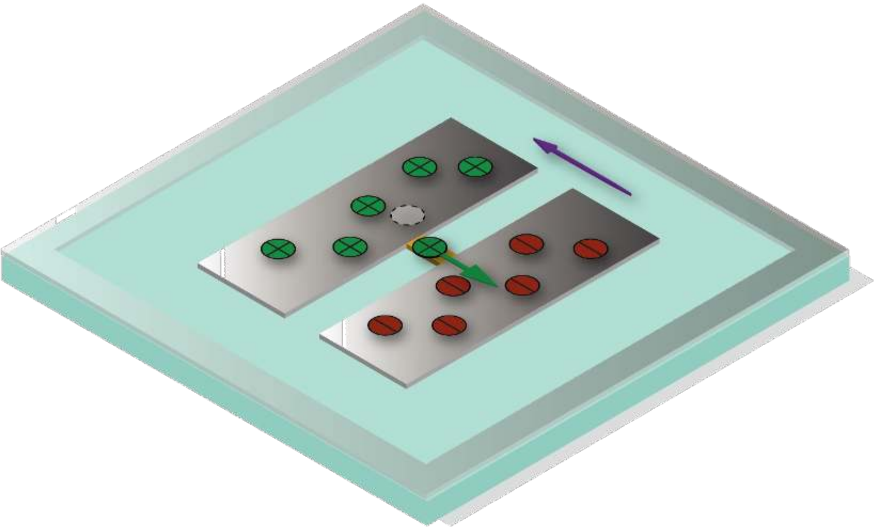
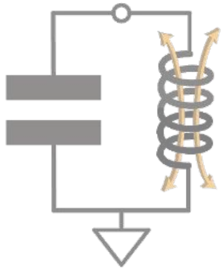
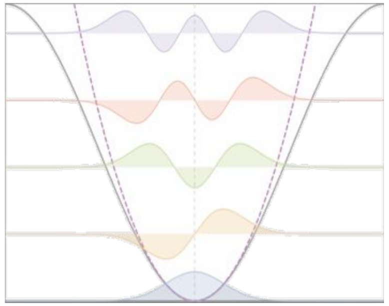
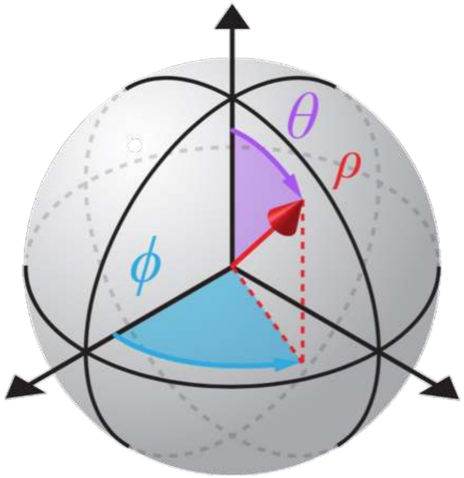
Quantum Hardware Design

Energy, Circuits, and Metal









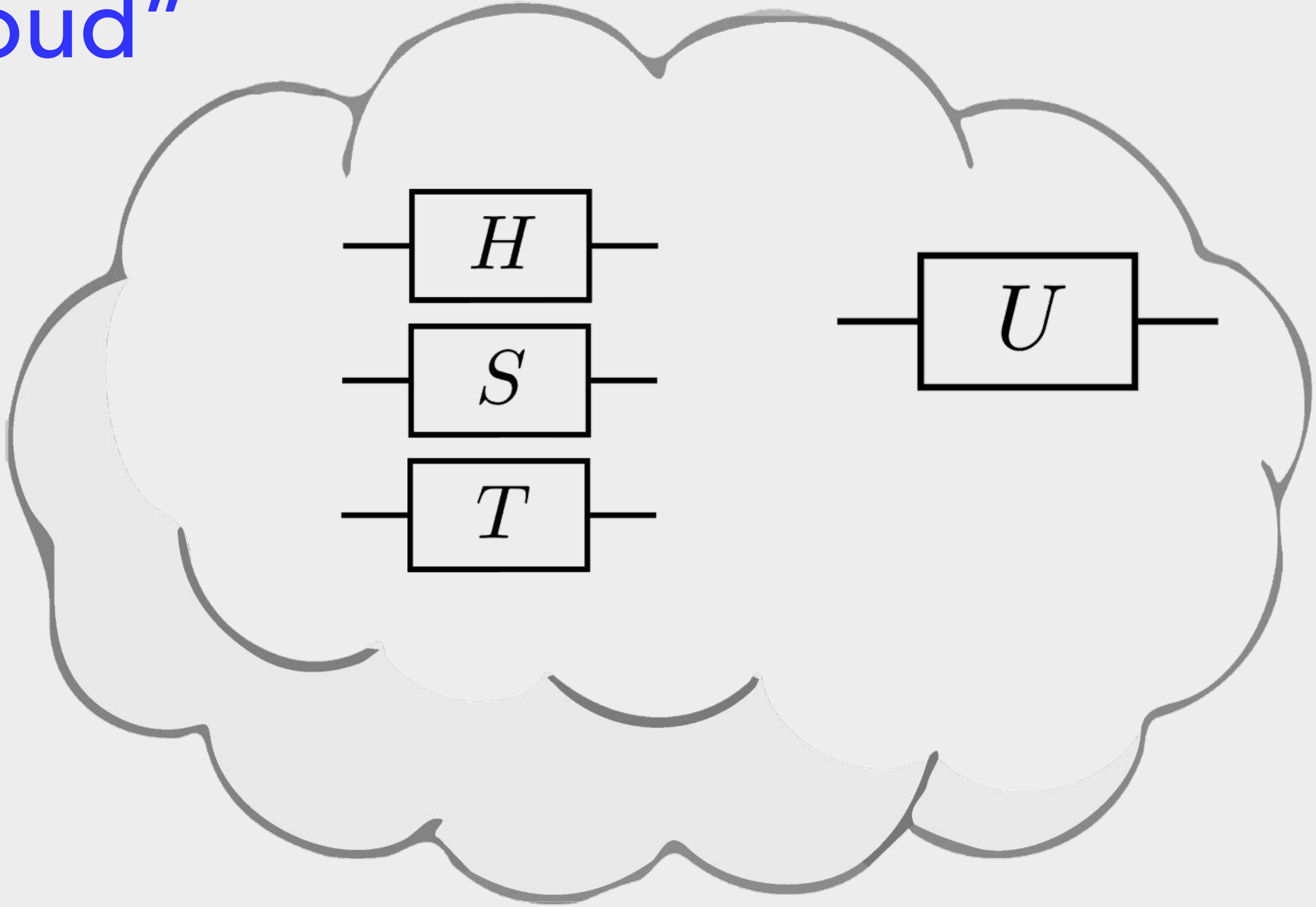
Zlatko K. Minev

IBM **Quantum**

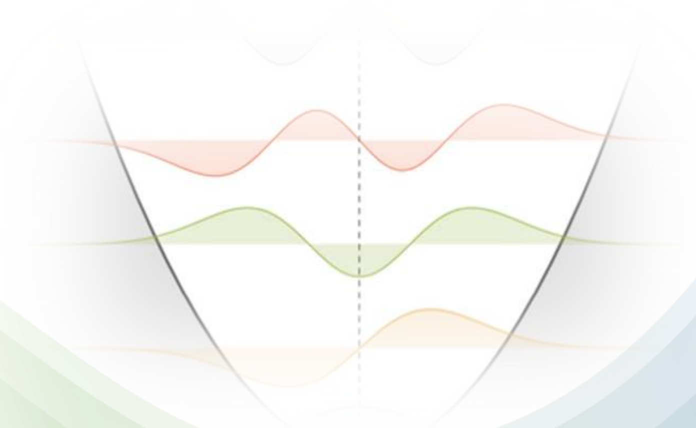
IBM T.J. Watson Research Center, Yorktown Heights, NY

@zlatko_minev zlatko-minev.com qiskit.org/metal

"Quantum cloud"

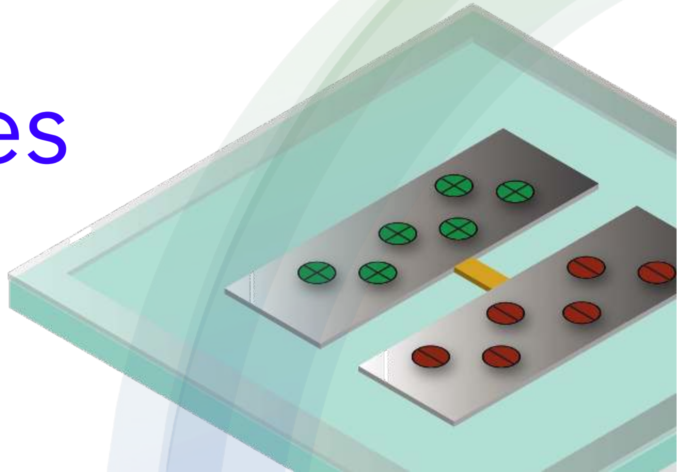


Laptop image: rawpixel.com; Photos: IBM



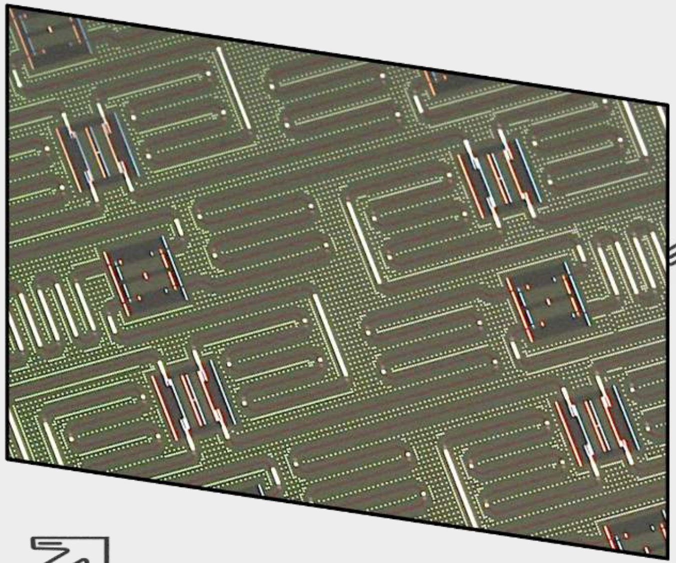
"Quantum phenomena
do *not* occur in a Hilbert space,
they occur in a laboratory."

Asher Peres



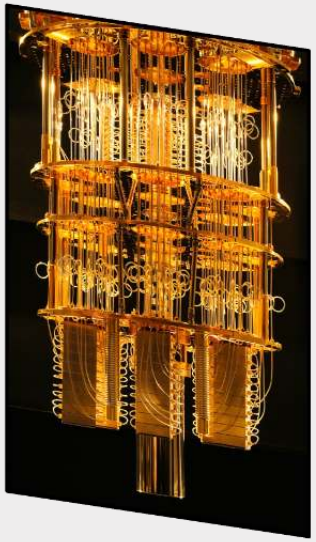
Quantum in the cloud or lab

Superconducting qubits



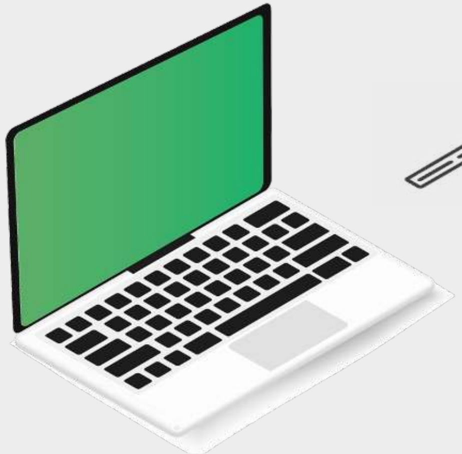
…

Quantum-device chip



Cryogenic environment

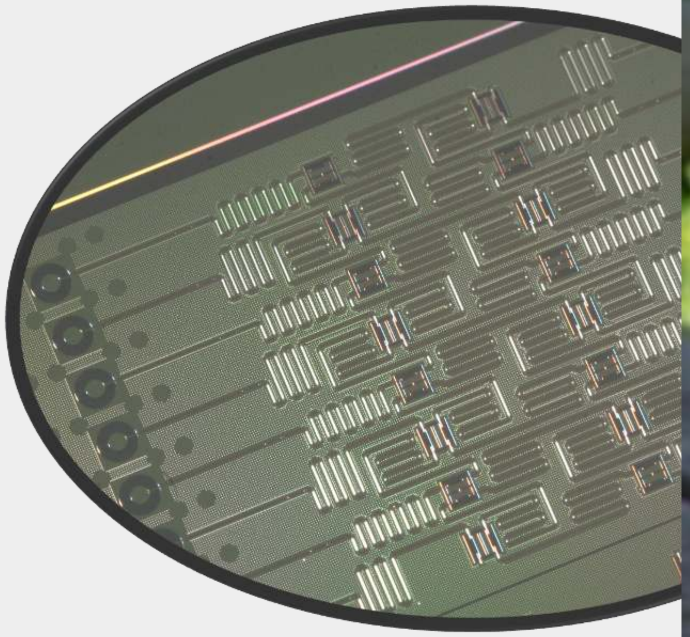
Lab / cloud facility

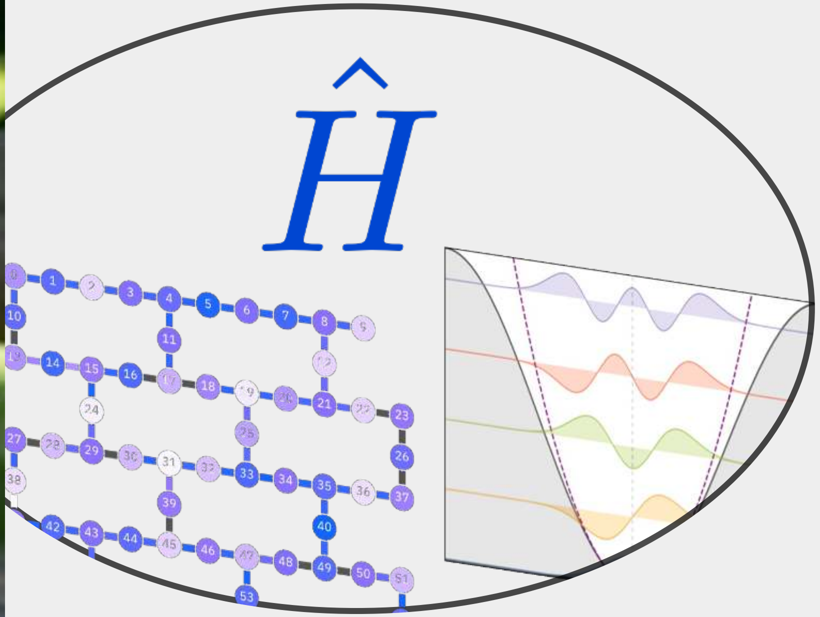


Quantum community

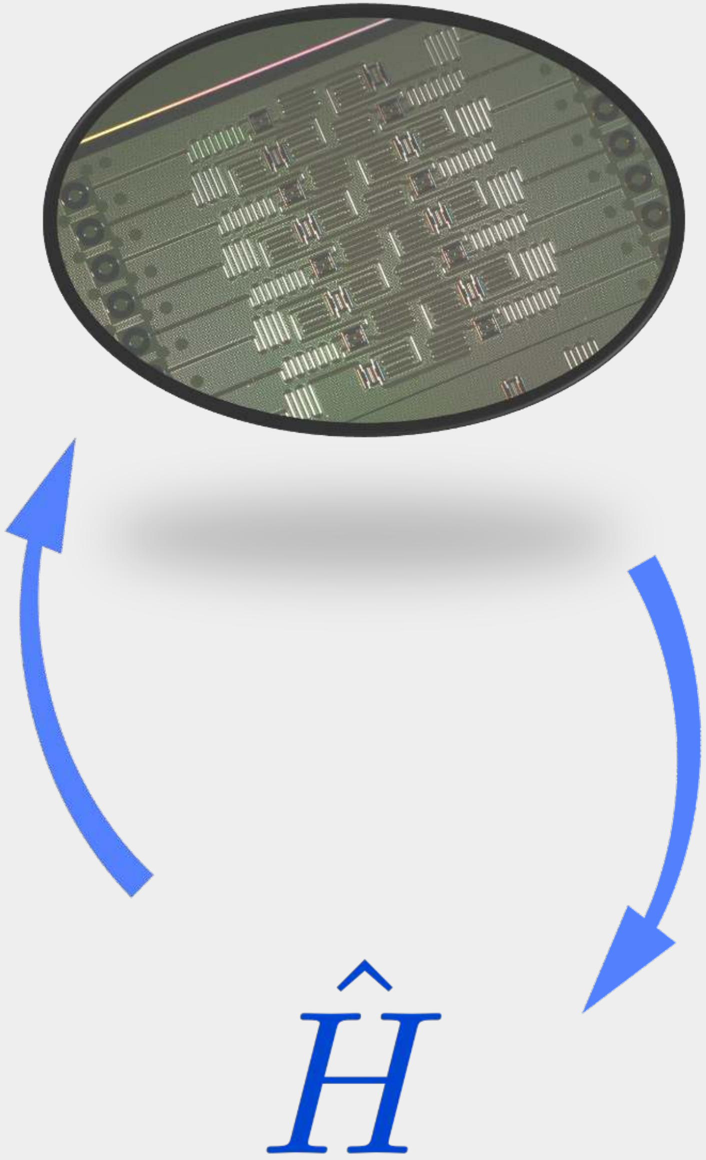
Laptop image: rawpixel.com; Photos: IBM

Physical Devices ↔ Quantum Hamiltonian





Physical Devices ↔ Quantum Hamiltonian



Overview of design

I just want the answer: Qiskit Metal it for me

You can design your own quantum chip! Open-source
(IBM)

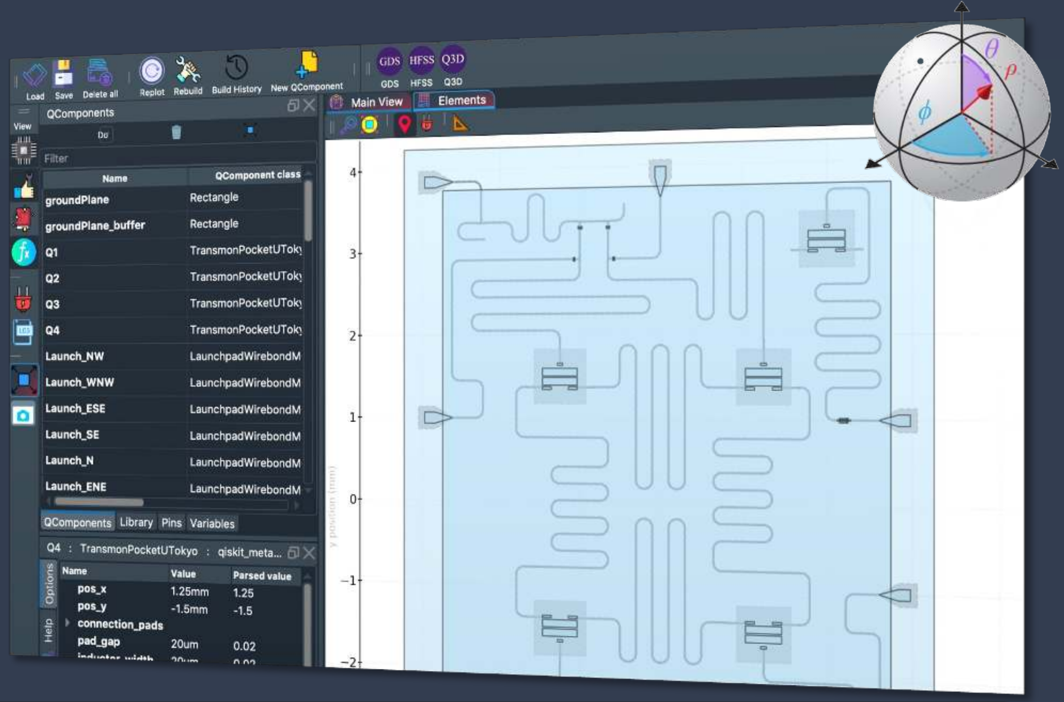
Energy-participation ratio (EPR)

Minev et al. arXiv:1902.10355 & arXiv:2010.00620
(Yale)

cQED with quasi-lumped models (LOM)

Minev et al. arXiv:2103.10344
(IBM)

Qiskit | quantum device design



Zlatko Minev
PI & Lead

Thomas McConkey
Co-PI

Open source
Apache 2.0!
qiskit.org/metal


Jeremy Drysdale


Priti Shah


Dennis Wang


Yehan Liu


Grace Harper


Marco Facchini


John Blair

Interns


Olivia Lanes

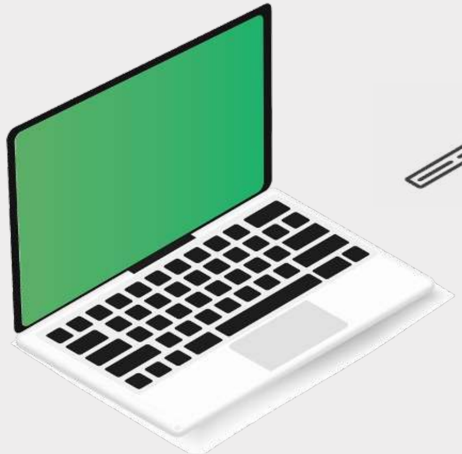

Will Shanks

Power-Ups

Close collab

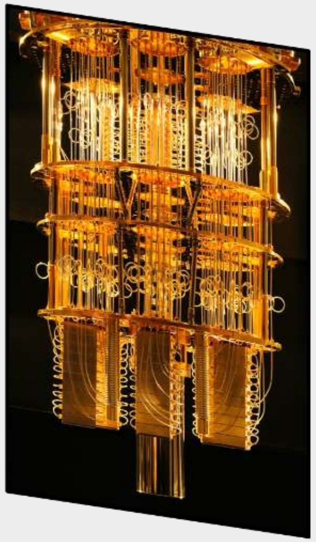
Quantum in the cloud or lab

Superconducting qubits

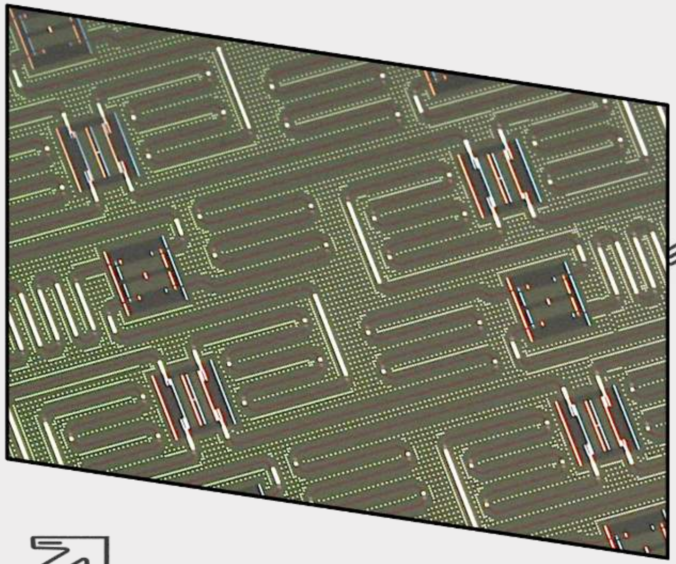


Quantum community

Lab / cloud facility



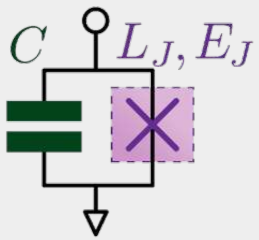
Cryogenic environment



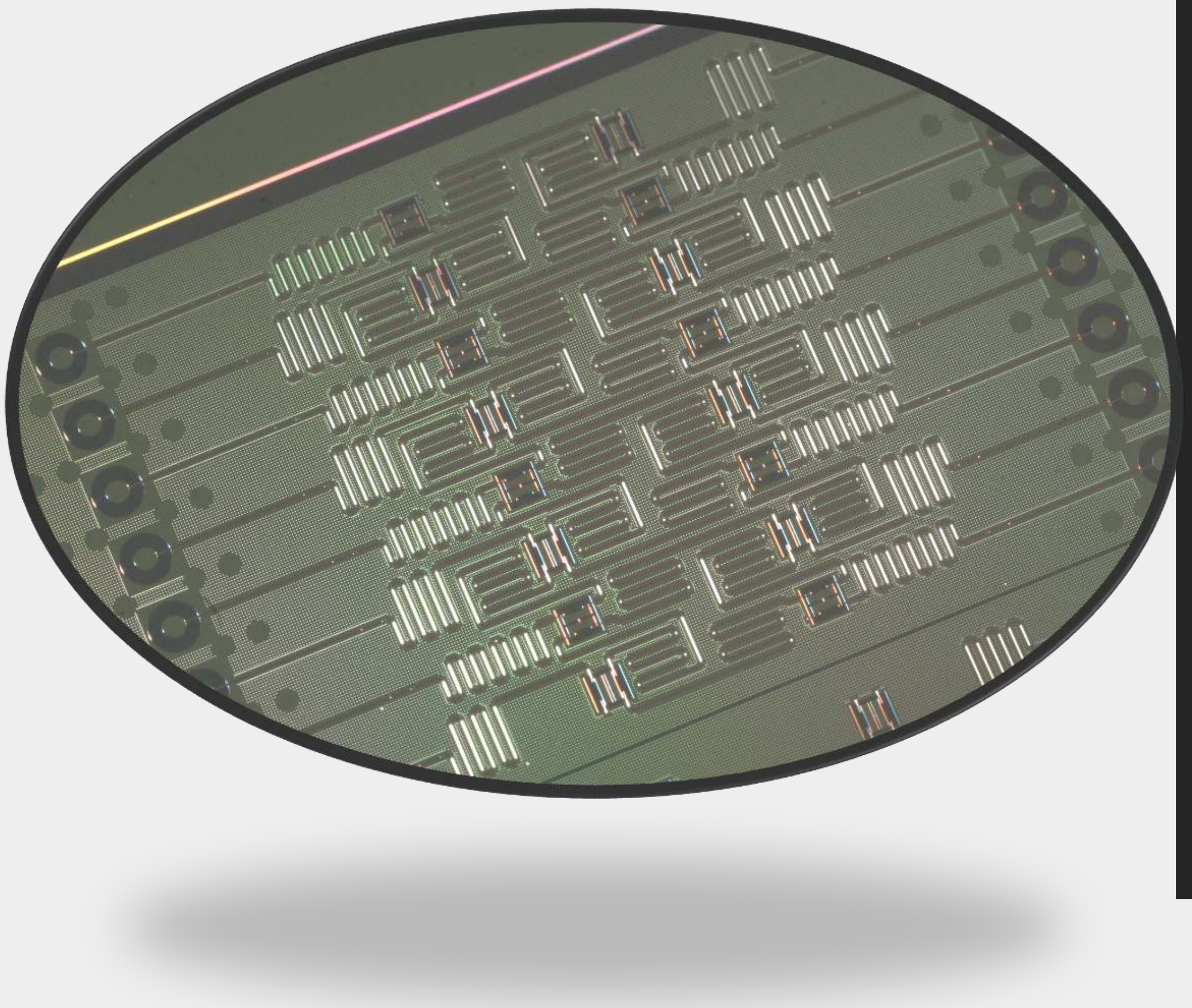
Quantum-device chip

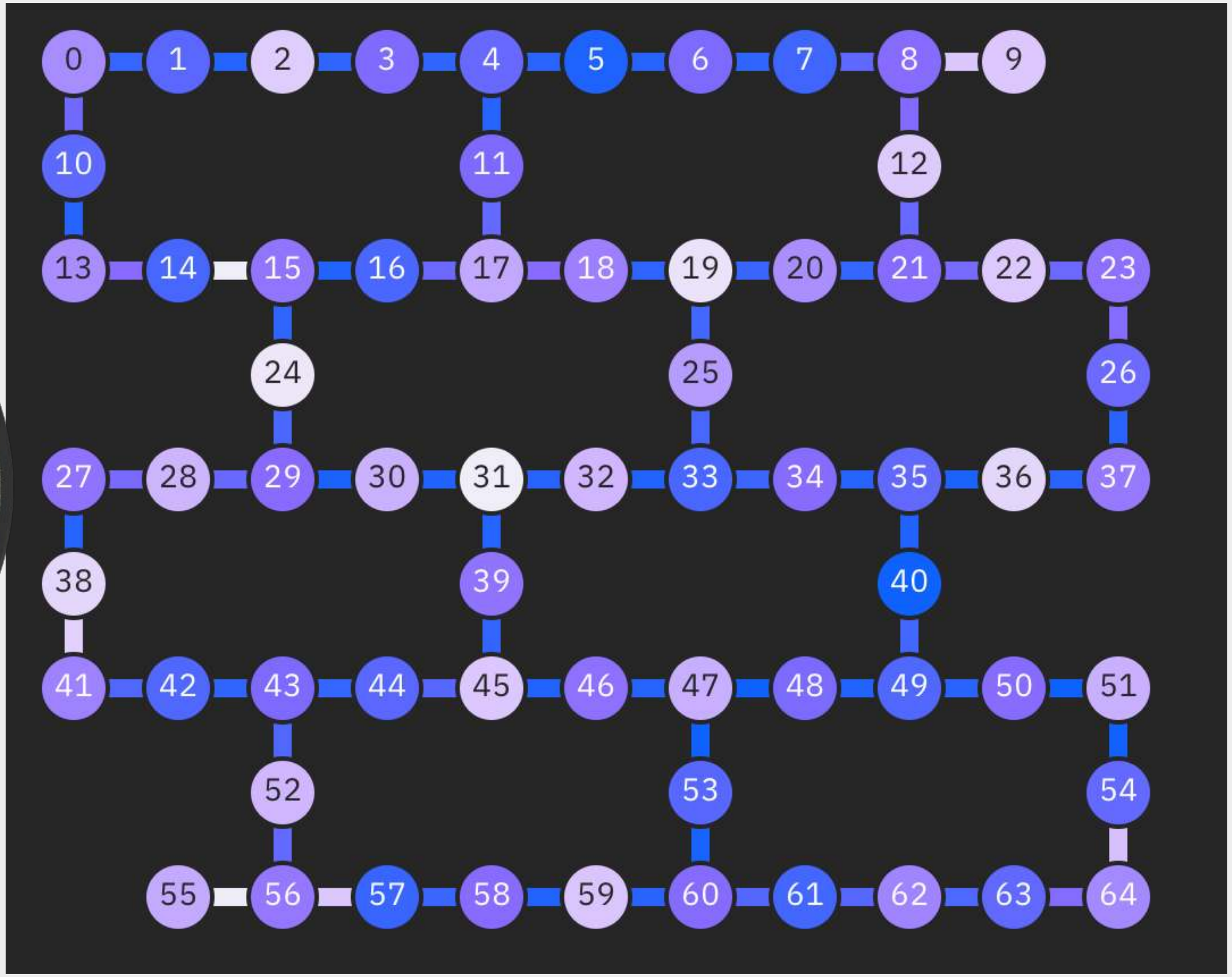
...

Laptop image: rawpixel.com; Photos: IBM



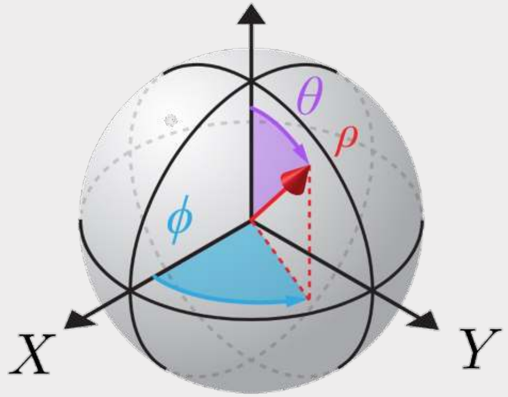
Quantum computer made from `artificial atoms’



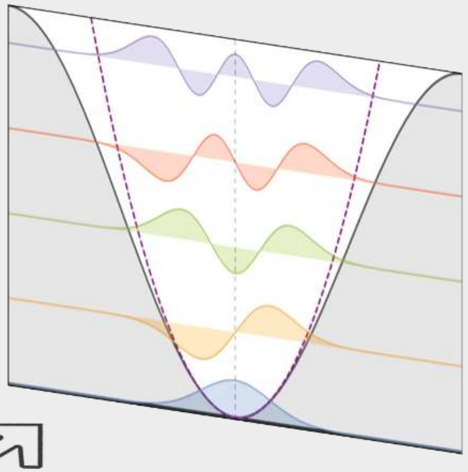


Quantum Device Design

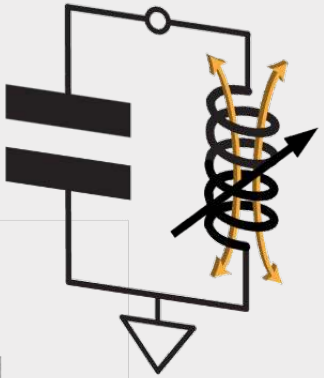
Superconducting circuits



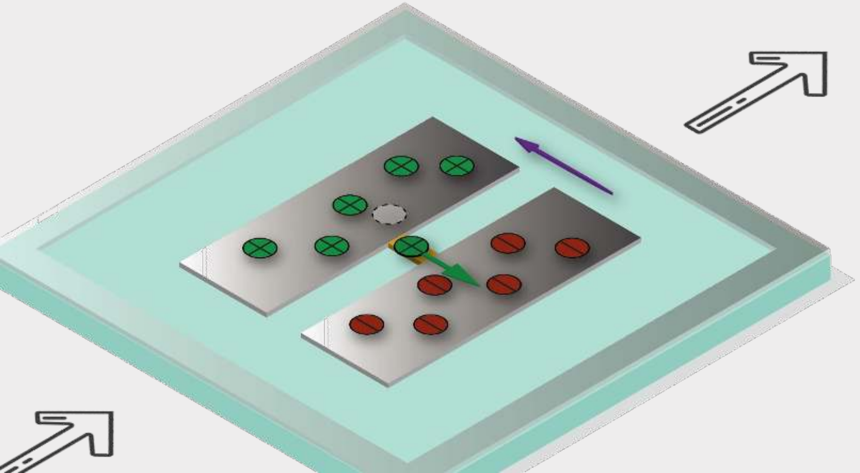
Qubit Hilbert space



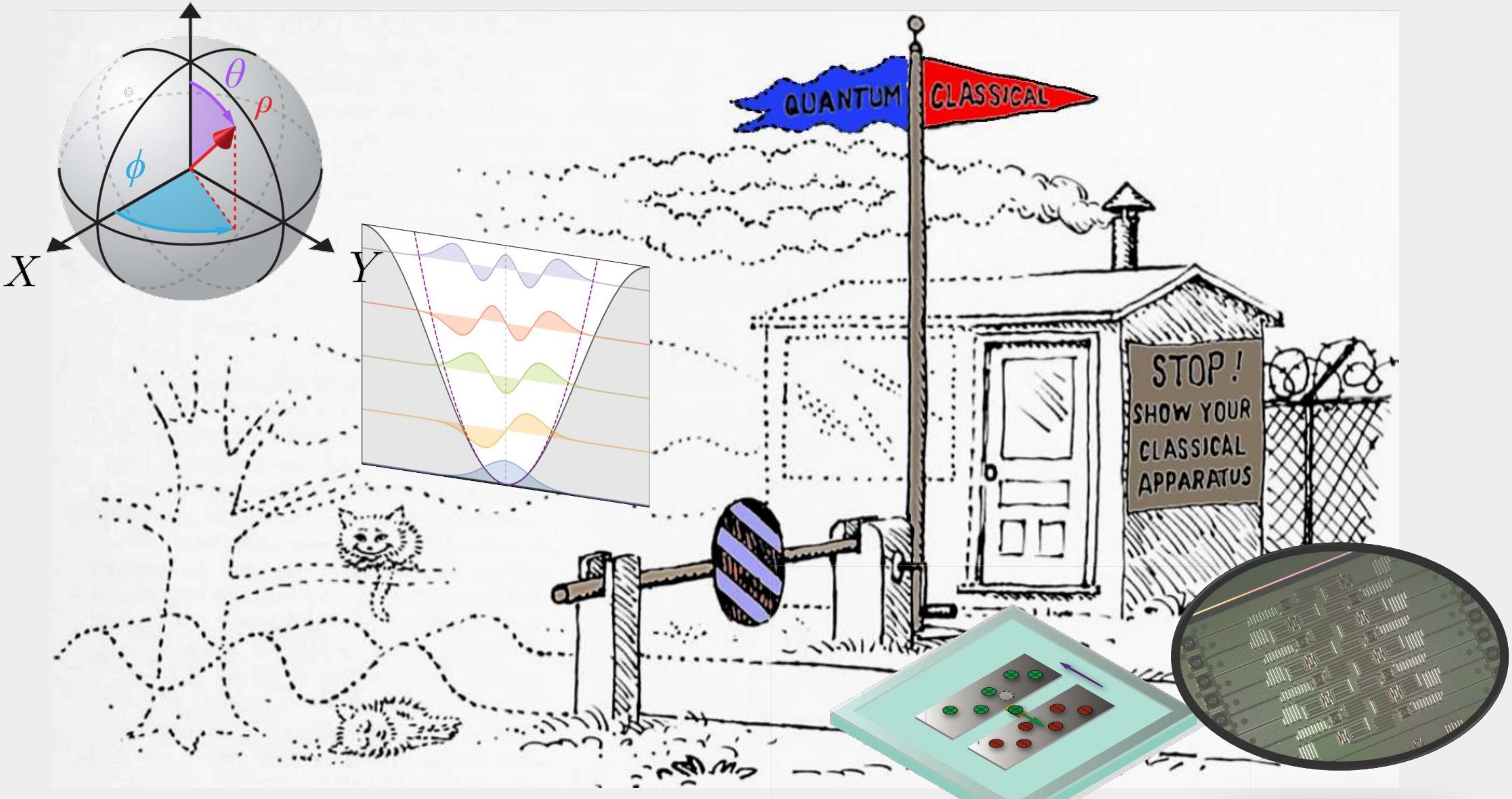
Quantum Hamiltonian analysis



Electromagnetic analysis



Physical layout



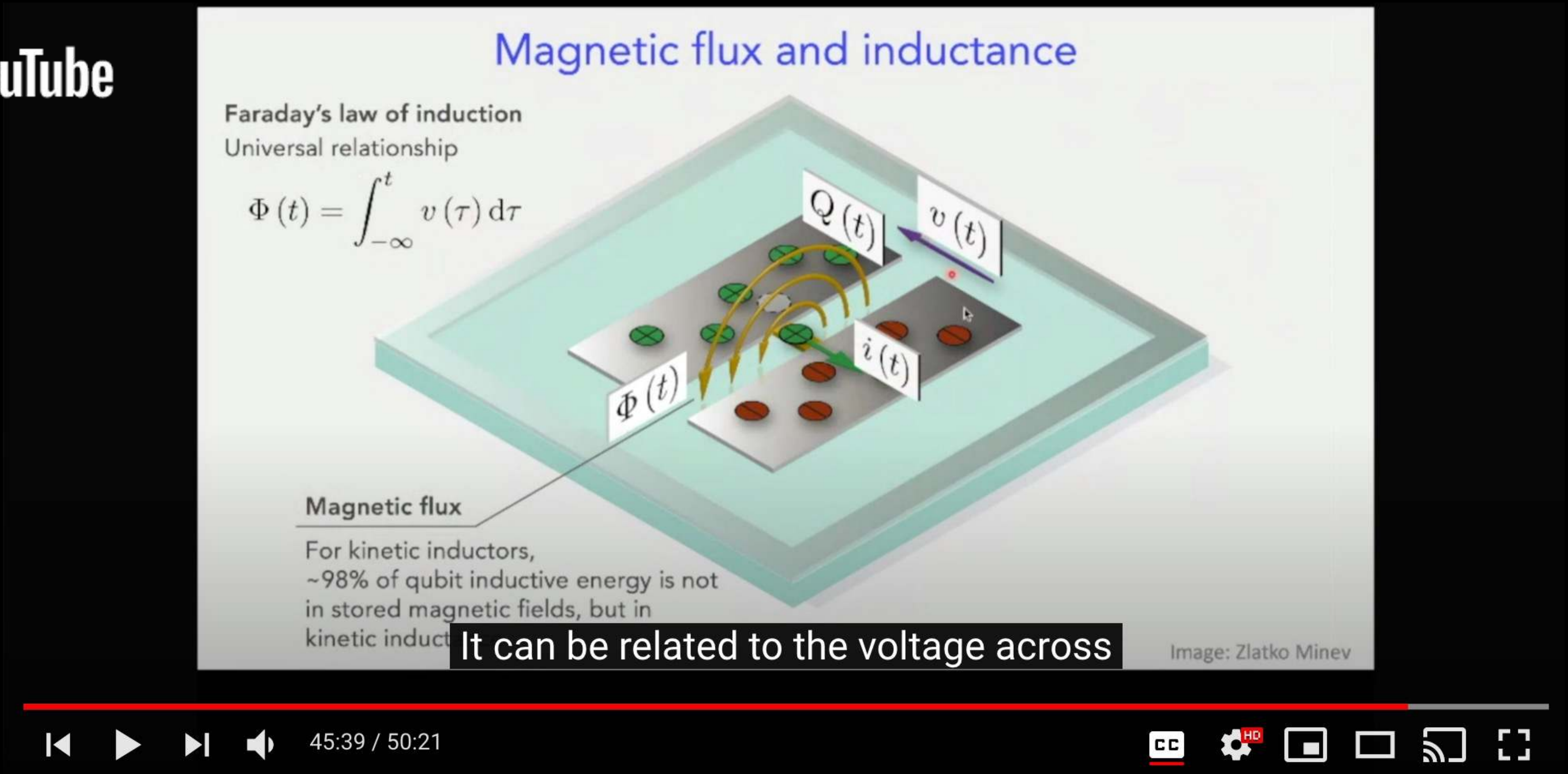
ing: Zurek, Physics Today (1991)

To do **quantum**,

start with **classical**

Summer School Lectures

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

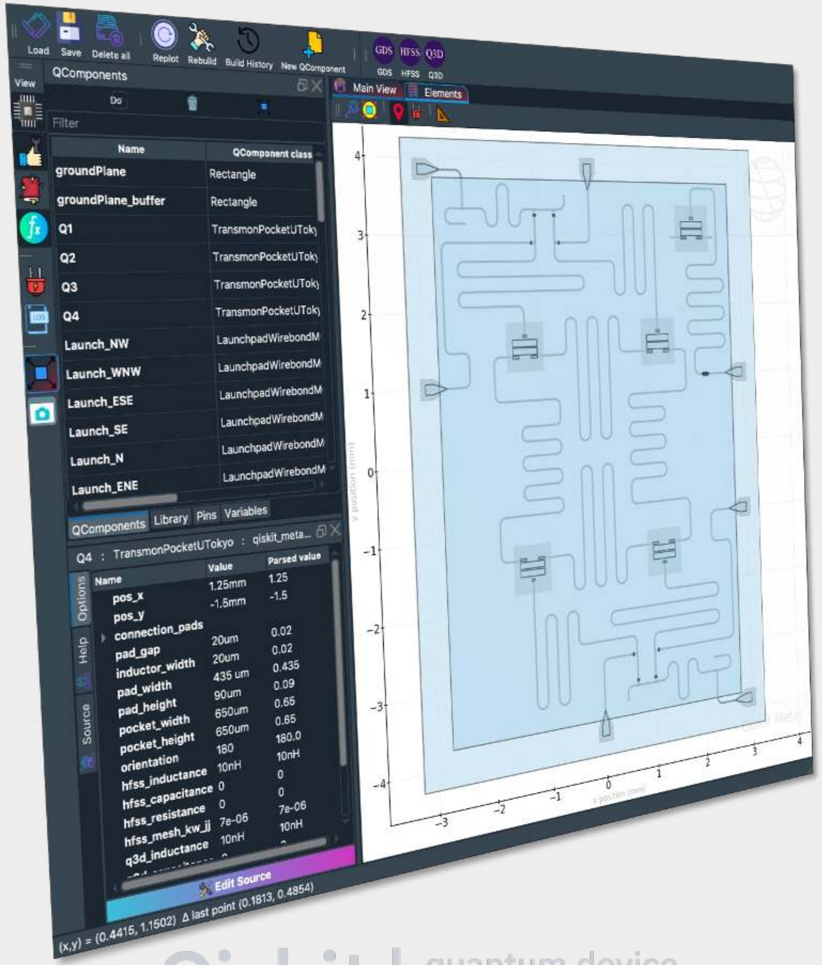


For more information, review the **Introduction to Quantum Computing and Quantum Hardware** lectures below

- Superconducting Qubits I: Quantizing a Harmonic Oscillator, Josephson Junctions Part 1 — Lecture Video | Lecture Notes | Lab
- Superconducting Qubits I: Quantizing a Harmonic Oscillator, Josephson Junctions Part 2 — Lecture Video | Lecture Notes | Lab
- Superconducting Qubits I: Quantizing a Harmonic Oscillator, Josephson Junctions Part 3 — Lecture Video | Lecture Notes | Lab
- Superconducting Qubits II: Circuit Quantum Electrodynamics, Readout and Calibration Methods Part 1 — Lecture Video | Lecture Notes | Lab
- Superconducting Qubits II: Circuit Quantum Electrodynamics, Readout and Calibration Methods Part 2 — Lecture Video | Lecture Notes | Lab
- Superconducting Qubits II: Circuit Quantum Electrodynamics, Readout and Calibration Methods Part 3 — Lecture Video | Lecture Notes | Lab

48:03 / 50:21

There's a description for every job



Qiskit | quantum device design

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

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

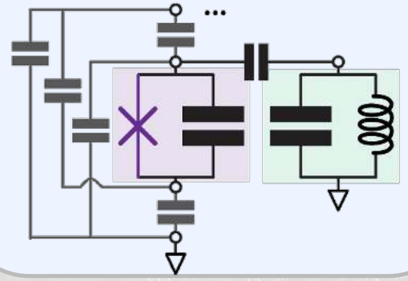
$$\hat{H}_{\mathrm{tot}} = \hat{H}_{\mathrm{lin}} + \hat{H}_{\mathrm{nl}}$$

Landscape of quantization methods

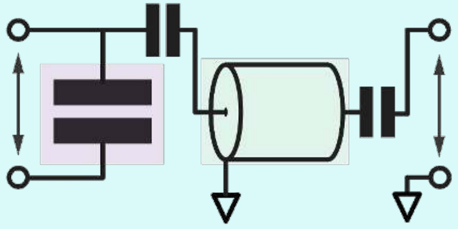
quasi-static

full-wave

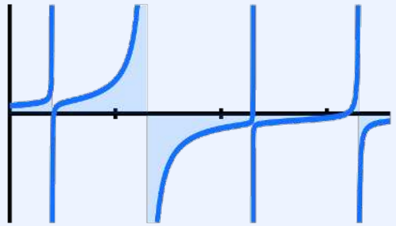
lumped



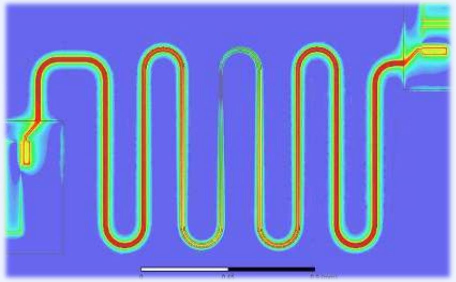
quasi-lumped



impedance



energy



fast

more information, complexity, accuracy

Qiskit | quantum device design
Metal

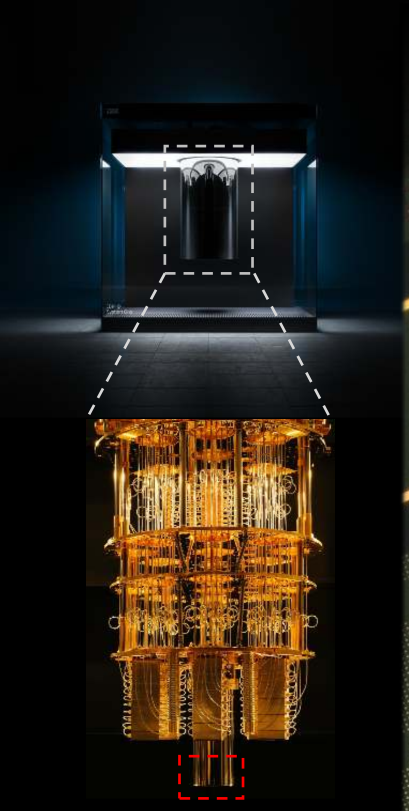
Yurke & Denker (1984), Devoret (1997), Burkard *et al.* (2004), Koch *et al*…

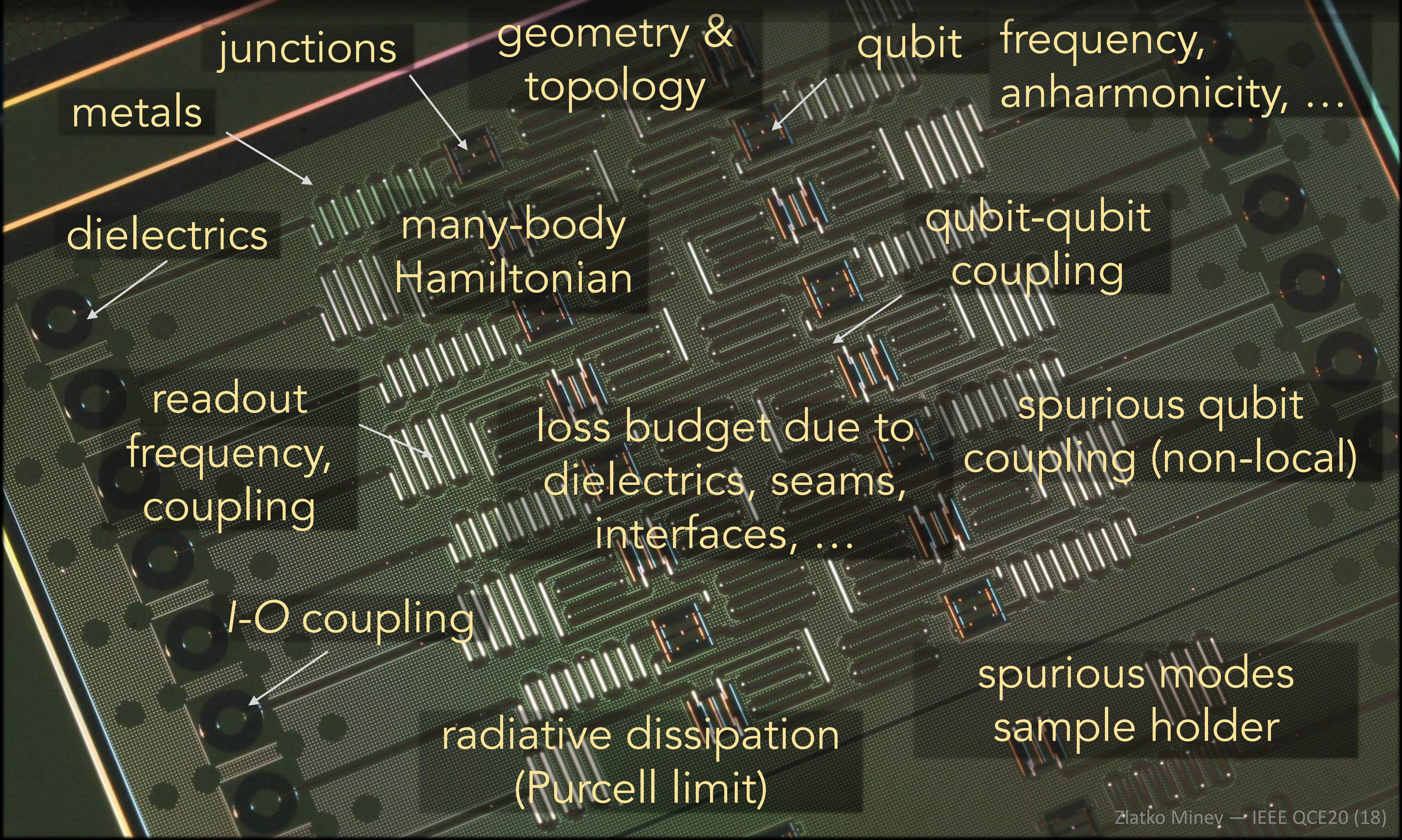
Malekakhlagh *et al.* (2017, 2019), Gely *et al.* (2019), Parra-Rodriguez *et al.* (2019), Minev *et al.* (2021), …

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

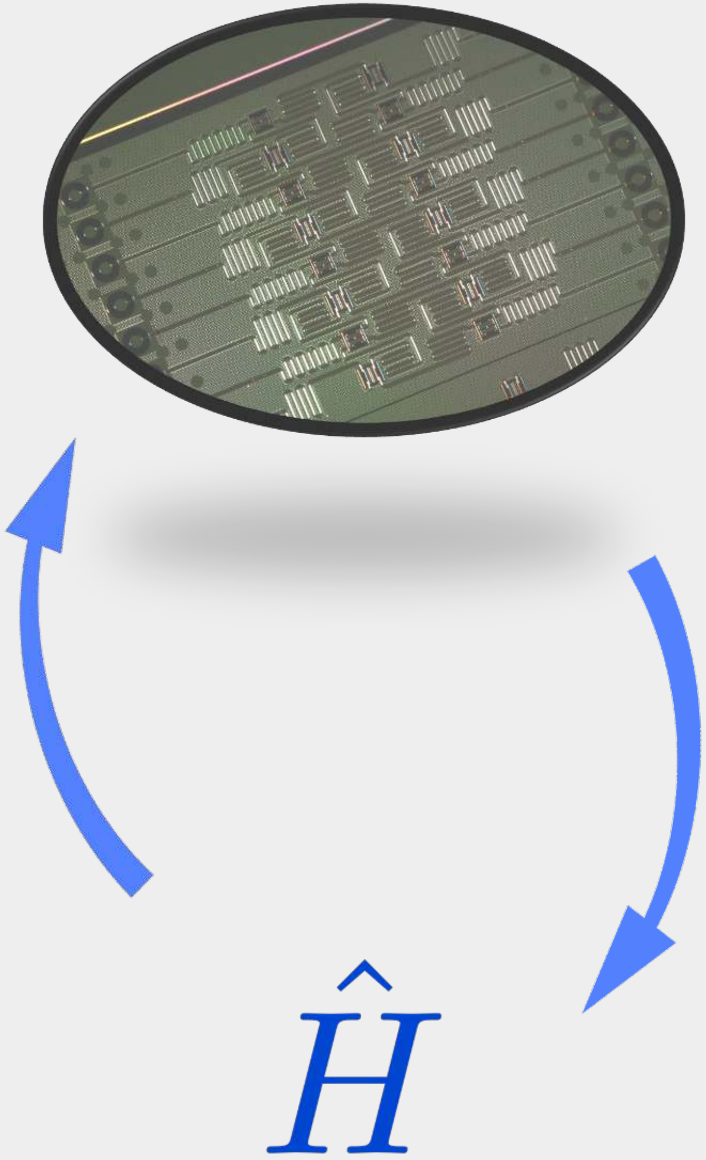
Minev (2018)
Minev *et al.* (2020)

What needs to be designed?





