Quantum Parity Detectors for ~~Astroparticle Applications~~ Dark Matter

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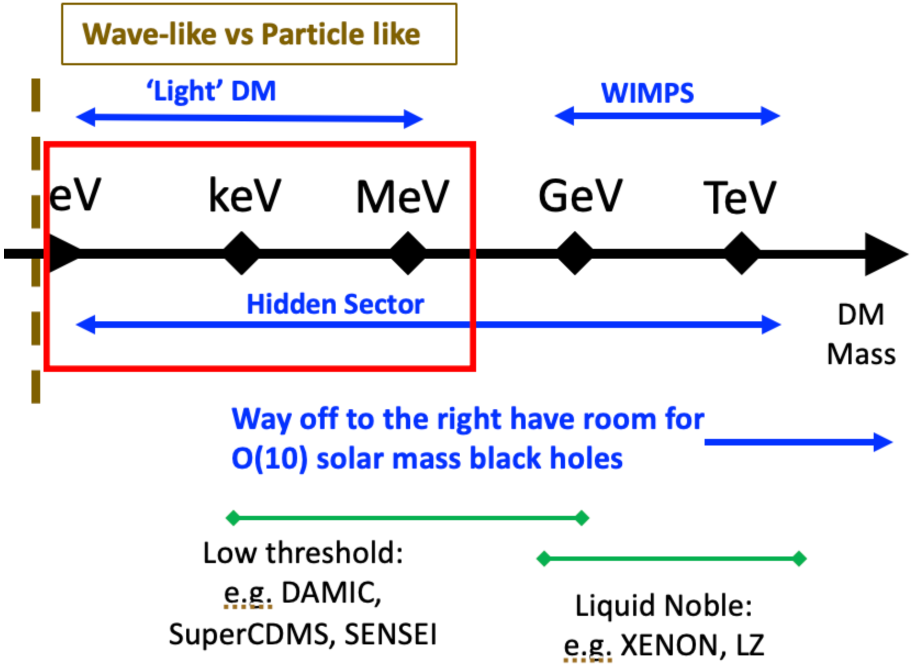
Weizmann: S. Rosenblum, L. Joshi

CPAD2023 RDC8

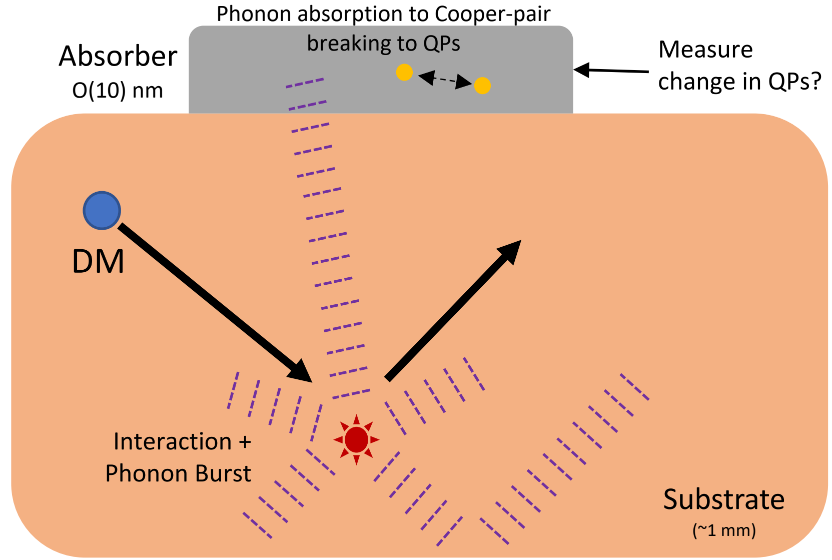
2023/11/09

Image courtesy of JPL Microdevices Laboratory

Dark Matter ←→ Phonon Channel



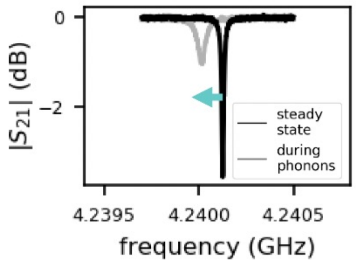
To probe certain masses of dark matter we need to achieve single phonon sensitivity O(10-100) meV



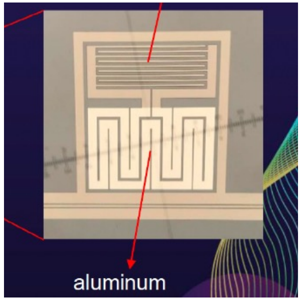
+ Phonon energies O(meV)
+ Information about interaction position and energy
+ Potentially thousands of phonon interactions
+ No relevant fluctuation background
  (thermal phonons suppressed by mK temp.)
- Phonon diffusivity → energy split across sensors

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.) - 2023
Quantum Limited Amplifier	1 eV (proj.) - 2023
Improve t_{qp} to 1 ms	0.5 eV (est.) - 2024
Lower T_c material	O(100) meV (est.) 2025+



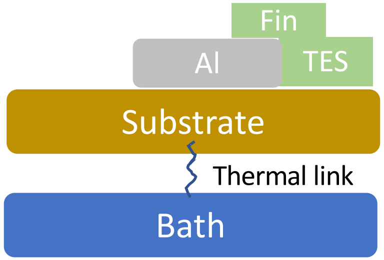
+ Highly multiplexable, kHz linewidths on GHz readout
+ Fundamentally non-dissipative

- 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.

See KIPM talk by O. Wen RDC8 Wed. 15:00

Transition Edge Sensors (TESs)

- Voltage biased to sit at superconducting transition



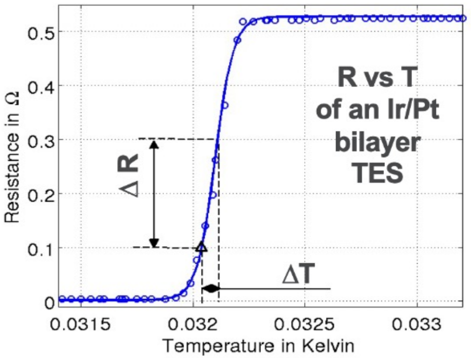


Figure from Chang, Wang Snowmass 2021 talk (2022)

+ 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!
See R. Romani talk RDC7+8 Thurs 16:00

