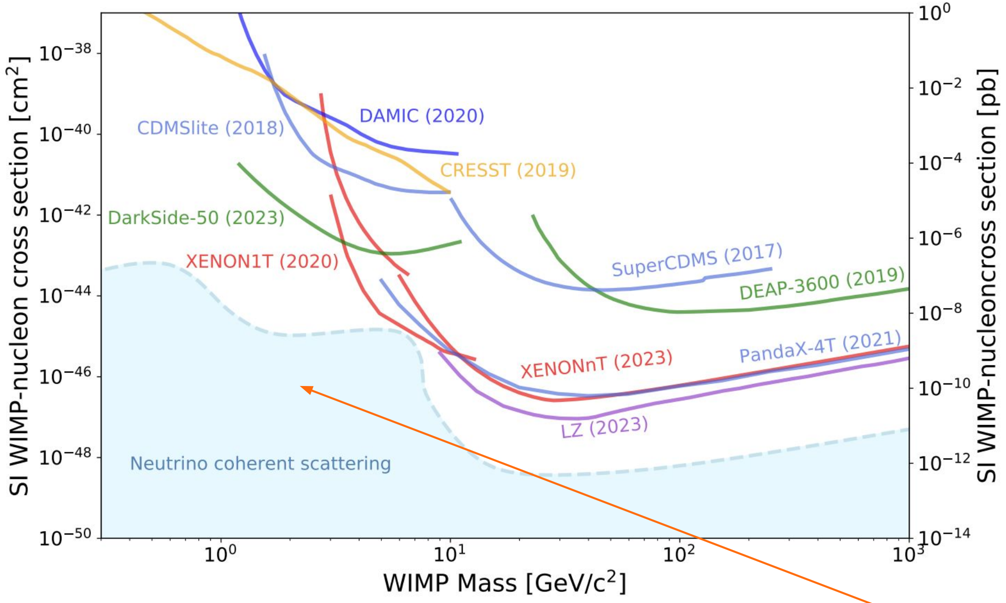
Qubit-based Sensors for Low-threshold Phonon Detection

Brandon Sandoval, bsandova@caltech.edu

Caltech: **S. Golwala**, J. Xiong, B. Sandoval, S. Ray
JPL: **P. Echternach**, A. Beyer, M. Shaw
WashU: **K. Ramanathan**, L. Yuan, W. Ho, M. Fritts
SLAC: **N. Kurinsky**, T. Aralis, H. Magoon, R. Carpenter, A. Droster, S. Stevens, J. Smith
UW Madison: **B. Plourde**, A. Huynh, J. Batarekh
Berkeley: **C. Salemi**, E. Perry, R. Gibbons, A. Fauquex, D. Gibson

Why do we need a lower threshold detector?

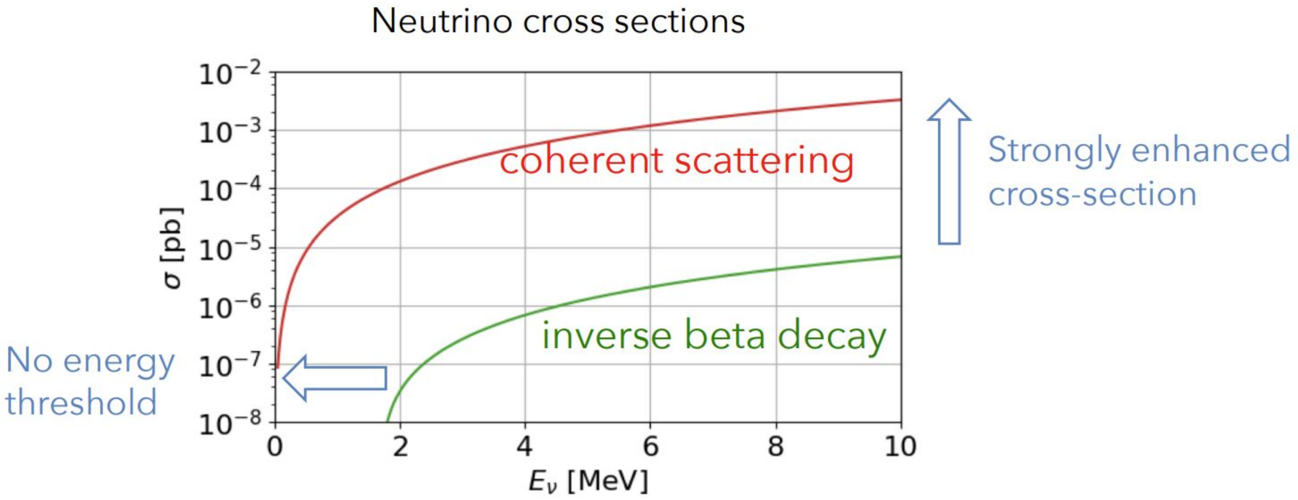


- **A lack of unambiguous signal for direct DM detection!**
- We have viable DM candidates below 1 GeV...
  - Hidden sector DM (nuclear recoil), dark/hidden photons (electron recoil)

New generation of detectors needed to probe deeper and wider parameter space!

Figure: Particle Data Group 2024, *Review of Particle Physics, https://doi.org/10.1103/PhysRevD.110.030001*

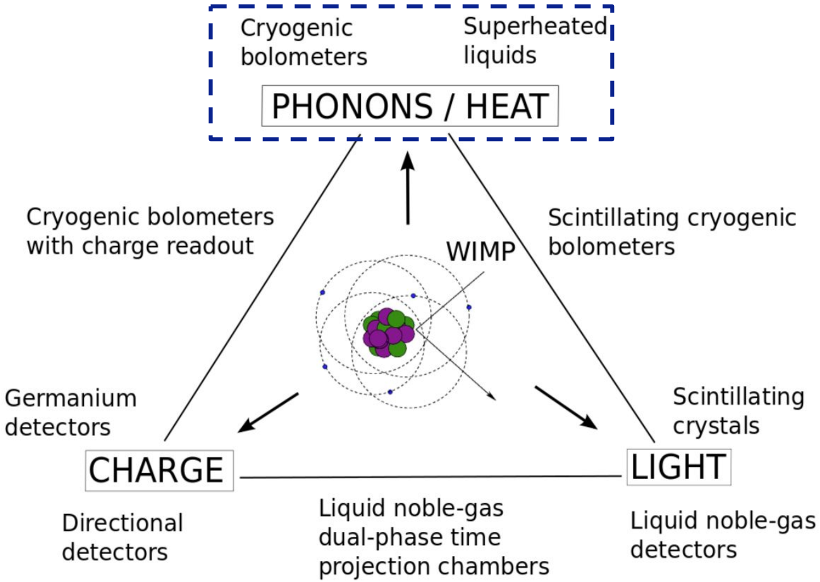
Why do we need a lower threshold detector?



- **CEνNS is interesting in its own right!**
  - Higher cross section than IBD, no minimum energy, roughly flavor-blind
  - Provides probe into neutrino properties, non-standard interactions, neutron skin-depth in nuclei

Figure: R. Strauss 2018, *Nu-cleus: Exploring coherent neutrino-nucleus scattering at low energies*

Why we turn to phonons



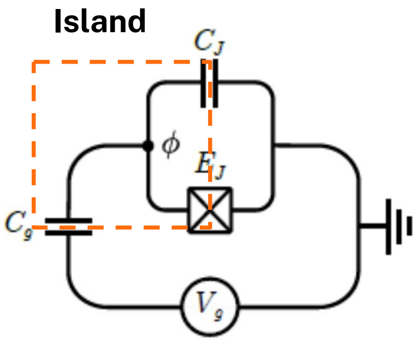
> 10 eV for gaseous and liquid detectors

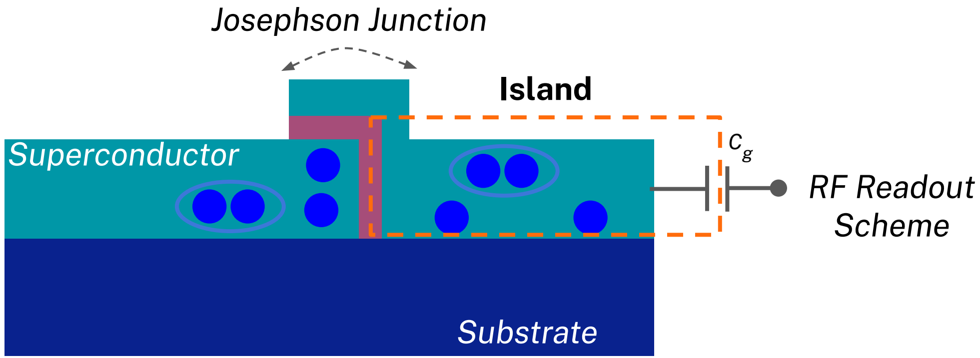
> 1 eV for e-h pair in semiconductors

> 1 eV to excite electrons to emit light.

