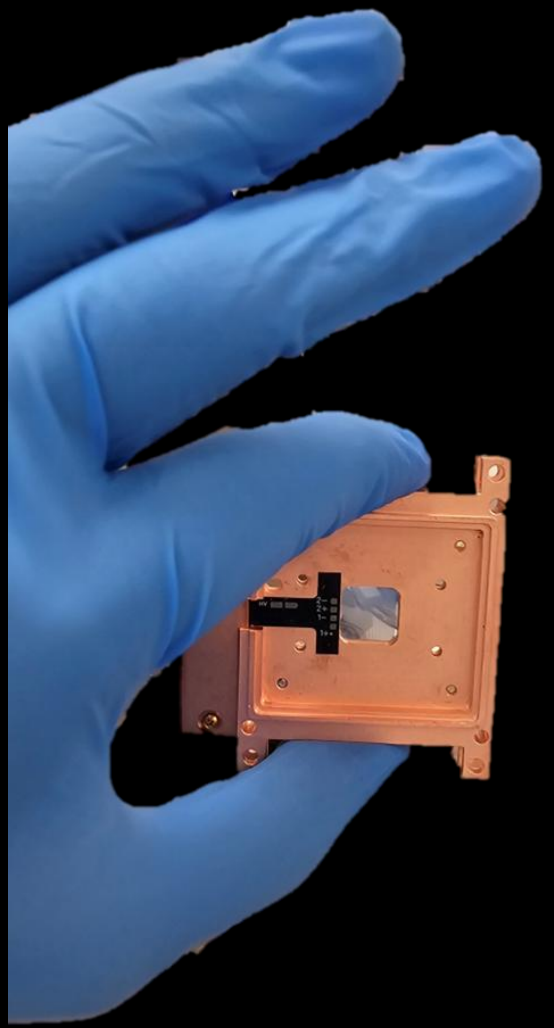
Technology Advances in the SuperCDMS HVeV Program



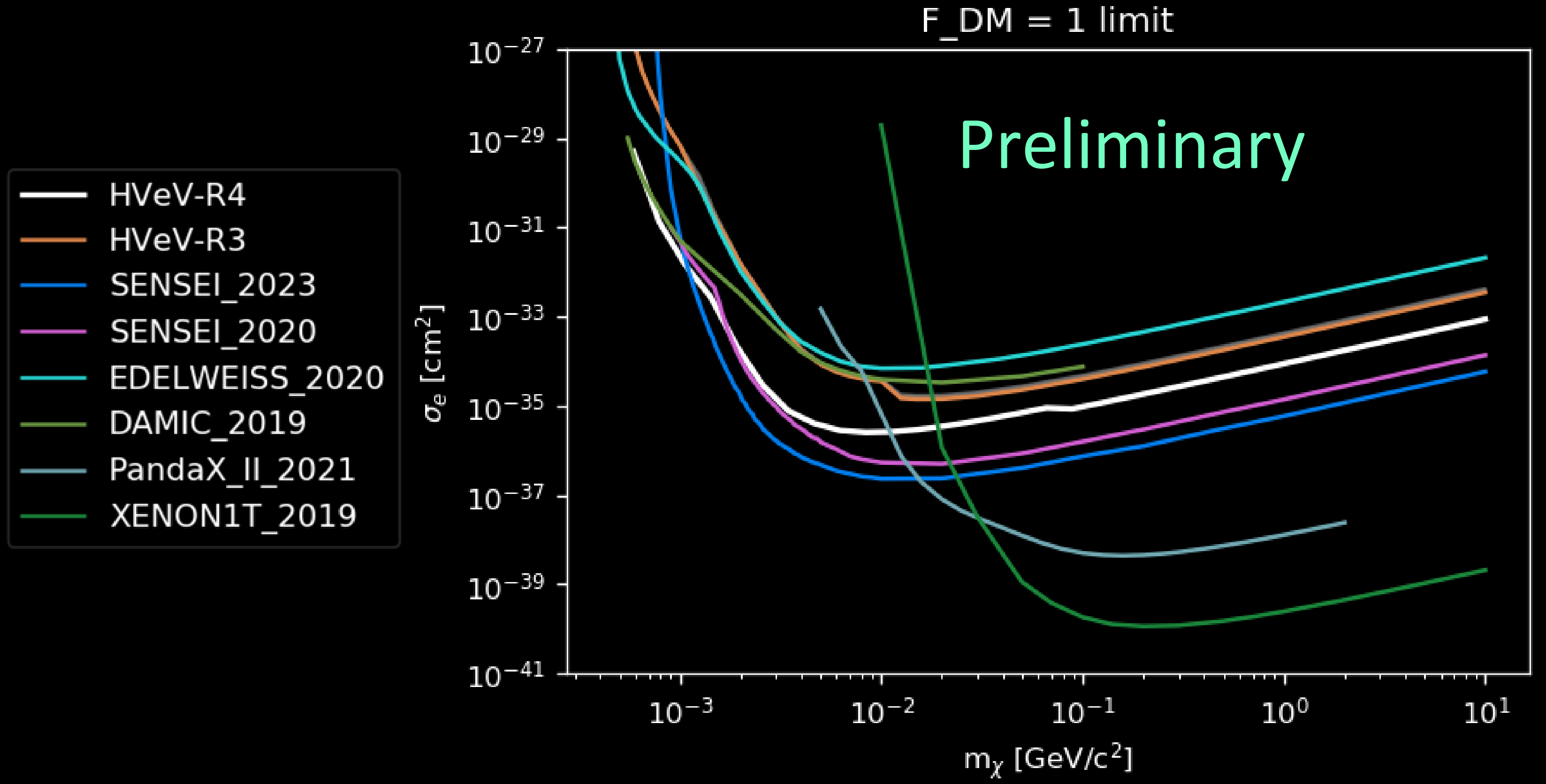
Position Dependent Calibration and Carbon Based Substrates

