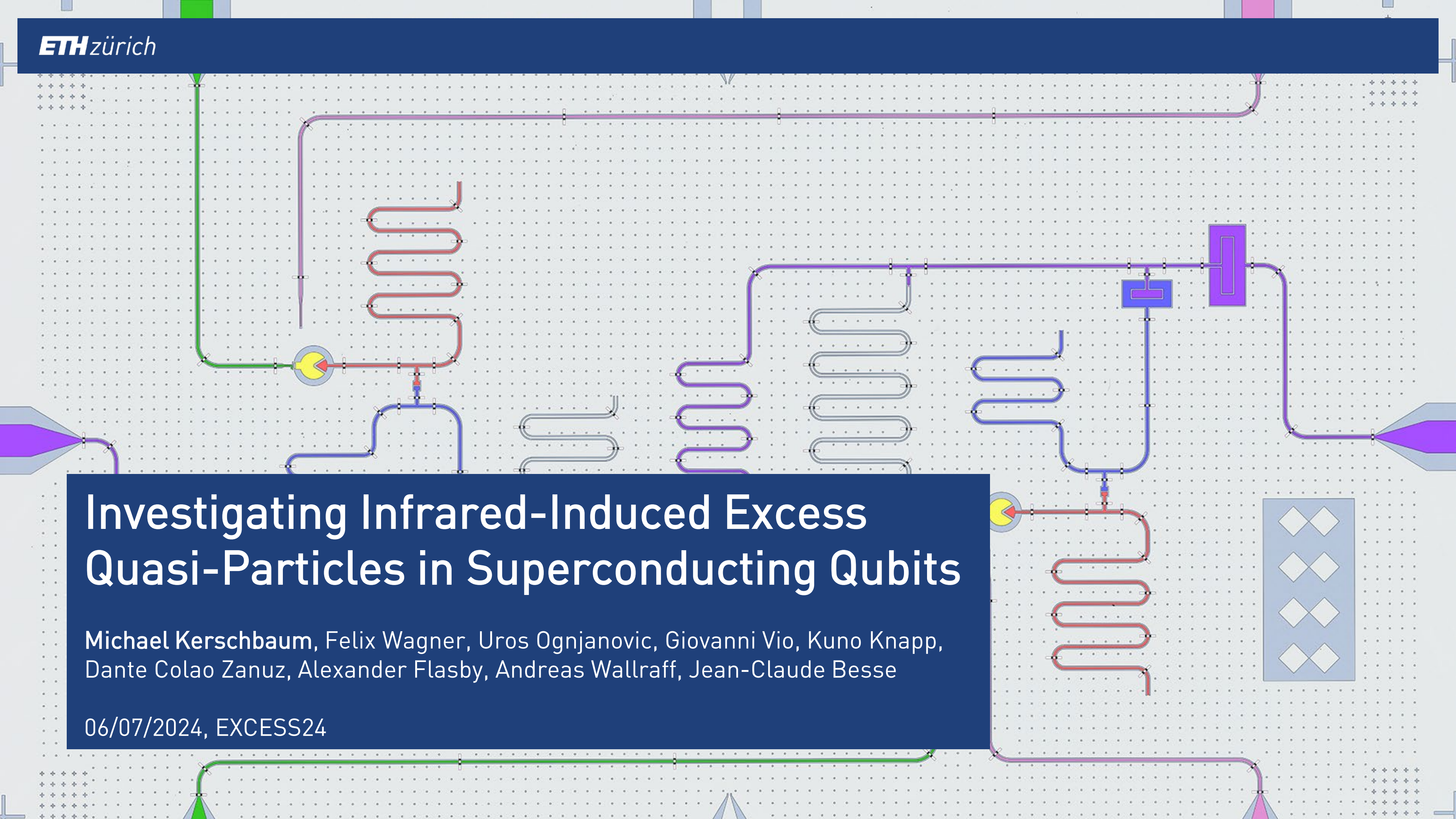

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Investigating Infrared-Induced Excess Quasi-Particles in Superconducting Qubits

Michael Kerschbaum, Felix Wagner, Uros Ognjanovic, Giovanni Vio, Kuno Knapp, Dante Colao Zanuz, Alexander Flasby, Andreas Wallraff, Jean-Claude Besse

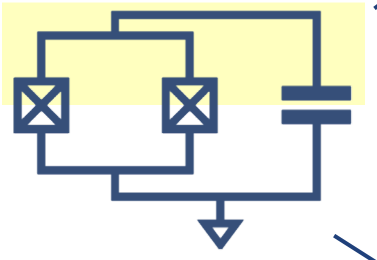
06/07/2024, EXCESS24

Superconducting Circuits as a Platform for Quantum Information Processing

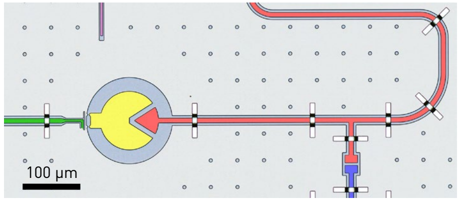
Energy levels of SQUID-capacitor circuit **non-equidistantly** spaced

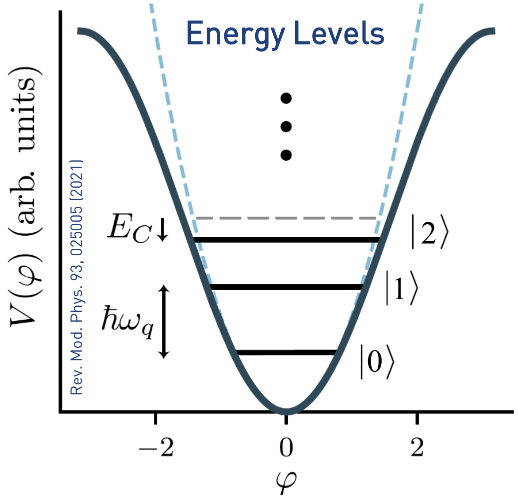
Restrict gates to act on **two-level subspace**

