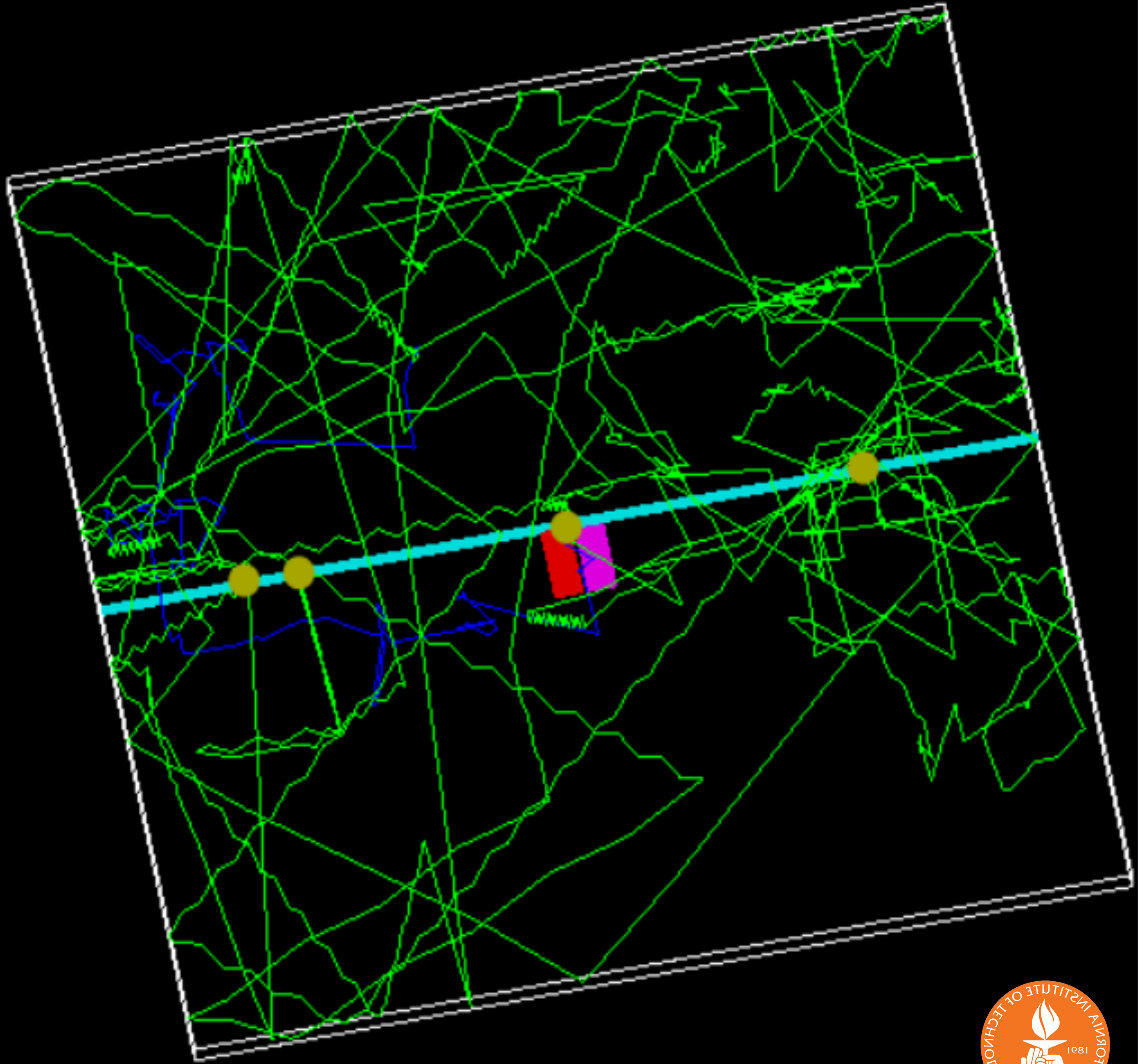
GEANT4/G4CMP WORK AT CALTECH

(ON KINETIC INDUCTANCE PHONON MEDIATED DETECTORS)

Karthik Ramanathan

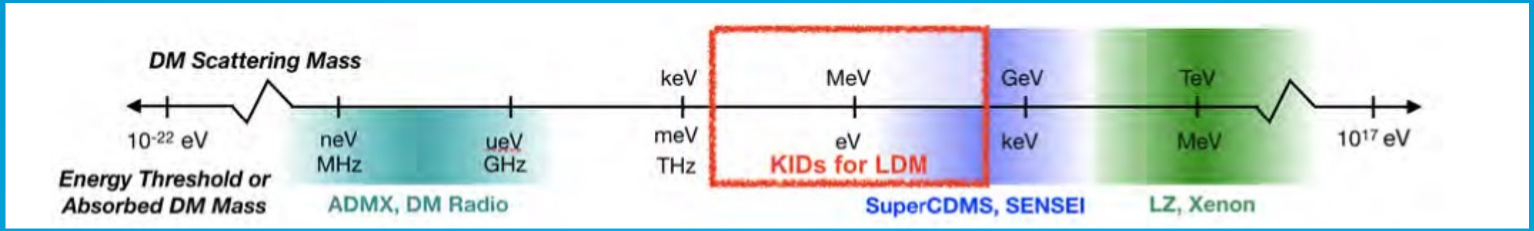
E. Lindeman, R. Berkun, M. Menezes, O. Wen, T. Aralis, Y.-Y. Chang, S. Golwala

