Characterization of Planar Transmon Qubits

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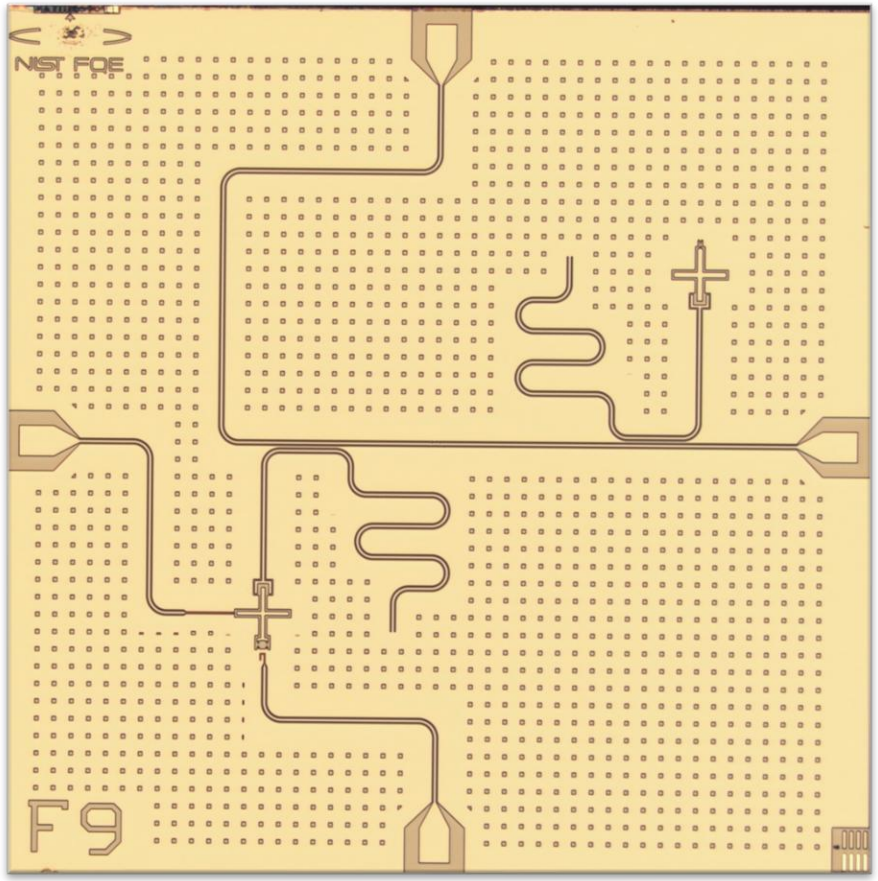
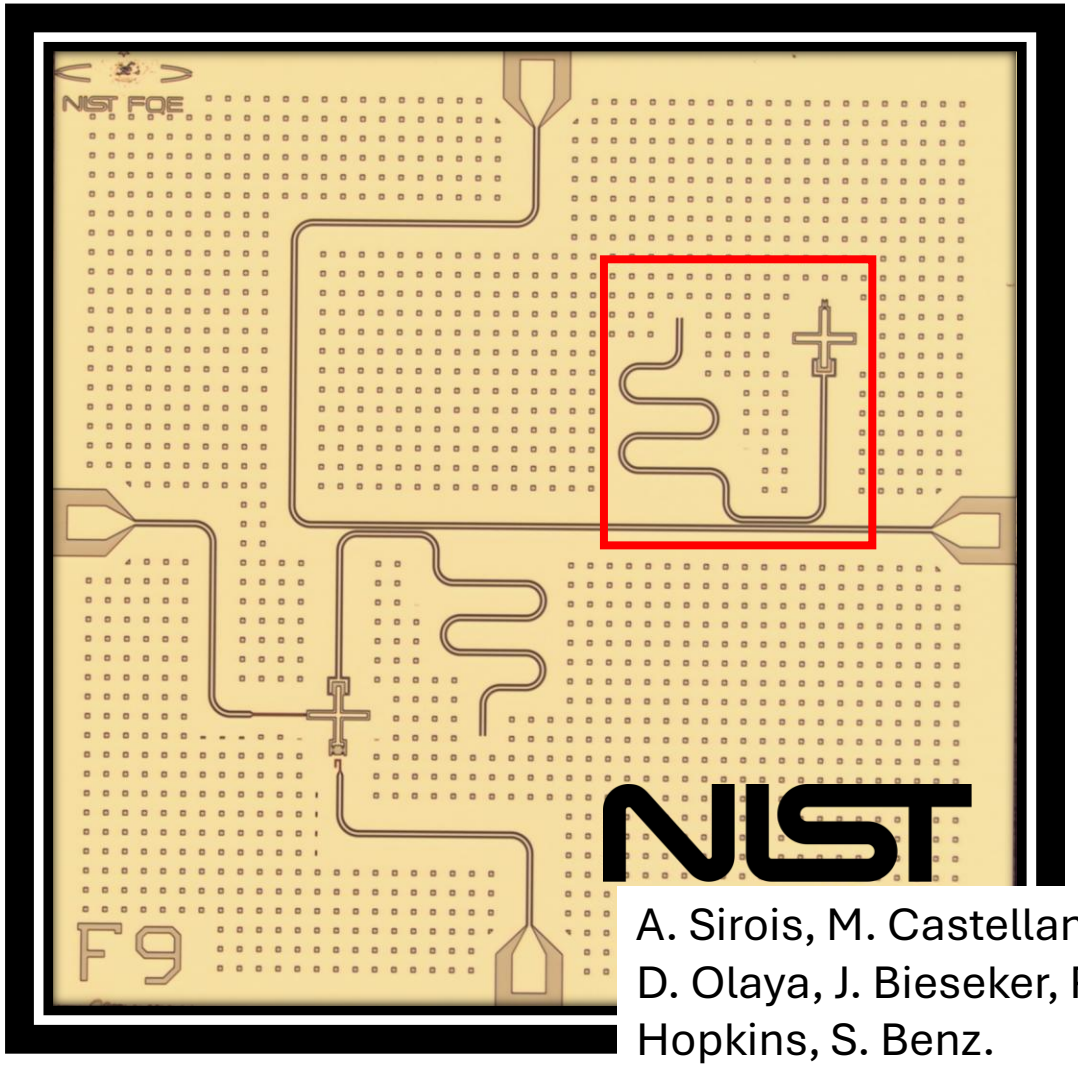


Transmon qubit chip design

- Need **good prediction** of the device parameters
- First design focuses on **simulation-experiment agreement**
- Two non-interacting qubits
- One is tunable with external flux and can be driven directly with a dedicated drive-line
- Each qubit features a simple coplanar resonator for readout



A. Sirois, M. Castellanos, D. Olaya, J. Bieseker, P. Hopkins, S. Benz.

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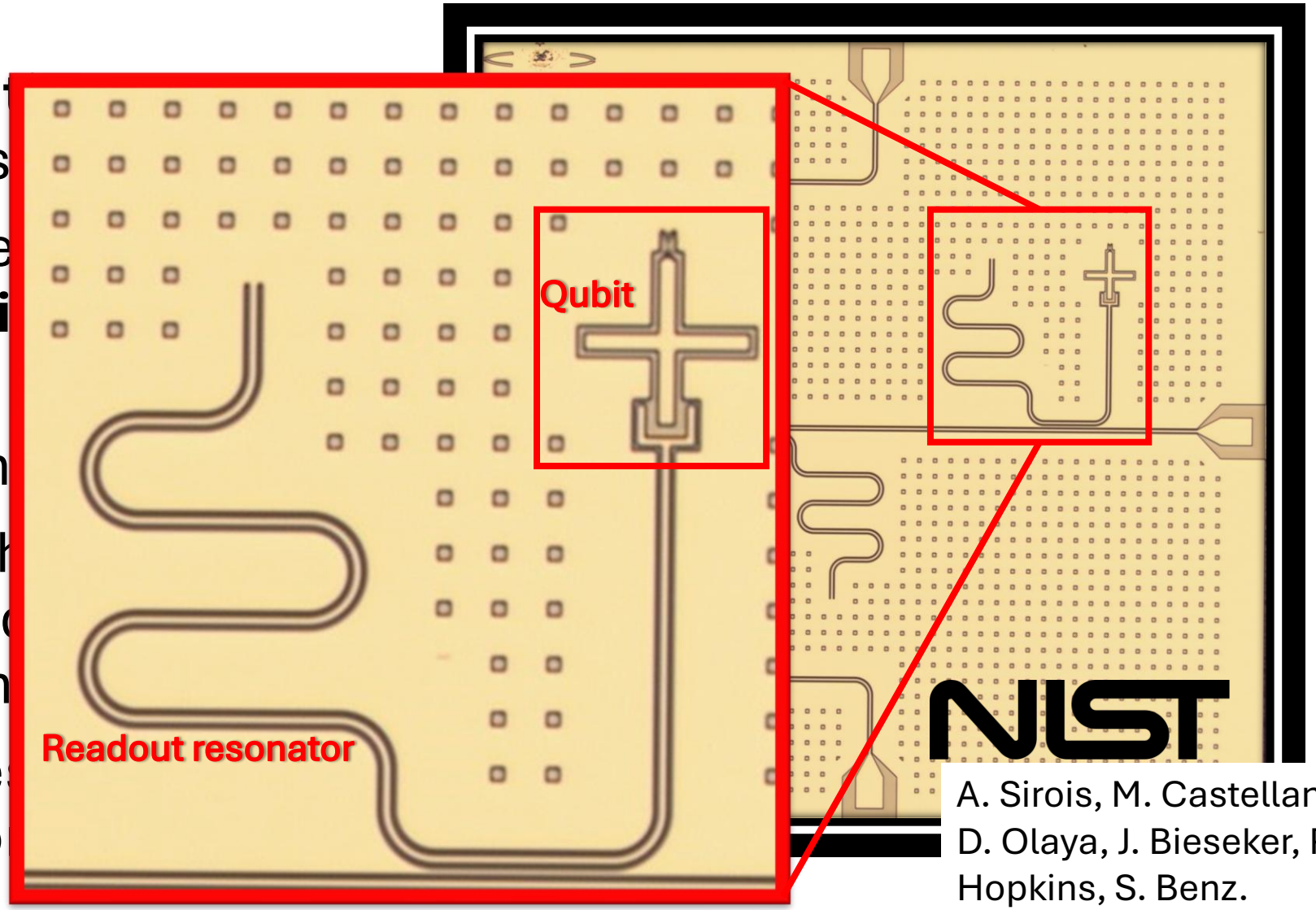

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Transmon qubit chip design

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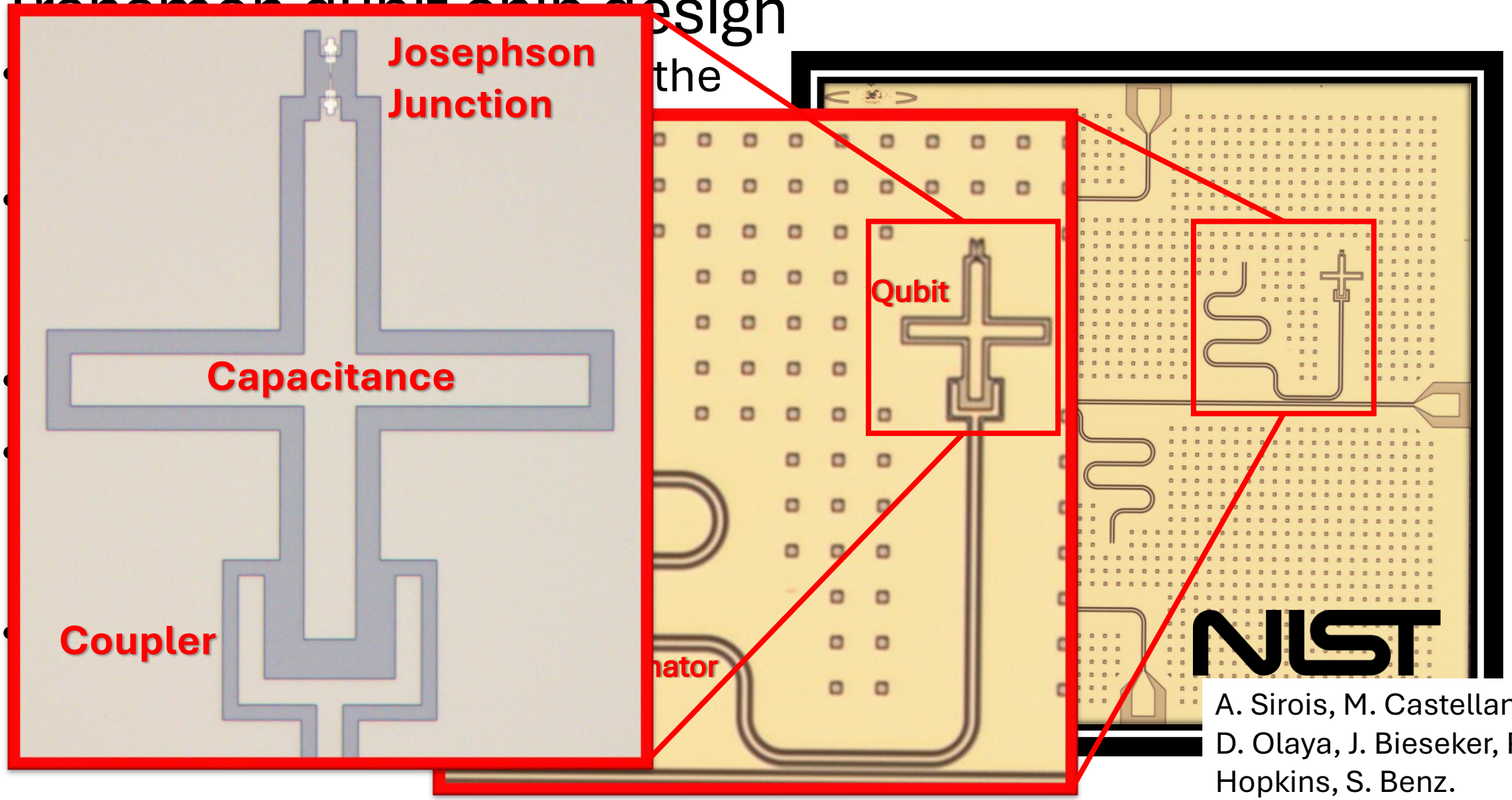