- For DM masses between **1 keV and 1 GeV**, we expect energy depositions on the order of **0.1 meV to 100 eV**
- A neutrino with energy between **0.1-1 MeV** will yield CEνNS recoil energies on the order of **0.1 to 10 eV**.
- Below ~1 eV, we expect collective excitations, like phonons, to be the only viable energy manifestation!
  - *Potentially except for small band gap materials being developed

Charge-sensitive qubits



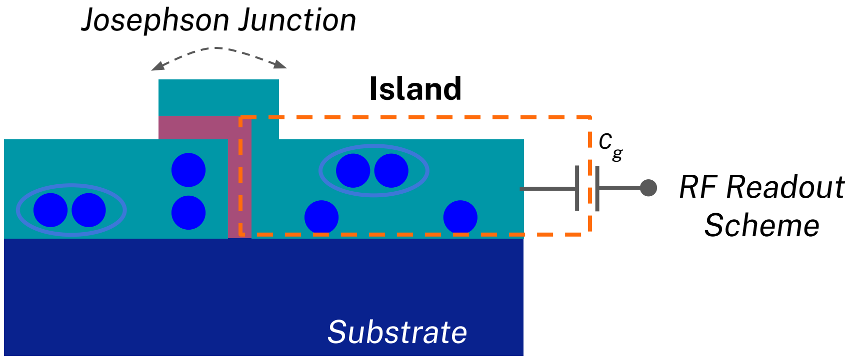


Capacitance energy | Cooper pairs on island | Gate charge | Parity of qp's on island (±1) | Josephson energy

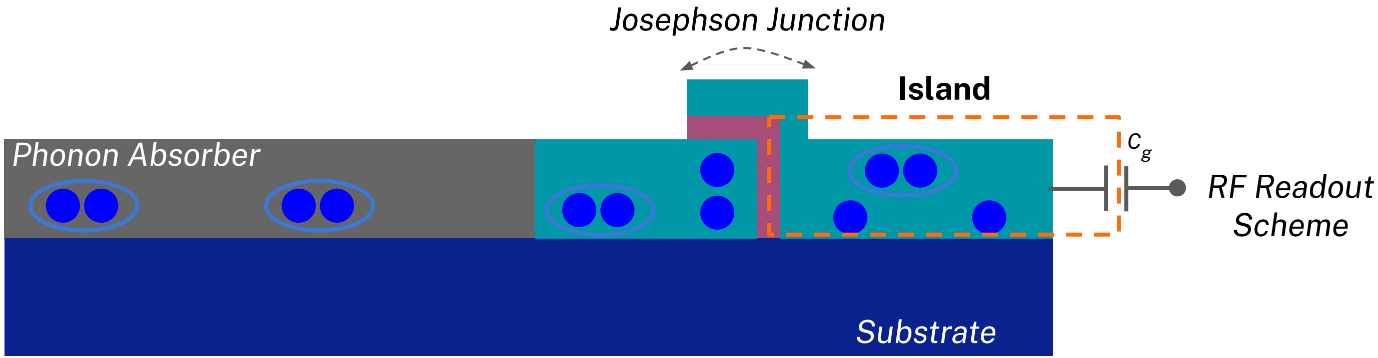
$$\hat{H} = 4E_C\left(\hat{n} - n_g + \frac{P-1}{4}\right)^2 - E_J\cos\hat{\phi}$$

- The energy spectrum of the qubit is sensitive to whether there is an even or odd number of quasiparticles on the island **(i.e. the parity of the quasiparticle number).**

