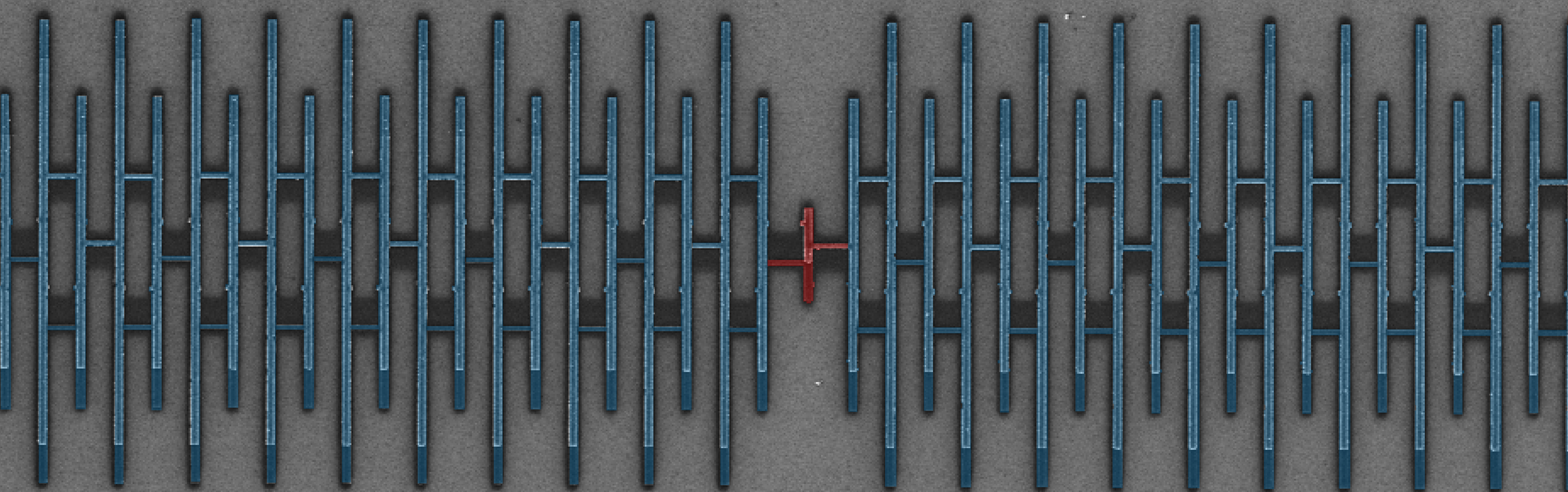
Many-body physics and superconducting quantum circuits



Nicolas Roch
Neel Institute, Grenoble, France
QuantECA (Quantum Electronics and Circuits Alpes)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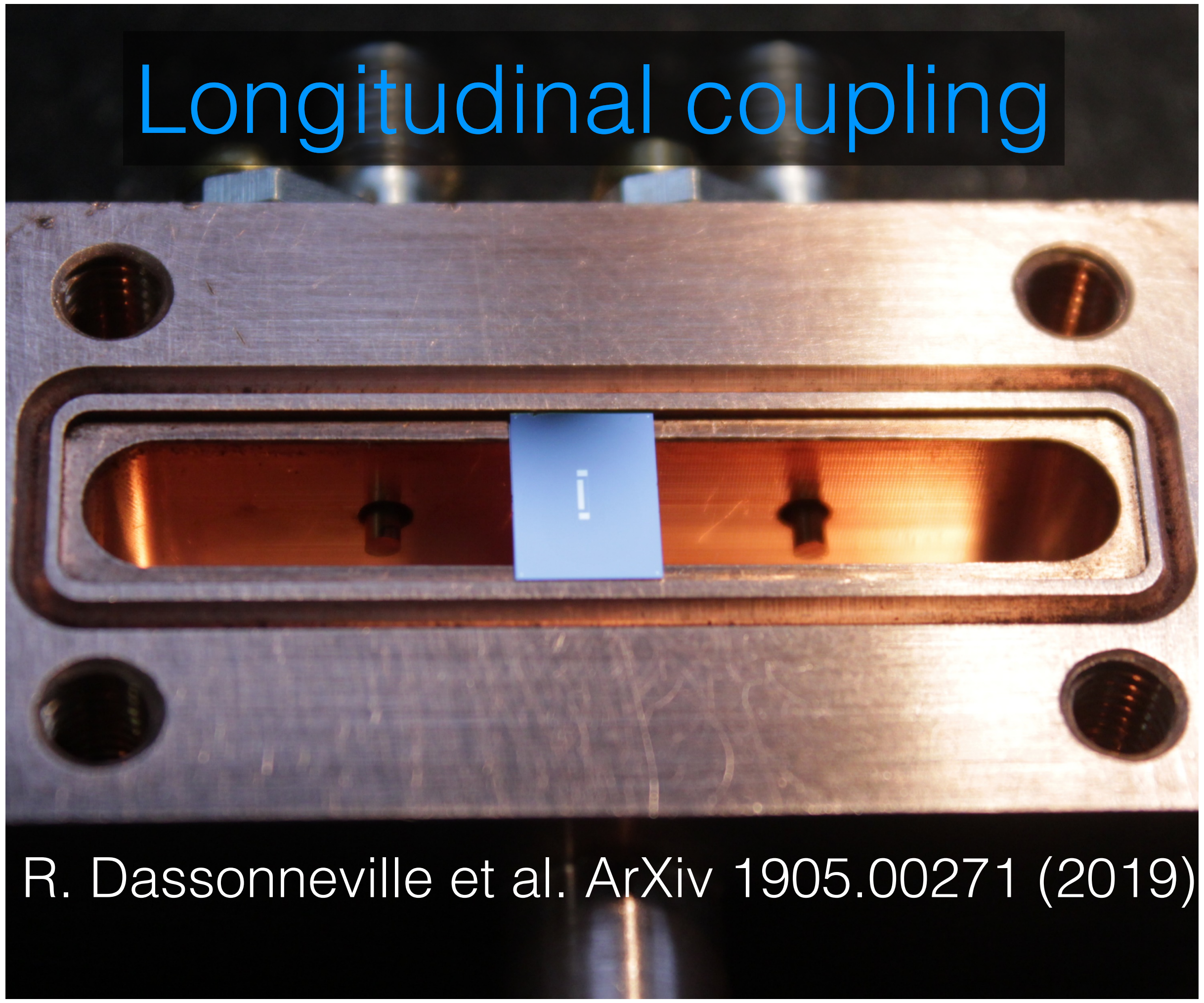
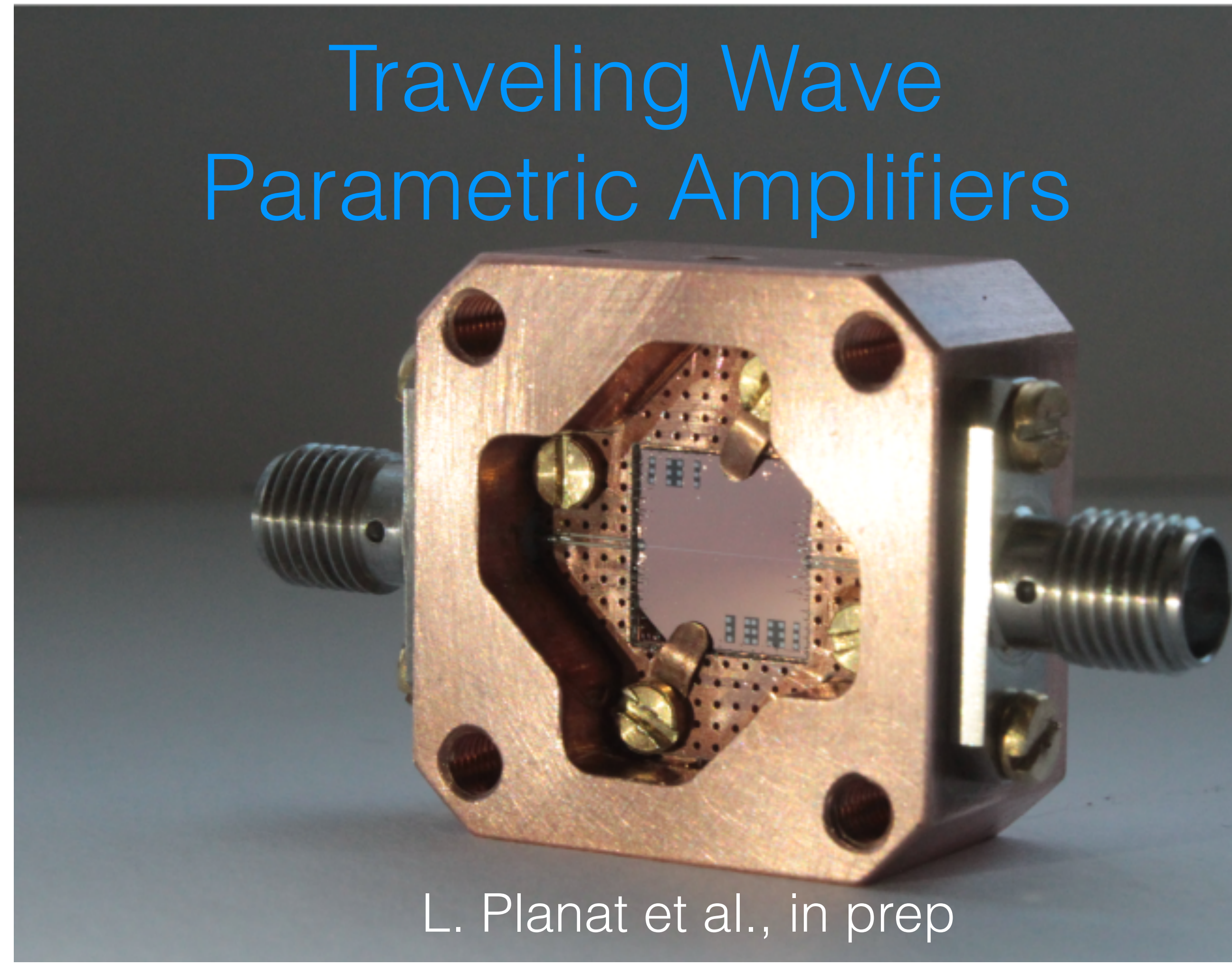
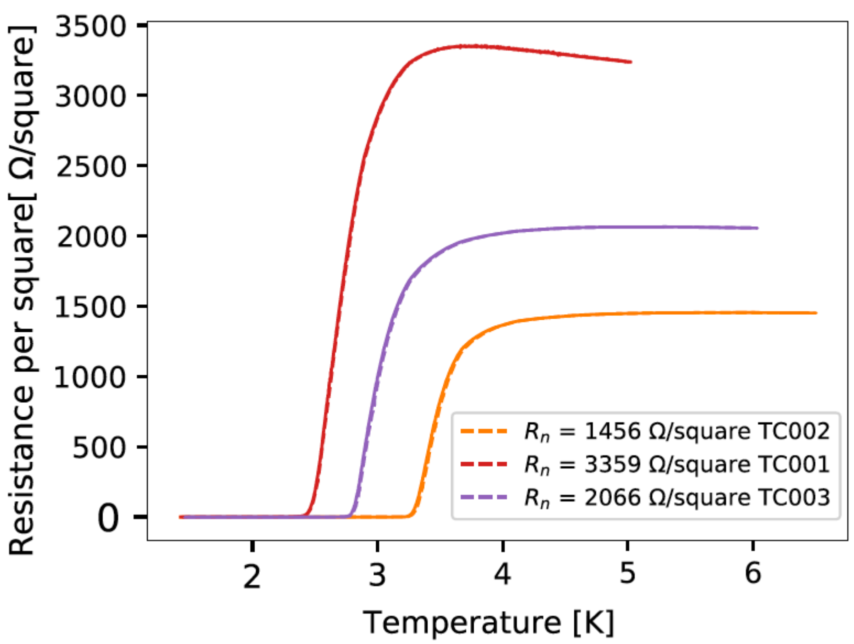
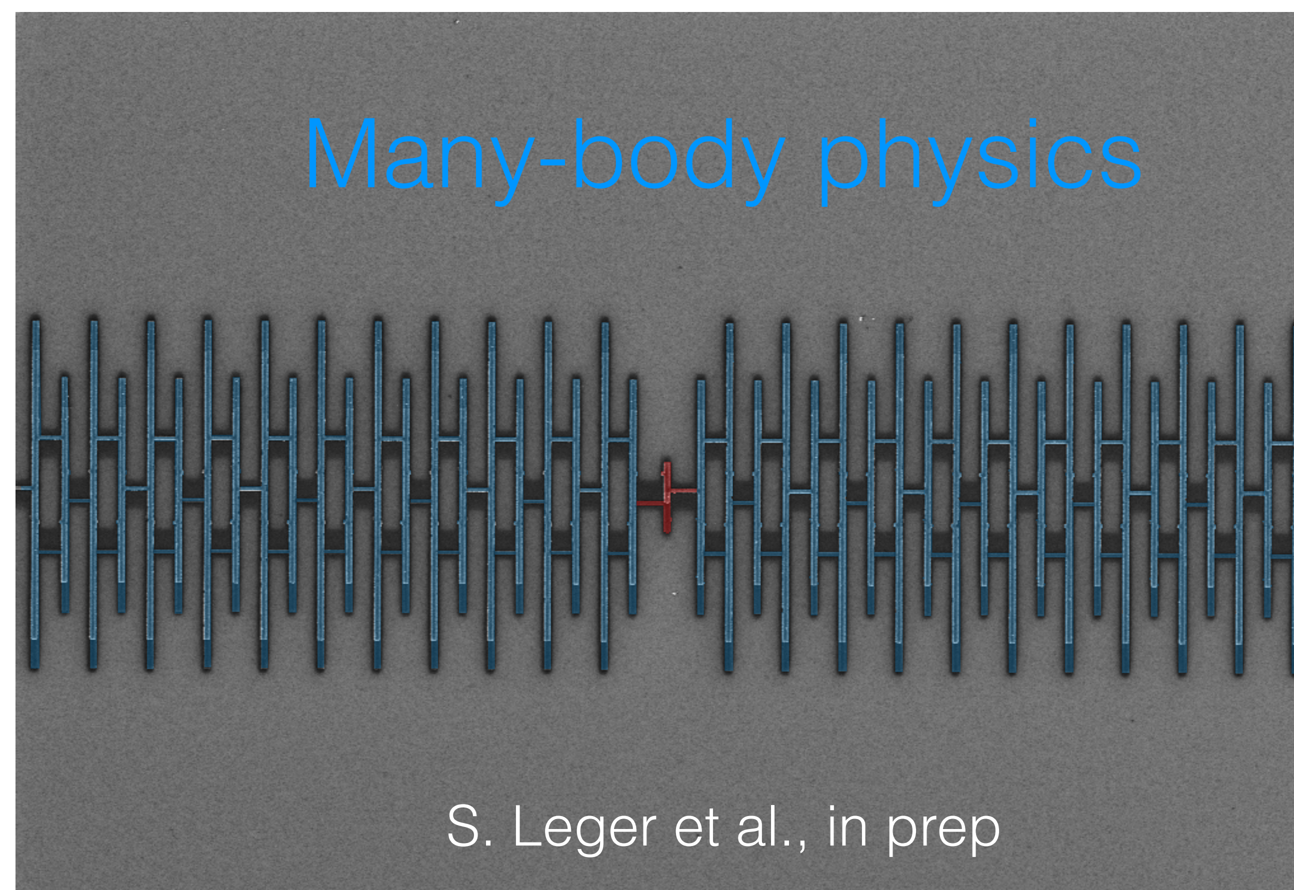


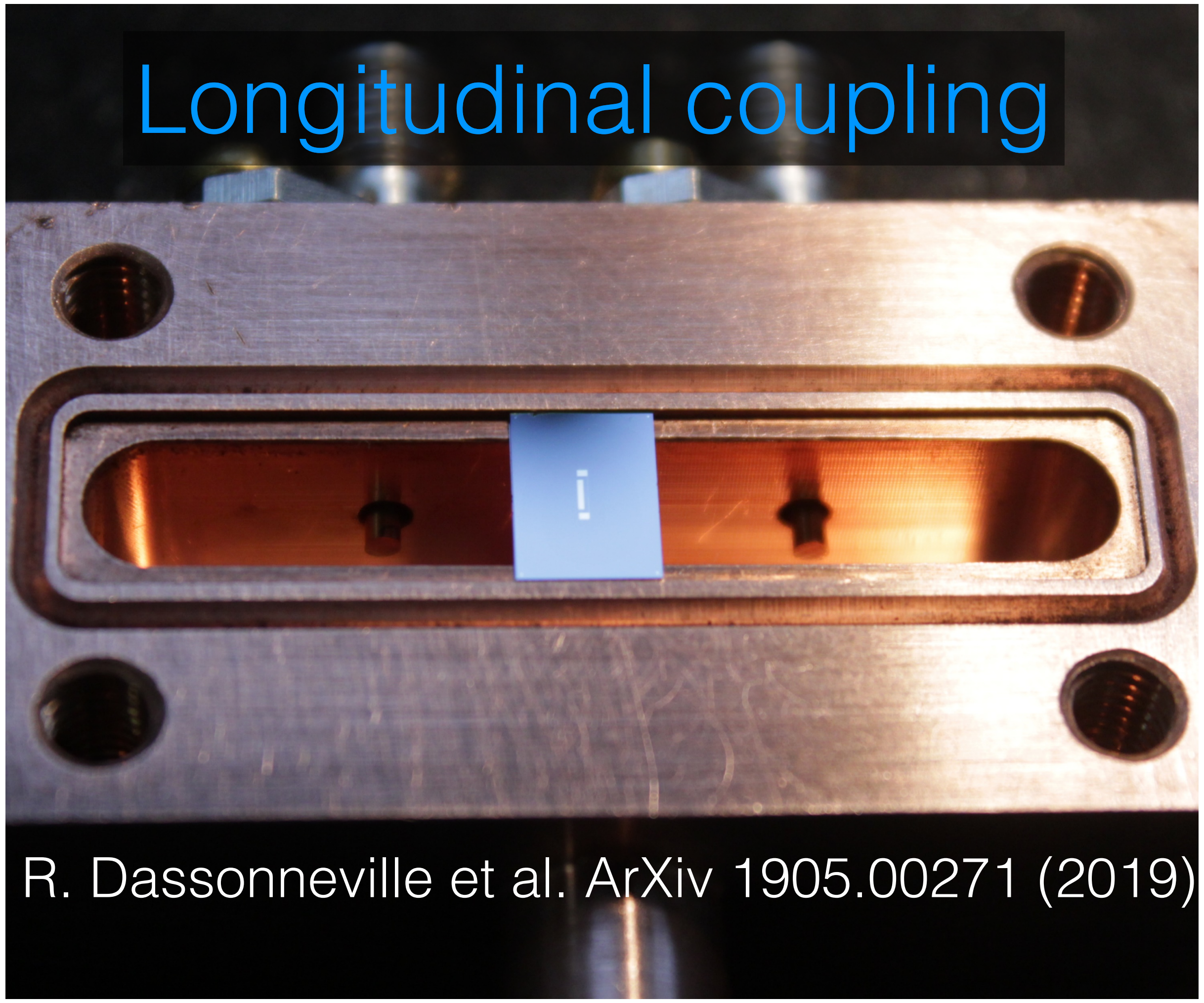


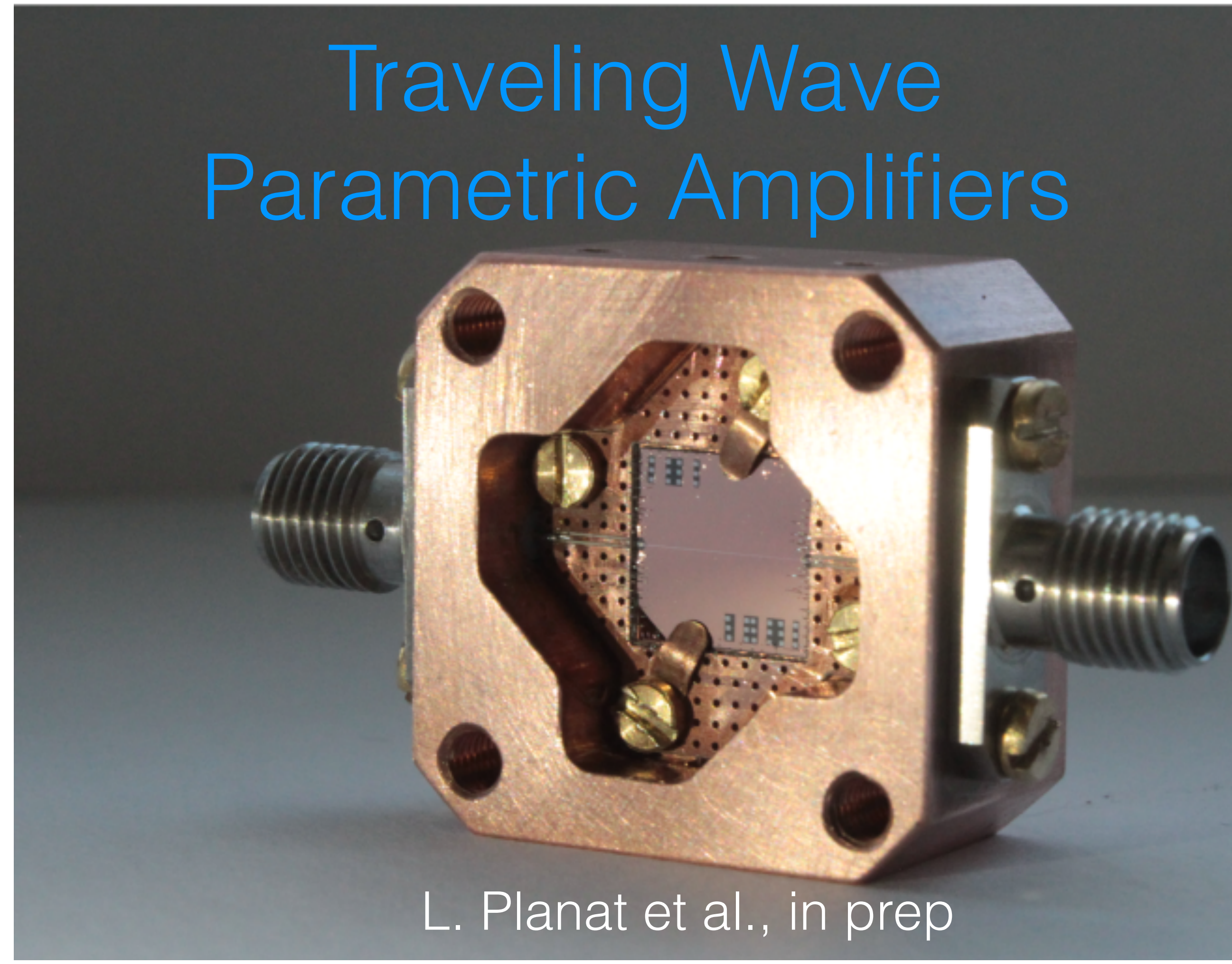
New Materials (Re, InOx)



T. Charpentier et al., in prep







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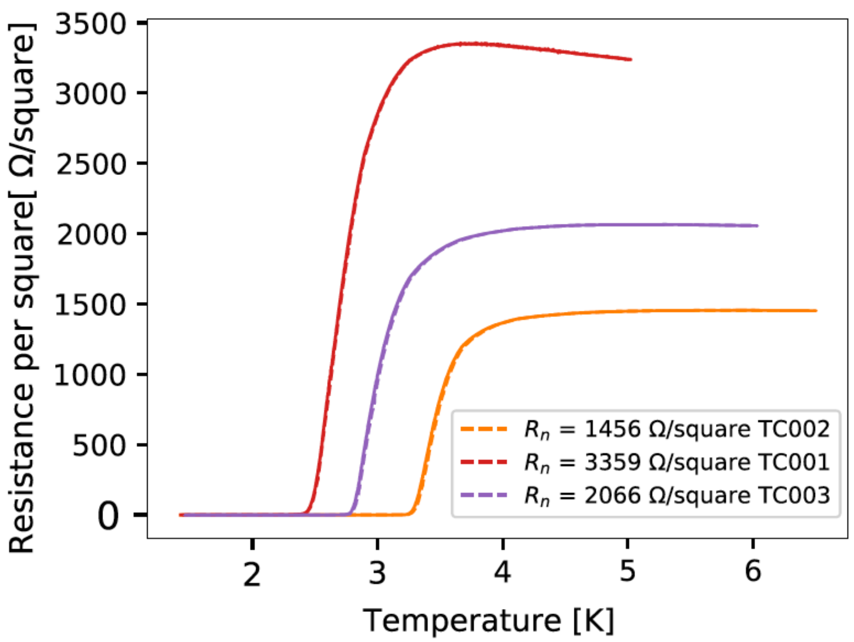

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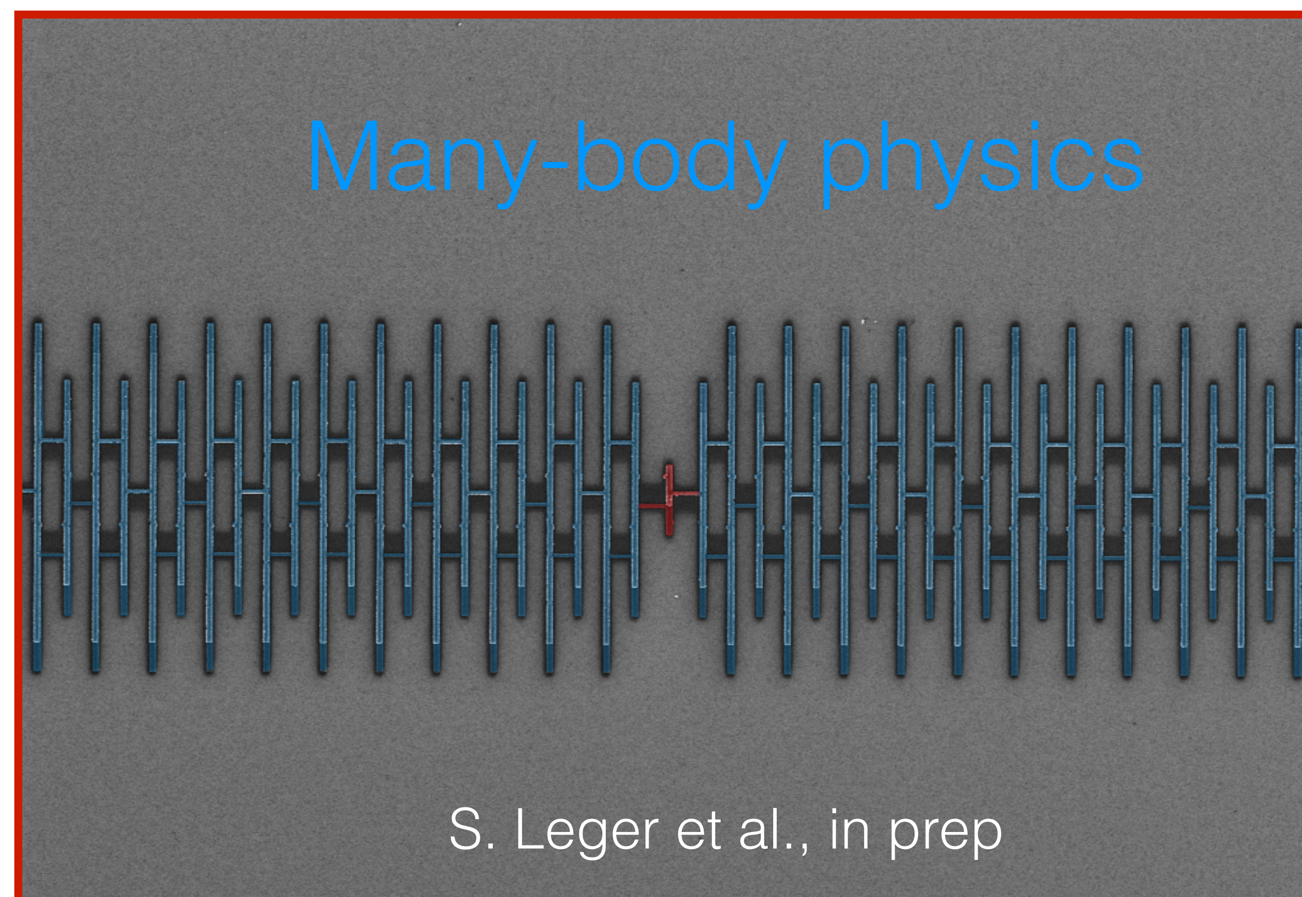
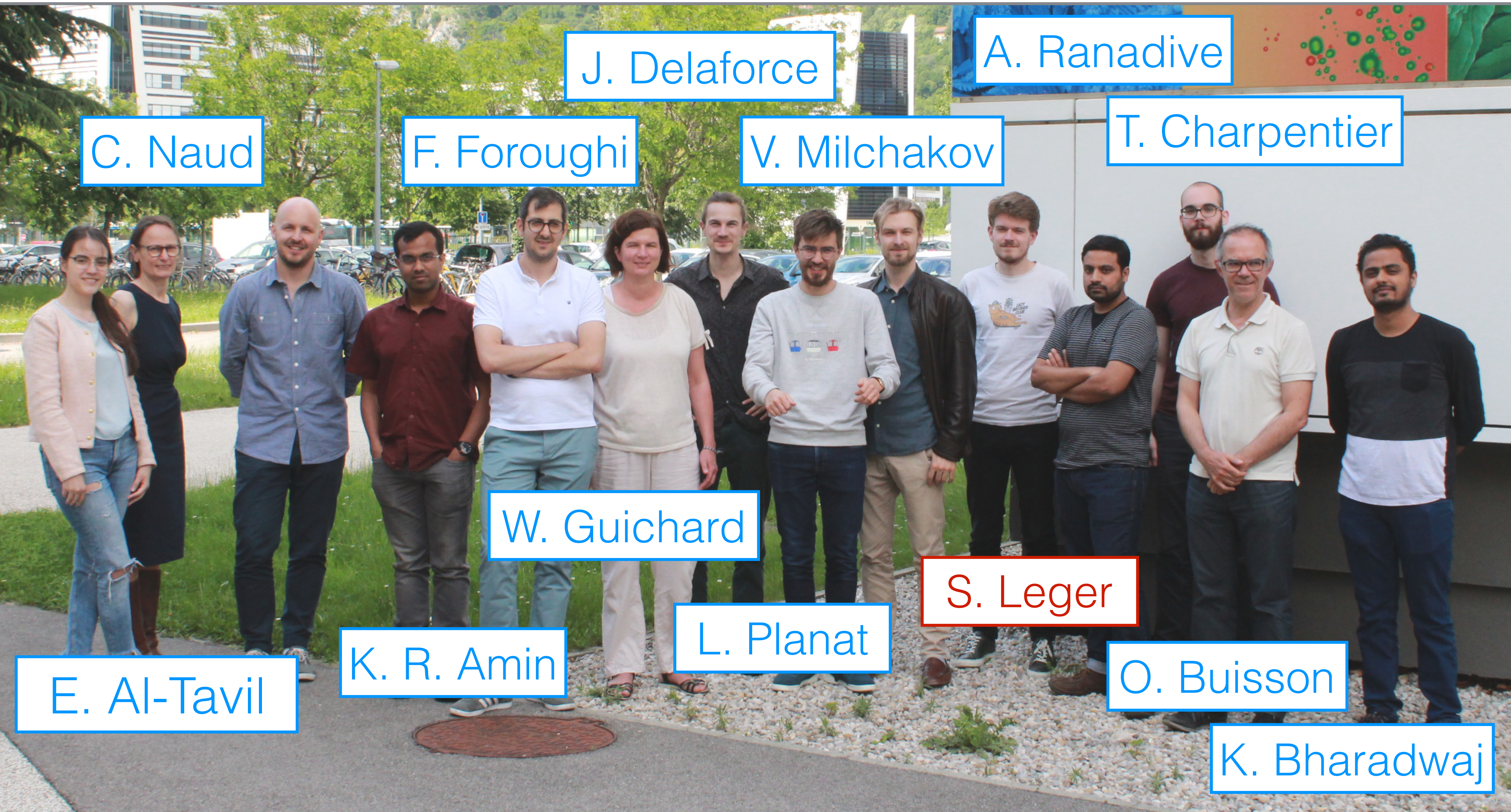


Superconducting quantum circuits team



cnrs advancing the frontiers

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Quantum Engineering Univ. Grenoble Alpes

Acknowledgments

Grenoble

Serge Florens

Nicolas Gheereart

Théo Sépulcre

U. Witwatersrand Johannesburg

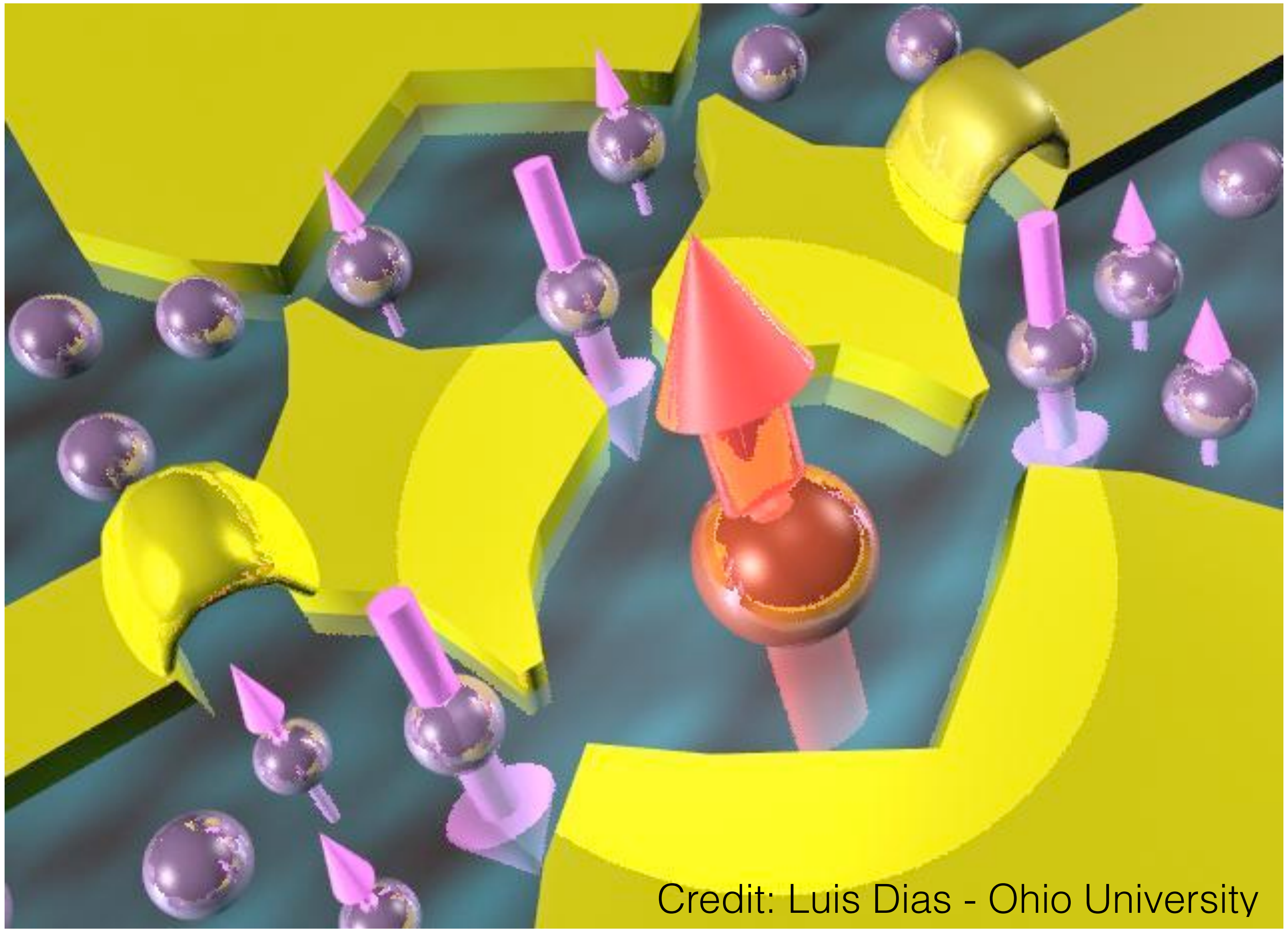
Izak Snyman

Denis Basko

Grenoble

What is many-body physics?

One example: strongly correlated nanostructures

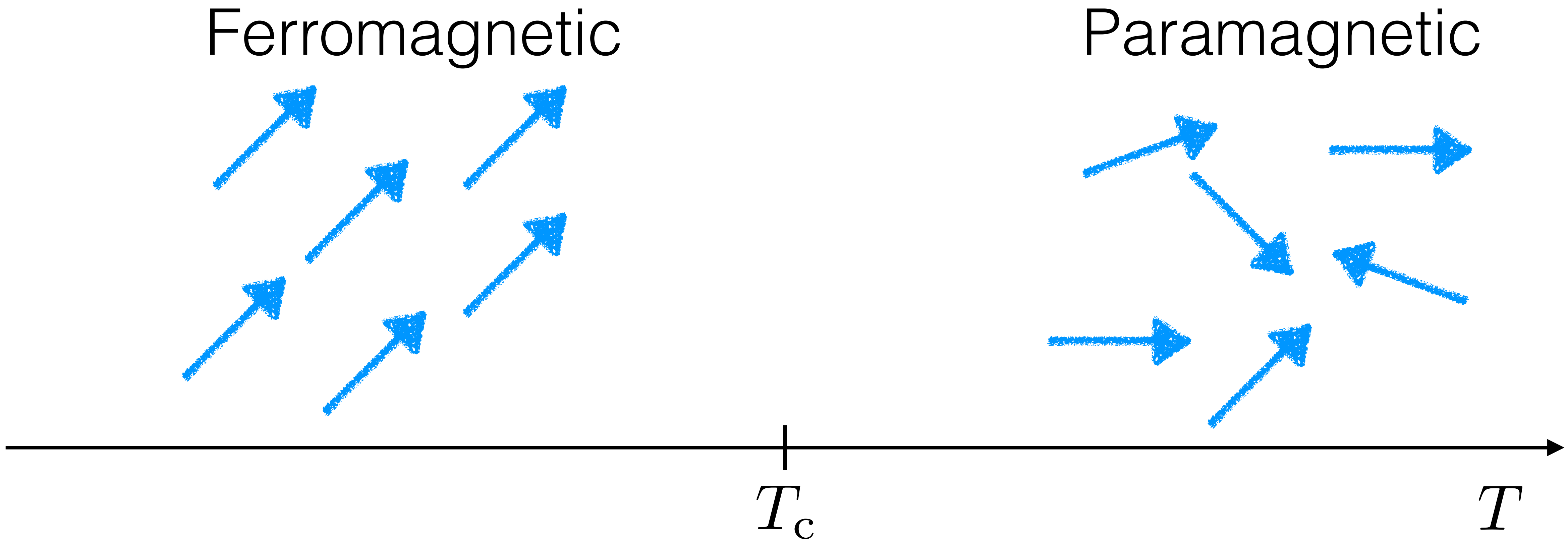


Many open questions: dynamics, entanglement…

Other examples: cold atoms, strongly correlated electron systems, high-Tc superconductors…..

