



Zlatko K. Minev

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



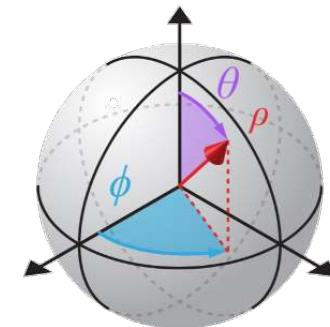
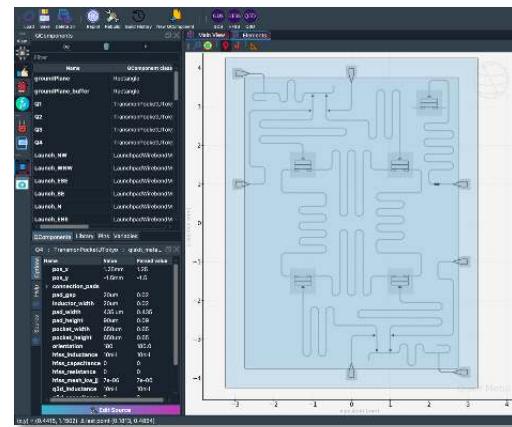
@zlatko_minev



zlatko-minev.com

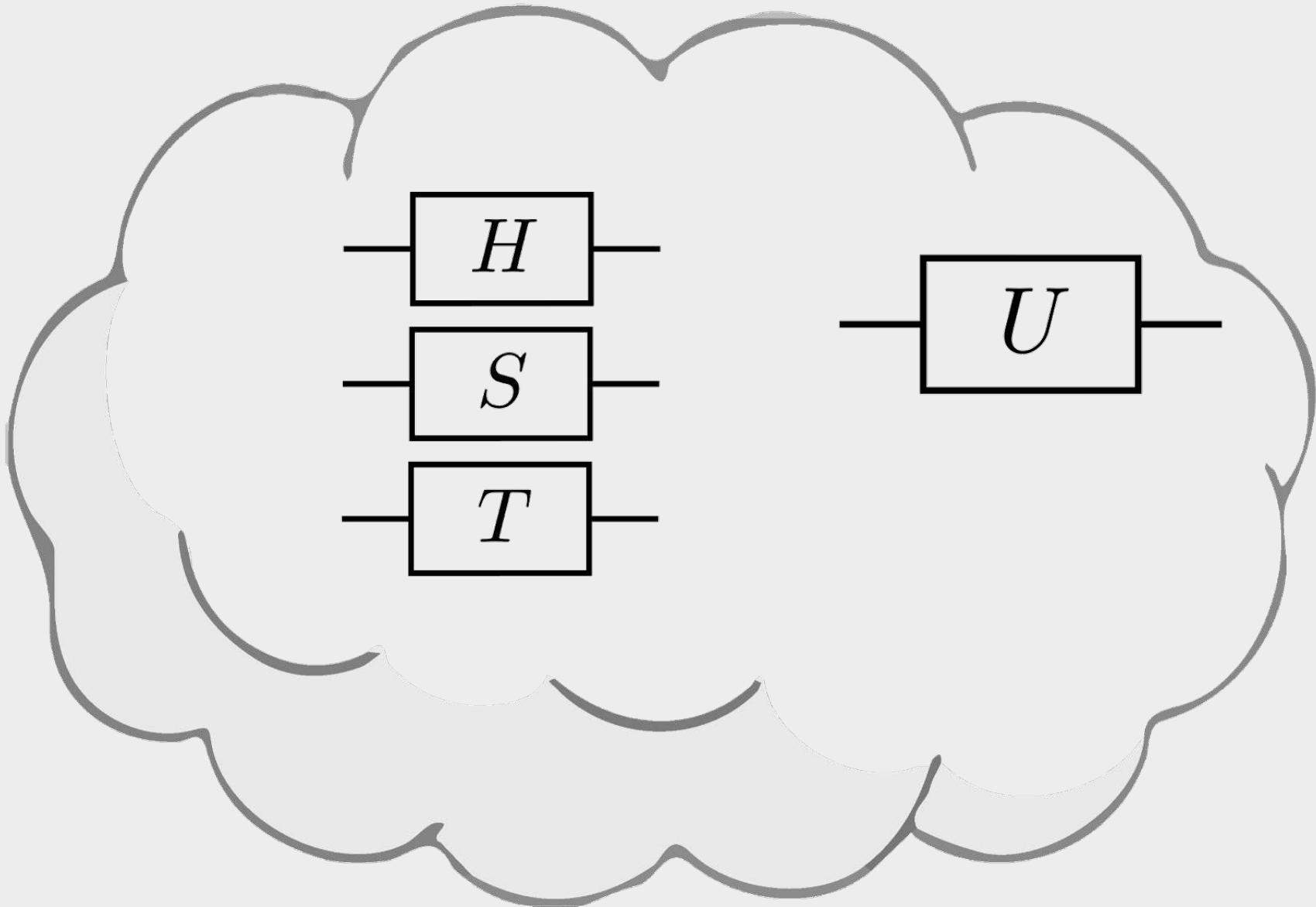
Overview of Quantum Hardware Design

Energy, Circuits, and Metal



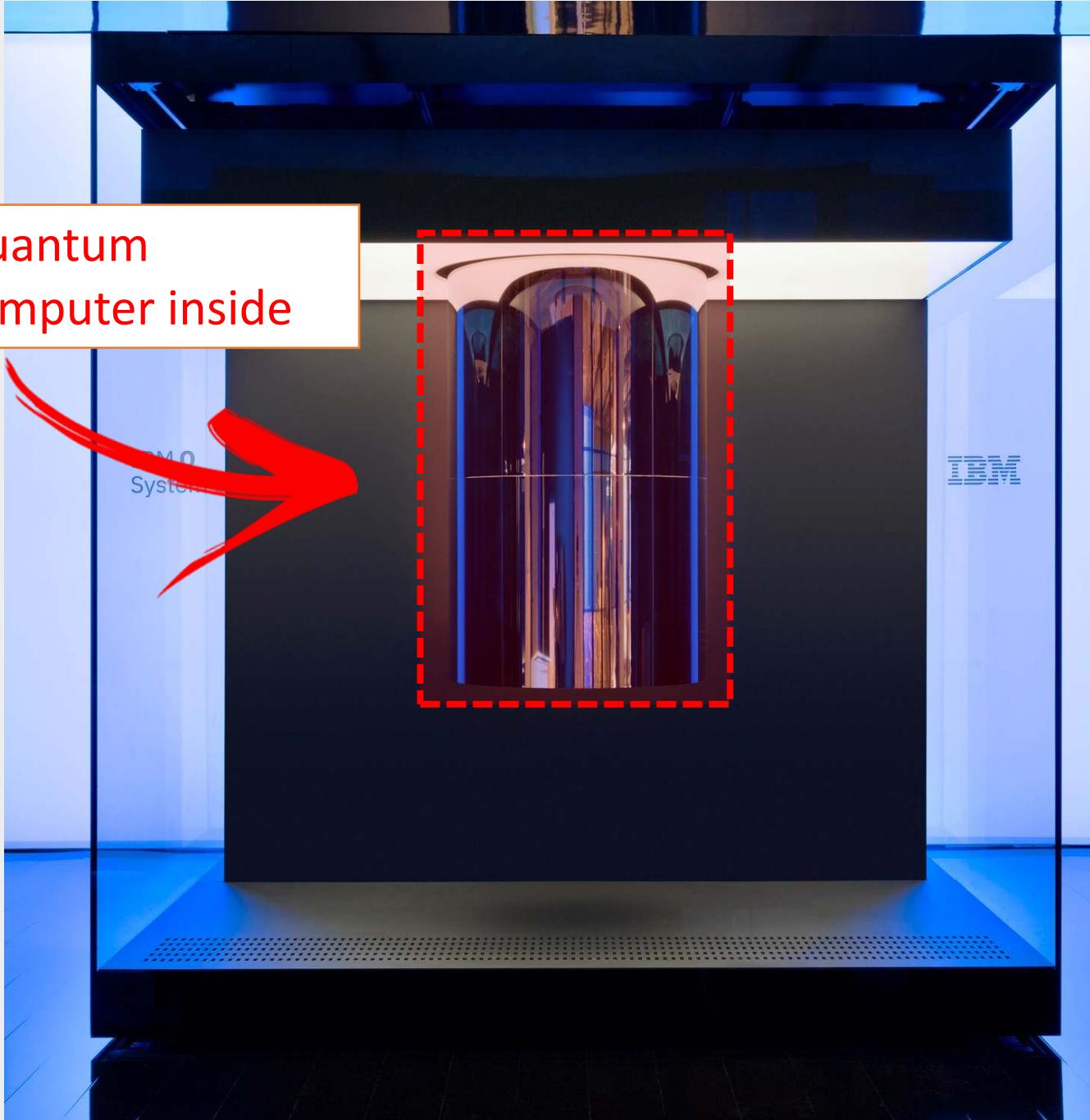
qiskit.org/metal

“Quantum cloud”

