Phonon Mediated Quantum Sensors for rare-event searches

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2024/07/09

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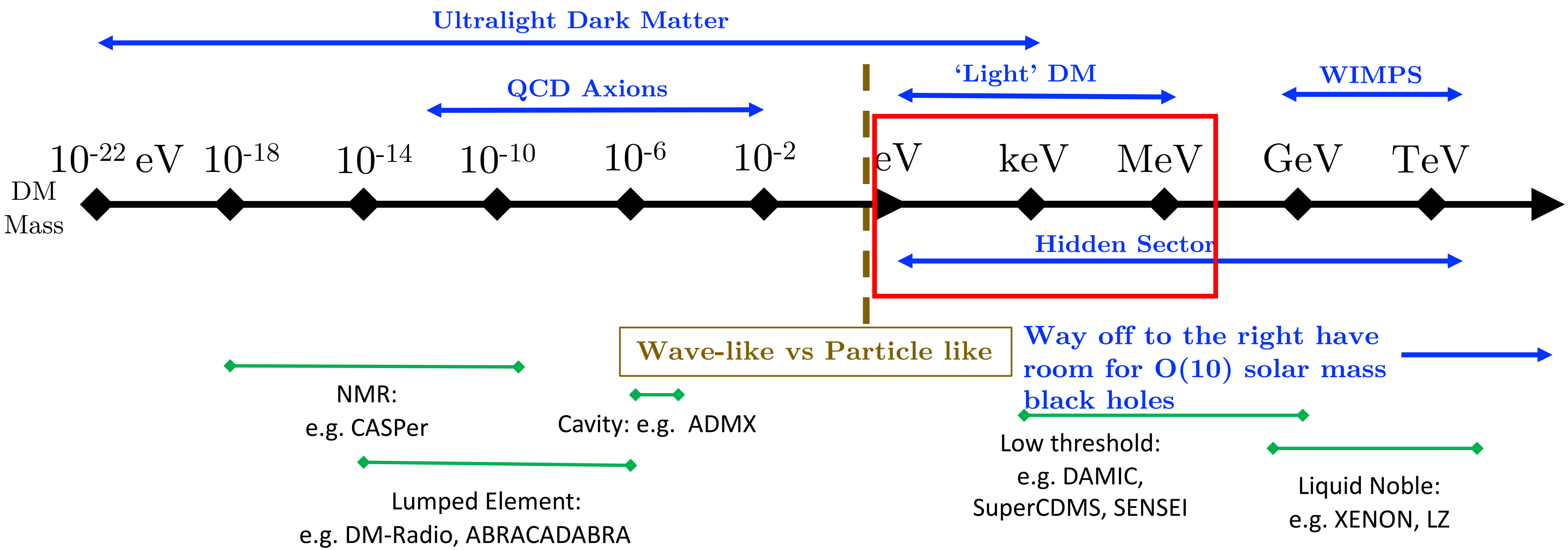
Caltech

Image courtesy of JPL Microdevices Laboratory

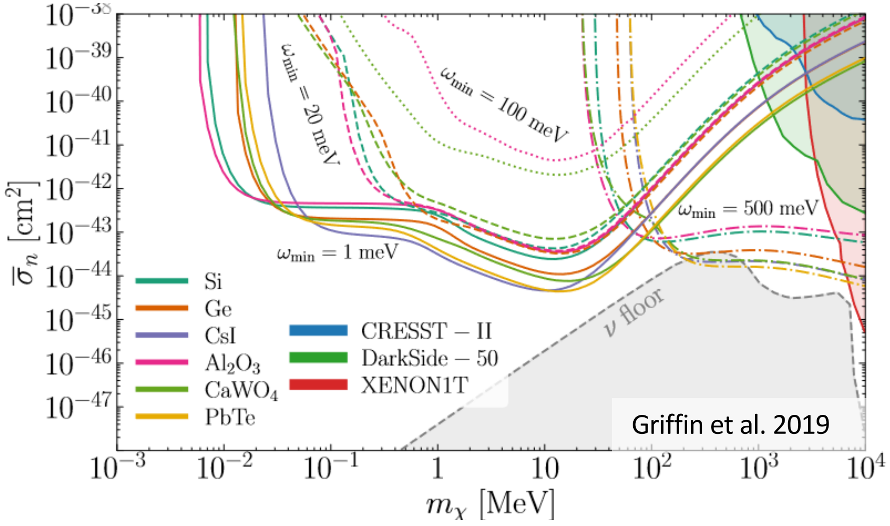
The (expanded) landscape of Dark Matter



US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Sub-GeV dark matter

DM-nucleon scattering with heavy scalar mediator



Can iterate on existing technology, but moving down the mass scale, energy deposits get much smaller:

$$\Delta E \lesssim 70 \text{ eV} \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{m_T}{28 \text{ GeV}}\right)^{-1} \quad (m_\chi << m_T)$$

$$\lesssim 4 \text{ eV} \left(\frac{m_T}{511 \text{ keV}}\right) \quad (m_\chi >> m_T)$$

Interaction rates for these light mass DM can be close to O(Hz)/kg!

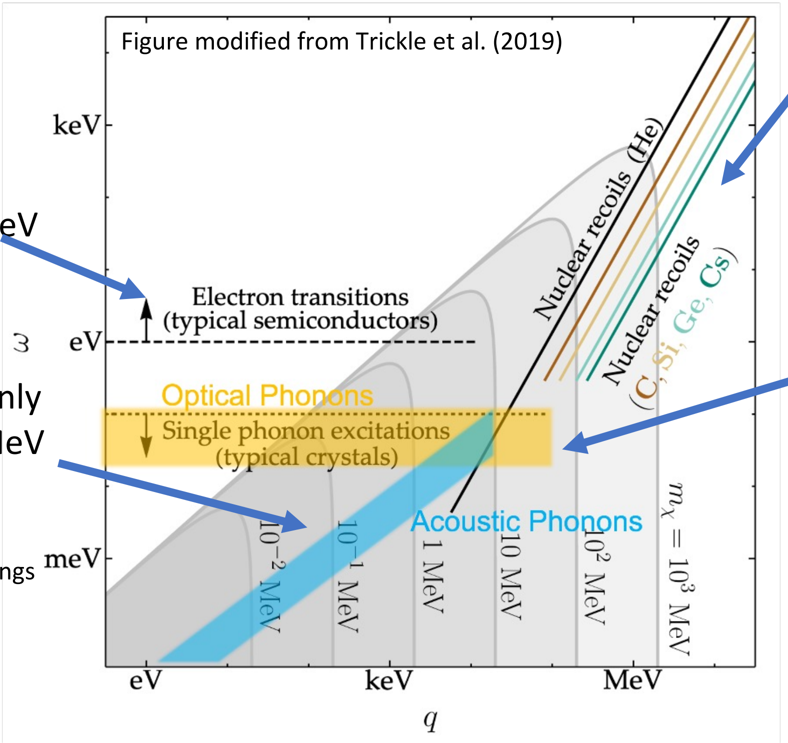
1. What tools exist to measure bulk energy deposits at O(ueV) to O(meV)?
2. Can we leverage techniques from our CM, AMO, Materials etc. colleagues?

Kinematic Space

Electronic transitions ~eV scale

Phonons are basically only game in town for <10 MeV couplings*

*assuming no EM or other couplings

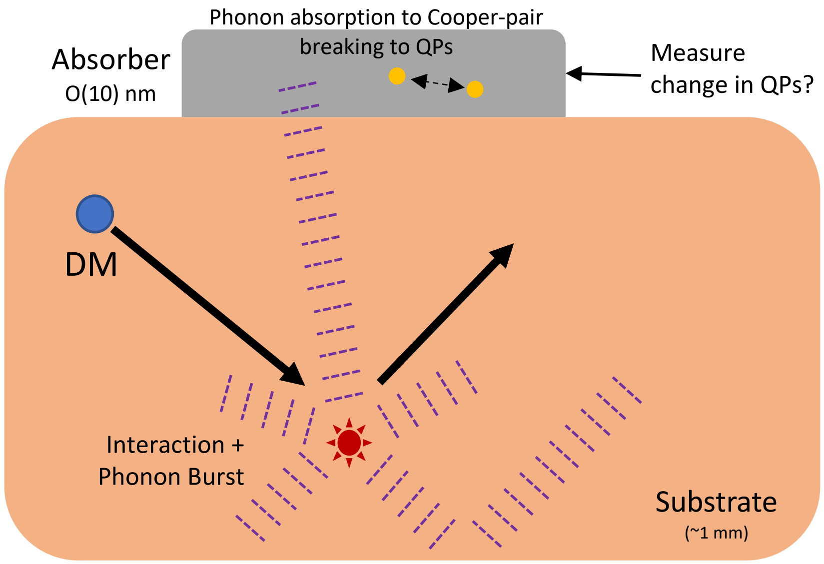


Nuclear recoil loci only goes down to where nuclei can be considered ~independent

Polar materials (e.g. GaAs, AlO3) can have strong optical phonon excitations for certain DM candidates with EM couplings

To probe certain masses of dark matter we need to achieve single phonon sensitivity O(10-100) meV

The (athermal) Phonon Channel



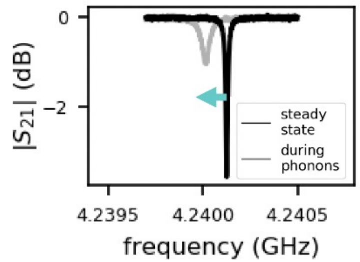
1. Fireball of O(THz) phonons at interaction site
2. Decay into lower energy phonons
3. "Quasiballistic" propagation – long MFP
4. Phonons encountering metallic interface (e.g. superconducting film) will be absorbed
5. Energy can break Cooper-pairs (pair breaking energy 2Δ) → produce "quasiparticles" → measure change?