Physical Devices ↔ Quantum Hamiltonian



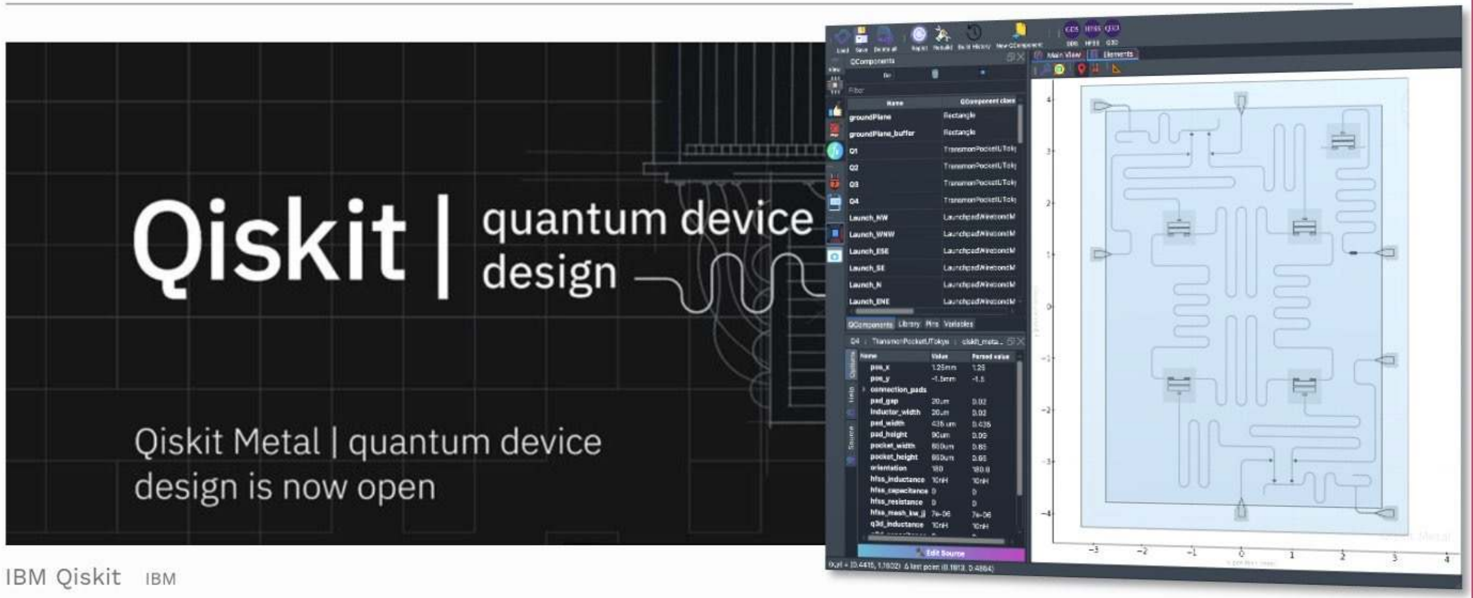
You can design your own quantum chip!

Open source
(IBM)

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

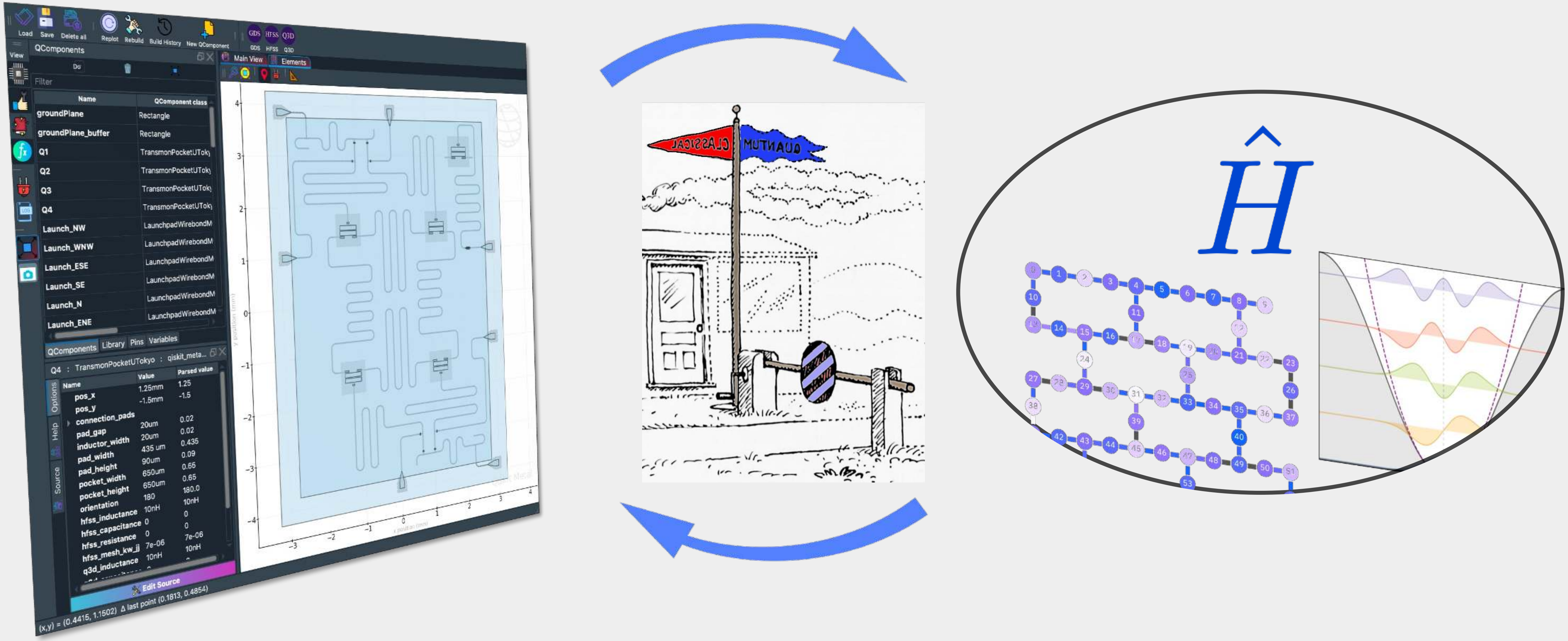
Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Group
Cloud
Analyst-in-residence, Quantum Computing



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

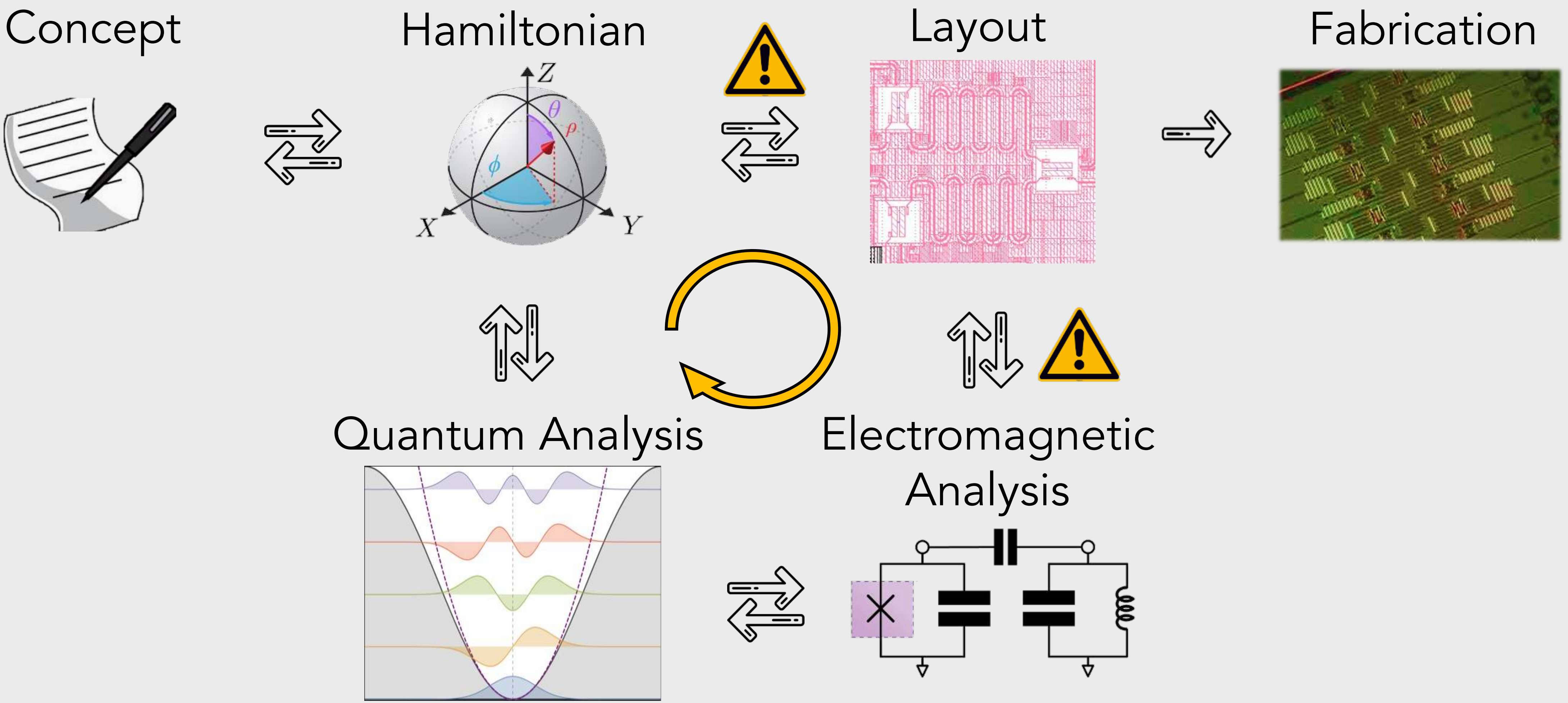
Make easy?


Load
Save
Delete all
Replot
Rebuild
Build History
New QComponent
GDS
HFSS
Q3D
QComponents
Main View
Elements
Filter
Name
QComponent class
groundPlane
Rectangle
groundPlane_buffer
Rectangle
Q1
Q2
Q3
Q4
Launch_NW
Launch_WNW
Launch_ESE
Launch_SE
Launch_N
Launch_ENE
QComponents
Library
Pins
Variables
Q4 : TransmonPocketUTokyo
Name
Value
Parsed value
pos_x
1.25mm
1.25
pos_y
-1.5mm
-1.5
connection_pads
pad_gap
inductor_width
pad_width
pad_height
pocket_width
pocket_height
orientation
hfss_inductance
hfss_capacitance
hfss_resistance
hfss_mesh_kw_jj
q3d_inductance
Edit Source
(x,y) = (0.4415, 1.1502) Δ last point (0.1813, 0.4854)
$\hat{H}$

Quantum chip design flow

Complexity, Information, Accuracy

Risk, Cost, Time, Resources



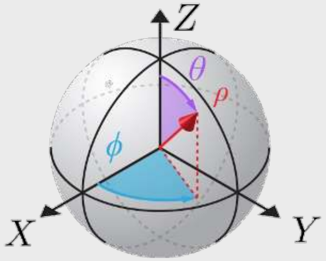
Quantum chip design flow

Complexity, Information, Accuracy

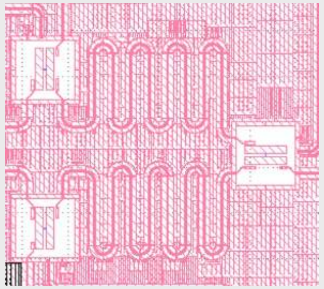
Risk, Cost, Time, Resources

Concept

Hamiltonian

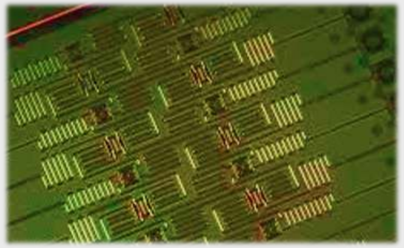


Layout

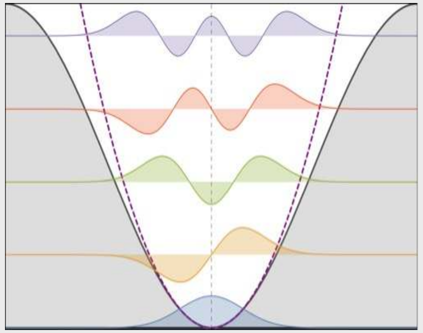


DRC
LVS

Fabrication

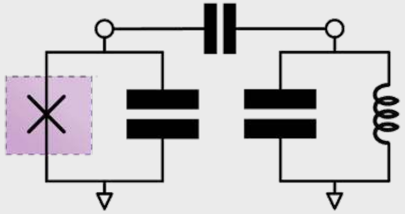


Quantum Analysis



Project
Metal

Electromagnetic Analysis



Let's layout, analyze, and optimize a four-qubit chip…

Open source
qiskit.org/metal

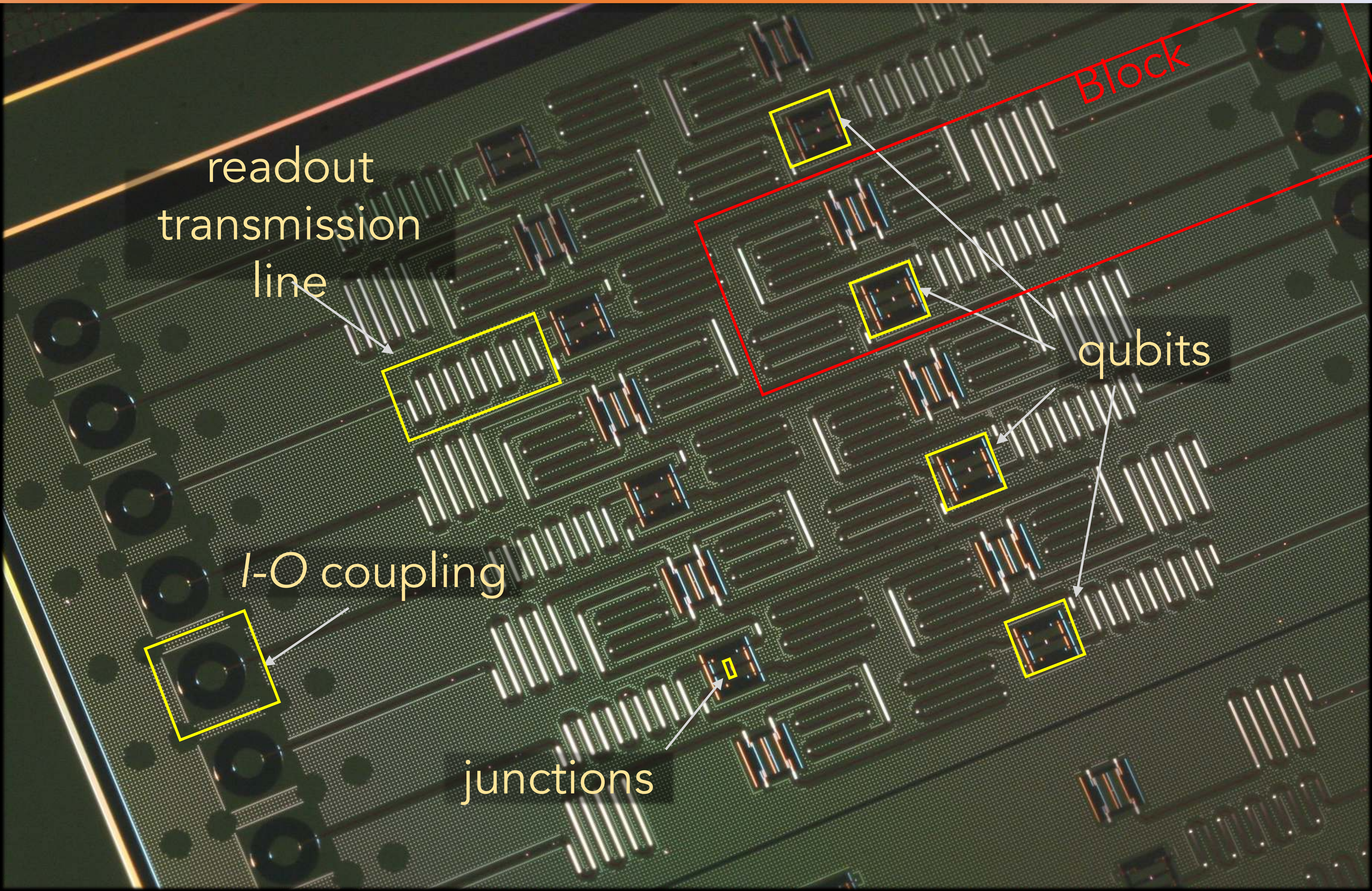
Regularity is our greatest ally in chip design

Reuse

Fine-tune

Automate

Extend



Device Library

Qiskit | quantum device design

Qiskit   Learning Resources   Slack Support   IBM Quantum Dashboard   Github

0.0.2

Search Docs

Home
Installing Qiskit Metal
Frequently Asked Questions
Roadmap
Qiskit Metal Workflow
Quantization Methods Overview

Contributor Guide

Contributing to Qiskit Metal
Where Things Are
Reporting Bugs and Requesting Enhancements
Contributing Code
Contributing to Documentation

Docs > Qiskit Metal | Quantum Device Design & Analysis (Q-EDA) 0.0.2

Qiskit Metal | Quantum Device Design & Analysis (Q-EDA) 0.0.2

ATTENTION

This is an alpha version of Qiskit Metal, the code is still under development. Please let us know about anything you might want us to add or elaborate upon in the Slack channel #metal in the qiskit workspace.

HINT

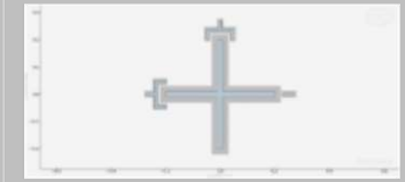
You can open this documentation using

```
import qiskit_metal
qiskit_metal.open_docs()
```

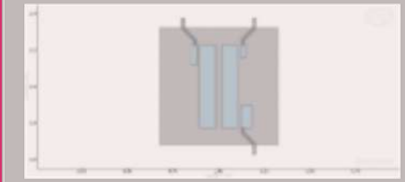
Circuit Example Library

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

Qubits



Single Transmon - Grounded (xmon)



Single Transmon - Floating

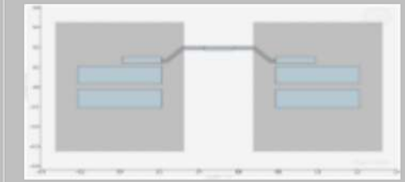
Concentric Transmon

Resonators

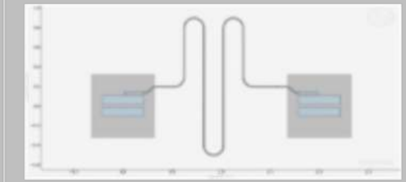
Simple CPW Meander

Qubit Couplers

Tunable Coupler (MIT)

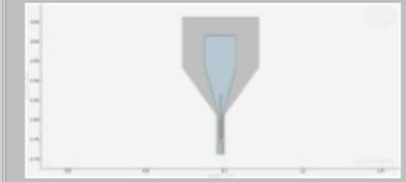


Direct Coupler (transmon-transmon)



Bus Resonator Coupler (transmon-transmon)

Input-Ouput Coupling



CPW Launch Pad

Readout line

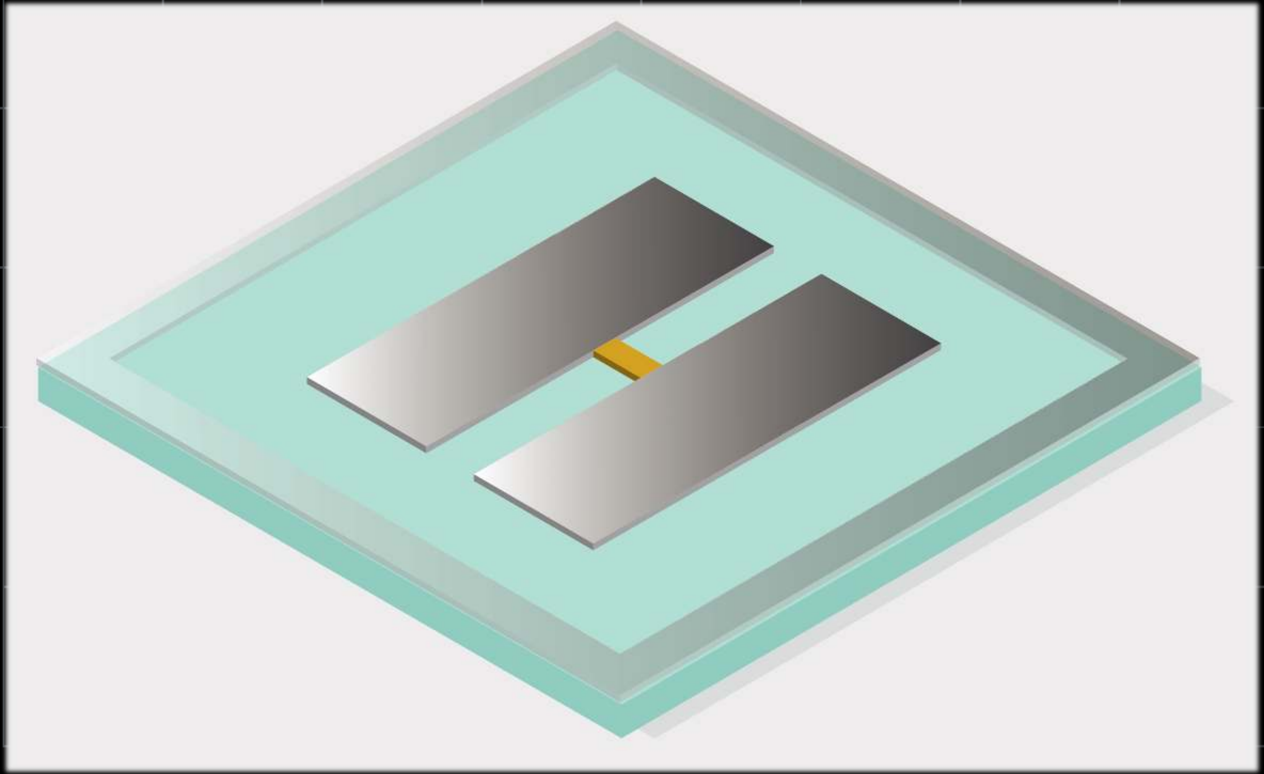
...

qiskit.org/documentation/metal

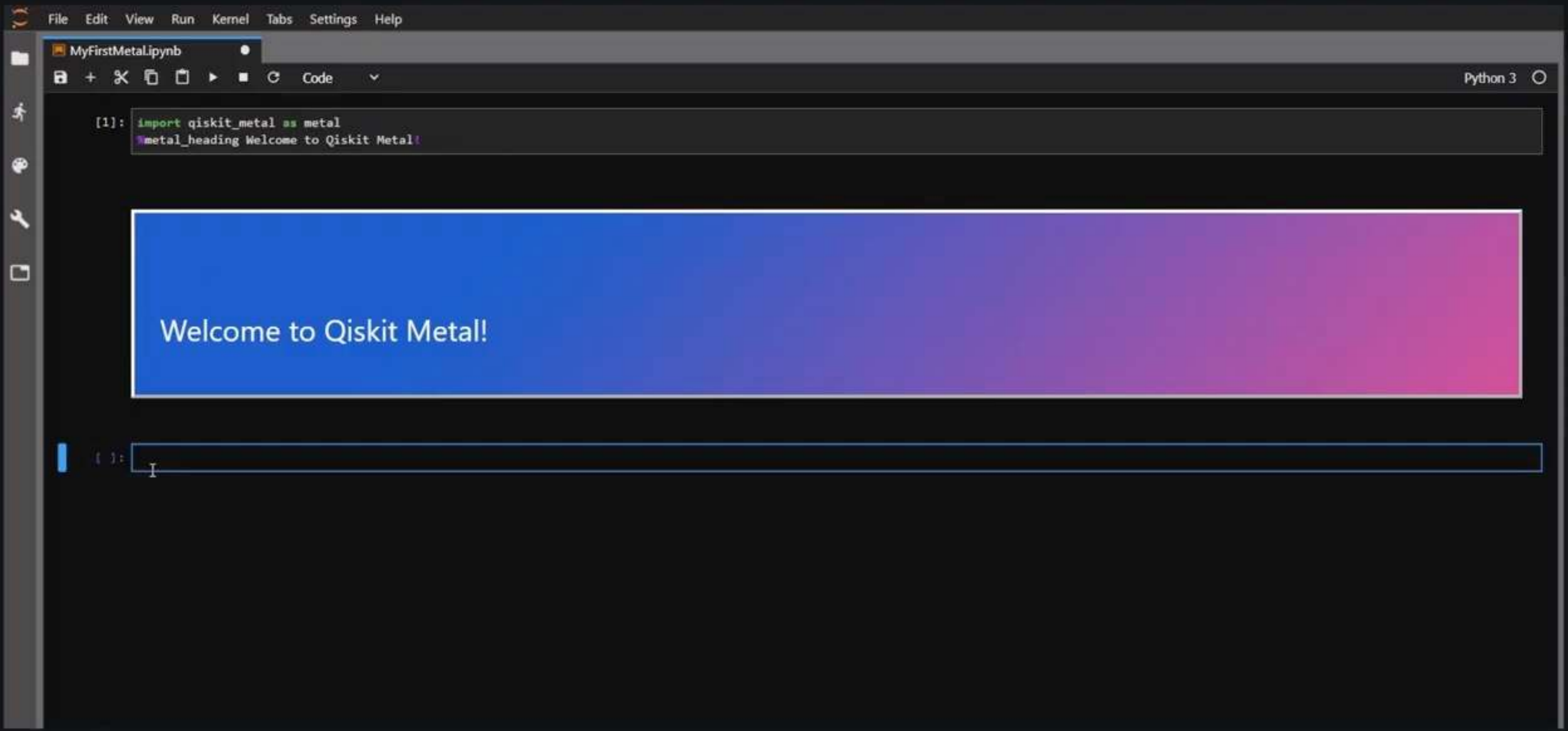
Create a transmon qubit

```
from qiskit_metal.qlibrary import qubits
q1 = qubits.TransmonPocket('Q1', options=dict(...))
```

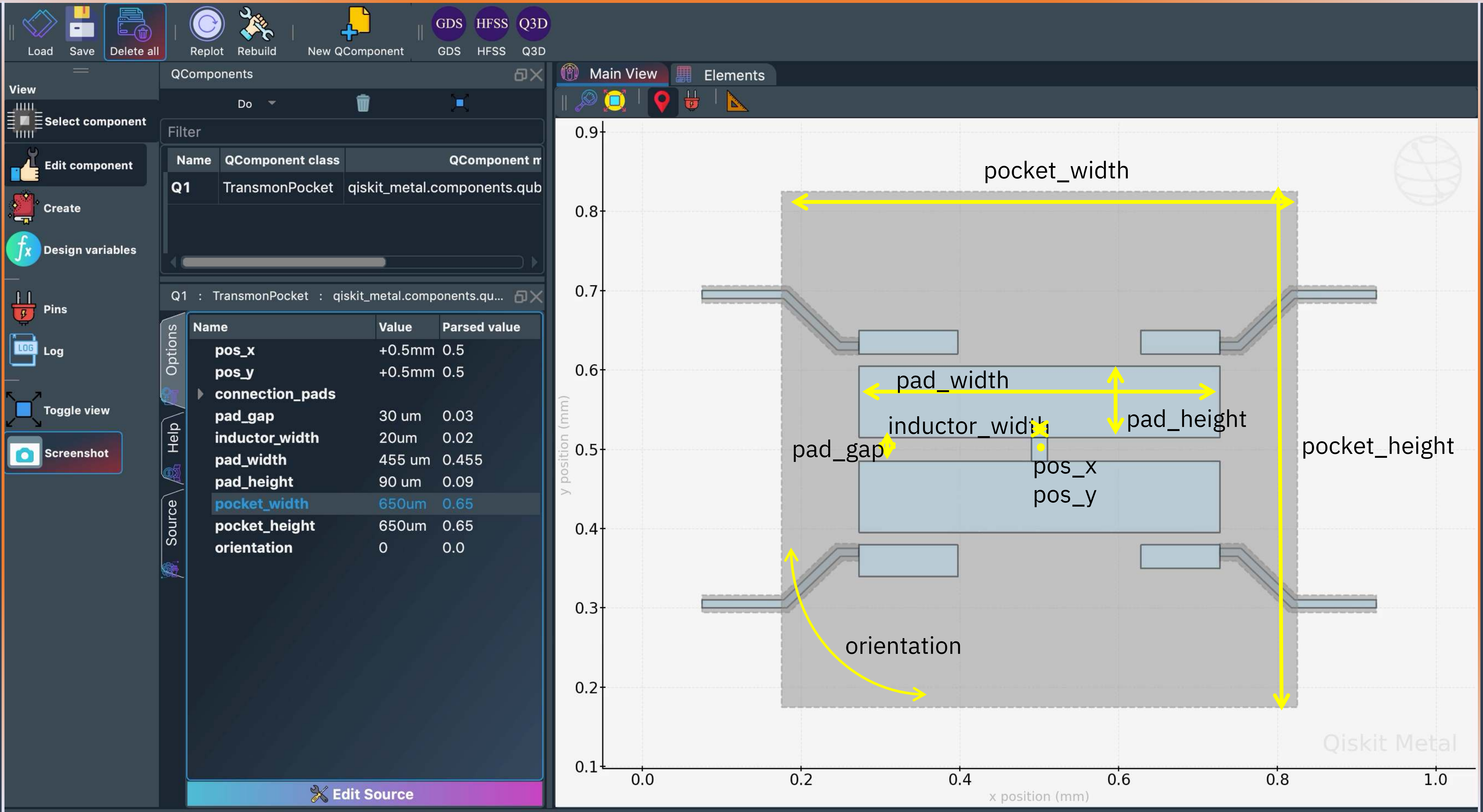
```
from qiskit_metal import MetalGUI
MetalGUI()
```



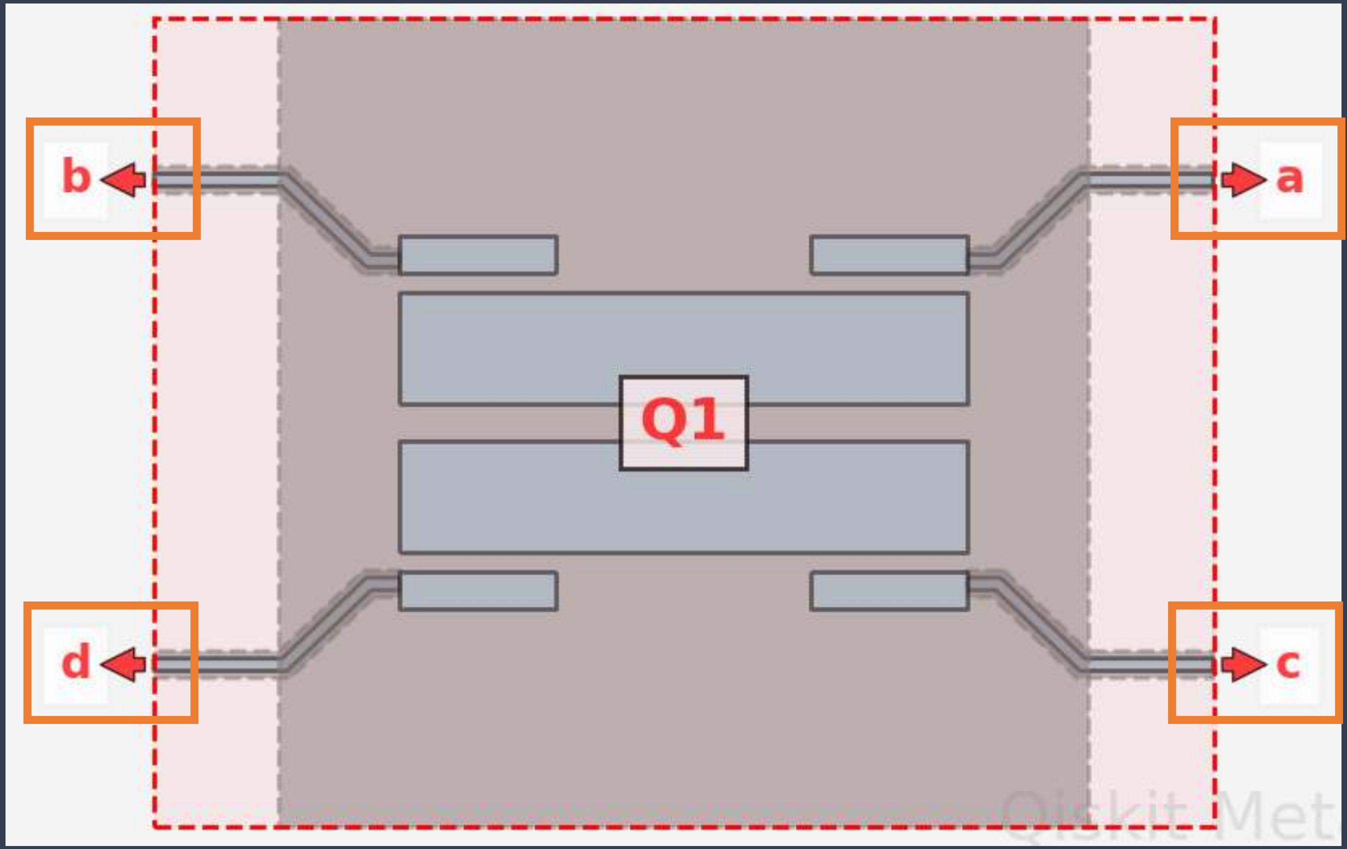
qiskit.org/metal

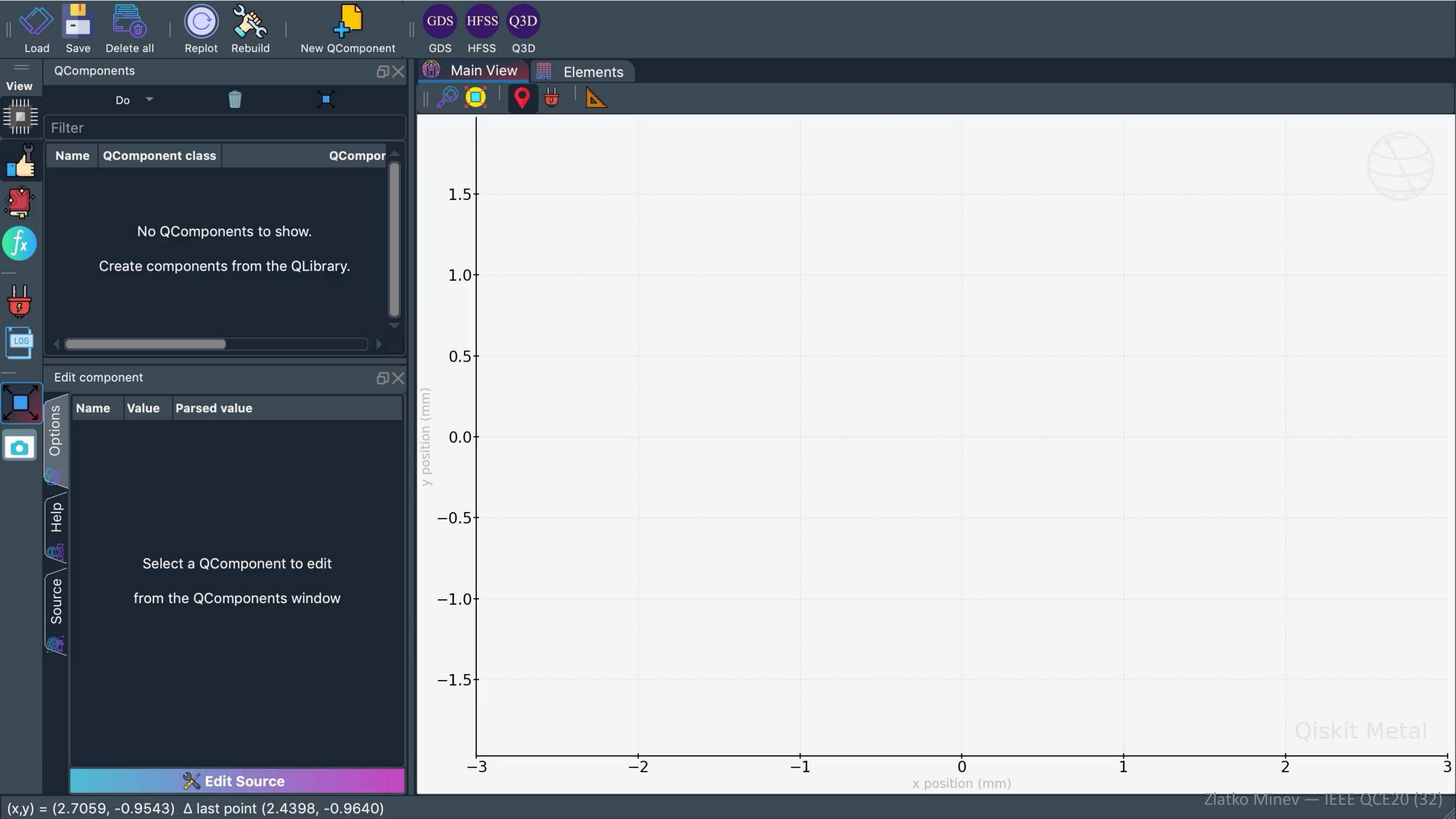

File Edit View Run Kernel Tabs Settings Help
MyFirstMetal.ipynb
Code
Python 3
[1]: import qiskit_metal as metal
%metal_heading Welcome to Qiskit Metal!
Welcome to Qiskit Metal!
[ ]:

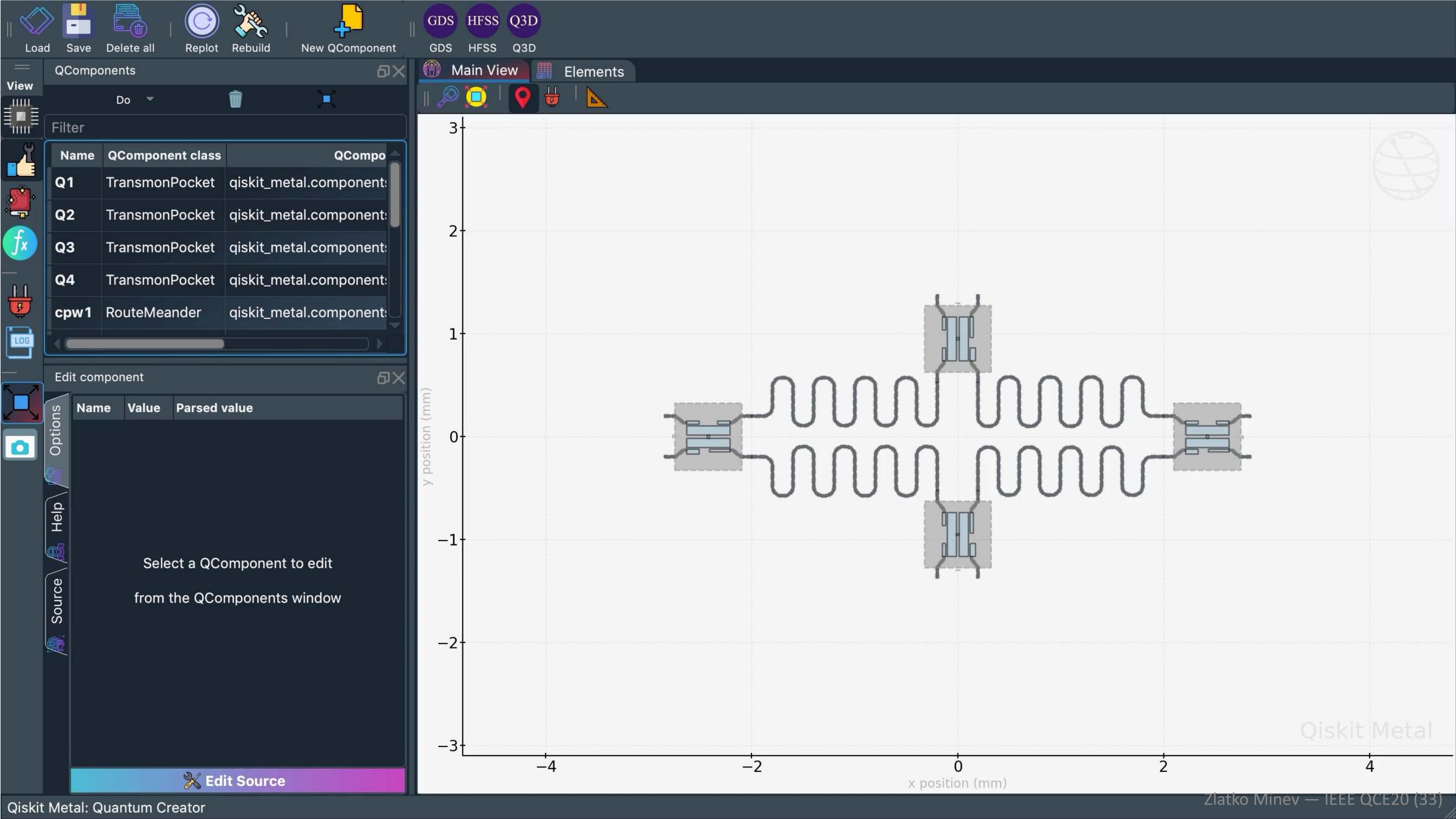
Fine-tune and automate parameters

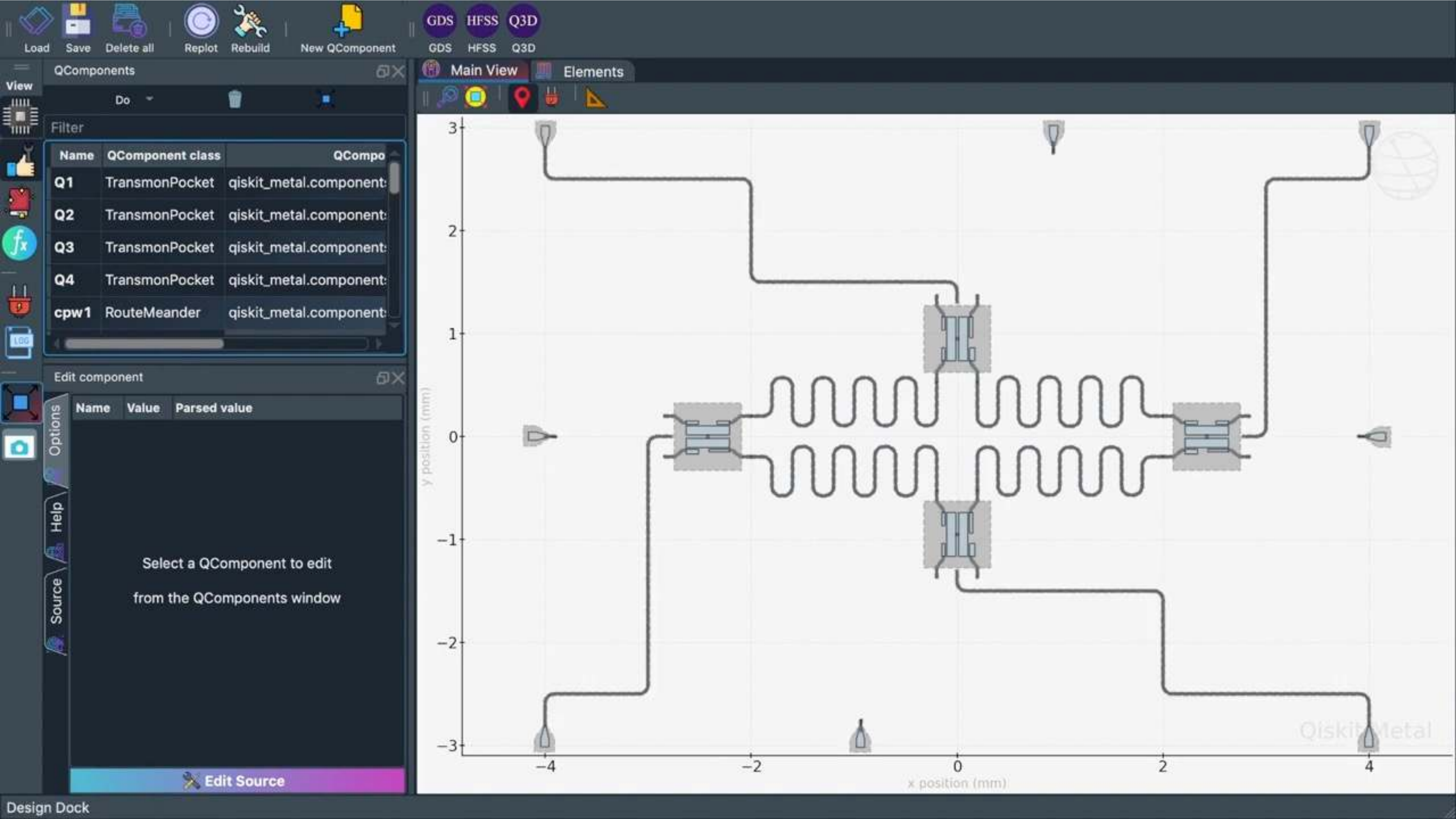


Dynamically –connected quantum devices



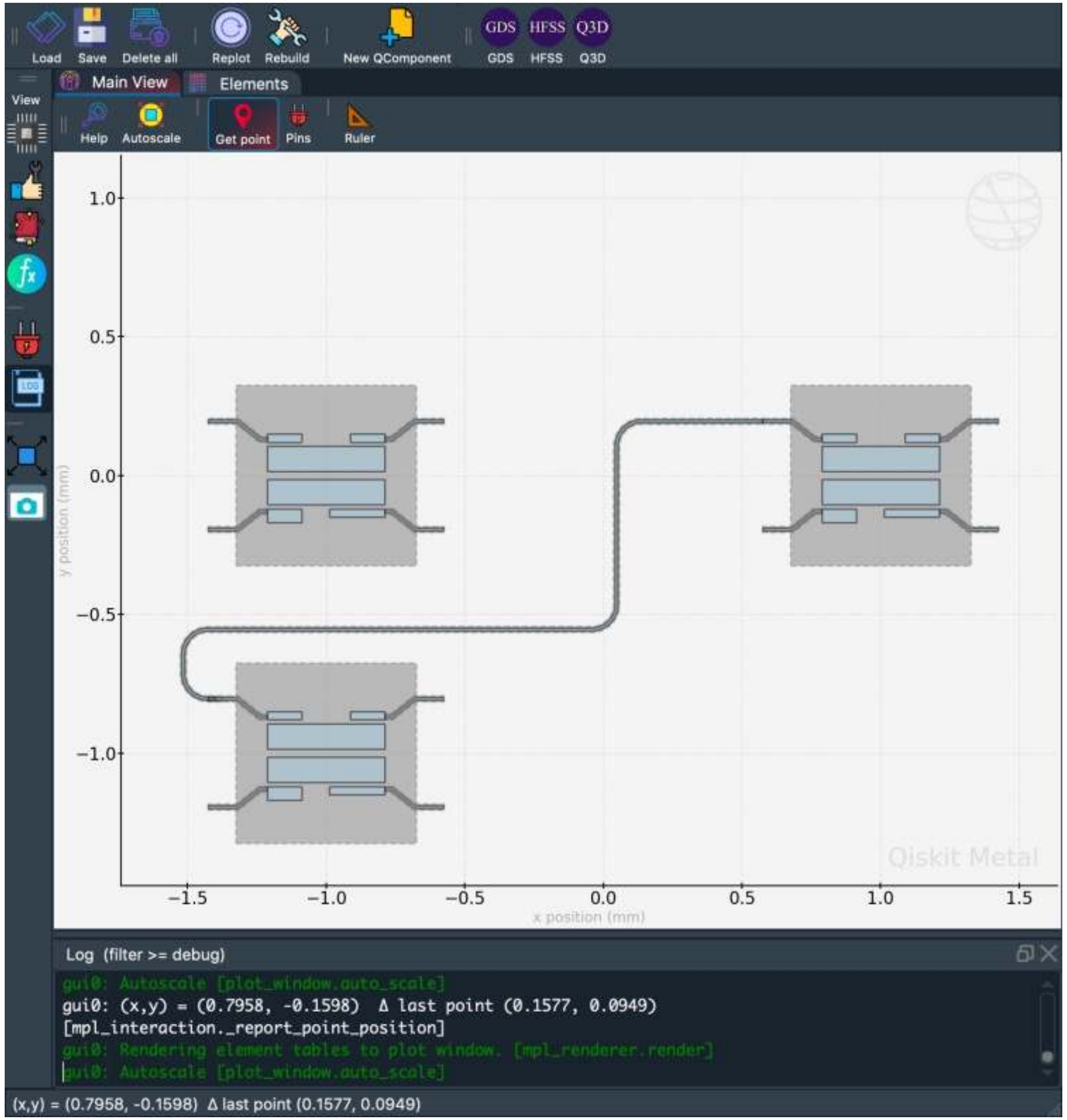

Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
View
QComponents
Do
Filter
Name
QComponent class
QCompor
No QComponents to show.
Create components from the QLibrary.
Edit component
Name
Value
Parsed value
Options
Help
Source
Select a QComponent to edit
from the QComponents window
Edit Source
Main View
Elements
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y position (mm)
−3
−2
−1
0
1
2
3
x position (mm)
Qiskit Metal
(x,y) = (2.7059, -0.9543) Δ last point (2.4398, -0.9640)
Zlatko Minev — IEEE QCE20 (32)

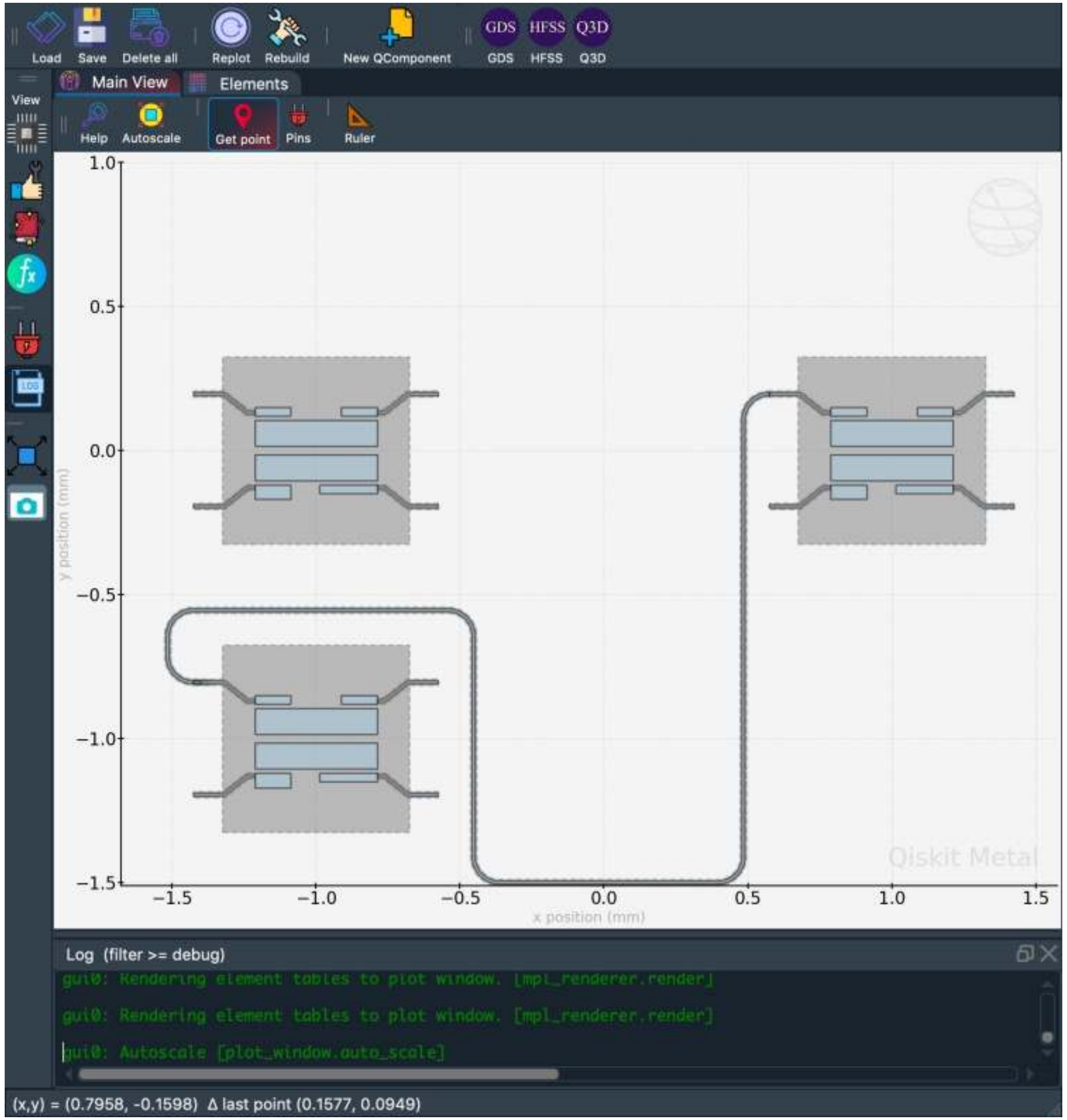

Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
View
QComponents
Do
Filter
Name
QComponent class
QCompo
Q1 TransmonPocket qiskit_metal.component
Q2 TransmonPocket qiskit_metal.component
Q3 TransmonPocket qiskit_metal.component
Q4 TransmonPocket qiskit_metal.component
cpw1 RouteMeander qiskit_metal.component
Edit component
Name
Value
Parsed value
Options
Help
Source
Select a QComponent to edit
from the QComponents window
Edit Source
Qiskit Metal: Quantum Creator
Main View
Elements
y position (mm)
x position (mm)
Qiskit Metal

