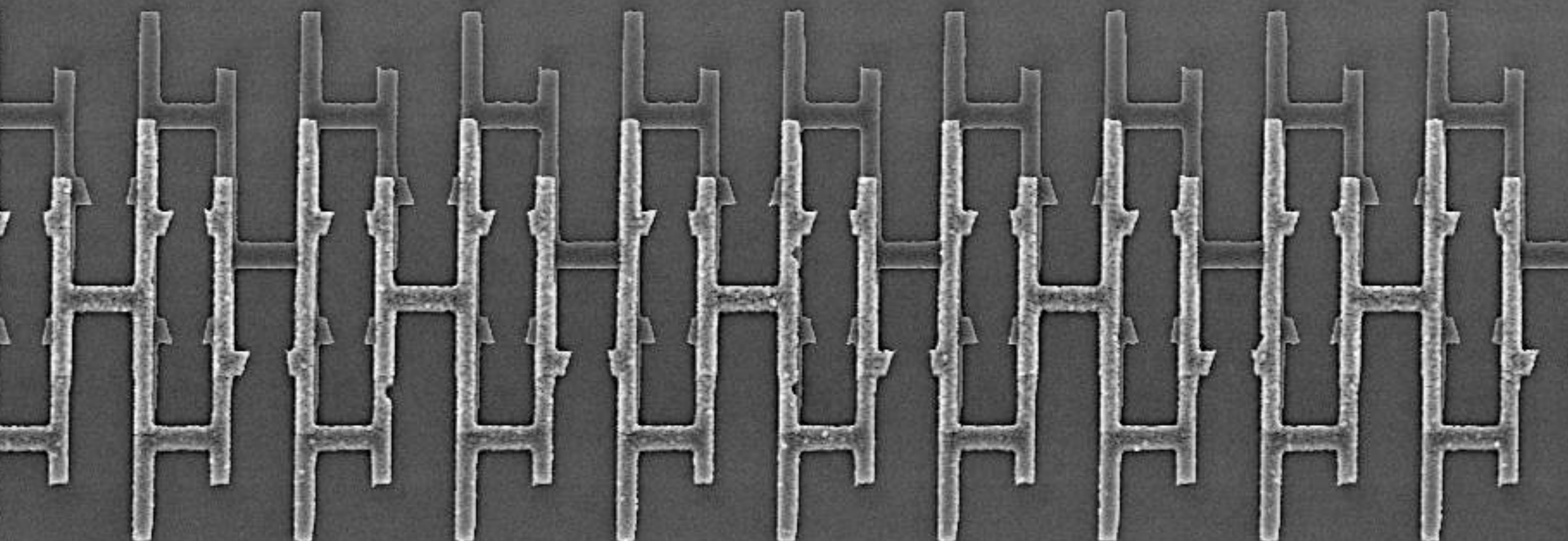
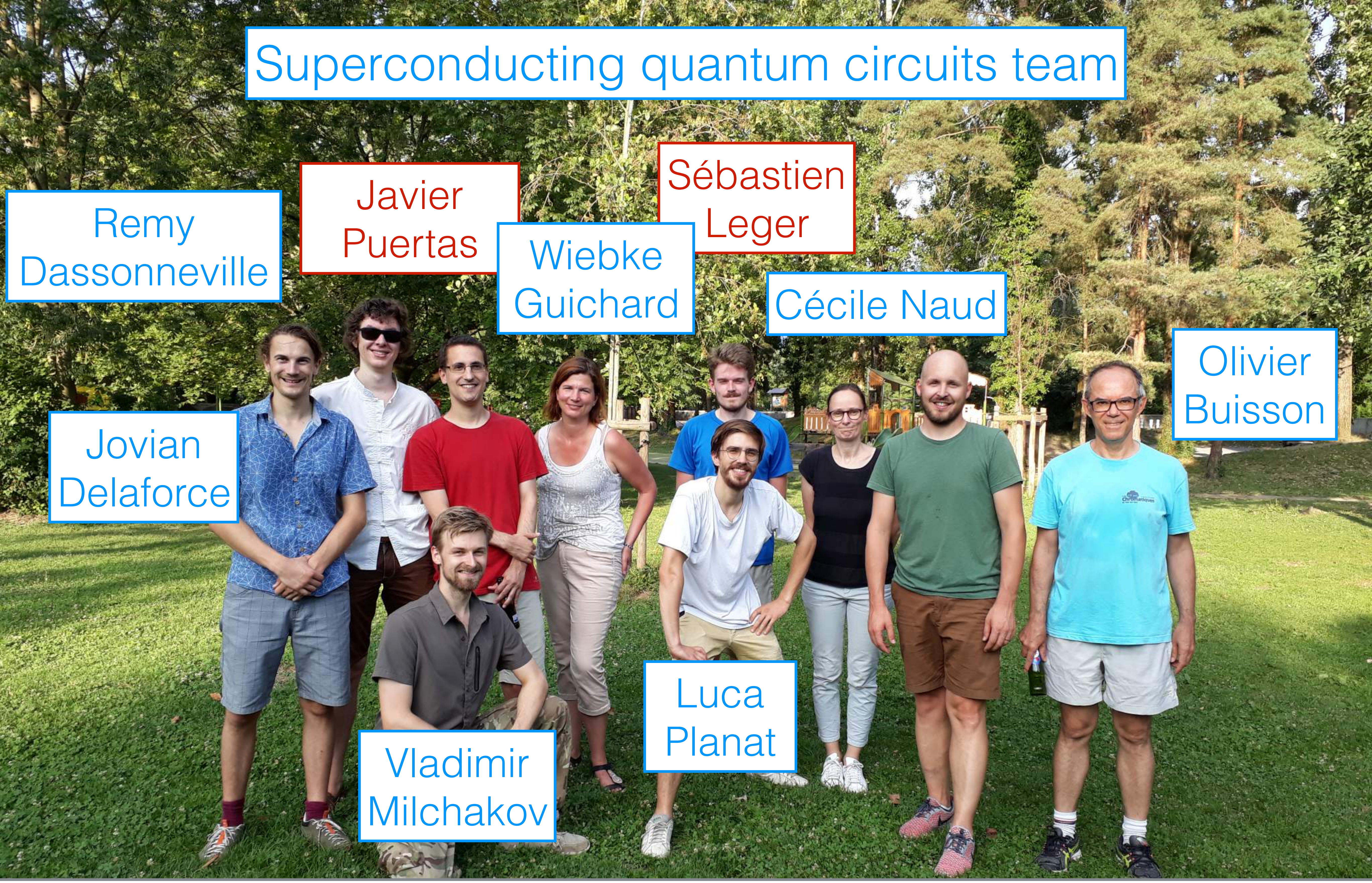
High impedance (meta)-materials for quantum circuits



Nicolas Roch
Neel Institute, Grenoble, France

Superconducting quantum circuits team



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Quantum Engineering Univ. Grenoble Alpes

Acknowledgments

Grenoble

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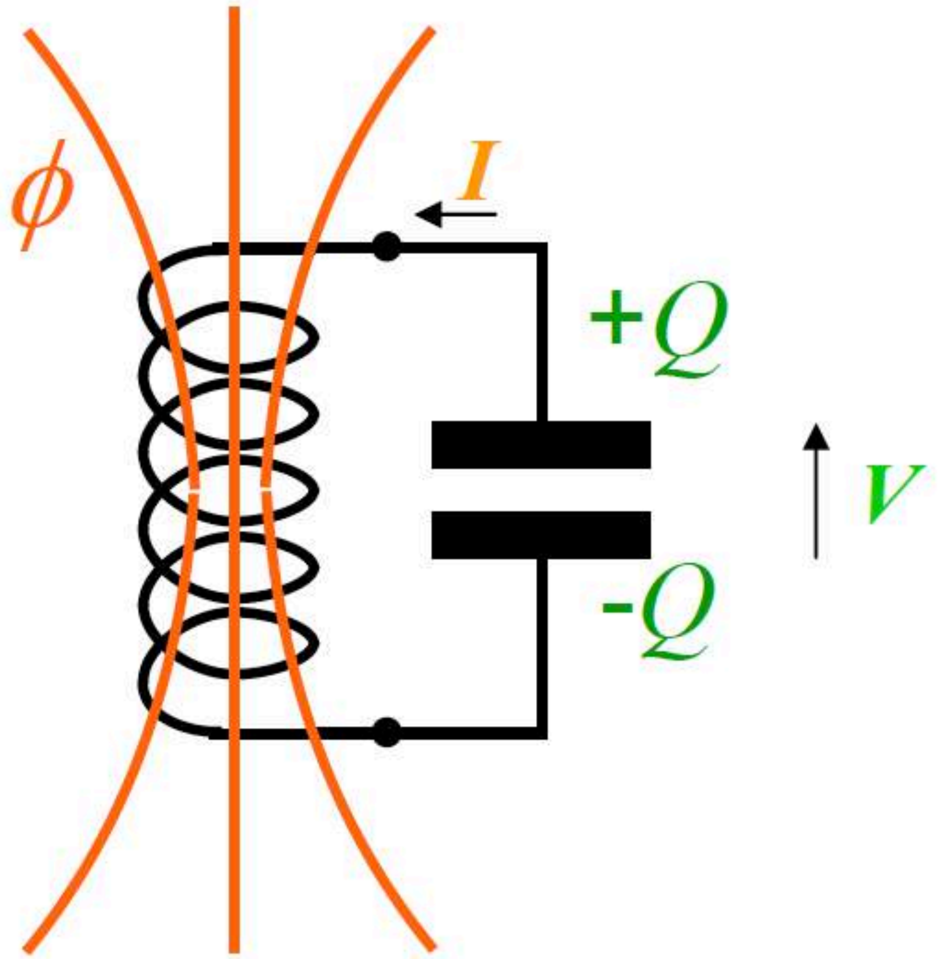
Izak Snyman

Denis Basko

laboratoire de physique et de modélisation des milieux condensés

Grenoble

Quantum circuits: harmonic oscillator



Resonant frequency

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

Impedance

$$Z_0 = \sqrt{\frac{L}{C}}$$

Flux in inductor

$$\phi(t) = \int_{-\infty}^{t} V(t')dt'$$

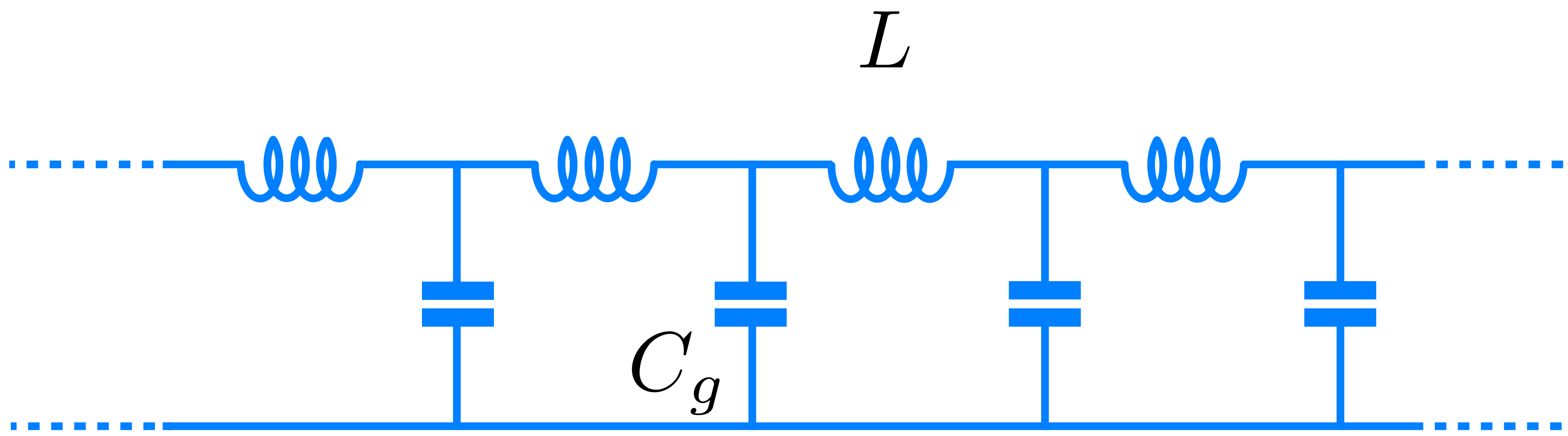
$$\langle \phi^2 \rangle = \frac{\hbar Z_0}{2} \coth\left(\frac{\beta \hbar \omega_0}{2}\right)$$

Charge on capacitor

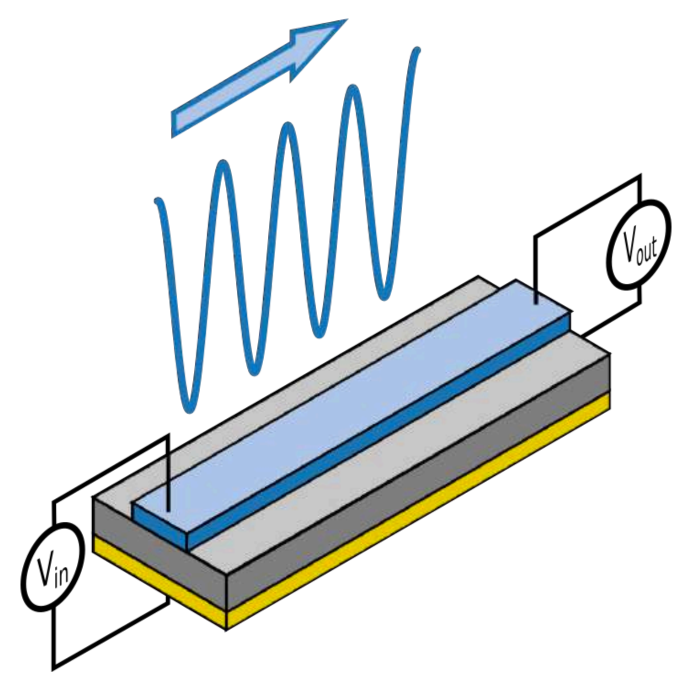
$$Q(t) = \int_{-\infty}^{t} I(t')dt'$$

$$\langle Q^2 \rangle = \frac{\hbar}{2 Z_0} \coth\left(\frac{\beta \hbar \omega_0}{2}\right)$$

Quantum circuits: transmission line

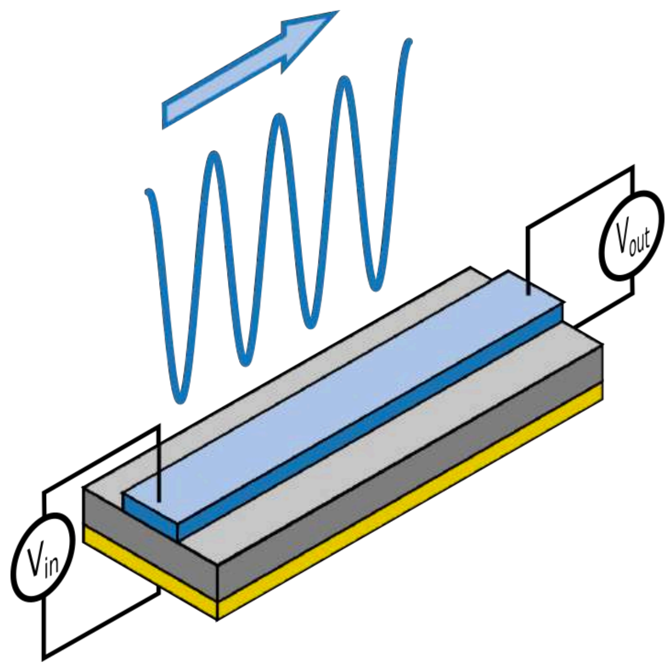


$$Z_c = \sqrt{L/C_g}$$



Why high impedances?

Physics of the (meta)-materials

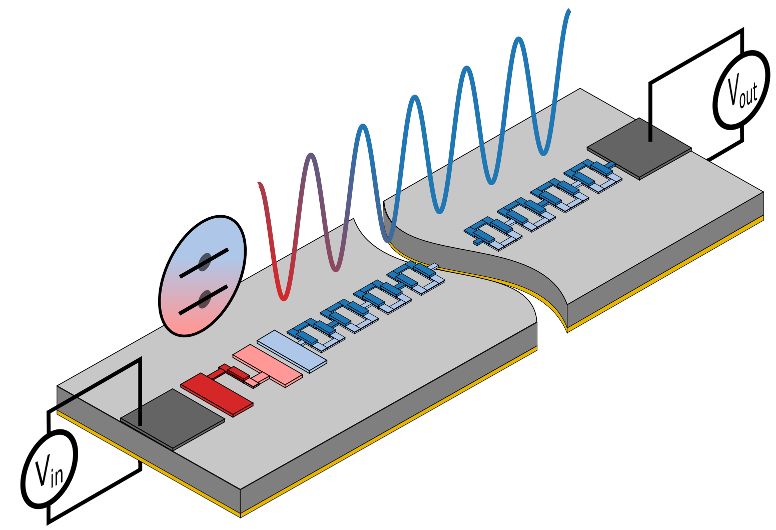


e.g. superconductor close to the SIT

$$Z_c \sim h/(2e)^2 = 6.45\ k\Omega$$

R. Fazio & H. van der Zant, Physics Reports (2001)

Model systems



e.g. dissipative quantum circuits

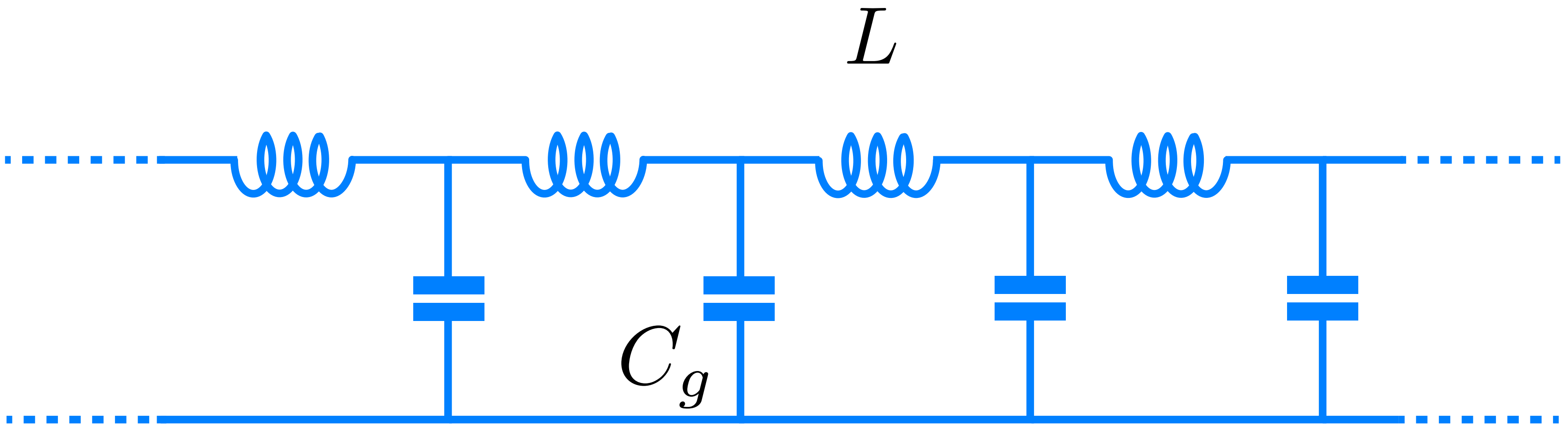
strong phase fluctuations across a single Josephson junction

