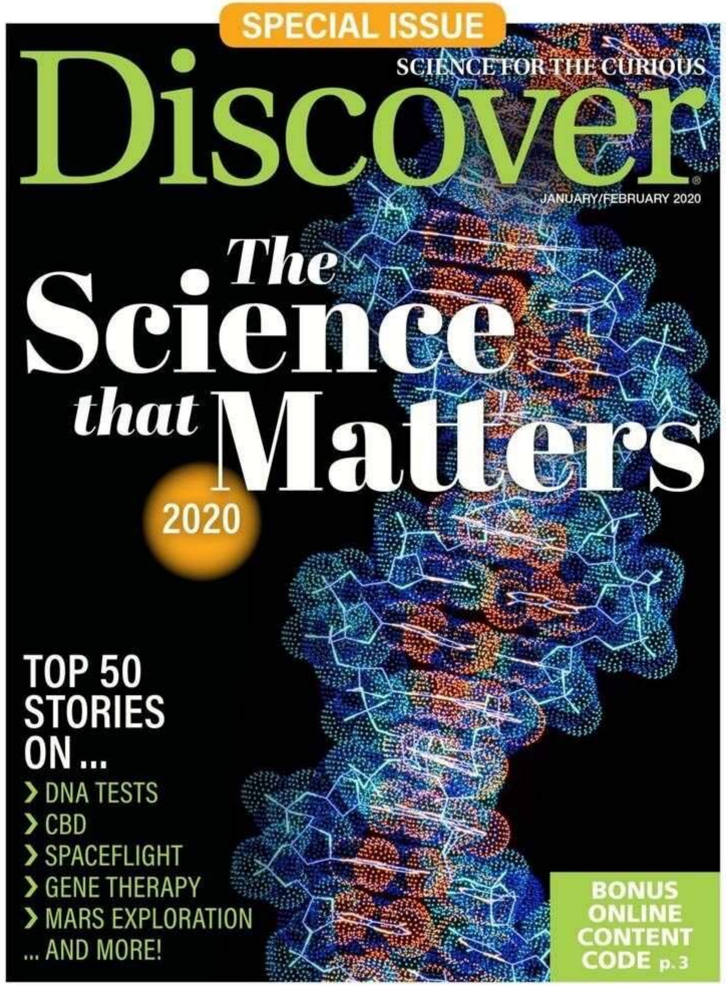
MDCCCXLVII

LUX ET VERITAS

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

Some highlights



MIT Technology Review

INNOVATORS UNDER 35

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.

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

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

Quantum Jumps

H.J. Carmichael

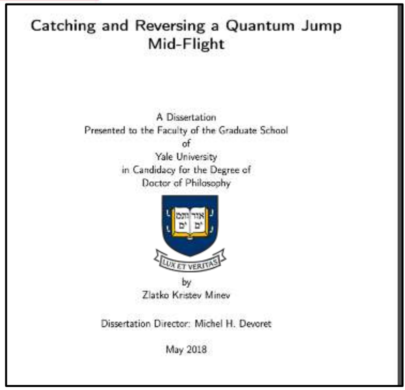
nature
International journal of science

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


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

LUX ET VERITAS

by
Zlatko Kristev Minev

Dissertation Director: Michel H. Devoret

May 2018

656

Le Monde theguardian npr RT SEPA MÁS The Christian Science Monitor GIZMODO

WIRED physicsworld Популярная Механика Discover SCIENCE FOR THE CURIOUS Quantamagazine

Economy.bg Бизнесът в България btv THE QUANTUM DAILY QUANTUM COMPUTING AND BEYOND MIT Technology Review

. . .

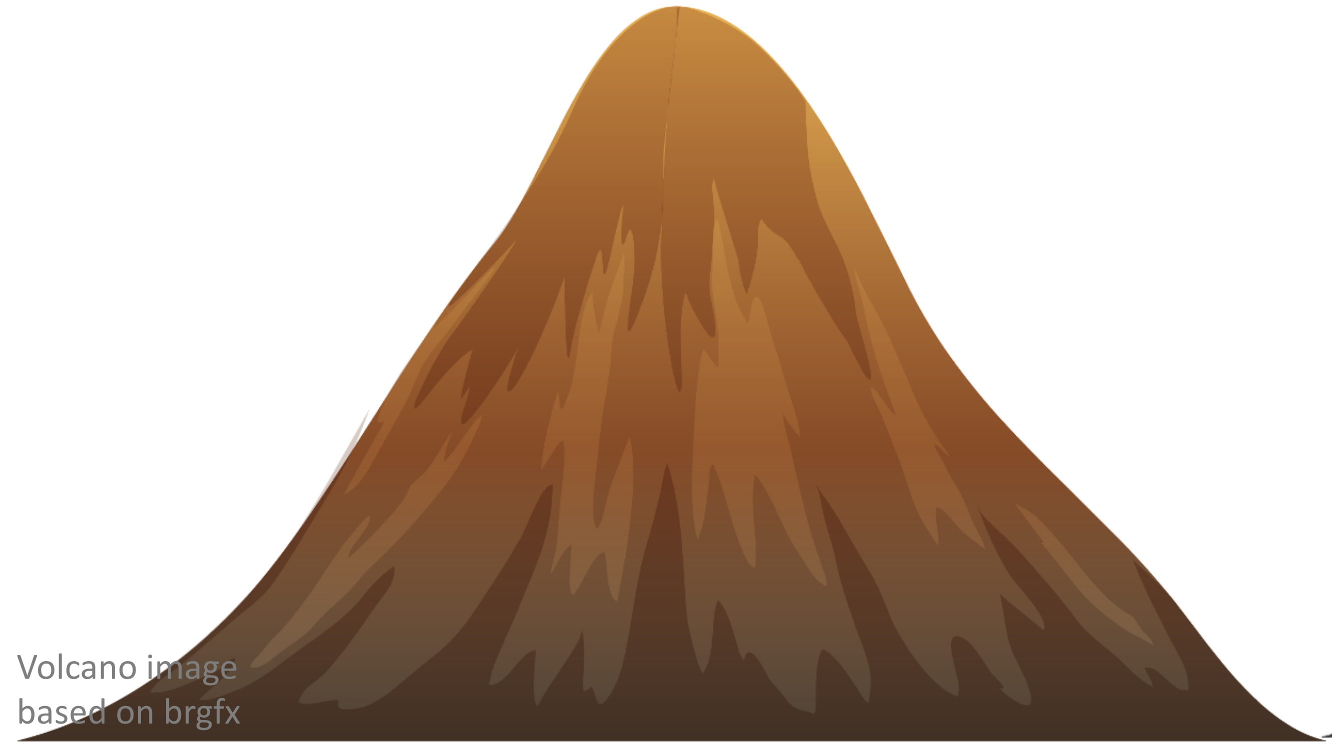
Quantum

Discreteness

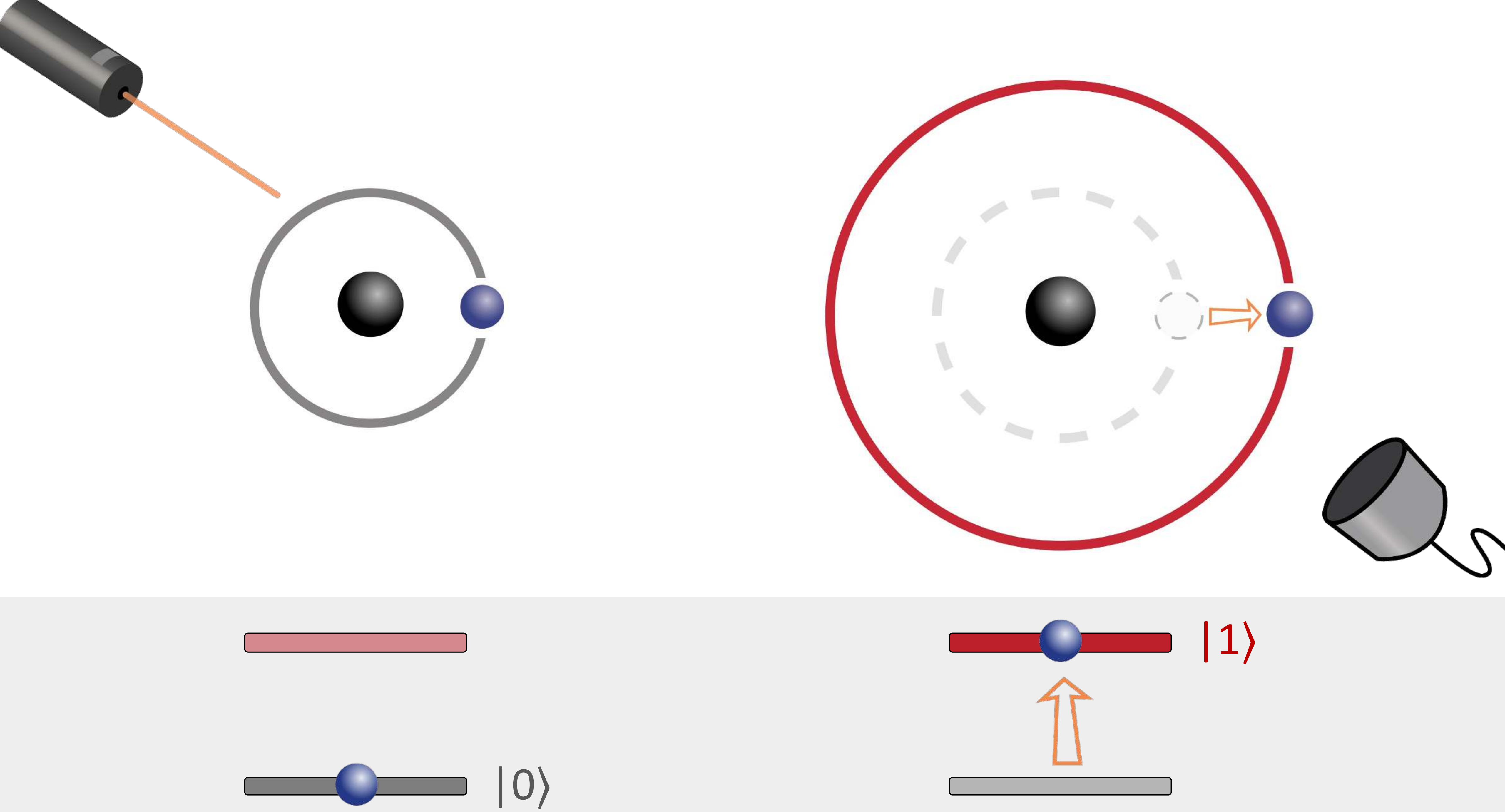
Unpredictability

column: vectorpocket

Predict?

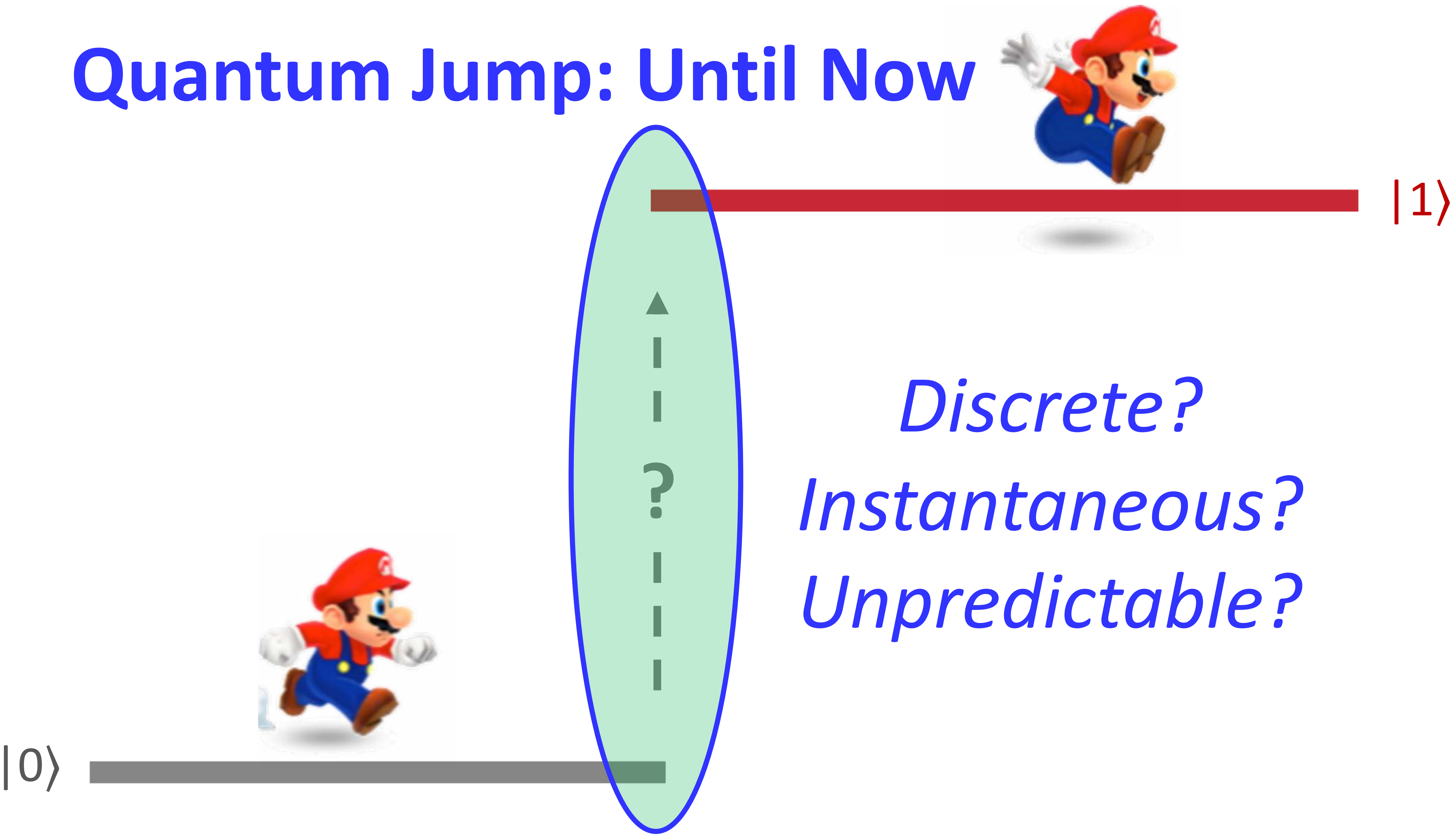


Volcano image
based on brgfx



Zlatko Minev, MIT TR35

Quantum Jump: Until Now

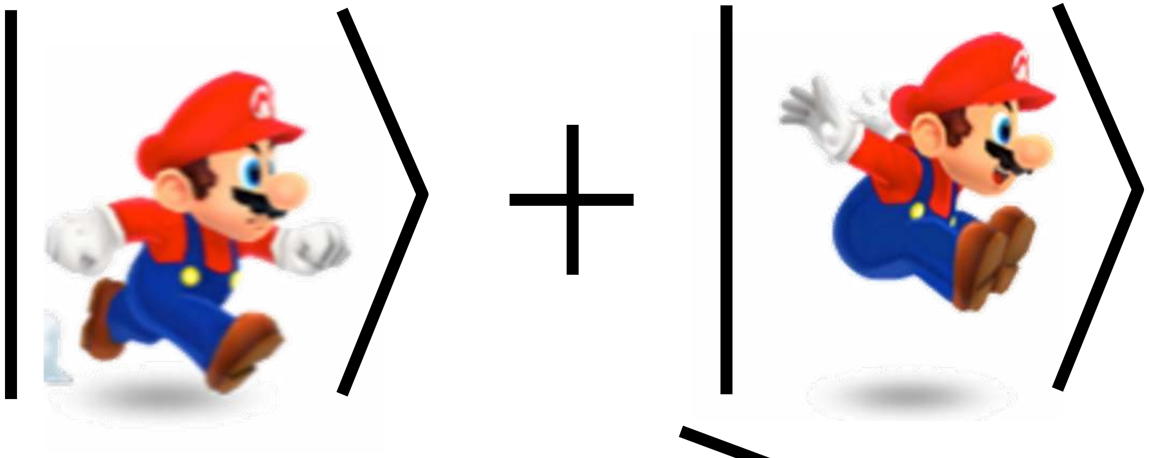


Discrete?

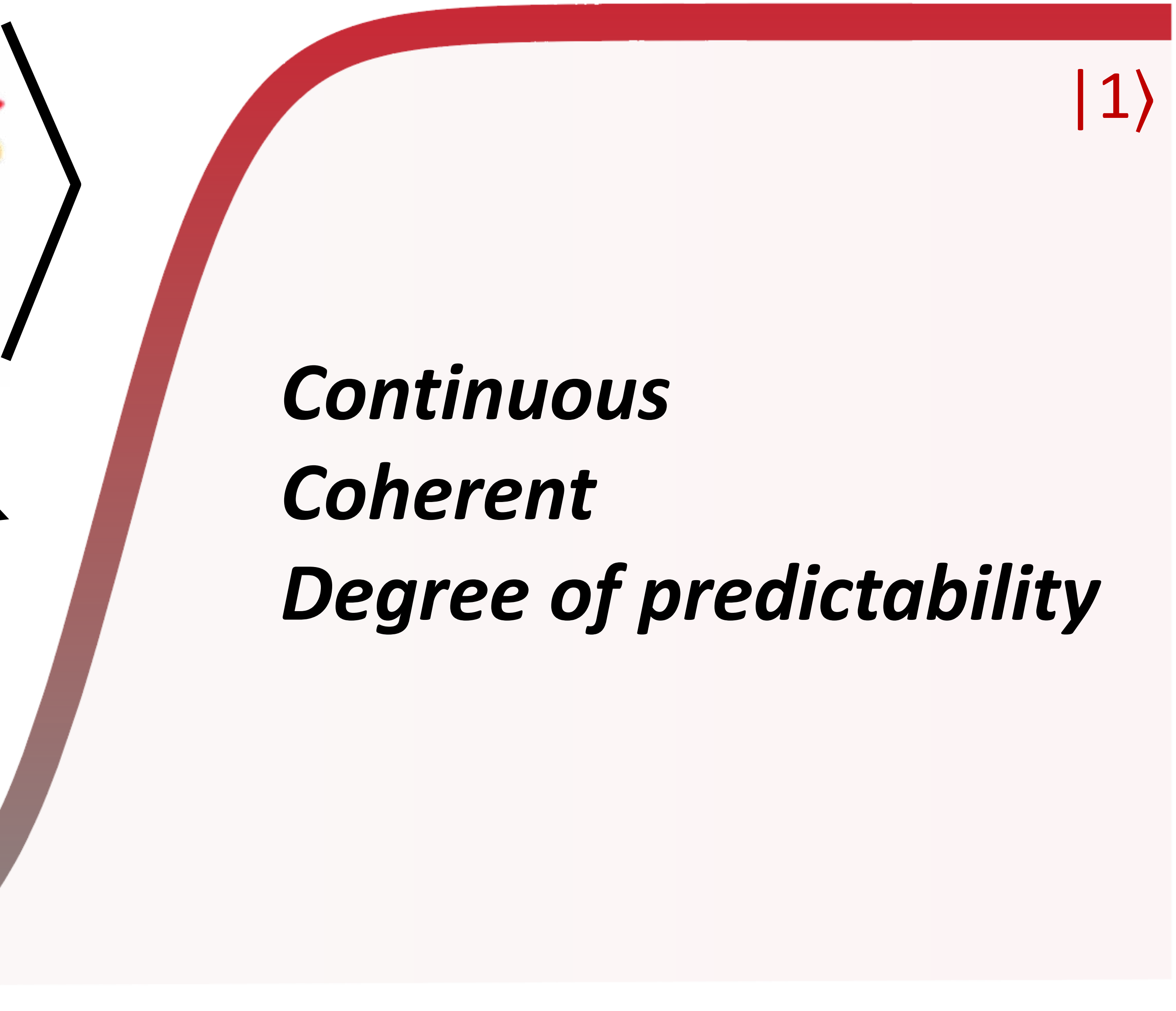
Instantaneous?

Unpredictable?

The Real Quantum Jump



Coherent superposition!

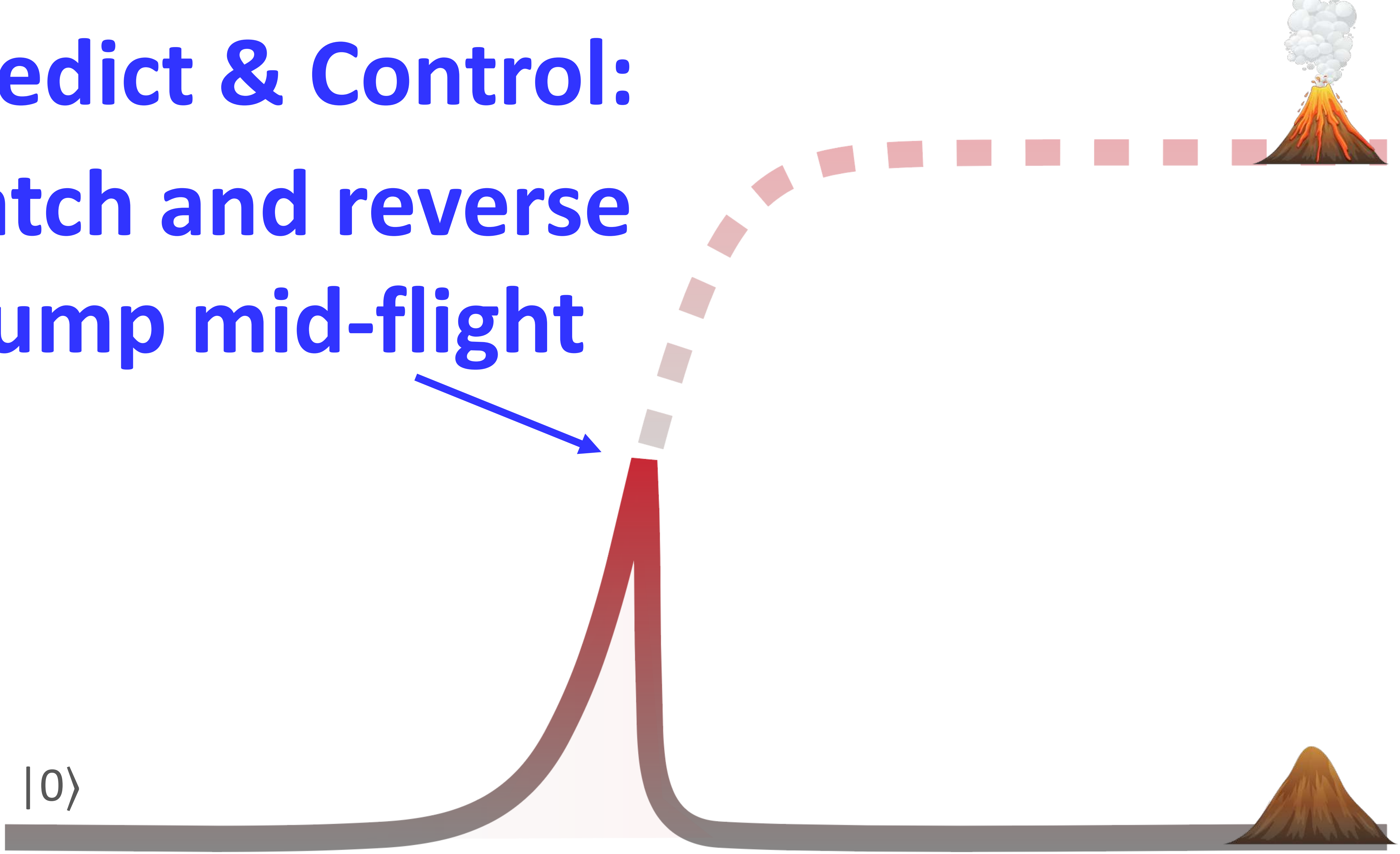


Continuous

Coherent

Degree of predictability

Predict & Control:
Catch and reverse jump mid-flight

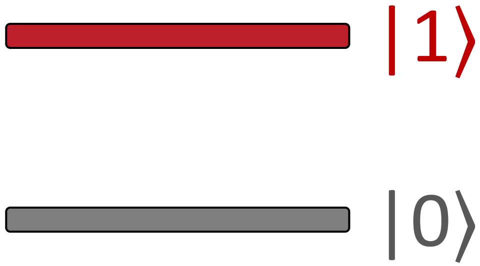


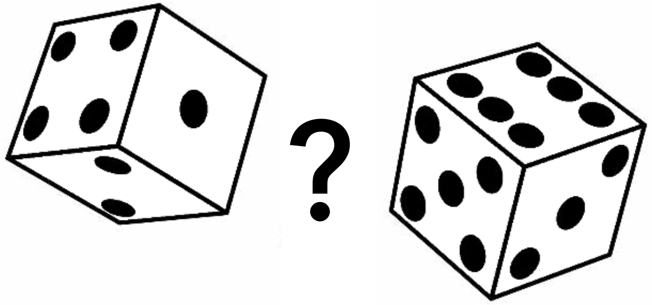
Zlatko Minev, MIT TR35

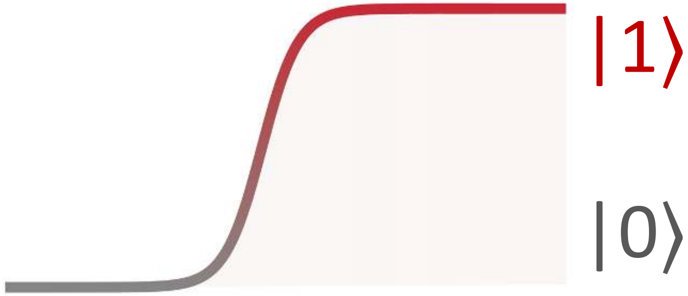
Bohr

Einstein

Schrödinger





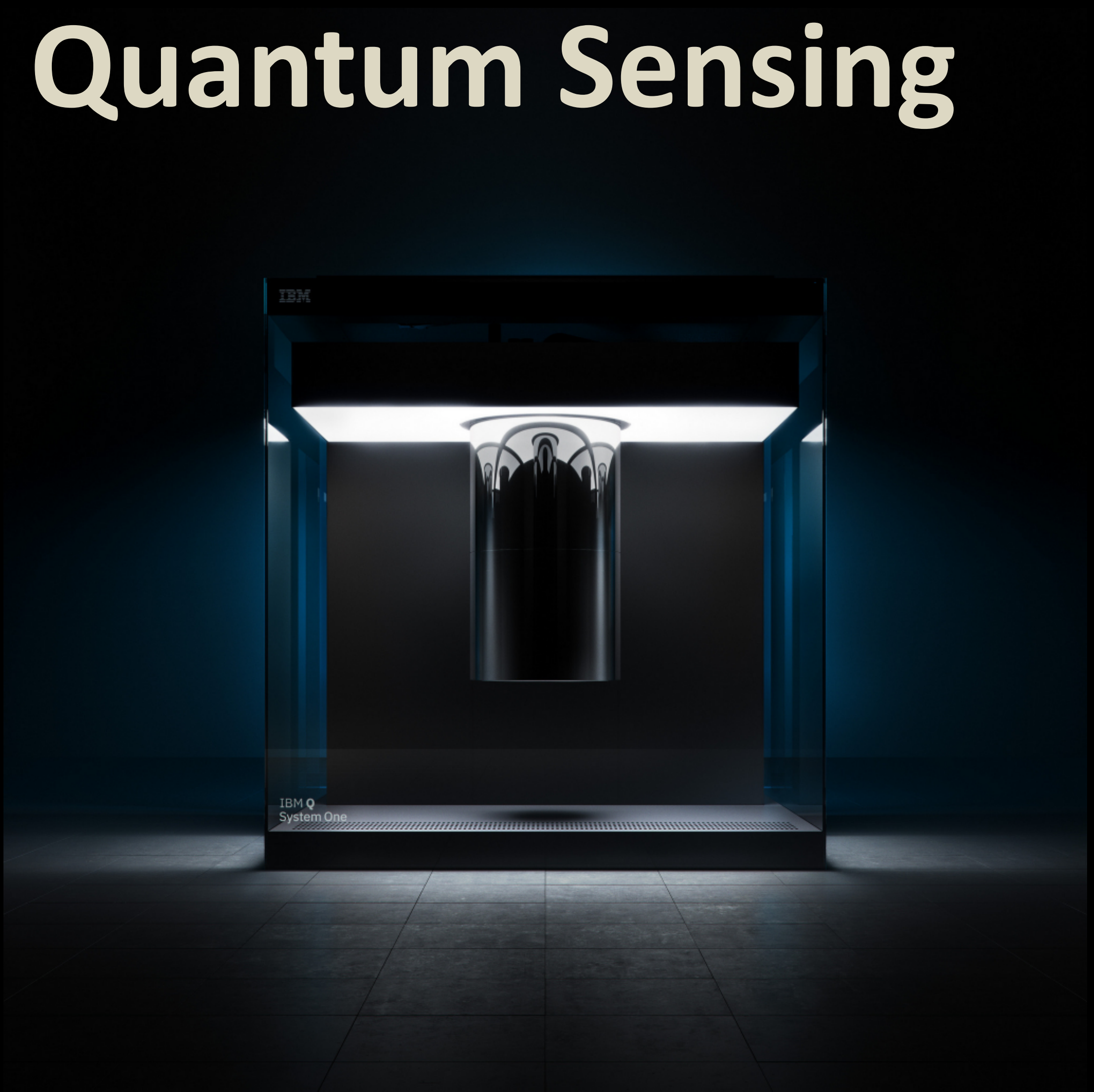


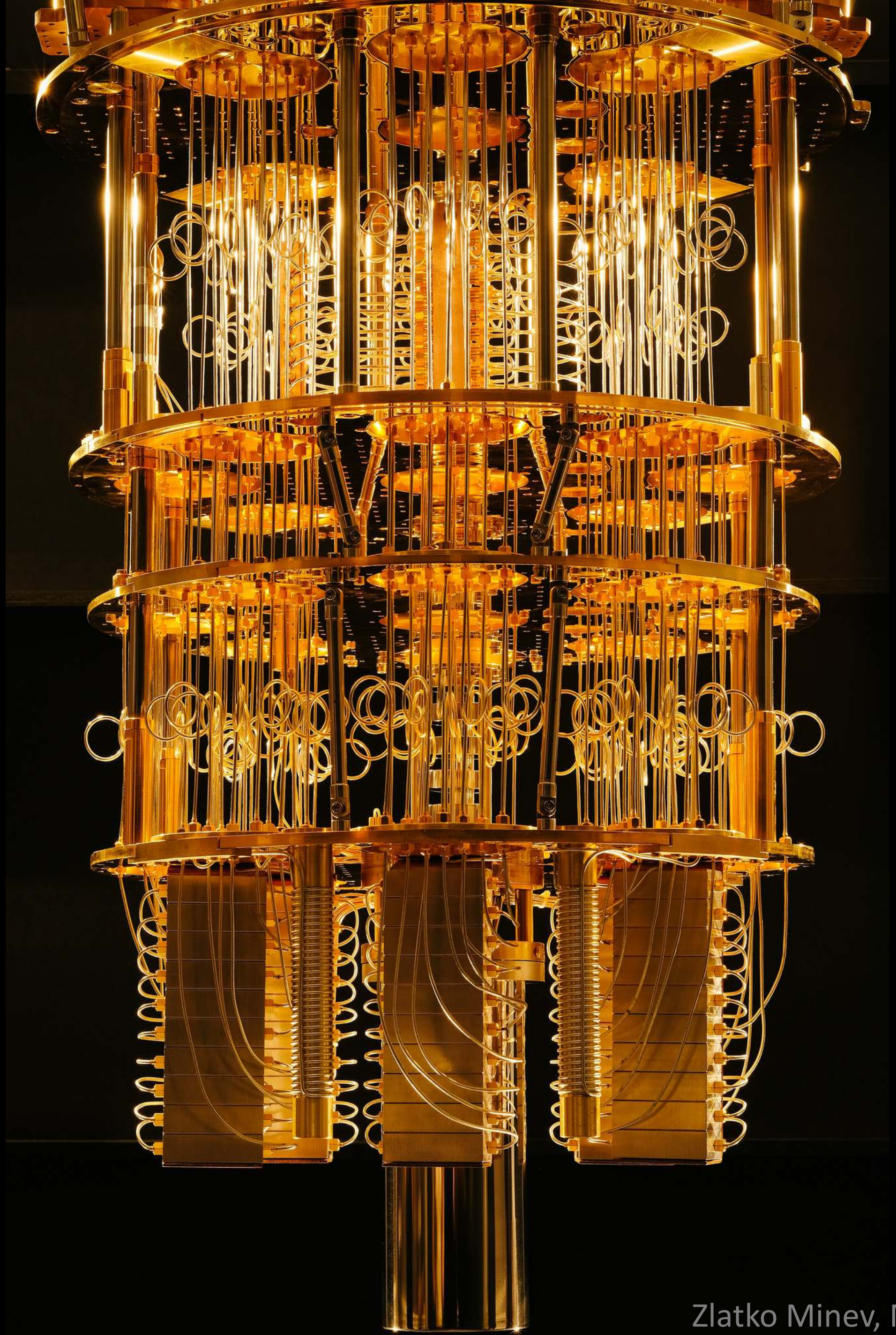
Zlatko Minev, MIT TR35

Quantum Computing:

