# Progress on a KID-Based Phonon-Mediated Dark Matter Detector


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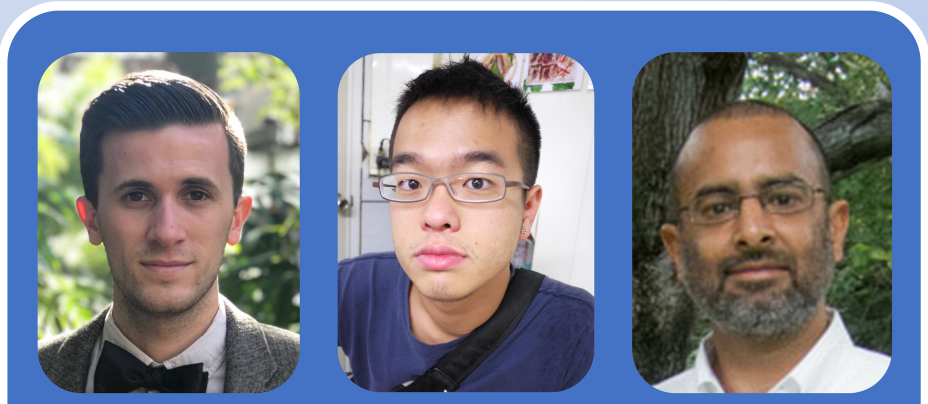
**Abstract:**

- **Status of a prototype dark matter detector being developed at Caltech**
- **Designed for use with crystalline target mass**
- **Utilizes highly-multiplexable kinetic inductance detectors (KIDs) as phonon sensing pixels**
- **First-pass single-KID resolution measurement of 12. 6 eV for in-KID quasiparticle energy**

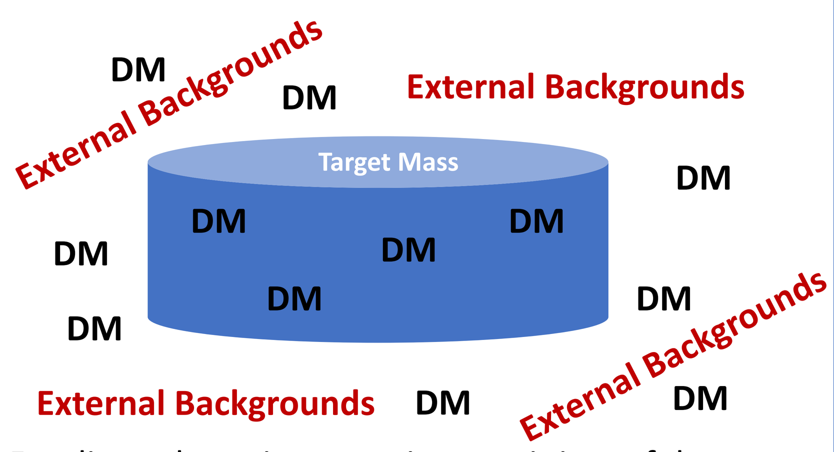

Taylor Aralis *Presenter* | Yen-Yung Chang | Sunil Golwala


## Motivation

- Using astronomical observations, it can be shown that 85% of matter is dark (non-interacting with EM)
- Direct detection experiments seek to observe dark matter passing through local target masses
- For some targets, dark matter interaction would produce propagating athermal phonons
- Athermal phonons can be observed using detectors such as KIDs
- Direct detection experiments want to maximize search time, mass, and sensitivity while minimizing background events
  - Backgrounds which cannot be avoided at runtime should be removed during analysis
  - Background removal is aided by additional event information, such as the location of the initial interaction
- Also of interest is the search for sub-GeV dark matter, where low thresholds ($< 1$ eV) are required