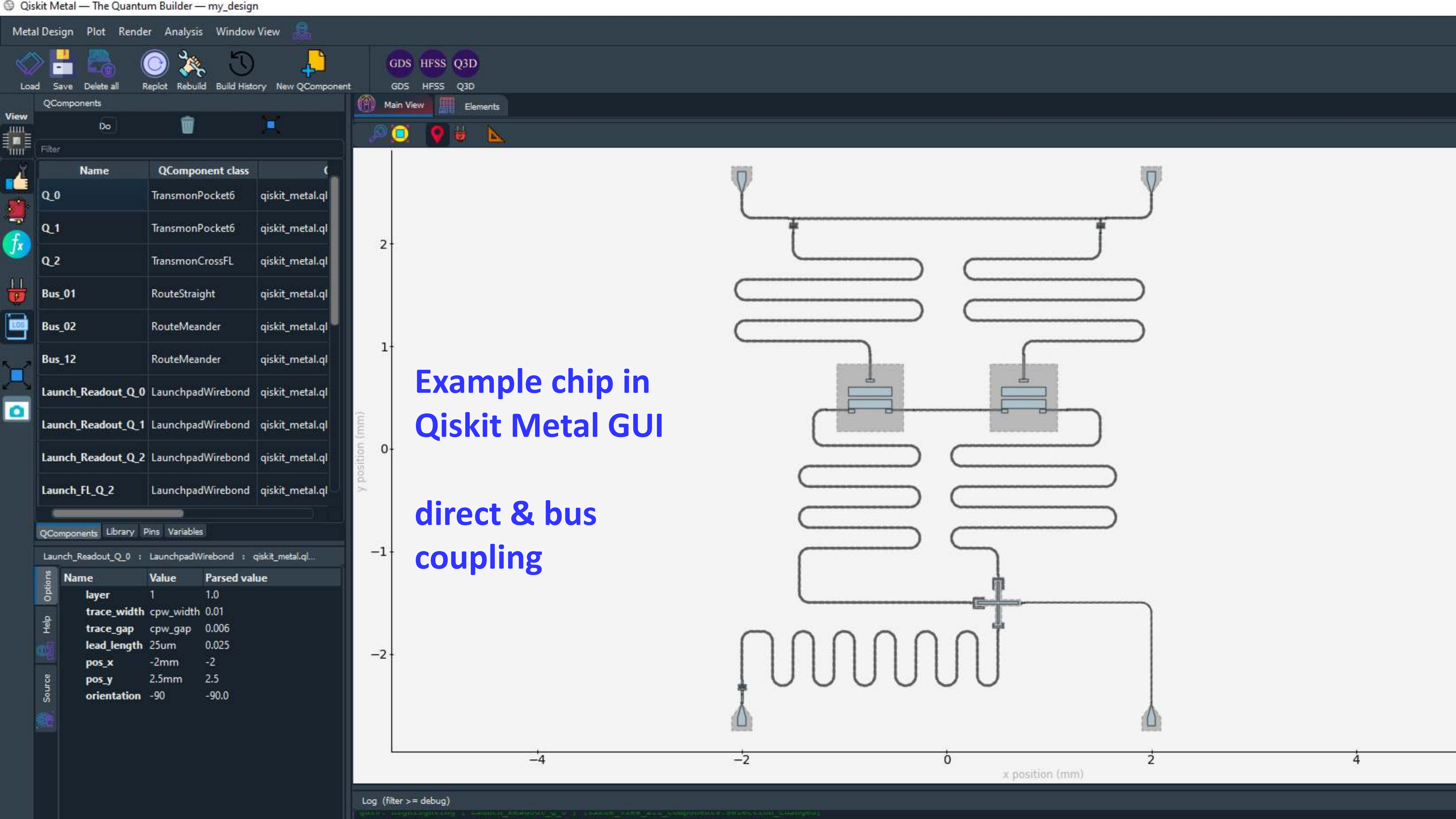

Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
View
QComponents
Do
Filter
Name
QComponent class
QCompo
Q1
TransmonPocket
qiskit_metal.component:
Q2
TransmonPocket
qiskit_metal.component:
Q3
TransmonPocket
qiskit_metal.component:
Q4
TransmonPocket
qiskit_metal.component:
cpw1
RouteMeander
qiskit_metal.component:
Edit component
Options
Help
Source
Name
Value
Parsed value
Select a QComponent to edit
from the QComponents window
Edit Source
Main View
Elements
y position (mm)
x position (mm)
Qiskit Metal
Design Dock

Demo Notebook for Hybrid CPW Algorithm with Anchors (Dennis Wang Talk in Session J30)

CPW Hybrid Auto and AStar.ipynb





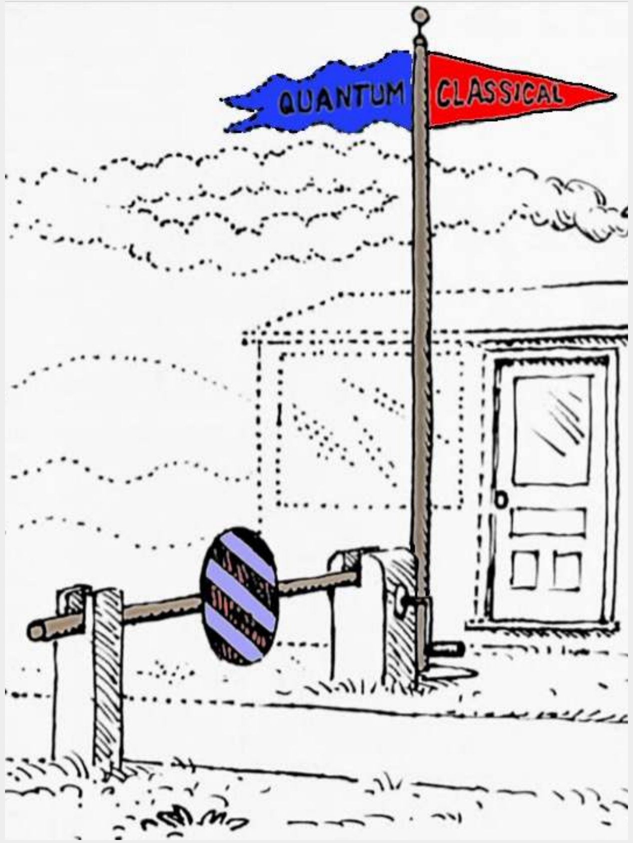

Qiskit Metal — The Quantum Builder — my_design
Metal Design
Plot
Render
Analysis
Window View
Load
Save
Delete all
Replot
Rebuild
Build History
New QComponent
GDS
HFSS
Q3D
View
QComponents
Main View
Elements
Filter
Name
QComponent class
Q_0 TransmonPocket6 qiskit_metal.ql
Q_1 TransmonPocket6 qiskit_metal.ql
Q_2 TransmonCrossFL qiskit_metal.ql
Bus_01 RouteStraight qiskit_metal.ql
Bus_02 RouteMeander qiskit_metal.ql
Bus_12 RouteMeander qiskit_metal.ql
Launch_Readout_Q_0 LaunchpadWirebond qiskit_metal.ql
Launch_Readout_Q_1 LaunchpadWirebond qiskit_metal.ql
Launch_Readout_Q_2 LaunchpadWirebond qiskit_metal.ql
Launch_FL_Q_2 LaunchpadWirebond qiskit_metal.ql
QComponents
Library
Pins
Variables
Launch_Readout_Q_0 : LaunchpadWirebond : qiskit_metal.ql...
Options
Help
Source
Name
Value
Parsed value
layer 1 1.0
trace_width cpw_width 0.01
trace_gap cpw_gap 0.006
lead_length 25um 0.025
pos_x -2mm -2
pos_y 2.5mm 2.5
orientation -90 -90.0
Example chip in Qiskit Metal GUI
direct & bus coupling
y position (mm)
x position (mm)
2
1
0
−1
−2
−4
−2
0
2
4
Log (filter >= debug)

Can I make my own qubit?

```
smile = draw.shapely.geometry.Point(0, 0).buffer(0.8)
cut_sq = draw.shapely.geometry.box(-1, -0.3, 1, 1)
smile = draw.subtract(smile, cut_sq)
face = draw.subtract(face, smile)
face = draw.subtract(face, eye_r)
face = draw.subtract(face, eye_l)
face
```

[7]:

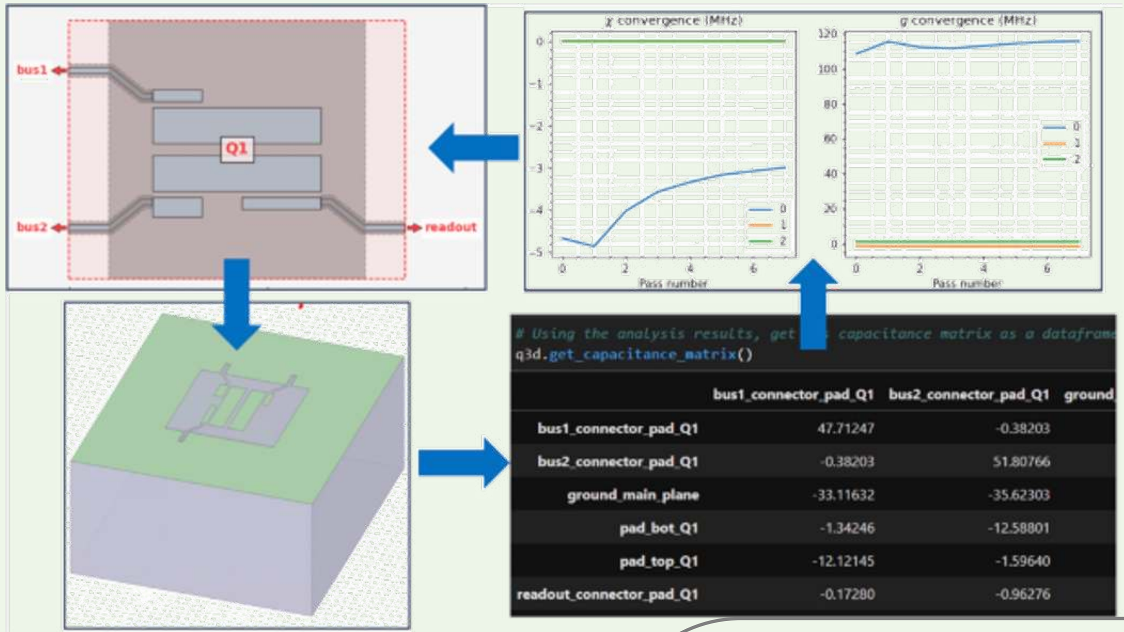
Analysis



Quantum analysis library

arXiv: 2010.00620
arXiv: 1902.10355

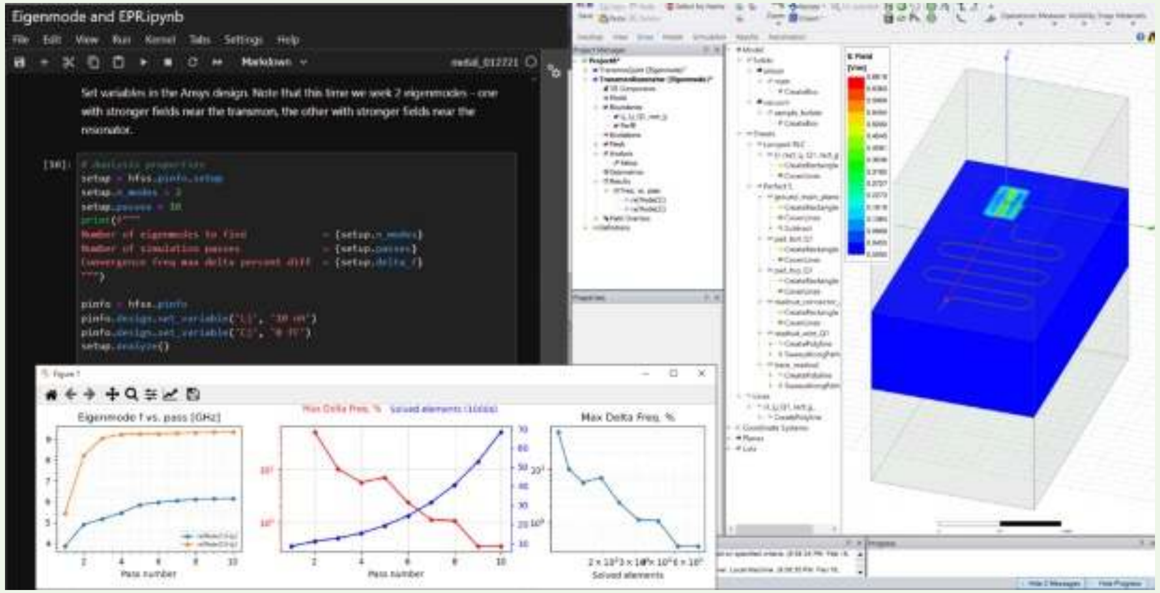
Capacitive



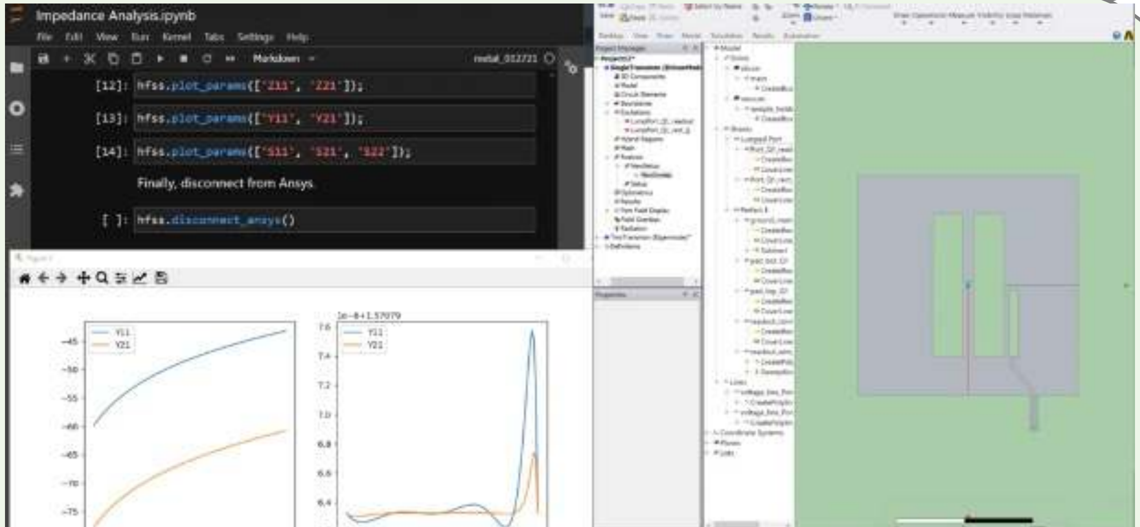
	bus1_connector_pad_Q1	bus2_connector_pad_Q1	ground
bus1_connector_pad_Q1	47.71247	-0.38203	
bus2_connector_pad_Q1	-0.38203	51.80766	
ground_main_plane	-33.11632	-35.62303	
pad_bot_Q1	-1.34246	-12.58801	
pad_top_Q1	-12.12145	-1.59640	
readout_connector_pad_Q1	-0.17280	-0.96276	

arXiv:2103.10344 ...

Eigenmode



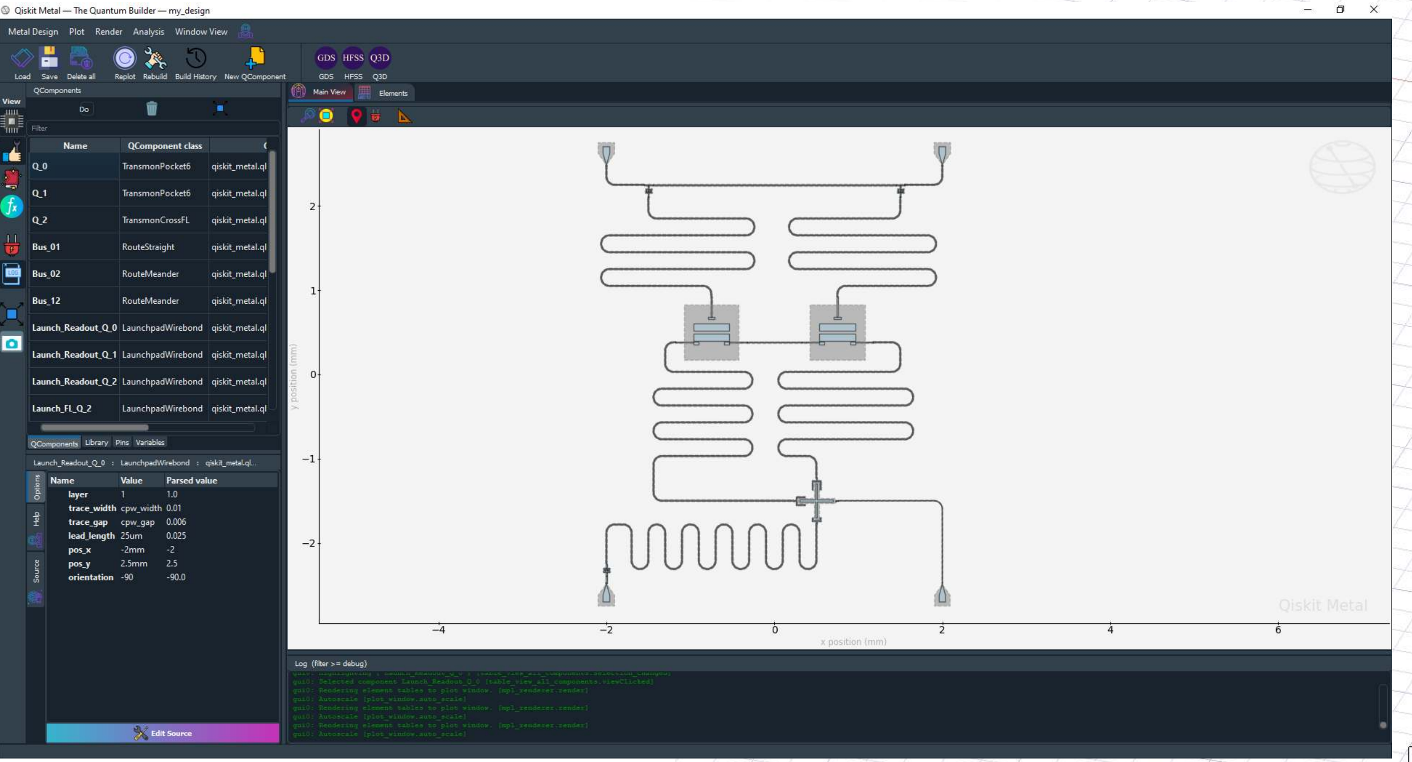
S, Z, Y
Impedance
Scattering



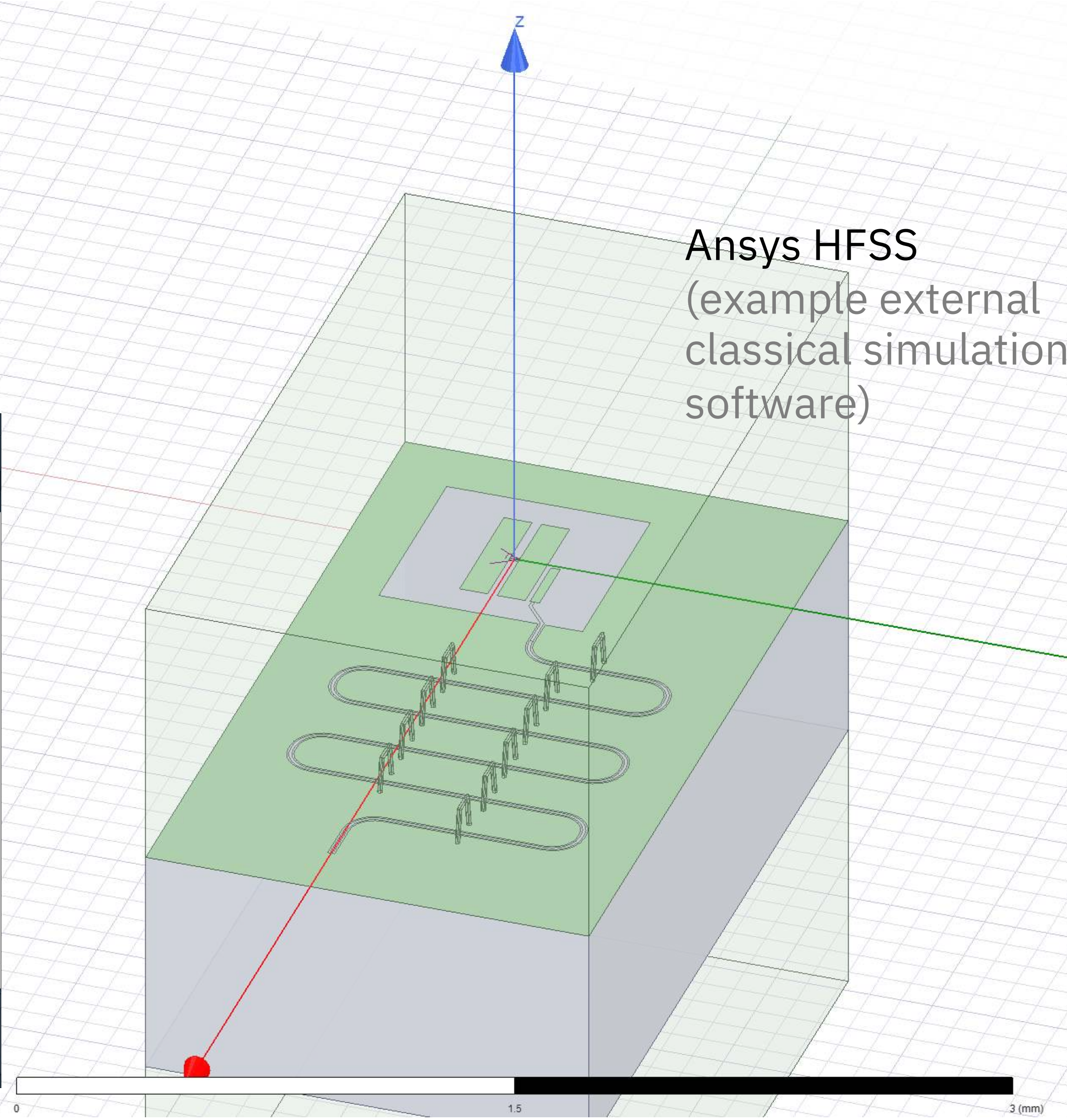
arXiv:1204.0587 ...

Automated with

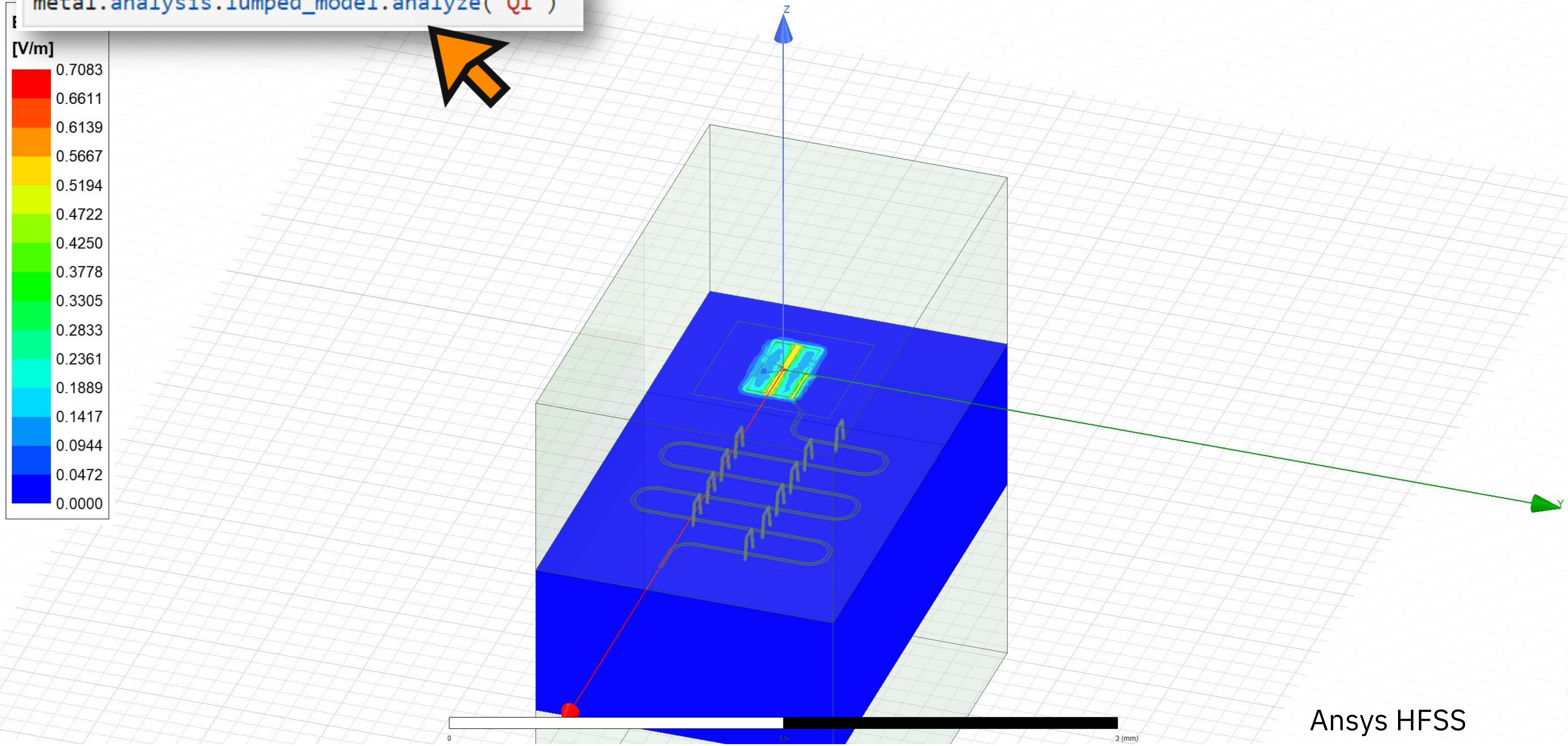
Qiskit | quantum device design



Ansys HFSS
(example external classical simulation software)



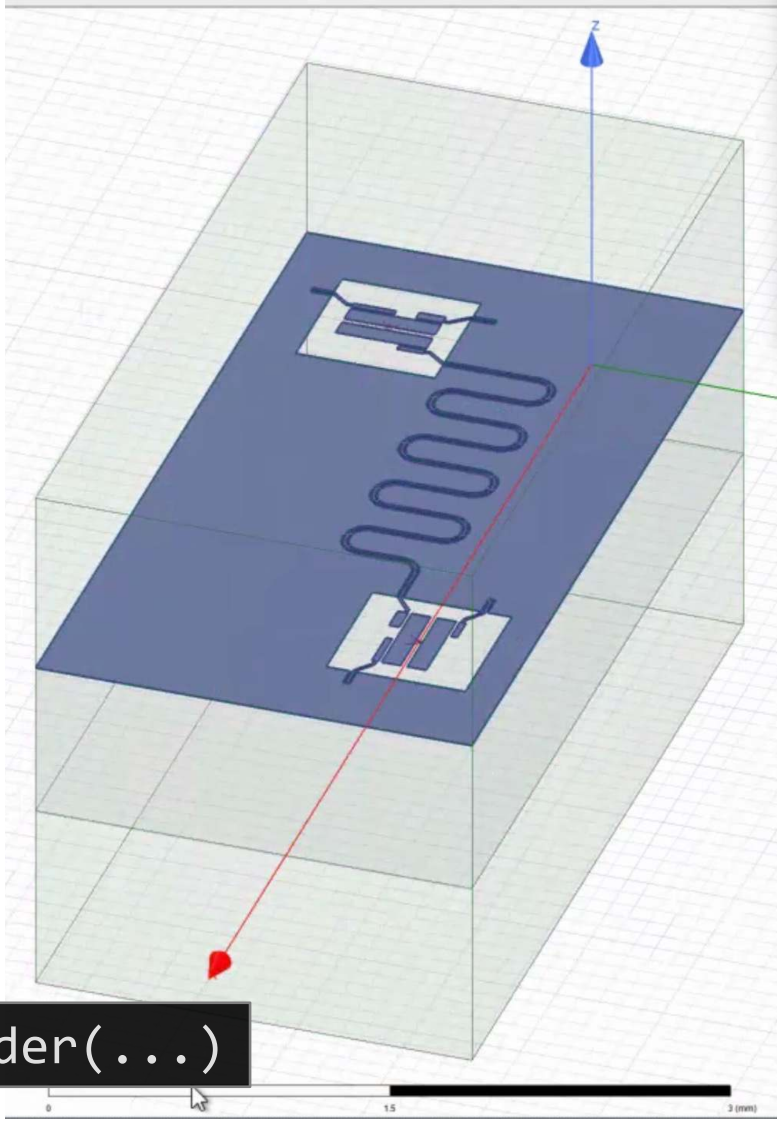
```
metal.analysis.lumped_model.analyze('Q1')
```



Ansys HFSS

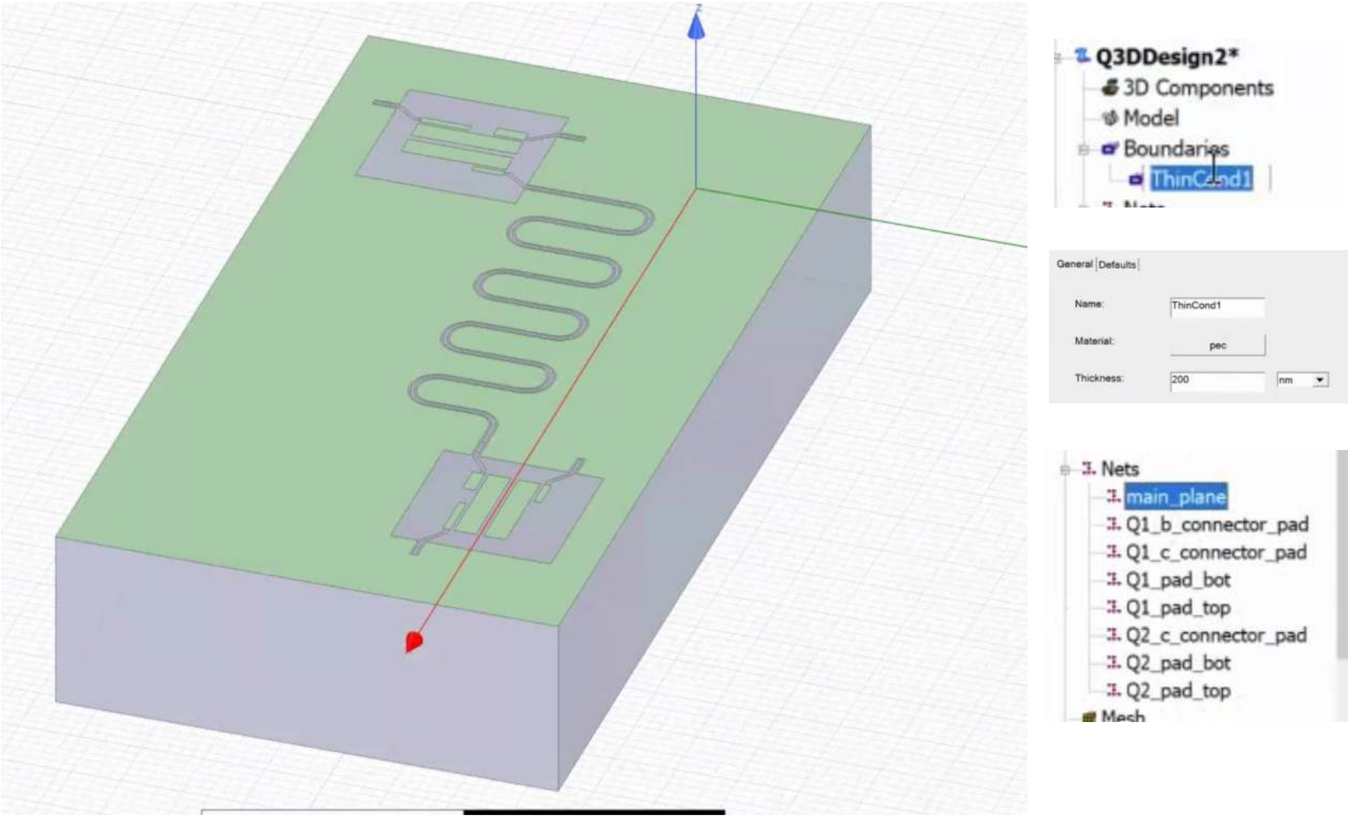
Qiskit Metal render & electromagnetic analysis

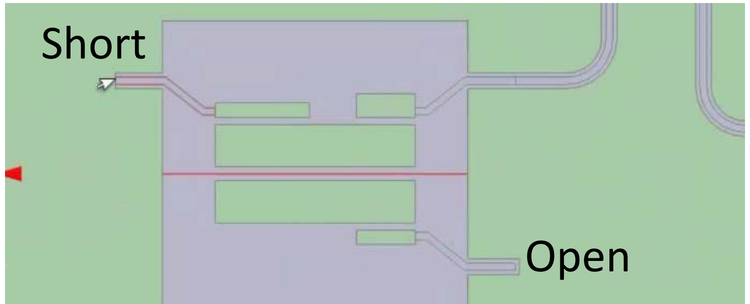
For example: Ansys HFSS



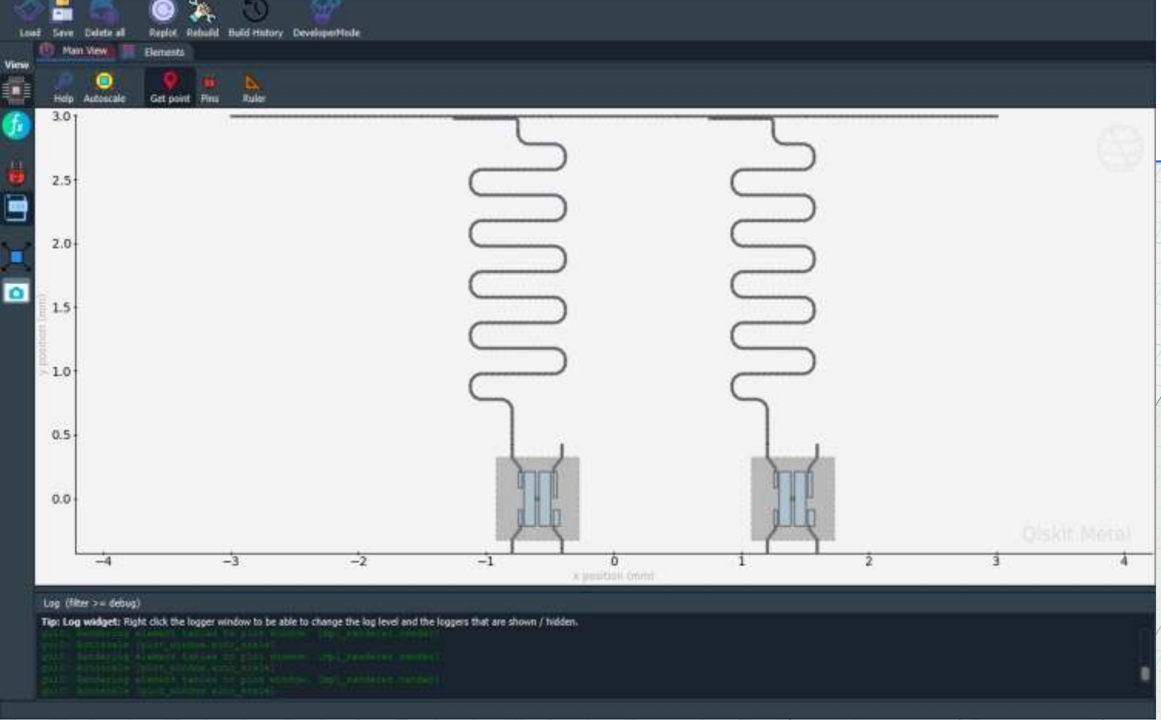
```
design.render(...)
```

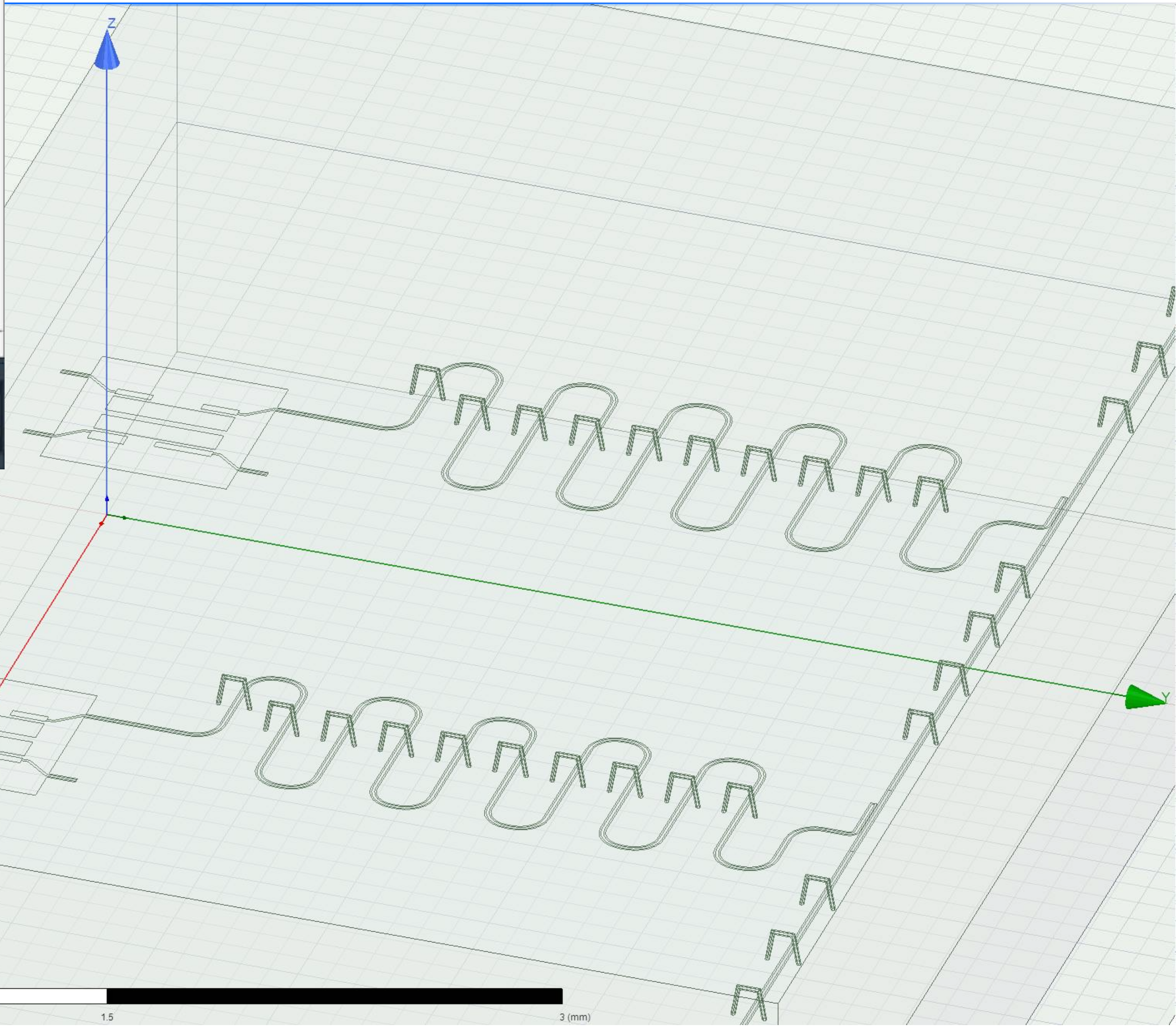
Q3D





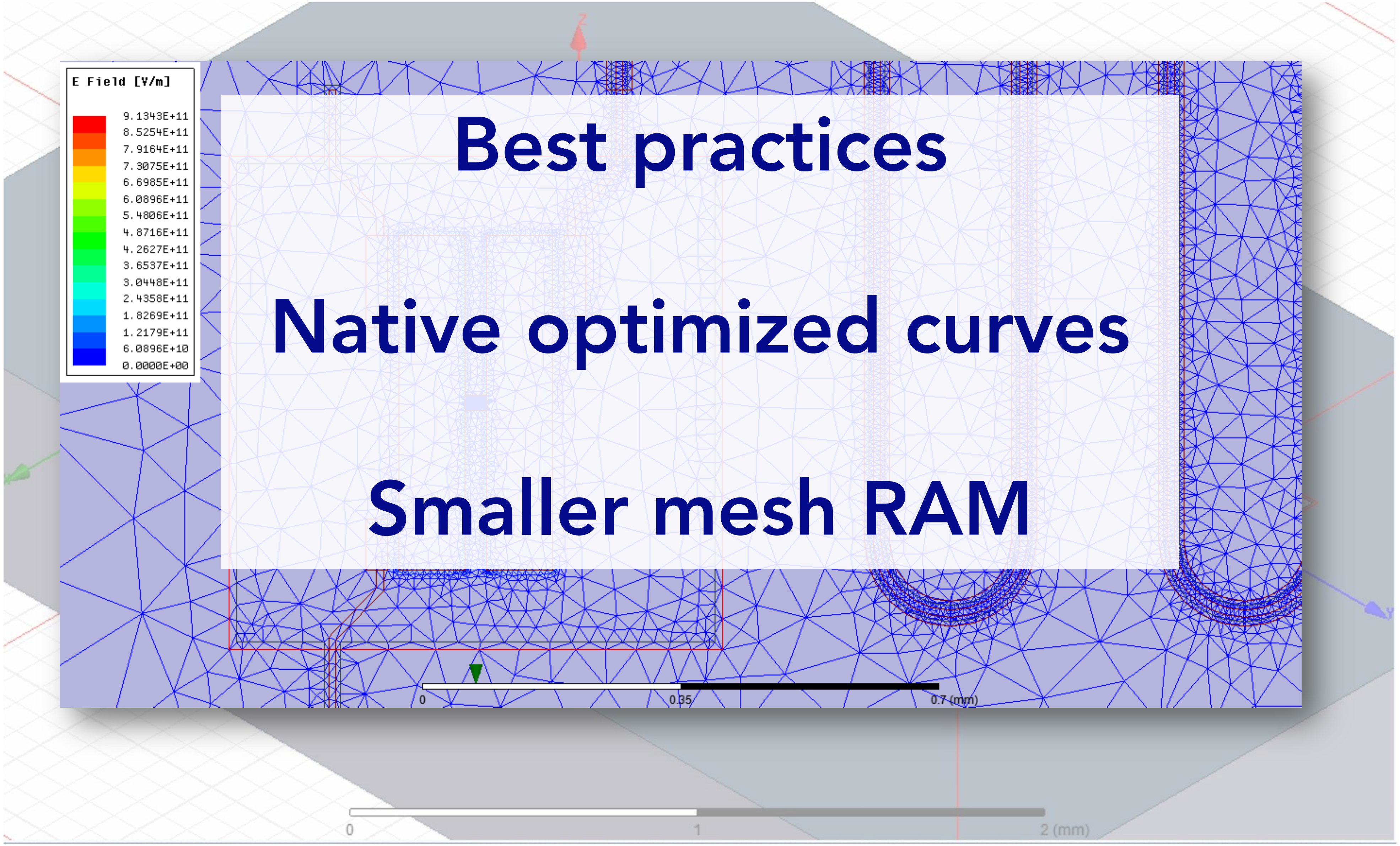
More complex designs





Qiskit Metal

Sub-Circuit Analysis

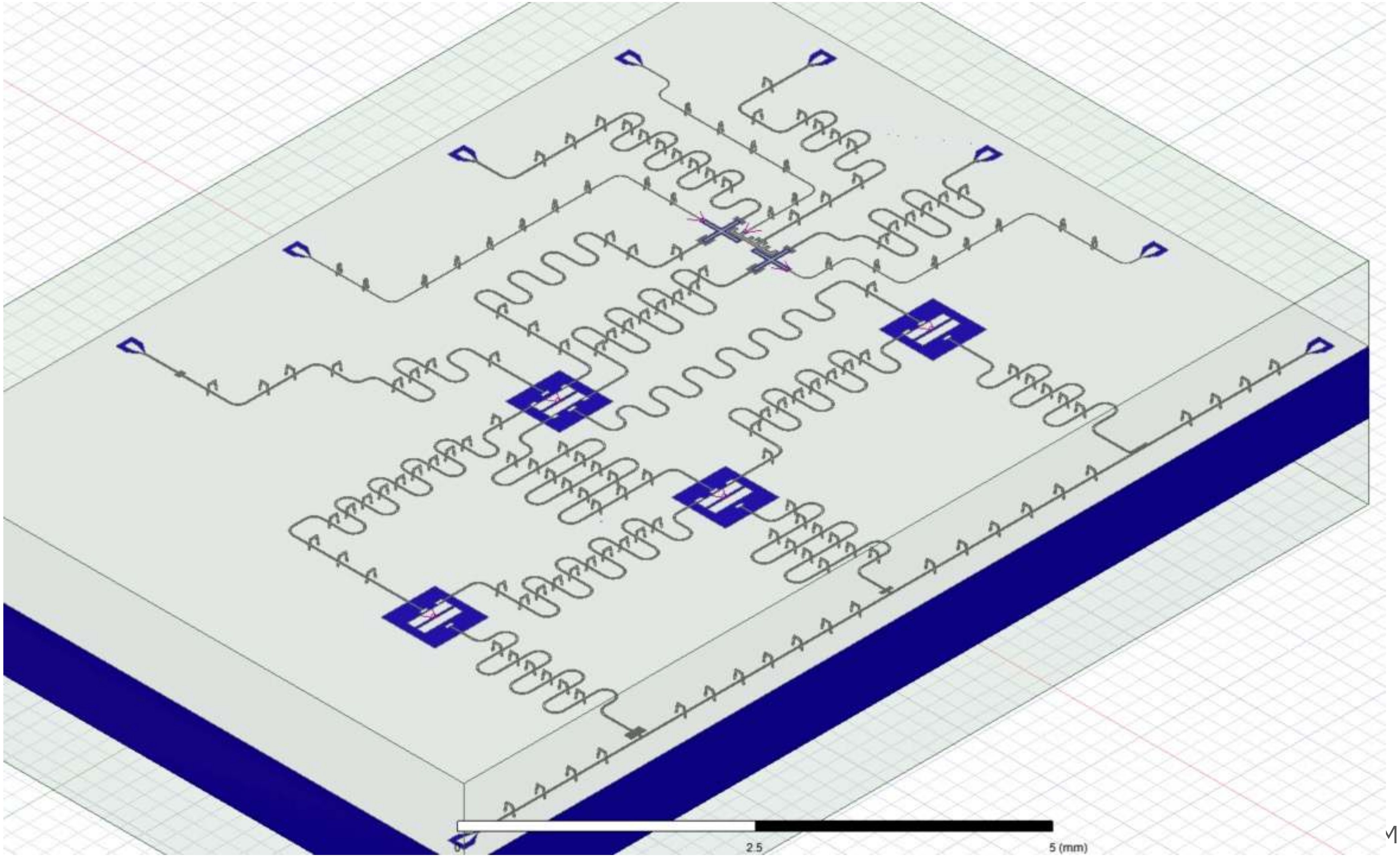


Best practices

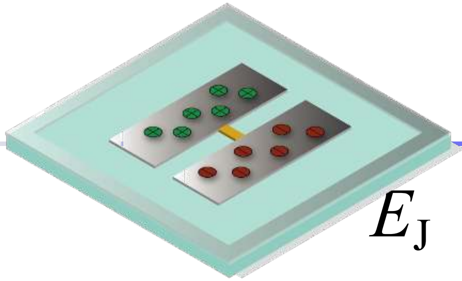
Native optimized curves

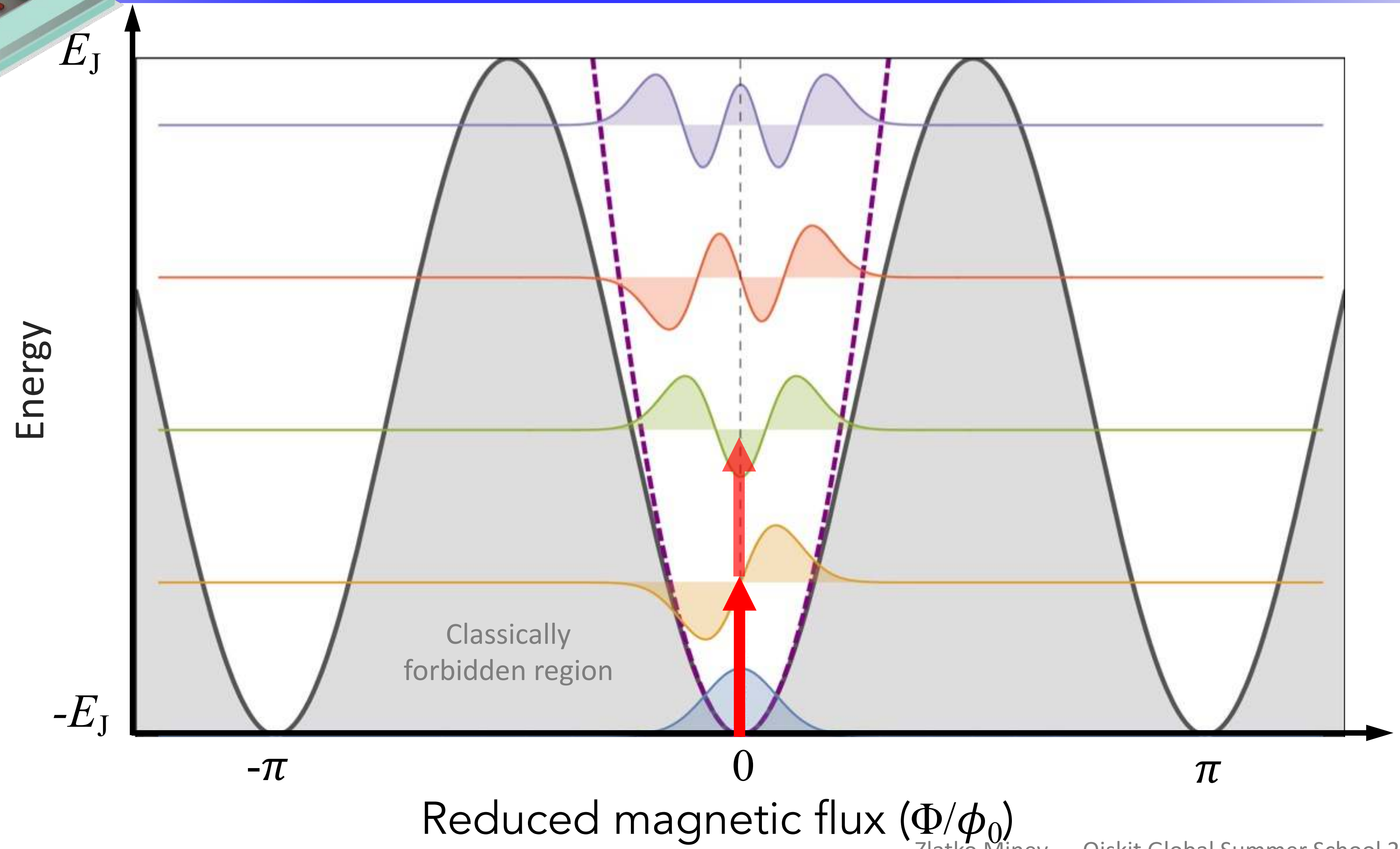
Smaller mesh RAM

More complex quantum chips – see next tutorial



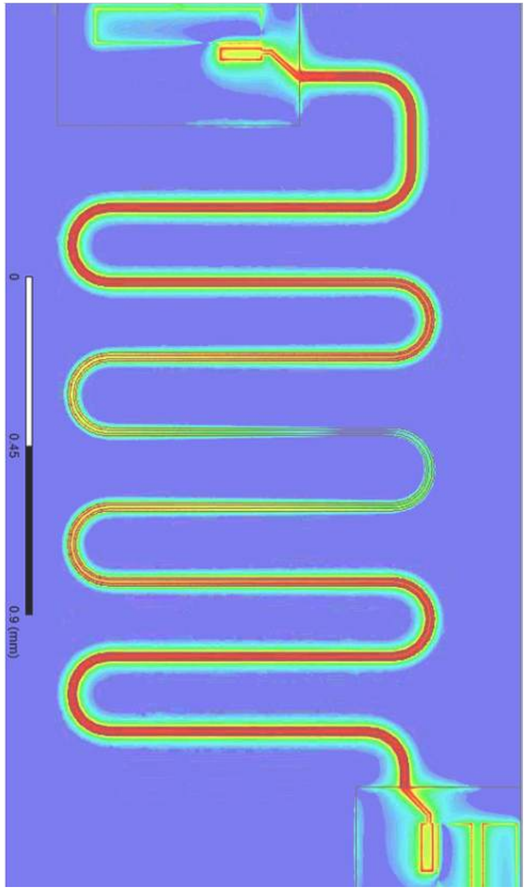
Exploring a transmon qubit



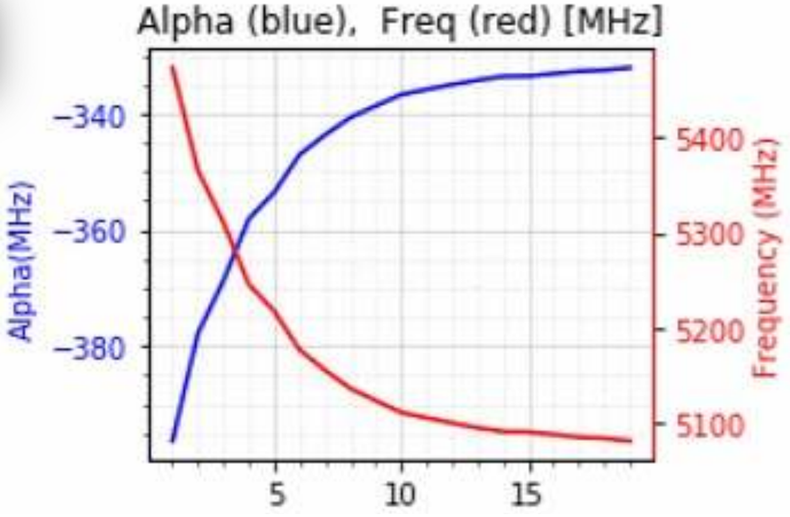


Automated analysis and reports

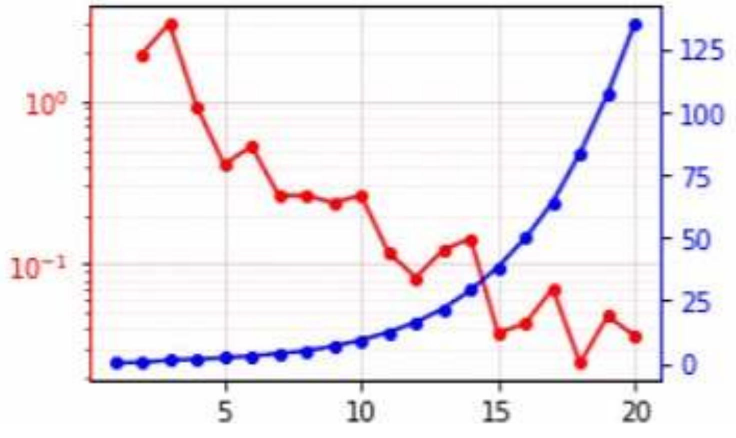
```
metal.analysis.lumped_model.analyze('Q1')
```



