IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 Sept 2024. Presentation given at WOLTE-16 2024, June 2024, Cagliari, Italy.

# Quantum Sensing with superconducting qubits for Fundamental Physics

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On behalf of the **Qub-IT** collaboration

Qub-IT

IEEE 16th Workshop on Low Temperature Electronics
WOLTE16
Cagliari, Sardinia, Italy | June 3-6, 2024

$16^{th}$ Workshop on Low Temperature Electronics

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
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# Low-mass Dark Matter

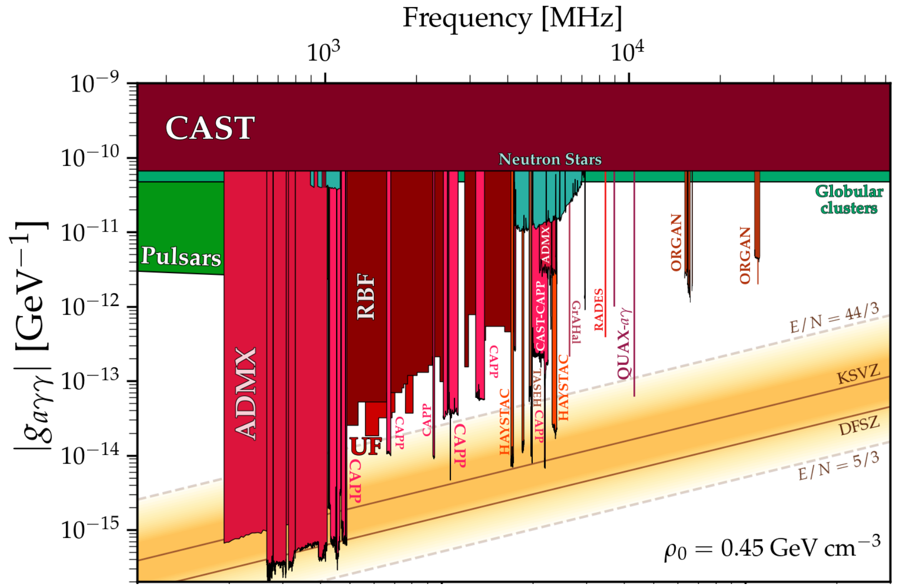


## Axion

- Would solve the strong CP problem.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \theta\frac{\boldsymbol{g}^2}{32\pi^2}F^{\mu\nu}\tilde{F}_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

- Single-photon conversion is expected (inverse Primakoff).
- Strong magnetic field required to boost conversion.

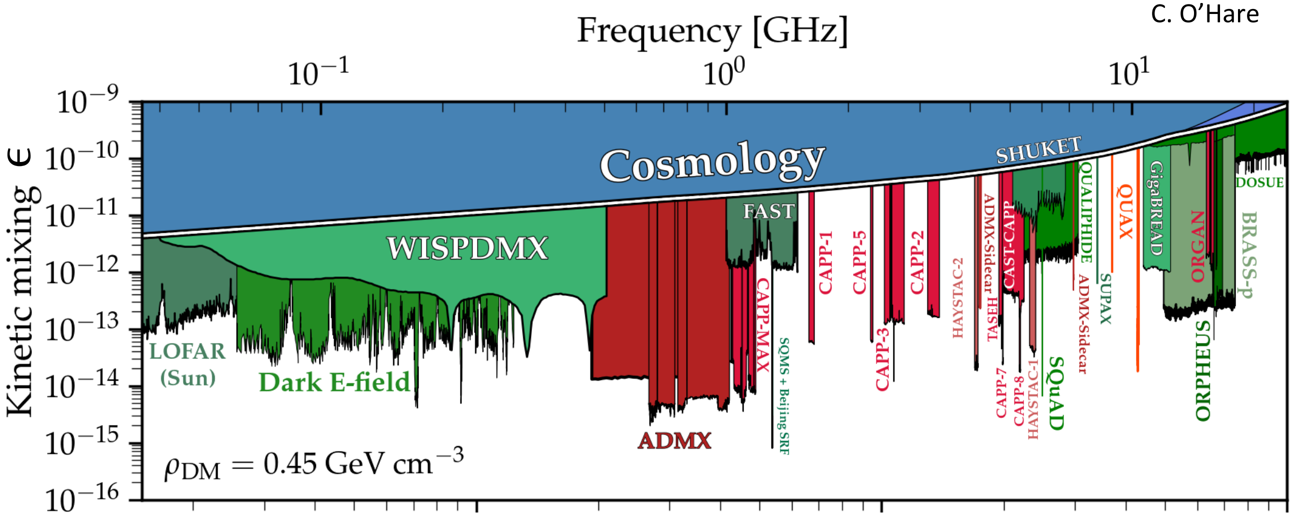



10.5281/zenodo.3932430
C. O'Hare

## Dark Photon

- Gauge U(1) symmetry not included in the Standard Model
- Kinetic mixing with the EM field

$$\mathcal{L} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2A'^{\mu}A'_{\mu} + \epsilon eA'^{\mu}J_{\mu}^{EM}$$



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# Transmon as QND detection platforms

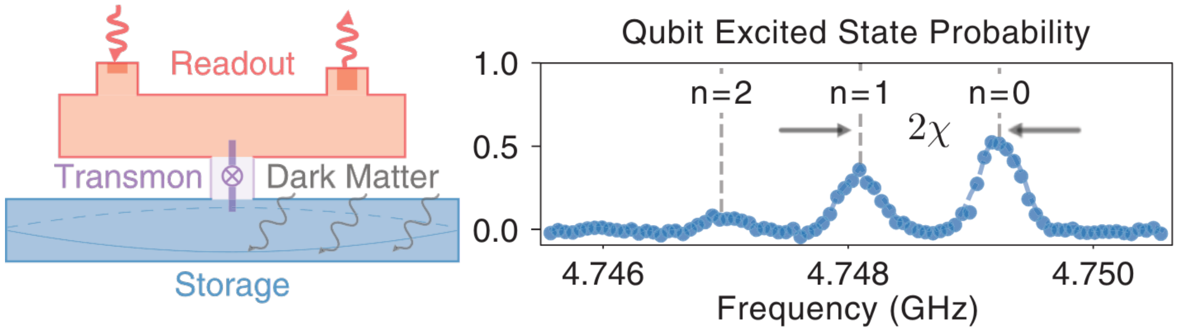


## Quantum Non-Demolition

The interaction between Dark Matter candidates and EM field leads to a photon deposited in a storage cavity.

$$\hat{\mathcal{H}} = \omega_r a^\dagger a + \frac{1}{2}\left(\omega_q + 2\chi a^\dagger a\right)\hat{\sigma}_z$$

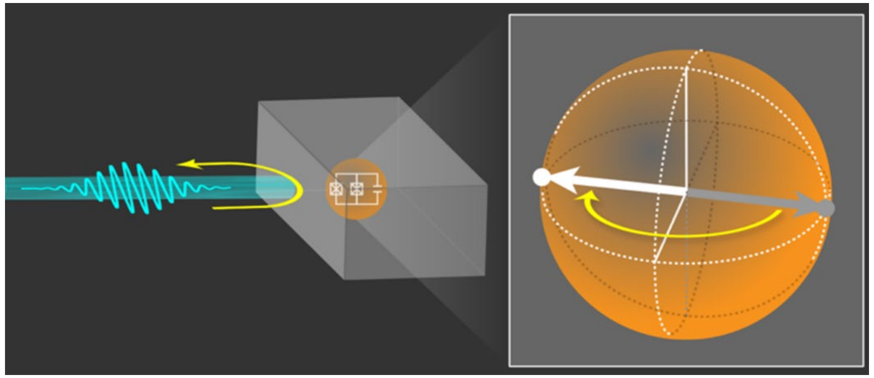
Photon-dependent precession term




10.1103/PhysRevLett.126.141302.
A. V. Dixit et al. (2021)

## Itinerant photon detection

- Transmon coupled to a cavity far from the magnetic field in $|+\rangle$ state.
- The microwave photon produced in the magnetic field region travels towards the cavity.
- Photon-qubit interaction acquires a $\pi$ phase shift.



