Jet Propulsion Laboratory
California Institute of Technology

Kinetic Inductance (& other) Phonon Sensors for Dark Matter Detection

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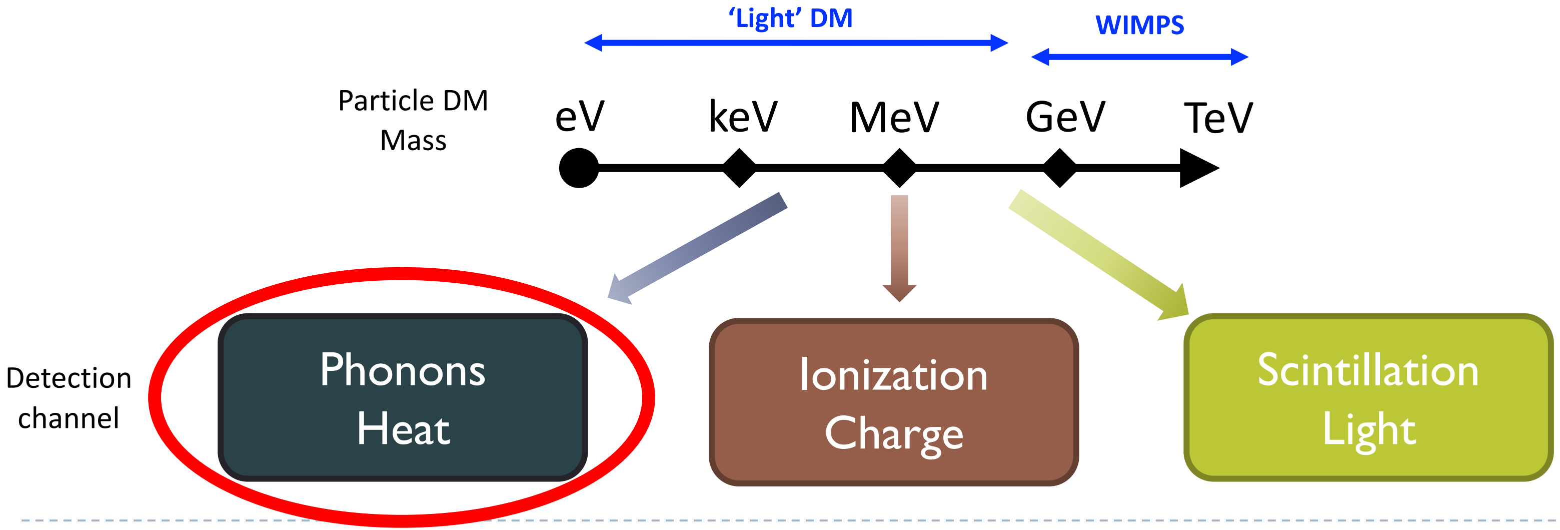
SLAC: Noah Kurinsky

IDM 2022 Vienna

Caltech

Dark Matter & Detection

- Strong cosmological and astrophysical evidence for matter that primarily interacts via gravity, comprising ~25% of the total mass-energy of the Universe.
- Amount of energy deposited in a detector model dependent, but generally scales with mass → O(100) MeVc^{-2} mass nuclear recoils can get you only O(eV) deposits in Si ☹



'Light' DM

WIMPS

Particle DM Mass

eV

keV

MeV

GeV

TeV

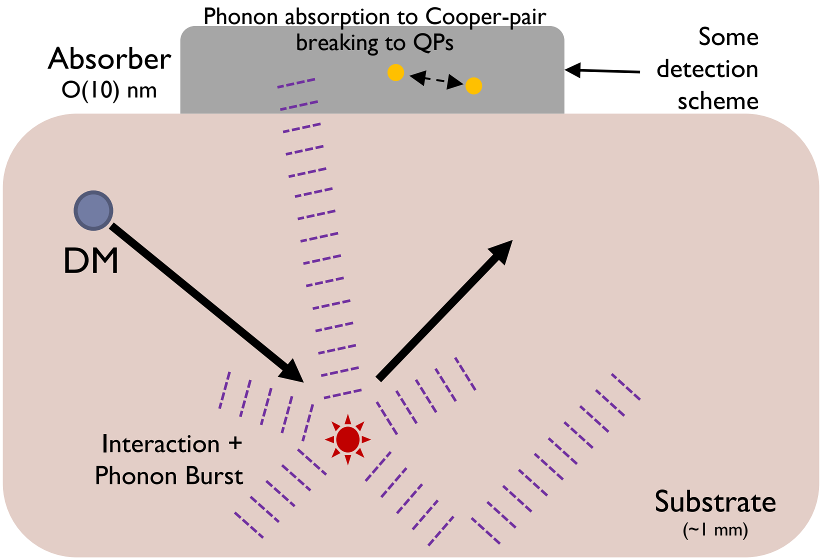
Detection channel

Phonons Heat

Ionization Charge

Scintillation Light

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

+ Long millisecond lifetime allows for many thousand attempts to be absorbed by the detector

+ No relevant fluctuation background, since thermal phonon bath suppressed by mK cryogenic operation

- Need to operate at mK temperatures

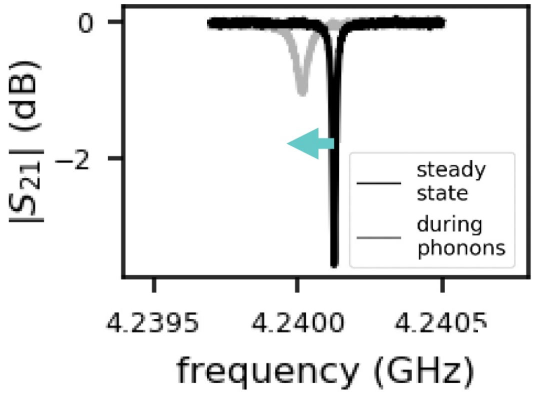
- Diffusive nature means phonon energy can be split across multiple sensors

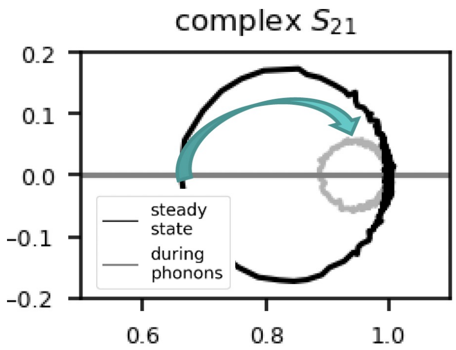
Kinetic Inductance Detectors (KIDs)

- Superconductors have an AC inductance due to physical inertia of Cooper pairs
  - Total induct. = geometric induct. + kinetic induct.
  - Kinetic induct. → dependent on Cooper pair density
- Measure the complex transmission S_{21} across **a superconducting LC-resonator**
- Microscopic BCS theory by Mattis-Bardeen to calculate response of superconductor to EM field → Measure surface impedance to infer changes in complex conductivity, thus QP density

Key point: superconductors provide very high Q ($Q_i \sim 10^7$ achieved), so thousands of O(GHz) resonators a single feedline with O(kHz) linewidths
→ Simple cryogenic multiplexing!

