

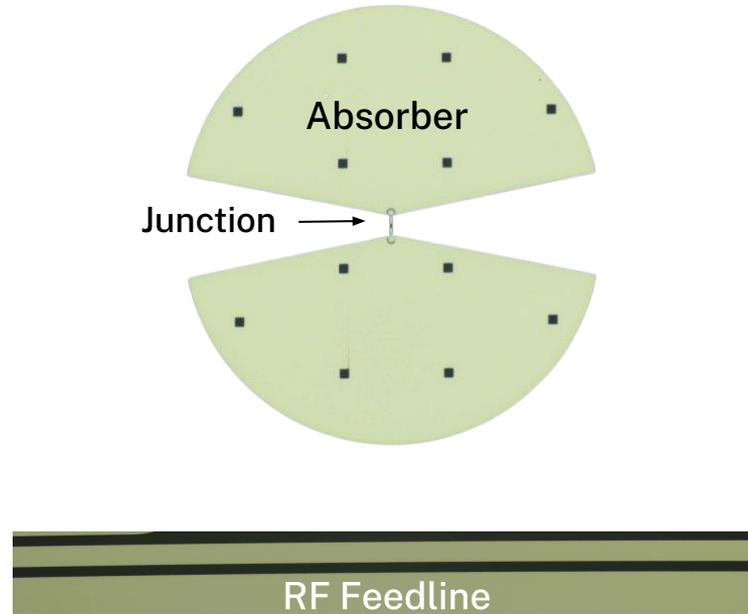
# The Quantum Parity Detector: Theory and Practice

Brandon Sandoval, [bsandova@caltech.edu](mailto:bsandova@caltech.edu)

**Caltech**

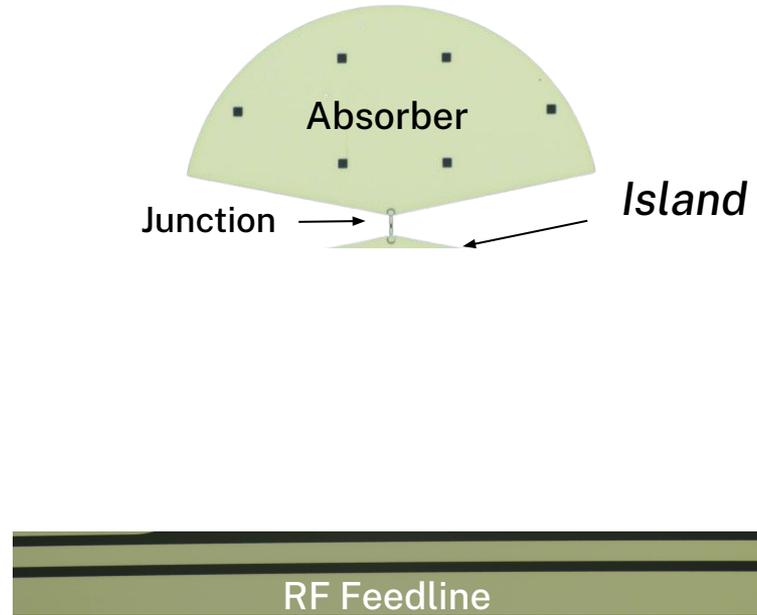
# From SQUAT to Cooper Pair Box (CPB)

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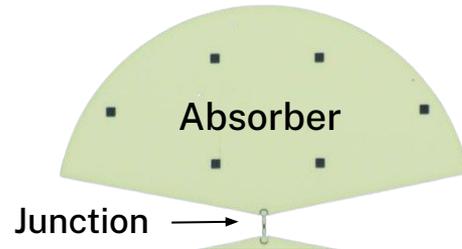
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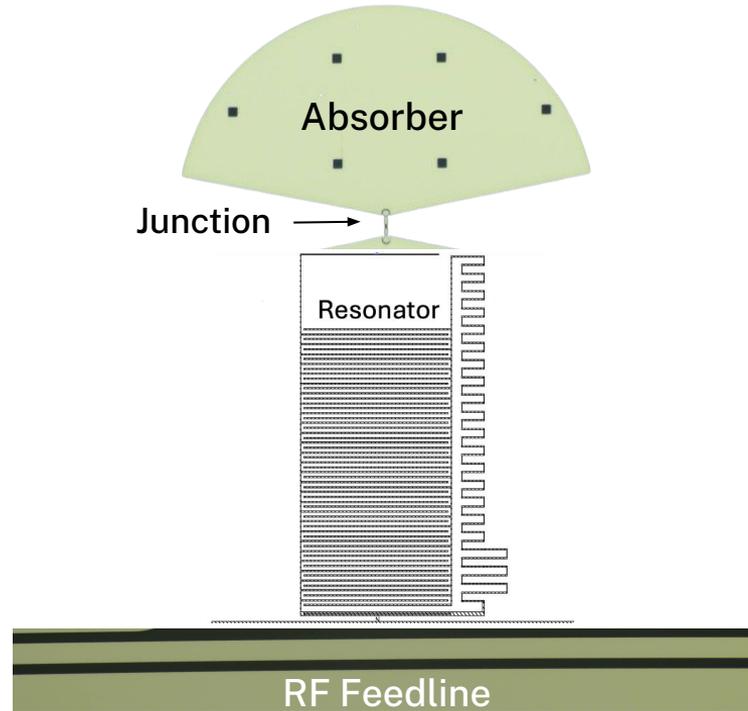
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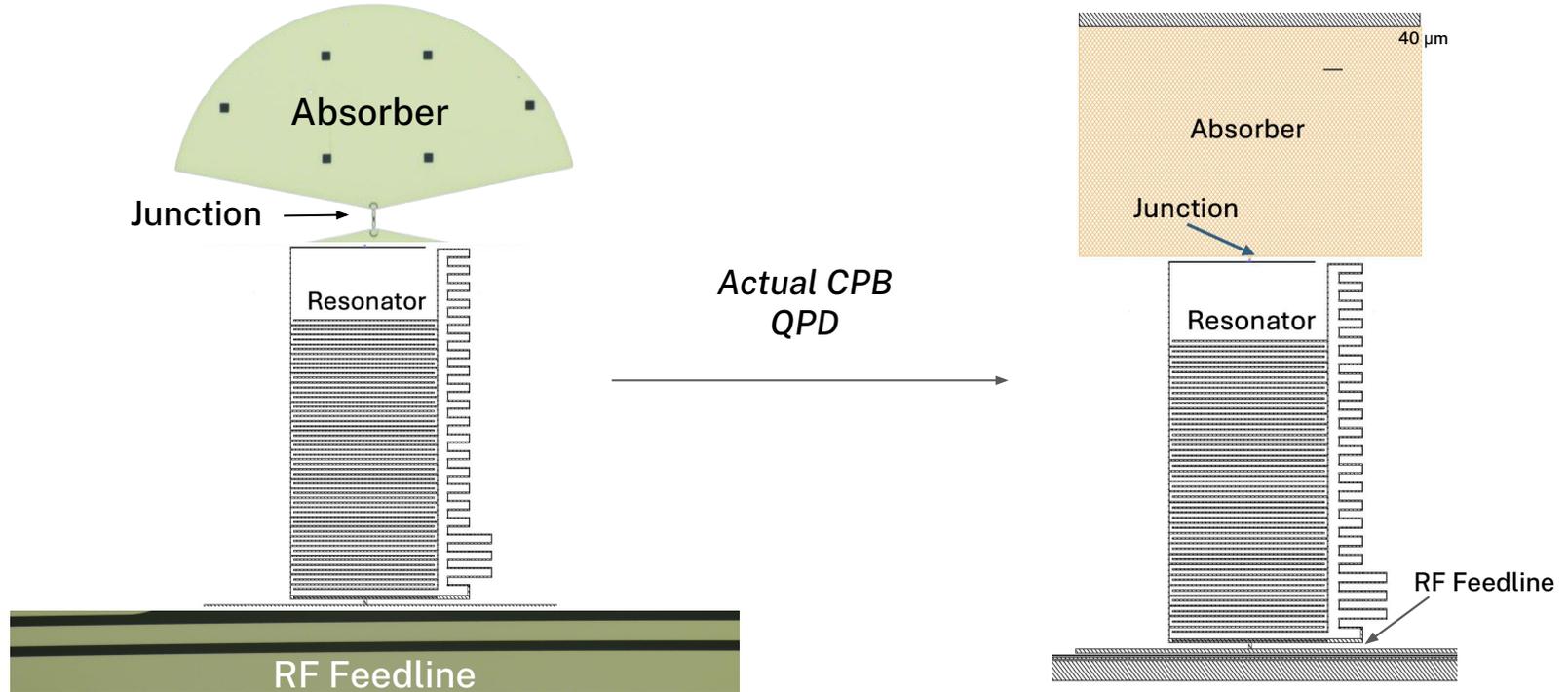


# From SQUAT to Cooper Pair Box (CPB)

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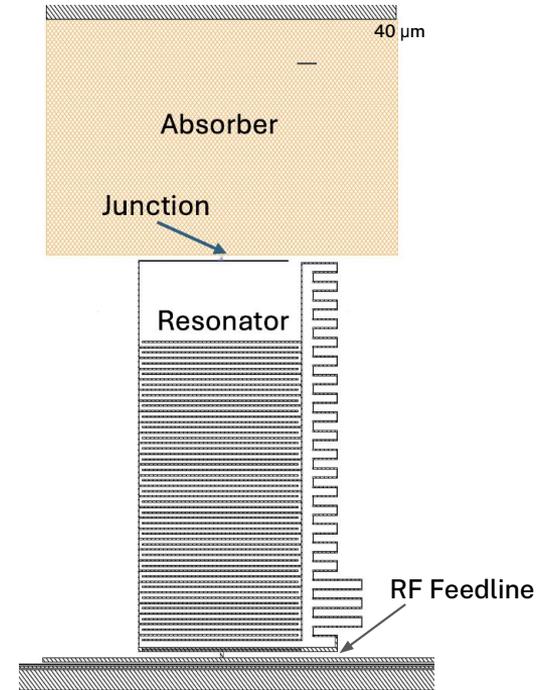
# From SQUAT to Cooper Pair Box (CPB)



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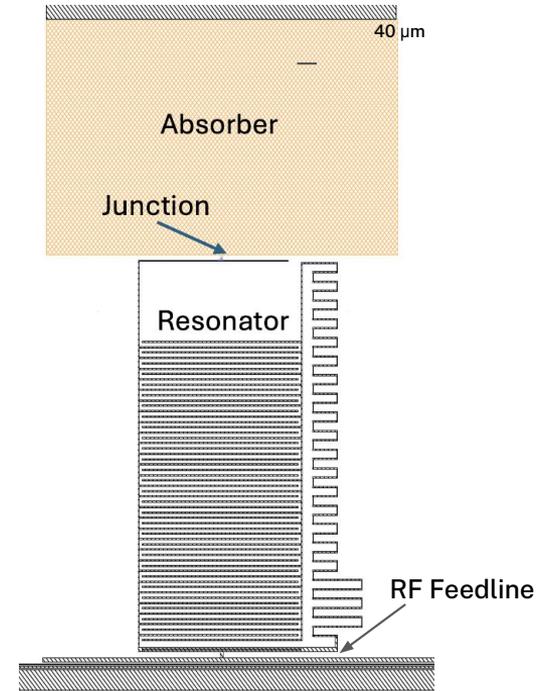
## Main Differences from SQUAT:

- 1. Asymmetric absorber**
  - a. *Smaller island capacitance -> smaller  $E_j/E_c$  ratio*
- 2. Qubit coupled to feedline via a readout-resonator**
- 3.  $V_g$  biasing done through feedline**



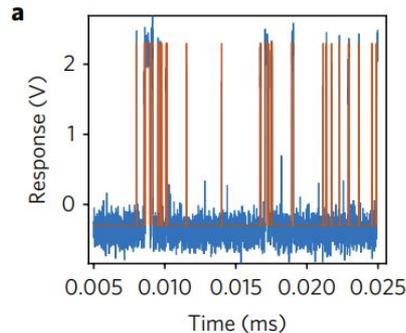
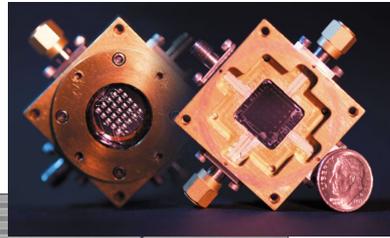
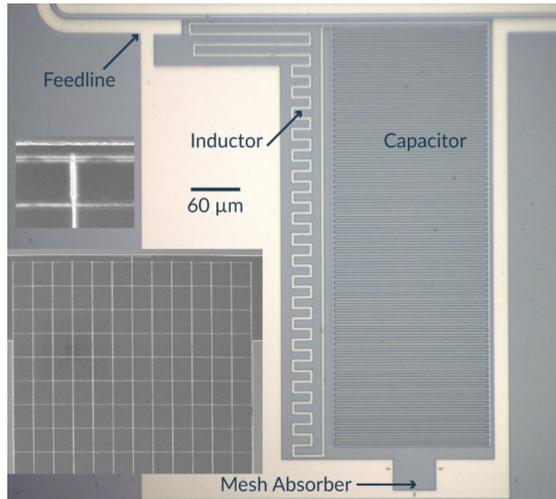
# CPB QPD: Where did it come from?

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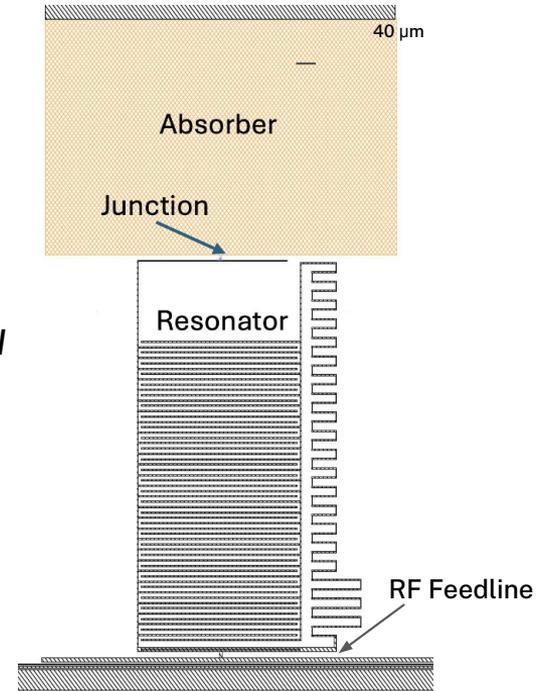


# CPB QPD: Where did it come from?

## *The Quantum Capacitance Detector*



**PHONON  
DETECTION**



# CPB QPD: Where did it come from?

The Qua

PHYSICAL REVIEW B **79**, 144511 (2009)

## Quantum capacitance detector: A pair-breaking radiation detector based on the single Cooper-pair box

M. D. Shaw,<sup>1</sup> J. Bueno,<sup>2</sup> P. Day,<sup>2</sup> C. M. Bradford,<sup>2</sup> and P. M. Echternach<sup>2</sup>

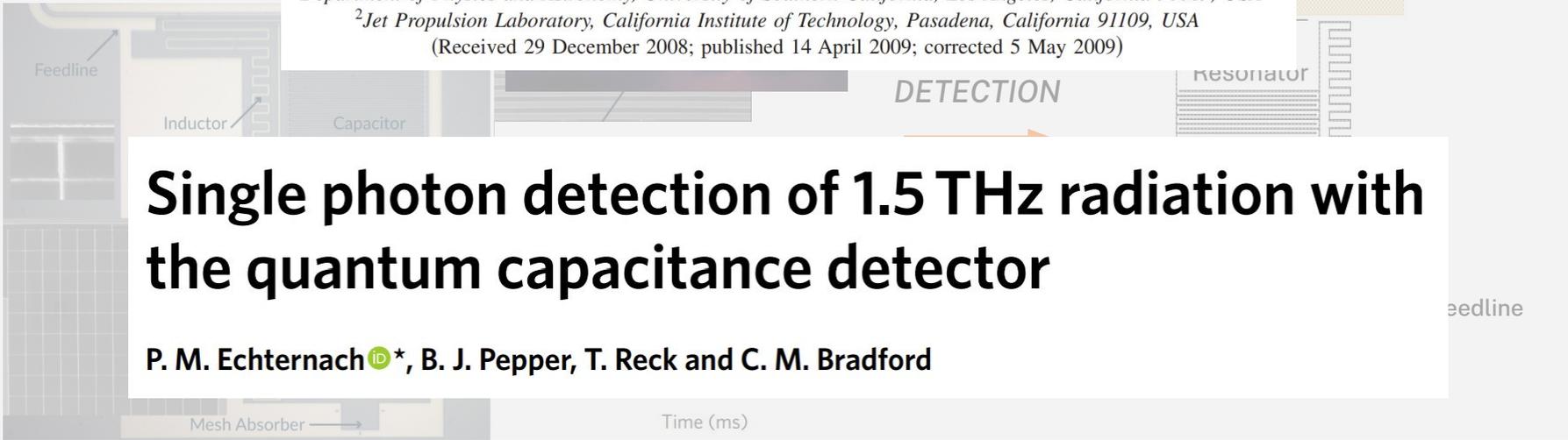
<sup>1</sup>Department of Physics and Astronomy, University of Southern California, Los Angeles, California 90089, USA

<sup>2</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA

(Received 29 December 2008; published 14 April 2009; corrected 5 May 2009)