RISQ 2024
05/29/2024

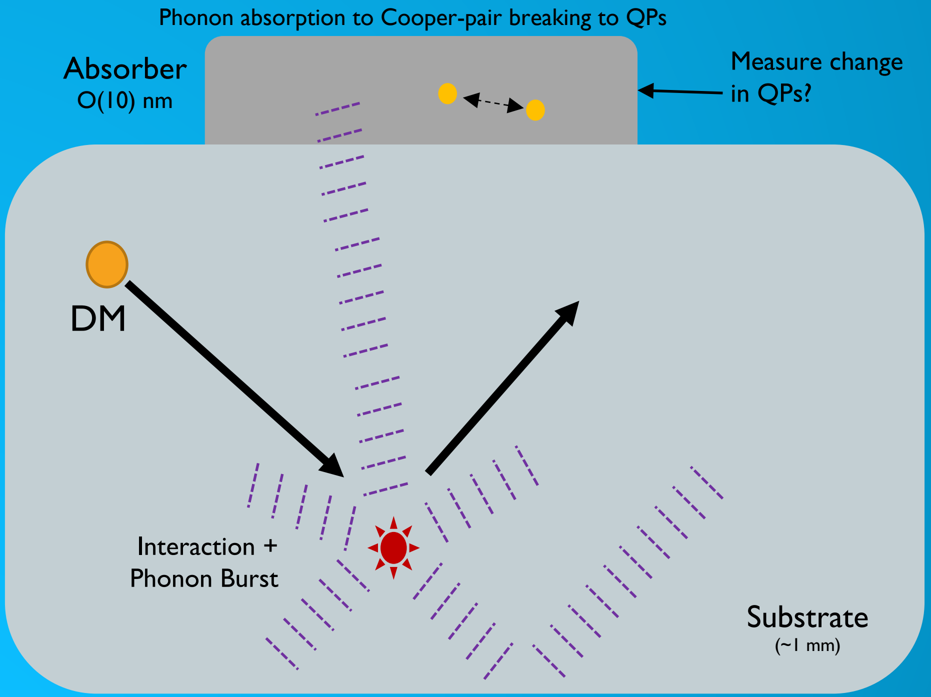


(Our) Science Case

- Strong cosmological and astrophysical evidence for some missing matter (“**Dark Matter**”) in the universe comprising ~25% of the total mass-energy of the Universe. If a new particle, can have a very wide mass range --- all the way from wave-like to particle like behavior.



- Principle behind terrestrial detection of dark matter:
  - Instrument some target material with sensors.
  - Wait for potential DM interaction (DM-nucleon, DM-electron scattering, absorption etc.)
  - Record signals (e.g. light, heat, ionization).
  - Reconstruct DM signature, given backgrounds.
- At the low-mass range of particle dark matter, may only expect O(meV-eV) worth of deposited energy manifesting itself as collective excitations (e.g. *phonons*)



Phonon absorption to Cooper-pair breaking to QPs

Absorber
O(10) nm

Measure change in QPs?

DM

Interaction + Phonon Burst

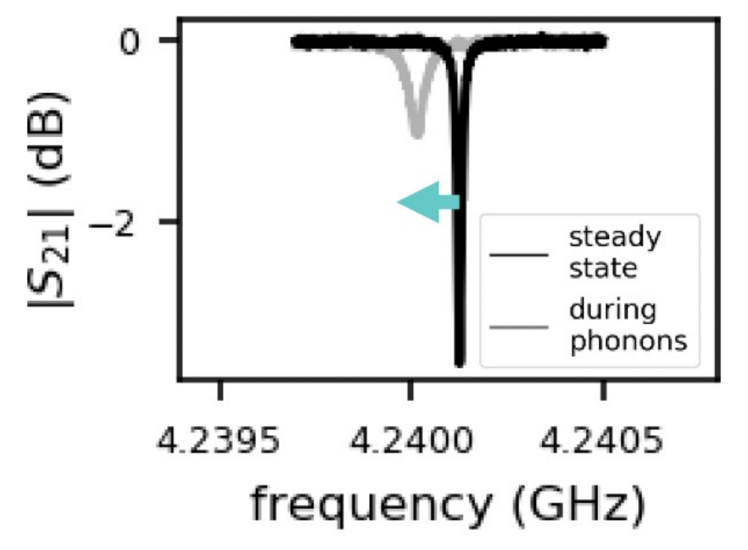
Substrate
(~1 mm)

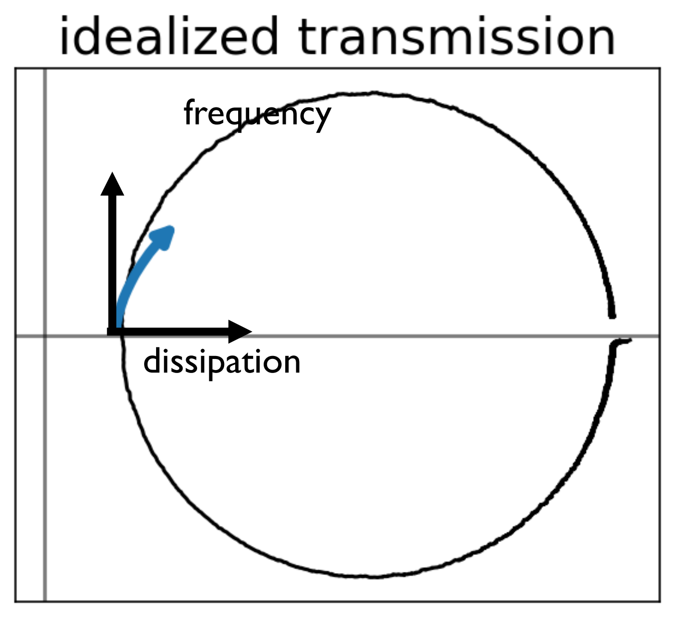
Kinetic Inductance Phonon Mediated Detectors