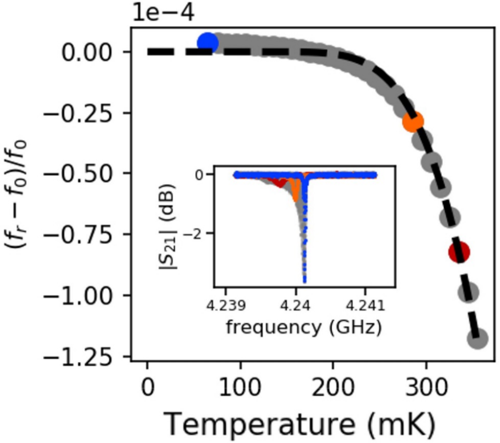
Generate tones and readout using off the shelf Ettus Research USRP software defined radio





$$S_{21}^{\mathrm{res}}(f) = 1 - \frac{Q/Q_c}{1+2jy}$$

$$\delta S_{21}^{\mathrm{res}} = \frac{Q^2/Q_c}{(1+2jy)^2}\left(\delta\frac{1}{Q_i} - 2j\frac{\delta f_{\mathrm{res}}}{f_{\mathrm{res}}}\right)$$



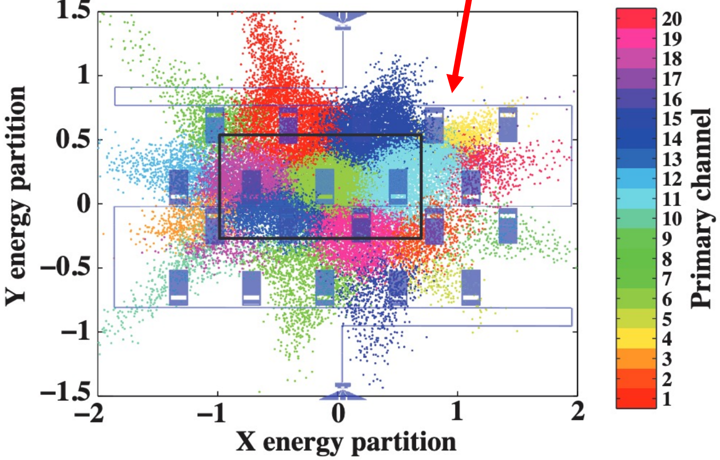
Prior Work Proof of Concept

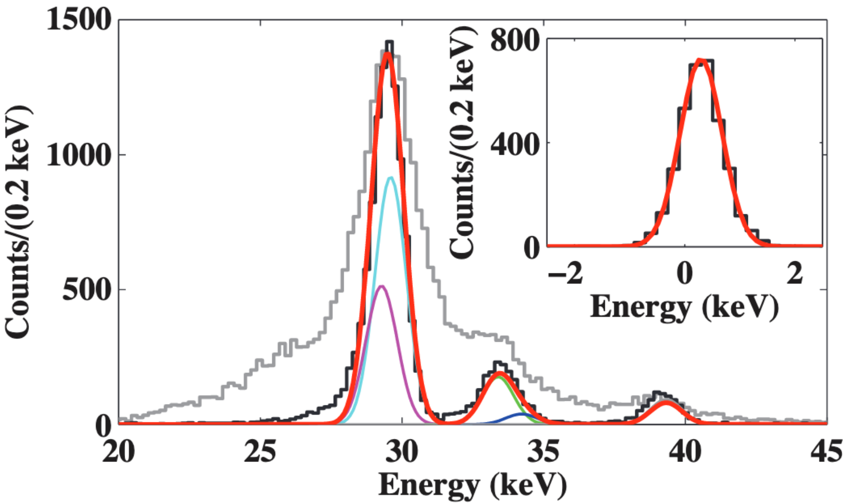
- 20 KID array on silicon exposed to ^{129}I source
    - 0.55 keV energy resolution
    - mm-scale position reconstruction

Position and energy-resolved particle detection using phonon-mediated microwave kinetic inductance detectors

Appl. Phys. Lett. **100**, 232601 (2012); https://doi.org/10.1063/1.4726279

D. C. Moore[1, a)], S. R. Golwala[1], B. Bumble[2], B. Cornell[1], P. K. Day[2], H. G. LeDuc[2], *and* J. Zmuidzinas[1,2]





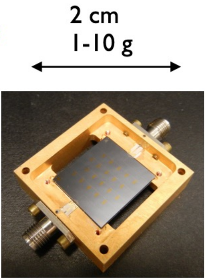
DM Architectures & Roadmap

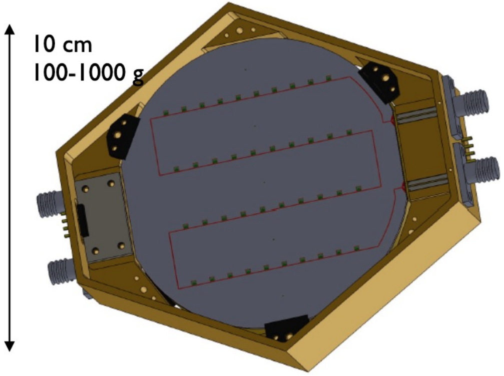
“Small”/Low-Threshold detector (gram-scale)

- Goal: detection of sub-eV energies from
  - Dark photon absorption
  - DM-e scattering
- Single mm-scale KID on few-mm target substrate

“Large” detectors (kg-scale)

- Goals:
  - Measure “NTL” phonons from ionization
  - Nuclear recoil search down to 10 eV_r
  - DM-e scattering at eV scales
- ~100 KIDs on 10-cm-scale substrate
  - Pixelization to provide fiducialization from surface effects, position correction for energy, NR/ER discrimination