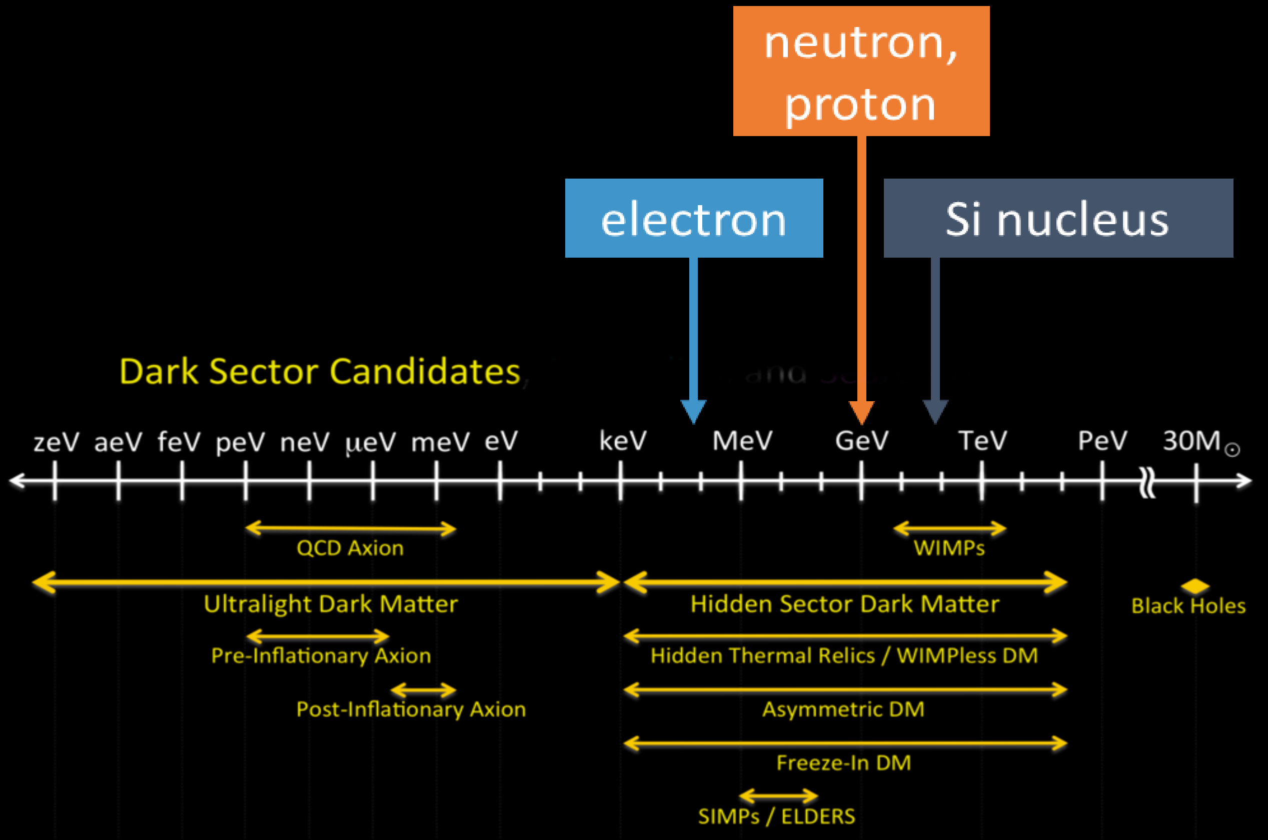
Aviv Simchony

DMQiS @ SLAC

Highlights of HVeV Science

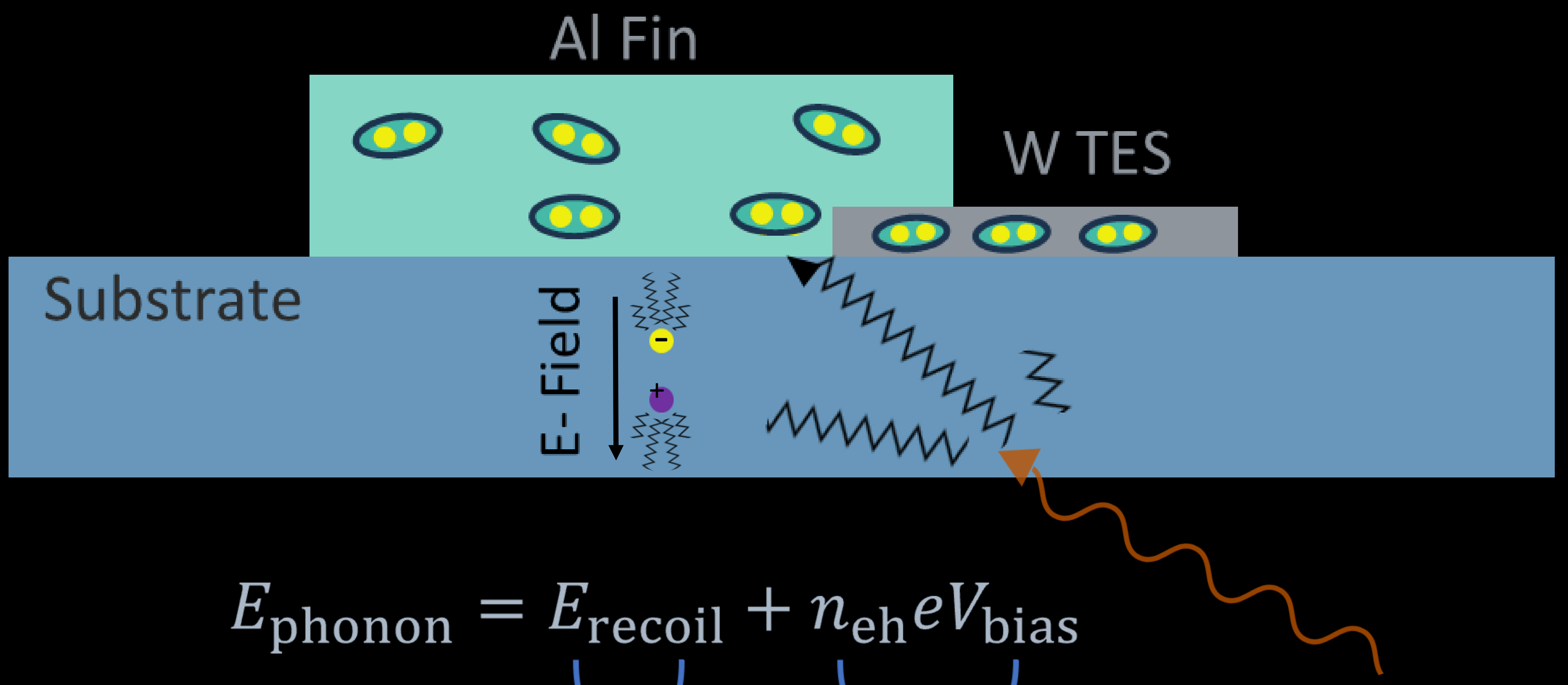
- Direct detection of hidden sector dark matter candidates requires pushing the boundaries of energy resolution
- HVeV-R4 has set competitive limits in the subGeV mass range
- Small scale R&D versions of these detectors allow rapid prototyping and pave the way for higher sensitivity searches
- We have Run 5 results! See Kyle Kennards talk tomorrow at 16:00 for first unveiling





Operating Principle

- When a particle scatters off the substrate, it can trigger an ionization event or generate athermal phonons. The resulting electron-hole pairs are accelerated by the applied electric field, producing additional phonons via the Neganov-Trofimov-Luke (NTL) effect



$$E_{\mathrm{phonon}} = \underbrace{E_{\mathrm{recoil}}}_{\text{Prompt phonons}} + \underbrace{n_{\mathrm{eh}} e V_{\mathrm{bias}}}_{\text{NTL phonons}}$$

Prompt phonons

NTL phonons

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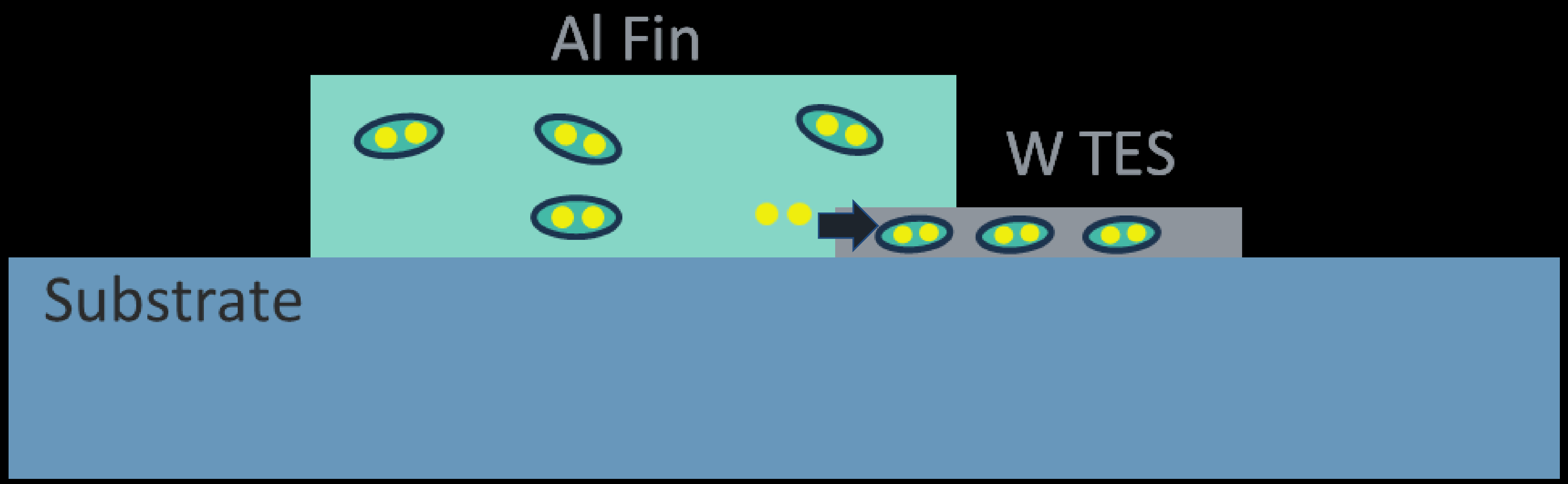
- Generated phonons are absorbed by the Al fin, which breaks Cooper pairs to form Bogoliubov quasiparticles