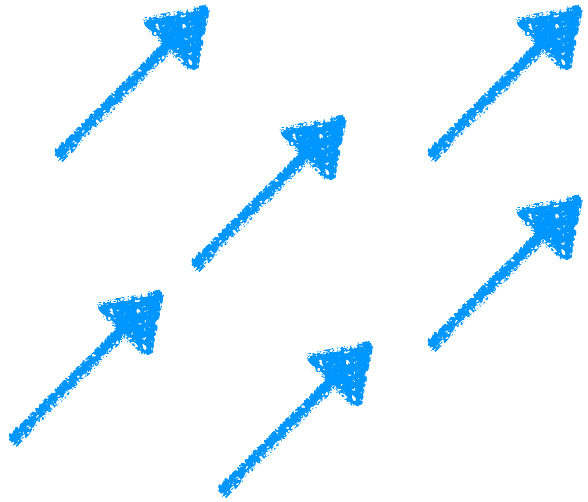
Why many-body physics?

Why many-body physics?

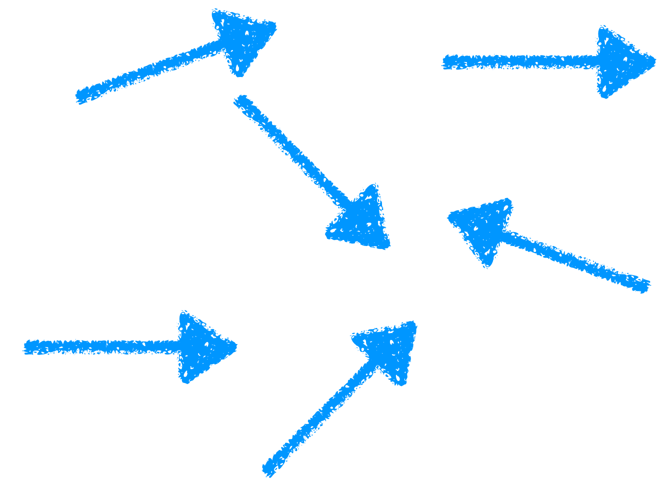


Why many-body physics?

Ferromagnetic



Paramagnetic



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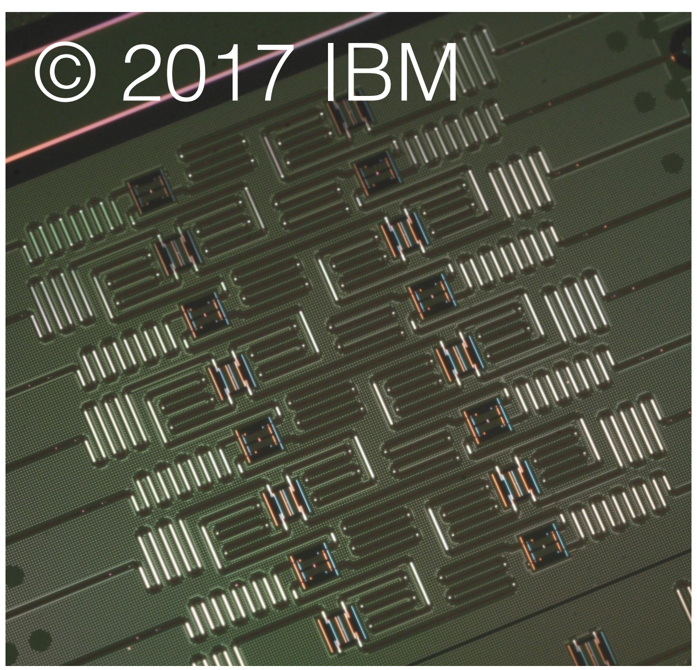
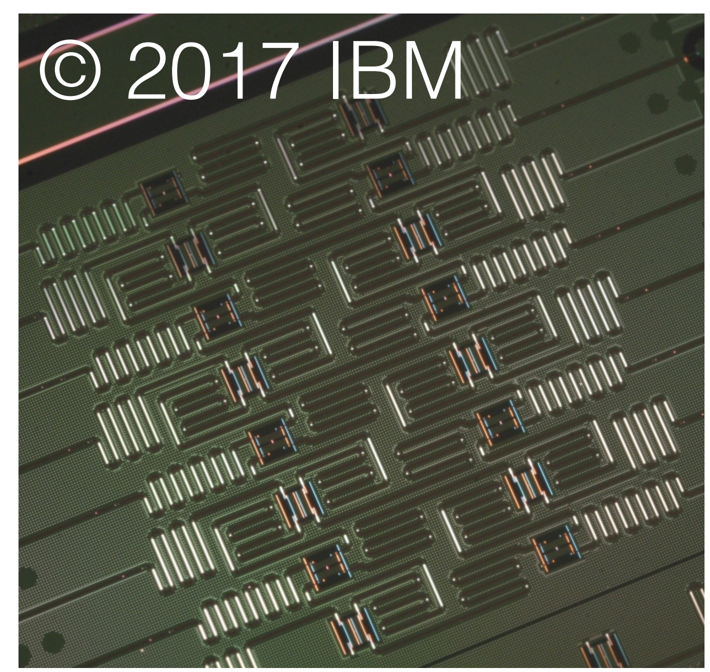
Topological phase



Trivial phase

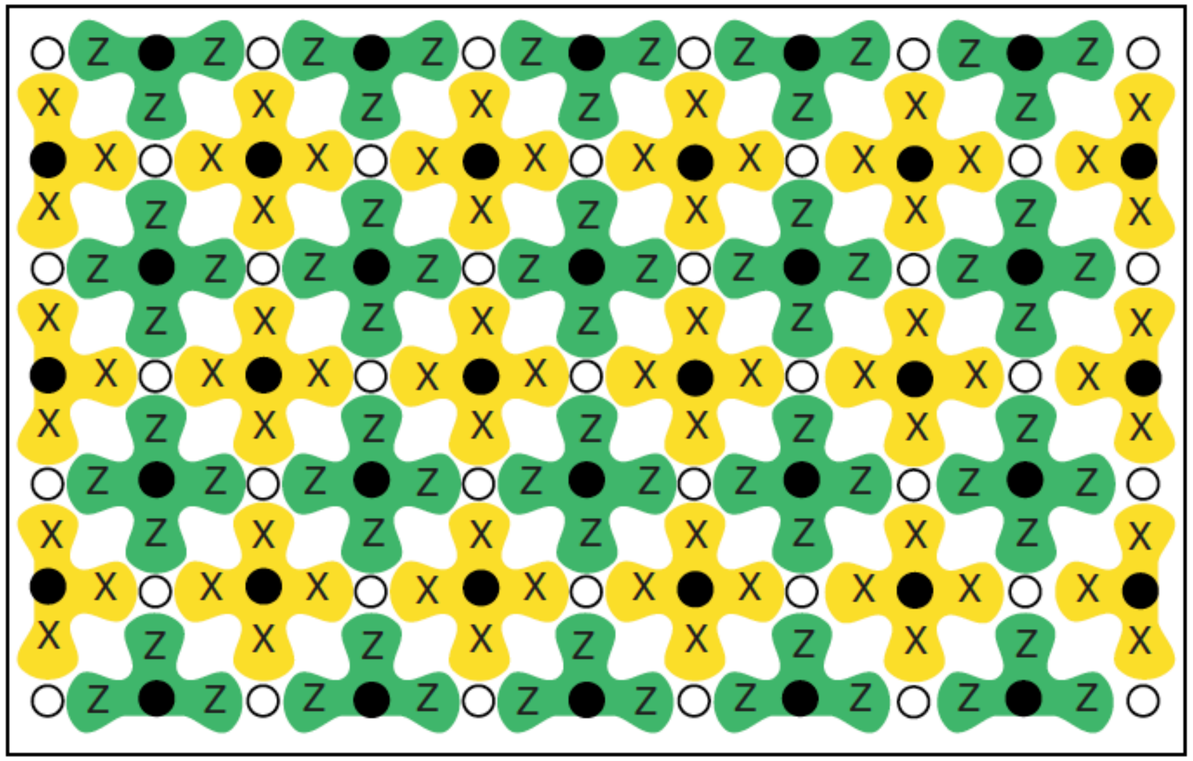


fault tolerant threshold

error rate

What kind of many-body system?

many qubits



Fowler, A., et al. Phys. Rev. A (2012)

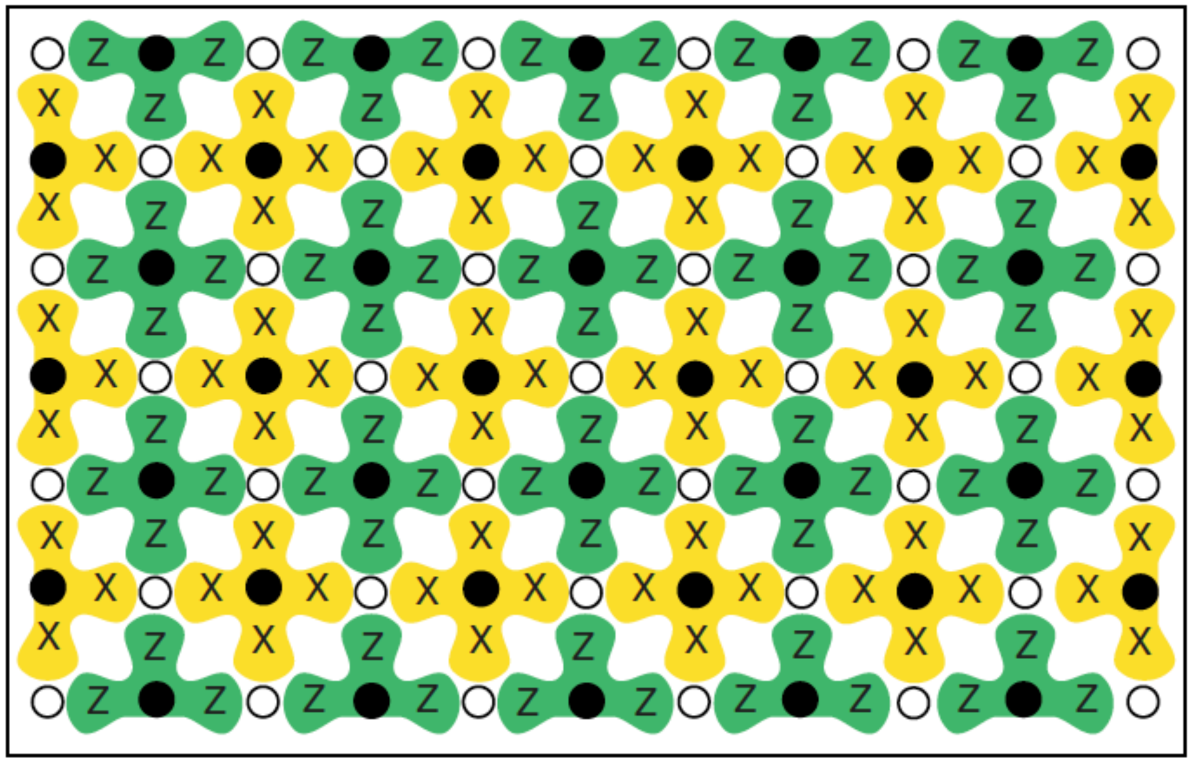
size of the Hilbert space

$$2^N$$

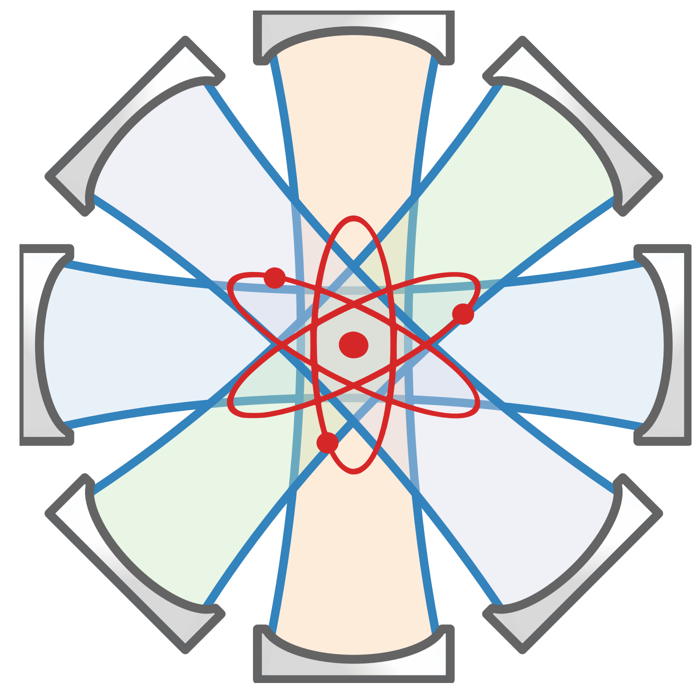
What kind of many-body system?

many qubits

one qubit, many cavities



Fowler, A., et al. Phys. Rev. A (2012)



size of the Hilbert space

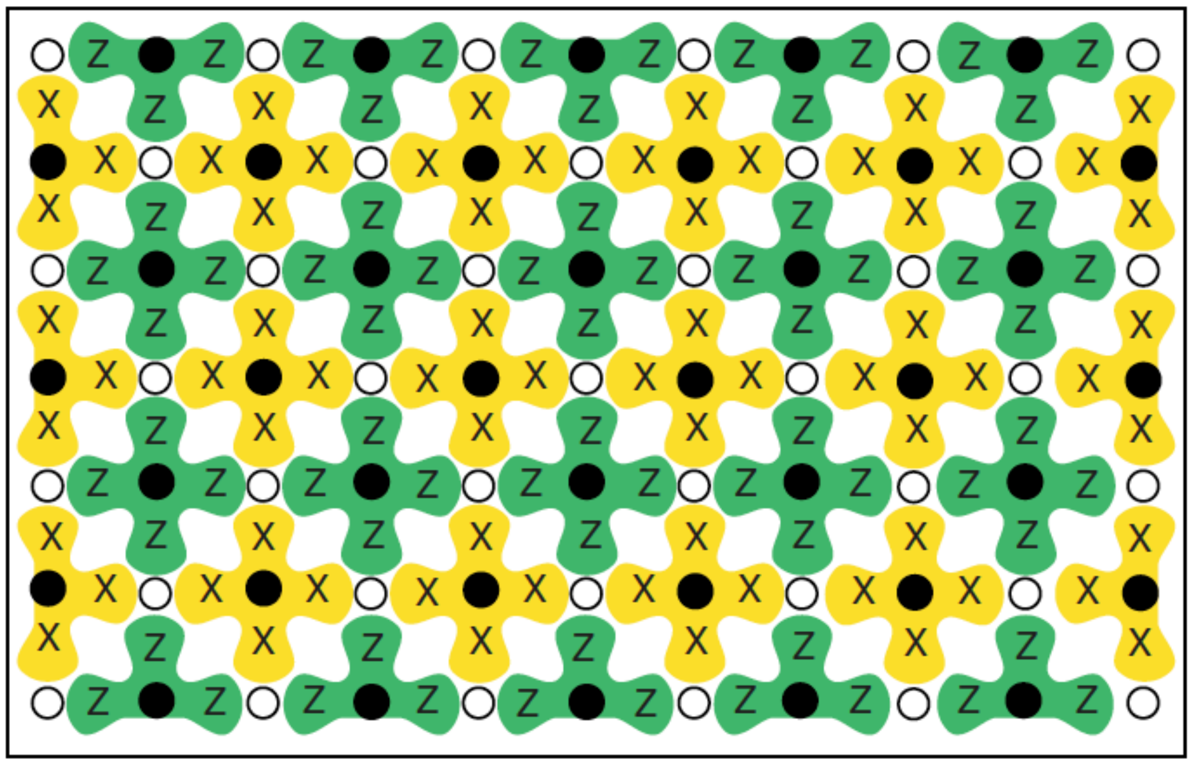
$$2^N$$

size of the Hilbert space

$$M^N$$

What kind of many-body system?

many qubits

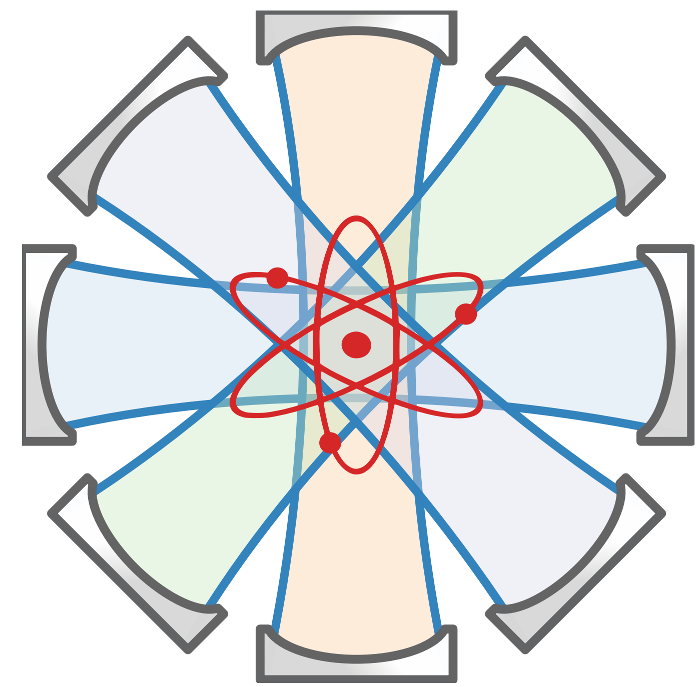


Fowler, A., et al. Phys. Rev. A (2012)

size of the Hilbert space

$$2^N$$

one qubit, many cavities



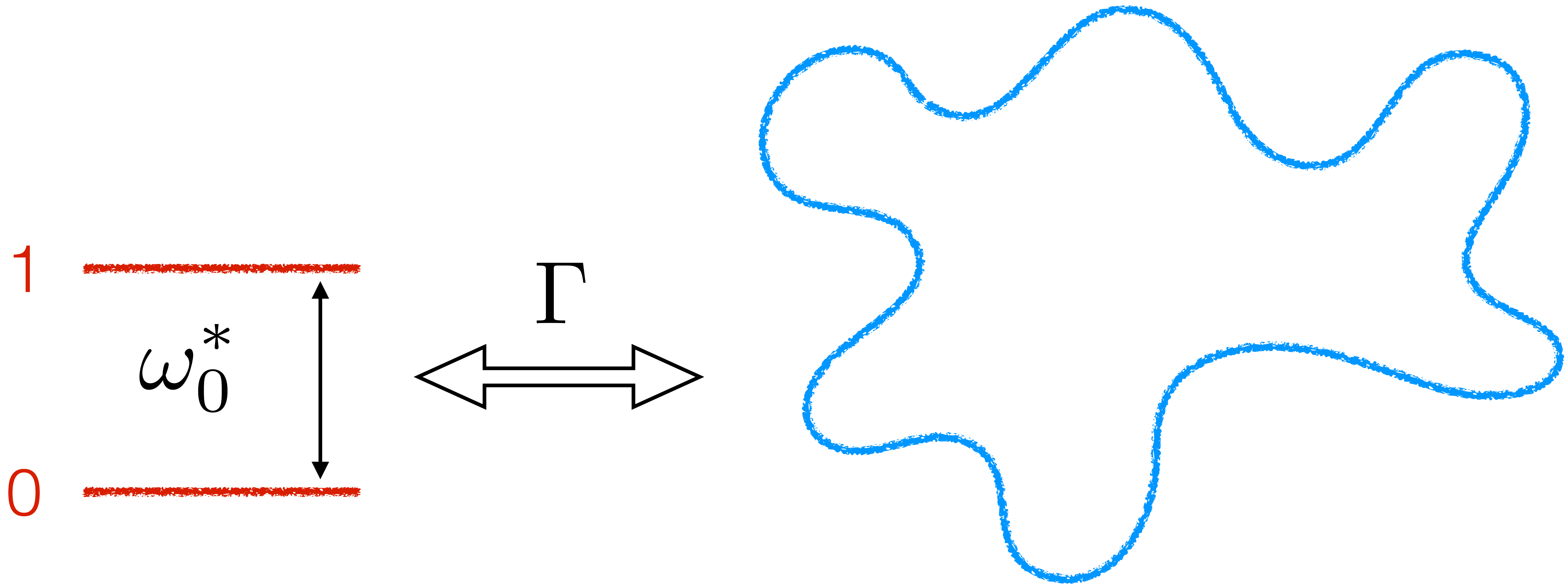
size of the Hilbert space

$$M^N$$

→ Hardware efficient

What kind of many-body system?

Our choice: quantum impurities



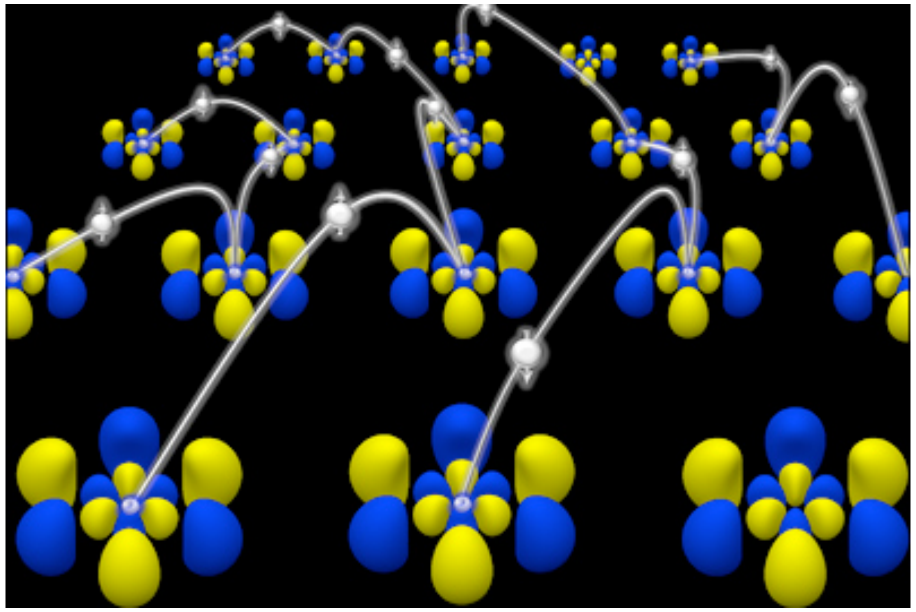
One quantum system coupled to a large bath:

The “hydrogen atom” of many-body physics

What kind of many-body system?

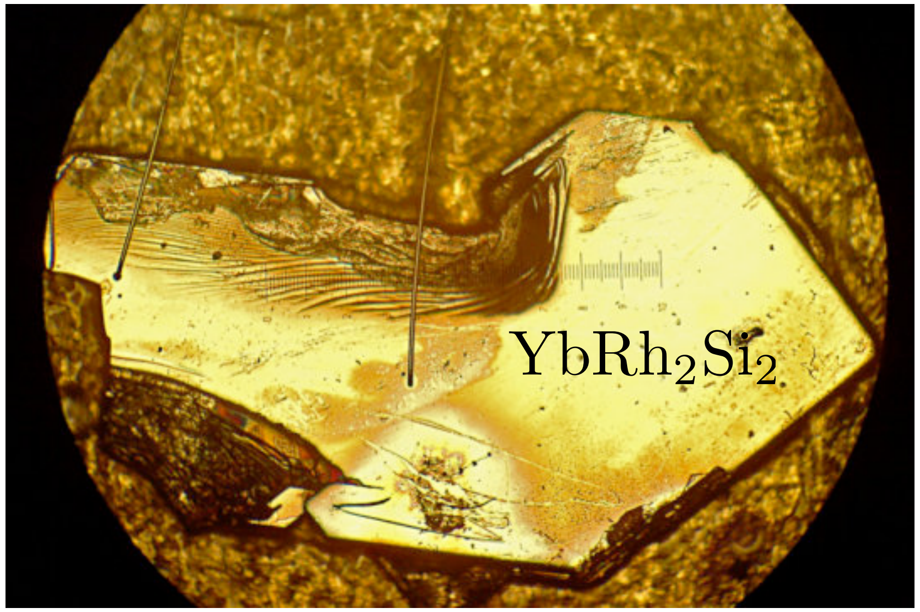
Quantum impurities: relevant to many physical systems

Heavy fermions



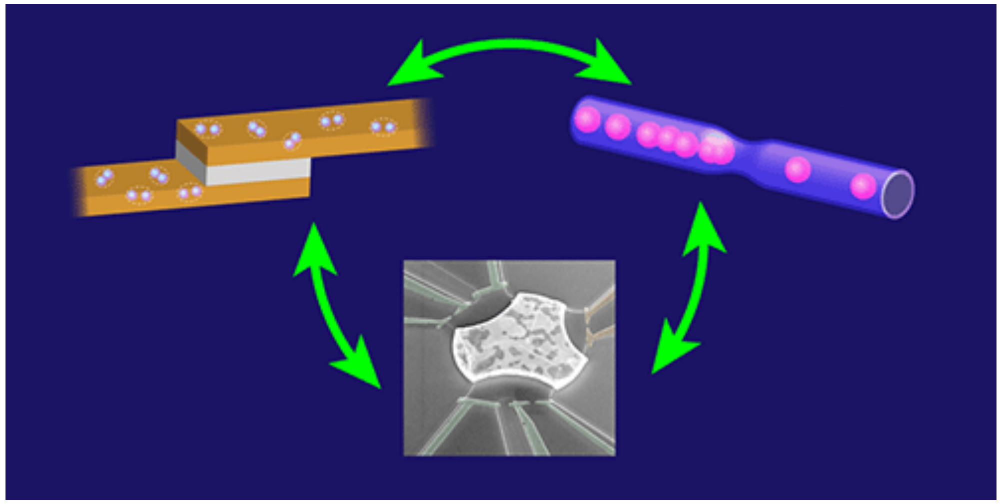
Credit: Mohammad Hamidian - Davis Lab

Exotic superconductors



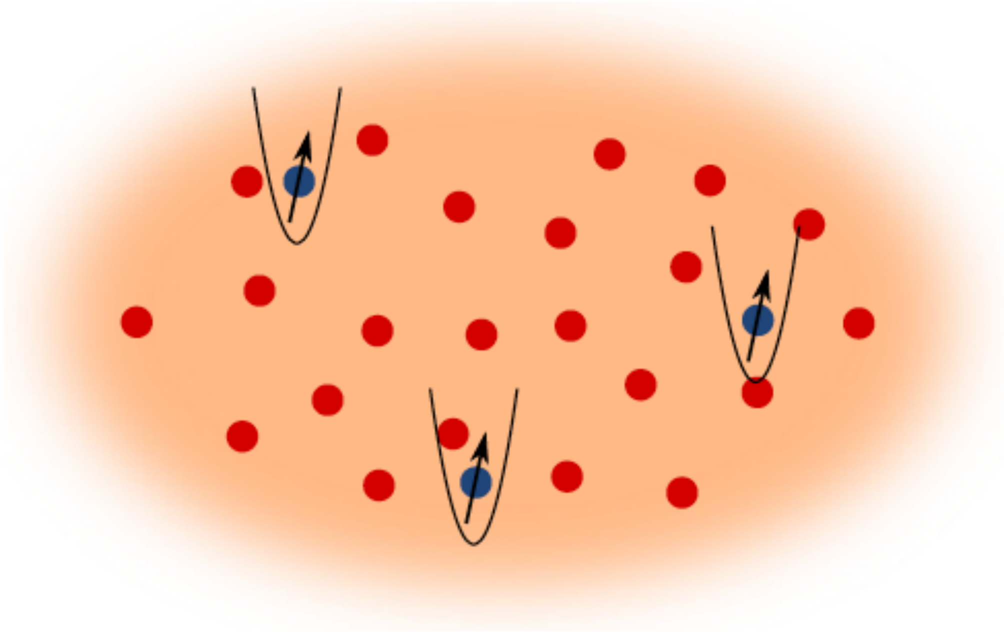
Credit: Marc Tippmann Munich

Nanostructures



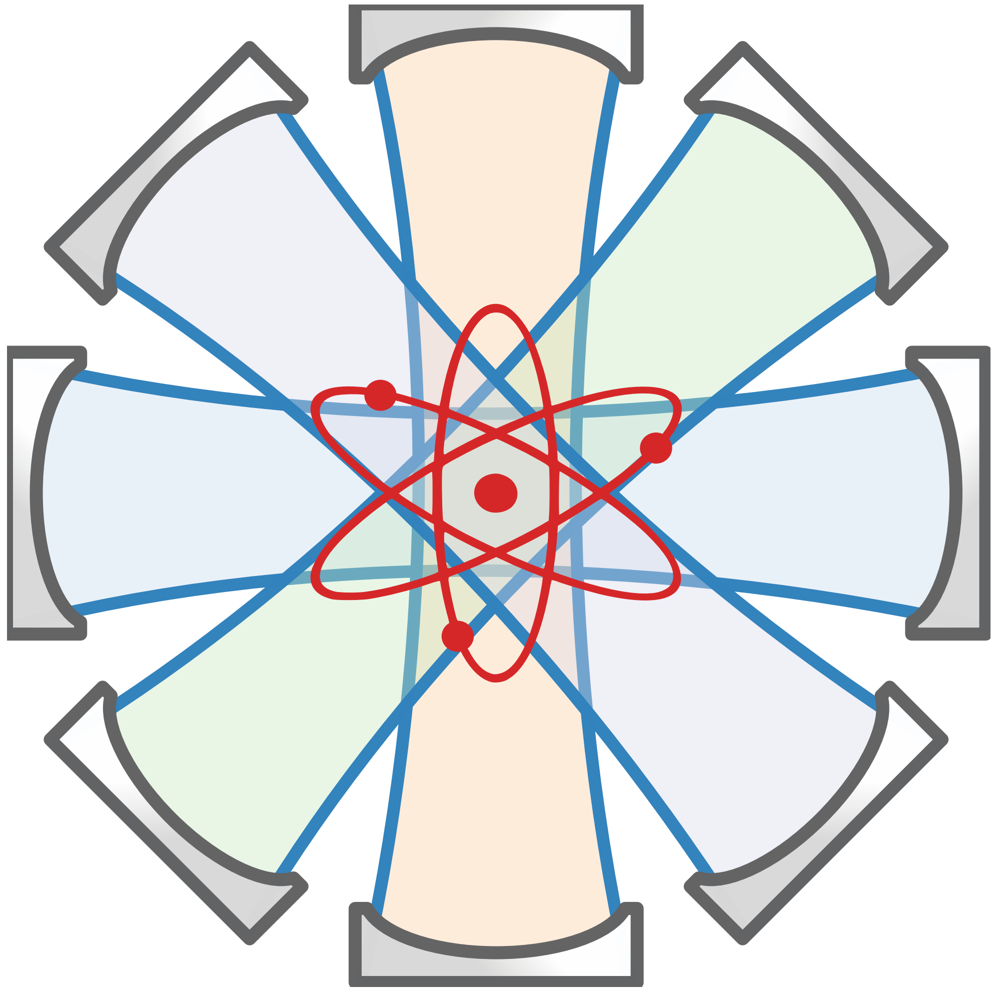
Credit: Dalla Torre & Sela - Physics (2018)

Cold atoms



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

How do we engineer our many body system ?