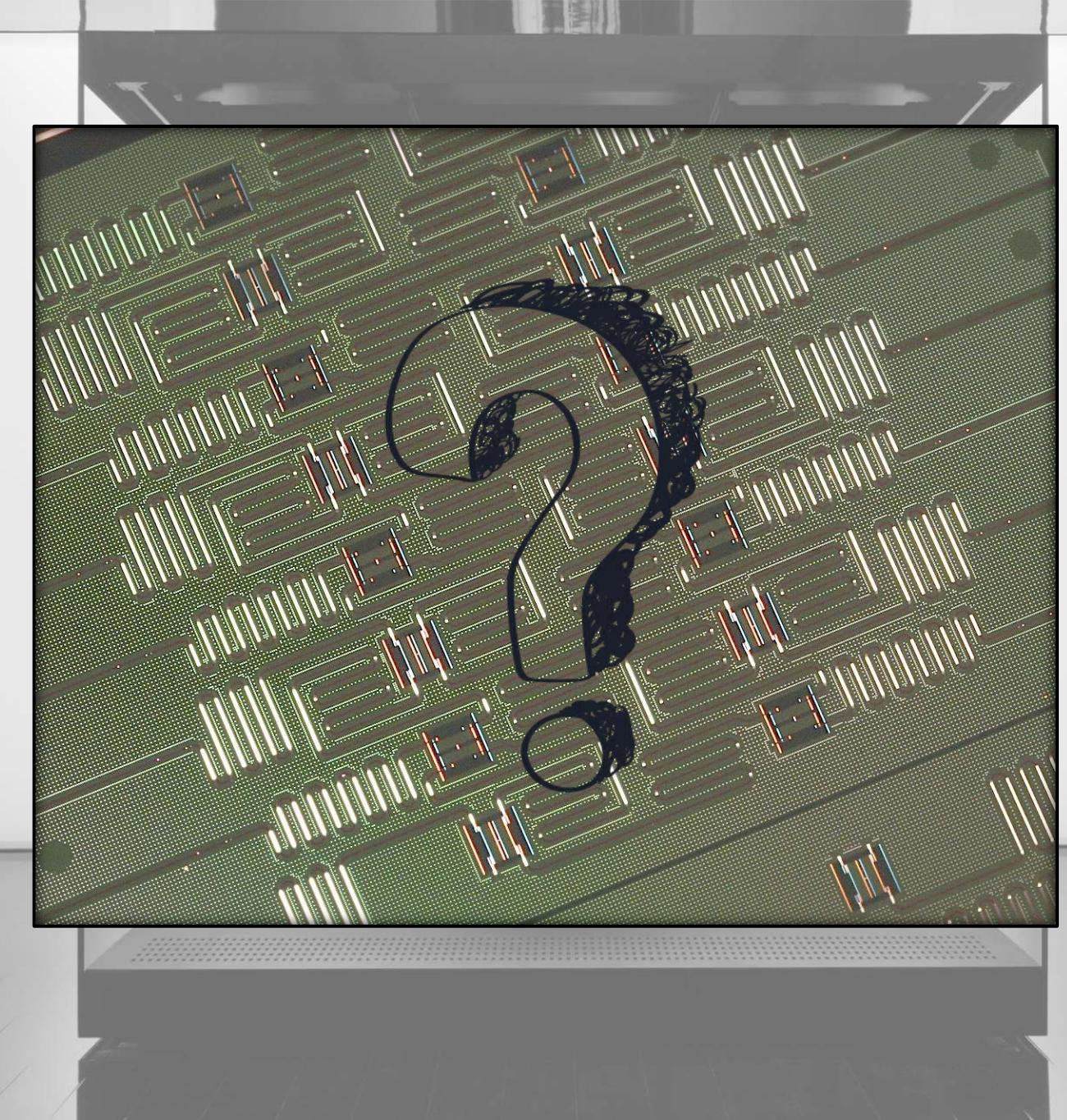




Quantum
computer inside



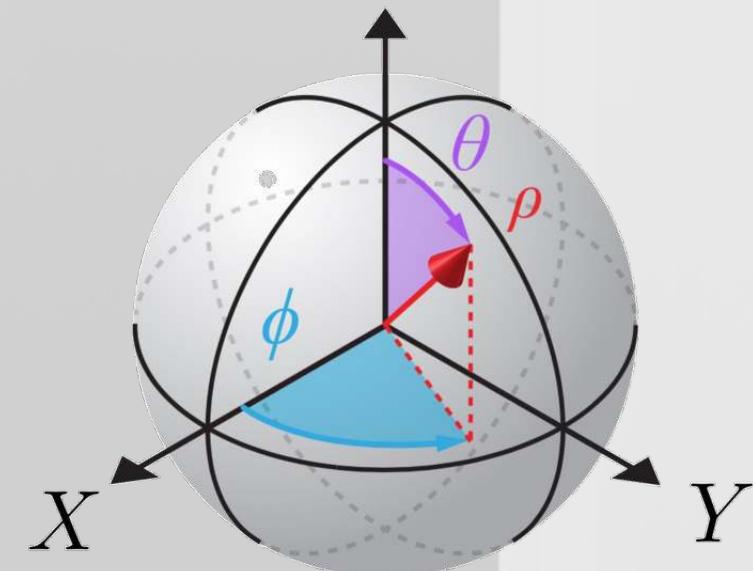
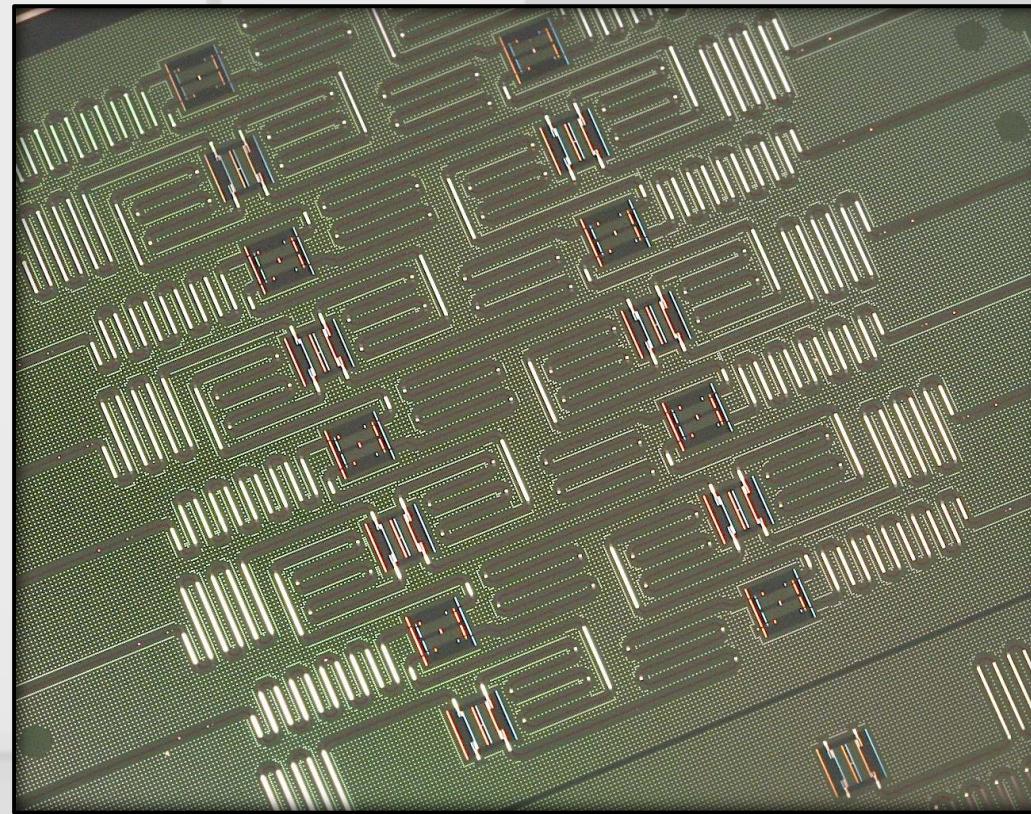
Quantum
processor



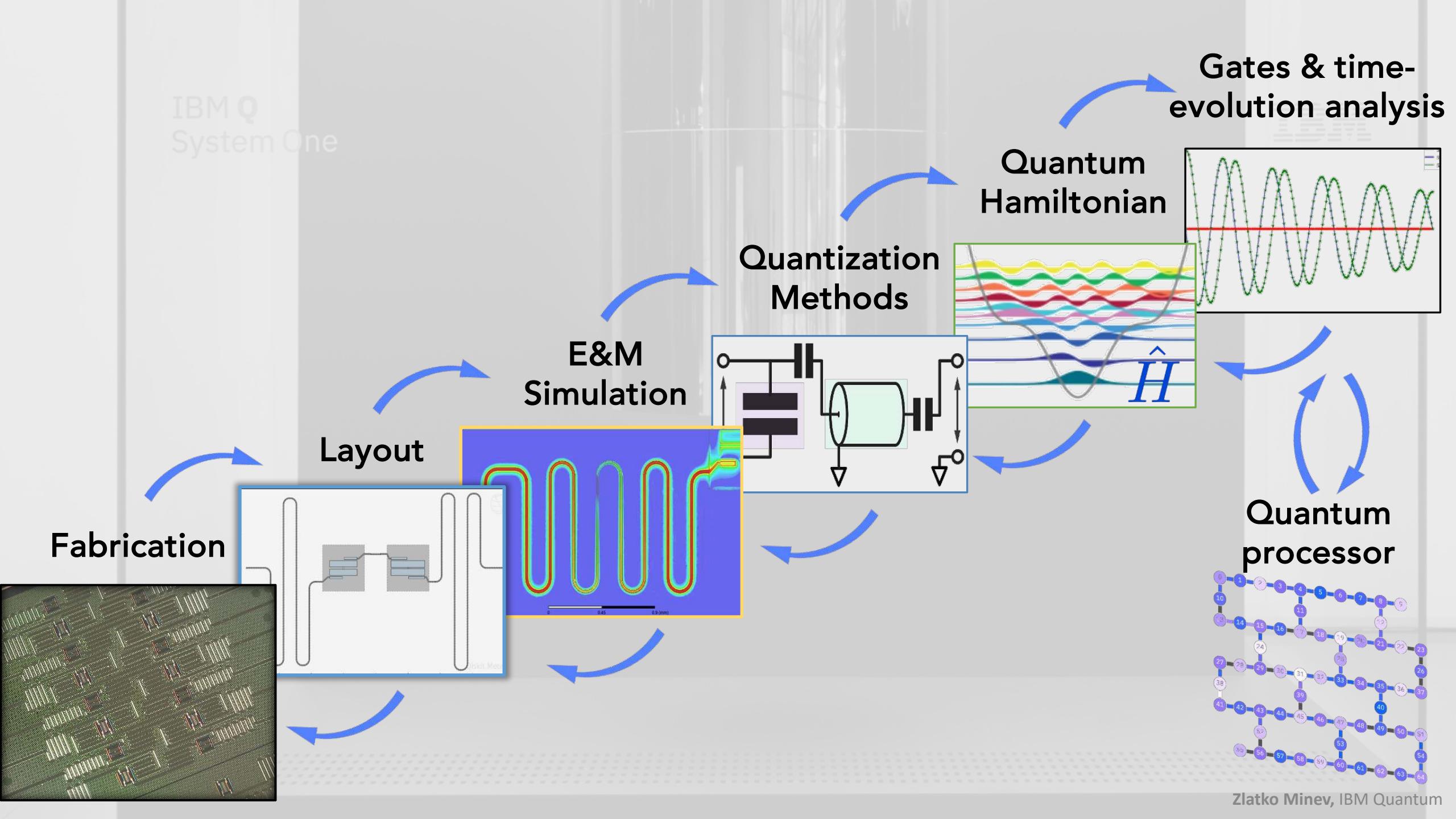
Zlatko Minev, IBM Quantum

IBMQ
System One

IBMQ

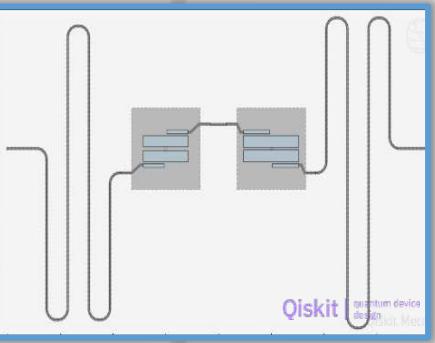


IBM Q
System One

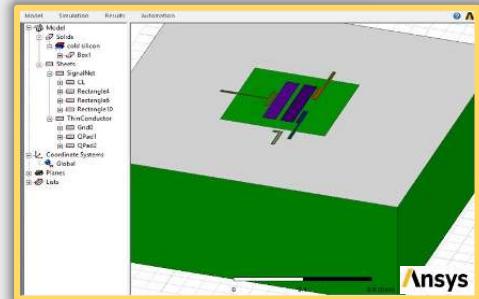




Layout

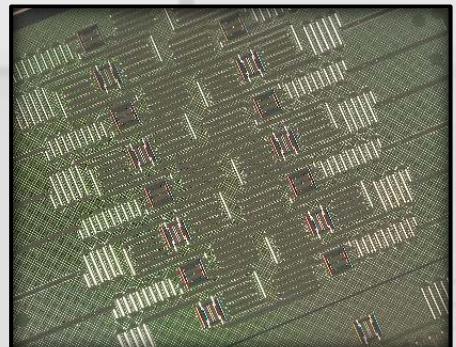


E&M Simulation



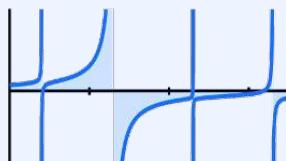
Fabrication

DRC, LVS

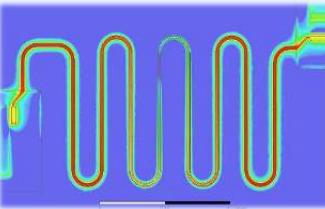


Quantization Methods

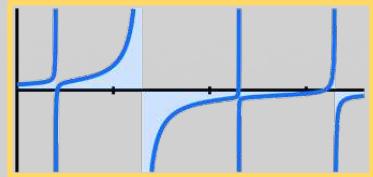
impedance



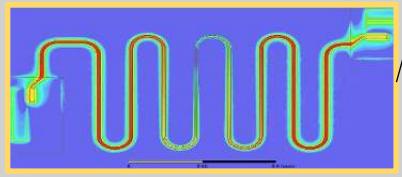
energy



impedance



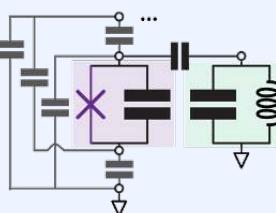
eigenmode



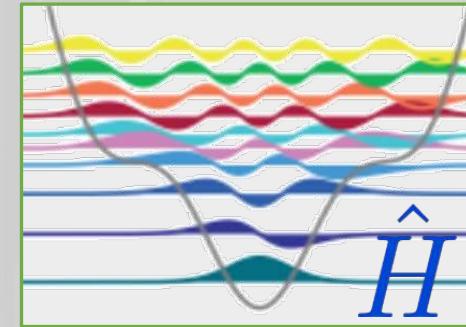
capacitive

n_0	n_1	n_2	n_3	n_4	n_5
n_0	$C_{0\Sigma}$	$-C_{01}$	$-C_{02}$	$-C_{03}$	$-C_{04}$
n_1	$C_{1\Sigma}$	$-C_{12}$	$-C_{13}$	$-C_{14}$	$-C_{15}$
n_2	$C_{2\Sigma}$	$-C_{23}$	$-C_{24}$	$-C_{25}$	
n_3	$C_{3\Sigma}$	$-C_{34}$	$-C_{35}$		
n_4	$C_{4\Sigma}$	$-C_{45}$			
n_5			$C_{5\Sigma}$		

lumped



Quantum Hamiltonian



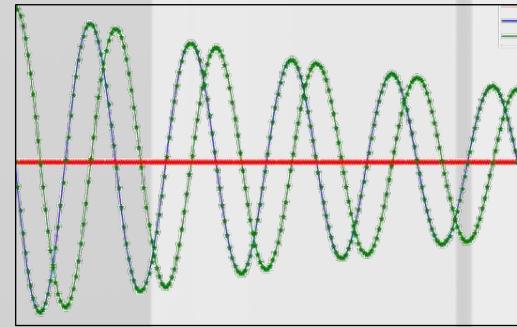
$$\hat{H} = \hat{H}_{\text{sys}} + \hat{H}_{\text{int}}$$

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

MPS
Diagonalization
Dissipation

..

Gates & time-evolution analysis



Rotating frames
Time evolution
Driven dynamics
Floquet
Dissipation

...

