Phonon-mediated Quantum Capacitance Detectors for astroparticle applications

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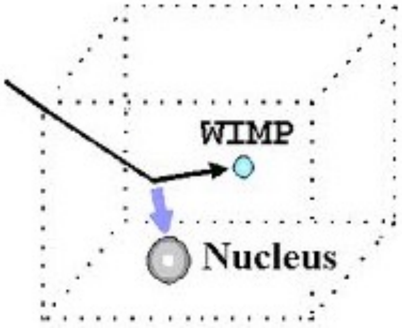
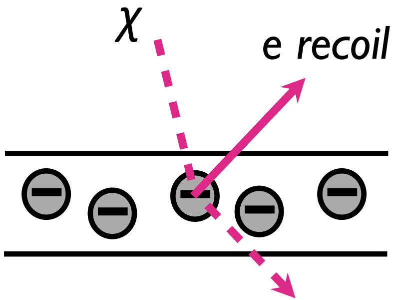
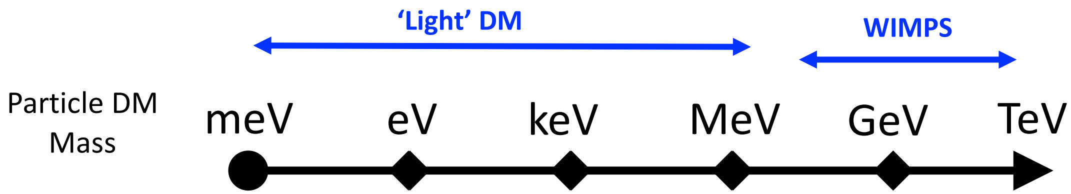
CPAD 2022 Stony Brook

Dark Matter

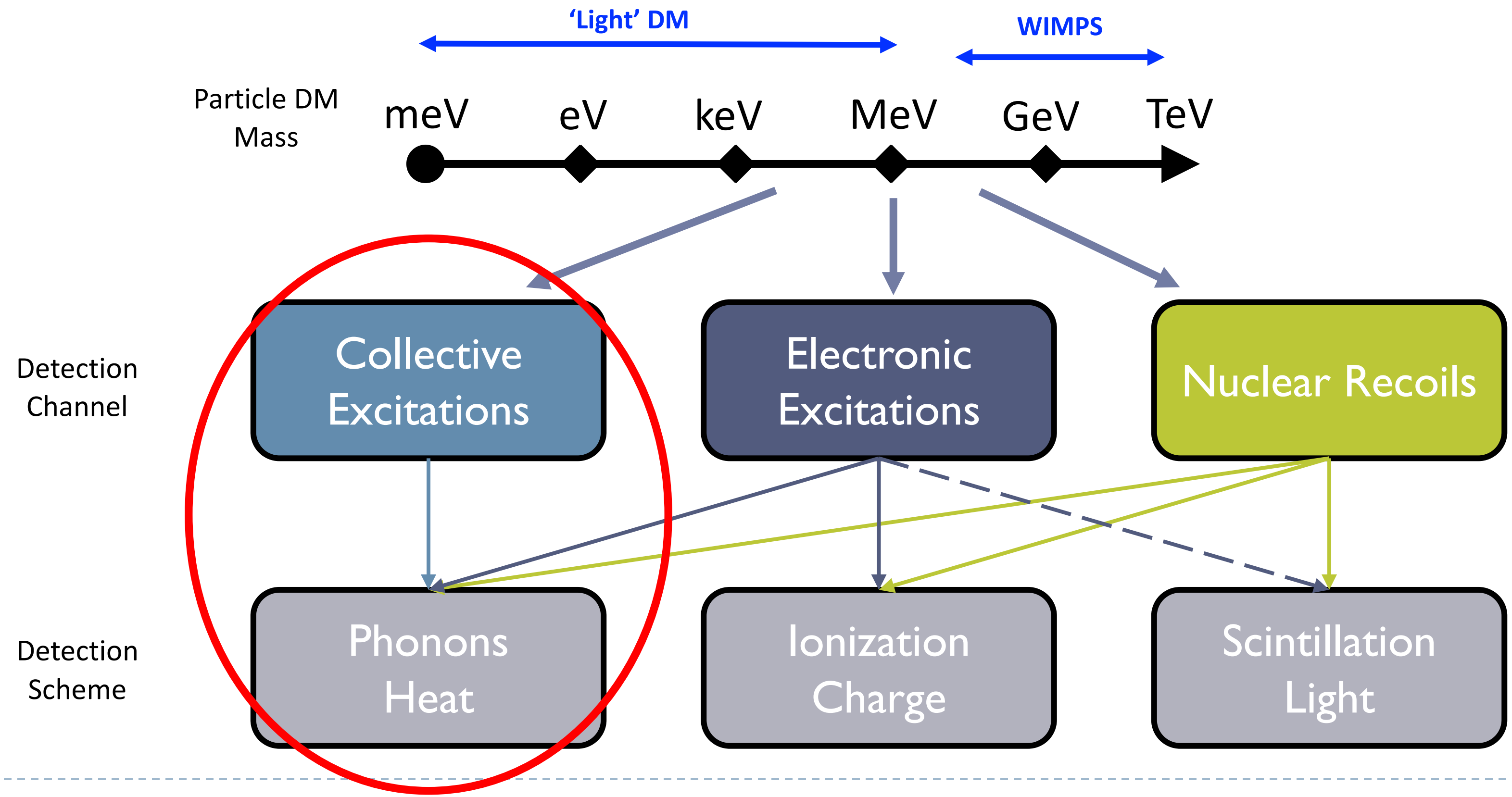
- Strong cosmological and astrophysical evidence for some missing matter in the universe comprising ~25% of the total mass-energy of the Universe.
- Assuming **Particle Dark Matter**, whole zoo of models:
  - Perhaps detectable by **DM-nucleus** scattering or **DM-electron** processes but name of the game is build a very sensitive detector and wait for clean signals from interactions
- Energy deposited in a detector model dependent, but generally scales with mass → O(100) $MeVc^{-2}$ nuclear recoils gets you only O(eV) deposits in Si ☹