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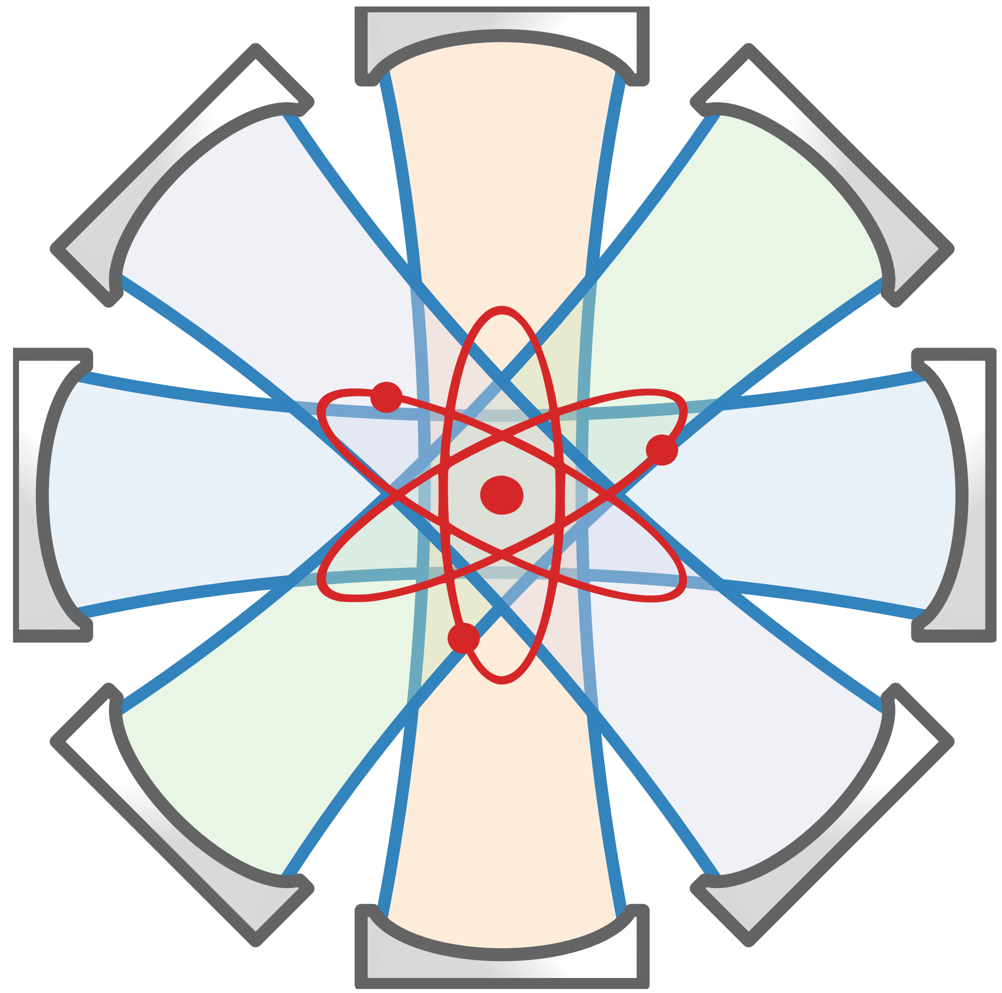

size of the
Hilbert space

M^N

Non-trivial many-body system if:

- ☐ Many degrees of freedom: M^N

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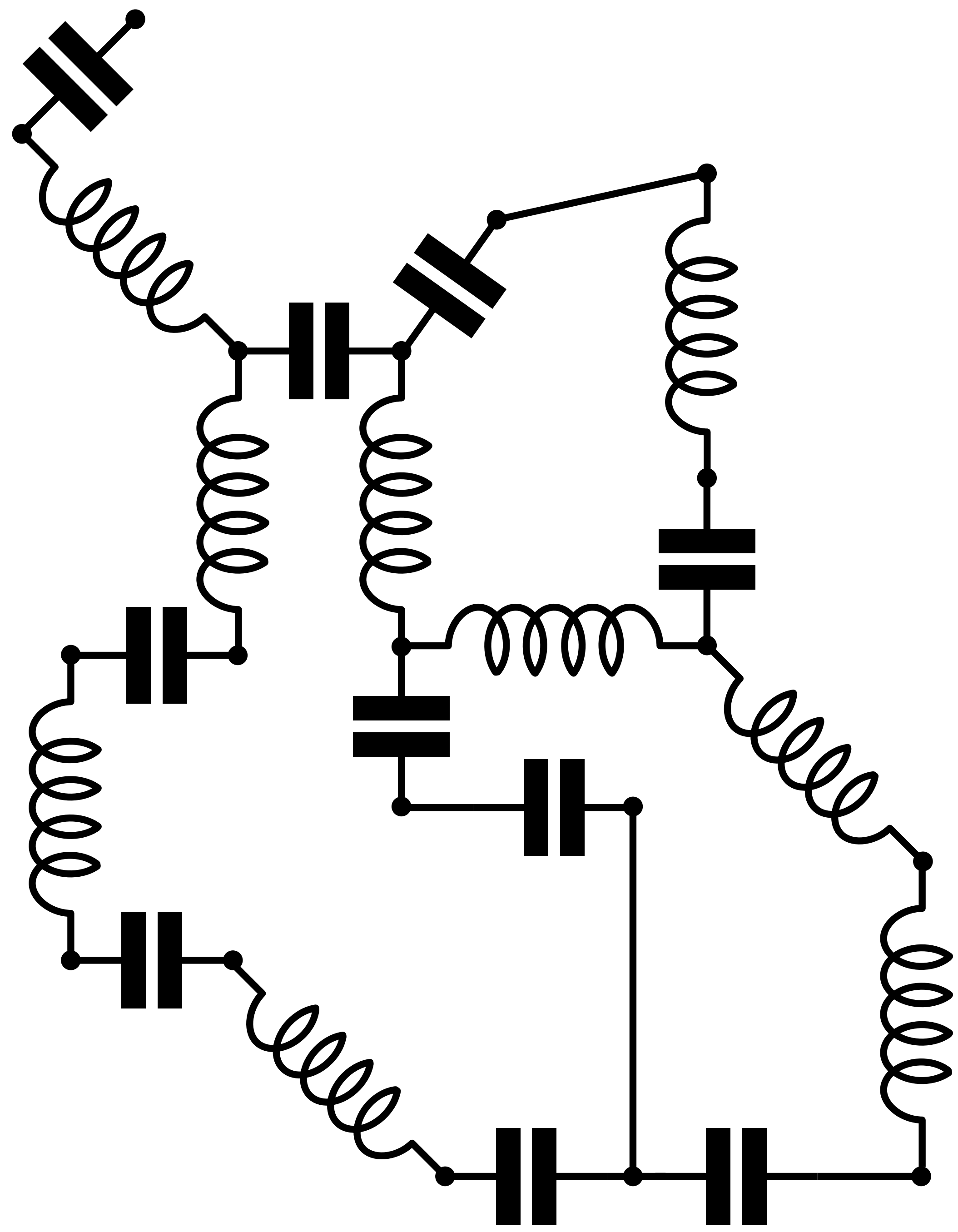

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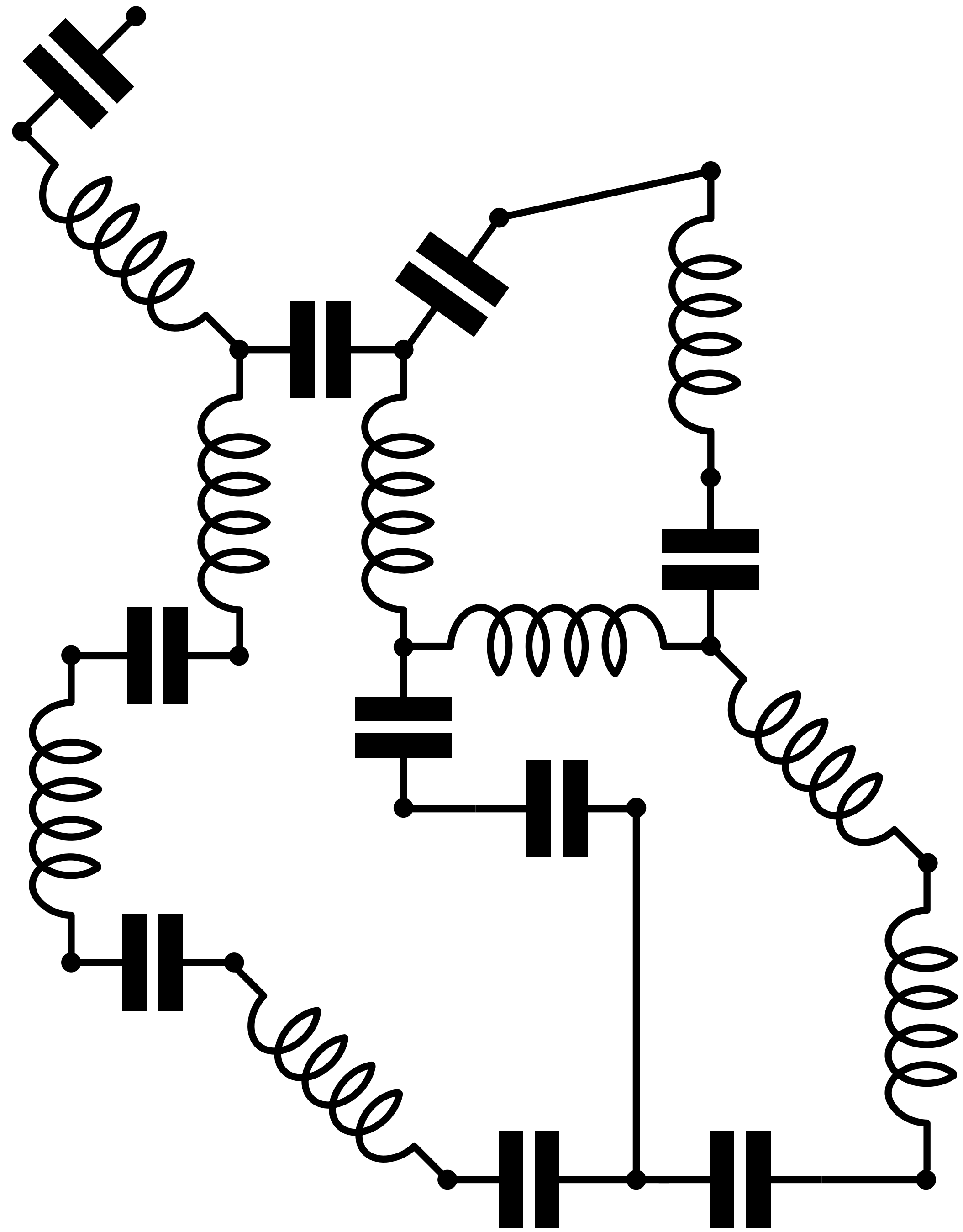
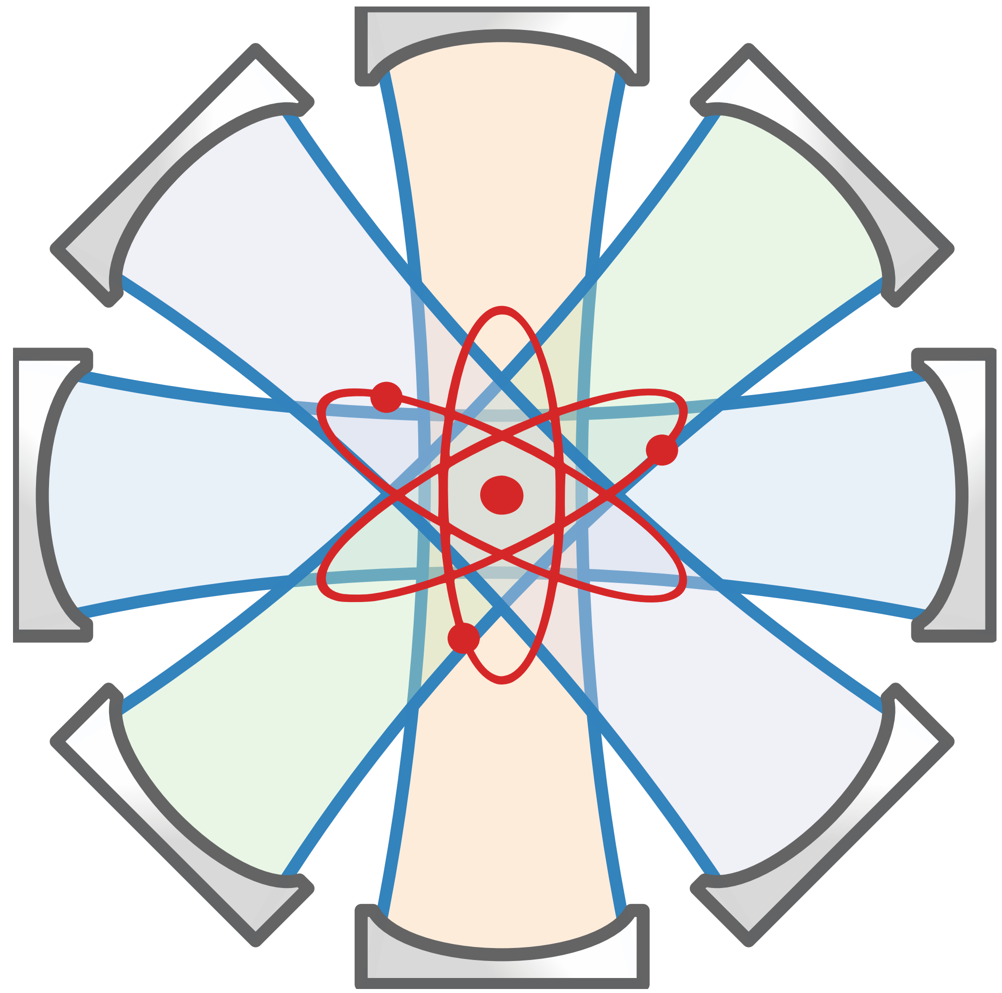


Linear system

→ Easy to diagonalize, no entanglement

How do we engineer our many body system ?



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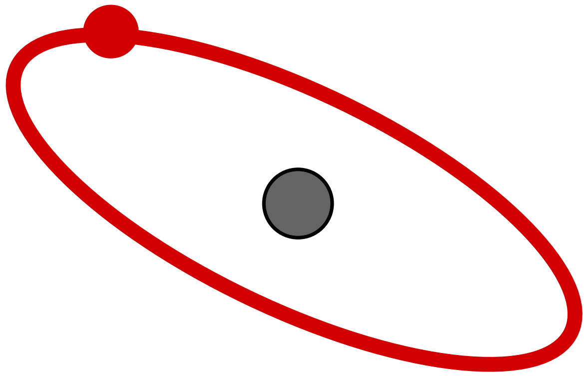
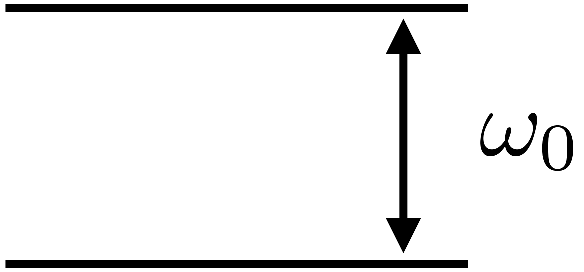
How do we engineer our many body system ?

effect of ZPF in quantum optics: Lamb shift





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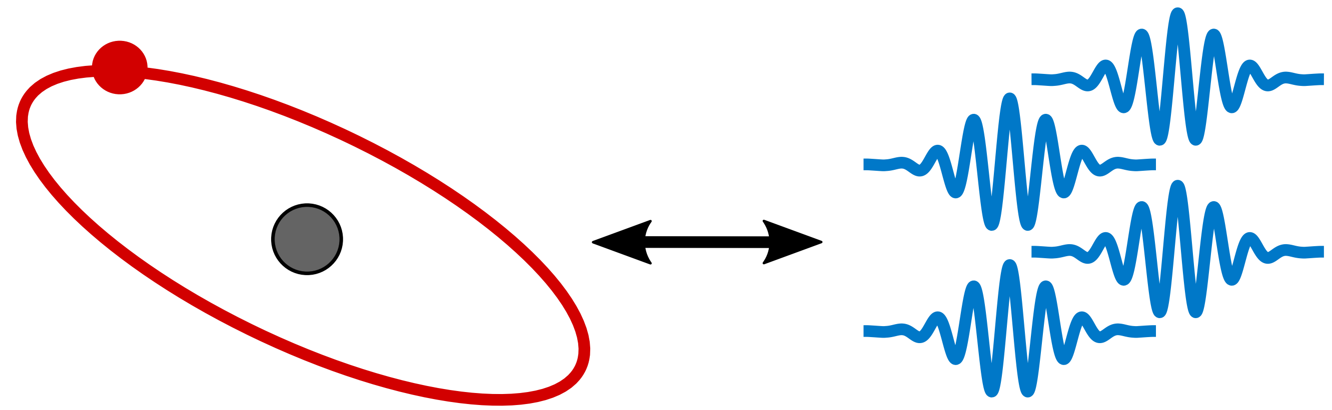
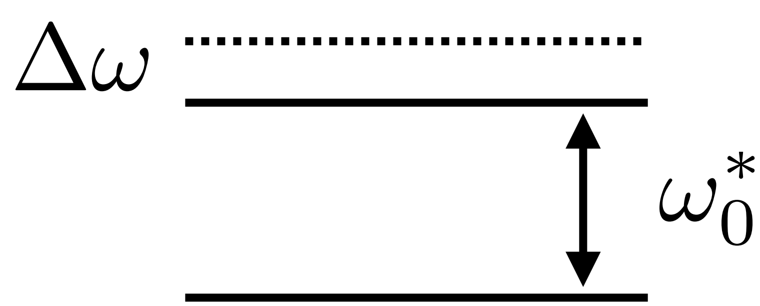


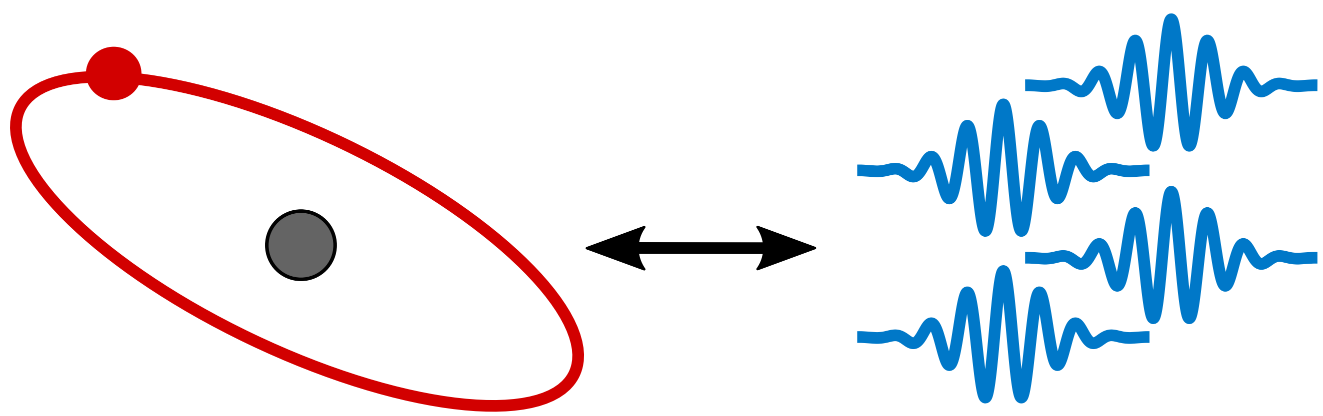


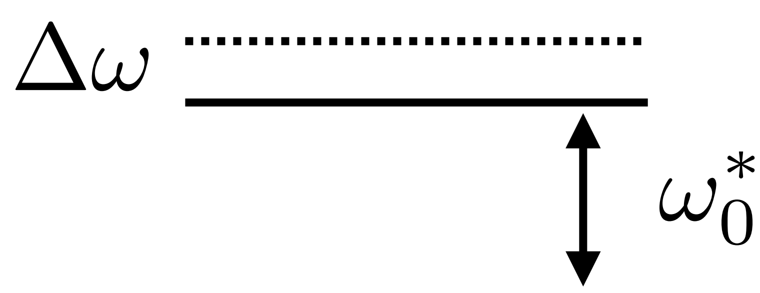
W. E. Lamb & R. C. Retherford, Phys. Rev. (1947)

Small effect $$\frac{\Delta\omega}{\omega_0} = 10^{-6}$$

How do we engineer our many body system ?

effect of ZPF in quantum optics: Lamb shift





W. E. Lamb & R. C. Retherford, Phys. Rev. (1947)

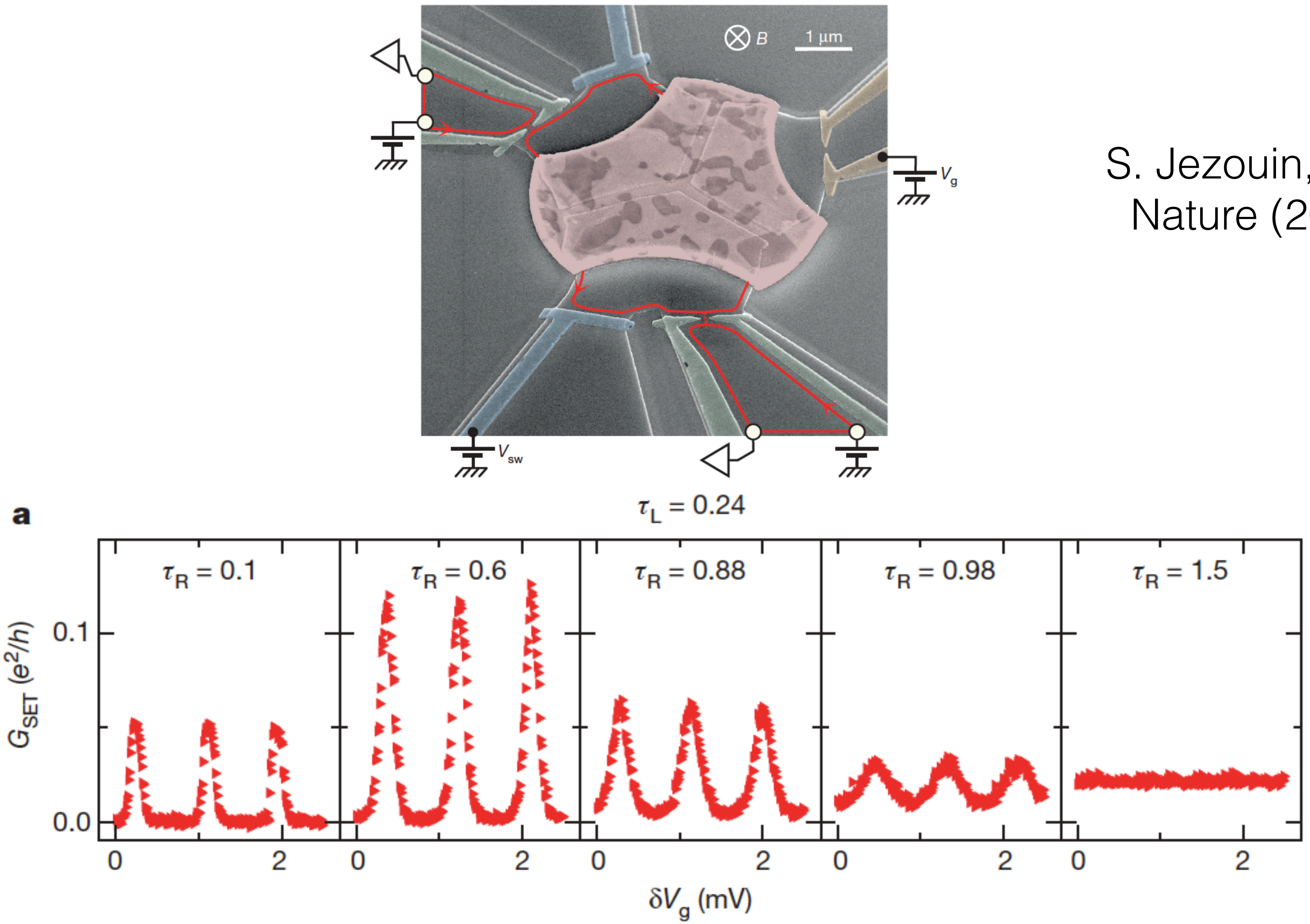
Interplay of non-linearity and ZPF

→ renormalization of the trapping potential

H. A. Bethe, Phys. Rev. (1947)

How do we engineer our many body system ?

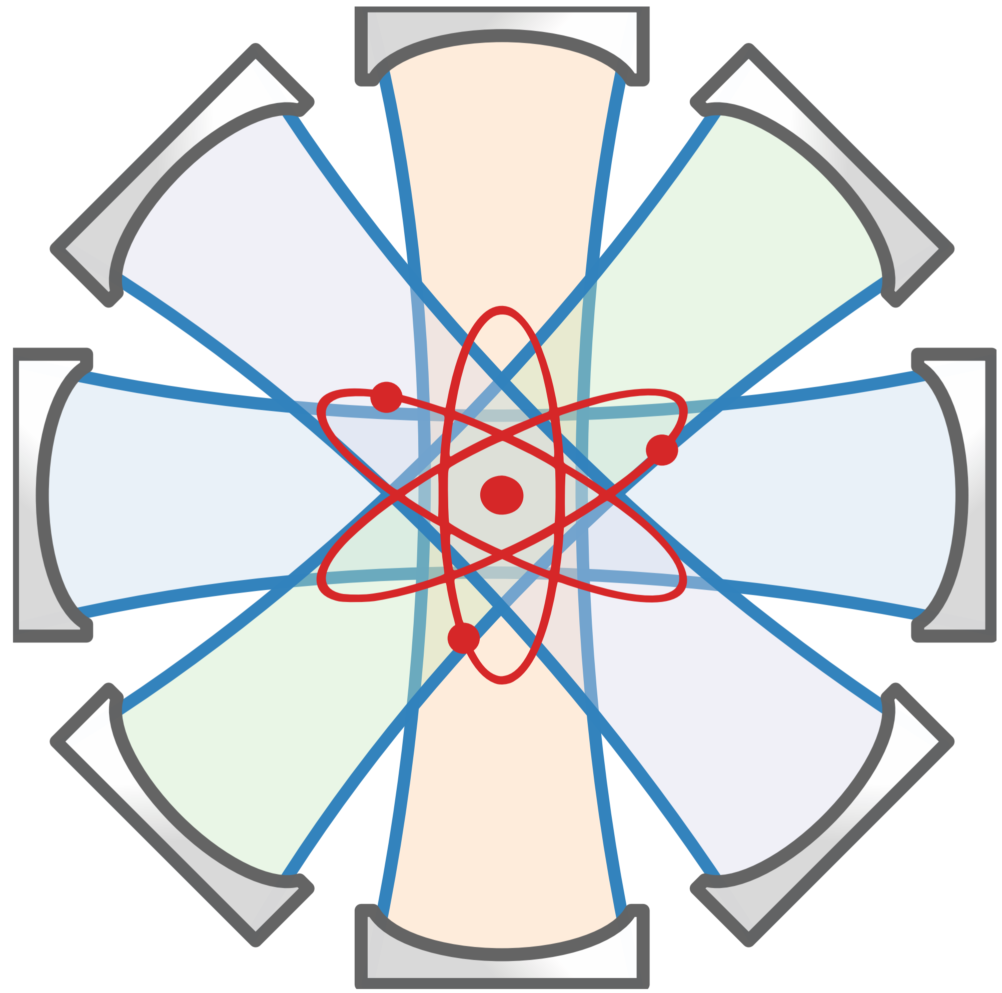
ZPF in circuits: destroying charge quantization



S. Jezouin, et al.
Nature (2016)

Ultra-strong (non-perturbative) effect

How do we engineer our many body system ?



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- ☐ Ultra-strong coupling regime: $\Gamma \simeq \omega_0^*$

Outline

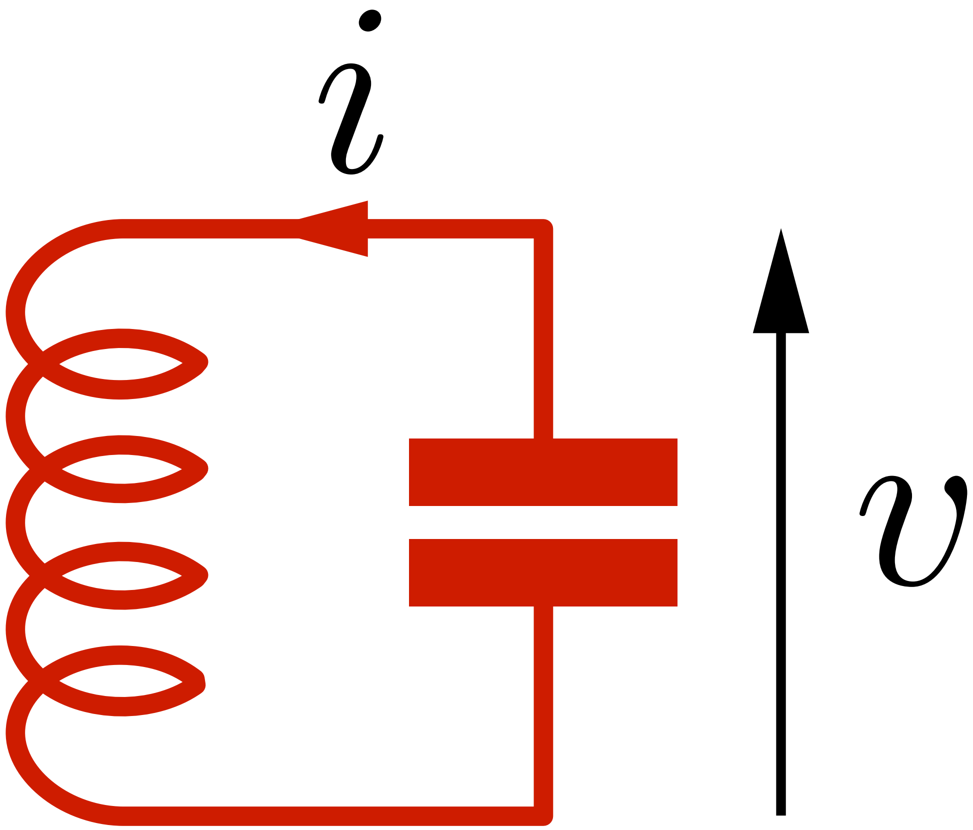
Quantum impurities in cQED: a recipe

Engineering high impedance environments

A small Josephson junction in a high impedance environment

Discussion and modelling

The LC circuit: a harmonic oscillator



Useful variables

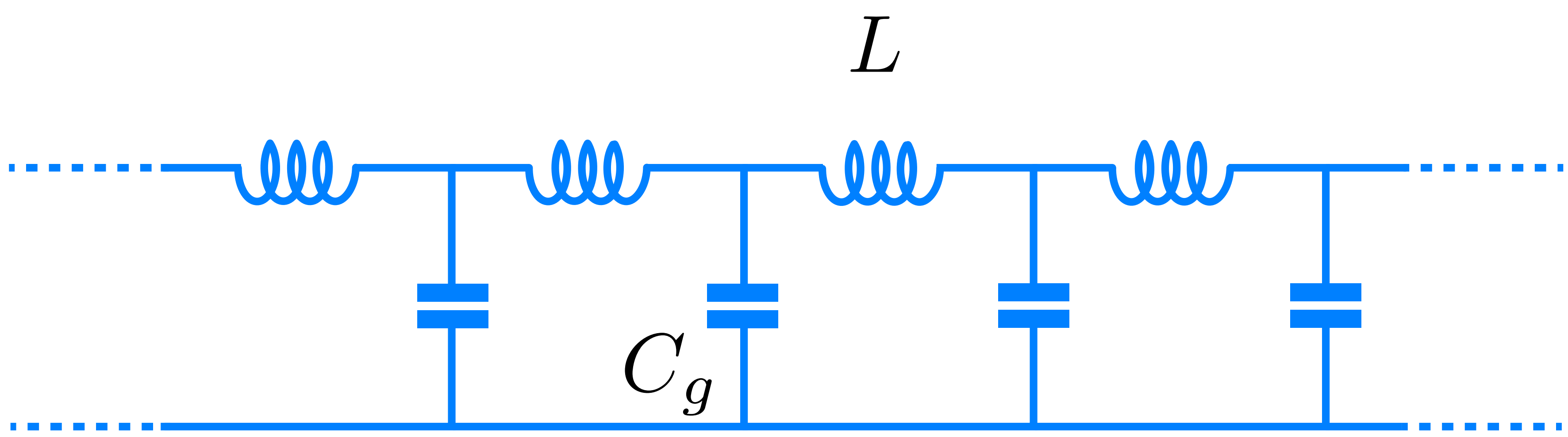
$$Q(t) = \int_{-\infty}^{t} i(t')dt'$$

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

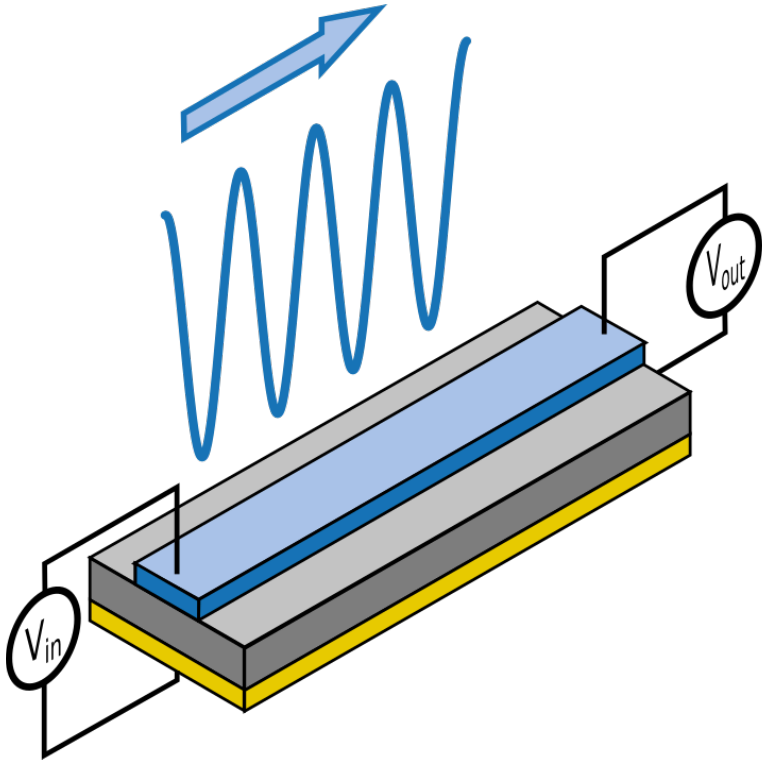
Fluctuations

$$\langle Q^2 \rangle = \frac{\hbar}{2Z_0} \qquad \langle \phi^2 \rangle = \frac{\hbar Z_0}{2} \qquad \text{with} \qquad Z_0 = \sqrt{\frac{L}{C}}$$

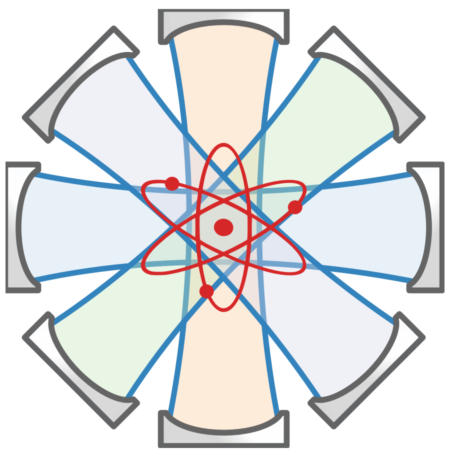
Quantum circuits: transmission line

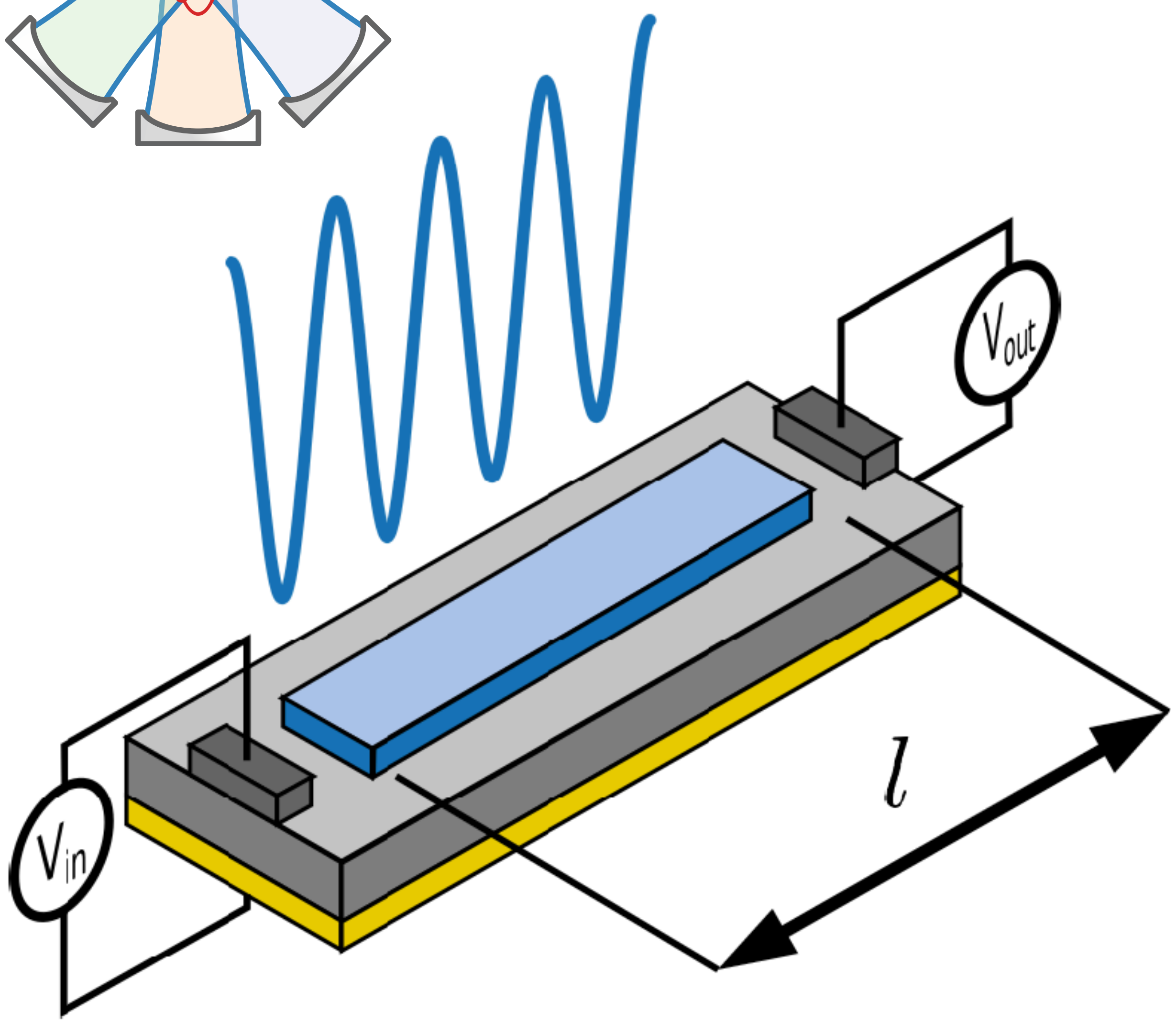


$$Z_c = \sqrt{L/C_g}$$

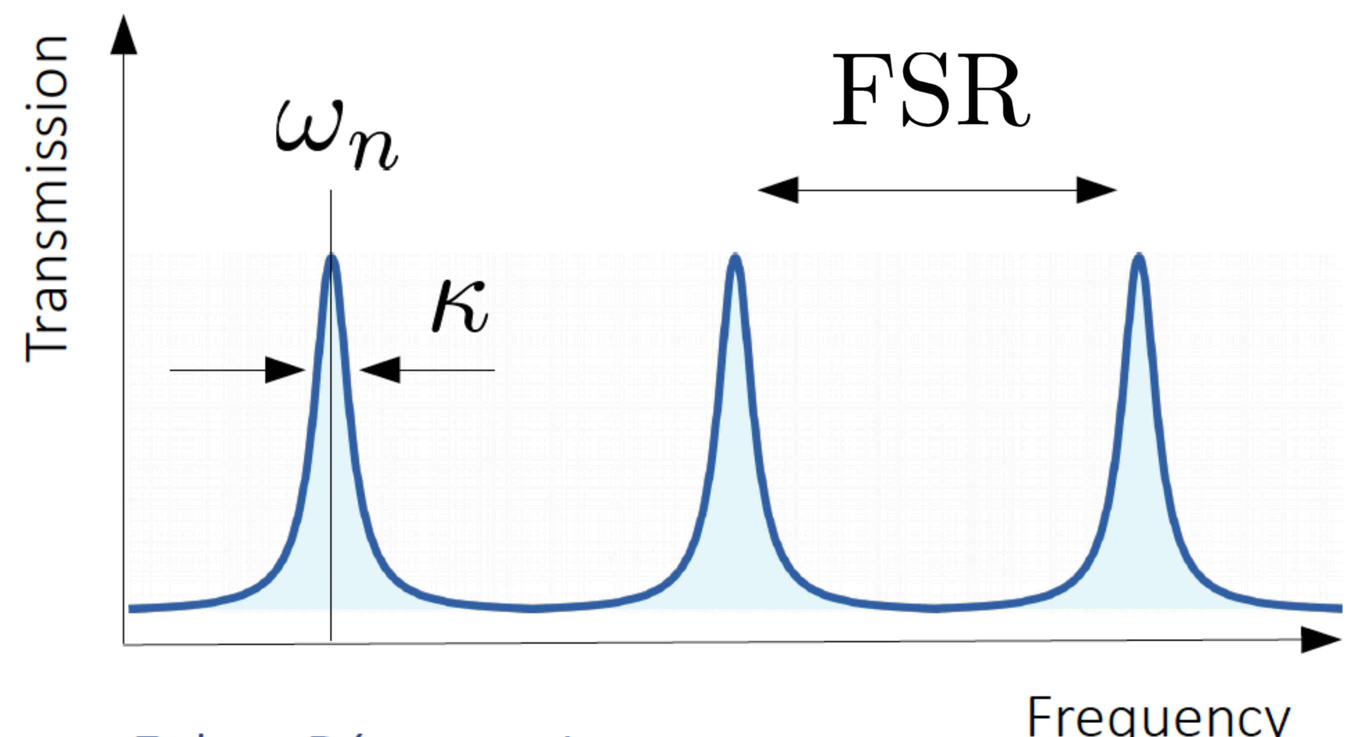


What about the many degrees of freedom?