- 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

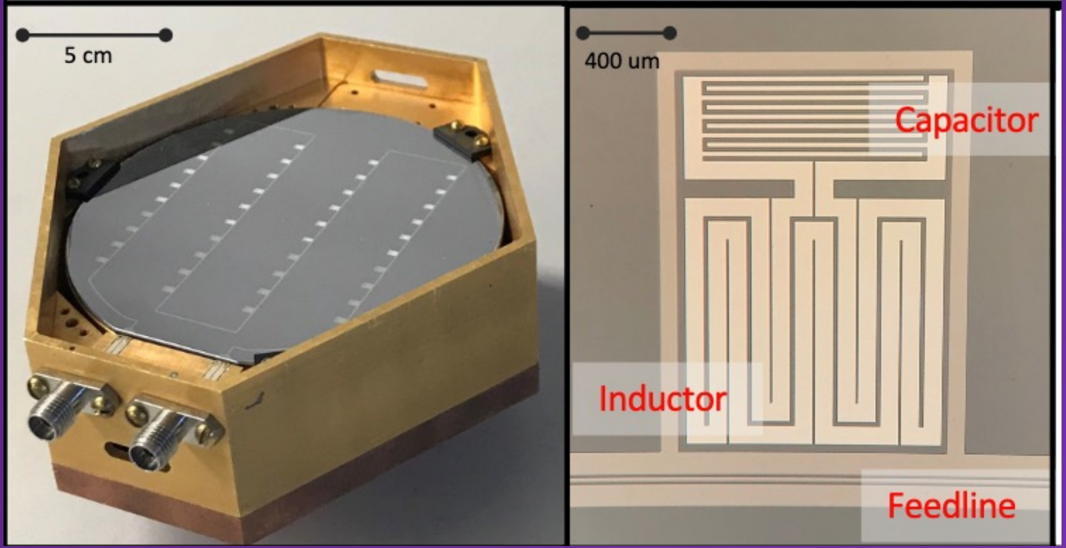
Key point: superconductors provide very high Q ($Q_i \sim 10^7$ achieved), so thousands of O(GHz) resonators a single feedline with O(kHz) linewidths
→ Simple cryogenic multiplexing!

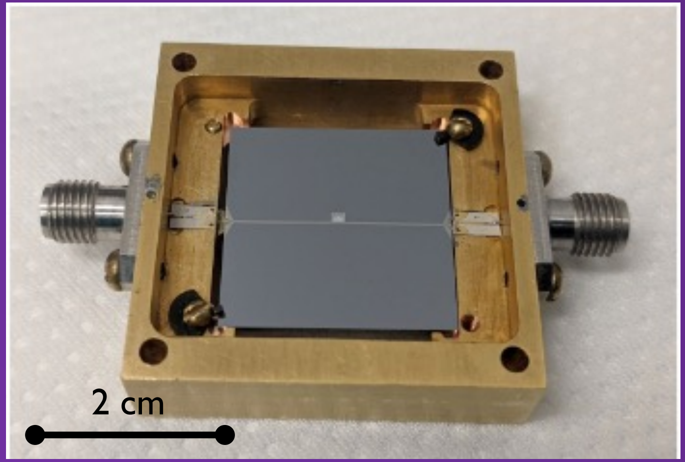
Generate tones and readout using off the shelf software defined radio (Ettus Research USRP)