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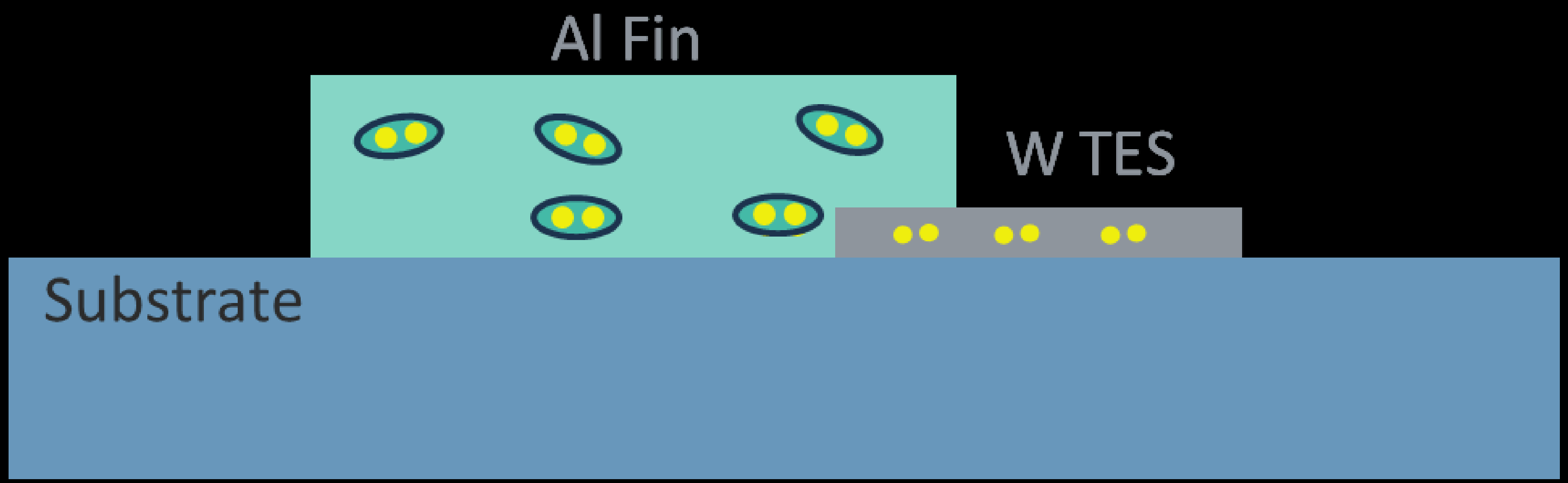
- Quasiparticles travel to the W TES, where they are downconverted into lower energy quasiparticles due to the lower gap - trapping them



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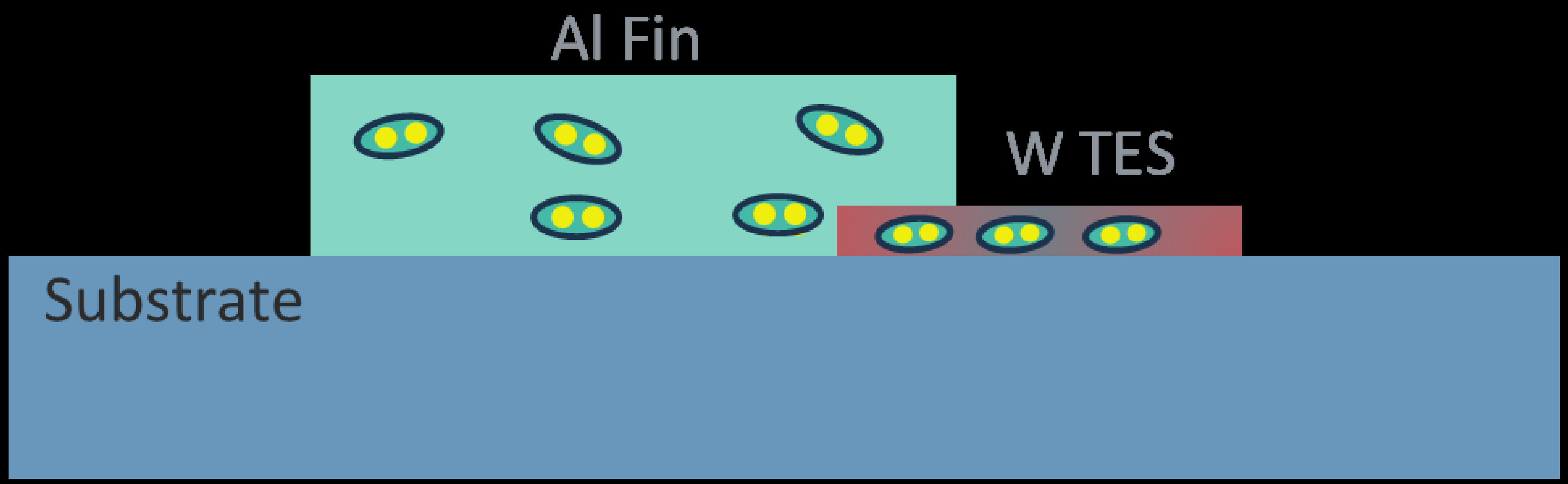
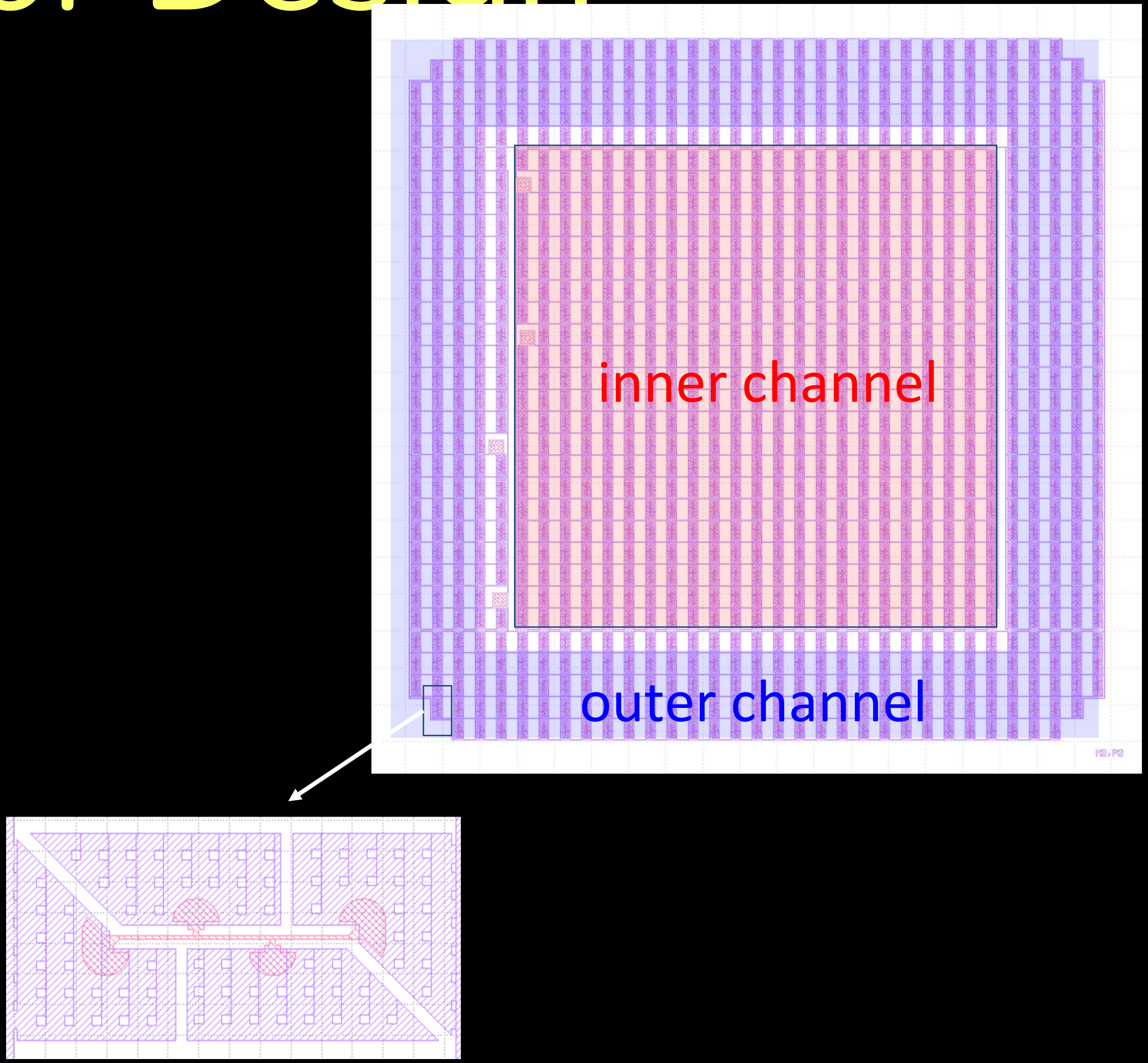
- Quasiparticles travel to the W TES, where they are downconverted into lower energy quasiparticles due to the lower gap - trapping them