## Multiplexability

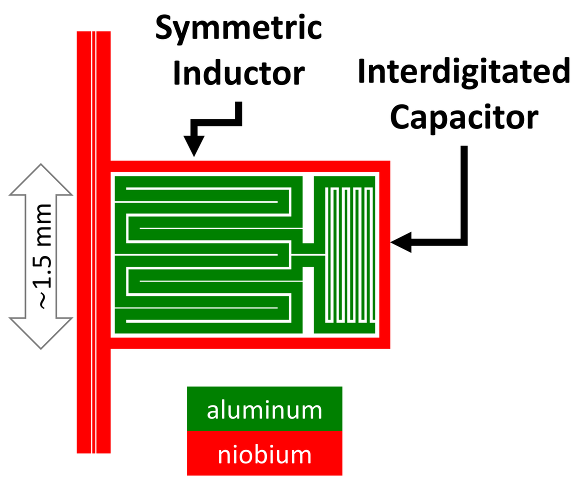
- Position reconstruction of a phonon-producing event requires a high detector density
- KIDs are highly multiplexable with simple cryogenic readout
- Fabricate many high-Q KIDs with varying resonant frequencies on one substrate
- Read them all using one feedline and a cryogenic amplifier

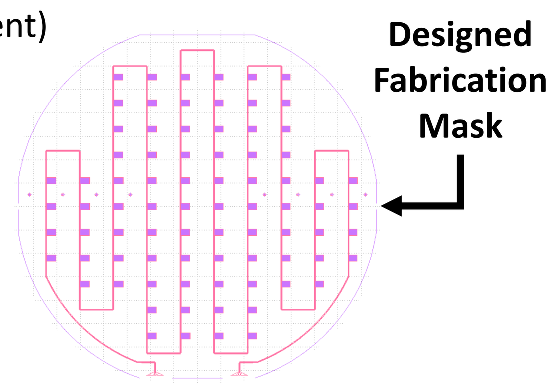



For direct detection experiments, it is useful to remove near-surface events. They are more likely to be weakly penetrating backgrounds. Dark matter will have a much longer mean free path.

## Design

- 80 MKIDs coupled to 1 coplanar waveguide feedline
  - KIDs are aluminum
    - $\Delta_{Al} \approx 0.2$ meV
  - Feedline is niobium
    - $\Delta_{Nb} \approx 1.5$ meV
    - Want phonon energy to be absorbed by KIDs, not feedline
    - $< 1\%$ of phonons are above $2\Delta_{\mathrm{Nb}}$ (for NTL phonons) **[1]**
  - $3.0\ GHz \leq f_r \leq 3.5\ GHz$
    - For CASPER ROACH readout (potential large-scale deployment)
  - Overcoupled KIDs
    - $Q_c \ll Q_i$
    - $Q_r \ll Q_i$
    - Need bandwidth $> 30$ kHz to preserve phonon rise time
- High-resistivity silicon substrate
  - 75 mm diameter
  - 1 mm thick



