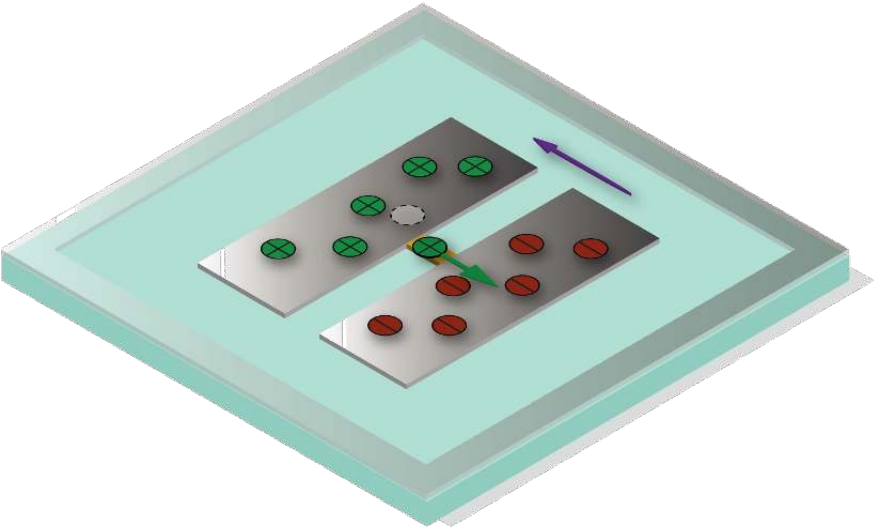
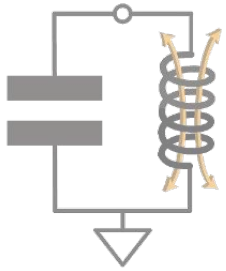
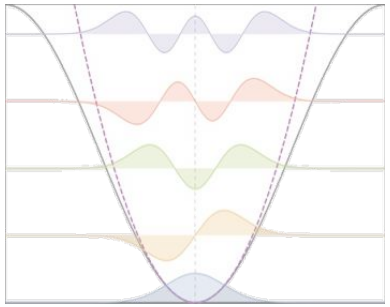
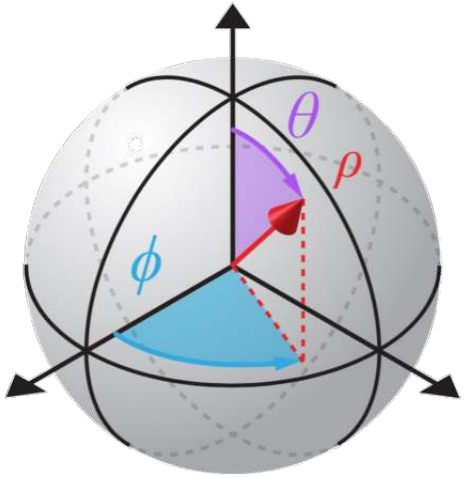
To design quantum hardware

Energy-participation-ratio (EPR) and Qiskit Metal









Zlatko K. Minev

IBM **Quantum**

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nature
International journal of science

Letter | Published: 03 June 2019

To catch and reverse a quantum jump mid-flight

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

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

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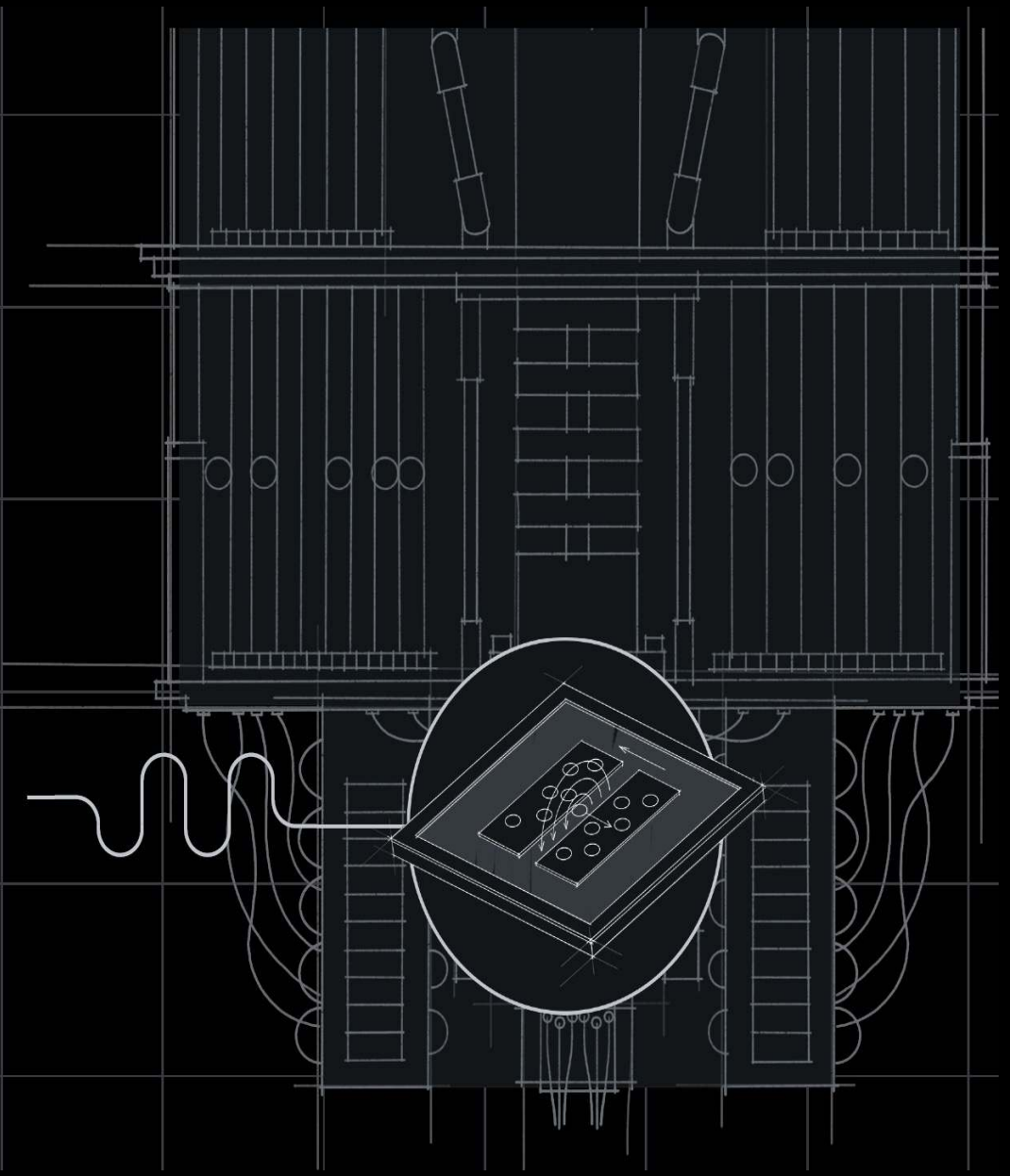


Today

Quantum device design overview

Energy-participation ratio (EPR)

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

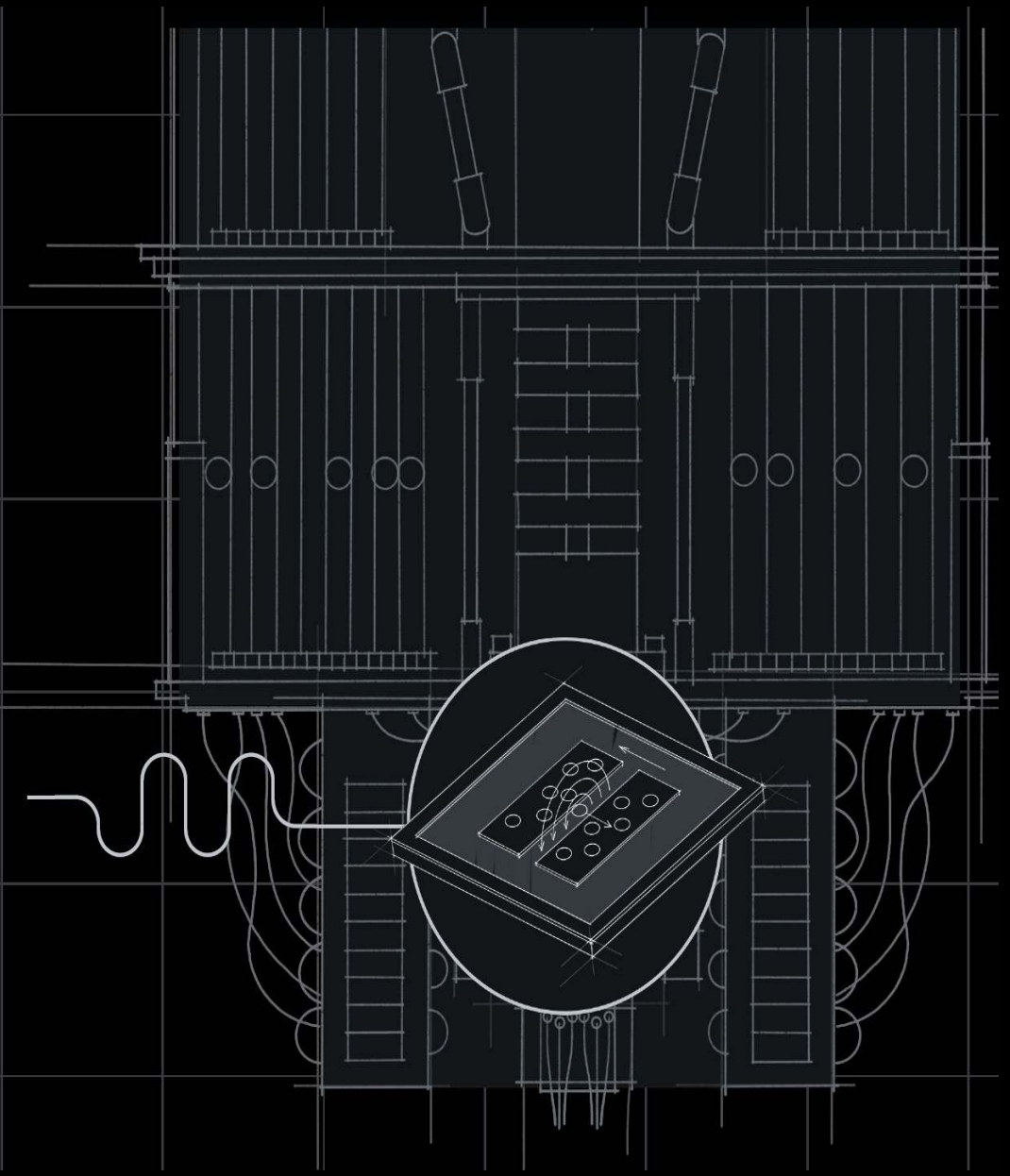
Qiskit | quantum device design

open source Q-EDA and analysis (IBM)

qiskit.org/metal

Modular lumped-oscillator method

Minev, Gambetta et al. (IBM)

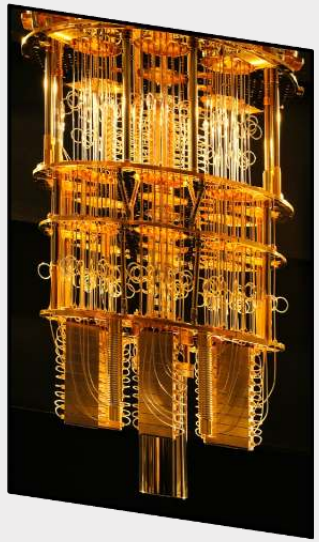


Quantum device design
in a nutshell

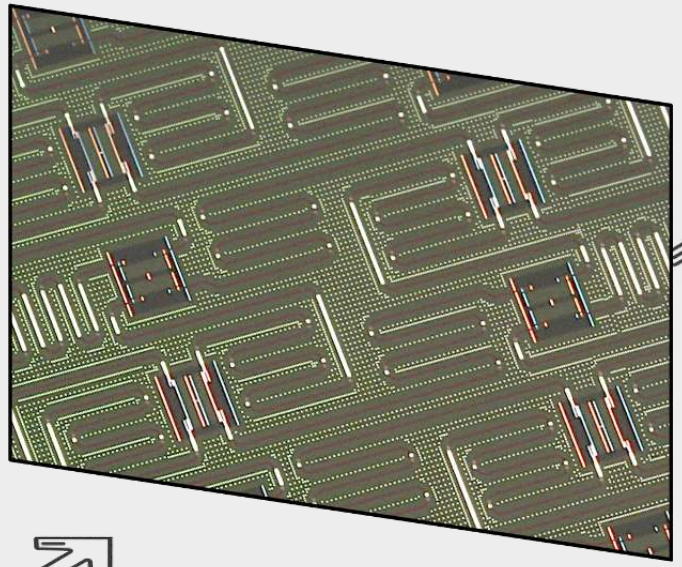
Quantum in the cloud or lab

Superconducting qubits

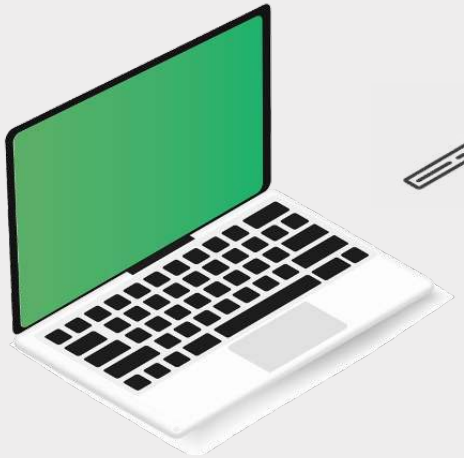
Lab / cloud facility



Cryogenic environment



Quantum-device chip

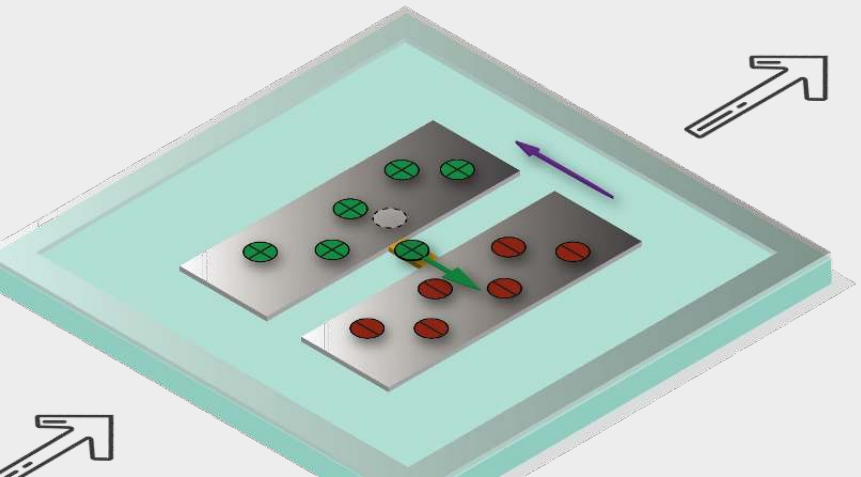


Quantum community

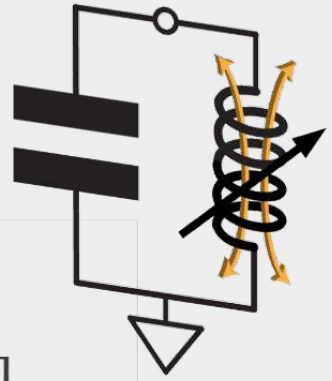
Laptop image: rawpixel.com; Photos: IBM

Quantum Device Design

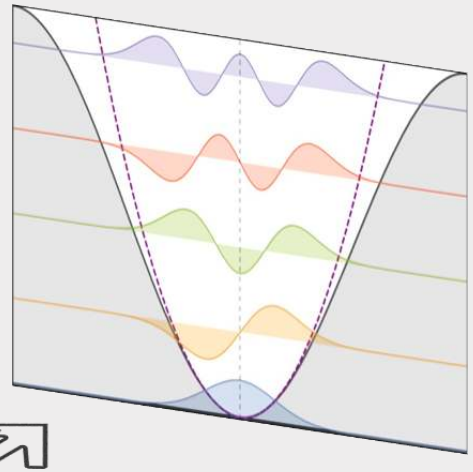
Superconducting circuits



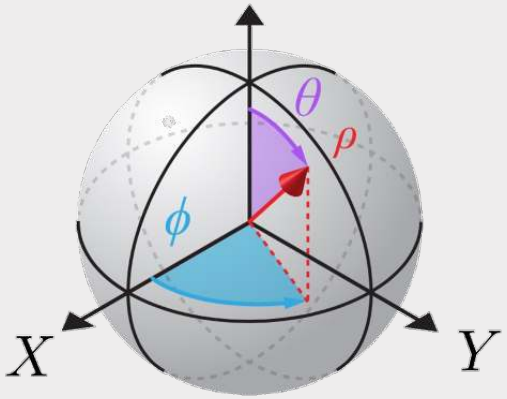
Physical layout



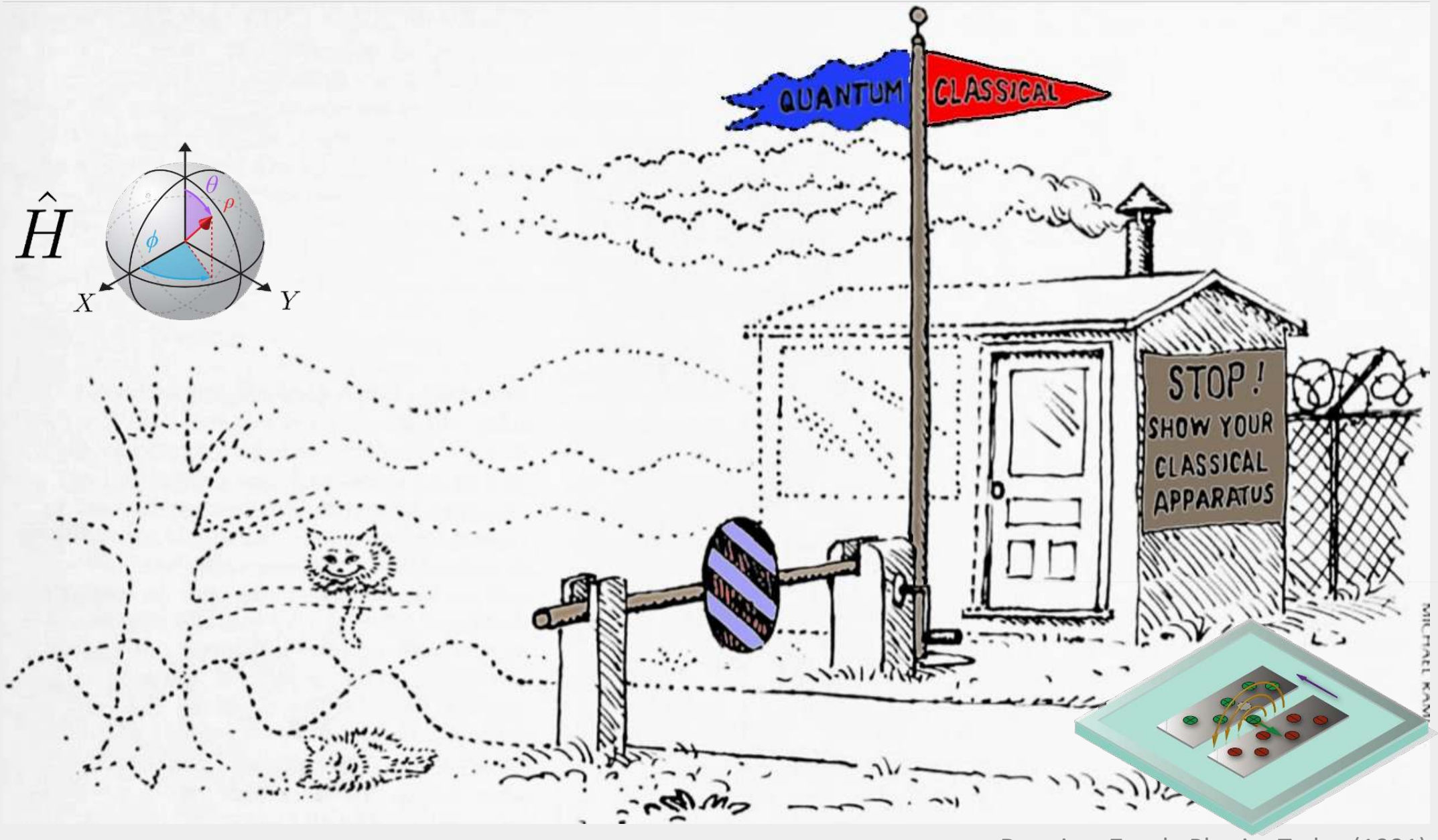
Electromagnetic analysis



Quantum Hamiltonian analysis



Qubit Hilbert space



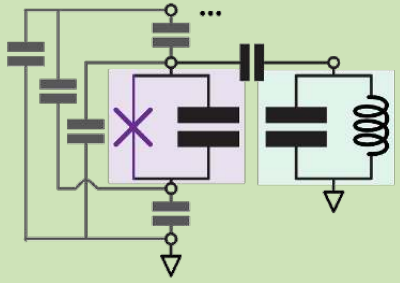
Drawing: Zurek, Physics Today (1991)

Quantization landscape

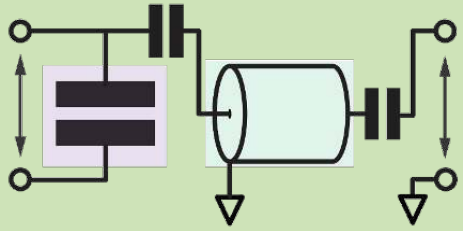
quasi-static

full-wave

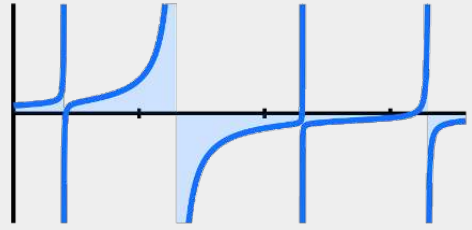
lumped



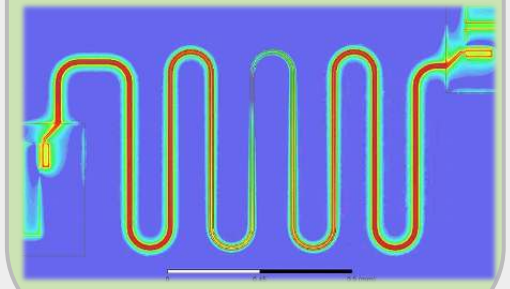
semi-analytic



impedance



eigenmode



Captures more information, complexity, accuracy

Yurke & Denker (1984), Devoret (1997), Burkard *et al.* (2004), Koch *et al.* (2007), Minev *et al.* (2021), …

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

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

Minev (2019)
Minev *et al.* (2020)

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)*

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.

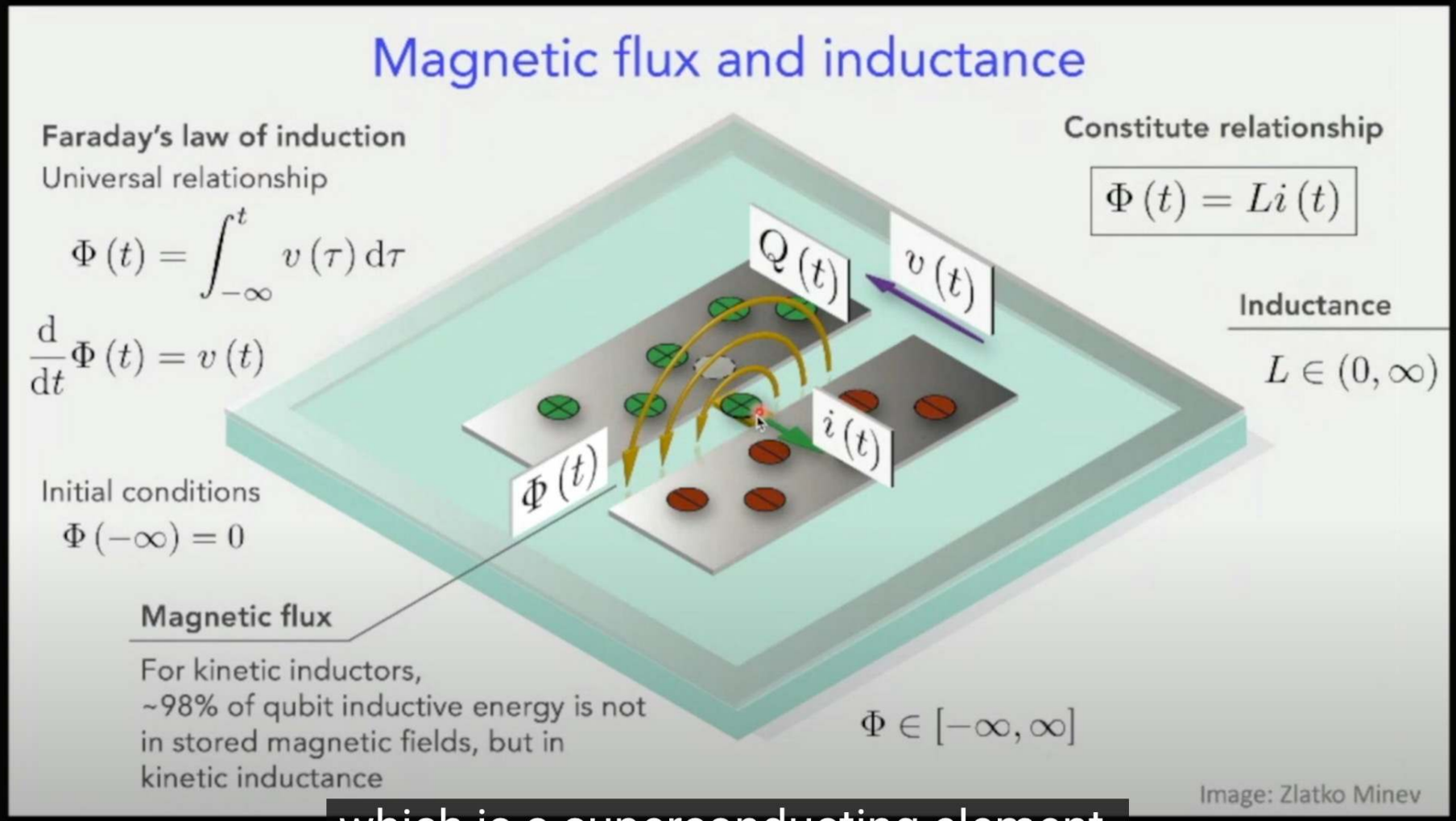
Clerk, A. A., Girvin, S. M., Marquardt, F., & Schoelkopf, R. J. (2010) Introduction to quantum noise, measurement, and amplification *Reviews of Modern Physics*, *82*(2), 1155–1208

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

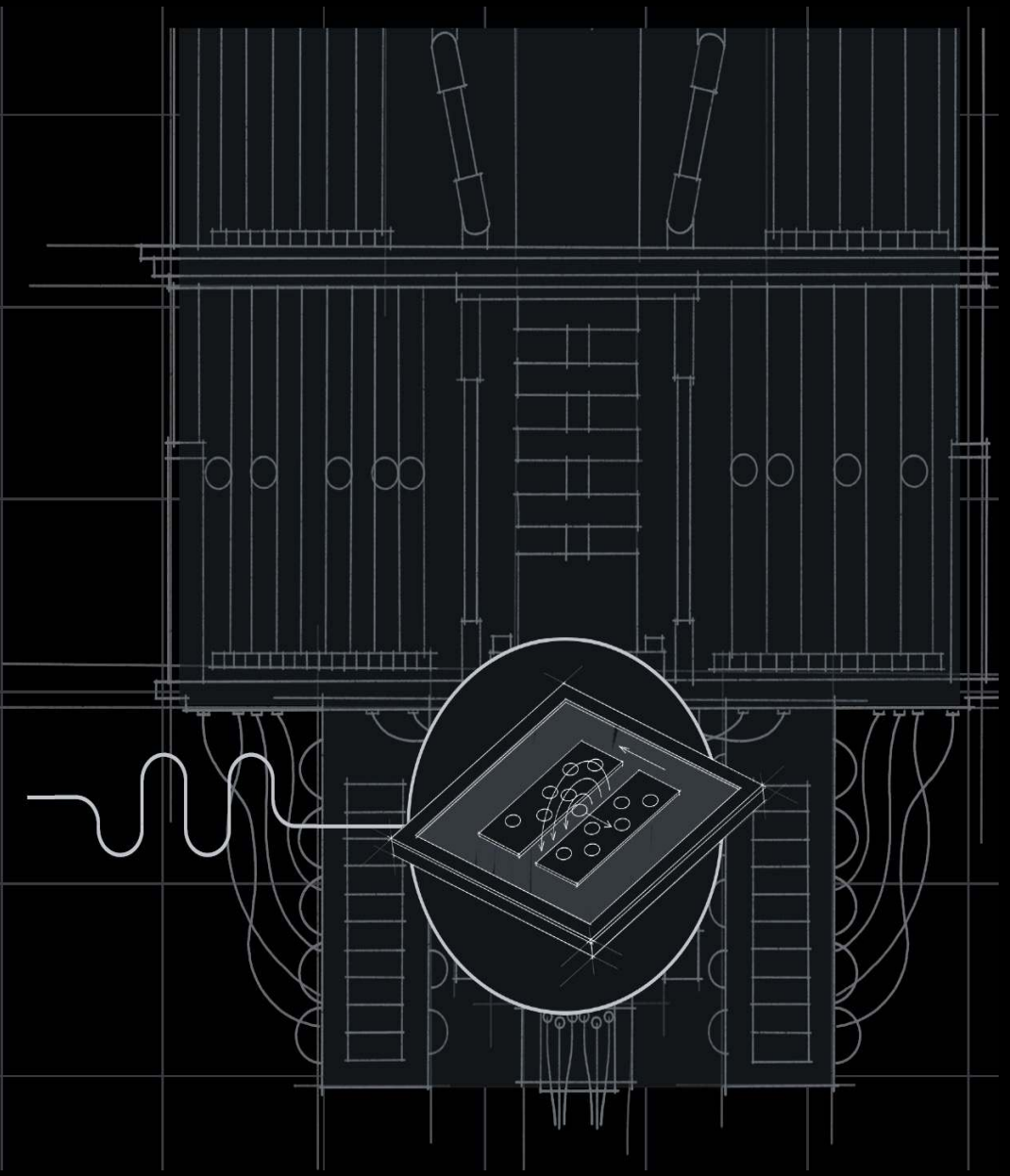
Devoret, M. H. (1997) Quantum Fluctuations in Electrical Circuits. In *Fluctuations Quantiques/Quantum Fluctuations* (p. 351)

…

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



which is a superconducting element.



Energy-participation ratio (EPR)

Quantum Physics

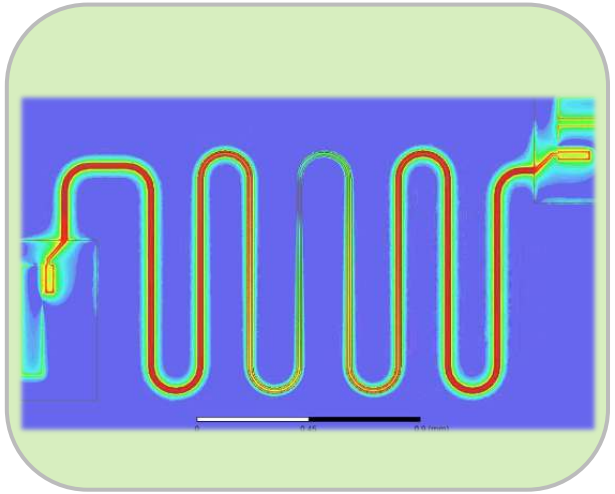
[Submitted on 1 Oct 2020]

Energy-participation quantization of Josephson circuits

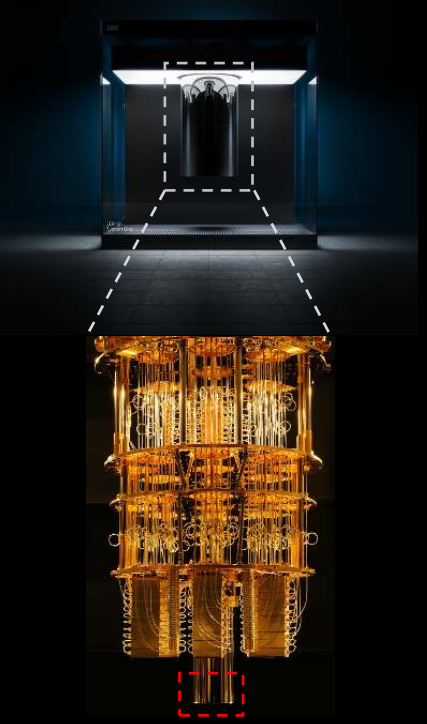
Zlatko K. Minev, Zaki Leghtas, Shantanu O. Mundhada, Lysander Christakis, Ioan M. Pop, Michel H. Devoret

Superconducting microwave circuits incorporating nonlinear devices, such as Josephson junctions, are one of the leading platforms for emerging quantum technologies. Increasing circuit complexity further requires efficient methods for the calculation and optimization of the spectrum, nonlinear interactions, and dissipation in multi-mode distributed quantum circuits. Here, we present a method based on the energy-participation ratio (EPR) of a dissipative or nonlinear element in an electromagnetic mode. The EPR, a number between zero and one, quantifies how much of the energy of a mode is stored in each element. It obeys universal constraints---valid regardless of the circuit topology and nature of the nonlinear elements. The EPR of the elements are calculated from a unique, efficient electromagnetic eigenmode simulation of the linearized circuit, including lossy elements. Their set is the key input to the determination of the quantum Hamiltonian of the system. The method provides an intuitive and simple-to-use tool to quantize multi-junction circuits. It is especially well-suited for finding the Hamiltonian and dissipative parameters of weakly anharmonic systems, such as transmon qubits coupled to resonators, or Josephson transmission lines. We experimentally tested this method on a variety of Josephson circuits, and demonstrated agreement within several percents for nonlinear couplings and modal Hamiltonian parameters, spanning five-orders of magnitude in energy, across a dozen samples.

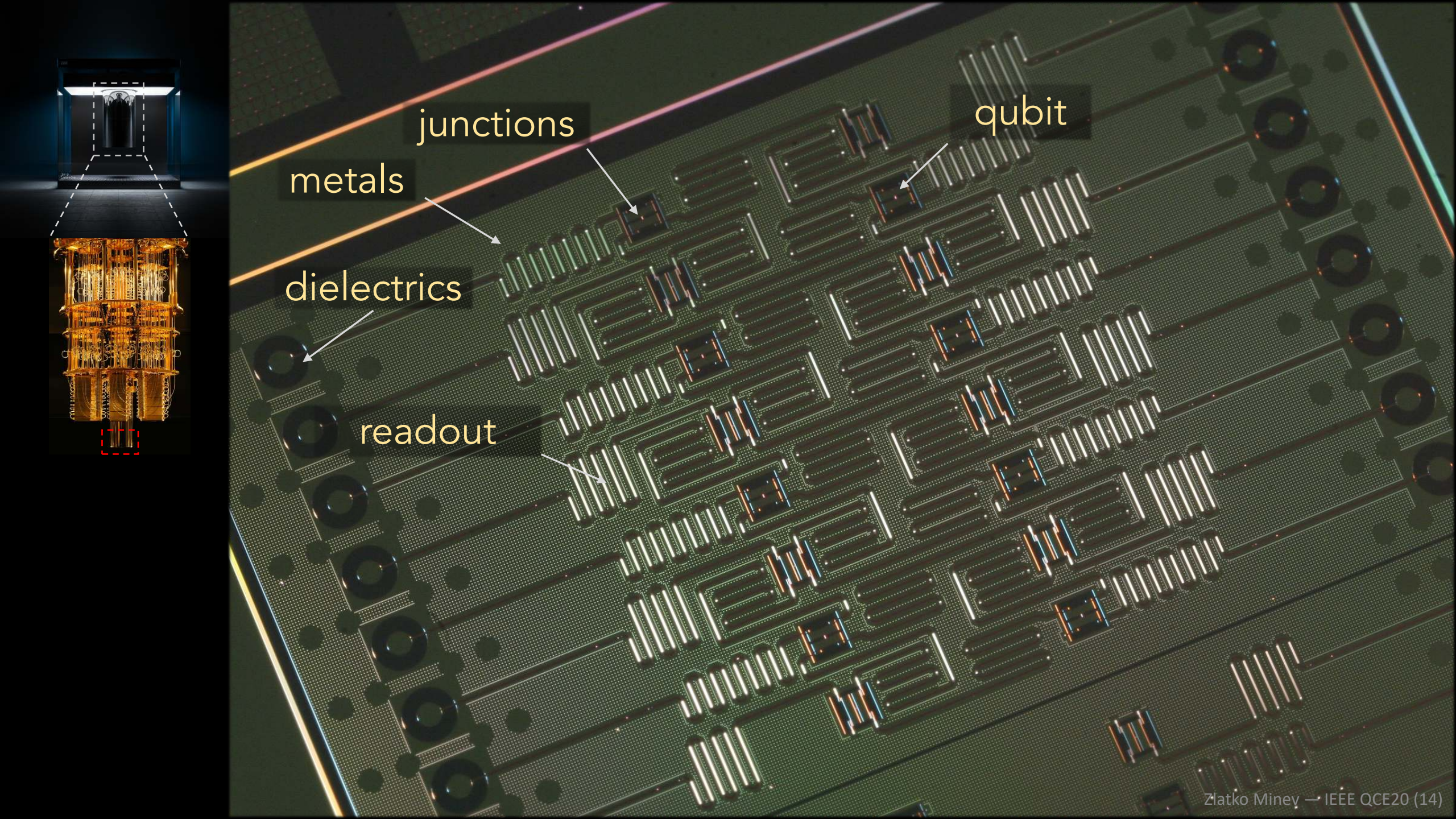
Comments: 15 Figures, 39 pages, 4 tables; See also this http URL Send feedback to zlatko.minev [@] this http URL
Subjects: **Quantum Physics (quant-ph)**; Superconductivity (cond-mat.supr-con)
Cite as: arXiv:2010.00620 **[quant-ph]**
(or arXiv:2010.00620v1 **[quant-ph]** for this version)

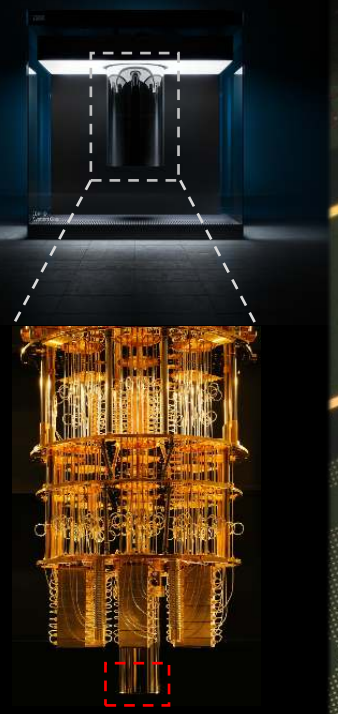


See also Minev dissertation Sec. 4.1 (arXiv: 1902.10355)



Anatomy of a quantum chip


junctions
qubit
metals
dielectrics
readout



What needs to be designed?

junctions

geometry & topology

qubit

frequency, anharmonicity, …

metals

dielectrics

many-body Hamiltonian

qubit-qubit coupling

readout frequency, coupling

loss budget due to dielectrics, seams, interfaces, …

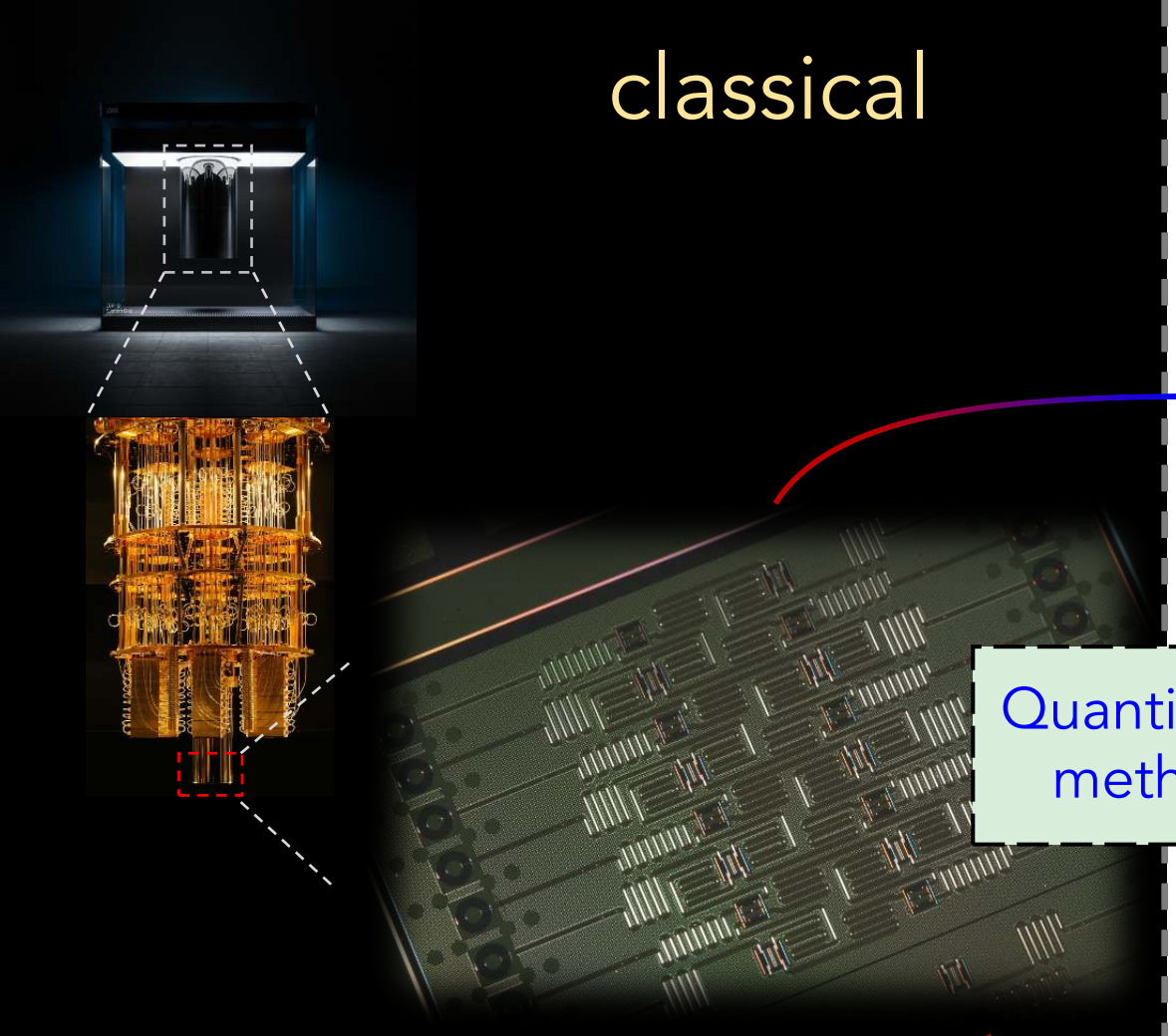
spurious qubit coupling (non-local)

I-O coupling

radiative dissipation (Purcell limit)

spurious modes sample holder

classical



Quantization methods

geometry, circuits, materials,
electromagnetic fields,
…

quantum

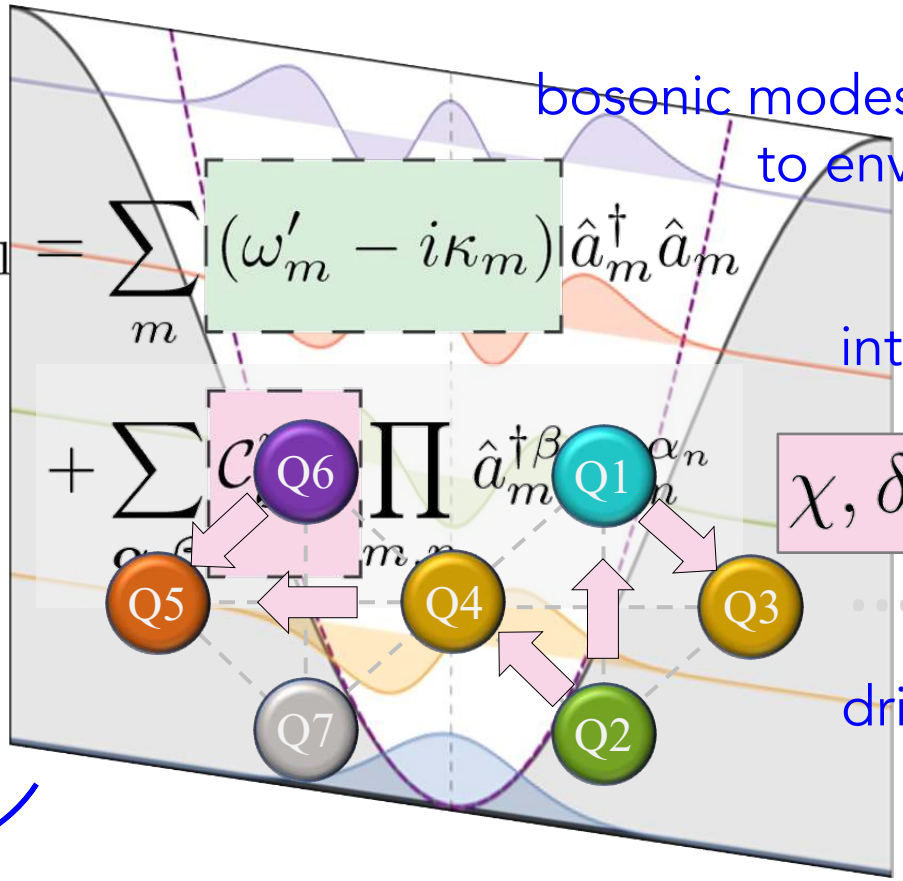
$$\hat{H}_{\text{full}} = \sum_m (\omega'_m - i\kappa_m)\hat{a}^\dagger_m \hat{a}_m + \sum_{\alpha} C^{\alpha} \prod_{m,n} \hat{a}^{\dagger\beta_m}_m \hat{a}^{\alpha_n}_n + \dots$$

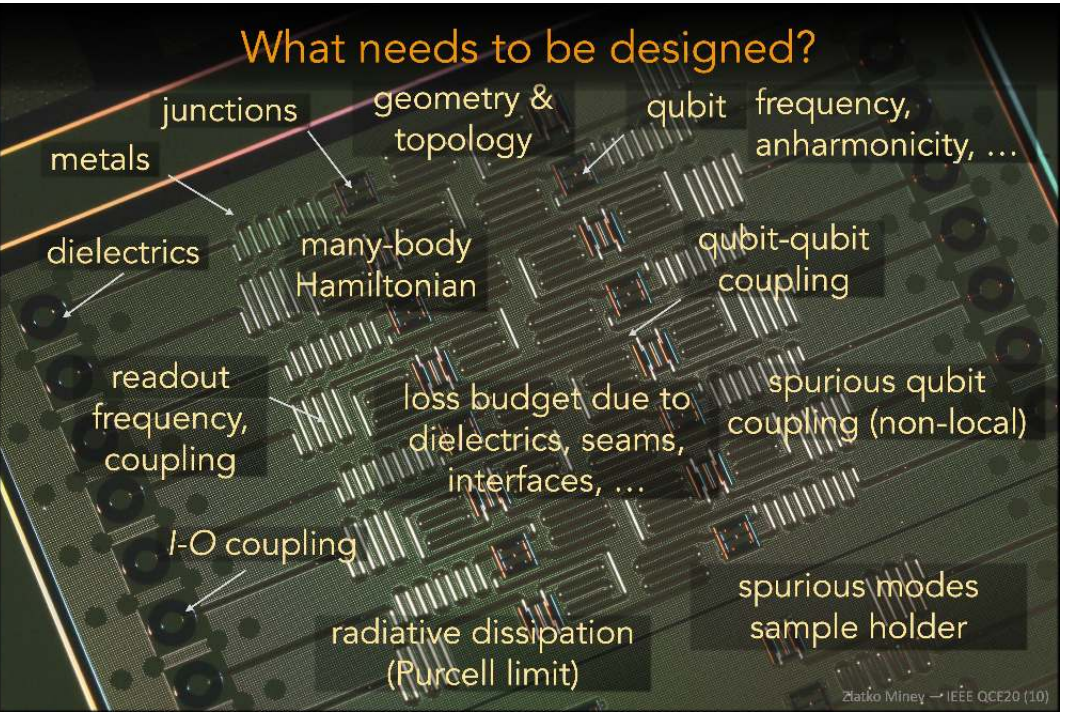
bosonic modes coupled to environment

interactions

$\chi, \delta, \alpha, \dots$

drive terms





The solution of all these questions reduces to:

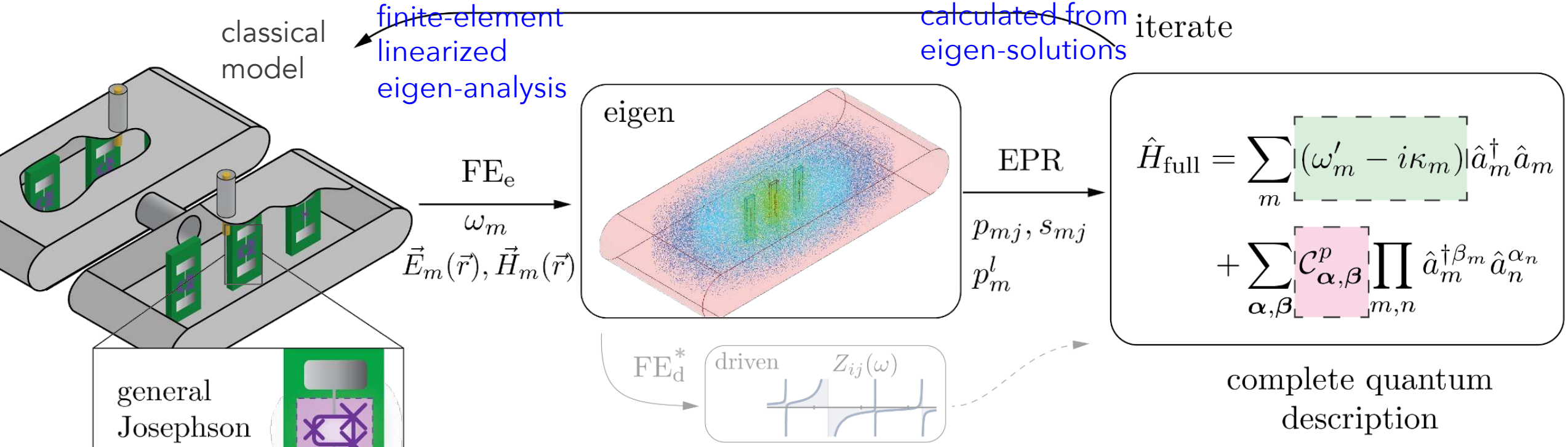
Where is the energy?