- Cooper pairs recombine, heating the TES and producing a pulse



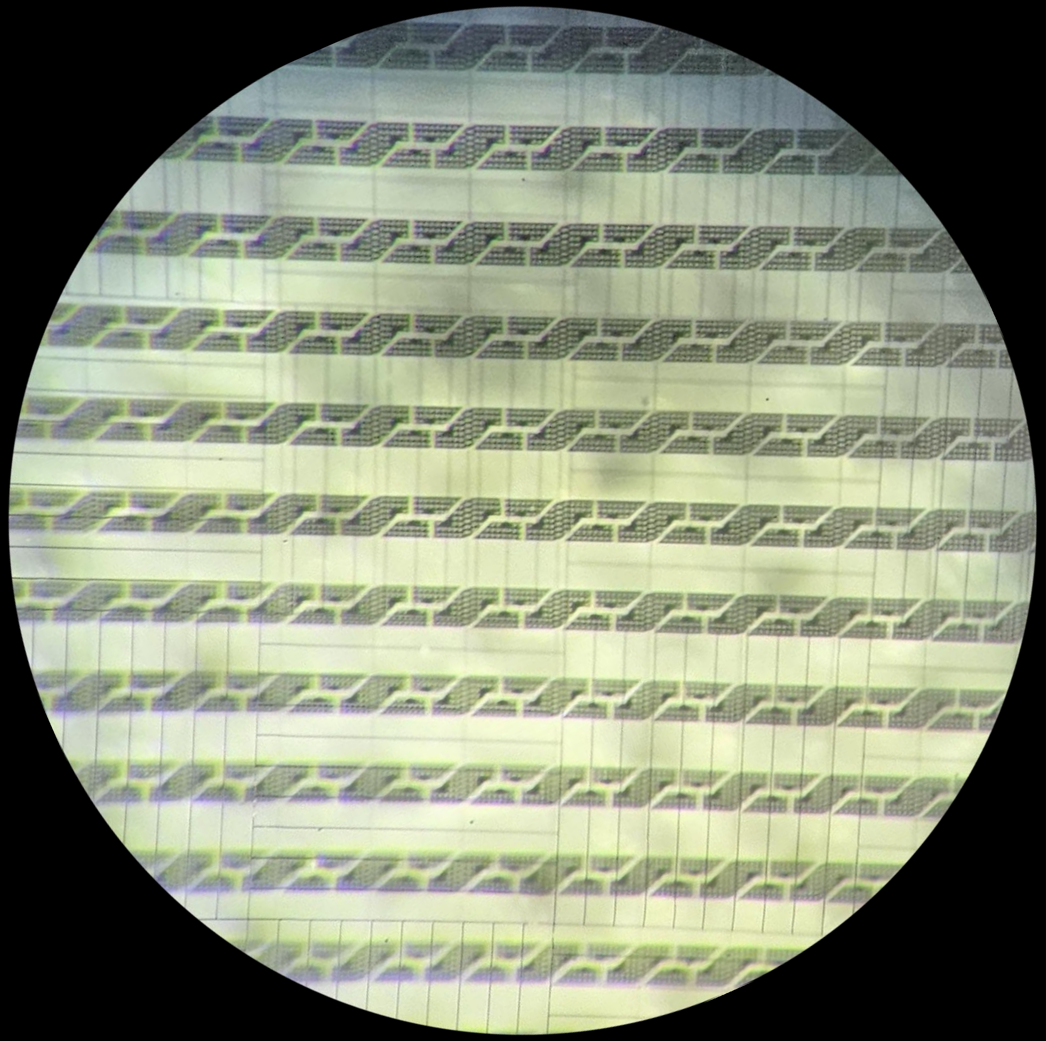
HVeV Detector Design

- Two channels of parallel QETs with similar TES volumes
- Al backside grid to allow high voltage biasing

