

CPAD 2026 - October 21, 2026

Progress on the Calibration of Quantum Parity Detectors for meV Energy Depositions

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Caltech: S. Golwala, J. Xiong, B. Sandoval, S. Ray

JPL: P. Echternach, A. Beyer

WashU: K. Ramanathan, L. Yuan, W. Ho

Caltech

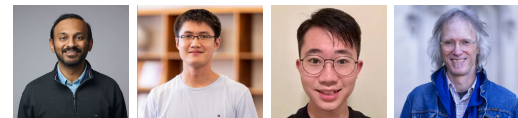
JPL



Sensing Of Neutrinos In Qubits (SONIQ)

Caltech

JPL

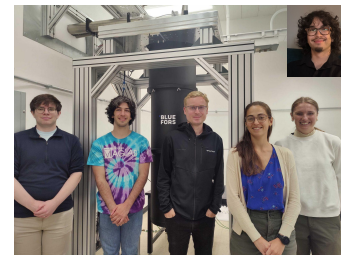


SONIQ
SENSING OF NEUTRINOS
IN QUBITS

SLAC

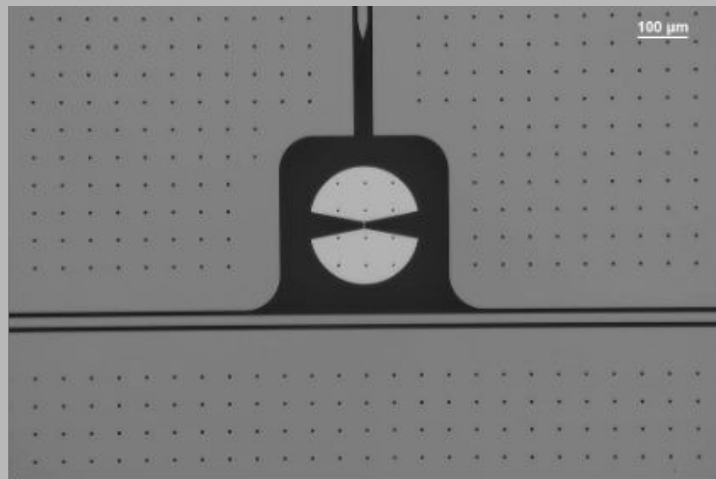


WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON



>25 members spanning 6 institutions/laboratories

Superconducting Quasiparticle Amplifying Transmons (SQUATs)



Investigating phonon response in qubit-based SQUAT sensors



Oct 21, 2026, 4:30 PM

15m

Auditorium (Alder Hall)

Presentation

RDC 8 Quantum & S...

RDC 8 Quantum & Sup...

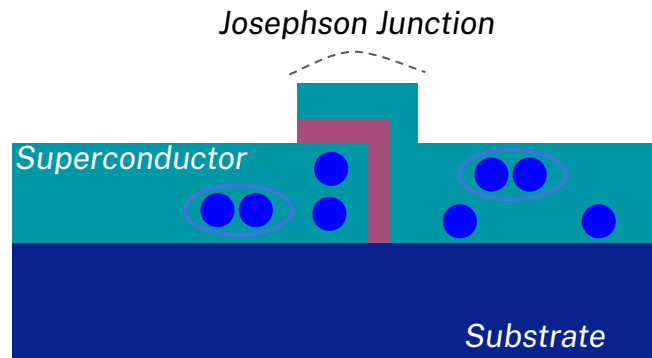
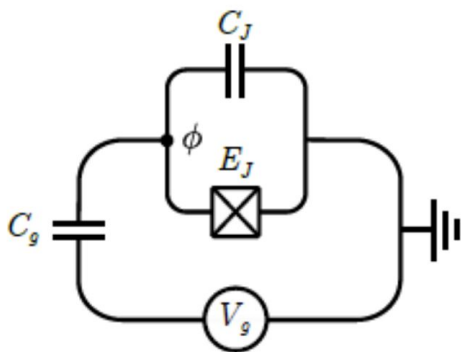
A First Demonstration of the SQUAT Detector Architecture: Direct Measurement of Resonator-Free Charge-Sensitive Transmons

H. Magoon,^{1,2,3,*} T. Aralis,^{1,2,†} T. Dyson,^{1,2,3} J. Anczarski,^{1,2,3} D. Baxter,^{4,5} G. Bratrud,^{5,4} R. Carpenter,^{1,2,6} S. Condon,^{1,2,3} A. Droster,^{1,2} E. Figueroa-Feliciano,^{5,4} C.W. Fink,^{7,8} S. Harvey,¹ A. Simchony,^{1,2,3} Z.J. Smith,^{1,2,6} S. Stevens,^{1,2} N. Tabassum,^{1,2} B.A. Young,⁹ C.P. Salemi,^{1,2,10,11} K. Stifter,^{1,2} D.I. Schuster,⁶ and N.A. Kurinsky^{1,2}

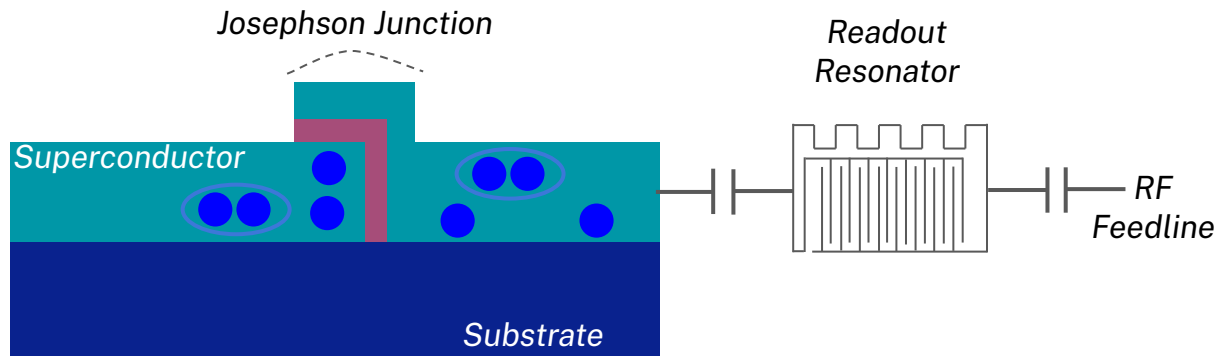
Quantum Parity Detector: Device Architecture



Charge-sensitive qubits

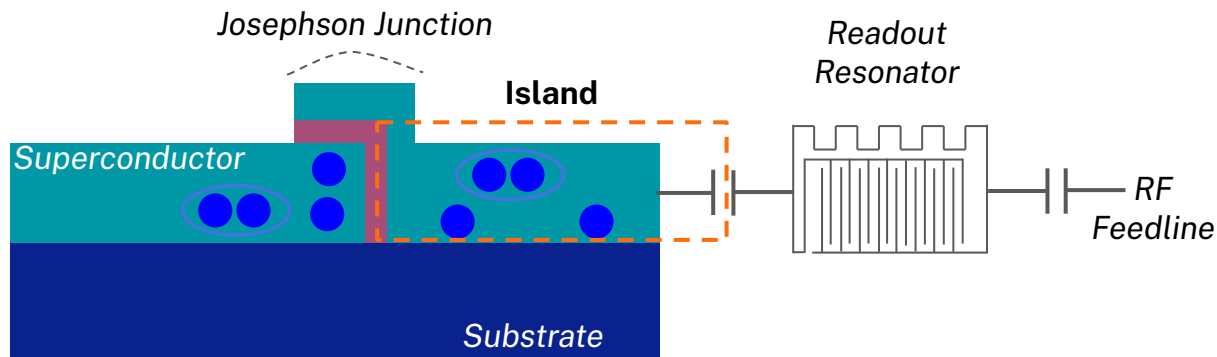
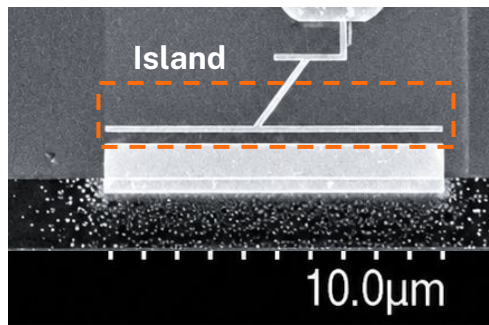


Charge-sensitive qubits



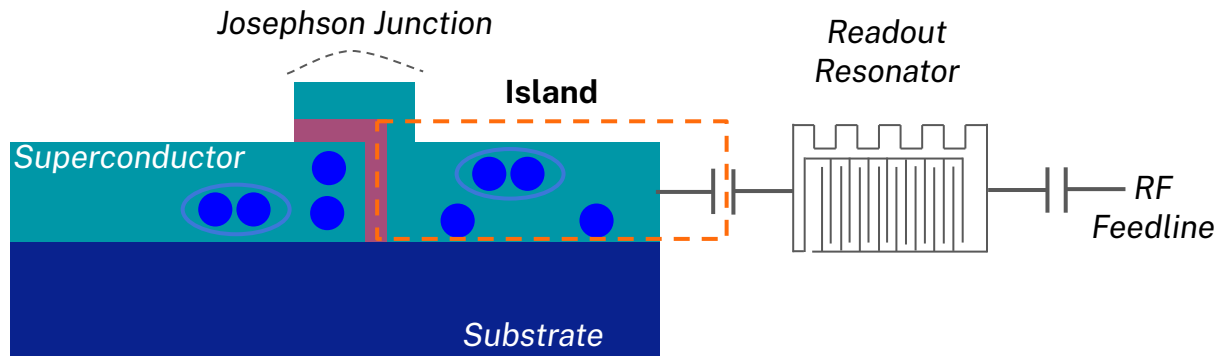
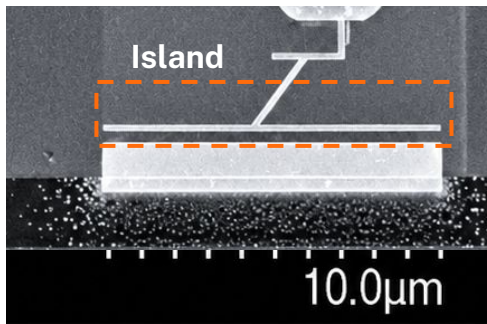
Charge-sensitive qubits