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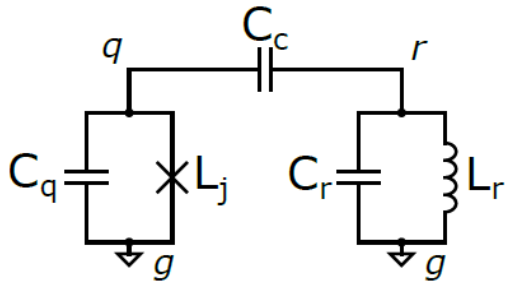
Chip simulation

- Lumped Oscillator Model (LOM)
  - Ansys Q3D extract the capacitance matrix of the qubit and the coupler
- Energy Participation Ratio (EPR)
  - Ansys HFSS to extract the resonant frequencies of the circuit

Both methods lead to the main Hamiltonian parameters of the circuit

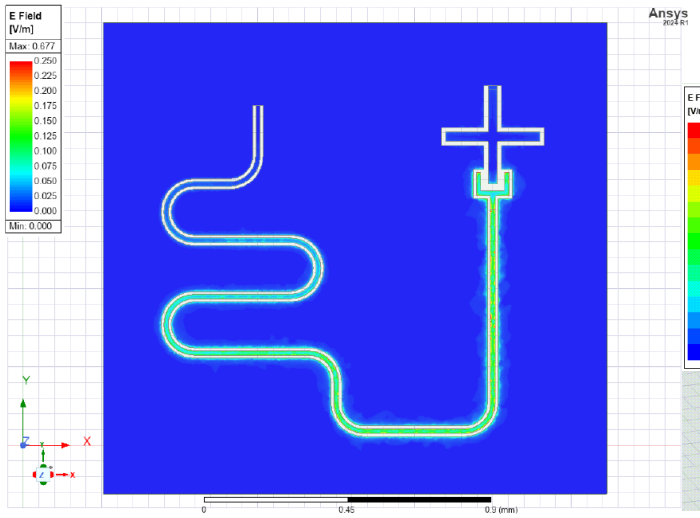


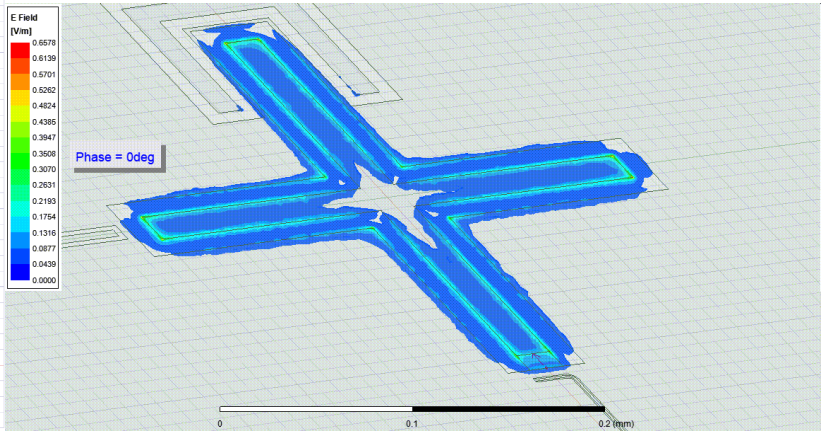
$$\hat{H}_{trunc} \approx \hbar\omega_r'\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_q'}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$$

$$\omega_r' = \omega_r - \frac{g^2}{\Delta - E_c/\hbar}$$

$$\omega_q' = \omega_q + \frac{g^2}{\Delta}$$

$$\chi = -\frac{g^2}{\Delta}\frac{E_c/\hbar}{\Delta - E_c/\hbar}$$

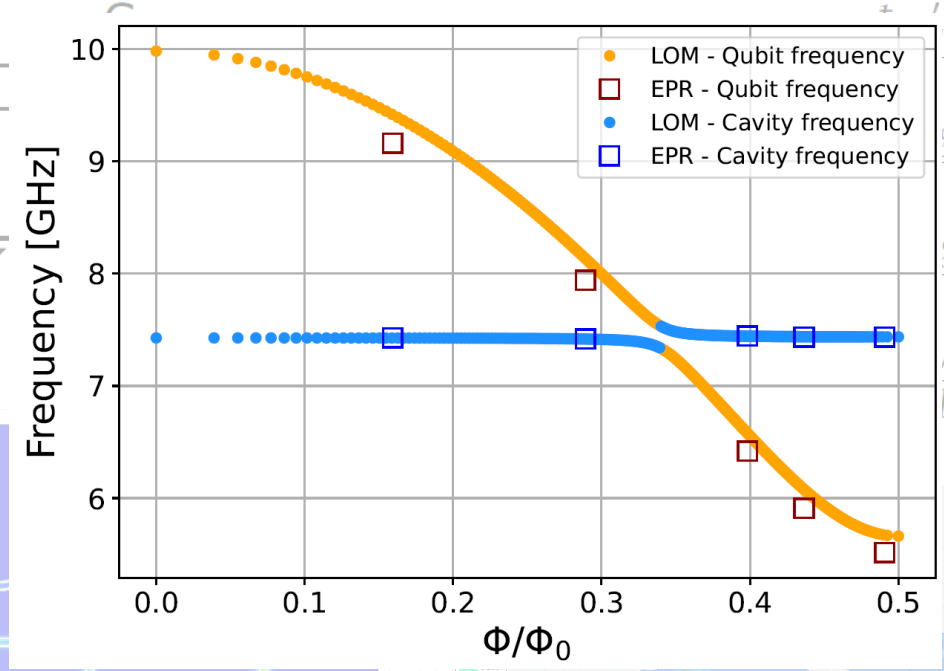


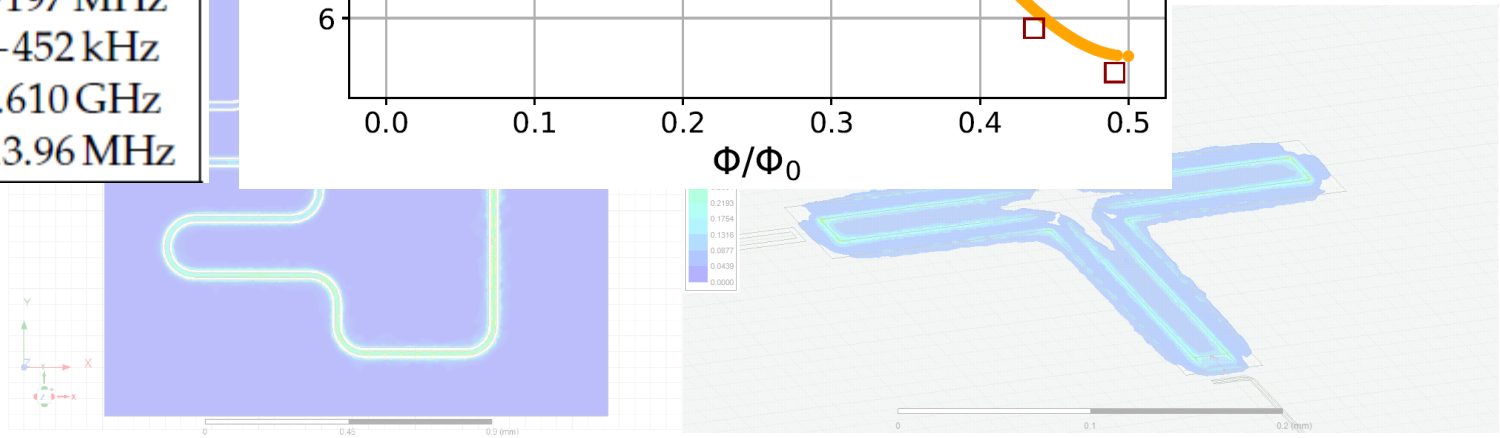


Chip simulation

- Lumped Oscillator Model (LOM)
  - Ansys capac qubit
- Energy P (EPR)
  - Ansys reson the cir

	LOM	EPR
L_j	8.03 nH	8.03 nH
I_c	41 nA	41 nA
E_j	20.36 GHz	20.36 GHz
E_c	194.44 MHz	188.40 MHz
E_j/E_c	104.73	108.40
$\omega_{01}/2\pi$	5.421 GHz	5.299 GHz
$\alpha/2\pi$	−211.4 MHz	−197 MHz
$\chi/2\pi$	−504 kHz	−452 kHz
$\omega_r/2\pi$	7.614 GHz	7.610 GHz
$g_{01}/2\pi$	110.39 MHz	113.96 MHz





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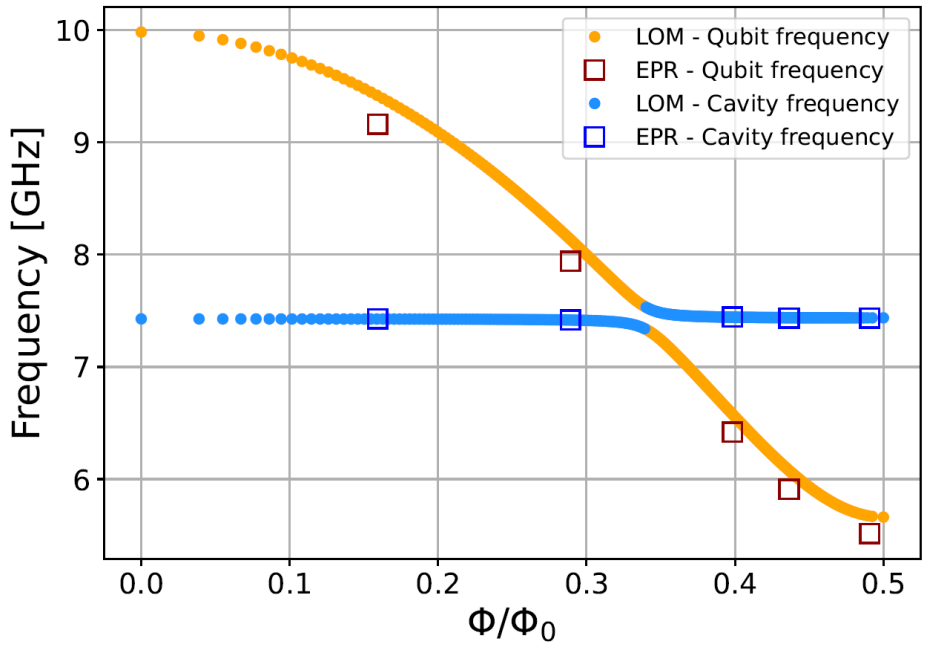

