# Phonon-mediated kinetic inductance detectors for sub-GeV dark matter searches

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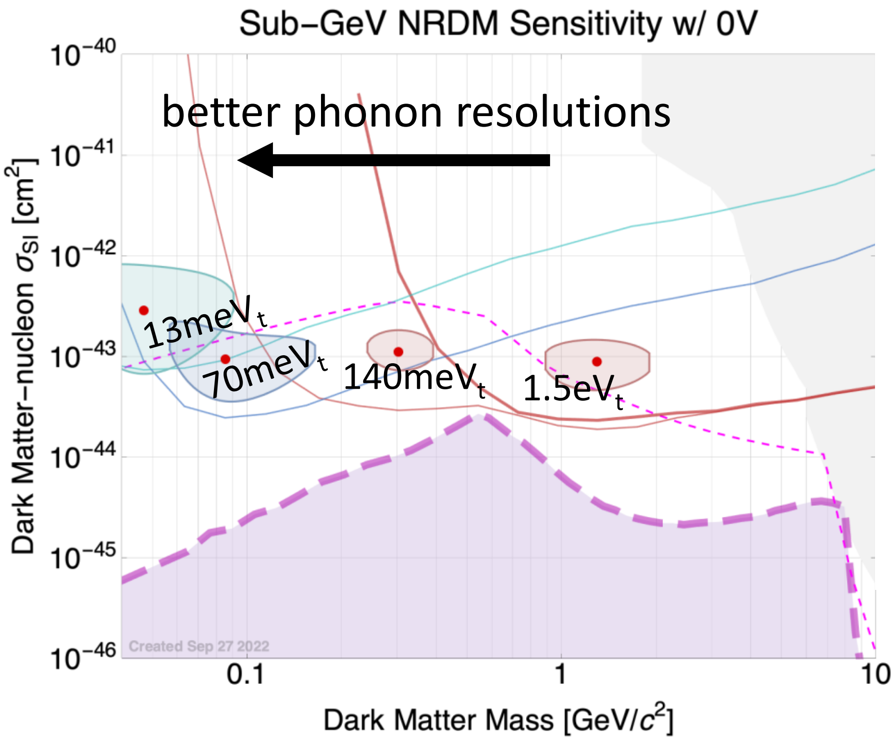
UCLA Dark Matter 2023

image credit: SuperCDMS collaboration

# Motivation: sub-GeV NRDM searches

- How can we use phonon-mediated detectors to probe unexplored parameter space?
  - **sub-eV$_t$ resolutions** for better mass reach
    - see talks by Rouven Essig and Tongyan Lin for further context
  - ER-rejection to enable neutrino-limited searches
    - attainable with a **pixelized & multiplexed phonon readout** to separately measure primary phonons and phonons produced by charge drift: “piZIP” (M. Pyle)