Island Volume $\sim 0.05 \mu\text{m}^3$



Charge-sensitive qubits

Island Volume $\sim 0.05 \text{ um}^3$

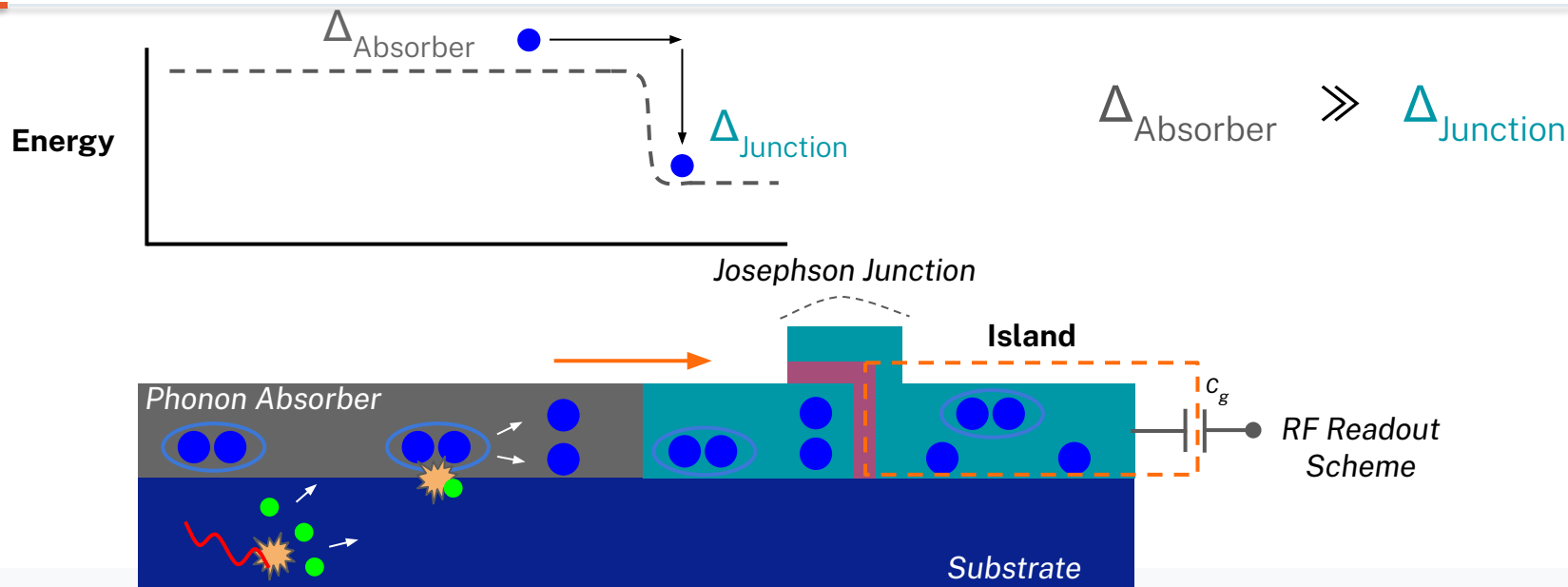


$$\hat{H} = 4E_C \left(\hat{n} - n_g + \frac{P-1}{4} \right)^2 - E_J \cos \hat{\phi}$$

Capacitance energy $\rightarrow 4E_C$
 Cooper pairs on island $\rightarrow \hat{n}$
 Gate charge $\rightarrow n_g$
 Parity of qp's on island (± 1) $\rightarrow P$
 Josephson energy $\rightarrow E_J$

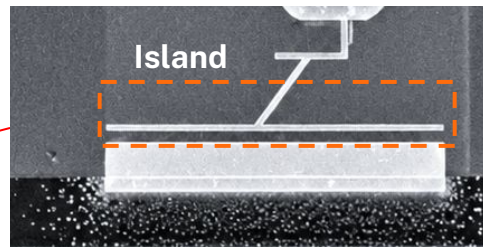
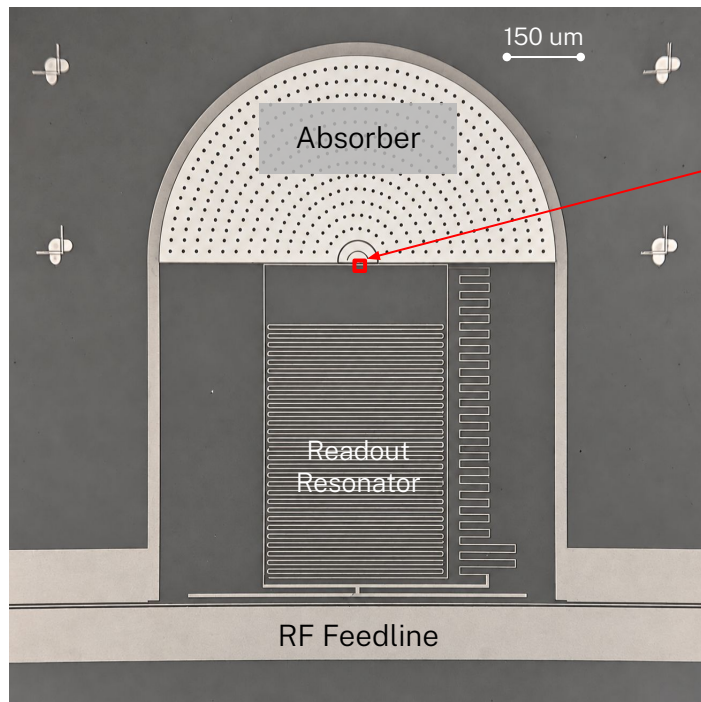
- The energy spectrum of the qubit is sensitive to whether there is an even or odd number of quasiparticles on the island (**i.e. the parity of the quasiparticle number**).

Qubit-based phonon sensor



- 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.

Physical realization: Quantum Parity Detector (QPD)



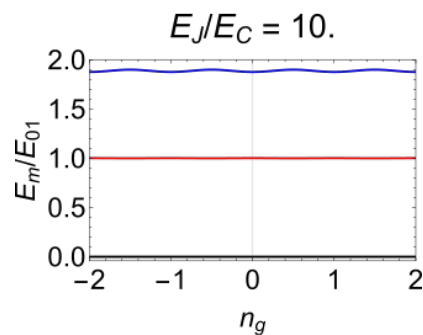
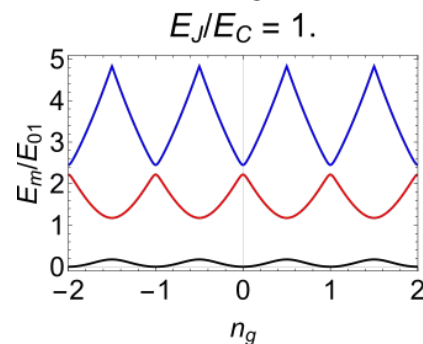
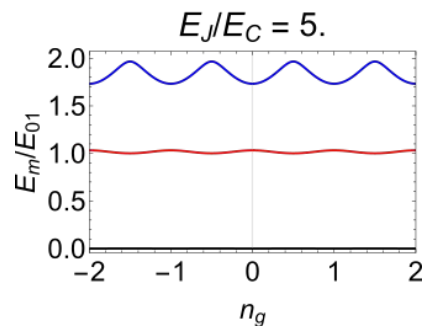
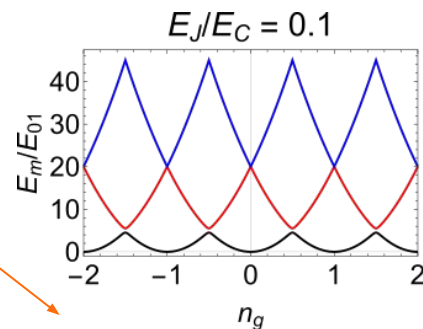
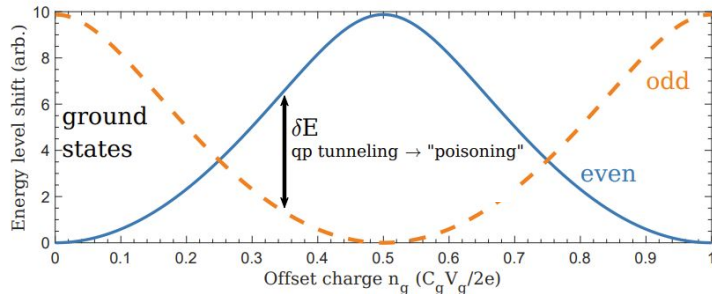
Island Volume $\sim 0.05 \text{ um}^3$

- The small island keeps the qubit capacitance low, which increases the charging energy, and keeps our qubit in the **Cooper-pair box** regime

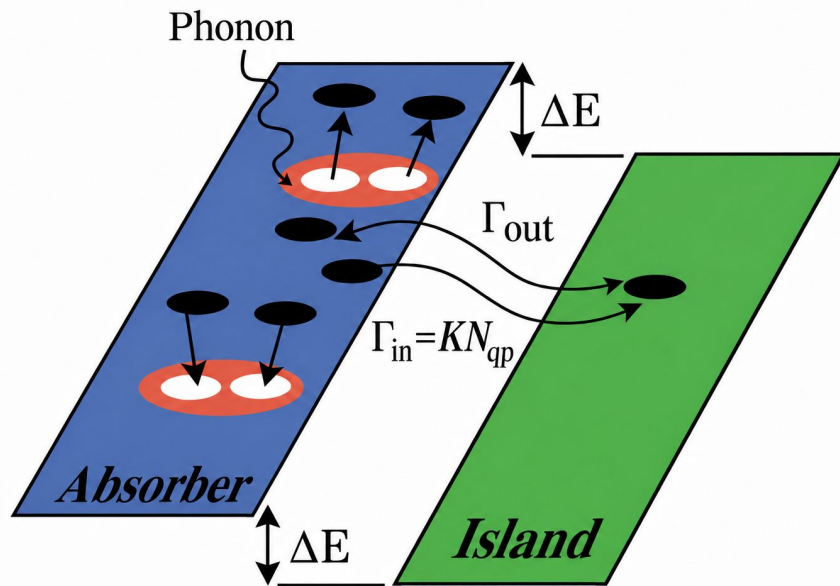
Cooper-pair box (CPB) qubits

- The CPB QPD operates in the E_J/E_C between $O(0.1)$ to $O(1)$ regime

In this regime, δE between the even and odd states can be quite large, $O(10s)$ μeV

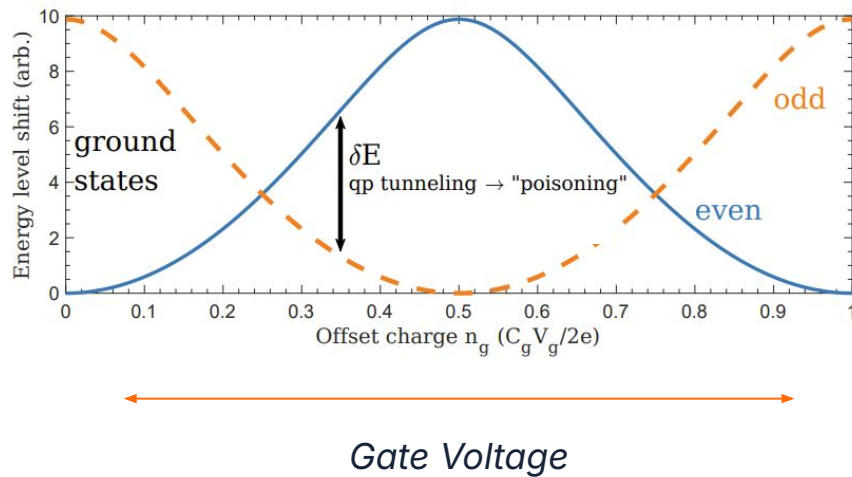


Why we use Cooper-pair box qubits

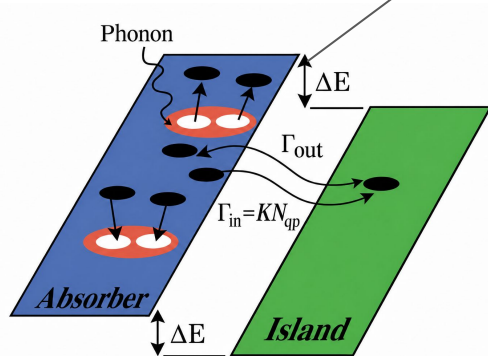
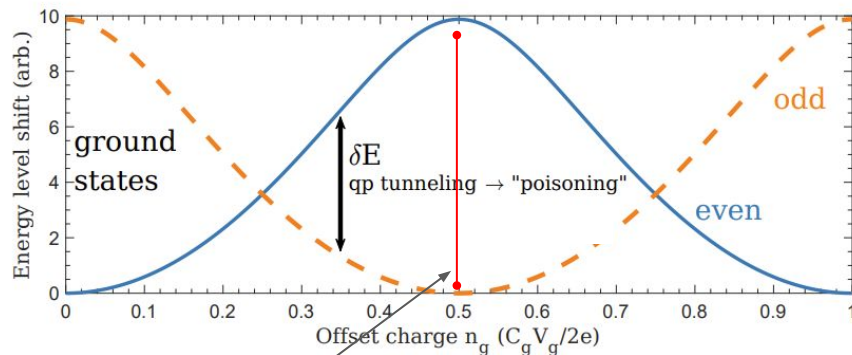