Circuit Model



Microscope Image





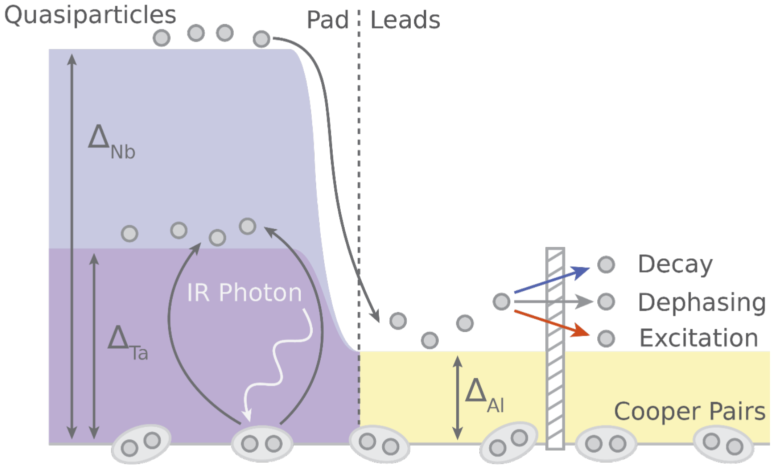
Inductively and **capacitively** coupled lines **control and read out** qubit state

System Hamiltonian

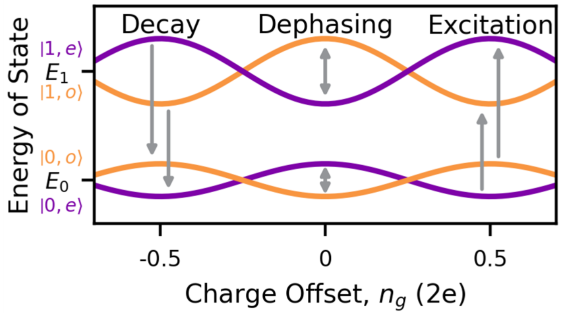
$$\hat{H}_T = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}$$

charge energy (E_C), charge number ($\hat{n}$), offset charge (n_g), Josephson energy (E_J), phase ($\hat{\varphi}$)

Quasiparticle Tunneling Causes Relaxation and Dephasing



- At T≈40 mK film electrons are paired, **binding energies 2Δ ≈ meV ≈ 250 GHz**
- Athermal photons/phonons can break pairs creating **quasiparticles (QPs)**
- QPs can **tunnel** through Josephson junctions (JJs)

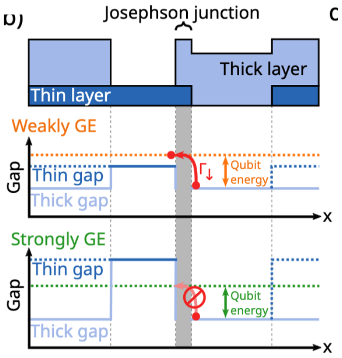


- Electrical field (≈kV/m) in JJ interacts with QPs → **decay**
- **Even/odd charge parity** (CP) island changes qubit energy
- Tunneling QP switches CP → **dephasing**

State-of-the-Art

Previously studied in literature:

- Phonon bursts from **high energy particles** as QP sources Nature Physics volume 18, pages 107–111 (2022)
- **Antenna modes** of the qubit island as QP sources arXiv:2103.06803 (2021) Phys. Rev. Lett. 132, 017001 (2024)
- Interaction of QP with qubit state PRX Quantum 3, 040304 (2022) Nature Communications volume 5, 5836 (2014)

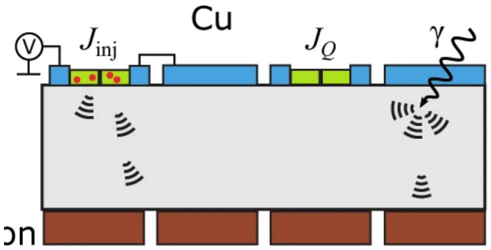


arXiv:2402.15644 (2024)

Suggested mitigation strategies:

- Normal conducting phonon and QP **traps**
- Increased **gap difference** left/right of JJ

Phonon Traps



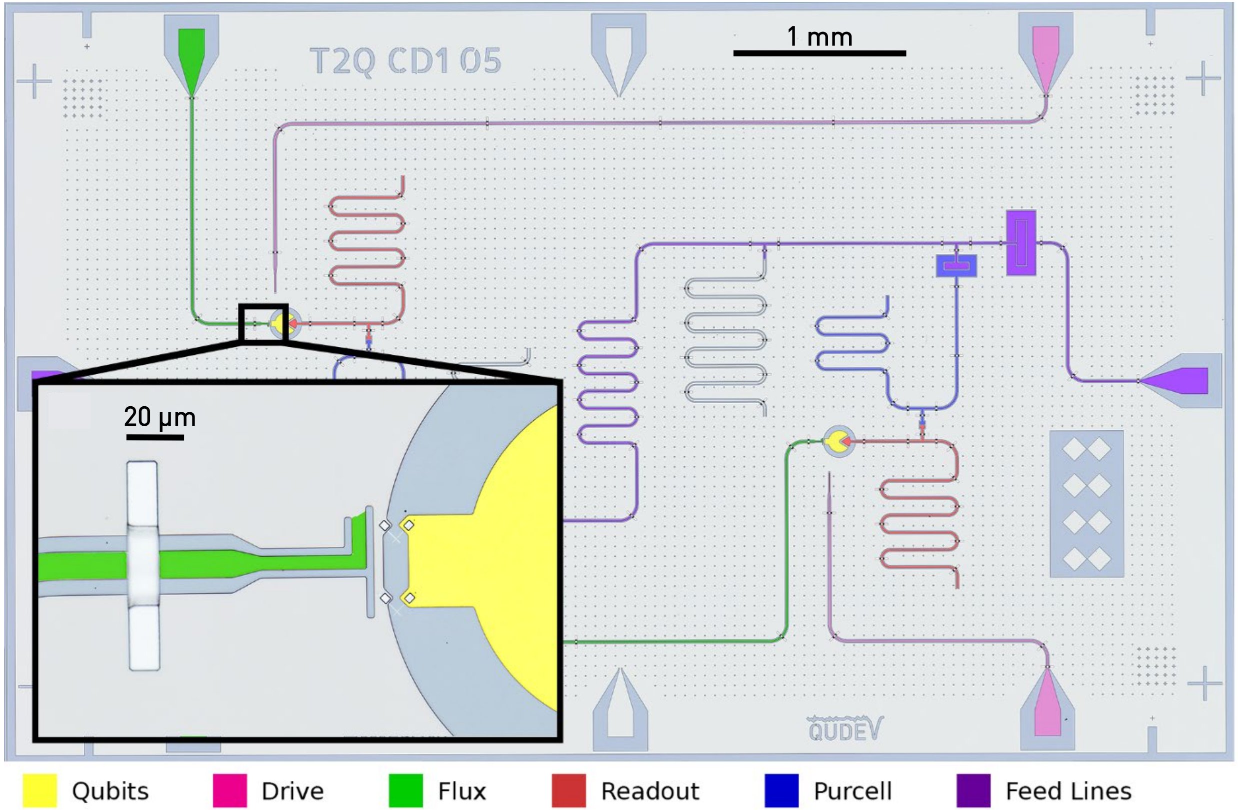
Nature Communications volume 13, 6425 (2022)