+ Phonon energies O(meV)
+ Information about interaction position and energy
+ Potentially thousands of phonon interactions
+ No relevant fluctuation background (thermal phonons suppressed by mK temp.)

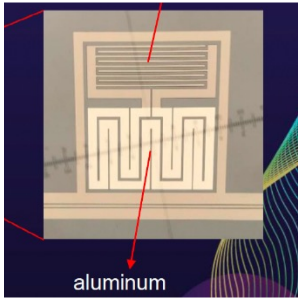
- Phonon diffusivity → energy split across sensors

Kinetic Inductance Detectors (KIDs)

- Superconductors have an AC inductance due to physical inertia of Cooper pairs → **Kinetic Inductance**



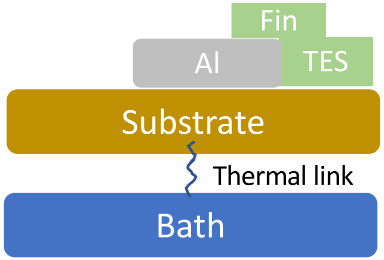
Design Stage	σ_{pt} 1g Si absorber
Current Technique	10-20 eV (meas.)
Optimized Single KID	5 eV (proj.) - 2024
Quantum Limited Amplifier	1 eV (proj.) - 2025
Improve t_{qp} to 1 ms	0.5 eV (est.) - 2025
Lower T_c material	O(100) meV (est.) 2025+



+ Highly multiplexable, kHz linewidths on GHz readout
+ Fundamentally non-dissipative
- High residual quasiparticle level ~10-1000 um^{-3} of unknown origin, suspected to be readout power generated → limits quasiparticle lifetime and worsens sensitivity and resolution.

Transition Edge Sensors (TESs)

- Voltage biased to sit at superconducting transition



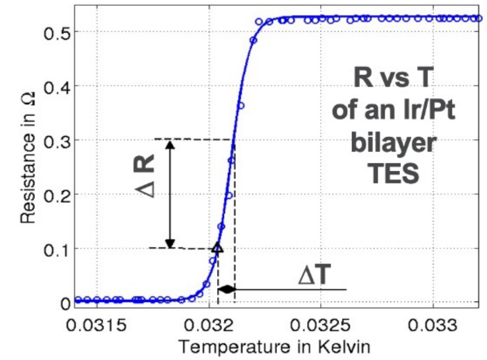
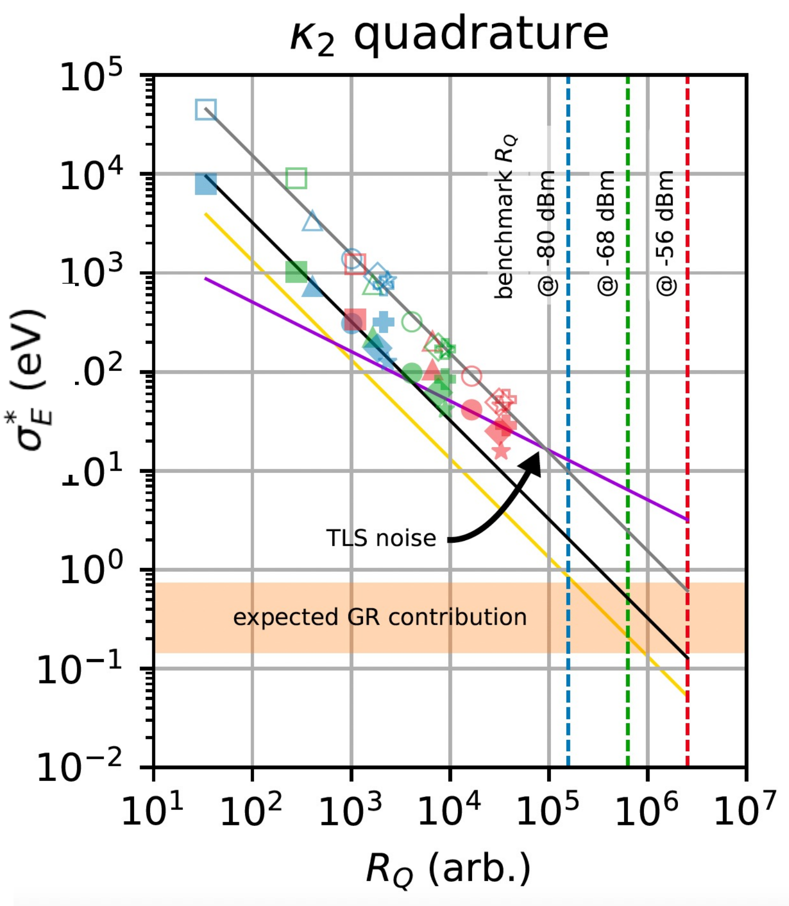


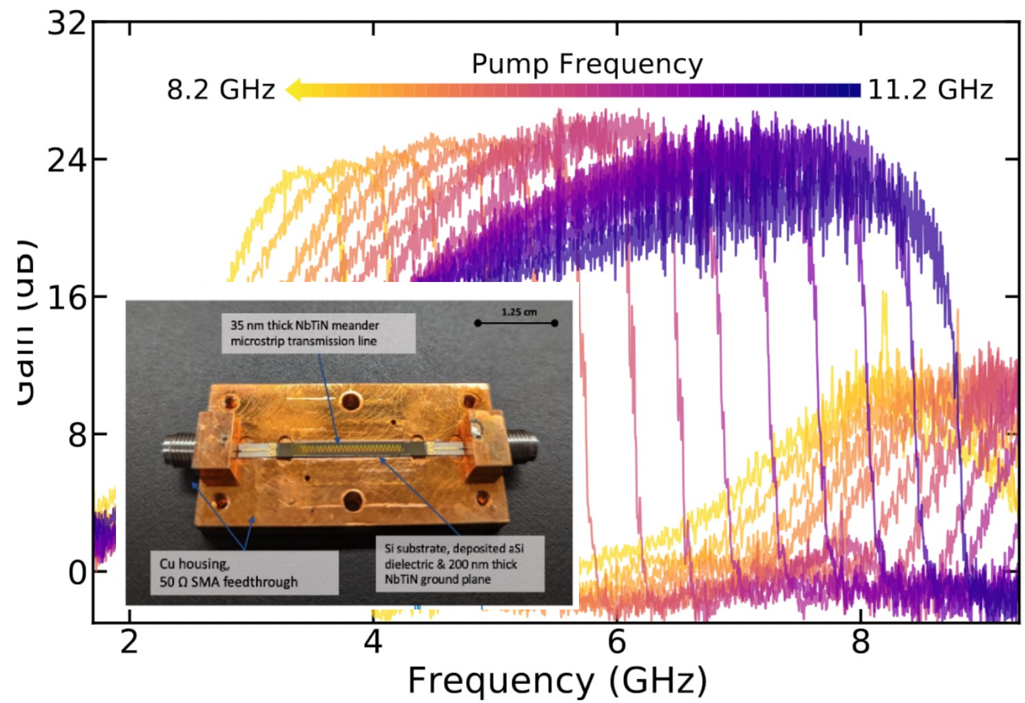
Figure from Chang, Wang Snowmass 2021 talk (2022)

+ 30 year history of development with validated noise modelling
- Need low T_c → 10 mK to improve performance - challenging materials + deposition/fabrication R&D
- $T_C^{3/2}$ & thermal conductance ~T^4 still valid?
- Parasitic power shielding getting onerous?

TESs demonstrated down to ~300 meV resolution!

Noise improvement in KIDs using Parametric Amplifier





Significant noise improvement in a Kinetic Inductance Phonon-Mediated Detector by use of a wideband parametric amplifier arXiv:2402.05419