Large dE “well” enhances quasiparticle tunneling into the island, **increasing sensitivity**

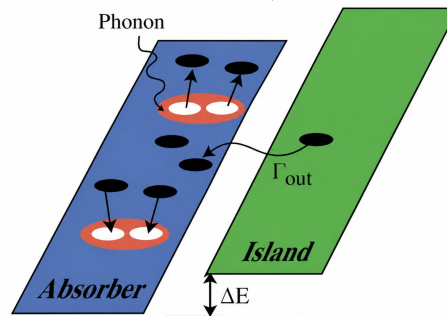
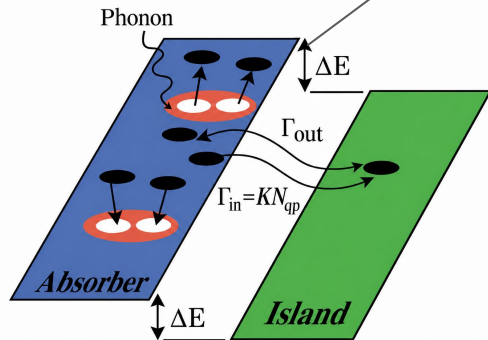
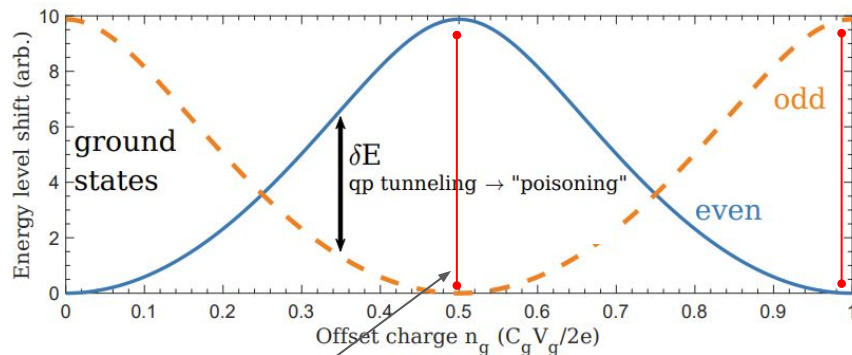
Why we use Cooper-pair box qubits



Why we use Cooper-pair box qubits

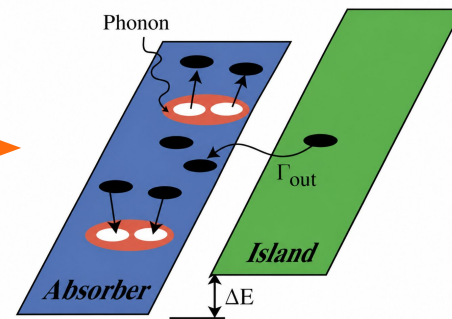
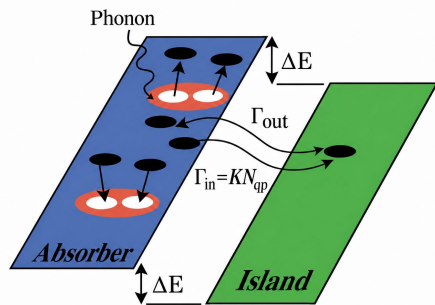
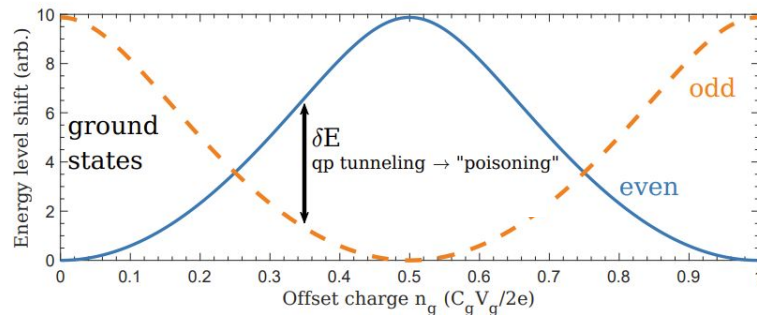


Why we use Cooper-pair box qubits



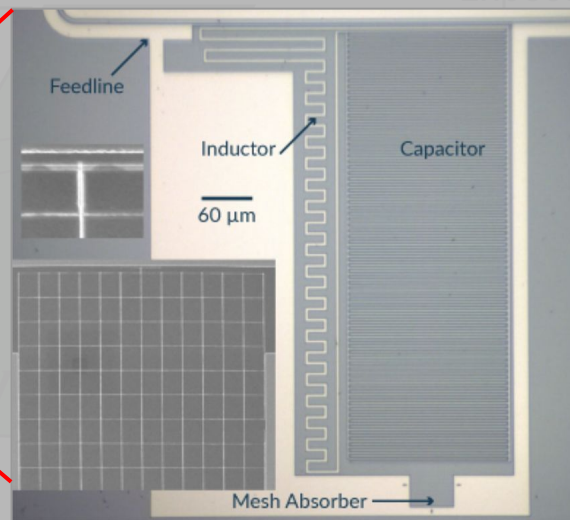
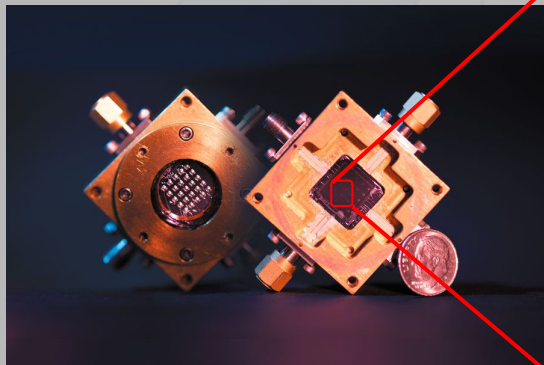
Why we use Cooper-pair box qubits

By controlling the gate charge, we can enhance or suppress tunneling onto the island



Single photon detection of 1.5 THz radiation with the quantum capacitance detector

P. M. Echternach *, B. J. Pepper, T. Reck and C. M. Bradford

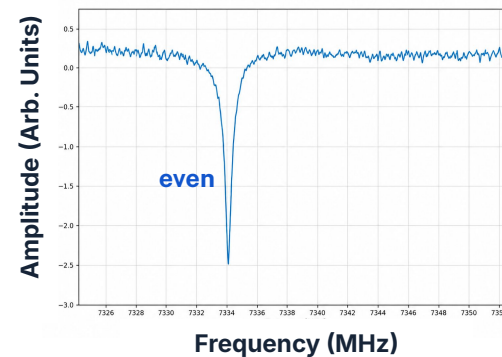
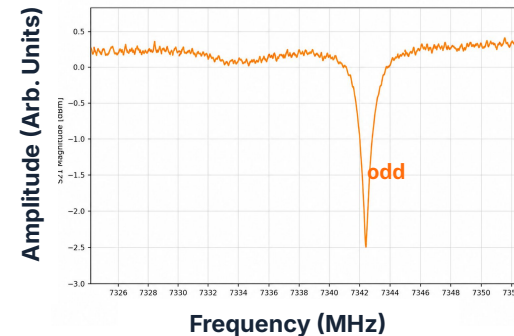
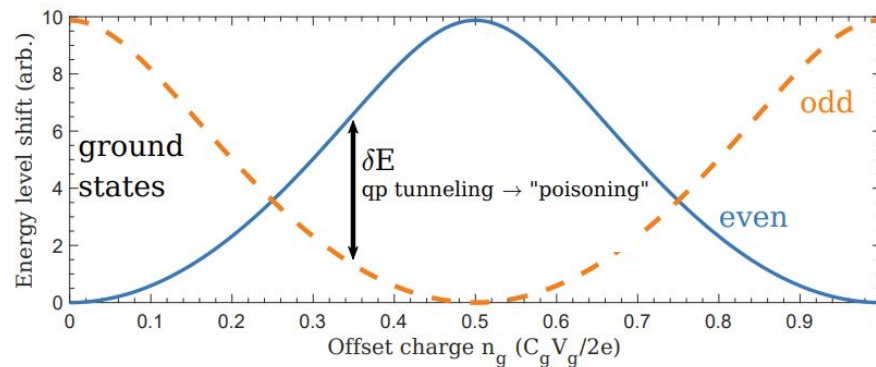


Base architecture
has been used to
detect meV photons
in the past

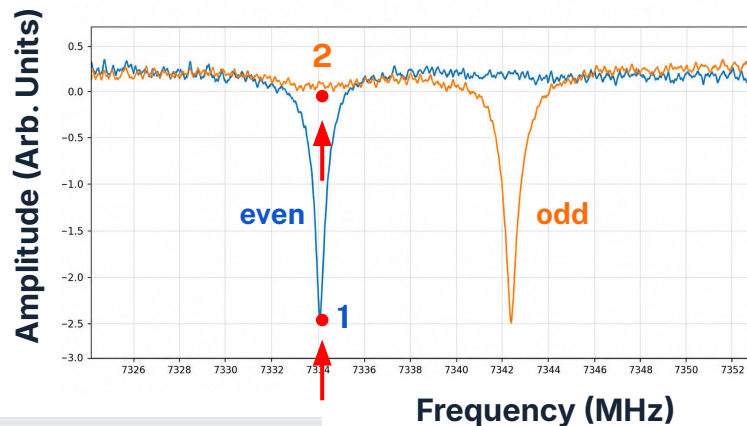
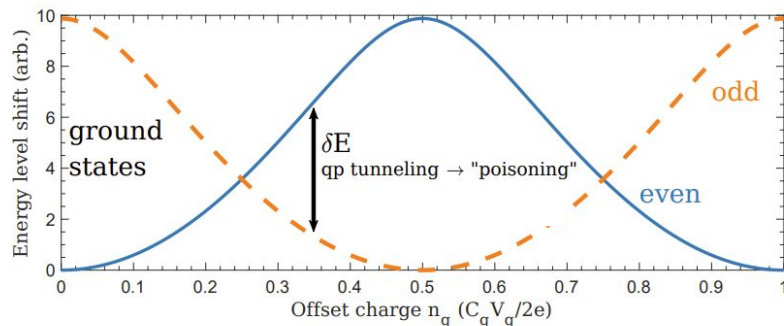
Readout Scheme