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

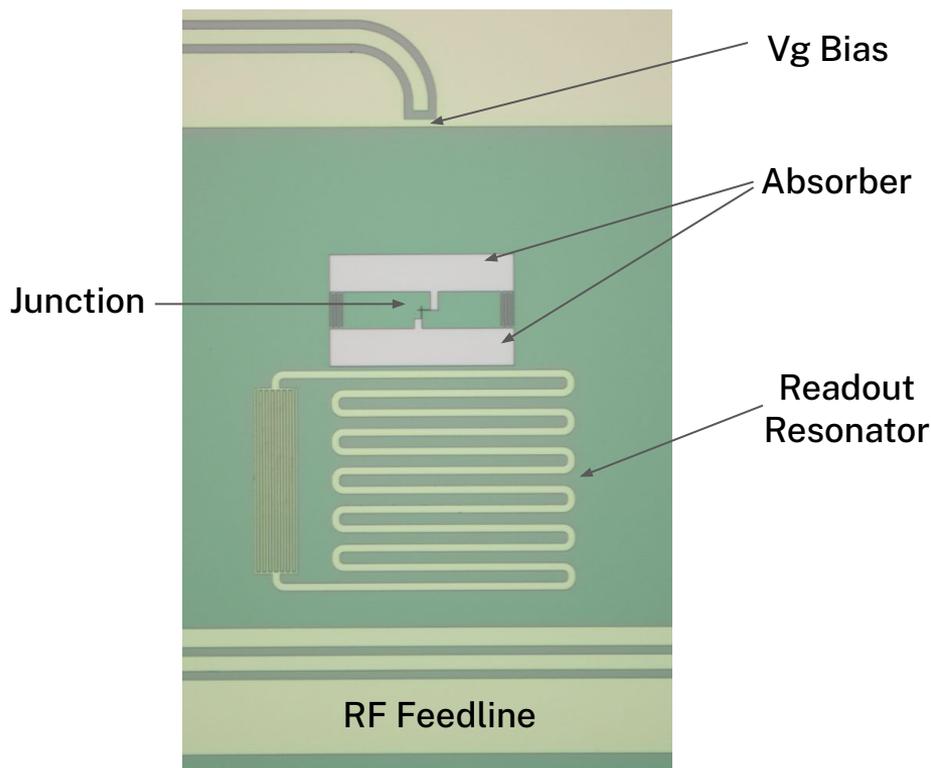
P. M. Echternach \*, B. J. Pepper, T. Reck and C. M. Bradford



# **OCS Transmon QPD: Resonator coupled transmon**

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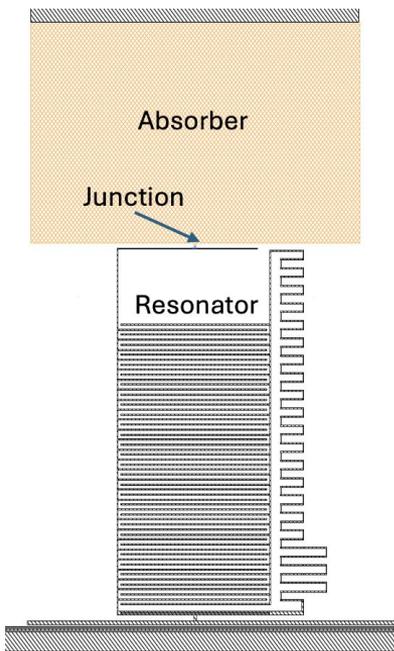
# OCS Transmon QPD: Resonator coupled transmon



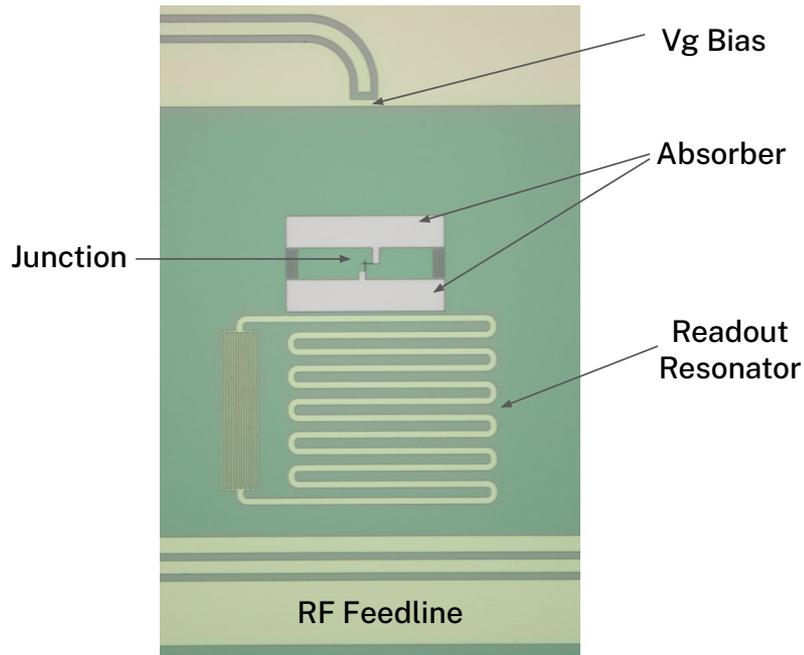
## **Offset Charge Sensitive (OCS) Transmon**

- 1. Symmetric absorber**
  - a. In the transmon regime ( $E_j > E_c$ ), like the SQUAT*
- 2. Qubit coupled to feedline via a readout-resonator**
- 3. Vg biasing done through dedicated line or feedline**

# Both are called Quantum Parity Detectors!

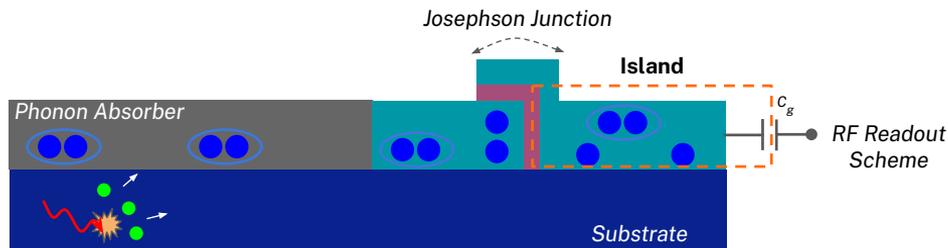


**Cooper Pair Box (CPB)**  
( $E_c > E_j$ )

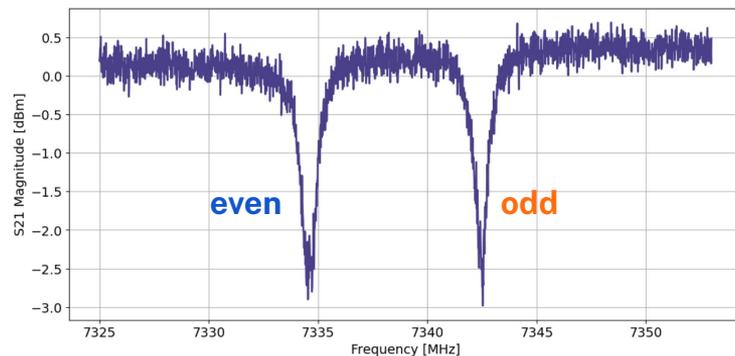
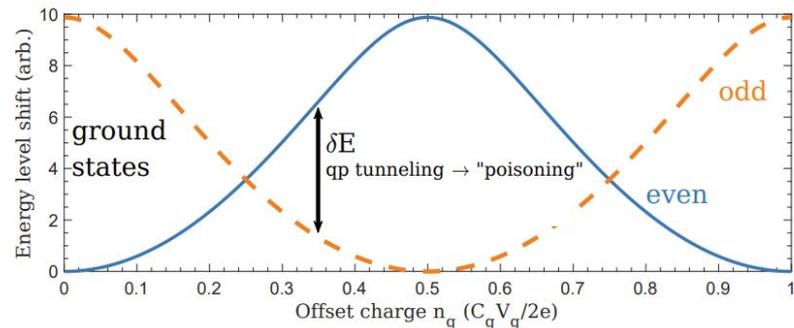
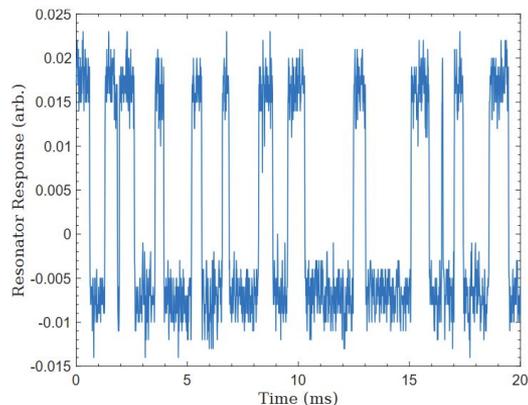


**Offset Charge Sensitive (OCS) Transmon**  
( $E_j > E_c$ )

# SQUATs & QPDs: More similar than they are different!



On-Resonance Timestream

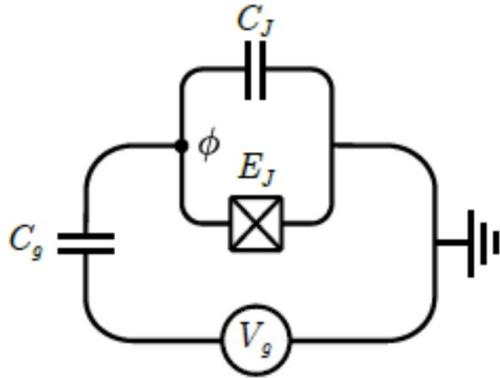


# QPD Theory: Cooper Pair Box Regime

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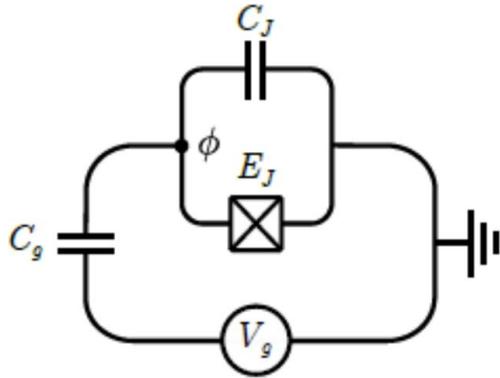
# QPD Theory: Cooper Pair Box Regime

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$$\hat{H} = \hat{H}_C + \hat{H}_J$$

# QPD Theory: Cooper Pair Box Regime

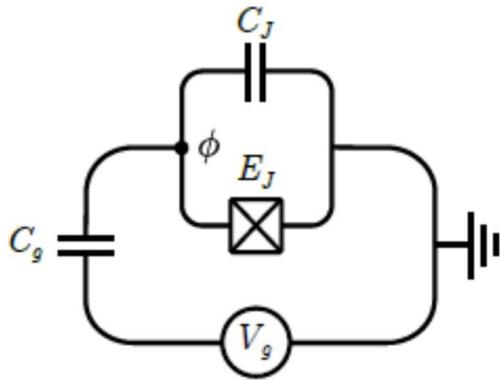


$$\hat{H} = \frac{\hat{Q}^2}{2C} - \frac{\hbar I_c}{4\pi e} \cos \hat{\phi}$$

$$I = I_c \sin \phi \quad V = \frac{\hbar}{2e} \frac{\partial \phi}{\partial t}$$
$$E = \int IV dt$$

# QPD Theory: Cooper Pair Box Regime

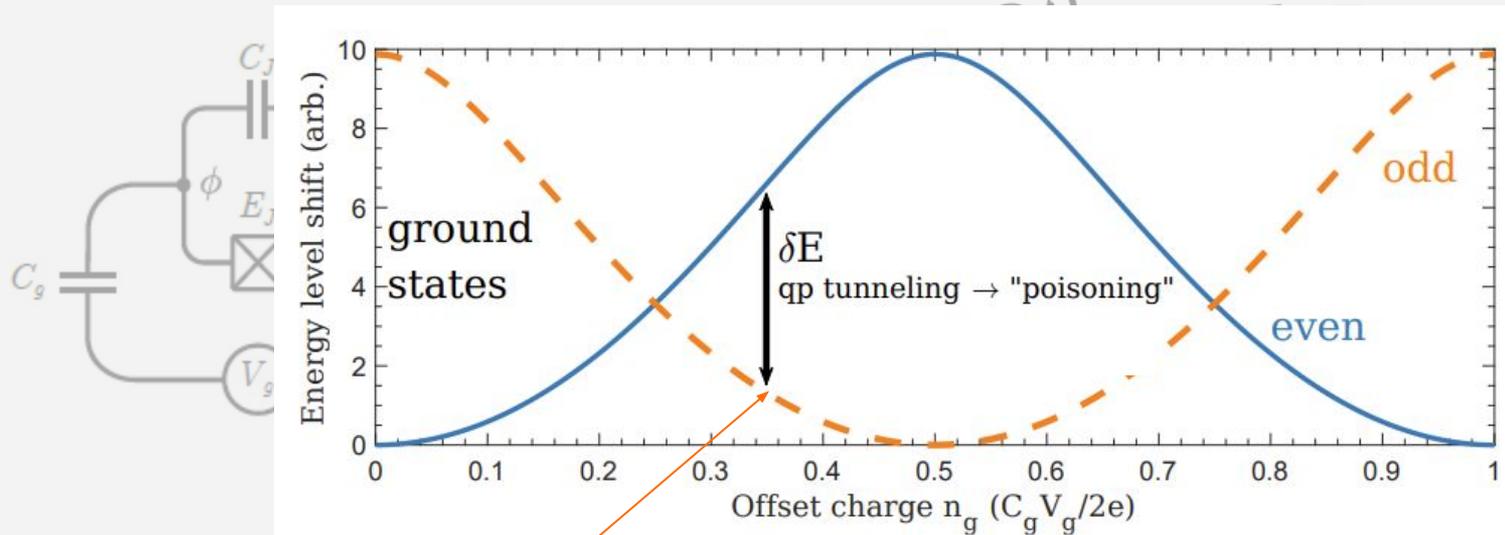
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$$\hat{H} = \frac{\hat{Q}^2}{2C} - \frac{hI_c}{4\pi e} \cos \hat{\phi}$$

$$\hat{Q}_{Cooper} = 2e \left( \hat{n} - n_g + \frac{P-1}{4} \right)$$

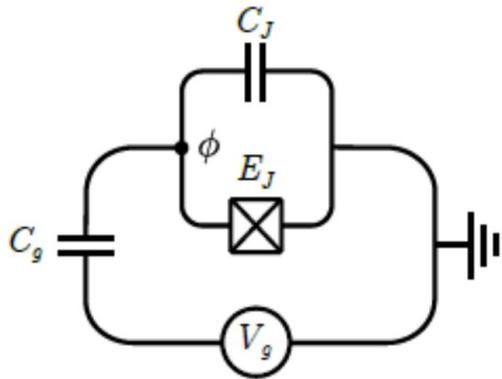
# QPD Theory: Cooper Pair Box Regime



$n_g$  determines where along these curves we operate

# QPD Theory: Cooper Pair Box Regime

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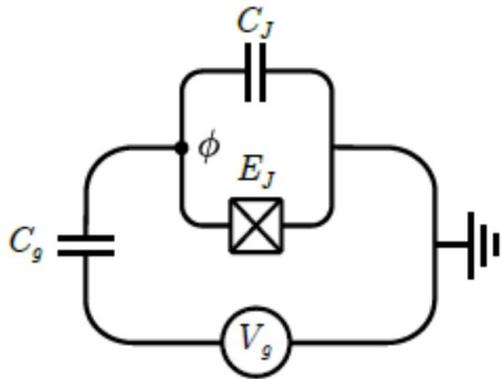


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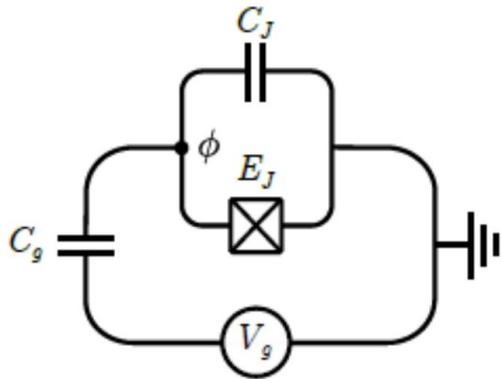
# QPD Theory: Cooper Pair Box Regime

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$$\hat{H} = \frac{4e^2}{2C} \left( \hat{n} - n_g + \frac{P-1}{4} \right) - \frac{\hbar I_c}{4\pi e} \cos \hat{\phi}$$

# QPD Theory: Cooper Pair Box Regime



$$\hat{H} = \frac{4e^2}{2C} \left( \hat{n} - n_g + \frac{P-1}{4} \right) - \frac{\hbar I_c}{4\pi e} \cos \hat{\phi}$$

$$E_C = \frac{e^2}{2C} \qquad E_J = \frac{\hbar I_c}{4\pi e}$$

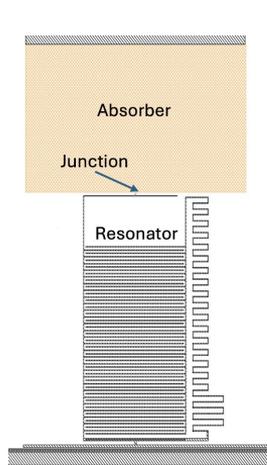
# QPD Theory: Cooper Pair Box Regime

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Capacitance energy   Cooper pairs on island   Gate charge   Parity of qp's on island ( $\pm 1$ )   Josephson energy

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

# QPD Theory: Cooper Pair Box Regime



Capacitance energy    Cooper pairs on island    Gate charge    Parity of qp's on island ( $\pm 1$ )    Josephson energy

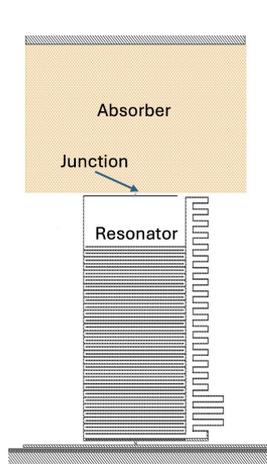
$$\hat{H} = 4E_C \left( \hat{n} - n_g + \frac{P-1}{4} \right)^2 - E_J \cos \hat{\phi}$$

$$E_c = \frac{e^2}{2C_\Sigma}$$

Smaller  
Capacitance

$$\begin{aligned} E_J / E_C &\sim 1 \\ E_J / E_C &< 1 \end{aligned}$$

# QPD Theory: Cooper Pair Box Regime



Capacitance energy    Cooper pairs on island    Gate charge    Parity of qp's on island ( $\pm 1$ )    Josephson energy

