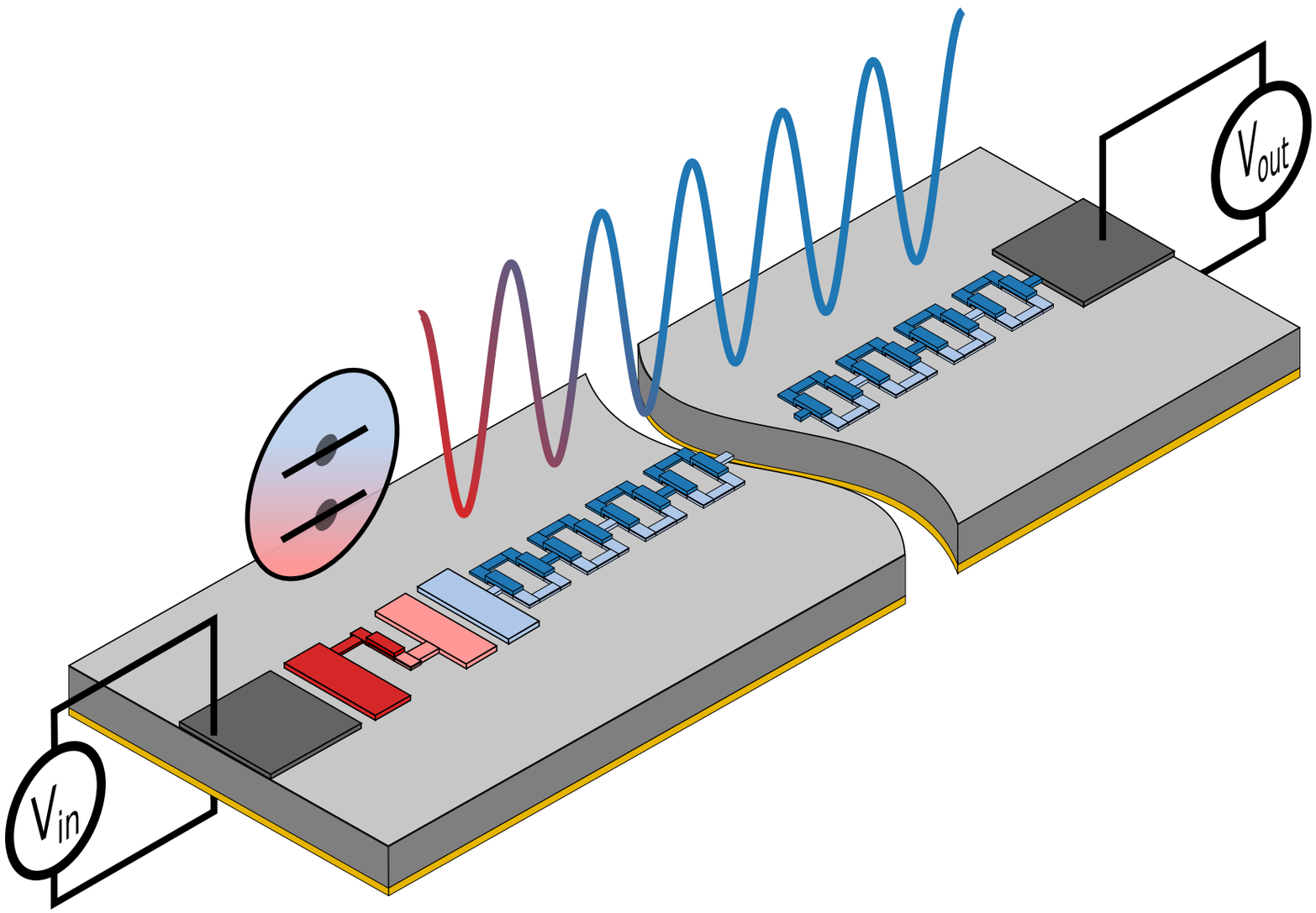
Circuit-QED based spectroscopies of quantum impurities



Nicolas Roch
Superconducting quantum circuits team
Neel Institute, Grenoble, France

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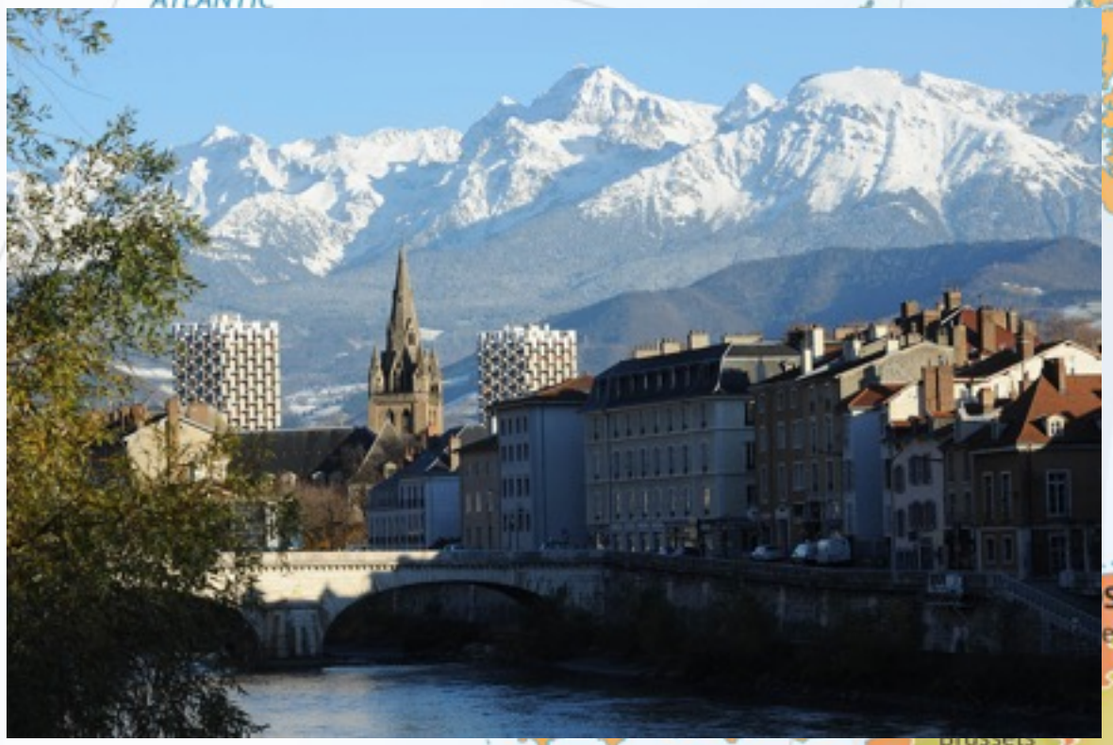

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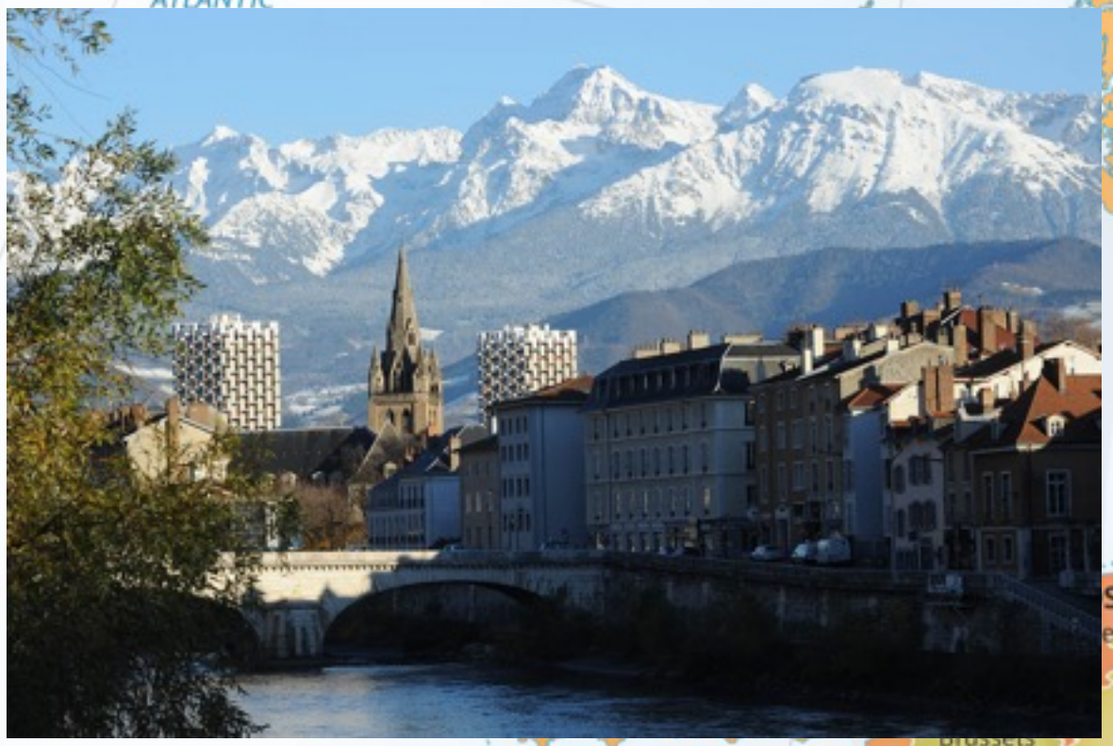

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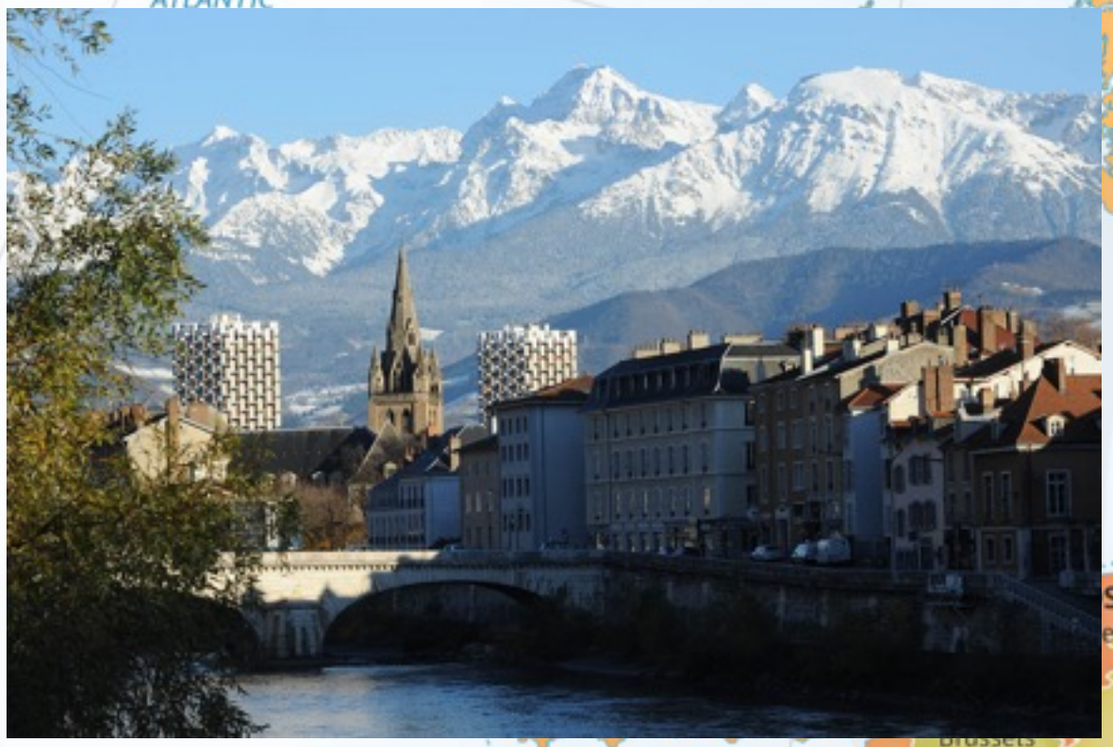

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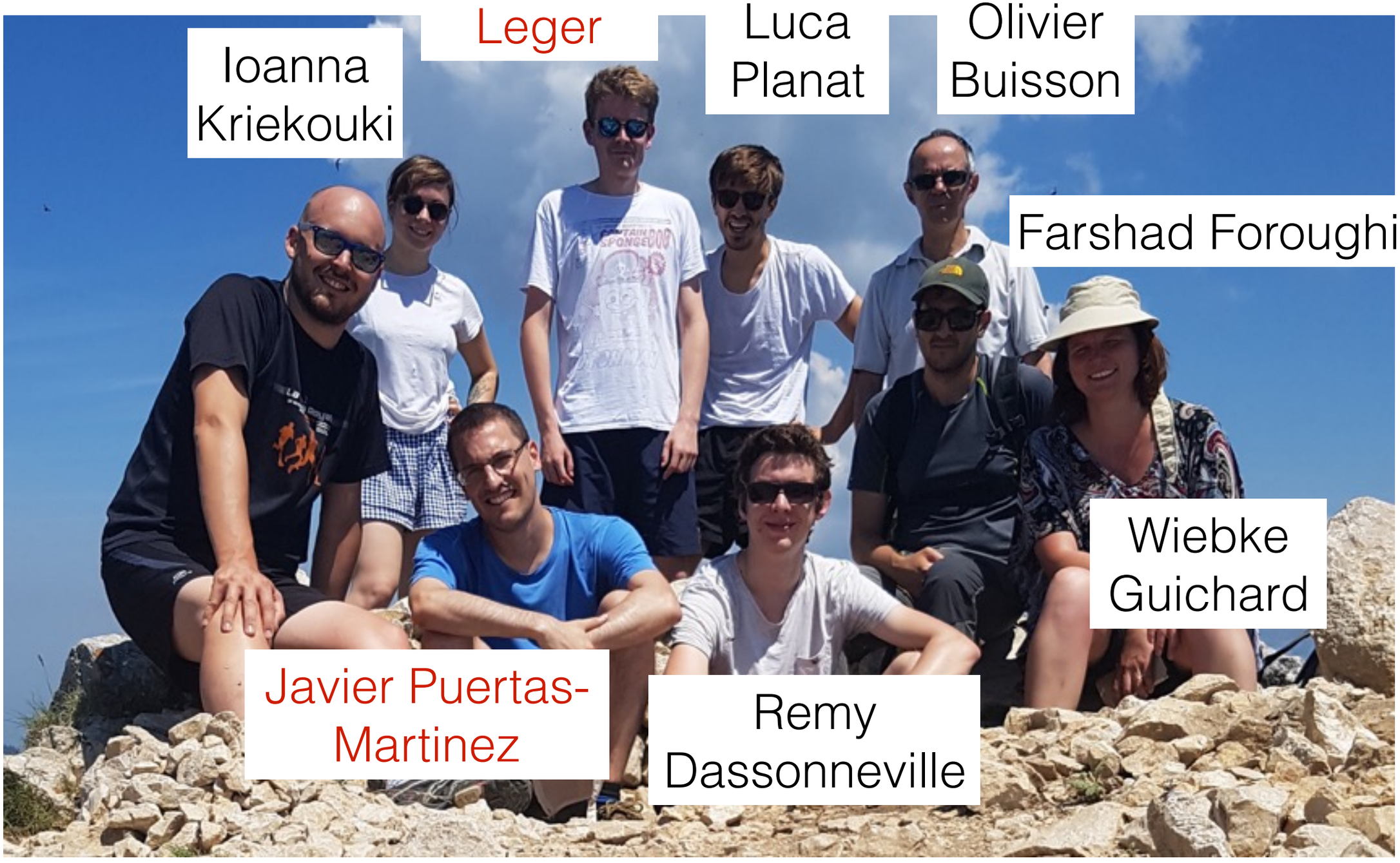
Superconducting quantum circuits team



cnrs advancing the frontiers

lanef Laboratoire d'Alliances Nanosciences-Energies du futur

NÉEL institut

AGENCE NATIONALE DE LA RECHERCHE ANR

Quantum Engineering
Univ. Grenoble Alpes

Acknowledgments

Néel Institute
Grenoble

Serge
Florens

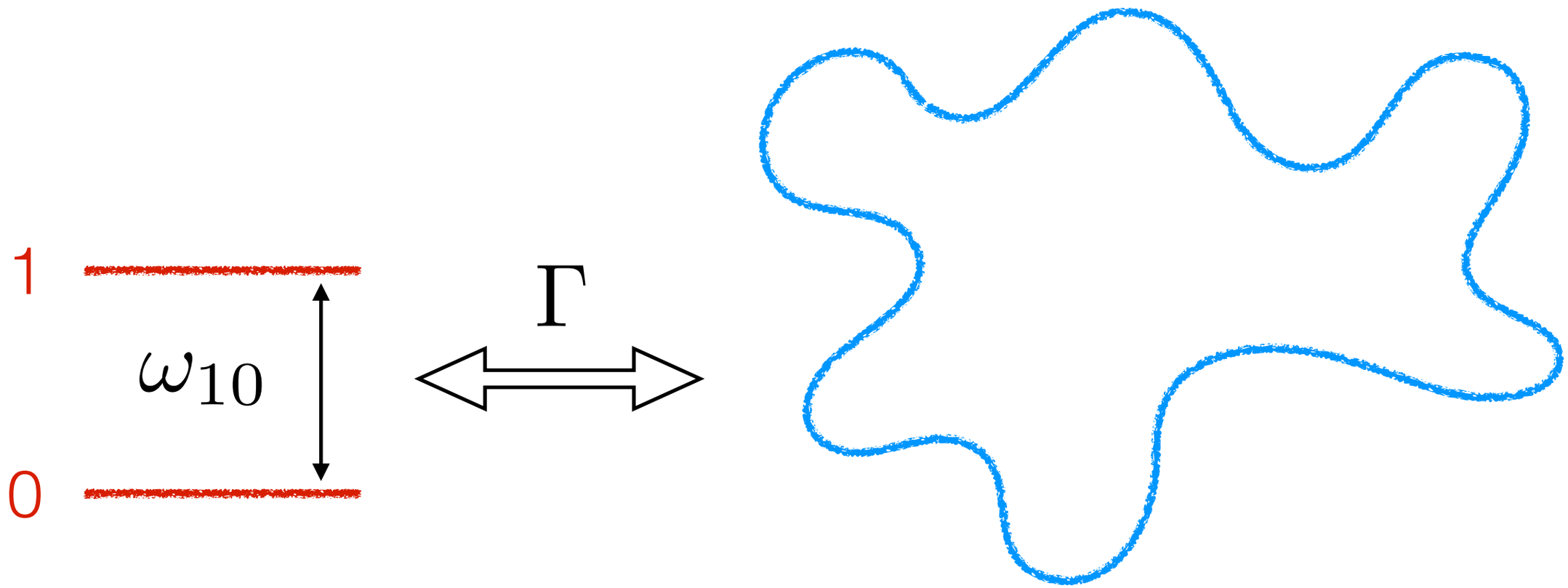
Nicolas
Gheereart

See Poster!