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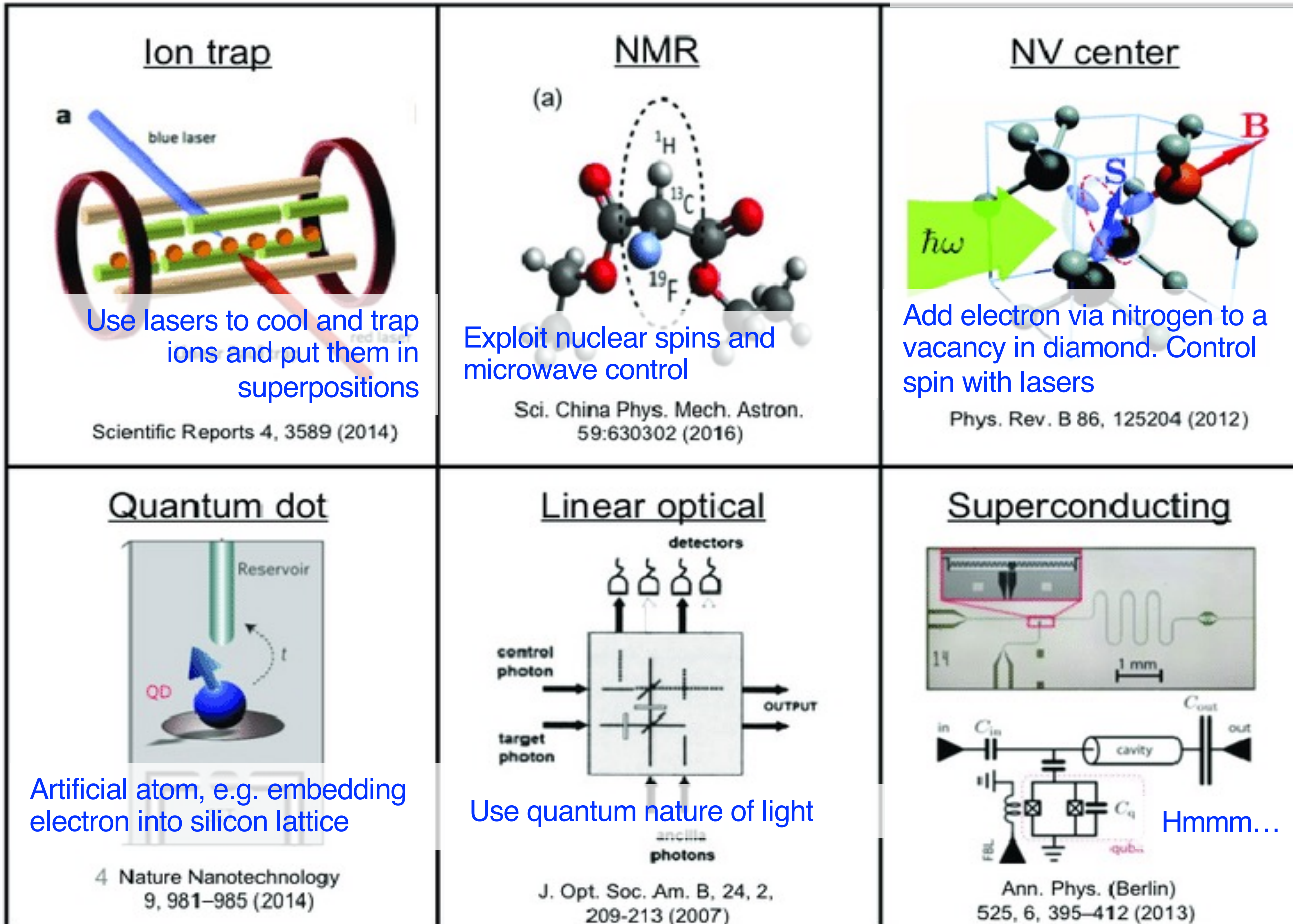
(Dated: January 19, 2024)

Qubits

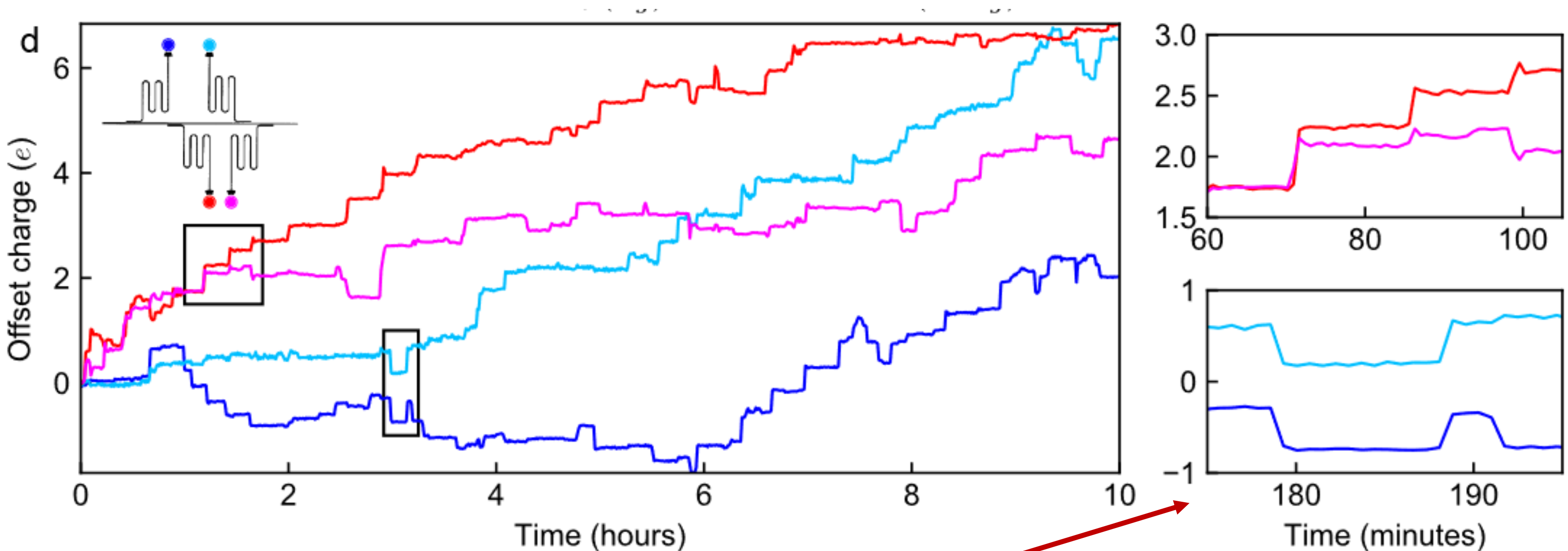
- Quantum mechanical two-level systems, well defined “states” |0⟩, |1⟩ that you can *superpose, entangle, interfere*
- Why? Allows you to do exciting things in computing. This isn’t a quantum computing talk…
- What makes these interesting for non-QIS practitioners? **Relevant energy scales can be << eV**
- *Environmental effects at those energies affect/modify the qubits → e.g. radiation detection*

Amundsen, 2019 (CHEP 2018)



Correlated Charge Noise

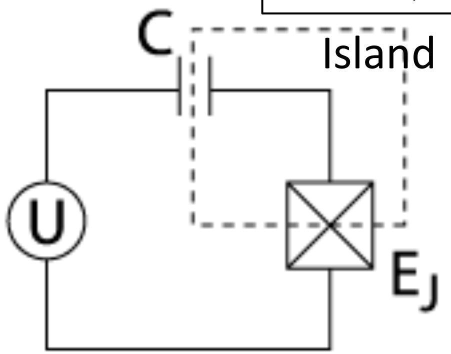
Wilen et al., Correlated Charge Noise and Relaxation Errors in Superconducting Qubits, Nature, 2021

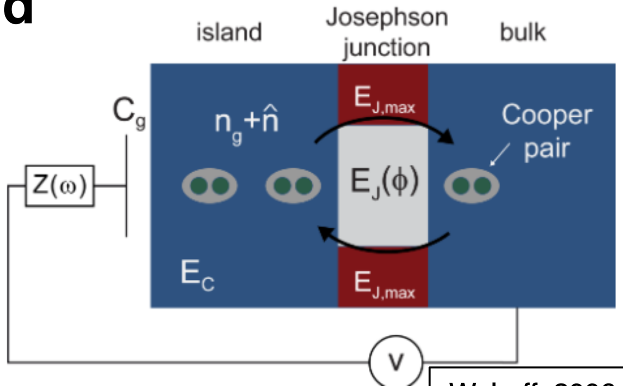


- Noted changes in certain parameters (“offset charge”) across multiple qubits on same substrate
- Traced to likely muon and gamma energy absorption events within wafer

Cooper-pair Box (CPB)

Wikimedia, 2018





Walraff, 2006

- Stick Josephson Junction (SIS sandwich) into a circuit with a capacitance and a voltage bias, creates a superconducting *island* that is connected to a bulk reservoir.
- Relevant D.O.F: **# of Cooper pairs on the island**

Serniak et al. 2019

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

Charging energy (energy to add another Cooper pair to the island): $(2e)^2/2C_g$

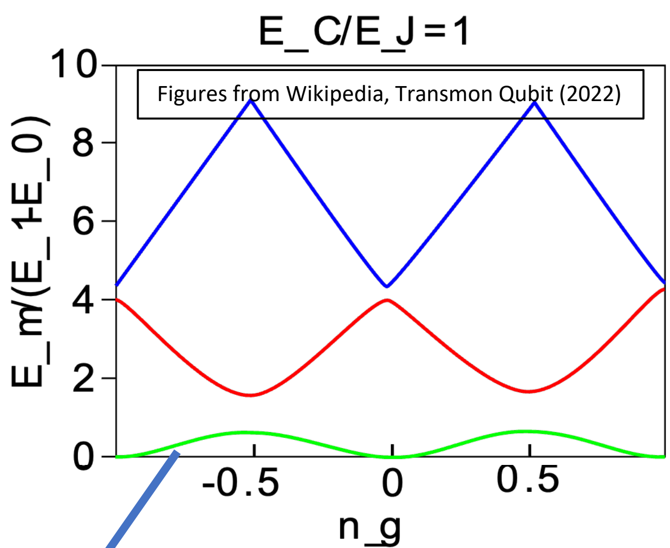
Josephson energy

Parity: ± 1, measure of number of electrons (even/odd)) that have traversed the junction

Dimensionless *offset charge*: $C_gV_g/2e$

Quantum Capacitance Detector

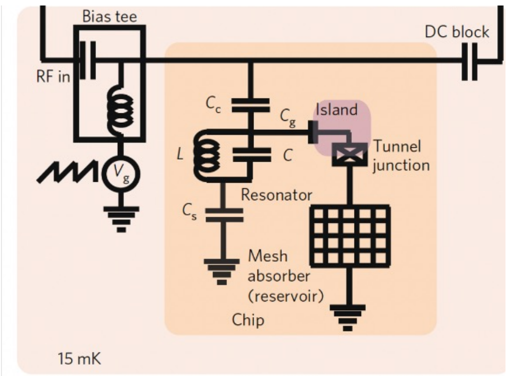
Shaw et al, 2009; Echternach et al. 2017