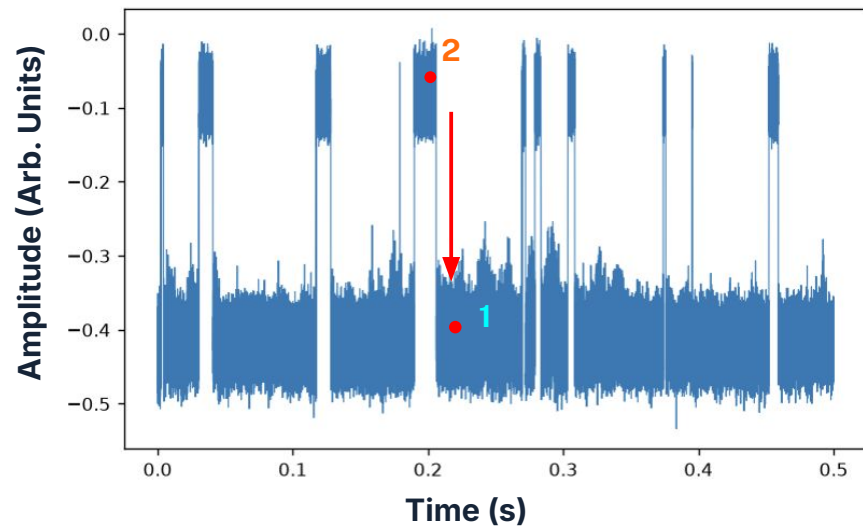
Signal response



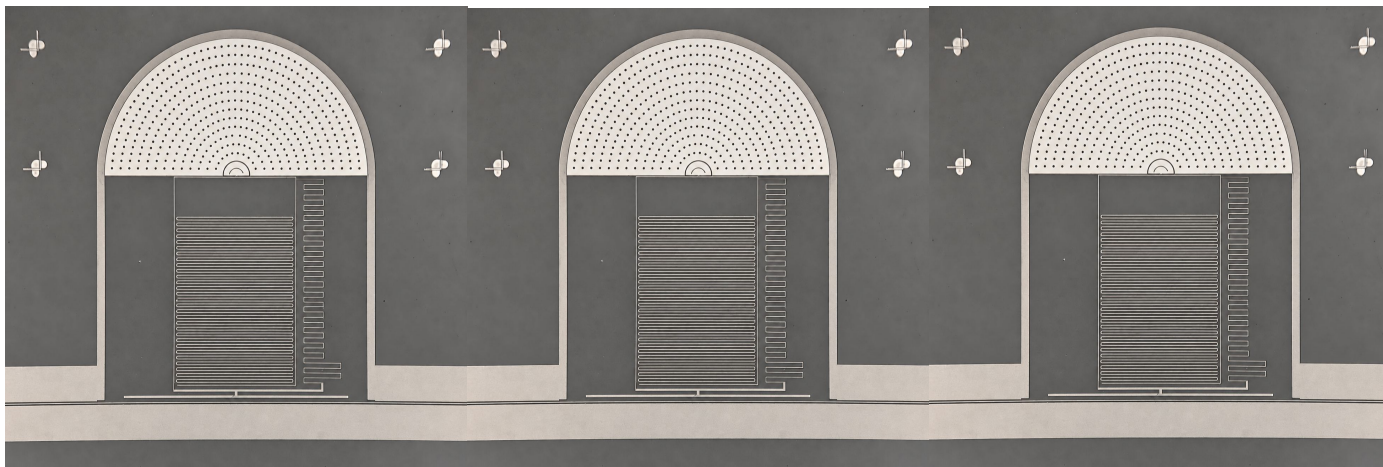
Signal response



On-Resonance Timestream

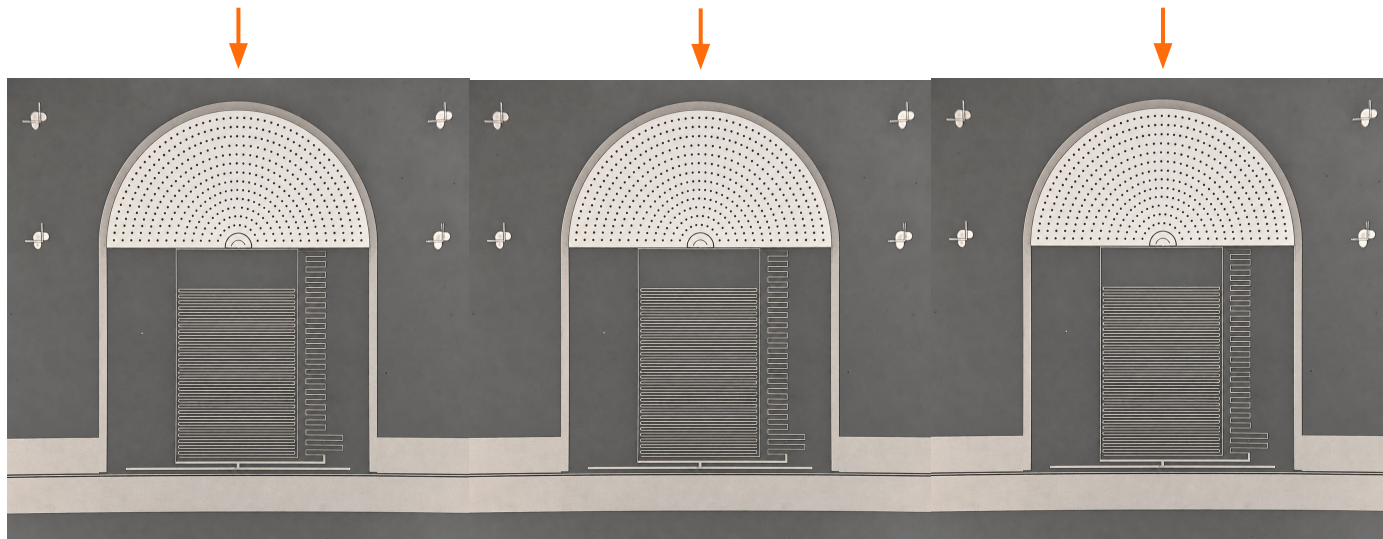


Multiplexed Readout Scheme

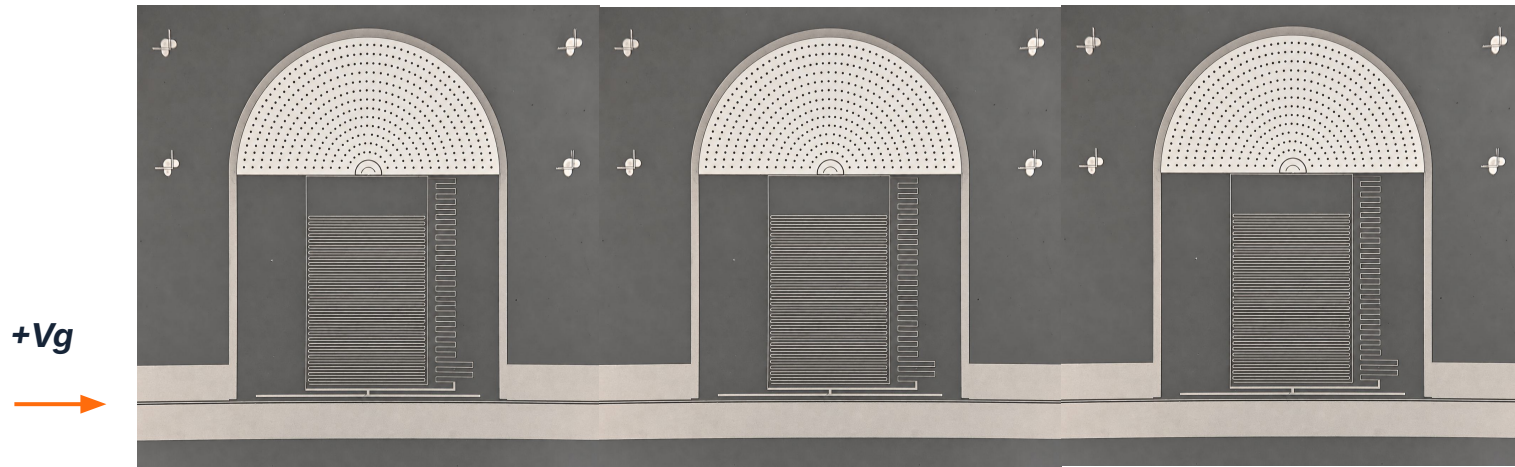


Multiplexed Readout Scheme

Gate charge can be control through individual bias lines

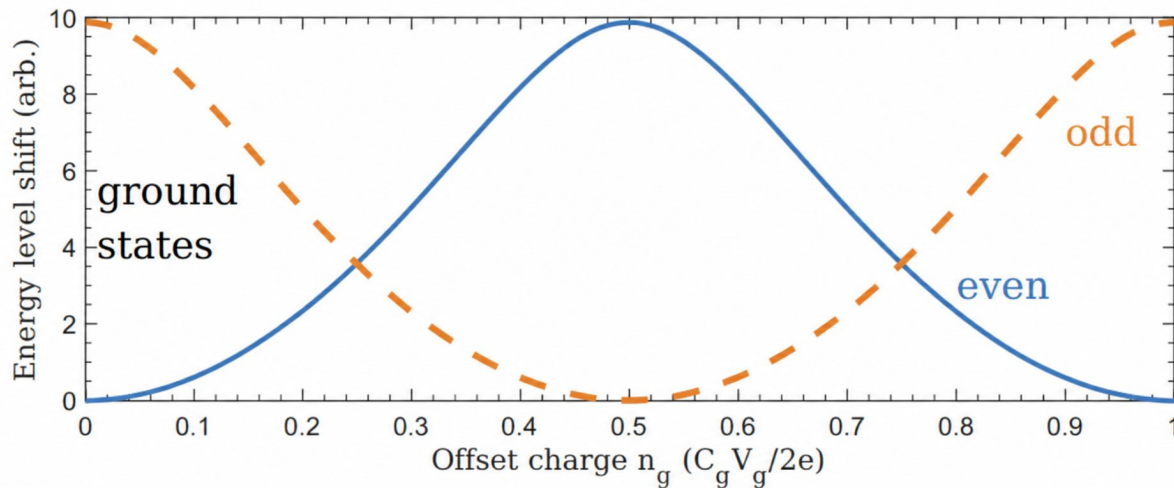


Multiplexed Readout Scheme

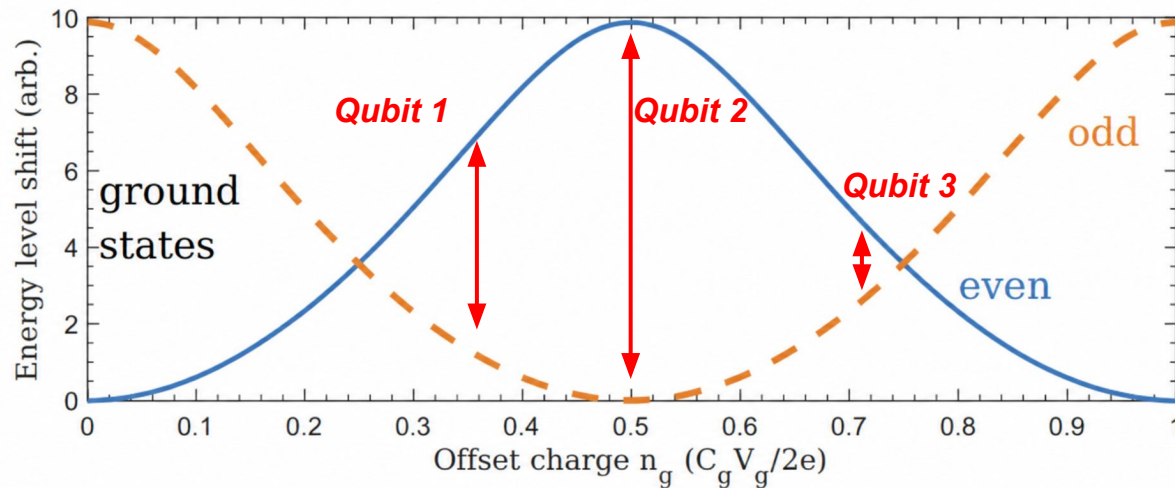


Simpler: Gate charge can be biased for all devices at once through feedline

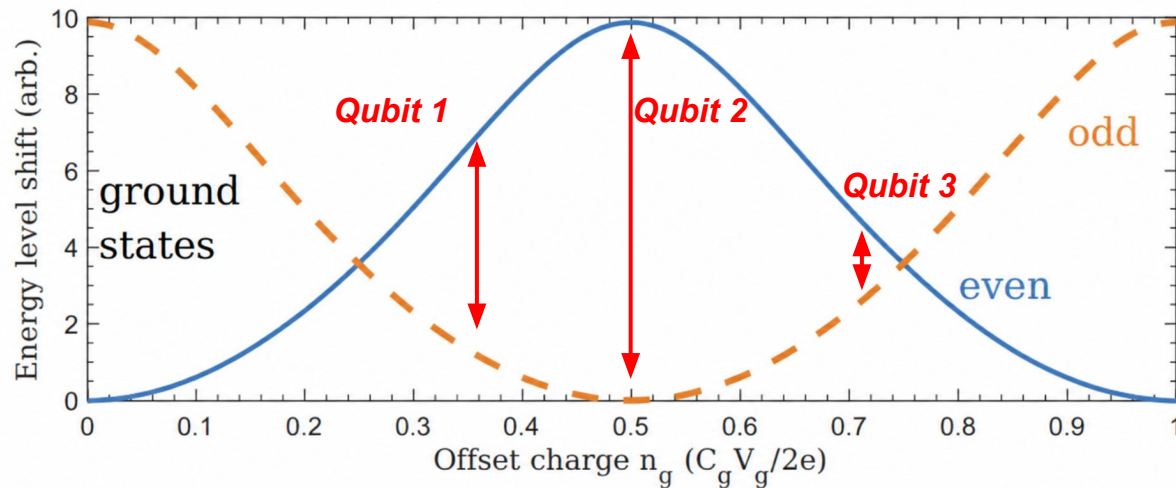
Multiplexed Readout Scheme



