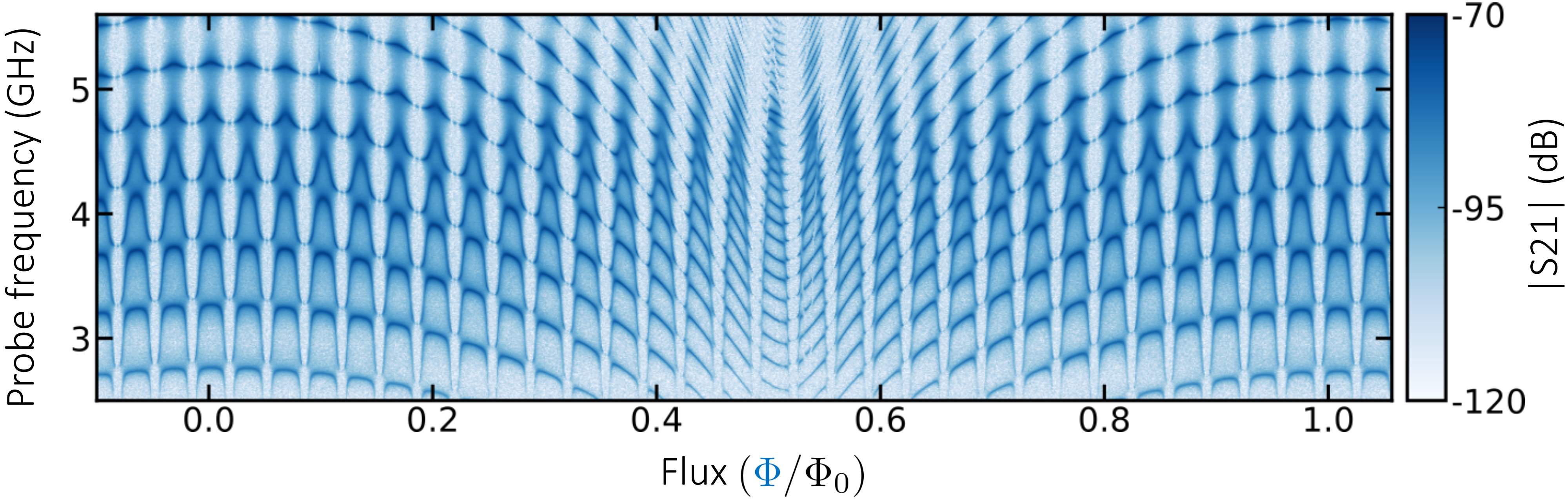
Open quantum systems in Circuit-QED: Monitoring the bath

Javier Puertas Martínez Néel Institute, Grenoble (France)



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Superconducting quantum circuits team

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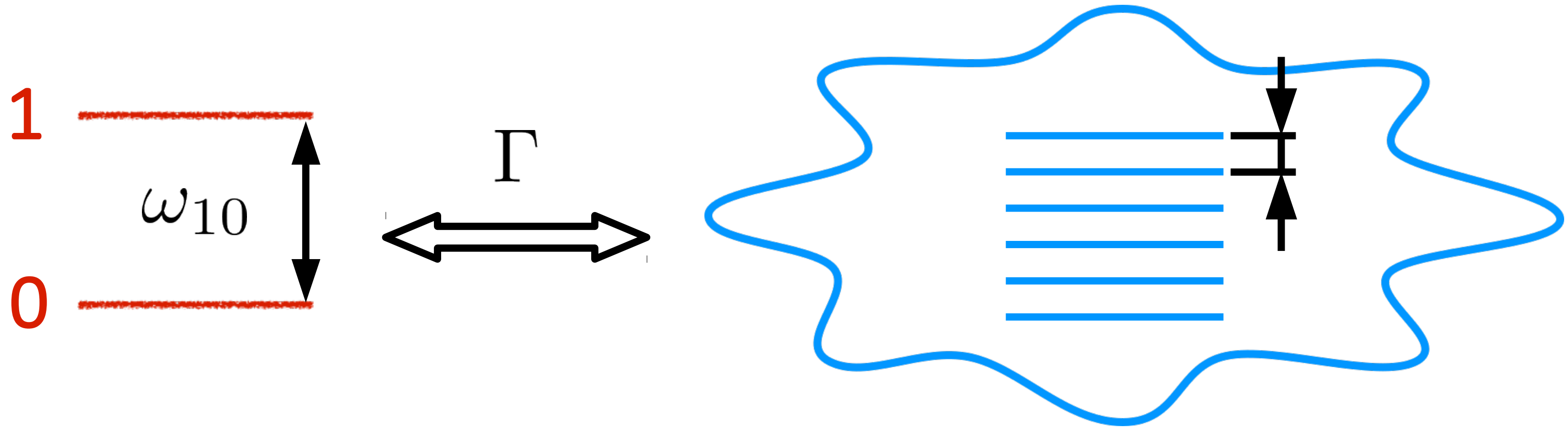
Izak Snyman (MITP)

Quantum system coupled to an environment

$$\mathrm{FSR} = \omega_n - \omega_{n-1}$$

(Free Spectral Range)



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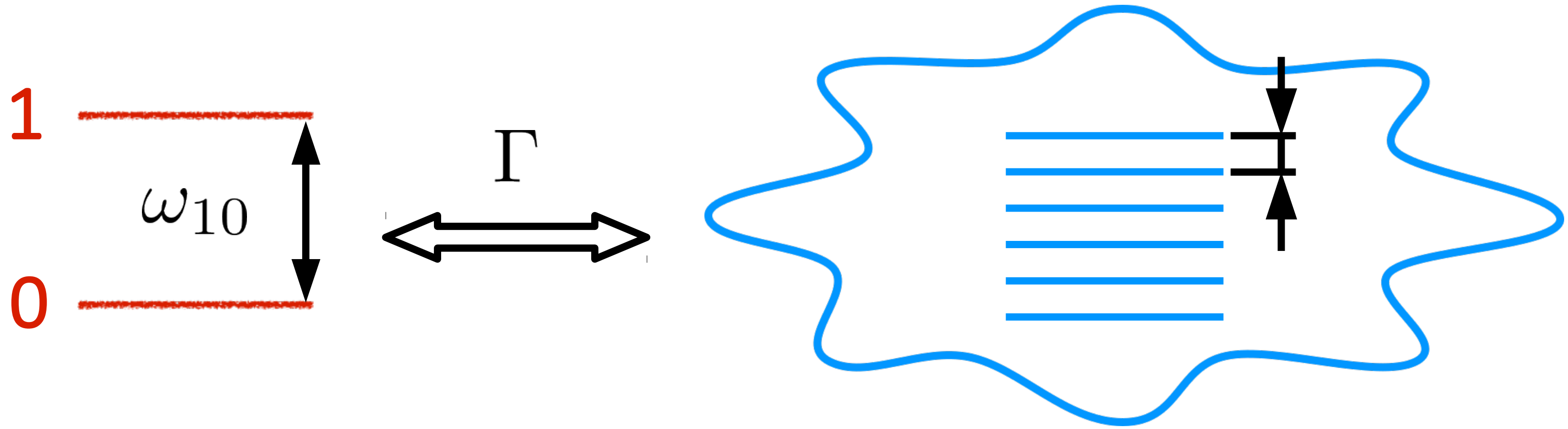
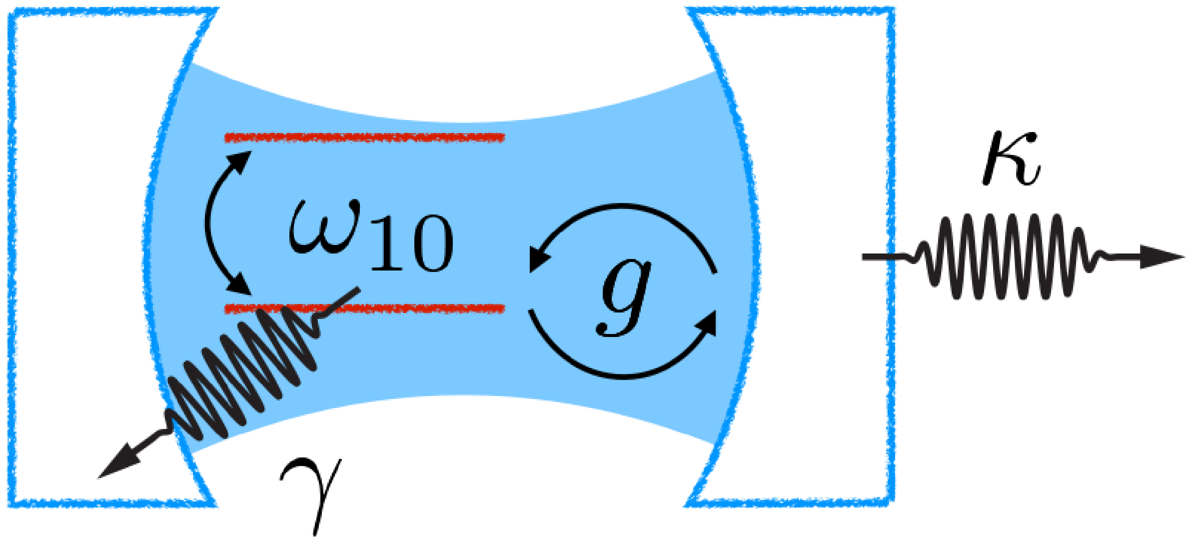


Non-trivial many-body system if

- The environment has many degrees of freedom
- System ultra-strongly coupled to the environment $\quad \Gamma \sim \omega_{10}$
- System fully hybridized with the environment $\quad \Gamma \sim \mathrm{FSR}$

Example: atom in a cavity



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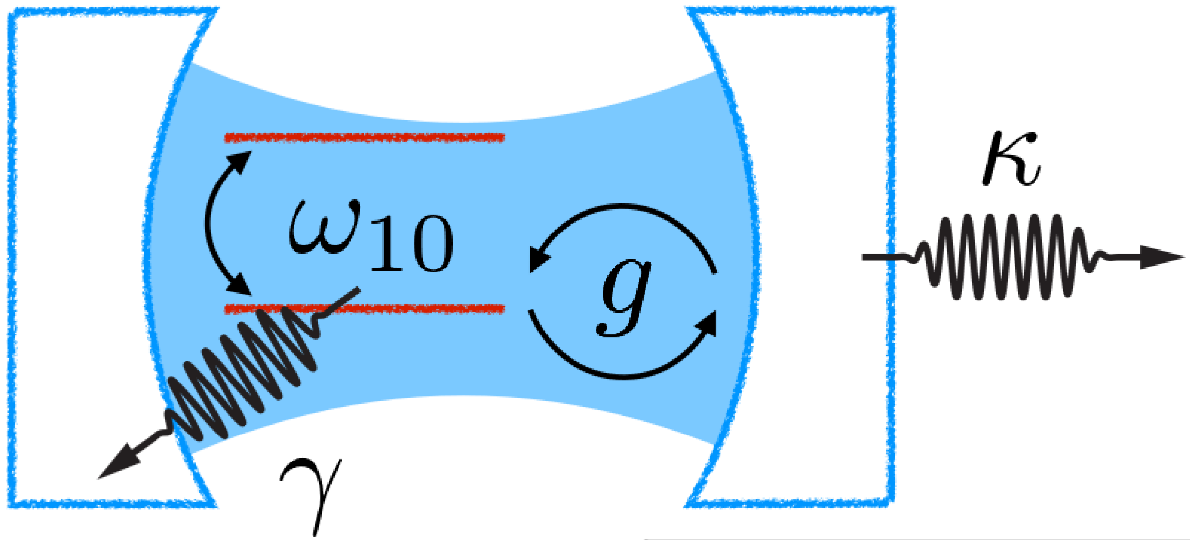
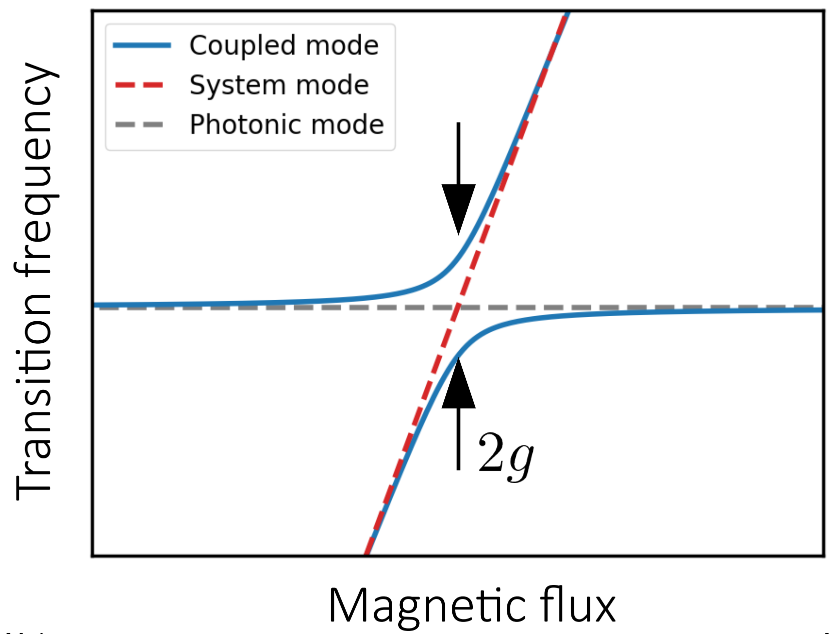


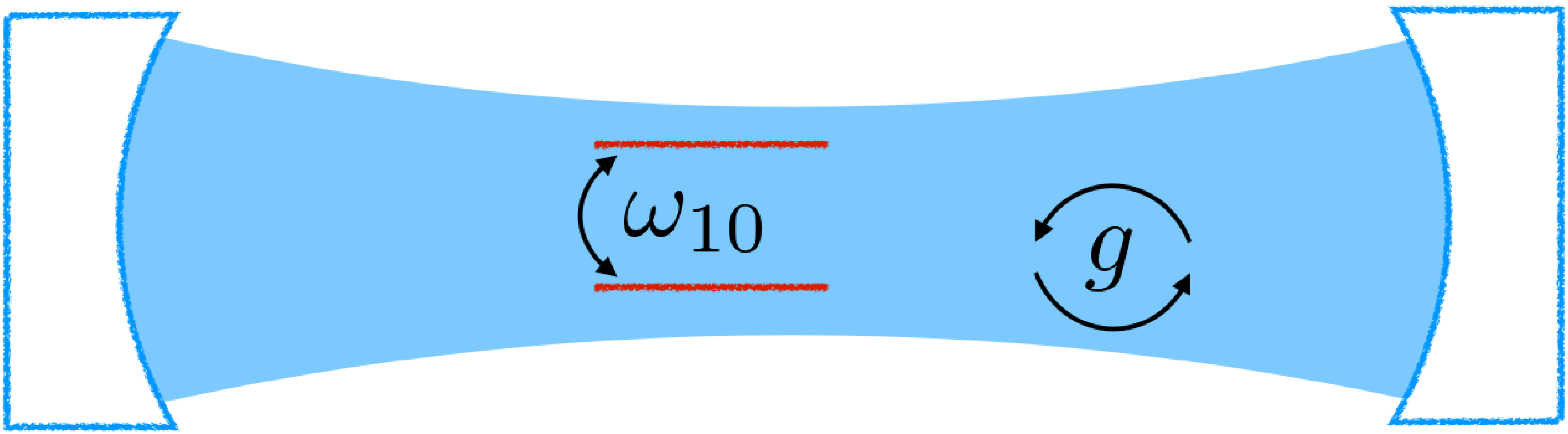
Strong coupling $g \gg \kappa, \gamma$

but $g \ll \omega_{10}$

Two-level system coupled to one photonic mode



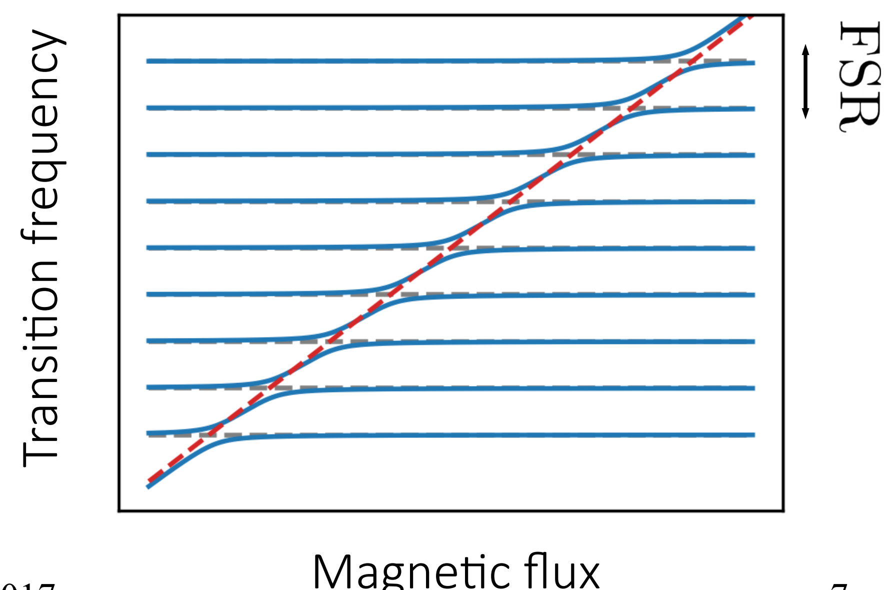
Example: atom in a large cavity



Several modes but $2g \ll \mathrm{FSR}$

$g \ll \omega_{10}$

Two-level system coupled to one photonic mode at once



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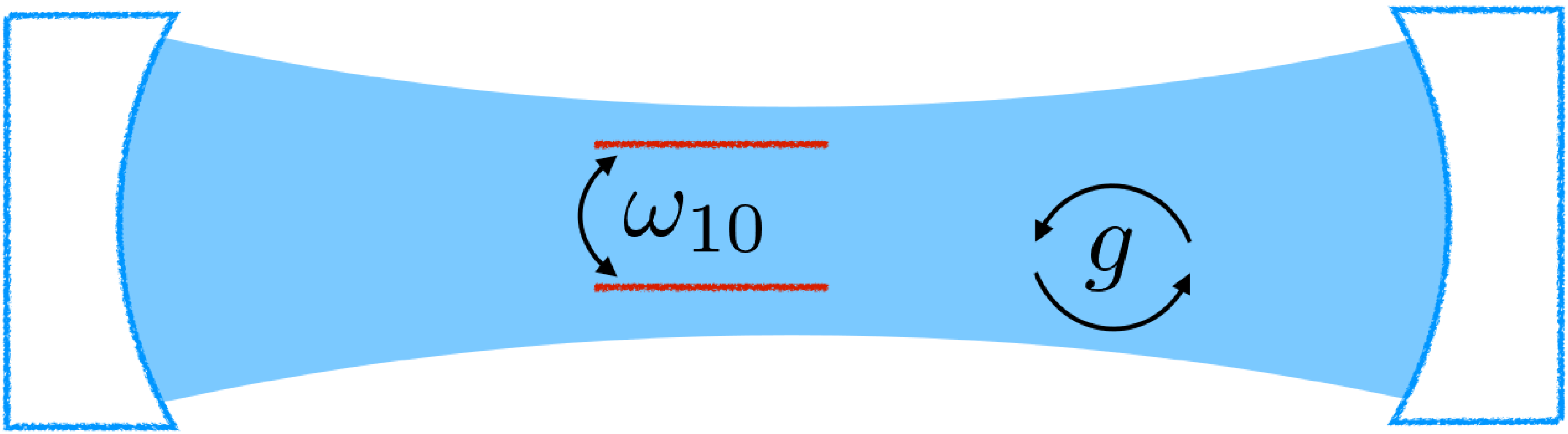
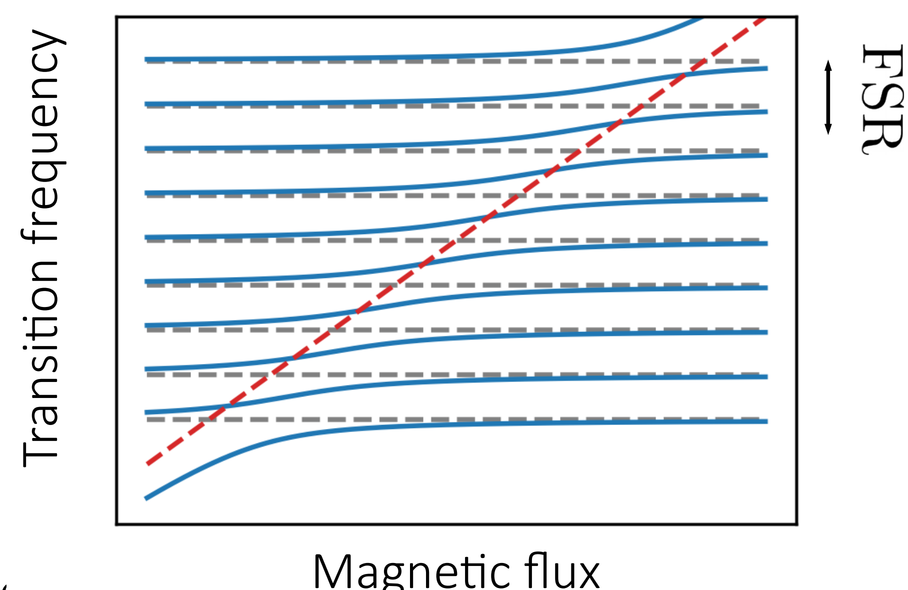


Several modes coupled $2g \sim \mathrm{FSR}$

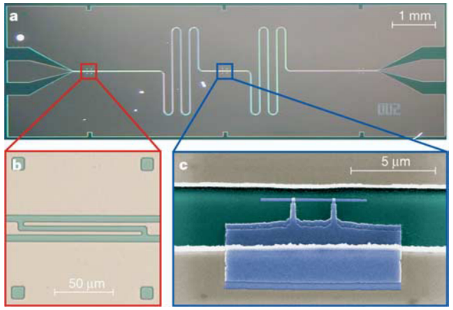
Ultrastrong coupling $g/\omega_{10} \sim 1$

At every point the system is entangled with several modes



How to get there?

Circuit QED: Superconducting circuits and microwave photons.



Circuits allow large system-environment coupling

- Strong coupling: A. Wallraff et al (2004)
- Ultra-strong coupling: T. Niemczyk et al (2010)
- Many-body ultra-strong coupling: P. Forn-Diaz et al (2017)

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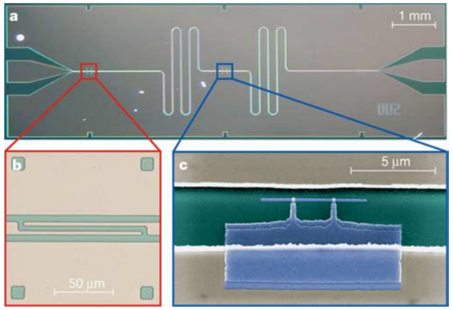


but also:

In situ tunability of the environment

Monitoring of the environment

Fully microscopic model from lumped elements

Outline

System-environment coupling in circuit QED

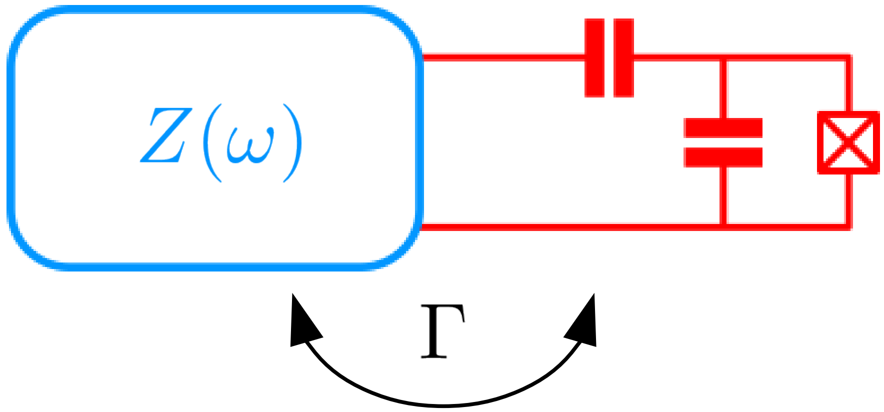
Tunable high impedance environment

Transmon qubit coupled to a JJ metamaterial

Monitoring the environment

Coupling between the system and the environment

Our system is a **transmon qubit**



$\Gamma \sim \omega_{10}$

Coupling between the system and the environment

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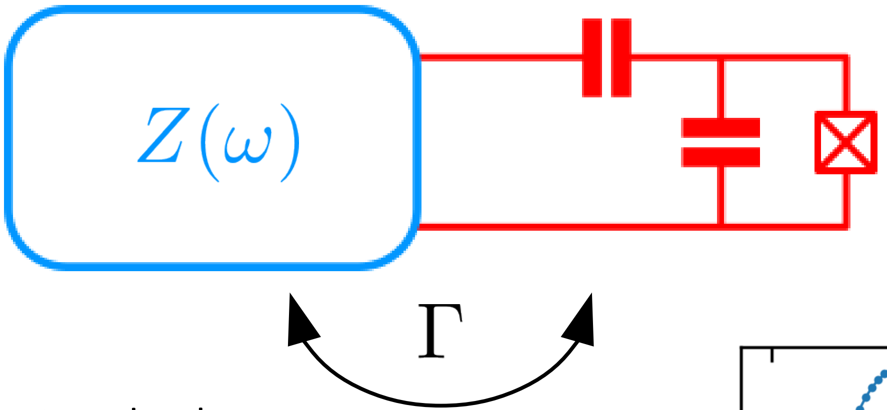
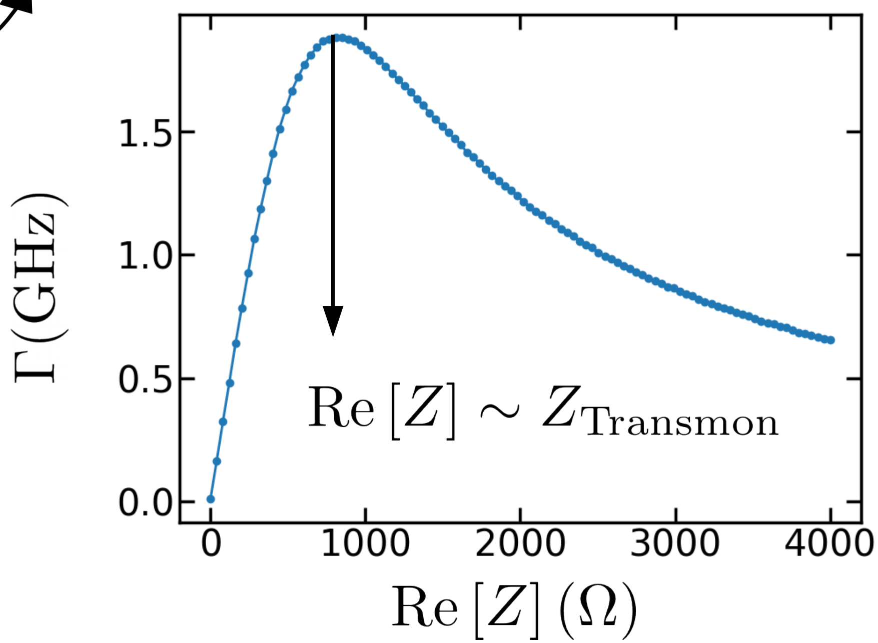


$$\Gamma \sim \omega_{10}$$

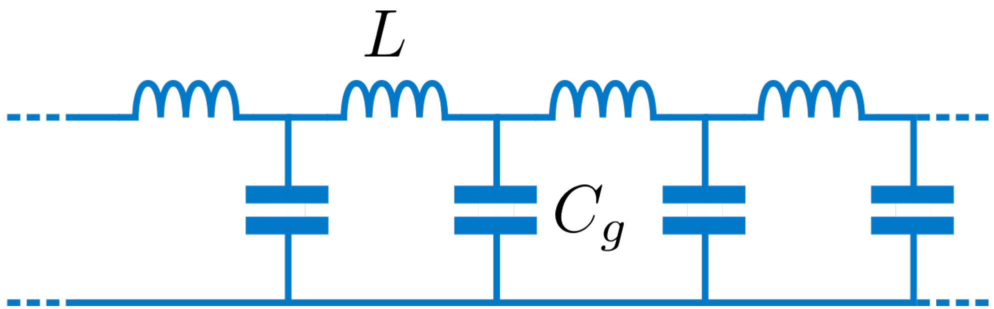
Largest coupling obtained when impedance matched to the environment

$$\mathrm{Re}\left[Z\right] \sim Z_{\mathrm{Transmon}} \sim \mathrm{k}\Omega$$

A high impedance environment is required



Tunable high impedance environment

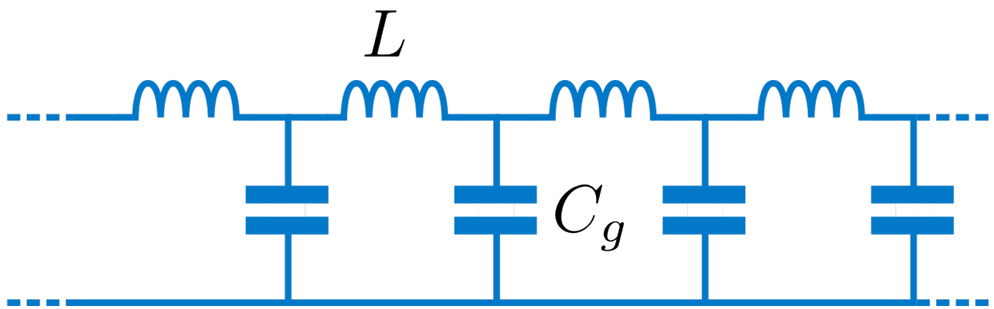


Standard transmission line

$$Z_0 = \sqrt{L/C_\mathrm{g}} = 50\,\Omega$$

Environment as an infinite number of harmonic oscillators

Tunable high impedance environment



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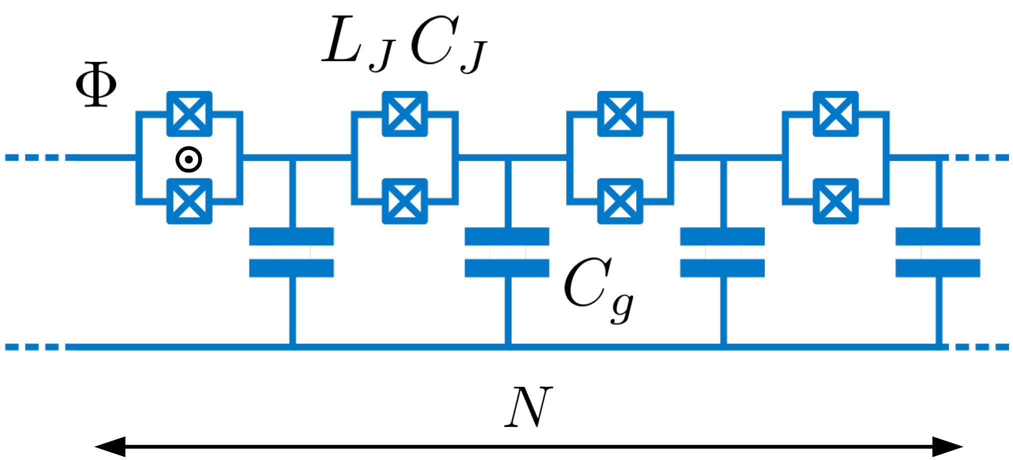


Array of N SQUIDs

$$Z_0(\Phi) = \sqrt{L_J(\Phi)/C_{\mathrm{g}}} \sim \mathrm{k}\Omega$$

In situ tunable environment

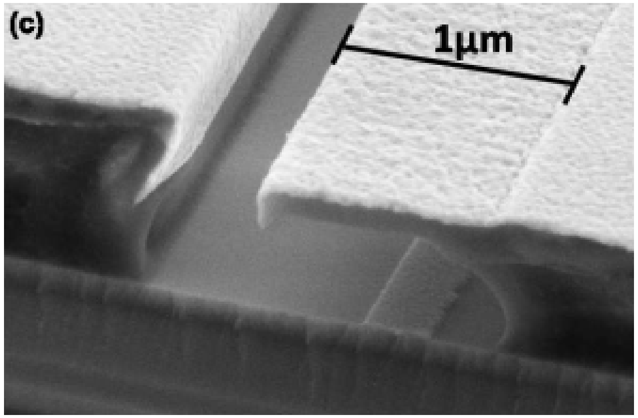
Great control on the environment parameters during fabrication.