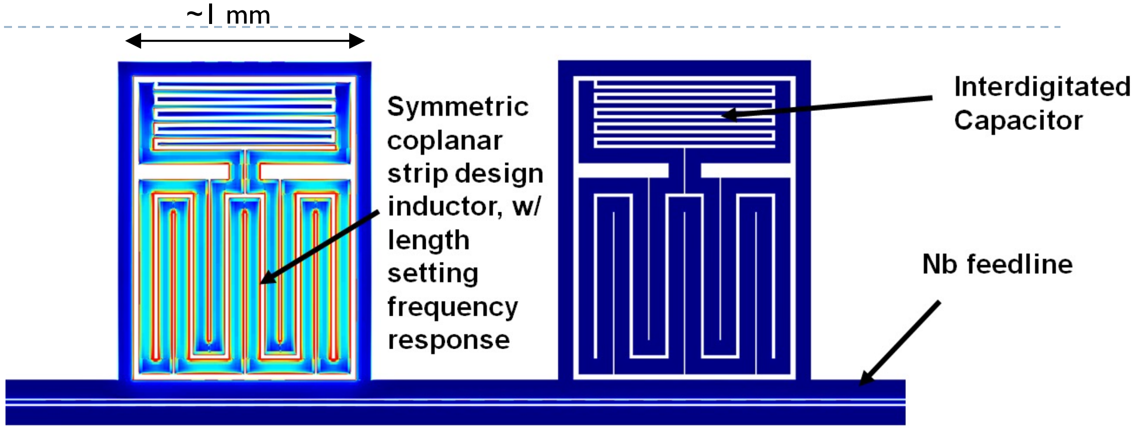




Design Stage	σ_{pt} Small	σ_{pt} Large
Current Technique	10-20 eV (meas.)	240 eV (est.)
Optimized Single KID	5 eV (proj.)	___
SQL Amplifier	1 eV (proj.)	50 eV (est.)
Improve t_{qp} to 1 ms	0.5 eV (est.)	25 eV (est.)
Lower T_c material (smaller gap, higher KI fraction)	O(100) meV (est.)	5 eV (est.)
??	O(10) meV	___

Modern KID Design

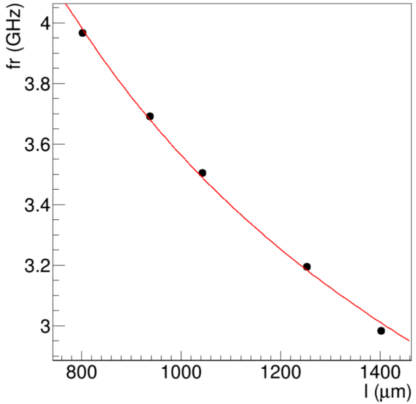
- Aluminum ($\Delta \sim 200$ ueV)
- 10-30 nm thick film inductor
- Frequency tuning done by adjusting inductor length
  - Operate around 3-5 GHz
  - $3\text{x}10^4$ μm^3 active volume
- Capacitor: Interdigitated capacitor to minimize TLS (two-level system) noise
- Feedline can be made out of Nb ($T_c \sim 10K$) in long runs to preferentially avoid absorbing phonons

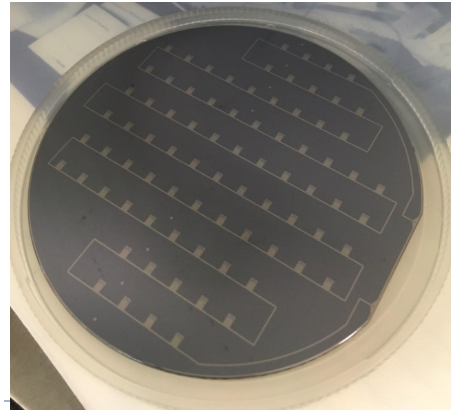


Symmetric coplanar strip design inductor, w/ length setting frequency response

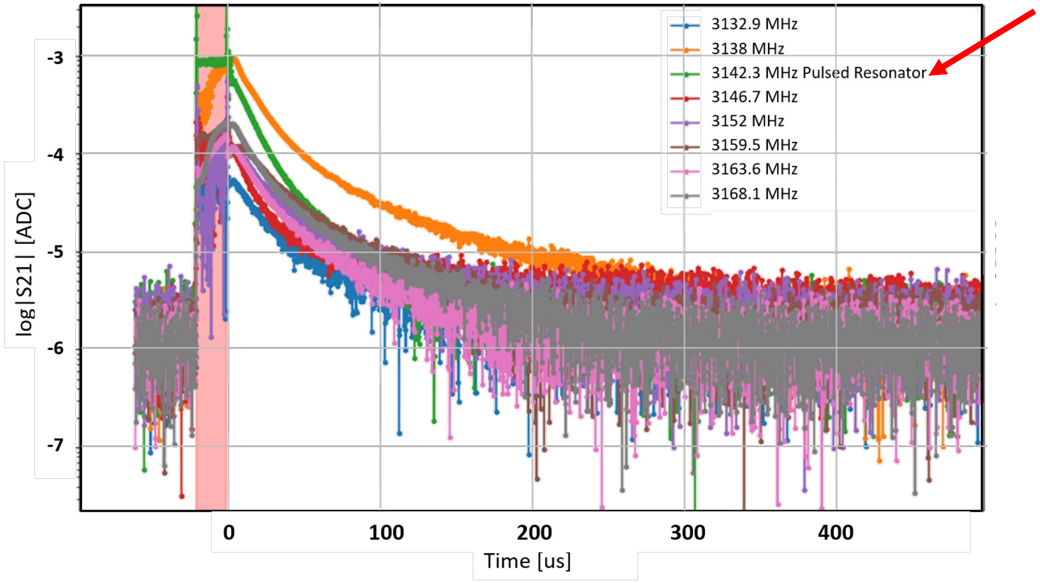
Interdigitated Capacitor

Nb feedline





Novel in-situ pulsing calibration scheme

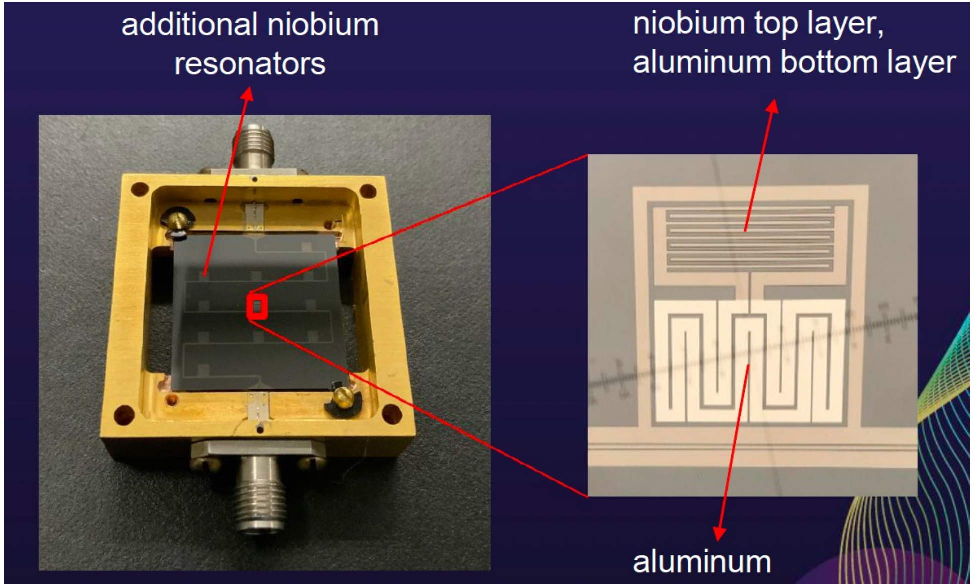


Pulse one resonator on array with lots of power → generates lots of QPs → Cascade *creates* phonons that travel in substrate → Picked up by other KIDs → Use M-B parameters to work out energy resolution

