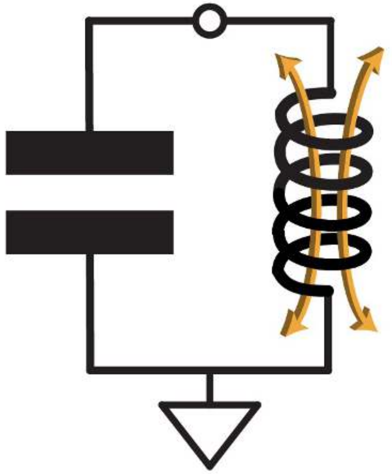
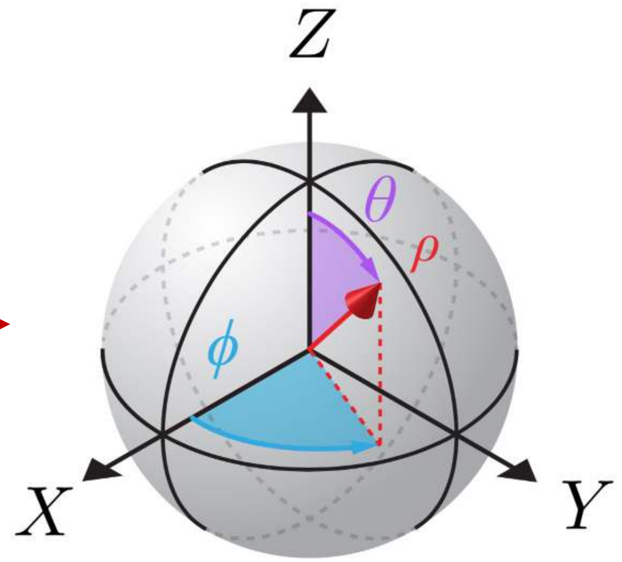
Superconducting Qubits 101

Making Your First Qubit From an Oscillator

Introduction to Circuit Quantum Electrodynamics (cQED)





Zlatko K. Minev

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

What is a real qubit?

How can you design, control, and measure a real qubit?

Easy?

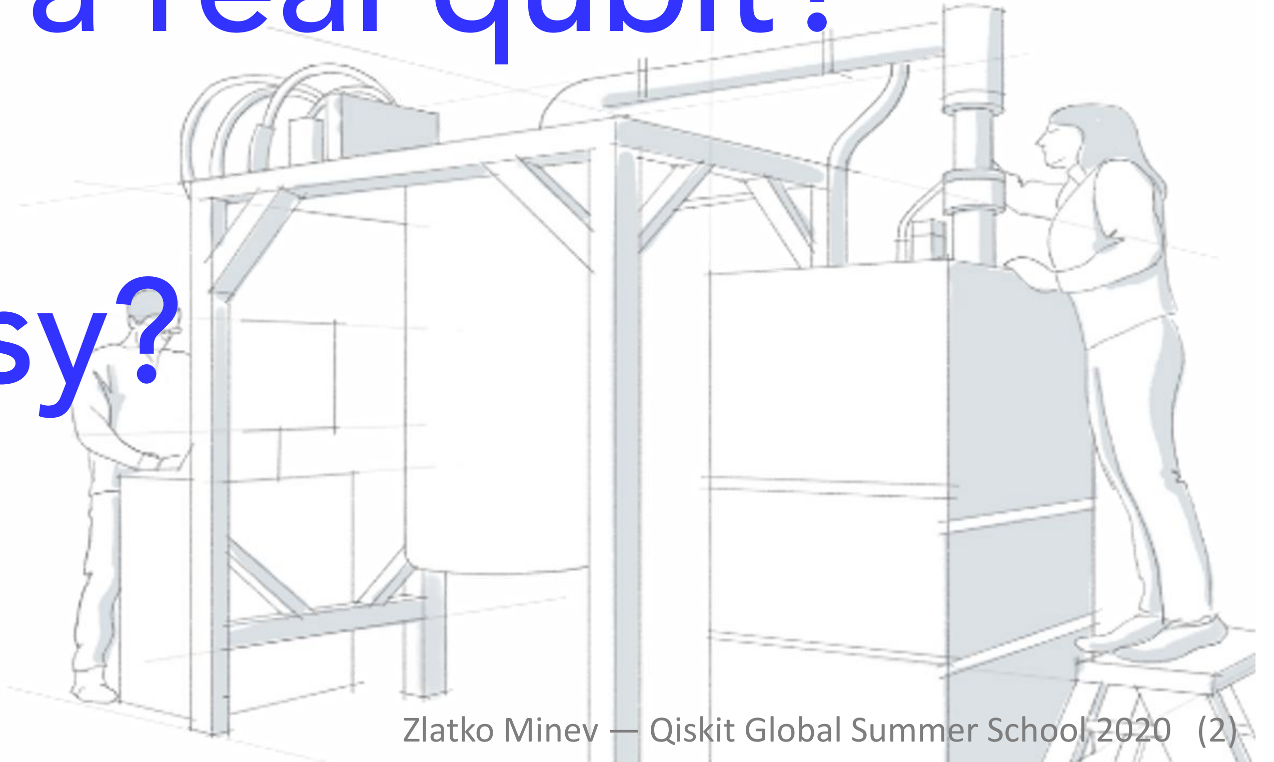
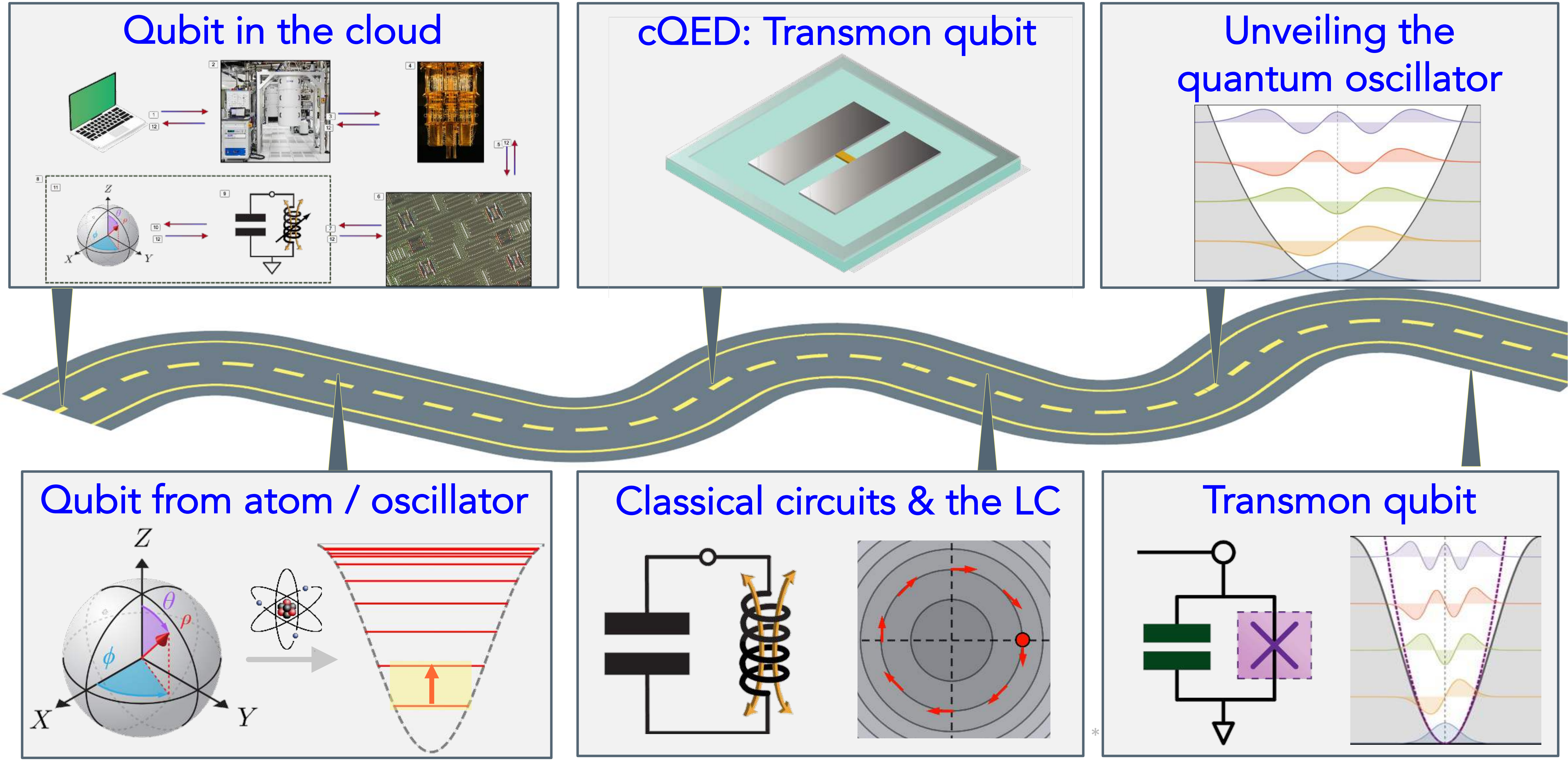
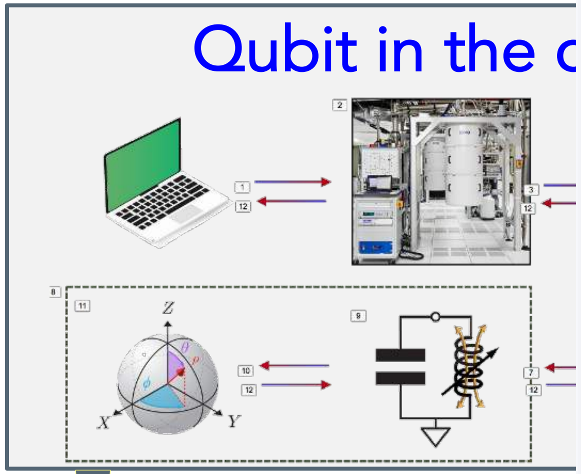
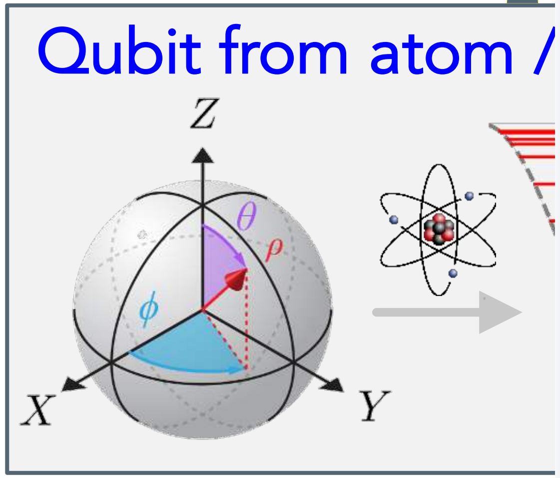


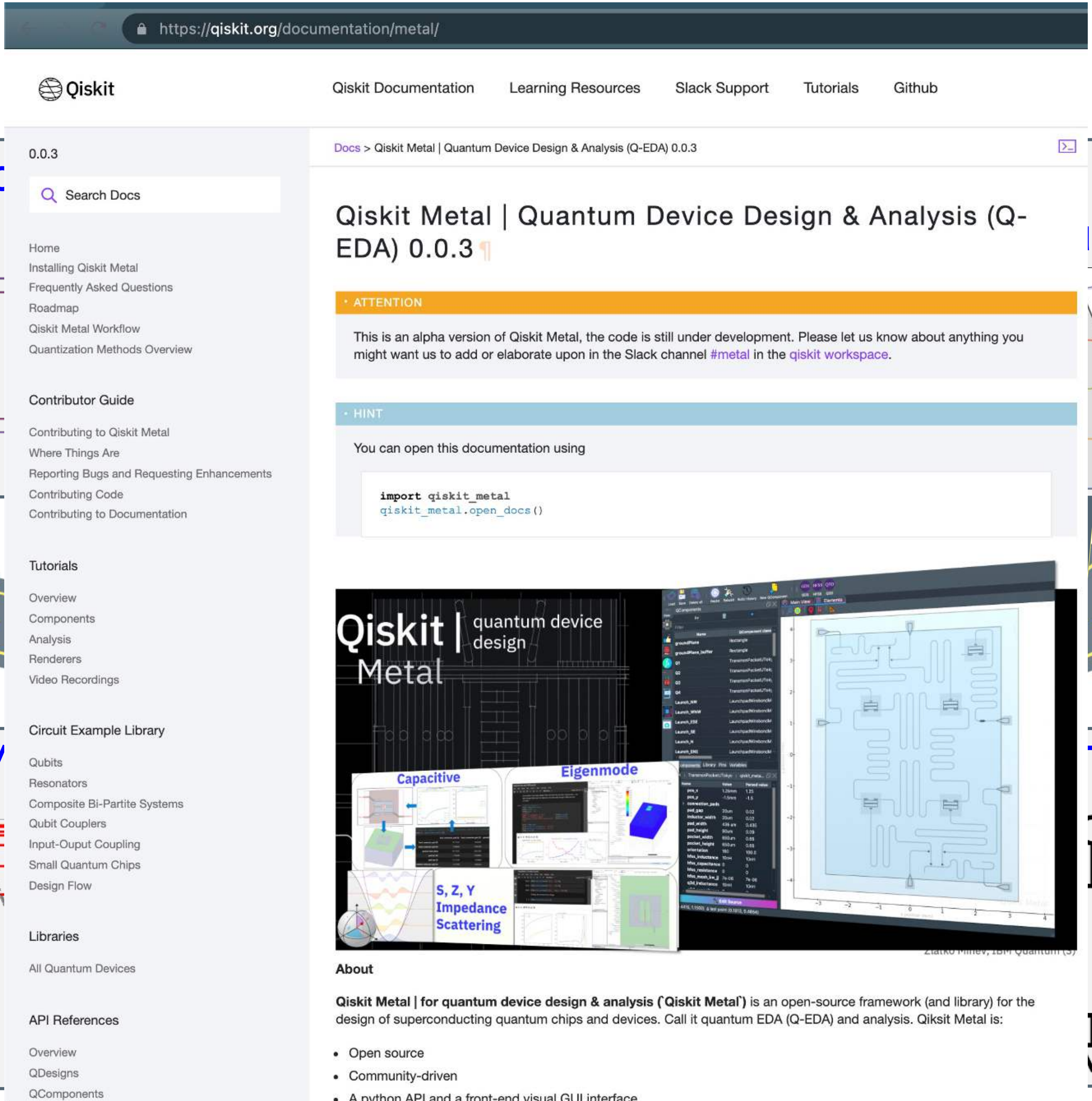
Illustration: IBM Qiskit Textbook

On the road ahead








https://qiskit.org/documentation/metal/

Qiskit

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0.0.3

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Contributing to Documentation

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Circuit Example Library

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

Libraries

All Quantum Devices

API References

Overview
QDesigns
QComponents

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

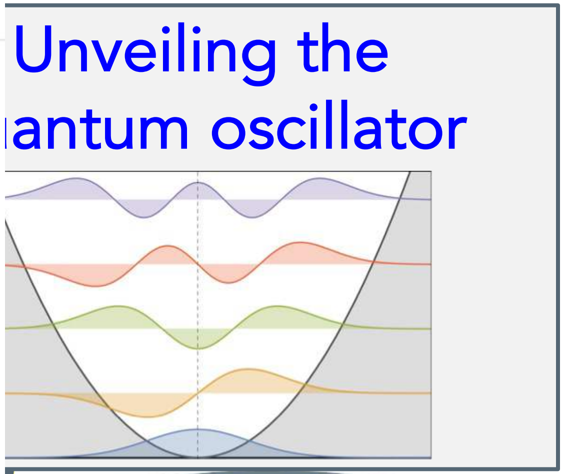
You can open this documentation using

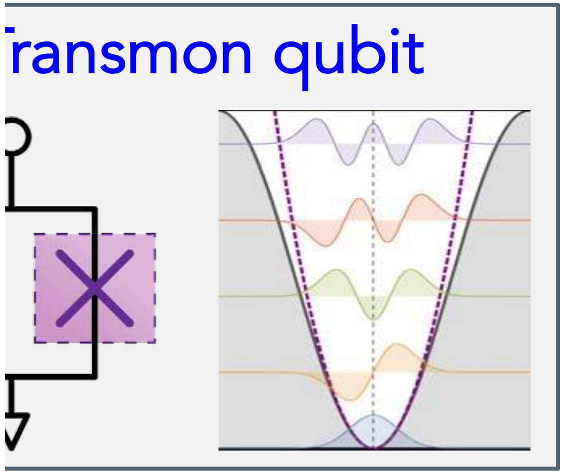
```
import qiskit_metal
qiskit_metal.open_docs()
```


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
- A python API and a front-end visual GUI interface





This Lecture

Introductory and skill reaffirming

Don't need to know much going in, but we will go far

Advanced material

Examples: simplest, most practical examples

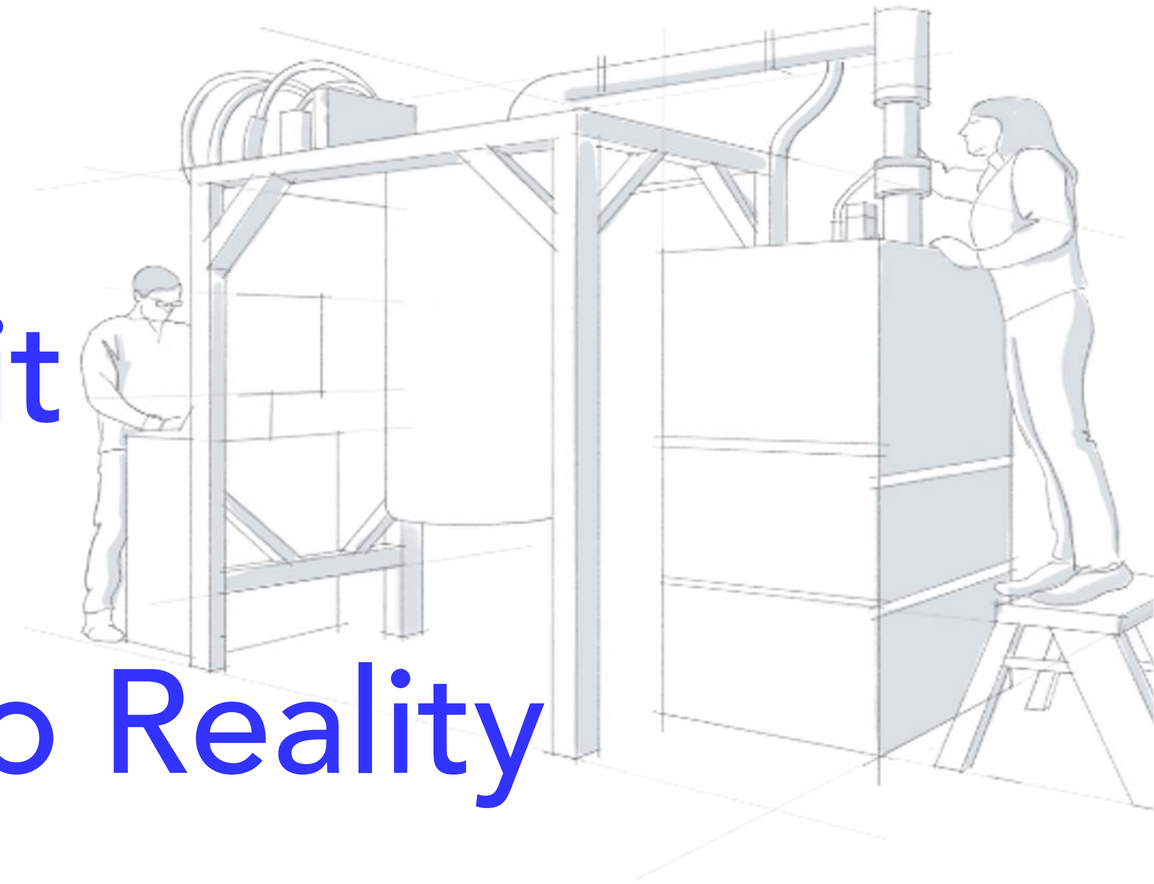
Step by step

Ask questions!

Tightly integrated work by Dr. Thomas McConkey!

qiskit.org/metal -> docs -> videos -> E02

Icons here by FreePik. Dangerous bend symbol based on Donald Knuth.

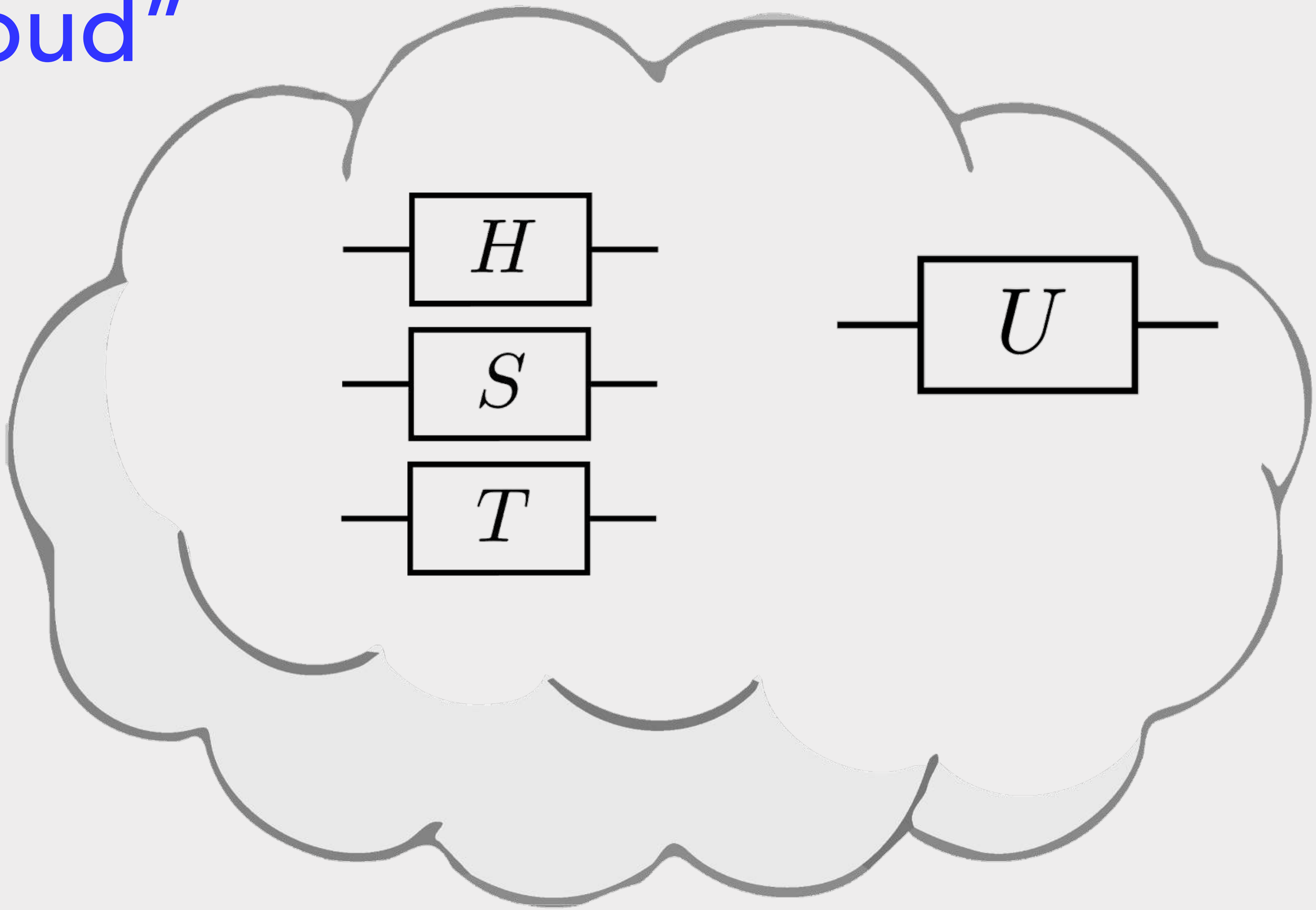


Qubit

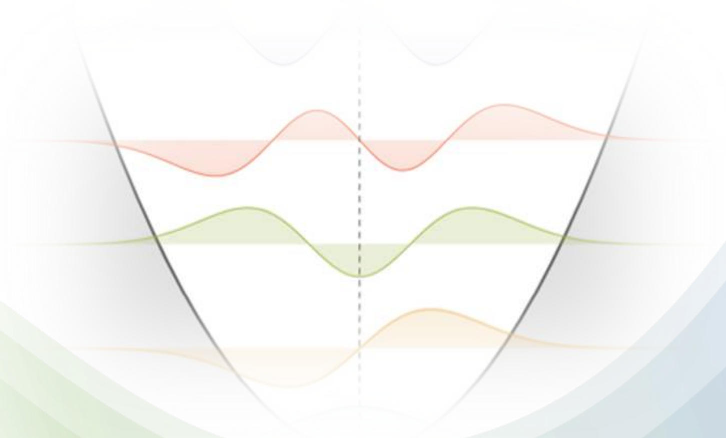
From Idea to Reality

THE BIG PICTURE
before calculations

“Quantum cloud”

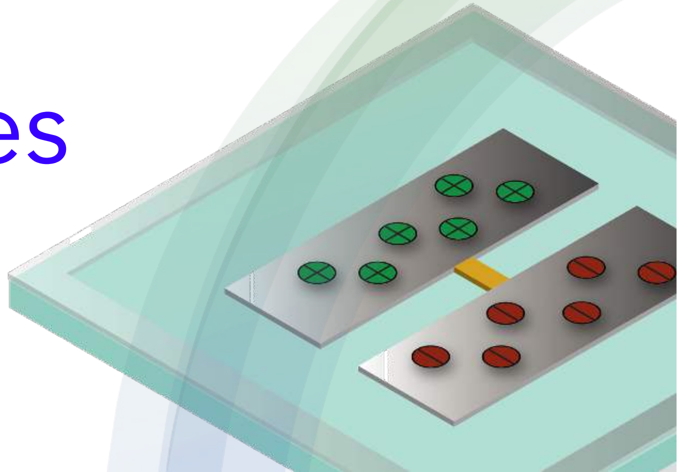


Laptop image: rawpixel.com; Photos: IBM



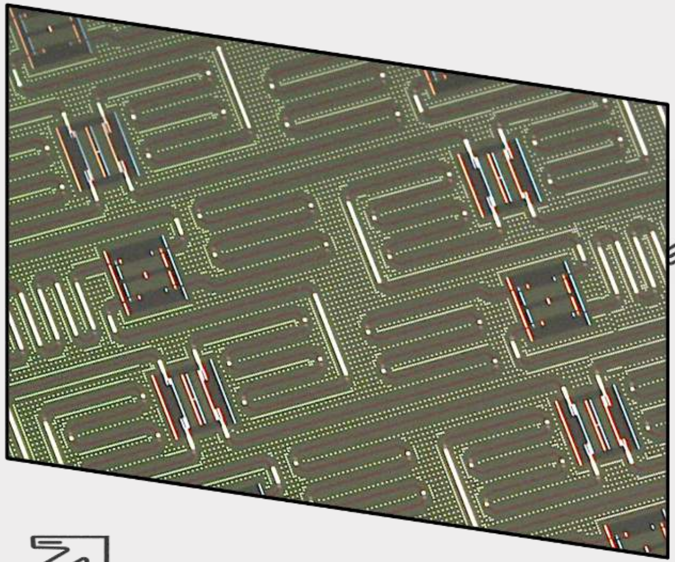
"Quantum phenomena do *not* occur in a Hilbert space, they occur in a laboratory."

Asher Peres

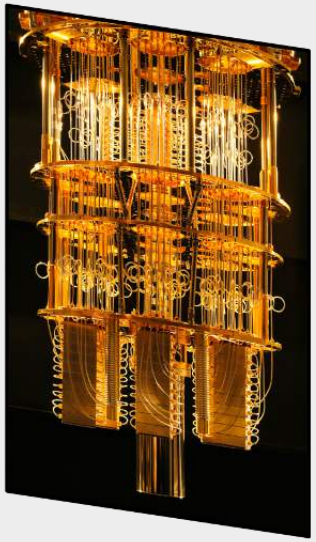


Quantum in the cloud or lab

Superconducting qubits

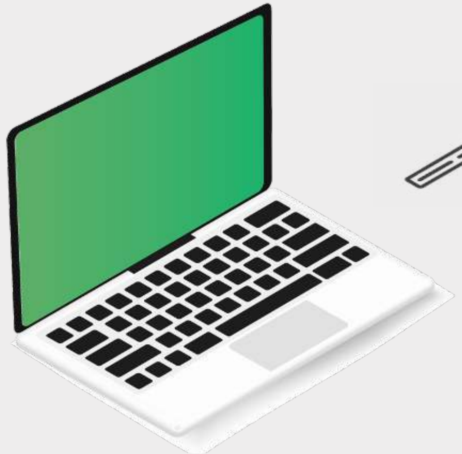


Quantum-device chip



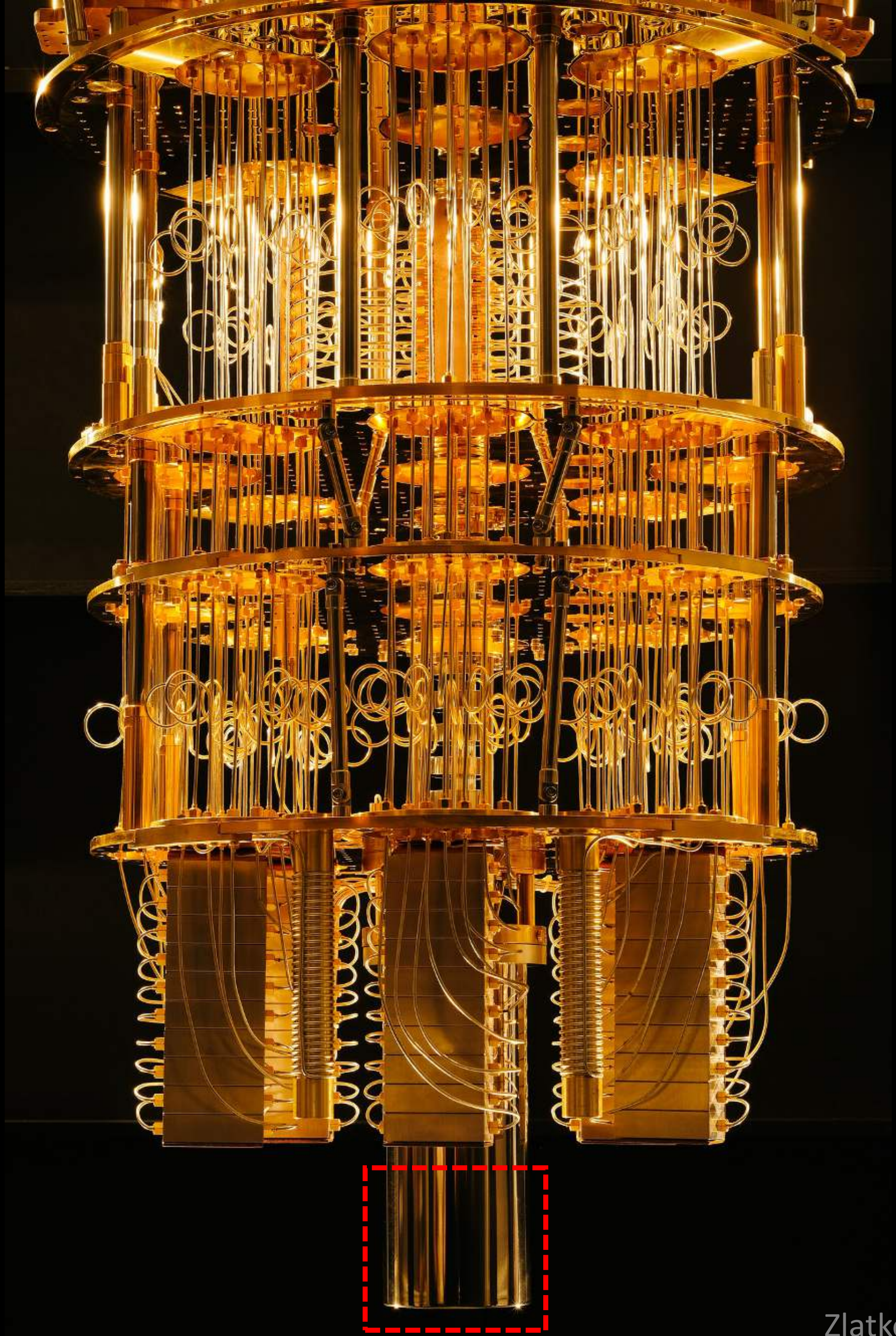
Cryogenic environment

Lab / cloud facility

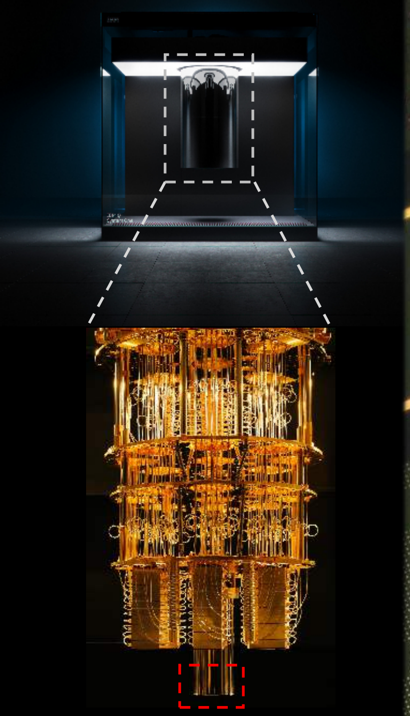


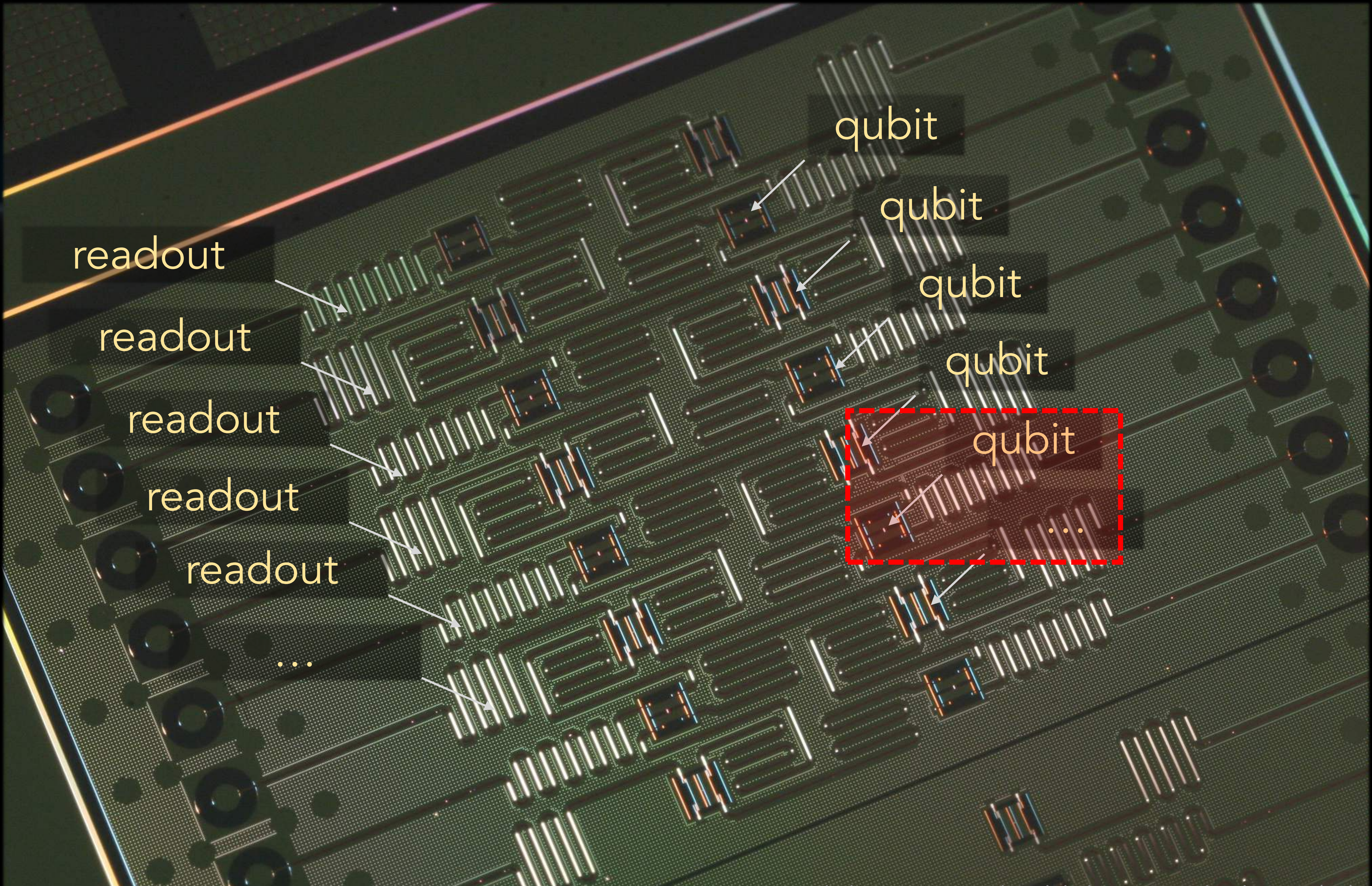
Quantum community

Laptop image: rawpixel.com; Photos: IBM

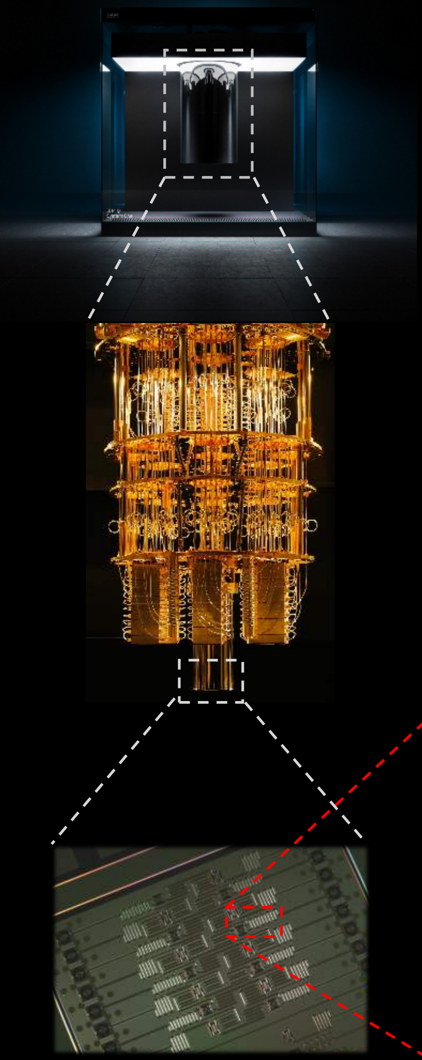


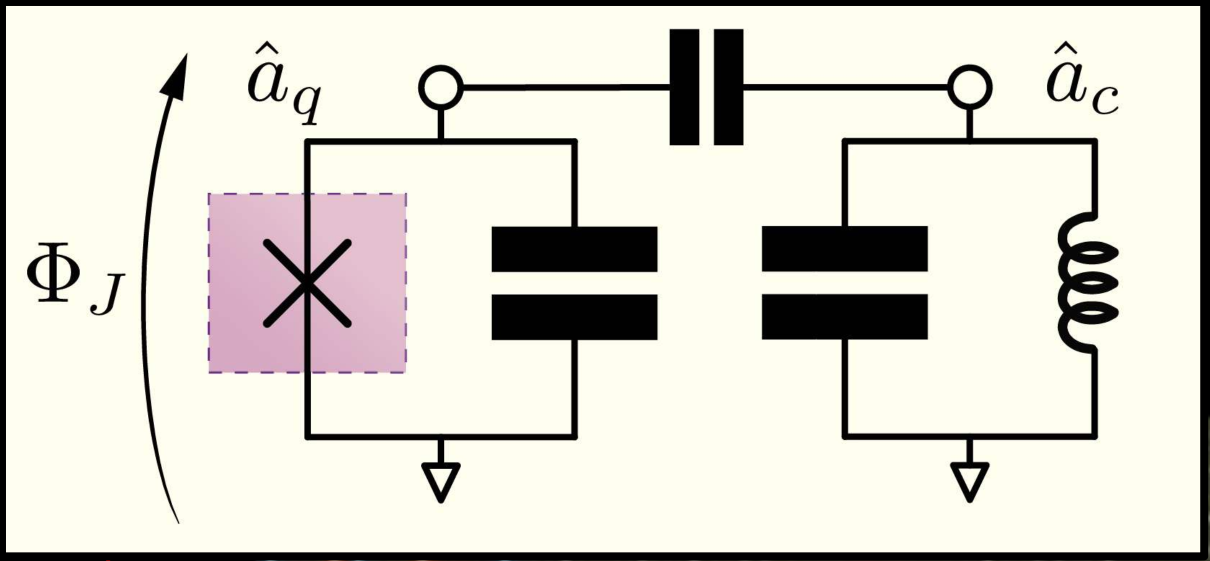
Operation at
15 mK (-273.13 °C)

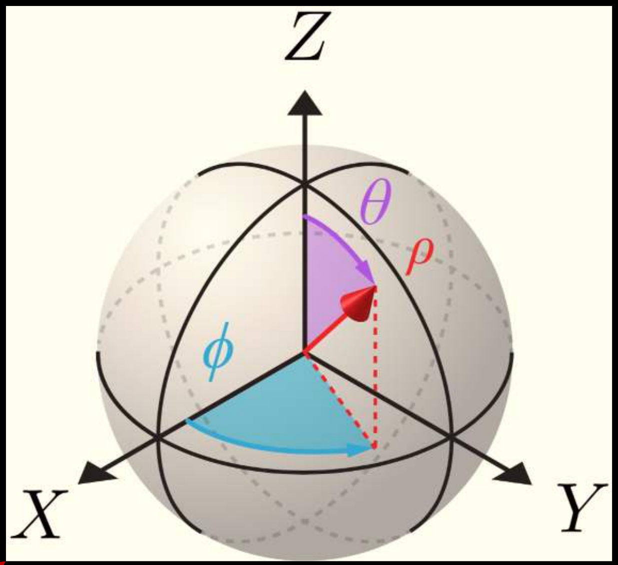


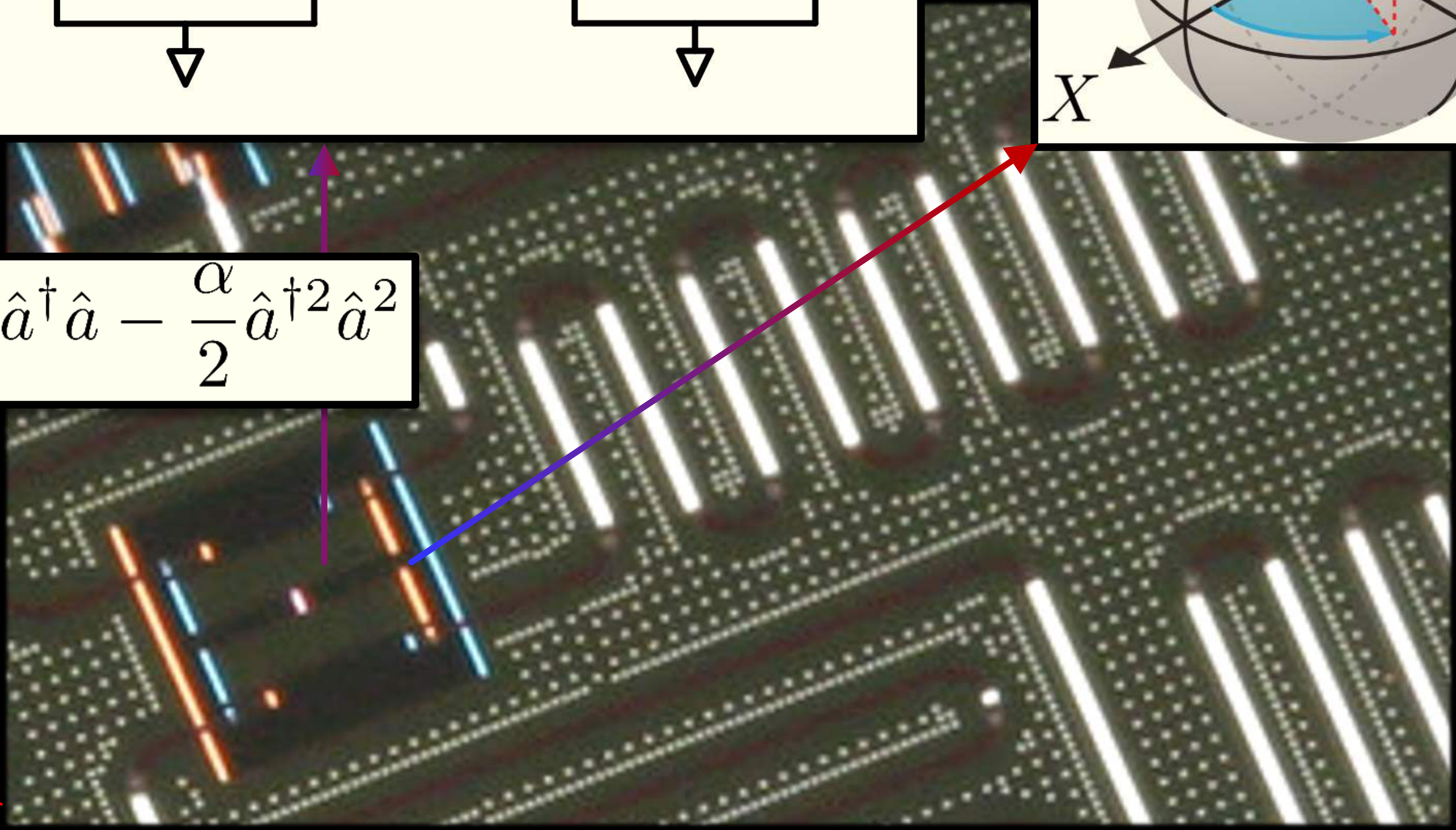


qubit
qubit
qubit
qubit
qubit
...
readout
readout
readout
readout
readout
...