Seminal work: S. Corlevi et al (2006)

See also: N. Masluk et al (2012) Bell et al (2012) C. Altimiras et al (2013)

Fabrication of the environment

Fabricating the environment: thousands of identical SQUIDs



Fabricated using the BFF technique

F. Lecocq et al (2011)

- No shadow pattern
- Allows cleaning of the substrate before evaporation

Fabrication of the environment

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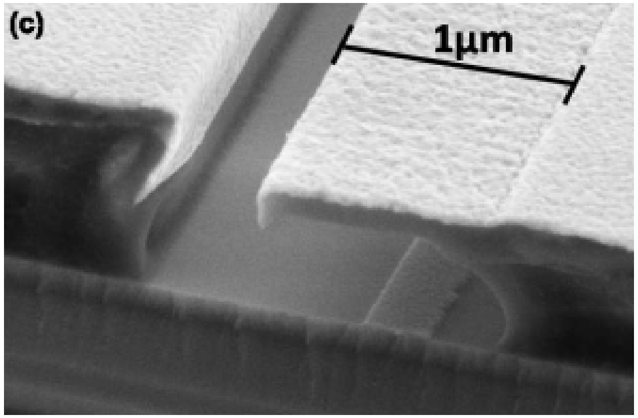

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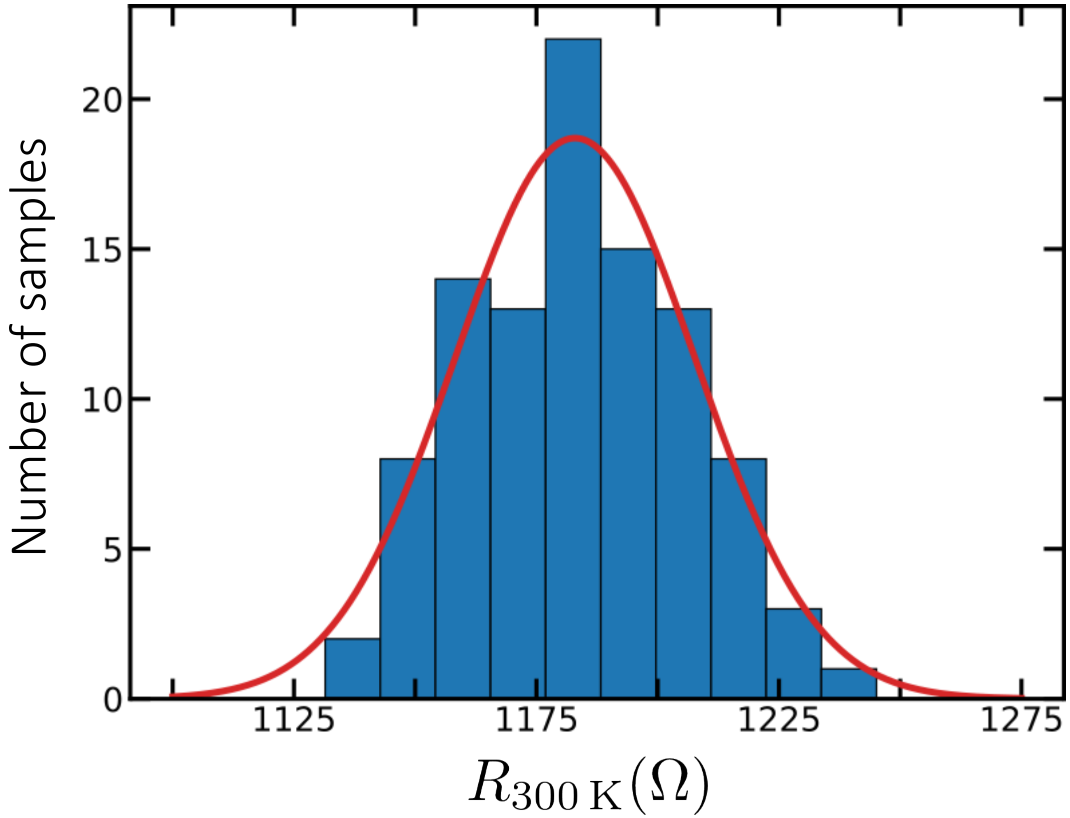
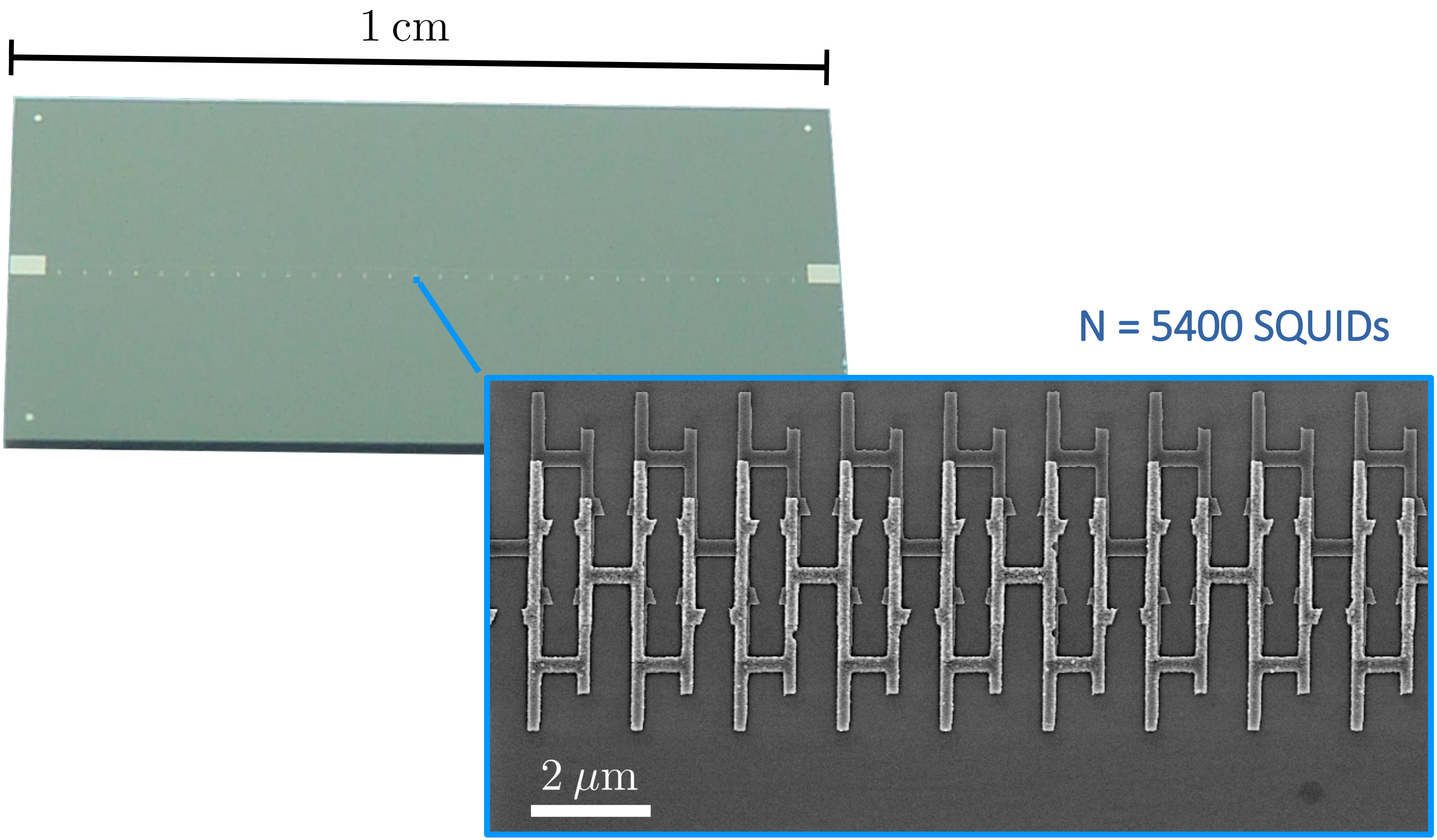


Mean $\mu = 1200\,\Omega$

Deviation $\sigma = 25\,\Omega$

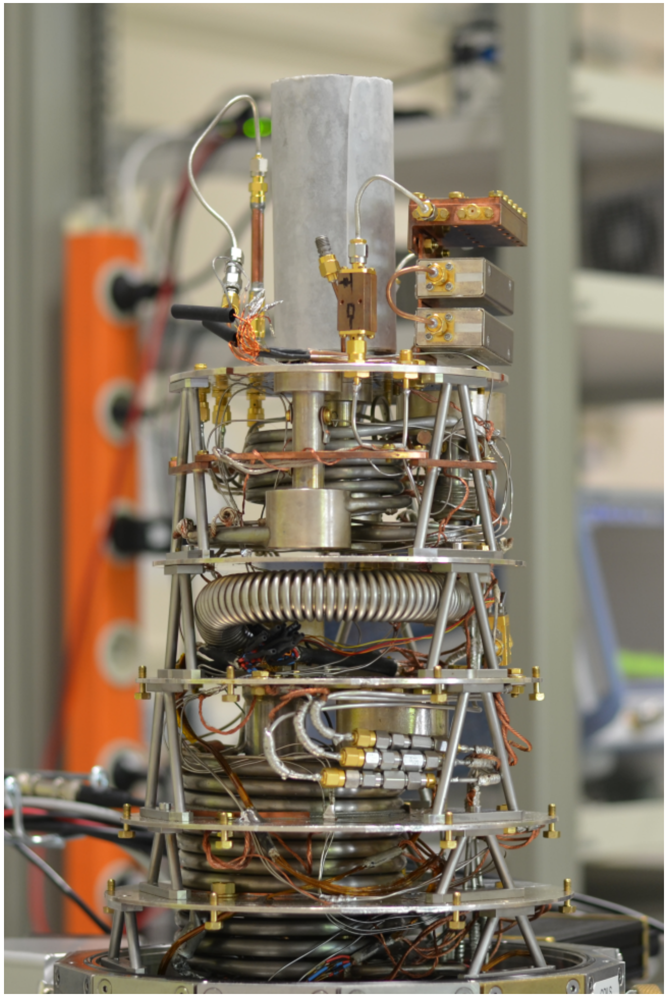
Very low disorder, around 2%

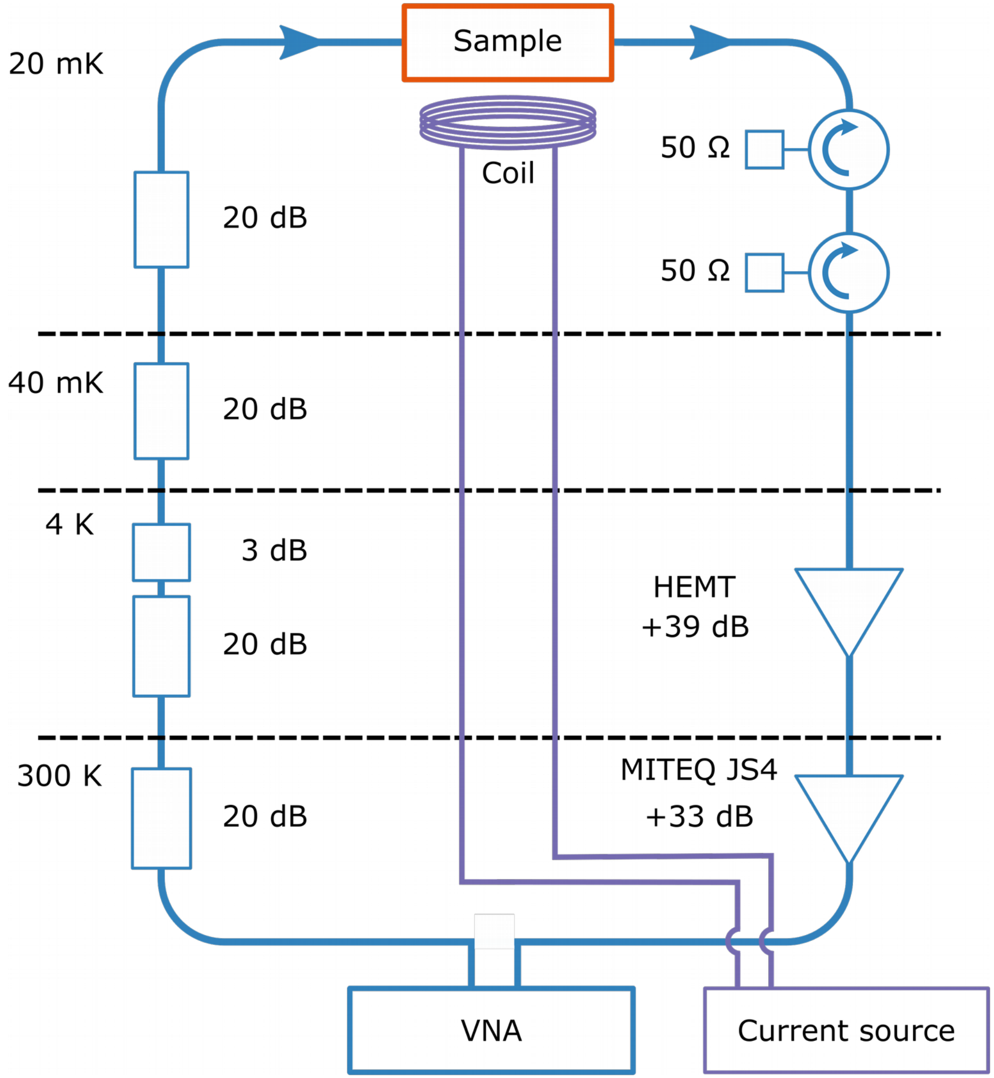
Fabrication of the environment



N = 5400 SQUIDs

Characterization of the environment





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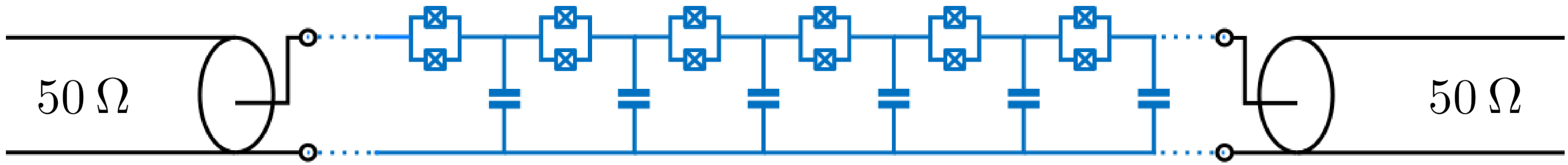
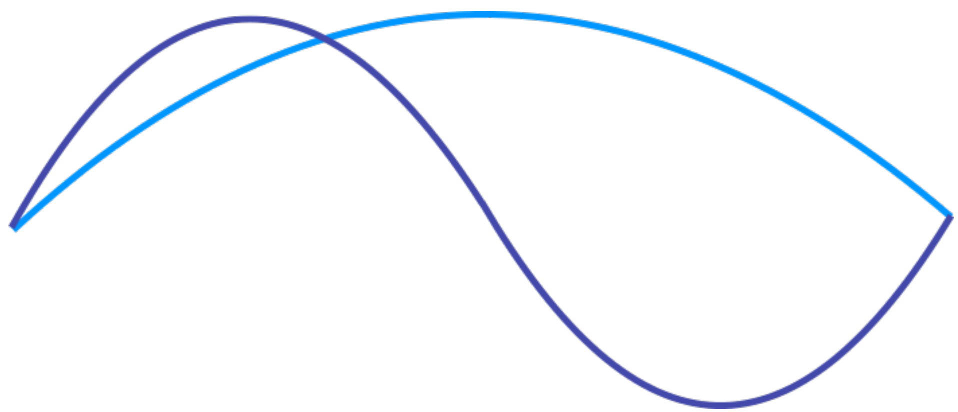


Fabry-Pérot cavity



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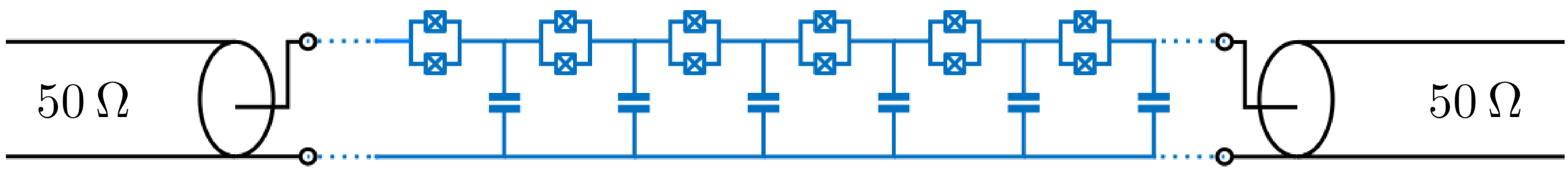

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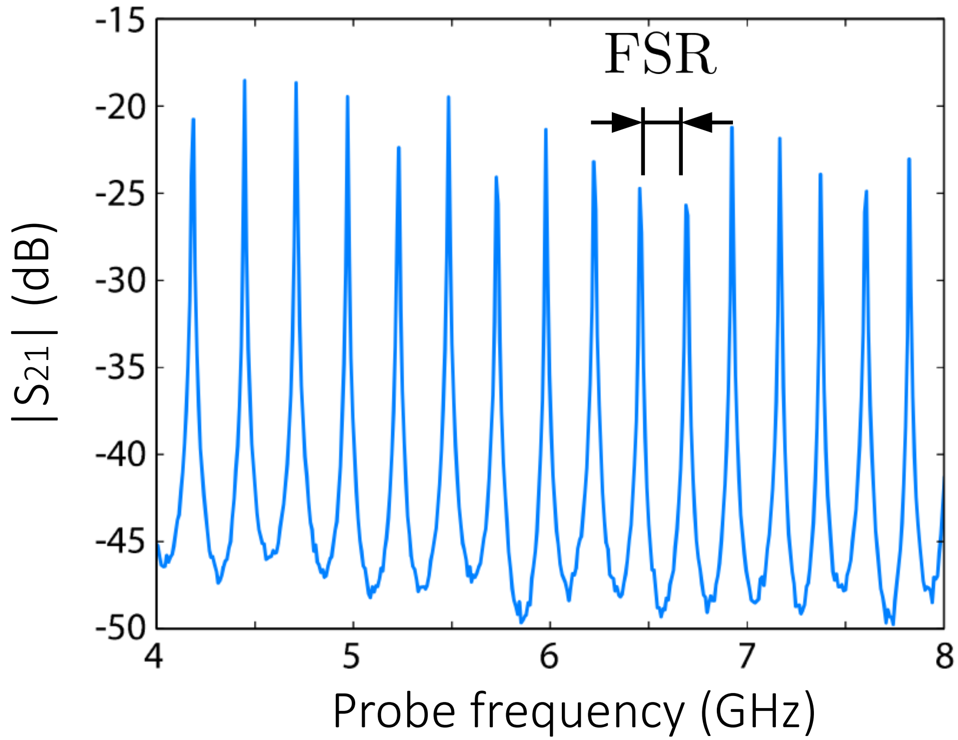


Free Spectral Range

$$\mathrm{FSR} = 300\,\mathrm{MHz}$$

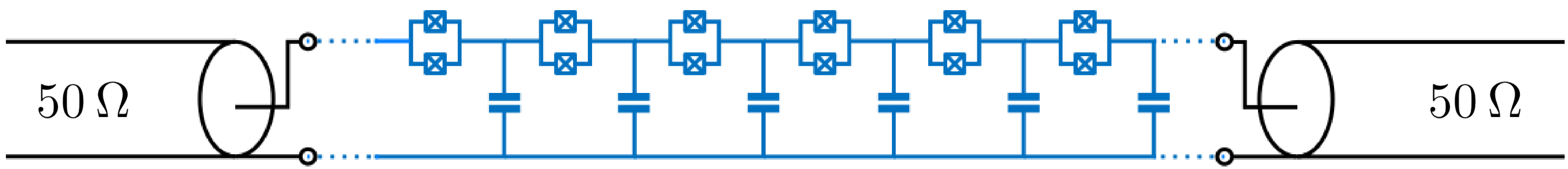
Internal losses

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

Impedance mismatch

$$Q_{\mathrm{ext}} = 10^2$$

Characterization of the environment



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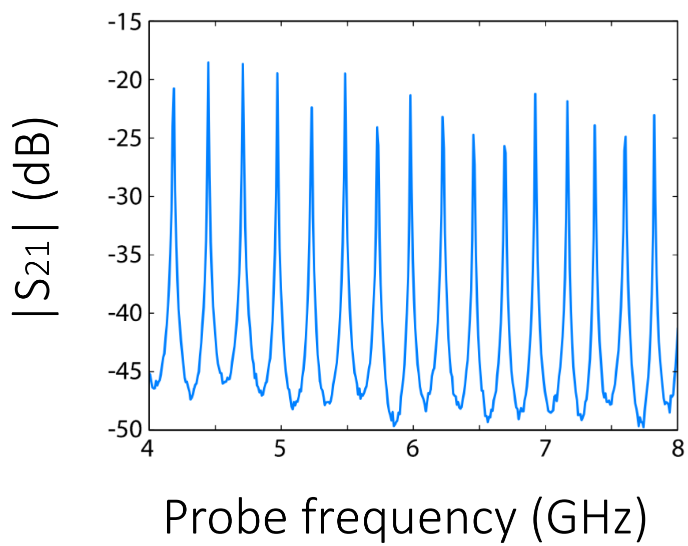

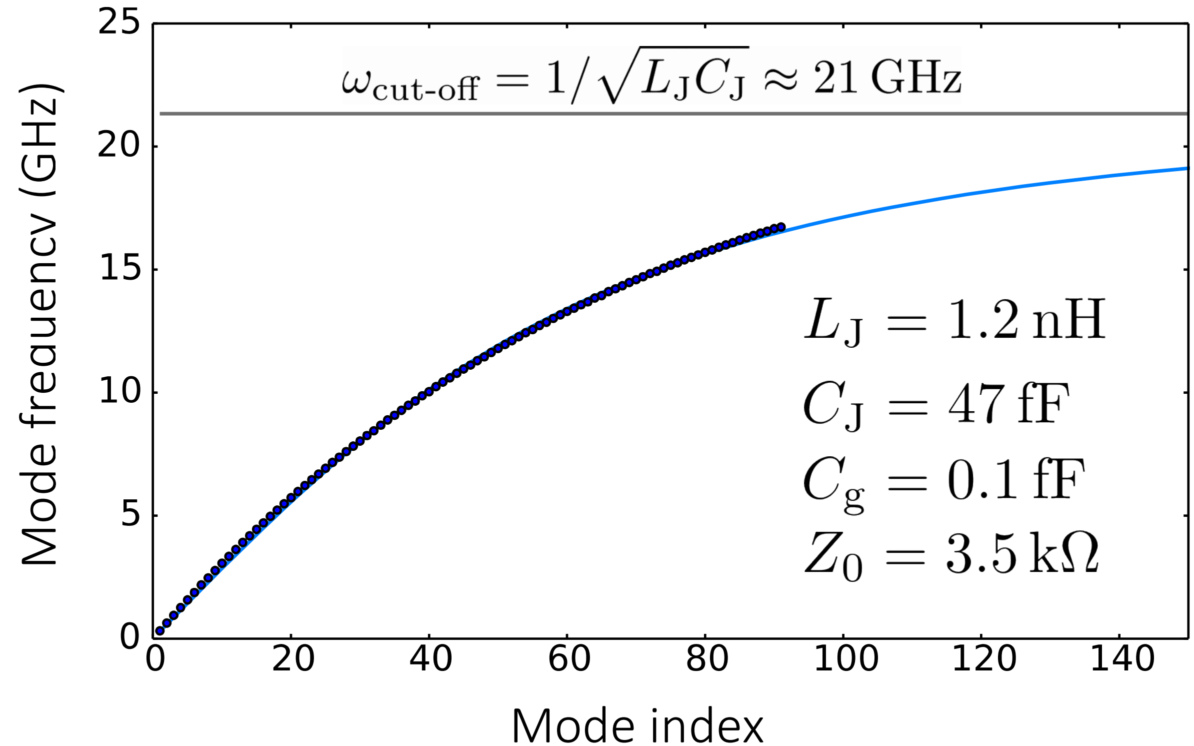

Y. Krupko *et al*. in prep.

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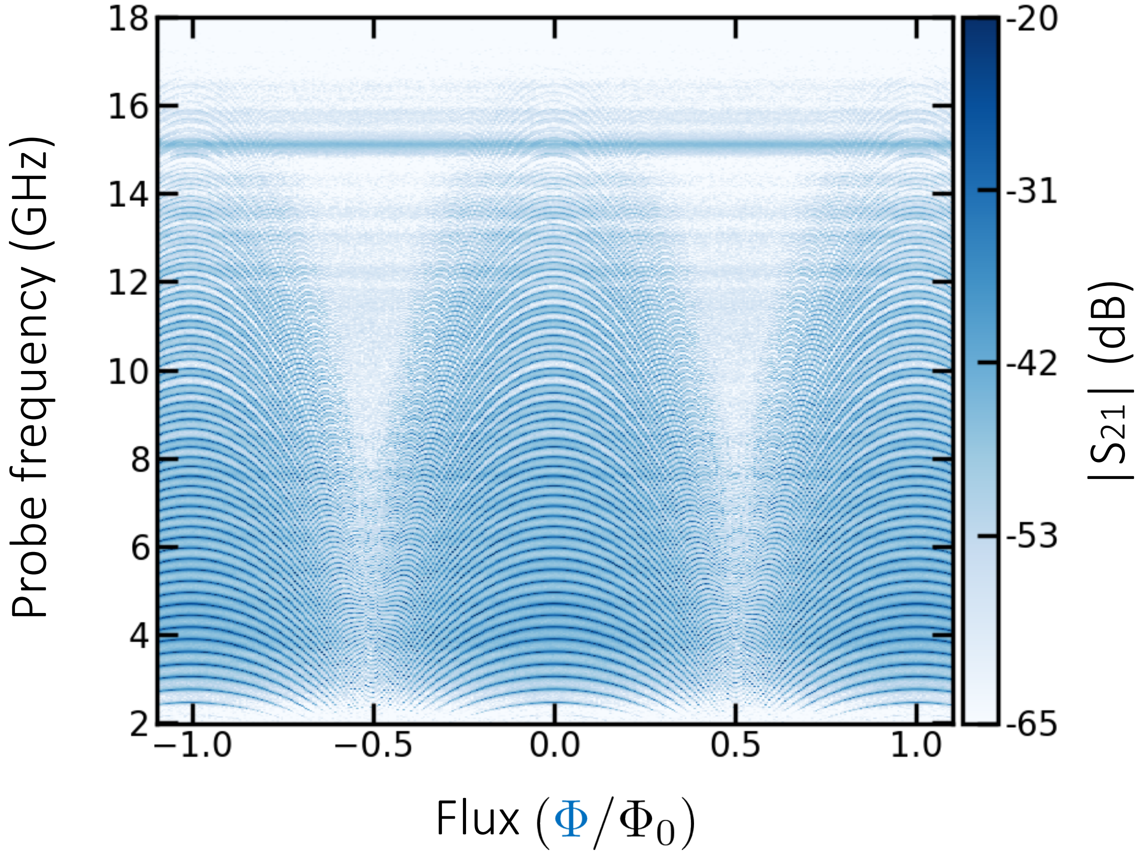

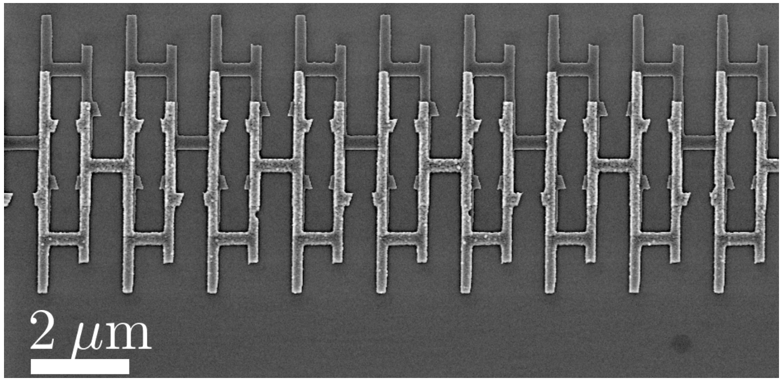

N = 5400 SQUIDs

Tunable impedance $$Z_c(\Phi) = \sqrt{\frac{L_J(\Phi)}{C_g}}$$

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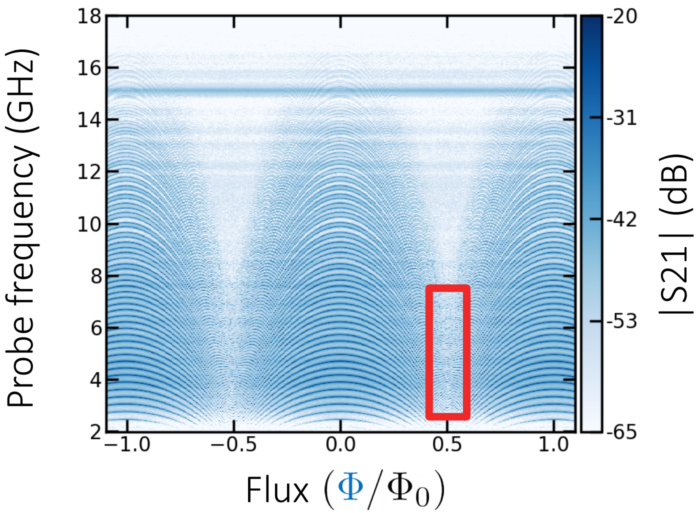
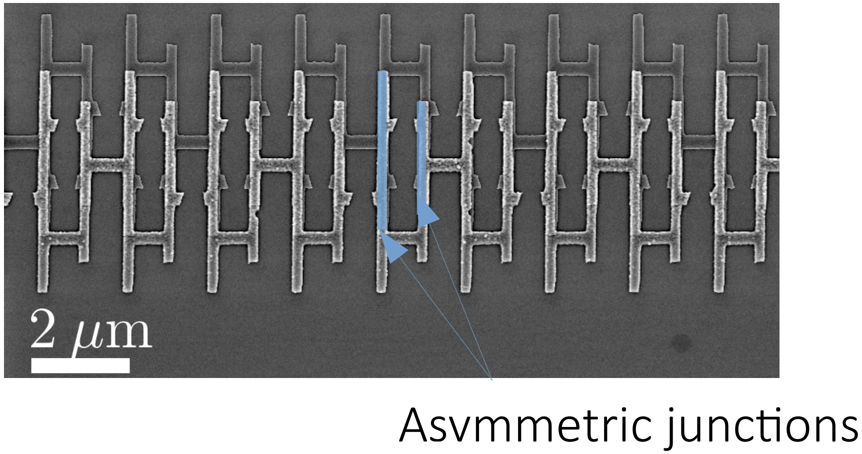
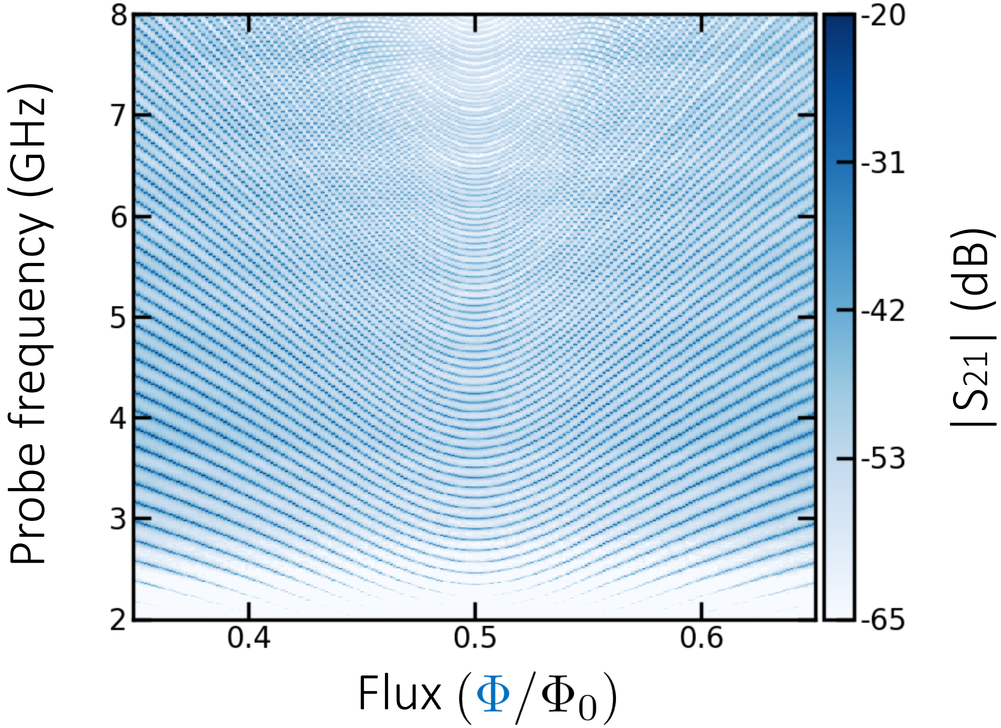




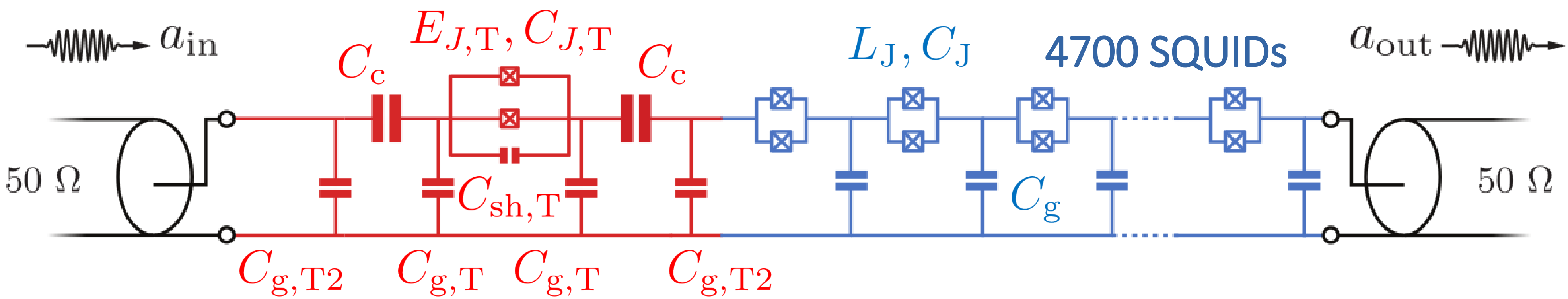


N = 5400 SQUIDs

Asymmetric SQUIDs :
Low Free Spectral Range at high impedance

$$\mathrm{FSR} \simeq 150\,\mathrm{MHz}$$

Transmon coupled to an array of SQUIDs



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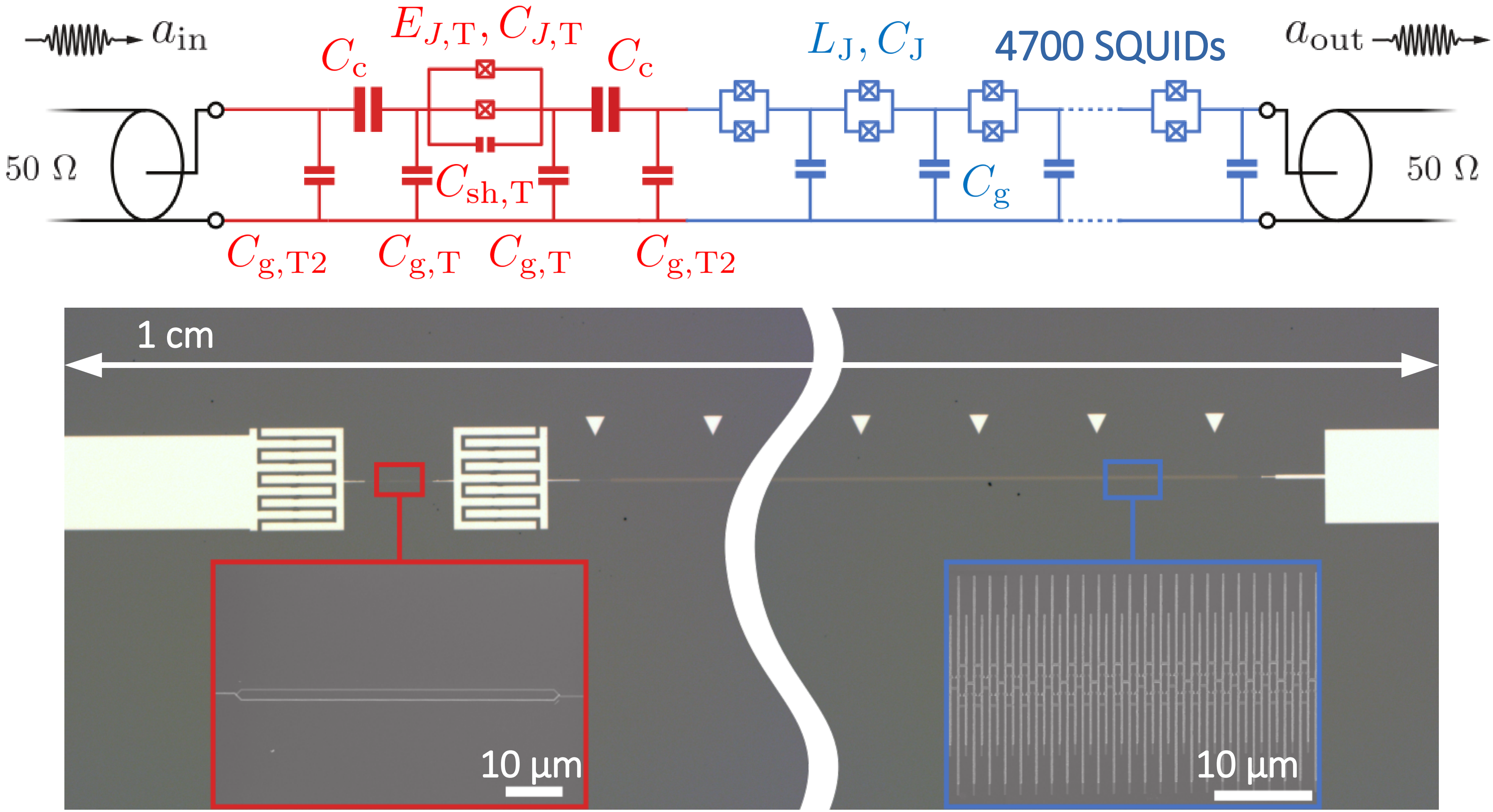