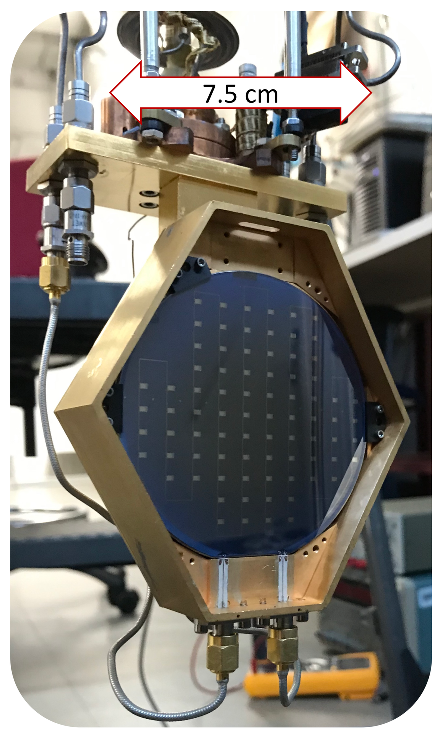



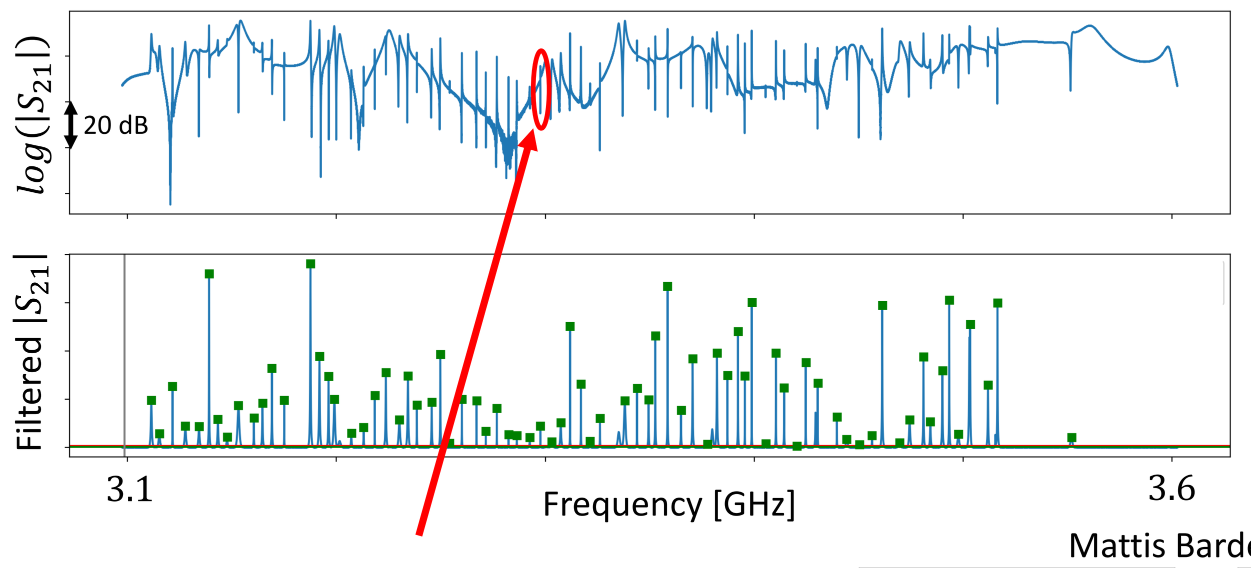

## Readout

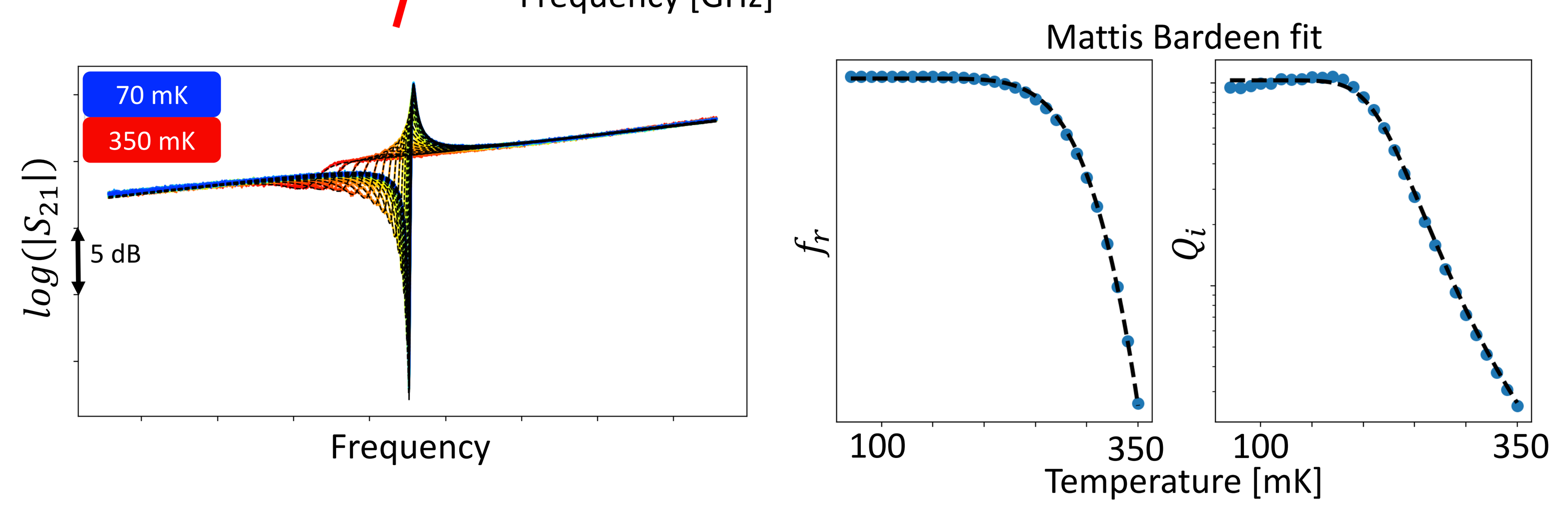
- Flexible GPU and SDR-based readout
  - Software developed by Lorenzo Minutolo of Caltech/JPL
    - See Lorenzo's poster (139-49 Session A)
  - Uses a server GPU to interface with an Ettus Research SDR
- Low-noise cryogenic HEMT amplifier
  - ~ 2.5 K noise temperature
- Plan to precede LNA with parametric amplifier currently being developed between Caltech/JPL
  - See Peter Day's poster (156-306 Session B)
  - Quantum-limited performance would give $T_N$~150 mK at 3 GHz