10.1038/s41567-018-0066-3
S. Kono et al. (2018)

10.1103/PhysRevX.8.021003
J. C. Besse et al. (2018)

Image credit: APS/Alan Stonebraker

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# Transmon as direct detection platforms



We can detect hidden AC field through the excitation of Transmons when on resonance with the Dark Photon's mass.

Dark photon field: $\vec{X} = X\vec{\eta}\cos(m_X t)$

Total field on qubit: $\vec{E}_{eff} = \vec{E}_{EM} + \vec{E}_X = \vec{E}_{EM} - \epsilon\vec{X}$

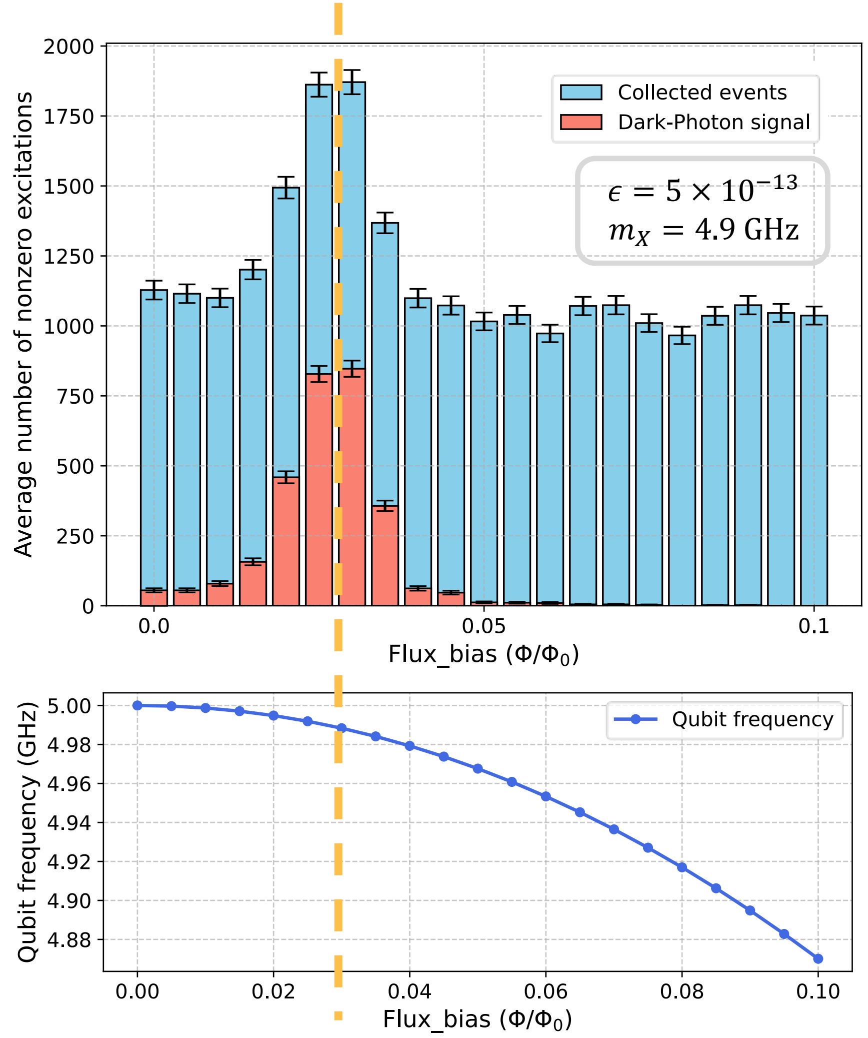
DM exerts a slow Rabi oscillation on a qubit state:

$$p_{ge}(\tau) \simeq 0.04 \times \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f}{1\ GHz}\right)\left(\frac{\tau}{100\ \mu s}\right)^2 \left(\frac{C}{0.1\ pF}\right)\left(\frac{d}{100\ \mu m}\right)^2 \left(\frac{\rho_{DM}}{0.45 GeV/cm^3}\right)$$

- $\epsilon$: Kinetic mixing
- $f$: Resonant frequency
- $\tau$: Evolution time
- $C$: Shunt capacitance
- $d$: Distance between plates
- $\rho_{DM}$: DM local density

10.1103/PhysRevLett.131.211001
S. Chen et al. (2023)

**MC simulation**



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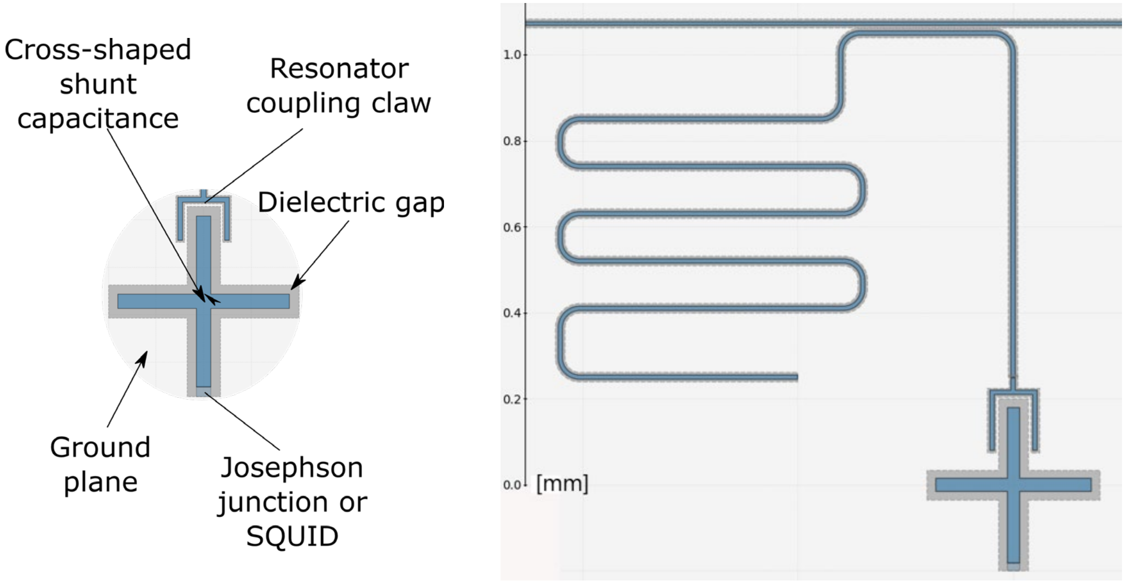
# Test chip design



## QND – v0

- Design software: Qiskit Metal (**IBM**).
- Grounded (X-mon) qubits.