Error correction

Quantum Sensing





Zlatko Minev, MIT TR35

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

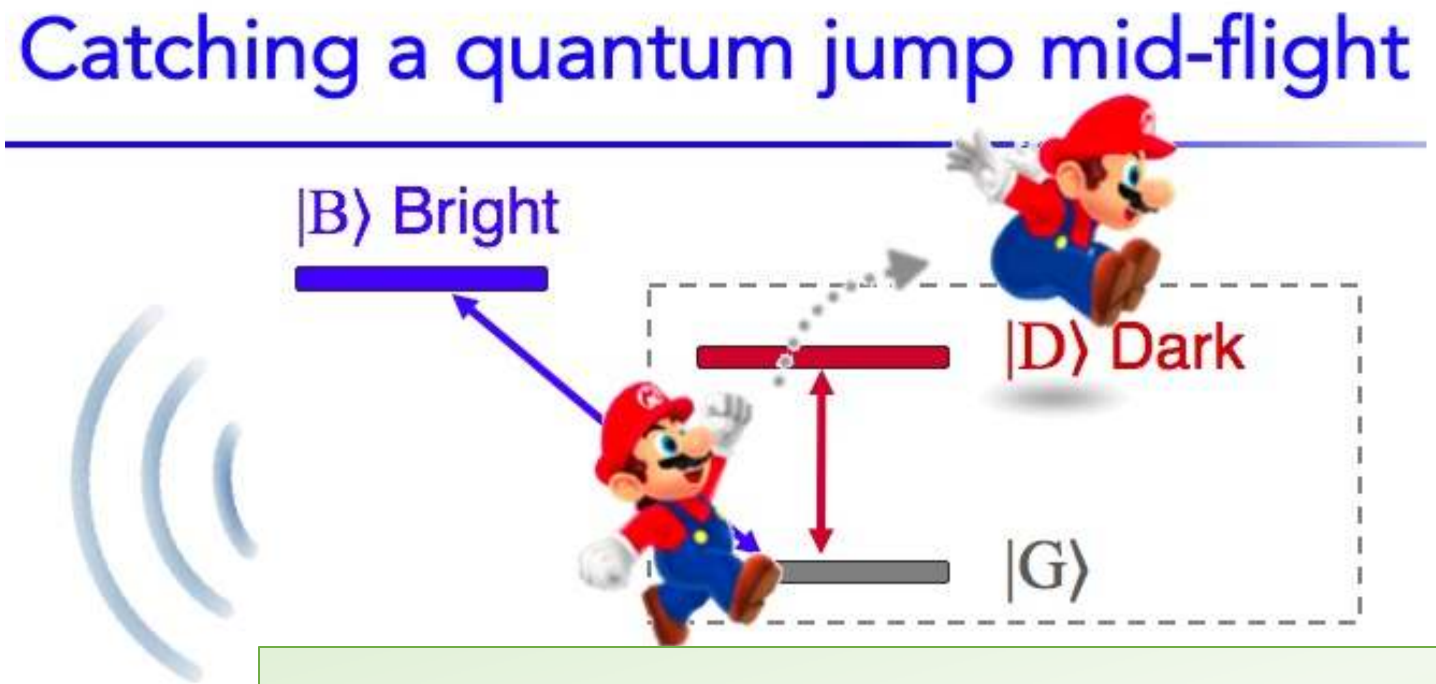
“It is by *logic* that we prove,
but by *intuition* that we discover.”

Henri Poincaré

Photo by Eugène Pirou

Believe in your ideas

Hear criticism,
then make a quantum leap



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)

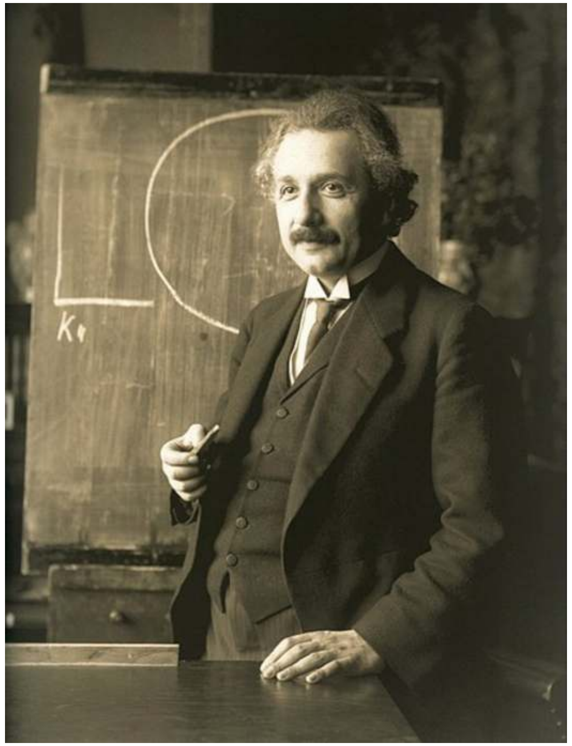


Photo: F. Schmutzer

Learn beyond apparent boundaries

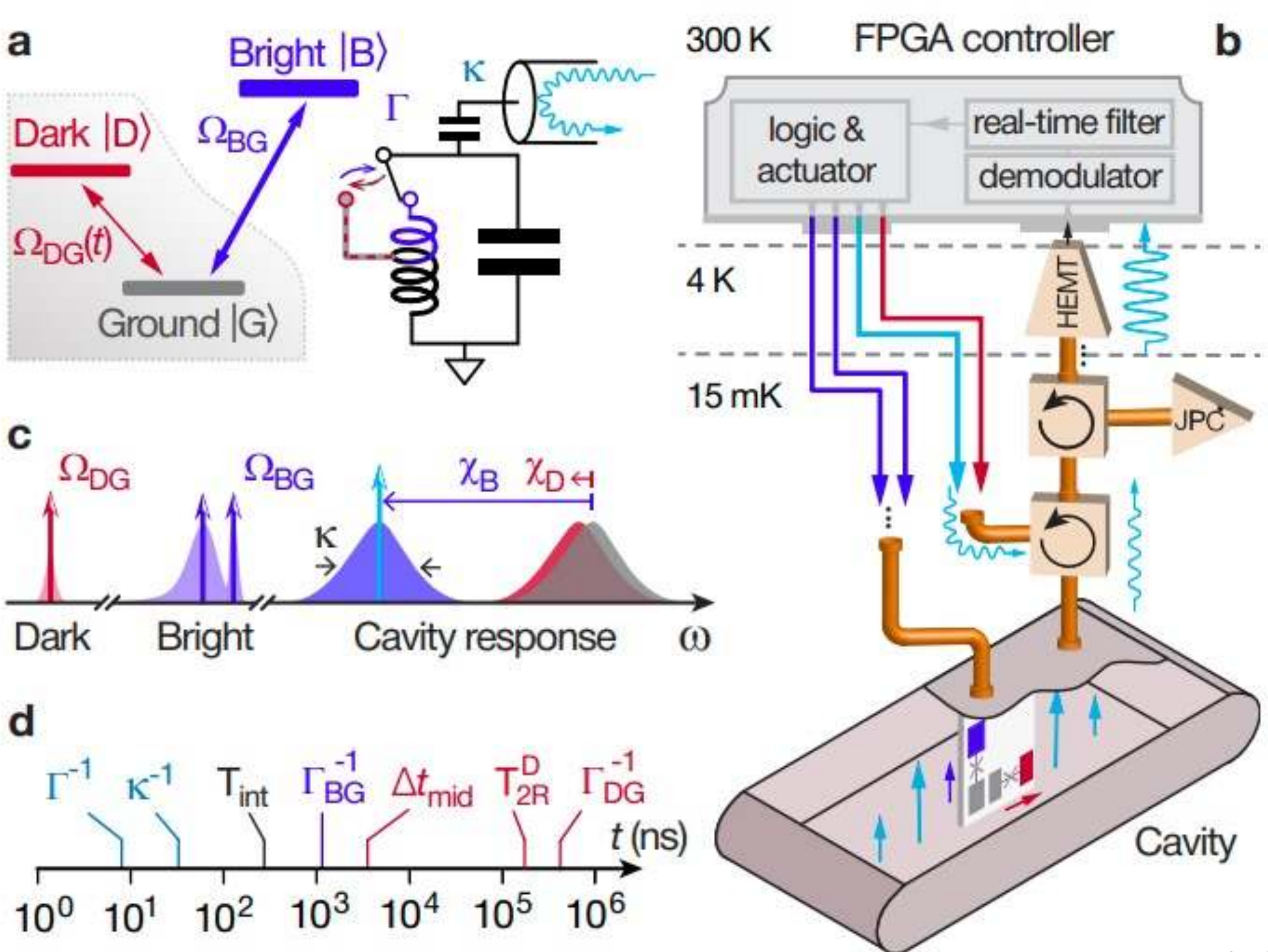
"We are not students of some subject matter, but students of problems. And problems may cut right across the borders of any subject matter or discipline."

Karl Popper

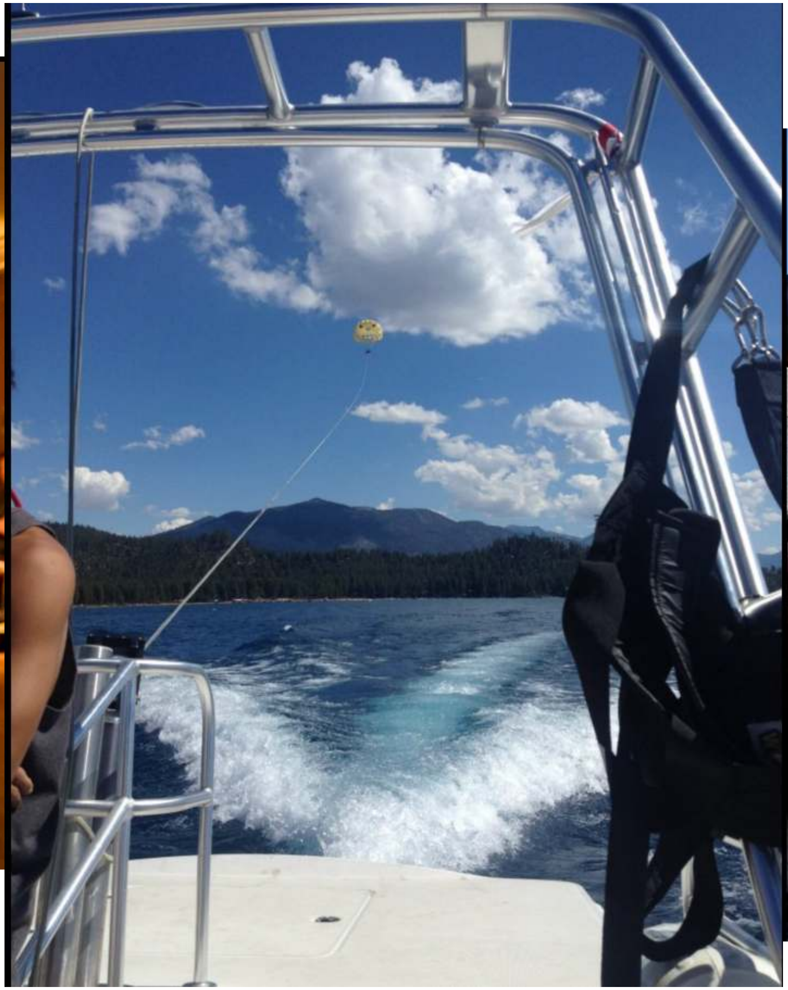
"I'M ON THE VERGE OF A MAJOR BREAKTHROUGH, BUT I'M ALSO AT THAT POINT WHERE CHEMISTRY LEAVES OFF AND PHYSICS BEGINS, SO I'LL HAVE TO DROP THE WHOLE THING."

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)



Yale Swing & Blues

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)

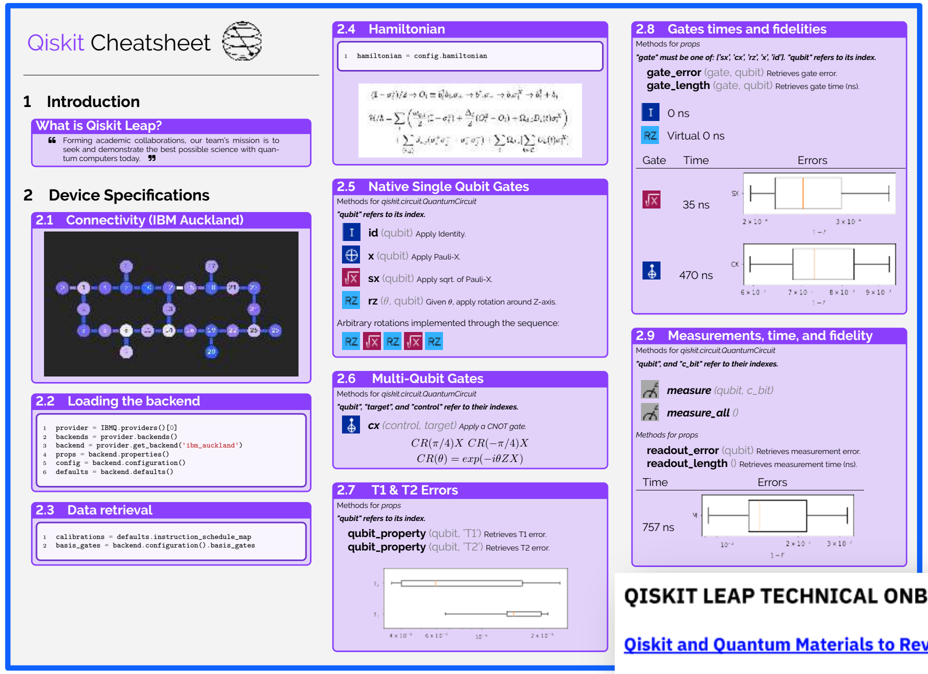
Nearly 26 million impressions (people who saw the video in their feed)

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

Educational, enablement, advocacy

Research enablement assets

researcher onboarding guide,
theorist cheat sheet,
researcher code assets,
…



QISKIT LEAP TECHNICAL ONBOARDING

Qiskit and Quantum Materials to Review

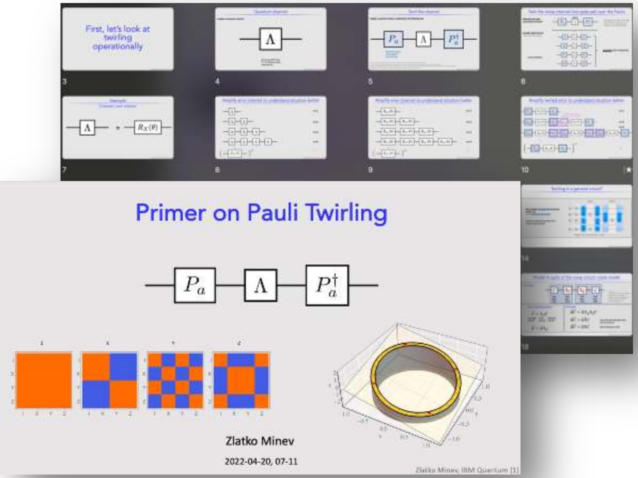
Optional/Advanced Topics

QC Resources

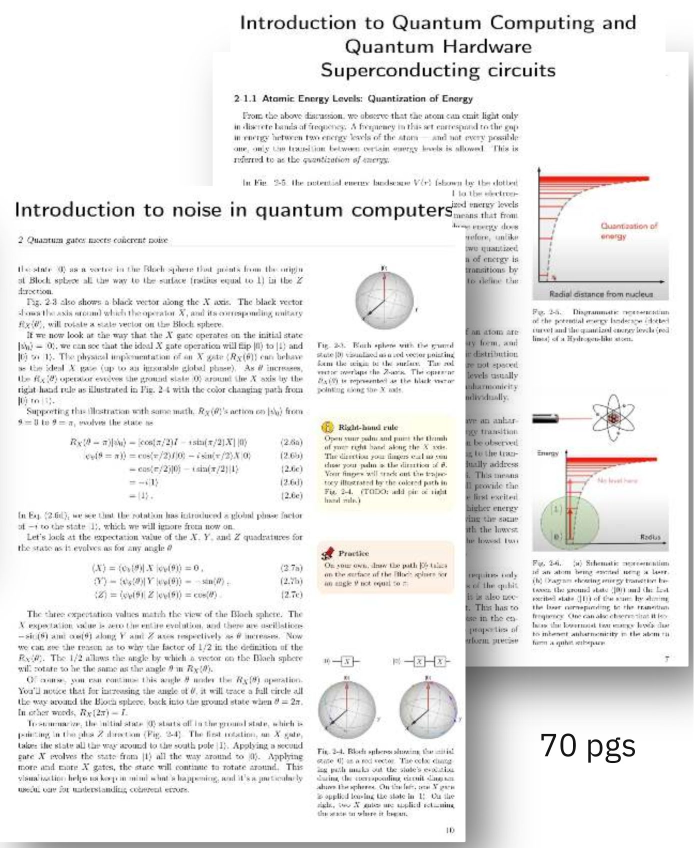
General Software Developer Resources

Educational assets

Tutorials, videos, manuscripts, …



4+ hours



70 pgs

70 pgs

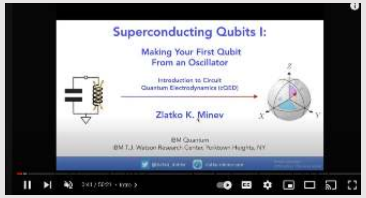
Global Summer Schools

4 years x 5,000+ students MOOC

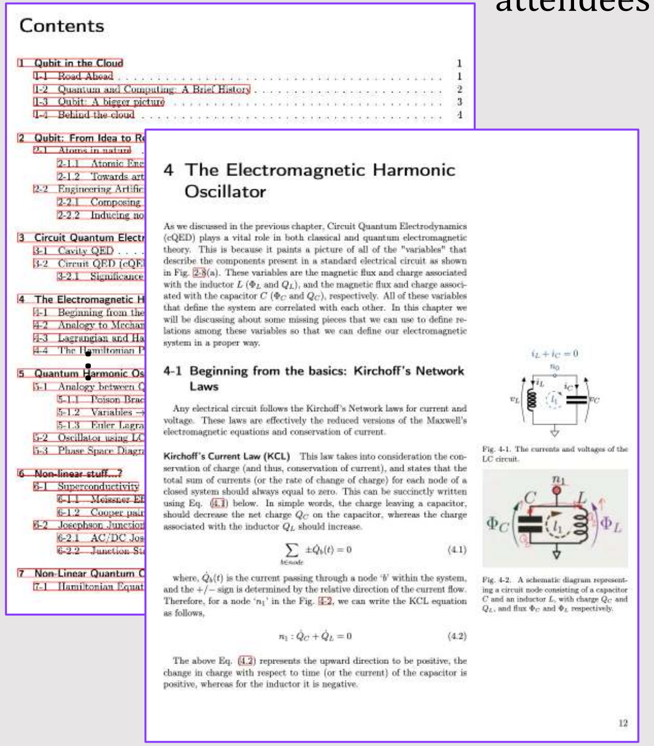
cQED book

WIP

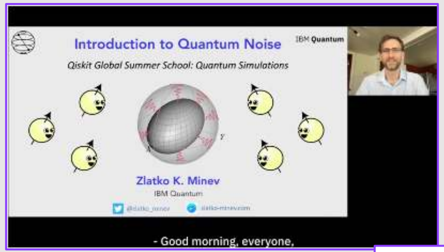
Introduction to Quantum Computing and Quantum Hardware Superconducting circuits



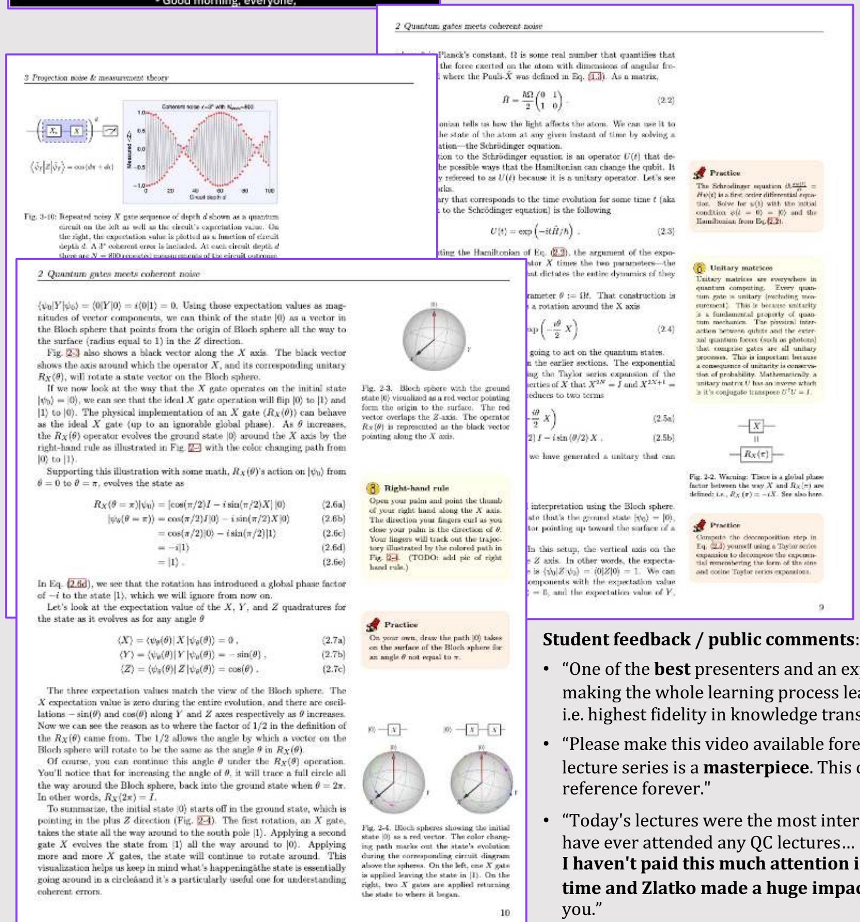
- 5,000+ live attendees



Introduction to noise in quantum computers



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

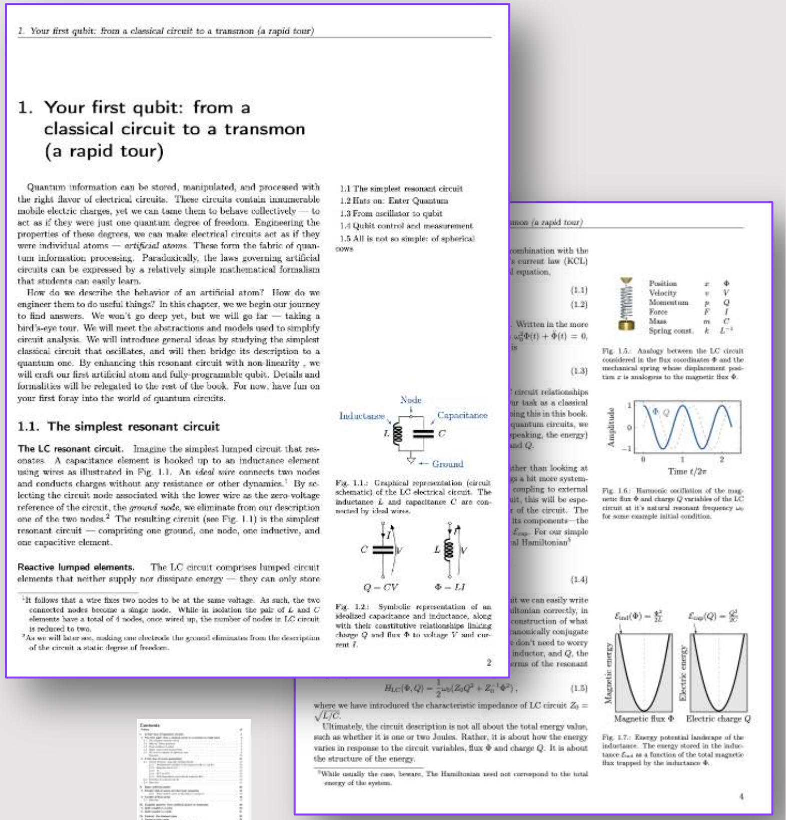


Student feedback / public comments:

- “One of the **best** presenters and an expert in making the whole learning process least noisy; i.e. highest fidelity in knowledge transferring.”
- “Please make this video available forever. This lecture series is a **masterpiece**. This can be our reference forever."
- “Today's lectures were the most interesting I have ever attended any QC lectures… **I haven't paid this much attention in long time and Zlatko made a huge impact,** Thank you.”