U. Witwatersrand
Johannesburg

Izak
Snyman

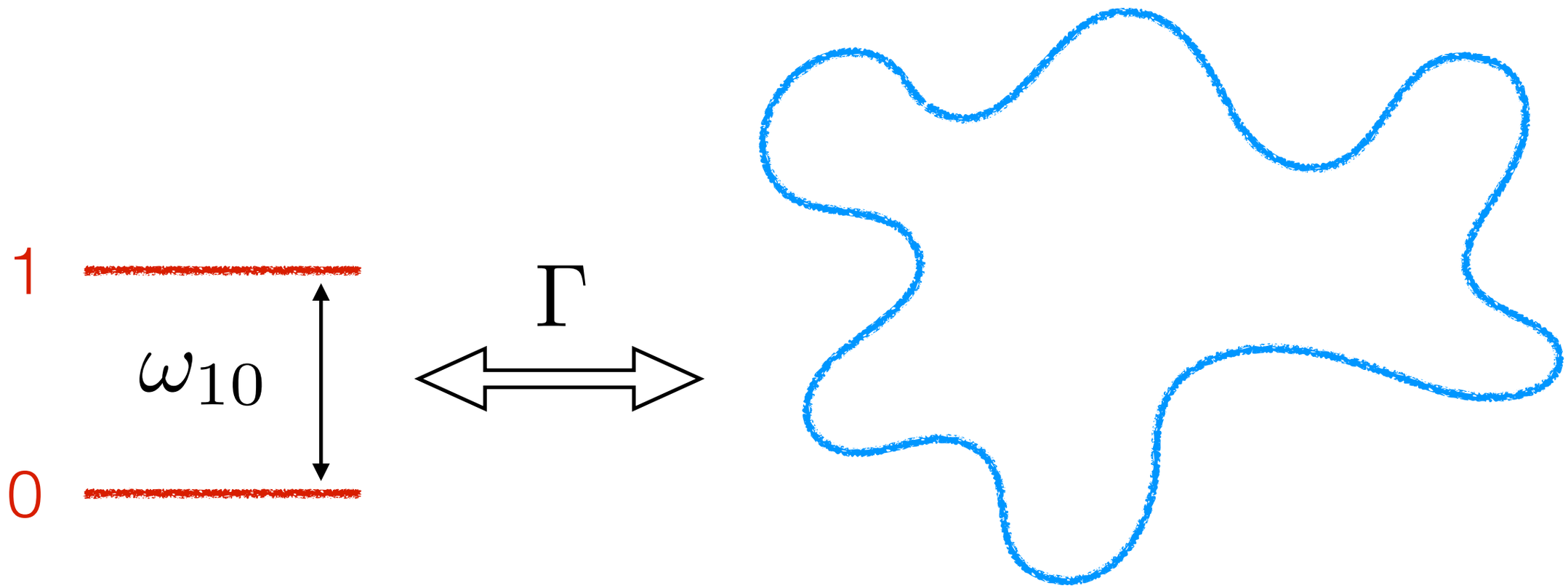
What is a quantum impurity?



Ingredients:

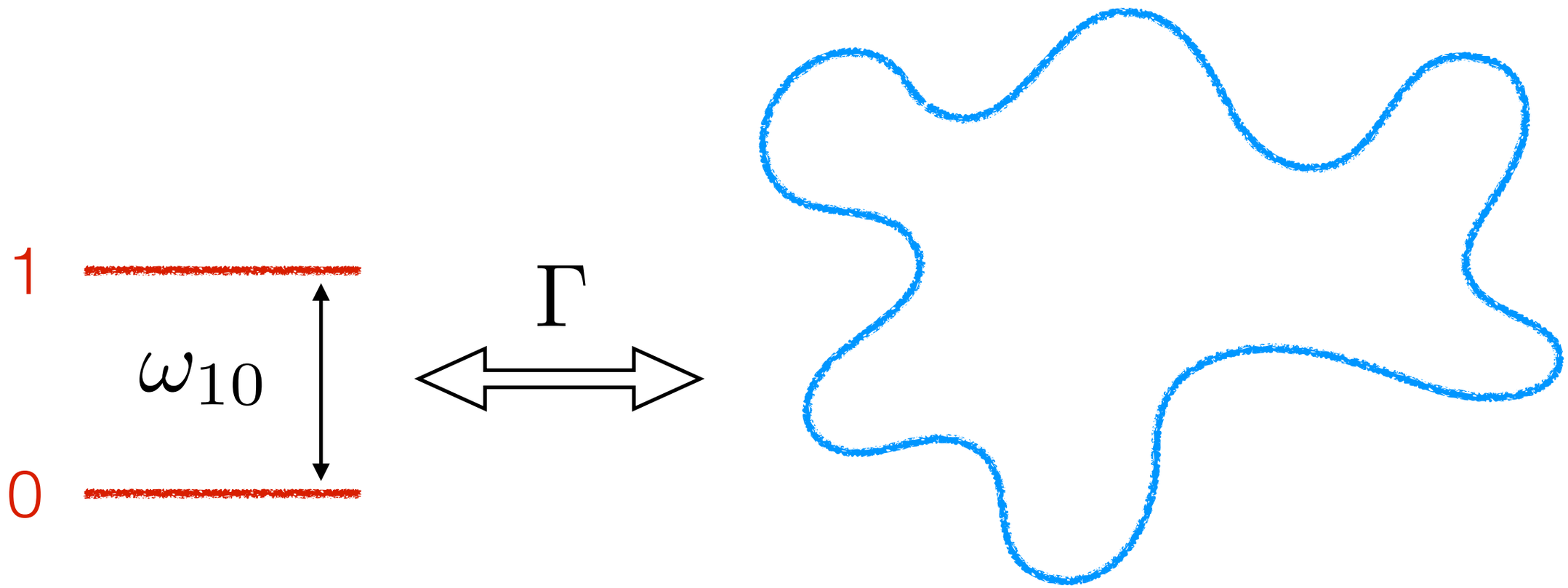
- ☑ one impurity
- ☑ many degrees of freedom
- ☑ Multi-Mode UltraStrong Coupling: $\Gamma \simeq \omega_{10}$

Why a quantum impurity?



The “hydrogen atom” of many-body physics

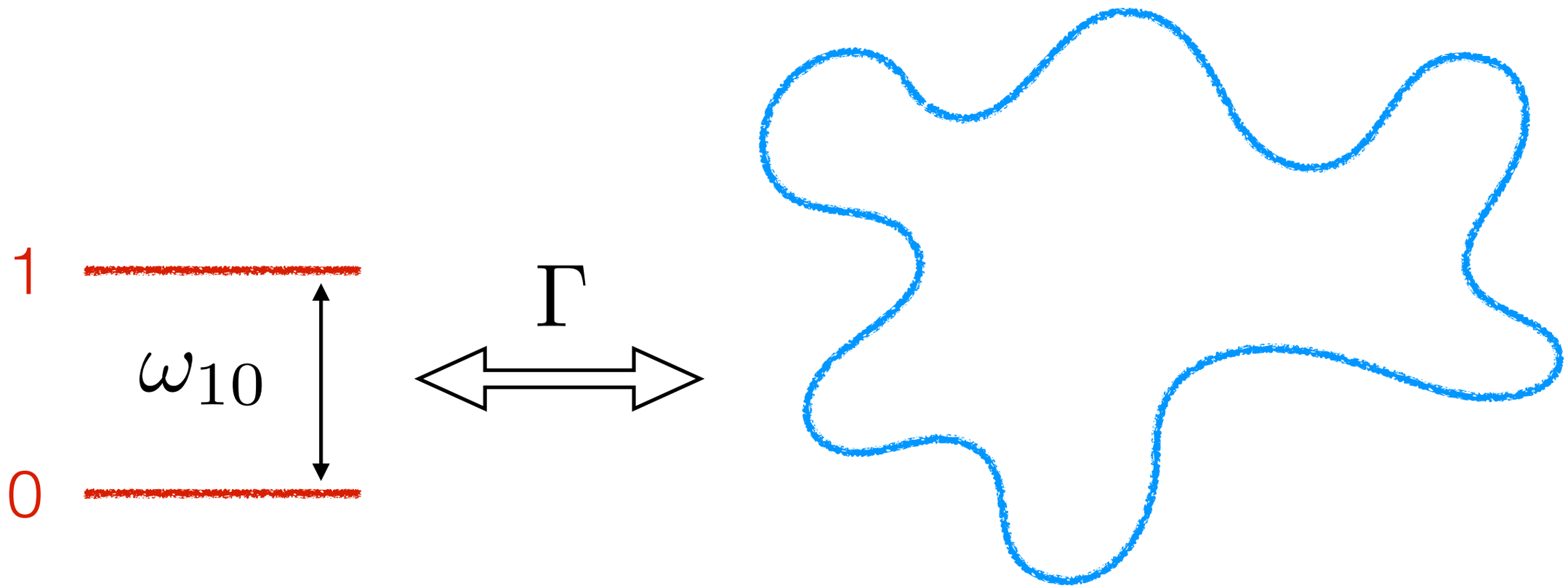
Why a quantum impurity?



The “hydrogen atom” of many-body physics

New physics: dynamics

Why a quantum impurity?



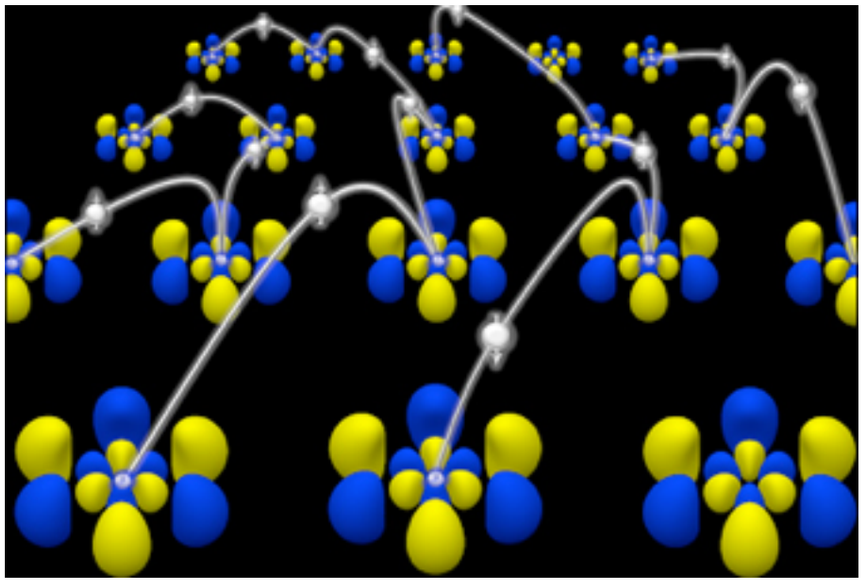
The “hydrogen atom” of many-body physics

New physics: dynamics

What about the bath? Non-markovianity, entanglement…

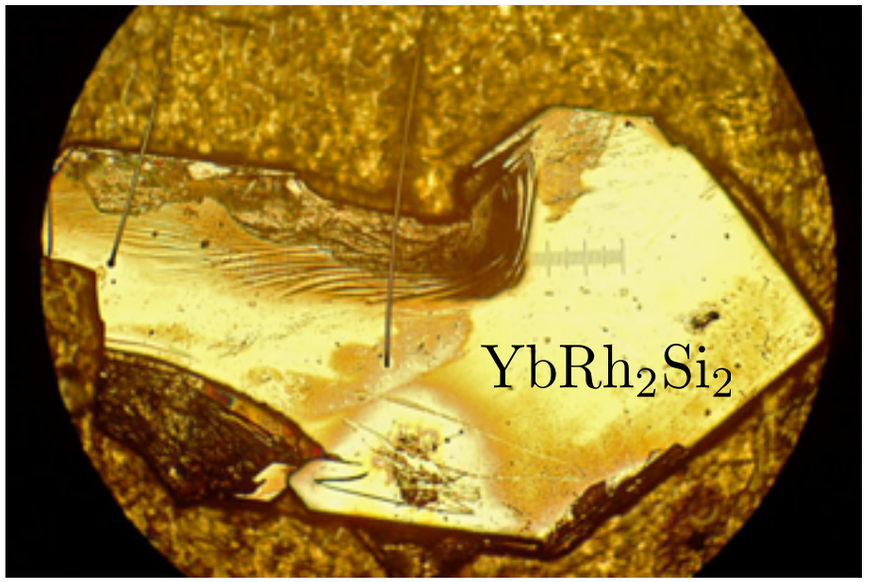
Fermionic bath

Heavy fermions



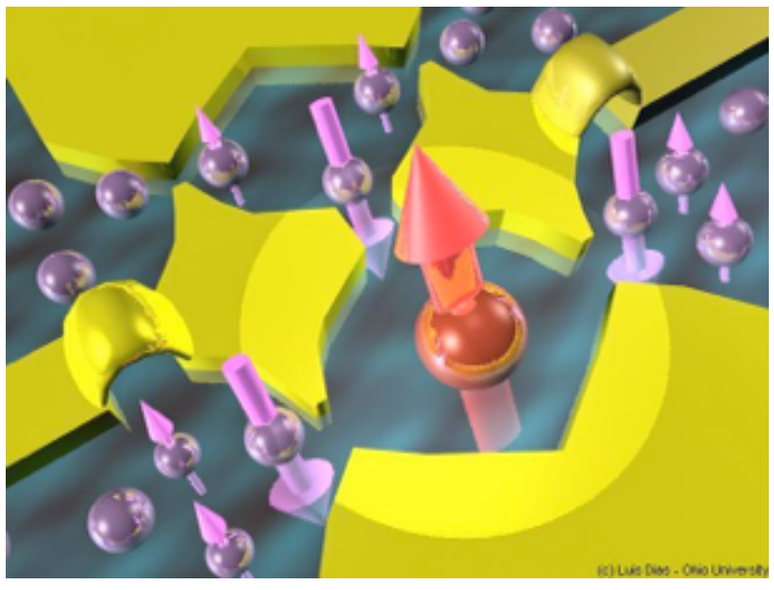
Credit: Mohammad Hamidian - Davis Lab

Exotic superconductors



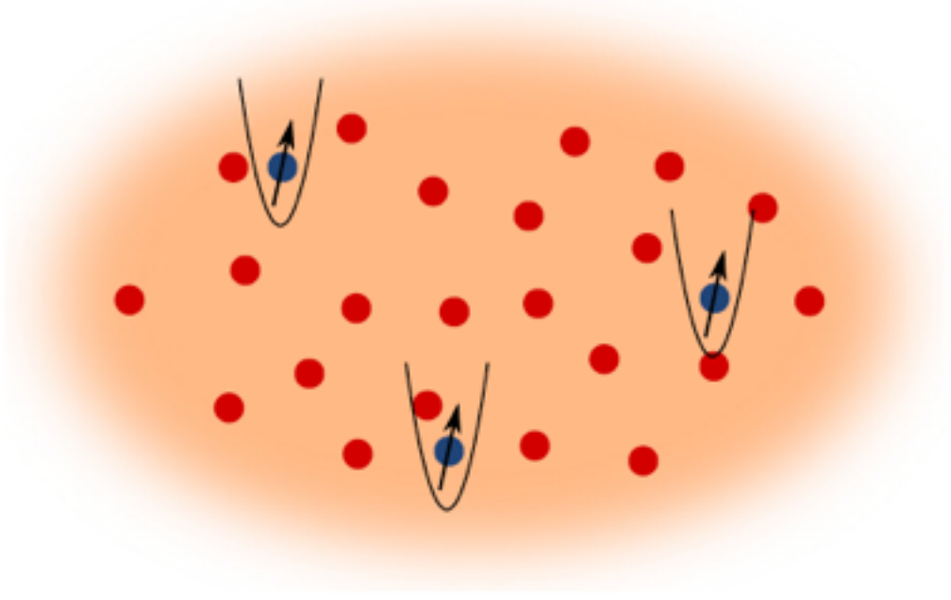
Credit: Marc Tippmann Munich

Nanostructures



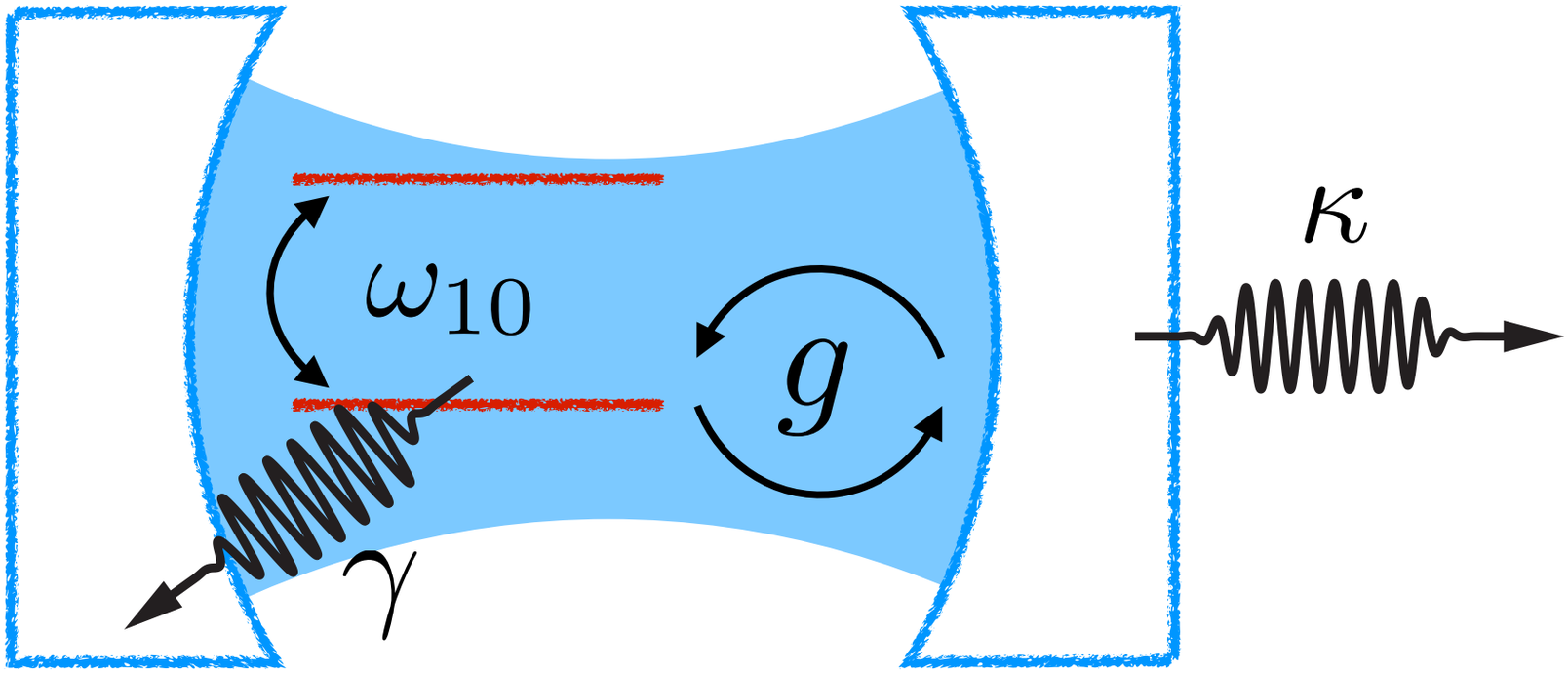
Credit: Luis Dias - Ohio University

Cold atoms



Knap et al., Phys. Rev. X (2012)