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# QPD Theory: Cooper Pair Box Regime

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# QPD Theory: Cooper Pair Box Regime

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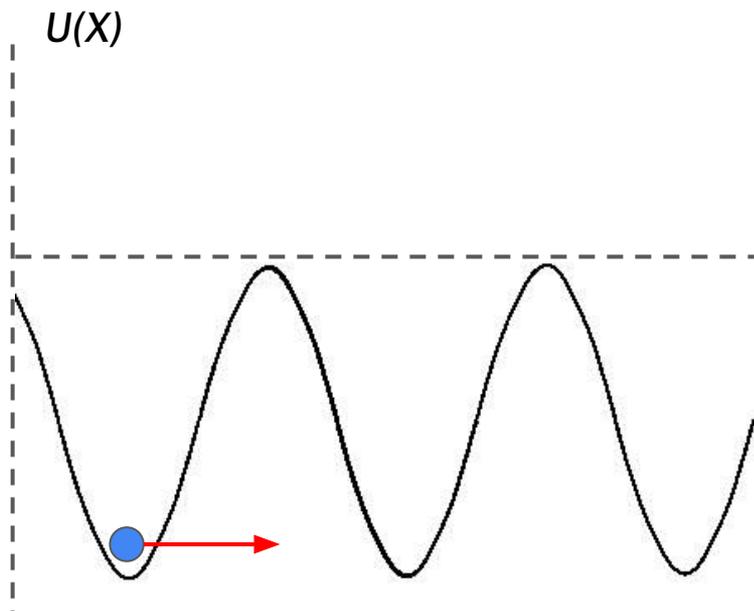
$$\hat{H}_{Lattice} = \frac{\hat{p}^2}{2m} - U \cos \hat{x}$$

# QPD Theory: Cooper Pair Box Regime

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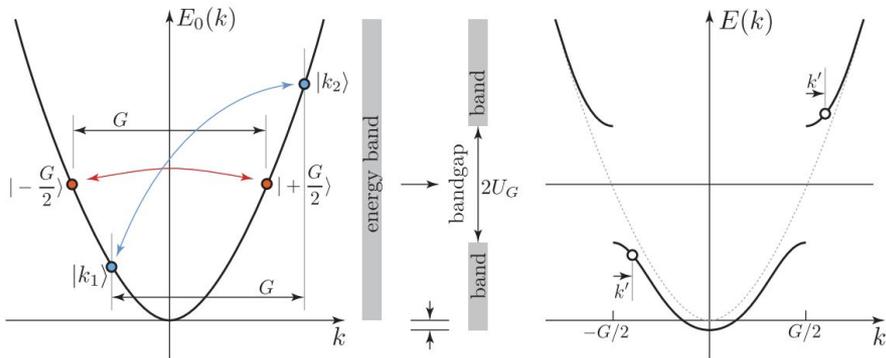
$$\hat{H}_{QPD} = \frac{\hat{Q}^2}{2C_{\Sigma}} - E_J \cos \hat{\phi}$$

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# QPD Theory: Cooper Pair Box Regime

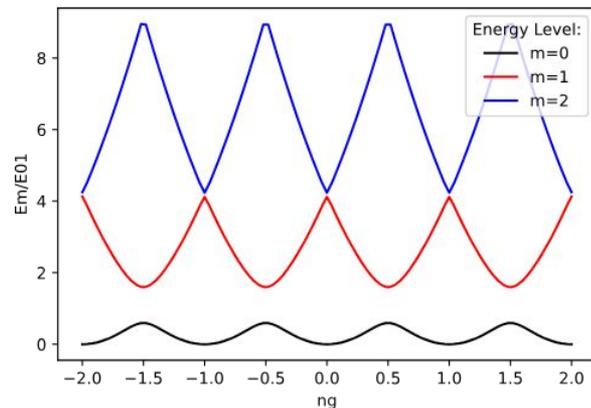
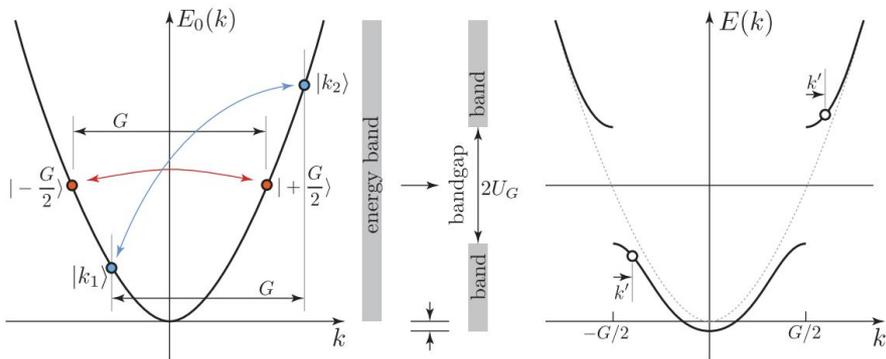
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# QPD Theory: Cooper Pair Box Regime

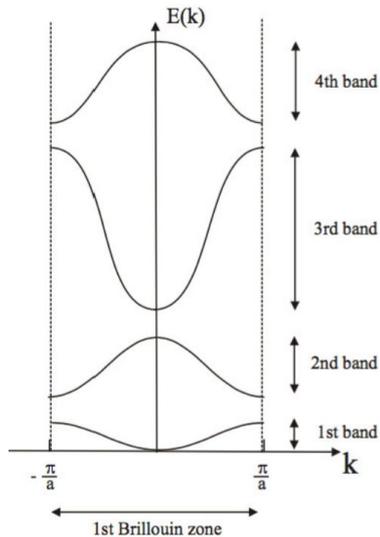
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# QPD Theory: Cooper Pair Box Regime

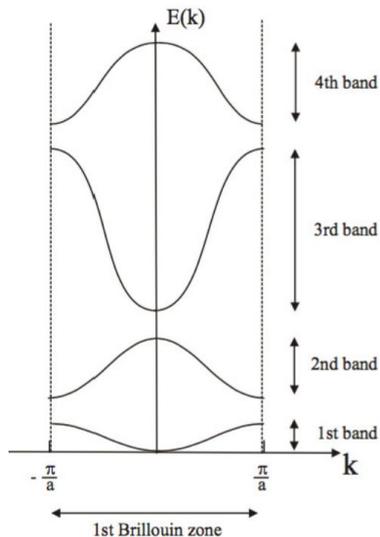
$$\hat{H}_{Lattice} = \frac{\hat{p}^2}{2m} - U \cos \hat{x}$$



$$m^* \implies \frac{d^2 E}{dk^2}$$

# QPD Theory: Cooper Pair Box Regime

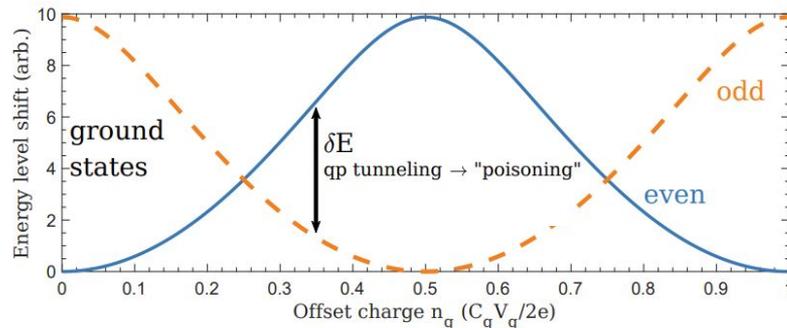
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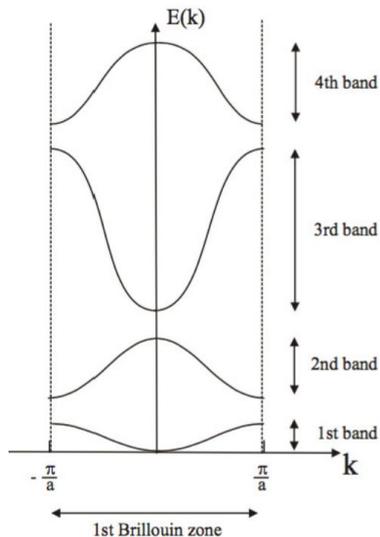
$$\hat{H}_{QPD} = \frac{\hat{Q}^2}{2C_\Sigma} - E_J \cos \hat{\phi}$$

$$C_Q \implies \frac{d^2 E}{dn_g^2}$$



# QPD Theory: Cooper Pair Box Regime

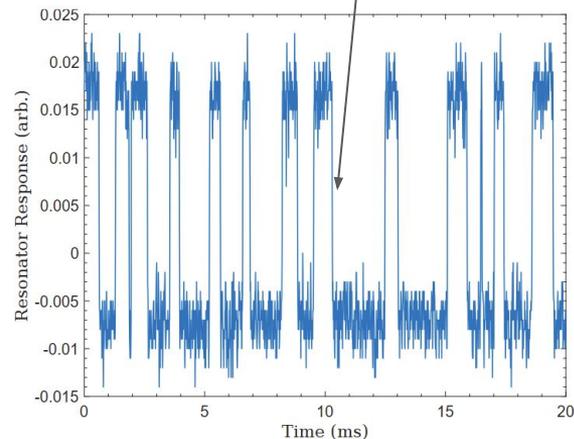
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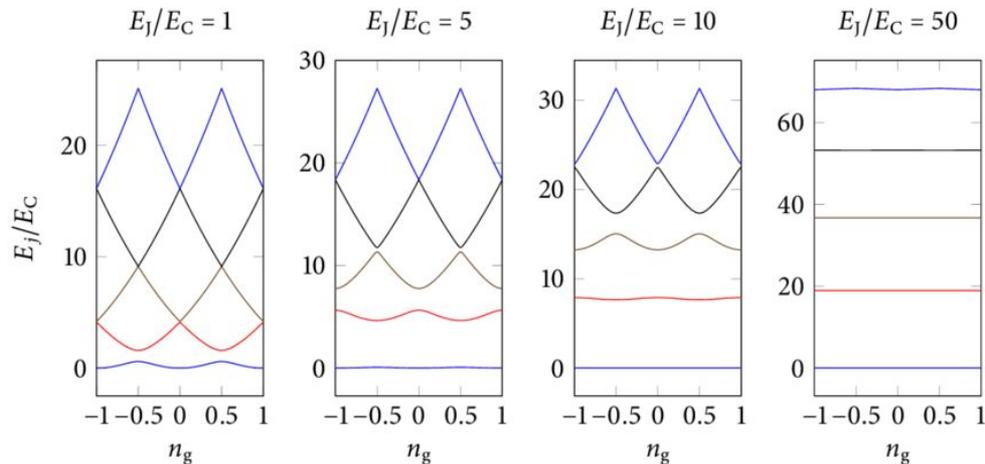
$$\hat{H}_{QPD} = \frac{\hat{Q}^2}{2C_\Sigma} - E_J \cos \hat{\phi}$$

Change in quantum capacitance



# QPD Theory: Cooper Pair Box Regime

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



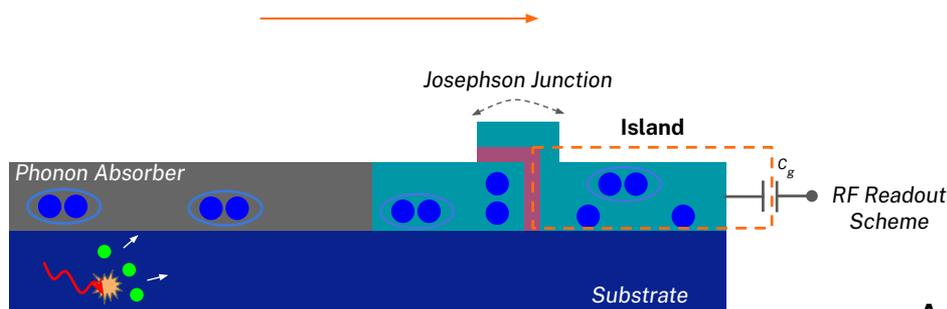
**CPB**  $\longleftrightarrow$  **SQUAT/OCS Transmon**

**Effect 1: Non-trivial  $\Gamma_{\text{out}}$**

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# Effect 1: Non-trivial $\Gamma_{\text{out}}$

Tunneling IN to the island



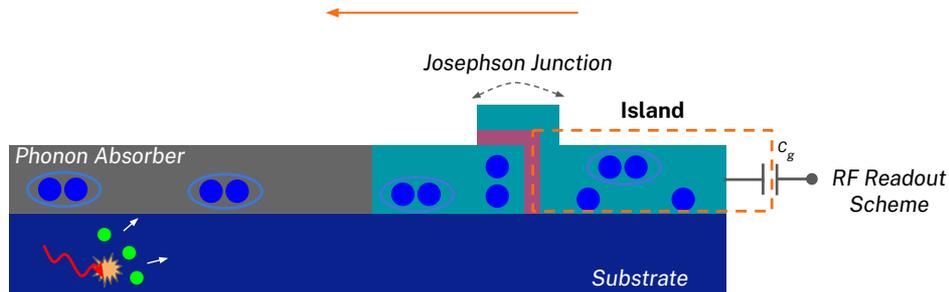
$$\Gamma_{in} = K n_{qp}$$

Approximate K for transmon...

$$E_J \gg E_C, \quad K \approx \frac{16E_J k_B T}{\mathcal{N} h \Delta}$$

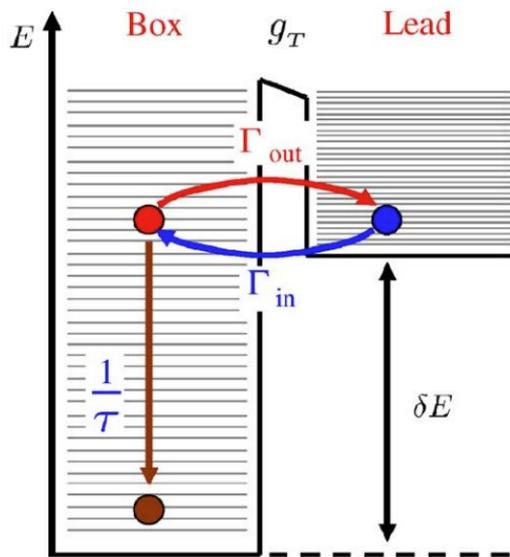
# Effect 1: Non-trivial $\Gamma_{\text{out}}$

*What about tunneling OUT of the island...?*

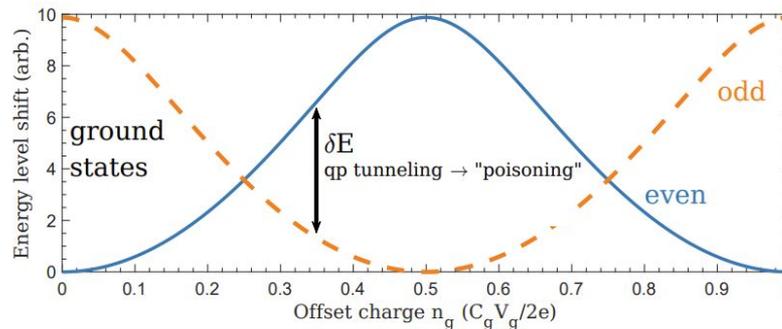




# Effect 1: Non-trivial $\Gamma_{\text{out}}$



$$\tau \propto \left( \frac{1}{\delta E} \right)^{7/2}$$

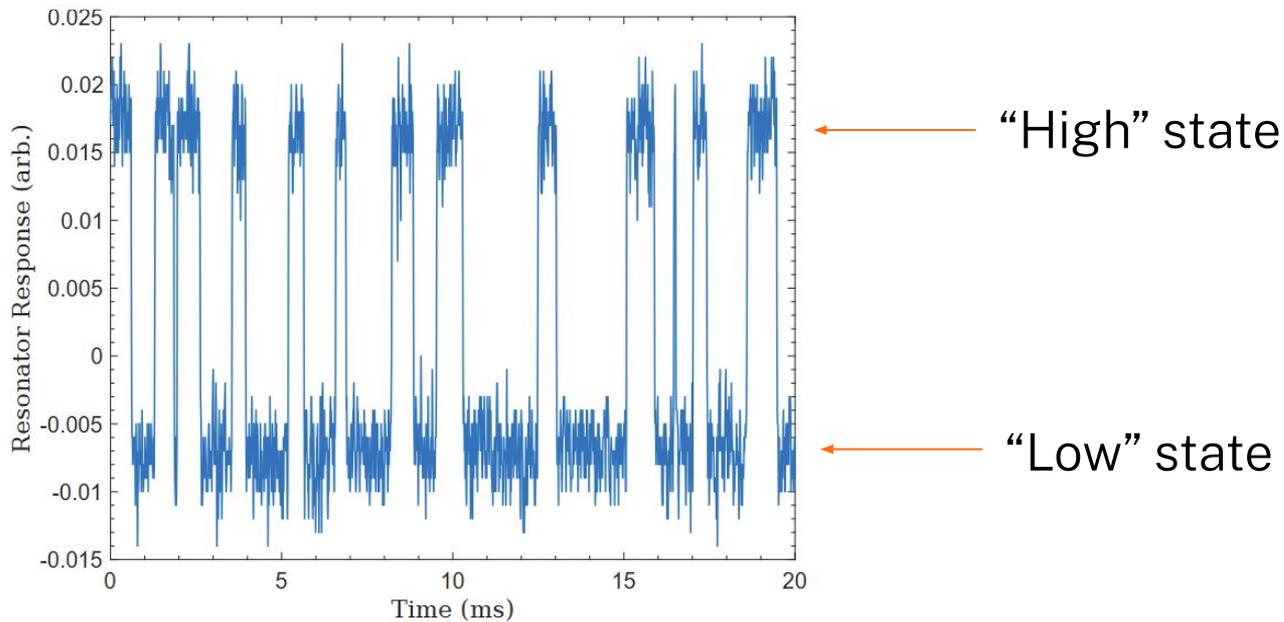


1. Tunnel in with energy  $E$ , then tunnel out before losing energy
2. Tunnel in with energy  $E$ , relax to the bottom of the  $\delta E$  trap, then wait until it is thermally kicked out