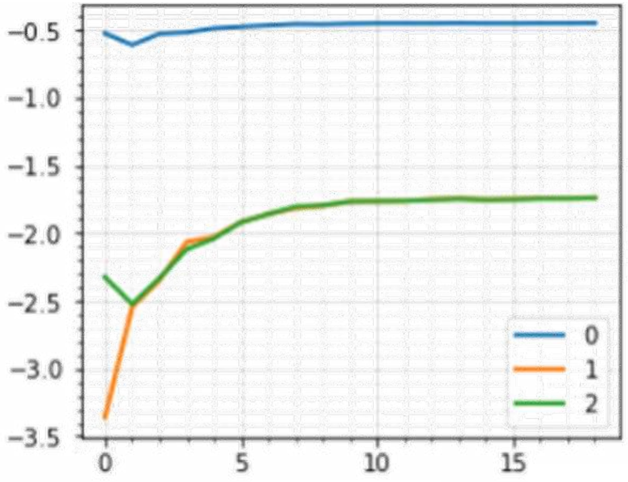
Qubit frequency & anharmonicity



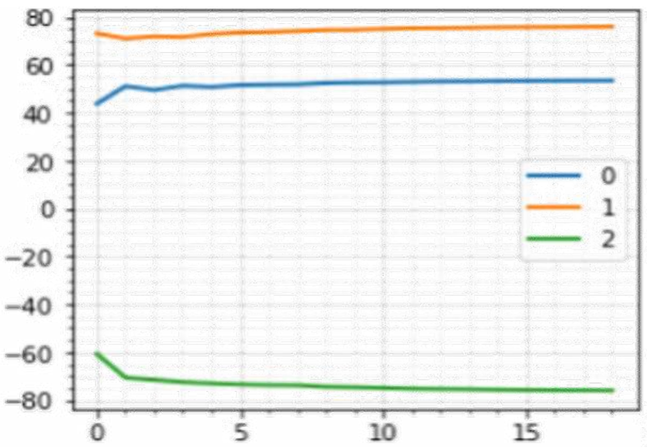
FE simulation convergence



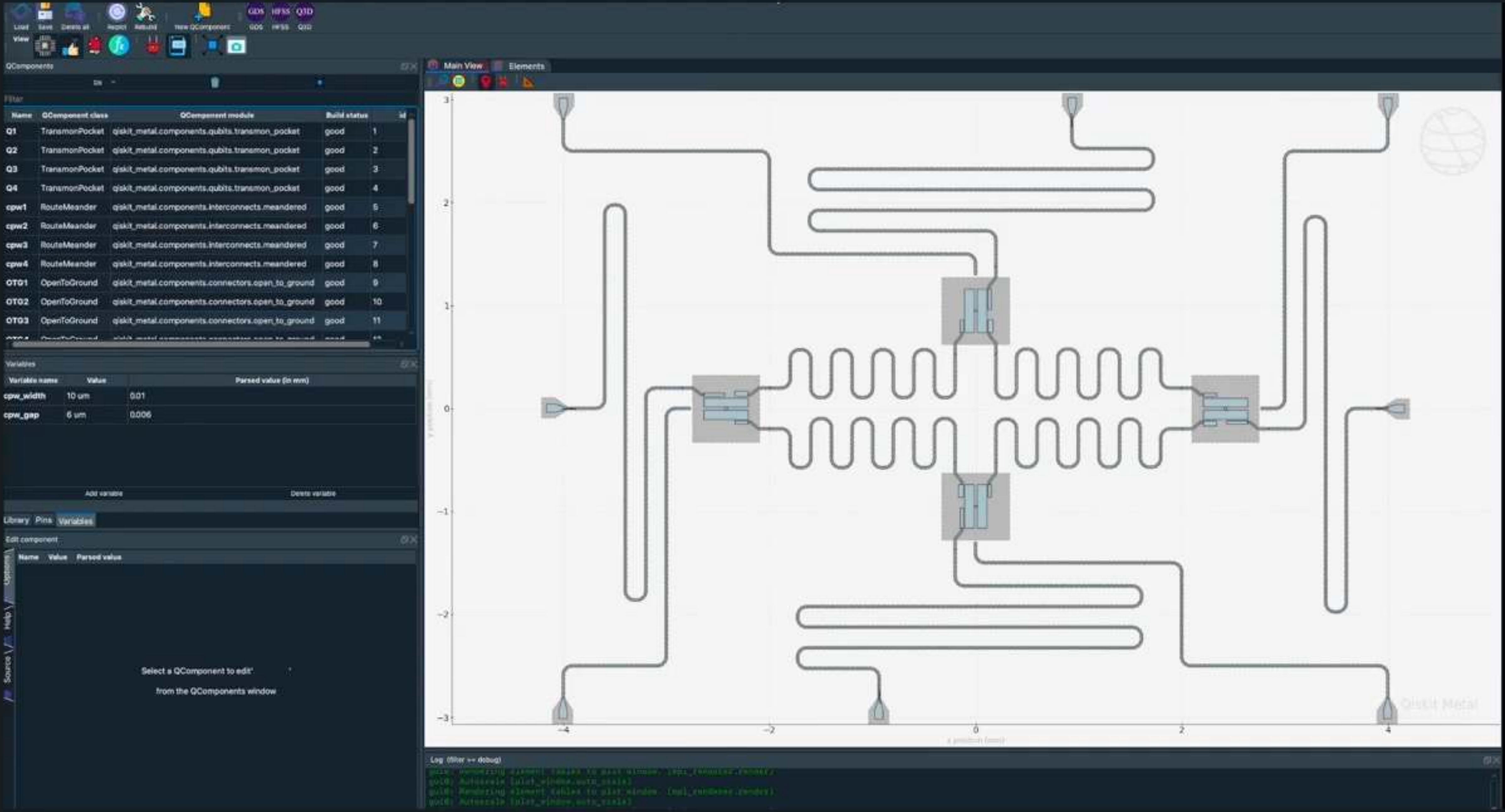
cross-Kerr χ coupling (MHz)



Linear g coupling (MHz)



Analysis pass number



QComponents
Filter
Name
QComponent class
QComponent module
Build status
id
Q1
TransmonPocket
qiskit_metal.components.qubits.transmon_pocket
good
1
Q2
TransmonPocket
qiskit_metal.components.qubits.transmon_pocket
good
2
Q3
TransmonPocket
qiskit_metal.components.qubits.transmon_pocket
good
3
Q4
TransmonPocket
qiskit_metal.components.qubits.transmon_pocket
good
4
cpw1
RouteMeander
qiskit_metal.components.interconnects.meandered
good
5
cpw2
RouteMeander
qiskit_metal.components.interconnects.meandered
good
6
cpw3
RouteMeander
qiskit_metal.components.interconnects.meandered
good
7
cpw4
RouteMeander
qiskit_metal.components.interconnects.meandered
good
8
OTG1
OpenToGround
qiskit_metal.components.connectors.open_to_ground
good
9
OTG2
OpenToGround
qiskit_metal.components.connectors.open_to_ground
good
10
OTG3
OpenToGround
qiskit_metal.components.connectors.open_to_ground
good
11
Variables
Variable name
Value
Parsed value (in mm)
cpw_width
10 um
0.01
cpw_gap
6 um
0.006
Library
Pins
Variables
Edit component
Name
Value
Parsed value
Select a QComponent to edit
from the QComponents window
Main View
Elements
Log (filter >= debug)

Use cases
Devices made with Qiskit Metal

First quantum-hardware hackathon

Project 1A : Metal - Designing a simple qubit chip

Abstract

The designing of a simple two qubit system using Qiskit Metal.

Description

Using Qiskit Metal, design a single plane, two-qubit chip using superconducting qubits, which are coupled together with a coplanar waveguide (CPW) bus resonator (capacitively), and with each qubit having a CPW readout resonator. The readout resonators should be capacitively coupled to transmission line(s) which connect to launcher pads for wire bonds. All qcomponents should be selected from those available in the qlibrary.
A simple model of the potential layout is shown below,

The project members are to determine the actual physical layout, with the below target parameters in mind.

Parameters	Target Value	Parameters	Target Value
Freq_Q1	5.5 GHz	Freq_readout_Q1	7.5 GHz
Freq_Q2	5.7 GHz	Freq_readout_Q2	7.7 GHz
Anharmonicity (Ec)	300 MHz	χ	400 kHz
		κ	2 MHz
Freq_bus	6.6 GHz		
g			

The project members can also decide on the chip size, though should consider issues such as, potential box/substrate modes, or cross talk between the different components on the chip. It can be assumed wirebonds are available to be added where desired.

Members

Project 1B : Metal - Designing a simple qubit chip

Abstract

The designing of a simple two qubit system using Qiskit Metal.

Description

Using Qiskit Metal, design a single plane, two-qubit chip using superconducting qubits, which are coupled together with a coplanar waveguide (CPW) bus resonator, and with each qubit having a CPW readout resonator. The readout resonators should be coupled to transmission line(s) which connect to launcher pads for wire bonds. The qubits should be newly written qcomponents, as should the capacitive couplers. Only the CPW transmission line qcomponents can be from the available qlibrary.

The project members are to determine the actual physical layout, with the below target parameters in mind.

Parameters	Target Value	Parameters	Target Value
Freq_Q1	5.5 GHz	Freq_readout_Q1	7.5 GHz
Freq_Q2	5.7 GHz	Freq_readout_Q2	7.7 GHz
Anharmonicity (Ec)	300 MHz	χ	400 kHz
		κ	2 MHz
Freq_bus	6.6 GHz		
g			

The project members can also decide on the chip size, though should consider issues such as, potential box/substrate modes, or cross talk between the different components on the chip. It can be assumed wirebonds are available to be added where desired.

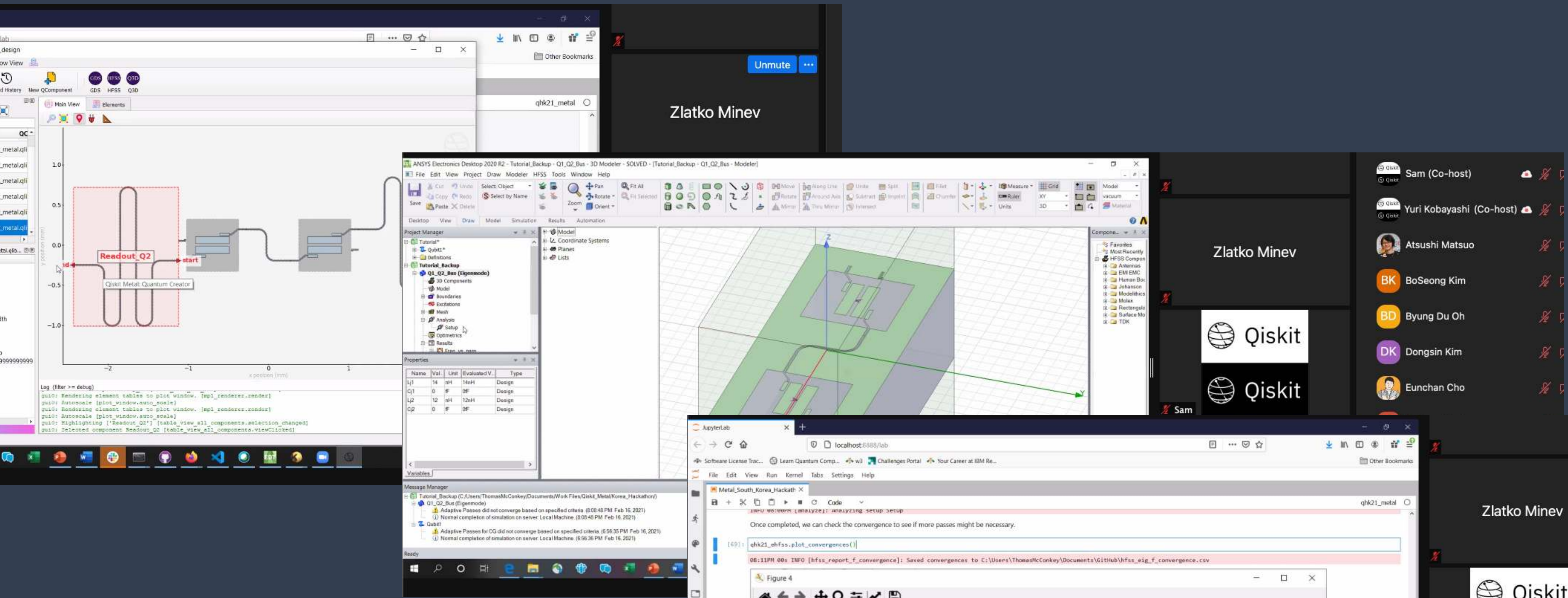
Members

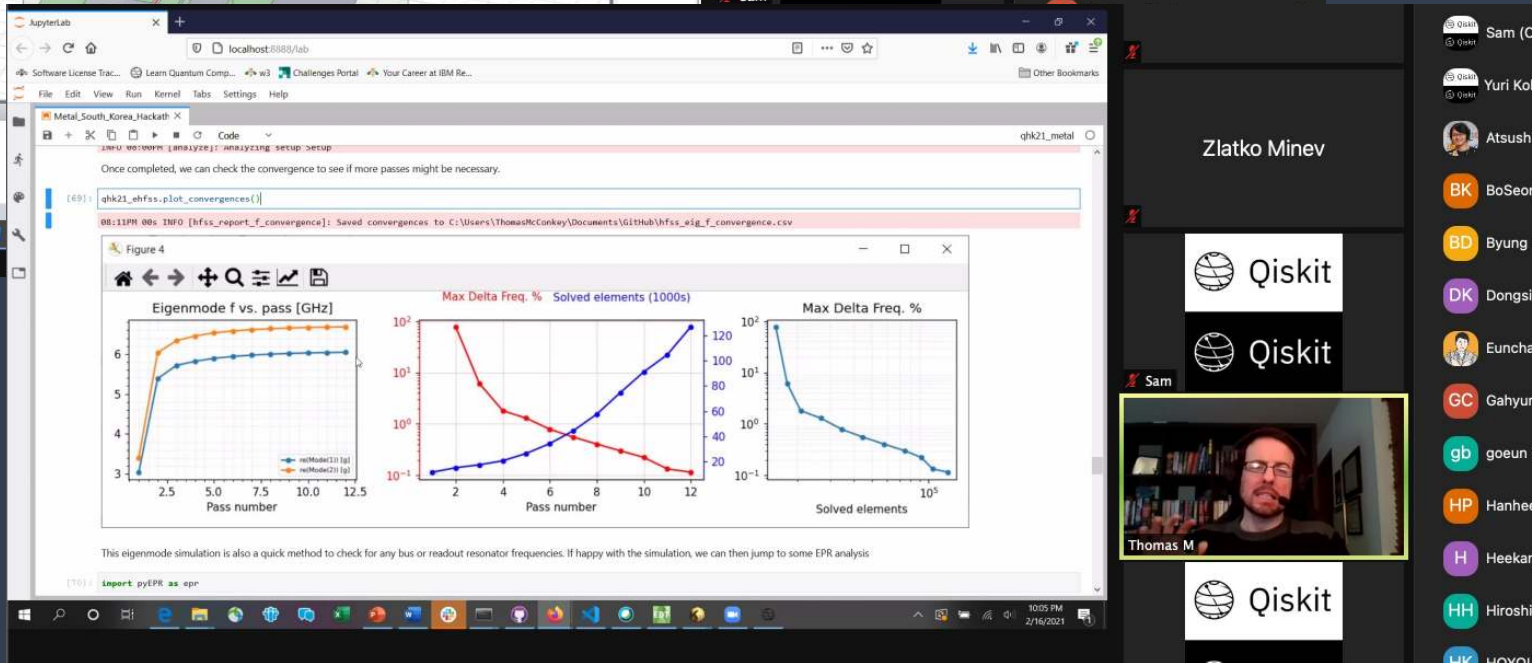
Deliverables

- The design notebook.
- Documentation showing the successful simulation/analysis of the chip design meeting the desired parameters

Qiskit | quantum device design

First quantum-hardware hackathon



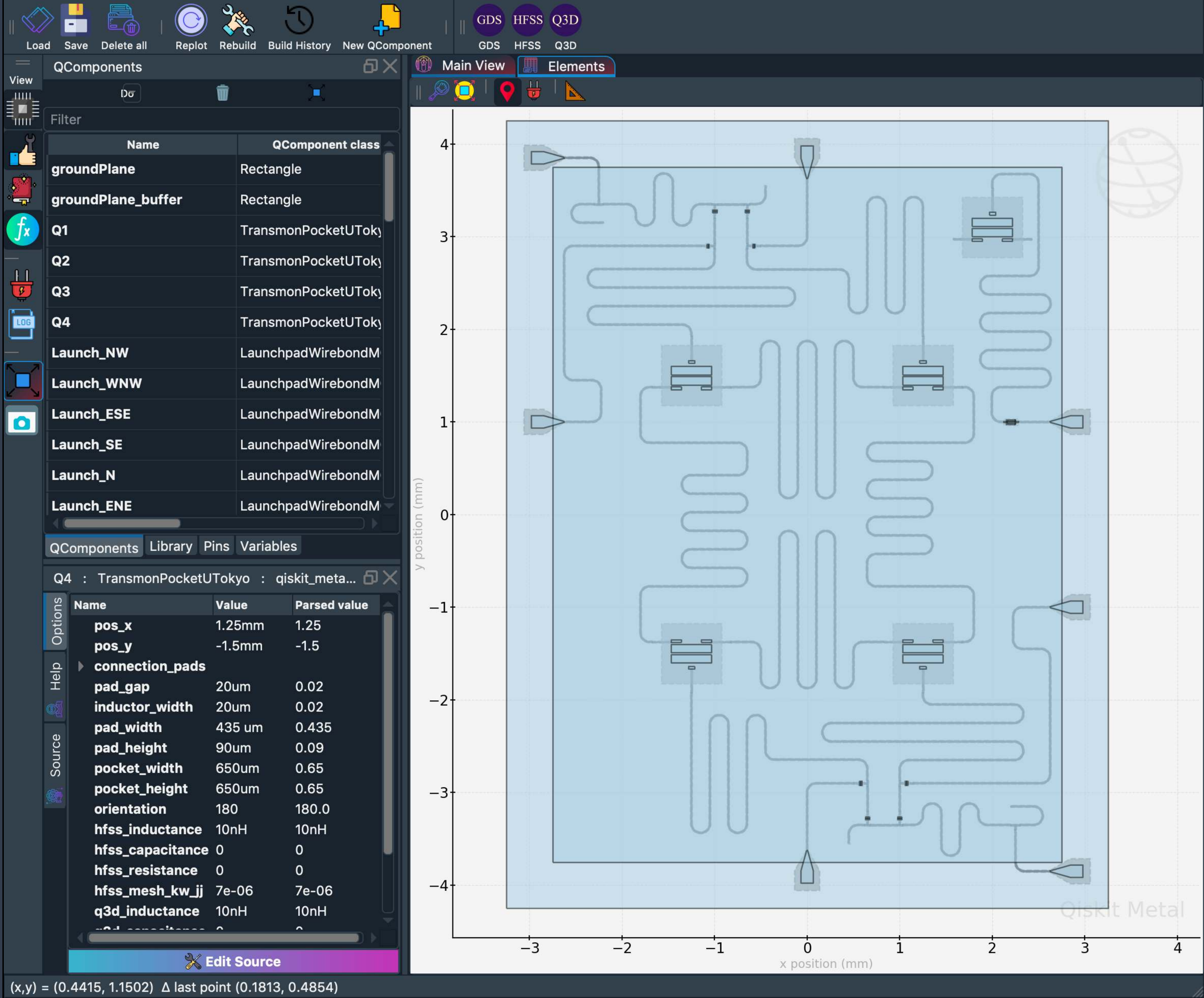


BIG BIG THANKS TO Yuri, Samanvay, Hanhee, Junye & team!!
Thomas, Dennis, Metal coaches, ...

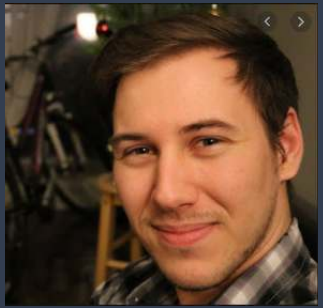
Qiskit | quantum device design

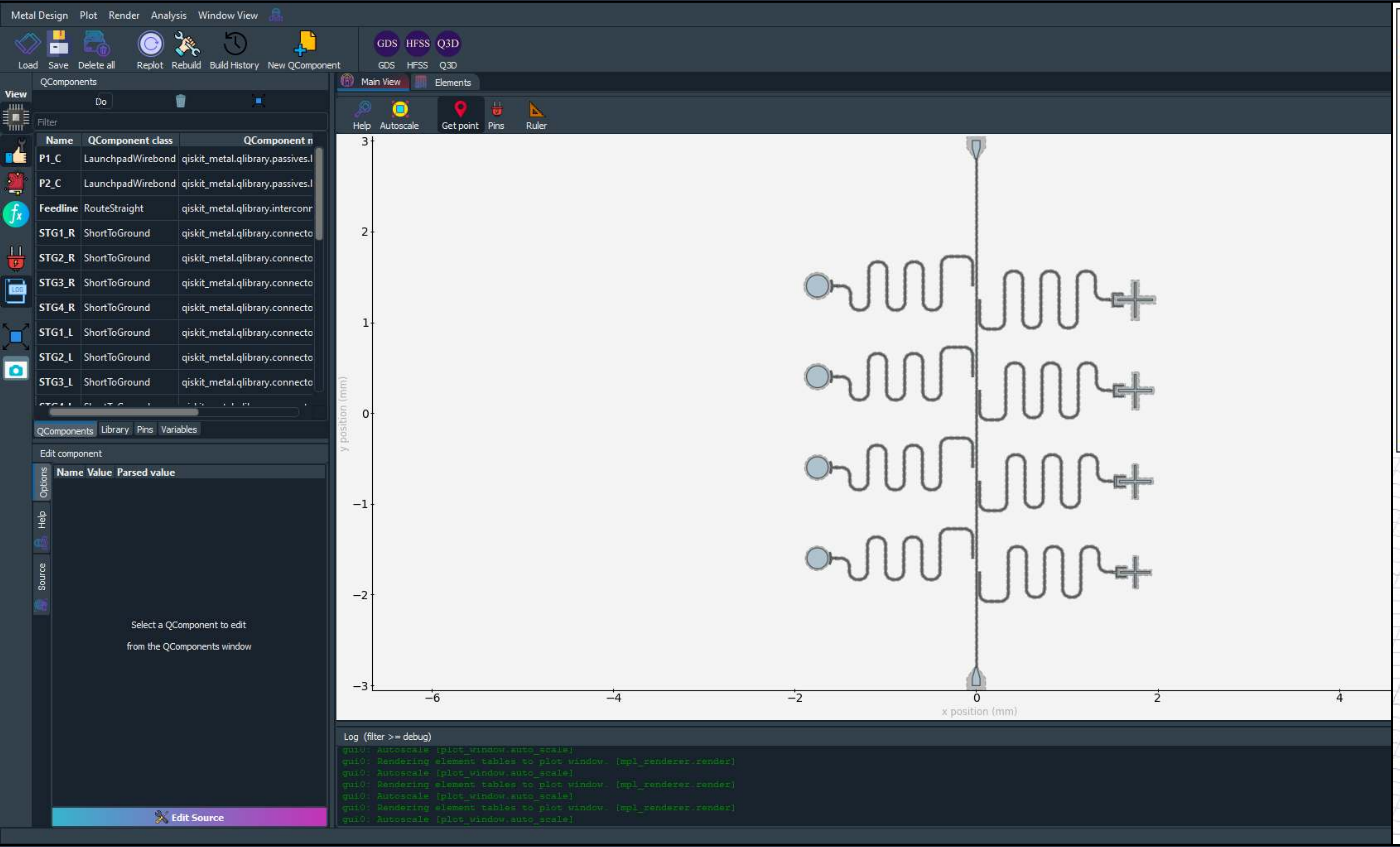
Devices made with Metal

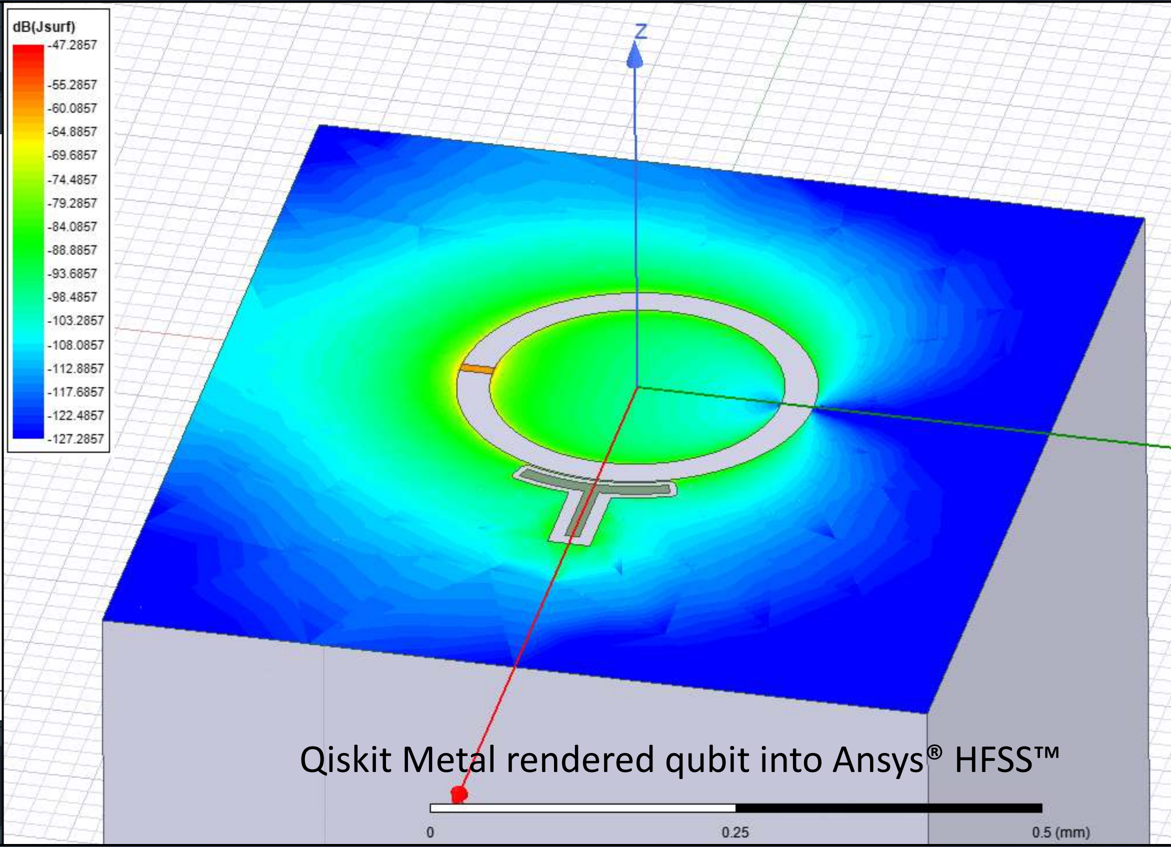
IBM 5Q Tsuru U Tokyo



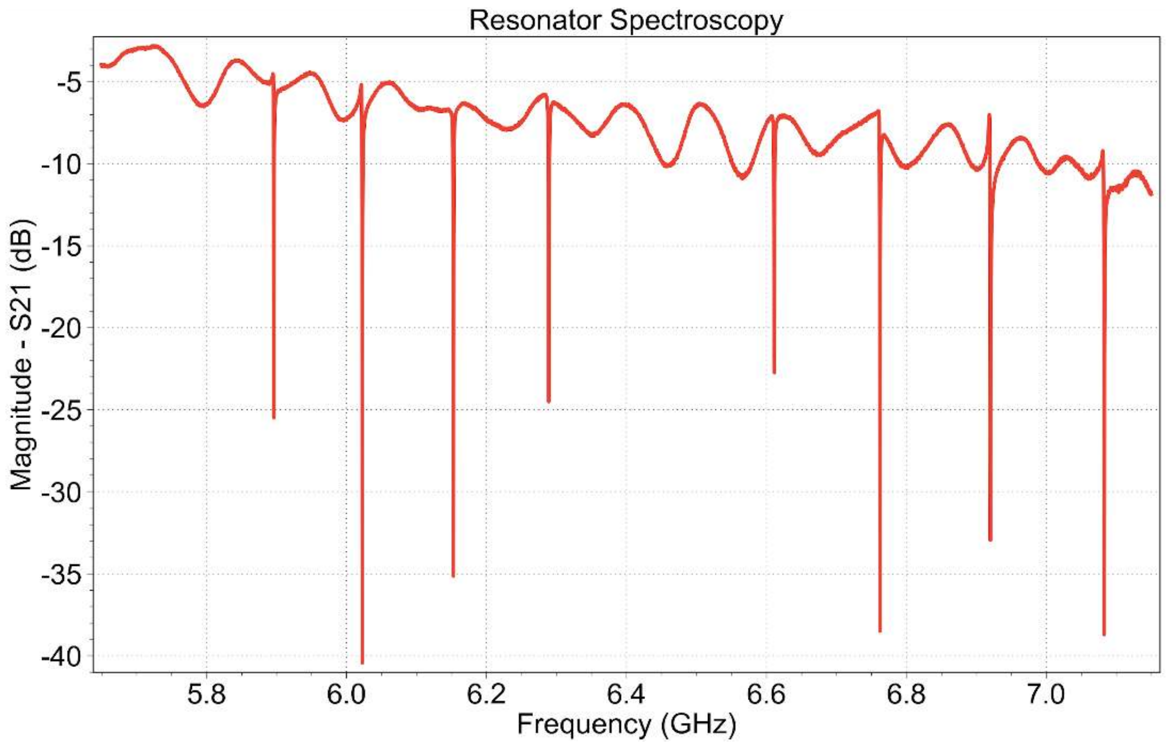
An 8-qubit chip designed by C. Warren, Amr Osman, and Bylander team (Chalmers) with the help of Qiskit Metal

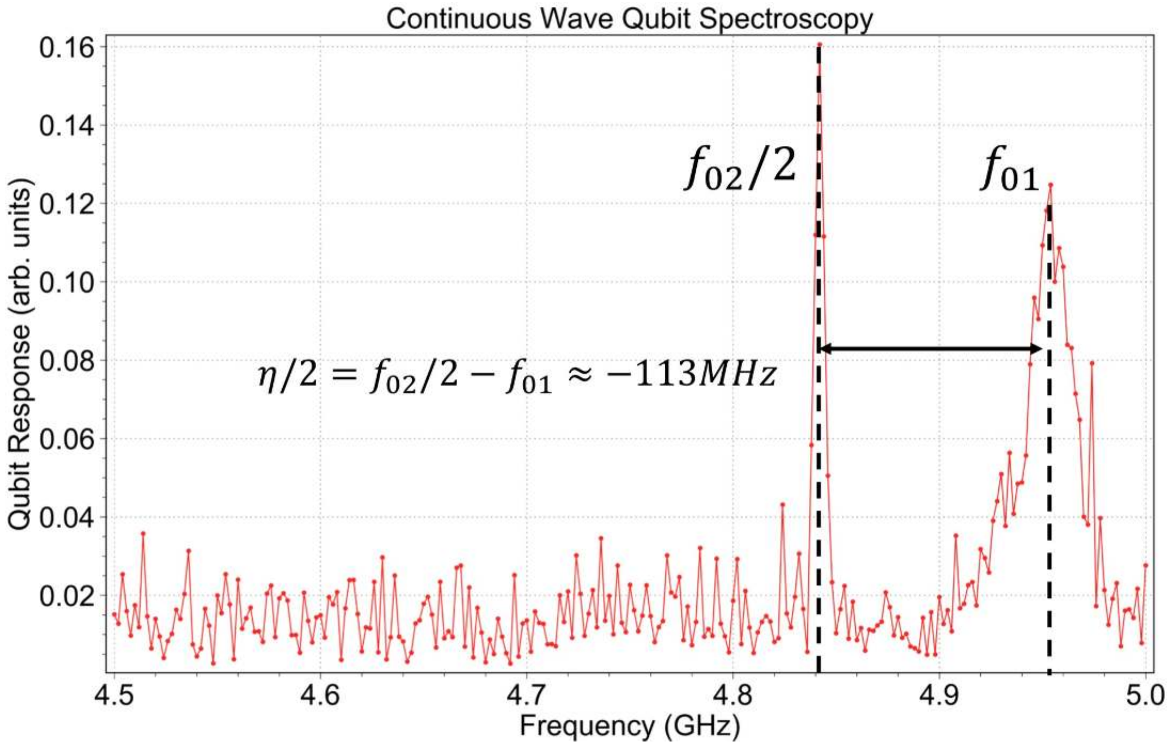






Experimental results of the Chalmers device designed with Qiskit Metal
Data courtesy of *C. Warren* & Amr Osman (Bylander, Chalmers)





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0.0.3

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- QDesigns

Docs > Qiskit Metal | Quantum Device Design & Analysis (Q-EDA) 0.0.3

Qiskit Metal | Quantum Device Design & Analysis (Q-EDA) 0.0.3

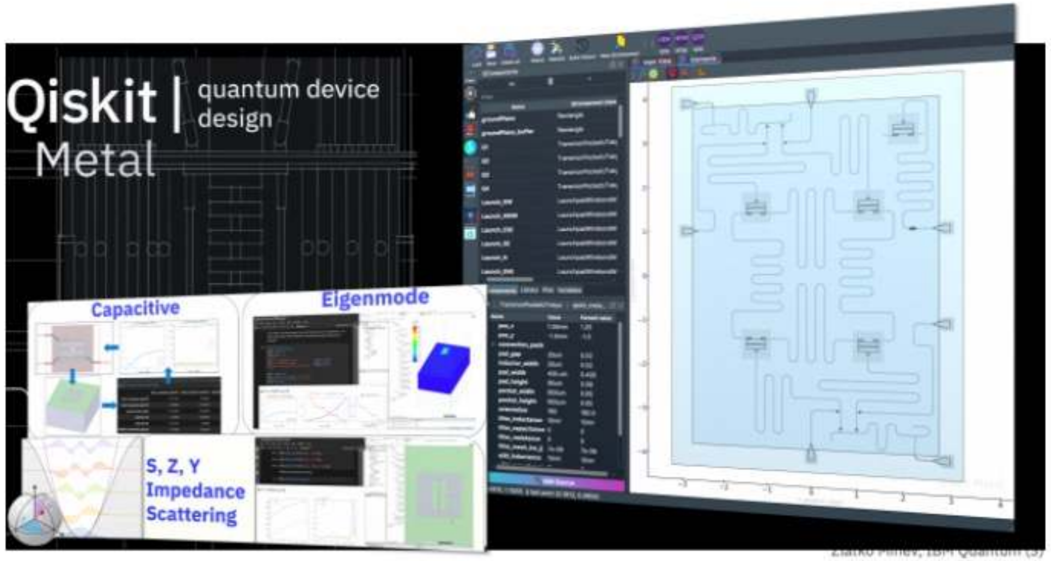
ATTENTION

This is an alpha version of Qiskit Metal, the code is still under development. Please let us know about anything you might want us to add or elaborate upon in the Slack channel #metal in the qiskit workspace.

HINT

You can open this documentation using

```
import qiskit_metal
qiskit_metal.open_docs()
```

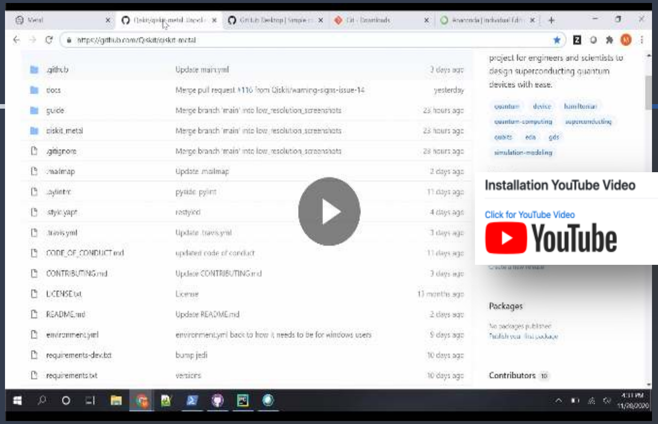


About

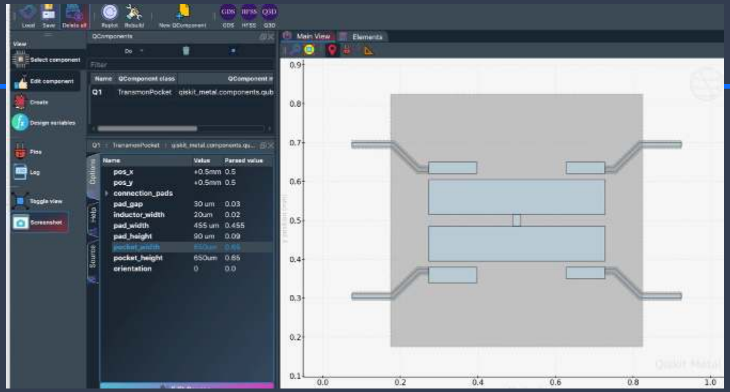
Qiskit Metal | for quantum device design & analysis (`Qiskit Metal`) is an open-source framework (and library) for the design of superconducting quantum chips and devices. Call it quantum EDA (Q-EDA) and analysis. Qiksit Metal is:

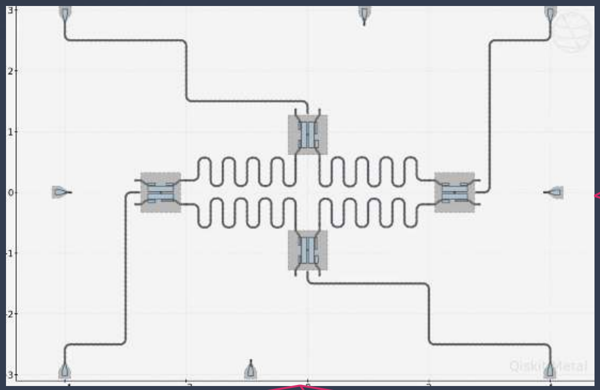
- Open source
- Community-driven

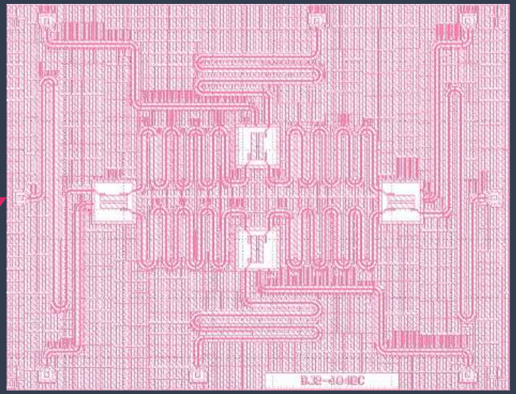
Tutorials

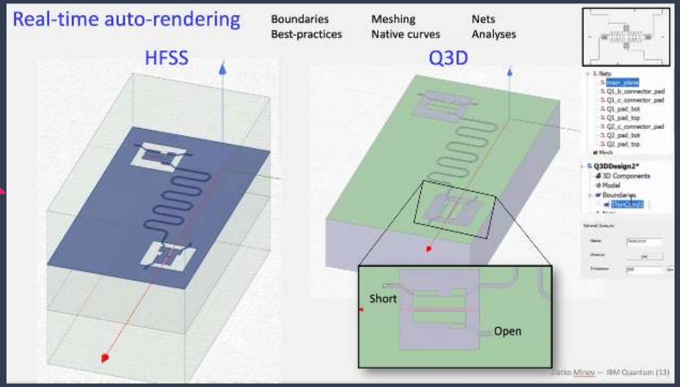


Installation YouTube Video
Click for YouTube Video
YouTube

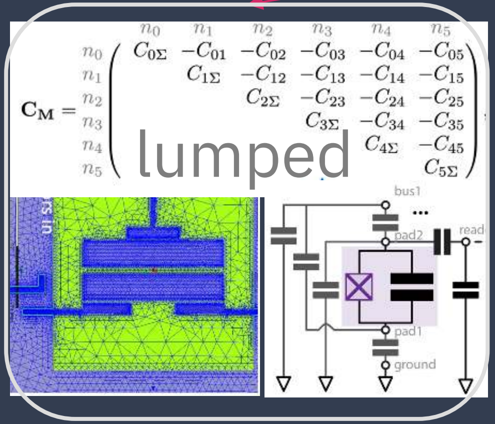






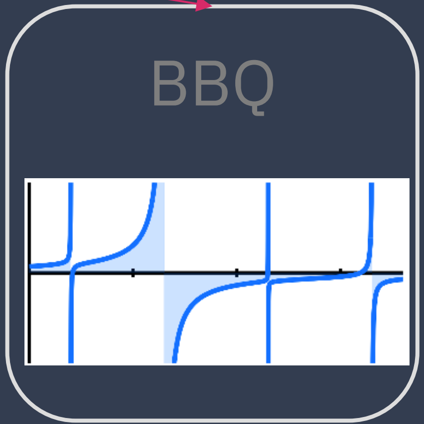


Real-time auto-rendering
Boundaries
Best-practices
Meshing
Native curves
Nets
Analyses
HFSS
Q3D
Short
Open



lumped
bus1
pad2
read
pad1
ground

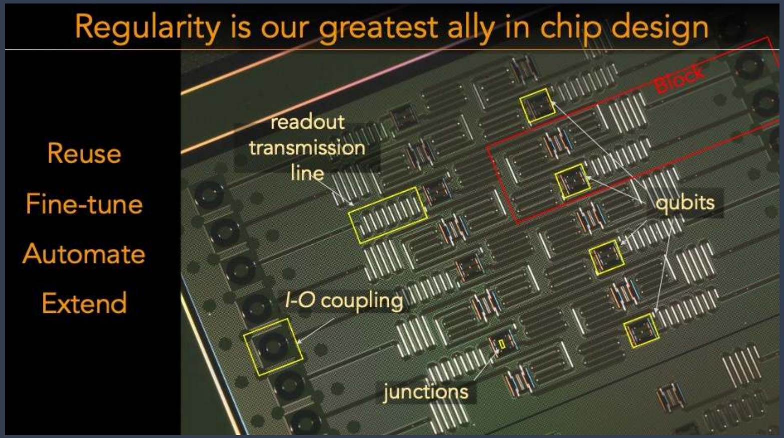
eigenmode

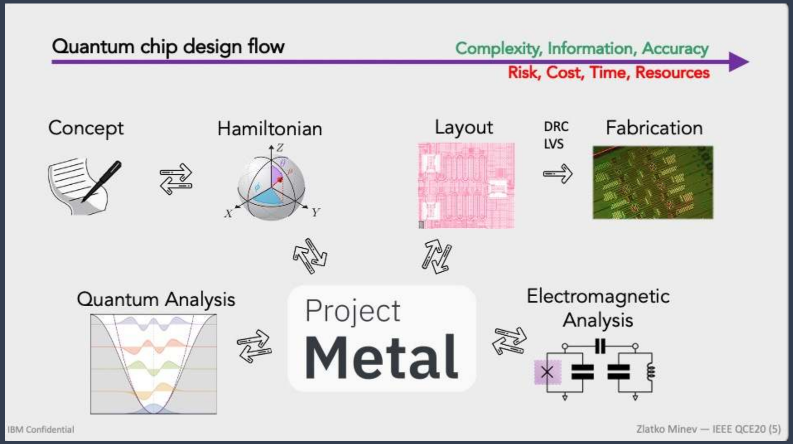


BBQ

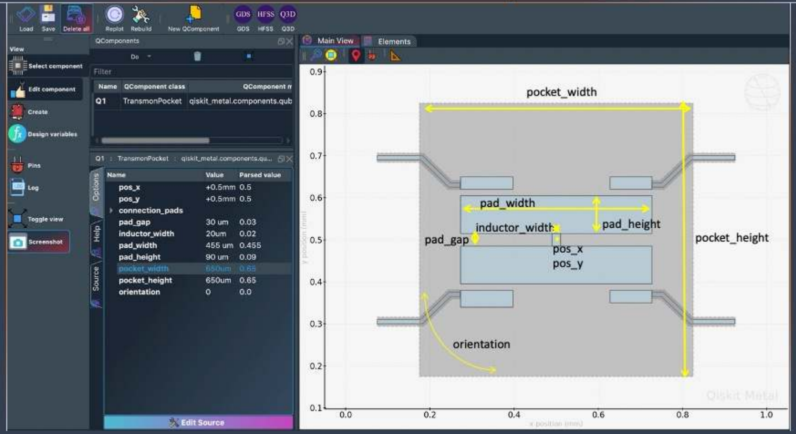
Qiskit | quantum device design

Tutorial 5

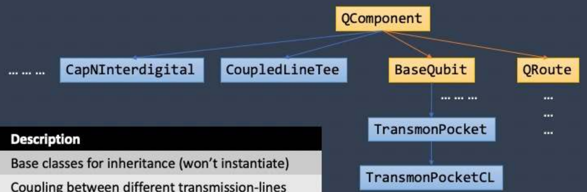




Fine-tune and automate parameters



Reuse and Extend the QLibrary

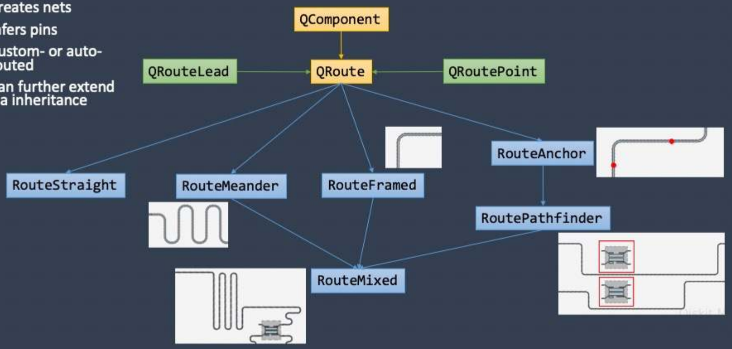


Folder	Description
Core	Base classes for inheritance (won't instantiate)
Couplers	Coupling between different transmission-lines
Lumped	Capacitive/Inductive elements
Qubits	Information
Sample Shapes	Geometries sand-box
Terminations	Single pin element to terminate transmission lines
Tlines	Two pins transmission lines

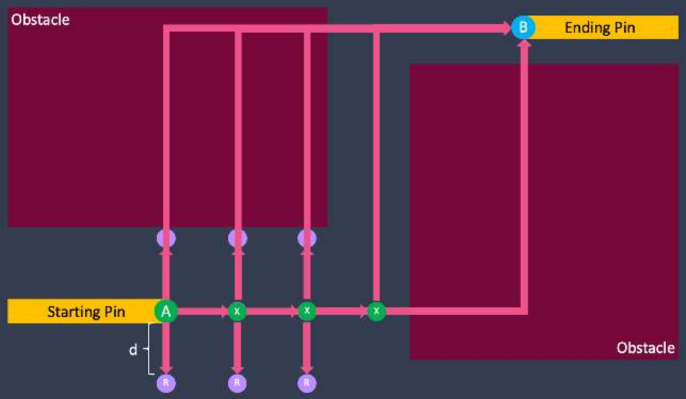
- Extensible horizontally and vertically
- Simple plug-n-play custom QComponents

Transmission Line

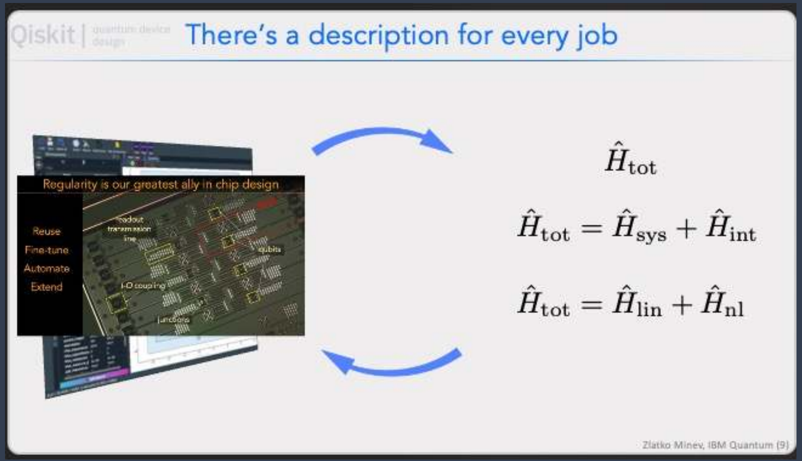
- Creates nets
- Infers pins
- Custom- or auto-routed
- Can further extend via inheritance