Layout



E&M Simulation



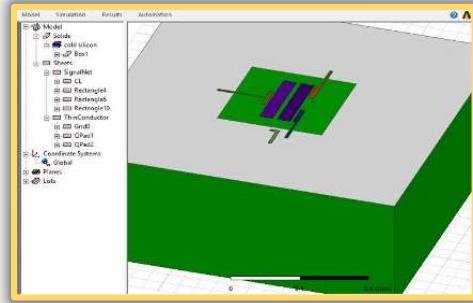
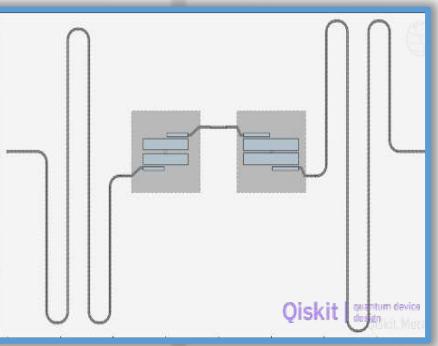
Quantization Methods



Quantum Hamiltonian



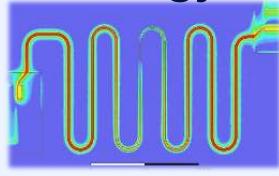
Gates & time- evolution analysis



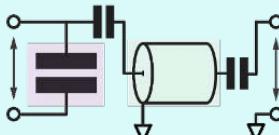
impedance



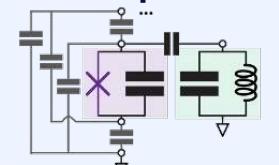
energy



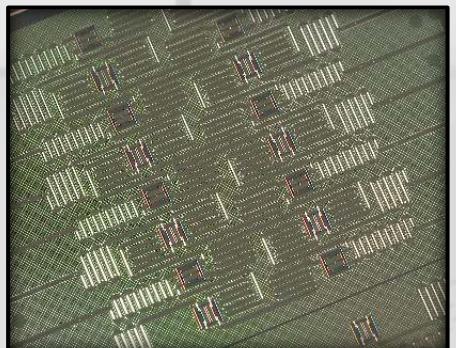
quasi-lumped



lumped

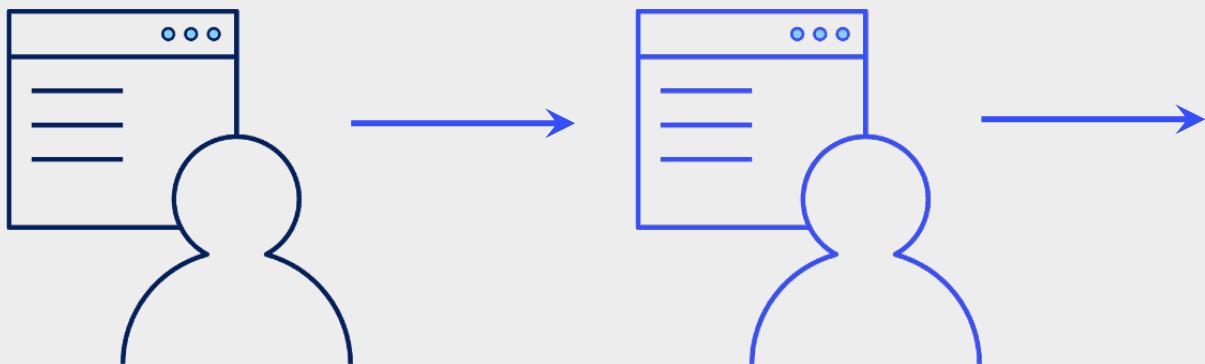


Fabrication



Quantum Device Design

Make it easy!



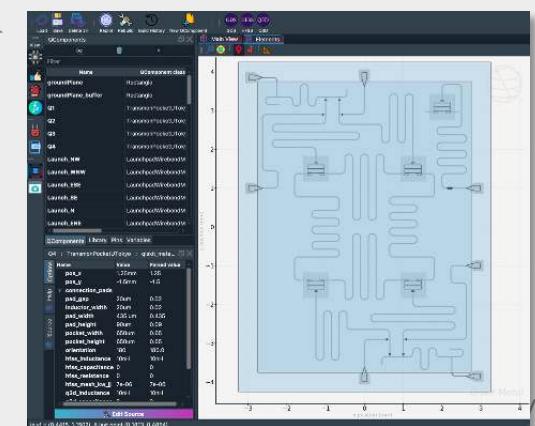
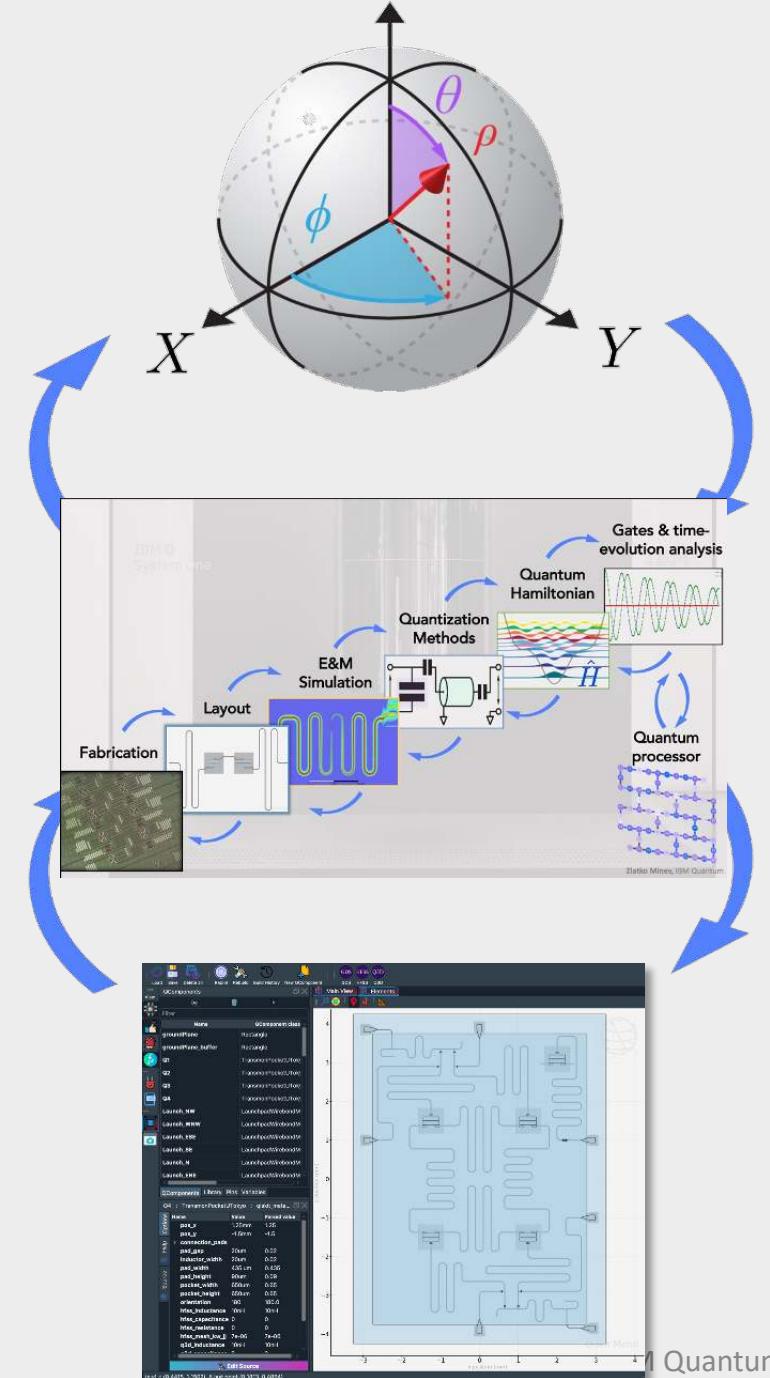
Quantum

Engineering

Software



Open
source



Quantum

A few introductory reviews

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

Minev, Z. Lec. 16-22, *Introduction to Quantum Computing and Quantum Hardware* (2020) qiskit.org/learn/intro-qc-qh

Blais, A., Grimsmo, A. L., Girvin, S. M., & Wallraff, A. (2020)
Circuit Quantum Electrodynamics ([arXiv:2005.12667](https://arxiv.org/abs/2005.12667))

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

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

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

Wendin, G. (2017) Quantum information processing with superconducting circuits. *RPP*, 80(10), 106001

Gambetta, J. M., Chow, J. M., & Steffen, M. (2017)
Building logical qubits in a superconducting quantum computing system. *Npj Quantum Information*, 3(1), 2

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

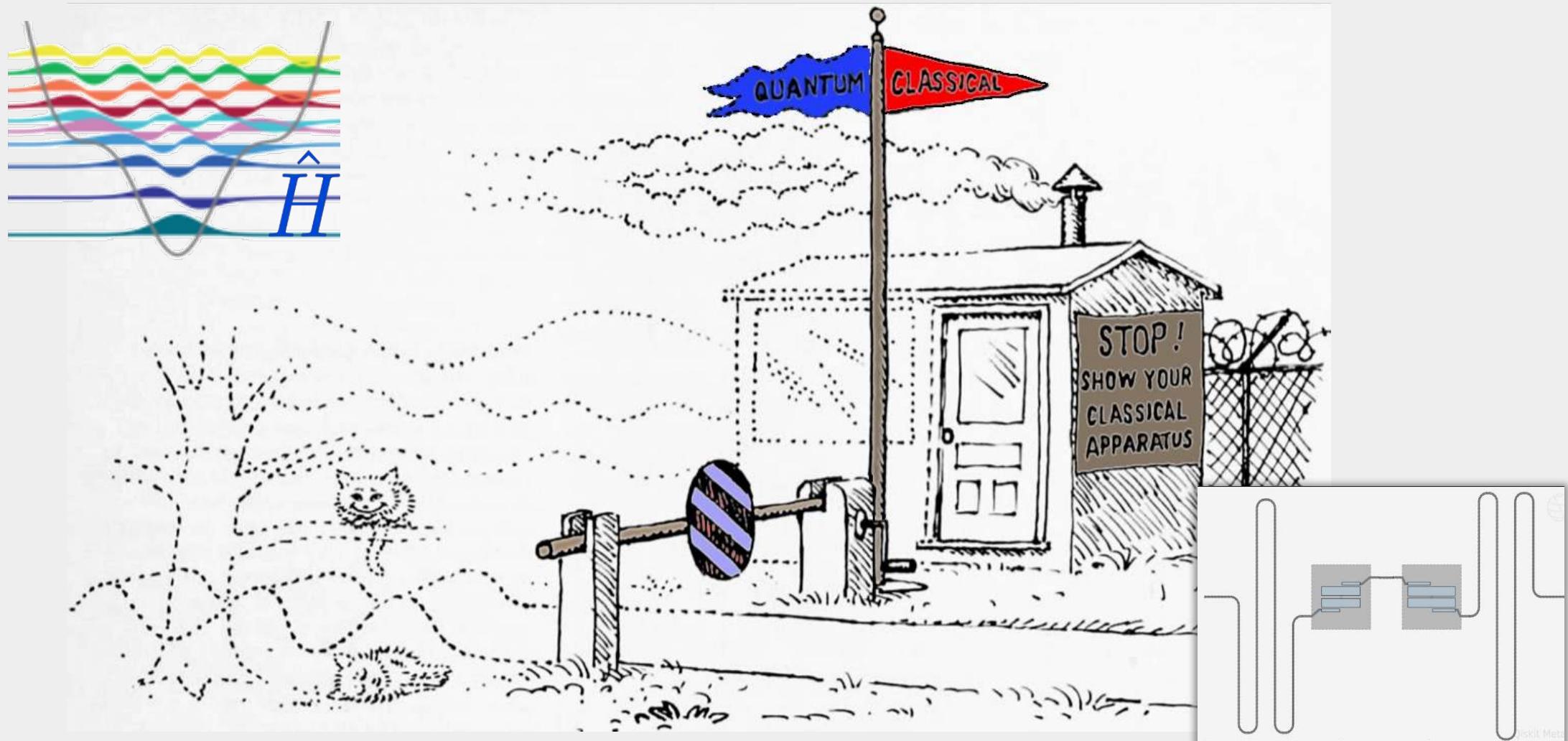
Clerk, A. A., Girvin, S. M., Marquardt, F., & Schoelkopf, R. J. (2010)
Introduction to quantum noise, measurement, and amplification
Reviews of Modern Physics, 82(2), 1155–1208