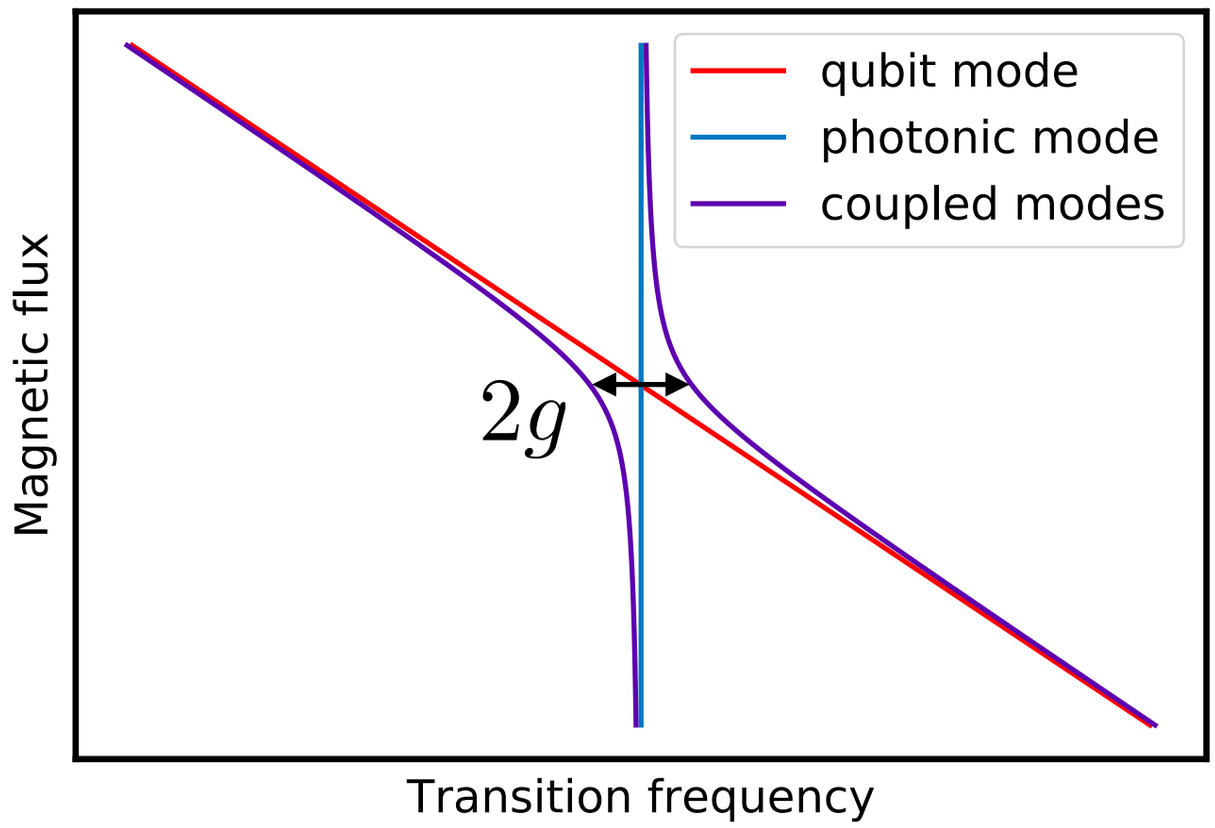
Bosonic bath: back to basics



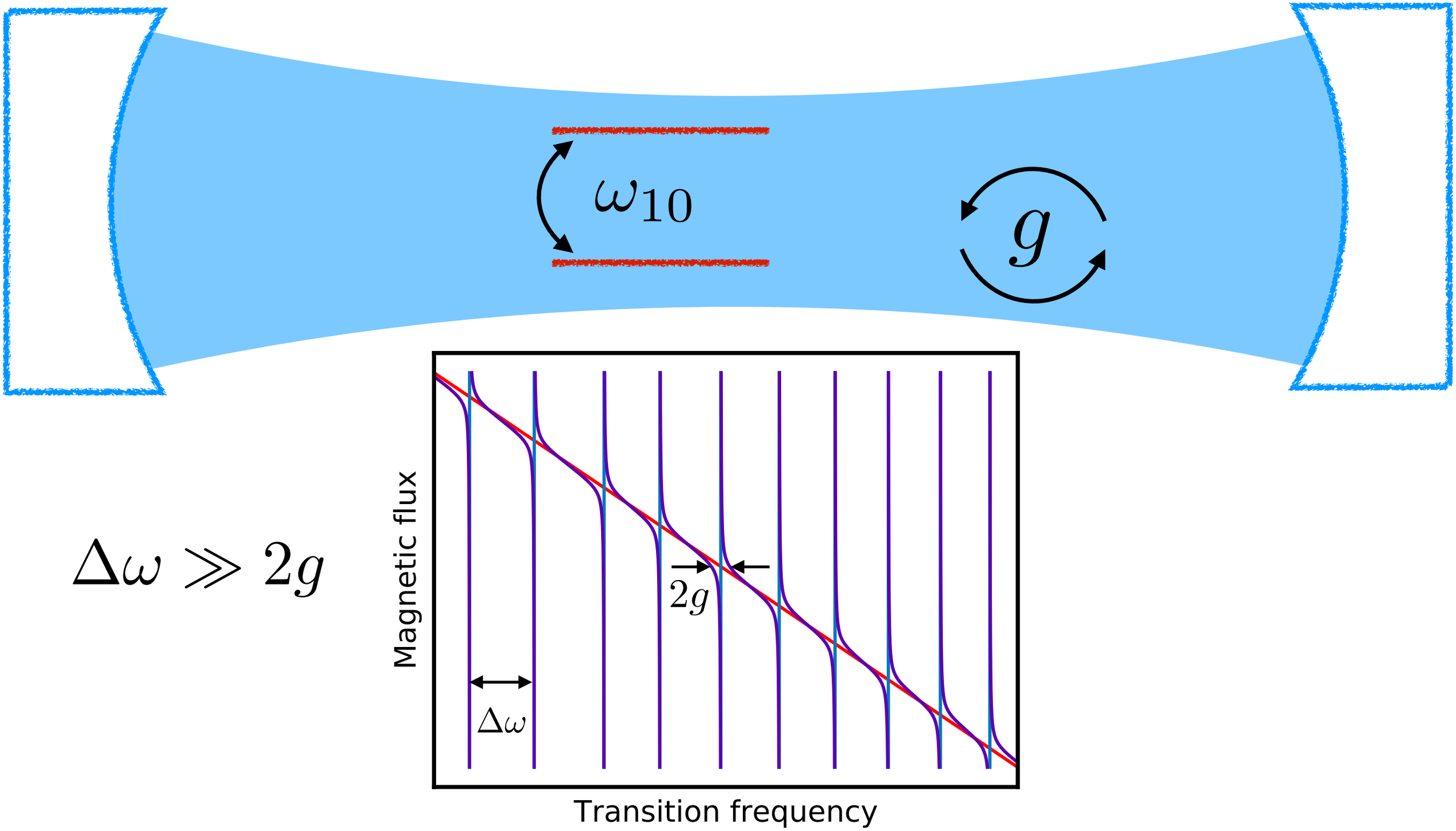
Two-level system
+ 1 bosonic mode

Strong coupling:

$$g \gg \kappa, \gamma$$



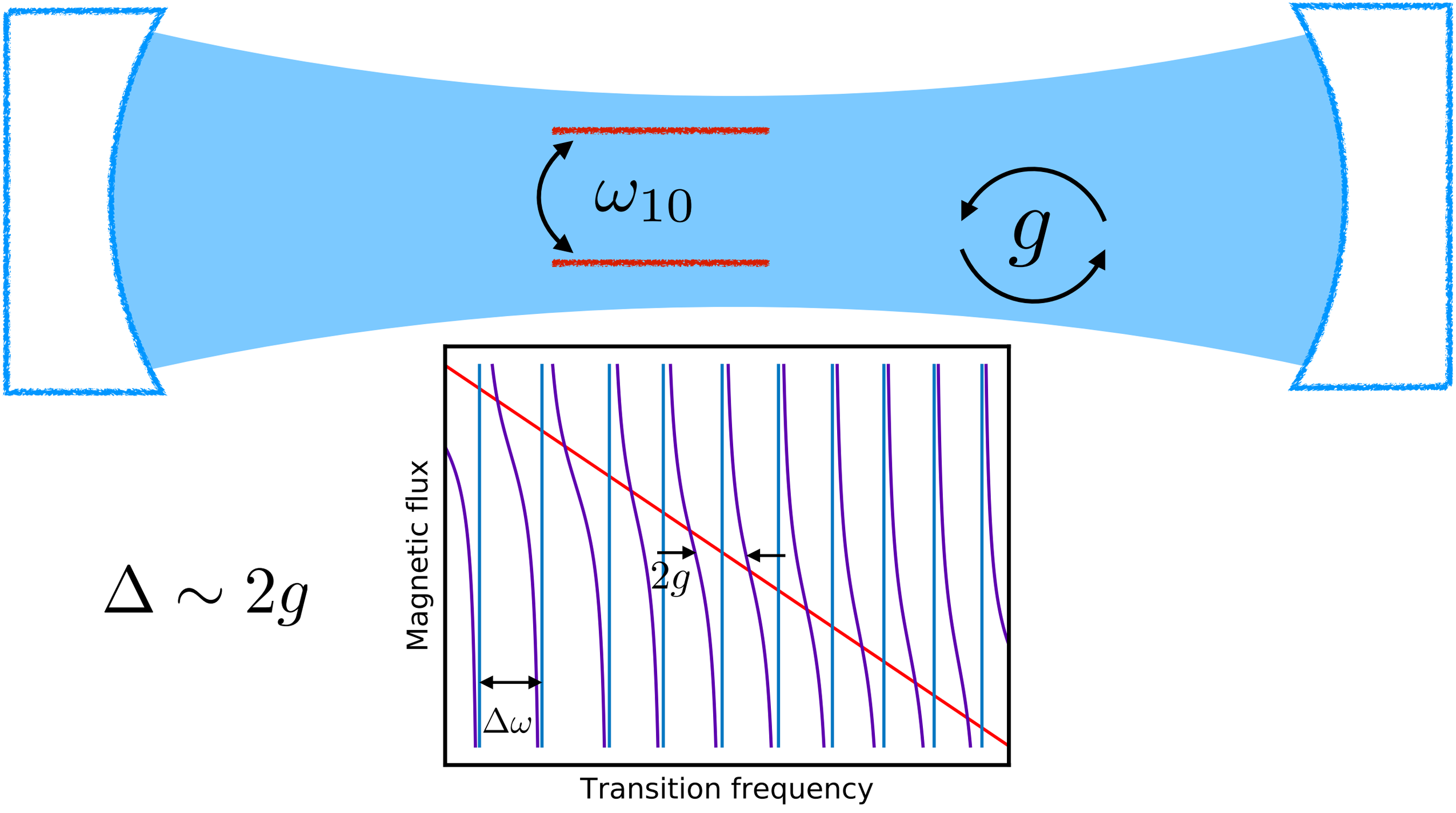
Bosonic bath: back to basics



$$\Delta\omega \gg 2g$$

Two-level system + 1 bosonic mode at once

Bosonic bath: back to basics



$$\Delta \sim 2g$$

Two-level system + N bosonic modes

(Spin-Boson model in the strong dissipative regime)

Outline

Q-impurities in circuit-QED: the recipe

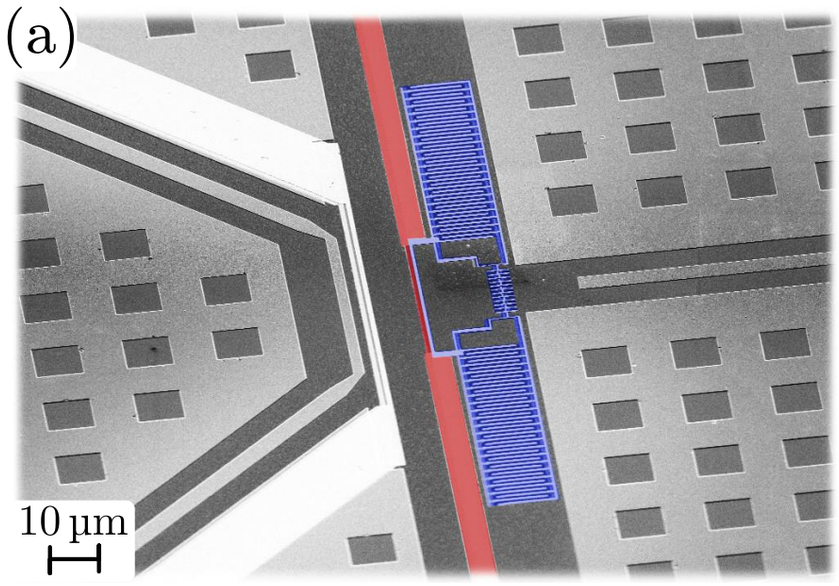
A low loss, high impedance meta-material

A Transmon qubit ultra-strongly coupled to a quantum meta-material

Circuit-QED:

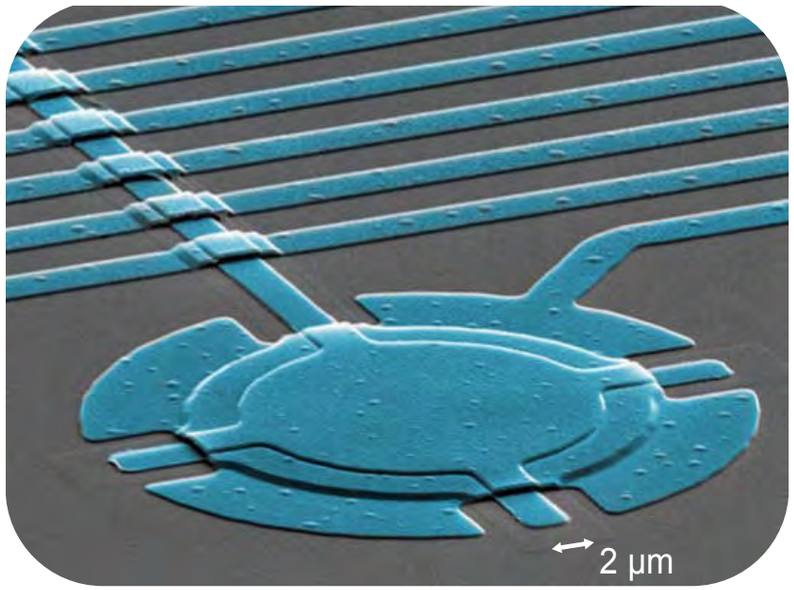
Superconducting circuits and microwave photons

Quantum bits



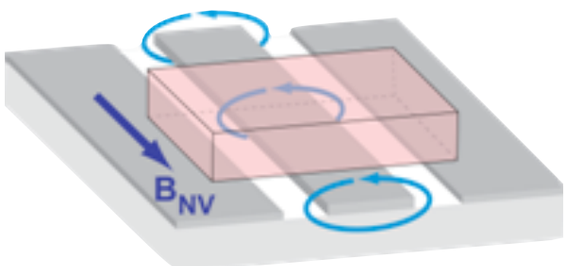
Dumur ‘15

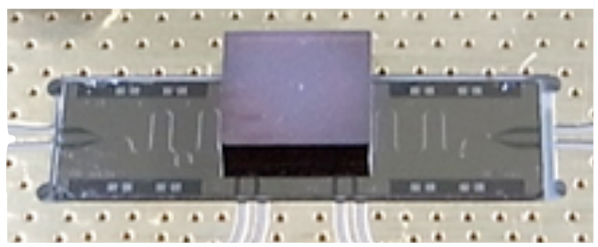
NEMS



Teufel ‘11

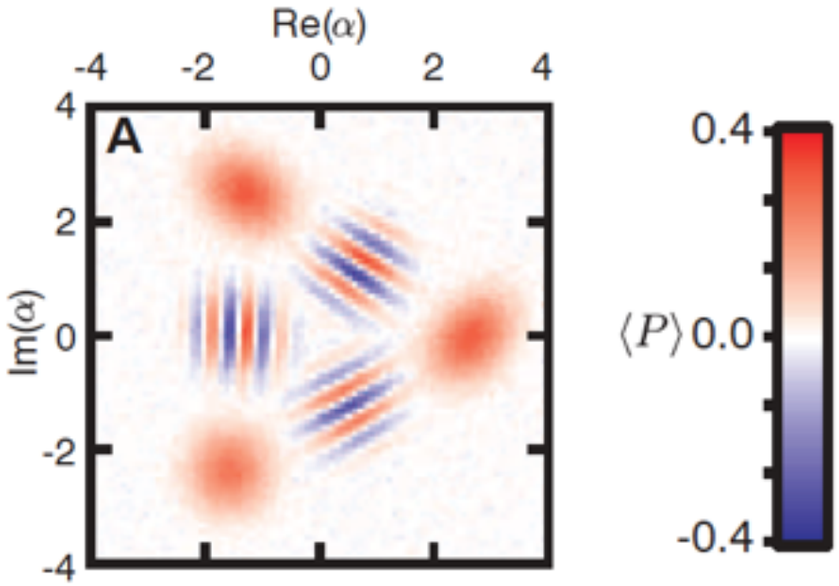
Hybrid systems





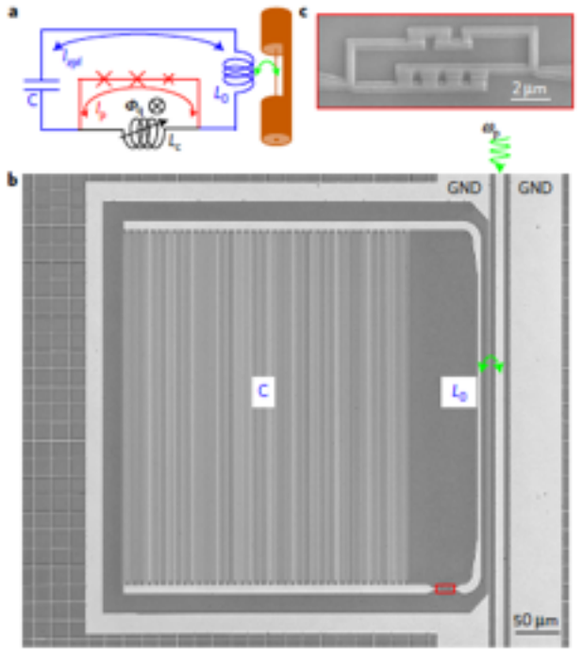
Kubo ‘11

Quantum optics



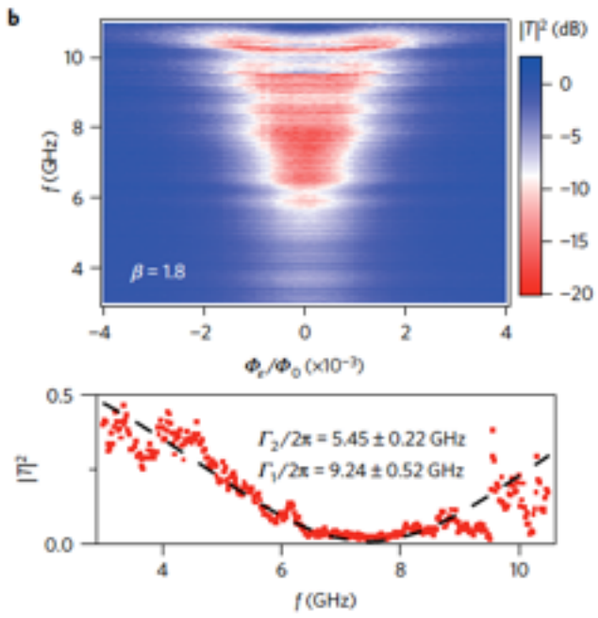
Vlastakis ‘13

Circuit-QED: coupling to many modes



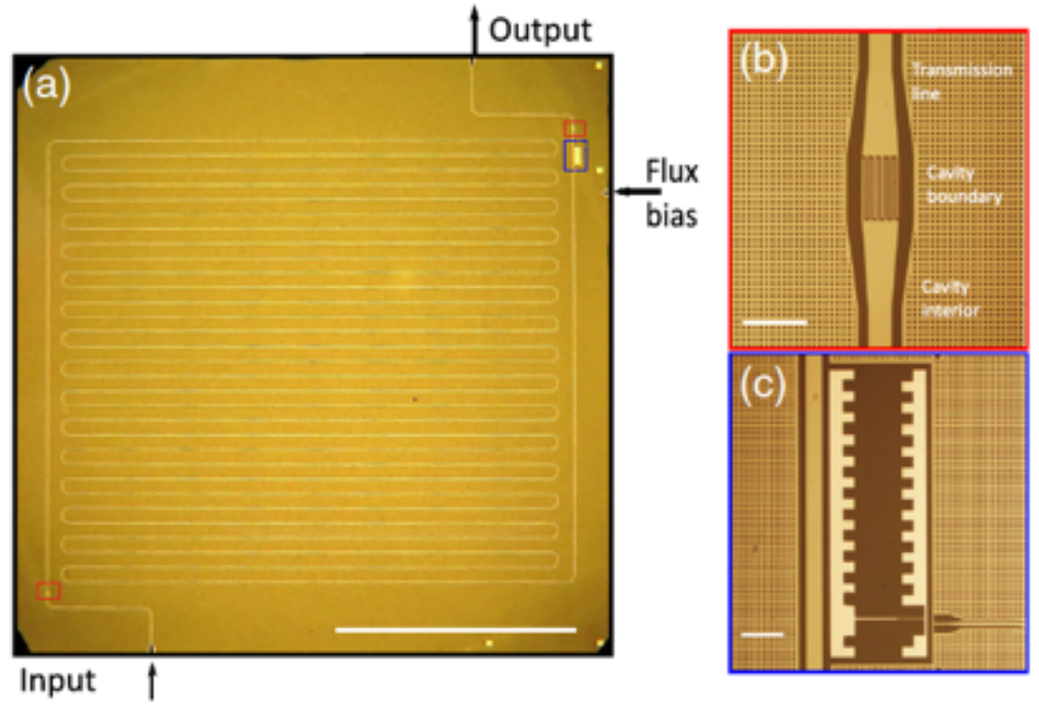
Yoshihara, F., et al. Nat. Phys. (2016)