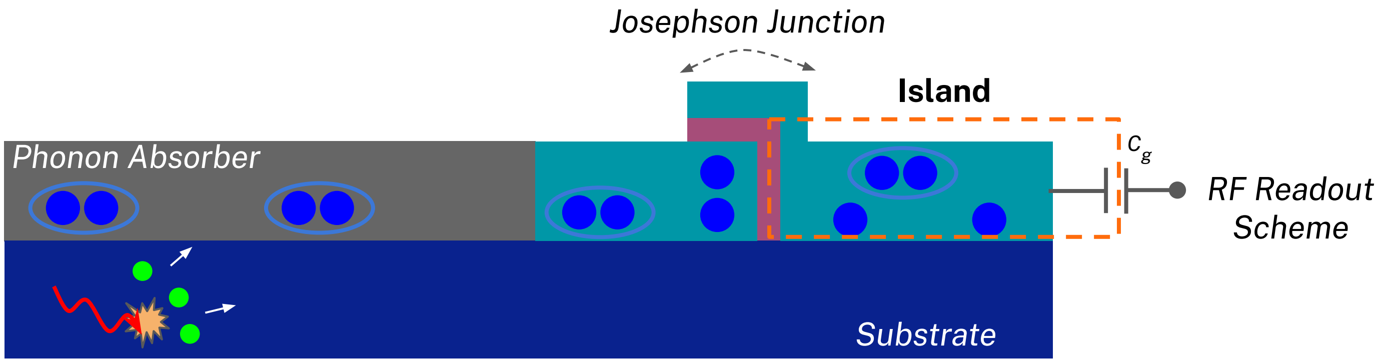
Qubit-based phonon sensor



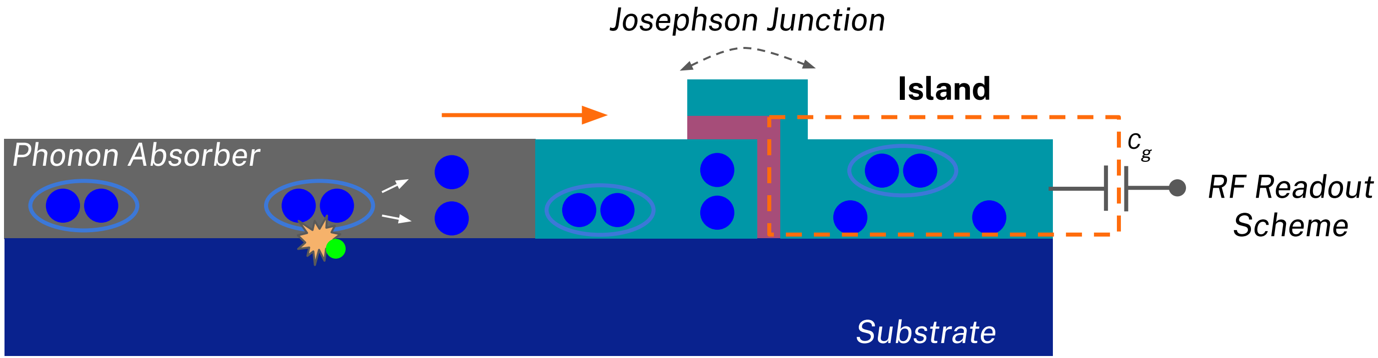
Qubit-based phonon sensor



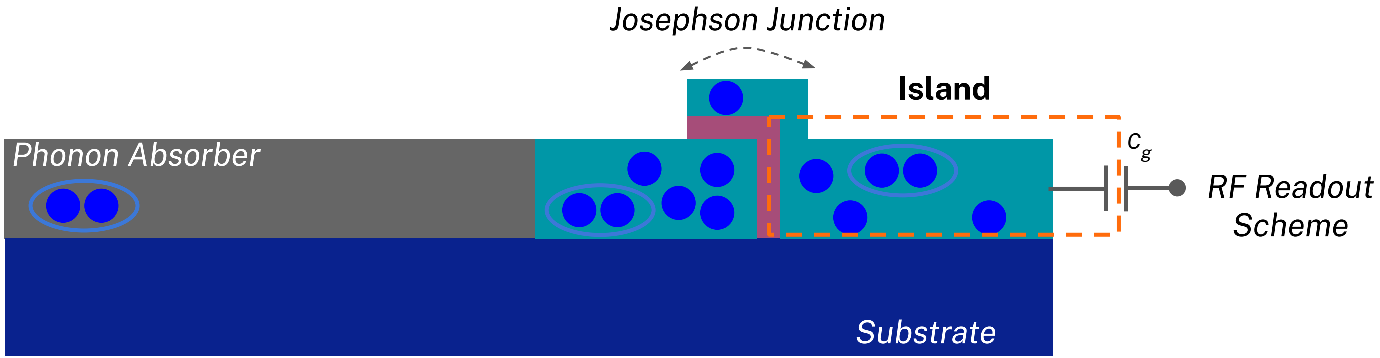
Qubit-based phonon sensor



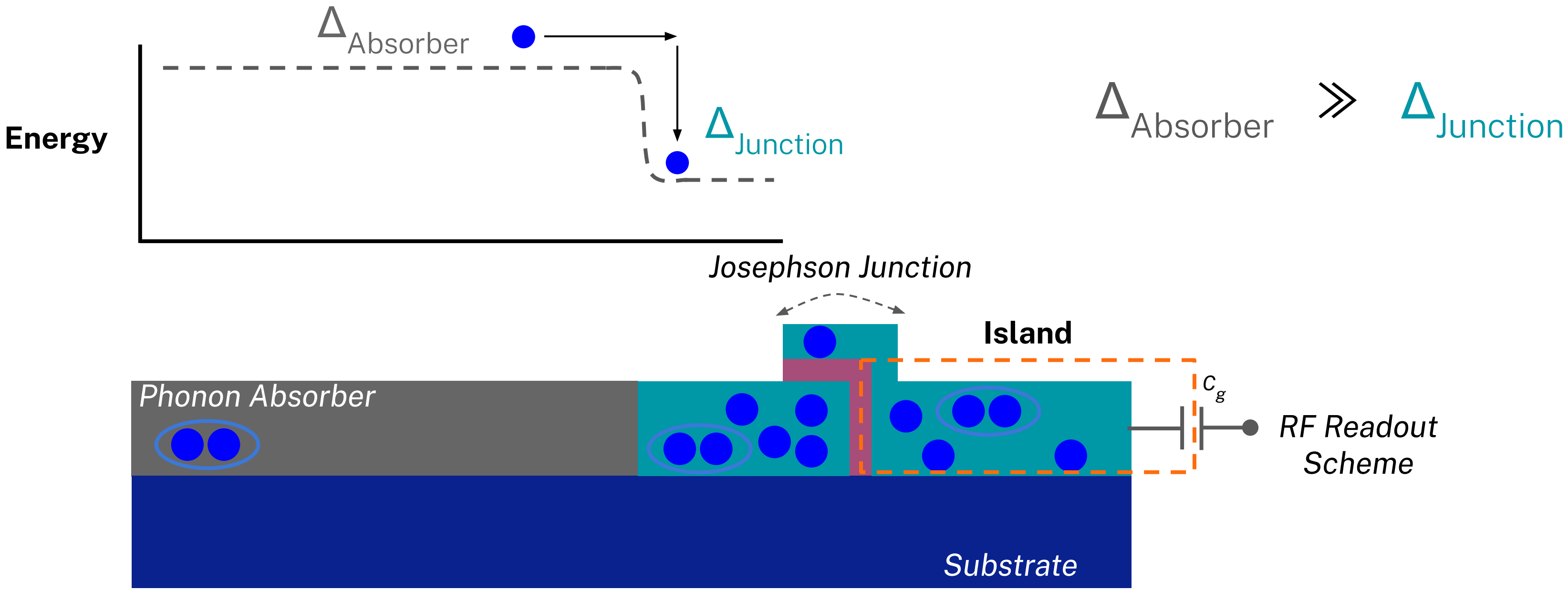
Qubit-based phonon sensor



Qubit-based phonon sensor

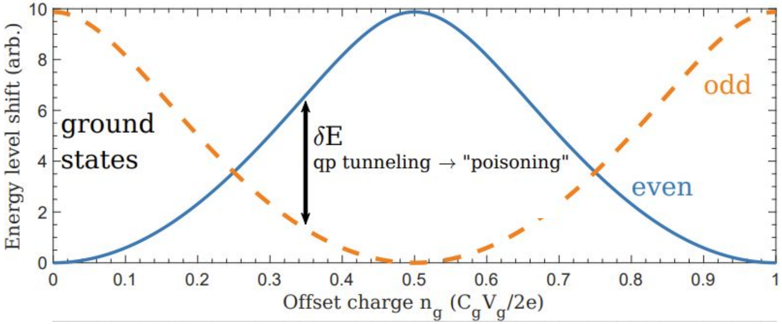


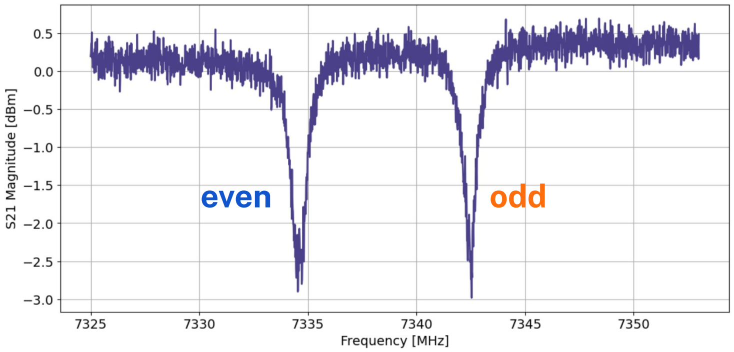
Qubit-based phonon sensor



- QPs diffuse into the junction, fall to the new bandgap (which may generate more QPs from the emitted phonons), become trapped, and tunnel back-and-forth across junction until they recombine.

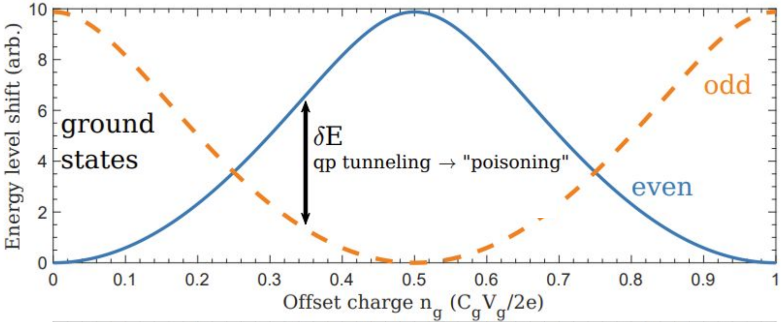
Signal response

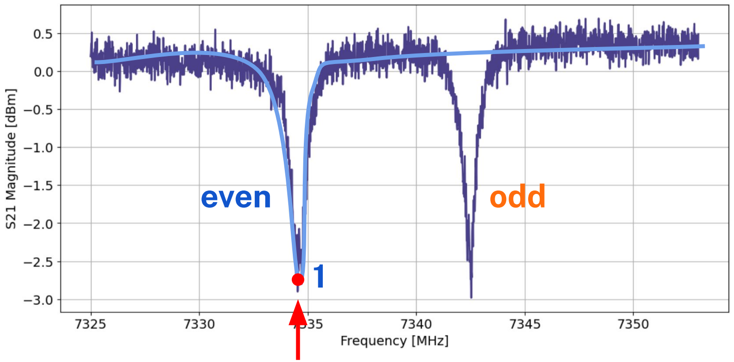




- Each tunneling event causes the qubit to switch parity, changing the energy of the qubit
- By probing the qubit with an RF tone, this leads to two distinct resonances corresponding to each parity state
- O(10 MHz) shift in resonant frequency expected from a parity shift

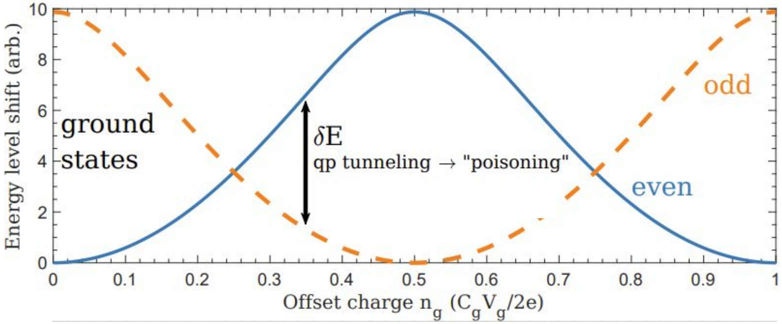
Signal response

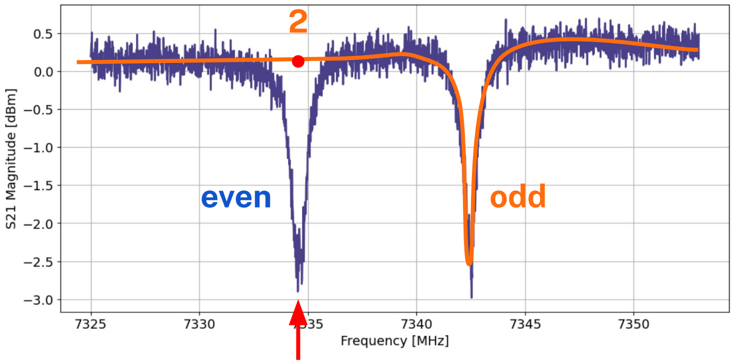




- Each tunneling event causes the qubit to switch parity, changing the energy of the qubit
- By probing the qubit with an RF tone, this leads to two distinct resonances corresponding to each parity state
- O(10 MHz) shift in resonant frequency expected from a parity shift