Detection Channels

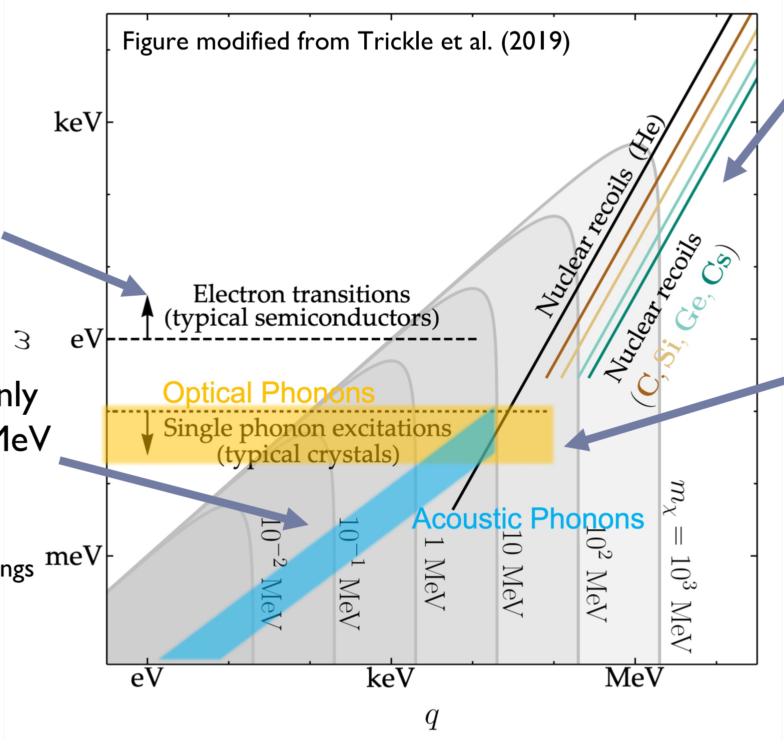


Kinematic Space

Electronic transitions ~eV scale

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

*assuming no EM or other couplings

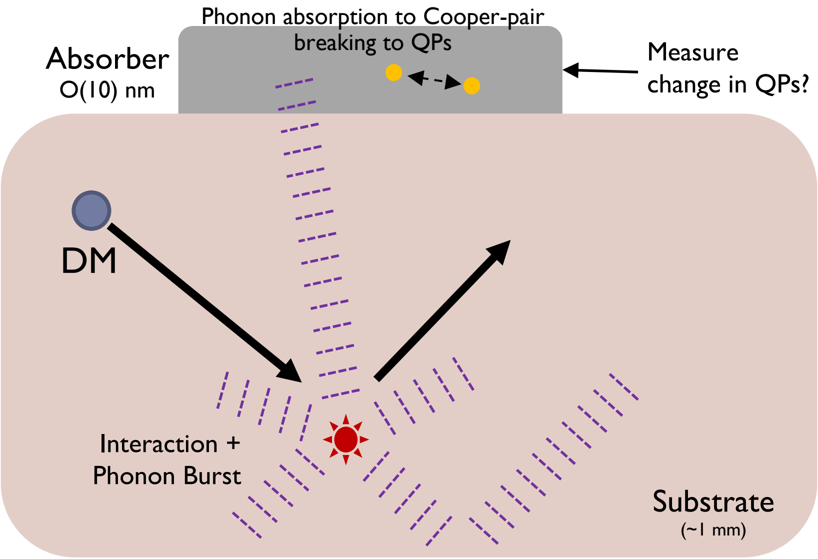


Nuclear recoil loci only goes down to where nuclei can be considered ~independent

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. Point like fireball of O(THz) phonons at interaction
2. Decay into lower energy phonons
3. Quasi-diffuse propagation → athermal and "ballistic"
4. Phonons encountering e.g. superconducting metallic interface can be absorbed
5. Break Cooper-pairs → QPs → subsequent cascades

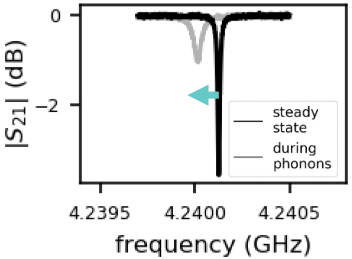
+ Phonon energies O(meV)
+ Preserves info about interaction position and energy
+ Many thousands of attempts to be absorbed by the detector
+ No relevant fluctuation background, since thermal phonon bath suppressed by mK cryogenic operation
- Diffusive nature means phonon energy can be split across multiple sensors

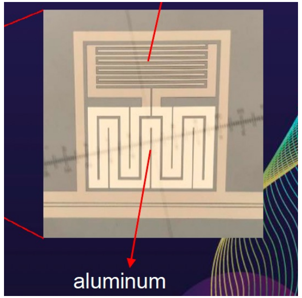
Path to sub-eV

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+

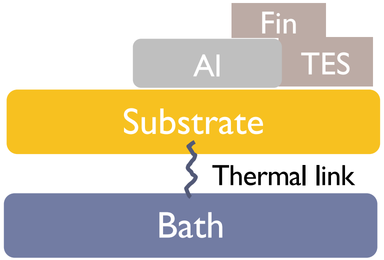




+ Highly multiplexable, kHz linewidths on GHz readout
+ Fundamentally non-dissipative
- High residual quasiparticle level ~10-1000 um^{-3} of unknown origin, suspected to be readout power generated → limits quasiparticle lifetime and worsens sensitivity and resolution.