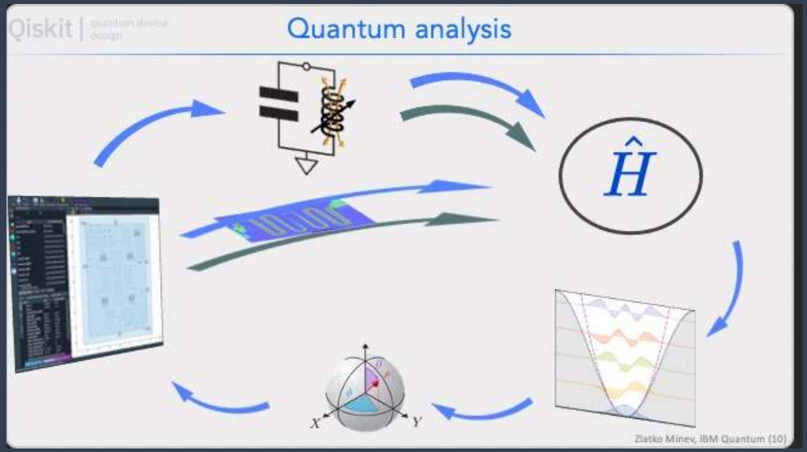


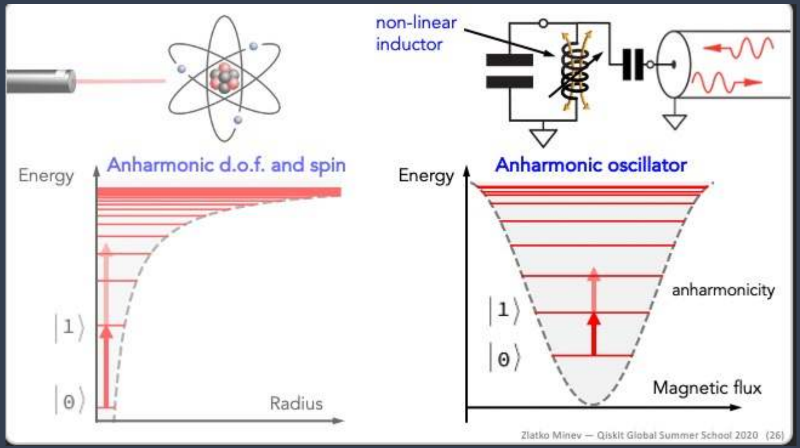
Making Connections

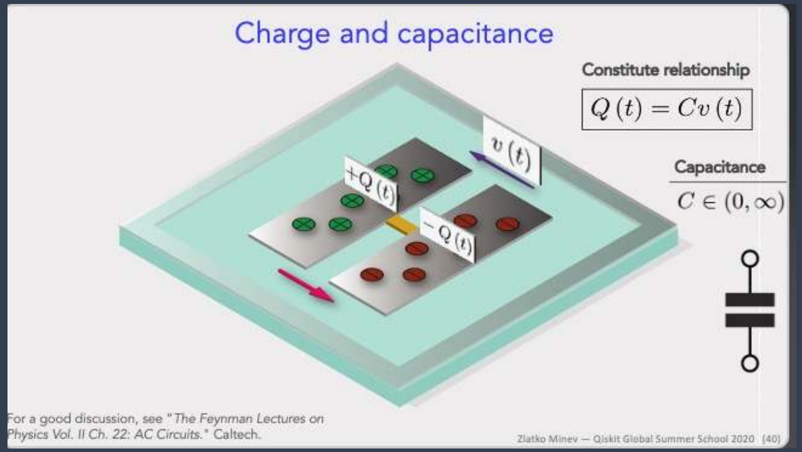


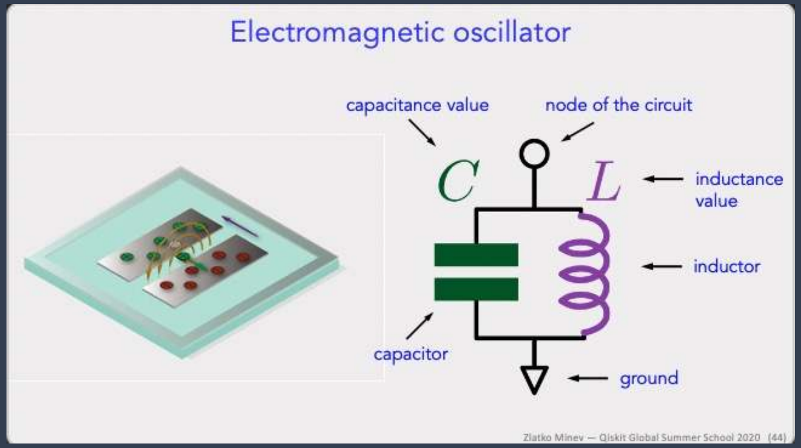
Tutorial 6

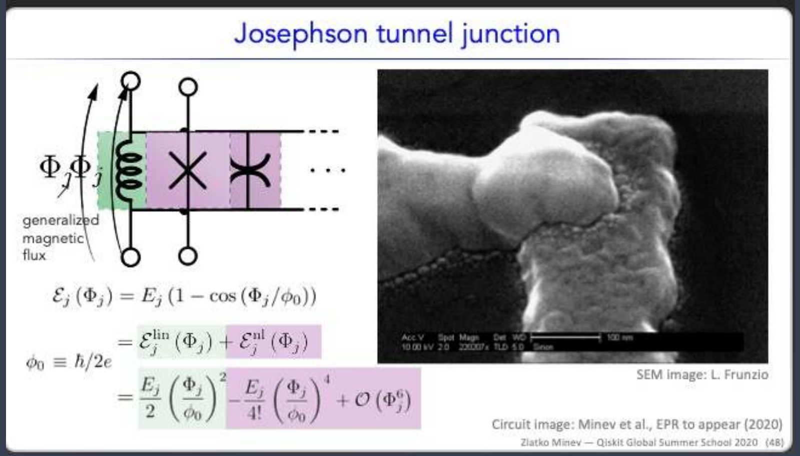

There's a description for every job
Regularity is our greatest ally in chip design
Reuse
Fine-tune
Automate
Extend
$\hat{H}_{\text{tot}}$
$\hat{H}_{\text{tot}} = \hat{H}_{\text{sys}} + \hat{H}_{\text{int}}$
$\hat{H}_{\text{tot}} = \hat{H}_{\text{lin}} + \hat{H}_{\text{nl}}$
Zlatko Minev, IBM Quantum (9)


Quantum analysis
$\hat{H}$
Zlatko Minev, IBM Quantum (10)

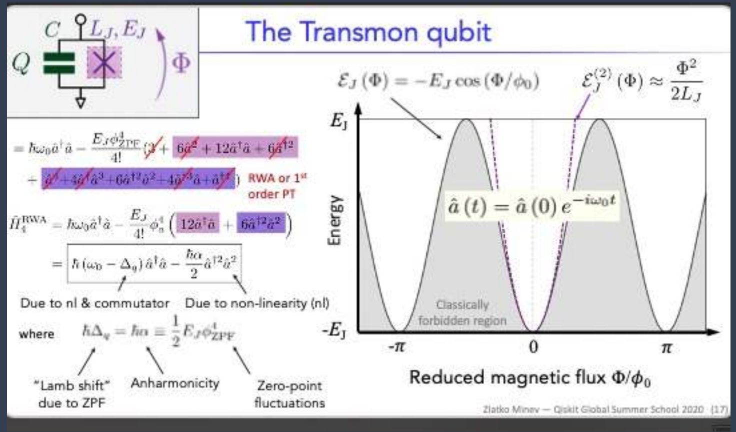

non-linear inductor
Energy
Anharmonic d.o.f. and spin
$|1\rangle$
$|0\rangle$
Radius
Energy
Anharmonic oscillator
anharmonicity
$|1\rangle$
$|0\rangle$
Magnetic flux
Zlatko Minev — Qiskit Global Summer School 2020 (26)

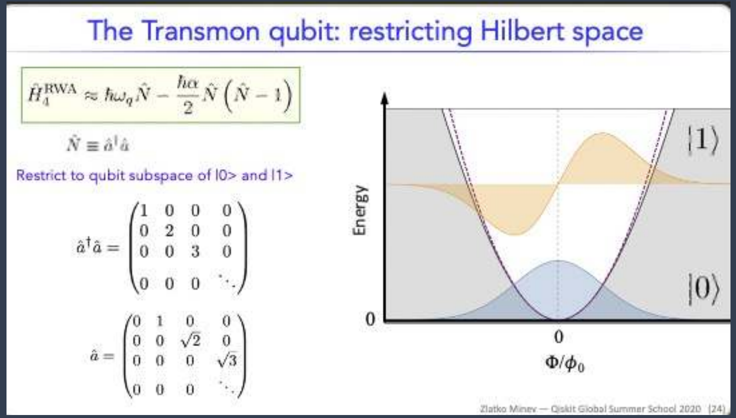

Charge and capacitance
Constitute relationship
$Q(t) = Cv(t)$
Capacitance
$C \in (0, \infty)$
$+Q(t)$
$-Q(t)$
$v(t)$
For a good discussion, see "The Feynman Lectures on Physics Vol. II Ch. 22: AC Circuits." Caltech.
Zlatko Minev — Qiskit Global Summer School 2020 (40)

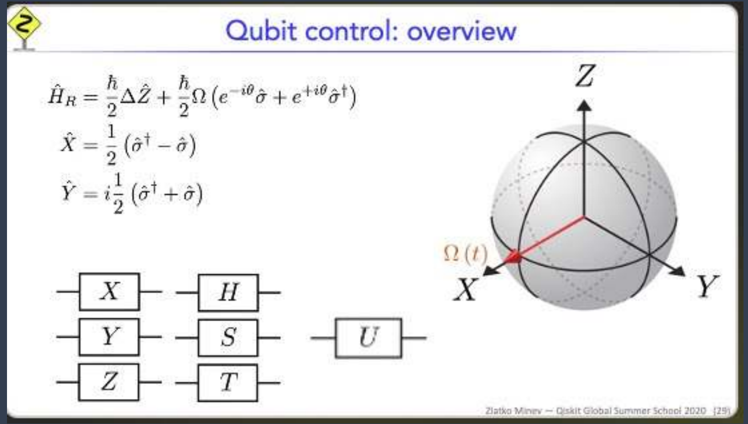

Electromagnetic oscillator
capacitance value
node of the circuit
C
L
inductance value
inductor
capacitor
ground
Zlatko Minev — Qiskit Global Summer School 2020 (44)

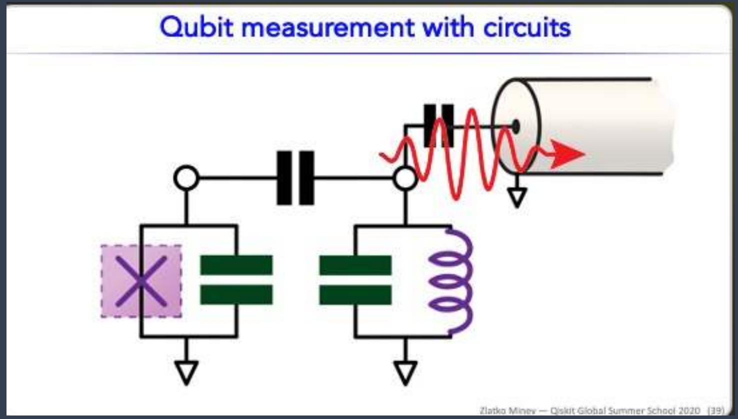

Josephson tunnel junction
Φ_j
generalized magnetic flux
$\mathcal{E}_j(\Phi_j) = E_j(1 - \cos(\Phi_j/\phi_0))$
$= \mathcal{E}_j^{\text{lin}}(\Phi_j) + \mathcal{E}_j^{\text{nl}}(\Phi_j)$
$\phi_0 \equiv \hbar/2e$
$= \frac{E_j}{2}\left(\frac{\Phi_j}{\phi_0}\right)^2 - \frac{E_j}{4!}\left(\frac{\Phi_j}{\phi_0}\right)^4 + \mathcal{O}(\Phi_j^6)$
SEM image: L. Frunzio
Circuit image: Minev et al., EPR to appear (2020)
Zlatko Minev — Qiskit Global Summer School 2020 (48)

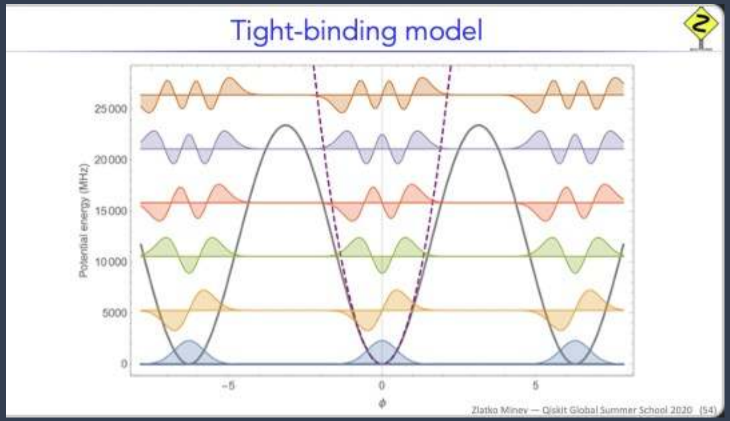
Tutorial 7











Demo notebook

Qiskit | quantum device design

Tutorials so far

YouTube

1 Qiskit Metal E01 - Overview
Qiskit
WATCHED 1:07:34

2 Qiskit Metal E02 - End to end example of Quantum Chip Design - Part 1 of 2
Qiskit
WATCHED 1:02:00

3 Qiskit Metal E03 End to end example of Quantum Chip Design - Part 2 of 2
Qiskit
WATCHED 59:11

4 Qiskit Metal E04 - QComponents for parametric design
Qiskit
52:46

11 Qiskit Metal E06 - Quantum Analysis 101 Prerequisites
Qiskit
1:03:27

12 Qiskit Metal E07 - Introduction to the transmon qubit
Qiskit
1:02:45

New analysis
(pre-recorded)

5 Qiskit Metal E05.1 - Analysis - Capacitance and Frequency Control
Qiskit
1:09:45

6 Qiskit Metal E05.2 - Analysis - Eigenmode and Energy Participation
Qiskit
1:07:02

7 Qiskit Metal E05.3 - Analysis - EPR Theory
Qiskit
1:18:26

8 Qiskit Metal E05.4 - Analysis - Summary EPR Quantization with Code Example
Qiskit
1:07:32

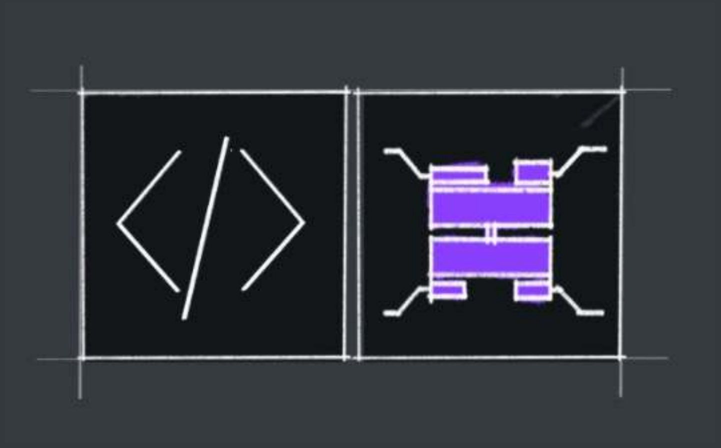
9 Qiskit Metal E05.5 - Analysis - Finish Eigenmode Start Impedance Analysis
Qiskit
54:27

10 Qiskit Metal E05.6 - Analysis - Extracting S Parameters for a Hanging Resonator
Qiskit
40:18

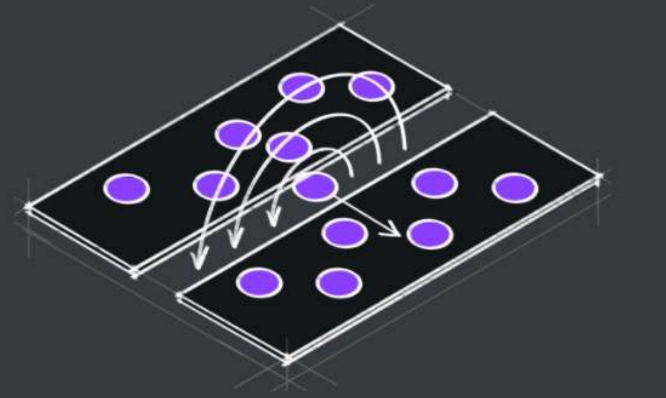
Why the Vision of Qiskit Metal

End-to-end automation

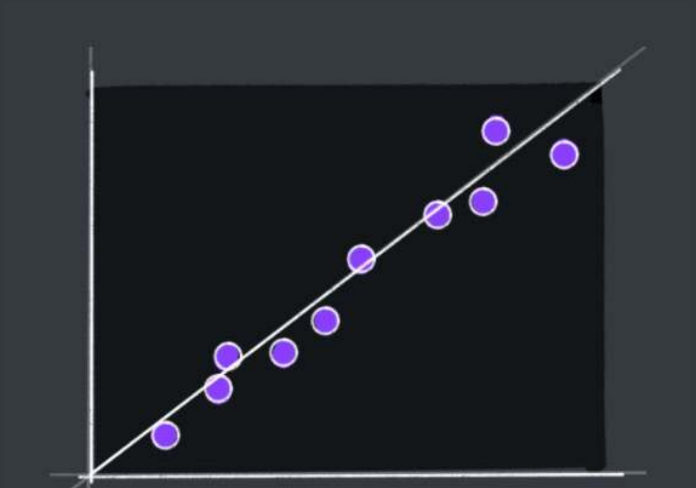
Flexible & extensible



Light-weight interoperability

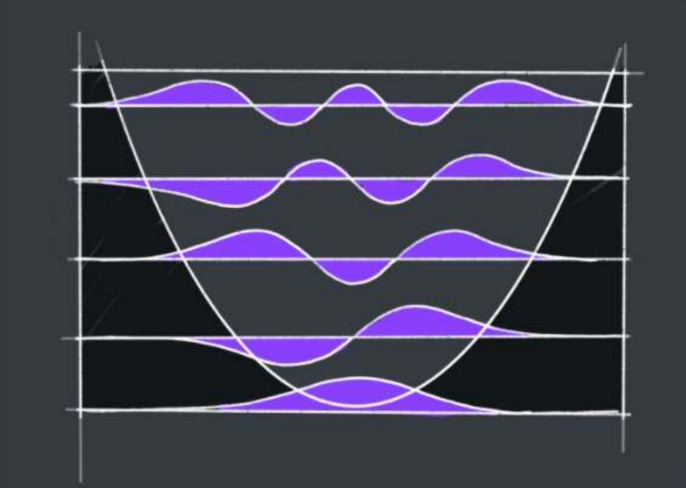


Experimentally tested



Library of components

Cutting edge resources



qiskit.org/metal

Thank you!

Building together

Call for community participation

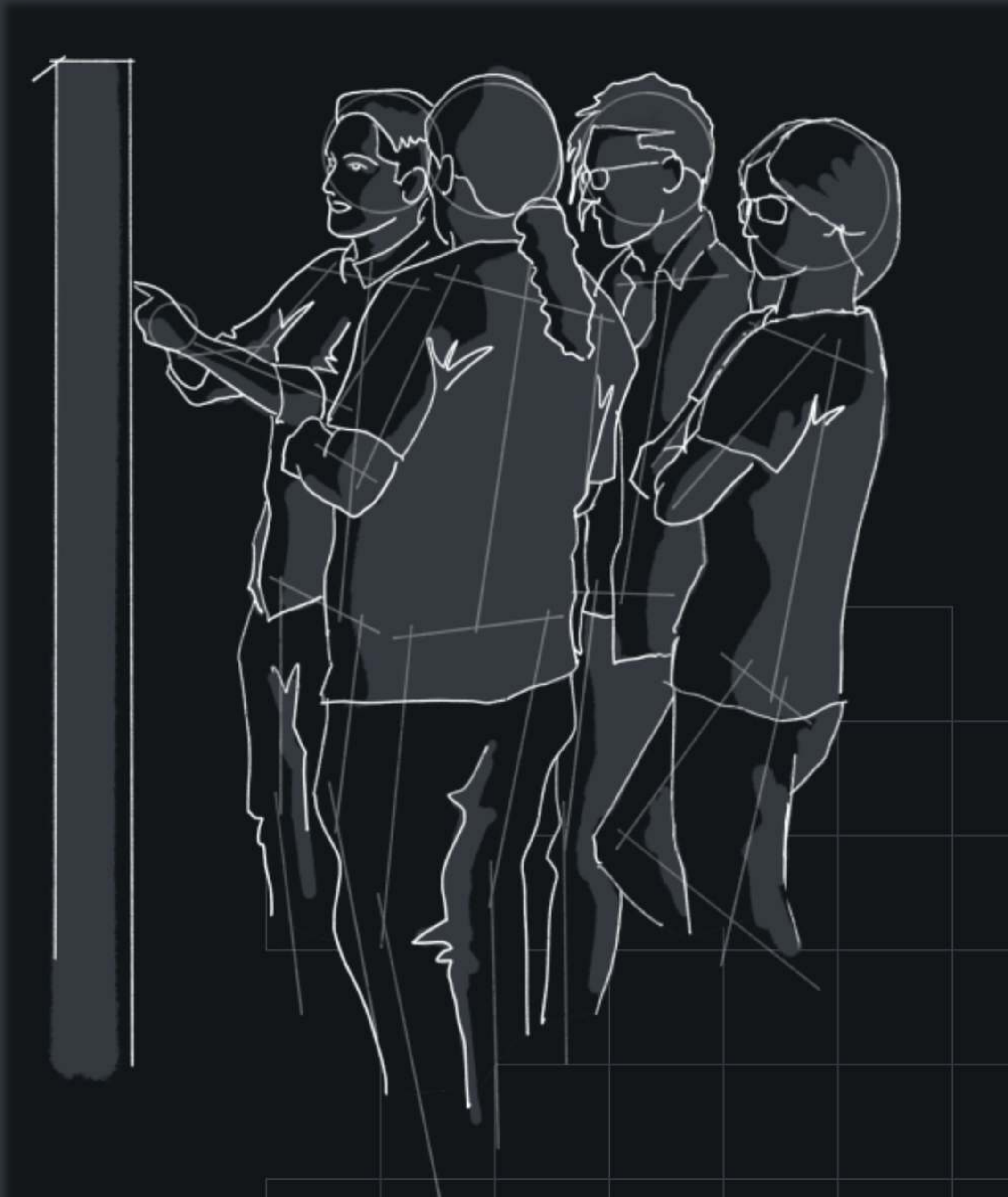
Open source

Education

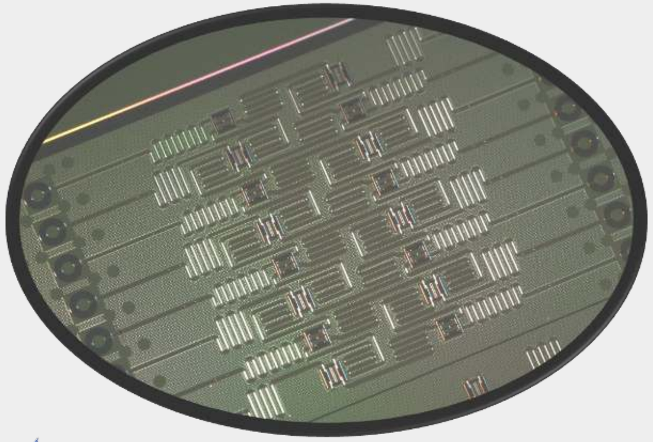
See summer school lectures 16-21 by Z. Minev from *Introduction to Quantum Computing and Quantum Hardware* and the *Qiskit Textbook*

qiskit.org/metal

@zlatko_minev



Physical Devices ↔ Quantum Hamiltonian



$\hat{H}$

Energy participation ratio (EPR)

Minev et al. arXiv:1902.10355 & arXiv:2010.00620 (Yale) arXiv.org > quant-ph > arXiv:2010.00620

Quantum Physics

[Submitted on 1 Oct 2020]

Energy-participation quantization of Josephson circuits

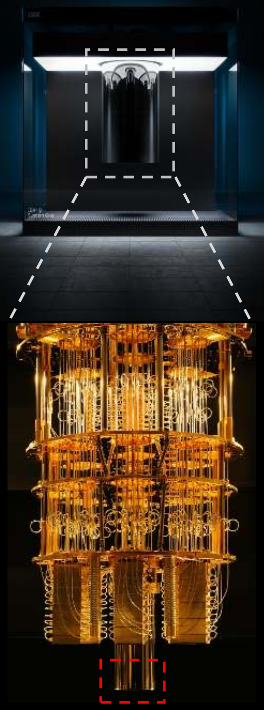
Zlatko K. Minev, Zaki Leghtas, Shantanu O. Mundhada, Lysander Christakis, Ioan M. Pop, Michel H. Devoret

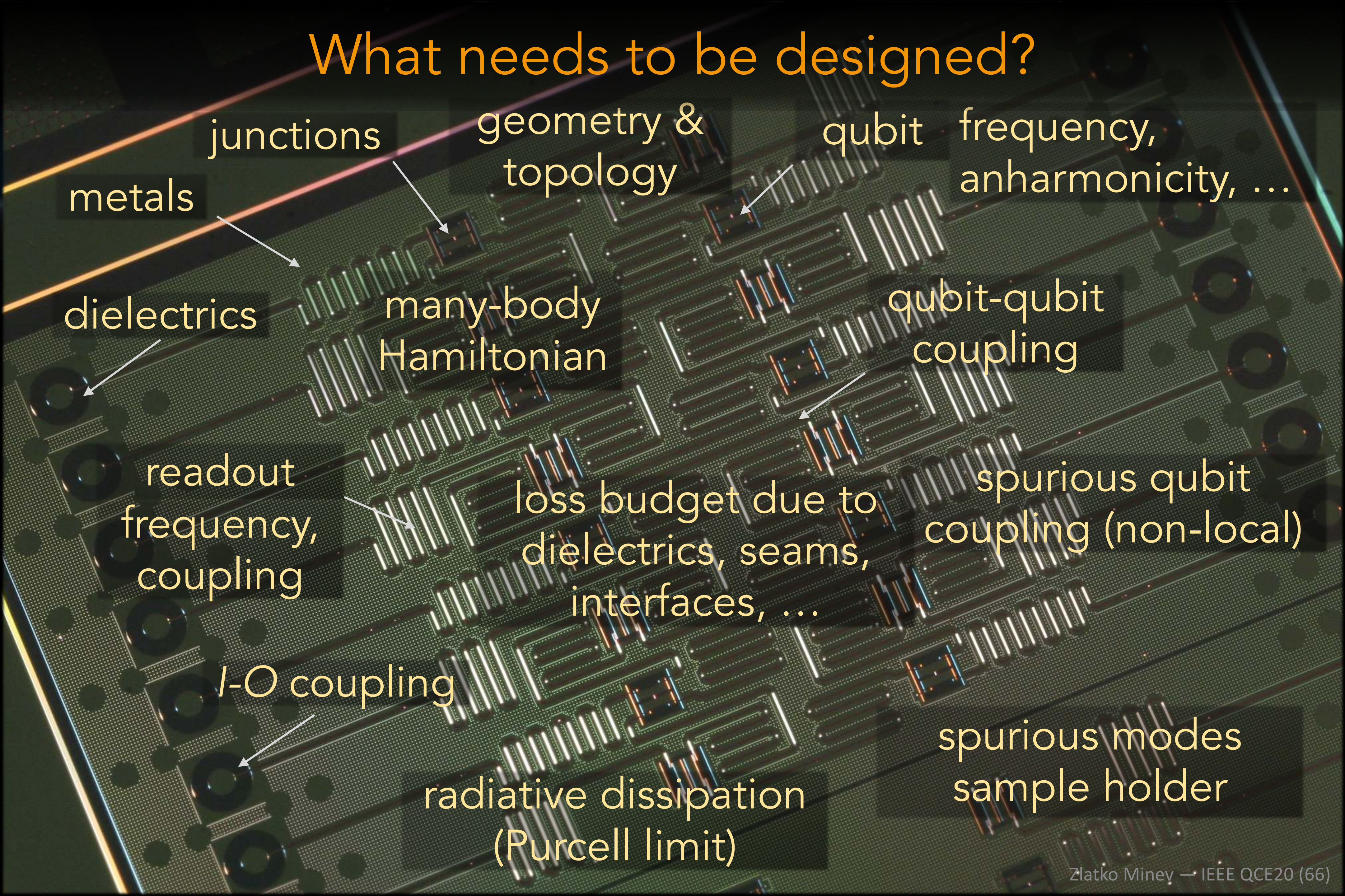
Accepted in principle: *Nature npj qi*

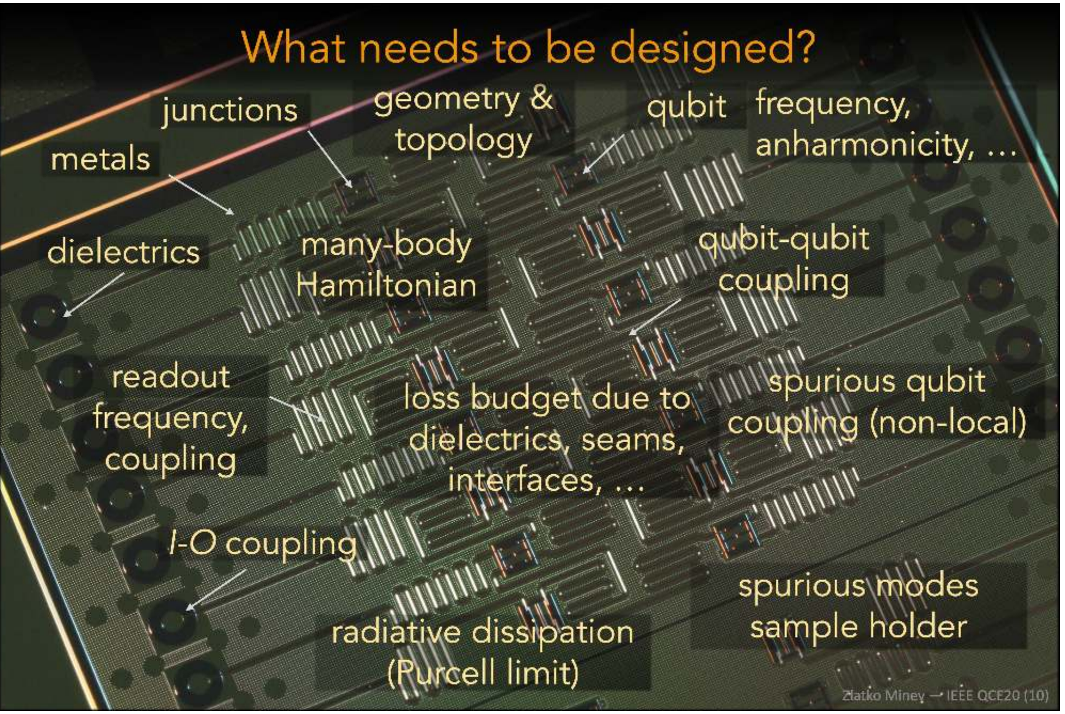
See also Minev Yale dissertation Sec. 4.1 (arXiv: 1902.10355)

Yale

What needs to be designed?







The solution of all these questions reduces to:

Where is the energy?

What *fraction of the energy* of a mode p_j (p_l)

is stored in the non-linear (dissipative) element?

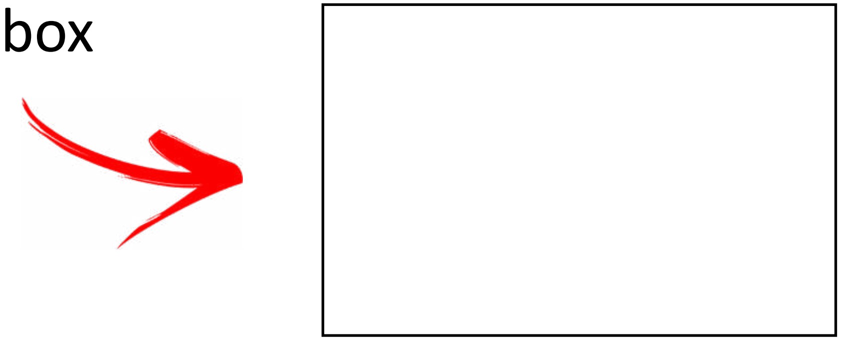
$$0 \leq p_j, p_l \leq 1$$

$$\hat{H}_{\mathrm{full}} \qquad \mathcal{D}[\sqrt{\kappa}\hat{a}]\rho$$

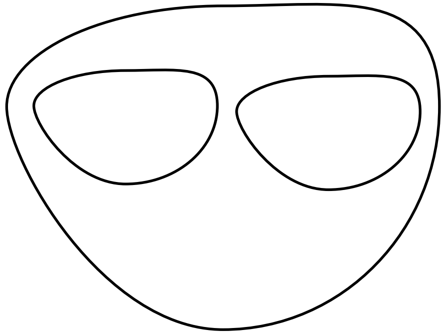
$$\hat{H}_{\mathrm{full}}$$

Hamiltonian of a linear distributed system

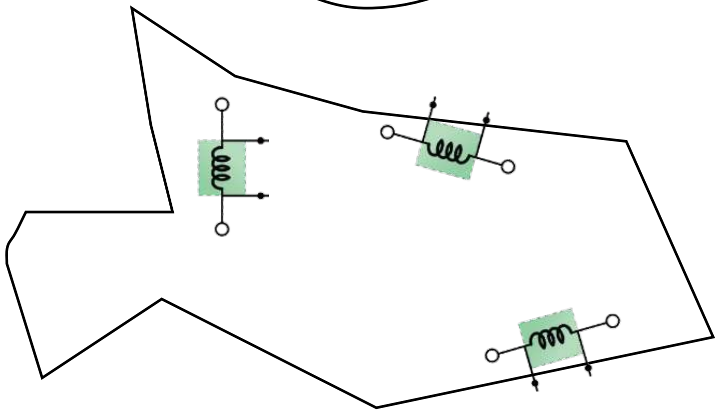
This is a box



$$\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m$$



$$\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m$$



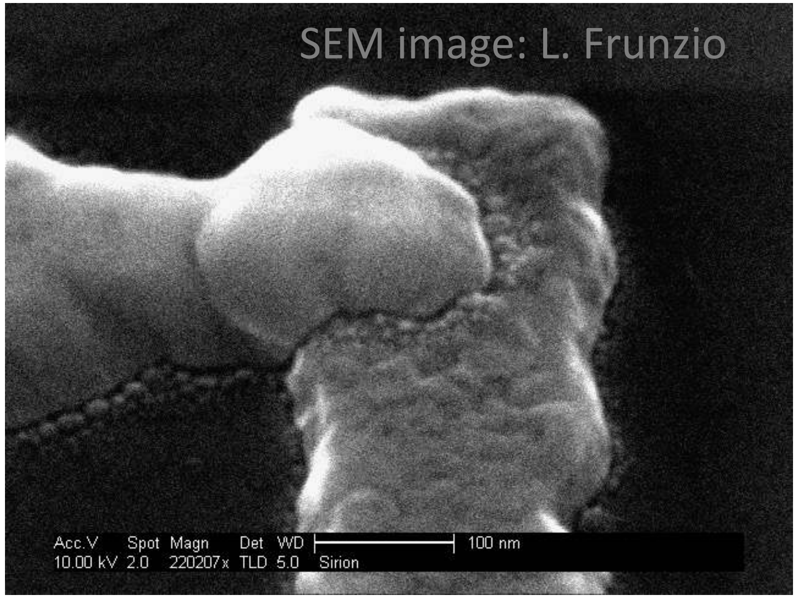
$$\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m$$

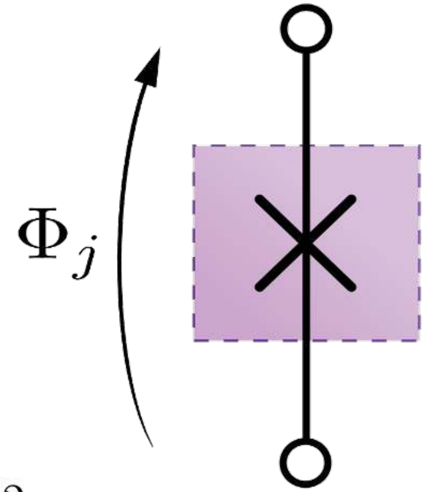
There are two kinds of physicists:

Those who believe all of physics is *spins*.

Those who believe all of physics is *oscillators*.

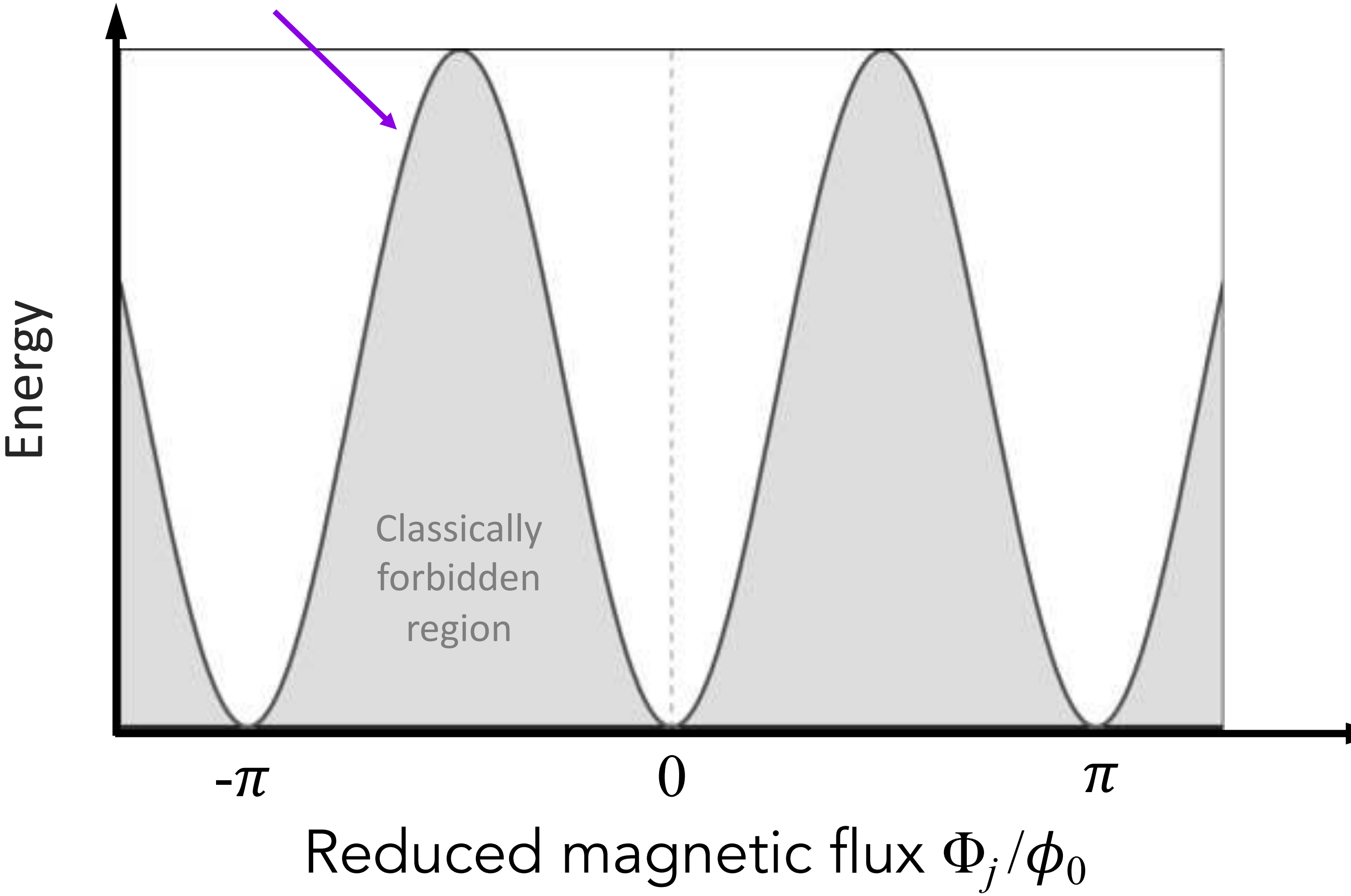
Energy of a non-linear element





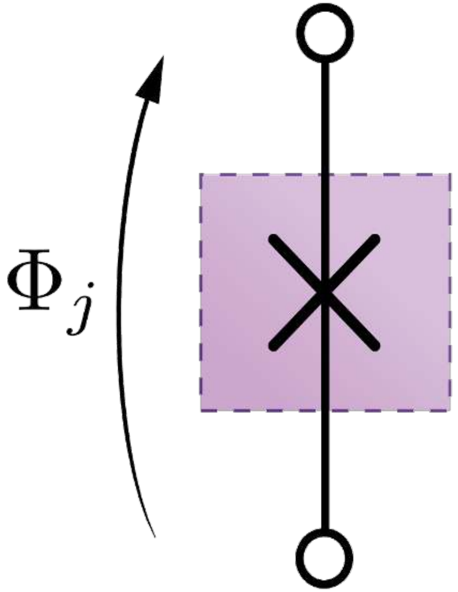
$\phi_0 \equiv \hbar/2e$

$$\mathcal{E}_j\left(\Phi_j\right) = E_j\left(1 - \cos\left(\Phi_j/\phi_0\right)\right)$$

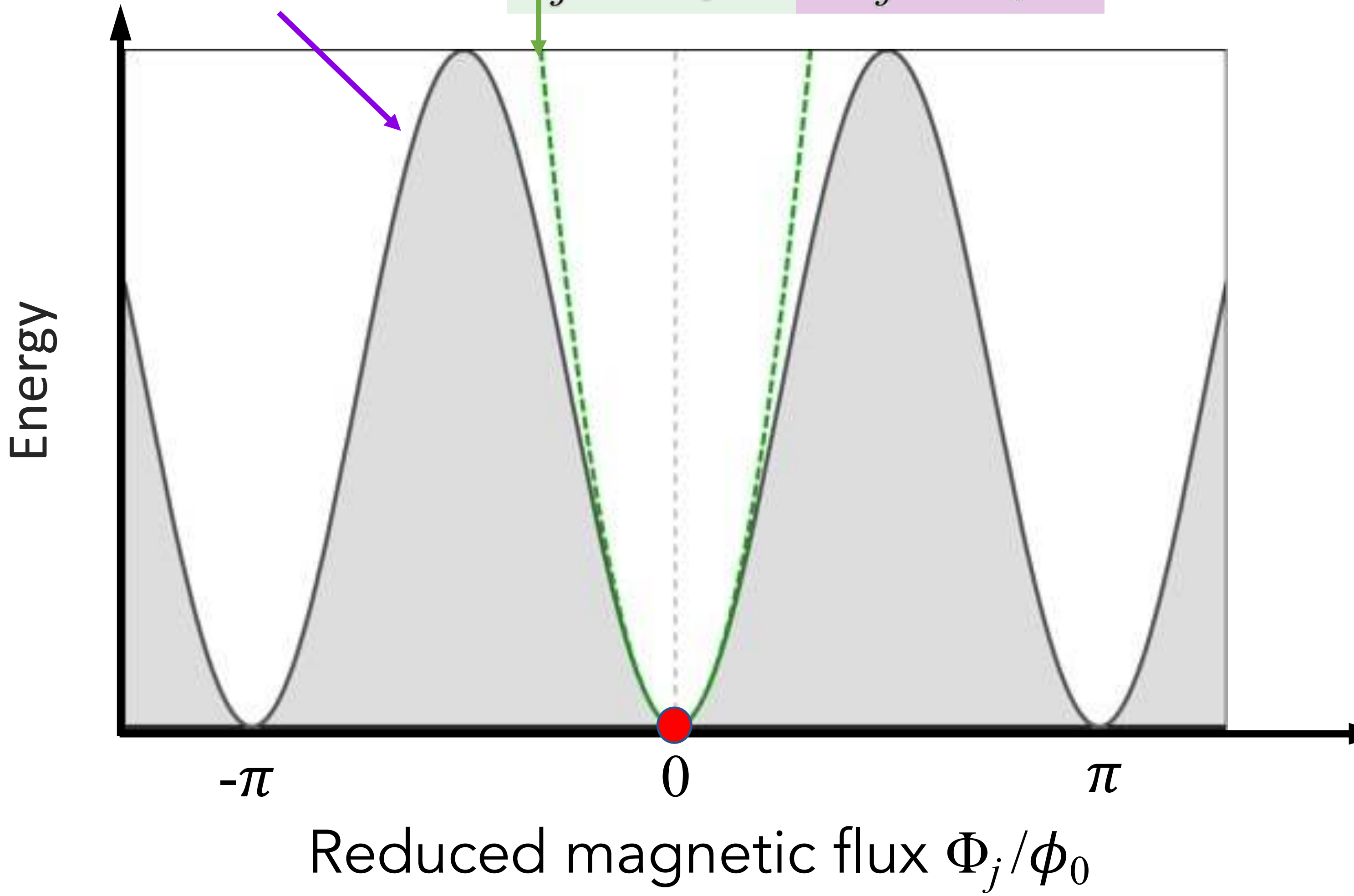


Energy of a non-linear element

Momentarily only

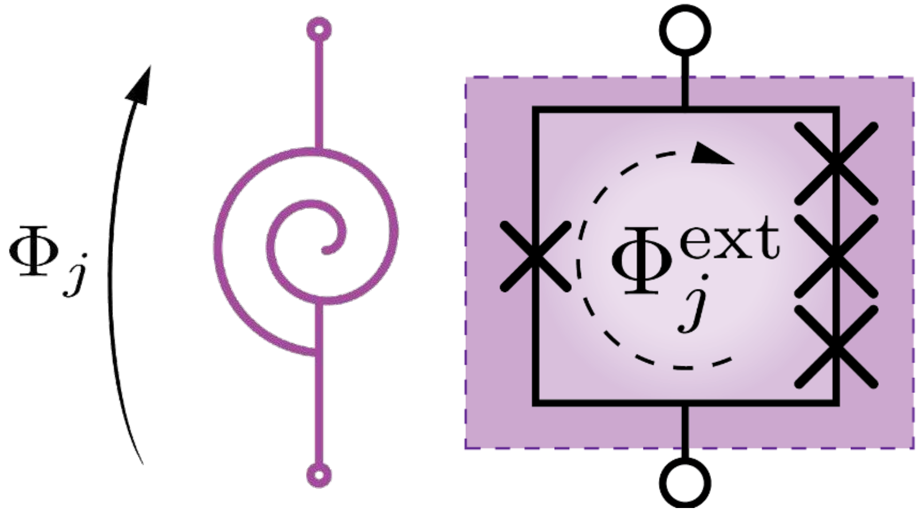


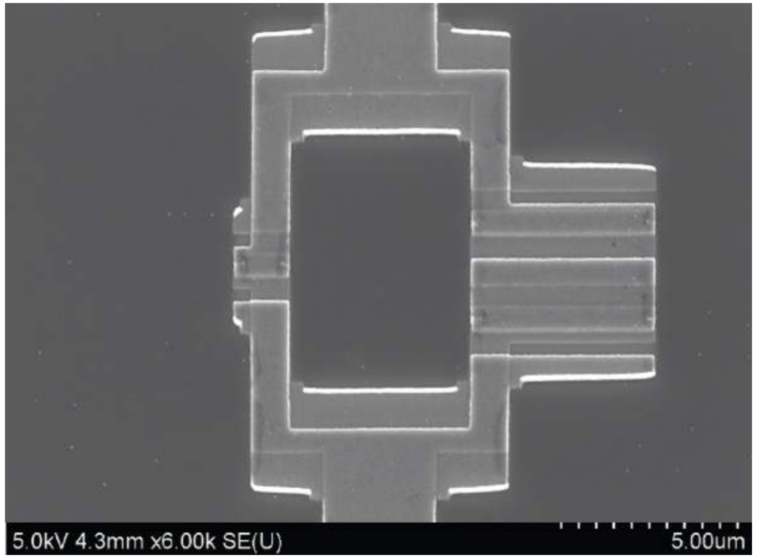
$$\mathcal{E}_j(\Phi_j) = \mathcal{E}_j^{\mathrm{lin}}(\Phi_j) + \mathcal{E}_j^{\mathrm{nl}}(\Phi_j)$$



$\phi_0 \equiv \hbar/2e$

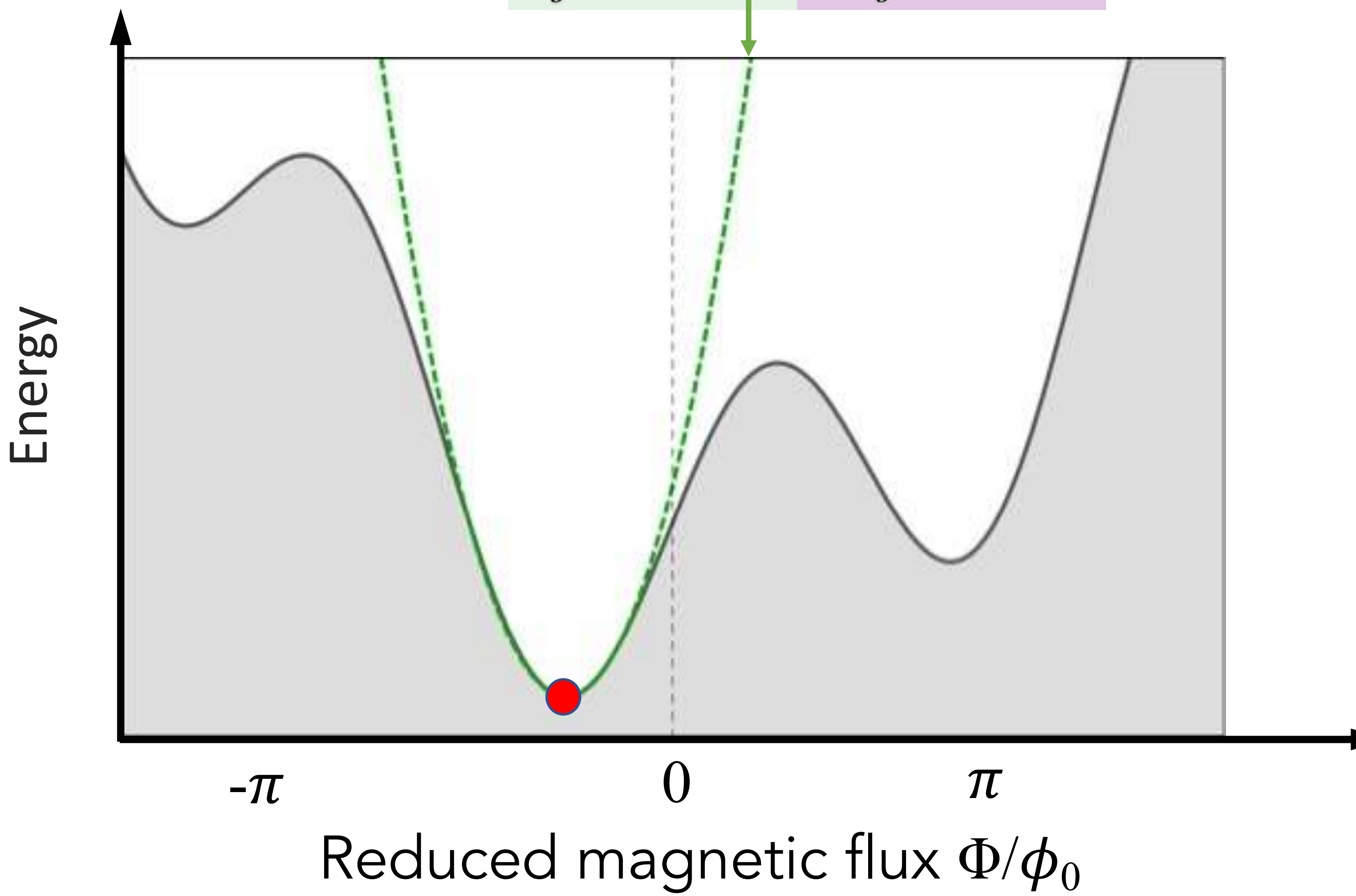
Composite-circuit non-linear dipole





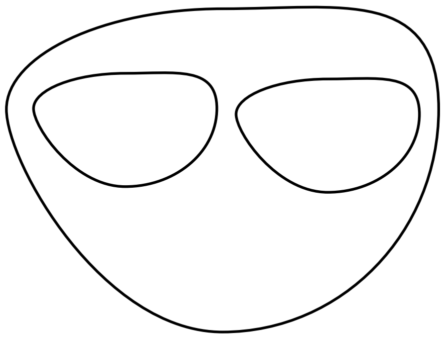
SEM image: Frattini & Sivak; see APL (2017)

$$\mathcal{E}_j(\Phi_j;\Phi_j^{\mathrm{ext}}) = \mathcal{E}_j^{\mathrm{lin}}(\Phi_j) + \mathcal{E}_j^{\mathrm{nl}}(\Phi_j)$$

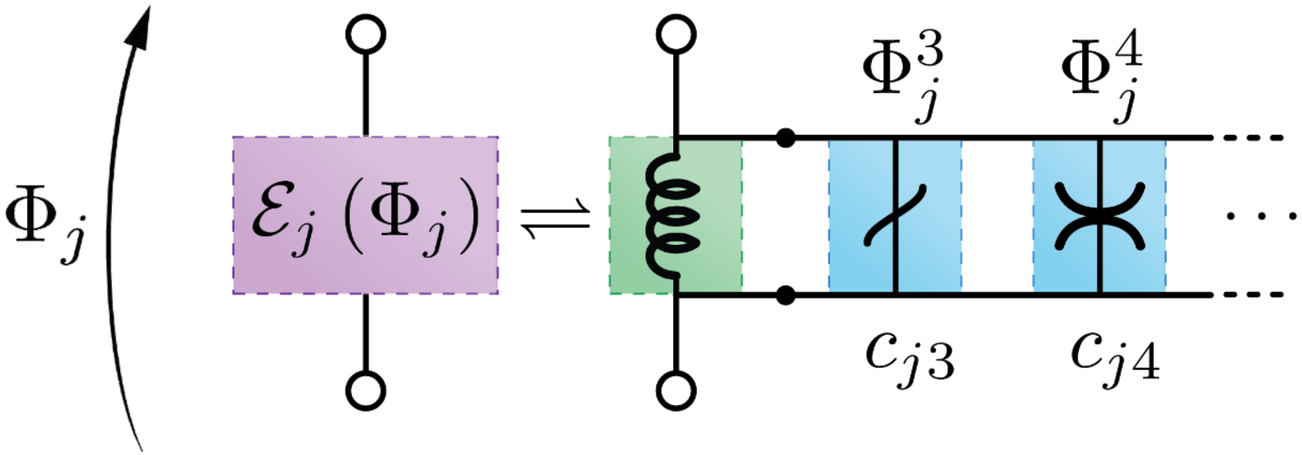


$\phi_0 \equiv \hbar/2e$

So far

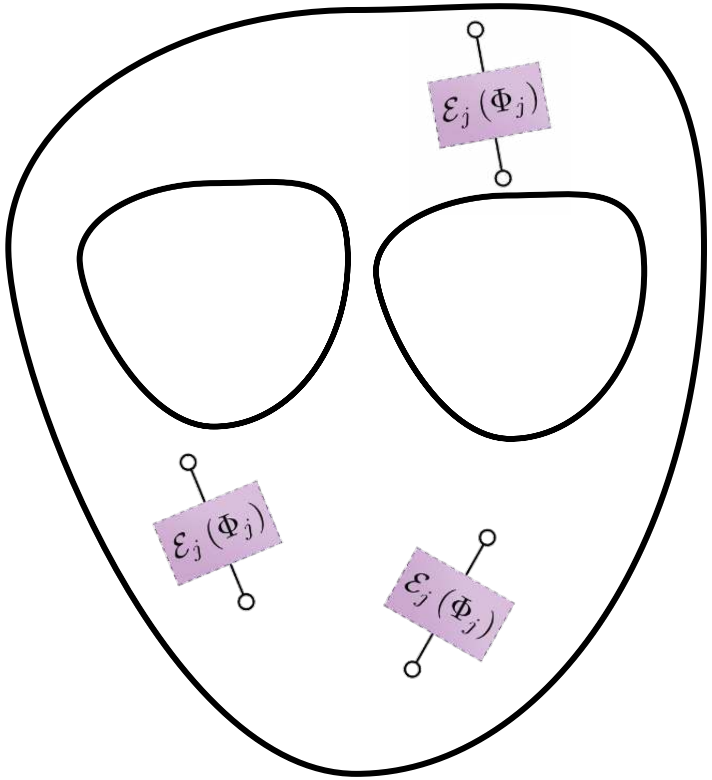


linear distributed system



non-linear dipole

Distributed system with non-linear dipoles



$$\hat{H}_{\text{full}}\left(\hat{\mathbf{\Phi}}_{\text{bare}}, \hat{\mathbf{Q}}_{\text{bare}}\right)$$

change basis

$$\hat{H}'_{\text{full}}\left(\hat{\mathbf{\Phi}}_{\text{eigen}}, \hat{\mathbf{Q}}_{\text{eigen}}\right)$$