$$\langle \varphi^2 \rangle \sim 2\pi$$

A. Schmid, Phys. Rev. Lett. (1983)

Reaching high impedances

Josephson junction meta-material



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Reaching high impedances

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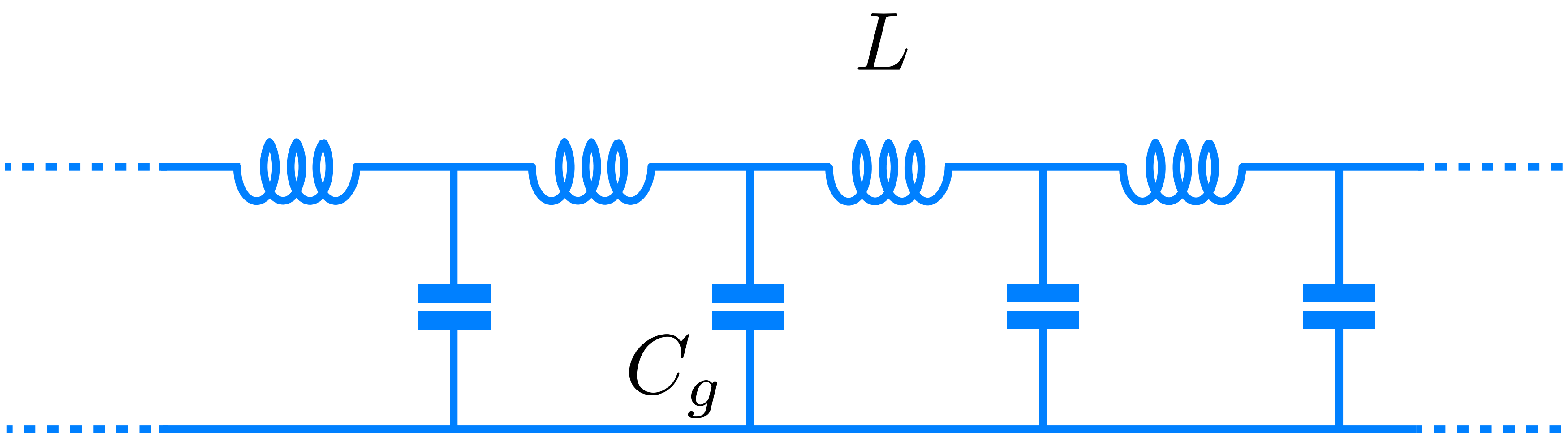
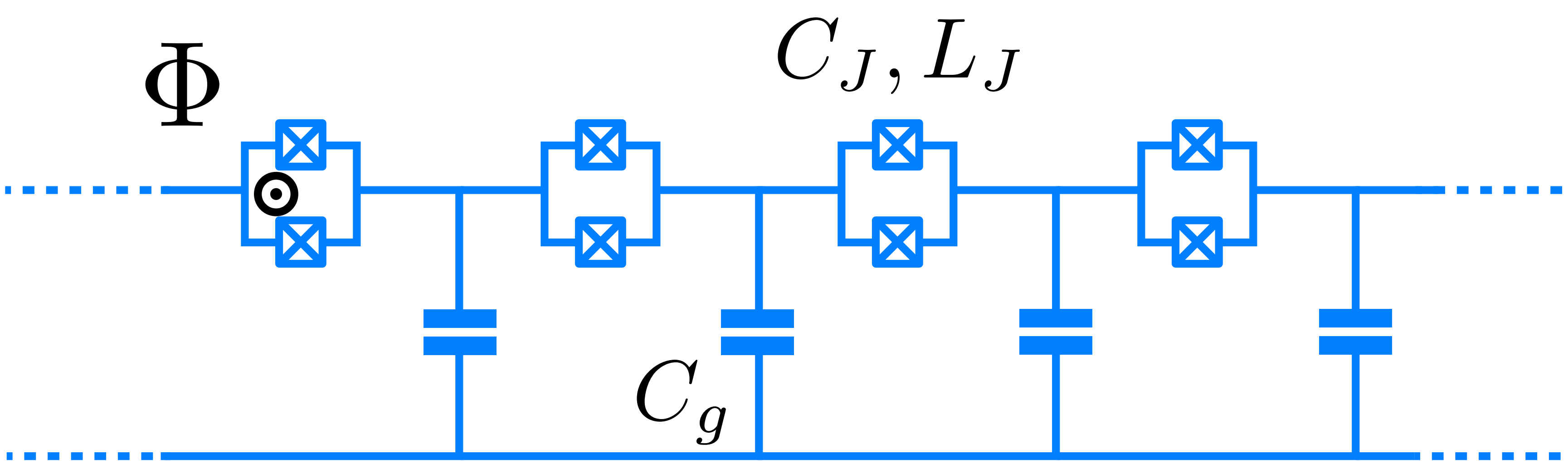


$$Z_c = \sqrt{L/C_g}$$



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

Seminal work:

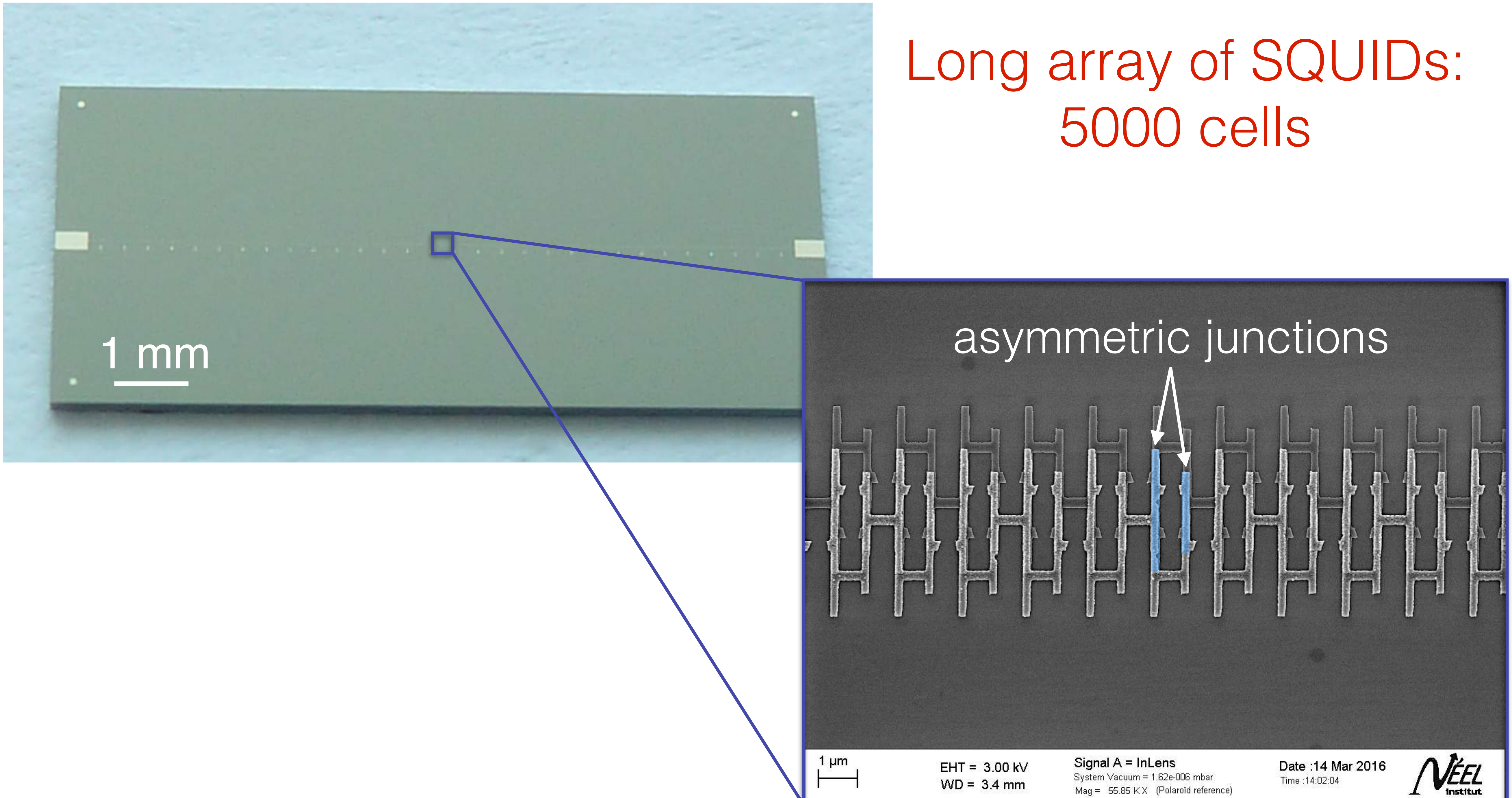
S. Corlevi et al 06' (Haviland's group)

See also:

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

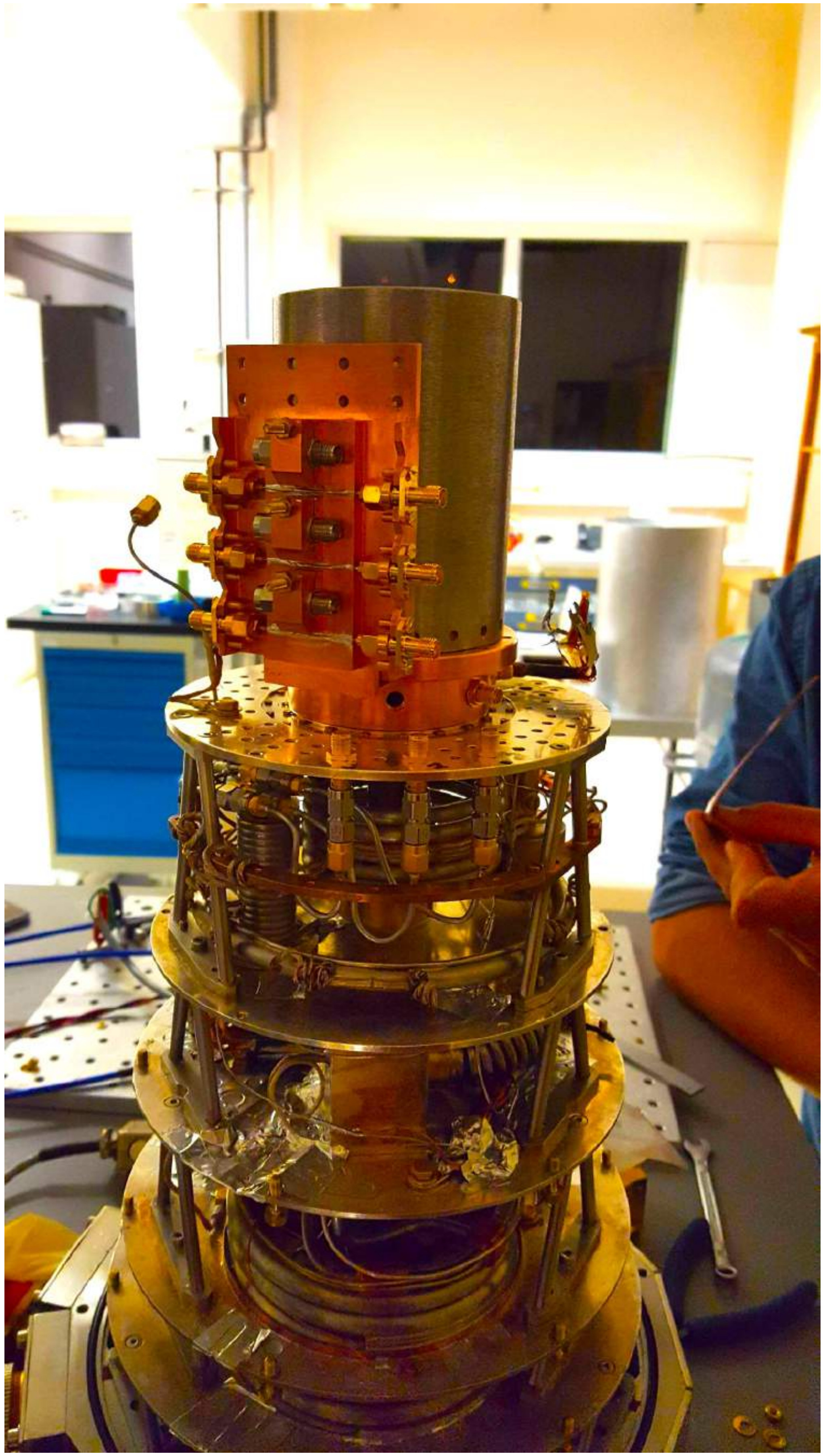
JJ meta-material: Bridge Free Fabrication