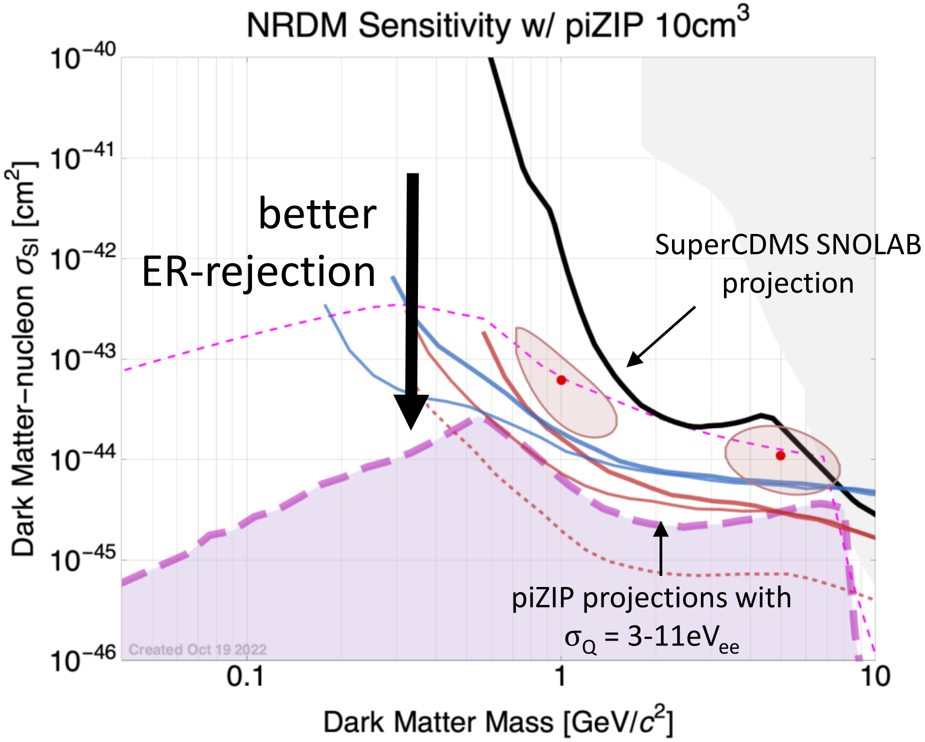
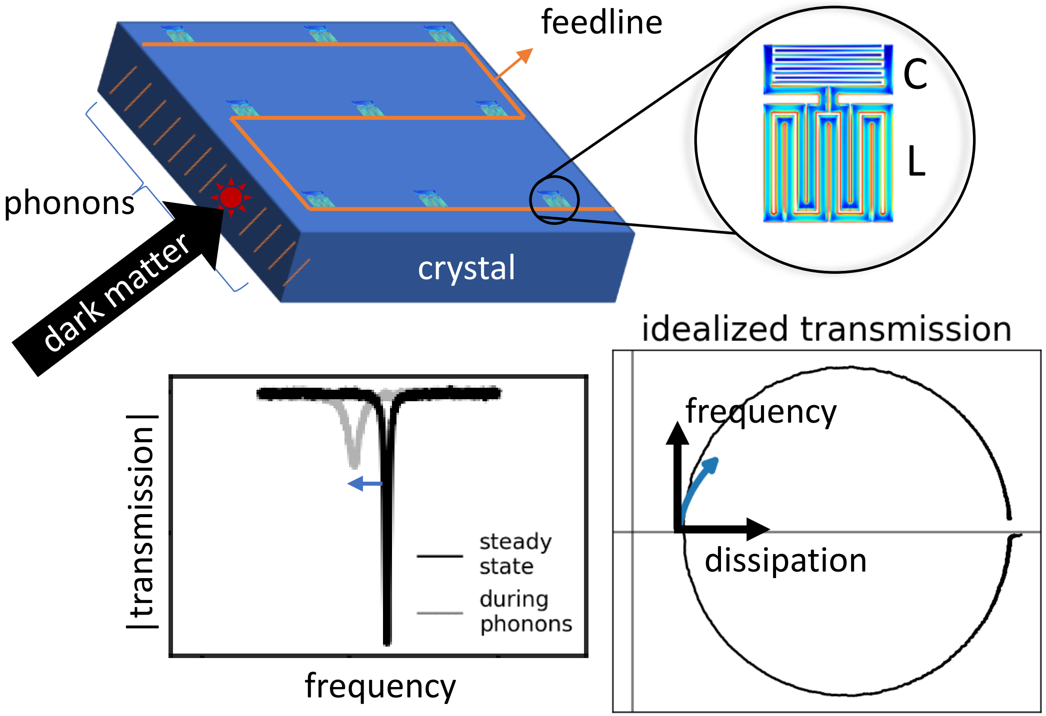


image credit: SuperCDMS limit plotter

# Kinetic inductance detectors (KIDs)

- superconducting microwave resonator
  - phonons in substrate → broken Cooper pairs → shifted resonance and RF transmission
  - two quadrature readout of RF transmission: dissipation and frequency
  - key advantage: natively multiplexable, i.e. simultaneous readout of many resonators coupled to one feedline



Main sources of noise

| type of noise | affected quadrature | source/description of noise |
|---|---|---|
| amplifier white noise | both | thermal noise from the cryogenic amplifier (typically at 4K) |
| two level systems | only frequency | loss from surface defects, e.g. metal oxides |
| generation-recombination (fundamental) | both | poissonian noise of Cooper pairs breaking and then recombining |

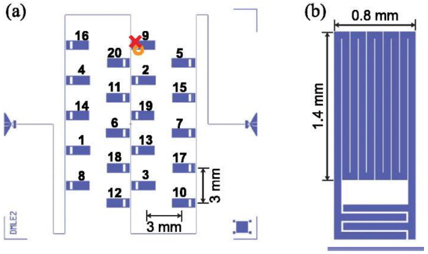
**KIDs offer a path to sub-eV resolutions while also being natively multiplexable**

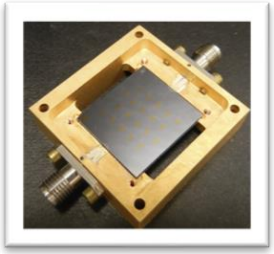
# An initial prototype: position and energy resolution

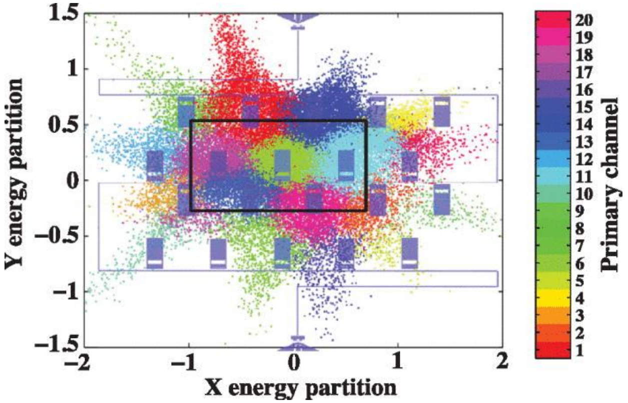
- 1-gram silicon substrate
  20 aluminum resonators
- $\lesssim$ 1mm position resolution
-

