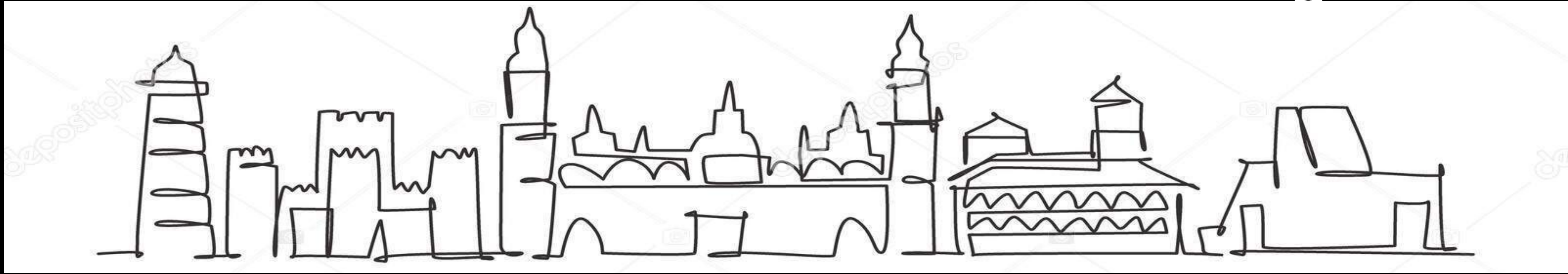
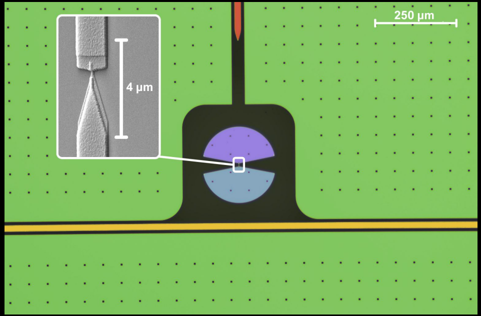
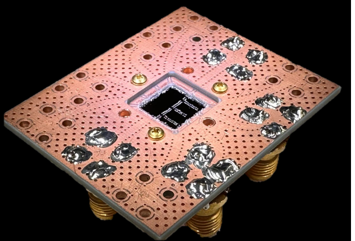
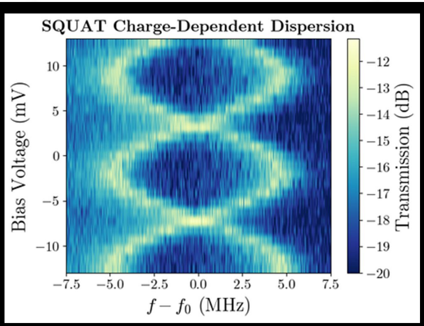
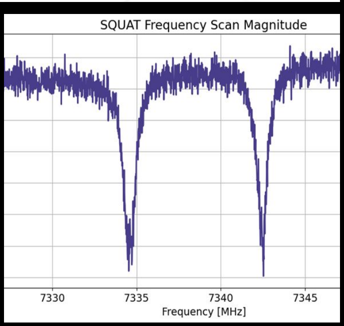
First demonstration of the Superconducting quasiparticle amplifying transmon (SQUAT) detector architecture for THz/meV sensing





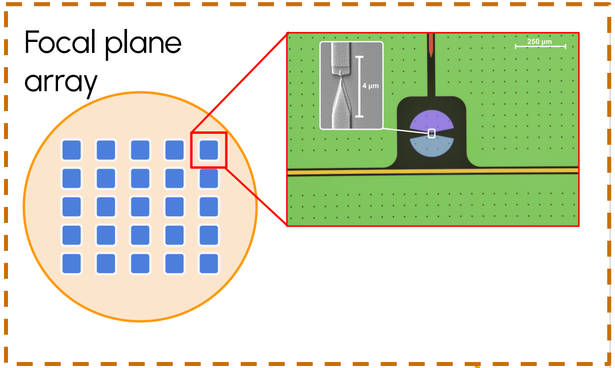


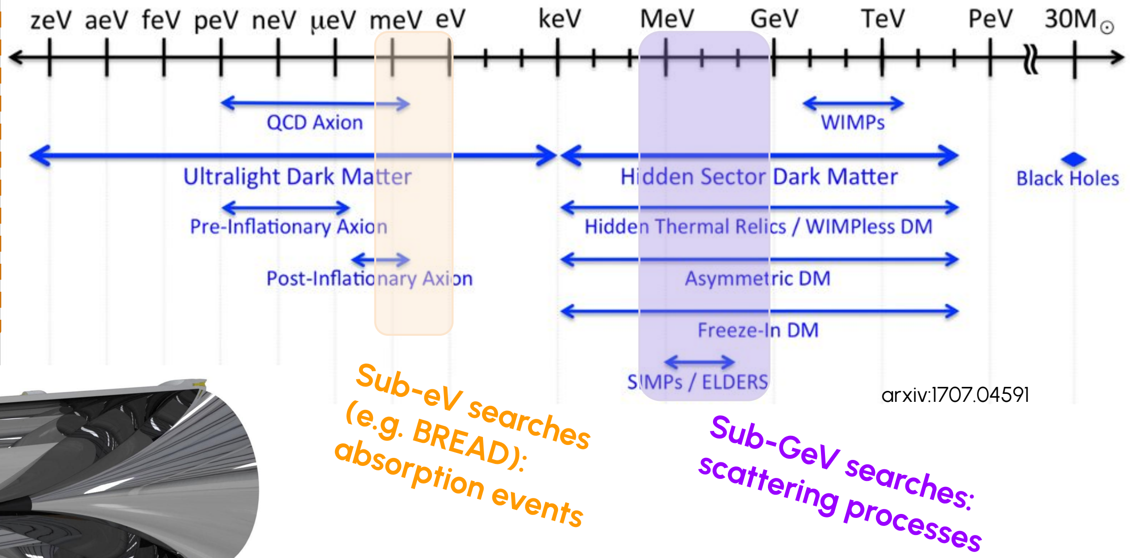




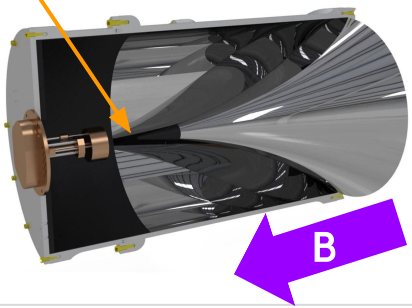
Alex Droster; postdoc, Stanford University/SLAC
June 6, 2026
IDM 2026, Zaragoza, Spain

Searching for high mass axions or sub-GeV dark matter requires detectors sensitive to **sub-eV** events





arxiv:1707.04591



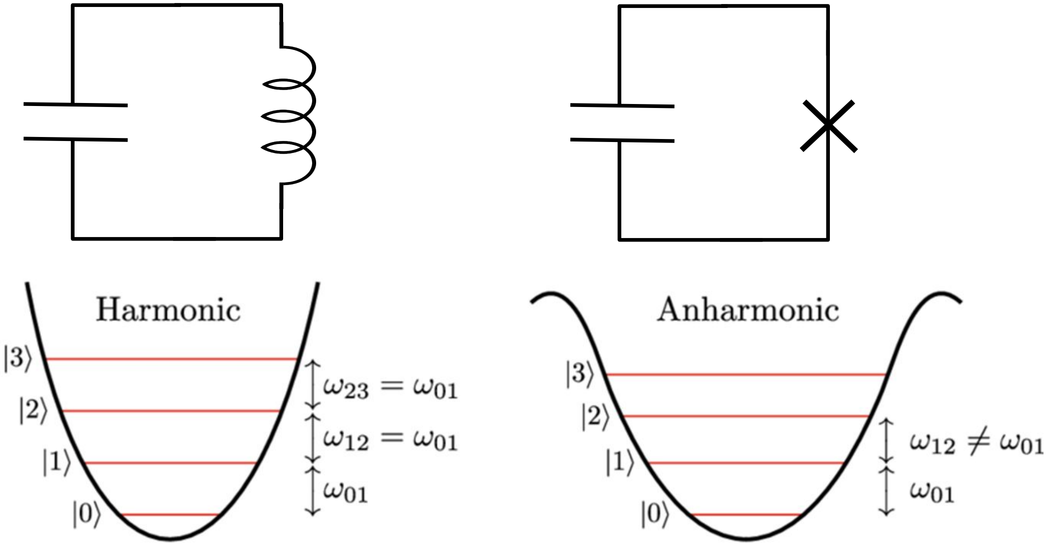
BREAD COLLABORATION

arXiv:2111.12103

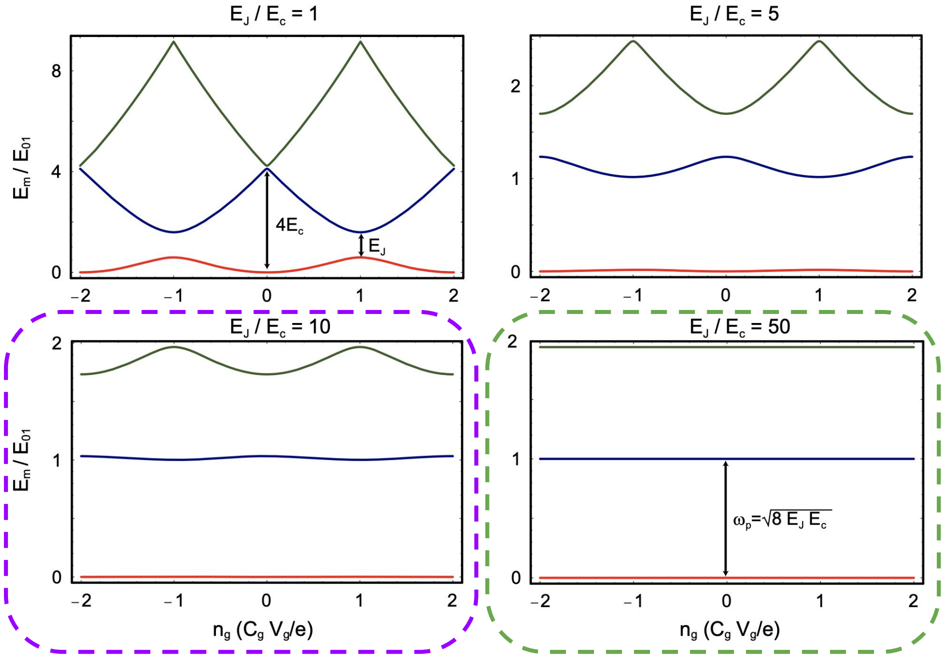
Superconducting transmon

Nonlinear inductance converts the harmonic LC oscillator to an *anharmonic* oscillator

- Energy levels are no longer evenly spaced
- By only driving at first transition frequency (ω_{01}) we create an effective two-level system (TLS)



Charge-sensitivity of transmons



SQUAT regime

Transmon qubit regime

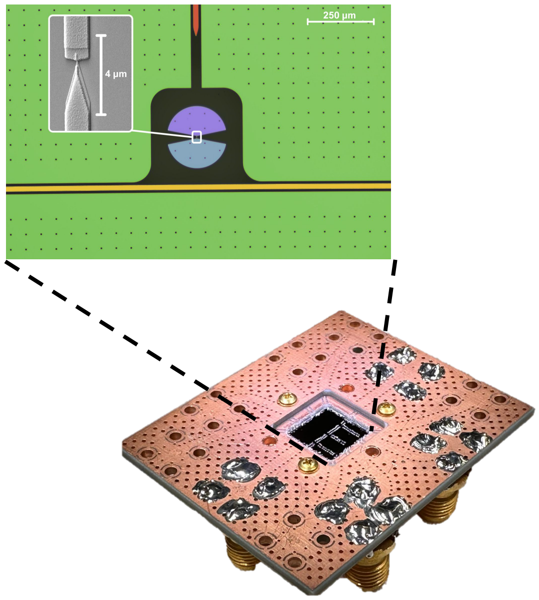
Transmon qubits for quantum computing are typically designed to be:

- Insensitive to charge noise
- Sufficiently anharmonic to be an effective two-level system

But if we retain some charge sensitivity, we have a detector sensitive to offset charge

SQUATs are designed to be weakly charge sensitive (E_J/E_C ~ 10-20)

Superconducting **Qu**asiparticle **A**mplifying **T**ransmon (SQUAT)



Design paper

The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons

C. Fink, C. Salemi, et al. (2024); **arXiv:2310.01345**

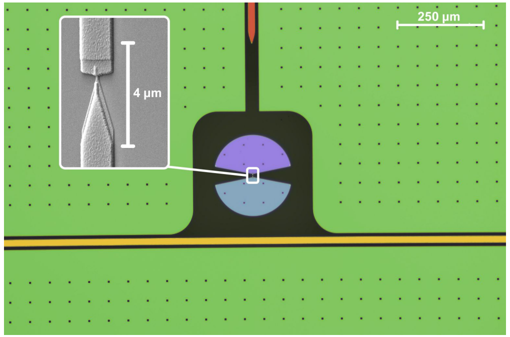
Characterization paper

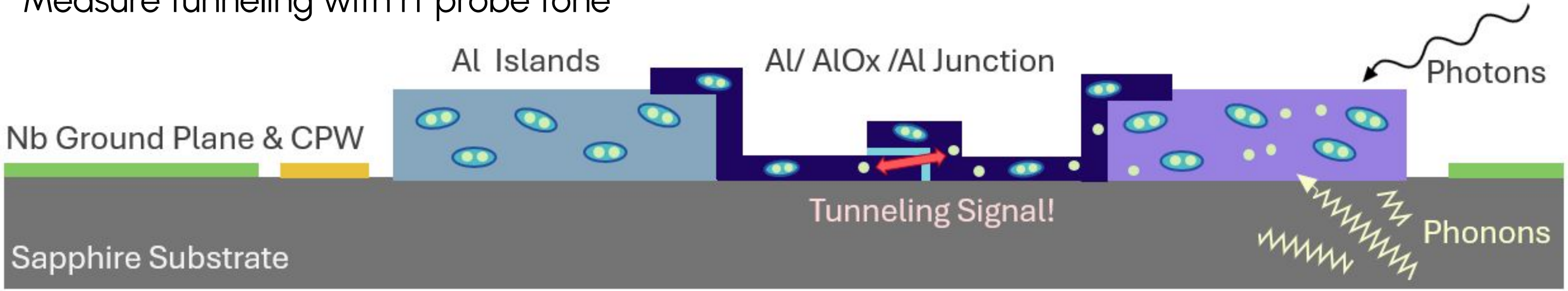
A First Demonstration of the SQUAT Detector Architecture: Direct Measurement of Resonator-Free Charge-Sensitive Transmons