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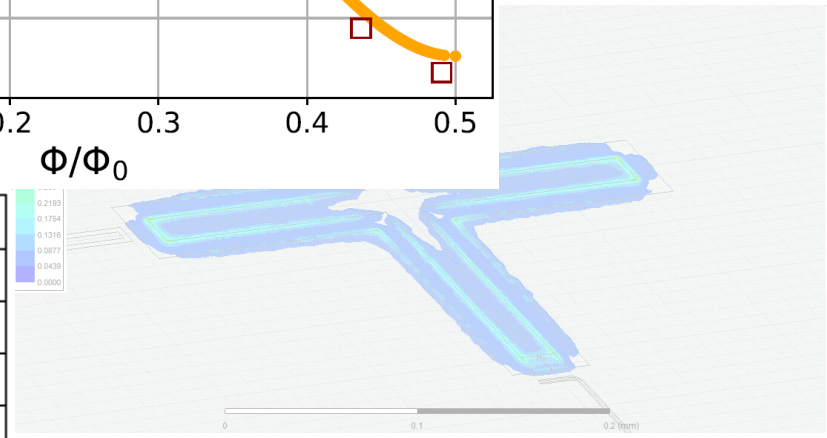
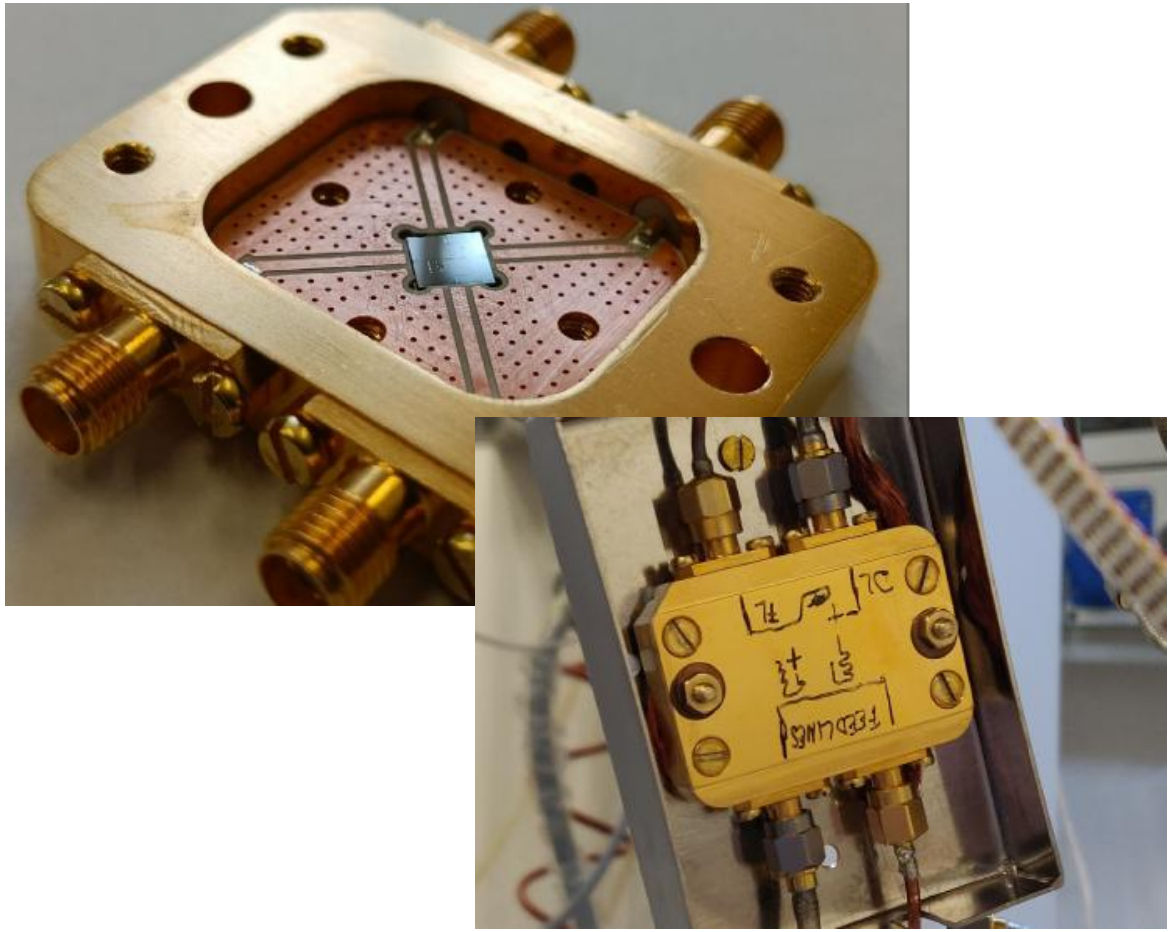
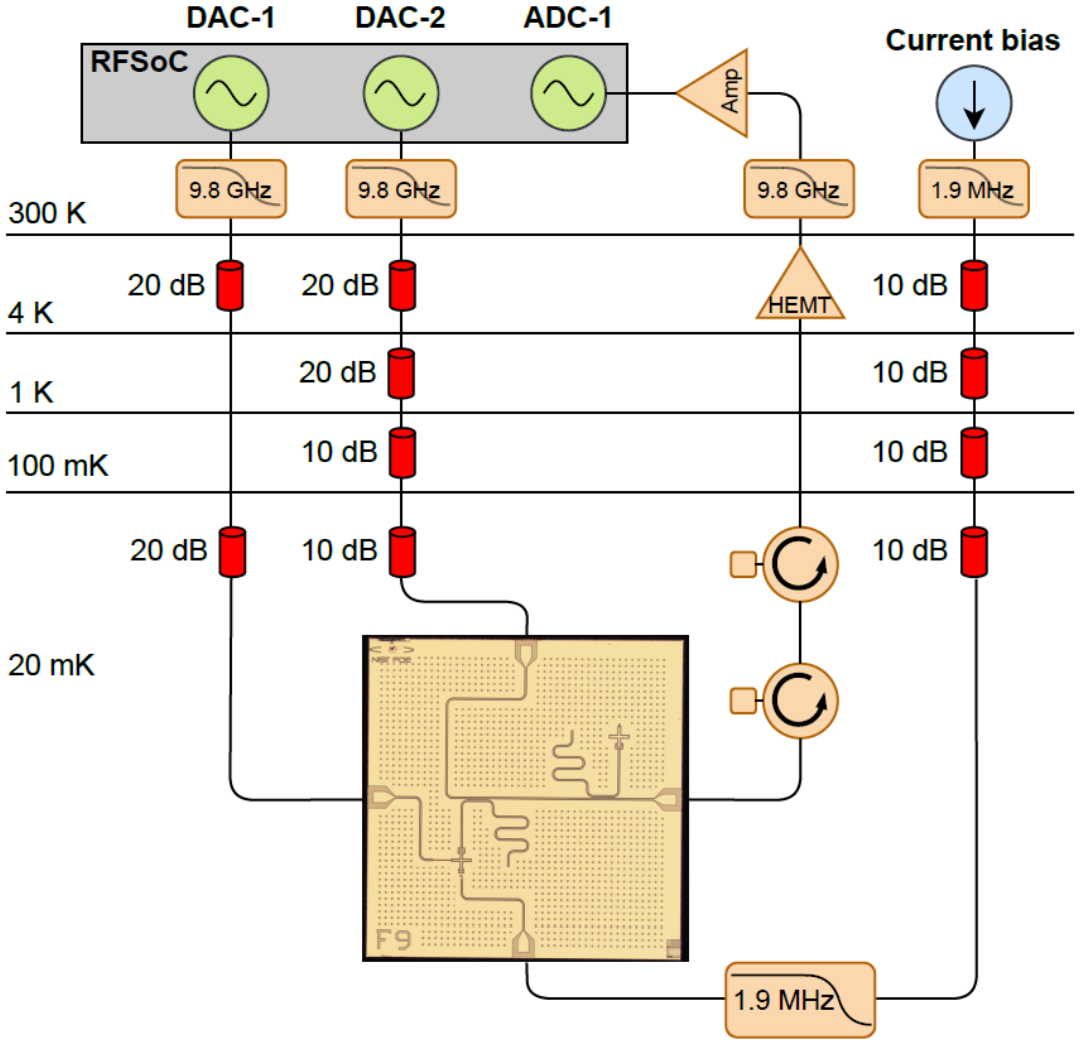
	Parameter	Design	Estimate
Junction 1	R_n	3.26 kΩ	3.24 kΩ
	I_c	82.00 nA	82.42 nA
	L_j	4.01 nA	3.99 nA
Junction 2	R_n	6.51 kΩ	6.20 kΩ
	I_c	41.00 nA	43.07 nA
	L_j	8.03 nA	7.64 nA



Measurement setup

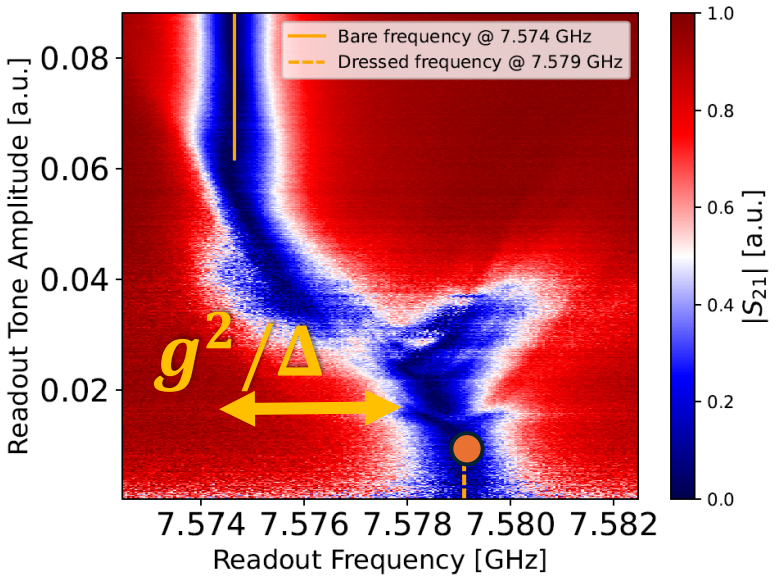




Resonator spectroscopy

- At high power:
  - The qubit energy levels are saturated
  - The resonator behaves like it is alone in the chip
- At low power:
  - The qubit is in the ground state and interacts with the resonator
  - The distance between the bare and dressed frequencies is

$$\omega_r^{bare} - \omega_r^{dressed} \approx \frac{g^2}{\Delta}$$

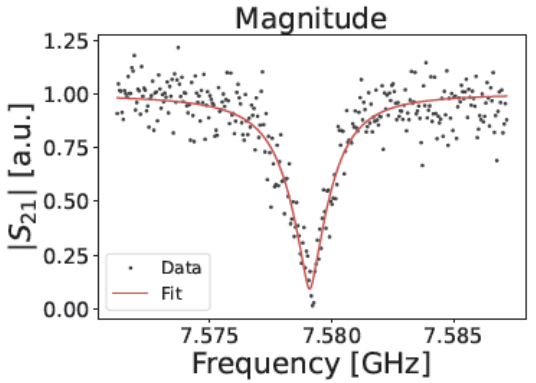


$$S_{21}(f) = 1 - \frac{\frac{Q_{tot}}{Q_c} e^{i\phi}}{1 + 2\,i\,Q_{tot}\left(\frac{f - f_r}{f_r}\right)}$$

ω_r	7.579 GHz
Q_i	3×10^4
Q_c	3034
Q_{tot}	2760

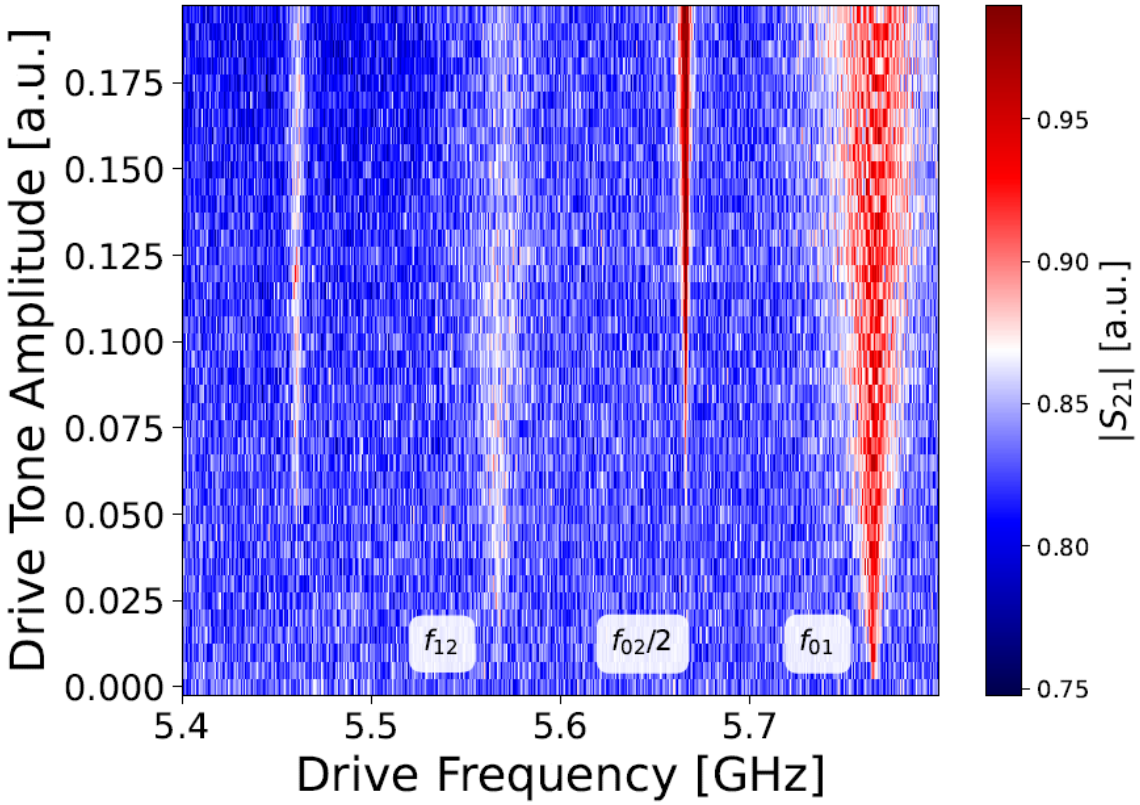
Q_c HFSS	10^4

$$k \approx 2\chi$$



Qubit spectroscopy

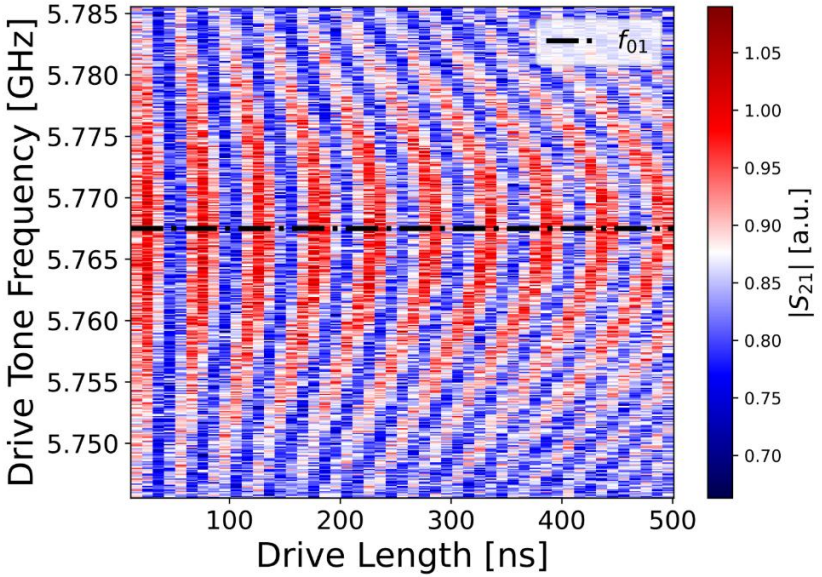
- One tone (**readout tone**) at $f_{readout} \approx 7.579$ GHz is used to continuously readout the resonator (the $|S_{21}|$)
- A second microwave tone (**drive tone**) is used to scan for the qubit frequency
- The $|S_{21}|$ changes when the qubit gets excited by this second pulse