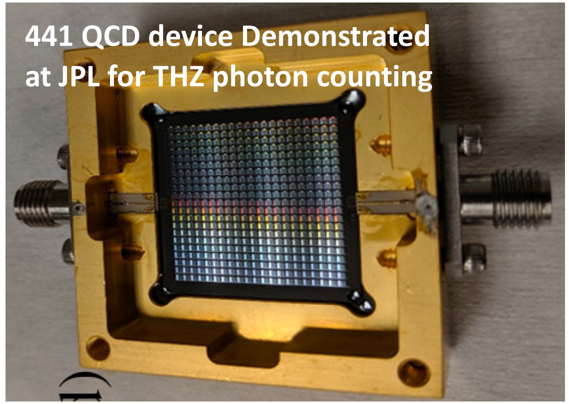


Note curvature of bands

$$C_i = -\frac{C_g^2}{e^2}\frac{\partial^2 E_i}{\partial n_g^2}$$

- Look at Cooper-pair box again, specifically lowest energy level
- Can interpret the curvature as a capacitive term → changes every time a quasiparticle tunnels over (i.e. shifts x-axis)
- Lots of potential for astronomical operation at low photon bkg. shot noise

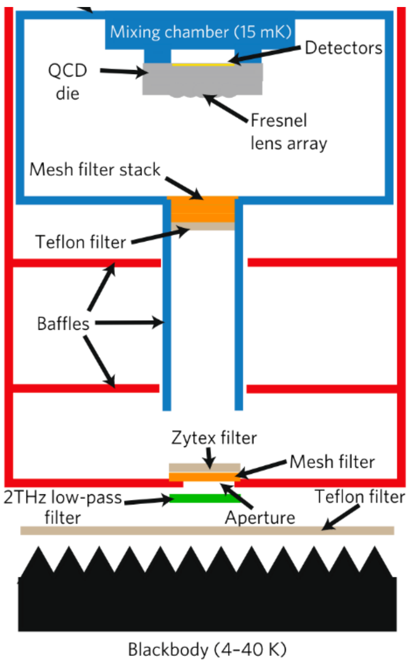




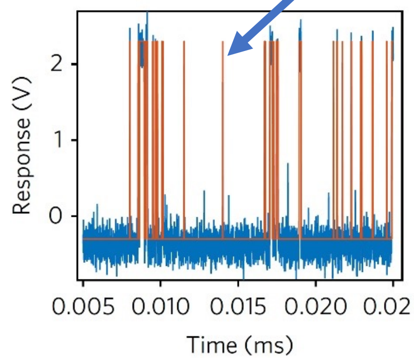
Make a O(GHz) LC resonator and couple this qubit to it – O(MHz) shift from this changing C

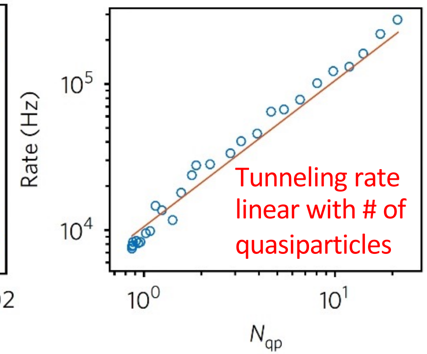
Far-IR Photon Counting @ JPL

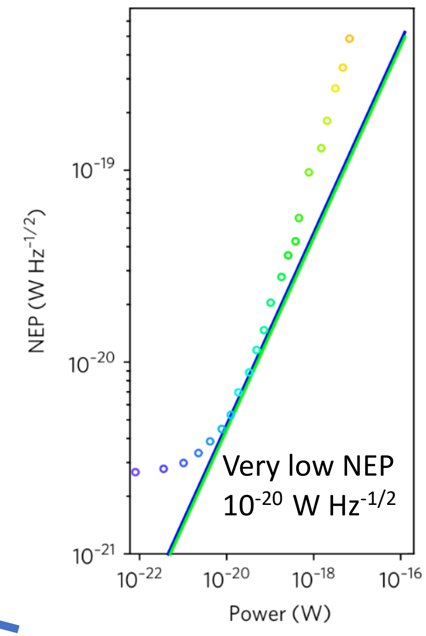
<u>1.5 THz FIR illumination setup</u>

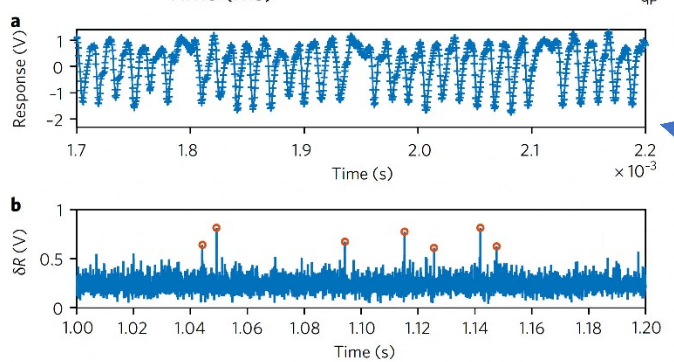


Tunneling trace of QP events





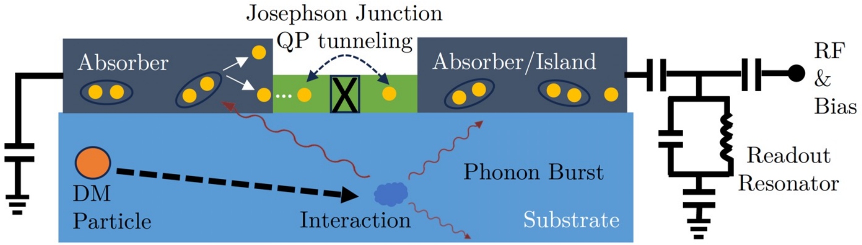




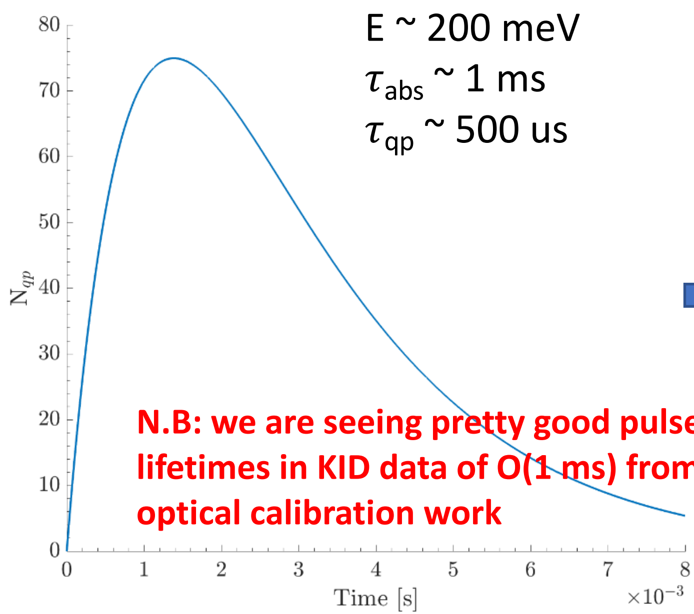
Gate charge drift + high background rate → sweep gate voltage. Photon events changes trace = 1 count

Inferred quiescent quasiparticle density < 1/um^3

Quantum Parity Detectors (QPDs)

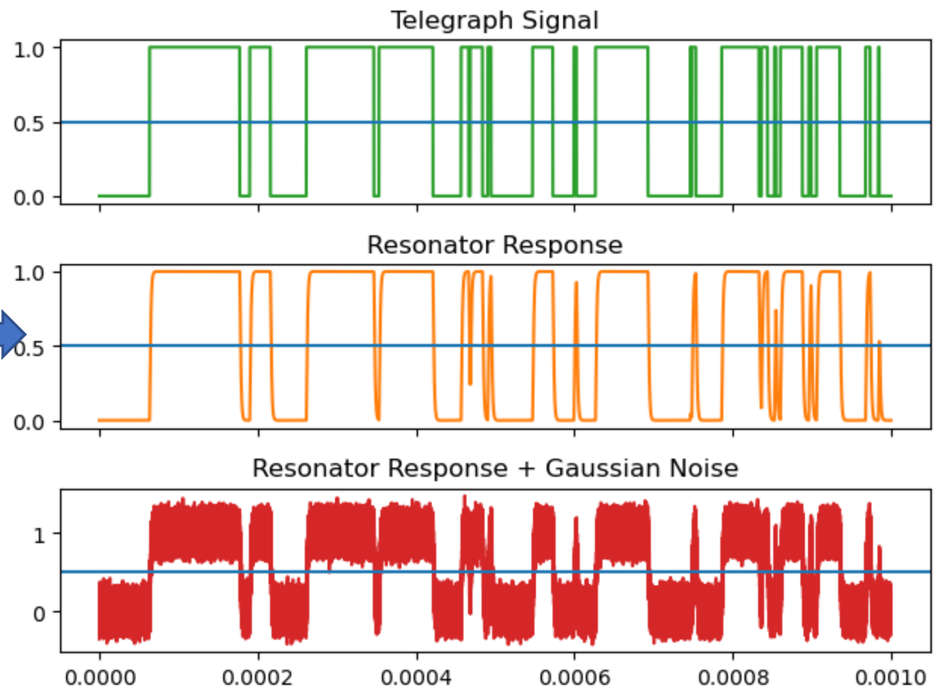


Quasiparticle production in “QPD” absorber



N.B: we are seeing pretty good pulse lifetimes in KID data of O(1 ms) from optical calibration work