H. Magoon, T. Aralis, T. Dyson, et al. (2026); **arXiv:2601.16261**

SQUAT sensing principle

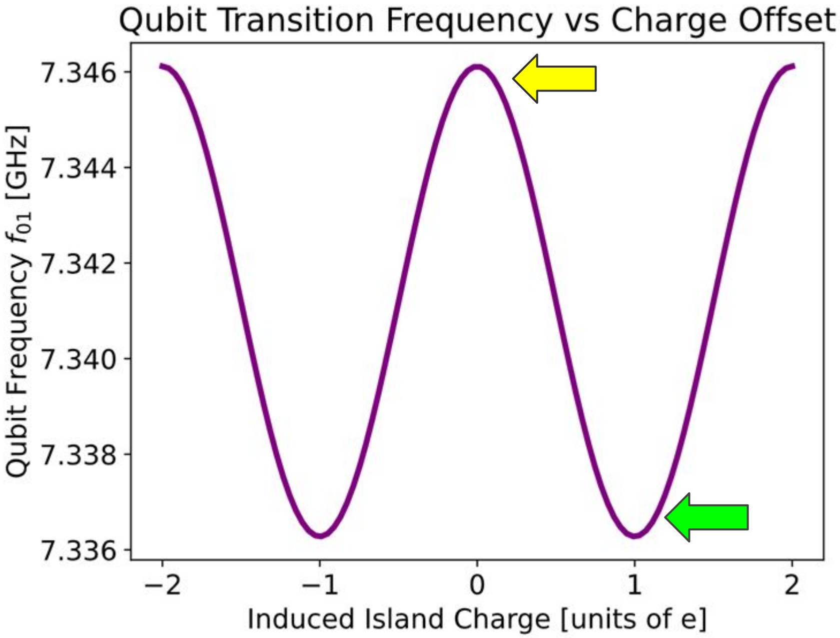
- Phonons in the substrate are absorbed by capacitor fins
- Absorbed energy breaks Cooper-pairs in the superconductor (Δ~0.2 eV)
  - With trapping: quasiparticles diffuse into lower-gap junction, lose energy, & get trapped
- Quasiparticles (QPs) tunnel across the Josephson junction
  - With trapping: trapped QPs tunnel more frequently, may tunnel more than once
- Measure tunneling with rf probe tone

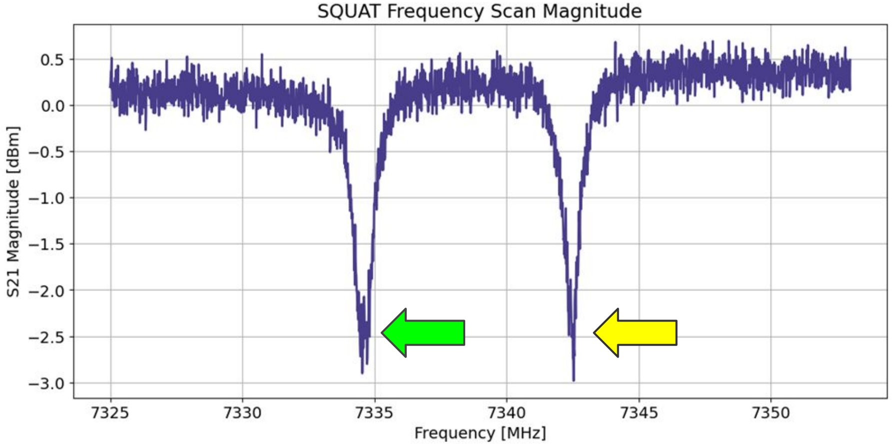




(Materials are those used in first demonstration)

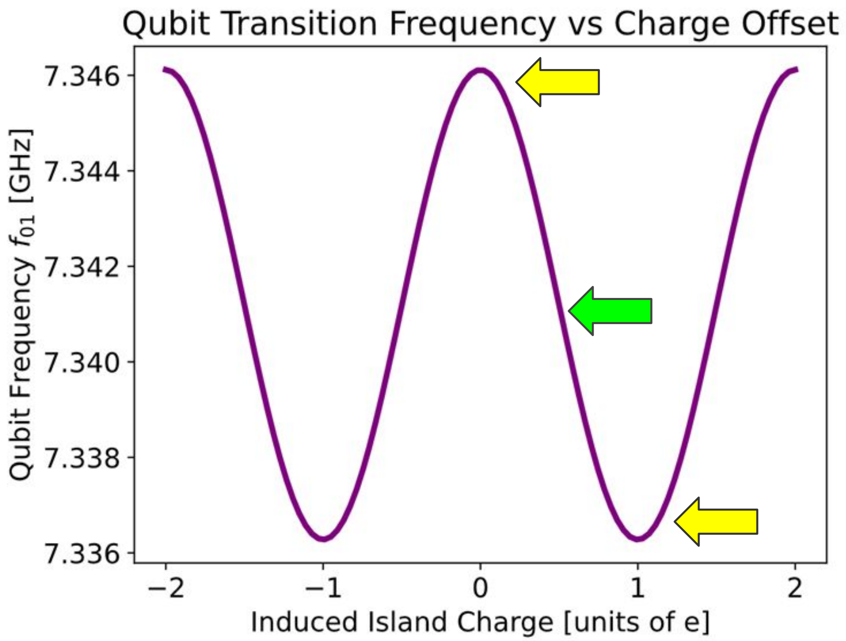
SQUAT charge sensitivity

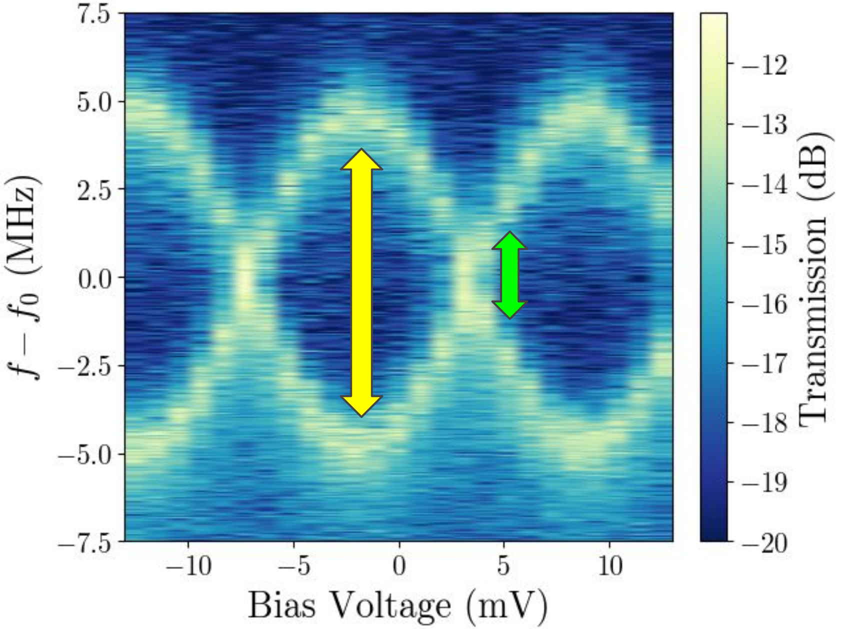




Quasiparticle tunneling causes qubit charge-parity state to flip, changing resonant frequency

SQUAT charge sensitivity



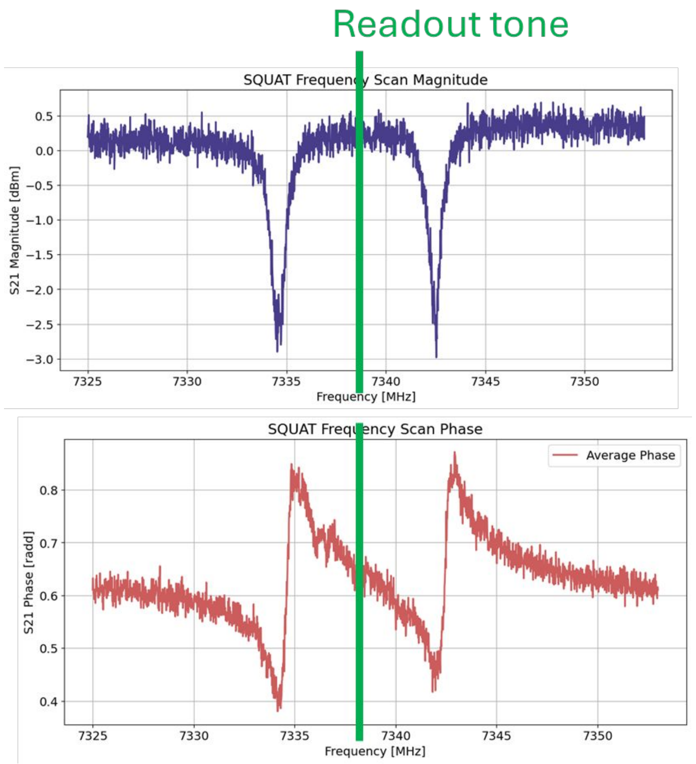


Similarly, we tune the resonant frequencies by changing bias voltage

Readout of SQUAT tunneling signal

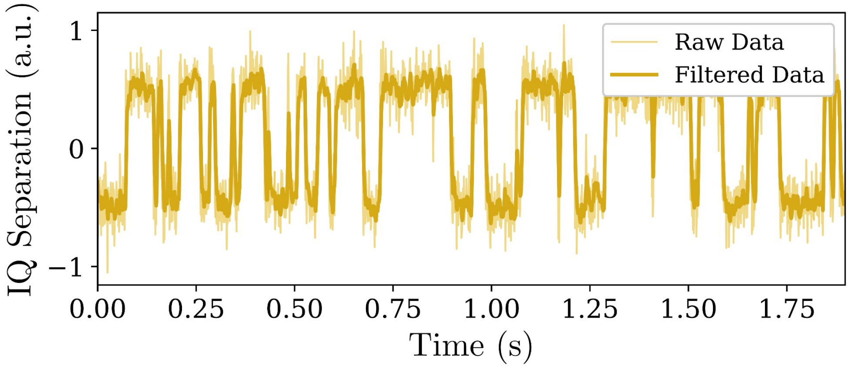
SQUATs are detectors →
continuous monitorings of state

We monitor the parity state of the SQUAT
with a CW microwave tone

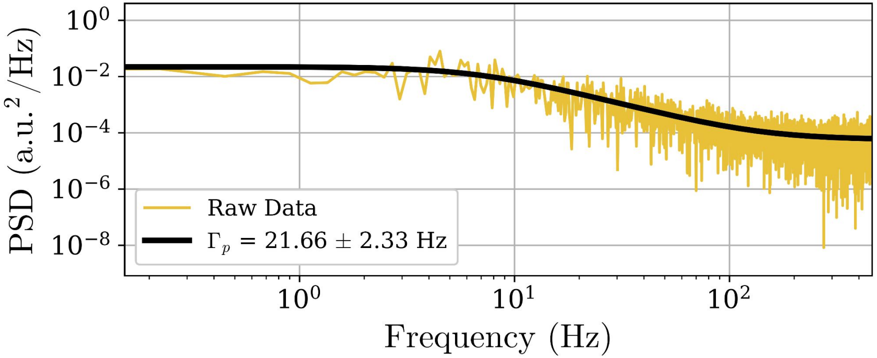


Readout of SQUAT tunneling signal

We extract tunneling rate, Γ_p, via a fit to the FFT



Tunneling signal, time domain

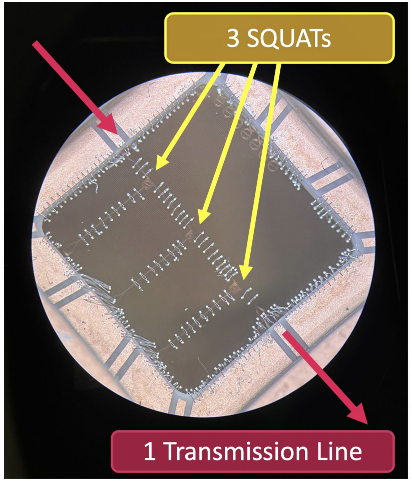


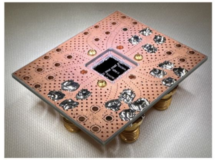
Tunneling signal, frequency domain

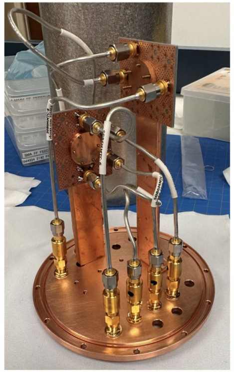
Prototype characterization

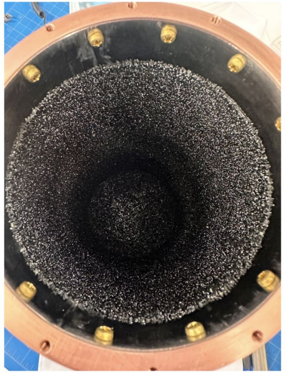
First prototypes fabricated at SLAC in 2023

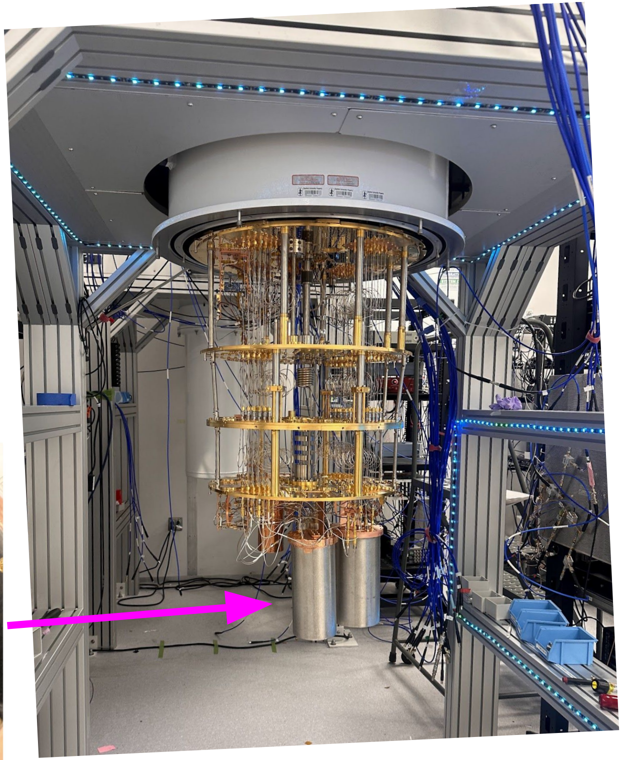
- Aluminum fins & junctions on sapphire wafers
- No quasiparticle trapping