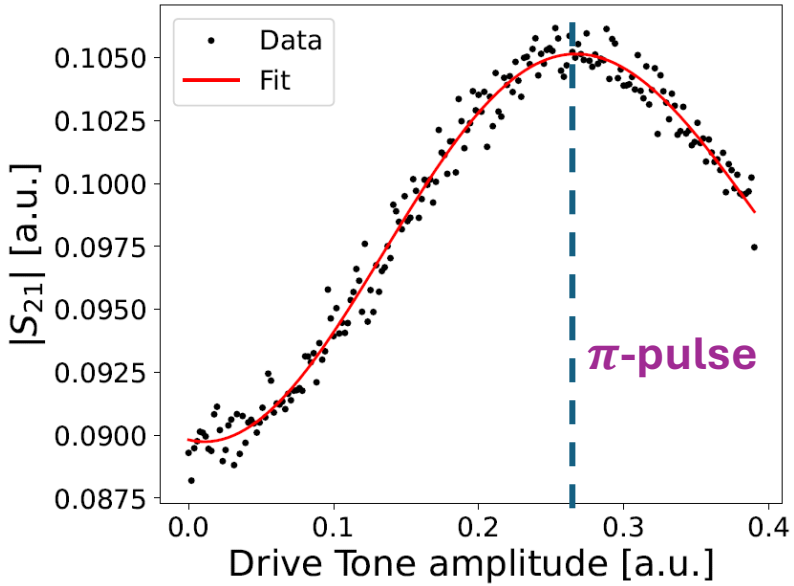
$\alpha/2\pi = (\omega_{01} - \omega_{12})/2\pi$ = -195.7 ± 1.7 MHz

Control pulse calibration

- The calibrated pulses are:
  - $\boldsymbol{\pi}$**-pulse**: prepares the qubit $|1\rangle$
  - $\frac{\boldsymbol{\pi}}{\mathbf{2}}$**-pulse**: prepares the qubit $|+\rangle = \frac{|0\rangle+|1\rangle}{2}$

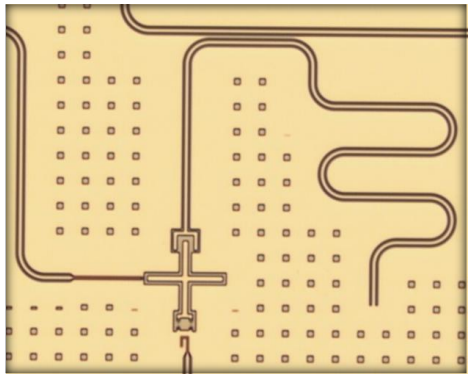


$\Delta t = 40$ ns



Frequency tunable transmon

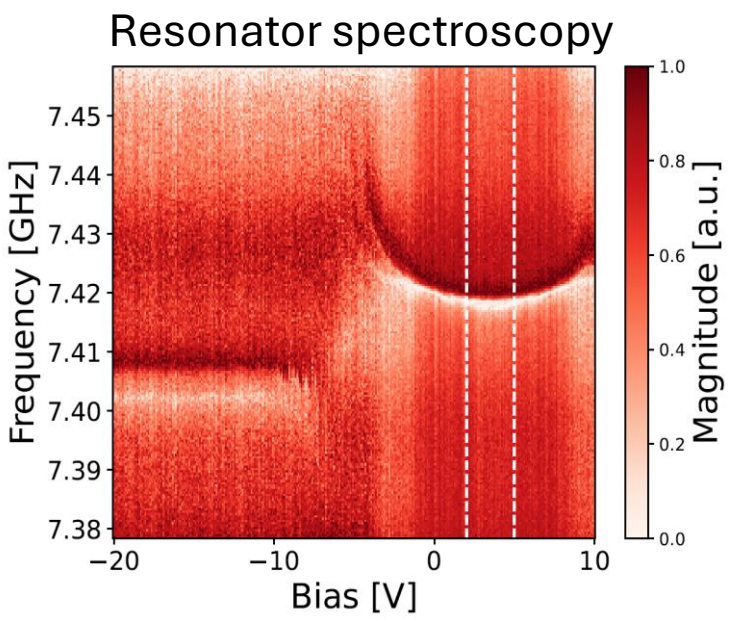
- **Resonator** and **qubit spectroscopy** as a function of **flux bias**
- Resonator spectroscopy shows the **avoided crossing**
- The full characterization is performed at the minimum frequency

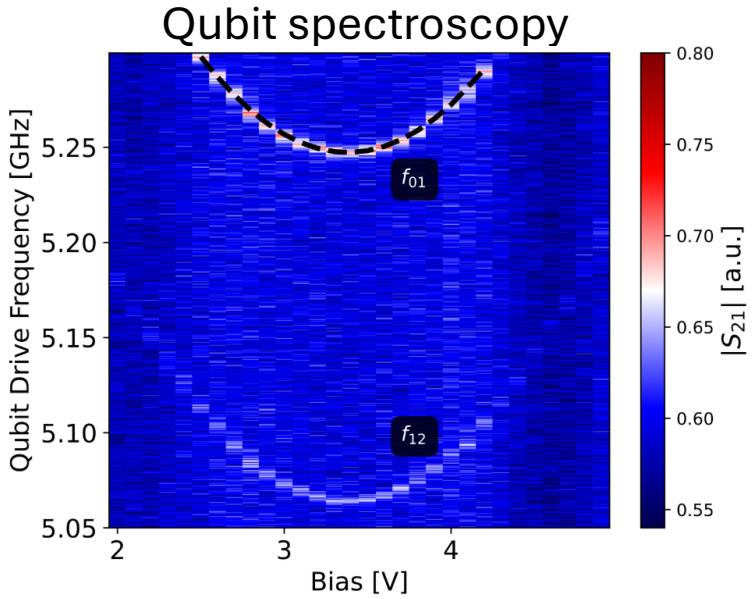


$$\omega_q(\Phi_{ext}) = \sqrt{8E_j(\Phi_{ext})E_c} - E_c$$

$$E_j(\Phi_{ext}) = E_j^{MAX}\left[\cos^2(\pi\Phi_{ext}/\Phi_0) + d\sin^2(\pi\Phi_{ext}/\Phi_0)\right]^{\frac{1}{2}}$$

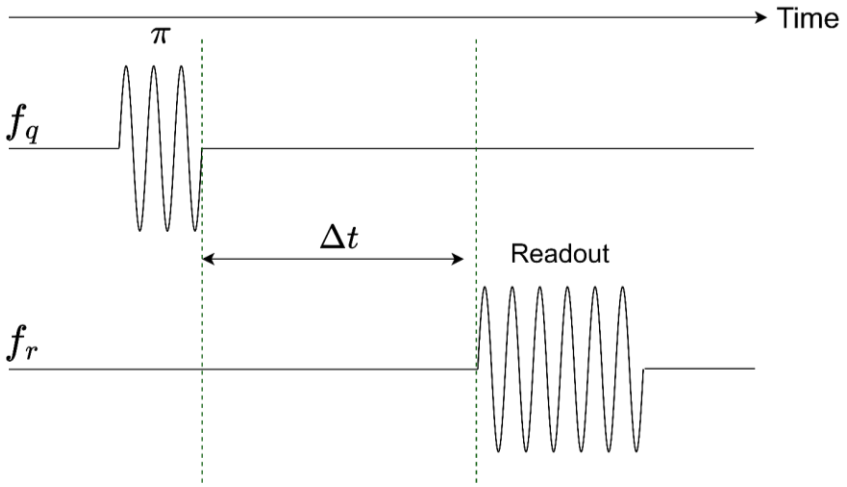
$$d = \frac{|L_{j1} - L_{j2}|}{L_{j1} + L_{j2}} \approx 0.29 \text{ from fit}$$

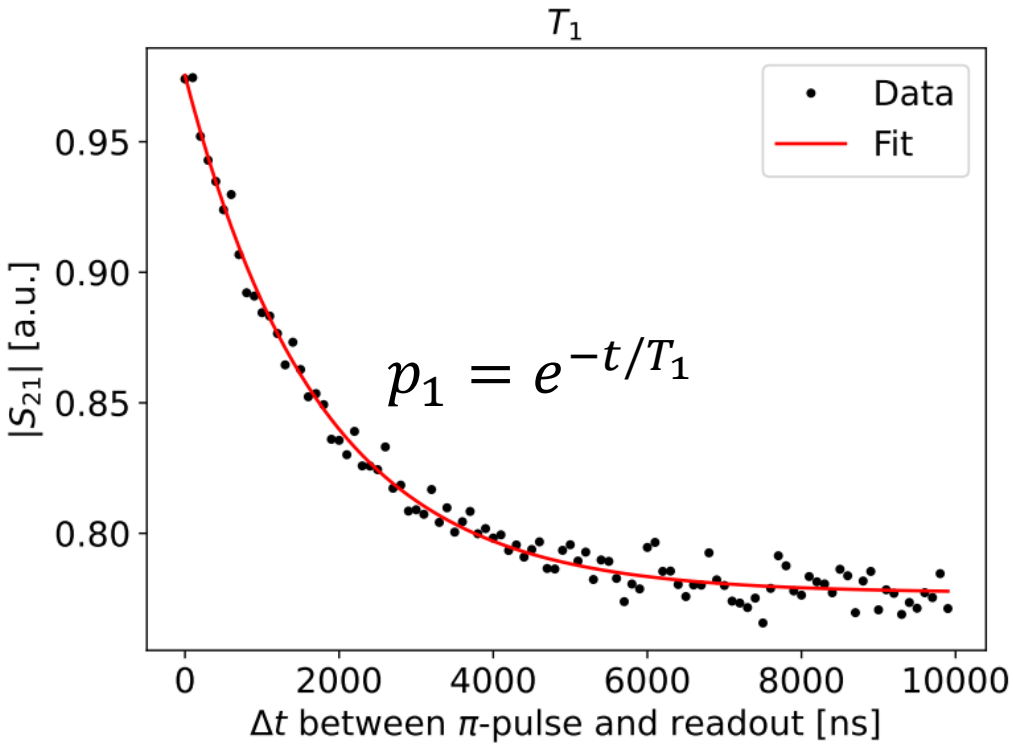




Relaxation time measurement

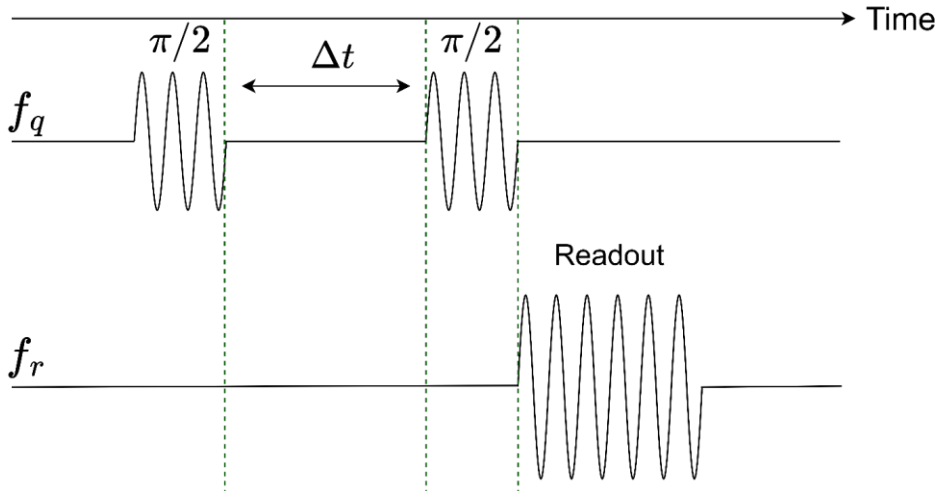
- The relaxation time T_1 is the mean time necessary for the qubit in the $|1\rangle$ to spontaneously relax into the $|0\rangle$ state