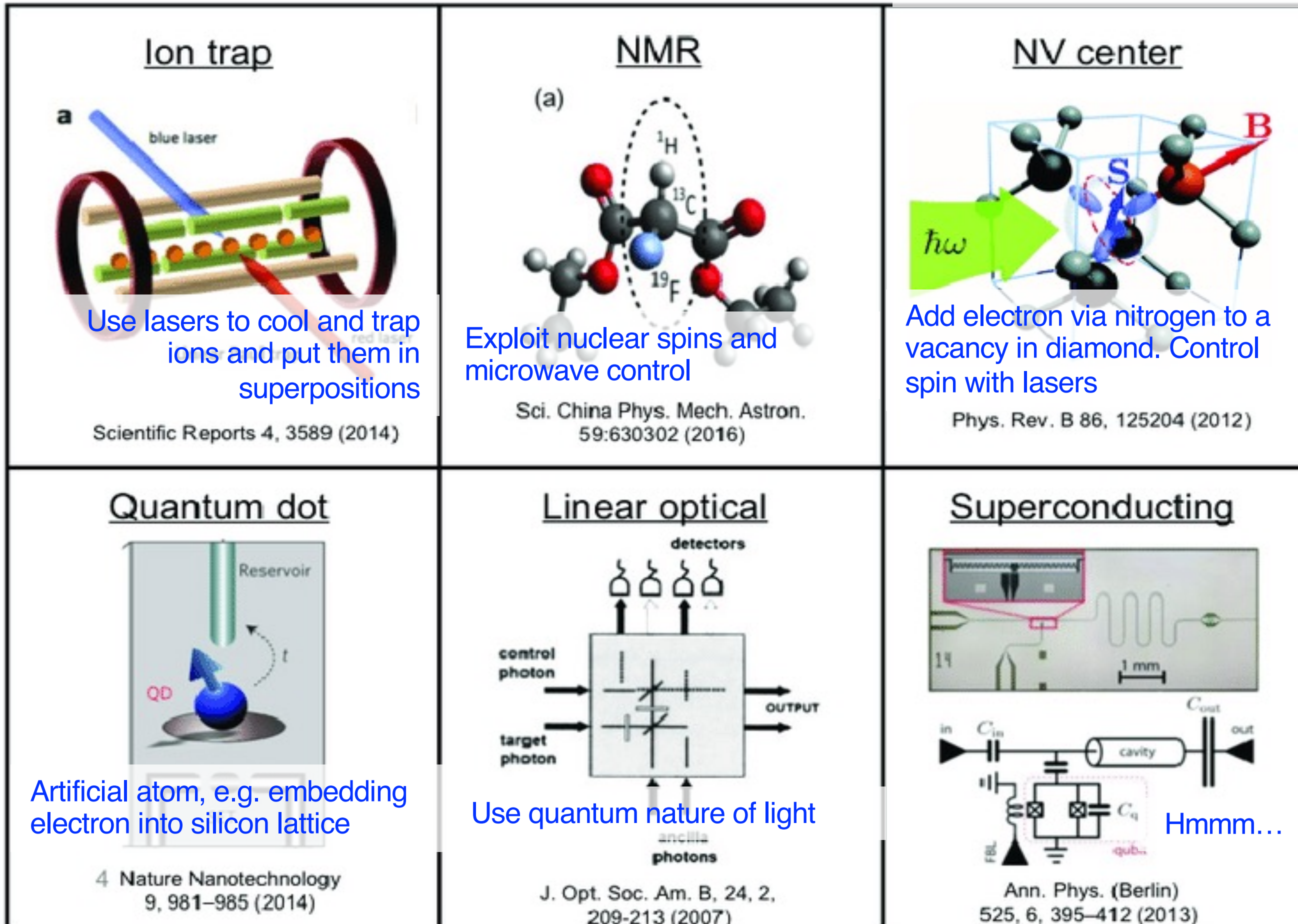
Qubits

Amundsen, 2019 (CHEP 2018)

Huge proliferation of techniques since 80s

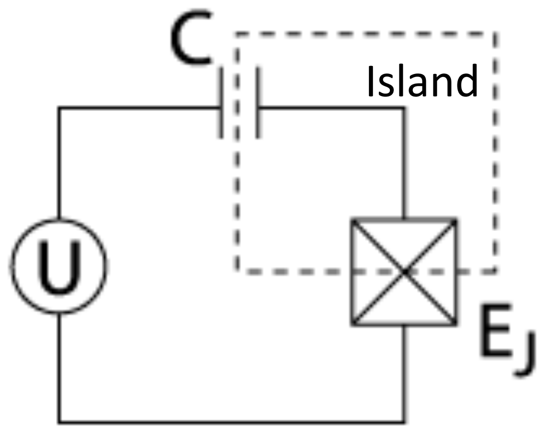
What makes these interesting for non-QIS practitioners?
Relevant energy scales << eV to few eV

Environmental effects at those energies affect/modify the qubits → e.g. radiation detection



Cooper-pair Box / Charge Qubit

- 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**



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

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

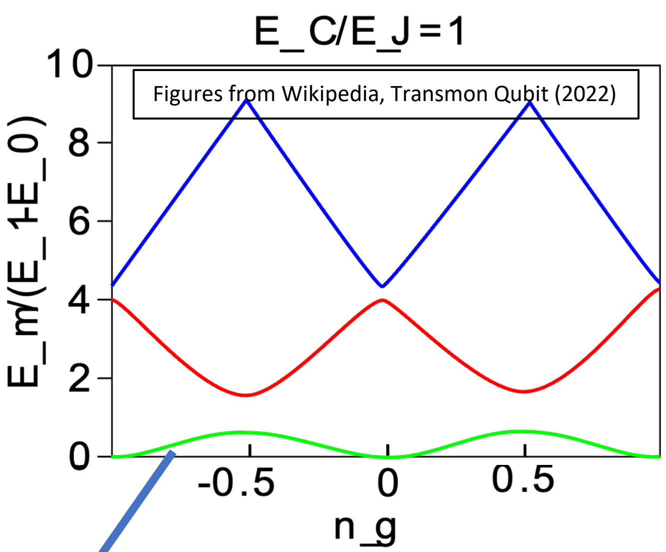
Josephson energy

Parity: **± 1, measure even/odd quasiparticle tunneling events that have traversed the junction**

Dimensionless *offset charge*: $C_g V_g/2e$

Quantum Capacitance Detector

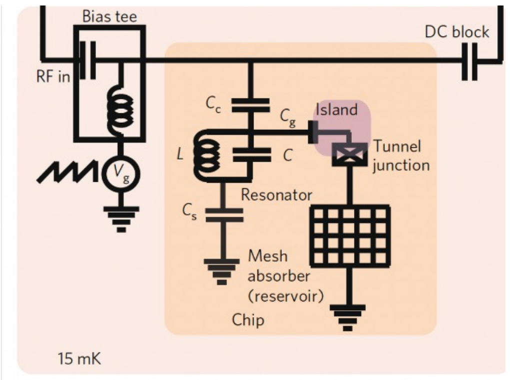
Shaw et al, 2009; Echternach et al. 2017