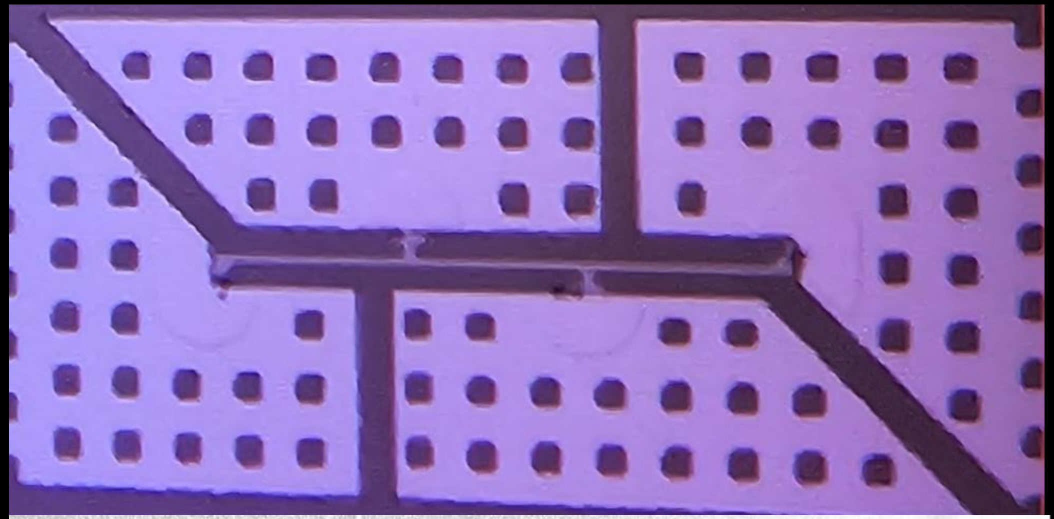


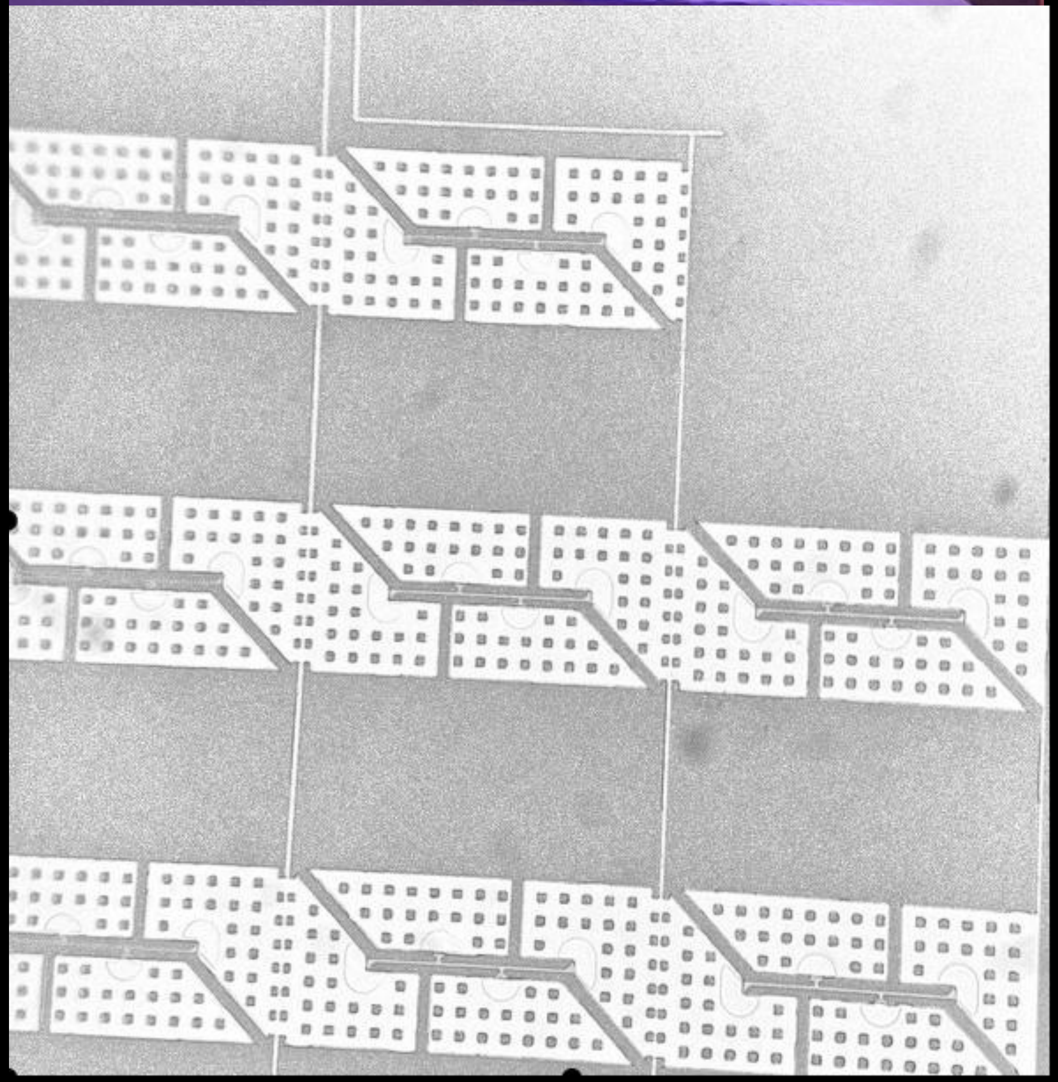
Fabrication Process

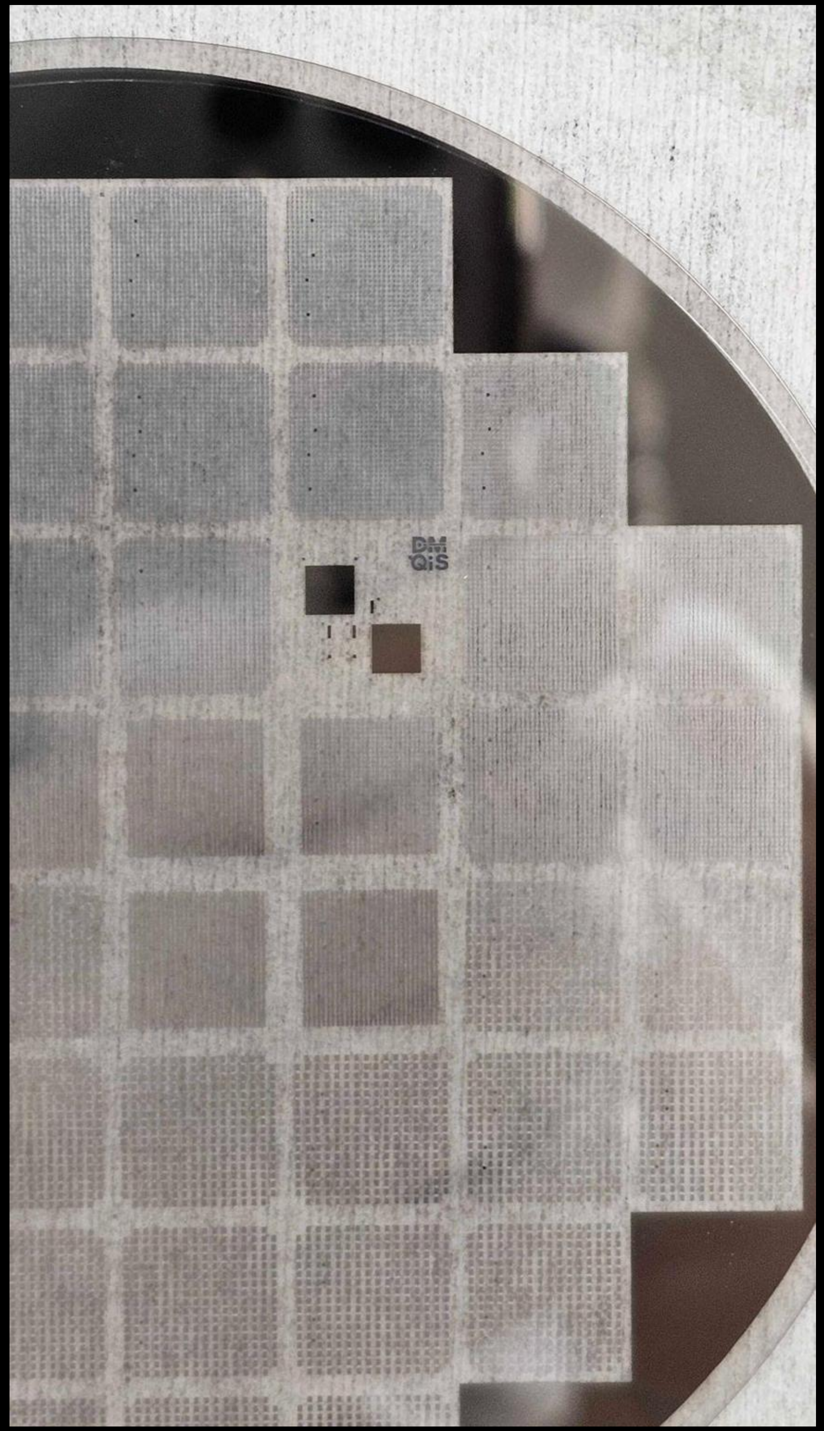
- Double sided fabrication process with 30 nm Al backgrid for HV biasing
- 40nm W tuned to 35-65mK Tc sputtered and TESs patterned using maskless photolithography and dry etch
- 600nm Al sputtered and patterned with a combo wet-dry etch
- Typically this has been done on 4” and 2” wafers, however all steps have been tested individually on chip scale. Integration remains a challenge