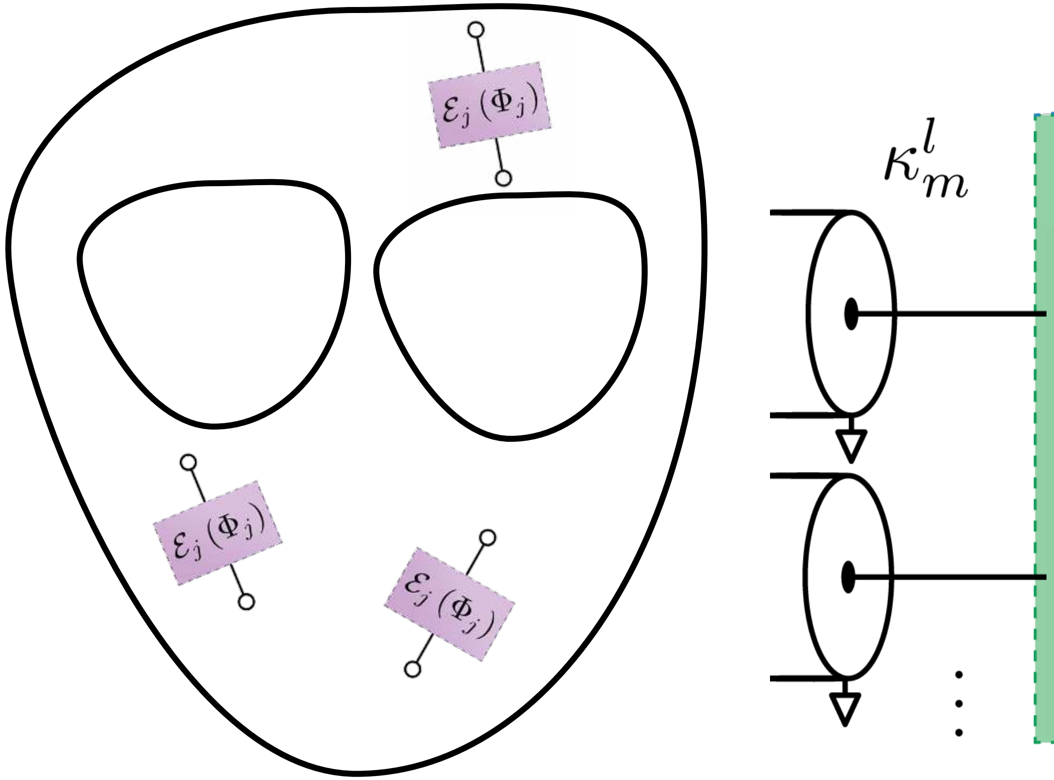
change basis

$$\hat{H}''_{\text{full}}\left(\hat{\mathbf{a}}_m, \hat{\mathbf{a}}_m^\dagger\right)$$

no approximation here

$$\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m + \sum_{j=1}^{J} \mathcal{E}_j^{\text{nl}}\left(\hat{\Phi}_j/\phi_0\right)$$

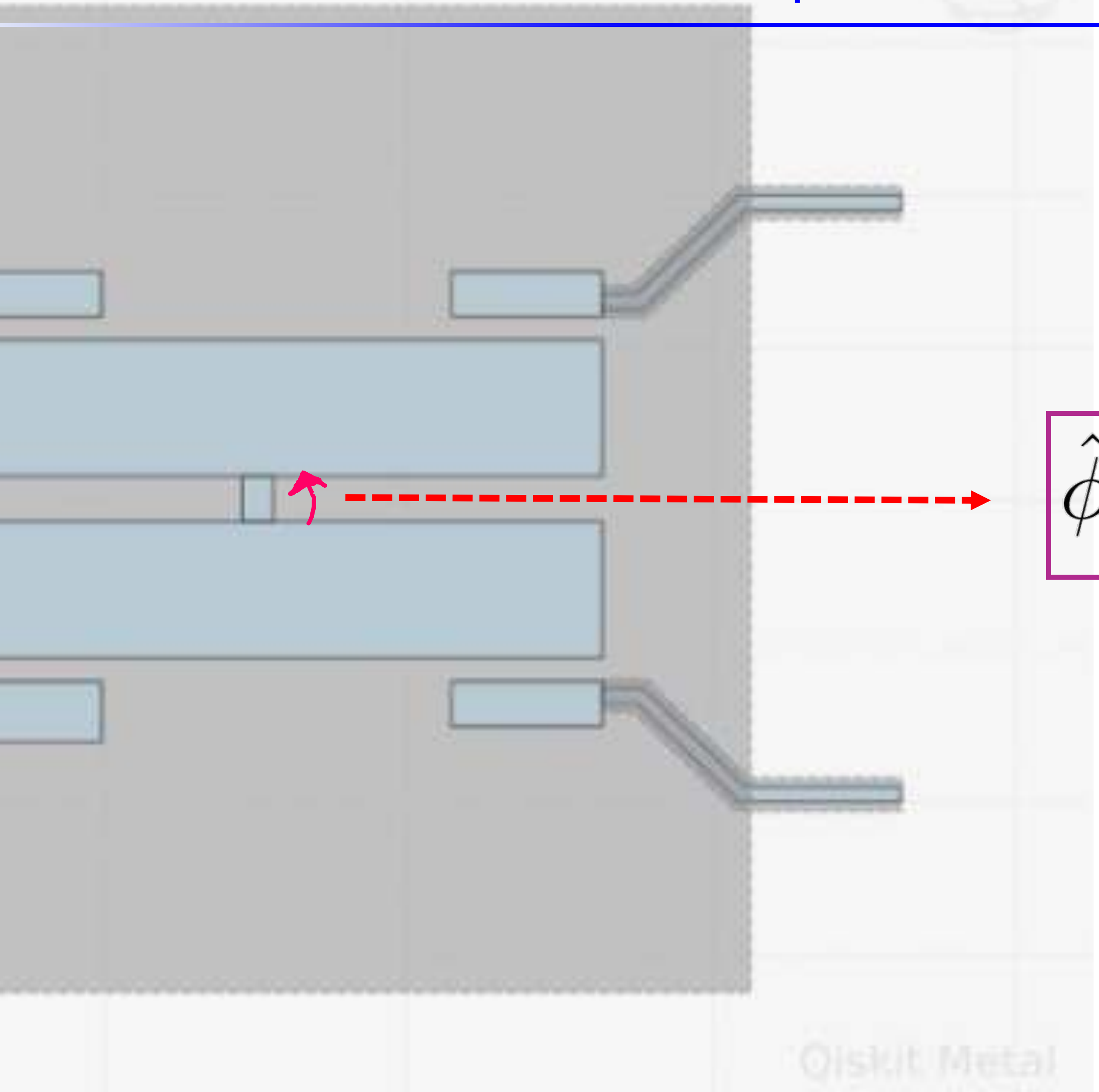
Distributed system with non-linear dipoles



$$\overbrace{\overbrace{\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m}^{\hat{H}_{\mathrm{lin}}} + \overbrace{\sum_{j=1}^{J} \mathcal{E}_j^{\mathrm{nl}}\left(\boxed{\hat{\Phi}_j}/\phi_0\right)}^{\hat{H}_{\mathrm{nl}}}}^{\hat{H}_{\mathrm{full}}}$$

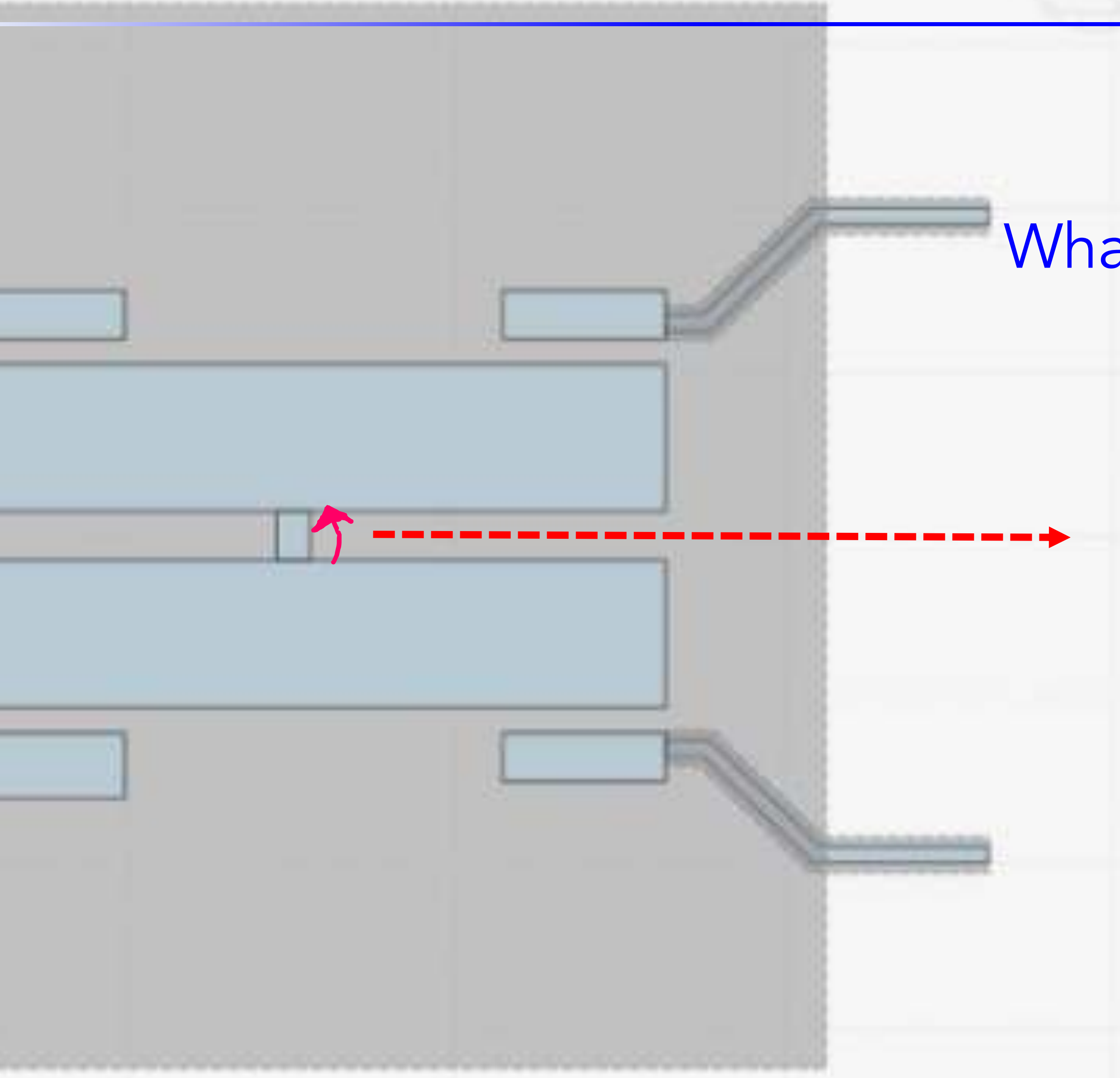
second quantization in eigen basis of linearized circuit

Quantum flux operator for the non-linear dipole



$$\boxed{\hat{\phi}_j}$$

Quantum operator

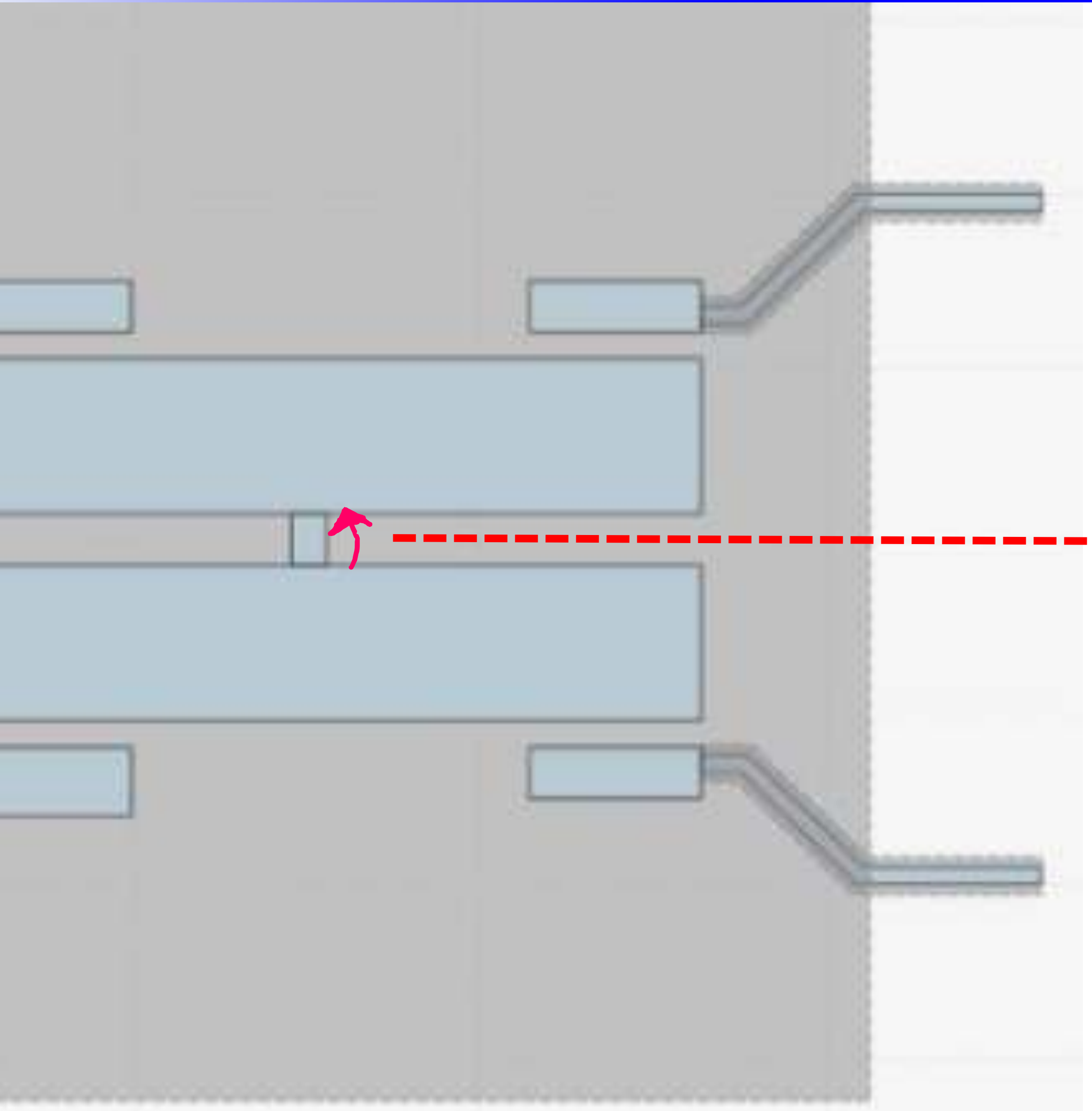


What is zero-point fluctuation of the phase of junction *j* due to mode *m*?

$$\boxed{\hat{\phi}_j} = \sum_{m=1}^{M} \boxed{\phi_{mj}} \left(\hat{a}_m^\dagger + \hat{a}_m\right)$$

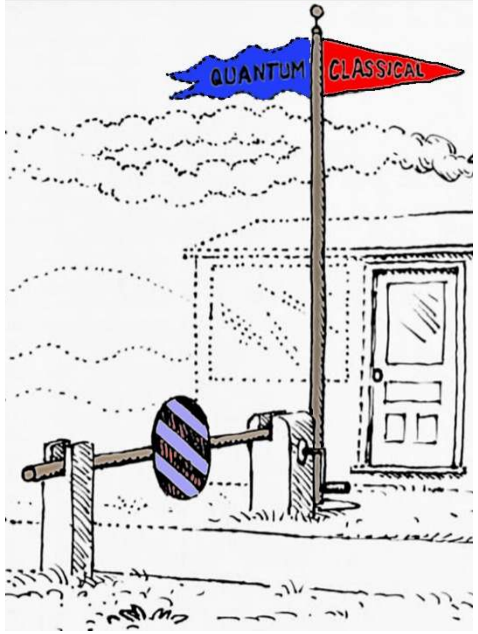
This equation is a basis change!!

EPR bridge from classical to quantum



What fraction of the energy of mode *m* is stored in junction *j*?

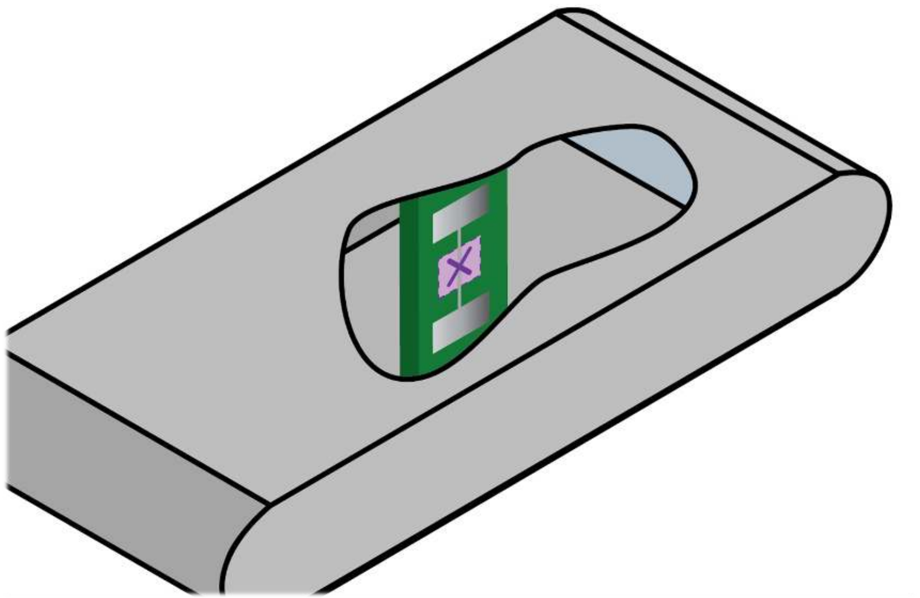
$$\boxed{\phi_{mj}} = p_{mj} \frac{\omega_m}{2E_j}$$



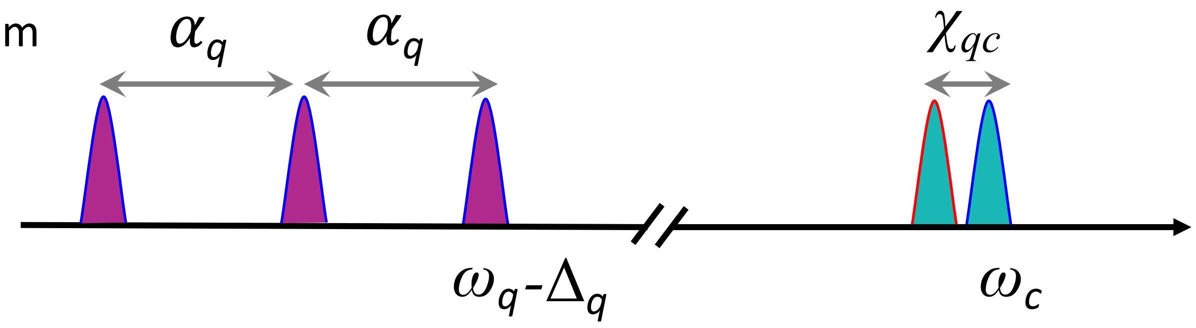
for j>1, root requires sign bit $s_{mj} = \pm 1$

Cartoon drawing: Zurek, Physics Today (1991)

Qubit-cavity system example



Transition spectrum



Qubit/cavity anharmonicity

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

Qubit-cavity dispersive shifty

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

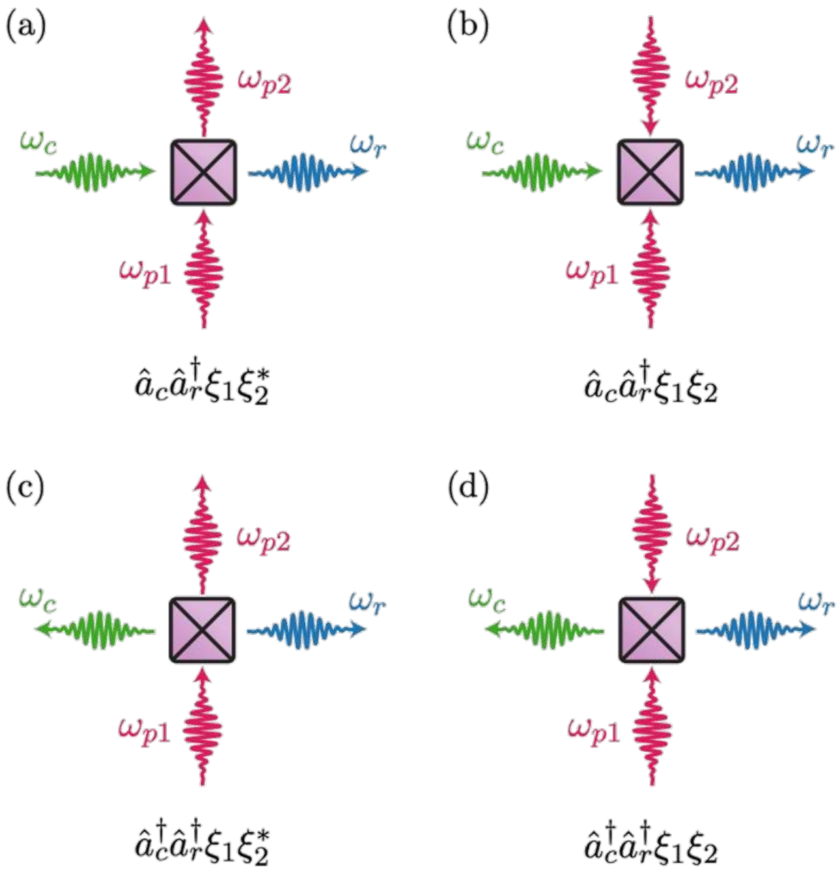
Qubit Lamb shift

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

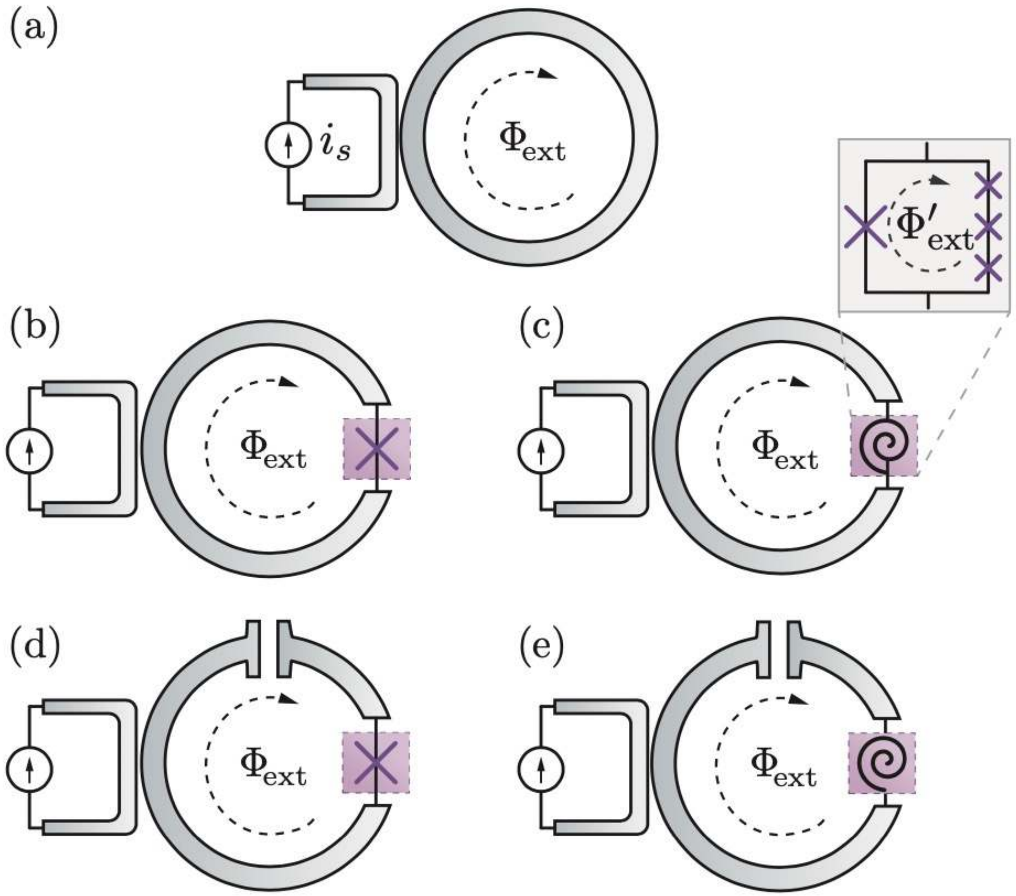
H_{eff}: for simplicity, showing up to $\mathcal{O}(\varphi^6)$ in RWA

Special features

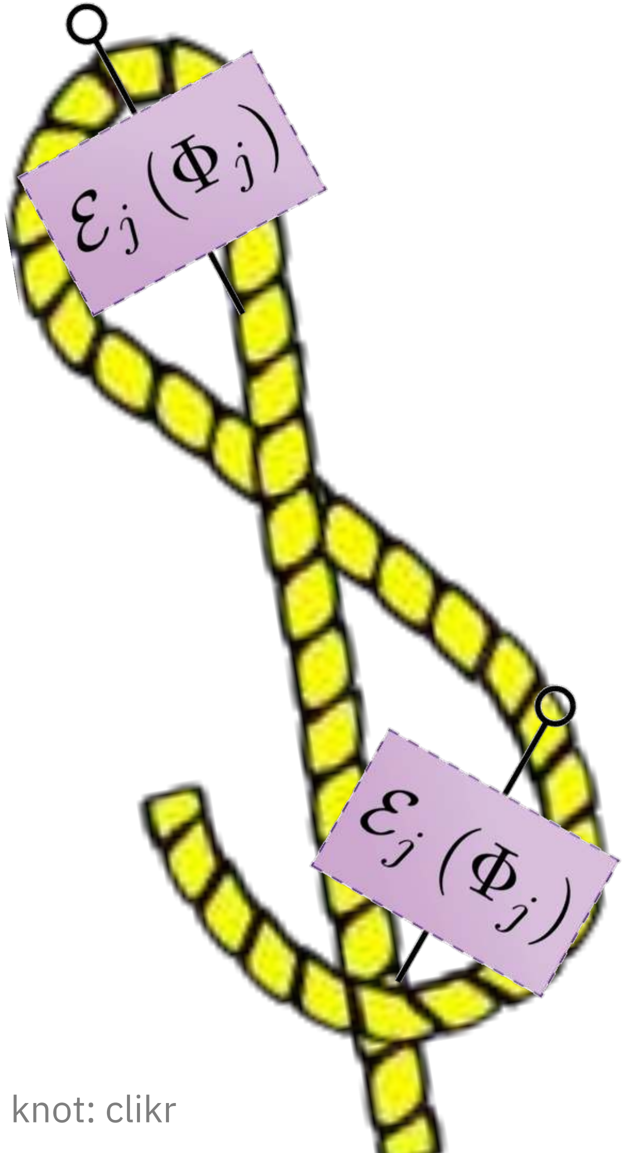
Reconstruct full Hamiltonian



Bias conditions



EPR monogamy & universal relations



I. A dipole brings 1 unit of EPR to be diluted in the modes

$$\sum_{m=1}^{M} p_{mj} = 1$$

II. A mode accepts max 1 unit of EPR

$$0 \leq \sum_{j=1}^{J} p_{mj} \leq 1$$

III. A dipole's EPRs are orthogonal

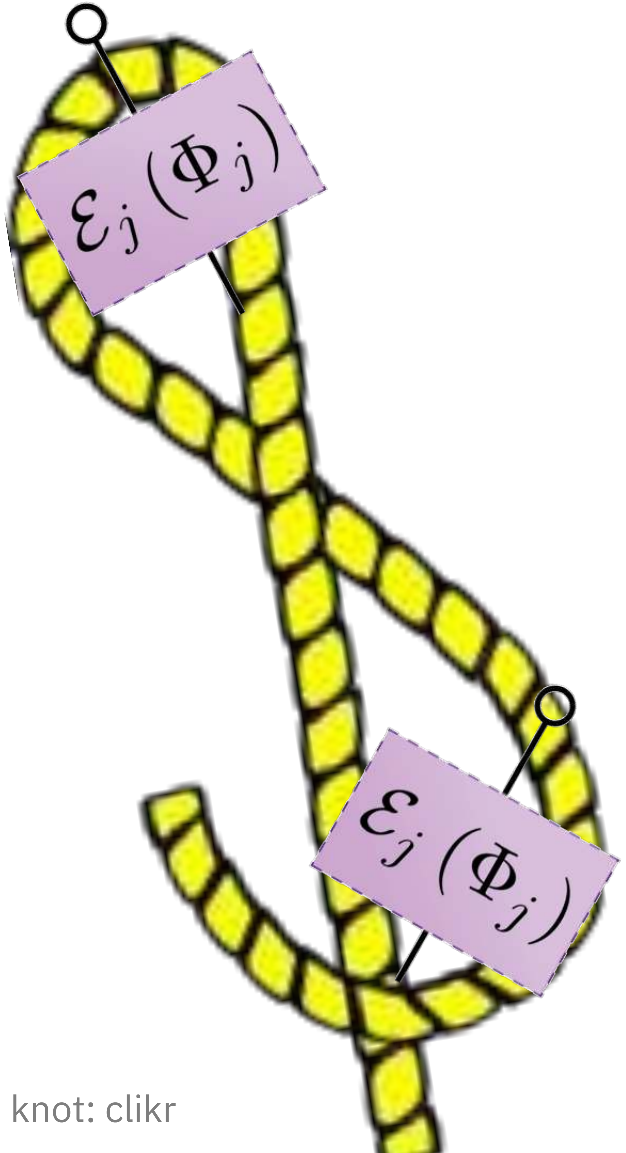
$$\sum_{m=1}^{M} s_{mj} s_{mj'} \sqrt{p_{mj} p_{mj'}} = 0$$

* EPR is bounded

$$0 \leq p_{mj} \leq 1$$

knot: clikr

EPR monogamy & universal relations



=>

zero-point quantum
fluctuations are
not independent

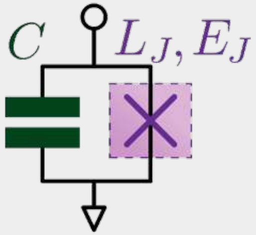
=>
design restrictions

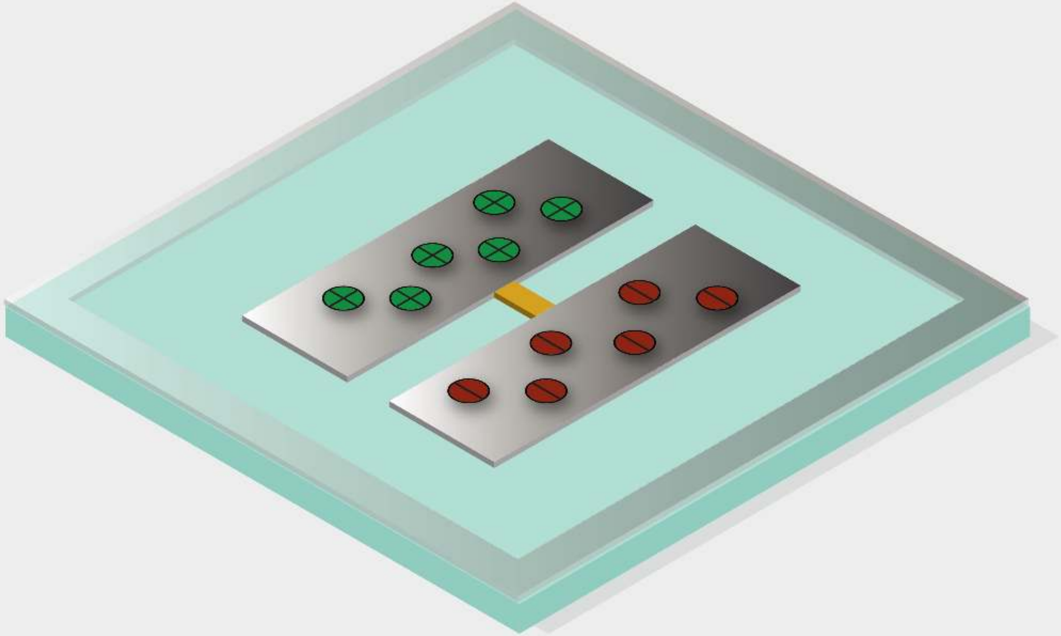
knot: clikr

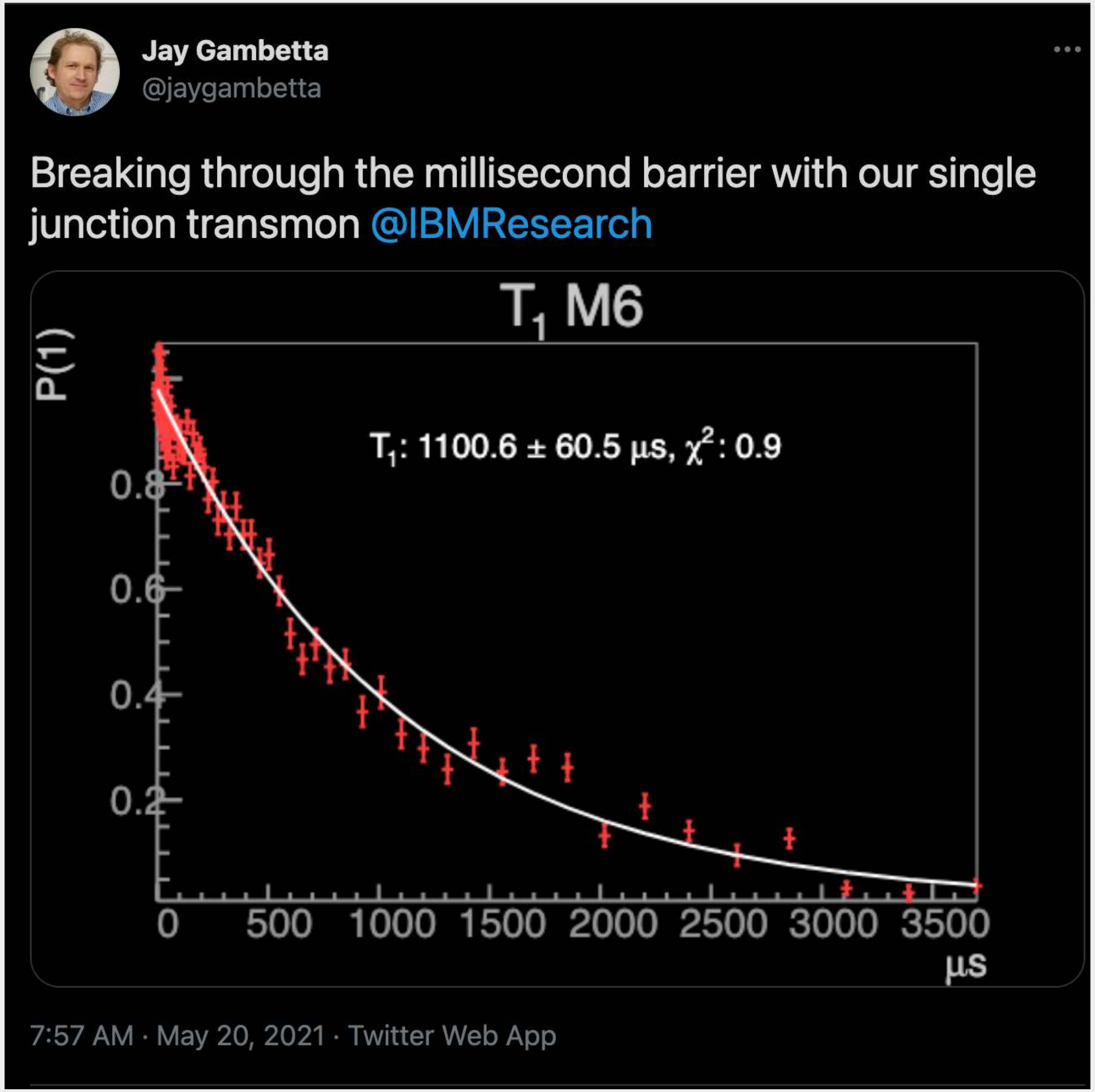
EPR & dissipation

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

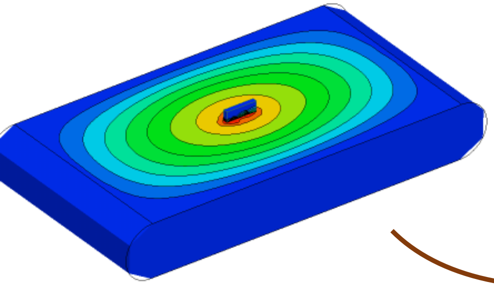
Transmon coherence

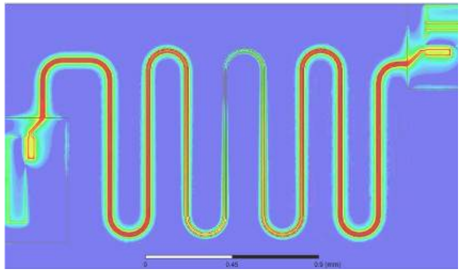




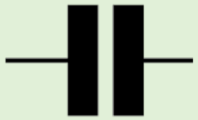


Lossy energy-participation ratios (EPRs)





Capacitive



bulk

$$p_{ml}^{\mathrm{cap}} = \frac{1}{\mathcal{E}_{\mathrm{elec}}} \frac{1}{4} \Re \int_{V_l} \vec{E}_{\max}^{*} \overleftrightarrow{\epsilon} \vec{E}_{\max} \, \mathrm{d}v \; ,$$

surface

$$p_{ml}^{\mathrm{cap,surf}} = \frac{1}{\mathcal{E}_{\mathrm{elec}}} \frac{t_l \epsilon_l}{4} \Re \int_{\mathrm{surf}_l} \left| \vec{E}_{\max} \right|^2 \mathrm{d}s \; ,$$

Inductive

bulk

$$p_{ml}^{\mathrm{ind,surf}} = \frac{1}{\mathcal{E}_{\mathrm{mag}}} \frac{\lambda_0 \mu_l}{4} \Re \int_{\mathrm{surf}_l} \left| \vec{H}_{\max,\parallel} \right|^2 \mathrm{d}s \; ,$$

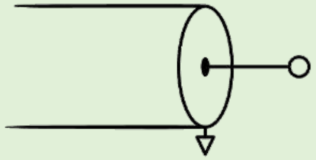
surface

$$p_{ml}^{\mathrm{ind,bulk}} = \frac{1}{\mathcal{E}_{\mathrm{mag}}} \frac{1}{4} \Re \int_{V_l} \vec{H}_{\max}^{*} \overleftrightarrow{\mu} \vec{H}_{\max} \, \mathrm{d}v \; .$$

seam

$$p_{ml}^{\mathrm{ind,seam}} = \frac{1}{\mathcal{E}_{\mathrm{mag}}} \frac{\lambda_0 t_l \mu_l}{4} \Re \int_{\mathrm{seam}_l} \left| \vec{H}_{\max,\perp} \right|^2 \mathrm{d}l \; ,$$

Radiative

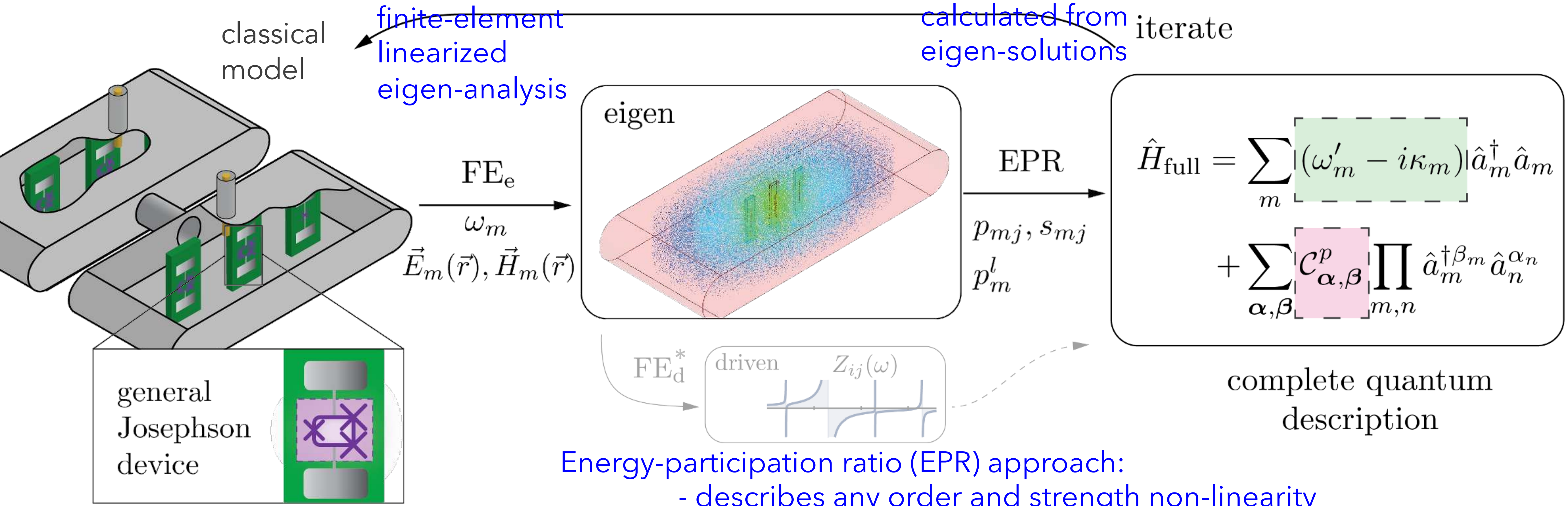


external

$$Q_{mp} = \frac{\omega_m \mathcal{E}_m(0)}{\frac{1}{2} R I_{mp}^2} \; .$$

Pozar (1990), Martinis *et al.* (2005), Gao (2008), Werner, *et al*. (2011), Zmuidzinas (2012), Megrant *et al.* (2012), Geerlings (2013), Quintana *et al.* (2014), Minev *et al.* (2013), Brecht *et al.* (2015), Wang *et al.* (2015), Dial *et al.* (2016), …

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) *** Jens
- fully automated in Qiskit Metal & in pyEPR

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), …

EPR theory vs. experiment

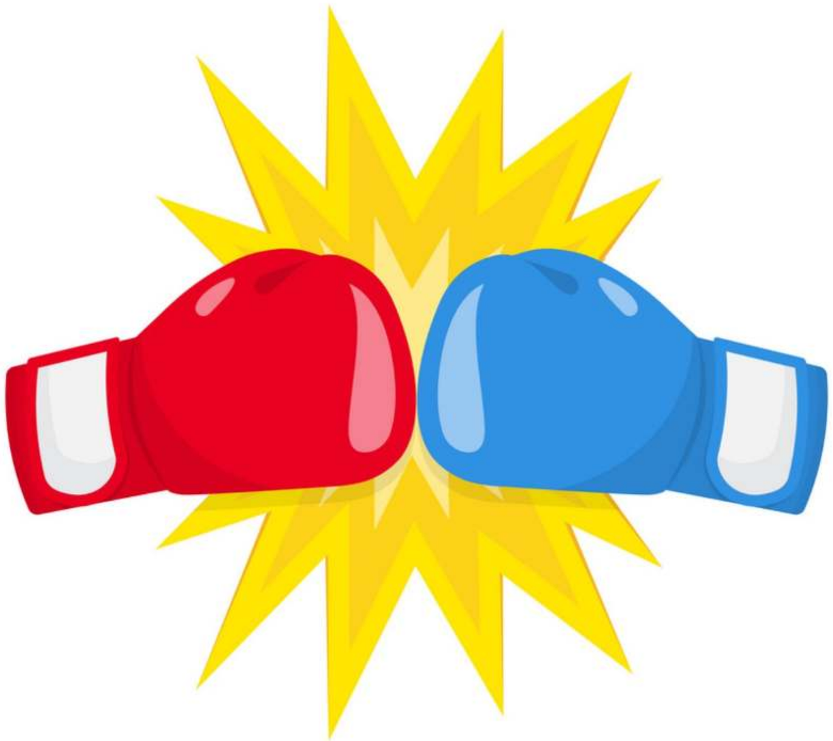
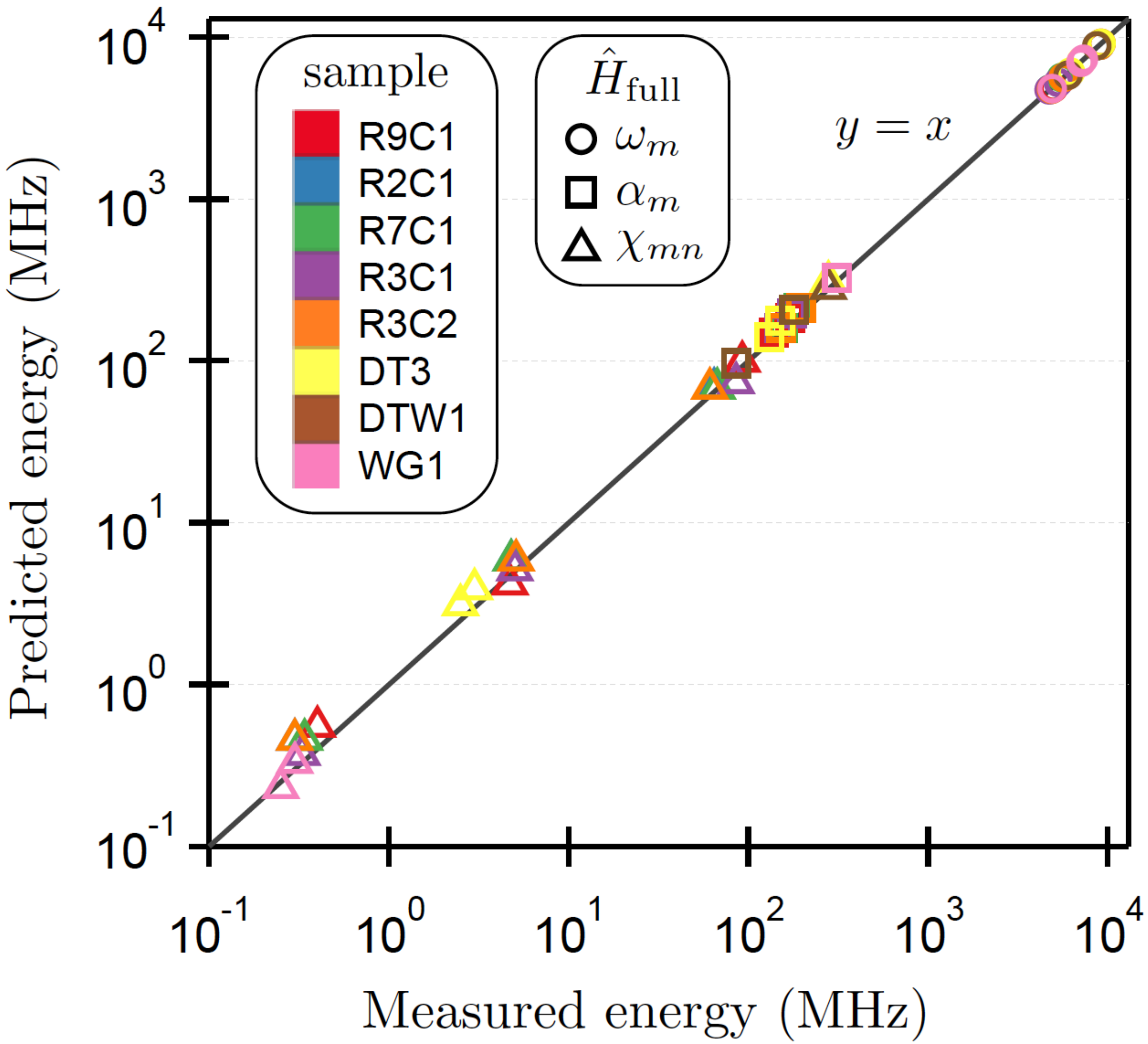
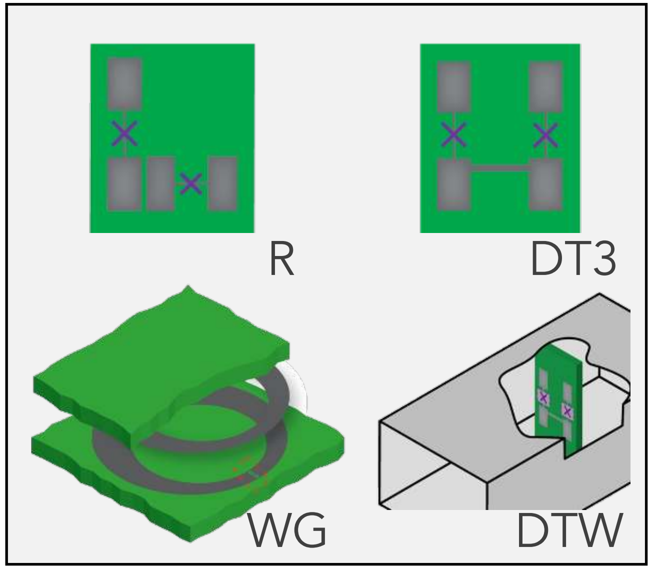


image: makc76

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)

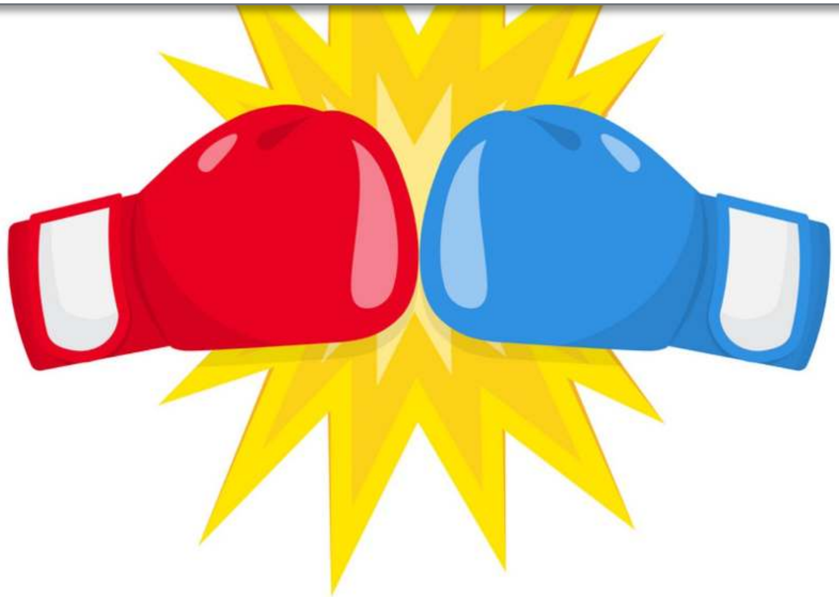
planar devices & comparison to other methods

Quantum Physics

[Submitted on 2 Feb 2021]

Exploiting dynamic quantum circuits in a quantum algorithm with superconducting qubits

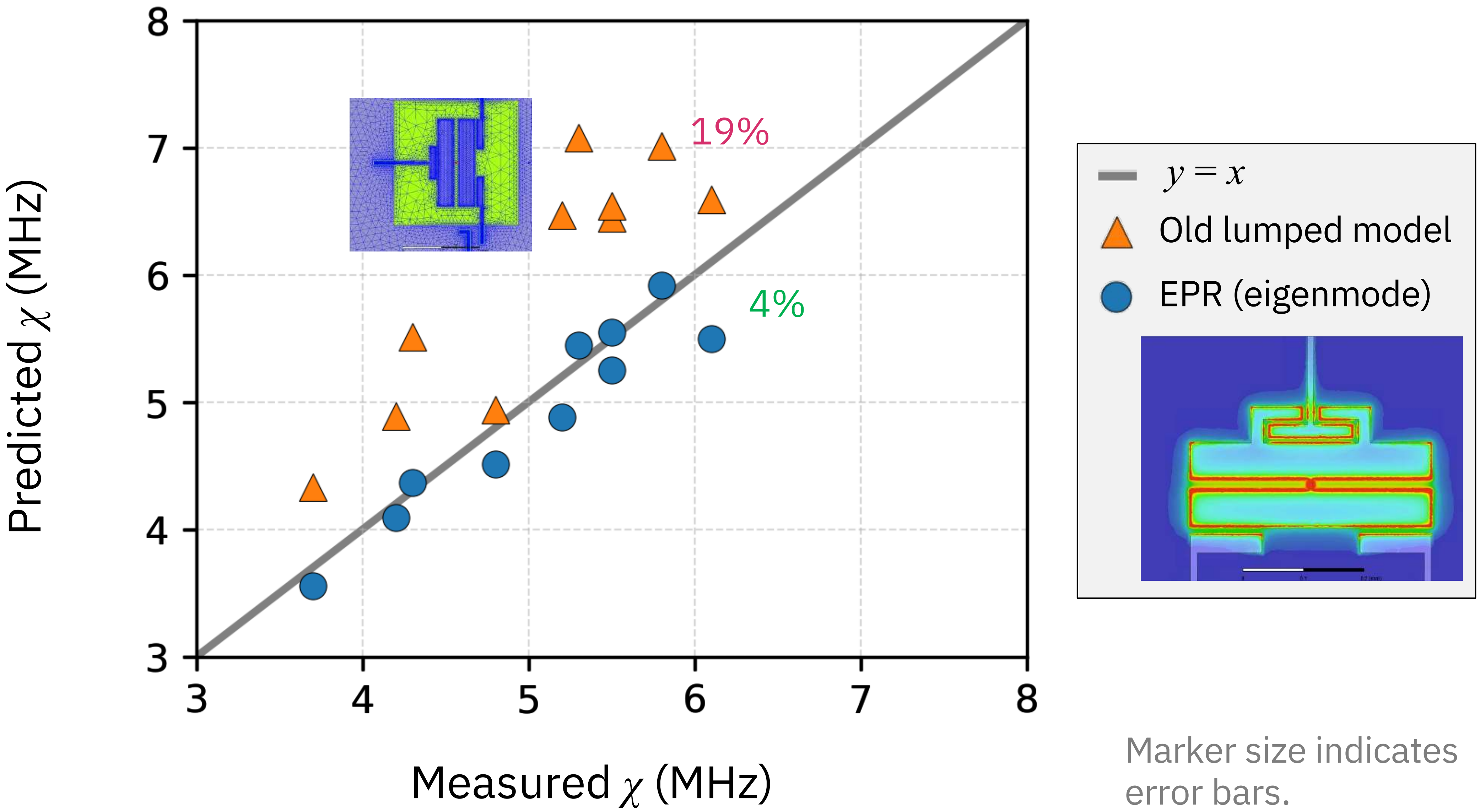
Antonio D. Corcoles, Maika Takita, Ken Inoue, Scott Lekuch, Zlatko K. Minev, Jerry M. Chow, Jay M. Gambetta



Automated with Qiskit | quantum device design

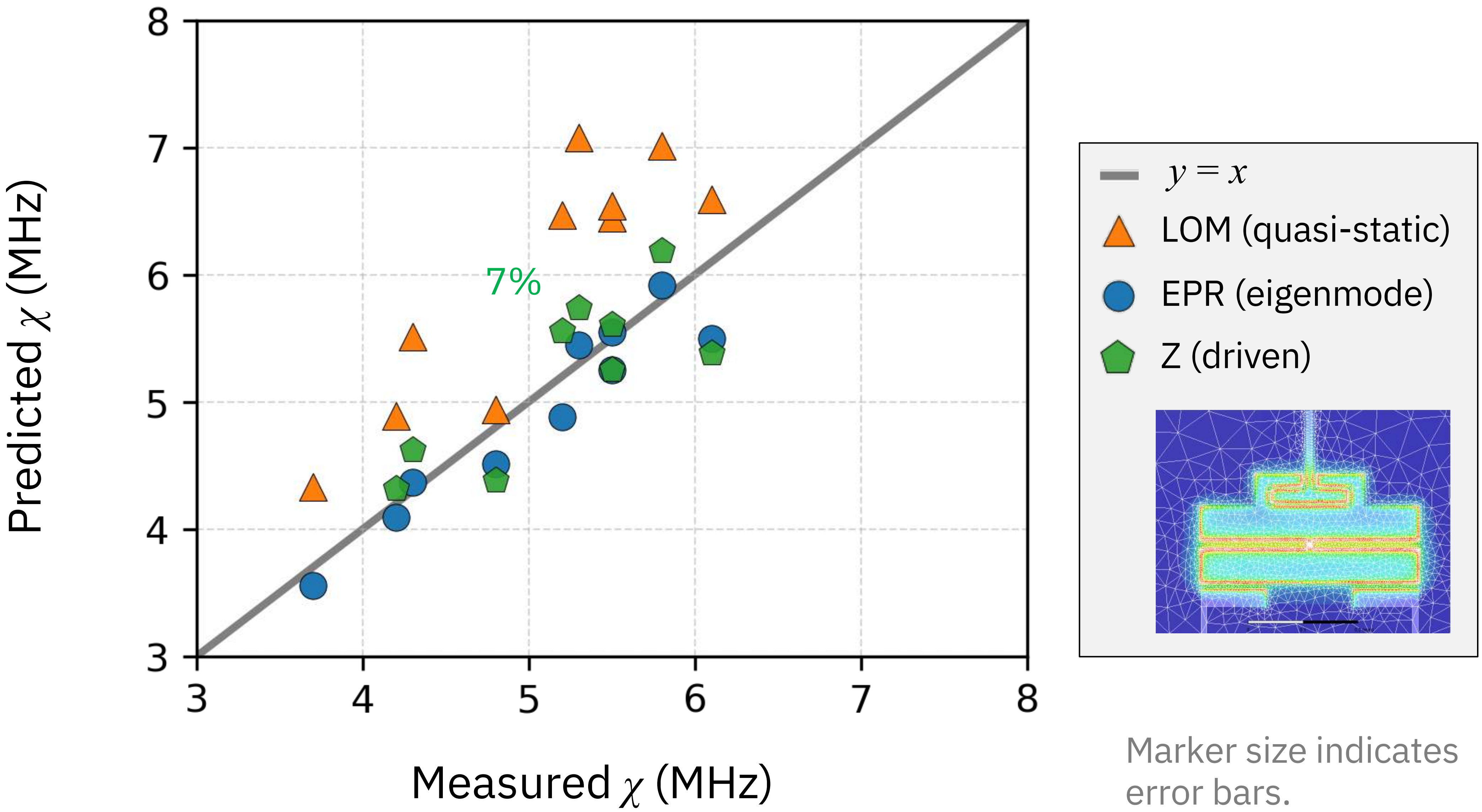
image: makc76

Measured vs. predicted: qubit-readout cross-Kerr



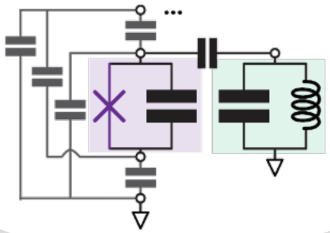
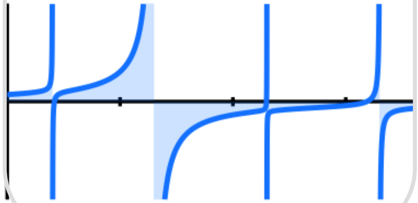
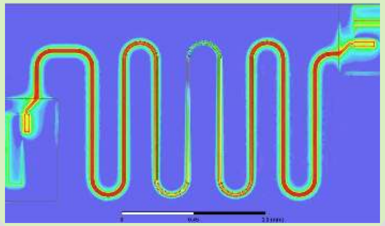
Marker size indicates error bars.