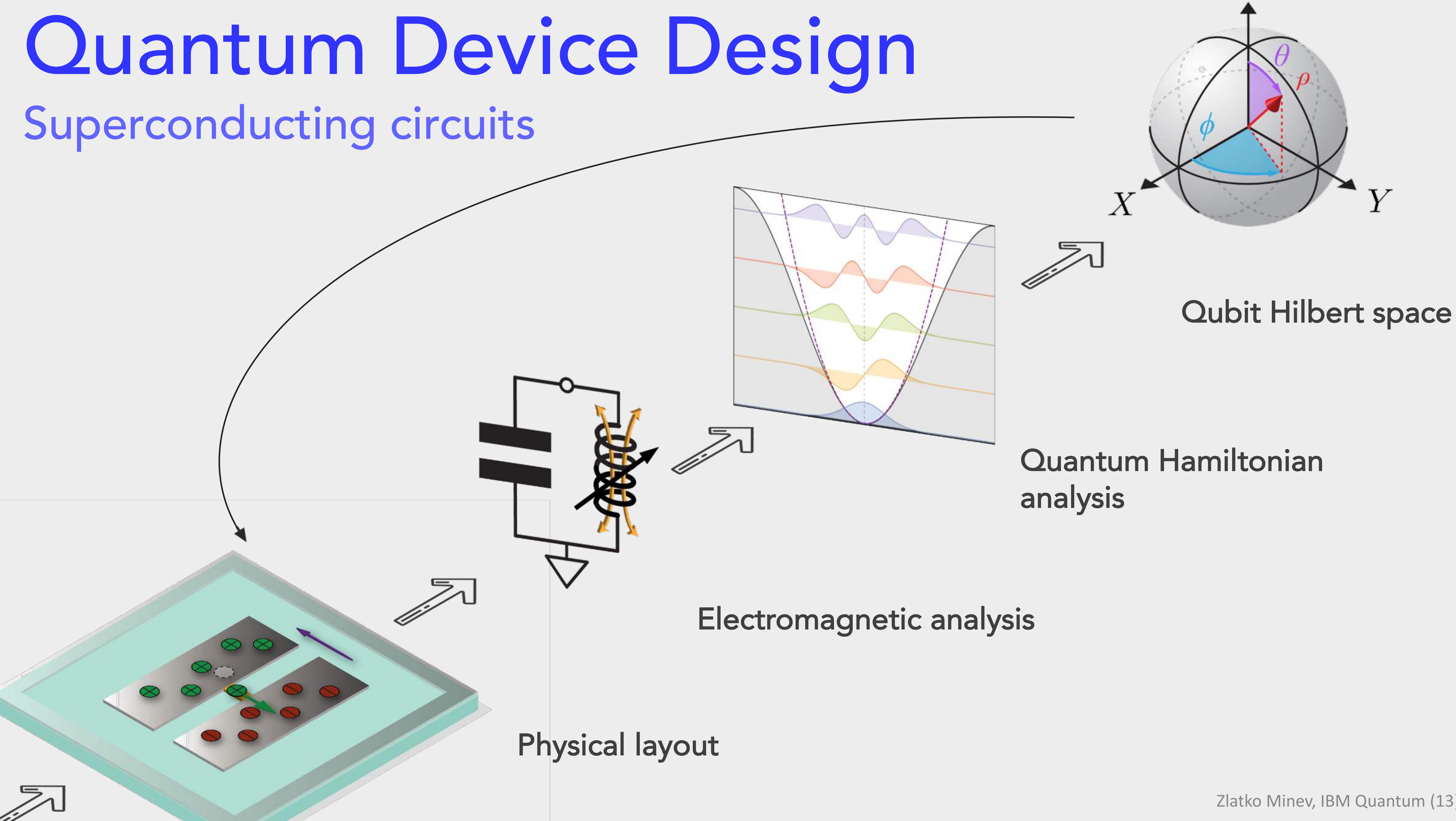


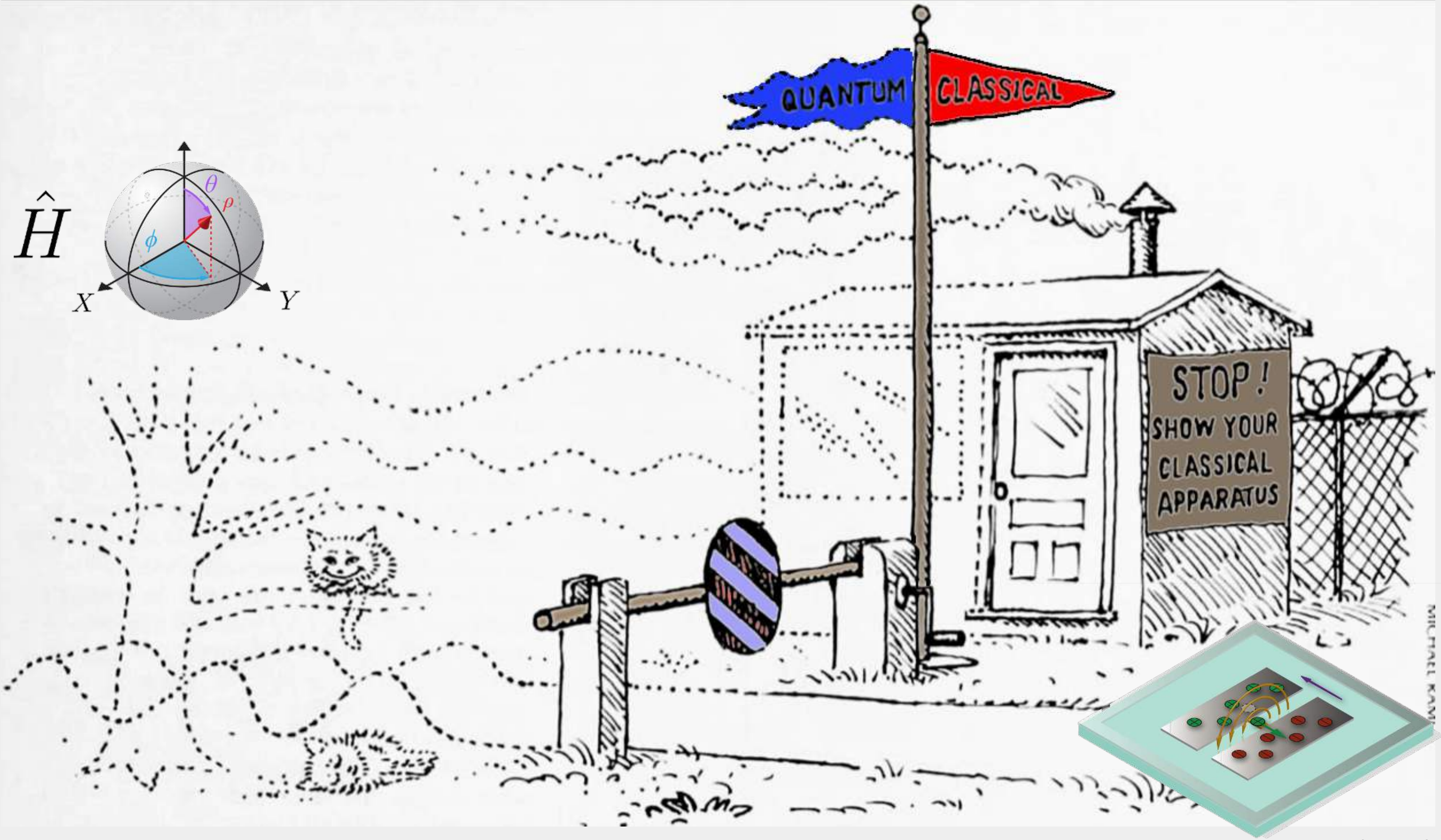


$$\hat{H} \approx \omega_0 \hat{a}^\dagger \hat{a} - \frac{\alpha}{2} \hat{a}^{\dagger 2} \hat{a}^2$$

Quantum Device Design

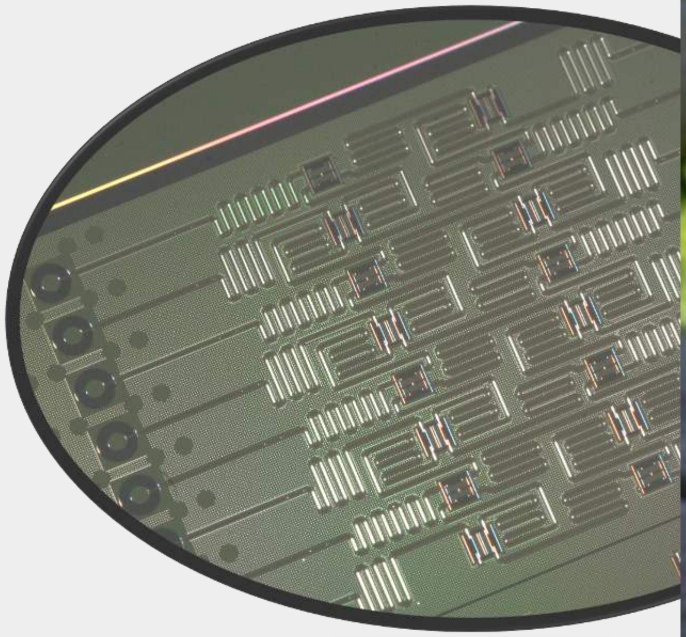
Superconducting circuits

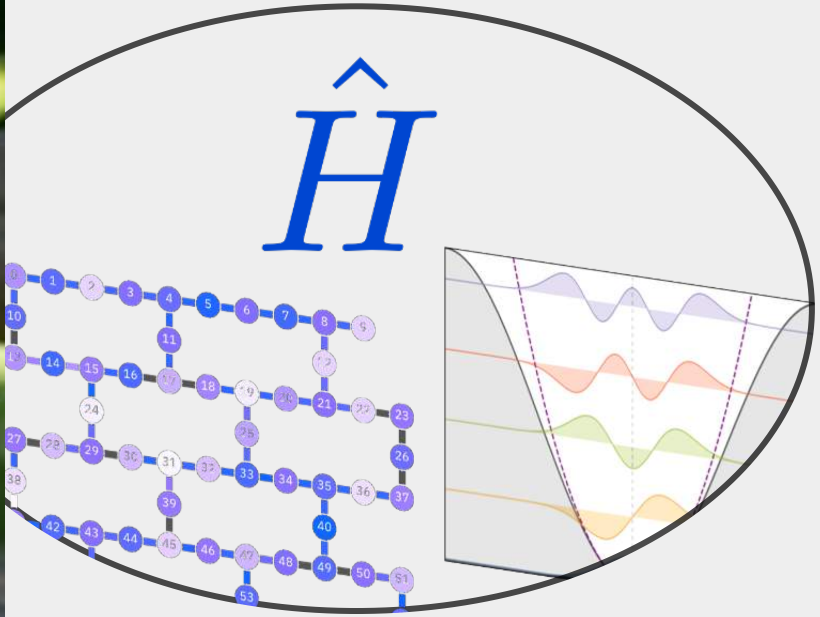




Drawing: Zurek, Physics Today (1991)

Physical Devices ↔ Quantum Hamiltonian





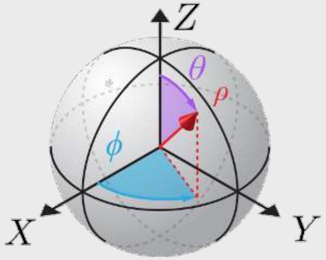
Quantum chip design flow

Complexity, Information, Accuracy

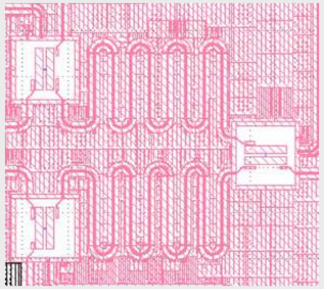
Risk, Cost, Time, Resources

Concept

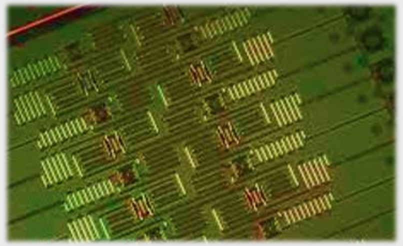
Hamiltonian



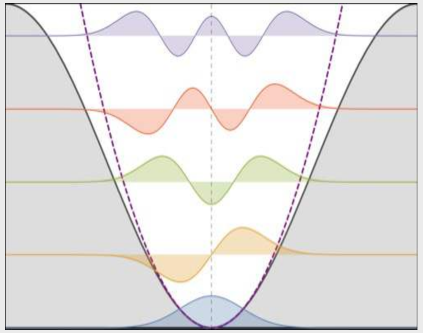
Layout



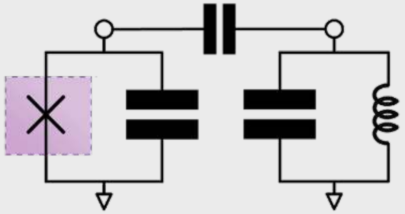
Fabrication



Quantum Analysis



Electromagnetic Analysis



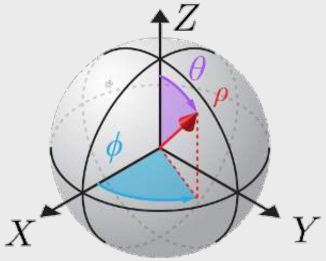
Quantum chip design flow

Complexity, Information, Accuracy

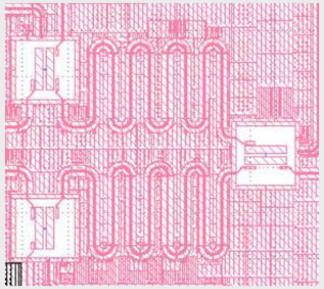
Risk, Cost, Time, Resources

Concept

Hamiltonian

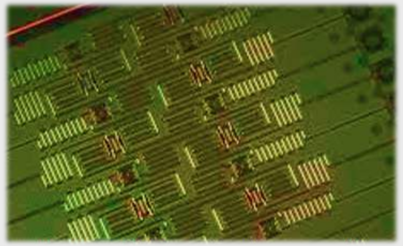


Layout

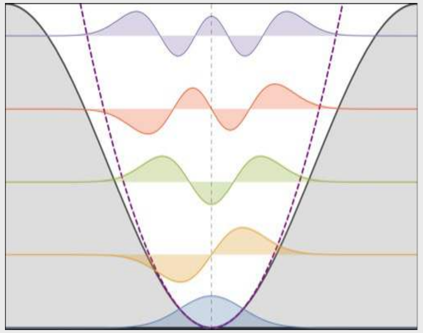


DRC
LVS

Fabrication

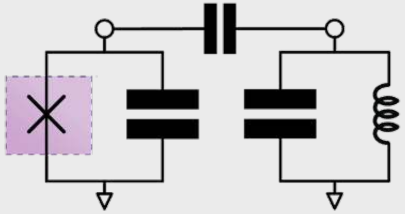


Quantum Analysis



Project
Metal

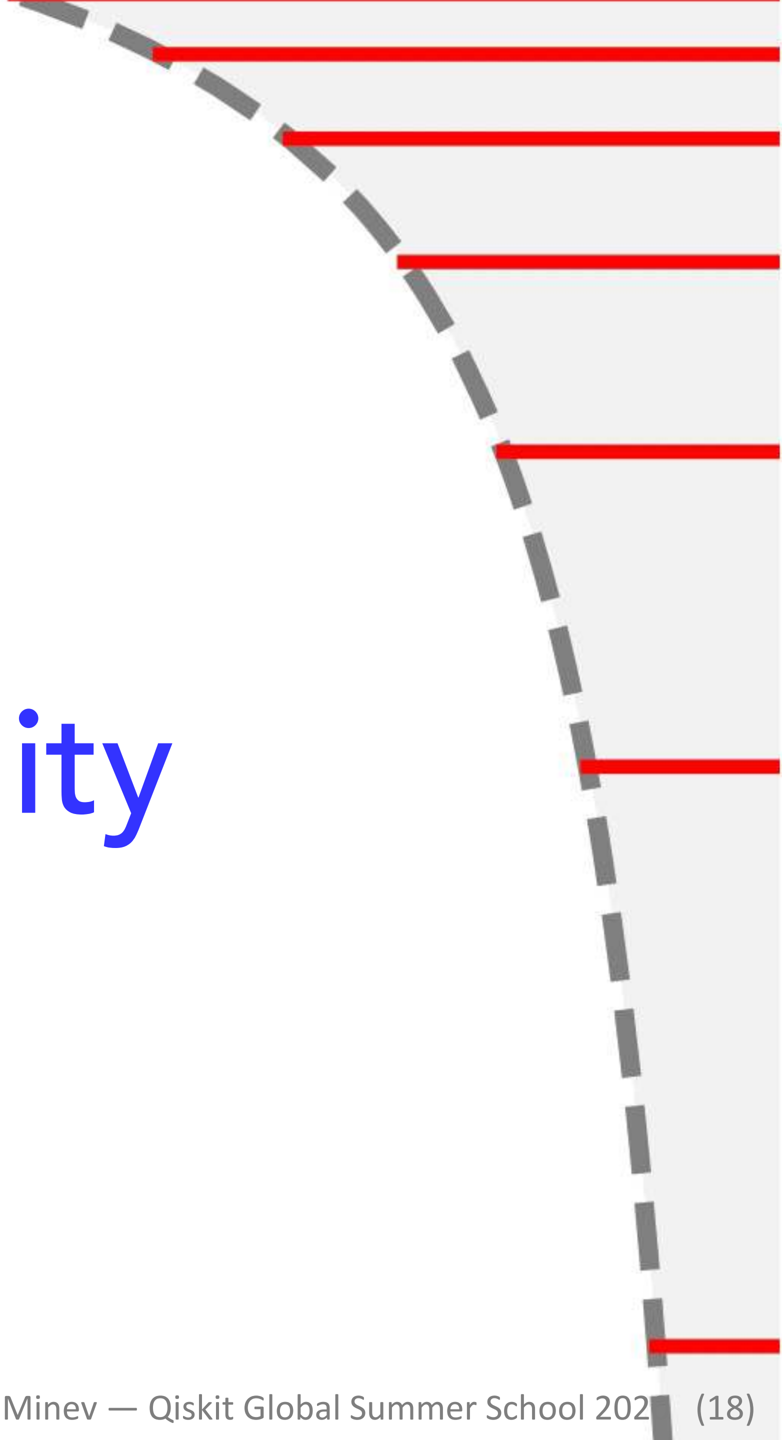
Electromagnetic
Analysis



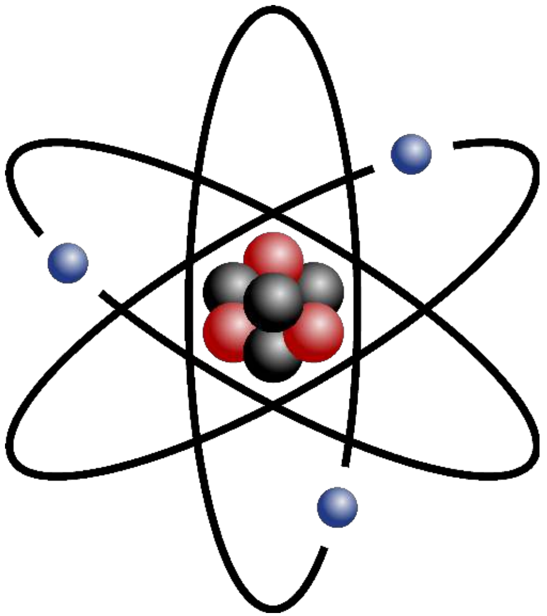
Qubit

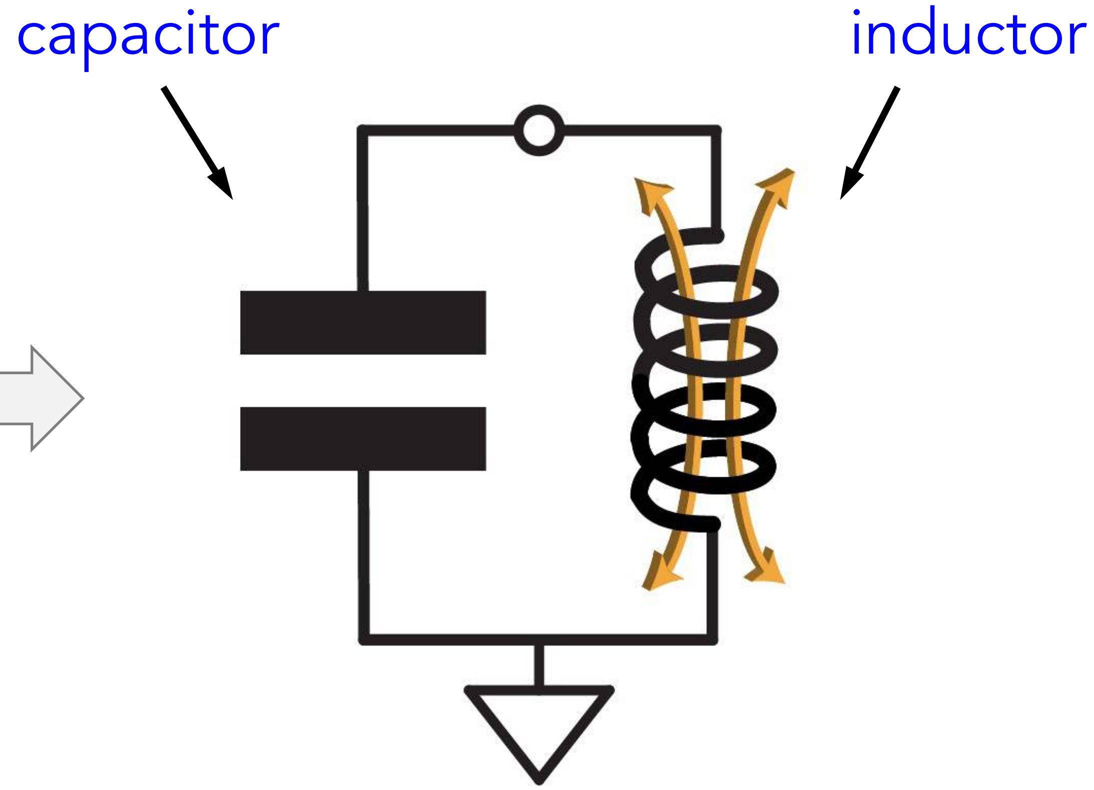
From Idea to Reality

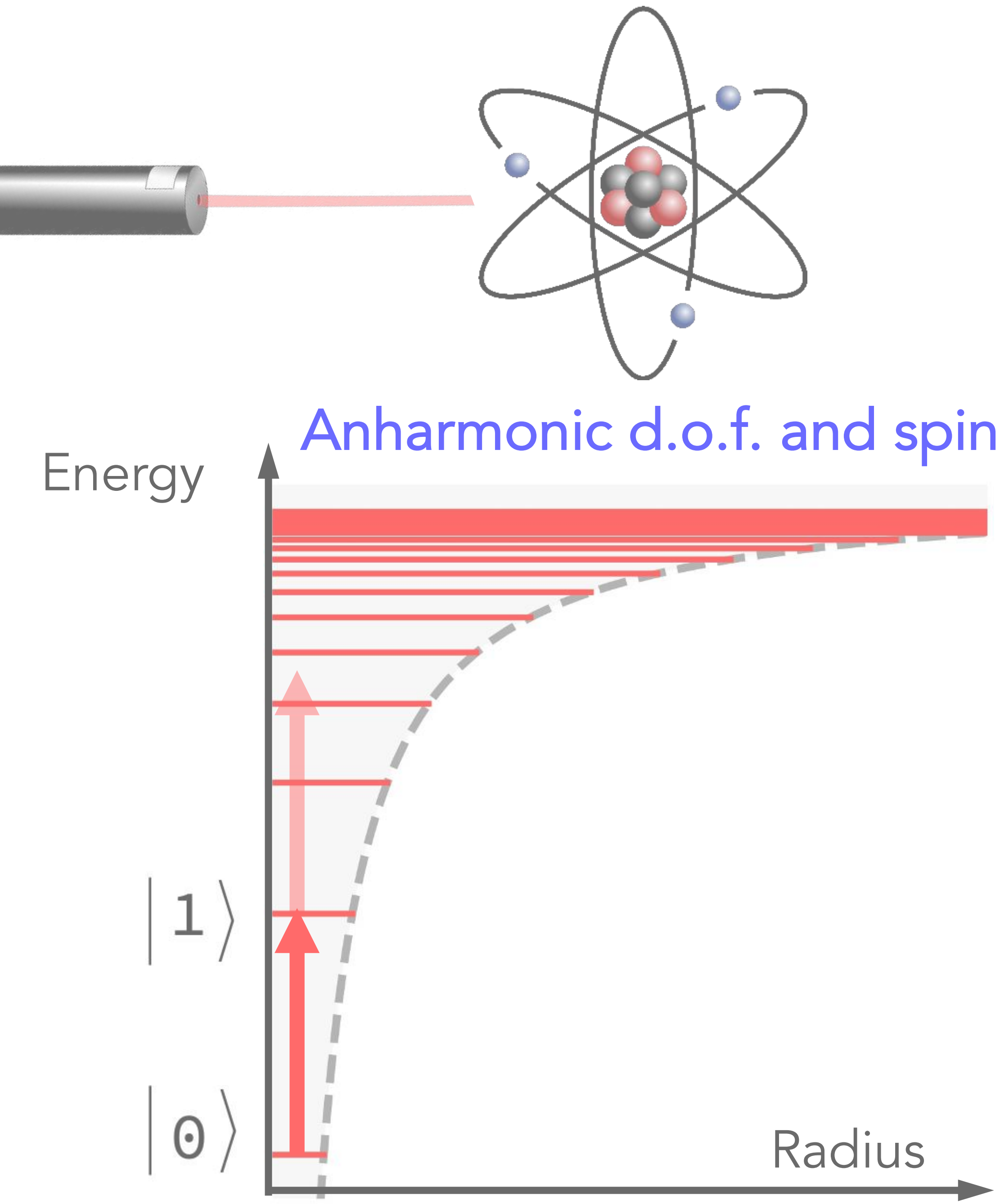
Concepts

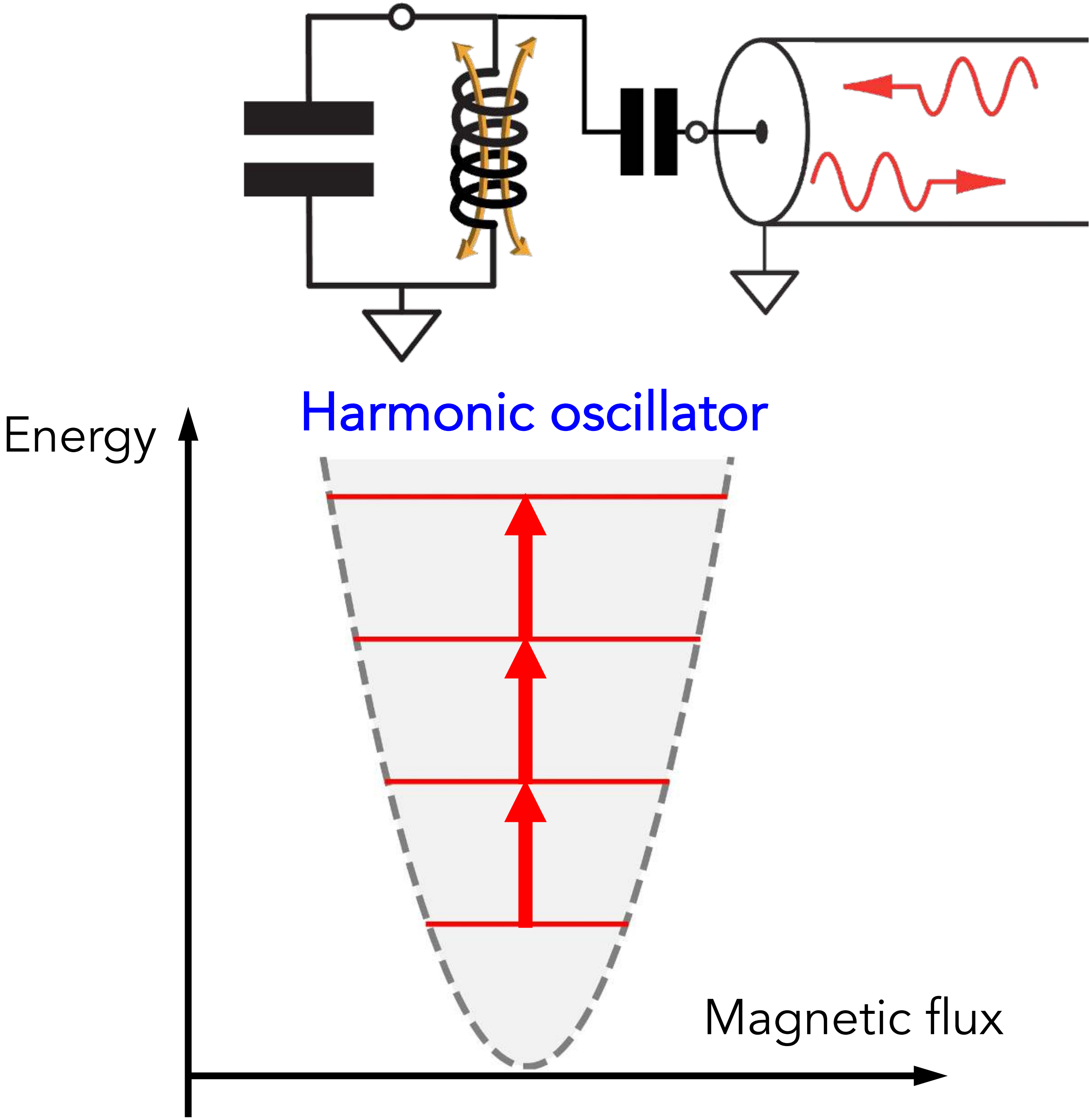


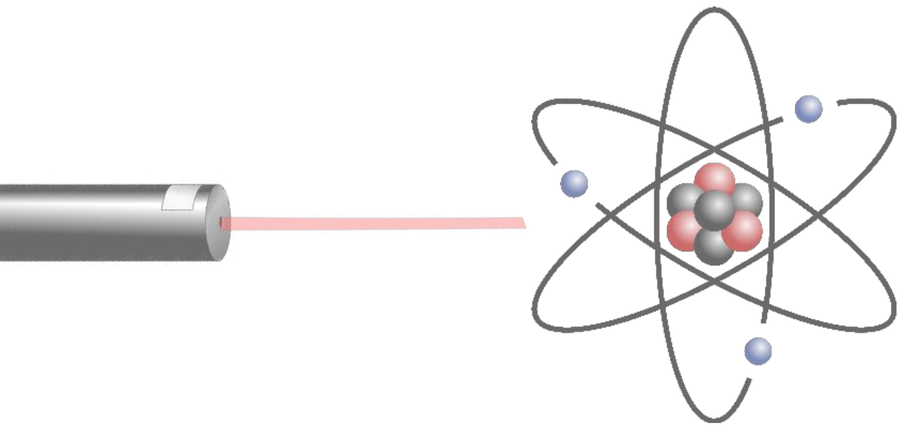
Artificial atoms



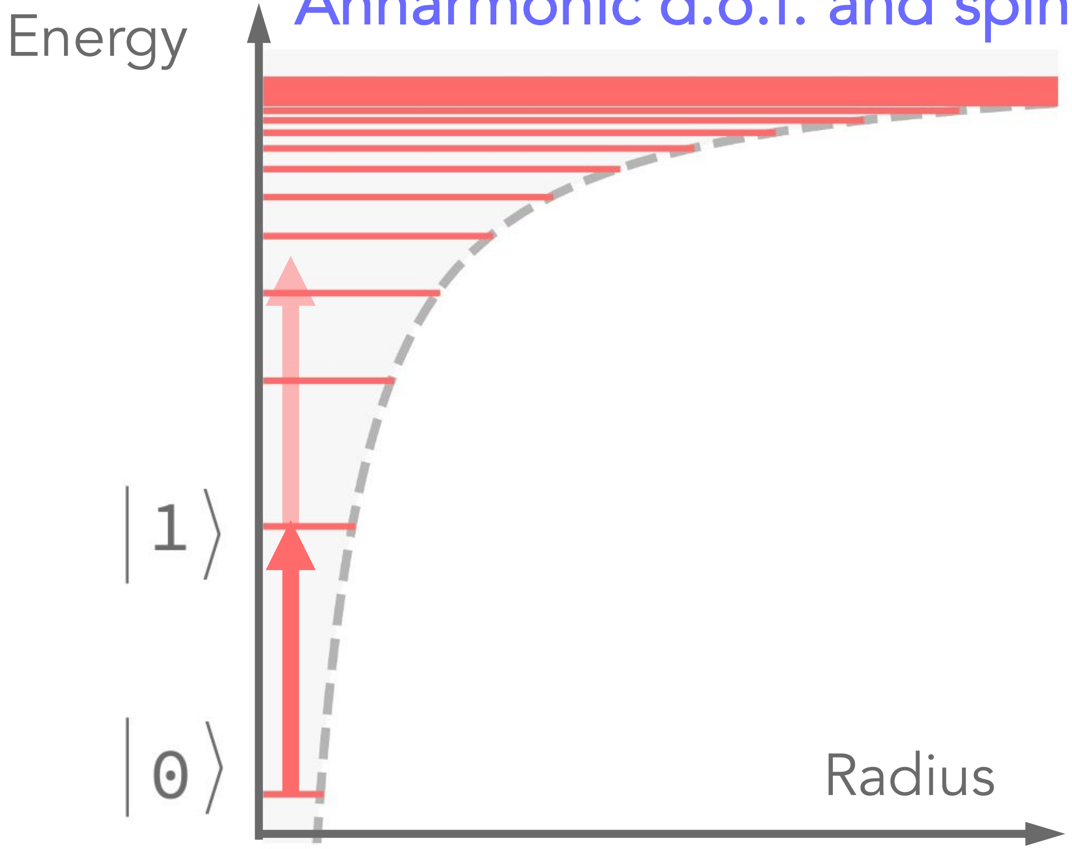


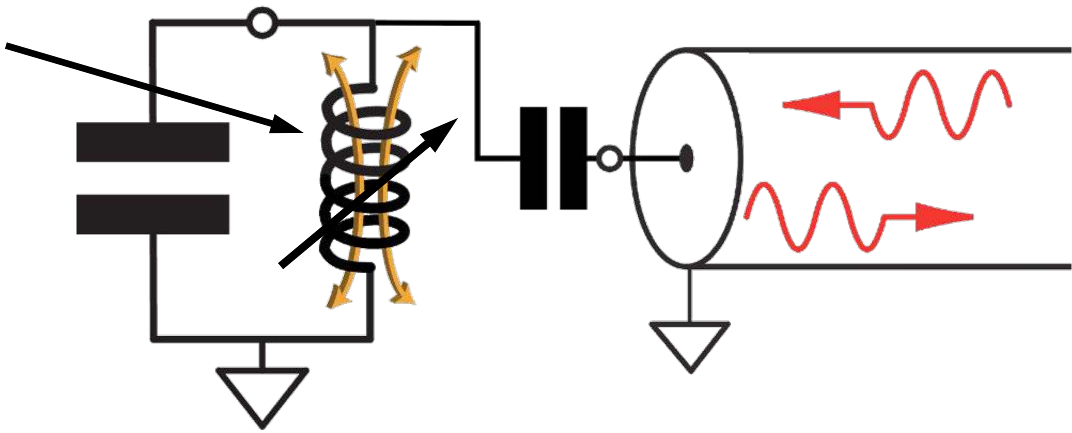

Anharmonic d.o.f. and spin
Energy
$|1\rangle$
$|0\rangle$
Radius


Harmonic oscillator
Energy
Magnetic flux

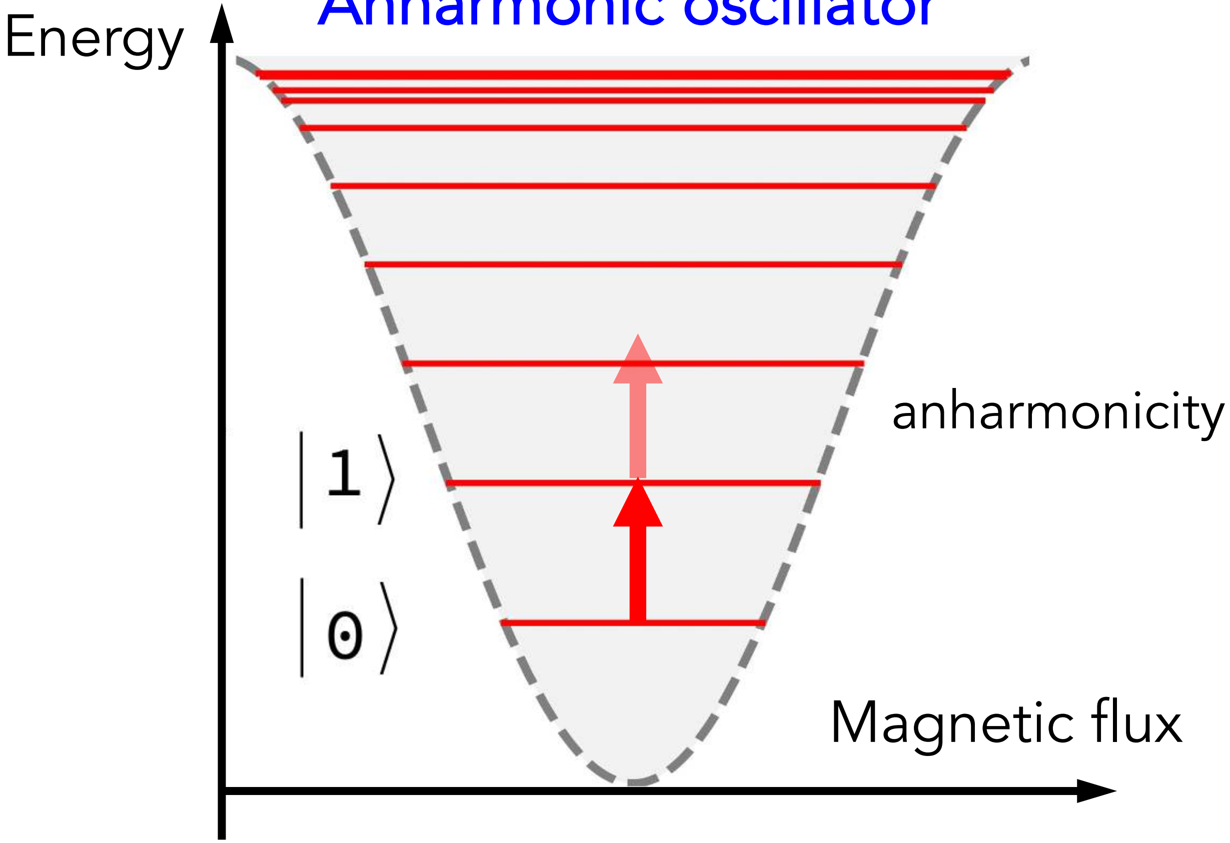


Anharmonic d.o.f. and spin



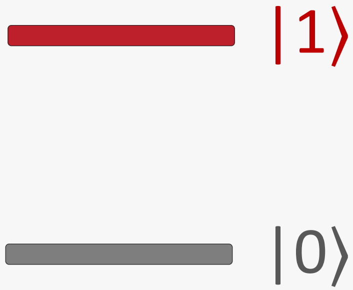


Anharmonic oscillator

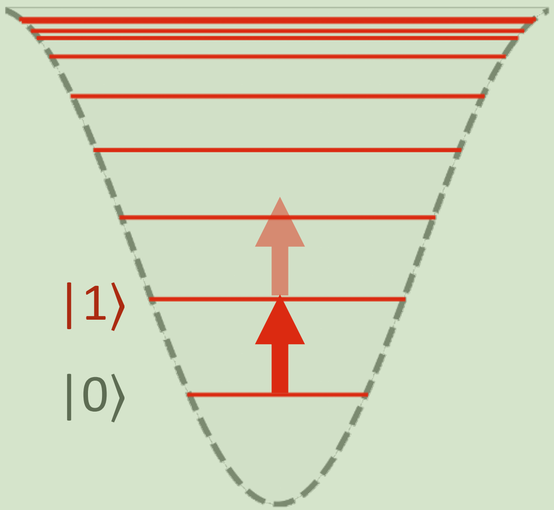


Big-picture connections

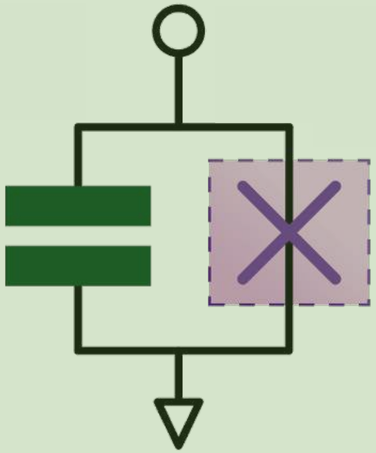
Idealization of *qubit*



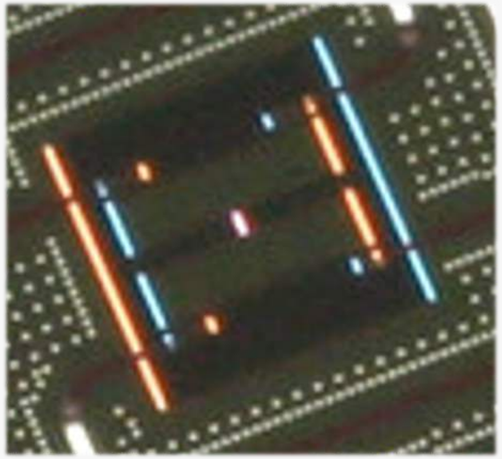
Anharmonic *oscillator*



Physical circuit model



Physical layout



Idealization

Physical reality

Circuit Quantum Electrodynamics (cQED)

Macro
overview

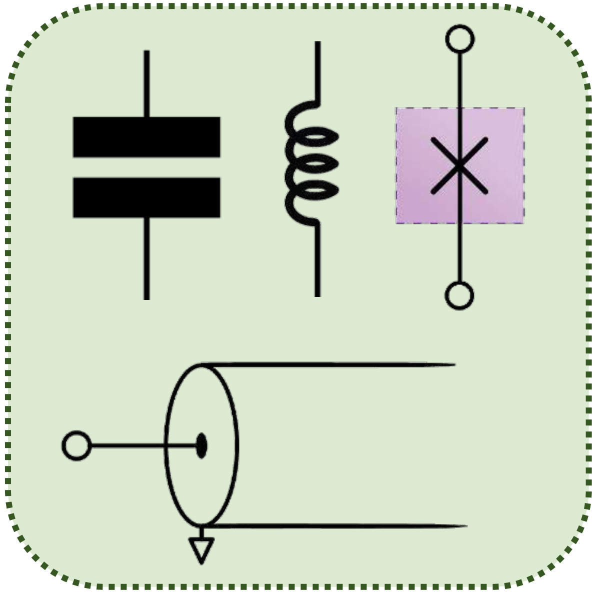
There are two kinds of physicists:

Those who believe all of physics is *spins*.

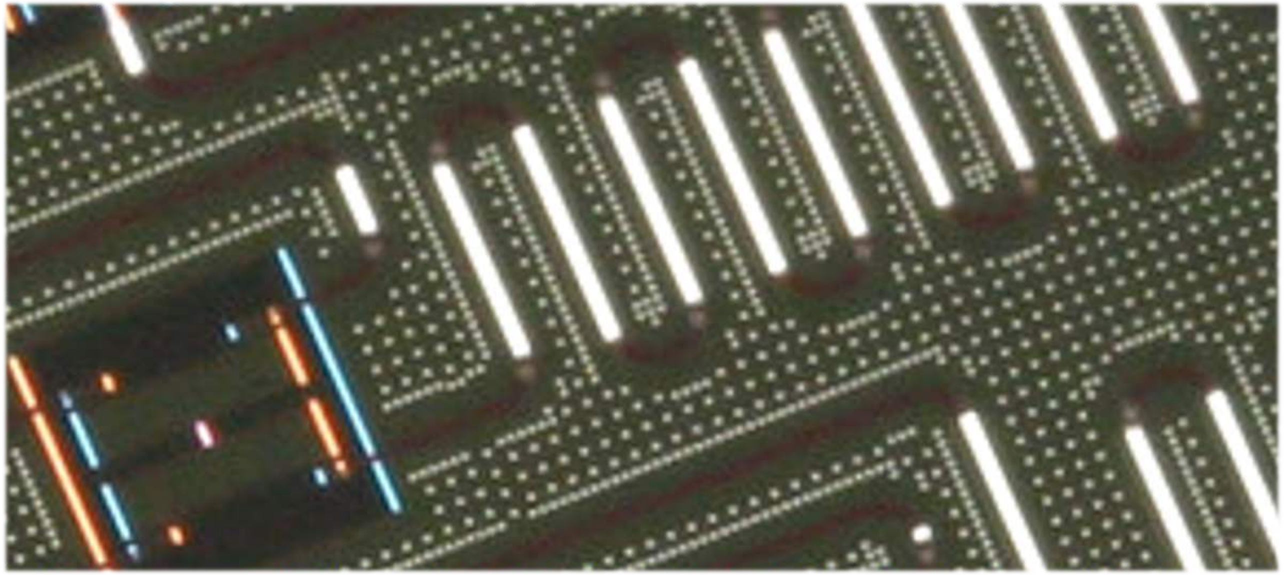
Those who believe all of physics is *oscillators*.

cQED Ingredients

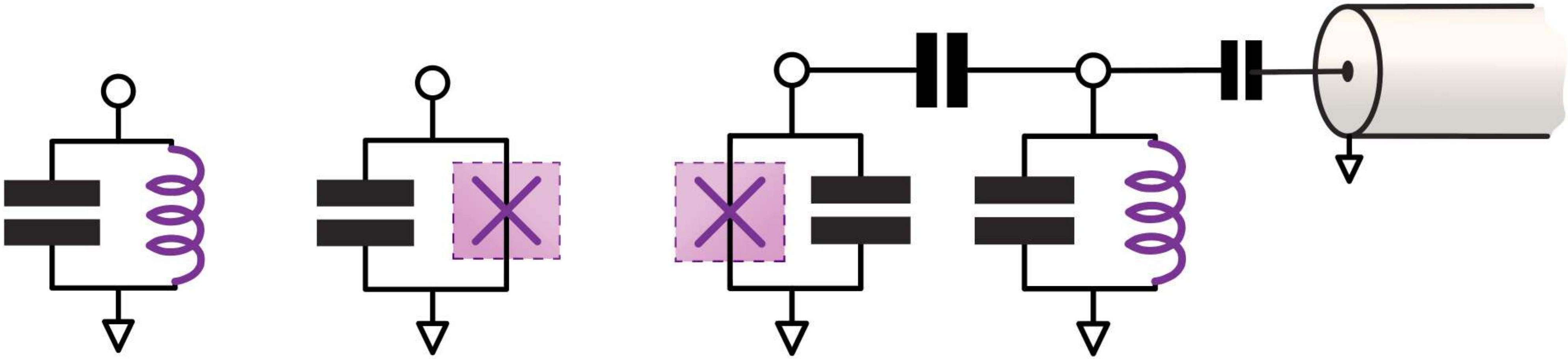
Circuit elements



Microwave oscillators



Combine



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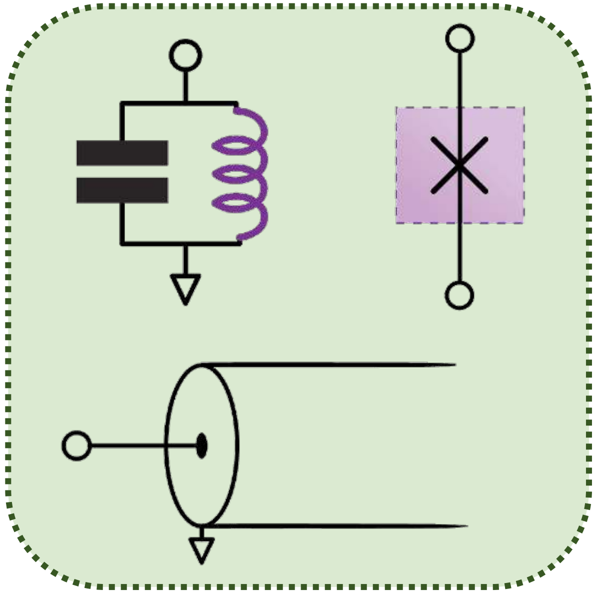
cQED Ingredients



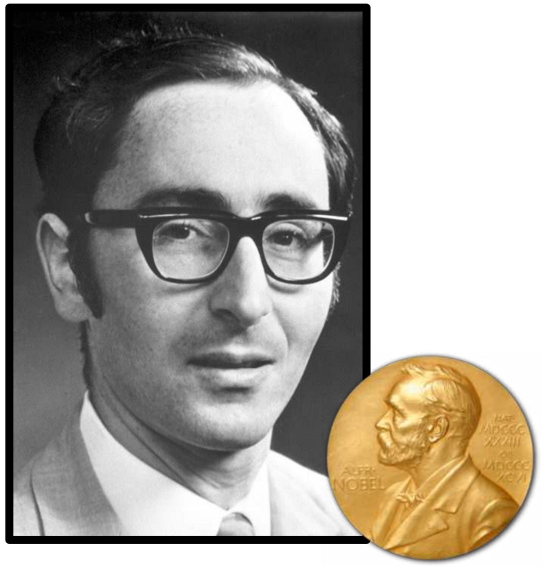
Small dissipation

Isolation from environment

Low temperature

Nonlinearity

Large vacuum fluctuations



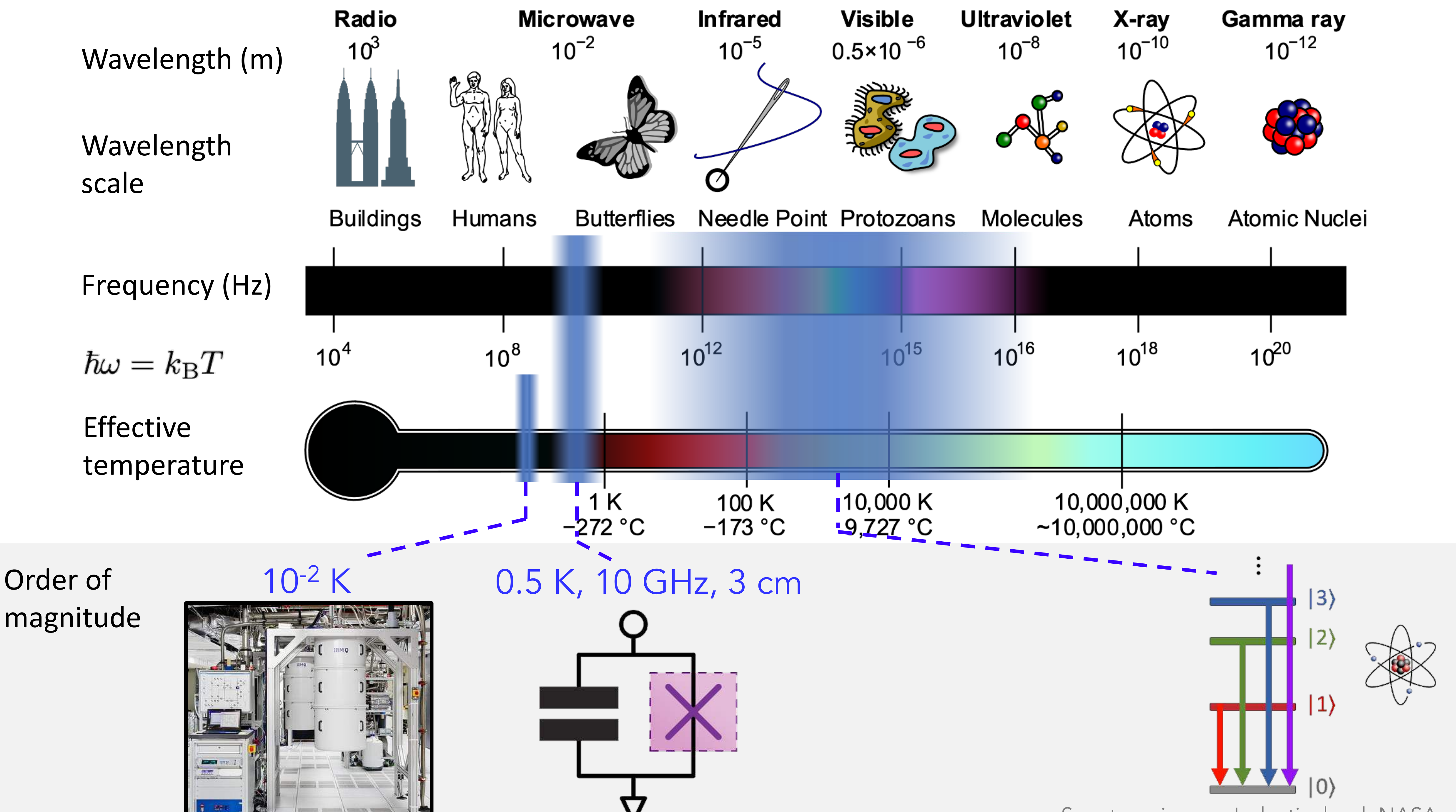
Superconductivity

Nominally zero intrinsic dissipation and heat

Nominal temperature far below energy level splitting

Non-linear, robust Josephson tunnel junction effect

* Low energy dynamics. Microwave image: vectorpocket; Nobel photograph: Jonathunder; Josephson photograph: Nobel Foundation archive.