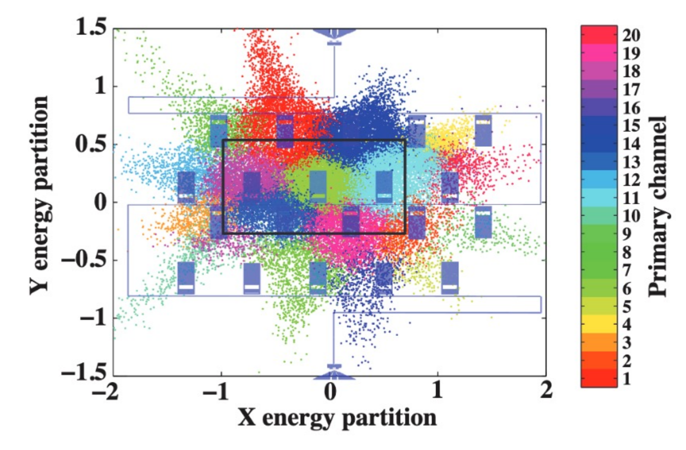


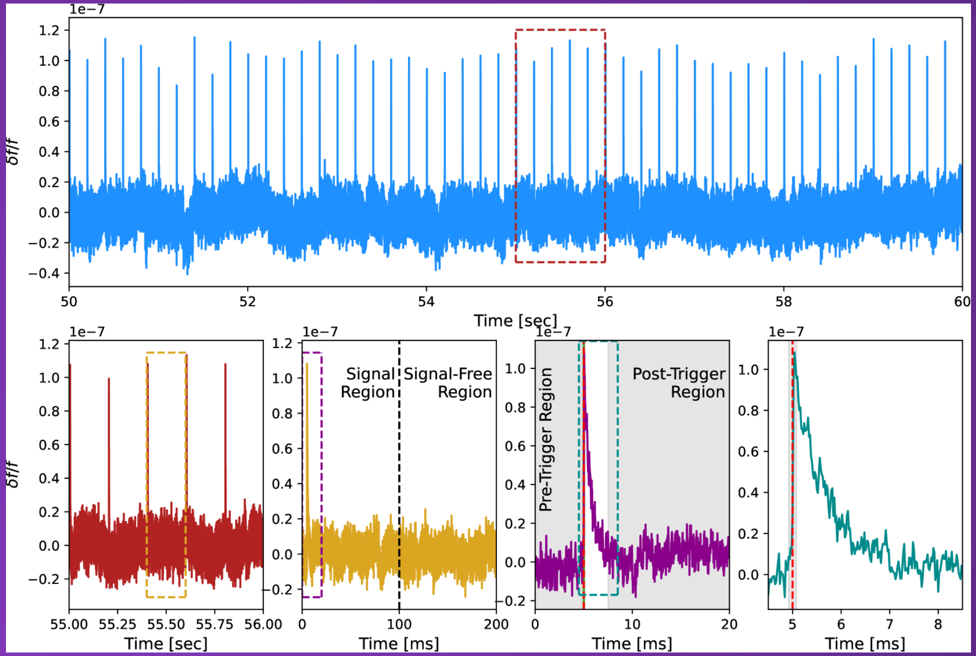


Kinetic Inductance Phonon Mediated Detectors









2 architectures built by Golwala group: Large, with O(10-100) KIDs, with position reconstruction; Small: single KID , optimized for energy resolution → **LED testing done at Fermilab**

Slide modified from O. Wen, UCLA DM 2023

Motivation

- From LED work we measure our phonon-to-quasiparticle efficiency n_ph to be < 1%. Seem to have high phonon losses somewhere

Where is all the energy going?

	small device	**prototype device**	**CALDER [link]**	**SuperCDMS**
fill fraction	0.07%	2.3%	0.45%	6-10%
η_{ph}	0.8%	7%	7%	30%

Plausible issues:

- Dead-metal down conversion in high gap material?
- Losses through the mounting?
- Surface mediated down-conversion (i.e. impurities, roughness)?

G4CMP Setup

Quasiparticle Physics

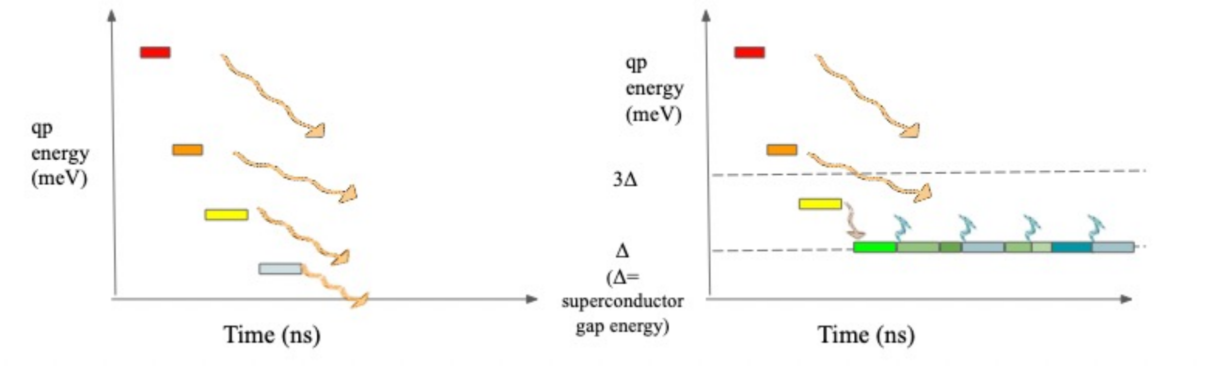
- Standard G4CMP has parametrized quasiparticles (no time-dependence or tracking)
  - Entering phonons create all QPs instantaneously and then exiting phonons created in a big dump
- Caltech group has added ad-hoc extension:

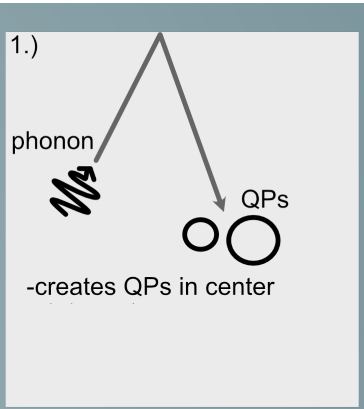
+ QP and phonon production list

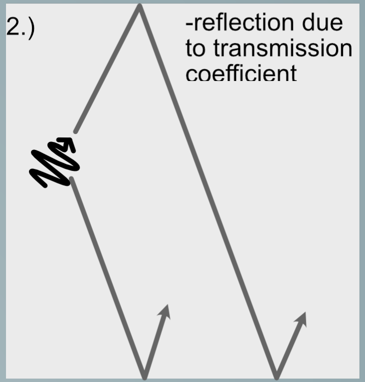
+ Phonon creation on QP recombination → can create subsequent QPs

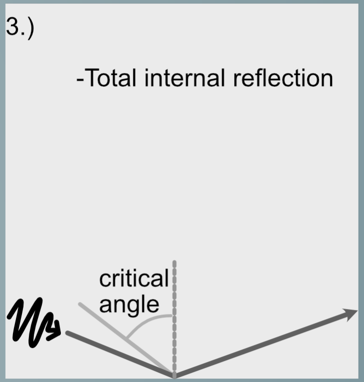
+ Basic angular information, transmission coefficient, and total internal reflection