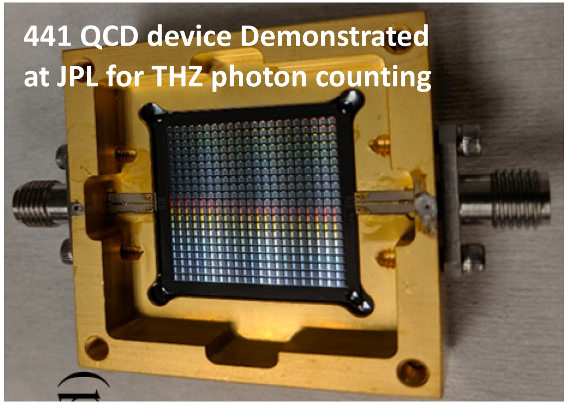


Note curvature of bands

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

- 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

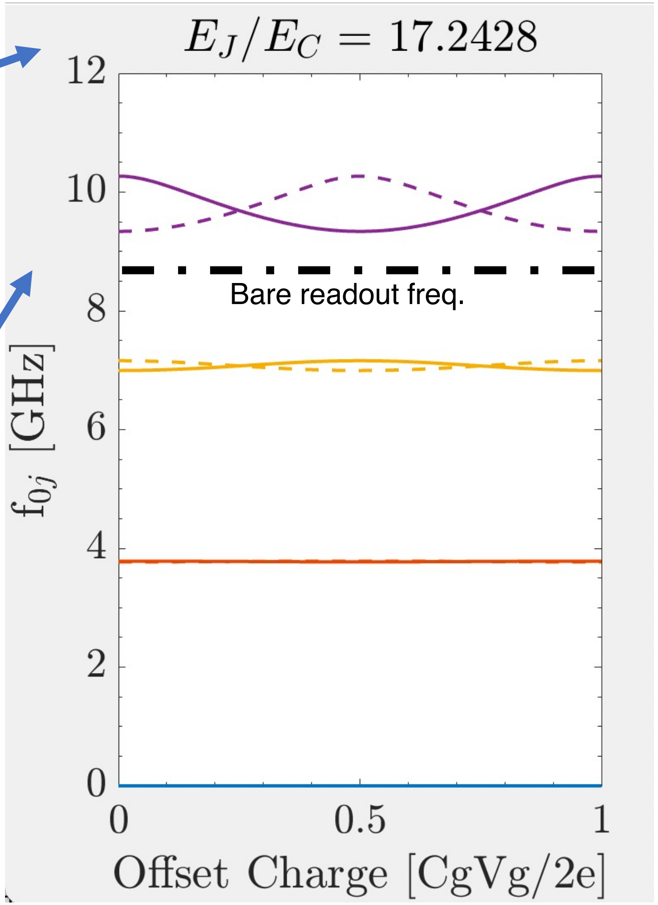
See QCD talk by J. Yu talk RDC8 Thurs. 11:45 & P. Echternach poster

Offset Charge Sensitivity (OCS)

Serniak et al. PRL, 2019

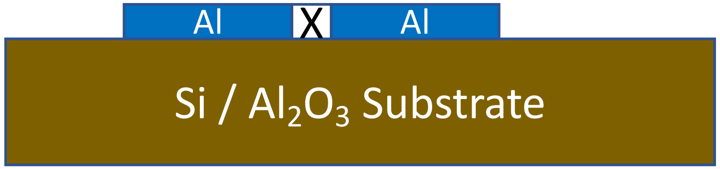
- Stiffen the energy ratios by increasing overall capacitance (e.g. making absorber pads larger) will enter ***transmon*** regime.
- Won't see capacitance shift anymore but will still see a *dispersive* shift in your resonator with tunneling.

$$\chi_{i,p} = g^2 \sum_{j \neq i} \frac{2\omega_{ij}^{pp} \left|\langle j,p|\hat{n}|i,p\rangle\right|^2}{(\omega_{ij}^{pp})^2 - \omega_r^2}.$$

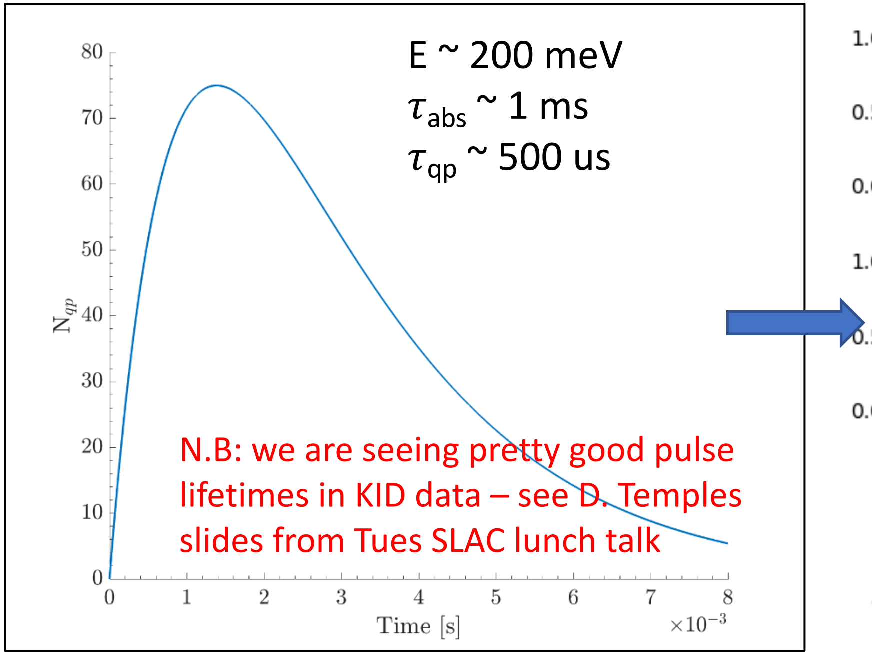


Quantum Parity Detectors

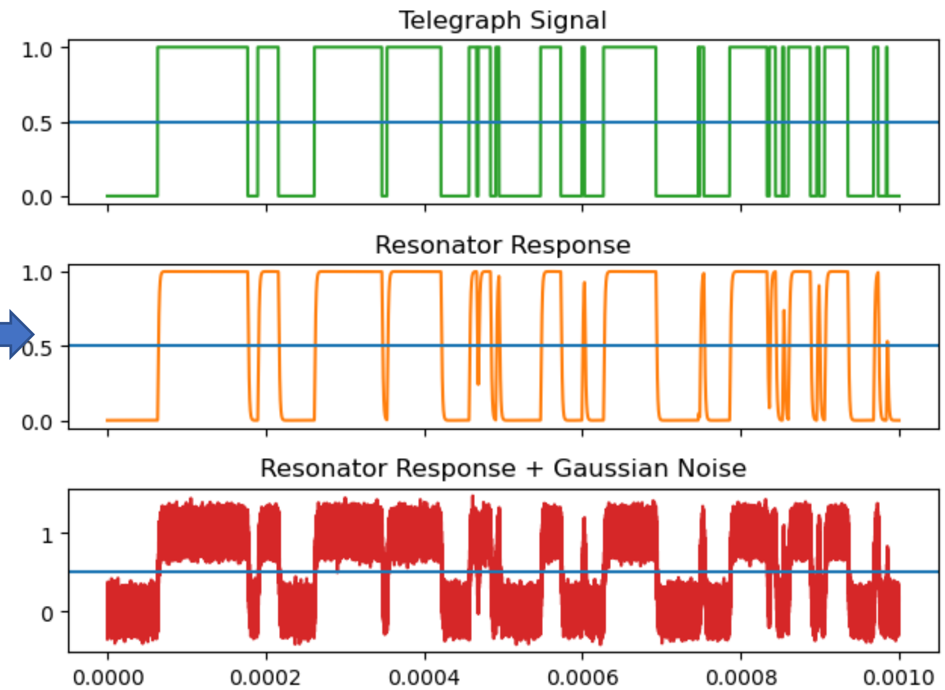
(similar concept to recent SQUAT proposal, see C. Fink RDC8 talk)