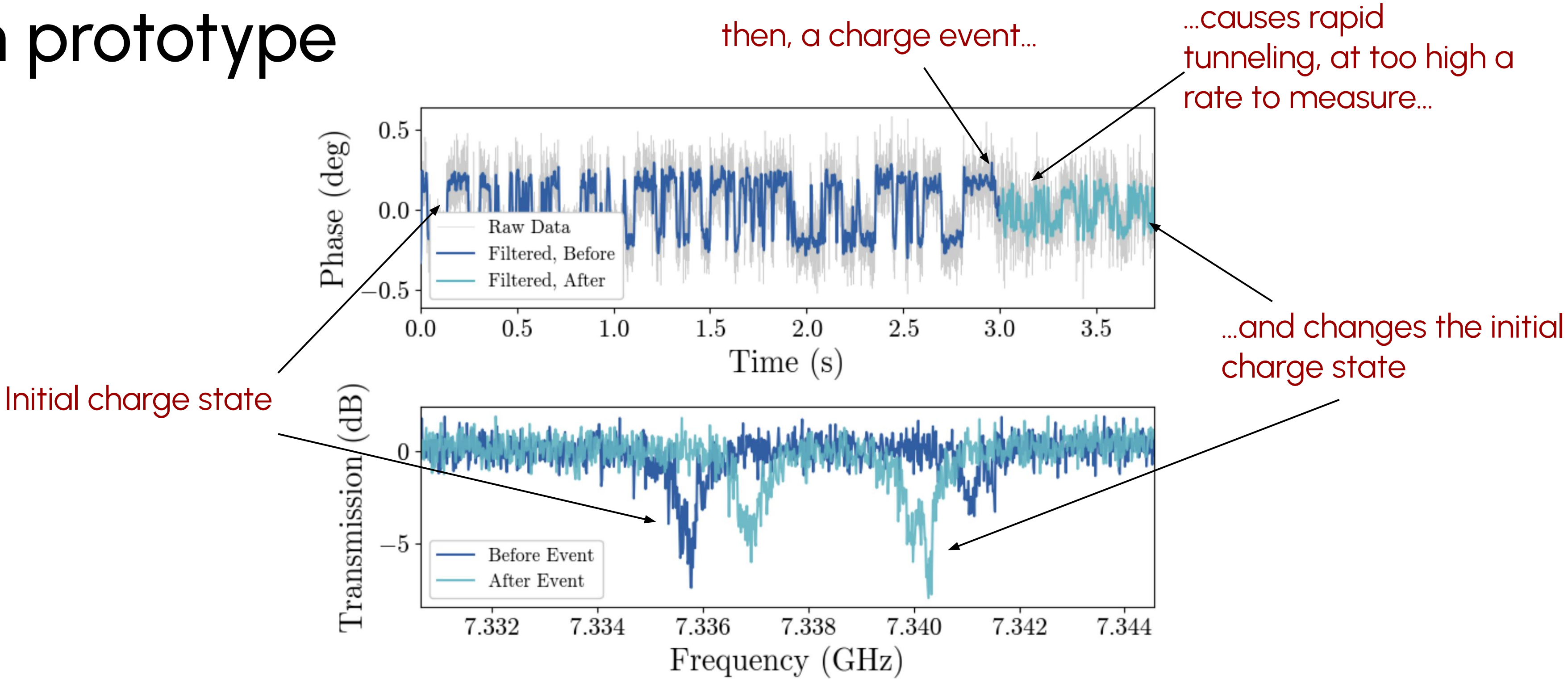








Simultaneous charge & tunneling event detection in prototype

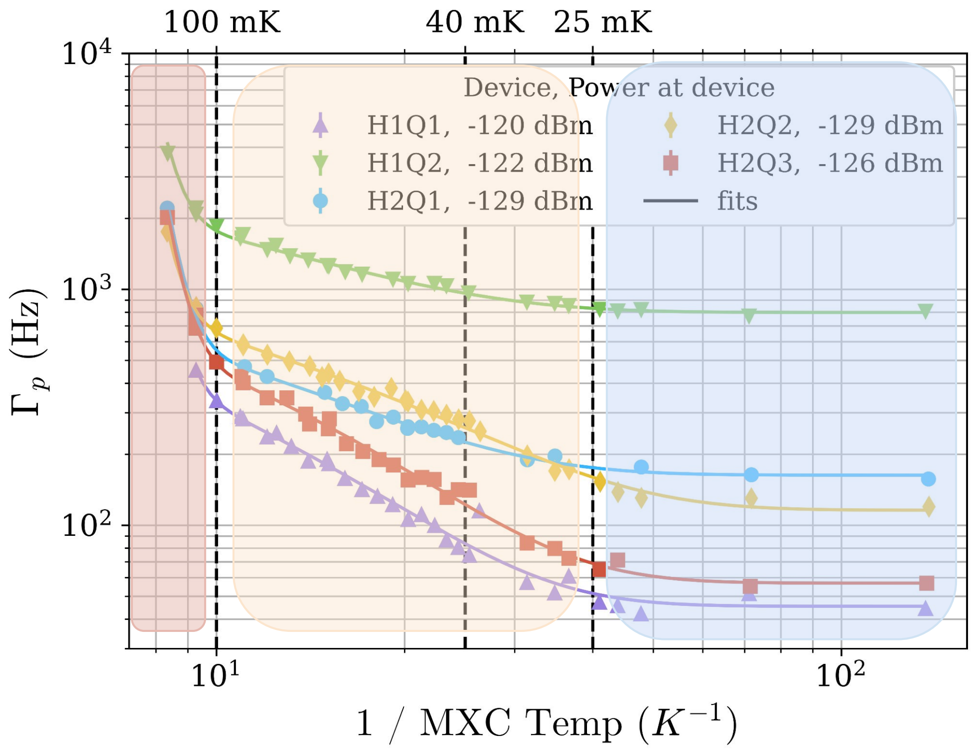


Parity switching rate temperature dependence

$$x_{\text{qp}} = x_{\text{qp}}^{\text{res}} + \sqrt{\frac{2\pi k_B T}{\Delta}} \exp\left(-\frac{\Delta}{k_B T}\right)$$ †

3 regimes:

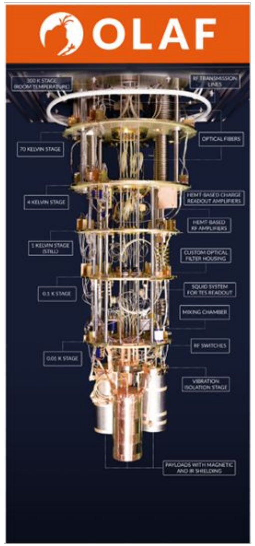
- Low temp: non-thermal backgrounds dominate
- Medium temp: thermal activation of quasiparticles
- High temp: x_{qp} increases, exponential increase in rate

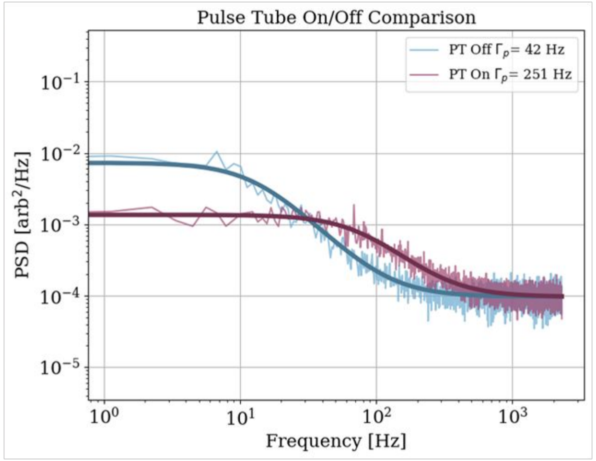


† Nho, et al., arXiv:2505.08104

Pulse tube vibrations also contribute to background rates

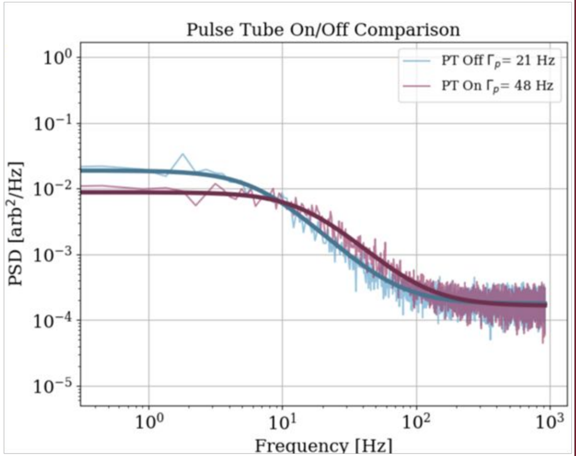
Oxford Proteox





~6x higher tunneling rate with PT on

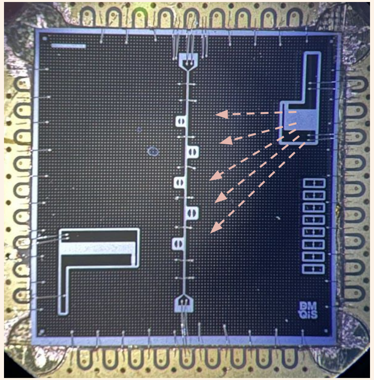
Bluefors XLD



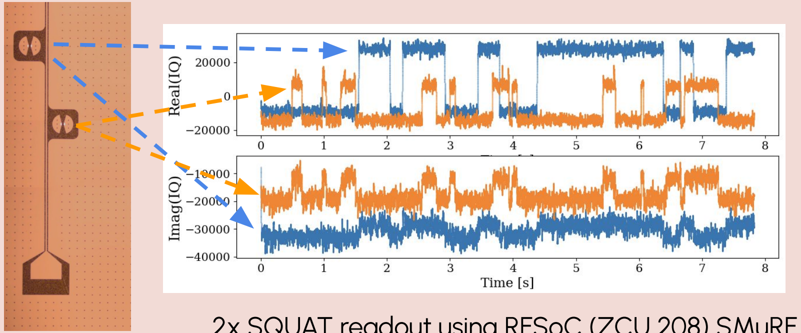
~2x higher tunneling rate with PT on

Next-gen SQUATs

Newest devices:
- Si substrate
- Mesh ground planes
  - Improved phonon collection efficiency
- α-Ta fins (Δ~0.7 meV)
  - Trapping!
- Phonon injectors

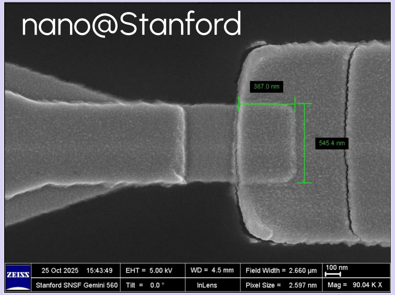


Multitone streaming to measure correlated events



2x SQUAT readout using RFSoC (ZCU 208) SMuRF

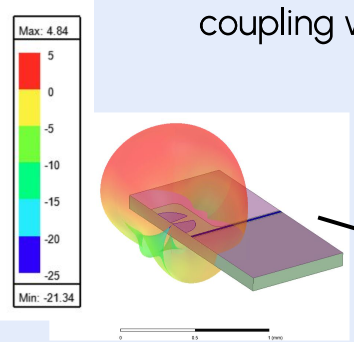
Low Tc junction development

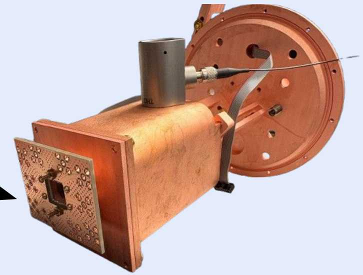


Junctions with low-gap materials improve trapping & sensitivity

Hf (Δ~0.017 meV) junctions shown to be viable (arXiv:2510.25203)

Optical/THz antenna mode coupling with frontside illumination

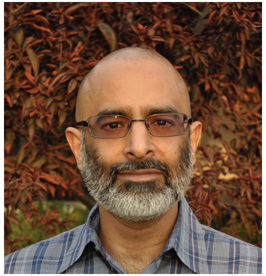




SoniQ Collaboration *(Sensing of Neutrinos In Qubits)*

WashU | Caltech | DMQiS SLAC | The University of Wisconsin Madison | The University of California Berkeley 1868 | JPL Jet Propulsion Laboratory California Institute of Technology

Karthik Ramanathan



Sunil Golwala

Noah Kurinsky

Britton Plourde

Chiara Salemi

Pierre Echternach

kg-scale SQUAT-based payload work funded as part of a pathfinder program for quantum-enabled neutrino detection - useful for understanding breeding processes in reactors through coherent neutrino scattering

Gracias!