Parity signal observed

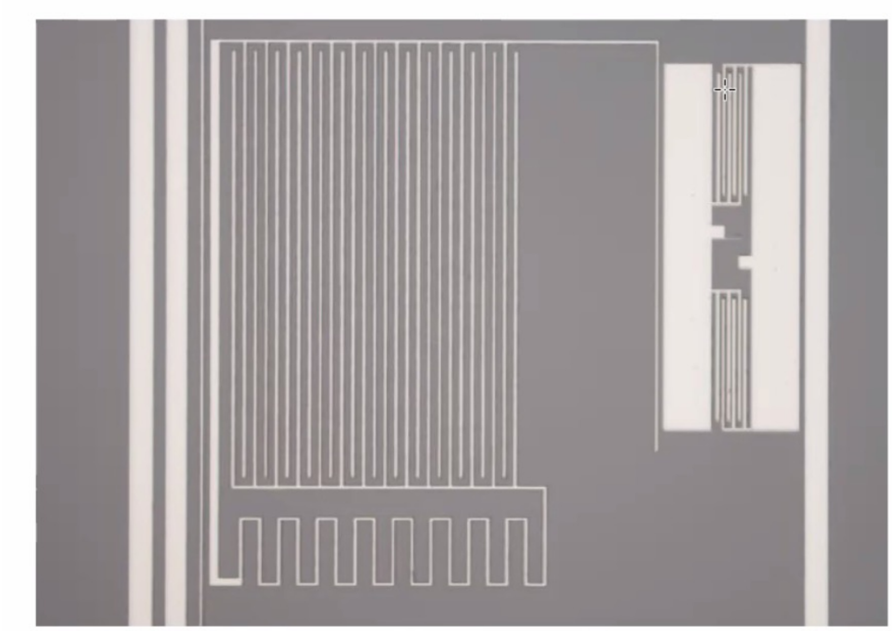


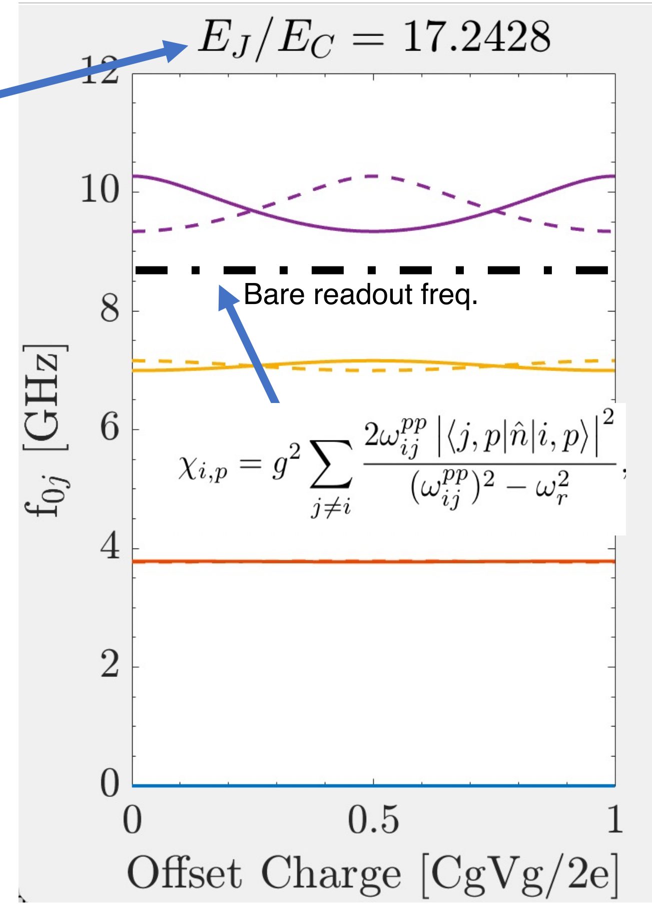
V ~ 100 um^3 Parameters same as FIR-QCD

Offset Charge Sensitivity (OCS)

Serniak et al. PRL, 2019

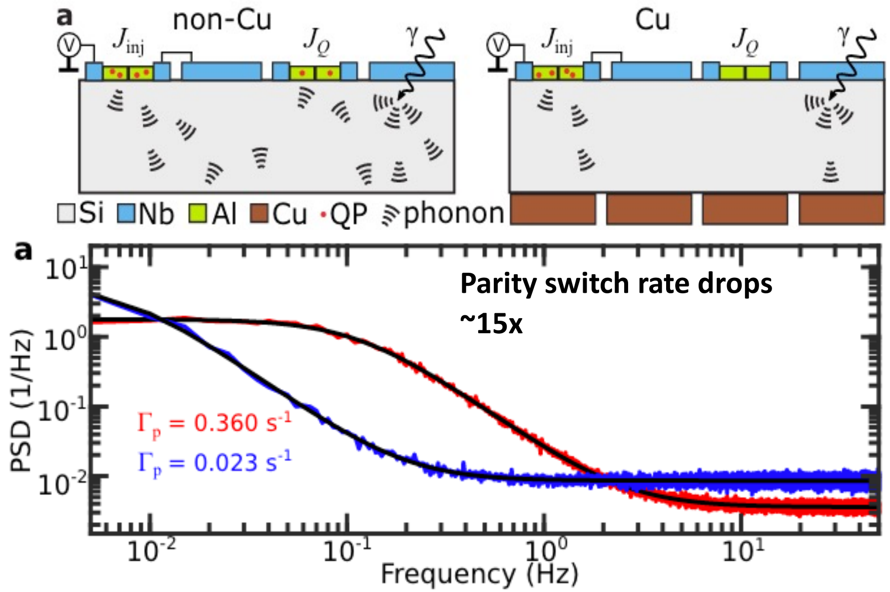
- Stiffen the energy ratios by increasing overall capacitance (e.g. making absorber pads larger) will enter ***transmon*** regime.





Phonons are an already known problem

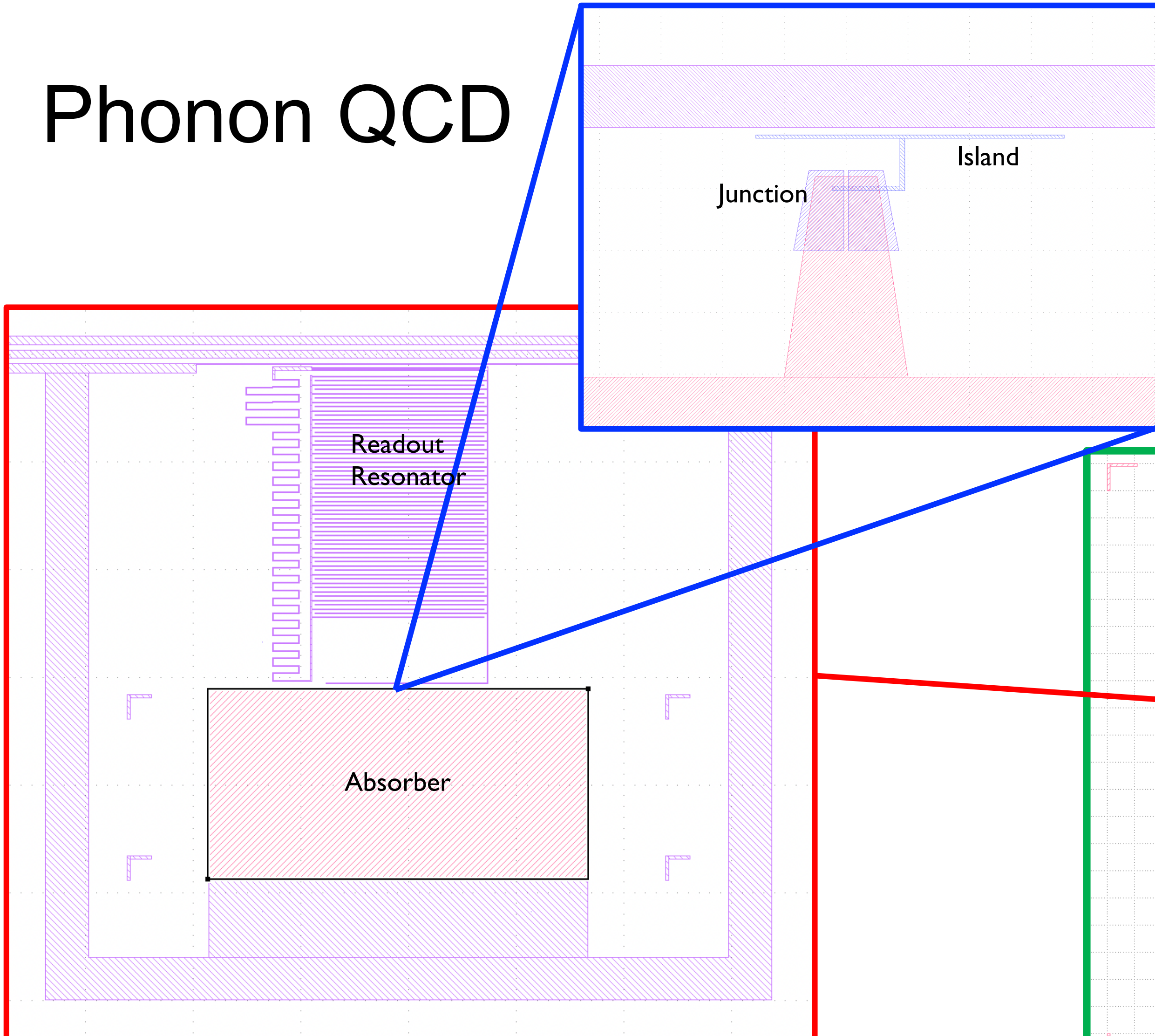
- For regular substrate devices, decoherence traced to *environmentally caused non-equilibrium quasiparticle population*
- Few key takeaways from QIS literature:
    1. Already sensitive to phonon backgrounds and correlated offset charge events
    2. Attempts to suppress these with normal metal absorbers