$$g/\omega_{01} \sim 1$$



Forn-Diaz, P., et al. Nat. Phys. (2016)

$$\Gamma/\omega_{01} \sim 1$$



Sundaresan, N. M., et al. Phys. Rev. X (2015)

$$\Gamma/\omega_{01} \sim 1\%$$

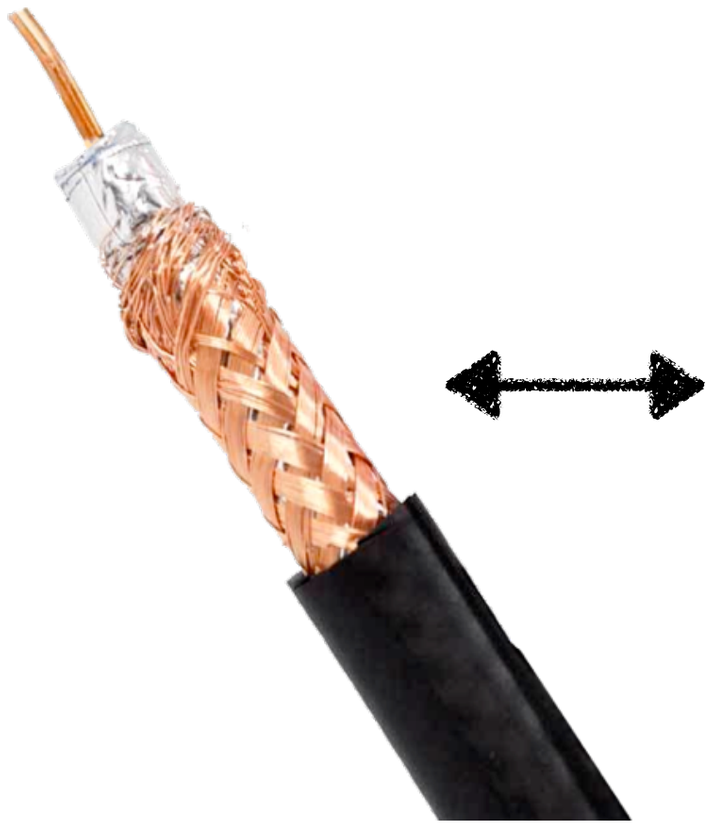
Mesoscopic bath

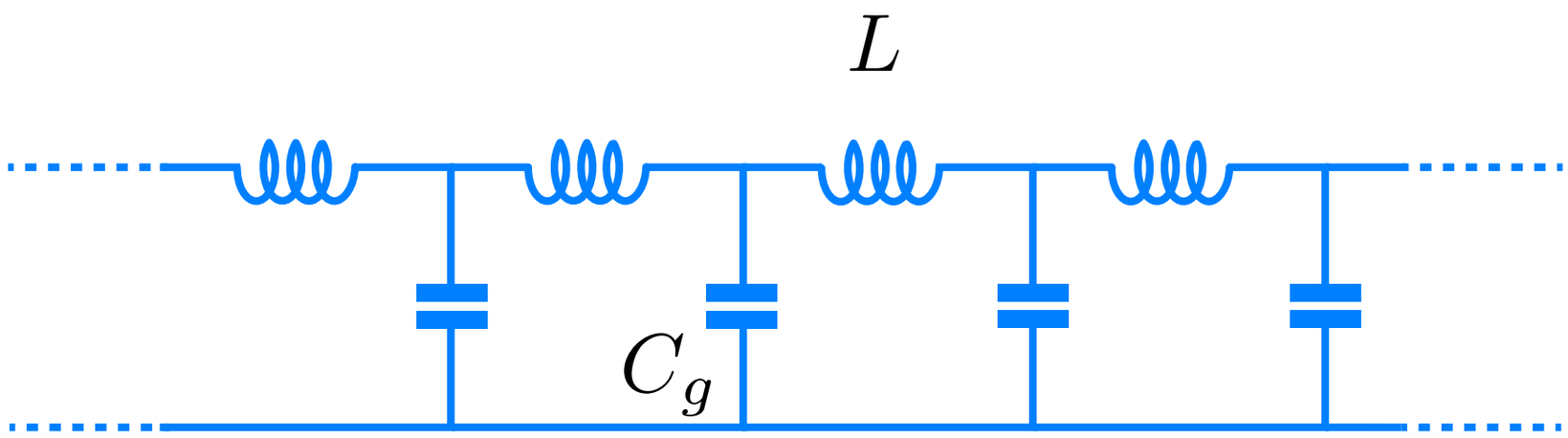
+

Ultrastrong coupling

What about the many modes (large N)?

What about the many modes (large N)?

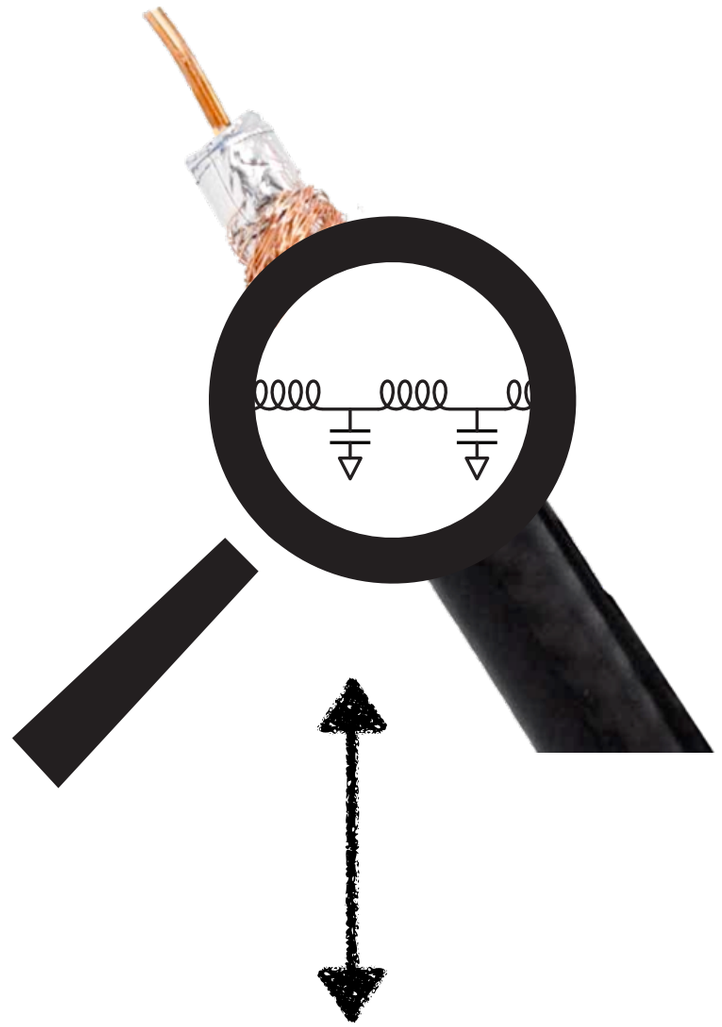




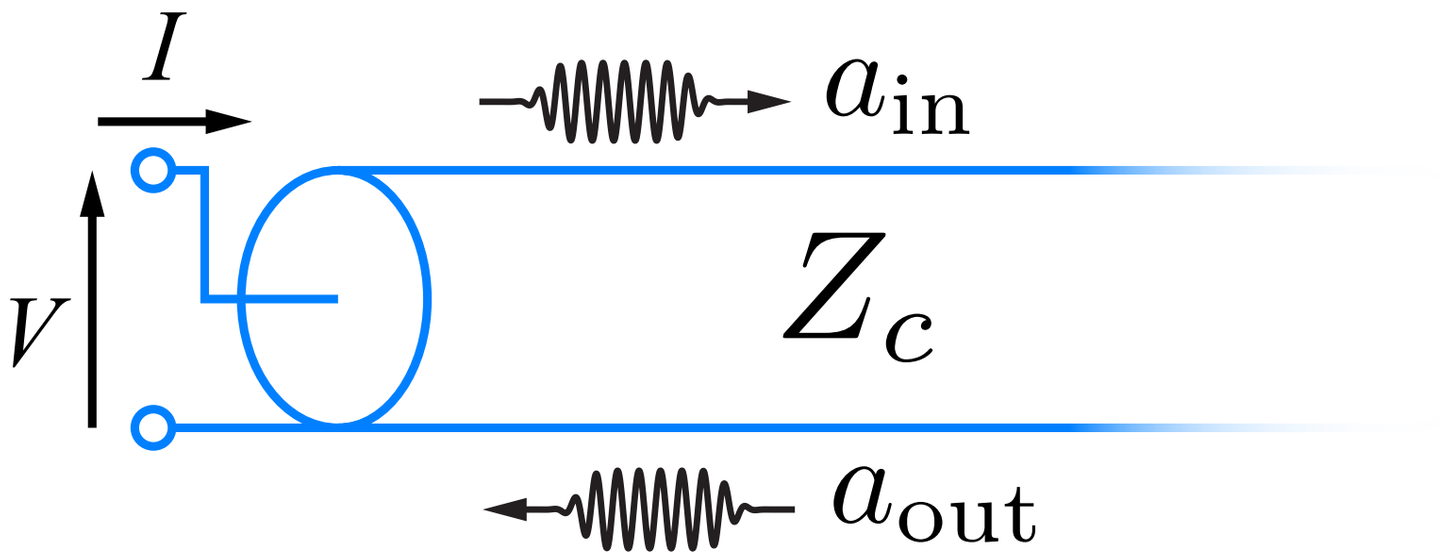
Infinite number of LC oscillators

A. Caldeira and A. J. Leggett ‘81

What about the many modes (large N)?



Monitoring the bath

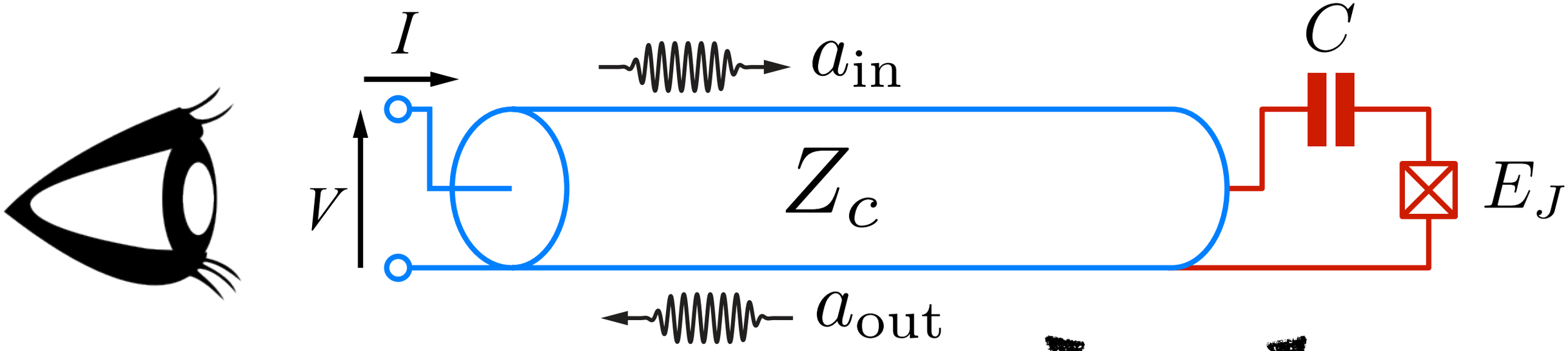


Coupling: a simple example

"Bath" or Environment

Superconducting qubit

ω_{q}



$\Gamma = 1/T_1$

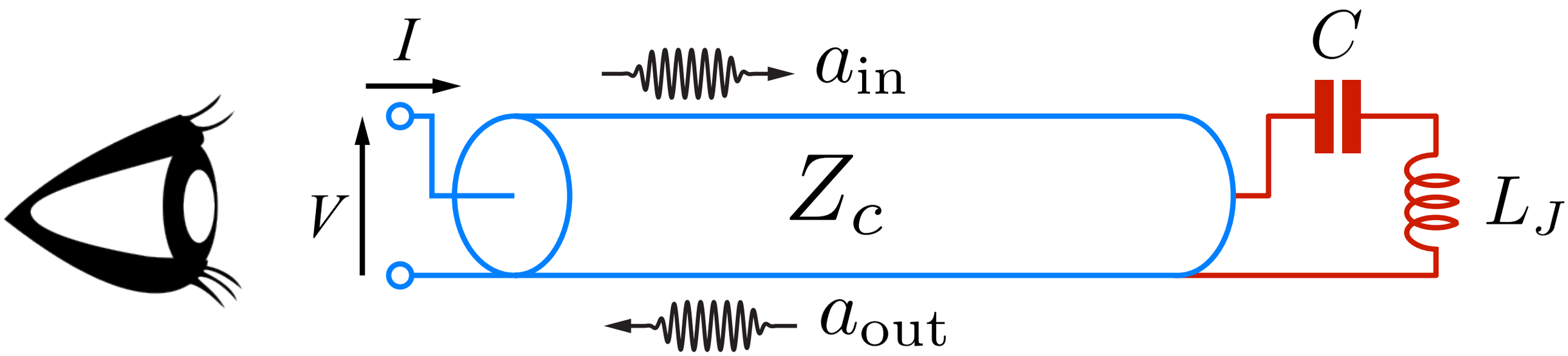
coupling strength
or inverse lifetime

Coupling: a simple example

"Bath" or Environment

Superconducting qubit

ω_{q}



Classical treatment

$$\omega_{\mathrm{q}} = \frac{1}{\sqrt{L_{\mathrm{J}} C}}$$

$$\Gamma = \frac{Z_c}{2L_J}$$

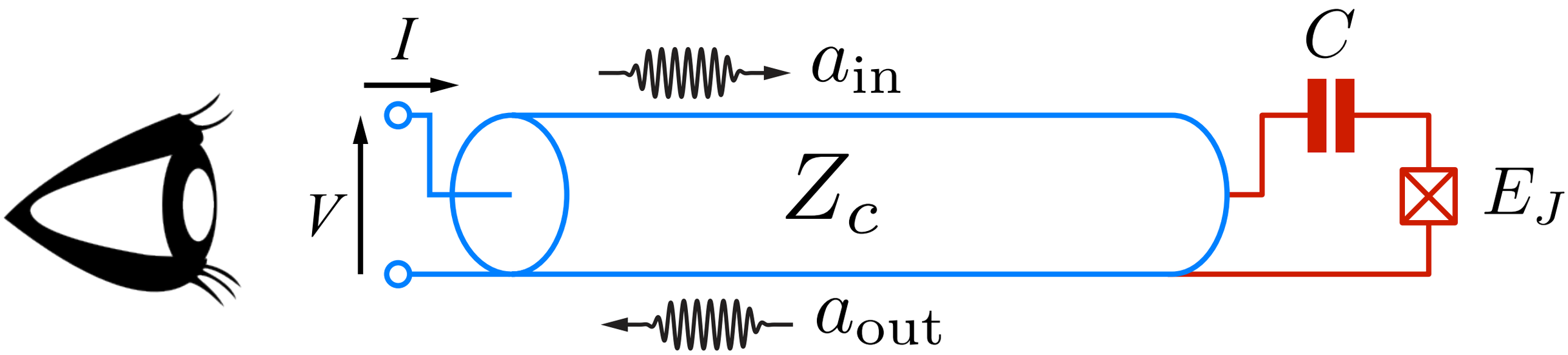
$$\frac{\Gamma}{\omega_{\mathrm{q}}} = \frac{Z_c}{2}\sqrt{\frac{C}{L_{\mathrm{J}}}}$$

Coupling: a simple example

"Bath" or Environment

Superconducting qubit

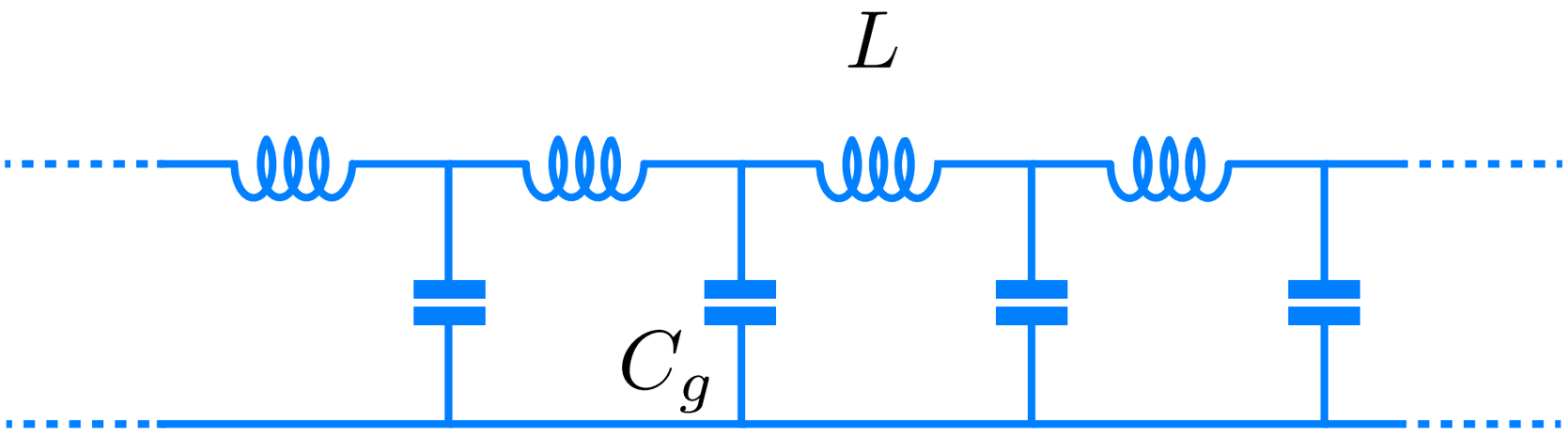
ω_{q}



Quantum treatment: $\dfrac{\Gamma}{\omega_{\mathrm{q}}} \sim \alpha$ ← fine structure constant

