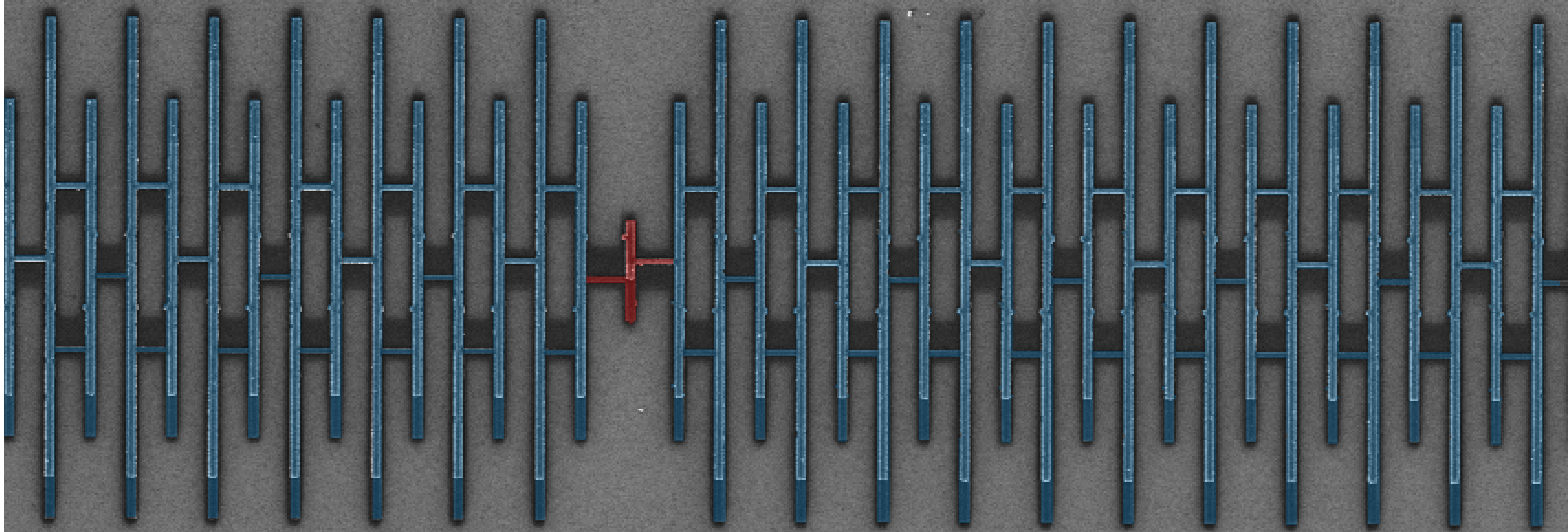
High-Impedance Circuits, Superinductances and Fluxonium Qubits

Nicolas Roch, Institut Néel, Grenoble, France



10μm

2025 Spring School on
Superconducting Qubit Technology

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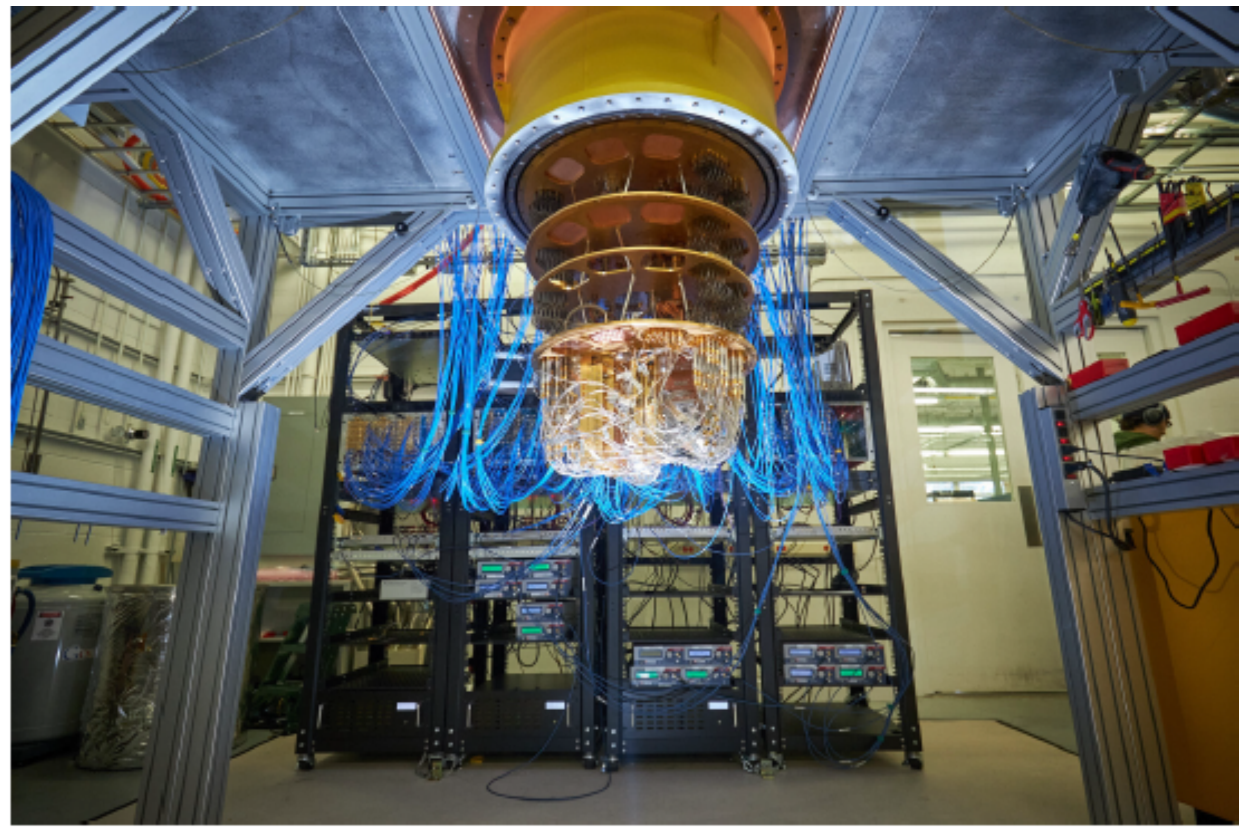
SQC

Understanding the quantum behaviour of superconducting circuits

Quantum computing

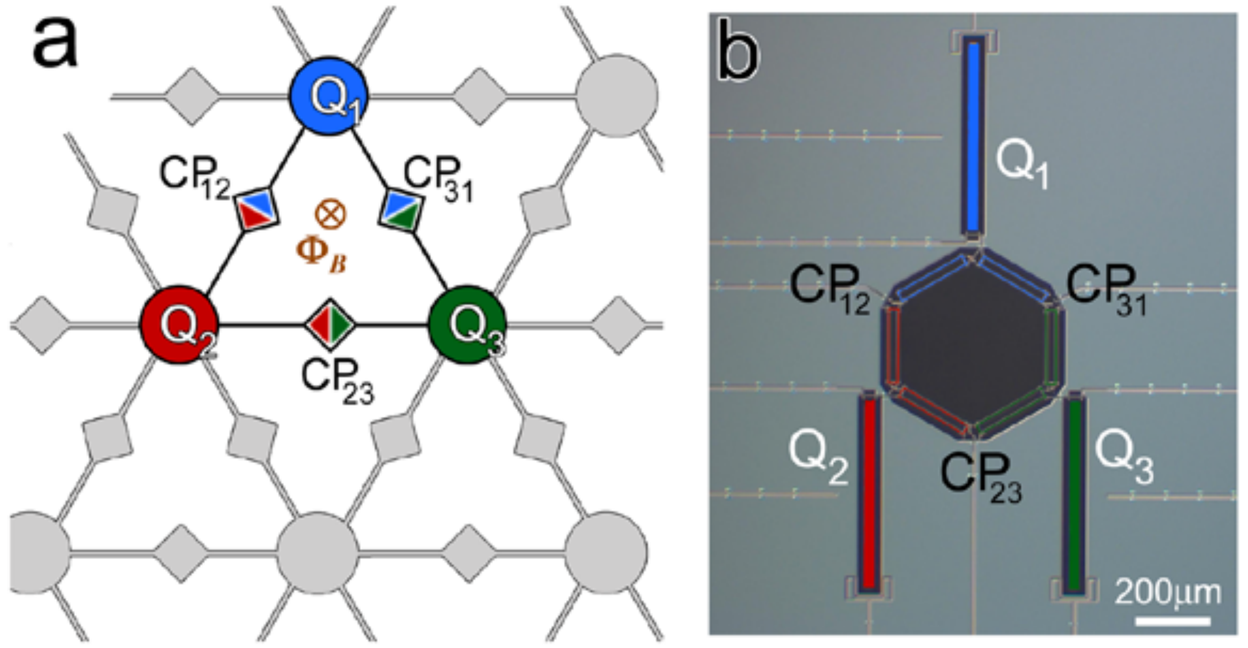


Credit: Google Quantum

Quantum communications

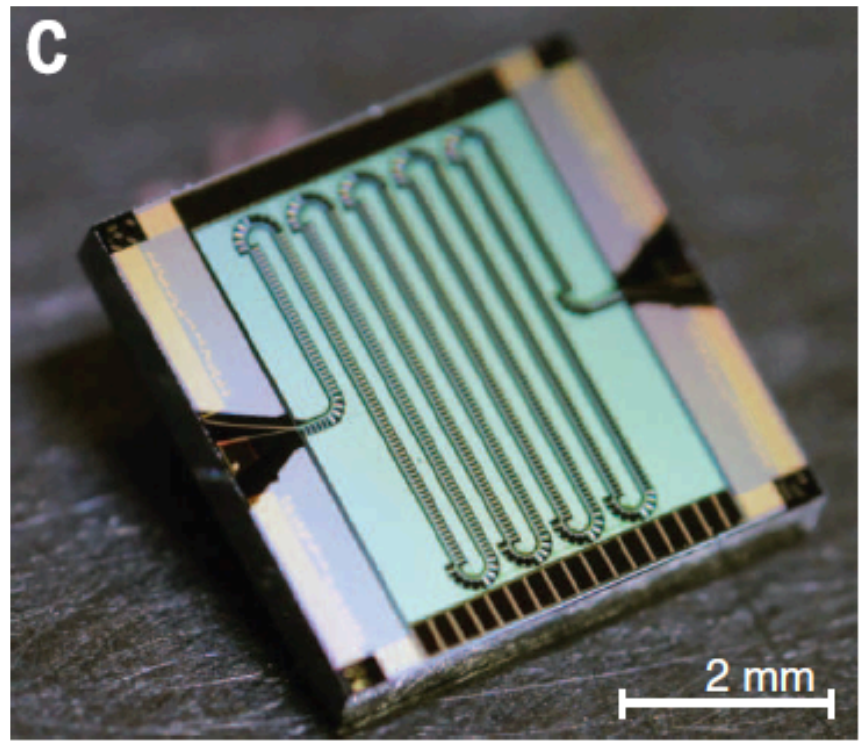
Credit: ETH Zurich Department of Physics

Quantum simulation



Roushan et al. 16'

Quantum sensing



Macklin et al. 15'

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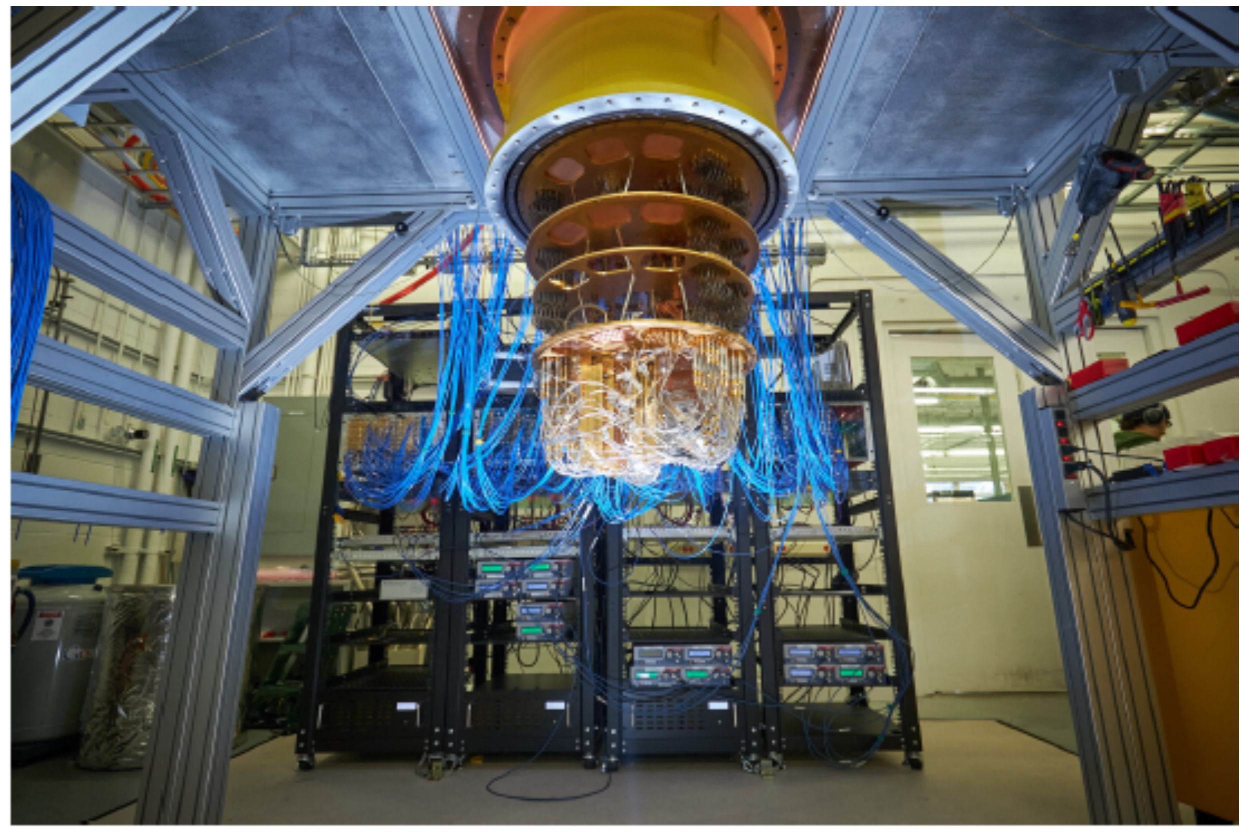

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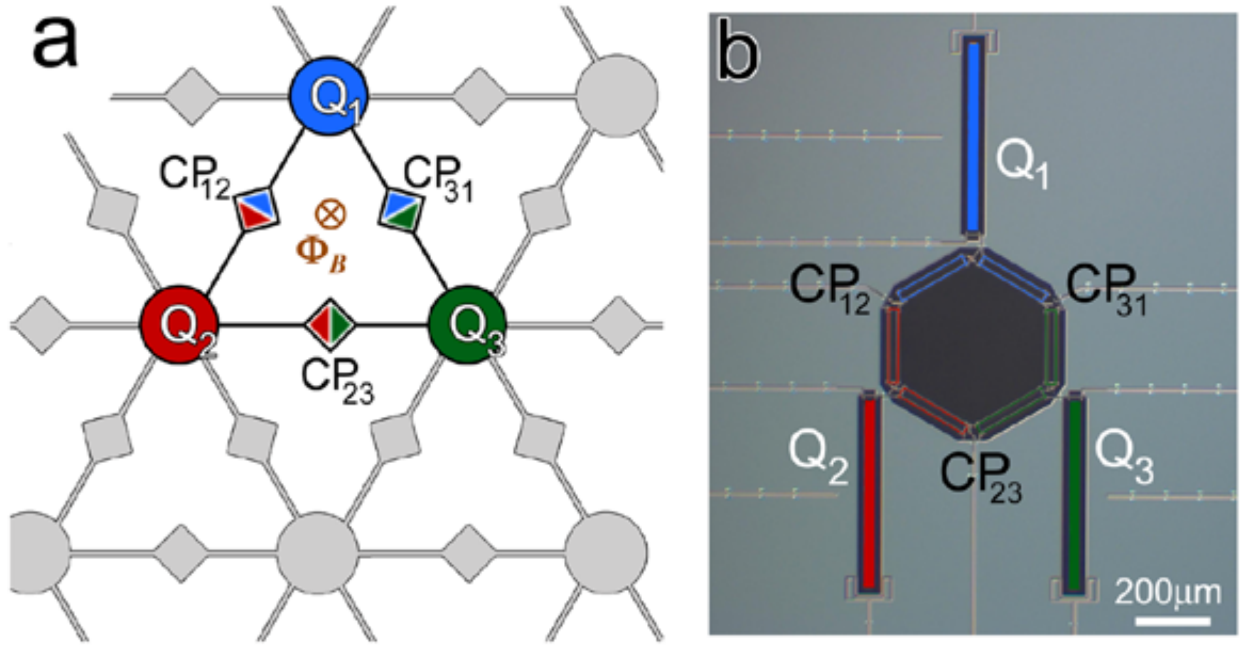
Still many open questions!

Ultimate limit of decoherence (quasi-particles, cosmic rays, materials..)

Large scale (many-body) system

Best way to protect coherence (a huge computer with decent qubits, a smaller computer with outstanding qubits…)

Quantum simulation



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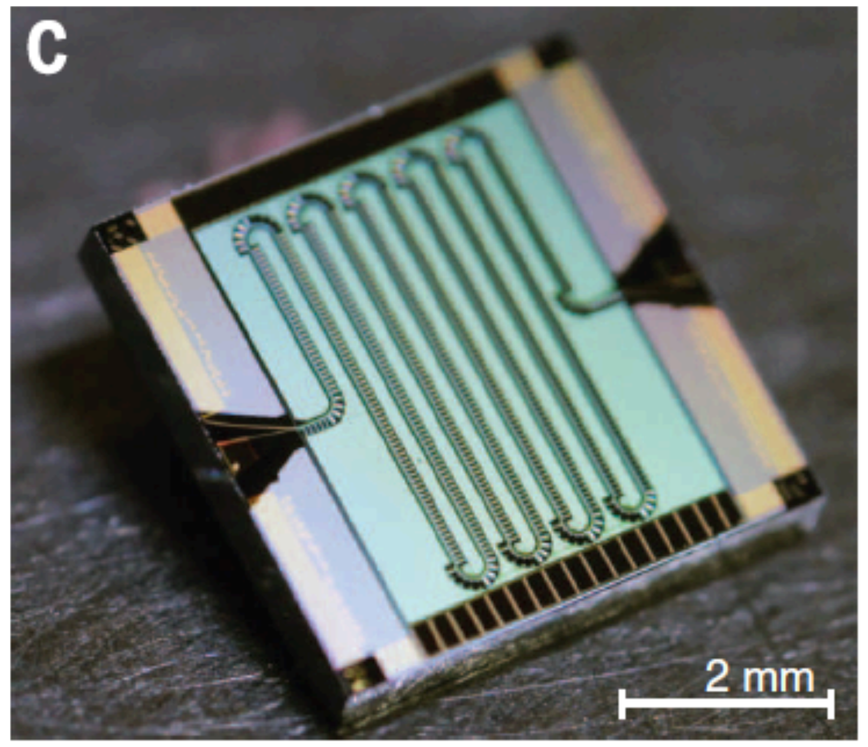

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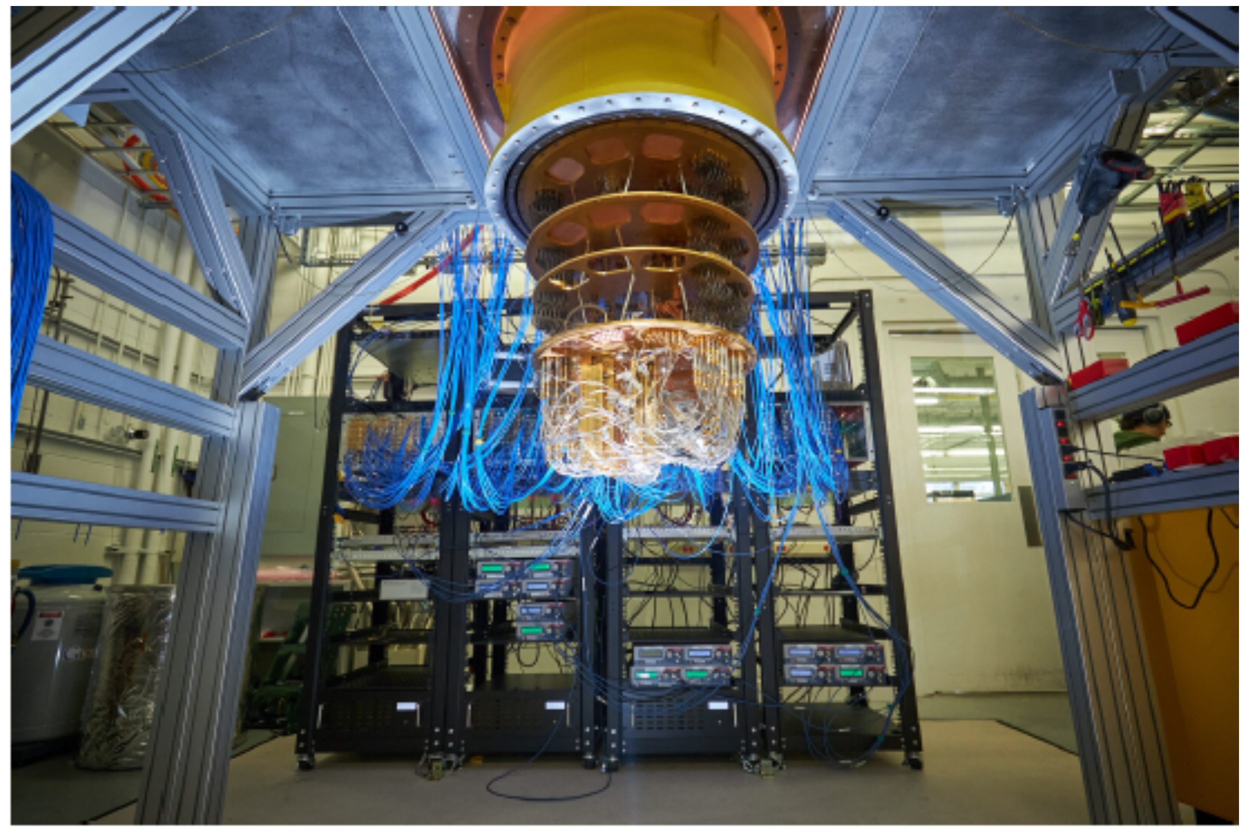

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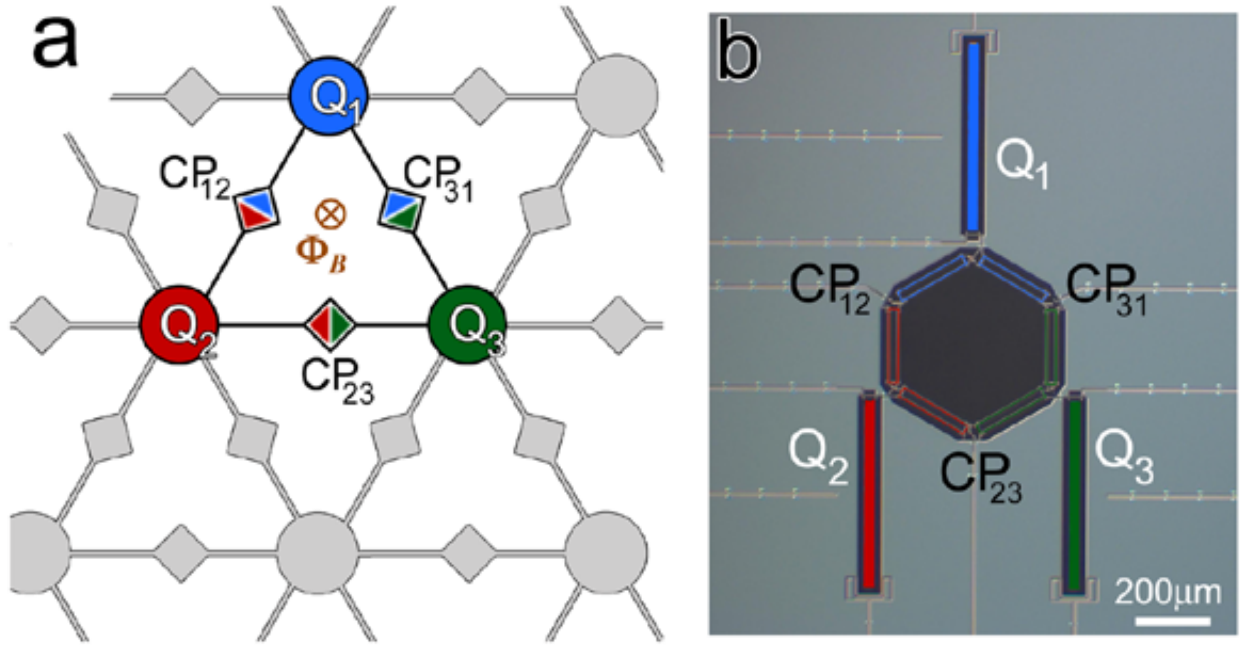

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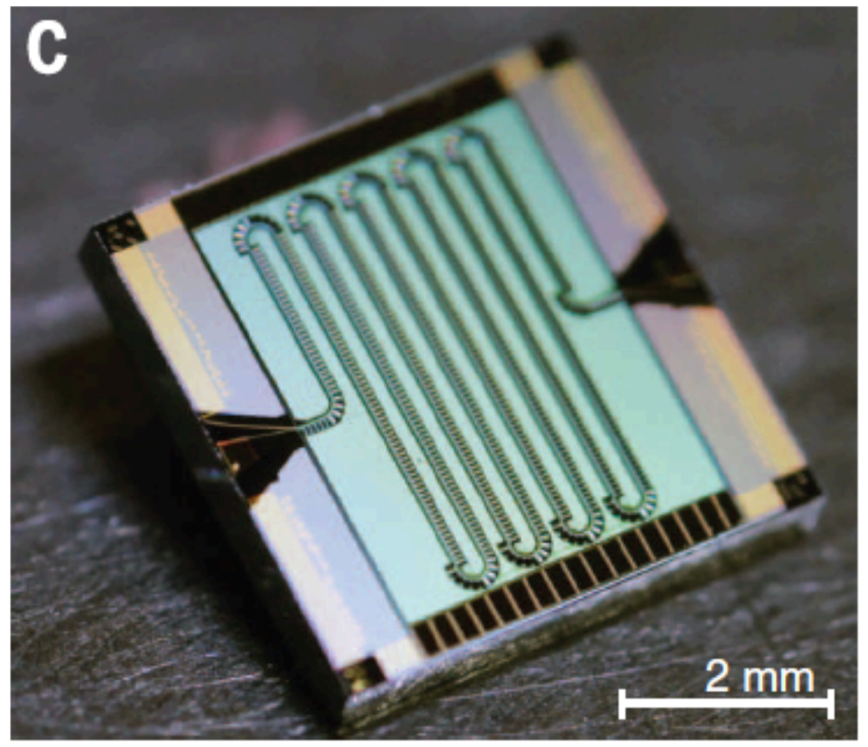

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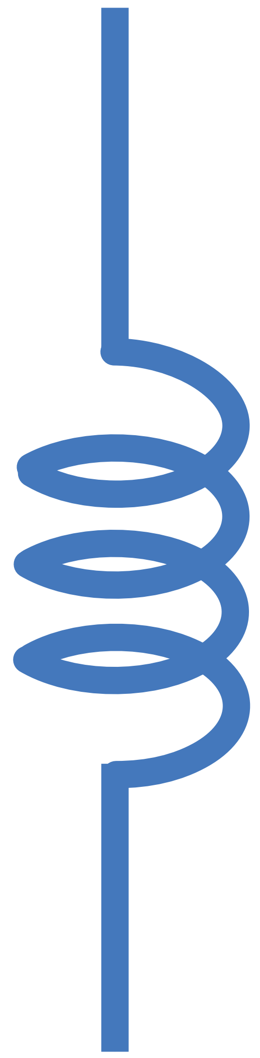
High impedance quantum circuits