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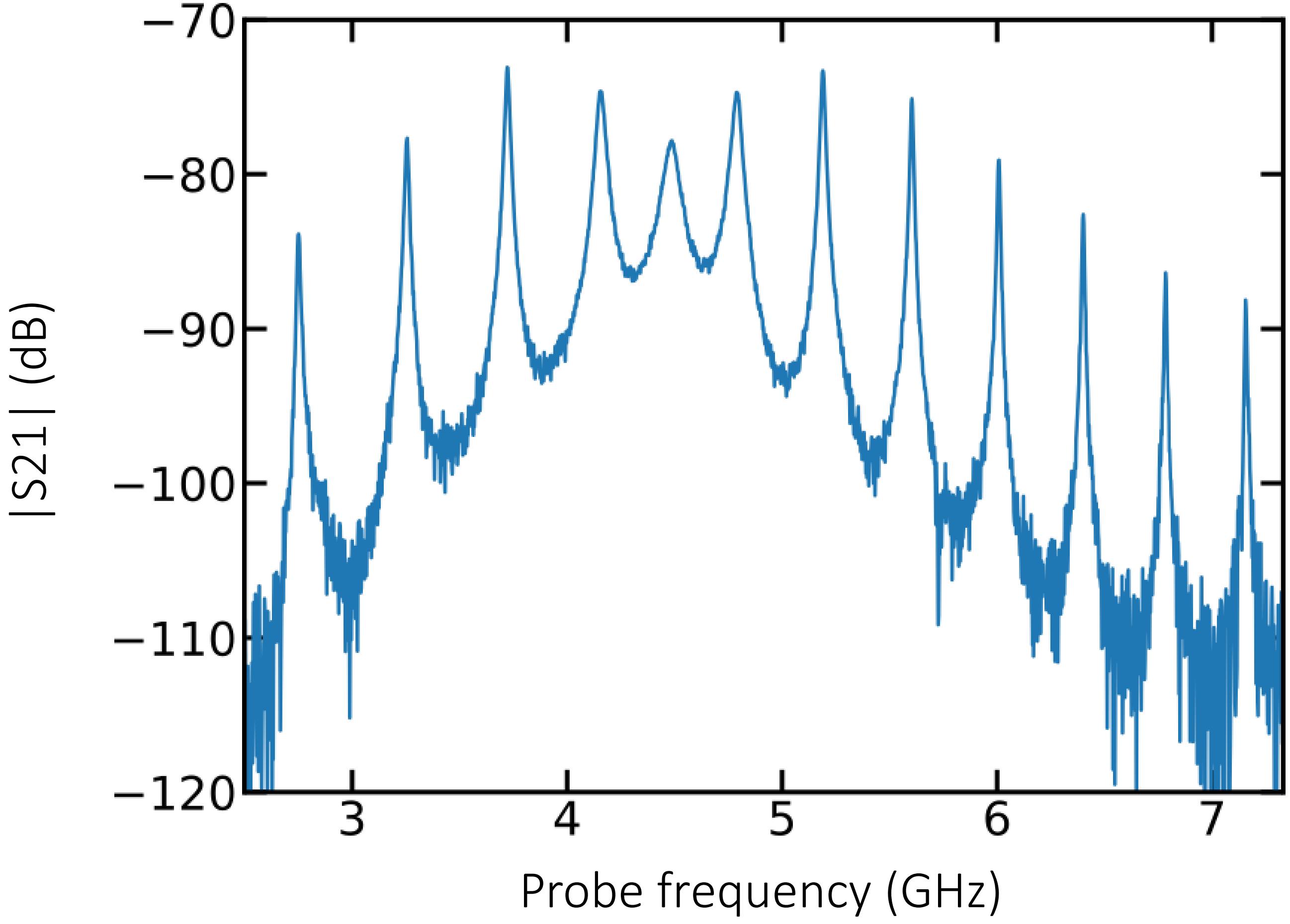

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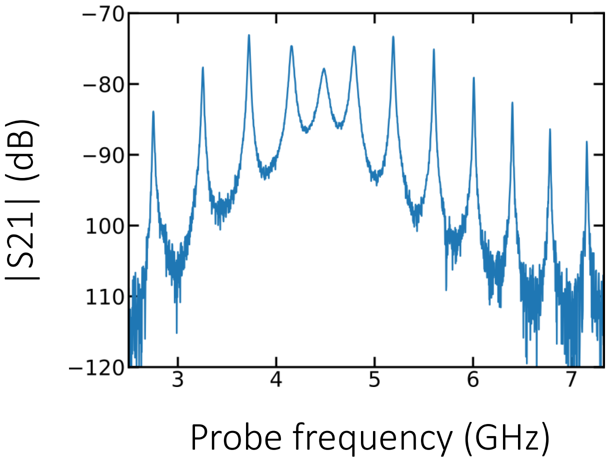

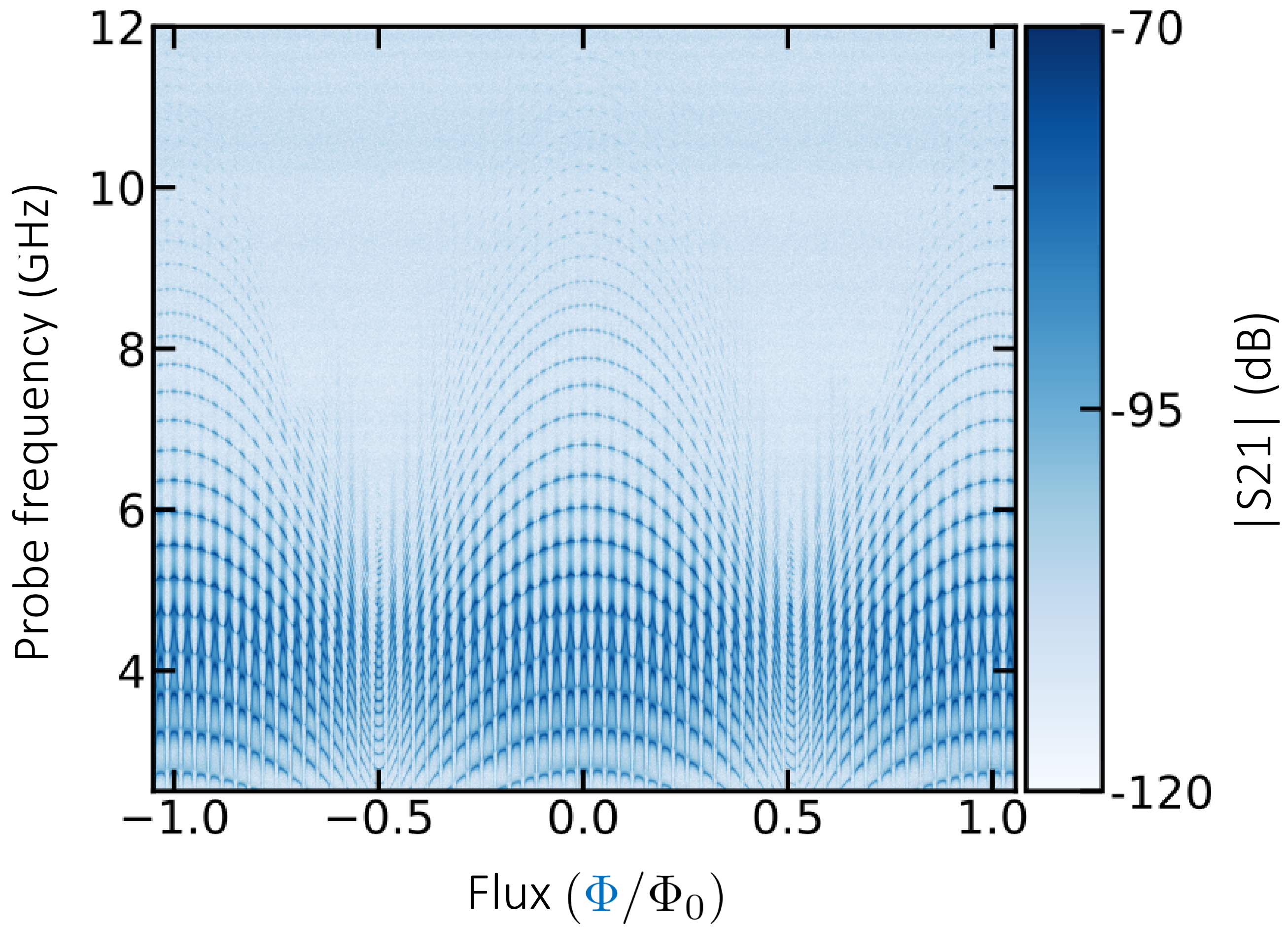

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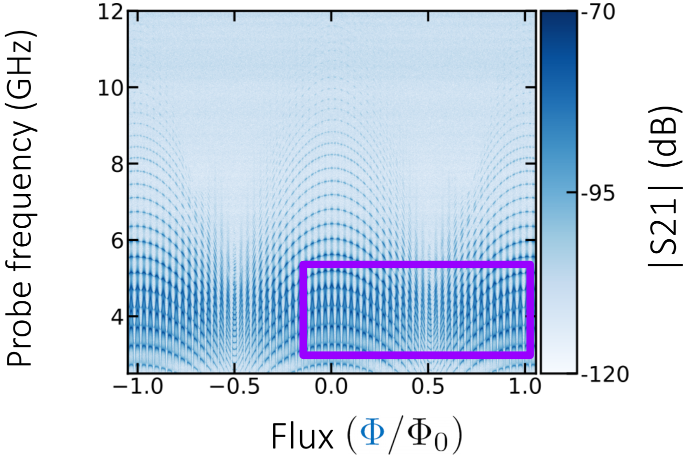

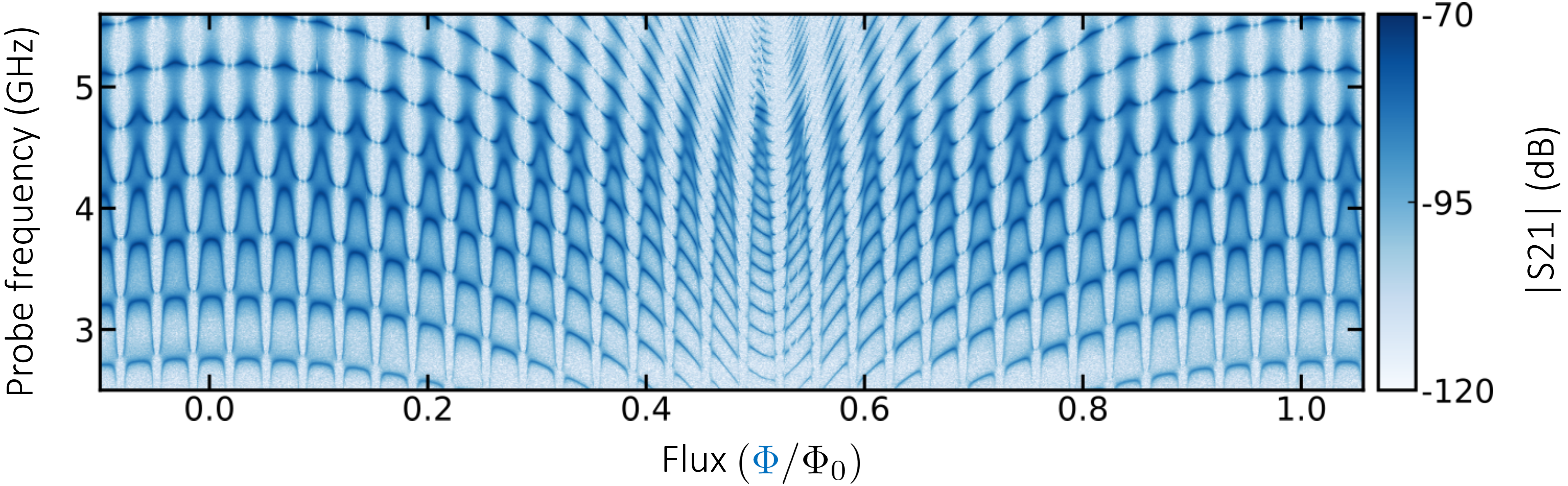

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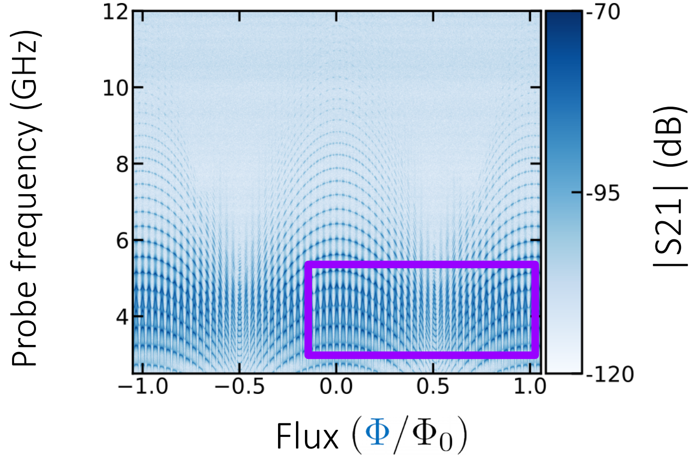

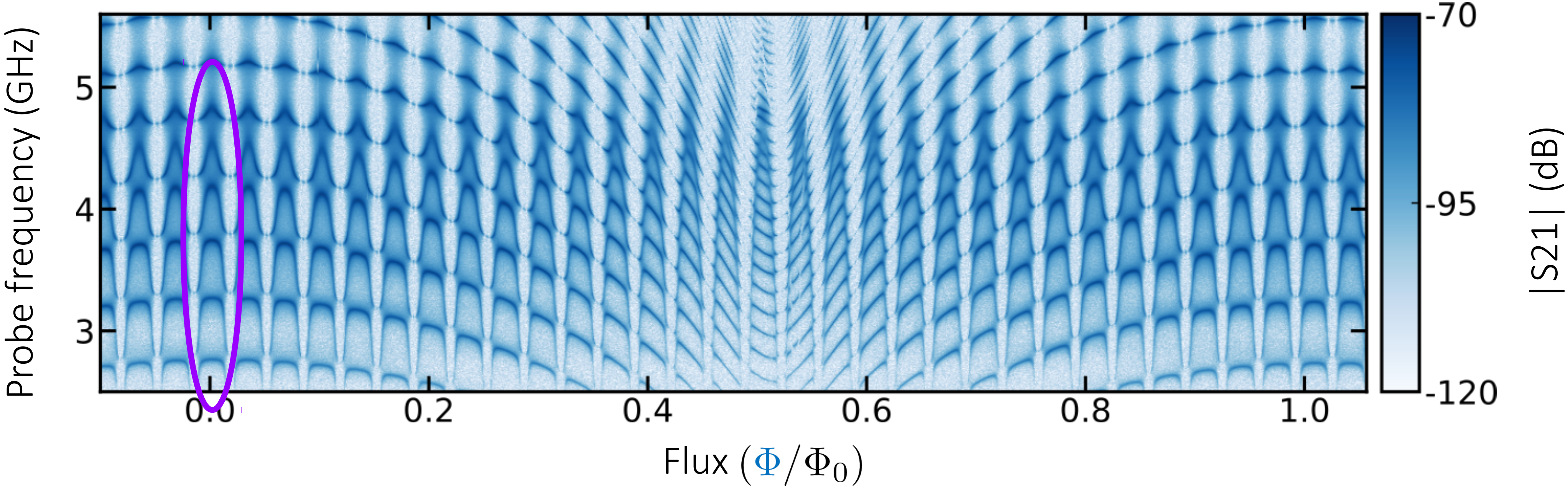

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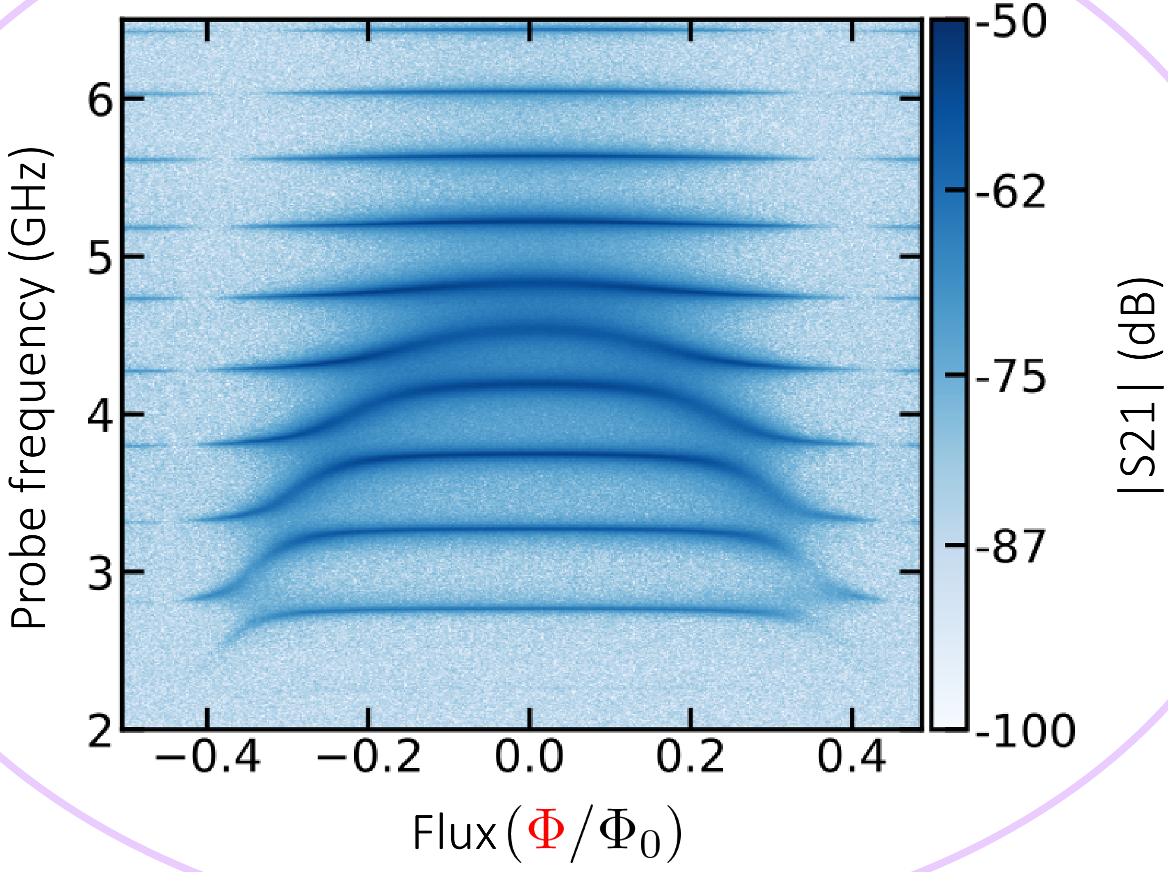
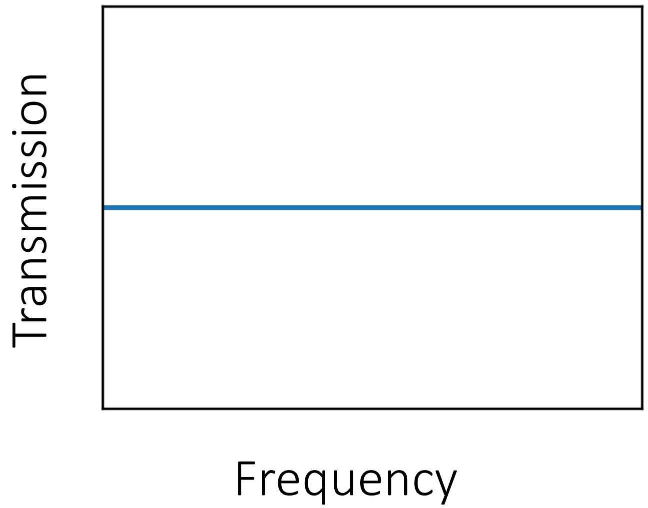
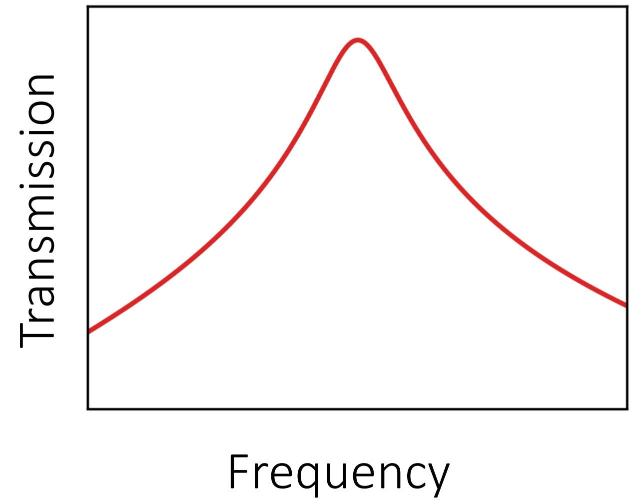


Transmon coupled to an array of SQUIDs

What is the qubit width ?





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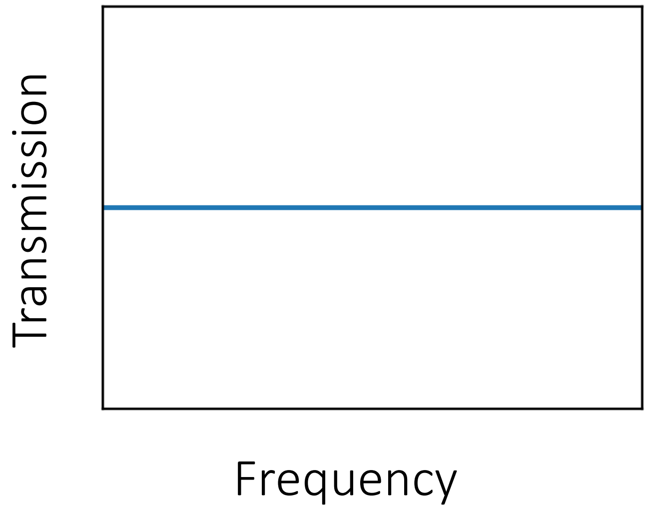
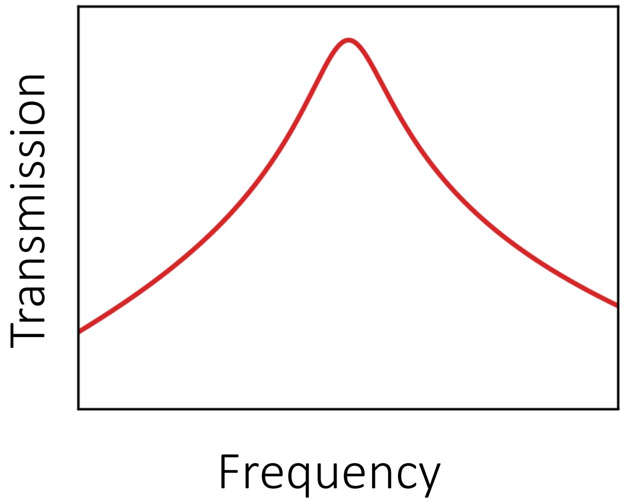
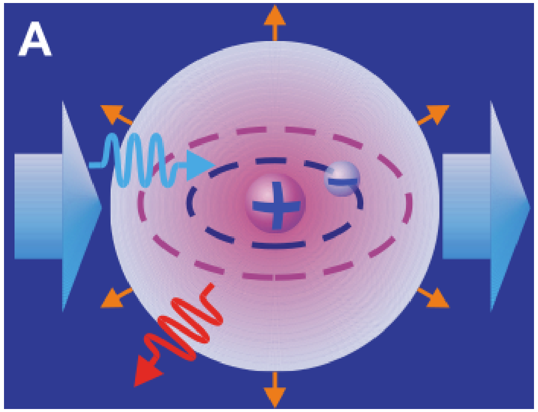
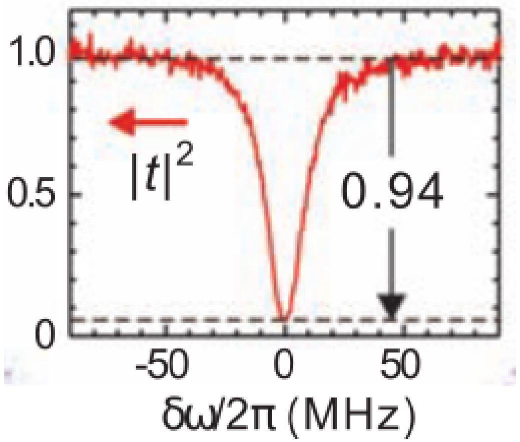




Resonance fluorescence

O. Astafiev et al (2012)





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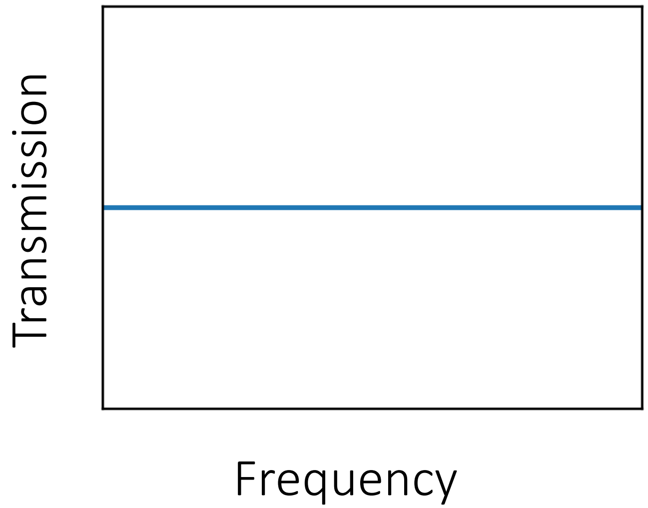

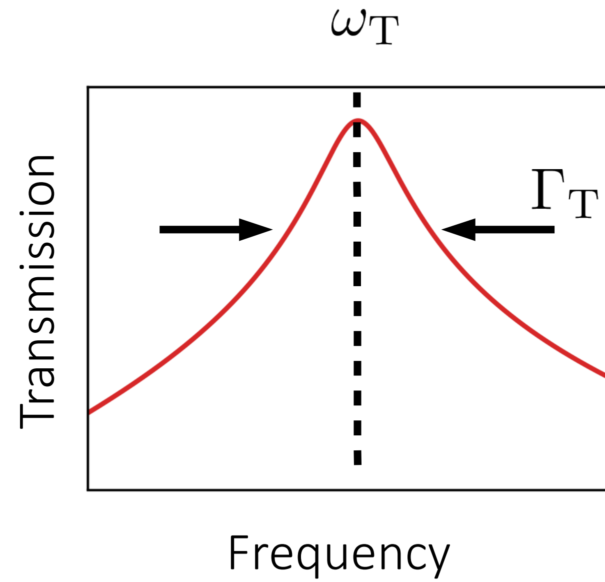

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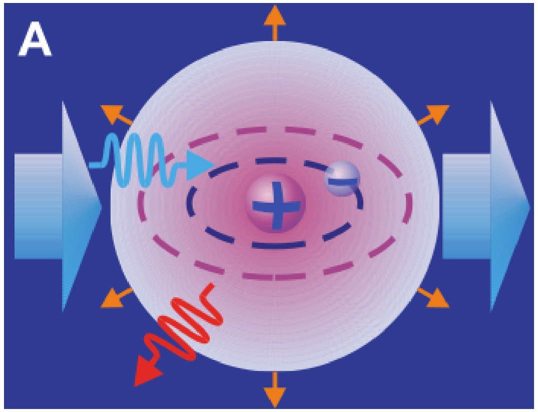

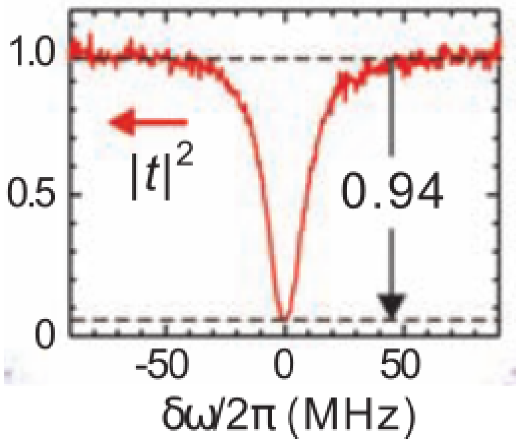

Transmon coupled to an array of SQUIDs

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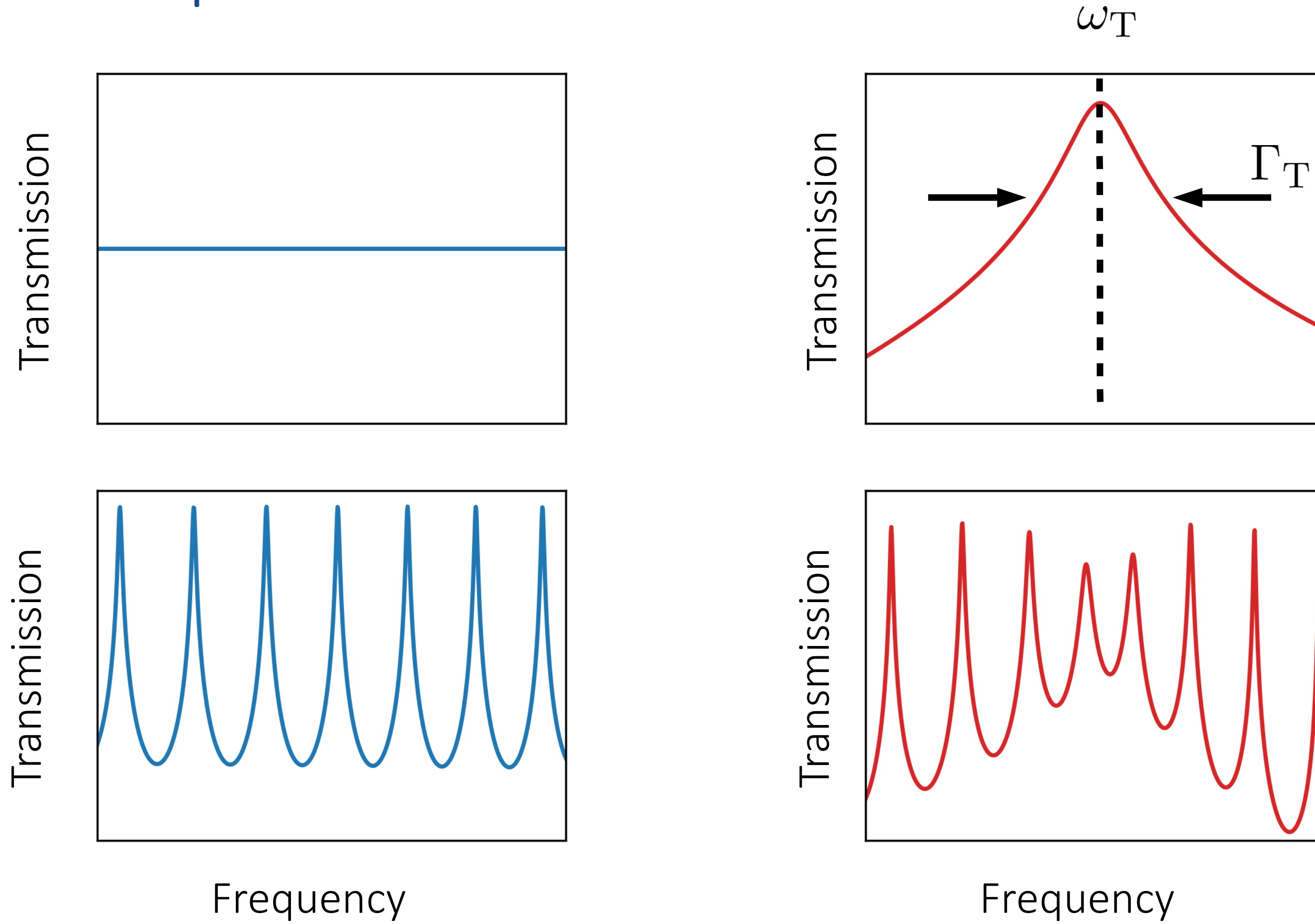