Focus of our study:

Infrared-induced QPs in different base layer materials

Measuring Quasiparticle-Tunneling with Offset-Charge Sensitive Devices

- Two-qubit device with smaller islands
- $E_C/E_J \approx 17$ at lower sweet spot
- Charge dispersion ≈ 1-5 MHz
- Materials: Niobium or Tantalum on Silicon substrate with Aluminum junctions

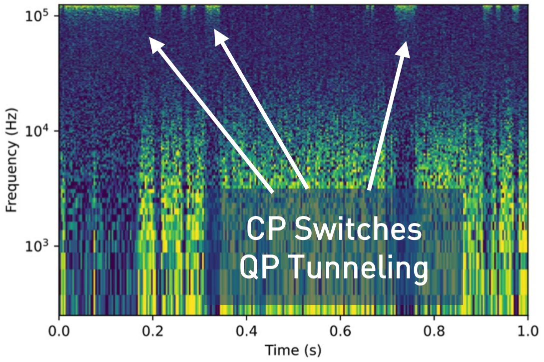


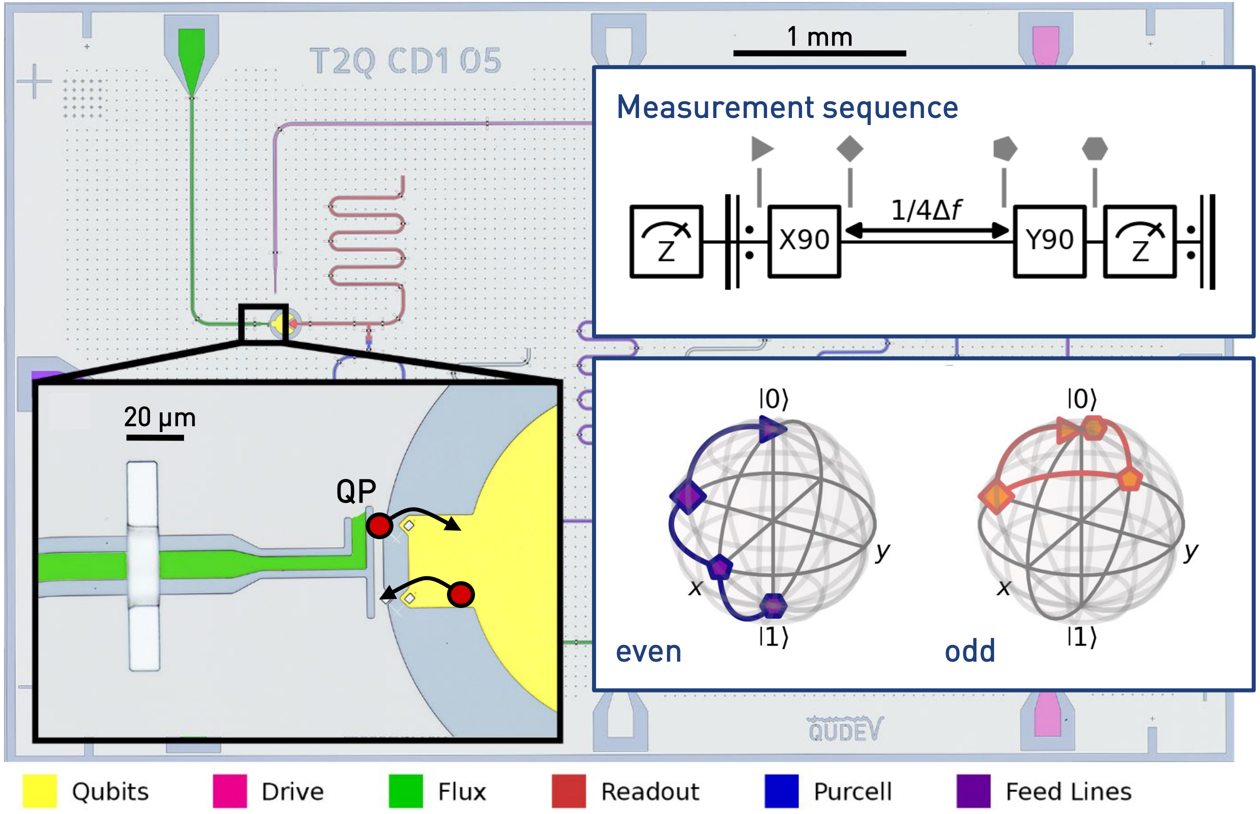
Measuring Quasiparticle-Tunneling with Offset-Charge Sensitive Devices

Ramsey sequence **maps CP state to qubit** state:

- **even**: state switches
- **odd**: state remains

Restless readout scheme
toggling/**steady** sequence





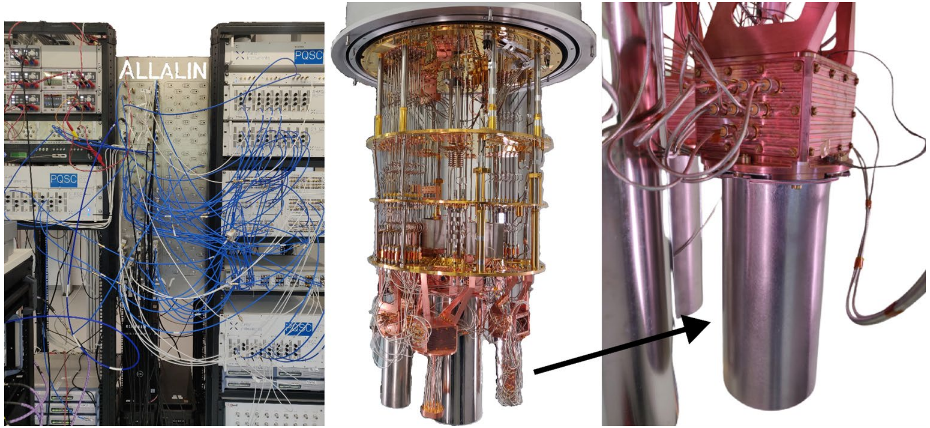
Investigating Quasiparticles at ETHZ-PSI Quantum Computing Hub

Measurement campaign started in early 2023

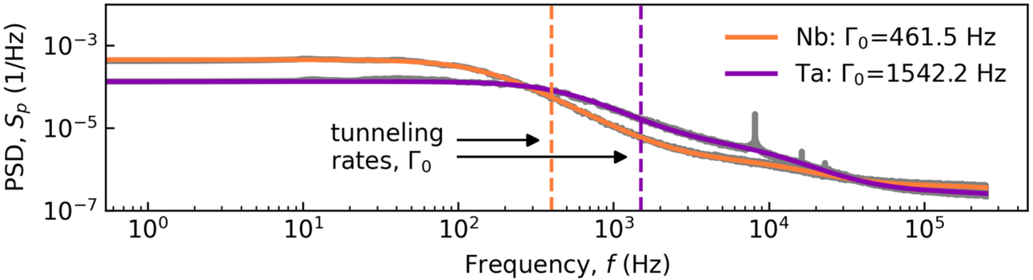
Goals:

- Understand QP dynamics in **Nb/Ta**-based quantum devices
- Study **infrared (IR) background** as QP source
- Develop **best practices** for superconducting qubit setups

$$\hat{S}(f, \Gamma, A) = \sum_{i=0}^{2} \frac{8A_i\Gamma_i}{(2\Gamma_i)^2 + (2\pi f)^2}$$

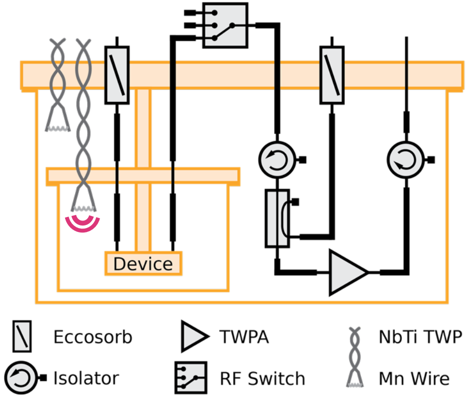


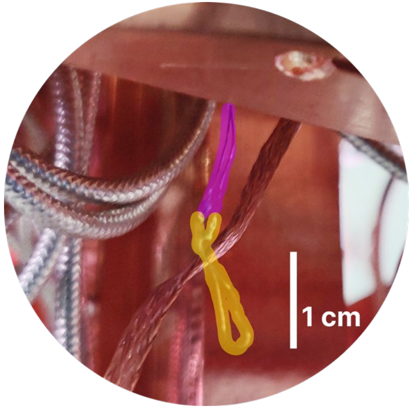
PSD of QP tunneling in Nb and Ta

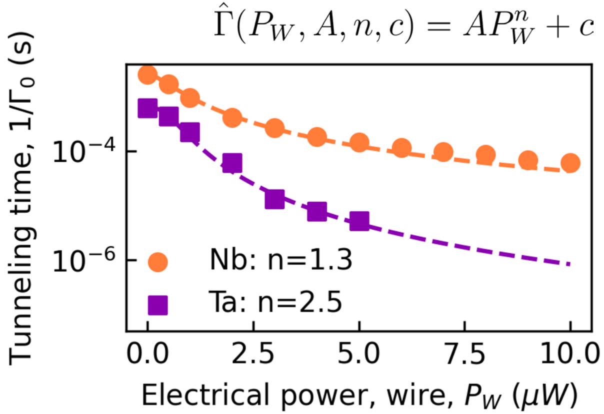


Investigating the Response of QP-Tunneling Rates to Far-Infrared-Radiation

- Operate **Manganin heating wire** inside shielding
  PRX Quantum 3, 040304 (2022)
- Wire temperature at maximal power **estimated ≈ 5 K**
- Wire emits **black body IR** radiation
- Measure tunneling time $1/\Gamma_0$, at given wire power







Observe:

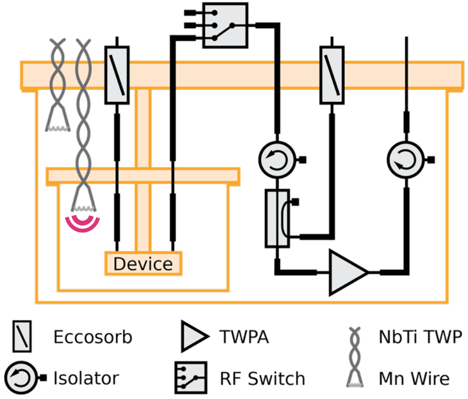
- $1/\Gamma_0$ lower in Ta
- $1/\Gamma_0$ scales steeper with IR in Ta
- Possibly effect of frequency spectrum, or QP termination: **recombination vs. trapping**