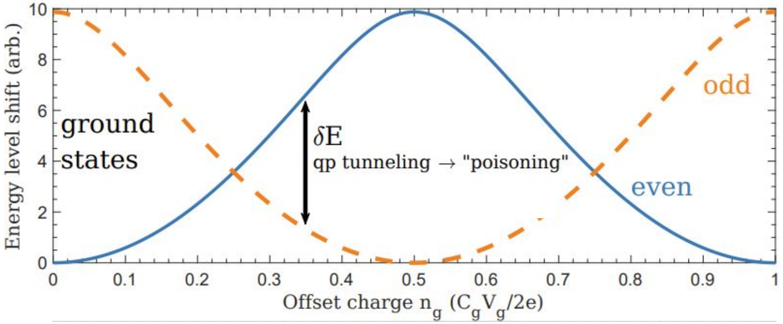
Signal response

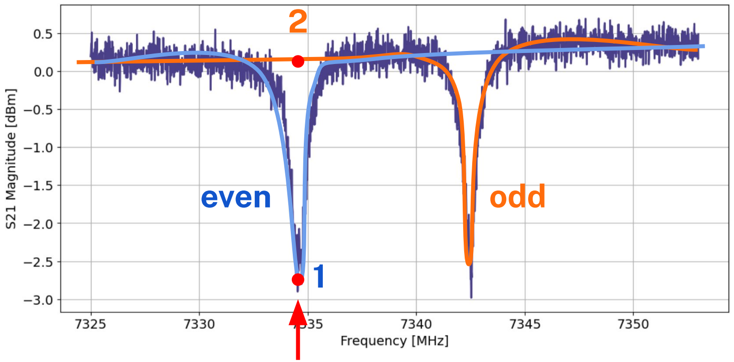


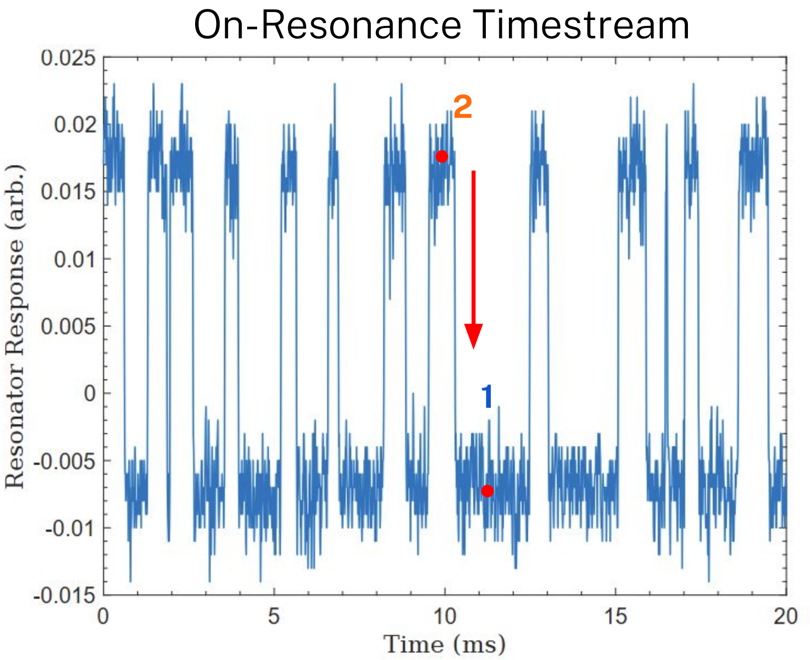


- Each tunneling event causes the qubit to switch parity, changing the energy of the qubit
- By probing the qubit with an RF tone, this leads to two distinct resonances corresponding to each parity state
- O(10 MHz) shift in resonant frequency expected from a parity shift

Signal response

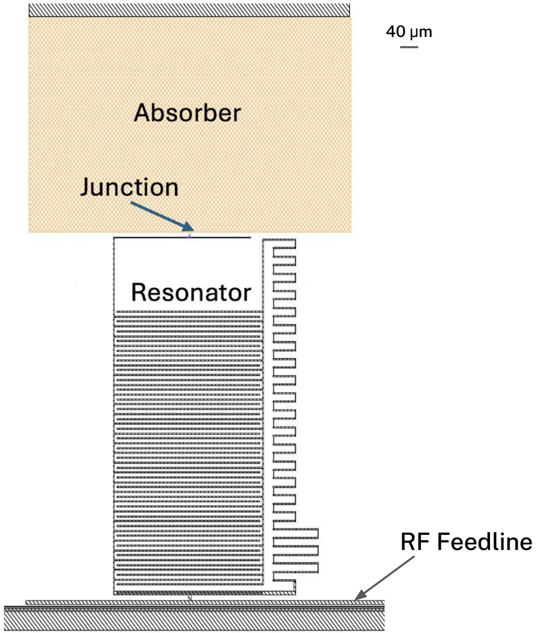




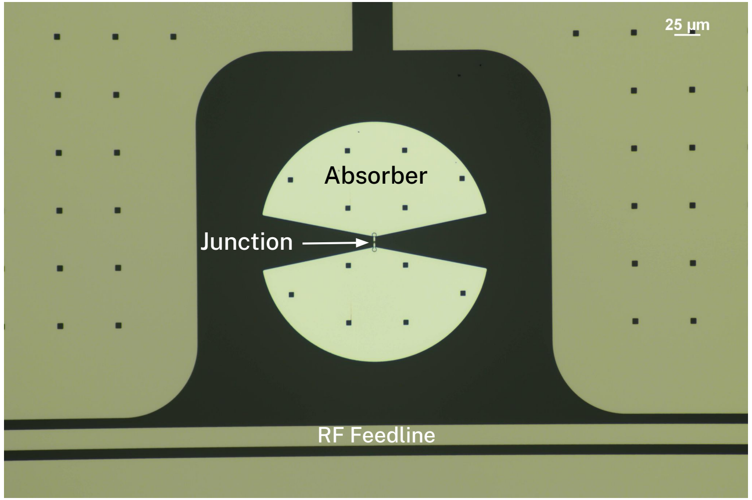


Physical realizations

Quantum Parity Detector (QPD)
Resonator Coupled



Superconducting Quasiparticle-Amplifying Transmon (SQUAT)
Direct-Feedline Coupled



Physical realizations

Quantum Parity Detector (QPD) Resonator Coupled

Quantum Parity Detectors: a qubit based particle detection scheme with meV thresholds for rare-event searches

K. Ramanathan,[1,2,*] J. E. Parker,[1] L. M. Joshi,[3] A. D. Beyer,[4] P. M. Echternach,[4] S. Rosenblum,[3] B. J. Sandoval,[1] and S R. Golwala[1]

[1]*Department of Physics, California Institute of Technology, Pasadena, CA, 91125, USA*
[2]*Department of Physics, Washington University in St. Louis, St. Louis, MO, 63130, USA*
[3]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel*
[4]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*

(Dated: July 2, 2024)

https://doi.org/10.48550/arXiv.2405.17192

Superconducting Quasiparticle-

Superconducting quasiparticle-amplifying transmon: A qubit-based sensor for meV-scale phonons and single terahertz photons

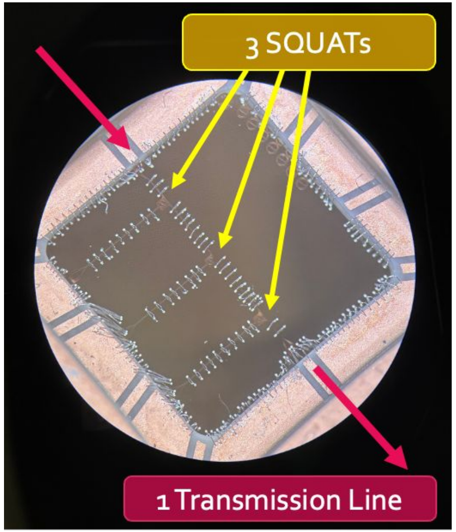
C.W. Fink,[1,*] C.P. Salemi,[2,3,†] B.A. Young,[4] D.I. Schuster,[5] and N.A. Kurinsky[2,3,‡]