Multiplexed Readout Scheme

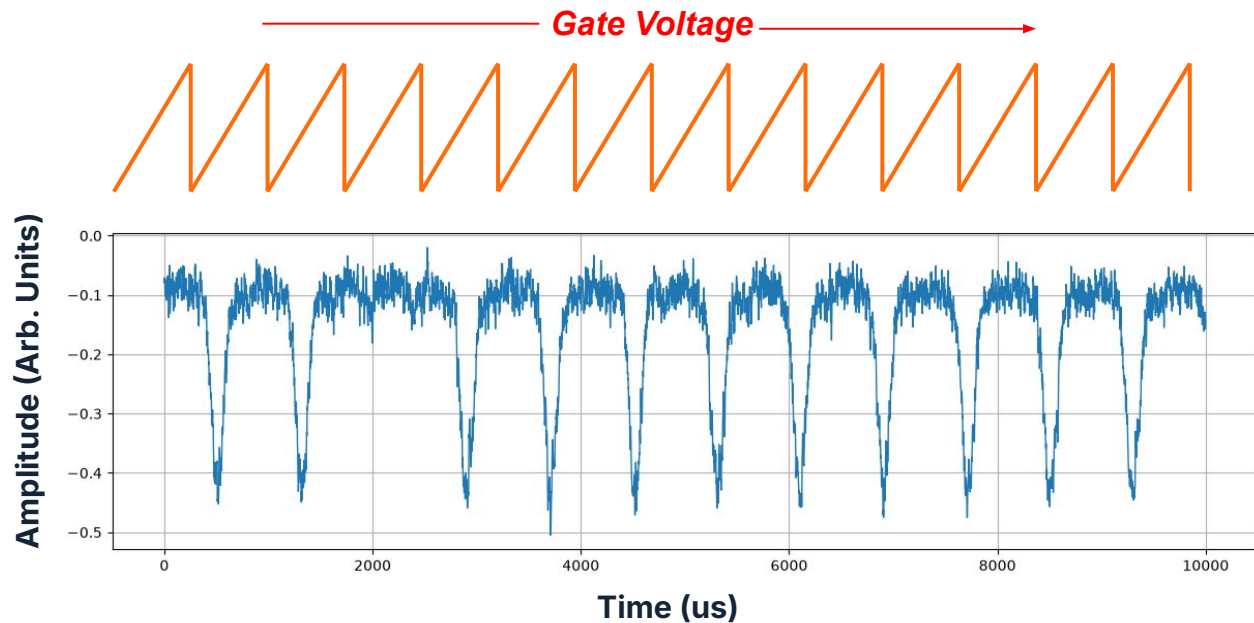


Multiplexed Readout Scheme

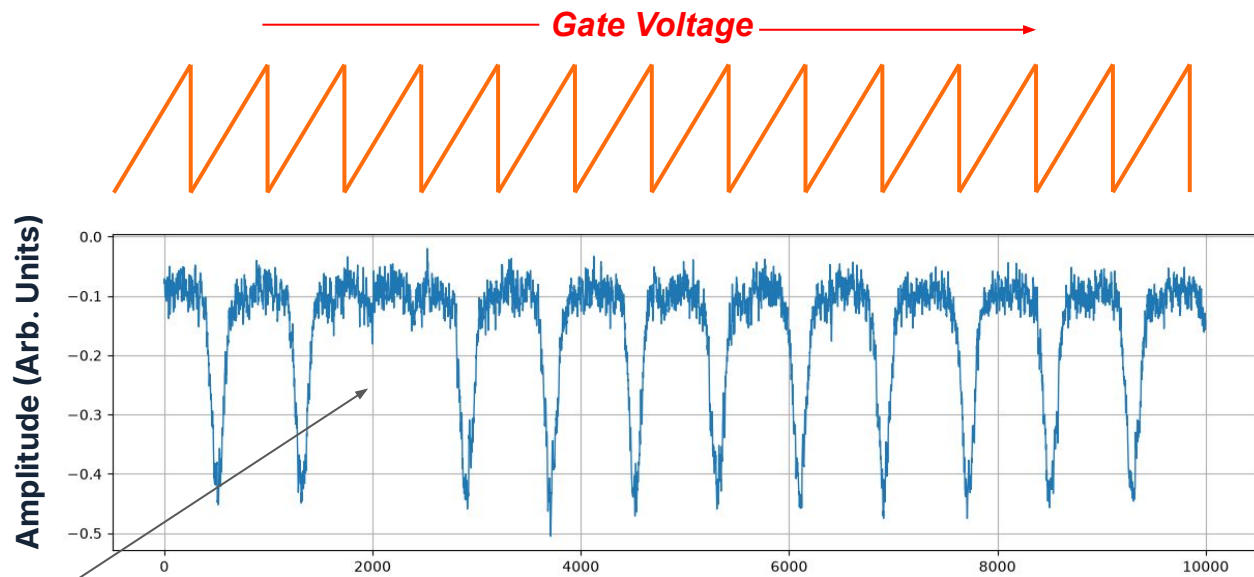


Periodically Swept Gate Voltage

Multiplexed Readout Scheme



Multiplexed Readout Scheme

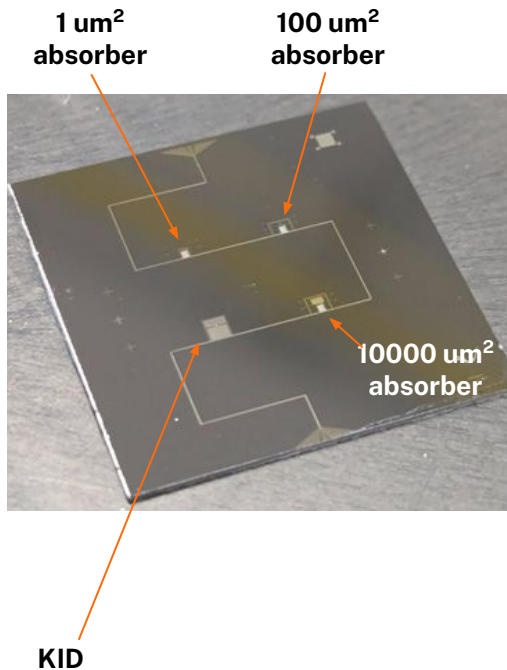


- A "detection" is now made when a transient elevated QP density causes a tunneling event, which suppresses the signal until the island is cleared by the sweep, and the QP density is reduced

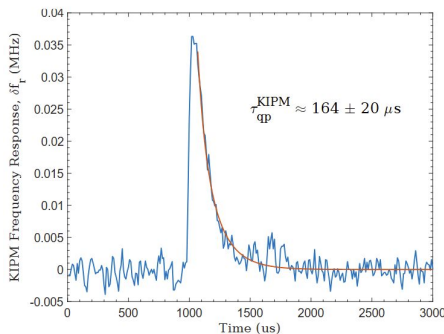
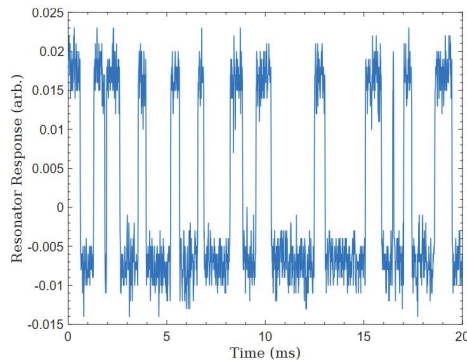
Current Testing Results



Status one year ago...