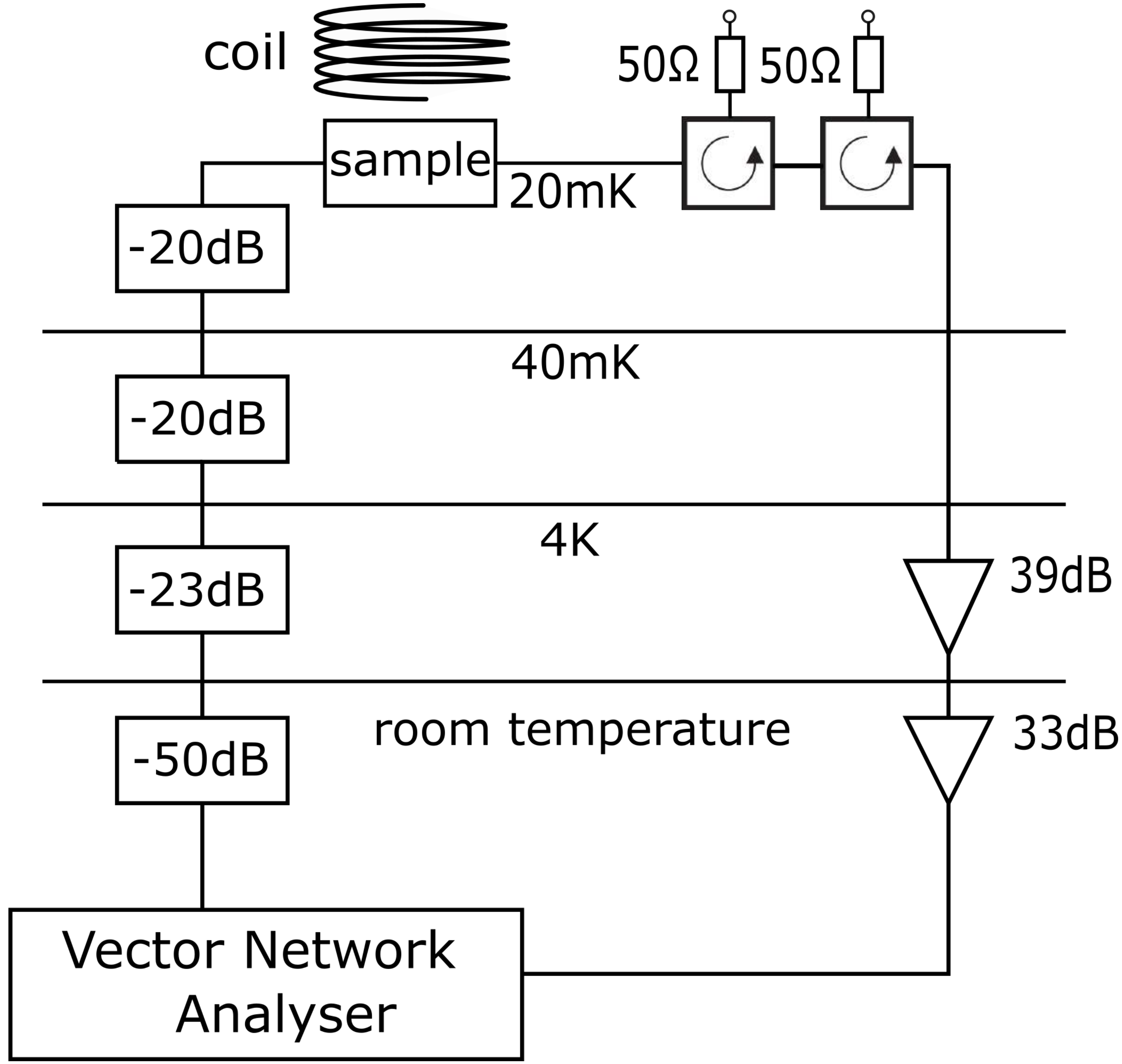
Long array of SQUIDs:
5000 cells



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

JJ meta-material: Measuring

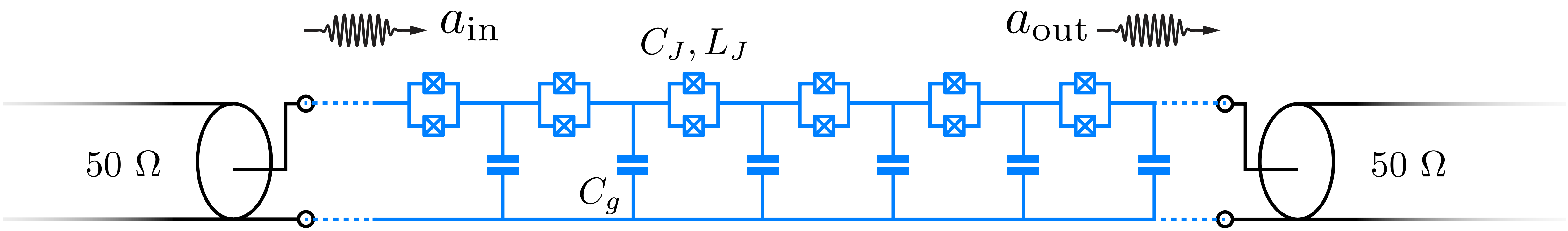


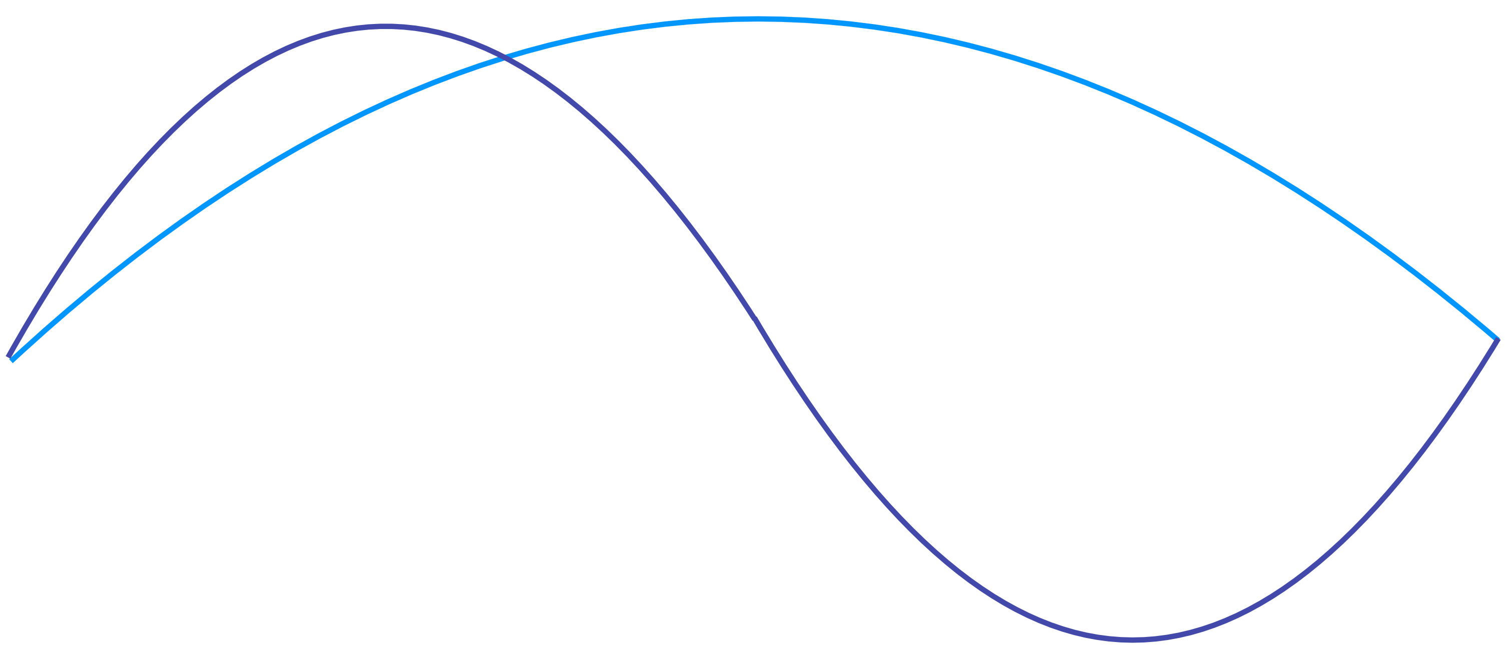


Quantum regime: $\hbar\omega \gg k_{\mathrm{B}} T$

Josephson junction meta-material

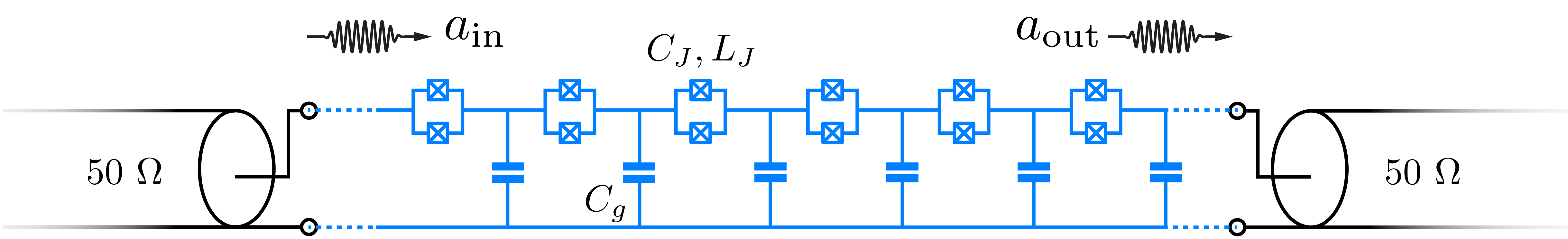
Fabry-Pérot

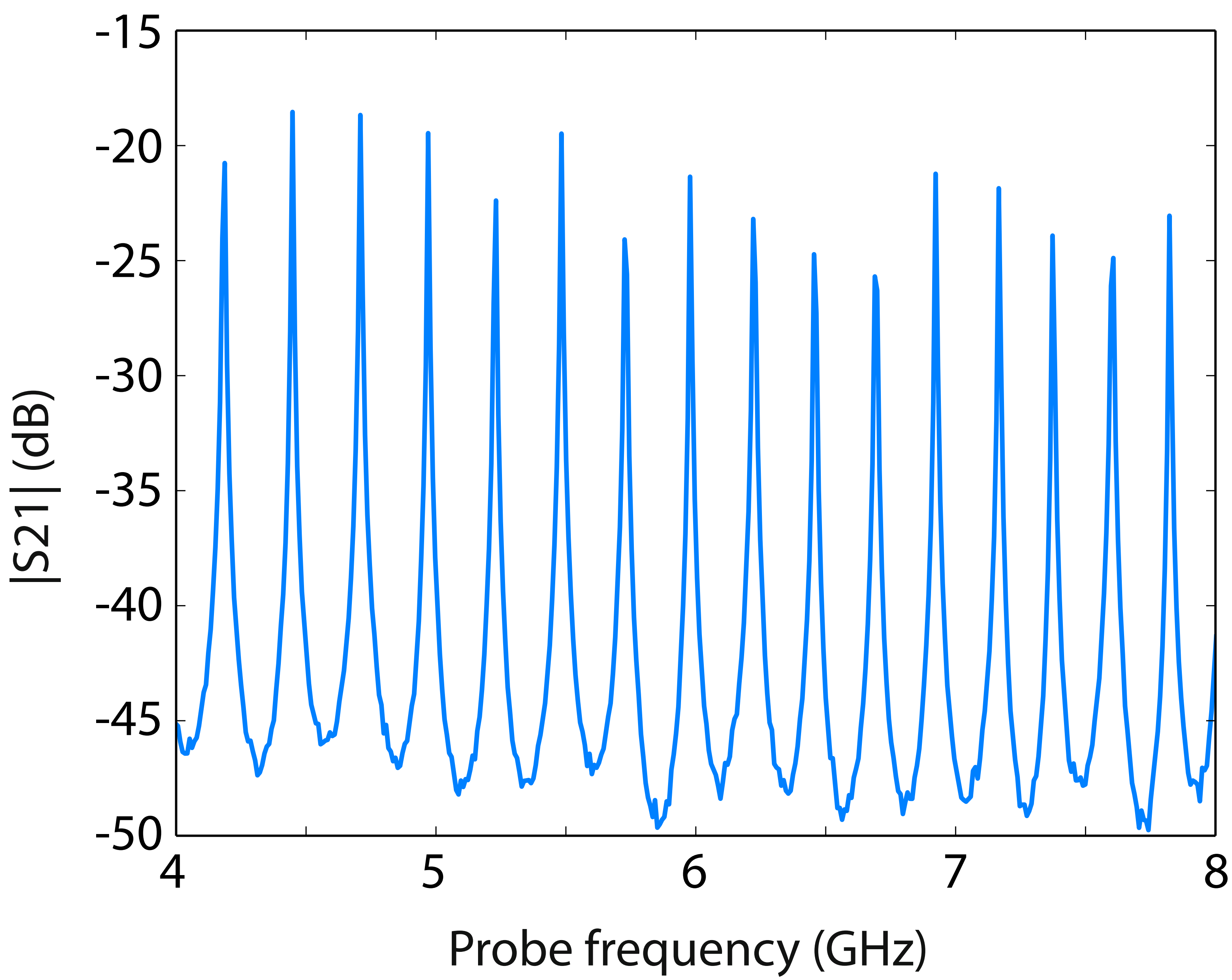




Quantum regime: $\hbar\omega \gg k_{\mathrm{B}}T \quad (T = 20\ \mathrm{mK})$

Josephson junction meta-material





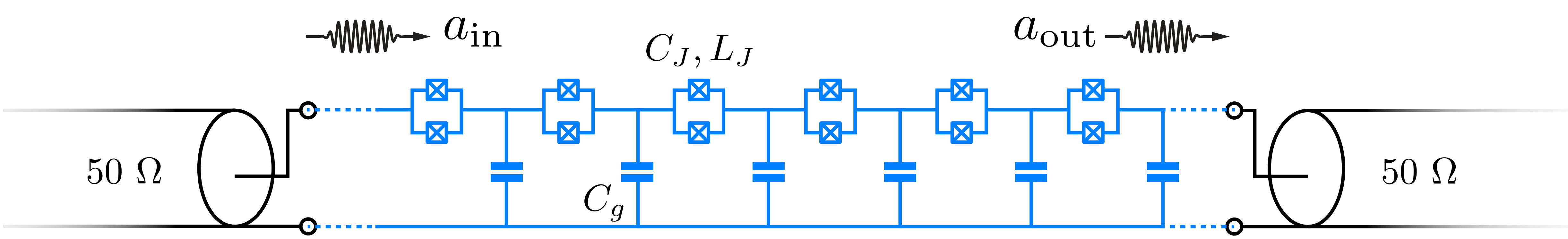
Fabry-Pérot

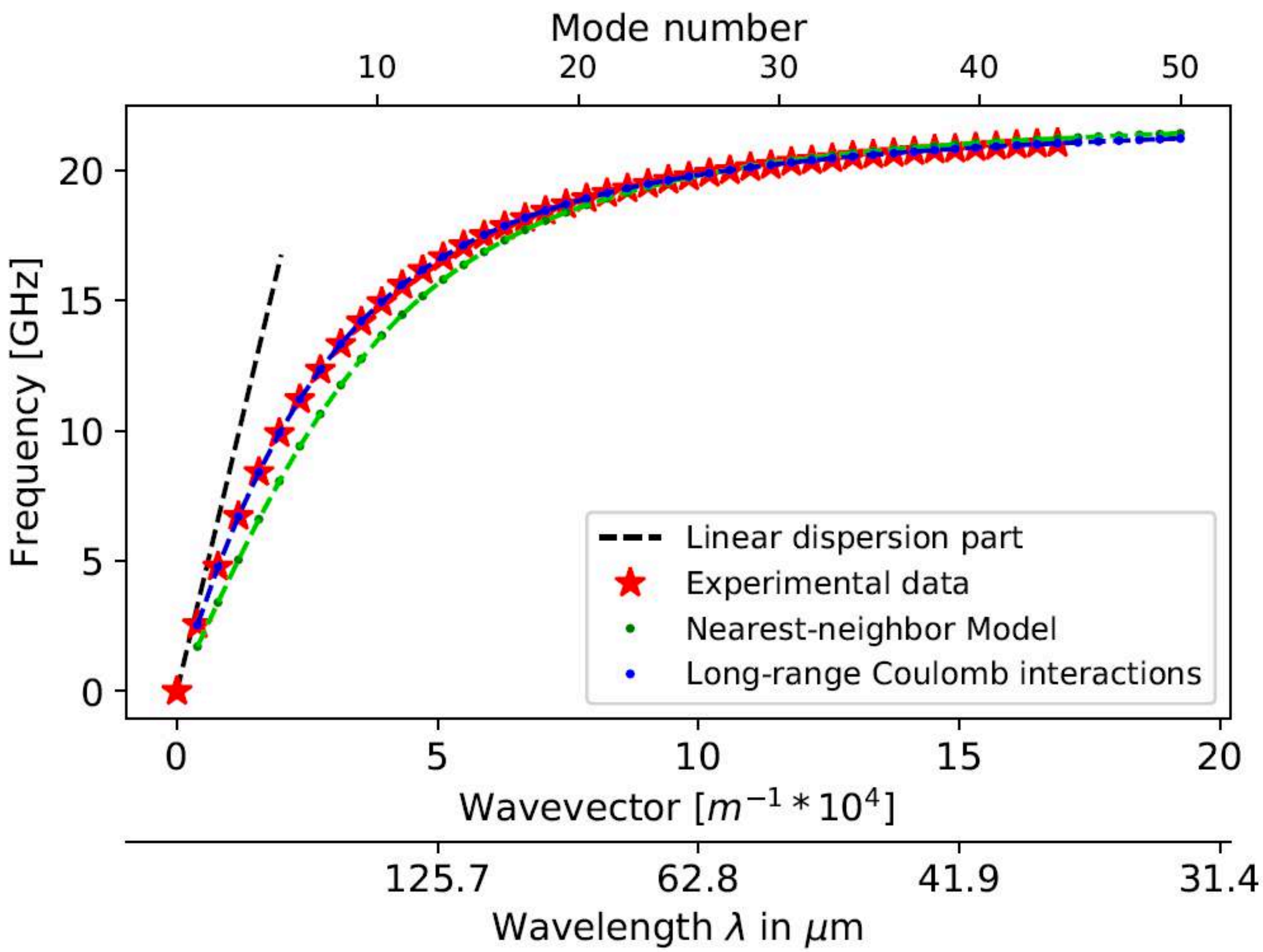
$Q_{\rm ext} \sim 10^2$

(Impedance mismatch)

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

Josephson junction meta-material





Y. Krupko et al., Phys. Rev. B (2018)

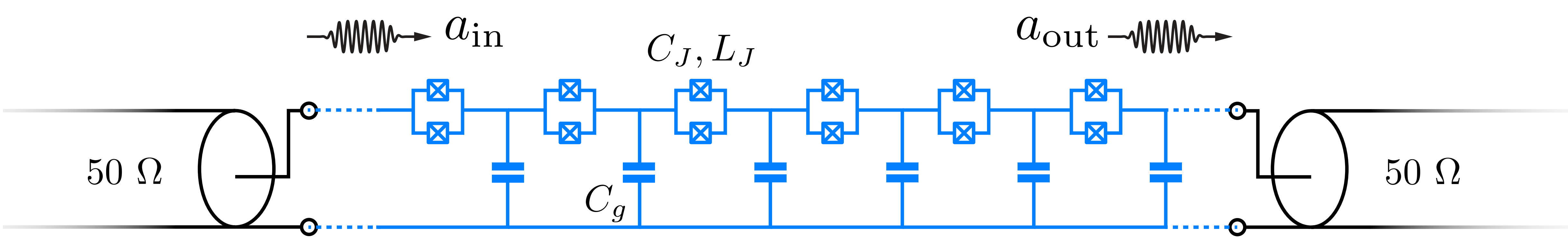
cQED wording:

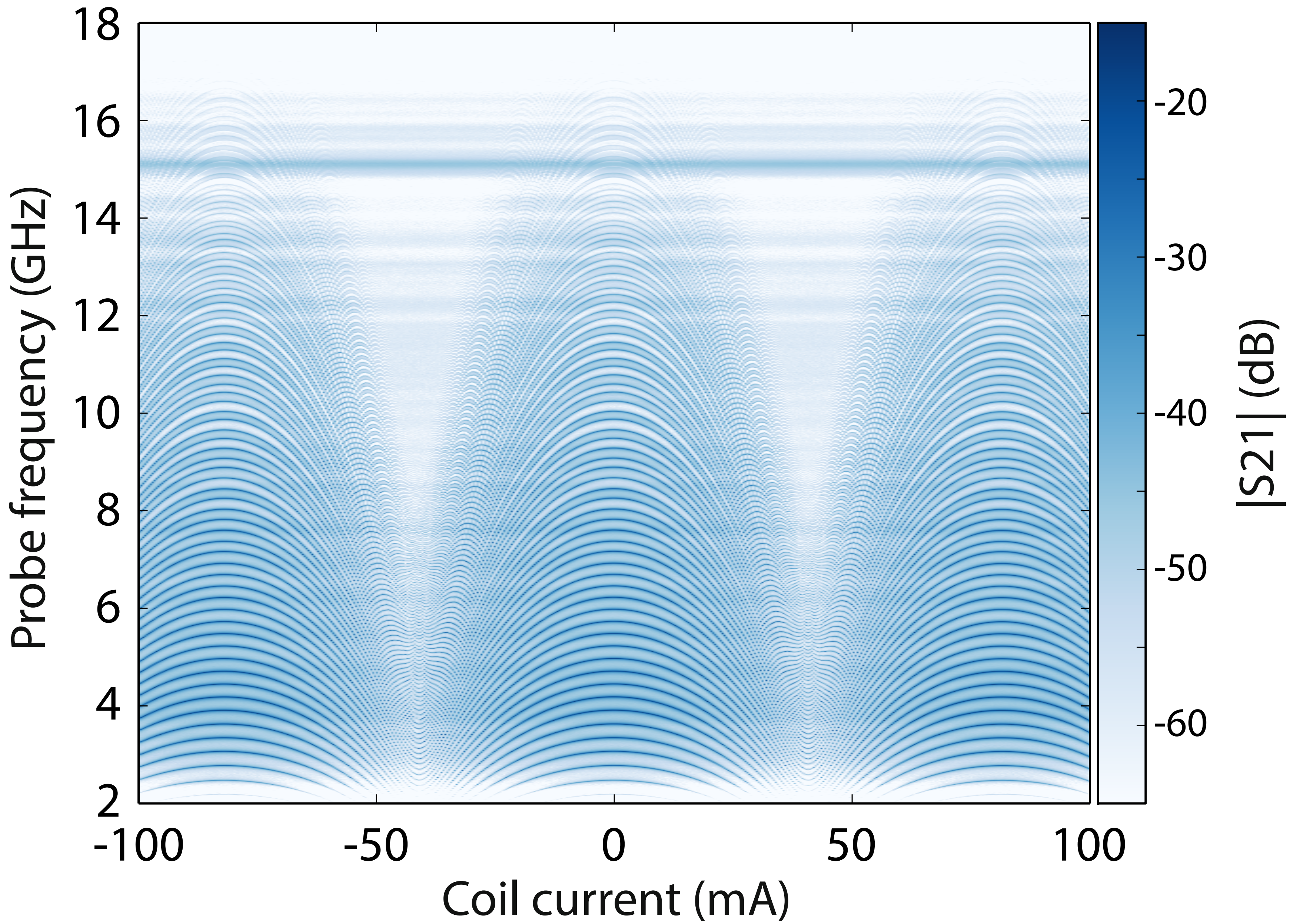
$$Z_c = \sqrt{L_J/C_g} \sim 3.5 \text{ k}\Omega$$

Optics wording:

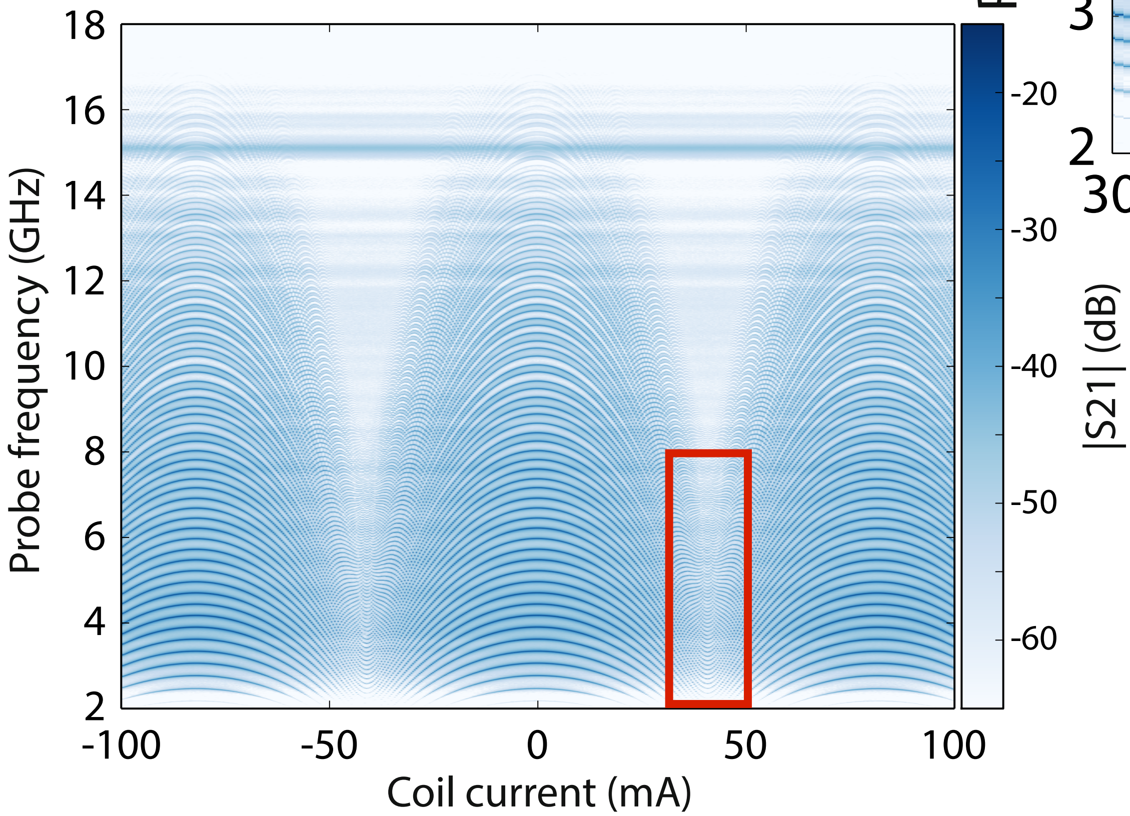
$$n \simeq 50$$

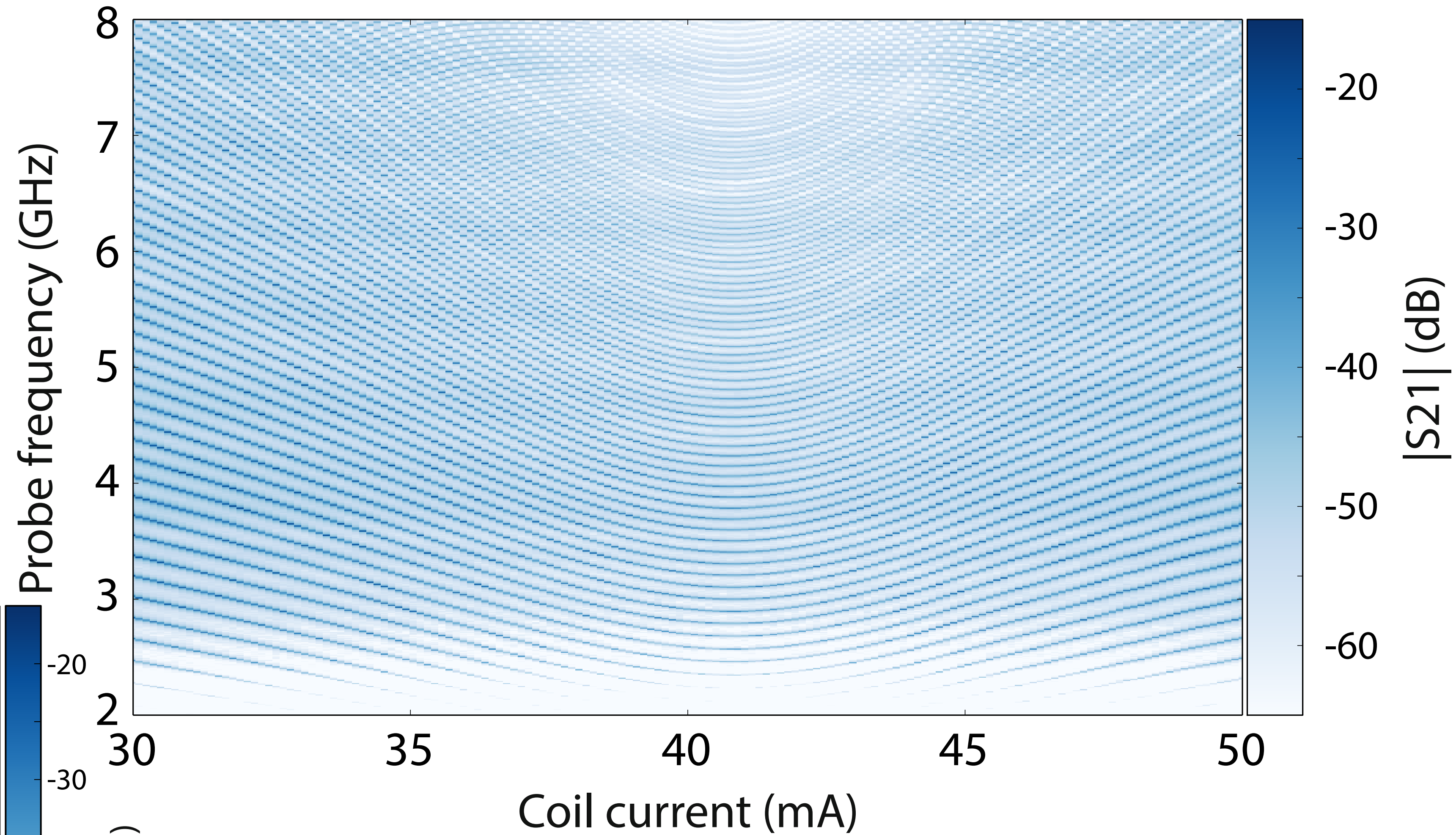
Josephson junction meta-material





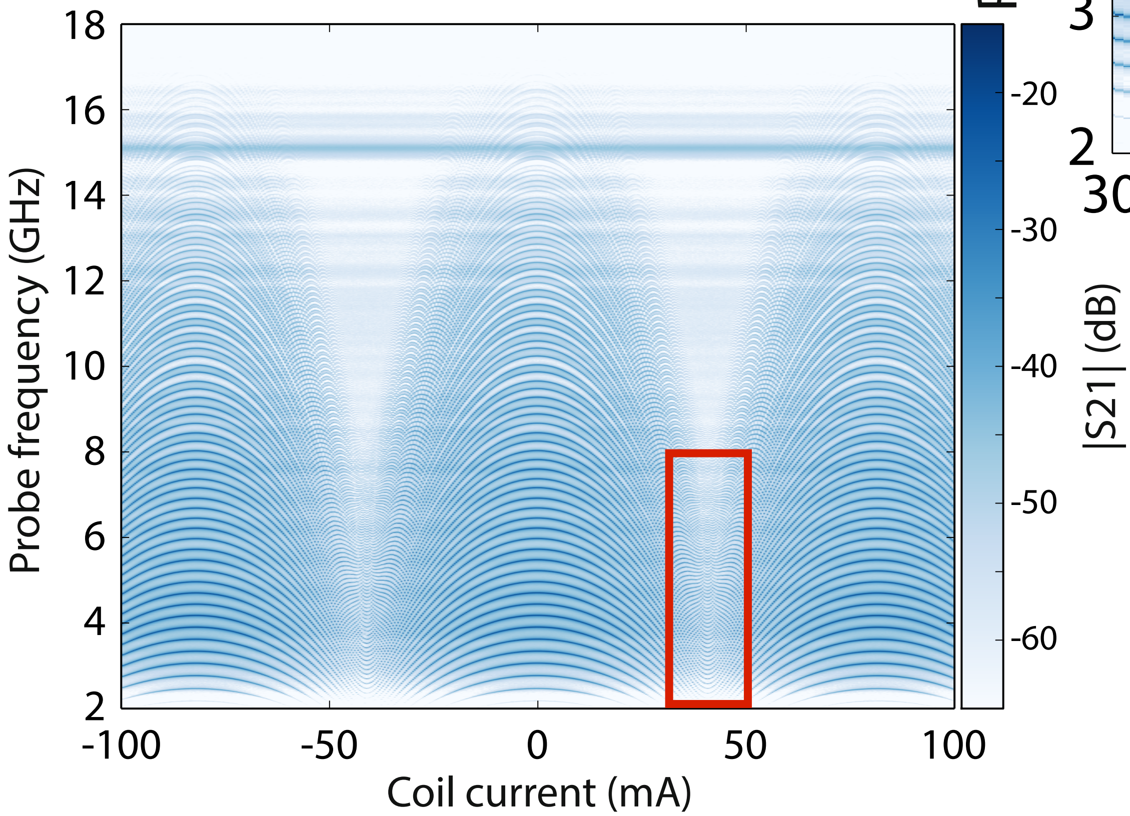
Josephson junction meta-material

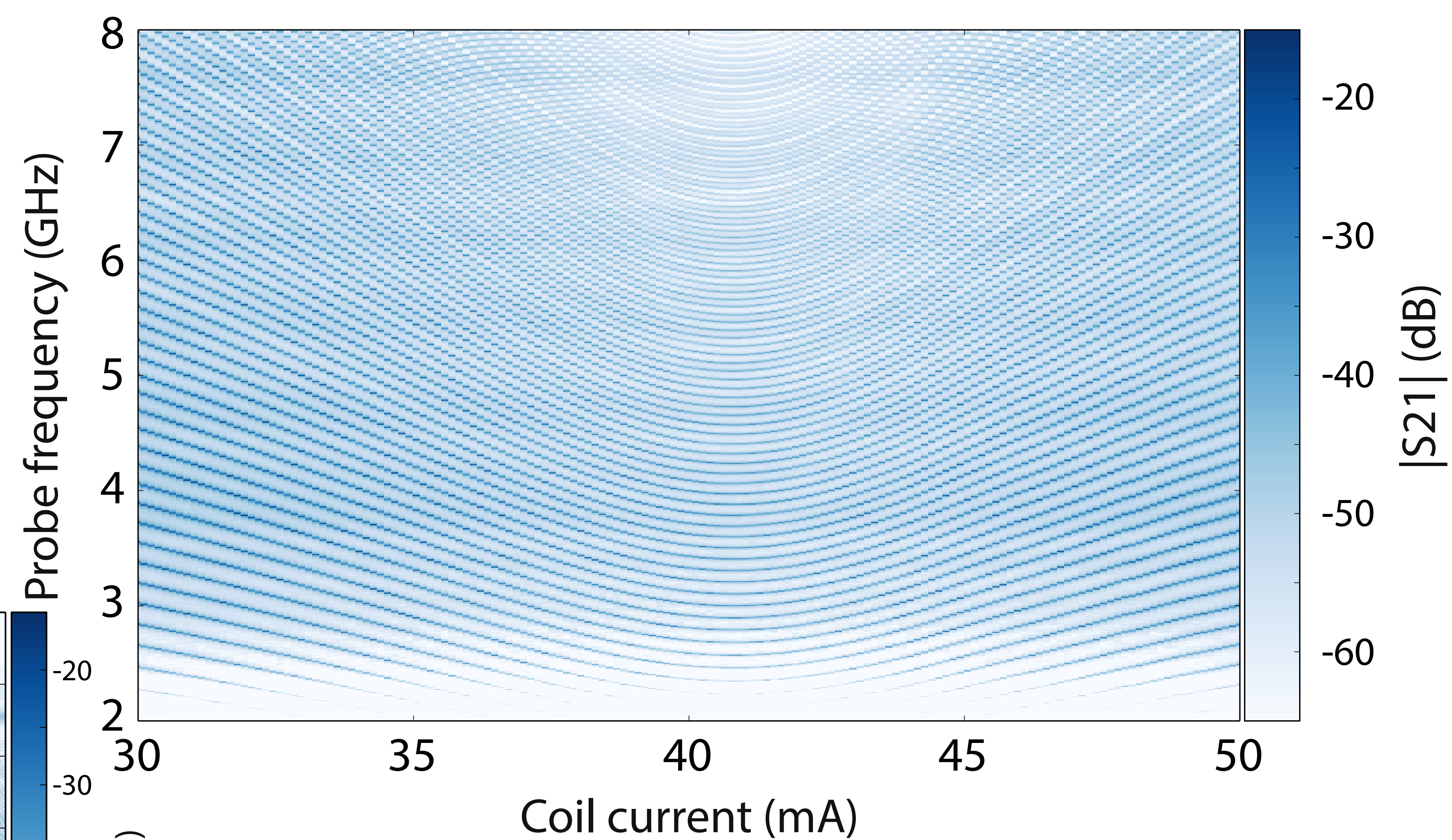




Low disorder

Josephson junction meta-material





Low disorder

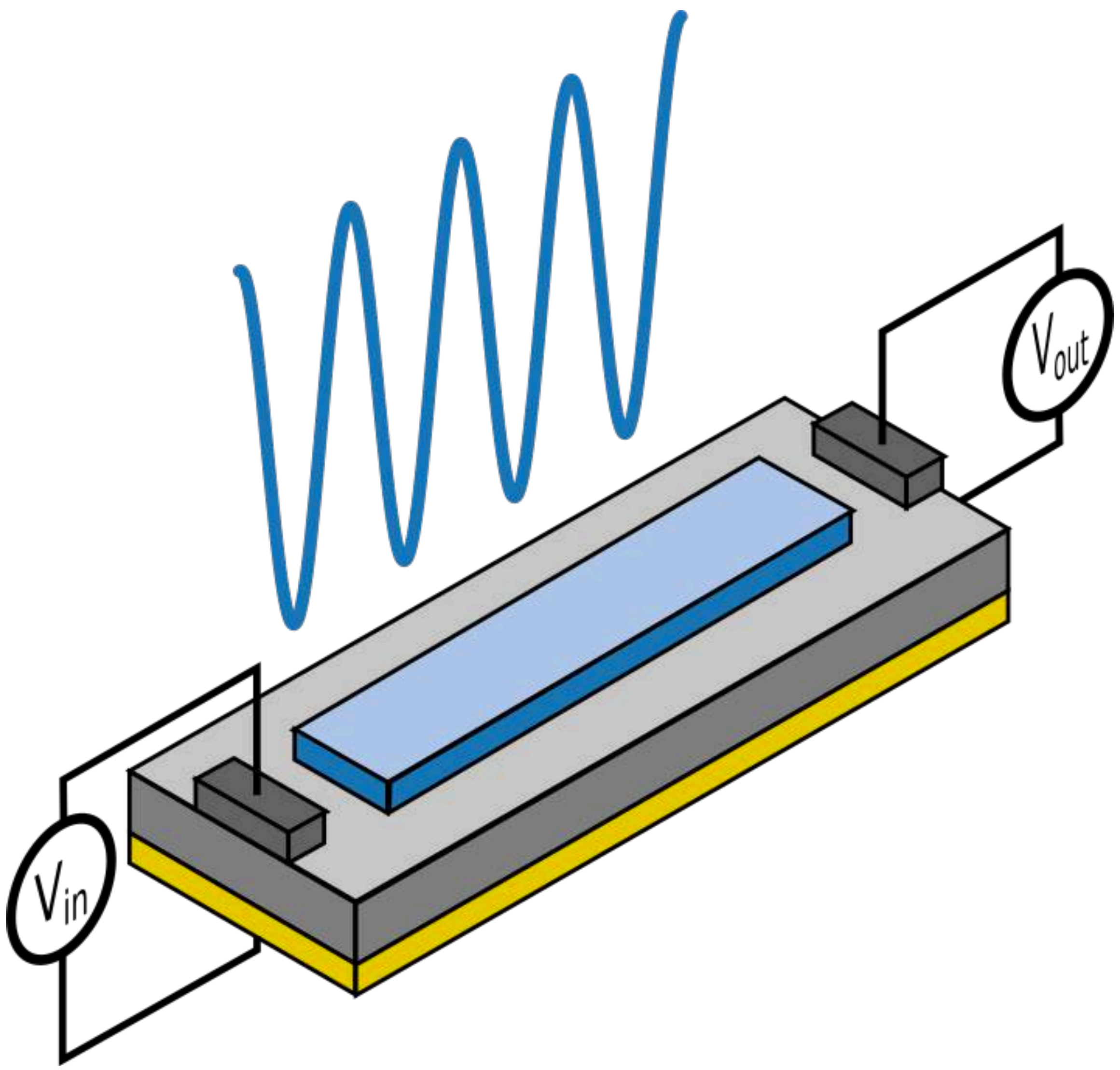
$$Z_c \sim 7\ k\Omega$$

Other recent experiments

K. Cedergren, et al., Phys. Rev. Lett. (2017)

R. Kuzmin et al., arXiv:1805.07379

Indium Oxyde

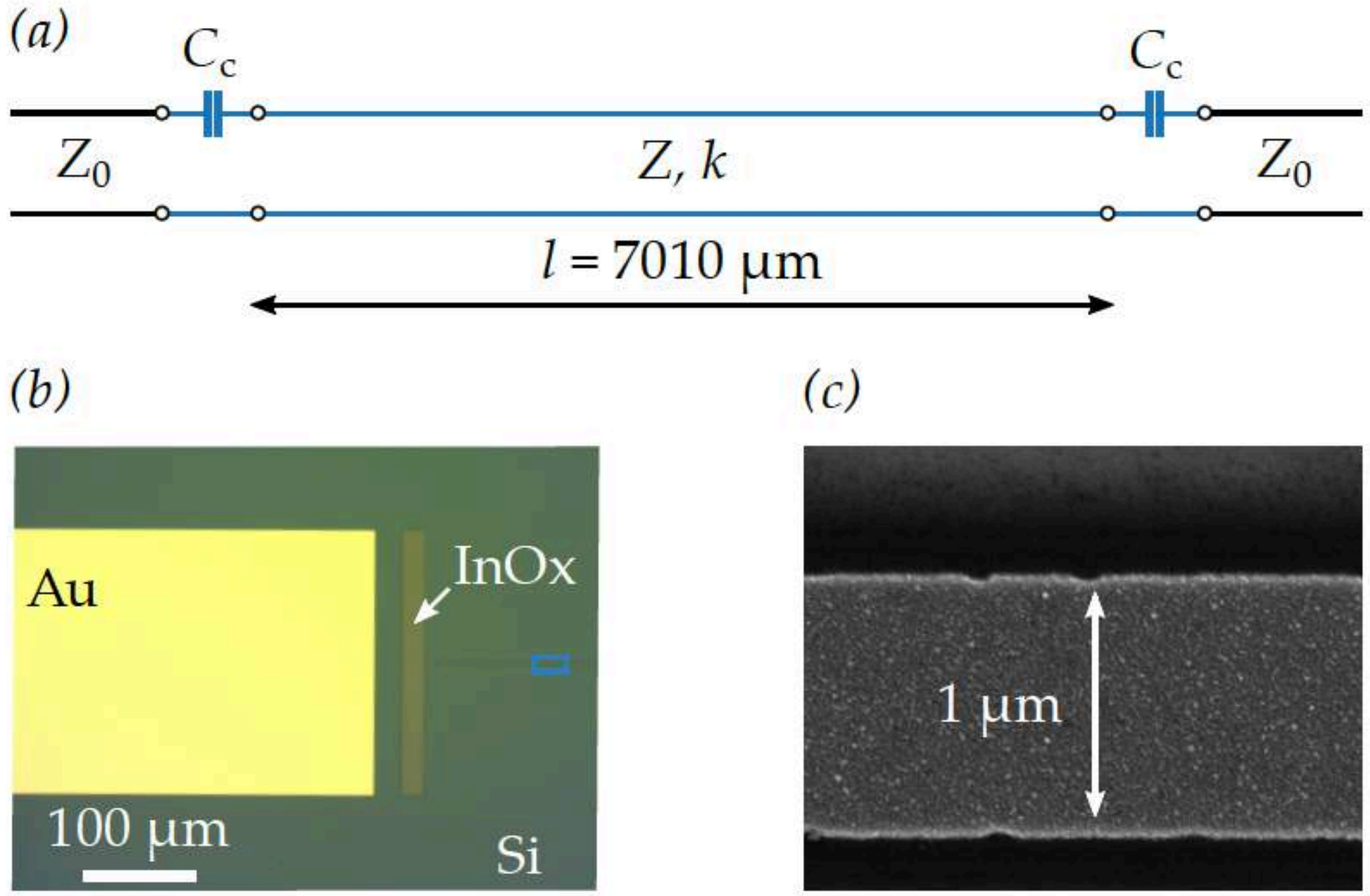


See also talks from:

F. Lévy-Bertrand

M. Scheffler

Indium Oxyde



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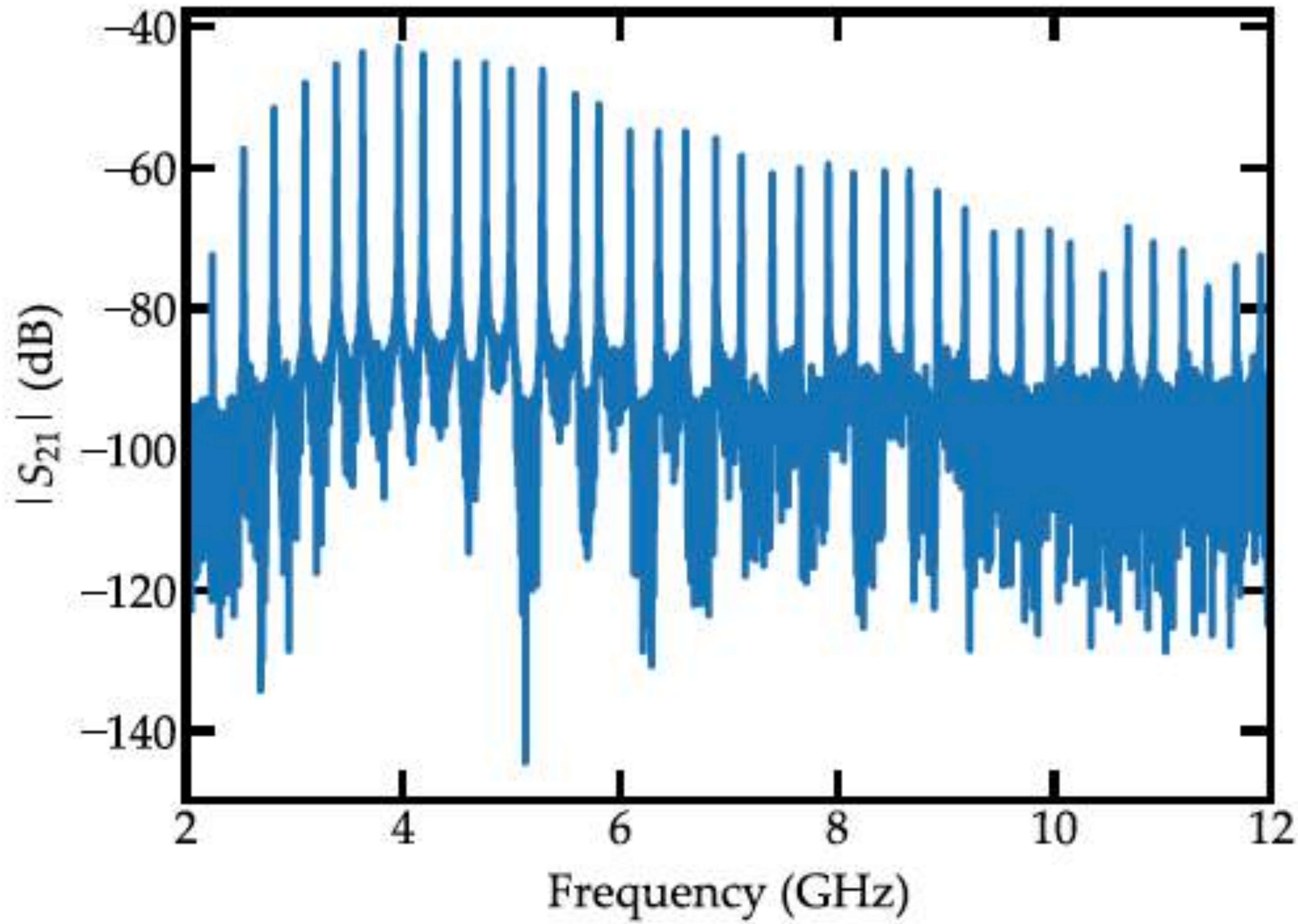

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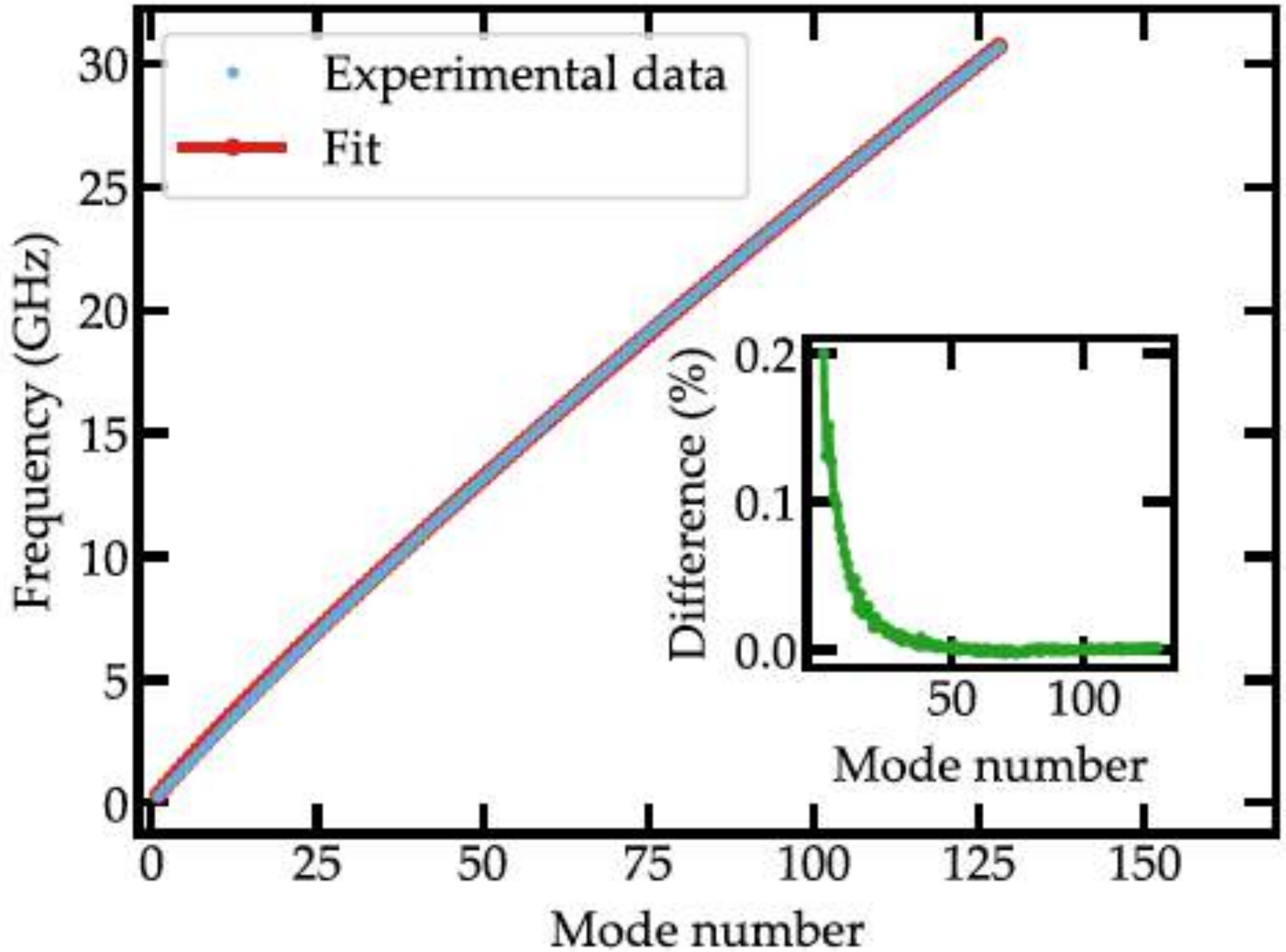


$$\omega_k^2 = \frac{r_0^2}{\epsilon_0 \mu_0 \epsilon \lambda_L^2(T)} k^2 \ln\left(\frac{1}{k r_0}\right)$$

Formula from Camarota et al. JLTP (2000)

radius of the wire

$r_0 = 0.2\ \mu m$

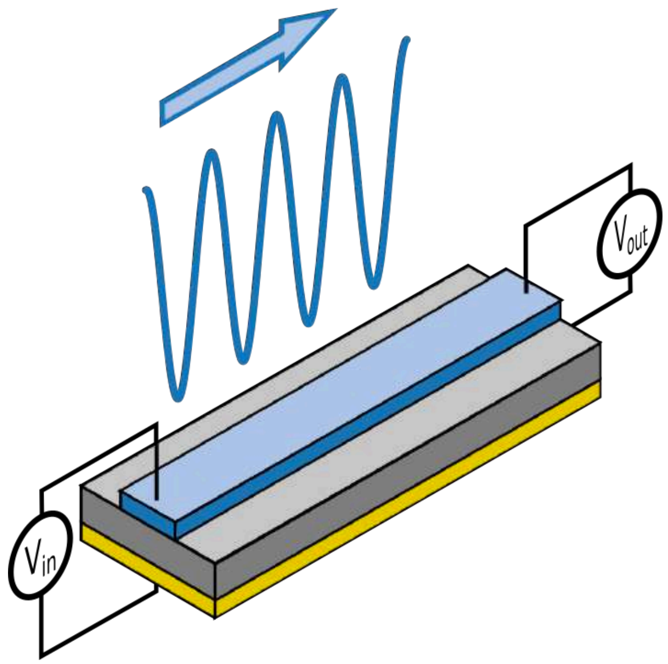
London penetration depth

$\lambda_L = 14\ \mu m$

$Z_c \sim 8\ k\Omega$

Why high impedances?

Physics of the (meta)-materials



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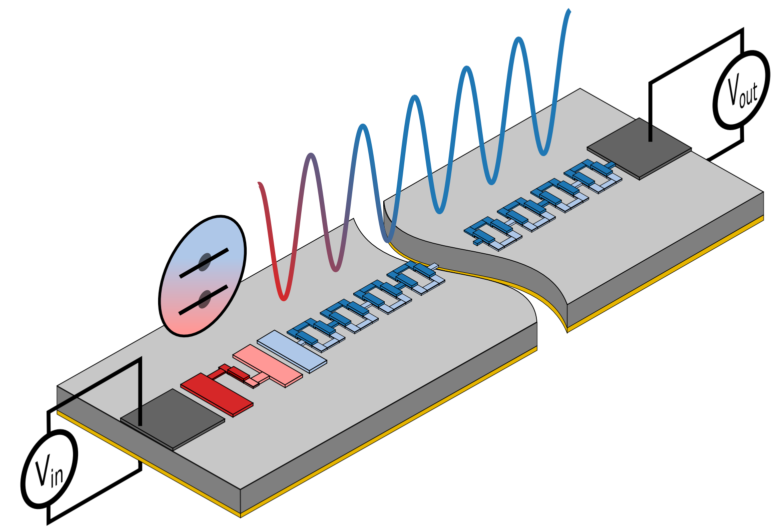
R. Fazio & H. van der Zant, Physics Reports (2001)

Model systems



e.g. dissipative quantum circuits

strong phase fluctuations across a single Josephson junction

$$\langle \varphi^2 \rangle \sim 2\pi$$

A. Schmid, Phys. Rev. Lett. (1983)

Dissipative quantum systems

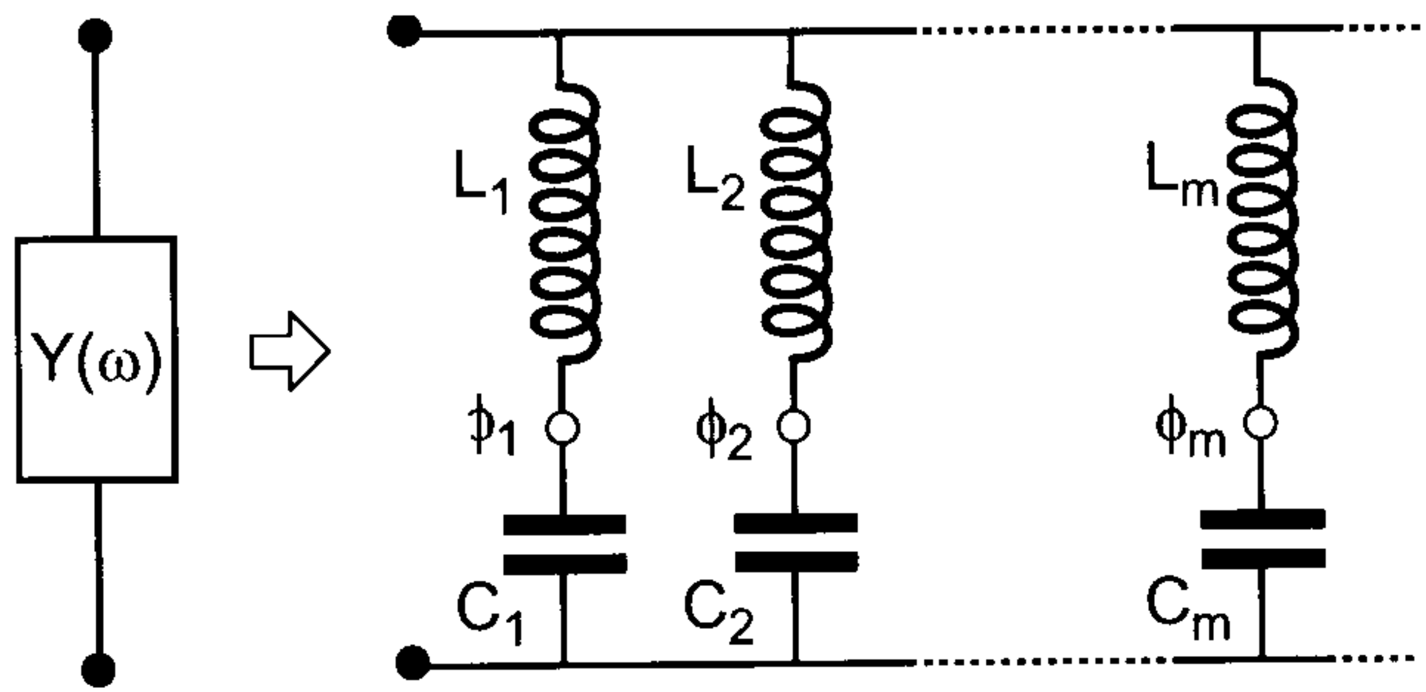


Fig. 7. Caldeira–Leggett model of an admittance $Y(\omega)$.

Figure from

Devoret M. H. in "Quantum Fluctuations", S. Reynaud, E. Giacobino, J. Zinn-Justin, Eds. (Elsevier, Amsterdam, 1997) p. 351-385

