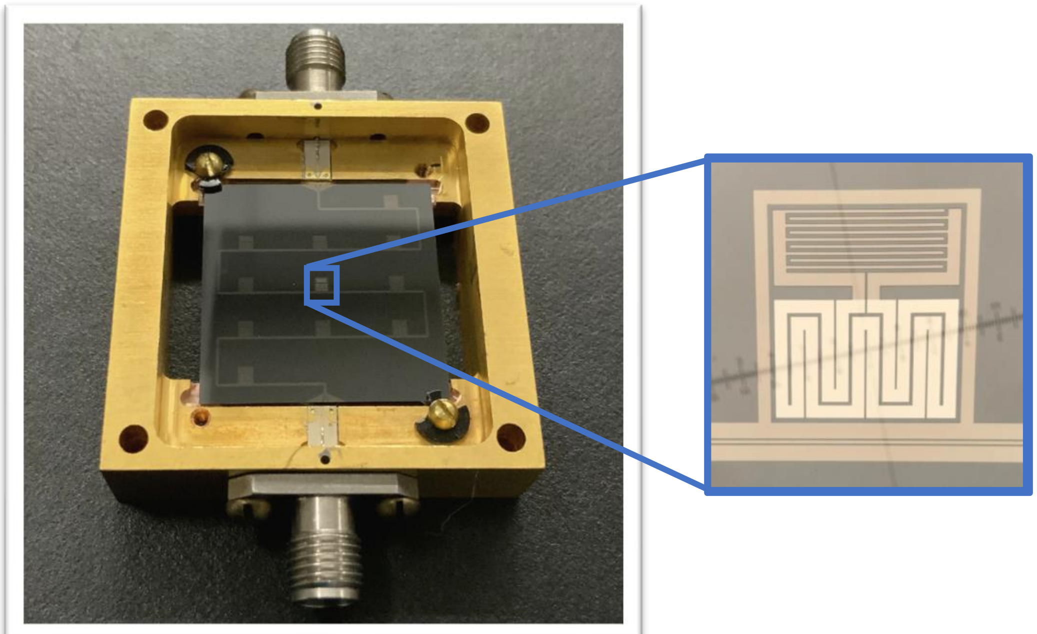
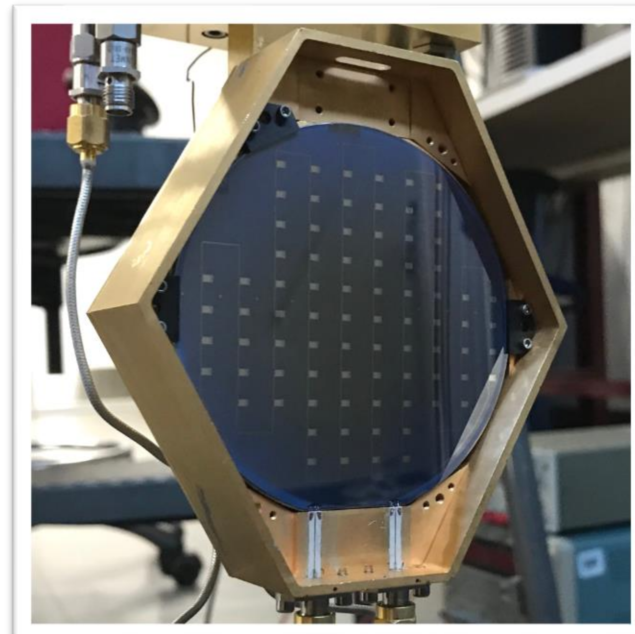
Phonon-mediated kinetic inductance detectors for low mass dark matter searches