Introduction to quantum circuits: artificial atoms and microwave photons

Book WIP: *Zlatko, Jens Koch, Michel Devoret*

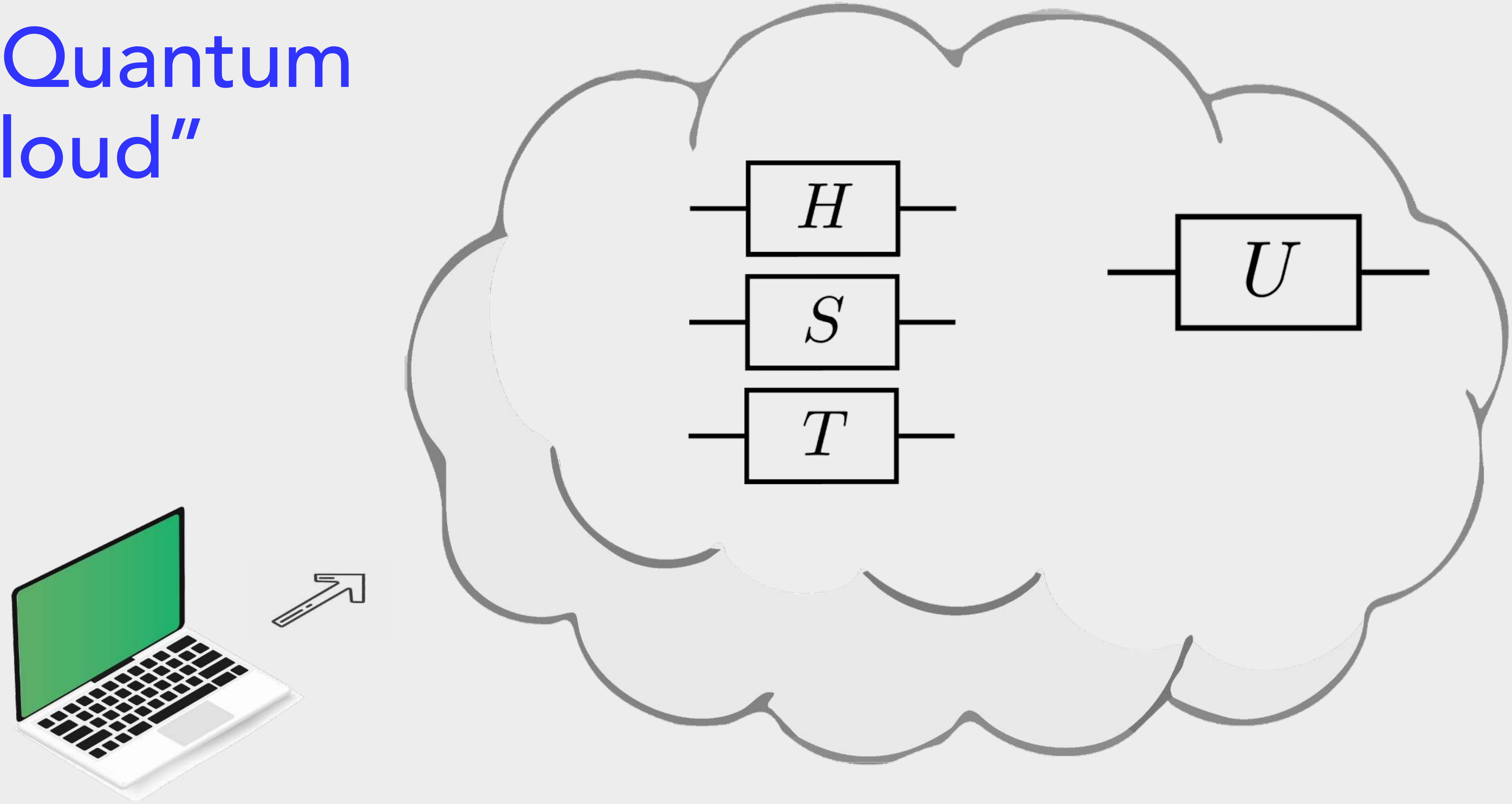


Z Minev


Open Labs
Est. 2012
OPEN LABS

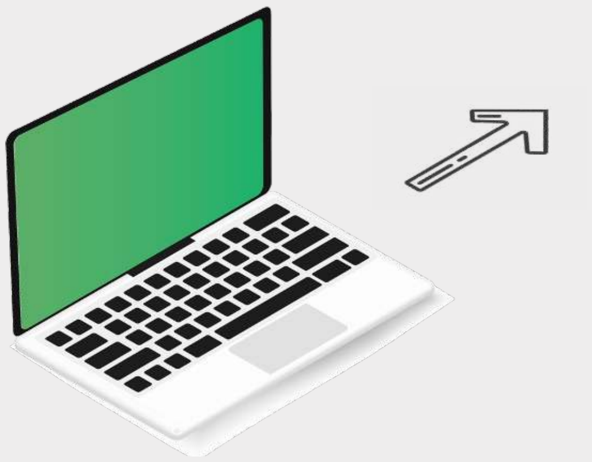
Quantum Computer and IBM Quantum

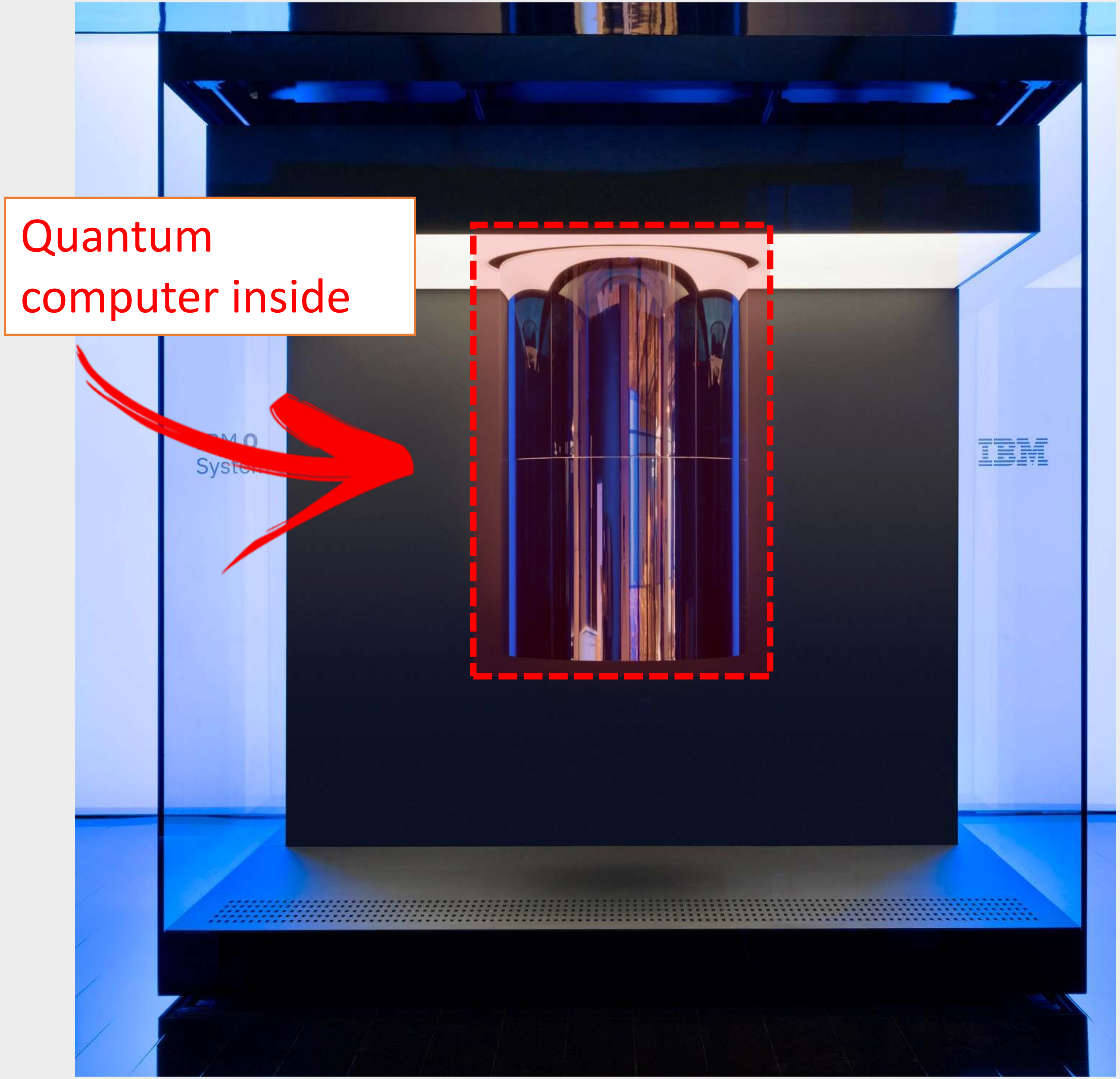
"Quantum cloud"



Laptop image: rawpixel.com

Quantum computer

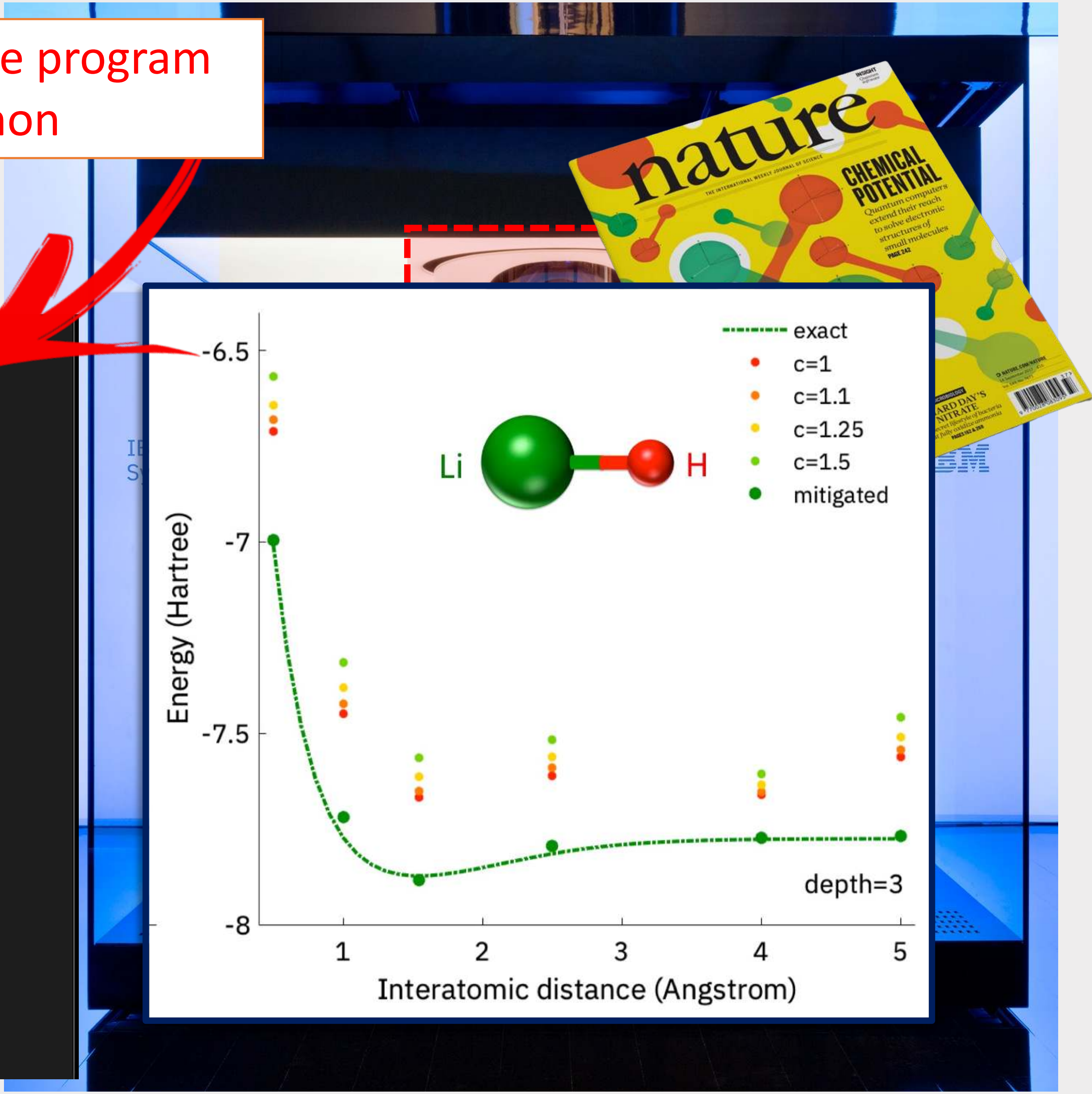




Programming quantum

execute program in Python

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



Zlatko Minev, IBM Quantum

Biggest challenge?

Please do share

Biggest challenge?

hardware development

decoherence

loss

stability

heat

algo development

error correction overheads

Noise (Errors)

high error rates

scalability

engineering

modularization

importance of N in NISQ

hype

need CS/EE talent

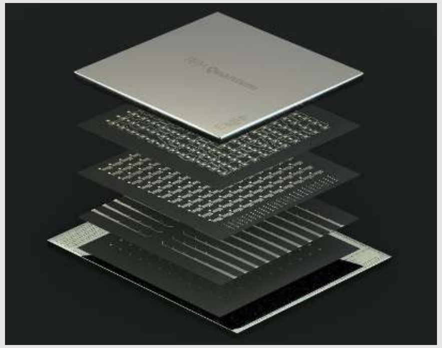
material quality

gravity

expectations

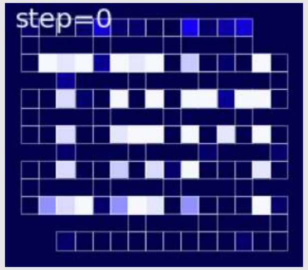
Biggest challenge

Noise
(Errors)



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

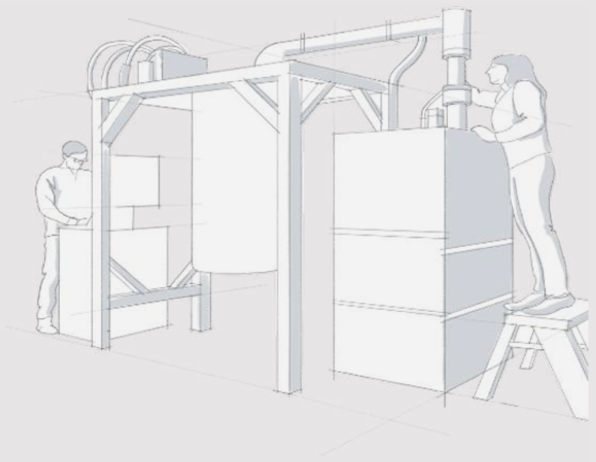
Quantum and Noise
Introduction in a nutshell

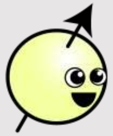


1 qubit (Hello World!)
to
100+ qubits (state of art)

Zlatko Minev, IBM Quantum

Hello World: Is it even or odd?



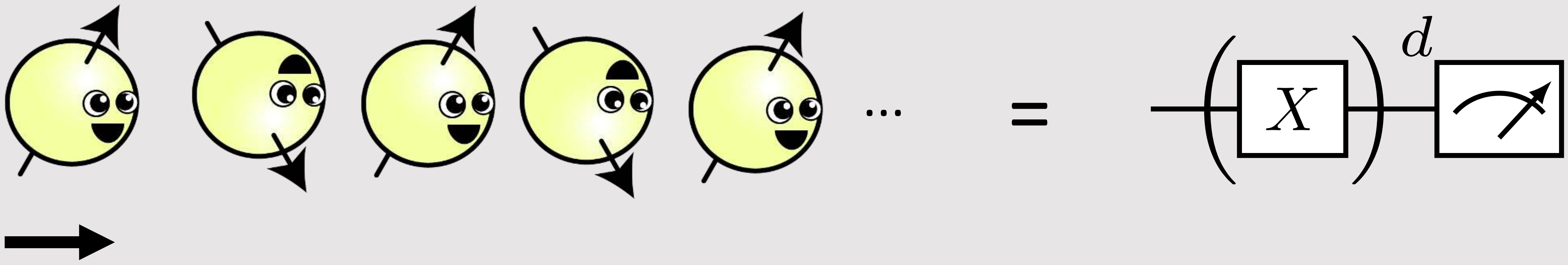
Compute resources 1 qubit 

Algorithm input an integer $d > 0$

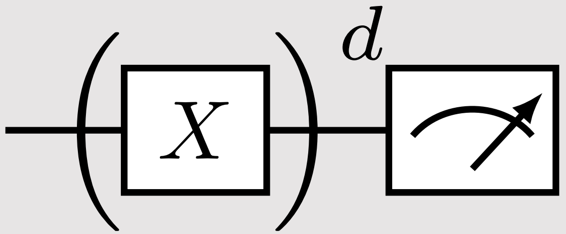
Task even or odd?