+ Sensor characterization with no external source

- Not absolute measurement of substrate resolution → systematics on energy deposited/received within substrate

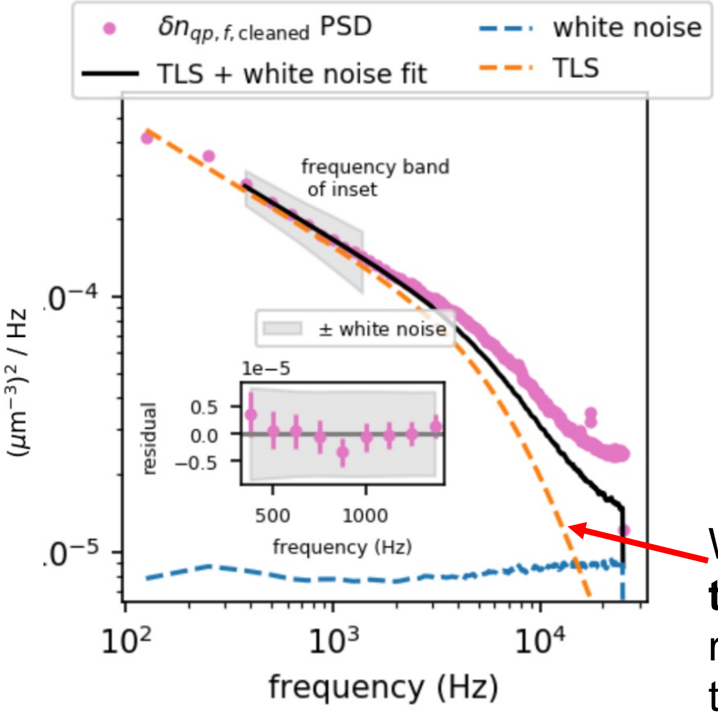
Single KID Device

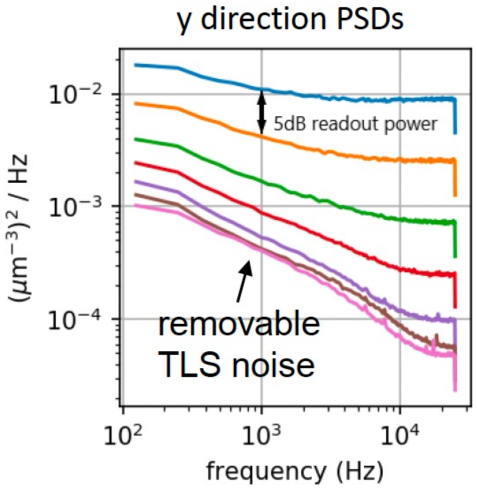


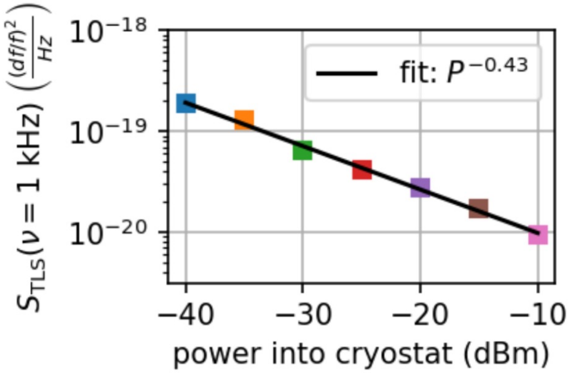
A single phonon-collecting resonator

- Single resonator → most energy collected
- Reducing "dead metal" (unnecessarily absorbs phonons and does not contribute to the signal)
- Bonding pads, feedline, and other resonators are all made with a higher T_c material than the signal resonator, leaving more phonons for the signal resonator
- Capacitor of the signal resonator has little current flowing through it → also dead metal

Device Results







We aim to **remove the TLS noise** by replacing/modifying the niobium top layer

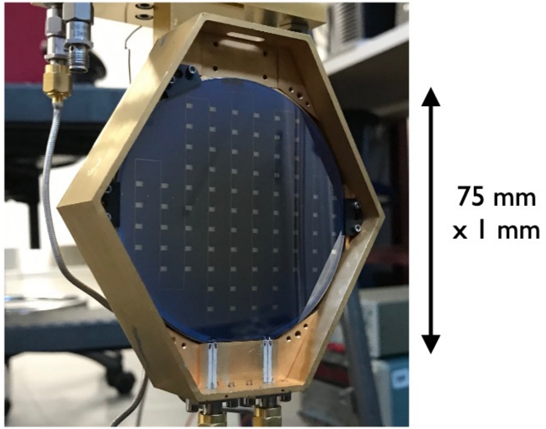
Energy resolutions	**TLS-limited (current)**	***Est. white noise only optimized***
σ_p absorbed by the resonator	**6 eV**	**1.5 eV**
Est. σ_p deposited in the substrate	**20 eV**	**5 eV**