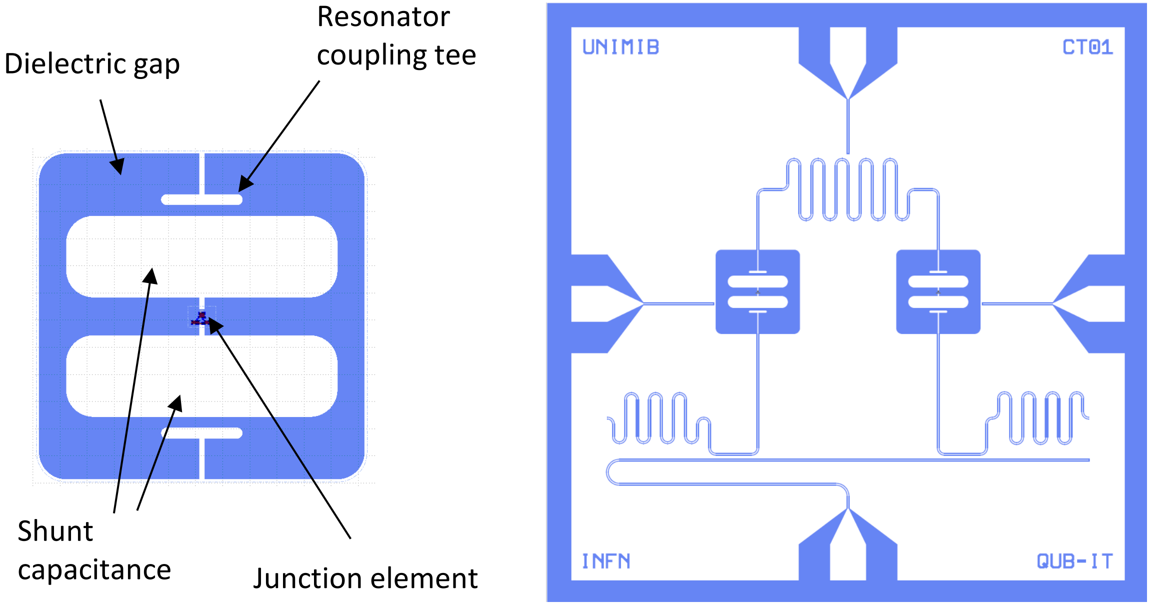



10.1109/TASC.2024.3350582
R. Moretti et al. (2024)

- High dispersive shift $\chi$ needed.
- Already **fabricated** and **tested.**

## QND – v1

- Design software: KQCircuits (**IQM**).
- Floating (Double-pads) qubits.




- High dispersive shift for both qubits $\chi_1, \chi_2$, with $\chi_1 \simeq \chi_2$
- Further dark count suppression.
- Allows experiments on entangled-states.
- **To be optimized**.

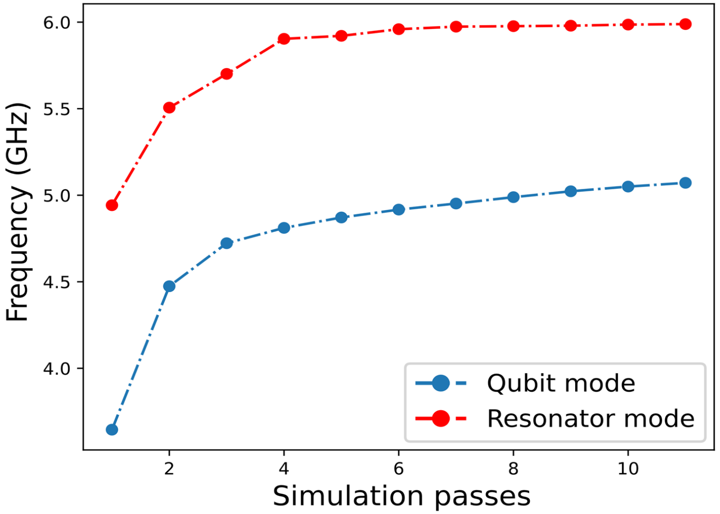
# Energy Participation Ratio

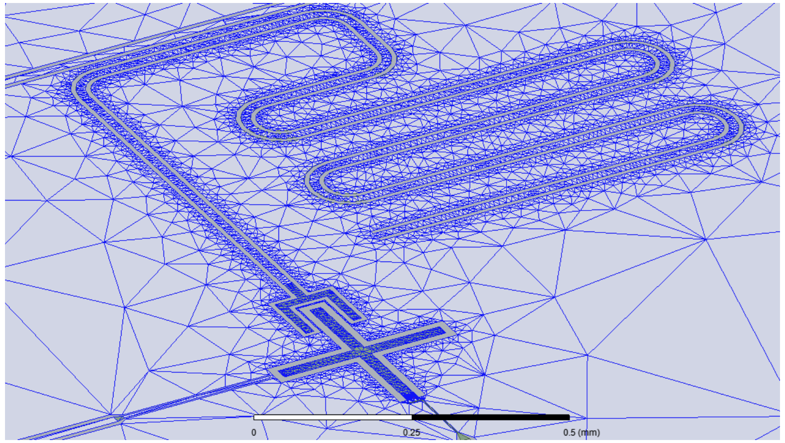


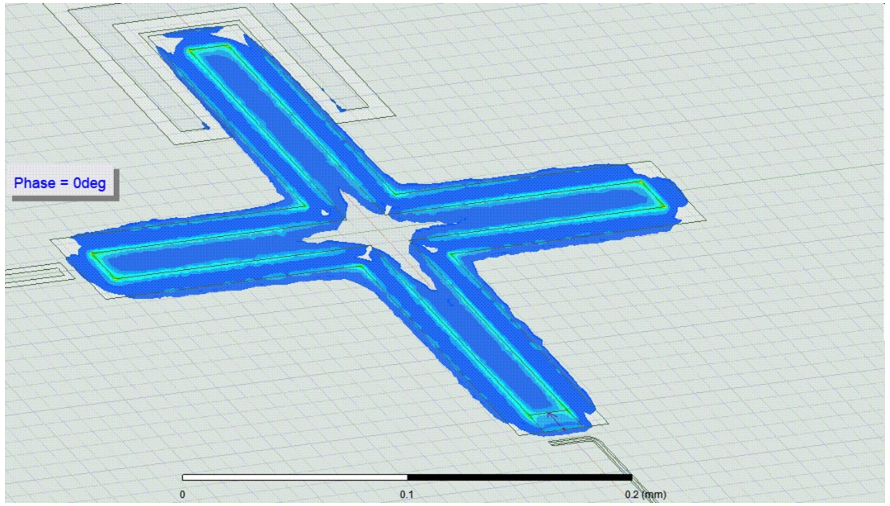
The EPR analysis computes the system eigenmodes $|\psi_m\rangle$ with $m \in$ {qubit, cavity} and computes the energy participation ratio:

$$p_m = \frac{\textit{Inductive energy in JJ}}{\textit{Inductive energy stored in mode}} = \frac{\langle \psi_m \left| \frac{1}{2} E_J \hat{\varphi}_J \right| \psi_m \rangle}{\langle \psi_m \left| \frac{1}{2} \hat{H}_{lin} \right| \psi_m \rangle}$$

Where $\hat{\mathcal{H}}_{lin} = \hbar\omega_c \hat{a}_c{}^\dagger \hat{a}_c + \hbar\omega_q \hat{a}_q{}^\dagger \hat{a}_q$






**Kerr matrix** $\chi_{mm'} = \frac{\hbar\omega_m\omega_{m'}}{4E_J} p_m p_{m'}$

10.1038/s41534-021-00461-8
Z. K. Minev et al. (2021)