Transition Edge Sensors (TESs)

- Voltage biased to sit at superconducting transition



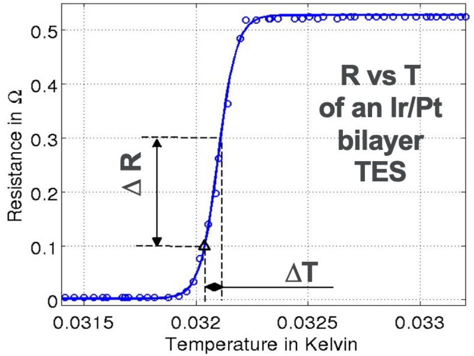


Figure from Chang, Wang Snowmass 2021 talk (2022)

+ 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?

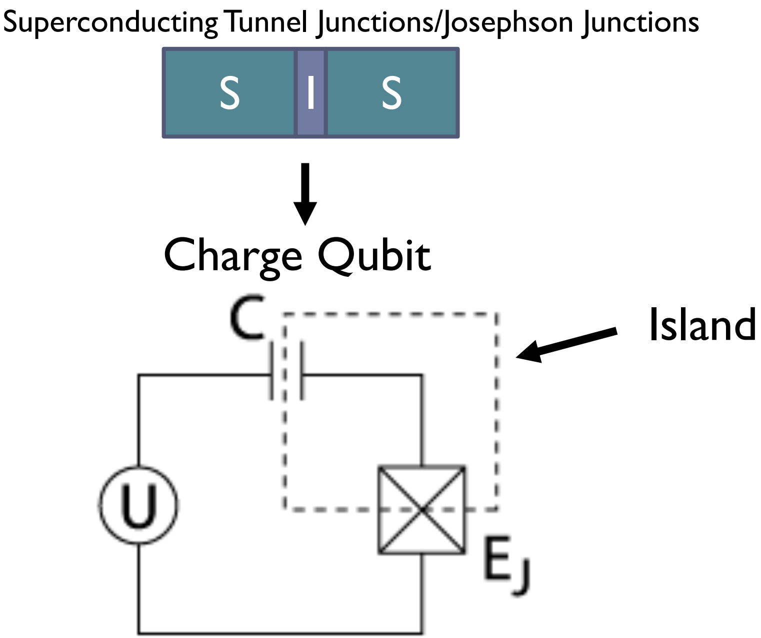
Demonstrated down to 2.26 eV baseline resolution on gm-scale absorber

See MKID talk by O. Wen WG4 on Thurs. 11:55am

See TESSERACT talk by X. Li WG4 on Thurs. 10:30am

Qubits

- Two-level systems |0>, |1>
- Building block of quantum computers. Heralded as the future of computing etc. etc.
- Superconducting materials are one scheme in realizing qubits (opposed to photonics, trapped atoms etc.)
- Early implementation: **Charge Qubit / Cooper-Pair Box**
  - Well defined charge states → presence or absence of Cooper pairs on the Island.
  - *However very sensitive to charge noise (quasiparticle poisoning), coherence times of only a few us*

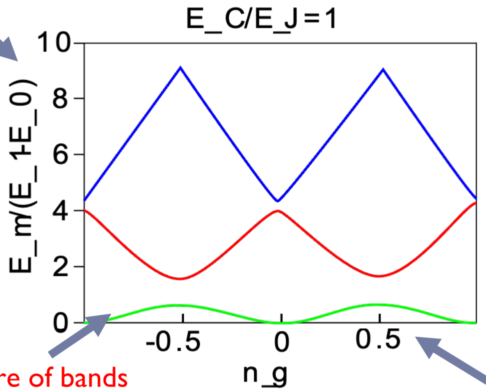


Charge ↔ Transmon Regime

Figures from Wikipedia, Transmon Qubit (2022)

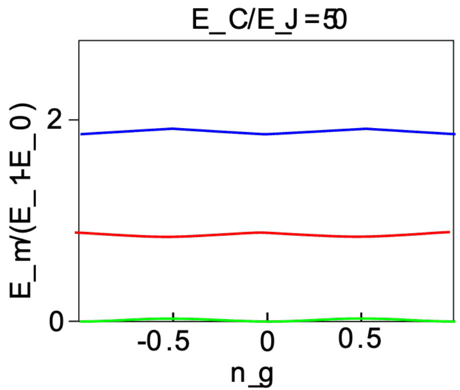
Charge $H = 4E_C(n - n_g)^2 - E_J\cos\phi$ Modern standard "Transmon"

Qubit energy levels



Introduce large capacitive shunting

modify ratio of charging energy to junction energy



Note curvature of bands

Gate charge in units of 2e,

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

Can interpret the curvature as a capacitive term → changes every time a quasiparticle tunnels over. Couple to a resonator and see change of resonant frequency

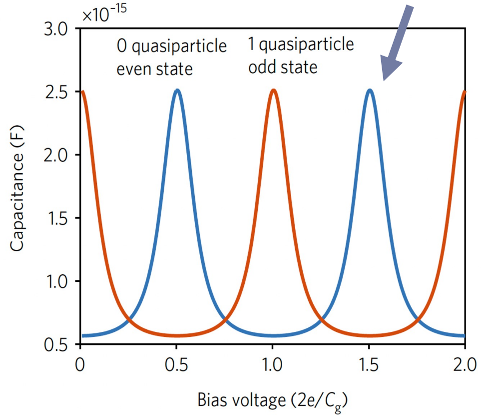
$$\delta C\Big|_{n_g=0}^{n_g=1/2} = \frac{C_g^2}{C_\Sigma}\frac{4E_C}{E_J}\left(1 - \left[1 + \left(\frac{E_C}{E_J}\right)^2\right]^{-\frac{3}{2}}\right) \approx \frac{C_g^2}{C_\Sigma}\frac{4E_C}{E_J}$$

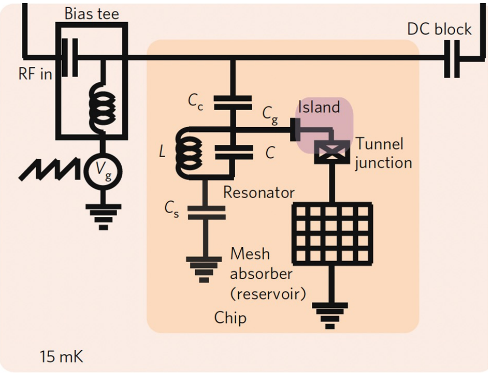
O(MHz)