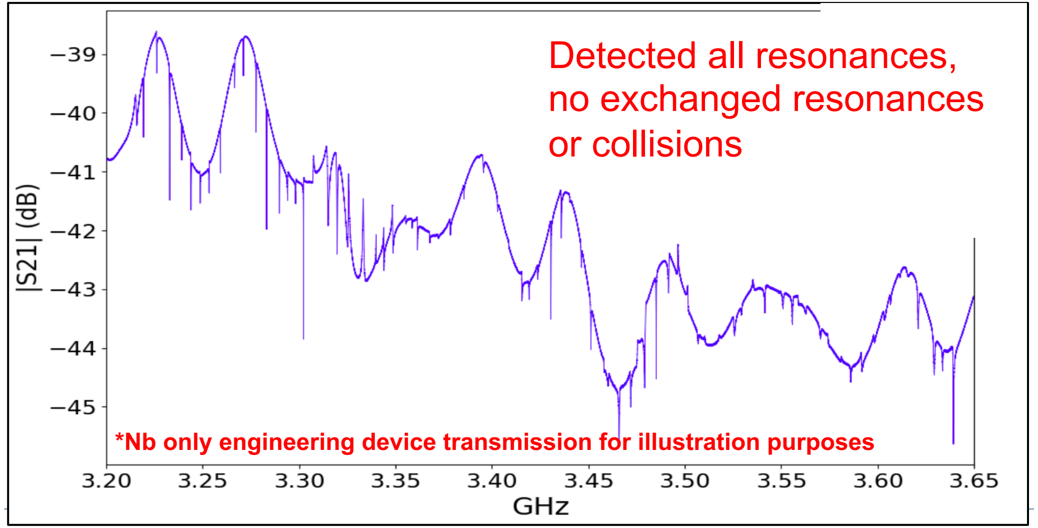
Results in: **Wen et al., Journal of Low Temperature Physics, 2022**

Larger 80 KID Device

Multiple phonon collecting Al resonators:

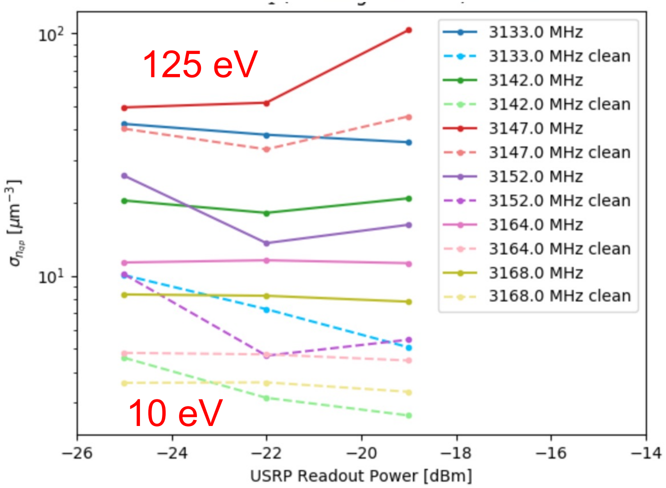
- Hybrid architecture - small device KIDs, used as testbed for running many KIDs on same feedline
- Energy resolution on sensor (not substrate) varies from O(10) to O(100) eV though?!





Detected all resonances, no exchanged resonances or collisions

*Nb only engineering device transmission for illustration purposes



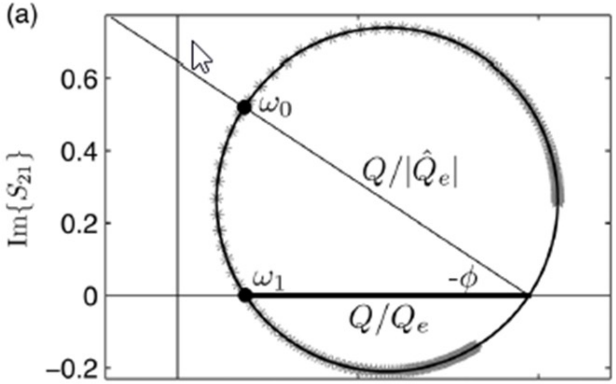
125 eV

10 eV

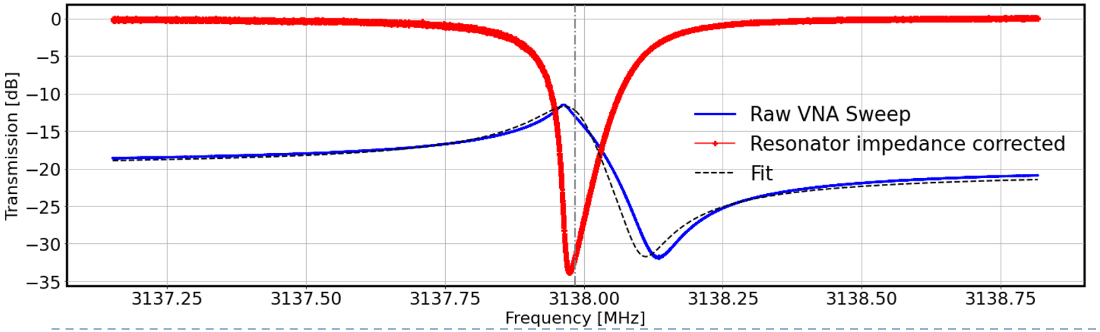
Impedance mismatches as the culprit?

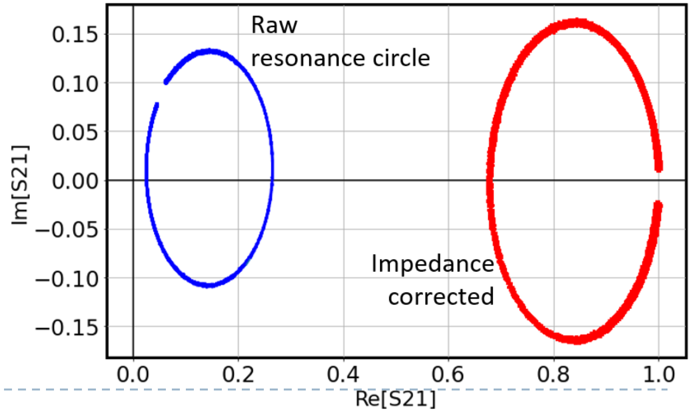
- One argument is that mismatched input and output transmission impedances in microwave transmission circuits lead to asymmetric transmission lineshapes, parametrized with rotation ϕ and scaling cos(ϕ)

$$S_{21}^{\mathrm{res}}(f) = 1 - \frac{1}{1+2jy}\frac{Q}{Q_c\cos\phi_c}e^{j\phi_c}$$