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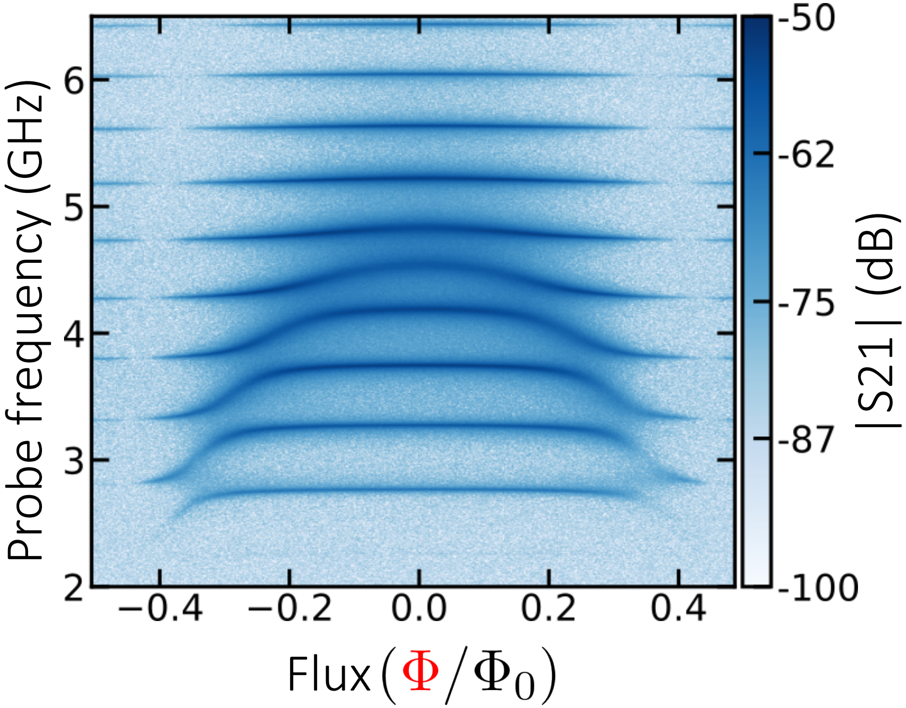
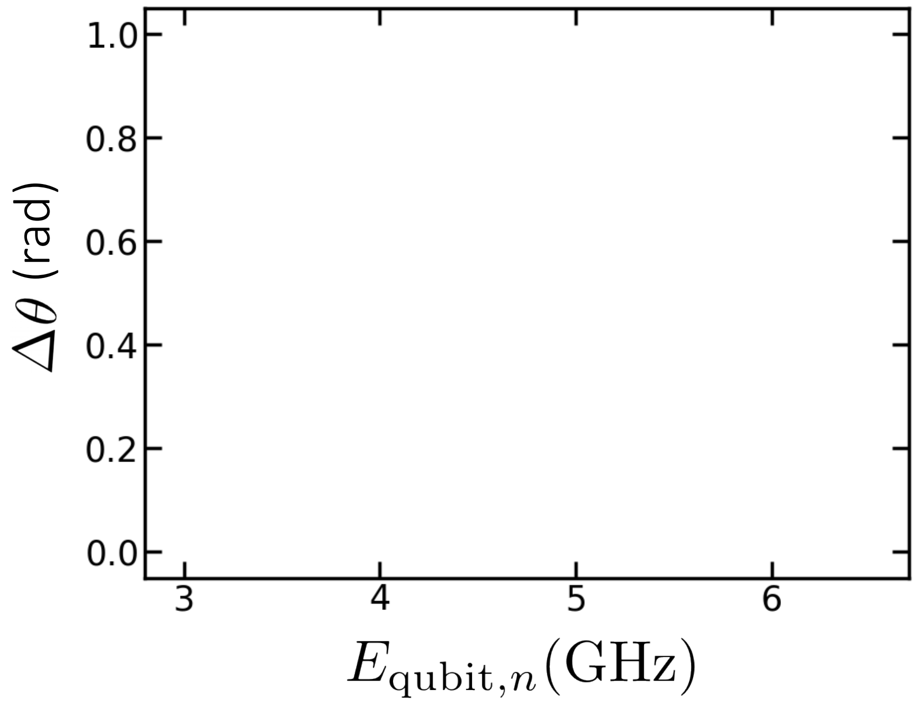


The transmon phase shift

$$\Delta\theta = \frac{E_{\text{bare, n}} - E_{\text{qubit, n}}}{E_{\text{bare, n + 1}} - E_{\text{bare, n}}}$$



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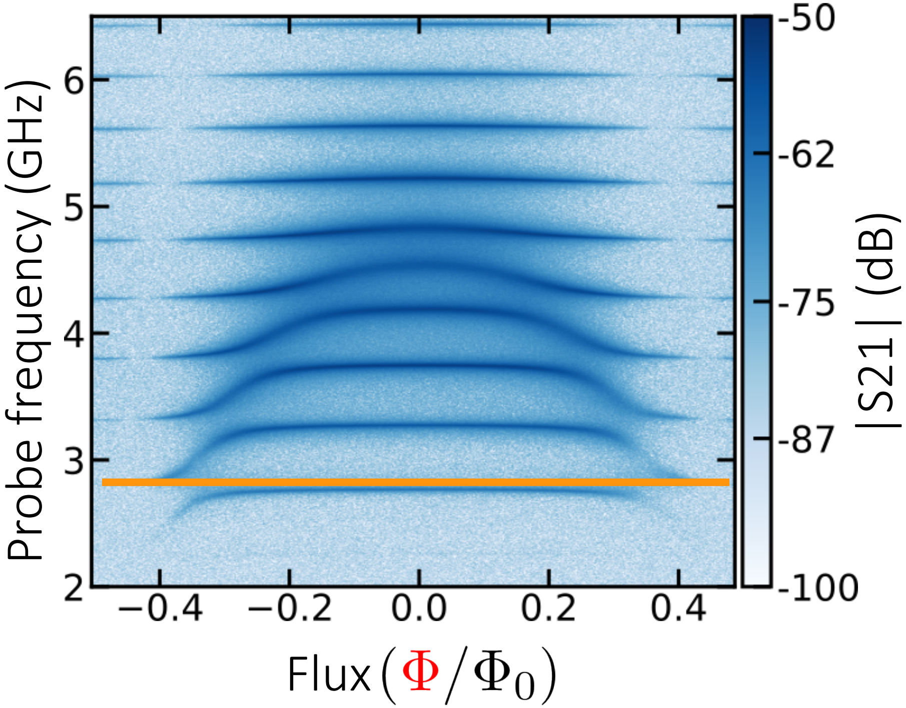

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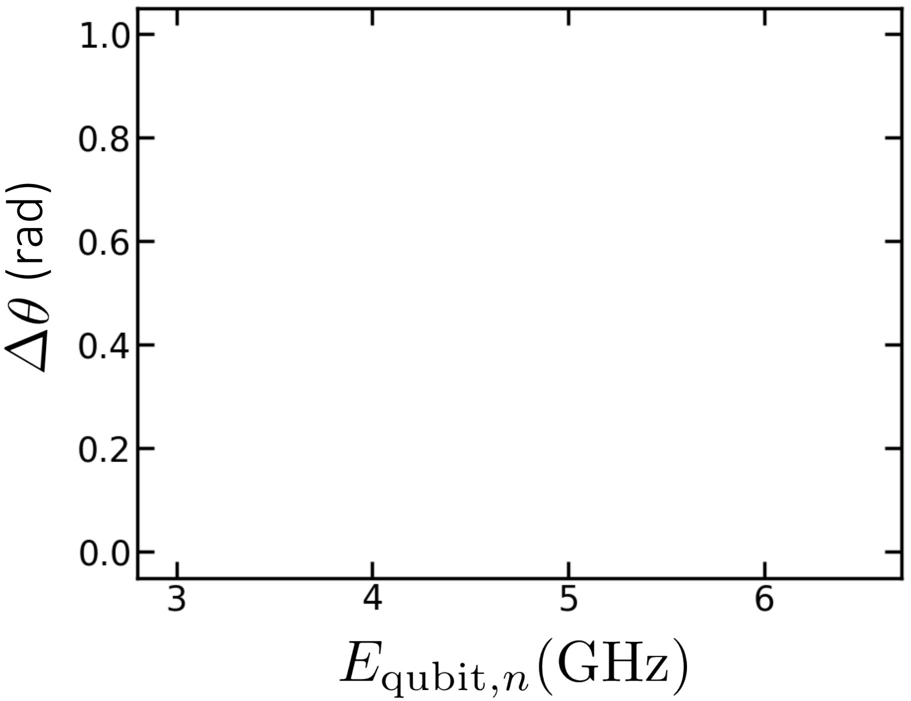
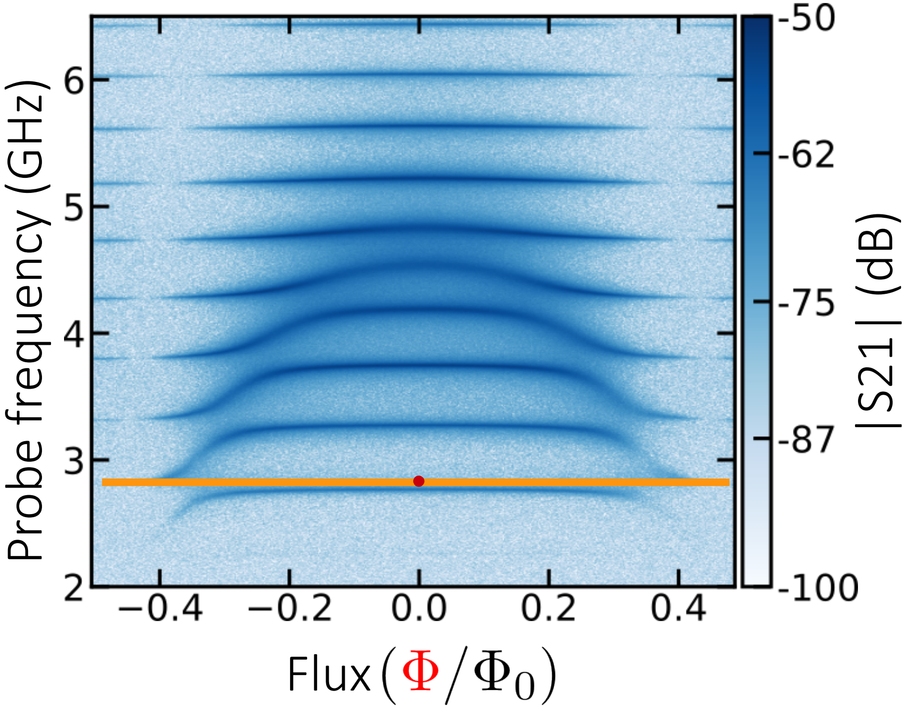


Transmon coupled to an array of SQUIDs



The transmon phase shift

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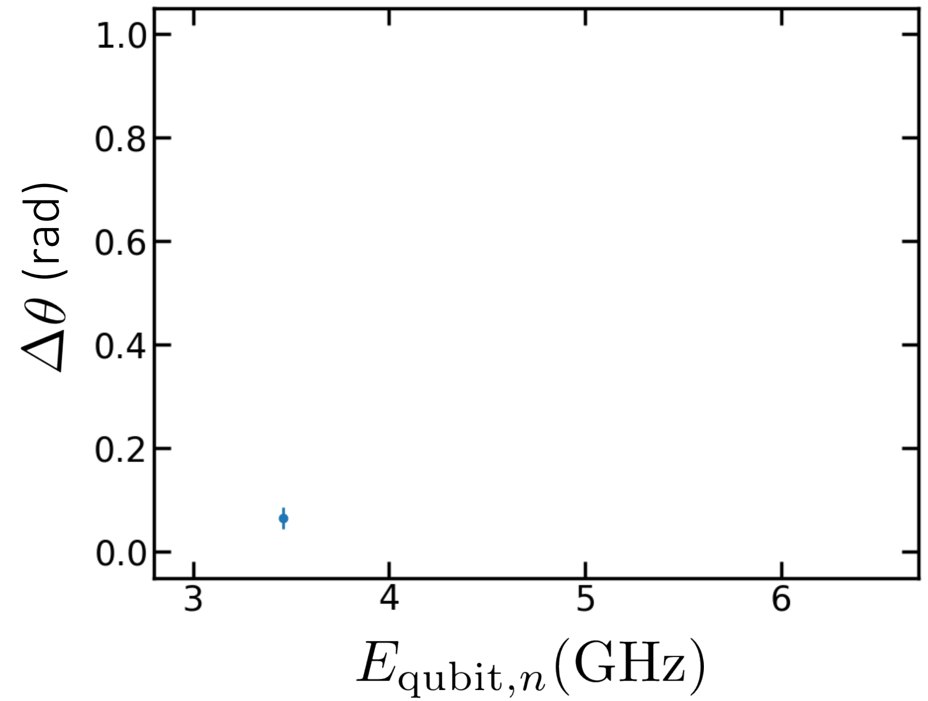

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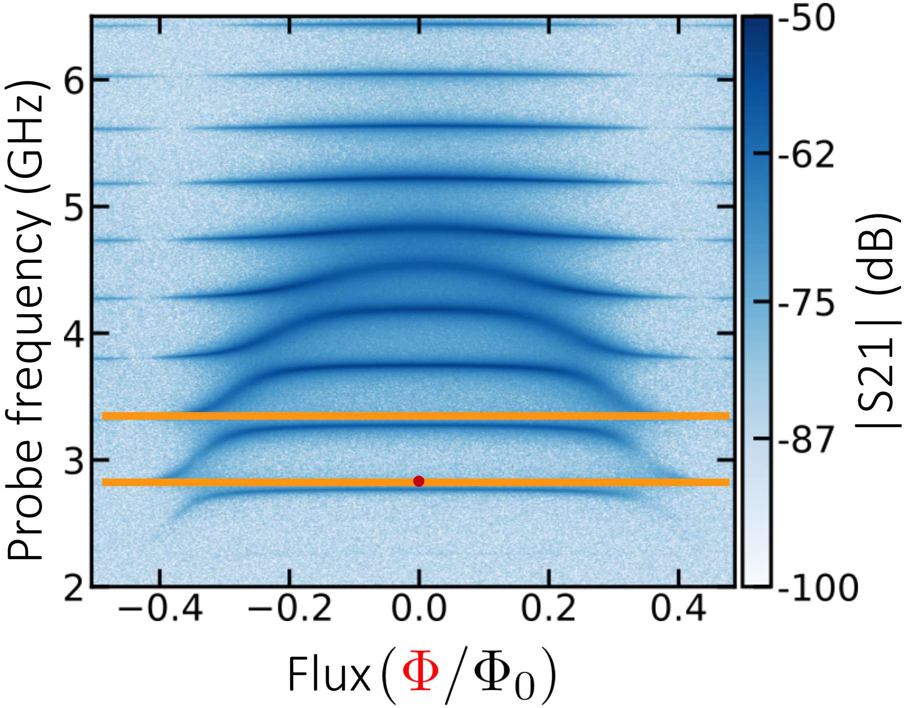

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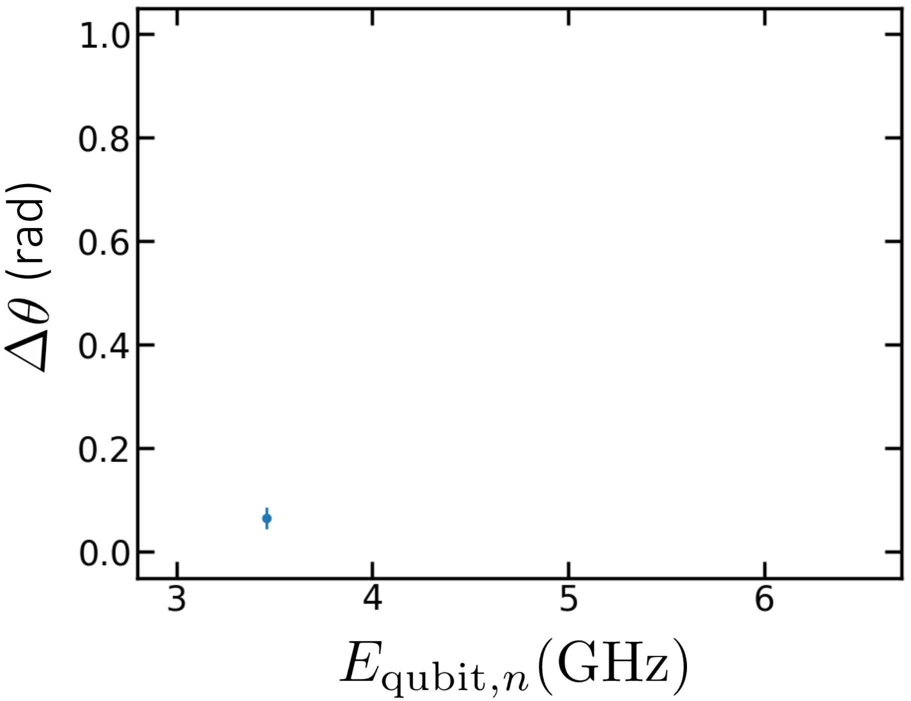

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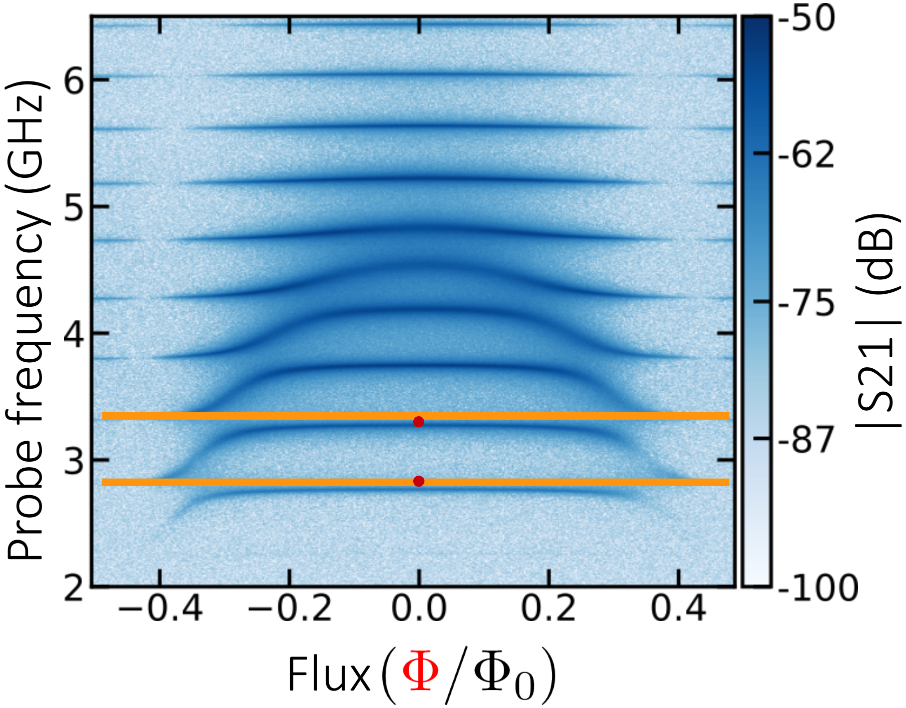

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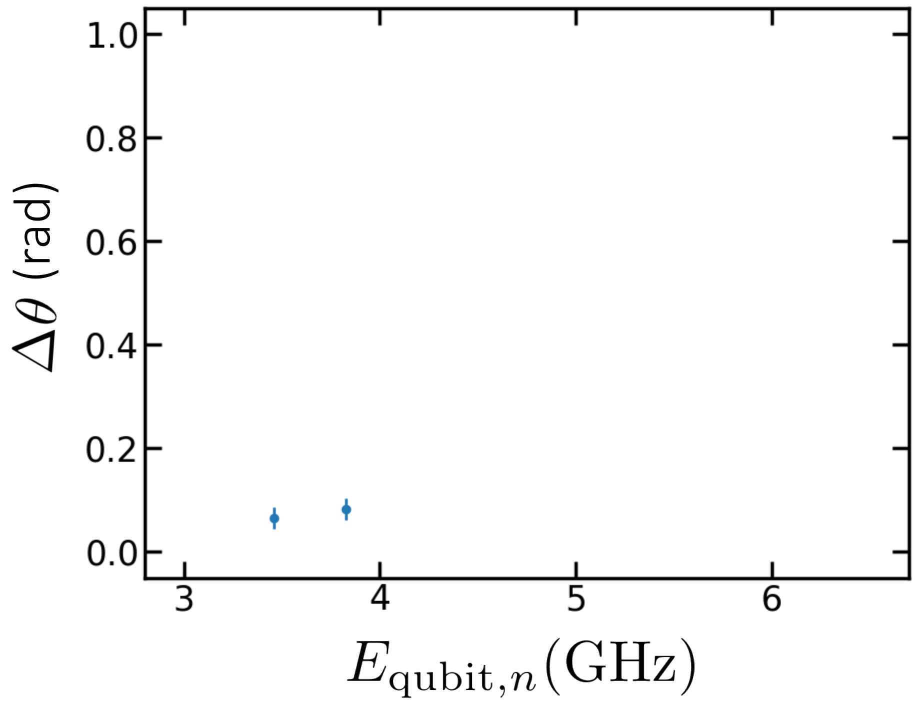

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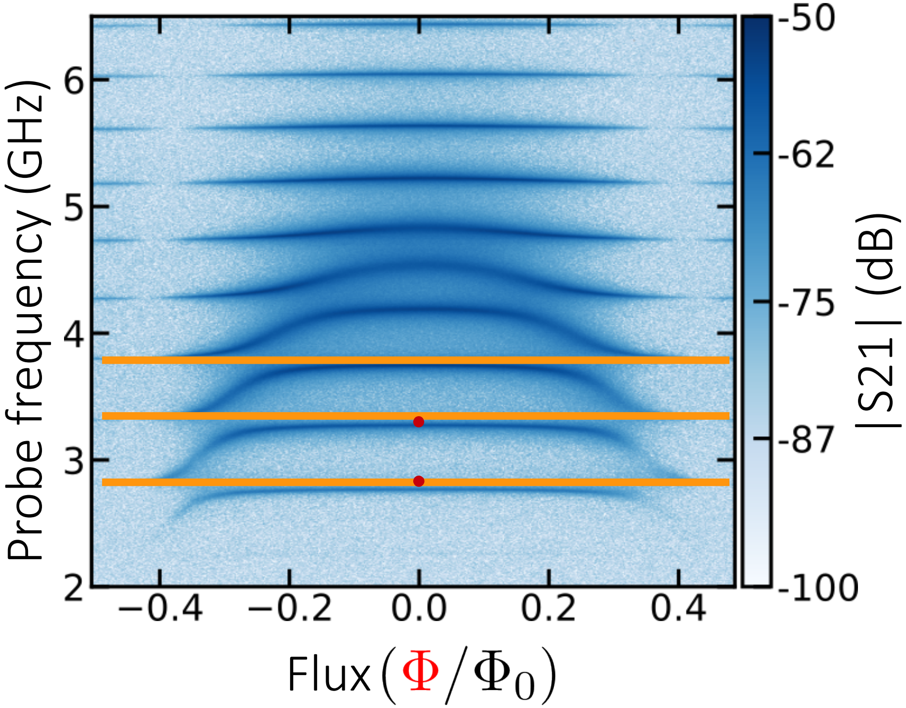

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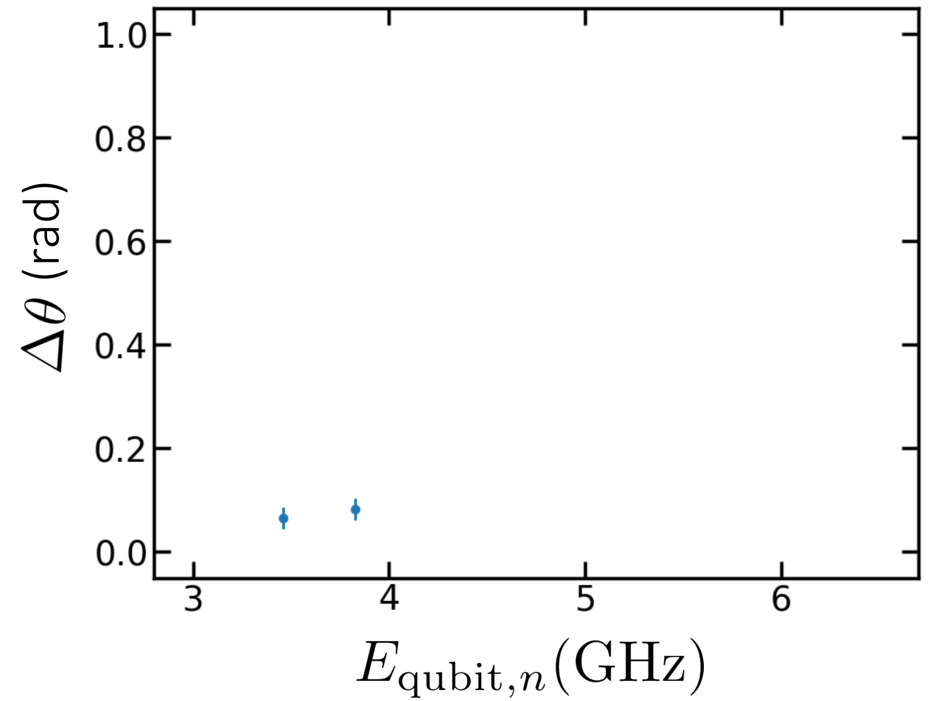

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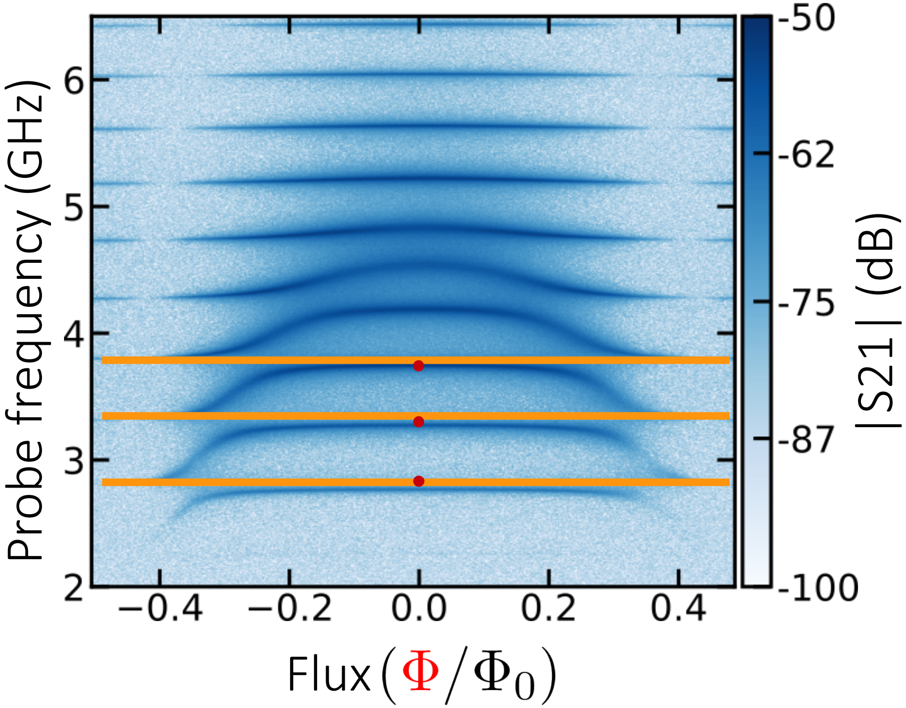

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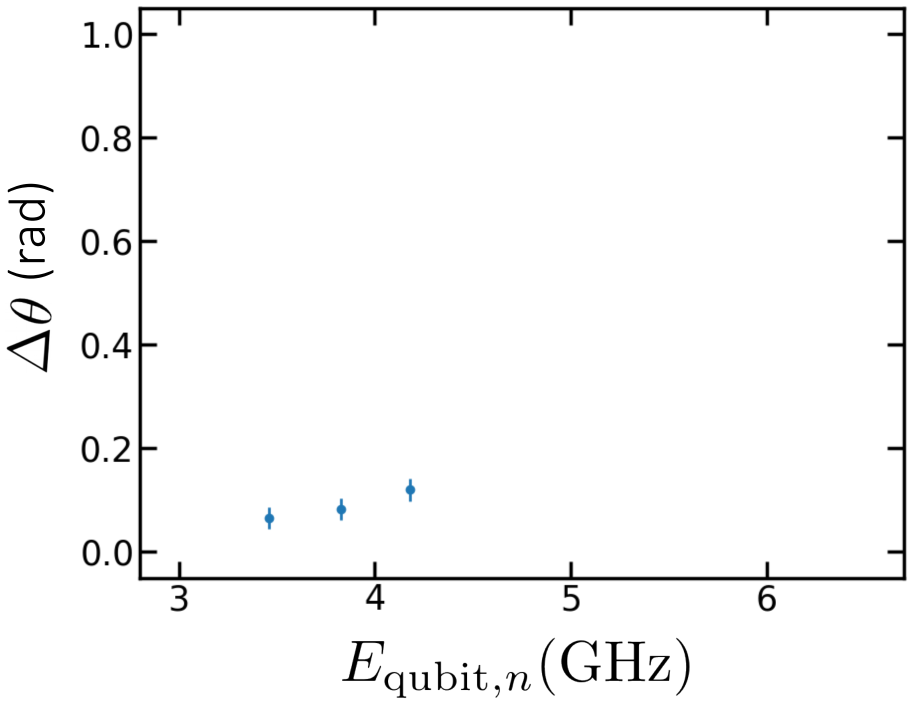

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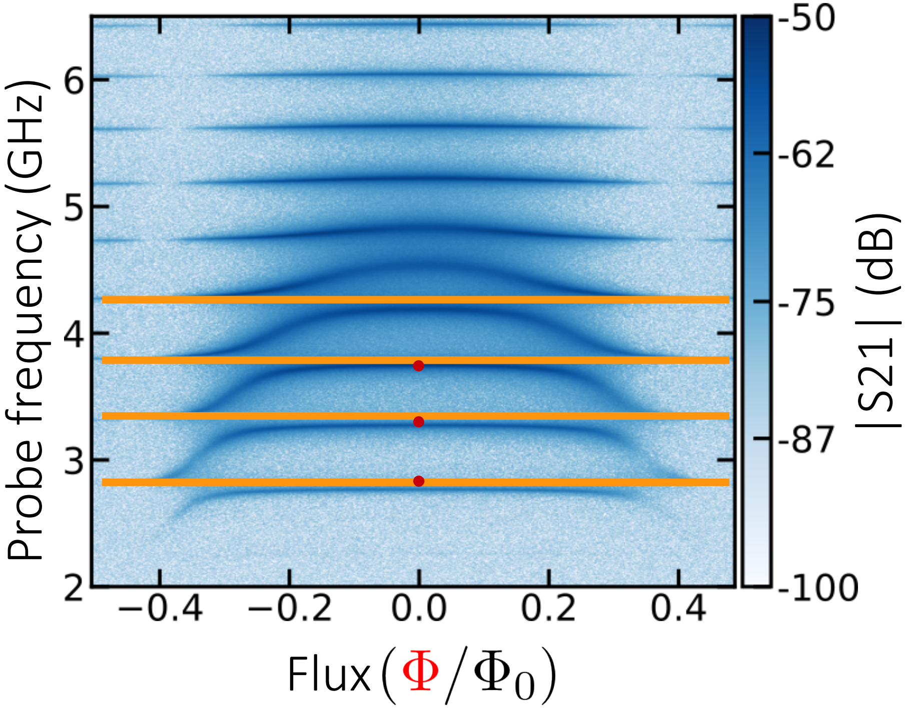

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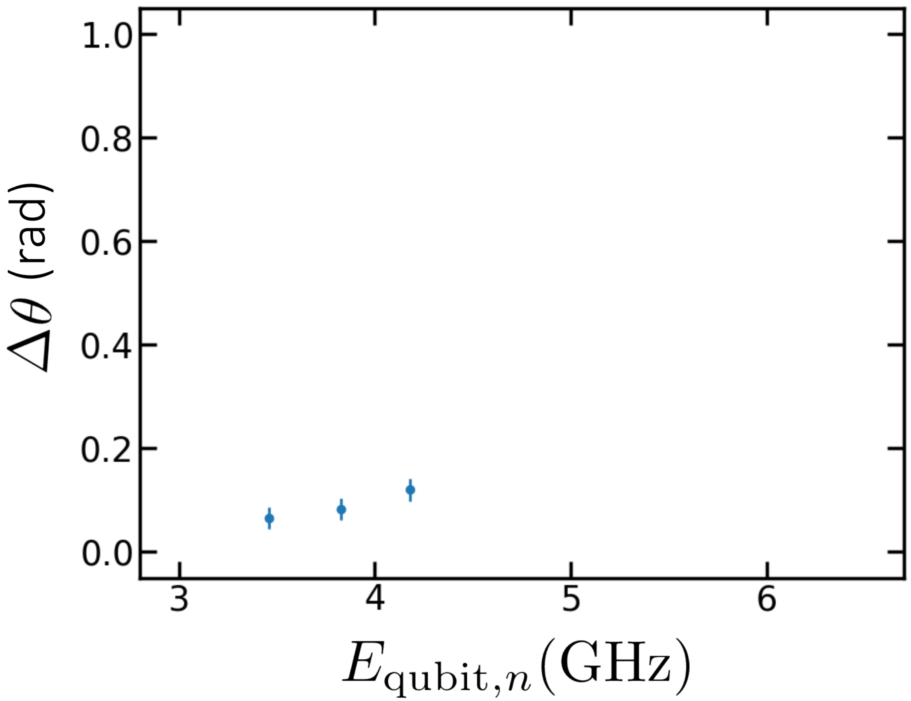