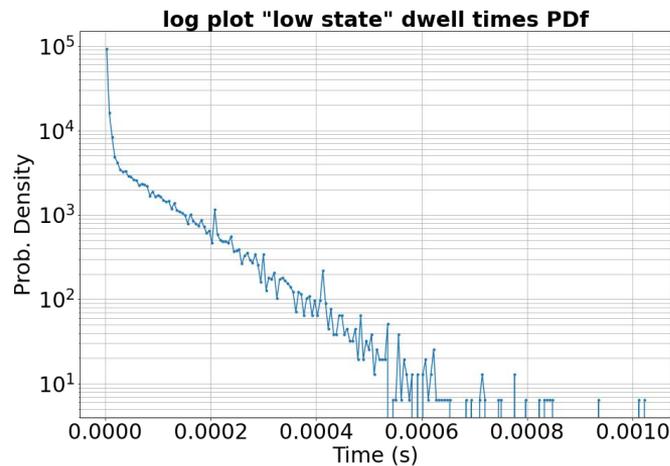
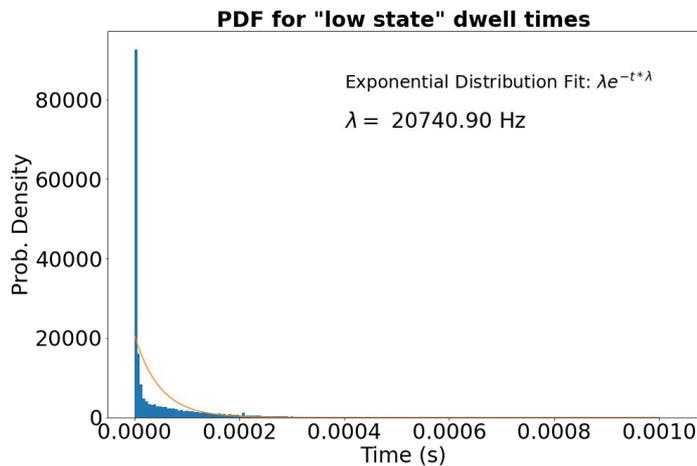
# Effect 1: Non-trivial $\Gamma_{\text{out}}$

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On-Resonance Timestream



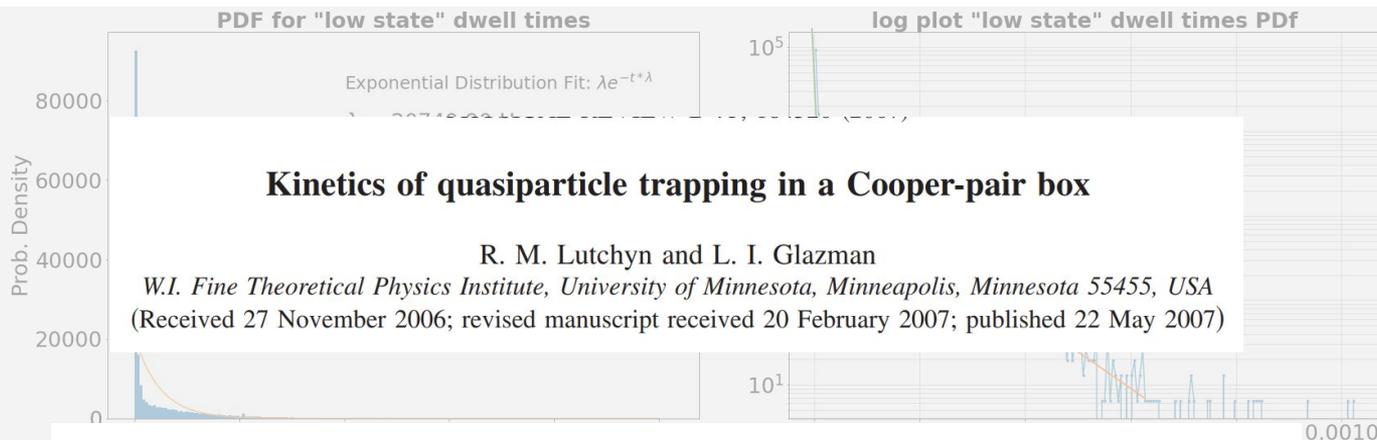
# Effect 1: Non-trivial $\Gamma_{out}$



$$P_{short}(t) \approx \frac{2^{4/3}}{\sqrt{3}} \frac{\Gamma^{el}}{(\Gamma^{el}t)^{1/3}} \exp\left[-3\left(\frac{\Gamma^{el}t}{2}\right)^{2/3}\right]$$

$$P_{long}(t) \approx \frac{\Gamma^{th}}{\pi(\tau\Gamma^{el})^2} \exp\left(-\frac{\Gamma^{th}t}{\sqrt{\pi\Gamma^{el}\tau}}\right)$$

# Effect 1: Non-trivial $\Gamma_{\text{out}}$



## Kinetics of quasiparticle trapping in a Cooper-pair box

R. M. Lutchyn and L. I. Glazman

*W.I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455, USA*  
 (Received 27 November 2006; revised manuscript received 20 February 2007; published 22 May 2007)

## Kinetics of nonequilibrium quasiparticle tunneling in superconducting charge qubits

M. D. Shaw,<sup>1</sup> R. M. Lutchyn,<sup>2</sup> P. Delsing,<sup>3,4</sup> and P. M. Echternach<sup>1,4,\*</sup>

<sup>1</sup>*Department of Physics and Astronomy, University of Southern California, Los Angeles, California 90089-0484, USA*

<sup>2</sup>*Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

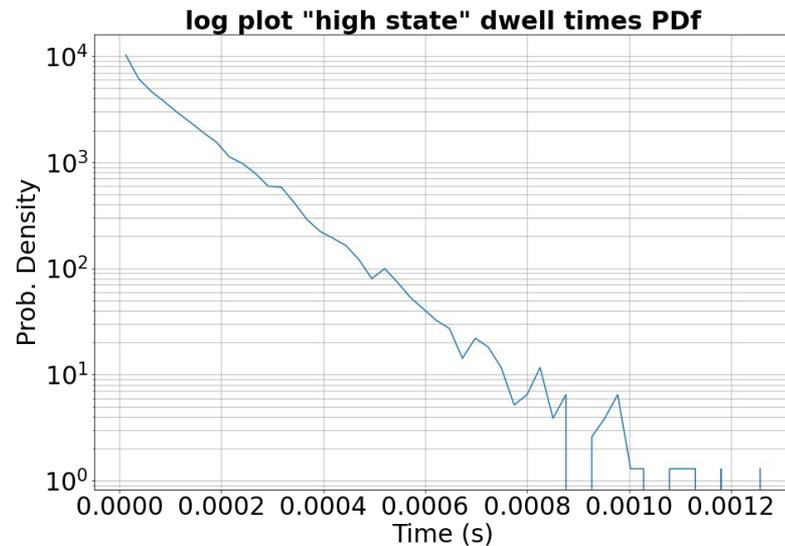
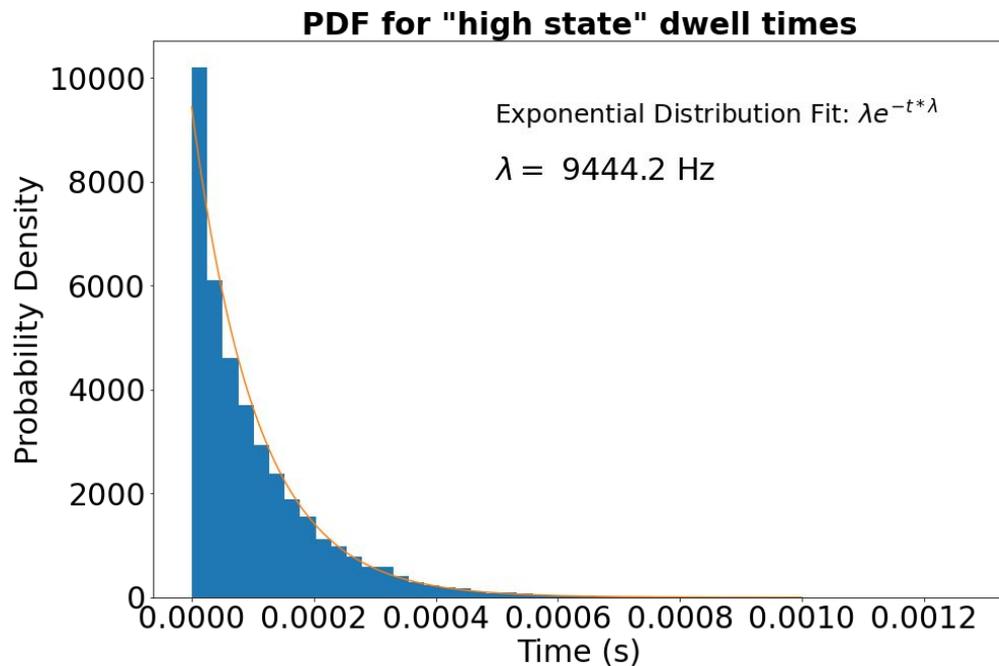
<sup>3</sup>*Microtechnology and Nanoscience, MC2, Chalmers University of Technology, 412 96 Göteborg, Sweden*

<sup>4</sup>*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA*

(Received 4 April 2008; revised manuscript received 20 May 2008; published 1 July 2008)

$$\Gamma_{\text{long}}(\nu) \approx \frac{1}{\pi(\tau\Gamma^{\text{el}})^2} \exp\left(-\frac{\nu}{\sqrt{\pi\Gamma^{\text{el}}\tau}}\right)$$

# Effect 1: Non-trivial $\Gamma_{\text{out}}$

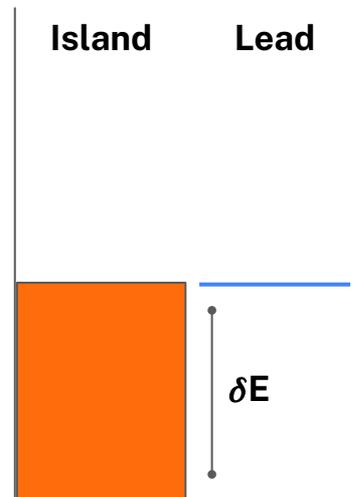
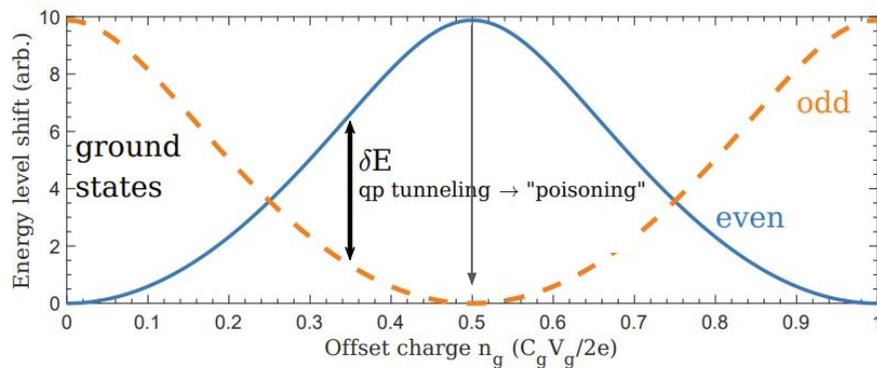


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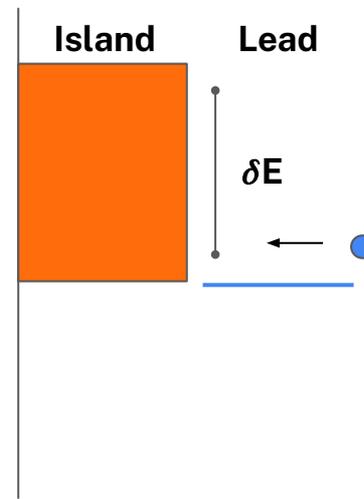
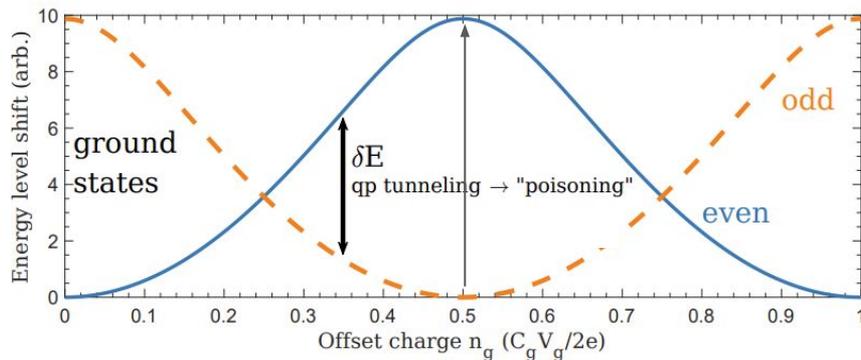
# Effect 2: Coulomb Blocking

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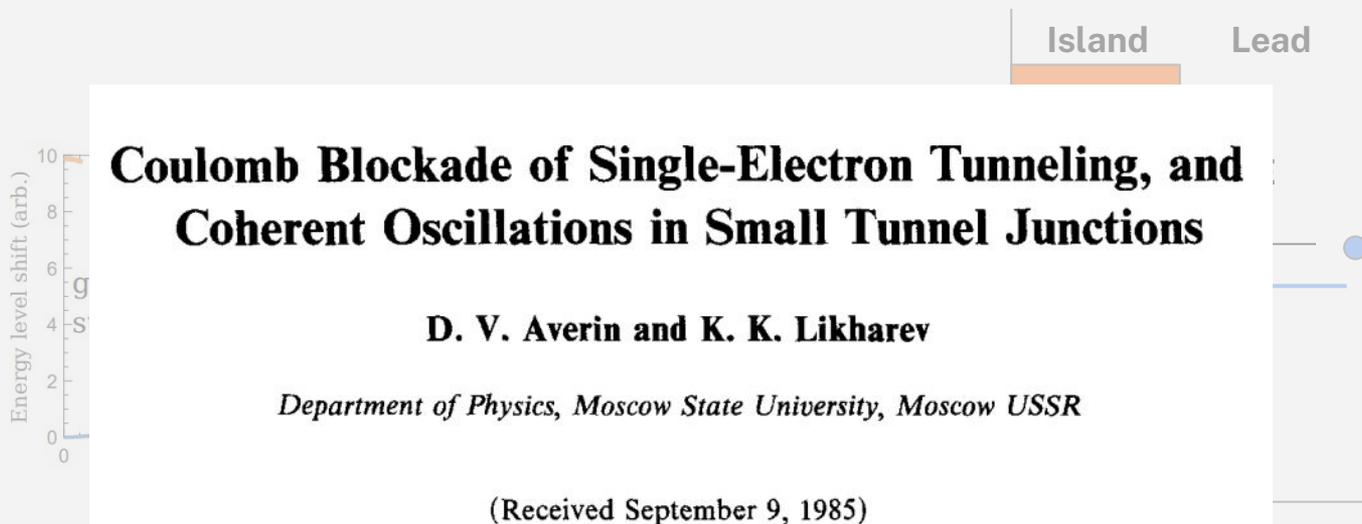


# Effect 2: Coulomb Blocking



- The second quasiparticle sees a  $dE$  block if it tunnels into the onto island
- In this regime,  $dE > kT$ , so second quasiparticle is suppressed
- **Only one quasiparticle on the island at a time!**

# Effect 2: Coulomb Blocking



- The second quasiparticle sees a  $dE$  block if it tunnels into the island
- In this regime,  $dE > kT$ , so second quasiparticle is blocked

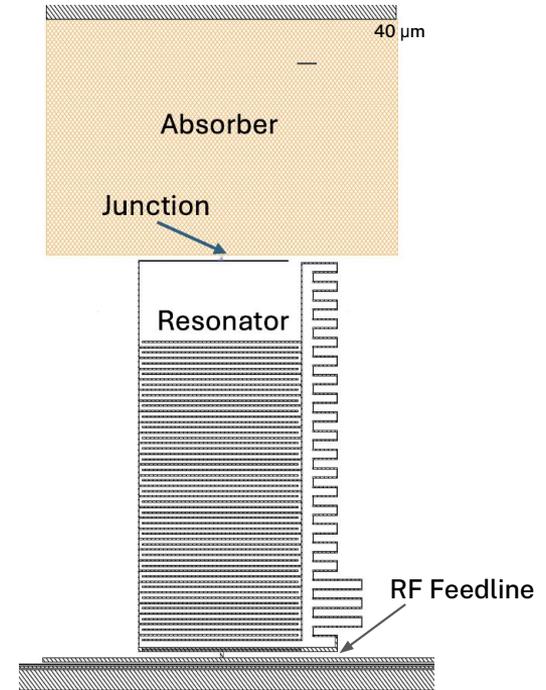
# Why the resonator?