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

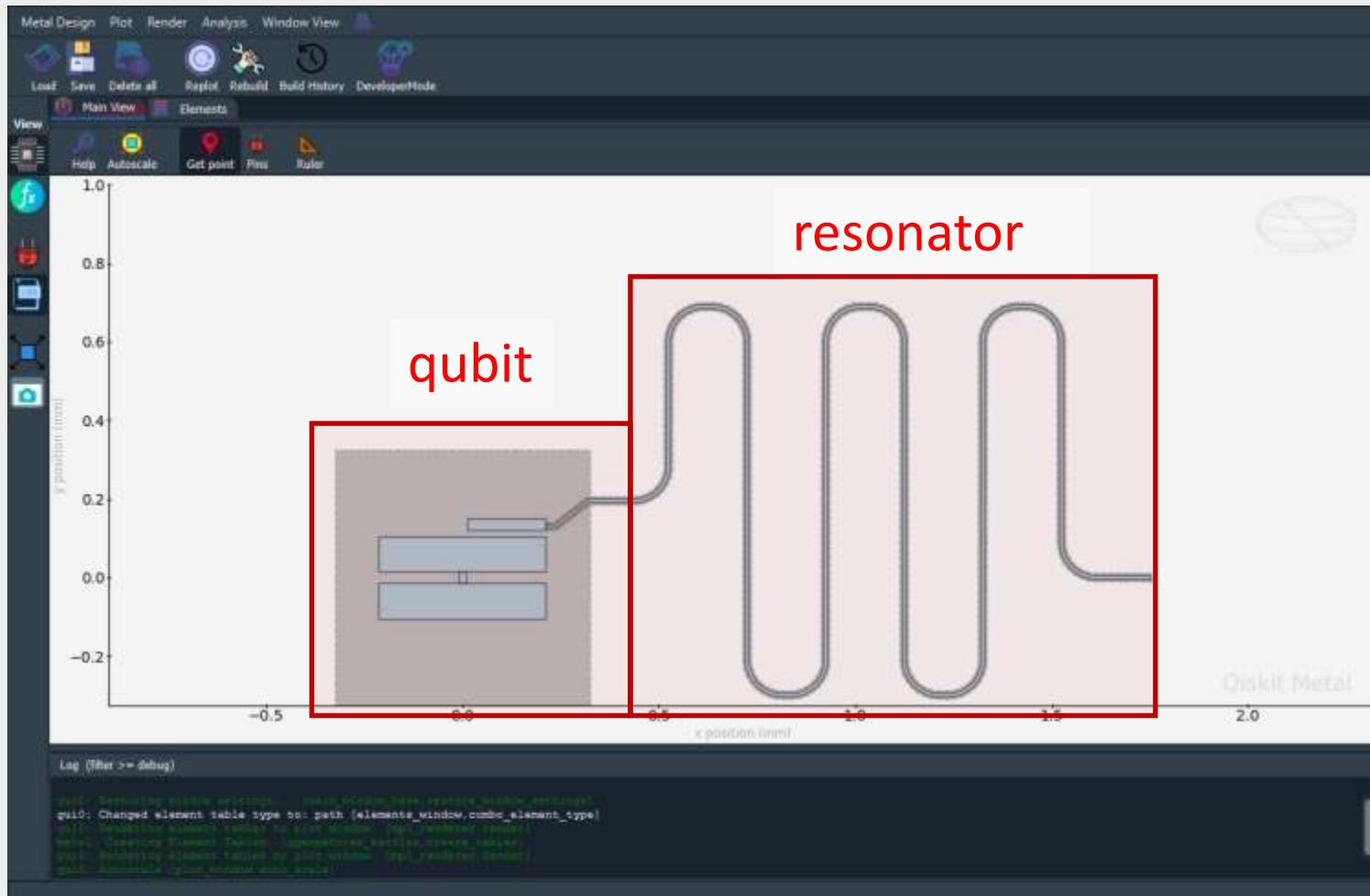
Devoret, M. H. (1997)
Quantum Fluctuations in Electrical Circuits.
In *Fluctuations Quantiques/Quantum Fluctuations* (p. 351)
...

Quantum Analysis

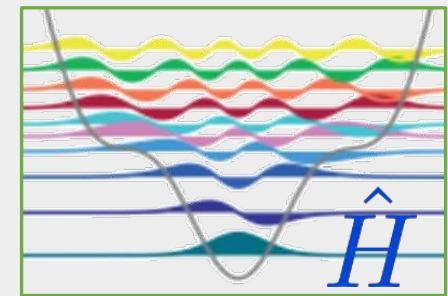
Quantum Analysis



Simple example

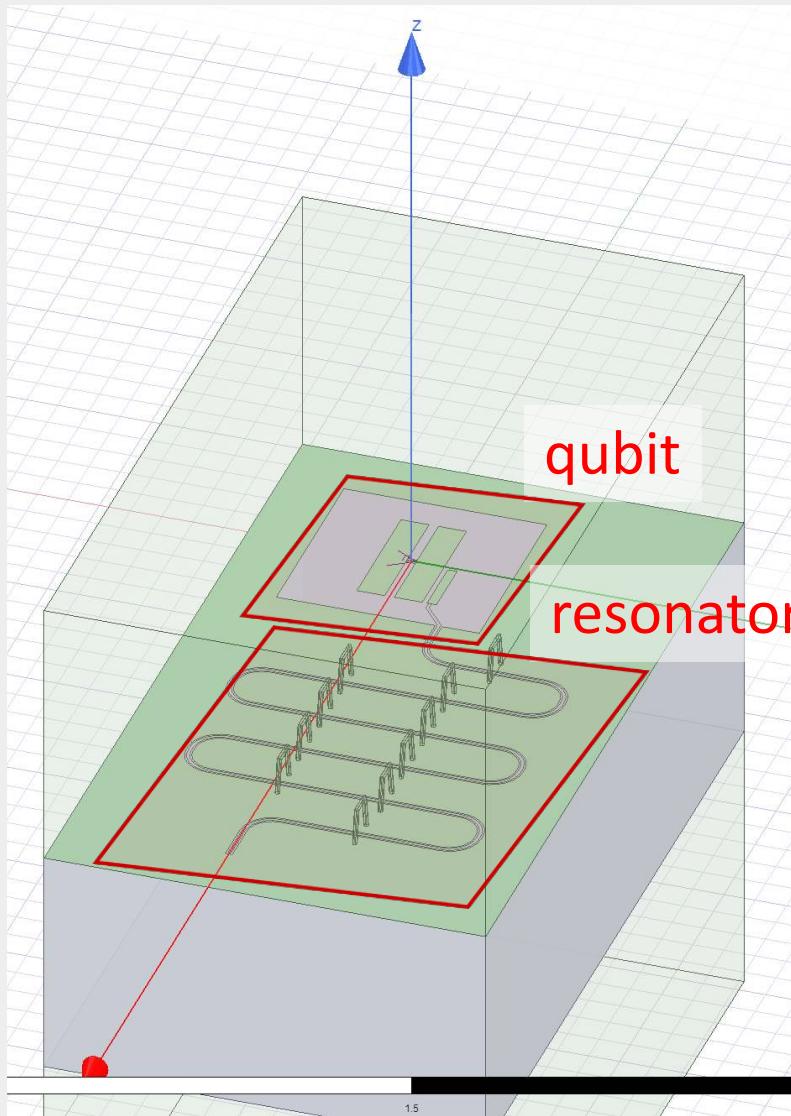


?