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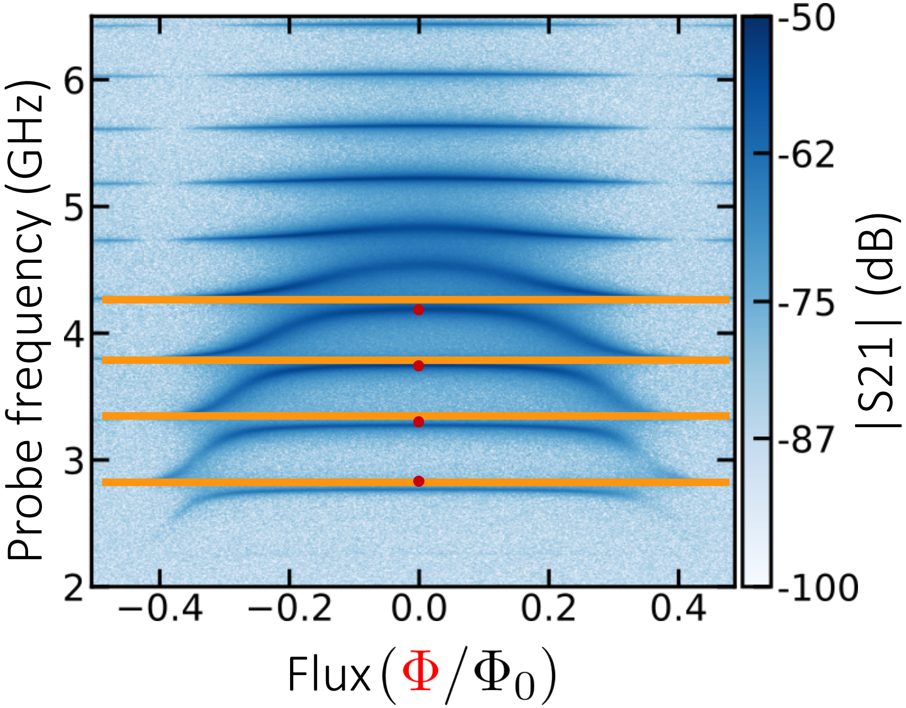

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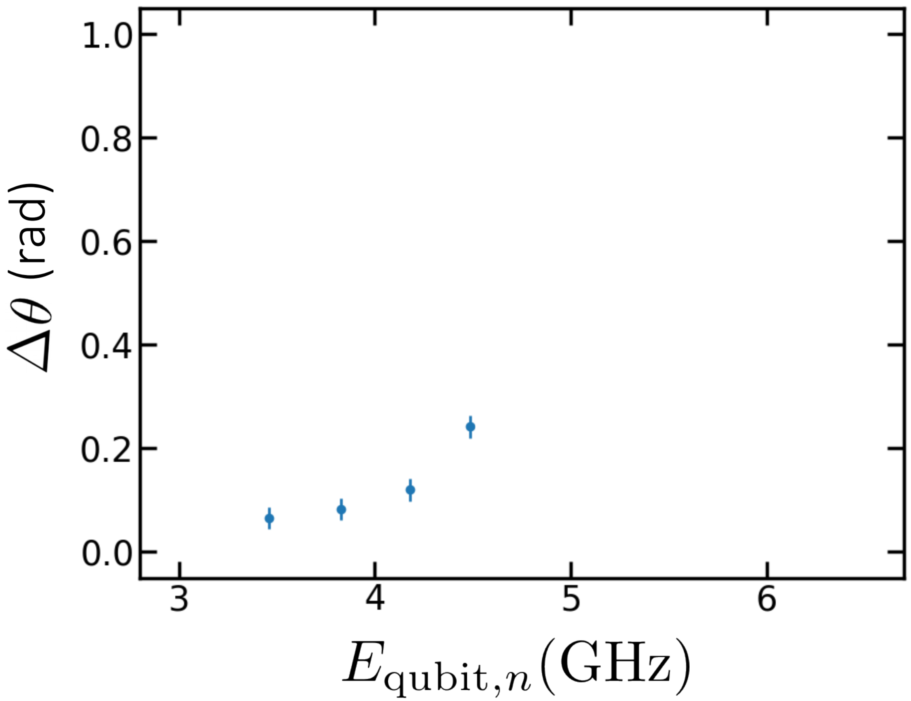

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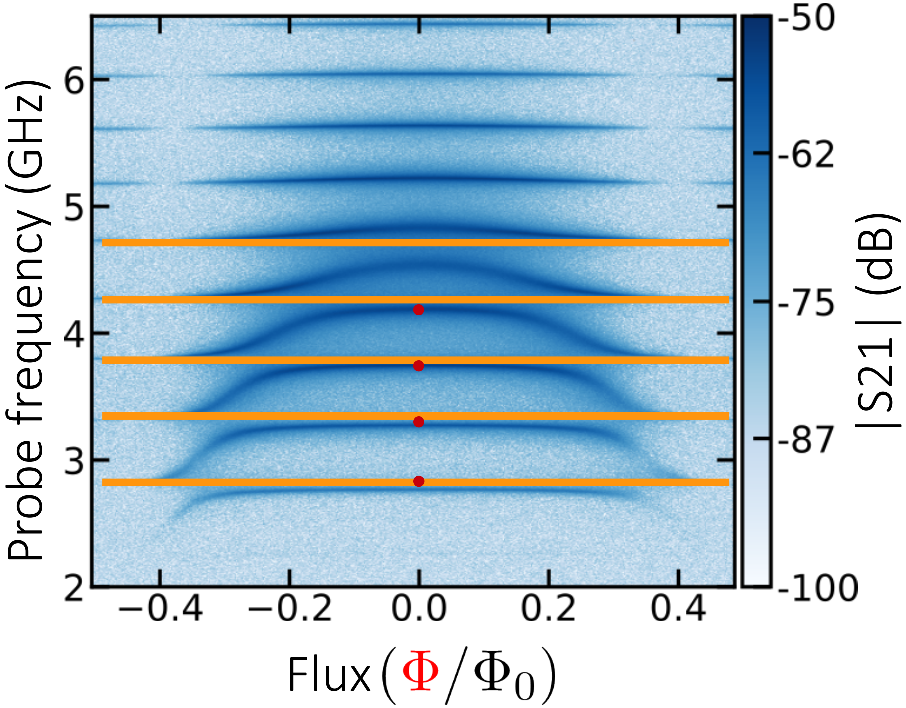

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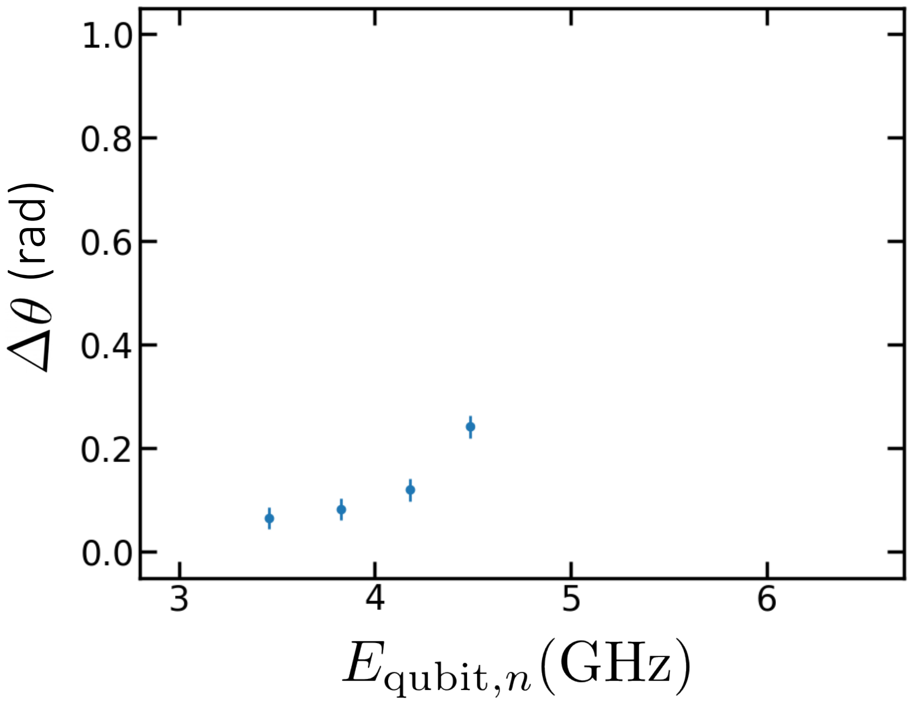

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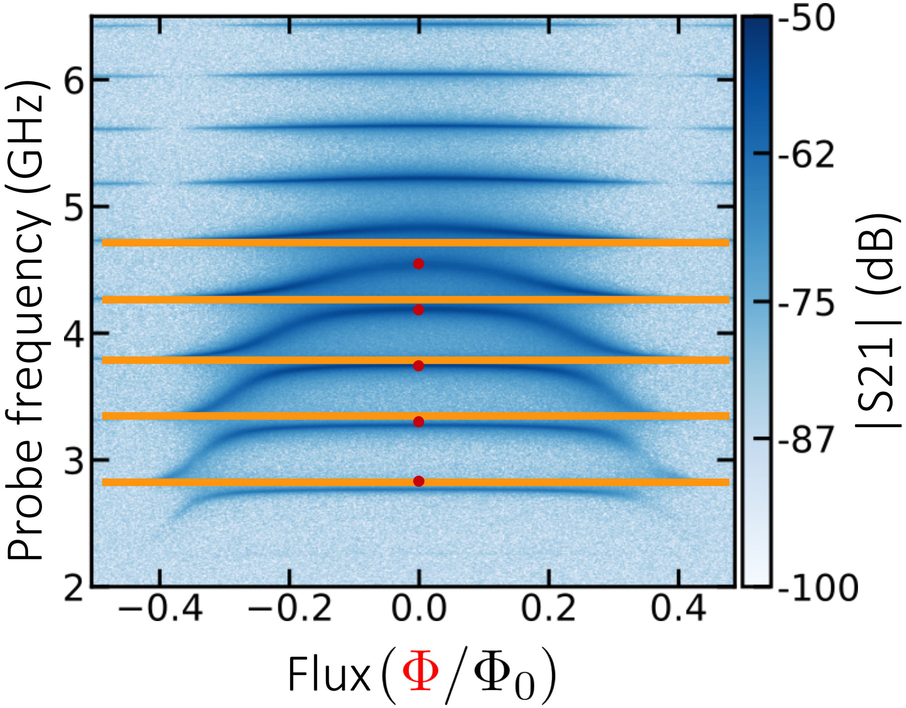

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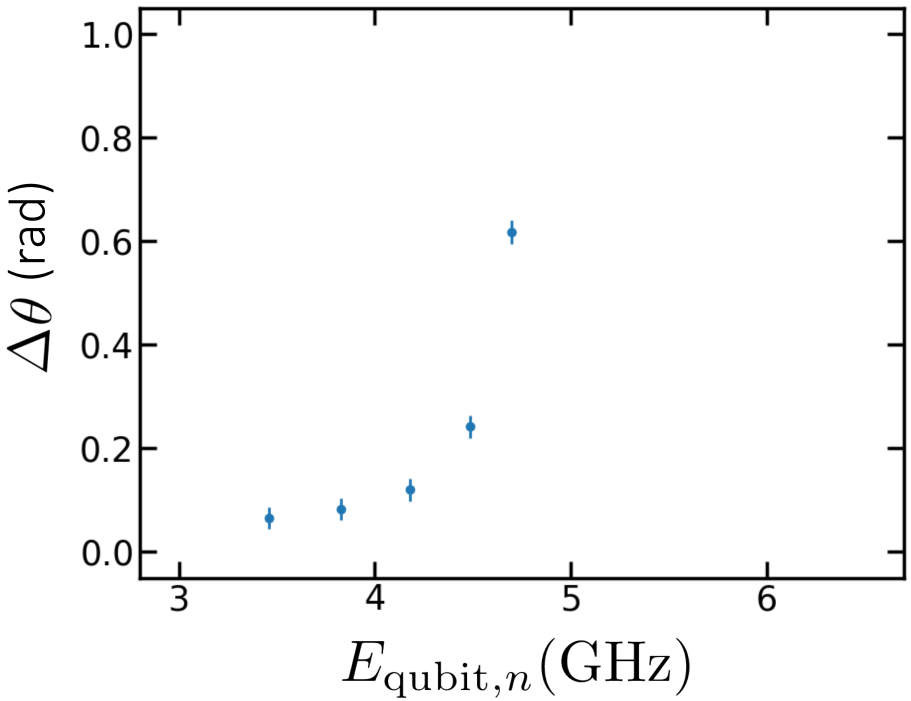

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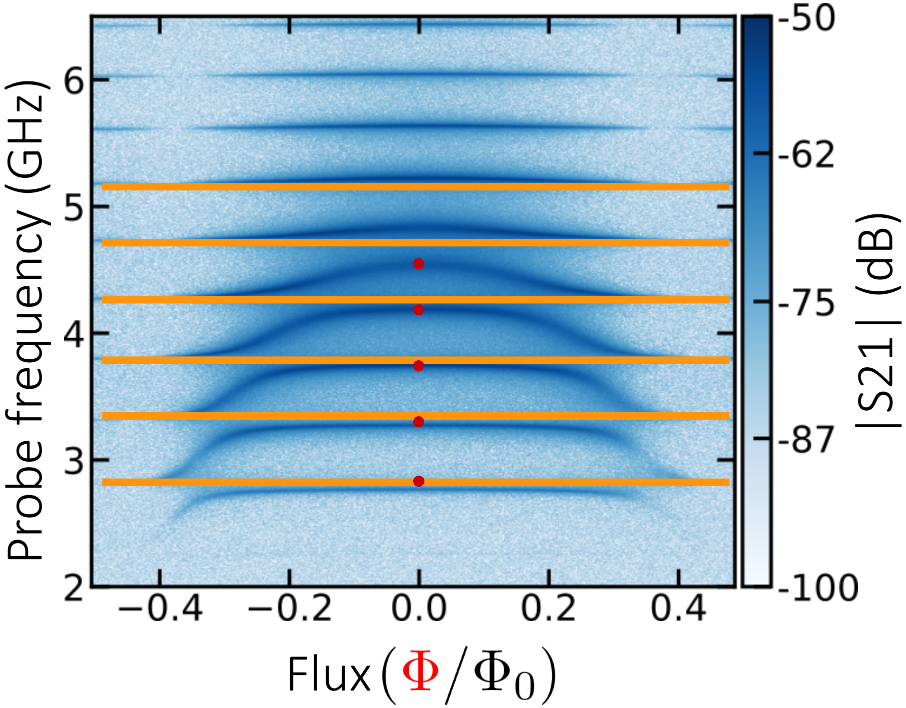

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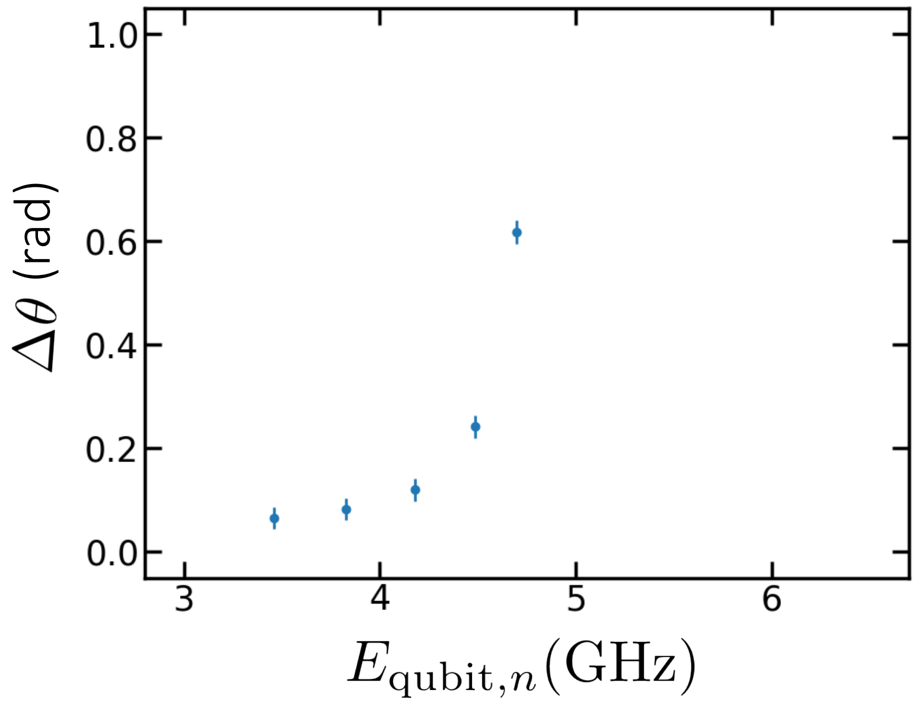

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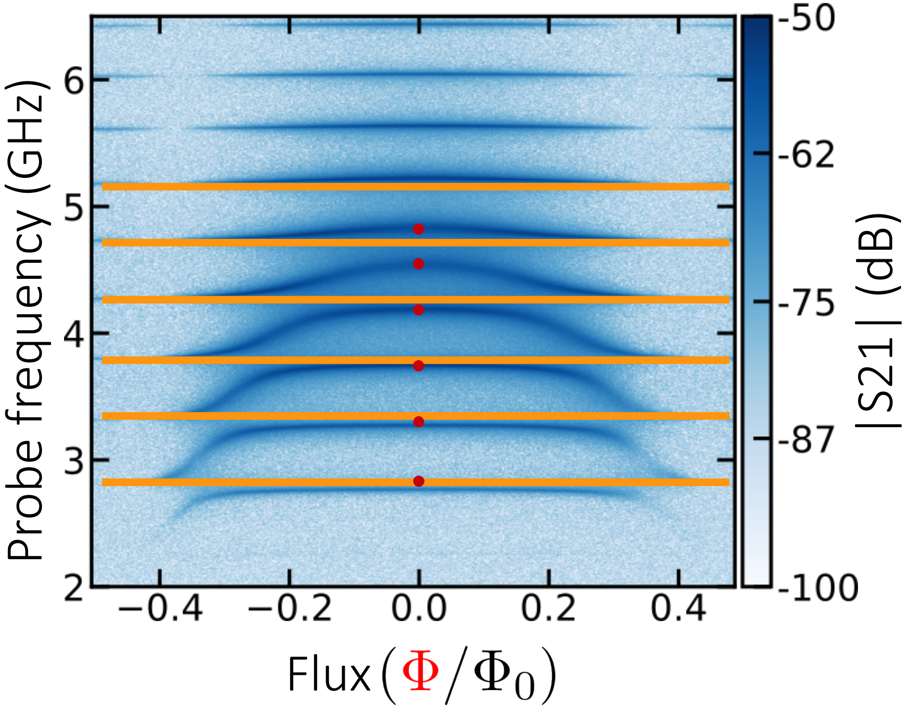

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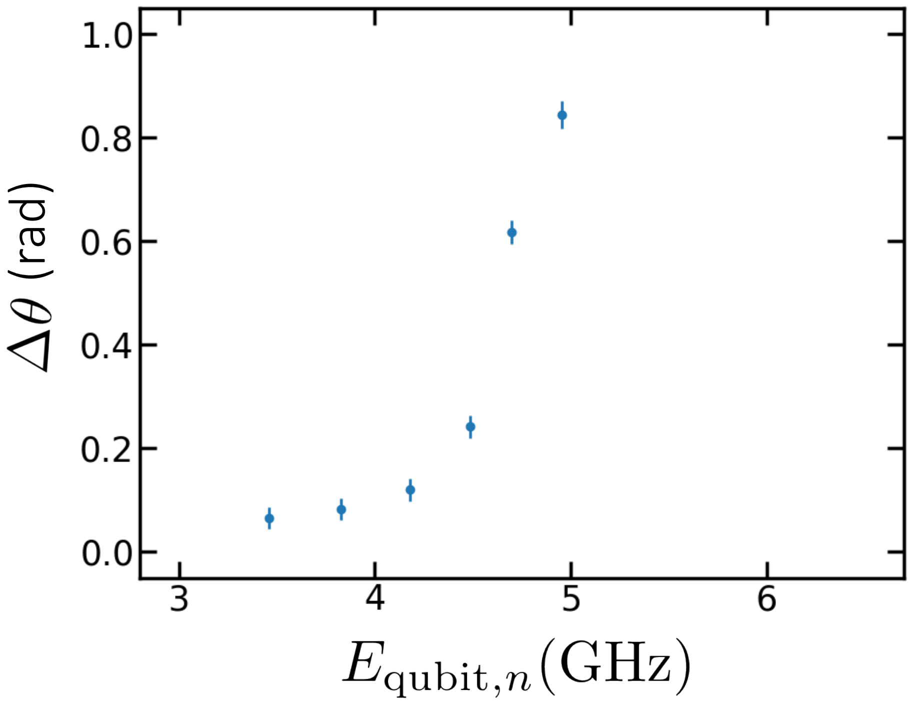

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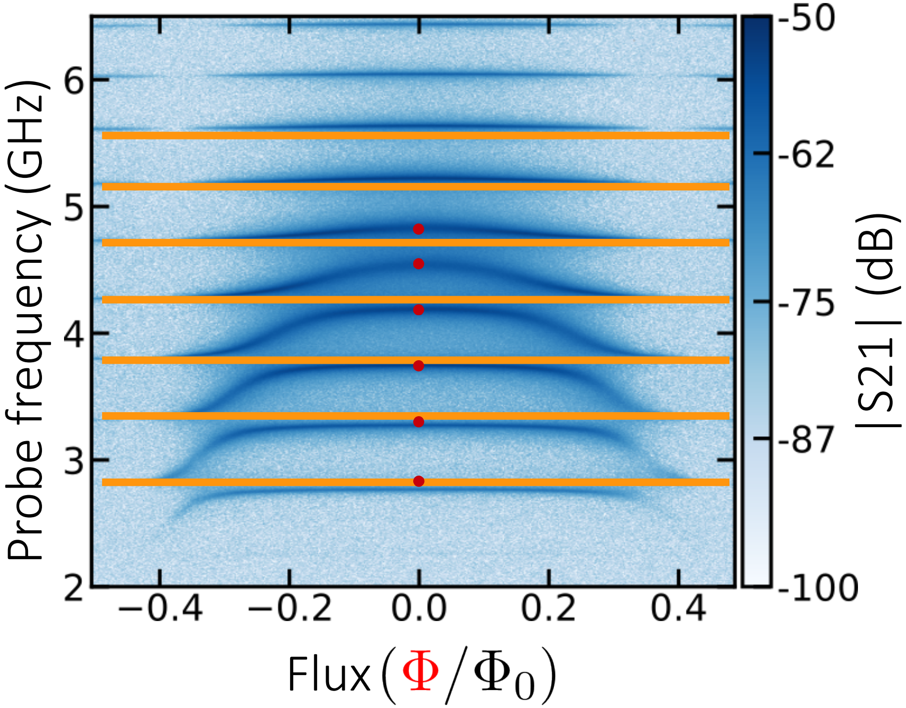

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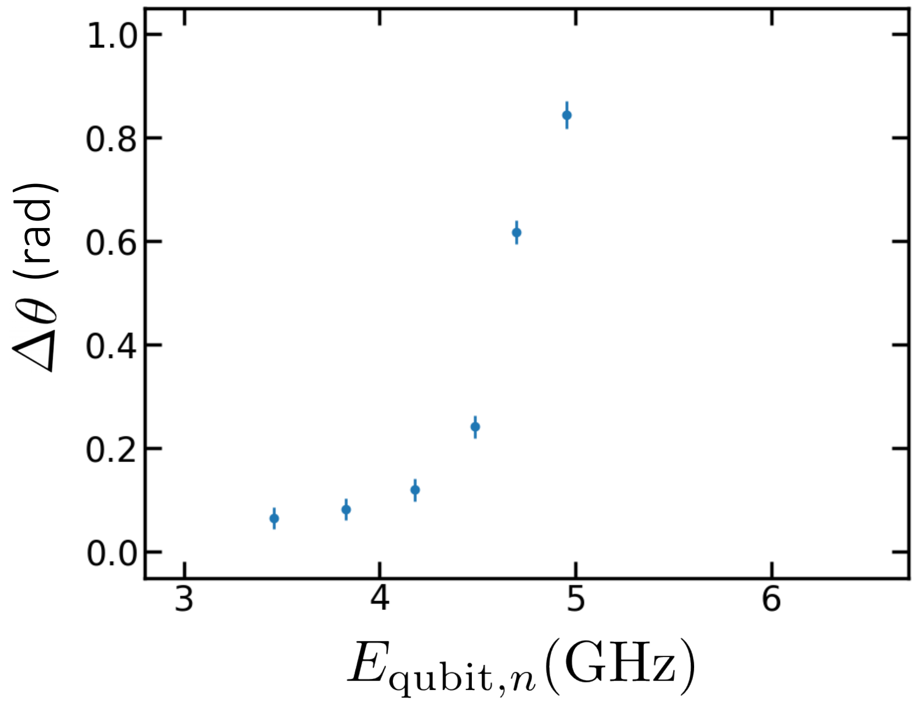

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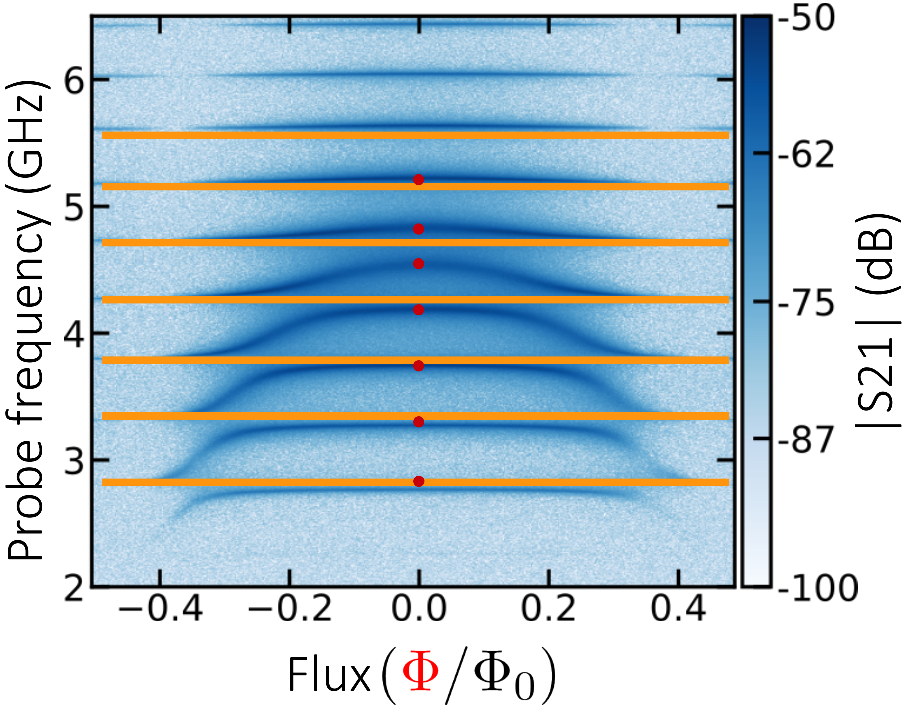

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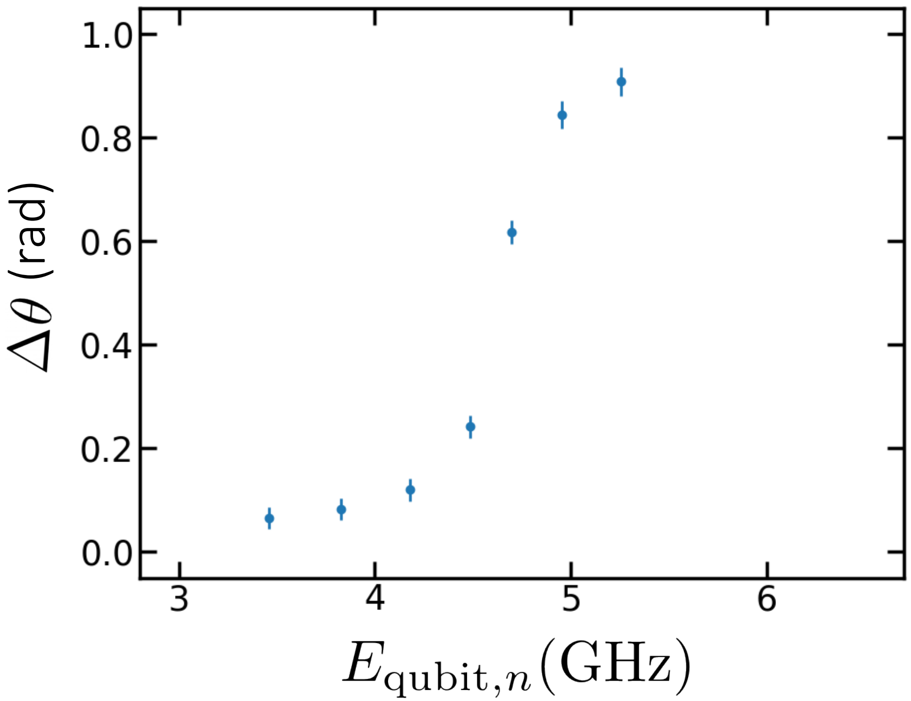

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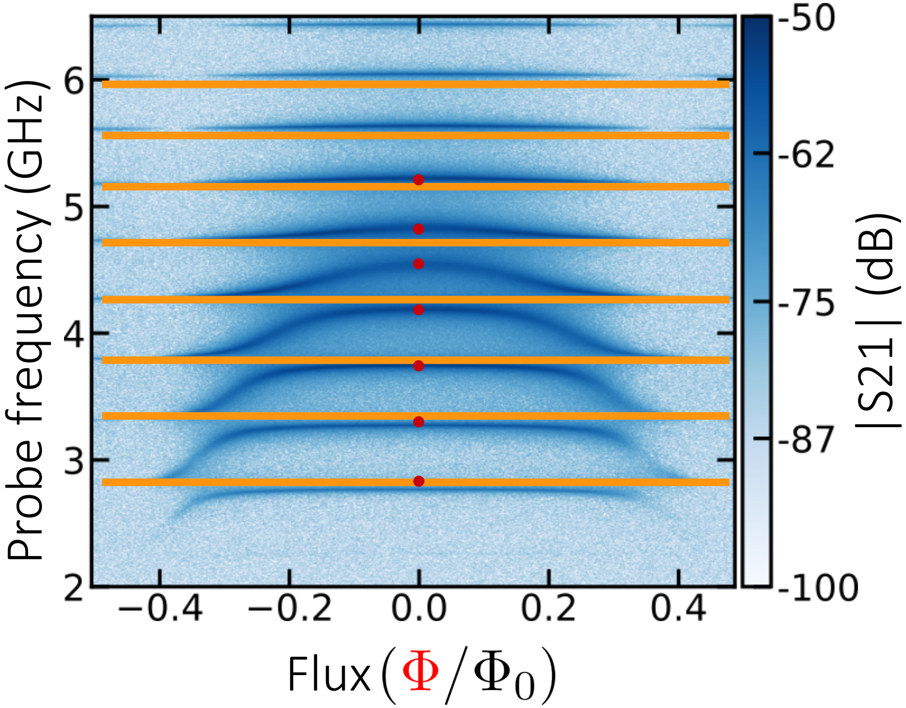

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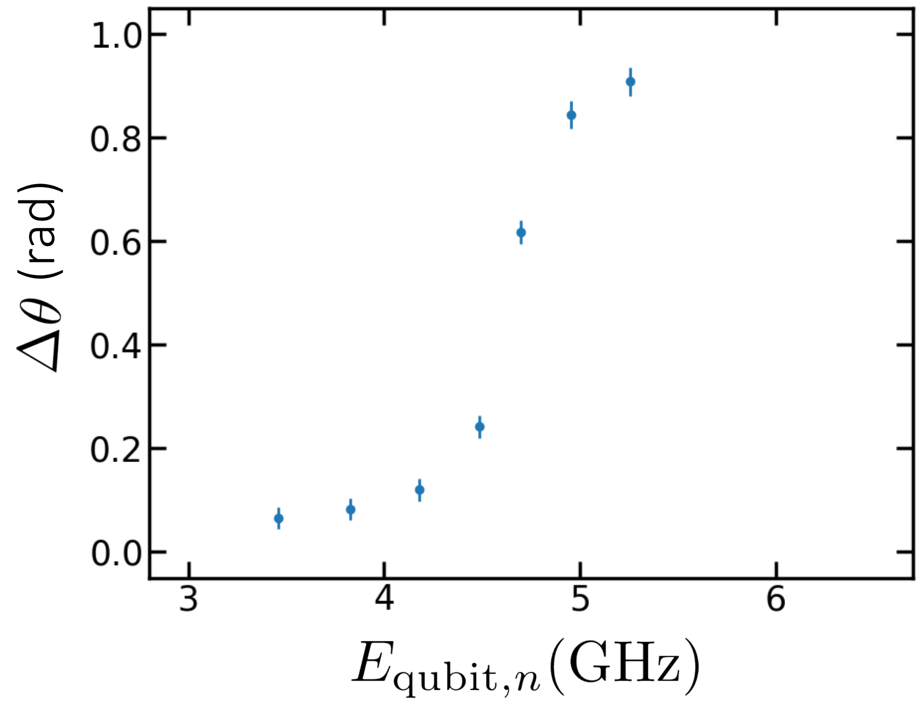