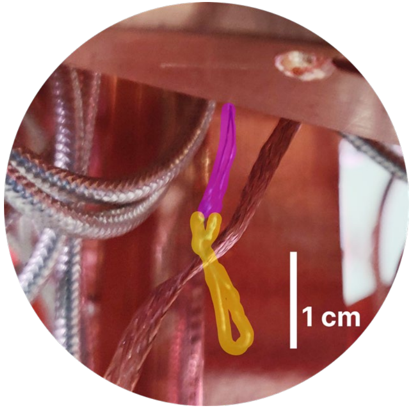
Investigating the Response of QP-Tunneling Rates to Far-Infrared-Radiation

Observe:

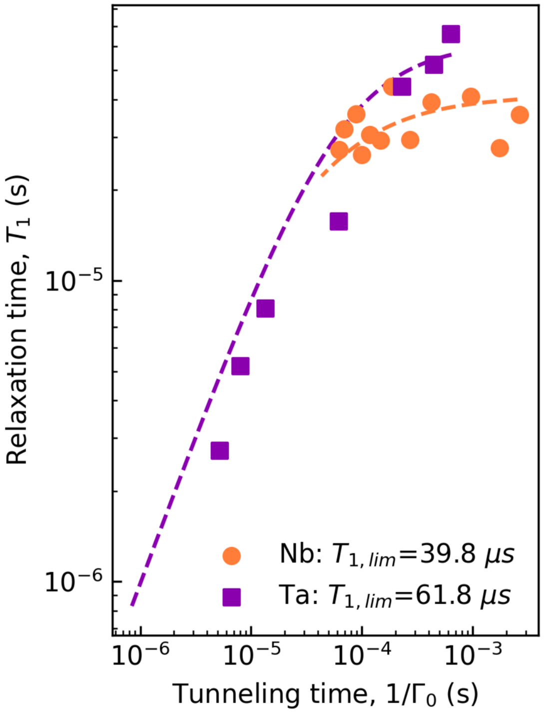
- In Ta devices T_1 **scales with tunneling time**
- Tunneling harmful for Ta devices already in background regime

→ Mitigation of QP tunneling **crucial for qubit coherence**



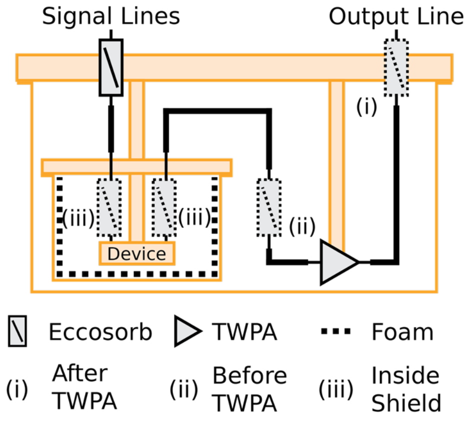


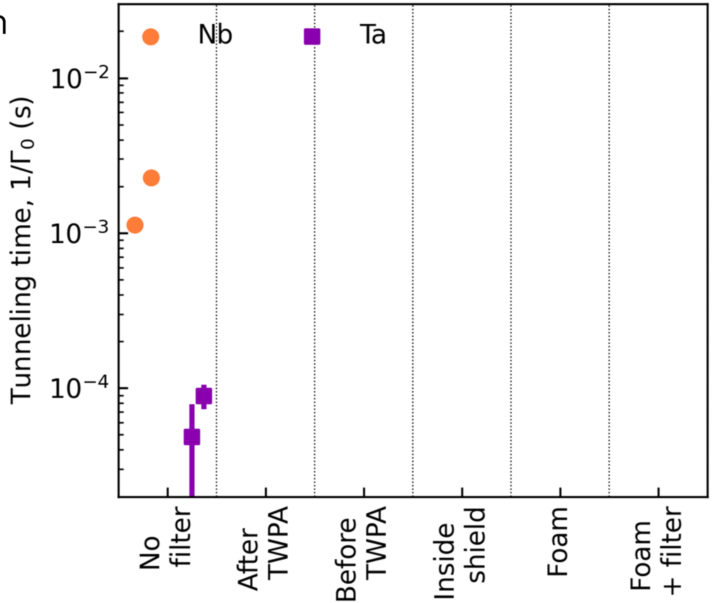
$$\hat{T}_1 = (\Gamma_0 + 1/T_{1,lim})^{-1}$$



Mitigating background tunneling rates

Test effect of in-line eccosorb filters and IR absorbing foam



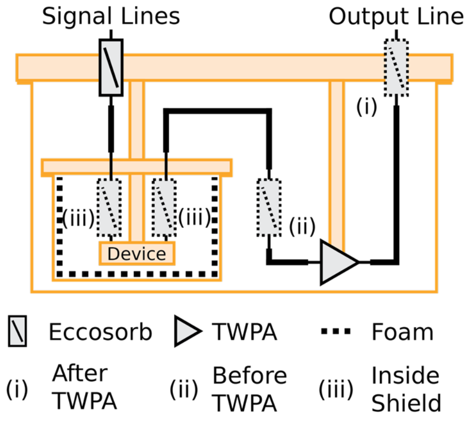


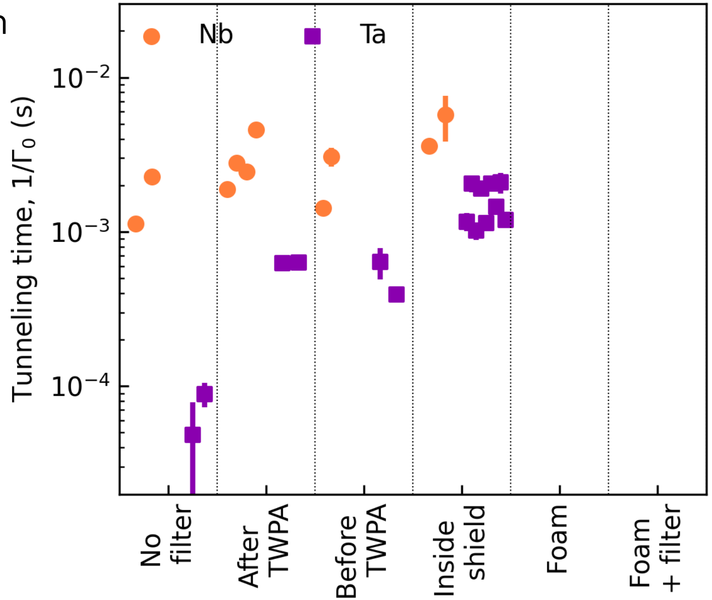
Mitigating background tunneling rates

Test effect of in-line eccosorb filters and IR absorbing foam

Observe:

- Position of filter impacts filtering efficiency



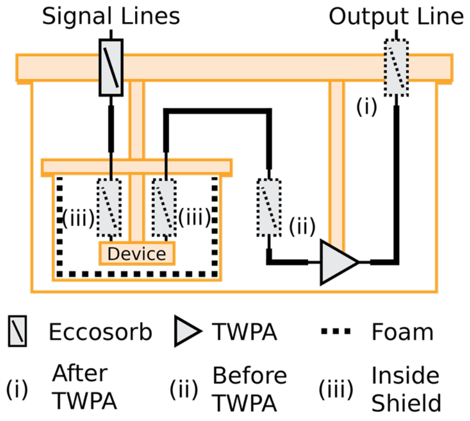


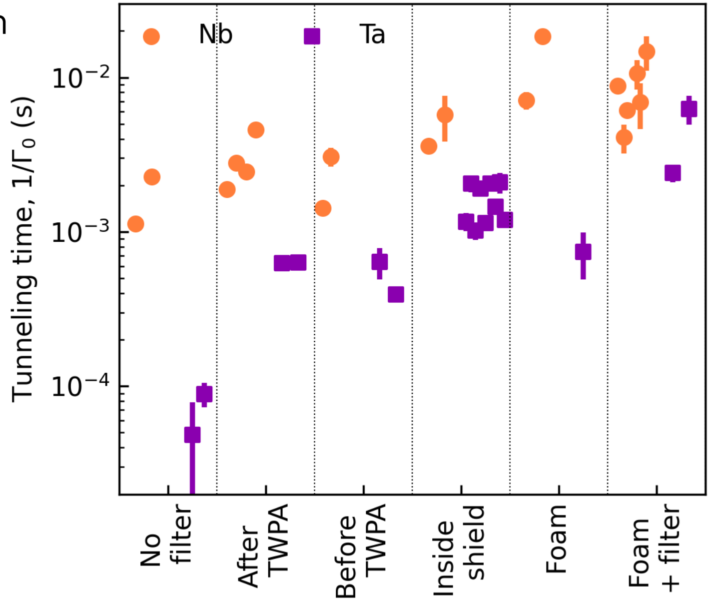
Mitigating background tunneling rates

Test effect of in-line eccosorb filters and IR absorbing foam

Observe:

- Position of filter impacts filtering efficiency
- IR travels through free space and in lines
- IR among main sources of background QPs

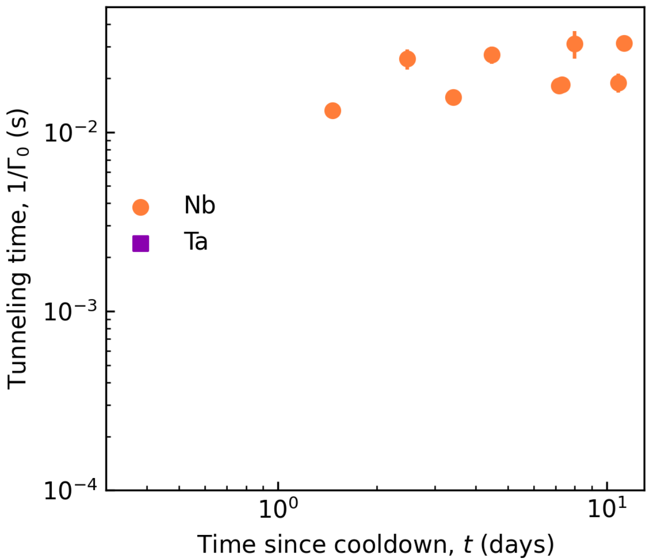




Towards understanding the origins of excess quasiparticles

Time-dependent analysis:

- Tunneling rate **decays**, starting from cooldown



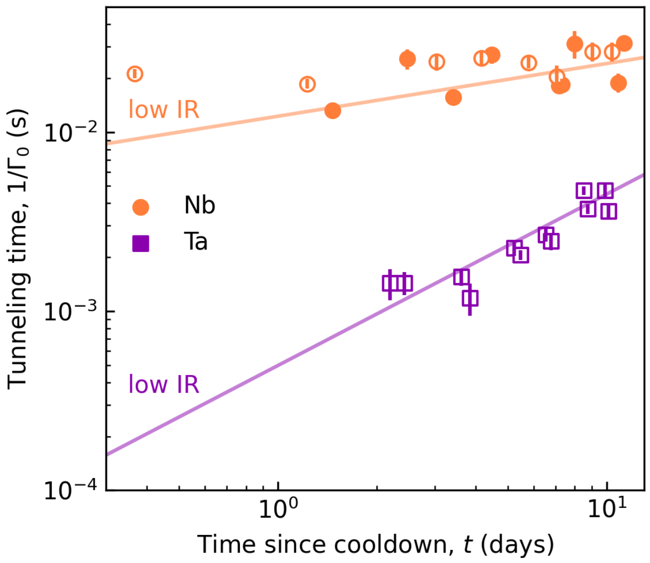
Towards understanding the origins of excess quasiparticles

Time-dependent analysis:

- Tunneling rate **decays**, starting from cooldown
- Rate **resets** after thermal cycle

  Nature Physics volume 18, pages 145–148 (2022)

- Decay is **steeper in Ta** devices → matching the steeper response of Ta devices to IR