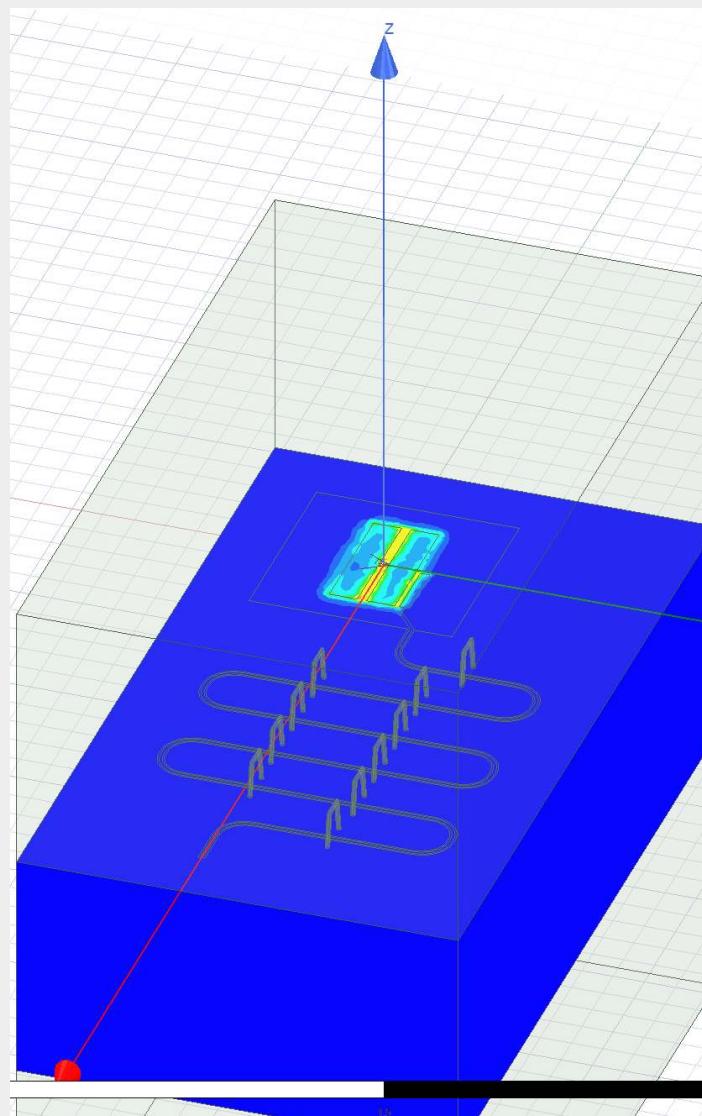


Modeling step 1: Classical E&M approximations

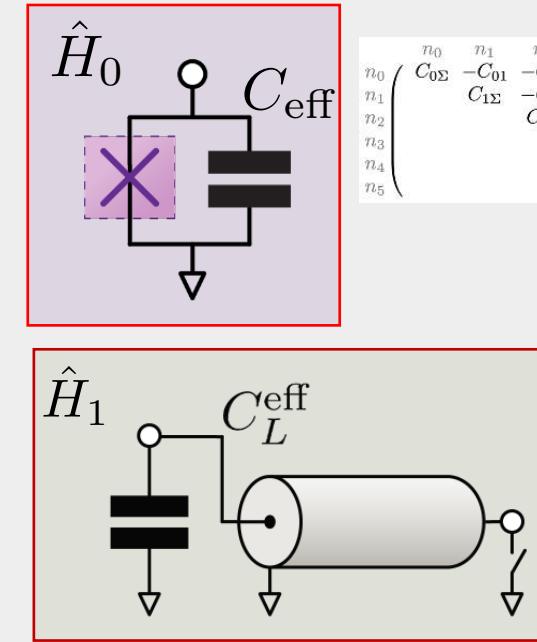
Physical (linear) model



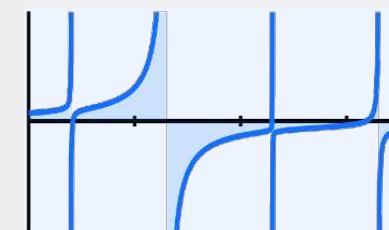
Eigenmodes



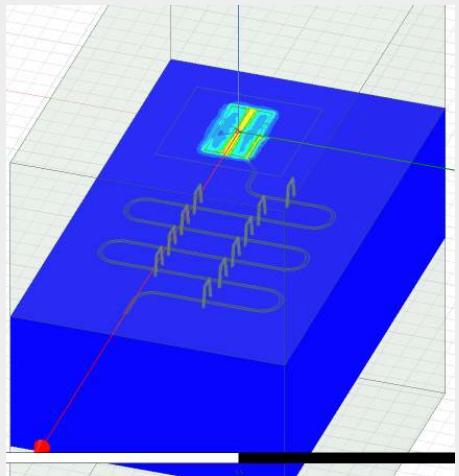
Quasi lumped models



Impedance

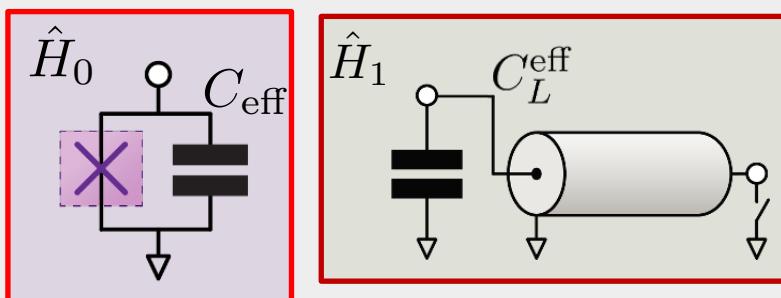


Modeling step 2: Quantize

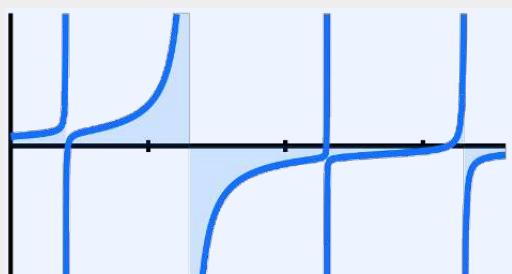


$$\hat{H}_{\text{tot}}$$

$$\hat{H}_{\text{tot}} = \hat{H}_{\text{sys}} + \hat{H}_{\text{int}}$$

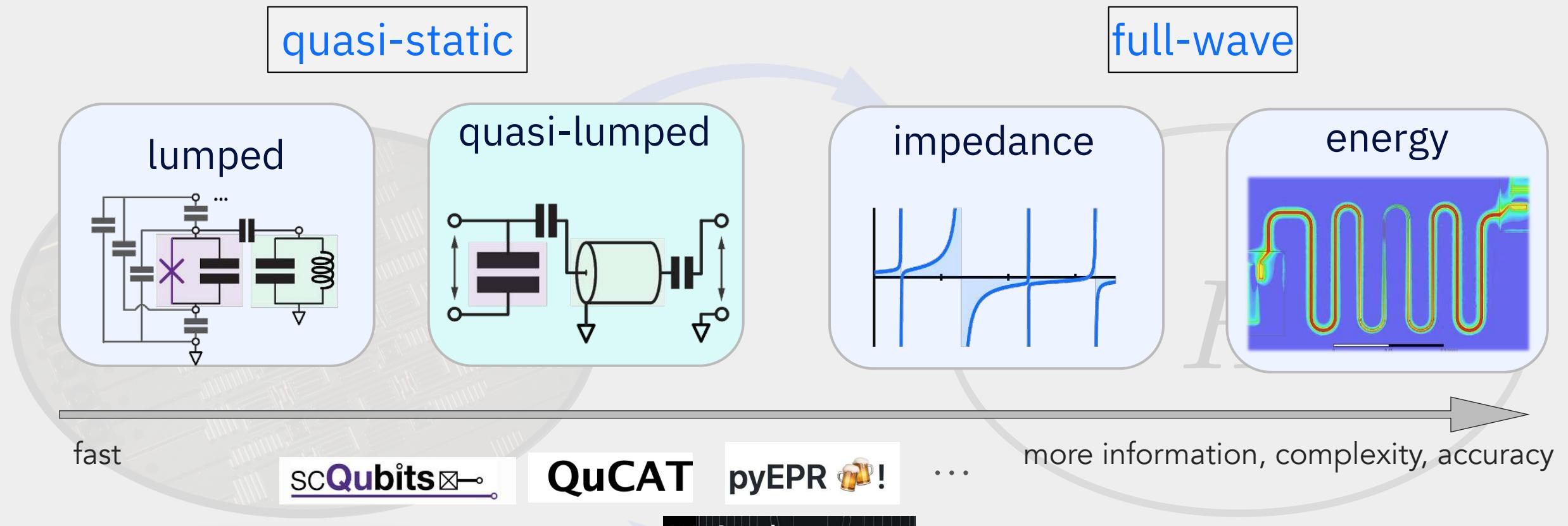


$$\hat{H}_{\text{tot}} = \hat{H}_{\text{lin}} + \hat{H}_{\text{nl}}$$



There's a description for
every job!

Step 2: Landscape of quantization methods



See Friday Workshop!

QuTiP

KQC
Qiskit | quantum device
Metal

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

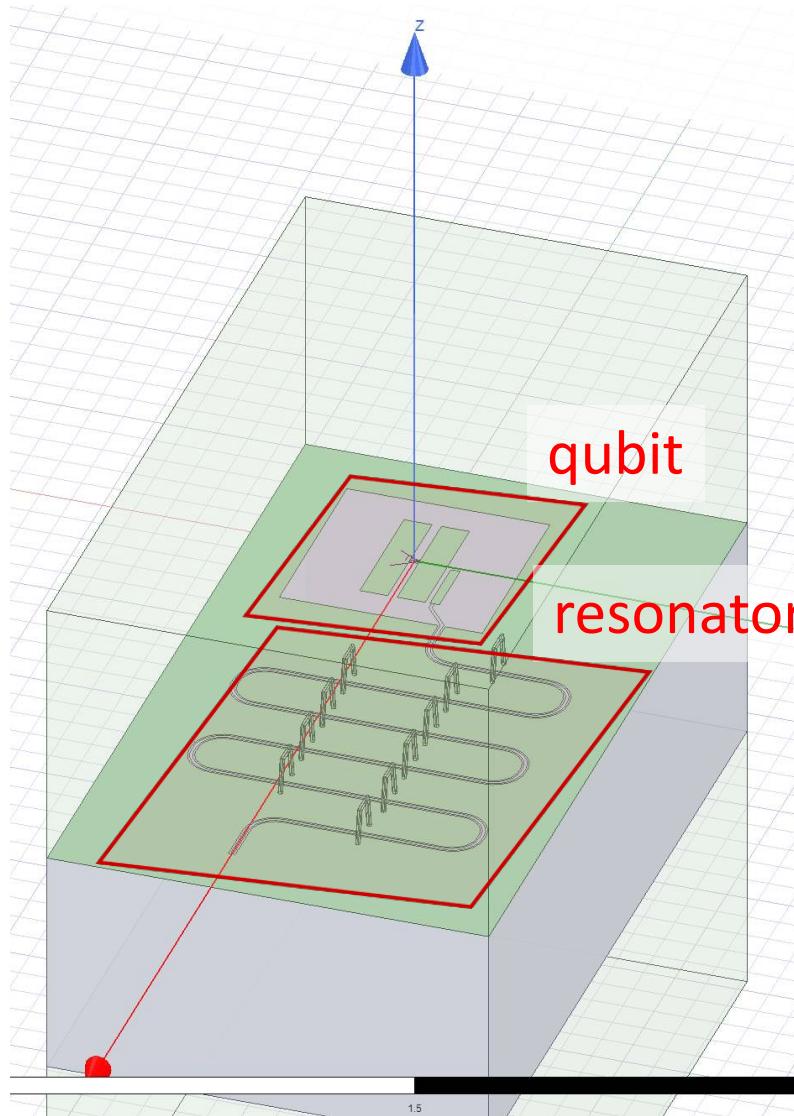
Malekakhlagh et al. (2017, 2019),
Gely et al. (2019), Parra-Rodriguez
et al. (2019), Minev et al. (2021), ...

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

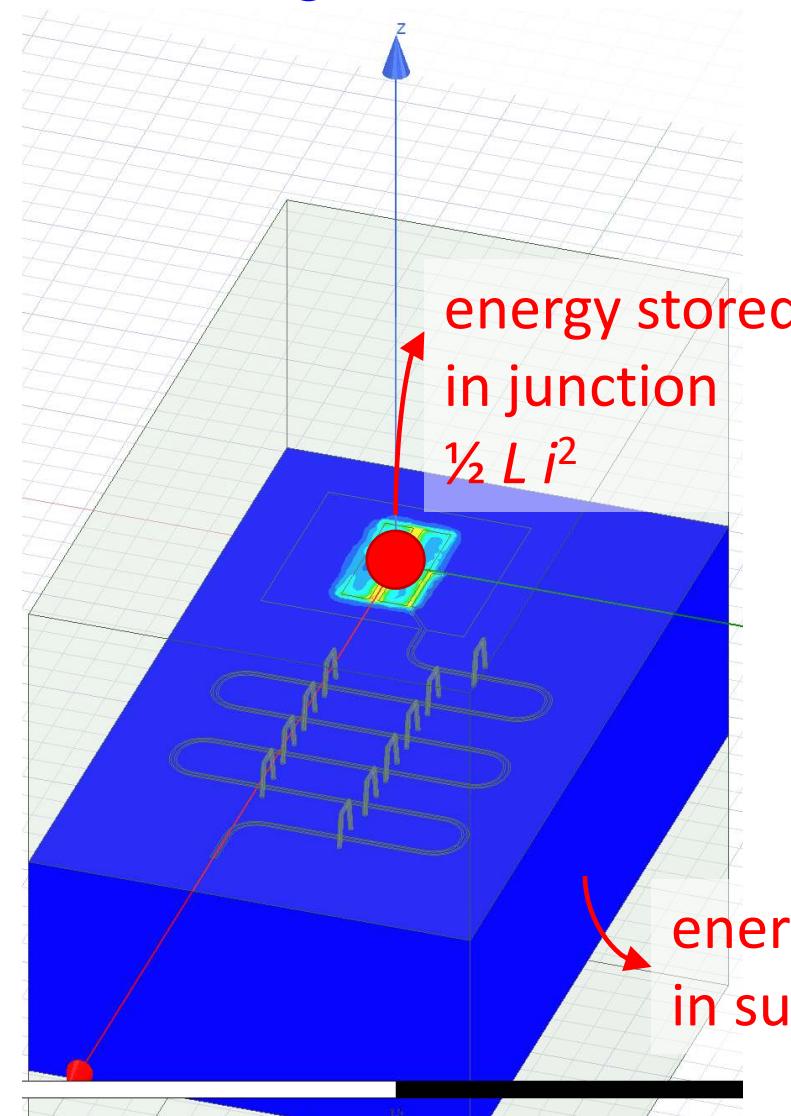
Minev (2018)
Minev et al. (2020)
Zlatko Minev, IBM Quantum (17)