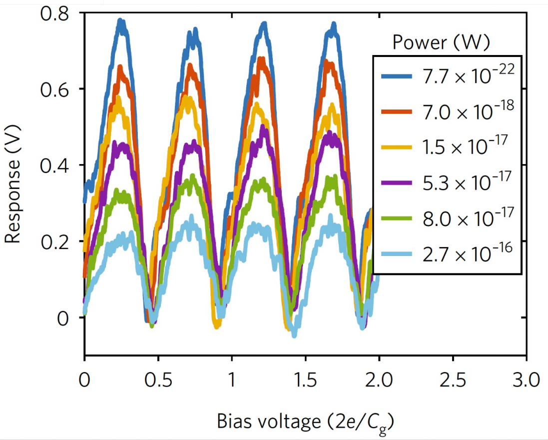
Quantum Capacitance Detectors

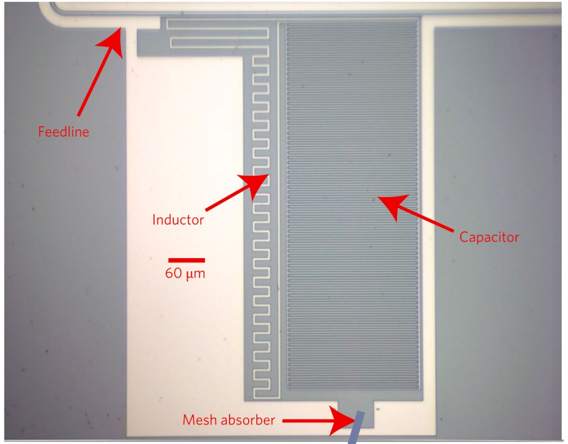
Echternach et al, Nature Astronomy, 2017

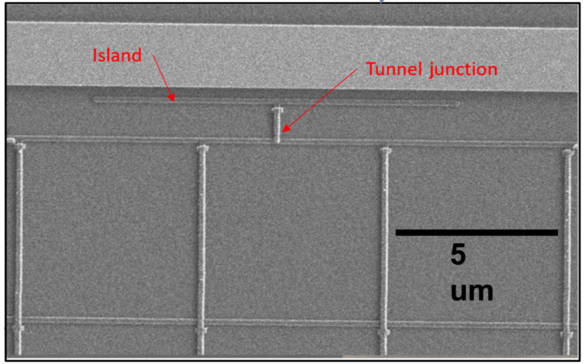
- Couple the circuit to an **absorber** and **resonator** and make a detector!
- Even-odd island QP occupancy → Relate the tunneling rate to the number of quasiparticles produced in an absorber element.









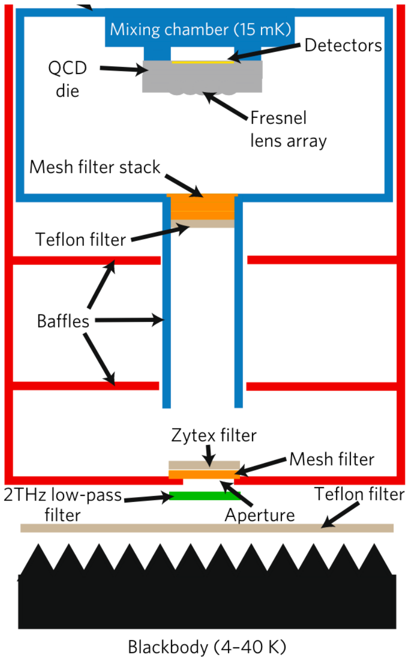


Lots of potential for astronomical operation at low photon bkg. shot noise.

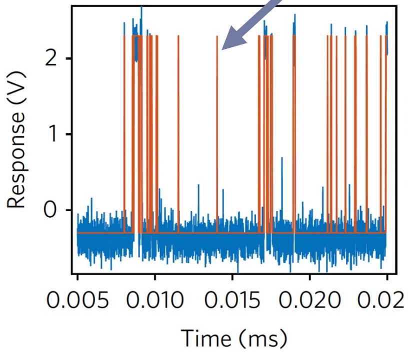
Optical Loading & Photon Counting

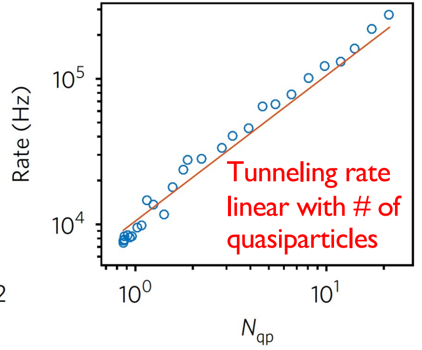
Echternach et al, Nature Astronomy, 2017