- However, QPs instantly scatter down to bandgap then decay over time back to Cooper pairs
- All QPs and phonons created in center of film. Probably ok for films with long phonon mean free path and coherence length like Aluminum but not appropriate for Niobium.
- No position information and no internal QP dynamics. All exiting phonons created as reflections of initial entering phonon

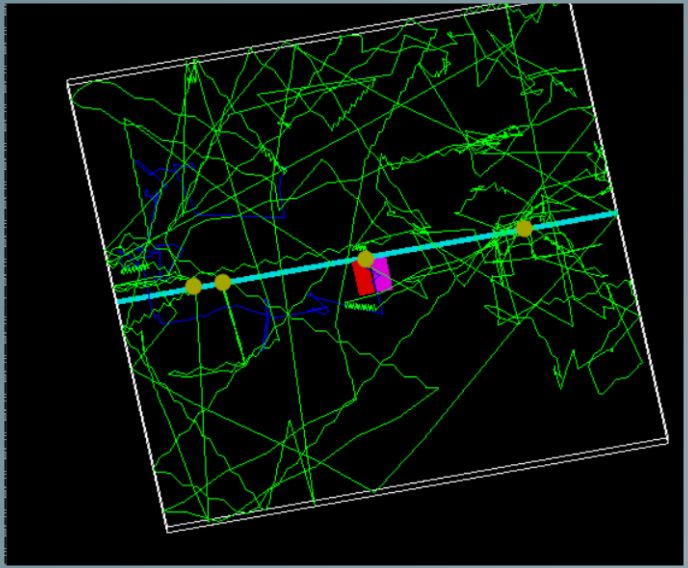




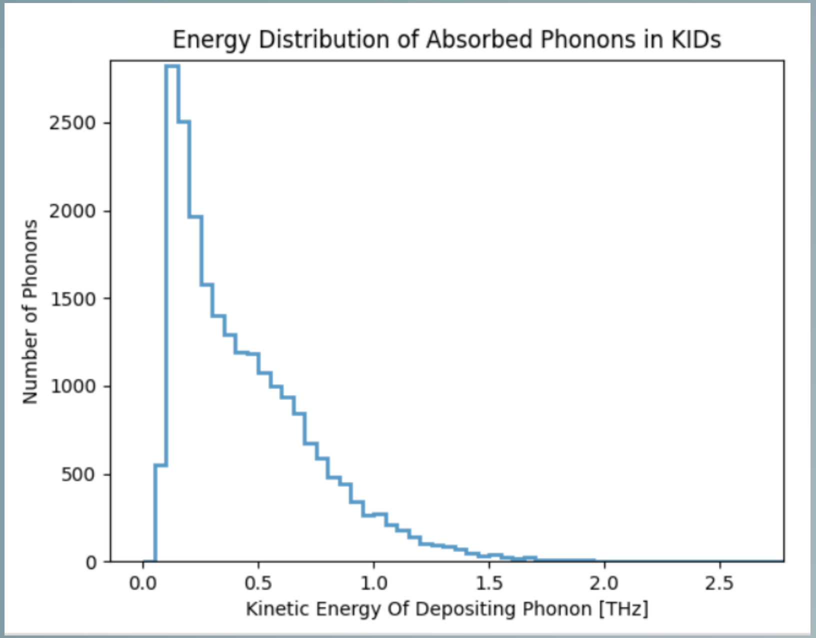