Spectrum image: Inductiveload, NASA

A few introductory reviews

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

Qiskit Textbook (2020; more chapters coming)

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. *Reports on Progress in Physics*, *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)

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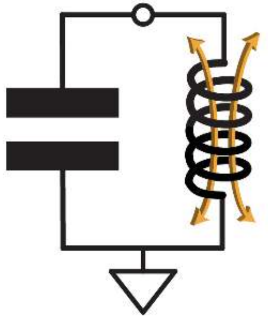
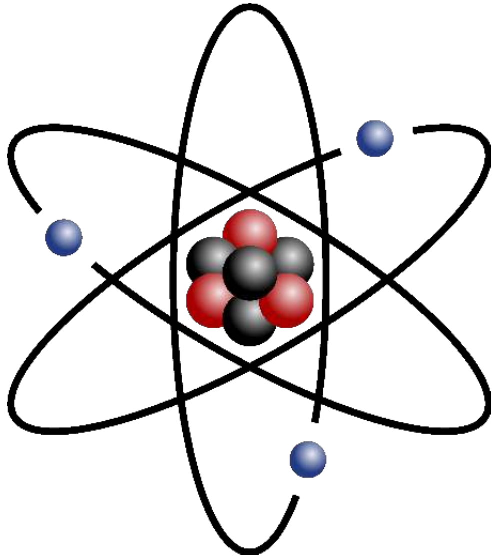


Circuit Quantum Electrodynamics

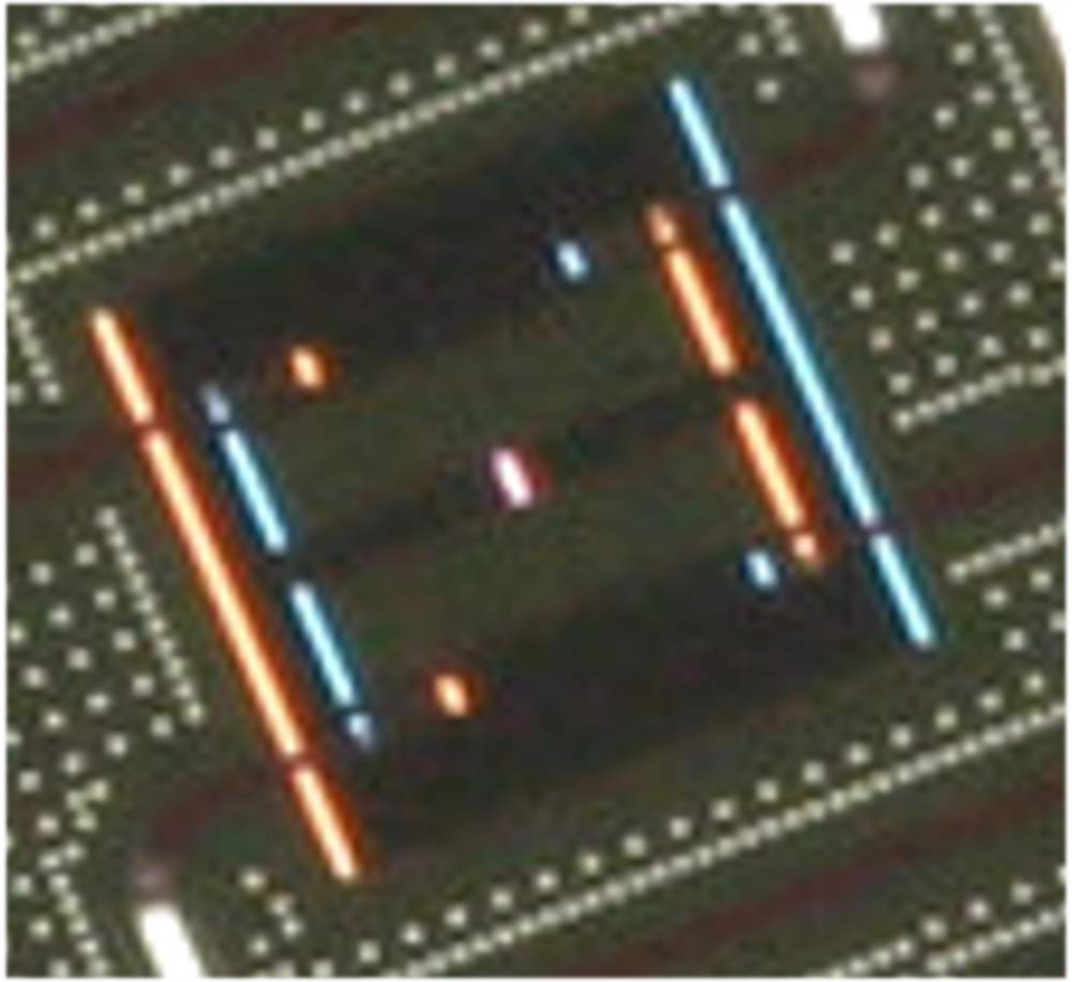


To do **quantum**,

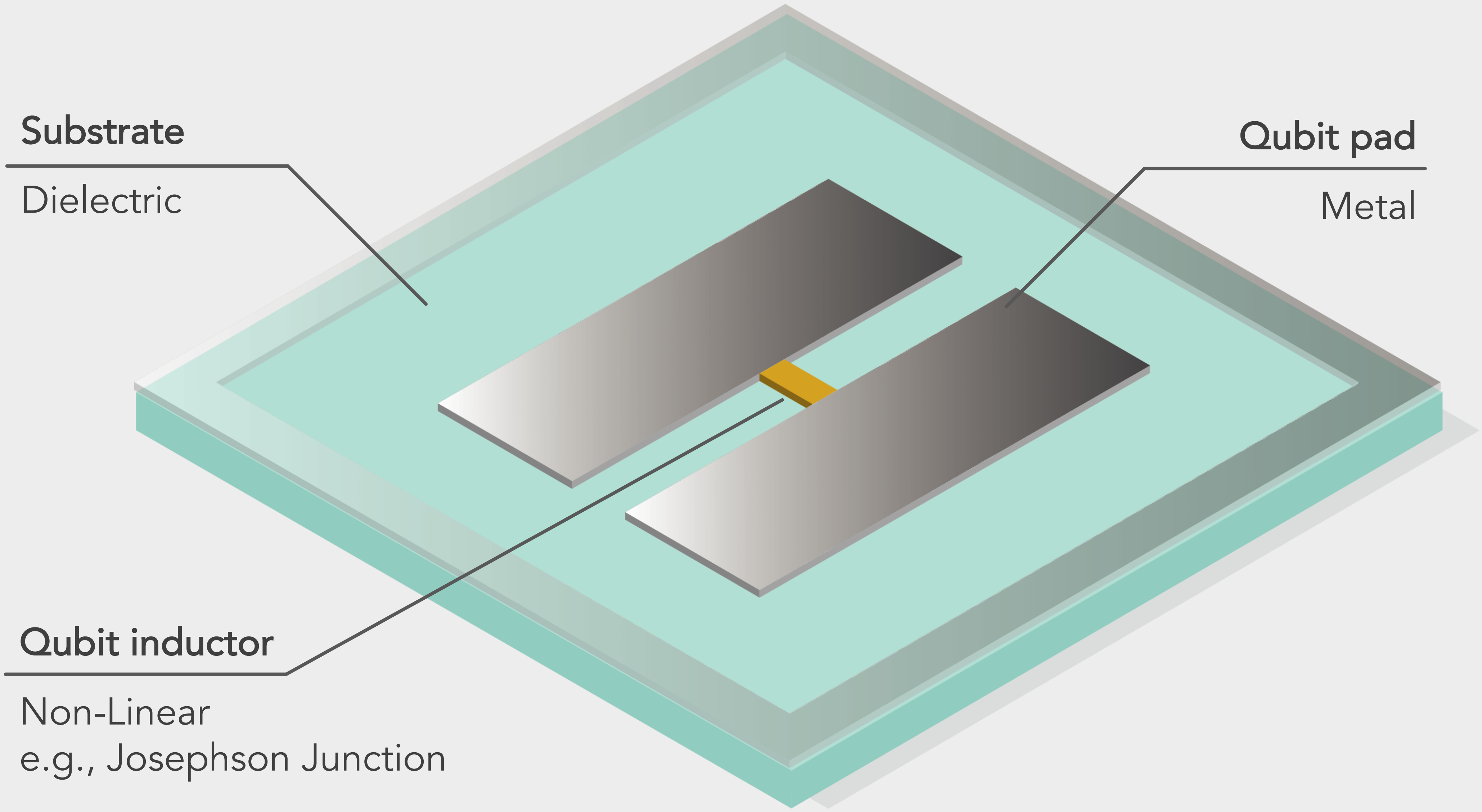
start with **classical**

Classical oscillator

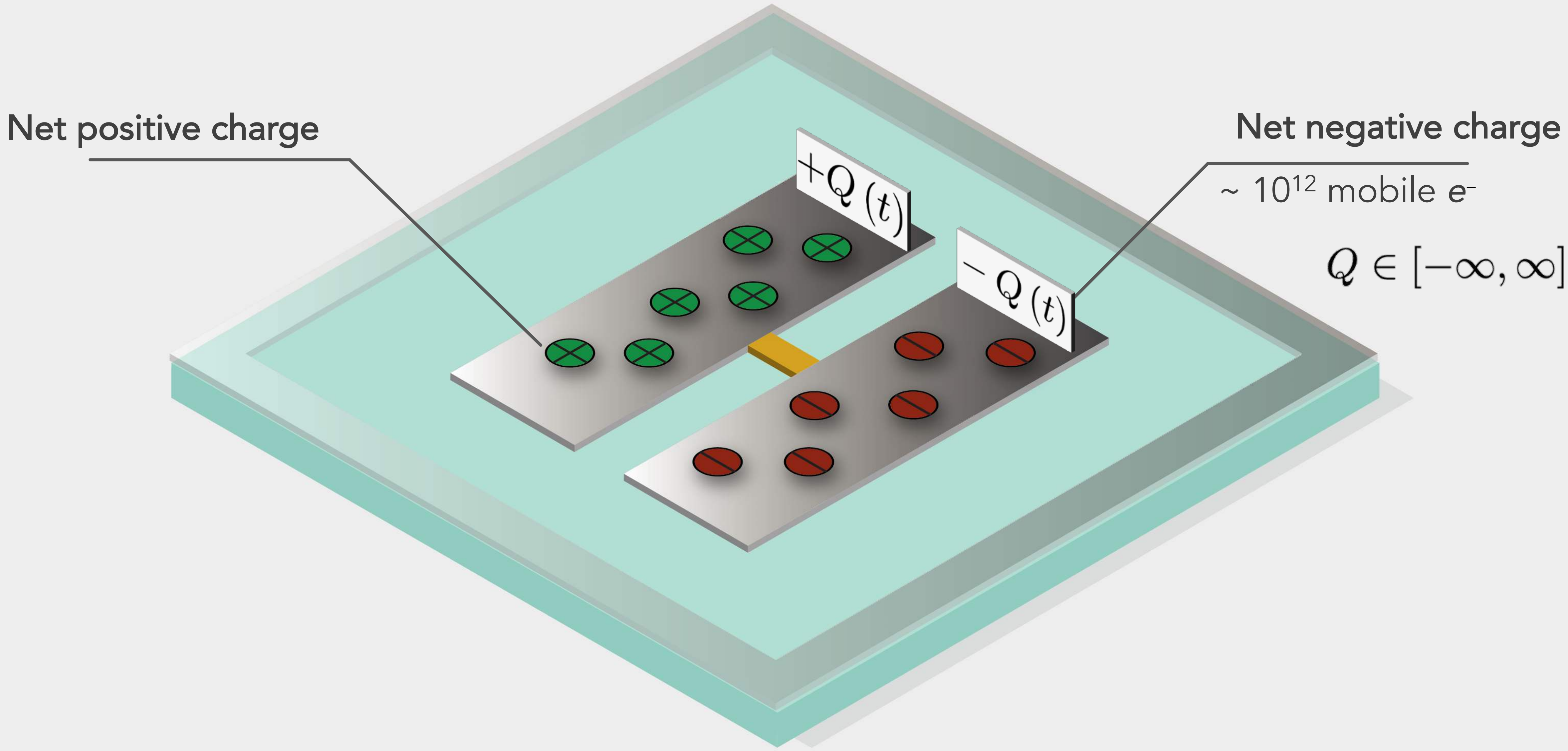
Transmon qubit



Transmon qubit

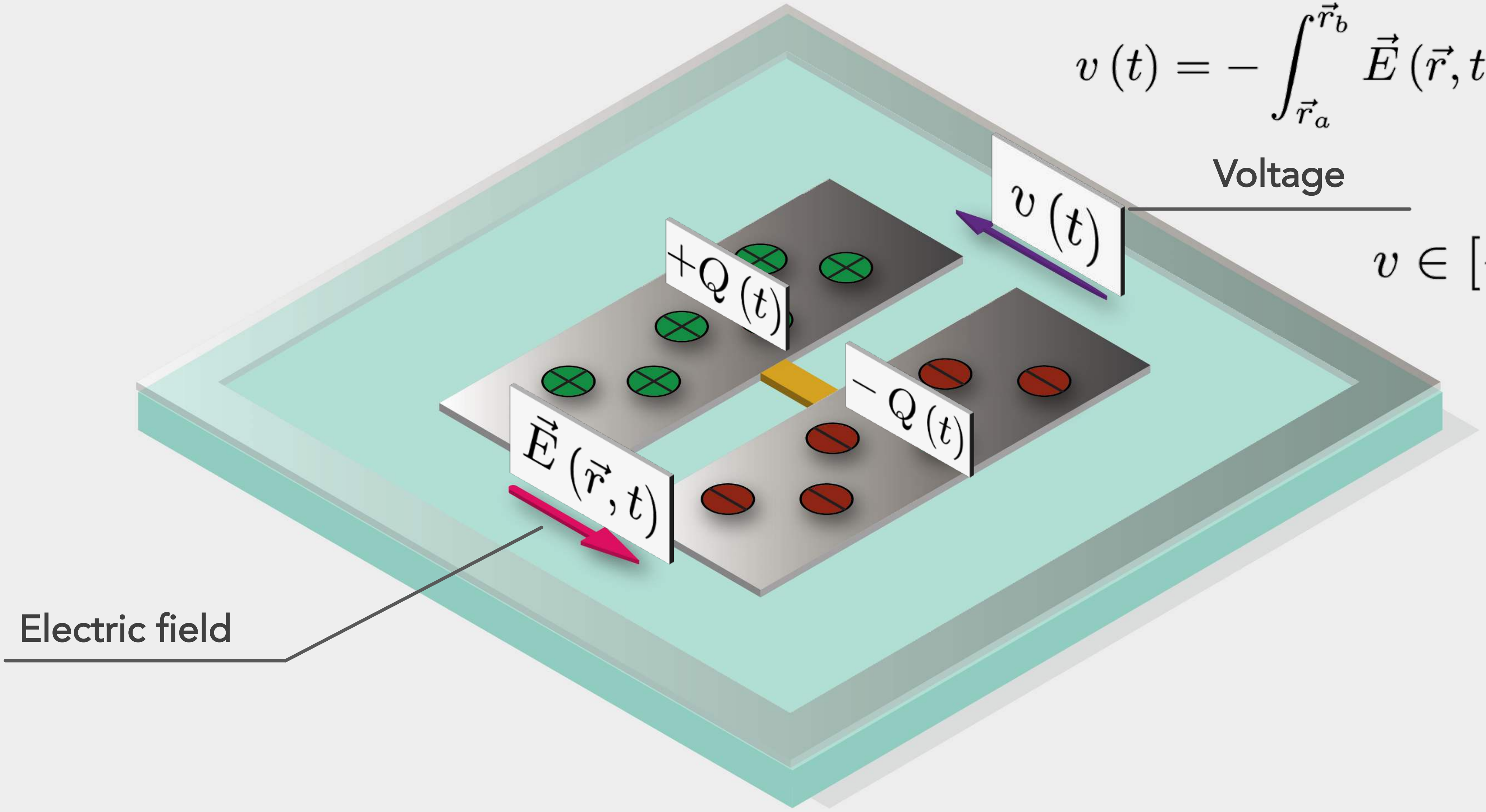


Transmon qubit: charge



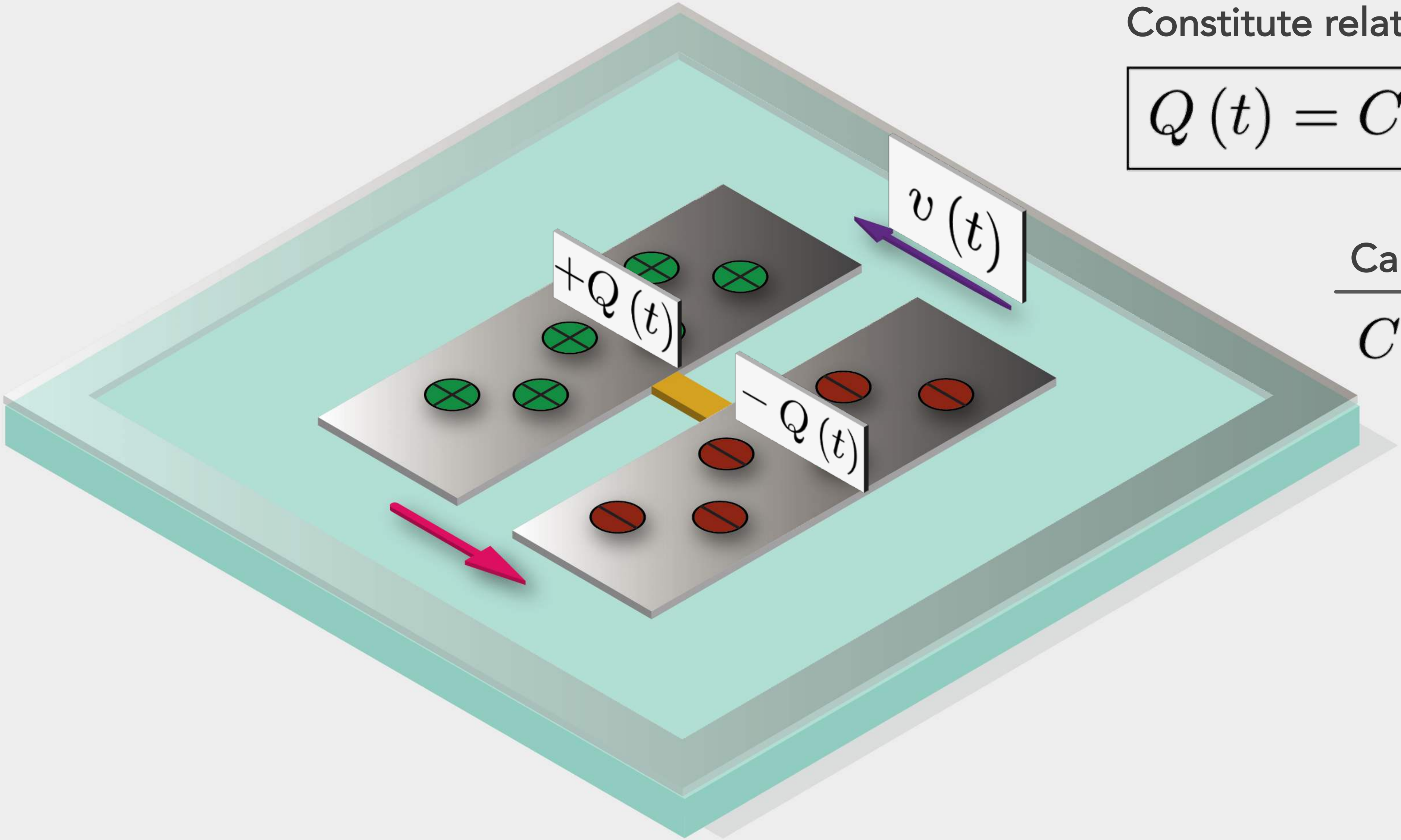
Electric field and voltage

$$v\left(t\right) = -\int_{\vec{r}_a}^{\vec{r}_b} \vec{E}\left(\vec{r},t\right)\cdot \mathrm{d}\vec{l}\left(\vec{r}\right)$$



$$v \in [-\infty, \infty]$$

Charge and capacitance

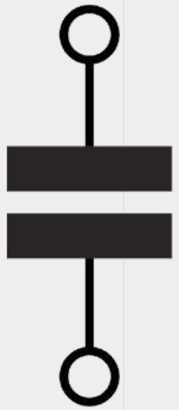


Constitute relationship

$$\boxed{Q(t) = Cv(t)}$$

Capacitance

$$C \in (0, \infty)$$



For a good discussion, see "*The Feynman Lectures on Physics Vol. II Ch. 22: AC Circuits.*" Caltech.

Charge and current

Conservation of charge

Universal relationship

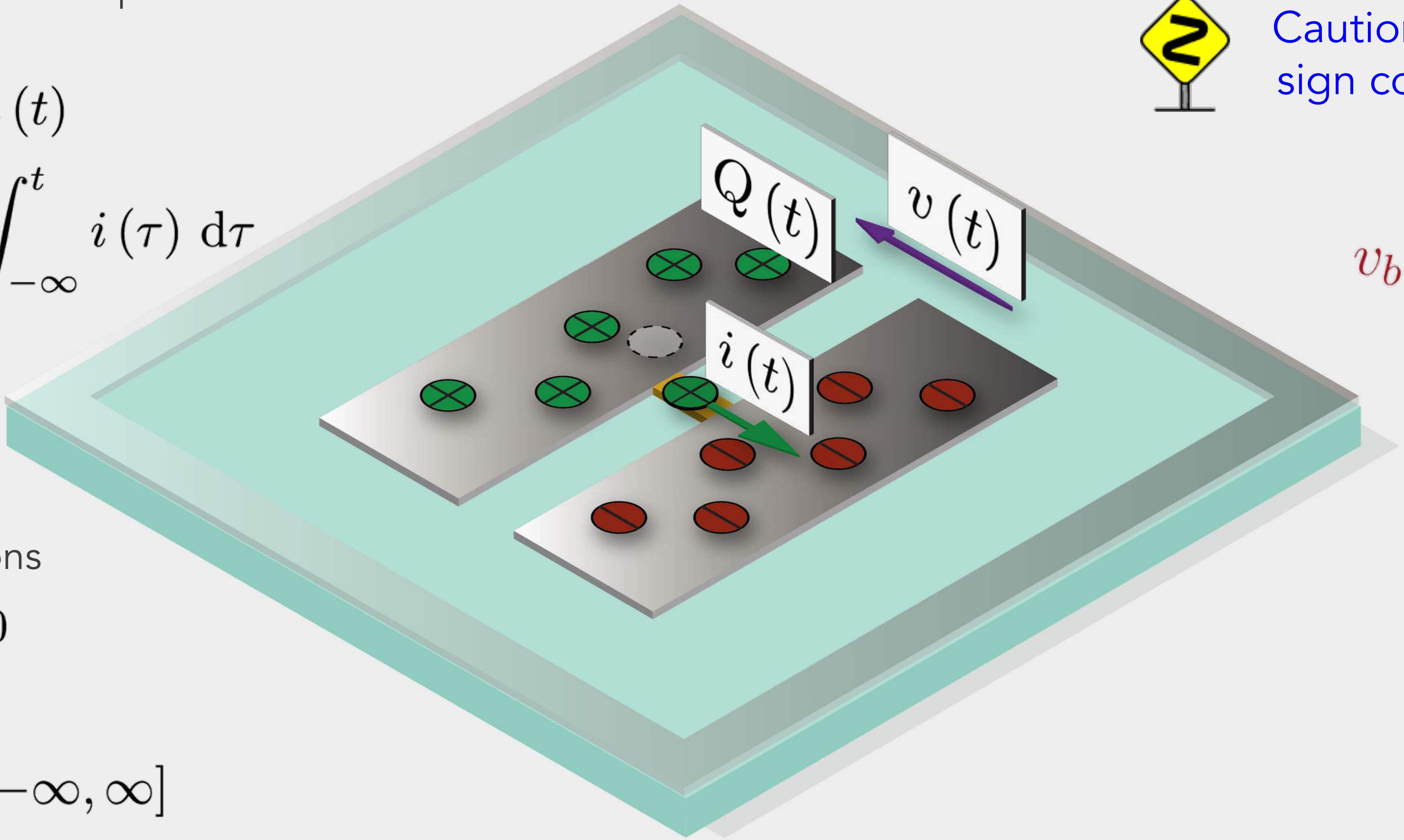
$$\frac{\mathrm{d}}{\mathrm{d}t}Q\left(t\right)=i\left(t\right)$$

$$Q\left(t\right)=\int_{-\infty}^{t}i\left(\tau\right)\,\mathrm{d}\tau$$

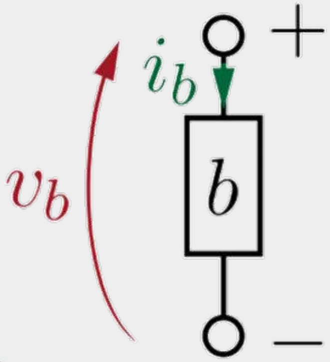
Initial conditions

$$Q\left(-\infty\right)=0$$

$$i\in\left[-\infty,\infty\right]$$



Caution: Passive sign convention



Magnetic flux and inductance

Faraday's law of induction

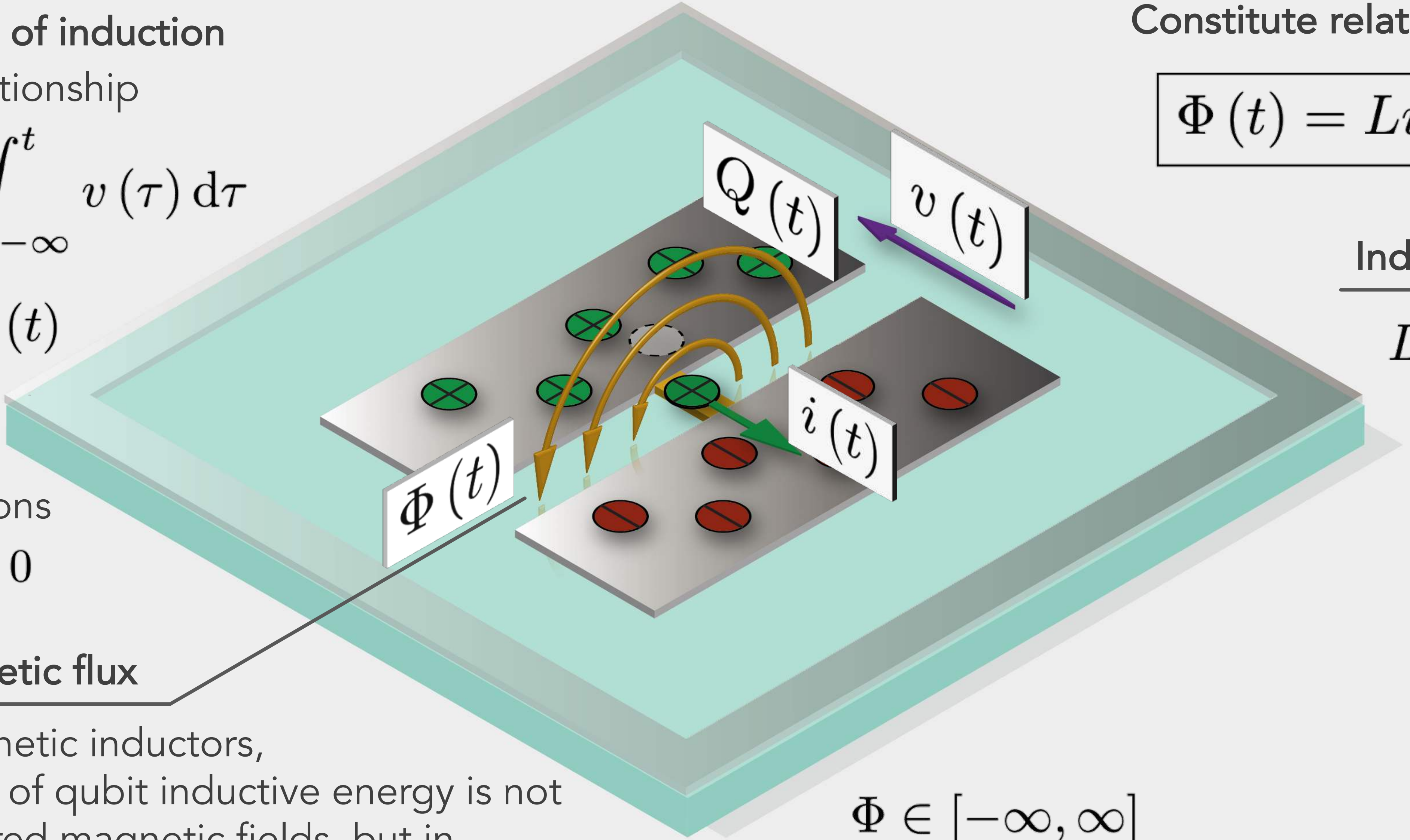
Universal relationship

$$\Phi\left(t\right)=\int_{-\infty}^{t} v\left(\tau\right)\mathrm{d}\tau$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\Phi\left(t\right)=v\left(t\right)$$

Initial conditions

$$\Phi\left(-\infty\right)=0$$



Magnetic flux

For kinetic inductors,
~98% of qubit inductive energy is not in stored magnetic fields, but in kinetic inductance

$$\Phi\in\left[-\infty,\infty\right]$$

Constitute relationship

$$\boxed{\Phi\left(t\right)=Li\left(t\right)}$$

Inductance

$$L\in\left(0,\infty\right)$$

Power and energy

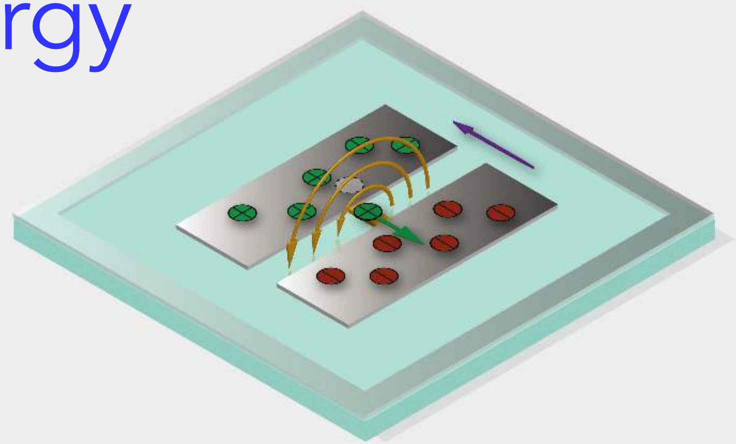
Universal

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathcal{E}(t) = p(t) \equiv v(t)\, i(t)$$

Energy stored *in* (delivered *to*) component

Instantaneous power flowing *to* component

$$\mathcal{E}(t) = \int_{-\infty}^{t} p(\tau)\, \mathrm{d}\tau$$



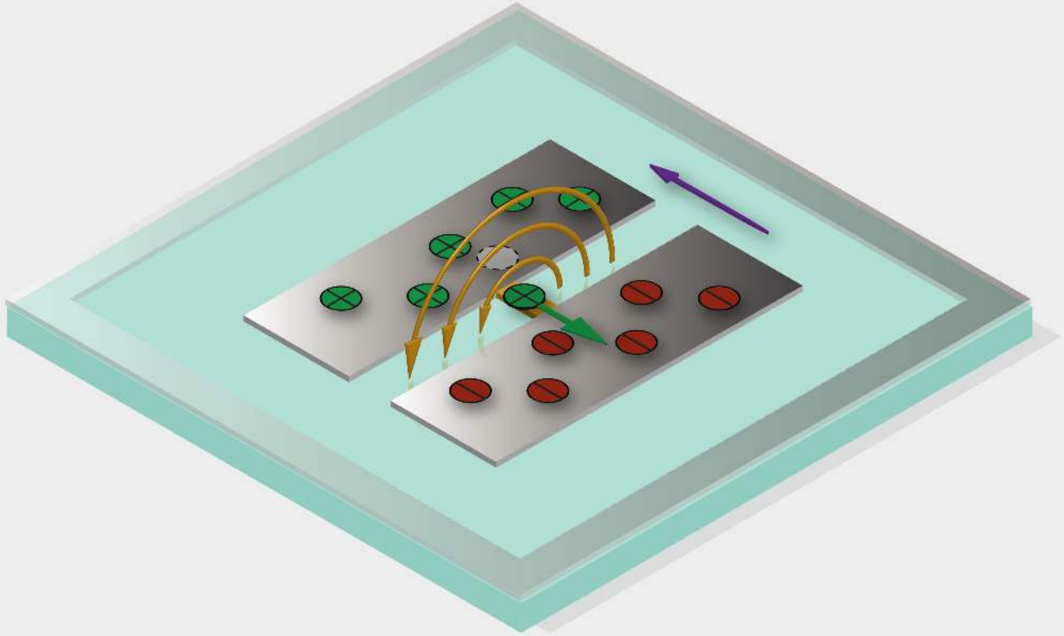
$$\mathcal{E}_{\mathrm{cap}}\left(\dot{\Phi}\right) = \frac{1}{2} C \dot{\Phi}^2$$

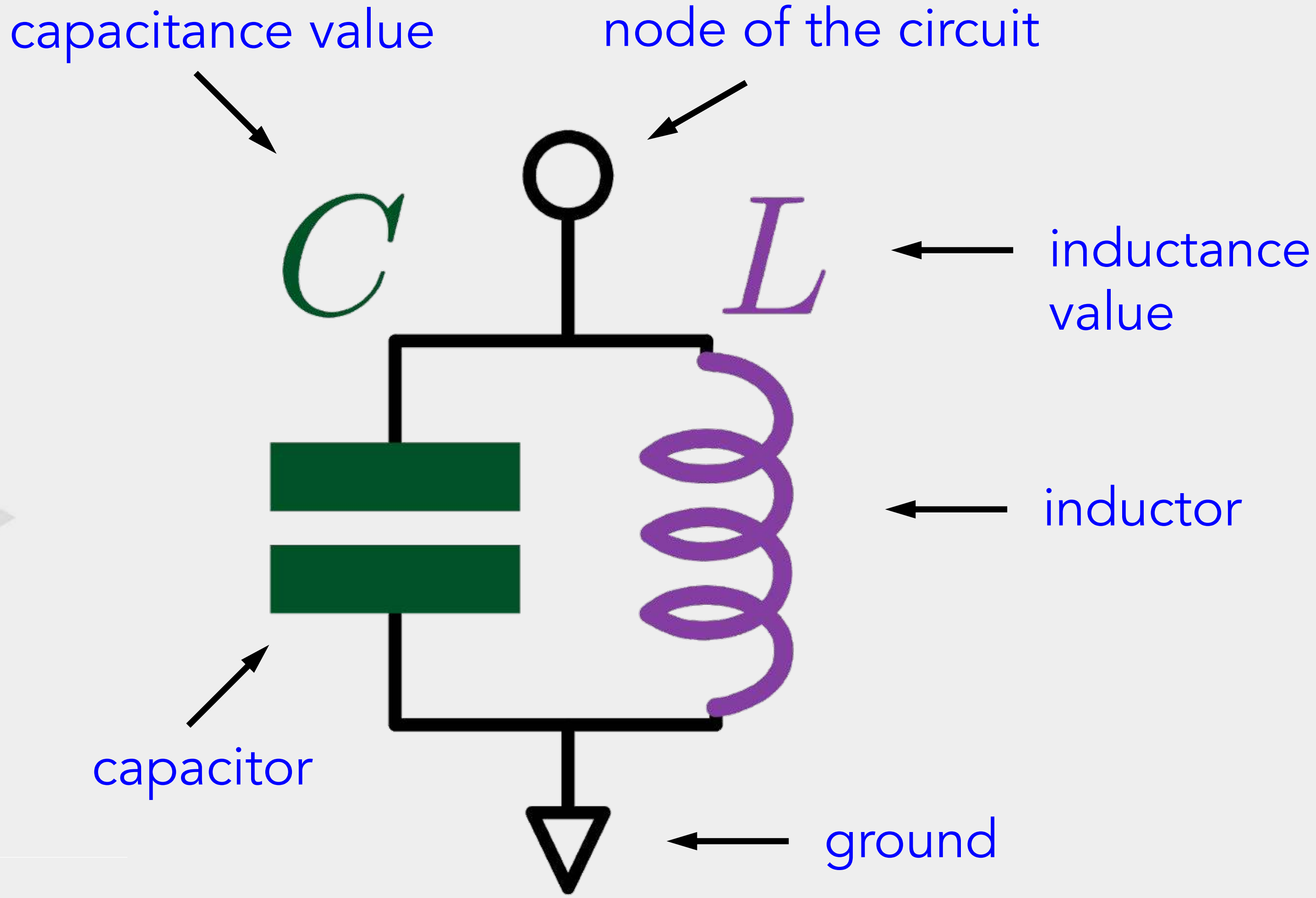
$$\mathcal{E}_{\mathrm{ind}}(\Phi) = \frac{\Phi^2}{2L}$$

$$\mathcal{E}_{\mathrm{cap}}(Q) = \frac{Q^2}{2C}$$

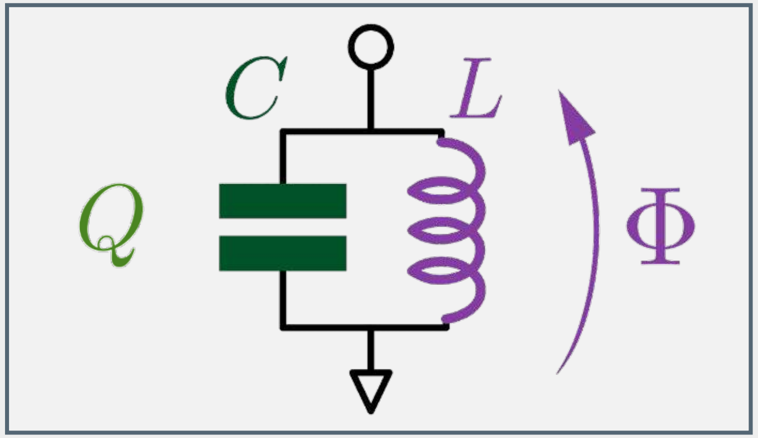
$$\mathcal{E}_{\mathrm{ind}}\left(\dot{Q}\right) = \frac{1}{2} L \dot{Q}^2$$

Electromagnetic oscillator





The LC classical harmonic oscillator



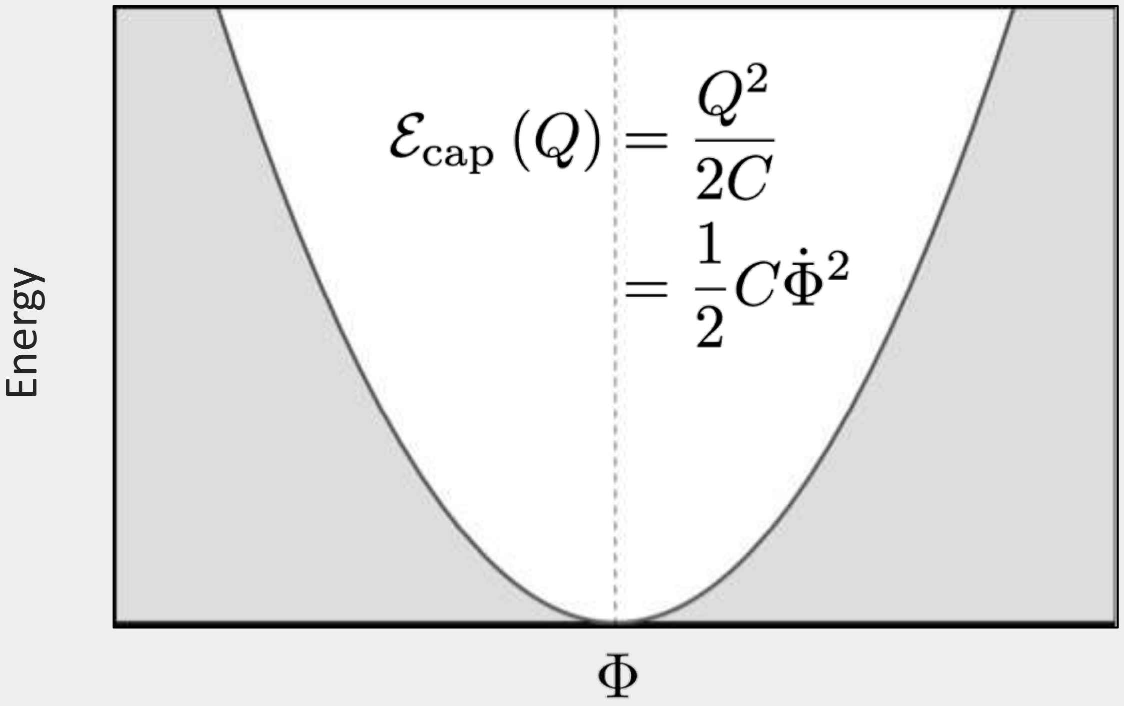
Position: $\Phi \mapsto x$ Momentum: $Q \mapsto p$

Mass: $C \mapsto m$ Spring constant: $L^{-1} \mapsto k$

$$\mathcal{H}(\Phi, Q) = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

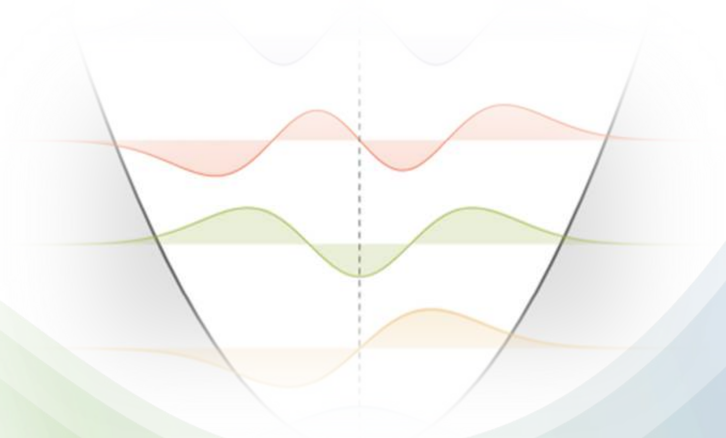
$$\omega_0^2 = \frac{1}{LC} \qquad Z_0 = \frac{L}{C}$$

$$\mathcal{E}_{\text{ind}}(\Phi) = \frac{\Phi^2}{2L}$$



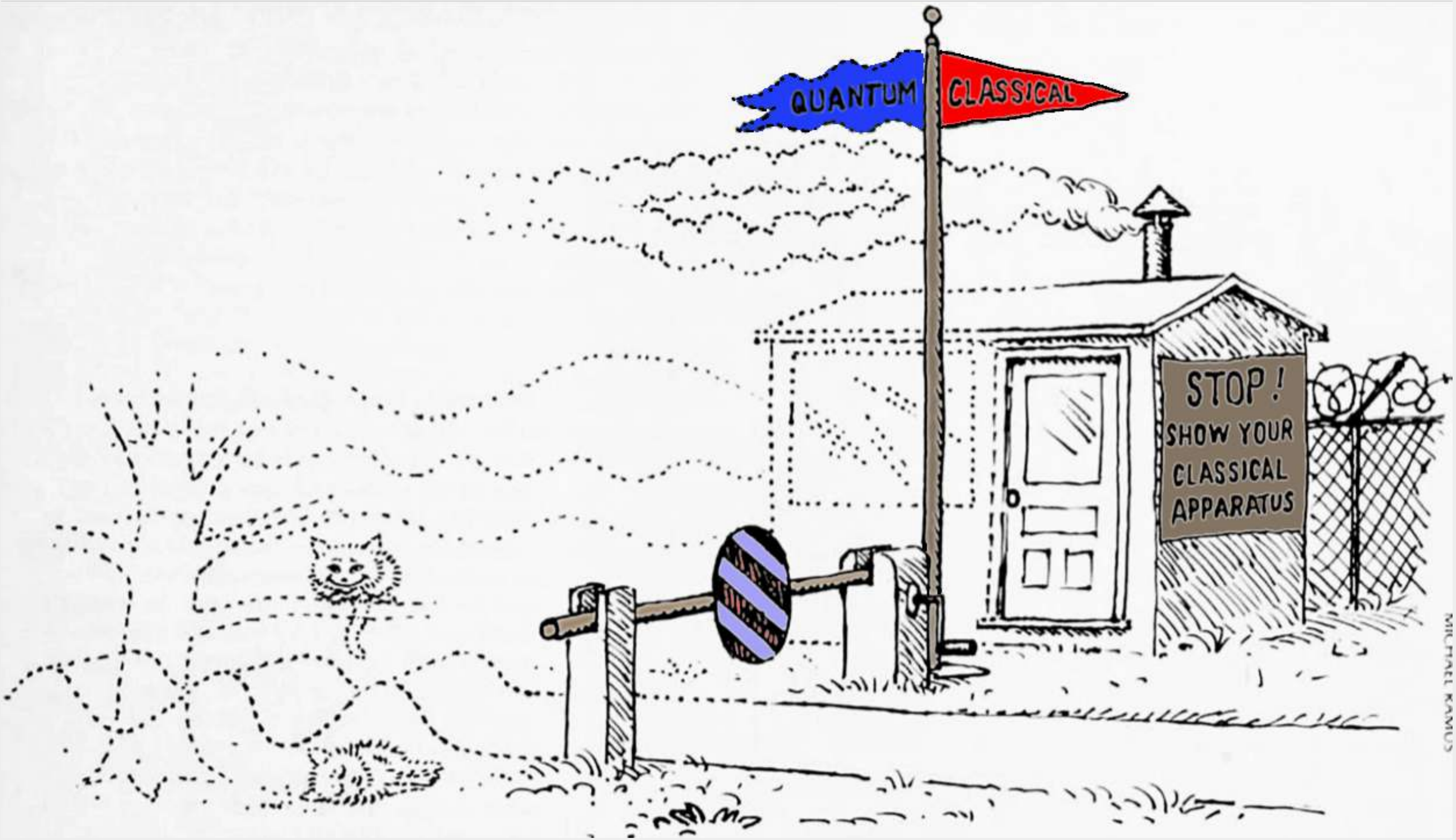
$$\mathcal{E}_{\text{cap}}(Q) = \frac{Q^2}{2C} = \frac{1}{2} C \dot{\Phi}^2$$

Graph: Minev; Spring-mass: Svjo

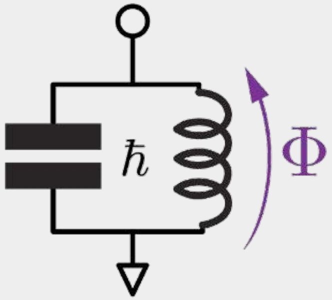


Unveiling the quantum

Quantum harmonic oscillator



Drawing: Zurek, Physics Today (1991)



The classical and quantum oscillator

Classical | Quantum

$$\Phi(t) \mapsto \hat{\Phi}$$

$$Q(t) \mapsto \hat{Q}$$

$$\mathcal{H}(\Phi, Q) \mapsto \hat{H}\left(\hat{\Phi}, \hat{Q}\right)$$

$$\{\Phi, Q\} = 1 \mapsto \left[\hat{\Phi}, \hat{Q}\right] = i\hbar\hat{1}$$

$$\{\alpha, \alpha^*\} = 1/(i\hbar) \mapsto \left[\hat{a}, \hat{a}^\dagger\right] = \hat{1}$$

$$\{A, B\} = \frac{\partial A}{\partial \Phi}\frac{\partial B}{\partial Q} - \frac{\partial B}{\partial \Phi}\frac{\partial A}{\partial Q} \qquad \left[\hat{A}, \hat{B}\right] = \hat{A}\hat{B} - \hat{B}\hat{A}$$