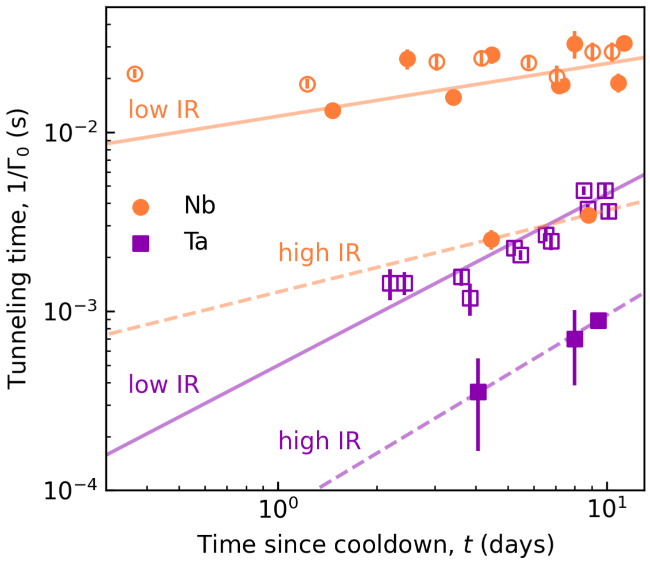
Towards understanding the origins of excess quasiparticles

Time-dependent analysis:

- Tunneling rate **decays**, starting from cooldown
- Rate **resets** after thermal cycle

Nature Physics volume 18, pages 145–148 (2022)

- Decay is **steeper in Ta** devices → matching the steeper response of Ta devices to IR
- Decaying rate **scales with IR background** (no foam, reduced light tightness)



Possible origin:

- IR from **slowly cooling components**
- Decaying rates attributed to stress relaxation

SciPost Phys. Proc. 12, 013 (2023)
arXiv:2208.02790 (2022)

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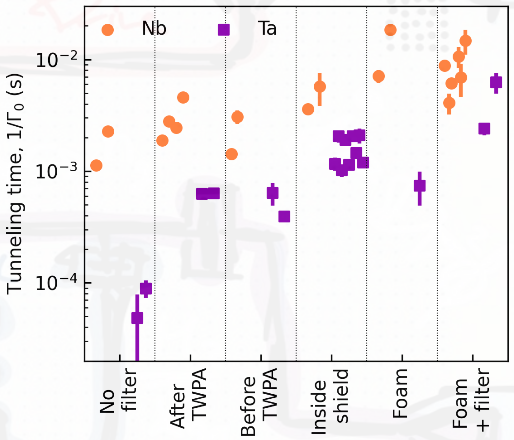
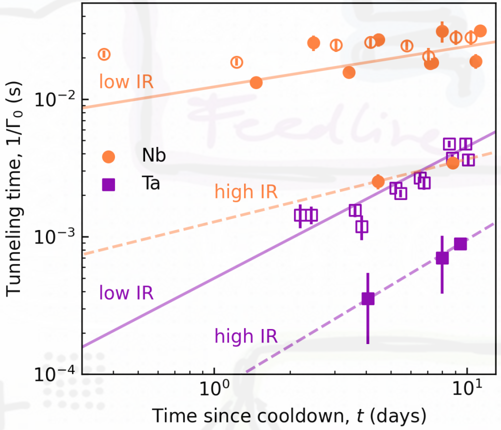
Summary and Outlook



Learnings:

- **In-line** and in **free space infrared radiation** are major sources of background quasiparticles in standard cryogenic setups
- Rate **decays** with time after cooldown and is reduced by **filtering** and **foam**
- Possible origin of infrared: **slowly cooling components**

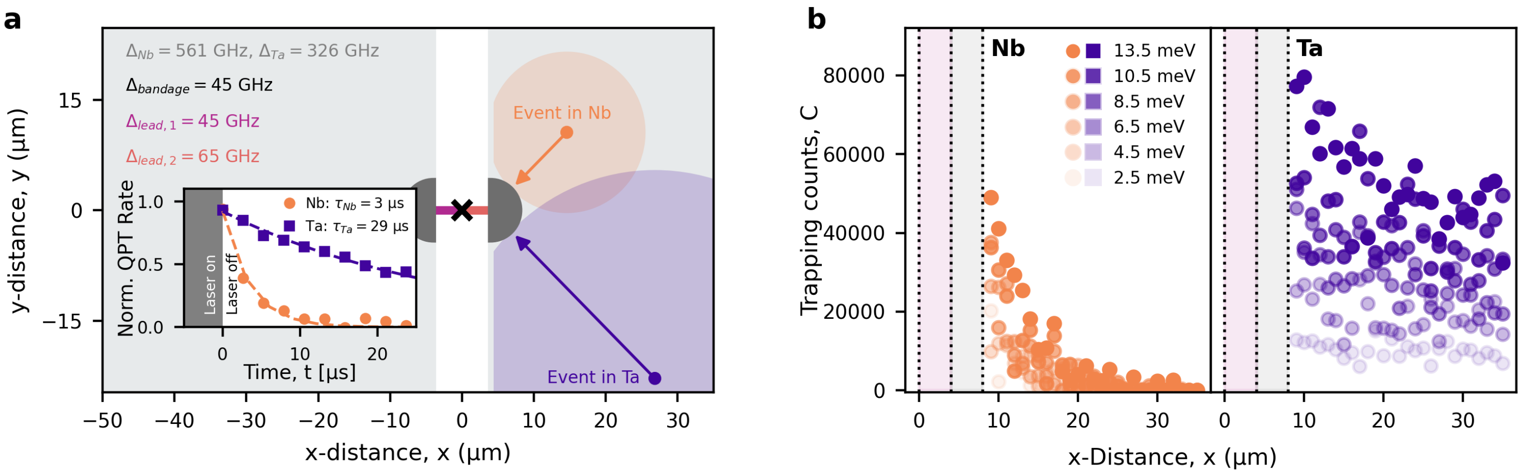


What's next?