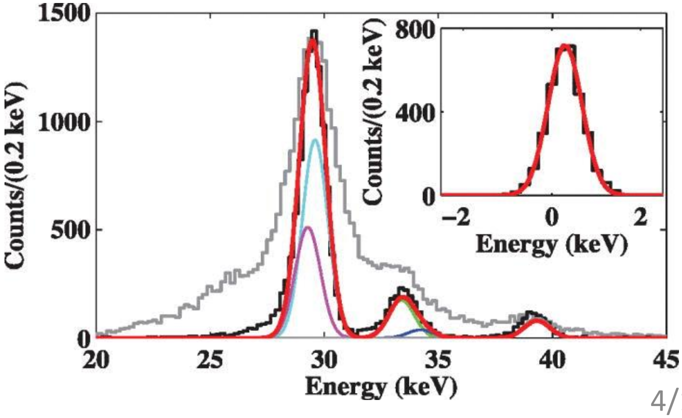
| energy performance | | |
|---|---|---|
| $\sigma_E$ | baseline resolution on energy deposited in the substrate | 380eV |
| $\eta_{ph}$ | phonon collection efficiency | 7% |
| $\sigma_{E,abs}$ | baseline resolution on energy absorbed by a single resonator; “intrinsic energy resolution” | 6eV |
| $$\sigma_E = \frac{\sqrt{N_r}}{\eta_{ph}} \sigma_{E,abs}$$ | | |

- Can we decrease the number of resonators while keeping the phonon collection efficiency high?
- What are the challenges to increasing multiplexability?






Position resolution

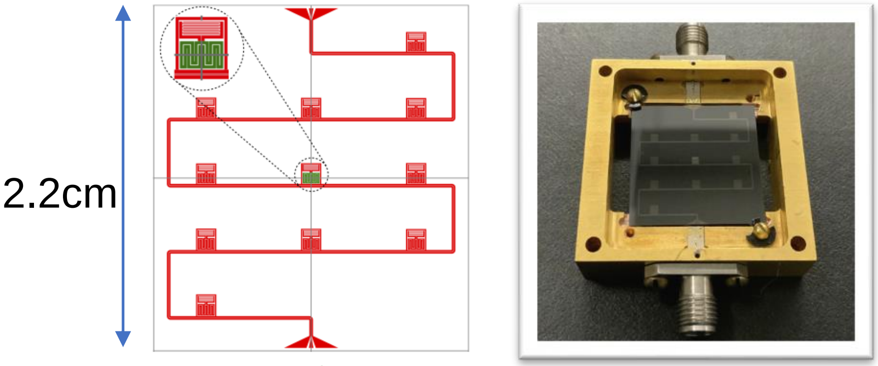

Energy resolution

slide credit: Moore 2012, https://arxiv.org/abs/1203.4549

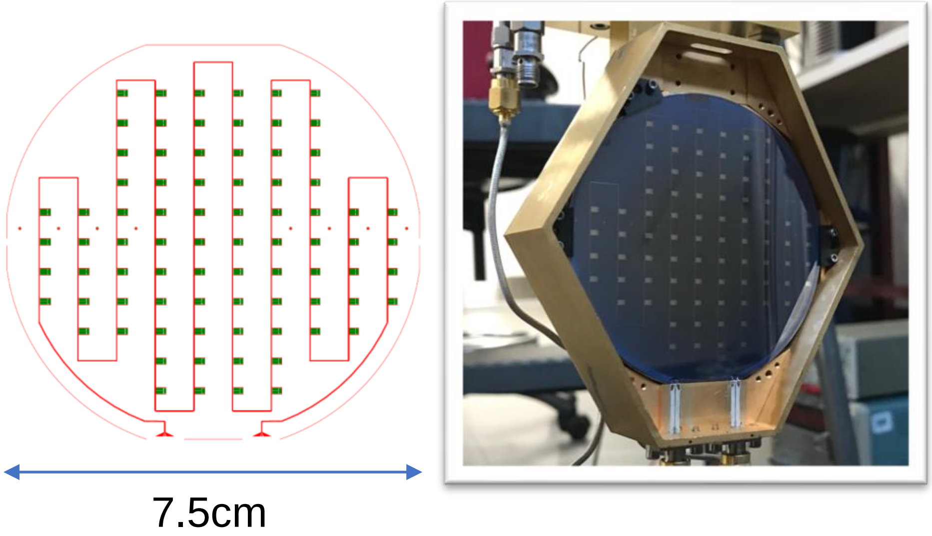
# Two goals → two new architectures

- Goal 1: optimizing for energy resolution with a **small device**
  - decrease $N_r$ from prototype design: 1-gram, 1-resonator
  - replaced "dead metal" with a higher-gap material
    - feedline
    - capacitor
    - calibration resonators