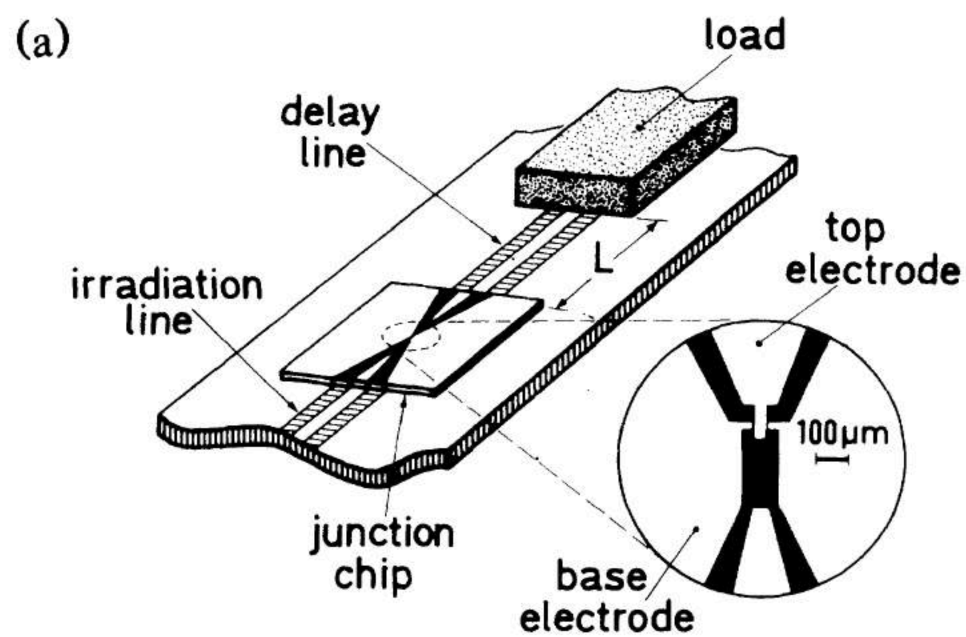
Review

A. O. Caldeira & A. J. Leggett, Annals of Physics (1983)

U. Weiss, Quantum Dissipative Systems (4 ed.). WORLD SCIENTIFIC (2012)

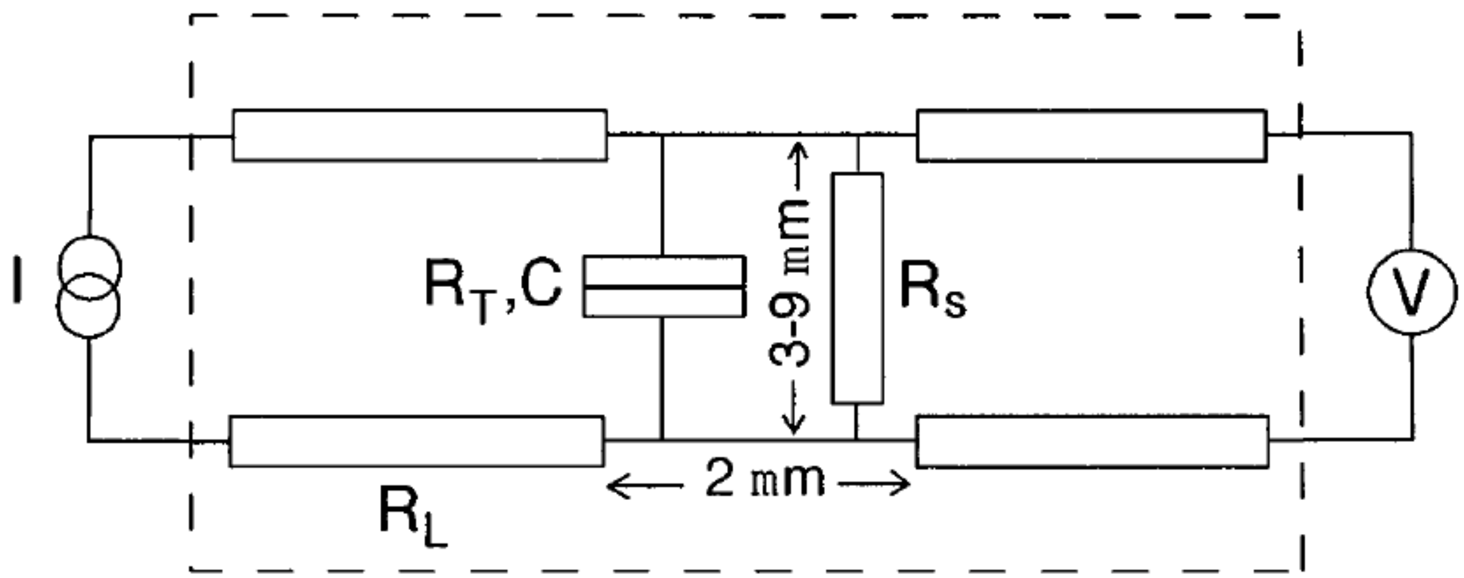
Dissipative quantum systems

Broadening of the quantum levels



E. Turlot, et al., Phys. Rev. Lett. (1989)

Renormalisation of the Josephson energy



J. S. Penttilä, et al., Phys. Rev. Lett. (1999)

Dissipative quantum systems

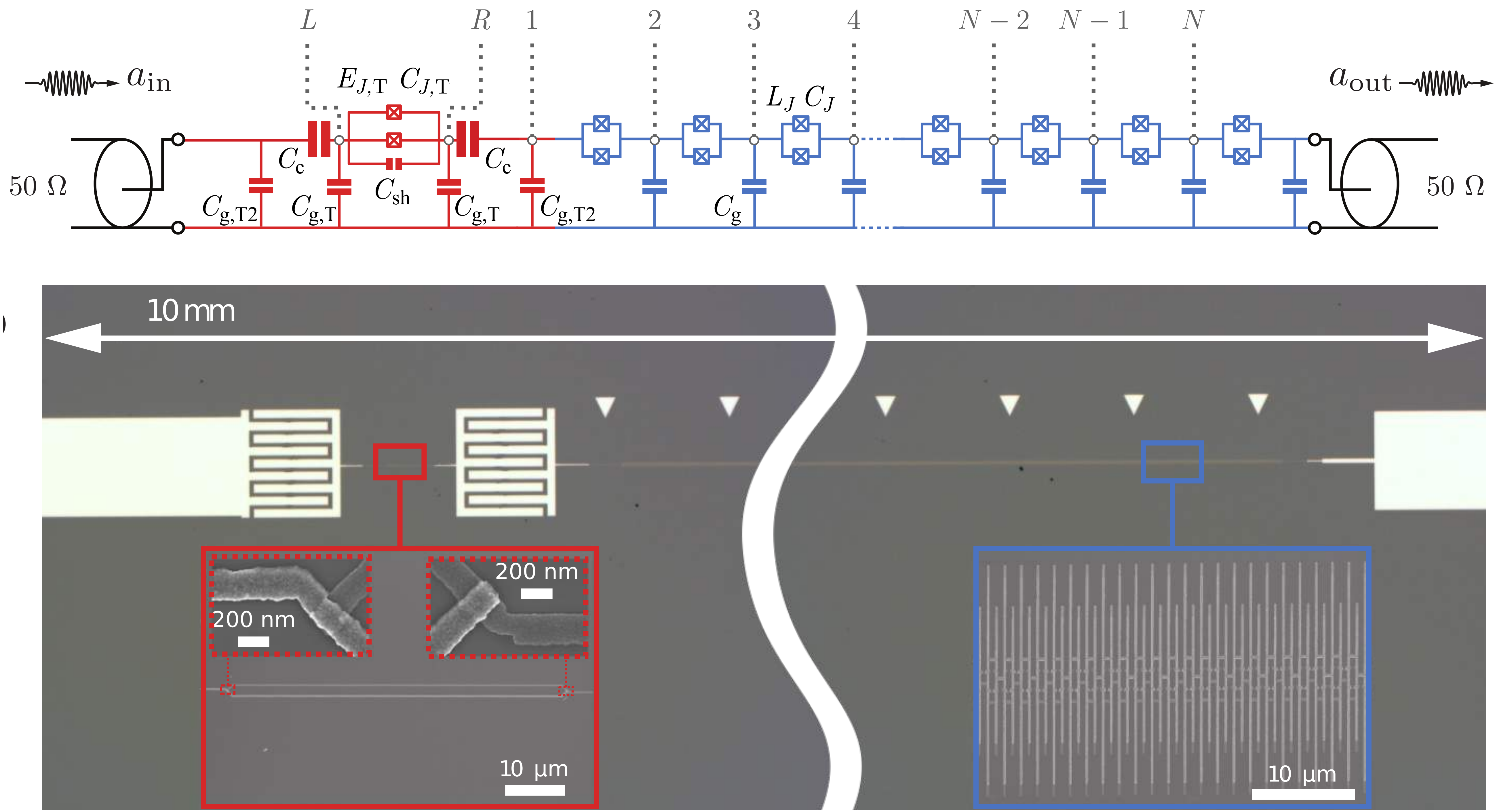
Our plan: make use of cQED to measure the spectrum of the system AND its bath

See also:

P. Forn Díaz, et al., Nat. Phys. (2016)

R. Kuzmin, et al., arxiv 1809.10739

A Transmon coupled to a JJ meta-material



$T = 20$ mK

J. Puertas-Martinez et al., arxiv 1802.00633

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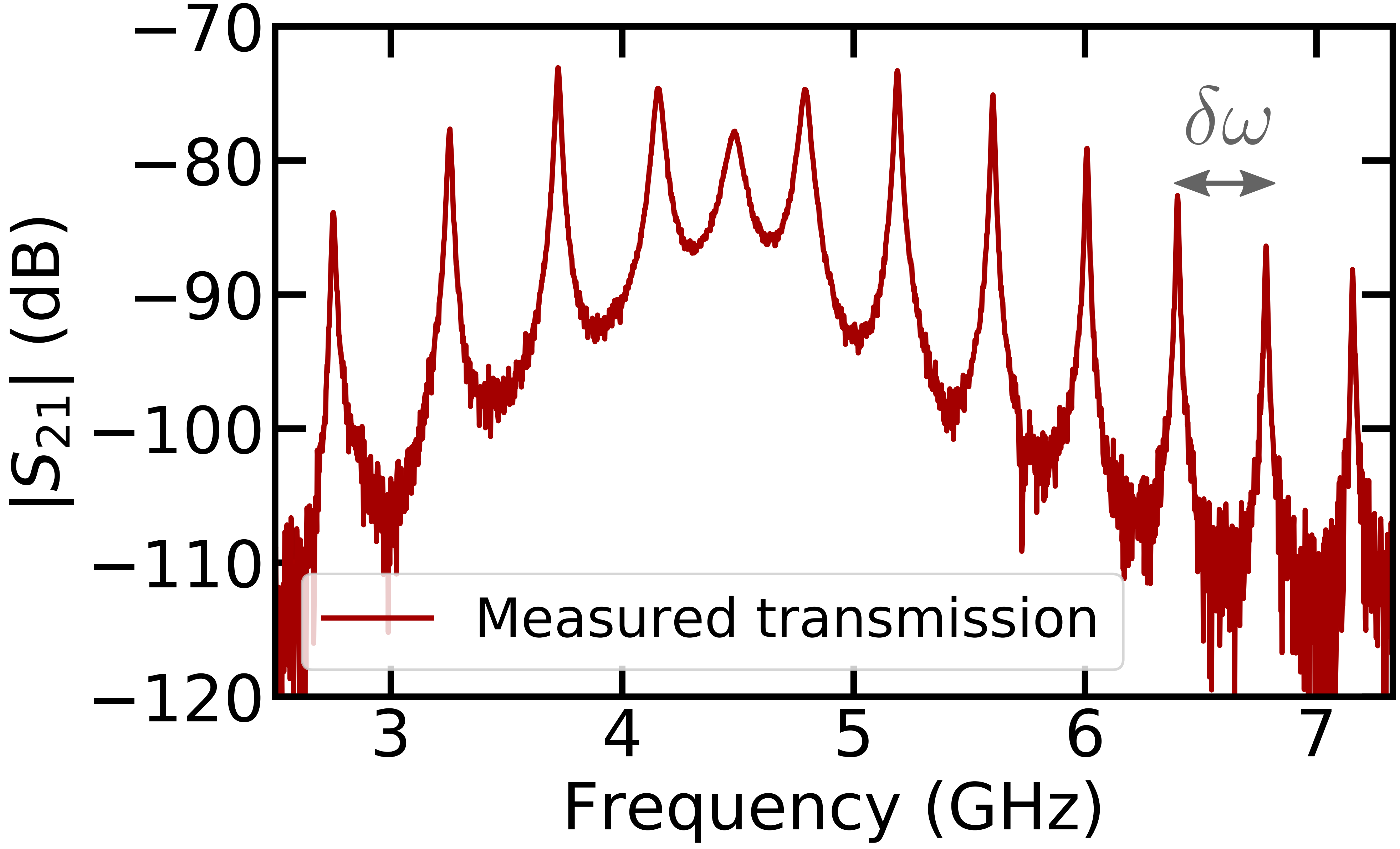

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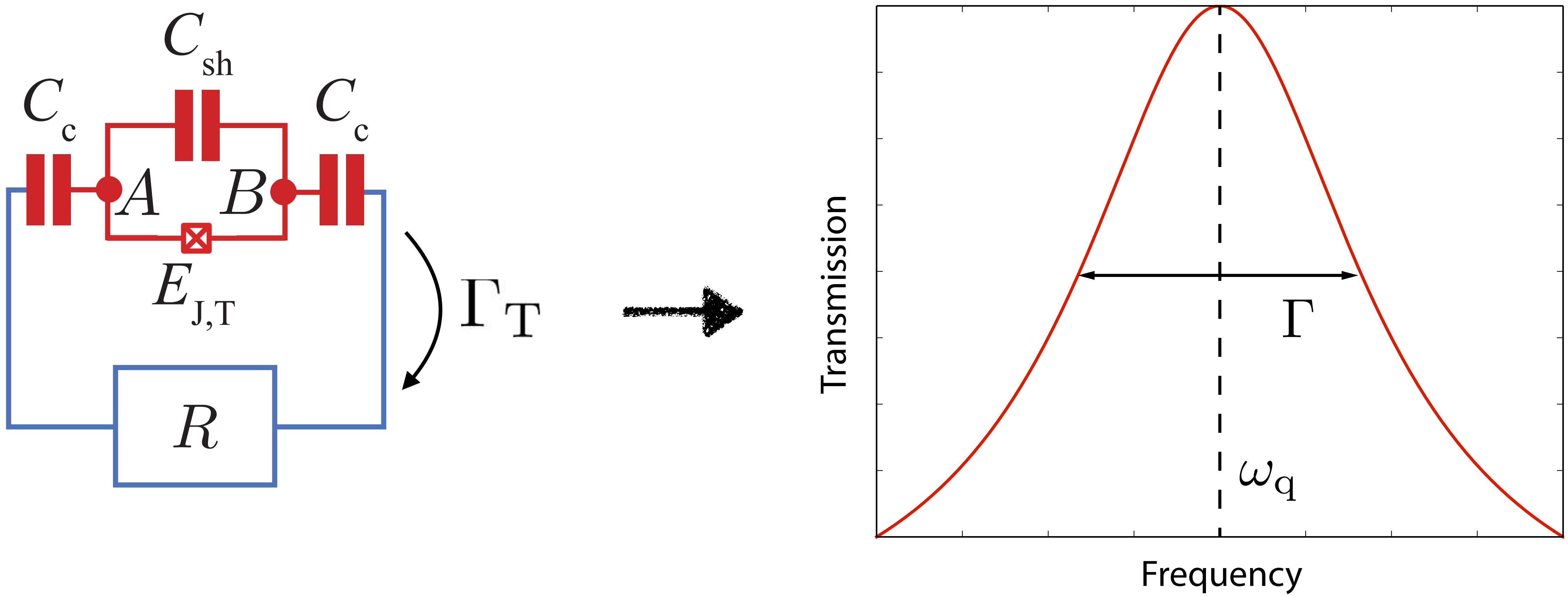
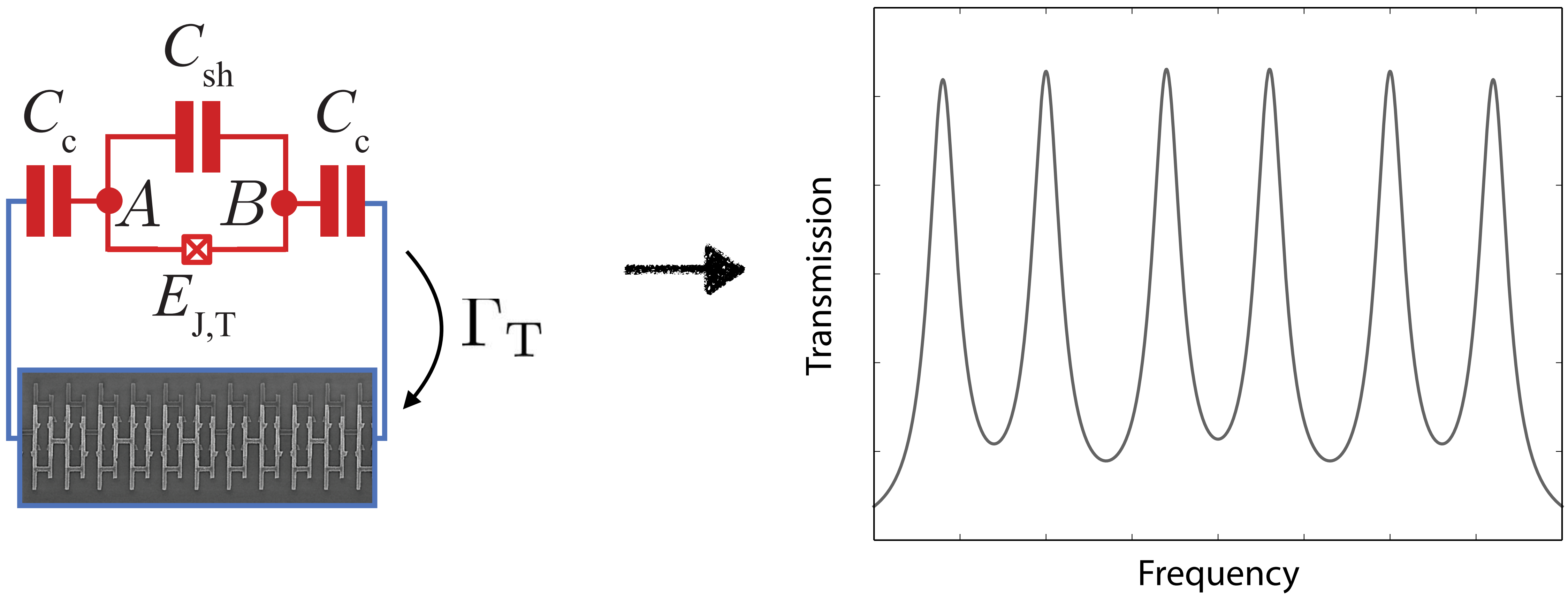
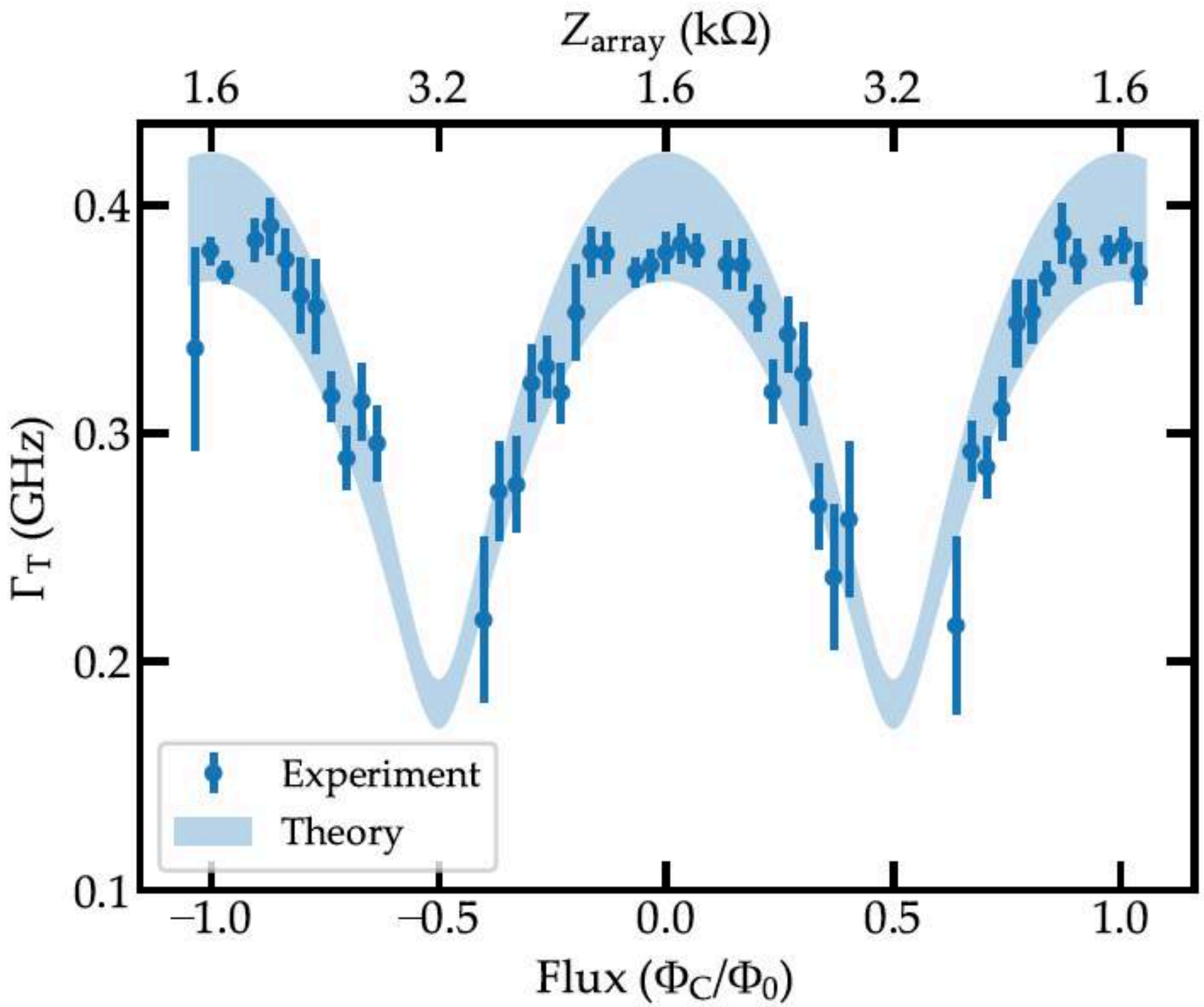




Reaching the ultrastrong coupling regime

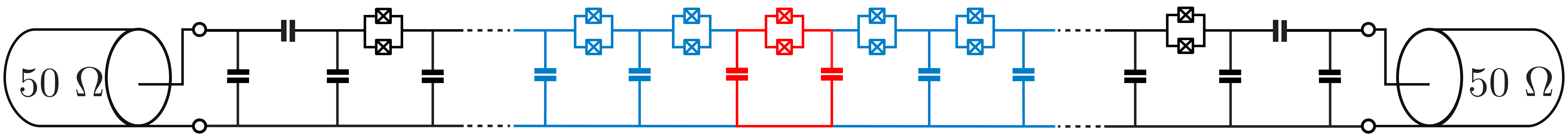


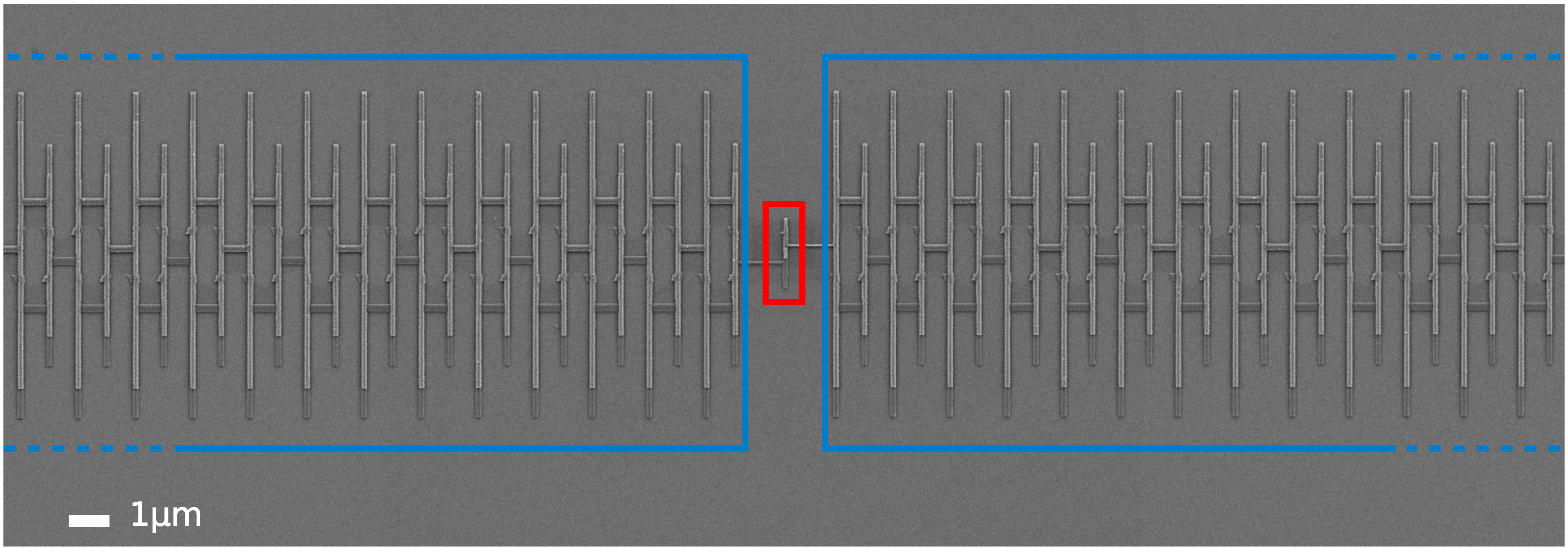
$$\Gamma/\omega_{01} \simeq 10\%$$

Finite-size chain equivalent to infinite one
(if $N_{site} \gtrsim 2000$)