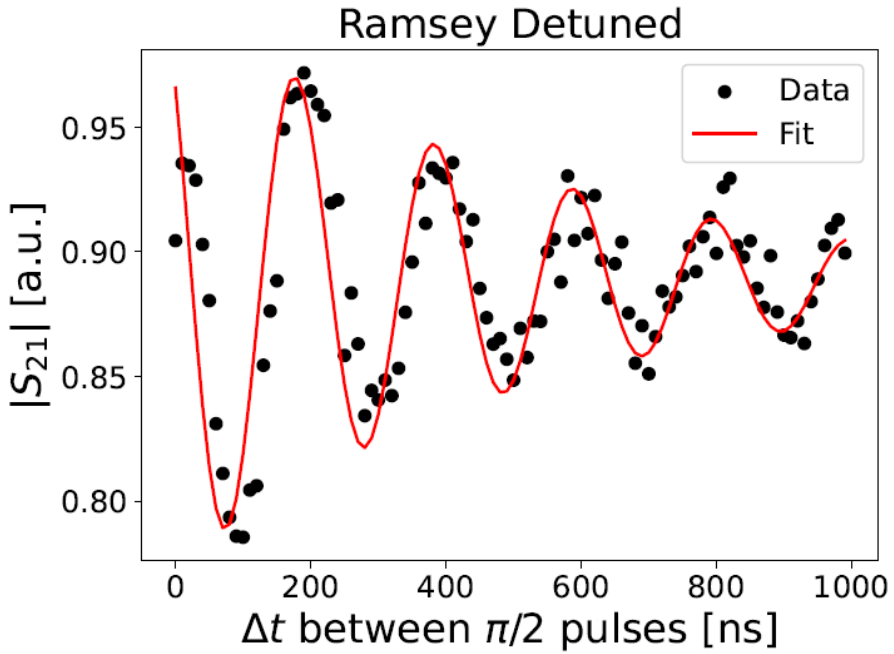




Coherence time measurement

- The decoherence time T_2^* is the mean time necessary for the qubit to lose the phase information



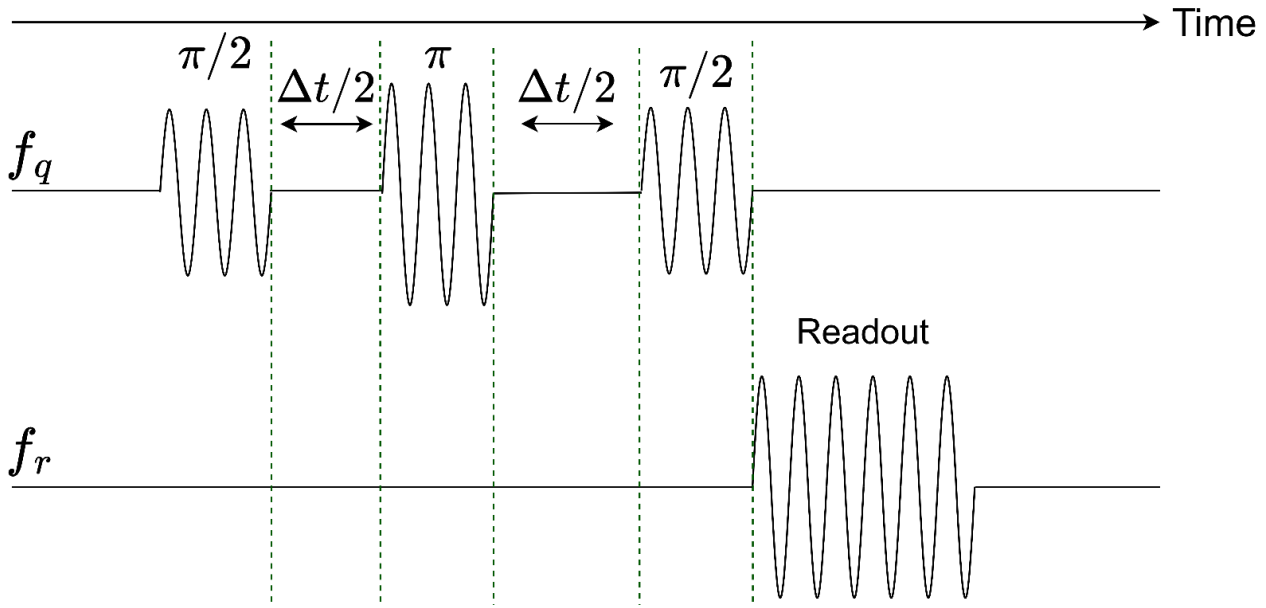


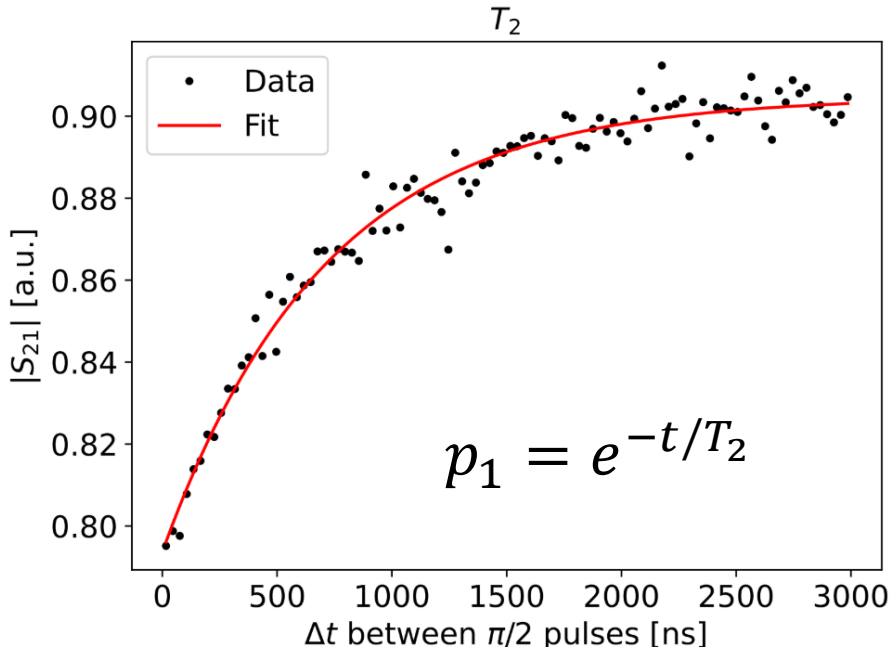
$$p_1 = \frac{1}{2} + \frac{1}{2} e^{-\Delta t / T_2^*} \cos(\delta \Delta t)$$

With $\delta = \omega_d - \omega_{01} \approx 5$ MHz $\quad T_2^* \approx 517$ ns

Spin-Echo measurement

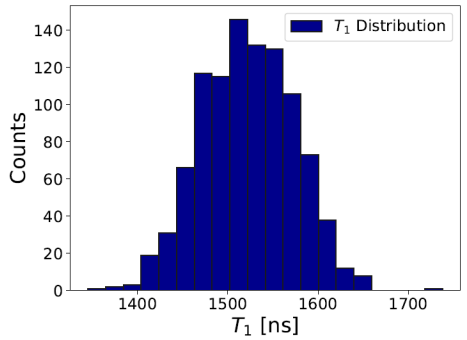
- Focusing $\boldsymbol{\pi}$-pulse at half pulse sequence refocuses the state
- Removes the inhomogeneous dephasing

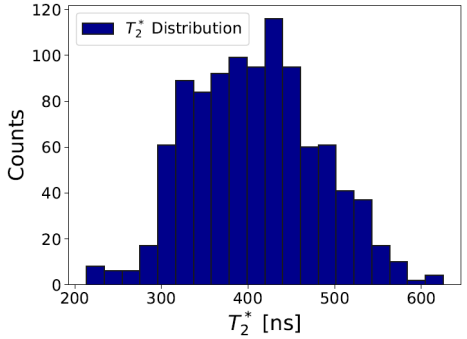




Relaxation and Coherence time measurement

- These measurement were performed multiple times (about 24 hours) for both qubits





	Fixed frequency qubit	Tunable qubit
T_1	1522 ± 51 ns	1928 ± 136 ns
T_2^*	408 ± 73 ns	585 ± 53 ns
T_2	611 ± 31 ns	1033 ± 105 ns

- The Purcell limit on the T_1 is approximately $20\ \mu s$
- The limiting factor:
  - Unoptimal setup
  - Ground loops
  - Substrate and interface losses

Summary of qubit characterization

Fixed frequency qubit

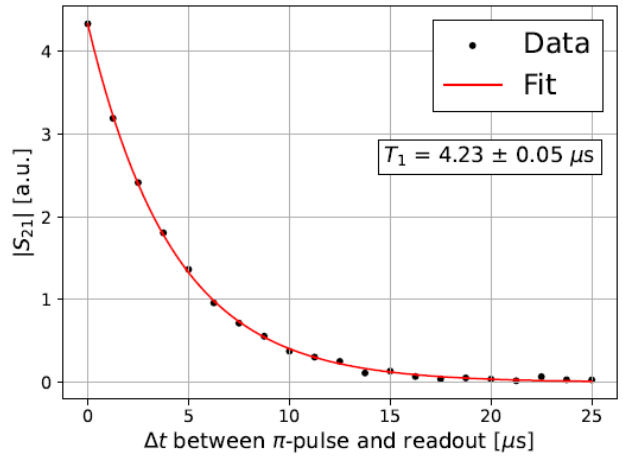
Parameter	LOM	EPR	Experiment
L_j	7.64 nH (Fixed)	7.64 nH (Fixed)	7.64 nH (Estimate)
$\omega_{01}/2\pi$	5.556 GHz	5.434 GHz	5.770 ± 0.001 GHz
$\alpha/2\pi = (\omega_{01} - \omega_{12})/2\pi$	-210.8 MHz	-196.5 MHz	-195.7 ± 1.7 MHz
$\omega_r/2\pi$	7.614 GHz	7.610 GHz	7.579 GHz
$\chi/2\pi$	-572 kHz	-508 kHz	-517.7 kHz
$g_{01}/2\pi$	110 MHz	114 MHz	97.2 MHz

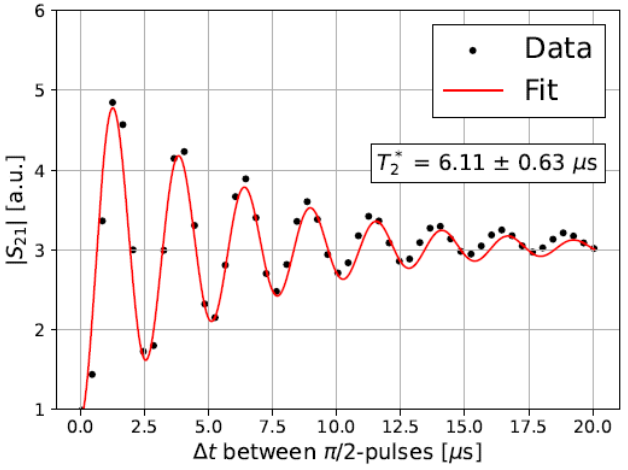
Tunable frequency qubit

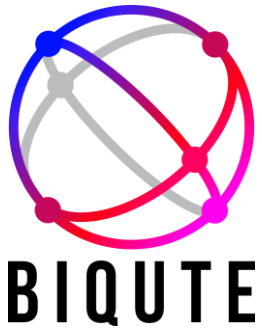
Parameter	Estimate	Fit
$d = \lvert L_{j1} - L_{j2} \rvert / (L_{j1} + L_{j2})$	0.31	0.29

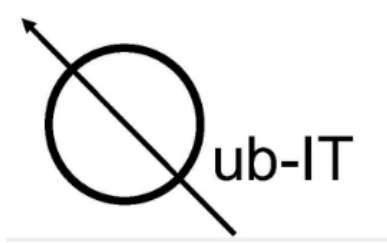
Summary of results and next steps

- The **simulation-experiment agreement** is very good:
  - **Within 6% for frequencies and 2% for dispersive shifts**
- The performance are not as high as expected
  - T_1 and T_2^* are limited to about $2\mu s$ and $500\ ns$ respectively
  - The **Purcell limited T_1 is $\approx 20\mu s$** and does not justify the measured values
- Possible causes for the lower performance:
  - **Unoptimized setup** (no IR filters, low attenuation, ground loop)
  - **Additional unaccounted losses** (interfaces and substrate)
- Measure the exact same chip again adjusting the measurement setup
- The measurement on the right were performed on the same design but in a different setup









Thank you!