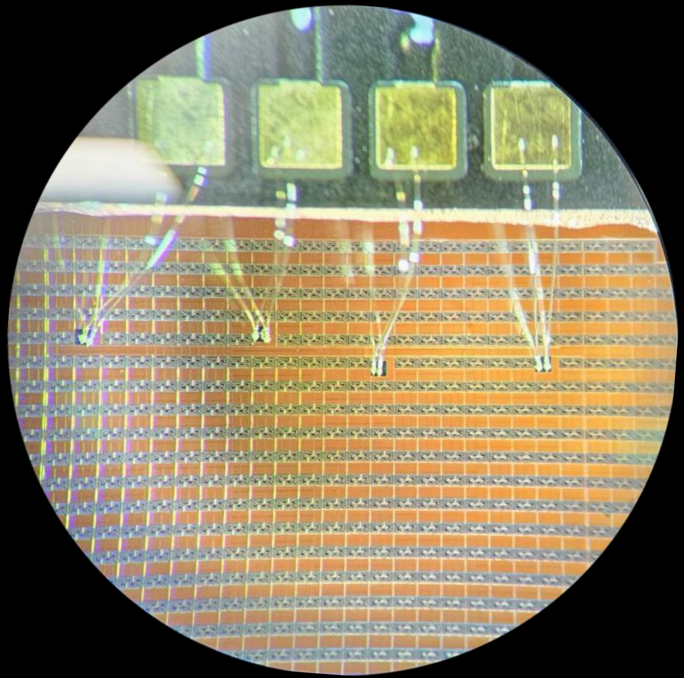
Fabrication Process

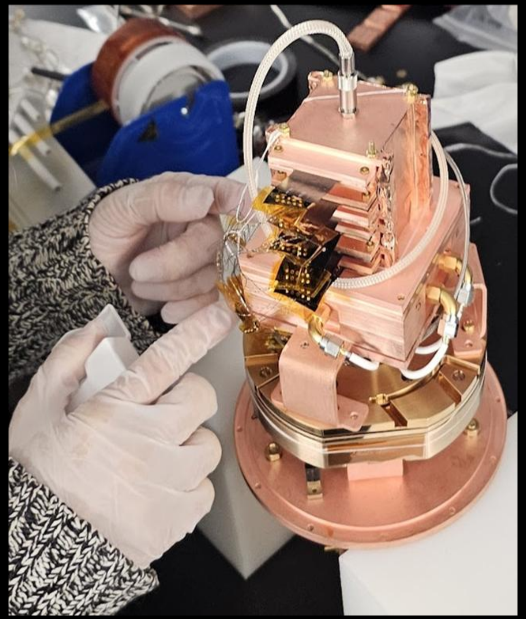


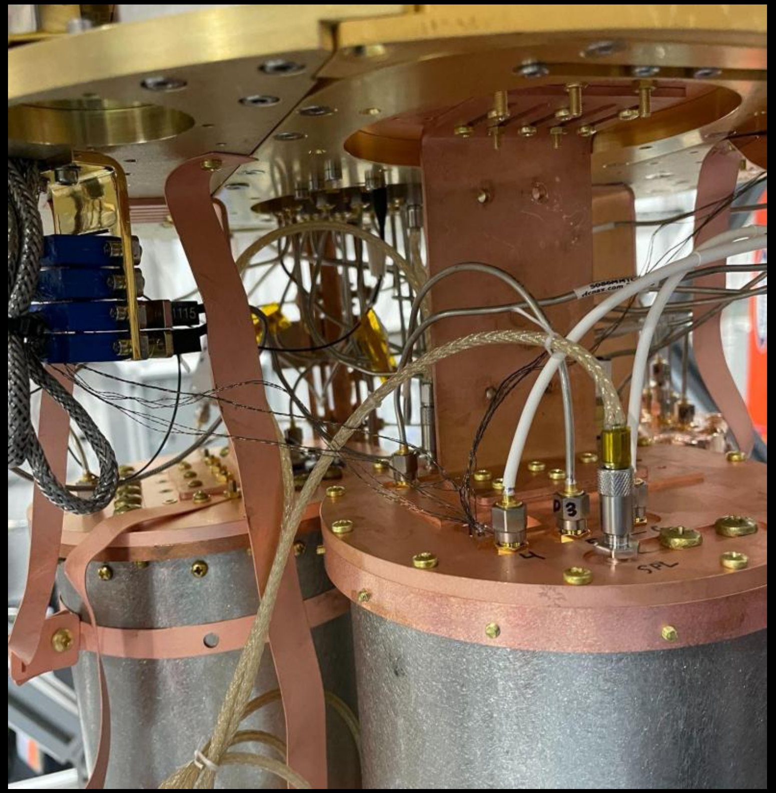


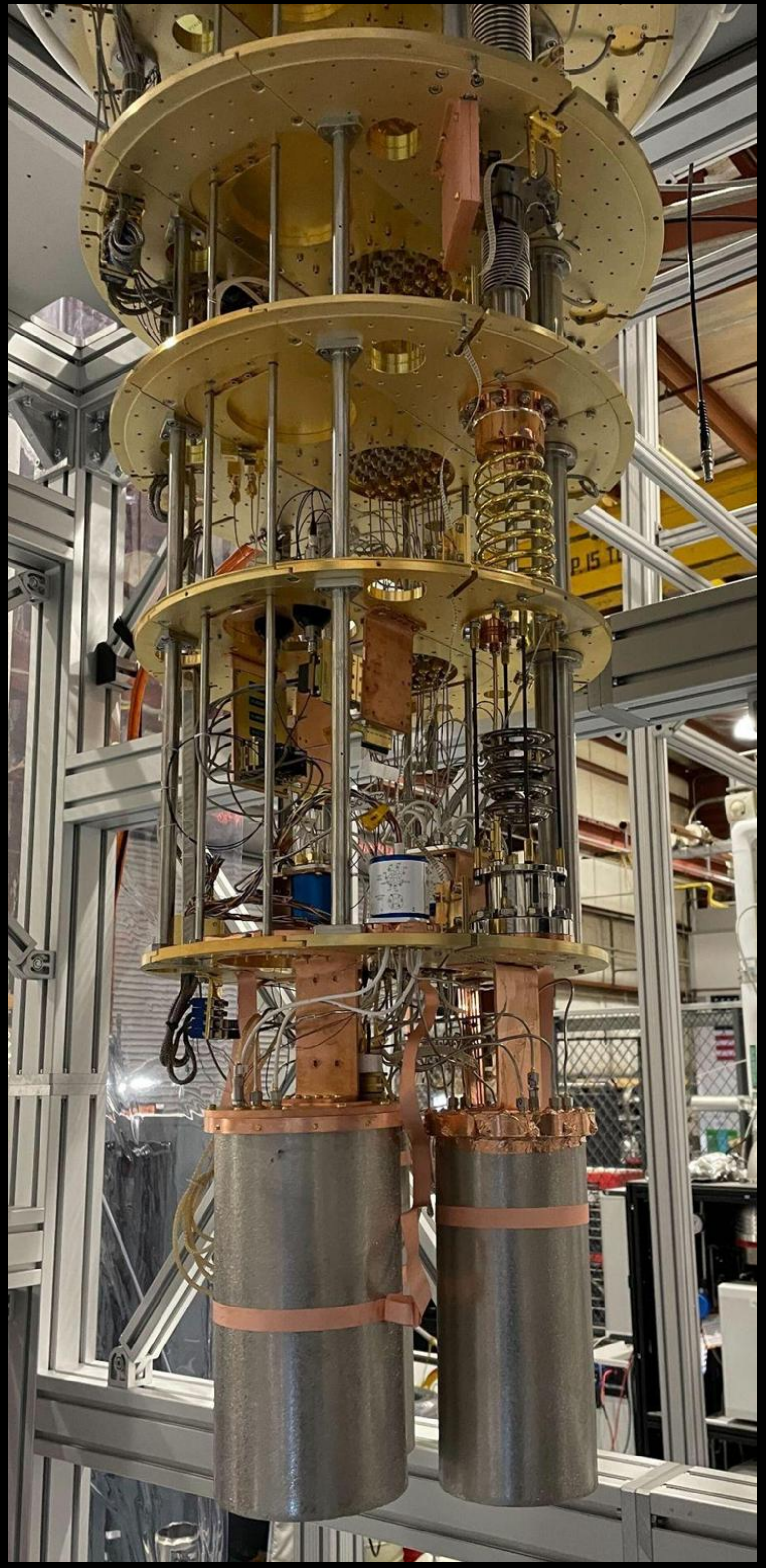


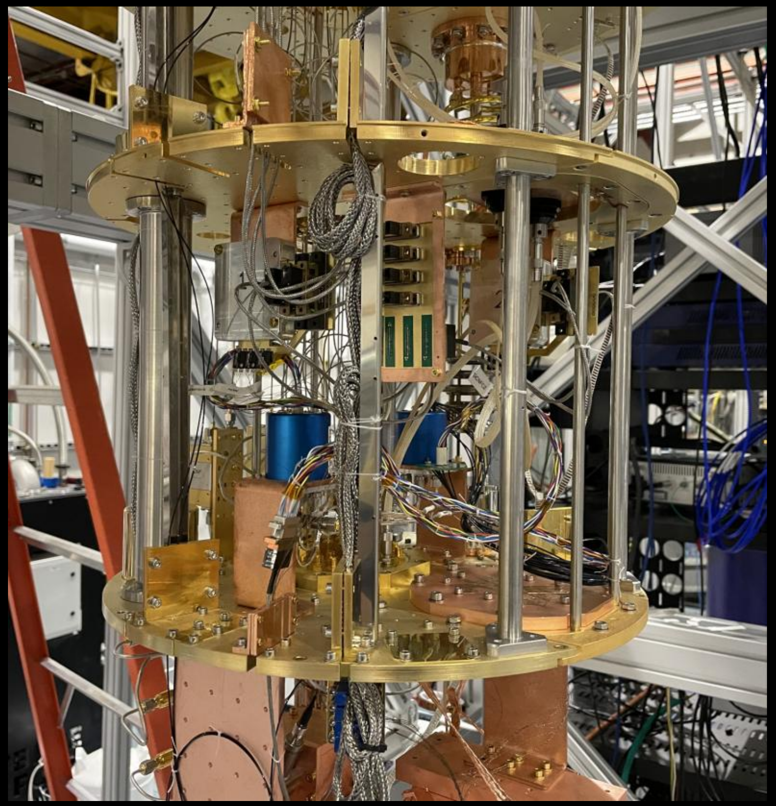
Measurement Setup











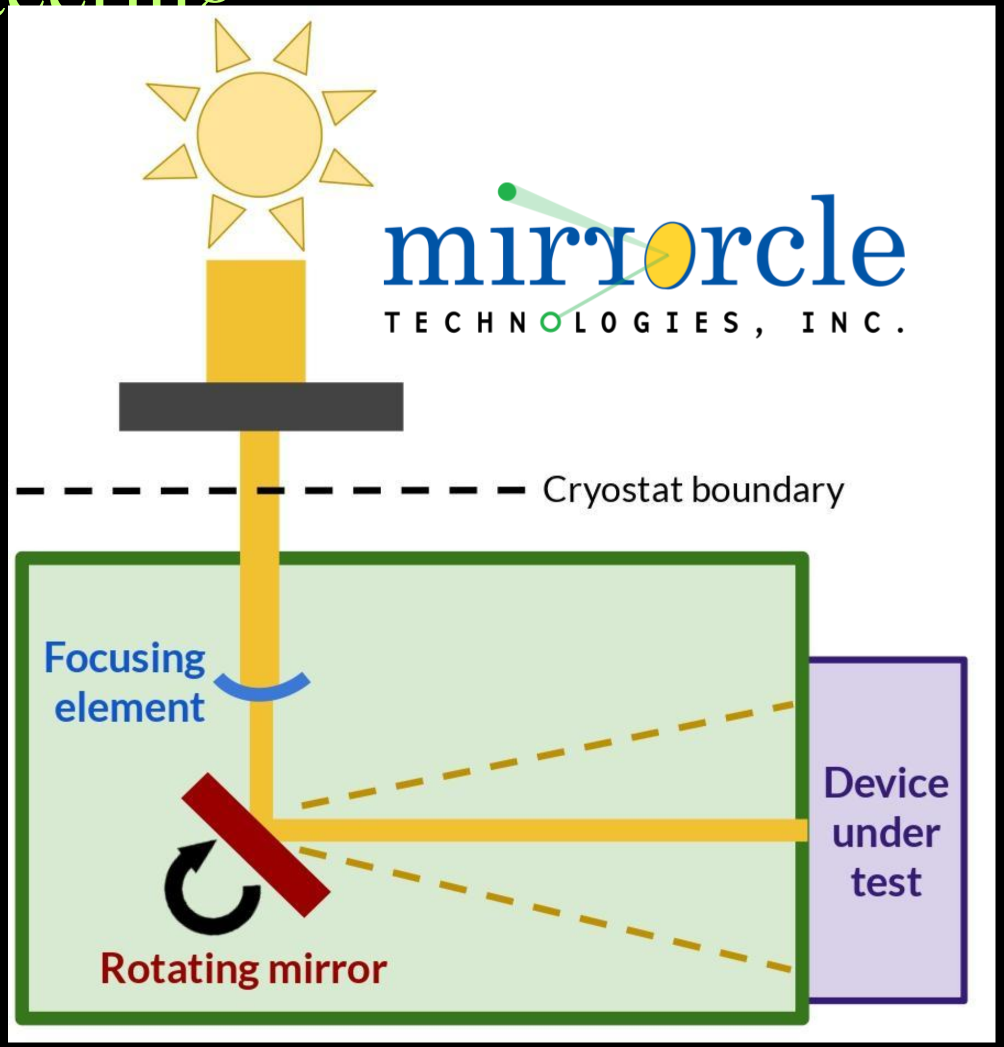
MEMS v.2 system

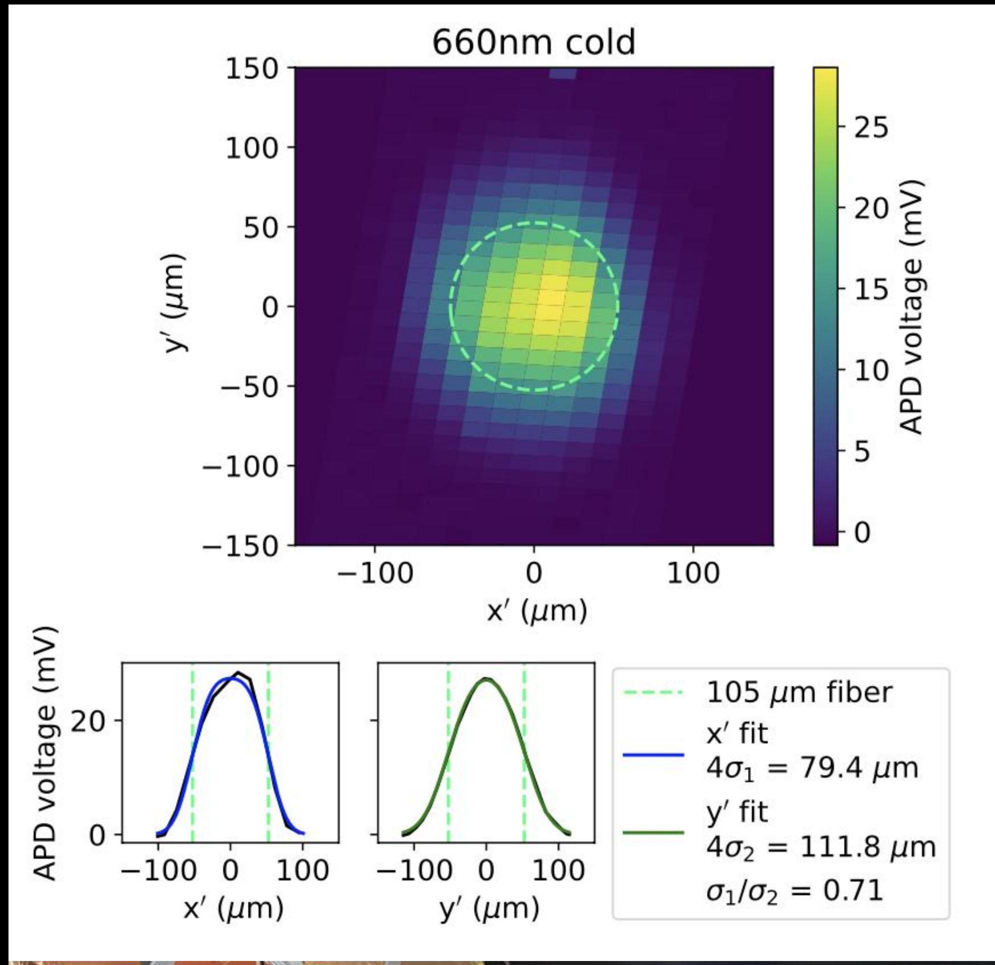