Quasiparticle production in "QPD" absorber



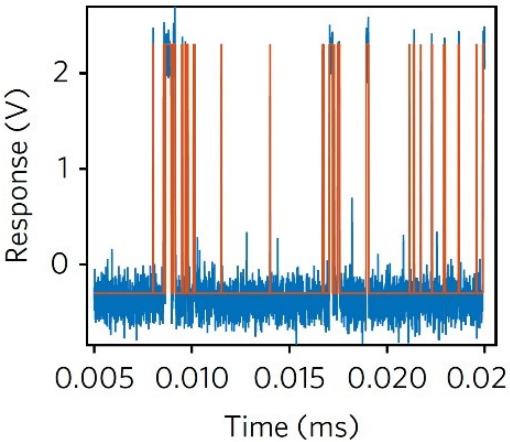
Parity signal observed

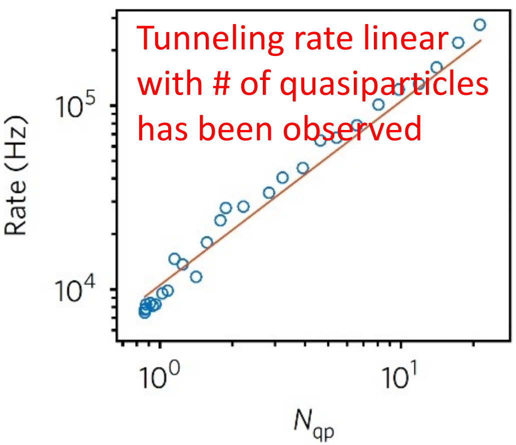


V ~ 100 um^3 Parameters same as FIR-QCD

Expected Signal

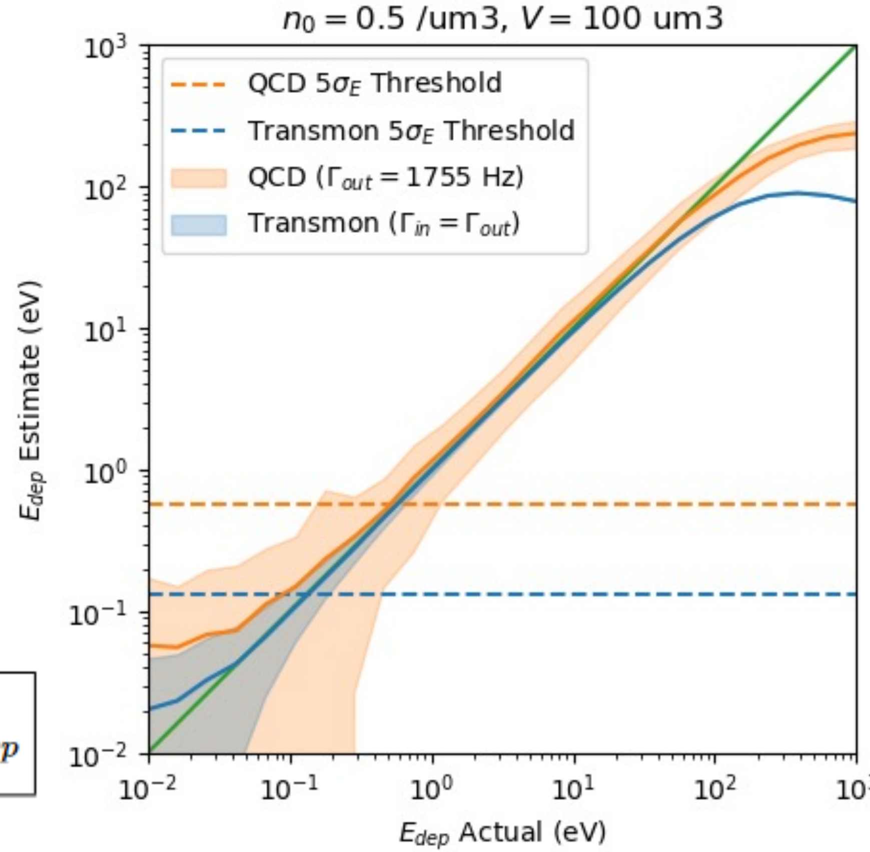
Tunneling trace of QP events in FIR device



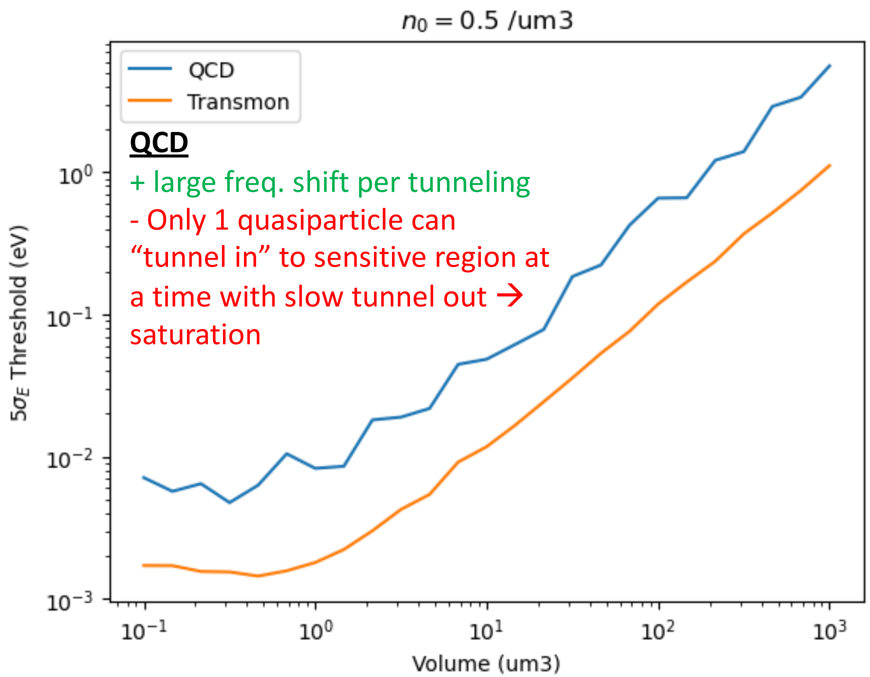


Phonon mediated signal linear with quasiparticle density. Also linear with temperature → There's no calibrated model of these processes, first devices will be needed to constrain tunneling, transport etc.