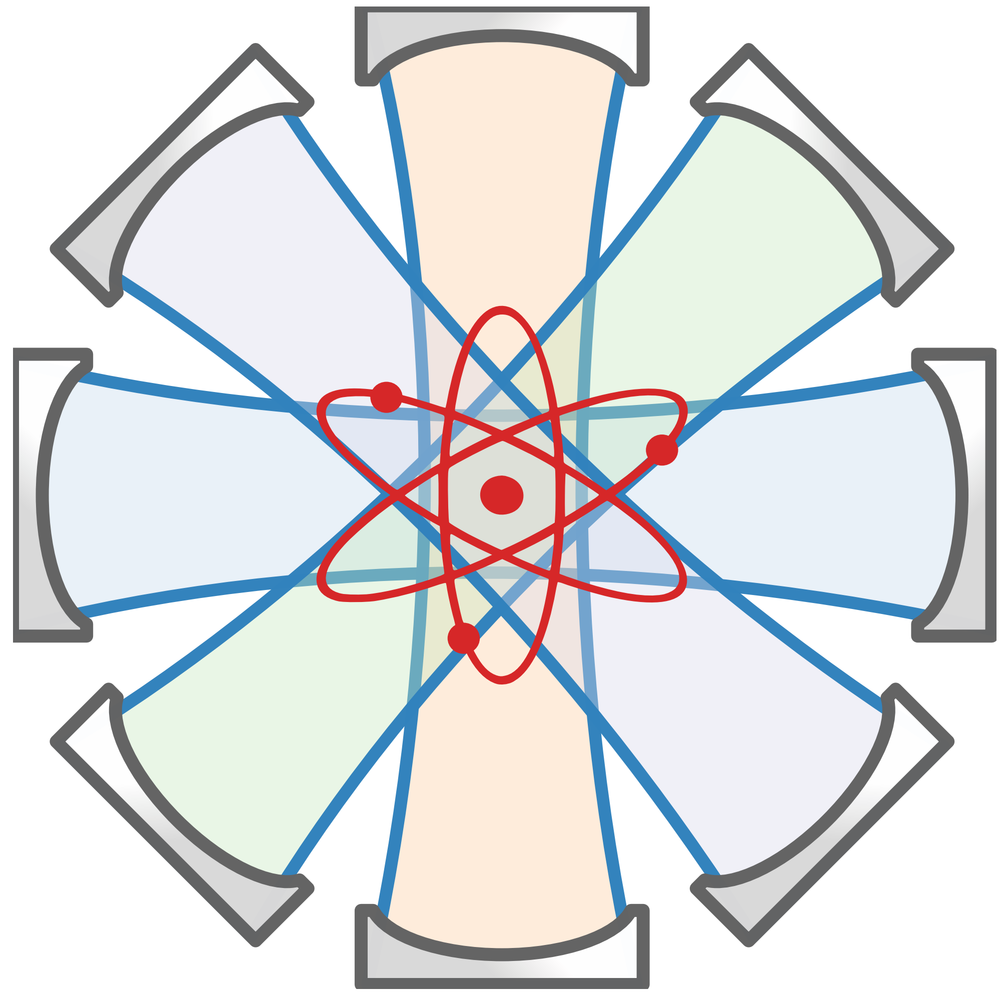


Microwave resonator



Fabry-Pérot cavity

How do we engineer our many body system ?



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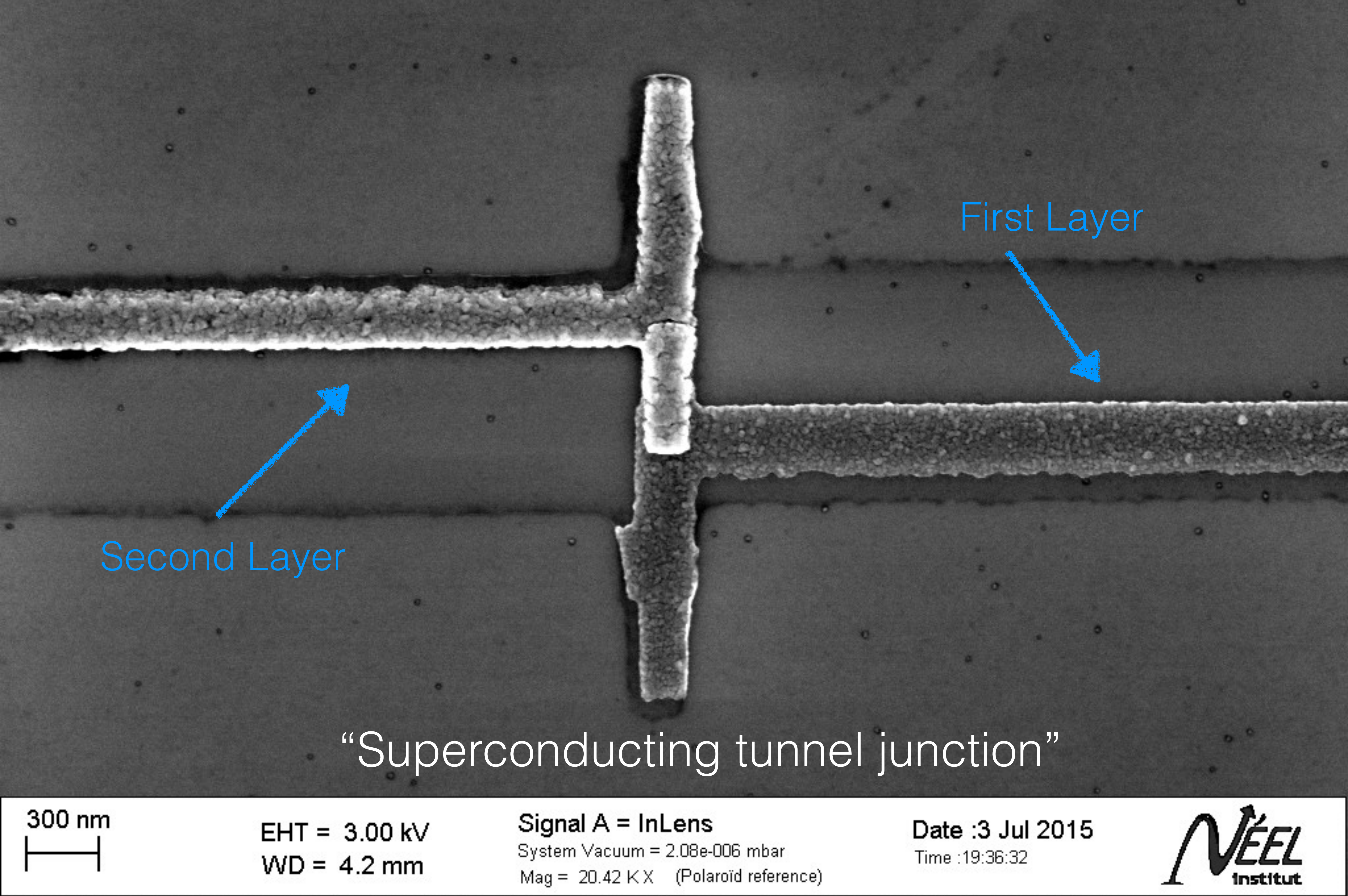
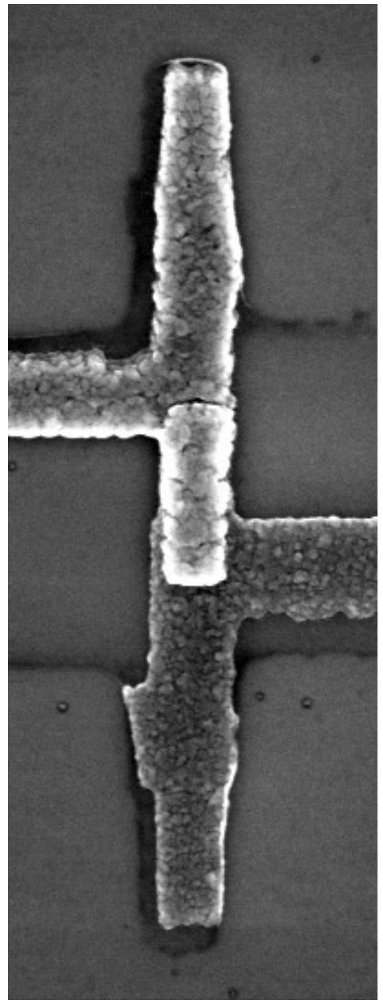
- ☐ Ultra-strong coupling regime: $\Gamma \simeq \omega_0^*$

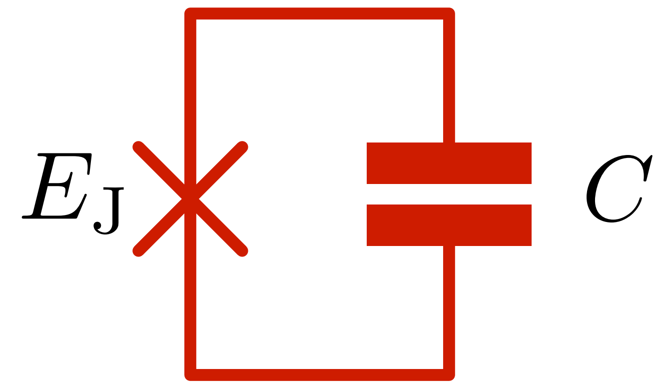
The Josephson junction



“Superconducting tunnel junction”

A Josephson junction shunted by a capacitor



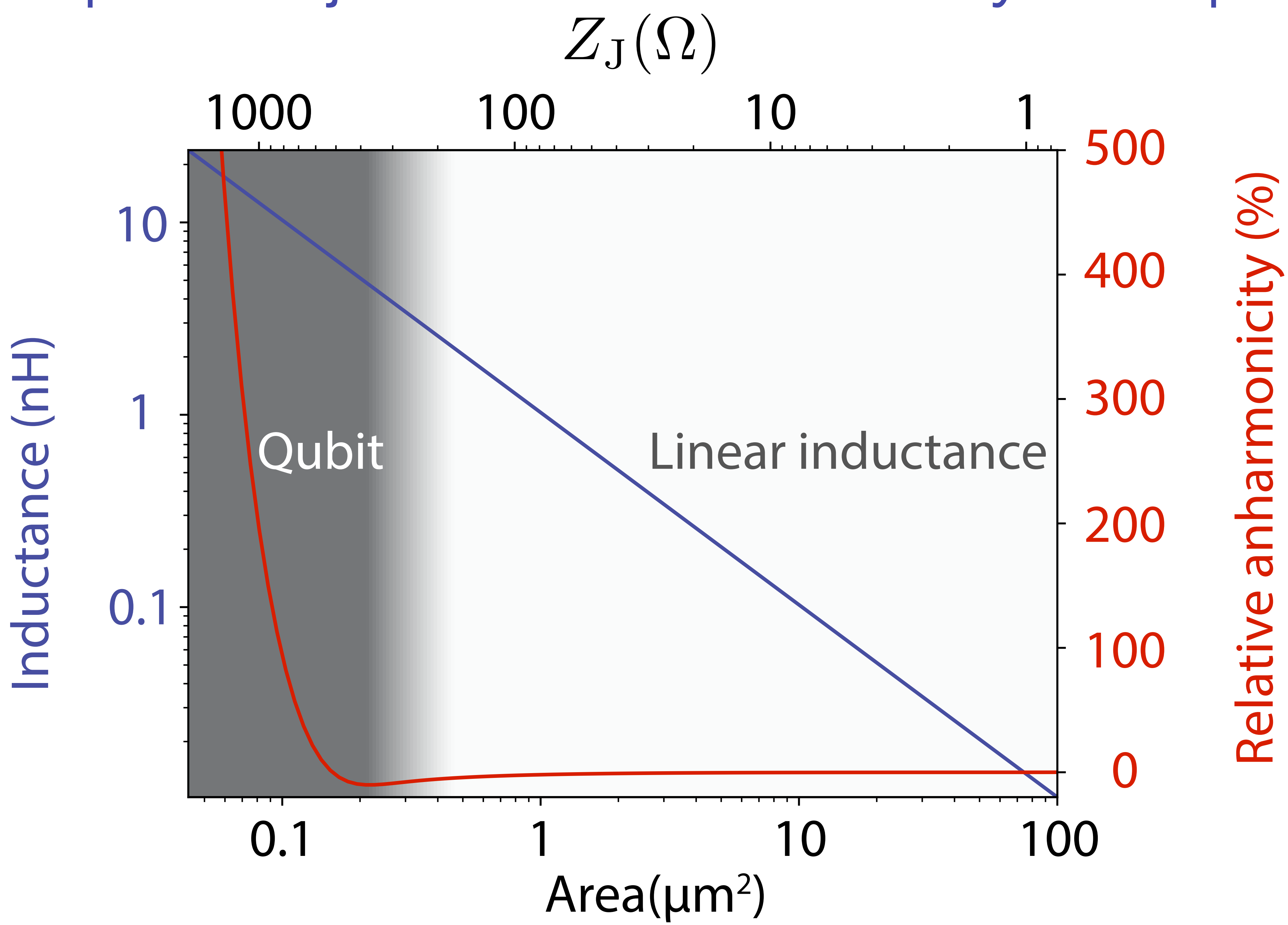


$$\hat{H} = E_{\rm c}(\hat{N} - n_{\rm g})^2 + E_{\rm J}(1 - \cos\hat{\phi})$$

Generalised impedance $Z_{\rm J} = \hbar/(2e)^2\sqrt{2E_{\rm c}/E_{\rm J}}$

! valid only if $\langle\phi^2\rangle \ll \pi^2$

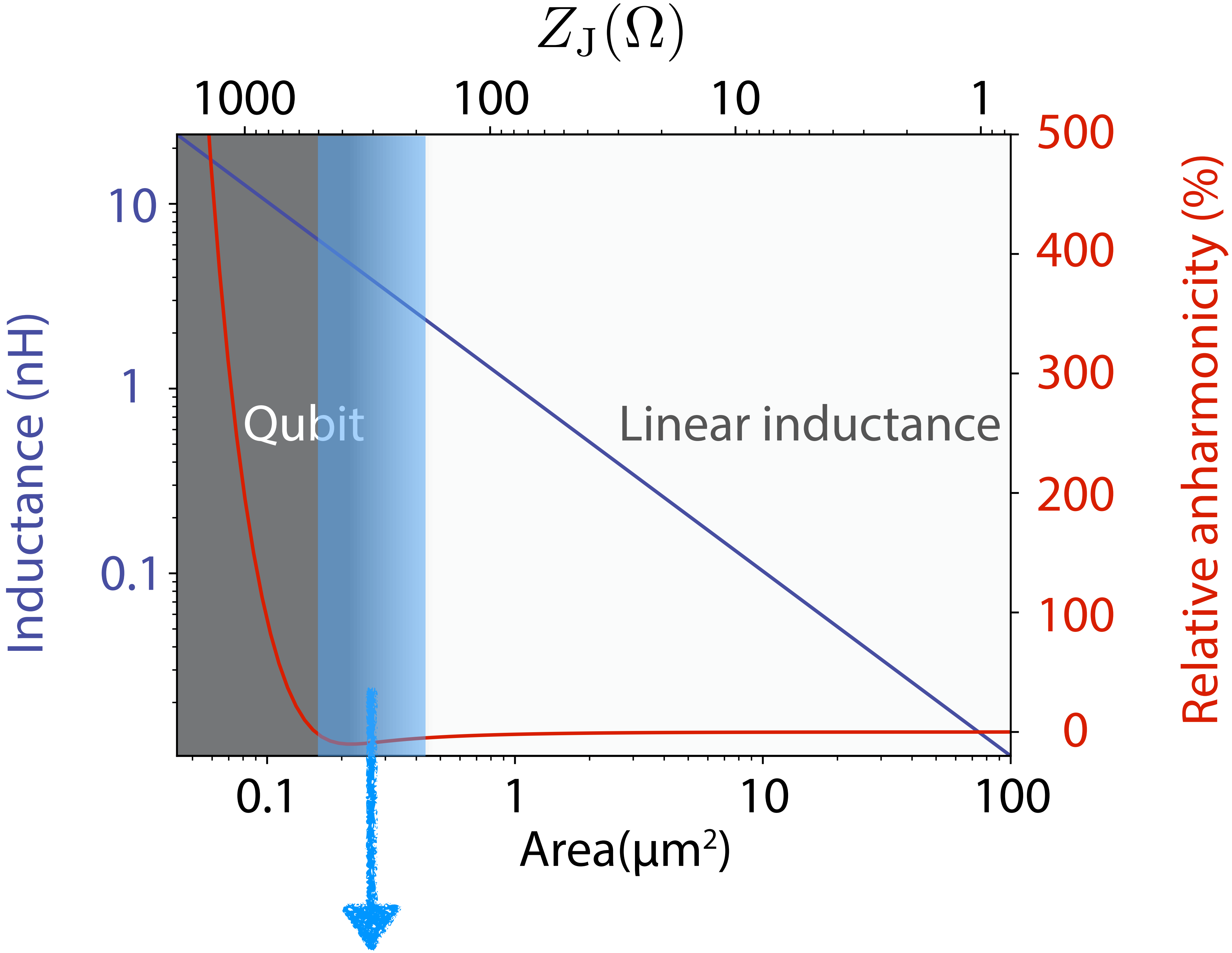
A Josephson junction shunted by a capacitor



Generalised impedance $Z_J = \hbar/(2e)^2\sqrt{2E_c/E_J}$

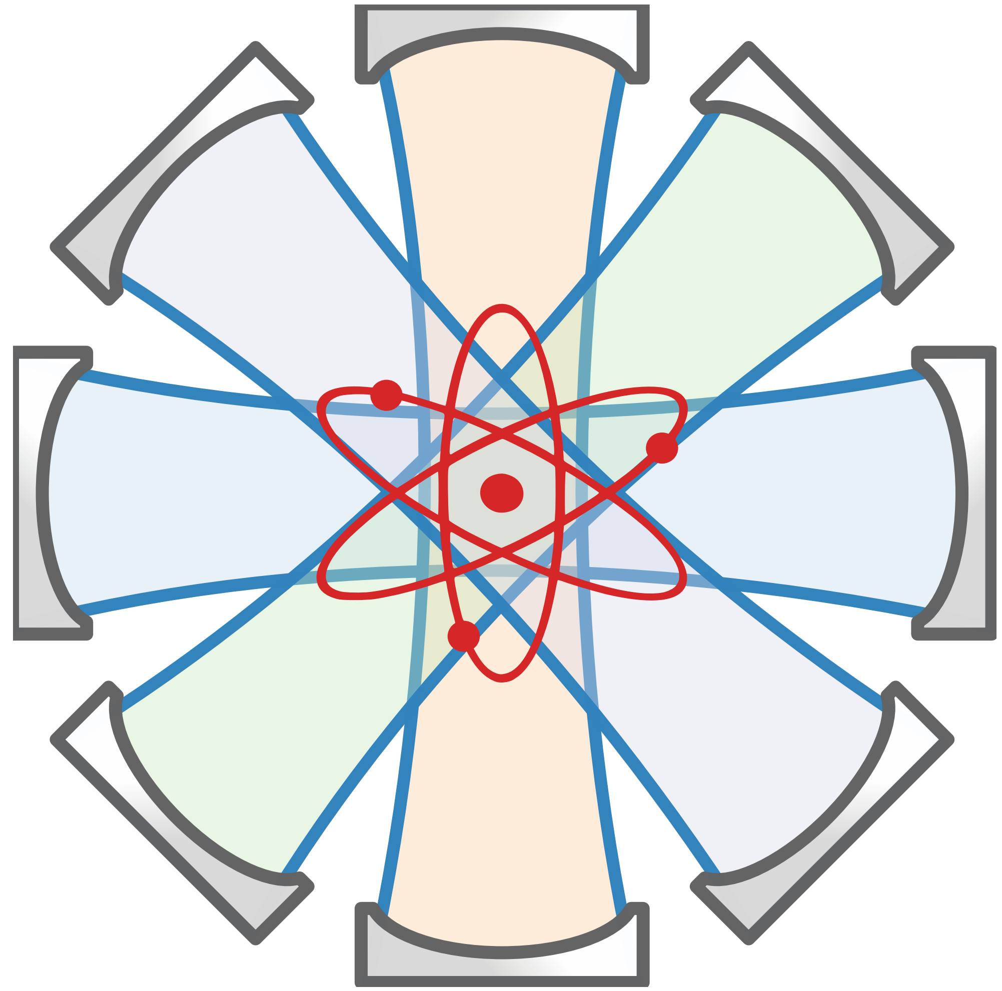
Relative anharmonicity $(\omega_{21} - \omega_{10})/\omega_{10}$

A Josephson junction shunted by a capacitor



“Transmon” qubit

How do we engineer our many body system ?



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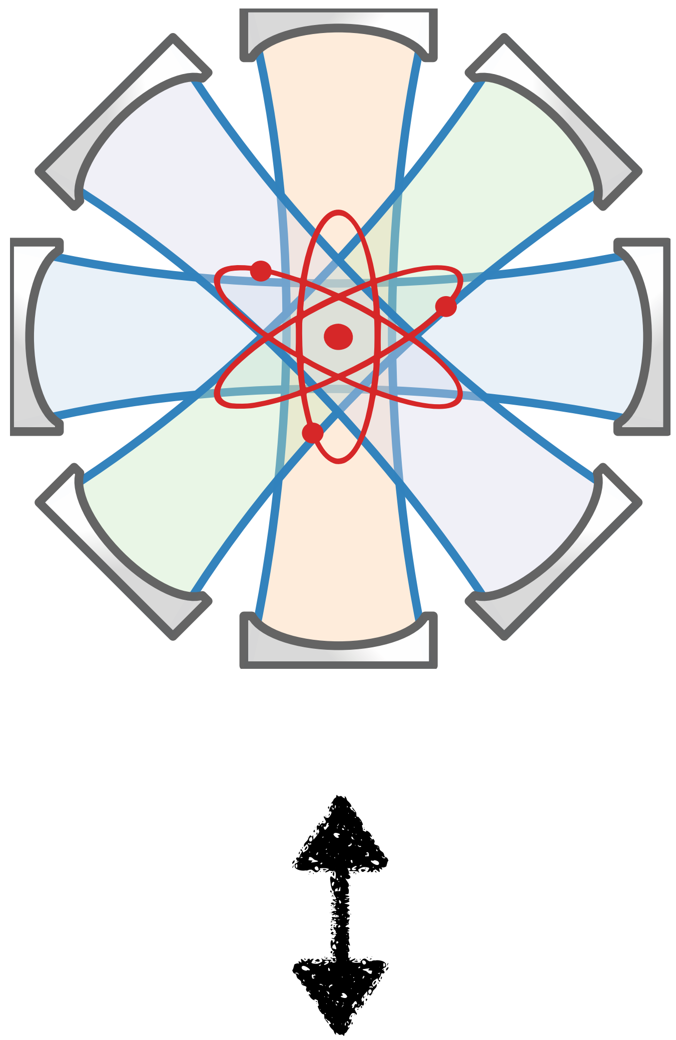
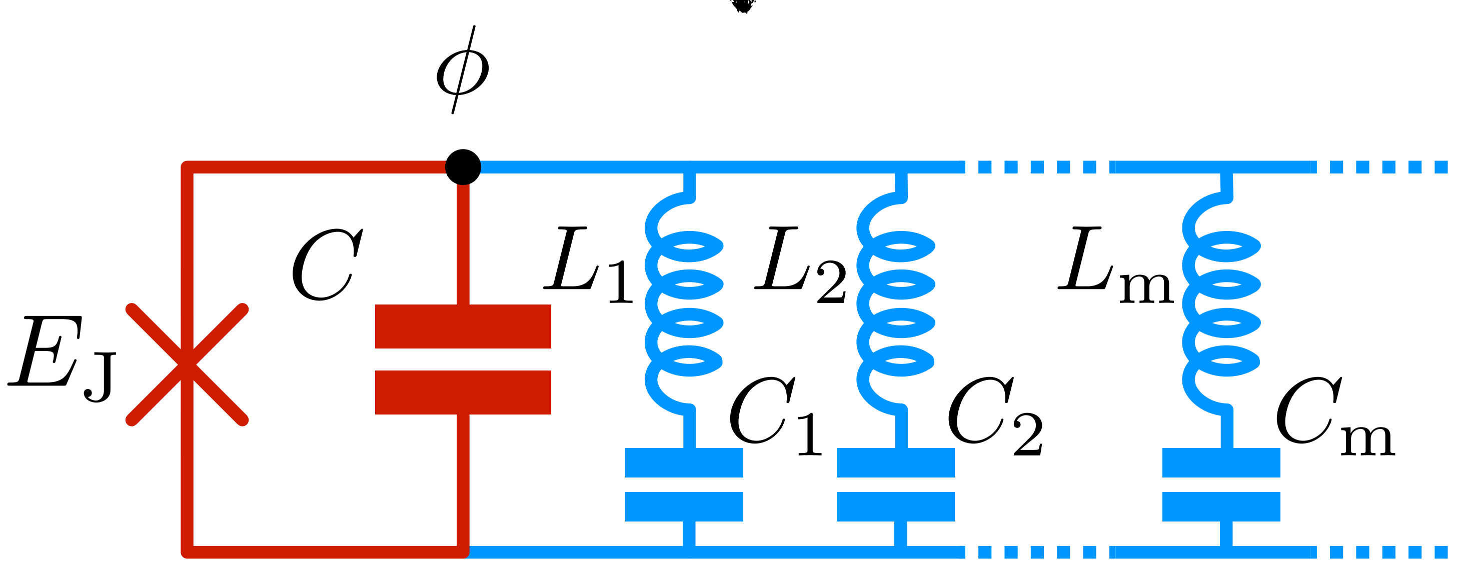
The JJ-C circuit: coupling





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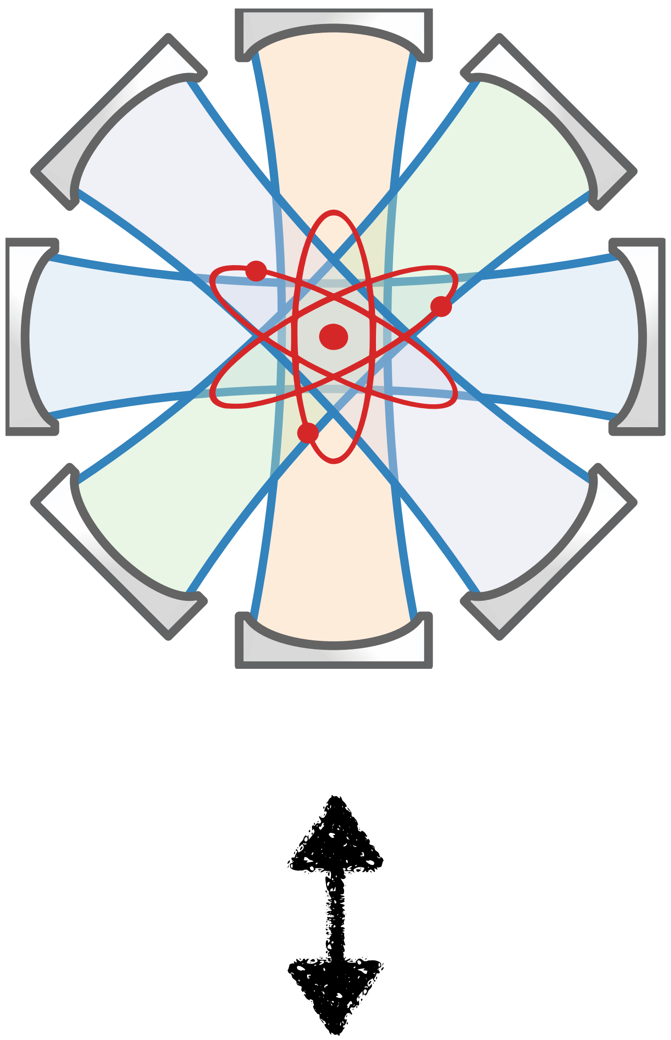
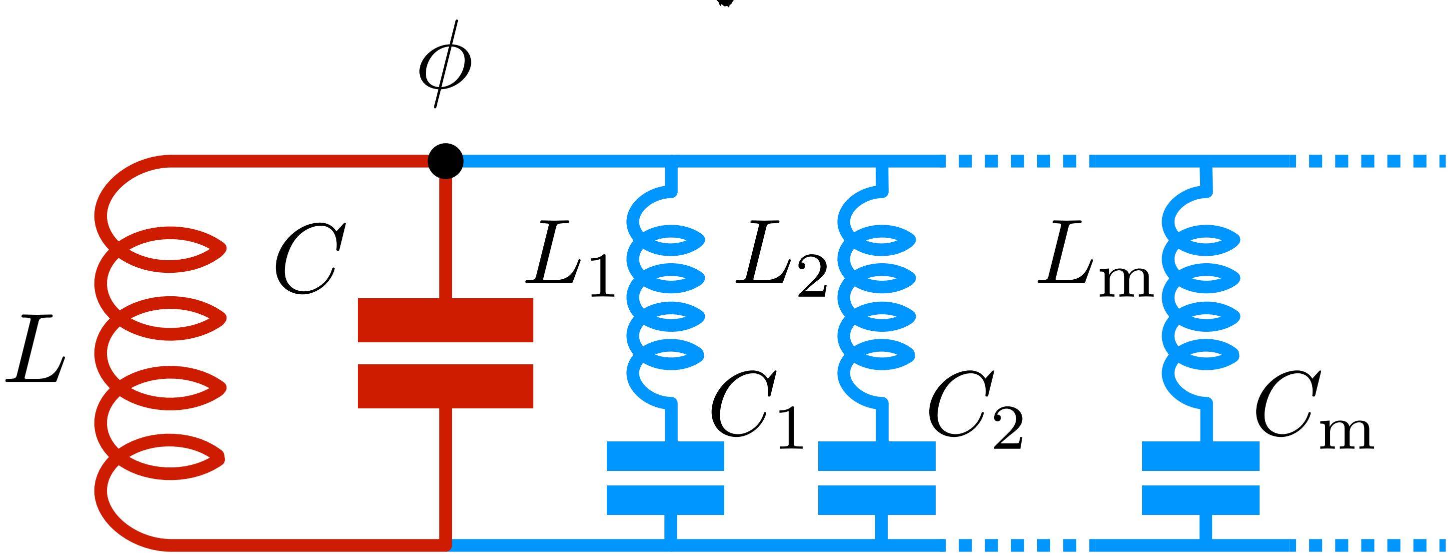
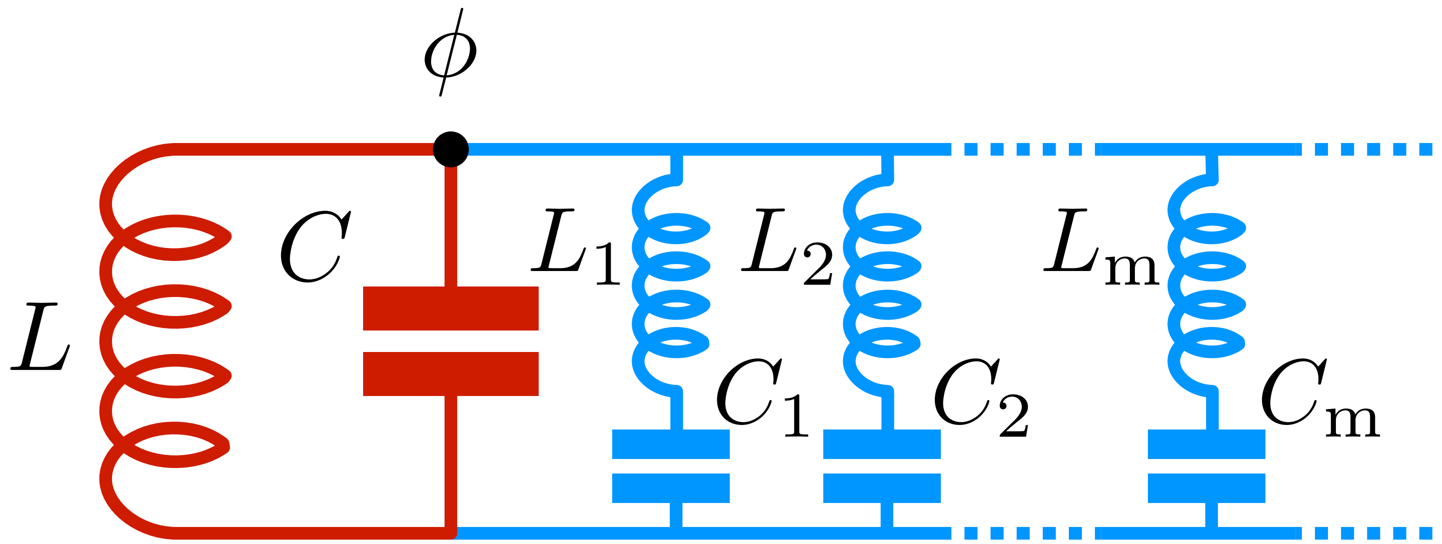




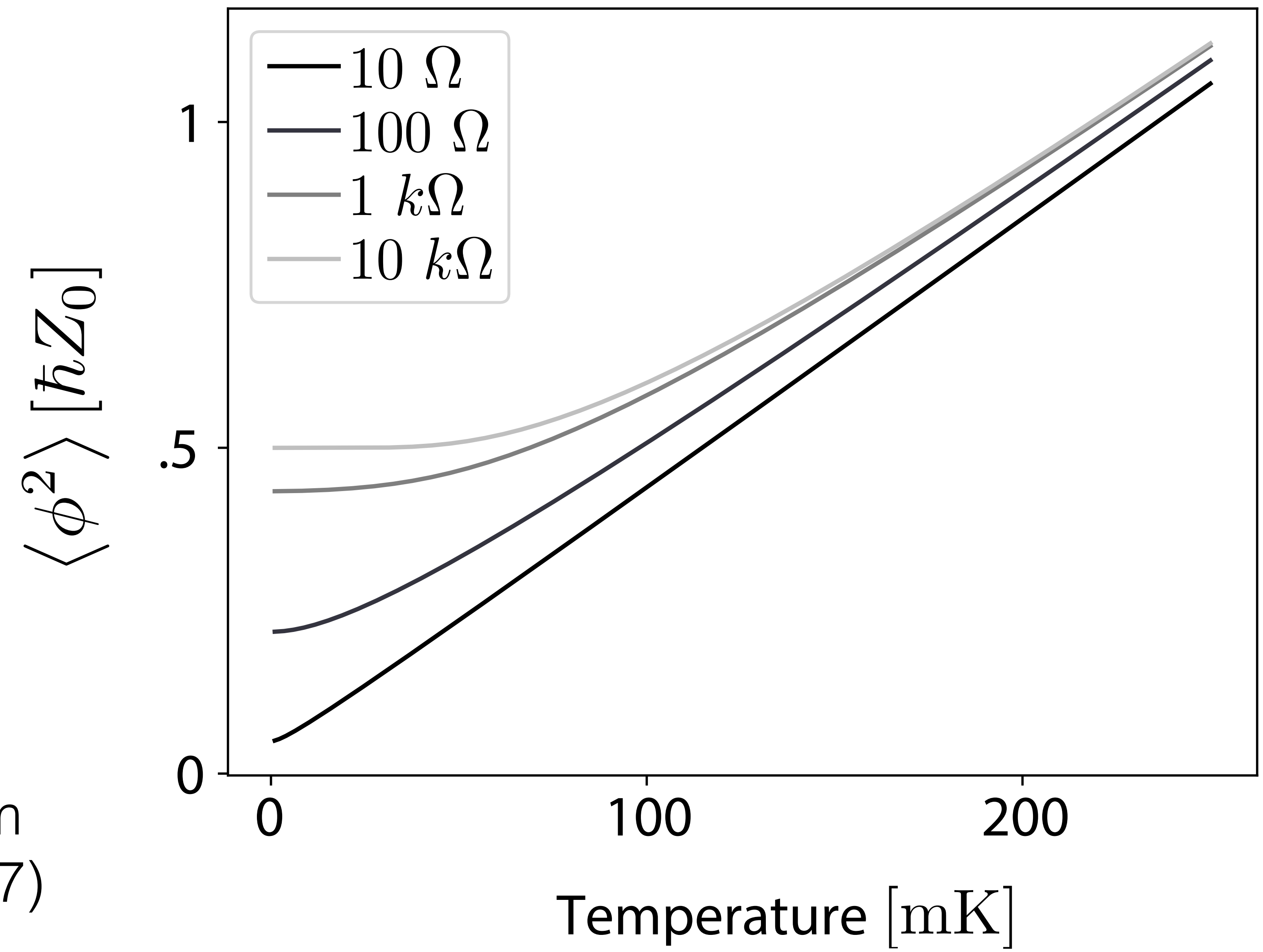
Simplified system: Caldeira Leggett treatment