Measured vs. predicted: qubit-readout cross-Kerr



Marker size indicates error bars.

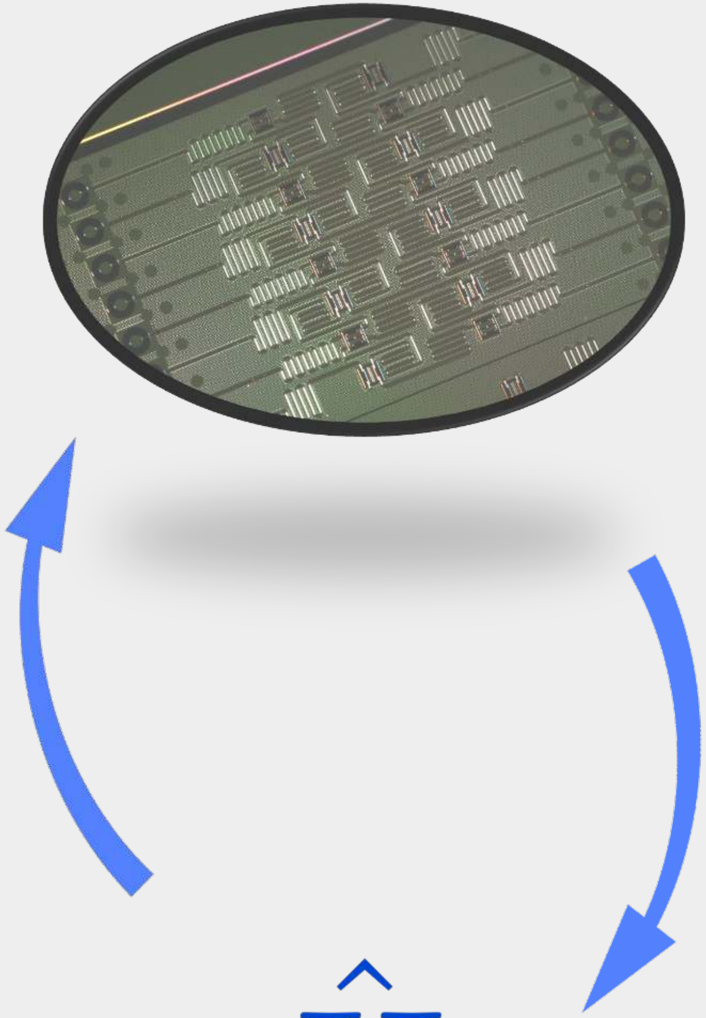
Quantization approaches

	Quasi-static	Full-wave	
	lumped (LOM)	impedance (Z)	eigenmode (EPR)
			
Agreement for presented results	19% / 10%	7%	4%
External inputs	higher	low	low
Speed	fastest and cheapest	moderate	moderate
Generality	low	high	highest*

pyEPR !

* includes dissipative params

Physical Devices ↔ Quantum Hamiltonian



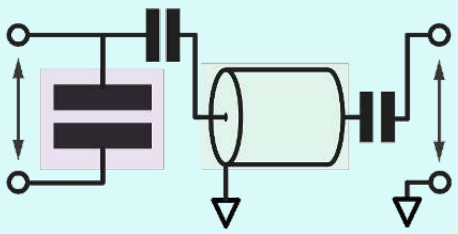
$\hat{H}$

cQED with quasi-lumped models (LOM)

Minev et al. arXiv:2103.10344
(IBM)

Modular quasi-lumped models

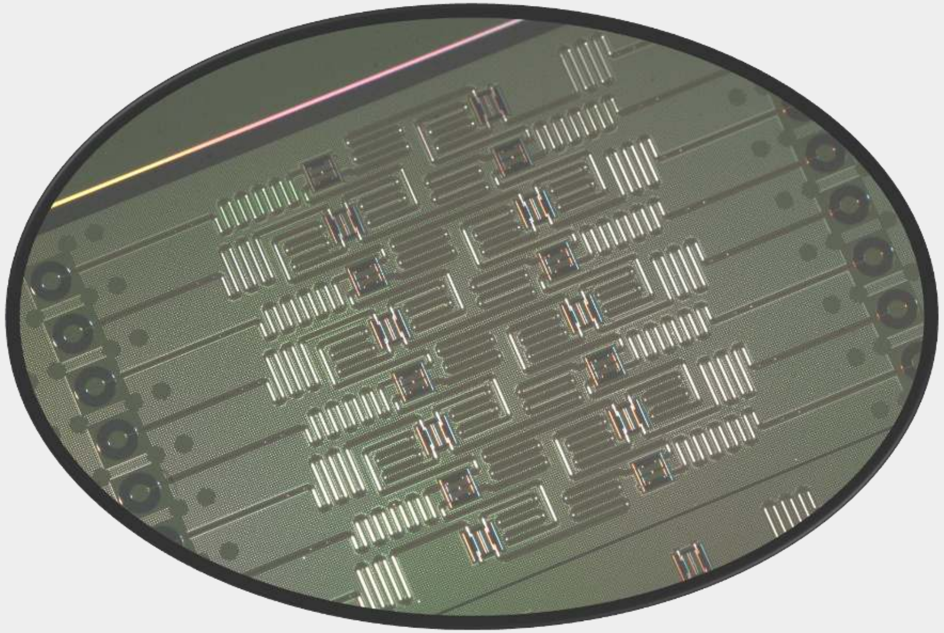
quasi-lumped



Desire:
fast
modular
precise

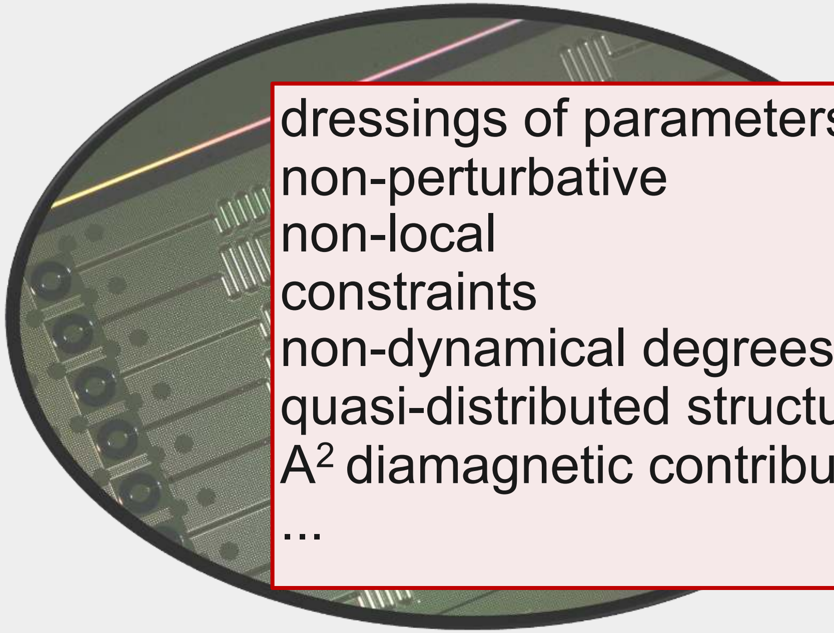
$\hat{H}$

Physical Hardware ↔ Modular Systems



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

Physical Hardware ↔ Modular Systems



dressings of parameters due to couplings
non-perturbative
non-local
constraints
non-dynamical degrees of freedom (Ding et al.)
quasi-distributed structures
A^2 diamagnetic contributions (Malekakhlagh et al.)
...

$$\hat{H}_{\text{sys}} = \sum_n \hat{H}_n$$

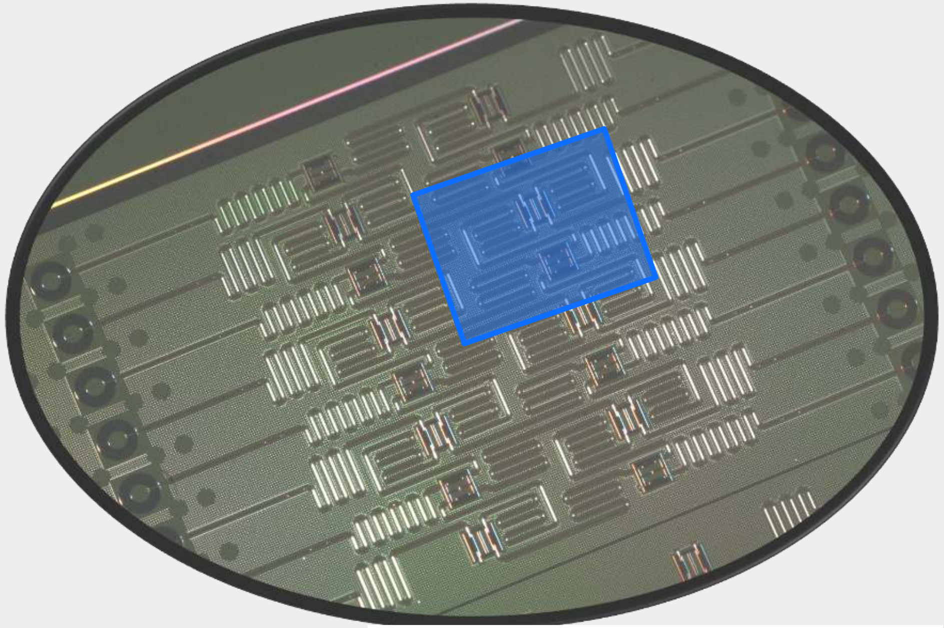
small,
known
building blocks

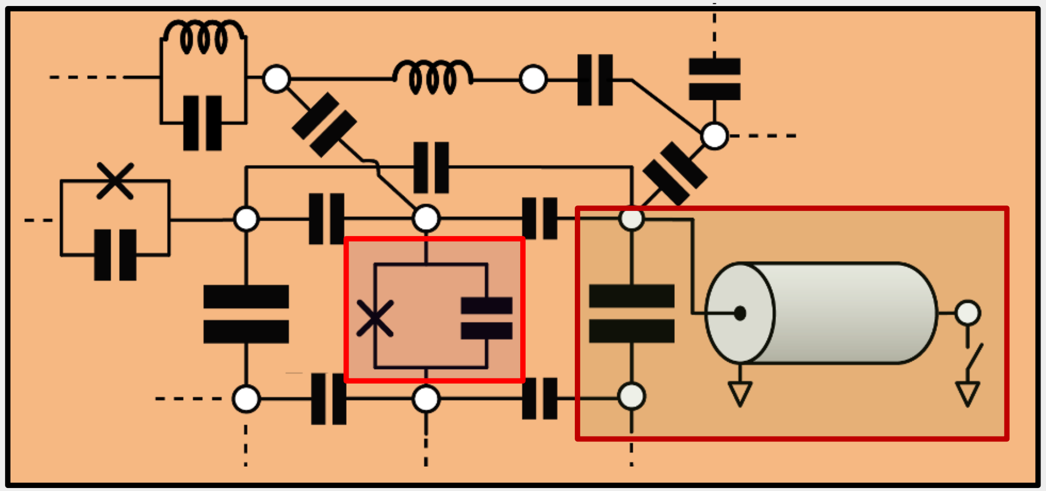
$$\hat{H}_{\text{int}} = \sum_n \sum_m \hbar g_{nm} \hat{A}_n \hat{B}_n$$

$$[\hat{H}_n, \hat{H}_m] = 0$$

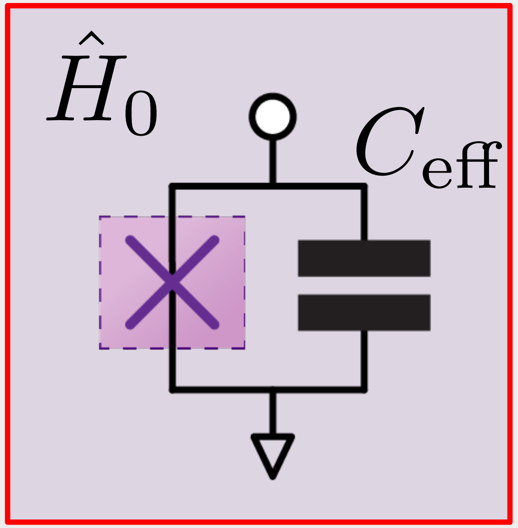
$$[\hat{A}_n, \hat{B}_m] = 0$$

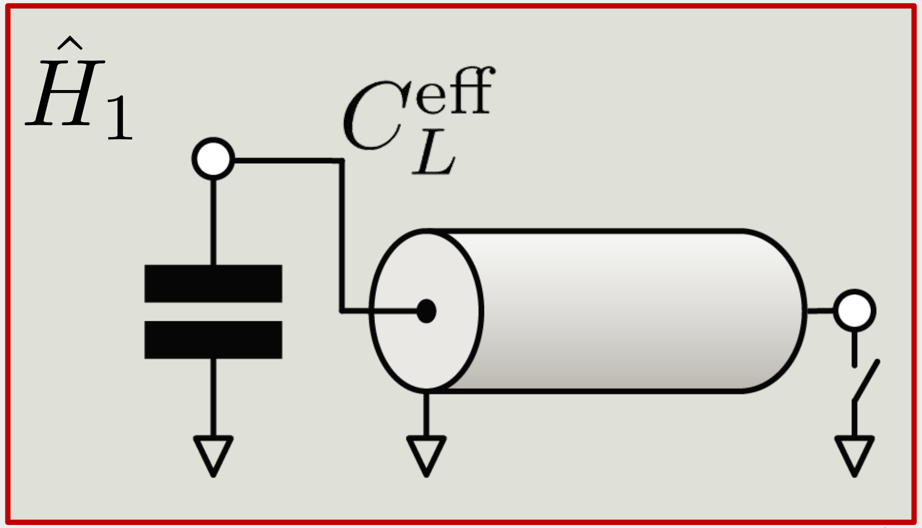
Method of this talk: Complex network to simple building blocks





$$\hat{H}_{01} \quad \Big| \quad \hat{Q}_0\hat{Q}_1/C_{01}^{\mathrm{eff}} + \hat{\Phi}_0\hat{\Phi}_1/L_{01}^{\mathrm{eff}}$$





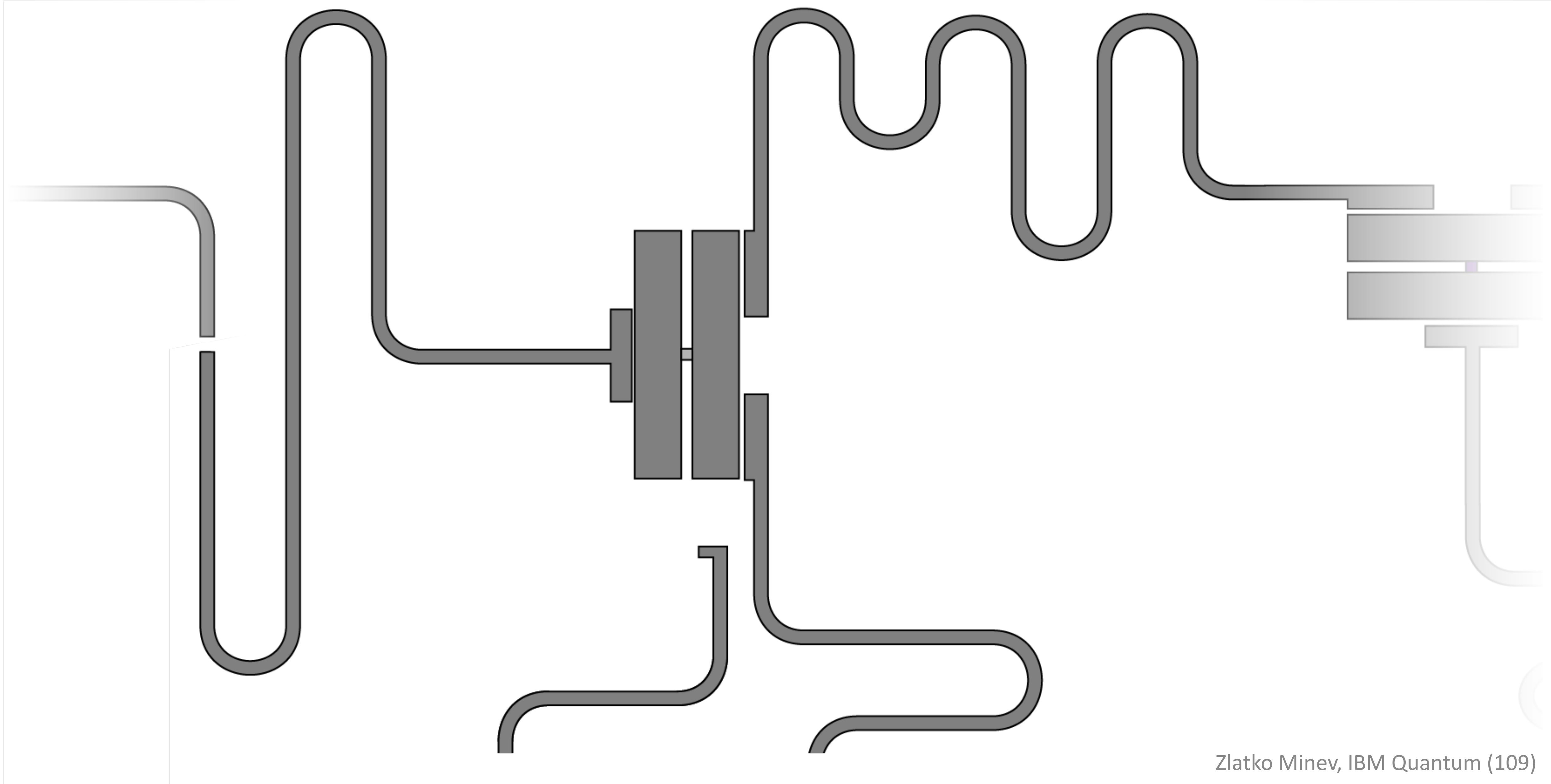
Jens Koch
Peter Groszkowski

- transmon (fixed | tunable)
- fluxonium
- 3-jct. flux qubit
- 0-π qubit
- cos(2φ) qubit NEW
- oscillator | Kerr oscillator NEW

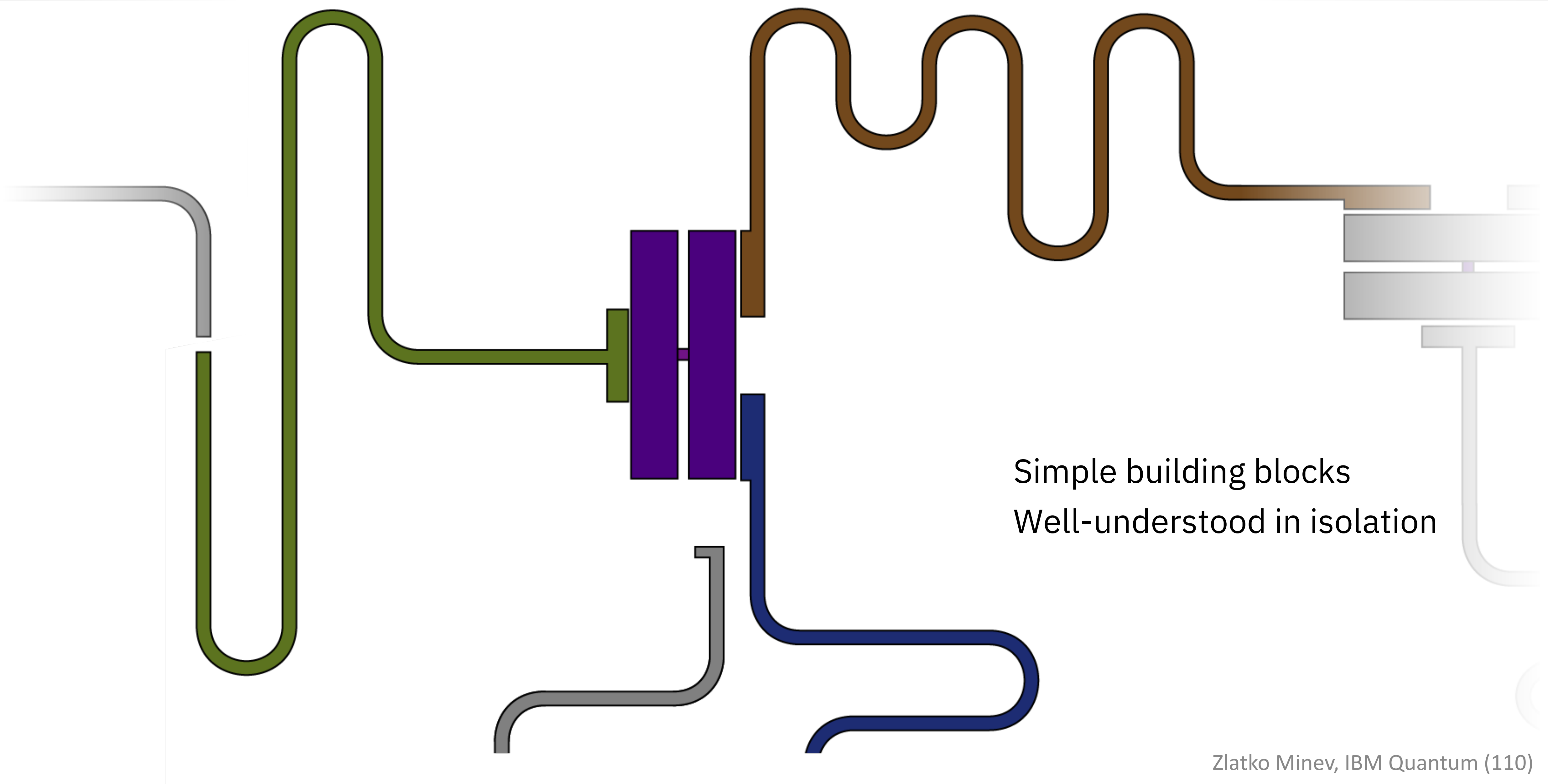
method

example

Physical layout zoom in



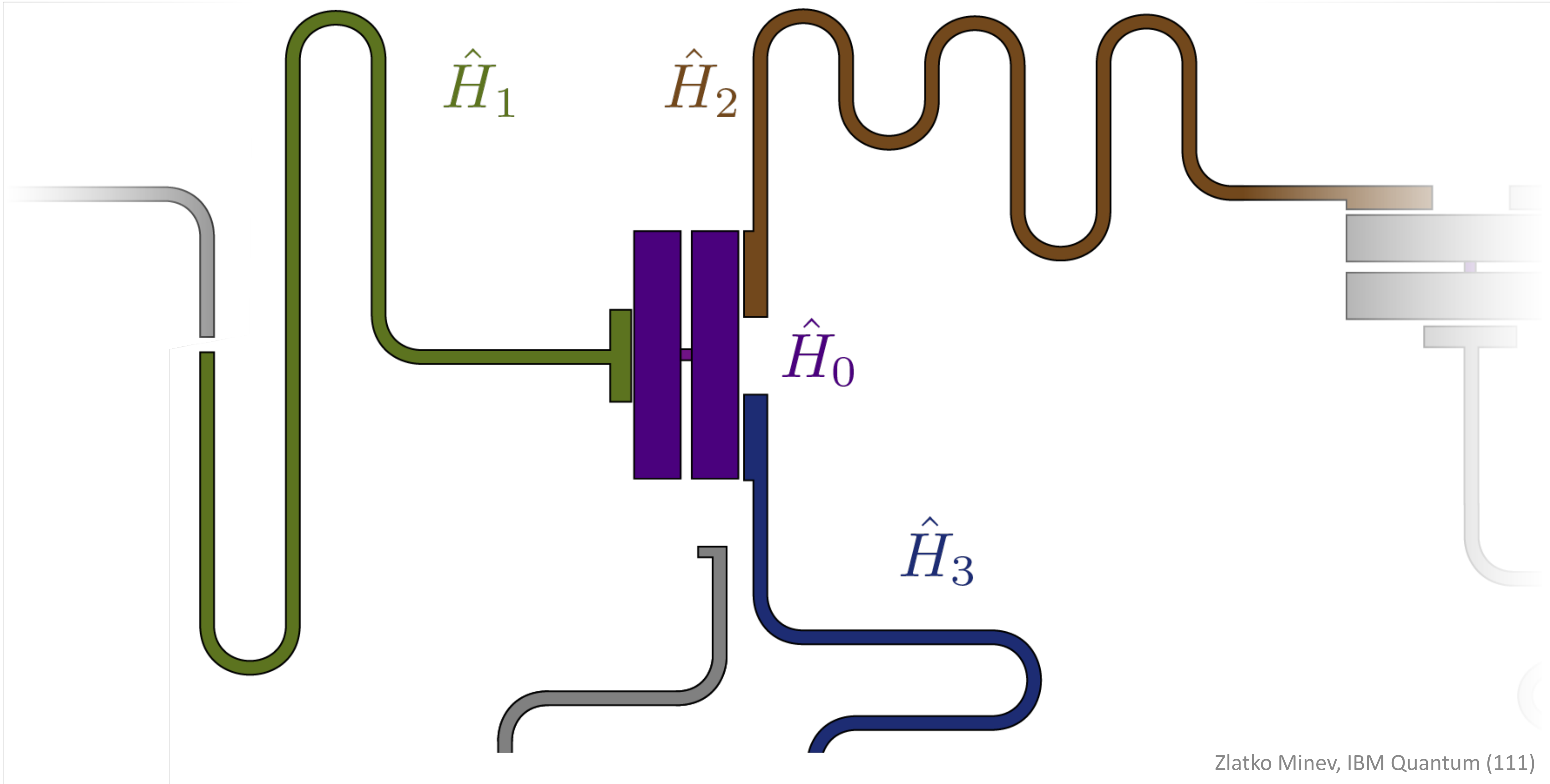
Identifying systems



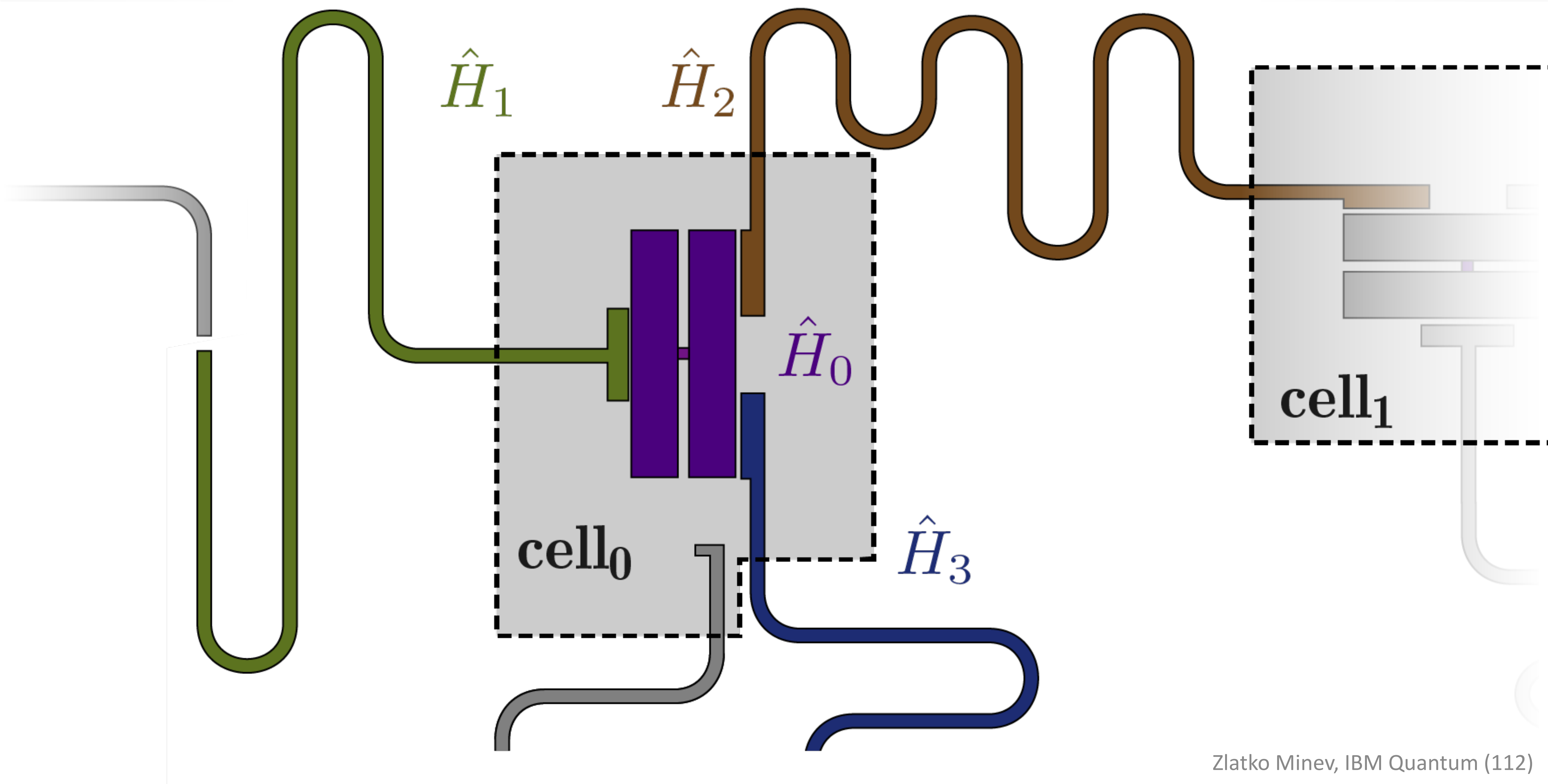
Simple building blocks

Well-understood in isolation

Dressed subsystem Hamiltonians

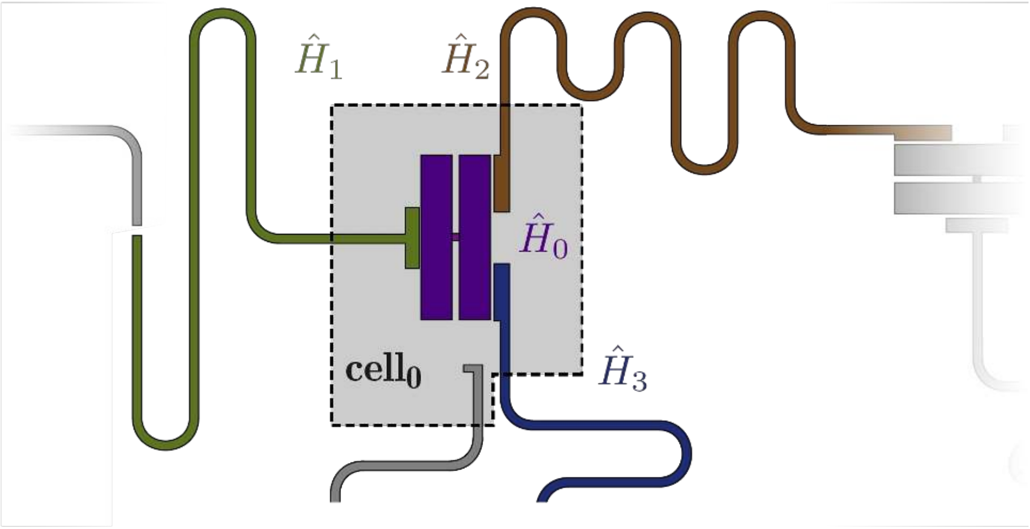


Subsystem & cell partitions



Simulating a cell

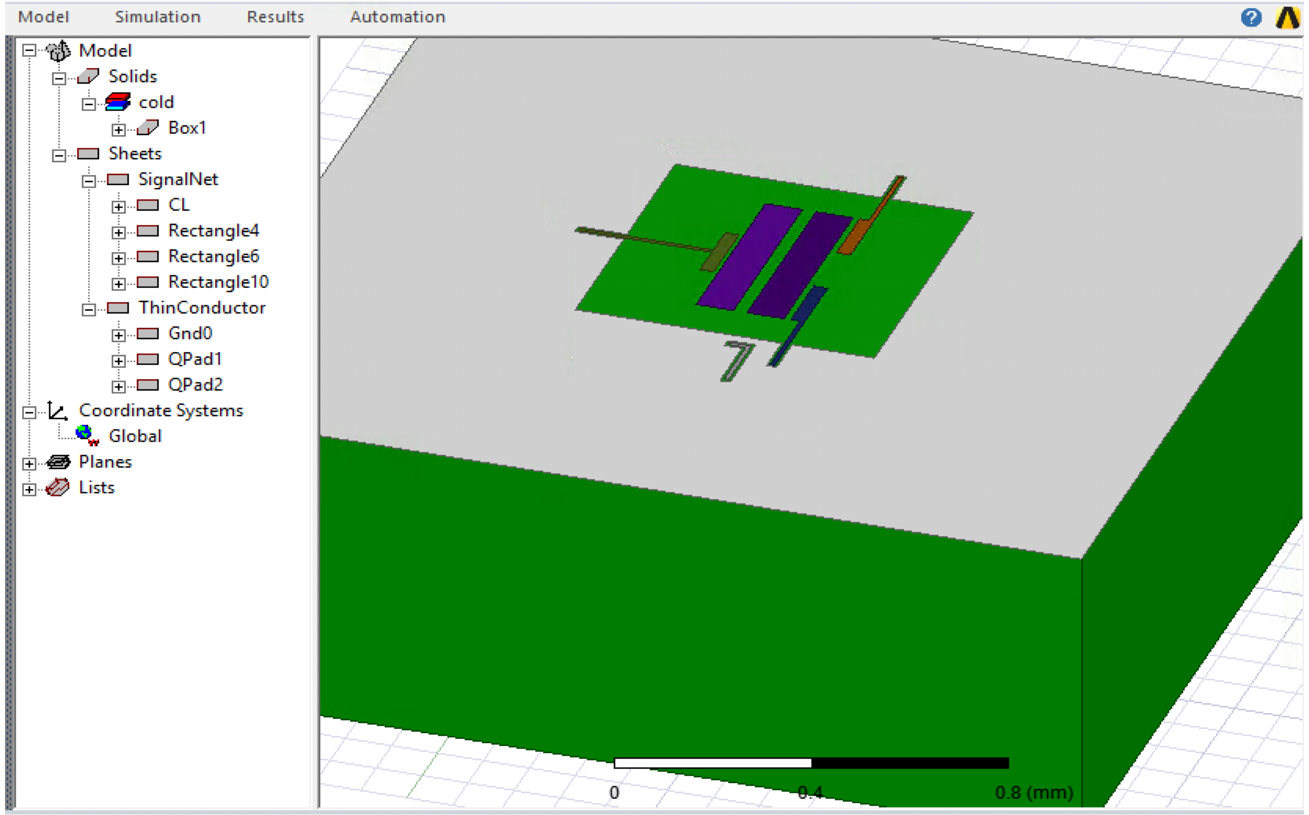
device layout



Automated with

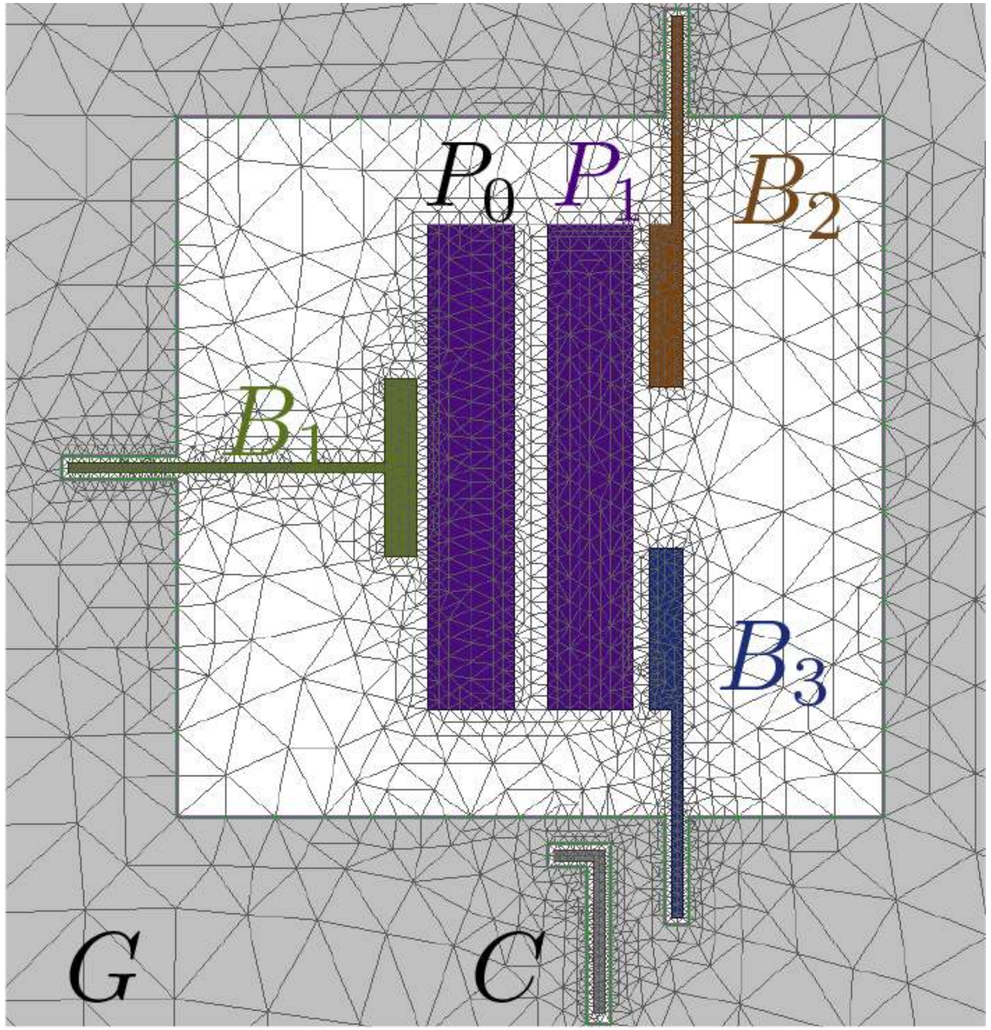
Qiskit | quantum device design

extractor model



Extracting cell parameters

netlist & simulation

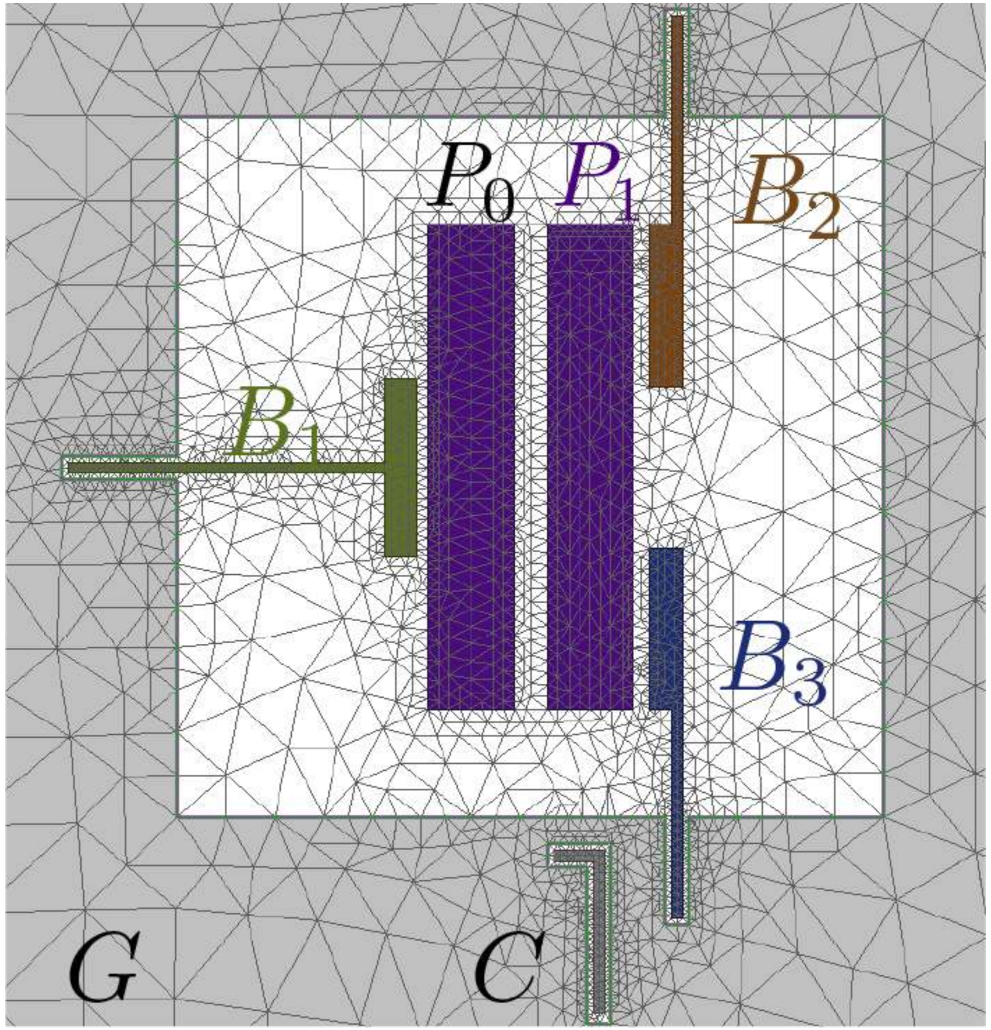


Maxwell capacitance matrix

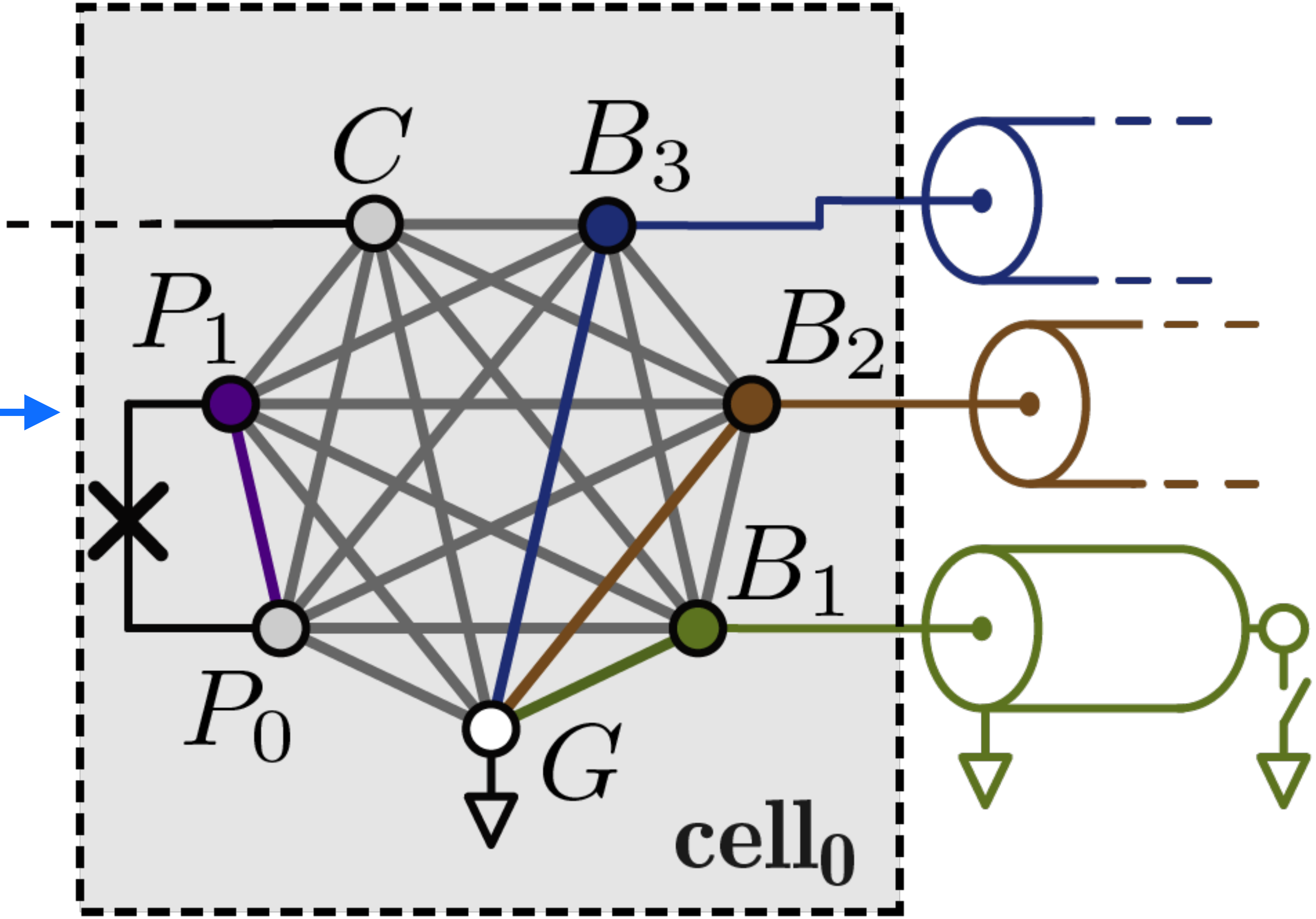
$$
\begin{array}{c|c}
 & \begin{array}{cccccc} n_0 & n_1 & n_2 & n_3 & n_4 & n_5 \end{array} \\
\begin{array}{c} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{array} &
\begin{pmatrix}
C_{0\Sigma} & -C_{01} & -C_{02} & -C_{03} & -C_{04} & -C_{05} \\
 & C_{1\Sigma} & -C_{12} & -C_{13} & -C_{14} & -C_{15} \\
 & & C_{2\Sigma} & -C_{23} & -C_{24} & -C_{25} \\
 & & & C_{3\Sigma} & -C_{34} & -C_{35} \\
 & & & & C_{4\Sigma} & -C_{45} \\
 & & & & & C_{5\Sigma}
\end{pmatrix}
\end{array}
$$