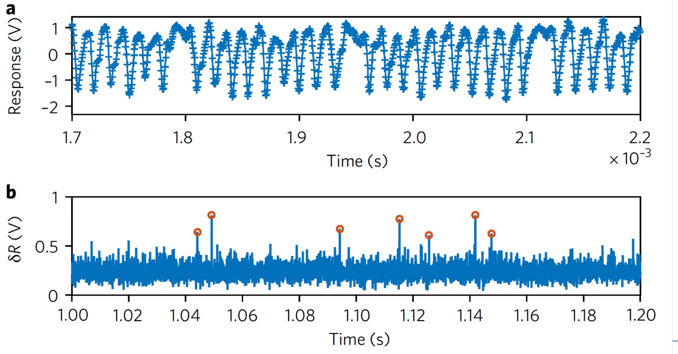
1.5 THz FIR illumination setup

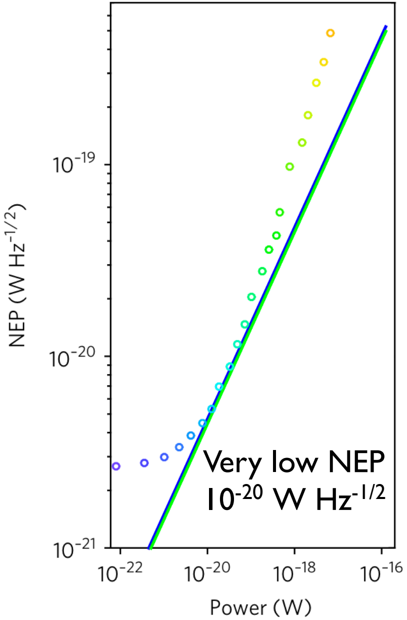


Tunneling trace of QP events





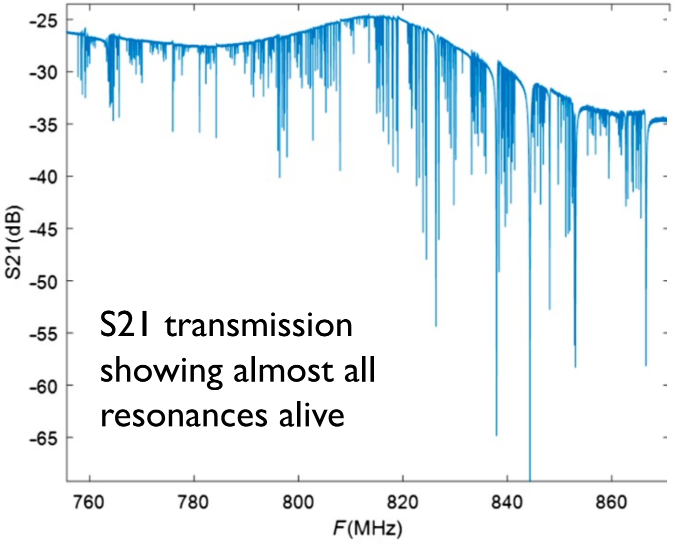


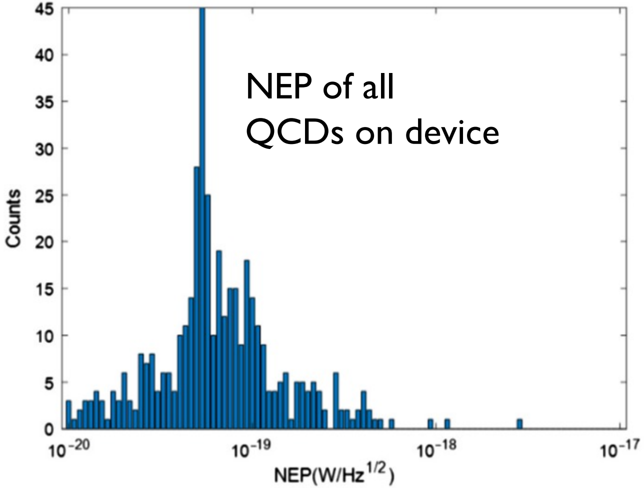


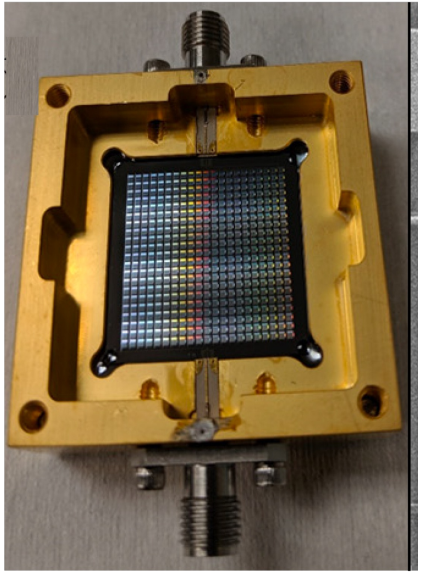
Gate charge drift + high background rate → sweep gate voltage. Photon events changes trace = 1 count

Semi-Latest Designs

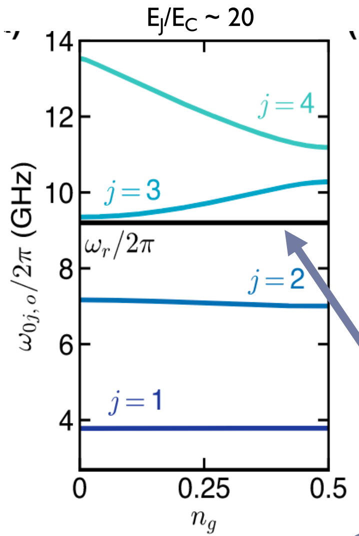
- 441 QCDs on a single array
- Al junctions and absorber, Niobium resonator
- 1.5 um^3 absorber volumes, 100x100 nm^2 junction dimensions