- Goal 2: creating a **large volume device** with massive multiplexability
  - scale size up and keep surface area coverage constant: 9-gram, 80-resonators
  - reduced mounting area relative to "live metal" area



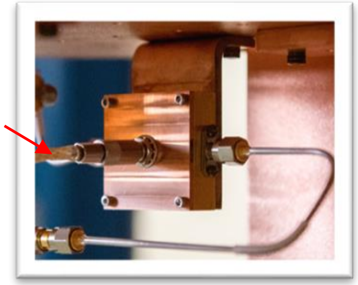
green: aluminum
red: higher-gap materials



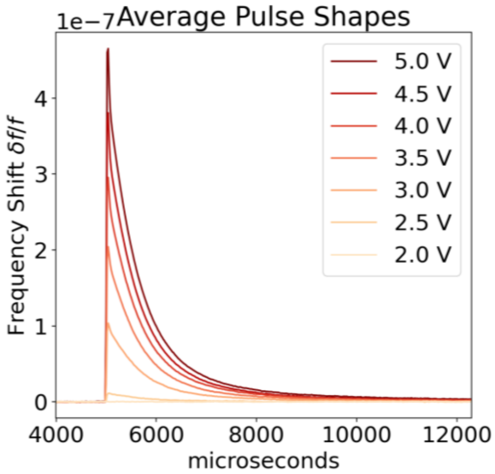
Fabrication done (by grad students!) at JPL in the Microdevices Lab using photolithography techniques

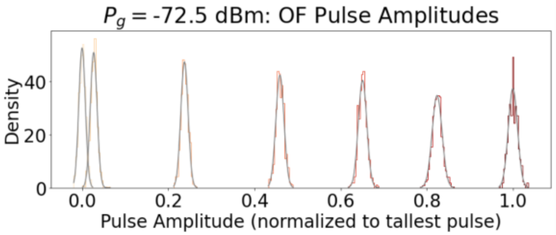
# Recent results: building a model for $\eta_{ph}$

- calibrated small device at Fermilab using optical photons (Dylan Temples poster)



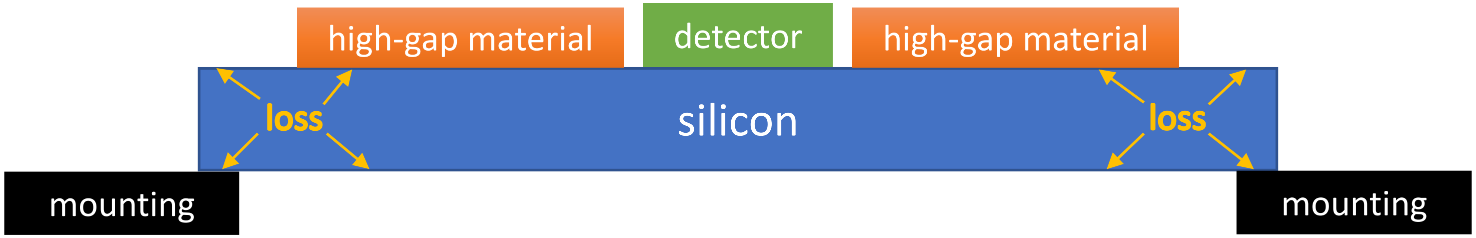
optical fiber





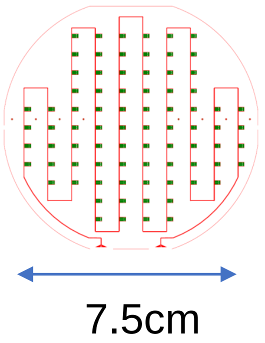
| | **small device** | **prototype device** |
|---|---|---|
| $\eta_{ph}$ | 0.8% | 7% |
| $\sigma_{E,abs}$ | 2.5eV | 6eV |

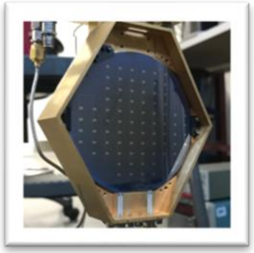
- Why is the phonon collection efficiency so poor? What are the dominant loss mechanisms?
  - down-conversions in the high-gap materials
    - recent simulations: these materials are more down converting than expected
  - mounting
  - surface-mediated down-conversions (fill fraction 2% in prototype → 0.1% now)