DMQiS
BREAD COLLABORATION
schuster.lab
SONIQ
SENSING OF NEUTRINOS IN QUBITS

Collaborators:
SuperCDMS
SPLENDOR Collaboration
KIPM Consortium
SoniQ Collaboration
BREAD Collaboration

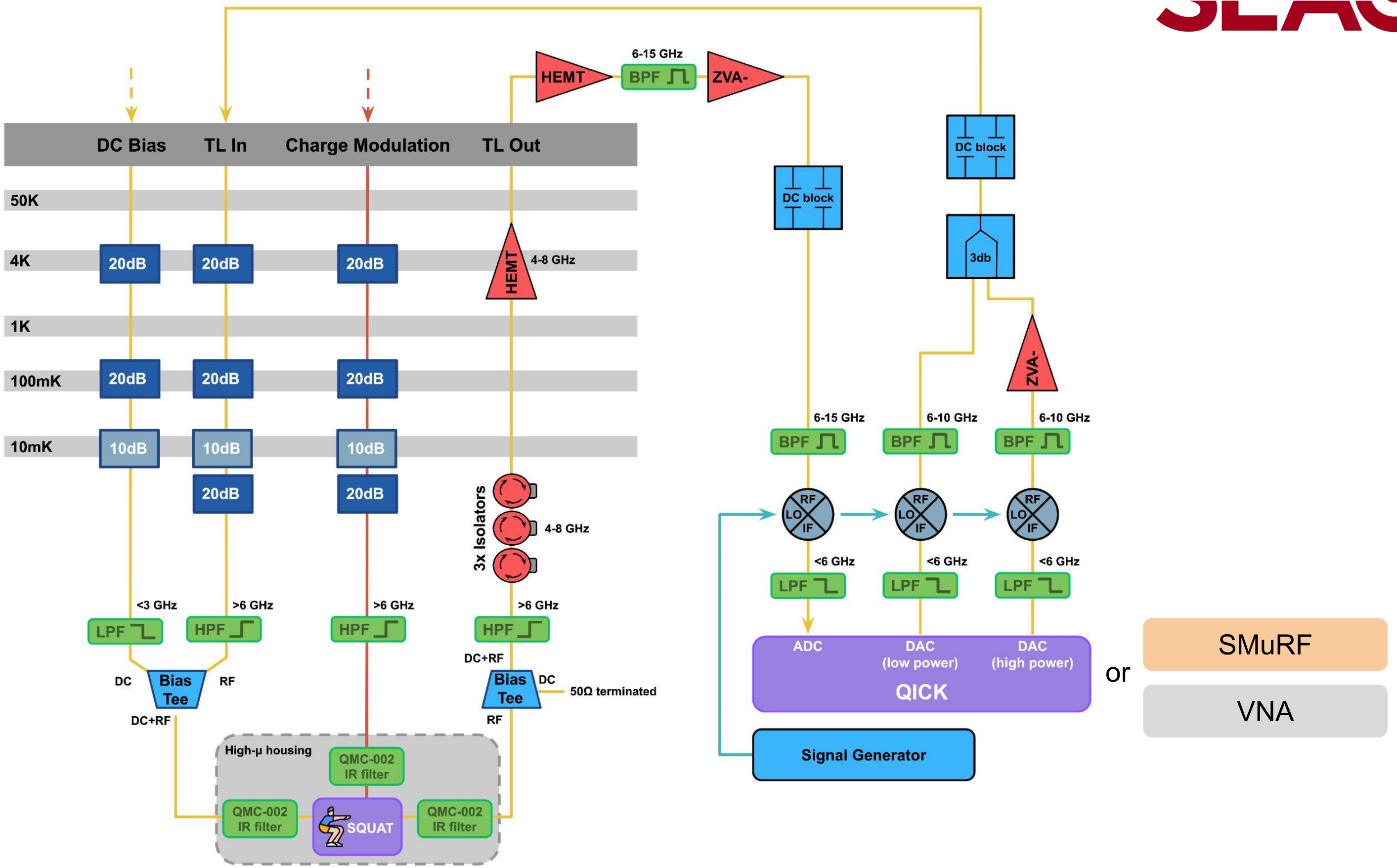
Funding Sources:
DARPA
Q-NEXT NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING
SLAC
KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Summary

1. Sensing single photons/phonons at THz/meV energies is a rapidly developing field
   a. Qubit-based sensors offer eV-scale sensing
2. Several SQUAT devices are fabricated & characterized with well-understood dynamics
   a. First measurement of background rates, energy deposition events in SQUATs
3. Next-generation SQUATs are fabricated, being studied
   a. Phonon, photon calibration studies
4. Future work will focus on understanding backgrounds, novel material development

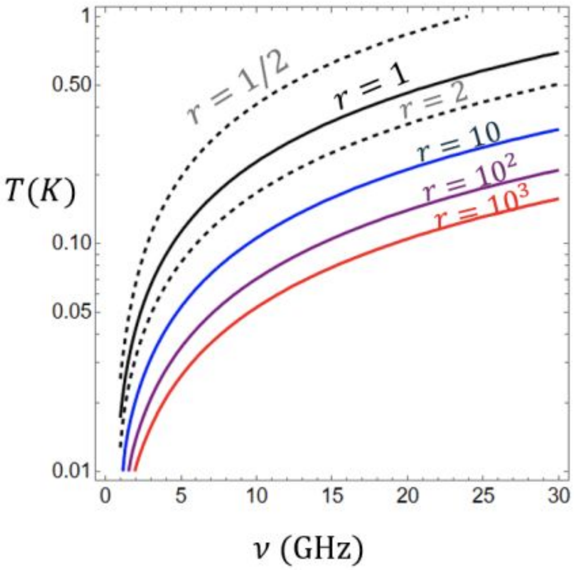
Extras

Measurement setup



Searching for high-mass axions requires new detector technology

SQL amplifier vs 100s^{-1} dark count rate SPD

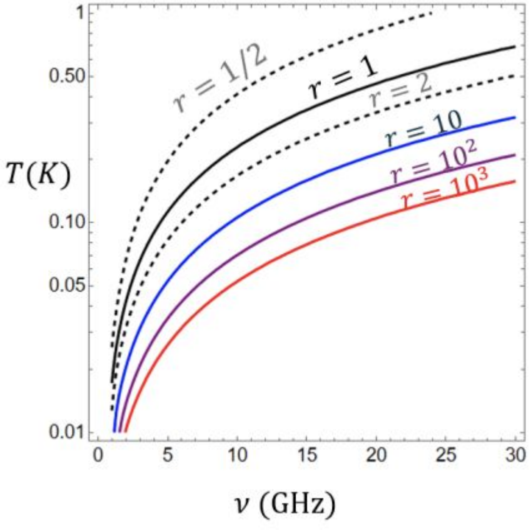


$$r = \frac{\text{Scan rate}_{SPD}}{\text{Scan rate}_{amp}}$$

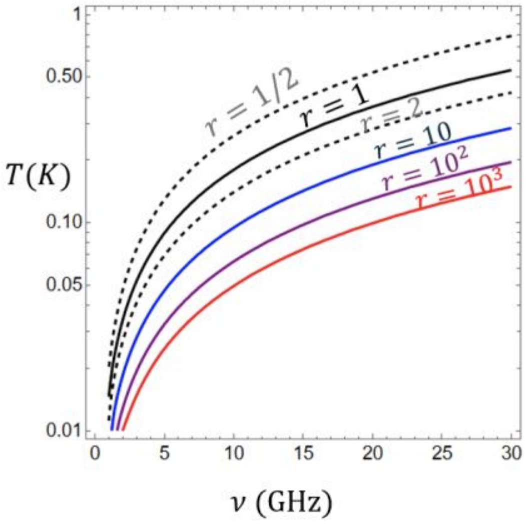
Maximizing Quantum Enhancement in Axion Dark Matter Experiments, *Phys. Rev. D.*, 2025

Searching for high-mass axions requires new detector technology

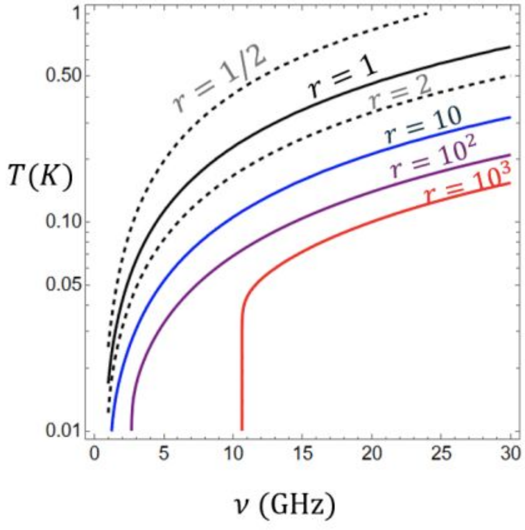
SQL amplifier vs 100s^{-1} dark count rate SPD



Squeezed amplifier vs 100s^{-1} dark count rate SPD

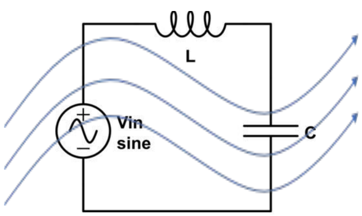


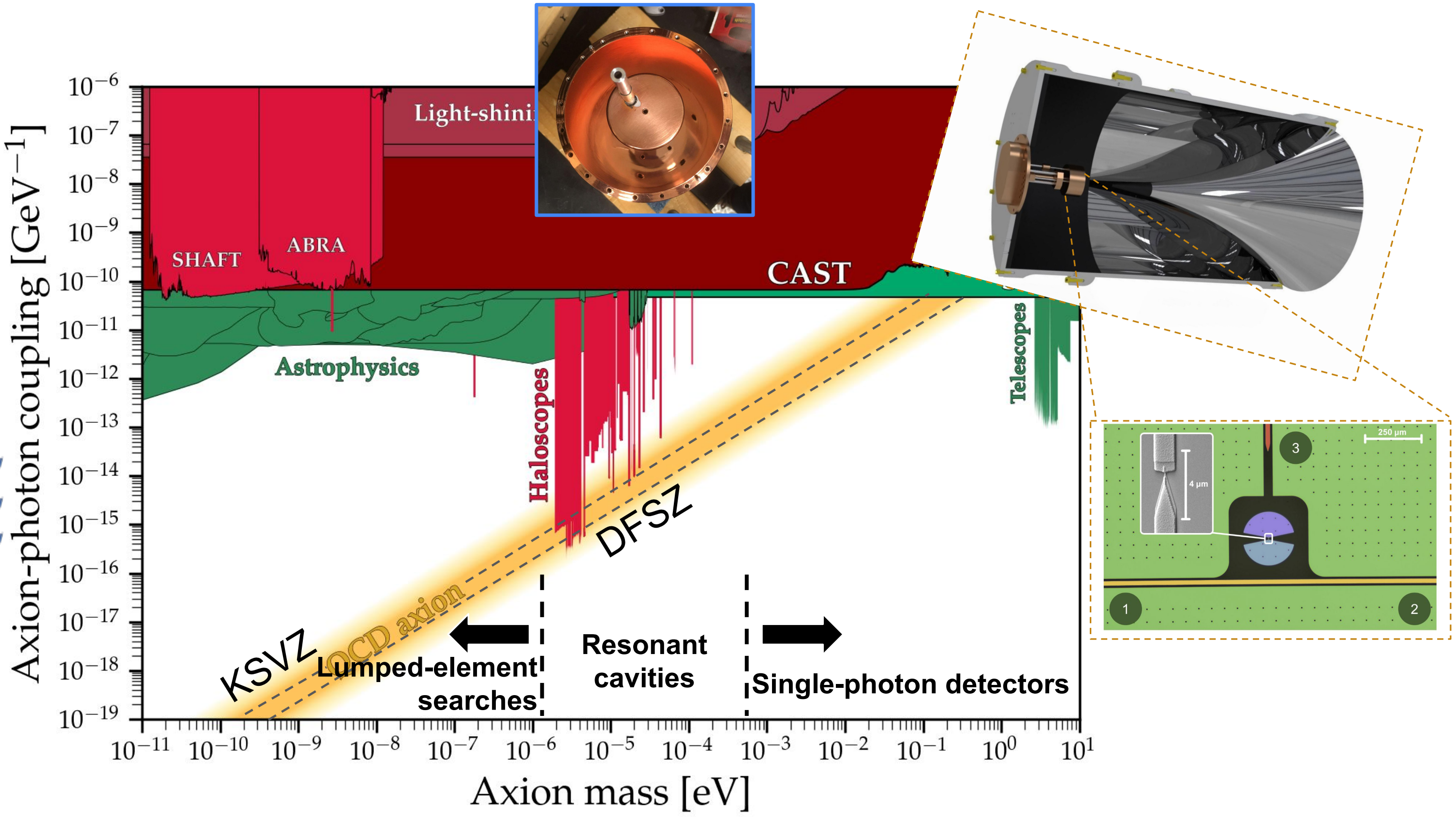
SQL amplifier vs 10^3s^{-1} dark count rate SPD



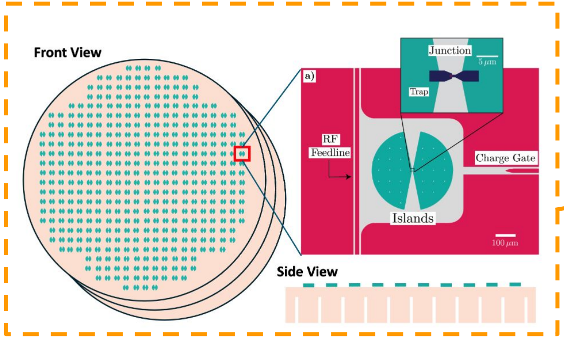
Maximizing Quantum Enhancement in Axion Dark Matter Experiments: arXiv:2411.13776