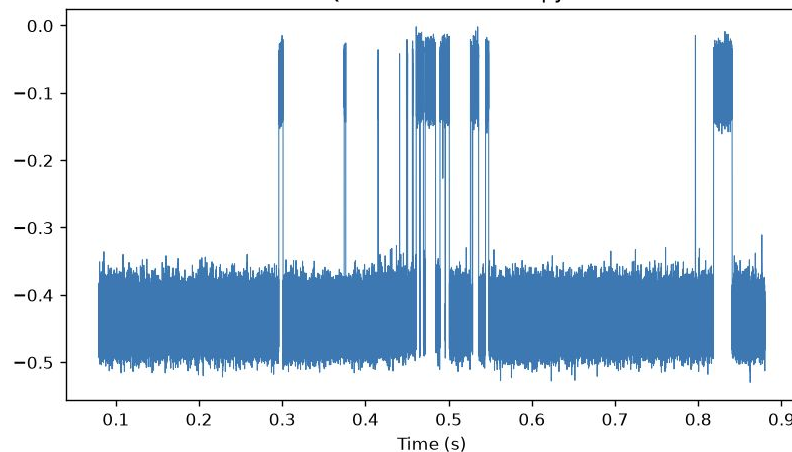
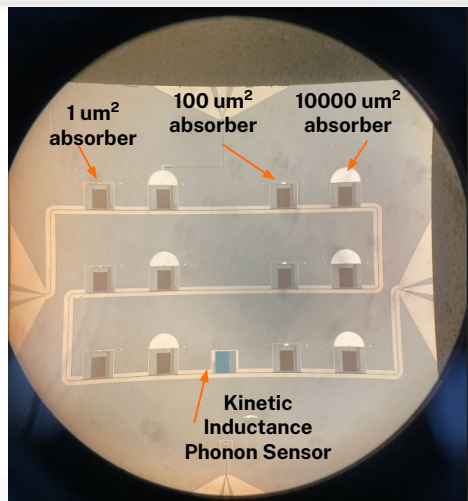


QPD Parity Signal



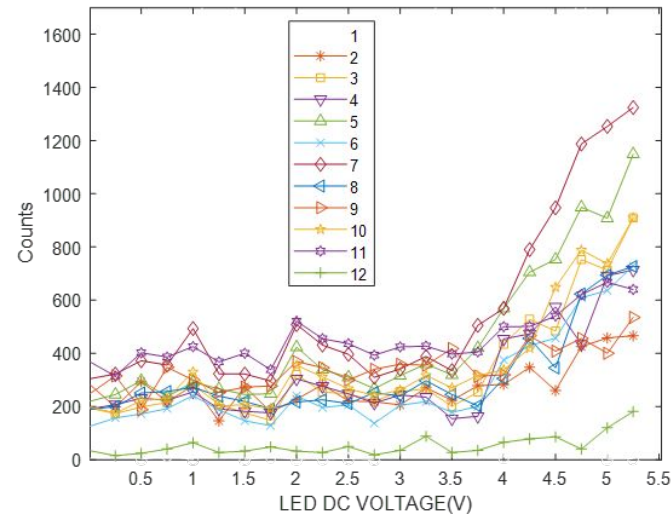
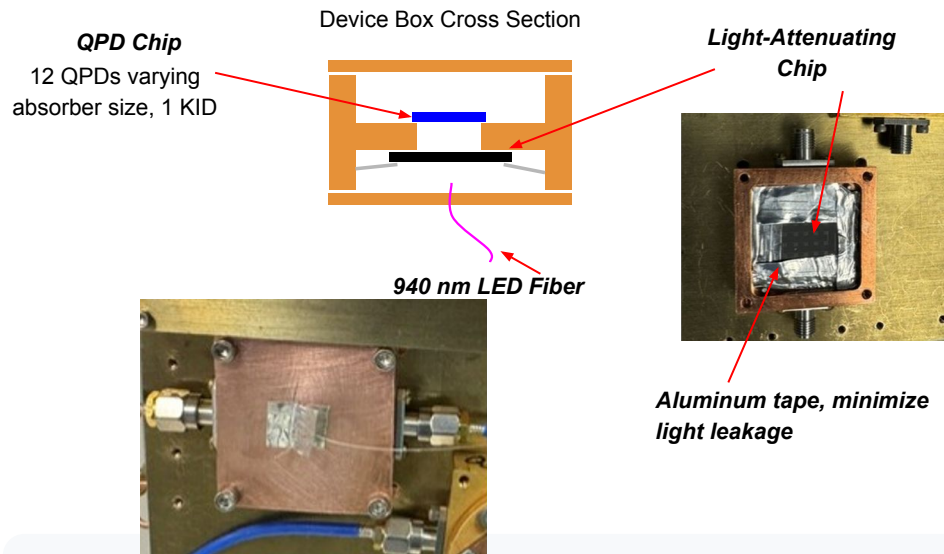
- Only 1 of 3 QPDs yielding a parity signal
- **O(1 kHz) parity switch rate** (quiescent background)
- Co-calibration KID on the chip is showing pulses in response to environmental radiation

Current Results: Backgrounds



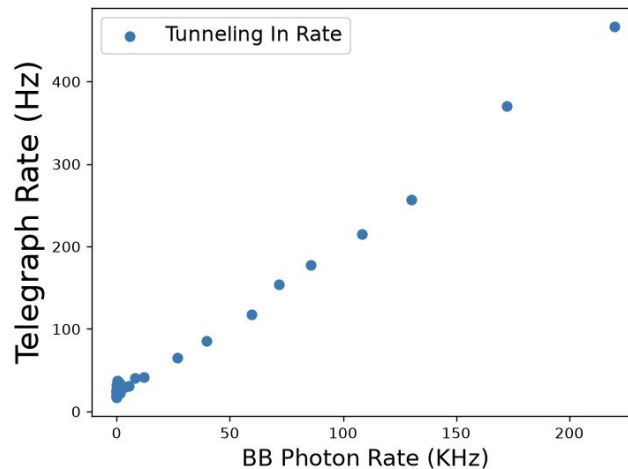
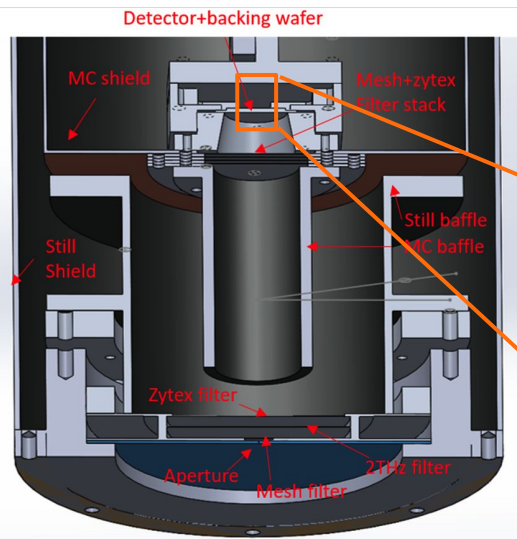
- Devices now showing **$O(10\text{Hz})$** quiescent tunneling-in rates
- Quiescent rate is dominated by non-thermal background
 - Could be cosmogenics, environmental radiation, or substrate events

Current Results: LED generated phonons



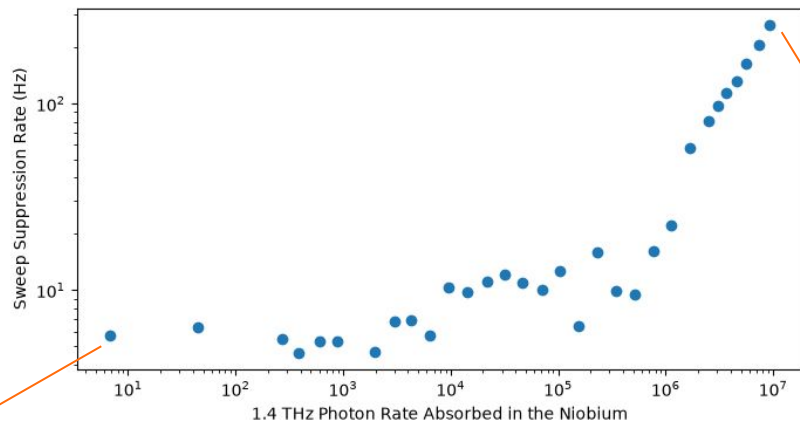
- By flashing the back of the device with a **940 nm LED**, we now see a signal response from **all 12 QPD devices** on the chip, using swept gate charge multiplexed readout

Current Results: 1.4 THz blackbody source

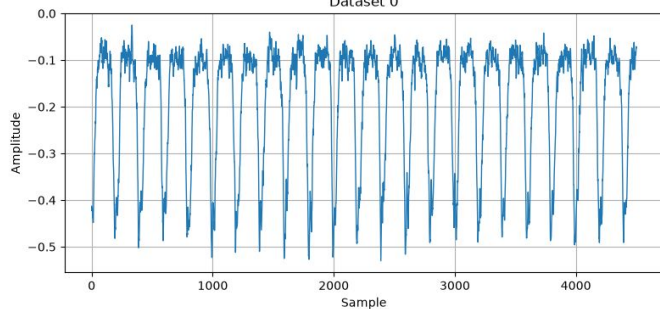


- We see a response to DC application of 1.4Thz photons, with a linear rise in tunneling rate as we increase the power incident on the back of the chip

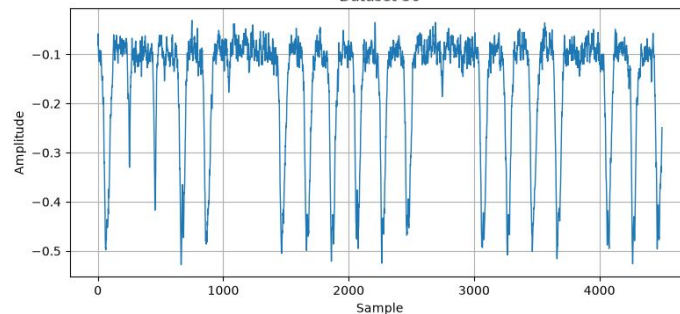
Multiplexing Scheme Results: 1.4 THz photon source



Dataset 0



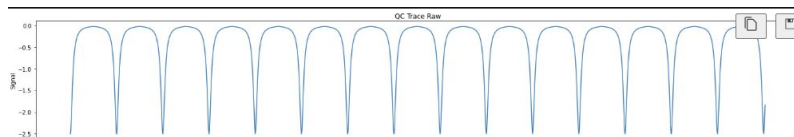
Dataset 30



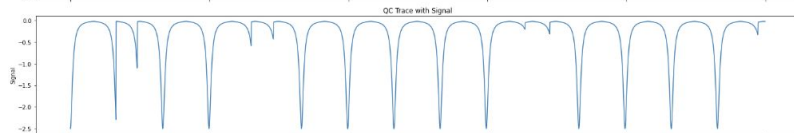
Other Avenues: Device and Response Simulations