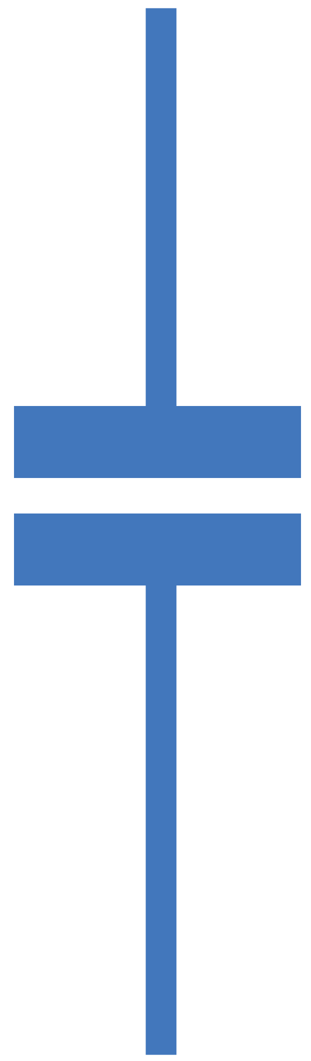
Nature prefers low impedance/low inductance

(passive) electric dipoles



Inductance

$$L = \frac{\mu_0 l}{2\pi}$$



Capacitance

$$C = \frac{\epsilon_0 S}{d}$$

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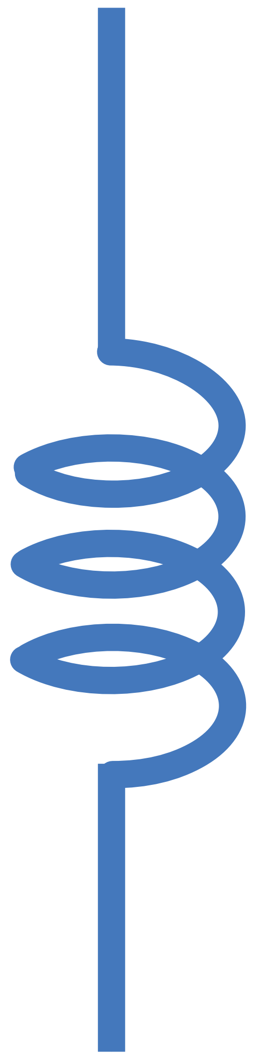

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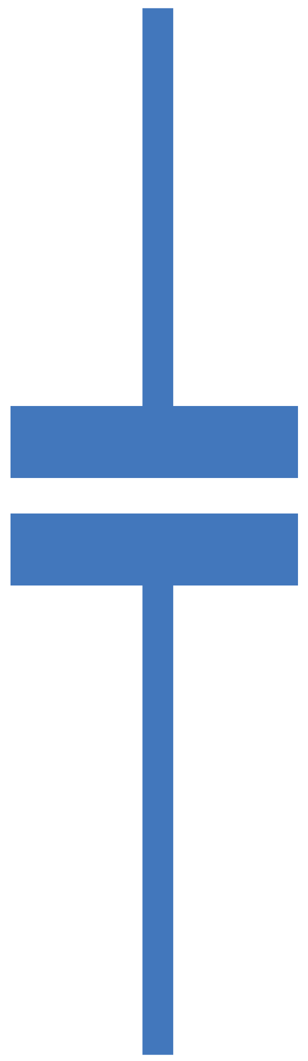

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Conductance quantum

Fine structure constant: $$\alpha = \frac{e^2}{2\epsilon_0 hc} = \frac{1}{4}\sqrt{\frac{\mu_0}{\epsilon_0}}\frac{2e^2}{h} \simeq \frac{1}{137}$$

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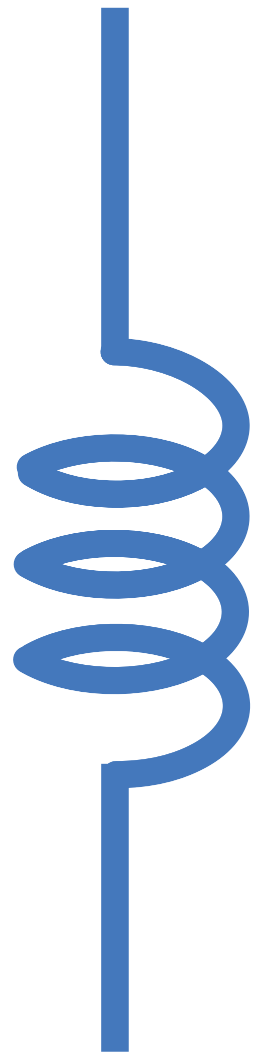

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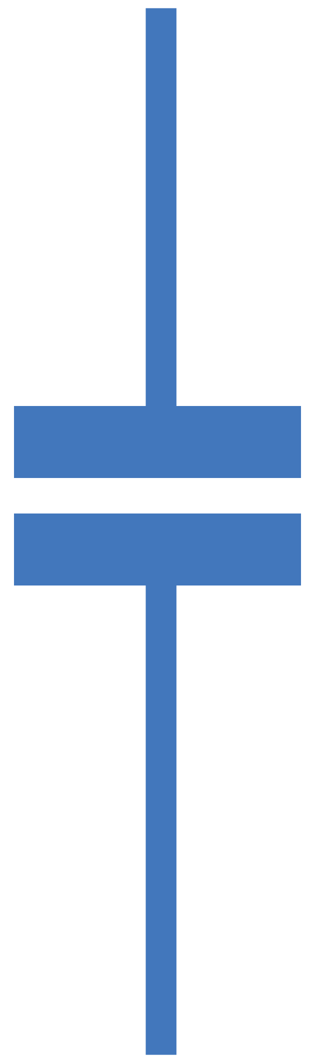

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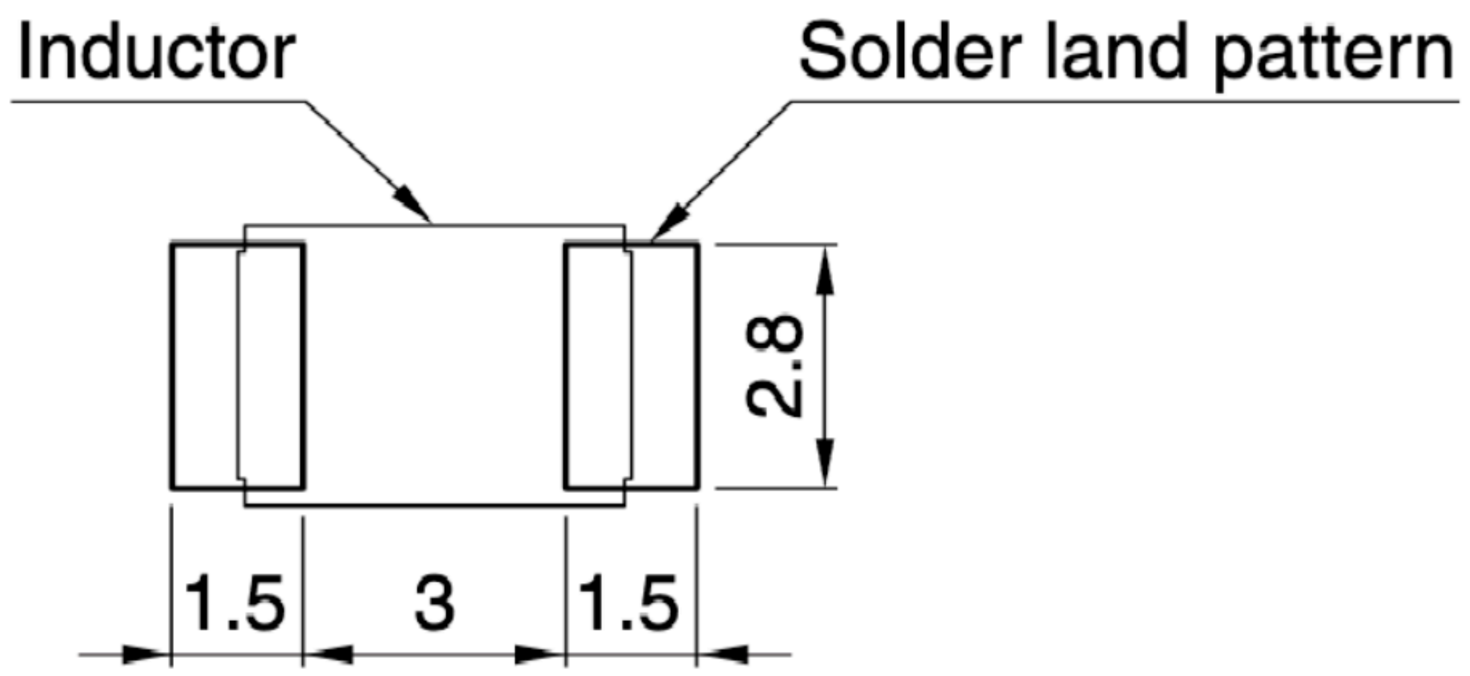
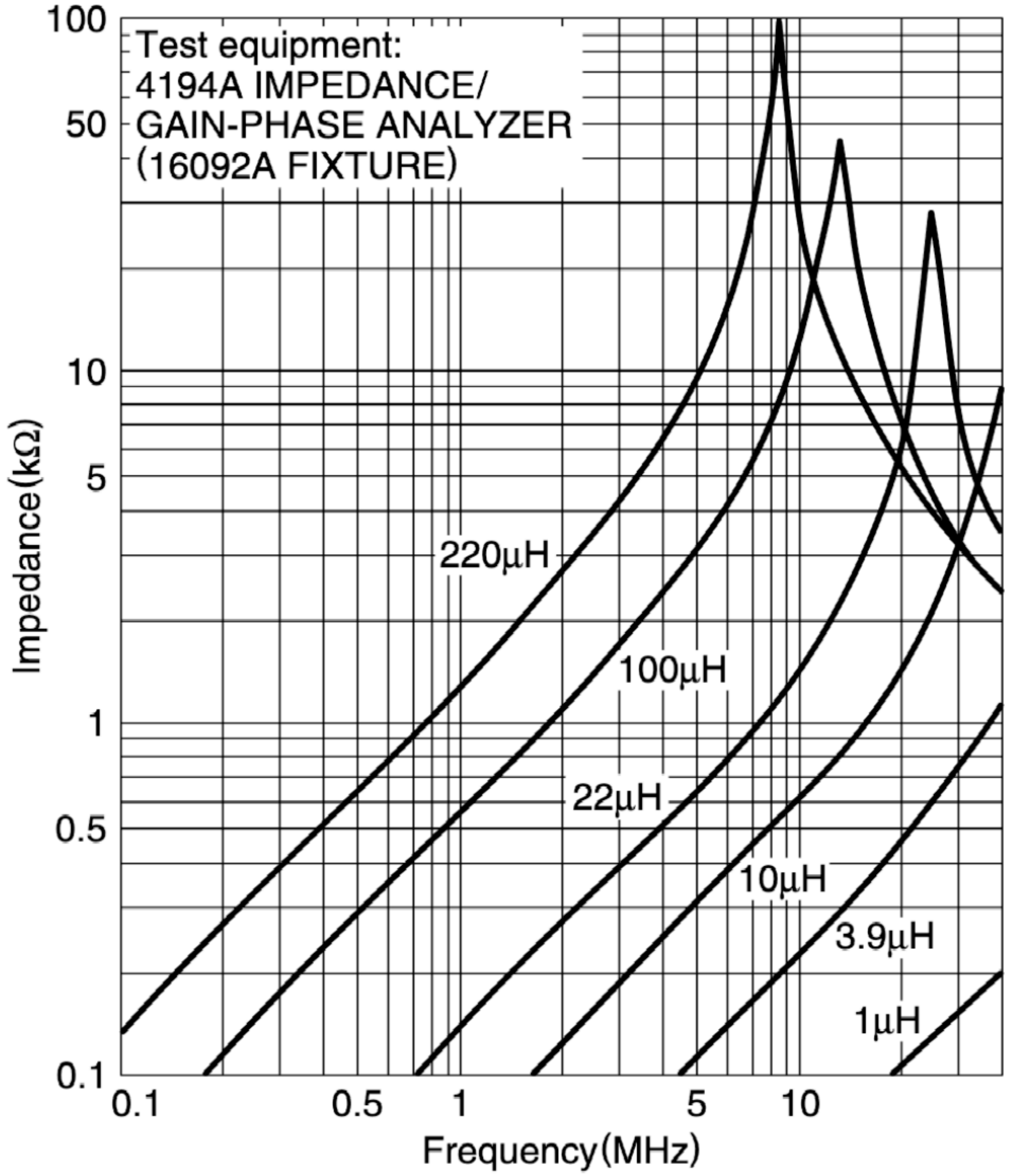
Can we build large inductance (quantum) circuits?

Large inductance (quantum) circuits: why is it difficult ?

NLC4532

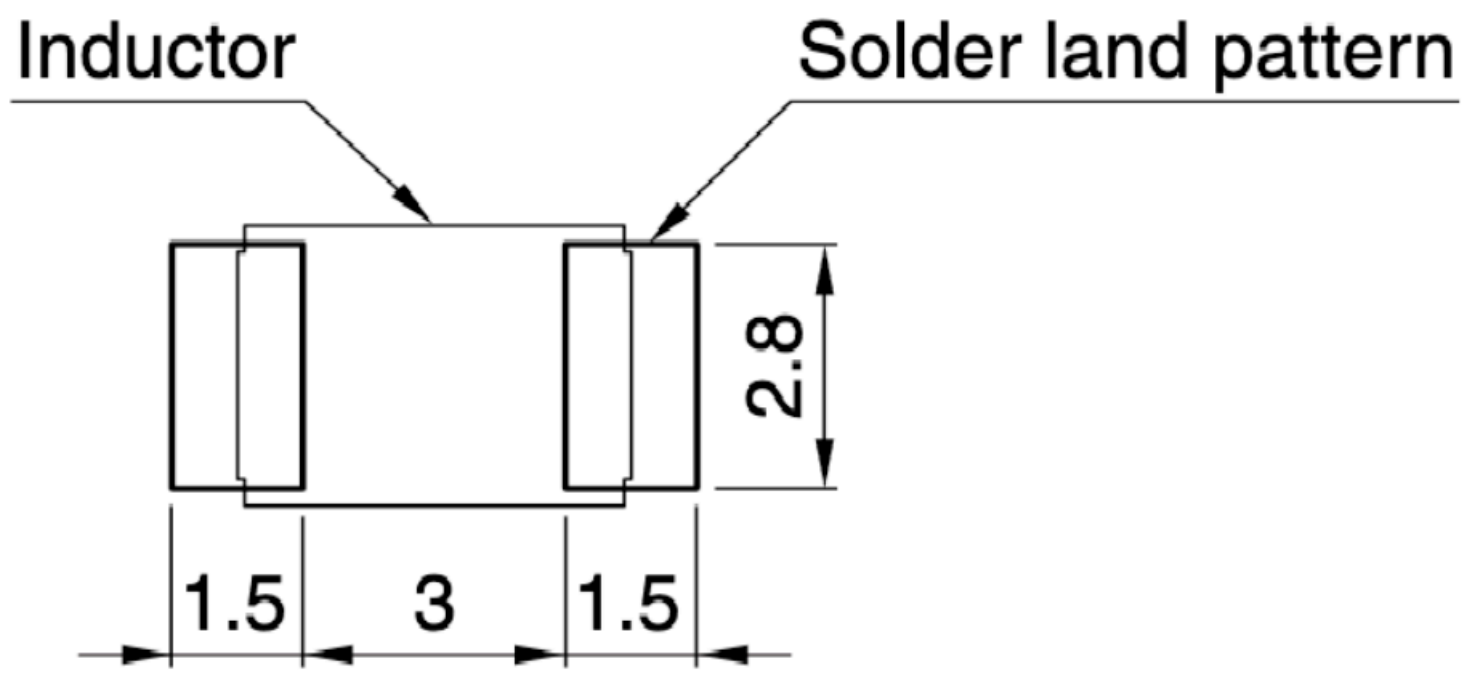


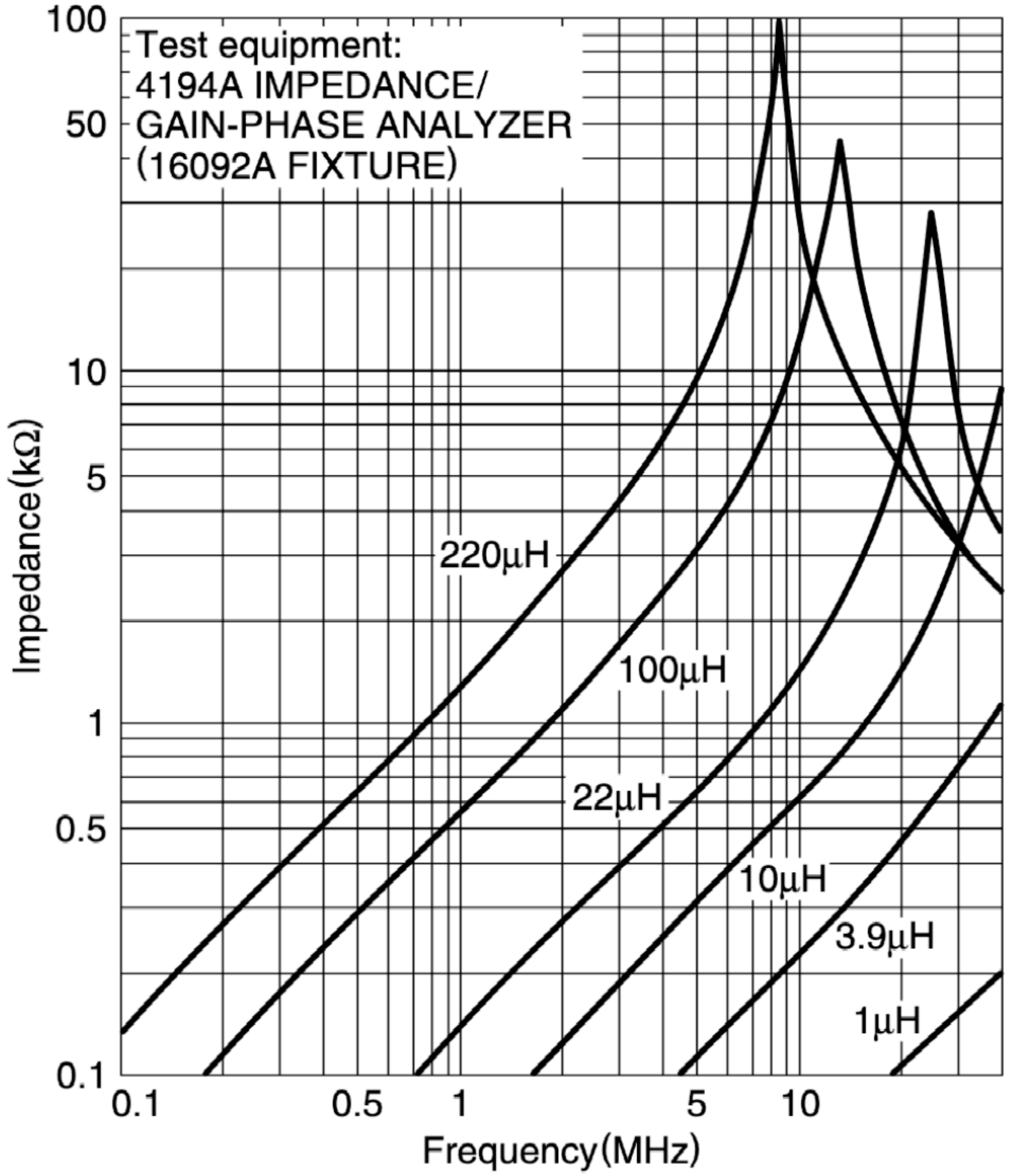


Large inductance (quantum) circuits: why is it difficult ?

TDK

NLC4532





same problem for
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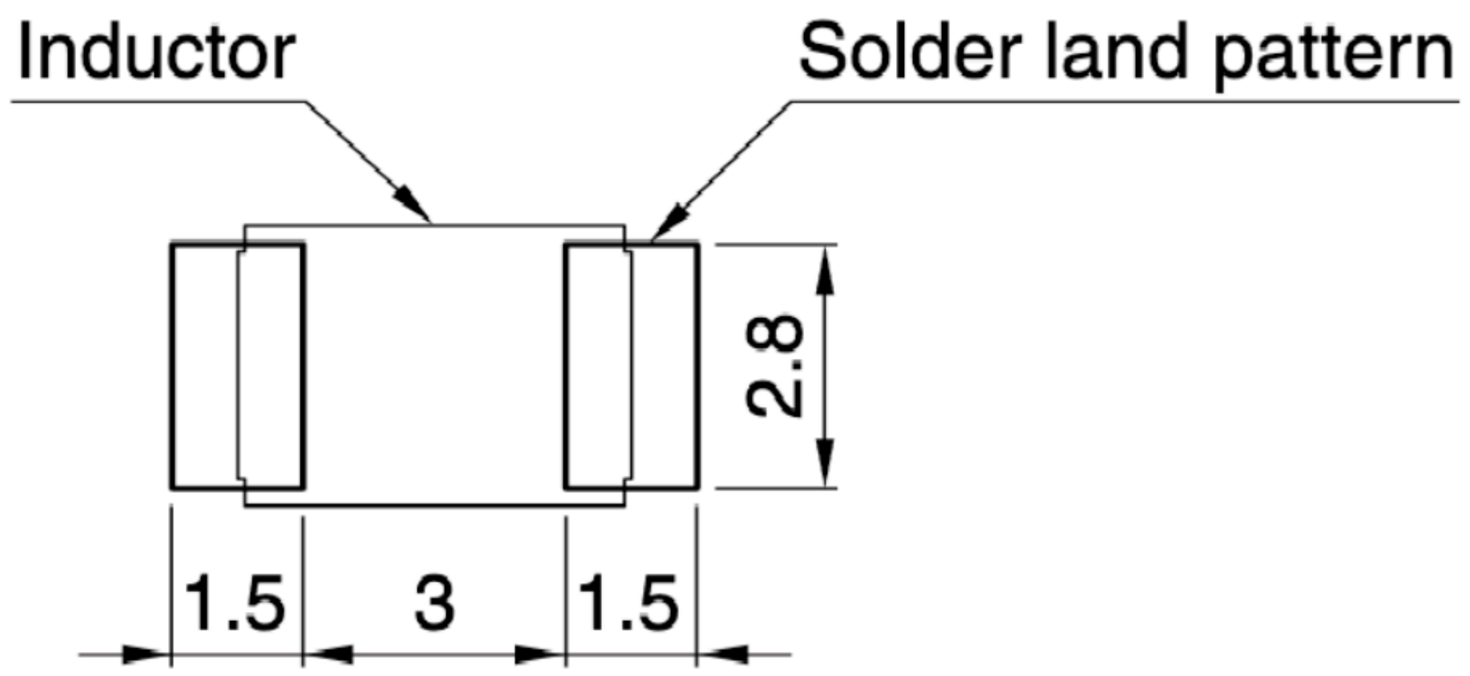

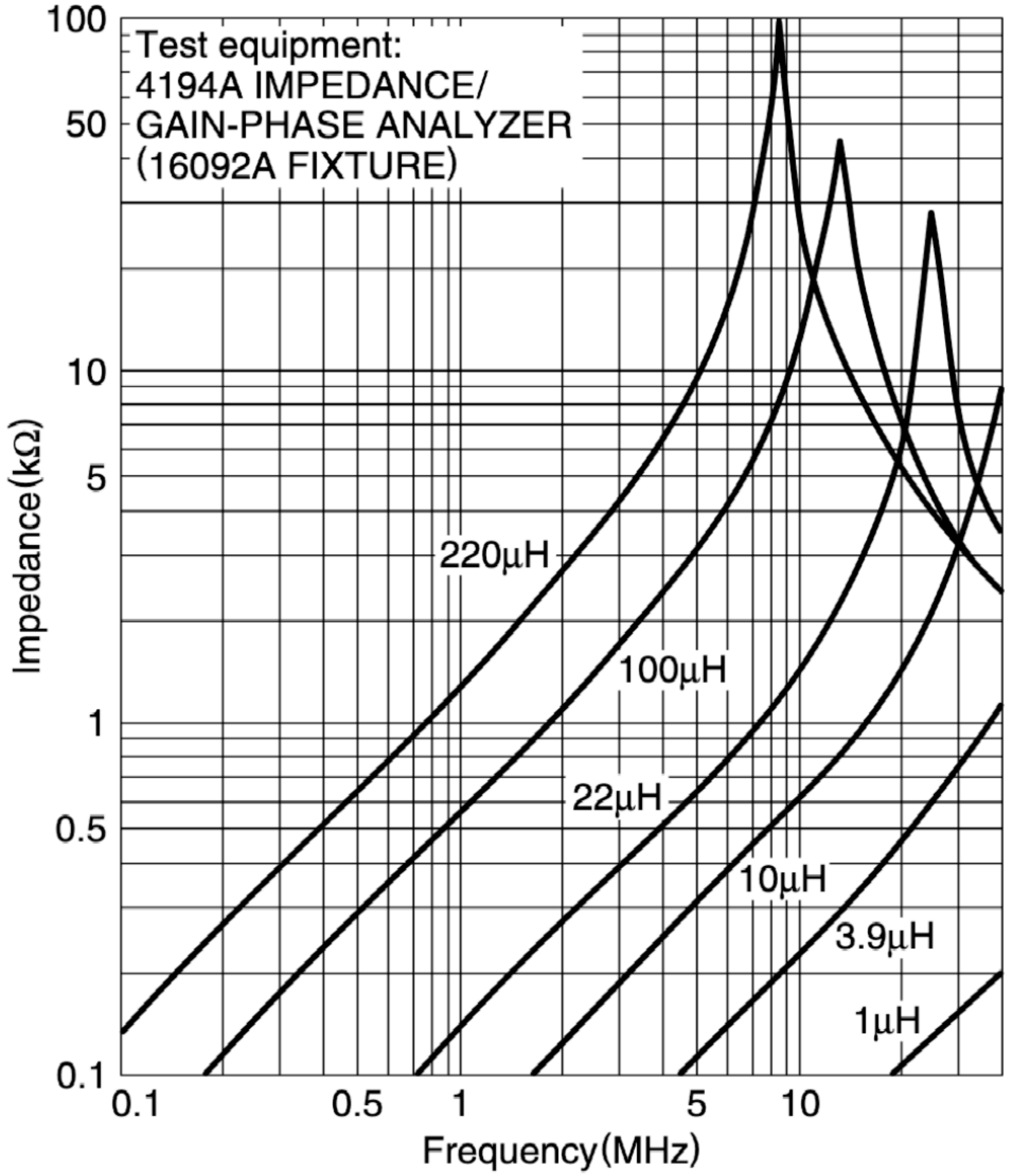

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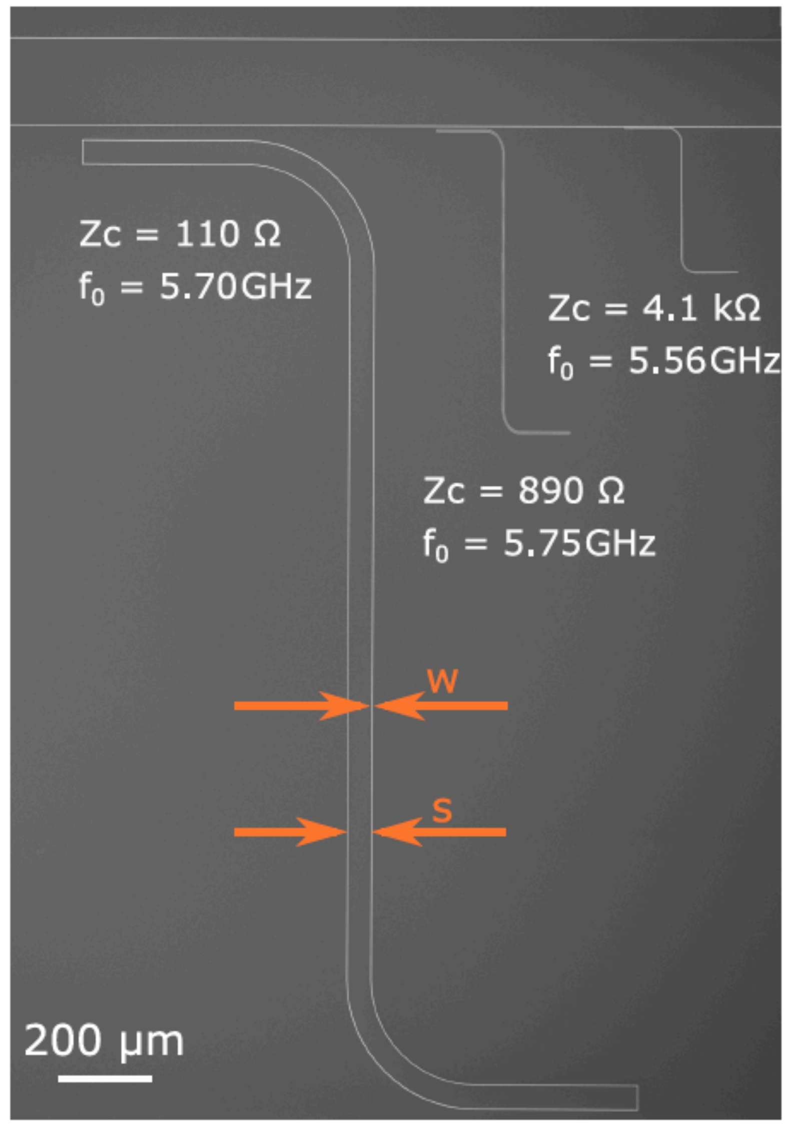
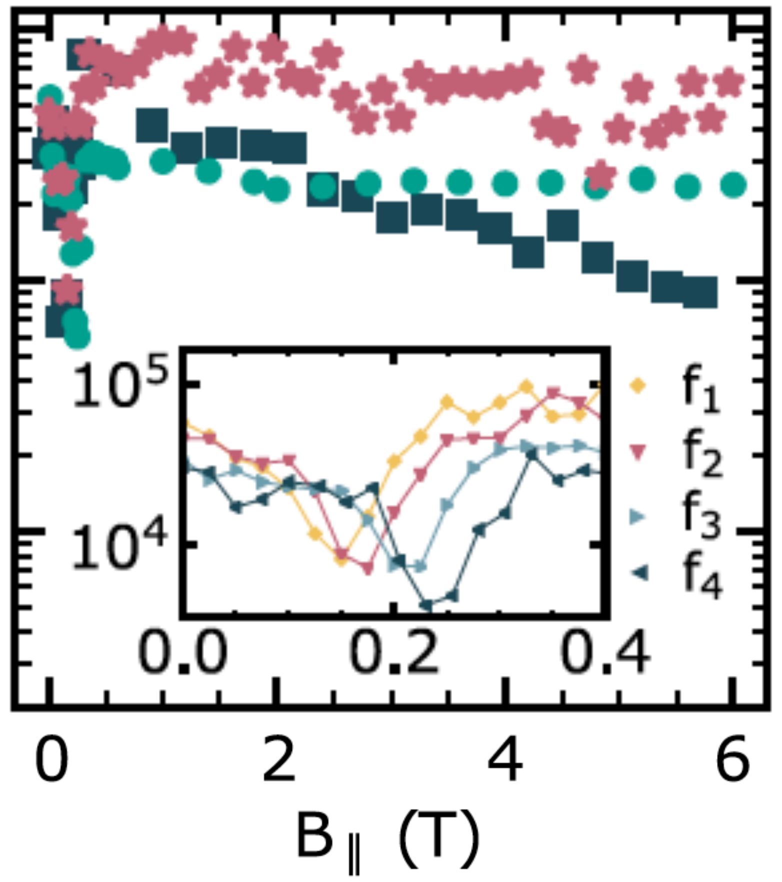
Wanted: parasitic capacitance under control AND Low loss

Large inductance quantum circuit: why should you care ?