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

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

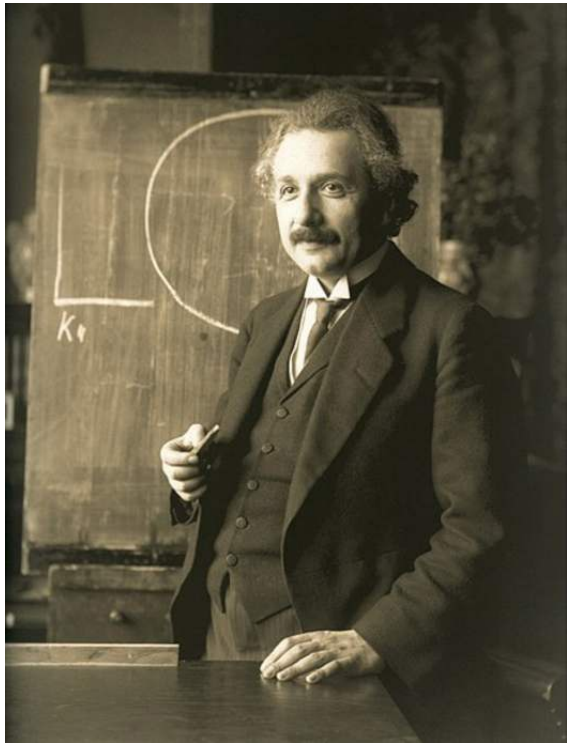
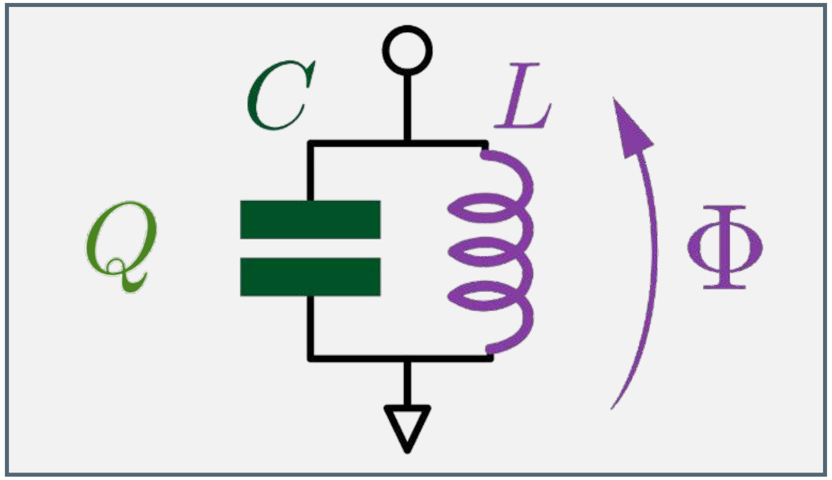
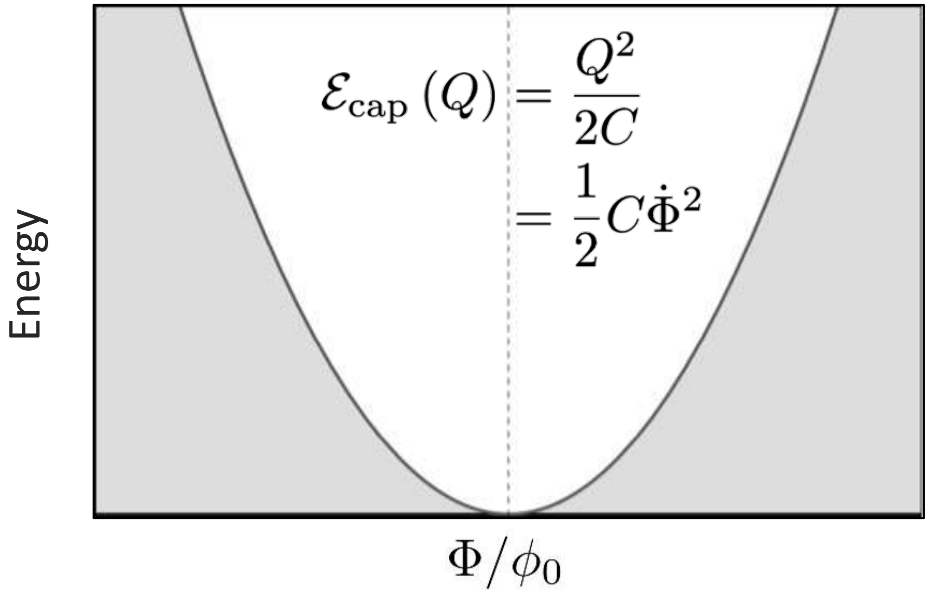


Photo: F. Schmutzer

The LC quantum harmonic oscillator



$$\mathcal{E}_{\text{ind}}\left(\Phi\right) = \frac{\Phi^2}{2L}$$



Position: $\Phi \mapsto x$ Momentum: $Q \mapsto p$

Mass: $C \mapsto m$ Spring constant: $L^{-1} \mapsto k$

$$\hat{H}\left(\hat{\Phi},\hat{Q}\right) = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega_0\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \qquad \omega_0^2 = \frac{1}{LC}$$

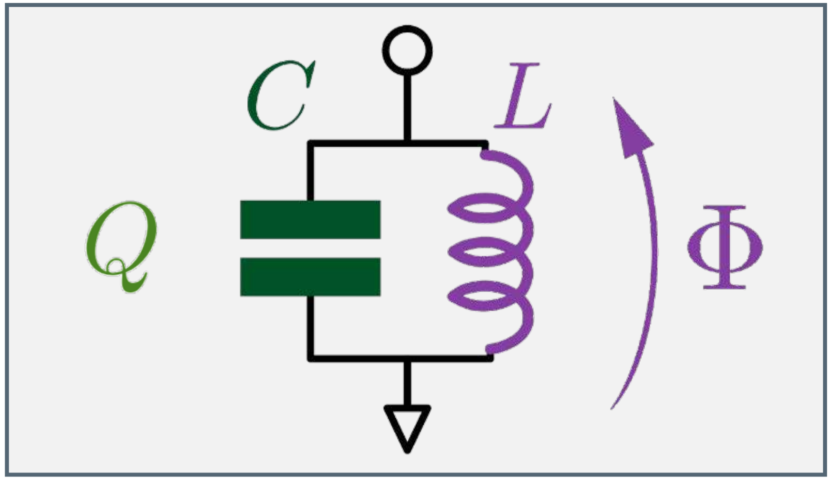
$$\hat{H}\left|n\right\rangle = \hbar\omega_0\left(n + \frac{1}{2}\right)\left|n\right\rangle \qquad Z_0 = \frac{L}{C}$$

$$\hat{\Phi} = \Phi_{\text{ZPF}}\left(\hat{a}^\dagger + \hat{a}\right) \qquad \Phi_{\text{ZPF}} = \sqrt{\frac{\hbar}{2}Z_0} = \Phi_0\sqrt{\frac{z_0}{2\pi}},$$

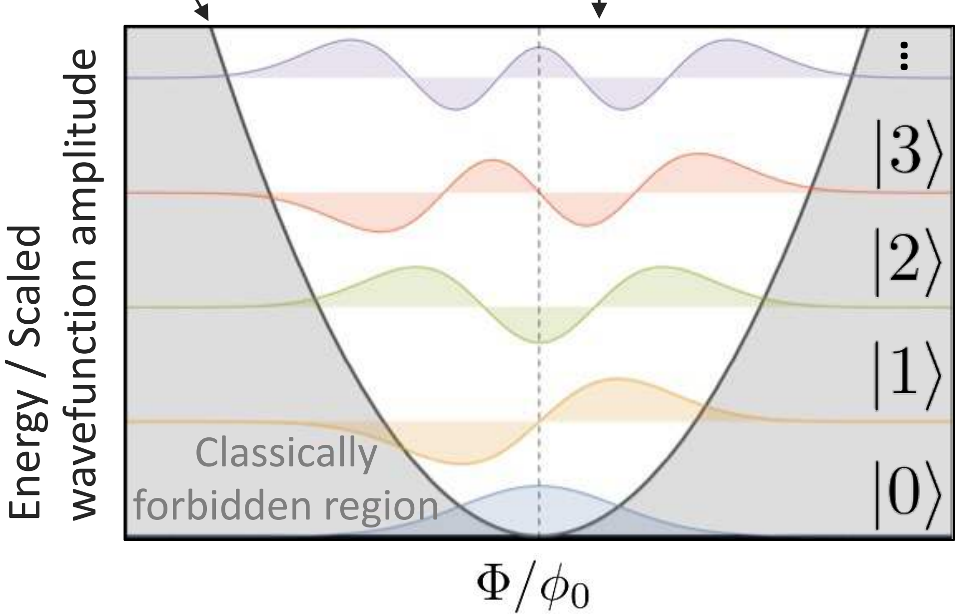
$$\hat{Q} = iQ_{\text{ZPF}}\left(\hat{a}^\dagger - \hat{a}\right) \qquad Q_{\text{ZPF}} = \sqrt{\frac{\hbar}{2}Z_0^{-1}} = (2e)\sqrt{\frac{1}{2\pi z_0}},$$

Graph: Minev; Spring-mass: Svjo

The LC quantum harmonic oscillator



$$\mathcal{E}_{\text{ind}}(\Phi) = \frac{\Phi^2}{2L} \qquad \psi_n(\Phi) \equiv \langle \Phi | n \rangle$$



Position: $\Phi \mapsto x$ Momentum: $Q \mapsto p$

Mass: $C \mapsto m$ Spring constant: $L^{-1} \mapsto k$

$$\hat{H}\left(\hat{\Phi}, \hat{Q}\right) = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega_0\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \qquad \omega_0^2 = \frac{1}{LC}$$

$$\hat{H}|n\rangle = \hbar\omega_0\left(n + \frac{1}{2}\right)|n\rangle \qquad \Phi_{\text{ZPF}} Q_{\text{ZPF}} = \frac{\hbar}{2} \qquad Z_0 = \frac{L}{C}$$

$$\hat{\Phi} = \Phi_{\text{ZPF}}\left(\hat{a}^\dagger + \hat{a}\right) \qquad \Phi_{\text{ZPF}} = \sqrt{\frac{\hbar}{2} Z_0} \qquad \left\langle 0\middle|\hat{\Phi}^2\middle|0\right\rangle = \Phi_{\text{ZPF}}^2$$

$$\hat{Q} = iQ_{\text{ZPF}}\left(\hat{a}^\dagger - \hat{a}\right) \qquad Q_{\text{ZPF}} = \sqrt{\frac{\hbar}{2} Z_0^{-1}} \qquad \left\langle 0\middle|\hat{Q}^2\middle|0\right\rangle = Q_{\text{ZPF}}^2$$

Ladder operators and matrix representation

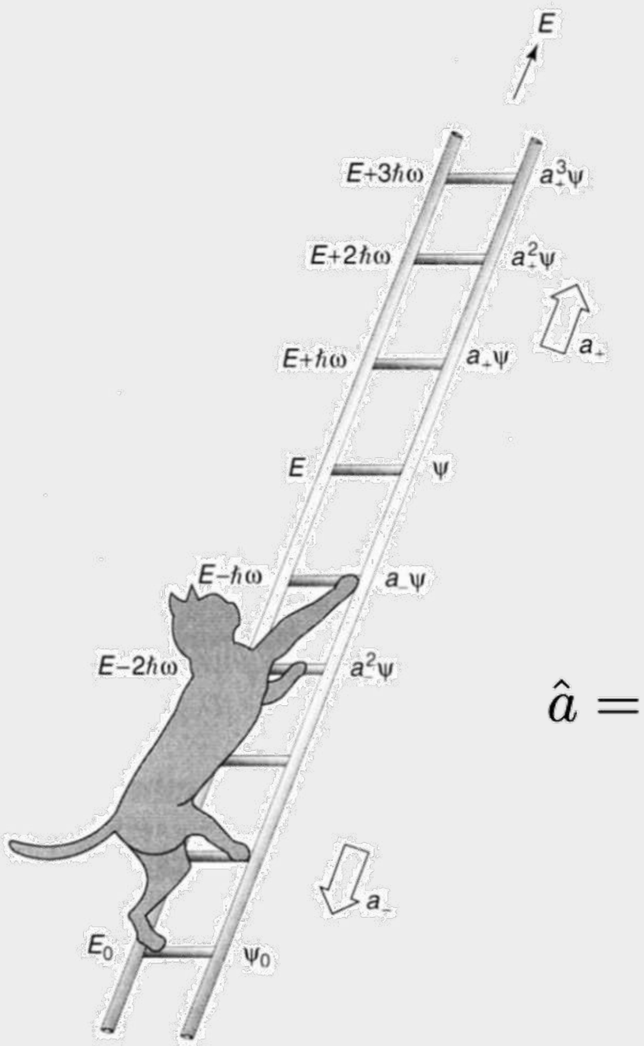
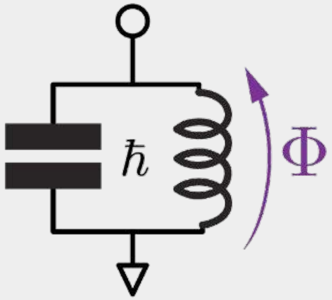


Image: Griffiths, D.J.

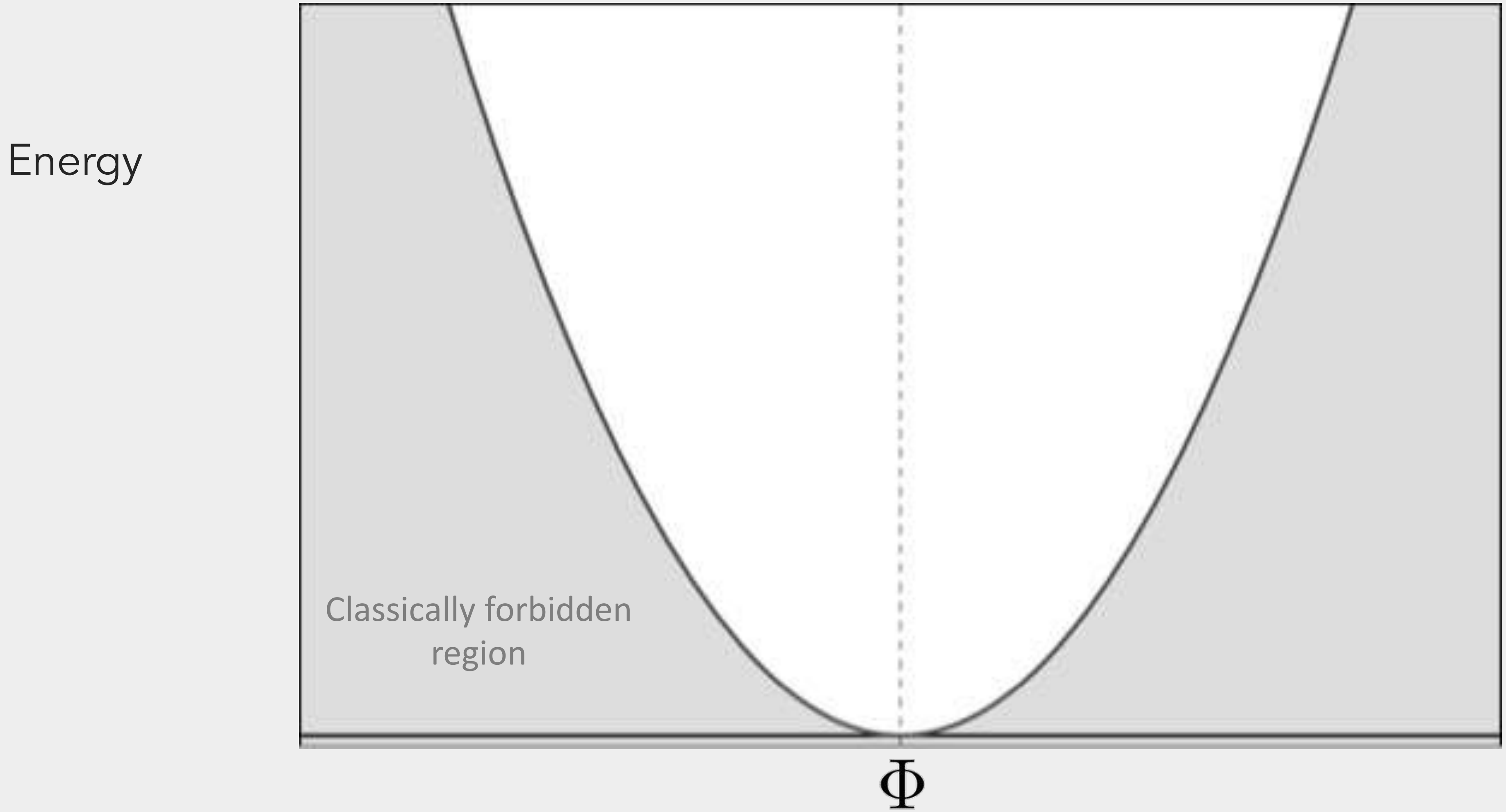
annihilation	creation	general hopping
$\hat{a}\,\vert 0\rangle = 0$	$\hat{a}^\dagger\,\vert 0\rangle = \sqrt{1}\,\vert 1\rangle$	$\hat{a}\,\vert n\rangle = \sqrt{n}\,\vert n-1\rangle$
$\hat{a}\,\vert 1\rangle = \sqrt{1}\,\vert 0\rangle$	$\hat{a}^\dagger\,\vert 1\rangle = \sqrt{2}\,\vert 2\rangle$	$\hat{a}^\dagger\,\vert n\rangle = \sqrt{n+1}\,\vert n+1\rangle$

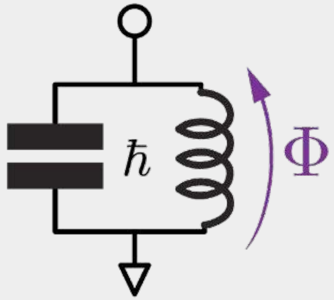
$$\hat{a} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{3} \\ 0 & 0 & 0 & \ddots \end{pmatrix} \quad \hat{a}^\dagger = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & \sqrt{2} & 0 & 0 \\ 0 & 0 & \sqrt{3} & \ddots \end{pmatrix} \quad \hat{a}^\dagger\hat{a} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Wavefunctions of the quantum oscillator



$$\mathcal{E}_{\mathrm{ind}}\left(\Phi\right) = \frac{\Phi^2}{2L}$$





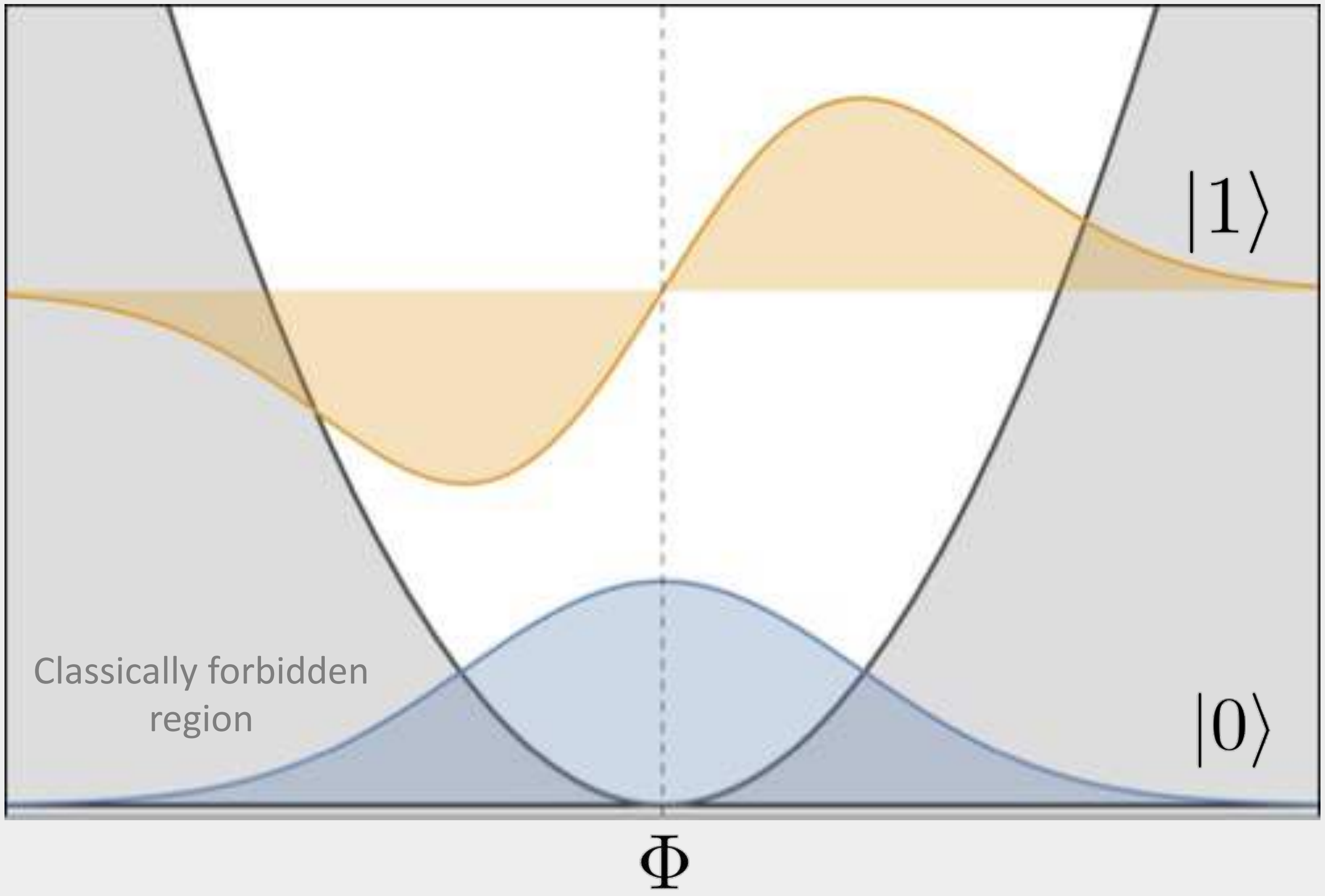
Wavefunctions of the quantum oscillator

$$\mathcal{E}_{\text{ind}}(\Phi) = \frac{\Phi^2}{2L}$$

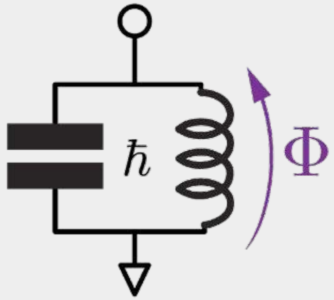
$$\psi_n(\Phi) \equiv \langle \Phi | n \rangle$$

Energy /

Scaled wavefunction amplitude



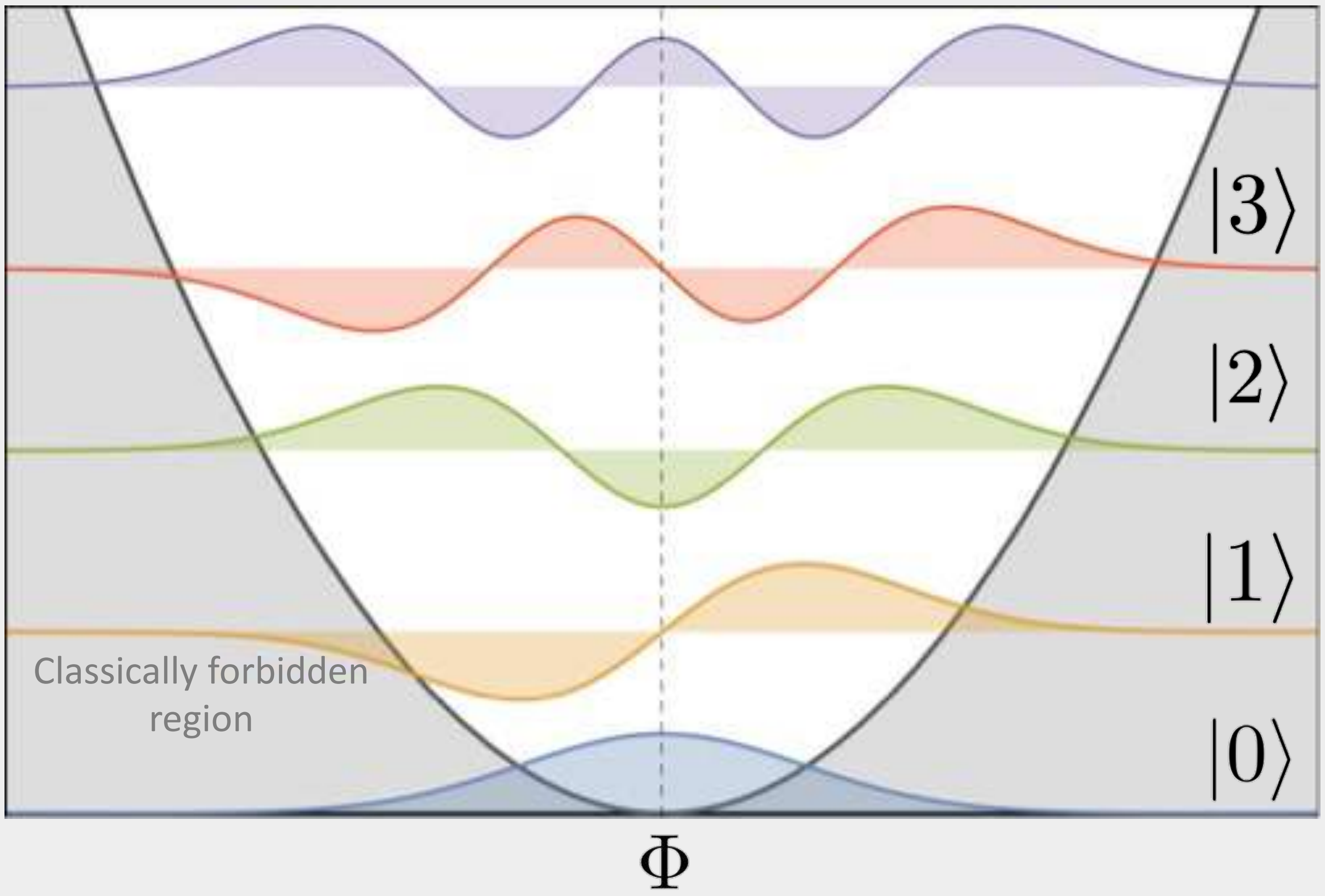
Wavefunctions of the quantum oscillator



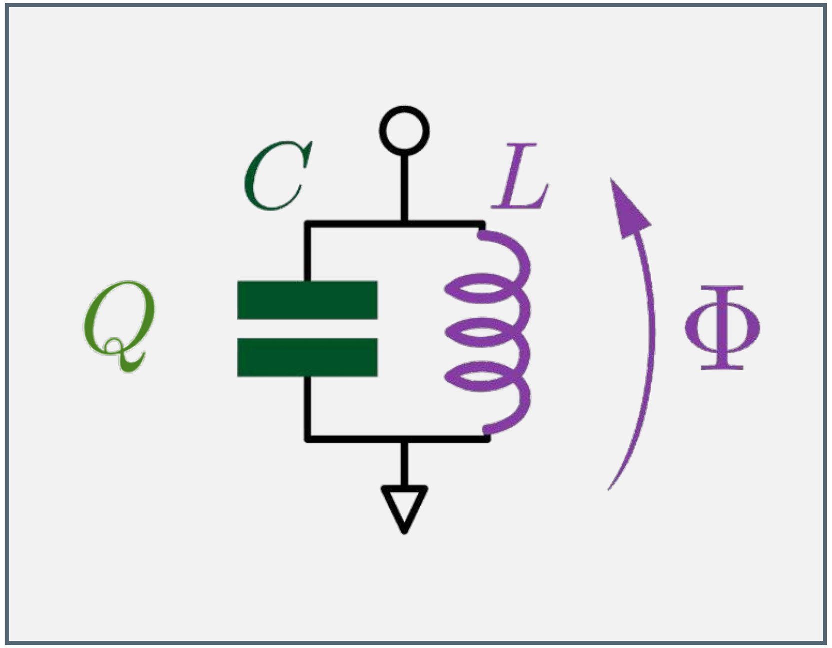
$$\mathcal{E}_{\text{ind}}(\Phi) = \frac{\Phi^2}{2L} \qquad \psi_n(\Phi) \equiv \langle \Phi | n \rangle$$

Energy /

Scaled wavefunction amplitude



Pop-up question



The flux and charge operators are Hermitian observables.

How can some expectations, such as

$$\left\langle 0 \middle| \hat{\Phi}\hat{Q} \middle| 0 \right\rangle = \frac{1}{4} i \; ,$$

be imaginary?

Or, others be negative…?

Advanced questions

1. What is $\hat{\Phi}(t)$ in terms of $\hat{a}$ in the Heisenberg picture?

2. **Autocorrelation.** Find the autocorrelation operator $\hat{C}_{\Phi\Phi}(t) = \hat{\Phi}(t)\,\hat{\Phi}(0)$. What frequency components does it have?

   (a) What is the flux autocorrelation expectation value $C_{\Phi\Phi}(t) = \left\langle n \middle| \hat{\Phi}(t)\,\hat{\Phi}(0) \middle| n \right\rangle$ for the Fock state $|n\rangle$? Is it real? Why not? What is the frequency spectrum?

   (b) Repeat for a coherent state $|\alpha\rangle$.

3. **Thermal state.** The thermal state is $\hat{\rho}_{\mathrm{th}} = \exp\left[-\beta\hat{a}^{\dagger}\hat{a}\right] / \operatorname{Tr}\left[\exp\left(-\beta\hat{a}^{\dagger}\hat{a}\right)\right]$, where $\beta = \hbar\omega_0/k_{\mathrm{B}}T$, and T is the temperature of the oscillator.

   (a) What is the mean and variance of the flux $\hat{\Phi}$ and charge $\hat{Q}$ operators?

   (b) How does the frequency spectrum of the autocorrelation $\left\langle \hat{C}_{\Phi\Phi}(t) \right\rangle = \operatorname{Tr}\left[\hat{\rho}_{\mathrm{th}}\hat{C}_{\Phi\Phi}(t)\right]$ change when with that for the state $|n\rangle$ and $|\alpha\rangle$?

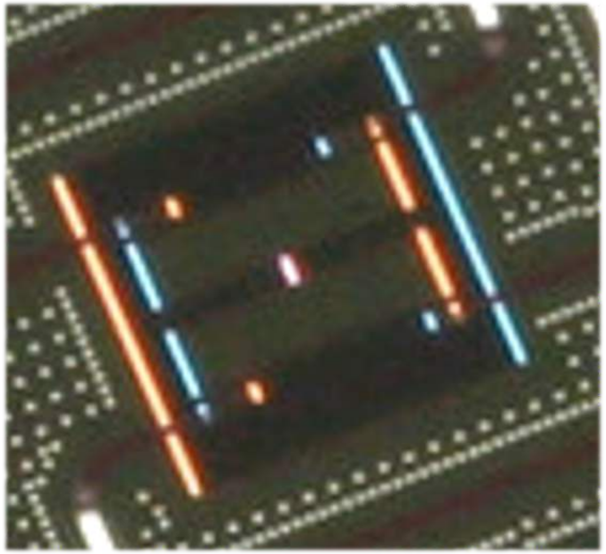
   (c) The spectrum is not symmetric in frequency. How can you interpret that positive and negative frequencies have different weights? How is this related to absorption and emission of the oscillator? (Consider Fermi's golden rule).

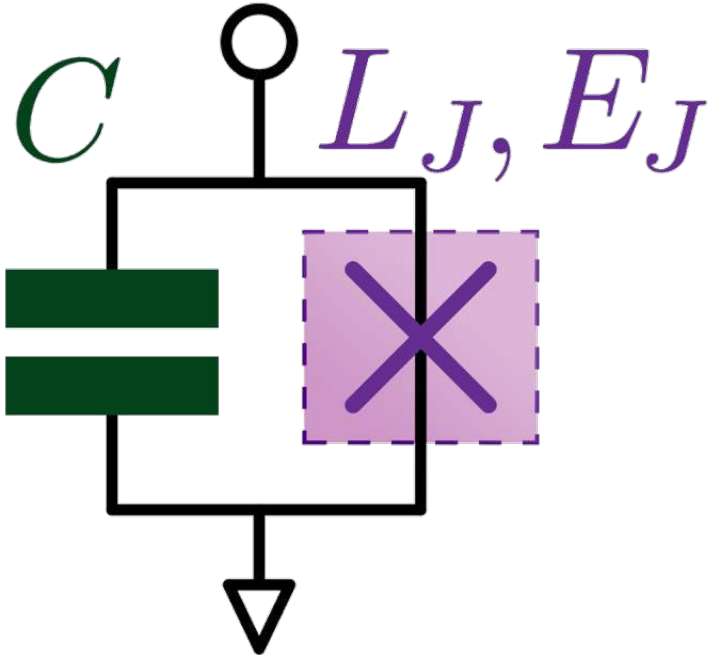
   (d) What happens to the spectrum in the limit of high temperature, $k_{\mathrm{B}}T \gg \hbar\omega_0$? How about low temperature, $k_{\mathrm{B}}T \gg \hbar\omega_0$?

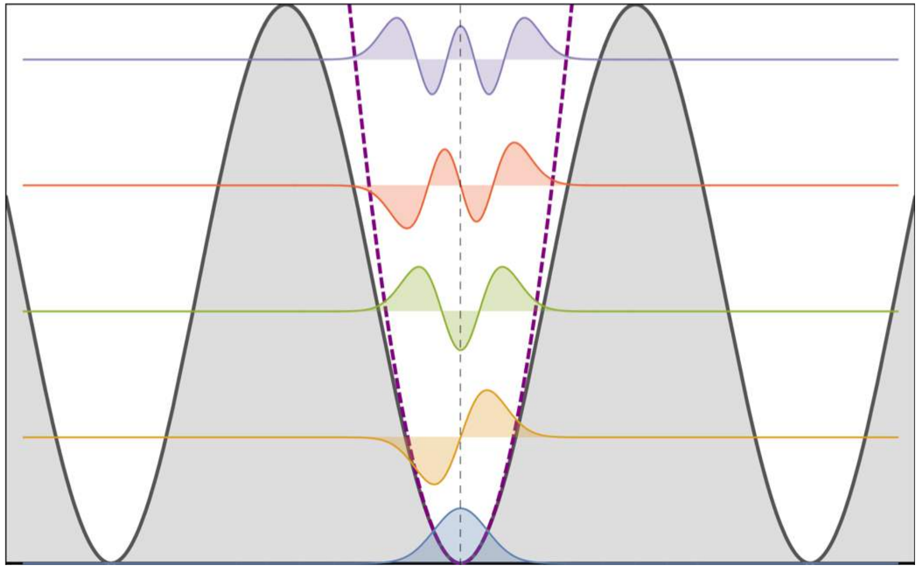
   (e) How do the above conclusions change for charge; i.e., for $\left\langle \hat{C}_{QQ}(t) \right\rangle = \operatorname{Tr}\left[\hat{\rho}_{\mathrm{th}}\hat{C}_{QQ}(t)\right]$?

Will discuss answers on my blog sometime soon

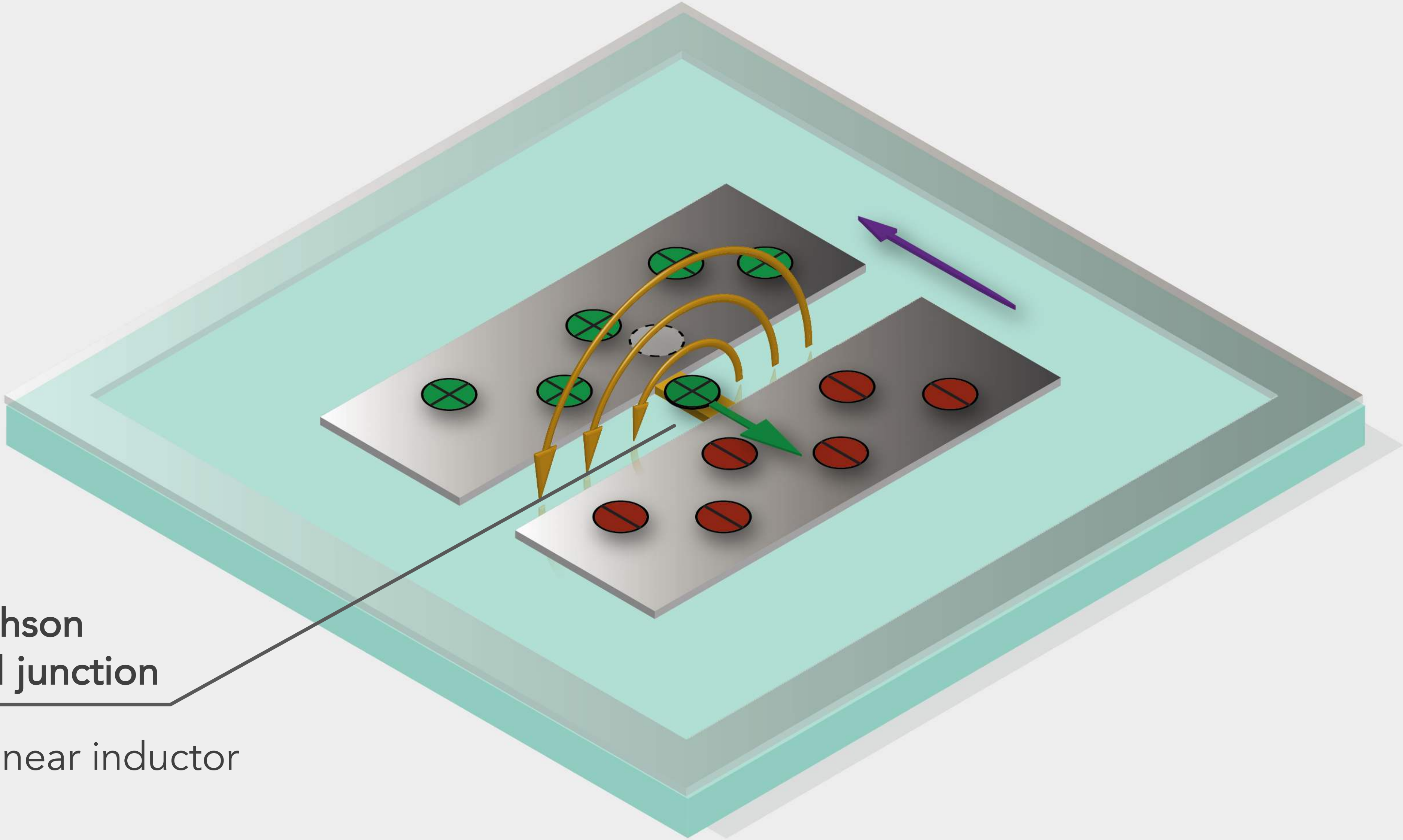
Transmon Qubit







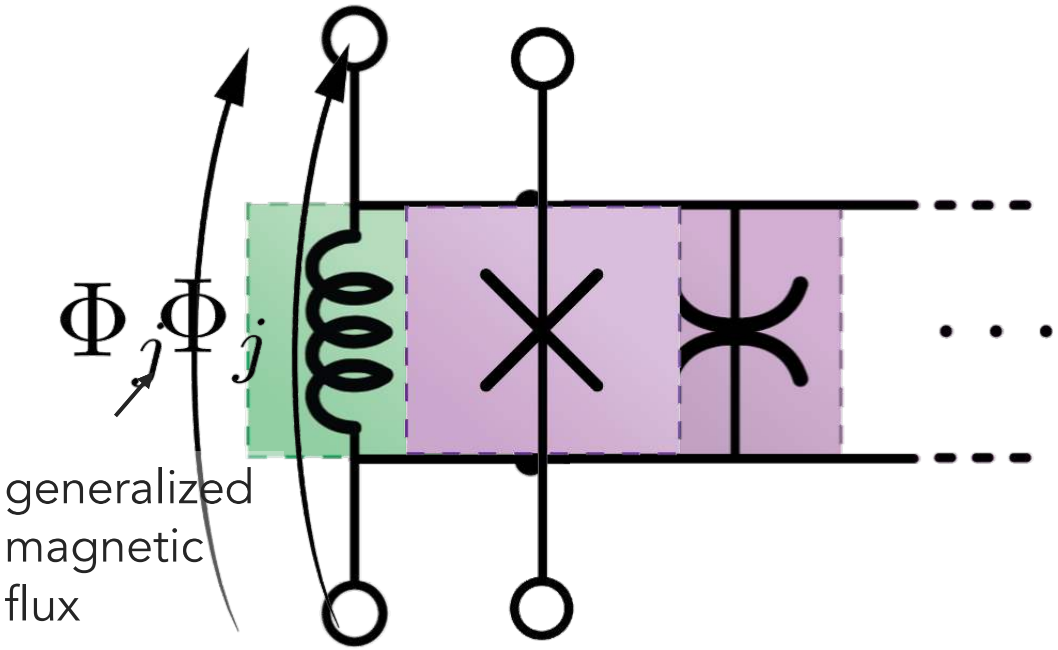
The transmon as a non-linear oscillator



Josephson tunnel junction

Non-linear inductor

Josephson tunnel junction

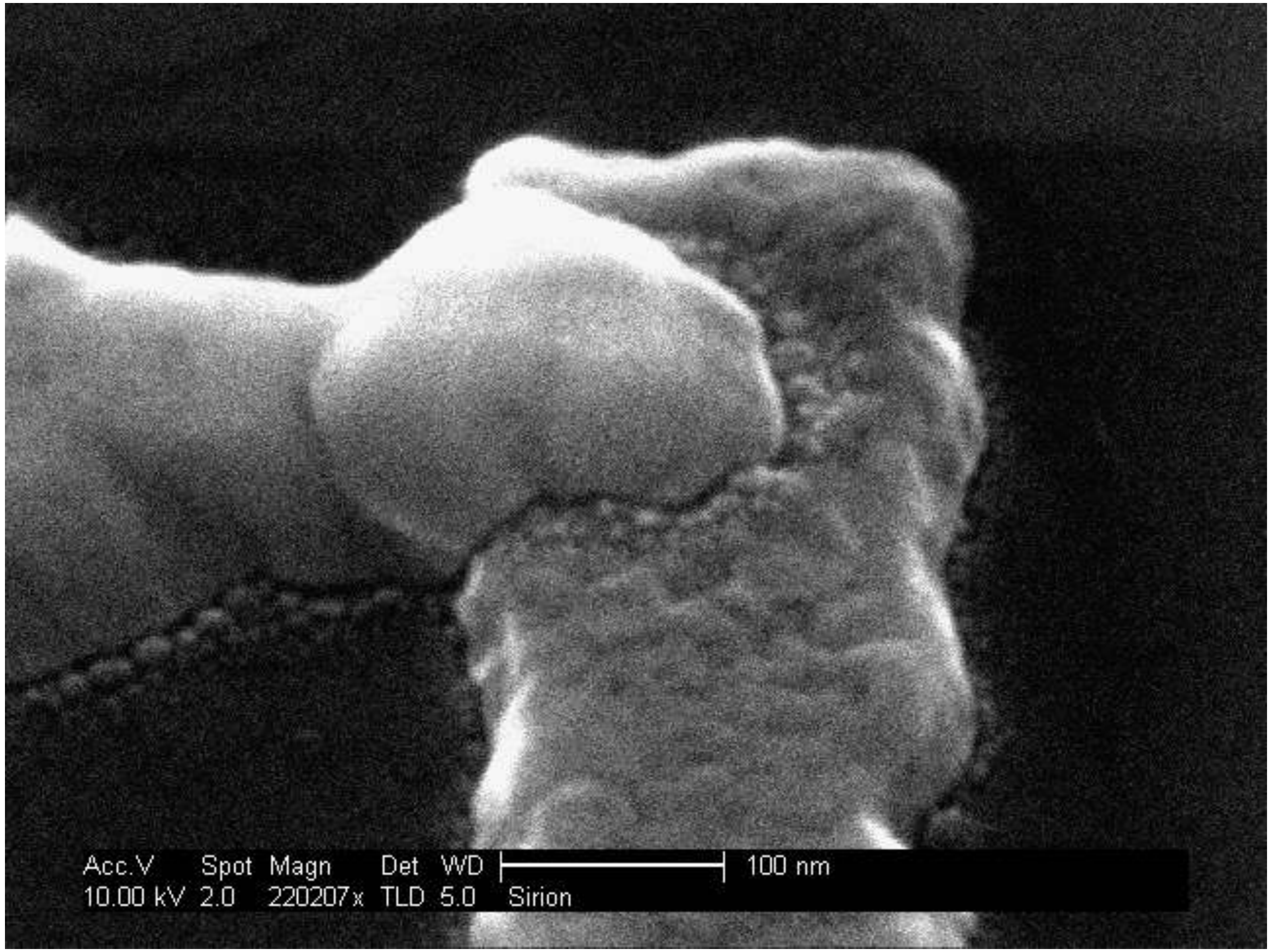


$$\mathcal{E}_j\left(\Phi_j\right) = E_j\left(1 - \cos\left(\Phi_j/\phi_0\right)\right)$$

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

$$\phi_0 \equiv \hbar/2e$$

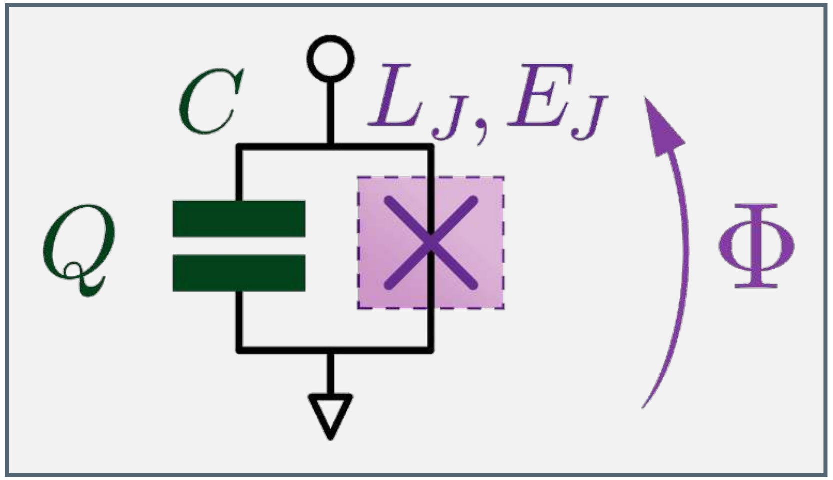
$$= \frac{E_j}{2}\left(\frac{\Phi_j}{\phi_0}\right)^2 - \frac{E_j}{4!}\left(\frac{\Phi_j}{\phi_0}\right)^4 + \mathcal{O}\left(\Phi_j^6\right)$$



SEM image: L. Frunzio

Circuit image: Minev et al., EPR to appear (2020)

The Transmon qubit



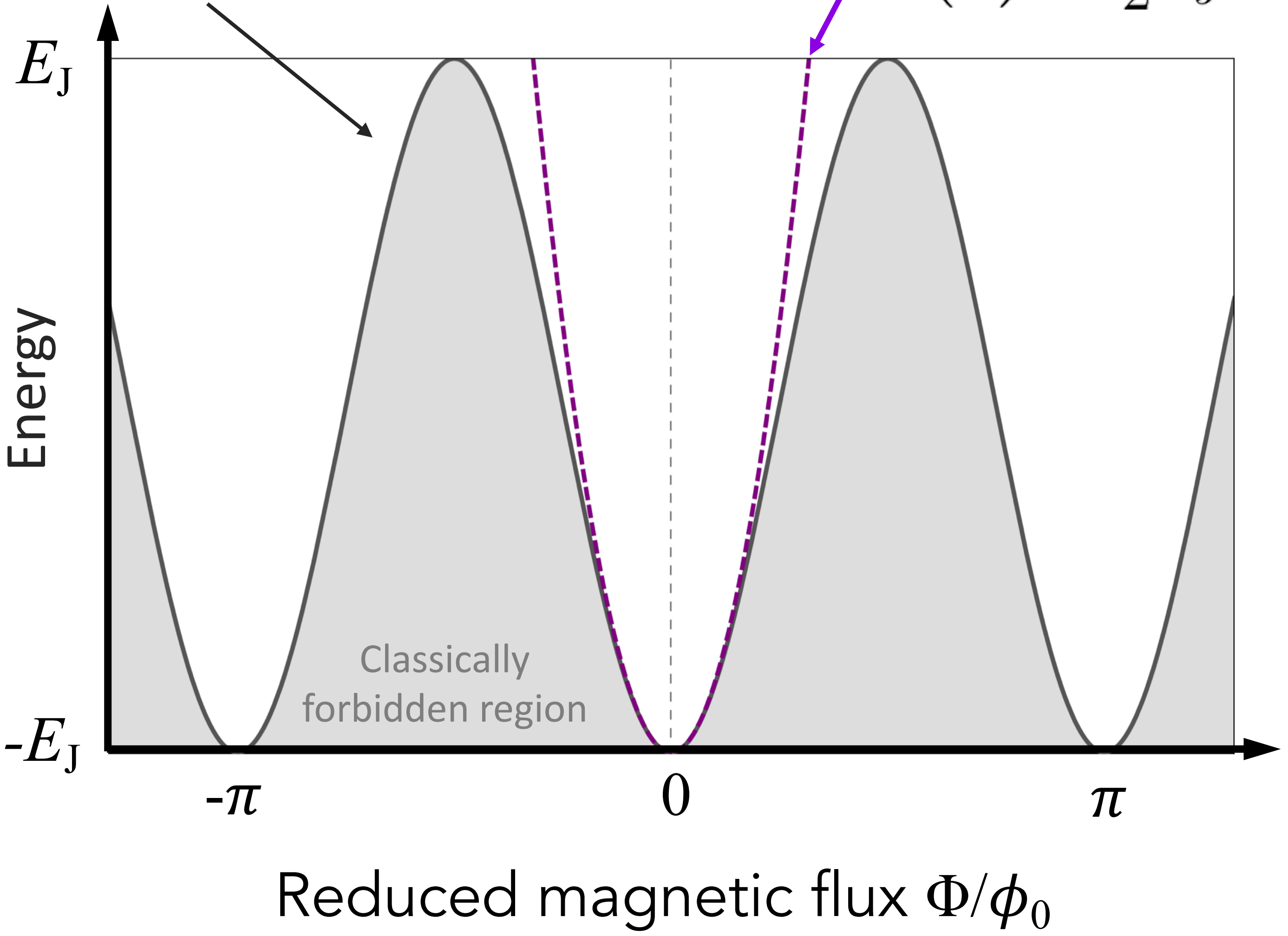
$$E_J = \frac{\phi_0^2}{L_J}$$

$$\phi_0 = \frac{\hbar}{2e}$$

$$\approx 3.3 \times 10^{-16}\ \mathrm{Wb}$$

$$\mathcal{E}_J\left(\Phi\right) = -E_J \cos\left(\Phi/\phi_0\right)$$

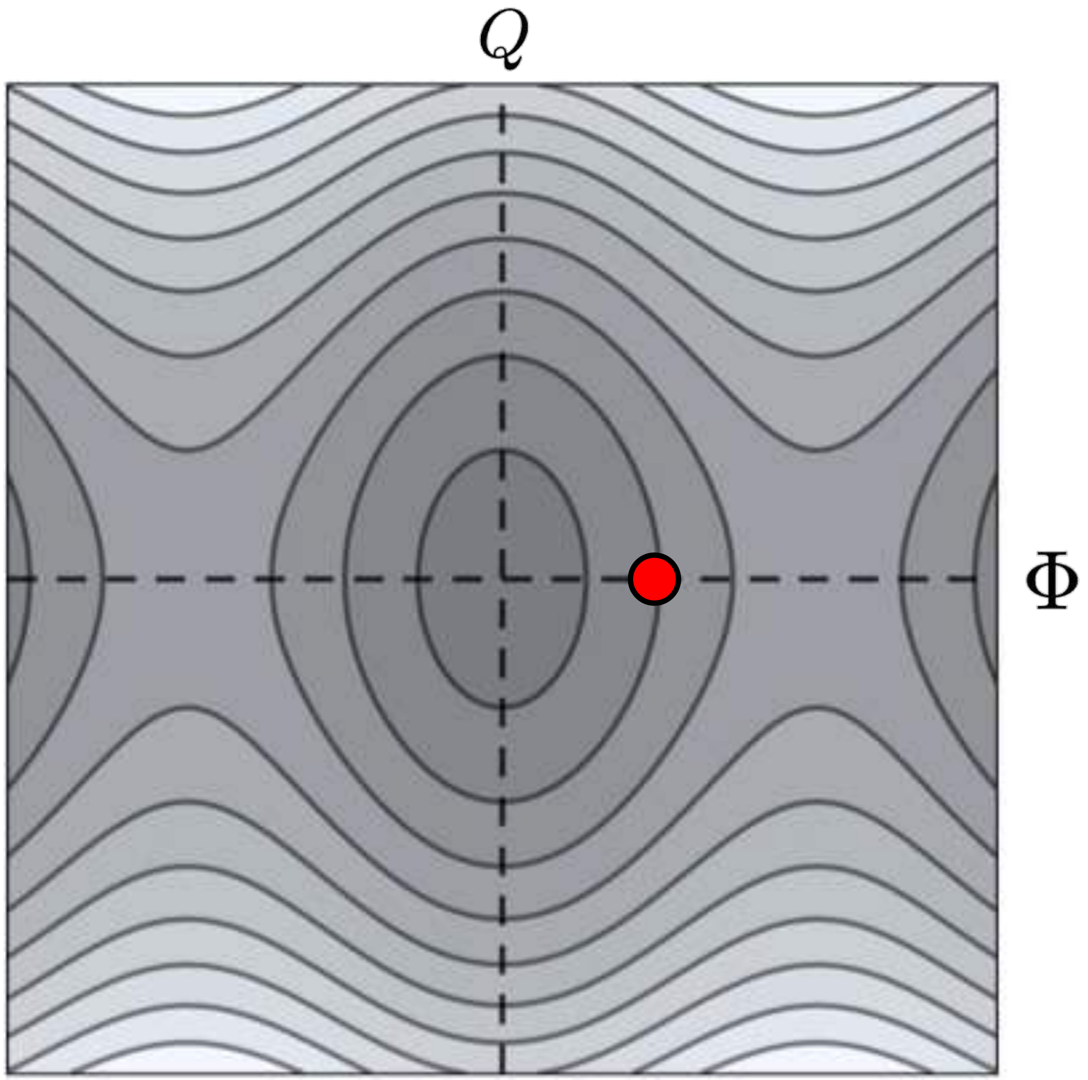
$$\mathcal{E}_J^{(2)}\left(\Phi\right) \approx \frac{\Phi^2}{2L_J} \qquad \mathcal{E}_{\mathrm{cap}}\left(\dot{\Phi}\right) \approx \frac{1}{2}C\dot{\Phi}^2$$