Speaker: Osmond Wen

Advisor/PI: Sunil Golwala

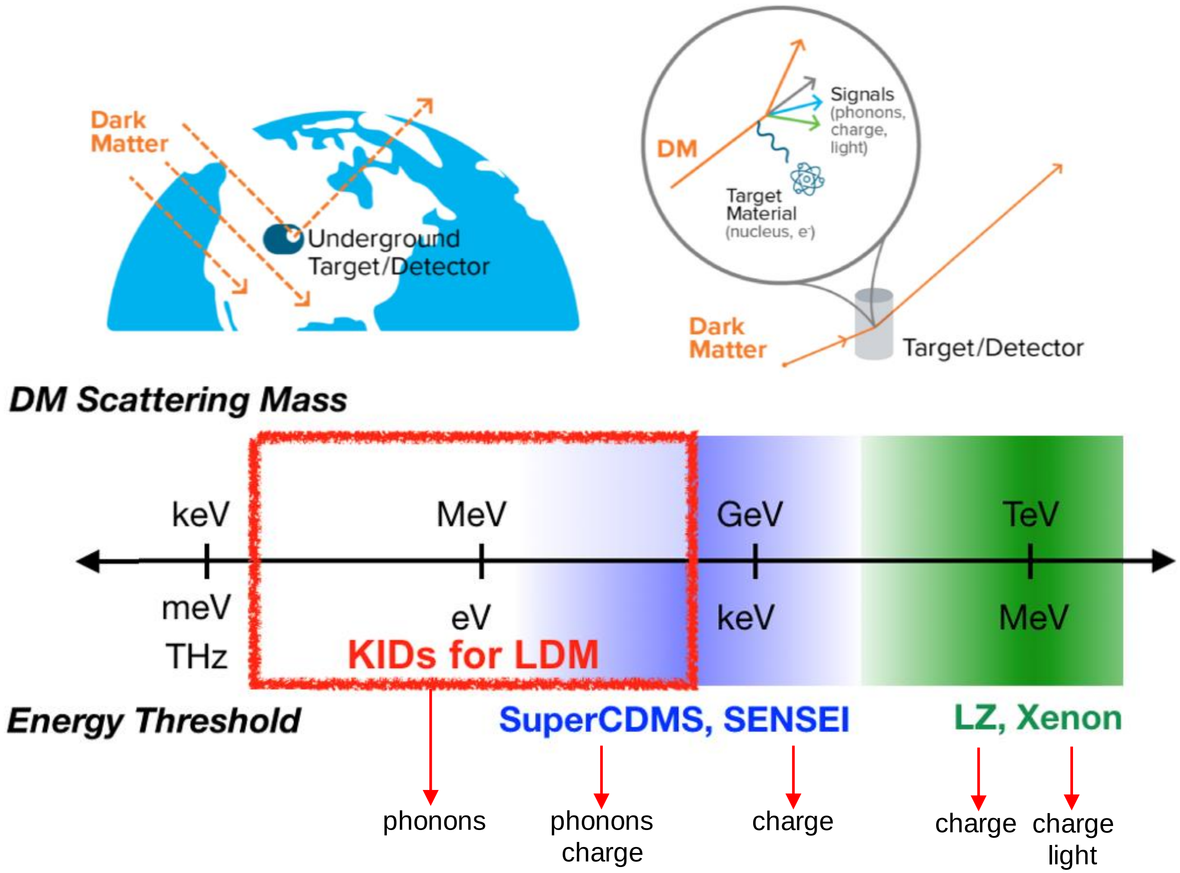
Caltech: Taylor Aralis, Ritoban Basu Thakur, Yen-Yung Chang, Karthik Ramanathan, Brandon Sandoval

JPL: Bruce Bumble, Peter Day, Byeongho Eom

Fermilab: Lauren Hsu and Dylan Temples

SLAC: Noah Kurinsky

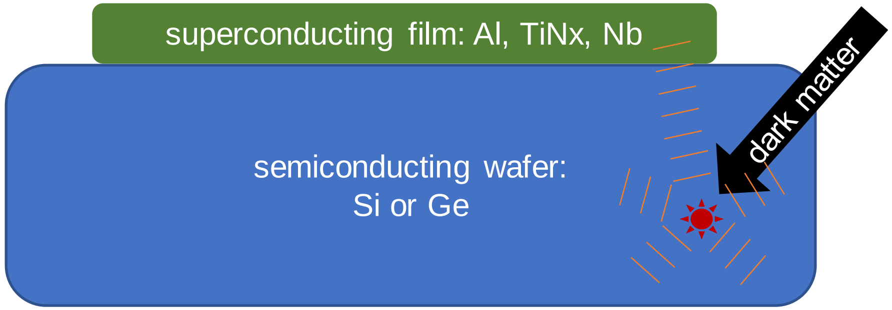
Dark matter direct detection using phonons

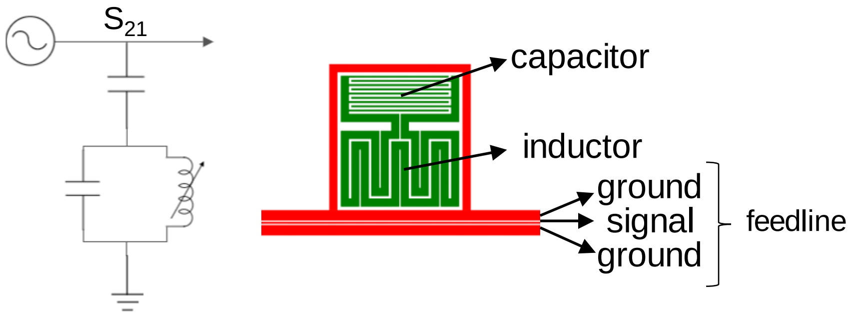


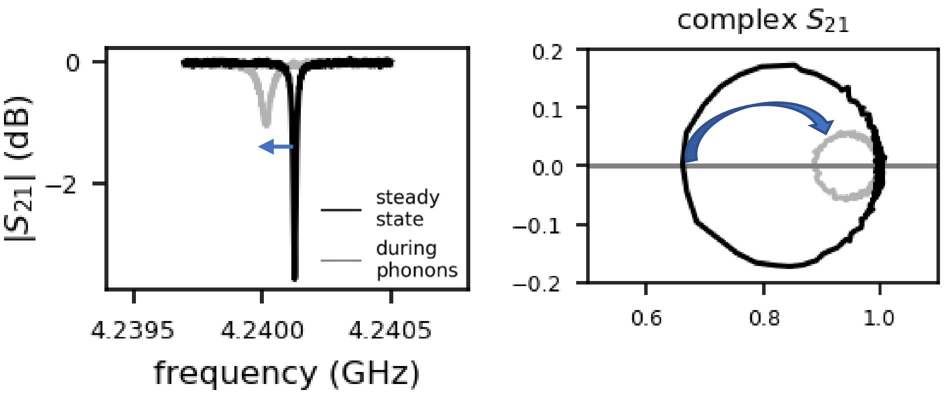
Sub-GeV dark matter particles deposit eV-scale energy in a silicon detector