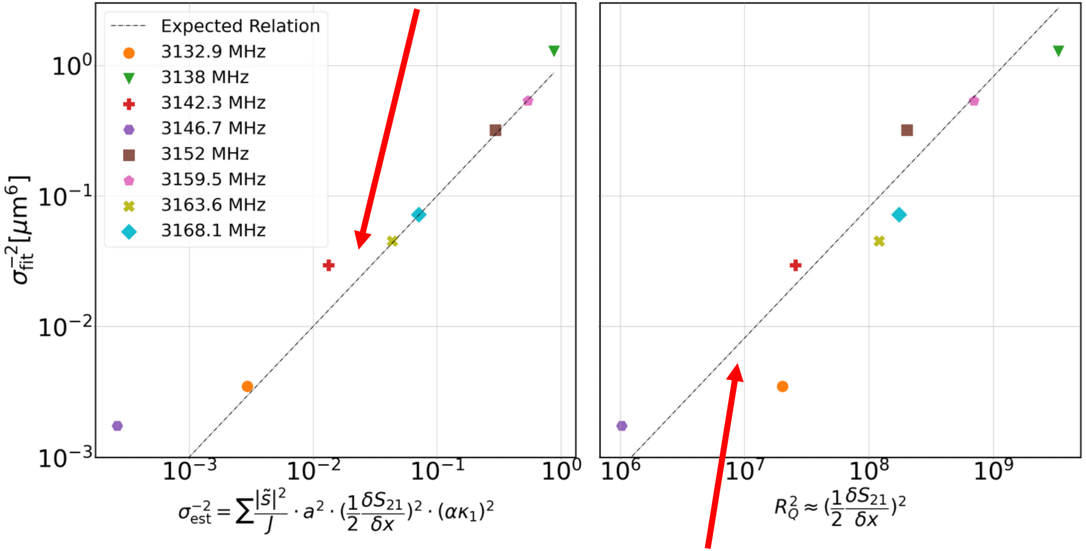
Khalil et al. 2012



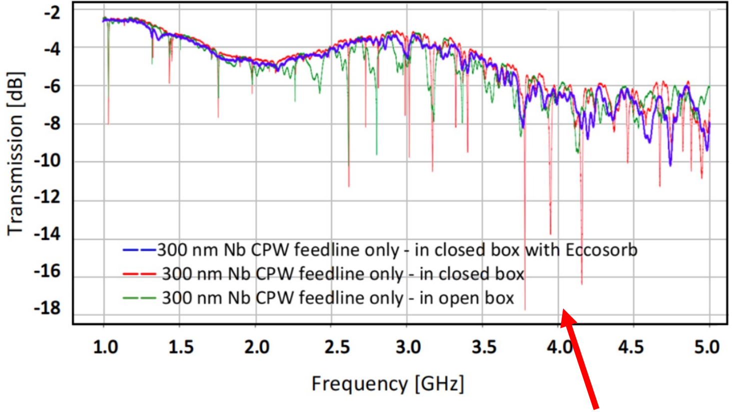


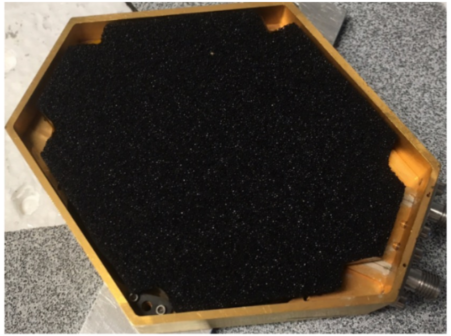
Resolution Variation

Resolution broken up into empirically estimated components



Box modes as an explanation?





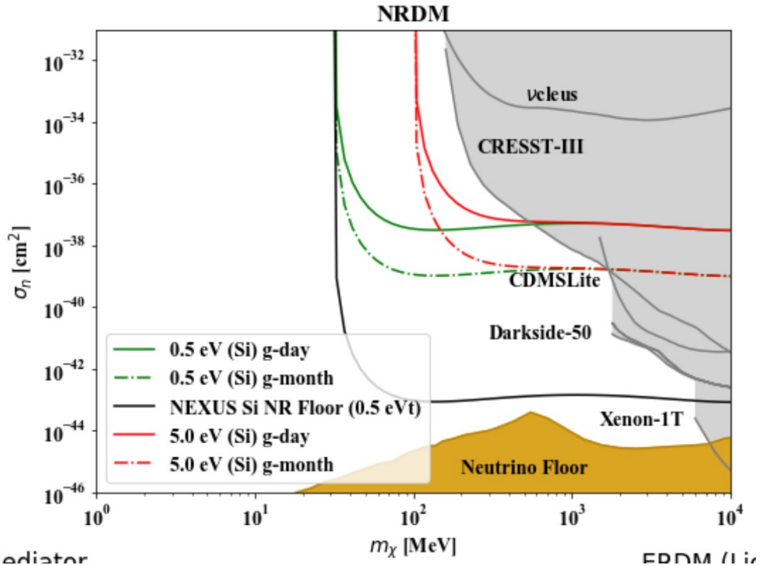
Applying Eccosorb foam filter

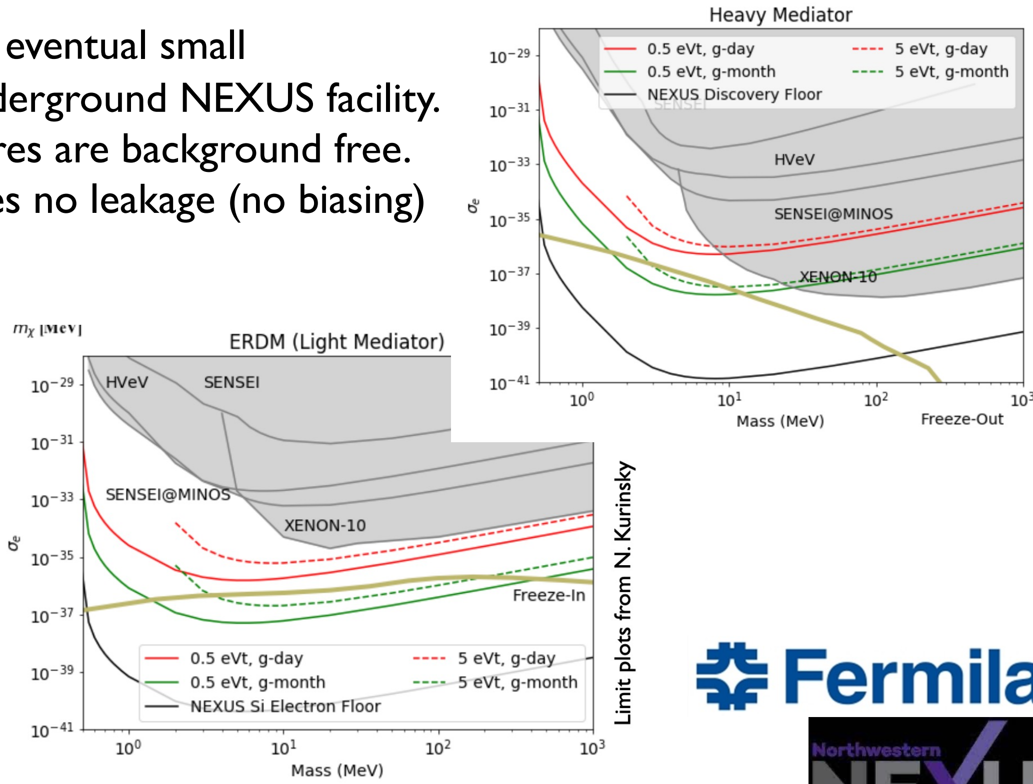
- Resolution variation appears driven by variation/interplay in overall "quality factor term" → Hard to pin down one of Q_c, Qi, ϕ