- Investigate response to IR with **monochromatic THz laser**
- **Simulate** QP diffusion for quantitative understanding

Appendix

Diffusion Simulation (WIP)



Device parameters and material constants

$$\dot{x} = D(D_n, E, \Delta)\nabla^2 x - sx - rx^2 - \text{downconversion} + g(\mathbf{r}, E, t, \Delta)$$

$$x = x(\mathbf{r}, E, t) \qquad D(D_n, E, \Delta) = D_n\sqrt{1 - (\frac{\Delta}{E})^2}$$

$$x = n_{QP}/n_{CP} \qquad \eta(e, E, \Delta) \sim (1.8/e)[(E/\Delta) - 1]^3$$

arXiv:2402.15471

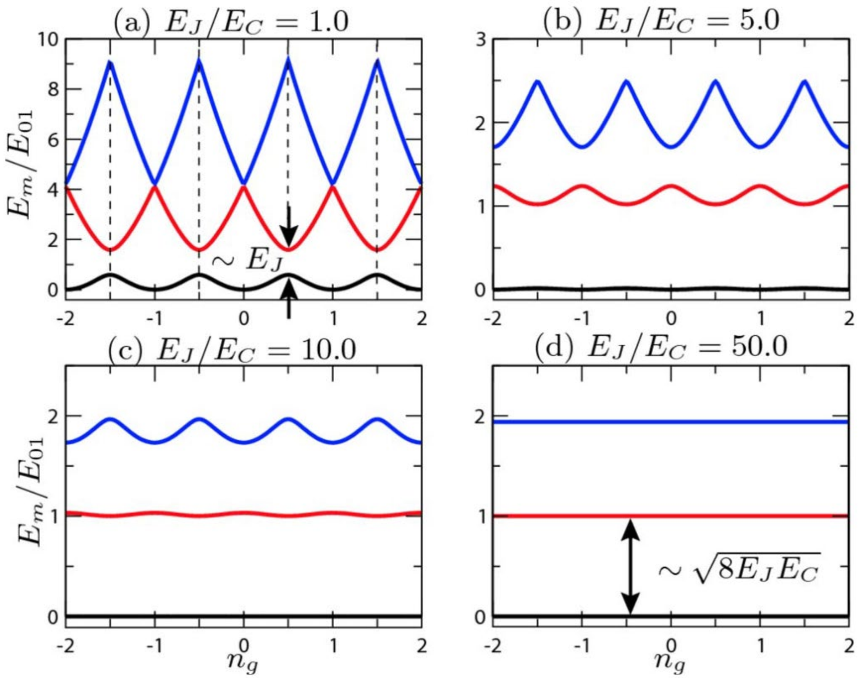
	Δ (meV)	r (1/ns)	s (1/ns)	e (1/ns)	D_n (μm²/ns)
Nb	2.32	1/0.149	1/3e3	0.15	0.12
Ta	1.35	1/1.78	1/25e3	1.78	0.8
Al	0.186	1/110	1/2e6	440	2.25

literature values

E_C (GHz)	0.384
E_J (GHz)	6.37
charge dispersion (MHz)	15.7
readout freq Q1 (GHz)	7.18
readout freq Q2 (GHz)	7.38
Purcell freq Q1 (GHz)	7.2
Purcell freq Q2 (GHz)	7.4

at lower sweet spot

Cooper - pair box and transmon regimes



Phys. Rev. A 76, 042319 (2007)

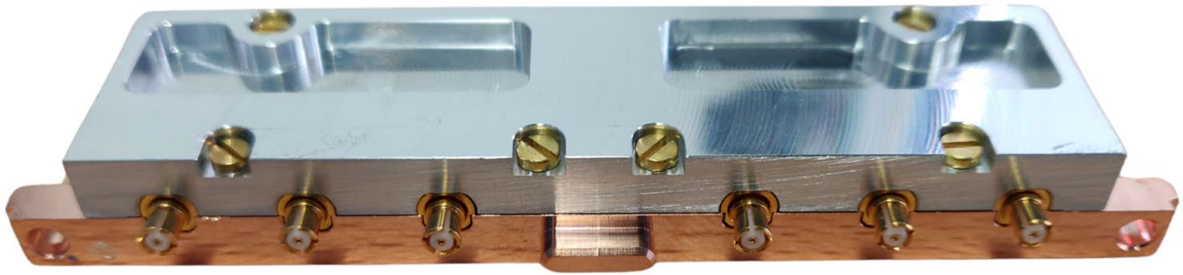
Charge-sensitivity of qubits can be controlled through Josephson-charge-energy ratio.

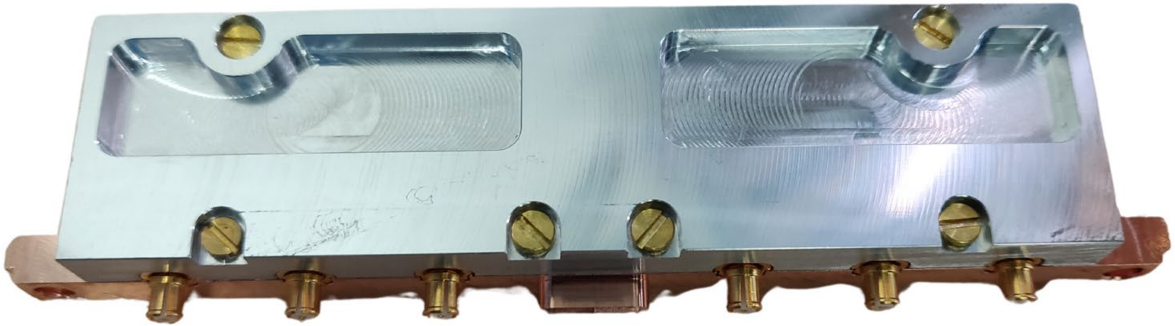
Low ratio called **"cooper pair box".**

High ratio called **"transmon".**

Sample box design

Photon transmission through slits around connectors possible.





Electronics device stack

ZI devices in use:

- SHFQA quantum analyzer for readout pulses and processing
- HDAWQ arbitrary waveform generator for drive pulses