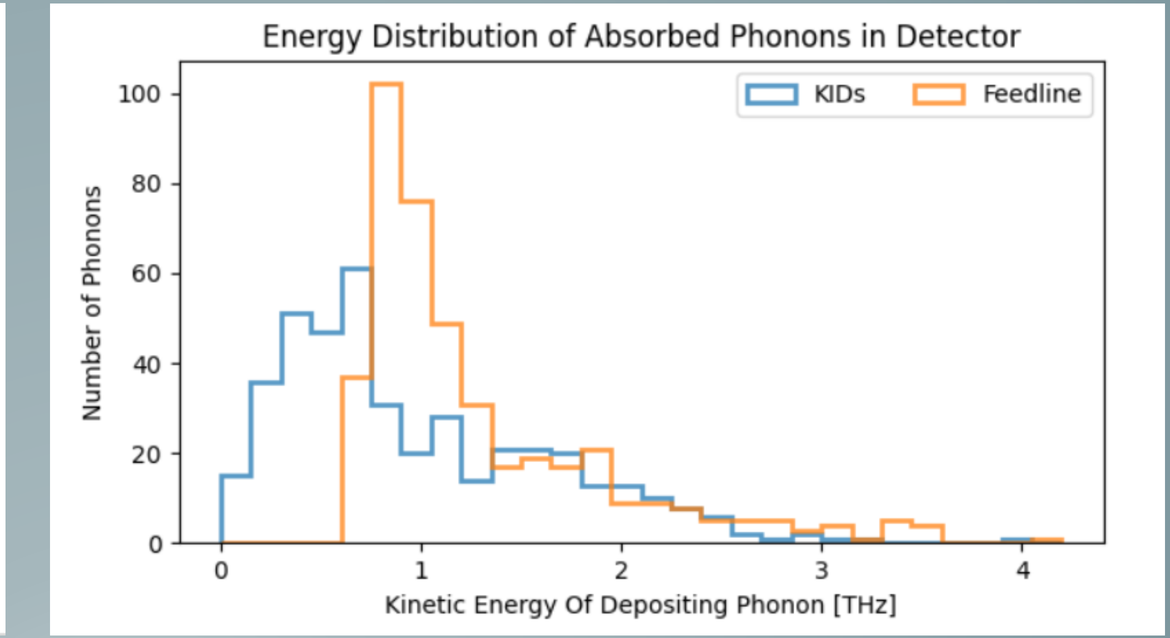


Small architecture



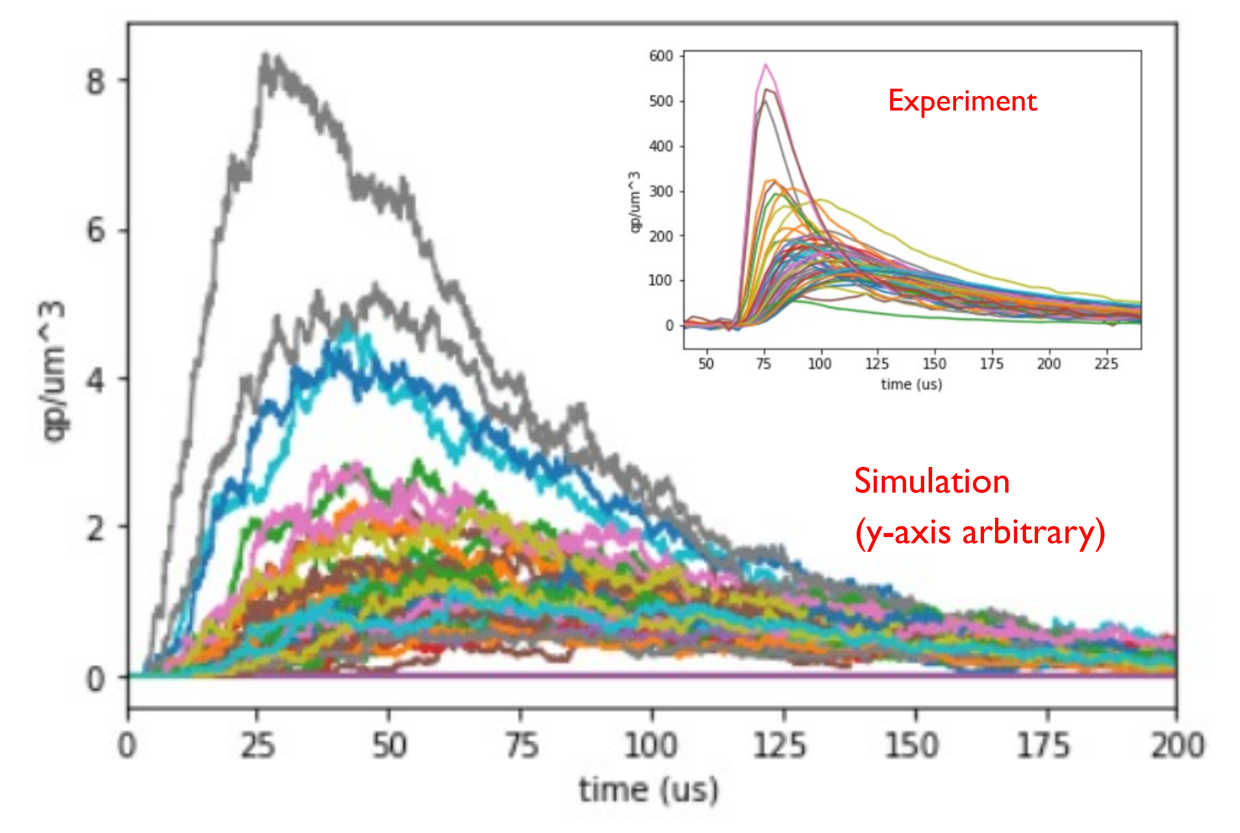
- Single material for feedline, inductor, capacitor
  - Would like to have different material e.g. Niobium, but right now use the "kill qps below gap" setting to speed up simulation. This is problematic because sub-Nb gap qps/phonons ***can*** affect Aluminum
- Used to understand phonon spectrum and splitting of energy across various features