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

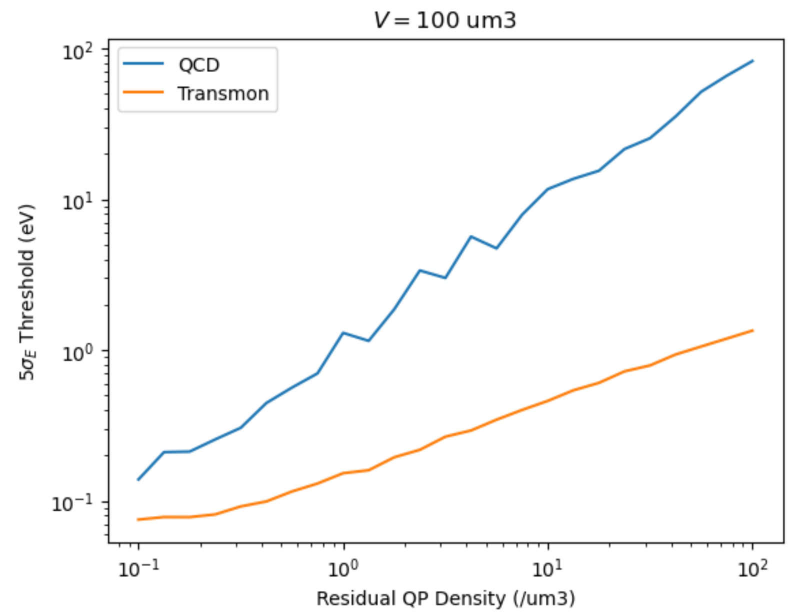


Background & Threshold



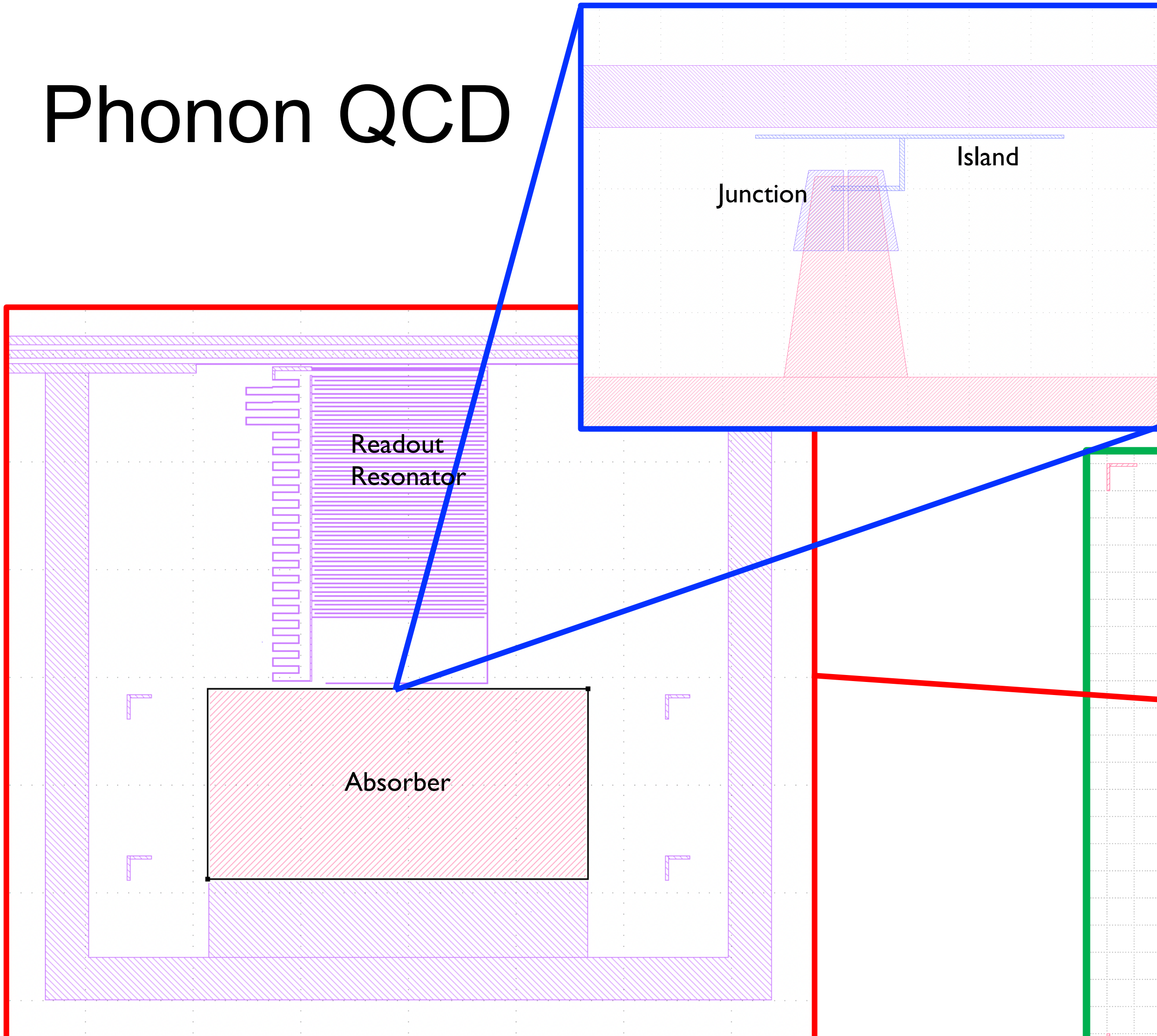
Threshold and background rate dependent on volume, quiescent QP density etc.

$$\sigma_{\mathcal{B}}^2 \approx \left(K\tau + 16\frac{K^2\tau^2}{V} \right) n_0$$



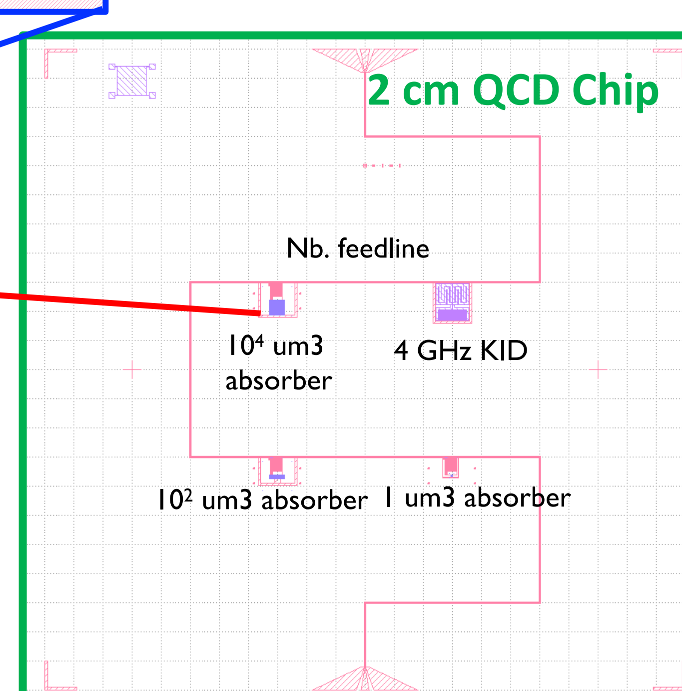
Don't necessarily need good qubit to be a sensor as long as residual QP induced effects are reduced.
Not penalized for having a better qubit.