What *fraction of the energy* of a mode p_j (p_l) is stored in the non-linear (dissipative) element?

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

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

Overview of energy-participation approach



Energy-participation ratio (EPR) approach:

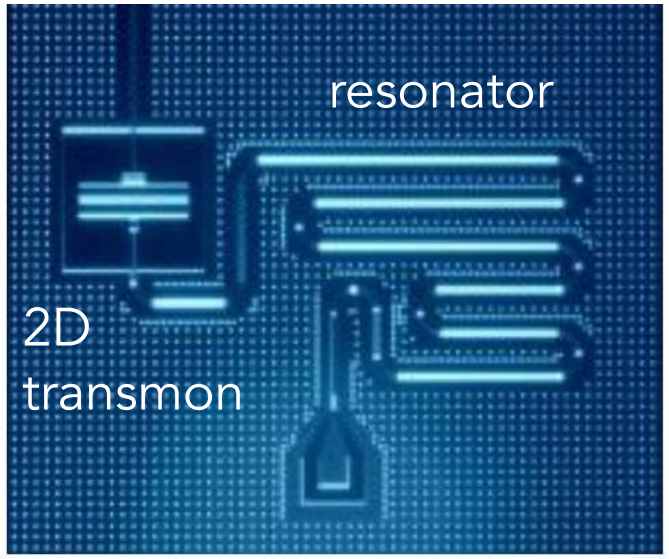
- describes any order and strength non-linearity
- describes arbitrary (composite) non-linear inductive devices
- first-principle derivation
- zero approximations (aside from truncation of modes)
- fully automated in python (github.com/zlatko-minev)

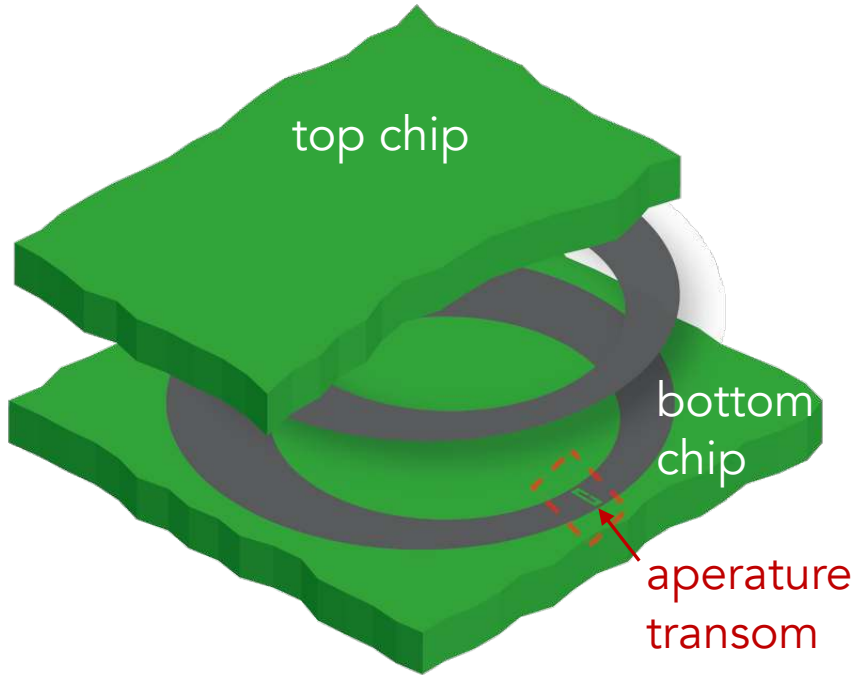
Practical limits: Fock and mode basis truncation due to computing power

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

A simple example:

transmon qubit coupled to resonator





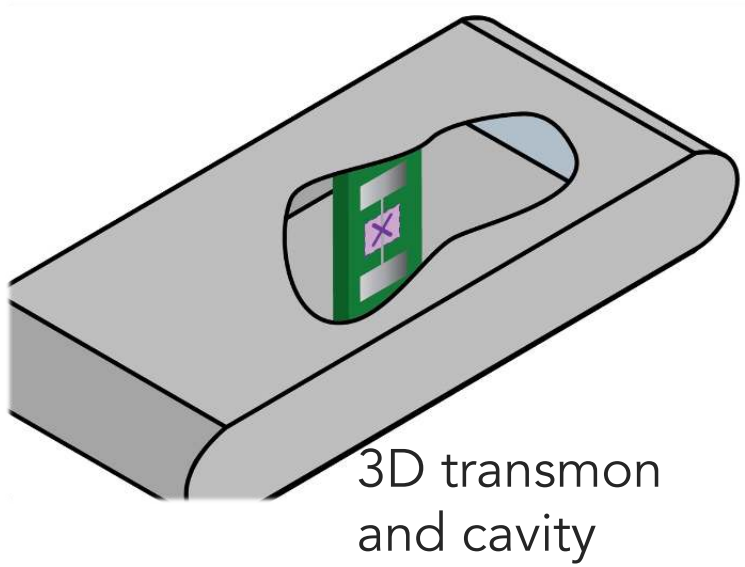
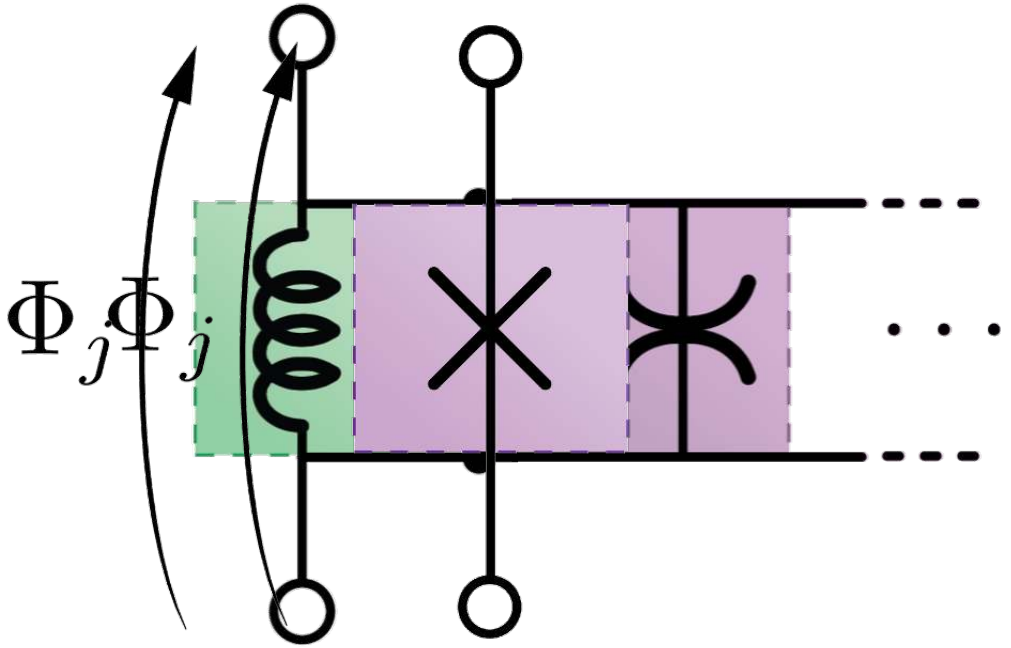


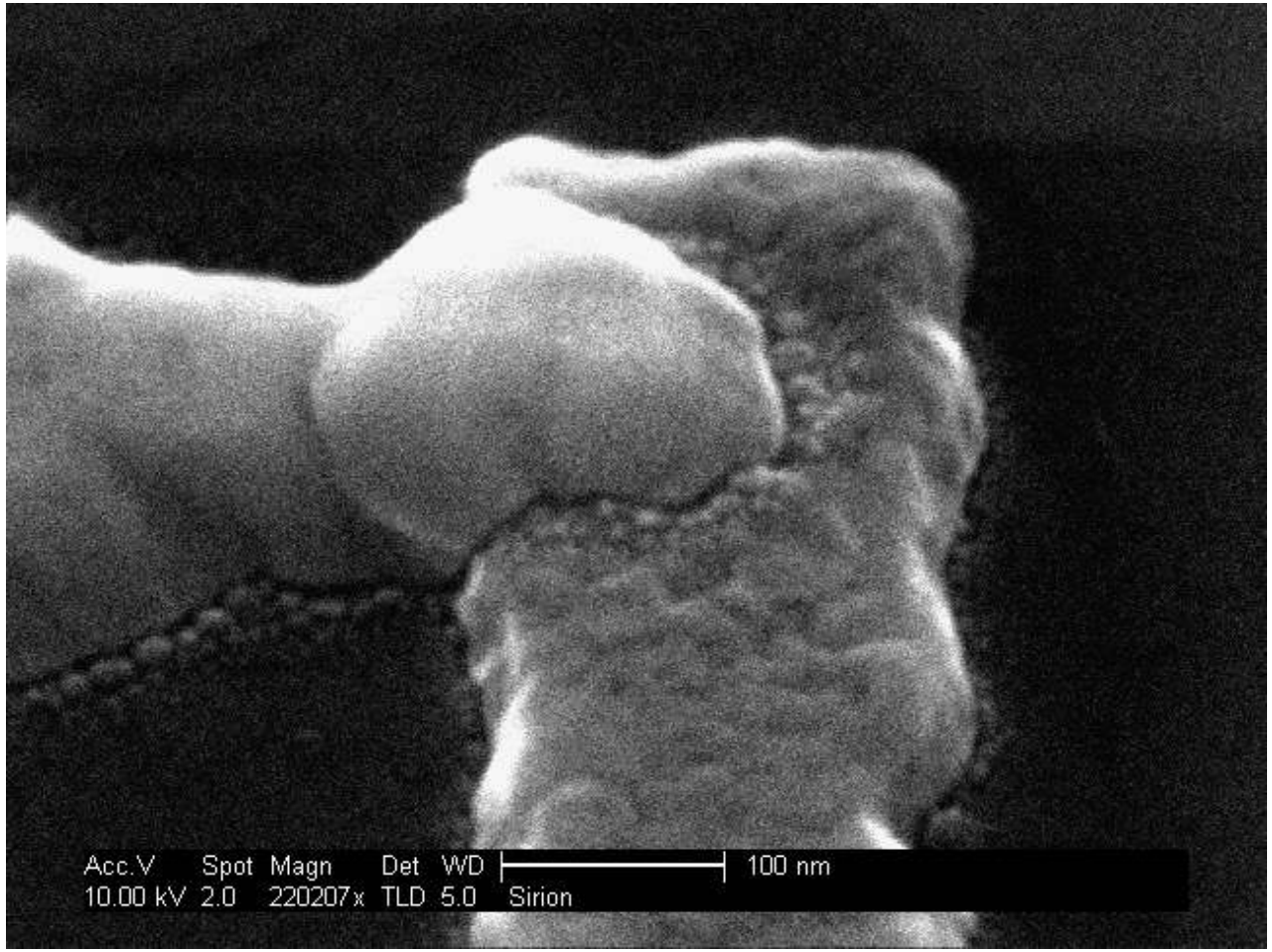
Image: Gambetta, Chow, and Steffen (2017)

Minev *et al.* (2013, 2016)

Paik *et al.* (2011), …

Josephson tunnel junction





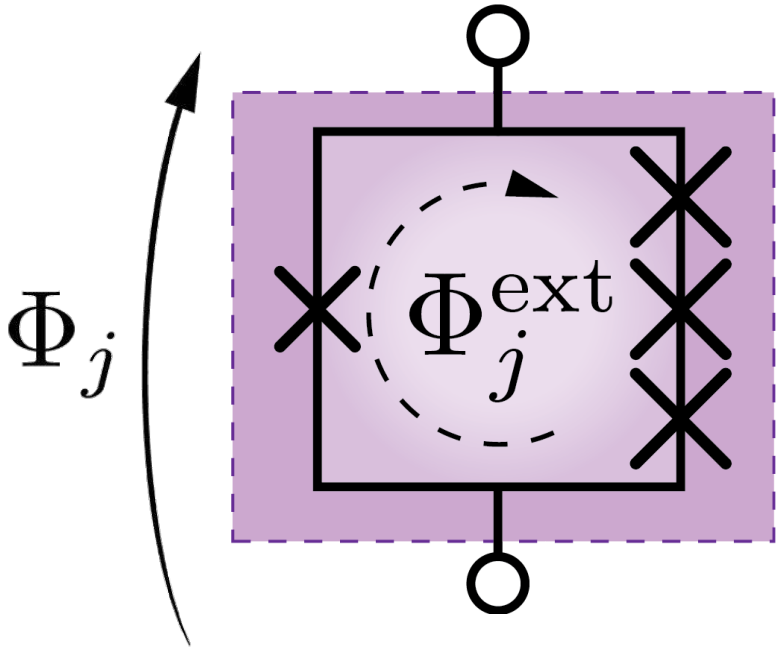
$$\mathcal{E}_j\left(\Phi_j\right) = E_j\left(1-\cos\left(\Phi_j/\phi_0\right)\right)$$

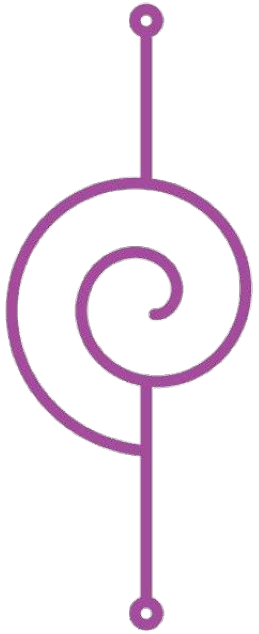
$$\phi_0 \equiv \hbar/2e\,\Phi_j) + \mathcal{E}_j^{\mathrm{nl}}\left(\Phi_j\right)$$

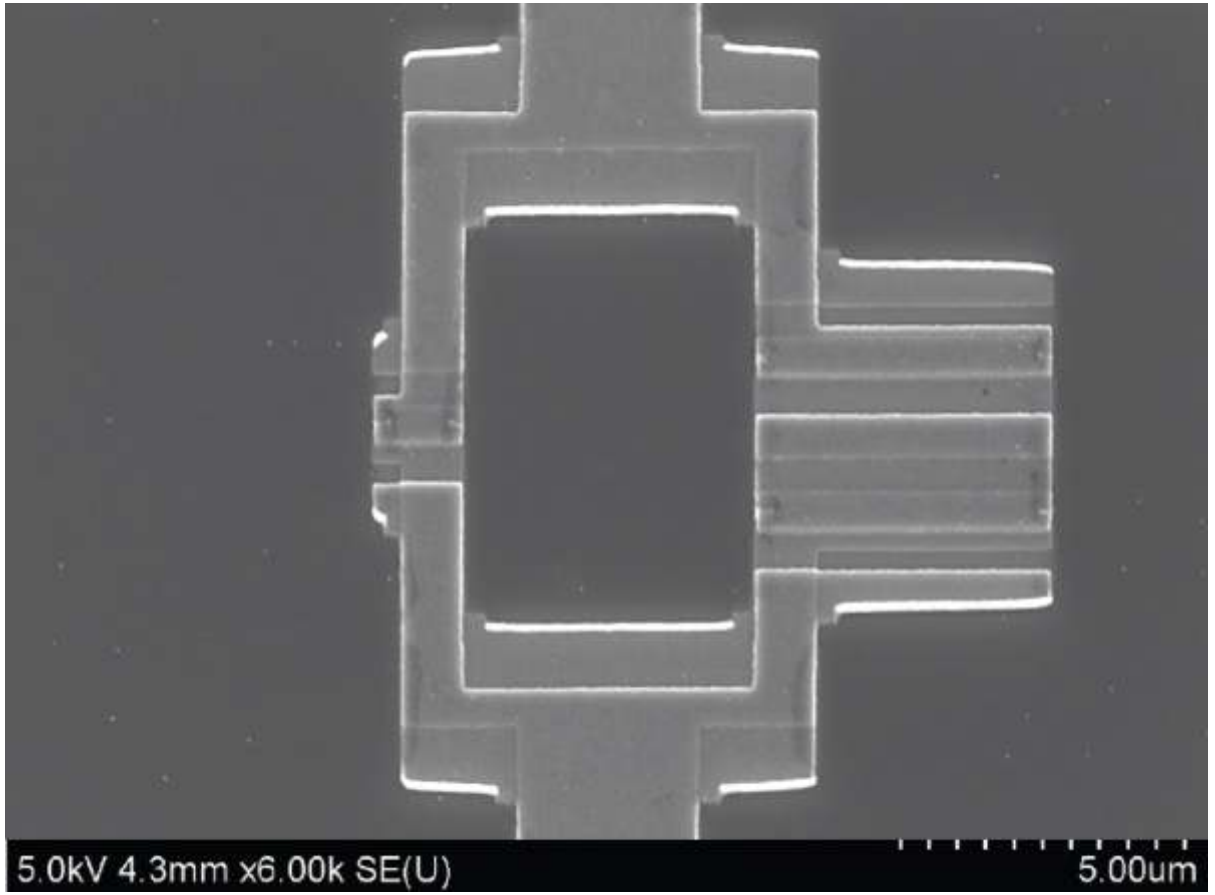
$$= \frac{E_j}{2}\left(\frac{\Phi_j}{\phi_0}\right)^2 - \frac{E_j}{4!}\left(\frac{\Phi_j}{\phi_0}\right)^4 + \mathcal{O}\left(\Phi_j^6\right)$$

SEM image: L. Frunzio

Composite Josephson device: example





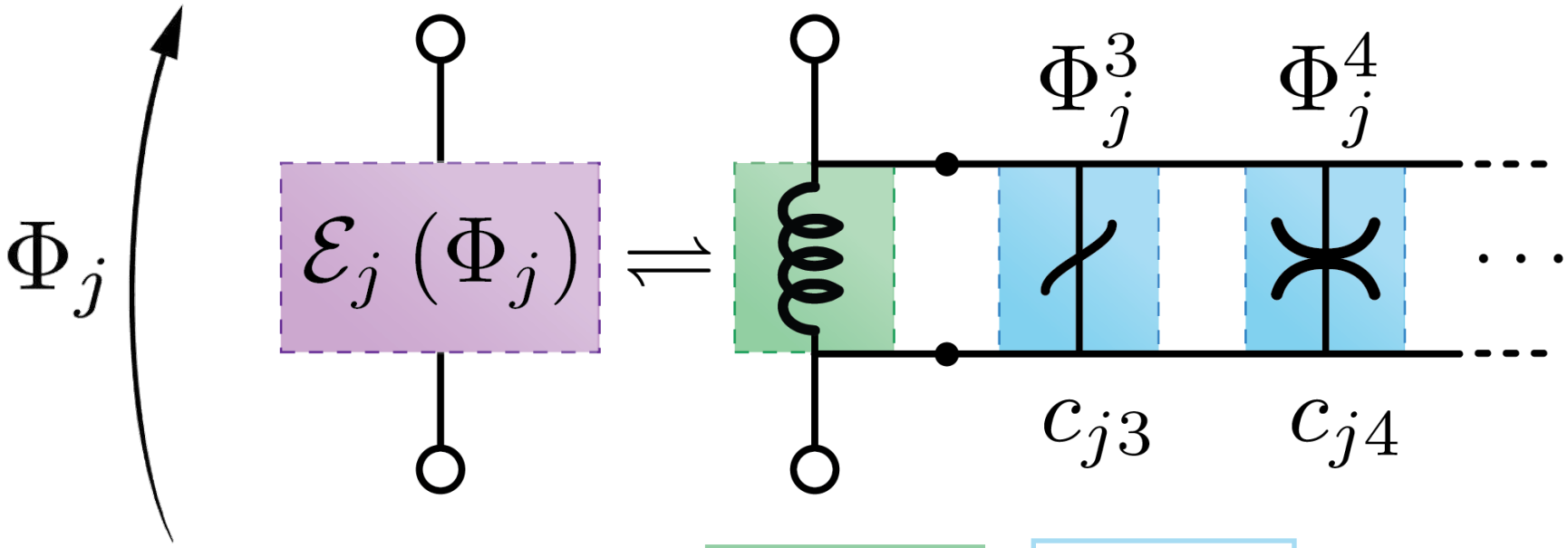


Energy function

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

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

General Josephson device



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

$$E_j \sum_{p=3}^{\infty} c_{jp} \left(\frac{\Phi_j}{\phi_0}\right)^p$$

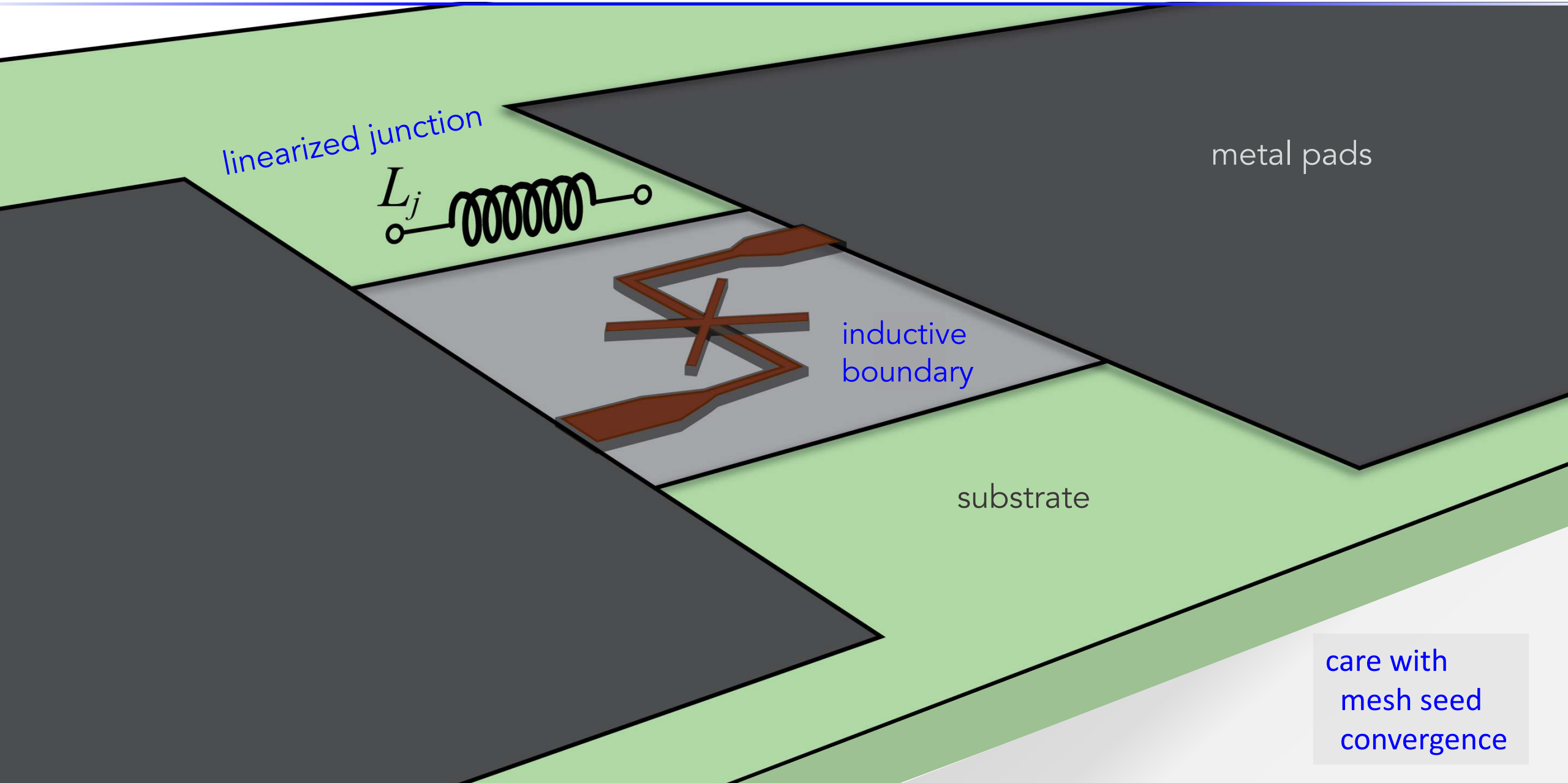
(expansion not necessary)

series with respect to operational equilibrium point

To do **quantum**,

start with **classical**

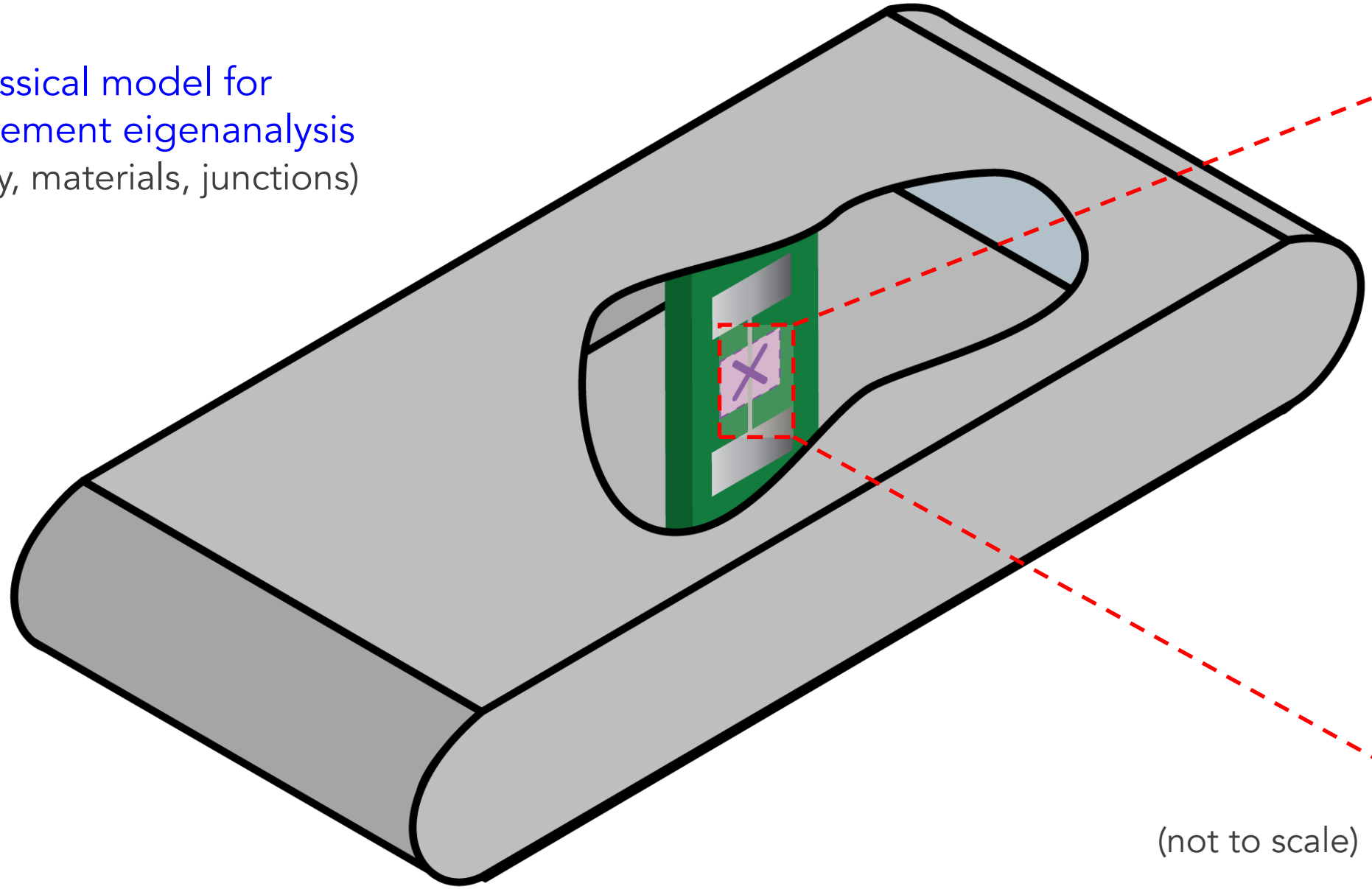
Finite-element model of linearized Junction



care with
mesh seed
convergence

Transmon qubit coupled to cavity

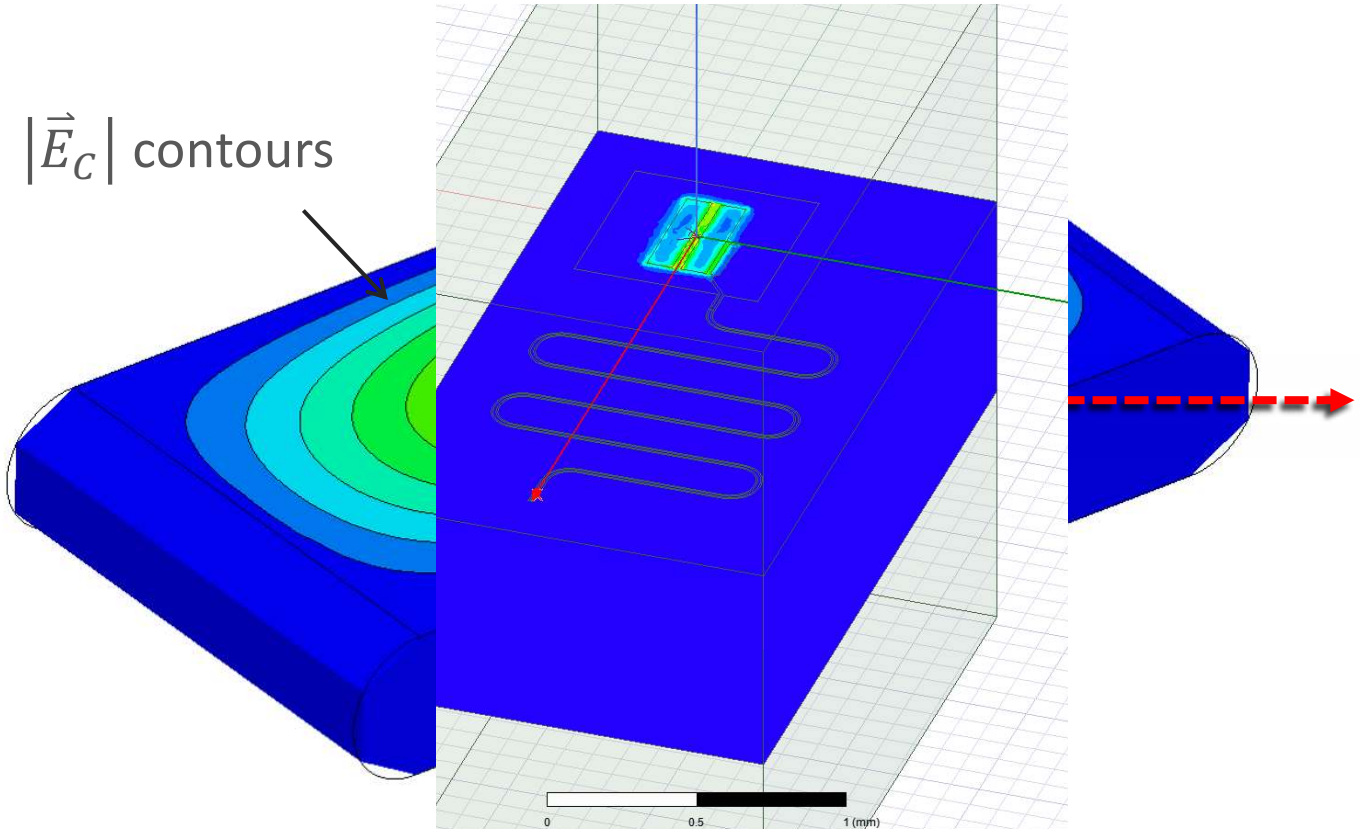
Classical model for
finite-element eigenanalysis
(geometry, materials, junctions)



(not to scale)

$\mathcal{H}_{\mathrm{lin}}$ eigen modes

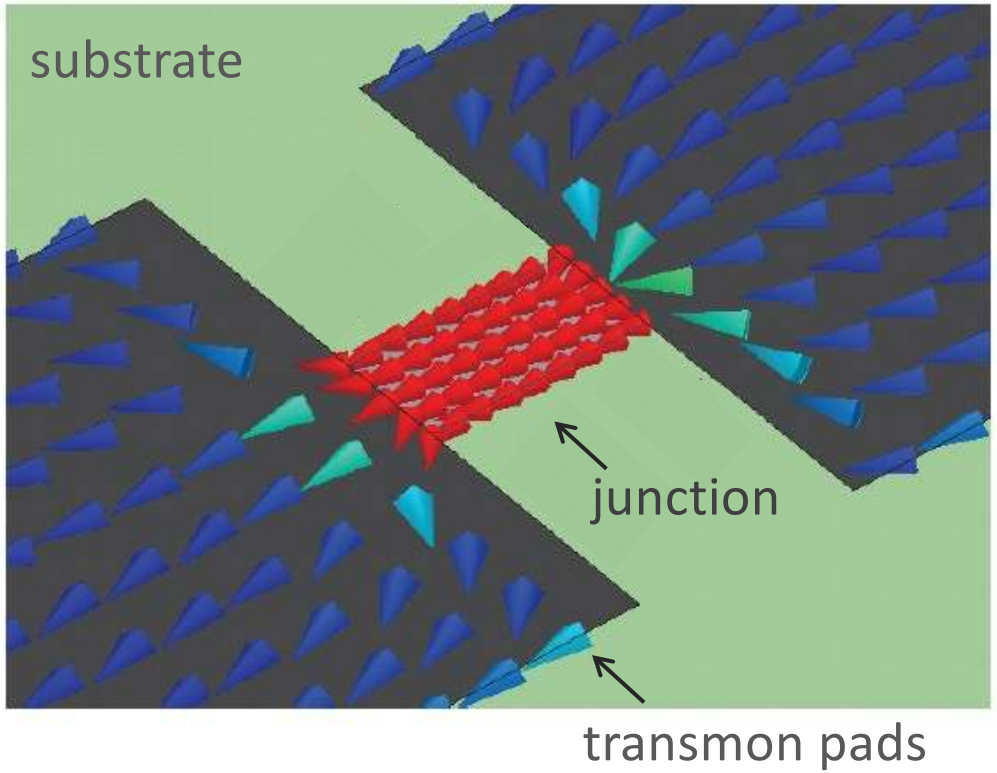
Cavity mode (7.0 GHz)



0 Max

E-field magnitude

Qubit mode (linearized, 5 GHz)



0 Max

Current-density magnitude

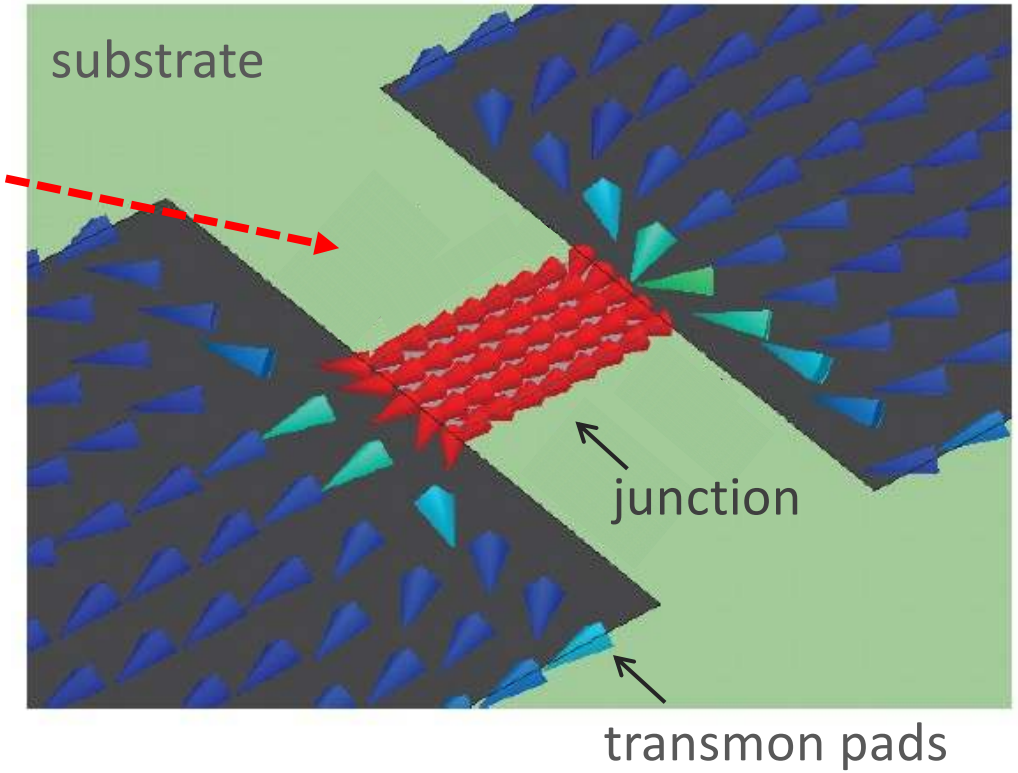
* Minev *et al.*, in prep. (2019) Impedances: Nigg *et al.*, PRL (2012); Bourassa *et al.* (2012); Solgun *et al.* (2014, 2015, 2017) …

Energy participation of the junction

$$p_m = \frac{\text{Energy stored in junction}}{\text{Inductive energy stored in mode } m}$$