$m \in [1, N]$

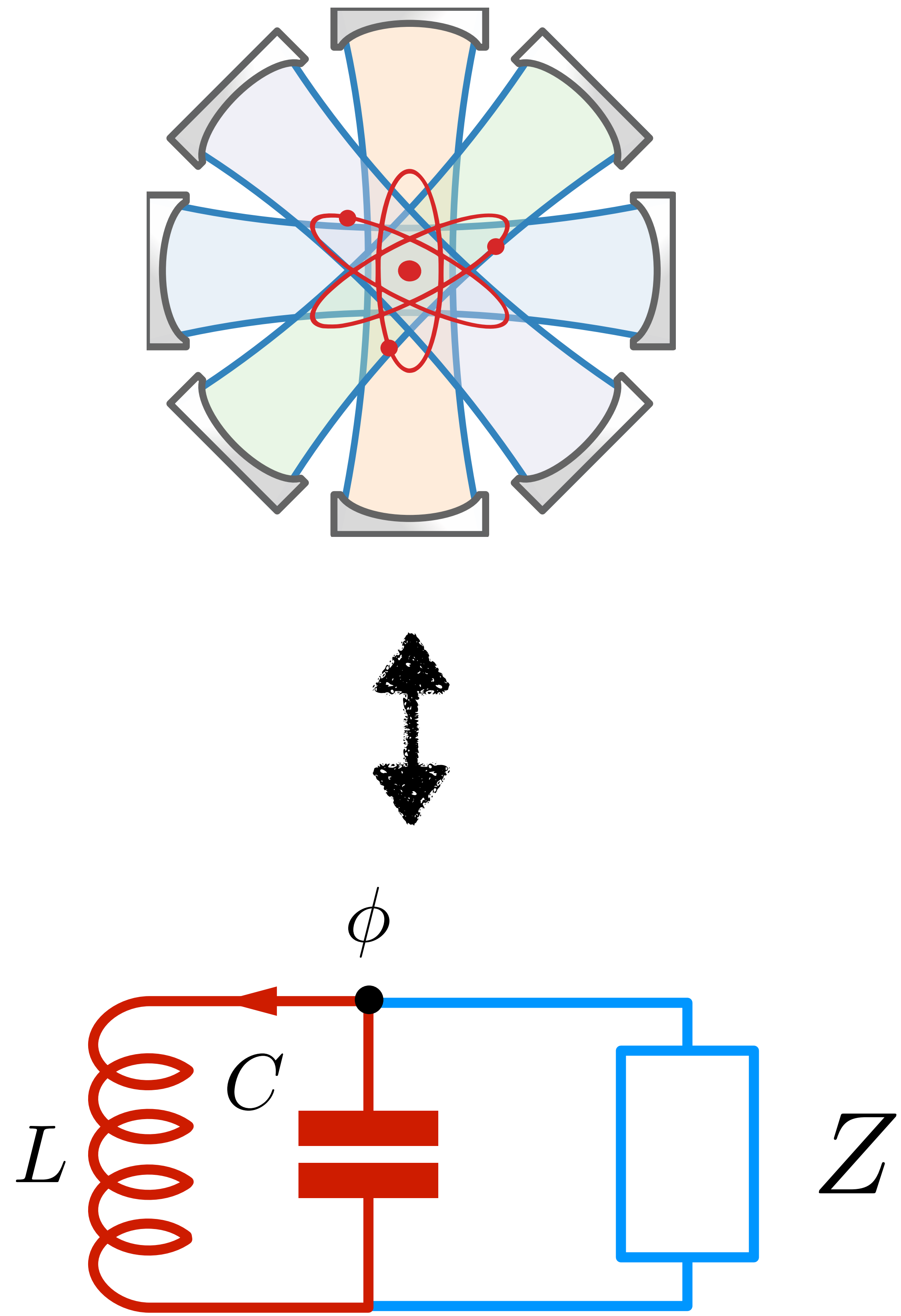
LC circuit:

$$Z_0 = \sqrt{L/C}$$
$$= 500\ \Omega$$
$$\omega_0/2\pi = 5\ \text{GHz}$$

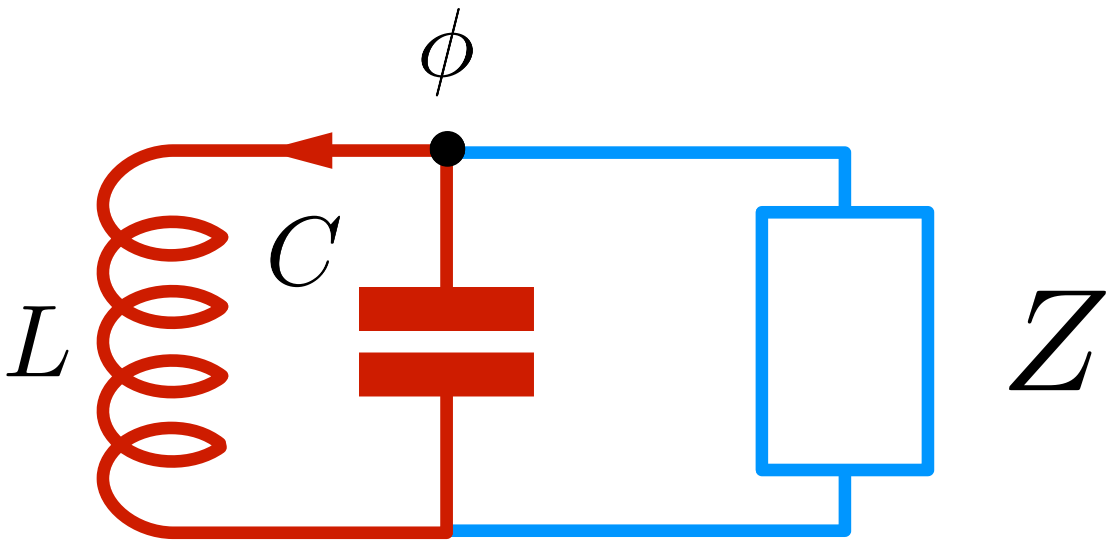


M. H. Devoret, in "Quantum Fluctuations", Elsevier (1997)

The JJ-C circuit: coupling



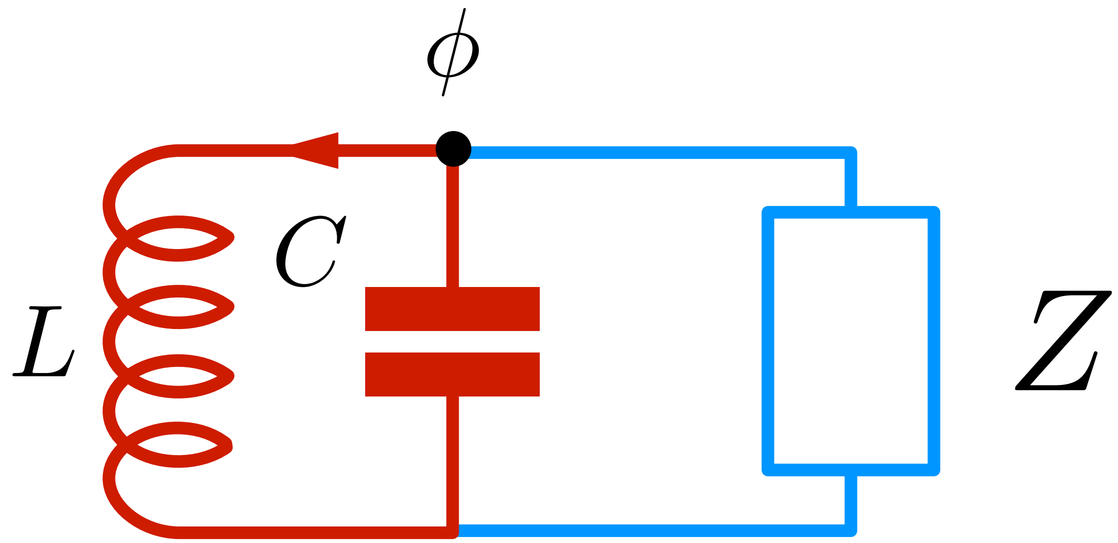
The JJ-C circuit: coupling



Microwave engineering argument:
impedance matching

$$Re\left(Z(\omega = \omega_0)\right) = \sqrt{L/C}$$

The JJ-C circuit: coupling

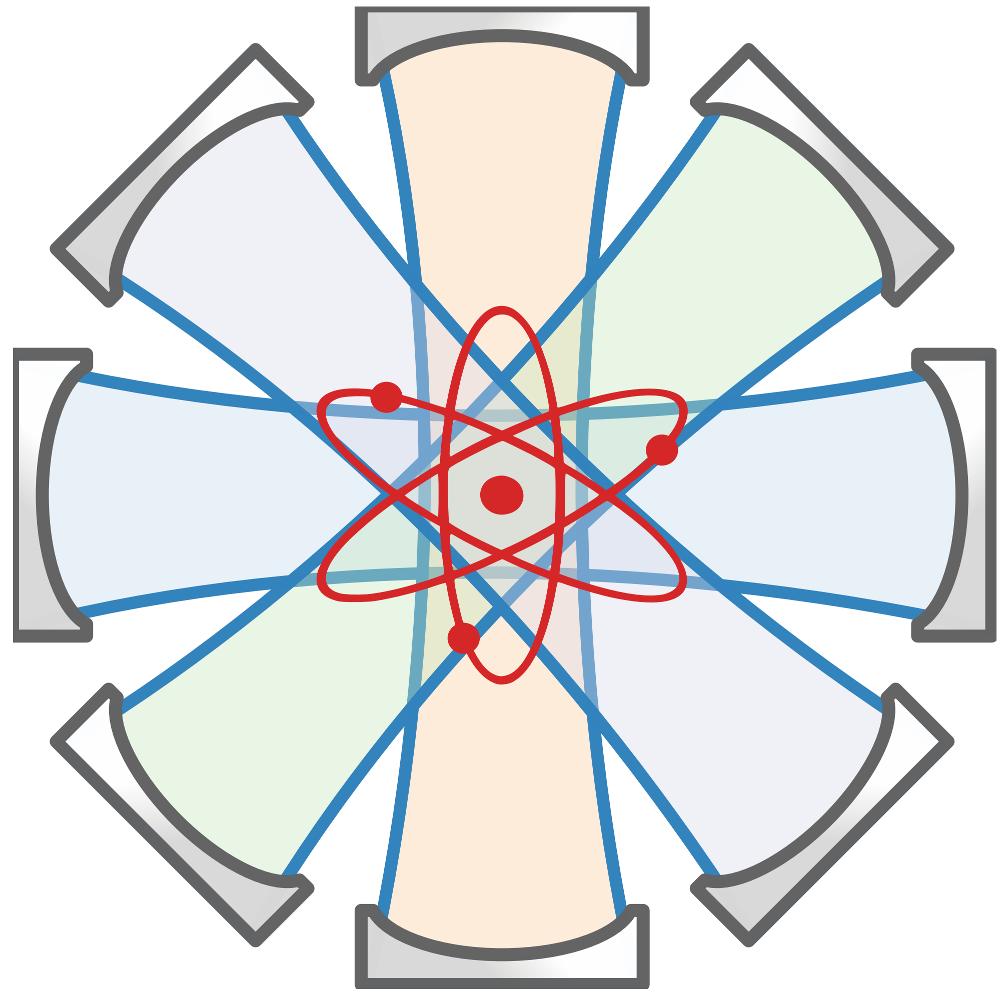


Microwave engineering argument:
impedance matching

$$Re\left(Z(\omega=\omega_0)\right)=\sqrt{L/C}$$

hence we need strong impedance environment as well

How do we engineer our many body system ?

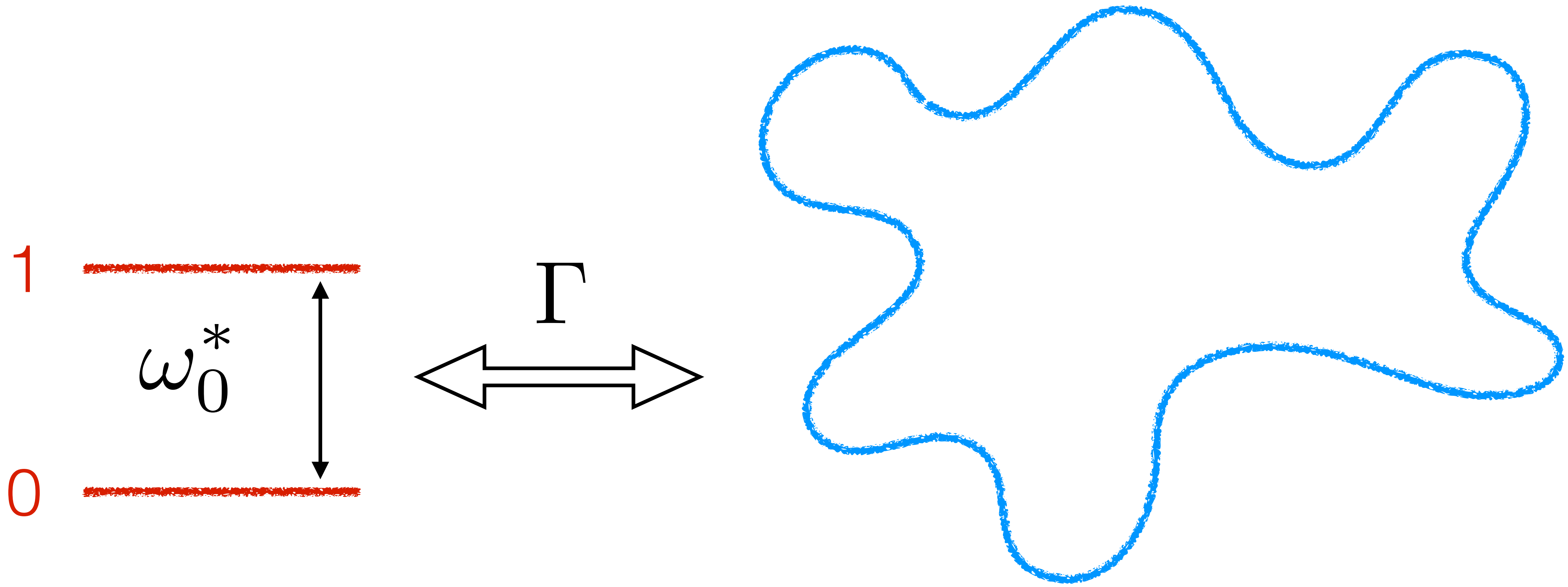


Non-trivial many-body system if:

- ☑ Many degrees of freedom: M^N
- ☑ Strong non-linearity: $\mathrm{anharmonicity} \gtrsim \Gamma$
- ☑ Ultra-strong coupling regime: $\Gamma \simeq \omega_0^*$

Many-body physics and circuitQED

Our choice: quantum impurities



Unexplored many-body physics ?

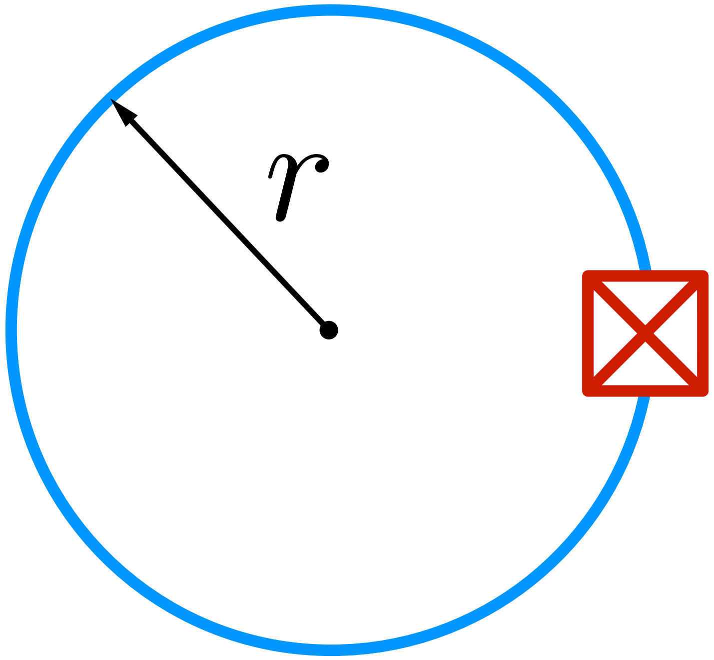
For a review see: G. Schön & A. D. Zaikin, Physics Reports (1990)

“Quantum fluctuations in the equilibrium state of a thin superconducting loop”

F. W. J. Hekking & L. I. Glazman, Phys. Rev. B (1997)

S. loop

“Plasma” or “Fabry-Pérot” modes



Josephson junction

E_J, C

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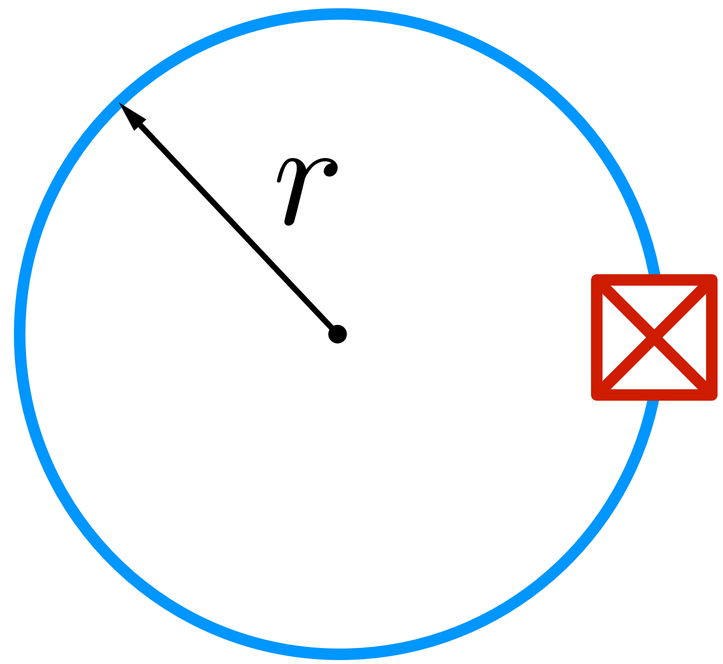

Josephson junction

E_J, C

Beyond Caldeira-Leggett:

modes are affected.

We will show that a finite renormalized Josephson energy can arise because the junction itself affects the fluctuations of the environment.[11] Simultaneously, the modes of the environment renormalize the plasmon oscillations in the junction.

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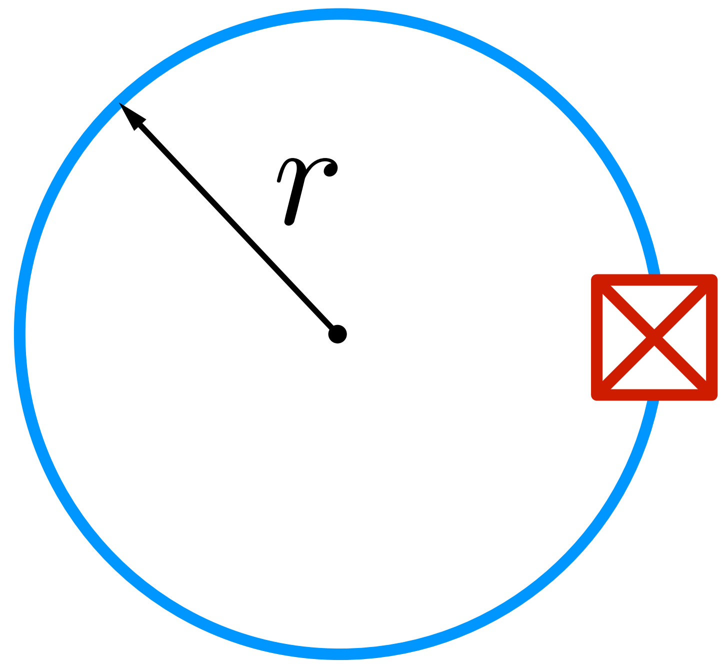

Josephson junction

E_J, C

Lamb shift cousin

$\omega_\mathrm{J}^* \neq \sqrt{2E_\mathrm{J}E_\mathrm{c}}$

Beyond Caldeira-Leggett:

modes are affected.

We will show that a finite renormalized Josephson energy can arise because the junction itself affects the fluctuations of the environment.[11] Simultaneously, the modes of the environment renormalize the plasmon oscillations in the junction.

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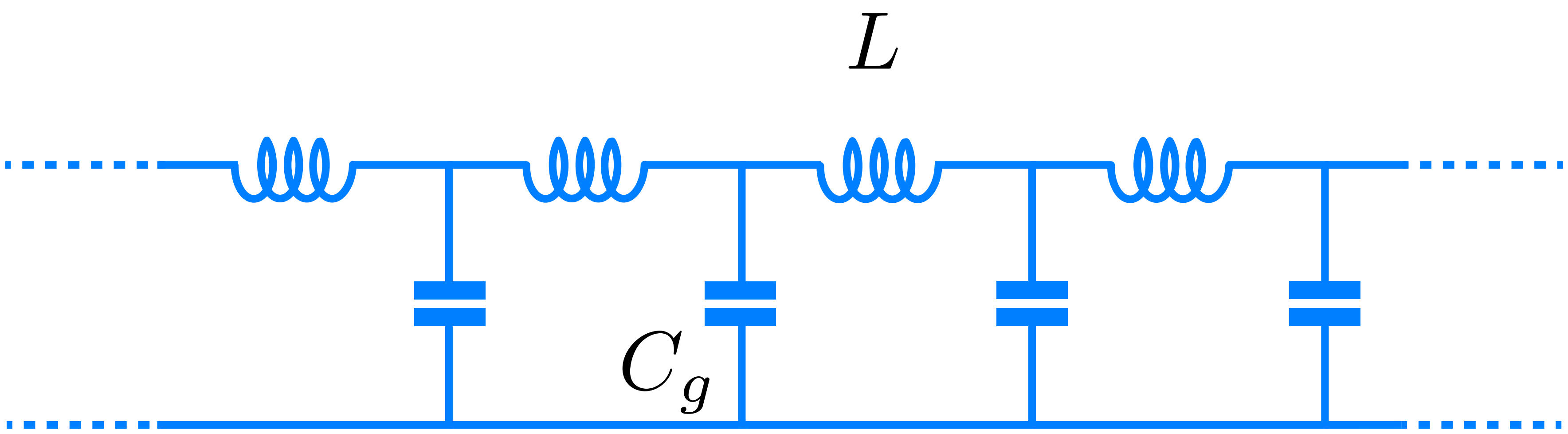
Reaching high impedances

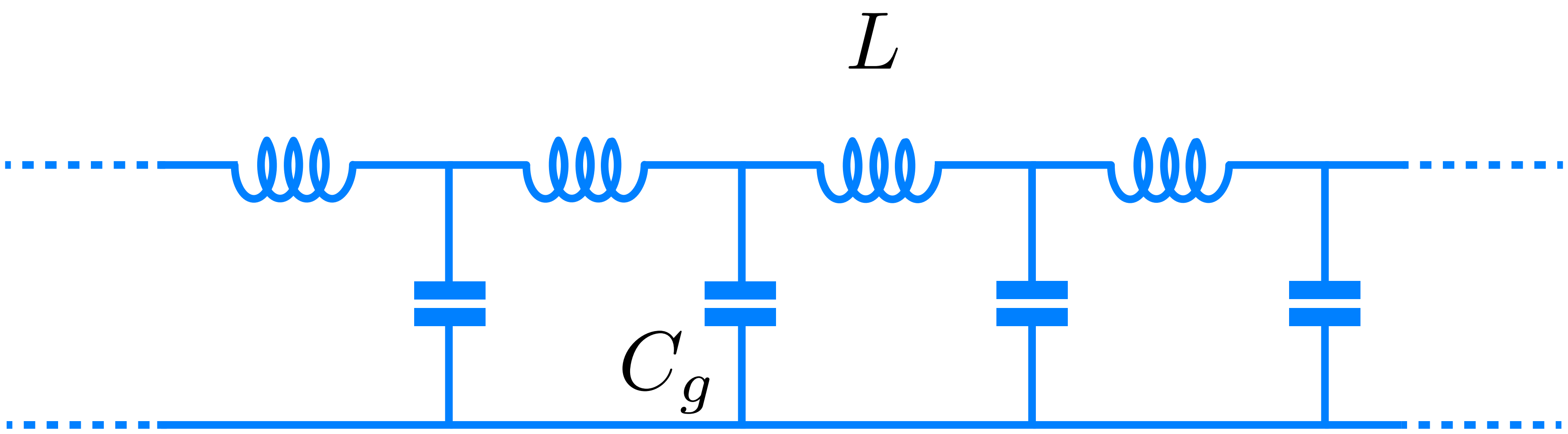
Josephson junction meta-material



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

Reaching high impedances

Josephson junction meta-material



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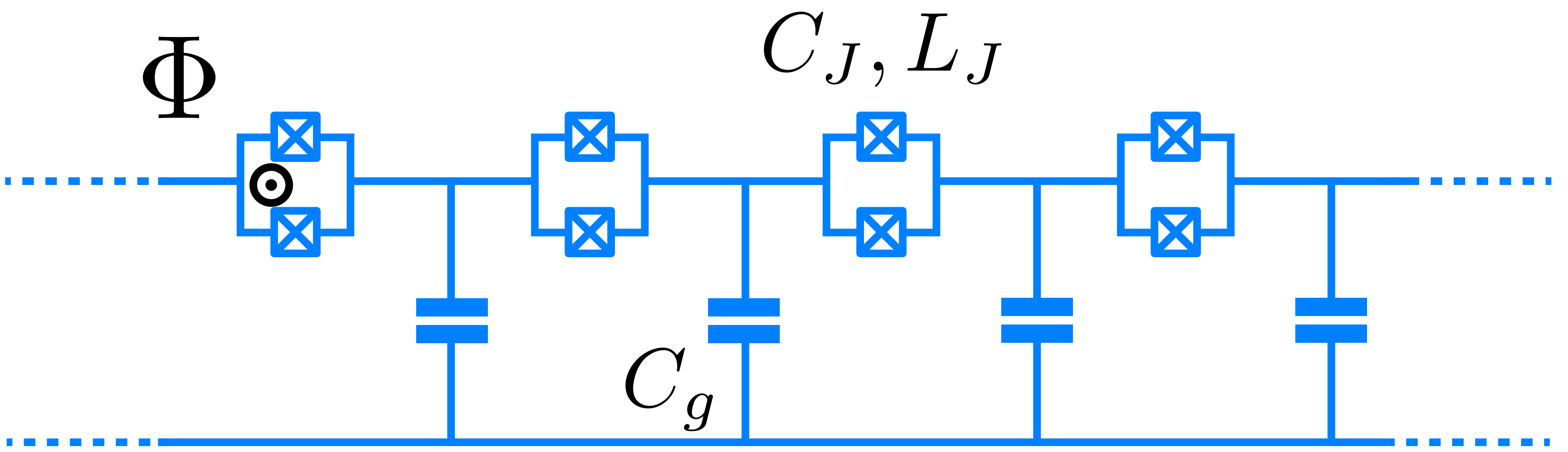


$$Z_c = \sqrt{L_J(\Phi)/C_g}$$

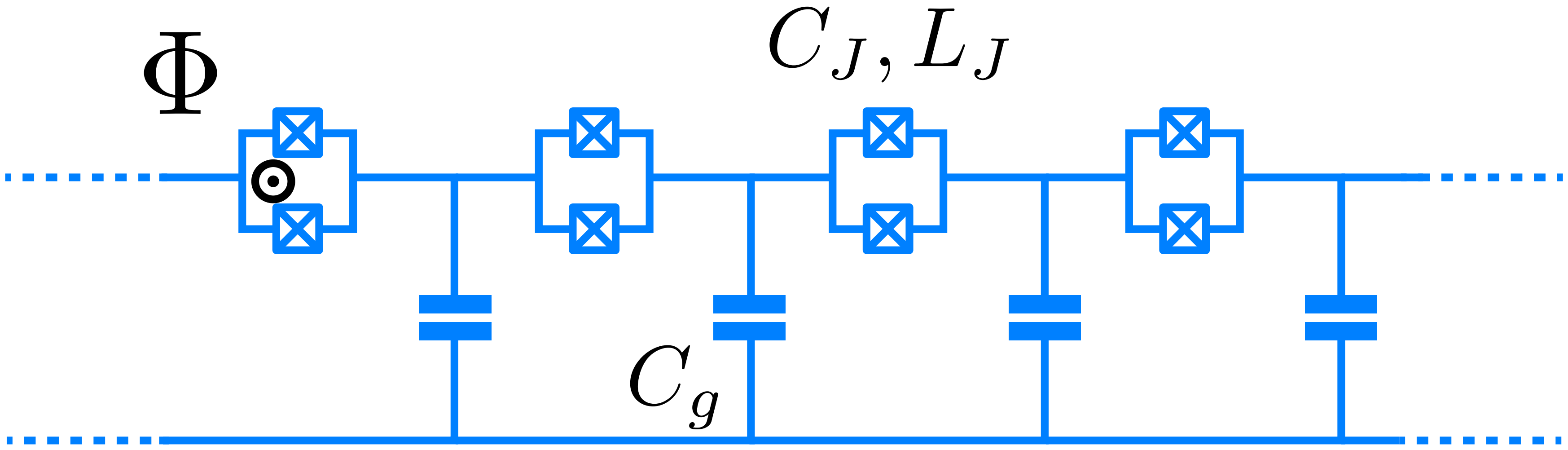
Seminal work:

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’, R. Kuzmin et al 18’….

Reaching high impedances
Josephson junction meta-material

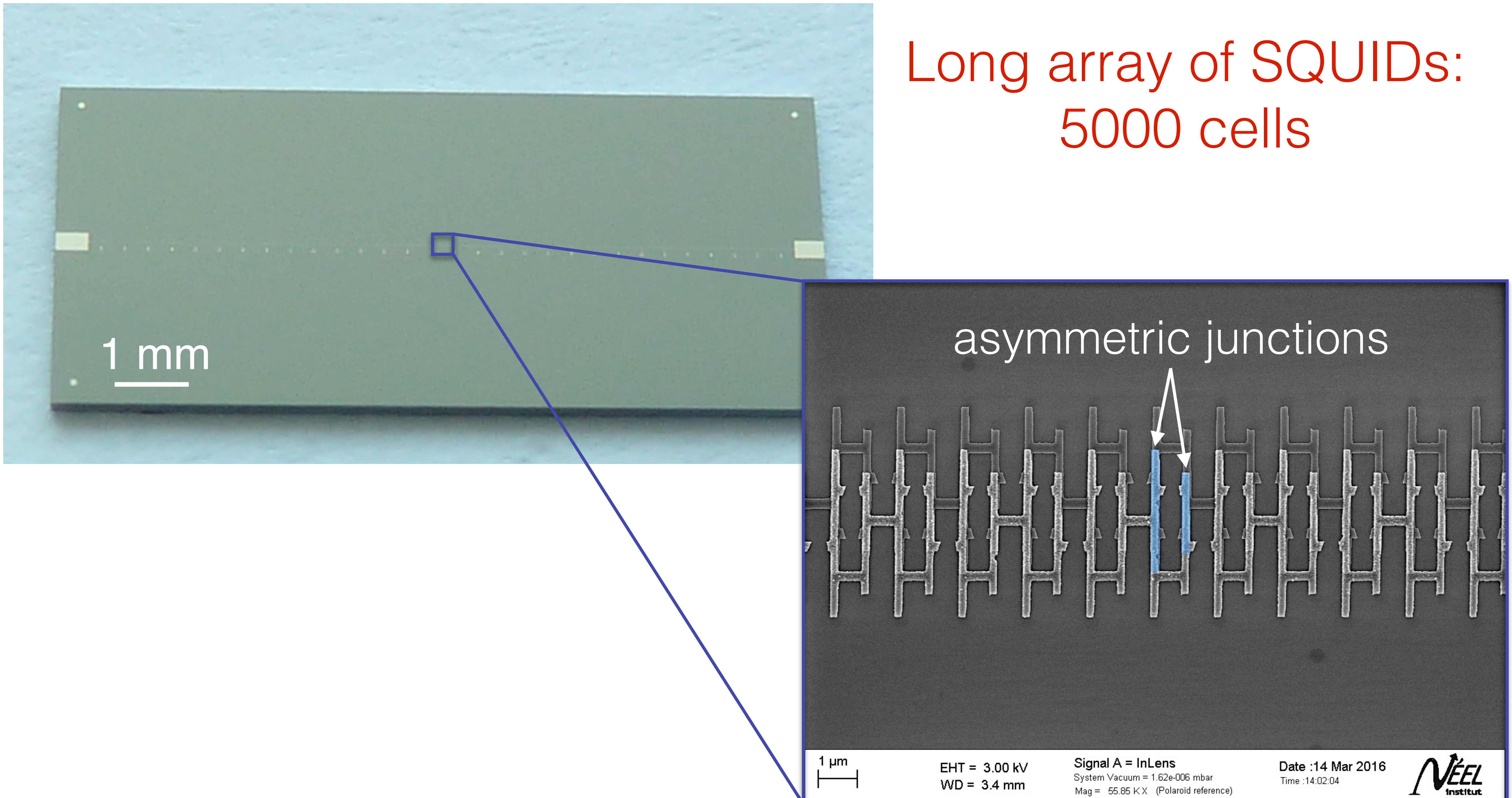


$$Z_c = \sqrt{L_J(\Phi)/C_g}$$

$$Z_J = \sqrt{L_J(\Phi)/C_J}$$

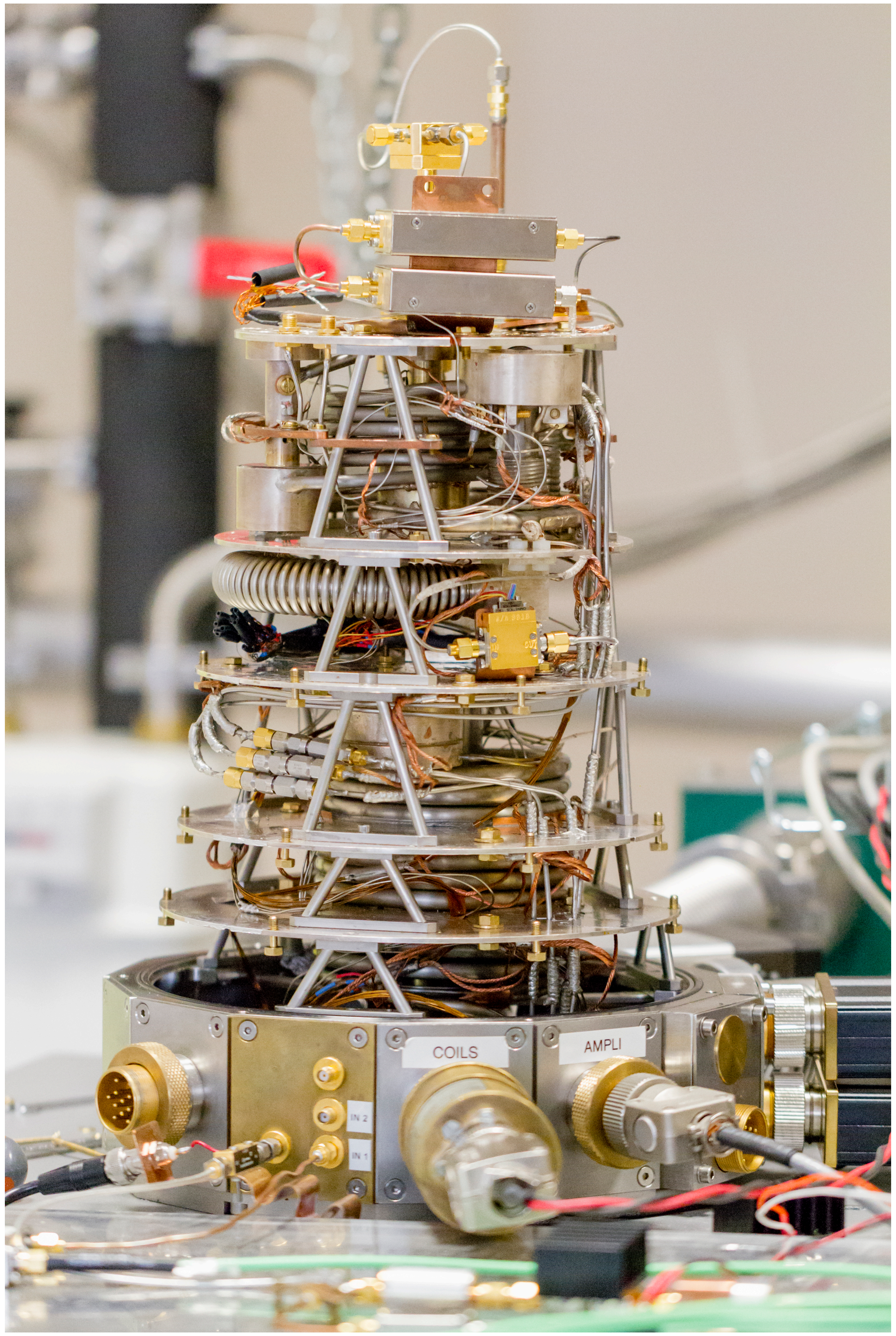
JJ meta-material: Bridge Free Fabrication