Phonon QCD



Keep it simple to start:

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



Phonon OCS

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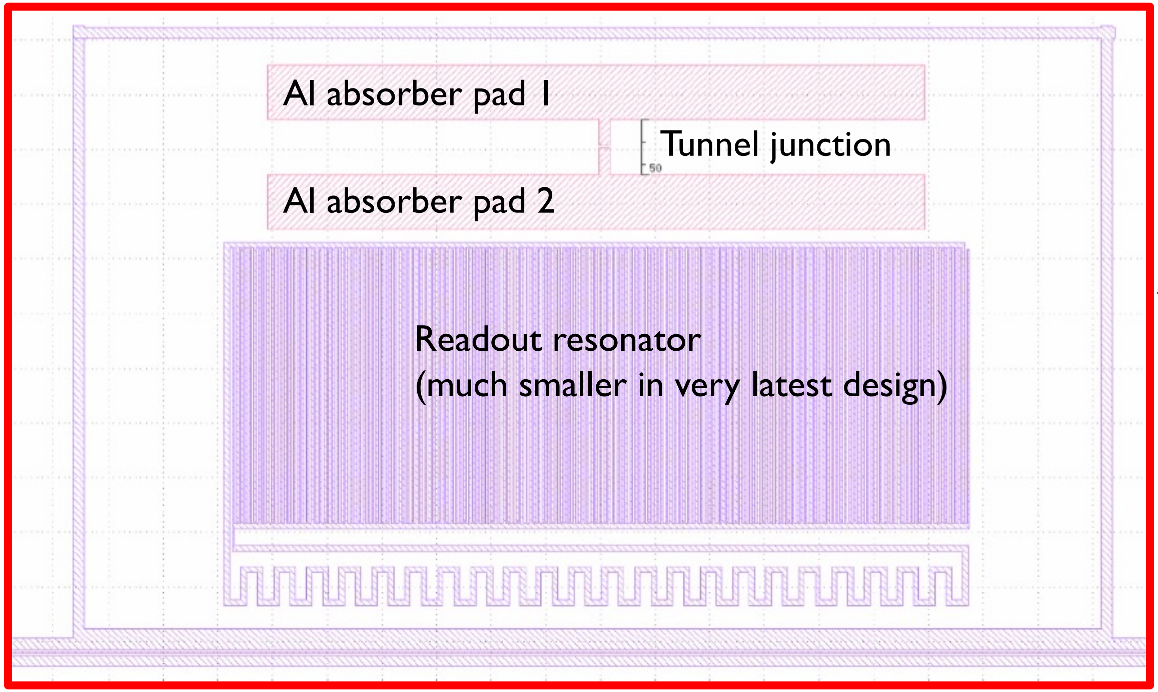
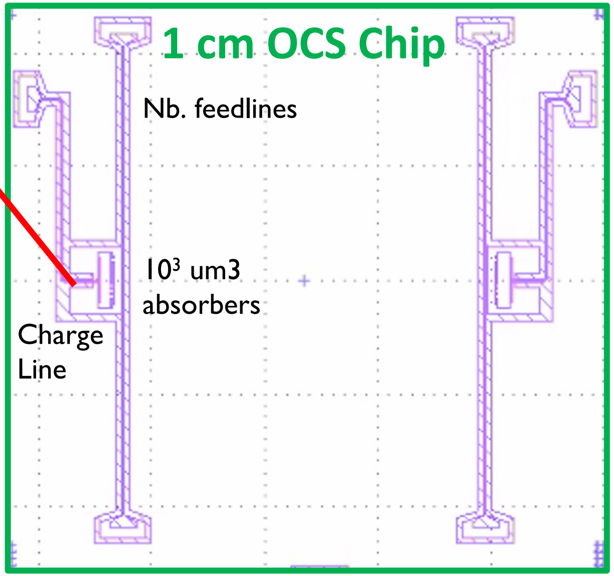
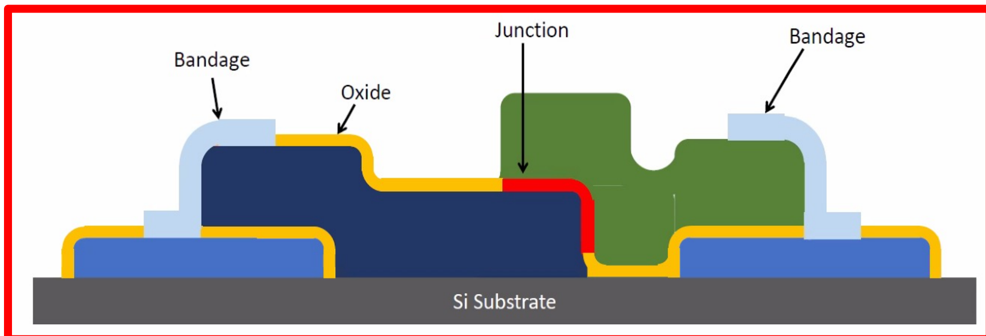


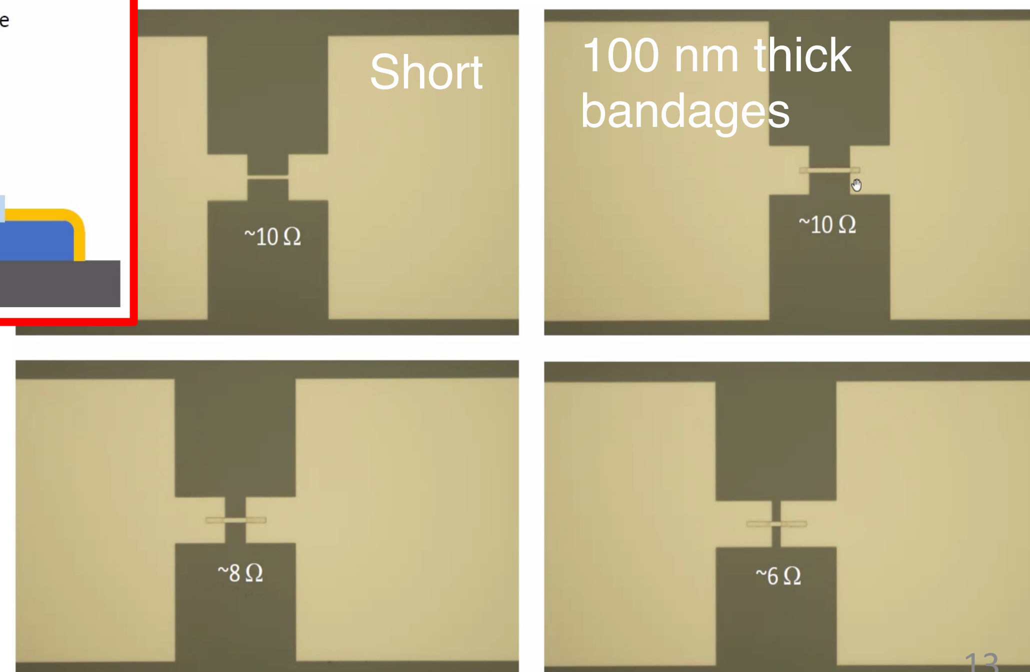
Again Si substrate with Al+Nb components