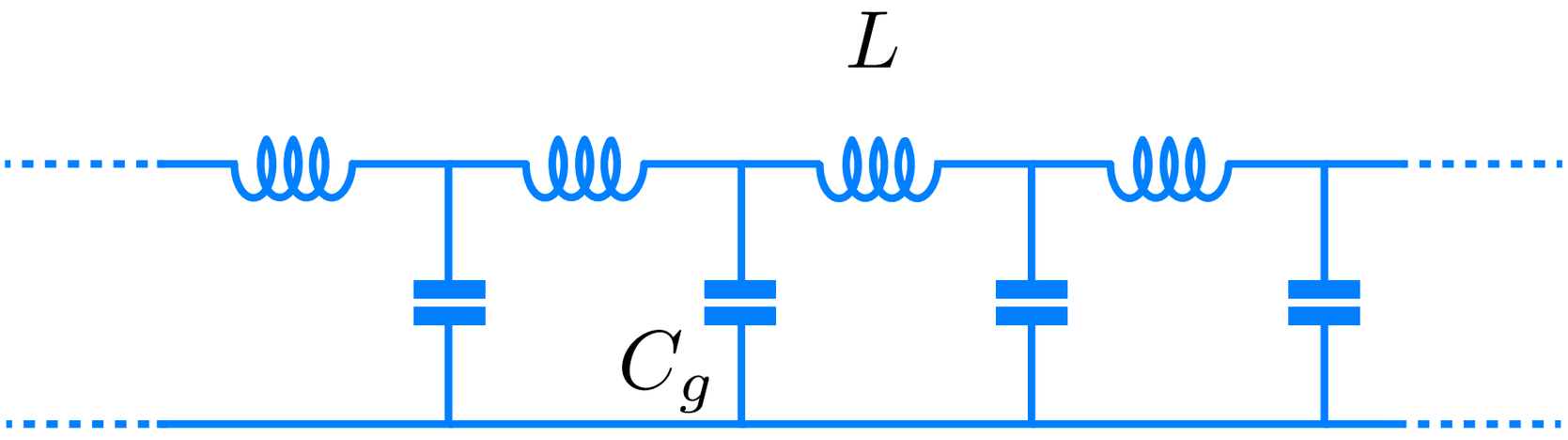
$$\alpha_{atoms} \sim \frac{1}{137} \qquad \alpha_{circuit} \sim \frac{Z_c}{R_Q} \text{ with } R_Q = \frac{h}{(2e)^2} \simeq 6.5k\Omega$$

Reaching high impedances
Josephson junction meta-material

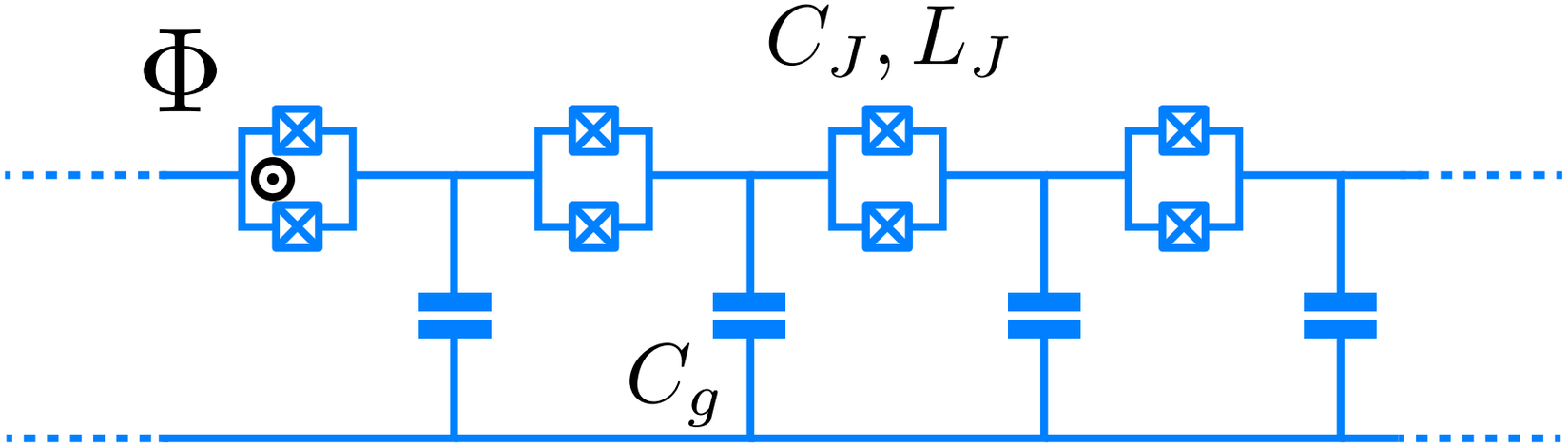


$$Z_c = \sqrt{L/C_g}$$

Reaching high impedances
Josephson junction meta-material



$$Z_c = \sqrt{L/C_g}$$



$$Z_c = \sqrt{L_J(\Phi)/C_g}$$

Seminal work:

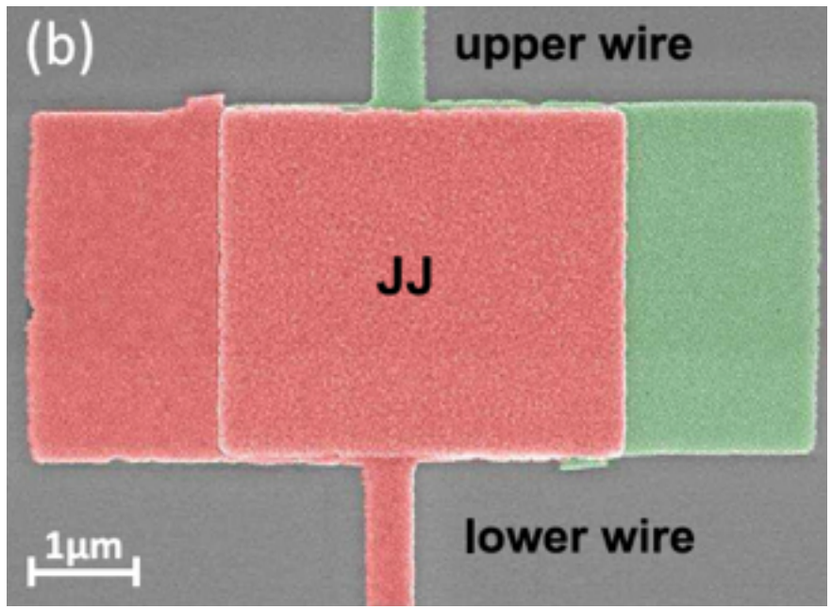
S. Corlevi et al 06’ (Haviland’s group)

See also:

N. Masluk et al 12’, Bell et al 12’, S. Butz et al. 13’, C. Altimiras et al. 13’

Reaching high impedances
Josephson junction meta-material

Low loss: superconducting state



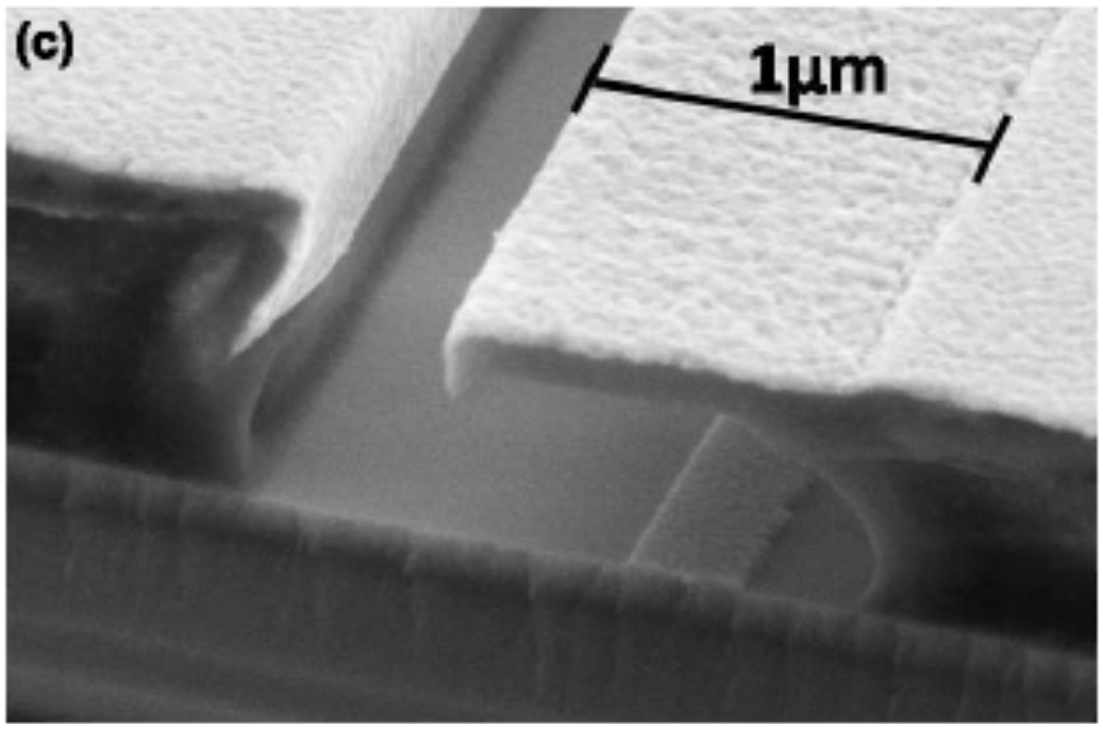
Josephson (kinetic) inductance
can be very large:

$$L_J \sim 10^4 L$$

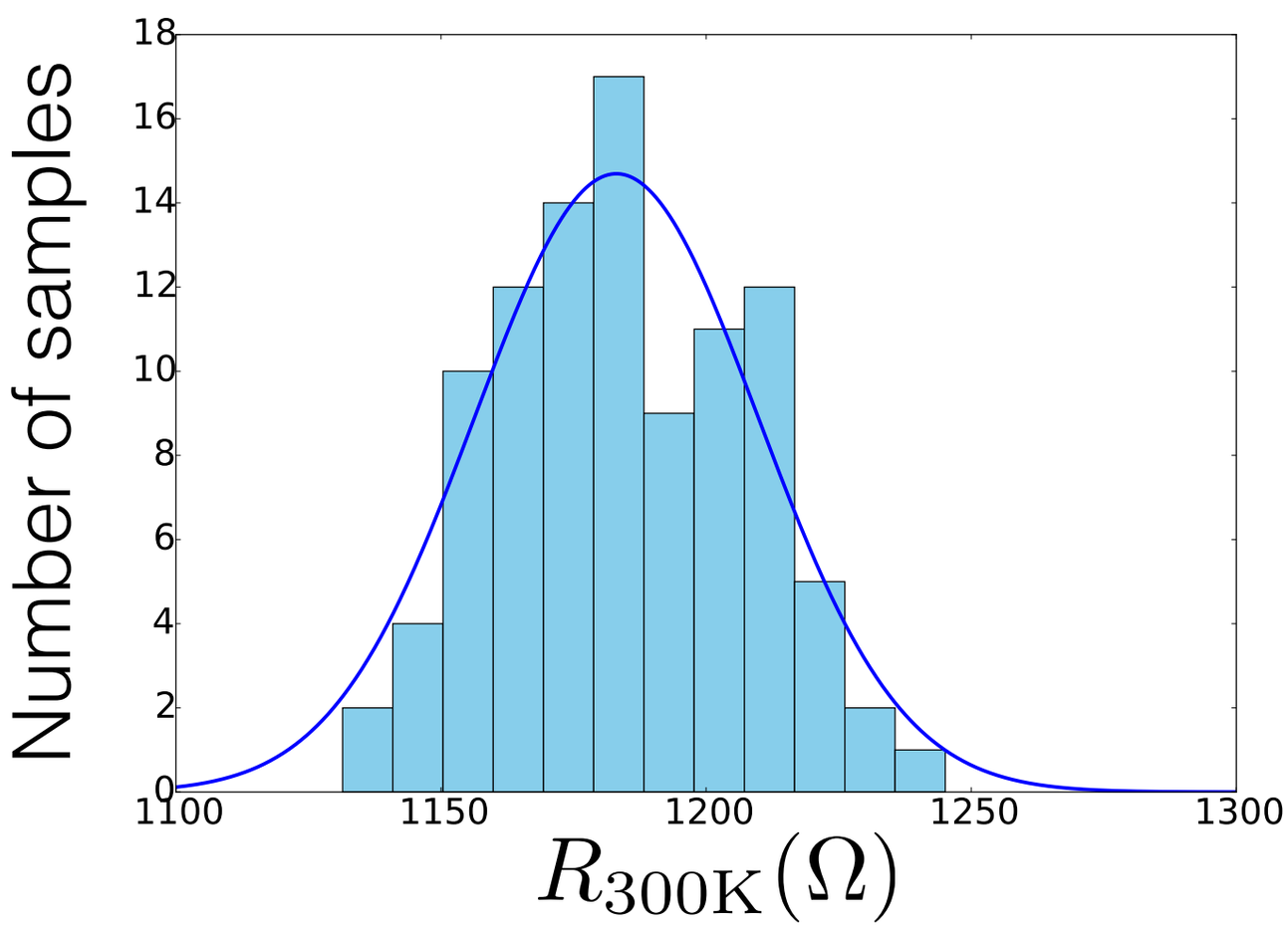
Josephson (kinetic) inductance
is tunable in-situ

Josephson junction = “superinductor”

JJ meta-material: Bridge Free Fabrication

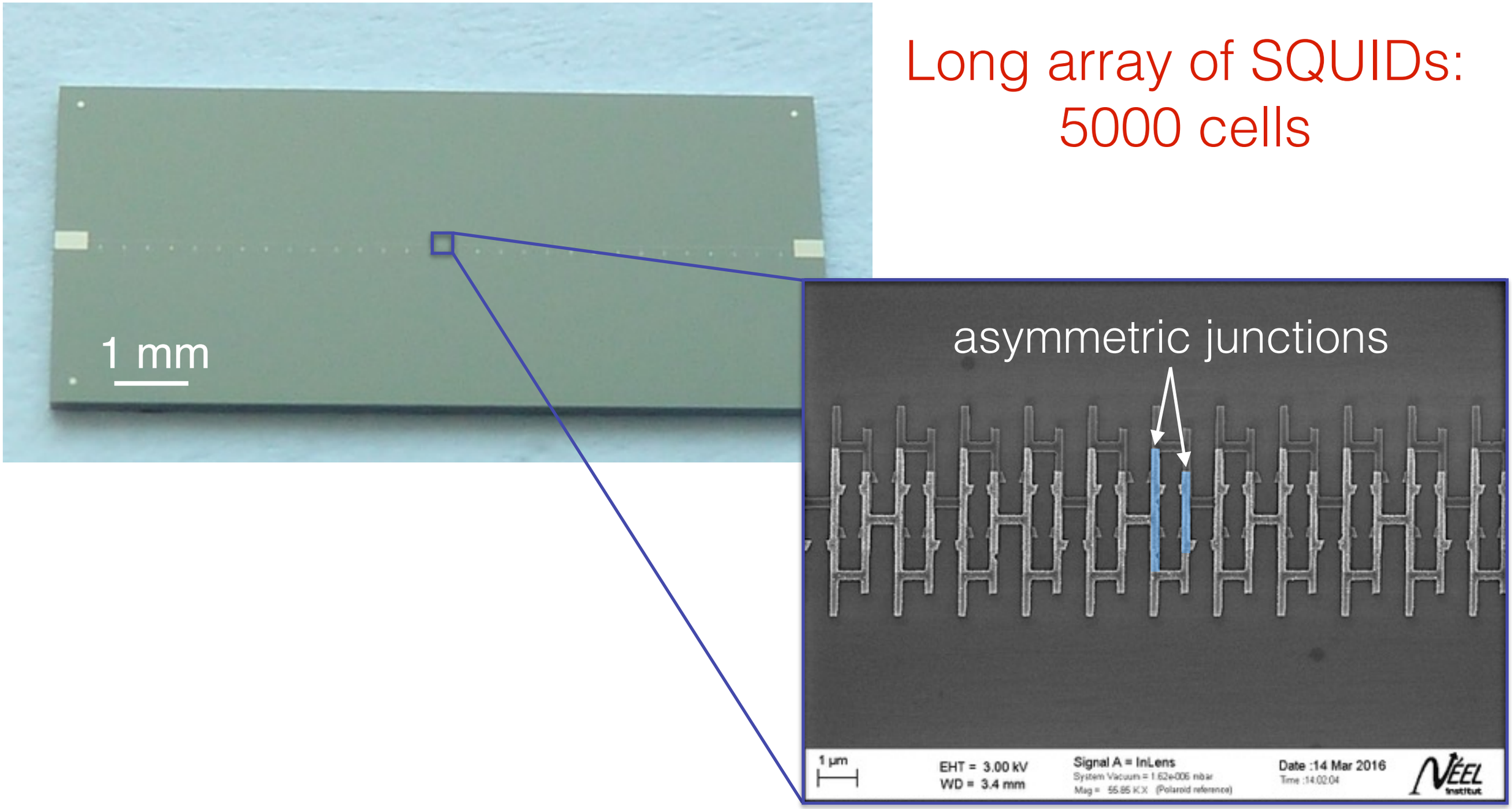


Lecocq et al.
Nanotechnology (2011)



Low disorder
Mean: 1.2 kOhms
Deviation: 22 Ohms

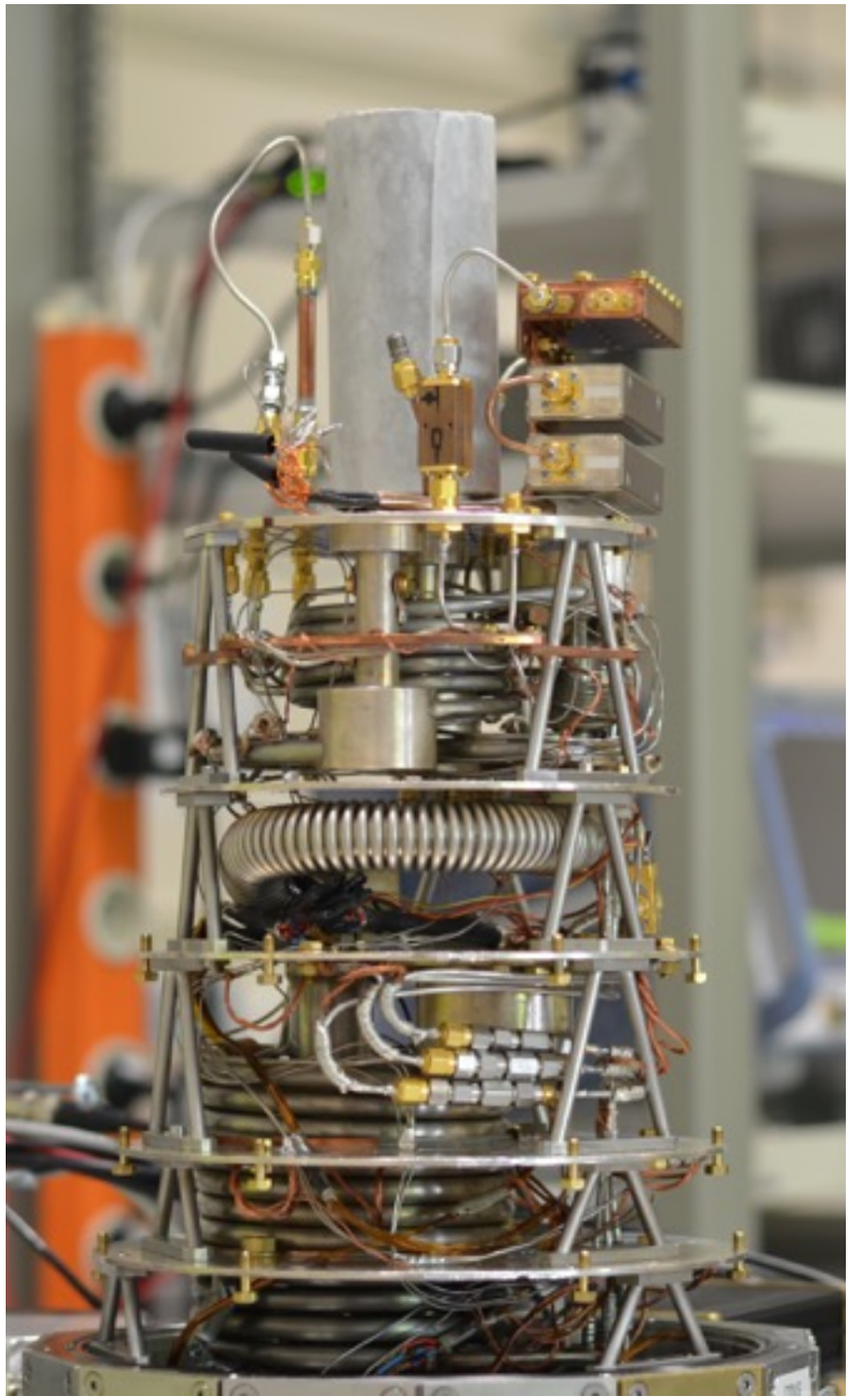
JJ meta-material: Bridge Free Fabrication