Results in: **Ramanathan et al., Journal of Low Temperature Physics, 2022**

DM Projections @ NEXUS underground facility

- Ongoing work by FNAL colleagues for eventual small architecture DM run in 100m deep underground NEXUS facility. Design of facility ensures small exposures are background free.
- 1 eV and 100 meV resolutions, assumes no leakage (no biasing)





Limit plots from N. Kurinsky

Fermilab

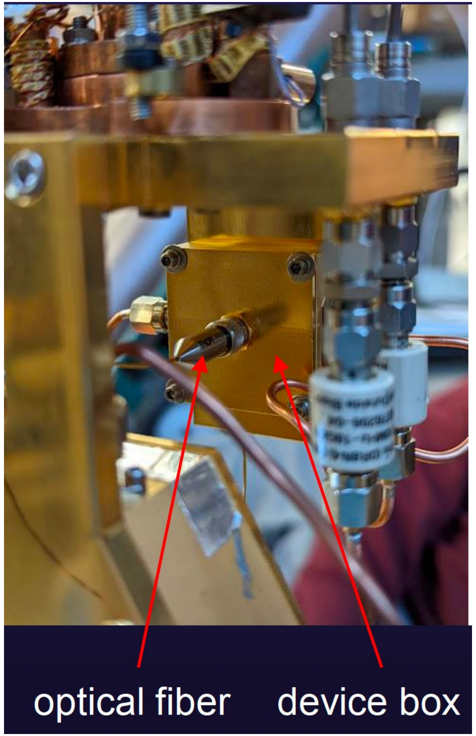
Northwestern NEXUS Experimental Underground Site @Fermilab

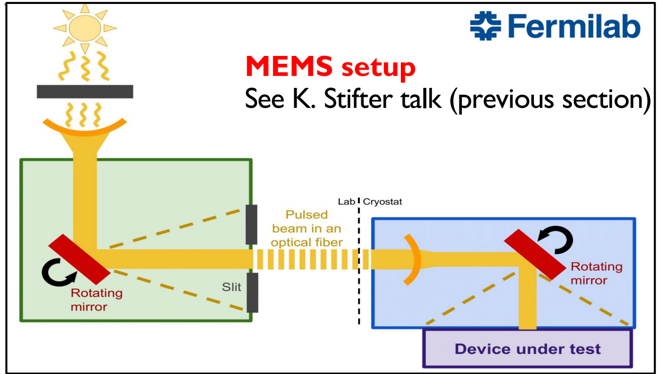
Ongoing Work

Absolute Calibration

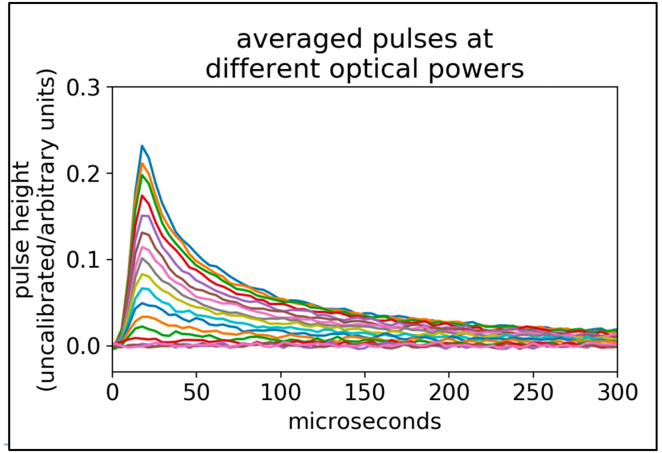
Optical fiber into fridge to bring optical photons down to the device.

- 475nm LED; 2.61eV per photon
- LED pulsed for 10 μs at a time
- Will infer based off the width of the distribution of amplitudes → expect Poissonian statistics
- Will give absolute scale on energy absorbed within substrate



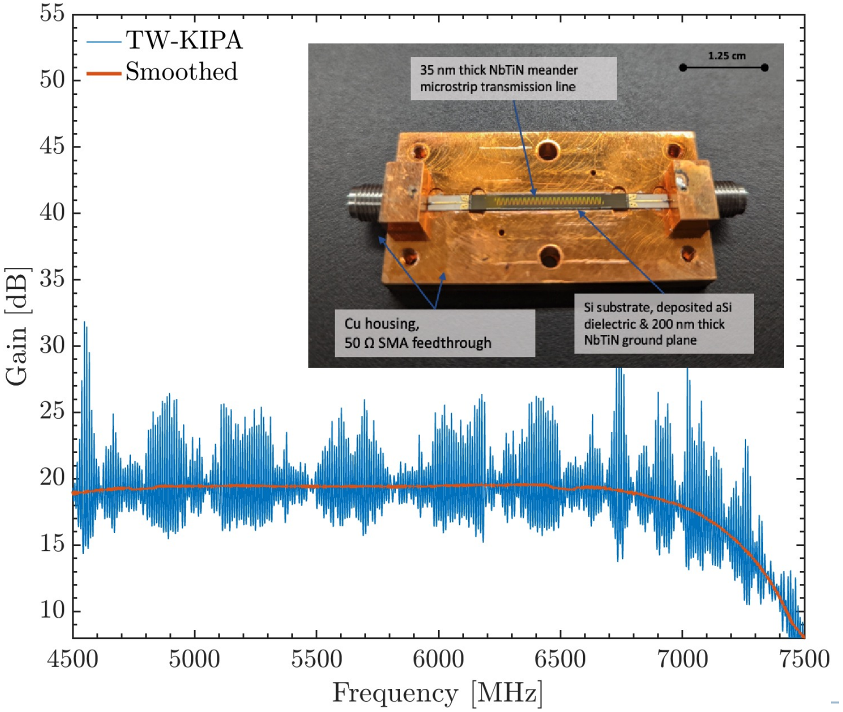


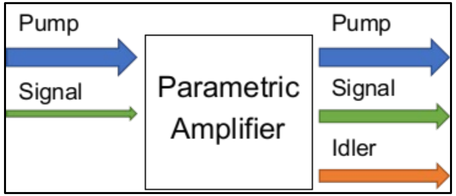
MEMS setup
See K. Stifter talk (previous section)


averaged pulses at different optical powers

Parametric Amplifiers

$$\sigma_E = (5\ \text{eV}) \frac{\Delta}{200\ \mu\text{eV}} \frac{0.3}{\eta_{ph}} \frac{\sqrt{\eta_{read}/p_t}}{0.8} \sqrt{\frac{0.1}{\alpha}} \sqrt{\frac{1}{\chi_{qp}}} \sqrt{\frac{1.6}{S_1(f_r, T_{qp}, \Delta)} \frac{2.5 \times 10^5}{Q_c}} \sqrt{\frac{100\ \mu s}{\tau_{qp}} \frac{T_N}{2.5\ \text{K}}} \sqrt{\frac{M_{sub}}{1\ \text{gm}} \frac{\lambda_{pb}}{1\ \mu\text{m}} \frac{7\ \text{km/s}}{c_s}}$$





If amplifier noise limited like we believe → benefit from lowering noise temperature.