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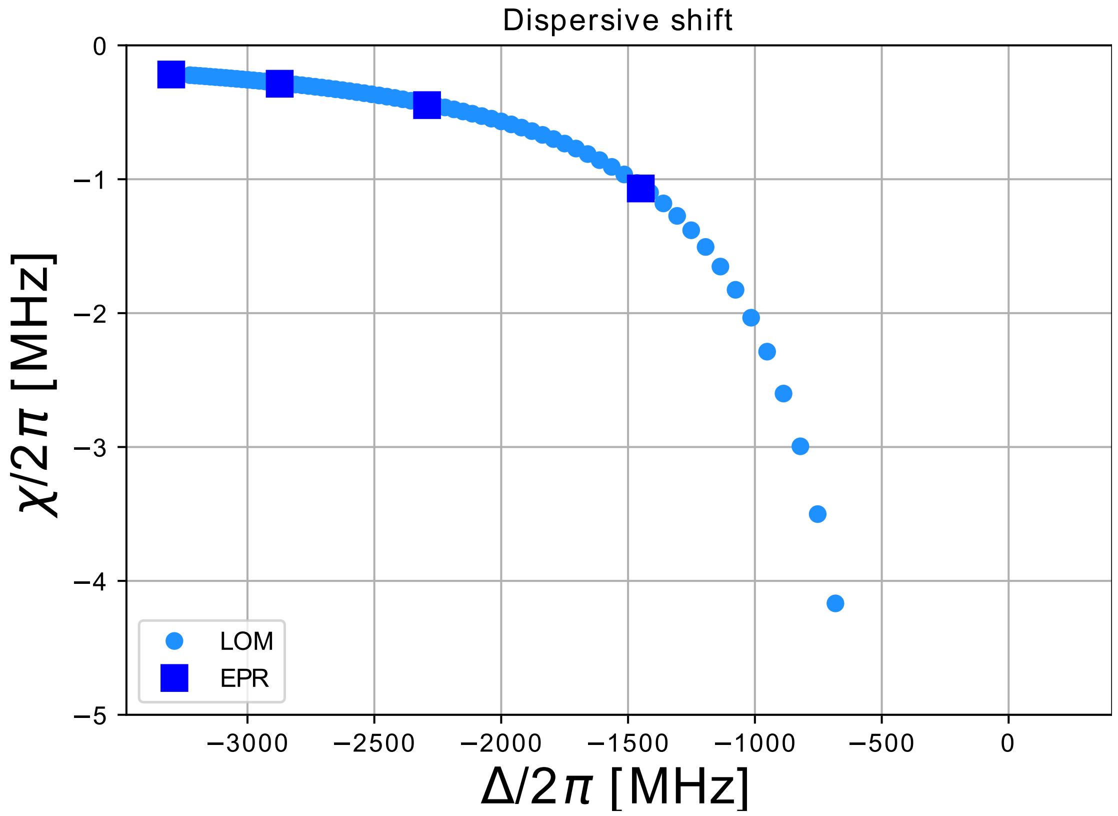
# EPR and Lumped Oscillator Model



- EPR: Energy Participation Ratio.
- LOM: Lumped Oscillator Model (analytical extraction).

| | Target | LOM | EPR |
|---|---|---|---|
| **JJ inductance $L_J$ [nH]** | 10 | 10 | 10 |
| **Transmon regime $E_J/E_c$** | >50 | 78.61 | 79.96 |
| **Anharmonicity $\alpha/2\pi$ [MHz]** | 202 | 230.62 | 216.44 |
| **Dispersive shift $\chi/2\pi$ [MHz]** | 0.30 | 0.31 | 0.35 |
| **Qubit frequency $\omega_q/2\pi$ [MHz]** | 5000 | 4995.79 | 4893.84 |
| **Cavity frequency $\omega_c/2\pi$** | 7400 | 7481.04 | 7435.44 |
| **Qubit-cavity coupling $C_g$ [fF]** | 4 | 3.93 | - |

$T_{1\ Purcell} \simeq 51\mu s$ for $Q_c \simeq 4 \times 10^3$



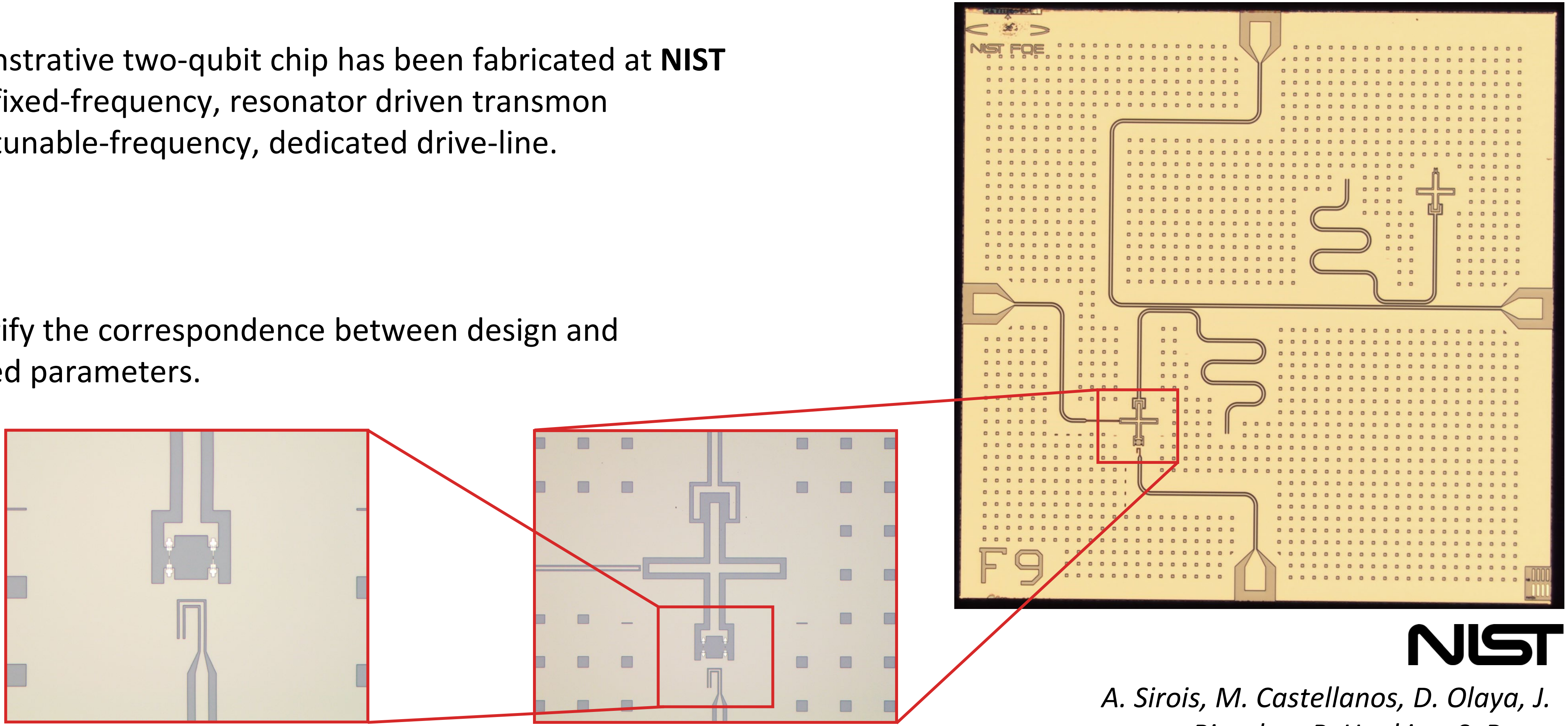
# First chip fabrication



A demonstrative two-qubit chip has been fabricated at **NIST**

- One fixed-frequency, resonator driven transmon
- One tunable-frequency, dedicated drive-line.