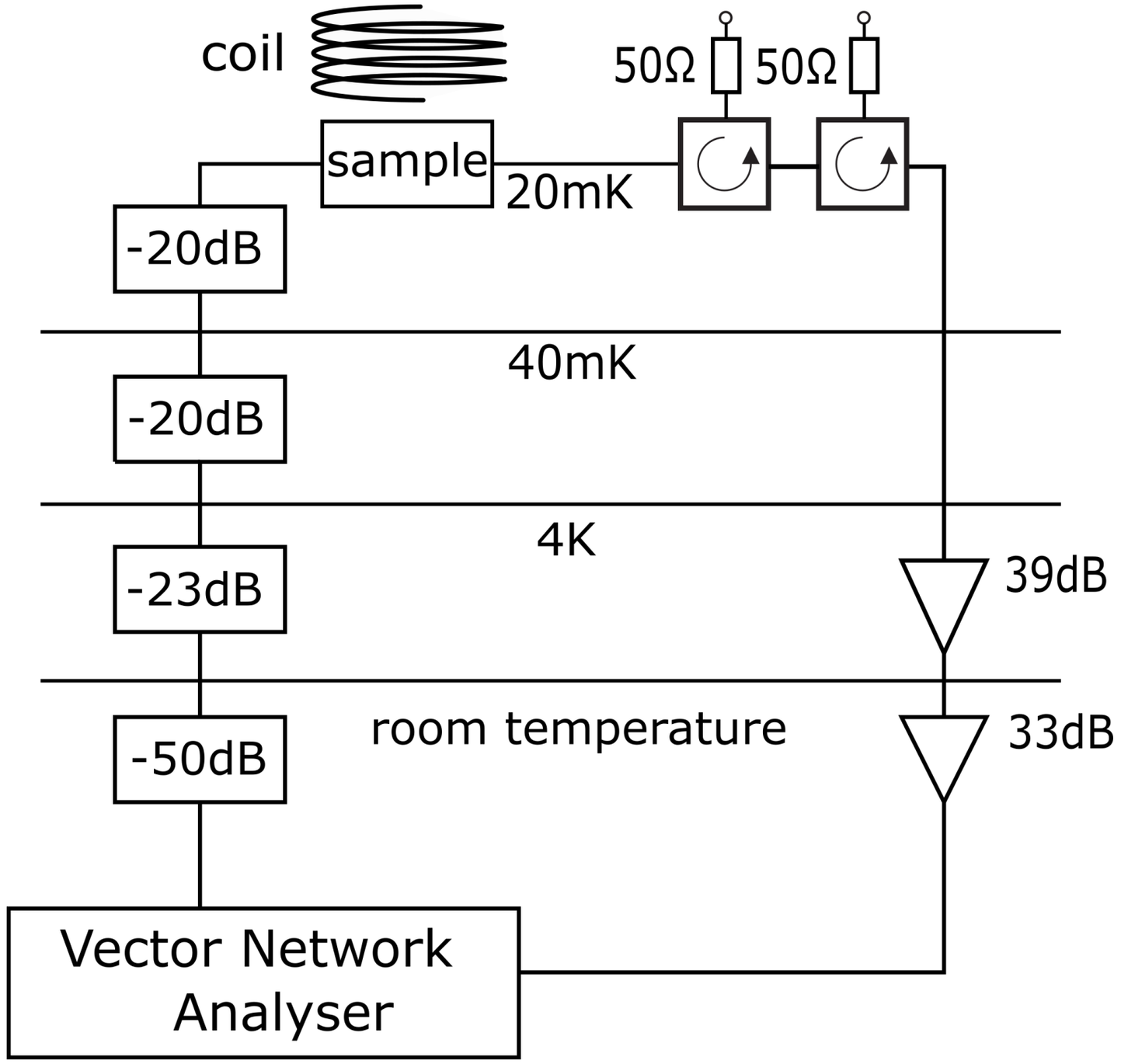


Long array of SQUIDs:
5000 cells

Challenges faced: stitching errors, resist homogeneity, focus homogeneity, proximity effect….

JJ meta-material: Measuring

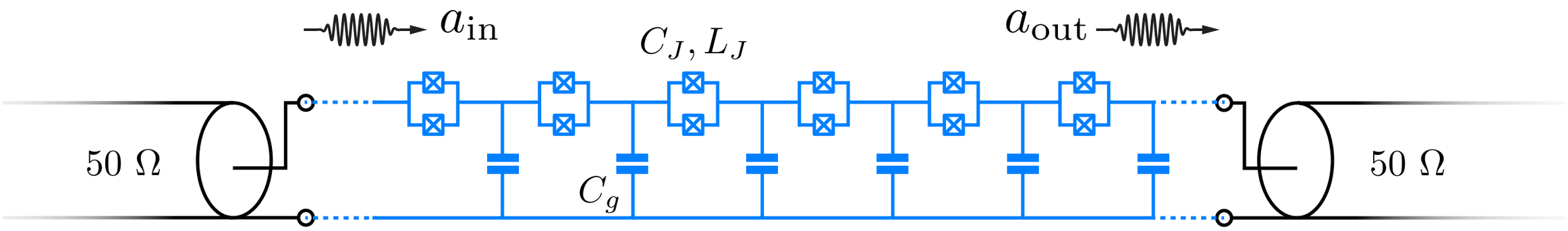


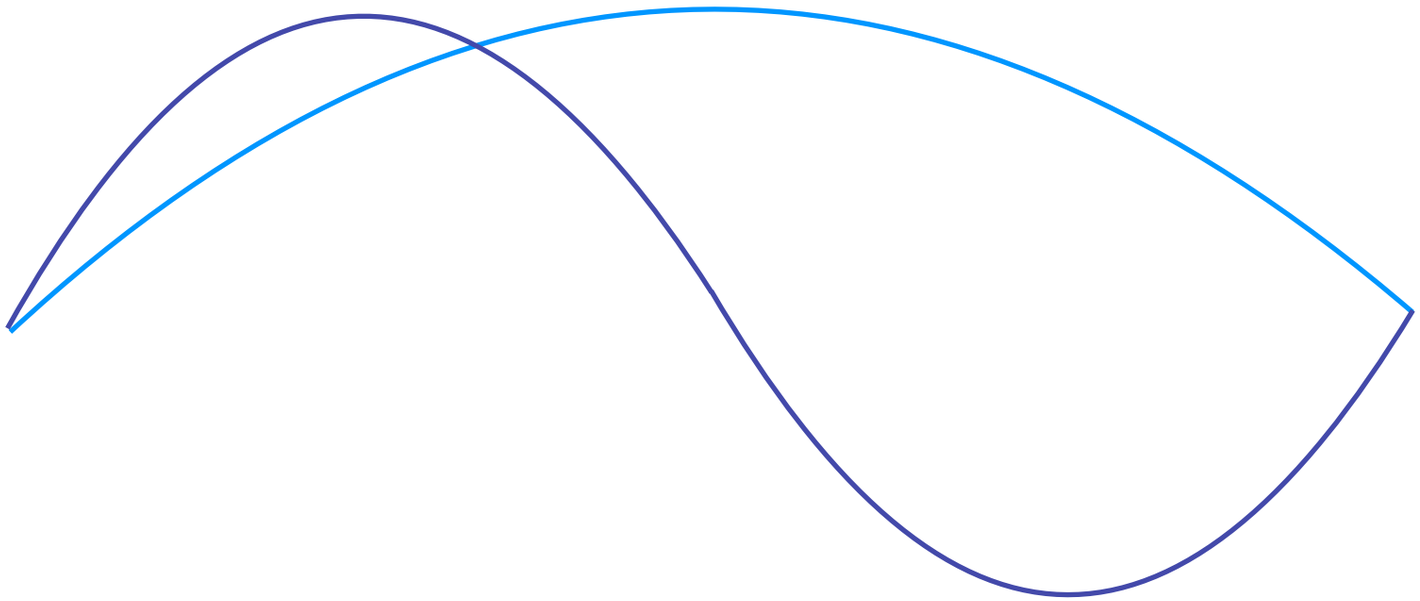


Quantum regime: $\hbar\omega \gg k_{\mathrm{B}}T$

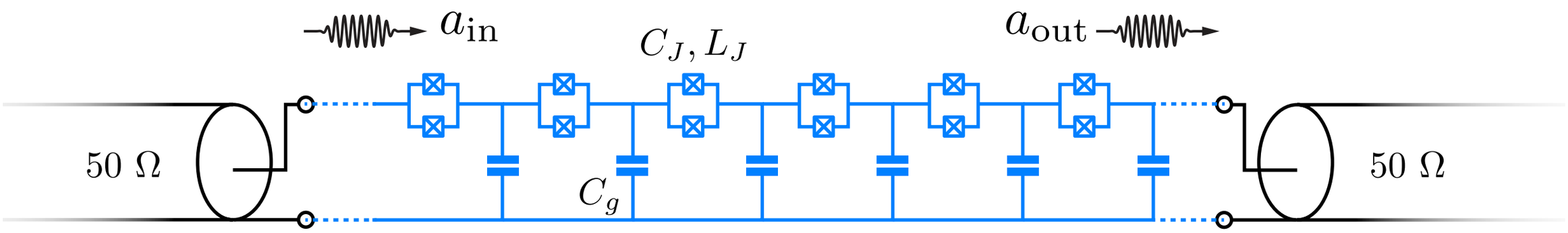
Josephson junction meta-material

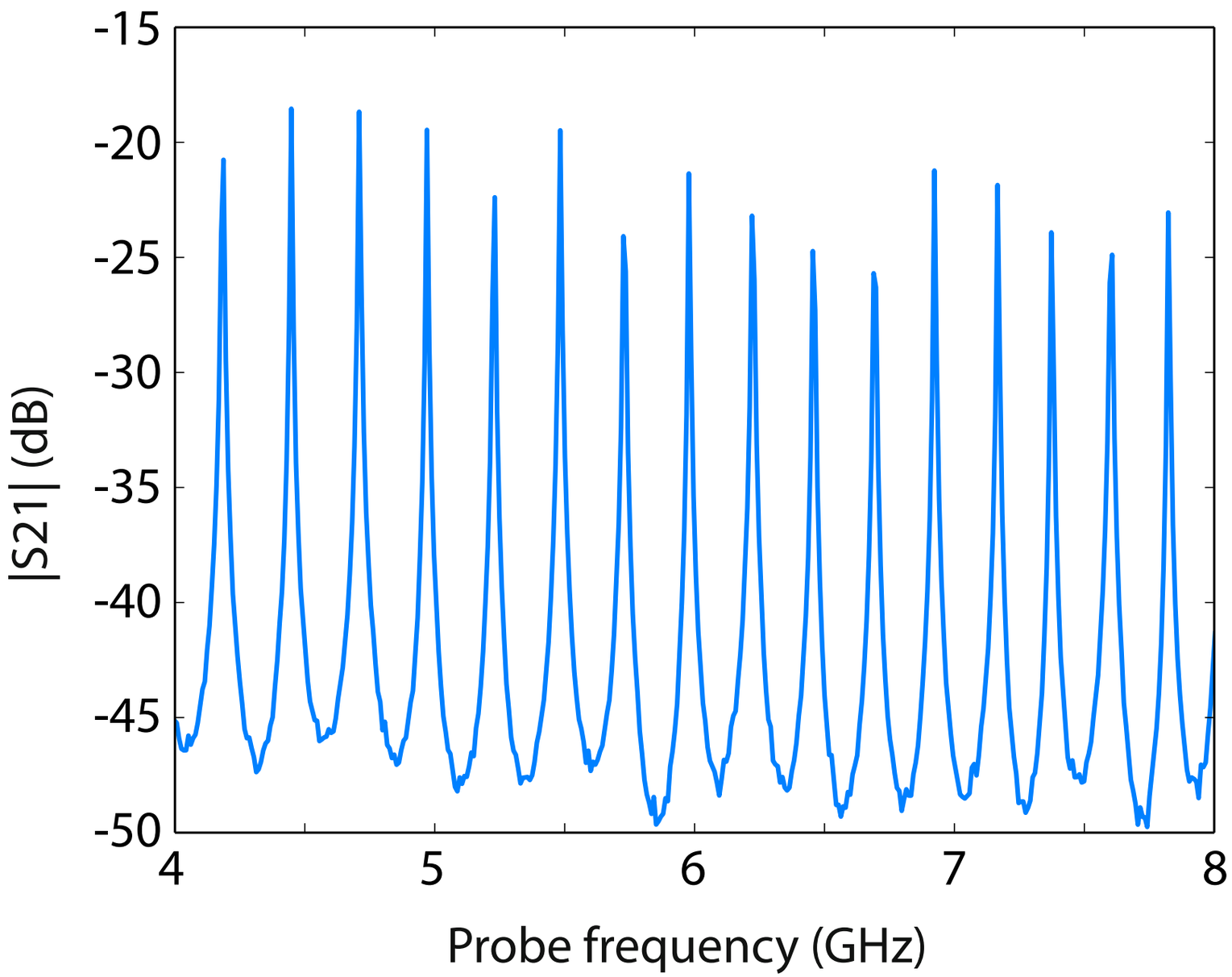
Fabry-Pérot





Josephson junction meta-material



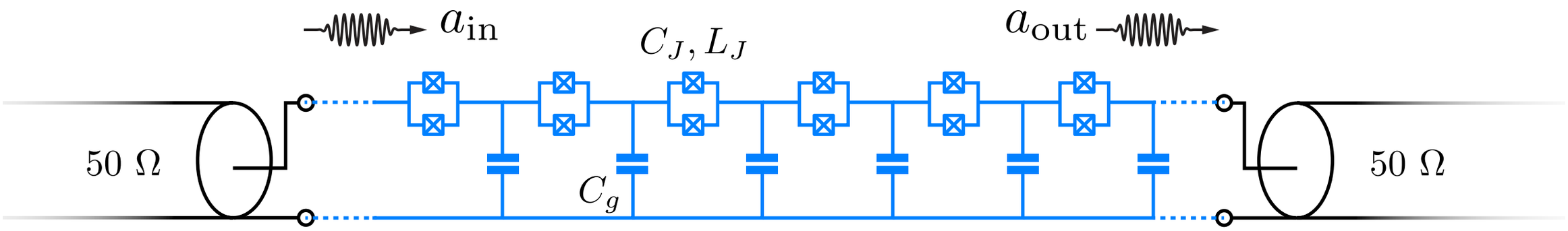


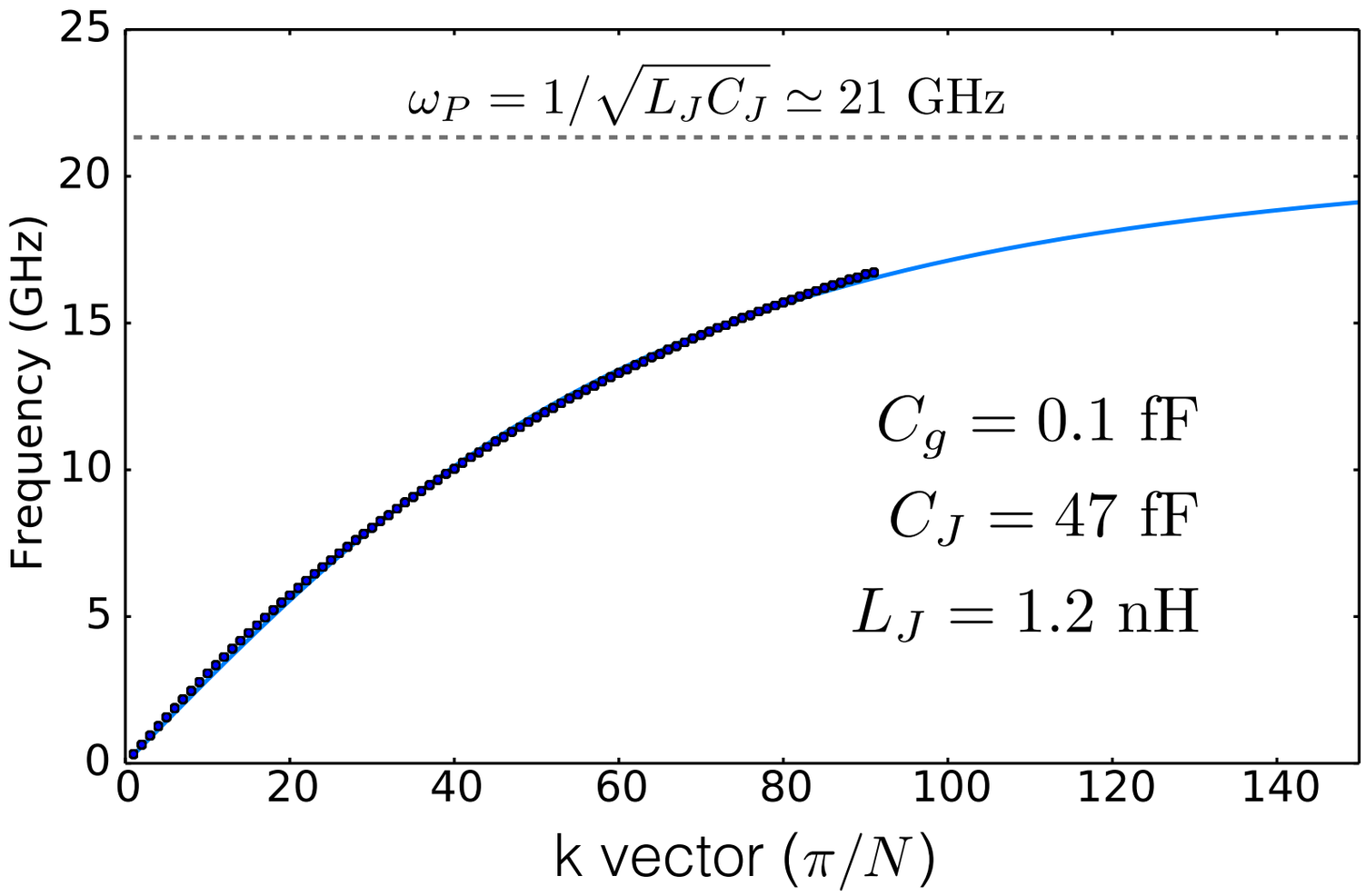
Fabry-Pérot

$Q_{\text{ext}} \sim 10^2$
(Impedance mismatch)