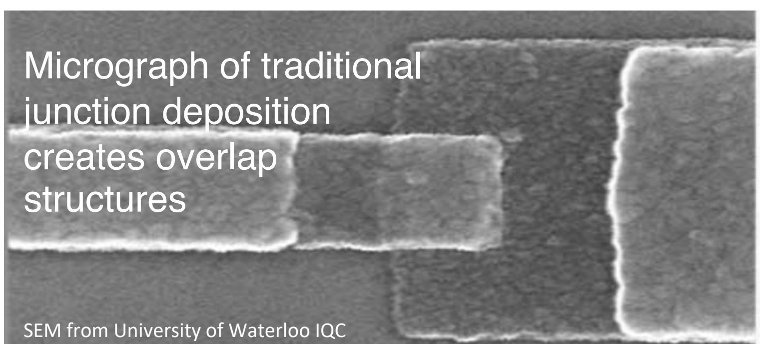


QPD Fabrication Challenges

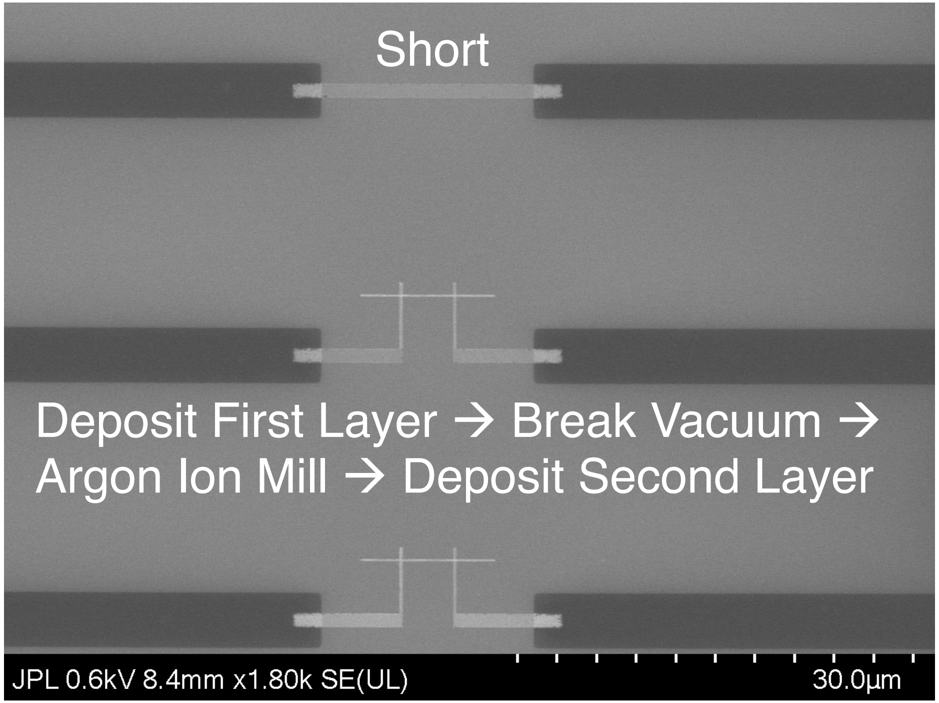
Requirements much different than Astronomy or QIS needs - need good contact between absorber/traps for quasiparticle transport. QIS devices lay down multiple overlapping layers → Needlessly introduces parasitics and increases volume. Workaround with "bandages" or by "junction milling"