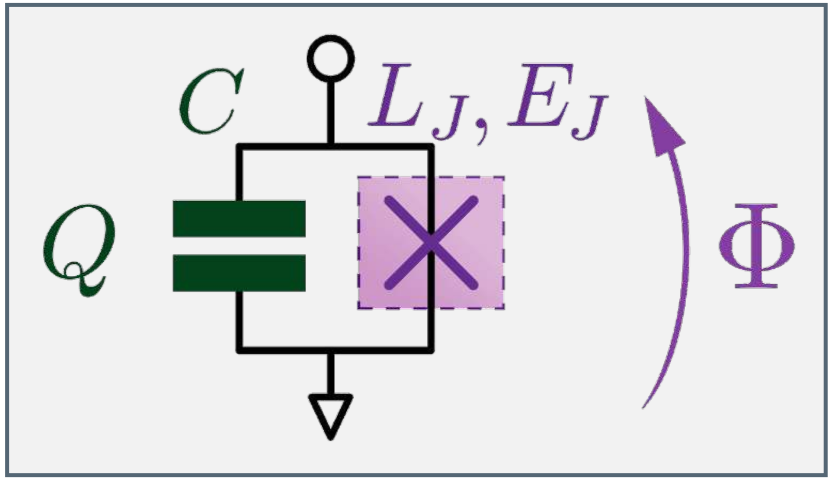
Semi-classical intuition: phase space picture

$$\mathcal{H}\left(\Phi, Q\right) = \frac{Q^2}{2C} - E_J \cos\left(\Phi/\phi_0\right)$$

$$\begin{aligned} E &= \hbar\omega_0 \left(n + \frac{1}{2}\right) \\ &= \frac{Q^2}{2C} - E_J \cos\left(\Phi/\phi_0\right) \end{aligned}$$



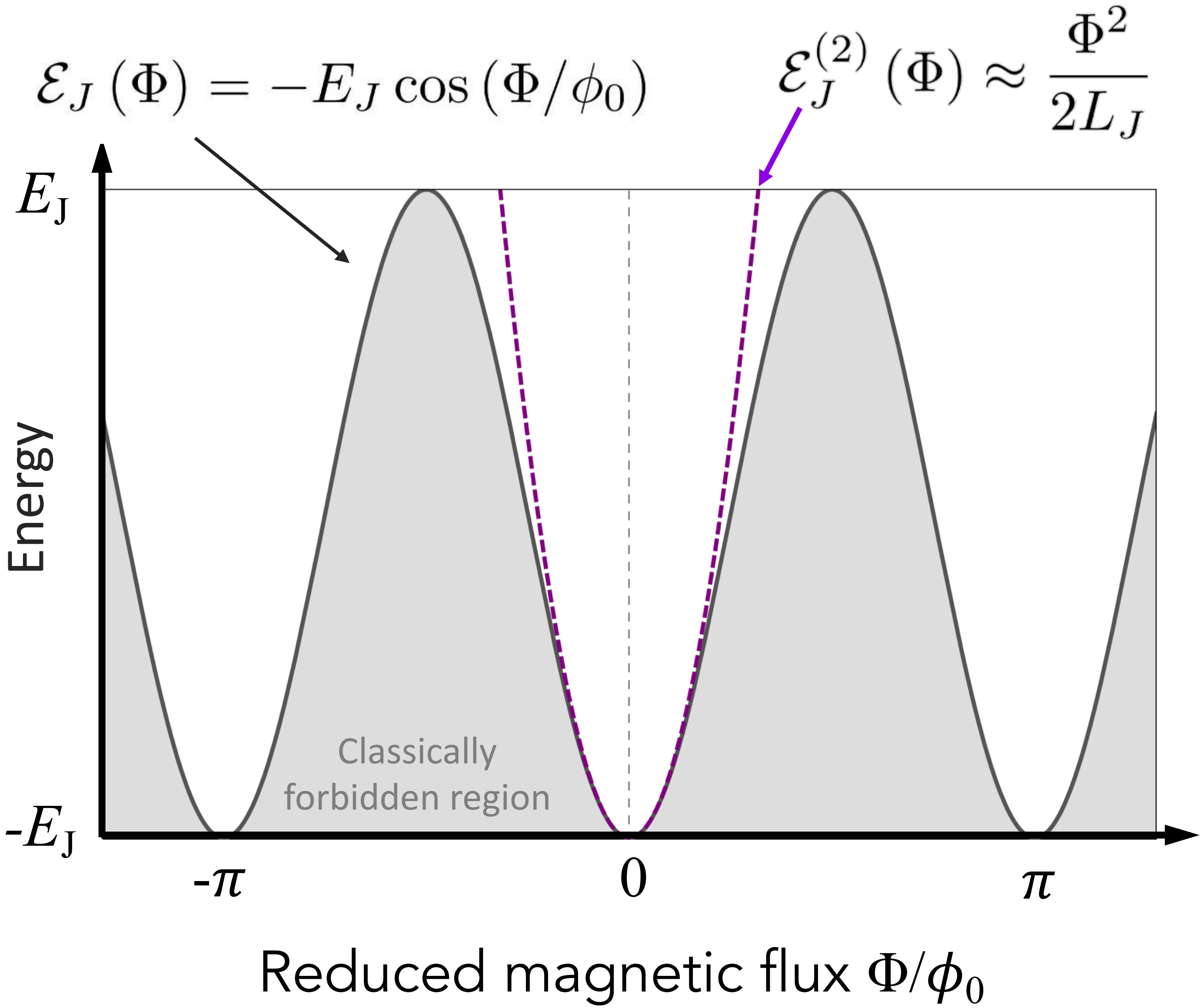
The Transmon qubit



$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\hat{\Phi}/\phi_0\right)$$

$$\approx \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L_J} - \frac{E_J}{4!}\left(\frac{\hat{\Phi}}{\phi_0}\right)^4$$

$$= \hbar\omega_0 \hat{a}^\dagger \hat{a} - \frac{E_J \phi_{\mathrm{ZPF}}^4}{4!}\left(\hat{a} + \hat{a}^\dagger\right)^4$$



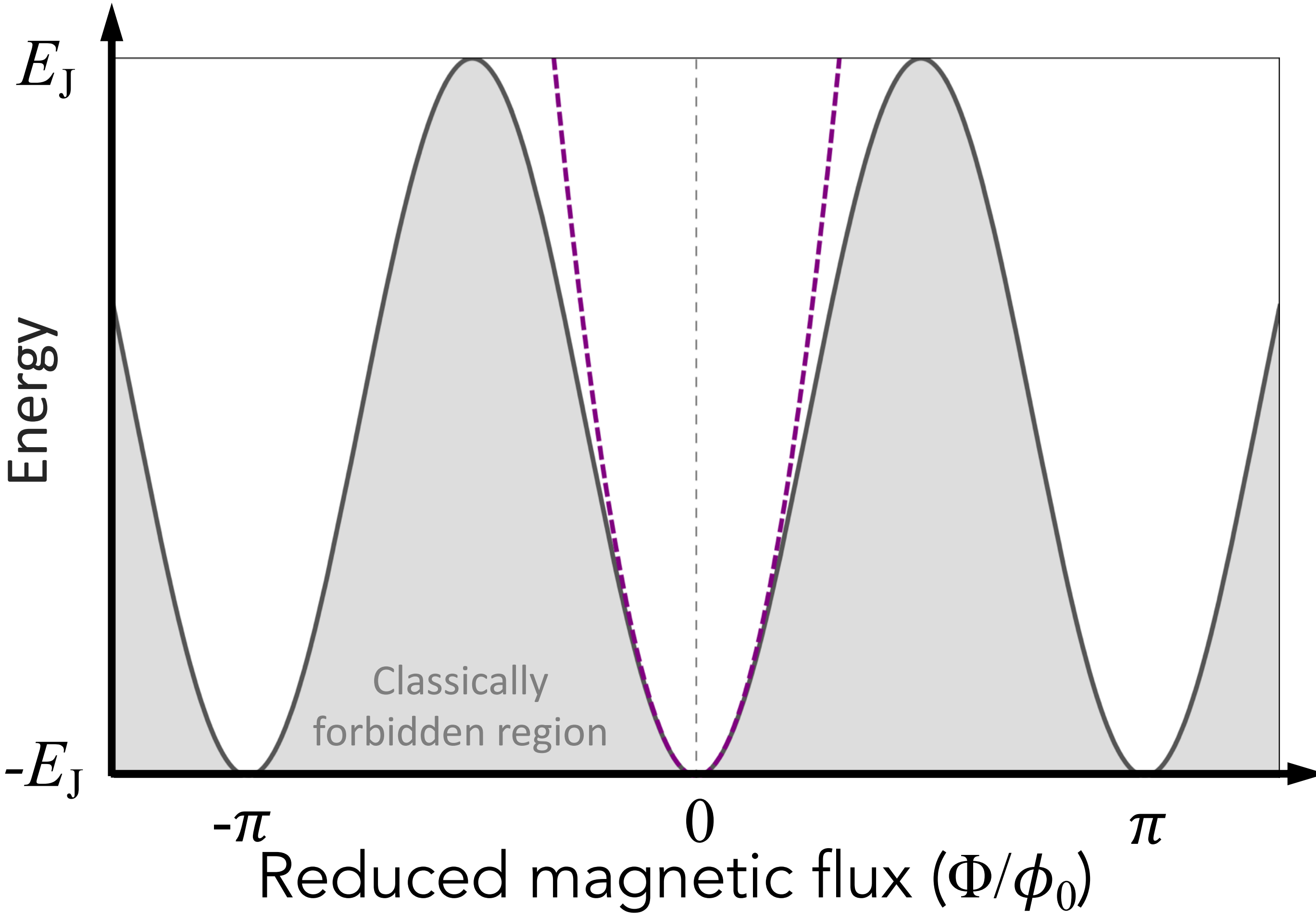
The Kerr Hamiltonian of the transmon

$$\hat{N} \equiv \hat{a}^\dagger \hat{a}$$

$$\boxed{\hat{H}_4^{\mathrm{RWA}} \approx \underbrace{\hbar\omega_q \hat{N}}_{\hat{H}_{\mathrm{lin}}} \underbrace{- \frac{\hbar\alpha}{2}\hat{N}\left(\hat{N}-1\right)}_{\hat{H}_{\mathrm{nl}}}}$$

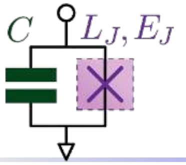
Solution known (SHO) — New from nonlinearity

$$\hat{H}_4^{\mathrm{RWA}} \left|n\right\rangle = \hbar\omega_q n \left(1 - \frac{\hbar\alpha_a}{2}(n-1)\right)\left|n\right\rangle$$



1st order correction to energy: $E_n^{(1)} = \left\langle n^{(0)}\right| \hat{H}_{\mathrm{nl}} \left|n^{(0)}\right\rangle$ and to eigenstates: $\left|n^{(1)}\right\rangle = \sum_{k\neq n} \frac{\left\langle k^{(0)}\right| \hat{H}_{\mathrm{nl}} \left|n^{(0)}\right\rangle}{E_n^{(0)} - E_k^{(0)}} \left|k^{(0)}\right\rangle.$

To first order perturbation theory the eigenstates do not change! Only the energy changes. Dispersive.



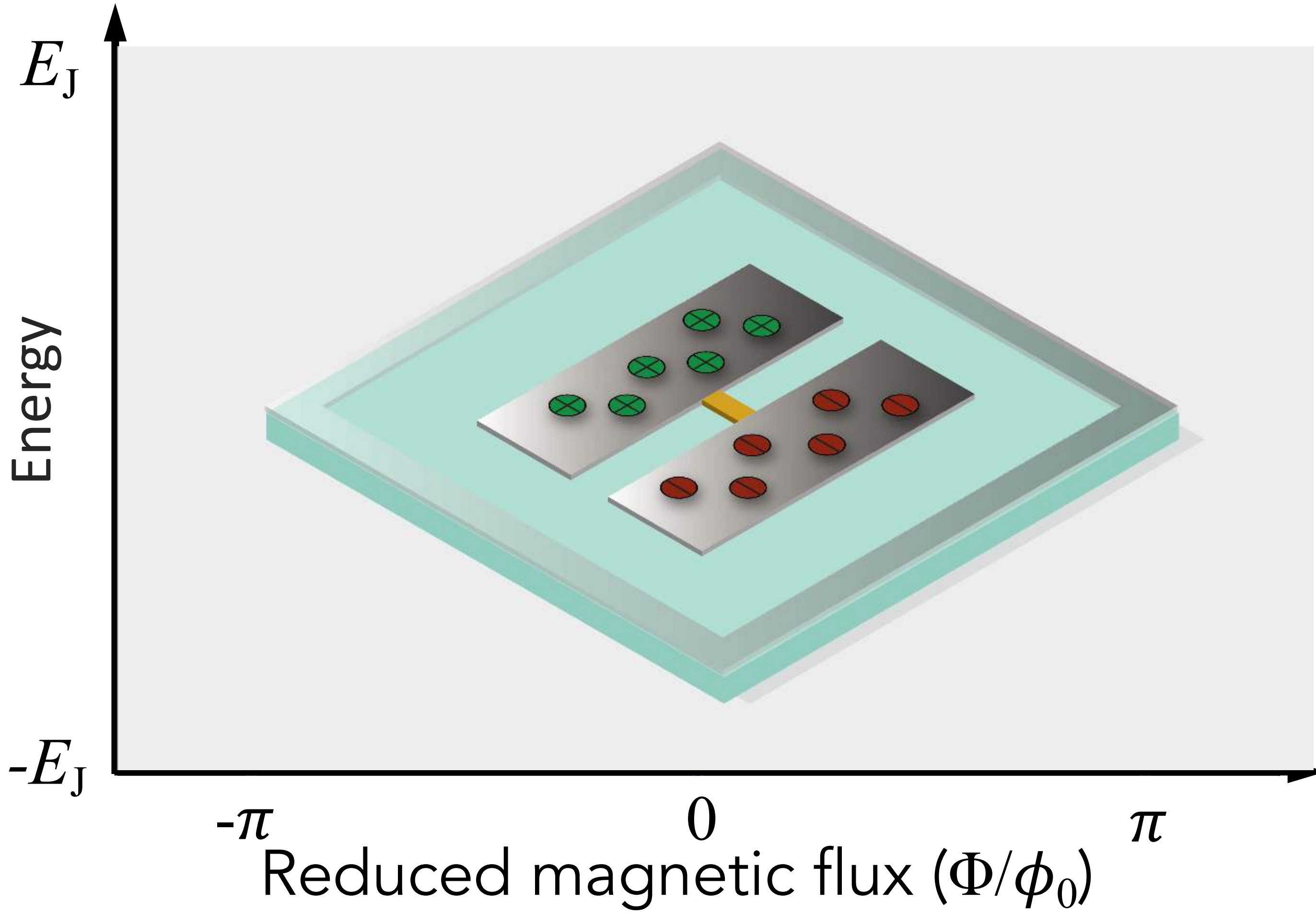
Exploring a real transmon qubit

$$\hat{N} \equiv \hat{a}^\dagger \hat{a}$$

$$\boxed{\hat{H}_4^{\mathrm{RWA}} \approx \underbrace{\hbar\omega_q \hat{N}}_{\hat{H}_{\mathrm{lin}}} \underbrace{- \frac{\hbar\alpha}{2}\hat{N}\left(\hat{N}-1\right)}_{\hat{H}_{\mathrm{nl}}}}$$

Solution known (SHO)

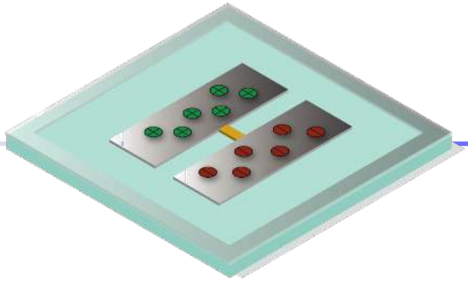
New from nonlinearity



Experimental parameters

$$L_J = 14 \text{ nH} \qquad E_J = \frac{\phi_0^2}{L_J} = 12 \text{ GHz}$$

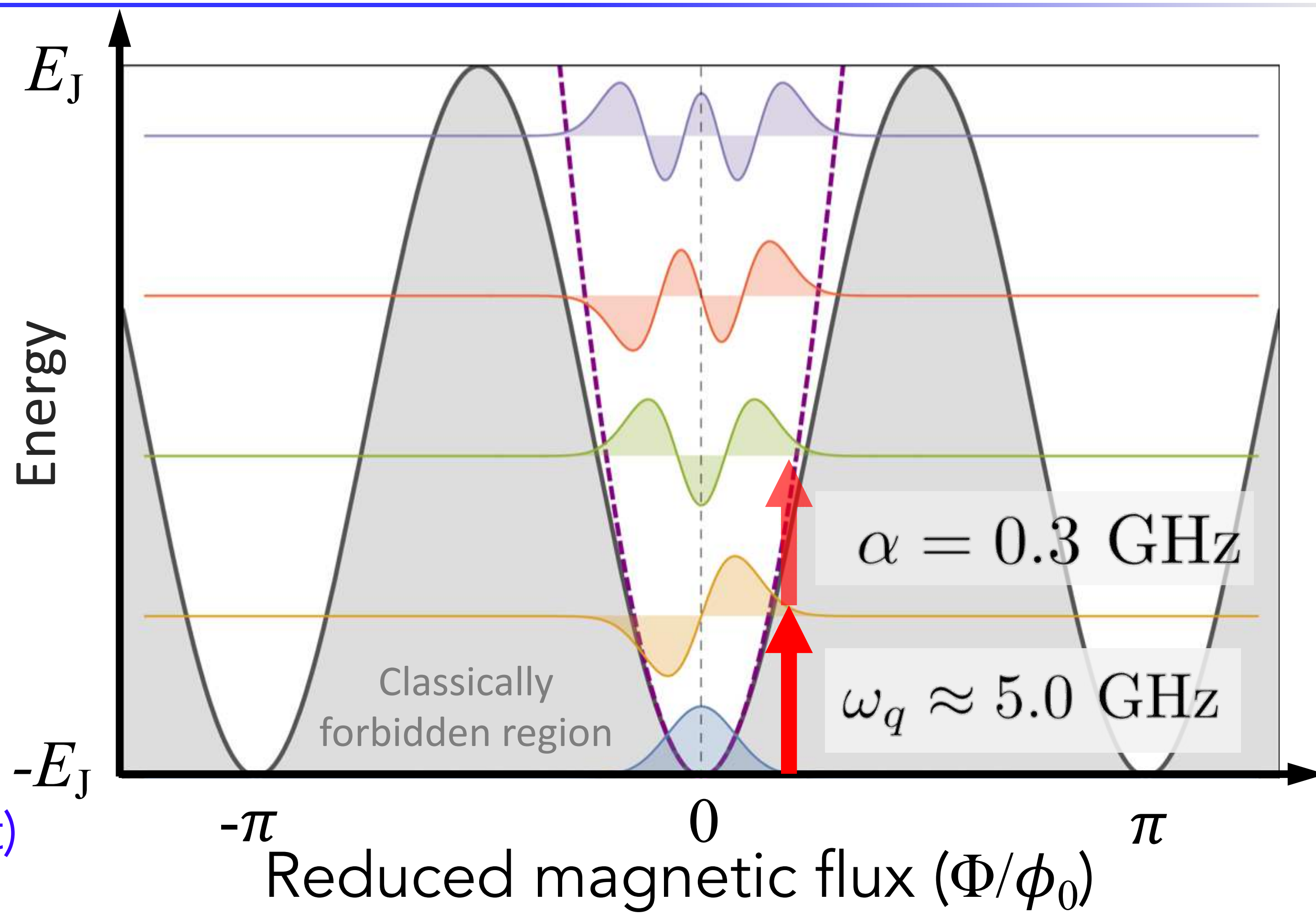
$$C_J = 65 \text{ fF} \qquad E_C = \frac{e^2}{2C} = 0.3 \text{ GHz}$$



Exploring a real transmon qubit

$$\boxed{\hat{H}_4^{\mathrm{RWA}} \approx \hbar\omega_q \hat{N} - \frac{\hbar\alpha}{2}\hat{N}\left(\hat{N}-1\right)}$$

Dispersive, states didn't change to 1st order
"Lamb shift" due to ZPF



Parameters used in figure (of a measured qubit)

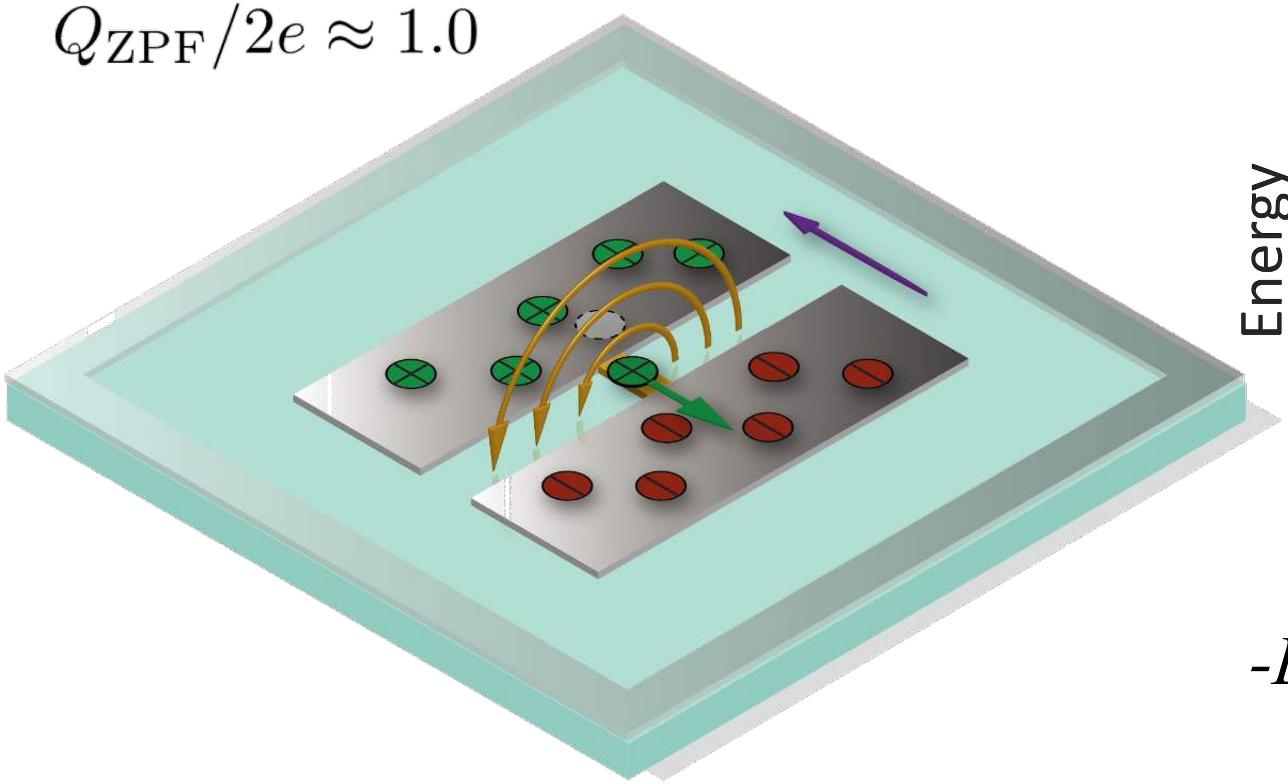
$$L_J = 14 \text{ nH} \qquad E_J = \frac{\phi_0^2}{L_J} = 12 \text{ GHz} \qquad \omega_0 = \sqrt{\frac{1}{LC}} = 5.3 \text{ GHz}$$

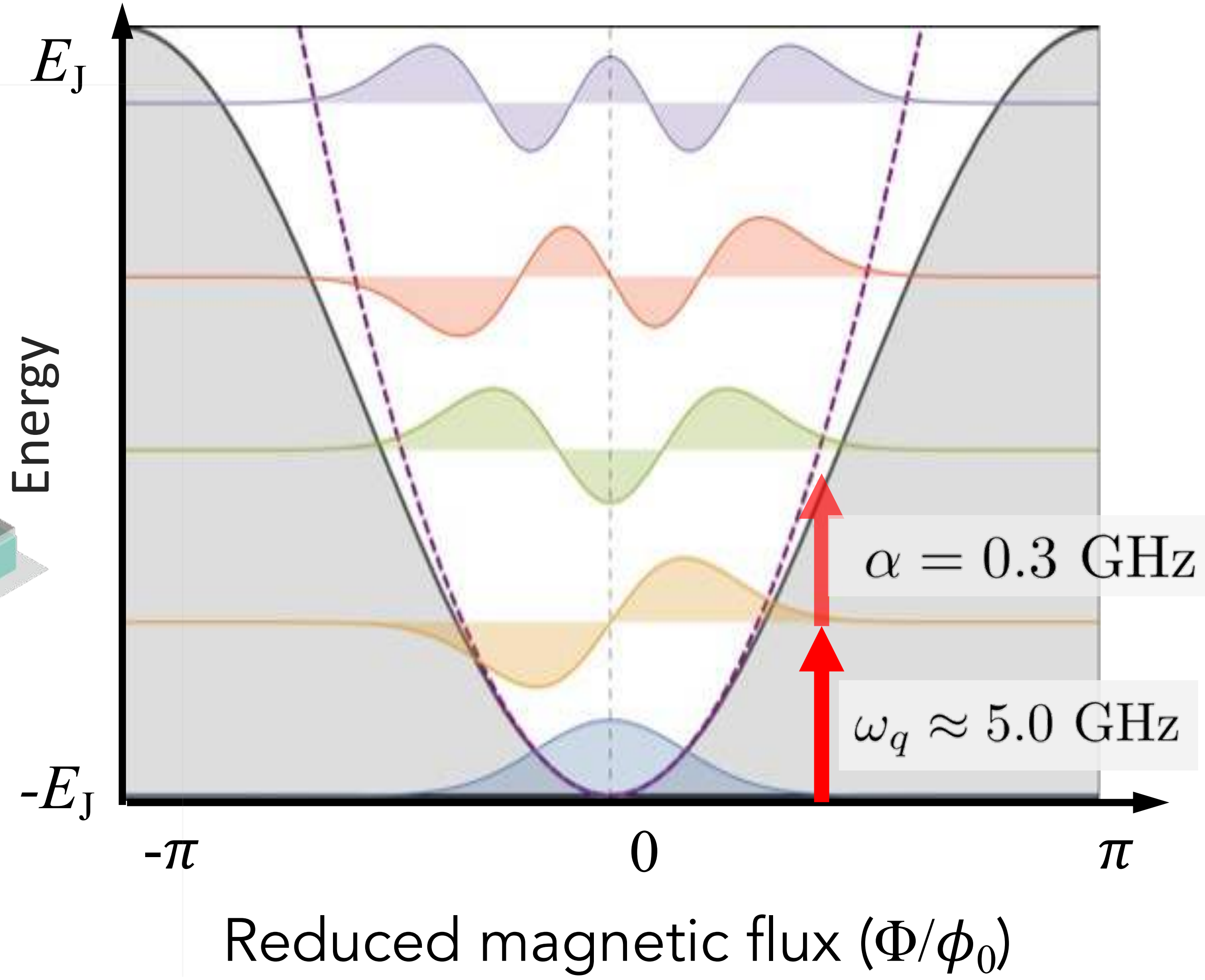
$$C_J = 65 \text{ fF} \qquad E_C = \frac{e^2}{2C} = 0.3 \text{ GHz} \qquad Z = \sqrt{\frac{L}{C}} \approx 450\ \Omega$$

Quantum fluctuations of the transmon qubit

$\Phi_{\mathrm{ZPF}}/\phi_0 \approx 0.5$

$Q_{\mathrm{ZPF}}/2e \approx 1.0$



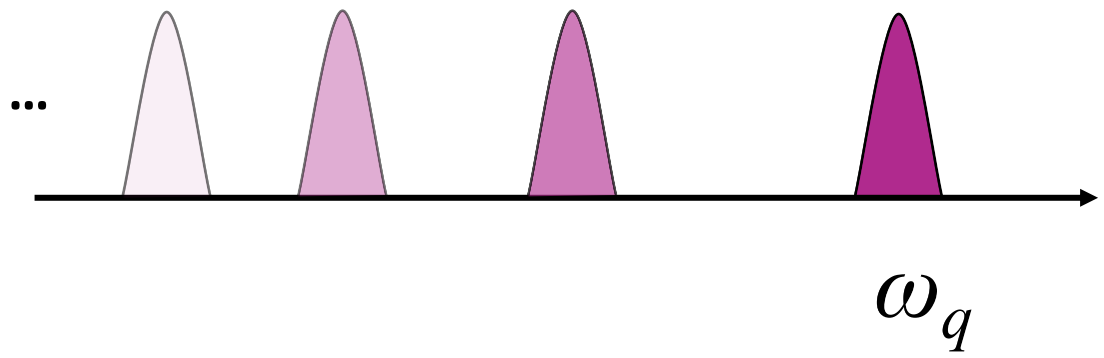


Energy diagram and transition spectrum

Energy levels

$$\hat{H} \approx \omega_0 \hat{a}^\dagger \hat{a} - \frac{\alpha}{2} \hat{a}^{\dagger 2} \hat{a}^2$$

Transition spectrum



The Transmon qubit: restricting Hilbert space

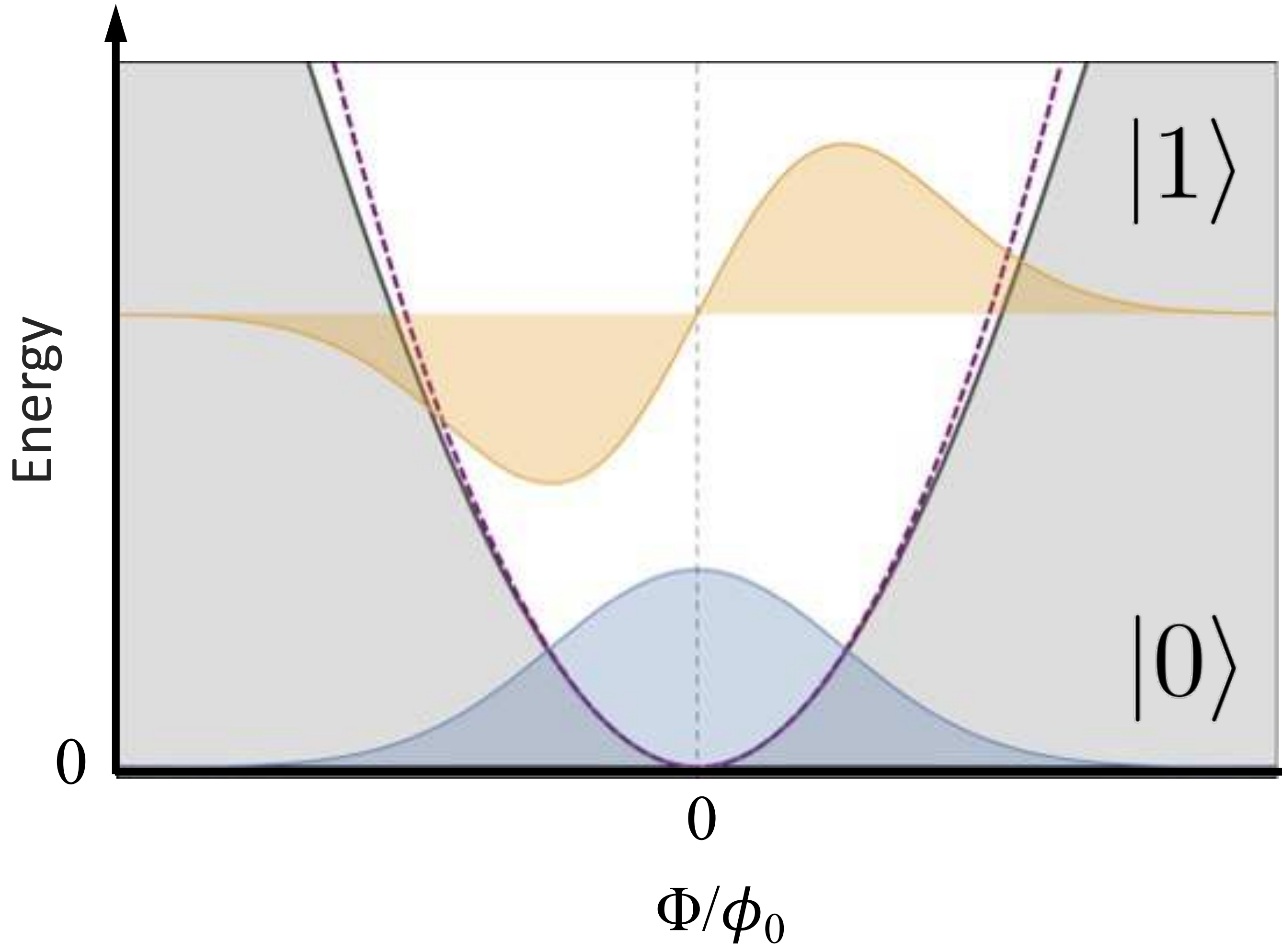
$$\boxed{\hat{H}_4^{\mathrm{RWA}} \approx \hbar\omega_q \hat{N} - \frac{\hbar\alpha}{2}\hat{N}\left(\hat{N}-1\right)}$$

$$\hat{N} \equiv \hat{a}^\dagger \hat{a}$$

Restrict to qubit subspace of |0> and |1>

$$\hat{a}^\dagger \hat{a} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

$$\hat{a} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{3} \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$



The Transmon qubit: restricting Hilbert space

$$\boxed{\hat{H}_4^{\mathrm{RWA}} \approx \hbar\omega_q \hat{N} - \frac{\hbar\alpha}{2}\hat{N}\left(\hat{N}-1\right)}$$

$$\hat{N} \equiv \hat{a}^\dagger \hat{a}$$

Restrict to qubit subspace of |0> and |1>

$$\left(\hat{N} - \frac{1}{2}\hat{I}\right) \mapsto -\frac{1}{2}\hat{Z} \qquad \hat{a} \mapsto \hat{\sigma}_- = \frac{1}{2}\left(\hat{X} - i\hat{Y}\right)$$

Fock number operator

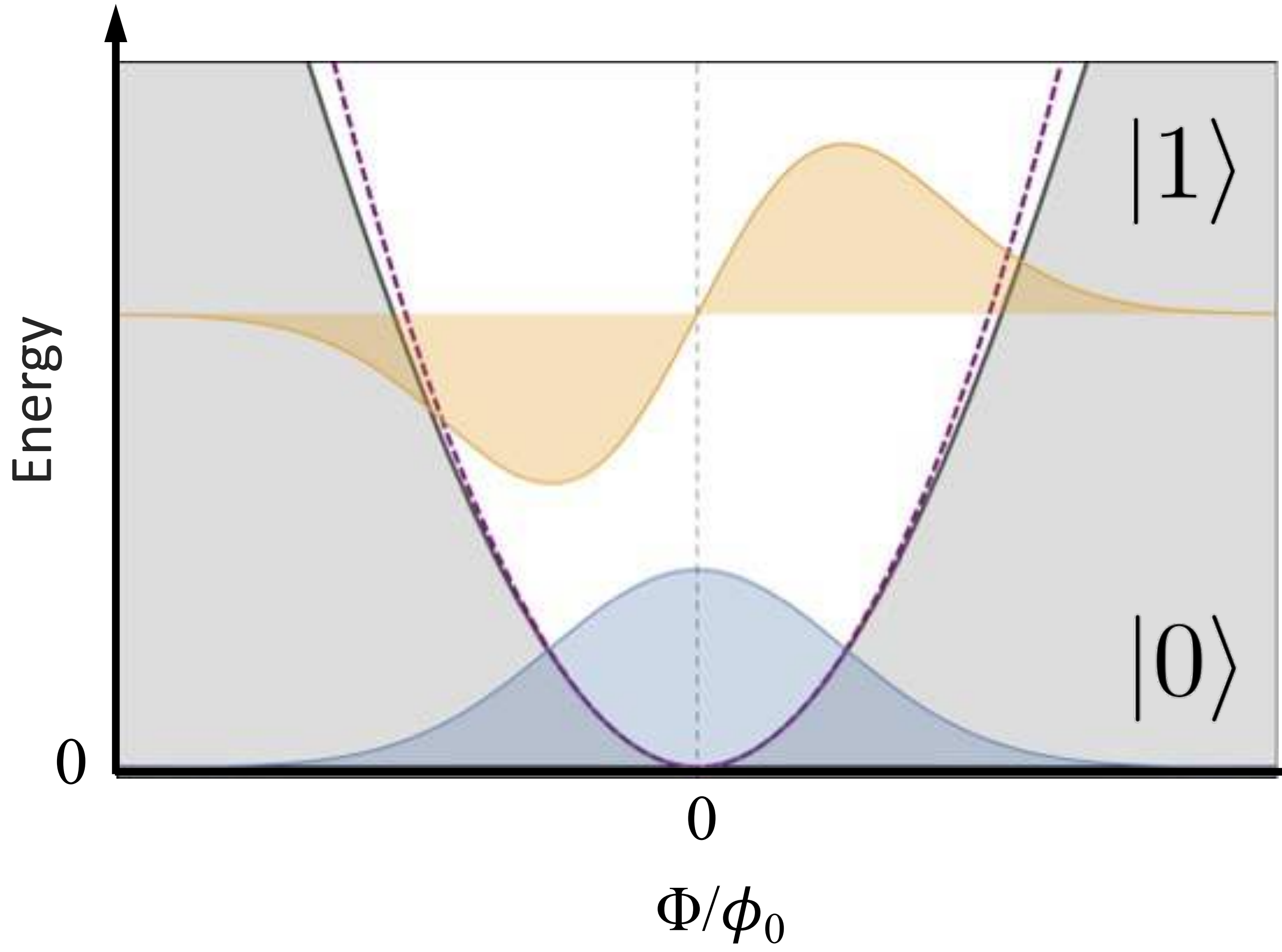
$$\begin{pmatrix} 1 & 0 & \cdots \\ 0 & 2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

Qubit Pauli Z operator

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Qubit Pauli X and Y operators

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$



Modeling transmon qubit Cooper-pair box Hamiltonian in the charge basis

(Zlatko Minev, Christopher Warren, Nick Lanzillo 2021)

This module models the transmon qubit in the cooper-pair charge basis, assuming wrapped junction phase variable. The Hamiltonian is given by:

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right) - E_J \cos\left(\hat{\phi}\right),$$

where E_C is the charging energy, E_J is the Josephson energy, $\hat{n}$ is the number of Cooper pairs transferred between charge islands, $\hat{\phi}$ is the gauge-i phase difference between charge islands, and n_g is effective offset charge of the device. Expressions for the charging energy, Josephson energy and charge can be written as:

$$E_C = \frac{e^2}{2C_\Sigma}, \qquad n_g = -\frac{C_d \Phi_s(t)}{2e}, \qquad E_J = \frac{\phi_0^2}{L_J},$$

where $C_\Sigma = C_J + C_B + C_g$ (the sum of the Josephson capacitance, shunting capacitance and gate capacitance), L_J is the inductance of the Jose junction, and ϕ is the magnetic flux.

The variables are

$$\hat{\phi} \equiv \frac{\hat{\Phi}}{\phi_0}, \qquad \hat{n} \equiv \frac{\hat{Q}}{2e},$$

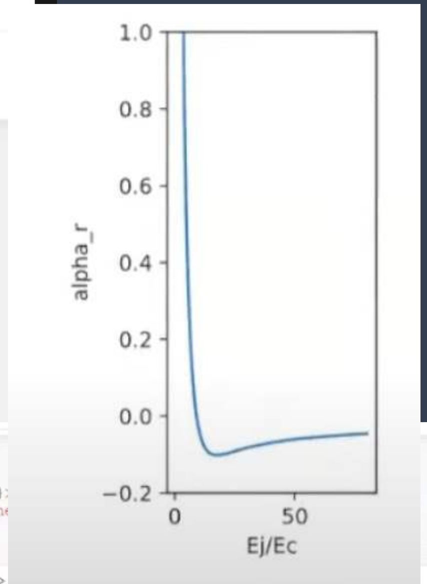
Observe that $\hat{\phi}$ and $\hat{n}$ are both dimensiuonless, and they obey the commutation relationship:

$$[\hat{\phi}, \hat{n}] = i$$

The Hamiltonian can be written in the charge ($\hat{n}$) basis as:

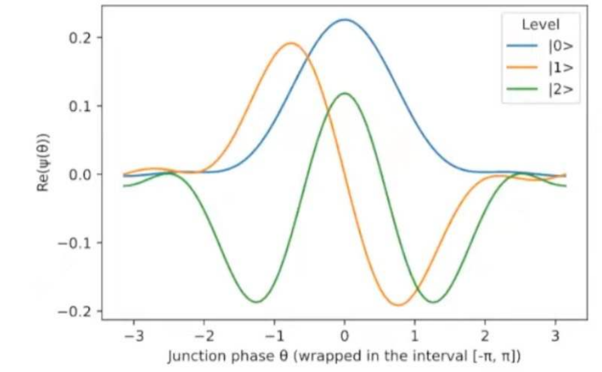
$$H = 4E_C(\hat{n} - n_g)^2 - \frac{1}{2}E_J \sum_n (|n\rangle\langle n+1| + \text{h.c.}),$$

Where $\hat{n} = \sum^{\text{inf}} \ldots |n\rangle\langle n|$



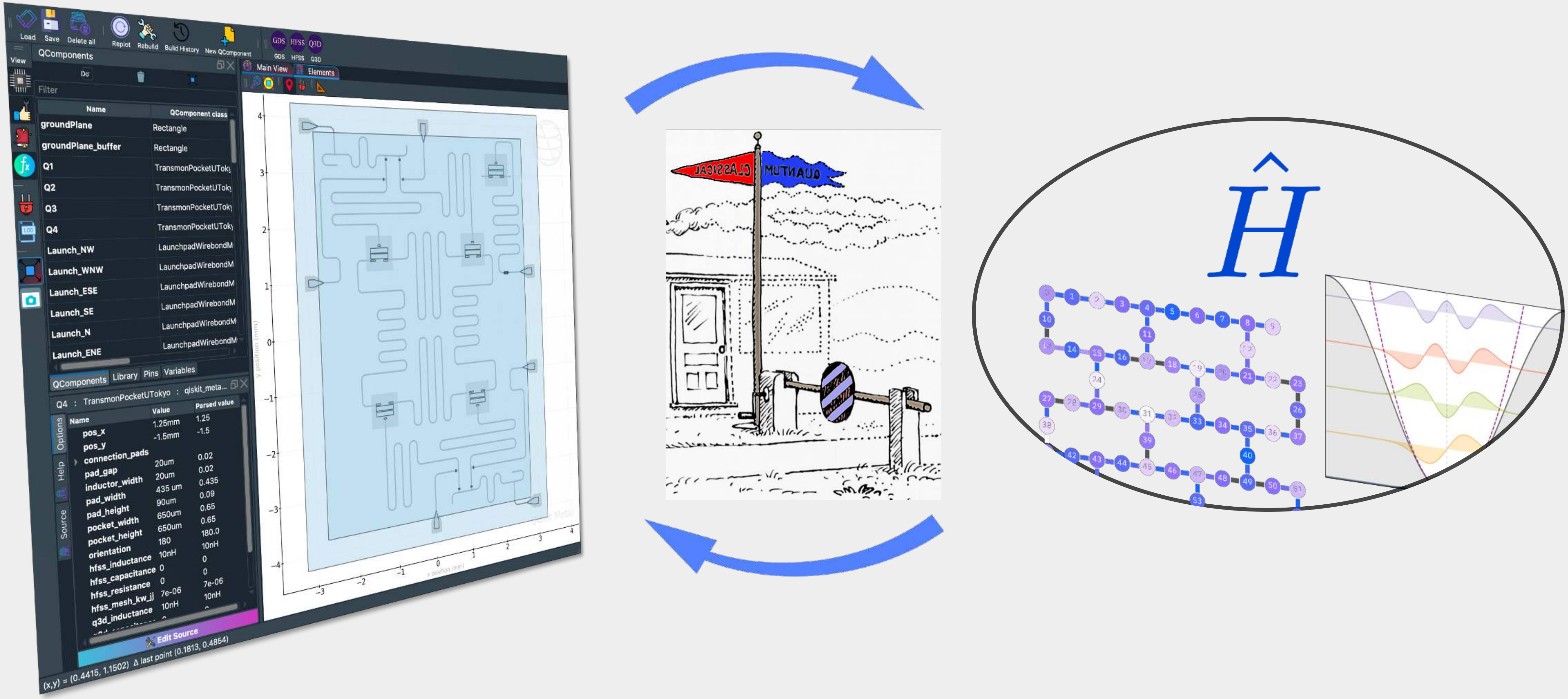

```python
import matplotlib.pyplot as plt
for k in range (3):
    ψ, θ = H.psi_k(k,101)
    plt.plot(θ, ψ.real+ψ.imag, label=f"|{k}
plt.xlabel("Junction phase θ (wrapped in the
plt.ylabel("Re(ψ(θ))")
plt.legend(title="Level")
```

```
<matplotlib.legend.Legend at 0x1fbfc29d7c8>
```



Qiskit | quantum device design

Make easy?