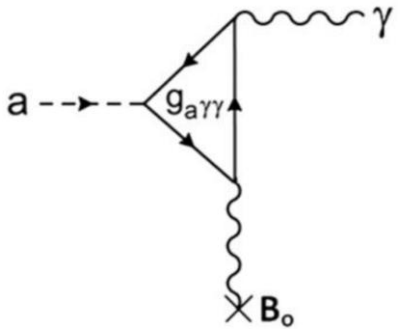
D. Labranca, R. Moretti, P. Campana, R. Carobene, M. Gobbo, M. A. Castellanos-Beltran, D. Olaya, P. Hopkins, L. Banchi, M. Borghesi, A. Candido, S. Carrazza, A. Cattaneo, H. A. Corti, A. D'Elia, M. Faverzani, E. Ferri, S. Gamba, A. Nucciotti, L. Origo, A. Pasquale, A. S. Piedjou Komnang, A. Rettaroli, S. Tocci, C. Gatti, A. Giachero

Backup slides

Light DM conversion into photons

Axions:

- Inverse Primakoff effect
  - In resonant cavities with $f = \frac{m_a c^2}{h}$
  - Large B fields → conversion probability scales as B^2



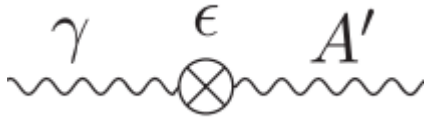
$$P_{a\to\gamma} = g_{a\gamma\gamma}^2 \rho_a B^2 V C \frac{Q}{m_a}$$

https://doi.org/10.48550/arXiv.2403.02321

Dark photons:

- Kinetic mixing
  - In resonant cavities with $f = \frac{m_{A'} c^2}{h}$
  - No need for B fields

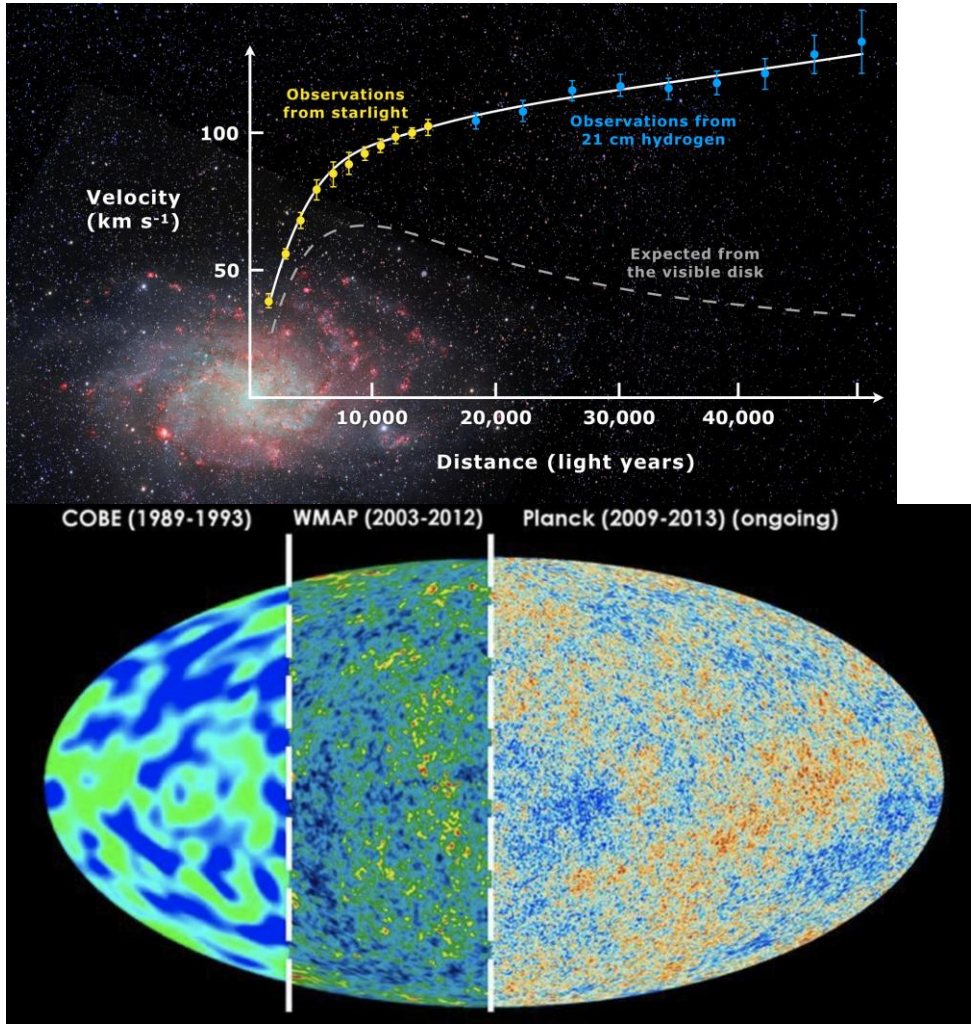
$$P_{A'\to\gamma} = \epsilon^2 \rho_{A'} V \frac{Q}{m_{A'}} \frac{1}{1 + 4\left[\frac{Q(f - f_0)}{f_0}\right]}$$



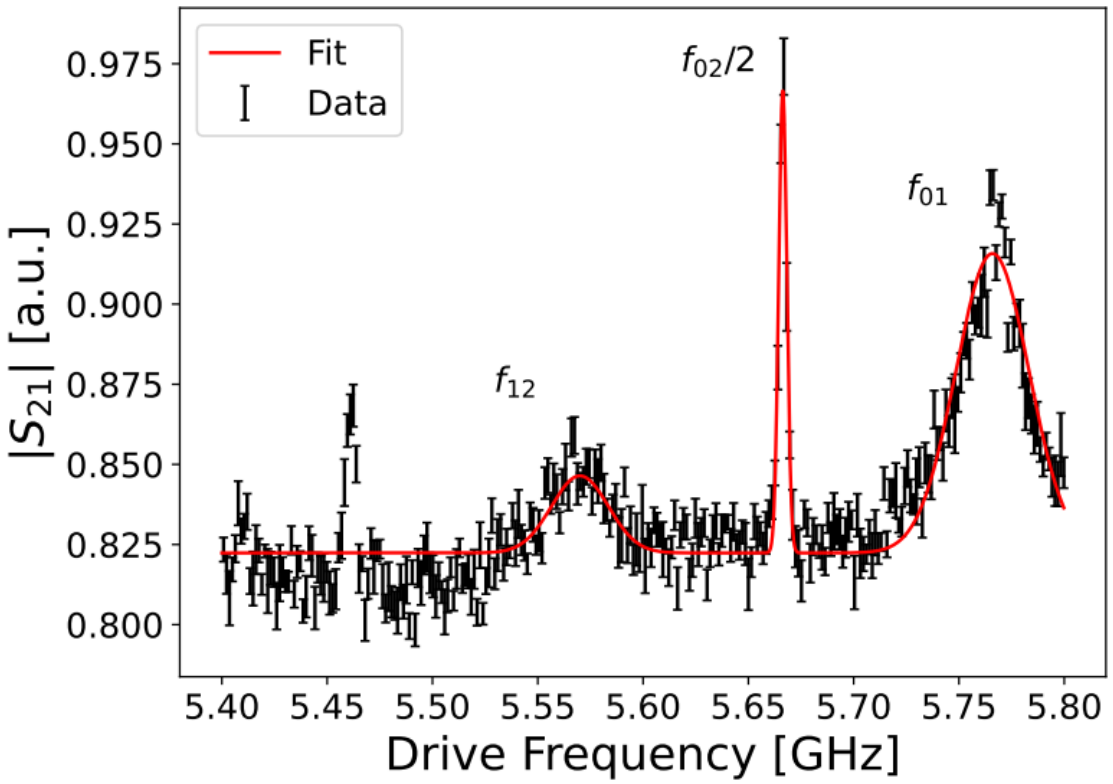
https://doi.org/10.1103/PhysRevD.110.043022

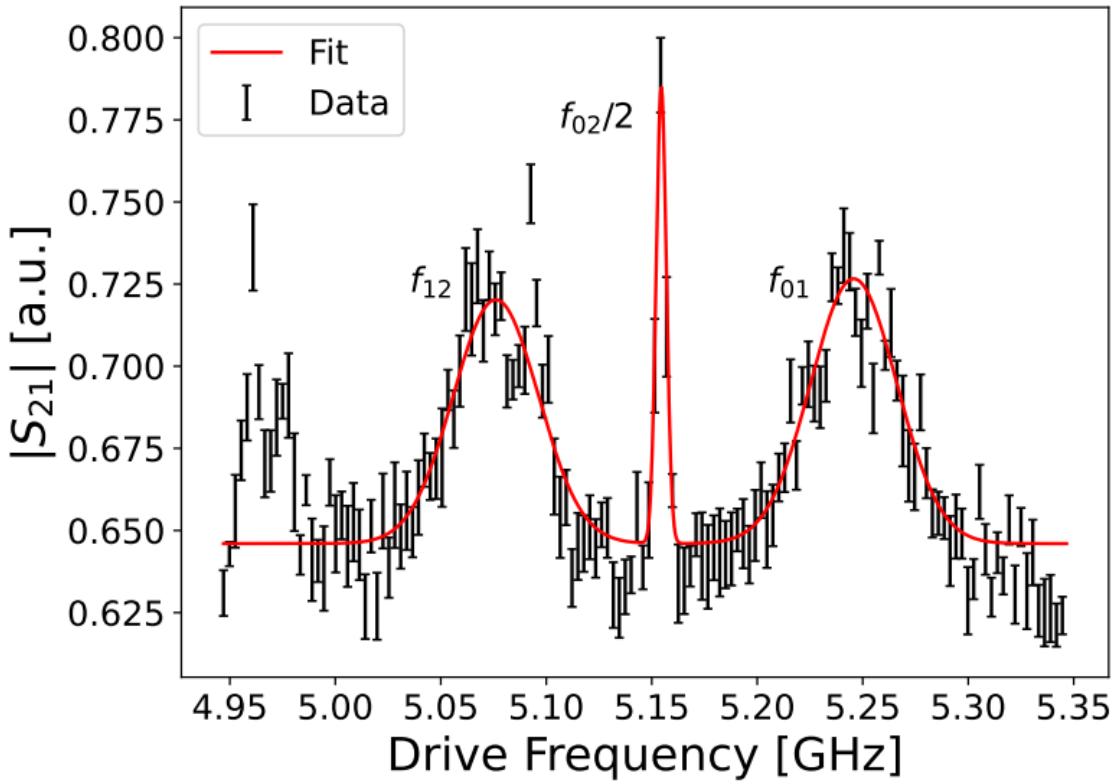
Dark Matter evidences

- Galaxy rotation curves
  - Visible matter does not explain the rotational speed of galaxies at large distances from the center
- Cosmic Microwave Background (CMB)
  - Measurements of the CMB anisotropies support the ΛCDM model with dark matter
- Galaxy clusters
  - Velocity of galaxies within cluster is too high to be explained by visible matter (as well as velocity dispersion)
- Gravitational Lensing