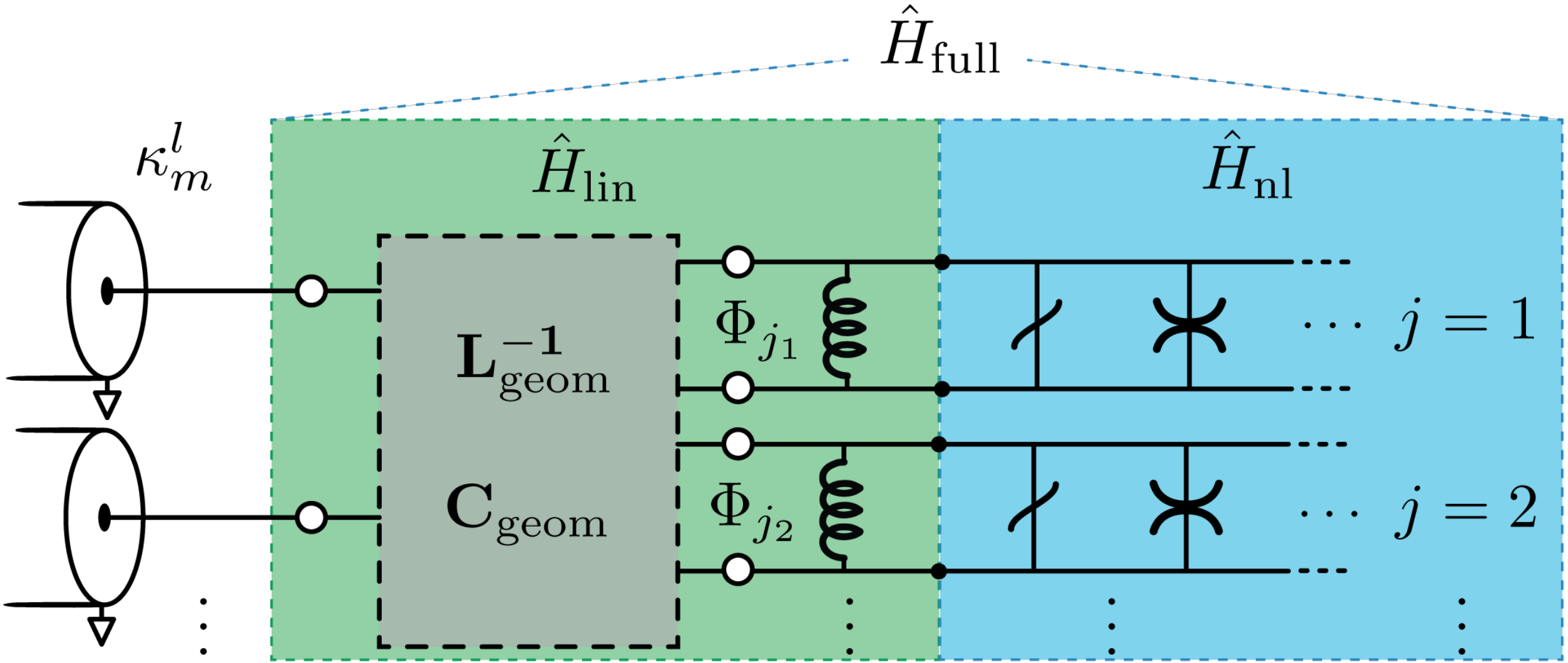
$$p_m = \frac{\frac{1}{2} L_j I_{j,m}^2}{\mathcal{E}_{ind,m}}$$

Qubit mode (linearized, 5 GHz)

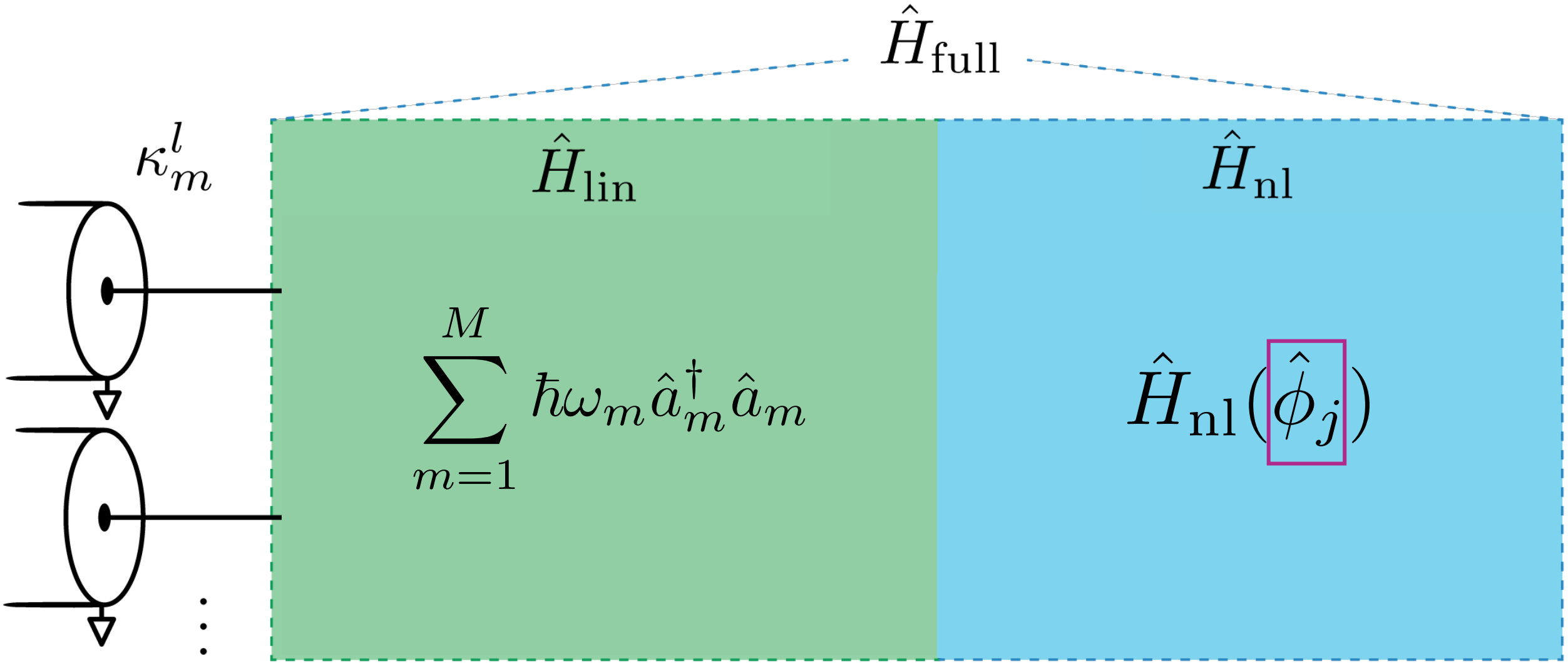


* Minev *et al.*, in prep. (2019)

Decomposition of a general circuit



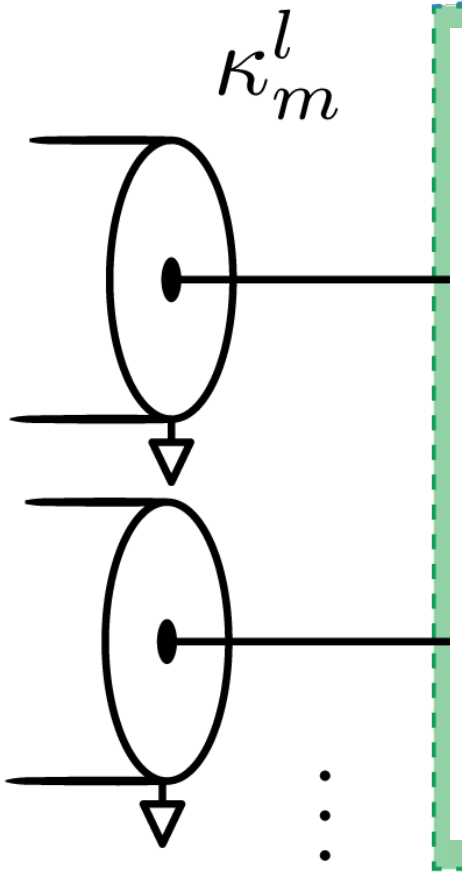
Decomposition of a general circuit



second quantization in eigen basis of linearized circuit

Decomposition of a general circuit

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

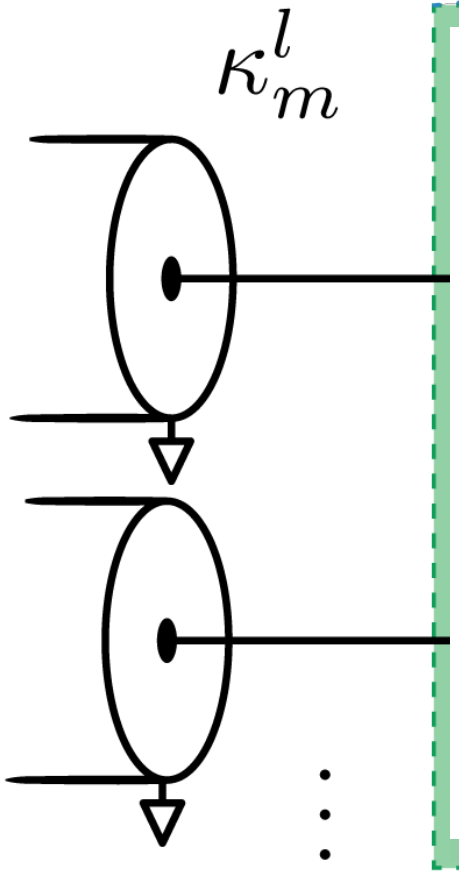


What is zero-point fluctuation of the phase of junction *j* due to mode *m*?

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

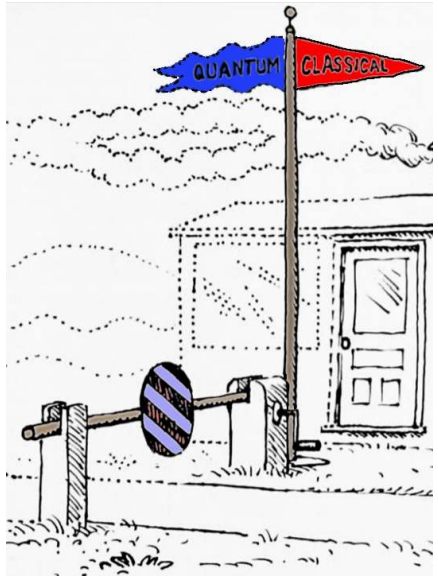
Decomposition of a general circuit

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



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

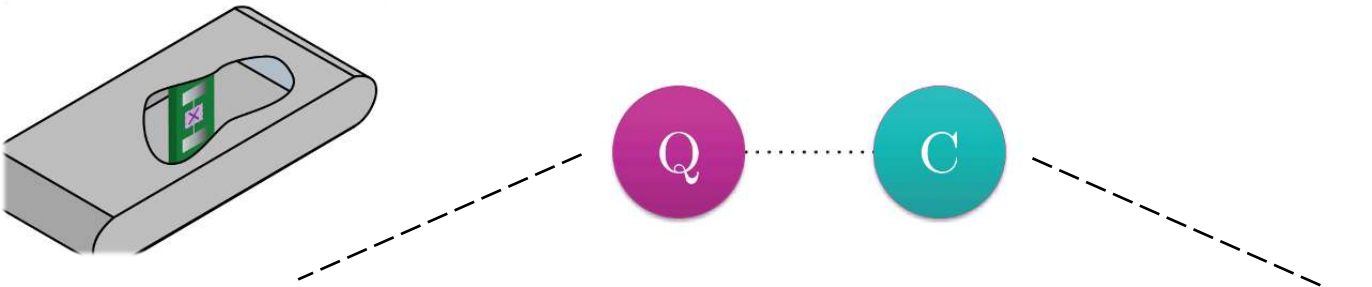
$$\frac{1}{\hbar}\phi_{mj}^2 = p_{mj}\frac{\omega_m}{2E_j}$$



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

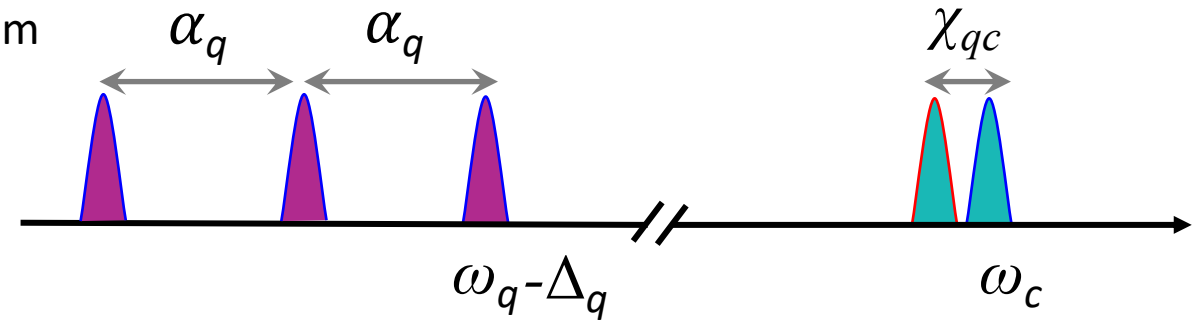
Drawing: Zurek, Physics Today (1991)

Quantum Hamiltonian from the EPR



$$\hat{H}_{\text{eff}} = (\omega_q - \Delta_q)\hat{n}_q + (\omega_c - \Delta_c)\hat{n}_c - \chi_{qc}\hat{n}_q\hat{n}_c - \frac{1}{2}\alpha_q\hat{n}_q\left(\hat{n}_q - \hat{1}\right) - \frac{1}{2}\alpha_c\hat{n}_c\left(\hat{n}_c - \hat{1}\right),$$

Transition spectrum



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

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

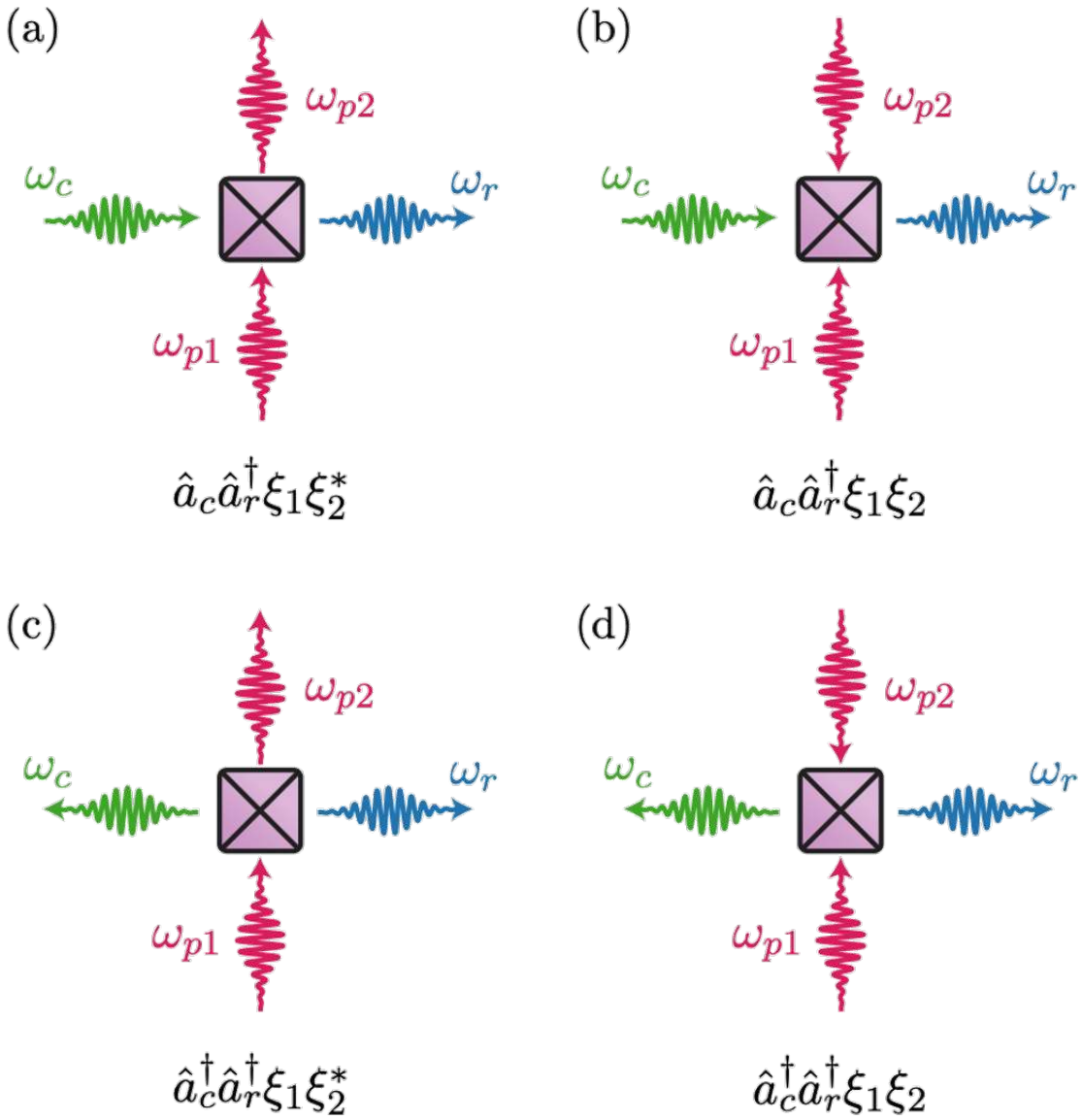
Qubit Lamb shift

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

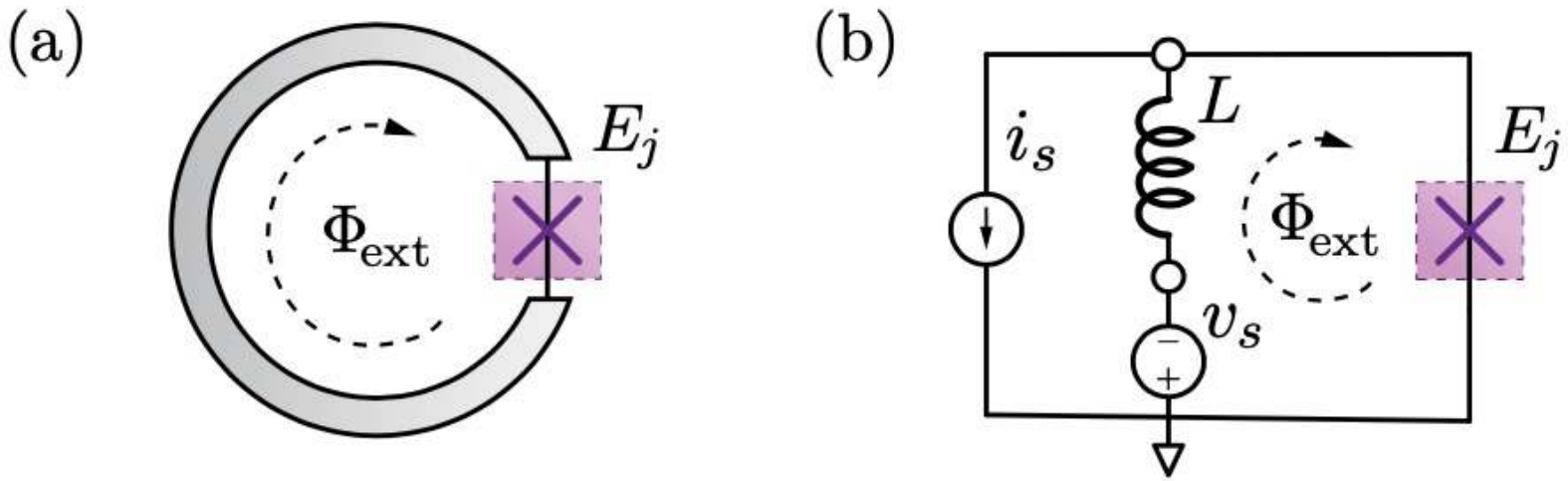
Reconstruct full Hamiltonian

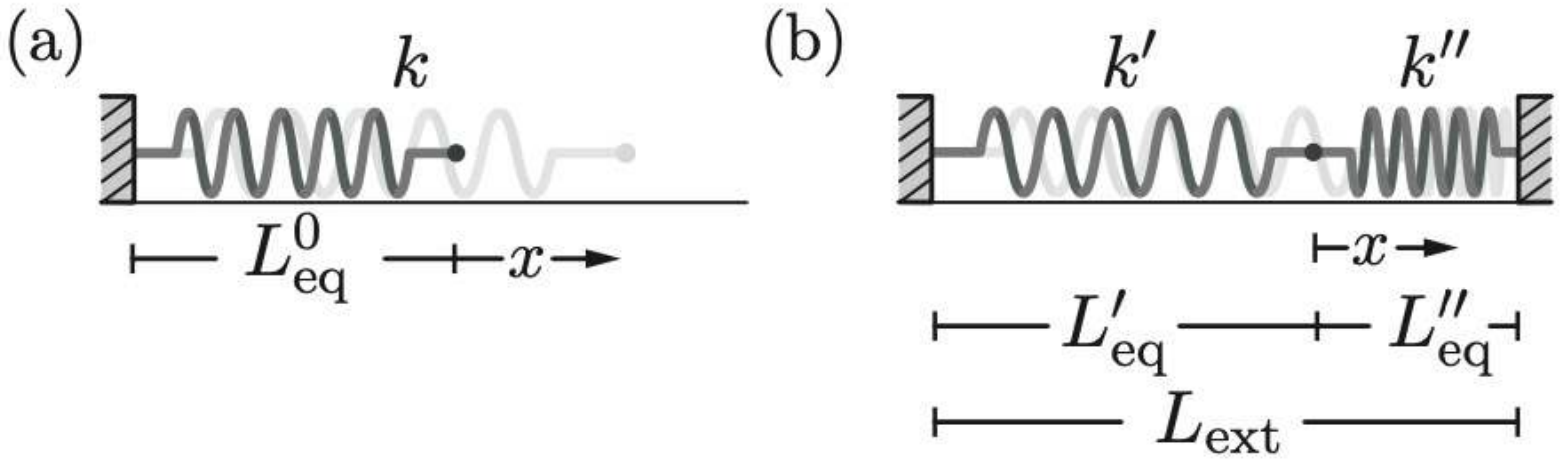
$$\sum_{m=1}^{M} \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m$$

$$+ \quad \hat{H}_{\mathrm{nl}}(\hat{\phi}_j)$$

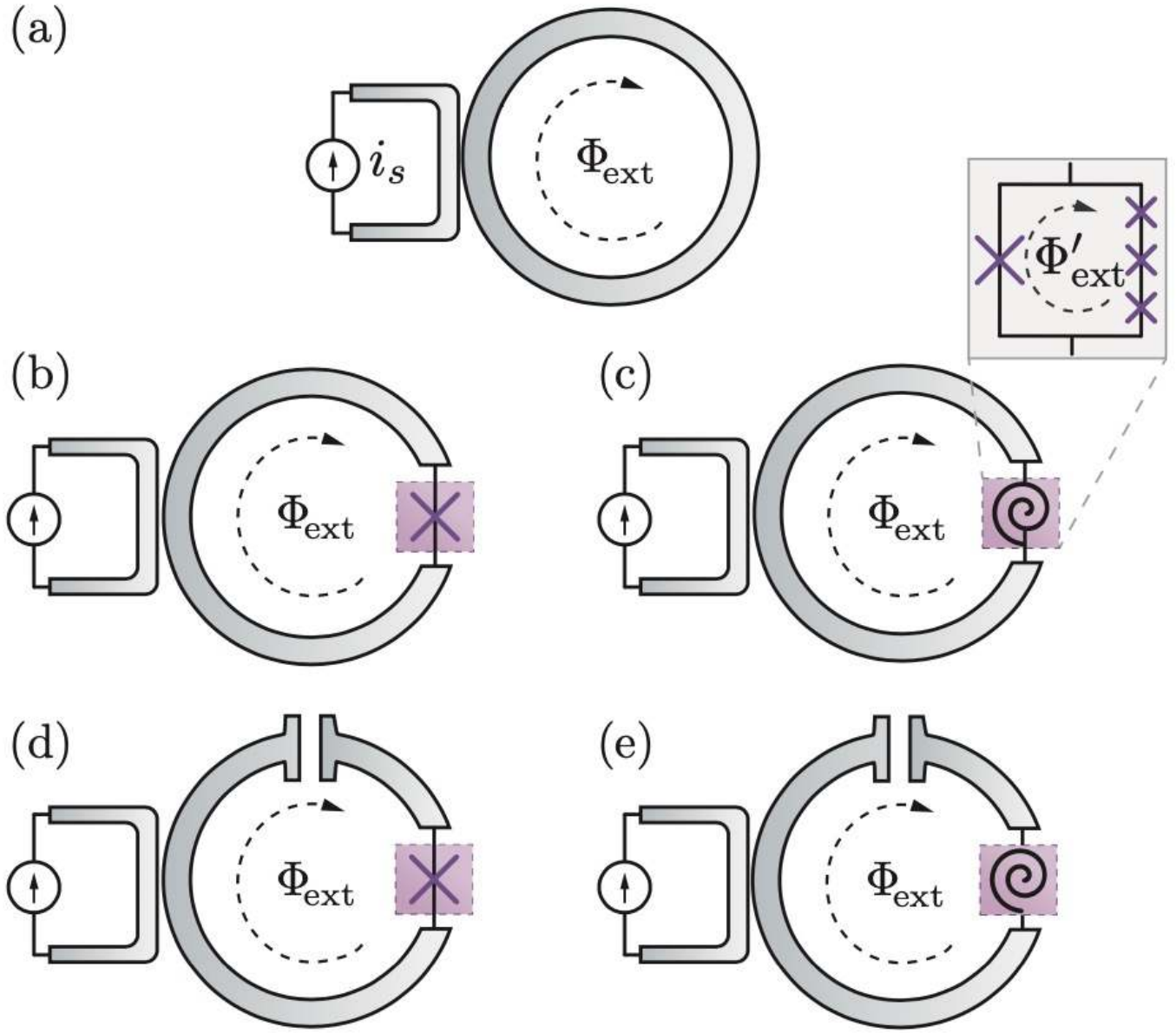


Flux conditions





Flux


(a)
i_s
Φ_{ext}
(b)
Φ_{ext}
(c)
Φ_{ext}
Φ'_{ext}
(d)
Φ_{ext}
(e)
Φ_{ext}

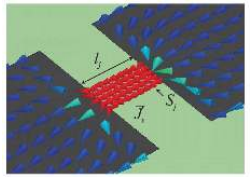
Universal EPR properties

ZPF are not independent of each other

The monogamy of EPR

Commandments of EPR
1. All modes and all dipole are created equal
2. Each dipole has exactly 1 EPR it must dilute among modes
3. Each mode receives exactly 1 EPR units

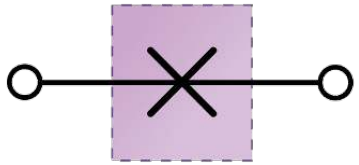
EPR



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

EPR is bounded

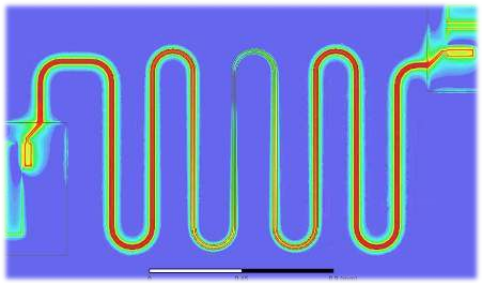
Non-linear dipole



$$\sum_{m=1}^{M} p_{mj} = 1 \quad \text{for } j \in \{1, \ldots, J\}$$

Every dipole comes w/ 1 unit of EPR

Mode



$$0 \leq \sum_{j=1}^{J} p_{mj} \leq 1 \quad \text{for } m \in \{1, \ldots, M\}$$

Every mode accepts at most 1 total unit of EPR

Orthogonality

$$\sum_{m=1}^{M} s_{mj} s_{mj'} \sqrt{p_{mj} p_{mj'}} = 0 \quad \text{for } j \neq j'$$

For a dipole, its EPRs across all modes are orthogonal

Dissipation budget & EPR

Coherence in superconducting circuits

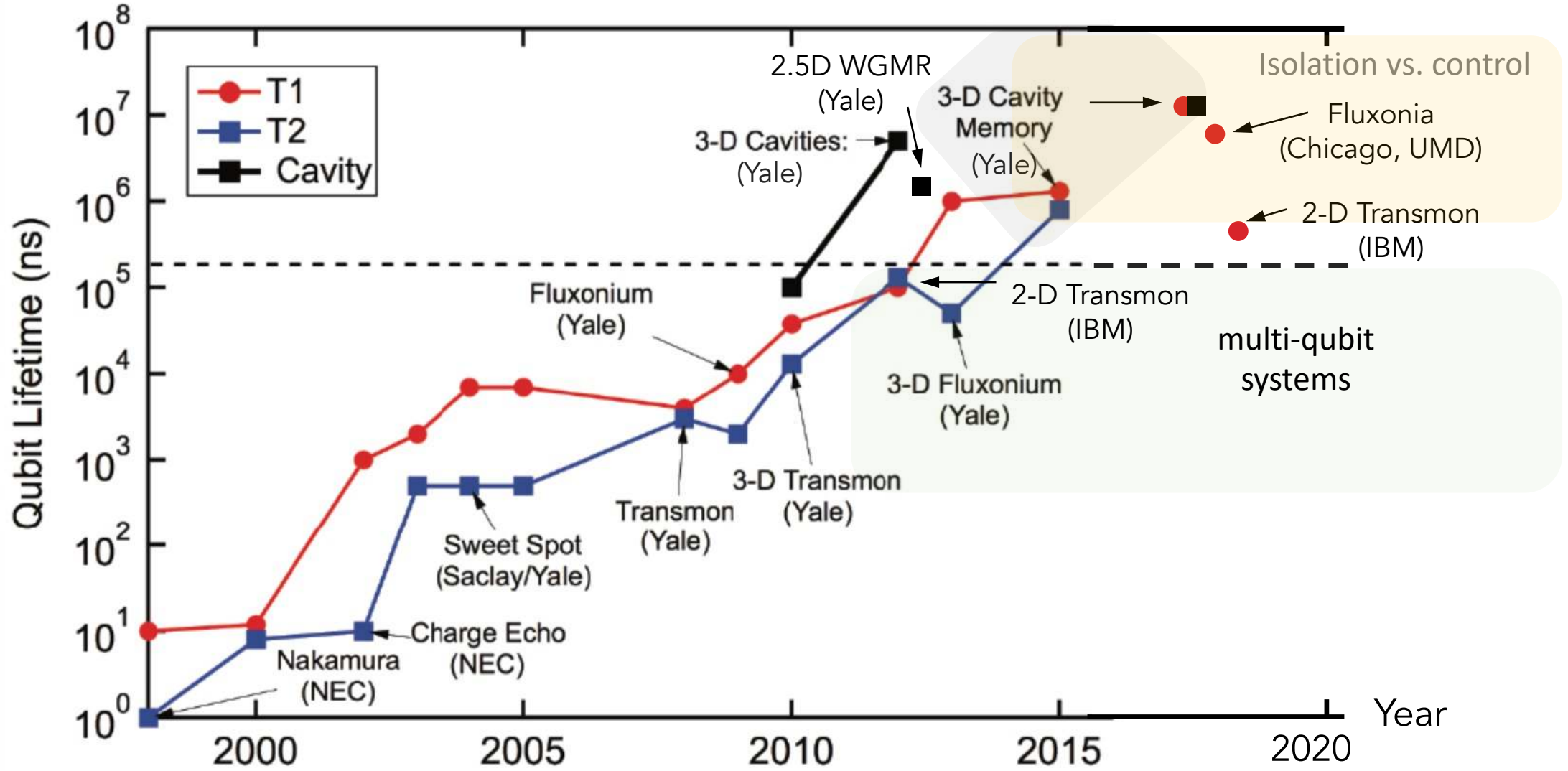
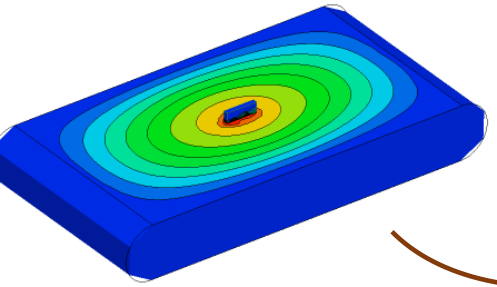
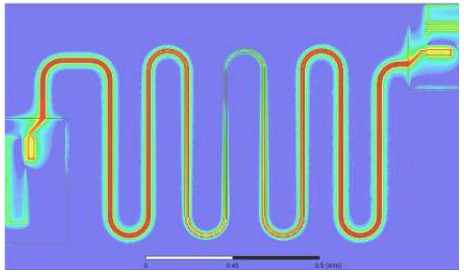


Image reproduced Reagor (2015), an update of Devoret and Schoelkopf (2013), and updated

Dissipation budget and the energy-participation ratio (EPR)





Quality factor of mode *m*

EPR of lossy element *l* in mode *m* (design)

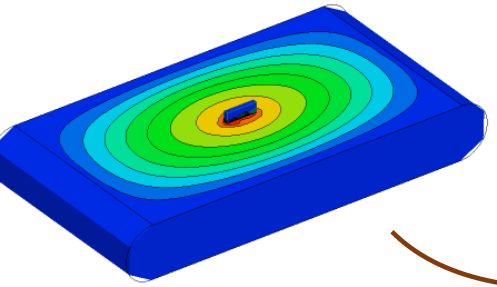
Quality of lossy element *l* (material property)

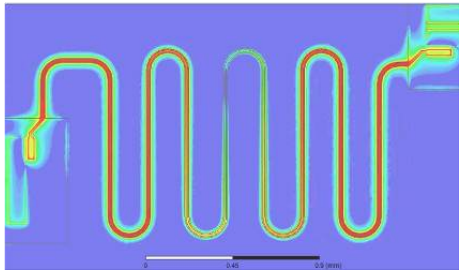
$$Q_{\mathrm{total},m}^{-1} = \sum_l p_{ml} Q_l^{-1}$$

$$= \frac{1}{Q_{\mathrm{cap}}} + \frac{1}{Q_{\mathrm{ind}}} + \frac{1}{Q_{\mathrm{rad}}}$$

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), …

Lossy energy-participation ratios (EPRs)





Capacitive

bulk

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

surface

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

Inductive

bulk

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

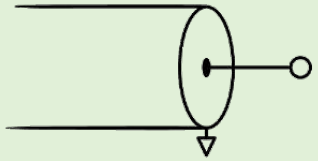
surface

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

seam

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

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), …

EPR theory vs. experiment

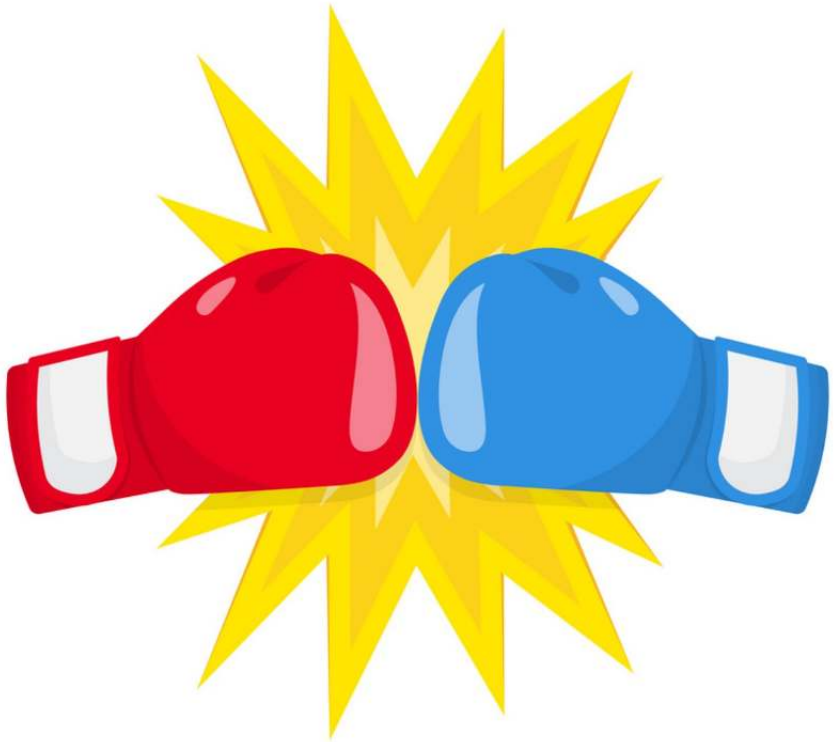
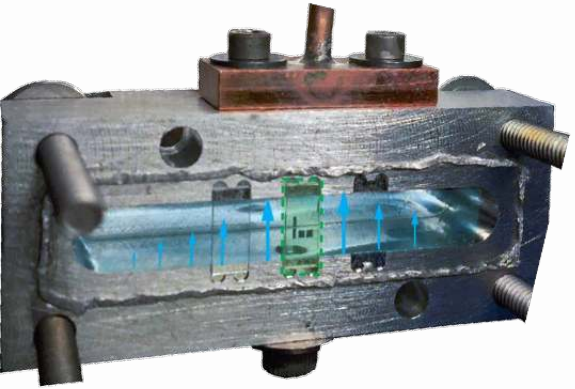
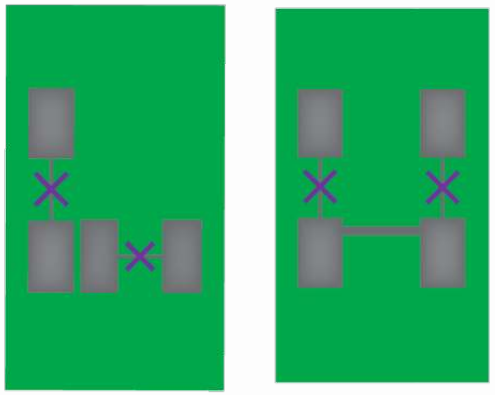


image: makc76

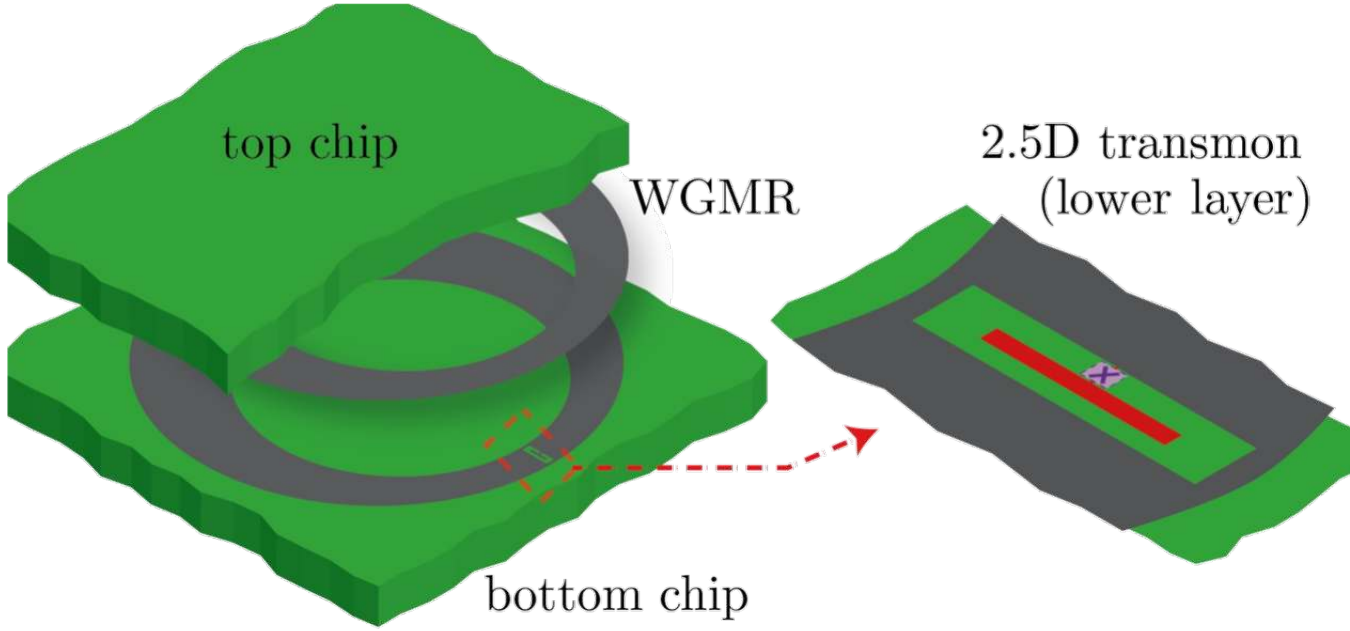
First set of measured architectures and devices

Three-dimensional (3D) *



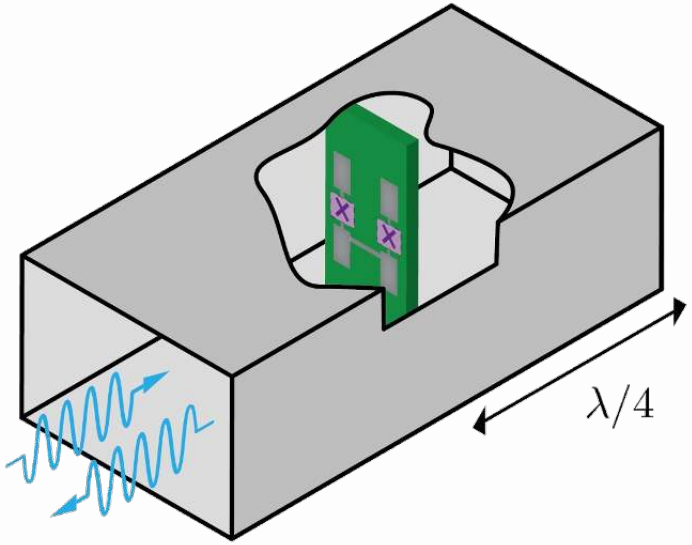


Multilayer (2.5D) cQED



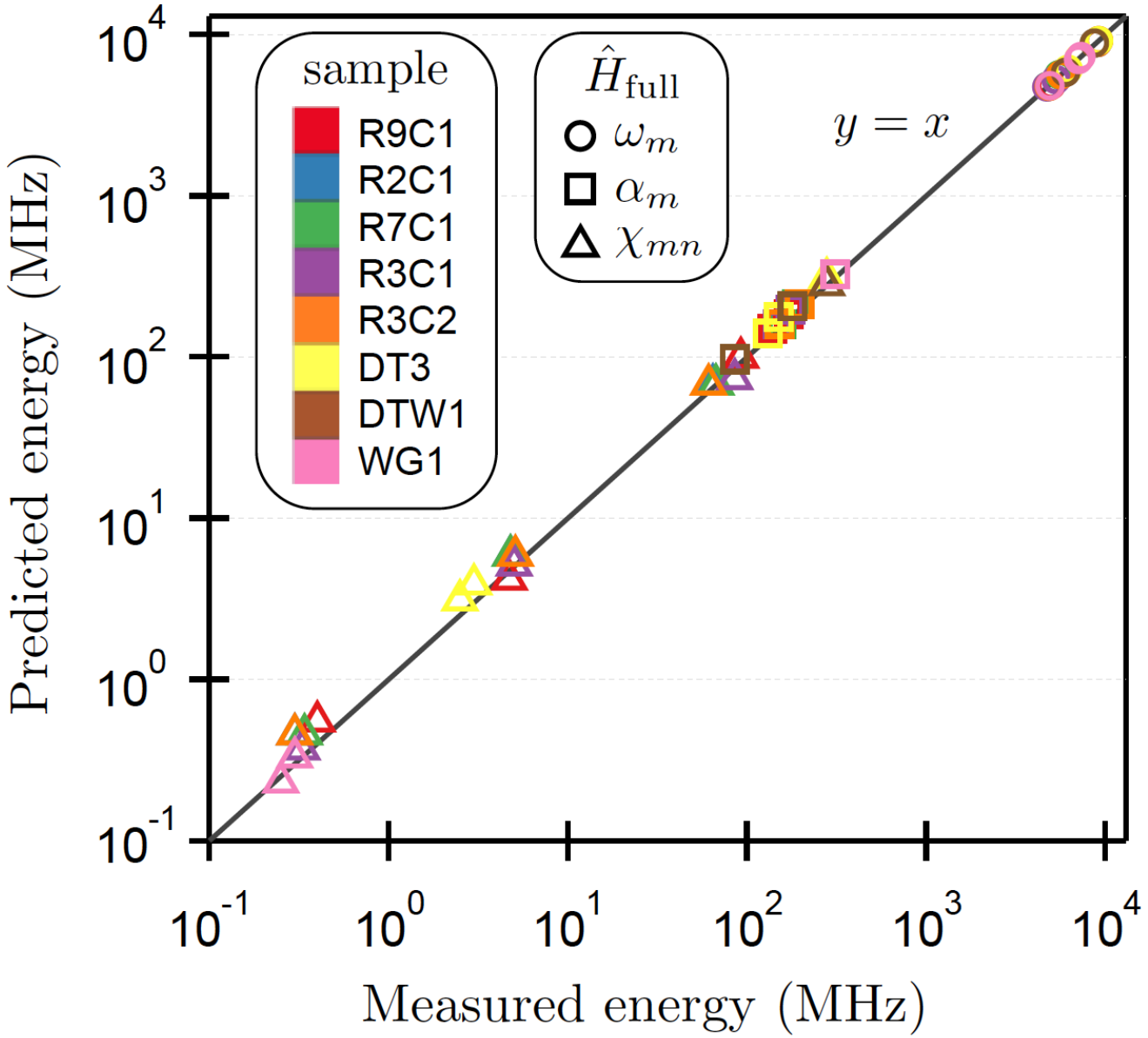
Minev *et al.*, APL (2013)
Minev *et al.*, WO/2016/138395 (2015)
Minev *et al.*, Phys. Rev. App. (2016)