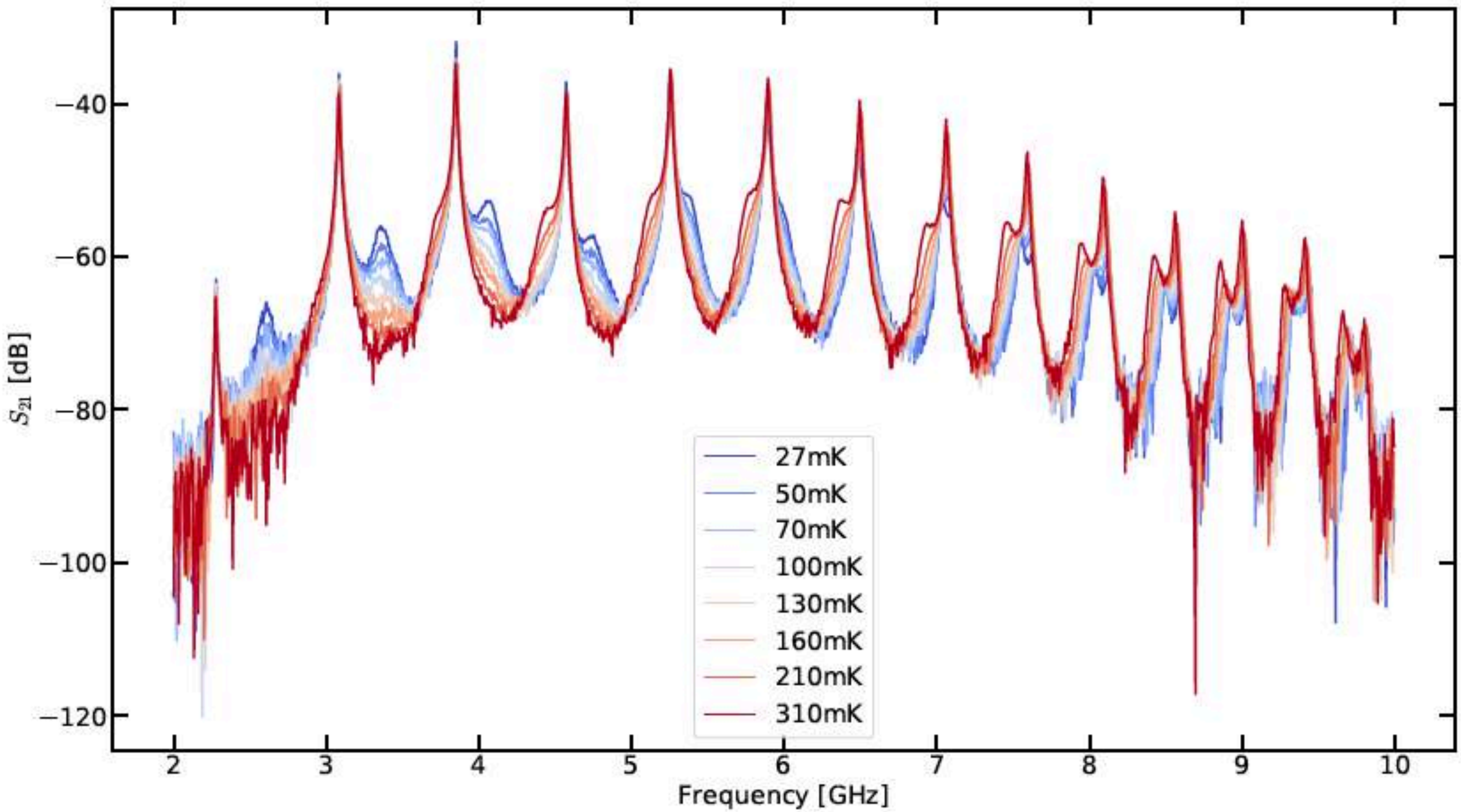
J. Puertas-Martinez et al., arxiv 1802.00633

Renormalisation of the Josephson energy ?





Renormalisation of the Josephson energy ?



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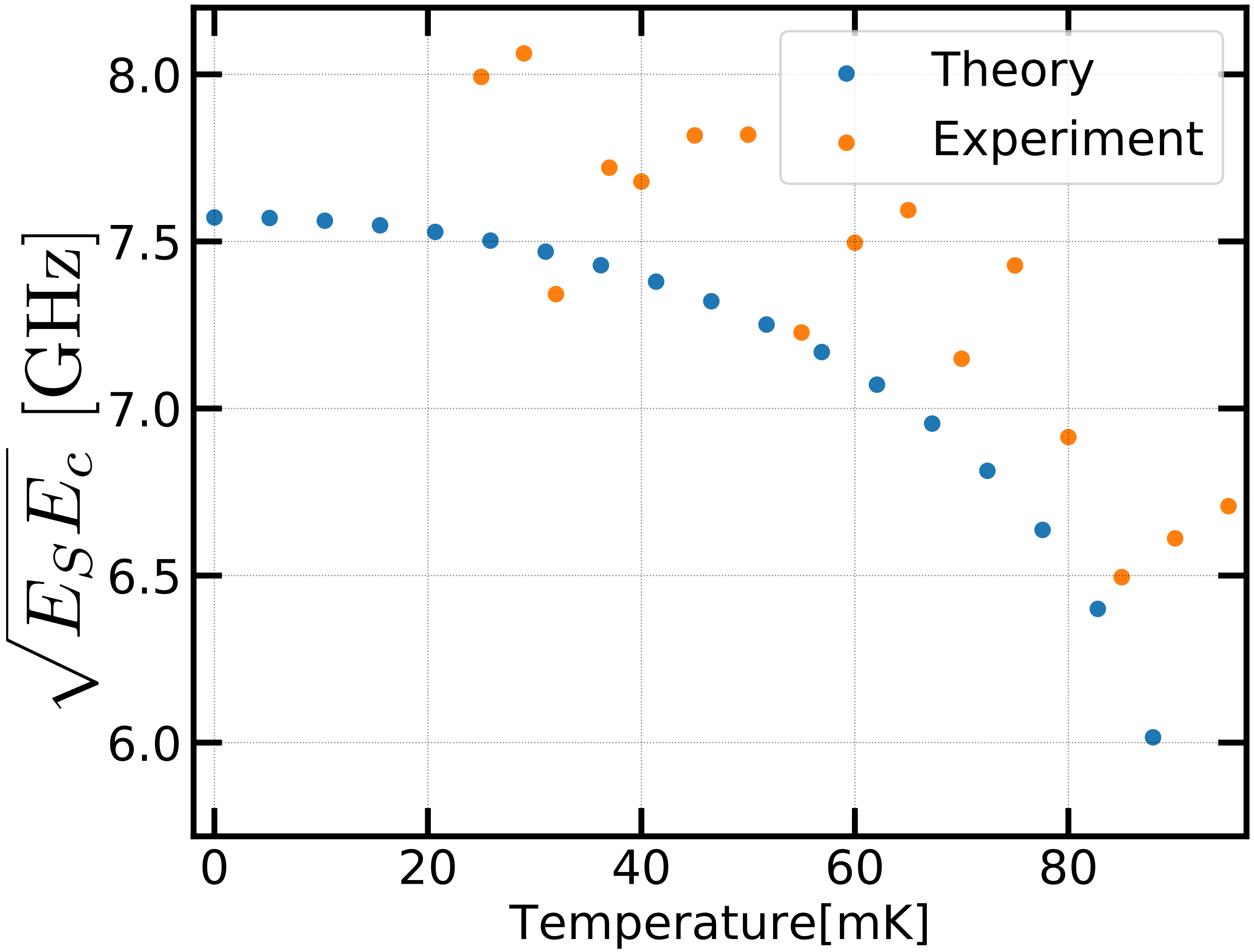


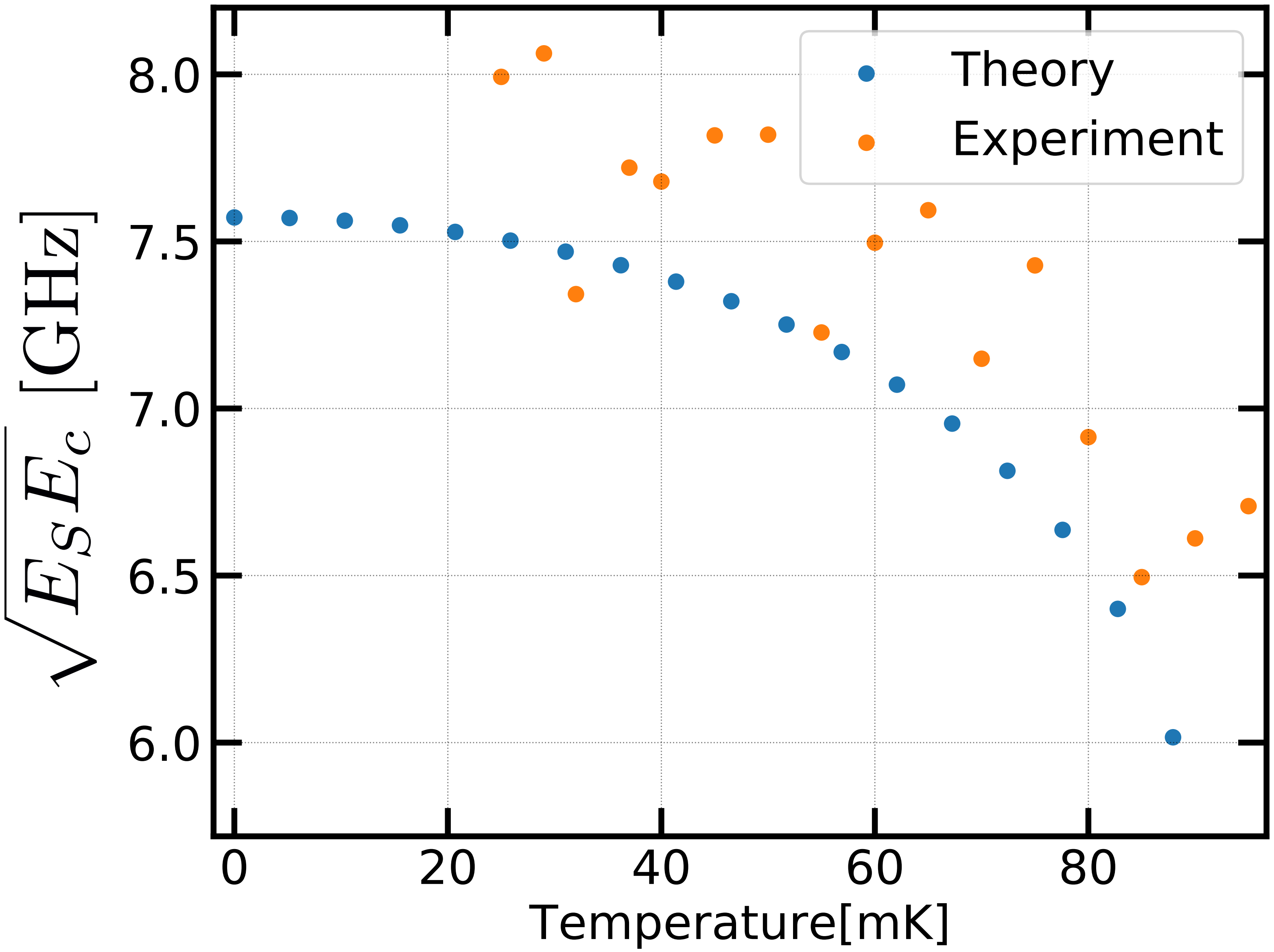
Preliminary data

No phase fluctuation

$$\langle \varphi_T^2 \rangle = 0$$

$$\longrightarrow \quad \sqrt{E_s E_c} \sim 16 \text{ GHz}$$

Renormalisation of the Josephson energy ?



Preliminary data

$$\mathcal{H} = \frac{(2e)^2}{2} \sum_{l,s} \widehat{C}^{-1}_{l,s}\, \widehat{n}_l\, \widehat{n}_s + \sum_l \frac{E_J}{2} \left(\widehat{\varphi}_l - \widehat{\varphi}_{l+1}\right)^2 - E_{J,\mathrm{T}} \cos \widehat{\varphi}_{\mathrm{T}}$$

Theory: Self-Consistent Harmonic Approximation

$$-E_{J,\mathrm{T}} \cos \widehat{\varphi}_{\mathrm{T}} \longrightarrow \frac{E_S}{2} \widehat{\varphi}^2_{\mathrm{T}}$$

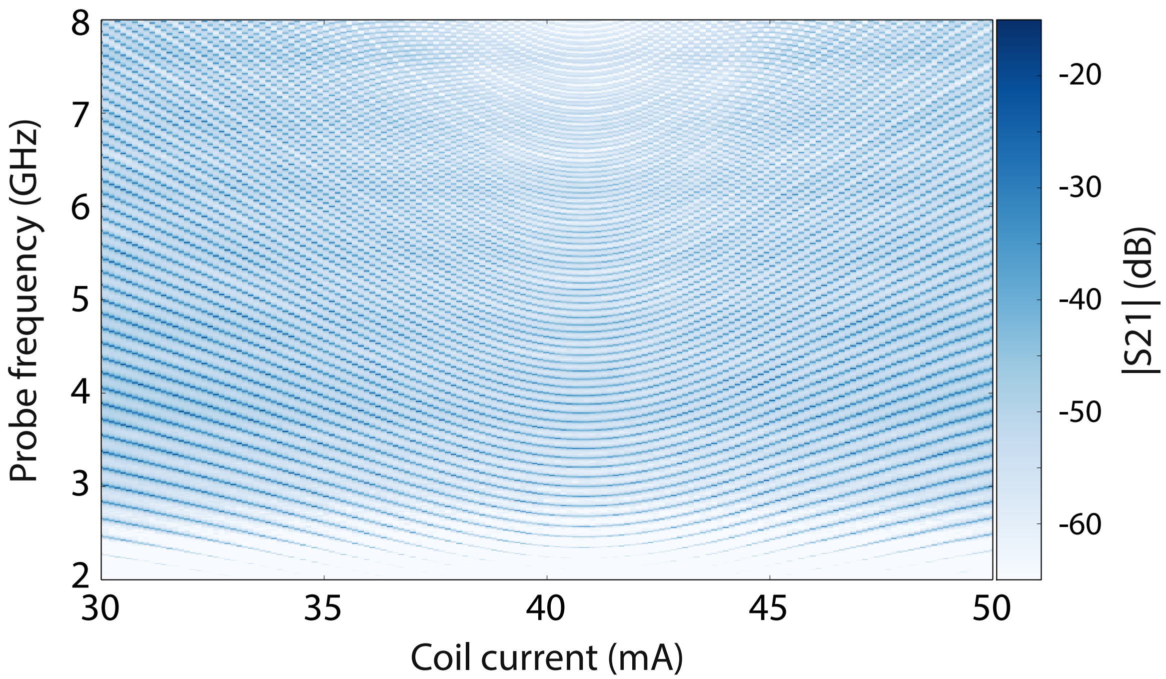
with

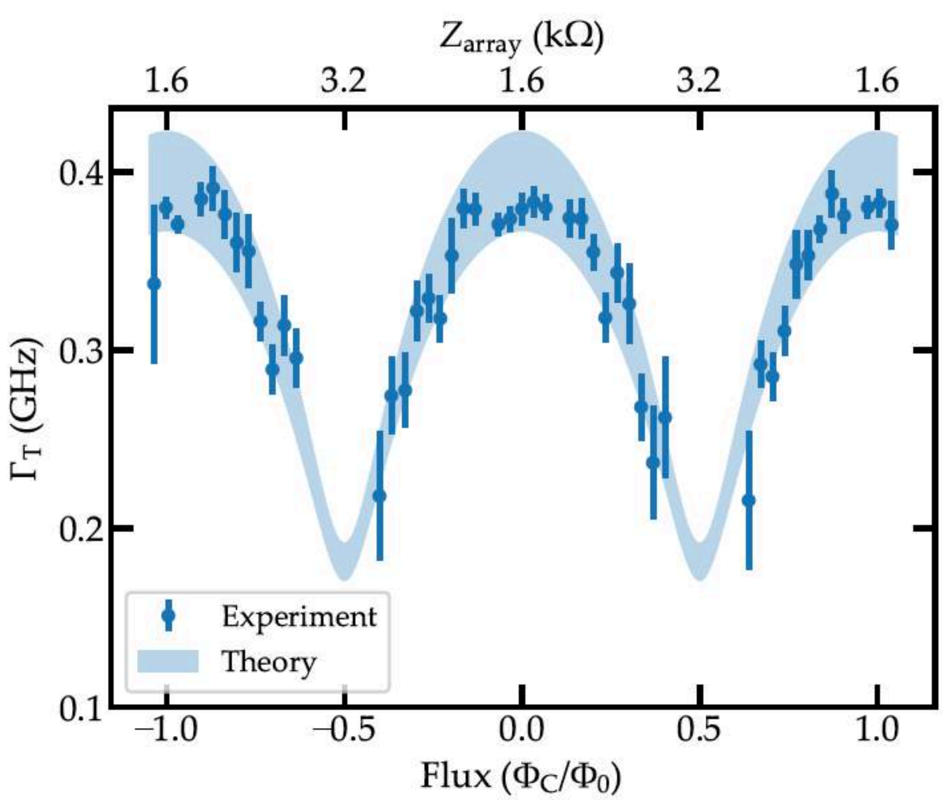
$$E_S = E_J e^{-\frac{1}{2}\langle \Psi | \widehat{\varphi}^2_{\mathrm{T}} | \Psi \rangle}$$