---

# QPD Resonator

## Benefits of a resonator:

1. *Decouple qubit design from readout requirements*
2. *No longer constrained to low readout powers*
3. *Less concerned about readout-power-generated quasiparticles*

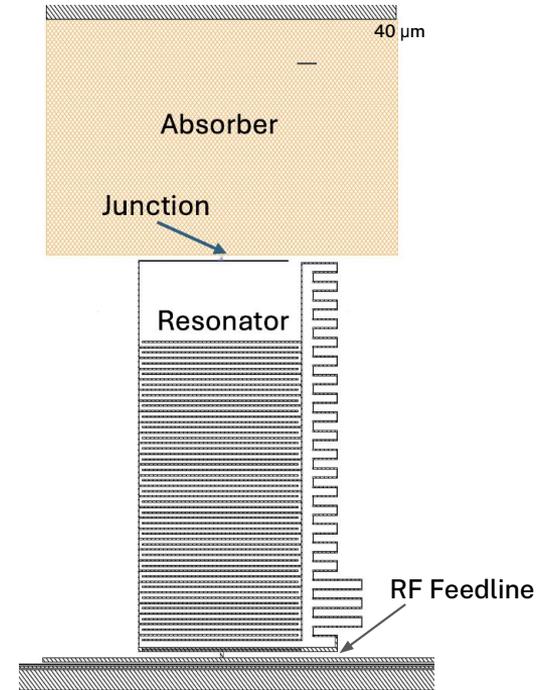


# QPD Resonator

## Cons of a resonator:

1. ***More signal-insensitive metal (dead metal) on the chip***
2. ***Larger device footprint, harder to populate a large-scale device***

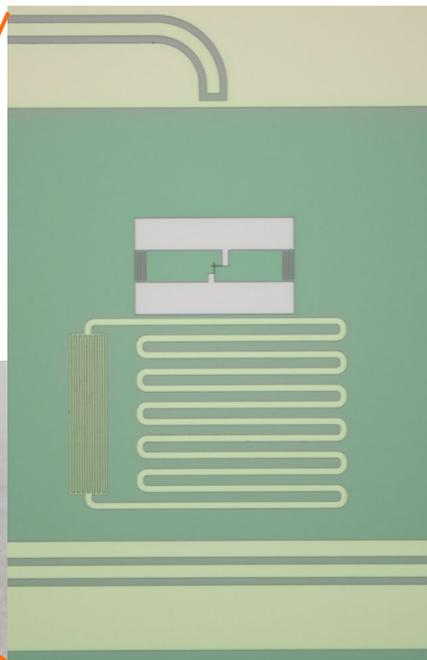
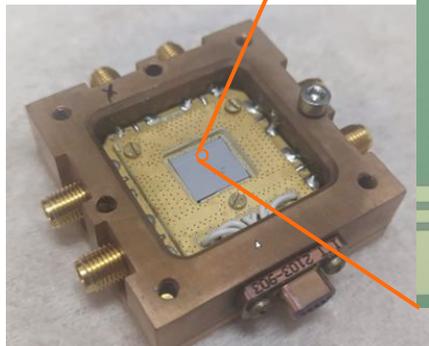
***\*Resonator has not yet been optimized for size.  
Can be made smaller!***



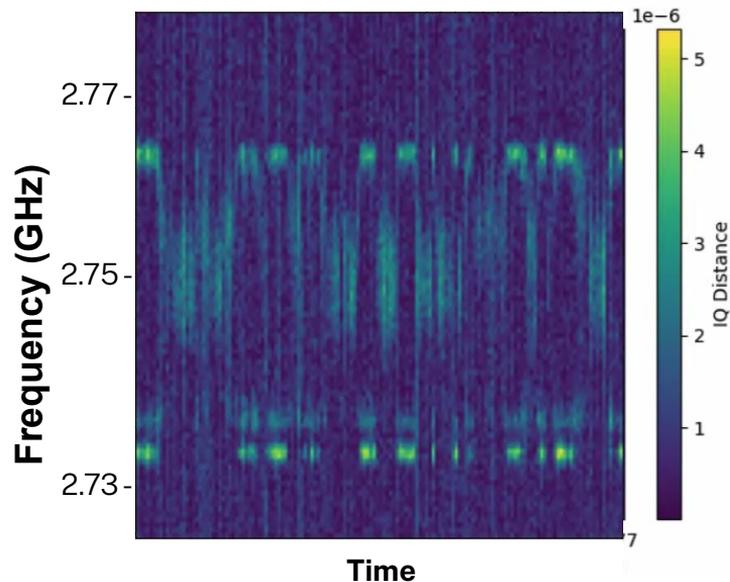
**What about a resonator-coupled transmon?**

---

# Offset Charge Sensitive (OCS) Transmon



Parity Signal of OCS

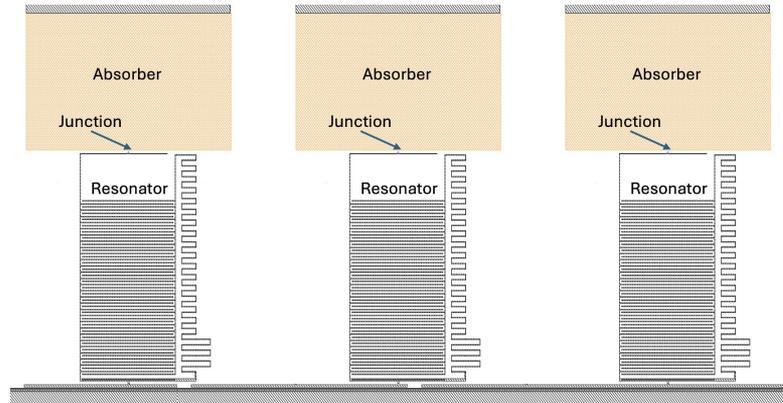


# How do we multiplex?

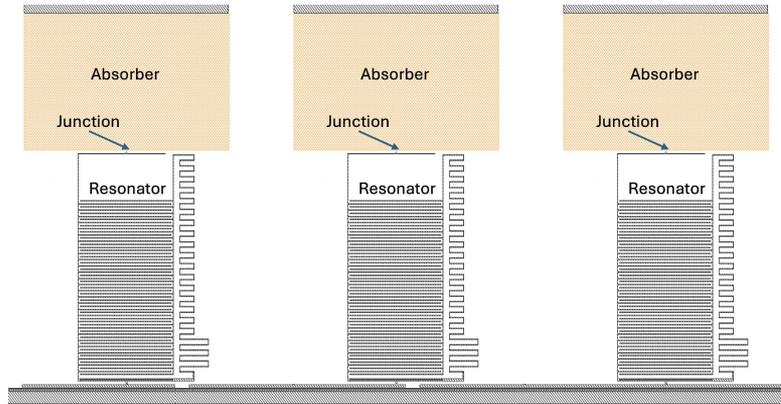
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# How do we multiplex: Why is it nontrivial?

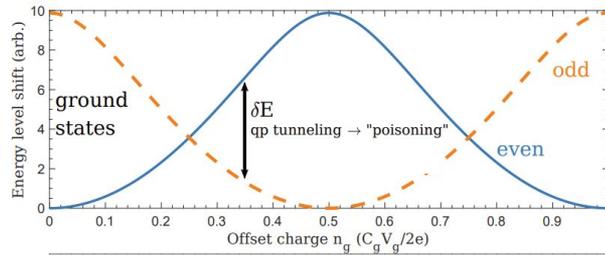
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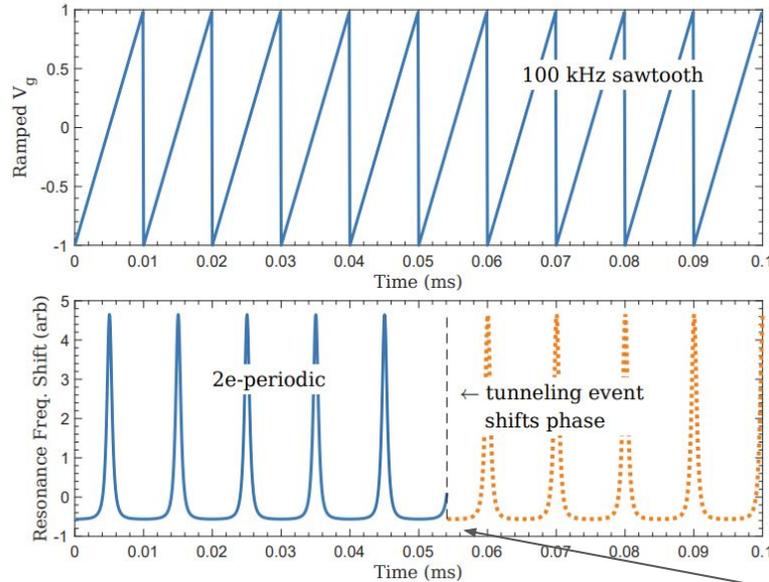
# How do we multiplex: Why is it nontrivial?



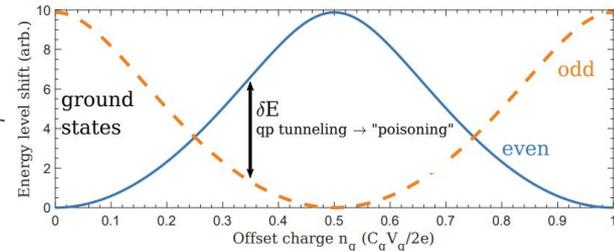
- $n_g$  will be different between sensors (uncorrelated charge drift)!



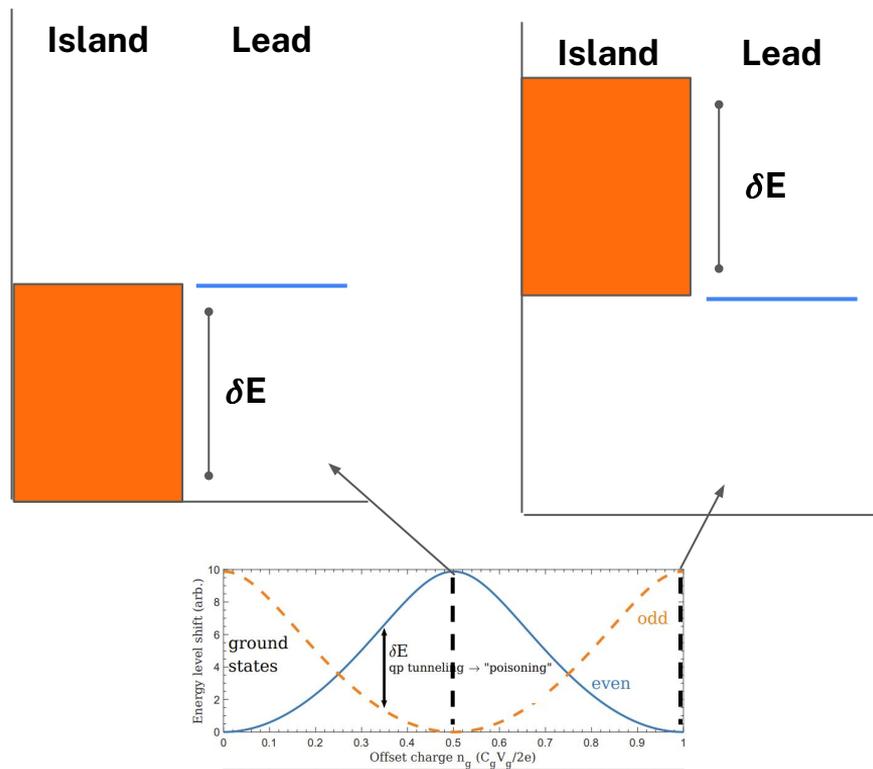
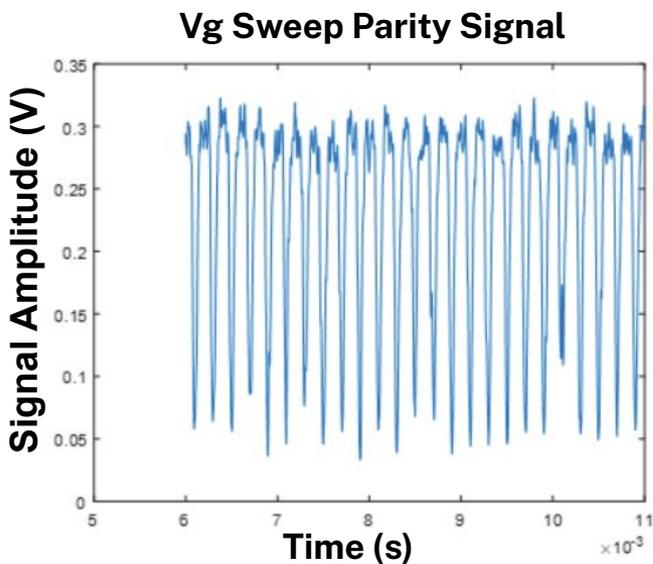
# How do we multiplex: OCS Transmon device



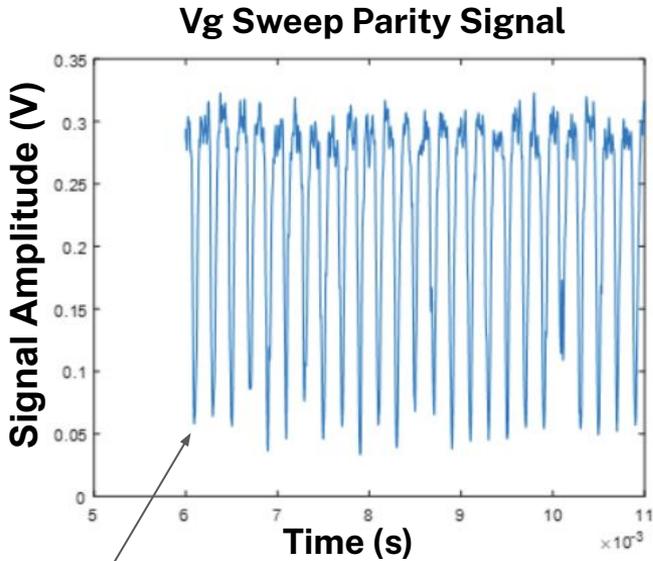
- We can sweep  $V_g$ , and a tunneling event now produces a 180 degree phase shift in the sweep signal
- No longer naively works with CPB style device: *coulomb blocking!*



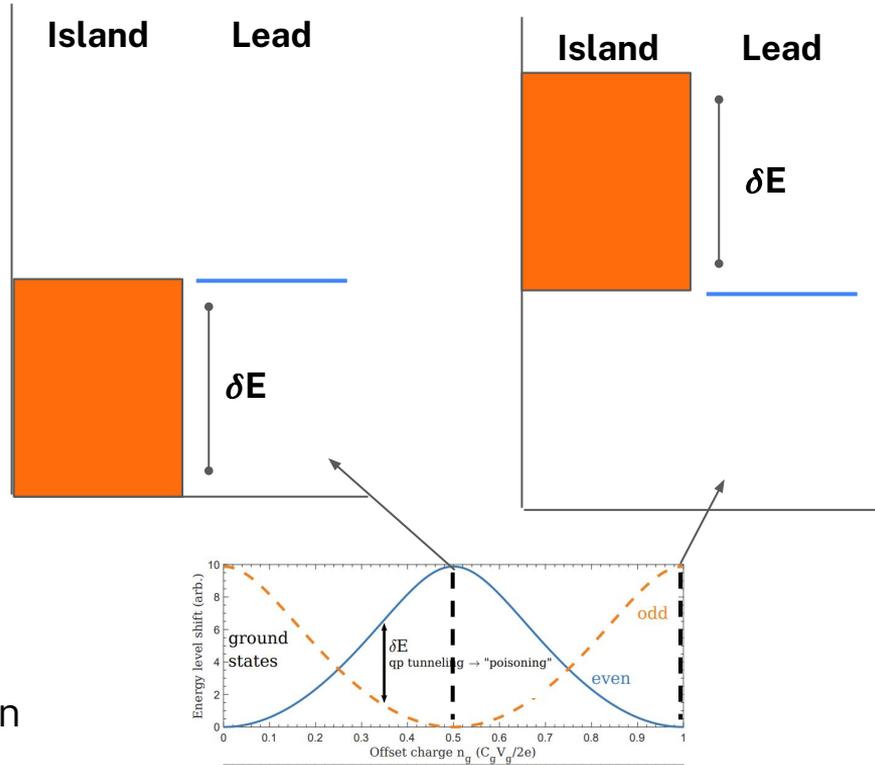
# How do we multiplex: CPB device



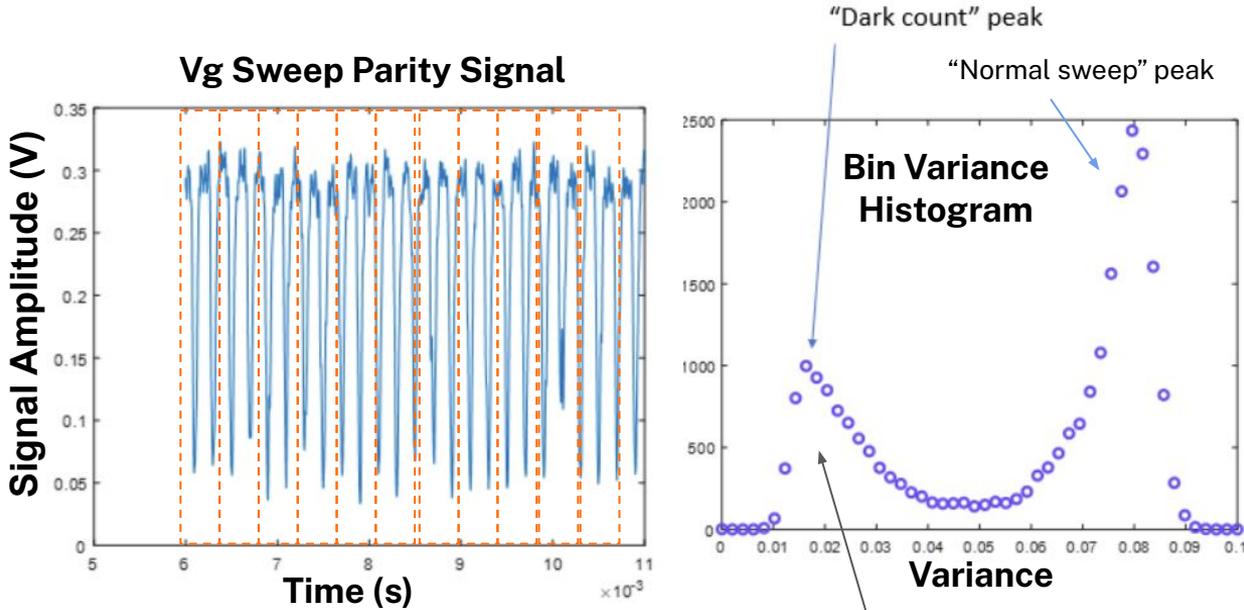
# How do we multiplex: CPB device



Sweep  $V_g$  quicker than the background tunneling rate! Preferentially keep qubit in even state