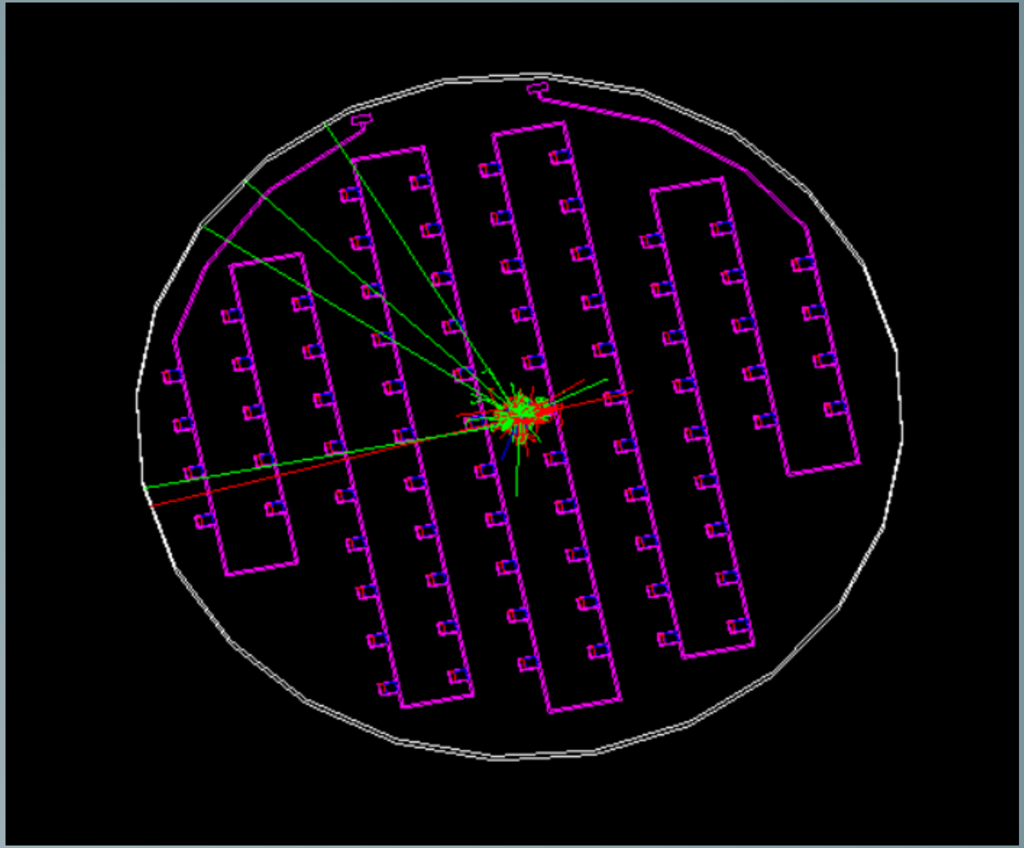




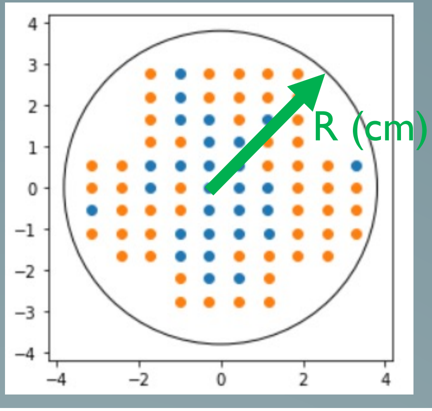
Large architecture

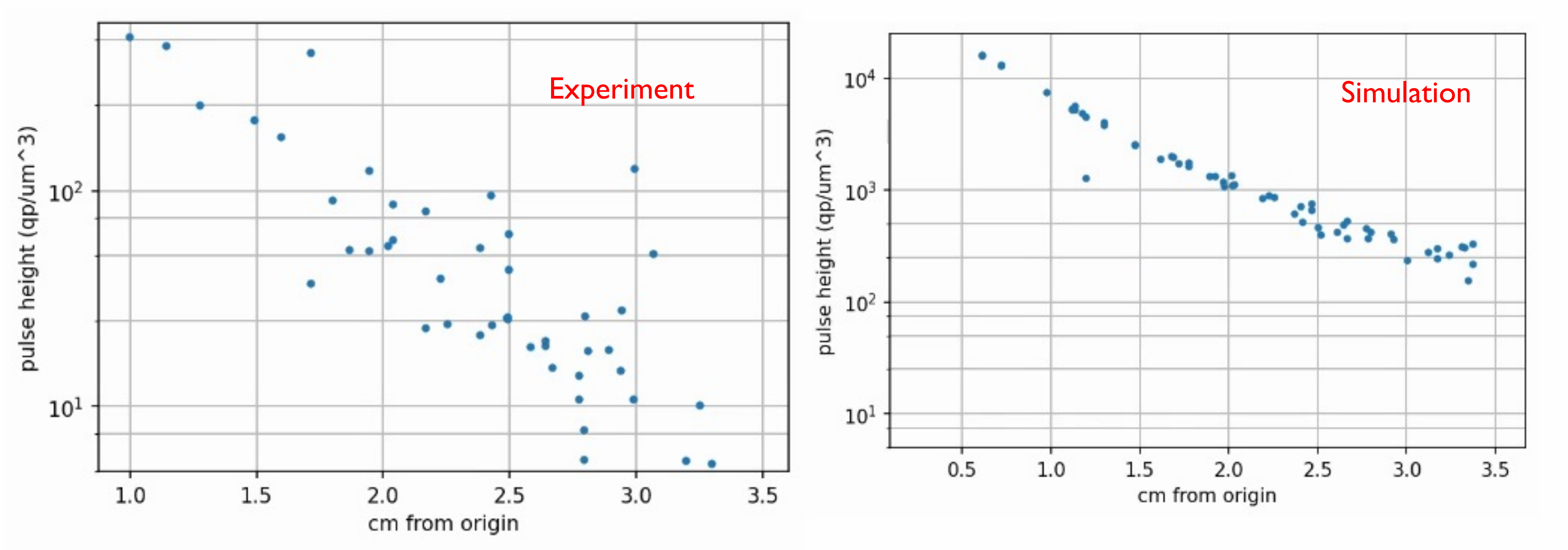
- Use same KID specification as small device
- Starting to reproduce pulse shapes seen in actual device (not perfect though)