**Aim**: verify the correspondence between design and measured parameters.




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

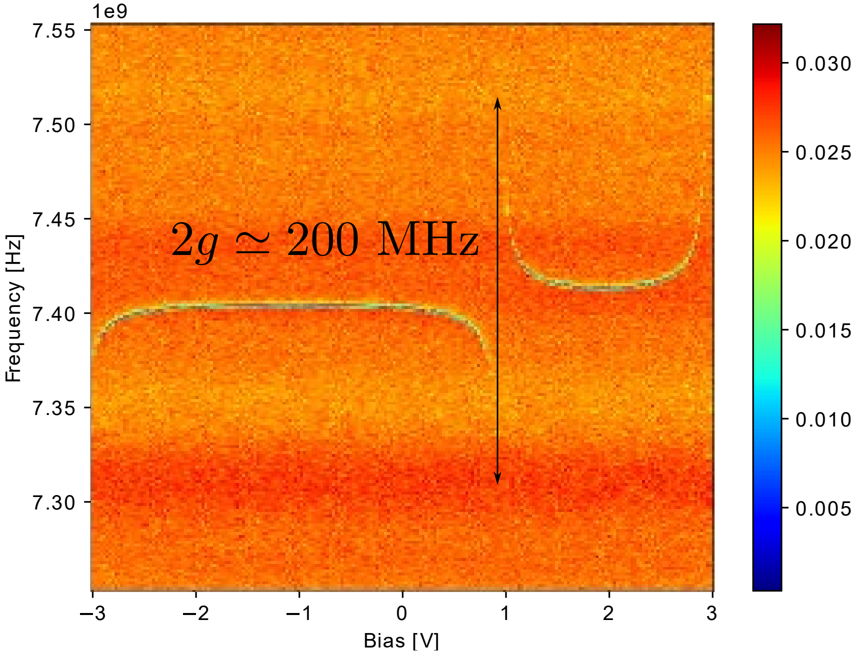
# Agreement with simulations

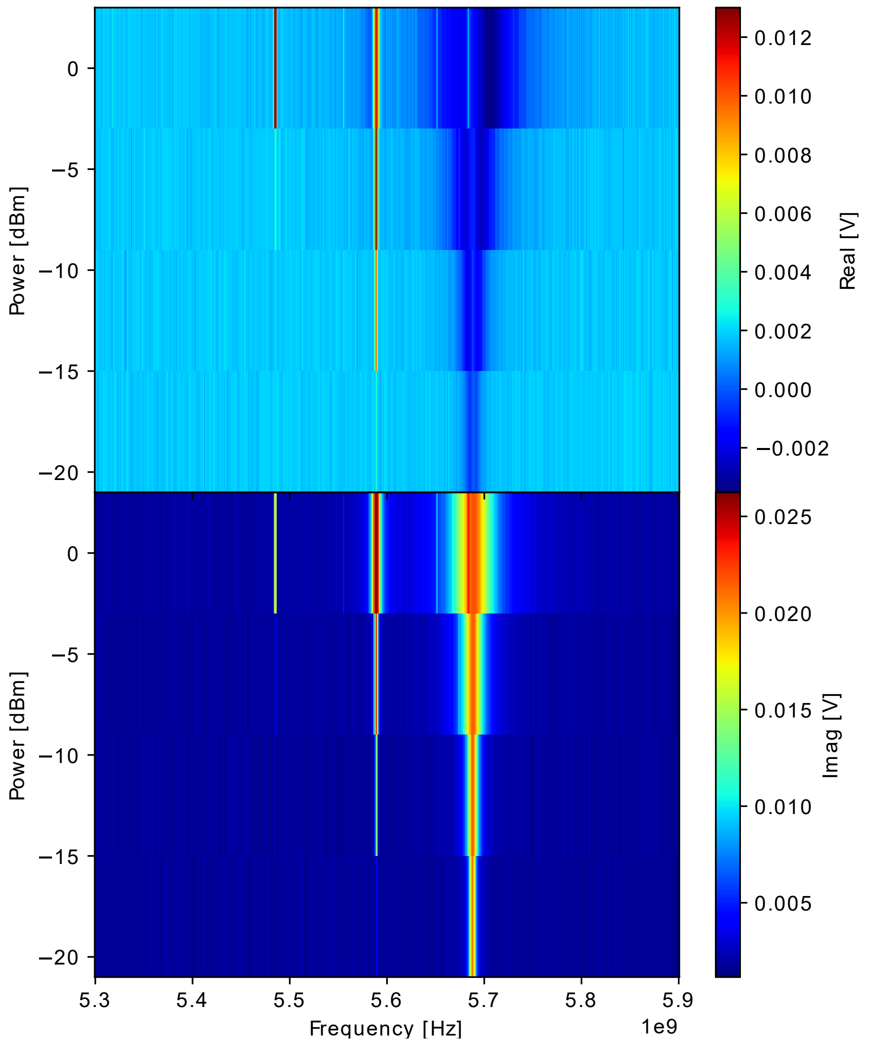


Standard characterization carried out at NIST.
Good agreement between experiments and simulations.

| Fixed qubit | Measured | LOM |
|---|---|---|
| $\omega_{0\to1}/2\pi$ [GHz] | 5.689 | 5.682 |
| $\frac{1}{2}\omega_{0\to2}/2\pi$ [GHz] | 5.589 | 5.579 |
| $\omega_{1\to2}/2\pi$ [GHz] | 5.485 | 5.476 |
| $\alpha/2\pi$ [MHz] | 204 | 206 |
| $L_J$ [nH] | 7.641 | 7.2 |

| Tunable qubit | Measured | LOM |
|---|---|---|
| $\omega_{0\to1}/2\pi$ [GHz] | 5.649 | 5.649 |
| $L_J$ [nH] | 8.364 | 7.9 |
| $g$ [MHz] | 98 | 100 |



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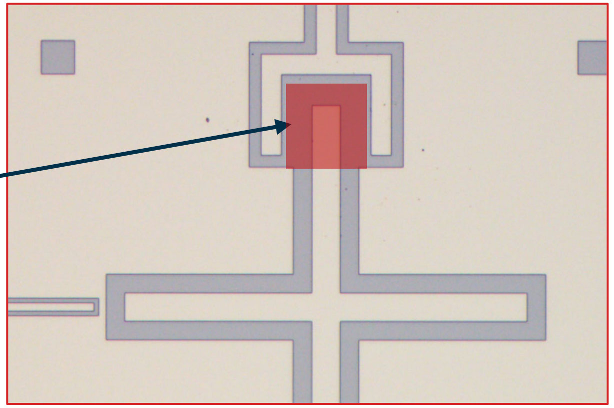
# Chip characterization