$Q_{\text{int}} \sim 10^4$

Josephson junction meta-material





Krupko et al., in prep

cQED wording:

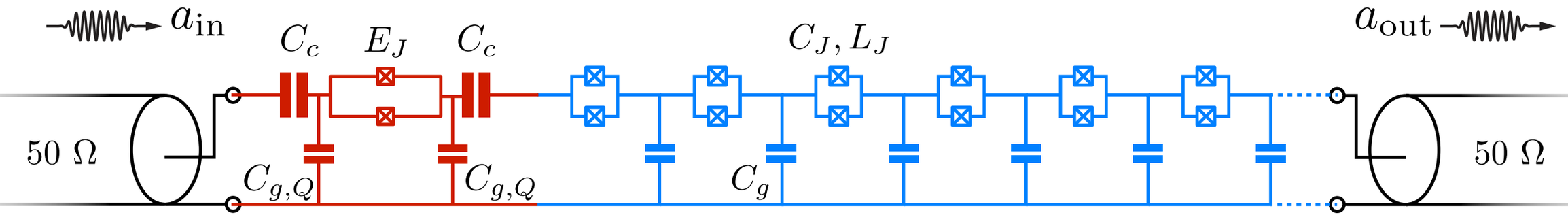
$$Z_c = \sqrt{L_J/C_g} \sim 3.5\ \mathrm{k\Omega}$$

Optics wording:

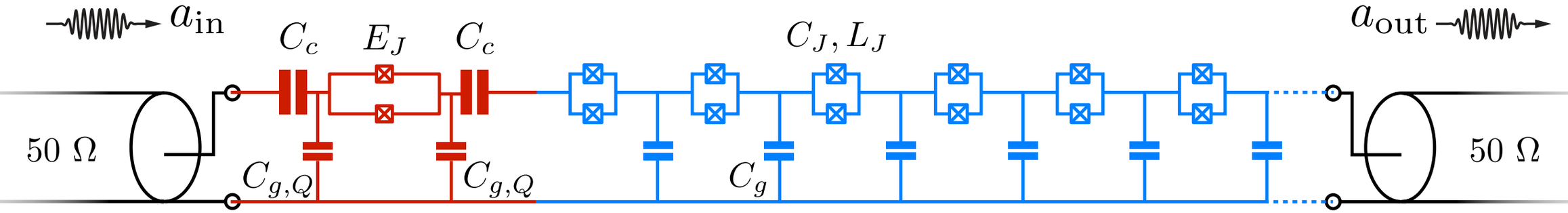
$$n \simeq 50$$

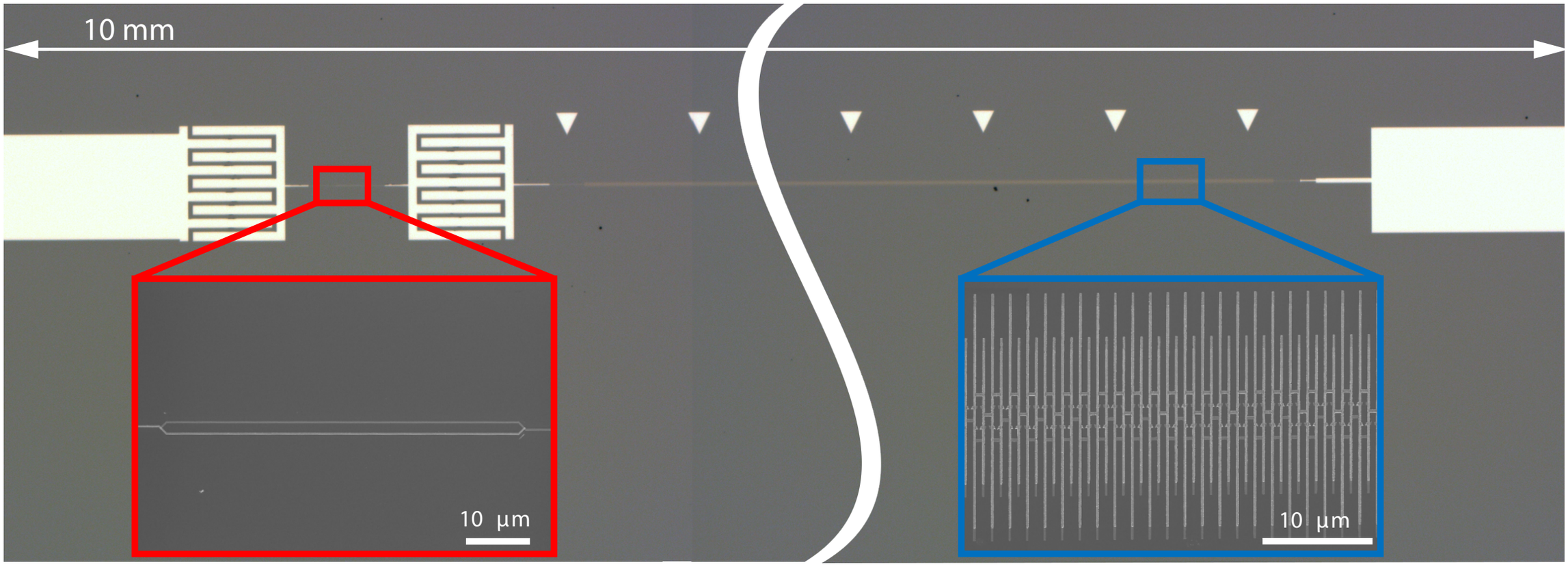
A Transmon coupled to a JJ meta-material

Our artificial atom: transmon qubit



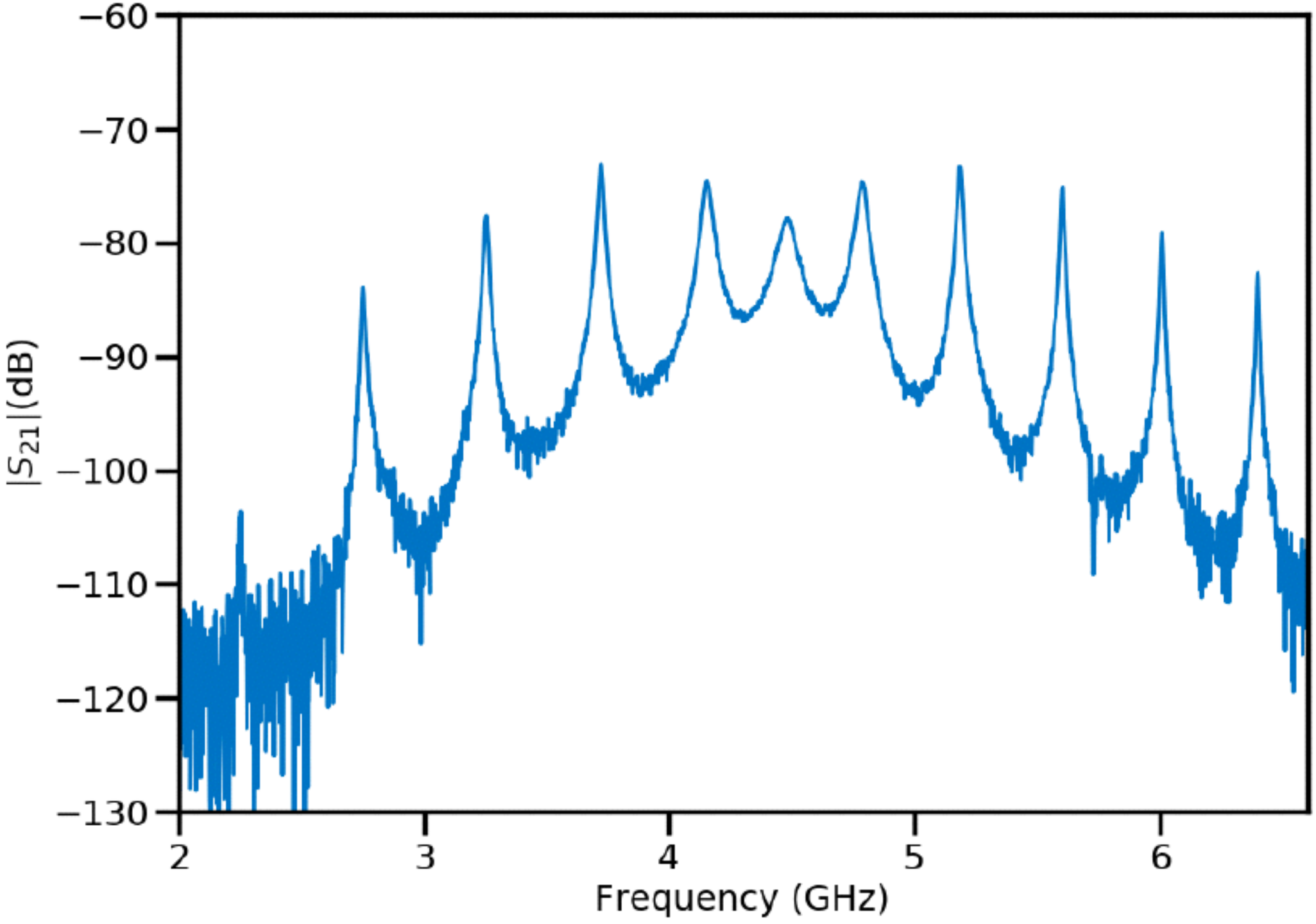
A Transmon coupled to a JJ meta-material