Device Response Simulations

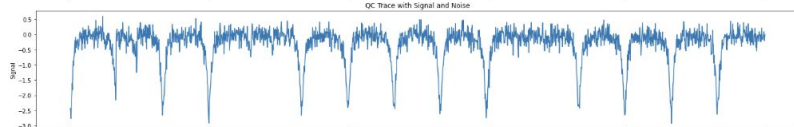
Raw sweep



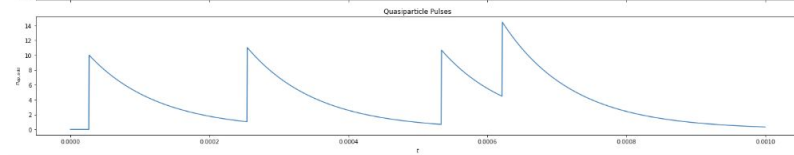
+ Tunneling



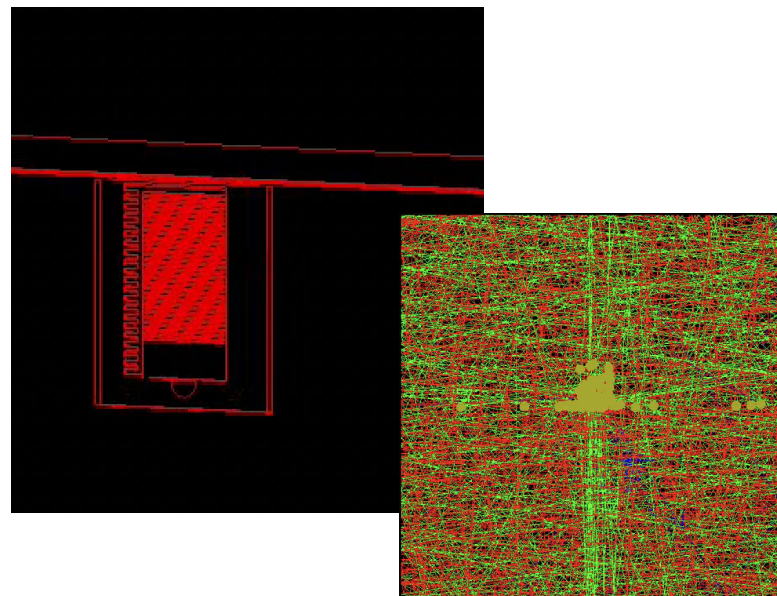
+ Noise



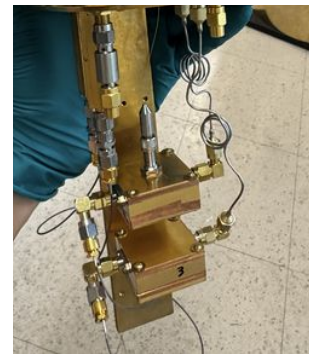
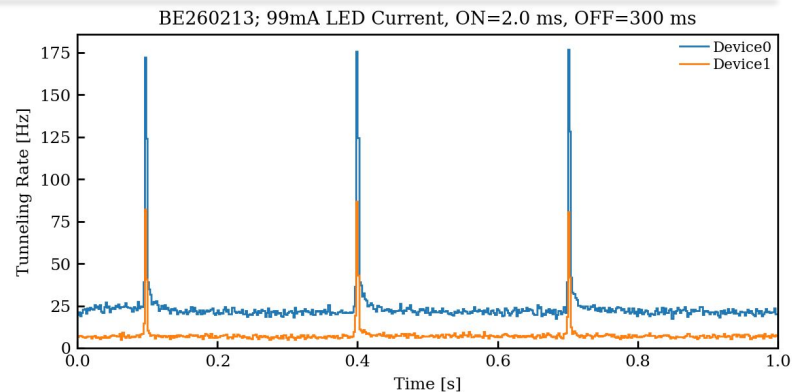
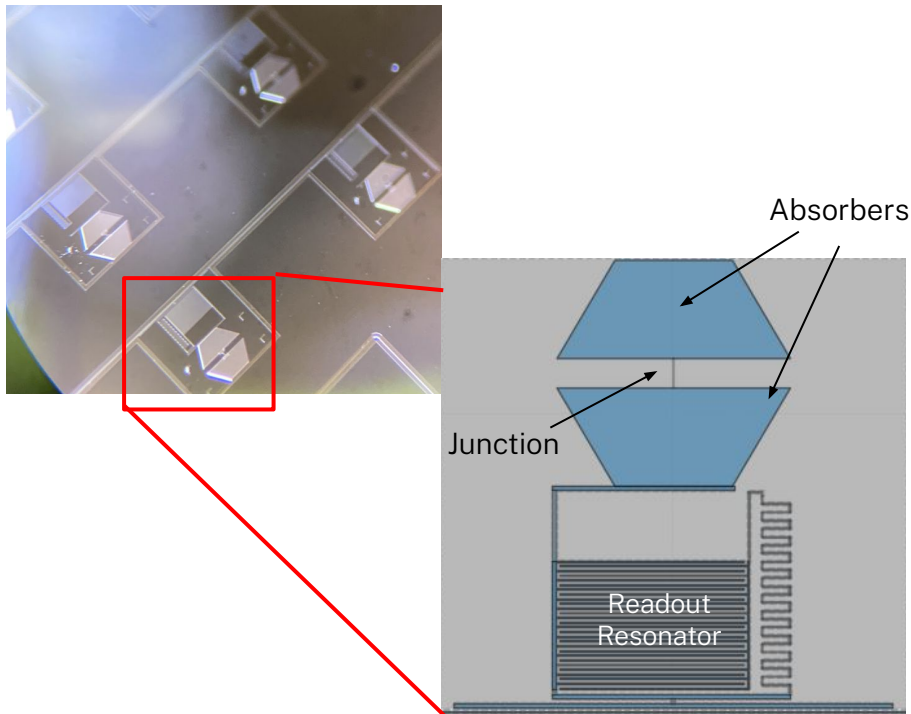
QP Pulses



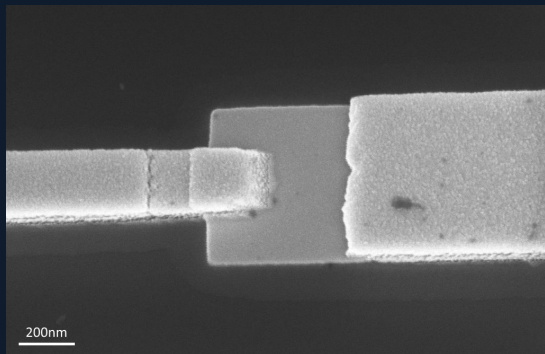
G4CMP Phonon Simulations



Other Avenues: Hybrid Transmon QPDs

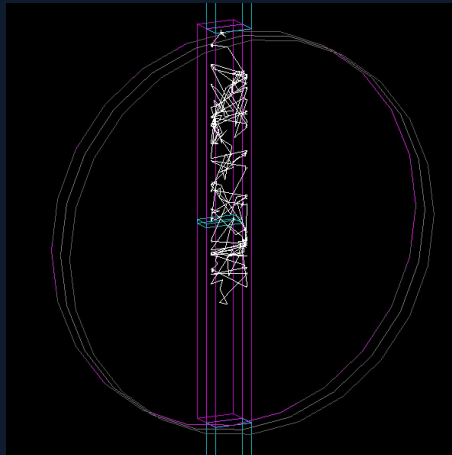


Conclusion: Sights set on meV resolution, lots of upcoming work

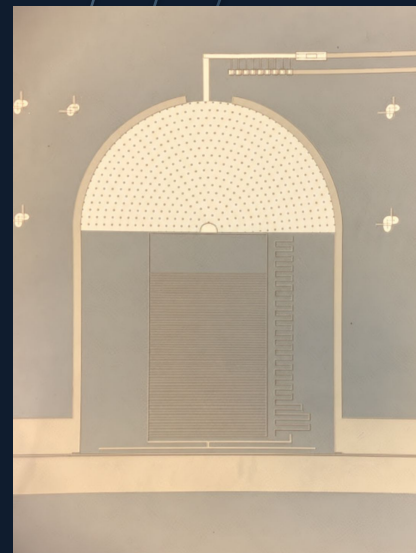


Hf-HfOx-Hf Dolan junction fabricated at the Molecular Foundry

Low-Tc junctions and trapping geometries



Improved G4CMP simulations for QP physics in the device
(*Tracked Film Response*)



QP diffusion studies using QP injector junctions

Questions?



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)
 Sensor Volume
 Fano Factor $\sim O(0.1)$
 Max no. of qp's generated from energy deposition

Tunneling Shot Noise
 Fano Noise

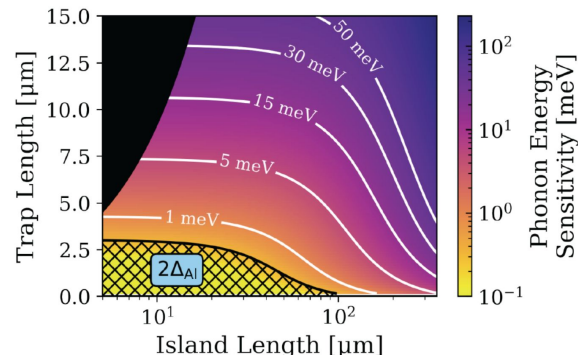
Resolution on number of background transitions → $\sigma_B^2 = \left(K t_w + 16 \frac{K^2 t_w^2}{V} \right) n_0$

Time window
 Tunneling Shot Noise
 Quiescent Quasiparticle Noise
 Quiescent Quasiparticle Density

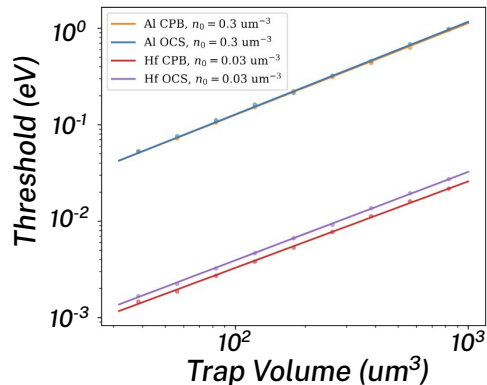
Expected number of switches → $S = K \frac{N_{qp} \tau_{qp}}{V}$

Conclusion: sights set on O(meV) resolution!