Kinetic inductance detectors (KIDs) overview

- The **complex transmission S_{21}** is measured across a superconducting LC-resonator
  - kinetic inductance = Cooper pair inertia, which is dependent on Cooper pair density
  - film absorbs phonons
    →Cooper pairs break and make quasiparticles
    →film inductance increases
    →transmission changes
- High Q resonances
  → can couple thousands of resonators to the same feedline
- RF readout: Software Defined Radio
  - Ettus USRP: https://www.ettus.com/all-products/x310-kit/

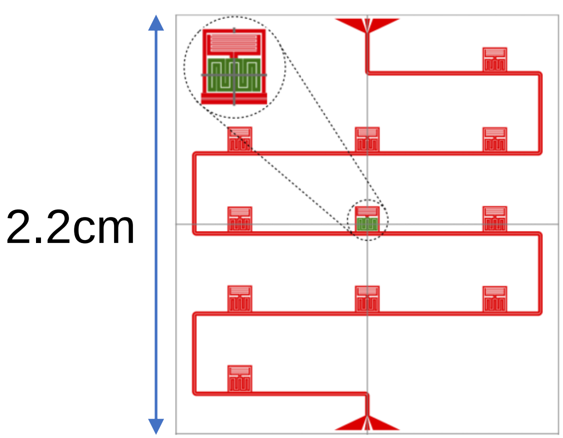






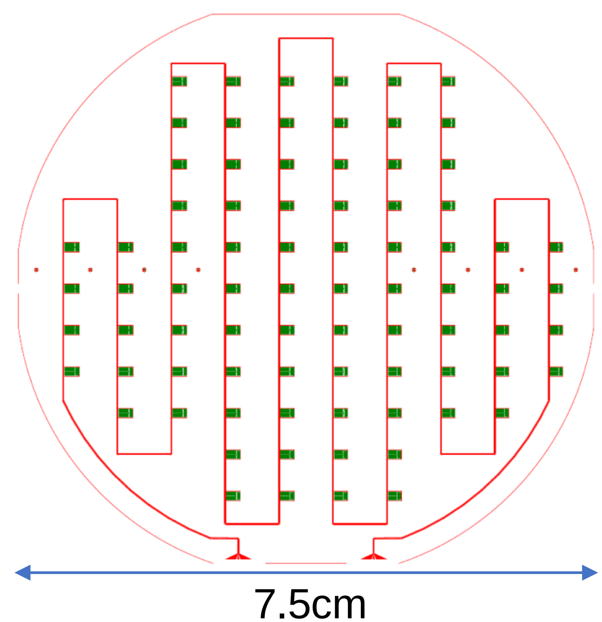
What advantages do KIDs provide as phonon detectors?

- A trajectory to sub-eV resolutions on deposited energy
  - Phonon-coupled TESs have demonstrated 2.65eV energy resolution
  - Direct sensitivity to pair-breaking phonons
    - no quasiparticle trapping needed
    - non-signal contributing components are made with a higher-gap material
  - **Design architecture choice**: a smaller single resonator device, optimizing for energy resolution



green: Al
red: higher-gap materials

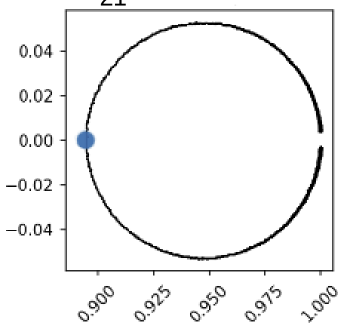
- Massively multiplexable → highly position-resolved
  - Improved discrimination between nuclear recoils and electron recoils
  - Improved rejection of surface events
  - **Design architecture choice**: a larger 80-resonator device



Measuring energy resolution

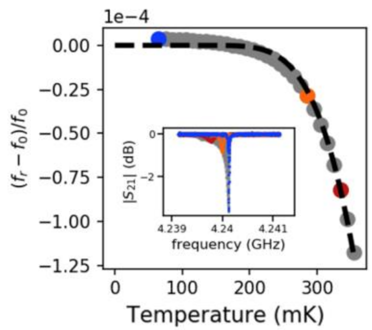
- Detector readout noise: calibrating the energy absorbed by resonator

S_{21} timestream



+

Mattis-Bardeen fit



=

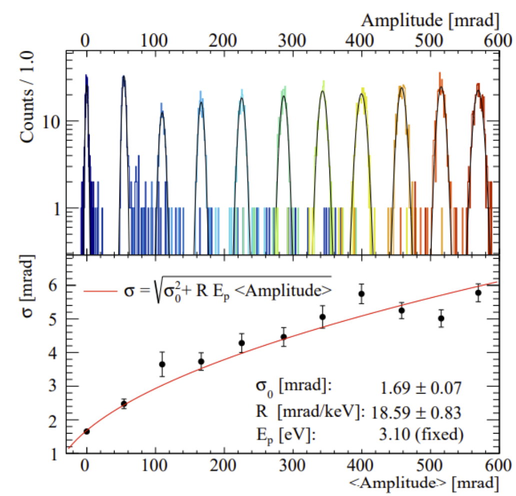
detector readout noise on energy absorbed by the resonator