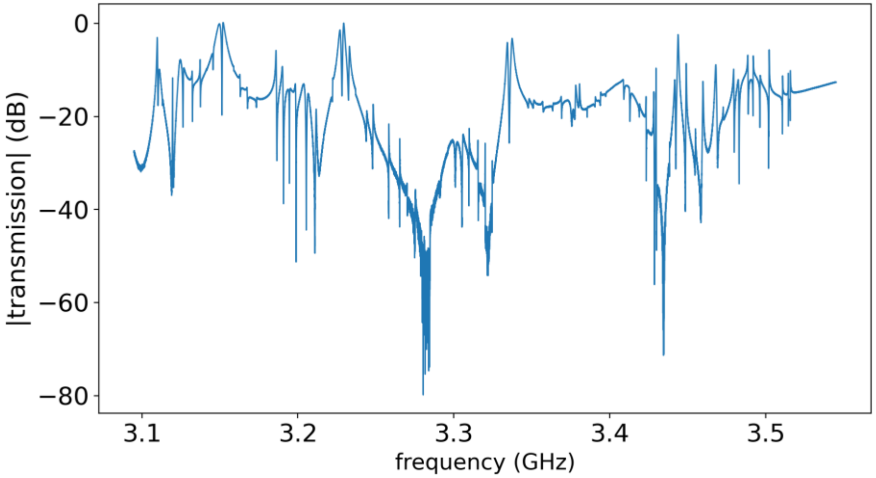


# Recent results: identifying drivers of $\sigma_{E,abs}$

- large device showed hugely varying transmission and resonator quality factors
  - hypothesis: RF excitations of the physical box and poor grounding of the CPW feedline







transmission variation

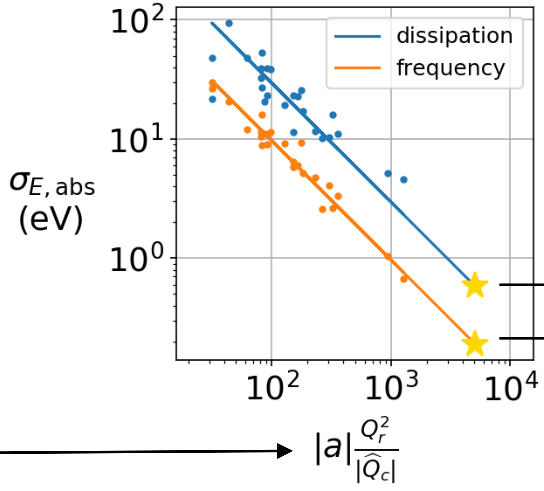
- for amplifier-dominated noise, variations in $\sigma_{E,abs}$ are due to RF responsivity

$$\frac{dV_{ADC}}{dE_{abs}} = \boxed{|a|\frac{Q_r^2}{|\widehat{Q_c}|}}\boxed{\alpha\gamma\kappa}\frac{1}{V_{sc}\Delta}$$