A toy algorithm

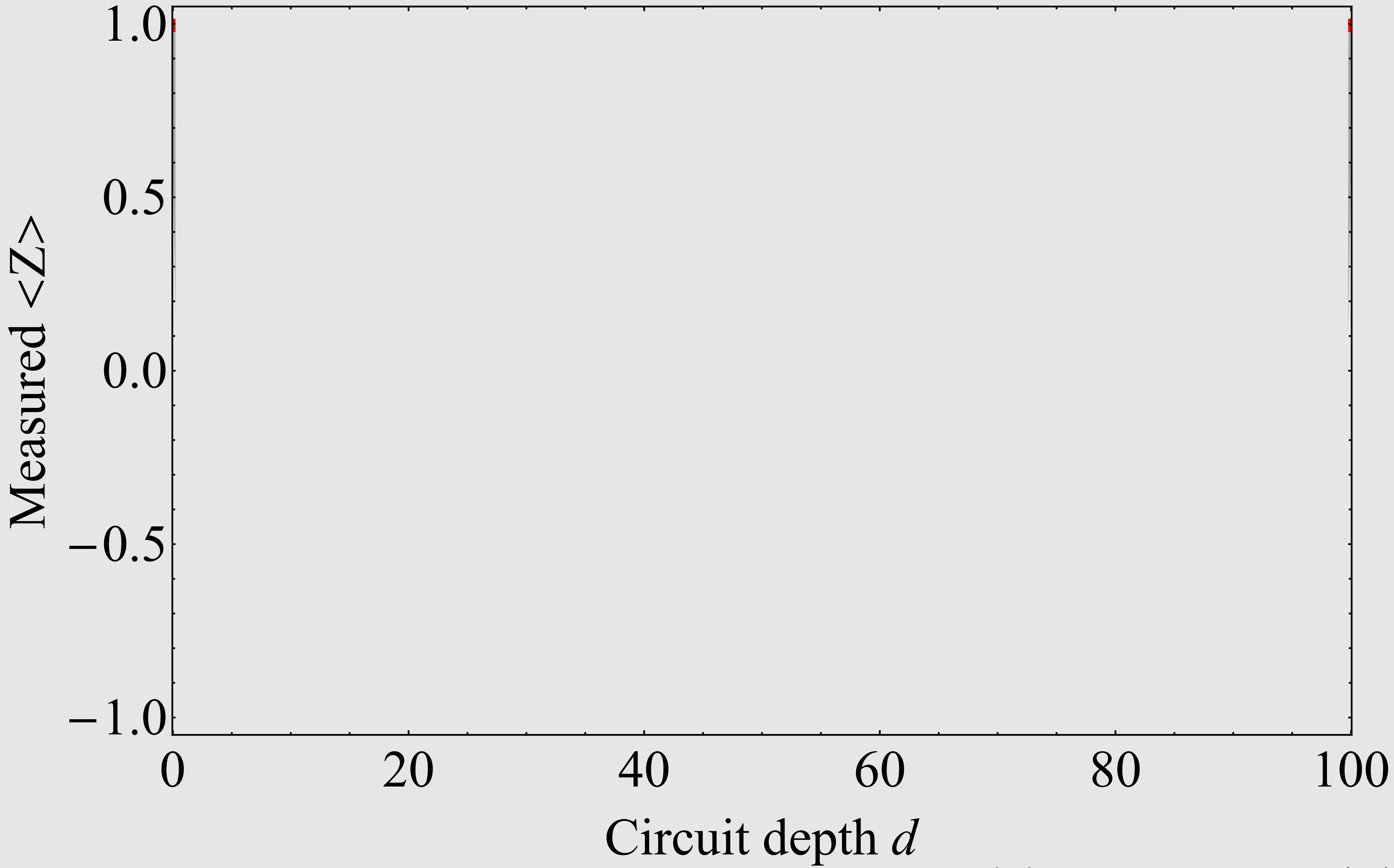
Start in 0, flip d times, measure



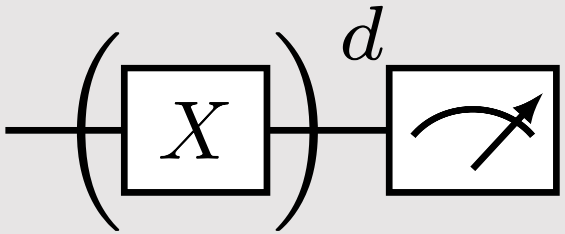
Hello World! Ideal expectation results

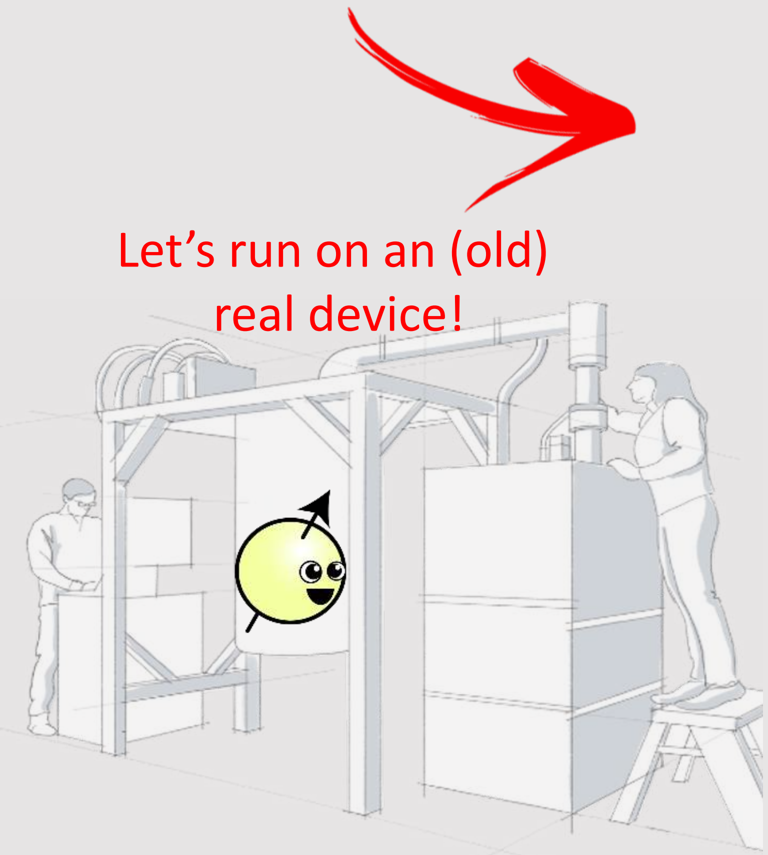


$$\langle Z \rangle = (-1)^d$$

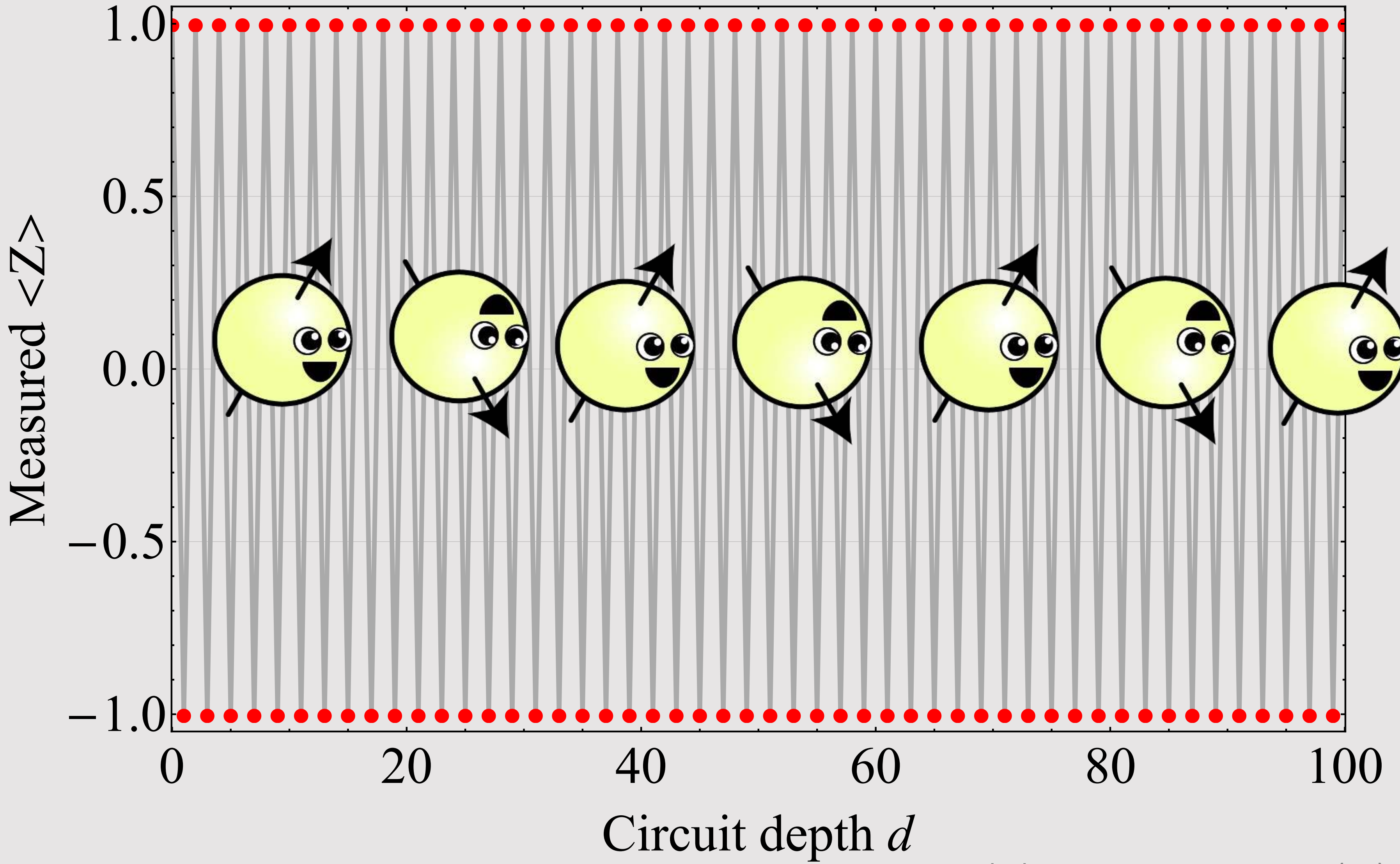


Hello World! Ideal expectation results

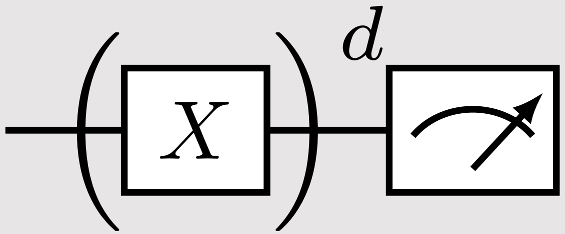




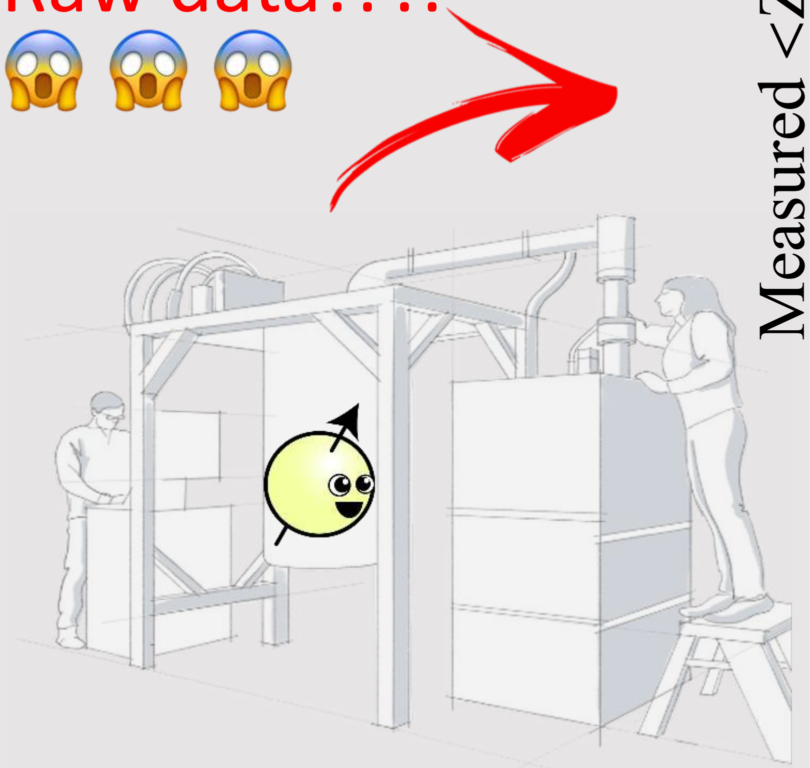
$$\langle Z \rangle = (-1)^d$$

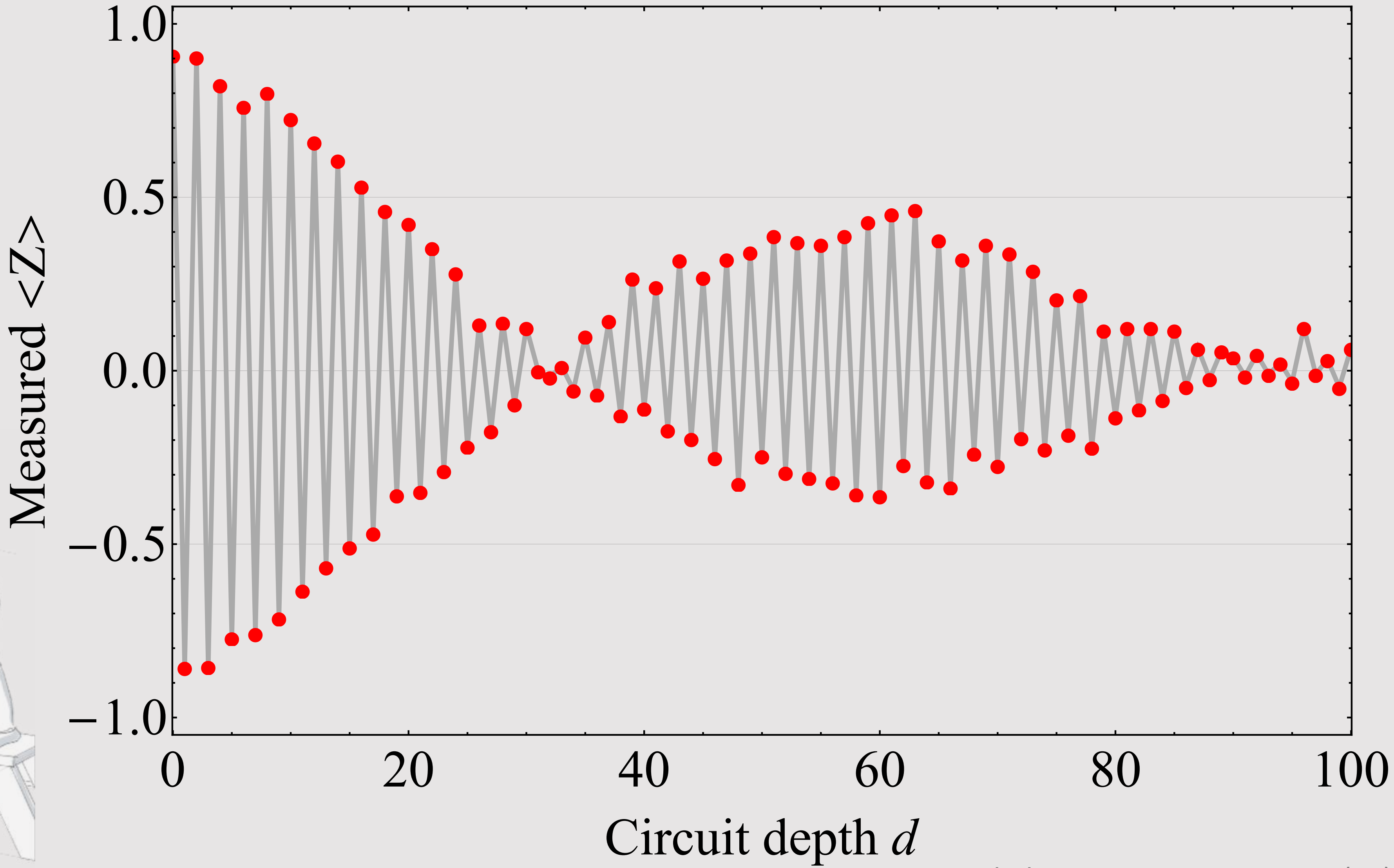


Hello World! Real expectation results

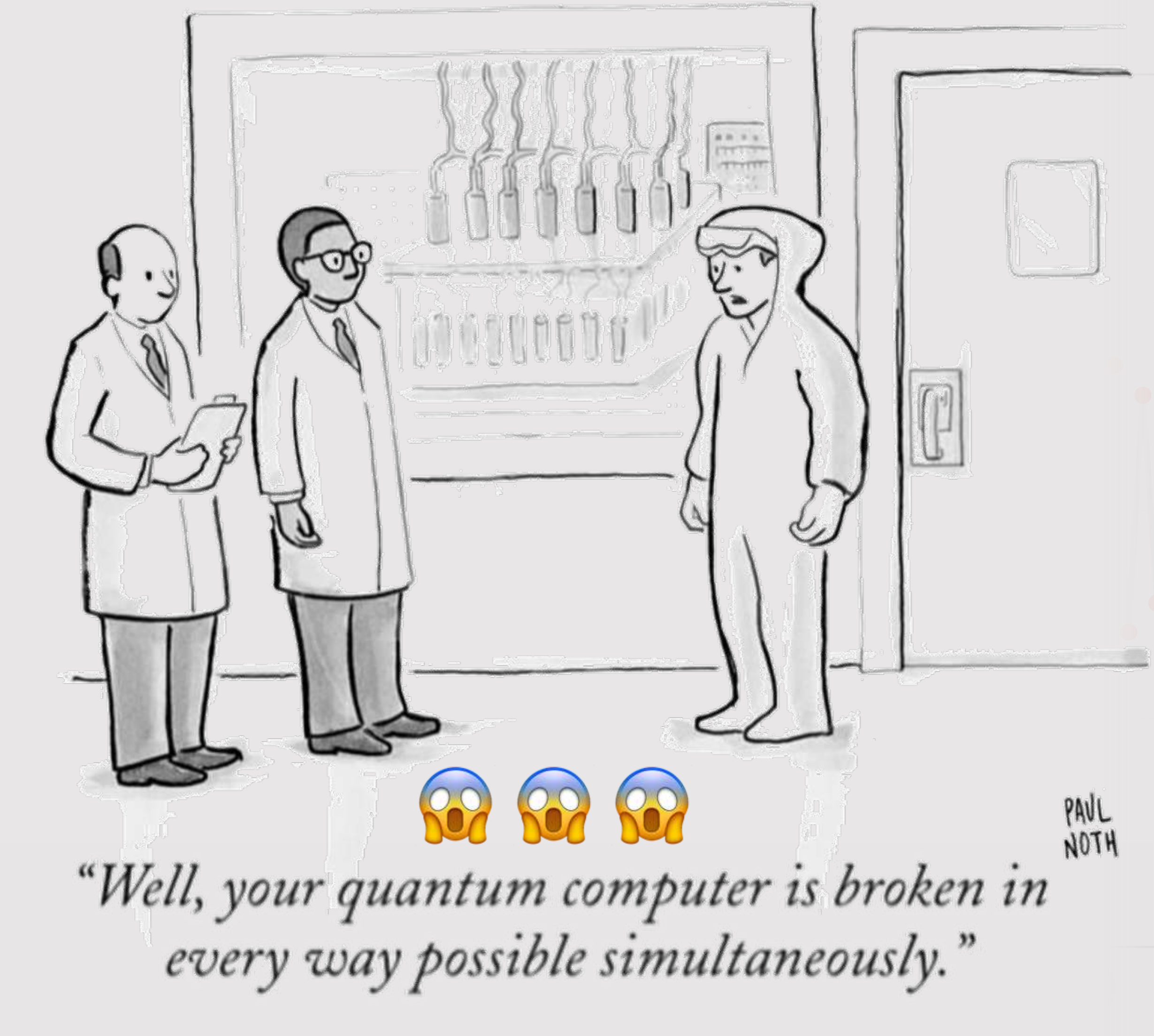


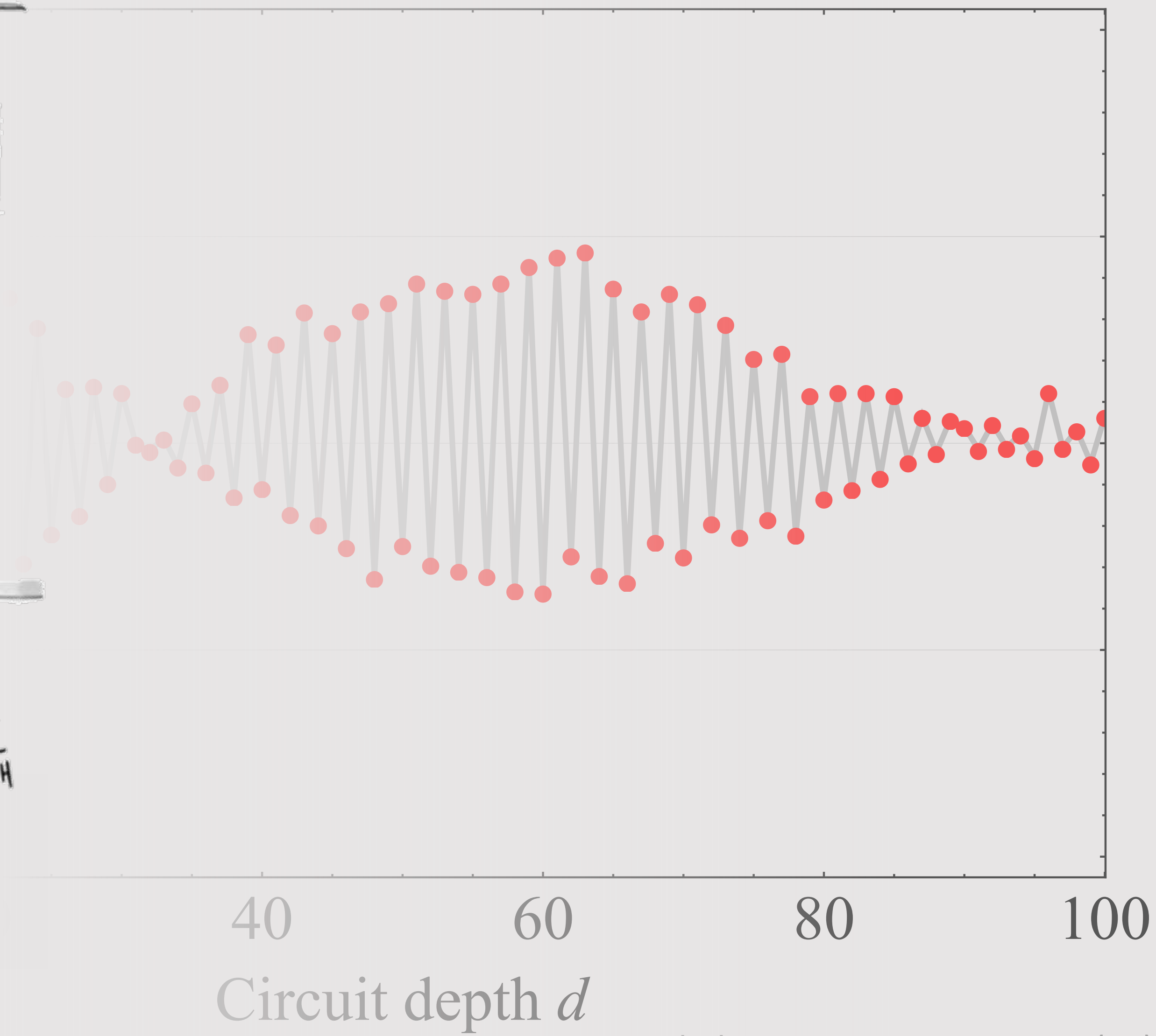
Raw data!?!! 😱 😱 😱



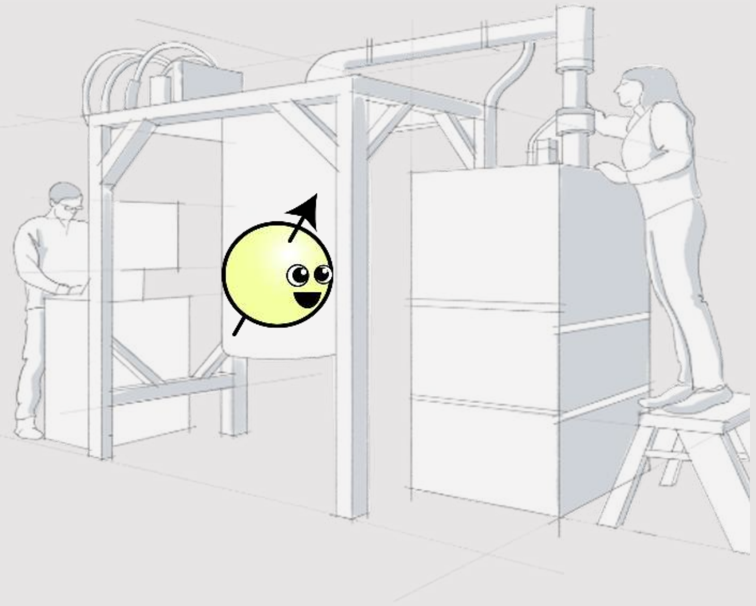


Real & noisy quantum processors: Why study noise?





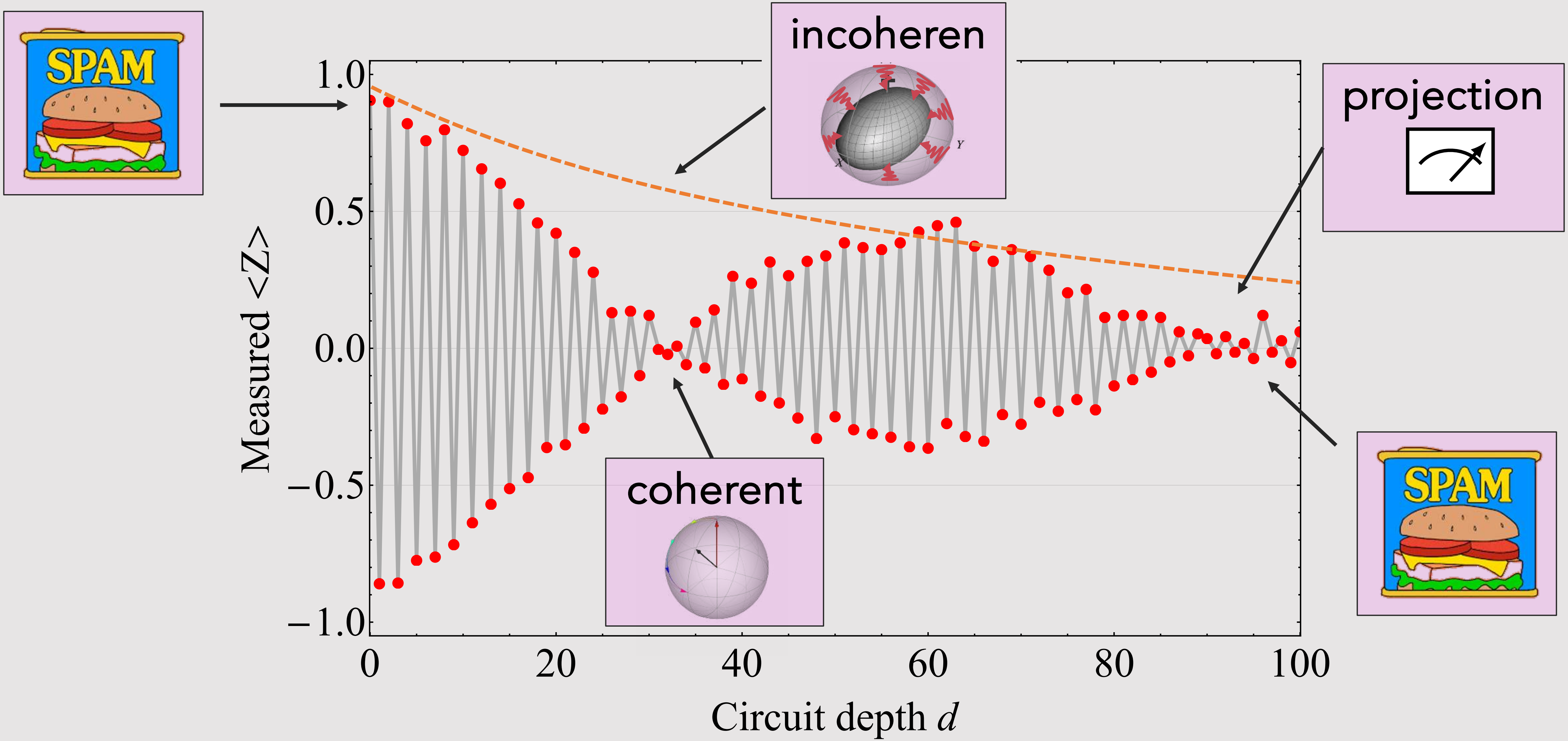
Cartoon: Paul Noth



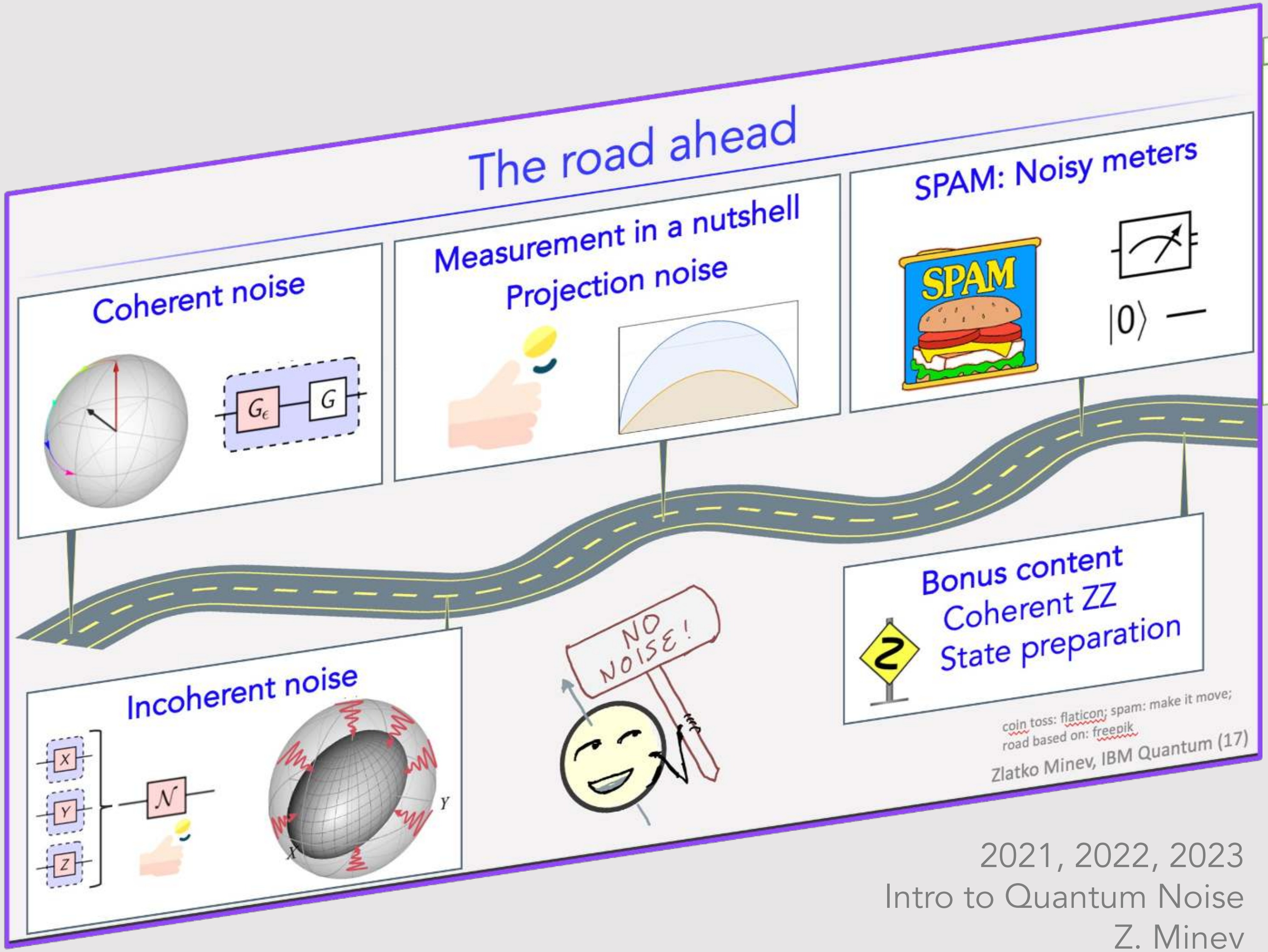
"Quantum phenomena
do *not* occur in a Hilbert space,
they occur in a laboratory."

Asher Peres

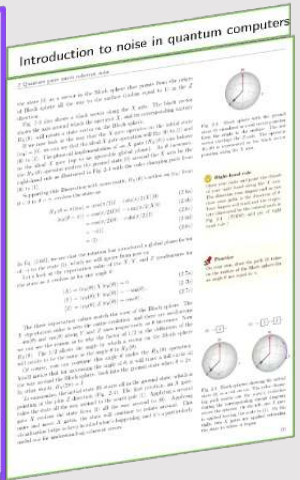
Elements of 😱 noise

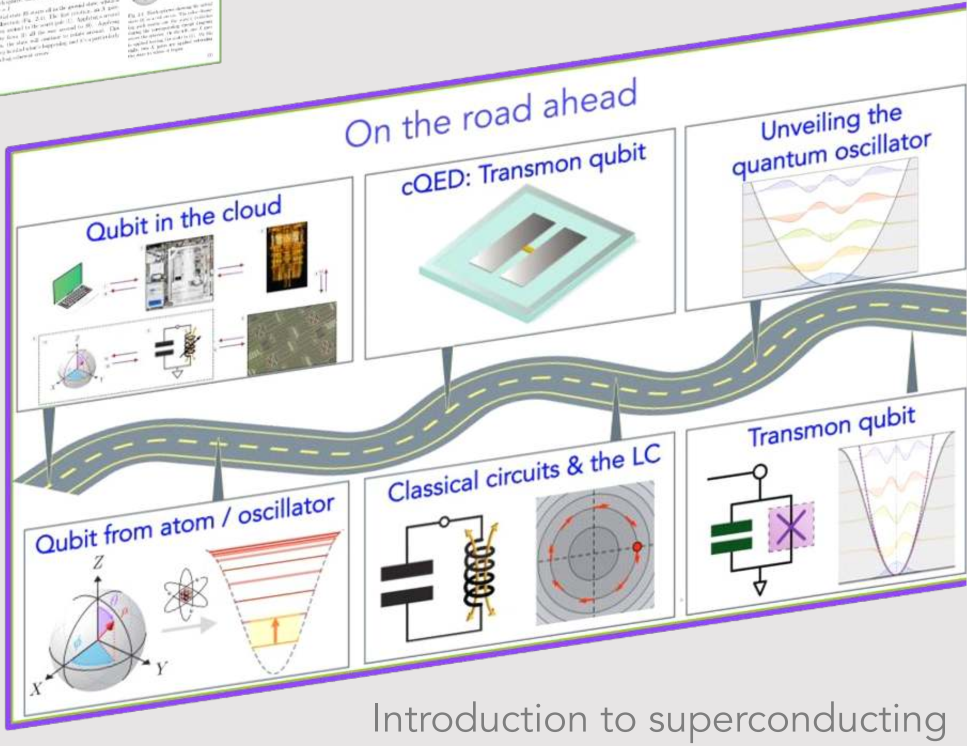


Learn the basics?



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





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

qiskit.org/learn
Qiskit Global Summer School 2023 coming up soon!
5,000+ students

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

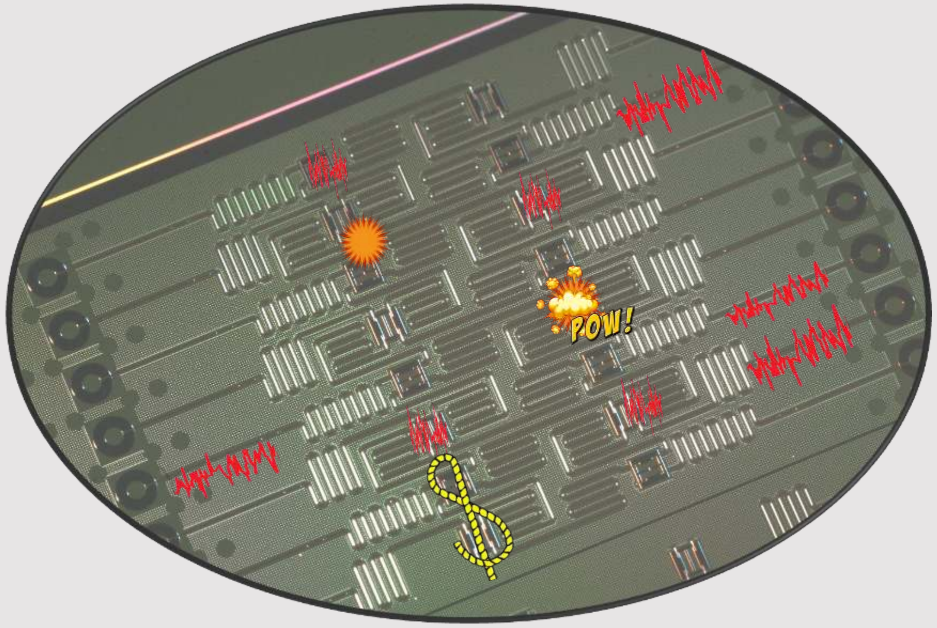
Minev, Nature (2019), ...

No monitor
Error occurs
Error undetected

Error mitigation

... subject of today

Error mitigation and error correction at a glance



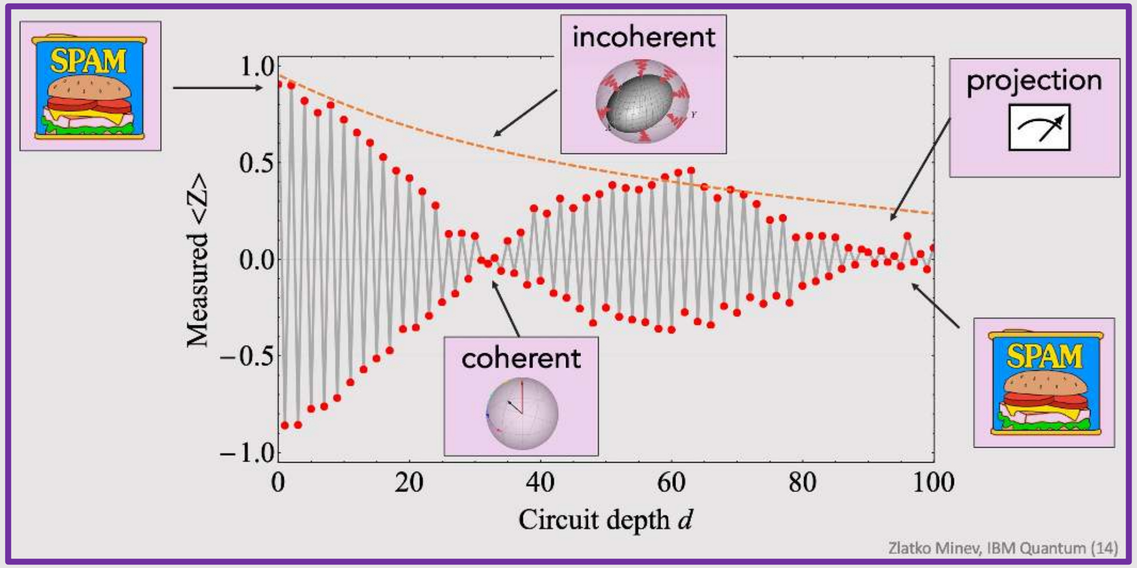
Error mitigation   Working with what you have

- **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

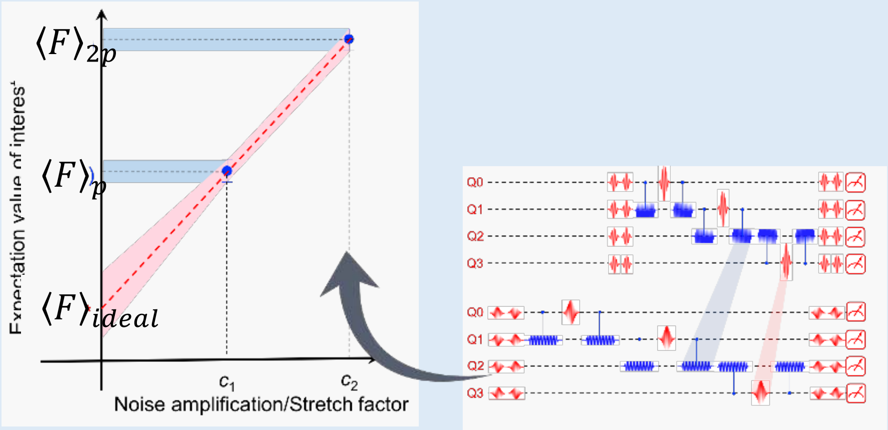


more speed

more information, accuracy

Error mitigation landscape

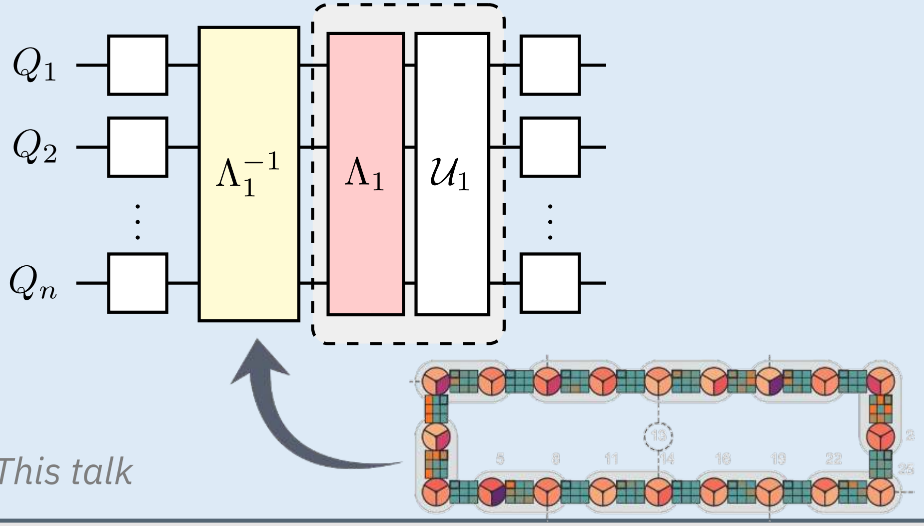
Zero-noise extrapolation (ZNE)



Nature 567, 491 (2019)

...