- Photons as an energy source: calibrating the deposited energy
  - use the poissonian noise on photons to count photons

$$\sigma(E) = \sqrt{\sigma^2(0) + \sigma^2_{\text{photons}}(E)} \qquad \sigma^2_{\text{photons}}(E) = N_{\text{photons}} = \frac{E}{h\nu}$$

$$\boxed{\sigma(E) = \sqrt{\sigma^2(0) + \frac{E}{h\nu}}}$$

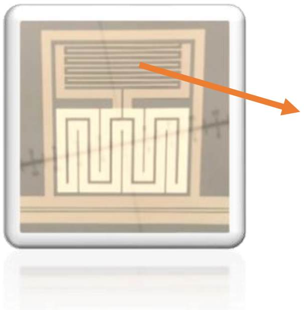
  - method demonstrated by CALDER:

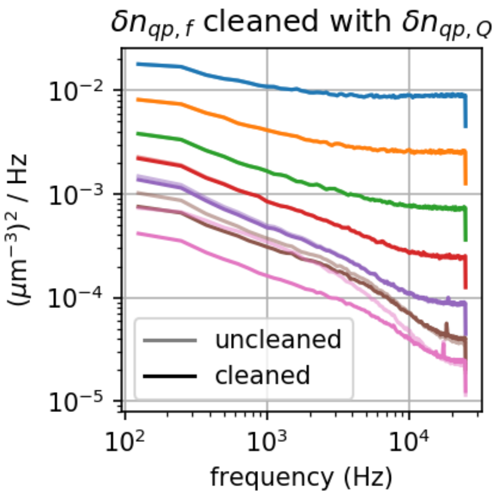


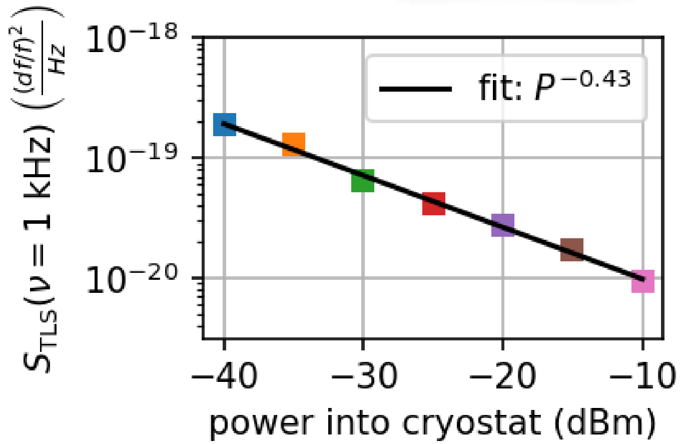
  - η_{ph} = Energy absorbed by resonator / energy deposited in substrate

Smaller device: current performance

- We placed a Nb cap layer on the capacitor to prevent phonons from being absorbed there
- This introduced unwanted two-level system (TLS) noise into our readout







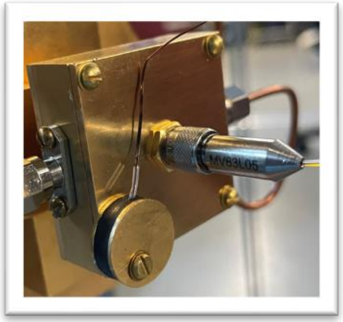
Energy resolutions	TLS-limited	amplifier-limited device
energy absorbed by the resonator	6 eV	1.5 eV
energy deposited in the substrate	20 eV	5 eV

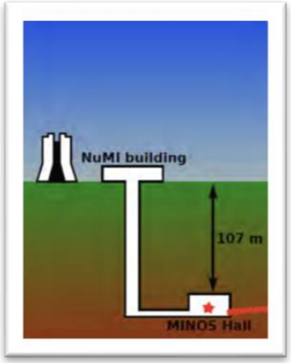
measurement done without a calibrated source; divide by η_{ph} = 0.3 (literature)

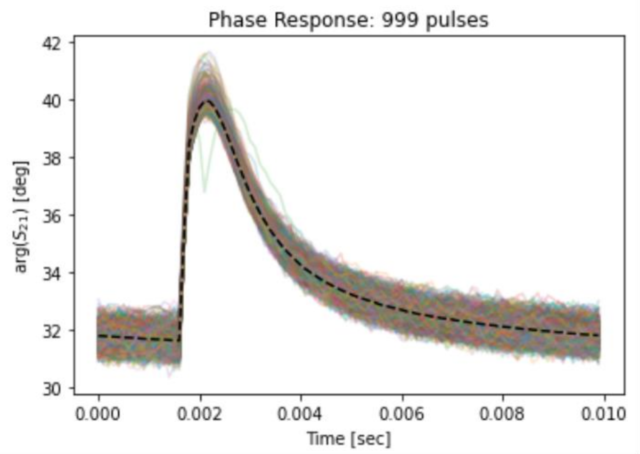
Wen et al., Journal of Low Temperature Physics, 2022. https://arxiv.org/abs/2111.08064