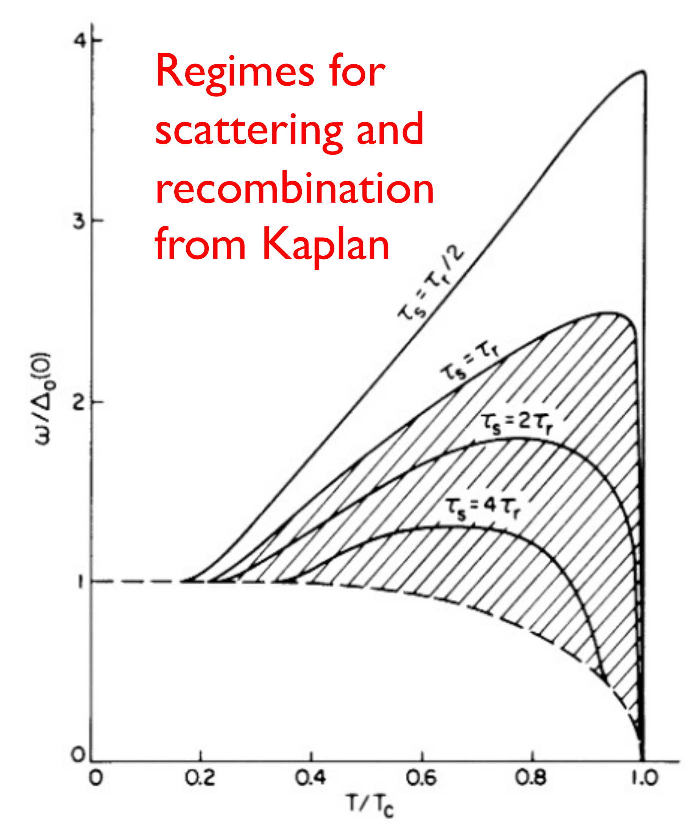
Phonon movie



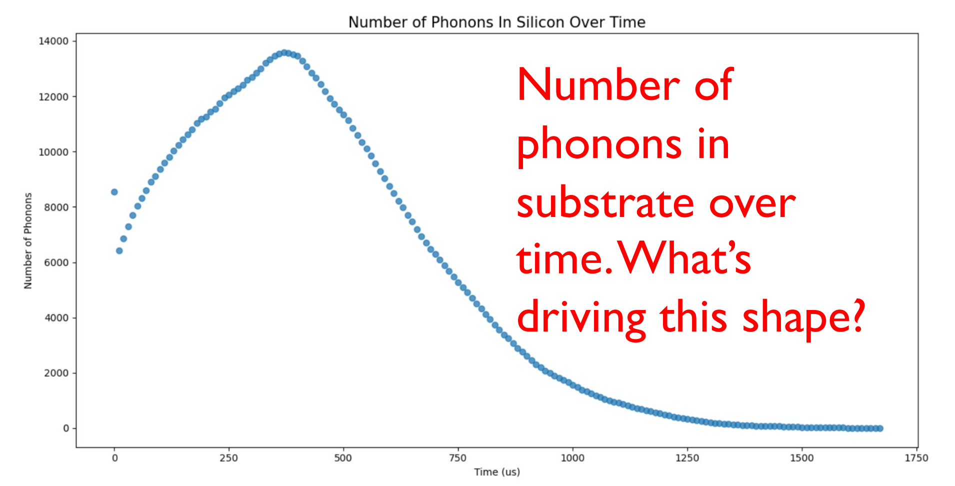


Future plans

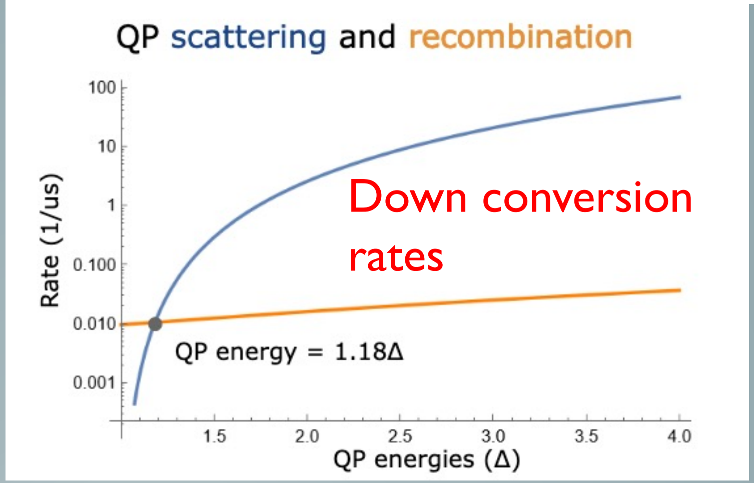
- Improve ad-hoc parametrization of quasiparticles by incorporating most quasiparticle physics outlined in "Quasiparticle and phonon lifetimes in superconductors" (Kaplan 1976)
  - e.g. recombination, scattering lifetimes – down to gap
- Include position and timing effects on phonon and quasiparticle production and propagation within film
- Include some form of material dependence
- Include loss mechanisms to mounting and surface downconversion
- MATCH TO DATA
  - Proportions of energy and pulse shape/lifetimes



Regimes for scattering and recombination from Kaplan



Number of phonons in substrate over time. What's driving this shape?



Down conversion rates

Like-to-haves

Primarily about quasiparticles. Since our schemes detect qps, huge systematics introduced if we don't model qps accurately. Base phonon implementation probably ok for now?

1. Include all relevant processes: recombination, scattering, down-conversion, phonon-production. Time dependent phonon emission back into substrate also important.
2. Account for thermal/quiescent bath qps
3. Quasiparticle tracking (may be very computationally intensive). Much more useful for our qubit sensors.

THANKS! QUESTIONS?

(karthikr@caltech.edu)