Example of step 2 with EPR

Physical (linear) model



Eigenmodes



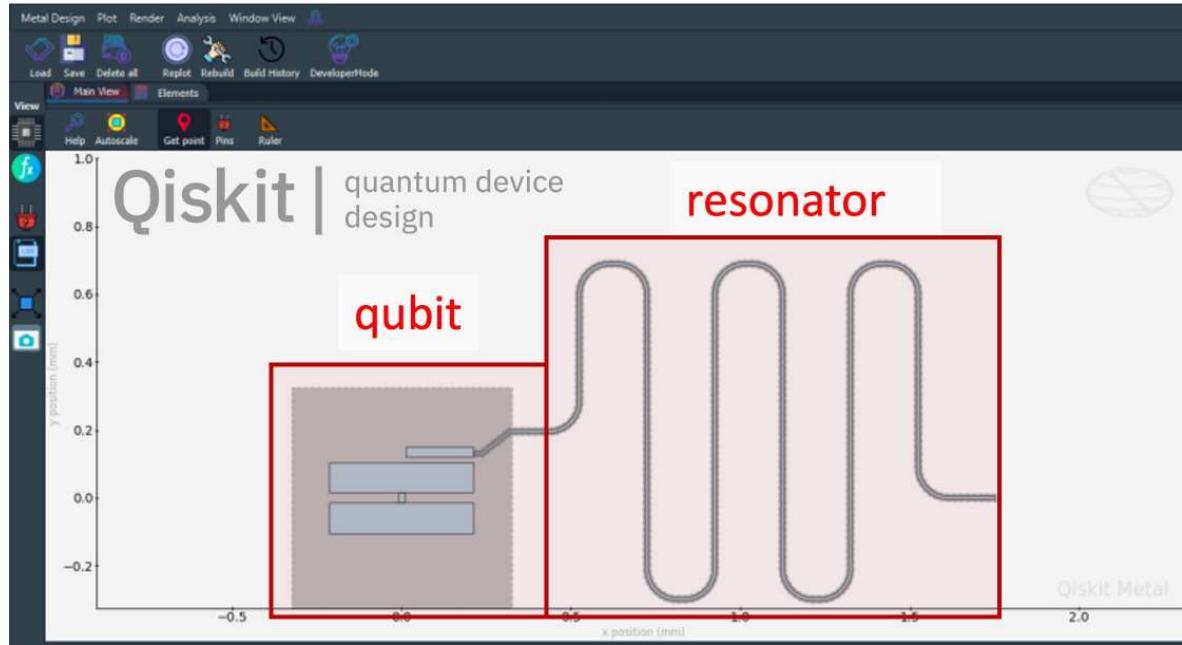
Non-linear device
params

$$p_j \rightarrow \hat{H}_{\text{full}}$$

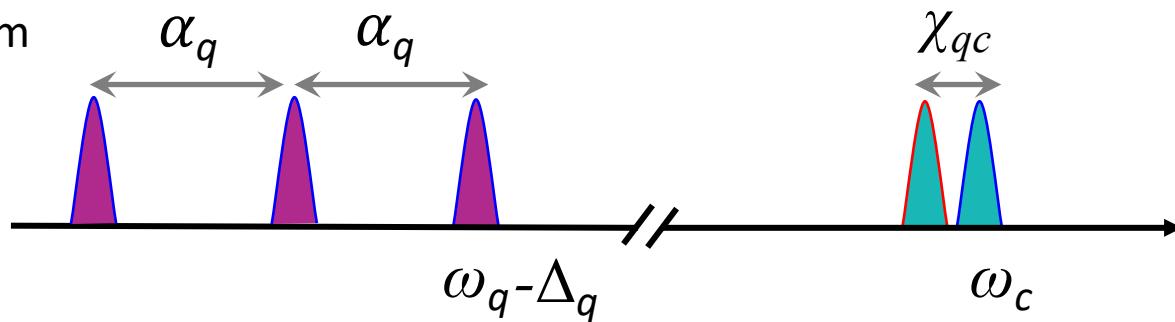
Dissipation
budget

$$p_l \rightarrow \mathcal{D}[\sqrt{\kappa \hat{a}}]$$

Step 3: Hamiltonian



Transition spectrum



H_{eff} : for simplicity, showing up to $\mathcal{O}(\varphi^6)$ in RWA

Qubit/cavity anharmonicity

$$\alpha_{q/c} = p_{q/c}^2 \frac{\hbar\omega_{q/c}^2}{8E_J}$$

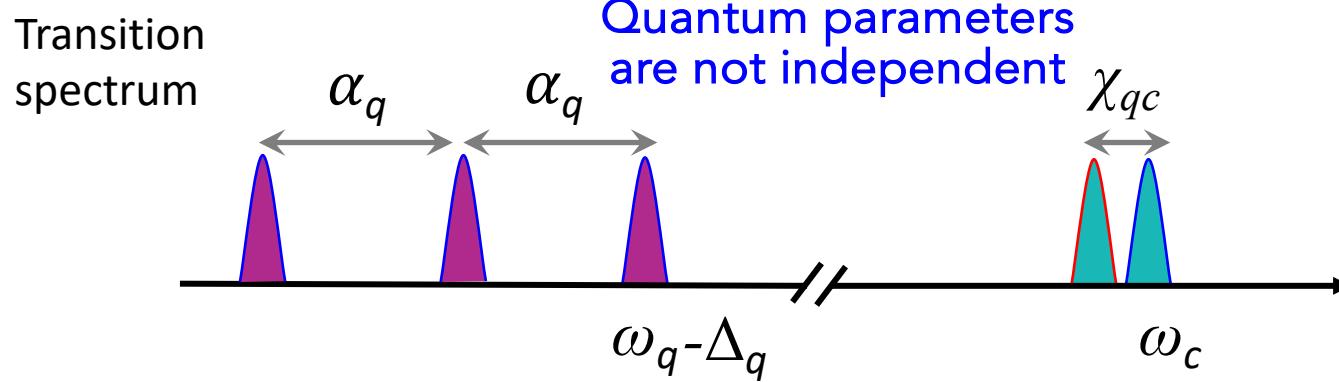
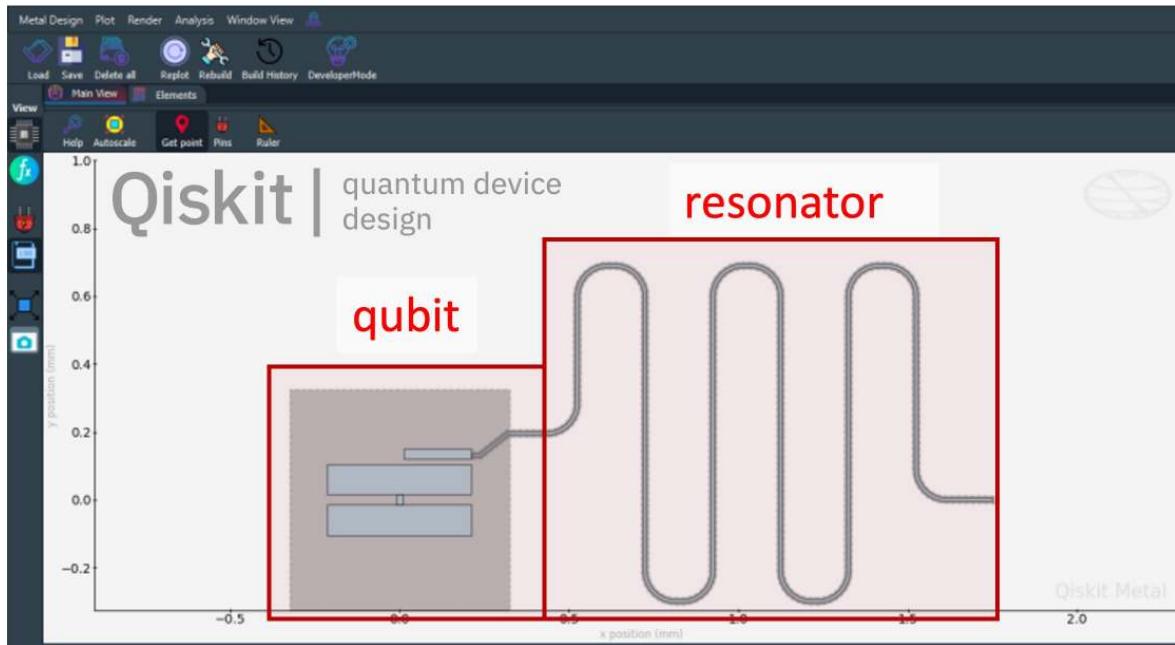
Qubit-cavity dispersive shifty

$$\chi_{qc} = p_q p_c \frac{\hbar\omega_q \omega_c}{4E_J}$$

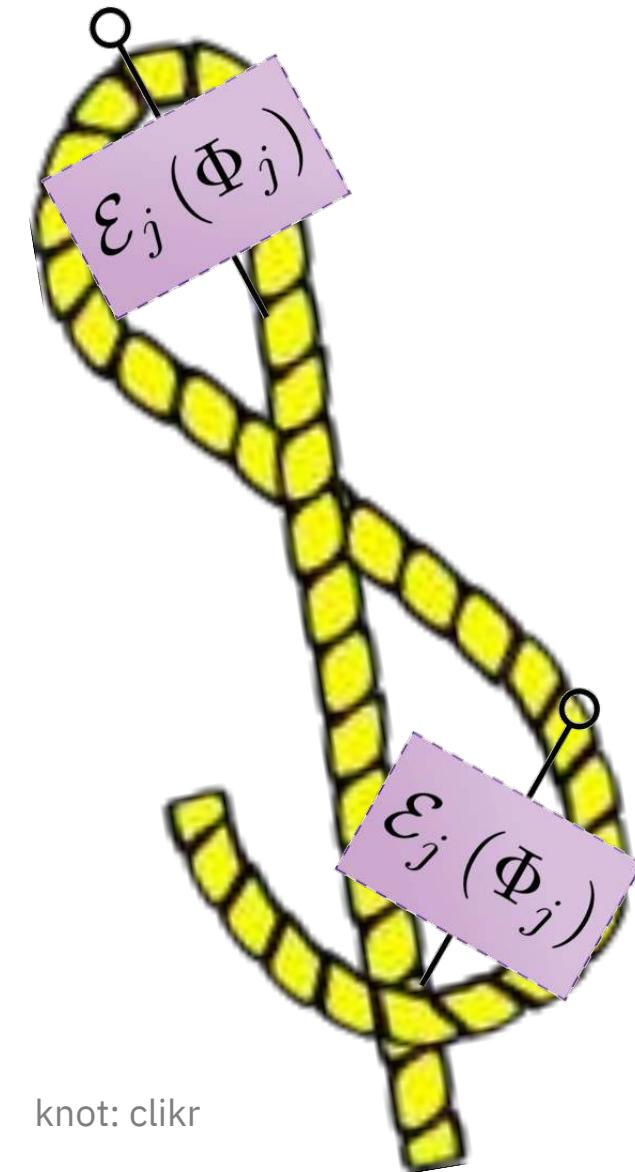
Qubit Lamb shift

$$\Delta_q = \alpha_q - \frac{1}{2}\chi_{qc}$$

Step 3: Hamiltonian: Universal constraints & EPR monogamy



H_{eff} : for simplicity, showing up to $\mathcal{O}(\varphi^6)$ in RWA



knot: clikr

Zlatko Minev, IBM Quantum (20)

EPR theory vs. experiment

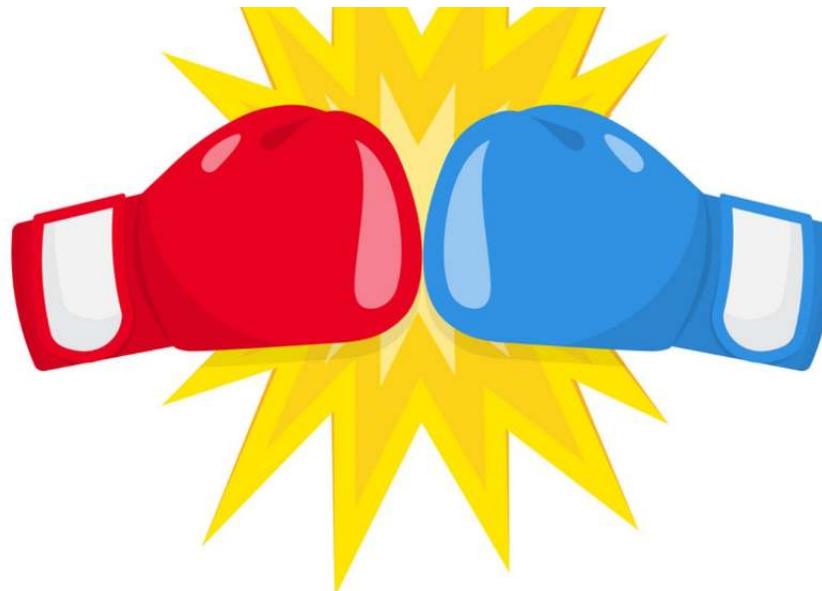
arXiv.org > quant-ph > arXiv:2010.00620

Quantum Physics

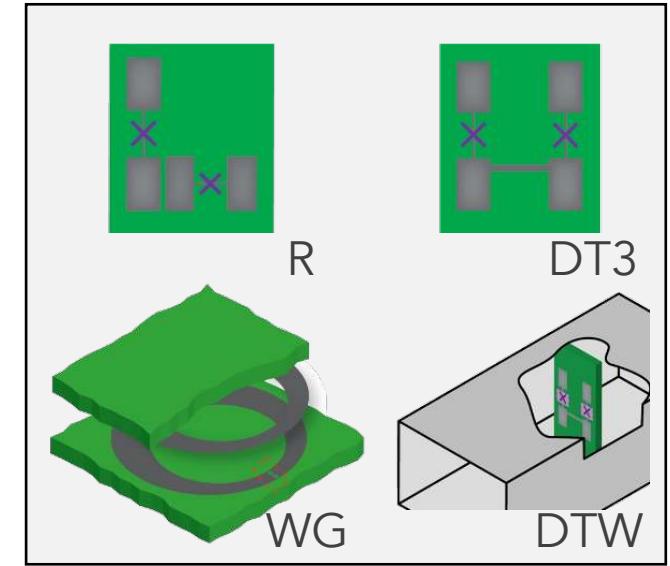
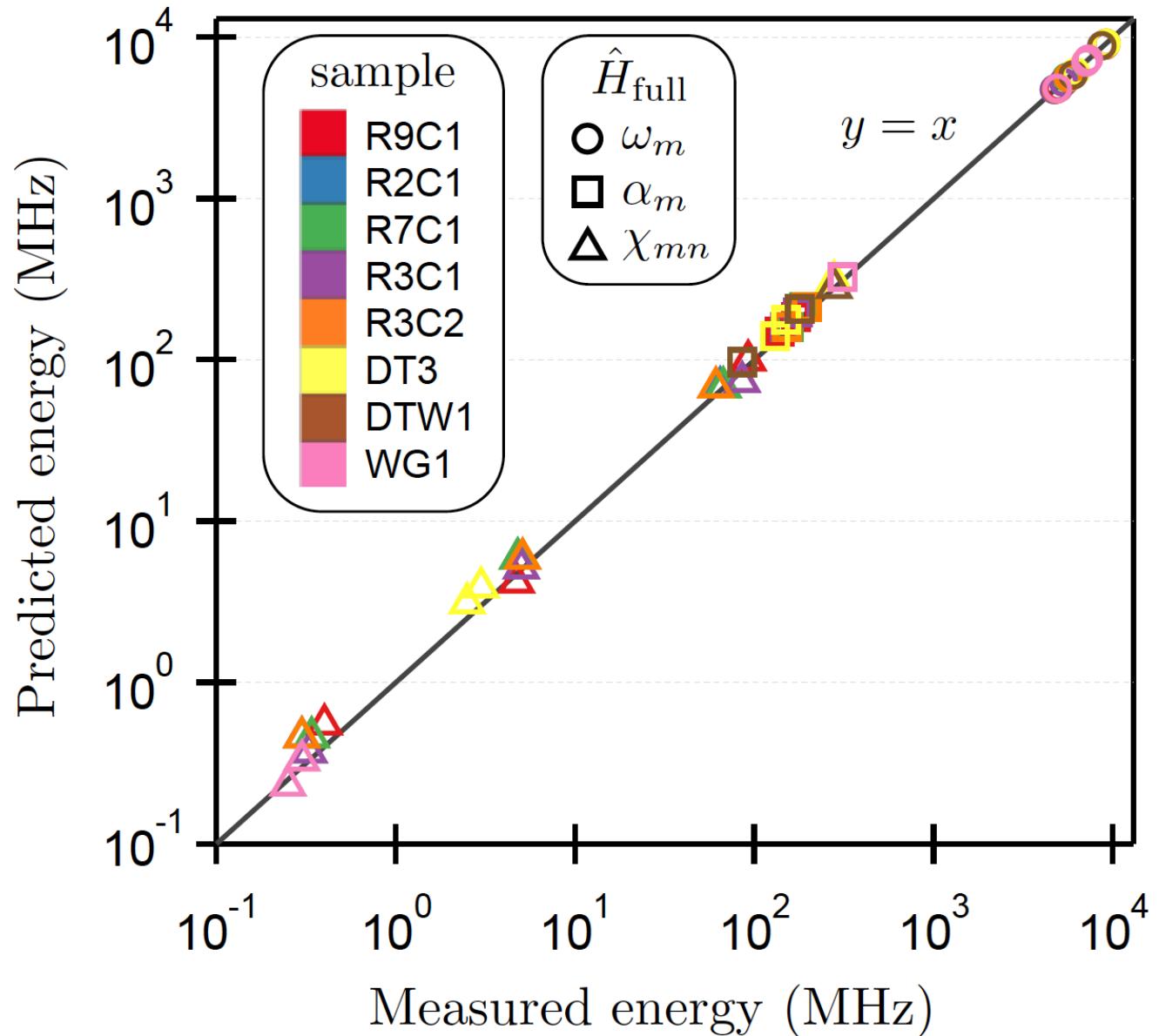
[Submitted on 1 Oct 2020]