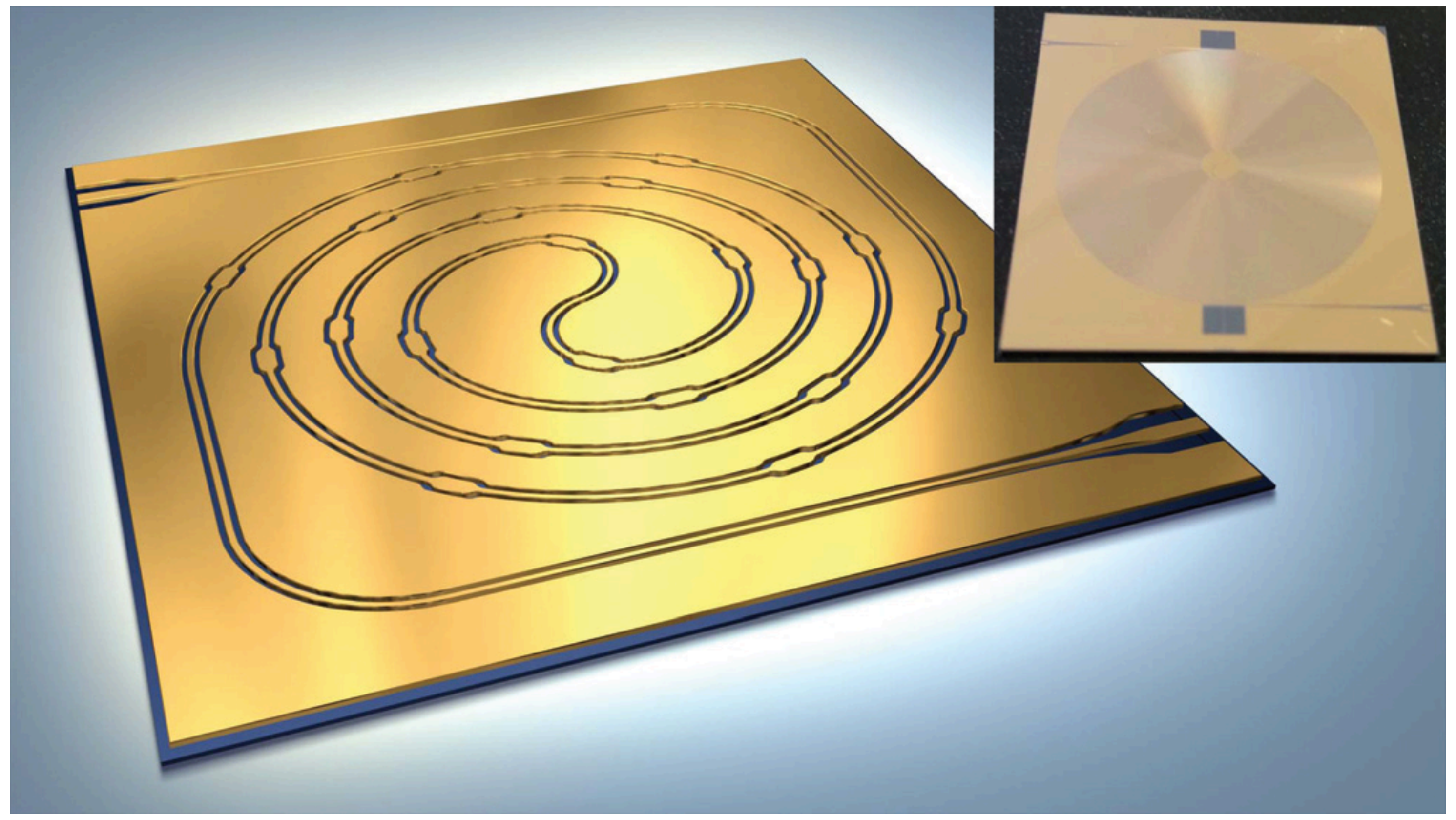
Small footprint/Magnetic field resilience





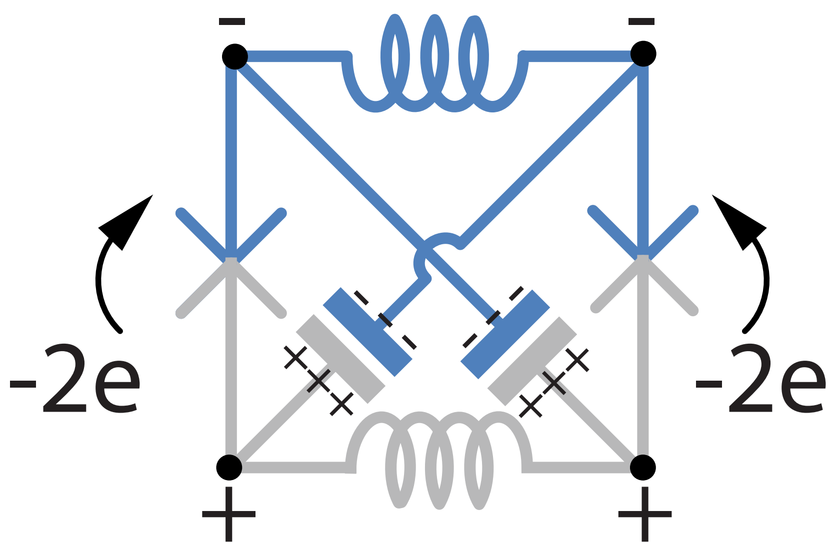
C. Yu et al., 21'

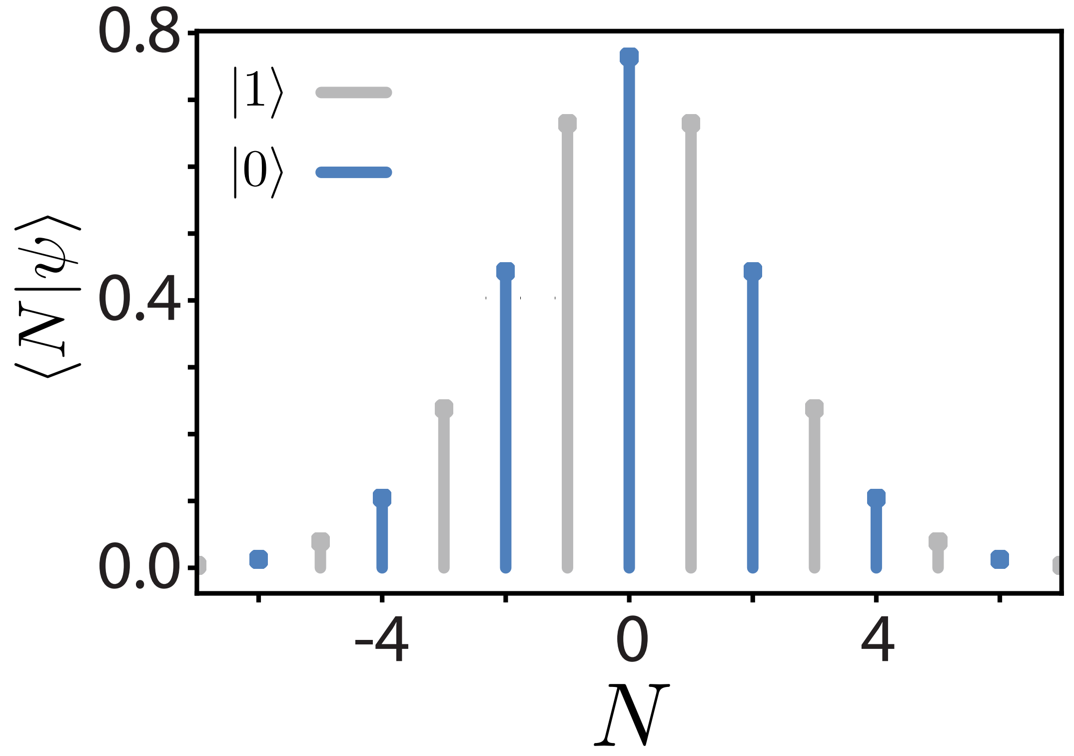
Slow light ($v = 1/\sqrt{lc}$)



M. R. Vissers et al., 16'

Large inductance: new devices





A. Kitaev, 06'

Large phase fluctuations: fundamental questions

$$Z = jL\omega$$

What about $L \to \infty$?

Large inductance quantum circuit: Josephson junctions

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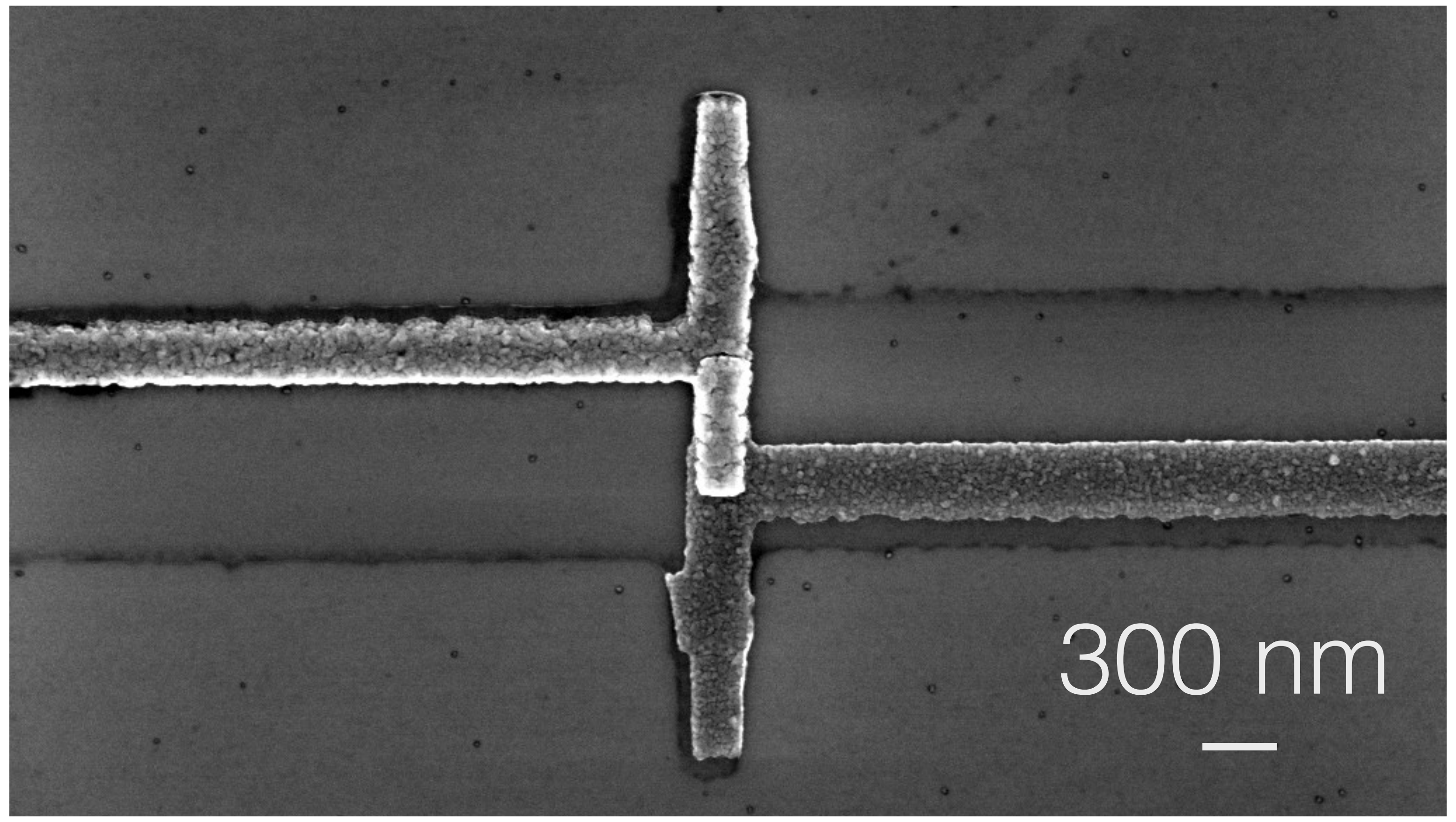
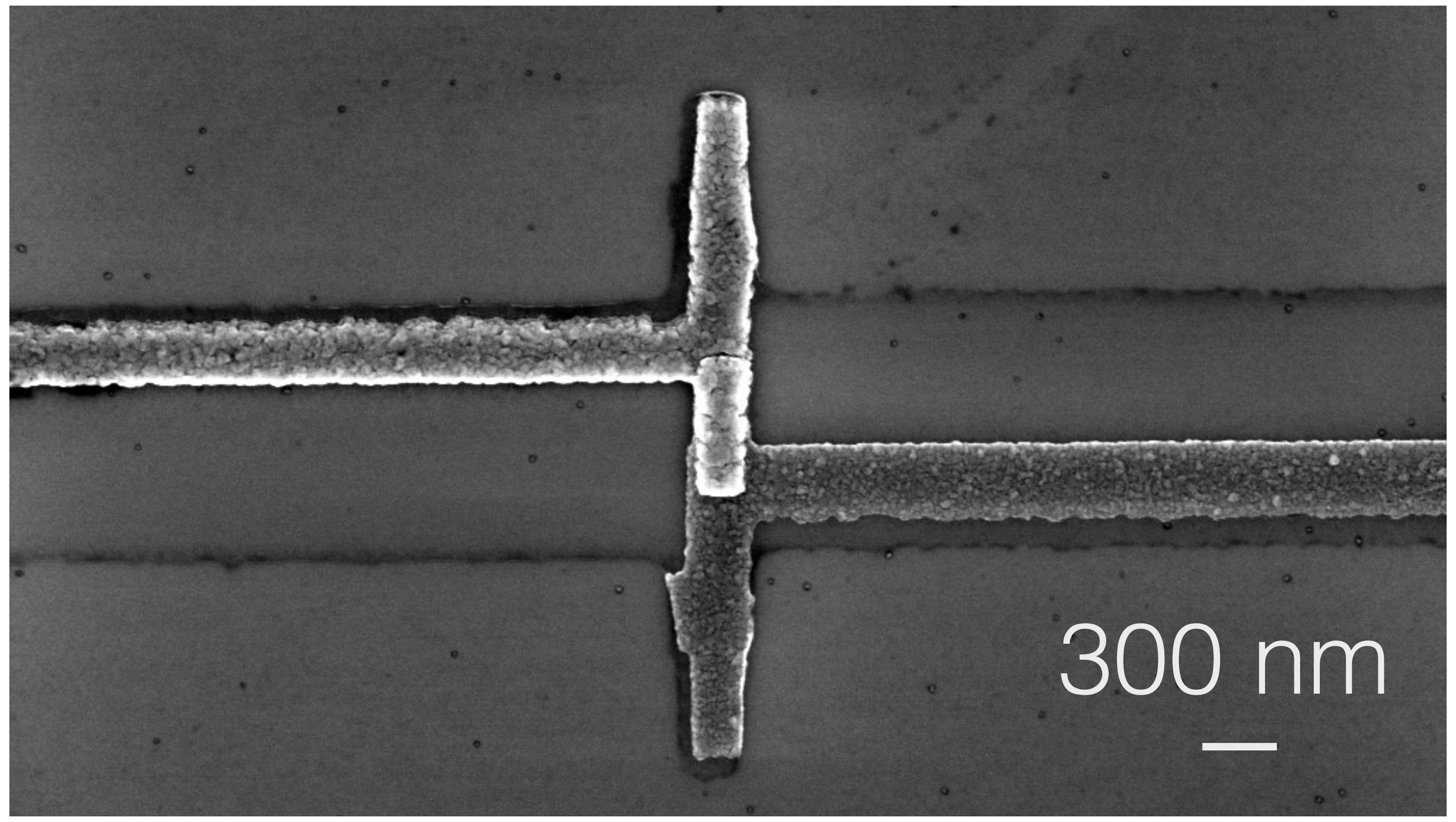


Current-phase relation (first Josephson relation)

$$i(t) = I_c \sin\left(\varphi(t)\right) \qquad \text{with} \quad \varphi(t) = \theta_1 - \theta_2$$

Large inductance quantum circuit: Josephson junctions



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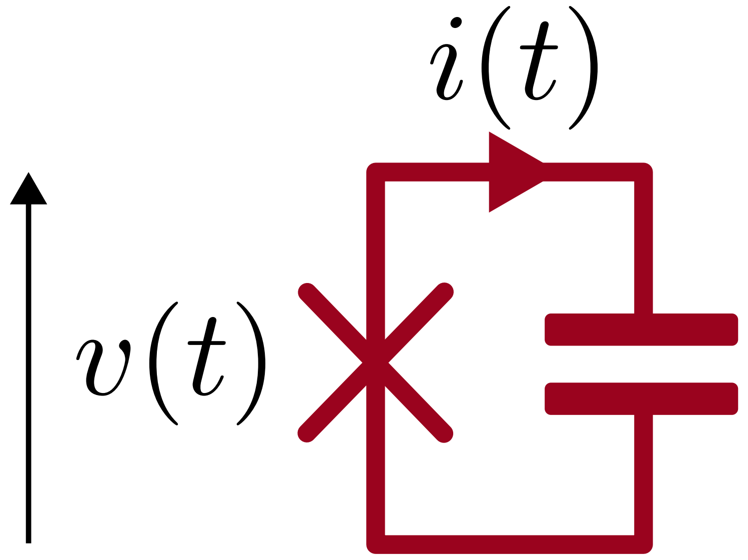

Superconducting phase evolution (second Josephson relation)

$$\frac{\partial \varphi}{\partial t} = \frac{v(t)}{\varphi_0} \qquad \text{with} \quad \varphi_0 = \hbar/2e$$

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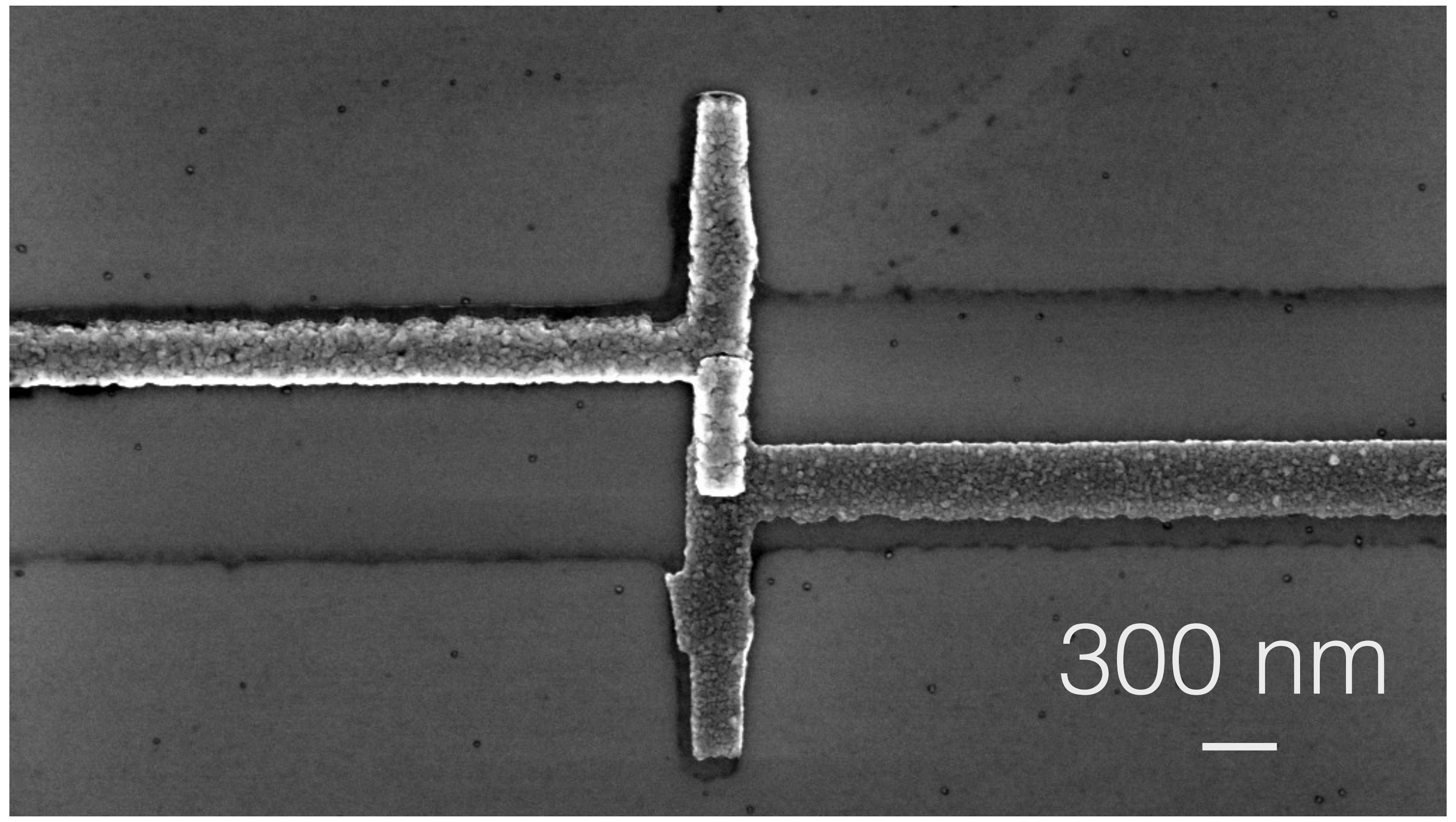

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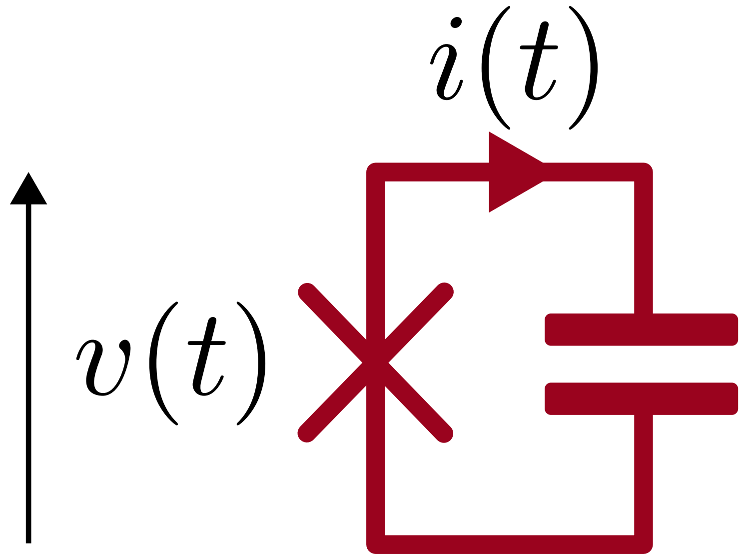

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Josephson (kinetic) inductance versus geometric inductance