Kinetic Inductance Parametric Amplifier

- Quantum-limited amplifiers uses a non-linearity in kinetic inductance to transfer power from a pump tone to a signal tone
- Made at JPL by Peter Day's group
- $k_b T_N = h\nu$ of total added noise to the vacuum noise at 4GHz: 25x reduction in noise temperature
- **Energy resolution goal O(1) eV**

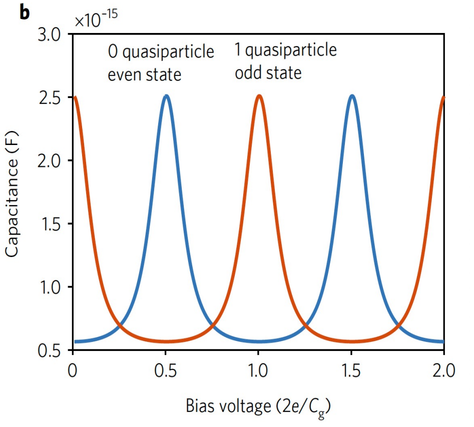
Summary

1. Kinetic inductance detectors are a promising sensor technology to get down to <O(eV) resolutions and thresholds
2. Ongoing work to design & characterize "small" and eventually true "large" detector architectures
3. Next iteration of single-KID detector will aim to have lower TLS noise, and once interfaced with a parametric amplifier can be used for a LDM search.

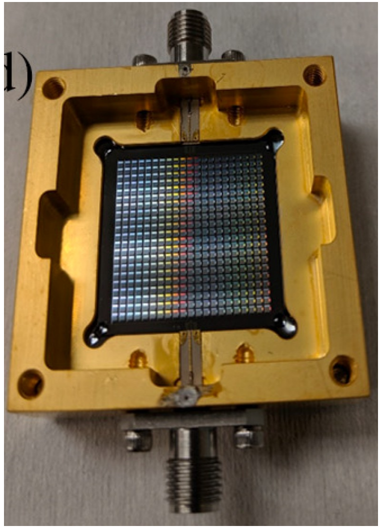
But… can we go to the single meV-scale?

QCDs (Quantum “Capacitance” Detectors)

- Quantum computing has exploded over last 20 years developing very sensitive qubits
    - Now even used in Axion DM hunting
- Cooper Pair Boxes → Earliest era superconducting qubits
    - Use Josephson Junctions to create a charge sensitive ‘island’.
    - Very sensitive to environmental QPs
- Crucially, state of device is sensitive to even/odd quasiparticle population within island → Get onto island by tunneling across JJ
- Coupled to O(GHz) resonator, will see O(MHz) shifts for change in even ←→ odd state

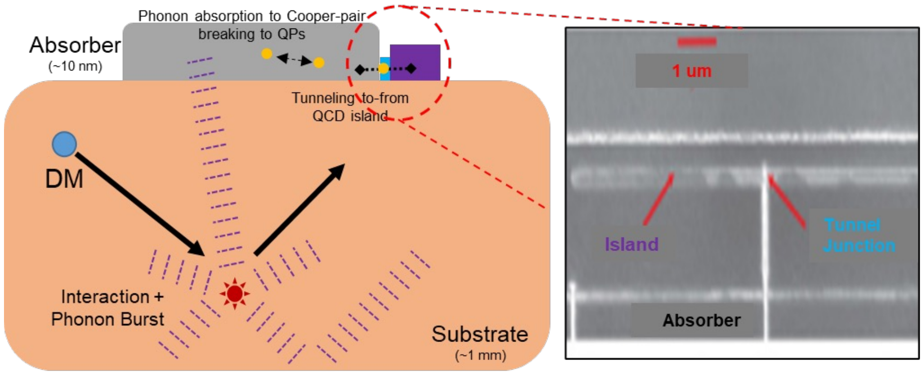


Echternach et al. Nature Astronomy 2017

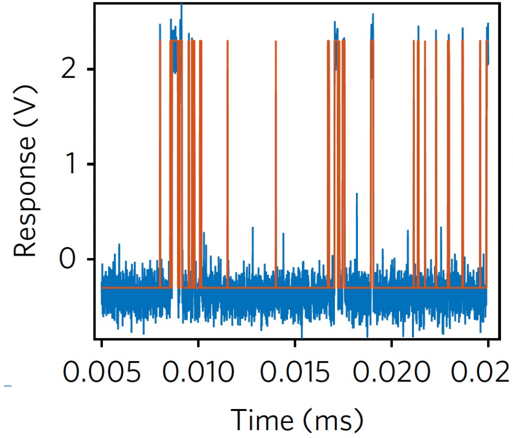


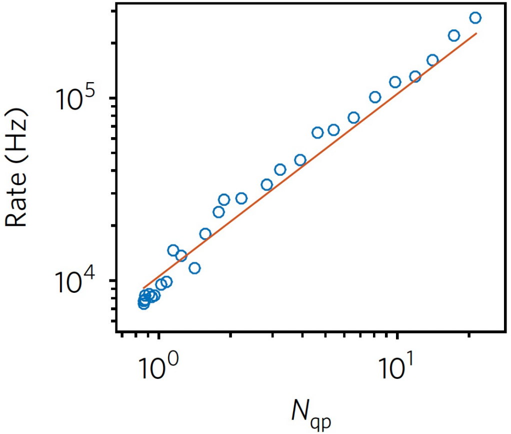
441 QCD device Demonstrated at JPL for THZ photon counting

QCDs II



Echternach et al. Nature Astronomy 2017





- For DM: couple it to substrate like a KID!
- Rapid tunneling observed in THz photon device, with strong linear relationship!
- With Al this would mean directly counting 200 μeV quanta to probe meV phonons directly!
- R&D detector program ongoing

1 quasiparticle
2 quasiparticle
...

Thanks! Questions?