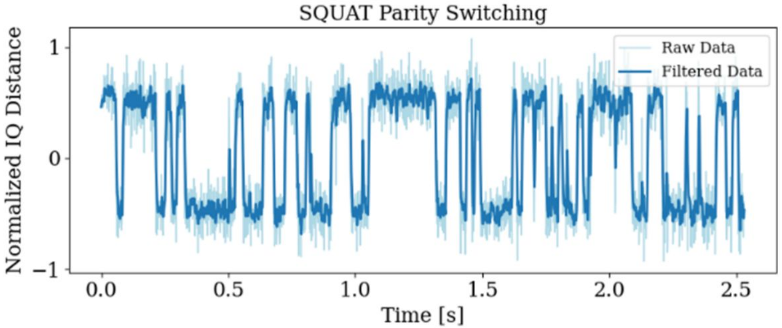
[1]*Materials Physics and Applications – Quantum, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94035, USA*
[4]*Santa Clara University, Santa Clara, California 95053, USA*
[5]*Department of Applied Physics, Stanford University, Stanford, CA 94035, USA*

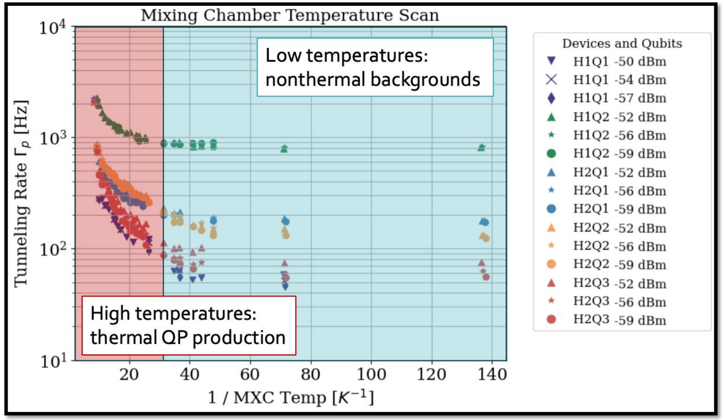
https://doi.org/10.1103/PhysRevApplied.22.054009

Magoon et al. in prep!

Current status of SQUAT devices

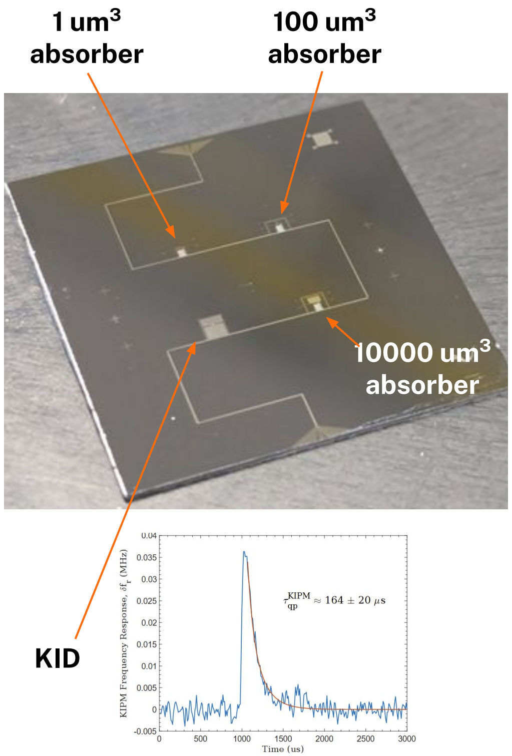




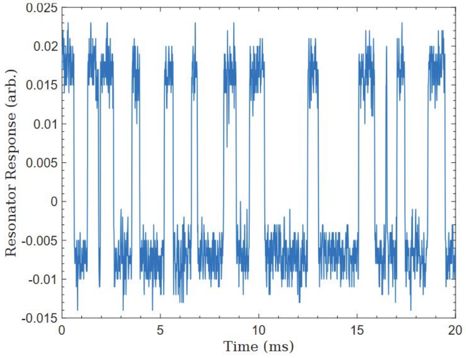


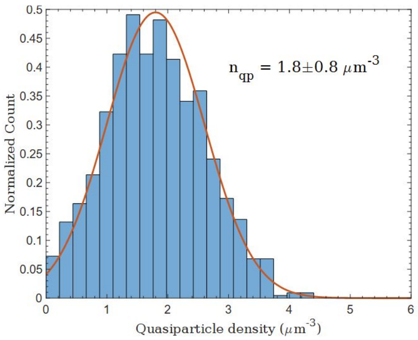
- Qubits able to be probed, and parity signal is observed
- **~20 Hz parity switch rate**, from nonthermal background
- Able to see tunneling rate become thermally dominated at higher temperatures
- Estimated quiescent quasiparticle density of **0.1 um^{-3}**

Current status of QPD devices



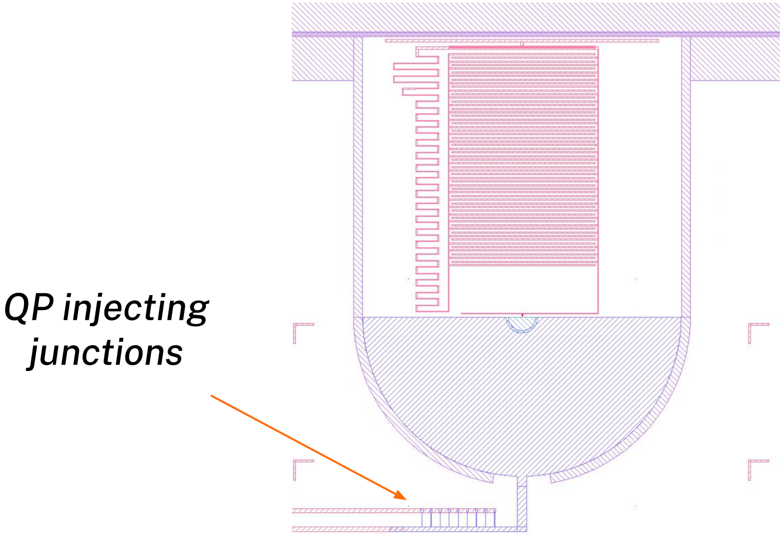
QPD Parity Signal

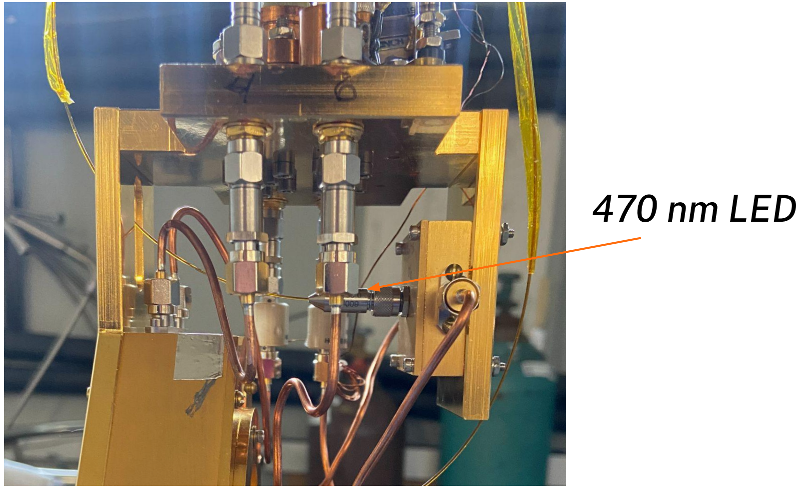




- 1 um^3 absorber QPD yielding a parity signal
- **~1 kHz parity switch rate** (quiescent background)
- Co-calibration KID on the chip is showing pulses in response to cosmogenic particles
- Estimates given the observed signal indicate a quiescent quasiparticle density of **1.8±0.8 um^{-3}**

Future device tests





STJ Quasiparticle Injectors

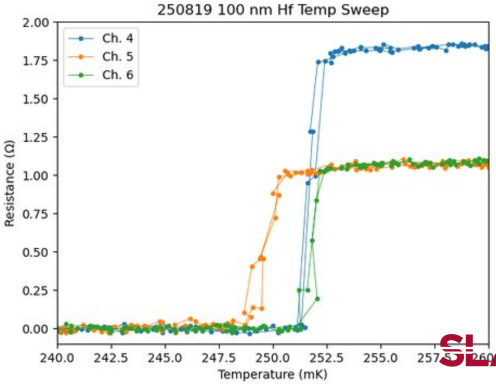
- Test tunneling efficiency & diffusion times
- Phonon generation in the substrate