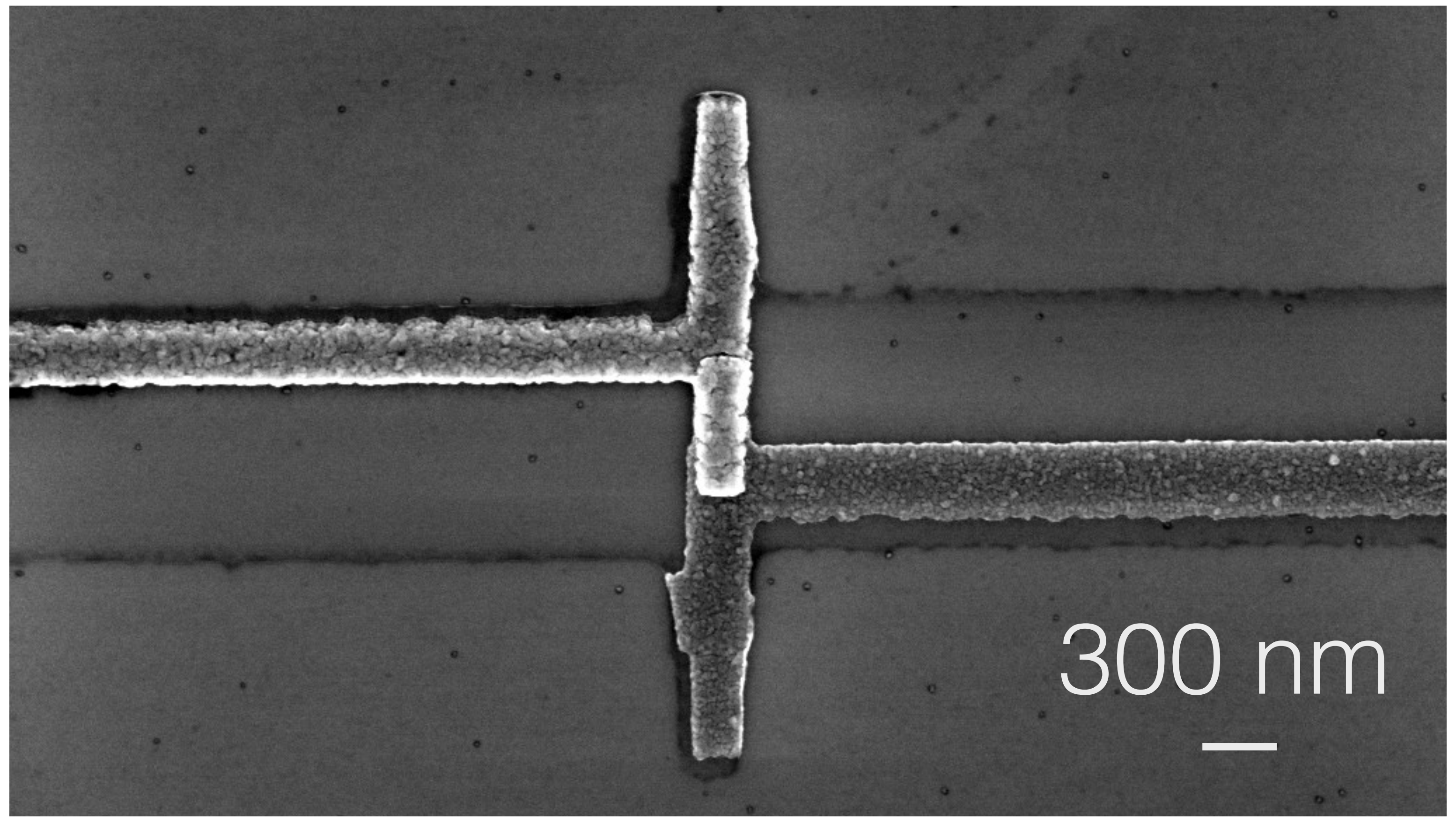
Geometric inductance: 0.2 pH/μm

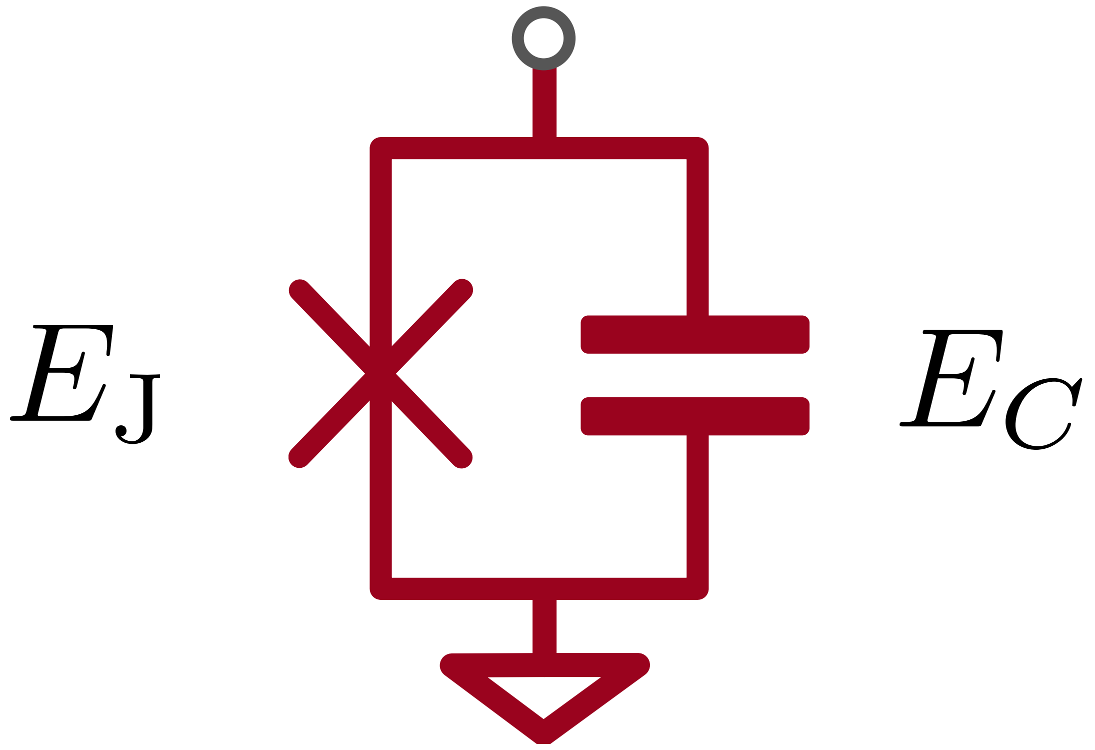
$$L = \frac{\mu_0 l}{2\pi}$$

Josephson inductance: 1 nH/μm

$$L_J = \varphi_0 \left(\frac{\partial i}{\partial \varphi}\right)^{-1} = \frac{L_{J,0}}{\cos\varphi} \quad \text{with} \quad L_J = \frac{\varphi_0}{I_c}$$

Non-linearity and Josephson junction





Current-phase relation

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Energy scales

Charging energy

$$E_C = \frac{(2e)^2}{2C_\mathrm{J}}$$

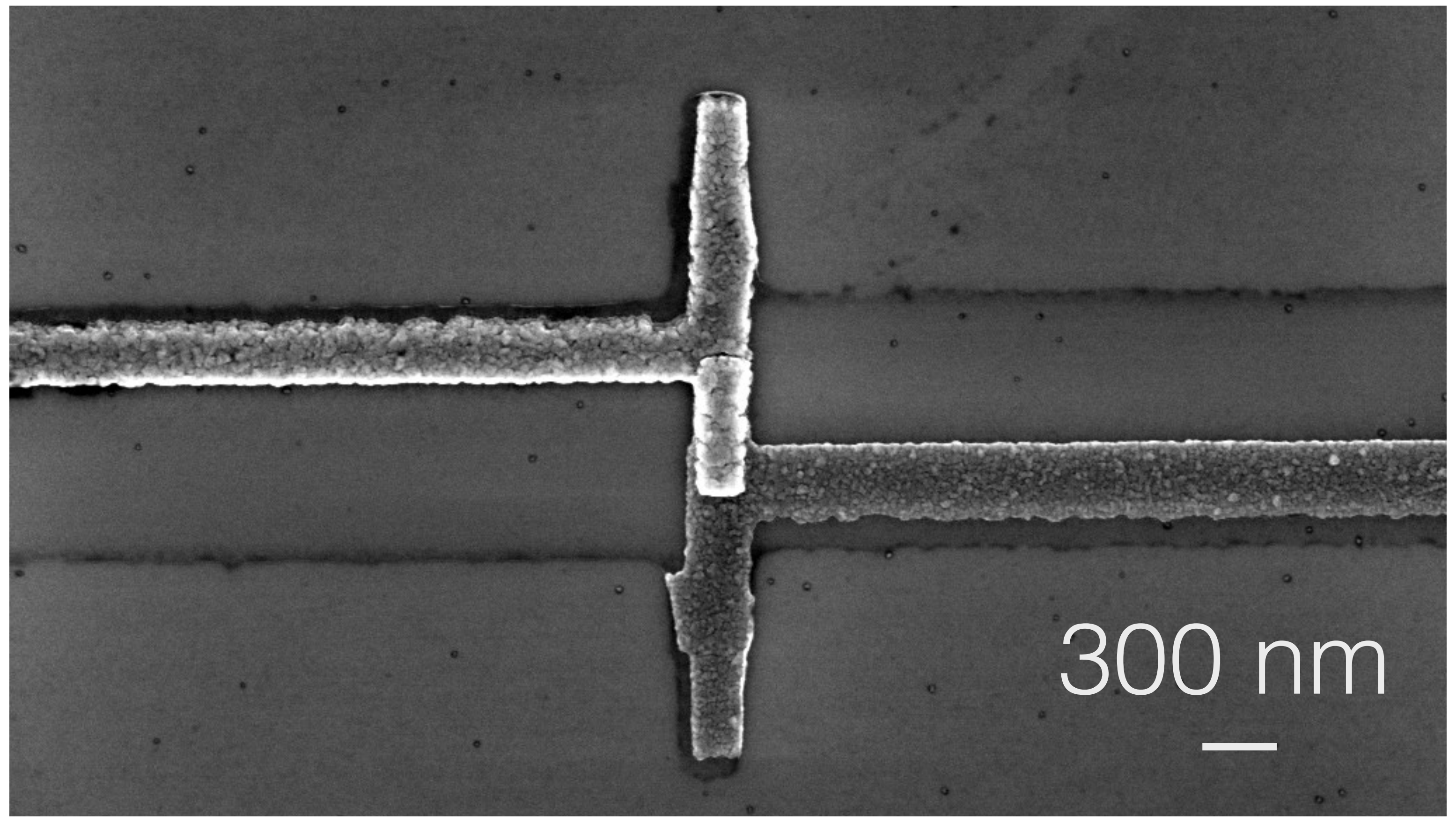
Josephson energy

$$E_\mathrm{J} = \varphi_0 I_c$$

Characteristic impedance

$$Z_\mathrm{J} = \frac{Z_\mathrm{q}}{2\pi}\sqrt{\frac{2E_\mathrm{C}}{E_\mathrm{J}}} \quad \text{with} \quad Z_\mathrm{q} = \frac{h}{(2e)^2} \simeq 6.5\mathrm{k}\Omega$$

Non-linearity and Josephson junction



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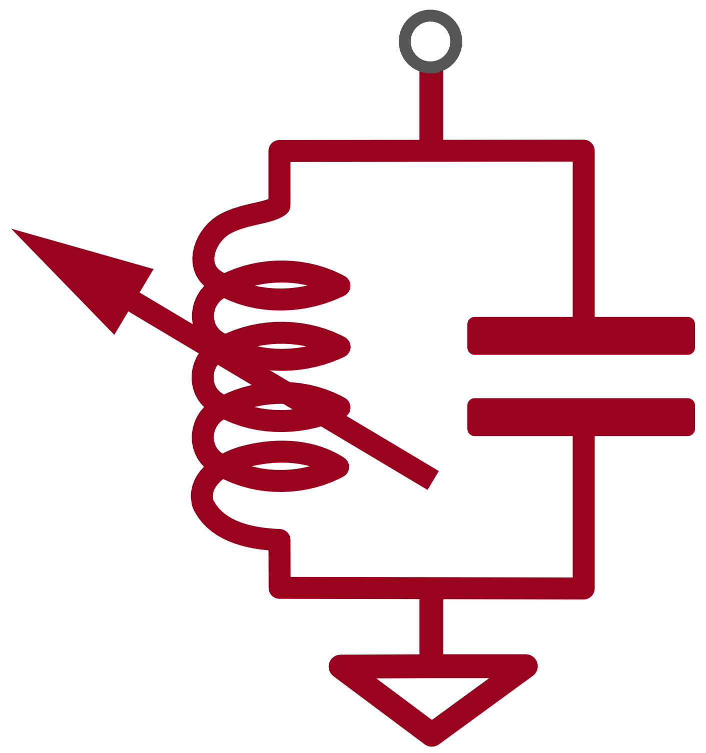
Two limits

$Z_\mathrm{J} \ll Z_\mathrm{q}$ $\qquad$ $Z_\mathrm{J} \gtrsim Z_\mathrm{q}$

$\langle \varphi(t)^2 \rangle \ll 1$ $\qquad$ $\langle \varphi(t)^2 \rangle \gtrsim 1$



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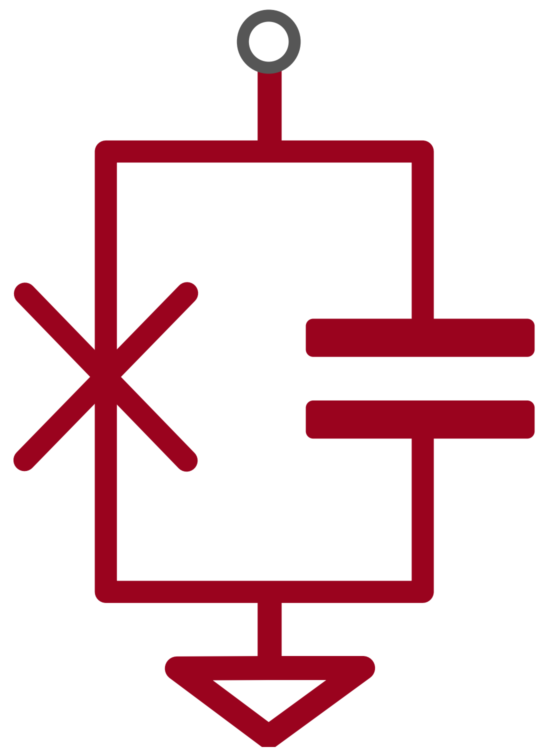
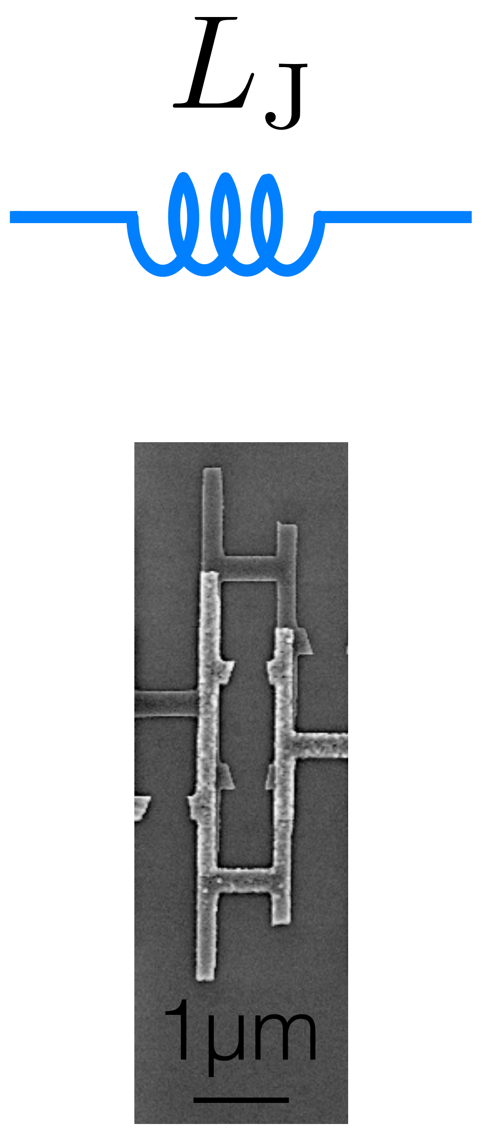
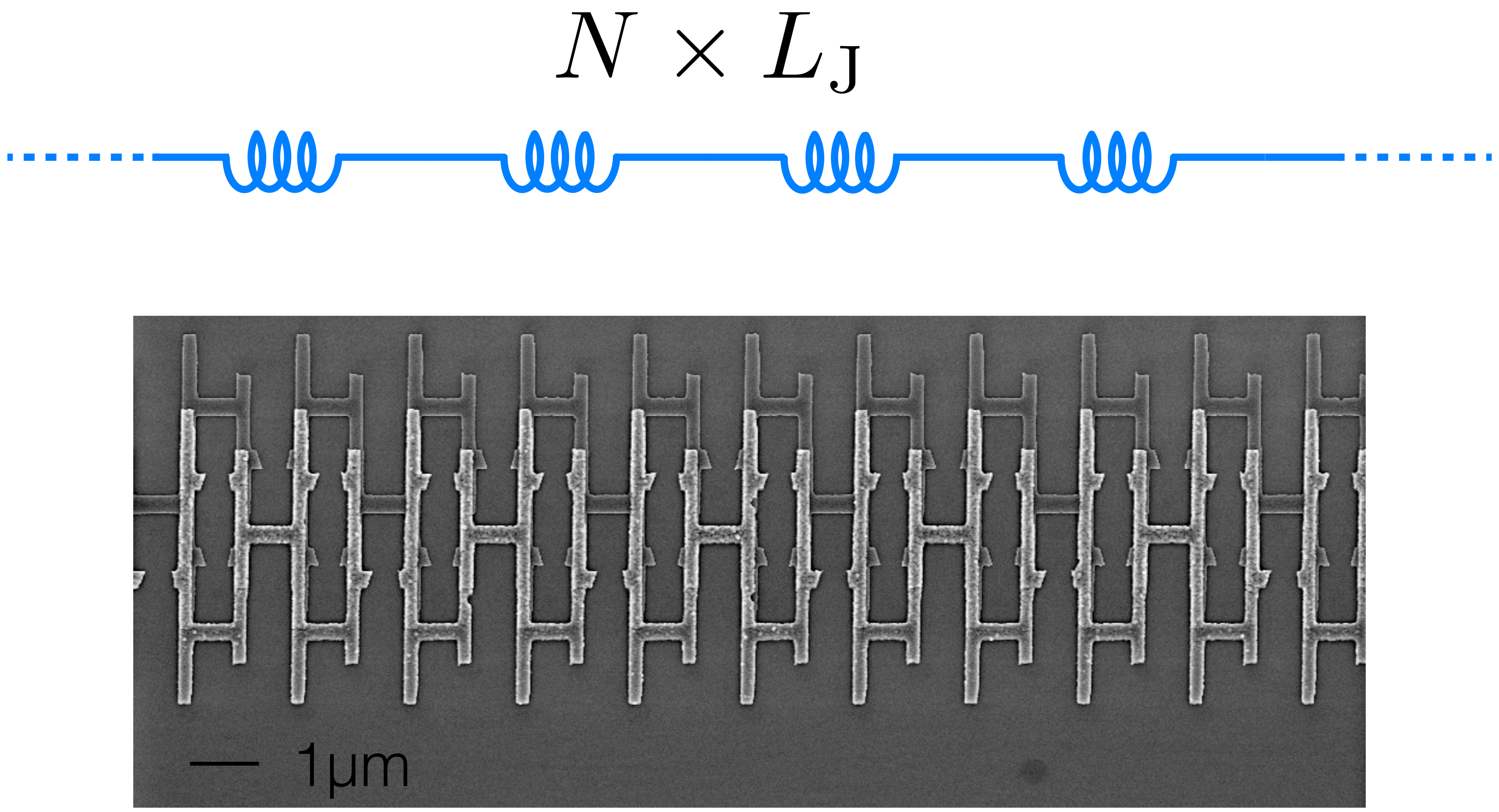


$$i(t) = I_c\varphi(t) + I_c\frac{\varphi(t)^3}{3!} + \ldots$$

$$i(t) = I_c \sin(\varphi(t))$$

Josephson junction meta-material





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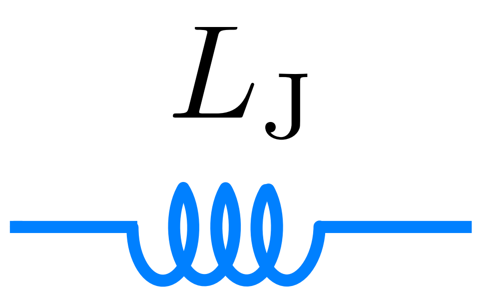
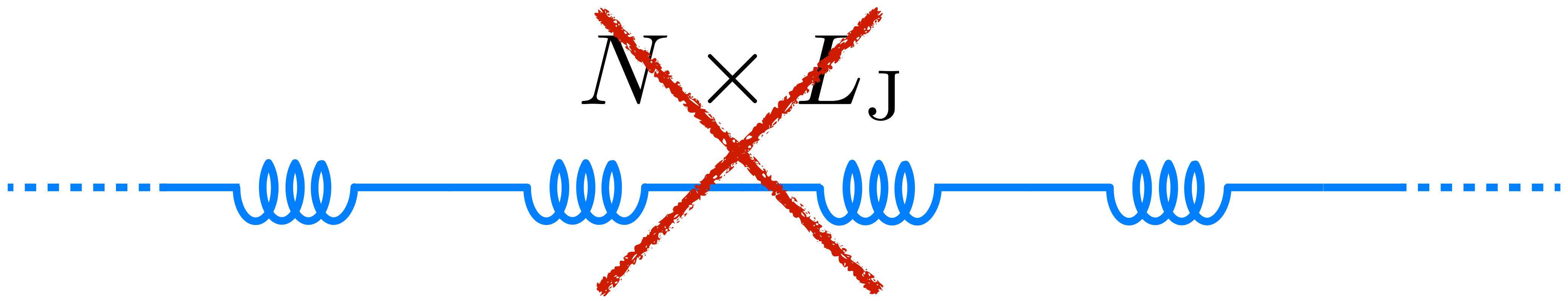
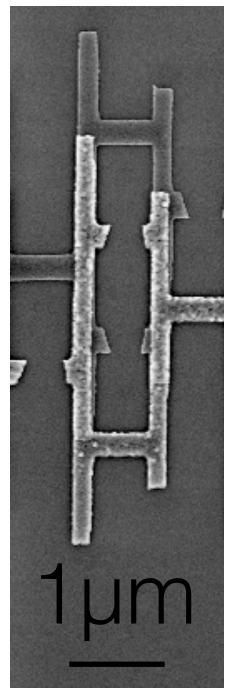
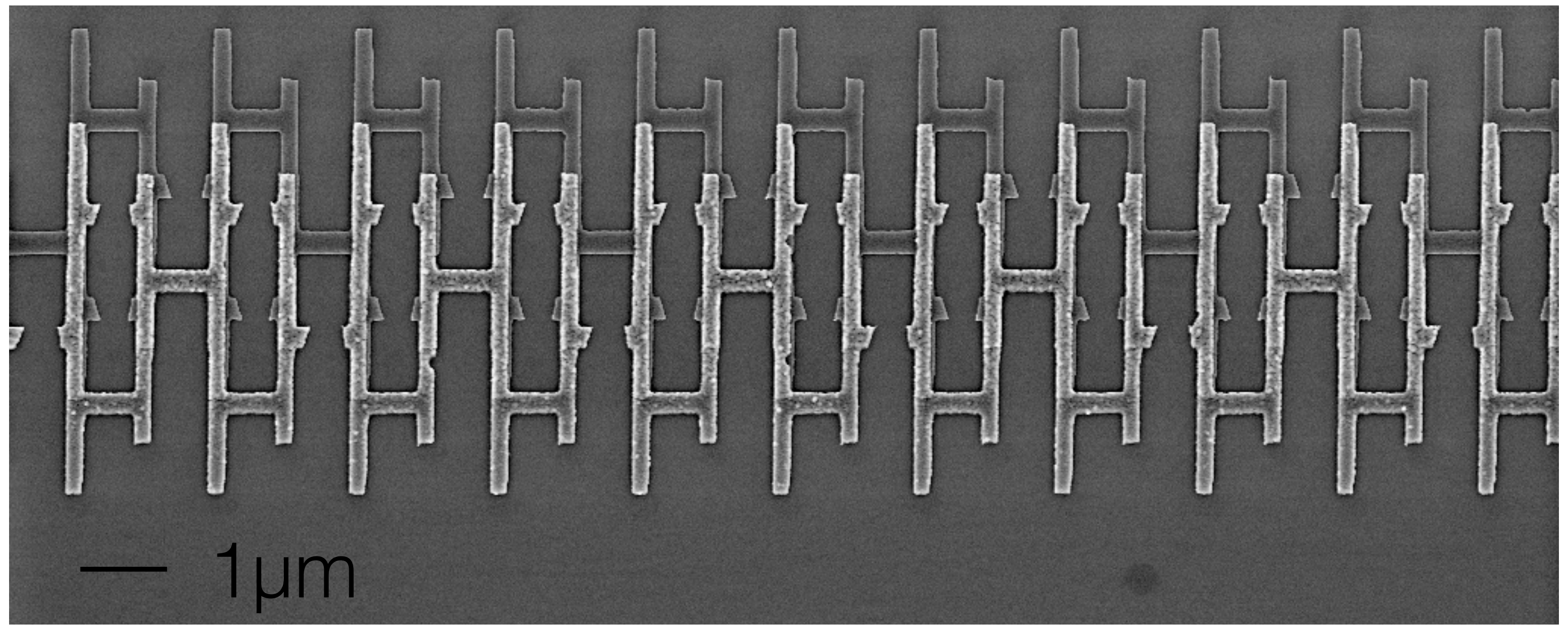
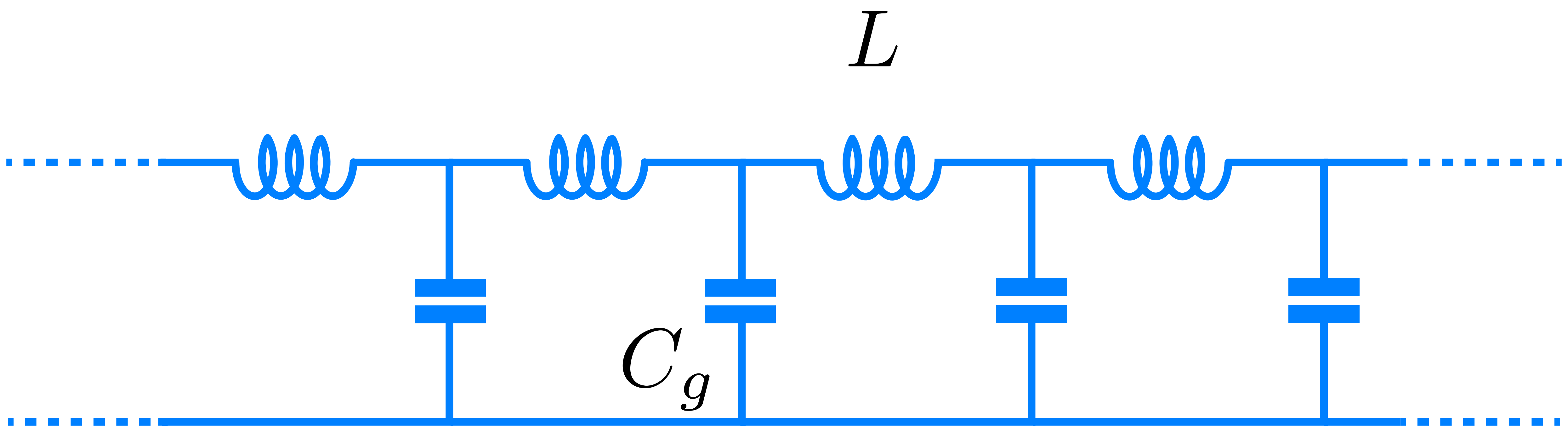








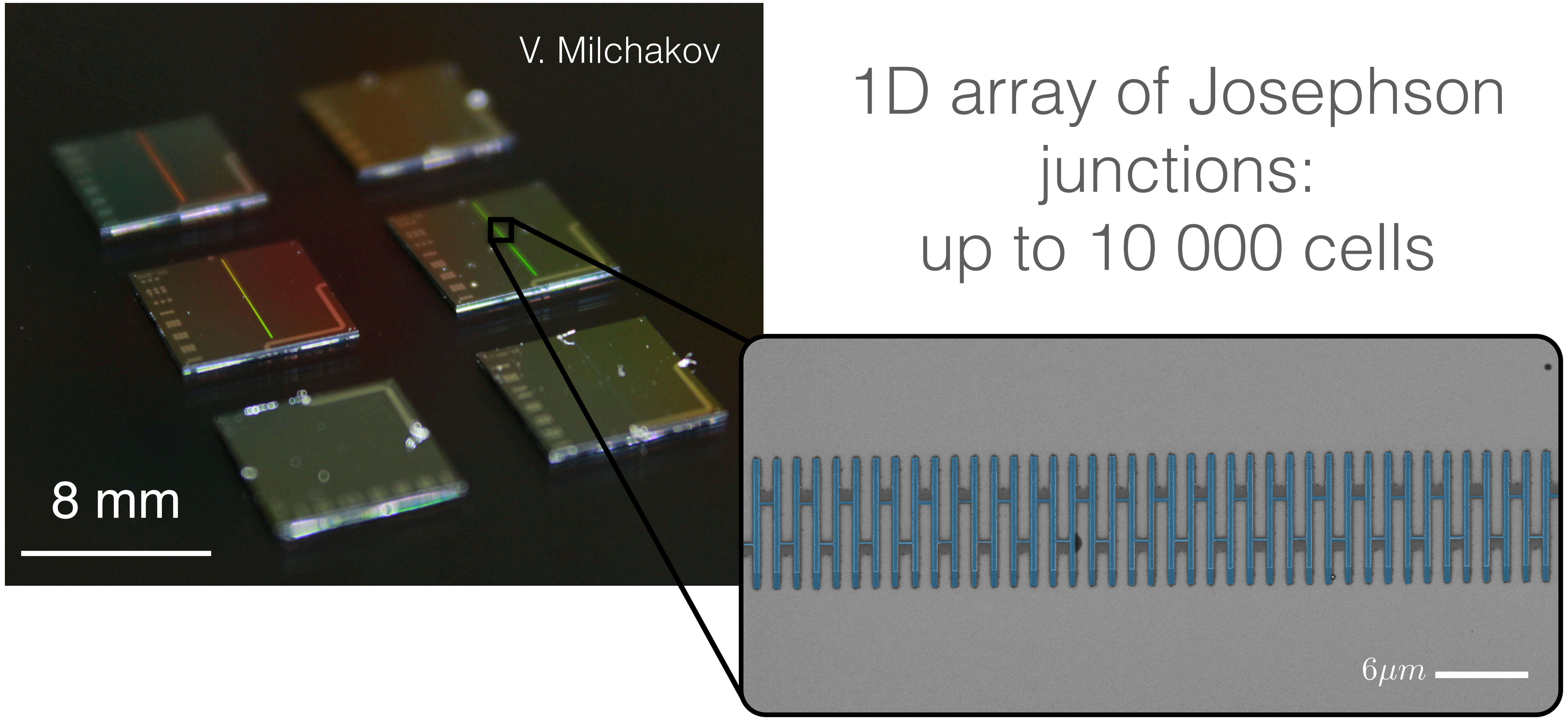
"Plasma" modes or transmission line modes J. E. Mooij and G. Schön, 85'



Plasma modes in JJ meta-material: N. Masluk et al 12', Bell et al 12', S. Butz et al. 13',C. Altimiras et al. 13', R. Kuzmin et al 18'….