transmission

film responsivity

RF responsivity



**@ optimal RF responsivity, $\sigma_{E,abs}$ given by:**

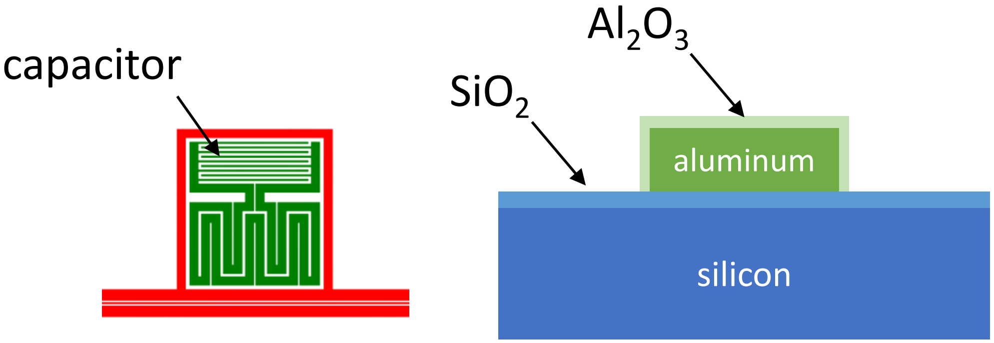
**580meV**

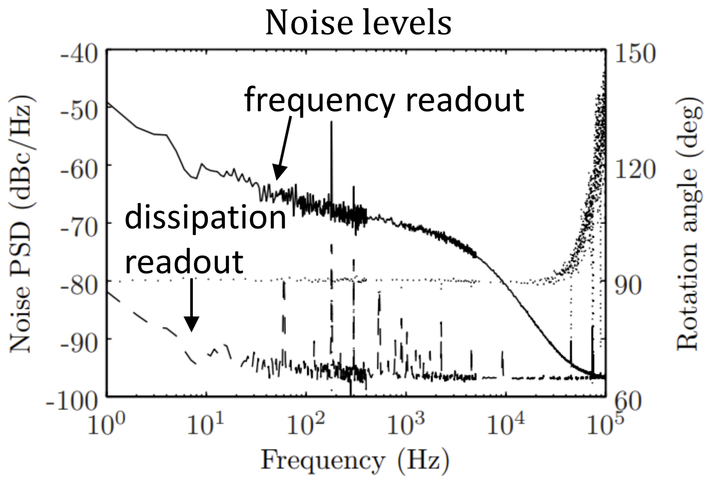
**190meV*** → **!**

*assumes no TLS

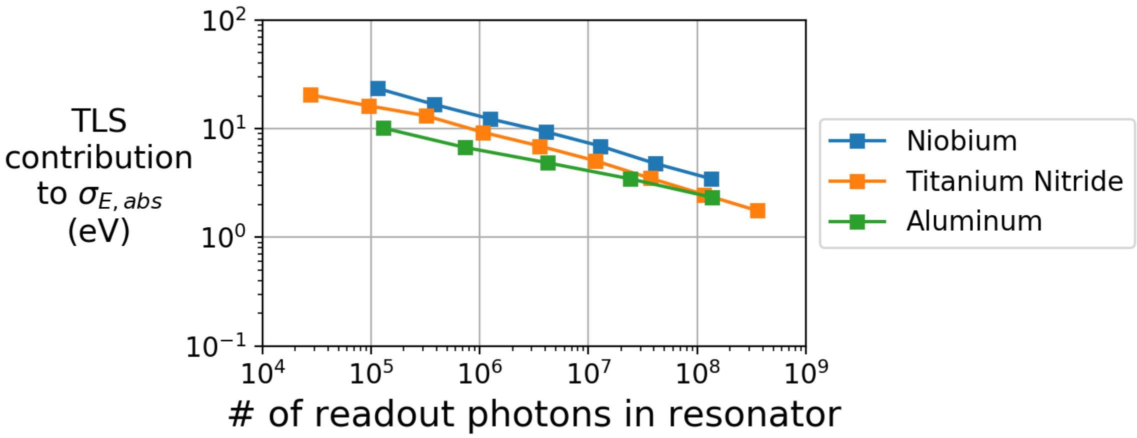
# Recent results: the TLS wall

- Two-level systems (TLS) are present in surface oxides and contribute noise in the capacitor
  - TLS cause fluctuating epsilon, leading to dissipation and thus noise (F-D theorem)
  - only affects frequency quadrature





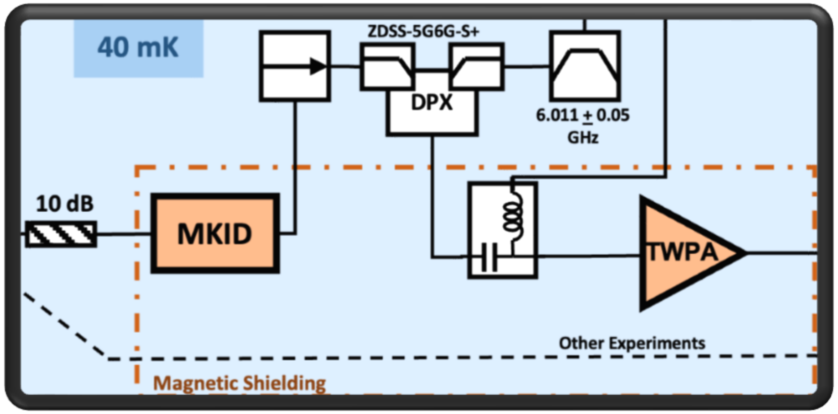
- We have seen some amount of TLS noise in all our detectors, regardless of capacitor metal choice



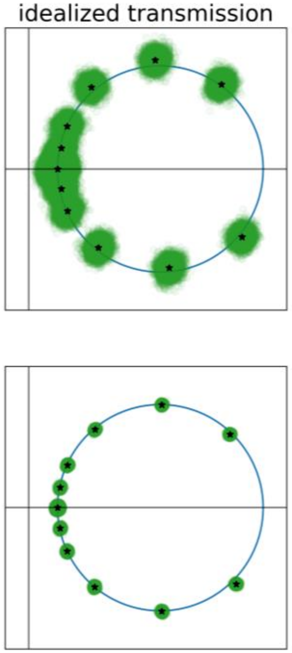
**TLS will limit $\sigma_{E,abs}$ in the frequency quadrature to ~1-5eV**

# Recent results: nearing quantum-limited amplification

- dissipation quadrature is still amplifier-noise-limited: $\sigma_{E,abs} \propto \sqrt{T_{amp}}$
  - currently using high-electron-mobility transistor (HEMT) amplifiers
    - $T_{amp}$ between 3-5K
  - standard quantum limit (SQL) is given by $T_{amp}$ = $h\nu$ ~ 200mK at our readout frequencies
    - 4-5x improvement in rms
    - achievable with new QIS-based technologies: JPA, J-TWPA, KI-TWPA
- noise improvement seen with KI-TWPA
  - shown basic KID+TWPA compatibility → still need to optimize TWPA performance



publication in process!