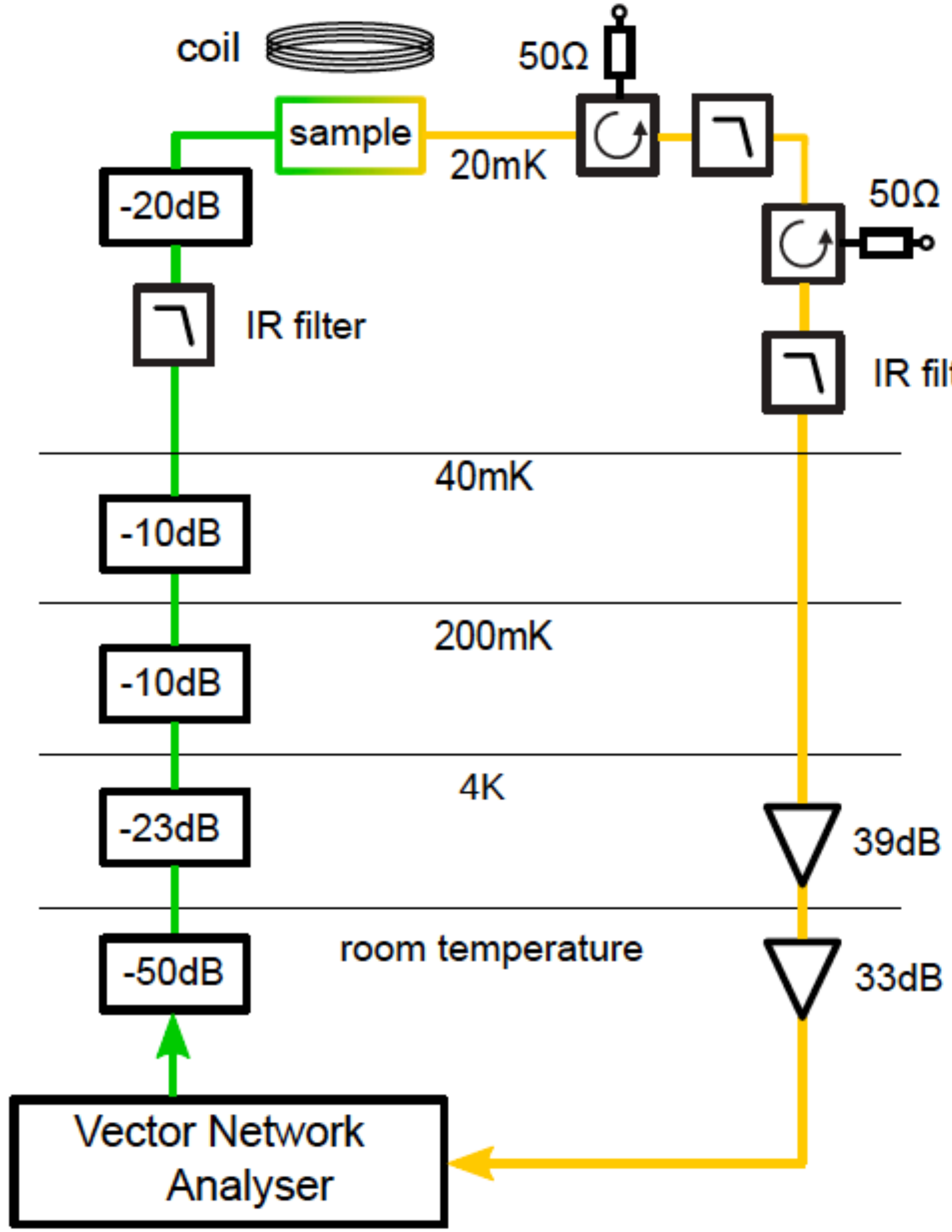
Long array of SQUIDs:
5000 cells



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

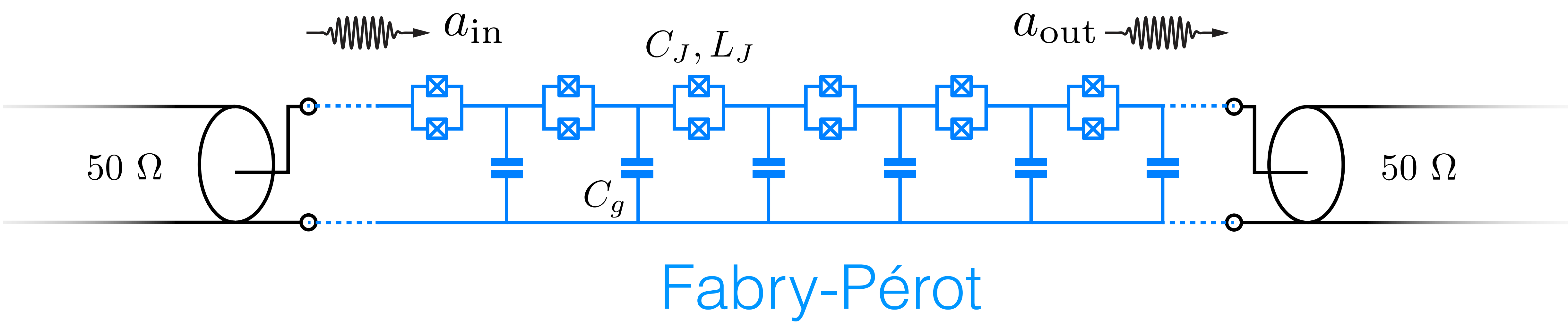
JJ meta-material: Measuring

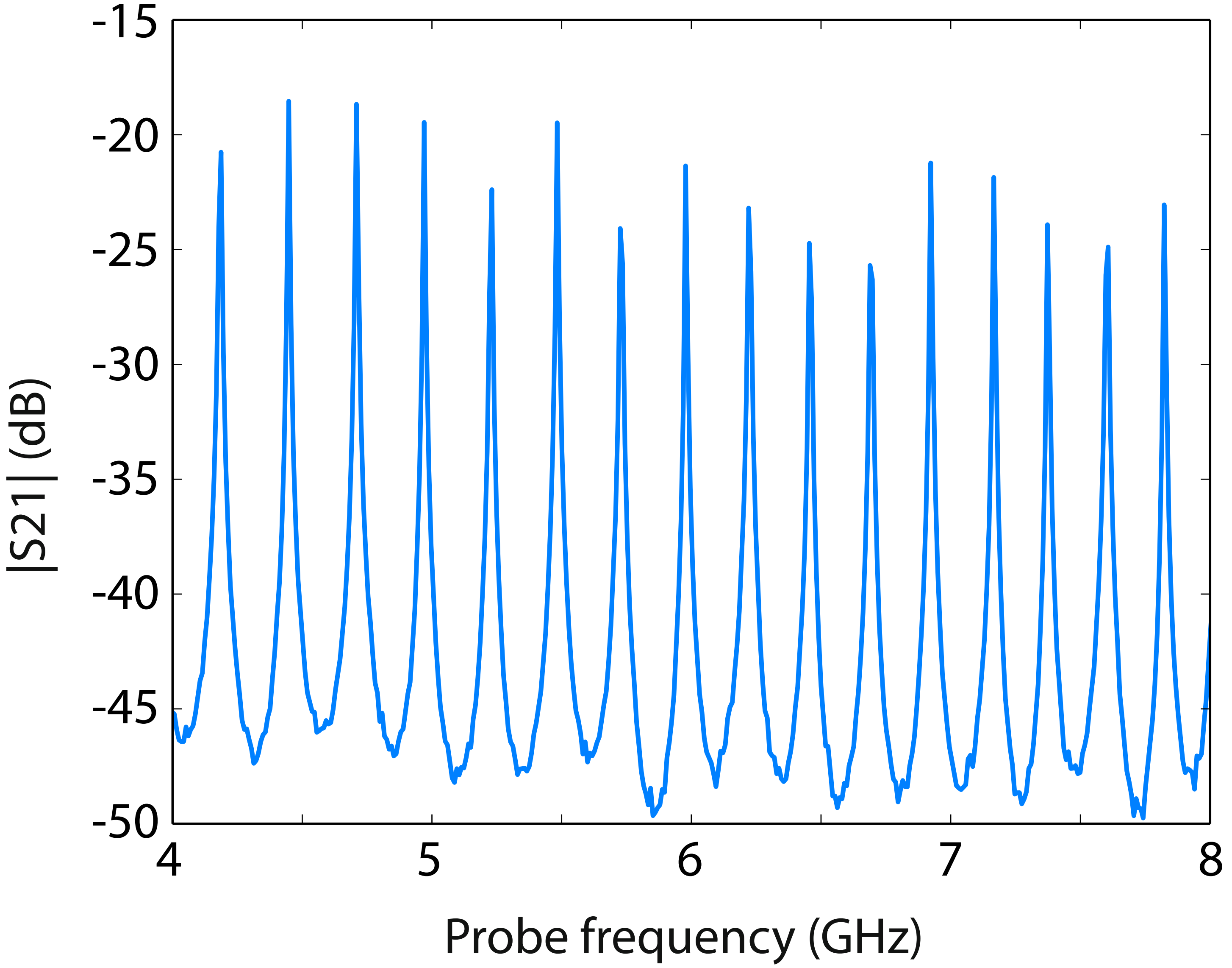




Quantum regime: $\hbar\omega \gg k_{\mathrm{B}}T$

Josephson junction meta-material





Quantum regime:

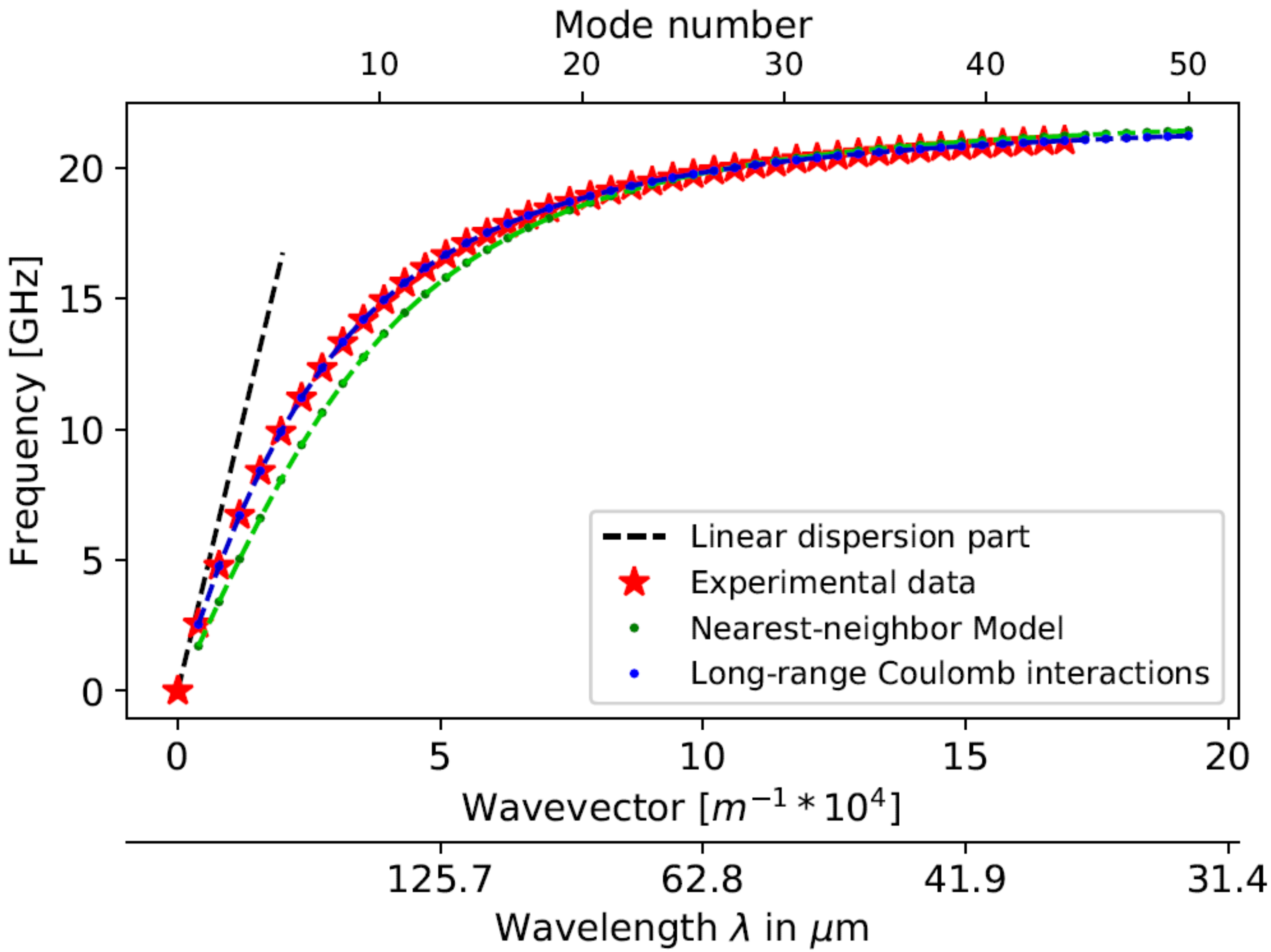
$$\hbar\omega \gg k_{\mathrm{B}}T$$

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

High-Q

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

Well controlled environment



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:

$$n \simeq 50$$

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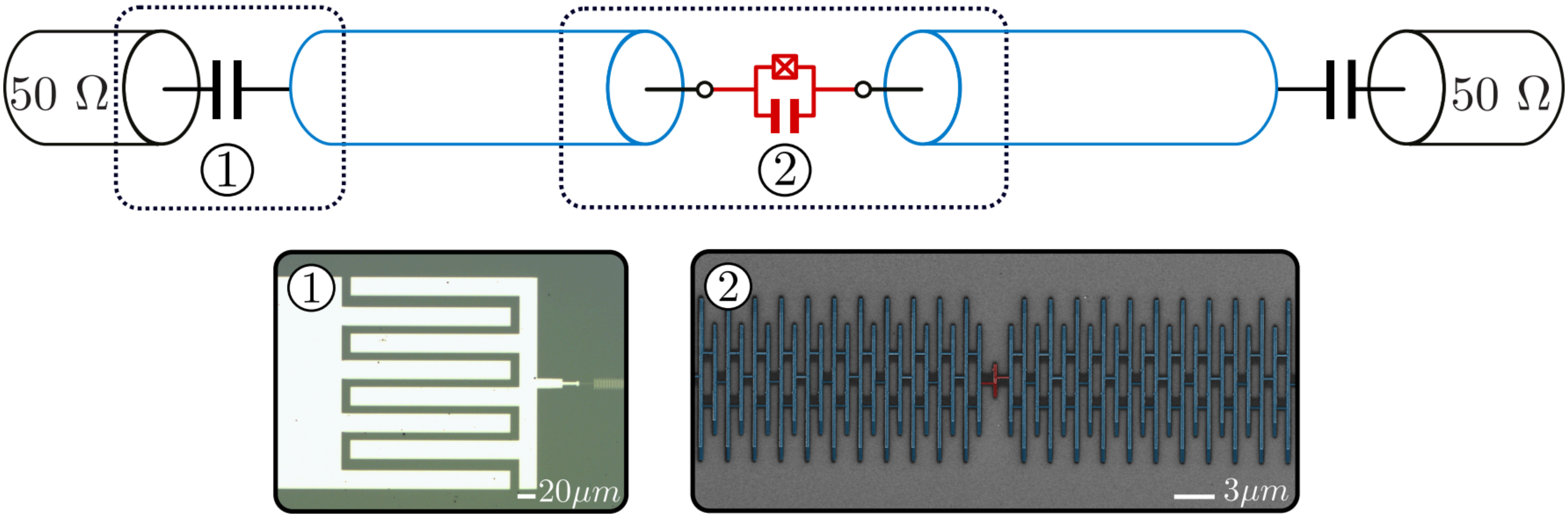
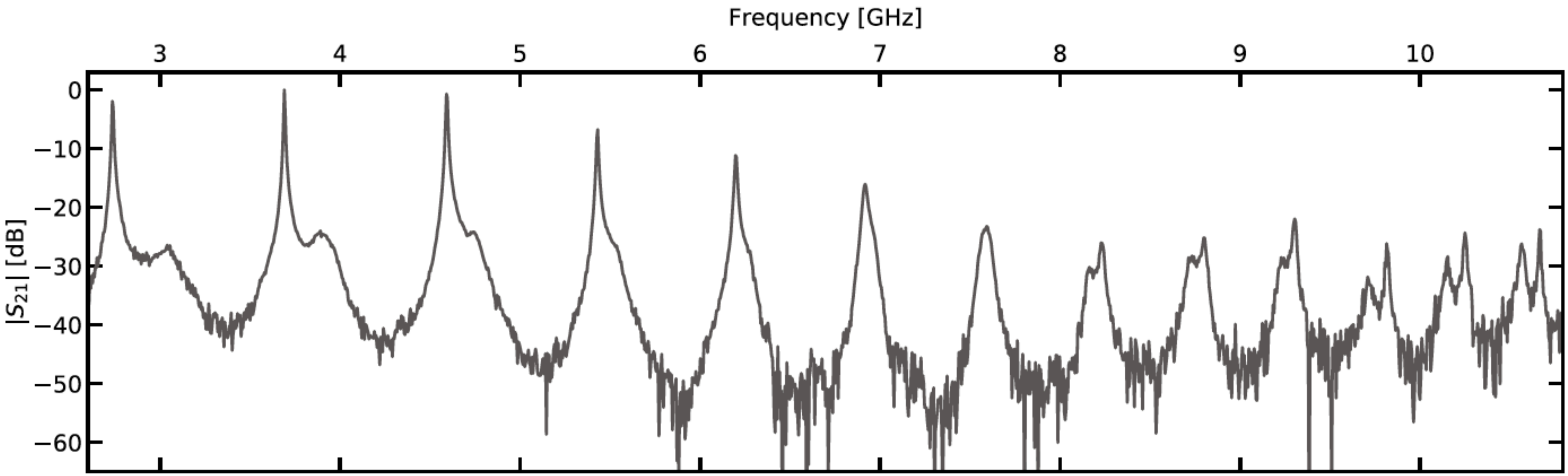


small junction (non-linear): $Z_{\rm J} \simeq 2k\Omega$

SQUID chains (linear): $Z_{\rm J} \simeq 10\Omega$

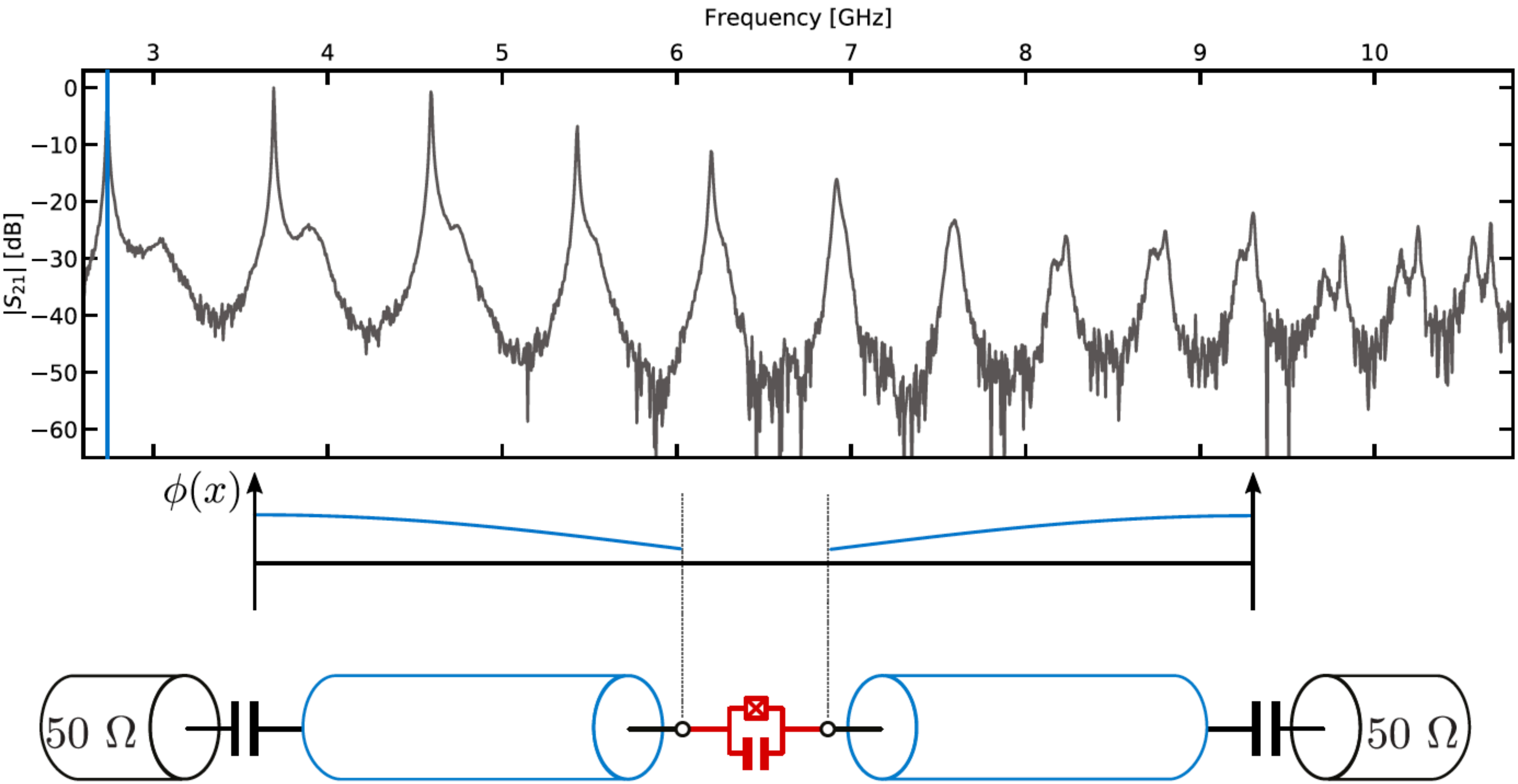
$Z_c = 1.8\ k\Omega$

Typical spectrum



$T = 24\ mK$

Typical spectrum



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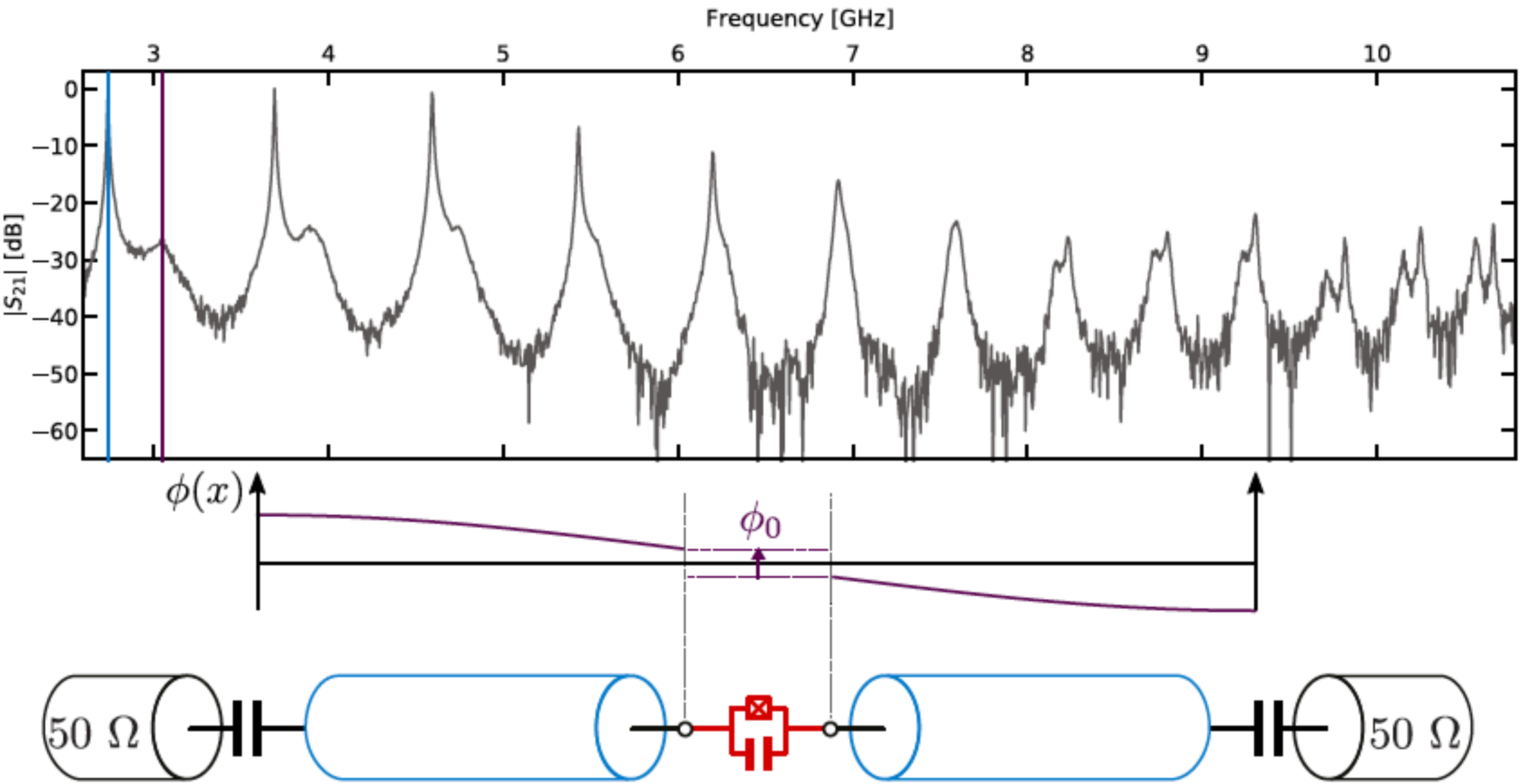

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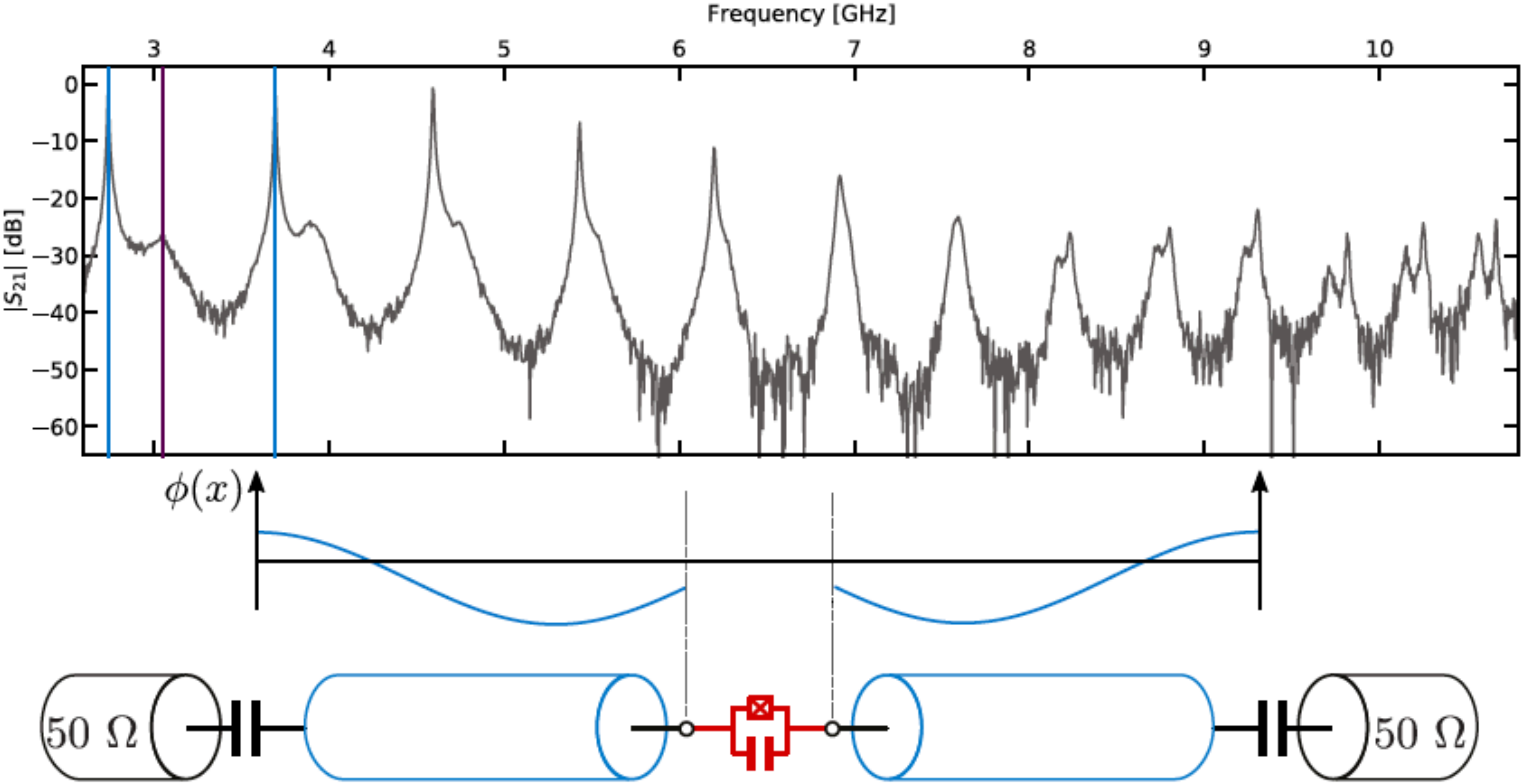

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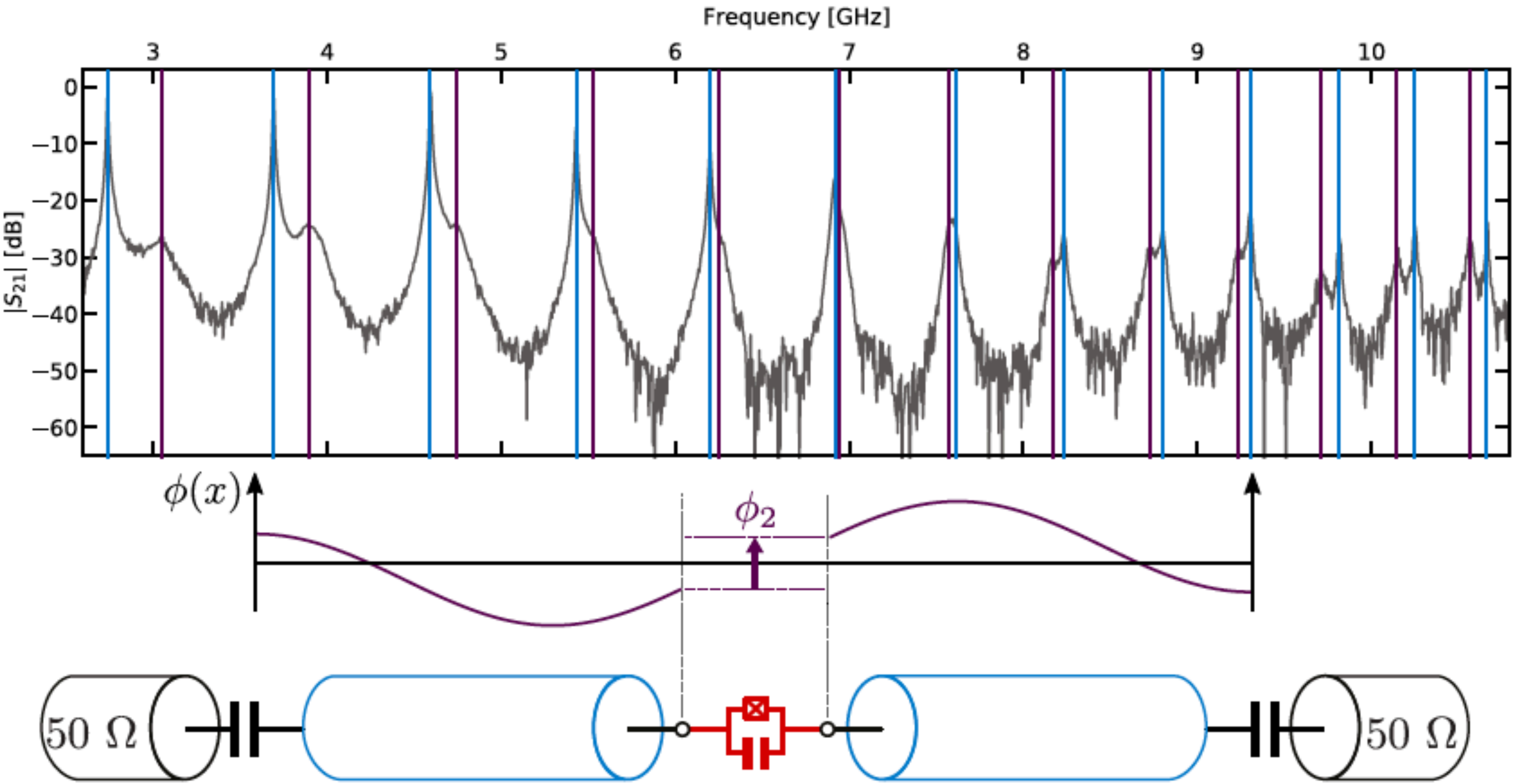
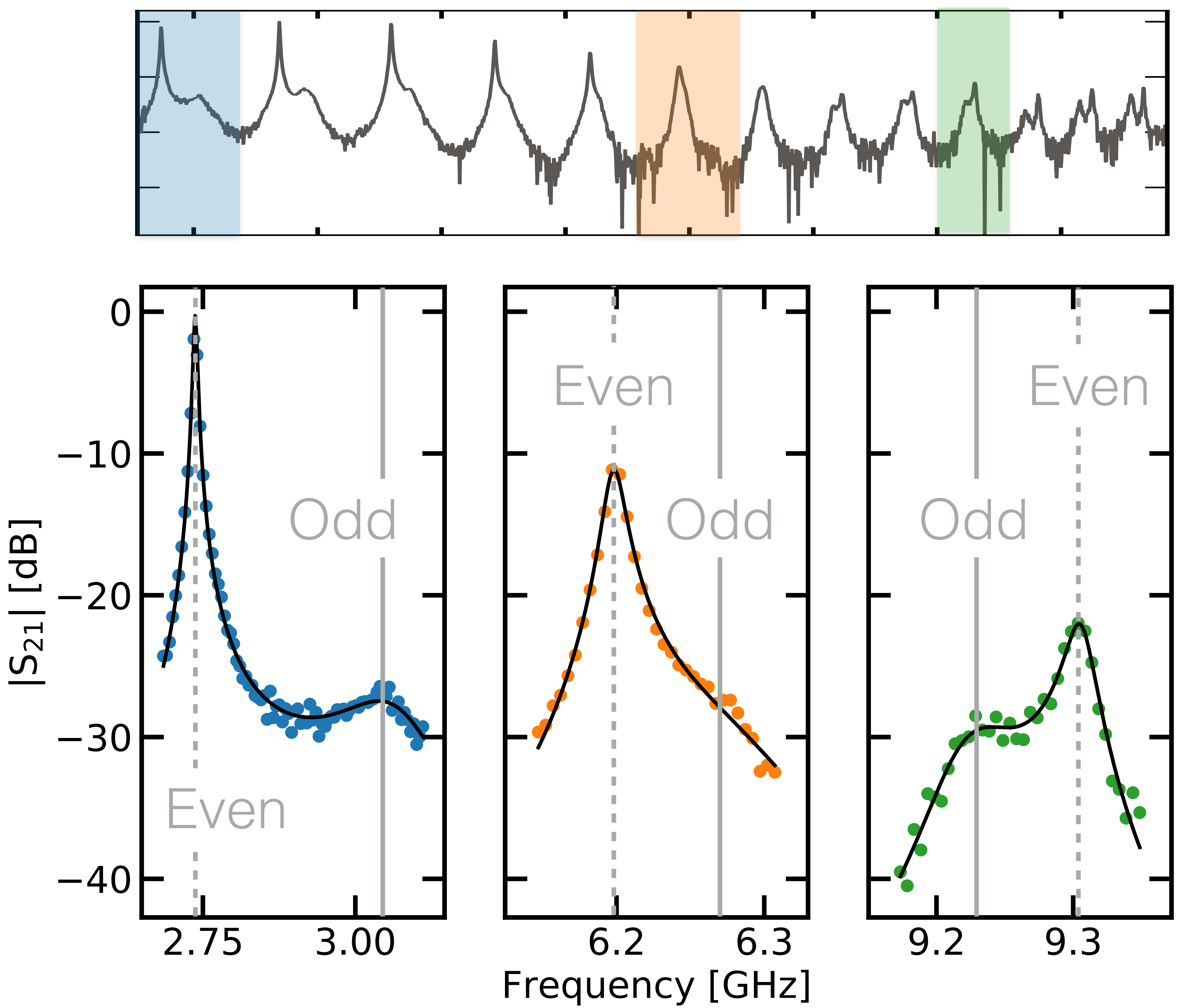
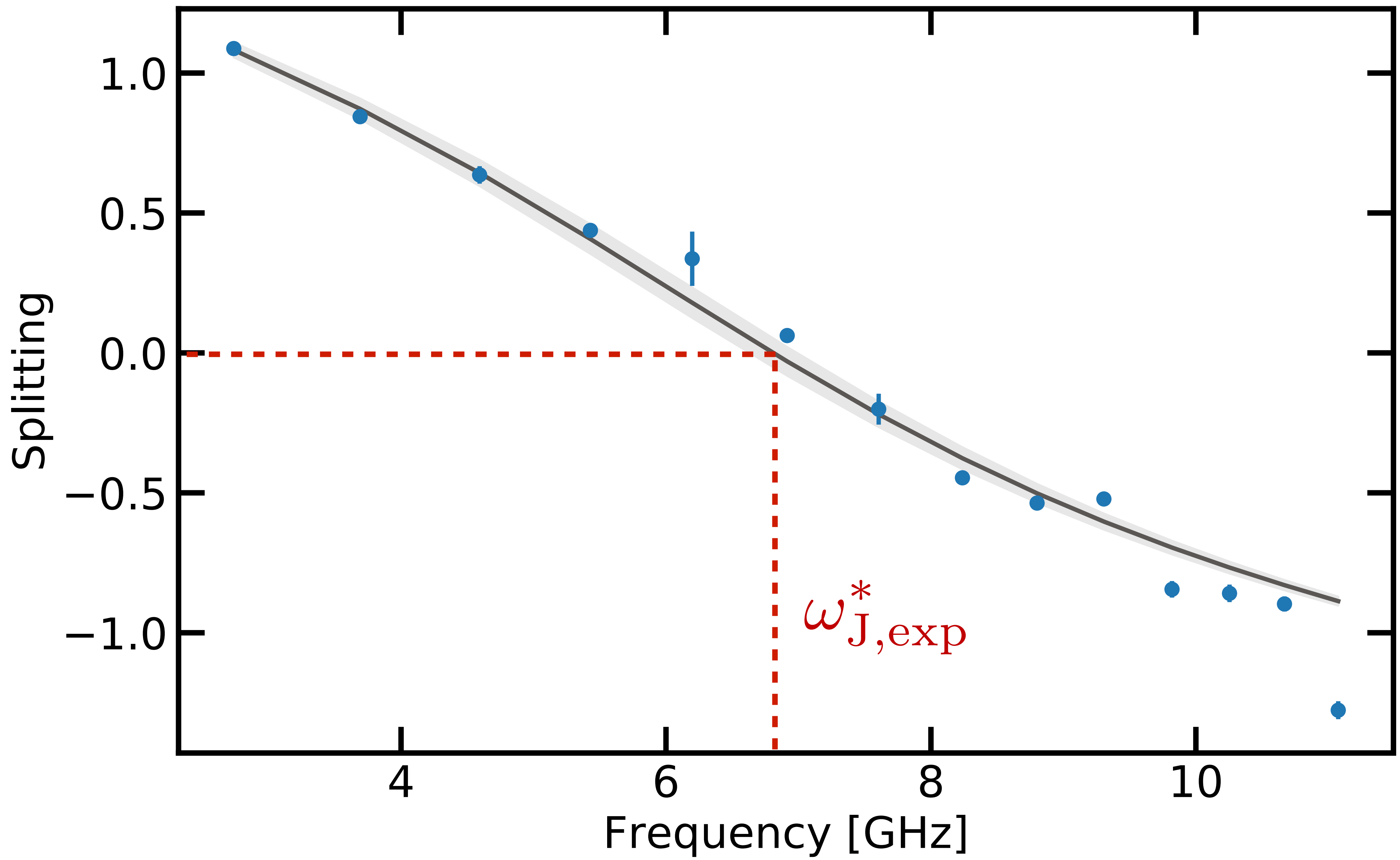


$T = 24\ mK$

Odd/Even modes



Plasma frequency of the small junction



Splitting: $$\pi \frac{\omega_{\mathrm{o,n}} - \omega_{\mathrm{e,n}}}{\omega_{\mathrm{e,n+1}} - \omega_{\mathrm{e,n}}}$$

Observation: $\omega^*_{\mathrm{J,exp}}/2\pi = 6.9 \pm 0.2\ \mathrm{GHz}$

Plasma frequency of the small junction

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$E_{\mathrm{J,bare}} = 3.76 \pm 0.24\ \mathrm{GHz}$ (Ambegaokar-Baratoff)

$E_{\mathrm{c}} = 14.3 \pm 0.8\ \mathrm{GHz}$ (High power measurements)

$\longrightarrow$ $\omega_{\mathrm{J,bare}}/2\pi = 10.4 \pm 0.7\ \mathrm{GHz}$

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Parameter	Sample A	Sample B	Sample C
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$\omega_{\mathrm{J,bare}}/2\pi$	10.4 +/- 0.7 GHz	12.4 +/- 0.8 GHz	11.8 +/- 0.9 GHz

Lamb shift like effect?