Smaller device: ongoing work

- KID + optical fiber installation in Caltech and NEXUS at Fermilab

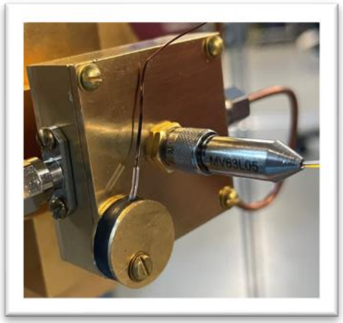


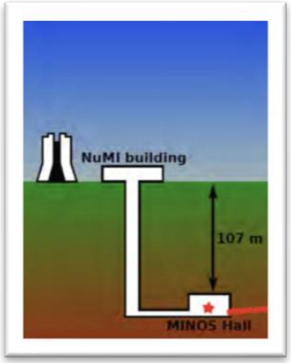


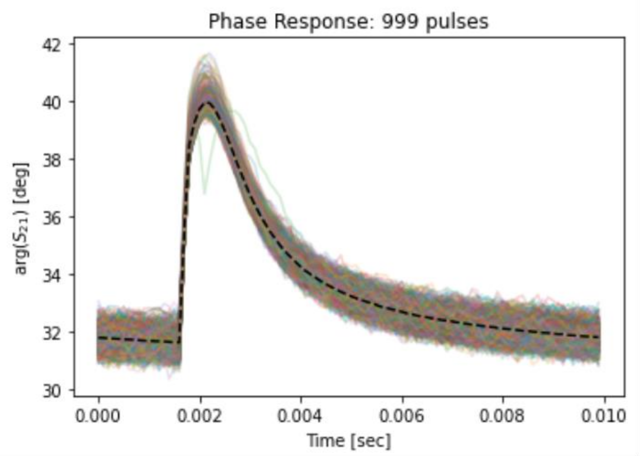


Smaller device: ongoing work

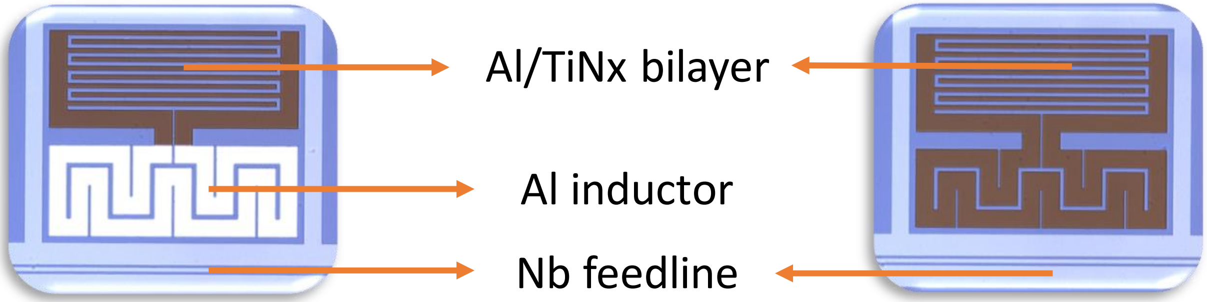
- KID + optical fiber installation in Caltech and NEXUS at Fermilab





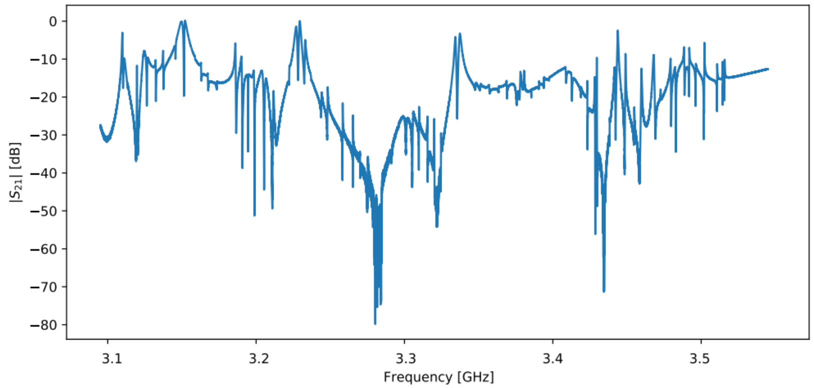


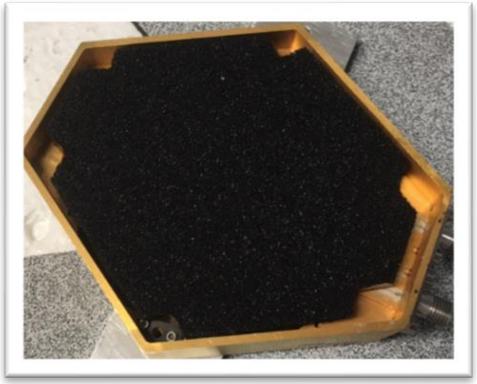
- New device fabrication
  - Fabrication done in the Microdevices Laboratory at JPL with Bruce Bumble
  - Al/TiNx bi-layer on capacitor
  - Frequencies adjusted to accommodate best performing parametric amplifiers