Automated with Qiskit | quantum device design

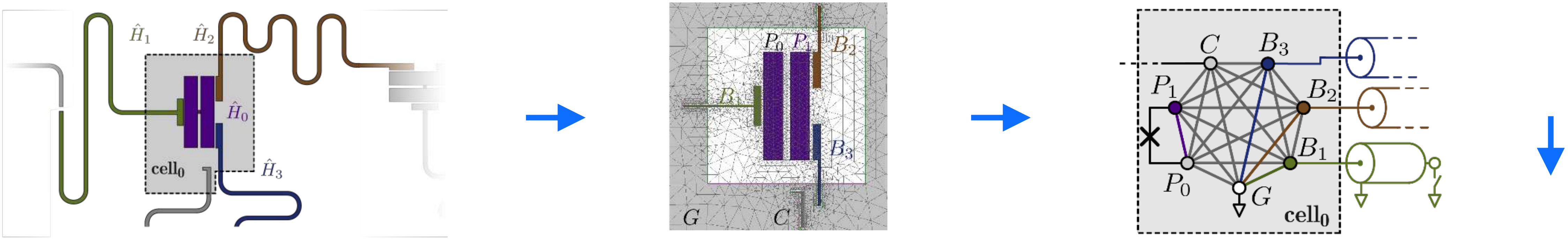
Cell & composite-system network

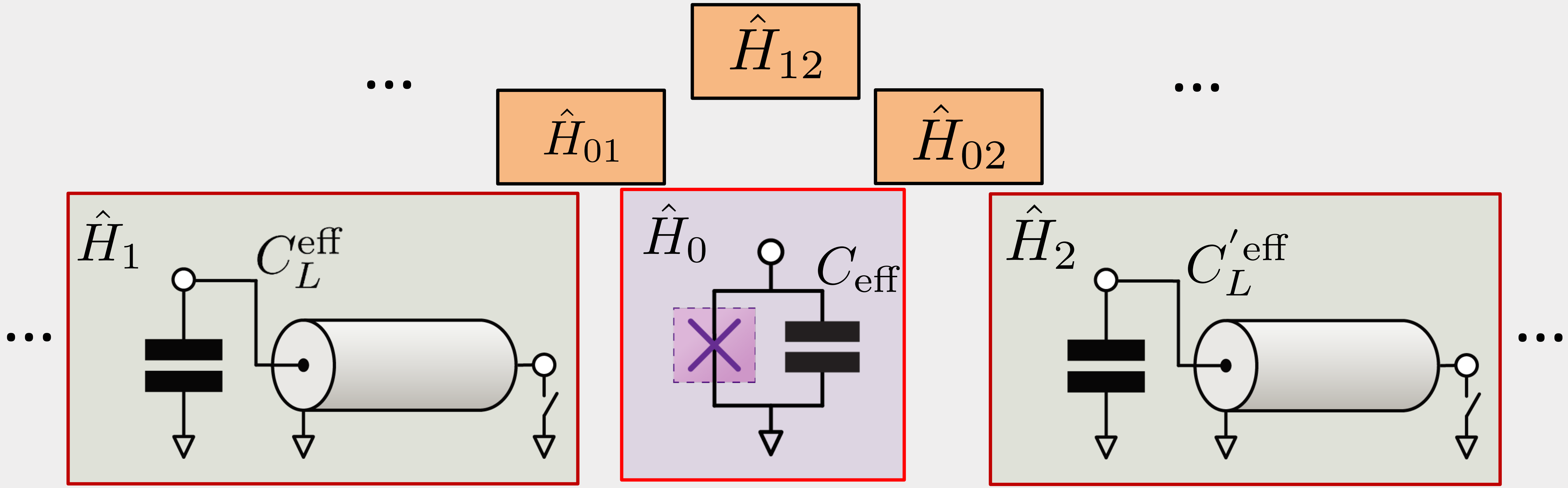


full network model



Reduction to dressed subsystems





LOM theory vs. experiment

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

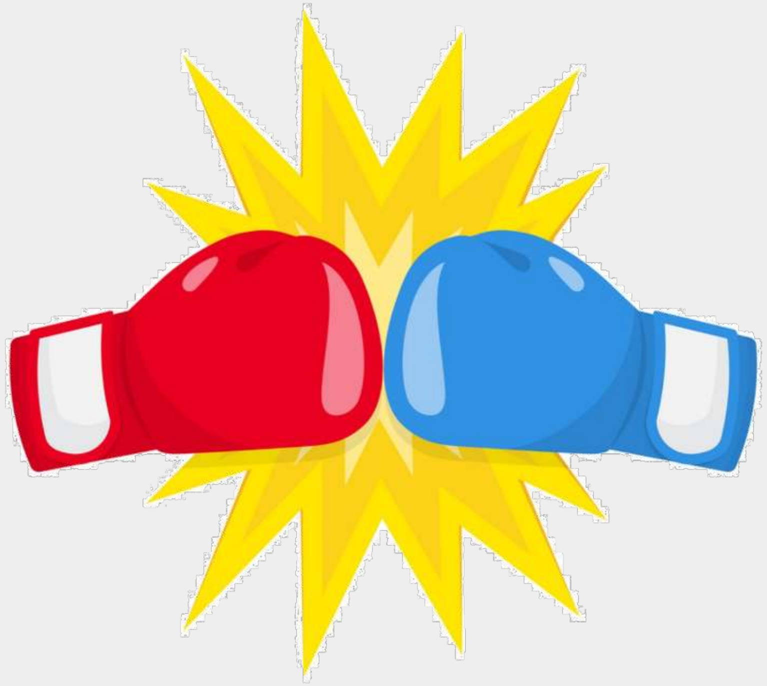
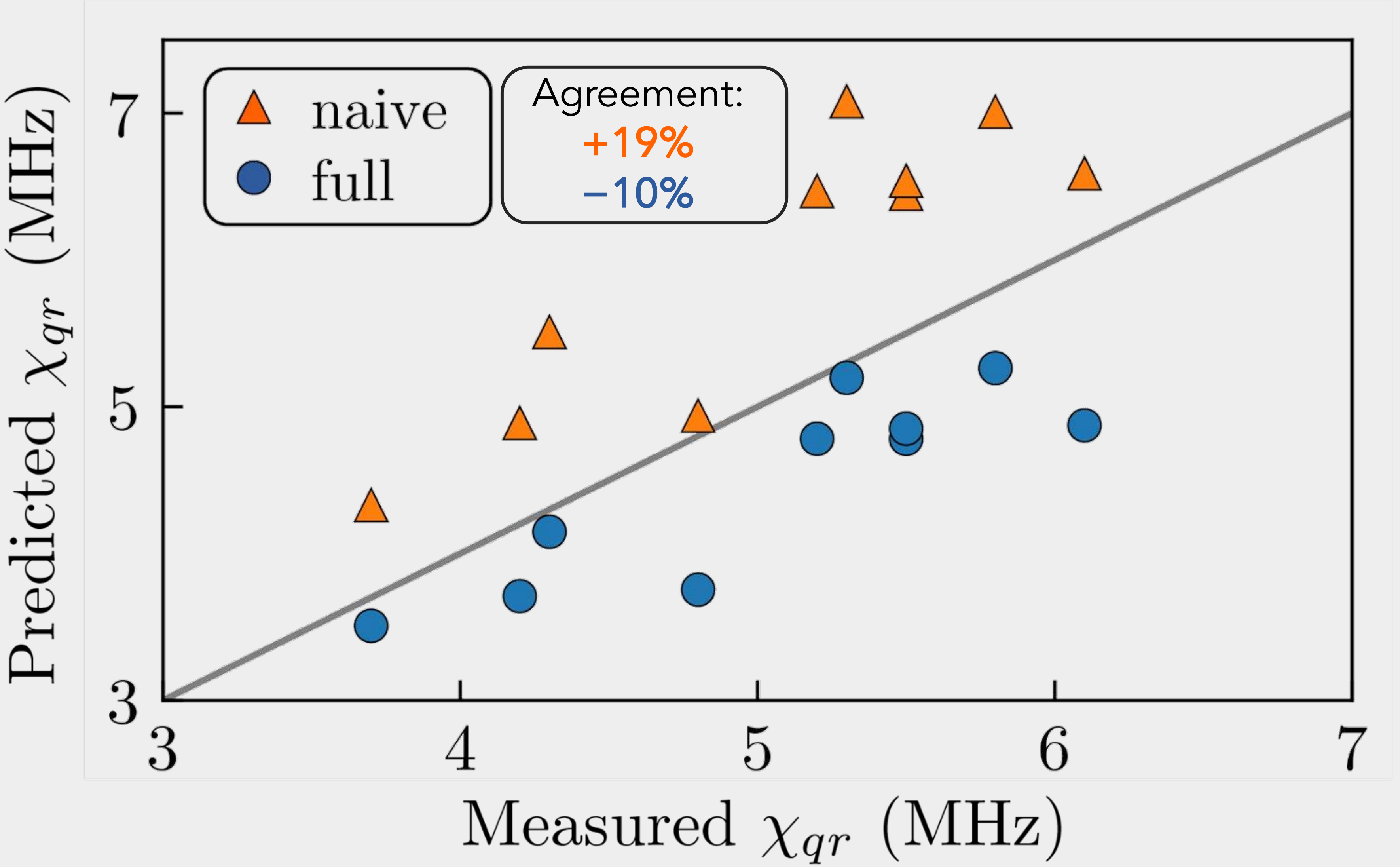


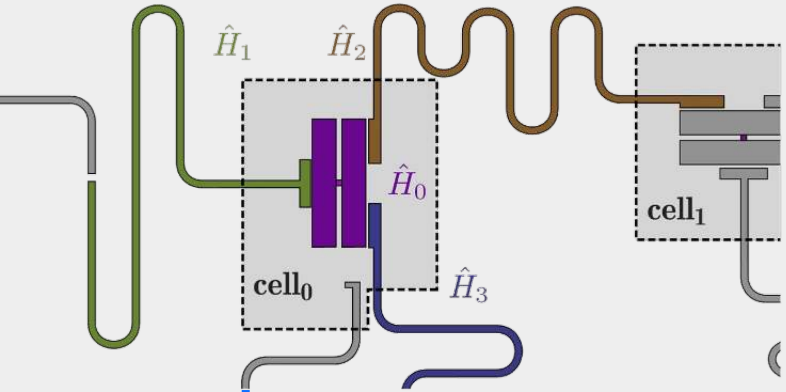
image: makc76

Improved precision



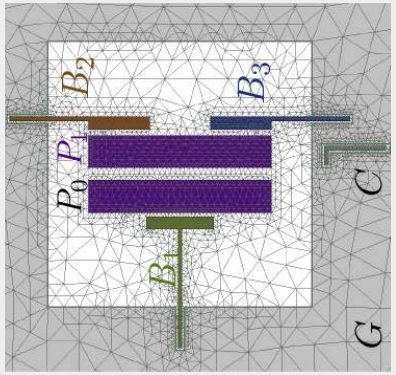
Data from Minev, *et al.* (to appear).
Tested on 2 larger-scale processors, see Corcoles *et al.* arXiv:2102.01682.

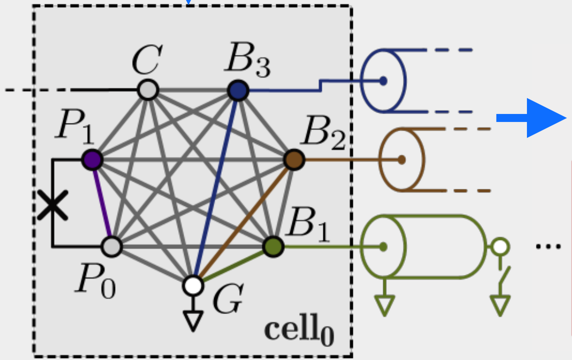
Summary Minev *et al.* arXiv:2103.10344



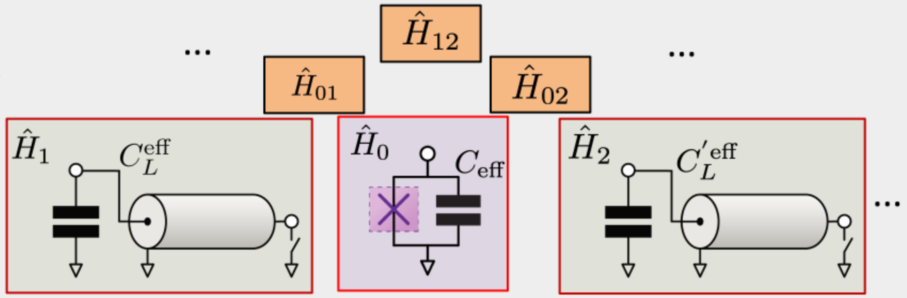
Circuit quantum electrodynamics (cQED) with modular quasi-lumped models

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





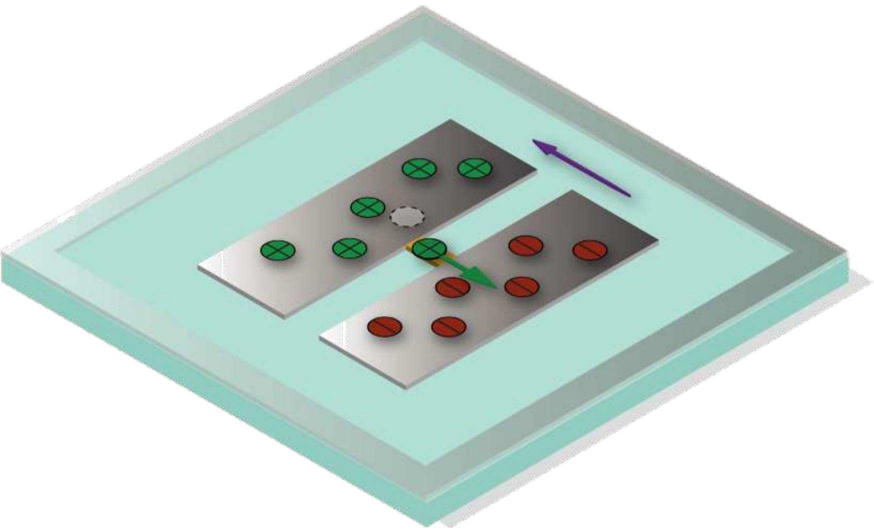
$$\hat{H} = \hat{H}_{\mathrm{sys}} + \hat{H}_{\mathrm{int}}$$

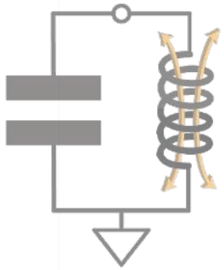


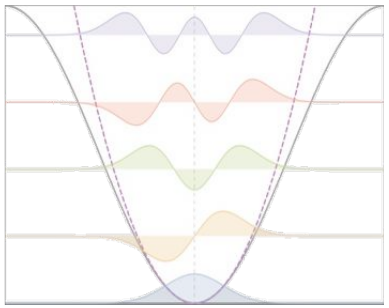
- accounts for device layout
- modular
- maps onto known building blocks
- computationally efficient
- incorporates dressings
- experimentally accurate
- widely-applicable to planar/quasi-planar
- (not suitable for 3D)

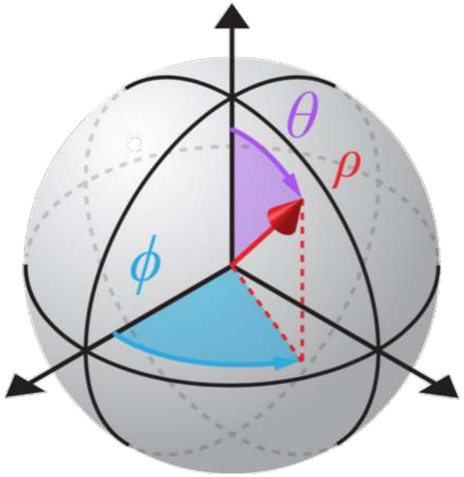
Superconducting quantum devices: design & analysis

Energy-participation-ratio (EPR)
Quasi-lumped oscillator models (LOM)
& Qiskit Metal









Zlatko K. Minev

IBM **Quantum**

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

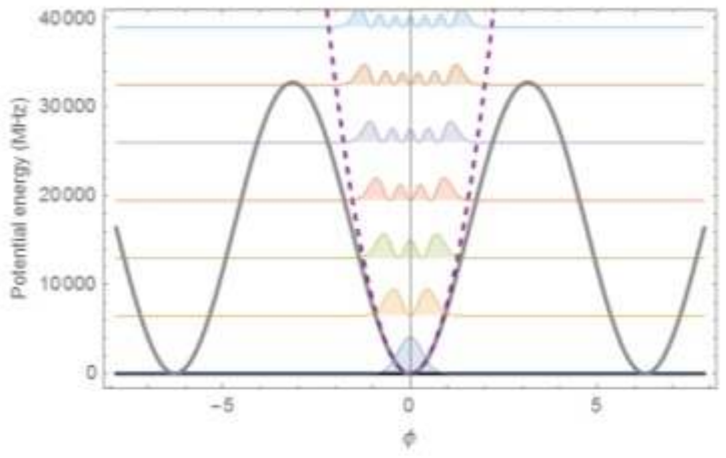
@zlatko_minev zlatko-minev.com

Thank you

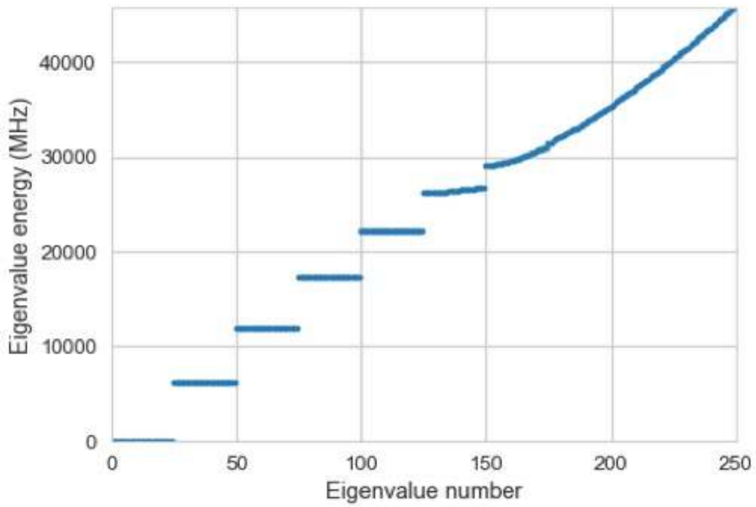
Charge dispersion

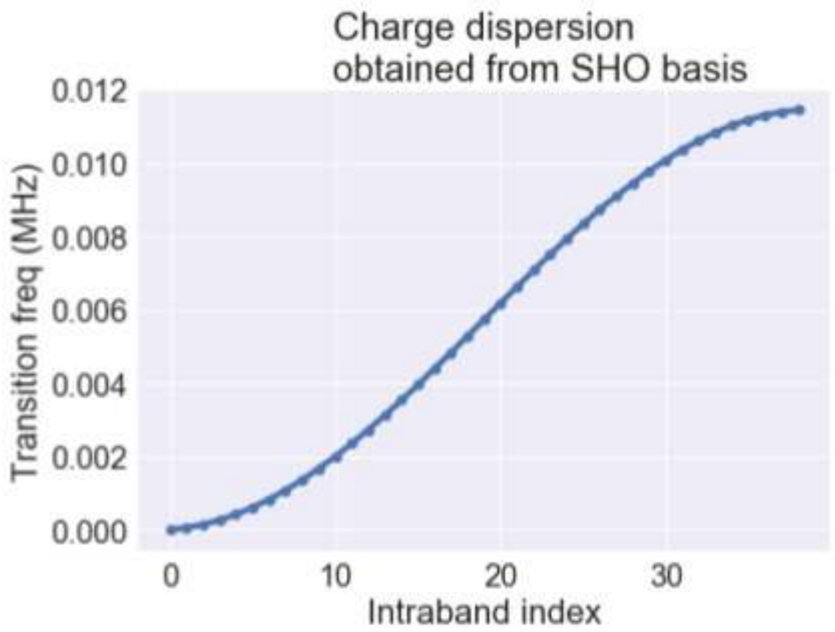
ω_0 = 6.50 GHz
$\alpha^{(4)}$ = 322.00 MHz
ϕ_{ZPF} = 0.45

E_J = 16.40GHz
E_C = 0.32 GHz (E_J/E_C=50.90)
Dispersion =-12.90 KHz

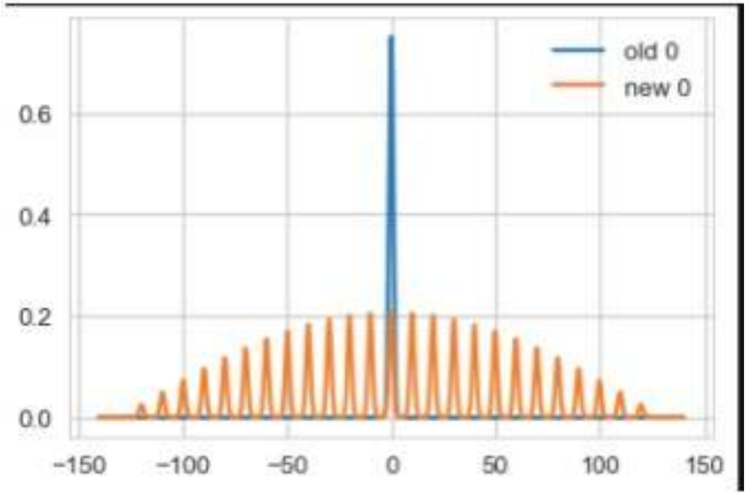


compare to charge basis numeric

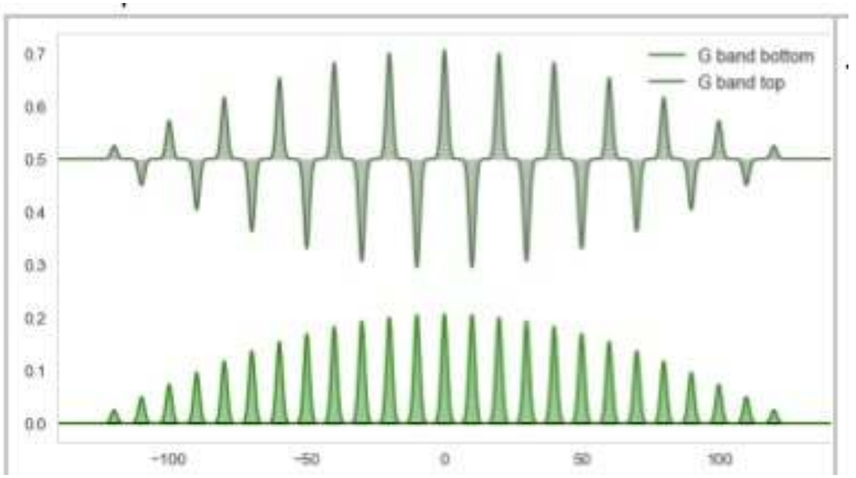




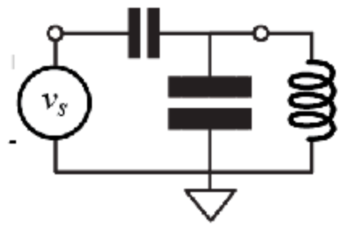
|psi|^2



\phi



a) external voltage bias



The Hamiltonian of a transmon qubits subject to a voltage bias, coupled by a coupling capacitance C_c and shunted by a capacitance C_s, is

$$H(\Phi, Q) = \frac{\left(Q + C_c \dot{\Phi}_s(t)\right)^2}{2(C_s + C_c)} - \frac{C_c}{2}\dot{\Phi}_s(t)^2 - E_J \cos(\Phi/\phi_0) \,, \tag{10.1}$$

where the canonically conjugate flux and charge variables are Φ and Q, resp, such that their Poison bracket is $\{\Phi, Q\}_p = 1$, E_J is the Josephson junction tunneling energy. and $\dot{\Phi}_s(t)$ is the voltage source flux bias, determined by the voltage source. The voltage of the source is $v_g = \dot{\Phi}_s(t)$, and the 'offset charge' is hence $Q_g := C_c v_g$, or in terms of cooper pairs, in units of $2e$, $n_g := Q_g/(2e)$; for consistence with other literature, we will choose the orientation such that there is a minus sign to the offset charge. Letting the total effective transmon capacitance be $C := C_s + C_c$,

$$\hat{H} = \frac{\left(\hat{Q} - Q_g\right)^2}{2C} - \frac{Q_g^2}{2C_c} - E_J \cos(\Phi/\phi_0) \,. \tag{10.2}$$

Note that there are now two partially counterbalancing constant terms in the Hamiltonian; however, the terms can vary in time.

Suppose that we fix the offset charge somehow and re-write the Hamiltonian in terms of a and $a^\dagger$. Define:

$$\begin{aligned}
\hat{\varphi} &:= \frac{\hat{\Phi}}{\phi_0}\,, & \hat{n} &:= \frac{\hat{Q}}{2e}\,, & n_g &:= \frac{Q_g}{2e}\,,\\
E_J &:= \frac{\phi_0^2}{L}\,, & E_C &:= \frac{e^2}{2C}\,, & &\\
Z_0 &:= \sqrt{L/C}\,, & \omega_0 &= 1/\sqrt{LC}\,, & &\\
\Phi_{\mathrm{ZPF}} &:= \sqrt{\frac{\hbar}{2}Z_0}\,, & Q_{\mathrm{ZPF}} &:= \sqrt{\frac{\hbar}{2}Z_0^{-1}}\,, & &\\
\hat{\Phi} &= \Phi_{\mathrm{ZPF}}\left(\hat{a}^\dagger + \hat{a}\right)\,. & \hat{\varphi}_{\mathrm{ZPF}} &:= \Phi_{\mathrm{ZPF}}/\phi_0\,, & &\\
\hat{Q} &= iQ_{\mathrm{ZPF}}\left(\hat{a}^\dagger - \hat{a}\right)\,. & \hat{n}_{\mathrm{ZPF}} &:= Q_{\mathrm{ZPF}}/(2e)\,. & &
\end{aligned}$$

In terms of these

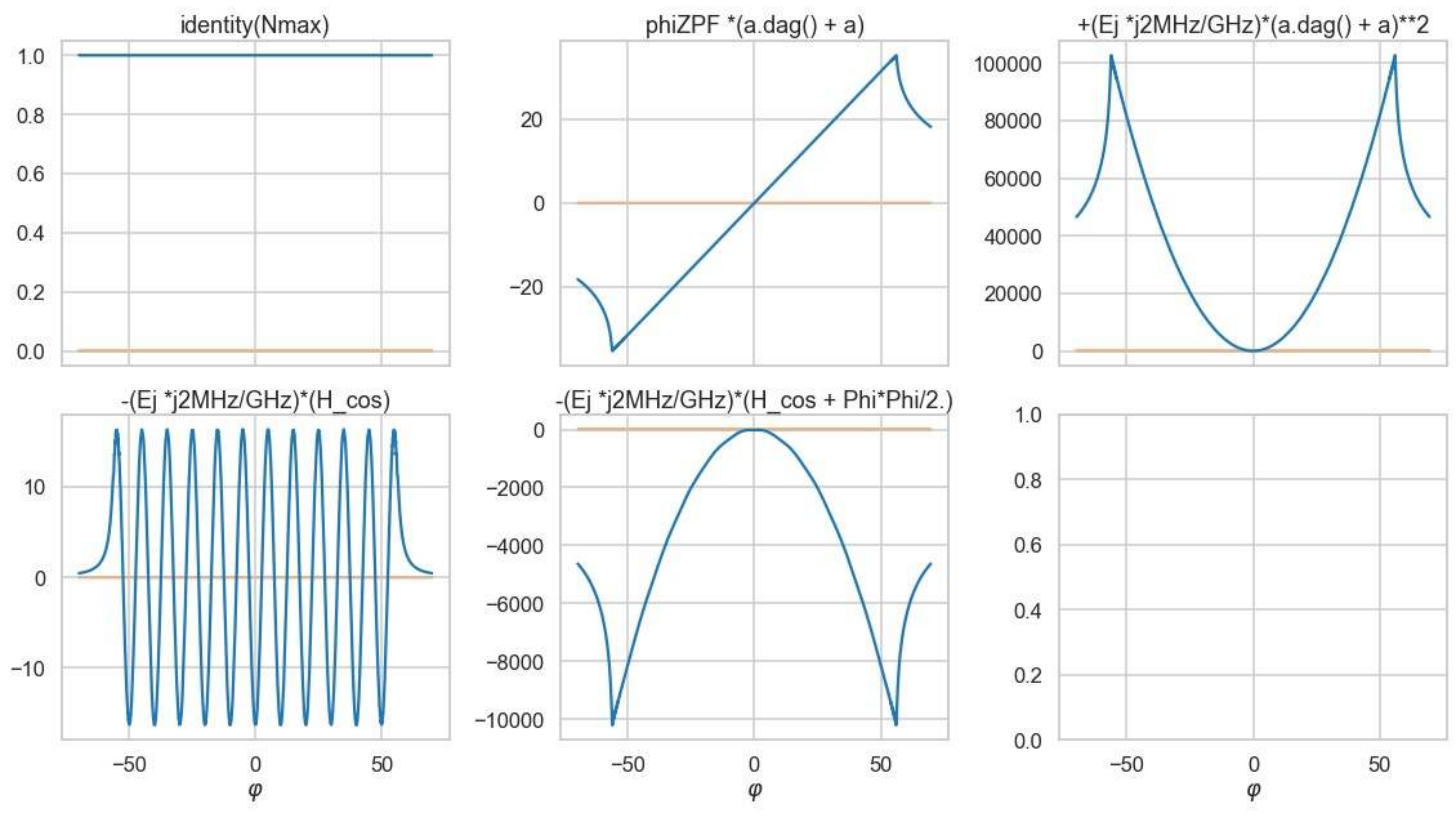
$$\begin{aligned}
\hat{H} &= \frac{\left(\hat{Q} - Q_g\right)^2}{2C} - \frac{Q_g^2}{2C_c} - E_J \cos(\Phi/\phi_0)\\
&= \hat{H}_{\mathrm{lin}} + \hat{H}_{\mathrm{nl}} + \hat{H}_{\mathrm{lin,ofst}}\,,
\end{aligned}$$

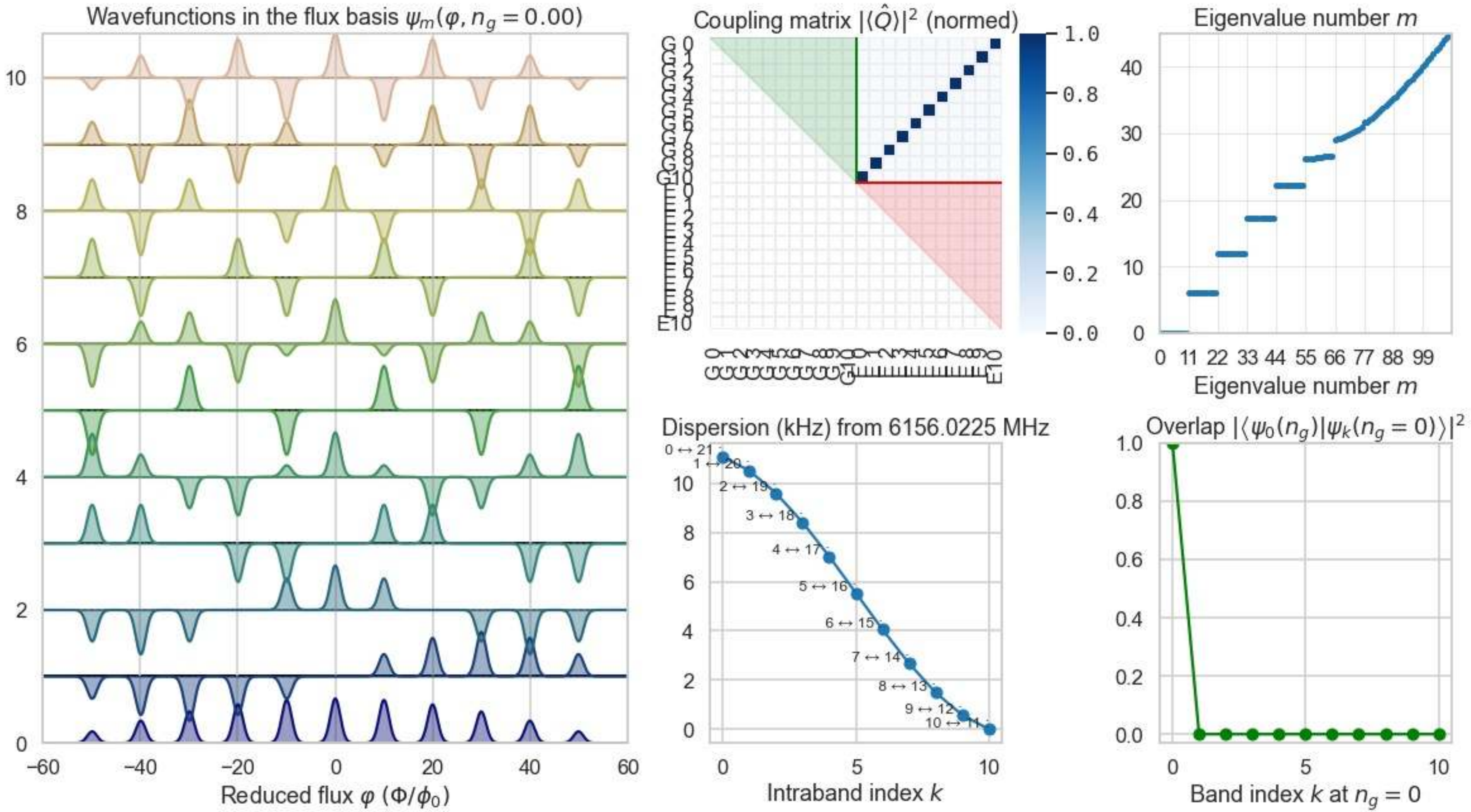
where

$$\begin{aligned}
\hat{H}_{\mathrm{lin}} &:= \frac{1}{2C}\hat{Q}^2 + \frac{1}{2L}\hat{\Phi}^2\,,\\
&= 4E_C\hat{n}^2 + E_J\hat{\varphi}^2\,,\\
&= \hbar\omega_0\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)\,,\\
\hat{H}_{\mathrm{lin,ofst}} &:= -\frac{Q_g}{C}\hat{Q} + \frac{Q_g^2}{2}\left(\frac{1}{C} - \frac{1}{C_c}\right)\,,\\
&= \boxed{-8E_C n_g \hat{n}} + 4E_C n_g^2\left(1 - \frac{C}{C_C}\right)\\
\hat{H}_{\mathrm{nl}} &:= -E_J\left[\cos(\hat{\varphi}) + \frac{1}{2}\hat{\varphi}^2\right]\,.
\end{aligned}$$

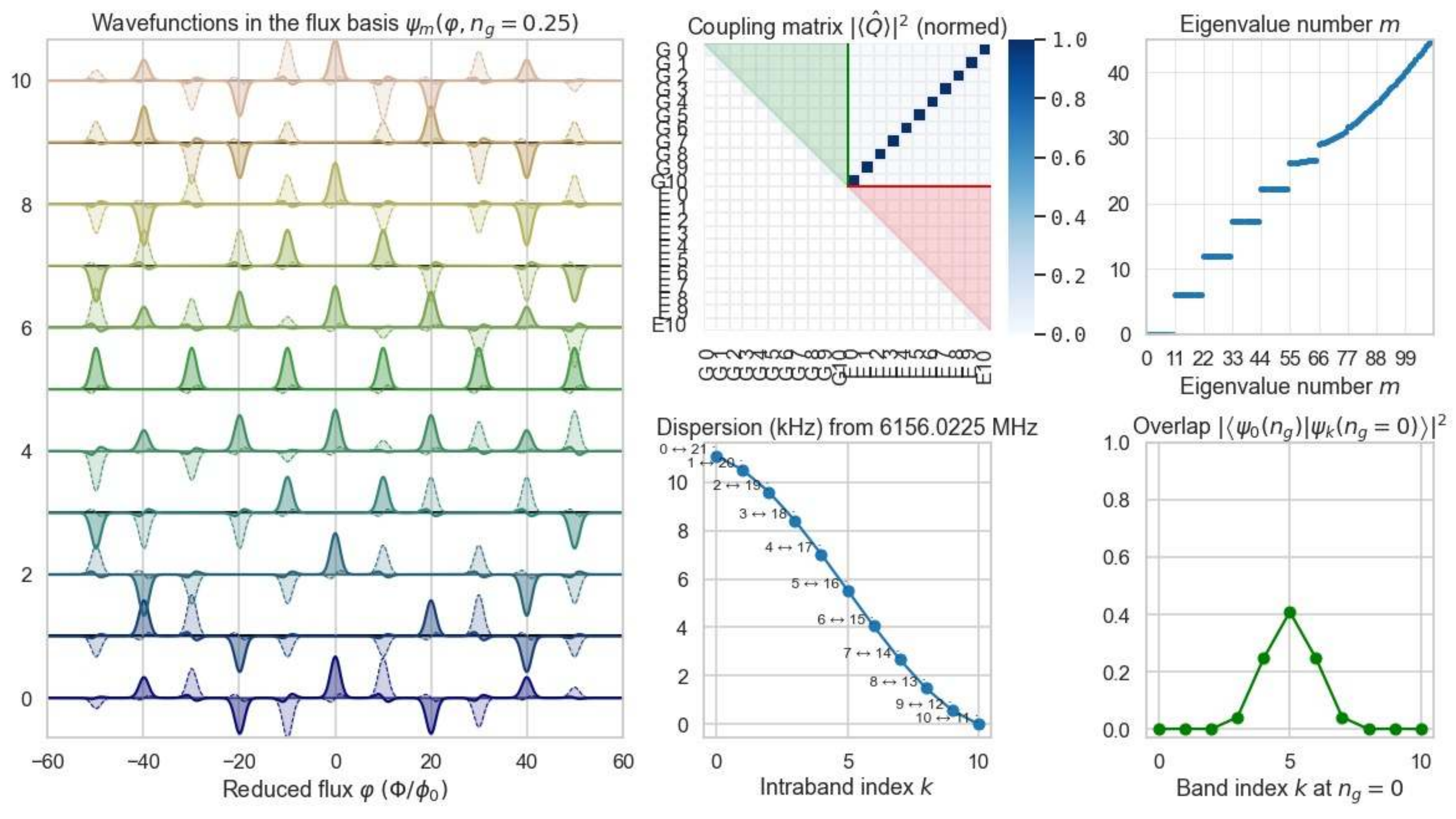
Note that in this form $\hat{H}_{\mathrm{nl}}$ actually has a constant $\cos(x) = 1 - x^2/2 + x^4/4! + \mathcal{O}(x^6)$.

$$= \boxed{-8E_C n_g \hat{n}} +$$

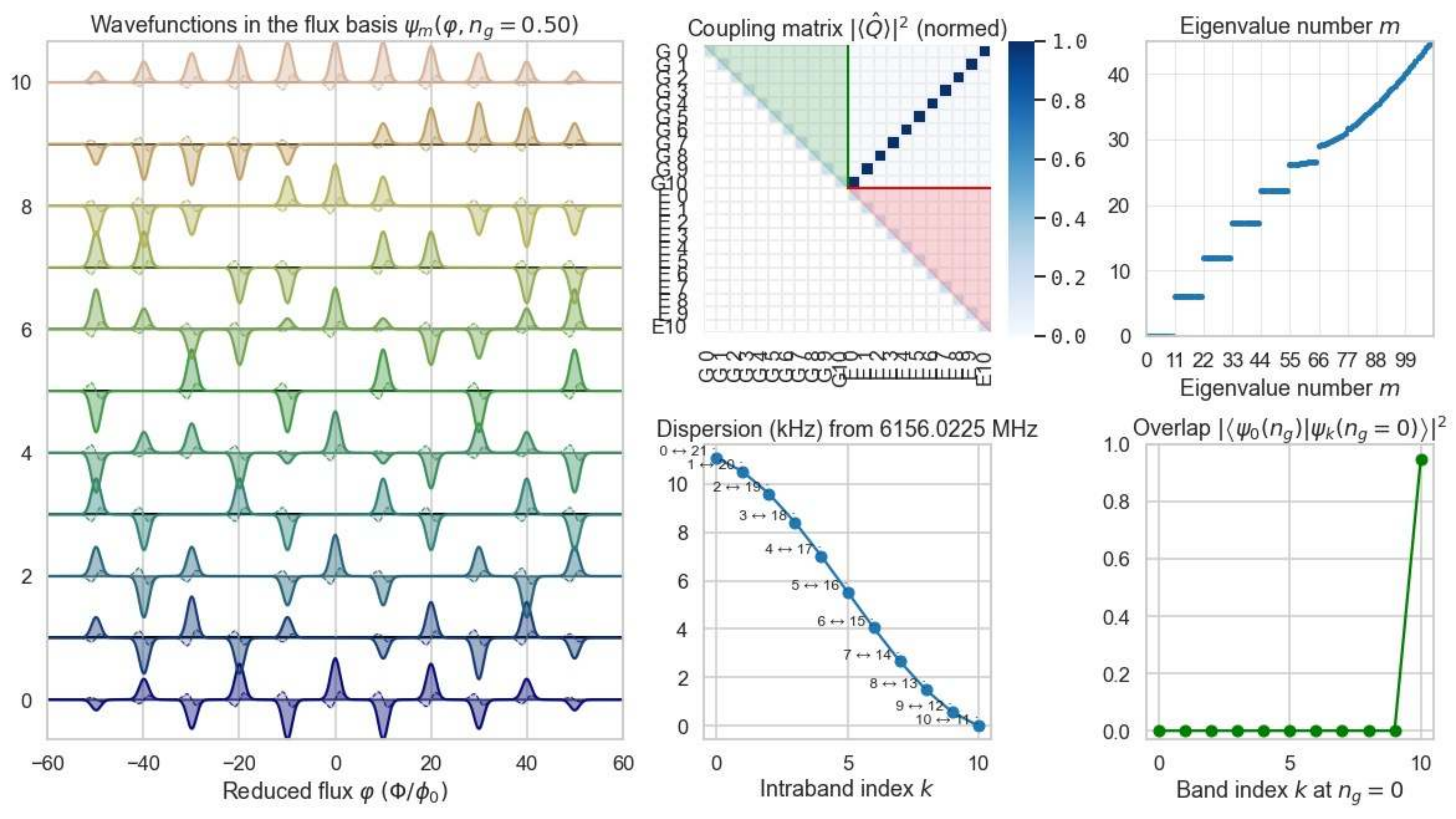

identity(Nmax)
phiZPF *(a.dag() + a)
+(Ej *j2MHz/GHz)*(a.dag() + a)**2
-(Ej *j2MHz/GHz)*(H_cos)
-(Ej *j2MHz/GHz)*(H_cos + Phi*Phi/2.)
φ
φ
φ



Wavefunctions in the flux basis $\psi_m(\varphi, n_g = 0.00)$
Reduced flux φ (Φ/ϕ_0)
Coupling matrix $|\langle\hat{Q}\rangle|^2$ (normed)
Eigenvalue number m
Dispersion (kHz) from 6156.0225 MHz
Intraband index k
Overlap $|\langle\psi_0(n_g)|\psi_k(n_g = 0)\rangle|^2$
Band index k at $n_g = 0$



Wavefunctions in the flux basis $\psi_m(\varphi, n_g = 0.25)$
Reduced flux φ (Φ/ϕ_0)
Coupling matrix $|\langle \hat{Q} \rangle|^2$ (normed)
Eigenvalue number m
Eigenvalue number m
Dispersion (kHz) from 6156.0225 MHz
0 ↔ 21
1 ↔ 20
2 ↔ 19
3 ↔ 18
4 ↔ 17
5 ↔ 16
6 ↔ 15
7 ↔ 14
8 ↔ 13
9 ↔ 12
10 ↔ 11
Intraband index k
Overlap $|\langle \psi_0(n_g)|\psi_k(n_g = 0)\rangle|^2$
Band index k at $n_g = 0$



Wavefunctions in the flux basis $\psi_m(\varphi, n_g = 0.50)$
Reduced flux φ (Φ/ϕ_0)
Coupling matrix $|\langle \hat{Q} \rangle|^2$ (normed)
Eigenvalue number m
Eigenvalue number m
Dispersion (kHz) from 6156.0225 MHz
$0 \leftrightarrow 21$
$1 \leftrightarrow 20$
$2 \leftrightarrow 19$
$3 \leftrightarrow 18$
$4 \leftrightarrow 17$
$5 \leftrightarrow 16$
$6 \leftrightarrow 15$
$7 \leftrightarrow 14$
$8 \leftrightarrow 13$
$9 \leftrightarrow 12$
$10 \leftrightarrow 11$
Intraband index k
Overlap $|\langle \psi_0(n_g) | \psi_k(n_g = 0) \rangle|^2$
Band index k at $n_g = 0$

Summary

Bare
$$\mathcal{H}(\Phi, Q) = \mathcal{H}_{lin}(\Phi, Q) + \mathcal{H}_{nl}(\Phi)$$
$$= \left[\frac{1}{2} Q^T C^{-1} Q + \frac{1}{2}\Phi^T L^{-1}\Phi\right] + \left[-\sum_{j=1}^{J} \mathcal{E}_j^{nl}(\Phi_j)\right]$$

$\uparrow\downarrow S$ CLT canonical linear transform

Eigenmode
$$\tilde{\mathcal{H}}(\Phi_m, Q_m) = \tilde{\mathcal{H}}_{lin}(\Phi_m, Q_m) + \tilde{\mathcal{H}}_{nl}(\Phi_m)$$
$$= \underbrace{\left[\frac{1}{2} Q_m^T \Omega^2 Q_m + \frac{1}{2}\Phi_m^T I \Phi_m\right]}_{\sum_{m=1}^{M} \hbar\omega_m a_m^\dagger a_m} + \left[-\sum_{j=1}^{J} \mathcal{E}_j^{nl}(\Phi_j)\right]$$

$$\Phi_j = \sum_{m=1}^{M} S_{jm}\Phi_m$$

Note

All we have done is a canonical linear transform
No loss of information or approximations
No assumption of strength or weakness of NL

The EPR helps find Sjm
The eigenmode simulation yields Omega

If we now want we can add back in the linear part and recombine to find Ej nl in full form

$$\tilde{\mathcal{H}} = \tilde{\mathcal{H}}_{lin} + \sum_j \mathcal{E}_j^{nl} + \mathcal{E}_j^{lin} - \mathcal{E}_j^{lin}$$
$$= \left(\tilde{\mathcal{H}}_{lin} - \sum_j \mathcal{E}_j^{lin}\right) + \sum_j \mathcal{E}_j^{lin} + \mathcal{E}_j^{nl}$$
$$= \tilde{\mathcal{H}}'_{lin} + \sum_{j=1}^{J} \underbrace{\mathcal{E}_j\left(\sum_{m=1}^{M} S_{jm}\Phi_m\right)}_{\text{full NL func recombined e.g., }\cos(\phi)}$$

in this normal mode basis

identity

$$\mathcal{H}_{lin}(\Phi, Q) \rightarrow \tilde{\mathcal{H}}_{lin}(\Phi_m, Q_m) = \frac{1}{2} Q_m^T \Omega^2 Q_m + \frac{1}{2} \Phi_m^T I \Phi_m \qquad \text{(Diagonal)}$$

Diagonal eigenfrequency matrix

Key

$$\mathcal{H}_{nl}(\Phi) \rightarrow \tilde{\mathcal{H}}_{nl}(\Phi_m) = - \sum_{j=1}^{N} \varepsilon_j^{nl} \left(\sum_{m=1}^{N} S_{jm} \Phi_m \right)$$

N×1 vector

scalar here, not vector

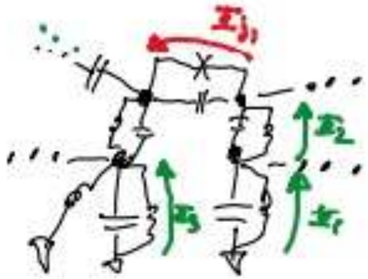
S_{jm} = jth -row m-th column element of S

This expression gives NL dipole flux Φ_j in terms of normal-mode fluxes Φ_m

this is essentially the equation from the talk

$$\hat{\phi}_j = \sum_{m=1}^{M} \phi_{mj}^{ZPF} (\hat{a}^+ + \hat{a})$$

Total-sys Lagrangian



in basis that includes all NL dipole fluxes

$$\Phi = \begin{pmatrix} \Phi_J \\ \Phi_L \end{pmatrix}$$

$J \times 1$ vec of Φ_j fluxes

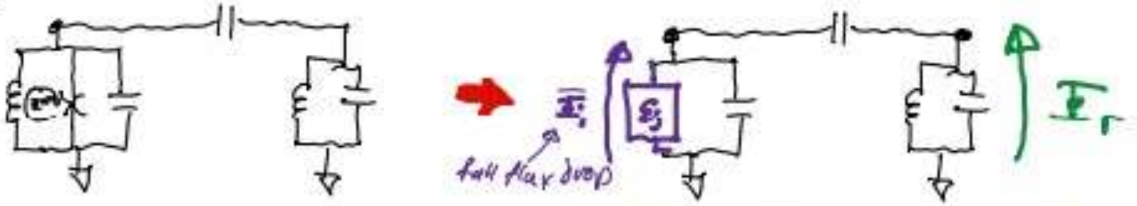
$(N-J)\times 1$ vec of non Φ_j-fluxes

minimal spanning tree vector

$\dim \Phi = N \times 1$

Example: Fluxonium

RAW

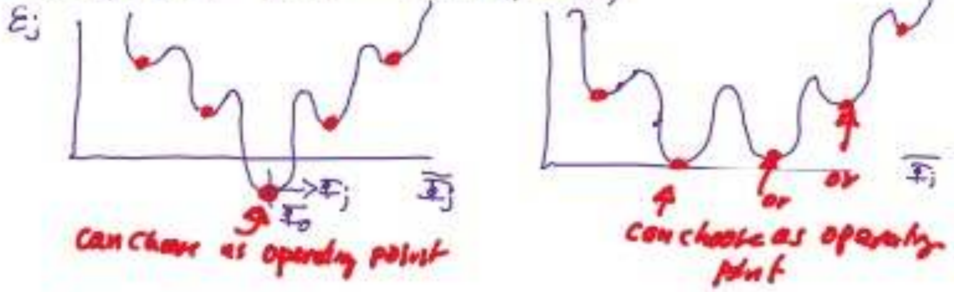


$$\mathcal{E}_j(\bar{\Phi}_j; \Phi_j^{ext}) = \frac{1}{2}L\bar{\Phi}_j^2 - E_J \cos(\bar{\Phi}_j - \Phi_j^{ext})$$

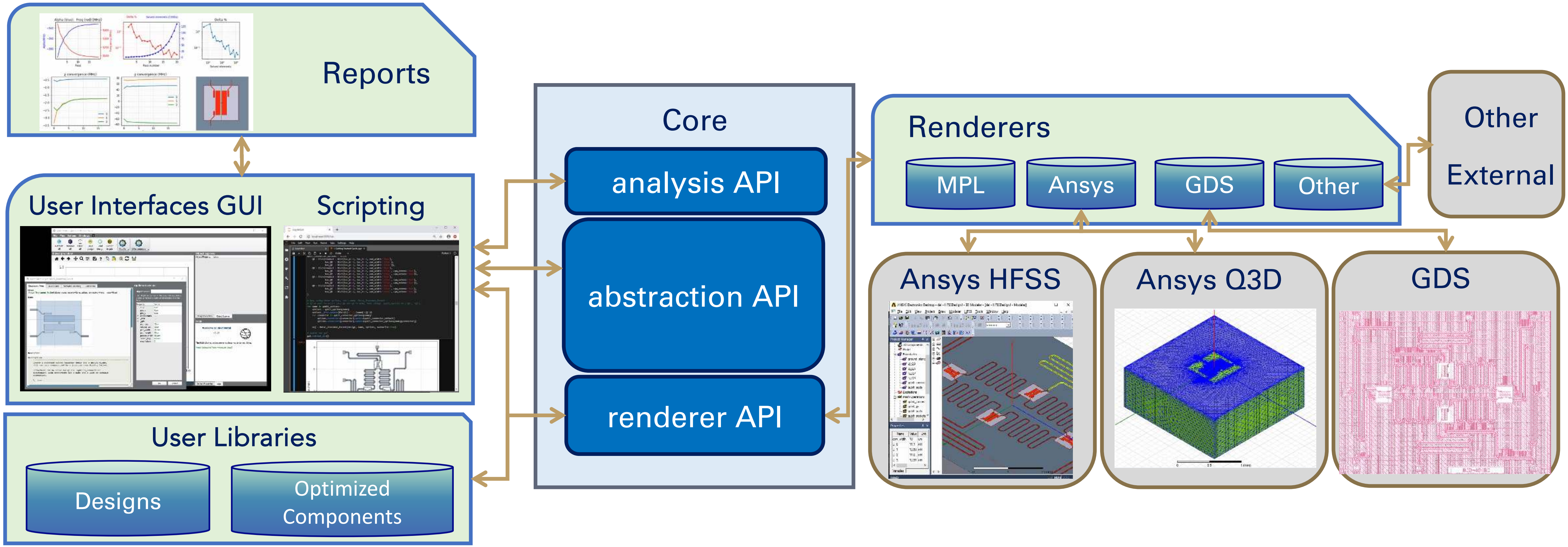
$\Phi_j = \bar{\Phi}_j - \Phi_0$ ← total flux

deviation away from equilibrium

equilibrium point



Qiskit Metal Container Diagram




#Quantum Seminar
Qiskit

Qiskit | quantum device design

THE QUANTUM DAILY

Medium

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Qiskit Metal is the first electronic design automation (EDA) tool specifically for quantum computers, aimed to help the community innovate and ...

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It's all possible because of the new Qiskit Metal program from IBM, which is part of their effort to bring open-source tools to the world of quantum ...

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Qiskit Metal is an open-source platform that automates parts of the design process for quantum chips. Image: IBM Quantum. Building the ...

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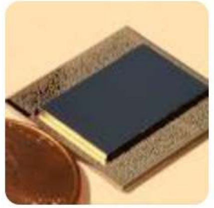

LeBigData

IBM Qiskit Metal permet à n'importe qui de concevoir une puce ...

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AG Connect

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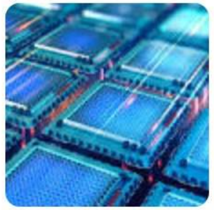

Open source EDA tool simplifies quantum device design

March 29, 2021 // By Rich Pell 0 Con

QUANTUM ZEITGEIST

BROOKHAVEN NATIONAL LABORATORY

Quantum Computing Report

Where Qubits Entangle with Commerce

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

KeysightQuantum @KeysightQ
Replying to @zlatko_minev @Fo
Congrats! Is there an eta

Analyst Notes:

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

2.) By reducing the complexity of chip design, IBM has eliminated a significant barrier that may make quantum attractive to more people.

3.) Qiskit Metal makes it possible for young K-12 students to have an understandable hands-on learning experience with quantum computing. Metal can turn an impossible task into a fun learning experience. A positive early learning experience with Metal could result in thousands of future quantum researchers.