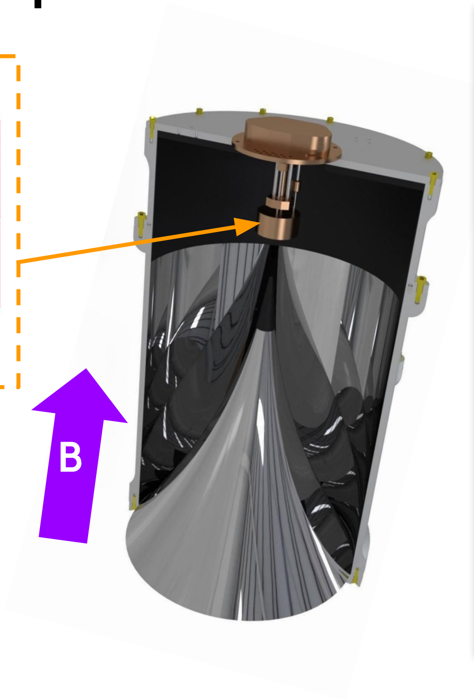
SQUATs as THz axion detectors

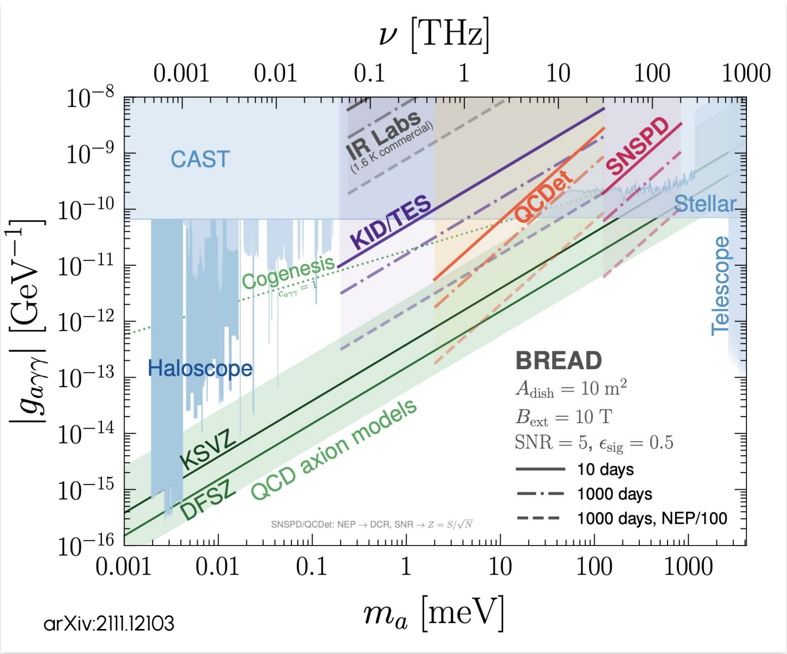




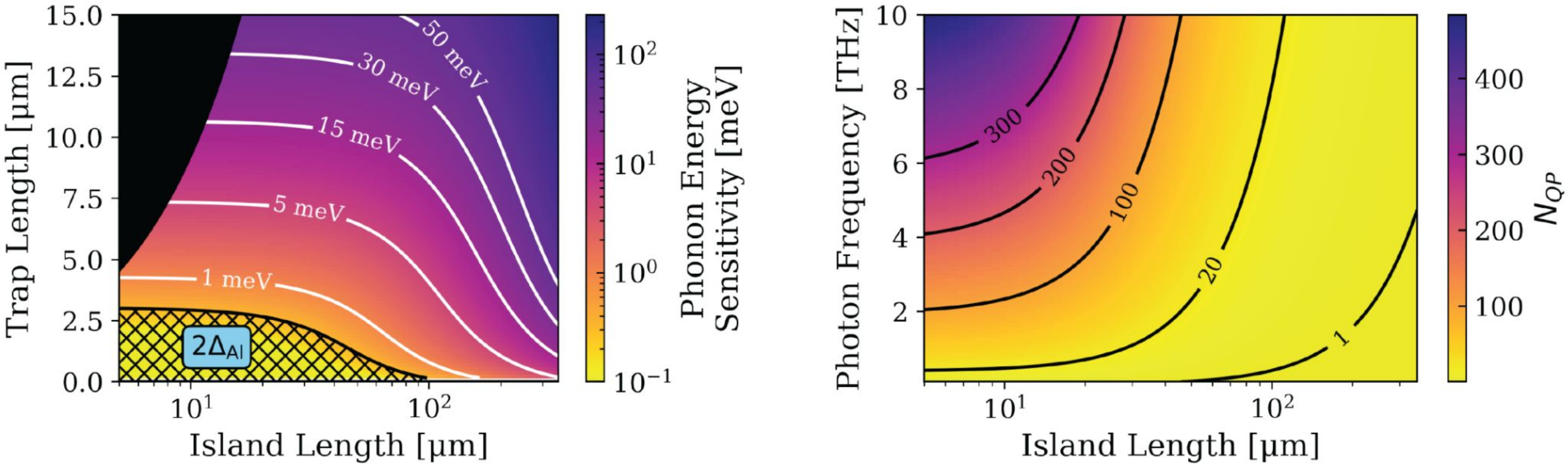
Sensing meV/THz axions (e.g. BREAD) will require low dark count photosensors







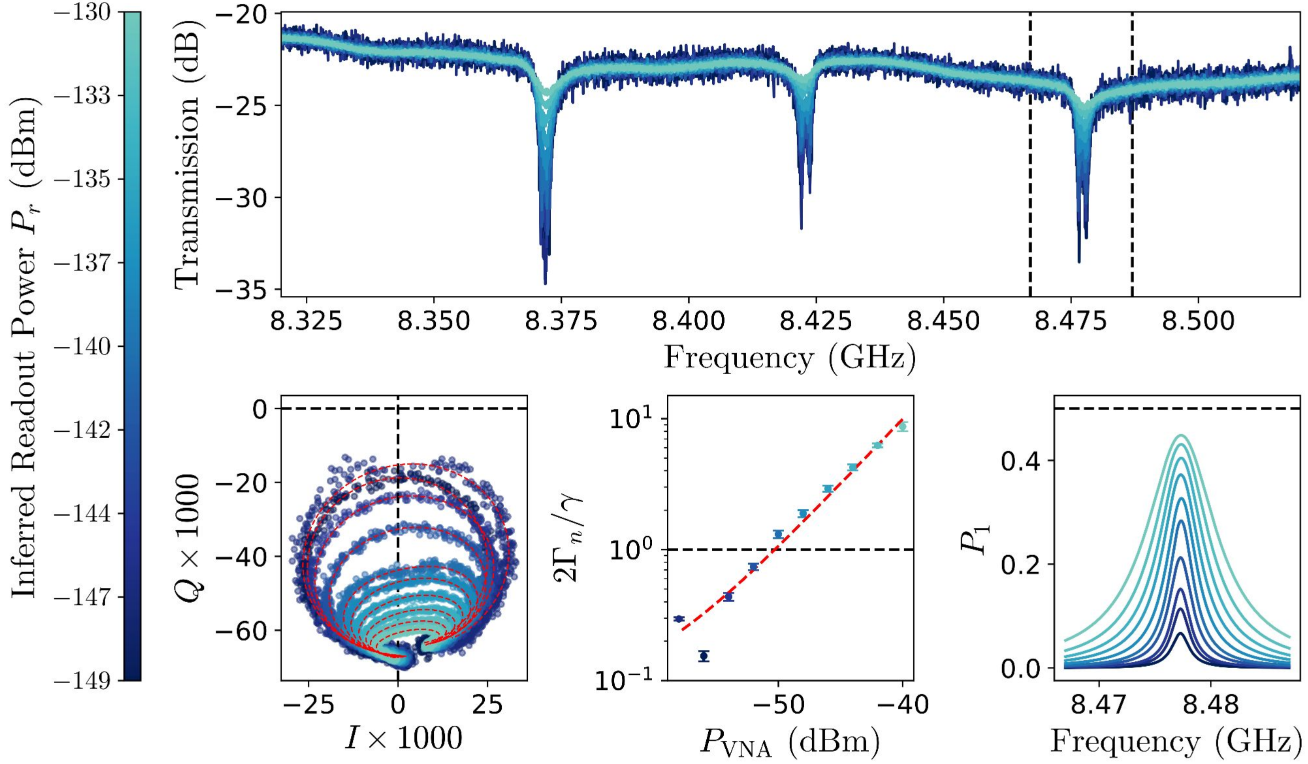
SQUATs will be made with *novel materials* to reach ~10-100 meV sensitivity to phonons, THz photons



SQUAT design paper: C. Fink, et al. *Phys. Rev. Appl.*, 2024

Making the junction of the qubit out of a **low-T_c material** (e.g. hafnium) **traps** and **multiples** quasiparticles

SQUAT properties vary with readout power

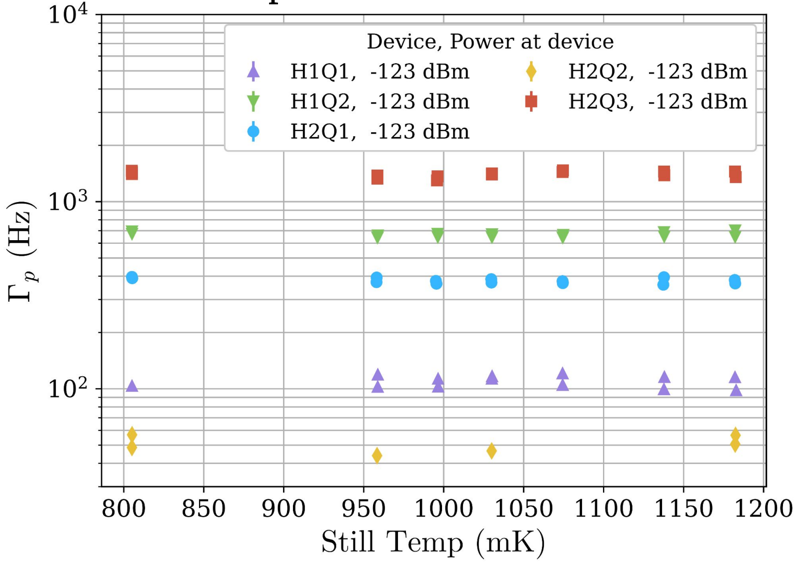


- As probe power increases, transition probability saturates at 50%
- Faster Rabi oscillations
- Probability bandwidth broadens

What drives background rates?

1. IR environment is sub-dominant contribution
2. Increasing readout power increases Γ_p. 3 likely mechanisms:
   a. Increases qubit transition probability
   b. Adds energy to quasiparticles
   c. Increased dissipation in attenuators changes blackbody environment
3. Pulse tube vibrations

Γ_p as vs still power



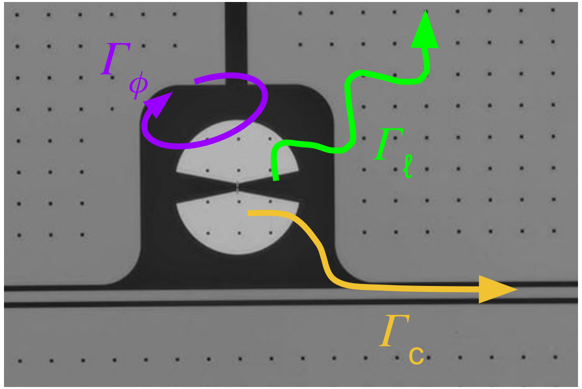
Pulsed measurements with QICK

$$H_{\text{system}} = H_{\text{qubit}} + H_{TL} + H_{int}$$

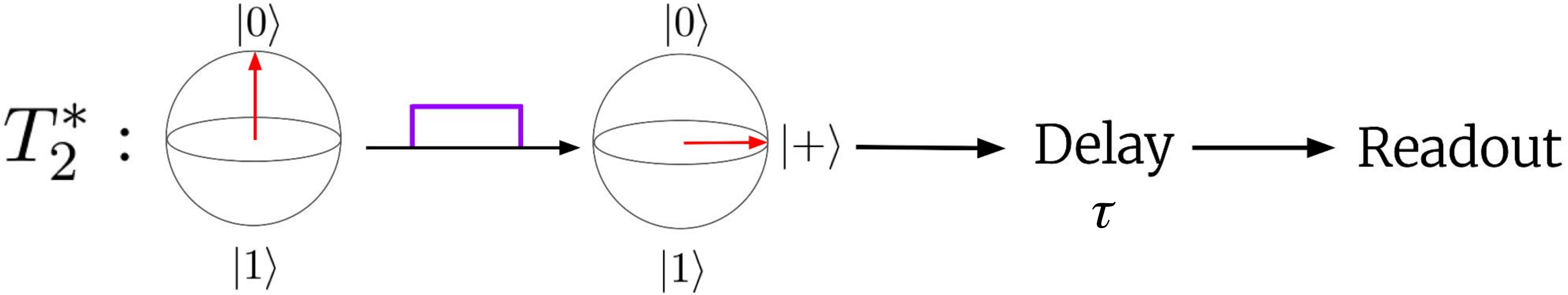
Contains three loss mechanisms:

- Γ_r: radiative decay rate, $\Gamma_r = 1/T_1$
  - $\Gamma_r = \Gamma_c + \Gamma_\ell$, where Γ_c is coupling to feedline, Γ_ℓ is loss rate
- Γ_ϕ: dephasing rate, $\Gamma_\phi = 1/T_2$
- Total decay rate:

$$\gamma \equiv \frac{\Gamma_r}{2} + \Gamma_\phi = \frac{1}{2}(\Gamma_c + \Gamma_l) + \Gamma_\phi$$



T_2^* (dephasing time) measurement

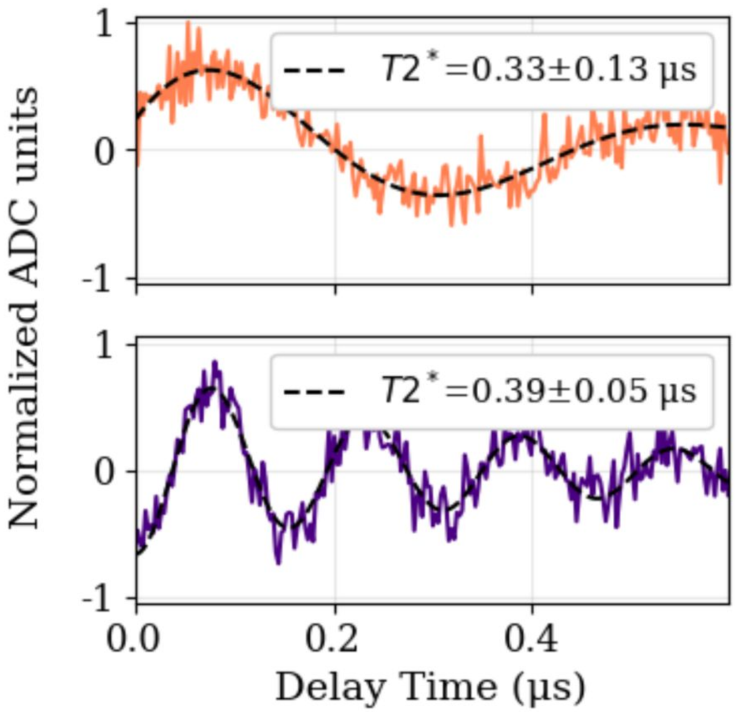


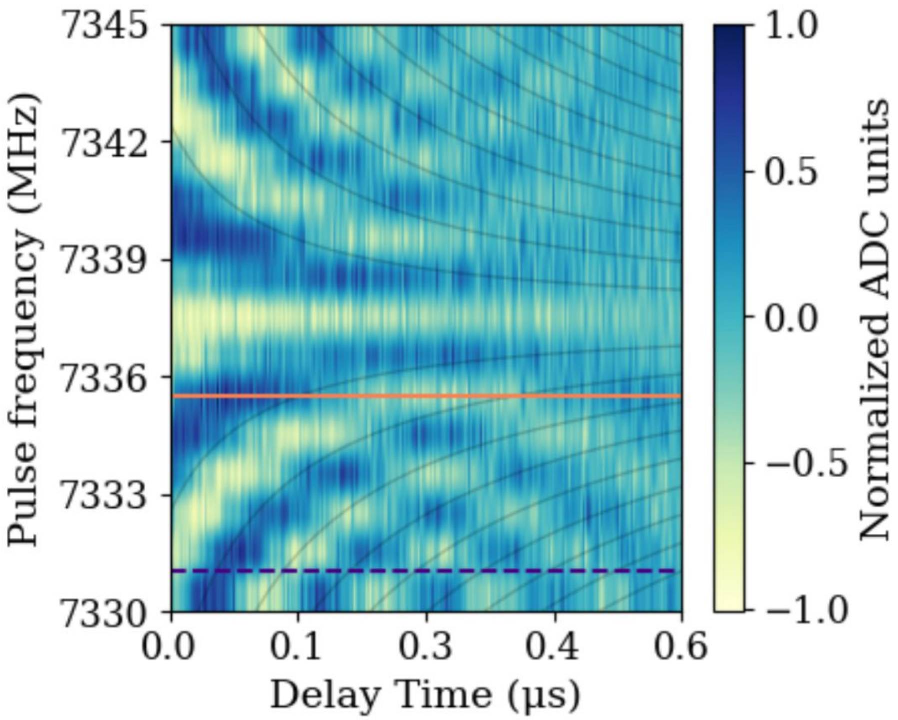
1. Prepare qubit in the ground state, apply $\pi/2$ pulse to rotate to the $|+\rangle$ state
2. The qubit precesses (not shown) about the Z axis at rate set by detuning, δf
3. Emitted field goes as