Probabilistic error cancelation (PEC)

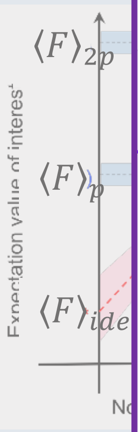


This talk

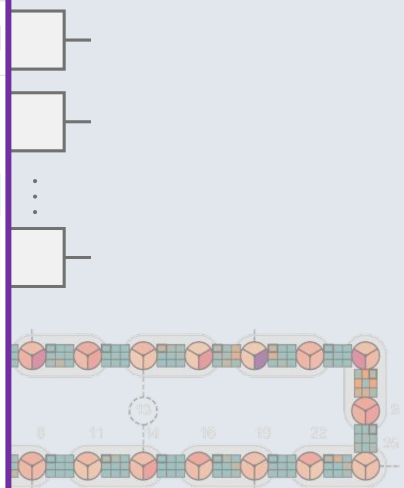
more speed → **more information, accuracy**

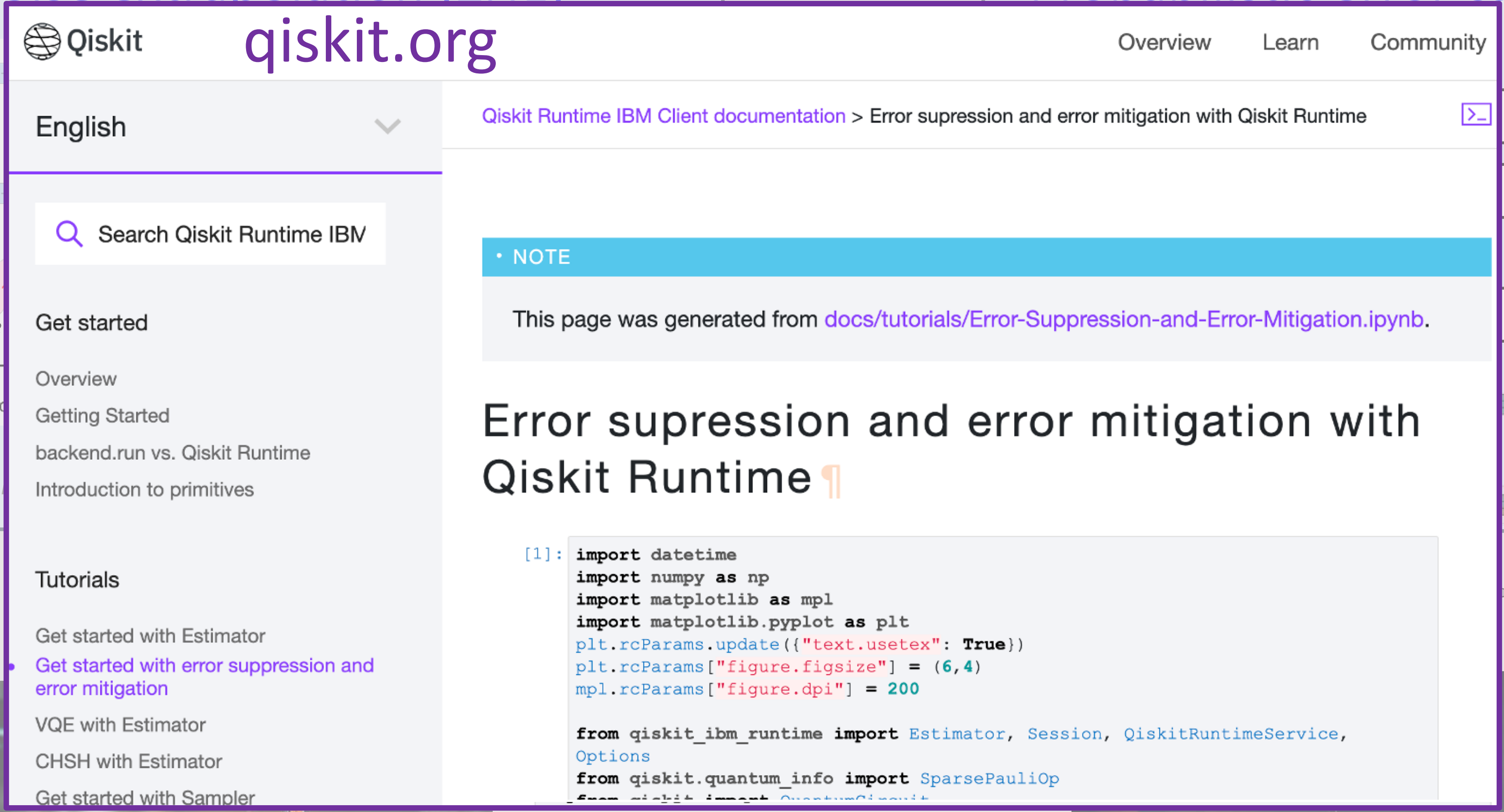
Error mitigation landscape

Zero-noise extrapolation (ZNE)



Probabilistic error cancelation (PEC)





Qiskit qiskit.org Overview Learn Community

English

Search Qiskit Runtime IBM

Get started

Overview

Getting Started

backend.run vs. Qiskit Runtime

Introduction to primitives

Tutorials

Get started with Estimator

Get started with error suppression and error mitigation

VQE with Estimator

CHSH with Estimator

Get started with Sampler

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

NOTE

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

Error supression and error mitigation with Qiskit Runtime

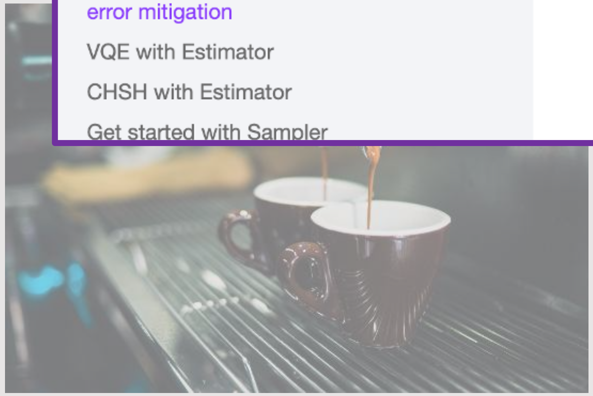
[1]:

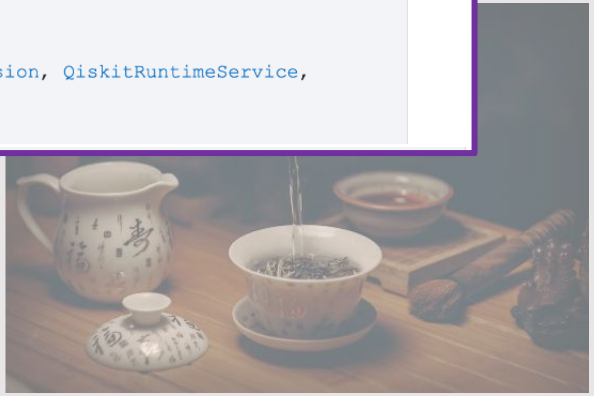
```
import datetime
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.rcParams.update({"text.usetex": True})
plt.rcParams["figure.figsize"] = (6,4)
mpl.rcParams["figure.dpi"] = 200

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

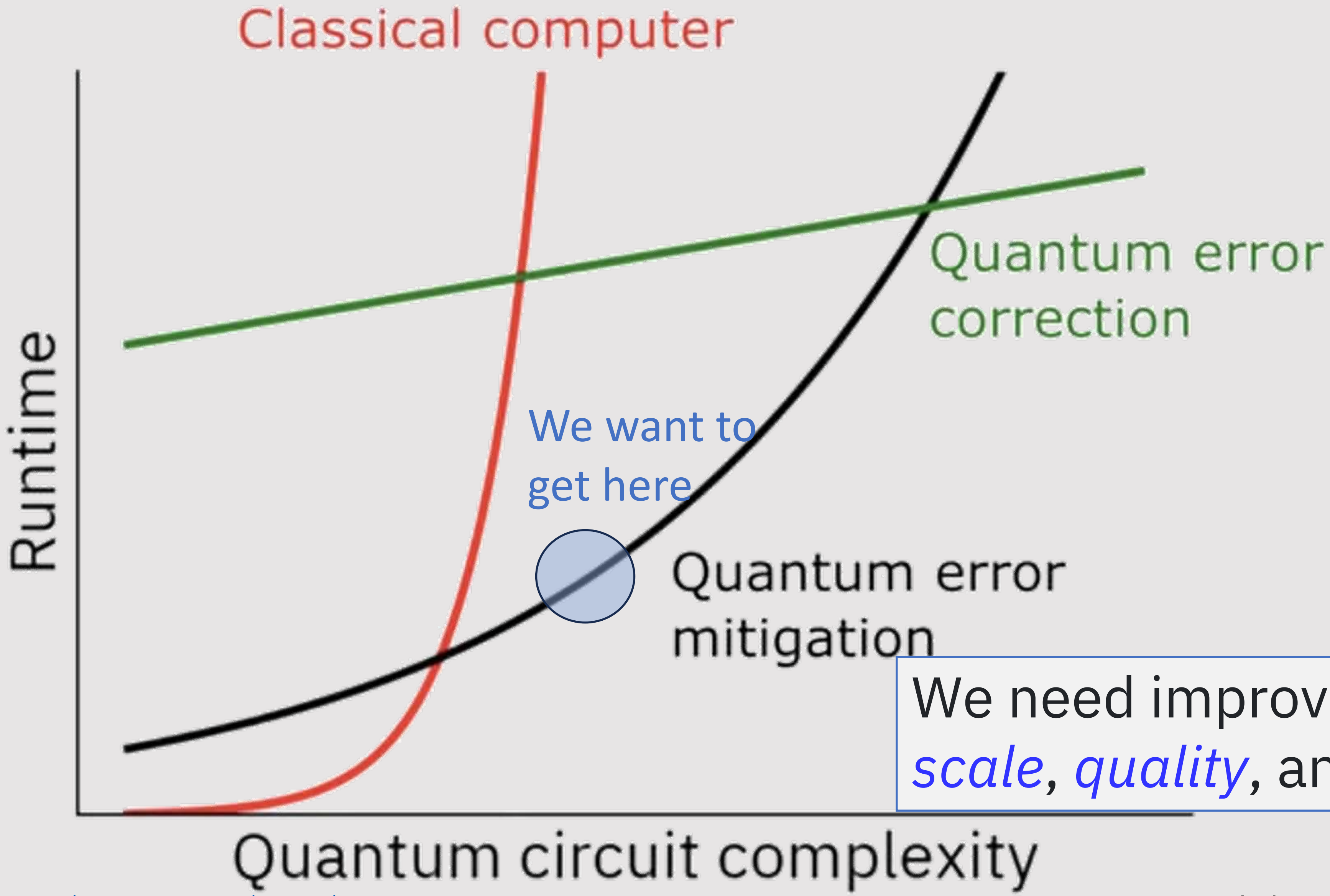
more speed

more information, accuracy





Path to utility of quantum computers before error correction

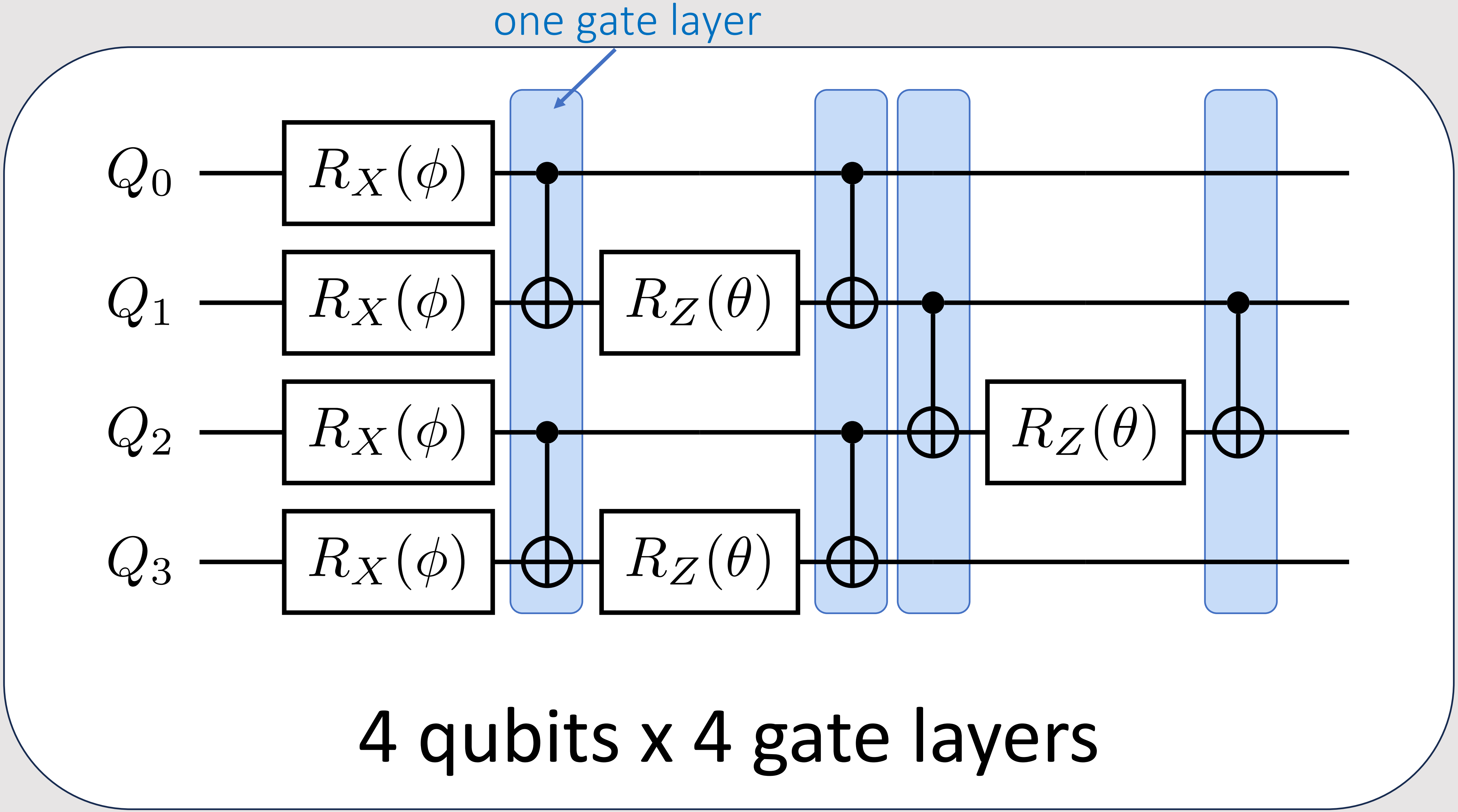


We need improvements in *scale*, *quality*, and *speed*.

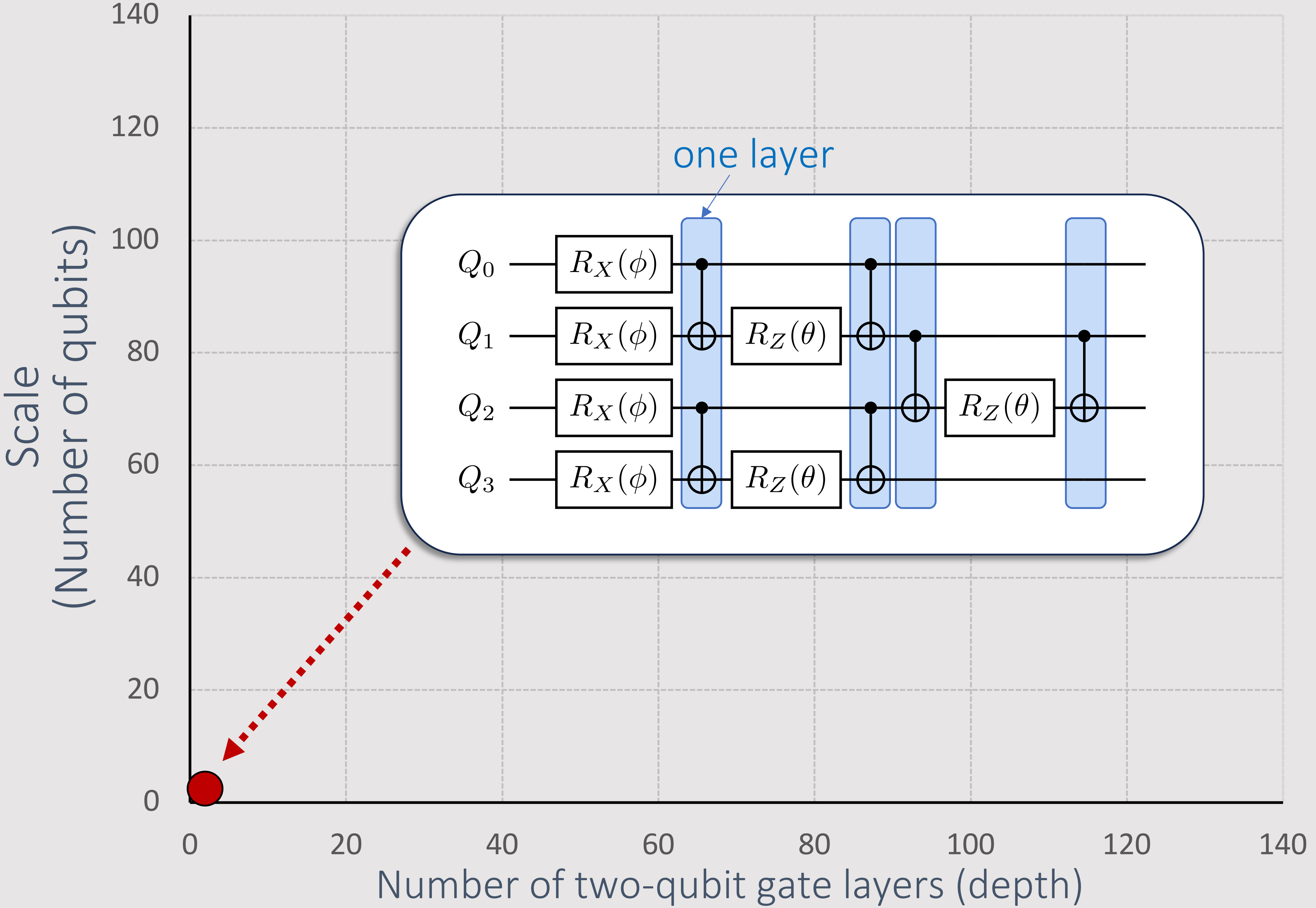
https://qiskit.org/documentation/partners/qiskit_ibm_runtime/tutorials/Error-Suppression-and-Error-Mitigation.html

Bring useful quantum computing

A prequel to the panel

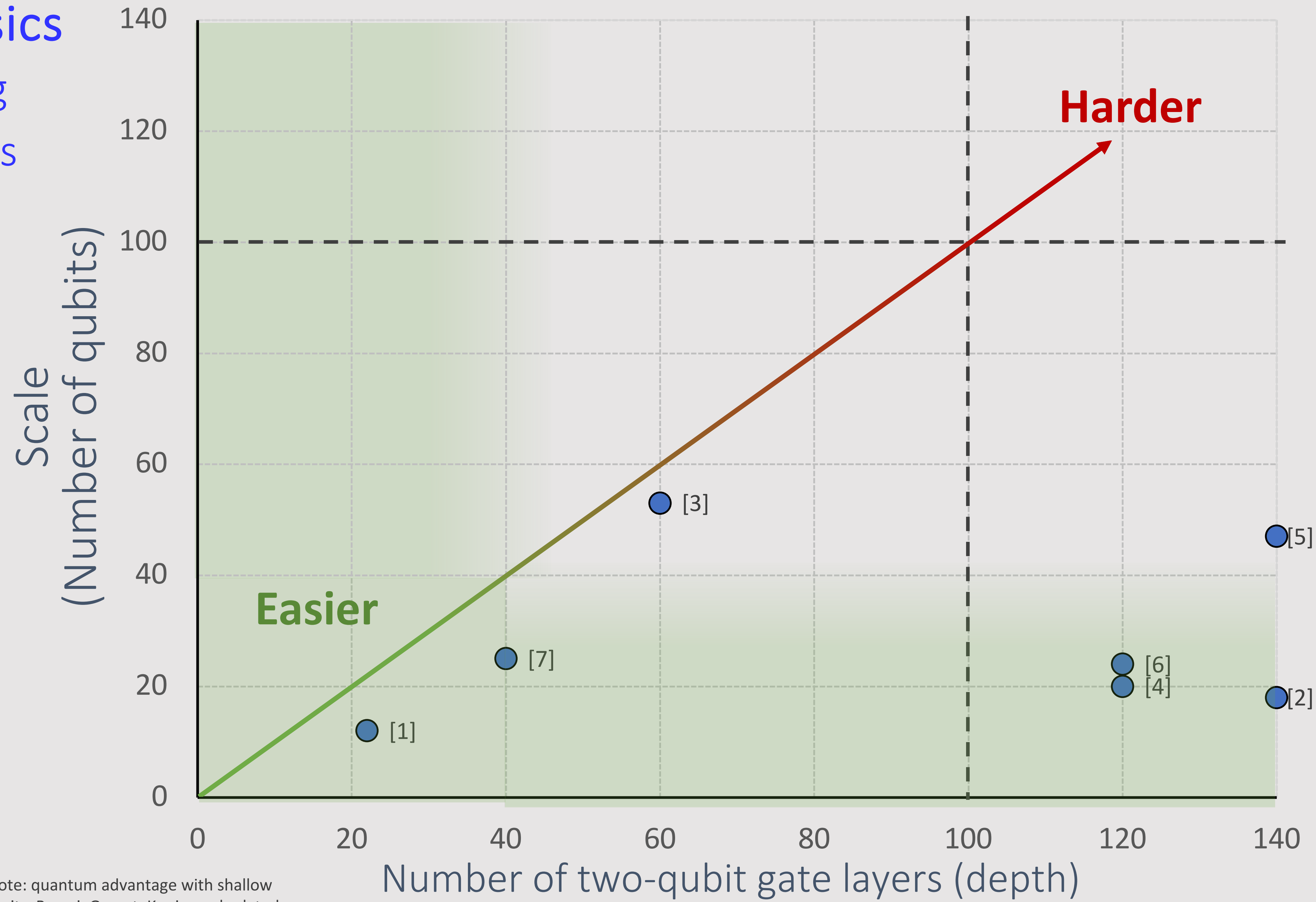

one gate layer
Q_0
Q_1
Q_2
Q_3
$R_X(\phi)$
$R_X(\phi)$
$R_X(\phi)$
$R_X(\phi)$
$R_Z(\theta)$
$R_Z(\theta)$
$R_Z(\theta)$
4 qubits x 4 gate layers

Circuit width × depth



Many-body physics
on superconducting quantum computers

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

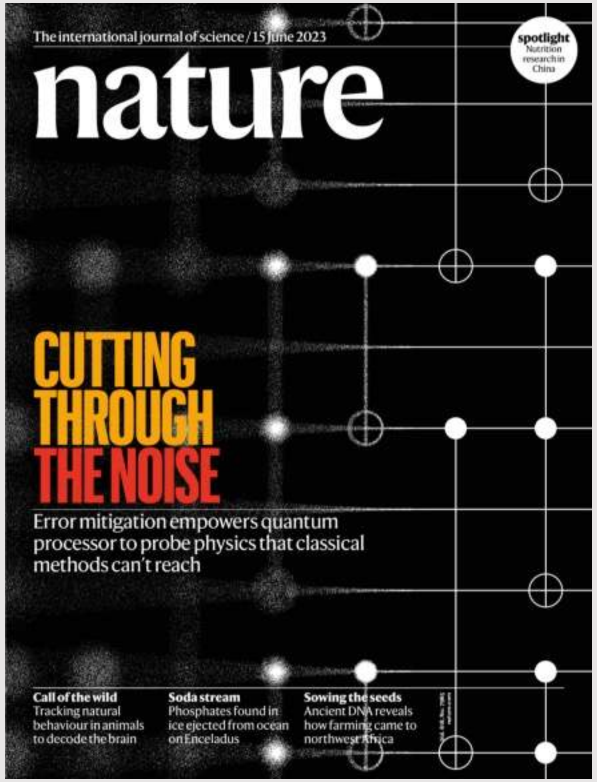


[1] Science 369, 1084 (2021)
[2] Nature 594, 508 (2021)
[3] Science 374, 1479 (2021)
[4] Nature 601, 531 (2022)
[5] Science 378, 785 (2022)
[6] Nature 612, 240 (2022)
[7] Nature 618, 264 (2023)
...

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

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

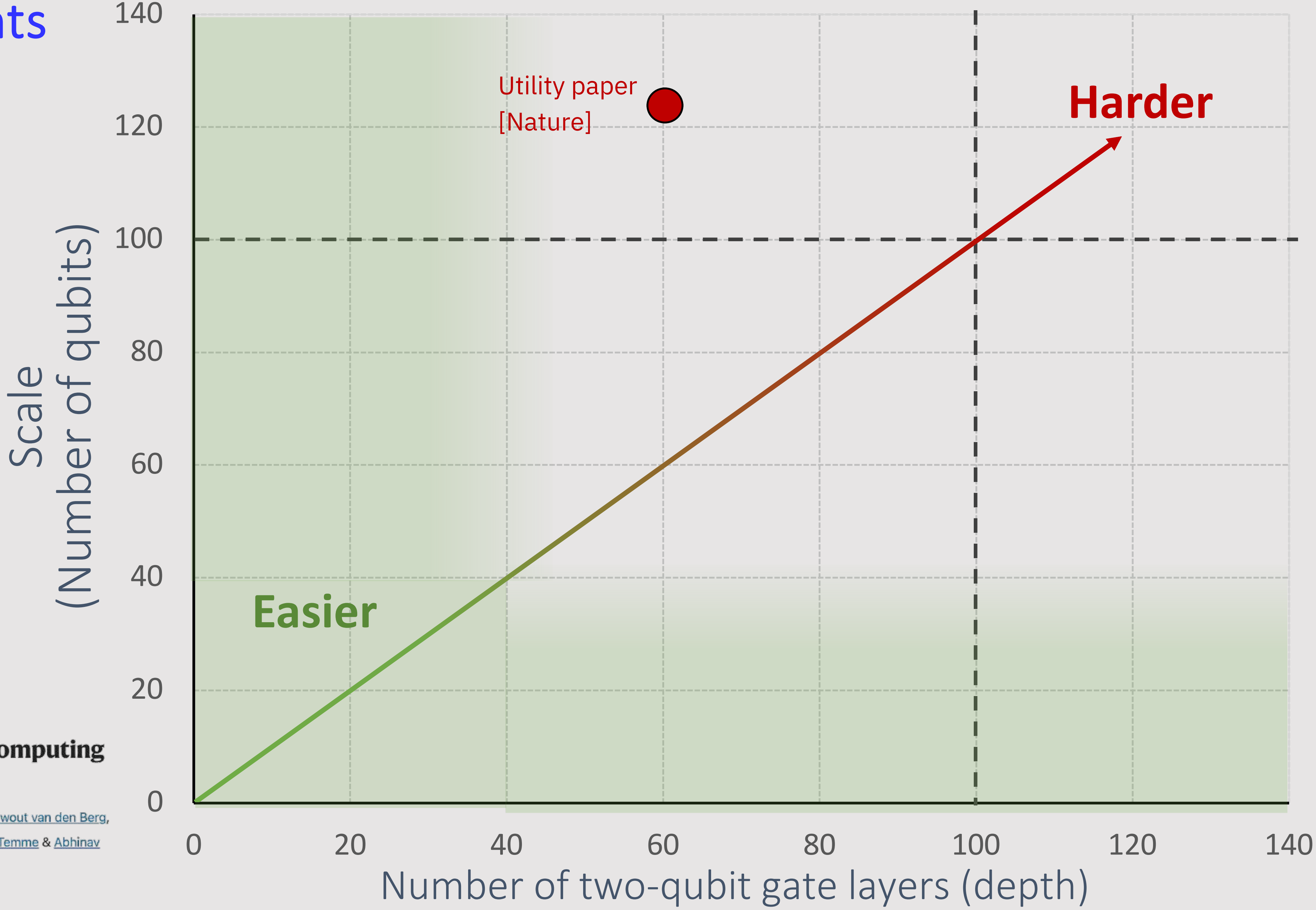
Some experiments in last 3 months



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)

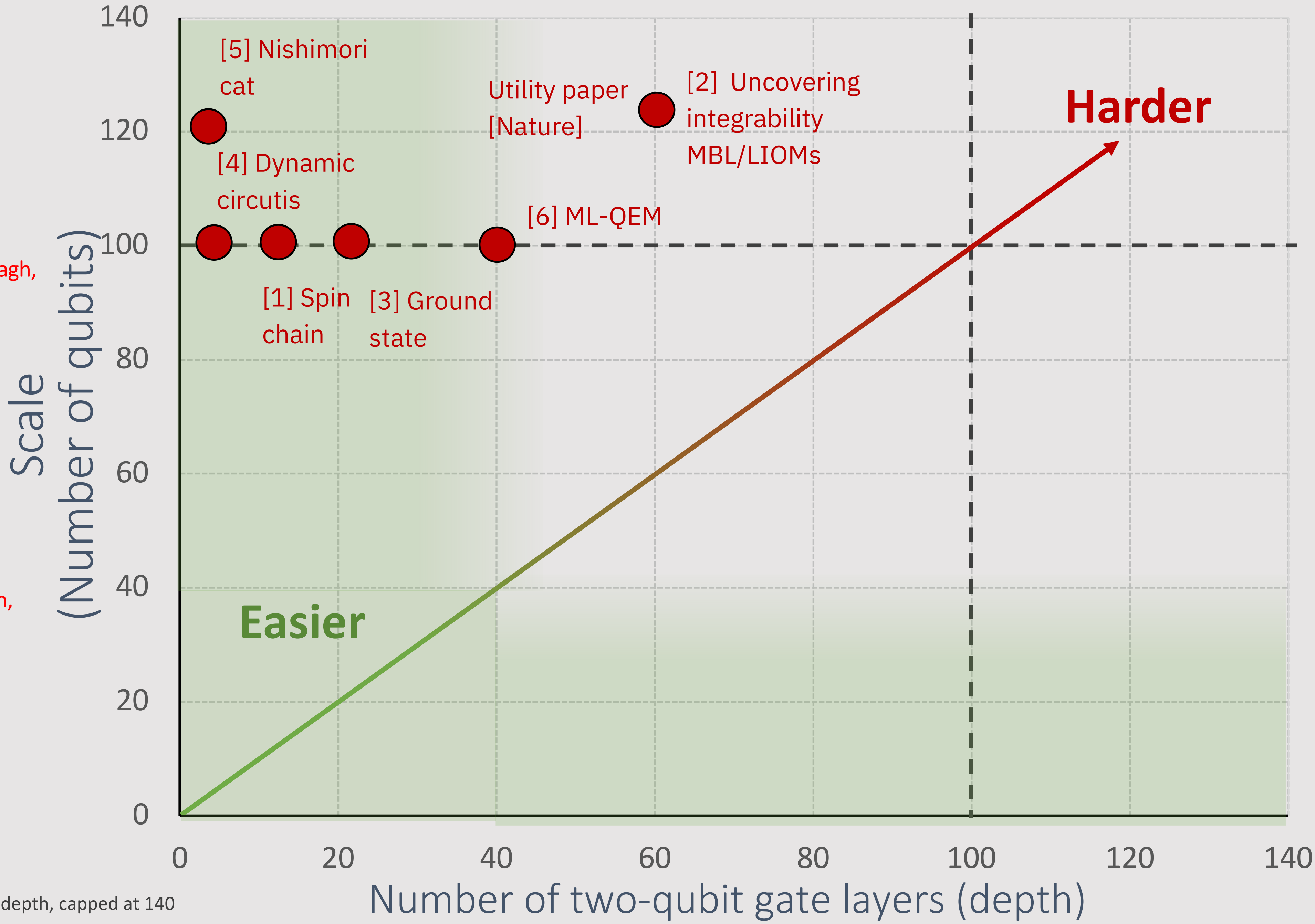
[3] Farrell, Illa, Ciavarella, Savage.
arXiv: 2308.04481 (2023)

[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, Sitdikov, Salcedo, Seif, Minev.
arXiv: 2308.13065 (2023)

...



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

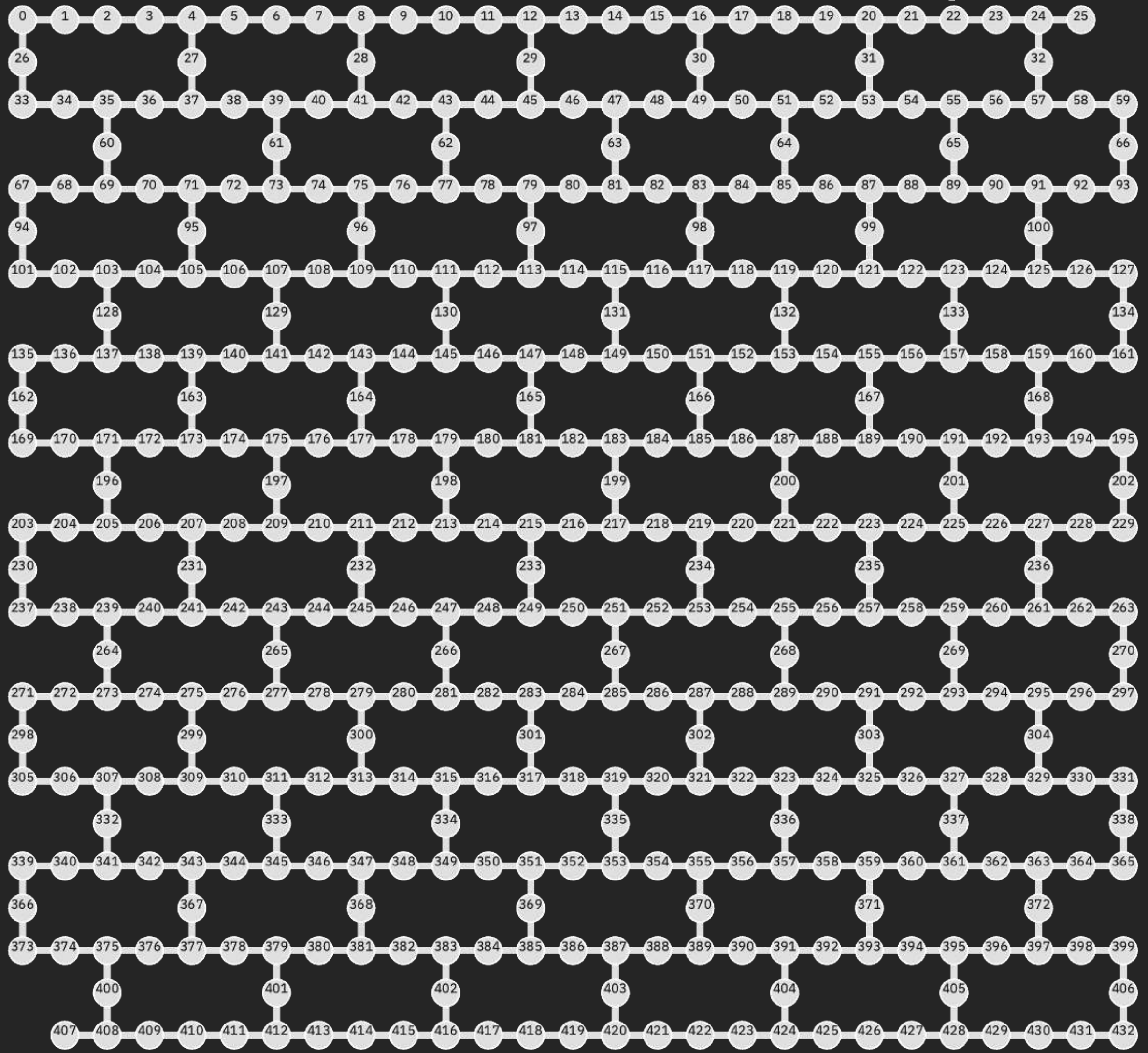
* note: quantum advantage with shallow circuits, Bravyi, Gosset, Konig, and related


IBM Quantum
Falcon
IBM Quantum
IBM Quantum
Eagle
IBM Quantum
Osprey
2019
Falcon
27 Qubits
2020
Hummingbird
65 Qubits
2021
Eagle
127 Qubits
2022
Osprey
433 Qubits


IBM Quantum
Osprey
Qubit
Readout
Wiring

Osprey – 433 Qubits

IBM **Quantum**



Osprey connectivity map

IBM **Quantum**

Performance =

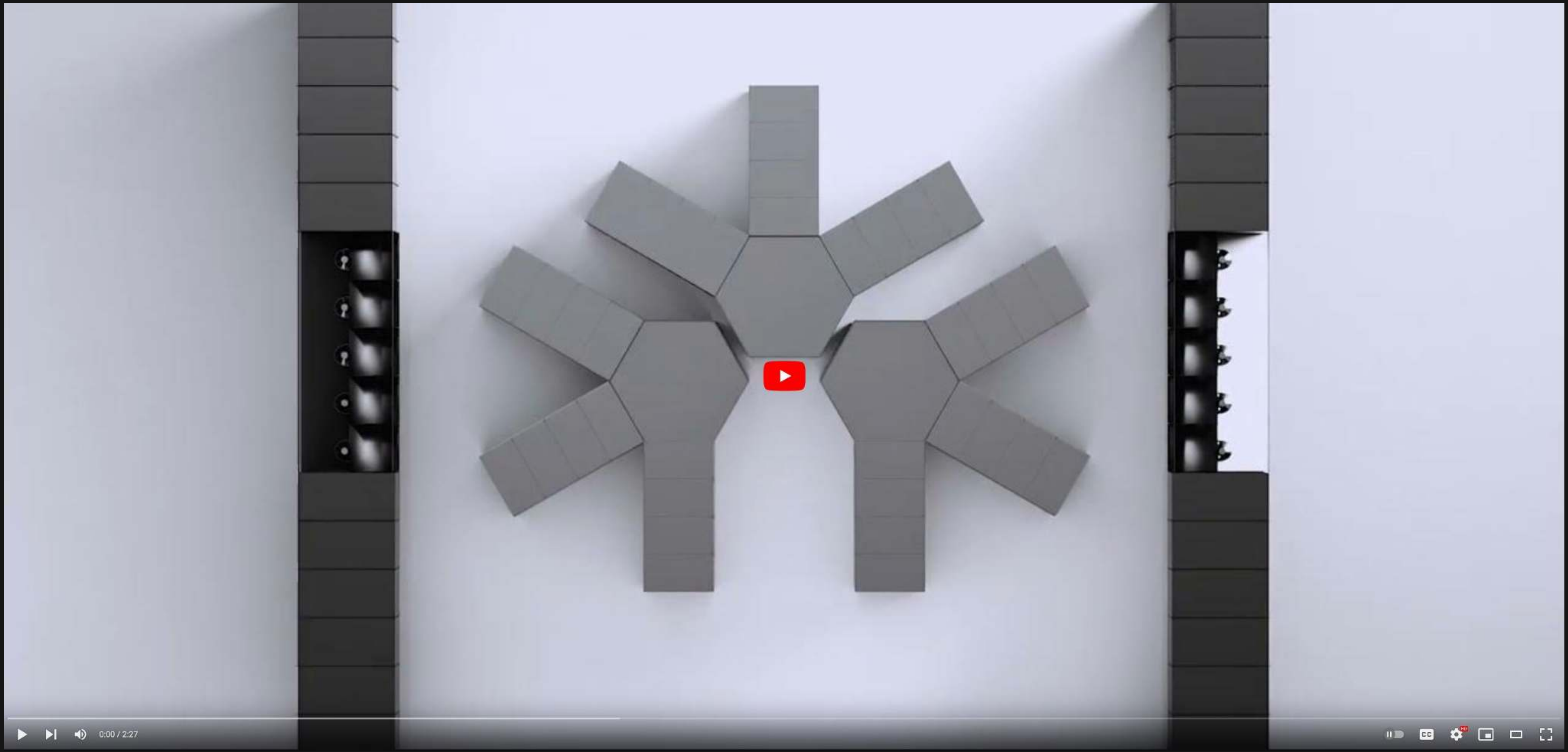
Scale — Number of qubits

\+ Quality — Circuit fidelity

\+ Speed — Circuit execution speed

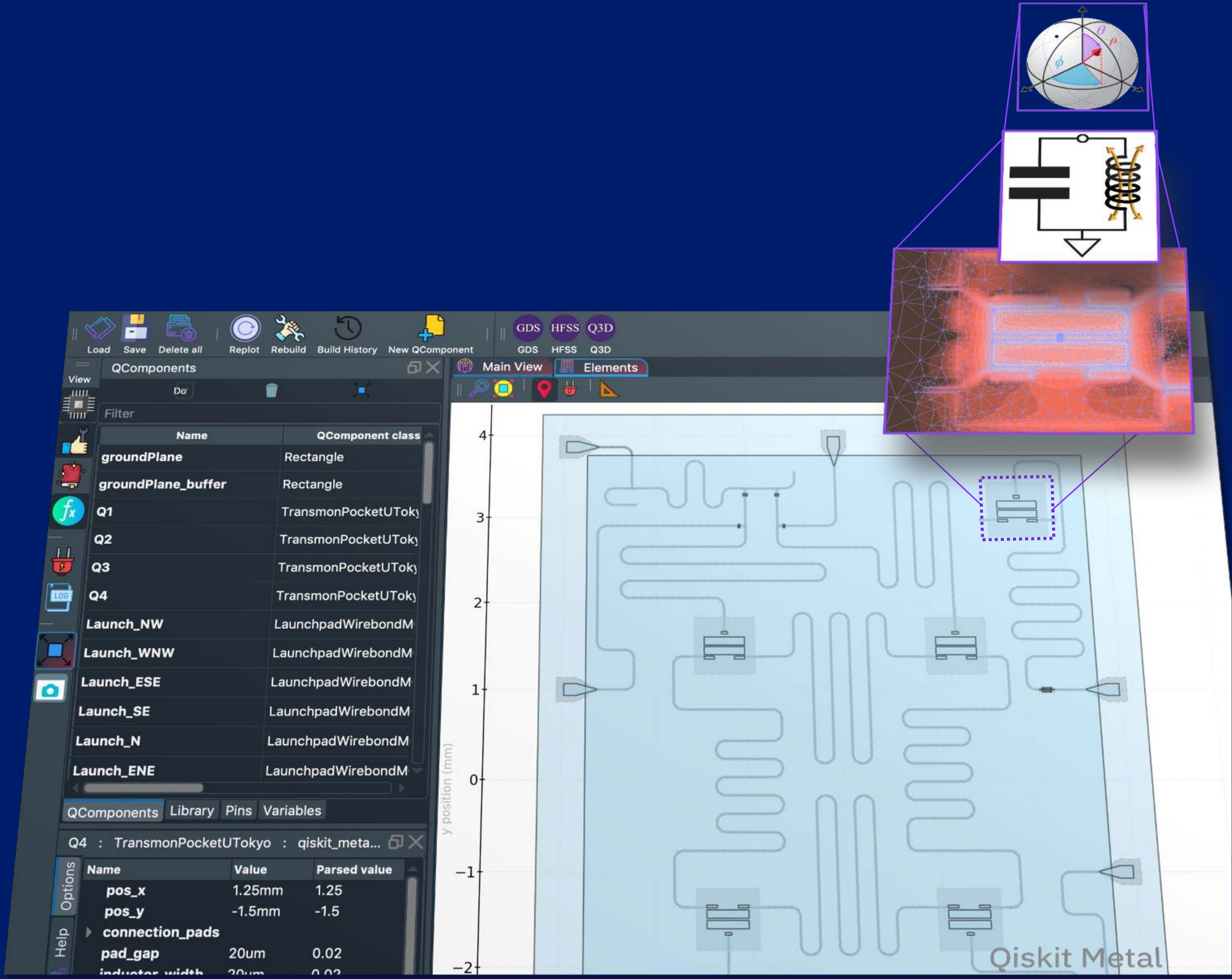
100K-qubit Quantum-Centric Supercomputer

IBM **Quantum**



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

Qiskit Metal

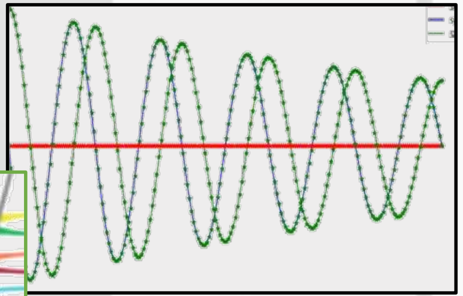


IBM **Quantum**

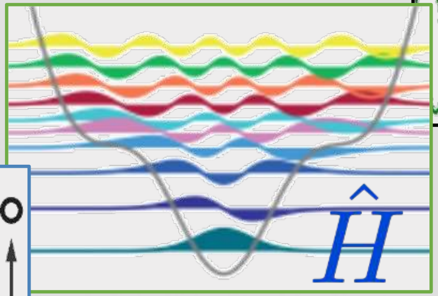
Qiskit | quantum device design

Technology stack

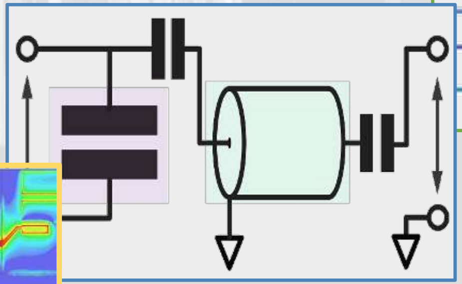
Gates & time-evolution analysis



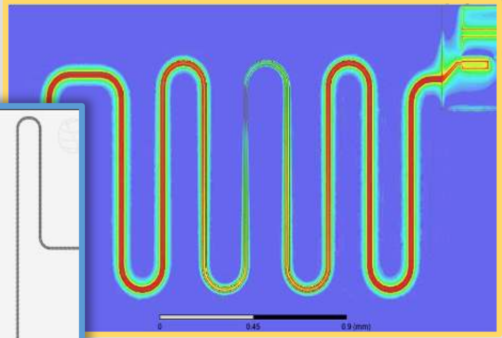
Quantum Hamiltonian



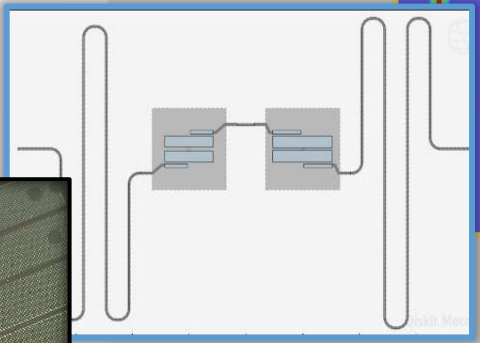
Quantization Methods



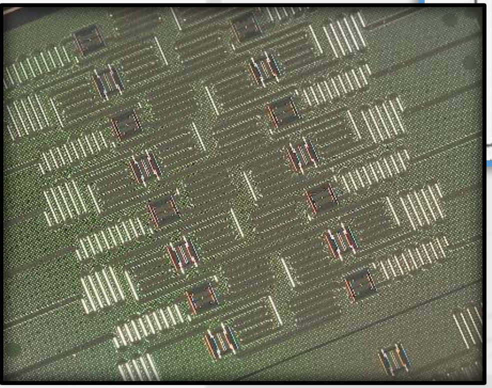
E&M Simulation

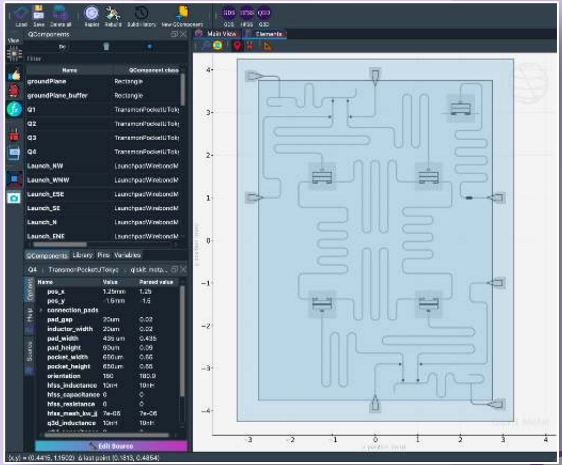


Layout



Fabrication



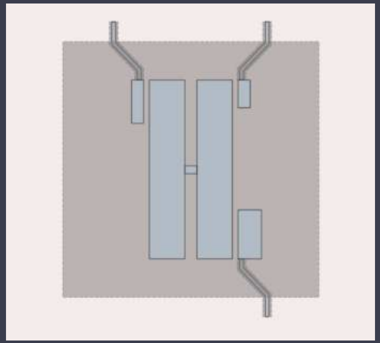


IBM Quantum

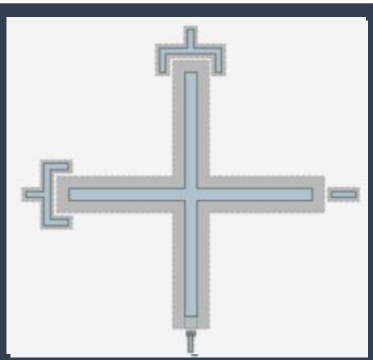
Qiskit | quantum device design

Device Library

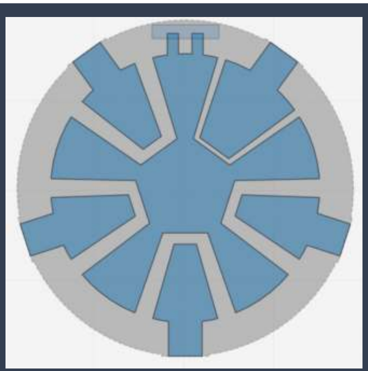
Qubits



Single transmon-floating

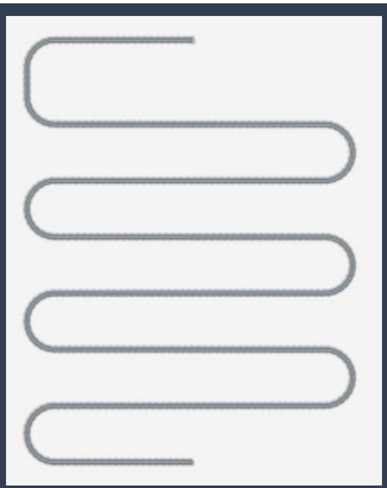


Single transmon-grounded flux lines



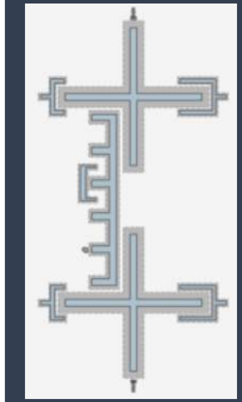
Star-shaped qubit

Resonators

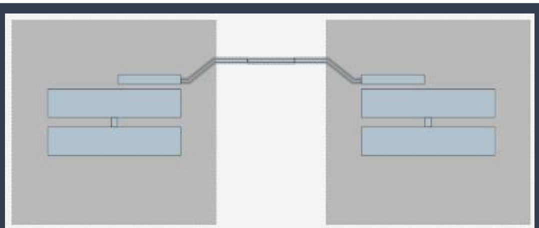


Simple coplanar waveguide (CPW) meander

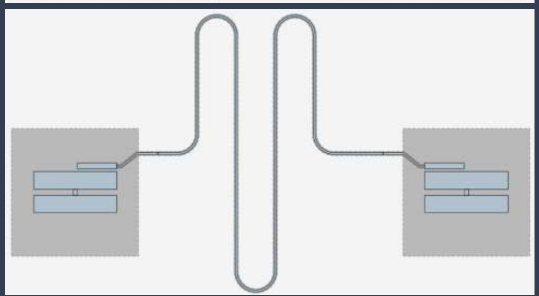
Qubit Couplers



Tunable coupler (MIT)

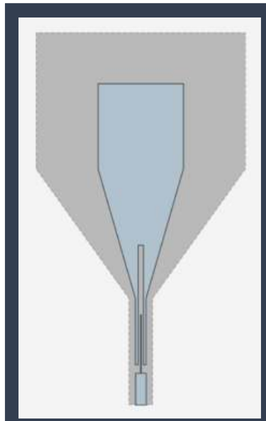


Direct coupler

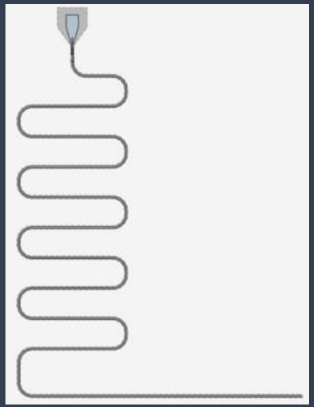


Bus resonator coupler

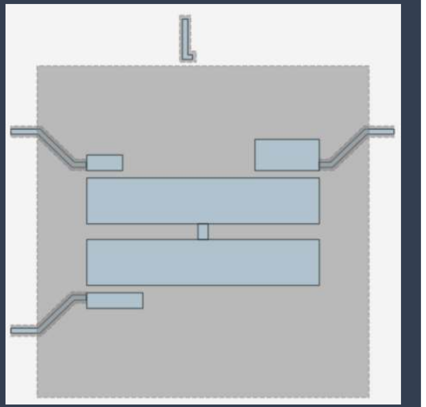
Input – Output Coupling



CPW launch pad



Readout line



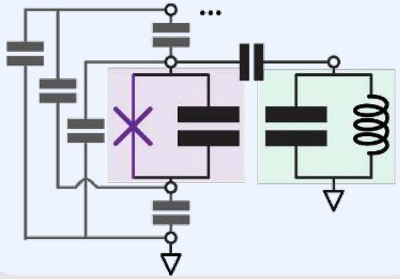
Charge line

Landscape of **quantization** methods

quasi-static

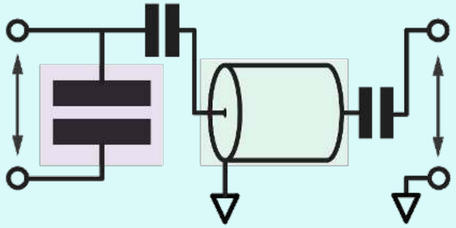
full-wave

lumped



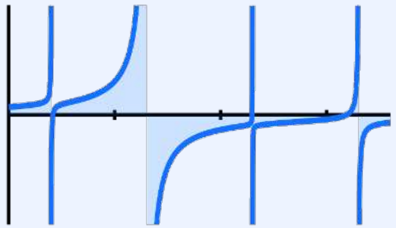
Yurke & Denker (1984), Devoret (1997), Burkard *et al.* (2004), Koch *et al.*…

quasi-lumped



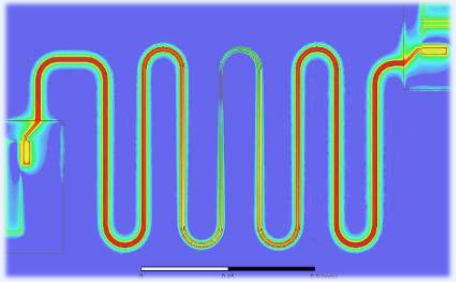
Malekakhlagh *et al.* (2017, 2019), Gely *et al.* (2019), Parra-Rodriguez *et al.* (2019), Minev *et al.* (2021), …

impedance



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

energy



Minev (2018)
Minev *et al.* (2020)

more speed

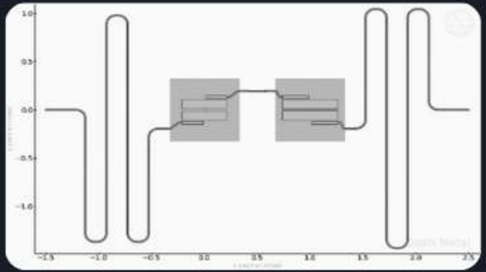
more information, accuracy

Zlatko Minev
IBM **Quantum**

Qiskit Metal lumped model framework

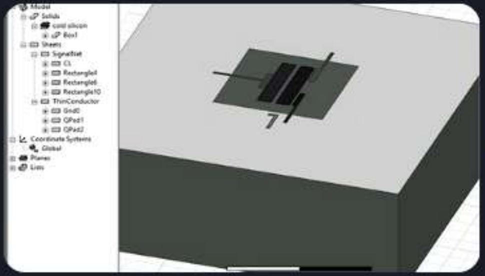
Qiskit | quantum device design

From layout to gates simulation in one notebook