Larger device: current performance

- Poor RF behavior caused massive variations in the transmission

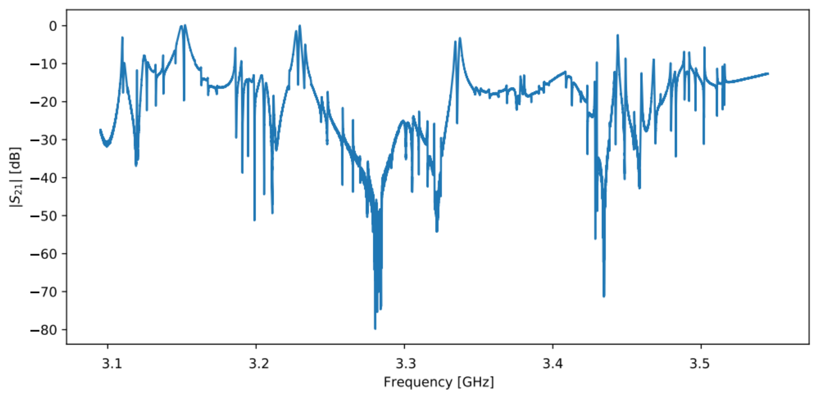


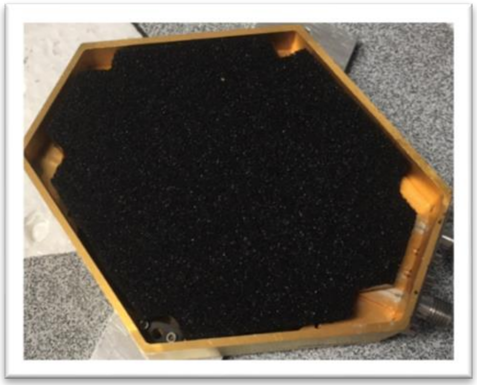


"box modes"

Larger device: current performance

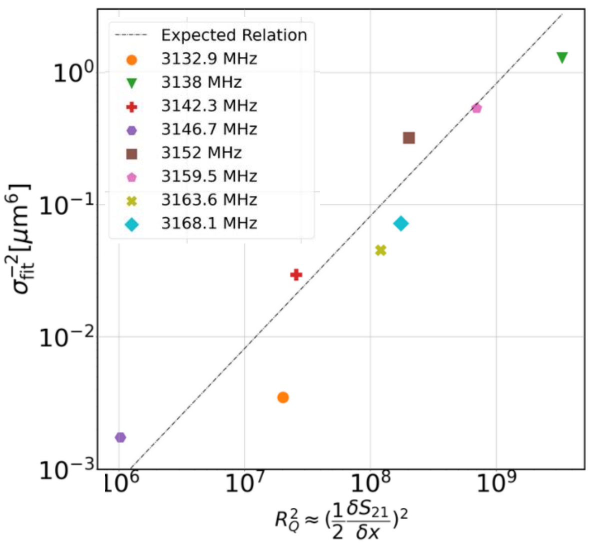
- Poor RF behavior caused massive variations in the transmission





"box modes"

- This caused absorbed energy resolution to vary up to a factor of 30



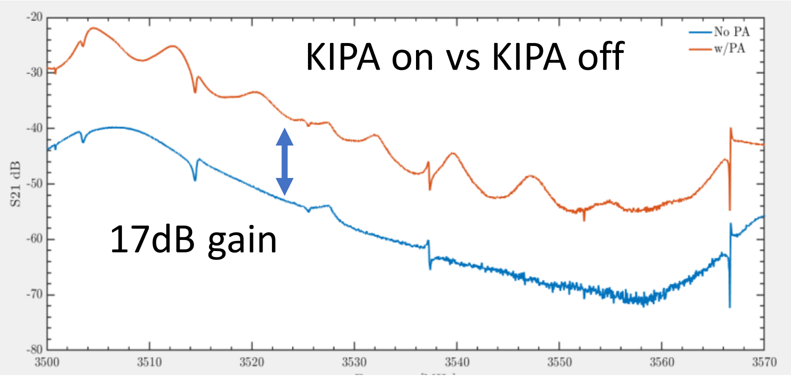
Ramanathan et al., Journal of Low Temperature Physics, 2022.
https://arxiv.org/abs/2111.02587

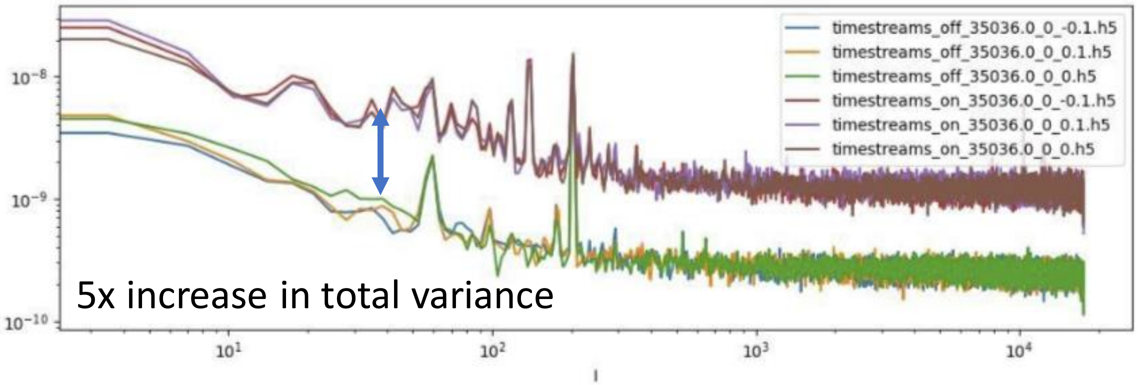
Next step:
improve the RF engineering

Energy resolutions	best resonator	extrapolated to 80 resonators
energy absorbed by the resonator	5.5 eV	50 eV
energy deposited in the substrate	18 eV	167 eV

Improving our energy resolution

- Quantum-limited low-noise amplifier
  - Kinetic Inductance parametric amplifier (KIPA) developed by Peter Day's group
  - Implemented KIPA + KID readout in Peter Day's fridge at JPL: first ever KIPA + phonon-mediated KID readout chain
  - 17dB gain / 5x increase in total variance = 10x improvement in noise temperature!