Offset Charge Sensitive

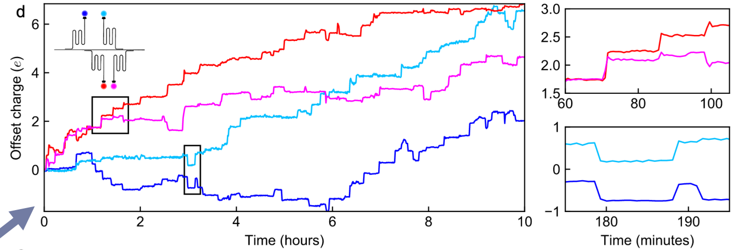


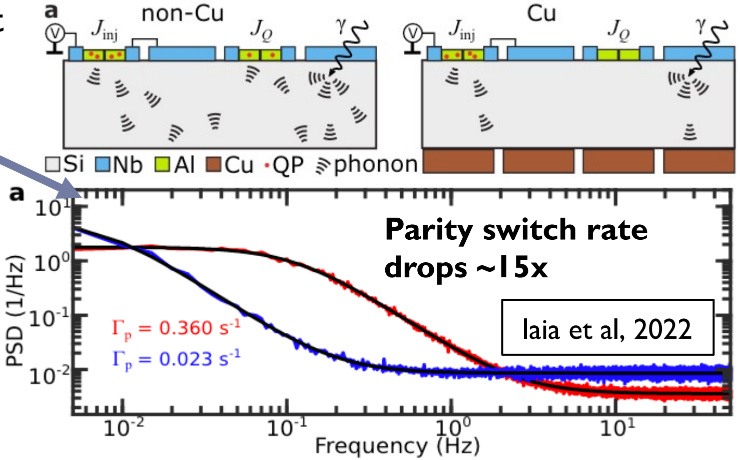
Serniak et al, 2019

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

- QIS qubits suffer from decoherence, traced to *environmentally caused non-equilibrium quasiparticle population*
- Offset Charge Sensitive protocols designed to study these
- Few key takeaways from QIS literature:
  1. Already sensitive to phonon backgrounds and correlated offset charge events
  2. Attempts to suppress these with absorbers
  3. Can measure quasiparticle tunneling rate even in Transmon regime by dispersive shift. Lamb shift of resonator strongly disperses near bare readout frequency → O(MHz) shift

Wilen et al. 2020

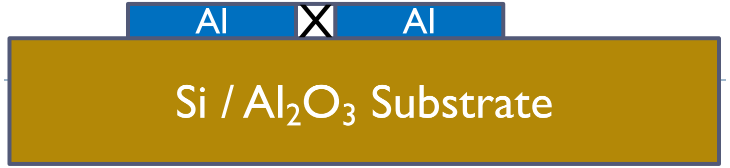




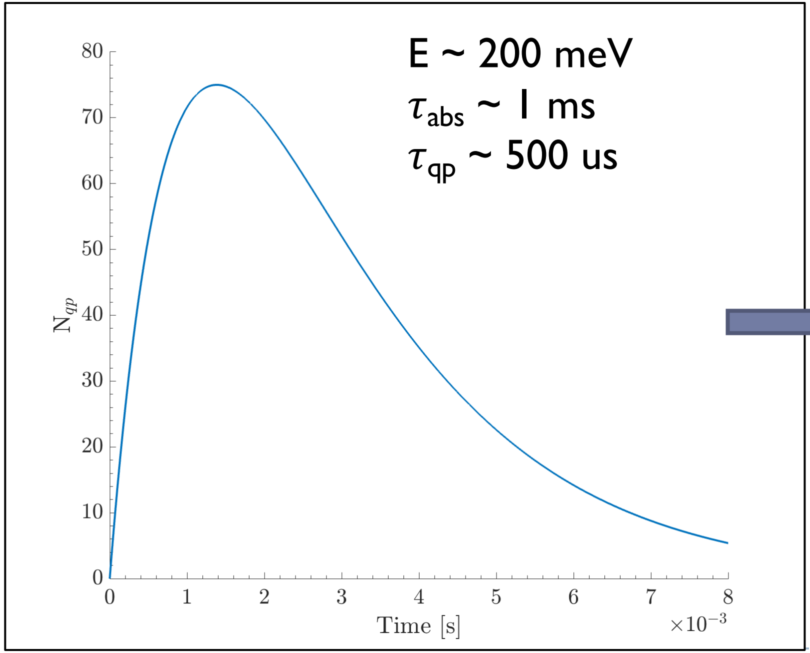
Parity switch rate drops ~15x

Iaia et al, 2022

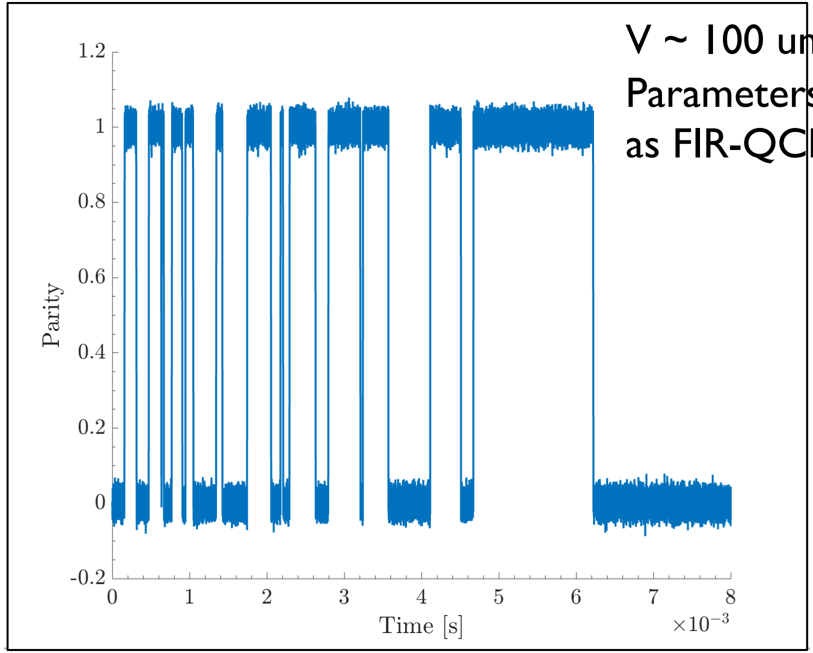
Dark Matter QCDs



Quasiparticle production in absorber



Parity signal observed



Design Considerations and Challenges

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)

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

Readout scheme

- Sweeping gate voltage
- Measurement bandwidth
- Resonator design

Absorber Volume

- Tunneling rate ←→ volume
- Saturation effects
- K~10 kHz um^3
- 1 → 10000 um^3 absorber means R~1 Hz which is not observable