# How do we multiplex: CPB device



- High-tunneling events will cause a gap in the sweep, which will be a low-variance signal within that bin

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

# Sensitivity & Backgrounds

---

# QPD sensor resolution and noise

Resolution on number of signal transitions  $\rightarrow \sigma_S^2 = \left( K \frac{\tau_{qp}}{V} + K^2 \left( \frac{\tau_{qp}}{V} \right)^2 F \right) N_{qp}^r$

$\Gamma_{in} = K n_{qp}$  (Quasiparticle Lifetime)  
 Sensor Volume  
 Fano Factor  $\sim O(0.1)$   
 Max. no. of qp's generated from energy deposition

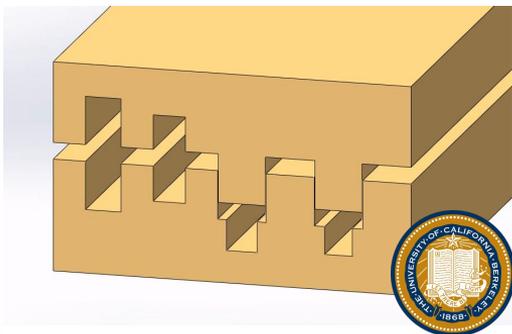
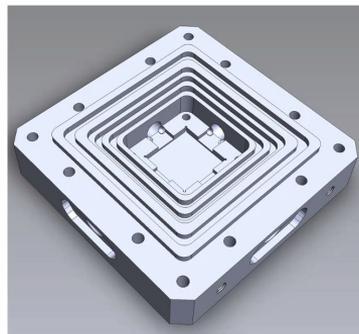
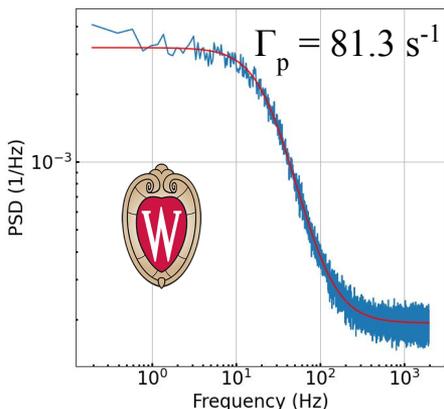
Tunneling Shot Noise      Fano Noise

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

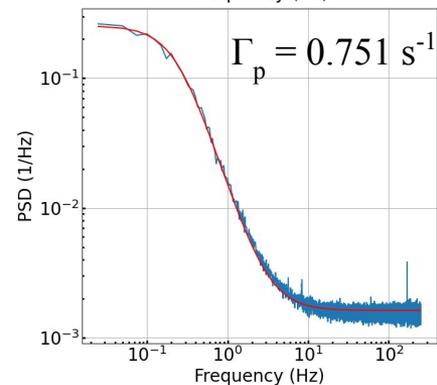
Resolution on number of background transitions  $\rightarrow \sigma_B^2 = \left( K t_w + 16 \frac{K^2 t_w^2}{V} \right) n_0$

Time window  
 Tunneling Shot Noise  
 Quiescent Quasiparticle Noise  
 Quiescent Quasiparticle Density

# Mitigating radiative backgrounds

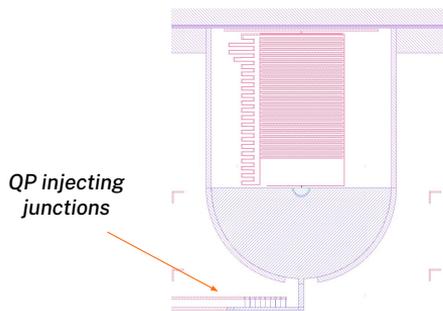
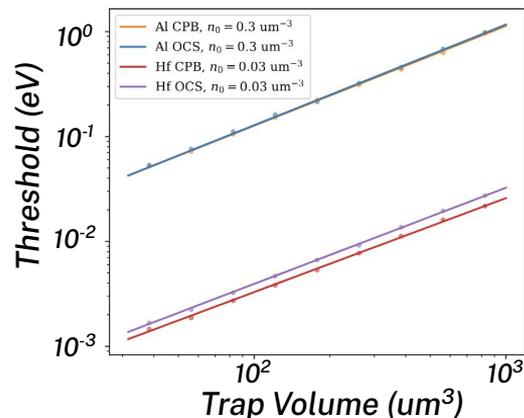


See: *“Toward a general-purpose ultra-low-external interference quantum device holder”*, Yen-Yung Chang, Oct. 9 @ 2PM



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

# Conclusion: Near term goals for QPDs



- **Bring down quiescent background!**
- **Calibrate devices**
  - **LED-generated phonon calibration**
  - **QP injecting junctions**
- **Understand phonon collection**
- **Begin testing QP trapping designs**
- **Understand phonon and QP dynamics through simulations**

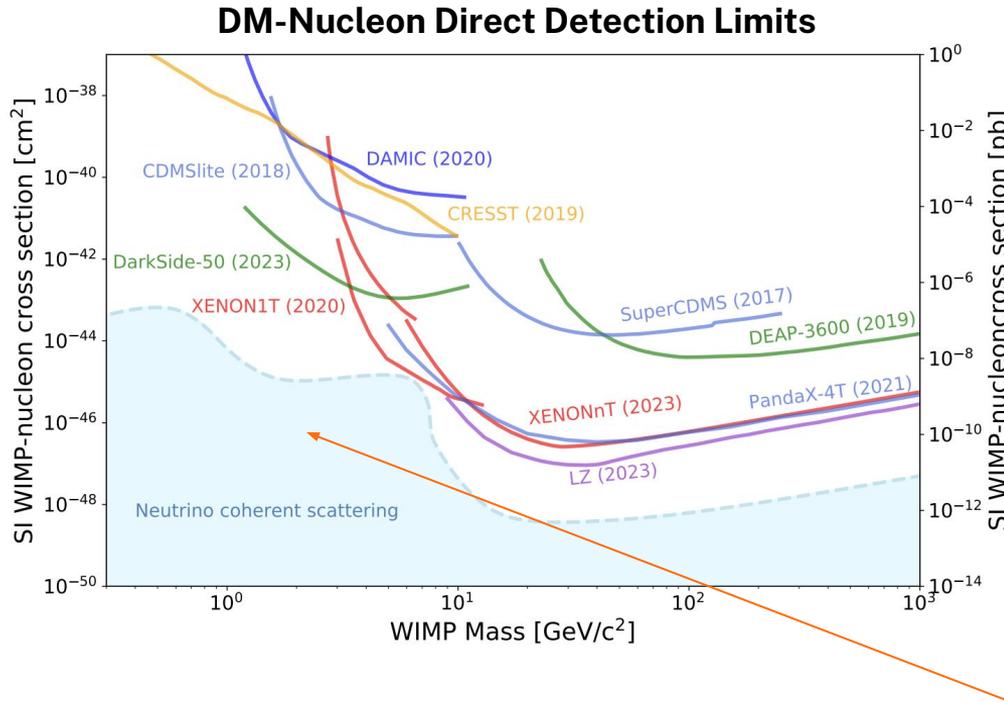
Quantum Parity Detectors: a qubit based particle detection scheme with meV thresholds for rare-event searches

K. Ramanathan,<sup>1,\*</sup> B. J. Sandoval,<sup>2</sup> J. E. Parker,<sup>2</sup> L. M. Joshi,<sup>3</sup> A. D. Beyer,<sup>4</sup> P. M. Echternach,<sup>4</sup> S. Rosenblum,<sup>3</sup> and S R. Golwala<sup>2</sup>

# BACKUP SLIDES

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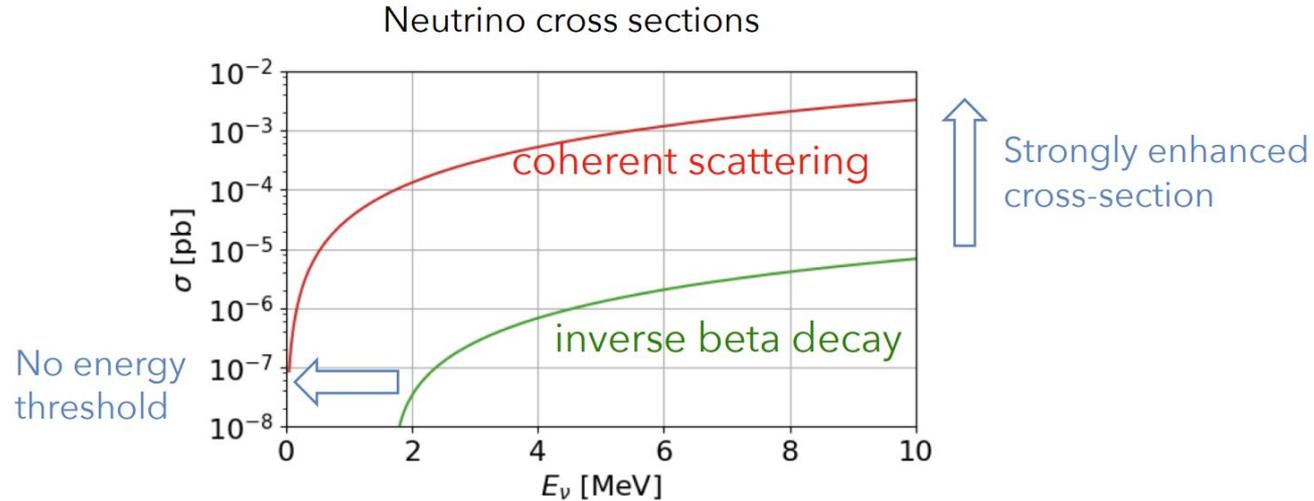
# Why do we need a lower threshold detector?



- **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!**

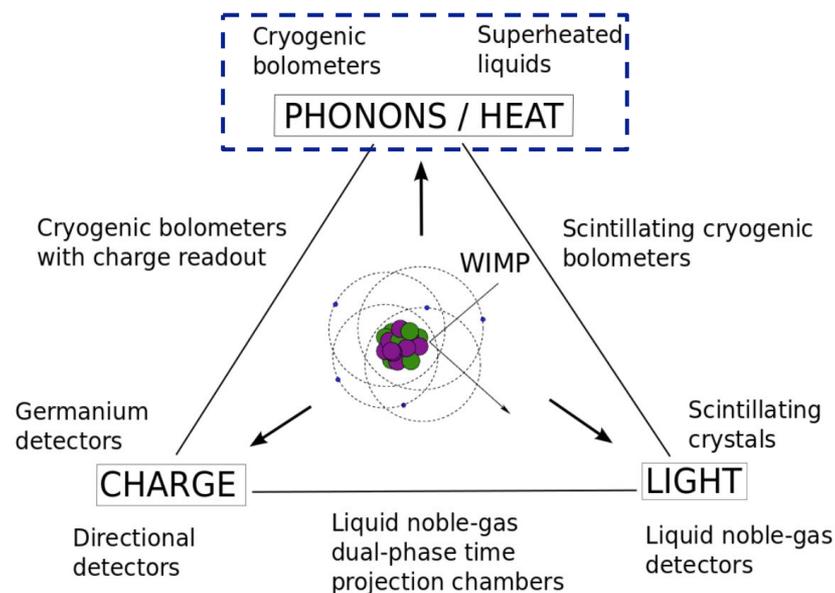
# Why do we need a lower threshold detector?



- **CE $\nu$ NS 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

# Why we turn to phonons



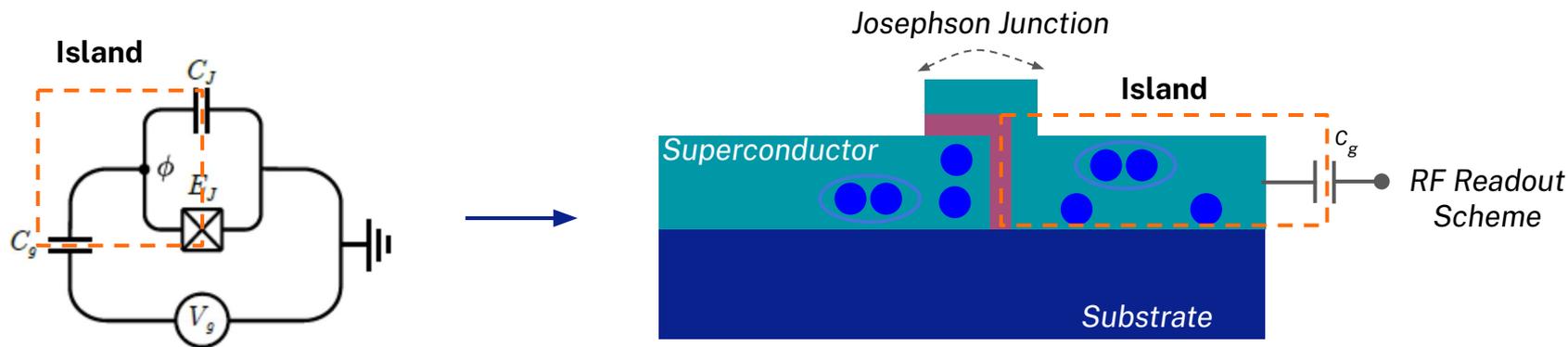
> 10 eV for gaseous and liquid detectors

> 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 CE $\nu$ NS recoil energies on the order of **0.1 to 10 eV**.
- Below  $\sim 1$  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



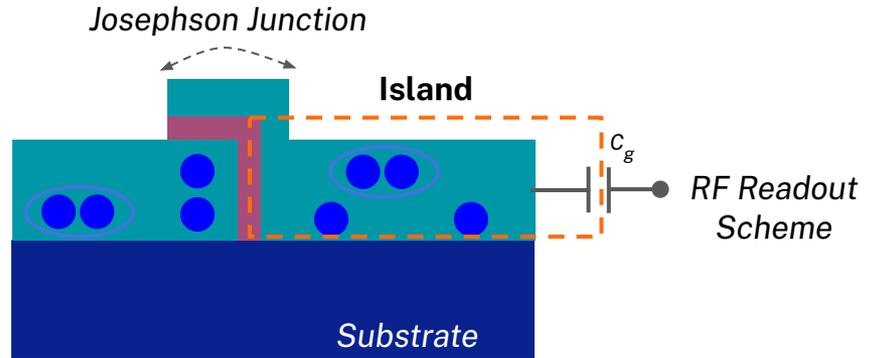
Capacitance energy    Cooper pairs on island    Gate charge    Parity of qp's on island ( $\pm 1$ )    Josephson energy

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

- 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**).