SQUAT Sensitivity Estimates

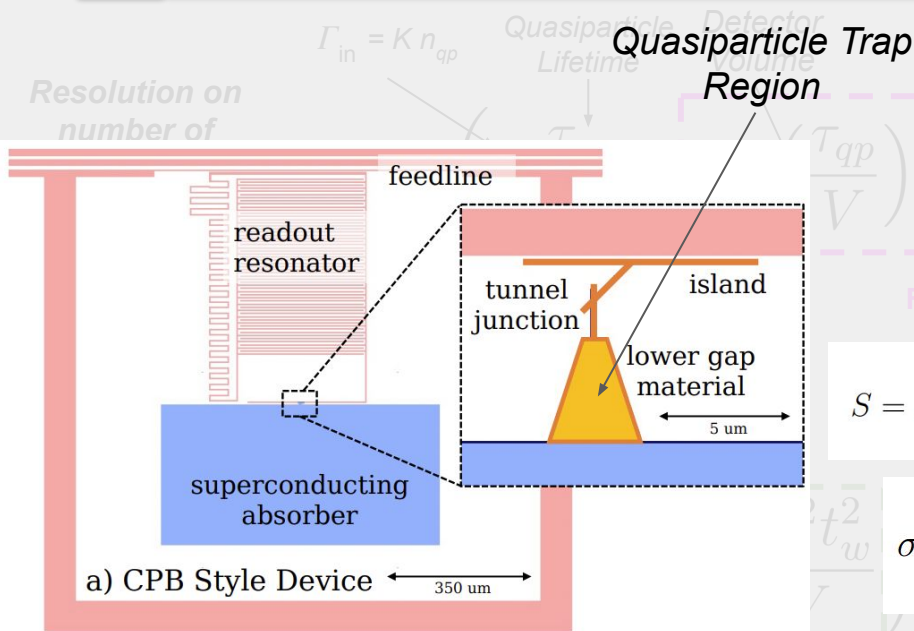


QPD Sensitivity Estimates



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

QPD Sensor Resolution and Noise



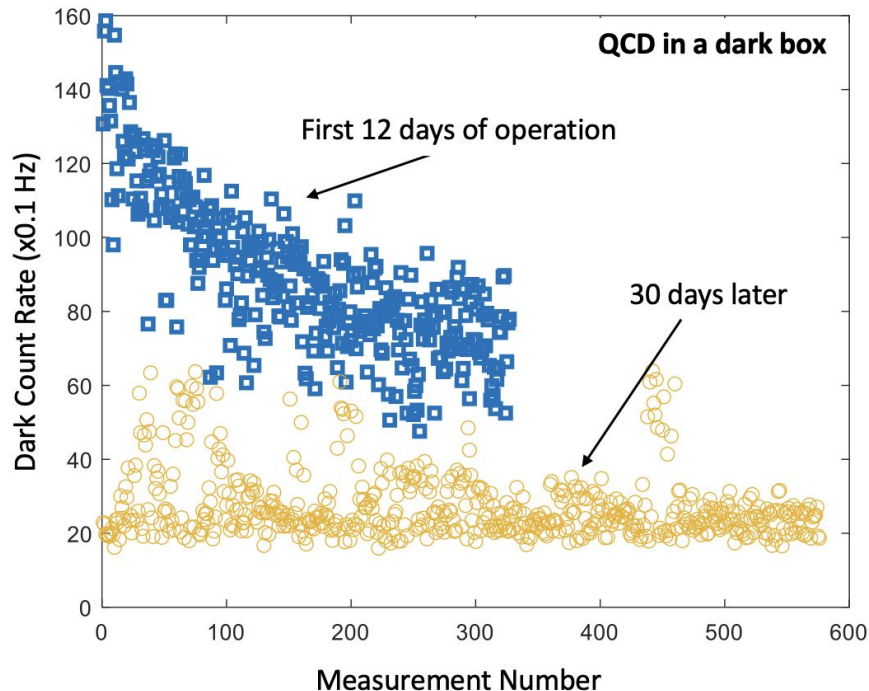
- Our signal benefits greatly from smaller QP collecting volume! **Investigating using QP trapping into small junction electrode volume** → will be needed for ultimate sub-eV substrate sensitivity

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

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

For a Hf device with $10 \mu\text{m}^3$ electrode volume, **we can estimate a 5 σ sensor energy resolution of ~25 meV**

Evidence of time-dependent DCR

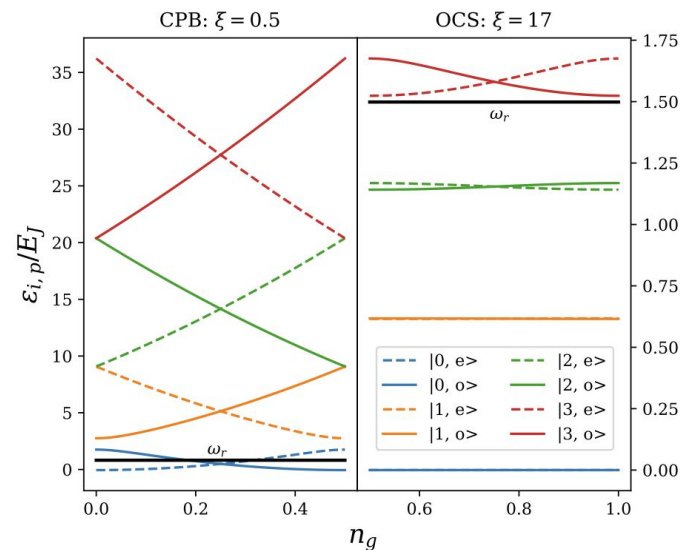


- Operation of a similar photon sensitive QCD in a dark box shows **dark count rate** reduction over O(month).
- Potentially similar source & mechanism as that contributing to Low Energy Excess identified in other cryogenic phonon sensing experiments.
- Eventual goal of measuring sub-eV energy spectrum.

CPB vs. OCS transmon

$$\xi = E_J / E_C$$

- ξ determines the sensitivity of energy levels to gate charge n_g
- For $\xi \approx 1$ (Quantum Capacitance Detector [QCD]), larger curvature of energy levels leads to large change in quantum capacitance with quasiparticle tunneling
 - O(MHz) resonance shift
- For $\xi \gg 1$ (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



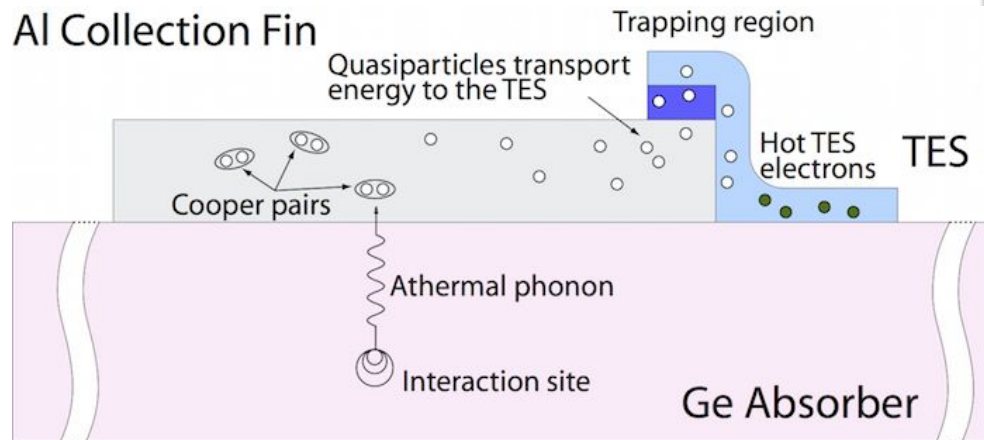
$$C_p = -\frac{C_g^2}{4e^2} \frac{\partial^2 \epsilon_p}{\partial n_g^2}$$

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

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

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

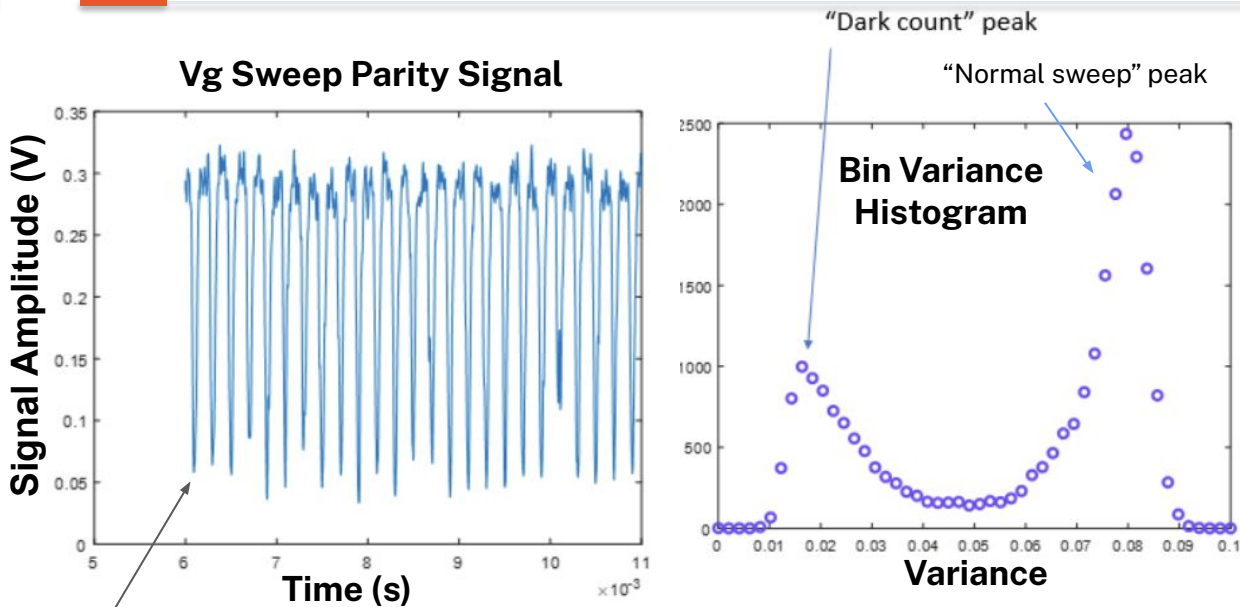
TES based phonon sensors



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

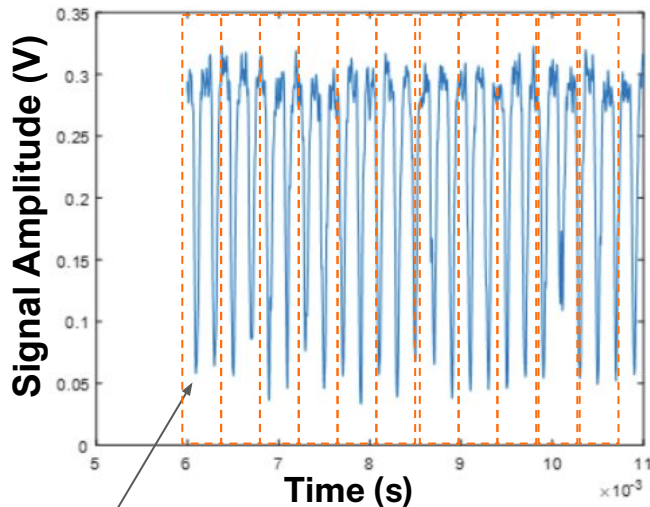
QCD Vg Sweep Test



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

QCD Vg Sweep Test

Vg Sweep Parity Signal

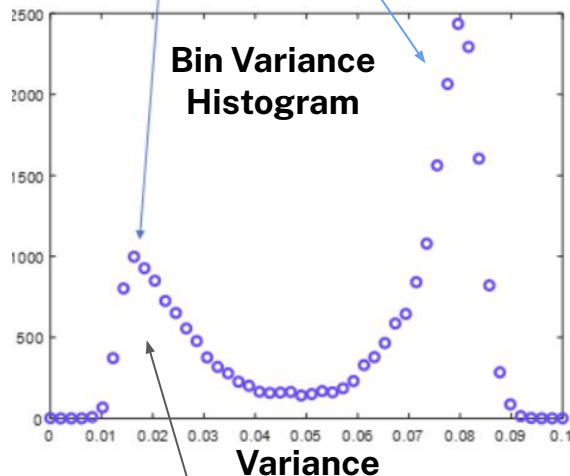


Sweep Vg quicker than the background tunneling rate, then look for gaps

"Dark count" peak

"Normal sweep" peak

Bin Variance Histogram



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 (S_{21}), we can calculate the change in inductance, and hence the change in quasiparticle density and resulting energy deposited.