Phonon-Film Coupling

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

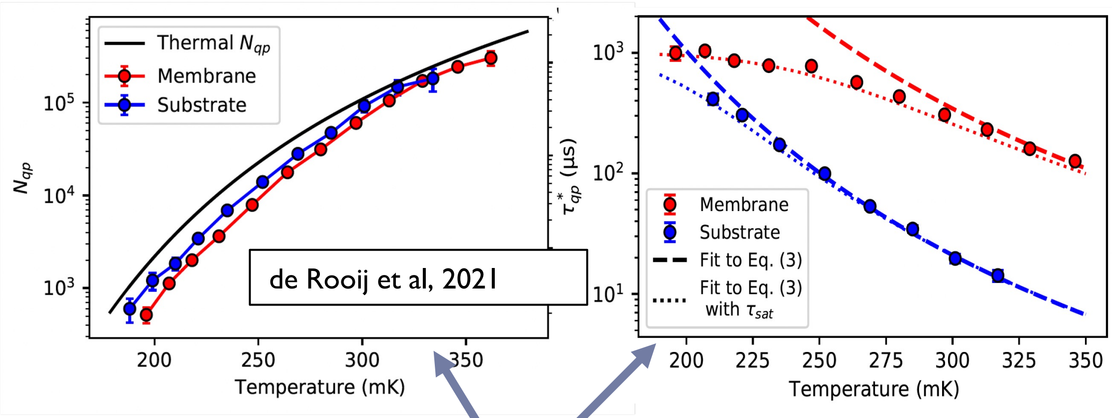
Tunnel Junction Properties

- Barrier resistance R_N below ~5 kΩ unstable junctions?
- Fab. yield 70-90% depending on geometry
- Increase junction size but E_C plays a role in sensitivity
  → Transmon readout?

Offset Charge Drift

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

Non-equilibrium quasiparticles



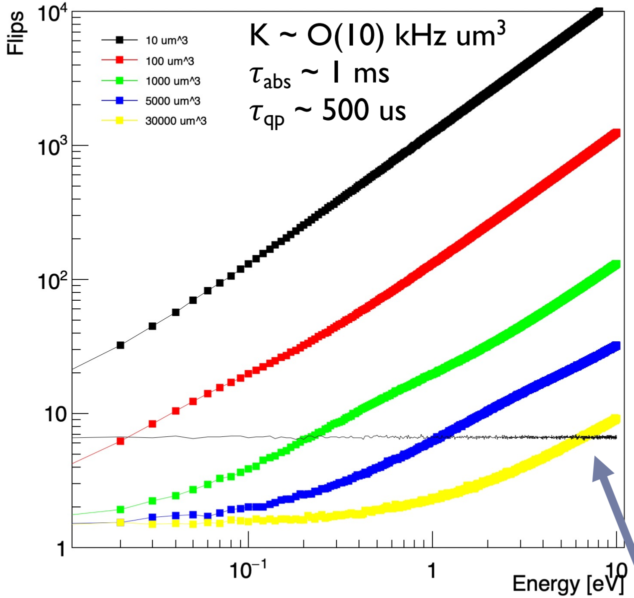
KID Generation-Recombination noise derived quasiparticle population follows thermal profile, but lifetime saturates!

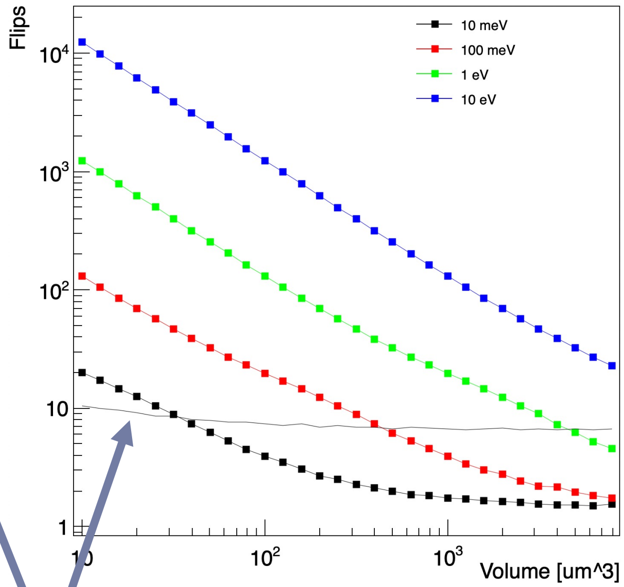
- Large uncertainty in non-equilibrium quasiparticle population.
- KID measured densities 10-1000 um^{-3} and lifetime measurements 100 us – 1 ms
- Background tunneling rates in QCD and OCS measurements range from few Hz → few kHz
- Lower values consistent with O(10^{-1}–10^{-2}) um^{-3}
- Residual QP density may consist of 'trapped' quasiparticles that limit lifetime, but such trapped QPs do not contribute noise because population does not fluctuate.

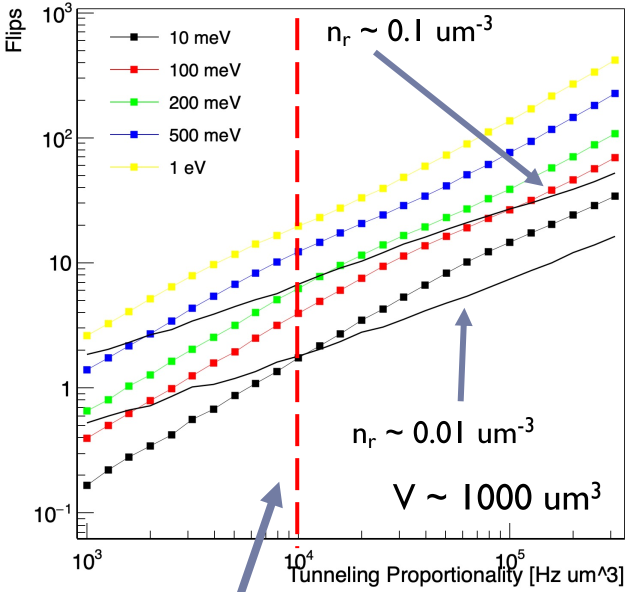
If true ramifications for QCDs because these trapped QPs will not tunnel into the SCB island, and thus not contribute to the background rate.

thermal vs. trapped vs. residual

Expected Sensitivity & Resolution







3σ threshold, assuming background qp density 0.1 um^{-3} and linear tunneling rate scaling