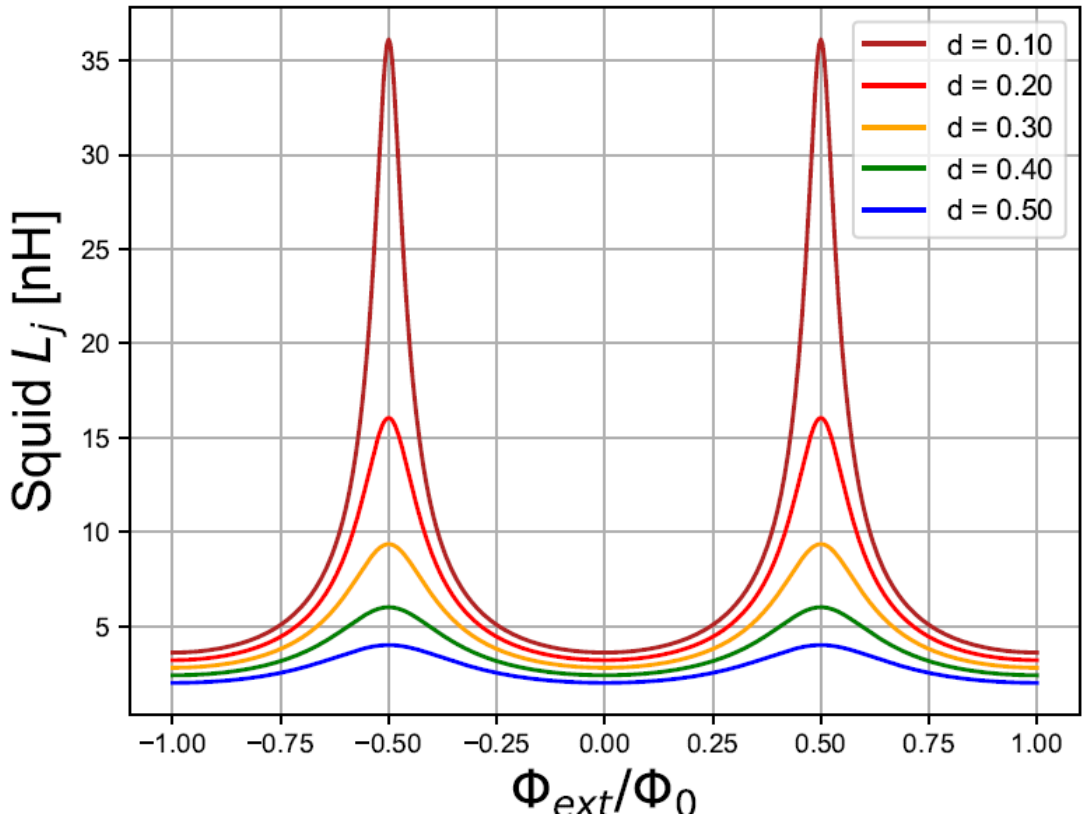


Qubit Spectroscopy

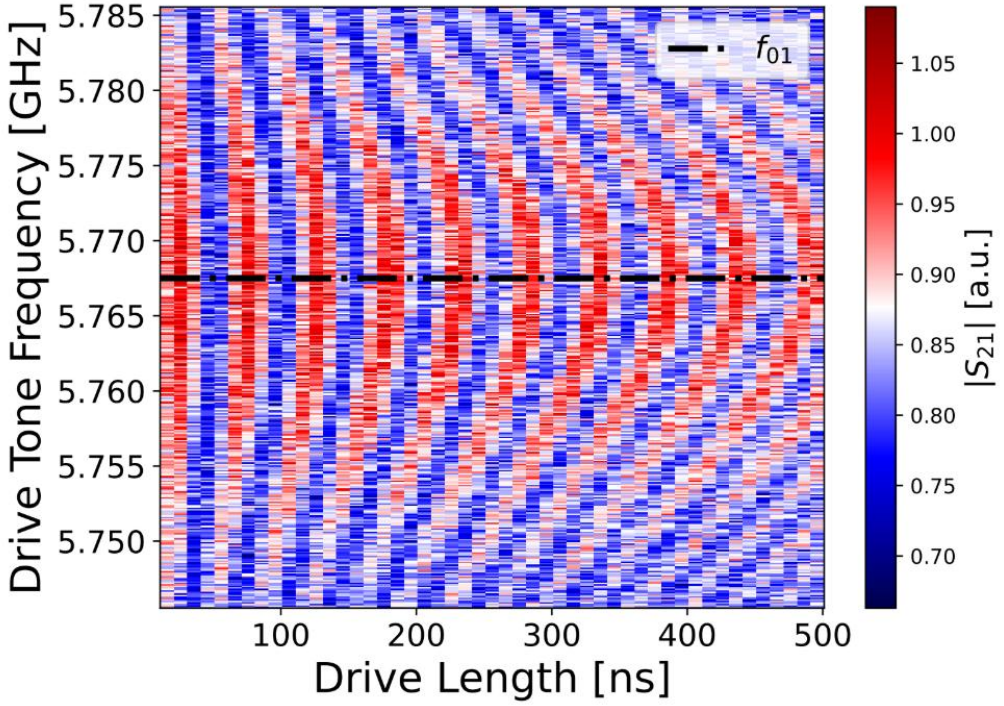


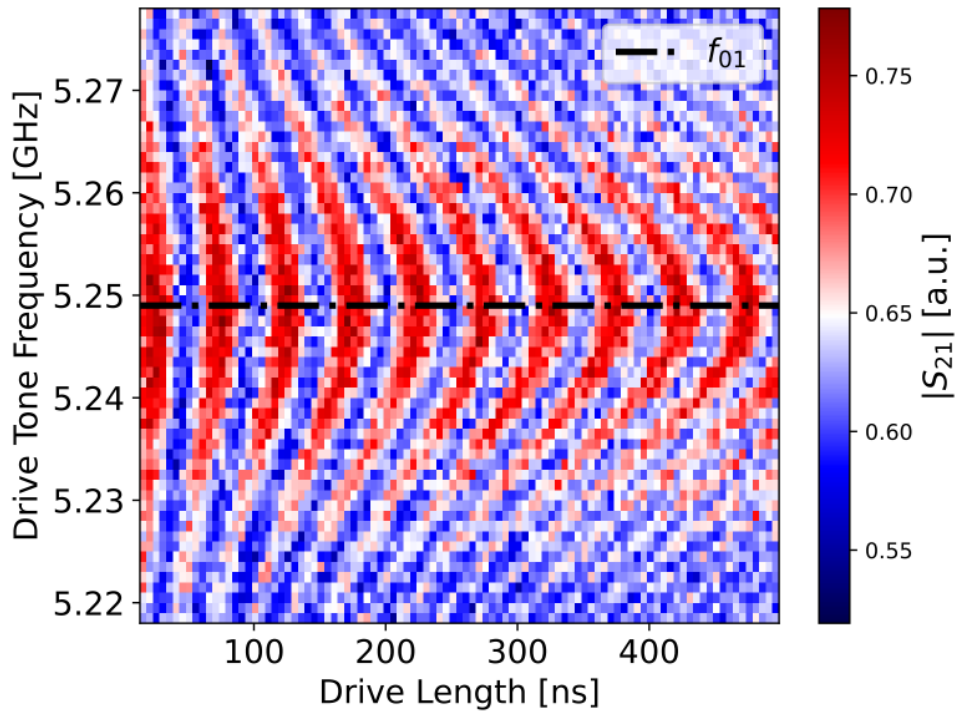


dc-Squid inductance

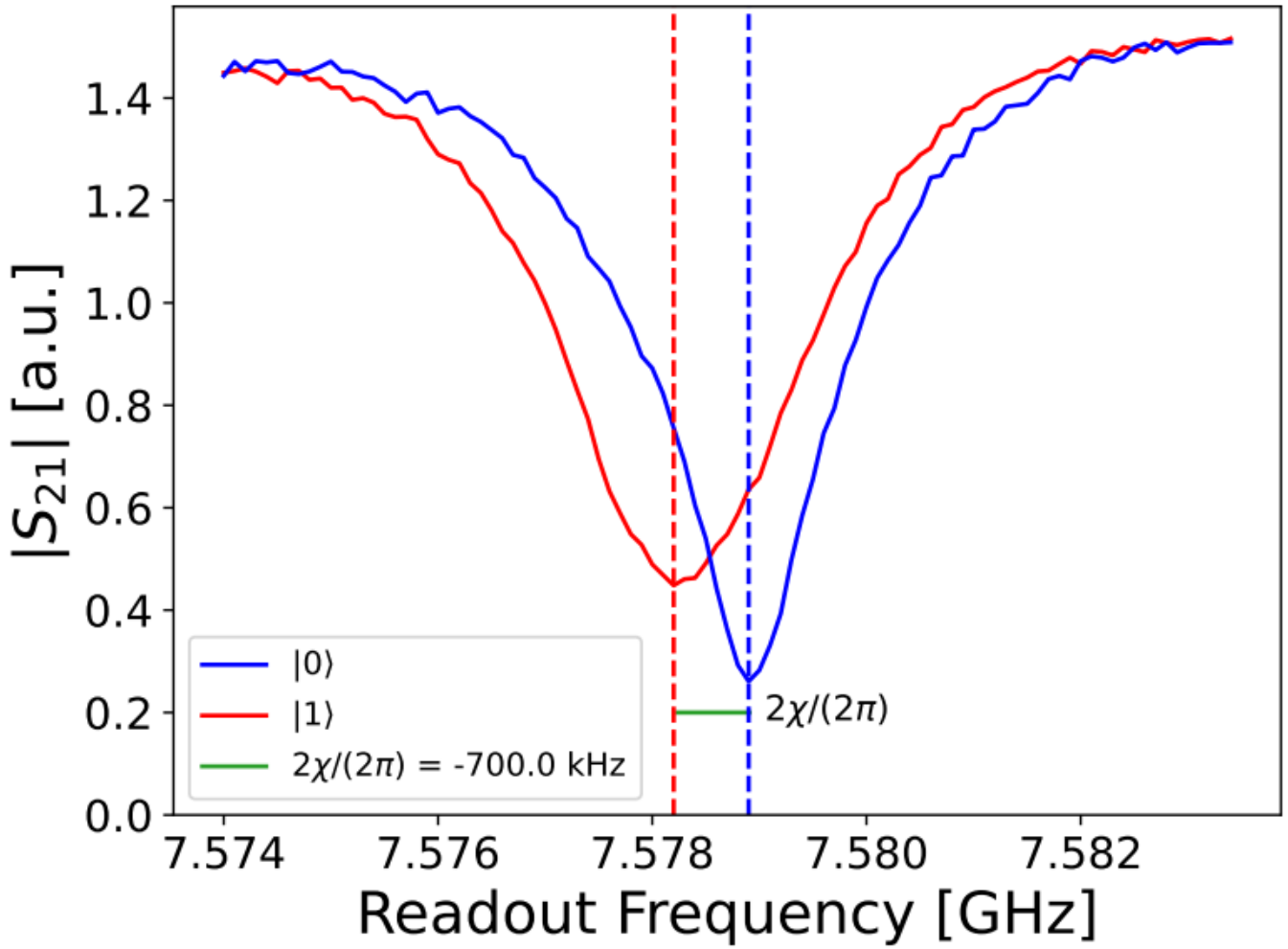


Rabi oscillations

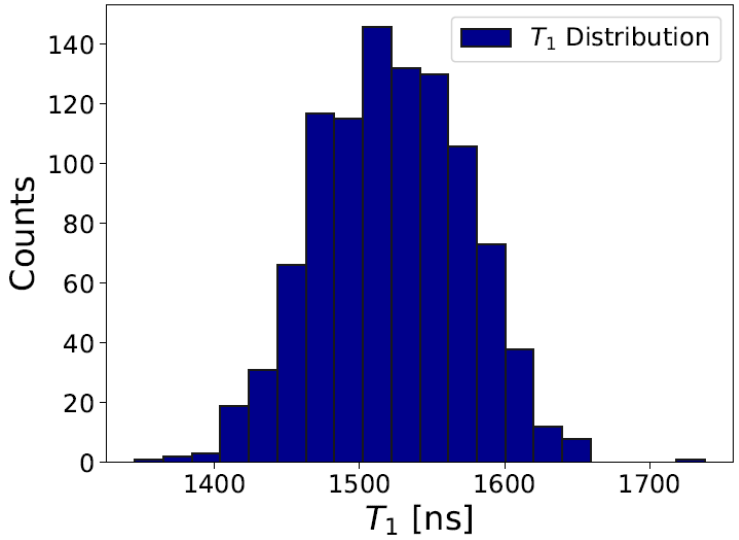


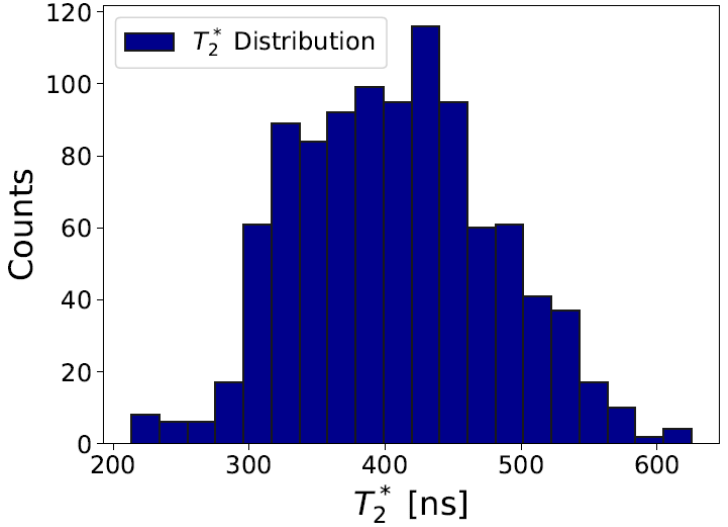


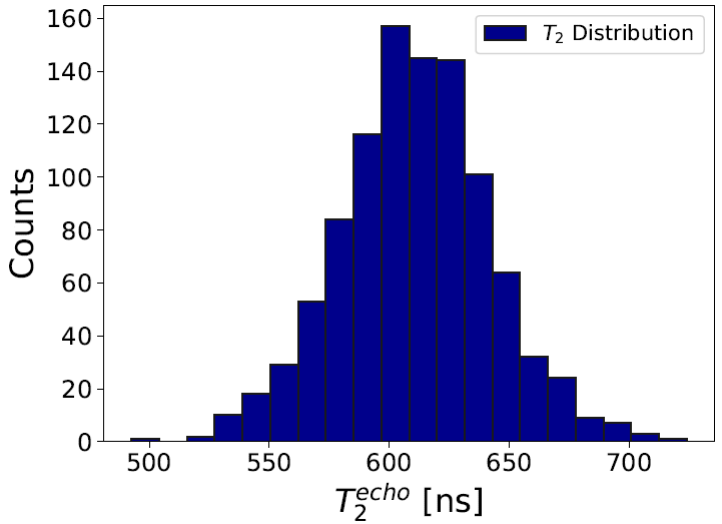
Dispersive shift

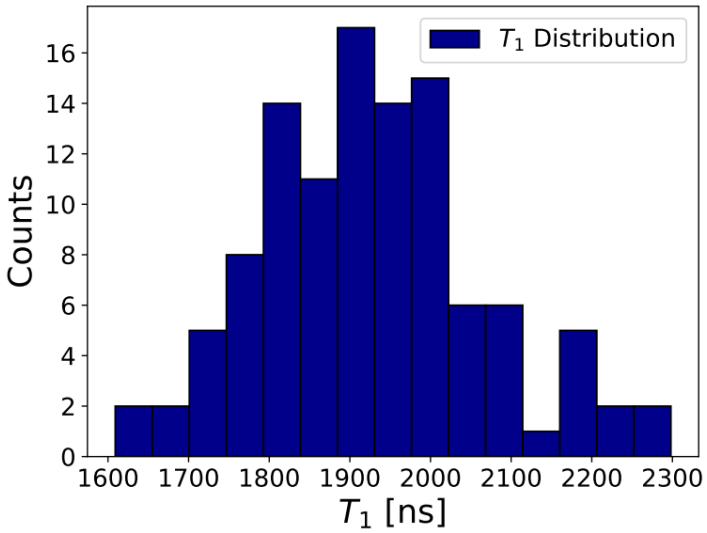


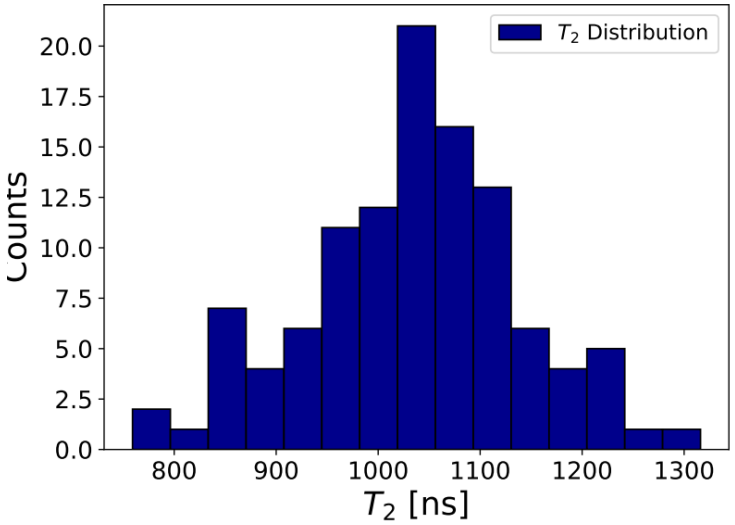
Relaxation and Coherence time measurement