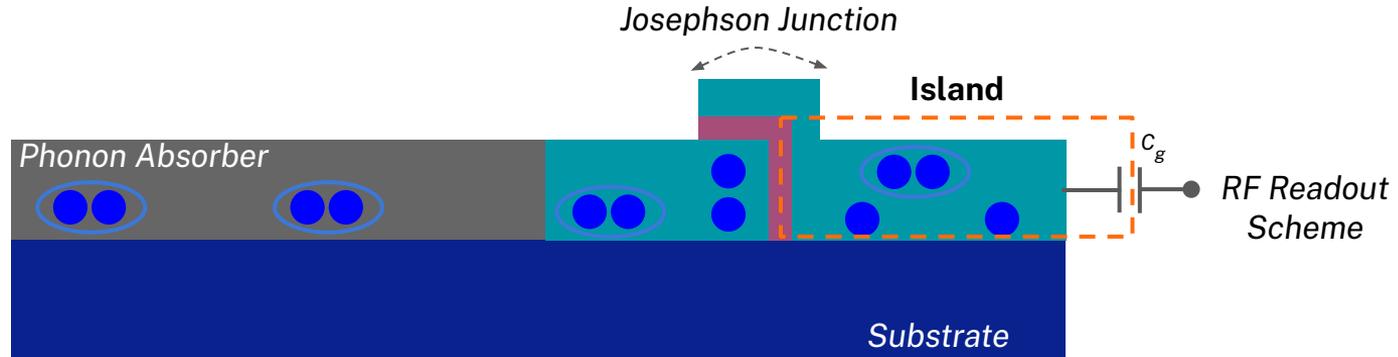
# Qubit-based phonon sensor

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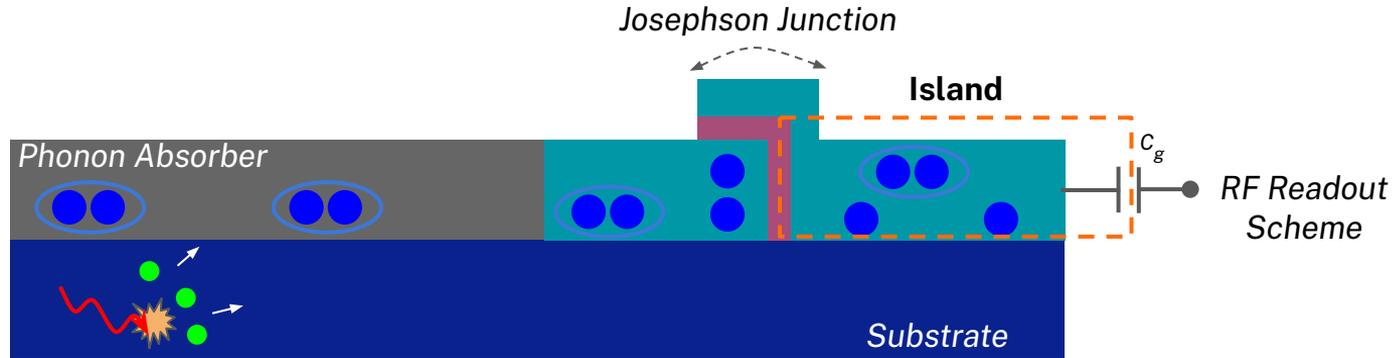


# Qubit-based phonon sensor

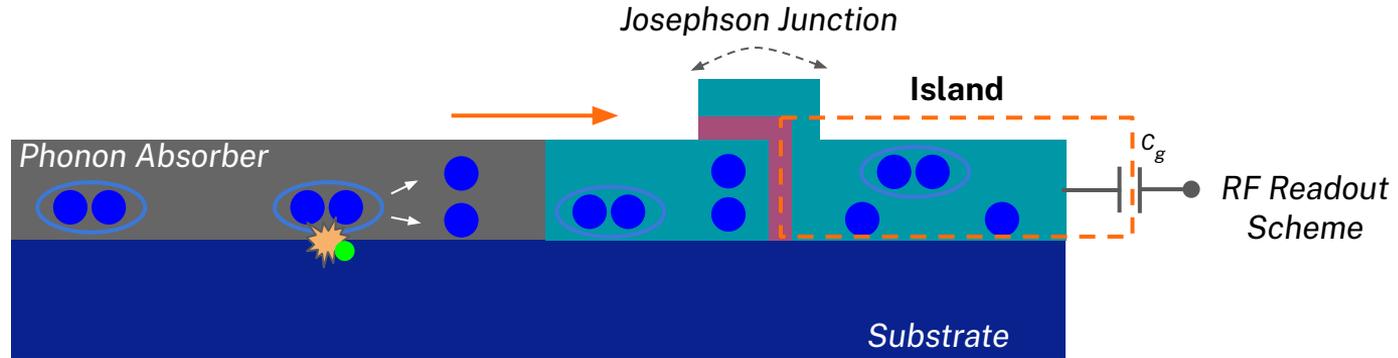
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# Qubit-based phonon sensor

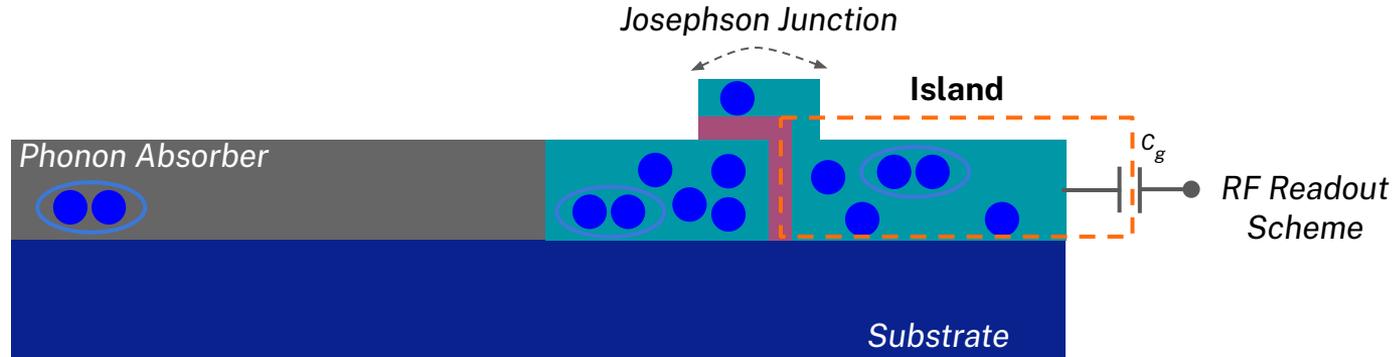


# Qubit-based phonon sensor

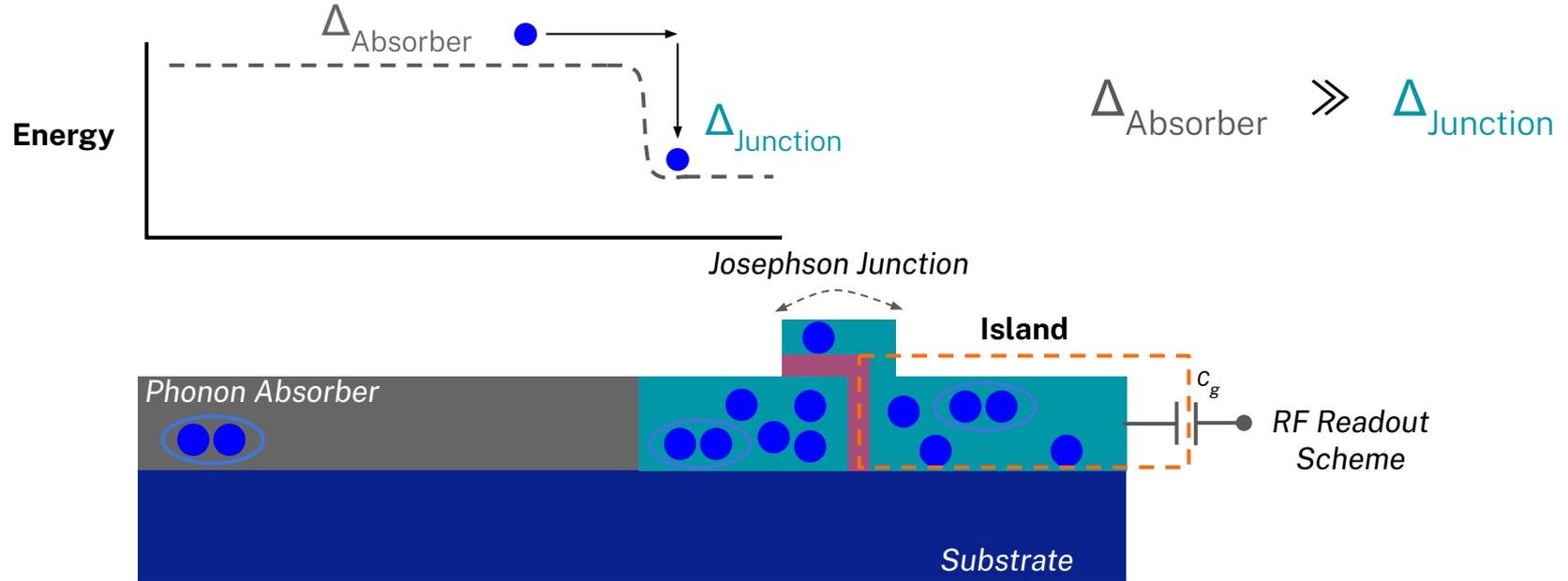


# Qubit-based phonon sensor

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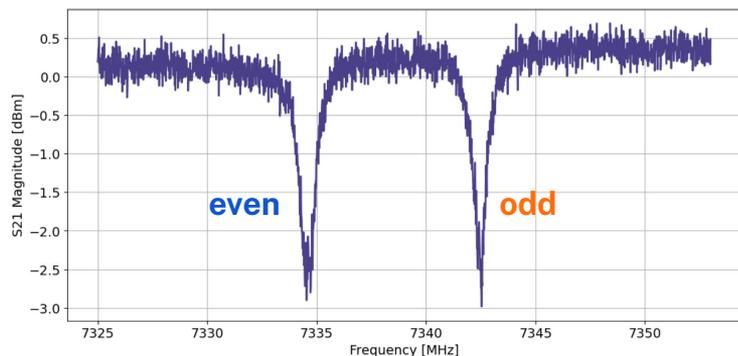
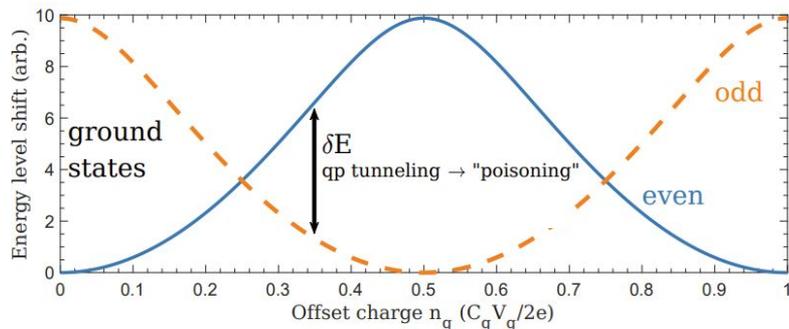


# Qubit-based phonon sensor



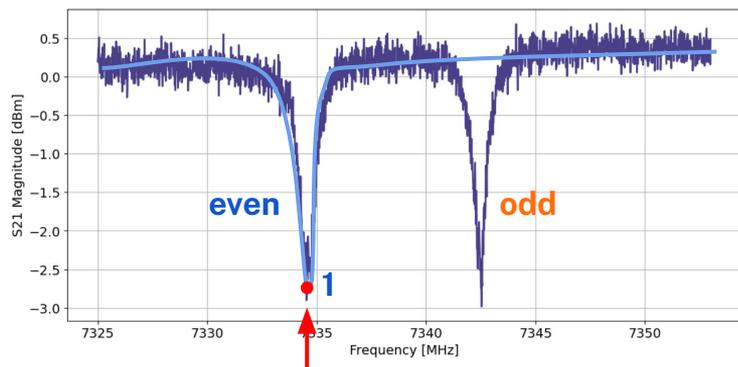
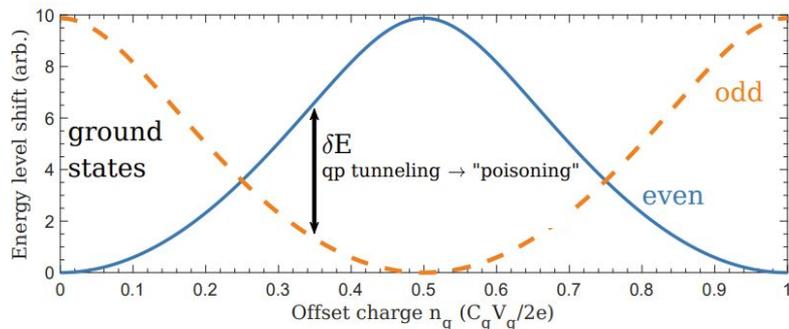
- QPs diffuse into the junction, fall to the new bandgap (which may generate more QPs from the emitted phonons), become trapped, and tunnel back-and-forth across junction until they recombine.

# Signal response



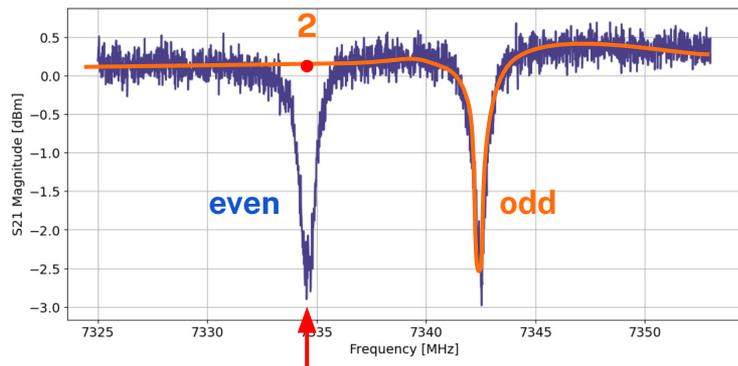
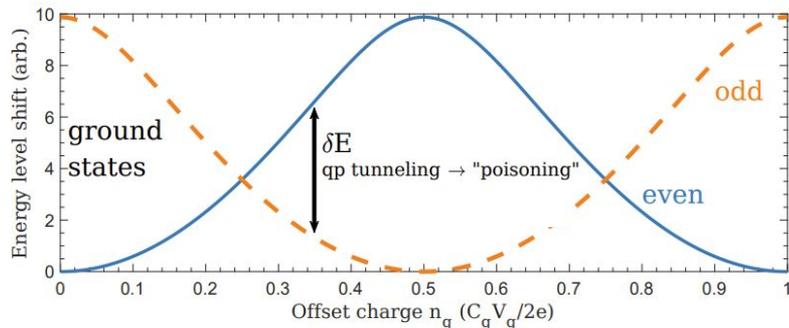
- Each tunneling event causes the qubit to switch parity, changing the energy of the qubit
- By probing the qubit with an RF tone, this leads to two distinct resonances corresponding to each parity state
- O(10 MHz) shift in resonant frequency expected from a parity shift

# Signal response



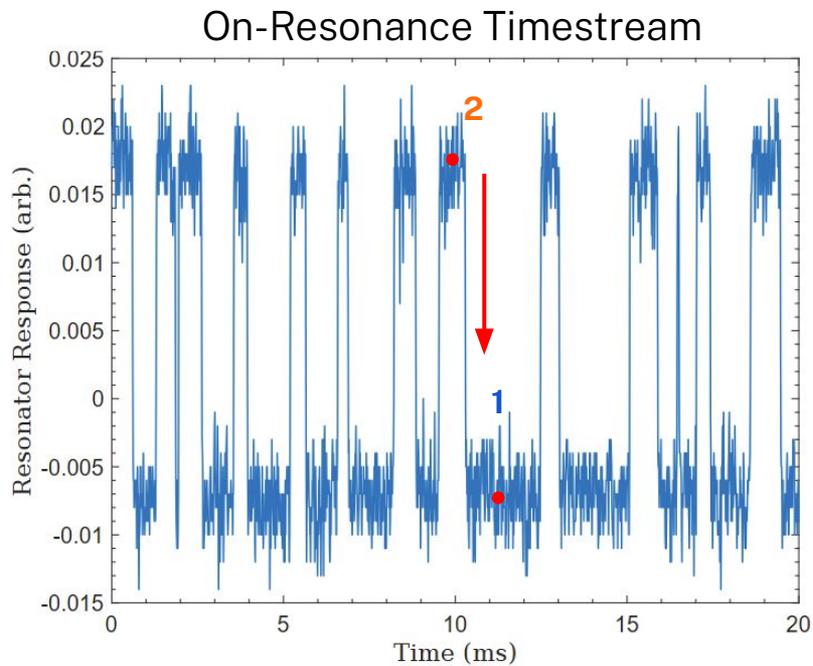
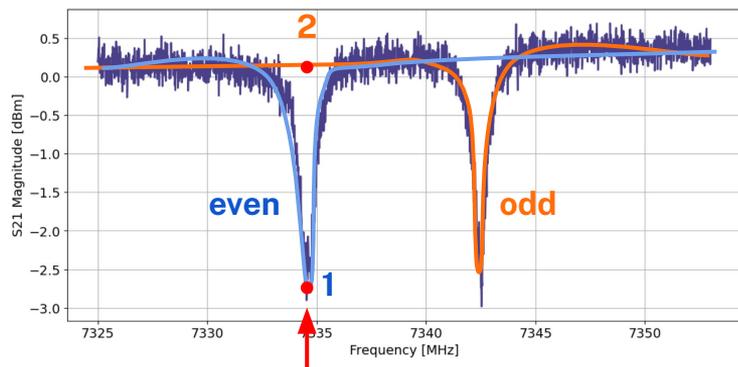
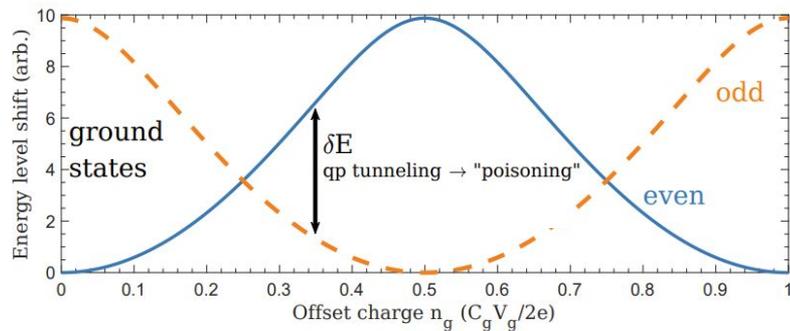
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# Signal response

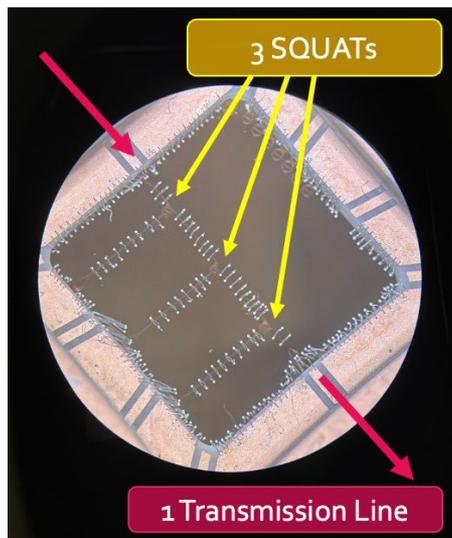


- Each tunneling event causes the qubit to switch parity, changing the energy of the qubit
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# Signal response



# Current status of SQUAT devices



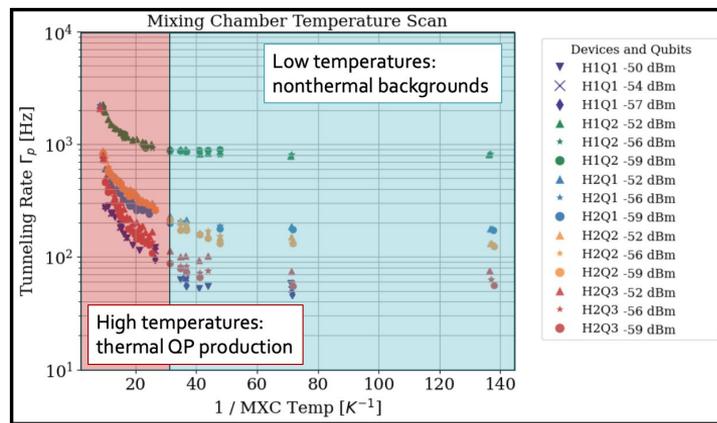
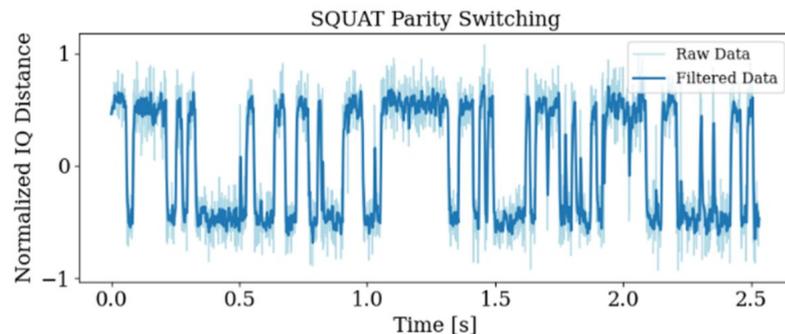
Calibrating Interactions in Low-Threshold, Phonon-Mediated Qubit Detectors

Grace Bratrud (Northwestern University)

10/9/25, 2:20 PM

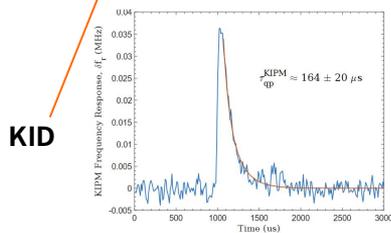
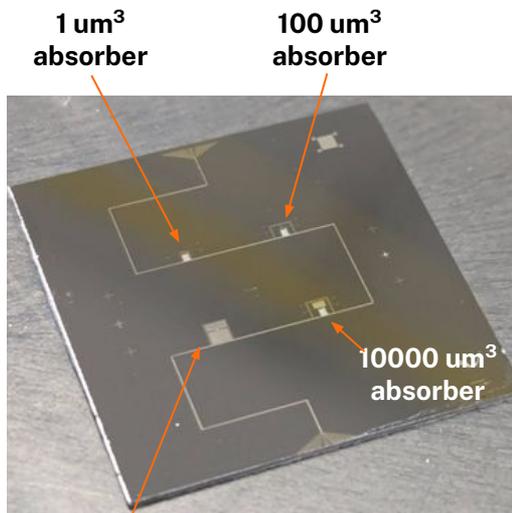
RDC 7 Low-Background ...