Observation in disordered superconductors (granular aluminium): O. Buisson et al., 94'

Josephson junction meta-material: Fabrication



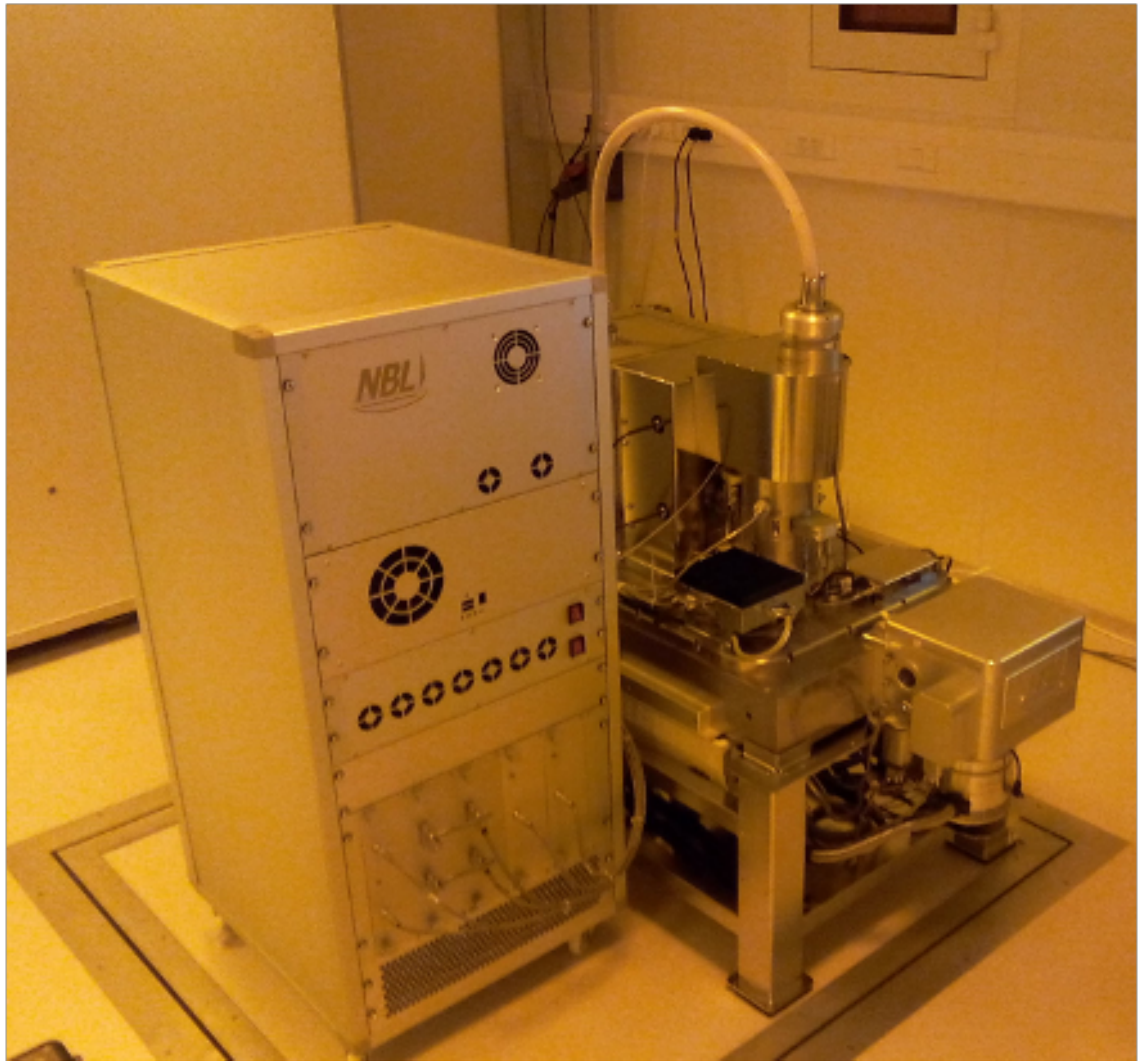
1D array of Josephson junctions:
up to 10 000 cells

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

Josephson junction meta-material: Fabrication

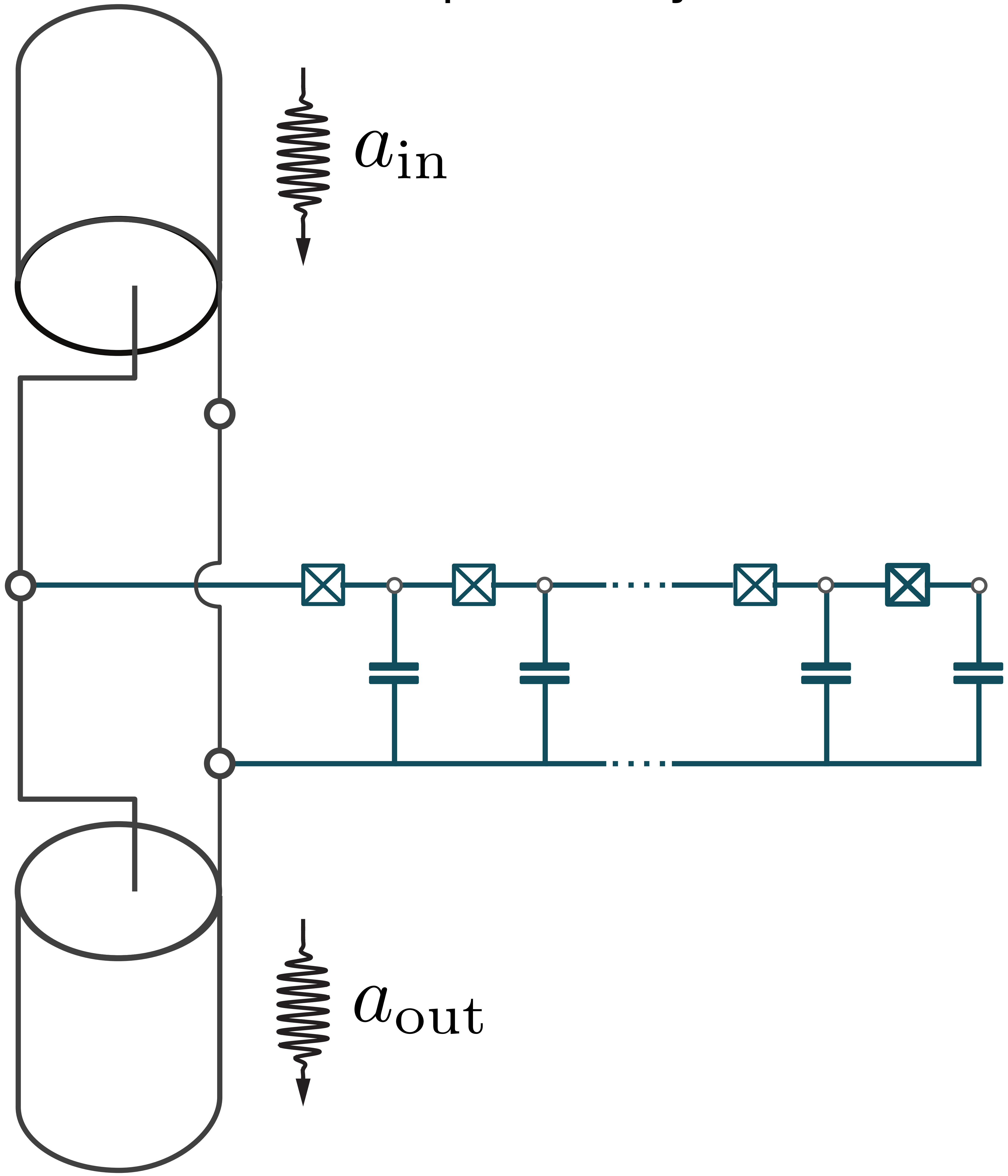
Pôle Nanofab

E-beam evaporator “Suprafab”



E-beam writer “Nanobeam”

Josephson junction meta-material

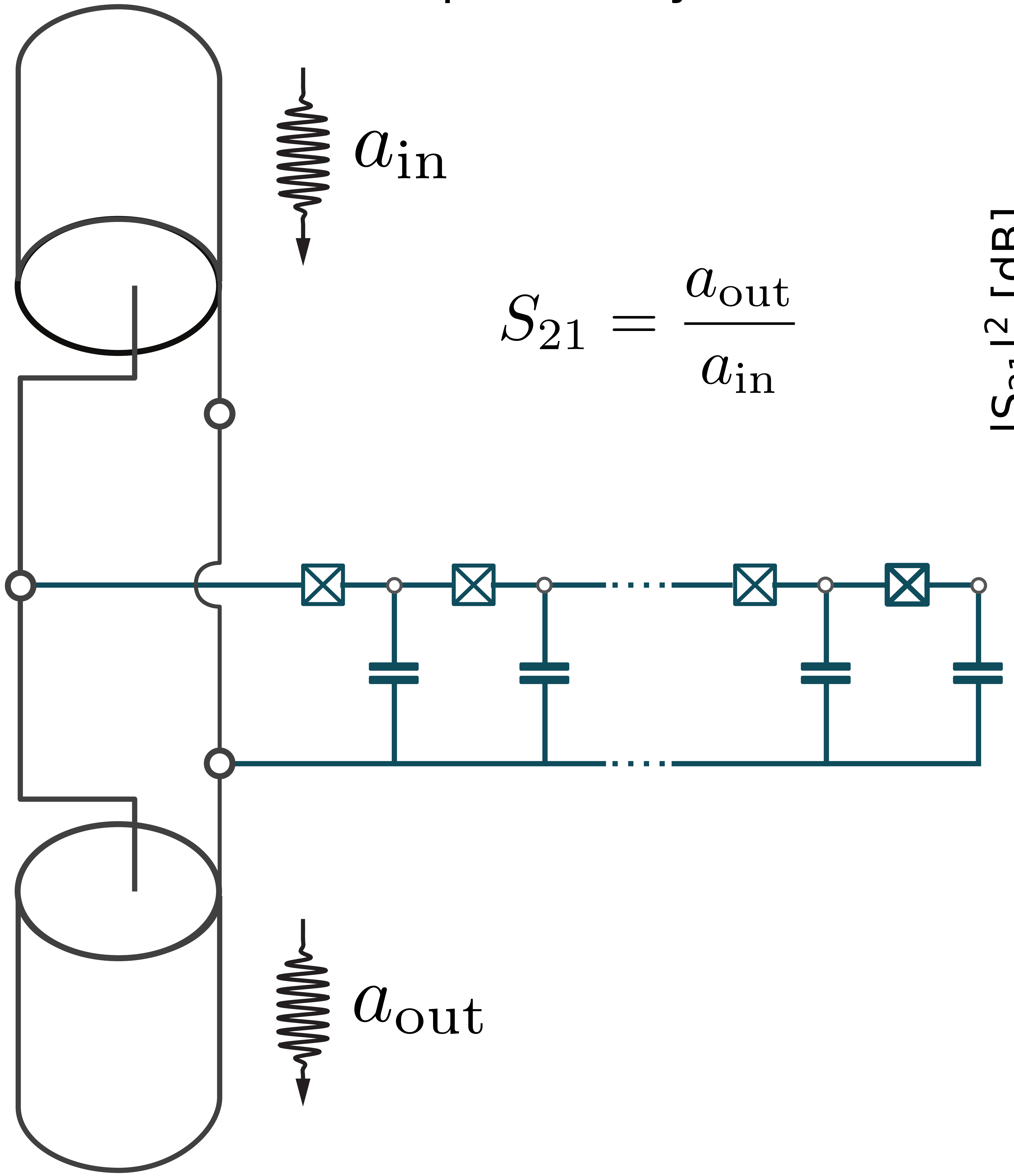


high frequency
& low temperature

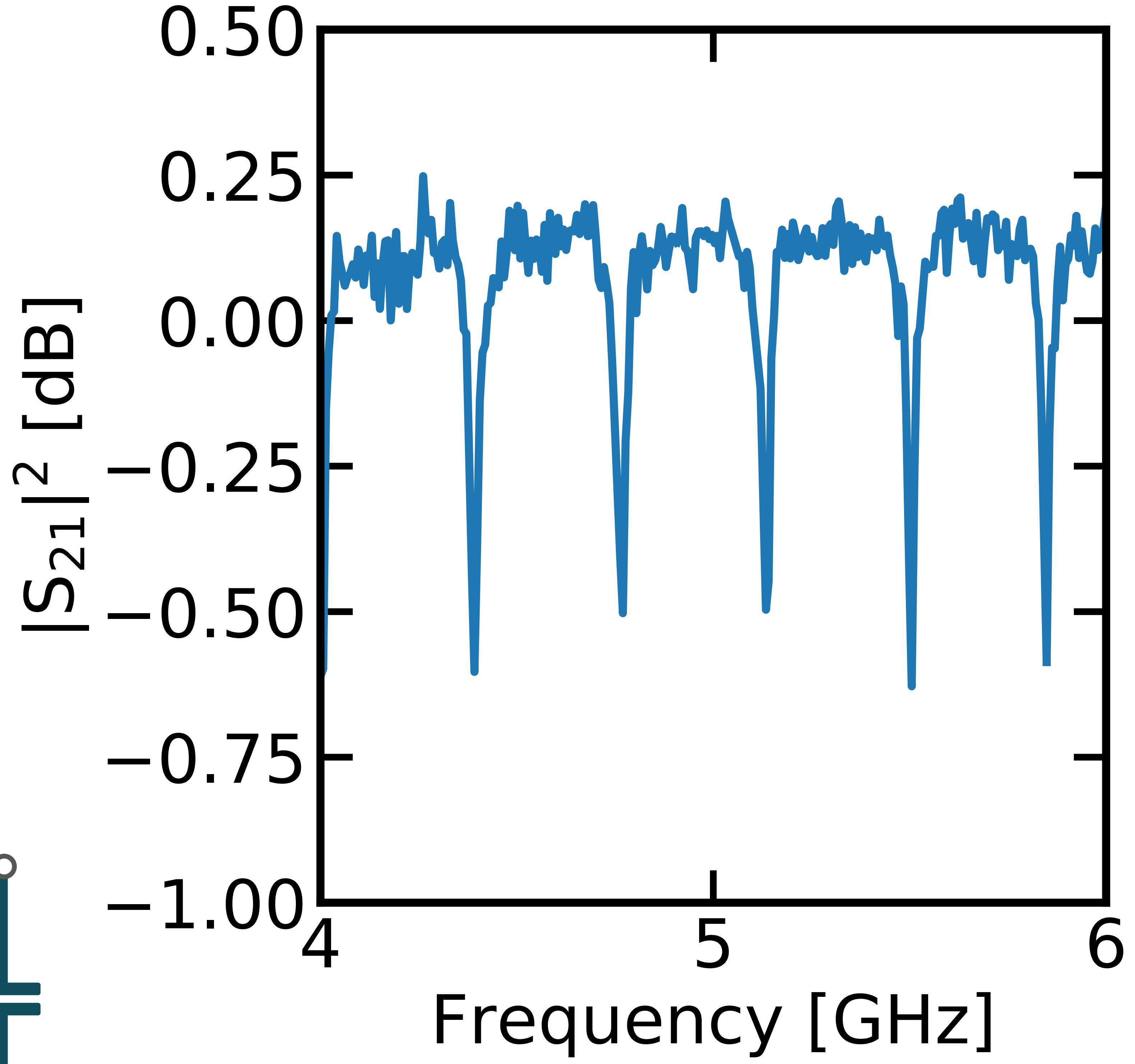
$$\hbar\omega \gg k_{\text{B}}T$$

$$(T = 20\ \text{mK})$$

Josephson junction meta-material



$$S_{21} = \frac{a_{\mathrm{out}}}{a_{\mathrm{in}}}$$



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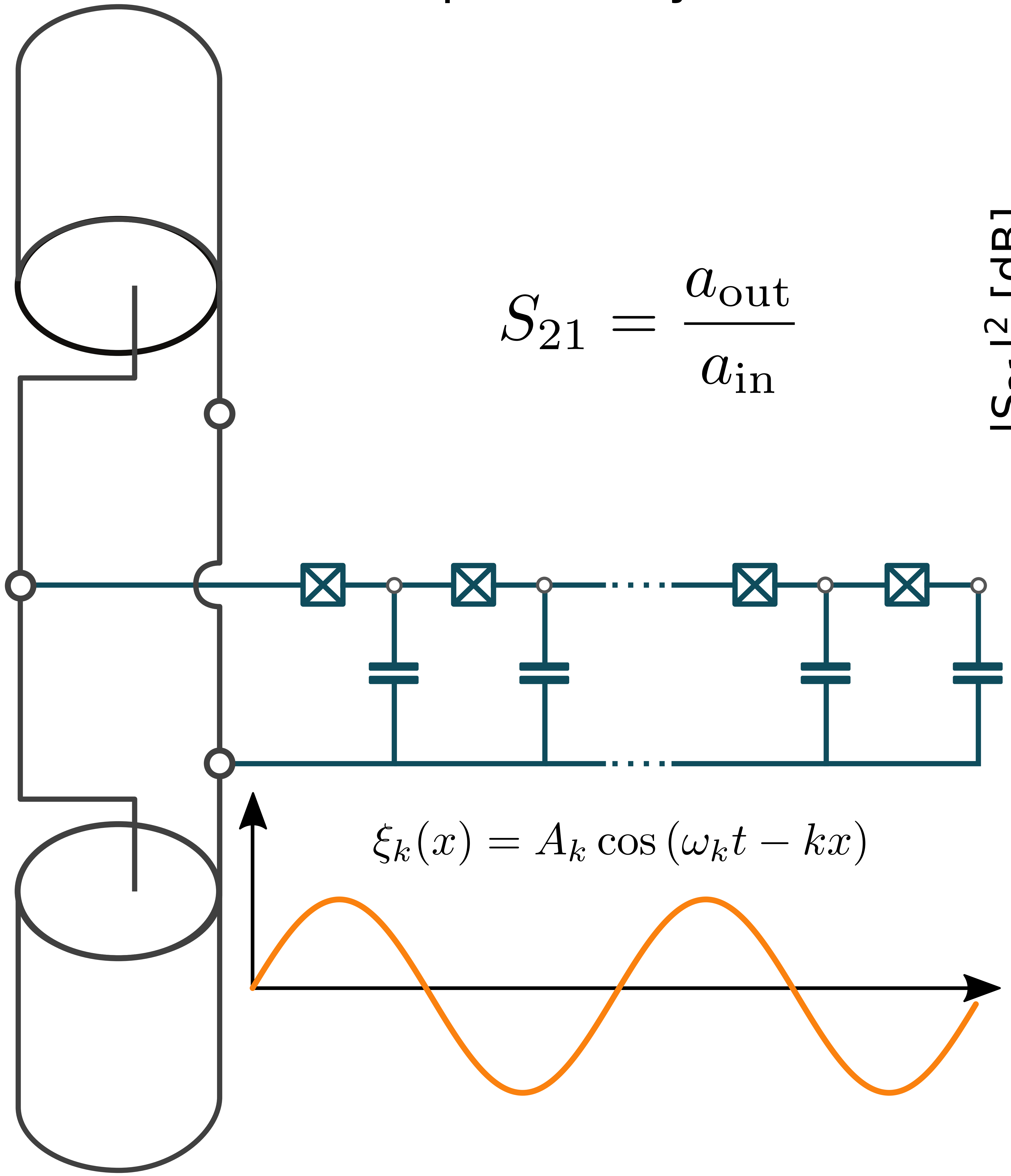

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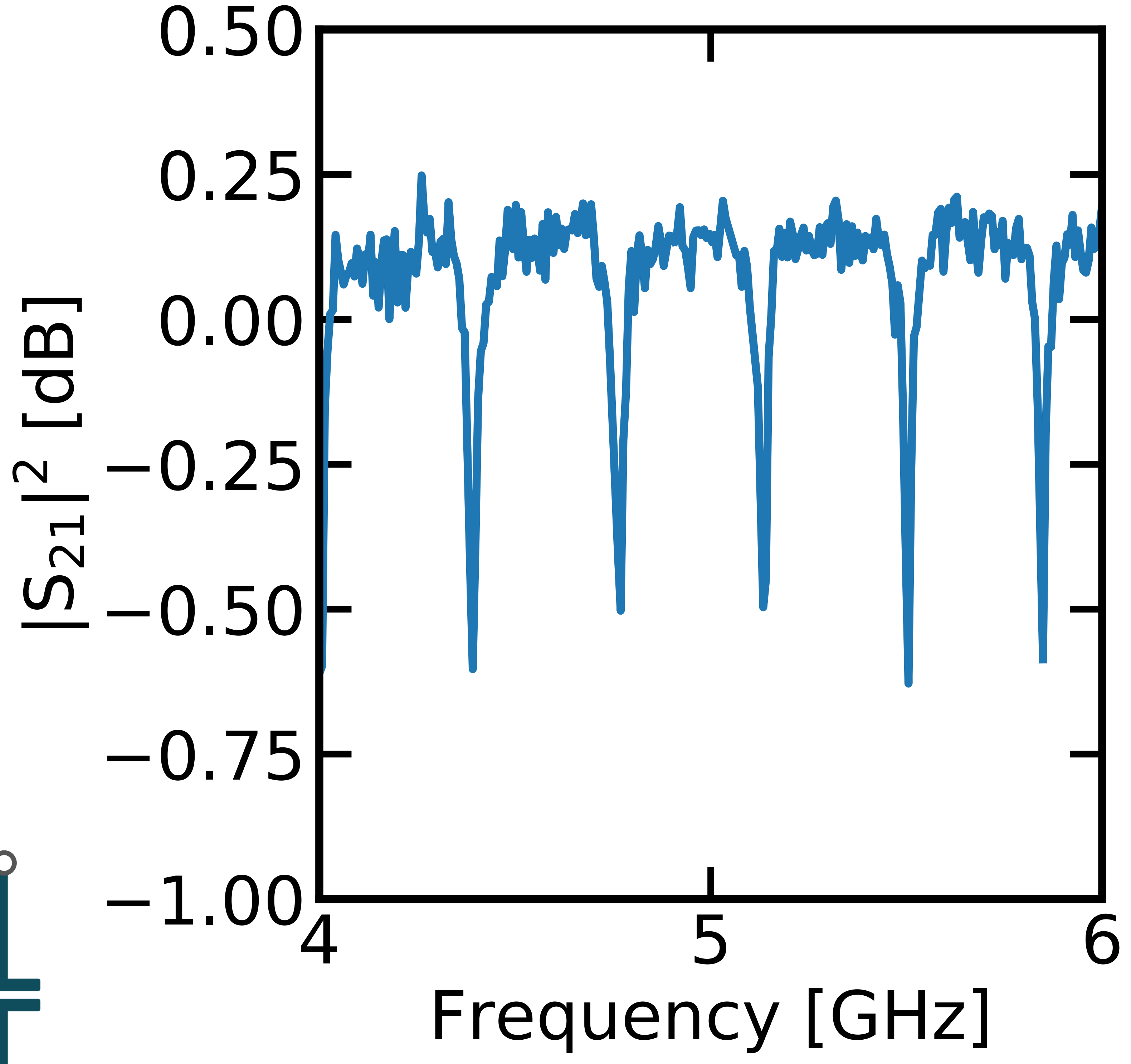

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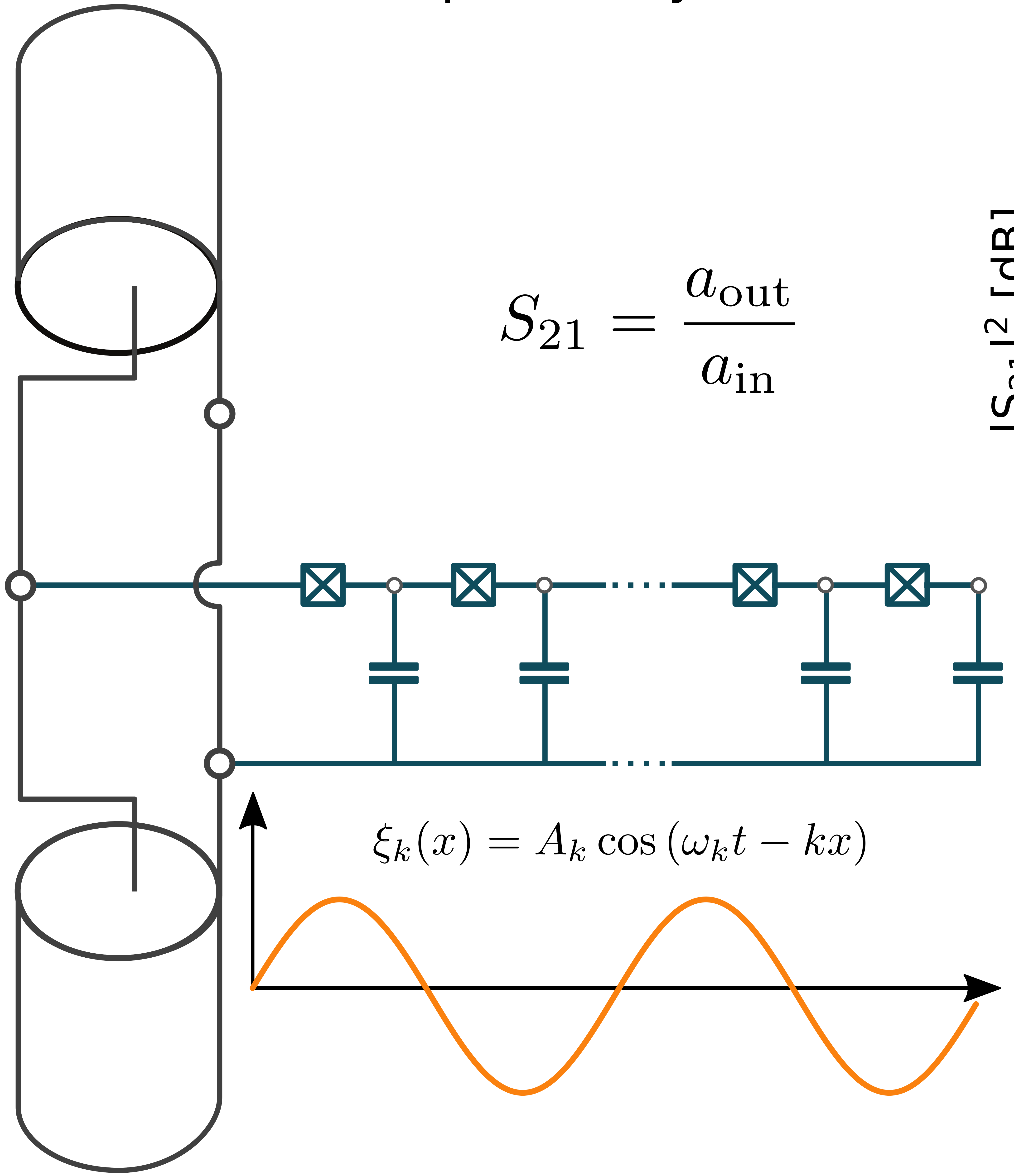