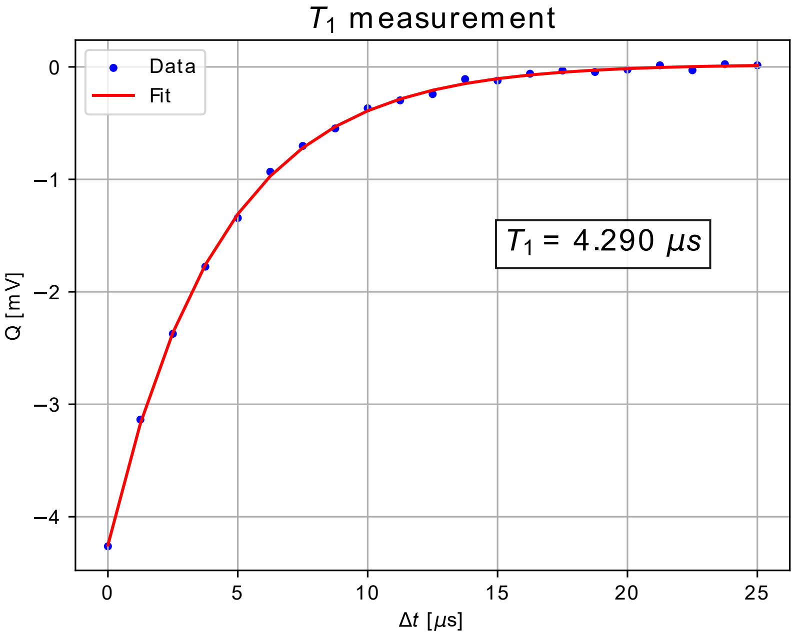


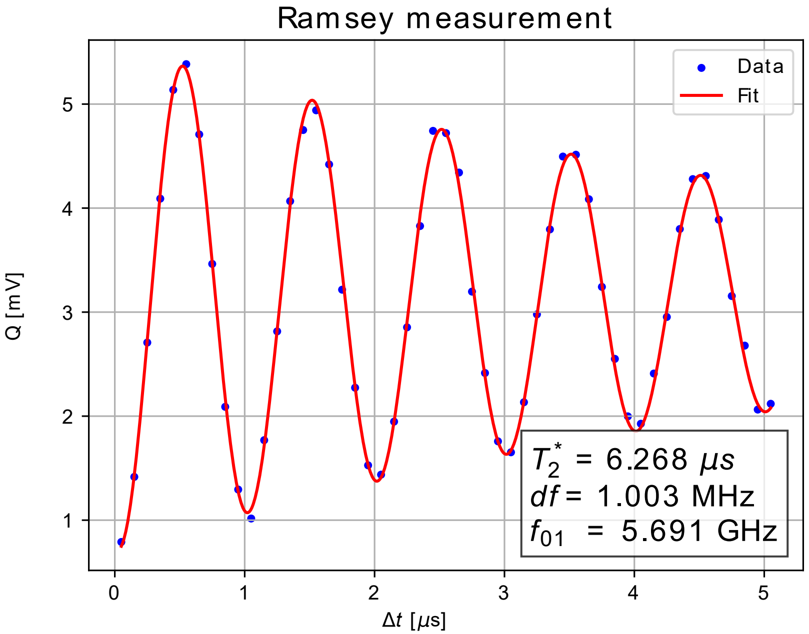
$T_1$ and $T_2$ are **lower than expected** for both qubits.
This can be due to:

- Possible fabrication issues.
- Qubit frequencies higher than expected.
- No ground between qubit and coupler.
- Insufficient modeling of **Two-Level System** (TLS) losses.



$$\frac{1}{T_{1\,TLS}} = \frac{\omega}{Q} = \omega \sum p_i \tan(\delta_i)$$



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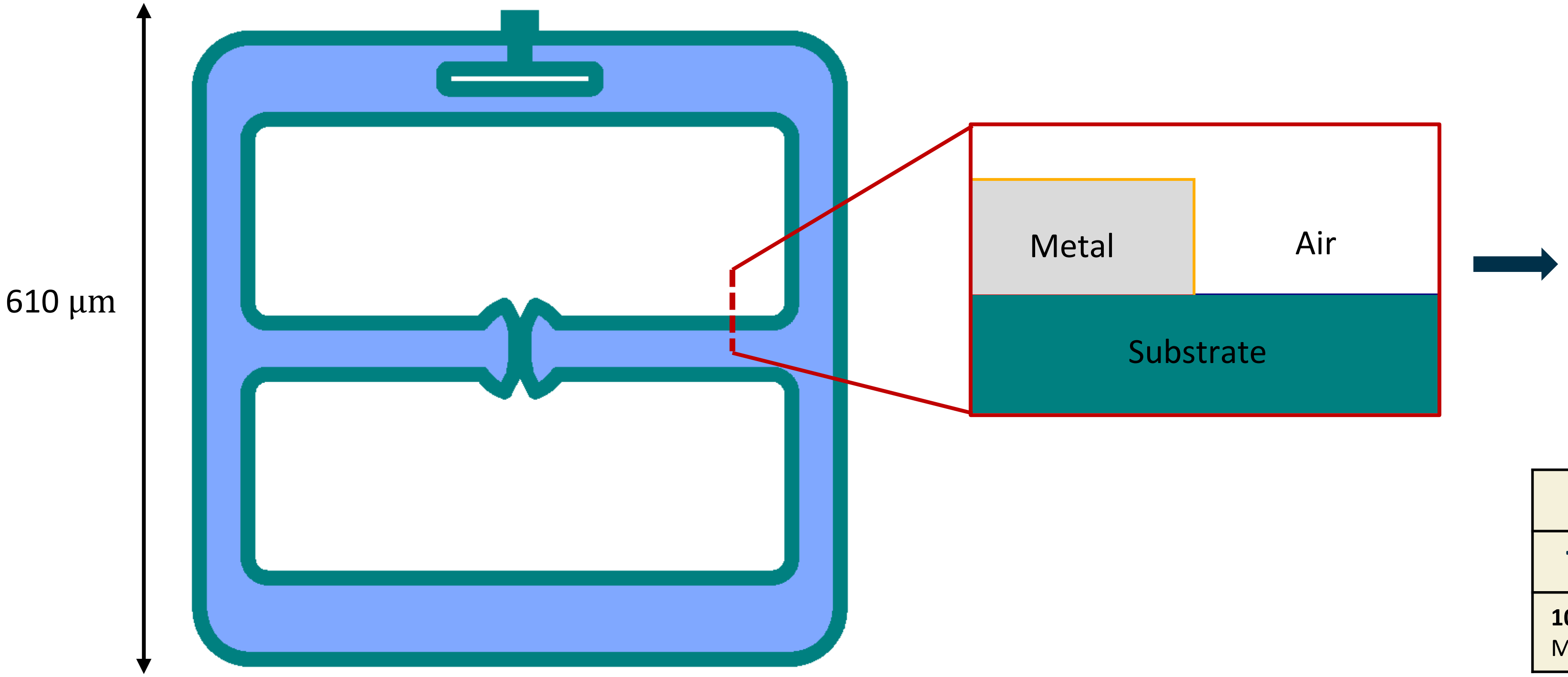
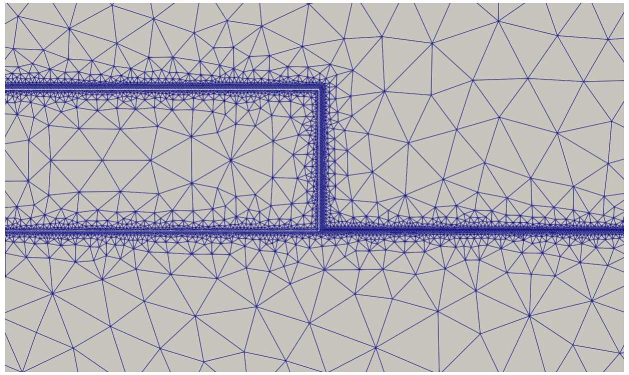
# Hybrid interface modeling



Leverage cross-section (**2D**) simulations on metal-edge regions (MER) to model surface losses.