LED-Generated Phonon Calibration

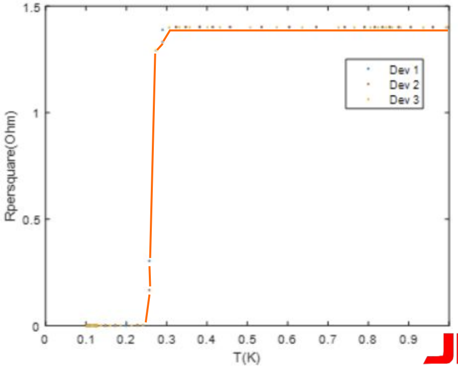
- Well tested on phonon-mediated KID sensors in the past

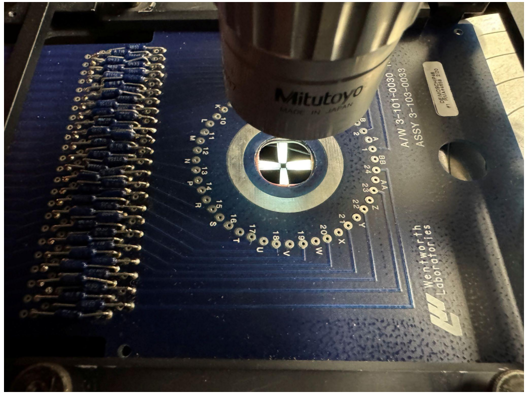
Low Tc junction R&D

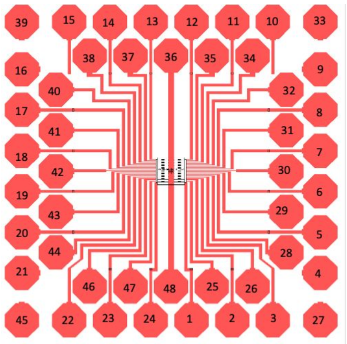
Hafnium RxT Test



Al-Ti-Au Trilayer Rxt Test

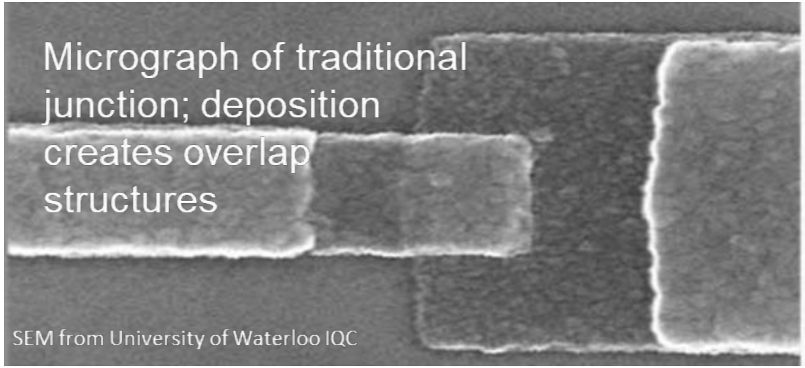


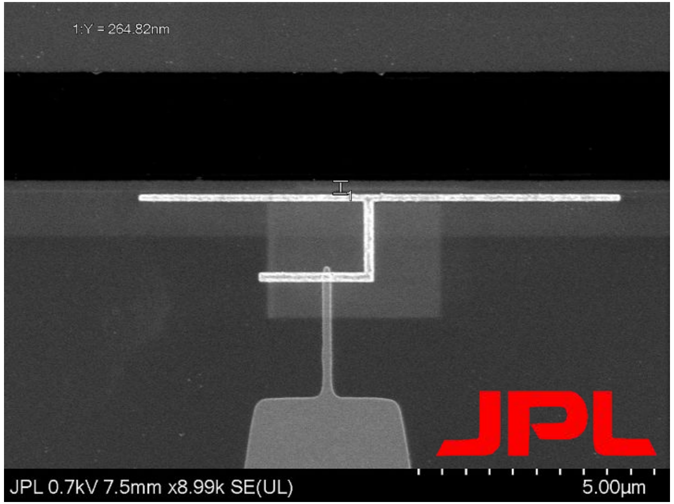




- QP trapping scheme requires low gap (and hence low Tc) junctions
- Testing currently undergoing for low-Tc materials including **Hf, Al-Ti-Au, AlMn, IrPt**

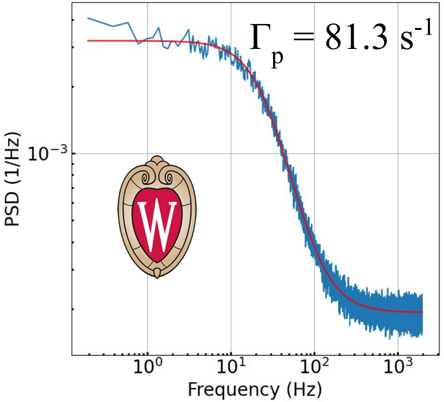
Junction fabrication techniques

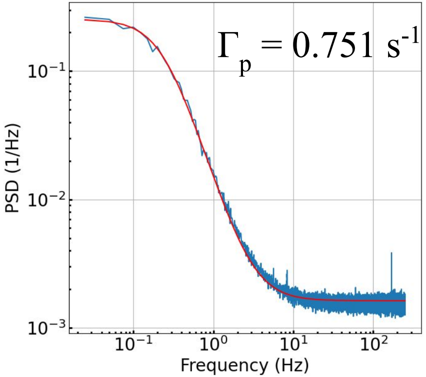


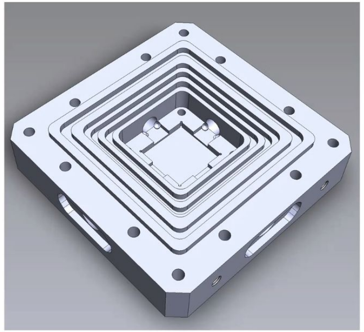


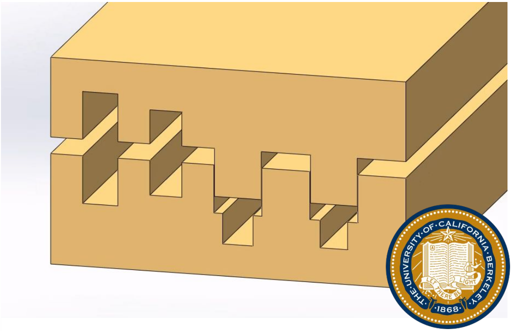
- Standard junction techniques (e.g. shadow evaporation) can create parasitic secondary junctions possibly blocking quasiparticle transport
- Utilizing and developing “ion-milled” junctions that do not suffer from parasitics

Mitigating radiative backgrounds





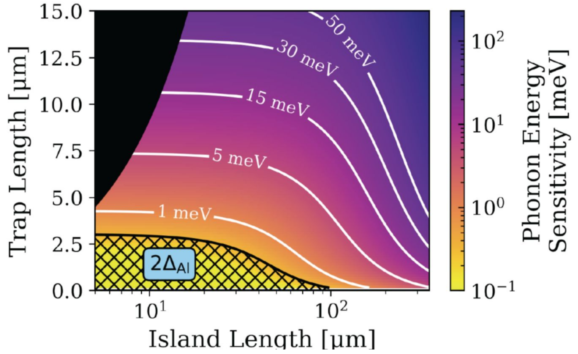




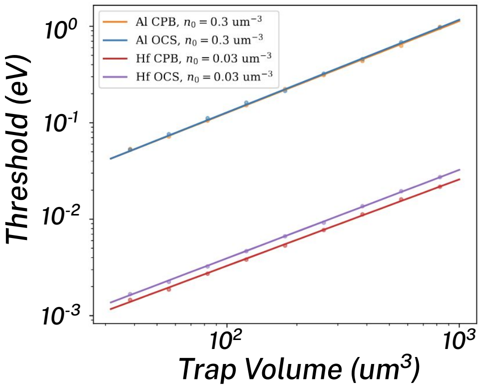
- $\sigma^2_{\text{background}} \propto n_{\text{quiescent}}$
- IR-absorbing coating and newly designed device box with blackbody radiation stub filters
- Careful treatment of signal-line filtering

Conclusion: sights set on O(meV) resolution!