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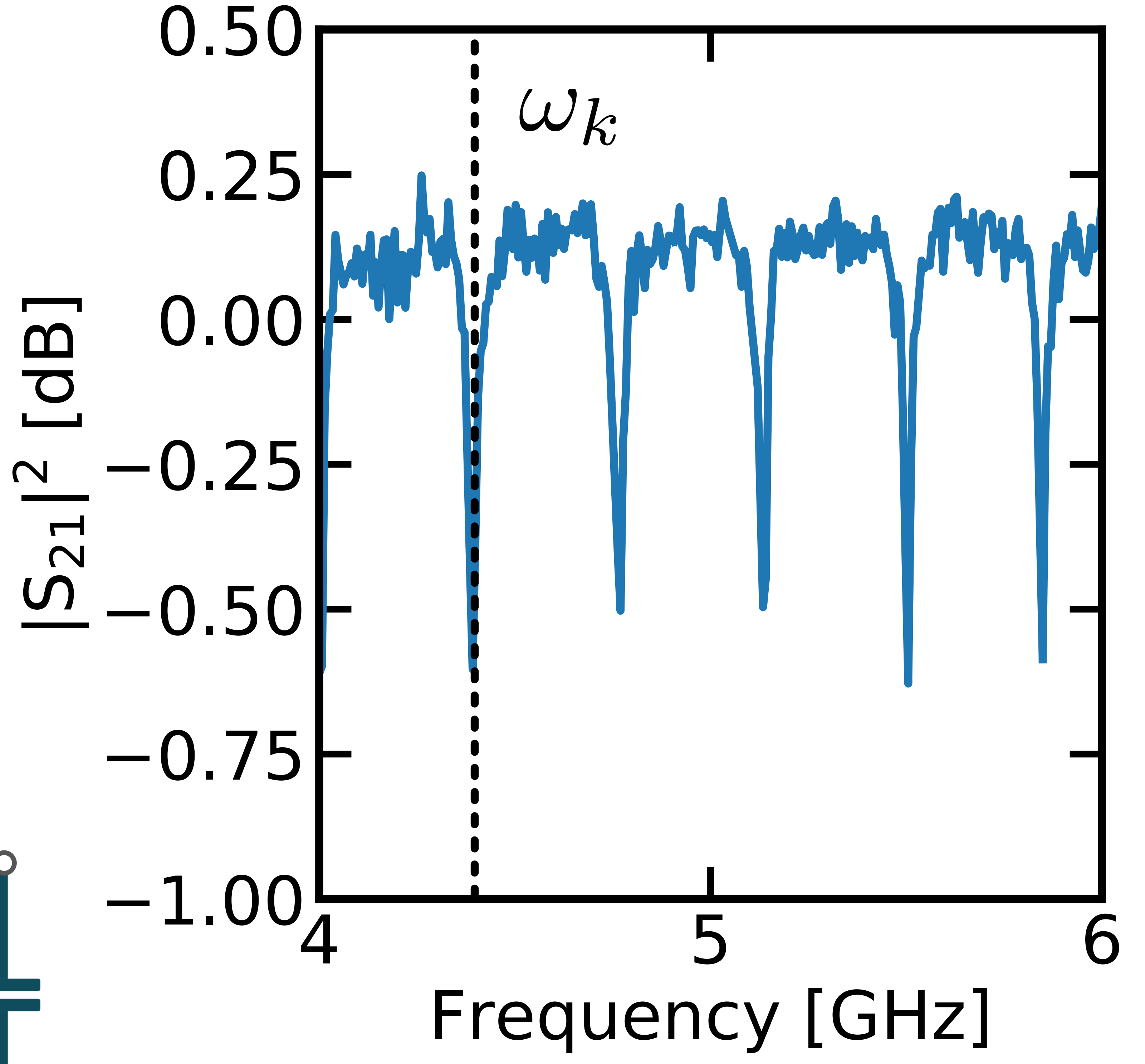

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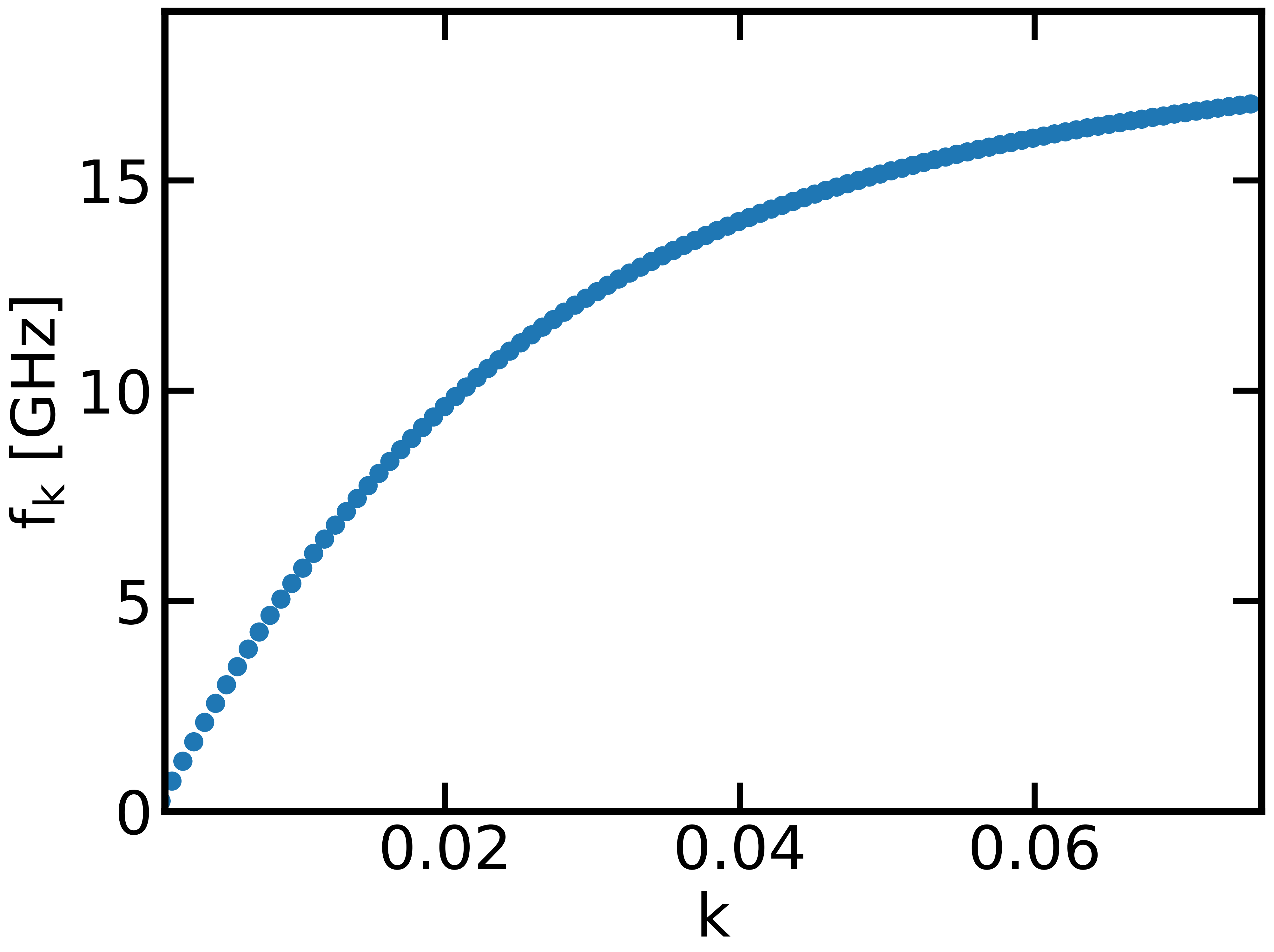
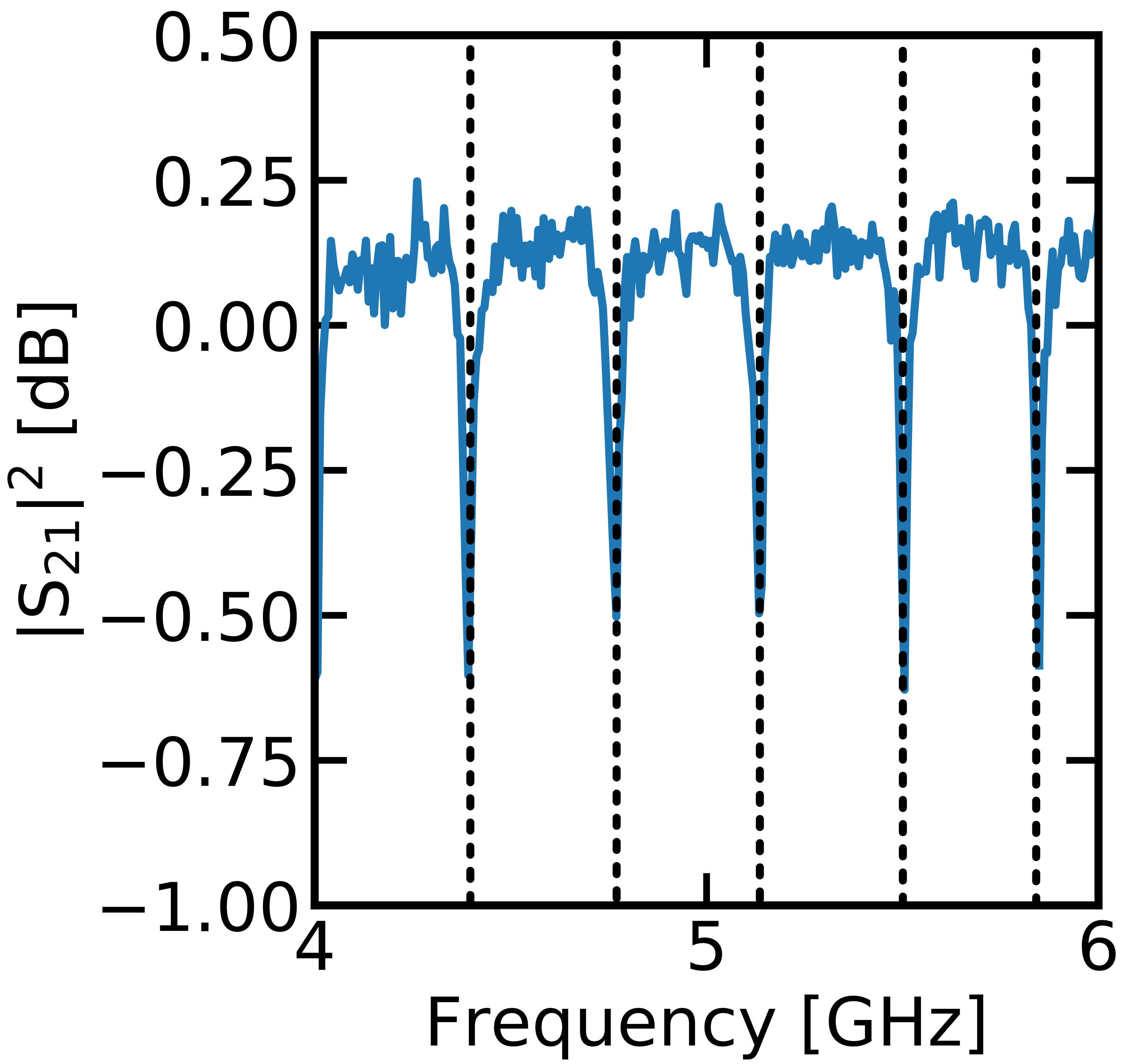
JJ meta-material: dispersion relation