- Achieve high-density meshing between interfaces, where the electric field is more intense.
- Computing EPRs on all surfaces, vacuum and substrate.
- Using 2D results to correct for Ansys Eigenmode EPR on customized-regions.
- Engineering shapes to reduce **surface** EPR.



| | MA | SA | MS |
|---|---|---|---|
| **Thickness (nm)** | 4.8 | 2.4 | 0.3 |
| **10.1103/PRXQuantum.3.020312**<br>M. V. P. Altoé et al. (2022). | | | |

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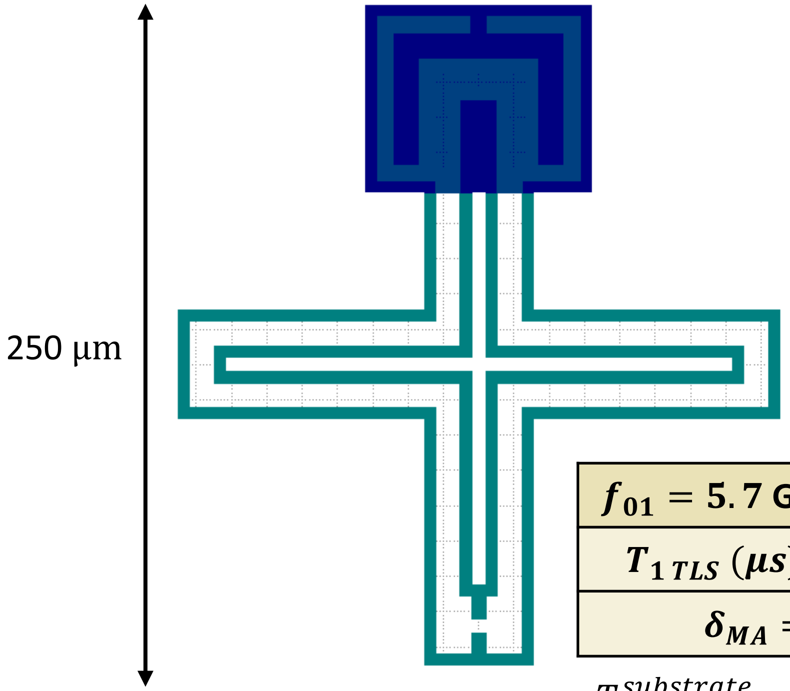
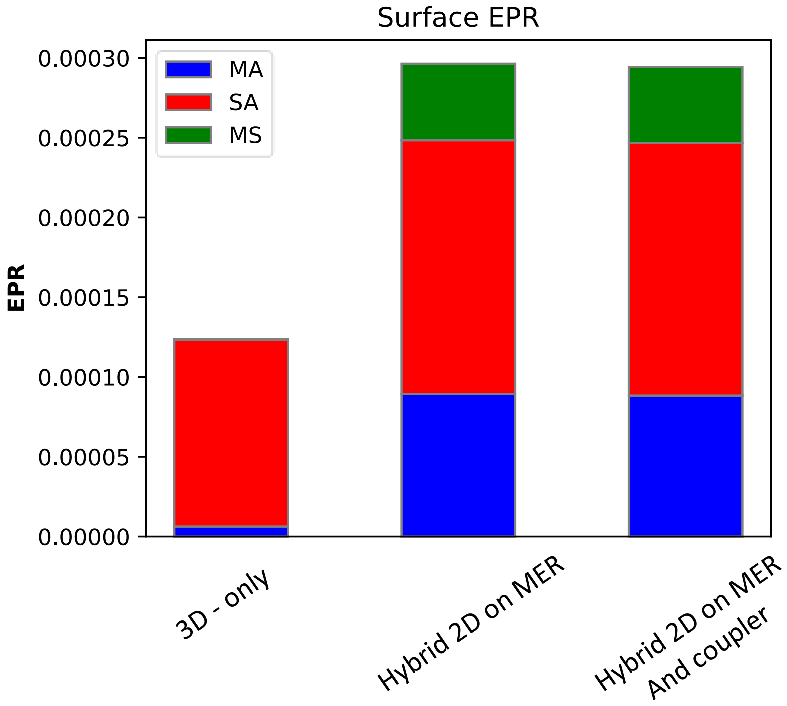
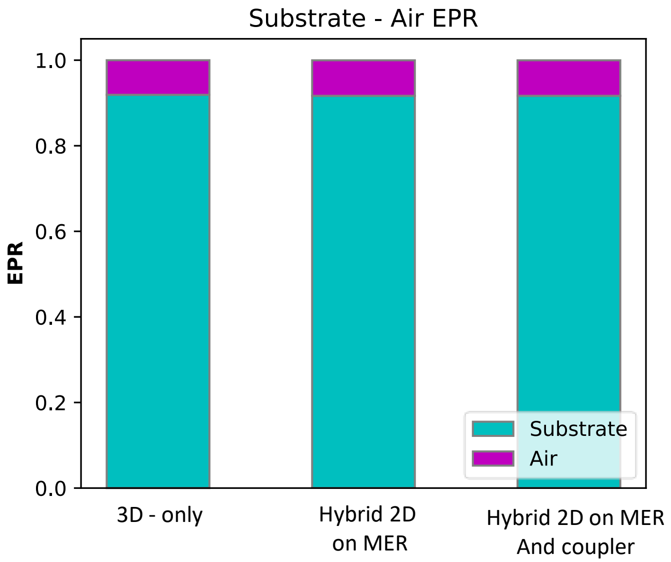
# Improving dielectric loss estimation

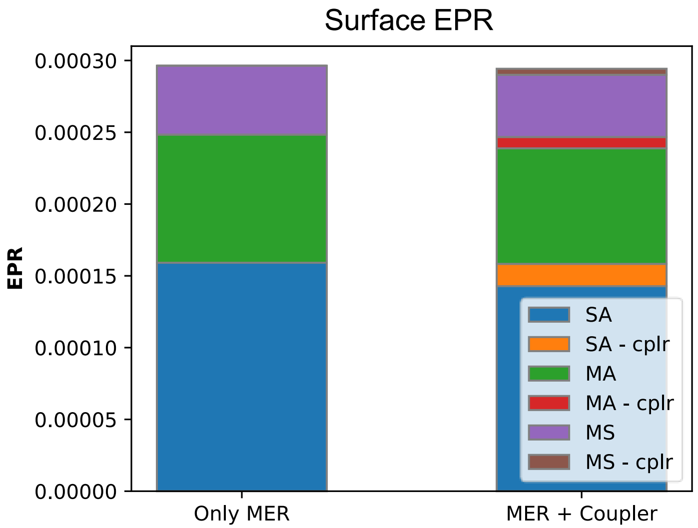


- We can select arbitrary regions of interest (MER, couplers, junctions, …) to carry out 2D simulations and correct the EPR.
- The 3D-only simulation does not capture surface EPR well enough.
- 44% decrease in $T_{1\,TLS}$ according to hybrid method.