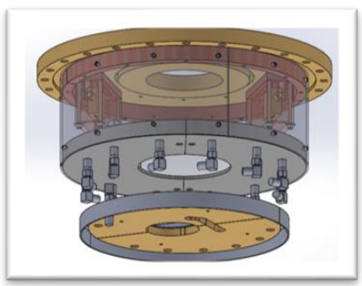


Improving our energy resolution

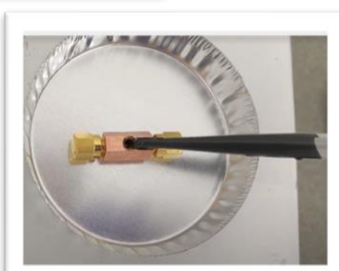
- Increasing quasiparticle lifetimes
  - can done by decreasing $n_{qp,0}$
  - tasks: → improve IR shielding in free space

    → improve IR filtering along coaxial cables

mixing chamber 2-layer can



4K shield to block 300K and HEMT radiation

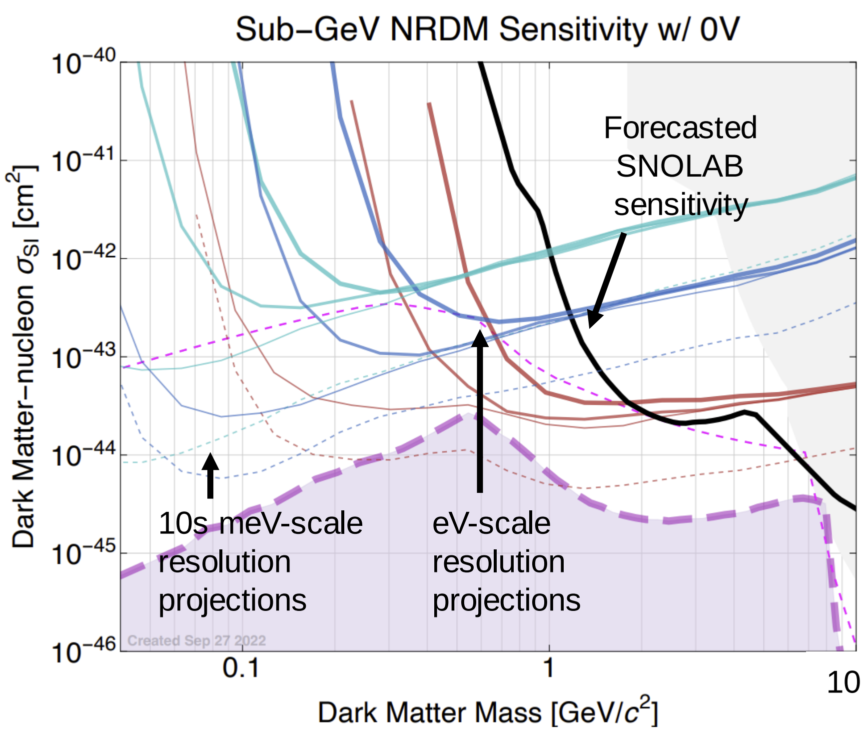


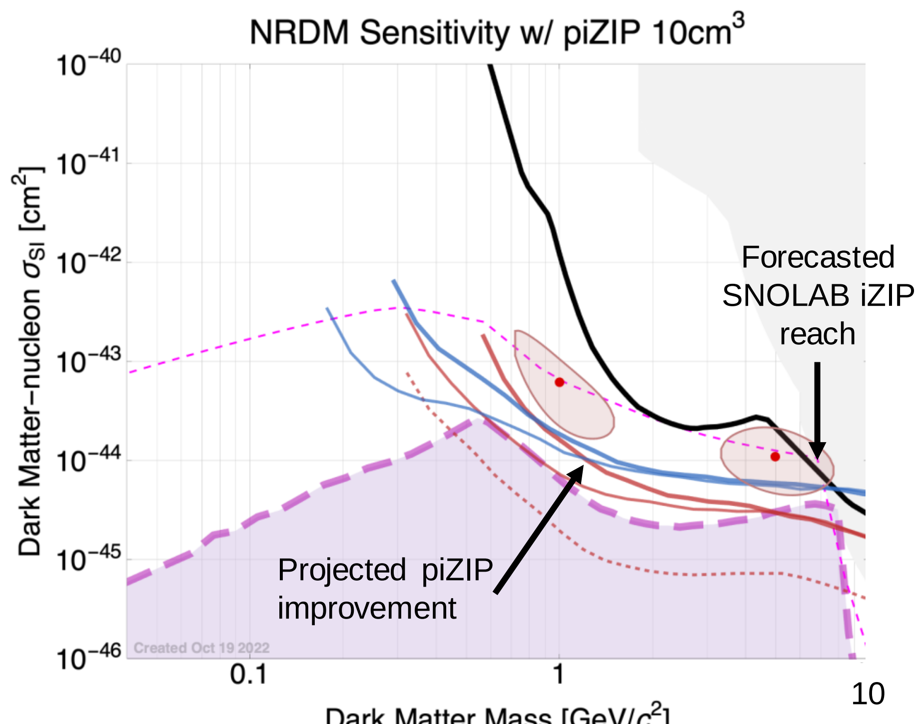
Eccosorb inline RF filters developed at FNAL