Docs & tutorials

qiskit.org/documentation/metal

Tutorial videos

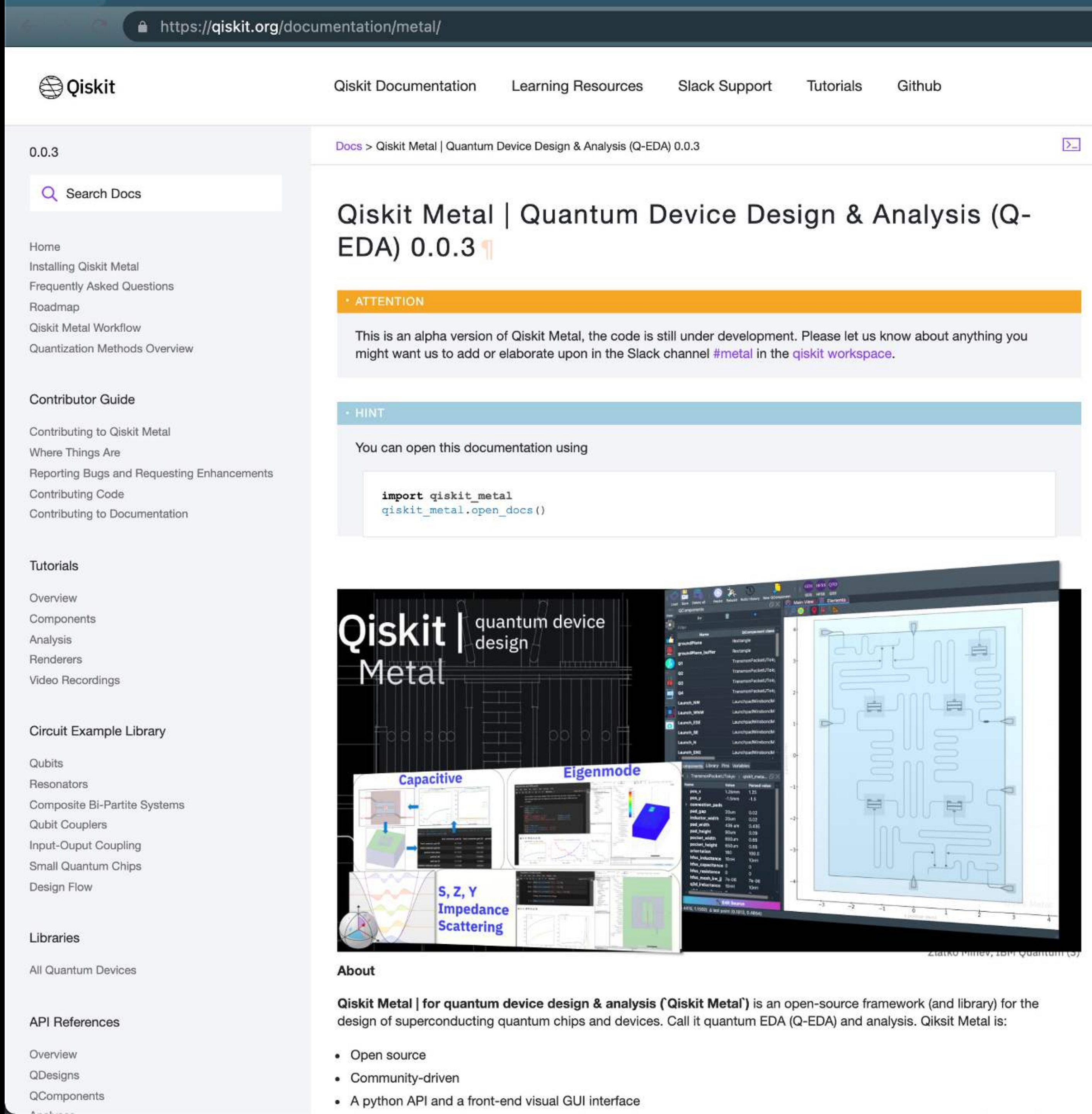
YouTube – see docs

Slack

#metal (qiskit workspace)

Live weekly tutorials

You are here ☺ - or check slack



Qiskit | quantum device design

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

Open source
qiskit.org/metal

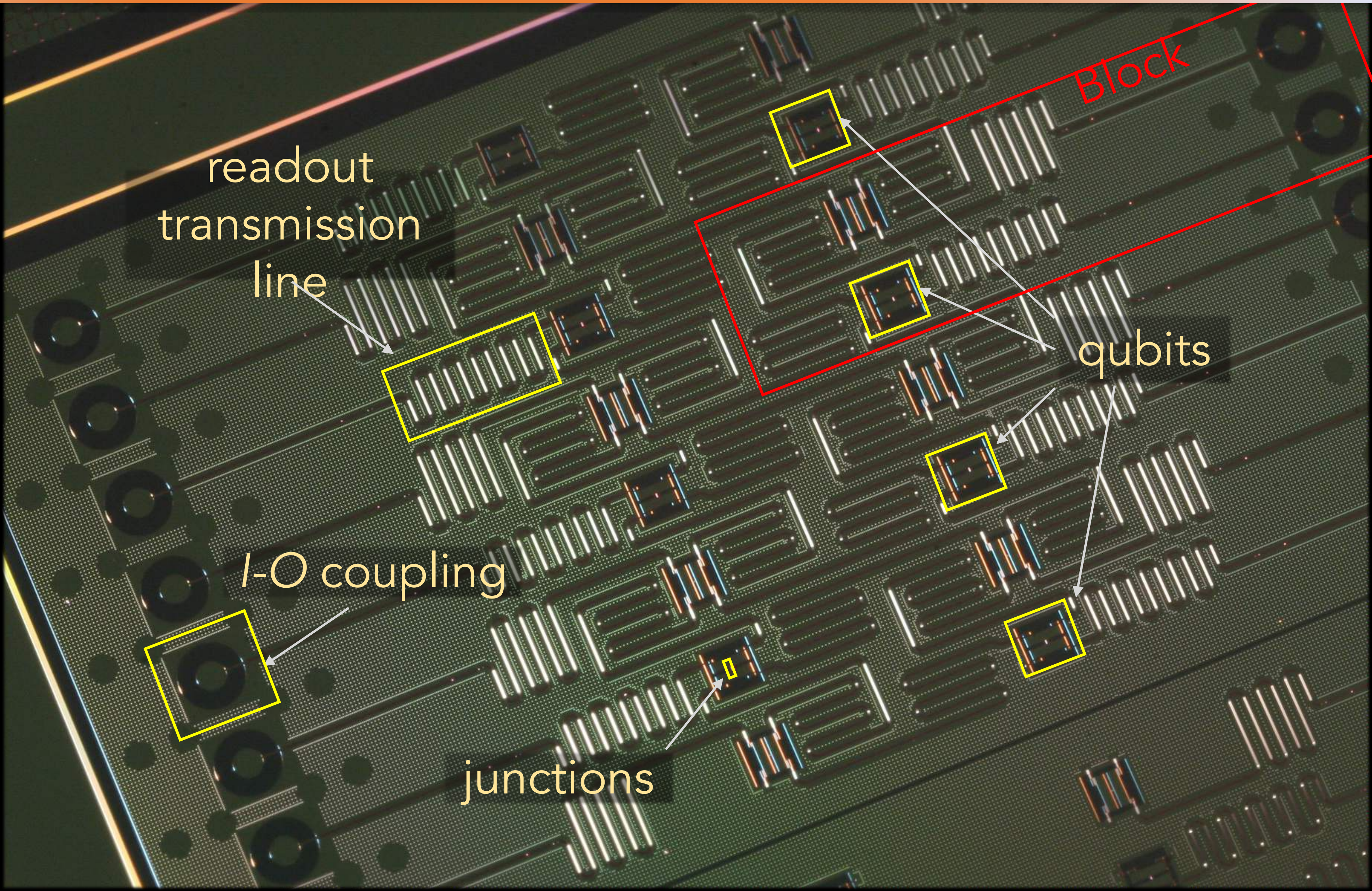
Regularity is our greatest ally in chip design

Reuse

Fine-tune

Automate

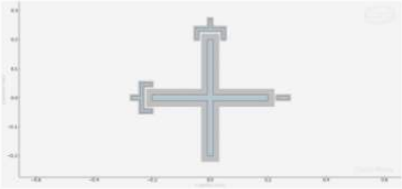
Extend



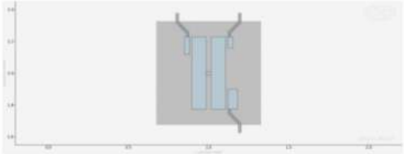
https://qiskit.org/documentation/meta

Device example library

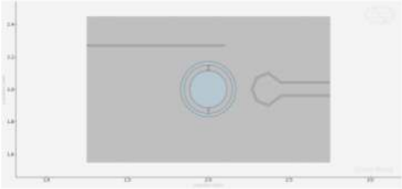
Qubits



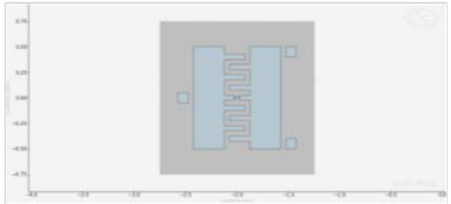
Single Transmon - Grounded (xmon)



Single Transmon - Floating



Concentric Transmon



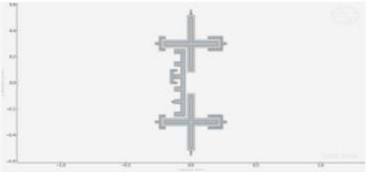
Interdigitated Transmon Qubits

Resonators

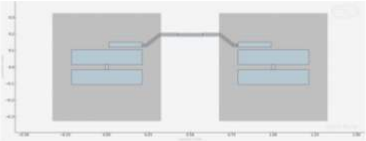
Simple CPW Meande

...

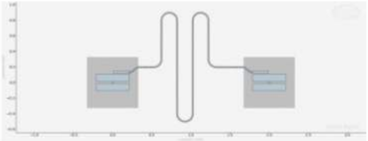
Qubit couplers



Tunable Coupler (MIT)

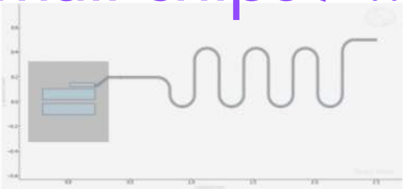


Direct Coupler (transmon-transmon)

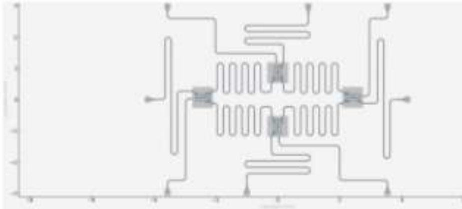


Bus Resonator Coupler (transmon-transmon)

Composite systems / small chips / ...



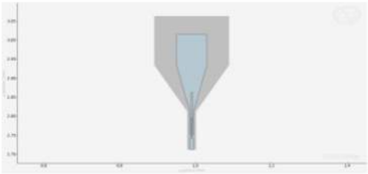
Transmon coupled to CPW resonator



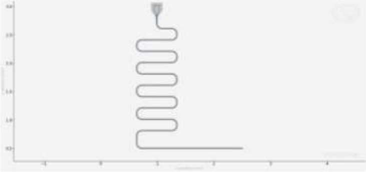
Four Qubit Chip Design

...

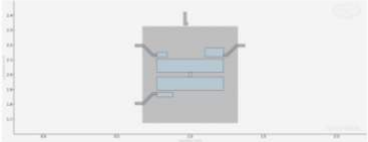
Input-output couplers



CPW Launch Pad

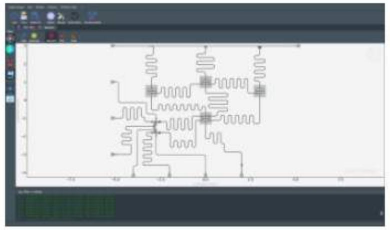


Readout line

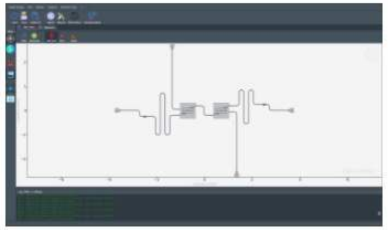


Charge Line

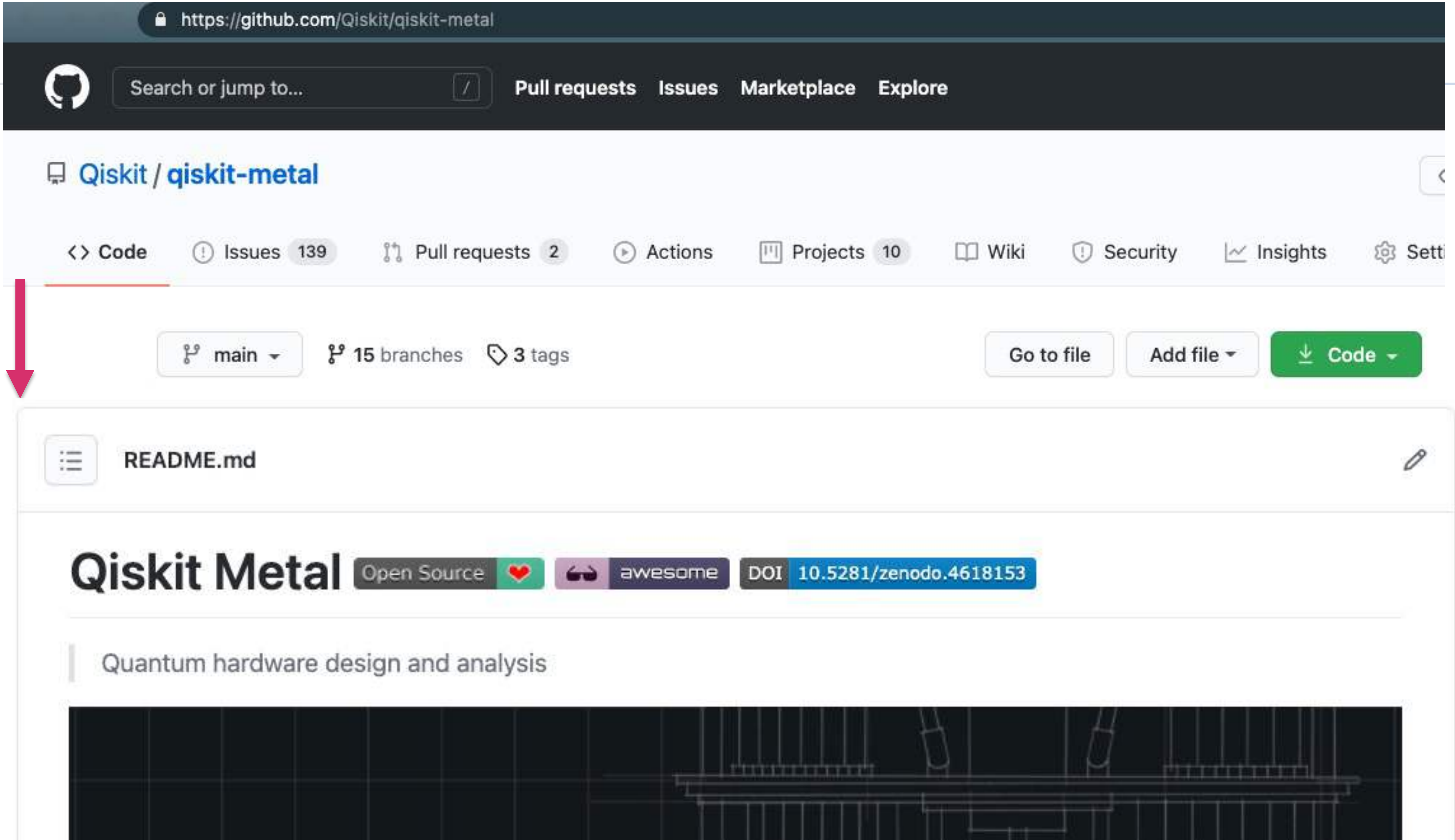
Design flow examples



Full Chip Design



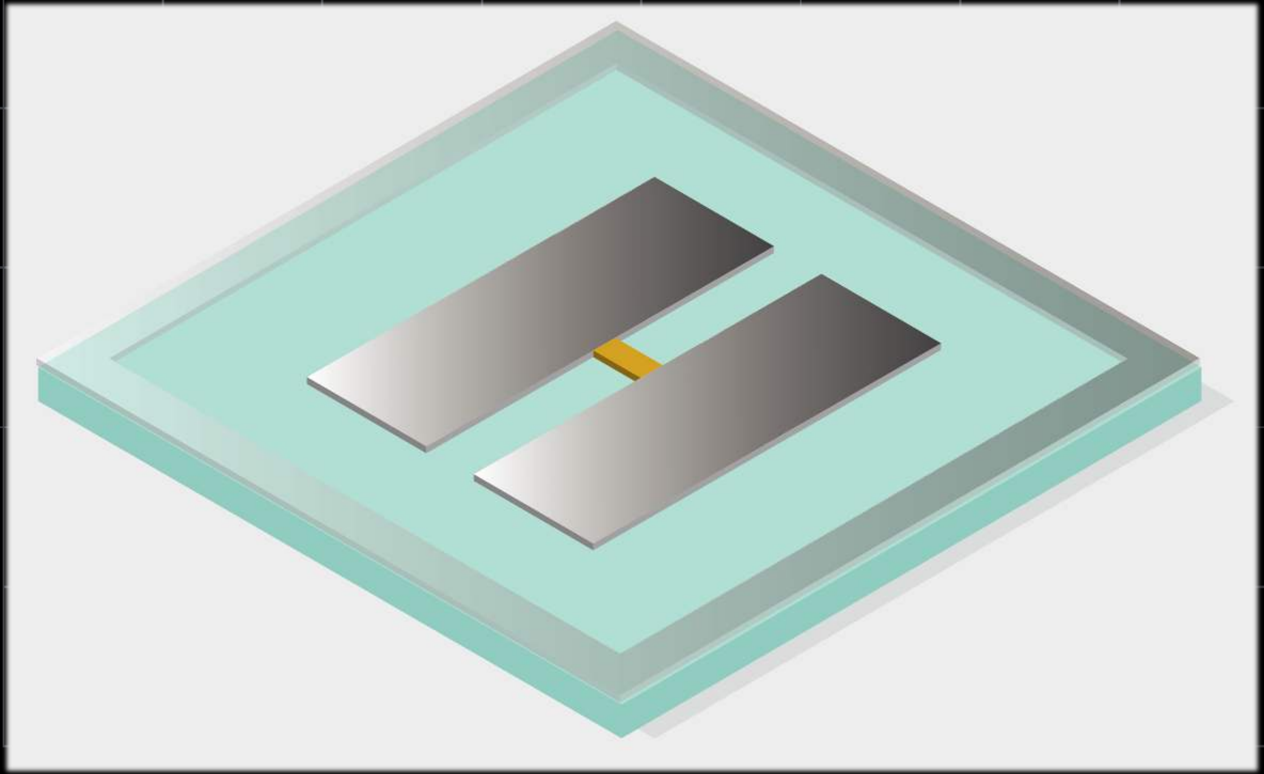
South Korea Qiskit Hackathon -


https://github.com/Qiskit/qiskit-metal
Search or jump to...
Pull requests
Issues
Marketplace
Explore
Qiskit / qiskit-metal
Code
Issues 139
Pull requests 2
Actions
Projects 10
Wiki
Security
Insights
main
15 branches
3 tags
Go to file
Add file
Code
README.md
Qiskit Metal
Open Source
awesome
DOI 10.5281/zenodo.4618153
Quantum hardware design and analysis

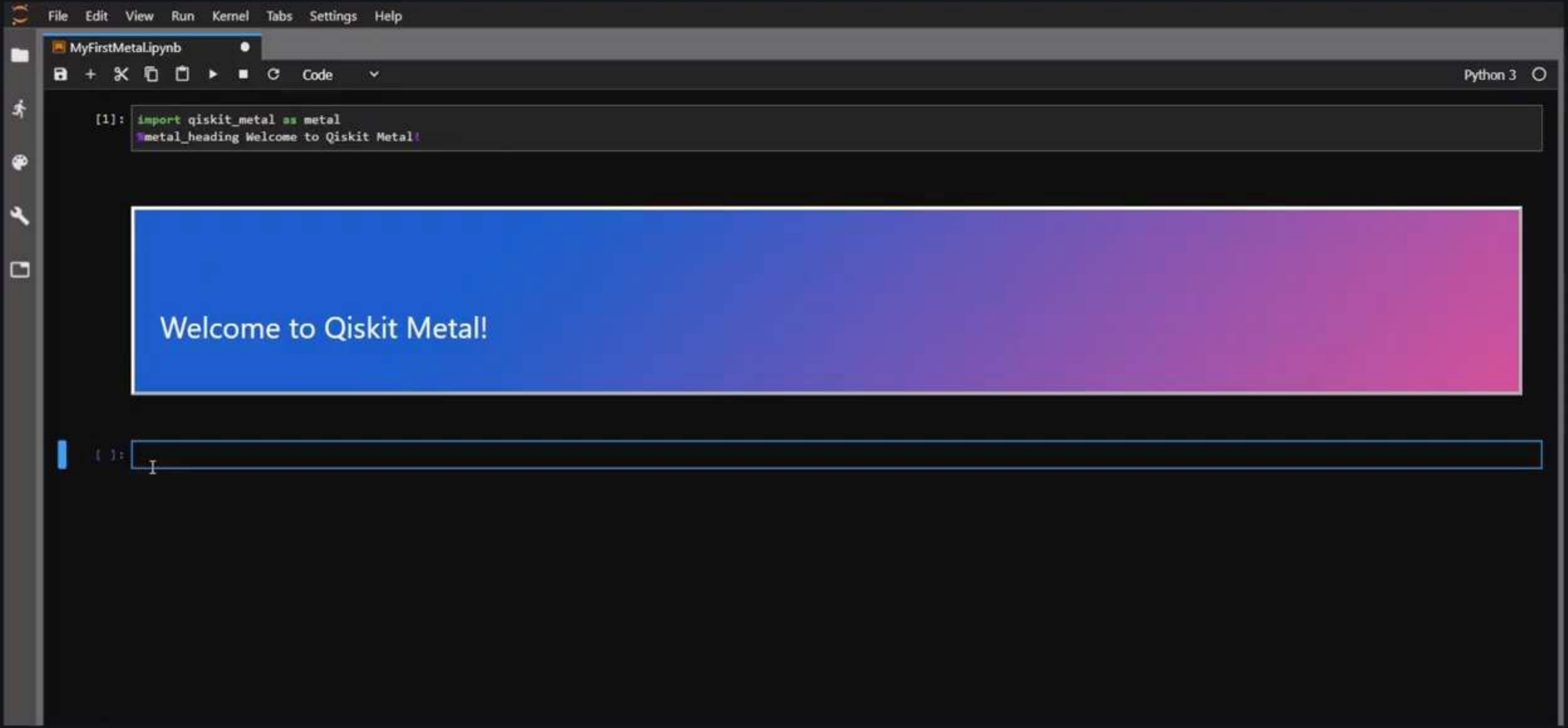
Create a transmon qubit

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

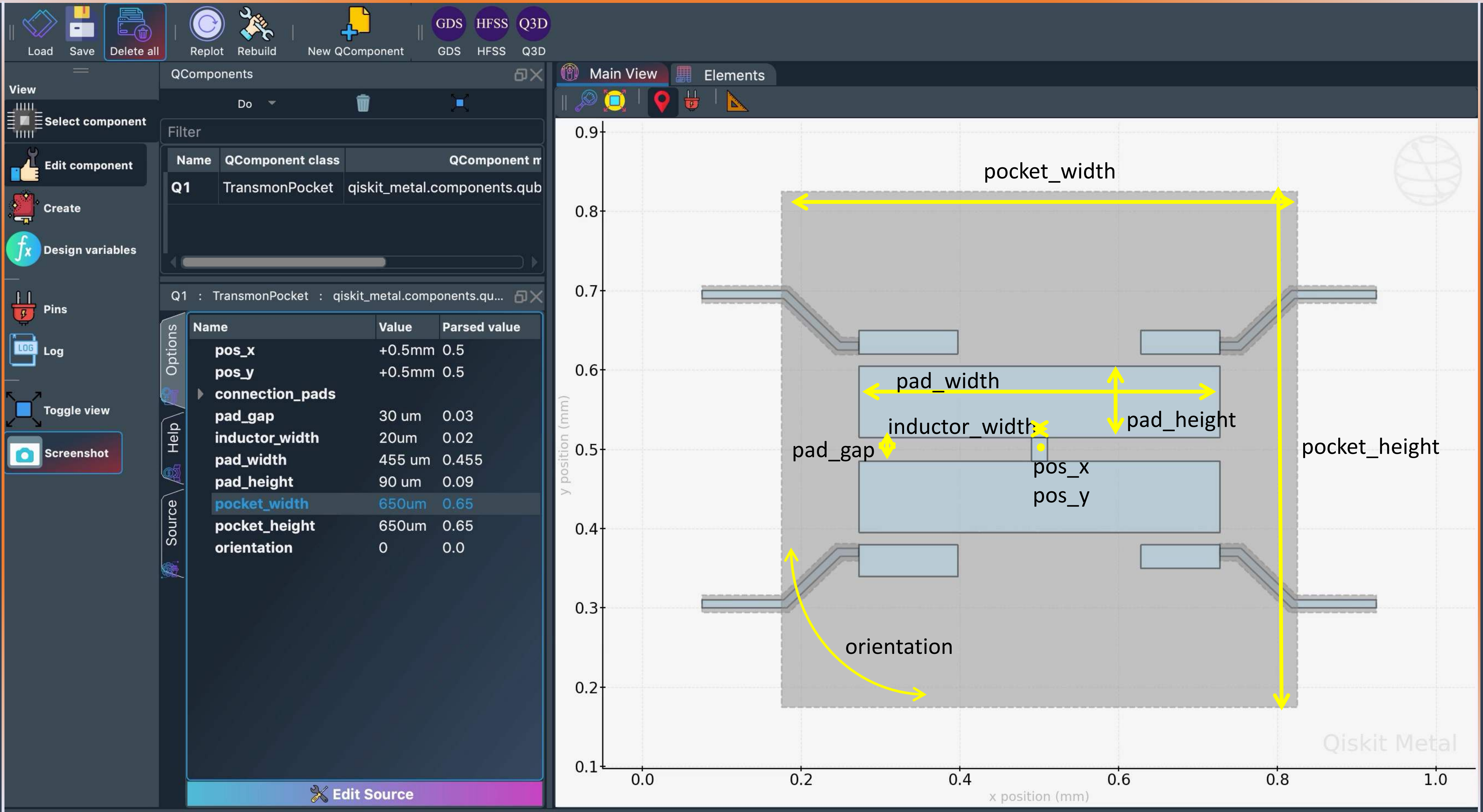
```
from qiskit_metal import MetalGUI
MetalGUI()
```



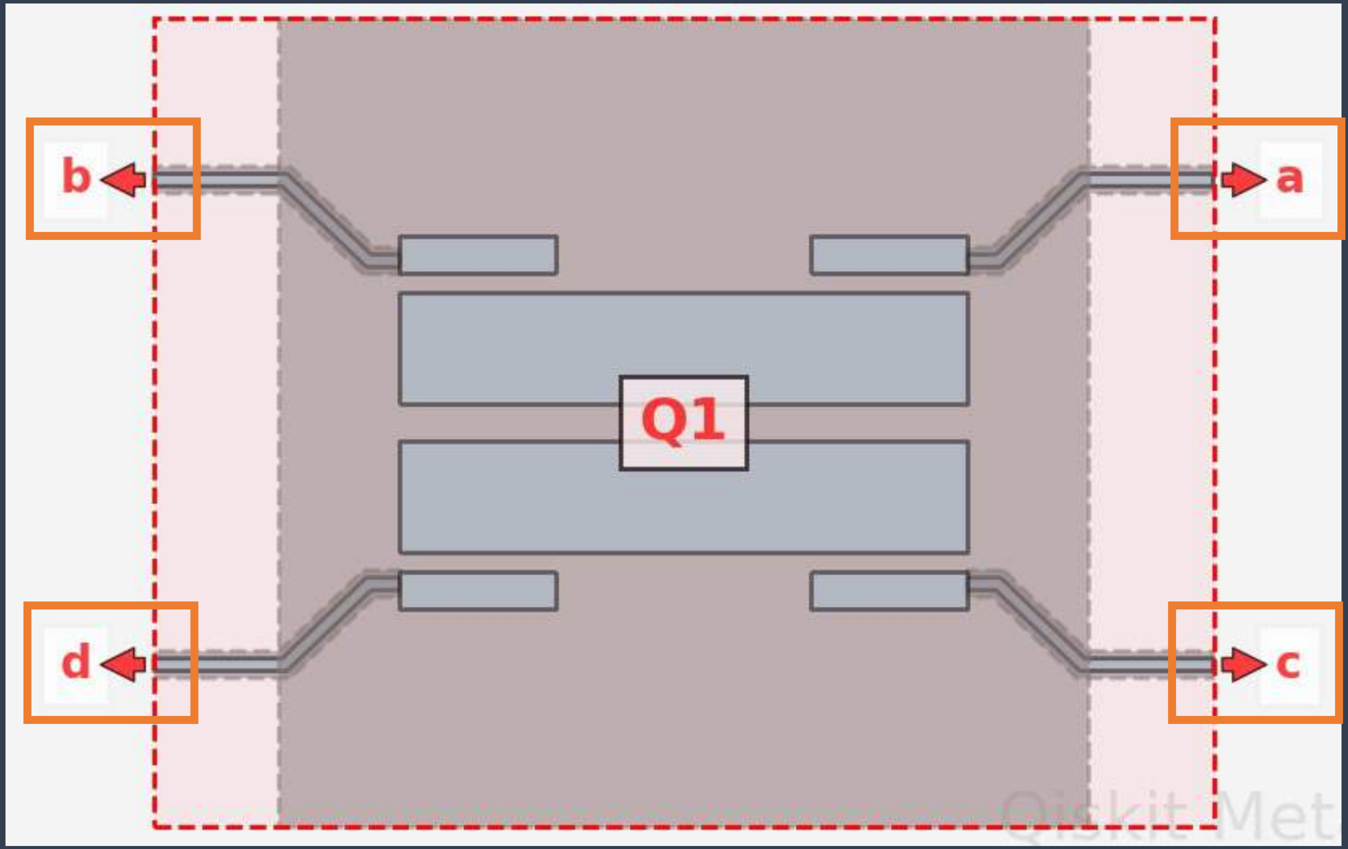
qiskit.org/metal

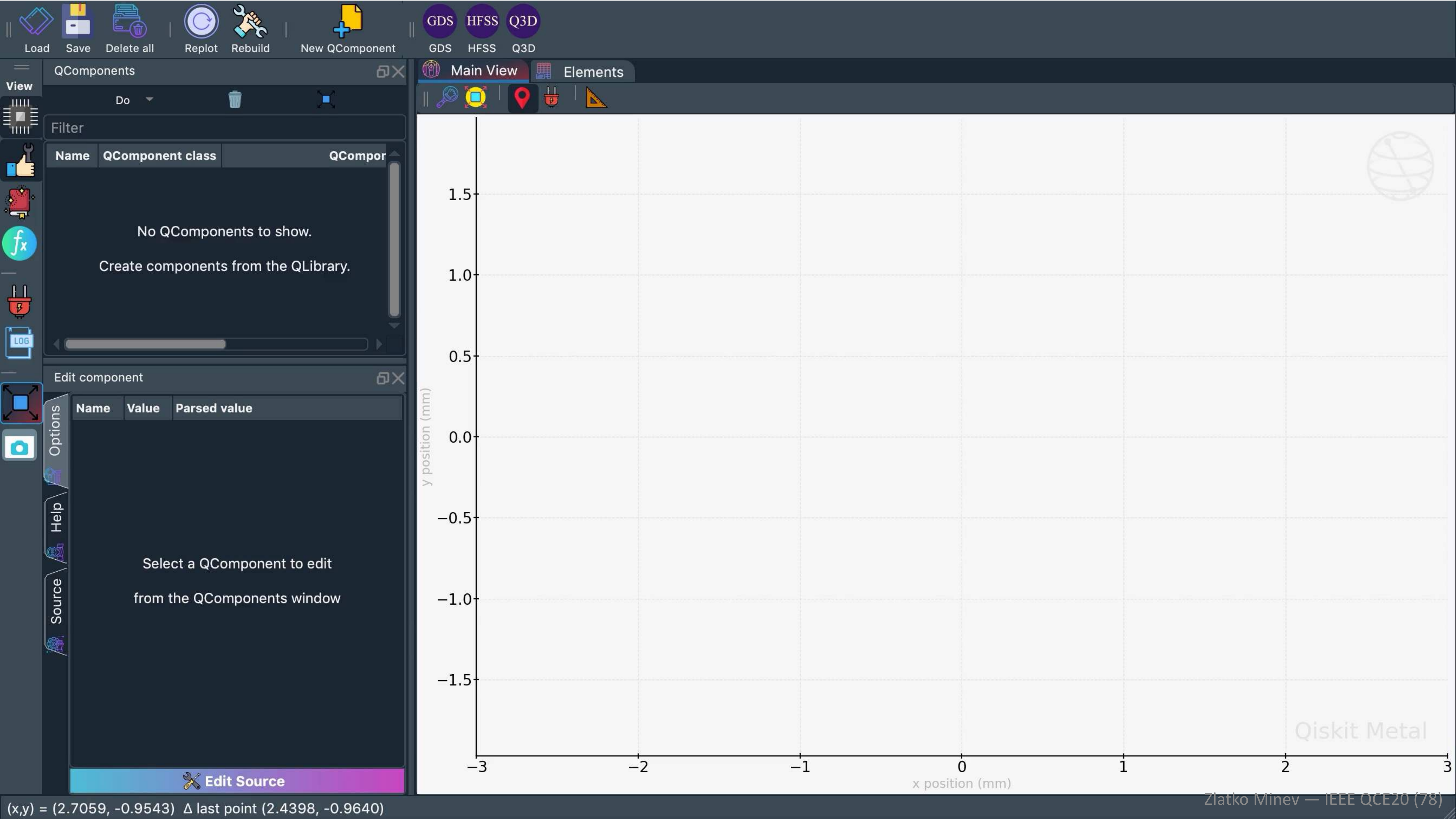

File Edit View Run Kernel Tabs Settings Help
MyFirstMetal.ipynb
Code
Python 3
[1]:
import qiskit_metal as metal
%metal_heading Welcome to Qiskit Metal!
Welcome to Qiskit Metal!
[ ]:

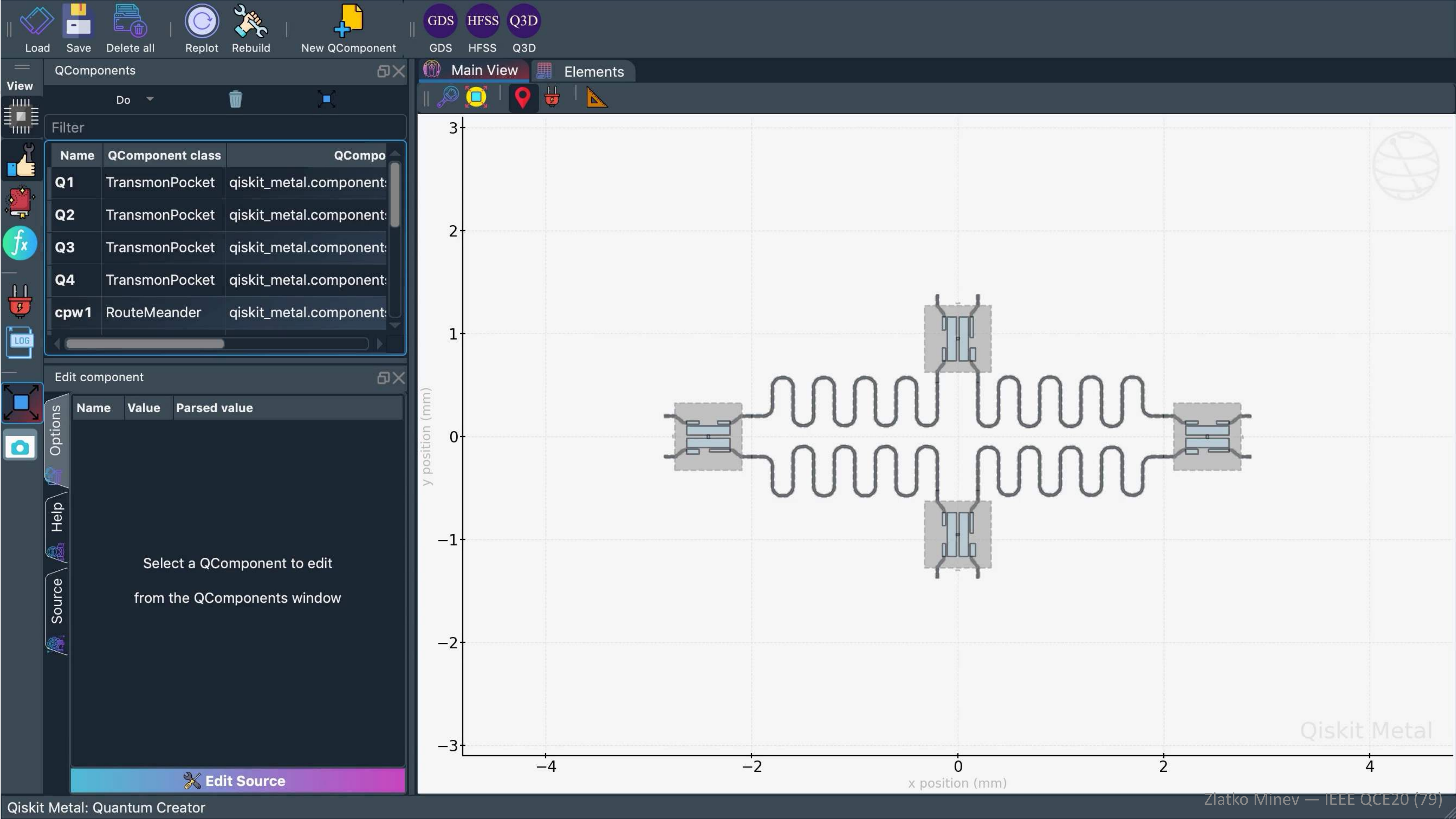
Fine-tune and automate parameters

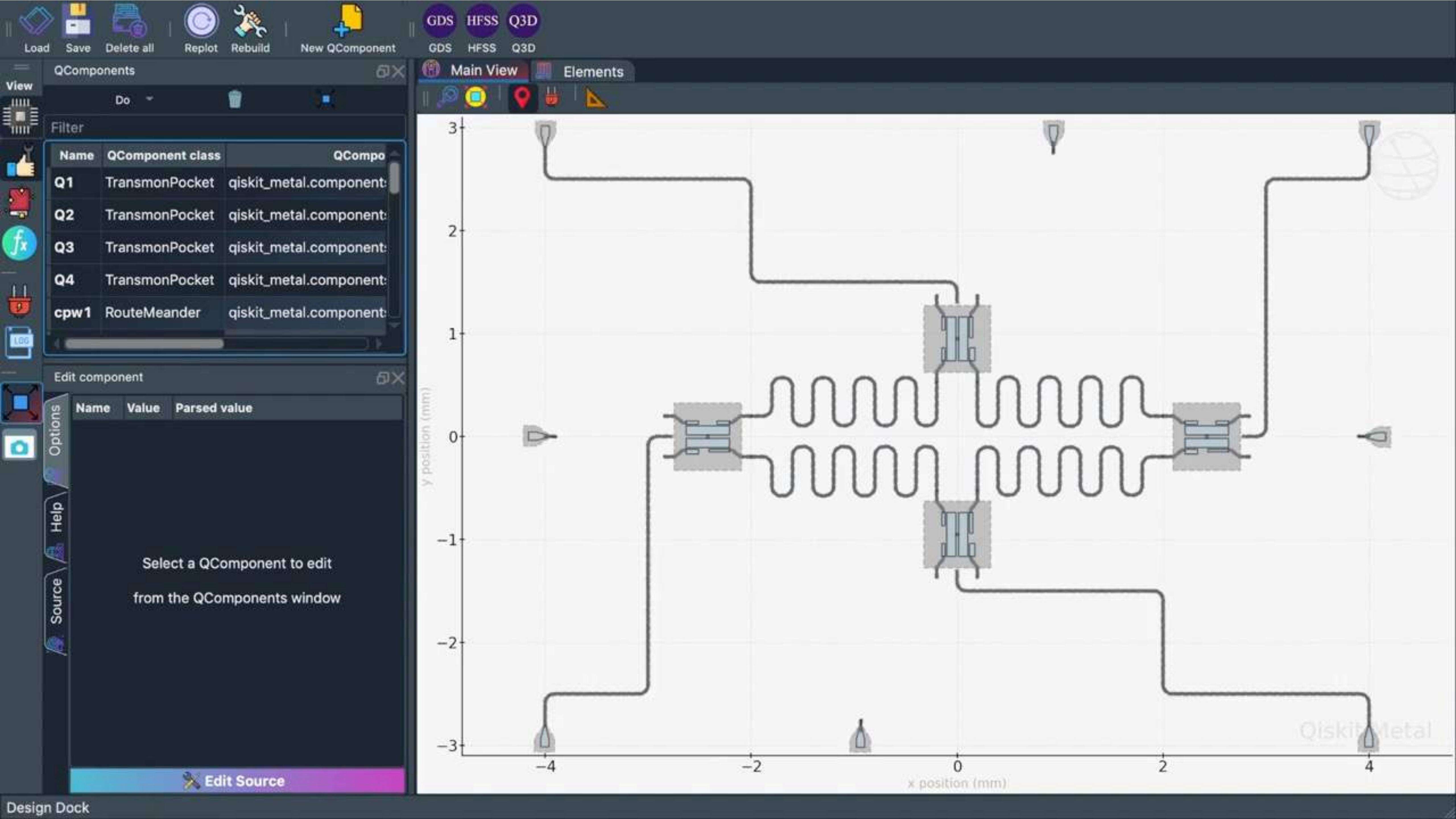


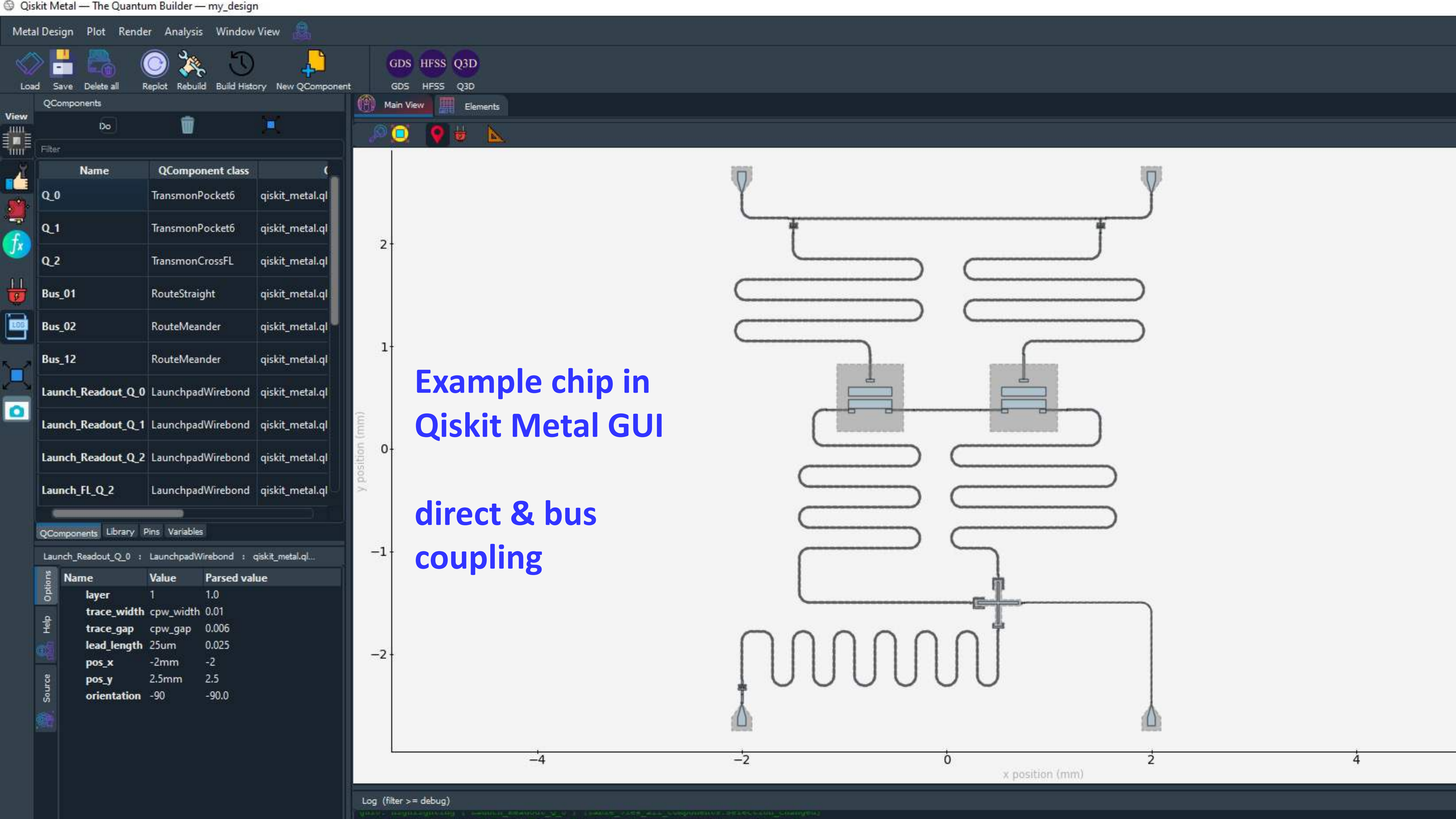
Dynamically –connected quantum devices




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)


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
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
Name
Value
Parsed value
Options
Help
Source
Select a QComponent to edit
from the QComponents window
Edit Source
Design Dock
Main View
Elements
y position (mm)
x position (mm)
Qiskit Metal



Example chip in Qiskit Metal GUI

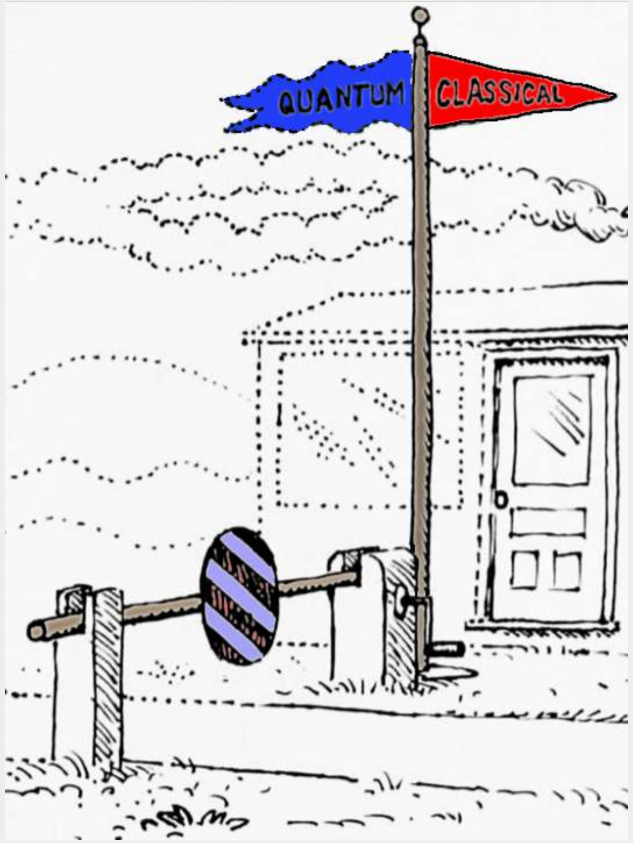
direct & bus coupling

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



Tutorials: Quantum analysis library

Qiskit

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

Tutorials: Quantum analysis library

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

Libraries

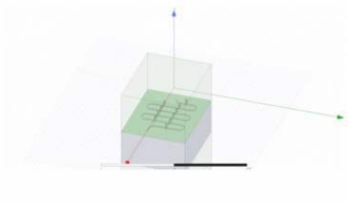
All Quantum Devices

API References

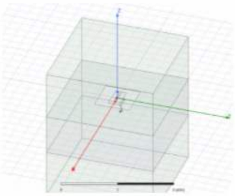
Overview
QDesigns
QComponents
Analyses
QRenderes
Toolbox
QGeometry
GUI

Code of Conduct

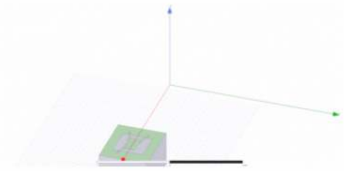
Qiskit



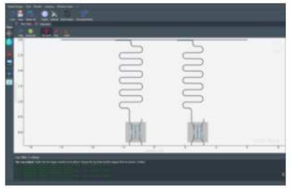
Eigenmode and EPR



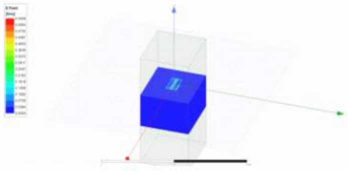
Impedance Analysis



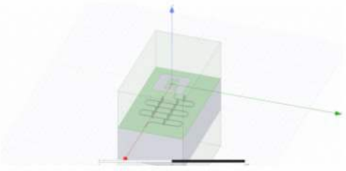
Capacitance Matrix and LOM Analysis



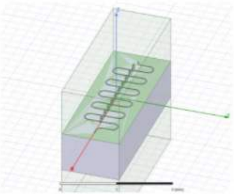
Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.