Micro-electro-mechanical system (MEMS) mirror-based calibration system

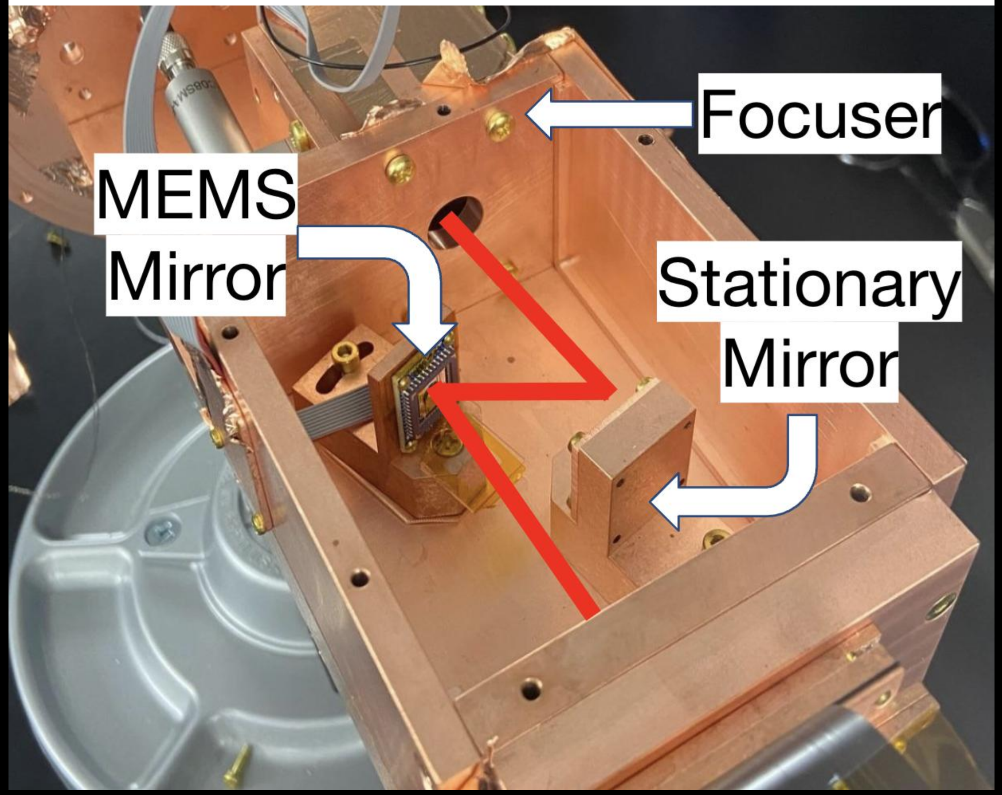
Compact cryogenic optical beam steering

At 10 mK:

- ~100 µm spot size
- ~4.5 µs pulse width
- 3 cm x 3 cm scan range
- 1.2 - 4.5 eV photon energy
- near 0 power dissipation







Ref: N. Tabassum et. al, "Broadband Optical Modulation and Control at Millikelvin Temperatures", 2025.