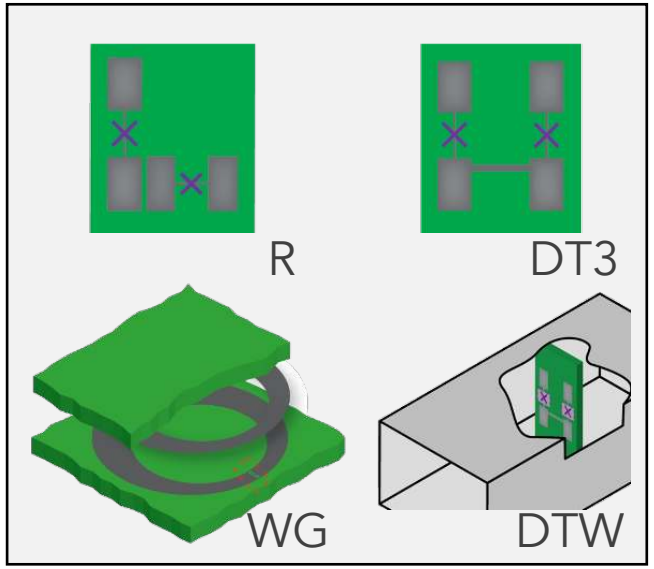
Waveguide



* Minev *et al.*, arXiv:1803.00545 (2018); Related: Gambetta *et al.*, PRL (2011), Srinivasan *et al.*, PRL (2011), Dumur *et al.*, PRB (2015), Zhang *et al.*, Nature JQI (2017) …

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

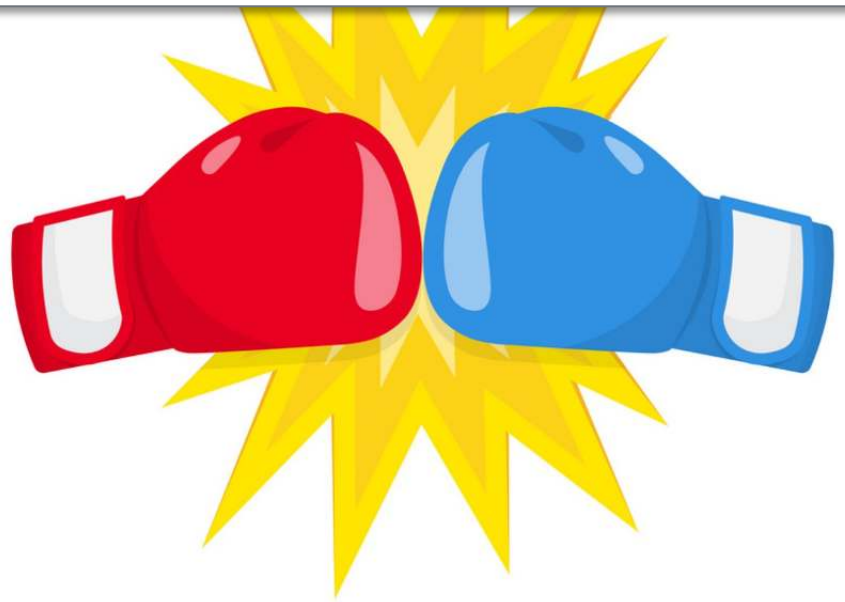
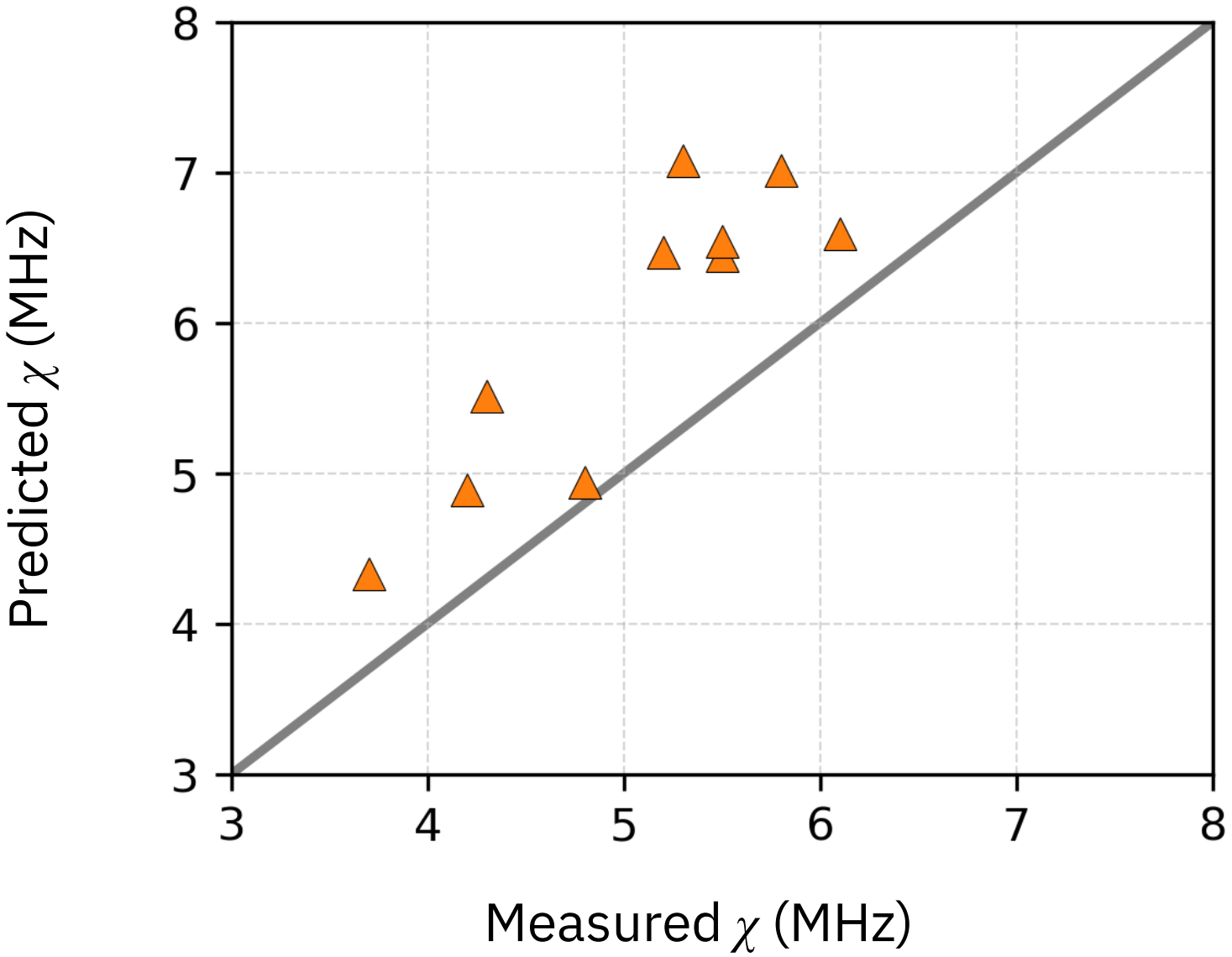
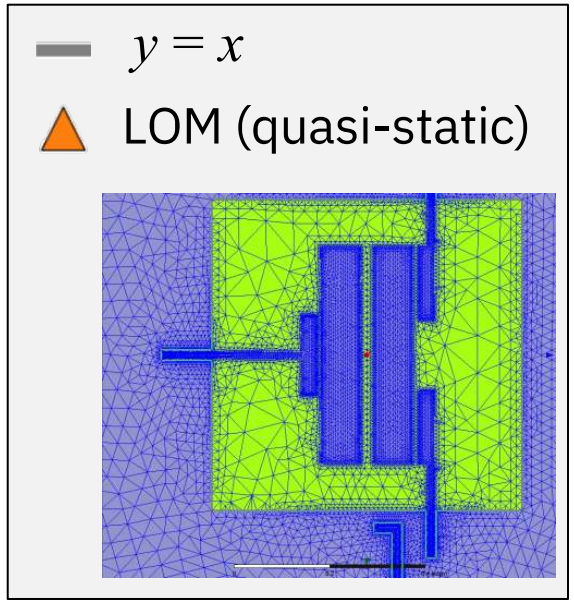


image: makc76

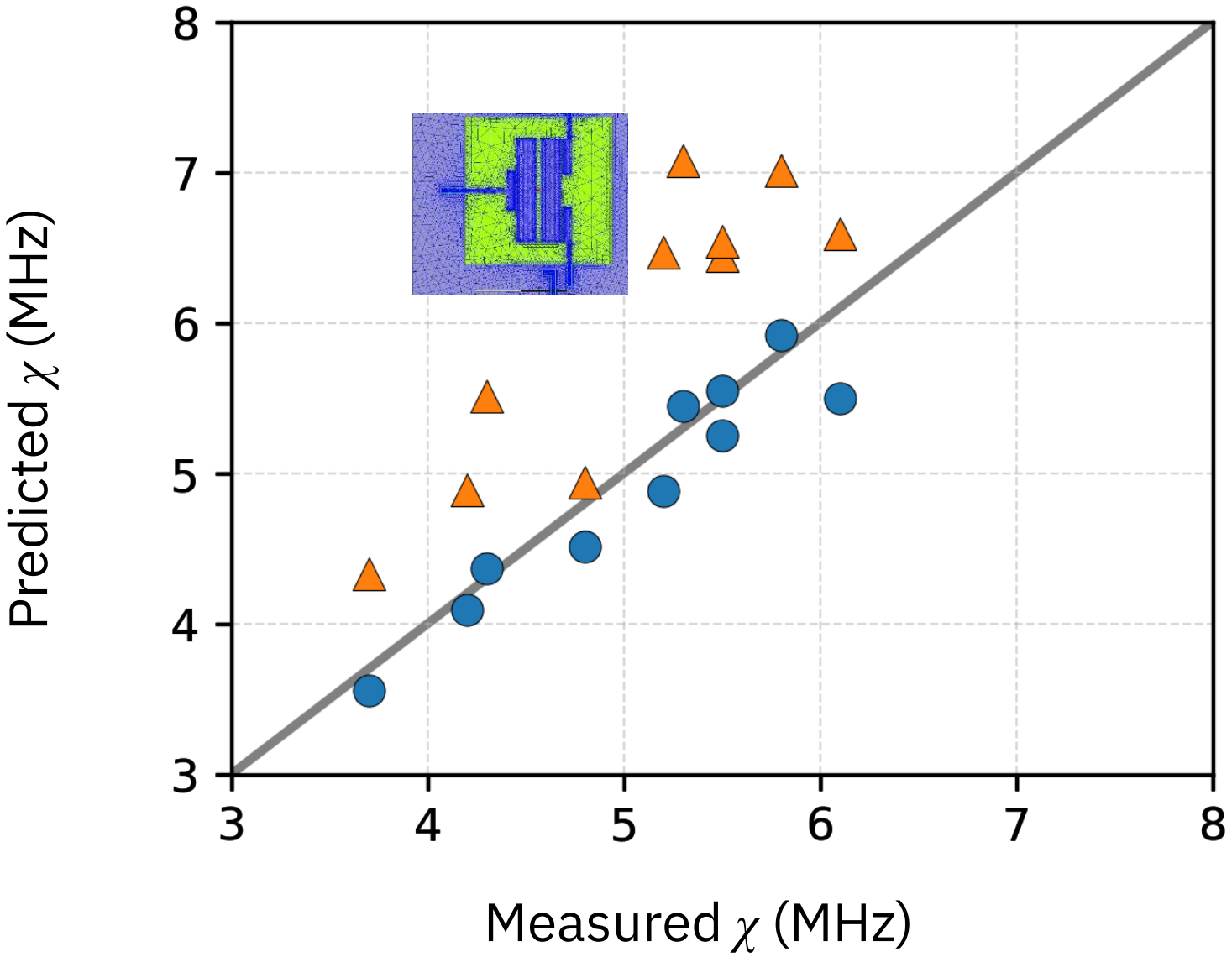
Measured vs. predicted: qubit-readout cross-Kerr

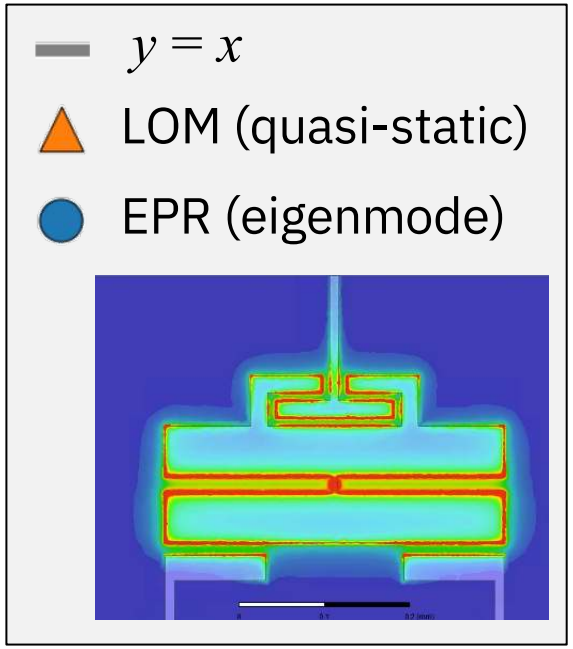




Marker size indicates error bars.

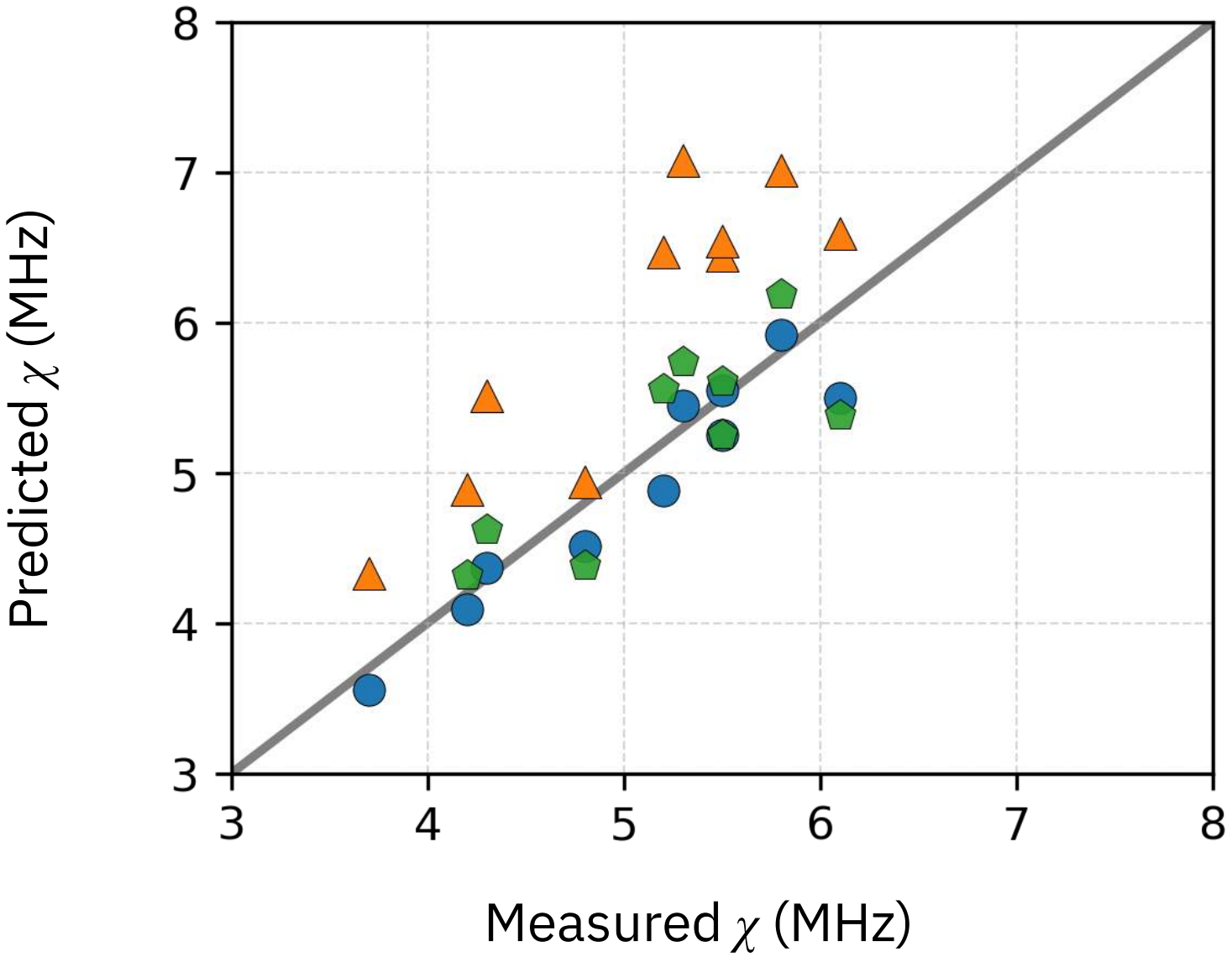
Measured vs. predicted: qubit-readout cross-Kerr

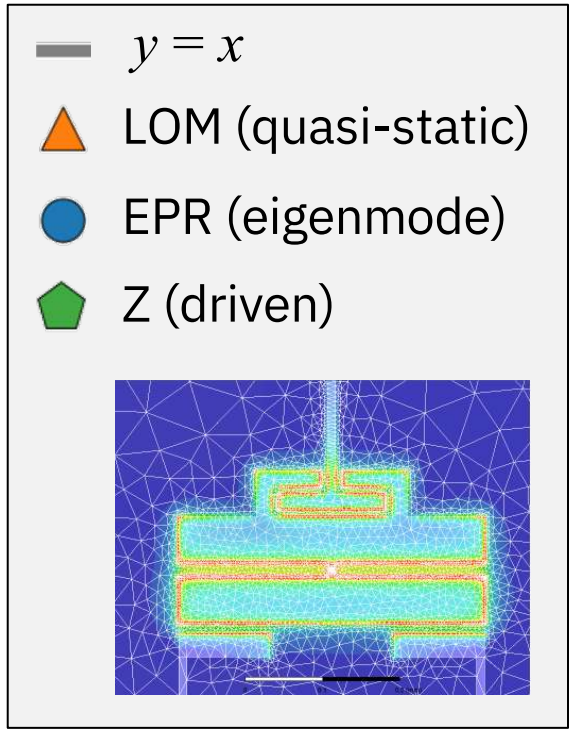




Marker size indicates error bars.

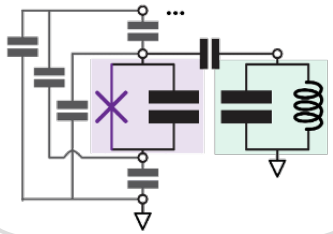
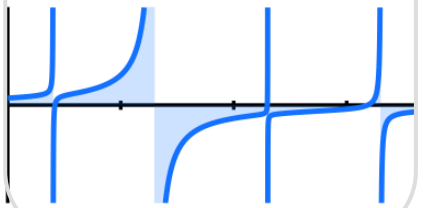
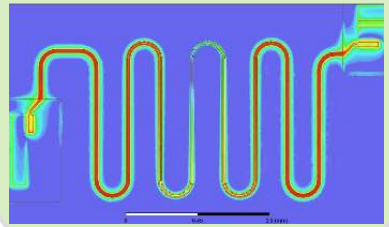
Measured vs. predicted: qubit-readout cross-Kerr



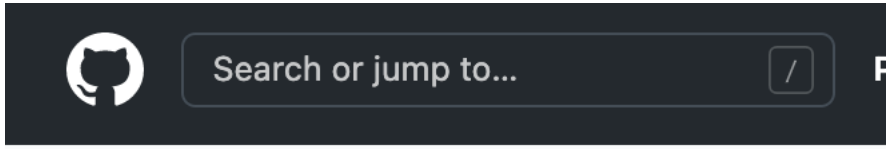


Marker size indicates error bars.

Quantization approaches

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

* includes dissipative params



zlatko-minev / pyEPR

Welcome to pyEPR 🍻! (see arXiv:2010.00620)

Automated Python module for the design and quantization of Josephson quantum circuits

pyEPR Working group meeting -- Planning for the future of pyEPR

- Please sign-up here: https://github.com/zlatko-minev/pyEPR/issues/45 or directly here ‼️ 🍻
- See pyEPR wiki for notes from first meeting.
- We will schedule a follow-up meeting in 1-2 mo.

Who uses pyEPR?

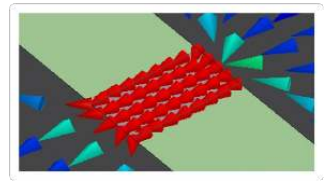
- Yale University, Michel Devoret lab QLab, CT, USA
- Yale University, Rob Schoelkopf lab RSL, CT, USA
- IBM Quantum
- QUANTIC (QUANTUM INFORMATION CIRCUITS), PARISINRIA, ENS, MINES PARISTECH, Groups of Zaki Leghtas and team. France
- Quantum Circuit Group Benjamin Huard, Ecole Normale Supérieure de Lyon, France
- Emanuel Flurin, CEA Saclay, France
- Ioan Pop group, KIT Physikalisches Institut, Germany
- UC Berkeley, Quantum Nanoelectronics Laboratory, Irfan Siddiqi, CA, USA
- Quantum Circuits, Inc., CT, USA
- Seeqc (spin-out of Hypres) Digital Quantum Computing, USA
- Serge [Rosenblum Lab] quantum circuits group (https://www.weizmann.ac.il/condmat/rc Weizmann Instatue, Israel
- University of Oxford - LeekLab - Peter Leek Lab, UK
- Britton Plourde Lab, Syracuse University, USA
- Javad Shabani Lab Quantum Materials & Devices, NYU, NY, USA
- UChicago Dave Schuster Lab, USA
- SQC lab - Shay Hacohen Gourgy, Israel
- Lawrence Berkeley National Lab
- Colorado School of Mines, USA
- Syracuse University, USA
- IPQC, SJTU, Shanghai, China
- Bhabha Atomic Research Centre, India
- Quantum Computing UK
- Alice&Bob, France
- Centre for Quantum Technologies / Qcrew
- Quantum Device Lab ETHZ; Andreas Wallraff
- ... and many more! (Please e-mail `zlatko.minev@aya.yale.edu` with updates.)

Energy-Participation-Ratio (EPR) Approach

Simple and unified analysis of dissipation and Hamiltonian

single-simulation efficient

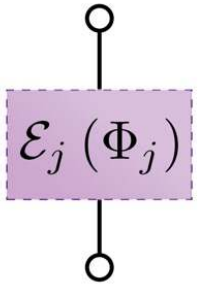
obviate driven simulations and notion of $Z_{ij}(\omega)$



General

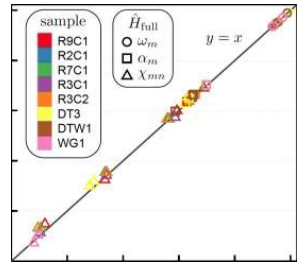
handle arbitrary architectures and non-linear devices

e.g., nanowires, …



Accuracy

experimental ten to percent level over 5 orders in $\widehat{H}_{\mathrm{full}}$

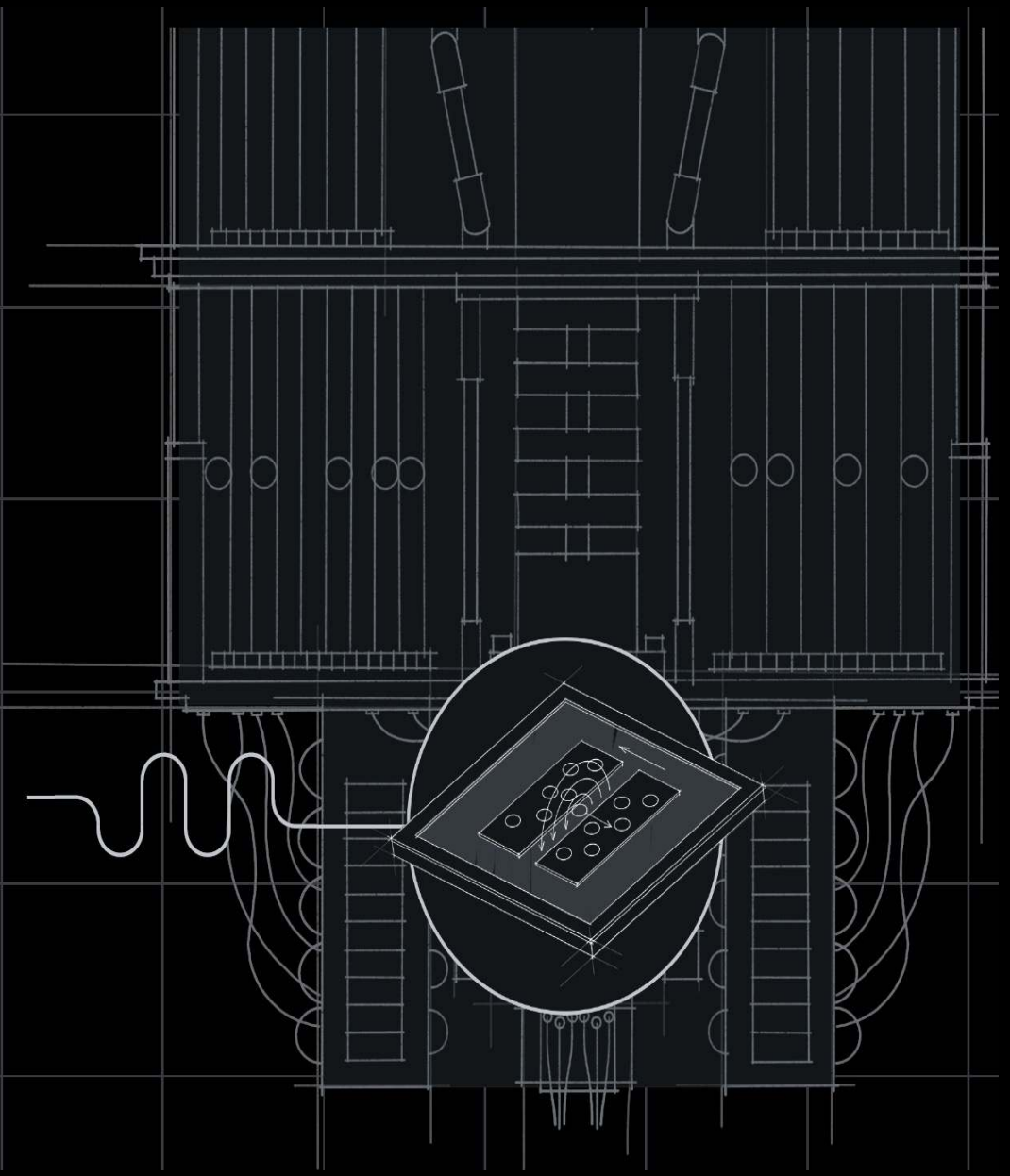


Suited for automated, robust analysis of large systems

fully automated and tested (see GitHub)

arXiv:1902.10355 (Ch. 4);

Application to *J* and CR gate, …



Qiskit | quantum device design

Qiskit | quantum device design

github.com/Qiskit/qiskit-metal

slack: #qiskit-metal-early-access

Project Metal

qiskit.org/metal

Open source
Early-access program (alpha version)

Zlatko Minev
PI & Lead

Thomas McConkey

Grace Harper

Priti Shah

John Blair

Dennis Wang

Marco Facchini

Jeremy Drysdale

Will Shanks

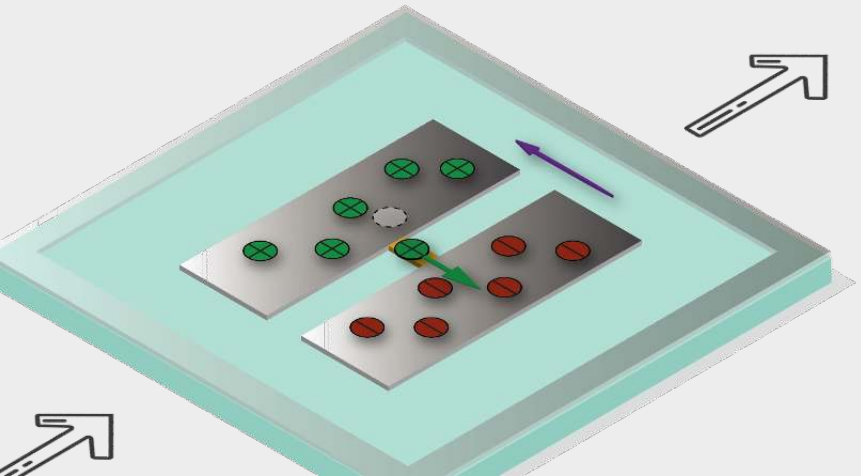
Olivia Lanes

Power-Ups:

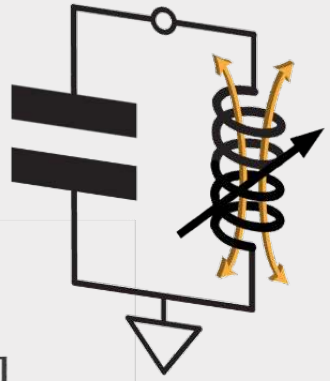
Close collab.:

Quantum Device Design

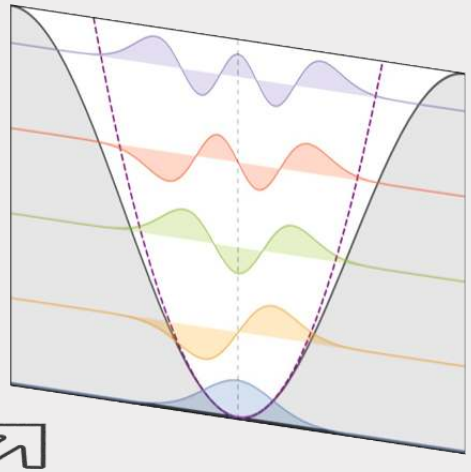
Superconducting circuits



Physical layout



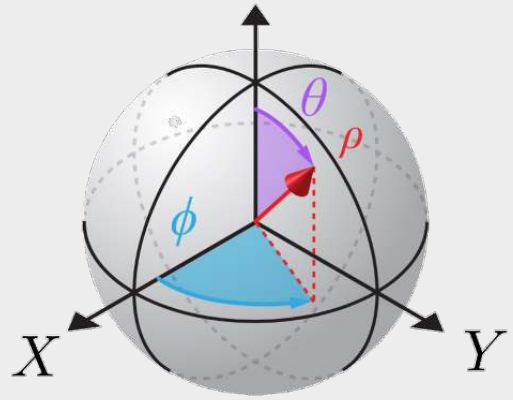
Electromagnetic analysis



Quantum Hamiltonian analysis

$$\hat{H}_{\text{full}} = \sum_m (\omega'_m - i\kappa_m)\hat{a}_m^\dagger \hat{a}_m + \sum_{\boldsymbol{\alpha},\boldsymbol{\beta}} C^p_{\boldsymbol{\alpha},\boldsymbol{\beta}} \prod_{m,n} \hat{a}_m^{\dagger\beta_m} \hat{a}_n^{\alpha_n}$$

$\chi, \delta, \alpha, \ldots$



Qubit Hilbert space

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

Qubit layout

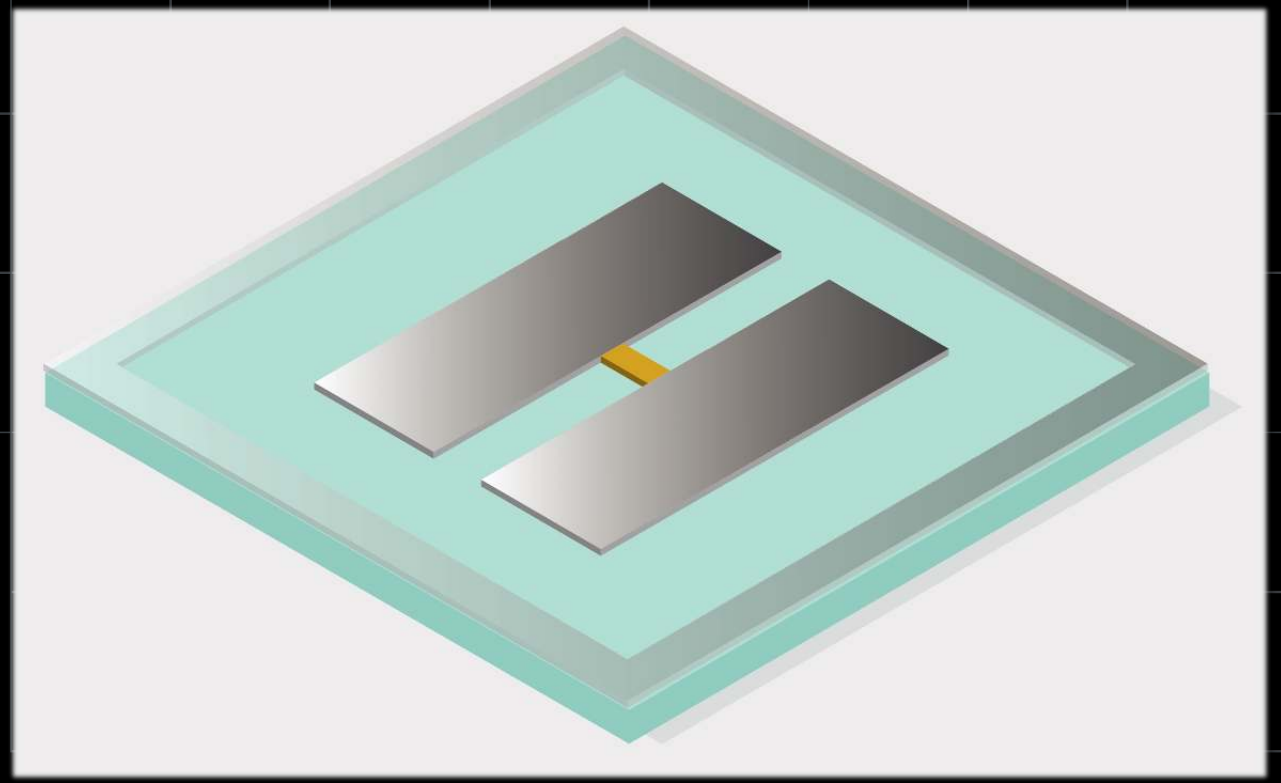
with project Qiskit Metal

qiskit.org/metal

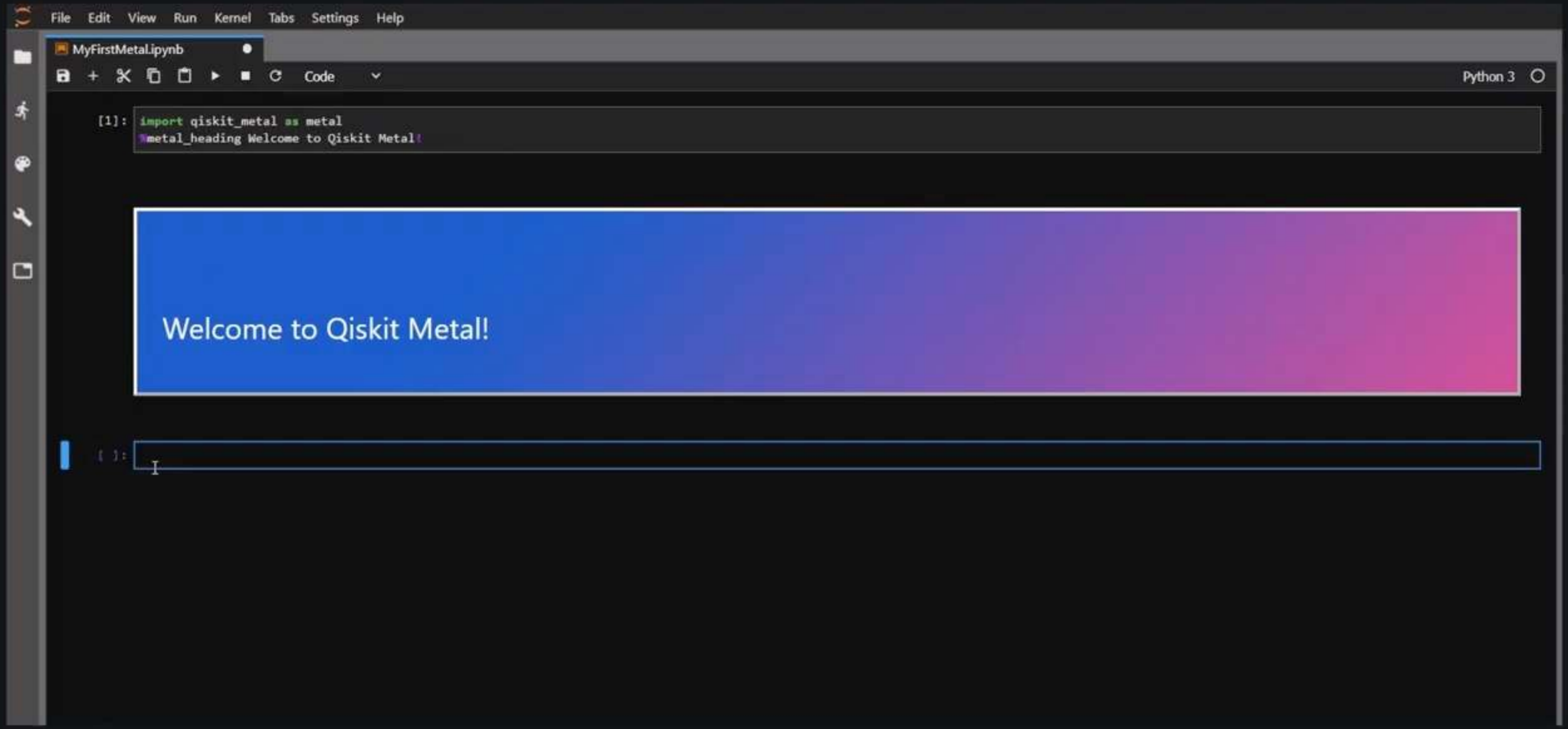
Create a transmon qubit

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

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

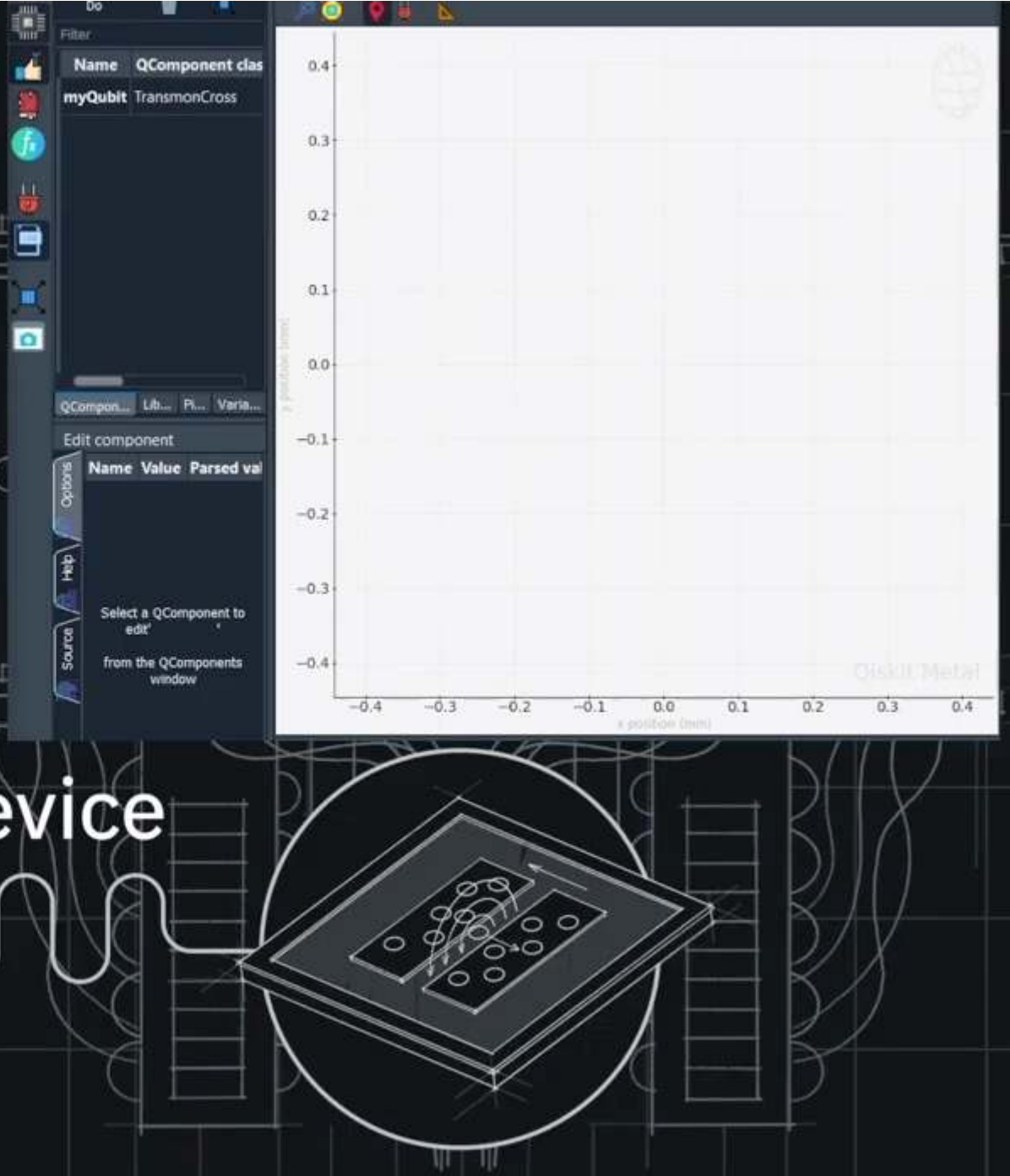


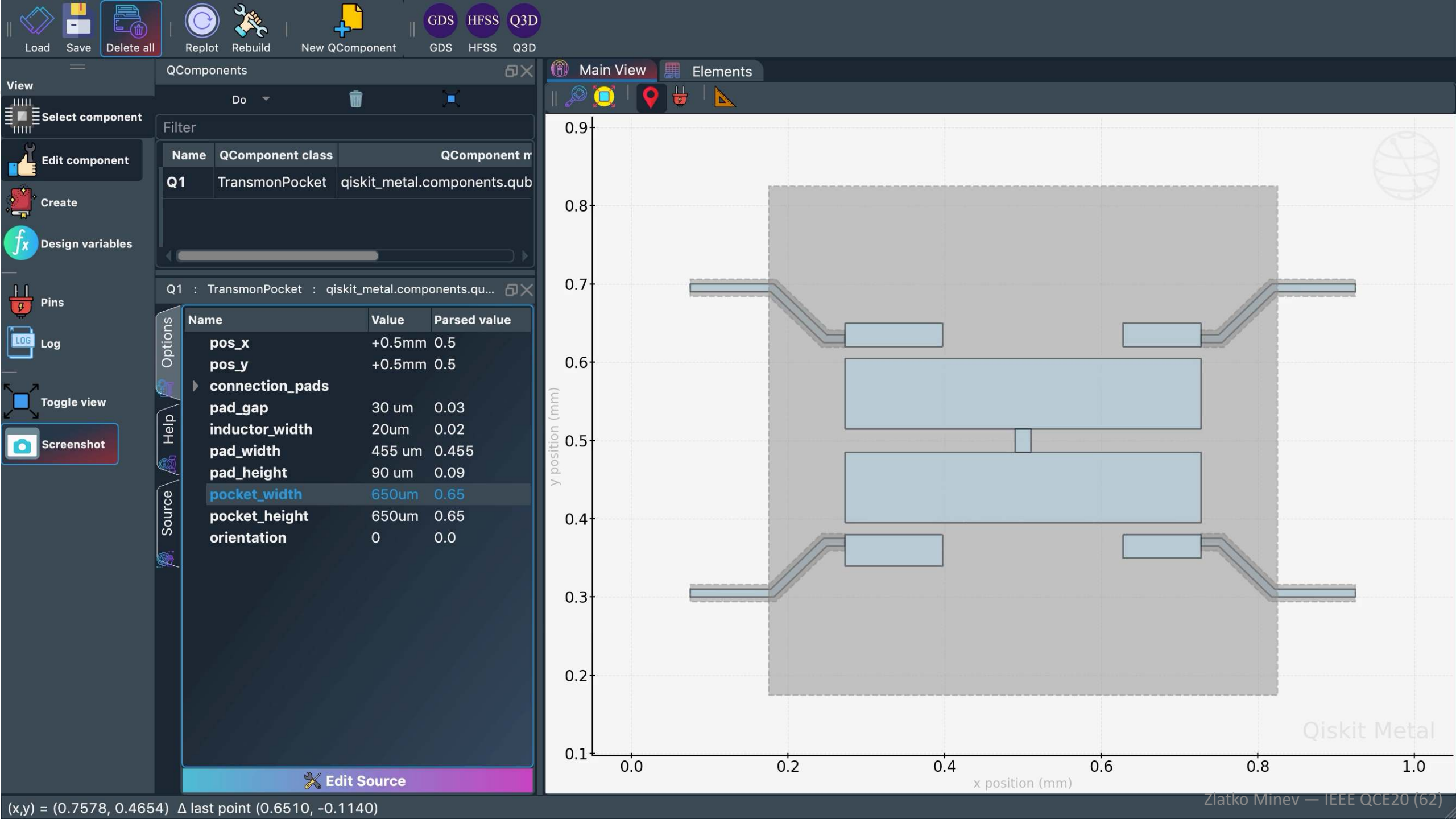
qiskit.org/metal

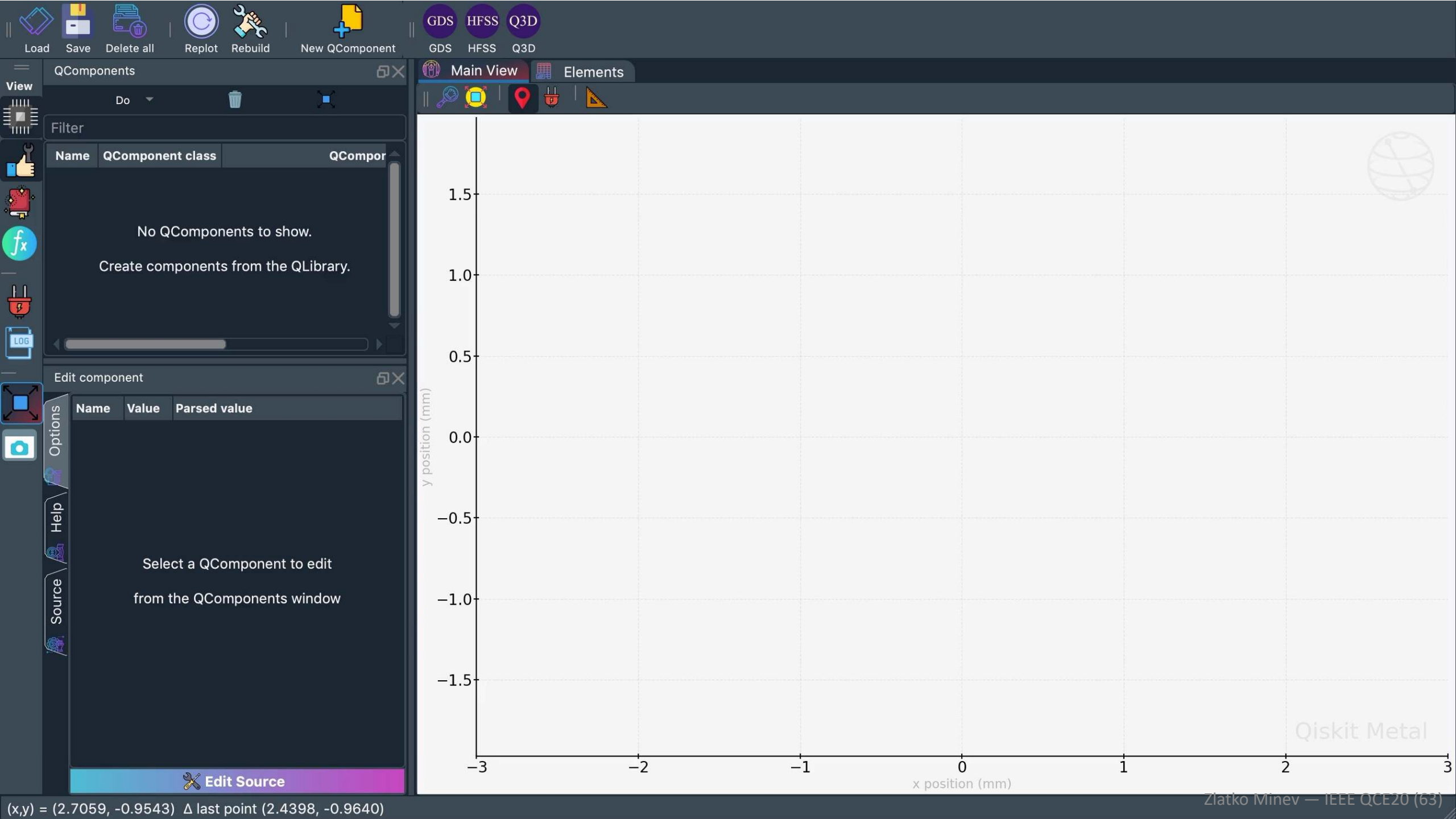

File Edit View Run Kernel Tabs Settings Help
MyFirstMetal.ipynb
Code
Python 3
[1]:
import qiskit_metal as metal
%metal_heading Welcome to Qiskit Metal!
Welcome to Qiskit Metal!
[ ]:

Qiskit | quantum device design

qiskit.org/metal




Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
View
Select component
Edit component
Create
Design variables
Pins
Log
Toggle view
Screenshot
QComponents
Do
Filter
Name
QComponent class
QComponent m
Q1
TransmonPocket
qiskit_metal.components.qub
Q1 : TransmonPocket : qiskit_metal.components.qu...
Options
Help
Source
Name
Value
Parsed value
pos_x +0.5mm 0.5
pos_y +0.5mm 0.5
connection_pads
pad_gap 30 um 0.03
inductor_width 20um 0.02
pad_width 455 um 0.455
pad_height 90 um 0.09
pocket_width 650um 0.65
pocket_height 650um 0.65
orientation 0 0.0
Edit Source
Main View
Elements
y position (mm)
x position (mm)
Qiskit Metal
(x,y) = (0.7578, 0.4654) Δ last point (0.6510, -0.1140)
Zlatko Minev — IEEE QCE20 (62)


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
Options
Help
Source
Name
Value
Parsed value
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 (63)

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

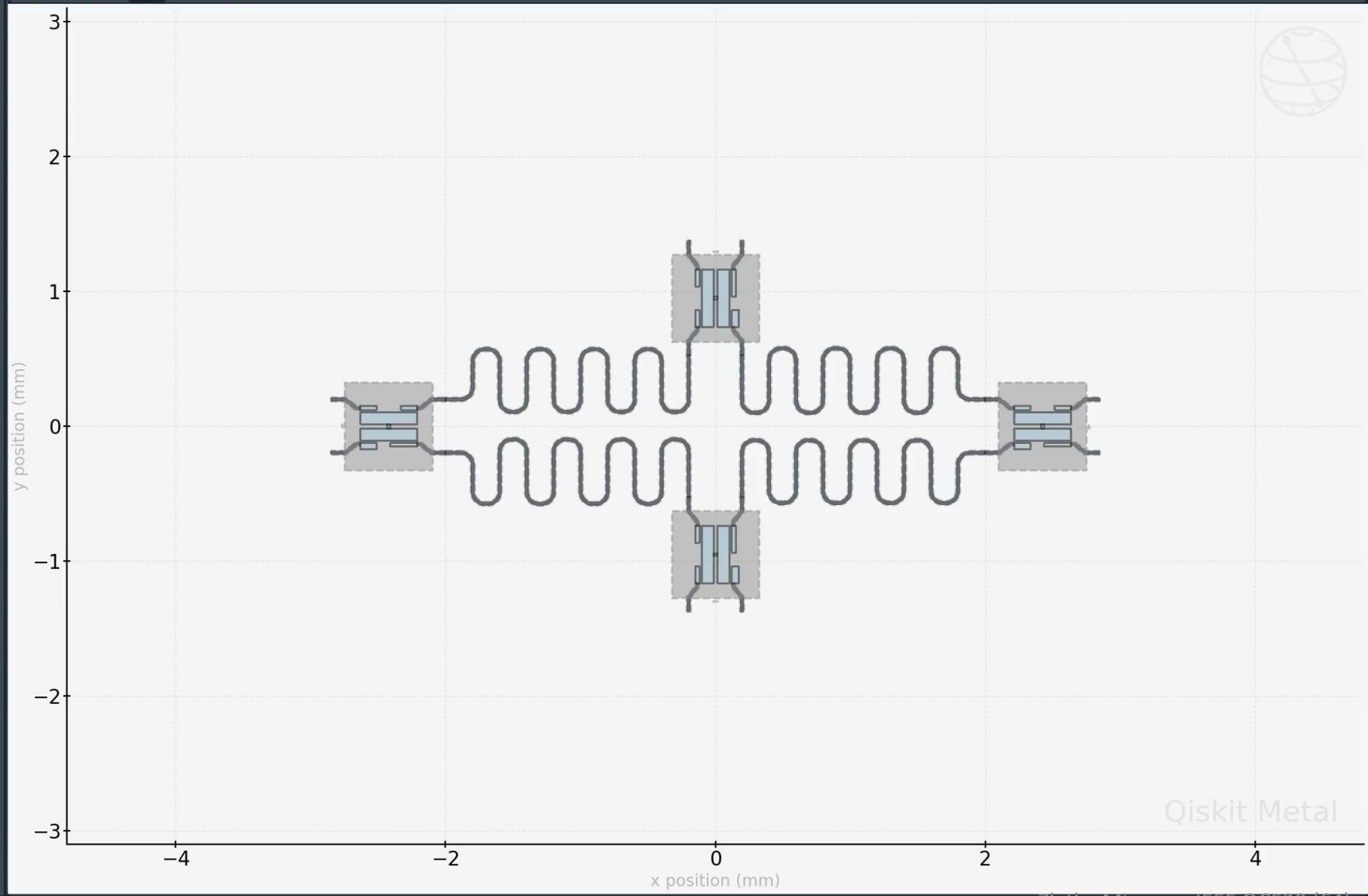
Name	Value	Parsed value

Select a QComponent to edit

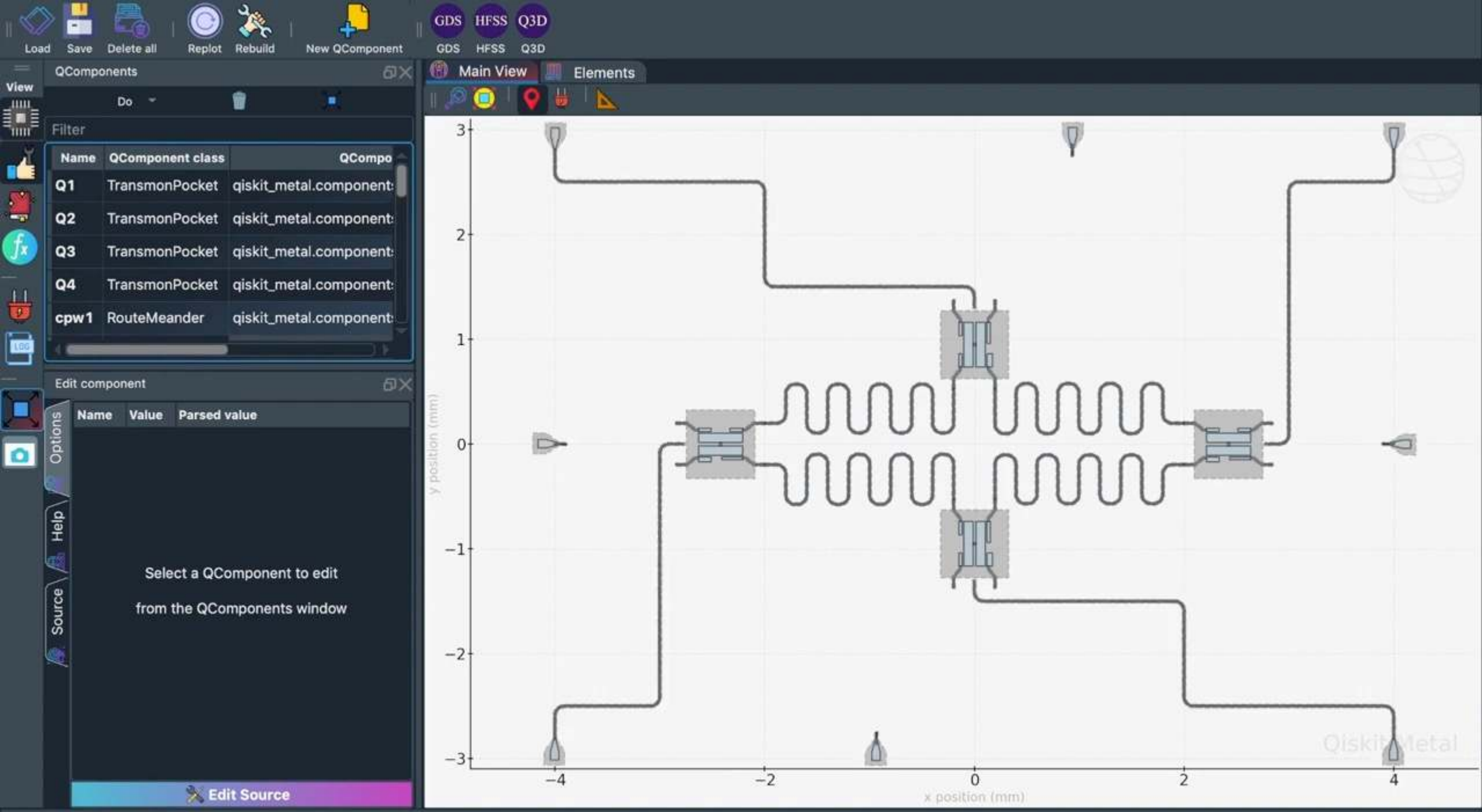
from the QComponents window

Edit Source

Main View Elements

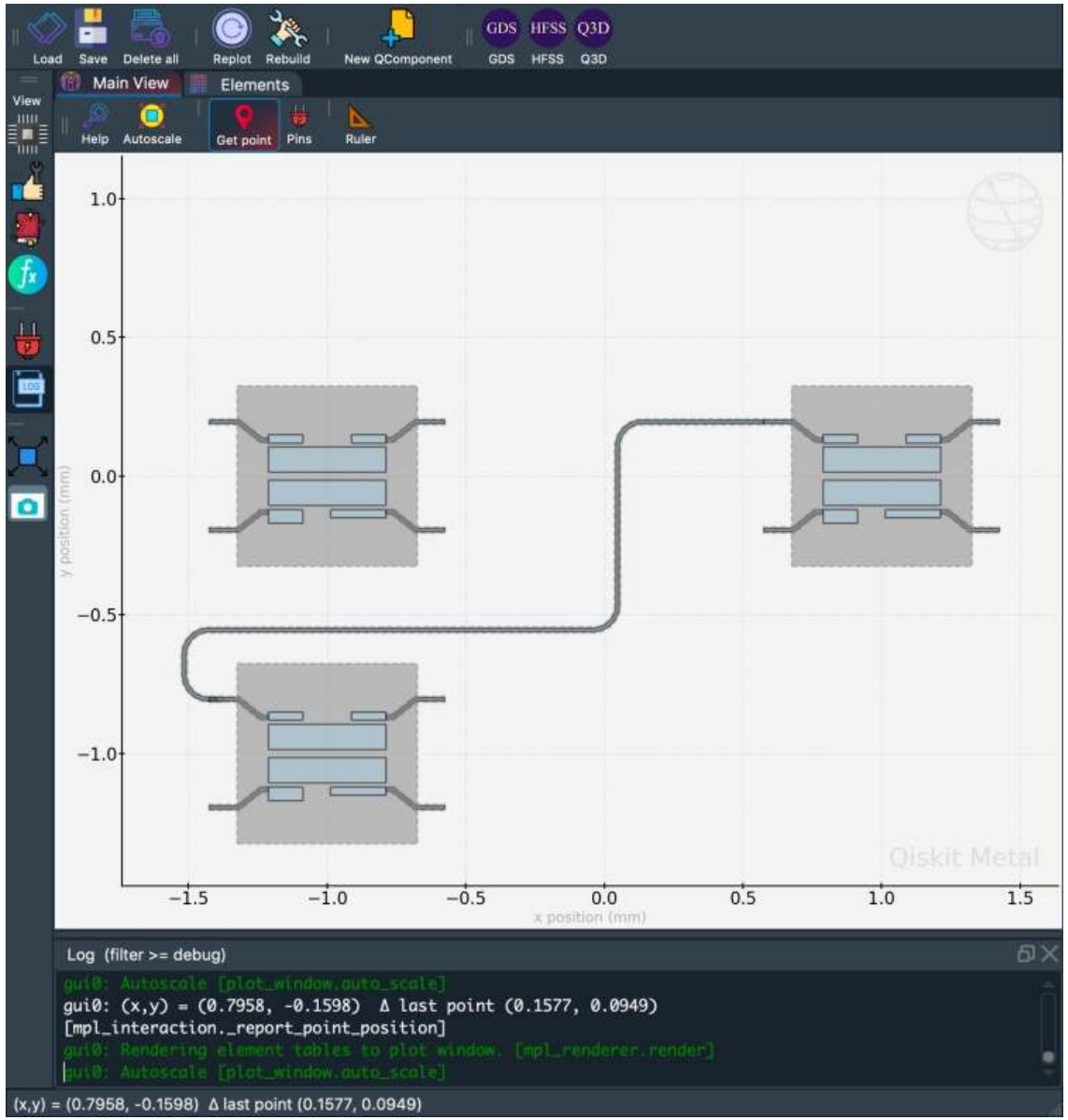


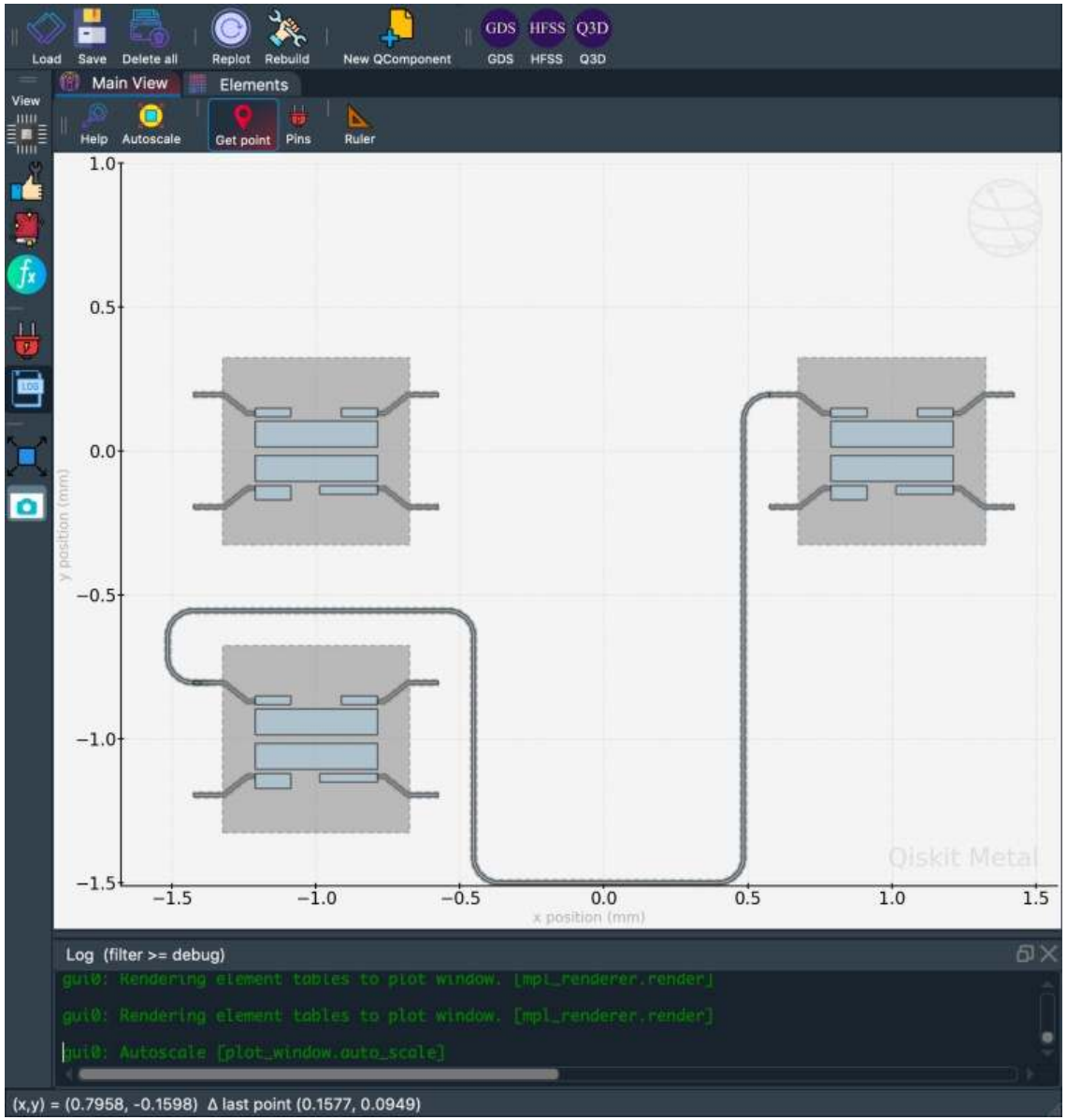
Qiskit Metal: Quantum Creator


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)
Design Dock

Demo Notebook for Hybrid CPW Algorithm with Anchors

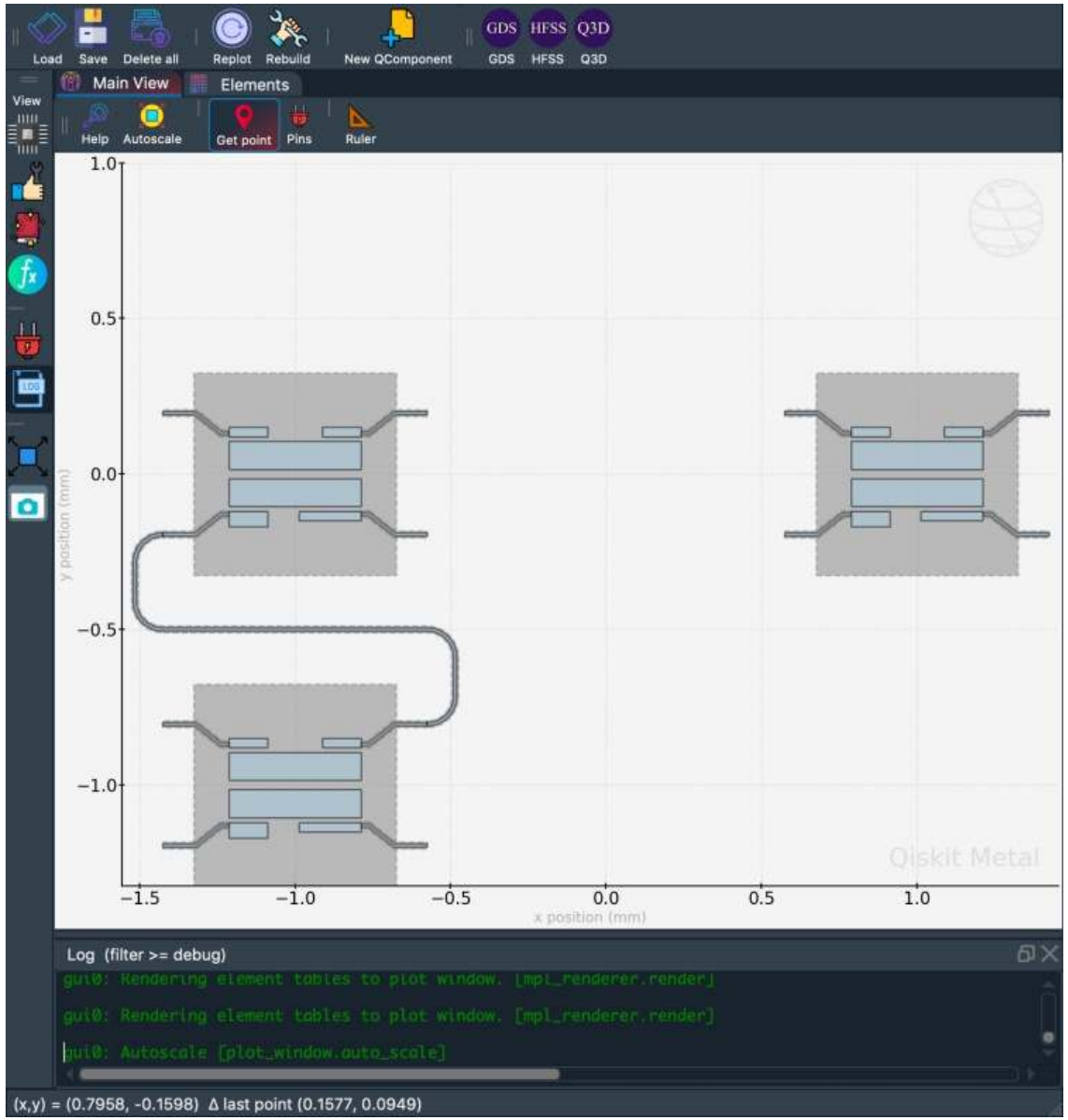
CPW Hybrid Auto and AStar.ipynb

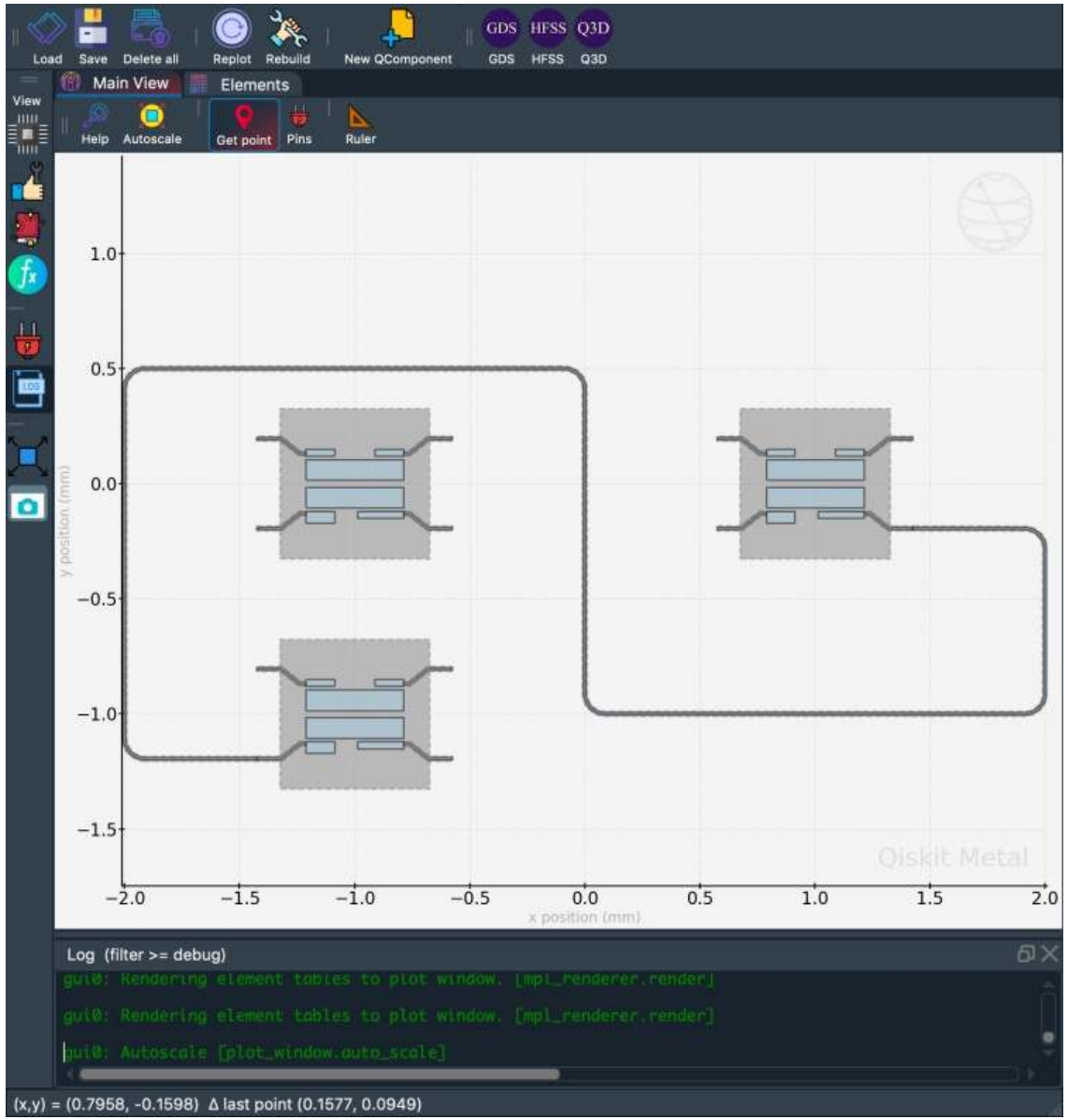


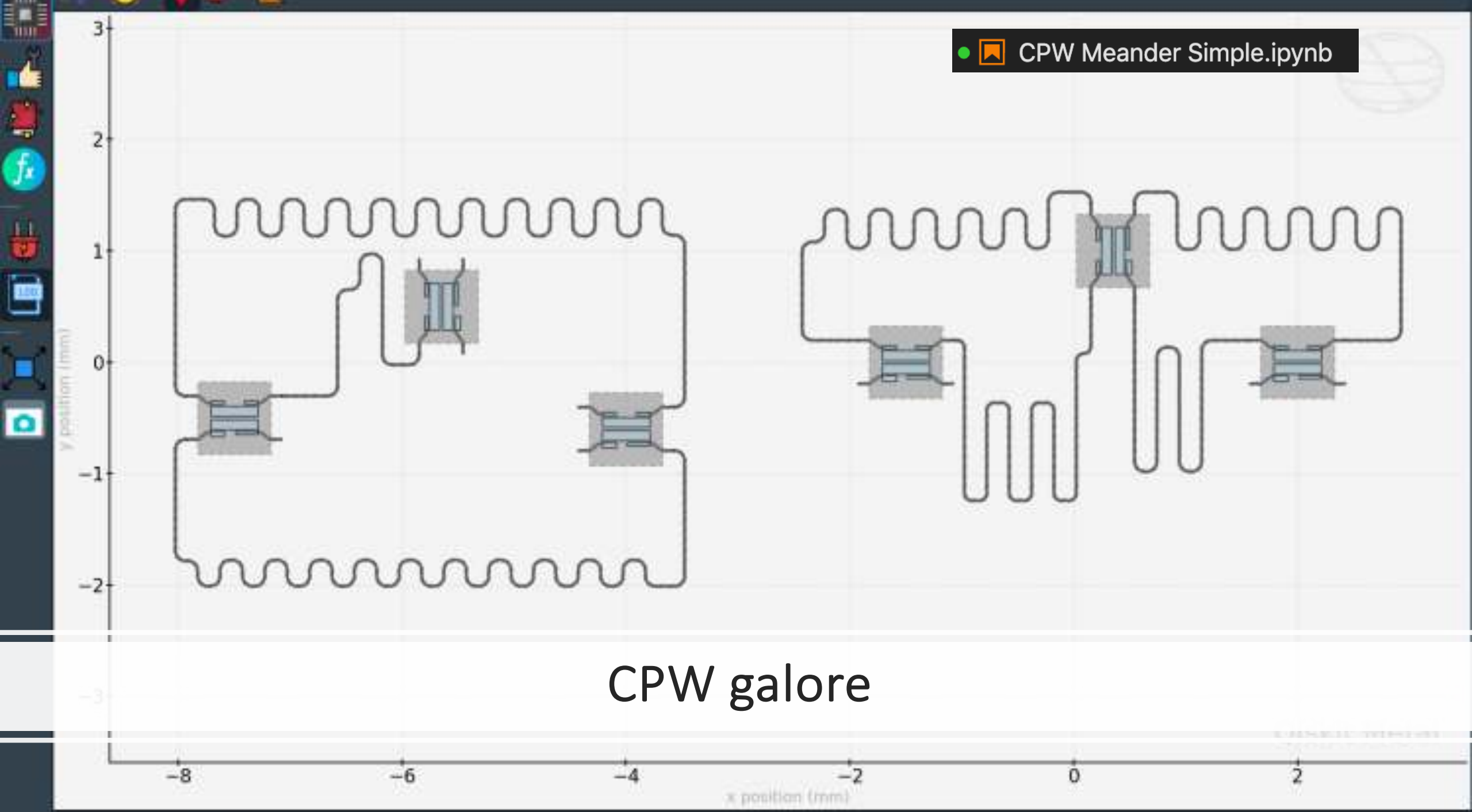


Demo Notebook for Hybrid CPW Algorithm with Anchors

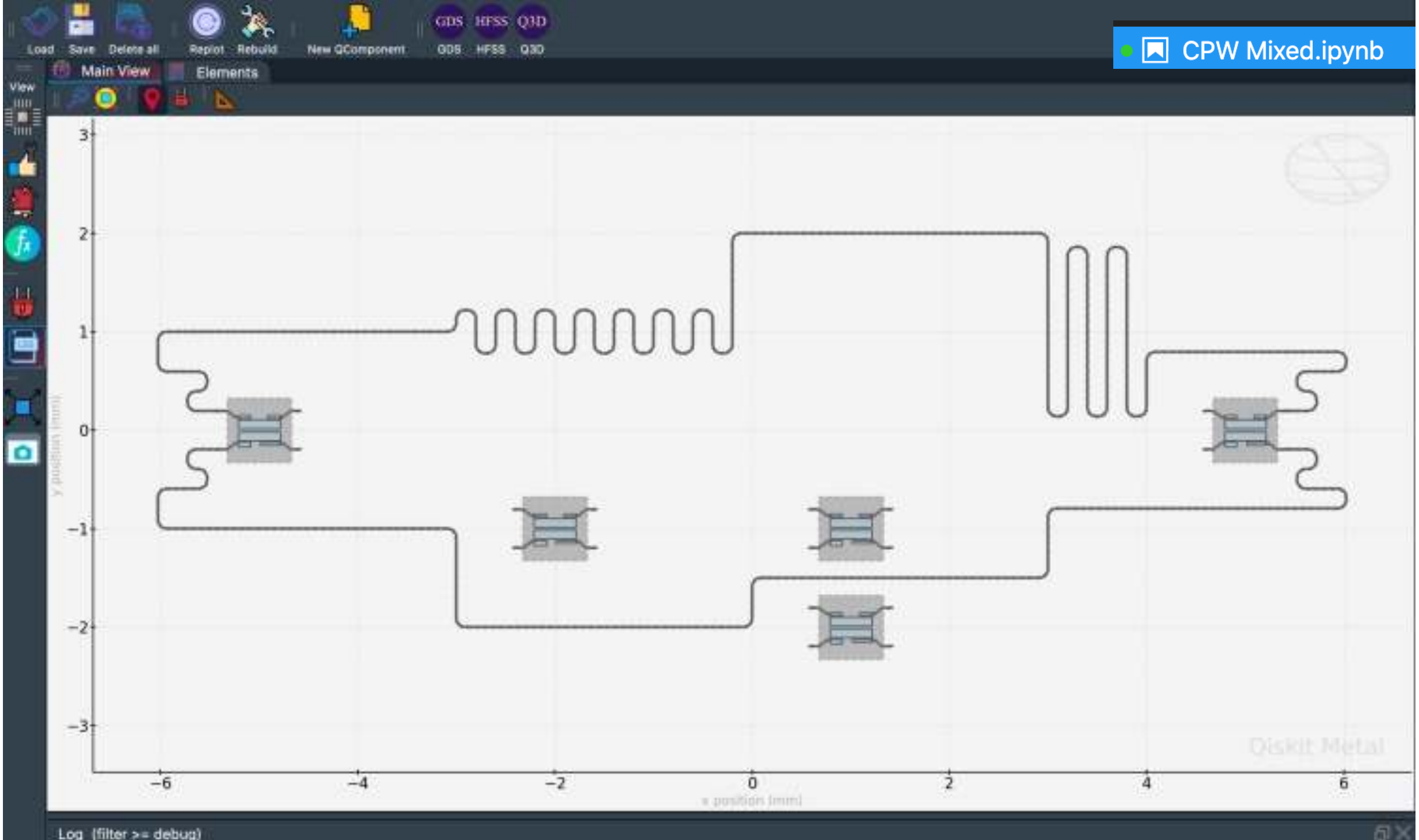
CPW Hybrid Auto and AStar.ipynb



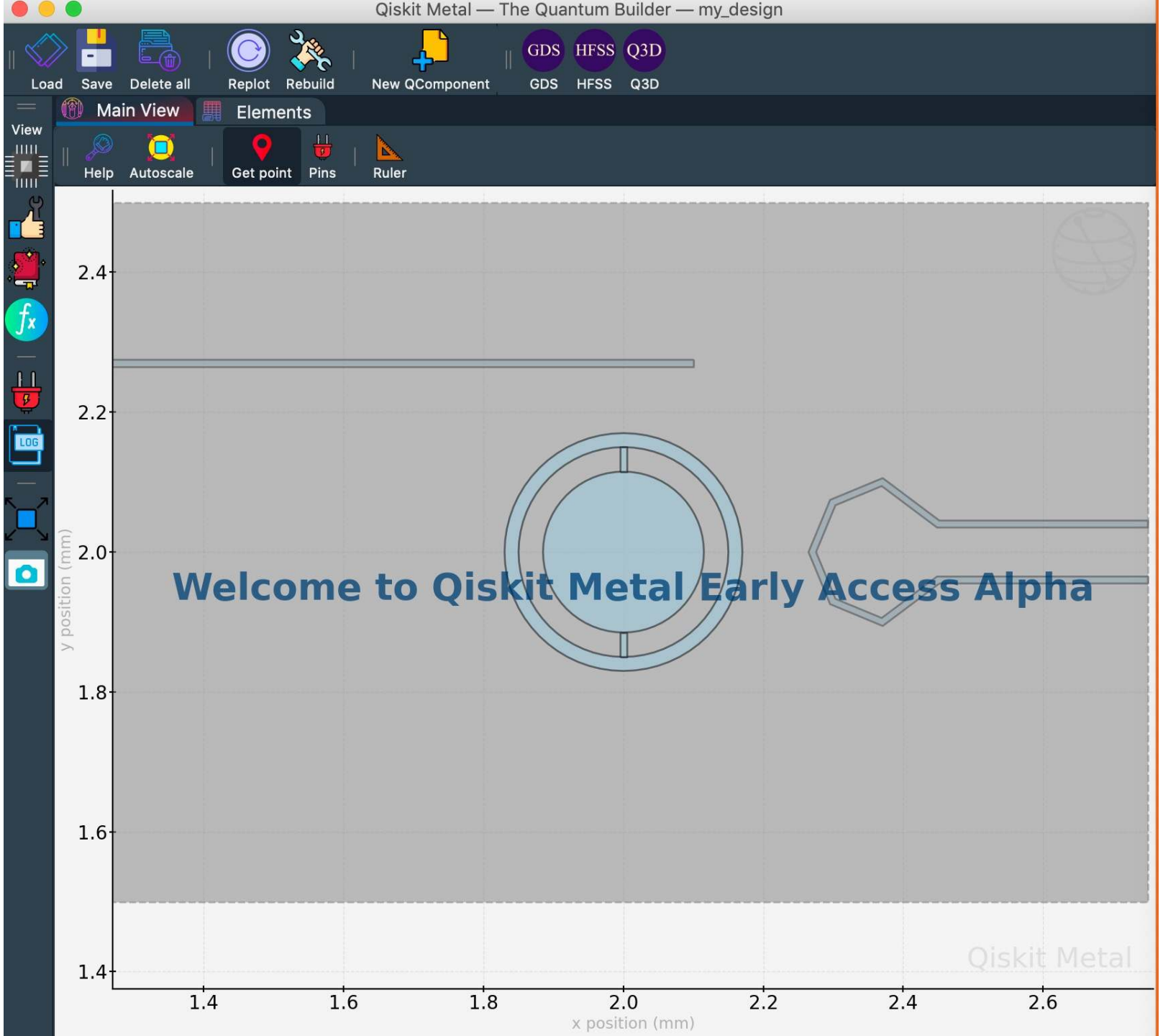



CPW Meander Simple.ipynb
3
2
1
0
−1
−2
y position (mm)
−8
−6
−4
−2
0
2
x position (mm)

CPW galore

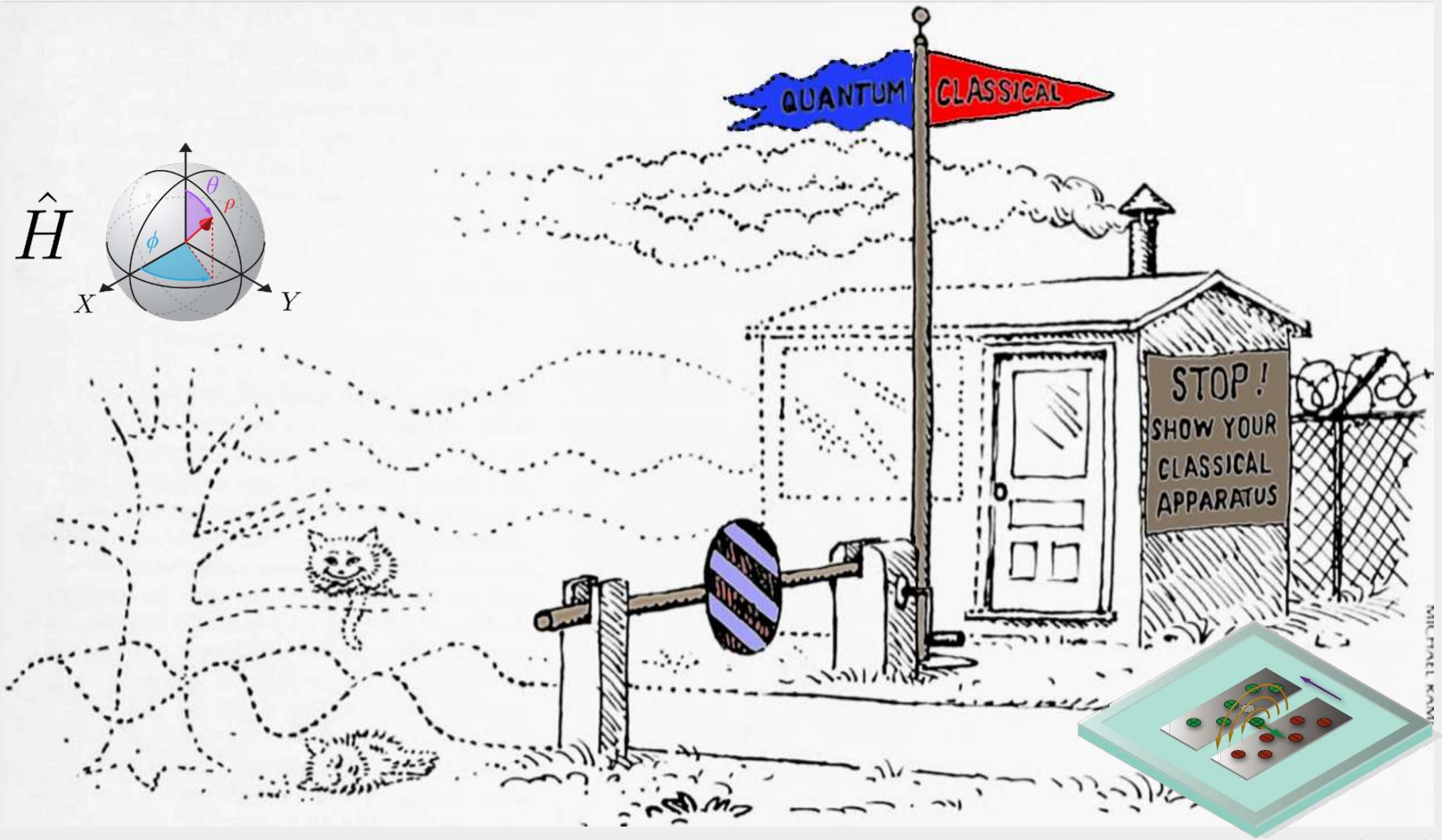

Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
GDS
HFSS
Q3D
CPW Mixed.ipynb
Main View
Elements
View
3
2
1
0
−1
−2
−3
−6
−4
−2
0
2
4
6
x position (mm)
y position (mm)
Diskit Metal
Log (filter >= debug)

Concentric transmon



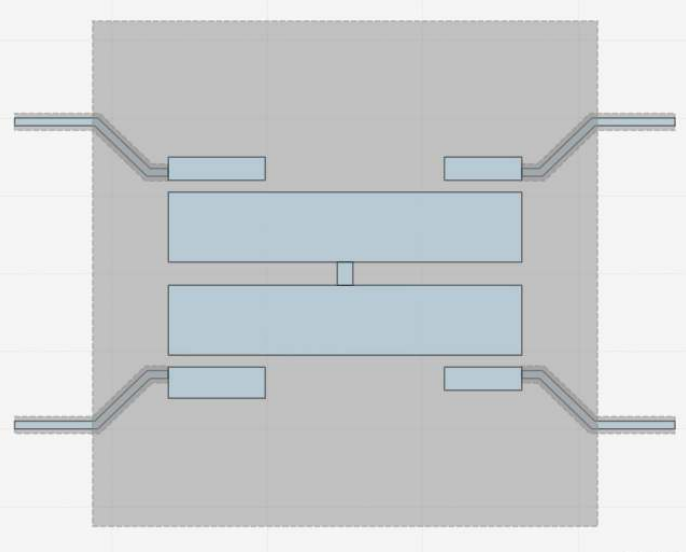
Braumüller et al. (2015)