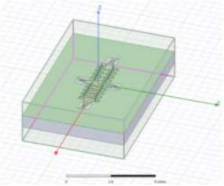
Analyizing and Tuning a Transmon Qubit



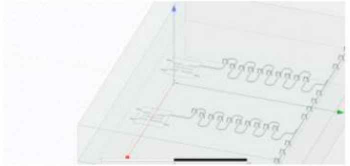
Analyzing a transmon and a resonator



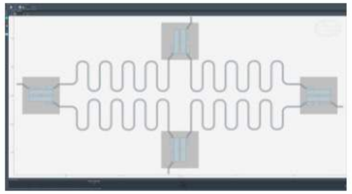
Analyzing a resonator



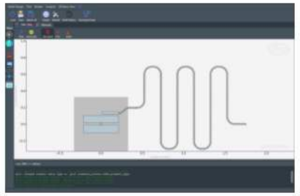
How to Render a Metal Design into Ansys



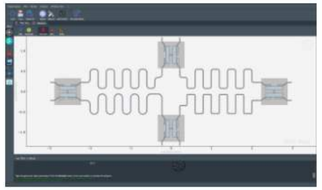
Driven Modal Simulation and S-Parameters



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

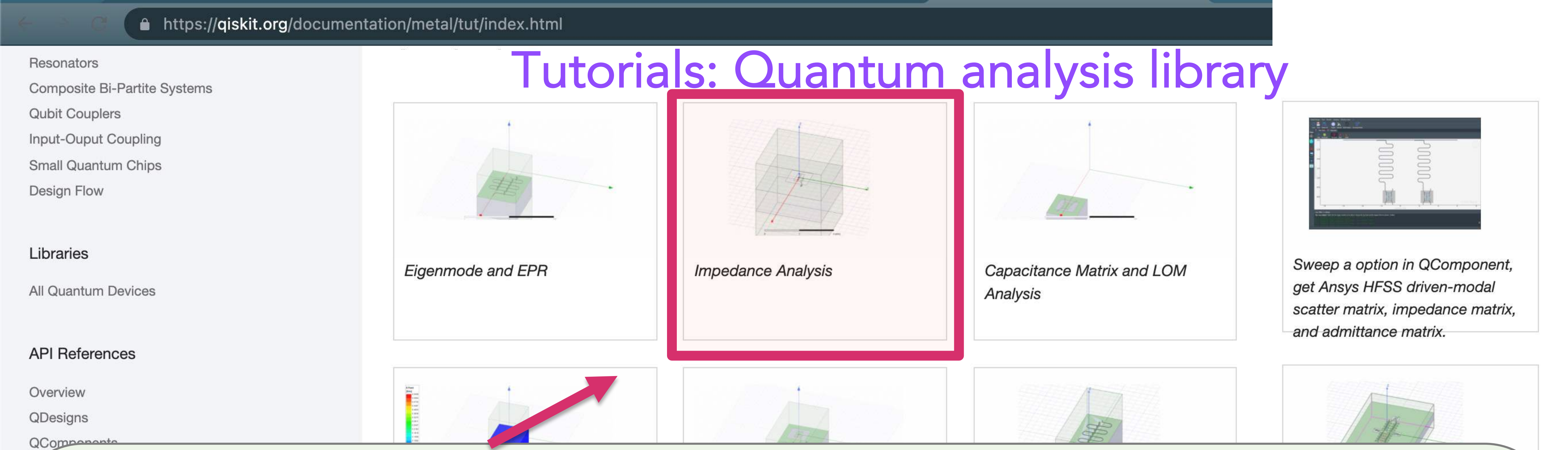


Sweep an option in QComponent, get Ansys HFSS eigenmode solution matrix.



How to Render a Metal Design into GDS

Tutorials: Quantum analysis library

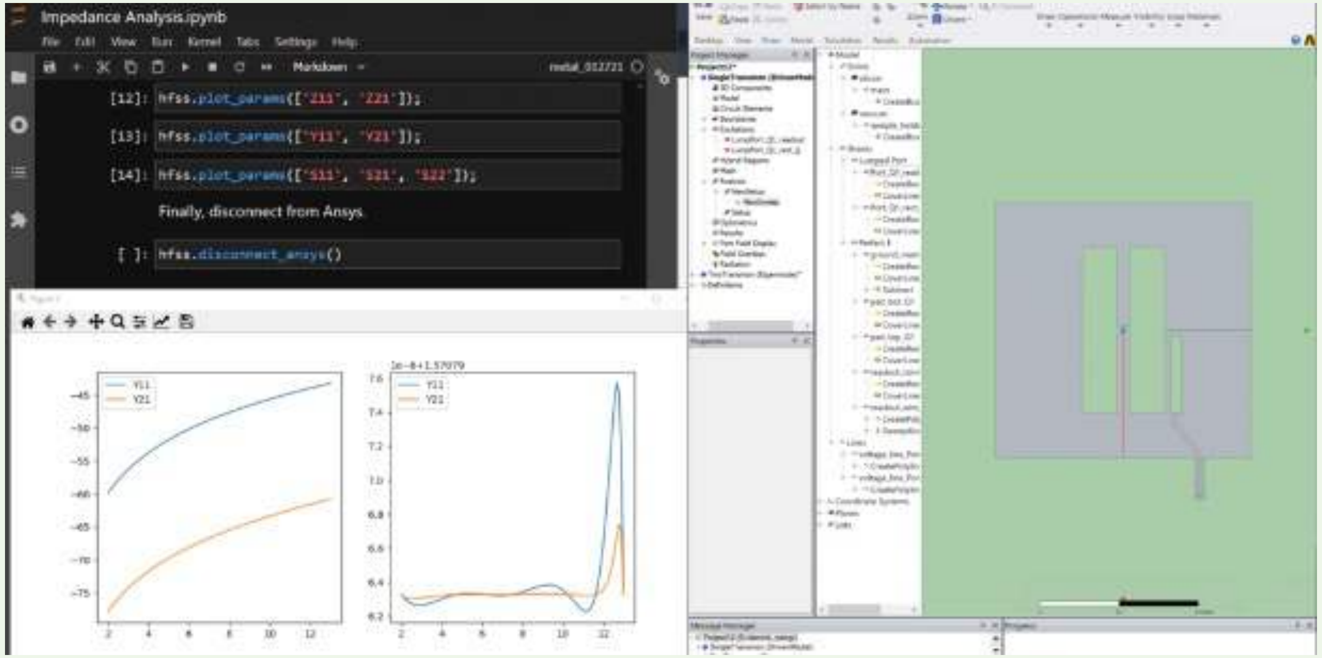


S, Z, Y

Impedance

Scattering

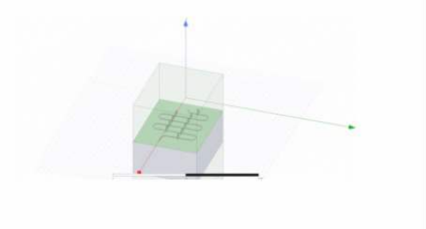
arXiv:1204.0587 ...
quanutm analysis part WIP



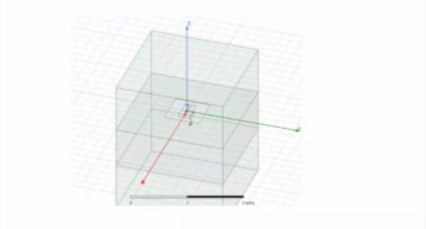
https://qiskit.org/documentation/metal/tut/index.html

Qisk

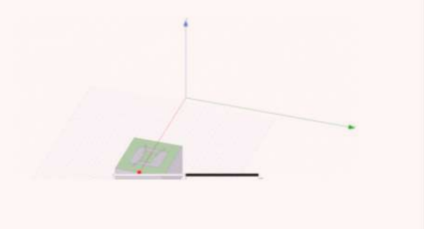
Tutorials: Quantum analysis library



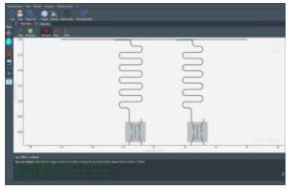
Eigenmode and EPR



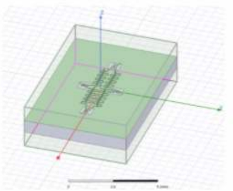
Impedance Analysis



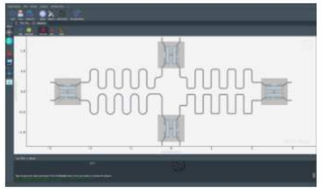
Capacitance Matrix and LOM Analysis



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



How to Render a Metal Design into Ansys

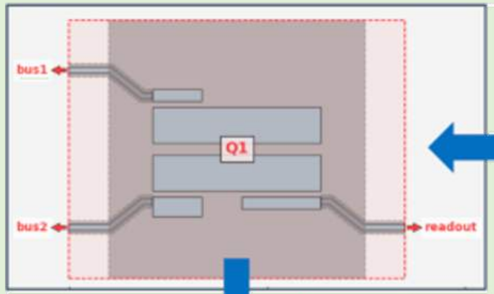


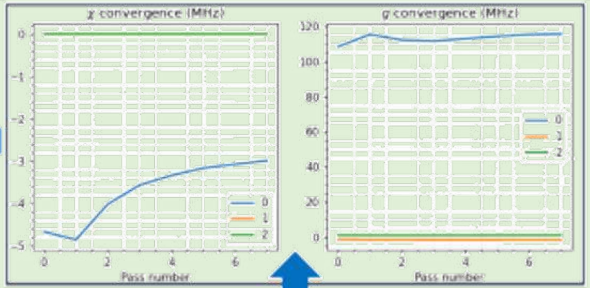
How to Render a Metal Design into GDS

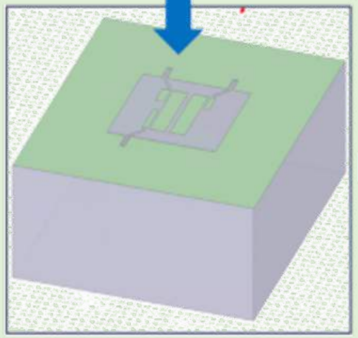
Capacitive

Jay's code

arXiv:2103.10344 ...







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

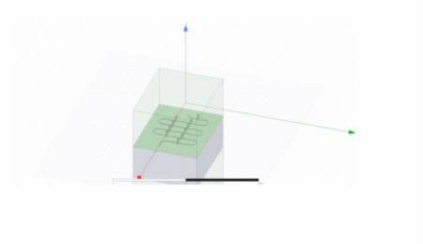
	bus1_connector_pad_Q1	bus2_connector_pad_Q1	ground
bus1_connector_pad_Q1	47.71247	-0.38203	
bus2_connector_pad_Q1	-0.38203	51.80766	
ground_main_plane	-33.11632	-35.62303	
pad_bot_Q1	-1.34246	-12.58801	
pad_top_Q1	-12.12145	-1.59640	
readout_connector_pad_Q1	-0.17280	-0.96276	

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

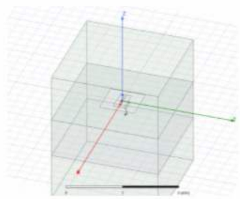
Tutorials: Quantum analysis library

Libraries

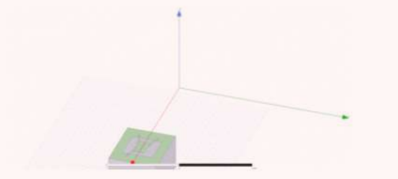
API References



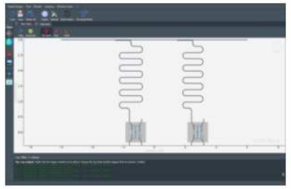
Eigenmode and EPR



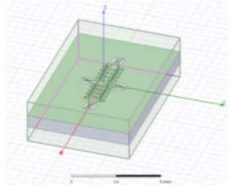
Impedance Analysis



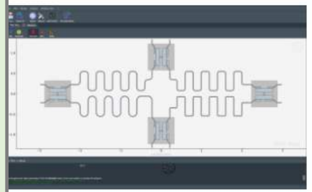
Capacitance Matrix and LOM Analysis



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



ow to Render a Metal Design to Ansys



ow to Render a Metal Design to GDS

Cornell University

arXiv.org > quant-ph > arXiv:2103.10344

Quantum Physics

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

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

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

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

Tutorials: Quantum analysis library

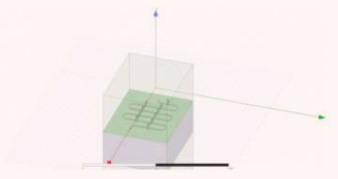
Resonators
Composite Bi-Partite Systems
Qubit Couplers
Input-Ouput Coupling
Small Quantum Chips
Design Flow

Libraries

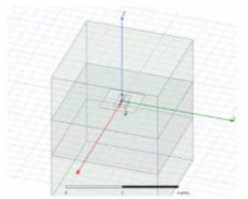
All Quantum Devices

API References

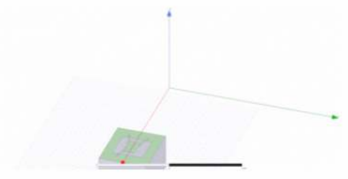
Overview
QD



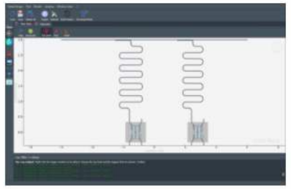
Eigenmode and EPR



Impedance Analysis



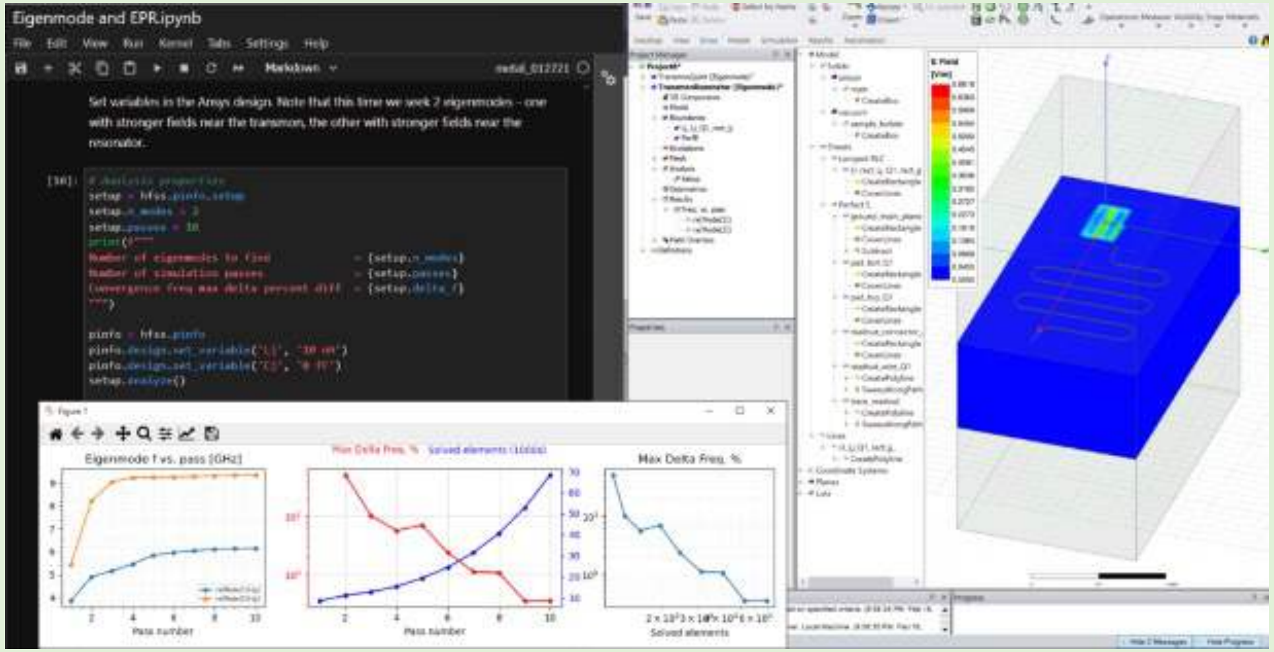
Capacitance Matrix and LOM Analysis



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

Eigenmode

arXiv: 2010.00620
arXiv: 1902.10355



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

Resonators

Composite Bi-Partite Systems

Qubit Couplers

Code of Conduct

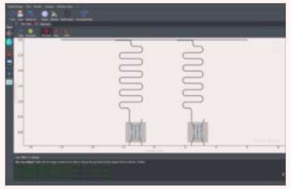
Qiskit

Tutorials: Quantum analysis library

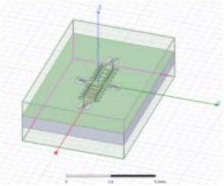
Sweeps

with

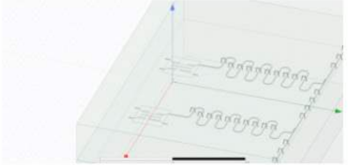
- Z S Y impedance, scattering params
- eigenmode / EPR
- capacititive / lumped model



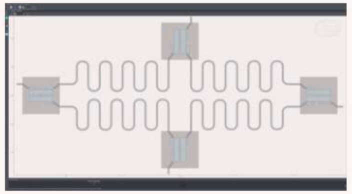
Sweep a option in QComponent, get Ansys HFSS driven-modal scatter matrix, impedance matrix, and admittance matrix.



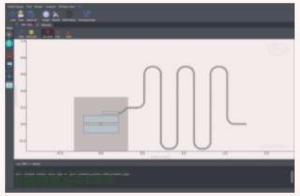
How to Render a Metal Design into Ansys



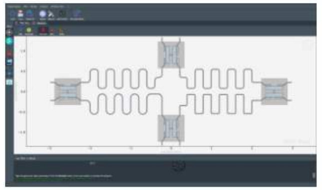
Driven Modal Simulation and S-Parameters



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



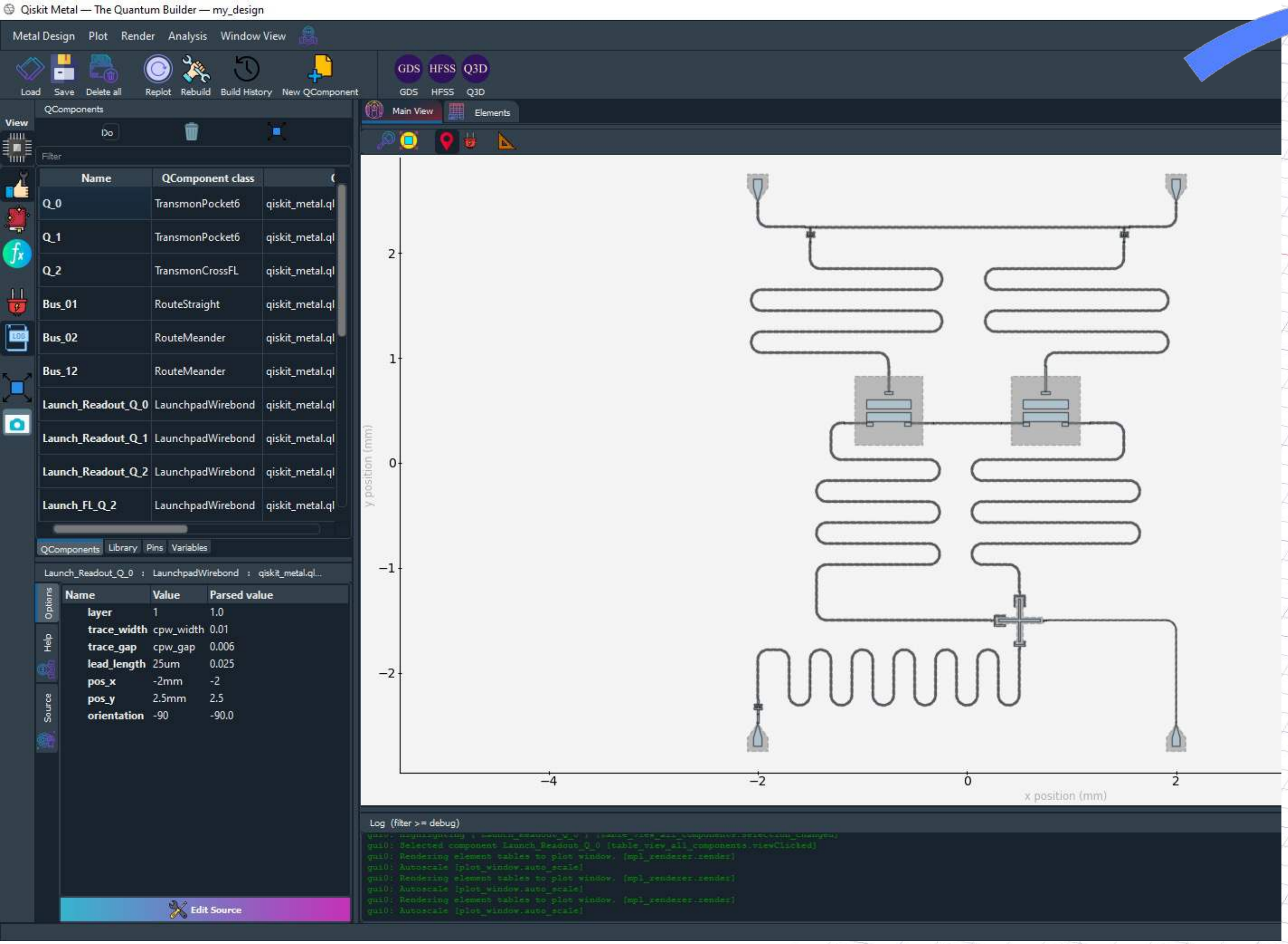
Sweep an option in QComponent, get Ansys HFSS eigenmode solution matrix.

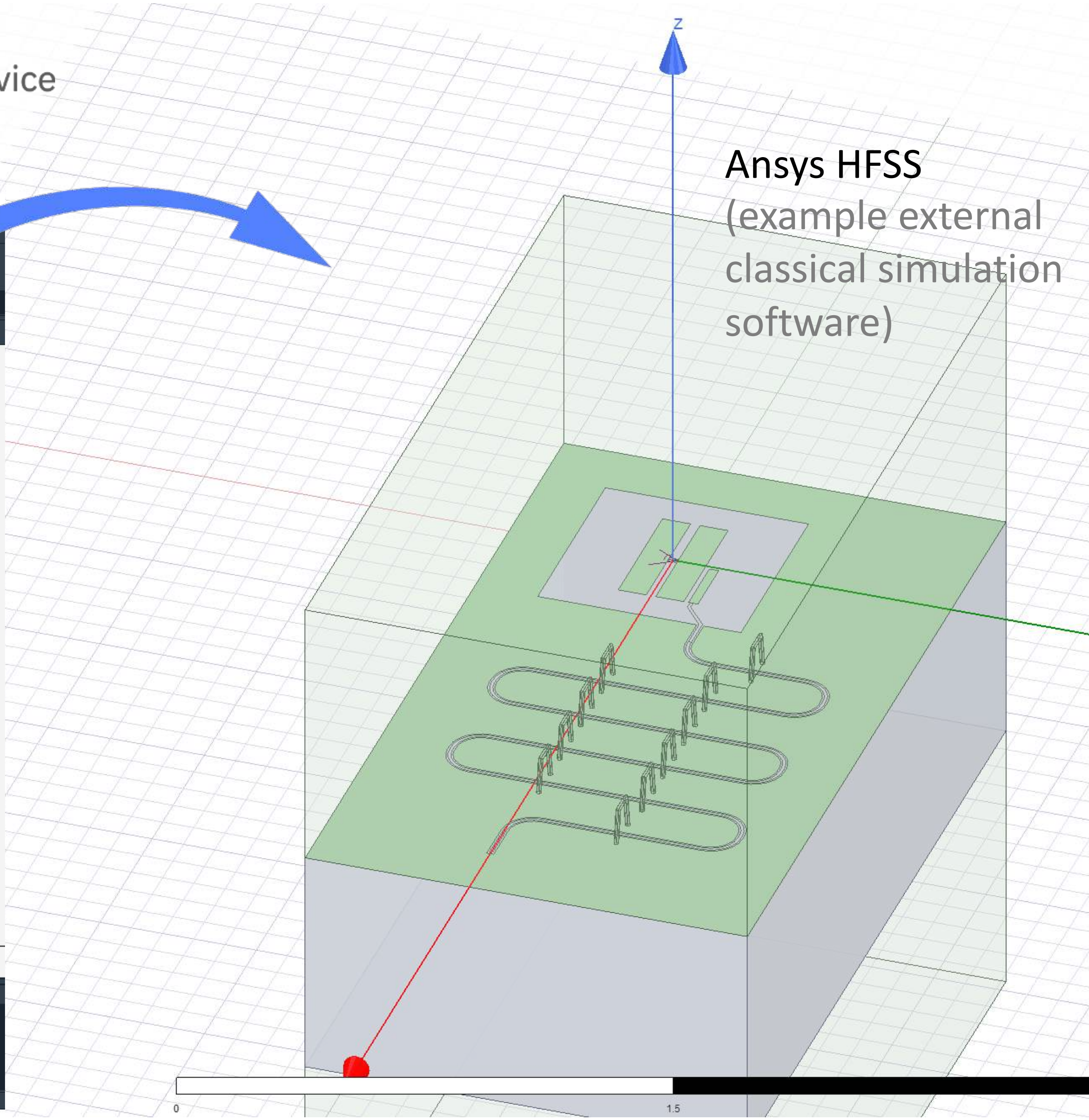


How to Render a Metal Design into GDS

Automated with

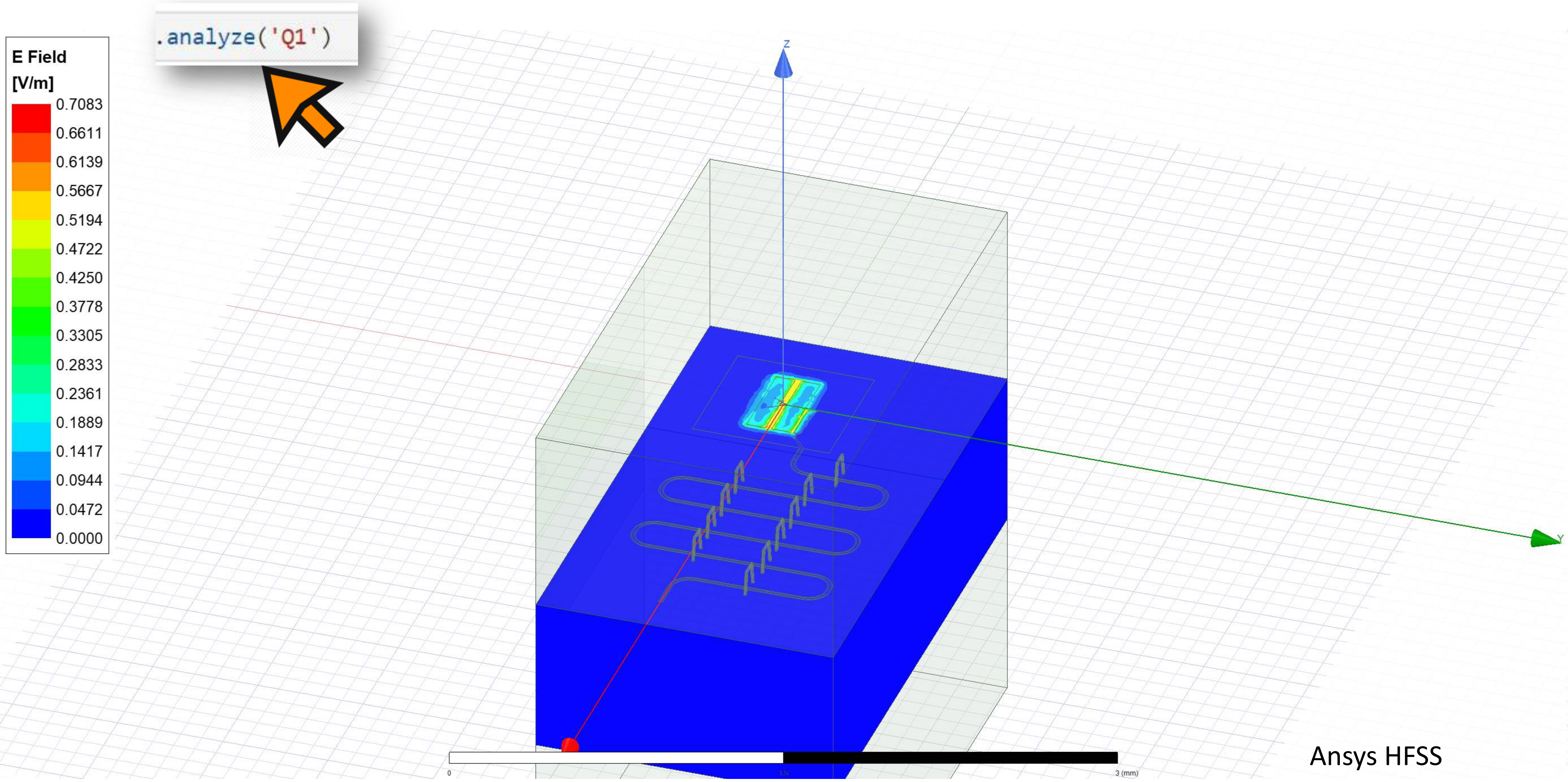
Qiskit | quantum device design





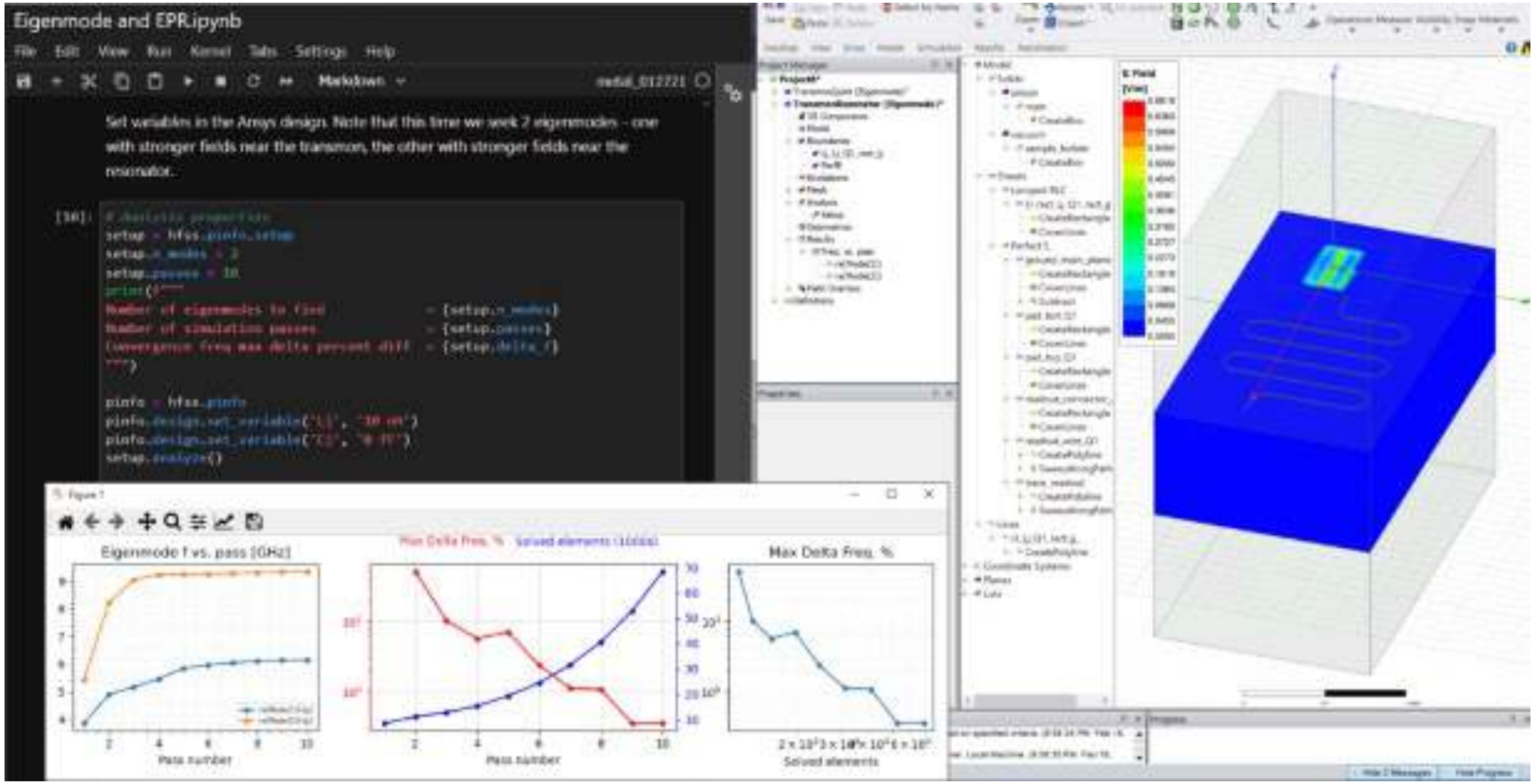
Ansys HFSS

(example external classical simulation software)


.analyze('Q1')
E Field
[V/m]
0.7083
0.6611
0.6139
0.5667
0.5194
0.4722
0.4250
0.3778
0.3305
0.2833
0.2361
0.1889
0.1417
0.0944
0.0472
0.0000
Z
Y
0
3 (mm)