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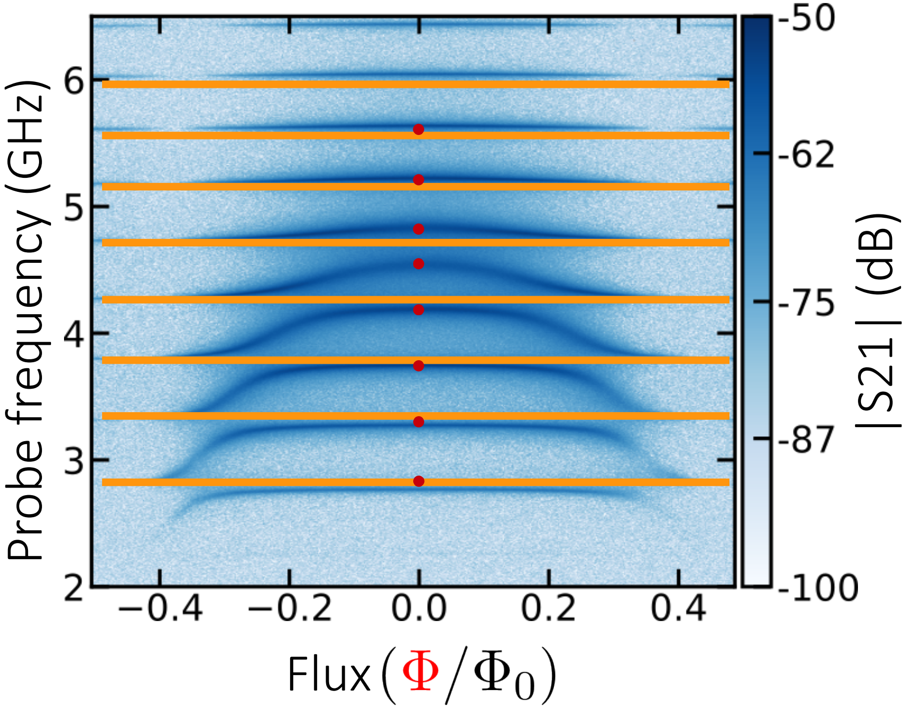

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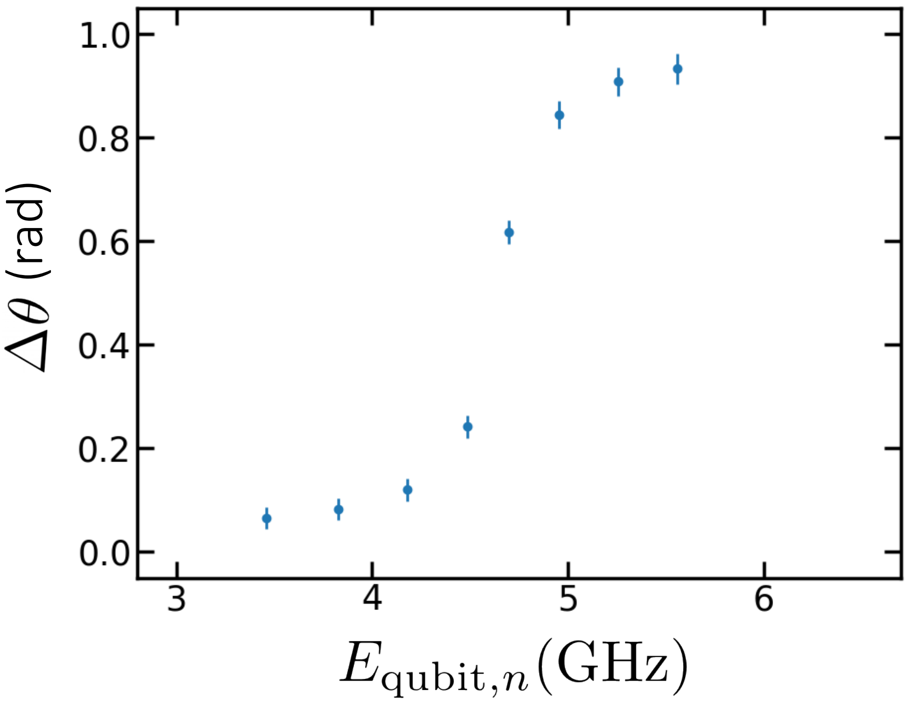

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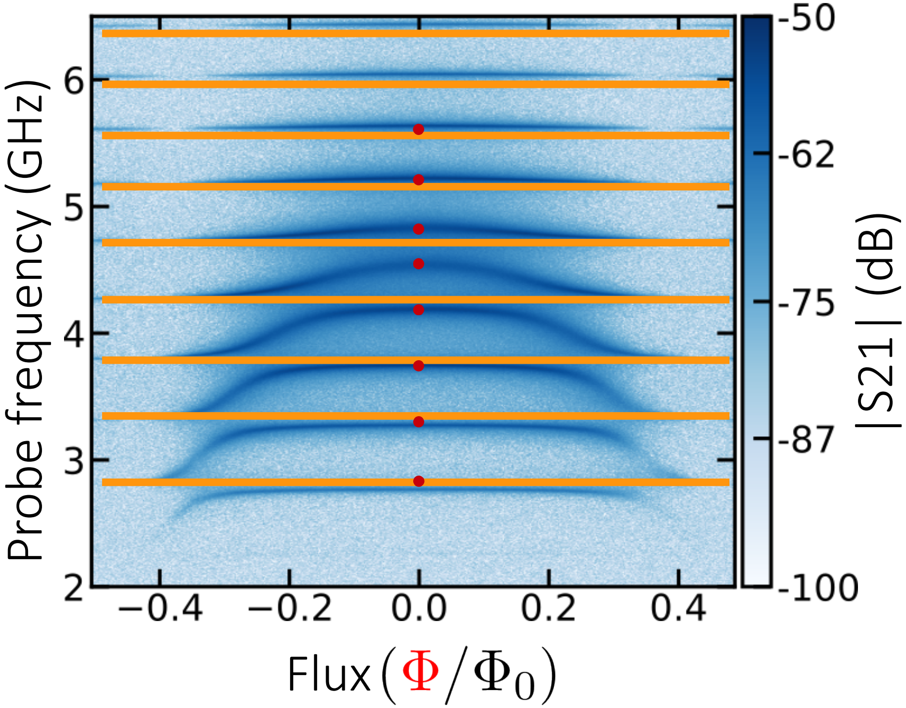

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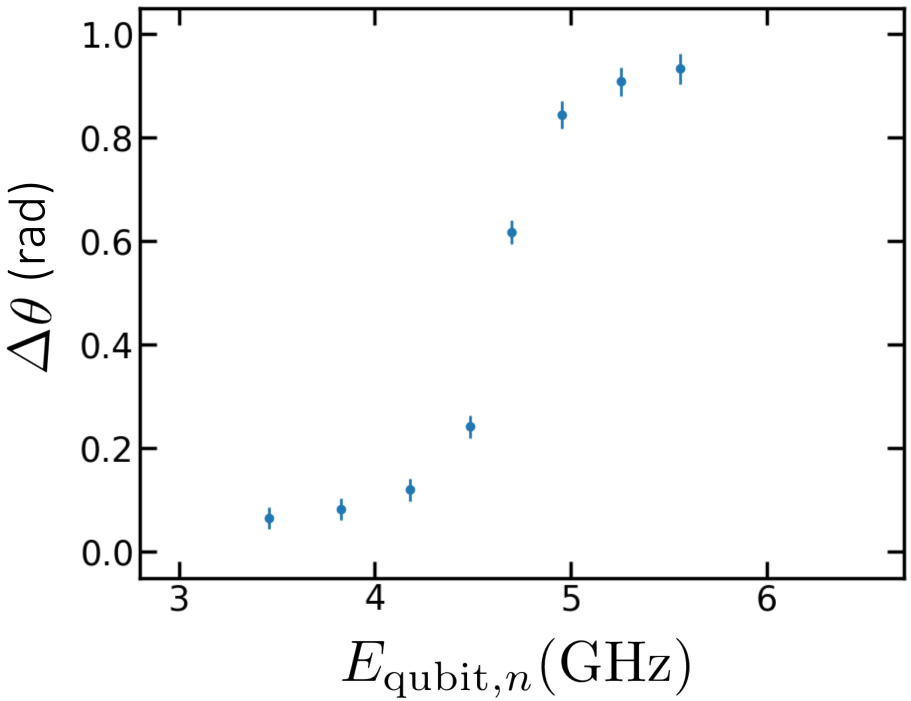

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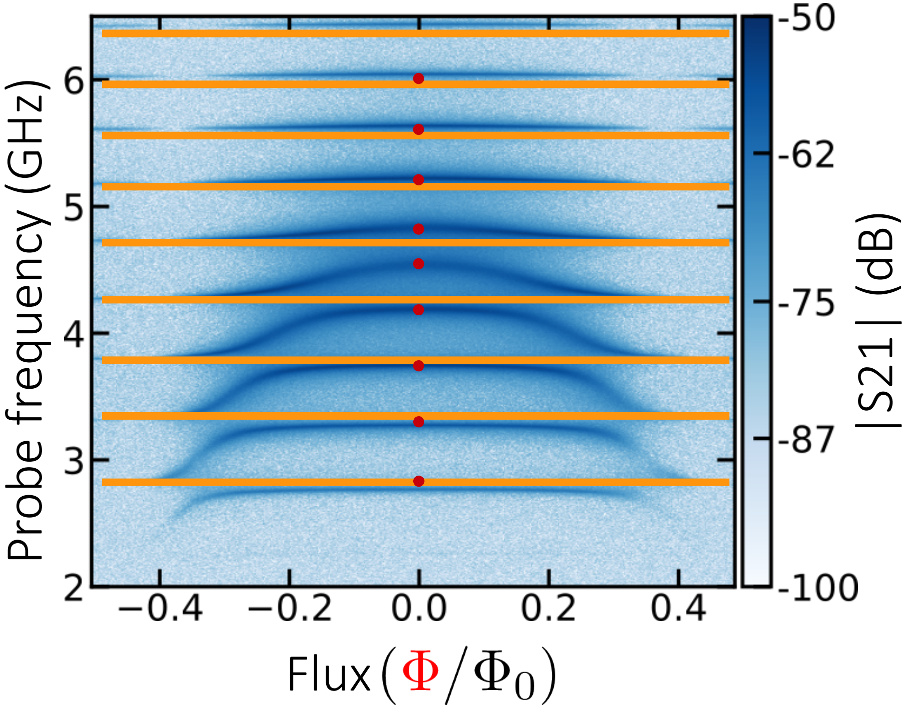

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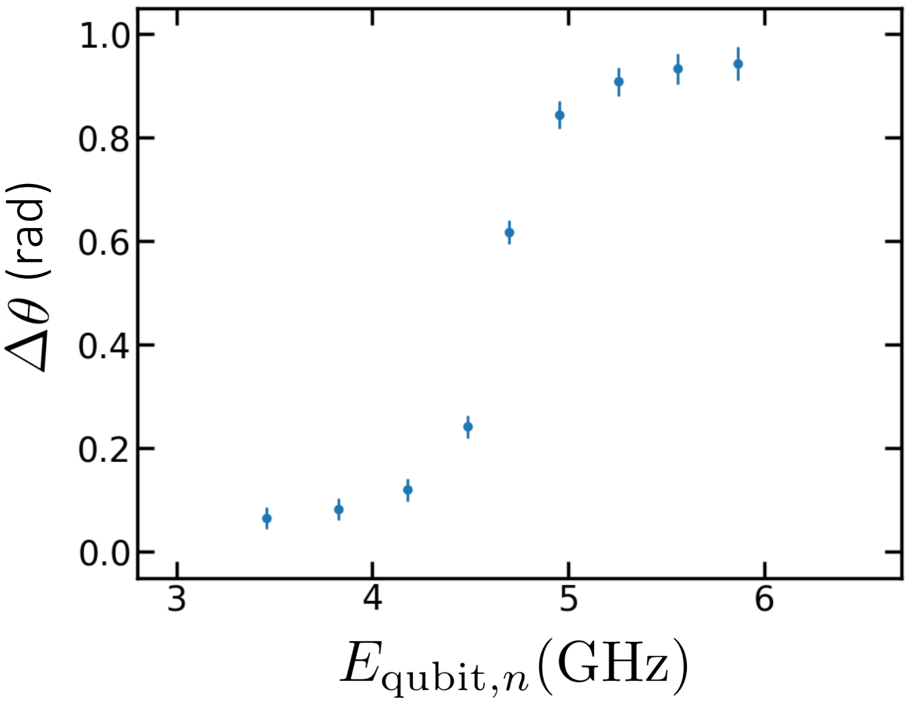

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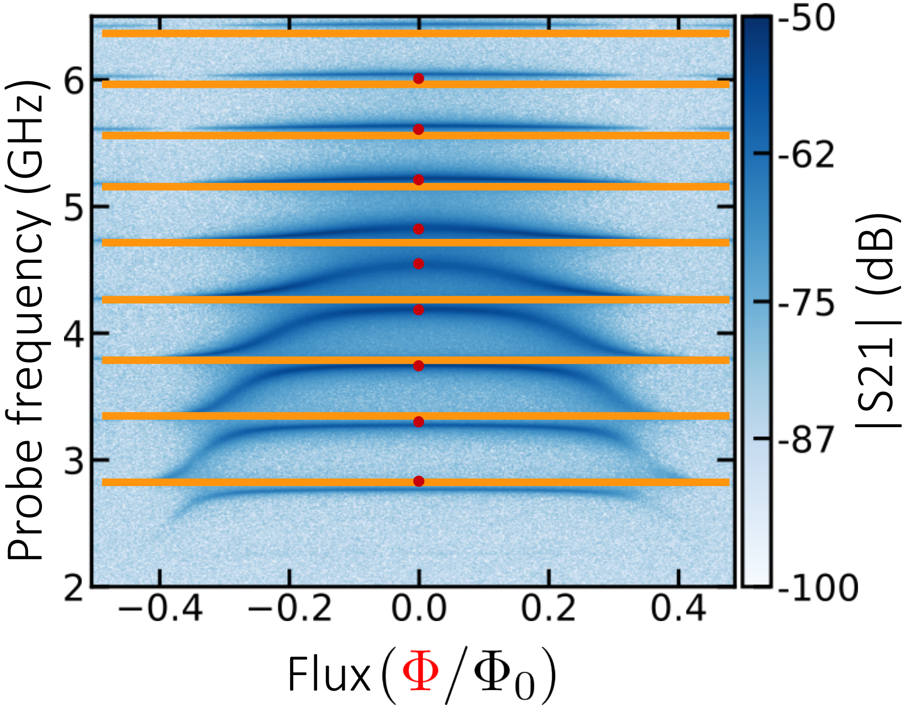
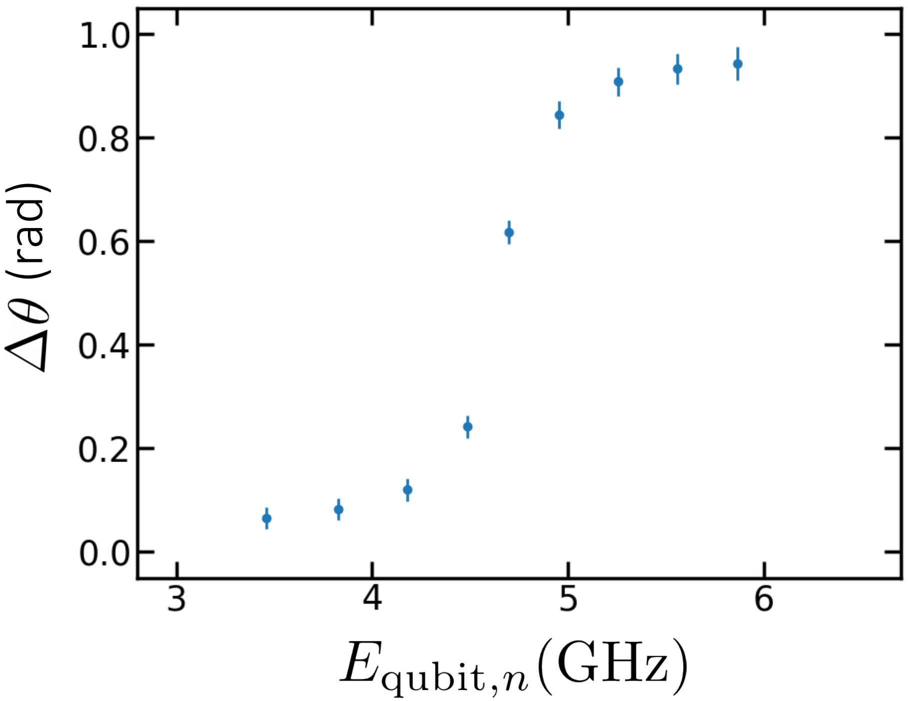


We need a theory to fit this data

The transmon phase shift

$$\Delta\theta = \frac{E_{\text{bare, n}} - E_{\text{qubit, n}}}{E_{\text{bare, n + 1}} - E_{\text{bare, n}}}$$



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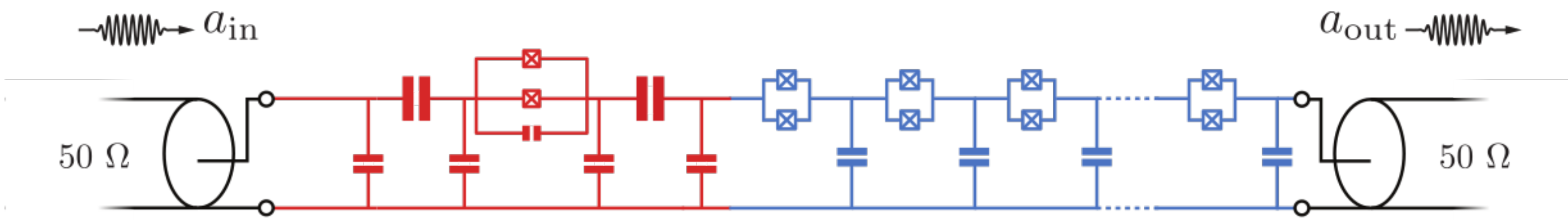


System

Array of 4700 SQUIDs = 4700 modes

$$\vec{n} = |n_1, n_2, \ldots, n_{N-1}, n_N\rangle$$

Transmon levels

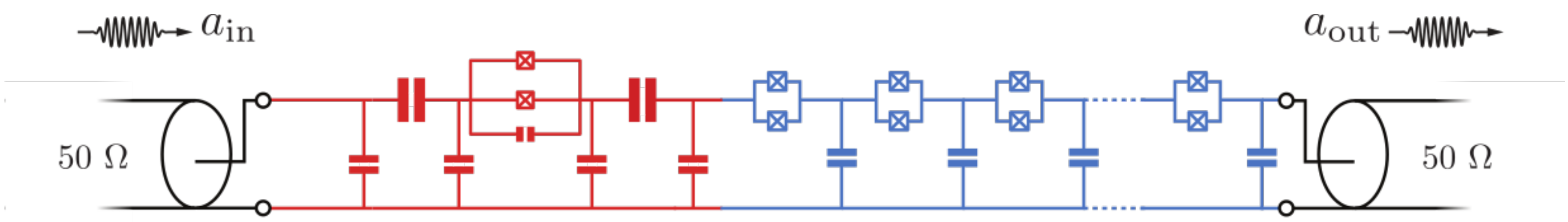
$$|t\rangle$$

Huge Hilbert space!

Brute force diagonalization is impossible

➡ Different approach

Transmon coupled to an array of SQUIDs



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Transmon levels

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Huge Hilbert space!

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→ Different approach

Theoretical assumptions

- Lumped element model with the chain assumed linear

$$E_{J,\rm chain}/E_{C,\rm chain} \simeq 8000$$

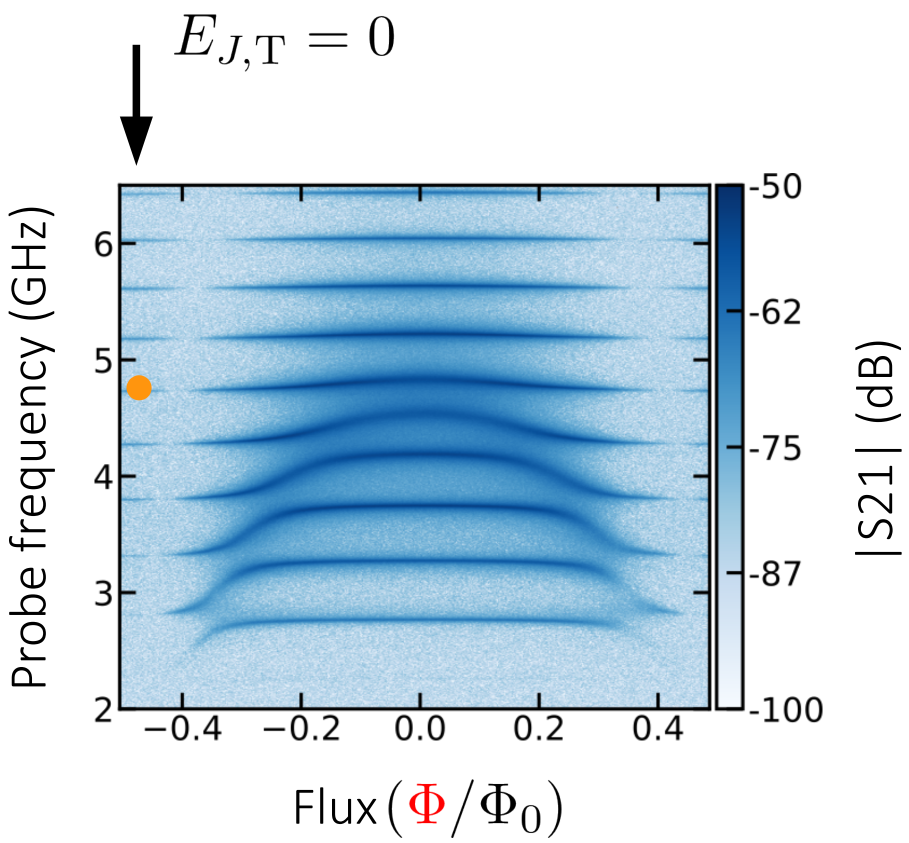
- Non-linearity of the transmon treated using the Self Consistent Harmonic Approximation.
- Thermodynamic limit, we assume that the chain is semi infinite

$$N \to \infty$$

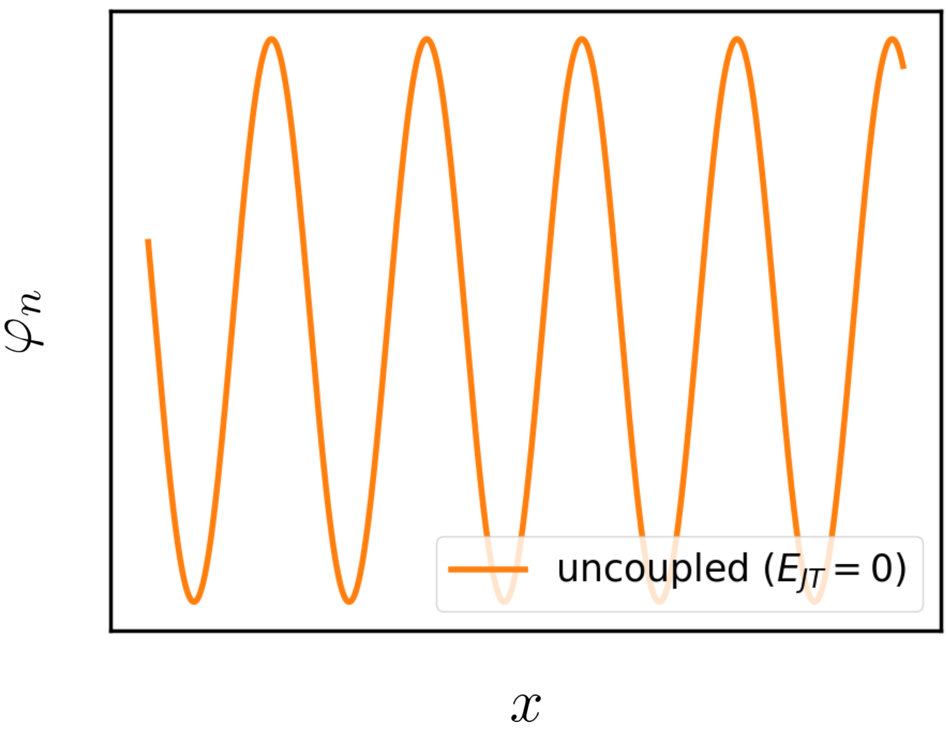
Analytically solvable

Transmon coupled to an array of SQUIDs

The transmon phase shift



$$\varphi_n \propto \cos\left[\kappa_n x - \phi\left(E_{J,\mathrm{T}} = 0\right)\right]$$



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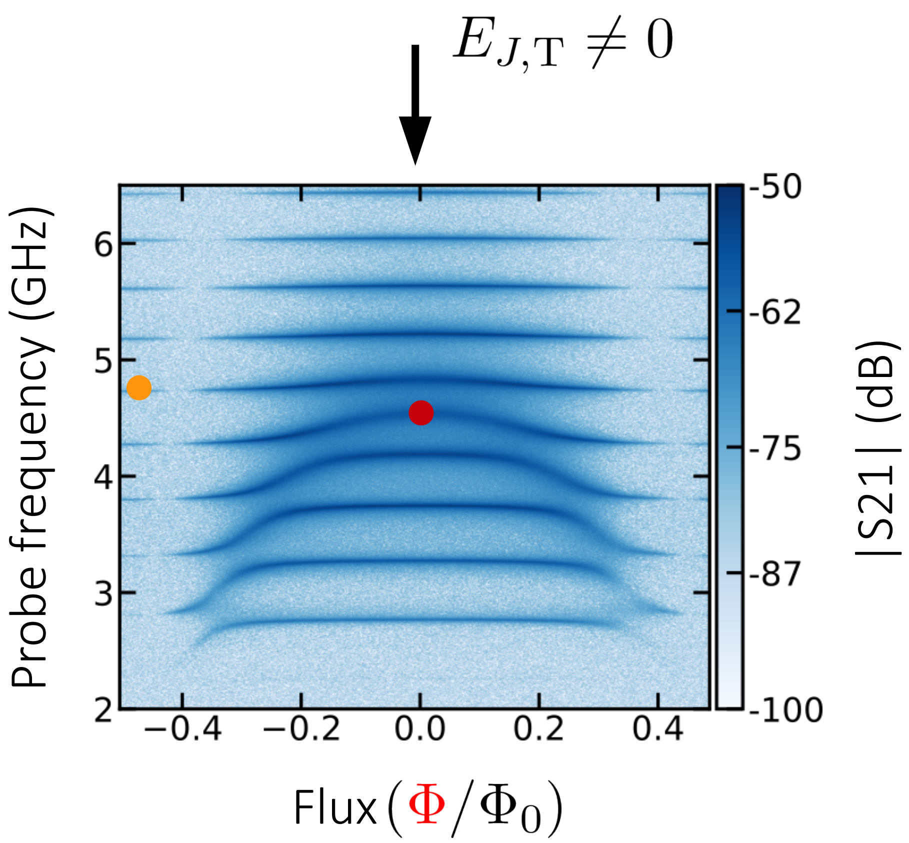
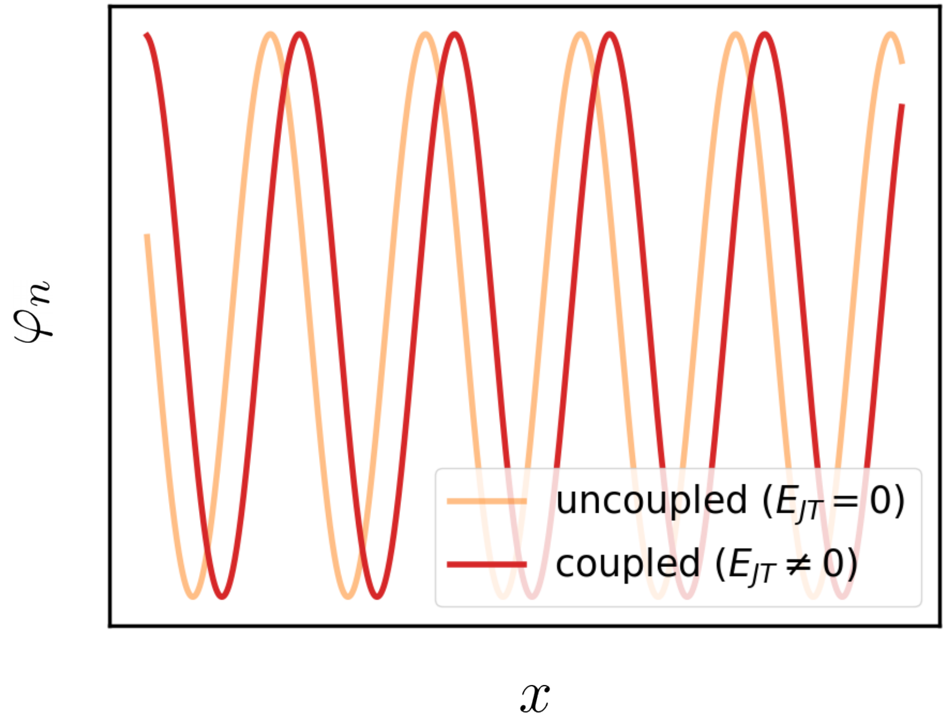


$$\varphi_n \propto \cos\left[\kappa_n x - \phi\left(E_{J,\mathrm{T}} \neq 0\right)\right]$$



$$\Delta\theta = \left[\phi\left(E_{J,\mathrm{T}} = 0\right) - \phi\left(E_{J,\mathrm{T}} \neq 0\right)\right]/\pi$$

$$\Delta\theta \sim 0.5$$

Transmon coupled to an array of SQUIDs

The transmon phase shift

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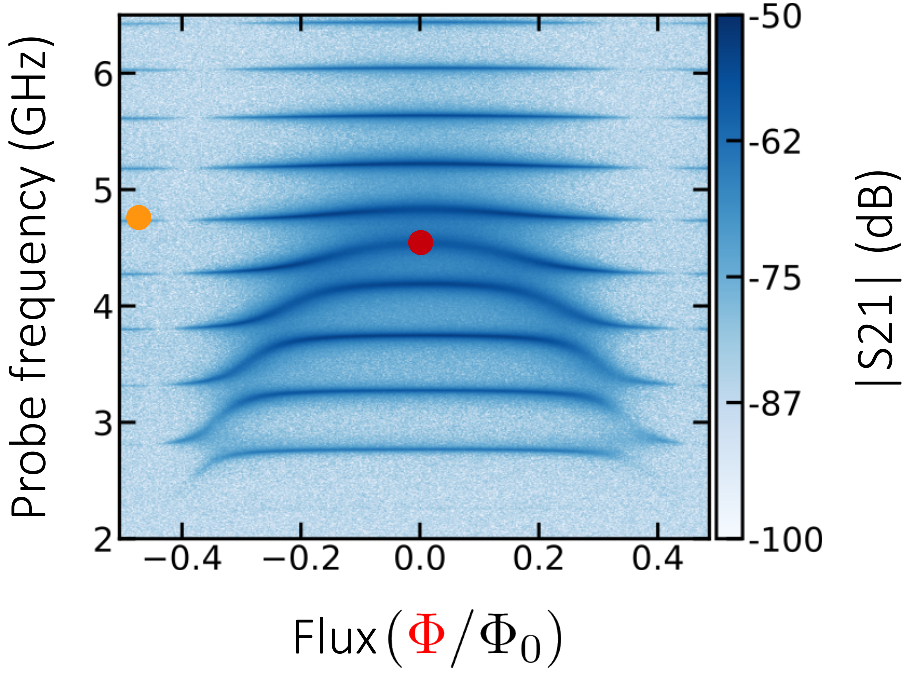
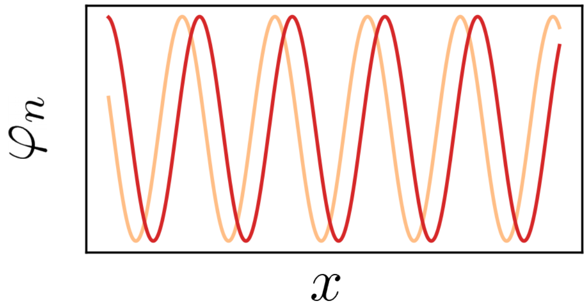
$$N \to \infty$$





$$\omega_{\mathrm{n}} \simeq \omega_{\mathrm{T}}$$

$$\Delta\theta \sim 0.5$$

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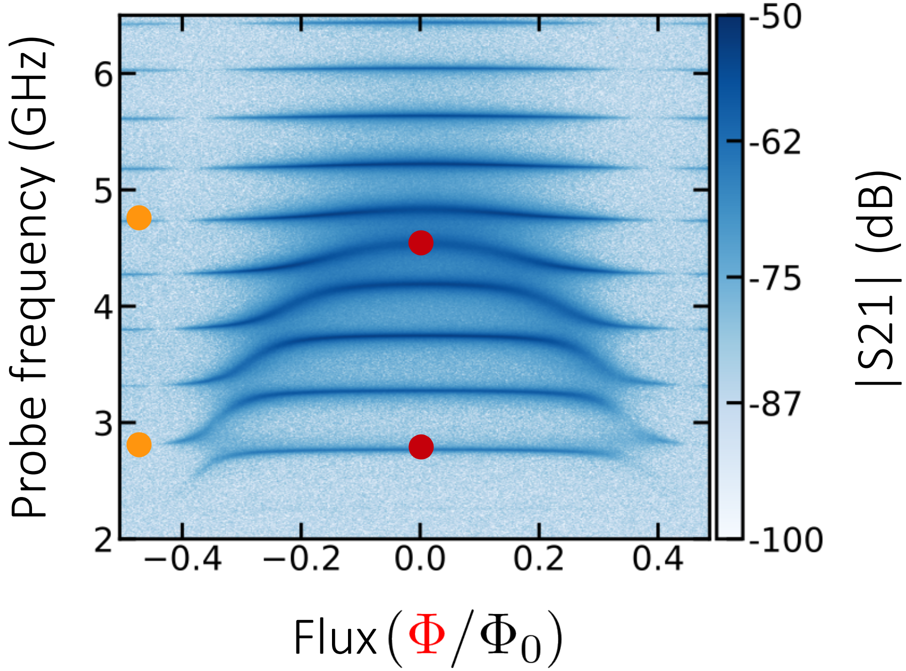