Analysis

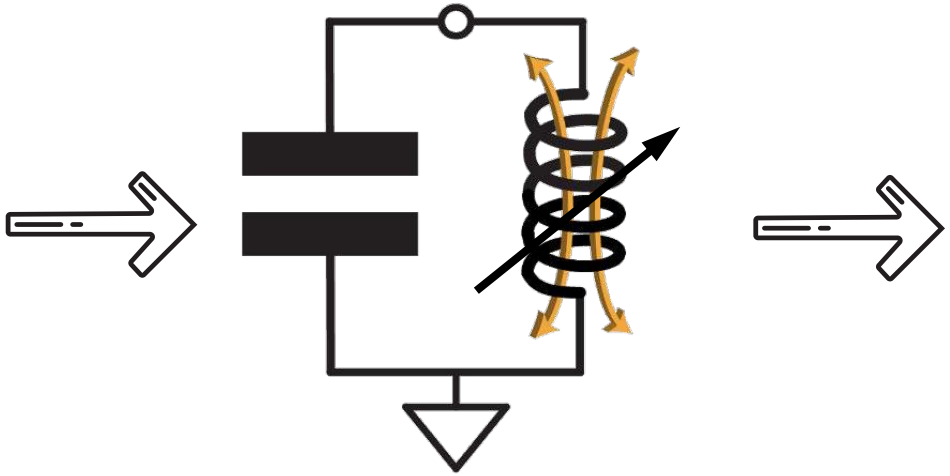


Drawing: Zurek, Physics Today (1991)

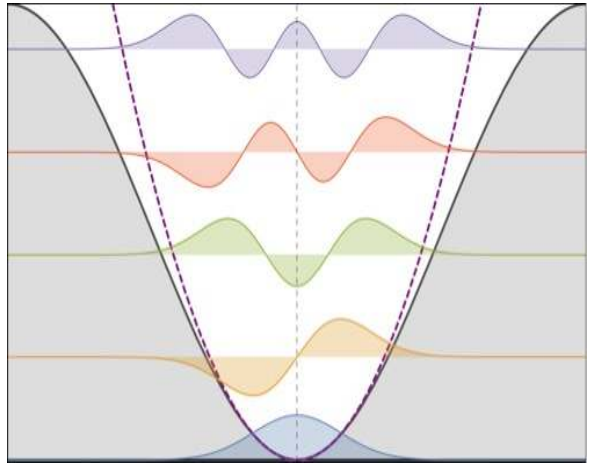
Rendering sub-component into simulation tool



Layout



Electromagnetic analysis

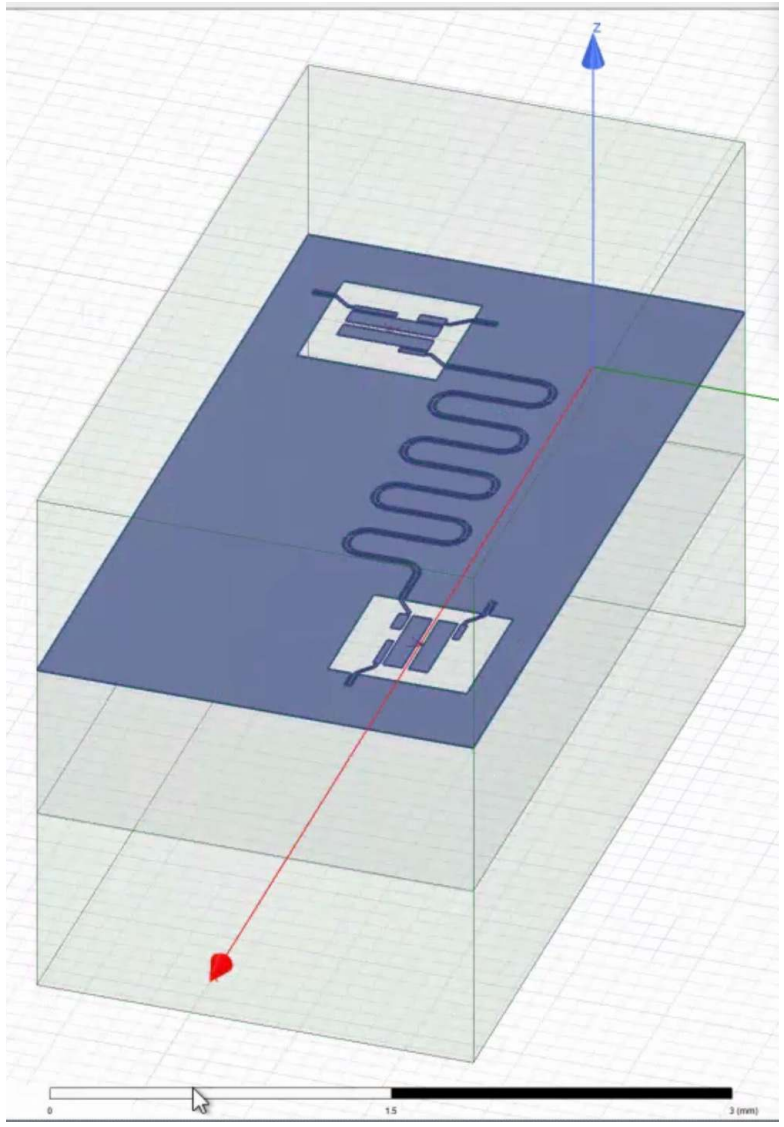


Quantum Hamiltonian analysis

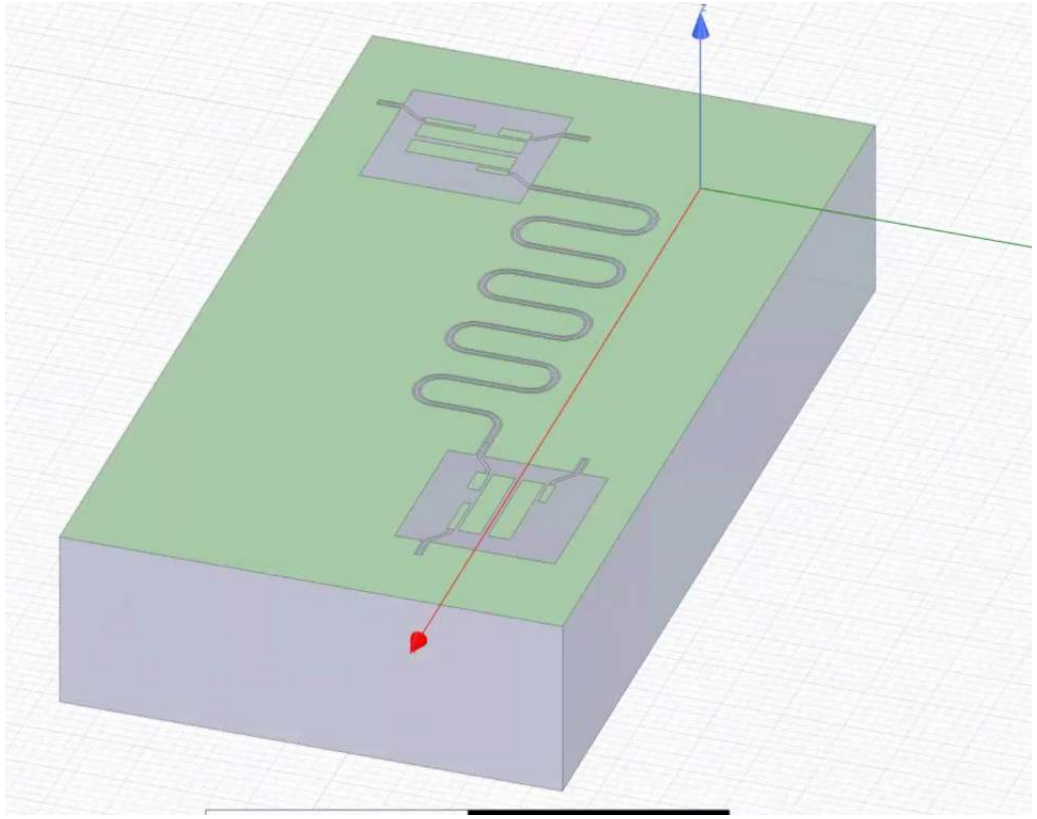
Qiskit Metal render & electromagnetic analysis

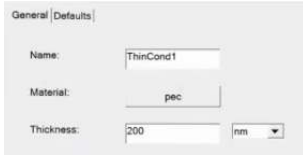
```
design.render(...)
```

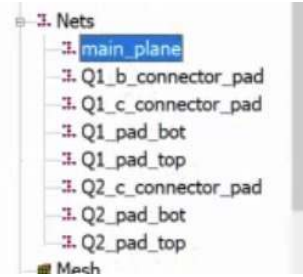
HFSS

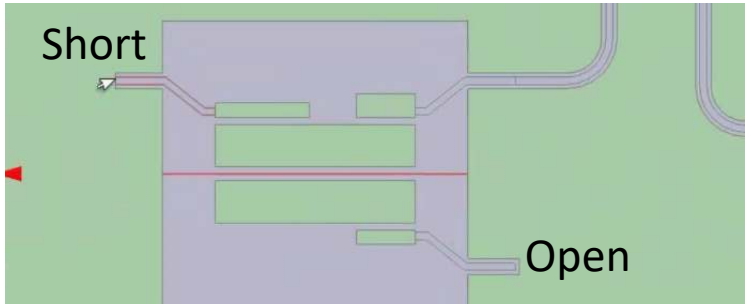


Q3D



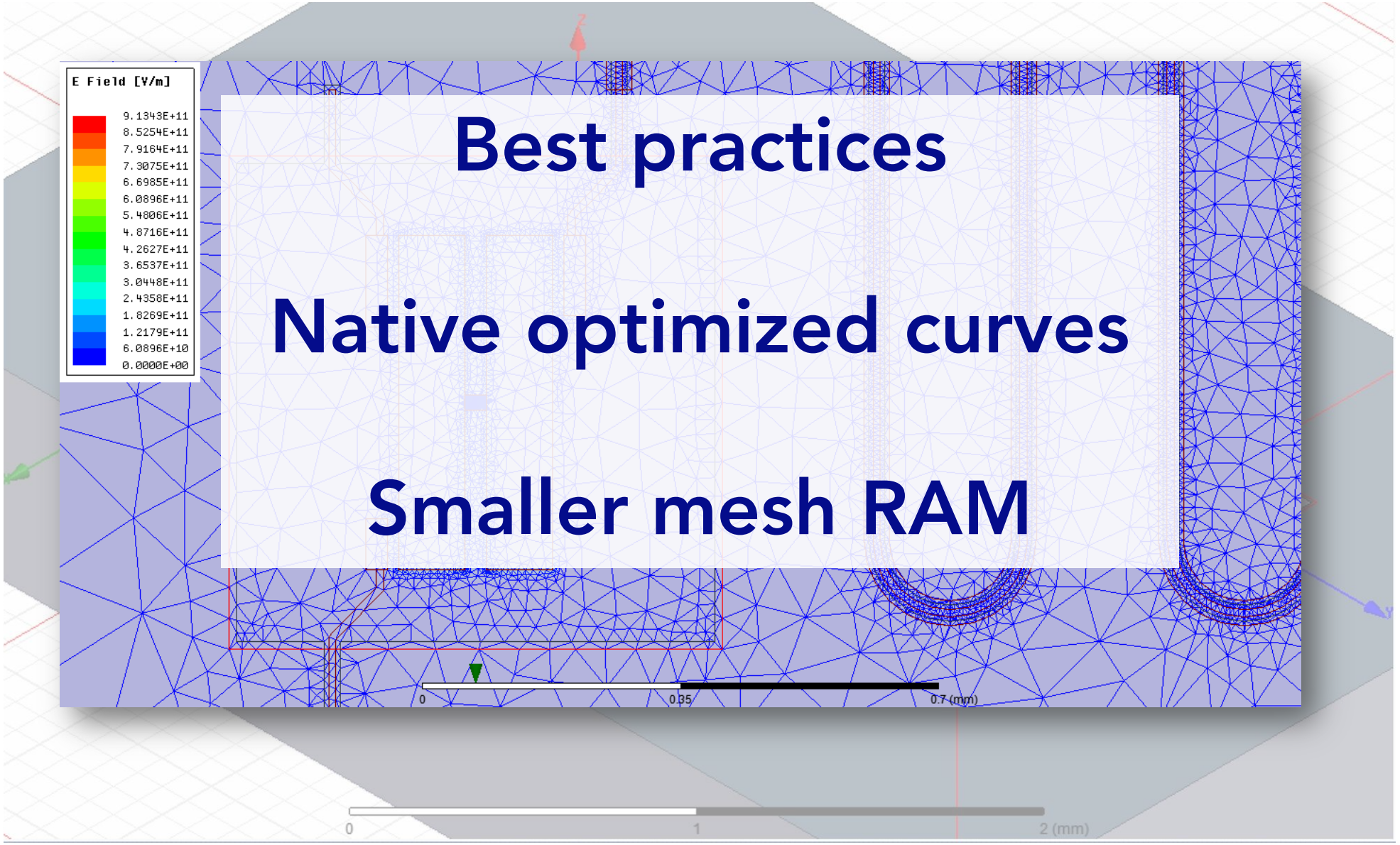






Qiskit Metal

Sub-Circuit Analysis



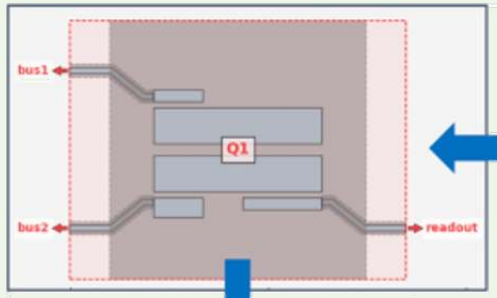
Best practices

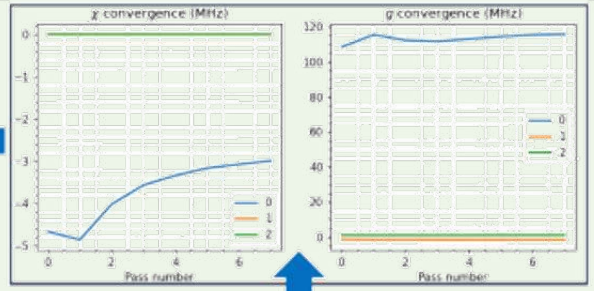
Native optimized curves

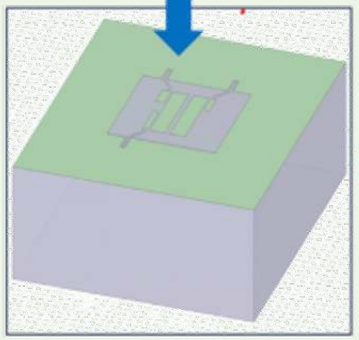
Smaller mesh RAM

Quantum analysis library

Capacitive



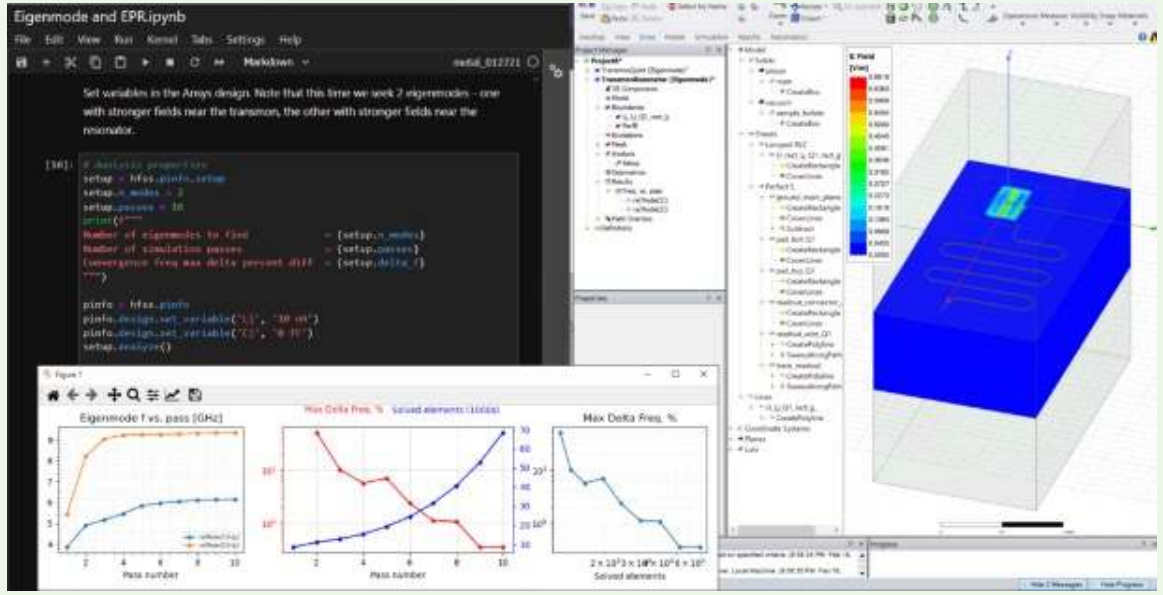




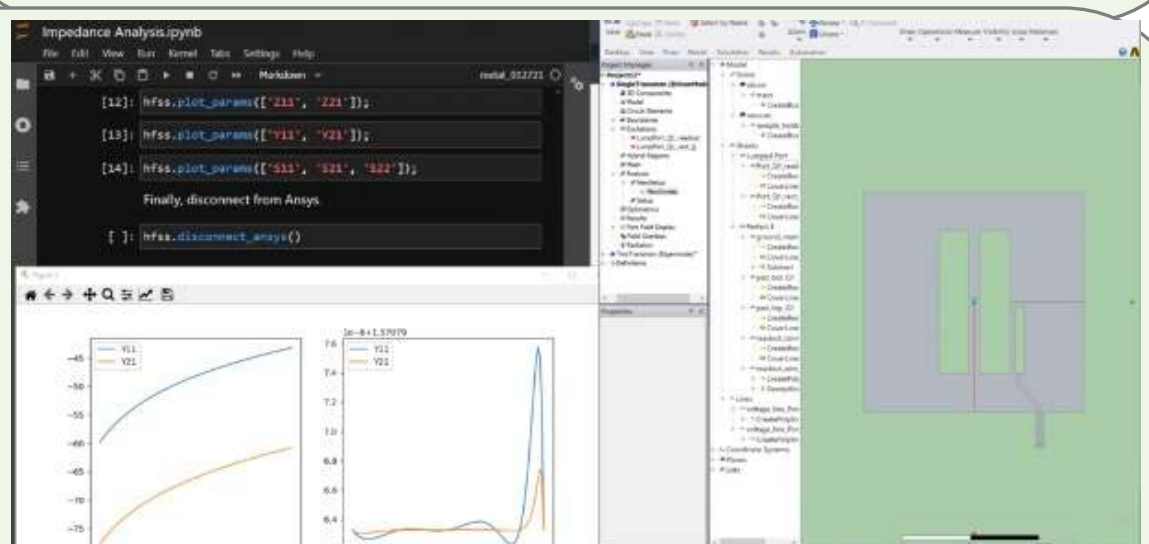
```
# Using the analysis results, get the capacitance matrix as a datafram
q3d.get_capacitance_matrix()
```

	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	

Eigenmode

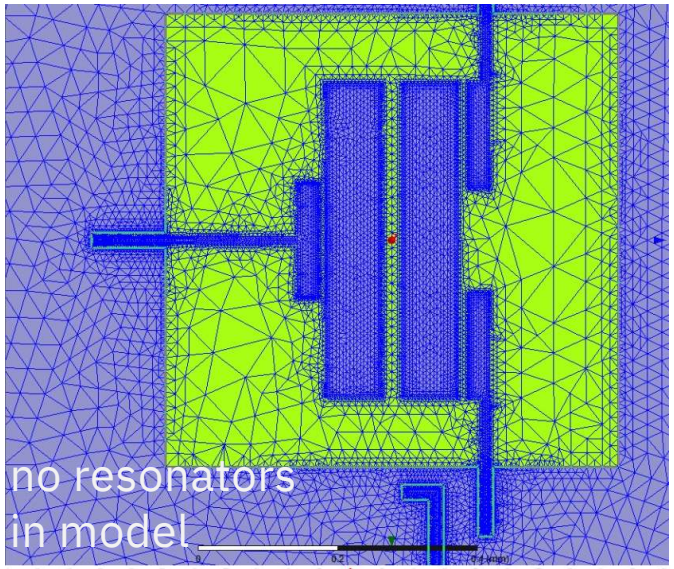


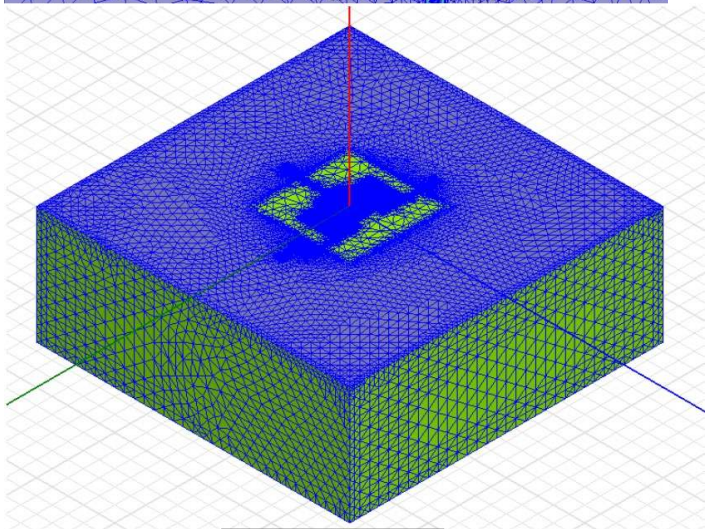
S, Z, Y Impedance Scattering



Lumped-oscillator model (LOM)

Quasi-static solver (Q3D)





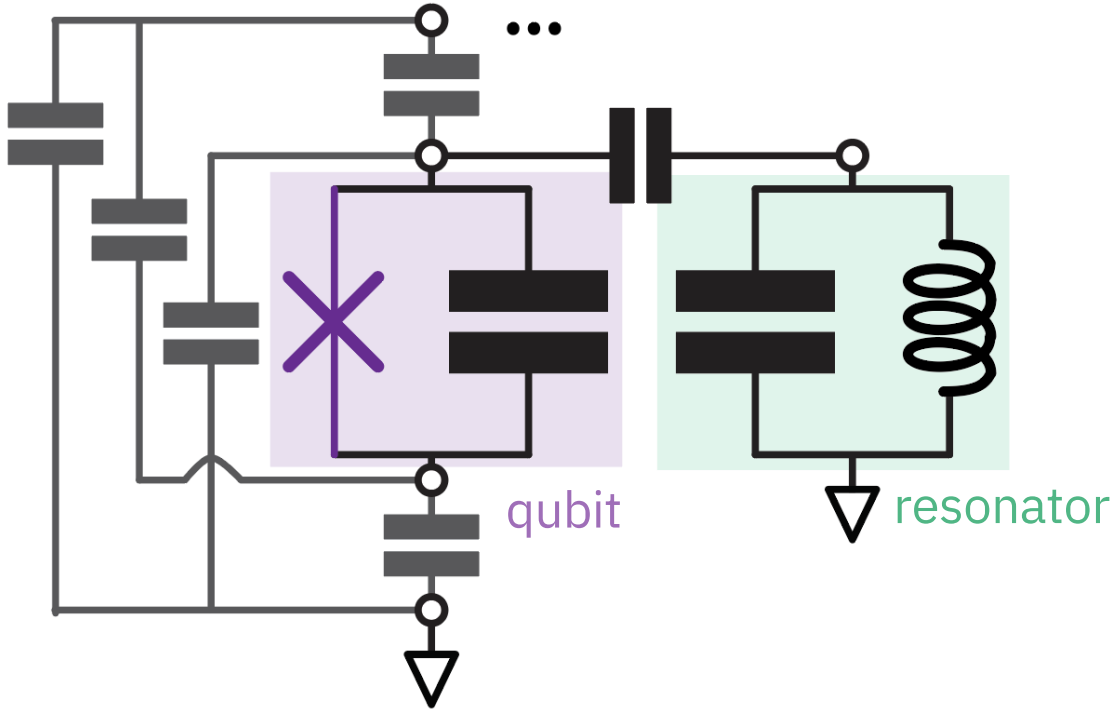
Provide

$C_{nn'}$

ω_q

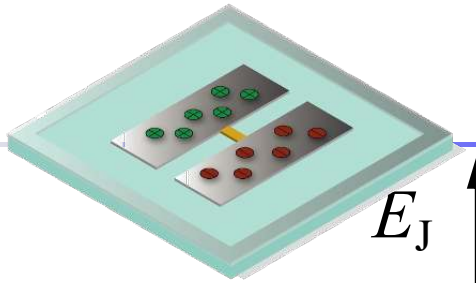
ω_r

Equivalent lumped model



approximate
not suitable for 3D
some distributed effects beyond capture

Yurke & Denker (1984); Devoret (1997); Burkard *et al.* (2004); Koch *et al.* (2007);… Minev *et al.*, in prep (2021) …



Exploring a transmon qubit

E_J

Energy

$-E_J$

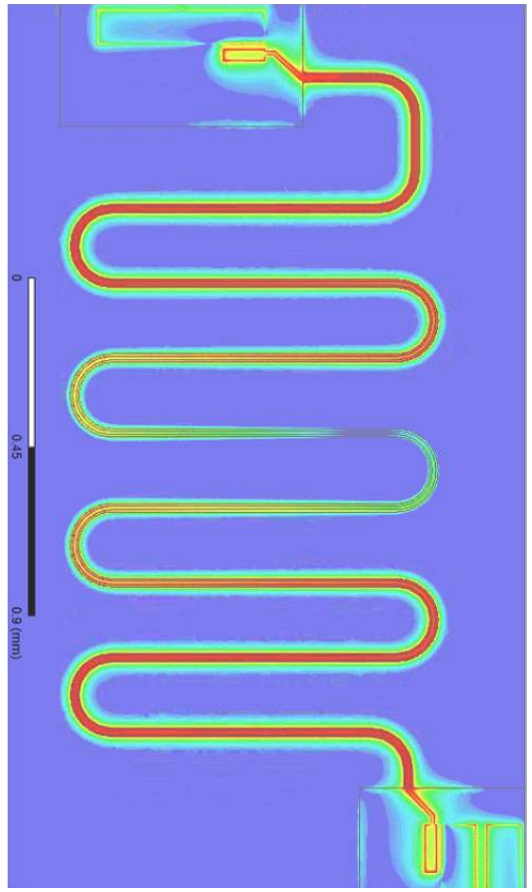
Classically
forbidden region

$-\pi$ 0 π

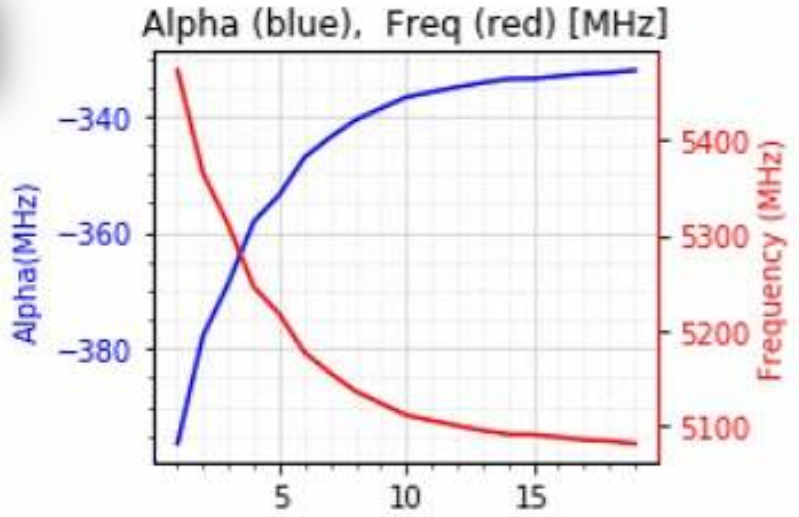
Reduced magnetic flux (Φ/ϕ_0)

Automated analysis and reports

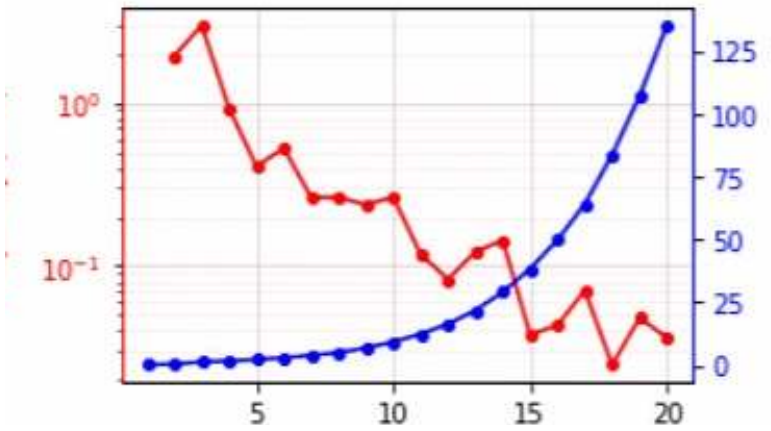
```
metal.analysis.lumped_model.analyze('Q1')
```



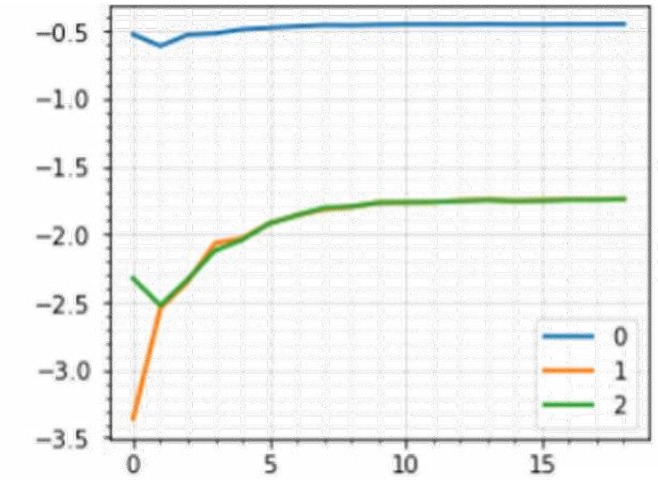
Qubit frequency & anharmonicity



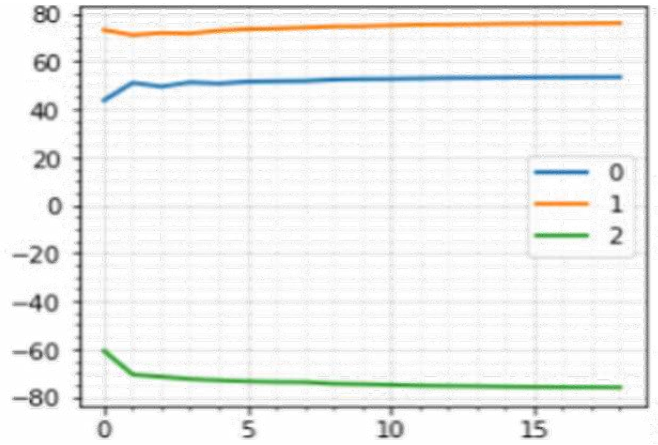
FE simulation convergence



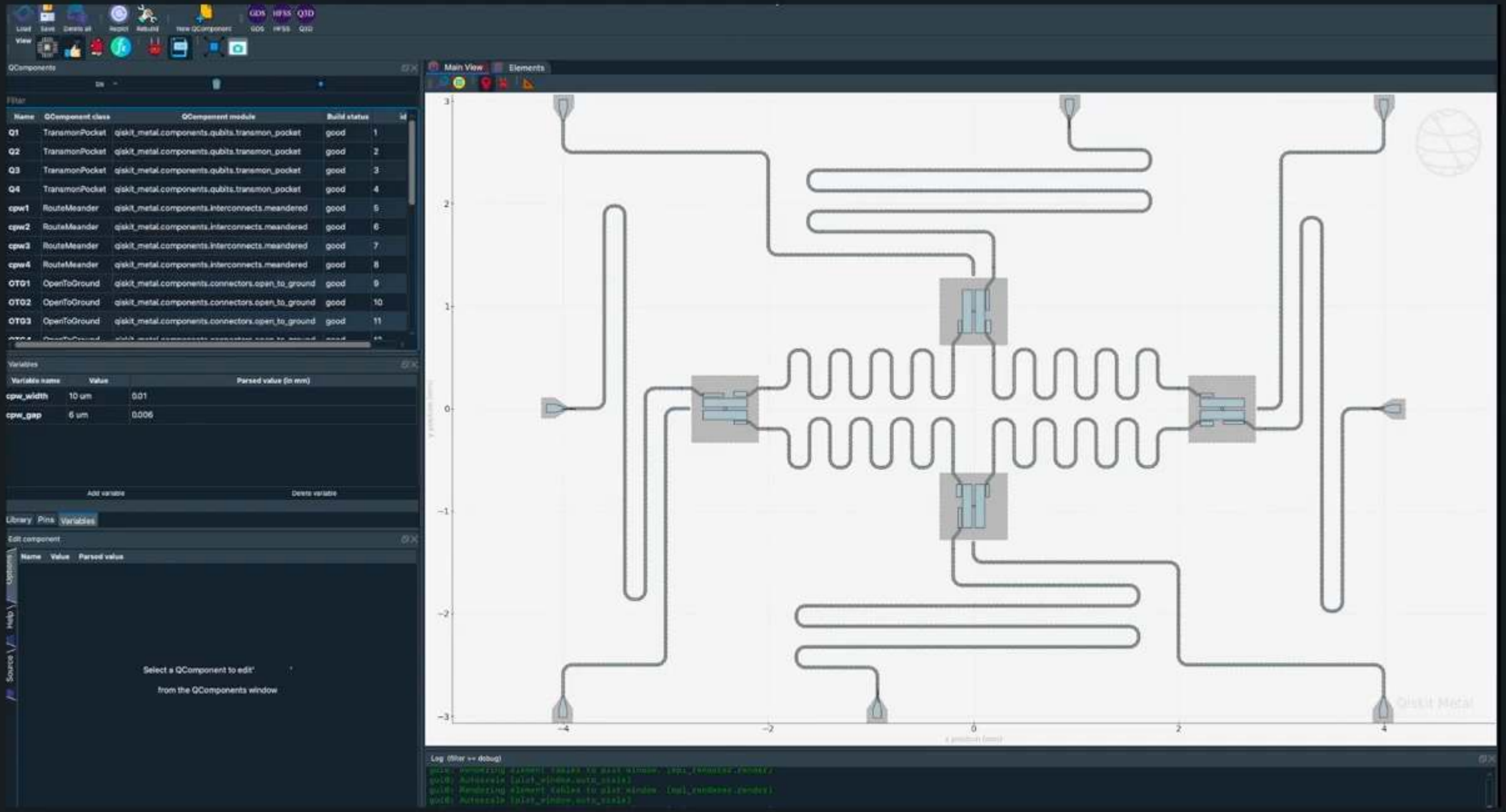
cross-Kerr χ coupling (MHz)



Linear g coupling (MHz)

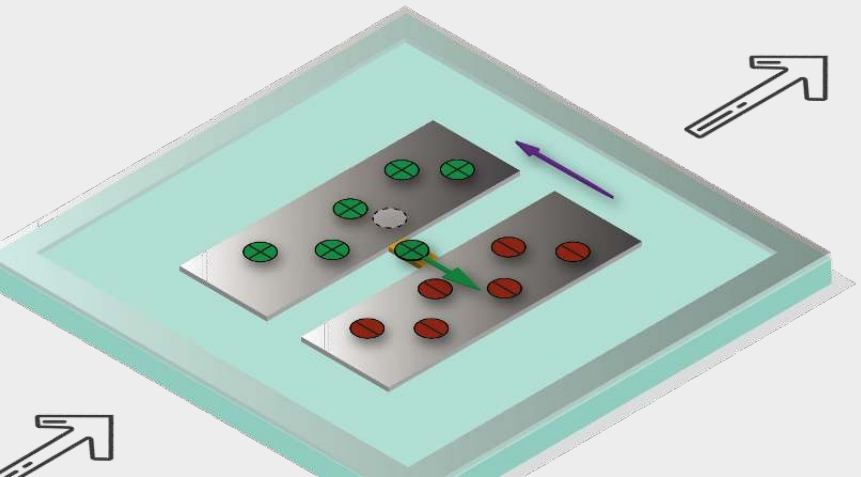


Analysis pass number

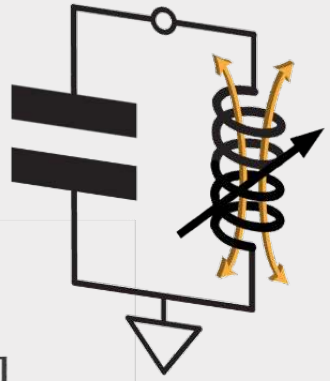

Load
Save
Delete all
Reset
Rebuild
New QComponent
GDS
HFSS
Q3D
QComponents
Filter
Name
QComponent class
QComponent module
Build status
id
Q1 TransmonPocket qiskit_metal.components.qubits.transmon_pocket good 1
Q2 TransmonPocket qiskit_metal.components.qubits.transmon_pocket good 2
Q3 TransmonPocket qiskit_metal.components.qubits.transmon_pocket 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
OT01 OpenToGround qiskit_metal.components.connectors.open_to_ground good 9
OT02 OpenToGround qiskit_metal.components.connectors.open_to_ground good 10
OT03 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
Add variable
Delete variable
Library
Pins
Variables
Edit component
Name
Value
Parsed value
Select a QComponent to edit
from the QComponents window
Main View
Elements
Log (filter >= debug)

Quantum Device Design

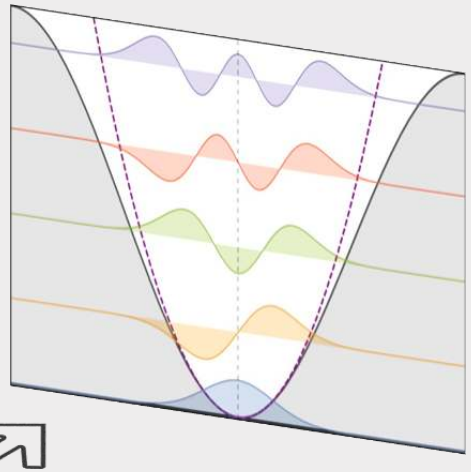
Superconducting circuits



Physical layout



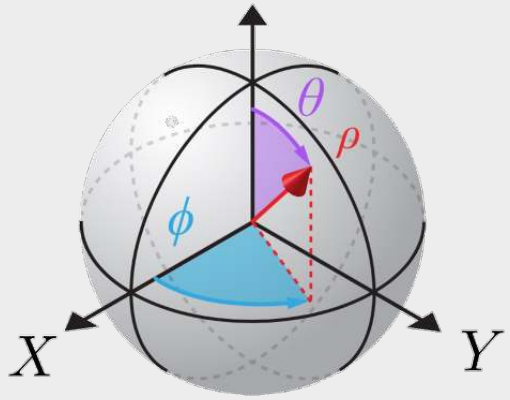
Electromagnetic analysis



Quantum Hamiltonian analysis

$$\hat{H}_{\text{full}} = \sum_m (\omega'_m - i\kappa_m)\hat{a}_m^\dagger \hat{a}_m + \sum_{\boldsymbol{\alpha},\boldsymbol{\beta}} \mathcal{C}^p_{\boldsymbol{\alpha},\boldsymbol{\beta}} \prod_{m,n} \hat{a}_m^{\dagger\beta_m} \hat{a}_n^{\alpha_n}$$

$\chi, \delta, \alpha, \ldots$



Qubit Hilbert space

• HINT

You can open this documentation using

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

• ATTENTION

This is an early-access alpha version of Qiskit Metal. This folder will be expanded throughout the early-access period, based on both planned training and your feedback. Please let us know about anything you might want us to add or elaborate upon.

Qiskit for quantum hardware design (`Qiskit Metal`) is a quantum device design and analysis SDK, library, and community. Call it quantum EDA (QEDA) and analysis.
About Metal

Designing quantum devices is the bedrock of the quantum ecosystem, but it is a difficult, multi-step process that connects traditionally disparate worlds.

Metal is automating and streamlining this process. Our vision is to develop a community-driven universal platform capable of orchestrating quantum chip development from concept to fabrication in a simple and open framework. Qiskit for quantum hardware design (*Qiskit Metal*) is: * Open source * Community-driven * Both a python API and a front-end visual GUI interface.

Metal & it's vision (read full Medium blog):

We want to accelerate and lower the barrier to innovation on quantum devices. Today at the IEEE Quantum Week Conference, the team discussed their vision for this first-of-its-kind project. Led by quantum physicist Zlatko Minev and developed with other IBM Quantum team members, this project is meant for those interested in quantum hardware design: a suite of design automation tools that can be used to devise and analyze superconducting devices, with a focus on being able to

Qiskit Metal Quantum Hardware Design Early-access program

Experiment

Theory

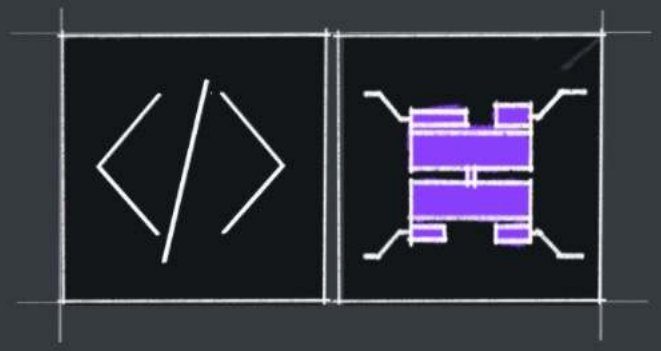
Advocate

qiskit.org/metal
github.com/Qiskit/qiskit-metal
#qiskit-metal-early-access

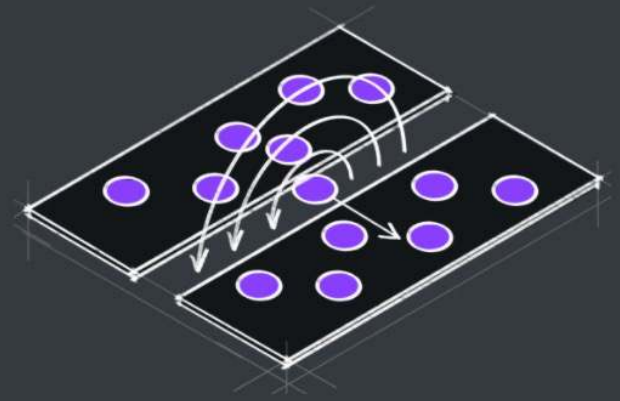
Why the Vision of Qiskit Metal

End-to-end automation

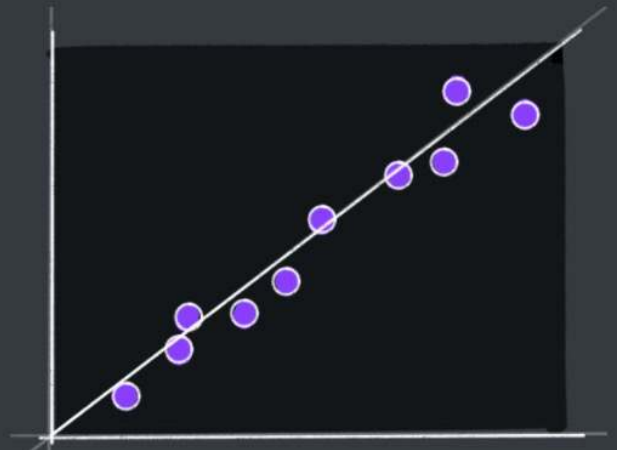
Flexible & extensible



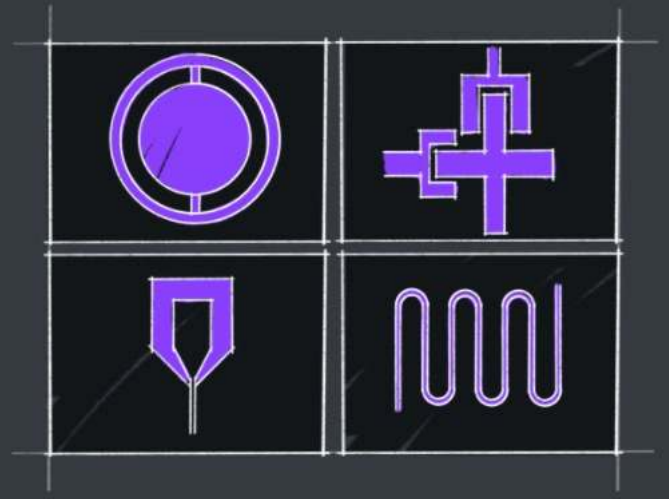
Light-weight interoperability



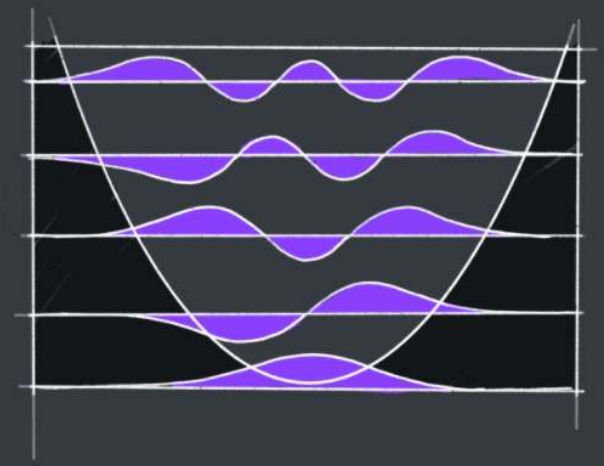
Experimentally tested



Library of components



Cutting edge resources



qiskit.org/metal

Thank you!