Parallel session talk

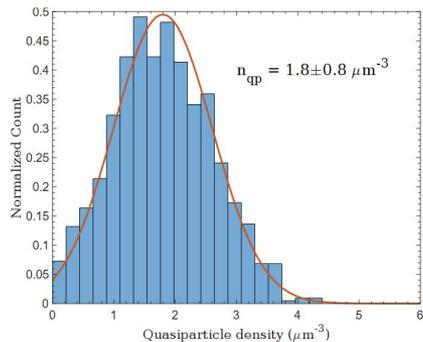
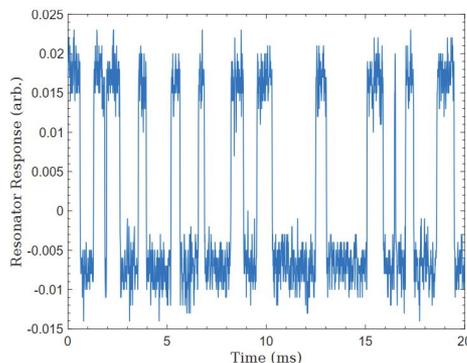


- Qubits able to be probed, and parity signal is observed
- **~20 Hz parity switch rate**, from nonthermal background
- Able to see tunneling rate become thermally dominated at higher temperatures
- Estimated quiescent quasiparticle density of  **$0.1 \mu\text{m}^{-3}$**

# Current status of QPD devices

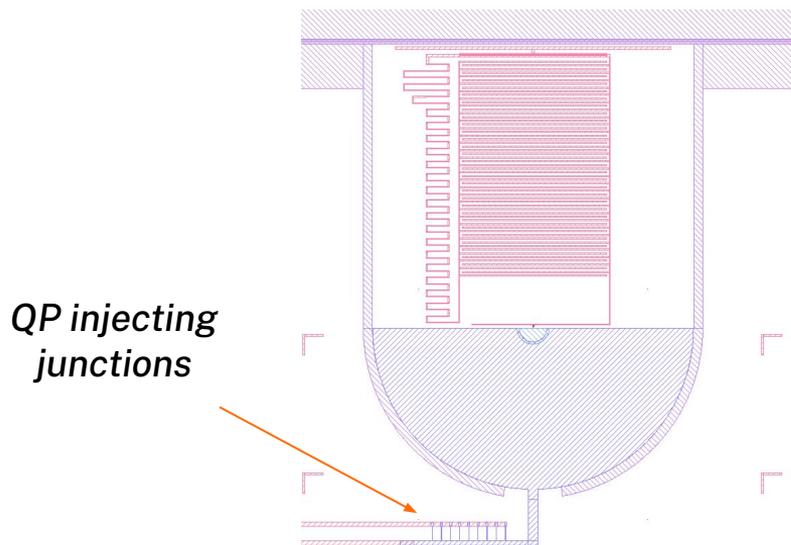


QPD Parity Signal



- 1  $\mu\text{m}^3$  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  **$1.8 \pm 0.8 \mu\text{m}^{-3}$**

# Future device tests



## ***STJ Quasiparticle Injectors***

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

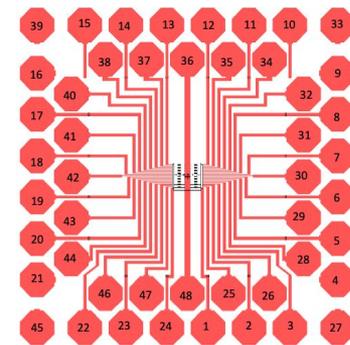
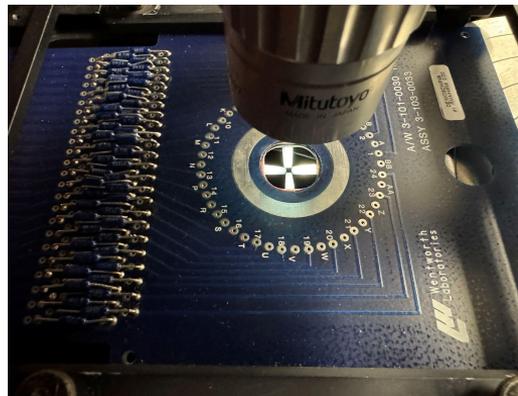
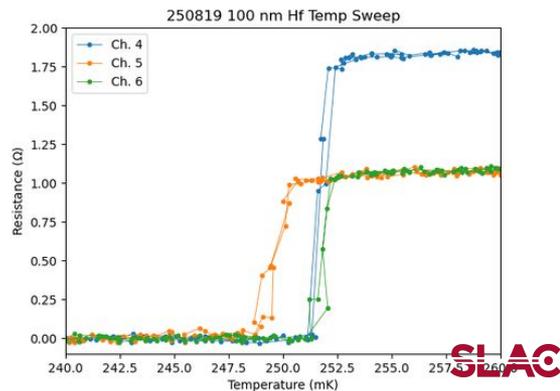


## ***LED-Generated Phonon Calibration***

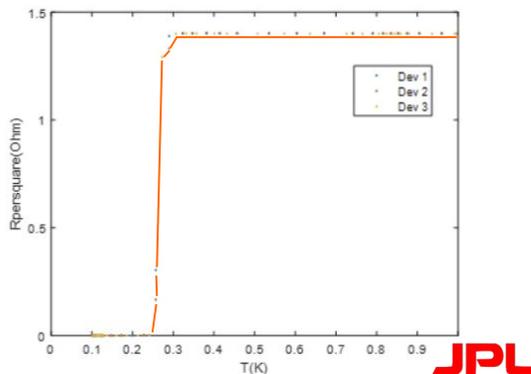
- Well tested on phonon-mediated KID sensors in the past

# Low Tc junction R&D

Hafnium  
RxT Test

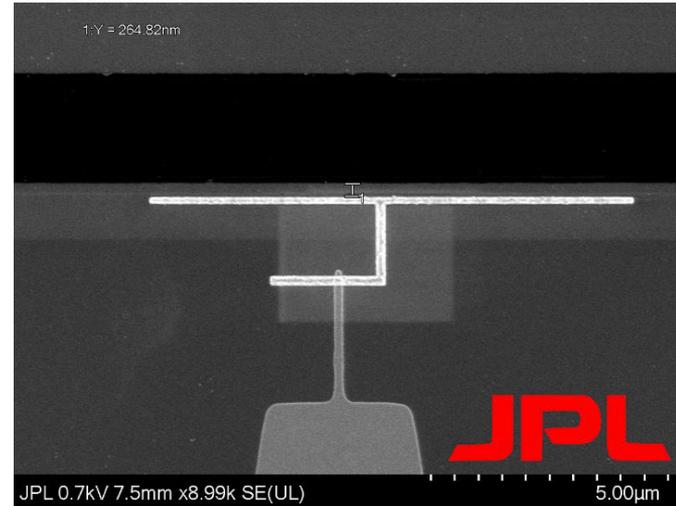
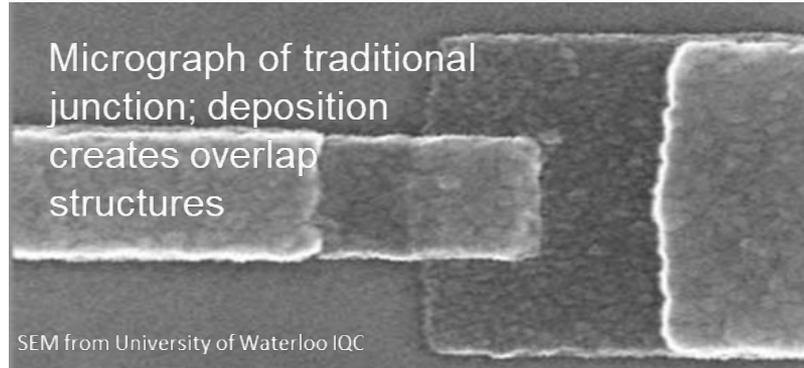


Al-Ti-Au Trilayer  
Rxt Test



- 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**

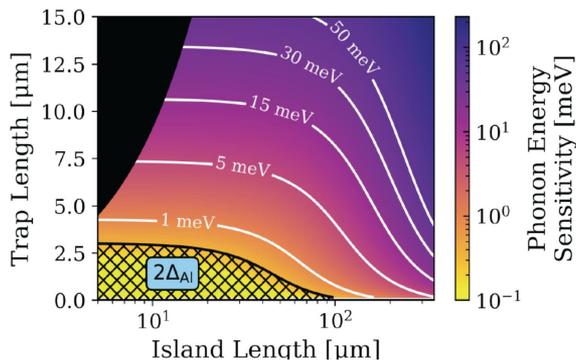
# Junction fabrication techniques



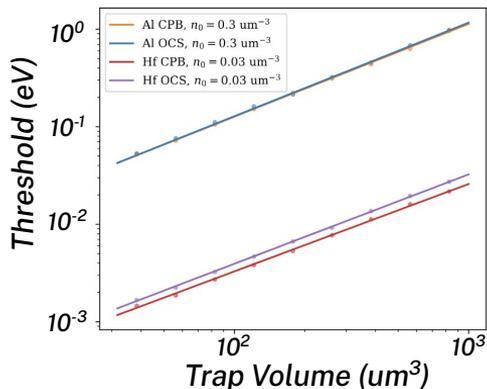
- Standard junction techniques (e.g. shadow evaporation) can create parasitic secondary junctions □ possibly blocking quasiparticle transport
- Utilizing and developing “ion-milled” junctions that do not suffer from parasitics

# Conclusion: sights set on $O(\text{meV})$ resolution!

SQUAT  
Sensitivity  
Estimates

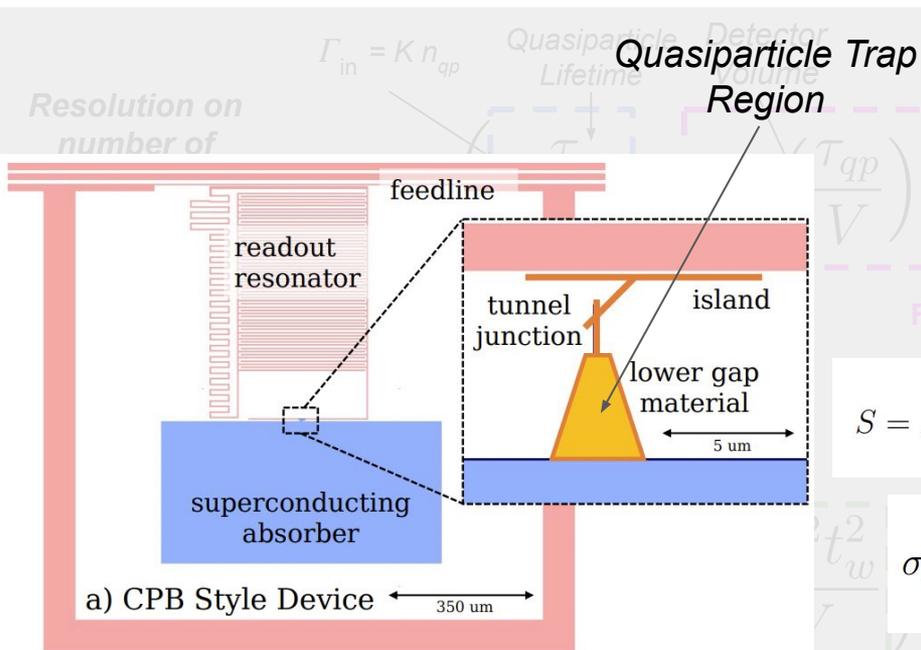


QPD  
Sensitivity  
Estimates



- 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  **$O(\text{meV})$**  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



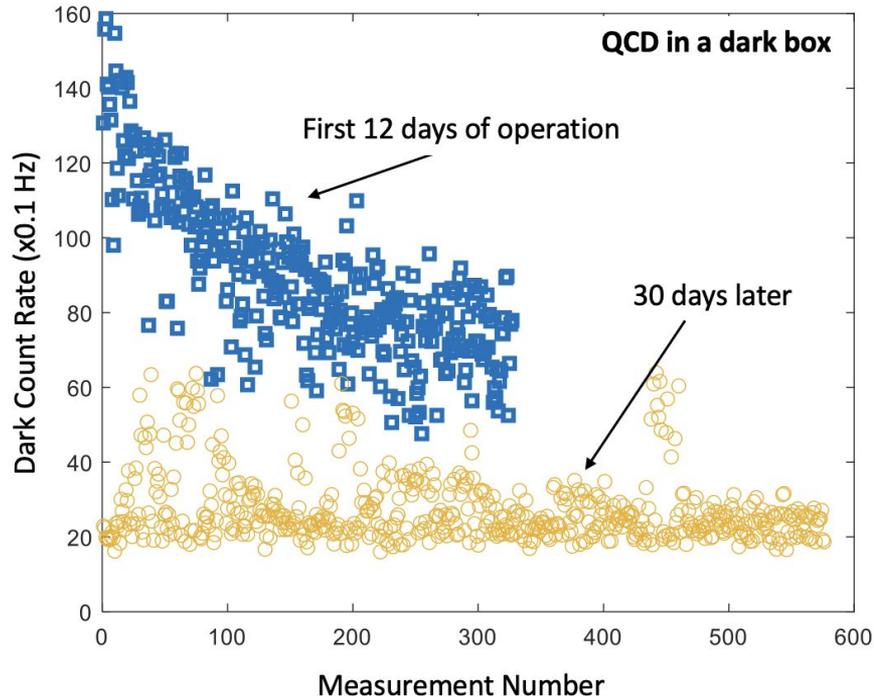
- Our signal benefits greatly from smaller QP collecting volume! **Investigating using QP trapping into small junction electrode volume** → will be needed for ultimate sub-eV substrate sensitivity

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

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

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

# Evidence of time-dependent DCR

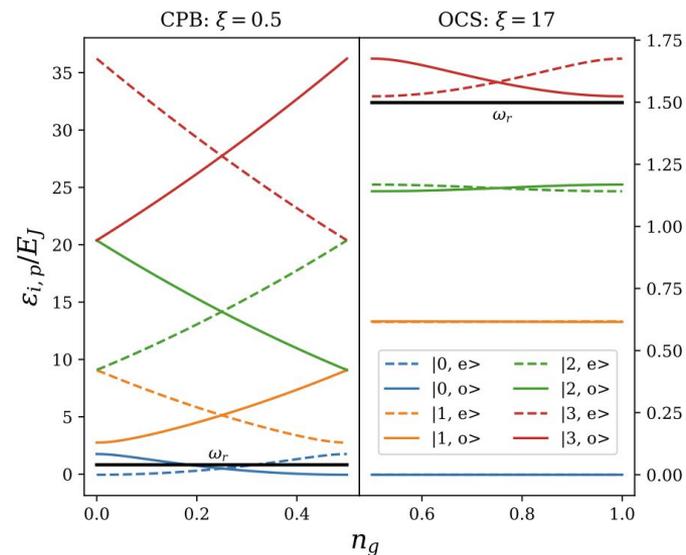


- Operation of a similar photon sensitive QCD in a dark box shows **dark count rate** reduction over O(month).
- Potentially similar source & mechanism as that contributing to Low Energy Excess identified in other cryogenic phonon sensing experiments.
- Eventual goal of measuring sub-eV energy spectrum.

# CPB vs. OCS transmon

$$\xi = E_J / E_C$$

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



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

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

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

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