Conclusion

High impedance
Josephson junction metamaterials

Y. Krupko et al., Phys. Rev. B (2018)

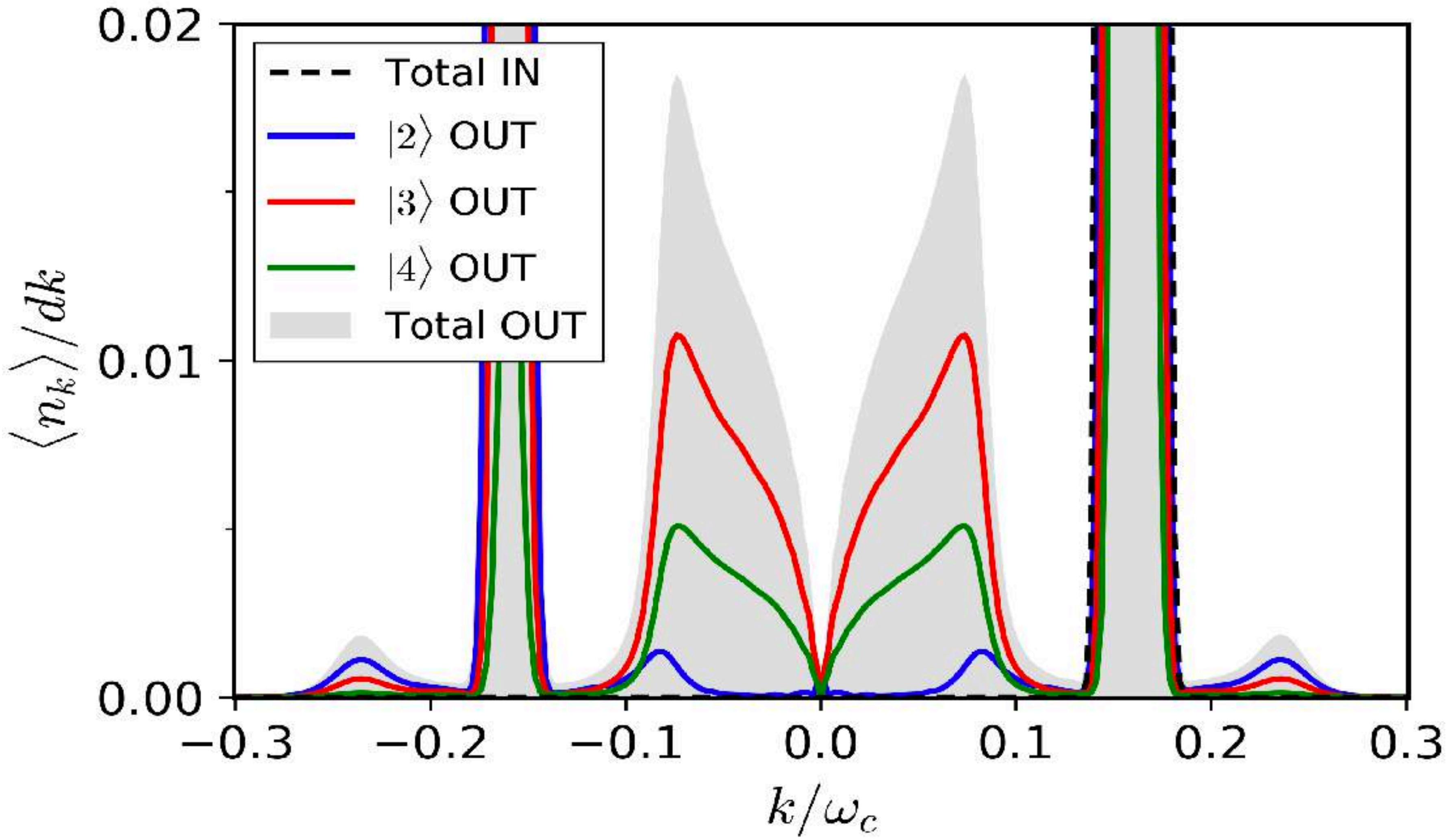




Dissipative quantum circuits:
monitoring the system AND its
bath

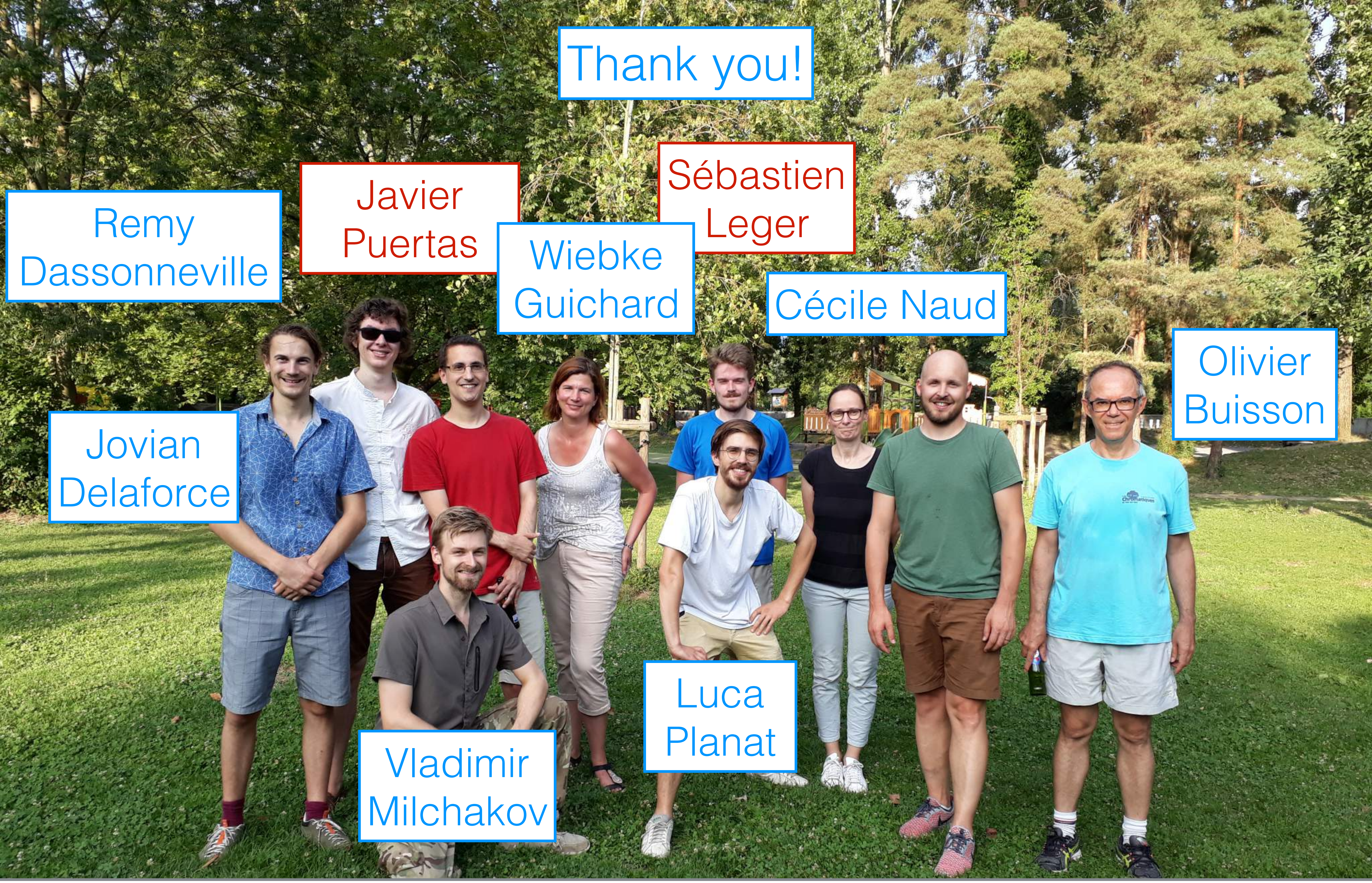
J. Puertas-Martinez et al.,
arxiv 1802.00633

Perspectives: linking quantum optics and many-body physics



Gheeraert et al., arXiv:1802.01665

Inelastic scattering
of coherent states on a many-body system



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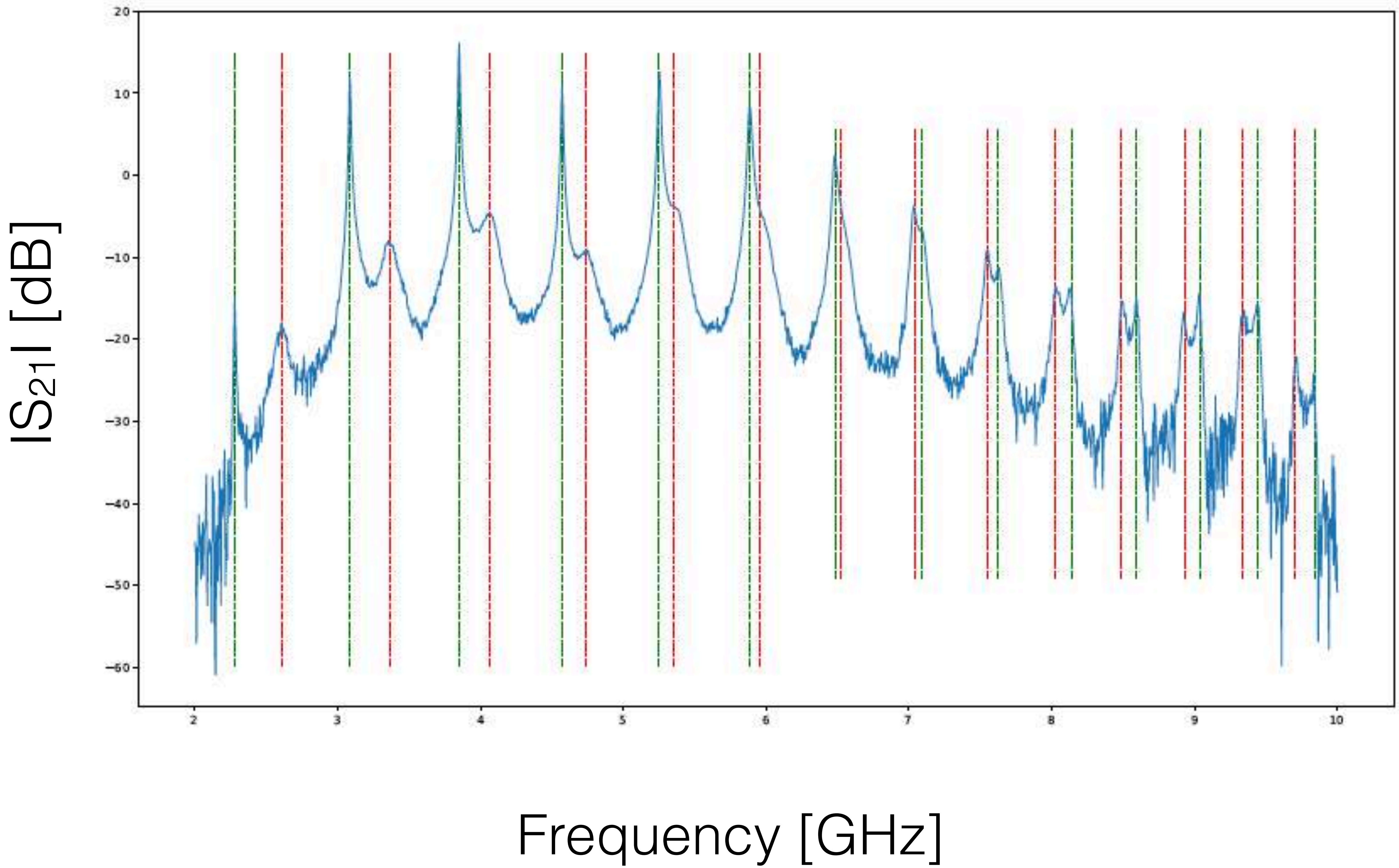
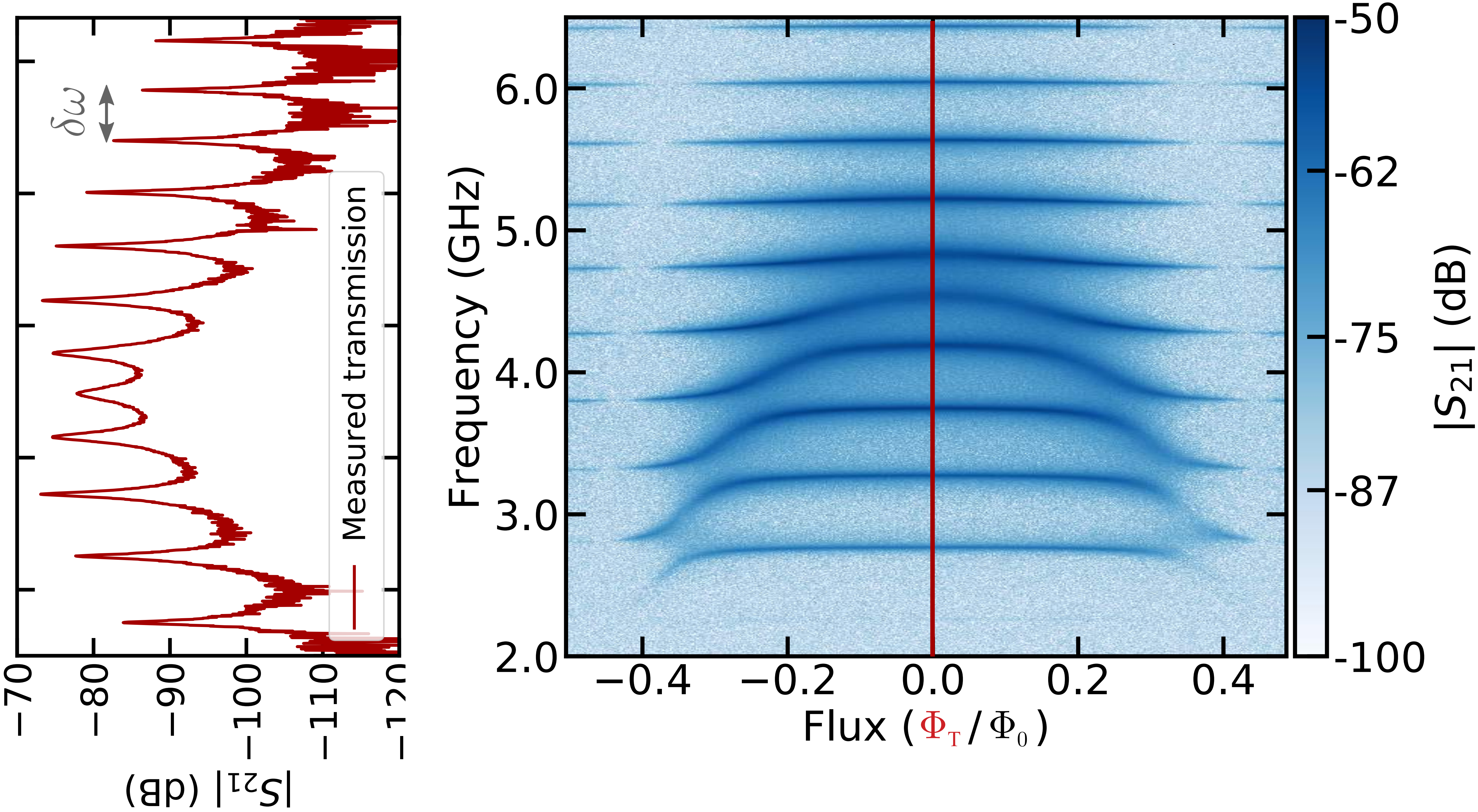

20
10
0
−10
−20
−30
−40
−50
−60
2
3
4
5
6
7
8
9
10
|S21| [dB]
Frequency [GHz]

A Transmon coupled to a JJ meta-material



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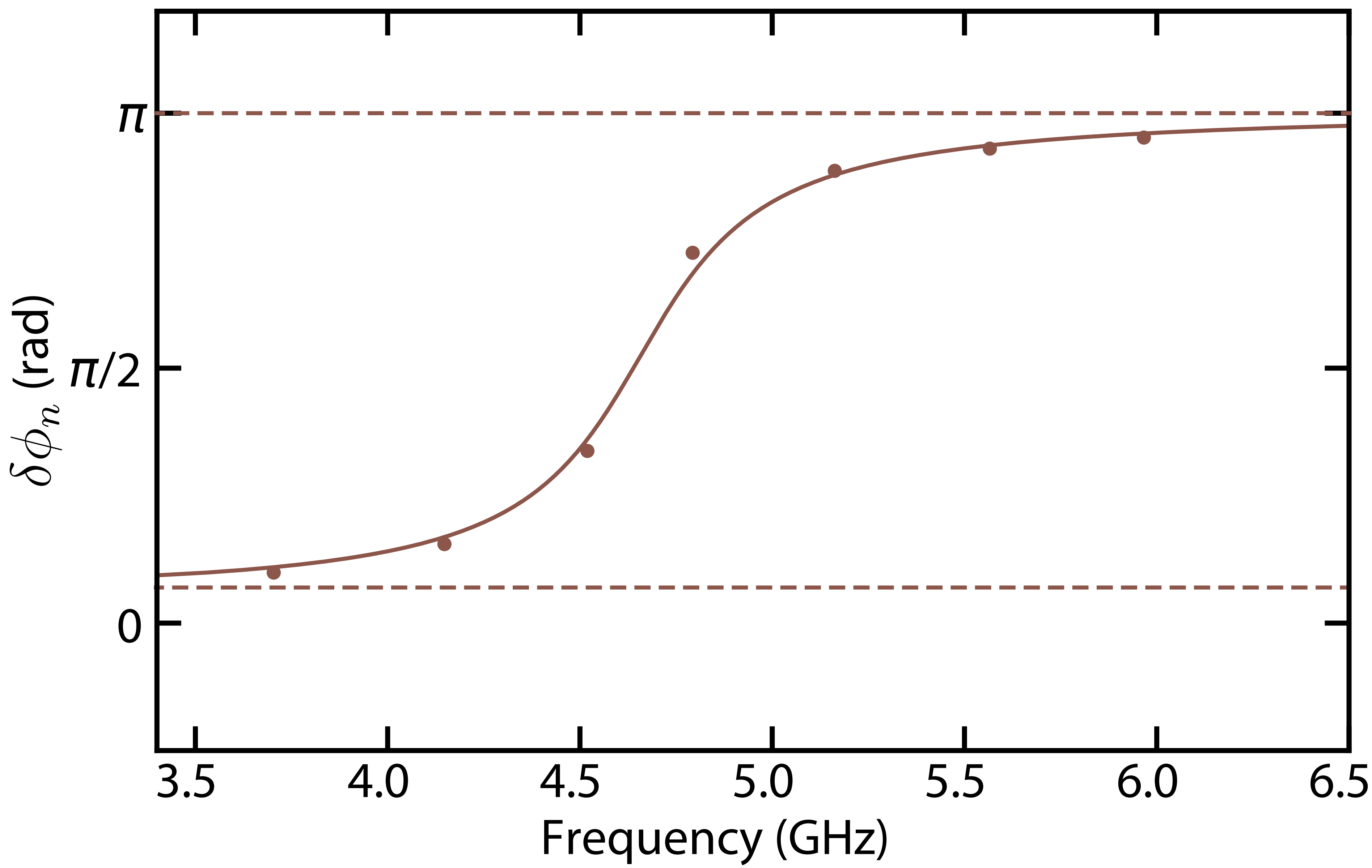

Transmon phase shift

$$\delta\phi_n = \pi \frac{\omega(E_\mathrm{J} = 0) - \omega(E_\mathrm{J} \neq 0)}{\mathrm{FSR}}$$

Theory without free parameter

Non-linearity