Iaia et al, 2022

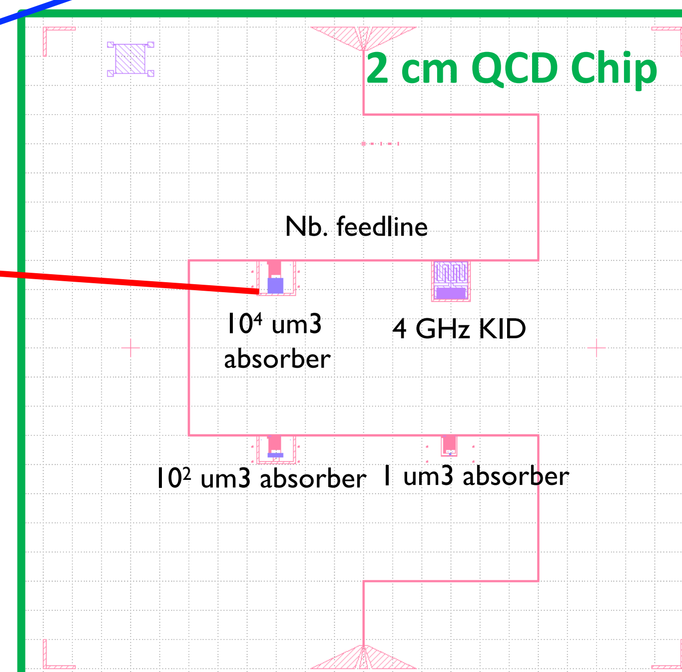
JPL

Phonon QCD



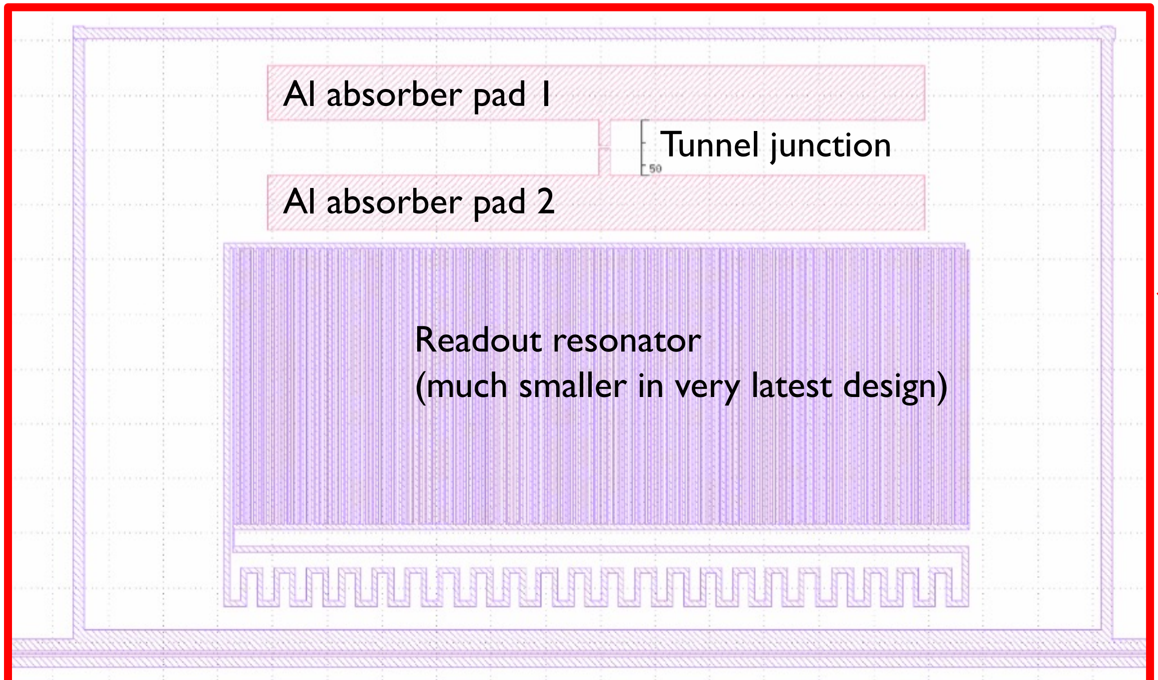
Keep it simple to start:

- **500 um Si substrate**
- **50nm thin Al sensor with Nb resonator/feedline**

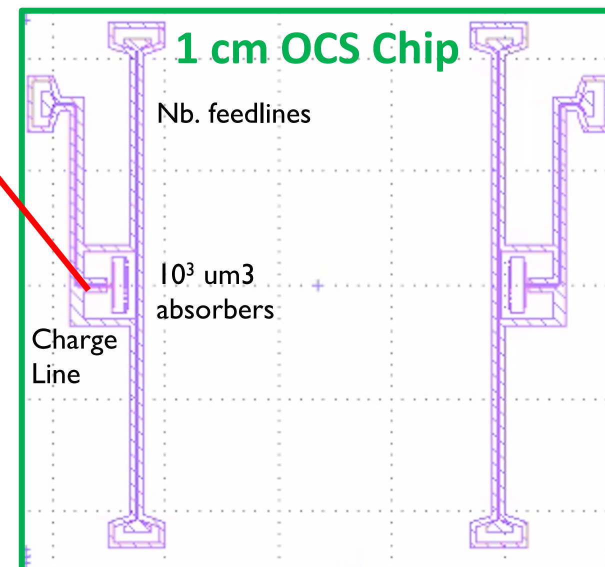


Phonon OCS

WEIZMANN INSTITUTE

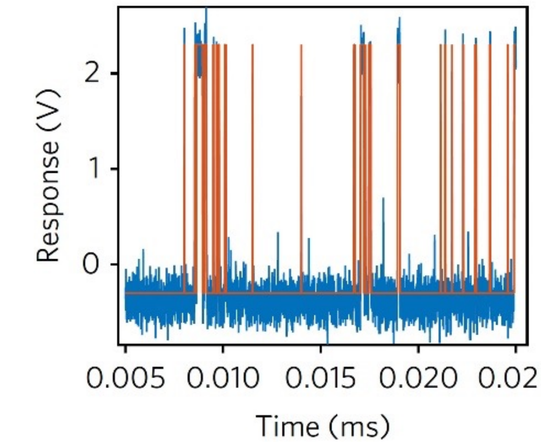


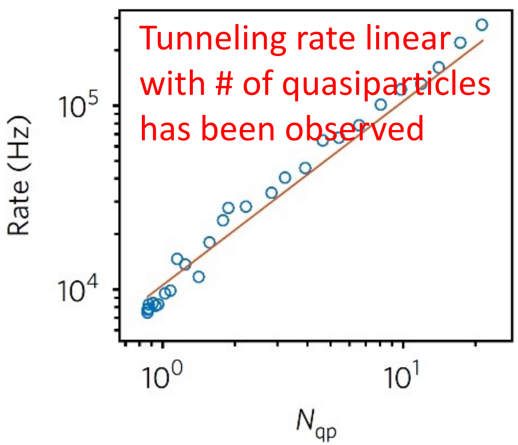
Again Si substrate with Al+Nb components



Expected Signals & Backgrounds

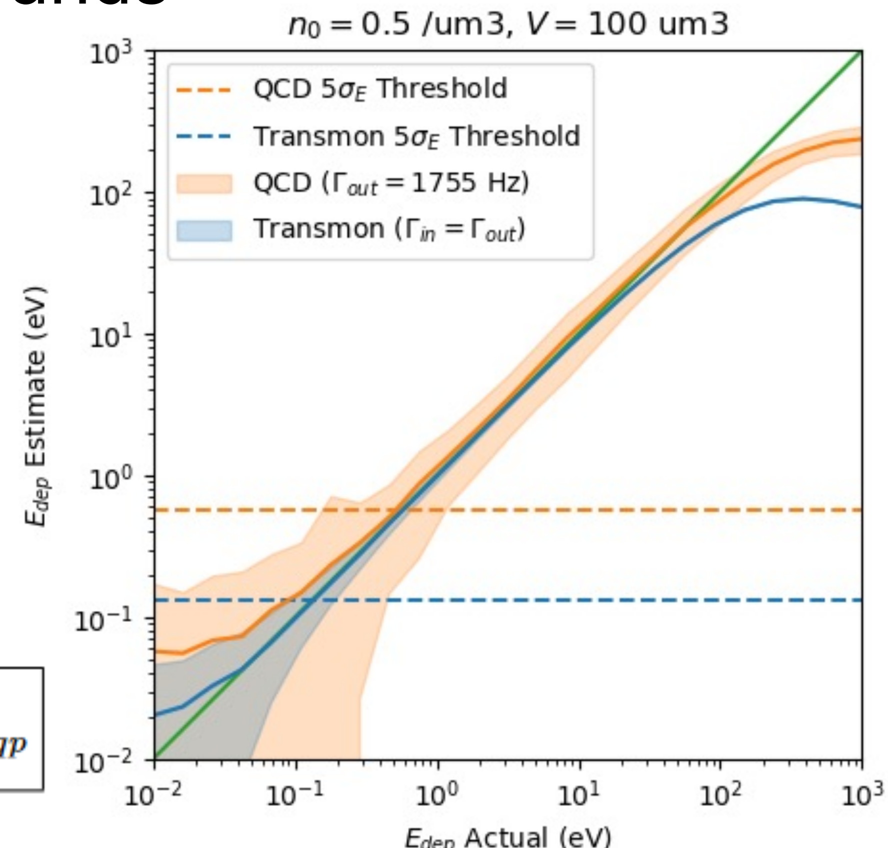
Tunneling trace of QP events in FIR device





Phonon mediated signal linear with quasiparticle density. Also linear with temperature → There's no calibrated model of these processes, first devices will be needed to constrain tunneling, transport etc.