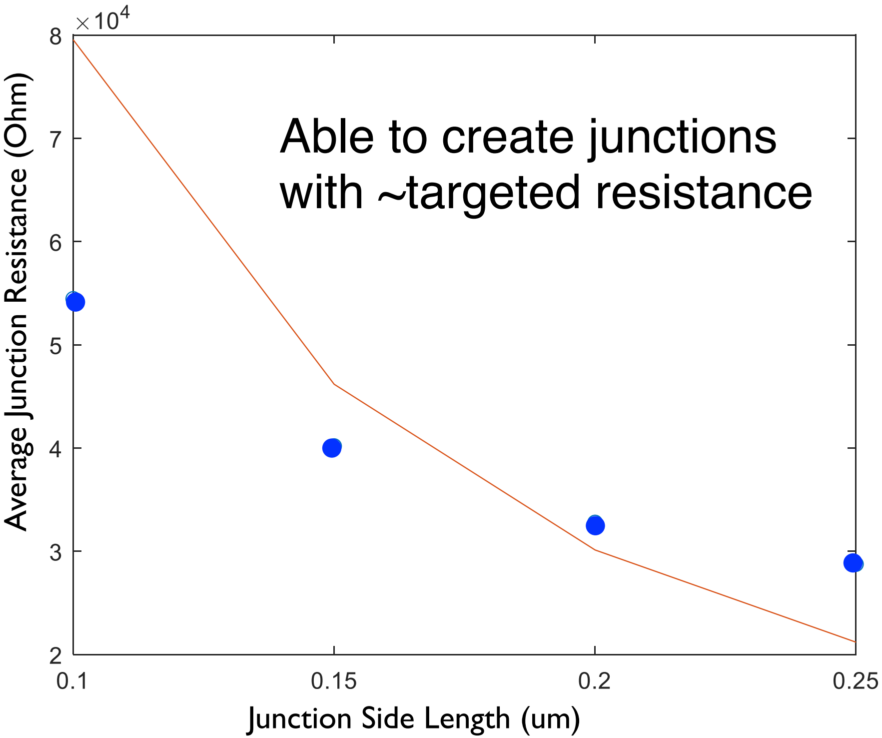






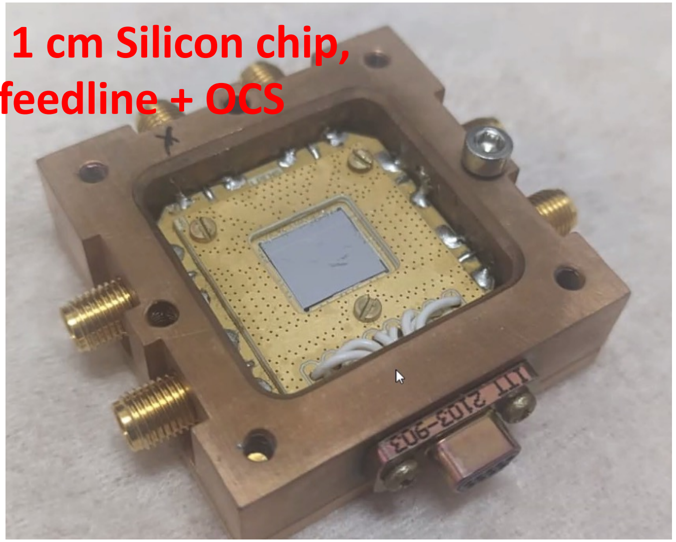
Junction Mill Tests

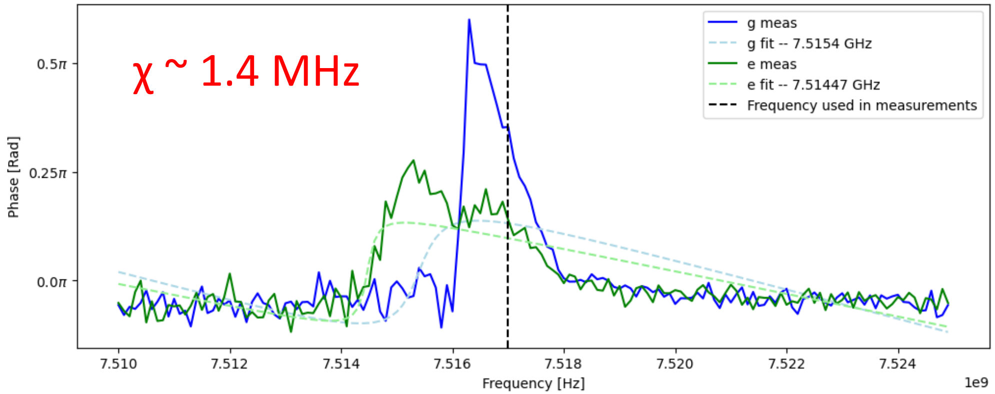


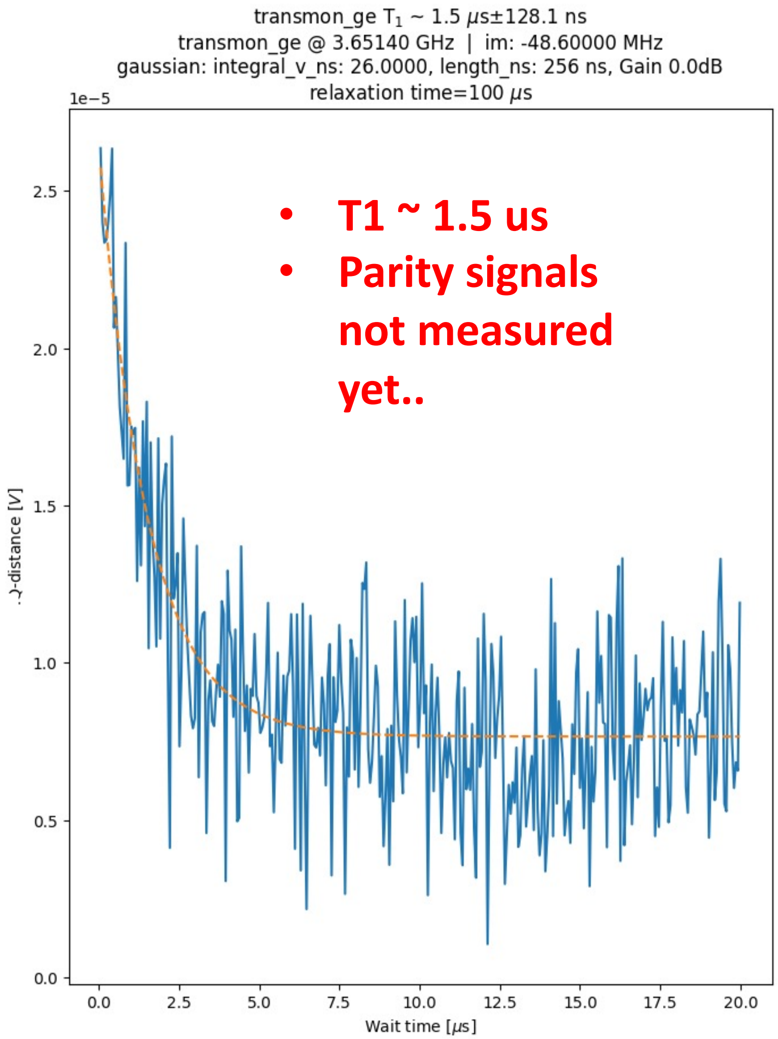


OCS v1

1 cm x 1 cm Silicon chip, single feedline + OCS







Lots of challenges to explore

Absorber Sizing

- Tunneling rate ←→ volume
- Does this match expectation with diffusion sizing?
- Saturation effects
- Improve on K~10 kHz um^3?
- 1 → 10000 um^3 absorber means R~1 Hz which is not observable

Material Selection

- Move to lower gap material, or introduce QP traps e.g. AlMn → Need to demonstrate able to make a junction
- KID experience with low Tc materials like AlMn has been… poor

Offset Charge Drift

- Gate charge drifts on O(10)s
- Currently experiments stabilize drift by using individual bias lines → lots of complexity for many QPDs

Readout scheme

- Sweeping gate voltage
- Measurement bandwidth
- Resonator design

Surface Fill Fraction

To completely absorb energy in phonon

$$f_{abs} \cdot N_{surf} \cdot f_{surf} \sim 1$$

(abs probability x num bounces x surface fill)

$N_{surf} \sim 10^{3\text{-}5}$ $f_{abs} \sim 10^{-2}$ → $f_{surf} \sim 0.01\%$ - 10%

Phonon-Film Coupling

- Coupling of energy from substrate to film η ~ 0.1-0.34 from different experiments
- QP breaking film thickness dependent (30-100 nm)
- Phonon absorption lifetime $\tau_{abs} \sim 1\text{ms} - 1\text{s}$?

Takeaway

1. Single phonon sensitivity is a driving design need for low-mass particle dark matter searches
2. Quantum Parity schemes are one avenue to achieve very low sensitivity
3. QPD demonstrator R&D, exploring factors in tunnel junction design, absorber volume, quasiparticle density etc. is underway
4. Descriptive paper coming soon!

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

Karthik Ramanathan,[1,2,*] John Parker,[1] Lalit M. Joshi,[3] Andrew Beyer,[4] Pierre Echternach,[4] Serge Rosenblum,[3] and Sunil Golwala[1]

Thanks! Questions?