SQUAT Sensitivity Estimates



QPD Sensitivity Estimates



- Charge-sensitive qubits exhibit a response to quasiparticle tunneling events
- With proper gap engineering with low Tc materials and sufficiently low backgrounds, we expect **O(meV)** sensitivities!
- Rigorous R&D underway, including: low Tc junctions, non-overlapping junction fabrication techniques, IR background mitigation, QP and phonon physics simulations

BACKUP SLIDES

QPD Sensor Resolution and Noise

Resolution on number of signal transitions →

$$\sigma_S^2 = \left(K\frac{\tau_{qp}}{V} + K^2\left(\frac{\tau_{qp}}{V}\right)^2 F \right) N_{qp}^r$$

- *$\Gamma_{in} = K\, n_{qp}$*
- *Quasiparticle Lifetime* (τ_{qp})
- *Sensor Volume* (V)
- *Fano Factor ~ O(0.1)* (F)
- *Max no. of qp's generated from energy deposition* (N_{qp}^r)

Tunneling Shot Noise (first term) — **Fano Noise** (second term)

Expected number of switches →

$$S = K\frac{N_{qp}\tau_{qp}}{V}$$

Resolution on number of background transitions →

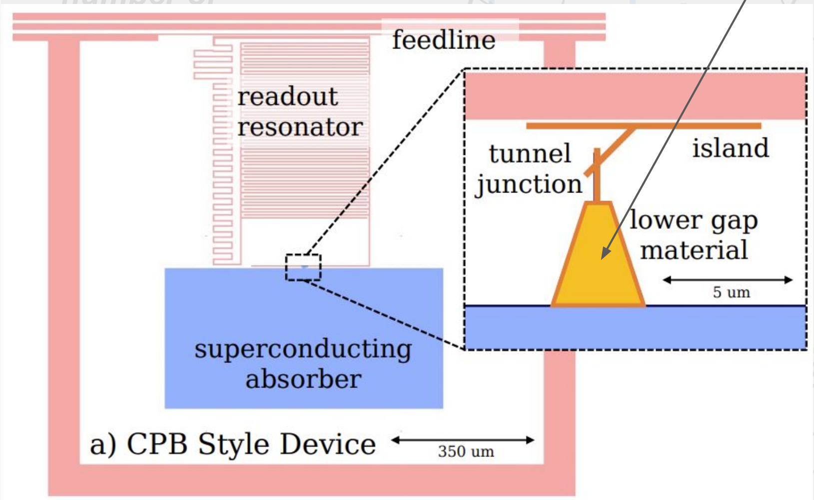
$$\sigma_B^2 = \left(K t_w + 16\frac{K^2 t_w^2}{V} \right) n_0$$

- *Time window* (t_w)
- *Quiescent Quasiparticle Density* (n_0)

Tunneling Shot Noise (first term) — **Quiescent Quasiparticle Noise** (second term)

QPD Sensor Resolution and Noise

Quasiparticle Trap Region



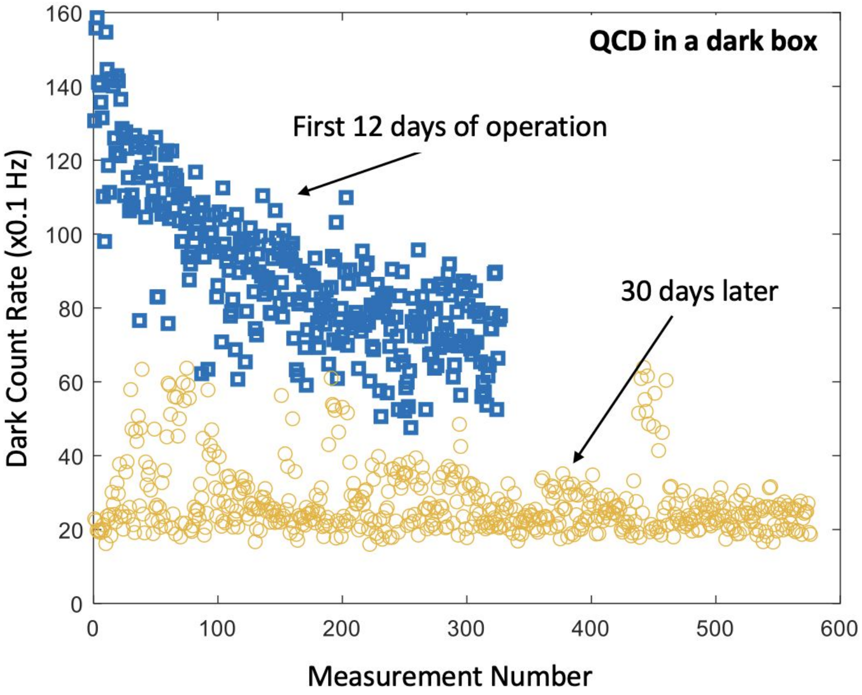
- Our signal benefits greatly from smaller QP collecting volume! **Investigating using QP trapping into small junction electrode volume → will be needed for ultimate sub-eV substrate sensitivity**

$$S = K\frac{N_{qp}\tau_{qp}}{V} = (750\ \text{switches})\left[\frac{K}{15\,\text{kHz}\cdot\mu\text{m}^3}\right]\left[\frac{E_{abs}^{\text{single}}}{20\,\text{meV}}\right]\left[\frac{\tau_{qp}}{1\,\text{ms}}\right]\left[\frac{10\,\mu\text{m}^3}{V}\right]$$

$$\sigma_B = \sqrt{\left(Kt_w + 16\frac{K^2t_w^2}{V}\right)n_0^{\text{trap}}} \approx 200\ \text{switches} \approx \boxed{5\ \text{meV}}$$

For a Hf device with 10 um^3 electrode volume, **we can estimate a 5σ sensor energy resolution of ~25 meV**

Evidence of time-dependent DCR

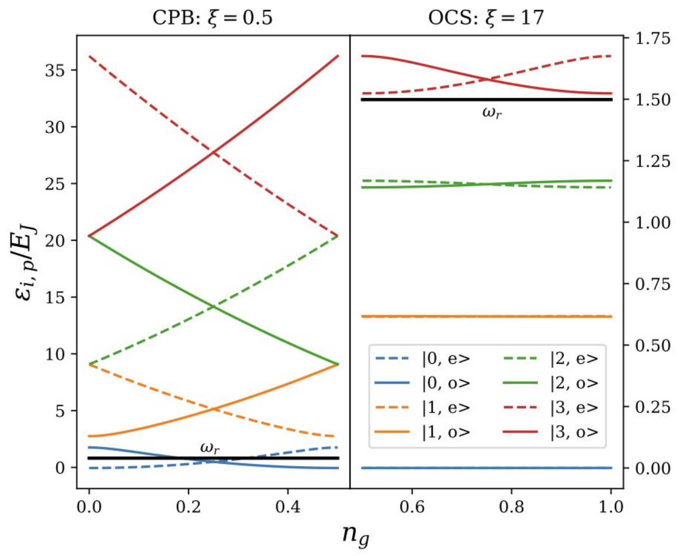


- Operation of a similar photon sensitive QCD in a dark box shows **d**ark **c**ount **r**ate reduction over O(month).
- Potentially similar source & mechanism as that contributing to Low Energy Excess identified in other cryogenic phonon sensing experiments.
- Eventual goal of measuring sub-eV energy spectrum.

QCD vs. OCS transmon

$$\xi = E_J / E_C$$

- ξ determines the sensitivity of energy levels to gate charge n_g
- For $\xi \lessapprox 1$ (*Quantum Capacitance Detector [QCD]*), larger curvature of energy levels leads to large change in quantum capacitance with quasiparticle tunneling
    - O(MHz) resonance shift
- For $\xi \gtrapprox 1$ (*Offset Charge Sensitive [OCS] Transmon*), we utilize dispersive shift from higher energy levels to readout resonance shift with quasiparticle tunneling
    - O(100 kHz) resonance shift