Energy–participation quantization of Josephson circuits

Zlatko K. Minev, Zaki Leghtas, Shantanu O. Mundhada, Lysander Christakis, Ioan M. Pop, Michel H. Devoret



Theory vs. experiment: agreement over 5 orders of magnitude



R: Minev *et al.* (2018)

WG: Minev *et al.* (2013, 2016)

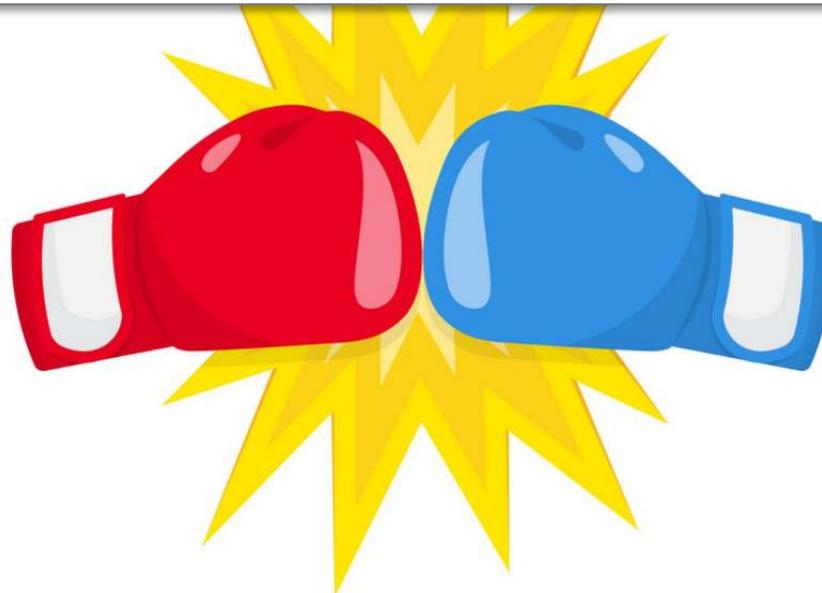
DT3, DTW: Minev *et al.* (2019)

Planar devices & comparison to other methods

Quantum Physics
[Submitted on 2 Feb 2021]

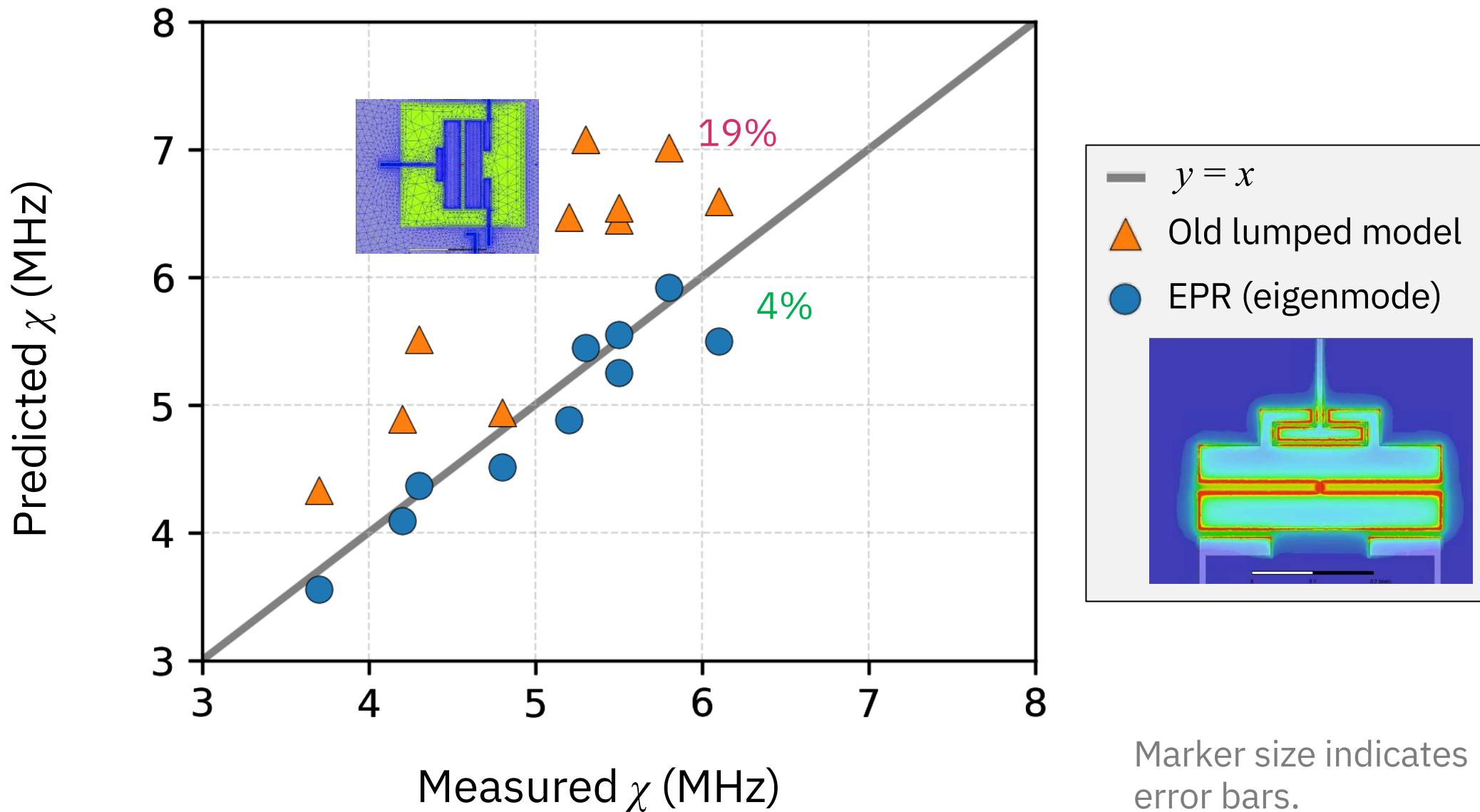
Exploiting dynamic quantum circuits in a quantum algorithm with superconducting qubits

Antonio D. Corcoles, Maika Takita, Ken Inoue, Scott Lekuch, Zlatko K. Minev, Jerry M. Chow, Jay M. Gambetta



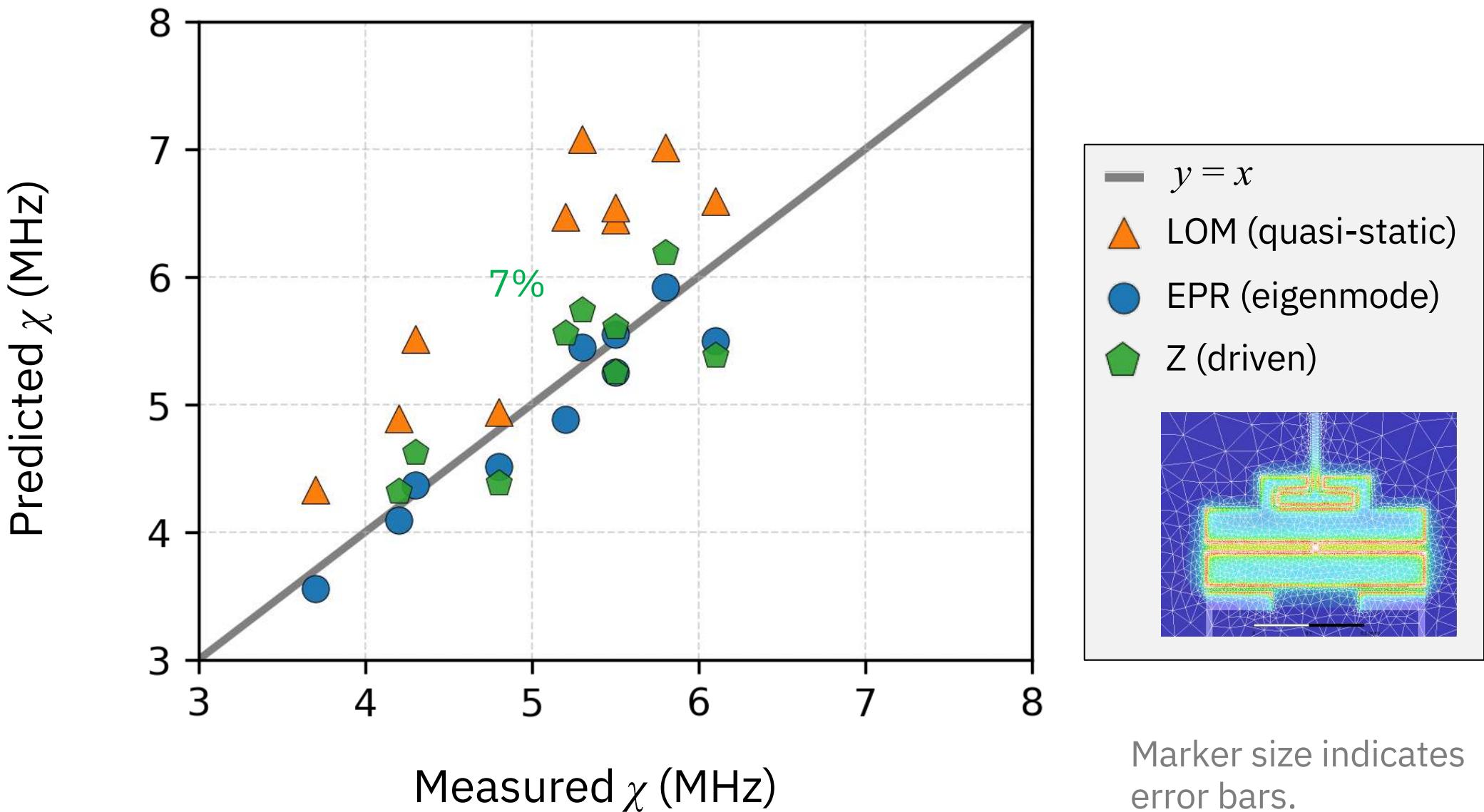
Automated with
Qiskit | quantum device
design

Measured vs. predicted: qubit-readout cross-Kerr



Marker size indicates
error bars.
Zlatko Minev, IBM Quantum (24)

Measured vs. predicted: qubit-readout cross-Kerr

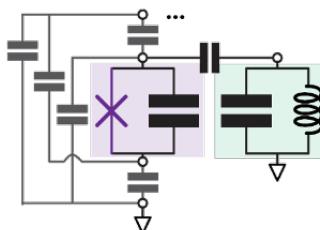


Quantization approaches



Quasi-static

lumped
(LOM)



Agreement
for presented results

19% / 10%

External inputs

higher

Speed

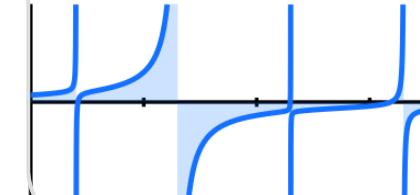
fastest and
cheapest

Generality

low

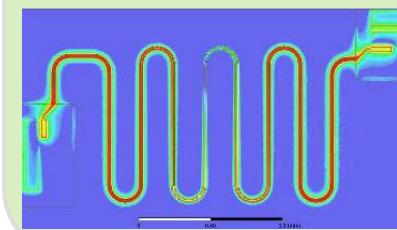
Full-wave

impedance
(Z)



7%

eigenmode
(EPR)



4%

low

moderate

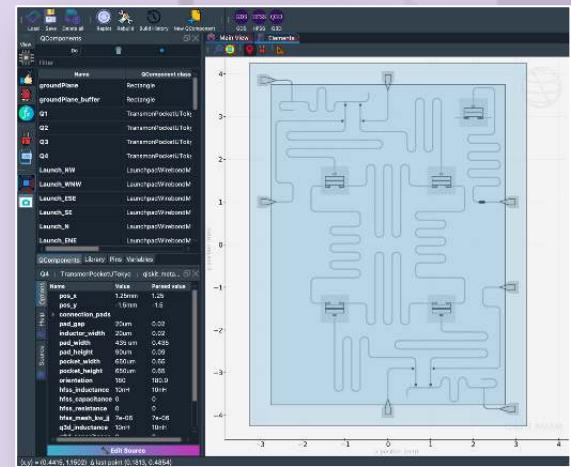
moderate

high

highest*

pyEPR 🍺!