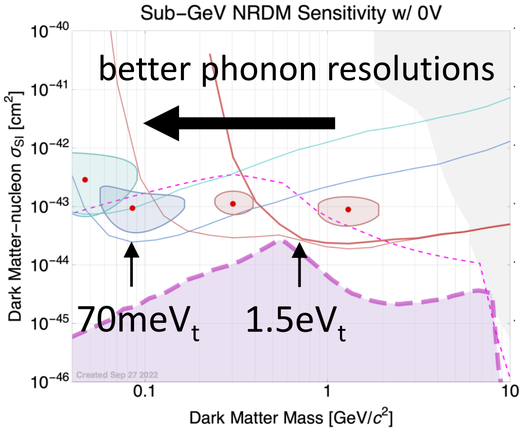


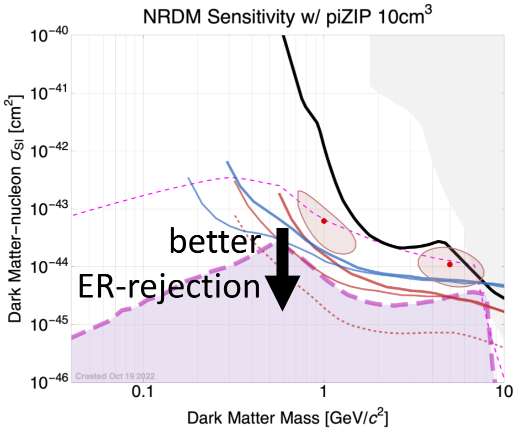
KIPA off

x4.2 improvement in rms!

KIPA on

# Summary & outlook





- Goal 1: optimizing for energy resolution

| | $\sigma_{E,abs}$ **(freq.)** | $\sigma_{E,abs}$ **(diss.)** | $\sigma_E$ **$\eta_{ph}$ = 0.8%** | $\sigma_E$ **$\eta_{ph}$ = 30%** |
|---|---|---|---|---|
| current performance | 2.5eV | 7.5eV | 316eV | 8.3eV* |
| improve RF behavior | **TLS wall** ↓ | 580meV* | 73eV* | 1.9eV* |
| SQL amplifier | | 138meV* | 17eV* | 460meV* |
| lower gap material | | 70meV* | 8.5eV* | 230meV* |

literature value

*projection

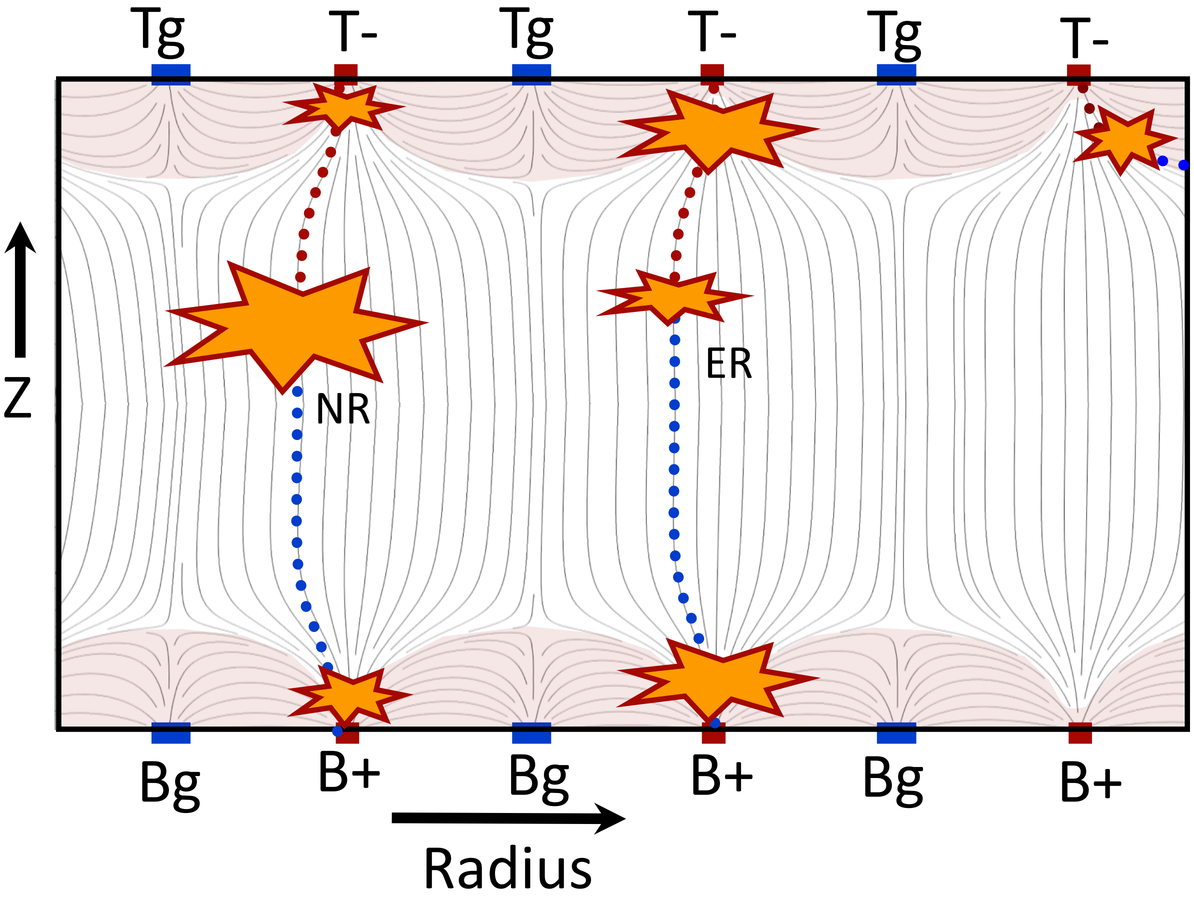
**Open questions:**
Can we get around the TLS wall?