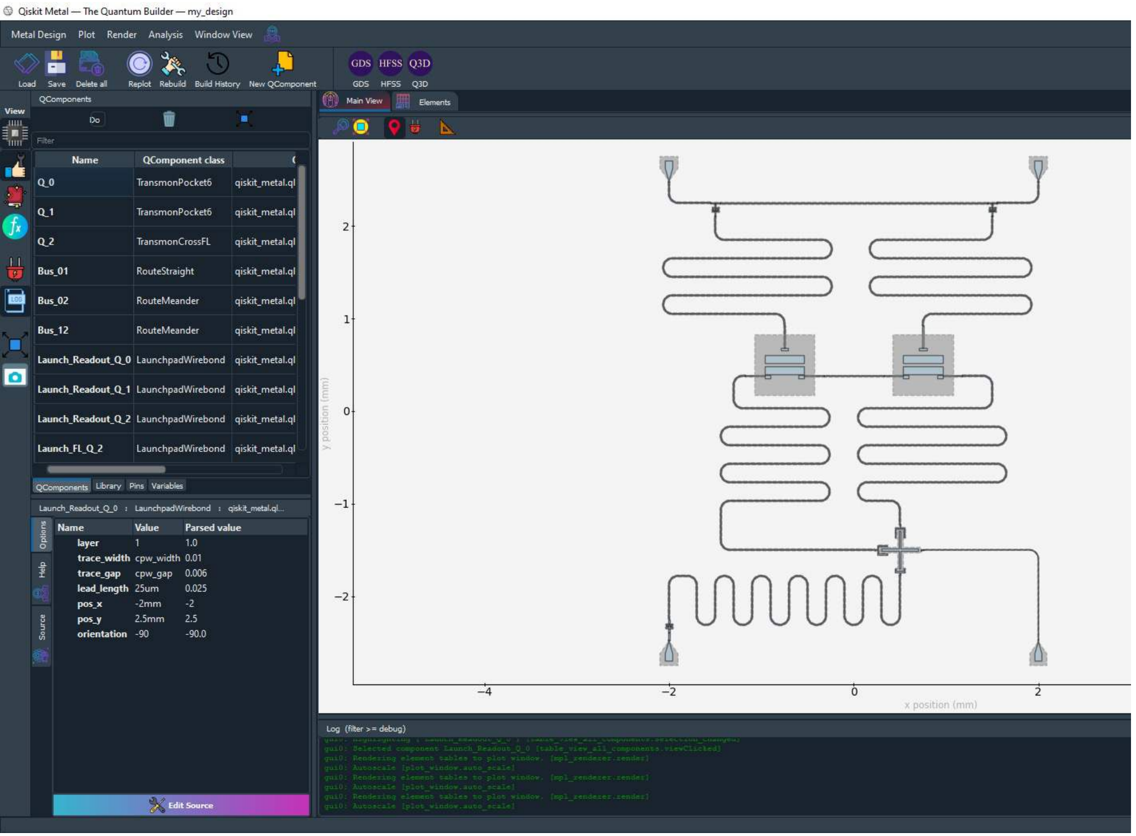
Ansys HFSS

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



Capacitive simulation

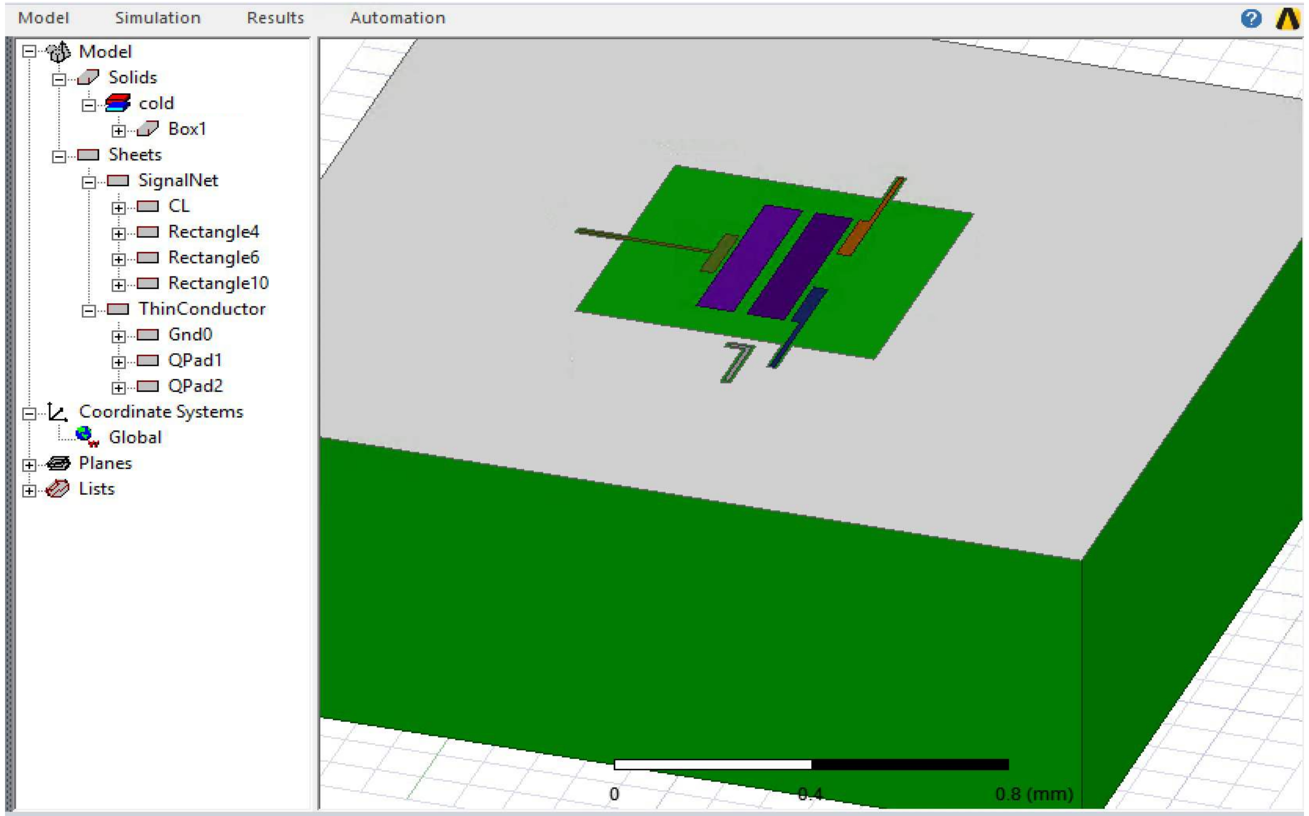
device layout



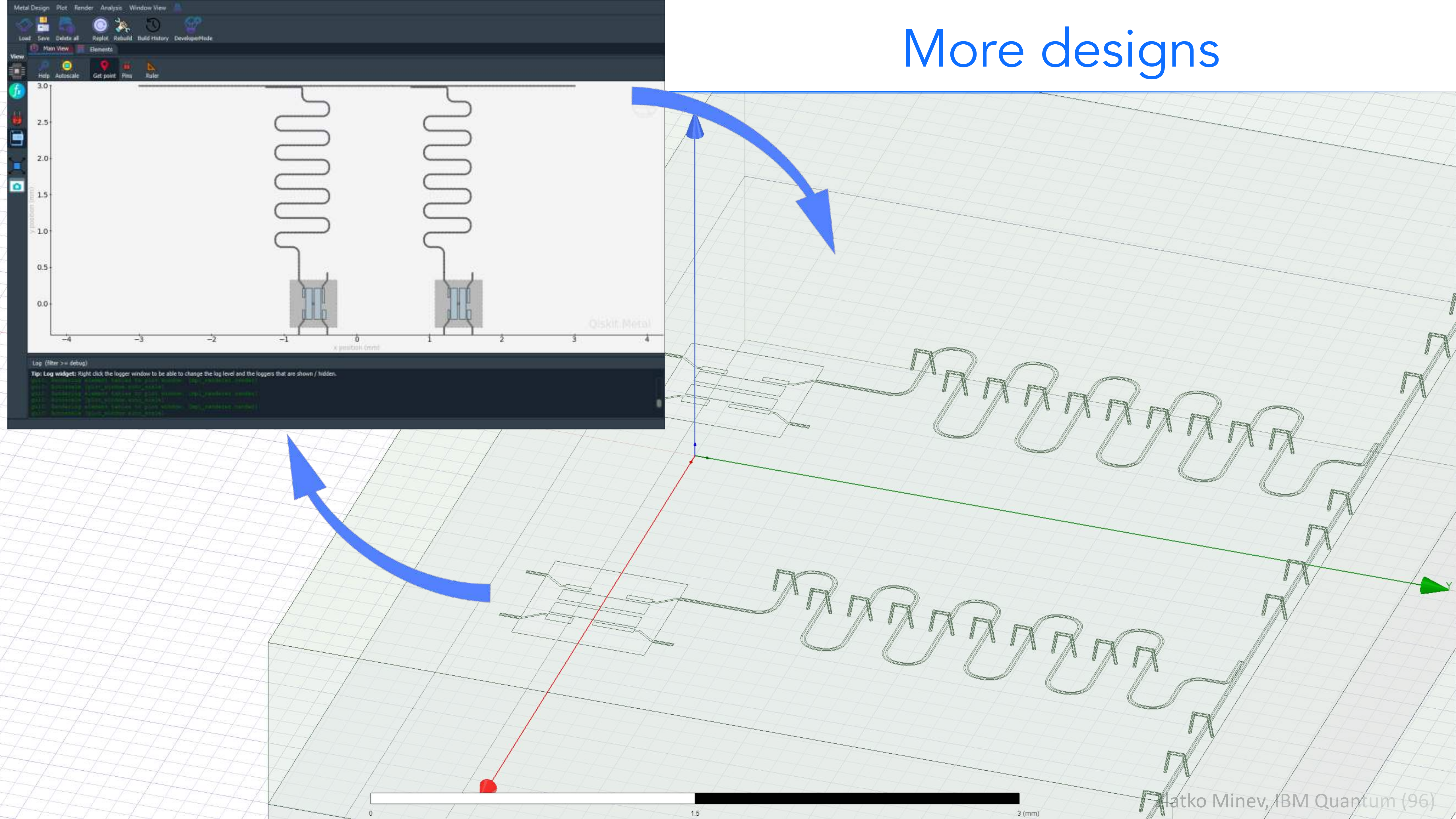
Automated with

Qiskit | quantum device design

extractor model

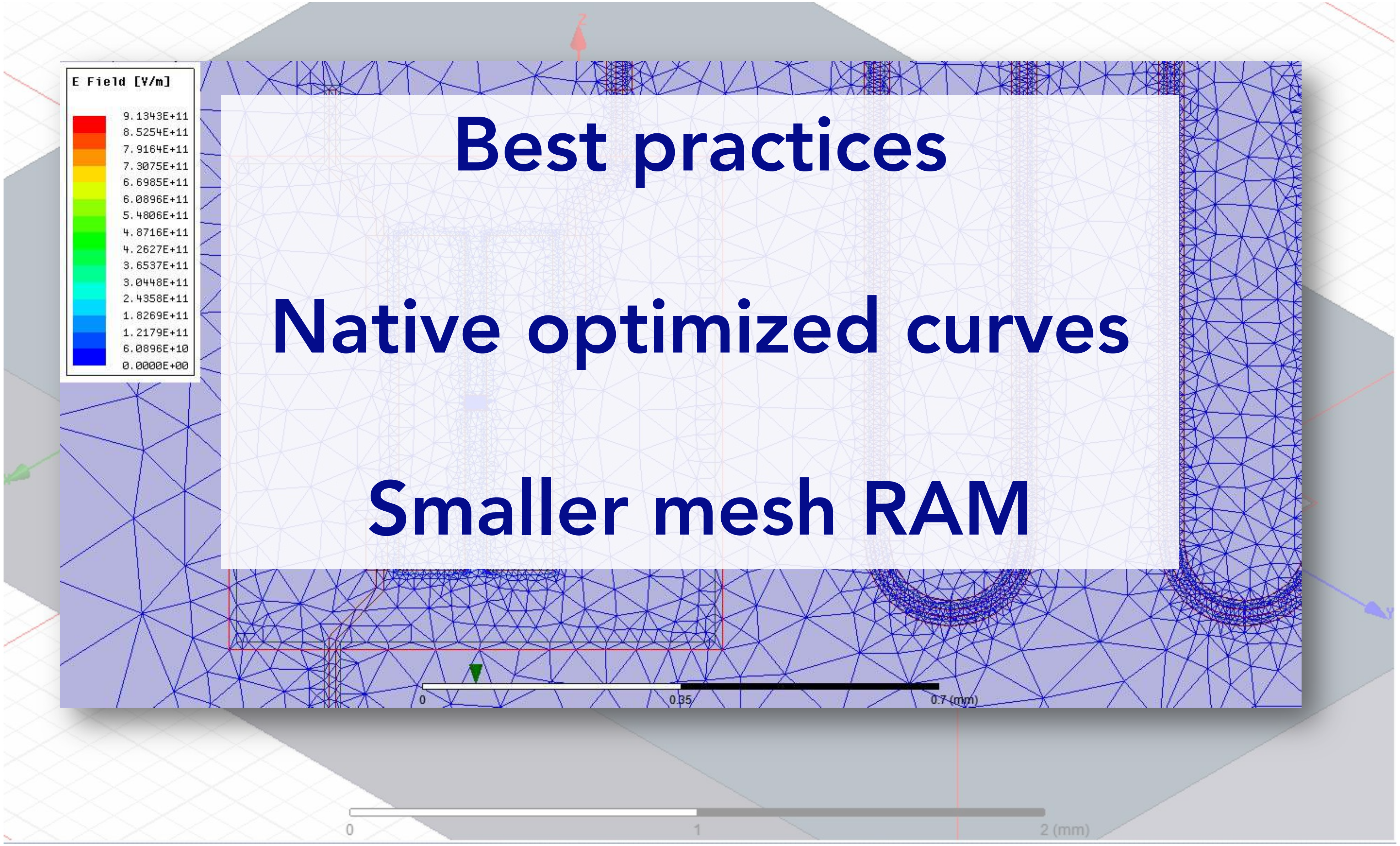


More designs



Qiskit Metal

Sub-Circuit Analysis

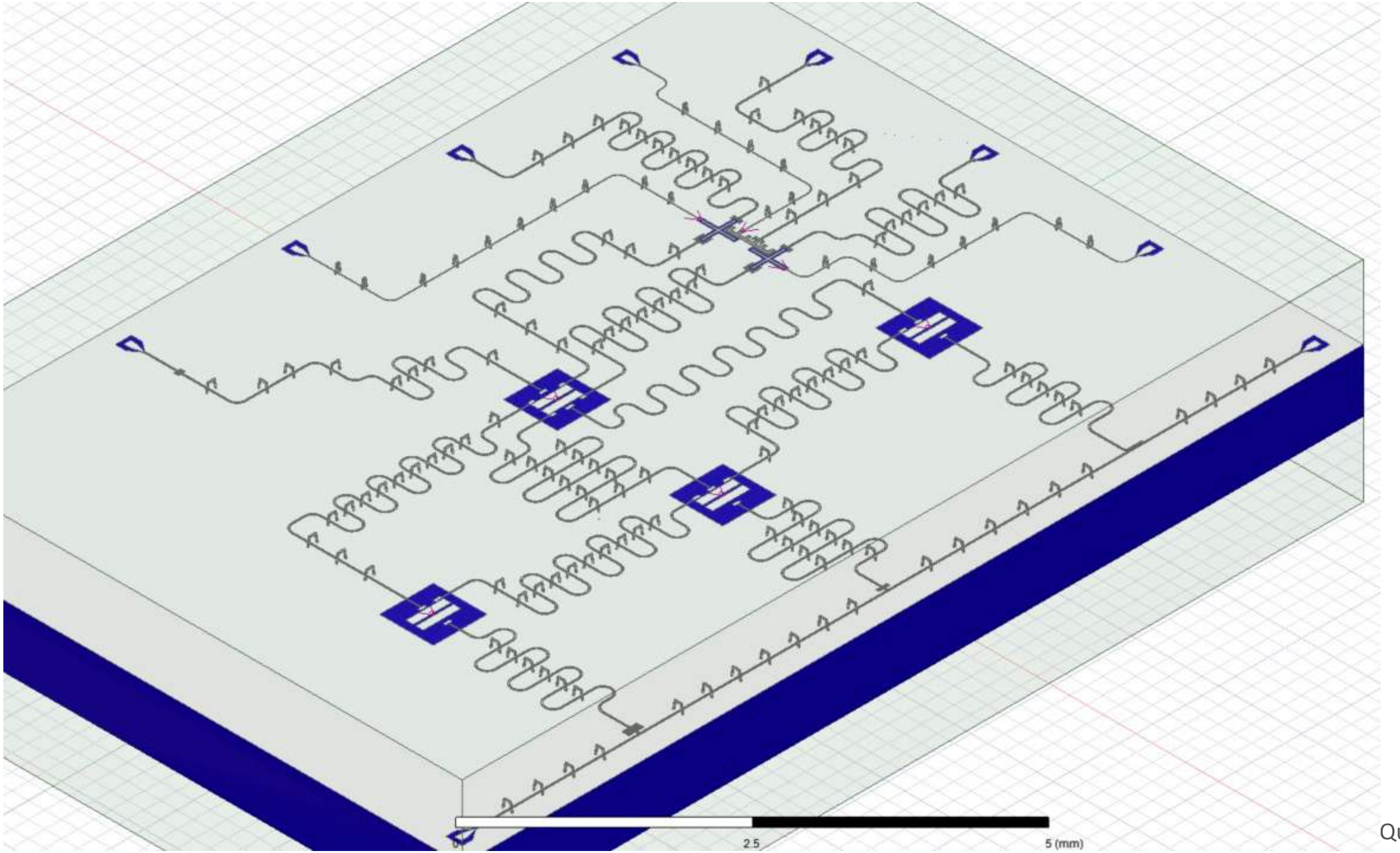


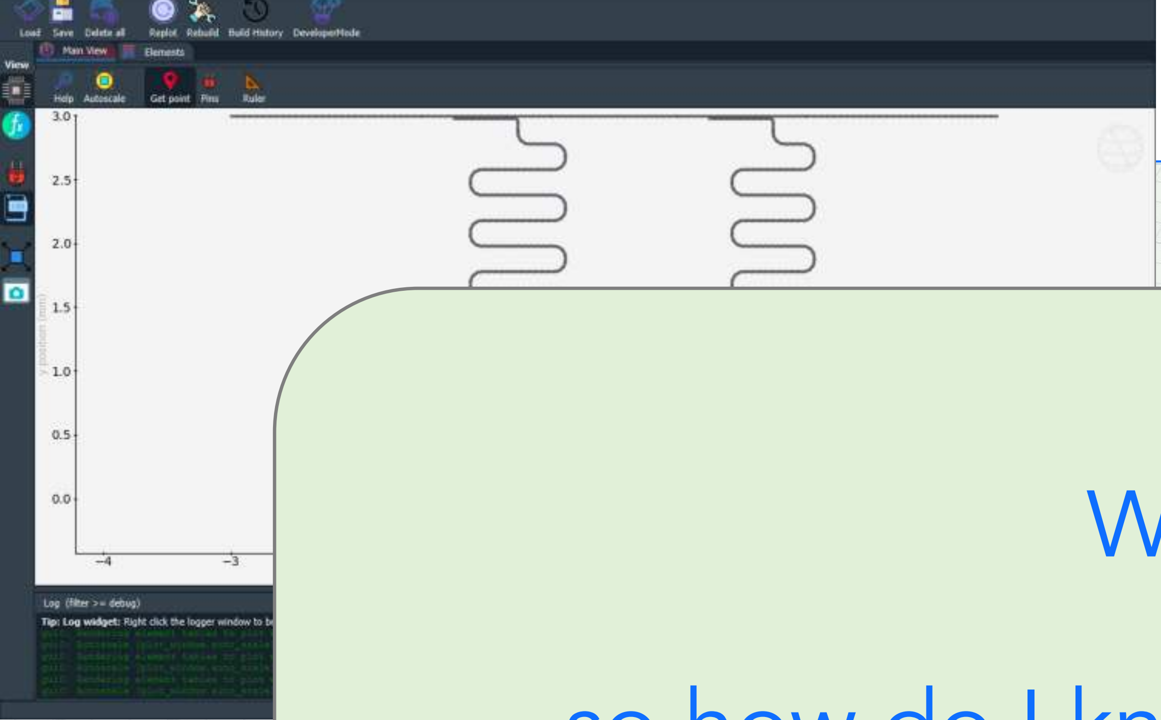
Best practices

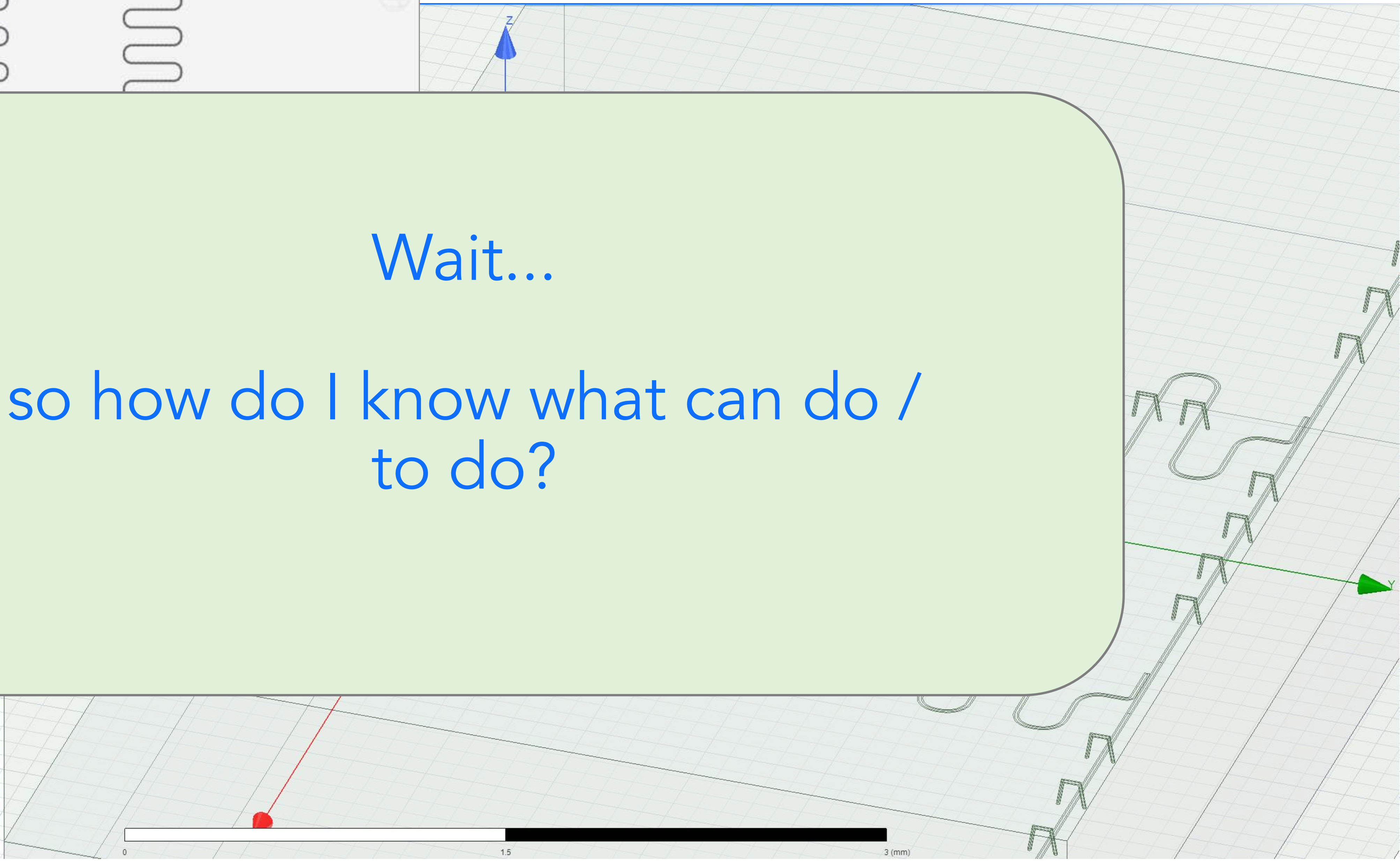
Native optimized curves

Smaller mesh RAM

More complex quantum chips – see next tutorial



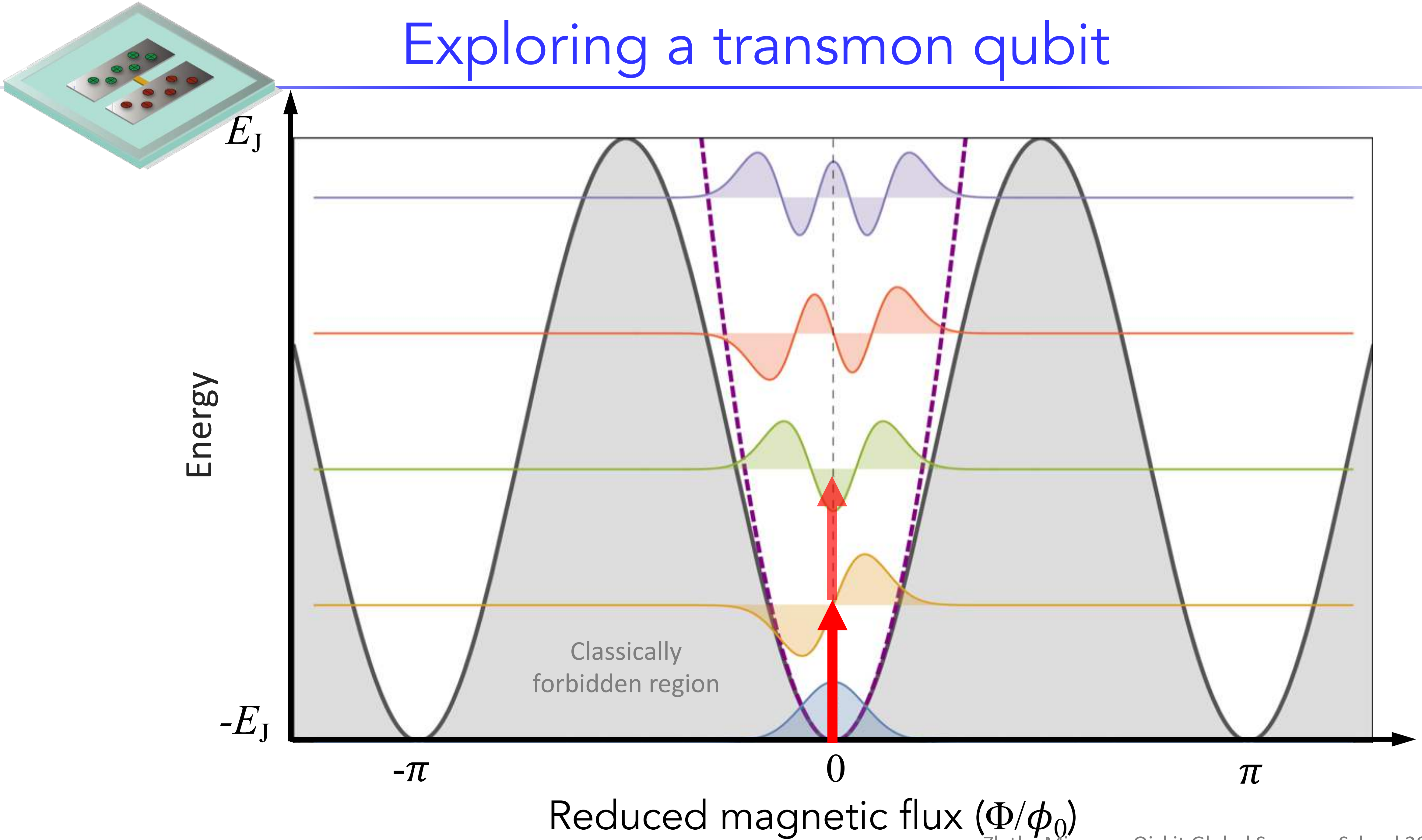




Wait…

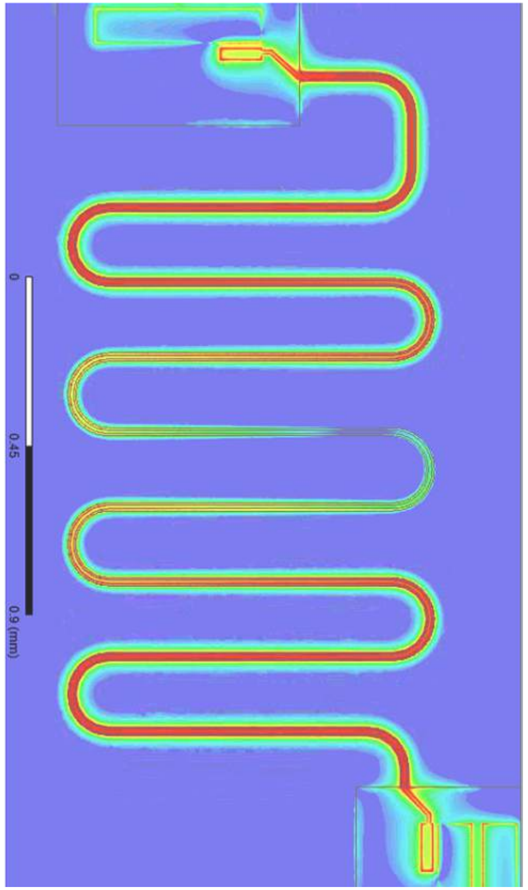
so how do I know what can do / to do?

Exploring a transmon qubit

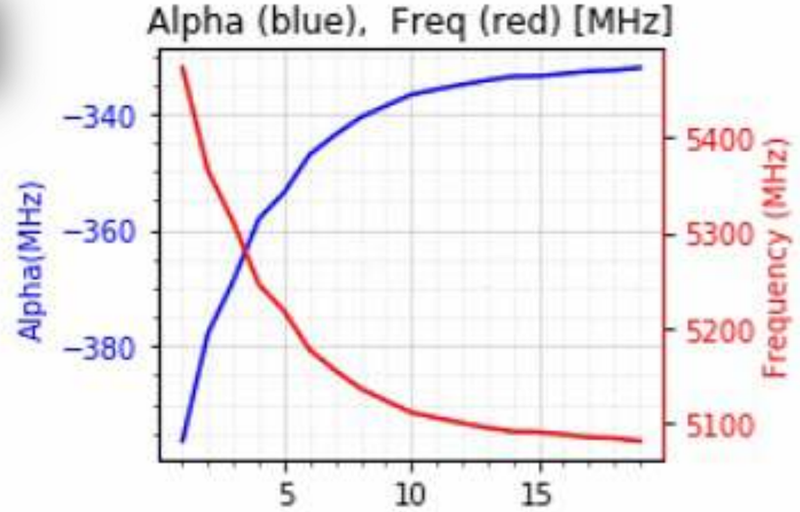


Automated analysis and reports

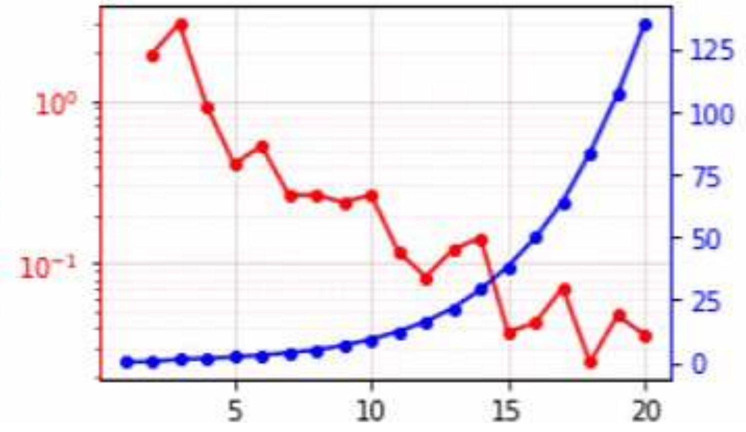
```
metal.analysis.lumped_model.analyze('Q1')
```



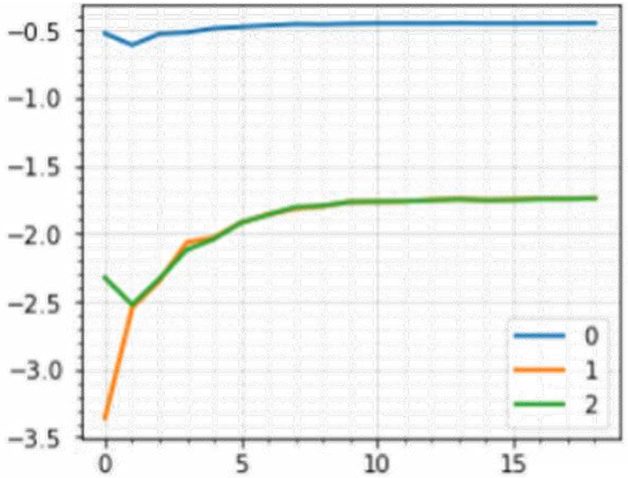
Qubit frequency & anharmonicity



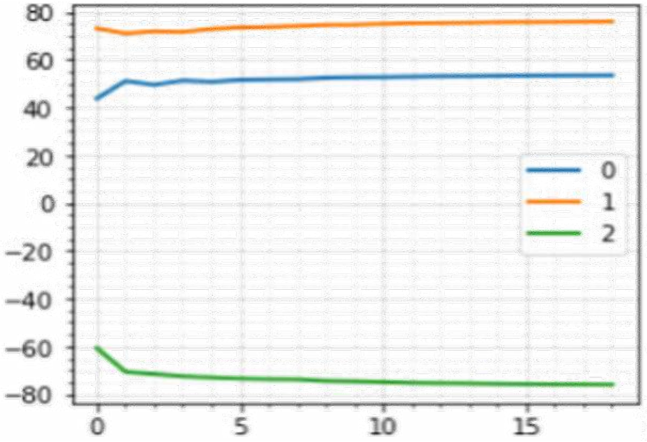
FE simulation convergence



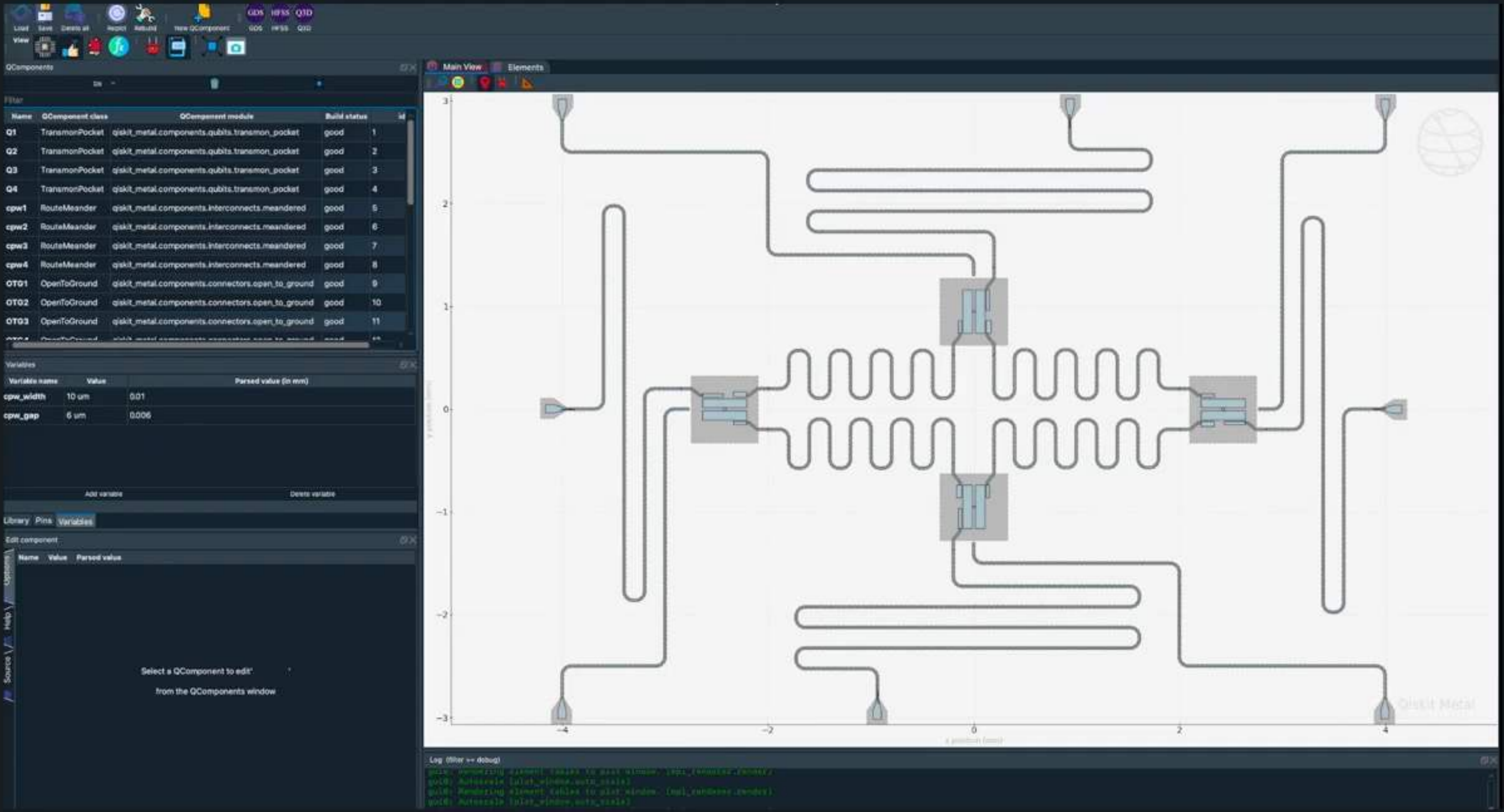
cross-Kerr χ coupling (MHz)



Linear g coupling (MHz)



Analysis pass number



Load
Save
Delete all
Replot
Rebuild
New QComponent
GDS
HFSS
Q3D
View
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
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
3
2
1
0
−1
−2
−3
−4
−2
0
2
4
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

Korea Hackathon – Metal Projects

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.

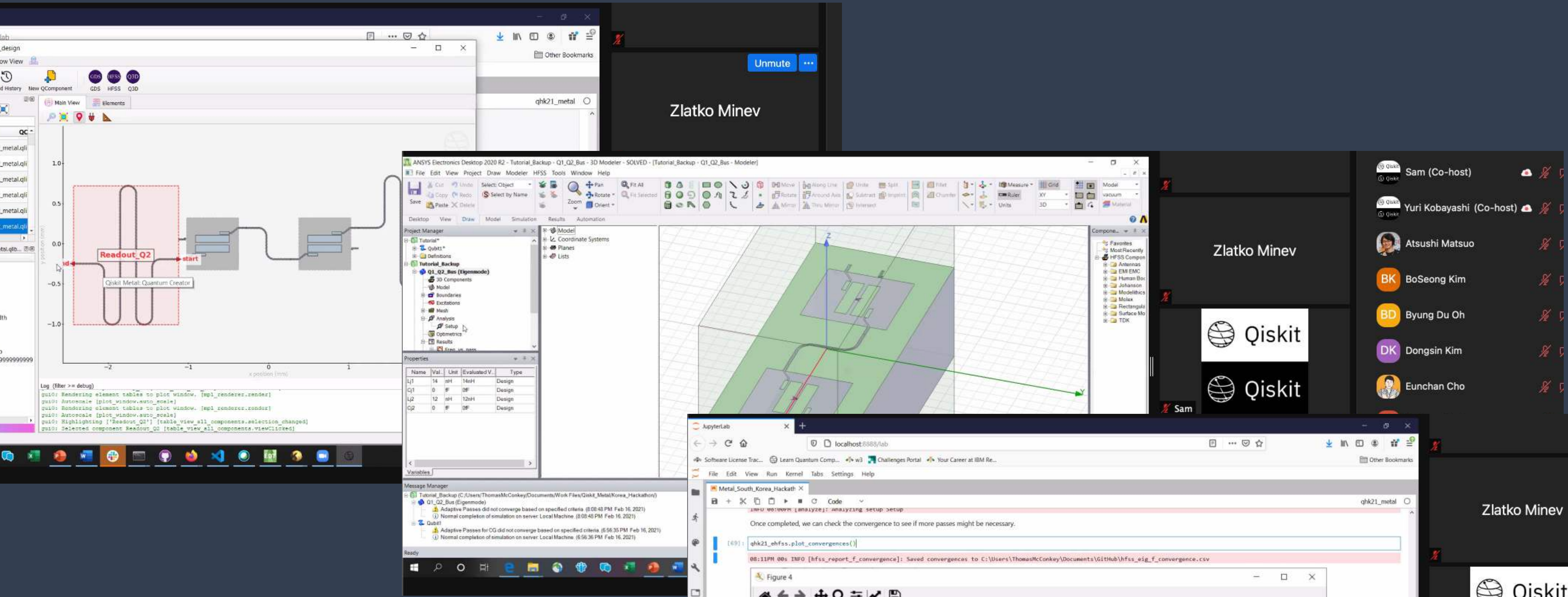
Members

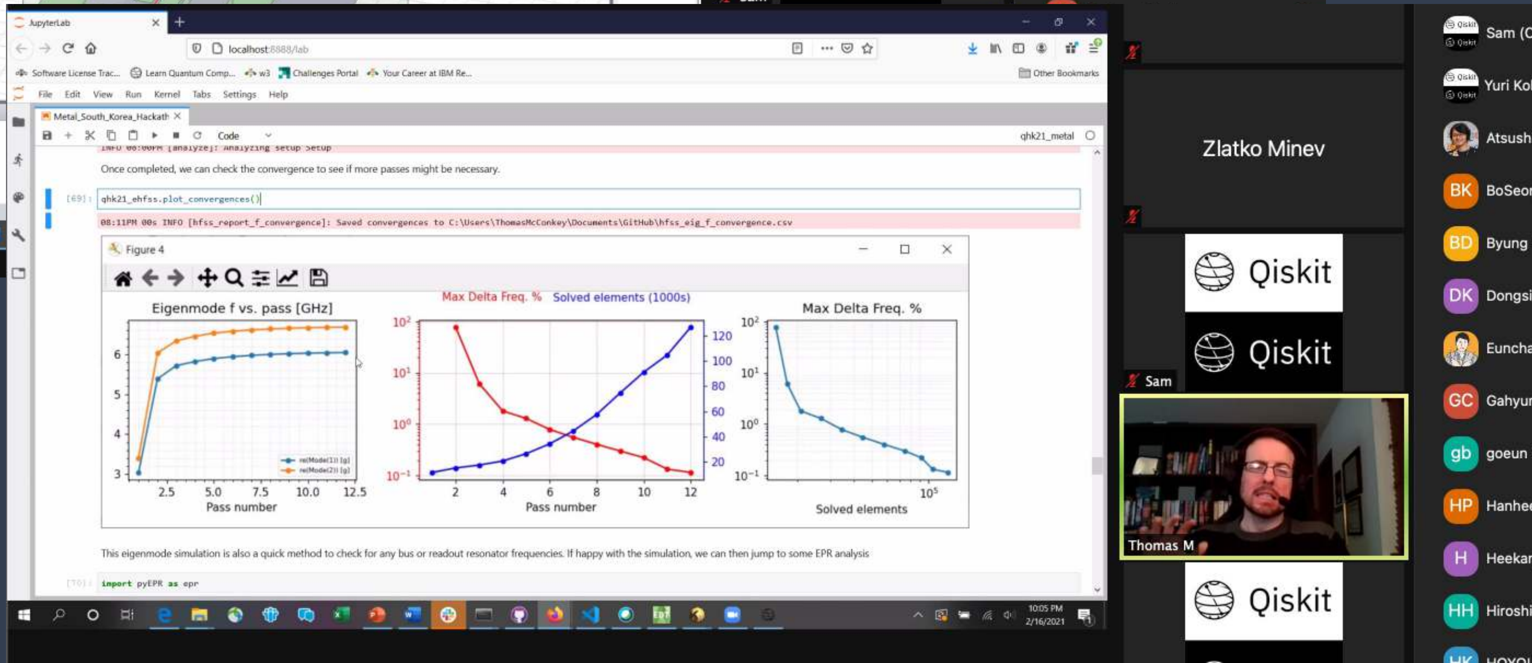
Deliverables

- 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





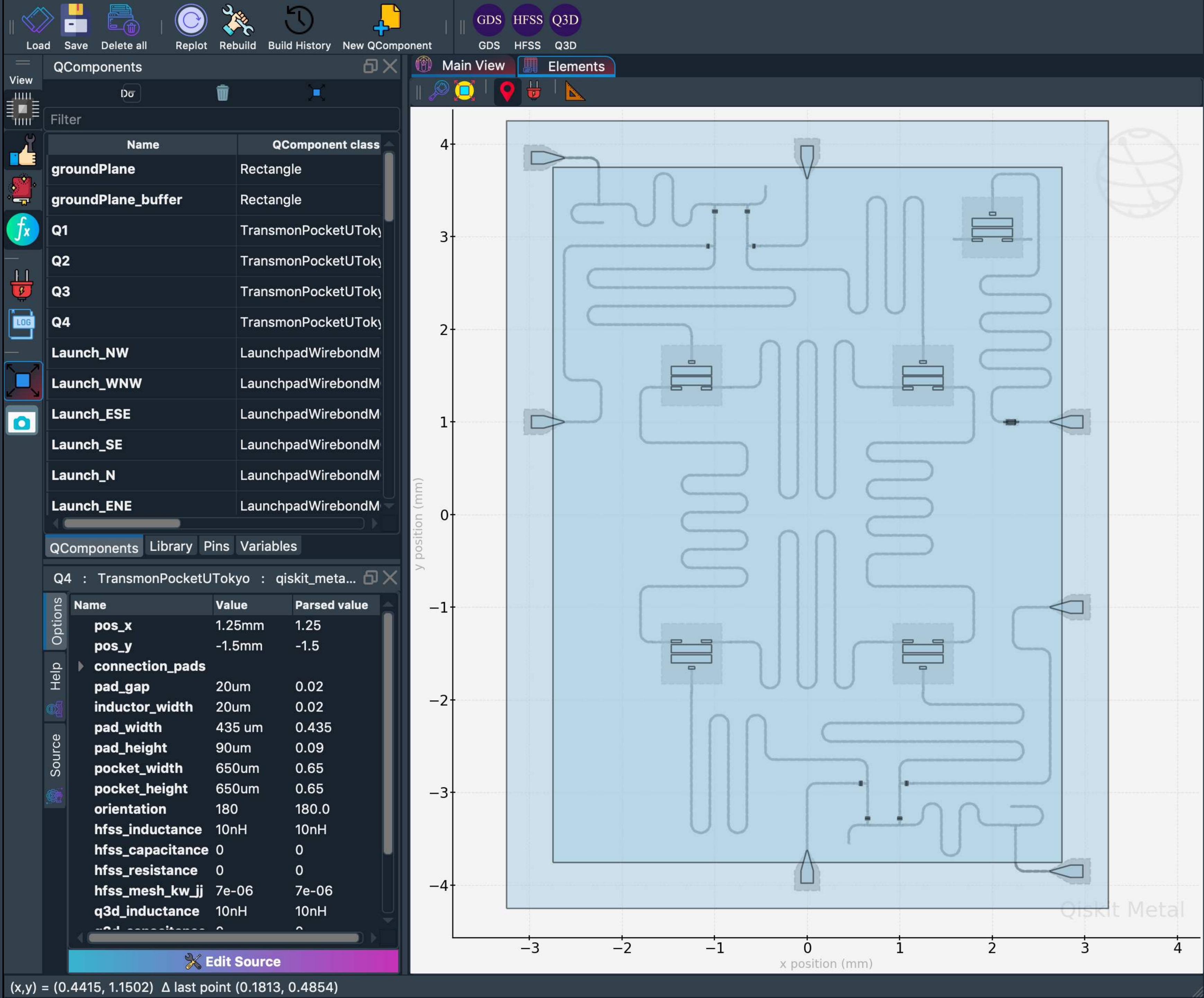
BIG BIG THANKS TO <u>Yuri</u>, Samanvay, Hanhee, Junye & team!!

Thomas, Dennis, Metal coaches, ...

Qiskit | quantum device design

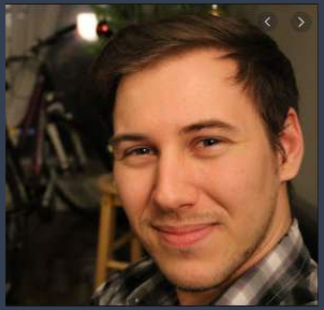
Devices made with Metal

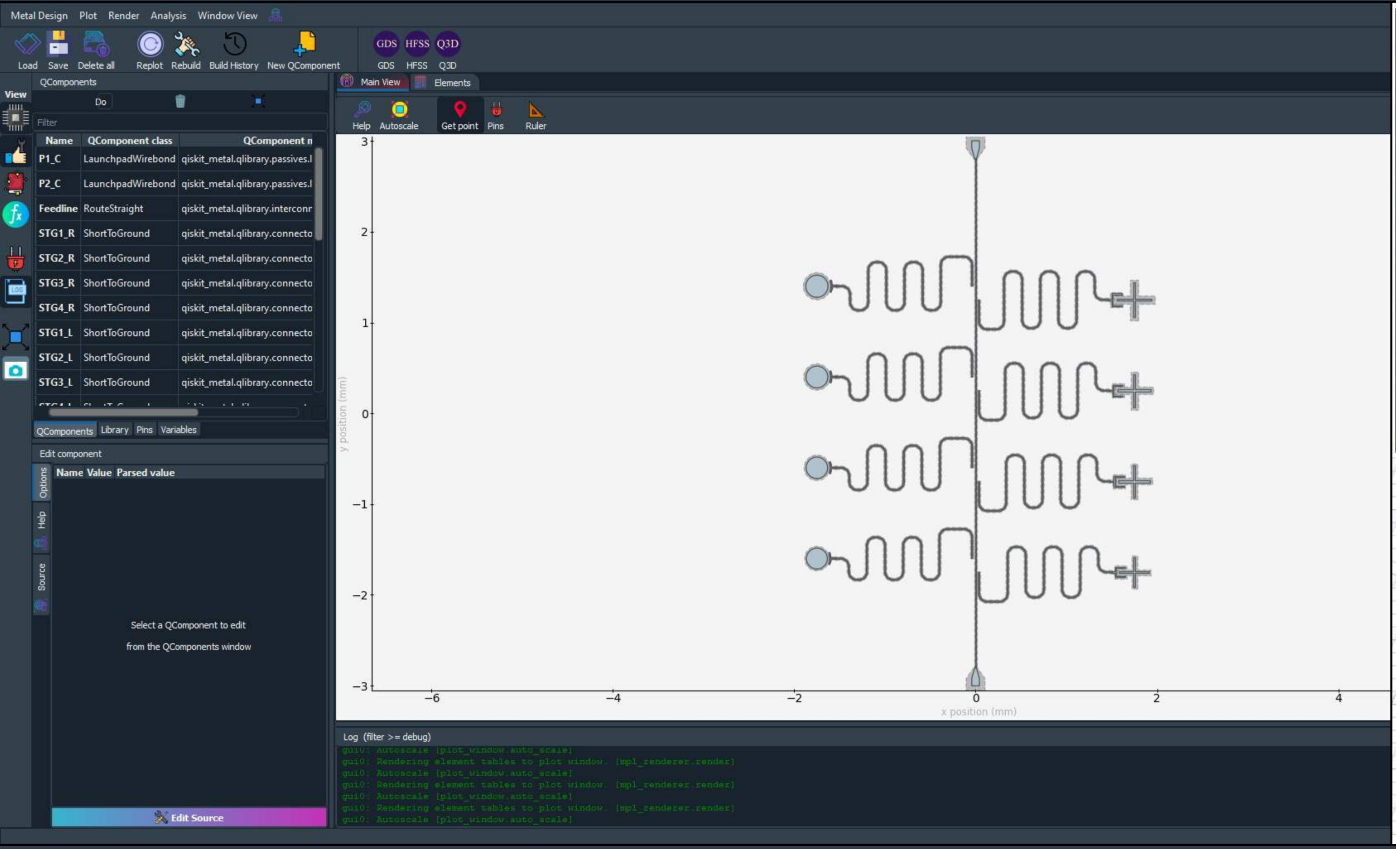
IBM 5Q Tsuru U Tokyo

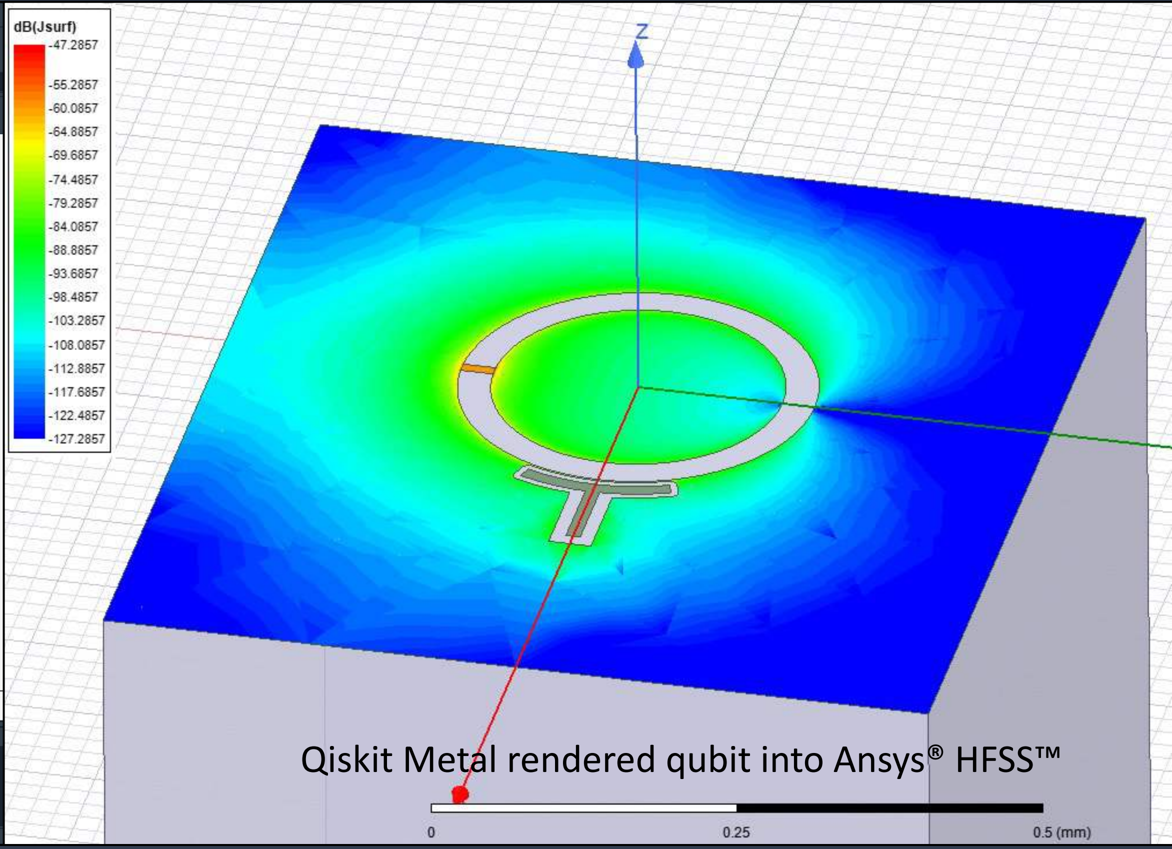


Qiskit | quantum device design

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

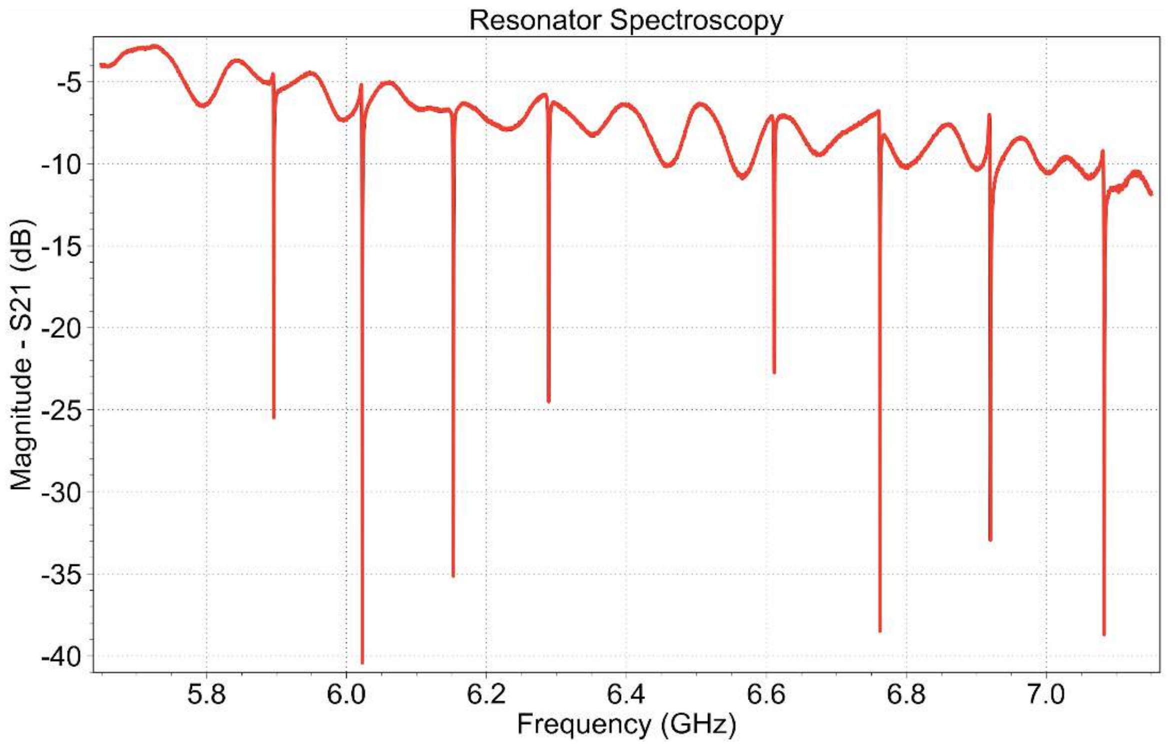


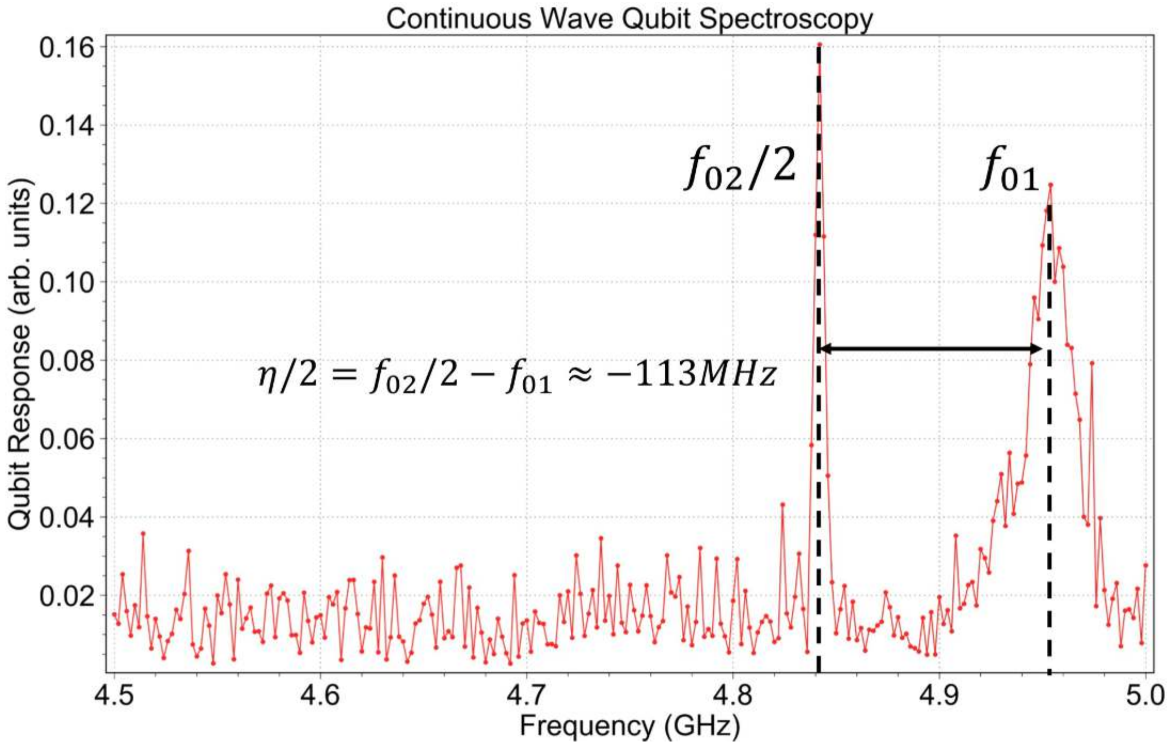




Qiskit Metal rendered qubit into Ansys® HFSS™

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





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.

image: *pikpng*

Docs & tutorials
qiskit.org/documentation/metal

Tutorial videos
YouTube – see docs

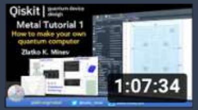
Slack
#metal (qiskit workspace)

Live biweekly tutorials

Qiskit | quantum device design

20+ Live tutorials & videos

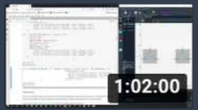
YouTube

1 

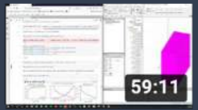
Qiskit Metal E01 - Overview
Qiskit

2 

Welcome to Qiskit metal: download and install instruction
Qiskit

3 

Qiskit Metal E02 - End to end example of Quantum Chip Design - Part 1 of 2
Qiskit

4 

Qiskit Metal E03 End to end example of Quantum Chip Design - Part 2 of 2
Qiskit

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Qiskit Metal E04 - QComponents for parametric design
Qiskit

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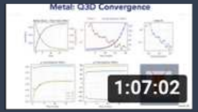
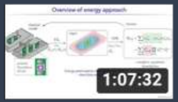
Qiskit Metal E05.1 - Analysis - Capacitance and Frequency Control
Qiskit

7 

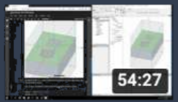
Qiskit Metal E05.2 - Analysis - Eigenmode and Energy Participation
Qiskit

8 

Qiskit Metal E05.3 - Analysis - EPR Theory
Qiskit

9 

Qiskit Metal E05.4 - Analysis - Summary EPR Quantization with Code Example
Qiskit

10 

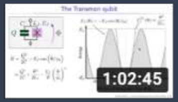
Qiskit Metal E05.5 - Analysis - Finish Eigenmode Start Impedance Analysis
Qiskit

11 

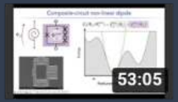
Qiskit Metal E05.6 - Analysis - Extracting S Parameters for a Hanging Resonator
Qiskit

12 

Qiskit Metal E06 - Quantum Analysis 101 Prerequisites
Qiskit

13 

Qiskit Metal E07 - Introduction to the transmon qubit
Qiskit

14 

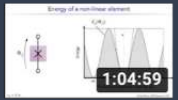
Qiskit Metal E08 - Physics of the Cooper Pair Box Transmon Qubit
Qiskit

15 

Qiskit Metal E09 - Parametric Sweep Analysis
Qiskit

16 

Qiskit Metal E10 - How to contribute to the code base
Qiskit

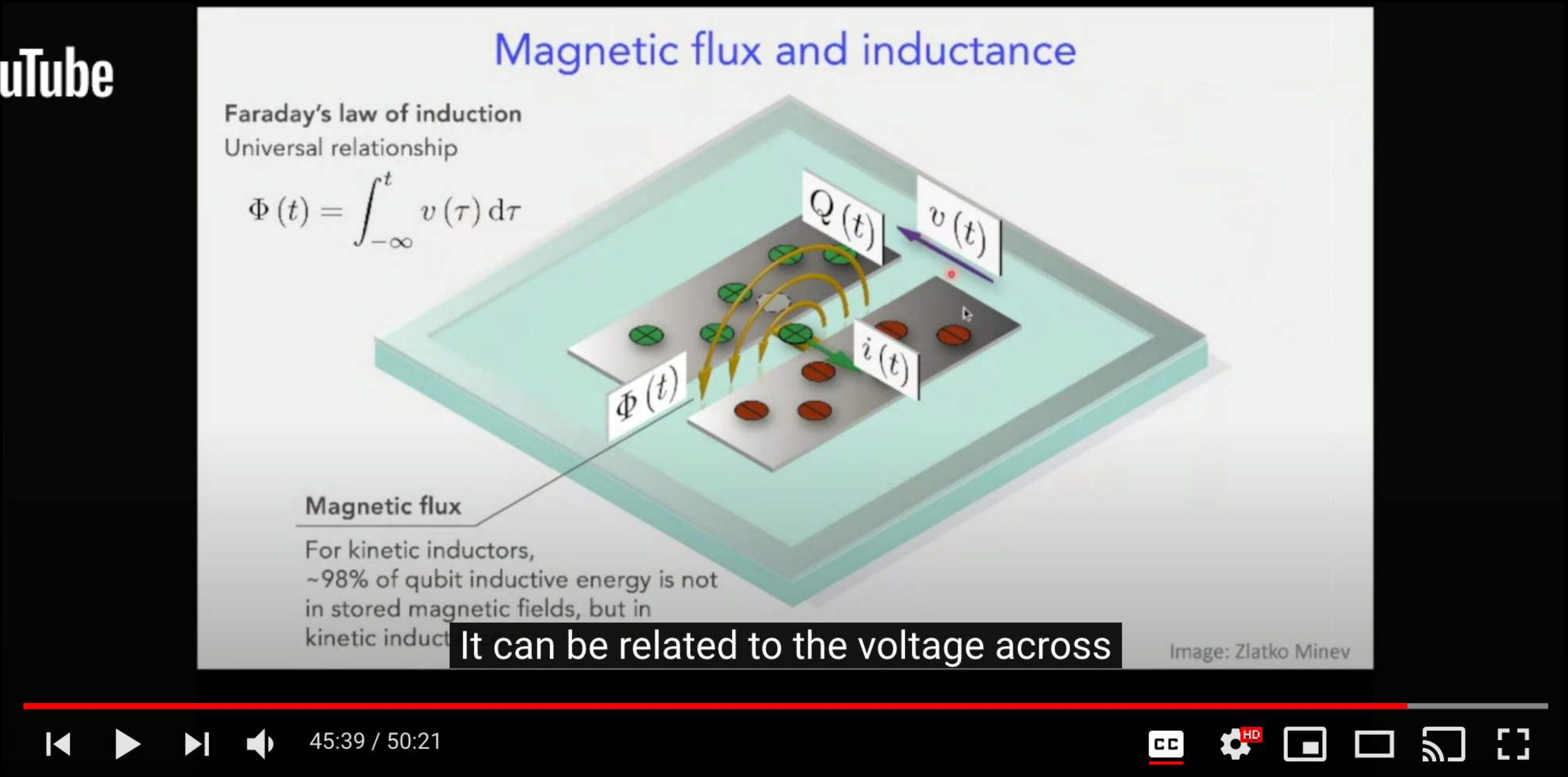
17 

Qiskit Metal E11 - Introduction to Energy Participation Ratio (EPR)
Qiskit

qiskit.org/metal

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

Next steps

Tightly integrated work by Dr. Thomas McConkey!

qiskit.org/metal -> docs -> videos -> E02

Check out references, problems given in the lecture, dangerous bends

Break away from the rules of today

Thank you!

Zlatko K. Minev

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

Henri Poincaré

Photo by Eugène Pirou