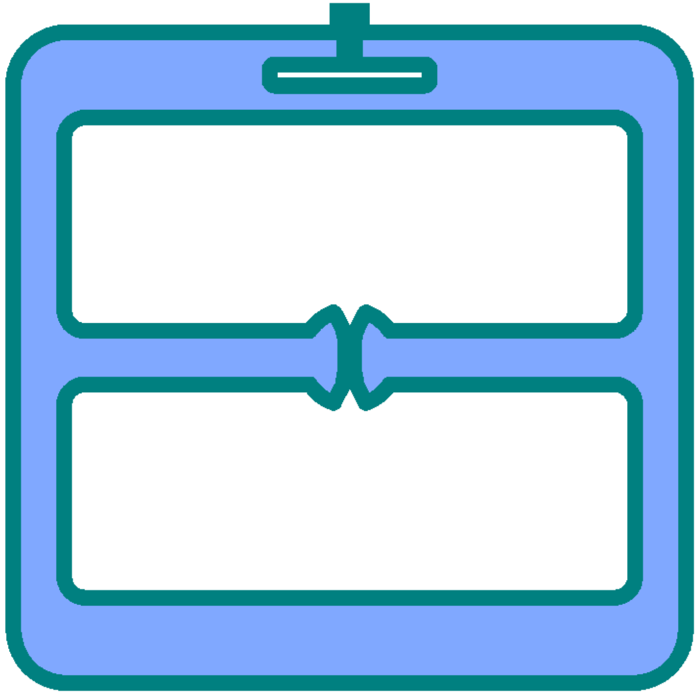

| $f_{01} = 5.7$ GHz | 3D - only | Hybrid (MER) | Hybrd (MER + cplr) |
|---|---|---|---|
| $T_{1\,TLS}\ (\mu s)$ | 25.9 | 14.4 | 14.5 |
| $\delta_{MA} = \delta_{SA} = \delta_{MS} = 5 \times 10^{-3}$ $\quad \delta_{substrate} = 5 \times 10^{-7}$ | | | |

$$T_{1\,TLS}^{substrate} = 61\ \mu s$$

# Double-pad transmon surface loss

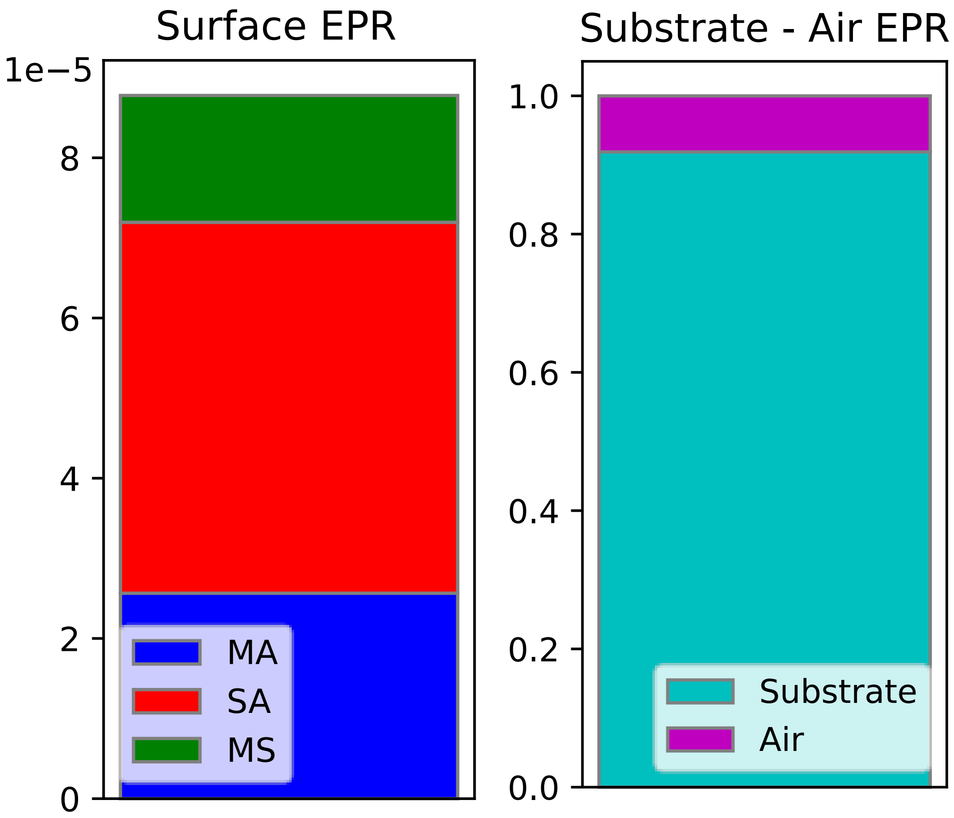


- Similar strategy has been carried out for double-pad.
- Bigger area and larger gaps lead to higher coherence time.
- Surface loss decreases by a factor of 3.5.



| $f_{01} = 5.7$ GHz | Hybrid (MER) |
|---|---|
| $T_{1\,TLS}\ (\mu s)$ | 31.1 |
| $\delta_{MA} = \delta_{SA} = \delta_{MS} = 5 \times 10^{-3}$<br>$\delta_{substrate} = 5 \times 10^{-7}$ | |

$T_{1\,TLS}^{substrate} = 61\ \mu s$



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# Future developments

- Modeling and simulation of single-qubit chip has been succesfully demonstrated.
- Fabrication and full characterization is being replicated within Qub-IT.
- Other multi-qubit detection schemes are being investigated for QND.
- Further refine the Direct Detection scheme modeling.
- Engineering detection setups.

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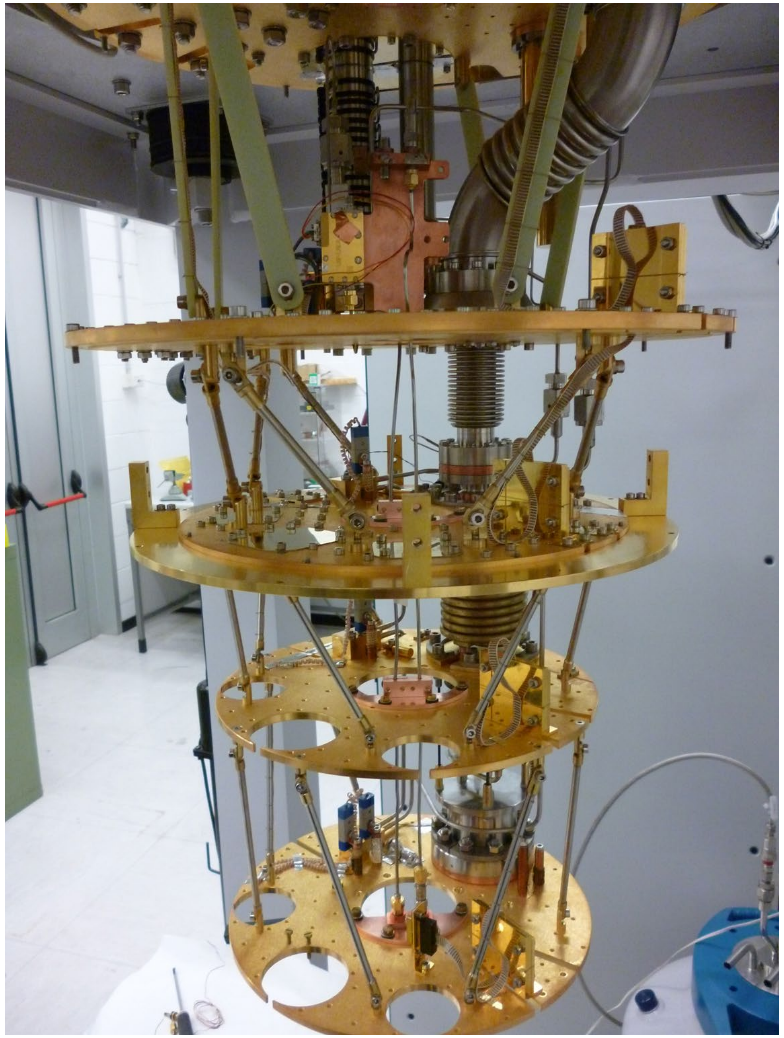

*Bicocca CryoLab refrigerator*