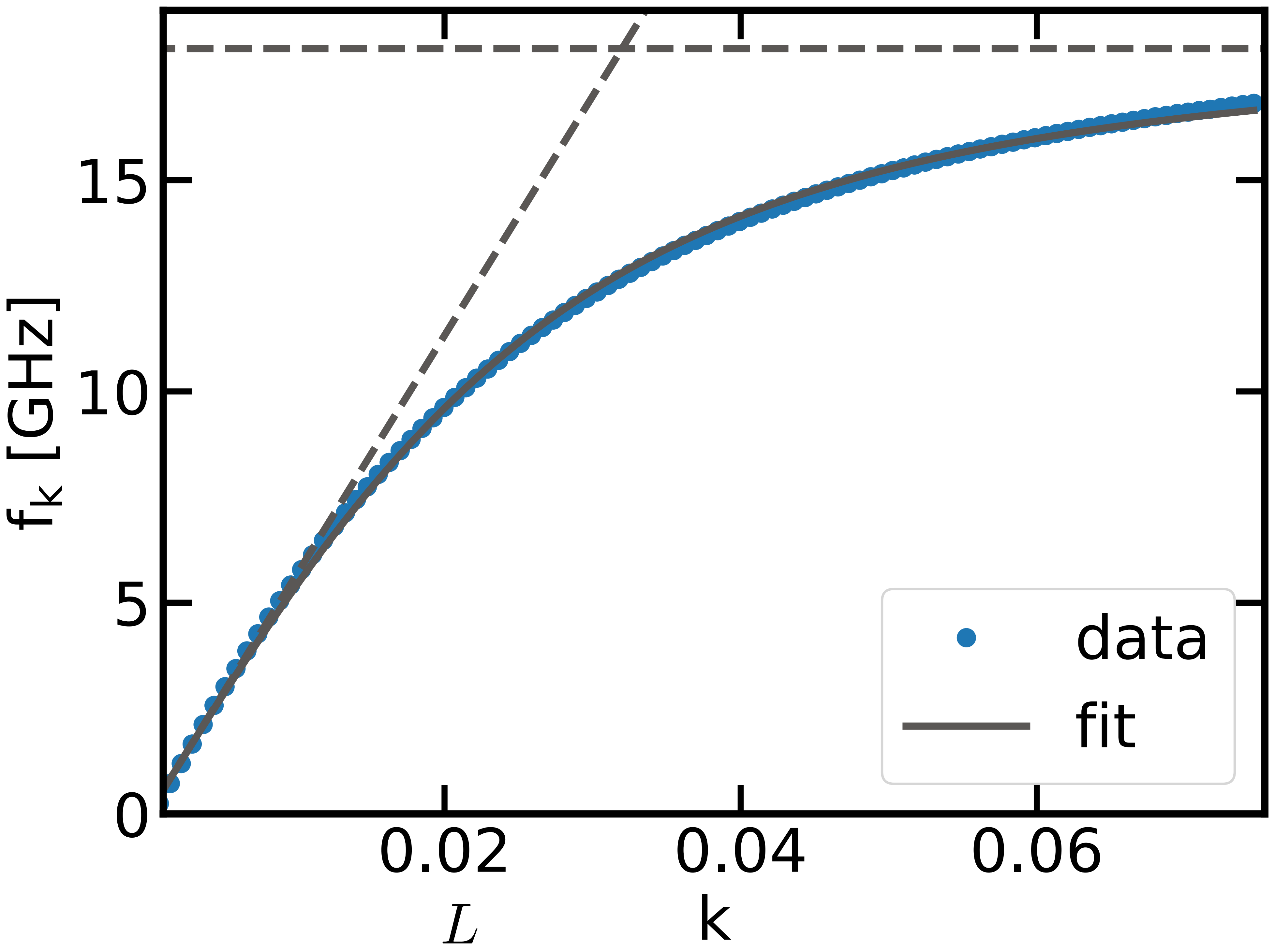


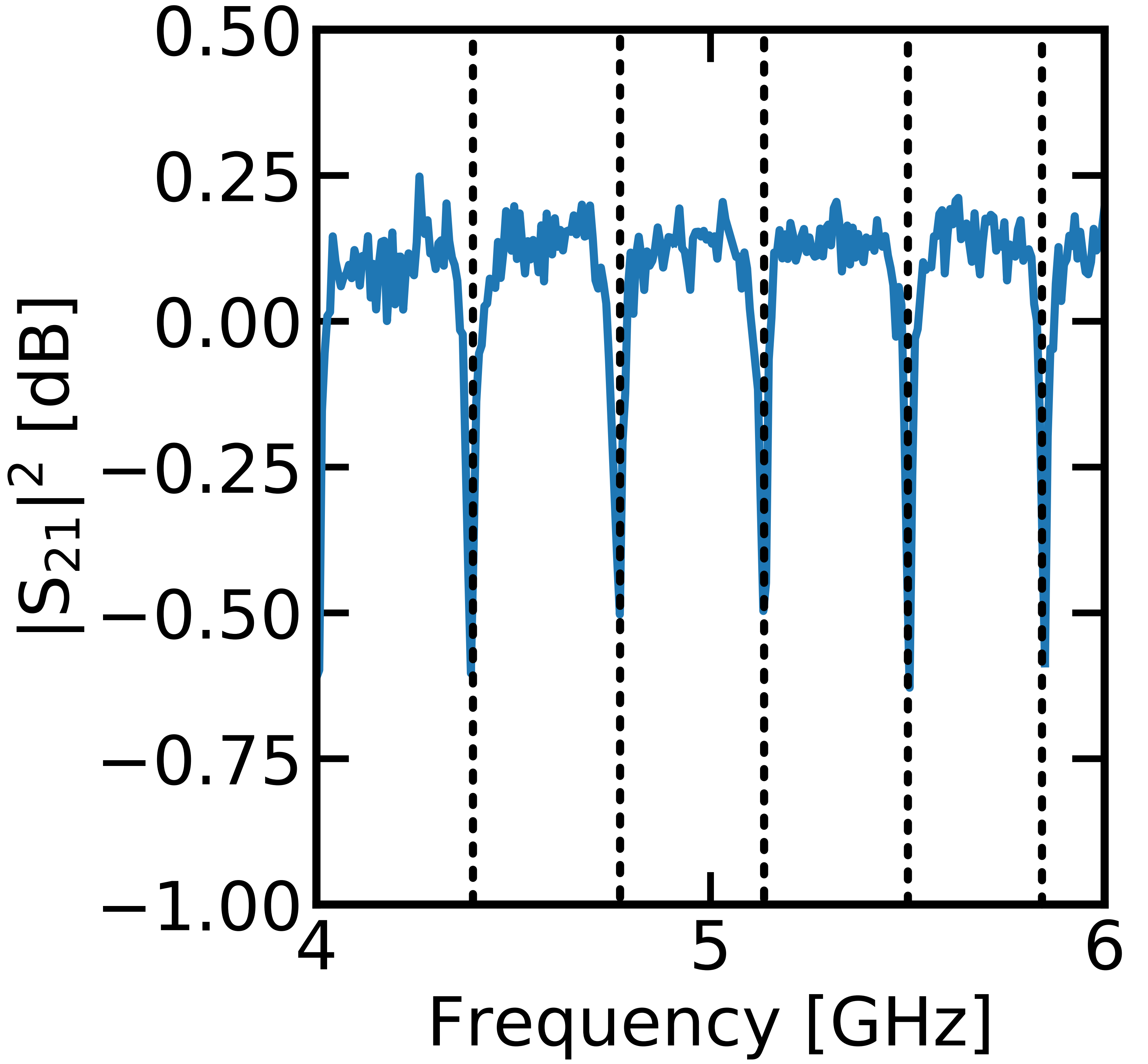
high frequency
& low temperature

$$\hbar\omega \gg k_{\mathrm{B}}T$$

$$(T = 20\ \mathrm{mK})$$

JJ meta-material: dispersion relation

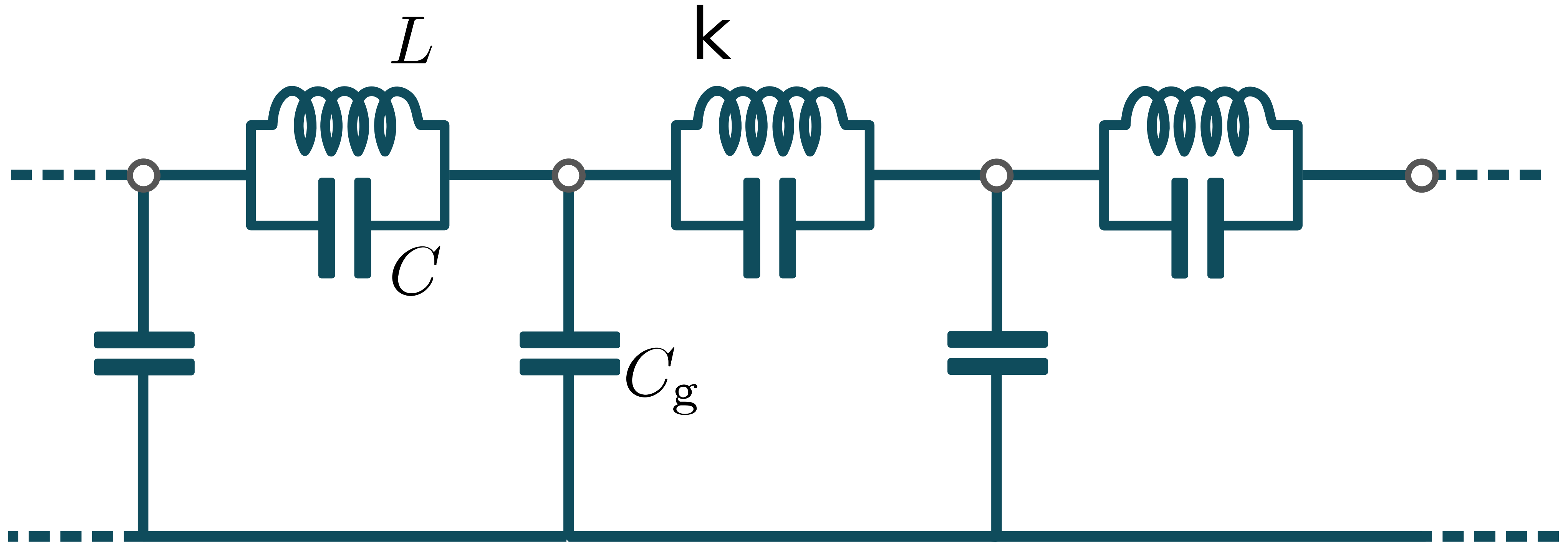




$L = 0.53\ \text{nH}$

$C = 144\ \text{fF}$

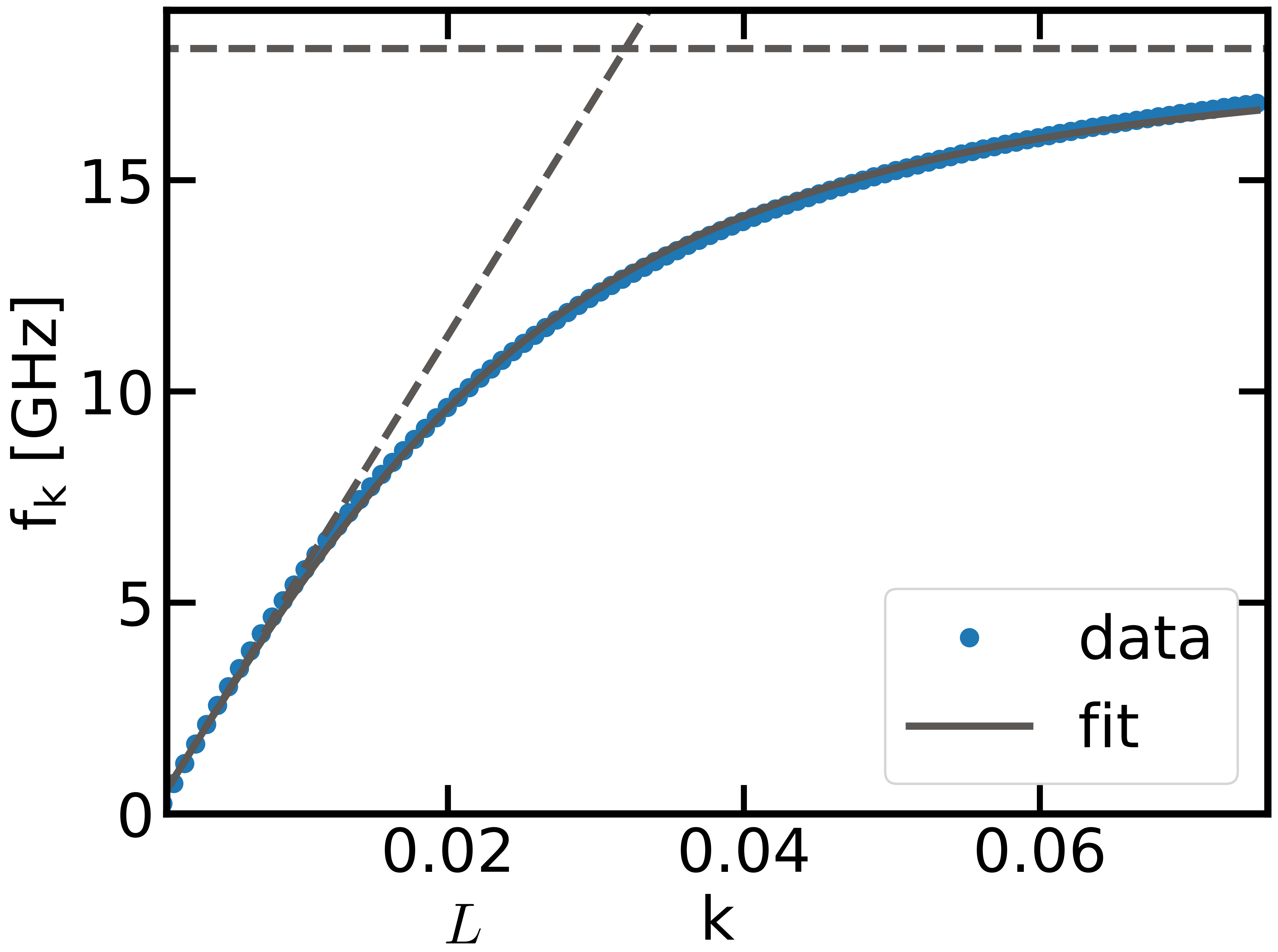
$C_\text{g} = 0.147\ \text{fF}$

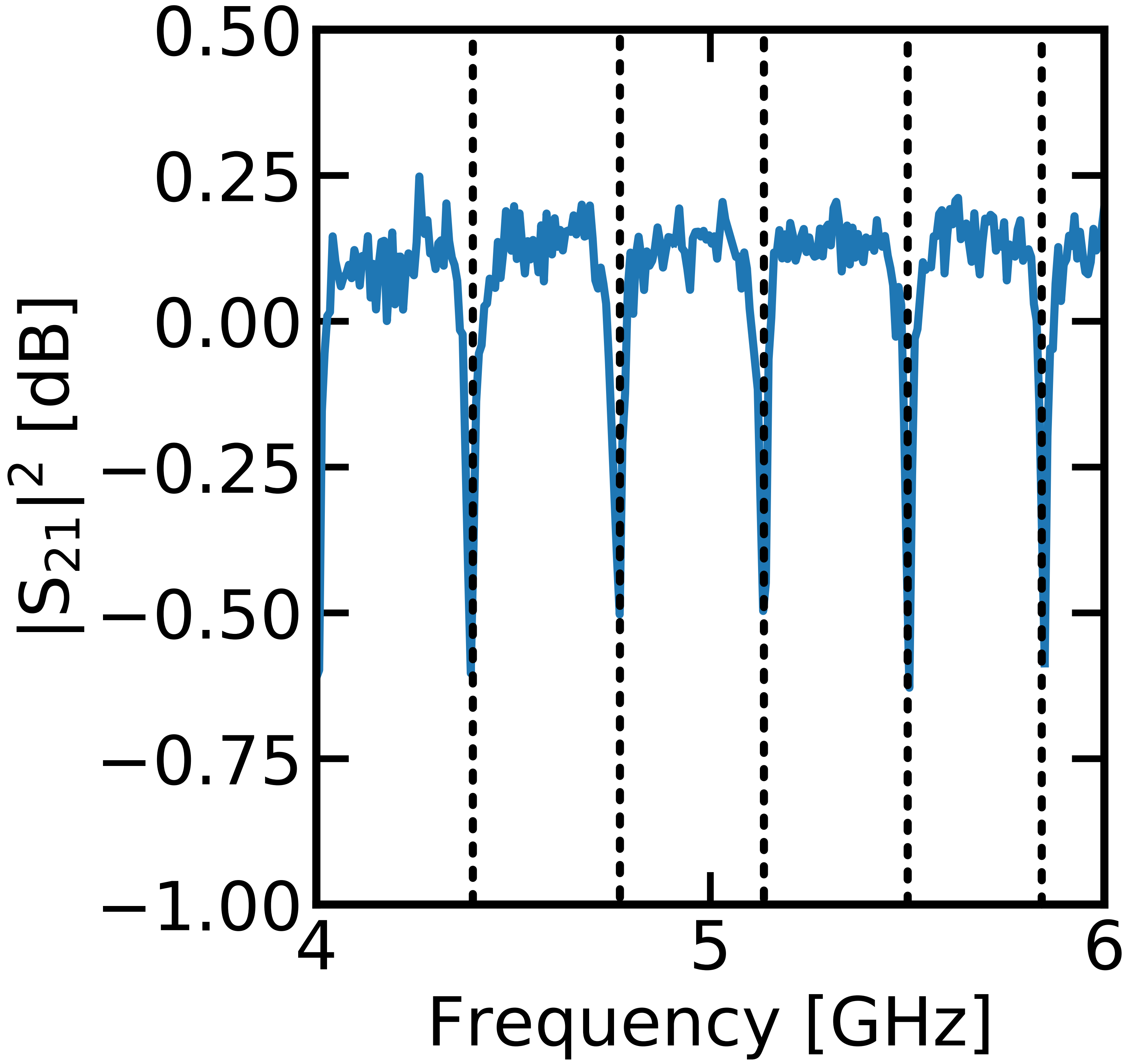


Characteristic impedance $Z_c = \sqrt{\frac{L}{C_g}} \sim 1.9\text{k}\Omega$

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

JJ meta-material: dispersion relation





$L = 0.53$ nH

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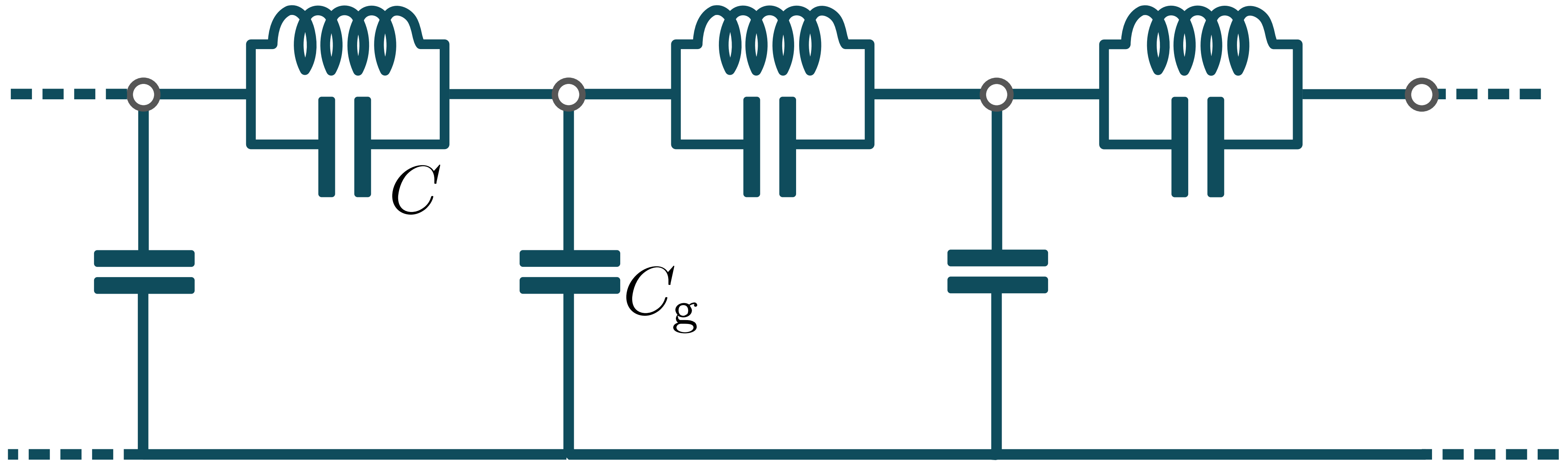


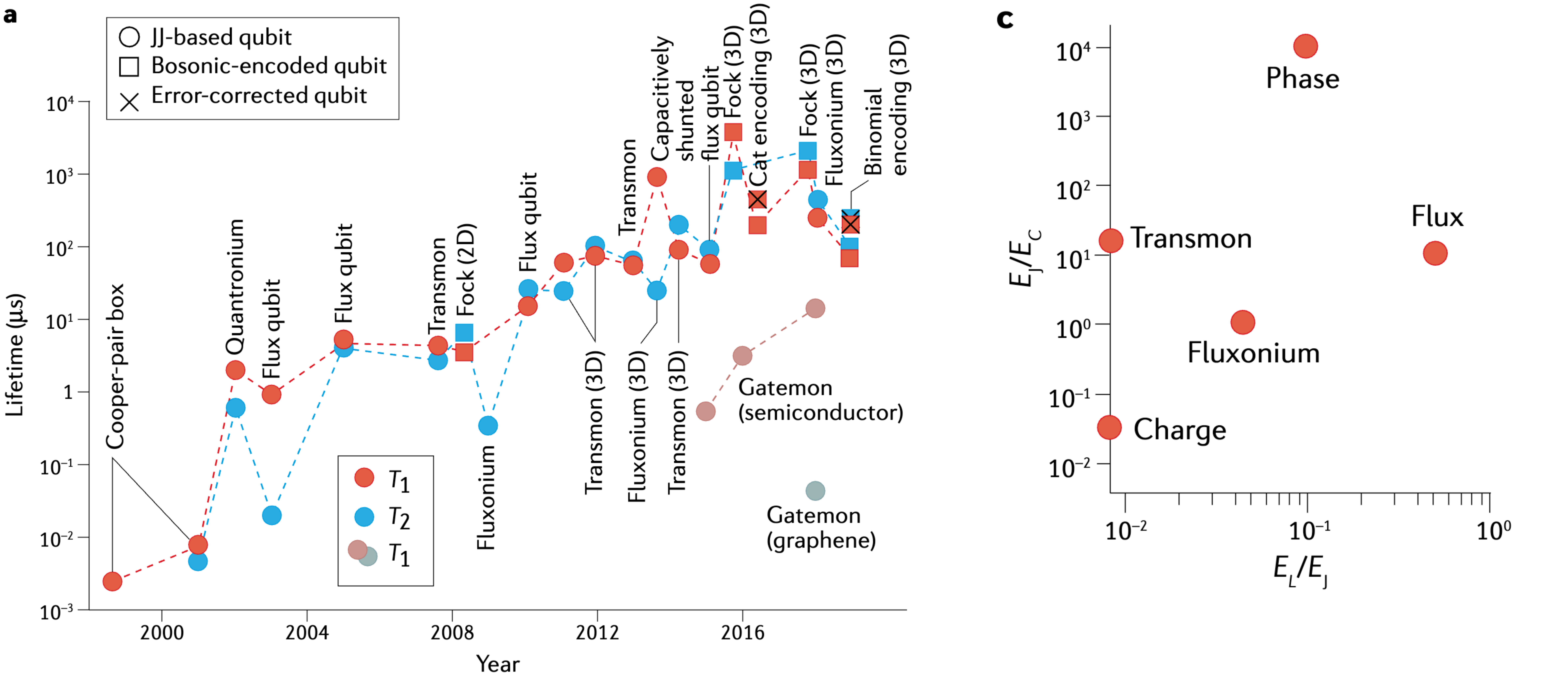
Characteristic impedance $Z_c = \sqrt{\frac{L}{C_g}} \sim 1.9\mathrm{k}\Omega$

Quality factor $Q_{\mathrm{int}} \sim 10^4$

Wanted: parasitic capacitance under control AND Low loss

Fluxonium devices:

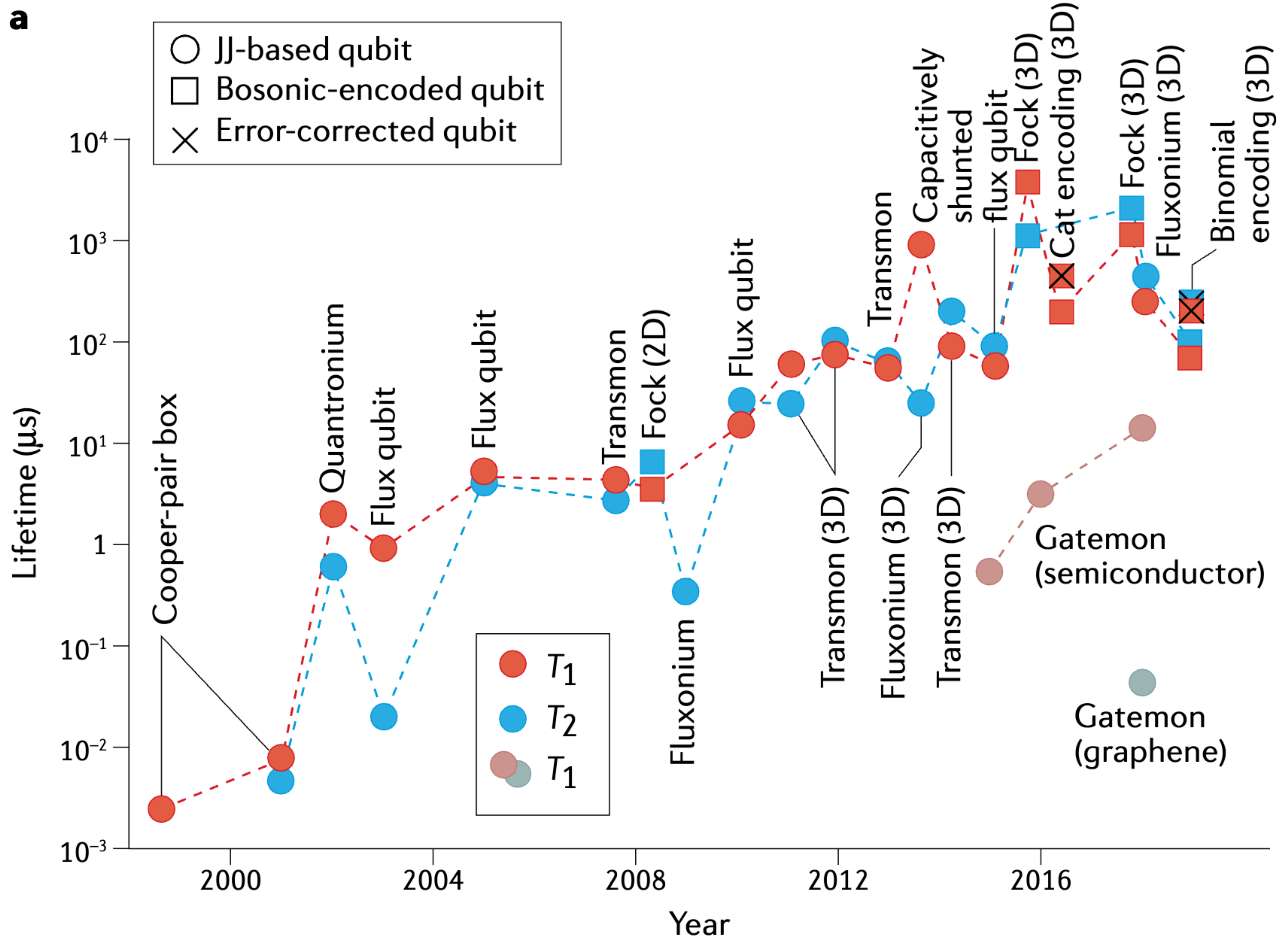
Comparison with other Josephson artificial atoms

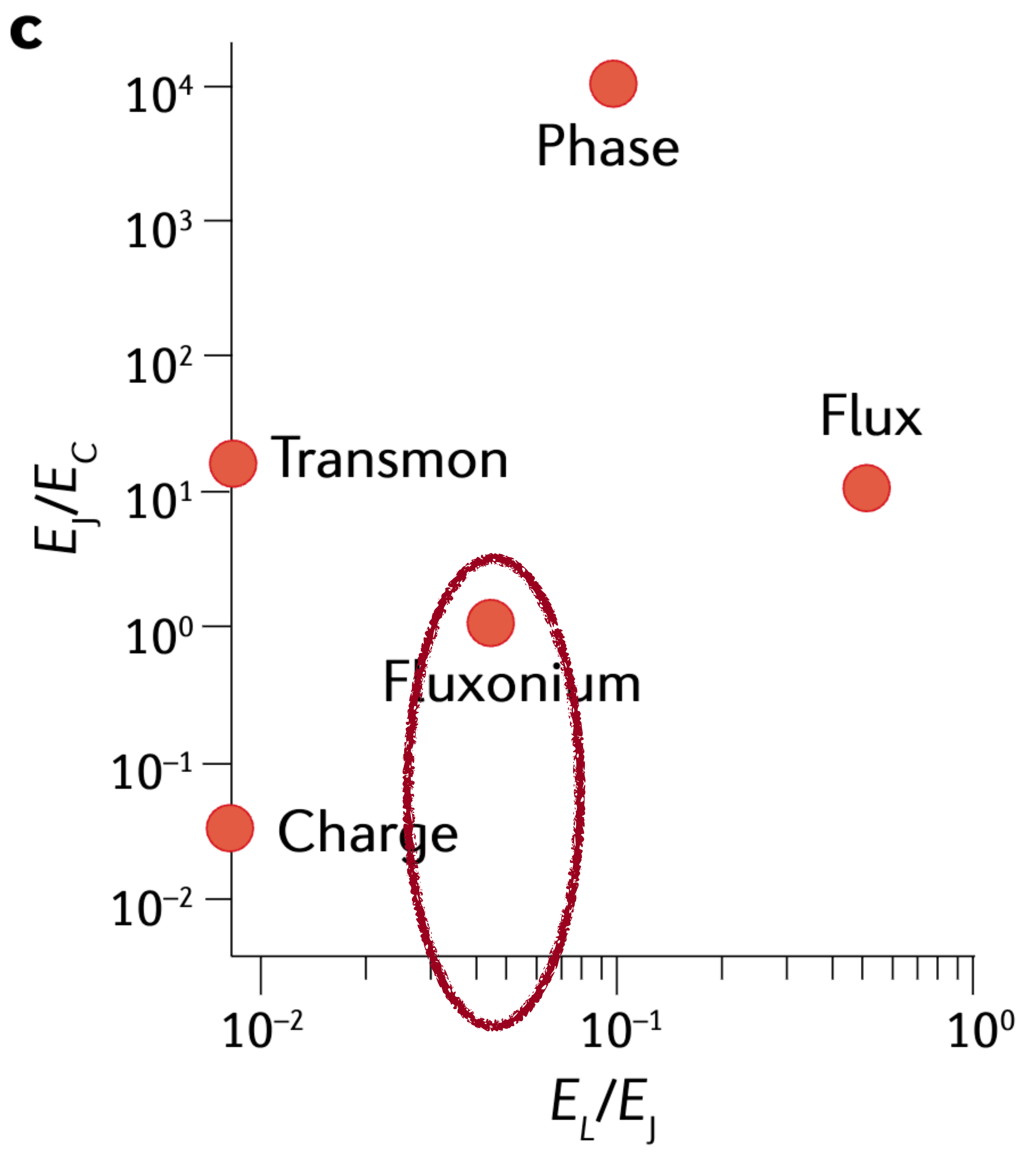


 I. Siddiqi Nature Review (2021)

Fluxonium devices:

Comparison with other Josephson artificial atoms





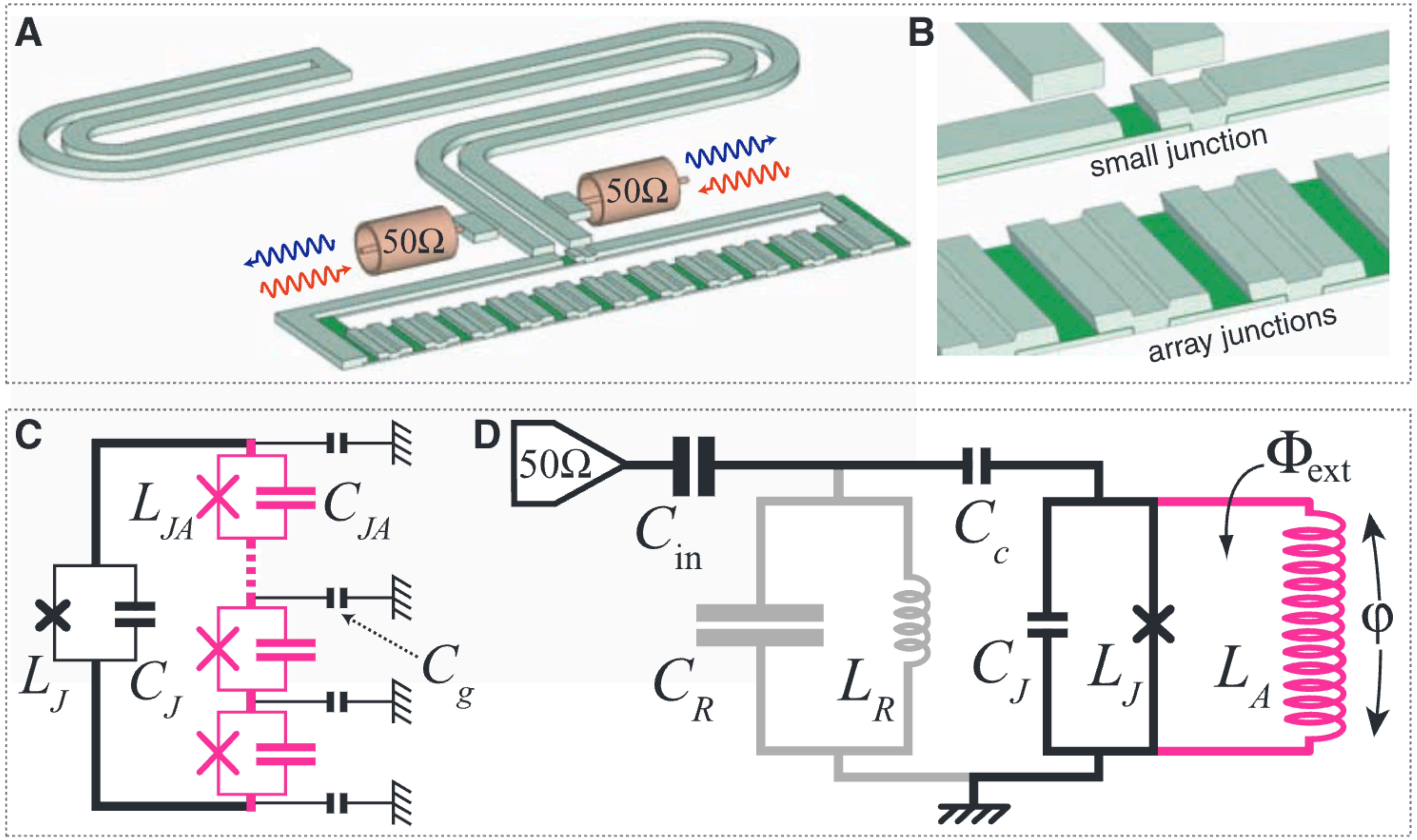
Very small E_L

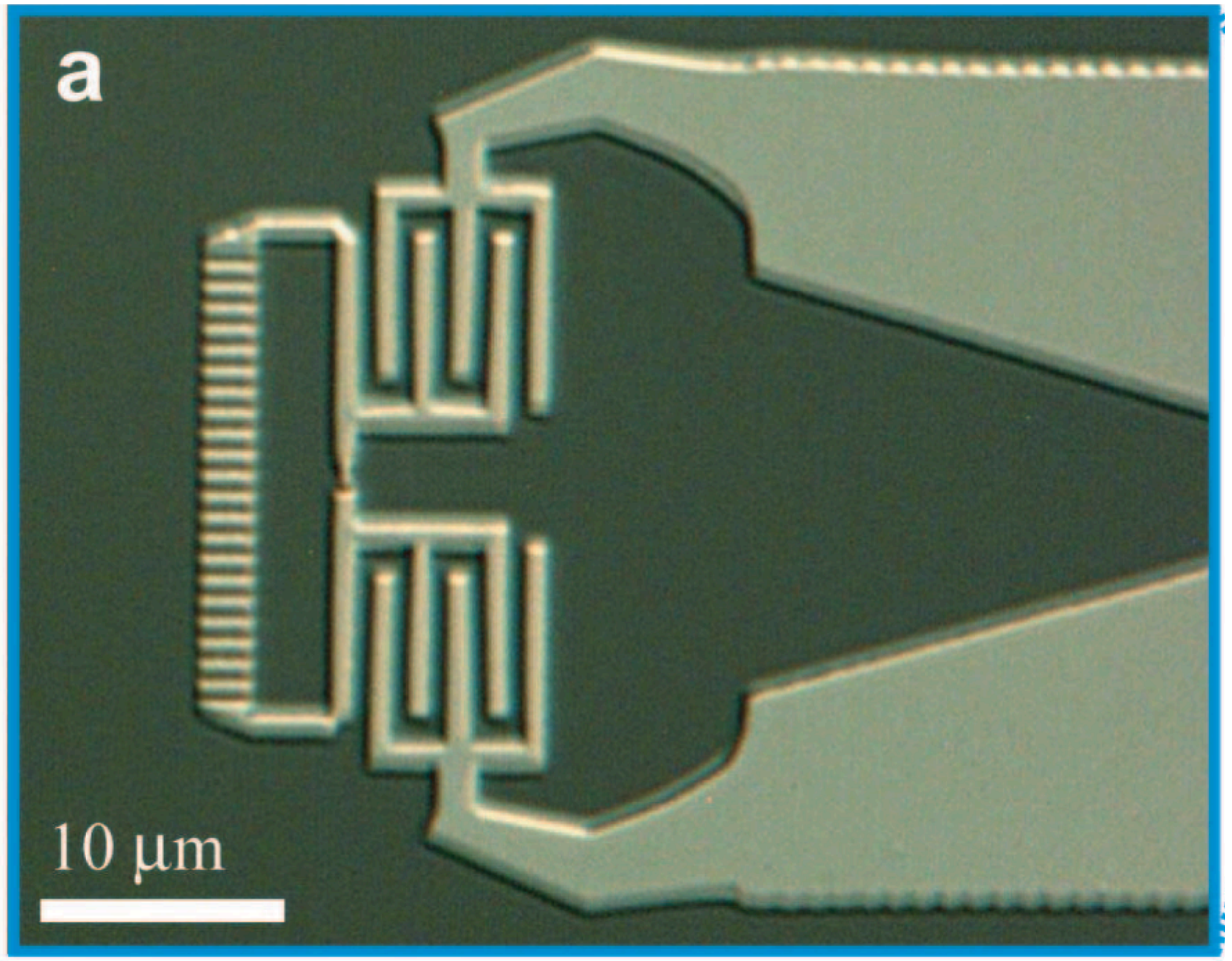
→ Very large inductance

I. Siddiqi Nature Review (2021)

Fluxonium devices:

First device:





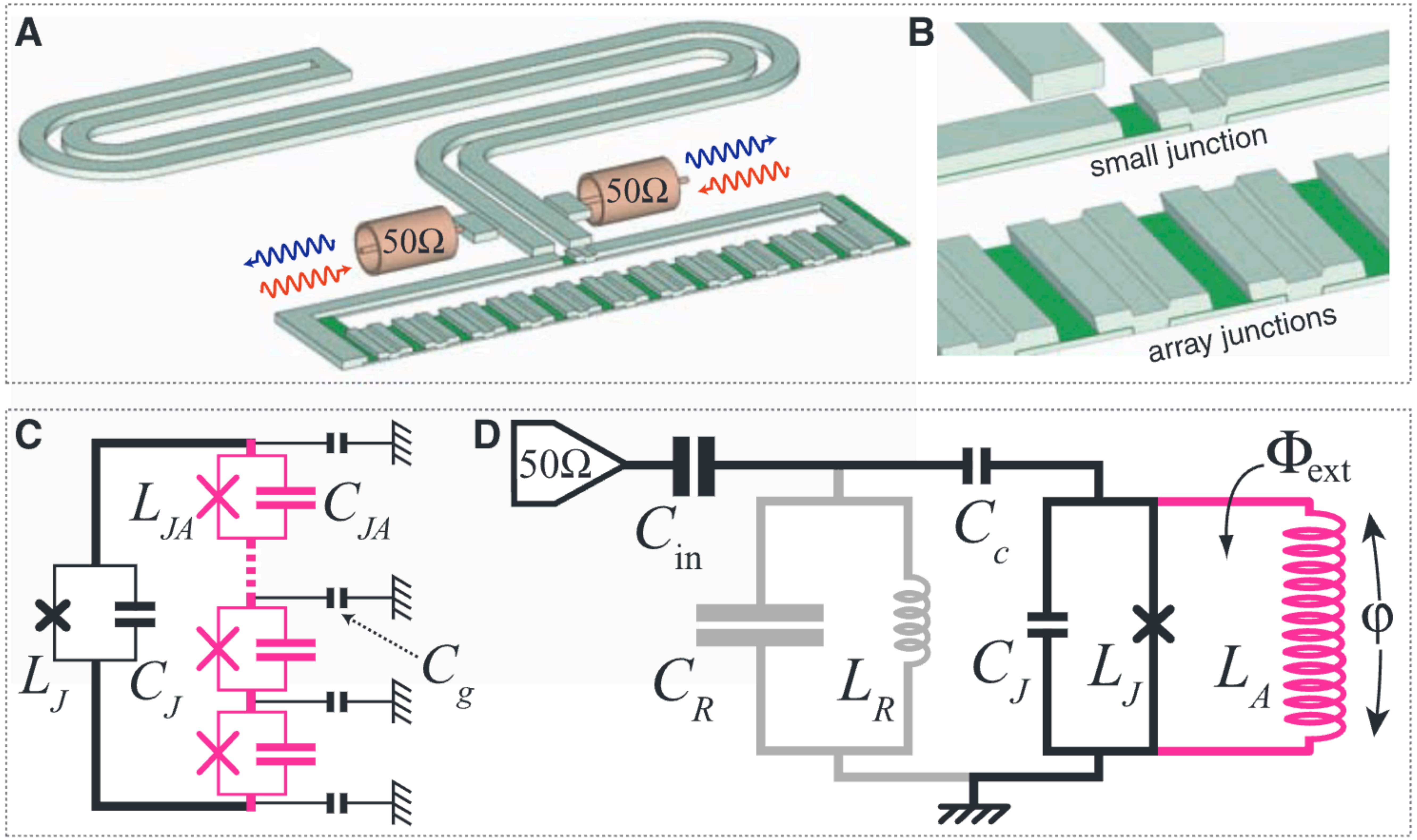
V. Manucharyan et al., Science (2009)