* includes dissipative params



+ pyEPR 🍻!

+ SCQubits ☒

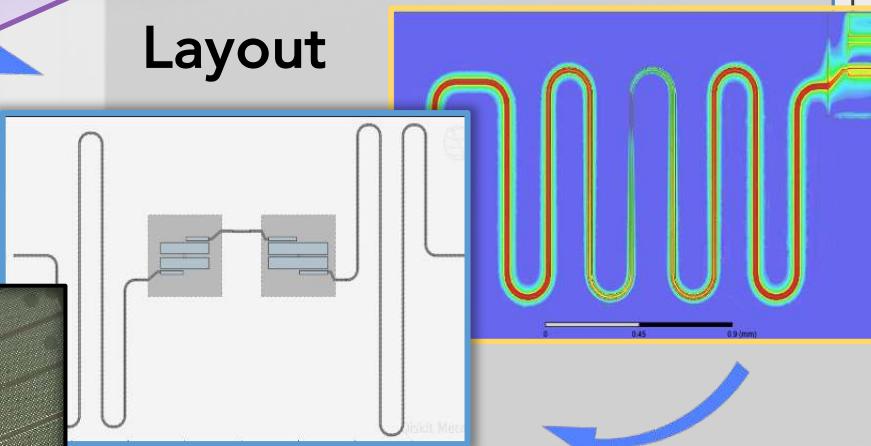
+ QuTiP

⋮

Layout

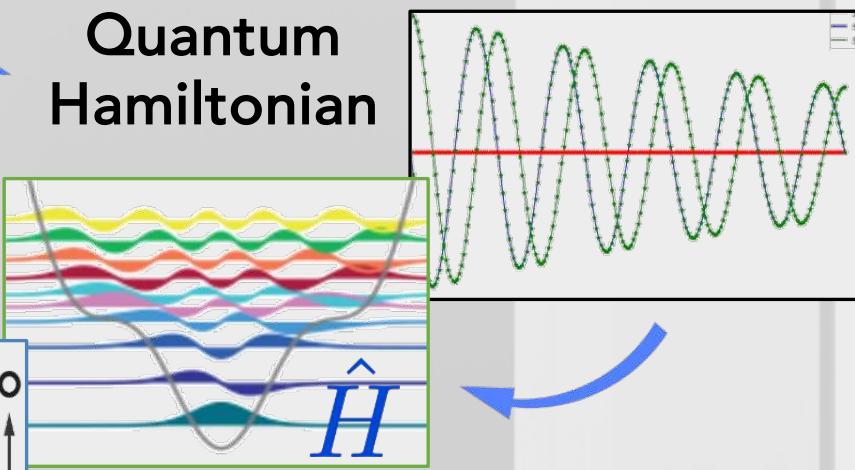
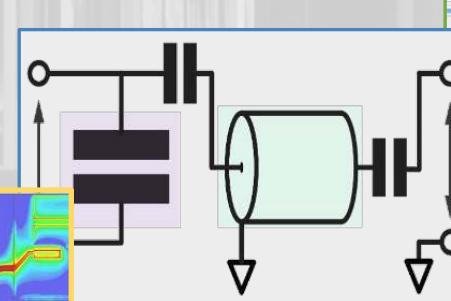
E&M
Simulation

Fabrication



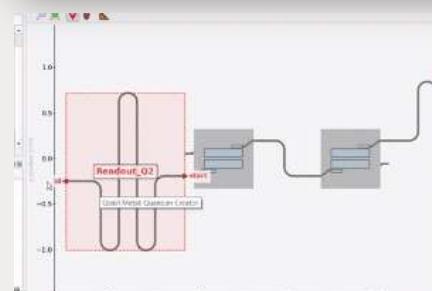
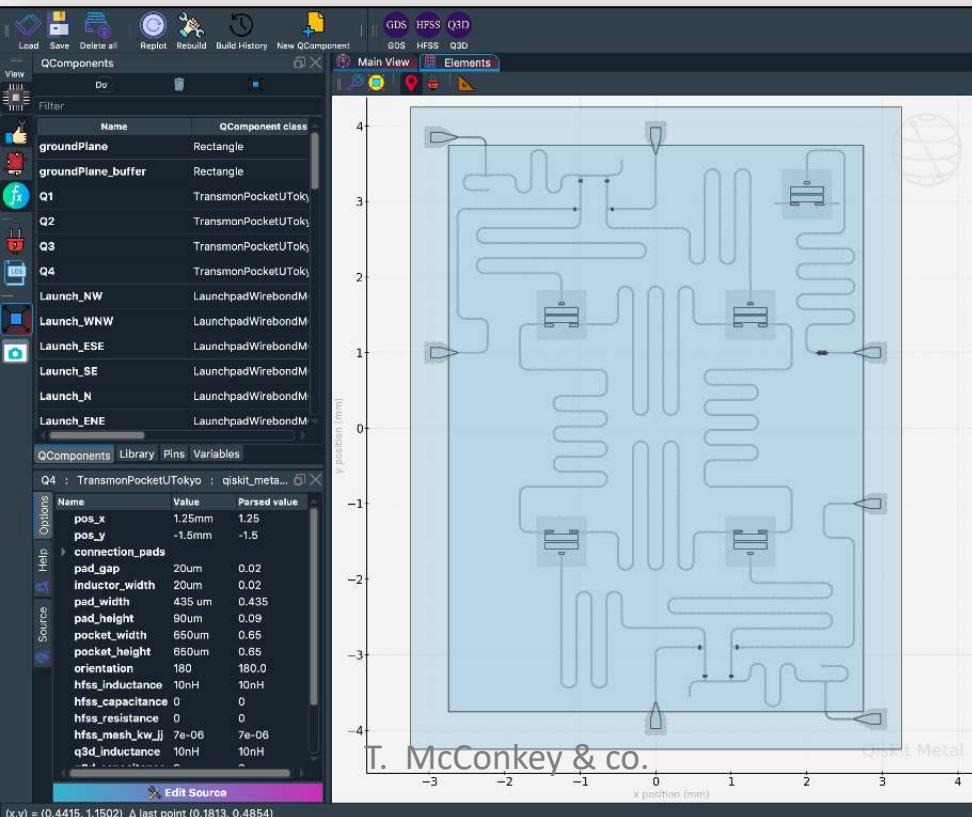
Quantization
Methods

Quantum
Hamiltonian



Gates & time-
evolution analysis

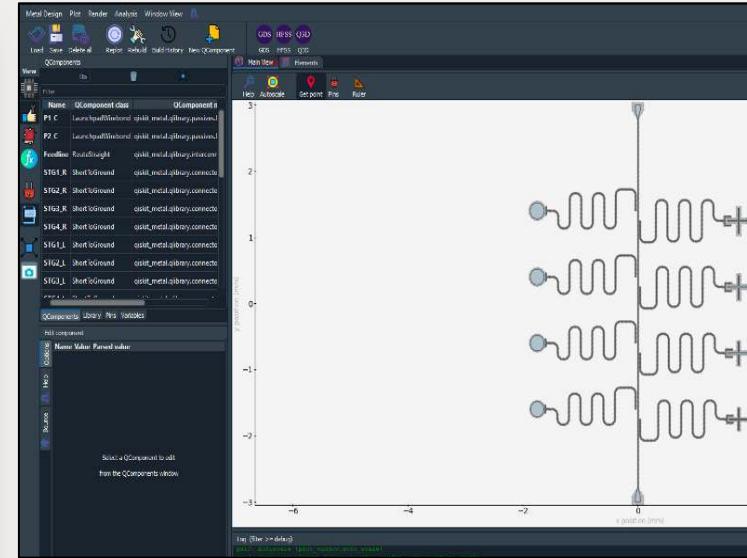
IBM 5Q Tsuru U Tokyo



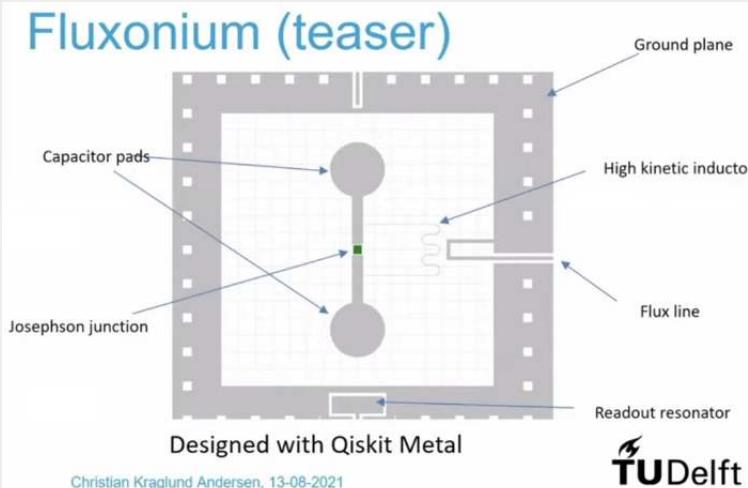
MARCH MEETING 2021
MARCH 15-19 ONLINE

CEC/ICMC 21
VIRTUAL CONFERENCE JULY 19-23
Cryogenics • Through • Collaboration

Chalmers 8Q



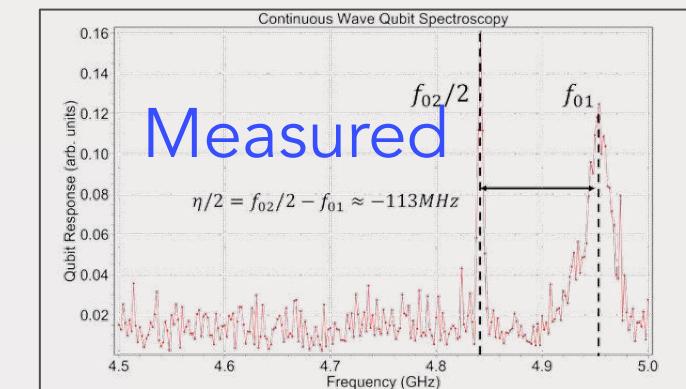
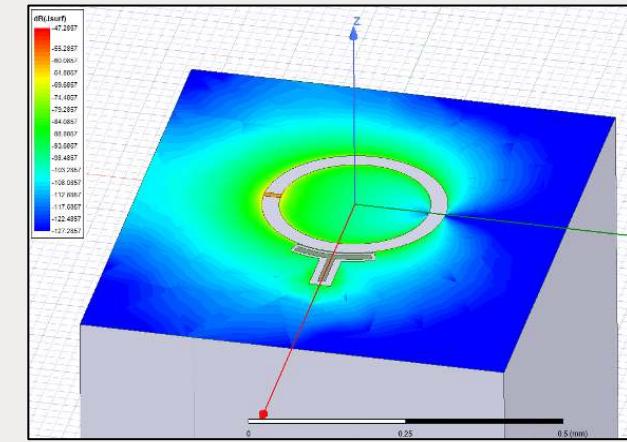
TU Delft Fluxonium Fluxonium (teaser)



Christian Kraglund Andersen, 13-08-2021

TUDelft

Simulated



Measured

• • •

IEEE QUANTUM WEEK

IEEE International Conference
on Quantum Computing
and Engineering — QCE21

Zlatko Minev, IBM Quantum

The Need for Open Quantum Hardware



Zlatko K. Minev

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

Thank you!

"It is enough if one tries merely to comprehend a little of this mystery each day."

A. Einstein



@zlatko_minev



zlatko-minev.com

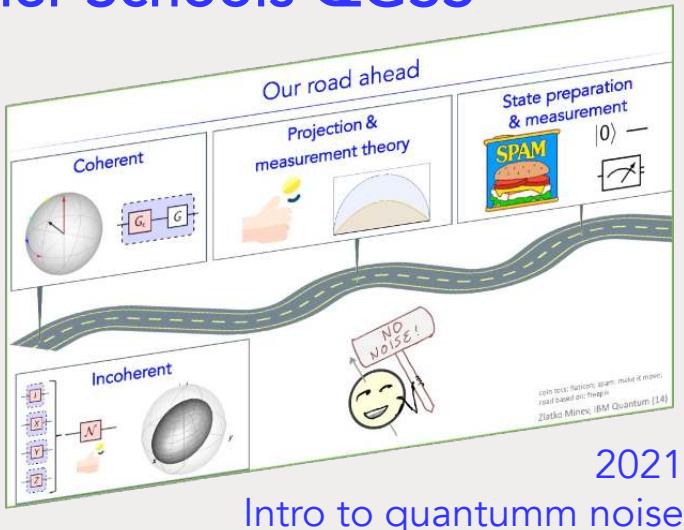


qiskit.org/metal

Ways to learn more



Global Summer Schools QGSS



Qiskit

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Start learning →

Feedback



Quantum Seminar Series

(host: Minev; level: advanced)



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open access

Qiskit SDK

An open-source SDK for working with quantum computers at the level of pulses, circuits, and algorithms.

🔗 <https://qiskit.org> 📧 hello@qiskit.org

Zlatko Minev, IBM Quantum