When will we hit GR noise?

- Goal 2: demonstrate multiplexability for desired ER-rejection
  - 20-resonator phonon readout multiplexing has been achieved → need to improve RF engineering for larger feedline devices

# Background: piZIP

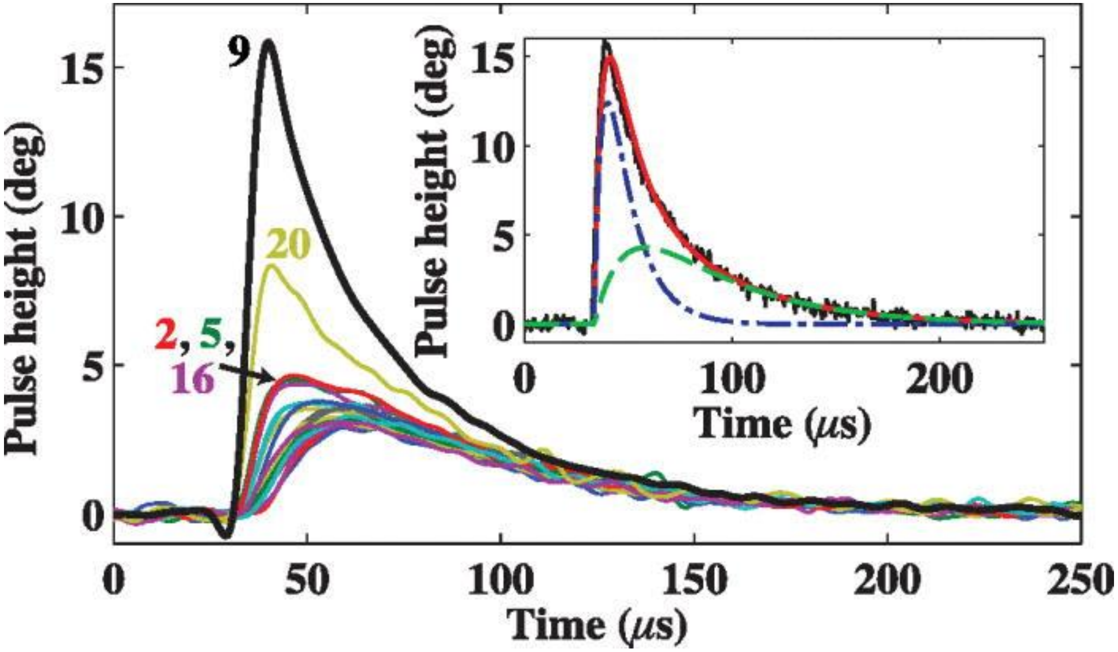
- nuclear recoils and electron recoils will have different ratios of primary phonons and phonons produced by charge drift

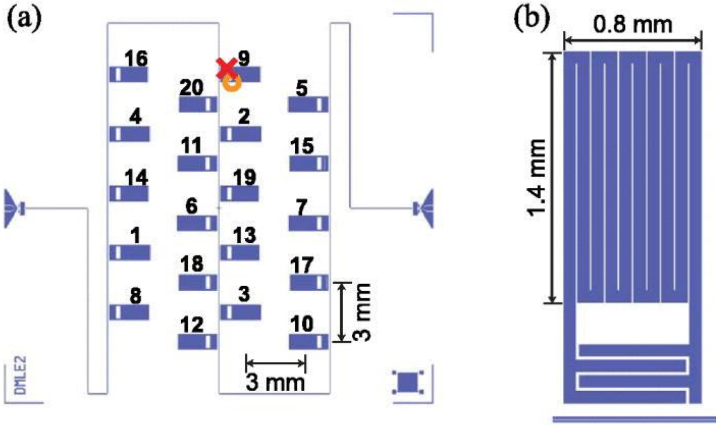


slide credit: Matt Pyle

# Background: pulse shapes in time

- In the prototype device, we observed a prompt Cooper pair time constant around 12ueV and a delayed phonon time constant around 50us





slide credit: Moore 2012, https://arxiv.org/abs/1203.4549