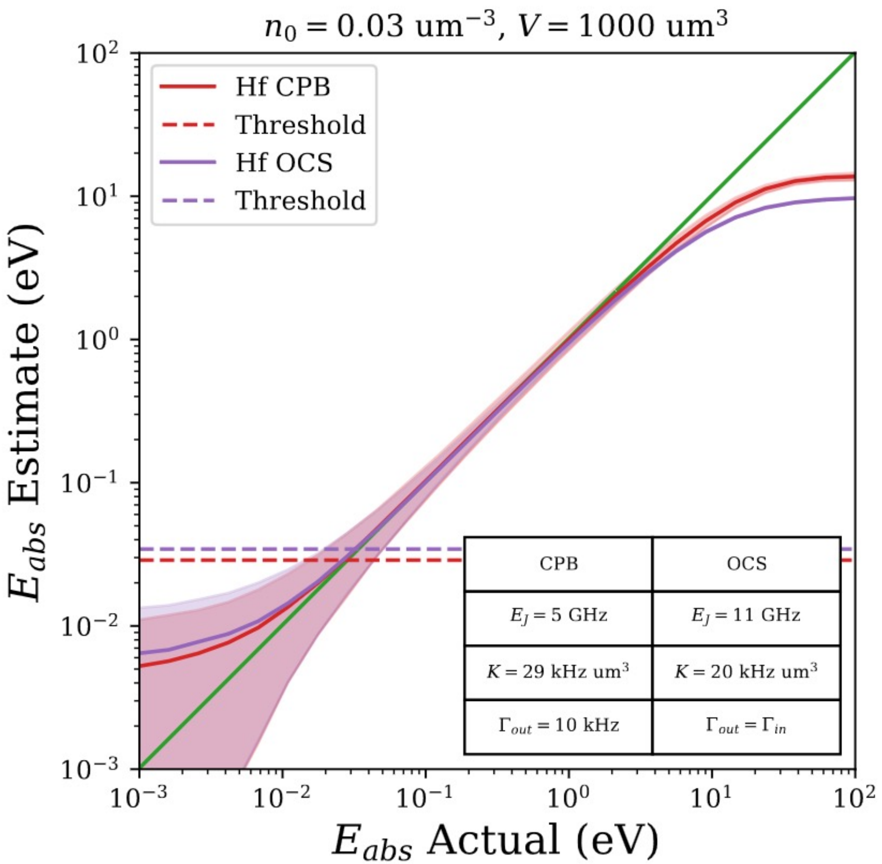
$$\frac{16E_J k_B T}{\mathcal{N}\Delta h} n_{qp} \equiv K n_{qp}$$



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

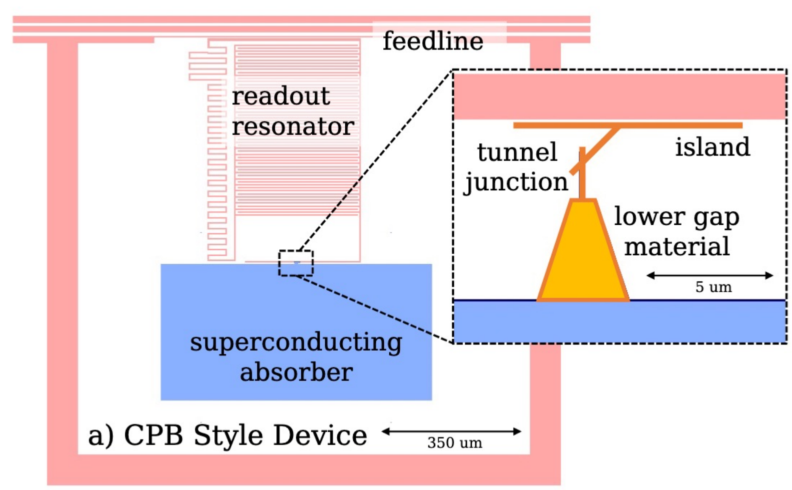
K. Ramanathan,[1,2,*] J. E. Parker,[1] L. M. Joshi,[3] A. D. Beyer,[4]
P. M. Echternach,[4] S. Rosenblum,[3] B. J. Sandoval,[1] and S R. Golwala[1]

Exploring other materials and trapping/multiplication

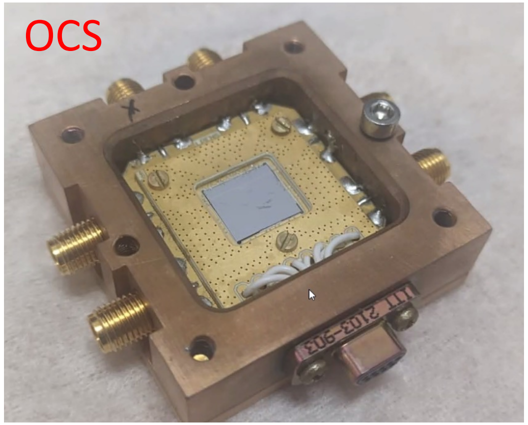


Hafnium is a potentially good candidate

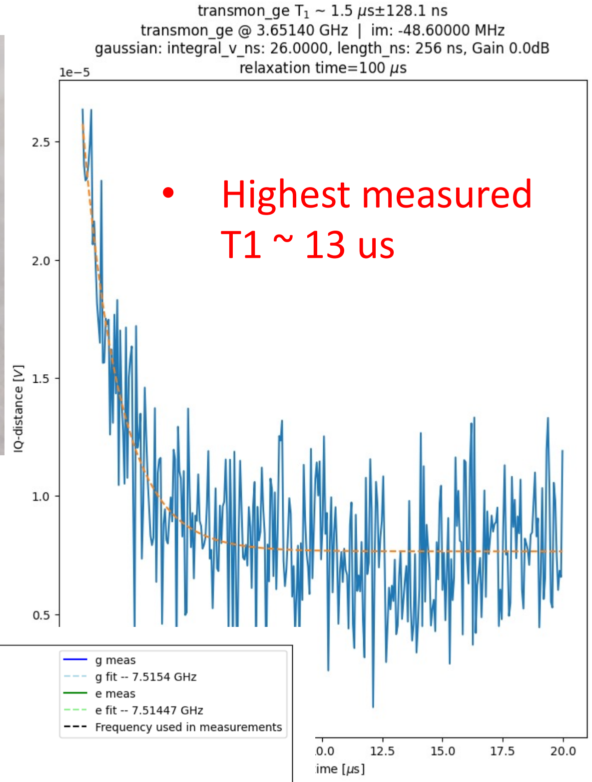
- 10x smaller band gap; tunnel junctions have been fabricated in literature.
- Make absorber and junction out of two different materials, promote quasiparticle trapping, leading to way more tunneling events
- Caution: can have significantly elevated QP densities within the trap!