Current tunneling proportionality

First Device & Roadmap

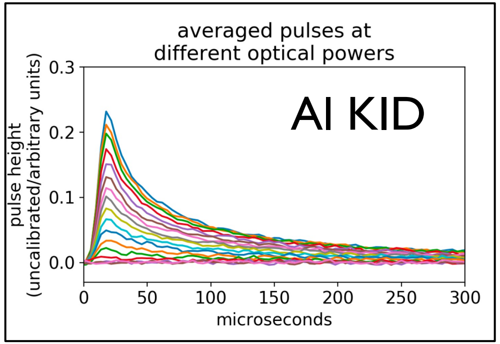
Design Stage	Details	To be studied

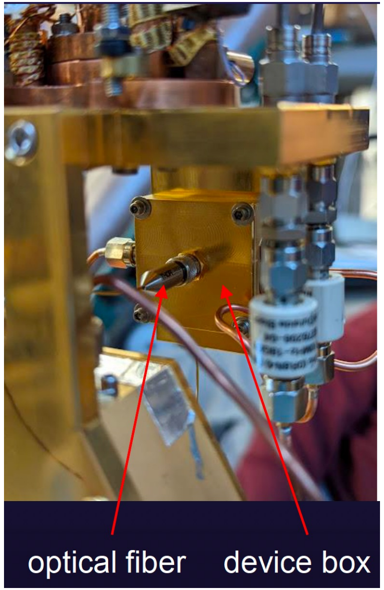
Device A 2023 Spring	• 2 x 2 cm x 500 um Si substrate
	• 4 QCDs + 1 Al KID, 50 nm thick
	• Volume 1, 100, 1000, 10000 um^3
	  • Direct copy of FIR QCDs
	  • Latter matching KID
		• Background & tunneling rate scaling
		• Energy resolution
		• Referencing device performance vs KID

Device B 2023 Fall	• 2 x 2 cm x 500 um Si substrate • 3 QCDs • Varying junction sizing	• Junction parameter effect on above quantities
Device C, D, E, … 2024 - 2025	• Will be informed by previous runs • Material, quasiparticle trapping, Transmon readout • Sapphire substrate – polar material • 10s-100s of QCDs on one array	• Eventual DM run at some facility like NEXUS Fermilab?

Calibration Schemes

Optical Pulses

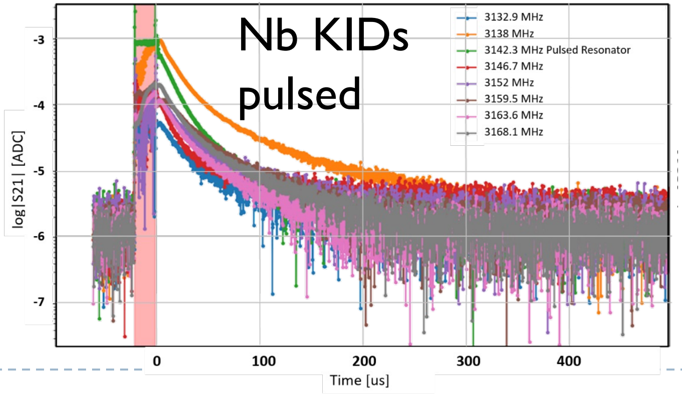




- Optical fiber into fridge to bring optical photons down to the device.
- Will infer based off the width of the distribution of amplitudes → expect Poissonian statistics
- Will give absolute scale on energy absorbed within substrate, **through the larger devices**

In-situ pulsing

- Pulse on-chip resonators to generate a phonon burst → into and out of substrate
- Calibrate small absorber volumes off of response of large volume devices matched to on-chip KIDs
- Prior demonstration of scheme with KIDs



Summary

1. Single phonon sensitivity is a driving design need for low-mass particle dark matter searches
2. Quantum Capacitance Detectors & generic "Offset Charge Sensitive" schemes are one avenue to achieve this sensitivity
3. Demonstrator R&D, exploring factors in tunnel junction design, absorber volume, quasiparticle density etc. is underway

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

JPL
Jet Propulsion Laboratory
California Institute of Technology

NSF

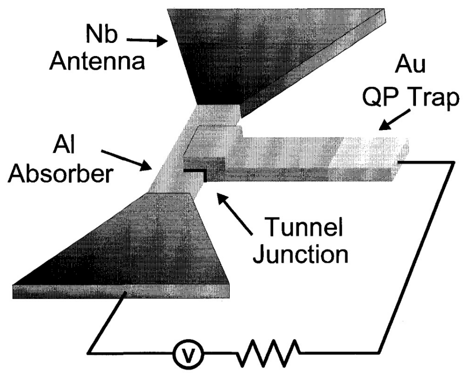
Thanks! Questions?

Caltech

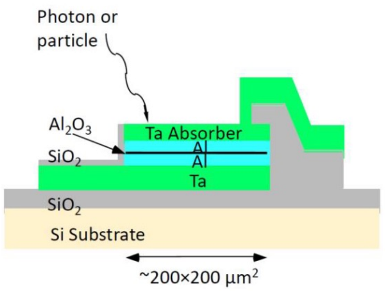
Prior Art

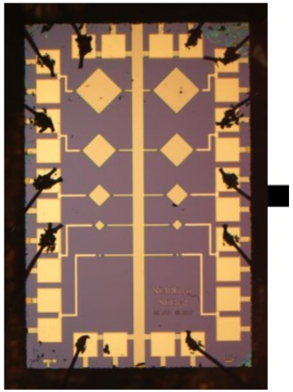
*STJ as photoconductors

Teufel, 2008



- STJs used for >2 decades as x-ray/optical photon detectors
- Excitations in absorber tunnel across detector junction, essentially becoming a photoconductor and inducing a tunneling current → FET pre-amp
- NEP 10^{-19} W $Hz^{-1/2}$ reported





Leach et al 2020

- Also now used for some nuclear physics applications (^{7}Be decay), BeEST experiment

No reported single quasiparticle sensitivity?