Layout

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



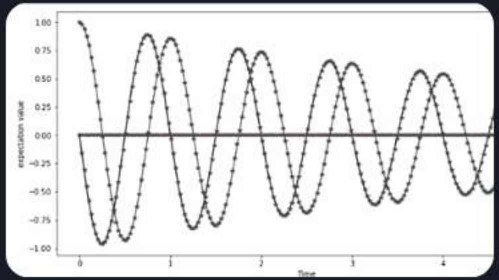
Electromagnetic simulation

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

https://qiskit.org/documentation/metal/tut/index.html

Tutorials: Quantum analysis library

Resonators
Composite Bi-Partite Systems
Qubit Couplers
Input-Ouput Coupling
Small Quantum Chips
Design Flow

Libraries

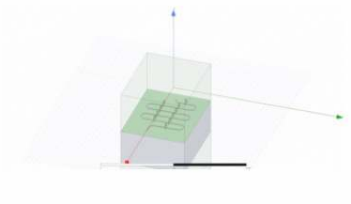
All Quantum Devices

API References

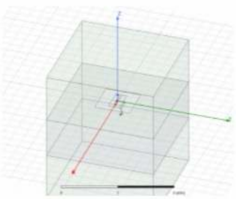
Overview
QDesigns
QComponents
Analyses
QRenderes
Toolbox
QGeometry
GUI

Code of Conduct

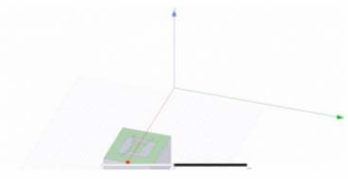
Qiskit



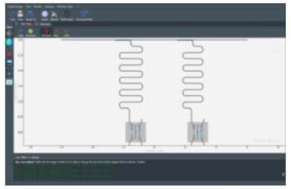
Eigenmode and EPR



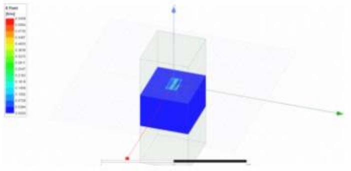
Impedance Analysis



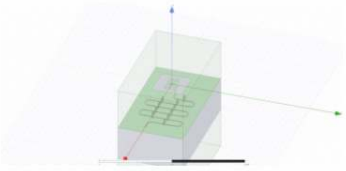
Capacitance Matrix and LOM Analysis



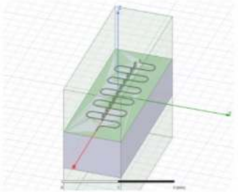
Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.



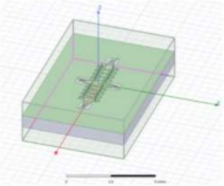
Analyizing and Tuning a Transmon Qubit



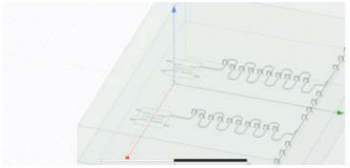
Analyzing a transmon and a resonator



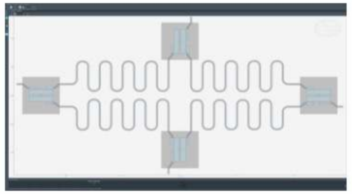
Analyzing a resonator



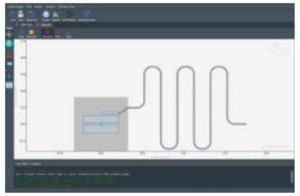
How to Render a Metal Design into Ansys



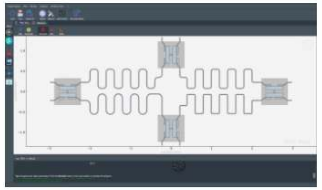
Driven Modal Simulation and S-Parameters



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

https://qiskit.org/documentation/metal/tut/index.html

Resonators
Composite Bi-Partite Systems
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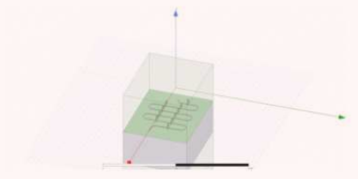
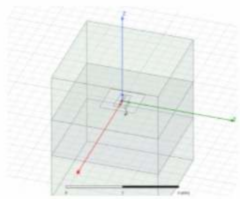
Overview

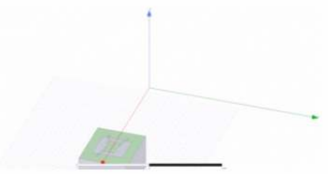
Tutorials: Quantum analysis library



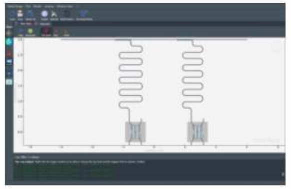
Eigenmode and EPR



Impedance Analysis



Capacitance Matrix and LOM Analysis



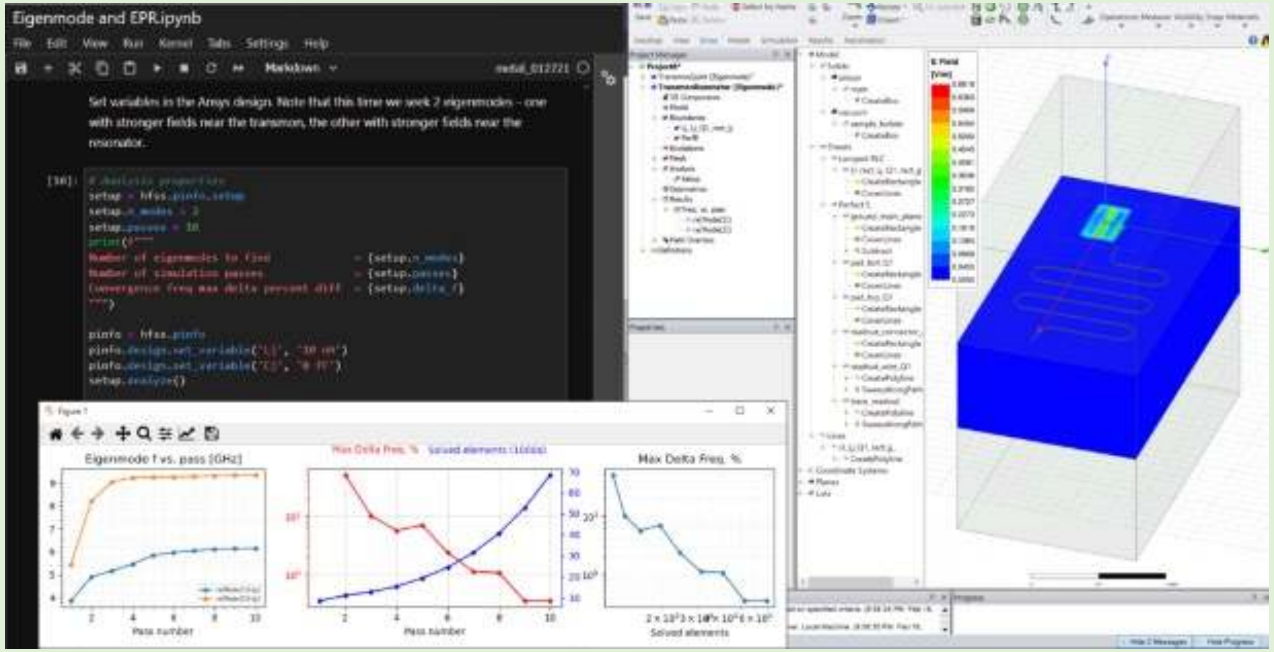
Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.

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

https://qiskit.org/documentation/metal/tut/index.html

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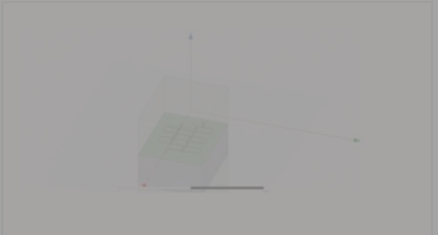
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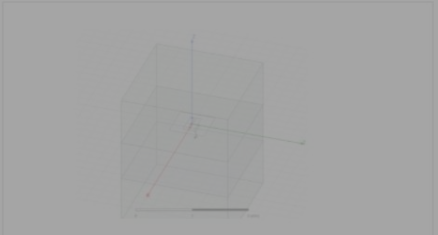
Impedance Analysis


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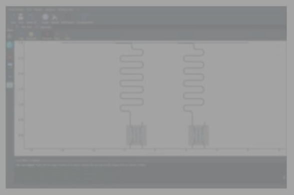
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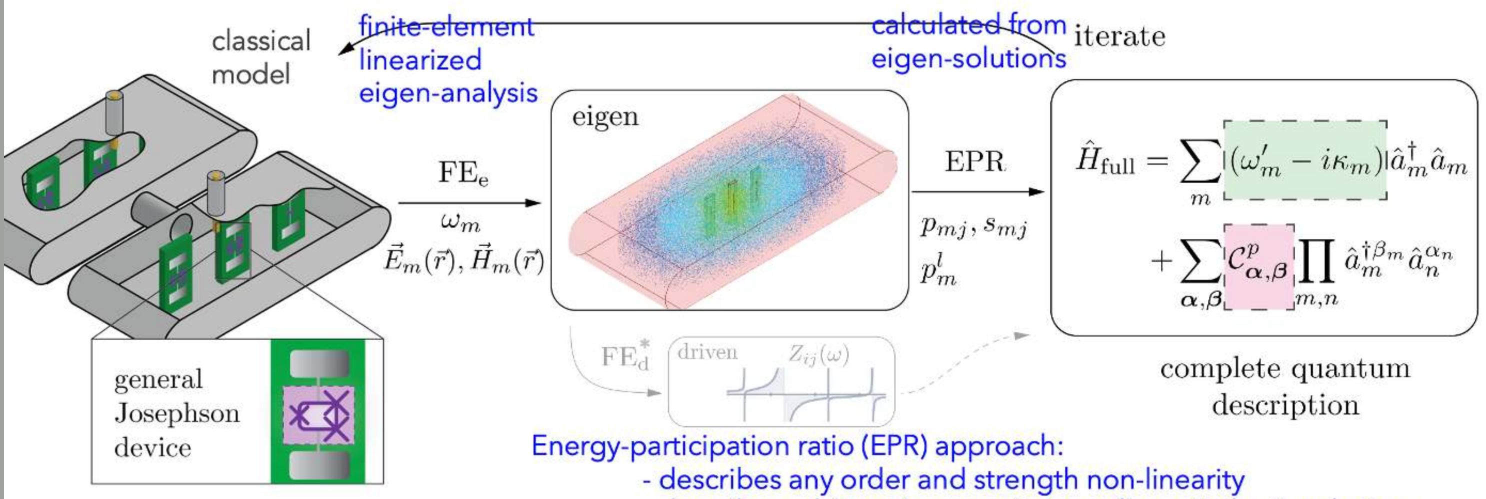
Overview of energy-participation approach

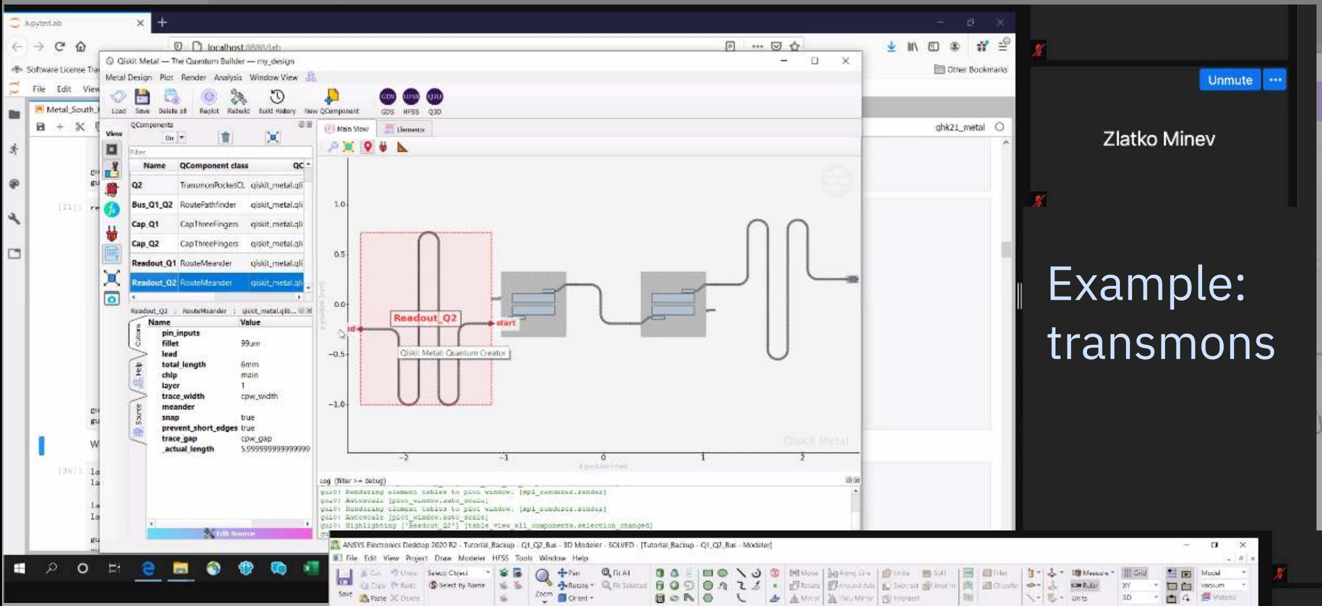


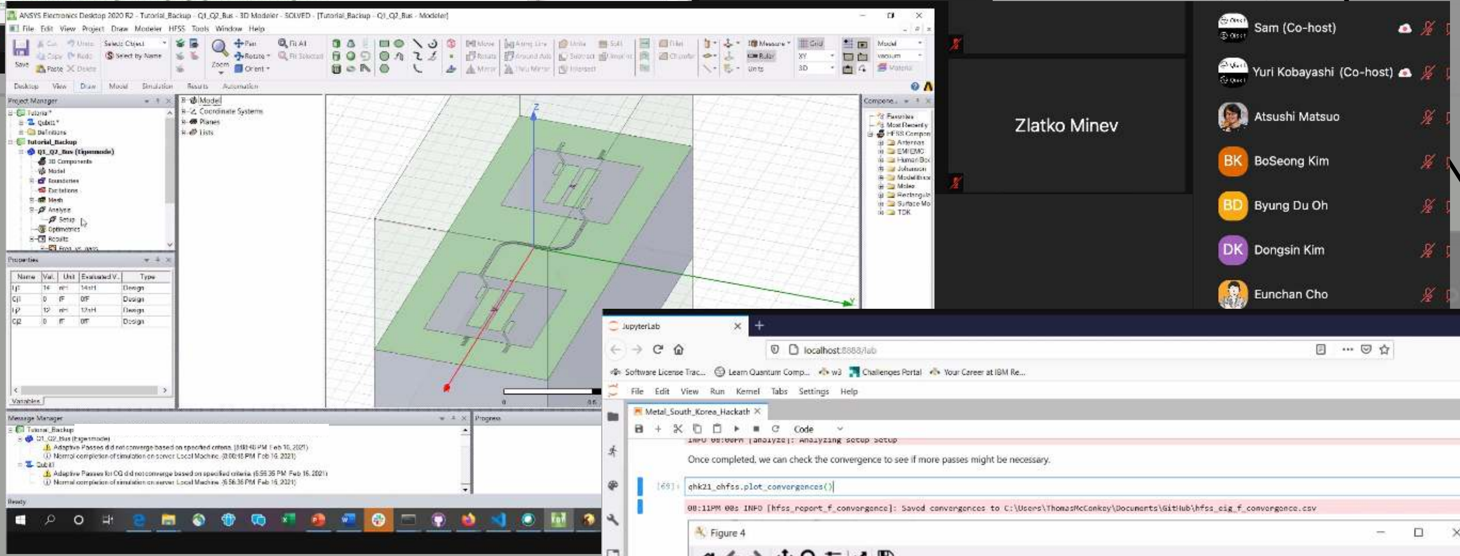
Energy-participation ratio (EPR) approach:
- describes any order and strength non-linearity
- describes arbitrary (composite) non-linear inductive devices
- first-principle derivation
- zero approximations (aside from truncation of modes)
- fully automated in python (github.com/zlatko-minev)

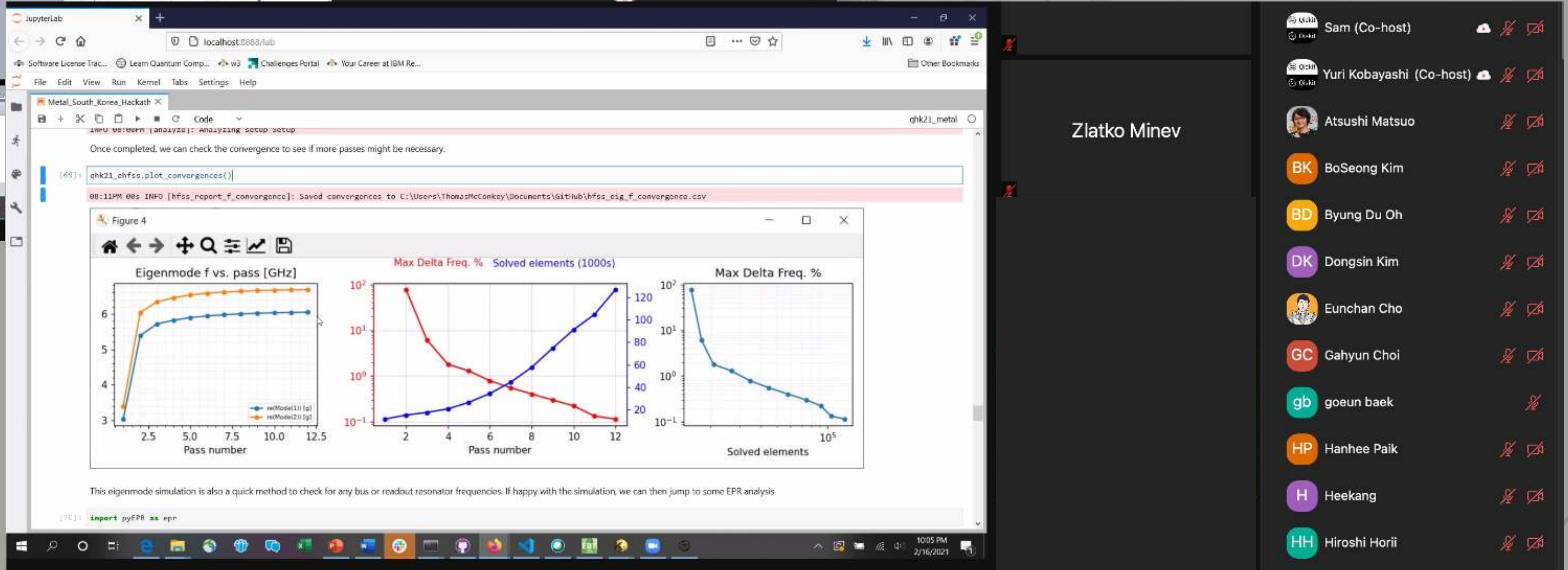
Practical limits: Fock and mode basis truncation due to computing power

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

Minev arXiv: 1902.10355
Minev arXiv: 2010.00620

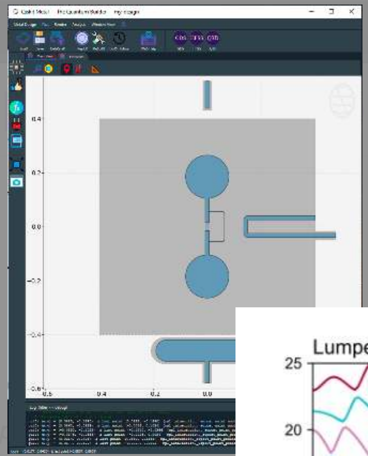


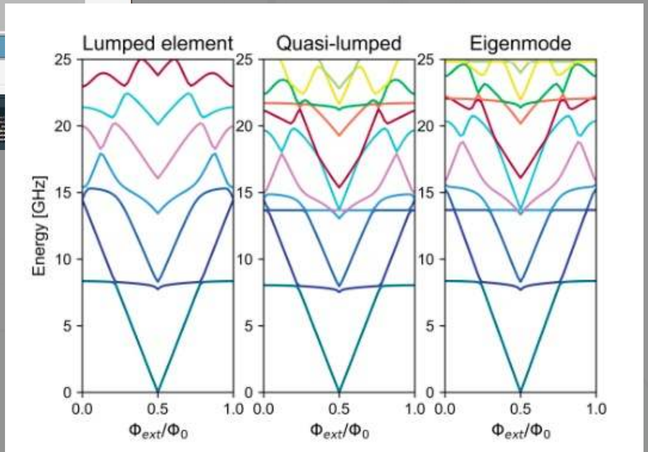




Example:
transmons

Example:
fluxonium
(Delft)





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Analyses
QRenderes
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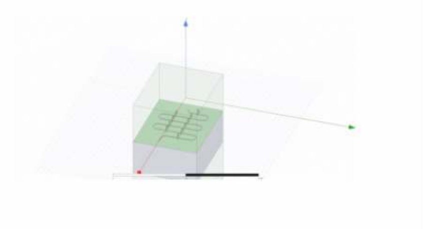
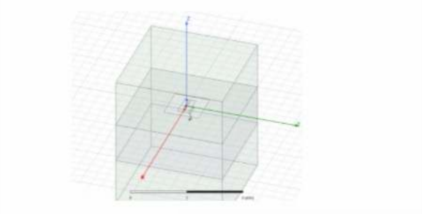
QGeometry
GUI

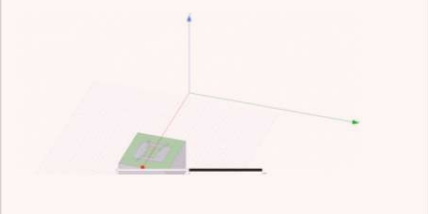
Code of Conduc



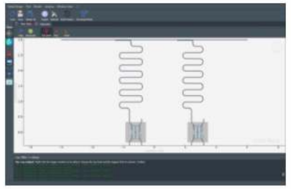
Eigenmode and EPR



Impedance Analysis



Capacitance Matrix and LOM Analysis



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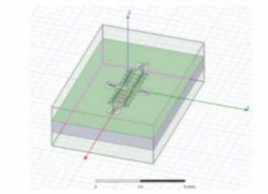
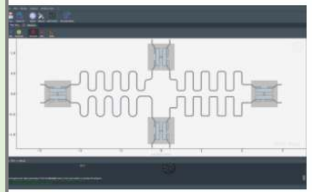


ow to Render a Metal Design to Ansys



ow to Render a Metal Design to GDS

Quasi-static

Cornell University

arXiv.org > quant-ph > arXiv:2103.10344

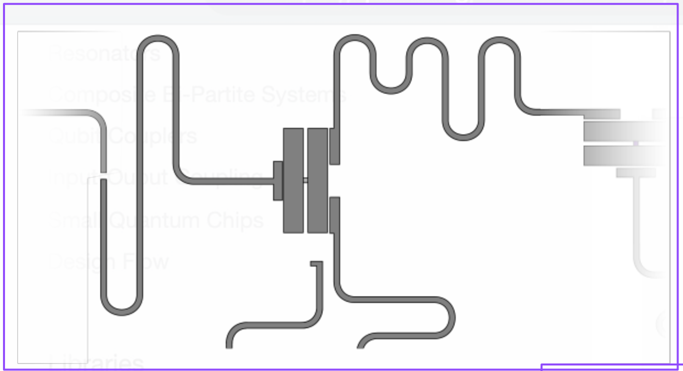
Quantum Physics

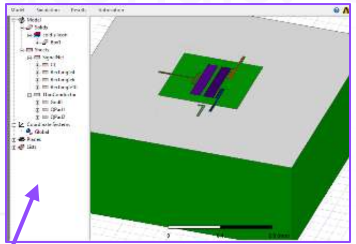
Circuit quantum electrodynamics (cQED) with modular quasi-lumped models

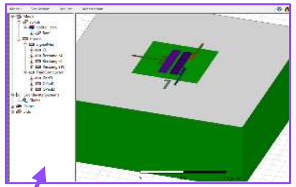
Zlatko K. Minev,* Thomas G. McConkey, Maika Takita, Antonio Corcoles, and Jay M. Gambetta
IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, US

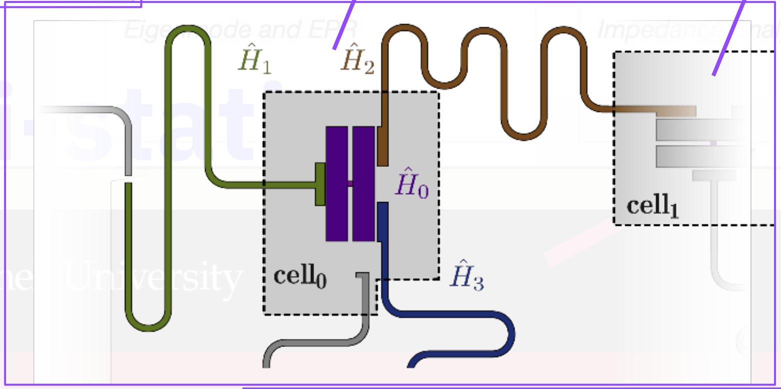
General capacitive analysis code
map to known building blocks: e.g.,
transmon, fluxonium, zero-pi, etc.

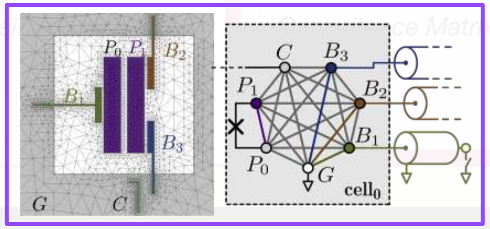
Simple example

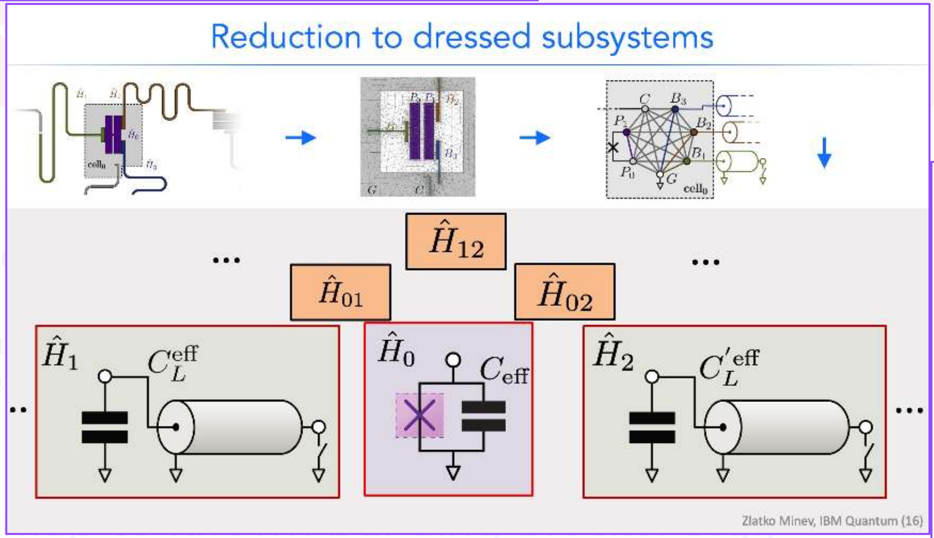


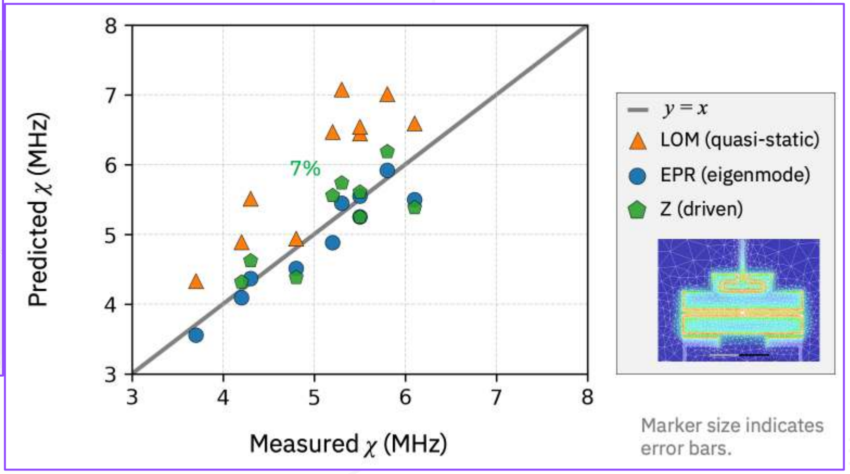












load transmon cell Q3d simulation results ¶