- Use a lower gap material for the phonon-absorbing component
  - Sensitivity improves linearly with Δ
  - Δ depends linearly on T_c
  - Aluminum manganese
    - Resonators at 600mK have been demonstrated
    - Possible to tune AlMn down to 100mK T_c
  - Hafnium
    - Resonators at 395mK have been demonstrated
    - Possible to reach 192mK

Long-term: a SuperCDMS style KID-based device

- Small detector architecture
  - SNOLAB forecasted phonon resolution: 13eV-34eV depending on detector
  - Potential reach shown for eV-scale and 10meV-scale resolutions
- Large detector architecture:
  - Current iZIP detectors use phonon + charge sensors for NR/ER discriminiation
  - A finely position resolved phonon detector could improve NR/ER disc. cutoff by using only phonon dectors: "piZIP"





Reported in a SuperCDMS SNOMASS white paper: https://arxiv.org/abs/2203.08463

Current results, performance forecasts, and ongoing work

stage	phonon energy rms	
	small architecture	**large architecture**
current (estimated)	20 eV	167 eV
immediate fixes (Q_c, TLS, EMI)	5 eV	45 eV
quantum-limited amplifier	830 meV	8 eV
increase τ_{qp} to 1 ms	250 meV	2 eV
T_c = 0.1 K	25 meV	200 meV

- Immediate goals
  - Measure η_{ph} in the small device at FNAL
  - Test the newly fabricated small devices
  - Use existing LED data to build a pulse model for large deviations to the quasiparticle density
  - Finalize the paramp-KID measurement: 10x improvement in noise temperature = 3x improvement in resolution!

Backup slides

KIDs: a pair-breaking alternative

- quasiparticle distribution resembles F-D statistics with a gapped density of states

single spin density of states

$$n_{qp}(T) = 4N_0 \int_0^\infty \frac{1}{1+e^{\frac{E}{kT}}} d\epsilon, \quad \epsilon = \sqrt{E^2 - \Delta^2}$$

$$= 2N_0\sqrt{2\pi kT\Delta}e^{-\frac{\Delta}{kT}}$$

modified dispersion

KIDs: a pair-breaking alternative

- quasiparticle distribution resembles F-D statistics with a gapped density of states

single spin density of states

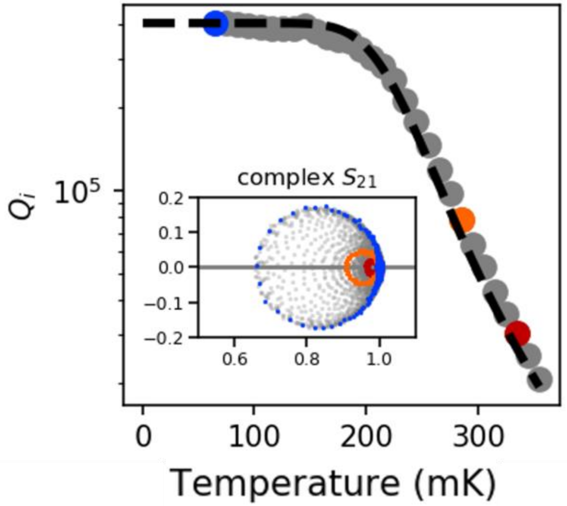
$$n_{qp}(T) = 4N_0 \int_0^\infty \frac{1}{1+e^{\frac{E}{kT}}} d\epsilon, \quad \epsilon = \sqrt{E^2 - \Delta^2}$$

modified dispersion

$$= 2N_0\sqrt{2\pi kT\Delta}e^{-\frac{\Delta}{kT}}$$

- order-of-magnitude estimate on the dynamic range:

$$\begin{aligned} n_{qp}(230\text{mK}) &\approx 590\mu\text{m}^{-3} & & E_{abs} \approx 2000\text{eV} & & E_{dep} \approx 6000\text{eV} \times N_{\text{KID}} \\ n_{qp}(200\text{mK}) &\approx 140\mu\text{m}^{-3} & \xrightarrow{\delta n_{qp} \times V_{sc}\Delta} & E_{abs} \approx 500\text{eV} & \xrightarrow{\div \eta_{ph} \times N_{KID}} & E_{dep} \approx 1500\text{eV} \times N_{\text{KID}} \\ n_{qp}(170\text{mK}) &\approx 20\mu\text{m}^{-3} & n_{qp,0} \overset{?}{\sim} 10\mu\text{m}^{-3} & E_{abs} \approx 70\text{eV} & & E_{dep} \approx 210\text{eV} \times N_{\text{KID}} \end{aligned}$$



Things to note:

Our quiescent qp population $n_{qp,0}$ is dominated by non-thermal qp's.

For $\delta n_{qp} \ll n_{qp,0}$, the response is linear and easy to model.

We are developing a non-linear model for the pulse response when $\delta n_{qp} \not\ll n_{qp,0}$