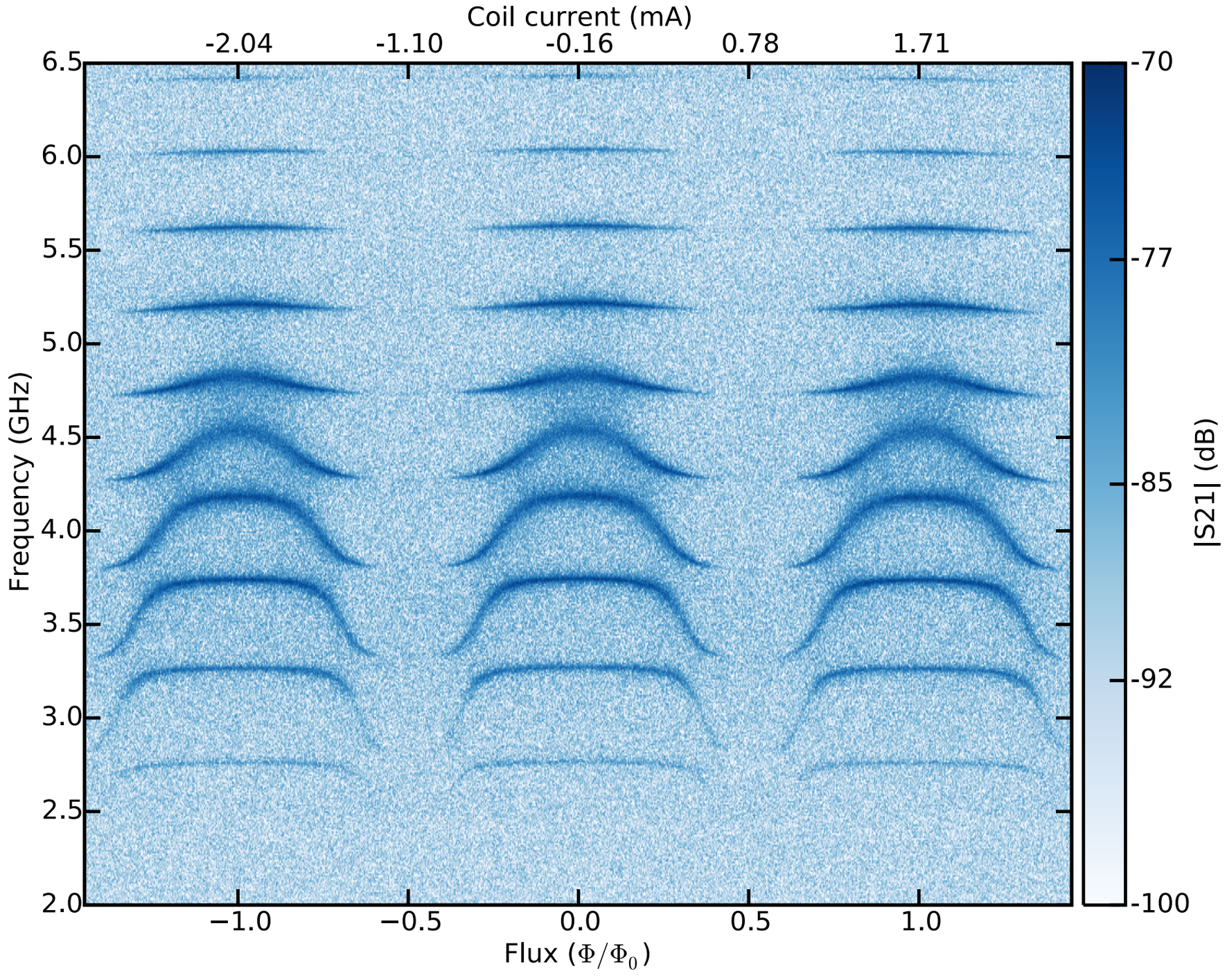


Puertas-Martinez et al., in prep

A Transmon coupled to a JJ meta-material

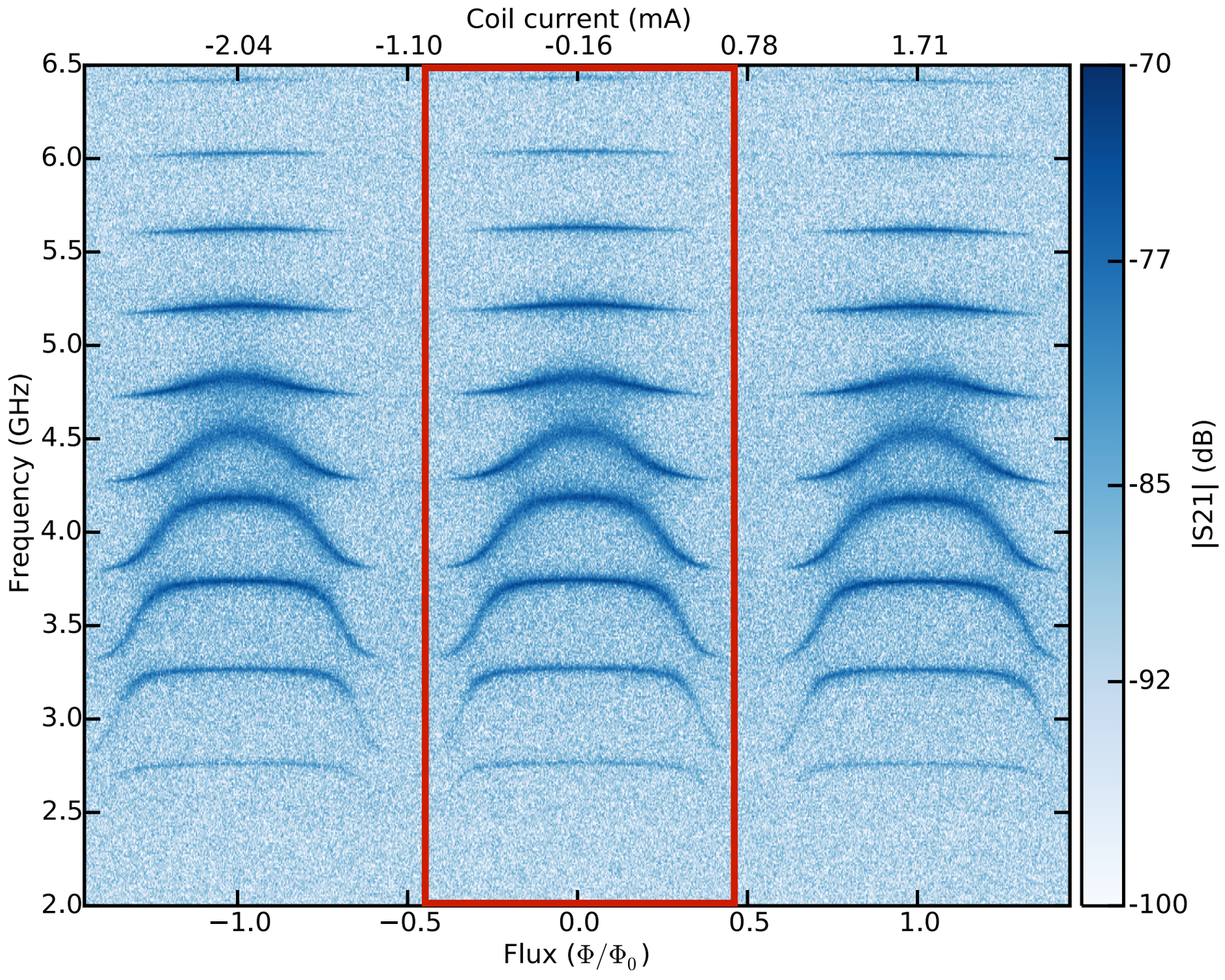


A Transmon coupled to a JJ meta-material



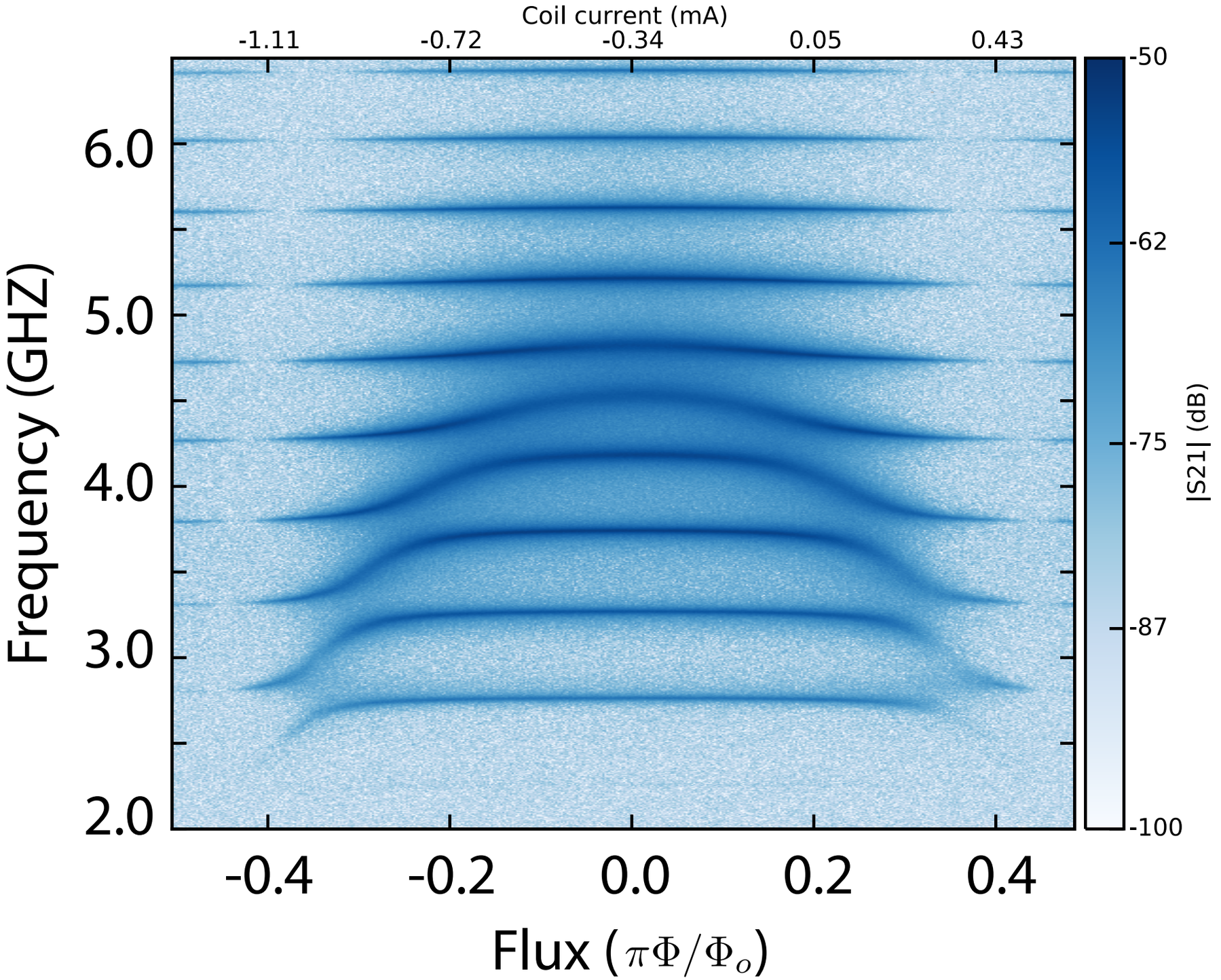
Puertas-Martinez et al., in prep

A Transmon coupled to a JJ meta-material



Puertas-Martinez et al., in prep

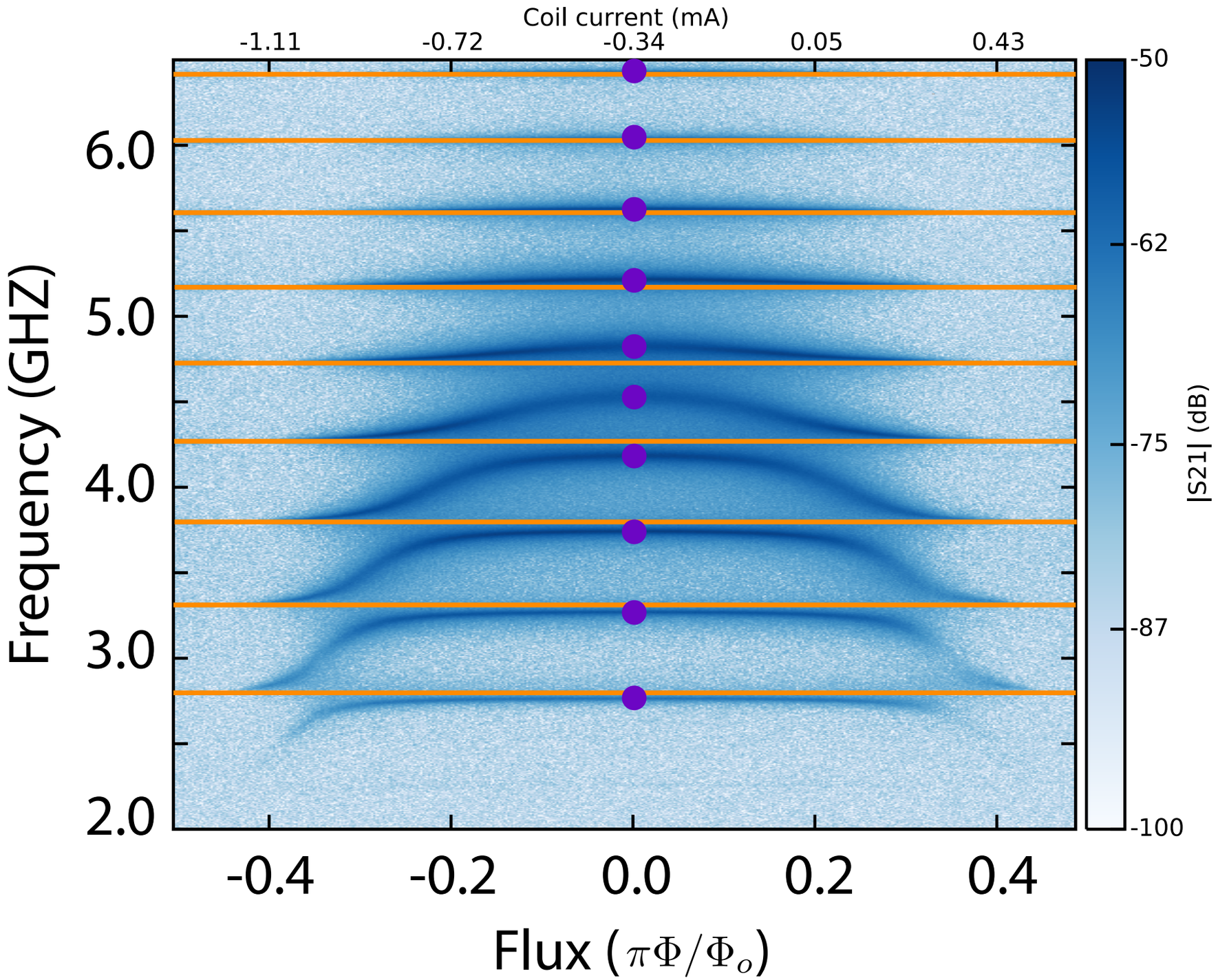
A Transmon coupled to a JJ meta-material



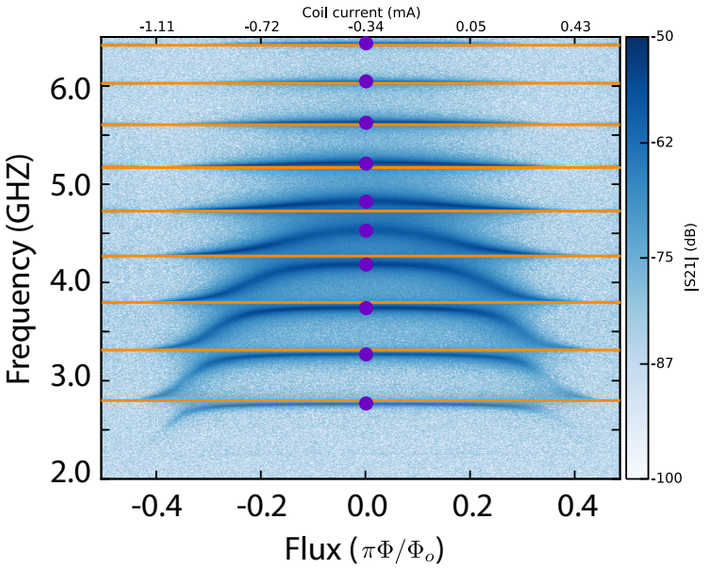
Puertas-Martinez et al., in prep

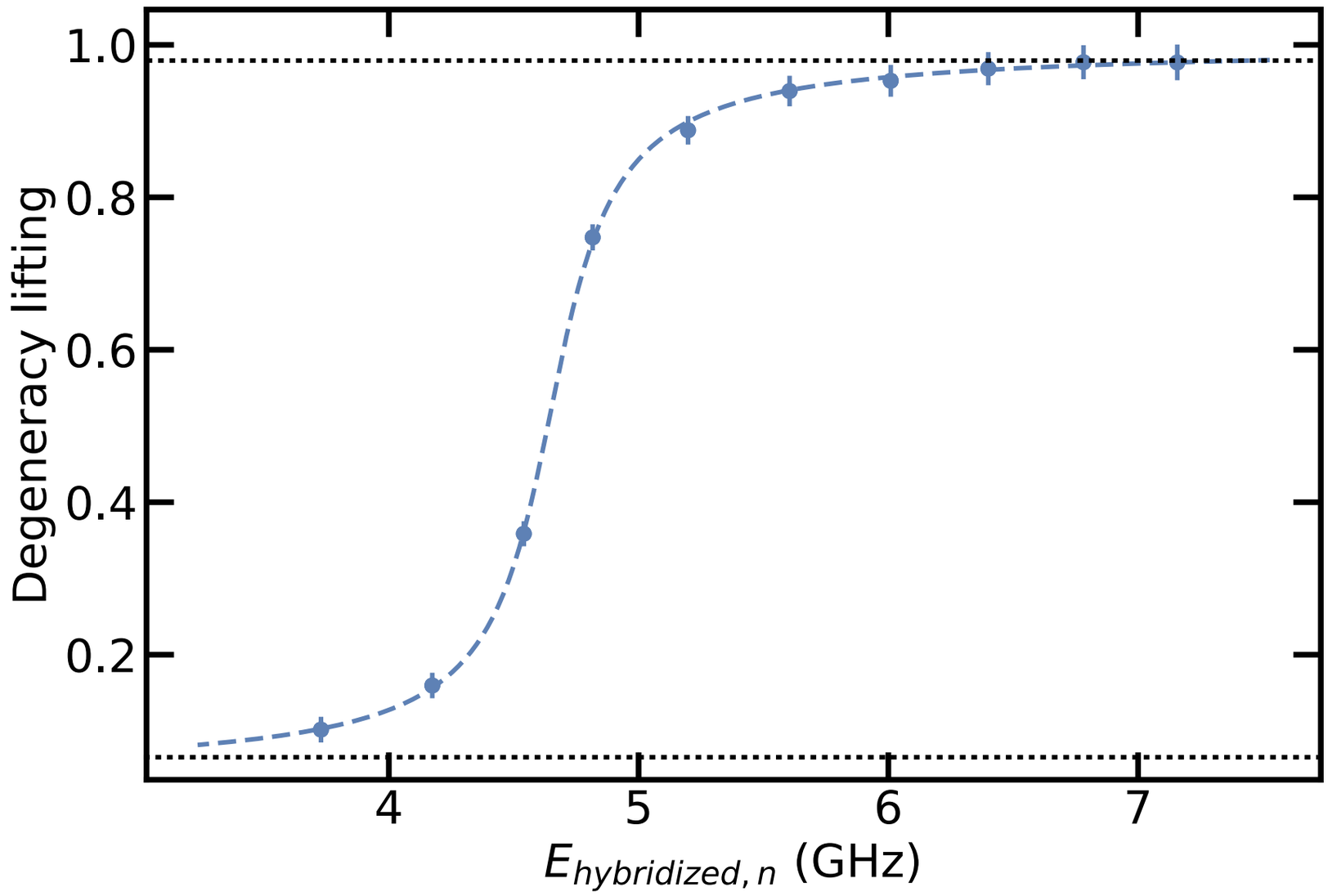
A Transmon coupled to a JJ meta-material

A Transmon coupled to a JJ meta-material



A Transmon coupled to a JJ meta-material

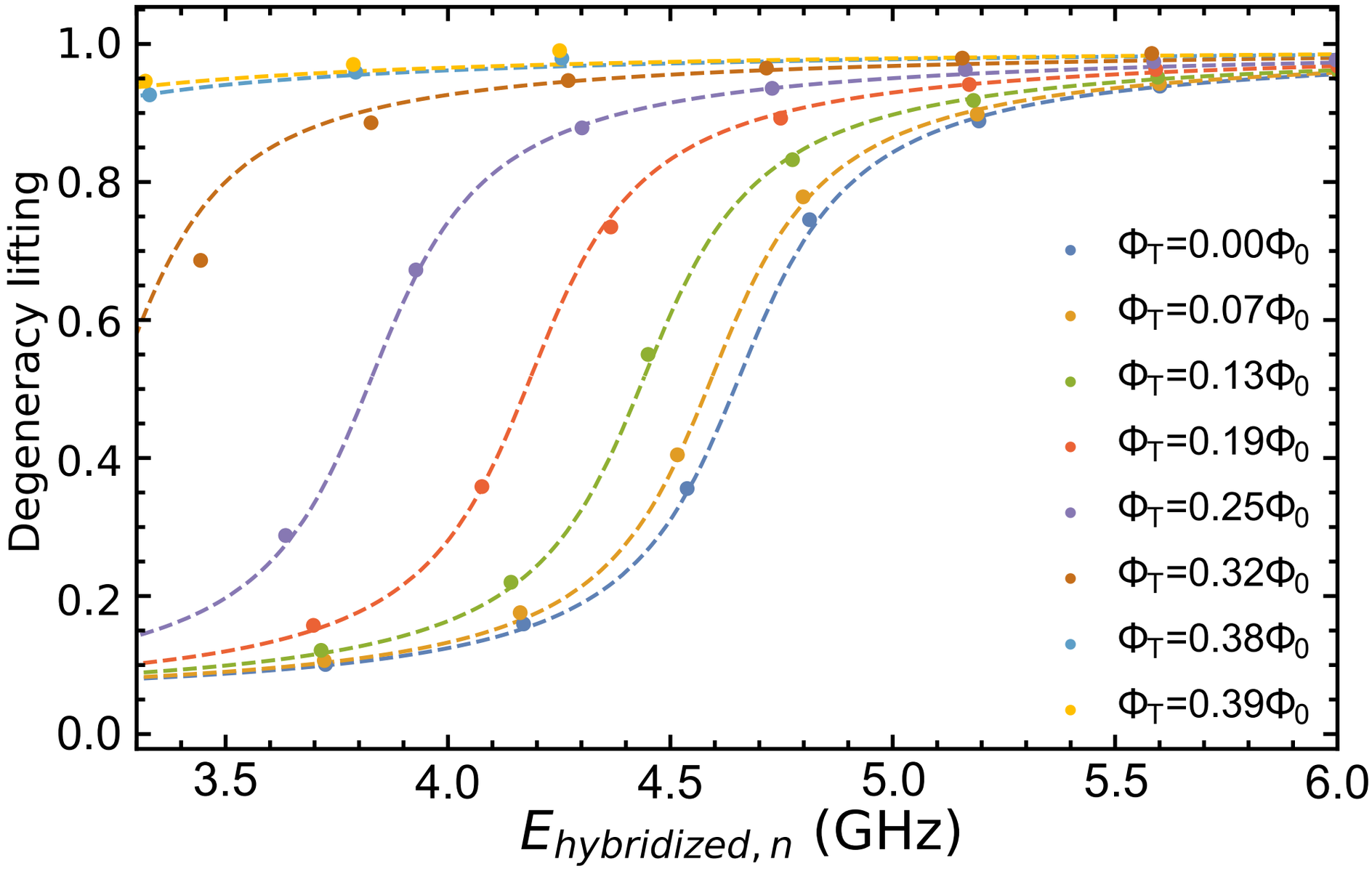




$$DL(E_{hybridized,n}) = \frac{E_{bare,n+1} - E_{hybridized,n}}{E_{bare,n+1} - E_{bare,n}}$$

10 strongly hybridized modes ! $\Gamma/\omega_{01} \sim 15\%$

A Transmon coupled to a JJ meta-material

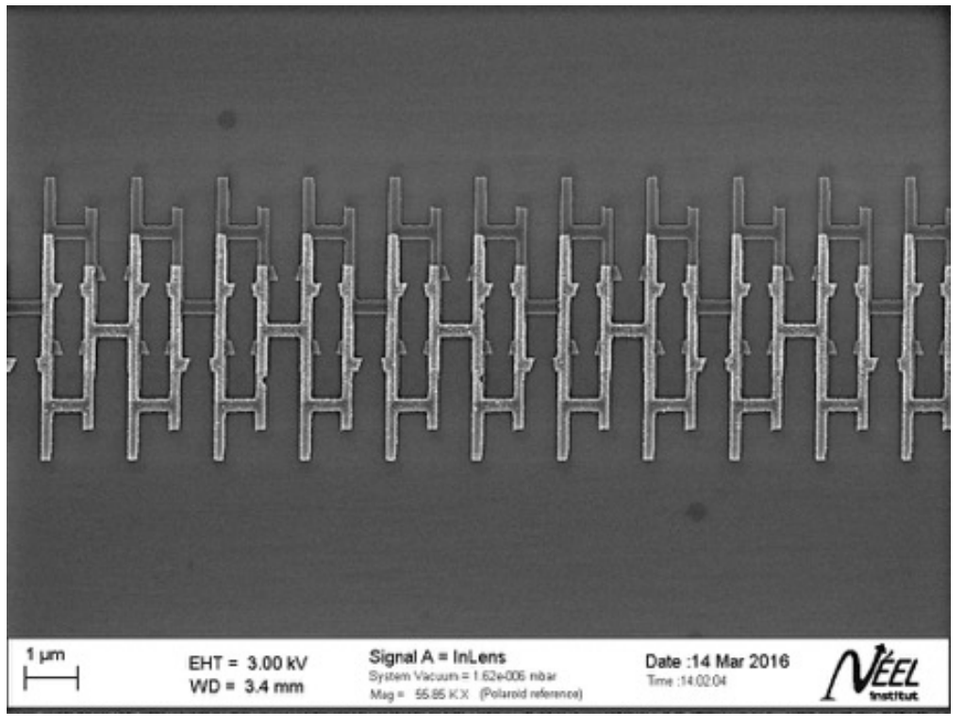


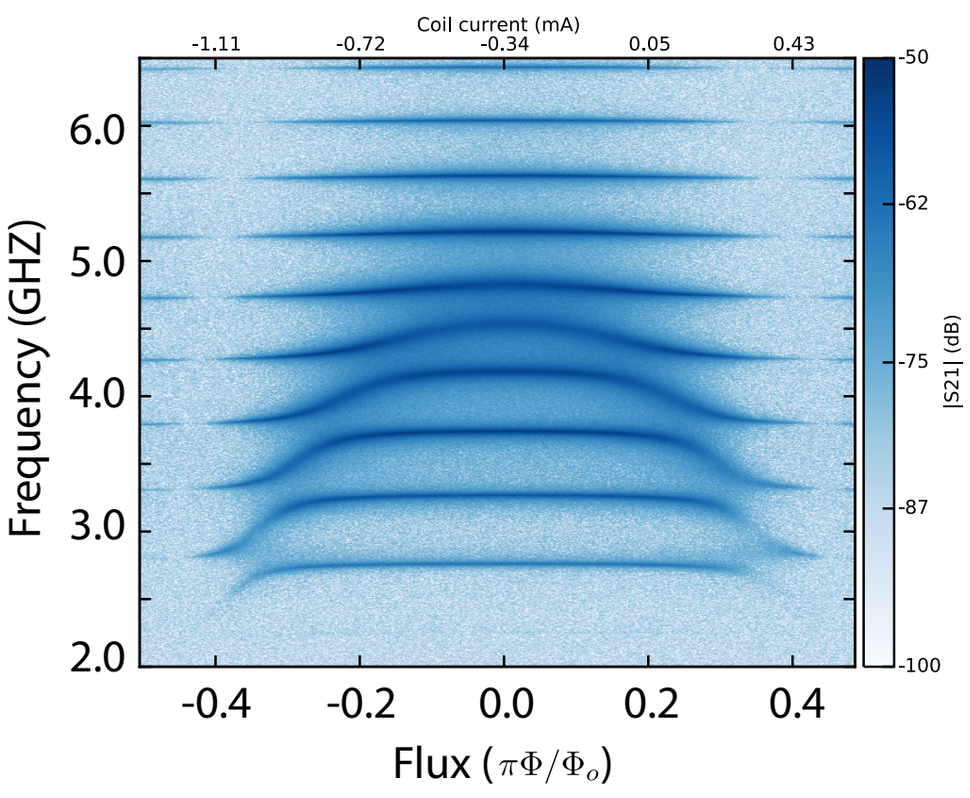
Theory: Self-Consistant Harmonic Approximation

For a review: Giamarchi and Orignac in “Theoretical Methods for Strongly Correlated Electrons", CRM Series in Mathematical Physics, Eds. D. Senechal et al., Springer, New York, 2003

Conclusion

High impedance
Josephson junction metamaterials





monitoring the qubit
AND the bath:
10 hybridized bosonic modes

Perspectives: linking quantum optics and many-body physics

Inelastic scattering
of coherent states on a many-body system

Gheeraert et al.,
in prep

Shape the bath:
Multi-bands, Edge states…

Other models:
Kondo model, Sine-gordon model….

Thank you!

Superconducting quantum circuits team

Serge Florens

Nicolas Gheereart

Izak Snyman