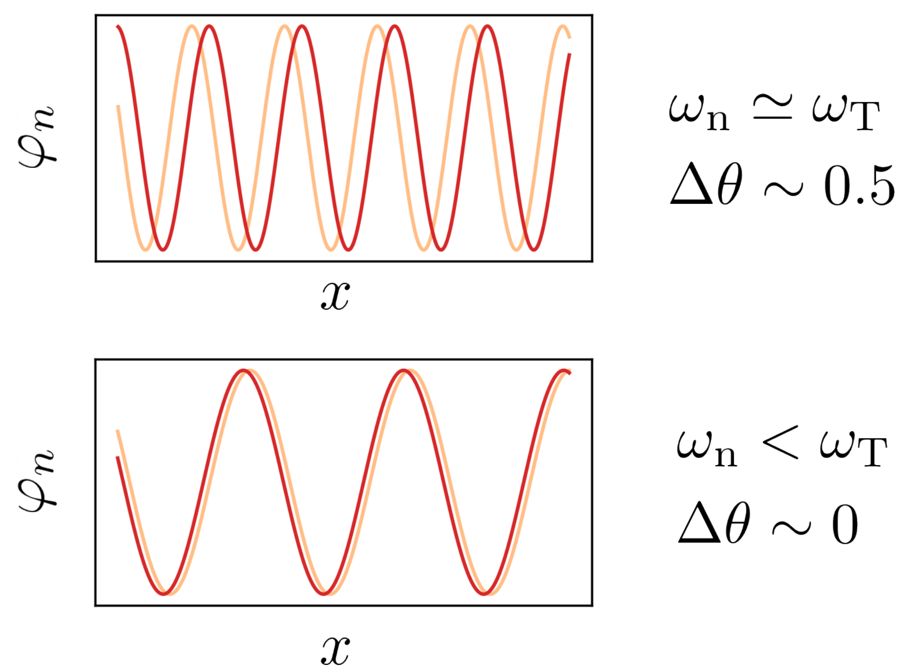

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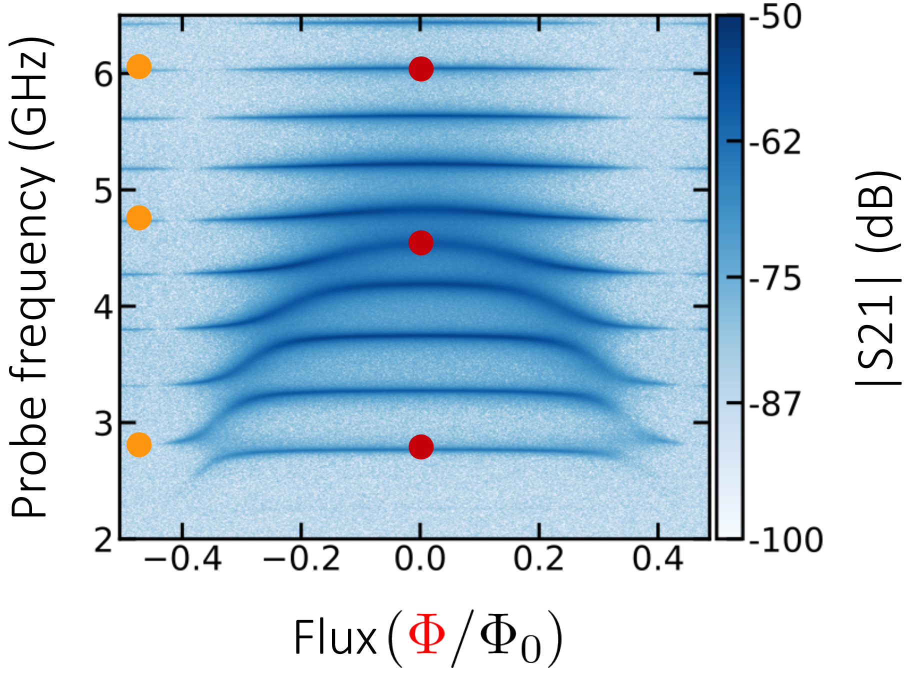

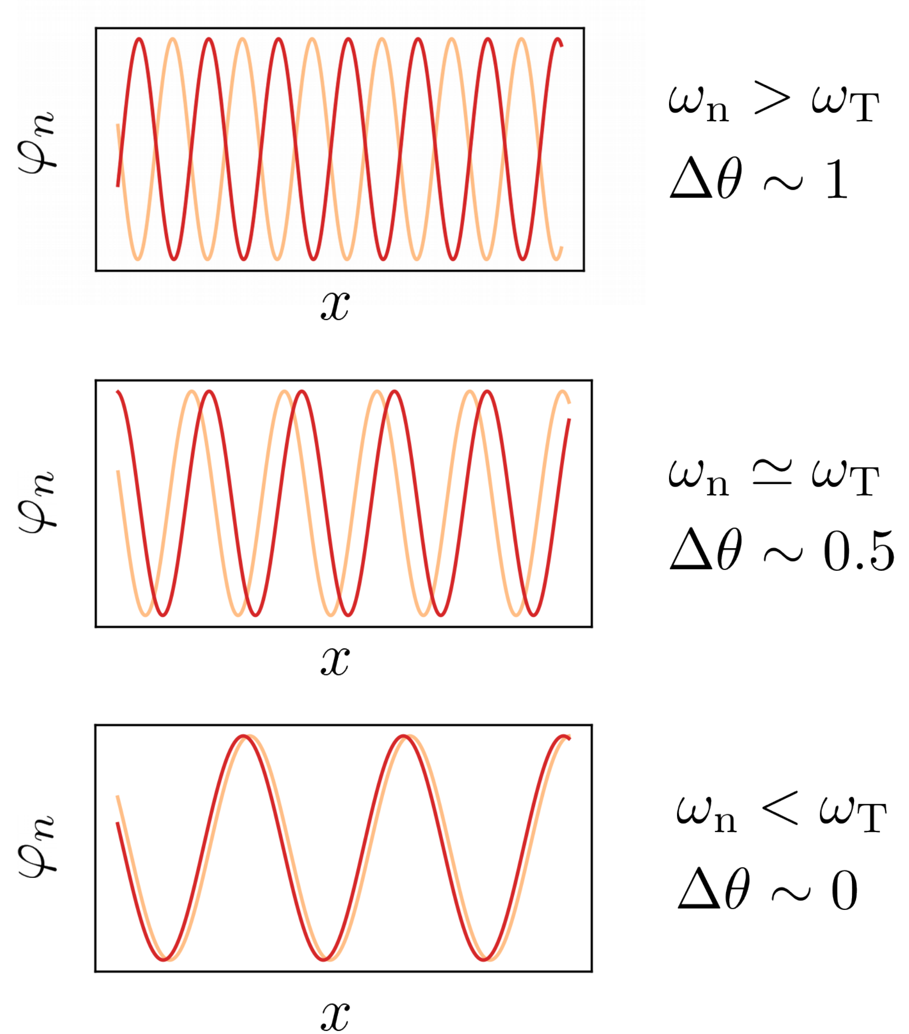

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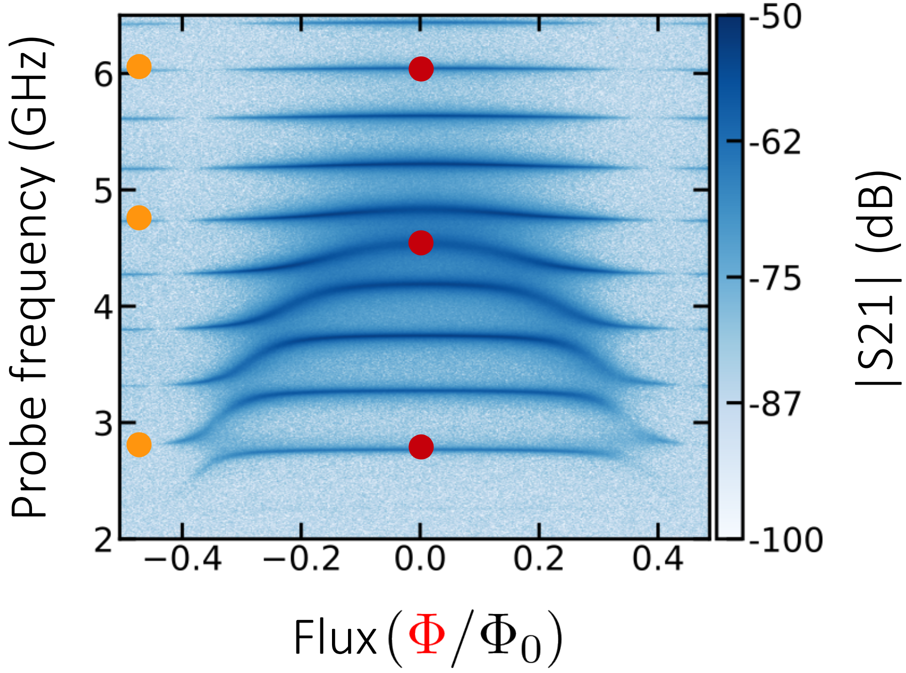

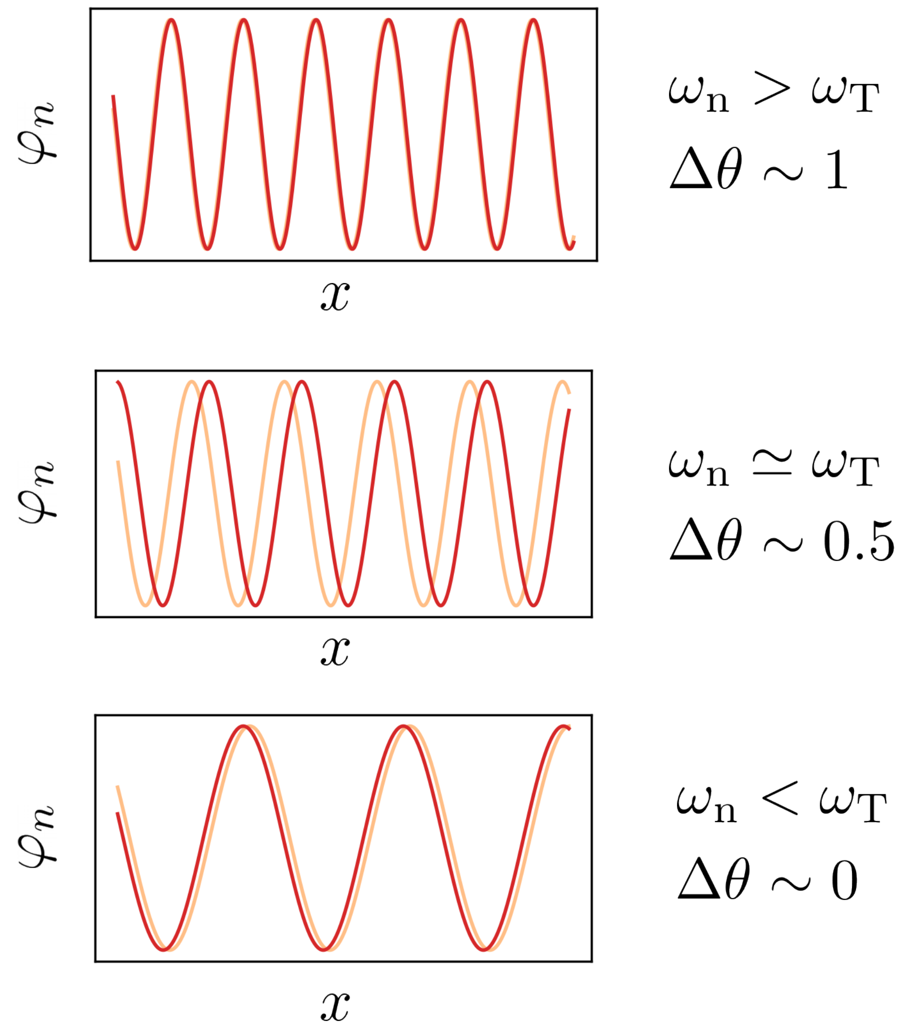

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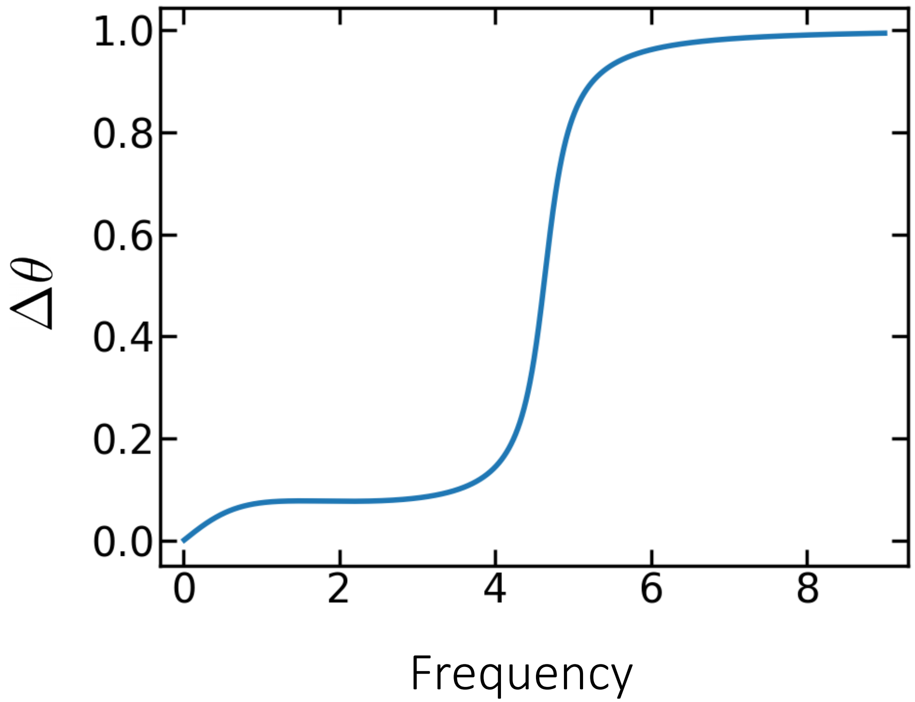

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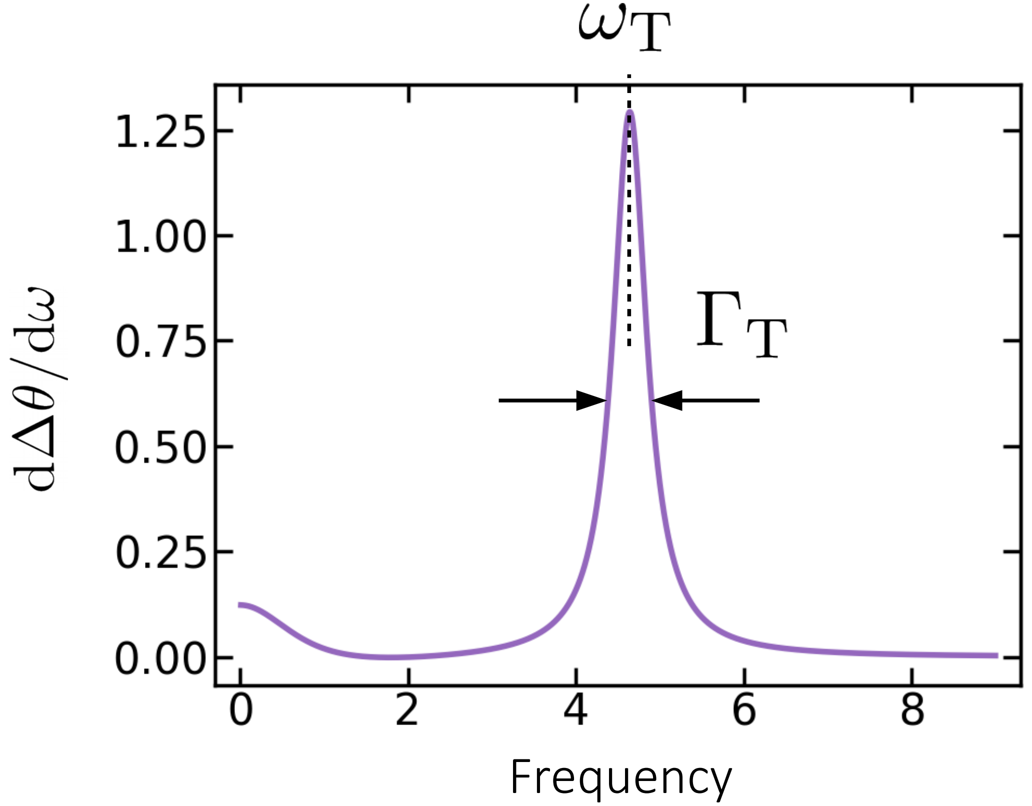

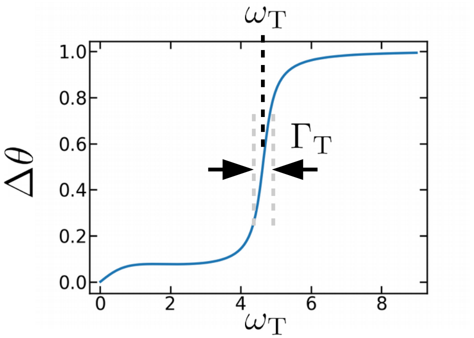

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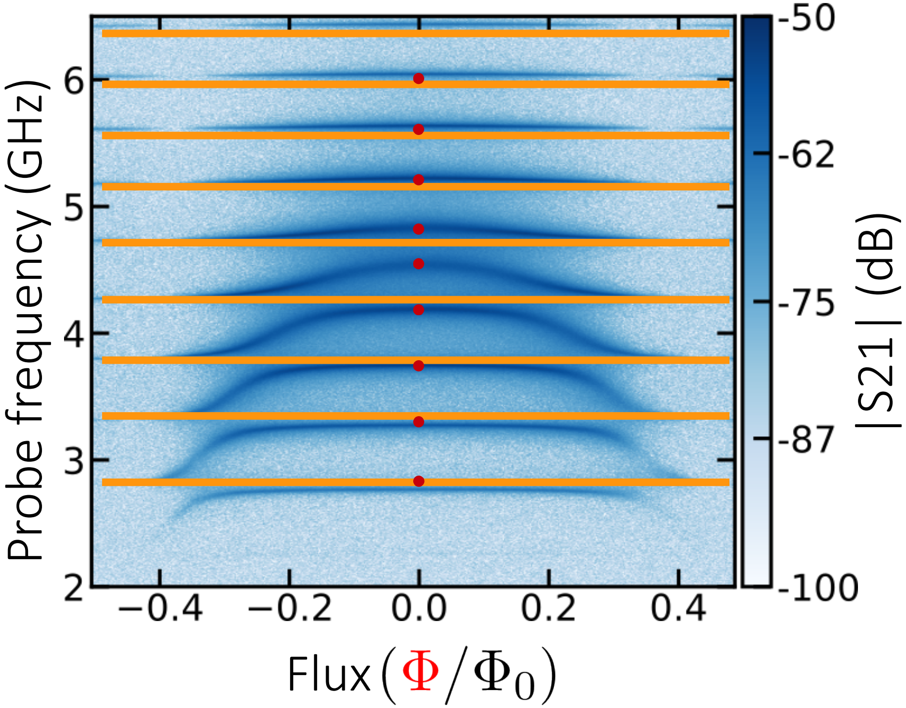

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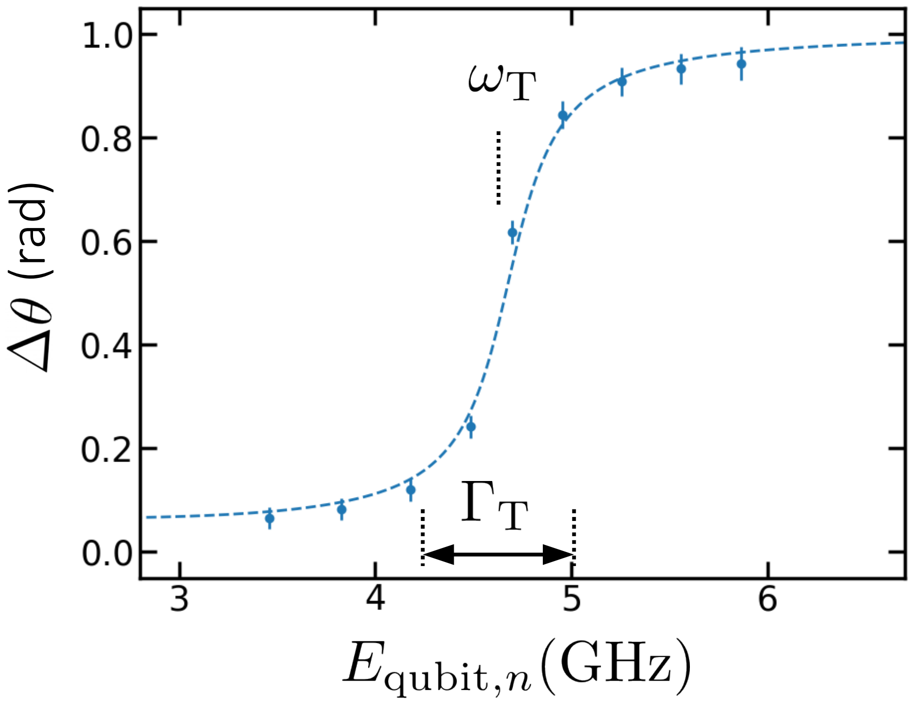
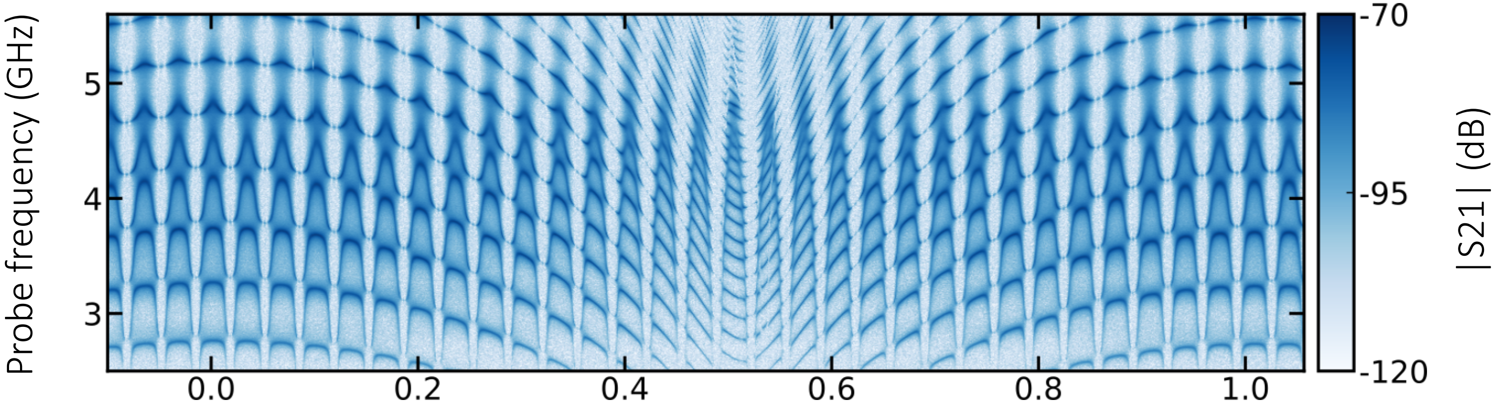


Good data theory agreement
with no fitting parameter

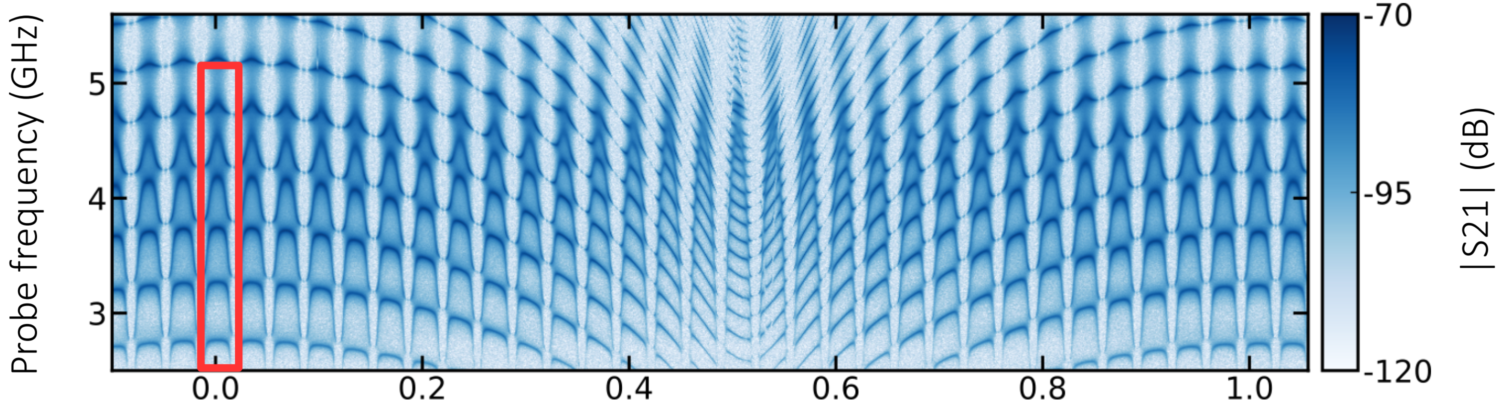
Mesoscopic environment effectively infinite

Up to 10 hybridized modes!

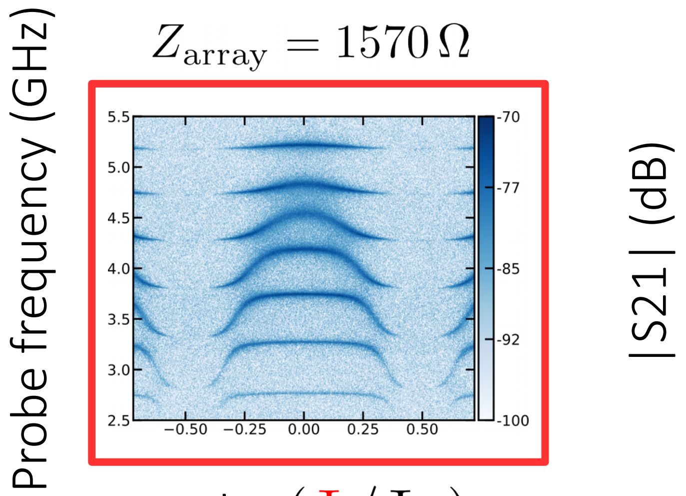
Tuning the environment



Tuning the environment

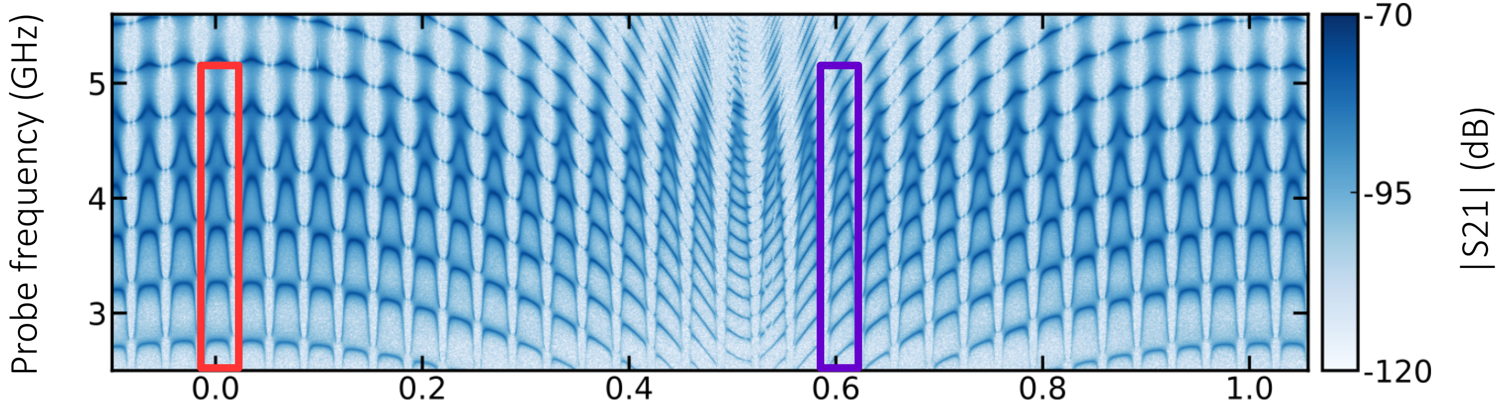


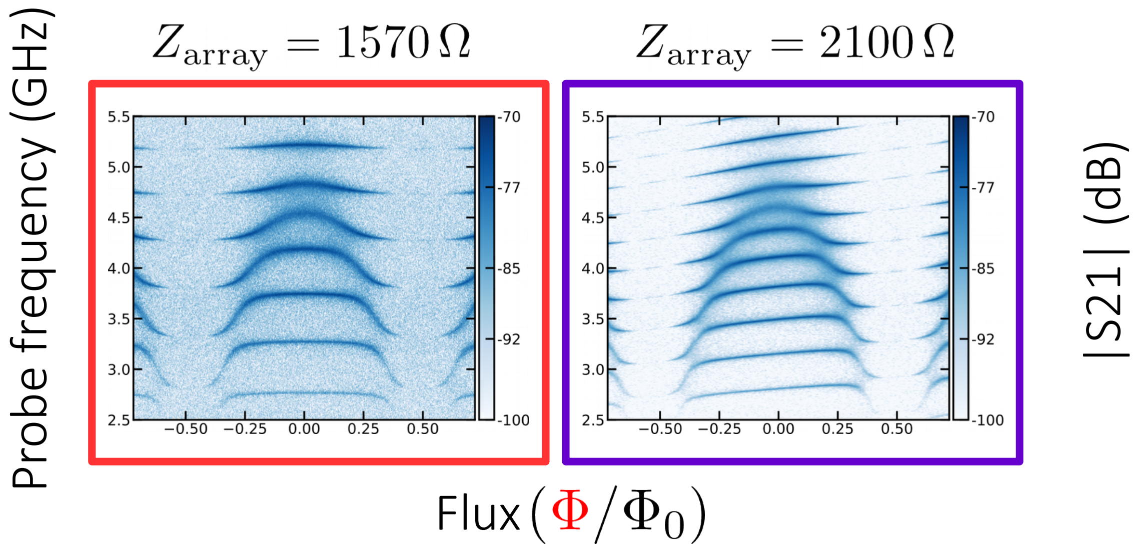
$Z_{\mathrm{array}} = 1570\,\Omega$



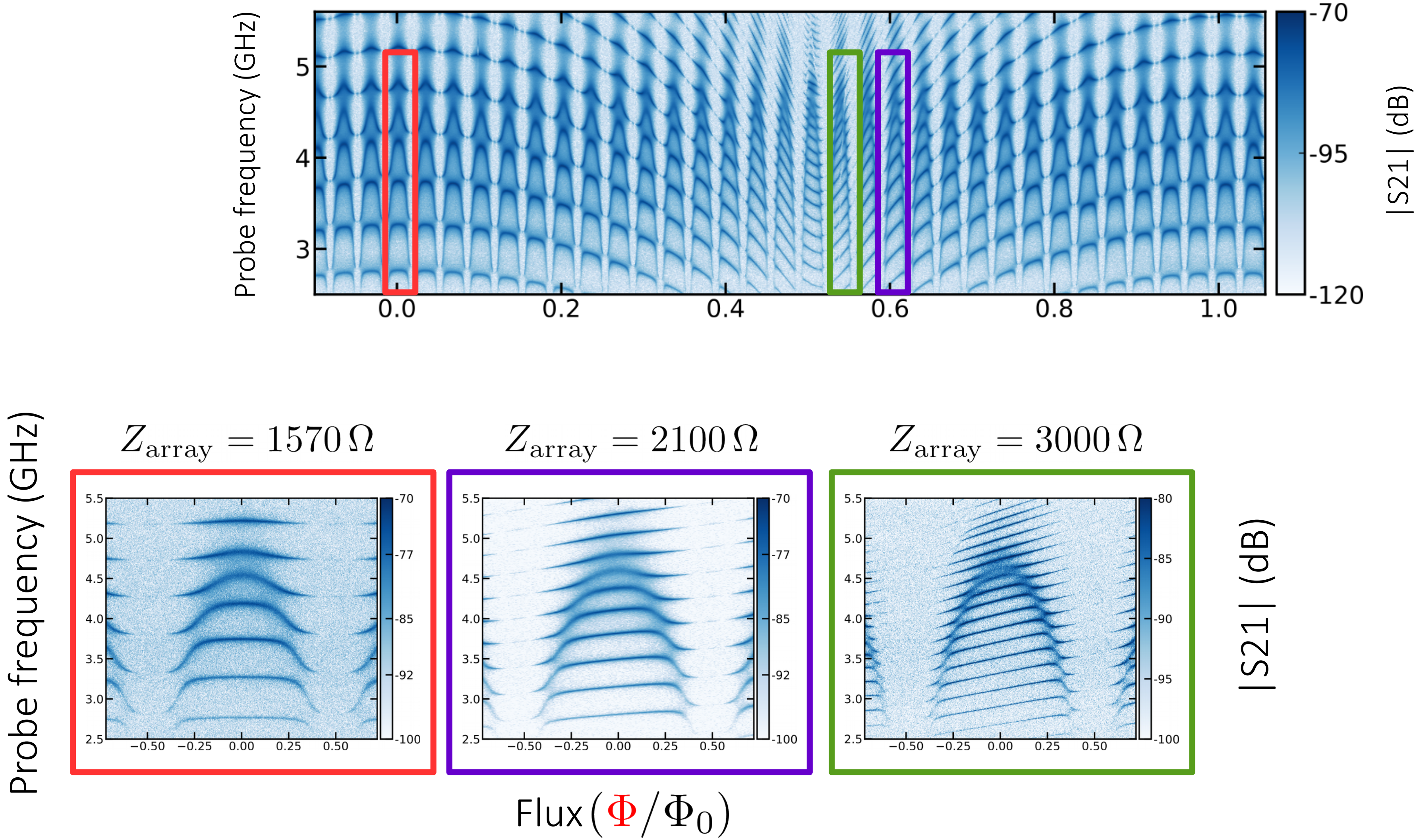
Flux (Φ/Φ_0)