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Lamb shift like effect?

Experiment in the single mode case: C. Rolland, A. Peugeot et al., Phys. Rev. Lett. (2019)

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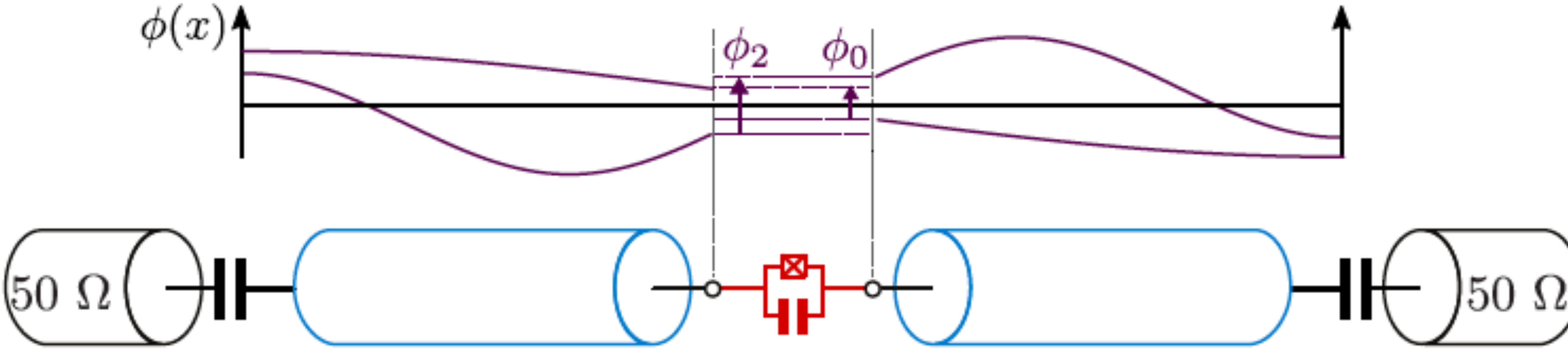
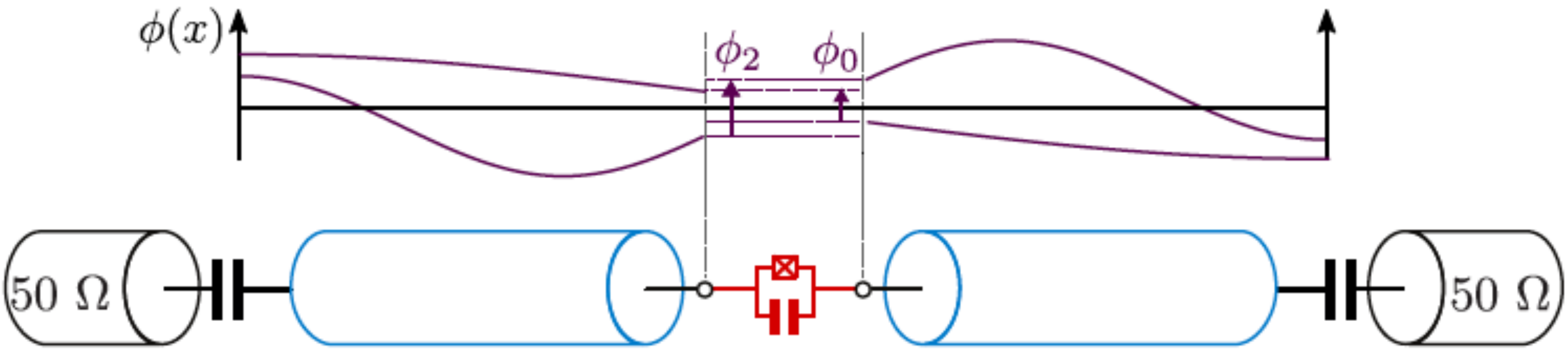
Modelling: Self-Consistent Harmonic Approximation



$$-E_{\mathrm{J}}\cos(\phi) \longrightarrow E_{\mathrm{J}}^{*}\frac{\phi^2}{2} \quad \text{with} \quad E_{\mathrm{J}}^{*} = E_{\mathrm{J}}e^{-\langle\phi(E_{\mathrm{J}}*)^2\rangle/2}$$

Modelling: Self-Consistent Harmonic Approximation

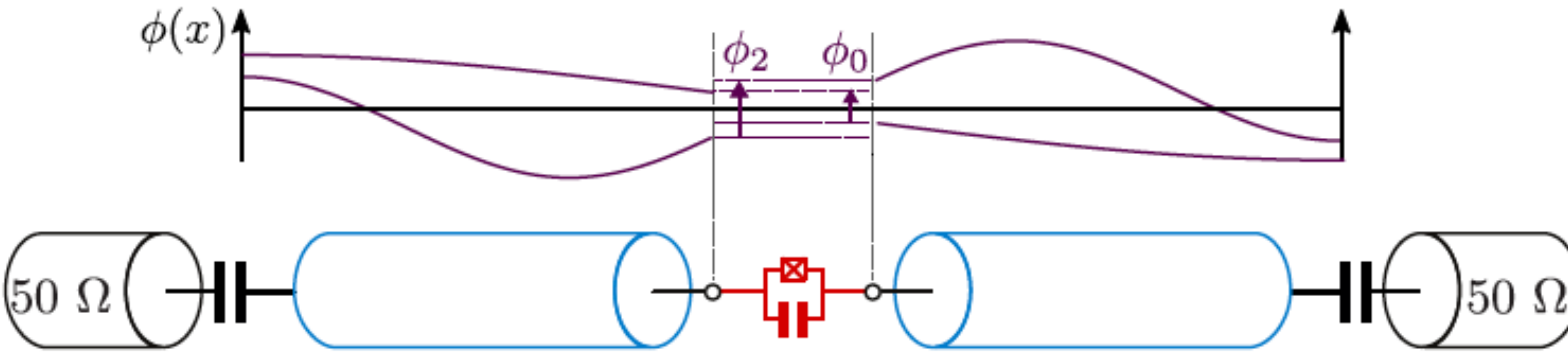


$$-E_\mathrm{J}\cos(\phi) \longrightarrow E_\mathrm{J}^*\frac{\phi^2}{2} \quad \text{with} \quad E_\mathrm{J}^* = E_\mathrm{J} e^{-\langle \phi(E_\mathrm{J}*)^2\rangle/2}$$

Similar to: $$E_\mathrm{J}^* = E_\mathrm{J}\left(\frac{E_\mathrm{J}}{\omega_\mathrm{c}}\right)^{1/(R_\mathrm{Q}/Z-1)}$$

F. W. J. Hekking & L. I. Glazman, Phys. Rev. B (1997)

Modelling: Self-Consistent Harmonic Approximation



$$-E_J \cos(\phi) \longrightarrow E_J^* \frac{\phi^2}{2}$$ with $$E_J^* = E_J e^{-\langle \phi(E_J *)^2 \rangle /2}$$

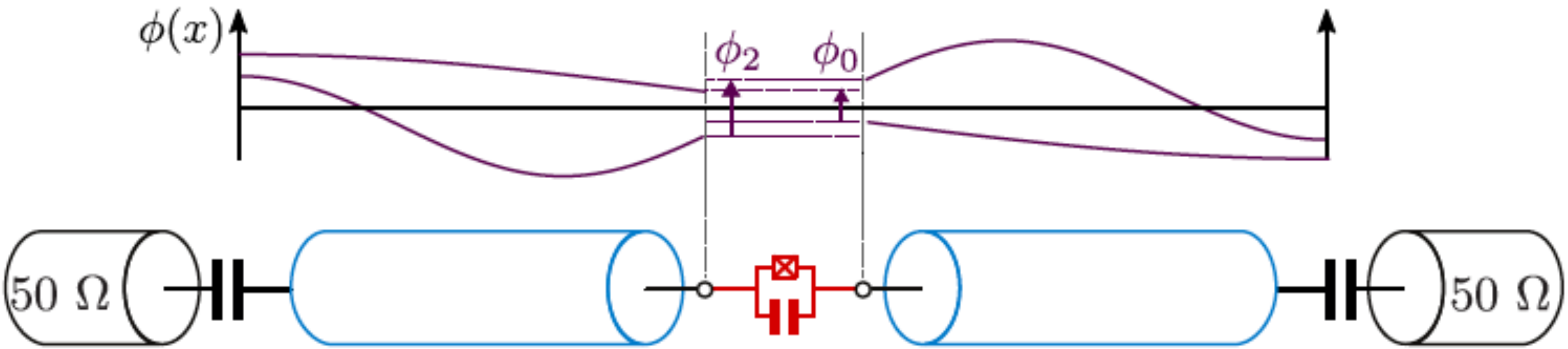
Similar to: $$E_J^* = E_J \left(\frac{E_J}{\omega_c} \right)^{1/(R_Q/Z-1)}$$

F. W. J. Hekking & L. I. Glazman, Phys. Rev. B (1997)

SCHA 1D problem: T. Giamarchi, "Quantum physics in one dimension" Oxford university press (2003)

SCHA cQED: P. Joyez, Phys. Rev. Lett. (2013)
J. Puertas-Martinez, Phd Thesis (2018)

Modelling: Self-Consistent Harmonic Approximation



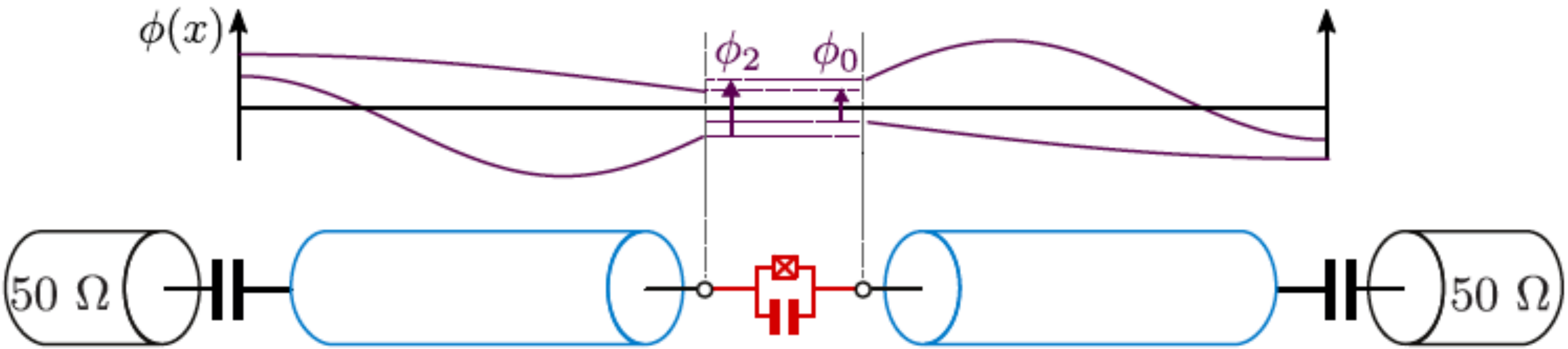
Implementation

calculate the normal modes

$$E_J^* = E_J e^{-\langle \phi(E_J*)^2 \rangle/2} \quad \text{with} \quad \langle \phi^2 \rangle = \sum_k^M \phi_k^2$$

$$\omega_{J,th}^* = \sqrt{2E_J^* E_c}$$

Modelling: Self-Consistent Harmonic Approximation



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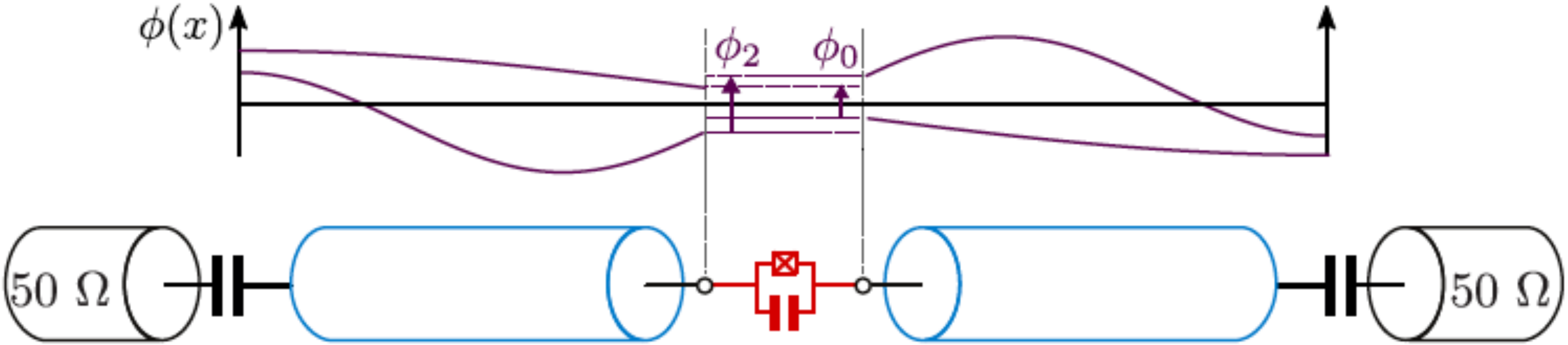
$\omega^*_{\mathrm{J,th}}/2\pi$	7.4 +/- 0.4 GHz	9.6 +/- 0.3 GHz	9.6 +/- 0.4 GHz

Modelling: Self-Consistent Harmonic Approximation



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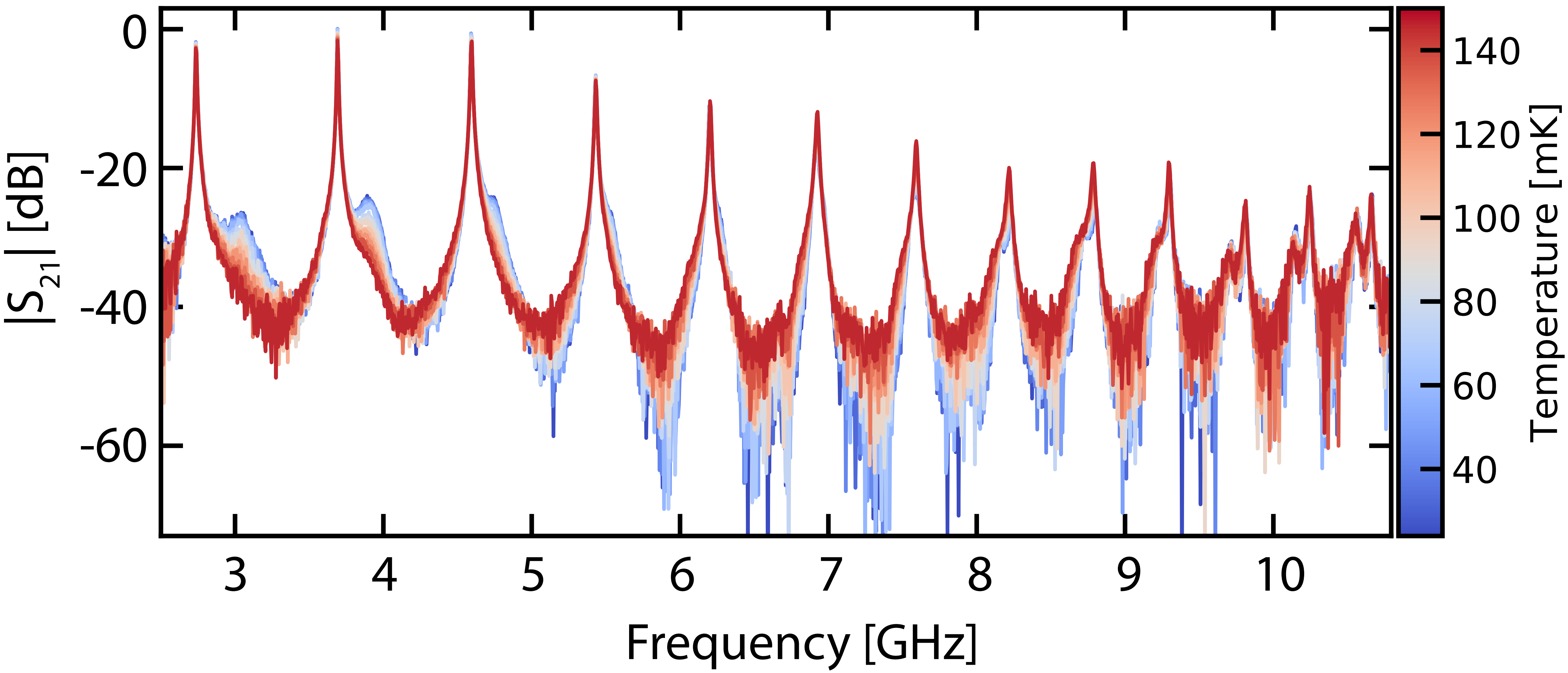
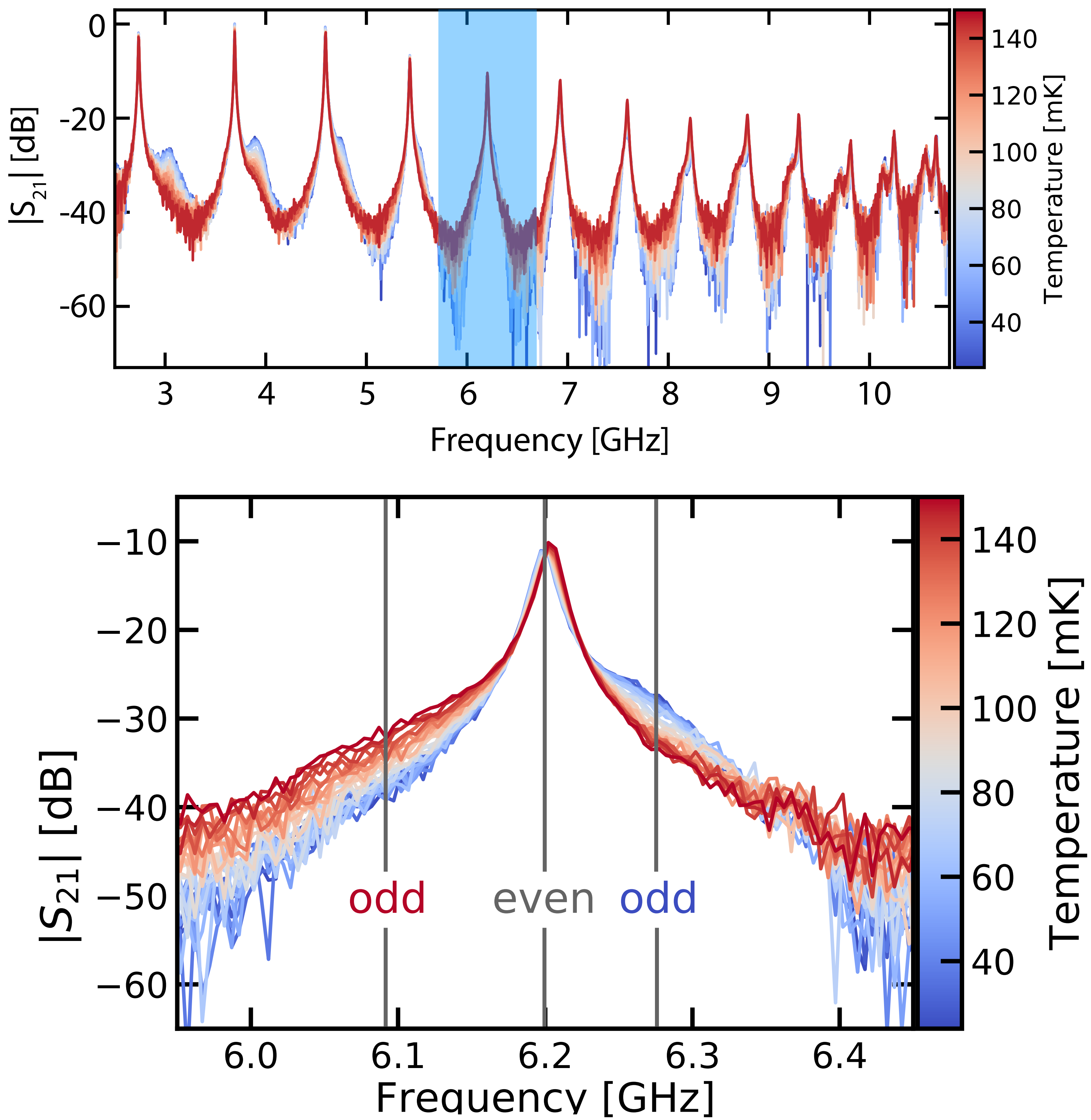
Is this quantum?

ZPF versus temperature

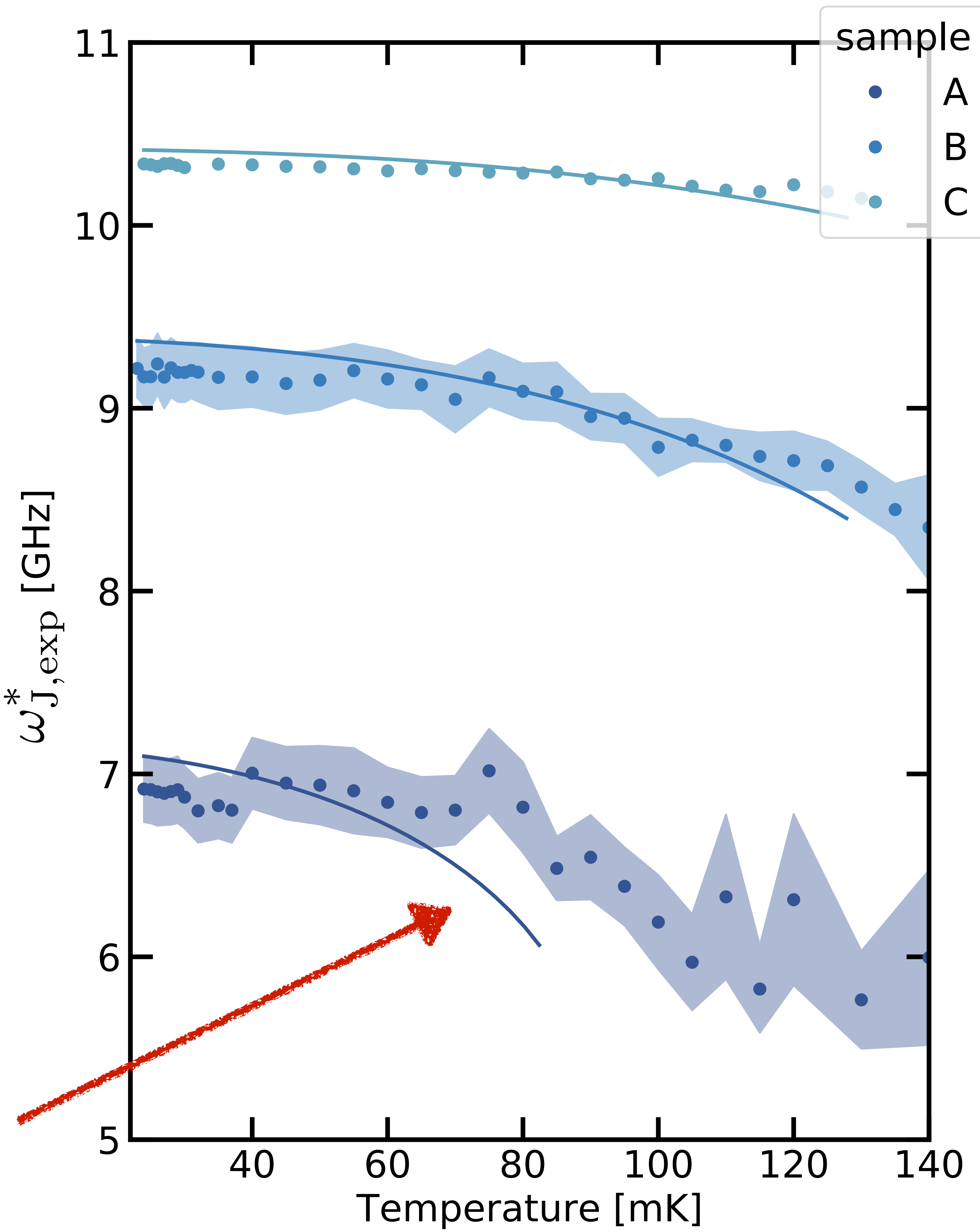


Influence of the small JJ on the environment



→ Strong back-action of the impurity on the environment

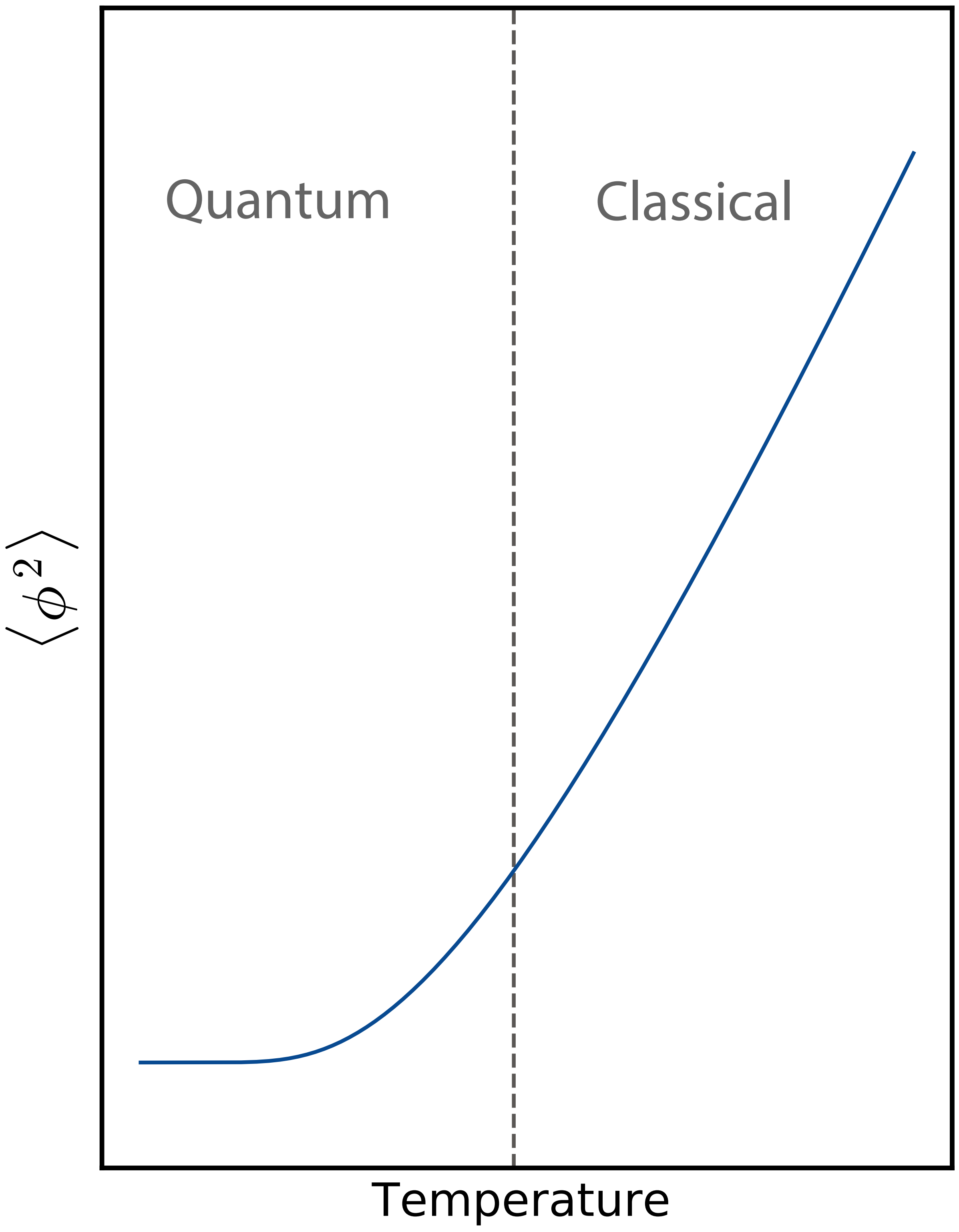
ZPF versus temperature



Deviation:
SCHA
breakdown

$\langle \phi^2 \rangle \simeq \pi^2$

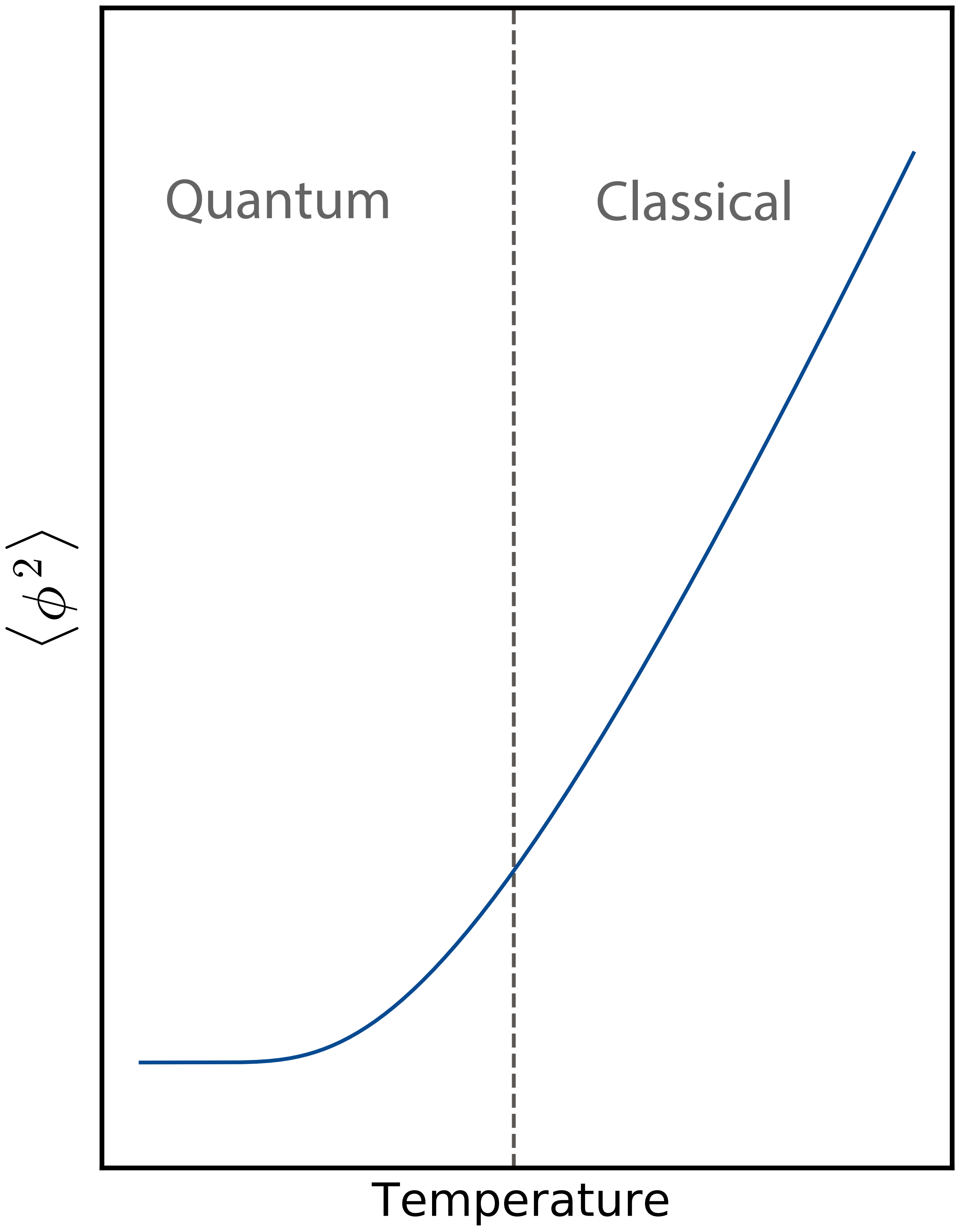
ZPF versus temperature

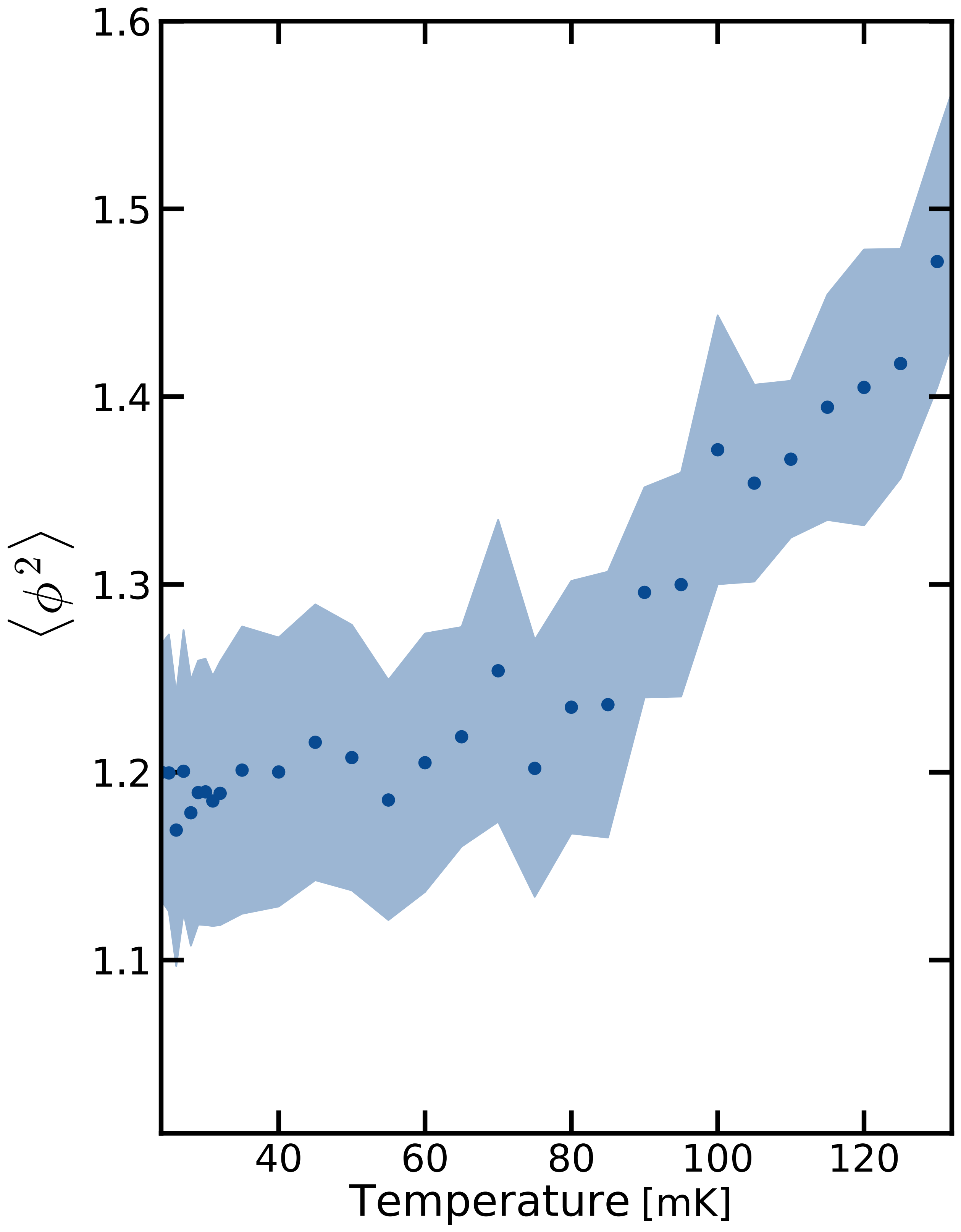


$$\omega^*_{\mathrm{J,th}} = \sqrt{2E^*_{\mathrm{J}} E_{\mathrm{c}}}$$

$$\langle \phi^2 \rangle = 4 \ln \left(\frac{\omega_{\mathrm{J,bare}}}{\omega^*_{\mathrm{J}}} \right)$$