## Device Under Test

- Cooled to ~50 mK in DR
- Can fit 74/80 KID resonances from our current device
- 31 have good fits to Mattis-Bardeen theory
  - Describes resonance change with temperature
  - Gives kinetic inductance fraction ($\alpha$) and band gap ($\Delta$)




## Energy Resolution

- Readout is designed to be cryogenic-amplifier-noise limited
  - TLS noise is subdominant due to large resonator size, high power-handling capacity, and expected signal timescale (~1 $\mu s$ arrival and < ~1 ms fall)
  - G-R noise is subdominant due to a lack of continuous quasiparticle creation mechanisms
- Expect dissipation change to dominate signal
- Measured using a new in-array self-calibration technique
  - See Yen-Yung Chang's poster (94-407 Session B)
- Found energy resolution $\sigma$~12.6 eV for a single KID on our detector
  - Resolution on absorbed quasiparticle energy within that KID
- For an array of $N_r$ KIDs, the resolution would degrade by $\sqrt{N_r}/\eta_{ph}$
  - Energy splits among $N_r$ KIDs
  - $\eta_{ph}$ is a phonon-to-quasiparticle efficiency factor
- The measured KID has $\tau_{qp}$~23 µs
  - This is low for aluminum
  - We believe black-body leakage may be the issue
    - Can be improved with well designed shielding

$$\sigma_E = \frac{\Delta}{\eta_{ph}} \sqrt{\frac{\eta_{read}}{2\pi\alpha p_t}} \sqrt{\frac{A_{sub}\lambda_{pb}}{f_r \tau_{qp}}} \sqrt{\frac{k T_N N_0}{\gamma_s S_1(f_r, T_{qp}, \Delta)}}$$

band gap; readout → qp efficiency; substrate area; Cooper-pair breaking length; amplifier noise; density of states (fermi level); MB function; film characterization factor; qp lifetime; resonance frequency; phonon transmission probability; kinetic inductance fraction; phonon → qp efficiency

## Conclusion and Future

- Have taken first device energy resolution measurement for large-array detector type
  - Suitable for 10s-100s kg target mass
  - Found a single-KID quasiparticle energy resolution of 12.6 eV
- Plan to:
  - Repeat measurement in multiple KIDs and compare
  - Check absolute calibration on energy deposited in substrate using radioactive spectral line
  - Install lower noise parametric amplifier
  - Improve fridge black-body shielding to enhance $\tau_{qp}$
    - 100 $\mu s$ is typical for aluminum
- Also, beginning development of a design optimized for threshold rather than background rejection
  - Single KID on a smaller substrate to avoid energy splitting
  - Use niobium KIDs for self-calibration technique


**[1] G. Wang. Journal of Applied Physics 107, 094504 (2010); https://doi.org/10.1063/1.3354095**



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