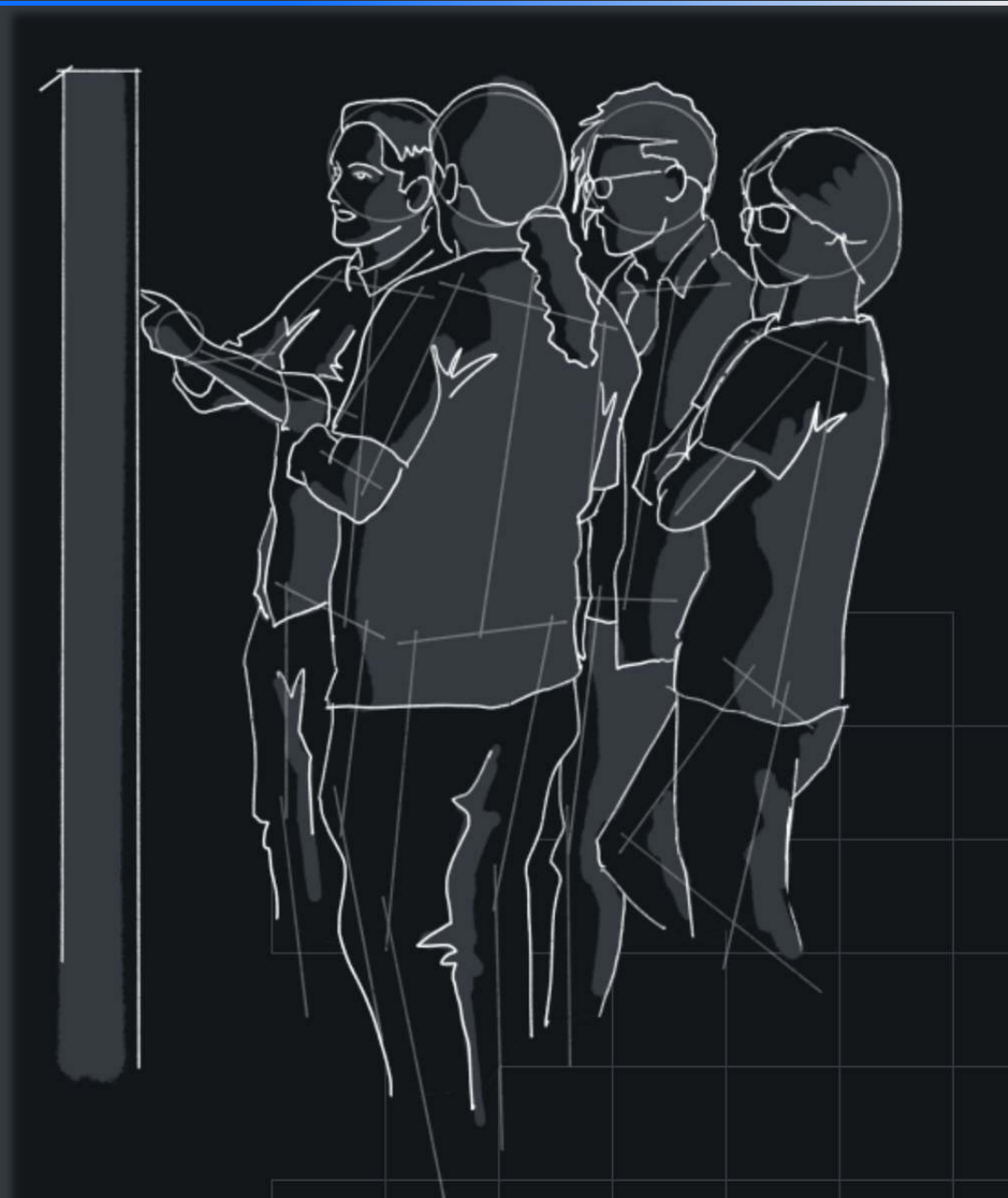
Building together

Call for community participation

Open source
Early access program

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

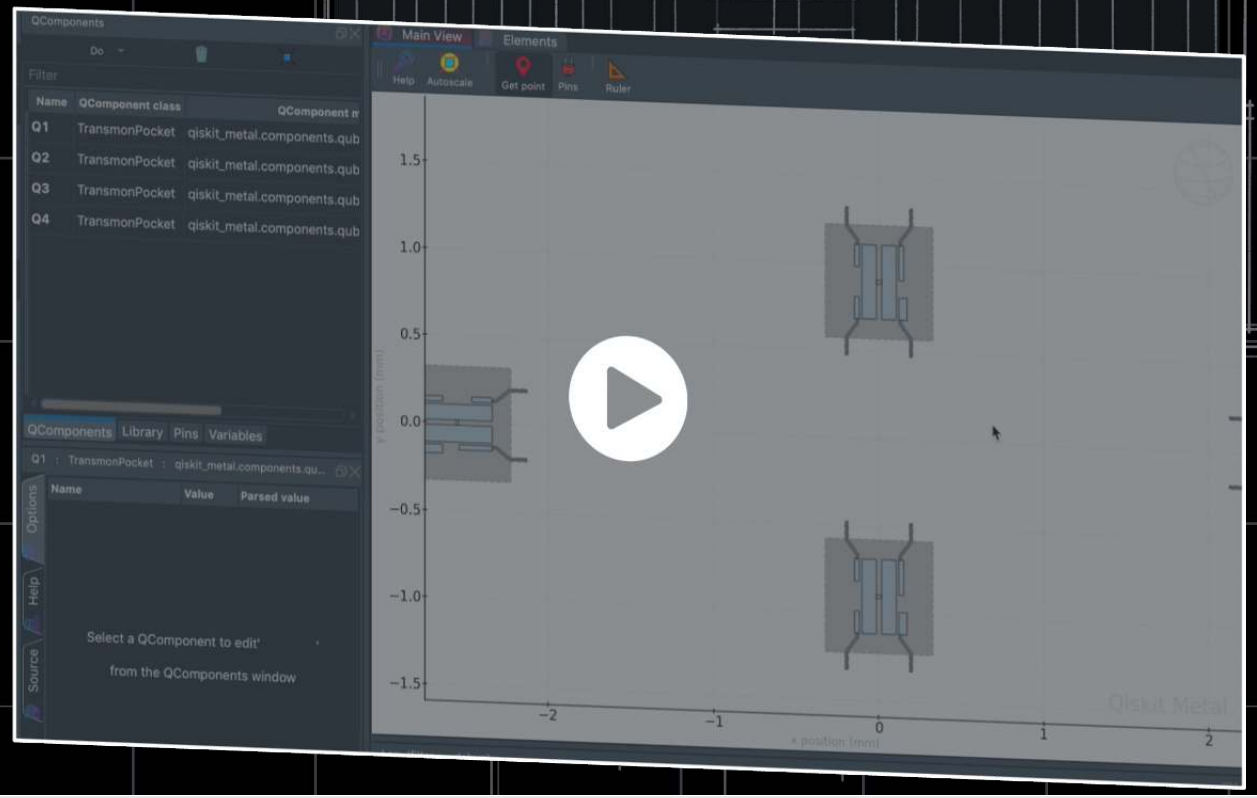


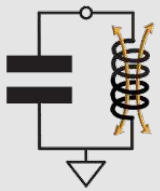
@zlatko_minev

Qiskit | quantum device design

Project Metal

Open source
Learn more / request early access:
qiskit.org/metal



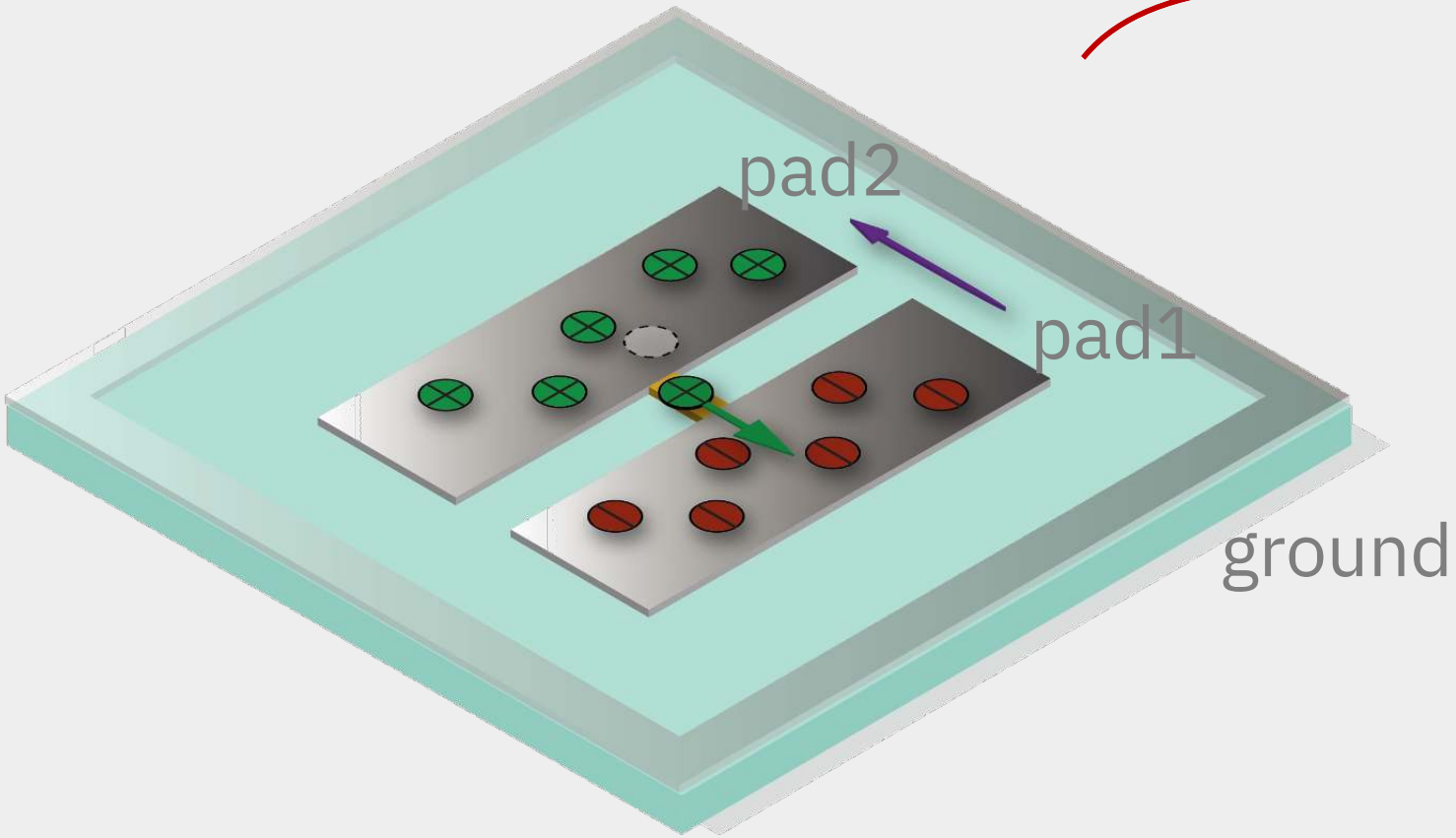


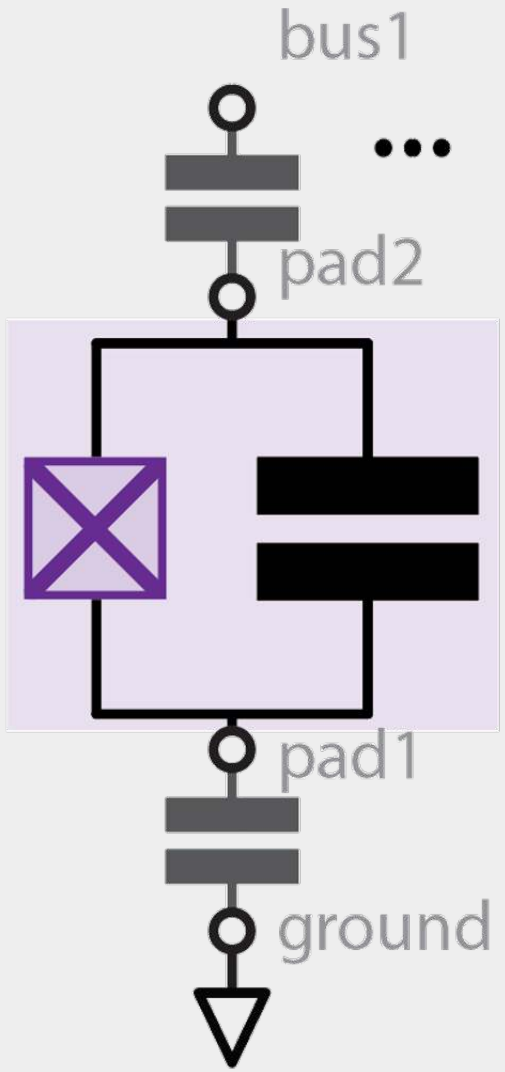
Zlatko K. Minev

IBM Quantum

@zlatko_minev zlatko-minev.com

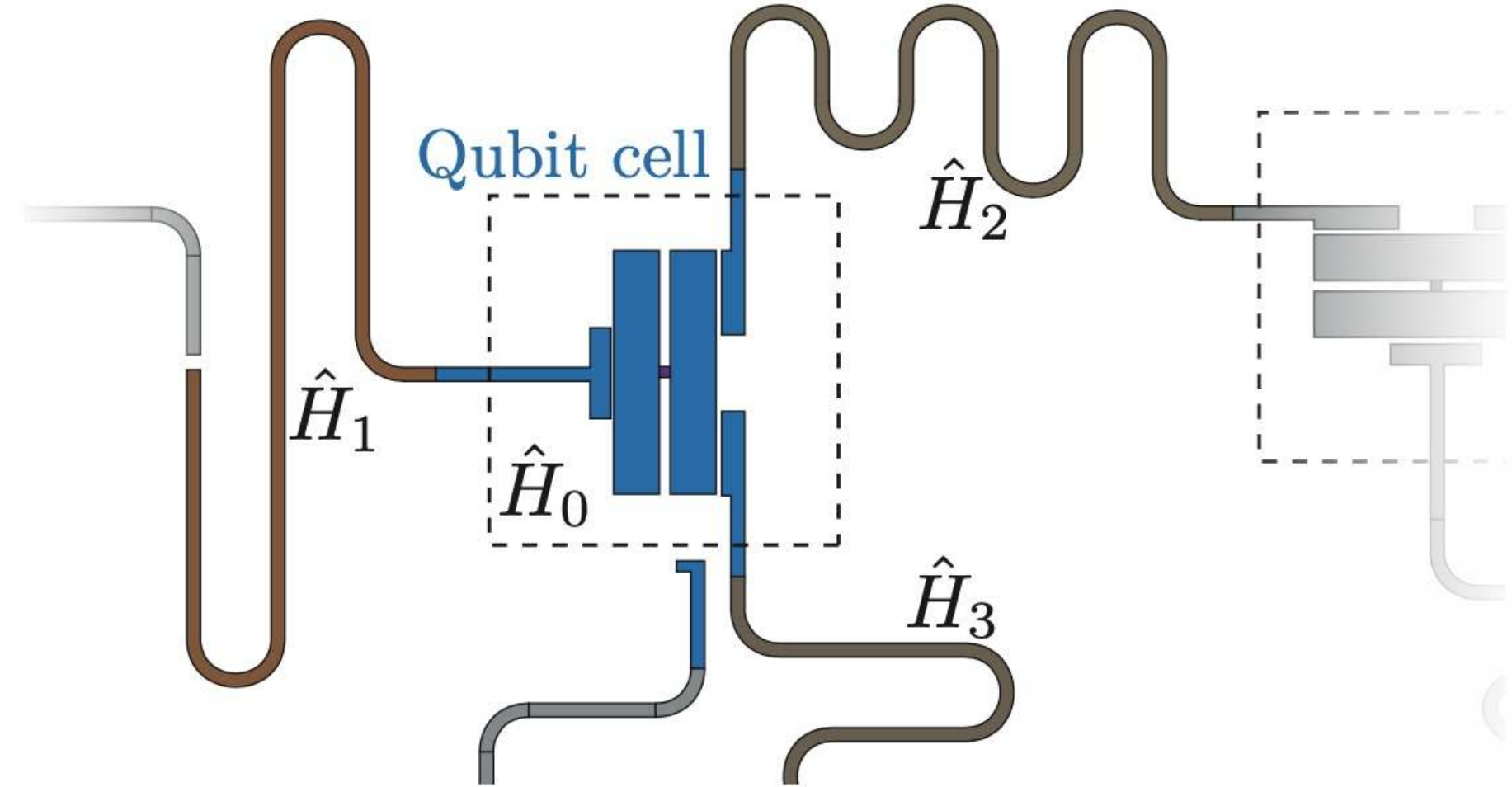
Floating transmon (lumped approximation)

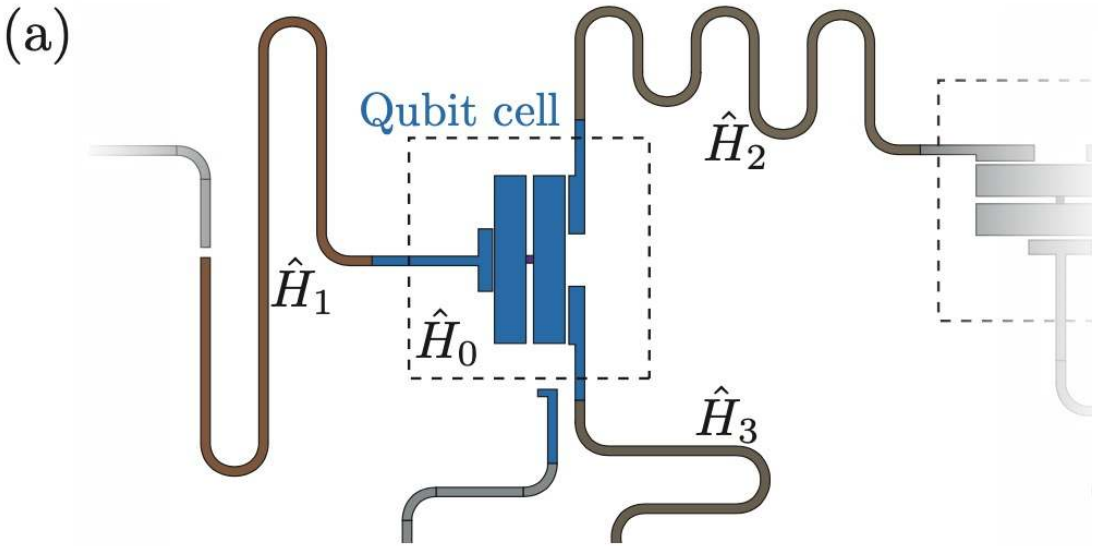


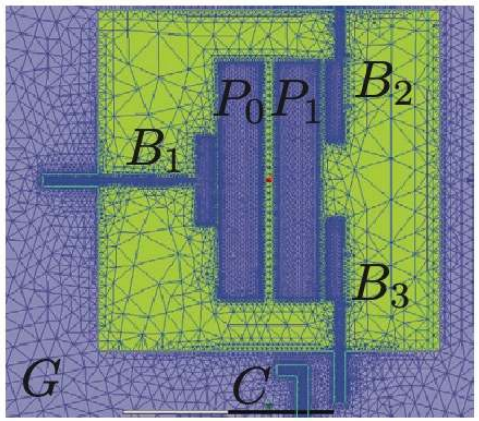


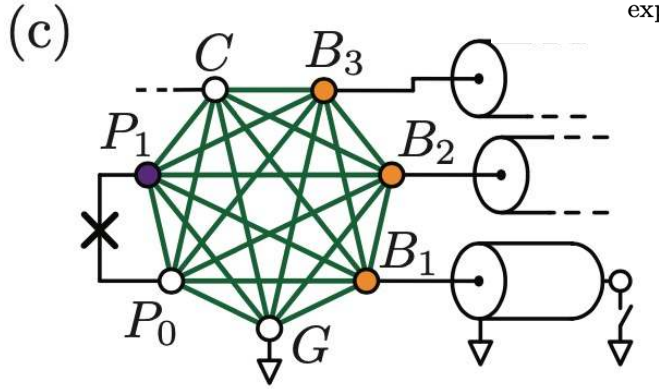
Quasi-lumped modular method

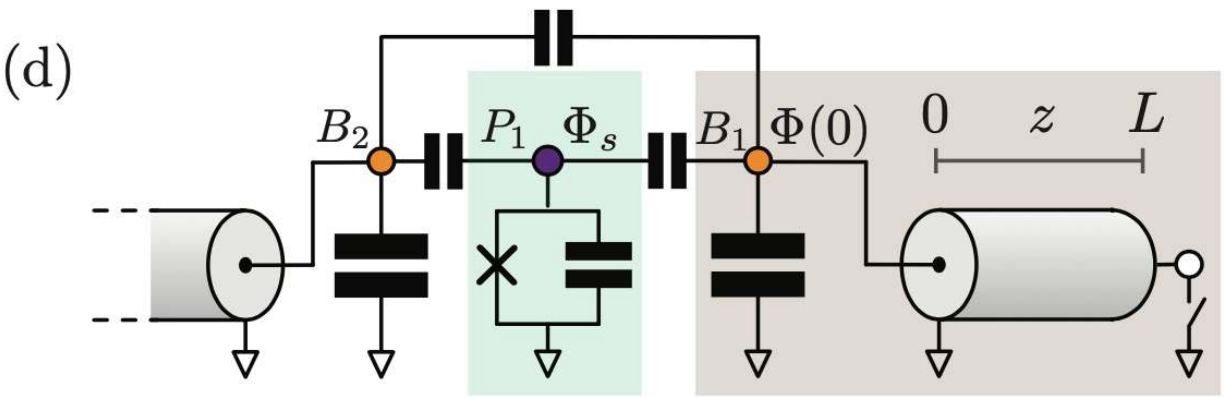
$$\hat{H}_{\text{full}} = \hat{H}_0 + \sum_{n=1}^{K} \hat{H}_n + \sum_{n=0}^{K} \sum_{m=n+1}^{K} \hat{H}_{nm} \,, \qquad (1)$$











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

Zlatko K. Minev,* ..., and Jay M. Gambetta
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA
(Dated: February 9, 2021)

Modeling the quantum electrodynamics of physical circuits is a keystone problem in the process of realizing complex superconducting quantum phenomena and building a quantum computer. The remarkable growth of the field increasingly requires ever-more precise, widely-applicable, and modular modeling methods that cans tie together the physical hardware to its quantum mechanical description to extract principal parameters of interest. Here, we build on previous work to present such a method based on interconnected cells, compactly represented as either lumped or distributed. We treat each lumped-model cell and its coupling to neighboring cells without further approximation, topologically in a generic way. The model construction natively accounts for large and potentially non-perturbative loading and coupling-induced effects. We verify the method experimentally on a large inter-connected quantum device and find a two-times improvement in the experimental agreement of dispersive non-linear couplings.

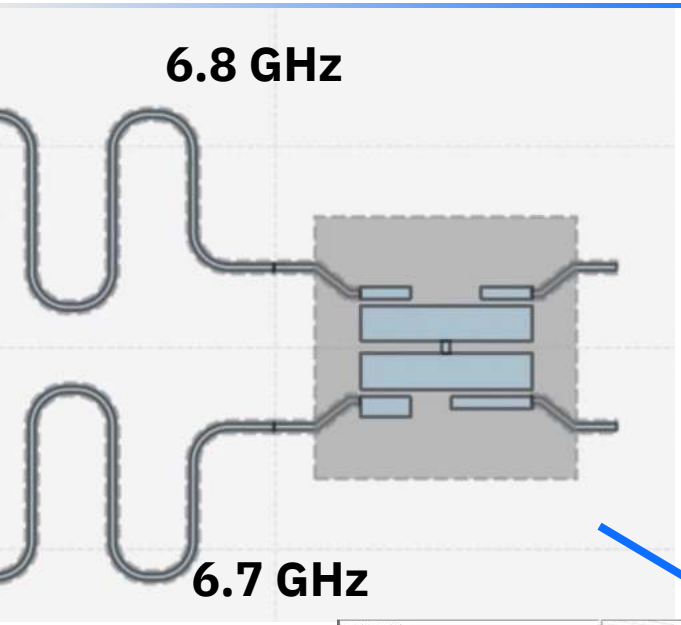
$$\hat{H}_{\text{full}} = \hat{H}_0 + \sum_{n=1}^{K} \hat{H}_n + \sum_{n=0}^{K} \sum_{m=n+1}^{K} \hat{H}_{nm} \,, \qquad (1)$$

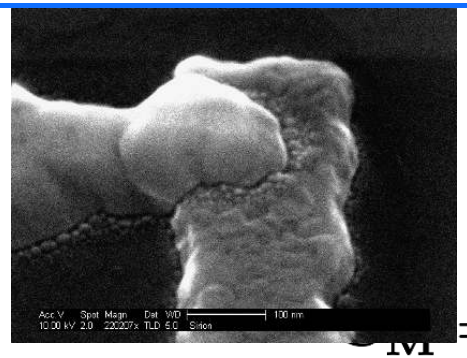
$$\hat{H}_{nm} = \hat{Q}_n \hat{Q}_m / C_{nm}^{\text{eff}} + \hat{\Phi}_n \hat{\Phi}_m / L_{nm}^{\text{eff}} \,, \qquad (2)$$

$$\hat{H}_{nm} = \hat{Q}_n \hat{Q}_m / C_{nm}^{\text{eff}} = \hbar g_{nm} \hat{A}_n \hat{B}_m \,,$$

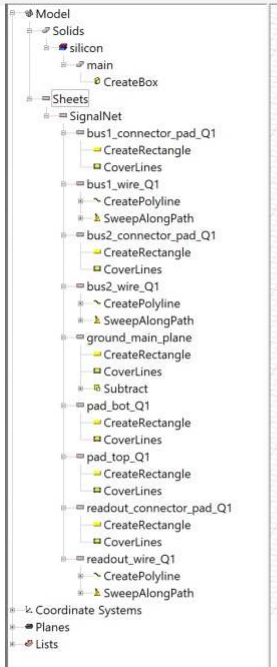
Yurke & Denker (1984), Devoret (1997), Burkard *et al.* (2004), Koch *et al.* (2007), …

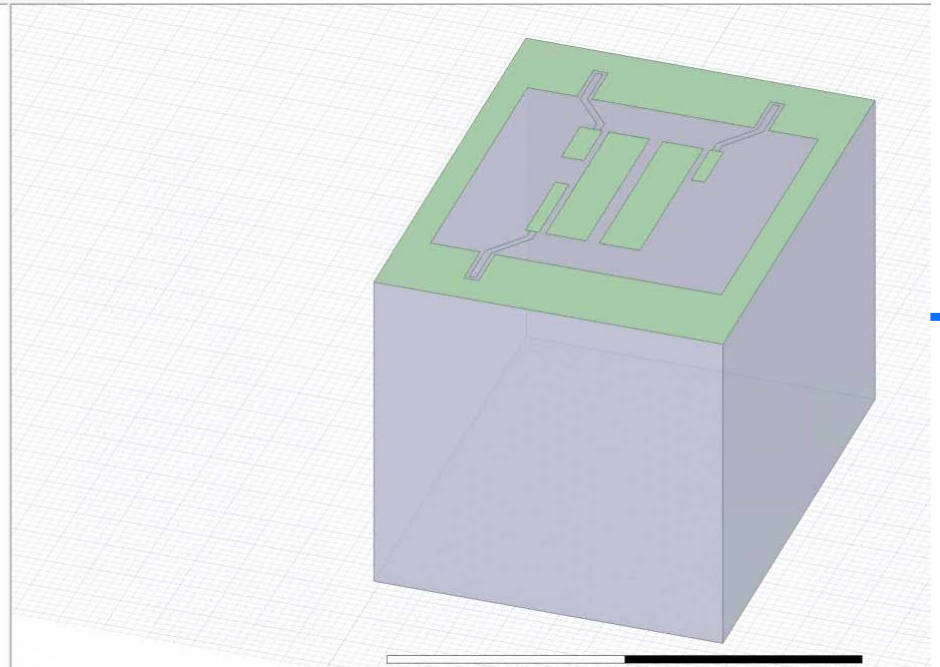
Metal -> Sim model/BC -> Analyze -> Capacitance matrix

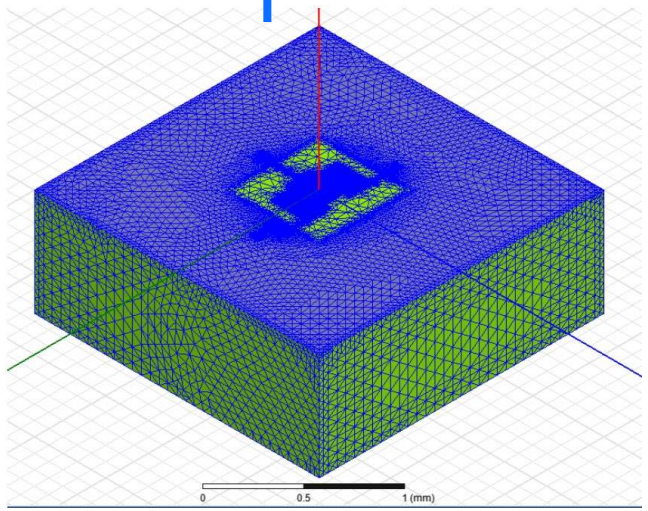




$$\mathbf{M} = \begin{array}{c} \\ n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{array} \begin{array}{c} \begin{array}{cccccc} n_0 & n_1 & n_2 & n_3 & n_4 & n_5 \end{array} \\ \begin{pmatrix} C_{0\Sigma} & -C_{01} & -C_{02} & -C_{03} & -C_{04} & -C_{05} \\ & C_{1\Sigma} & -C_{12} & -C_{13} & -C_{14} &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



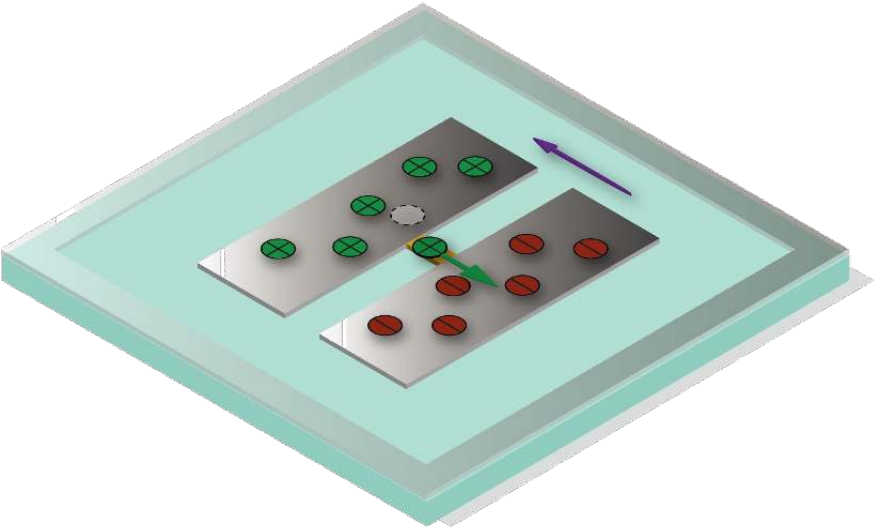


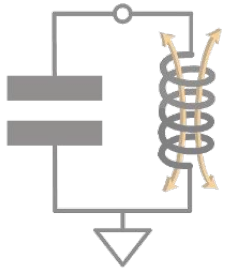


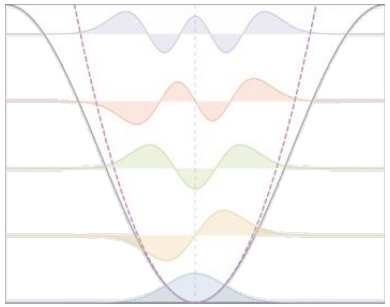
Minev & Gambetta, in prep (2020)

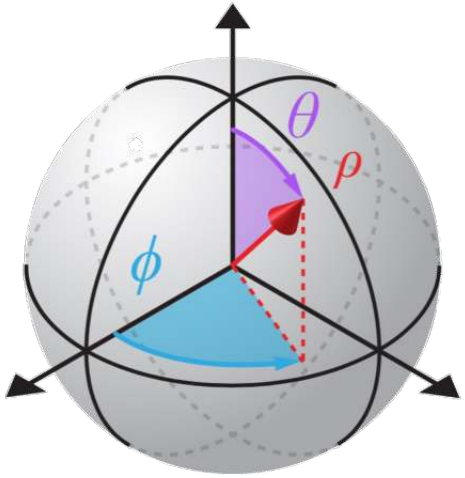
To design quantum hardware

Energy-participation-ratio (EPR) and Qiskit Metal









Zlatko K. Minev

IBM **Quantum**

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

@zlatko_minev zlatko-minev.com

Thank you

Quantum chip design flow

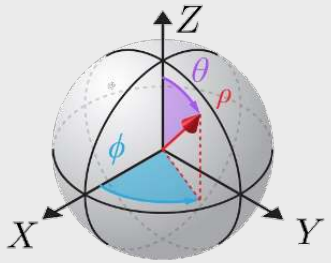
Concept

Quantum chip design flow

Complexity, Information, Accuracy

Concept

Hamiltonian

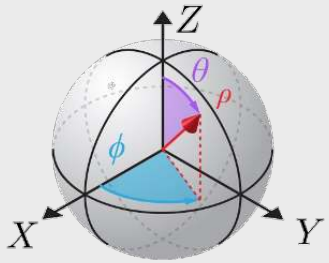


Quantum chip design flow

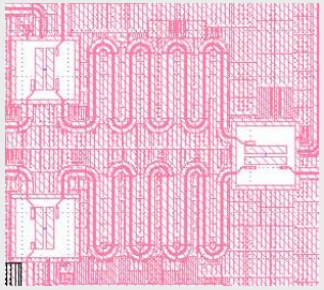
Complexity, Information, Accuracy

Concept

Hamiltonian



Layout

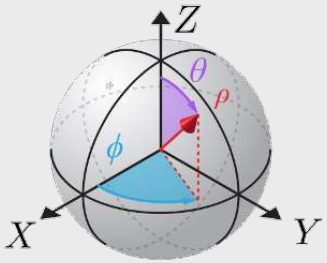


Quantum chip design flow

Complexity, Information, Accuracy

Concept

Hamiltonian



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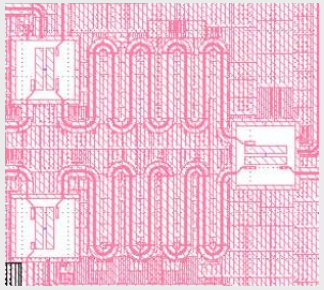
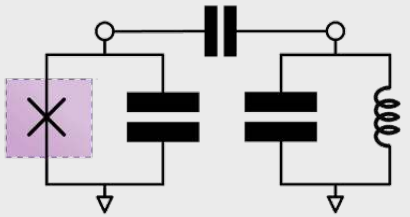


Electromagnetic Analysis

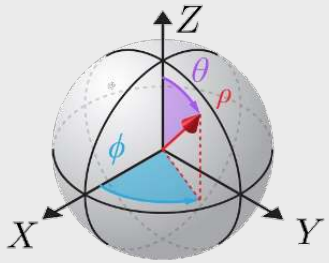


Quantum chip design flow

Complexity, Information, Accuracy

Concept

Hamiltonian



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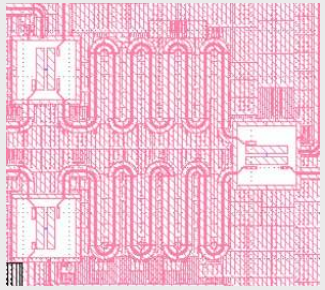
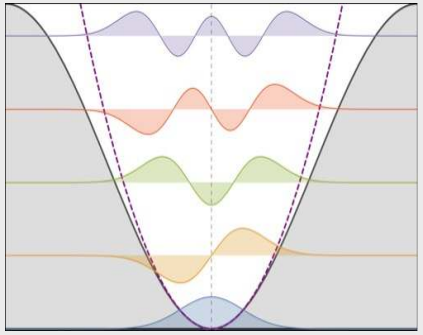
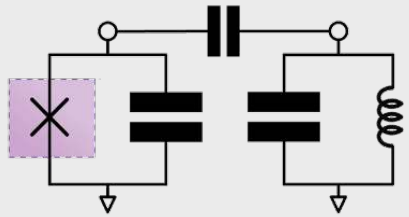