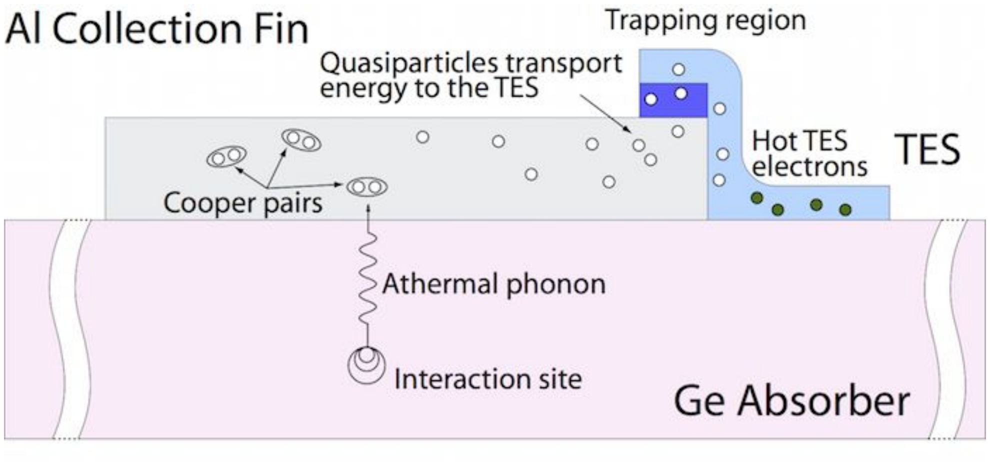
$$C_p = -\frac{C_g^2}{4e^2}\frac{\partial^2 \epsilon_p}{\partial n_g^2}$$

$$\chi_p = g^2 \sum_{j \neq 0} \frac{2\omega_{0j,p} |\langle j, p|\hat{n}|0, p\rangle|^2}{\omega_{0j,p}^2 - \omega_r^2}$$

$$\omega_r = 1/\sqrt{LC_{tot}}$$

$$2\chi_p = \Delta\omega_{resonance}$$

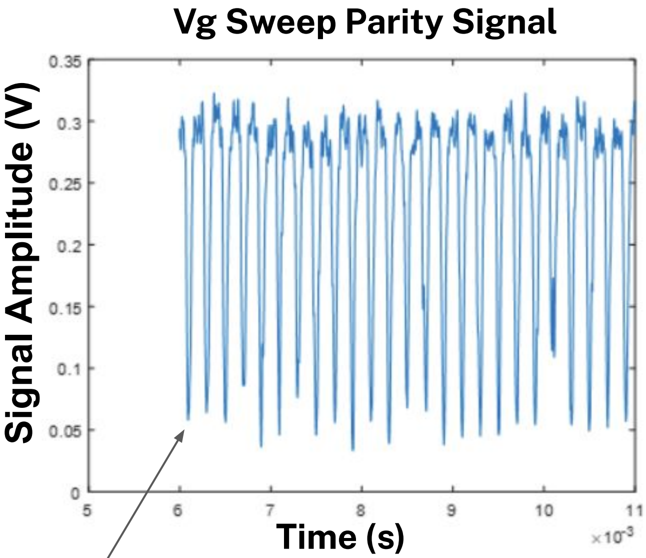
TES based phonon sensors

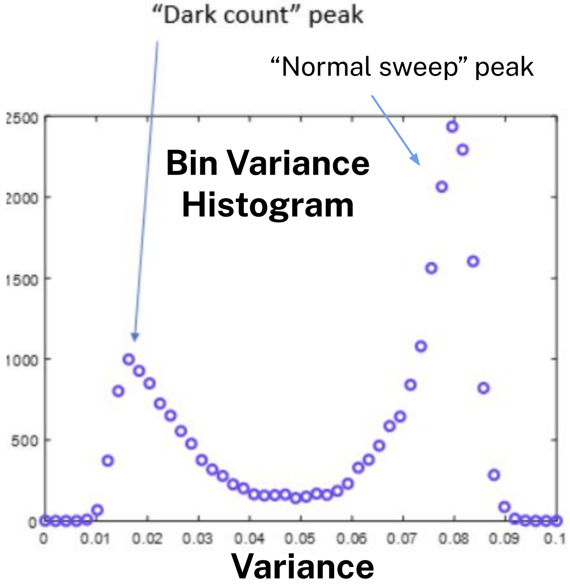


QP-trapping-assisted, electrothermal-feedback, transition-edge sensors ***(QET)***

- Current leading technology for phonon mediated detection
- Have achieved energy resolution of **375 meV** for energy deposited into the substrate
  - R. Anthony-Petersen et al., 2024
- TES devices are inherently thermal devices, and energy resolution scales as T^3
  - Worth considering non-dissipative devices

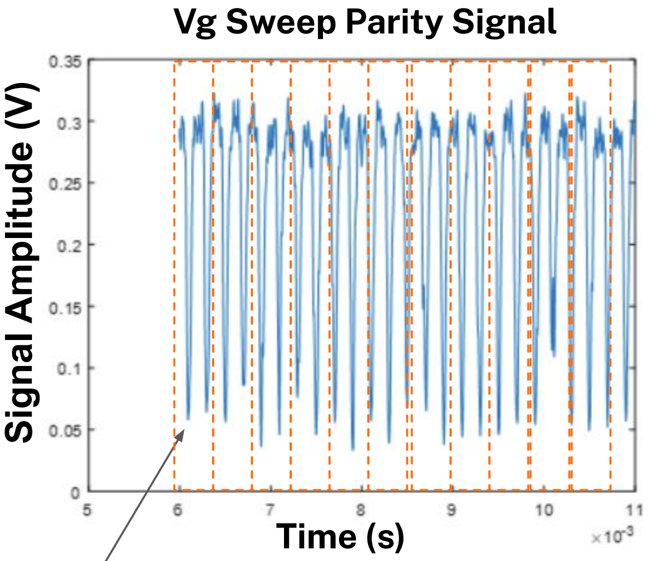
QCD Vg Sweep Test

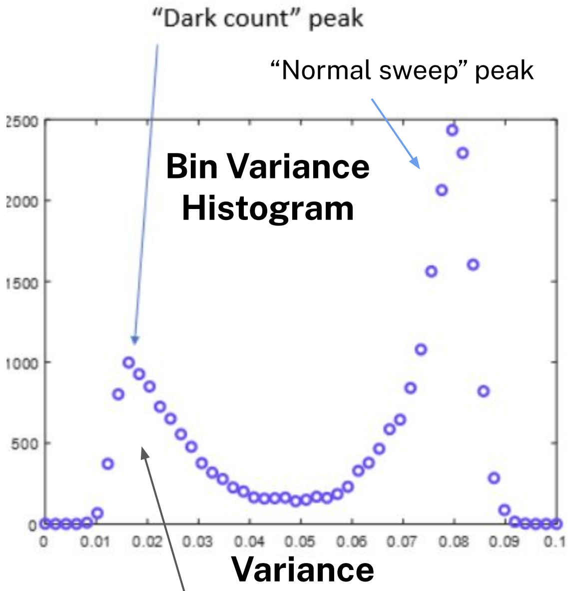




Sweep Vg quicker than the background tunneling rate, then look for gaps

QCD Vg Sweep Test



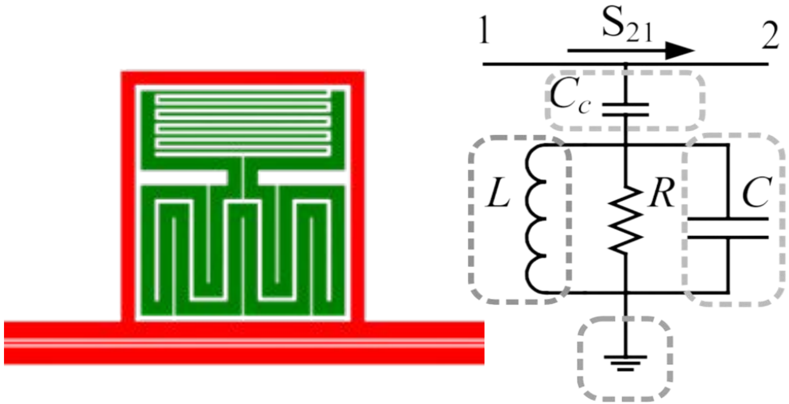


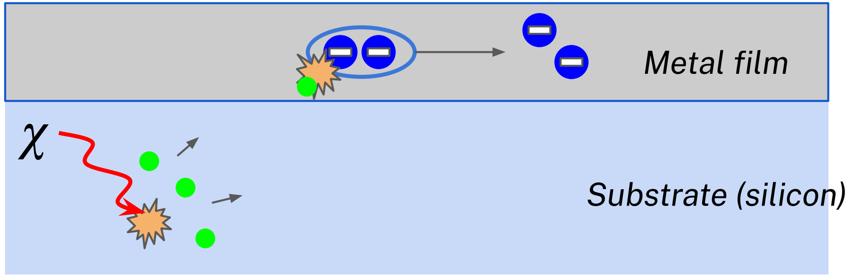
Sweep Vg quicker than the background tunneling rate, then look for gaps

Bins with low variance indicate gaps, where a high-tunneling-rate event likely occurs

KID based phonon sensors

- Cooper pairs in superconducting film “lag” behind the field due to their inertia: kinetic inductance
- Energy deposition in substrate generates phonons, which travel to break cooper pairs, which increases the kinetic inductance
- By measuring the ratio of power sent into the LC resonator to the power on the output (S21), we can calculate the change in inductance, and hence the change in quasiparticle density and resulting energy deposited.





$$L_k \sim \frac{m_e}{2e^2 n_{cp}}$$