$$\propto e^{-\tau/T_2^*} \cos\left(2\pi\delta f\tau + \phi_0\right)$$

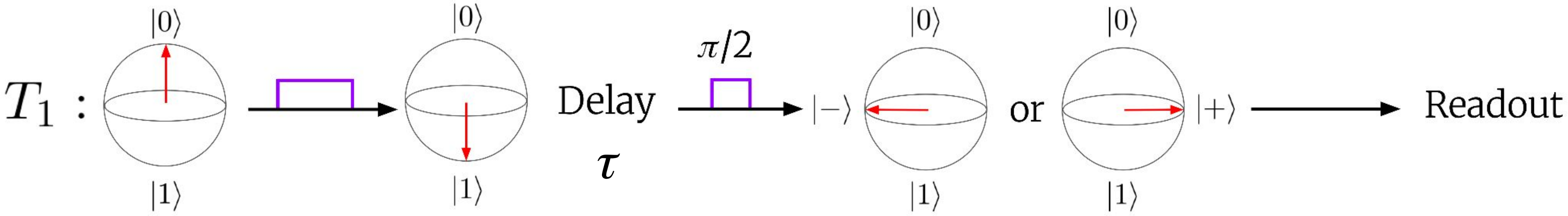
4. Vary τ, fit to extract T_2^*

T_2^* (dephasing time) measurement





T_1 (energy relaxation time) measurement

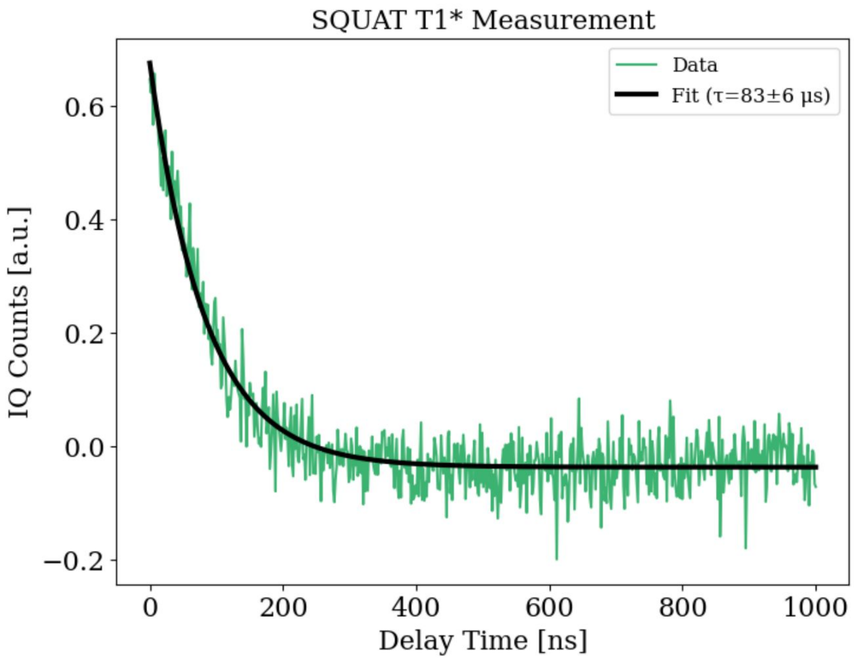


1. Prepare qubit in the excited state
2. The qubit precesses (not shown) about the Z axis at rate set by detuning, δf
3. Wait variable delay time τ, apply $\pi/2$ pulse to rotate qubit into the XY plane
4. Emitted field depends on whether the qubit decayed or not:

$$\propto \begin{cases} +1 & \text{if qubit decayed to } |0\rangle \\ -1 & \text{if qubit remained in } |1\rangle \end{cases}$$

5. Measure emission to the feedline, fit to extract T_1

T_1 (energy relaxation time) measurement

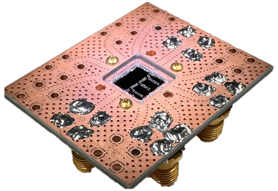


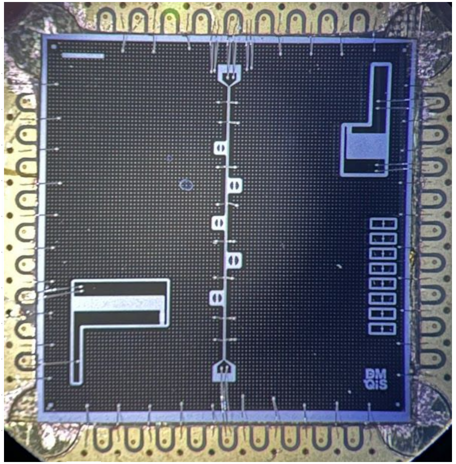
- Typical T_1 times are ~100 ns
- Significantly shorter than typical transmon qubits due to the fact that we desire quasiparticle tunneling

Next-Gen SQUATs

Newest devices:

- On Si
  - Well-understood photoelectric absorption
  - Ideal for photon-based energy calibration
- Using quasiparticle trapping
  - α Tantalum (Δ≈0.7 meV) fins -> aluminum (Δ≈0.2 meV) junctions
- Devices with mesh and no ground plane
  - To improve phonon collection
- Phonon injectors



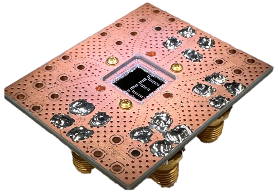


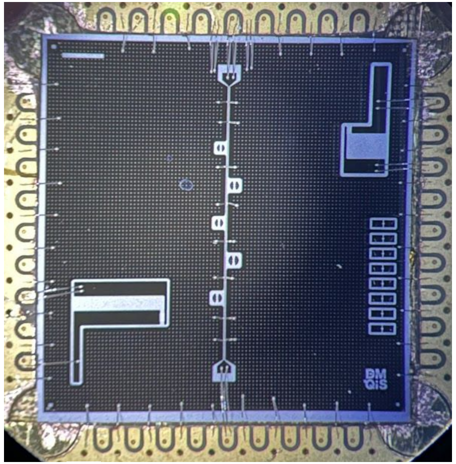
Slide credit: Hannah Magoon, Taylor Aralis

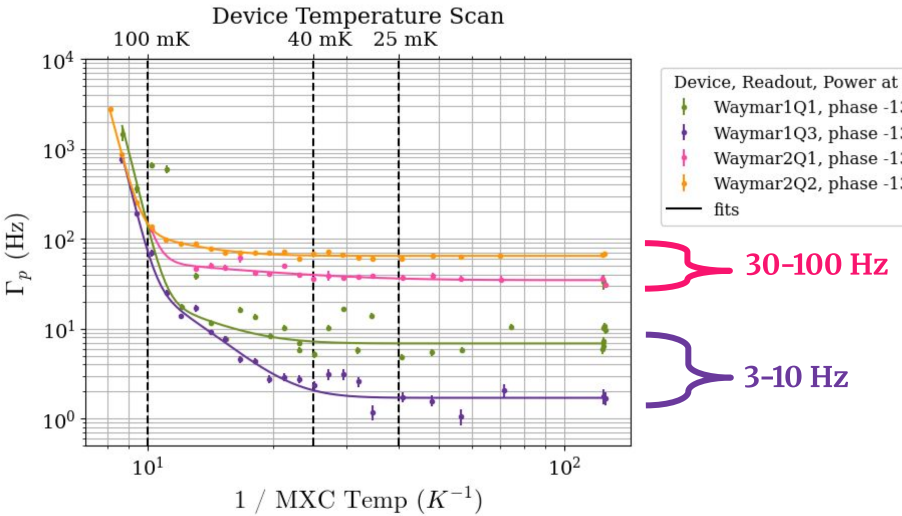
Next-Gen SQUATs

Initial results on Si:

- Imply lower quiescent quasiparticle density
  - Reflected in lower background rate
  - and weaker low-temperature dependence







Device	$x_{qp,res}$	$\delta\Delta$ [GHz]	T_c [K]	Γ_{other} [Hz]
Waymar1Q1	(2.0 ± 0.2)e-9	5.1 ± 0.6	0.994 ± 0.007	6.9 ± 0.1
Waymar1Q3	(4.1 ± 0.5)e-9	5.5 ± 0.4	1.030 ± 0.004	1.71 ± 0.09
Waymar2Q1	(1.3 ± 0.4)e-9	1.6 ± 0.6	1.04 ± 0.01	35 ± 1
Waymar2Q2	(5 ± 3)e-9	6.2 ± 0.1	1.06 ± 0.03	64.7 ± 0.6

Preliminary

But why?

- Ta T_c is higher -> base temp is a lower relatively
- Ta diffusion length < aluminum
- Ta ground plane more lossy than Nb
  - ~0.5 Δ
- Si vs Sapphire phonon propagation
- Something else?

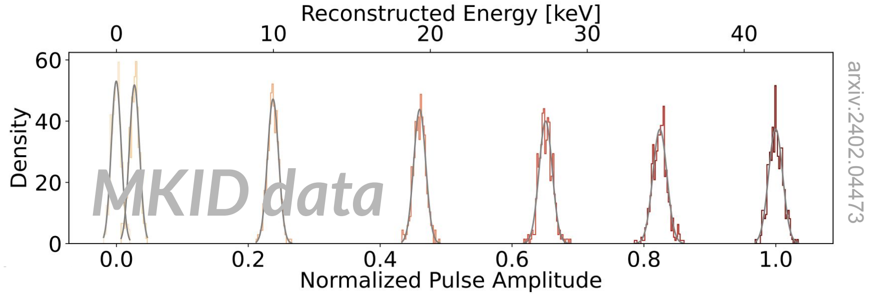
Slide credit: Hannah Magoon, Taylor Aralis

Next-Gen SQUATs

Zoë Smith
DMQIS grad student

Future studies on Si:

- LED-photon-based calibration

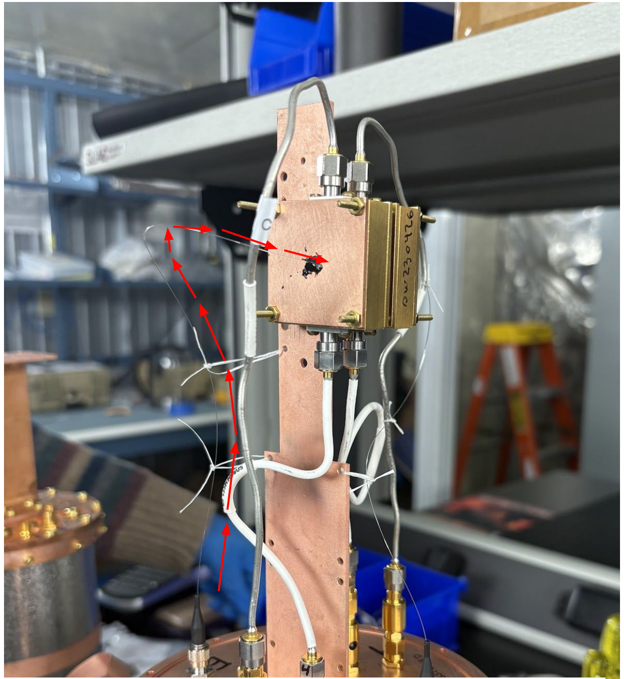


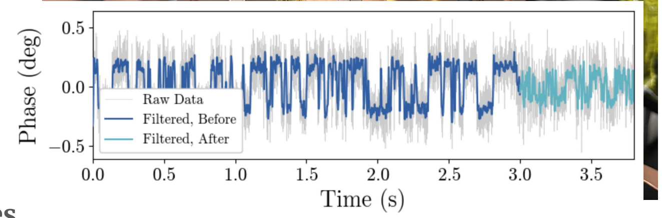
Record events of various amplitudes using single wavelength LED

Variance depends on *both* <u>intrinsic resolution</u> and <u>poisson fluctuation</u> in photon number

$$\sigma^2 = \sigma_0^2 + \sigma_{\mathrm{LED}}^2$$

calculating *amplitude* from rates, still an open question…





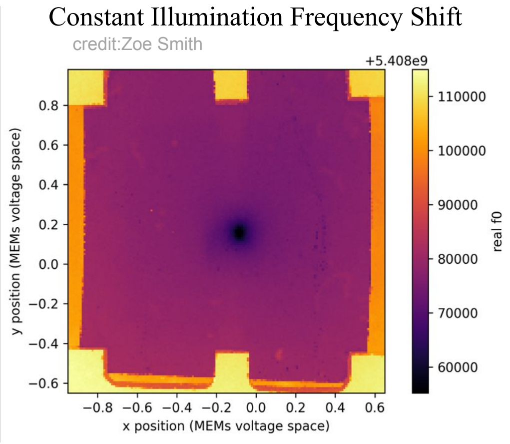
Slide credit: Hannah Magoon, Taylor Aralis