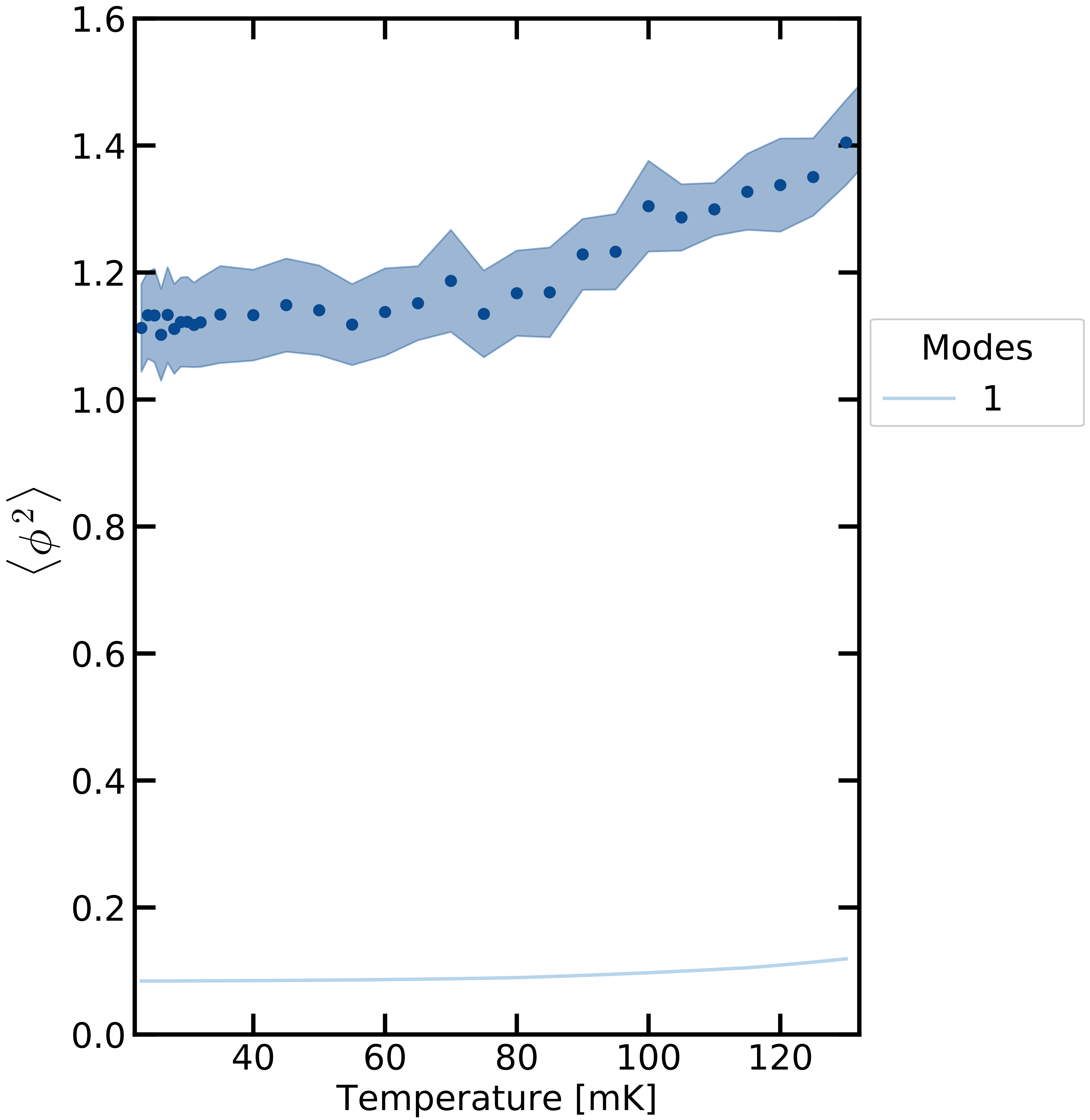
ZPF versus temperature



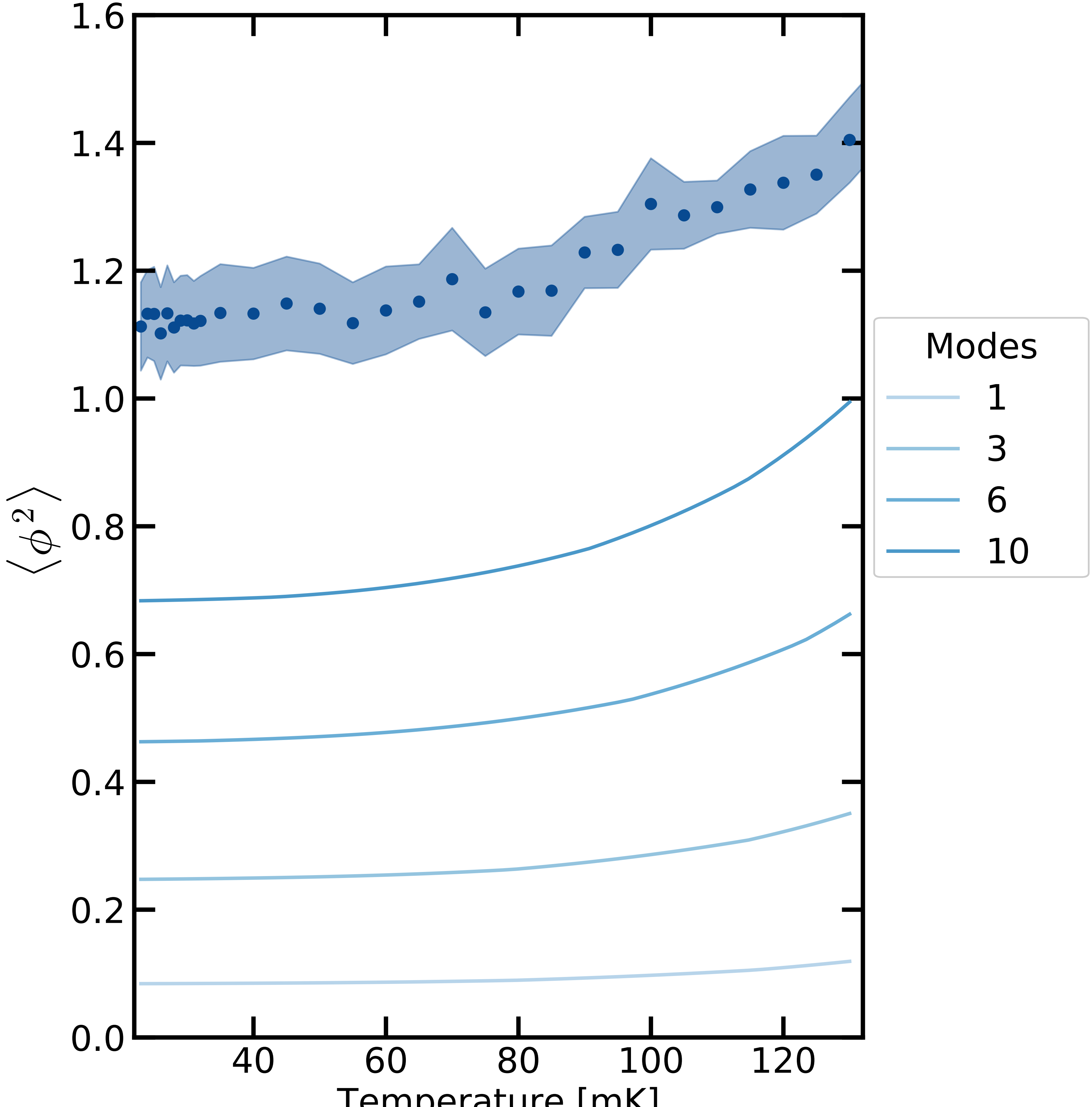


What about the many-body nature ?

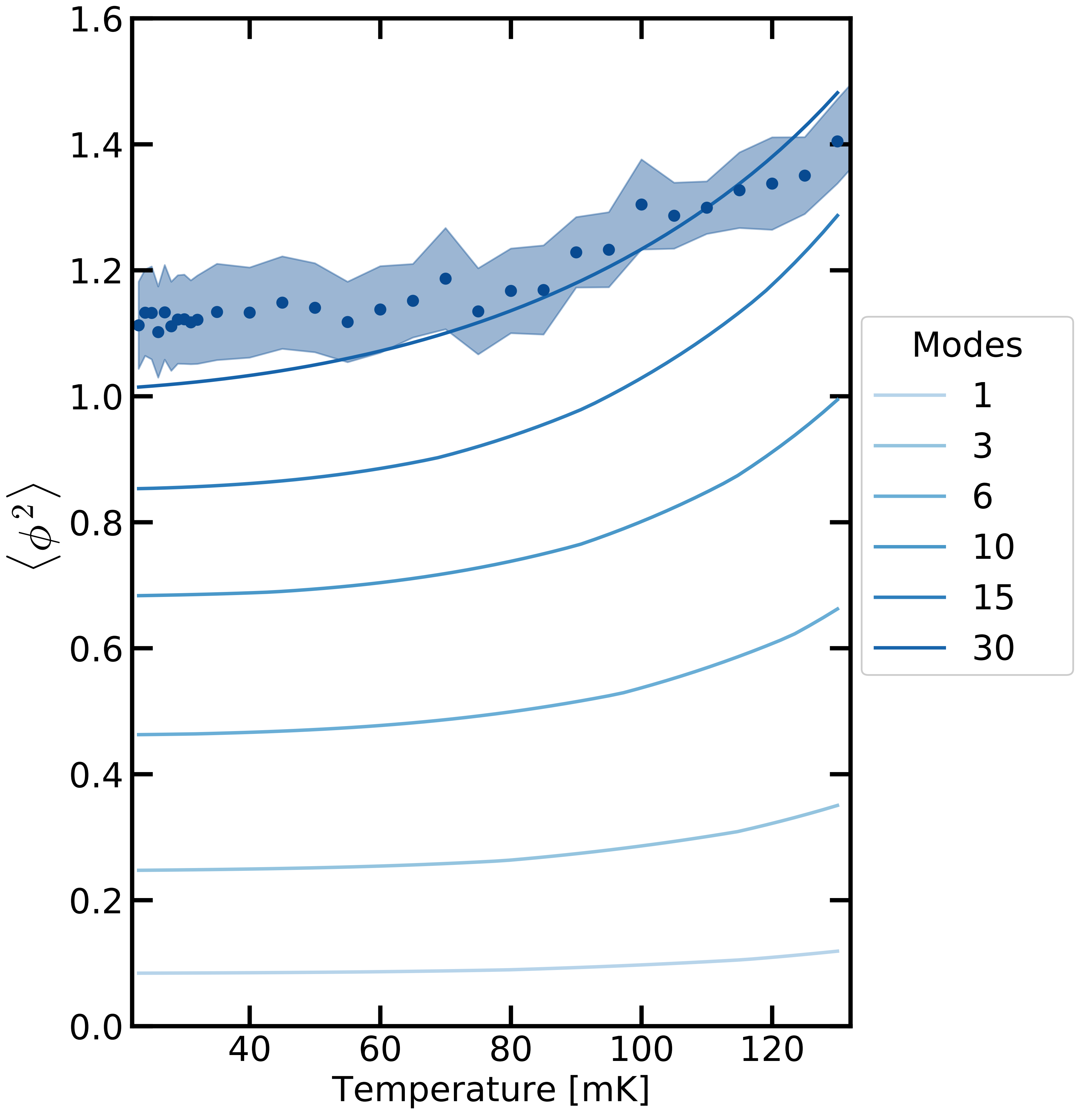
Many-body problem



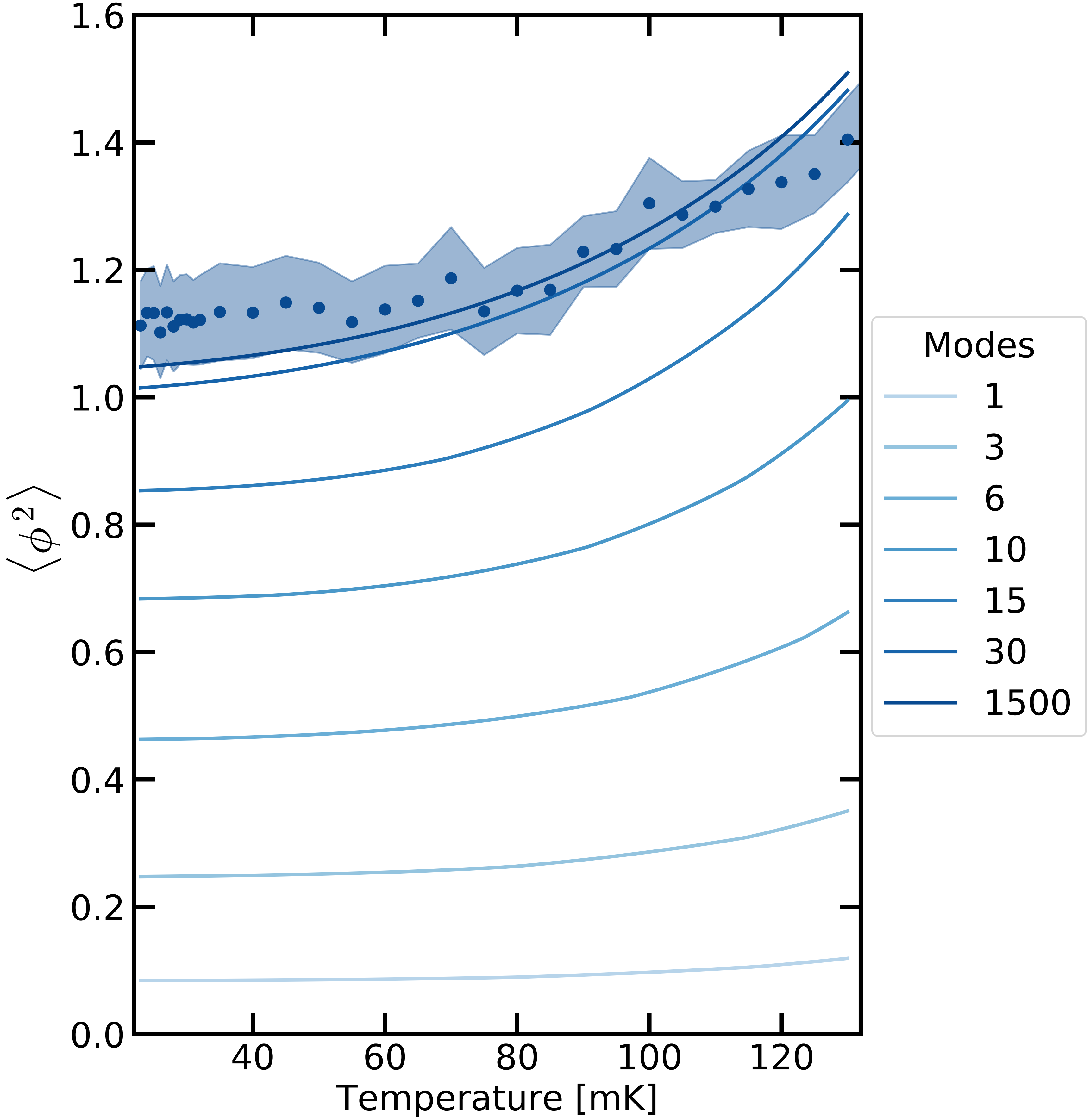
Many-body problem



Many-body problem



Many-body problem



Conclusion and Perspectives

A Josephson platform for many-body quantum optics

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

J. Puertas-Martinez et al., npjQI (2019)

(See also R. Kuzmin et al., npjQI (2019))

Effect of Many-body ZPF: Lamb shift cousin (> 30%) and back-action of the impurity on the bath

S. Leger et al., in prep

Quantitative understanding using a variational ansatz

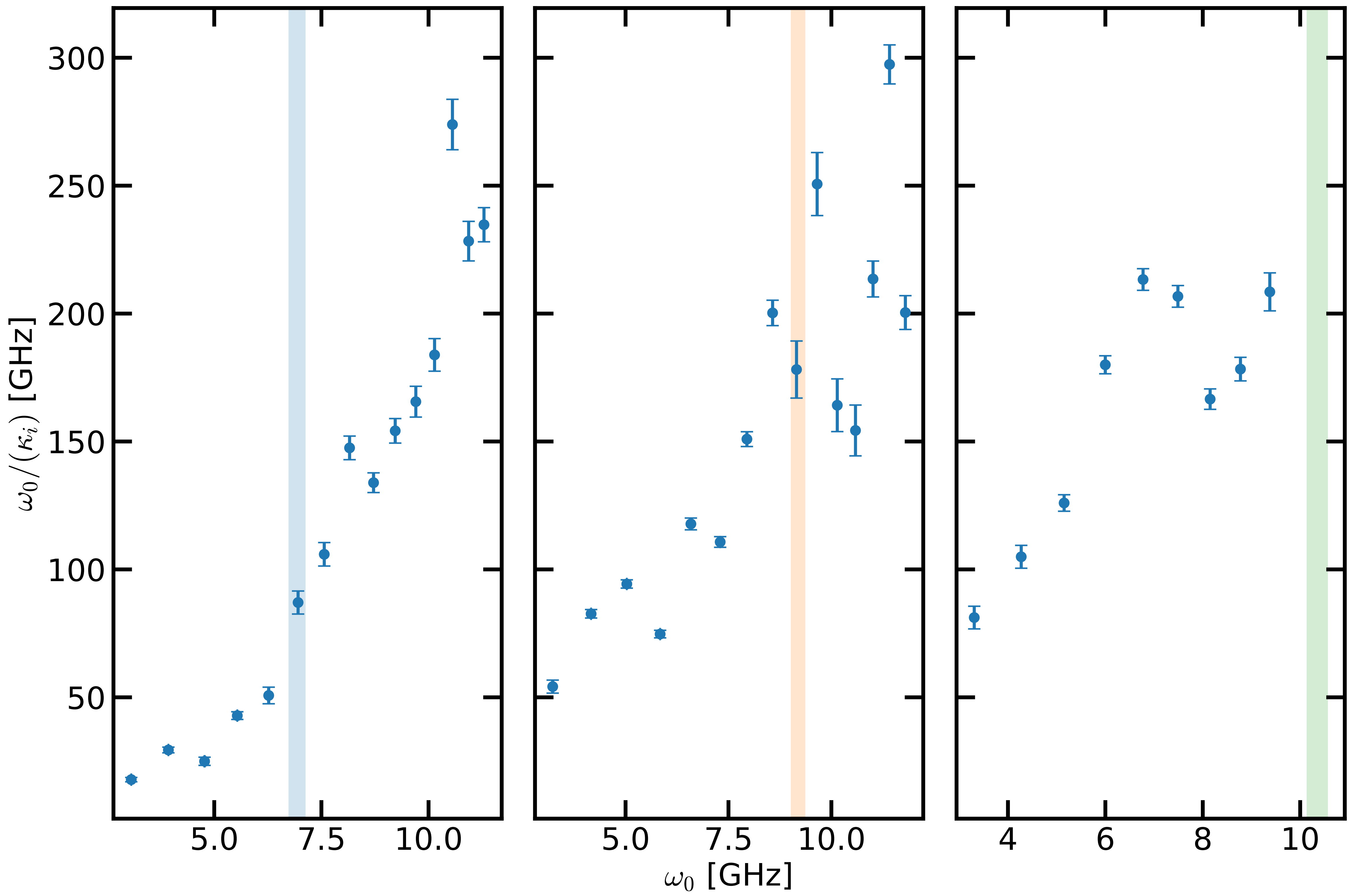
Non-linearity induced on the bath modes

Losses of the odd modes

Coherent manipulation of a many-body system

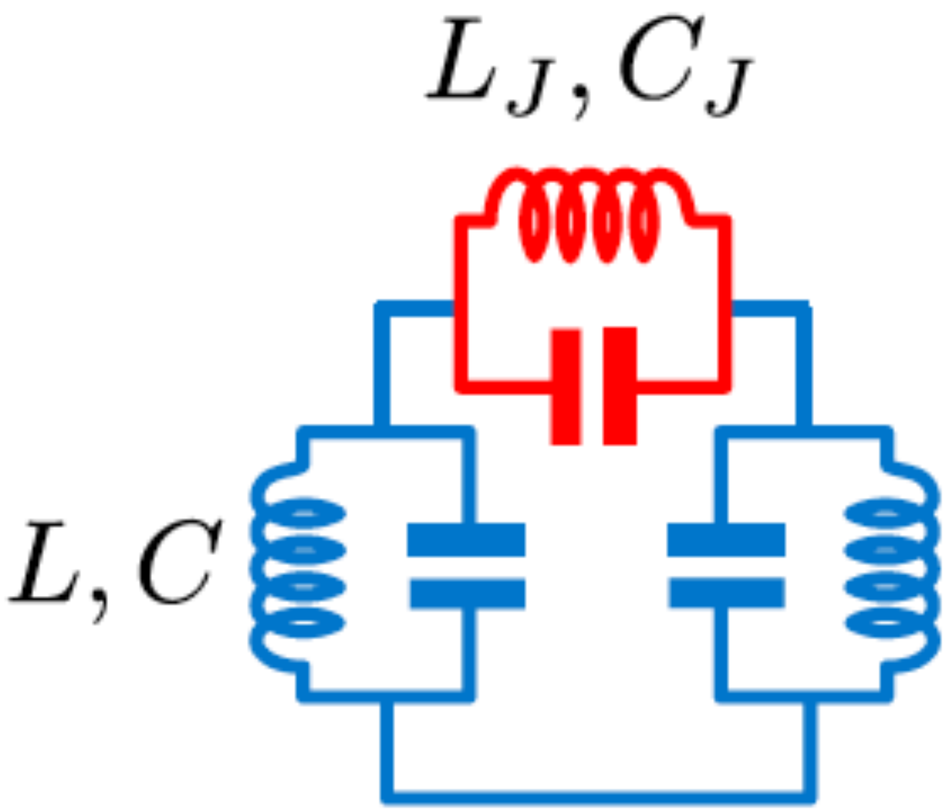
Thank you!

Quantum Engineering
Univ. Grenoble Alpes



300
250
200
150
100
50
$\omega_0/\langle\kappa_i\rangle$ [GHz]
5.0
7.5
10.0
5.0
7.5
10.0
ω_0 [GHz]
4
6
8
10

Extracting ω_J^*



Odd and Even modes :

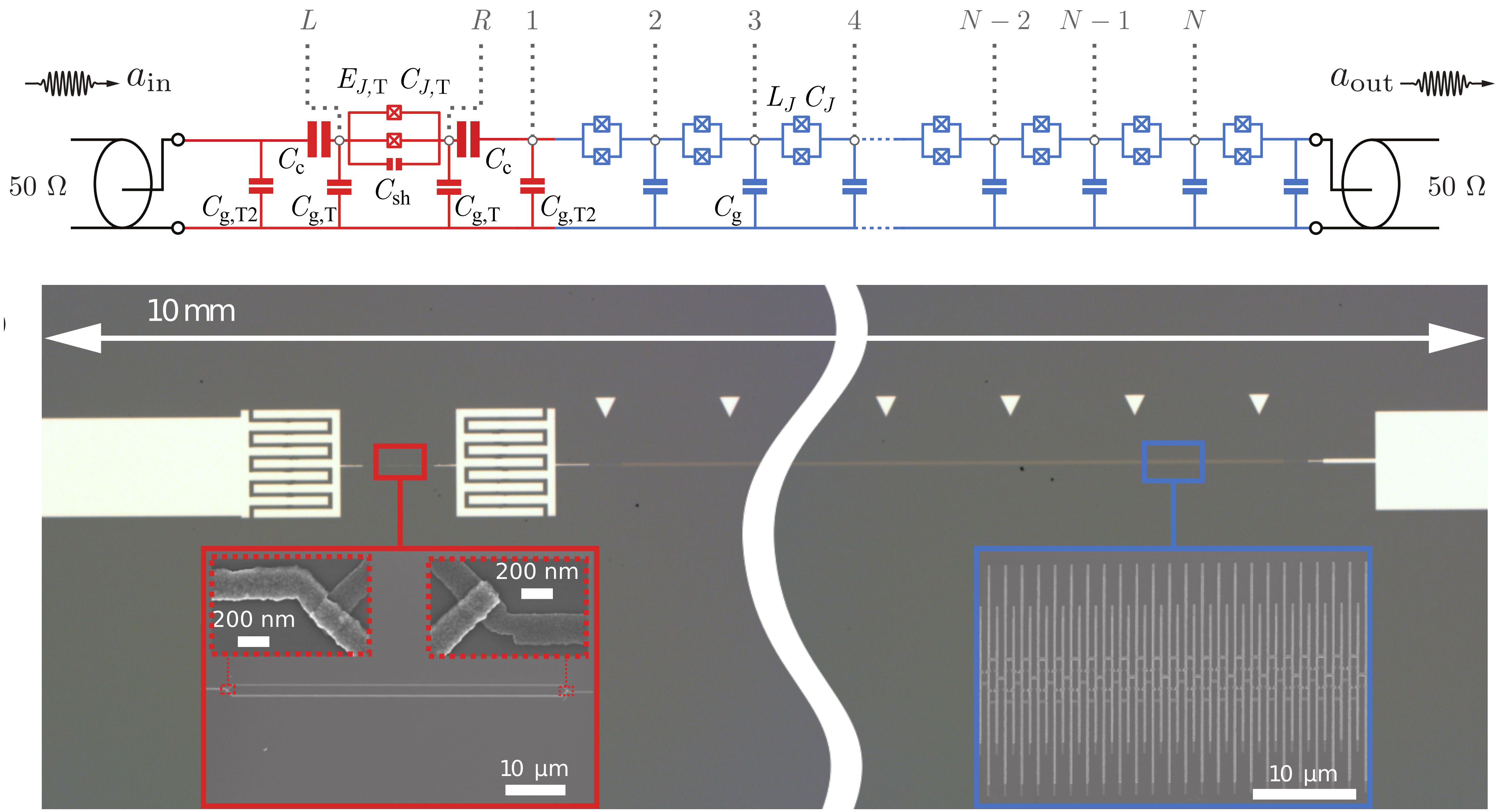
$$\omega_e = \frac{1}{\sqrt{LC}} \qquad \omega_o = \frac{1}{\sqrt{L_\Sigma C_\Sigma}}$$

$$\frac{1}{L_\Sigma} = \frac{1}{2L} + \frac{1}{L_J}$$

$$C_\Sigma = \frac{C}{2} + C_J$$

$\omega \ll \omega_J$	$\omega \gg \omega_J$	$\omega \sim \omega_J$
$\updownarrow$	$\updownarrow$	$\updownarrow$
$\omega_e < \omega_o$	$\omega_e > \omega_o$	$\omega_e \sim \omega_o$

Recent work: qubit coupled to high-impedance meta-materials

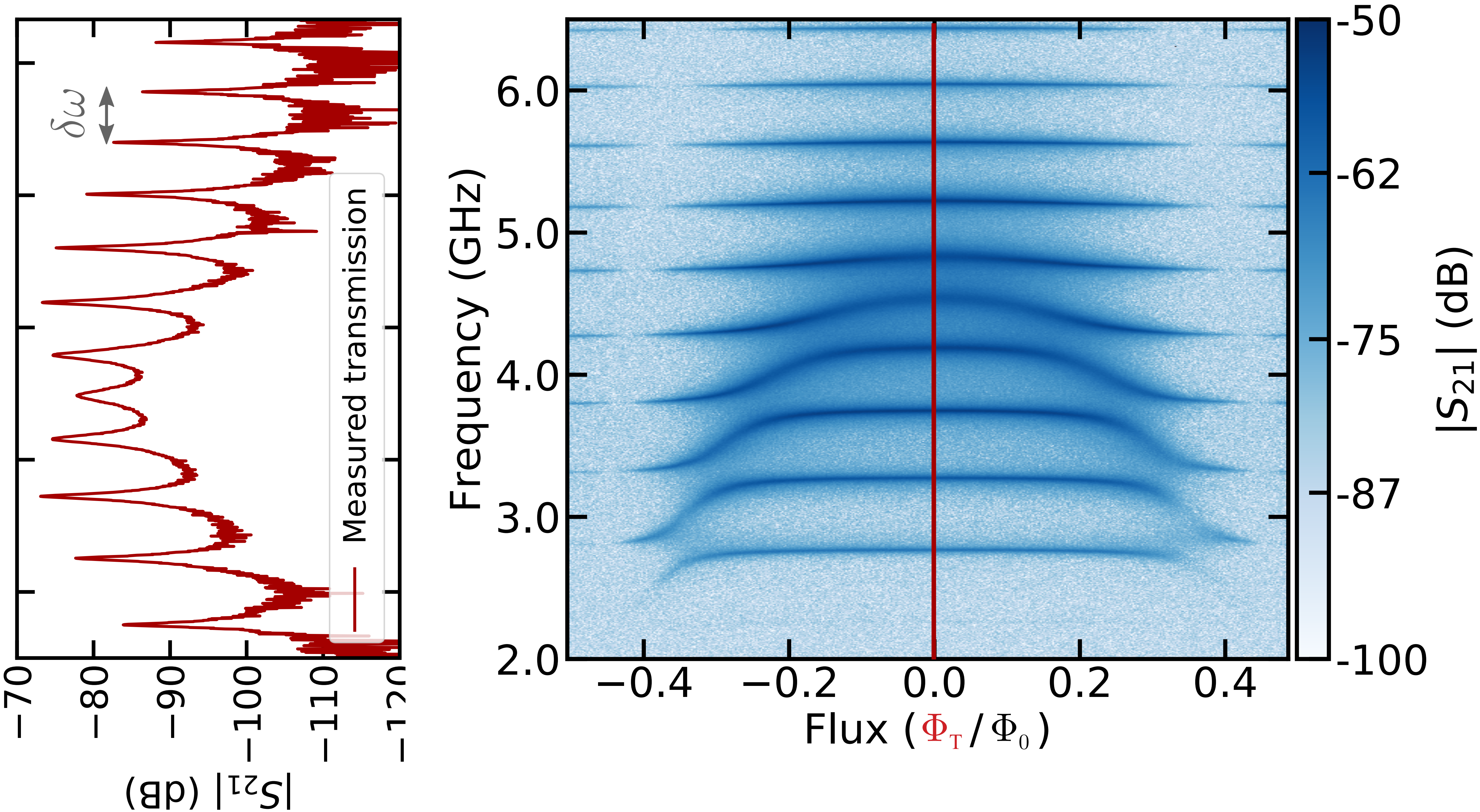


J. Puertas-Martinez et al.,
npj Quantum Information (2019)

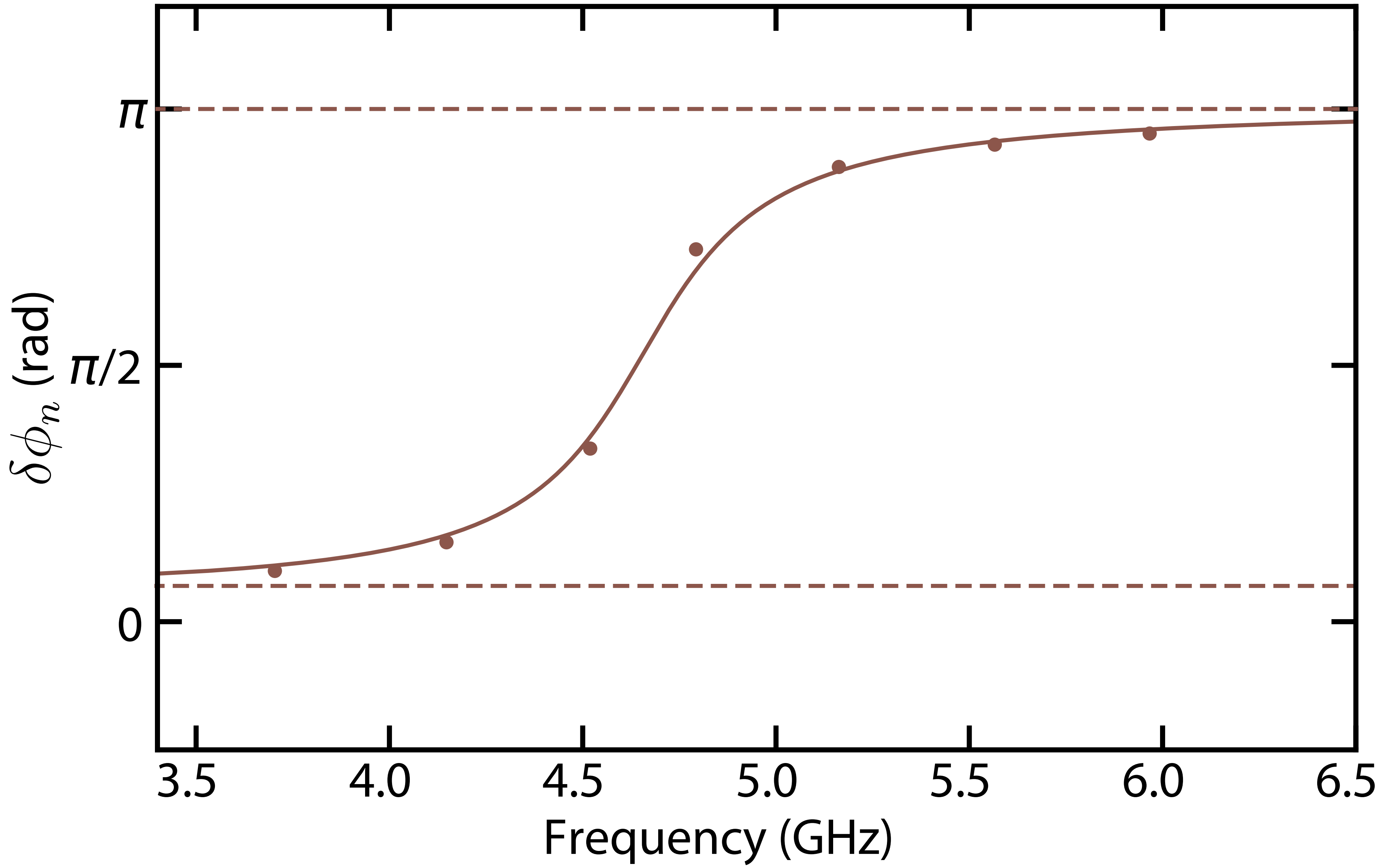
University of Maryland (Manucharyan group)

R. Kuzmin et al.,
npj Quantum Information (2019)

A Transmon coupled to a JJ meta-material



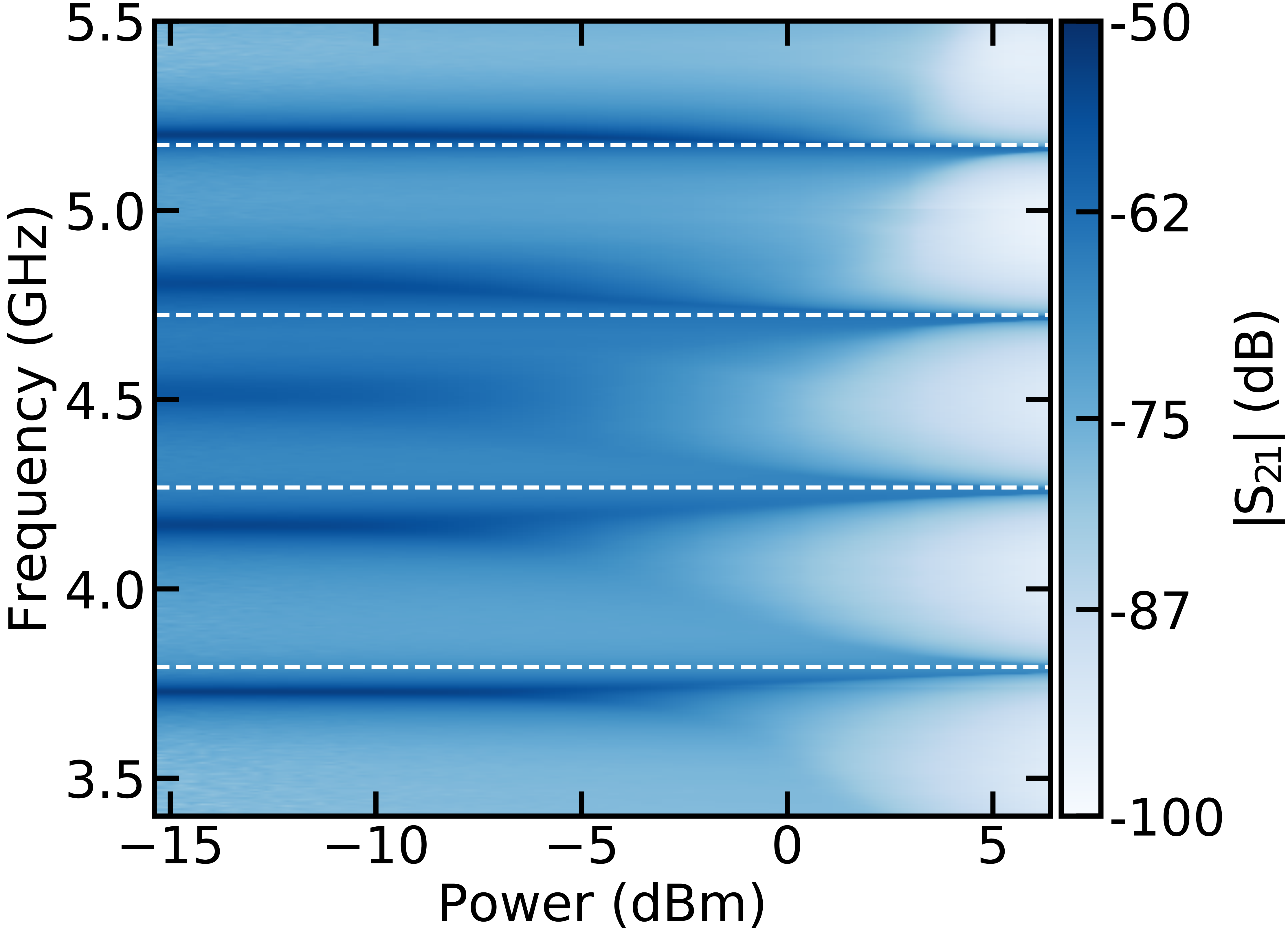
A Transmon coupled to a JJ meta-material



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



	E_c	E_J (from R_N)	E_J (from fit)	Z_c
Sample 0	14.1 GHz	3.77 +/- 0.25 GHz	3.50 +/- 0.02 GHz	1.87 kOhms
Sample 1	13.4 GHz	5.76 +/- 0.29 GHz	5.49 +/- 0.02 GHz	1.77 kOhms
Sample 2	10.2 GHz	6.84 +/- 0.49 GHz	7.78 +/- 0.005 GHz	1.84 kOhms