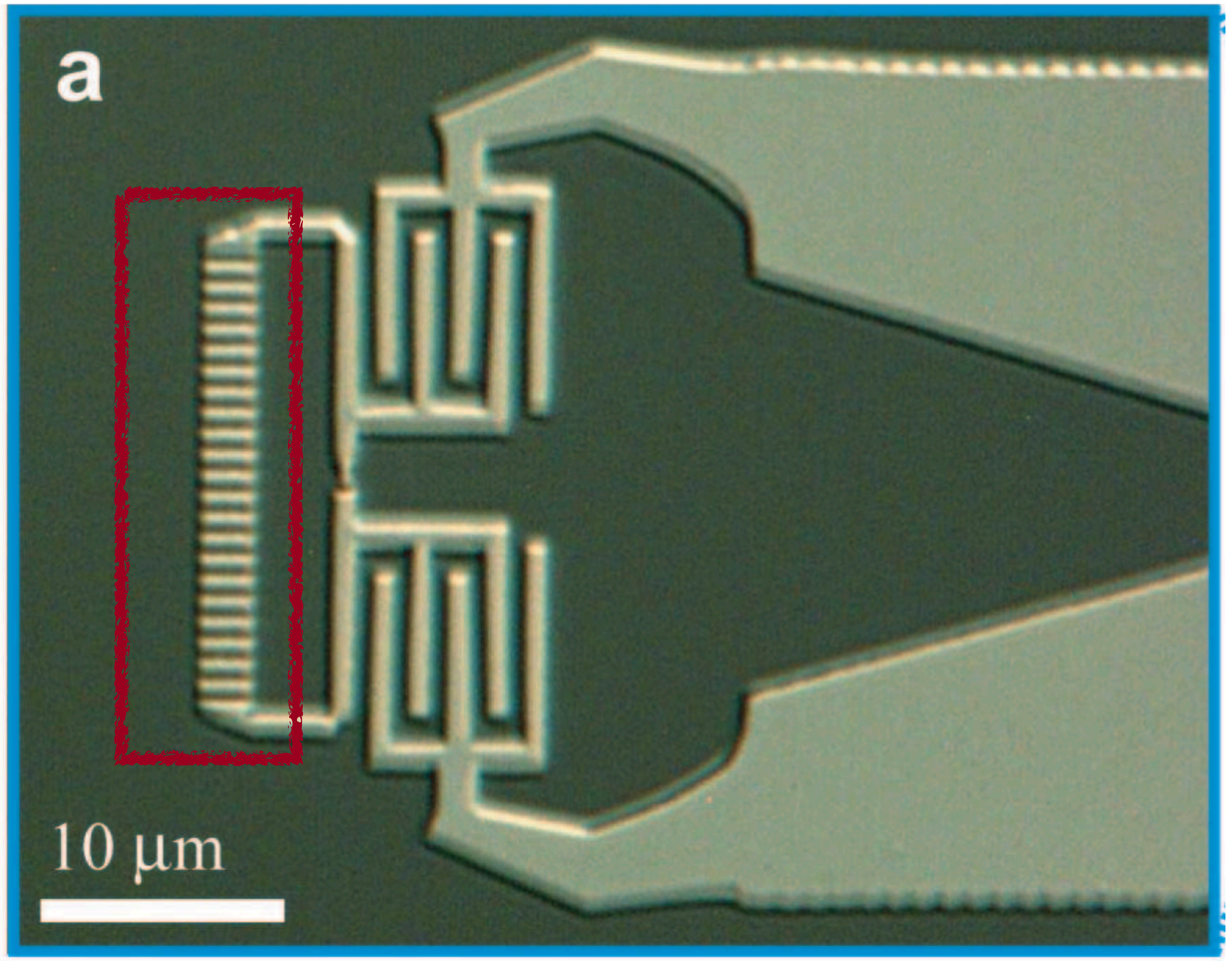
V. Manucharyan et al., arXiv 0910:3039 (2009)

V. Manucharyan et al., Phys. Rev. B (2012)

Fluxonium devices:

First device:





Very large inductance a.k.a "Superinductance"

Made from a JJ array

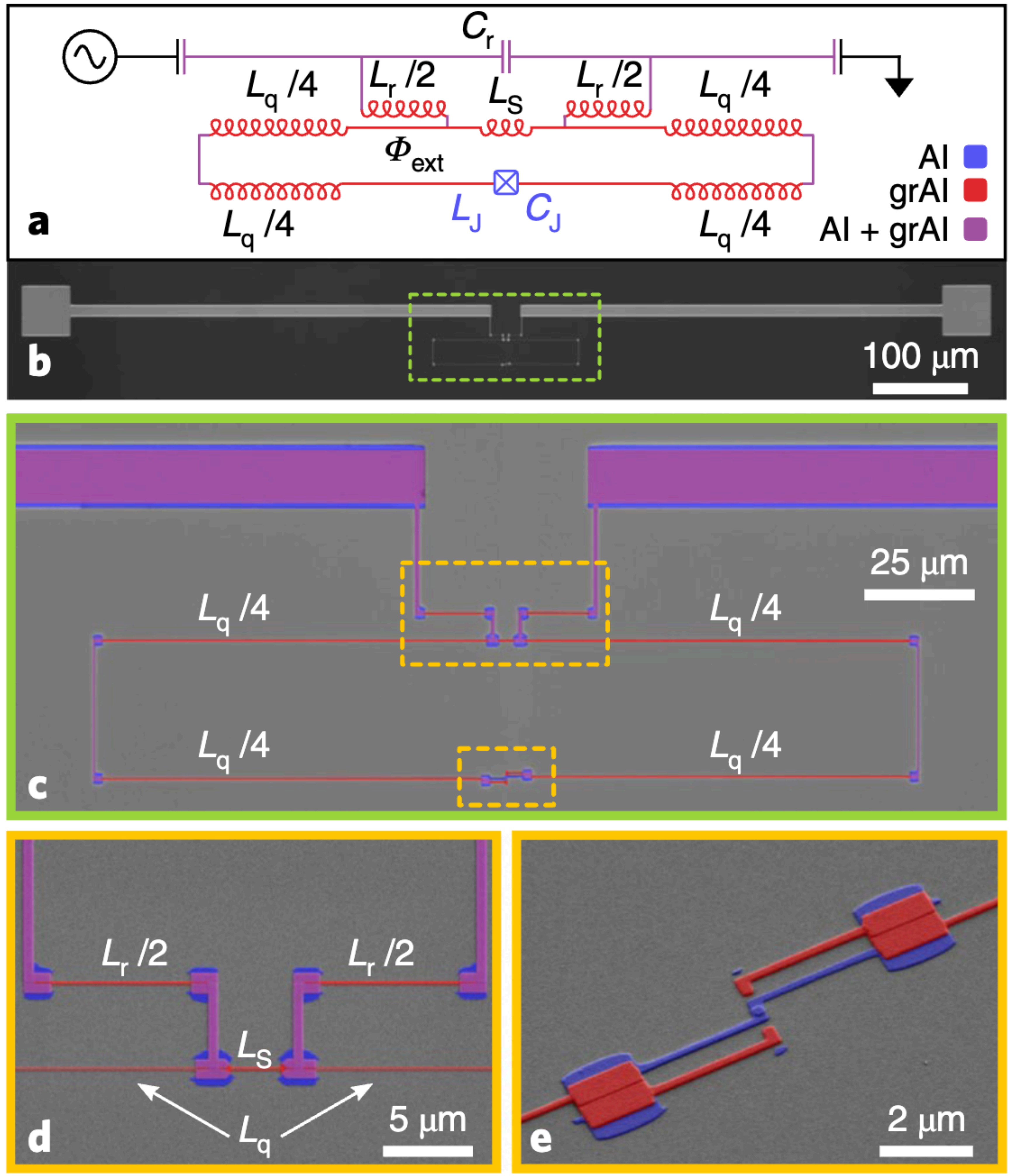
V. Manucharyan et al., Science (2009)

V. Manucharyan et al., arXiv 0910:3039 (2009)

V. Manucharyan et al., Phys. Rev. B (2012)

Fluxonium devices:

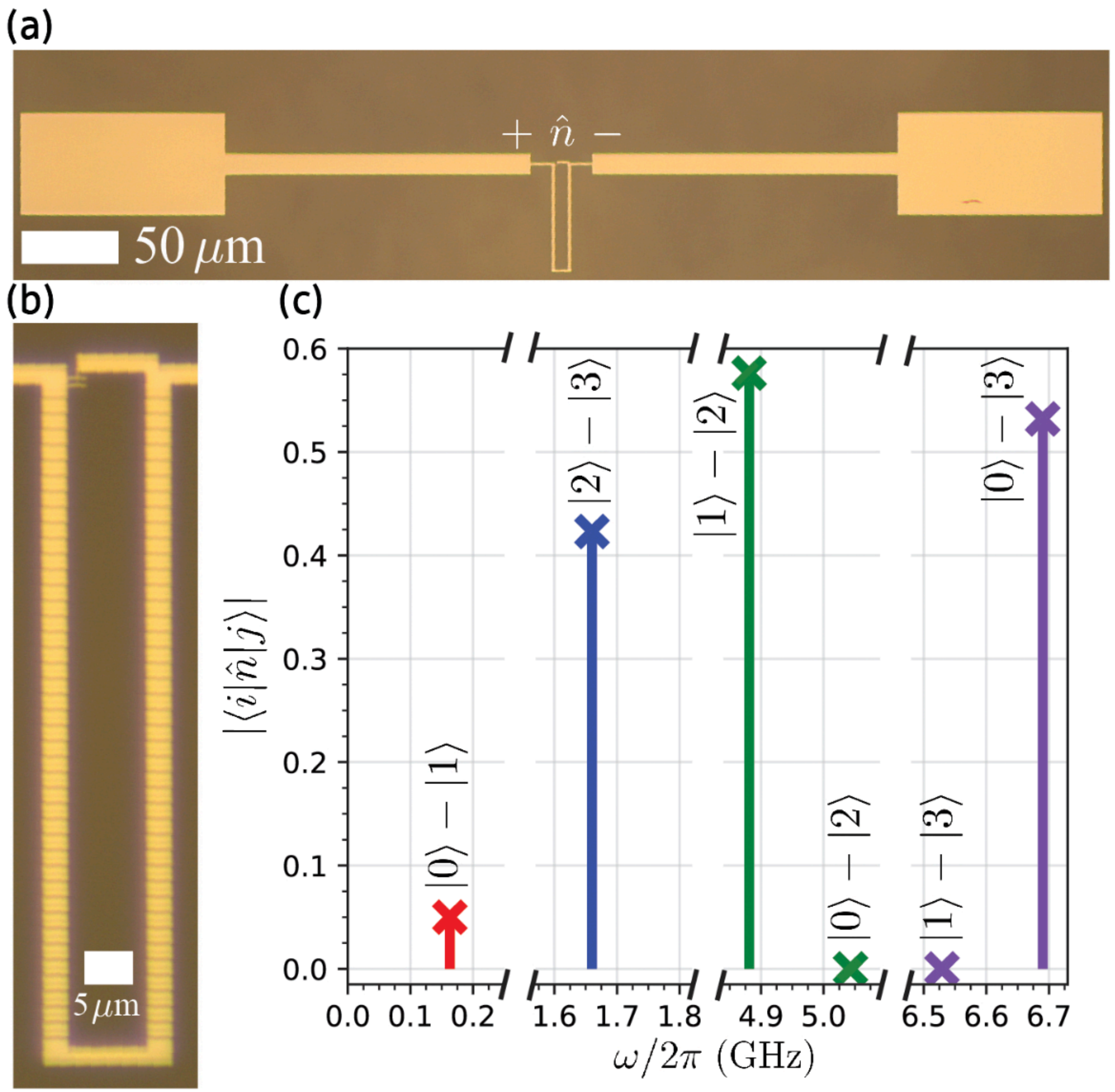
More recent devices
(inside a 3D cavity + super inductance made of granular aluminum):

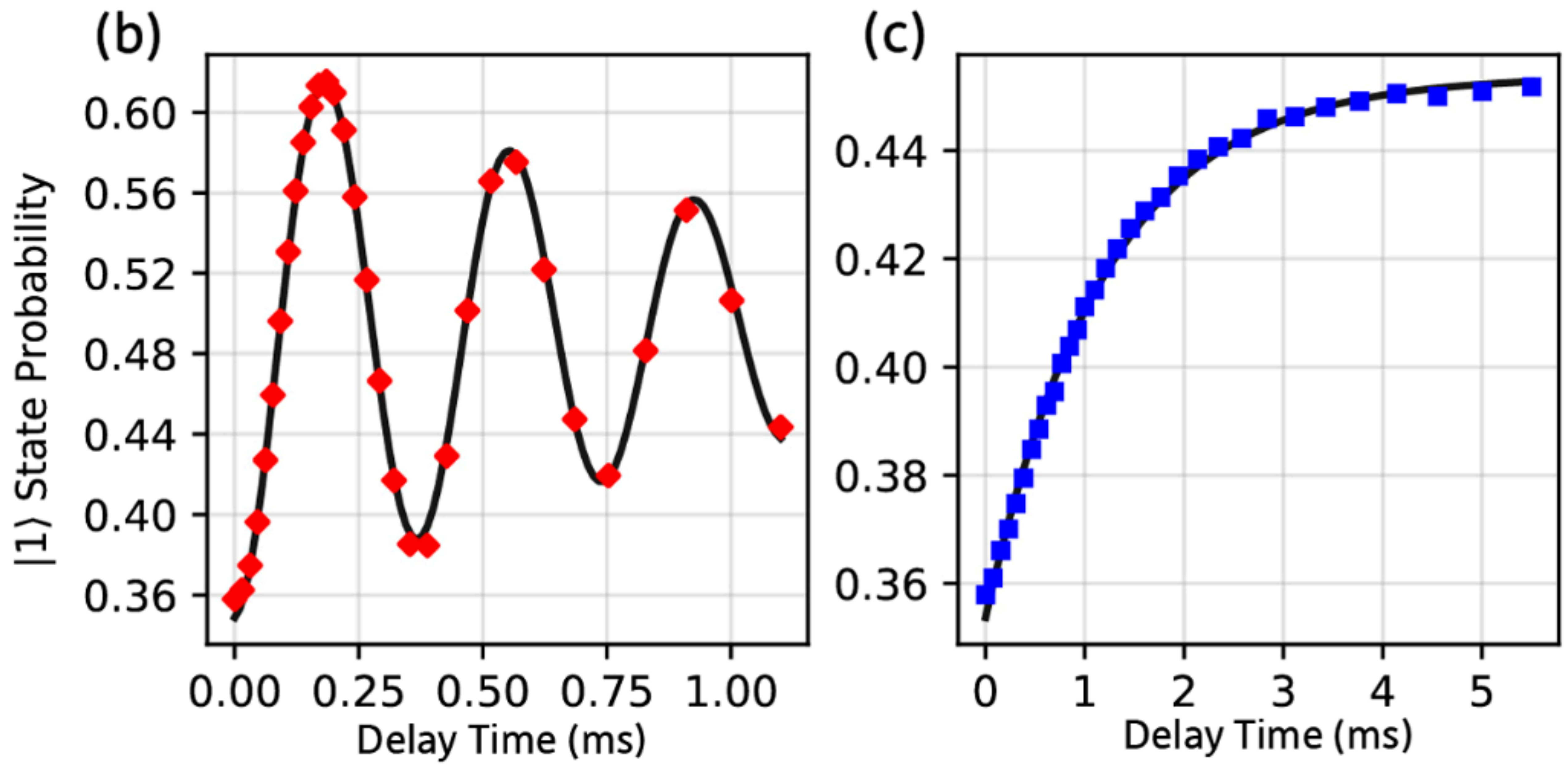


L. Grunhaupt et al., Nat. Material (2019)

Fluxonium devices:

More recent devices (inside a 3D cavity):

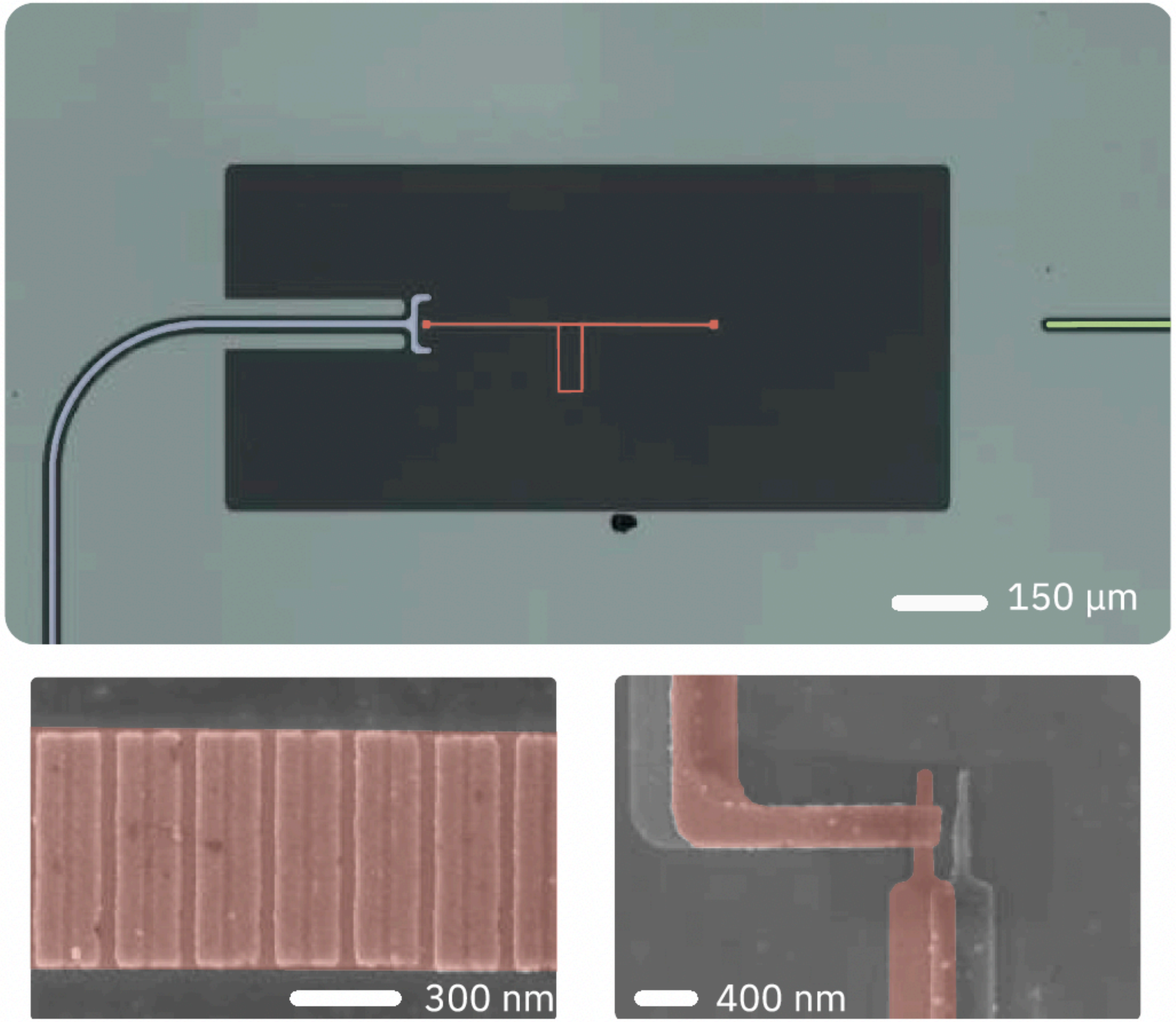




A. Somoroff, Q. Ficheux et al., Phys. Rev. Lett (2023)

Fluxonium devices:

More recent devices (in a 2D architecture):



W. Ardati et al., Phys. Rev. X (2024)

Why the Fluxonium?

Argument #1: in superconducting circuits there are “broken Cooper pairs” (a.k.a. quasiparticles) but there is no “broken Fluxons”.

Why the Fluxonium?

Argument #2: charge noise amplitude is two orders of magnitude higher than flux noise:

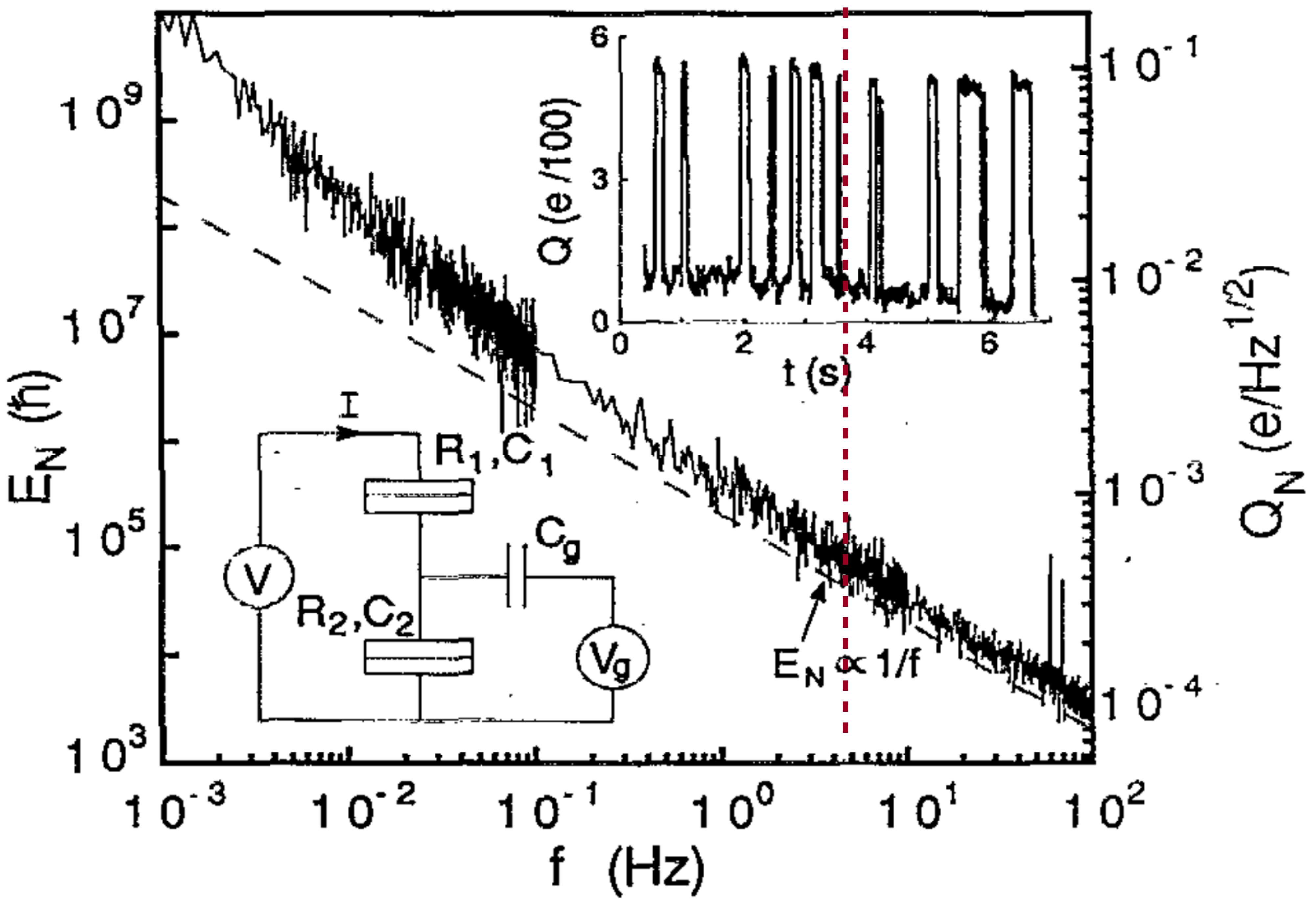
Charge noise

$S_N \sim 10^{-4} e/\sqrt{\mathrm{Hz}}$

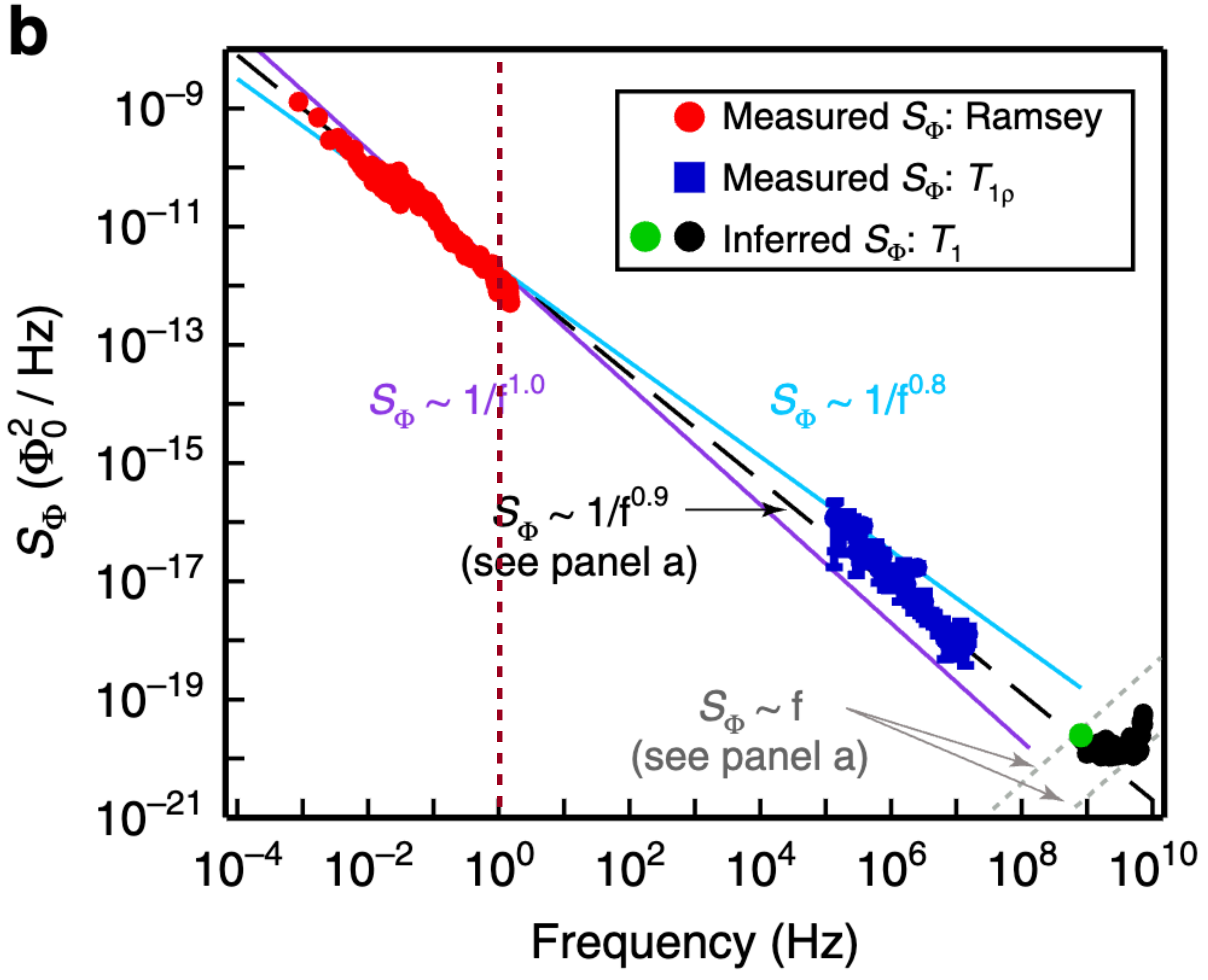
Flux noise

$S_\Phi \sim 10^{-6} \Phi_0/\sqrt{\mathrm{Hz}}$

Slope of the 1/f noise PSD



G. Zimmerli et al., App. Phys. Lett. (1992)



F. Yan et al., Nat. Commun (2016)

Outline

1. Large inductance: Josephson meta-materials
2. Traveling Wave Parametric Amplifiers
3. Quantum impurities