Tuning the environment

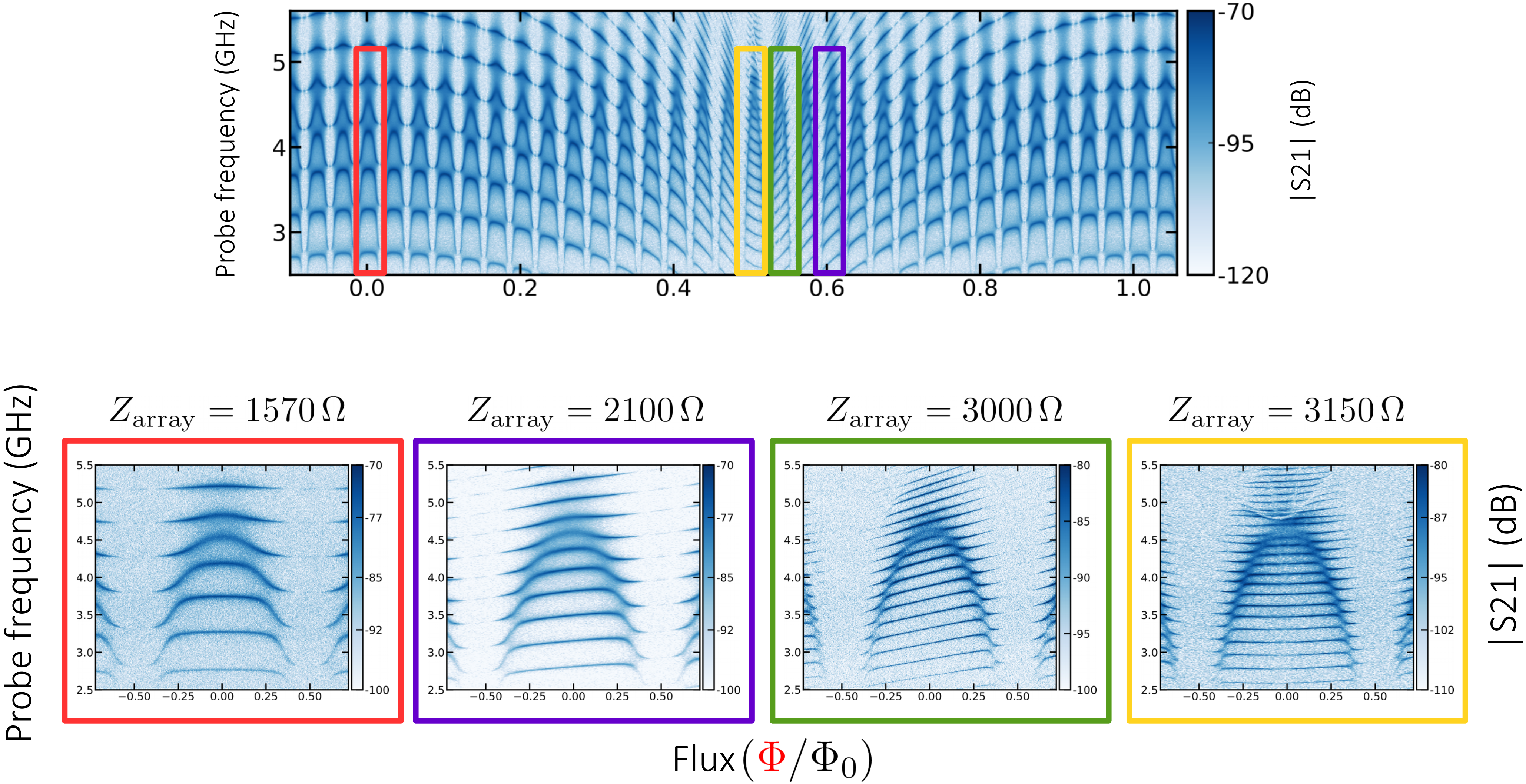




Tuning the environment



Tuning the environment



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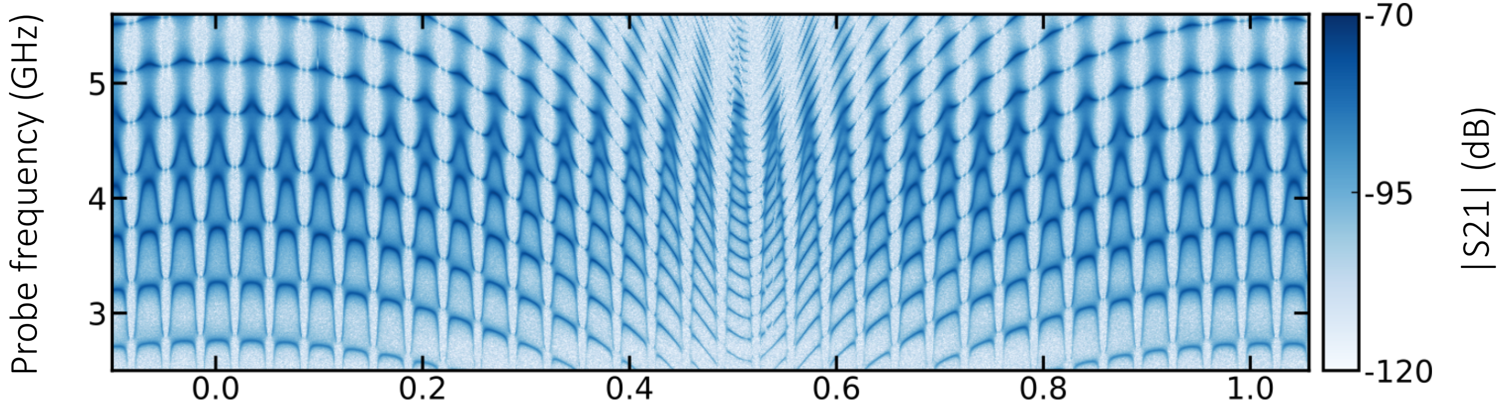

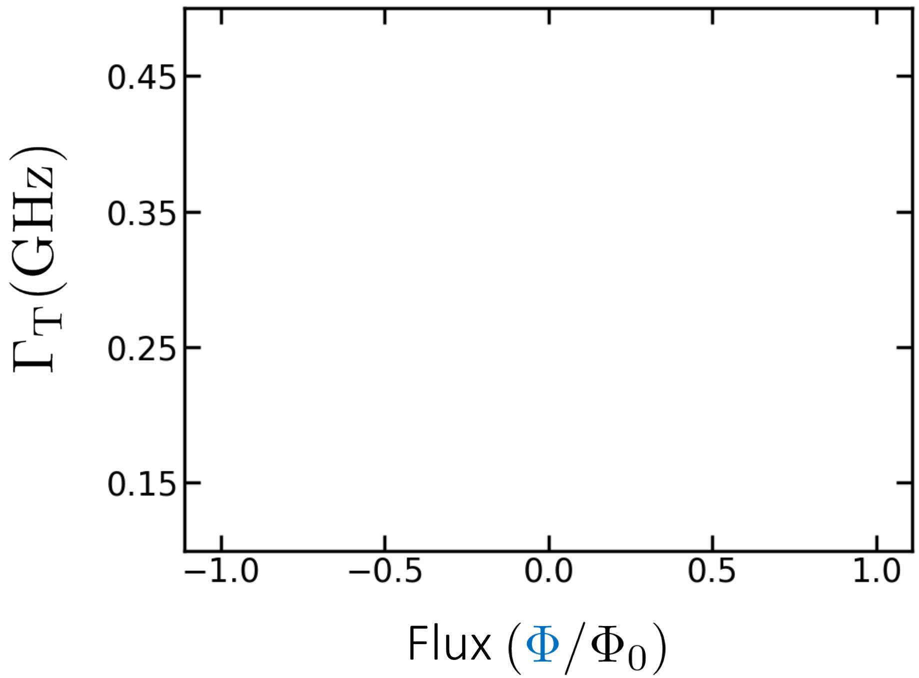

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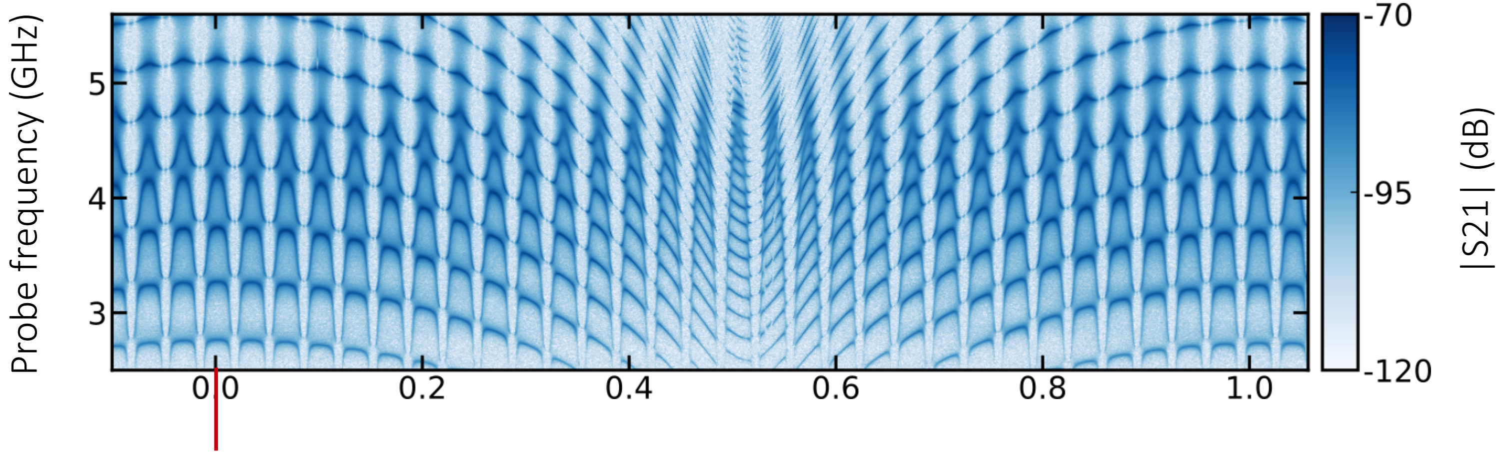
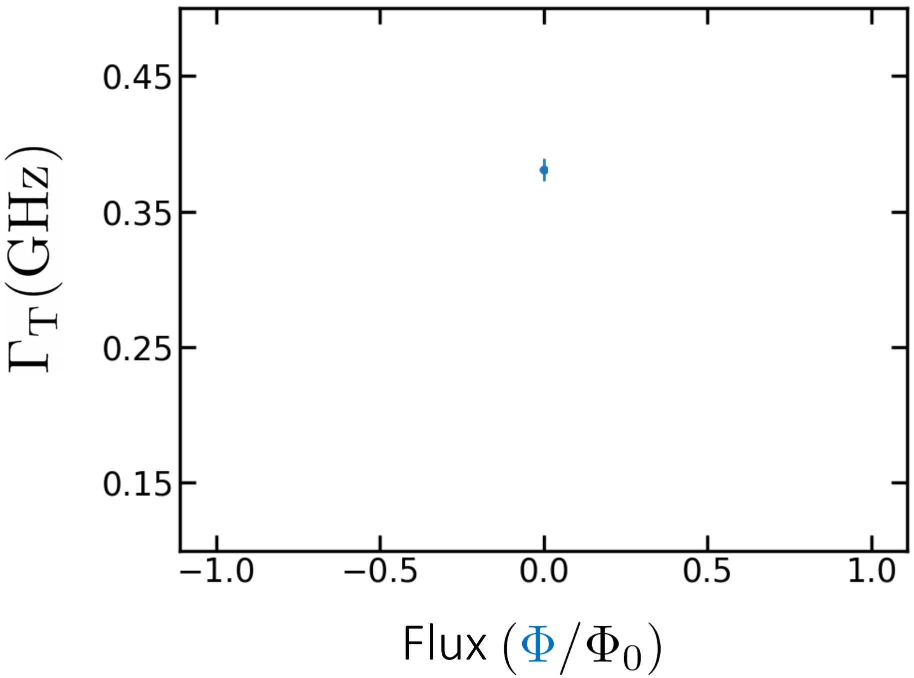
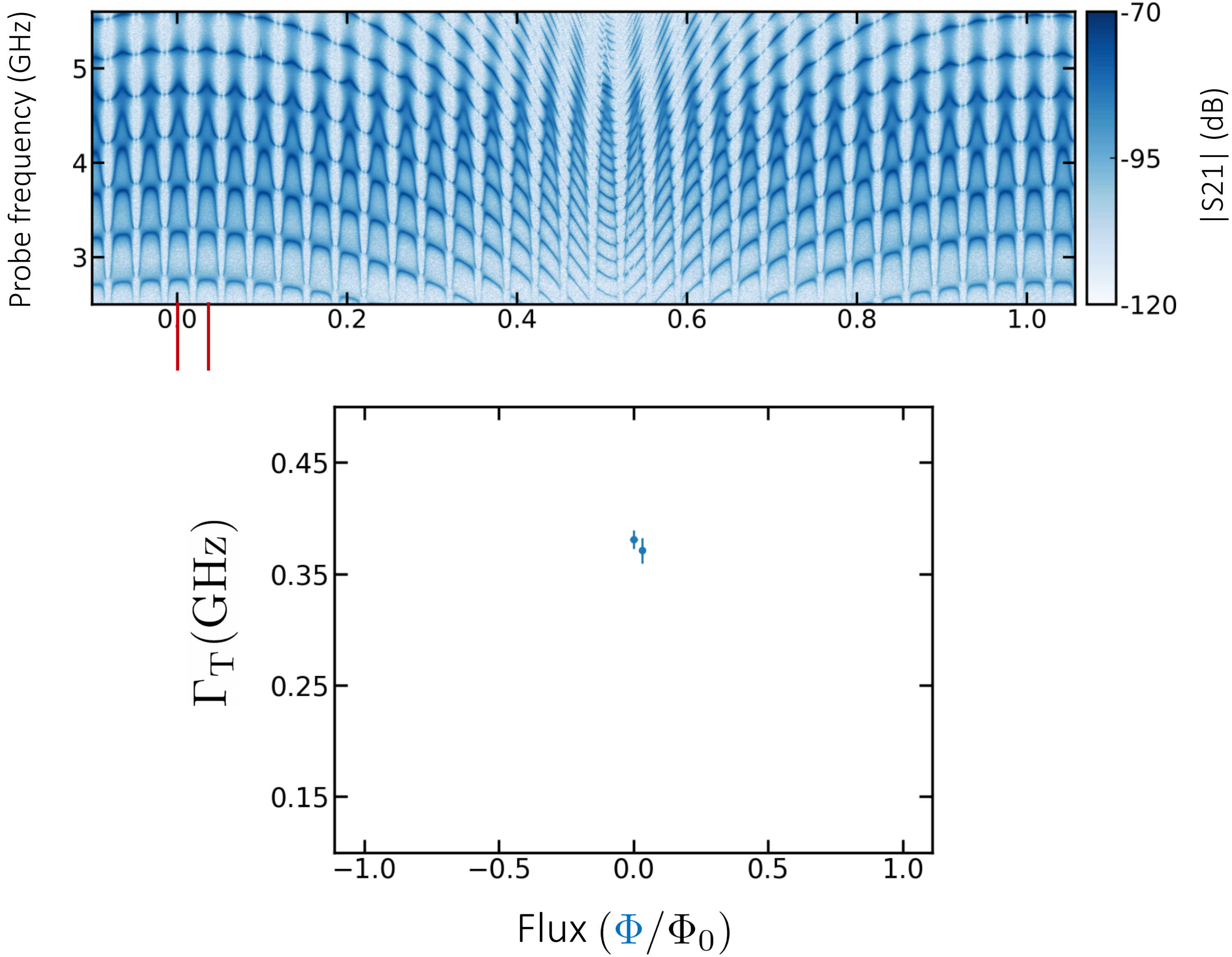




Tuning the environment



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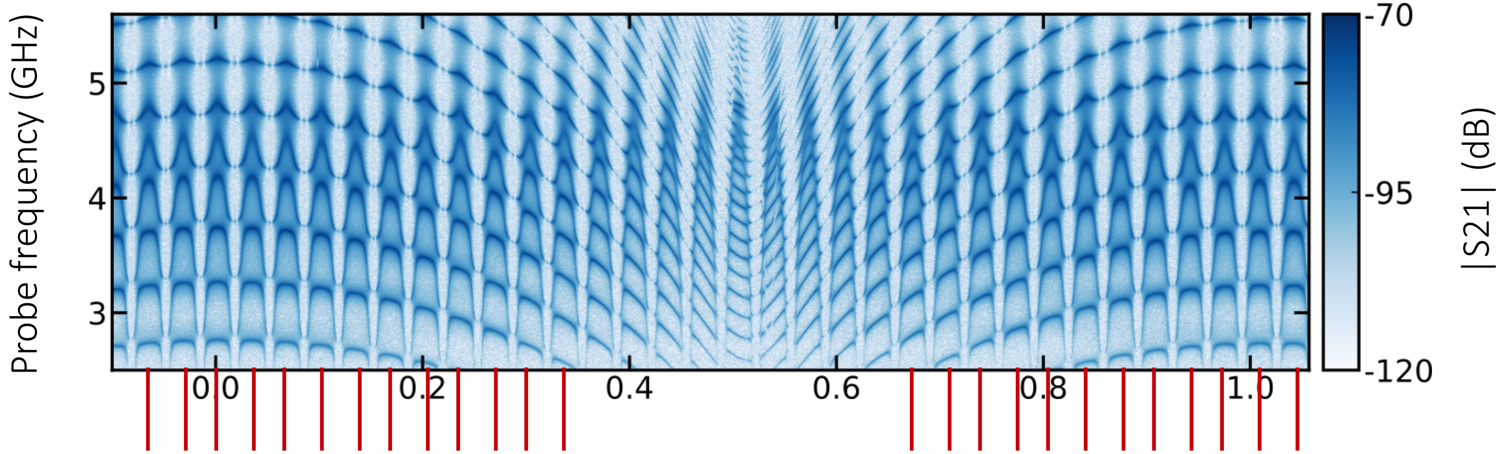

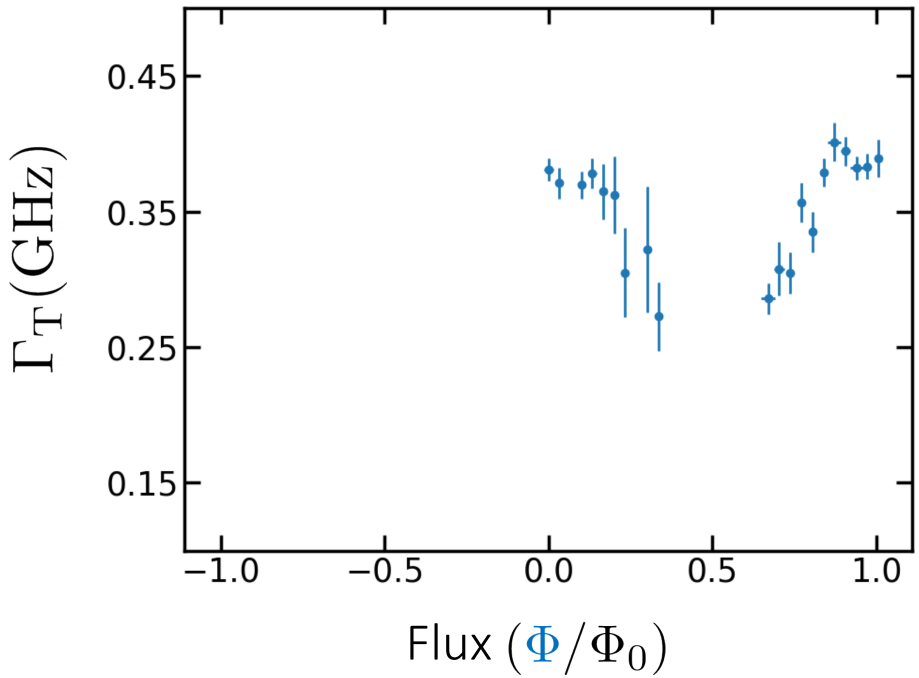

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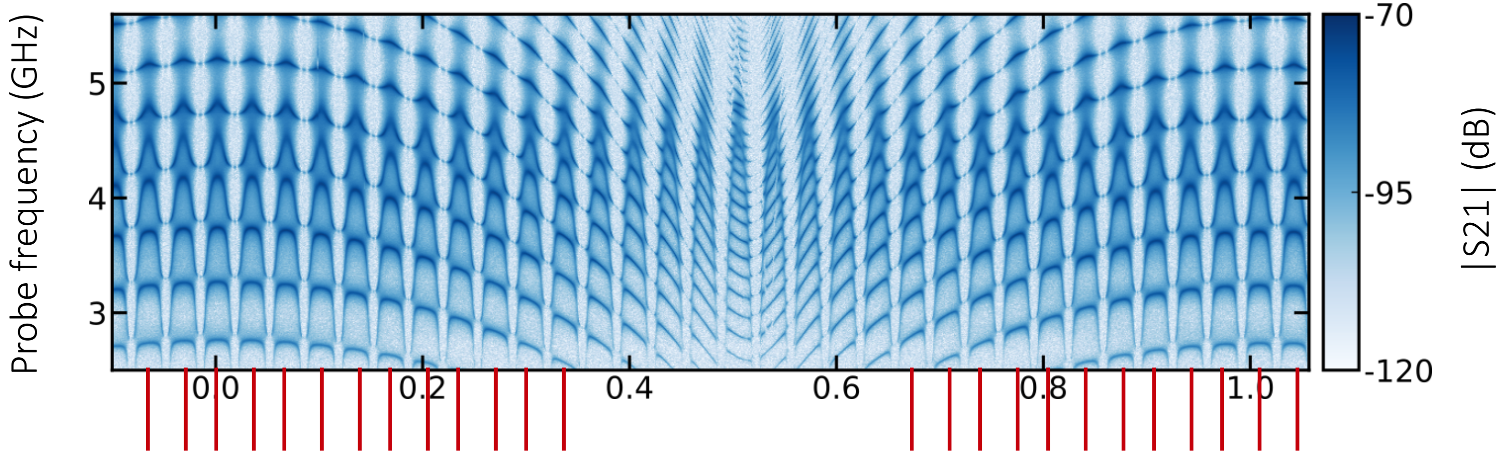
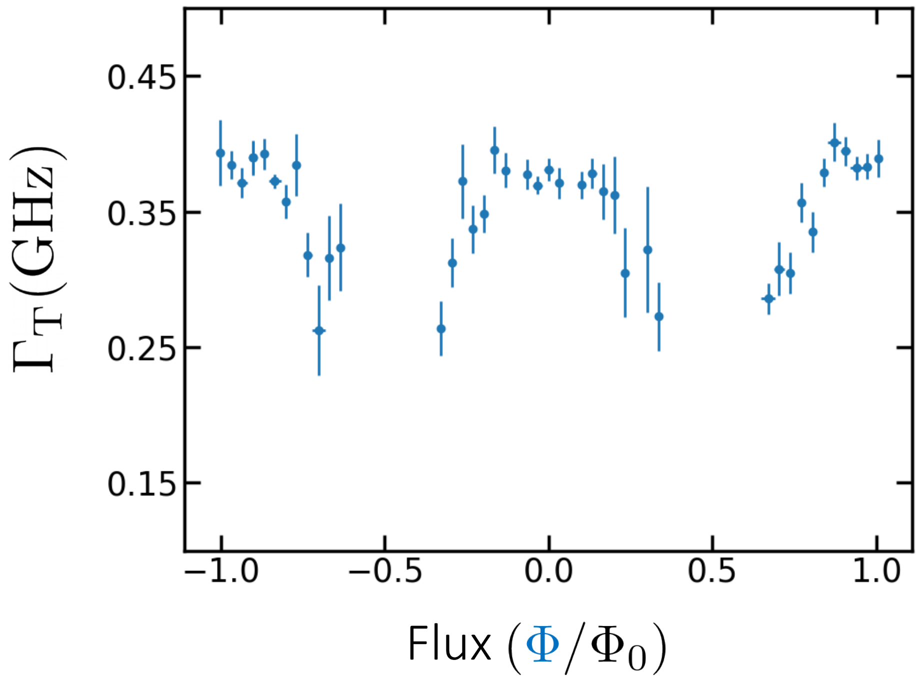
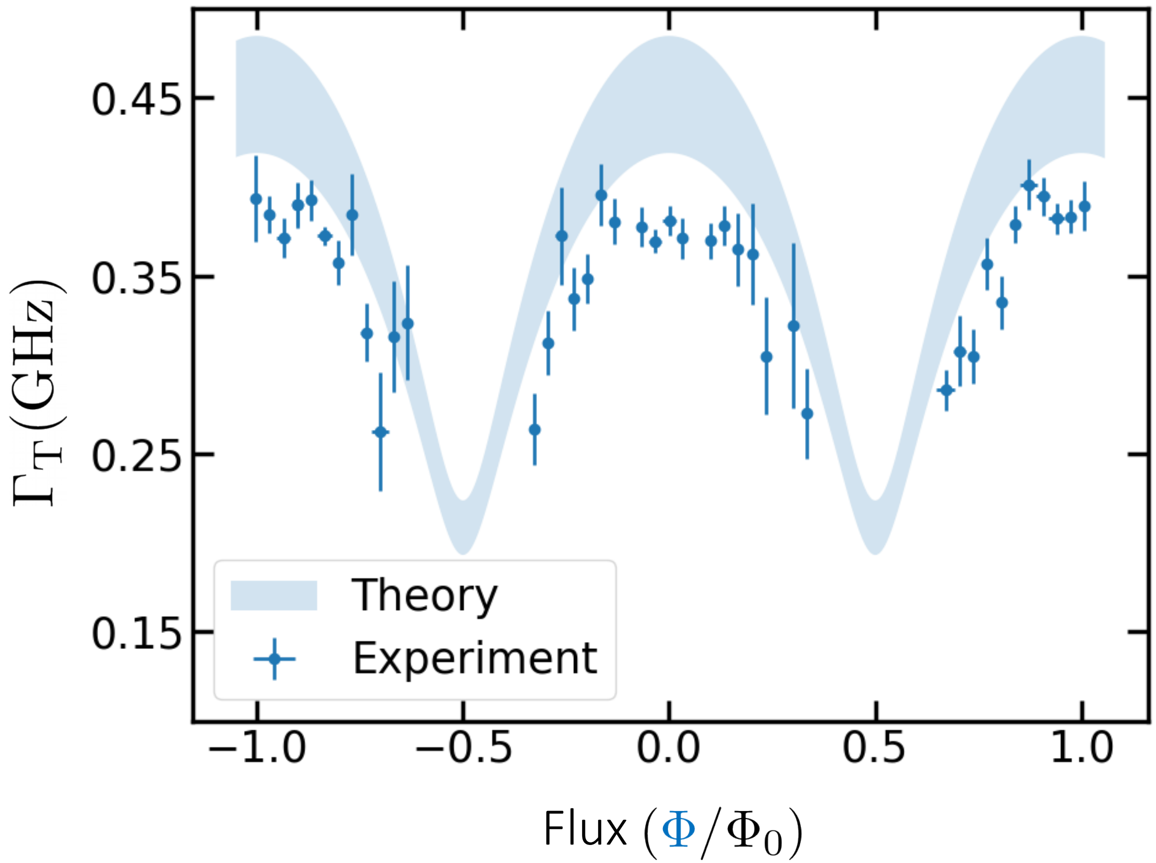




Tuning the environment



Coupling strength

$$\Gamma_T/\omega_T = 10\%$$

In situ environment tuning

Theory experiment agreement

- No fitting parameter
- Theory for an infinite environment

$$N \to \infty$$

System hybridization

$$\frac{\Gamma_T}{\mathrm{FSR}} = 0.96 \pm 0.7$$

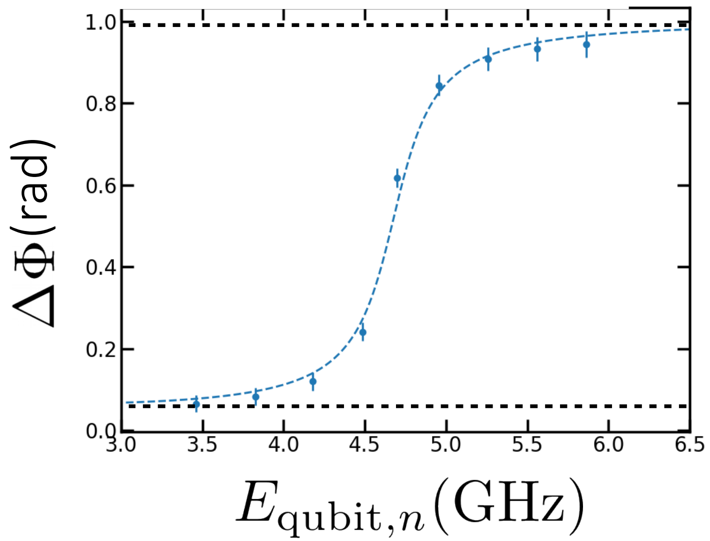
Conclusions

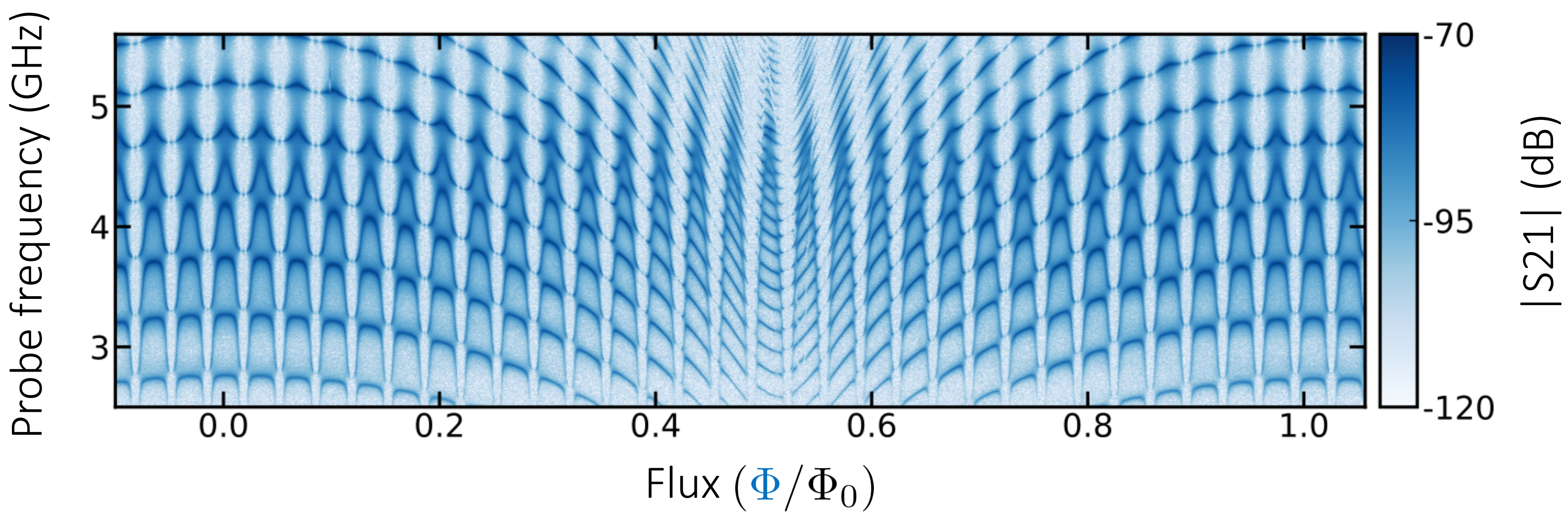
Transmon coupled to a mesoscopic tunable environment

- Mesoscopic environment effectively infinite
- Up to 10 modes coupled to the system
- Ultra-strong coupling and many-body system

$$\Gamma_{\mathrm{T}}/\omega_{\mathrm{T}} = 10\% \qquad \Gamma_{\mathrm{T}} \sim \mathrm{FSR}$$

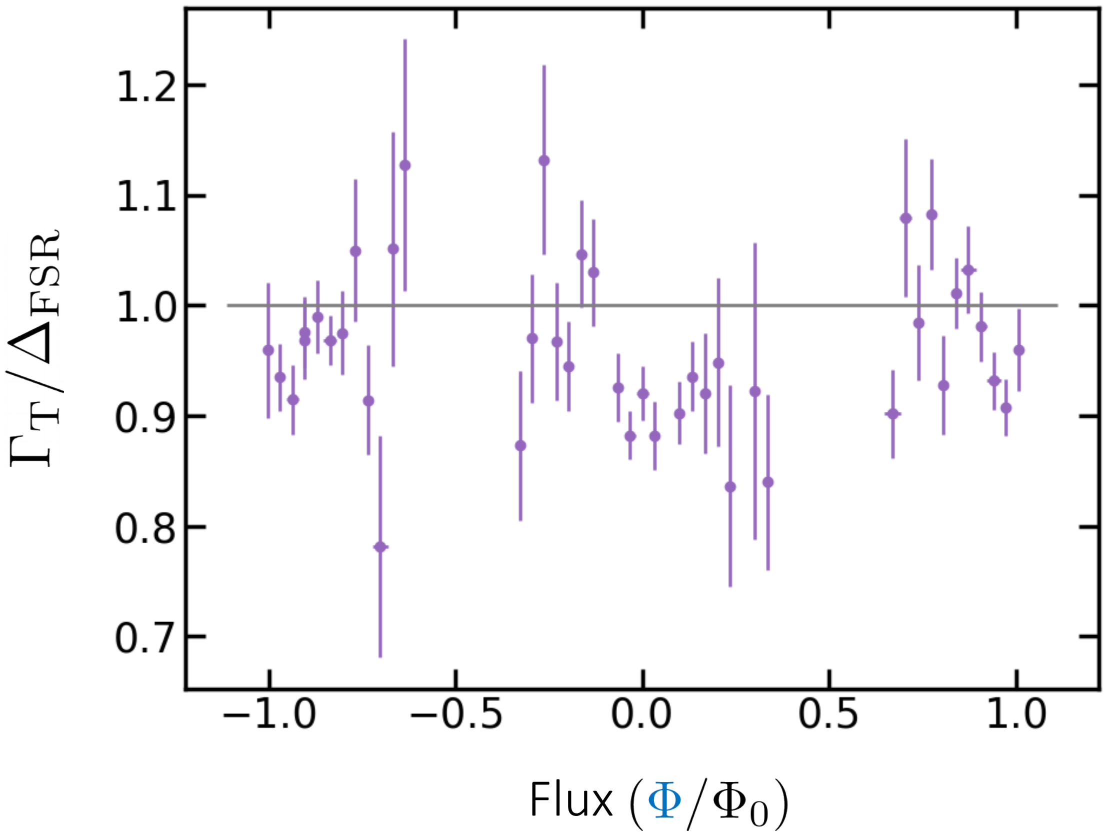
- Good data theory agreement with no fitting parameter





Thanks for your attention

Monitoring the environment



System hybridization

At every point the transmon width
Is of the same order that the FSR

$$\frac{\Gamma_T}{FSR} = 0.96 \pm 0.7$$