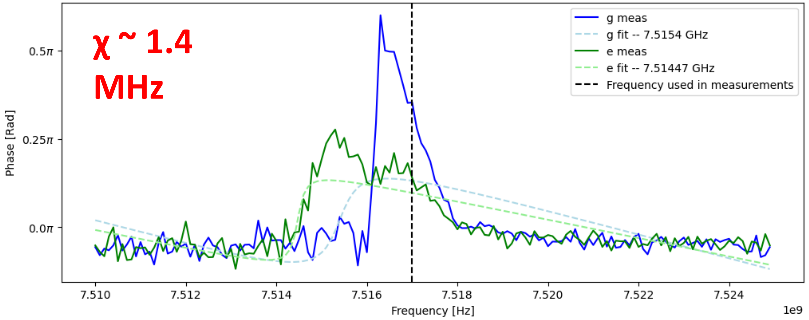


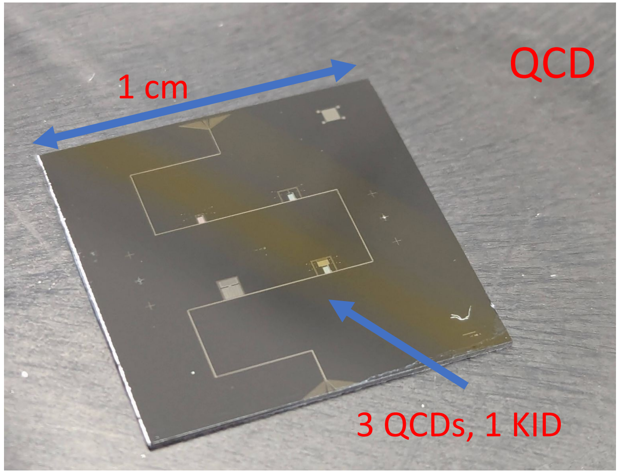
First Devices

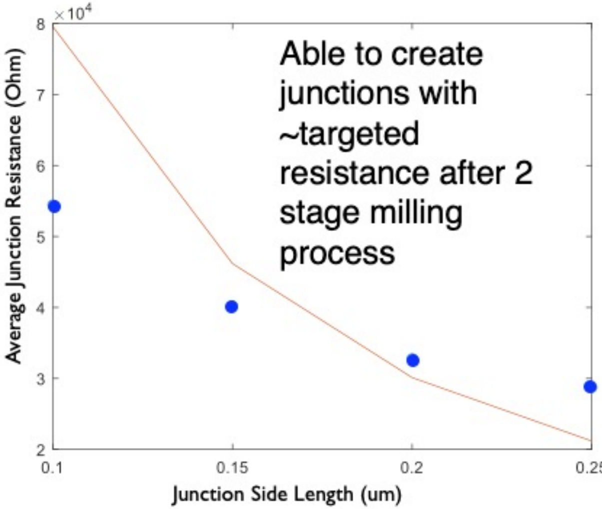


1 cm x 1 cm Silicon chip,
single feedline







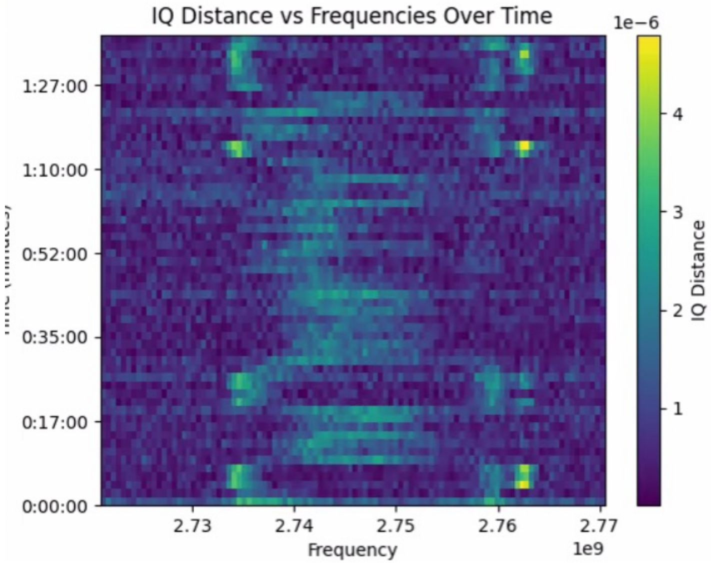


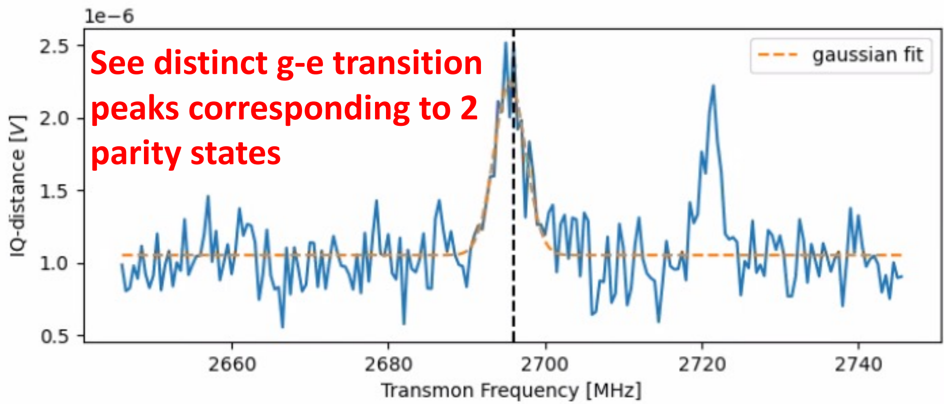
QPDs

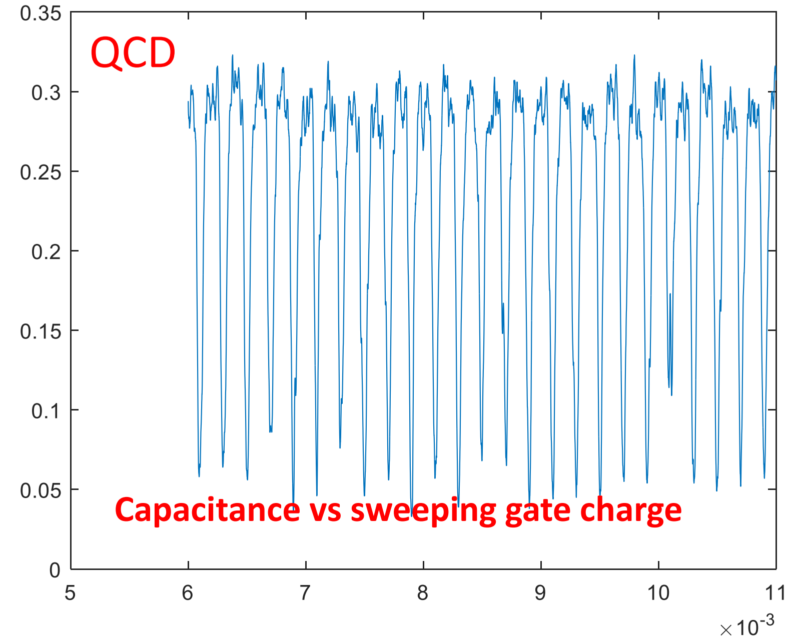
Some Preliminary Results

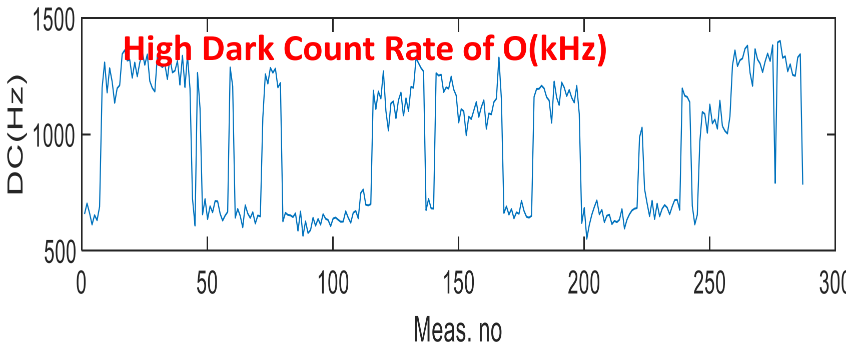
OCS

See drift in transition frequencies associated to drift in gate charge









Washington University in St. Louis

Caltech

Thanks! Questions?

(karthikr@wustl.edu)

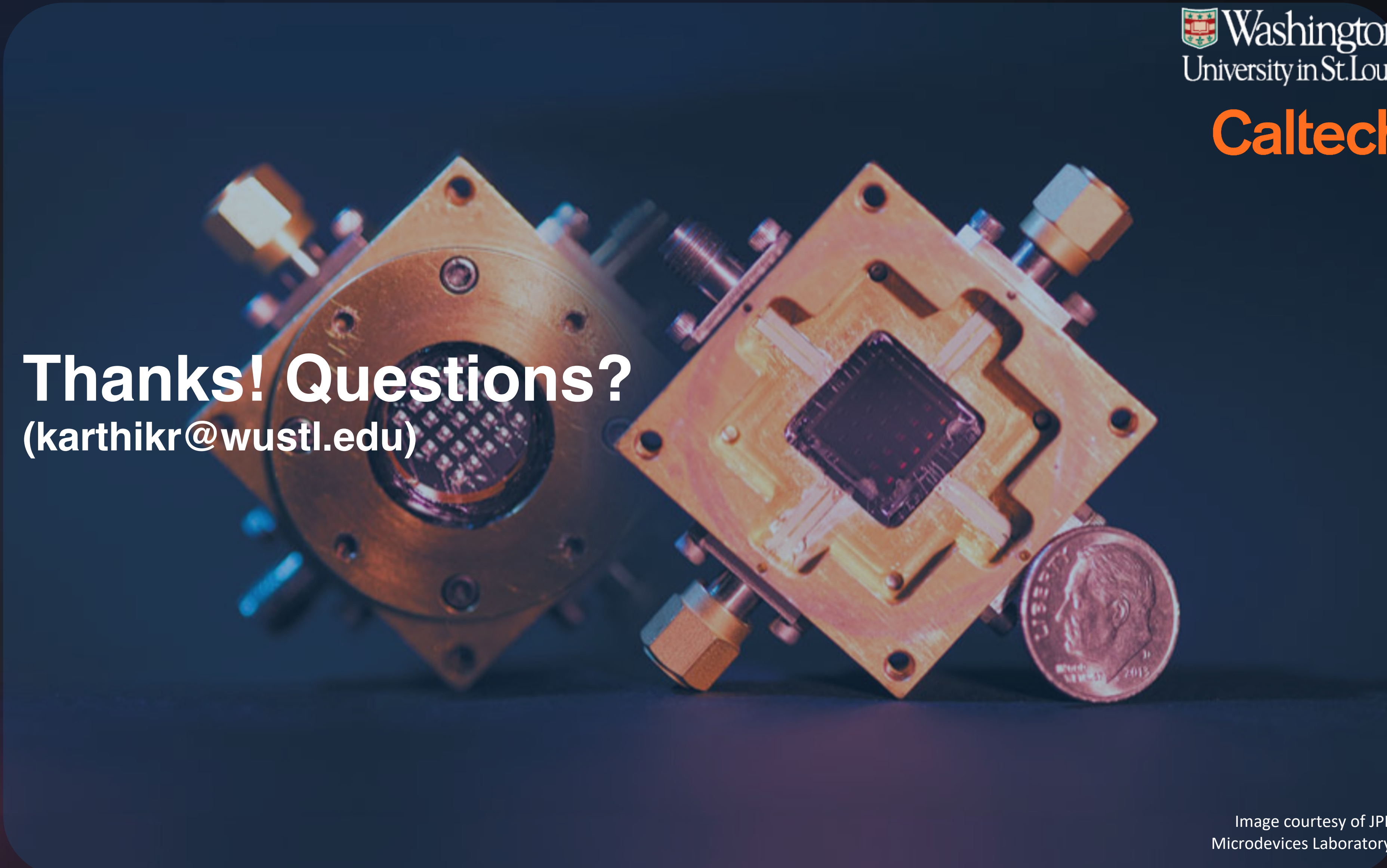


Image courtesy of JPL Microdevices Laboratory