Quantum Analysis



Electromagnetic Analysis



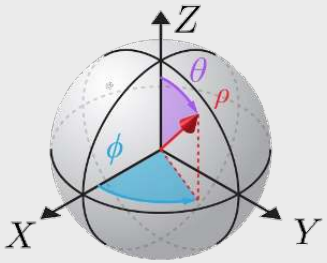
Quantum chip design flow

Complexity, Information, Accuracy

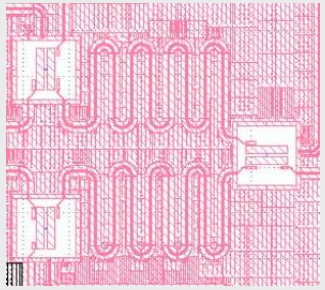
Risk, Cost, Time, Resources

Concept

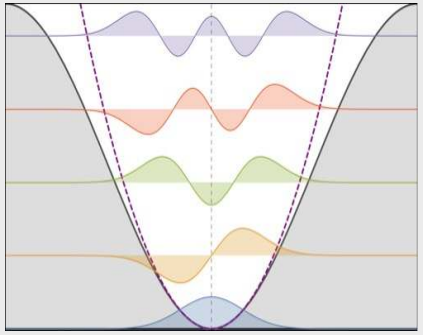
Hamiltonian



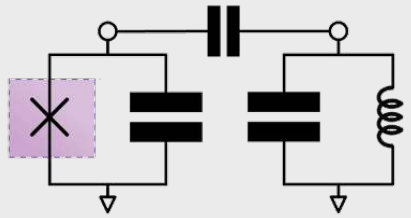
Layout



Quantum Analysis



Electromagnetic Analysis



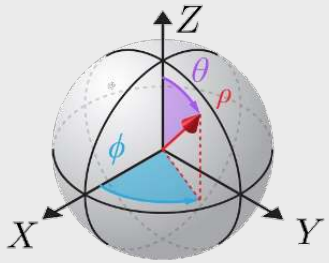
Quantum chip design flow

Complexity, Information, Accuracy

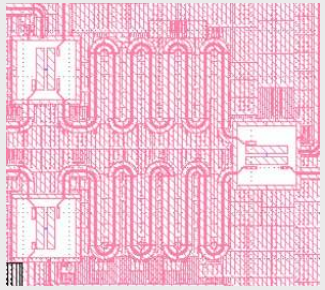
Risk, Cost, Time, Resources

Concept

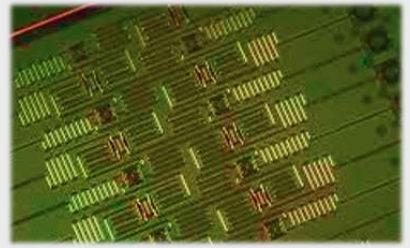
Hamiltonian



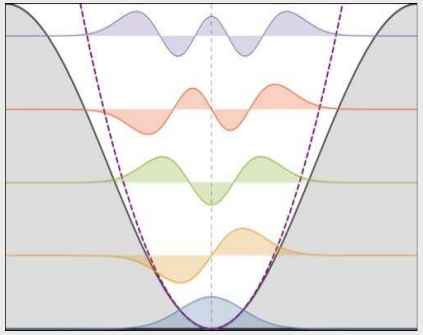
Layout



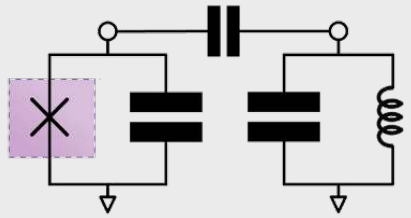
Fabrication



Quantum Analysis



Electromagnetic Analysis



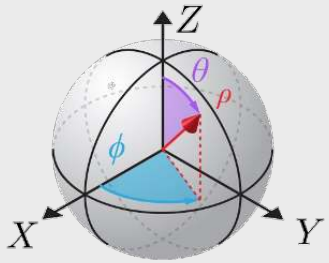
Quantum chip design flow

Complexity, Information, Accuracy

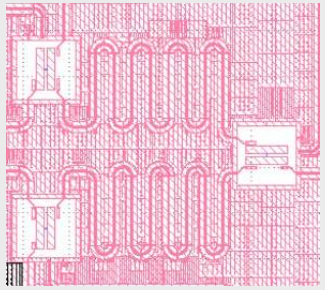
Risk, Cost, Time, Resources

Concept

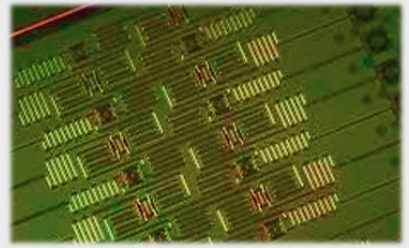
Hamiltonian



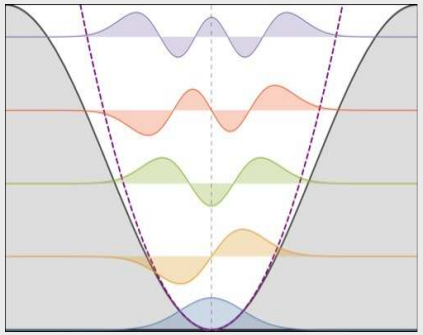
Layout



Fabrication

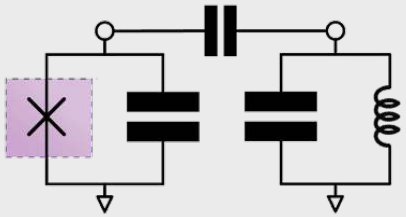


Quantum Analysis

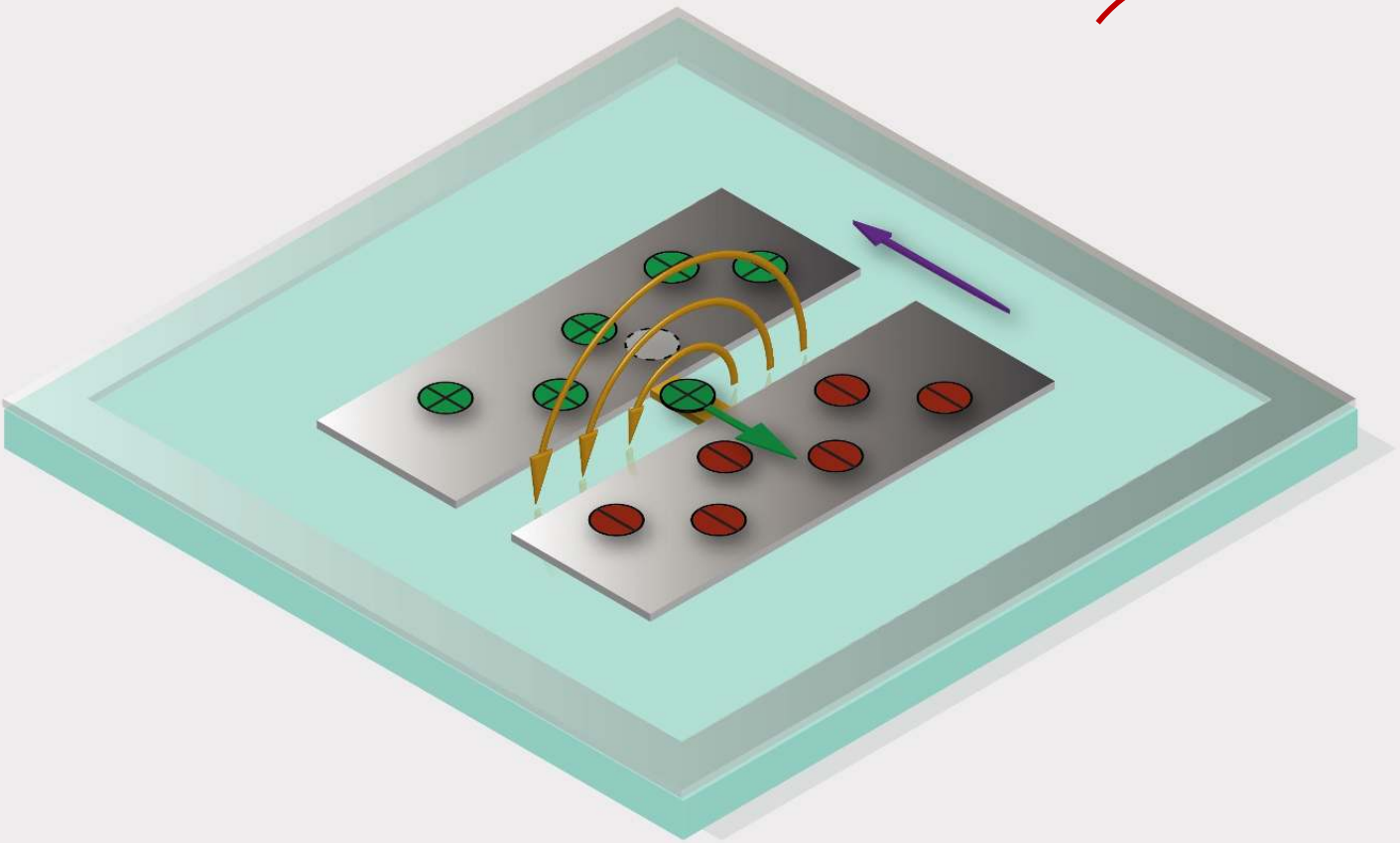


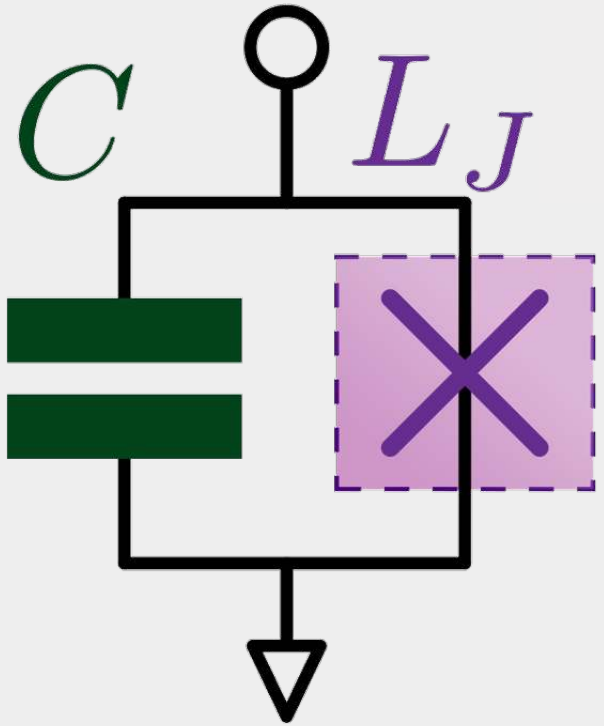
Project **Metal**

Electromagnetic Analysis



Transmon qubit: layout, electromagnetics, wavefunctions

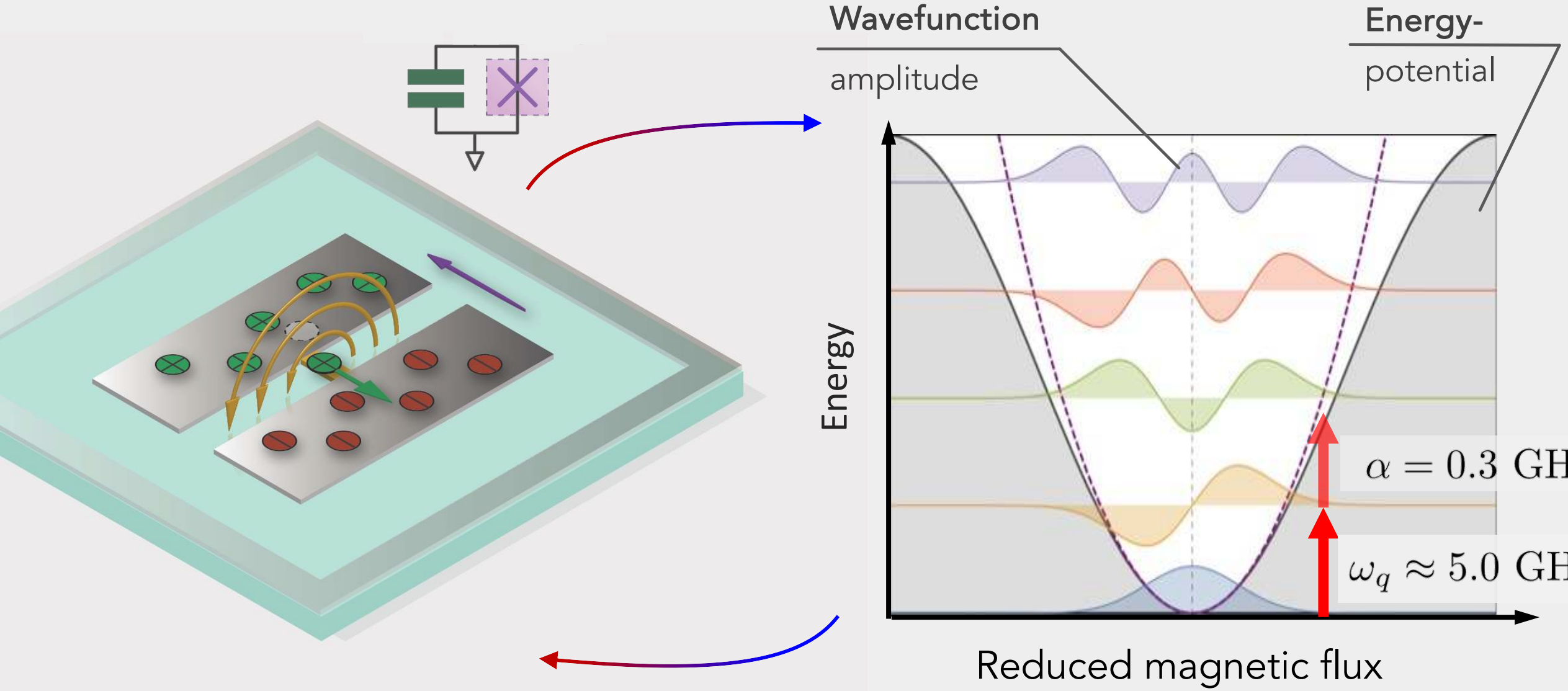




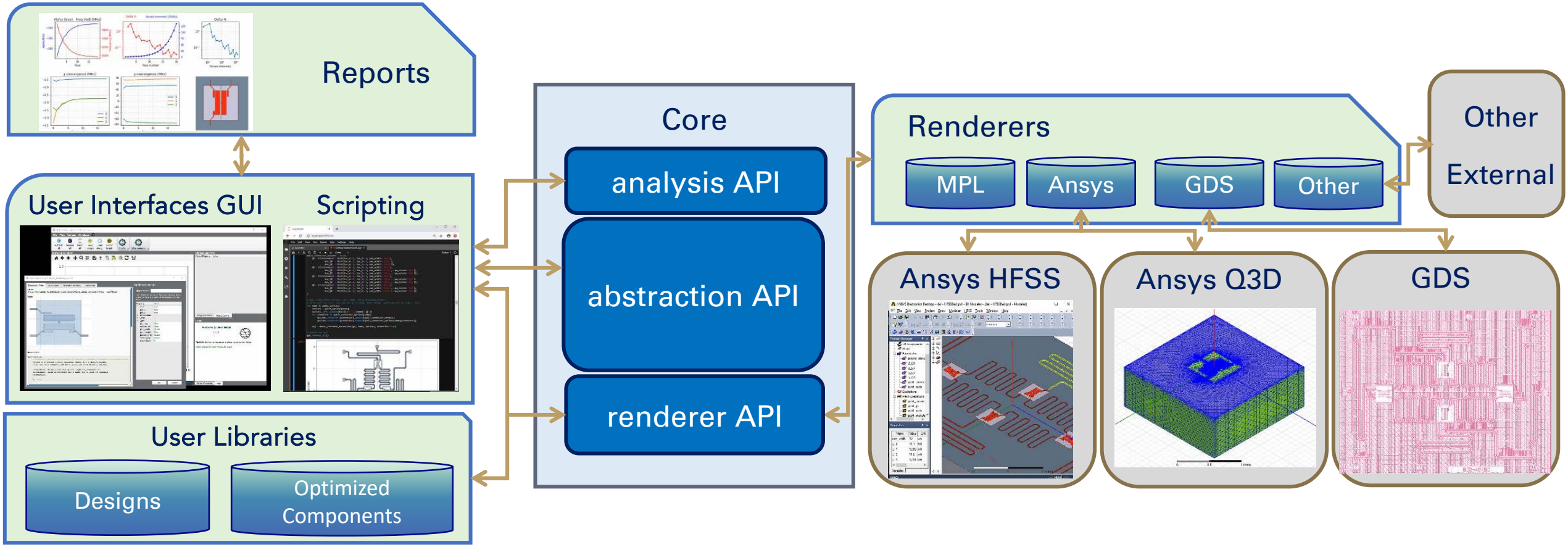
$$L_J = 14 \text{ nH} \qquad \omega_0 = \sqrt{\frac{1}{LC}} = 5.3 \text{ GHz}$$

$$C_J = 65 \text{ fF} \qquad Z = \sqrt{\frac{L}{C}} \approx 450 \ \Omega$$

Transmon qubit: layout, electromagnetics, wavefunctions



Qiskit Metal Container Diagram

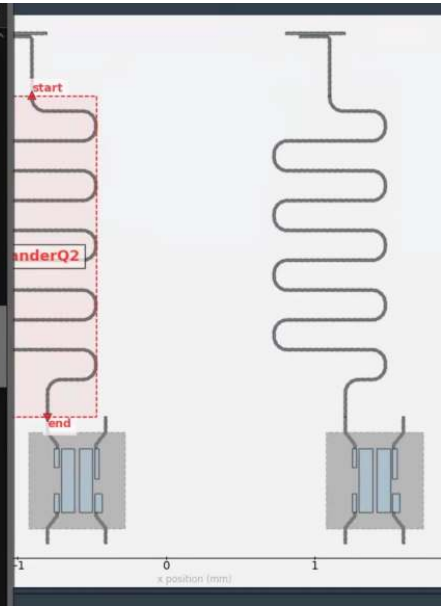


Hanger

```
    pin_inputs=Dict(
        start_pin=Dict(
            component='TQ2',
            pin='second_end'),
        end_pin=Dict(
            component='Q2',
            pin='a')),
    lead=Dict(
        start_straight='0.1mm'),
    **ops
)

meanderQ1 = RouteMeander(design, 'meanderQ1', options=options1)
meanderQ2 = RouteMeander(design, 'meanderQ2', options=options2)

gui.rebuild()
gui.autoscale()
```

Add 2 open to grounds at the ends of the horizontal CPW.

```
otg1 = OpenToGround(design, 'otg1', options = dict(pos_x='3mm',
                                                   pos_y='3mm'))
otg2 = OpenToGround(design, 'otg2', options = dict(pos_x = '-3mm',
                                                   pos_y='3mm',
                                                   orientation='1

gui.rebuild()
gui.autoscale()
```




```
WindowsPath('C:/_code_ibmq/qiskit-metal-public/guide/6 Analysis/ansys.png')
```

```
hfss.add_sweep(setup_name="Setup",
               name="Sweep",
               start_ghz=4.0,
               stop_ghz=8.0,
               count=2001,
               type="Interpolating")
```

```
INFO 10:41AM [get_setup]:       Opened setup `Setup`  (<class 'pyEPR.ansys.HfssDMSetup'>)
```

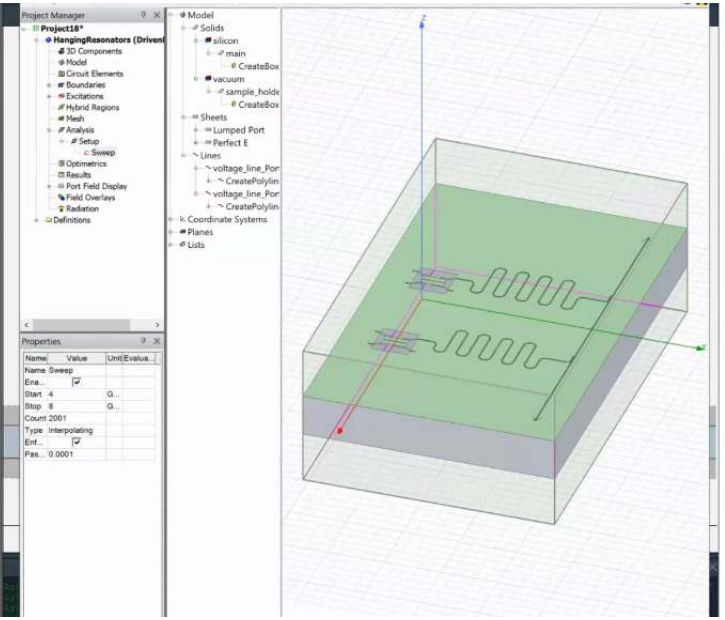
```
<pyEPR.ansys.HfssFrequencySweep at 0x28168fbbb88>
```

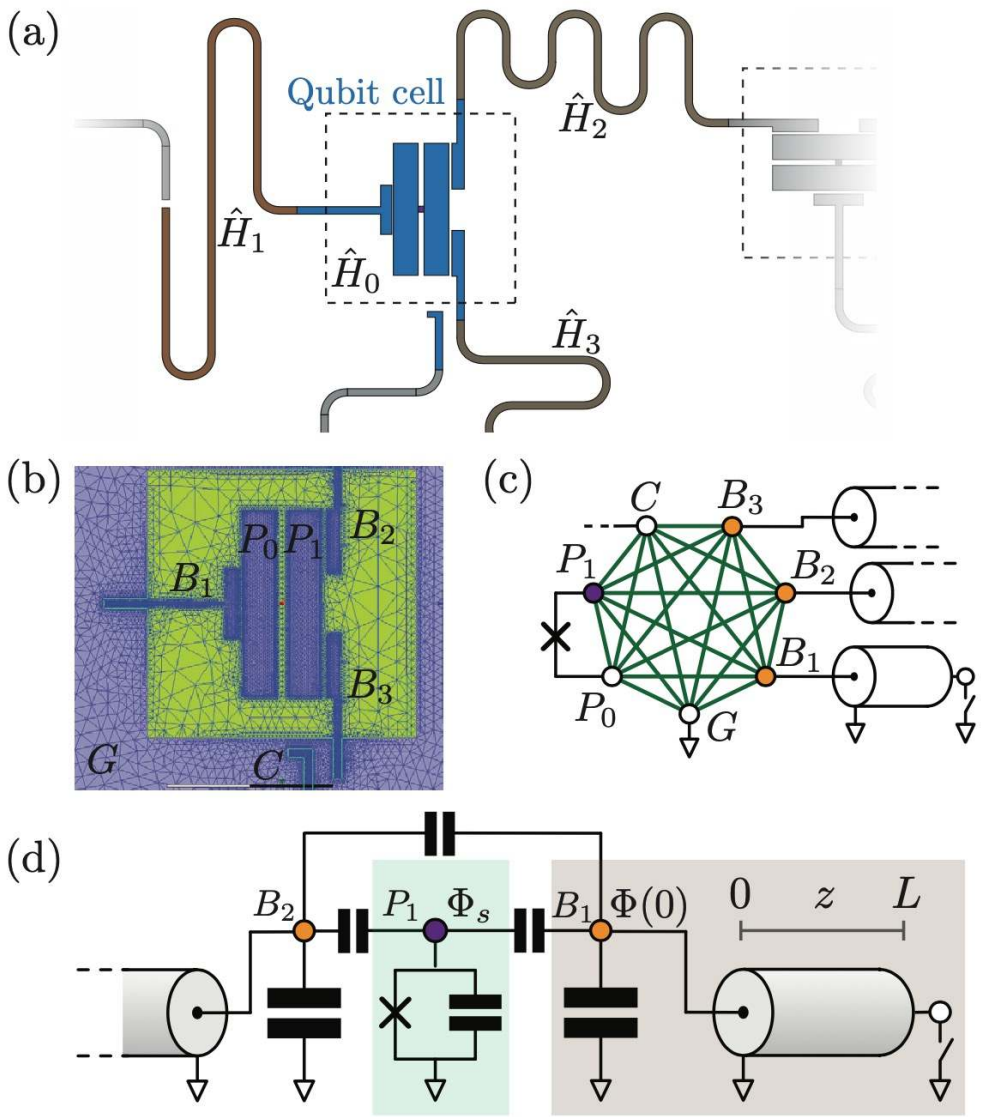
```
hfss.analyze_sweep('Sweep', 'Setup')
```

```
INFO 10:42AM [get_setup]:       Opened setup `Setup`  (<class 'pyEPR.ansys.HfssDMSetup'>)
INFO 10:42AM [analyze]: Analyzing setup Setup : Sweep
```

```
hfss.plot_params(['S11', 'S21'])
```

```
hfss.disconnect_ansys()
```



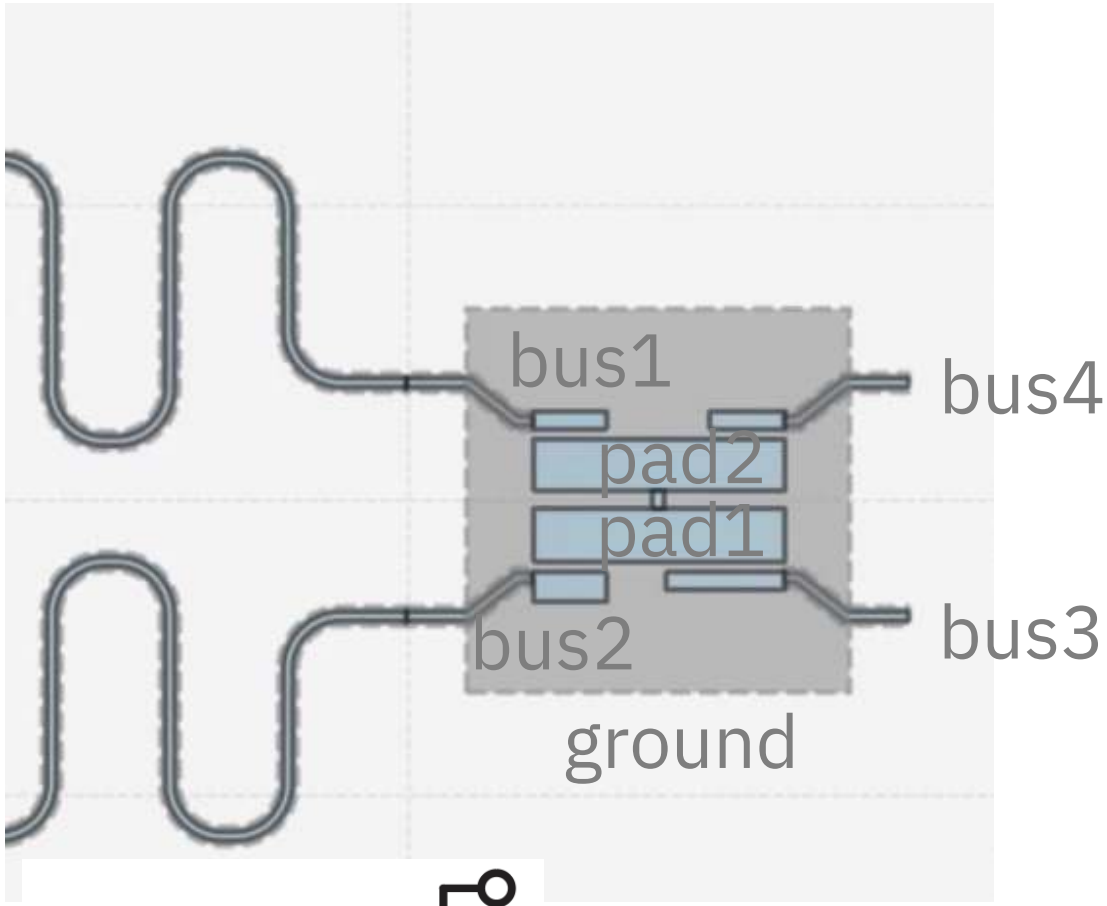


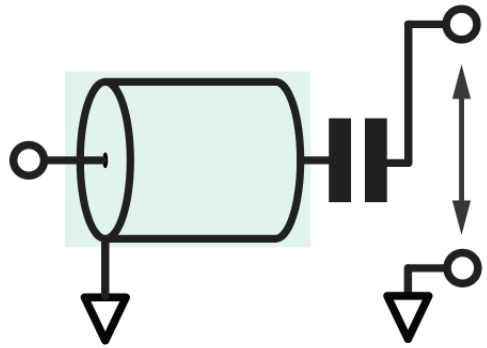
$$\hat{H}_{\text{full}} = \hat{H}_0 + \sum_{n=1}^{K} \hat{H}_n + \sum_{n=0}^{K} \sum_{m=n+1}^{K} \hat{H}_{nm} \,, \qquad (1)$$

$$\hat{H}_{nm} = \hat{Q}_n \hat{Q}_m / C_{nm}^{\text{eff}} + \hat{\Phi}_n \hat{\Phi}_m / L_{nm}^{\text{eff}} \,, \qquad (2)$$

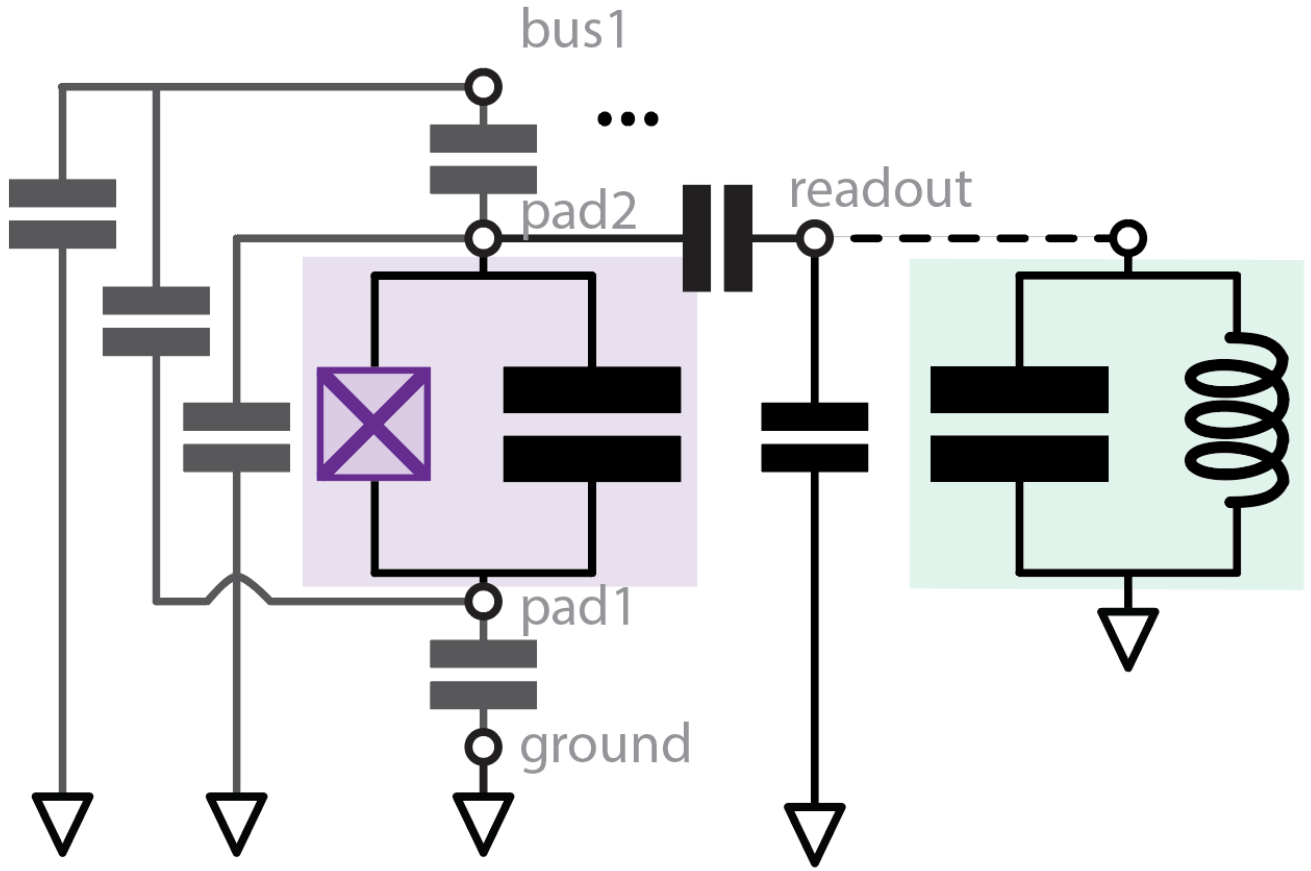
$$\hat{H}_{nm} = \hat{Q}_n \hat{Q}_m / C_{nm}^{\text{eff}} = \hbar g_{nm} \hat{A}_n \hat{B}_m \,,$$

Transmon coupled to other systems



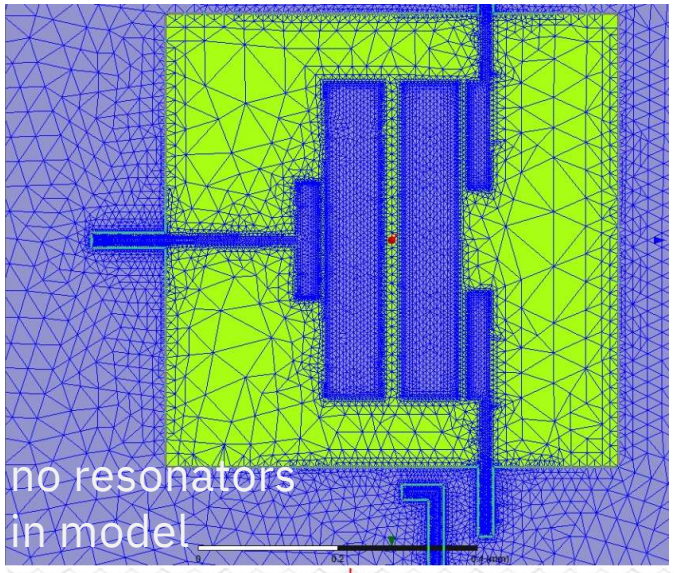


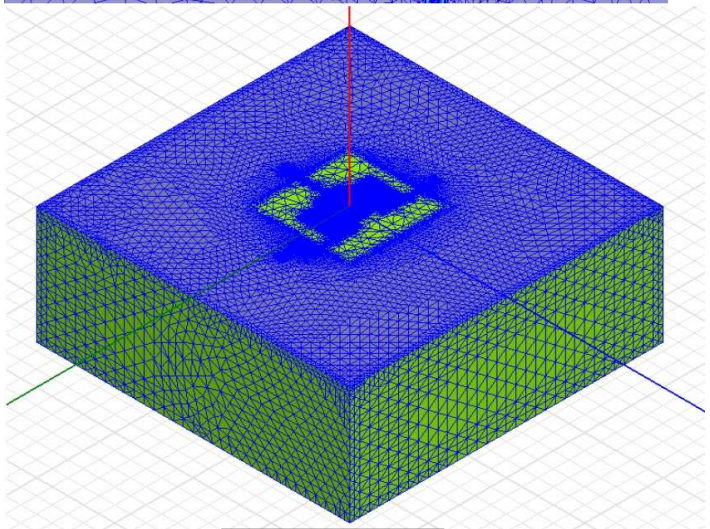
$$\hat{H}_{\text{full}} = \hat{H}_{\text{sys}}\left(\hat{a}\right) + \hat{H}_{\text{ext}}\left(\hat{b}_n\right) + \hat{H}_{\text{int}}\left(\hat{a}, \hat{b}_n\right)$$



Lumped-oscillator model (LOM)

Quasi-static solver (Q3D)





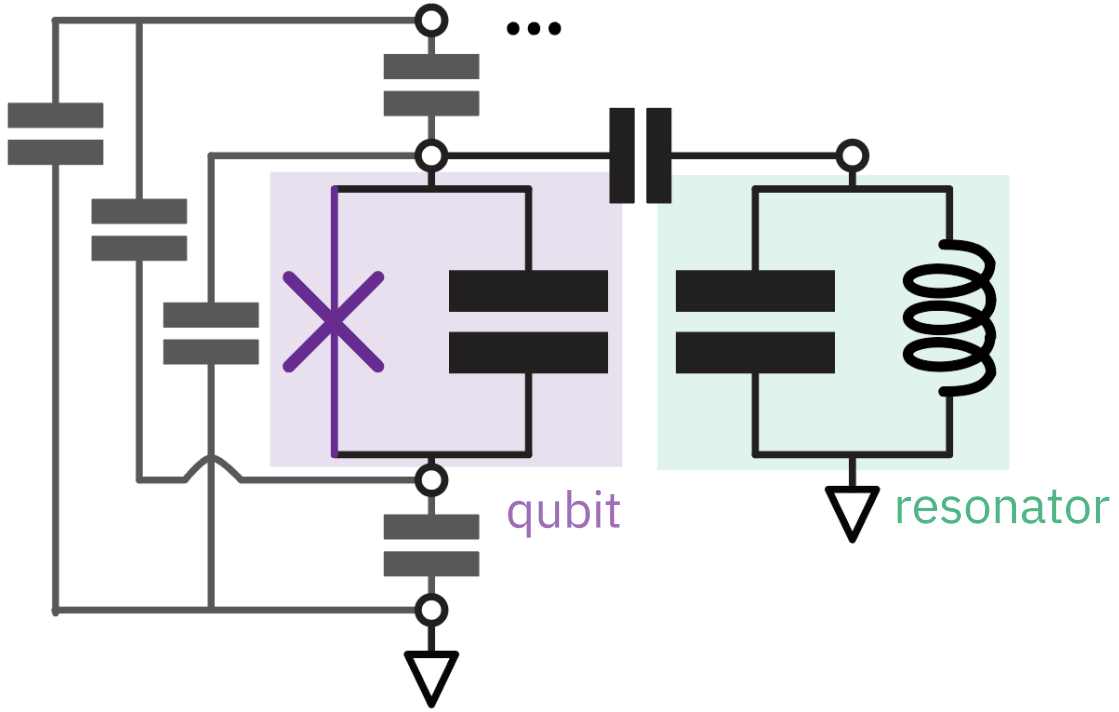
Provide

$C_{nn'}$

ω_q

ω_r

Equivalent lumped model

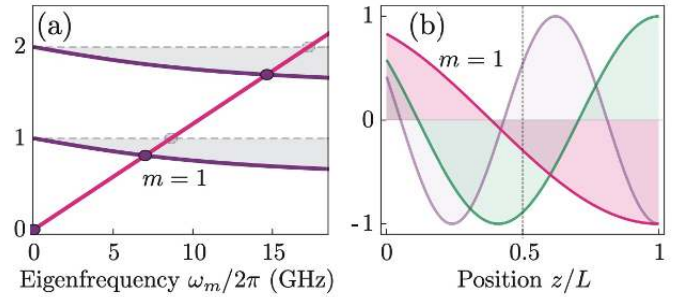


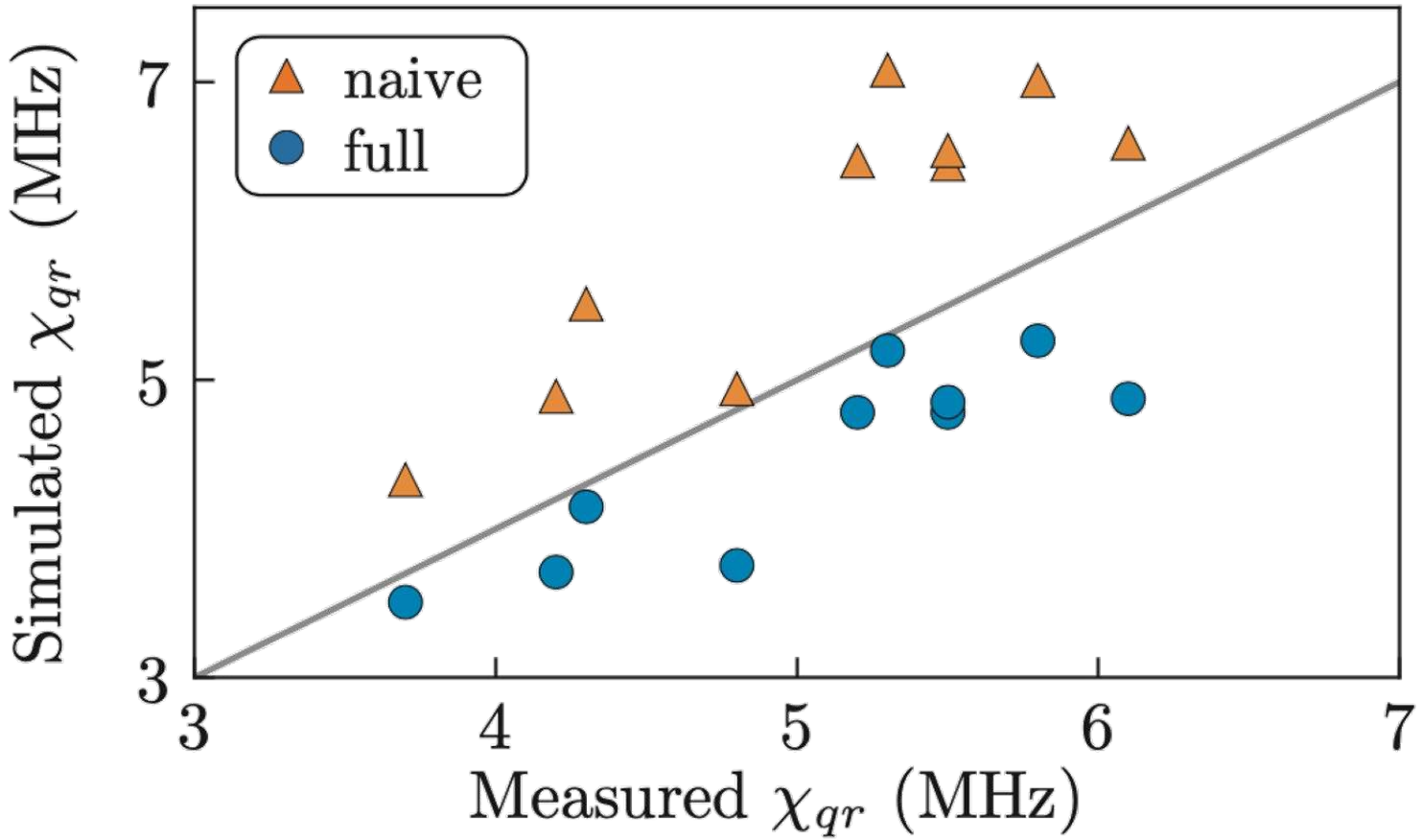
approximate
not suitable for 3D
some distributed effects beyond capture

Minev & Gambetta, in prep (2020)

Yurke & Denker (1984), Devoret (1997), Burkard *et al.* (2004), Koch *et al.* (2007), …

Improved precision and agreement





Non-linear interaction with EPR

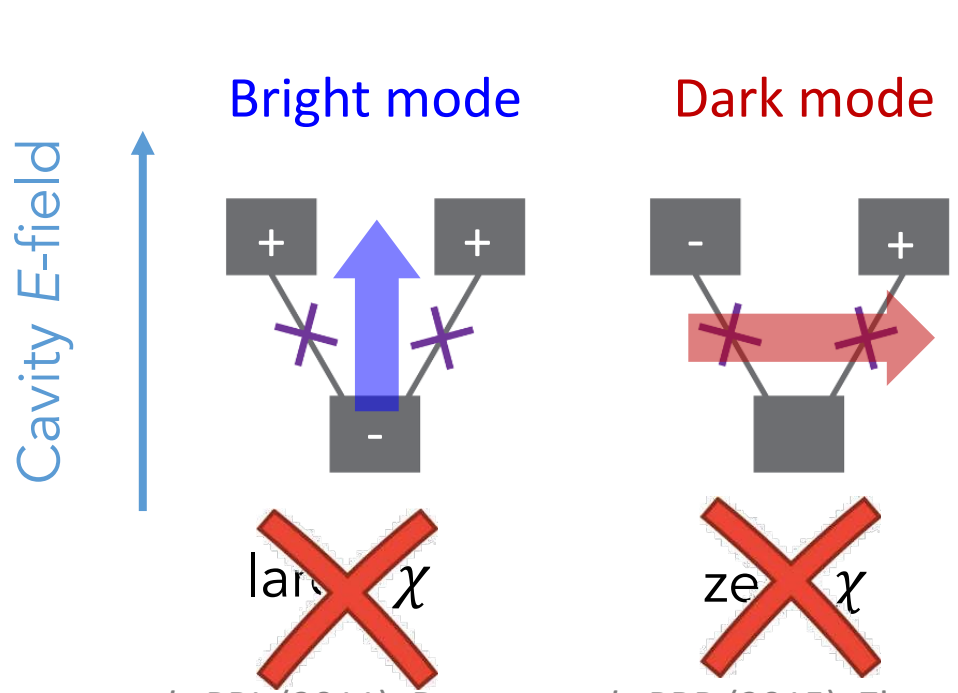
Non-linear interactions in terms of energy overlap

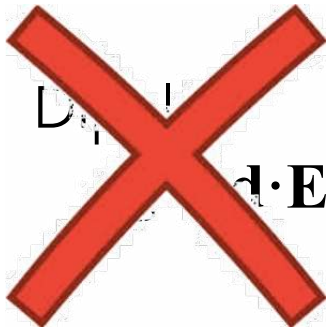
$$\chi_{mn} = \sum_{j=1}^{J} \frac{\hbar\omega_m\omega_n}{4E_j} p_{mj}p_{nj}$$

Energy participation overlap

(only variable subject to significant variation)

Intuition with dipole and EPR





same p_{mj} for both χs are ***equal***

For device, see

Gambetta *et al.*, PRL (2011), Srinivasan *et al.*, PRL (2011), Dumur *et al.*, PRB (2015), Zhang *et al.*, Nature JQI (2017), Minev *et al.*, arXiv (2018)

Physical insights with EPR

Non-linear interactions in terms of energy overlap

$$\chi_{mn} = \sum_{j=1}^{J} \frac{\hbar\omega_m\omega_n}{4E_j} p_{mj}p_{nj}$$

Energy participation overlap

(only variable subject to significant variation)

Fundamental constraints

What circuits/parameters can and cannot be realized?

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

Arbitrary strength non-linear interaction can be calculated

Charge dispersion

ω_θ = 6.50 GHz

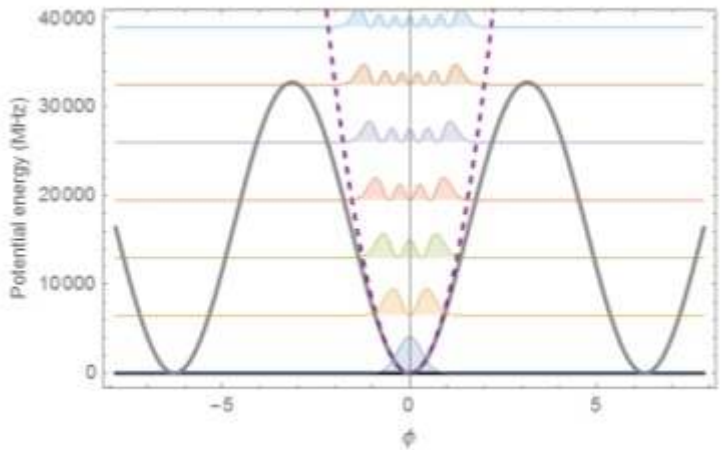
$\alpha^{(4)}$ = 322.00 MHz

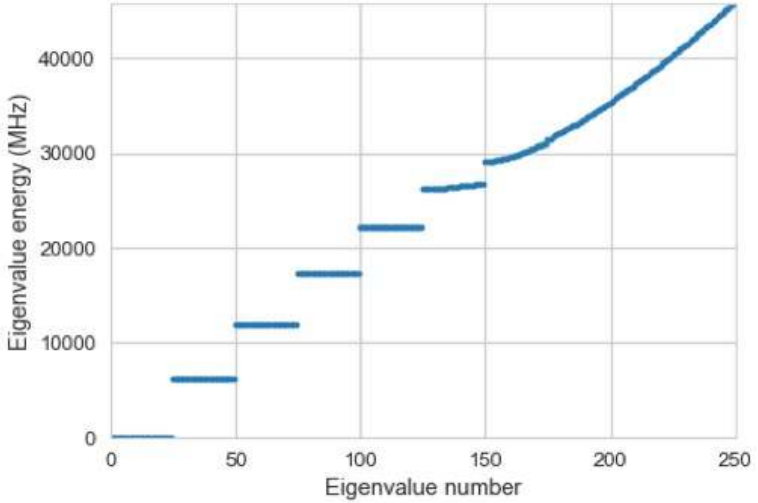
ϕ_{ZPF} = 0.45

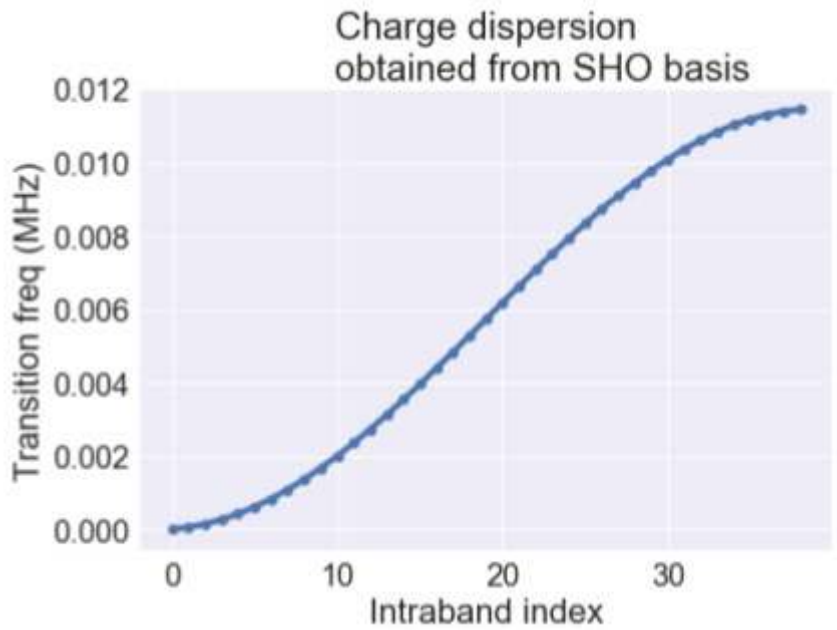
E_J = 16.40GHz

E_C = 0.32 GHz (E_J/E_C=50.90)

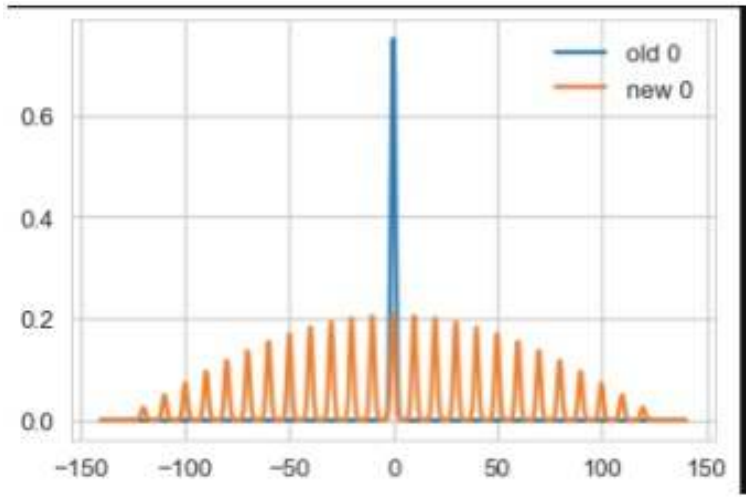
Dispersion =-12.90 KHz







|psi|^2



\phi