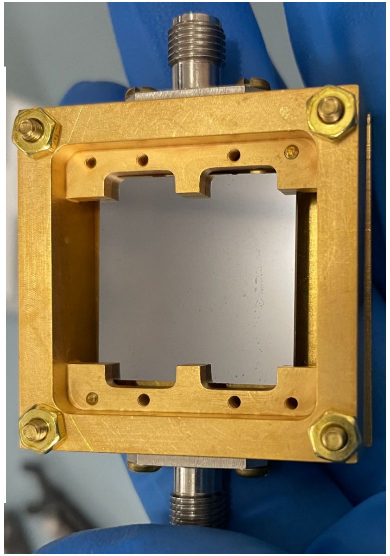
Next-Gen SQUATs

Slide credit: Hannah Magoon, Taylor Aralis

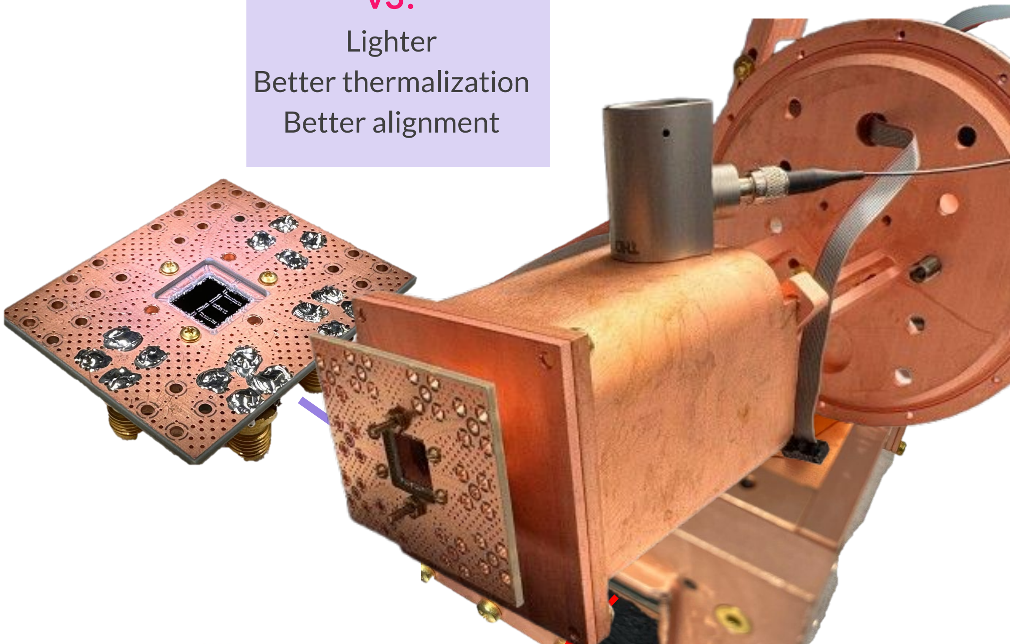
Future studies on Si:

- Phonon-collection studies...
- using the **MEMS cryogenic calibration system**





v3!
Lighter
Better thermalization
Better alignment



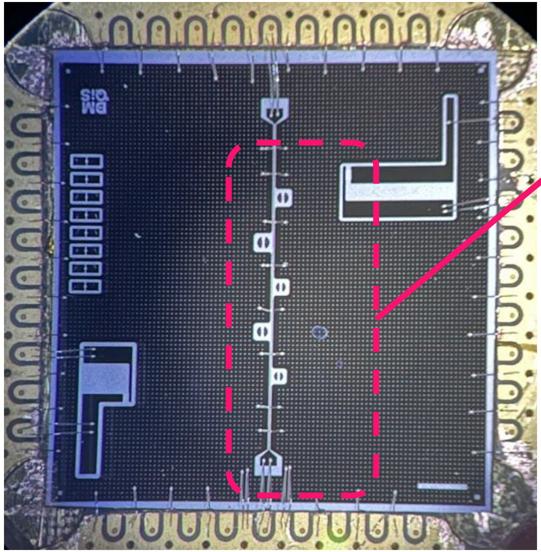
Zoë Smith
DMQIS grad student

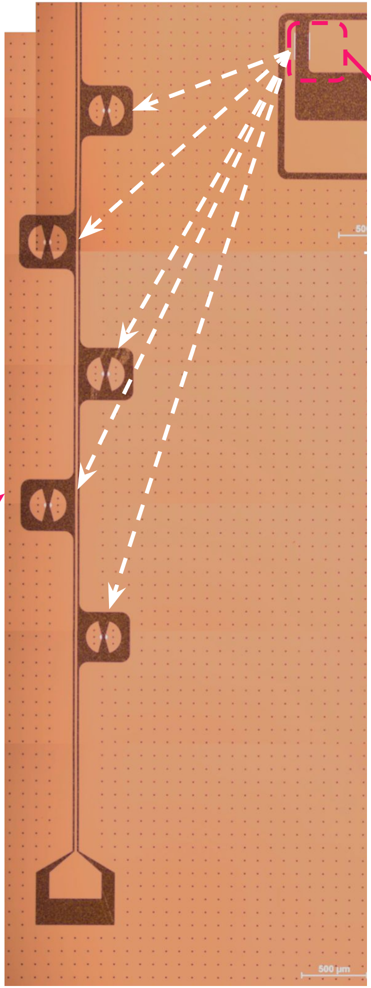
Sidney Stevens
Staff Mechanical Engineer

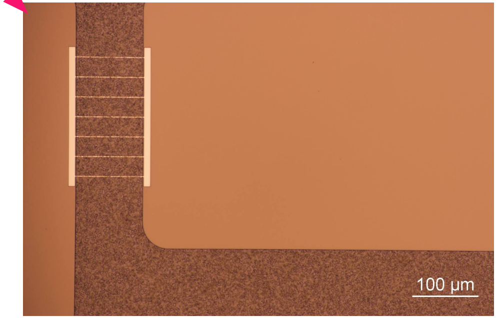
Next-Gen SQUATs

Future studies on Si:

- Phonon-collection studies…
- using phonon injectors on the device surface
- Validate/compare with MEMS study







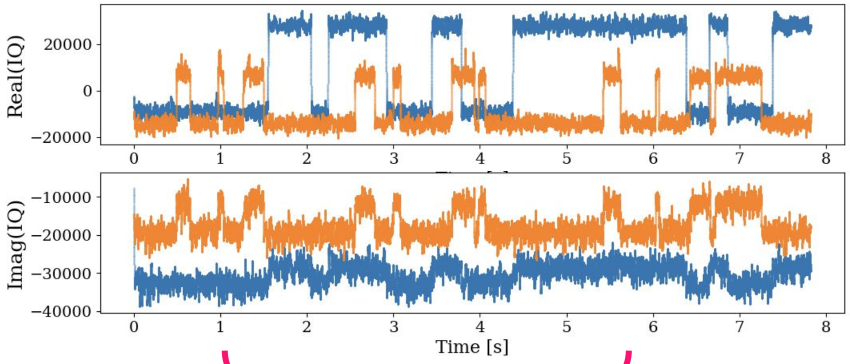
Josephson junctions:
A DC current produces quasiparticles that release phonon energy into the substrate upon recombination

Slide credit: Hannah Magoon, Taylor Aralis

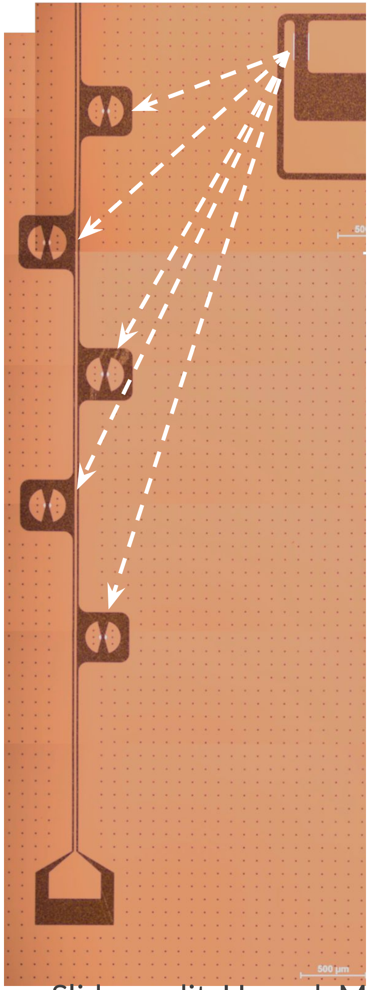
Next-Gen SQUATs

Future studies on Si:

- Phonon events should also be correlated between SQUATs
- Use multi-tone streaming to study such events and establish a trigger for DM-event searches



2x SQUAT readout (w/o phonon events)
Readout with RFSoC (ZCU 208) SmuRF



Alex Droster
DMQIS postdoc
KIPAC fellow

Shawn Henderson
Staff Scientist,
SMURF Extraordinaire

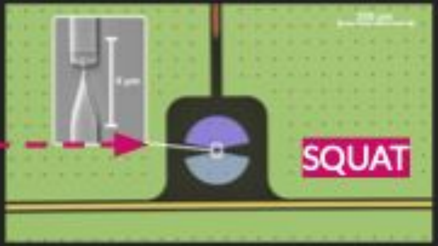
Jenny Smith
Staff Engineer,
Firmware Hero

Slide credit: Hannah Magoon, Taylor Aralis

Principle of Operation - why 2 PCS heads?

Goal:

THz photons

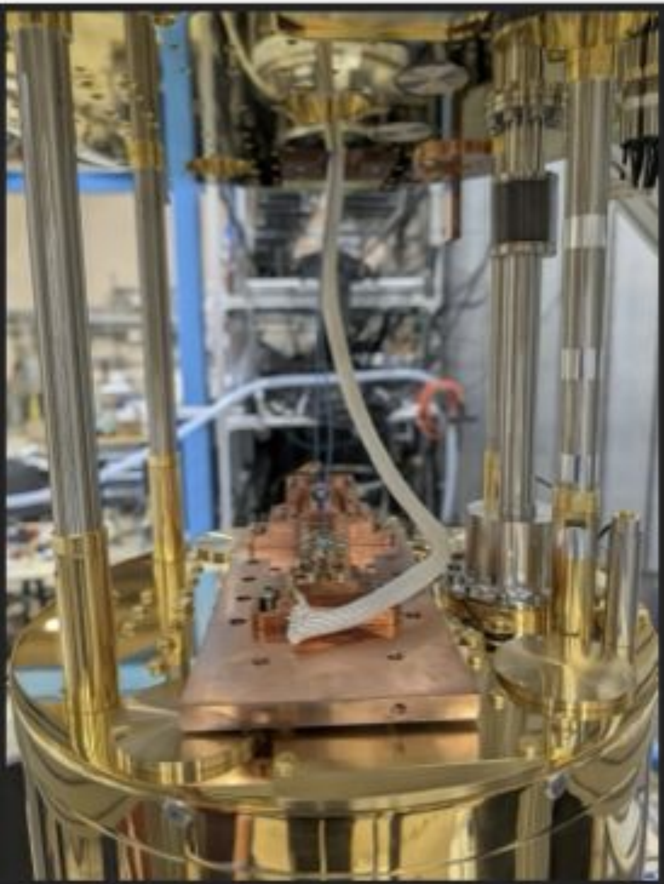


Interim demonstration :

Current set up is an interferometer!

Same combined laser beam sent down a longer optical path to detector PCS onto which the THz signal is incident

Will transition to source-only in near future.



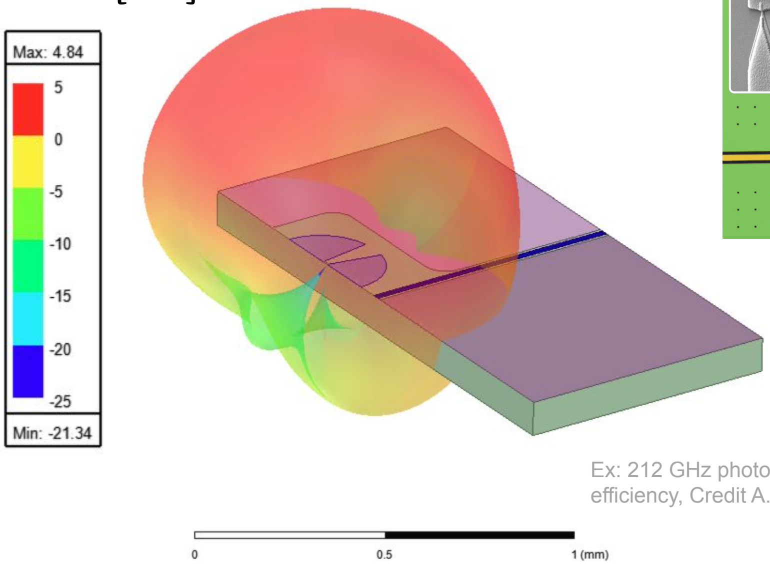
Emily Perry (eaperry@lbl.gov)

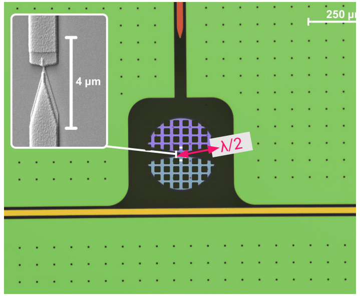
Next-Gen SQUATs

Future studies on Si:

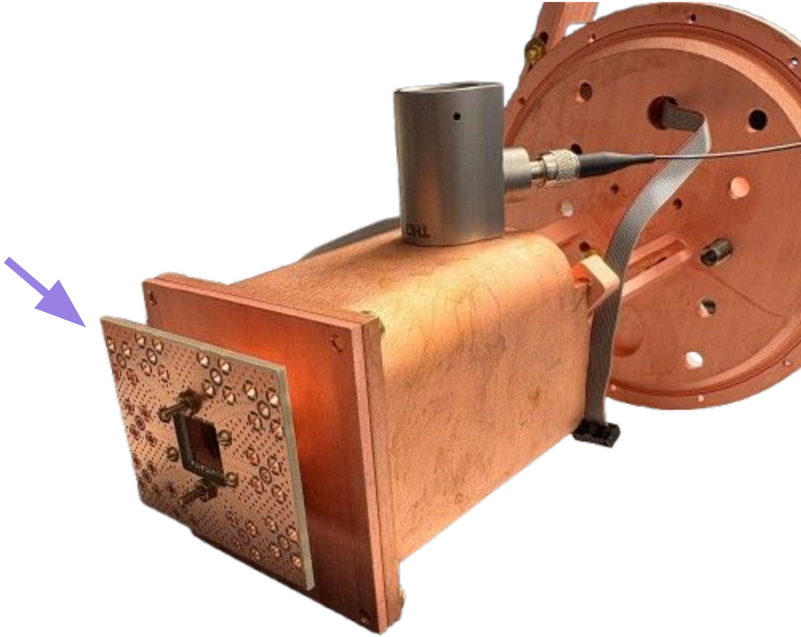
- Use MEMS with front-side illumination to study SQUAT antenna coupling
- Validate simulations and improve designs

Alex Droster
DMQIS postdoc
(KIPAC fellow)





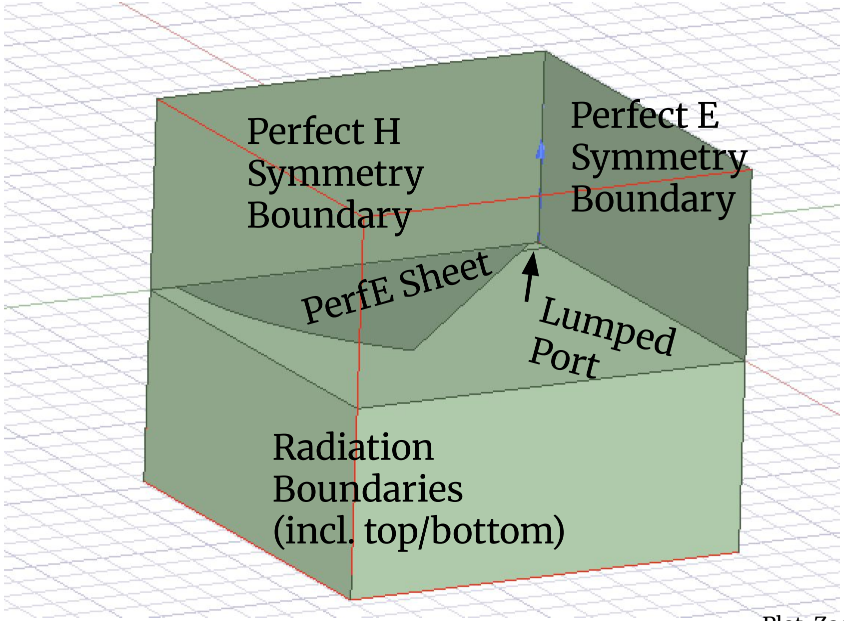
Ex: 212 GHz photon coupling efficiency, Credit A. Droster

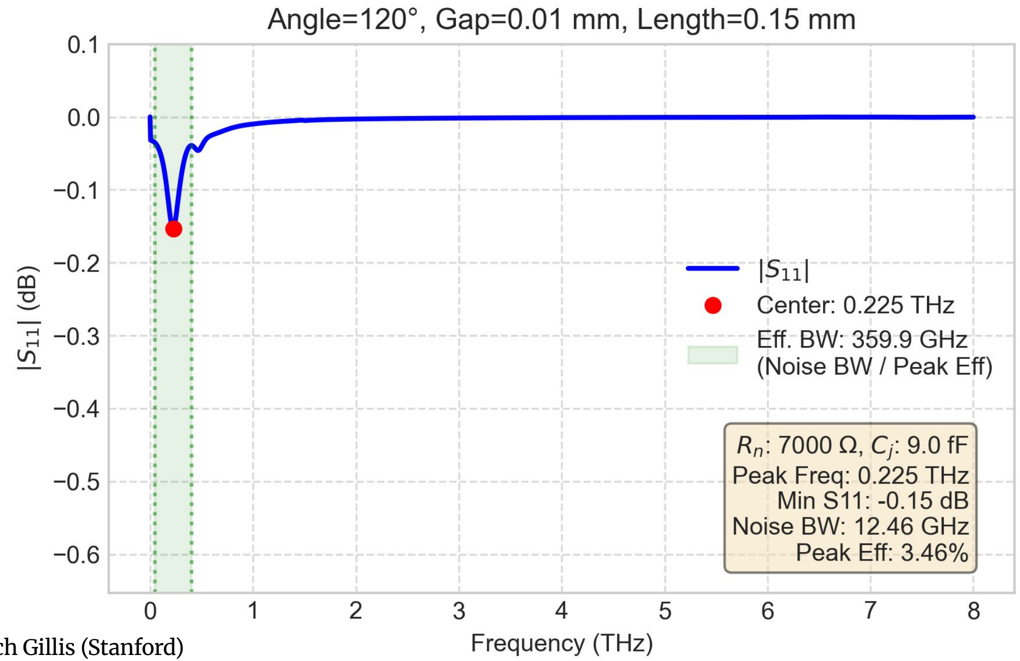


Slide credit: Hannah Magoon, Taylor Aralis

SQUATs have well-understood coupling to THz radiation

HFSS model



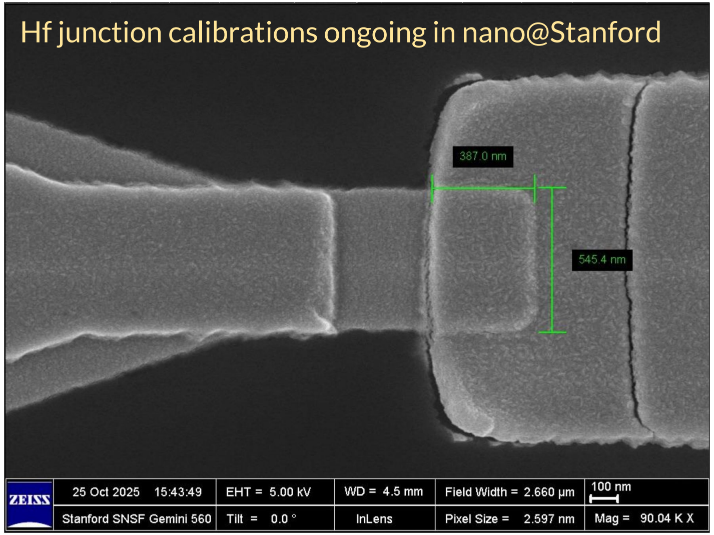


Plot: Zach Gillis (Stanford)

Method follows Rafferty, et al. arXiv:2103.06803

Low-Tc Junction Development

- Improved trapping and sensitivity
- Hf (Δ≈0.017 meV) Junctions shown viable

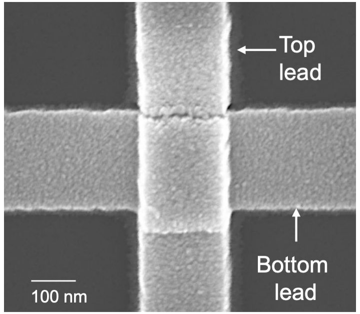


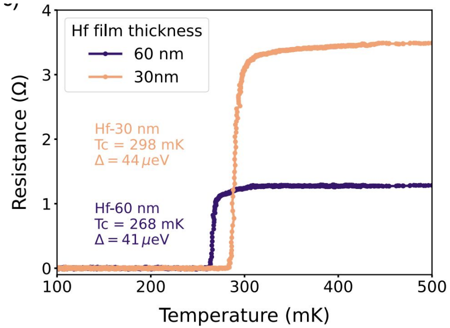
Low-Gap Hf–HfO_x–Hf Josephson Junctions for meV-Scale Particle Detection

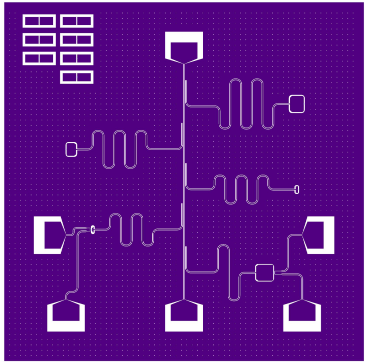
Y. Balaji[1], M. Surendran[1], X. Li[2], A. Kemelbay[1], A. Gashi[1], C. Salemi[2,3], A. Suzuki[2], S. Aloni[1], A. Tynes Hammack[1], and A. Schwartzberg[1]

[1] *Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA*
[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA and*
[3] *Department of Physics, University of California Berkeley, Berkeley, CA-94720, USA*

(Dated: November 11, 2025)







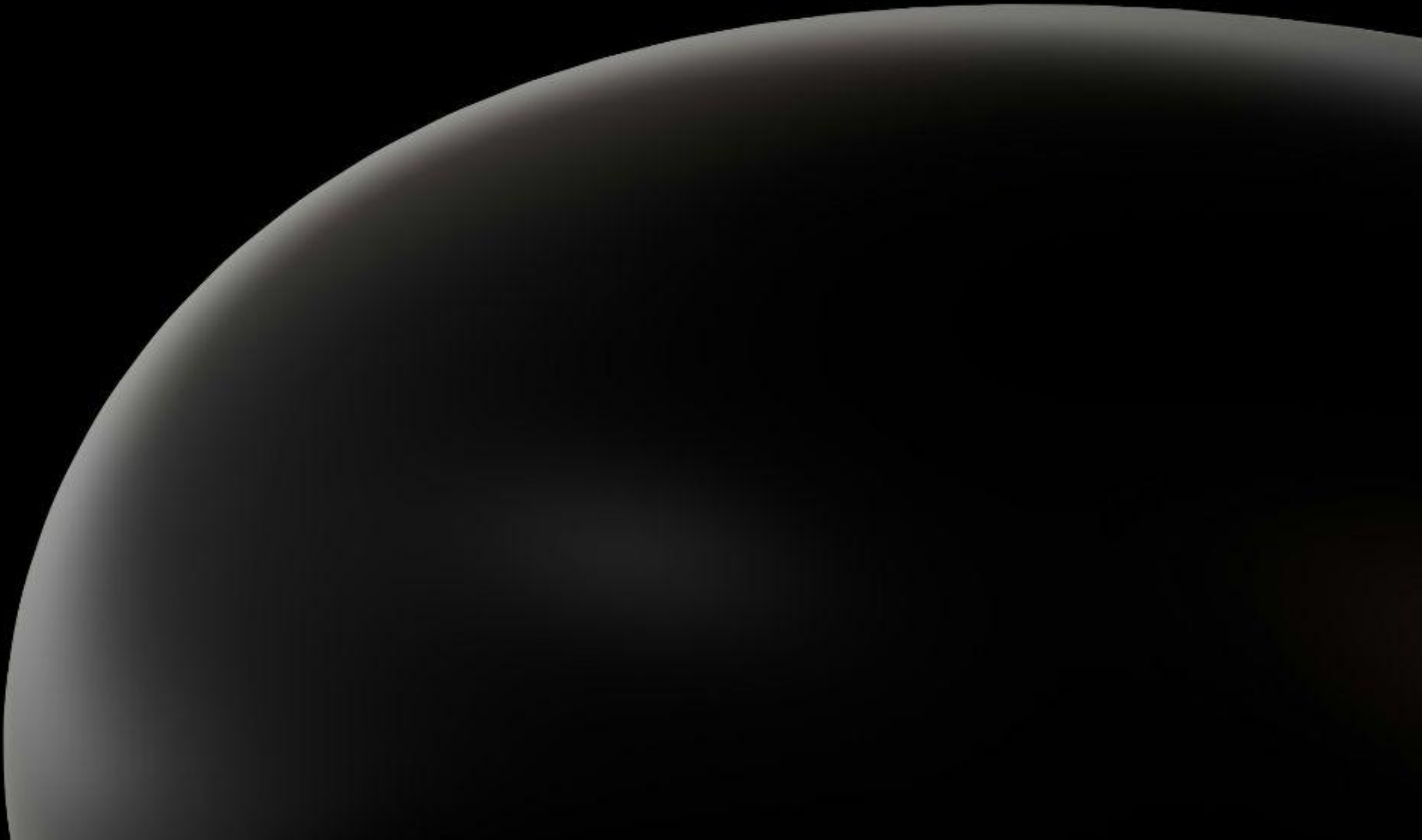
Transmon qubit designed to benchmark coherence & critical current density

Riley Carpenter

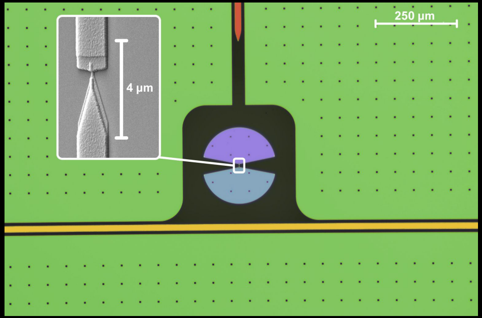
DMQIS/Schuster lab grad student

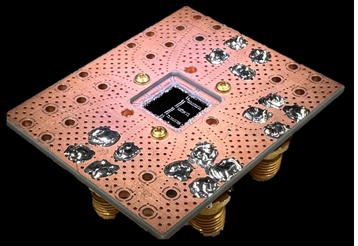
Slide credit: Hannah Magoon, Taylor Aralis

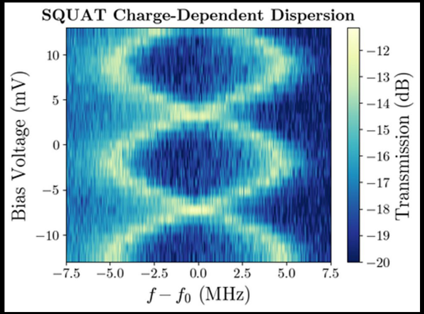
Trash

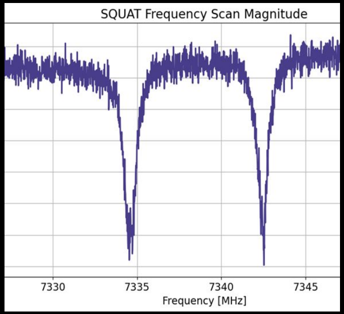


Superconducting quasiparticle amplifying transmon (SQUAT) detector architecture for THz/meV sensing









Alex Droster; postdoc, Stanford University/SLAC
June 6, 2026
IDM 2026, Zaragoza, Spain