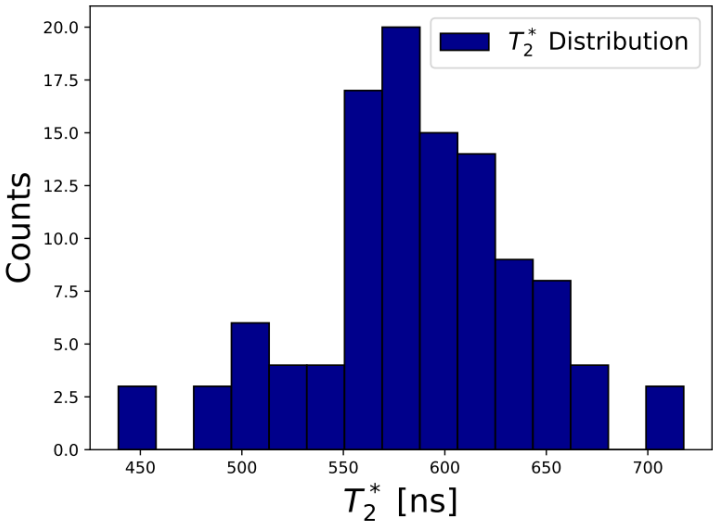




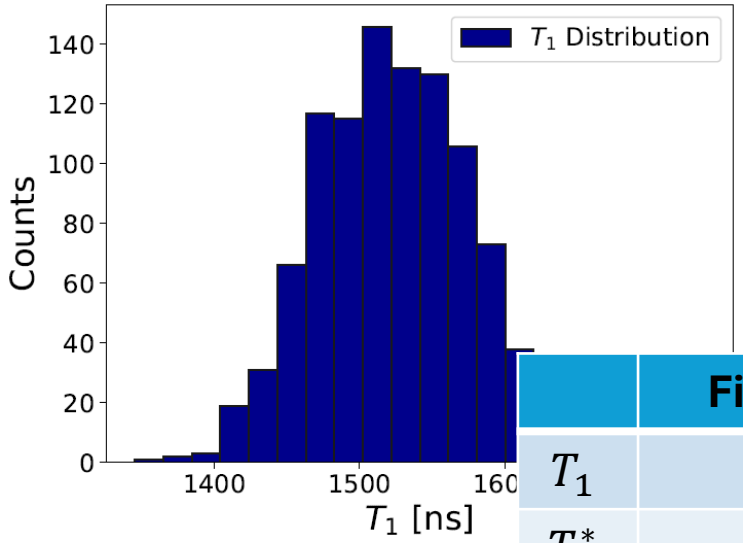


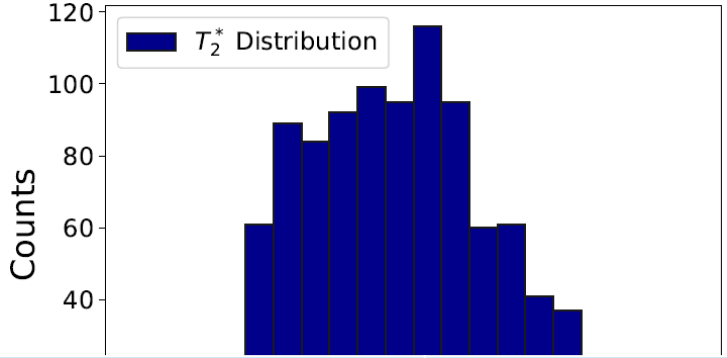


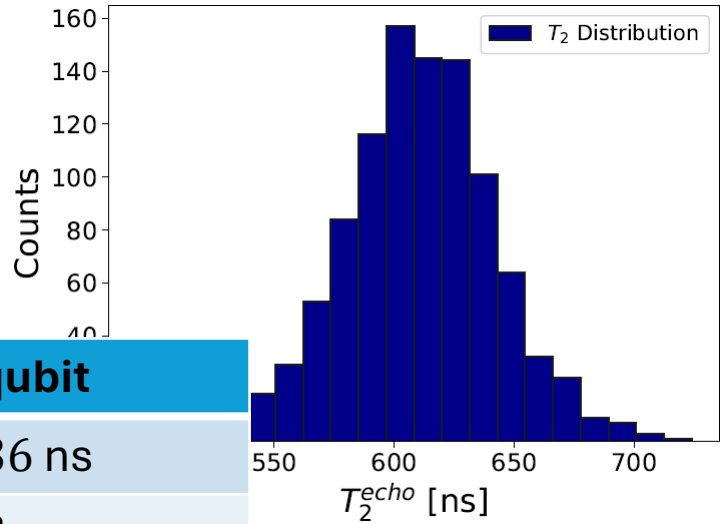




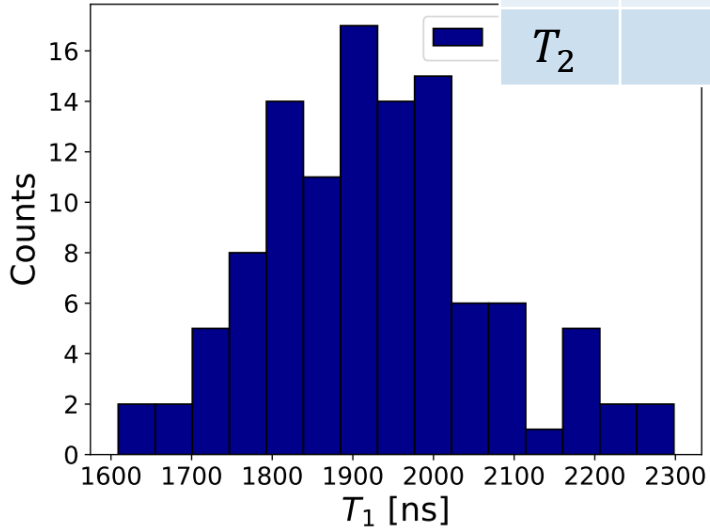
Relaxation and Coherence time measurement

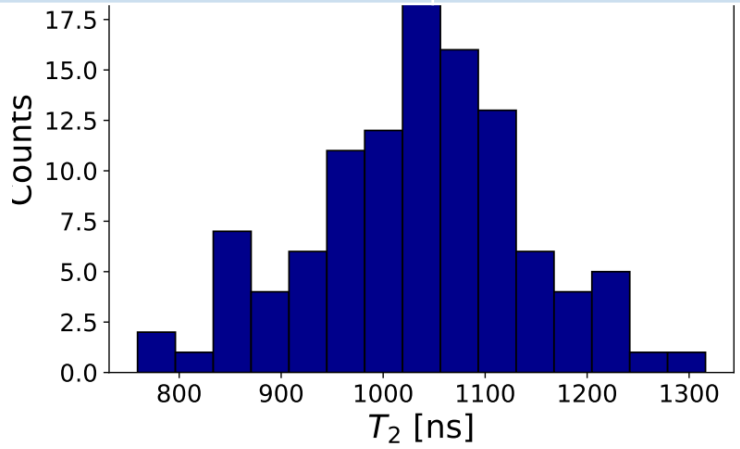


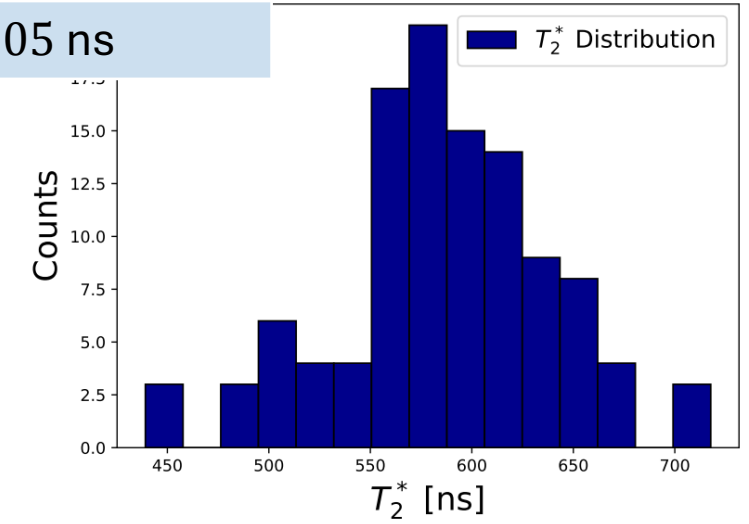




	Fixed frequency qubit	Tunable qubit
T_1	1522 ± 51 ns	1928 ± 136 ns
T_2^*	408 ± 73 ns	585 ± 53 ns
T_2	611 ± 31 ns	1033 ± 105 ns

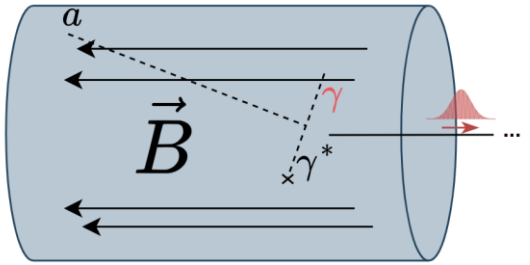






Light DM conversion into photons

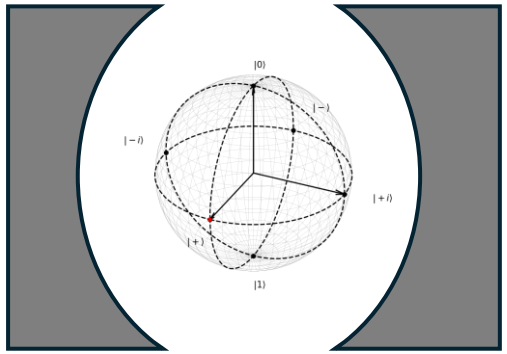
Axions: **itinerant photon detection** scheme



Axion conversion cavity

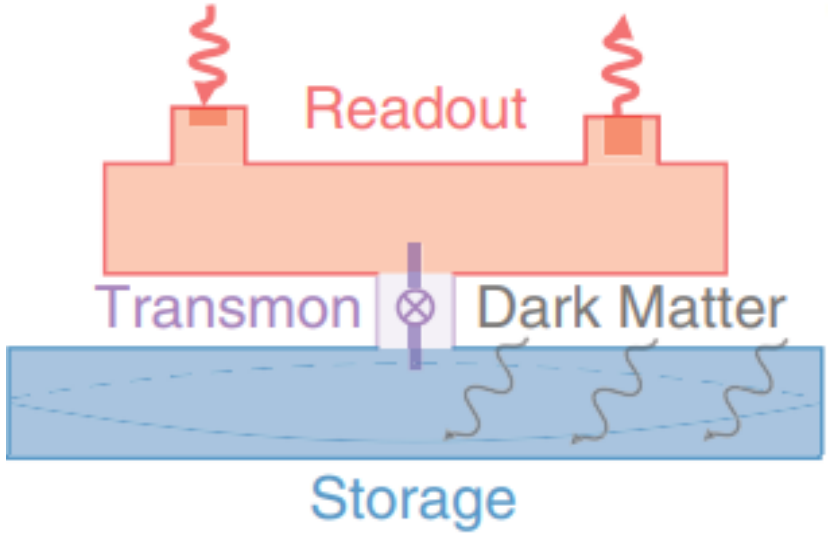
Transmission line

Resonator + Qubit



Dark photons: **localized dection** scheme

Readout cavity



Dark photon conversion cavity