```
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_Q1': 'coupling', 'readout_connector_pad_Q1': 'readout_alice'},
    cap_mat = ta_mat,
    ind_dict = {('pad_top_Q1', 'pad_bot_Q1'):10},
    jj_dict = {('pad_top_Q1', 'pad_bot_Q1'):'j1'},
    cj_dict = {('pad_top_Q1', 'pad_bot_Q1'):2}, #
)
cell_1 = Cell(opt1)


# cell 2: transmon Bob cell
opt2 = dict(
    node_rename = {'coupler_connector_pad_Q2': 'co
    cap_mat = tb_mat,
    ind_dict = {('pad_top_Q2', 'pad_bot_Q2'): 12},
    jj_dict = {('pad_top_Q2', 'pad_bot_Q2'):'j2'},
    cj_dict = {('pad_top_Q2', 'pad_bot_Q2'):2}, #
)
cell_2 = Cell(opt2)
```

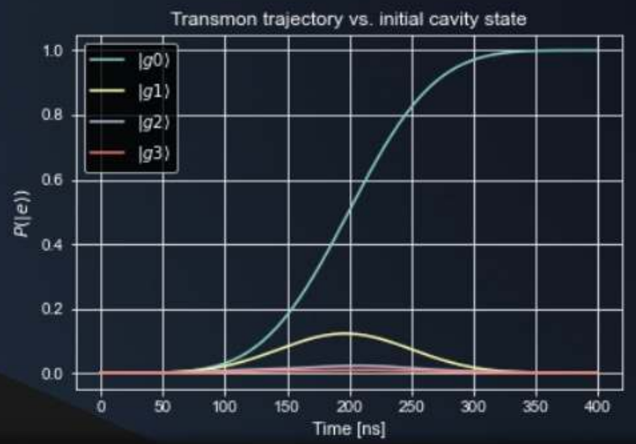
Make subsystems

```
# 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)
```

Creat 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],
    grd_node='ground_main_plane',
    nodes_force_keep=['readout_alice', 'readout_bob']
)
```

	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	-19.21994
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



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

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
        )
```

```
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)
```

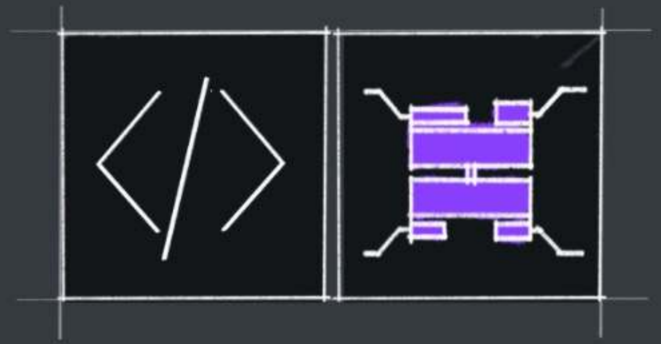
Apply a selective pi pulse that is resonant with the qubit when the cavity is in |0>.

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

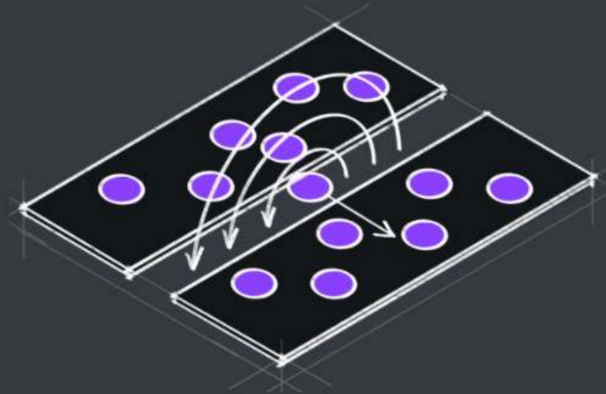
Qiskit Metal: Key features and content

End-to-end automation

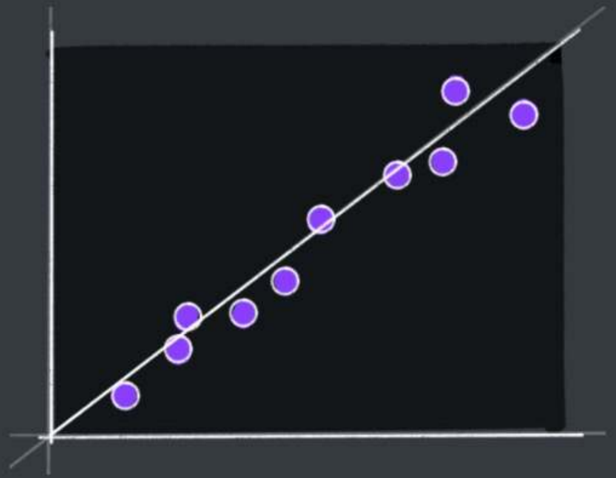
Flexible & extensible



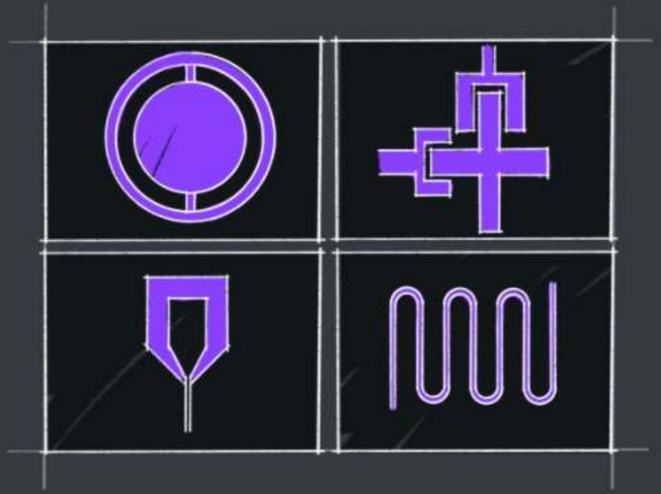
Light-weight interoperability



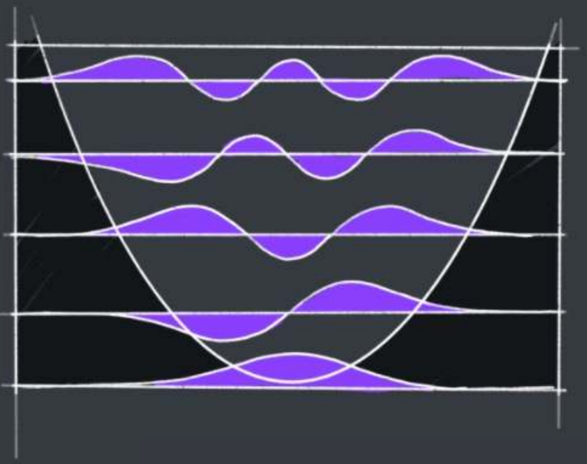
Experimentally tested



Library of components



Cutting edge resources



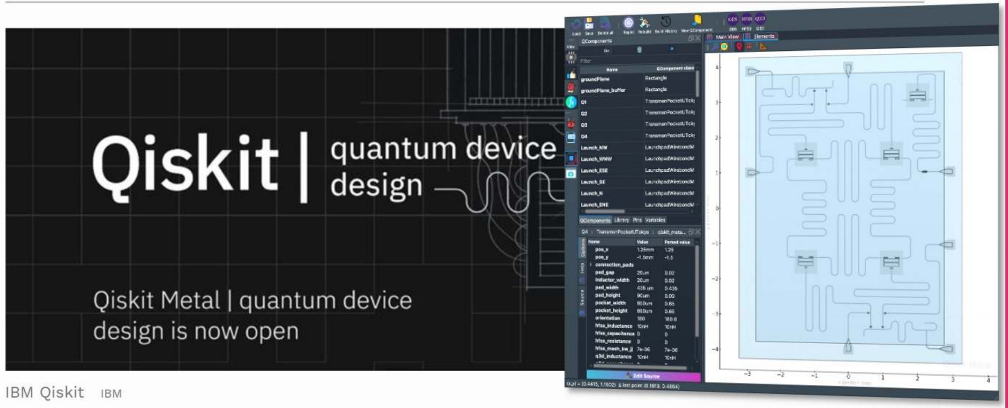
The buzz…

Qiskit Metal

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



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

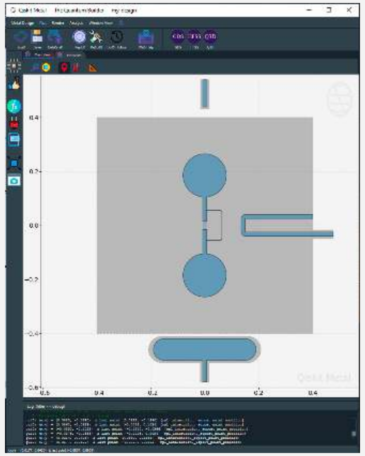
Qiskit | quantum device design

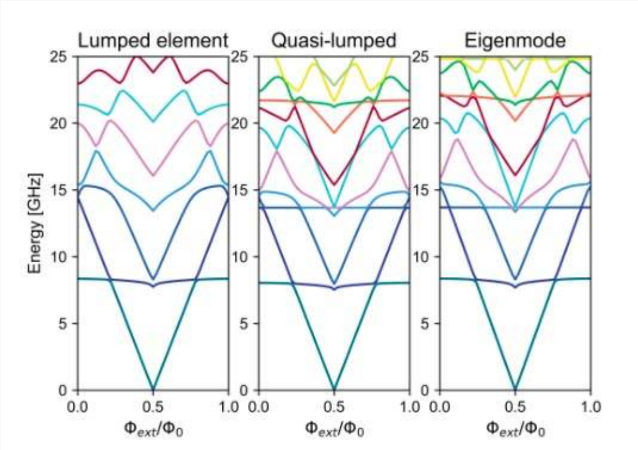
Use case example

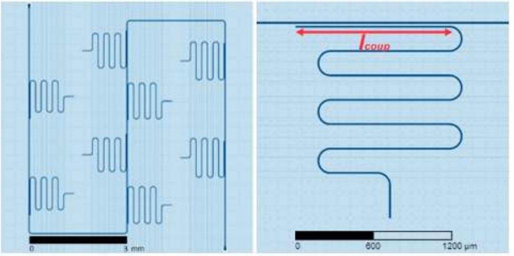
Qiskit Metal

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 x 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.

(a) Final design (b) Single resonator geometry

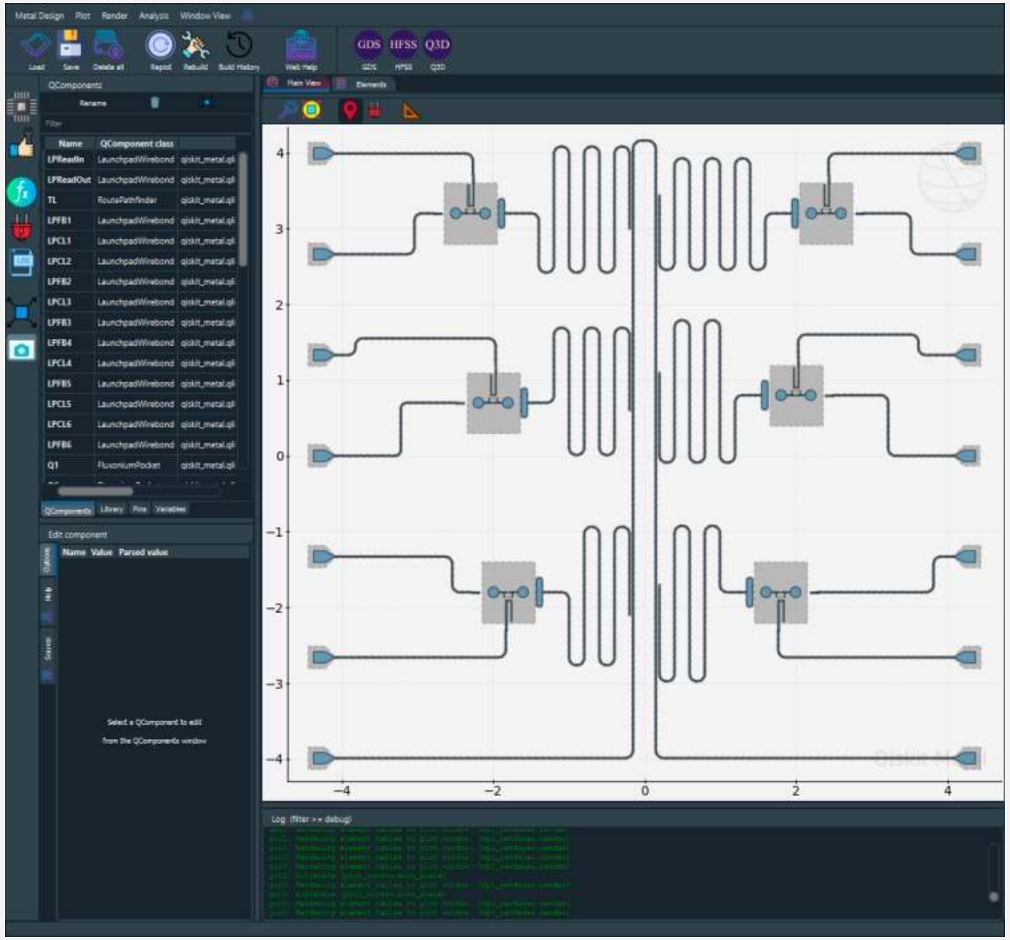
Figure 6: Schematic representations of the final design and single resonator geometry. Each resonator is capacitively coupled to the feedline. The resonator coupling length is denoted by l_{coup}.

"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

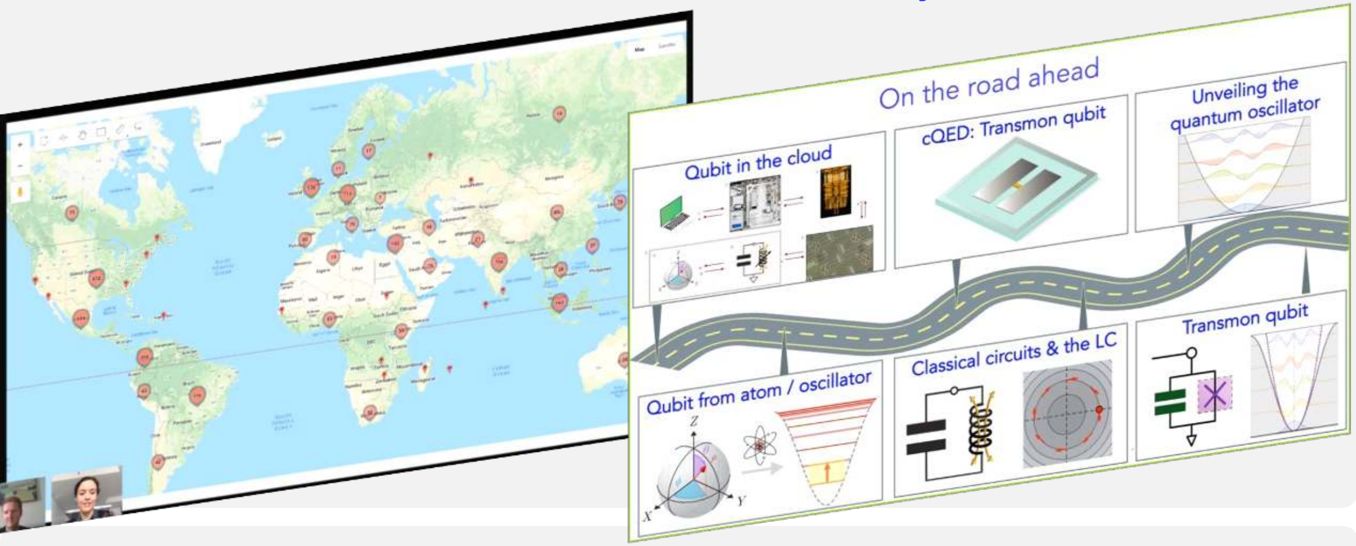


Zlatko Minev, IBM **Quantum**

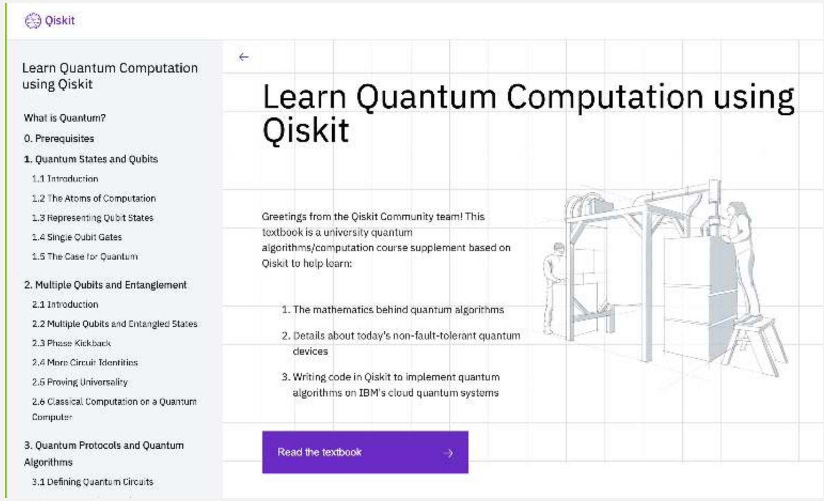
Ways to learn more

Qiskit Global Summer School

Qiskit YouTube (Lec. 16-21 by Z. Minev)

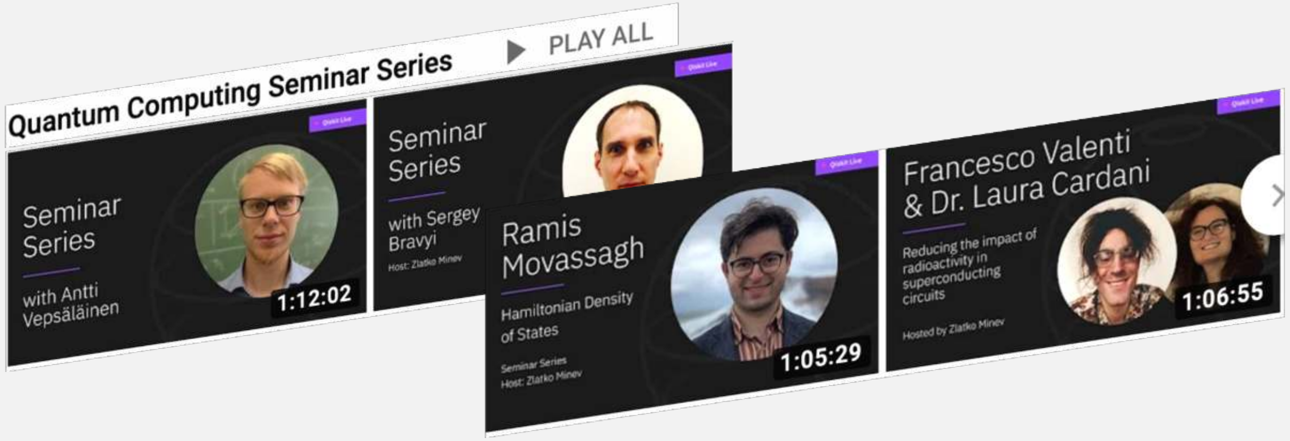


qiskit.org/textbook



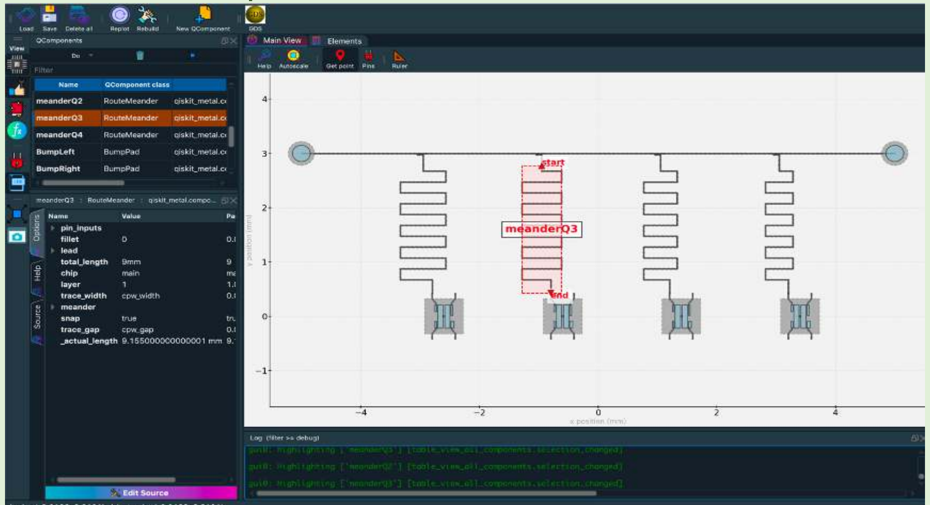
Quantum Information Seminar Series

(Qiskit YouTube Host: Z. Minev)



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

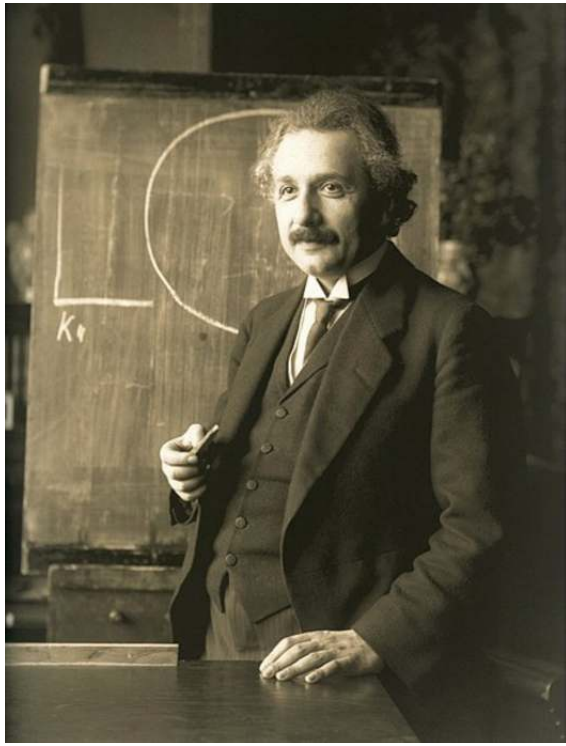


Photo: F. Schmutzer

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, ...

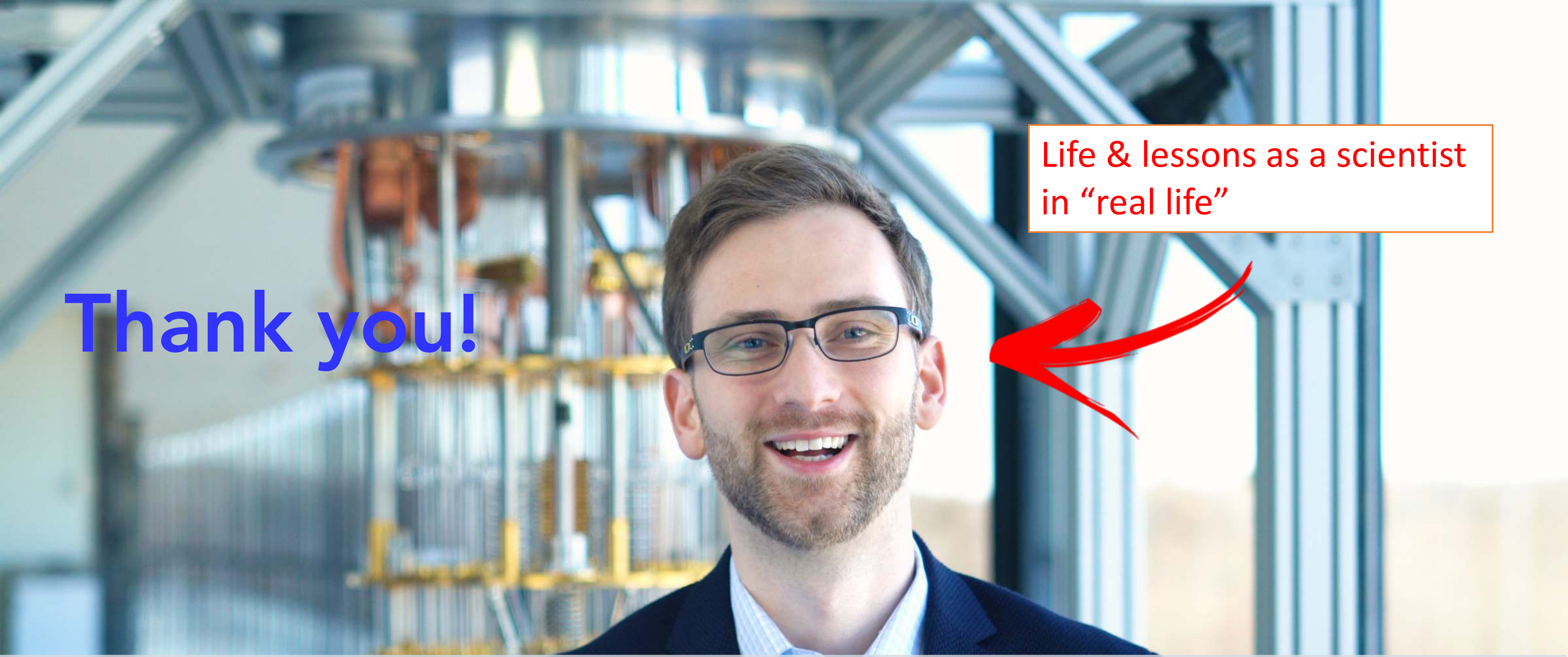
6. **How to overcome noise in real quantum processors?**

   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. Haffezi, 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”

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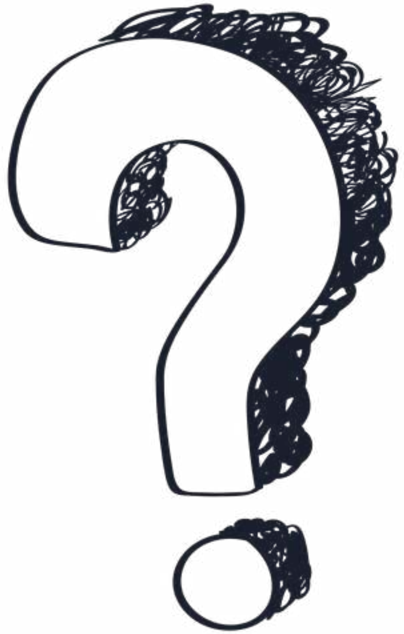
Merriam-Webster

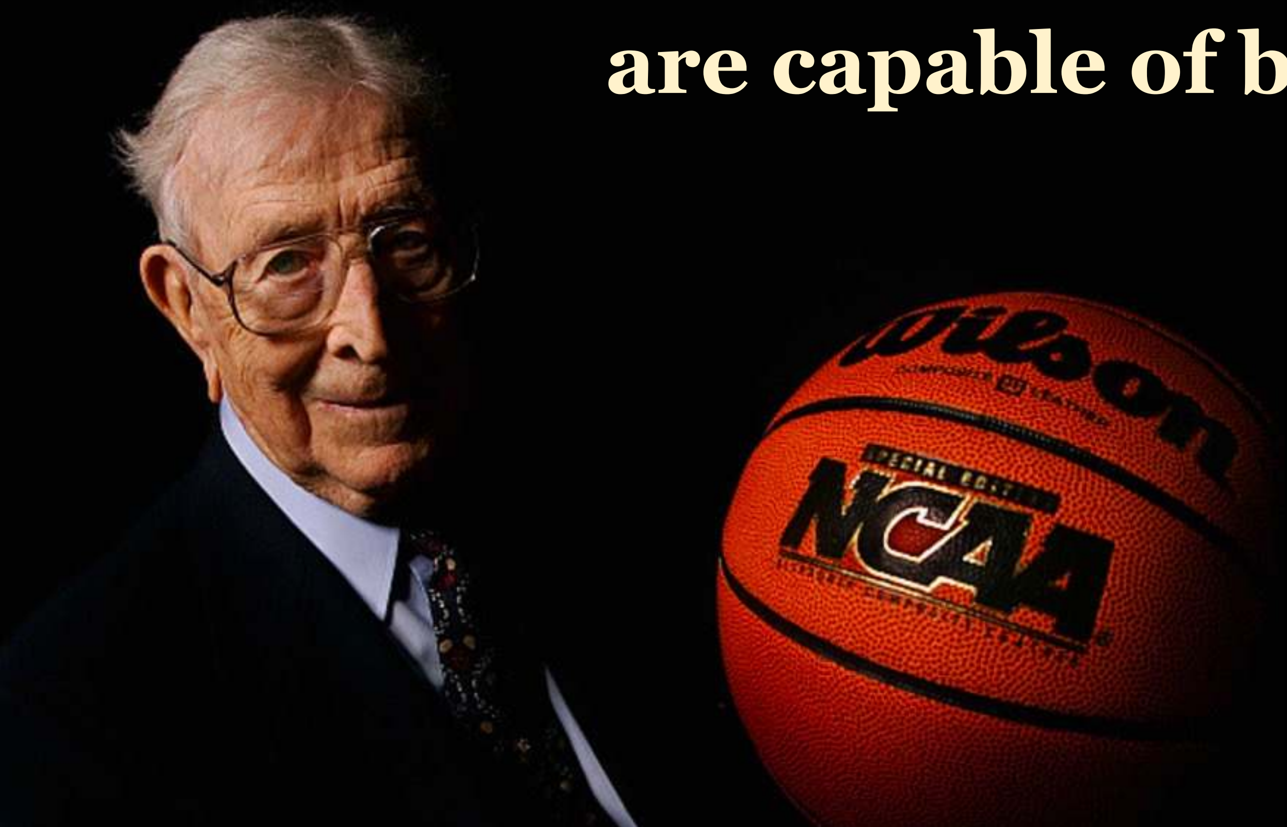
success noun

suc·cess | \ sək-ˈses \

Definition of *success*



the attainment of wealth, favor, or eminence



“<u>Success</u> 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)

Image: Newscom