MEMS ~~v.2 system~~ v3 system

Micro-electro-mechanical system (ME mirror-based calibration system

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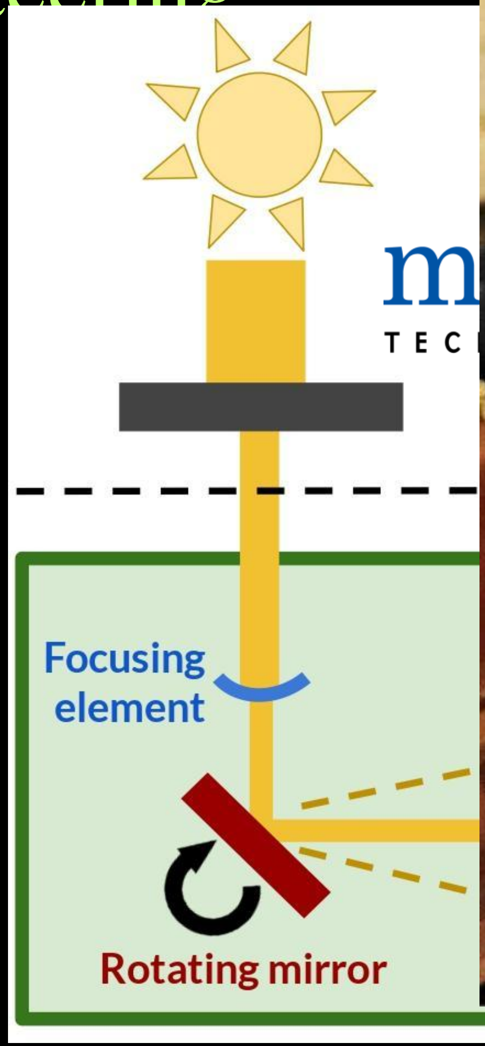

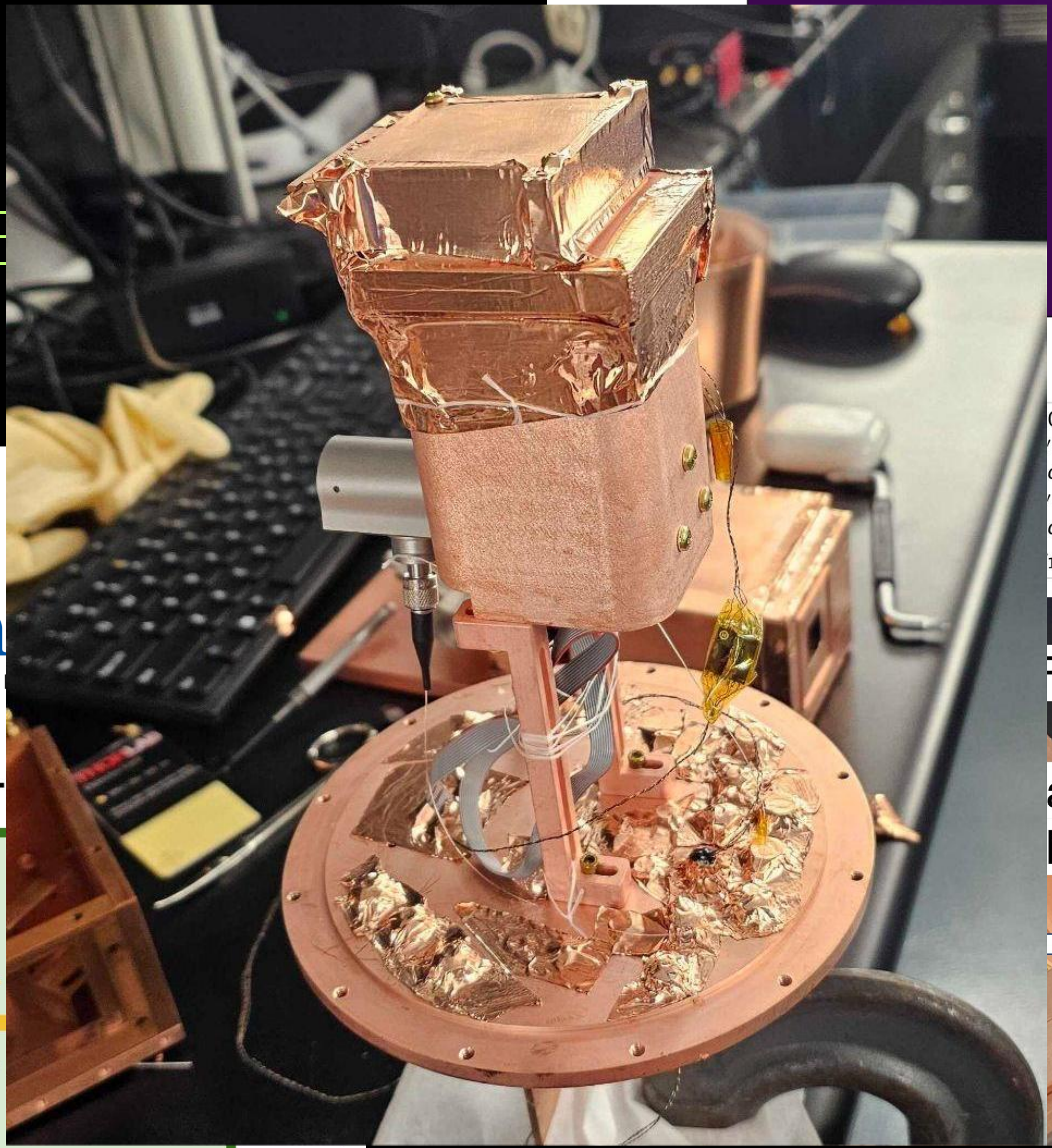

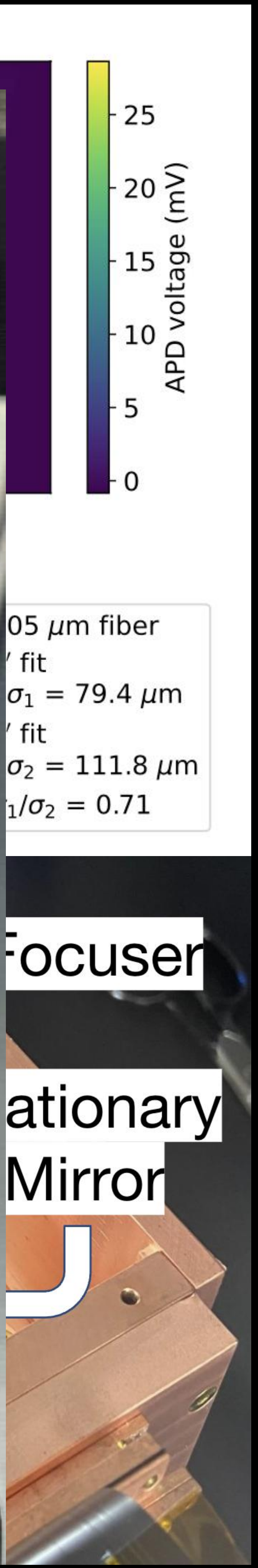

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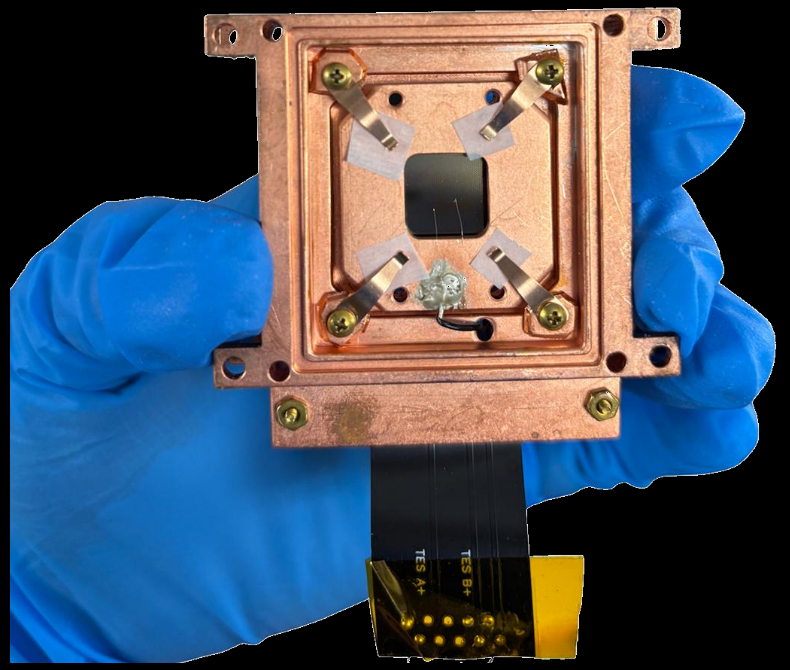
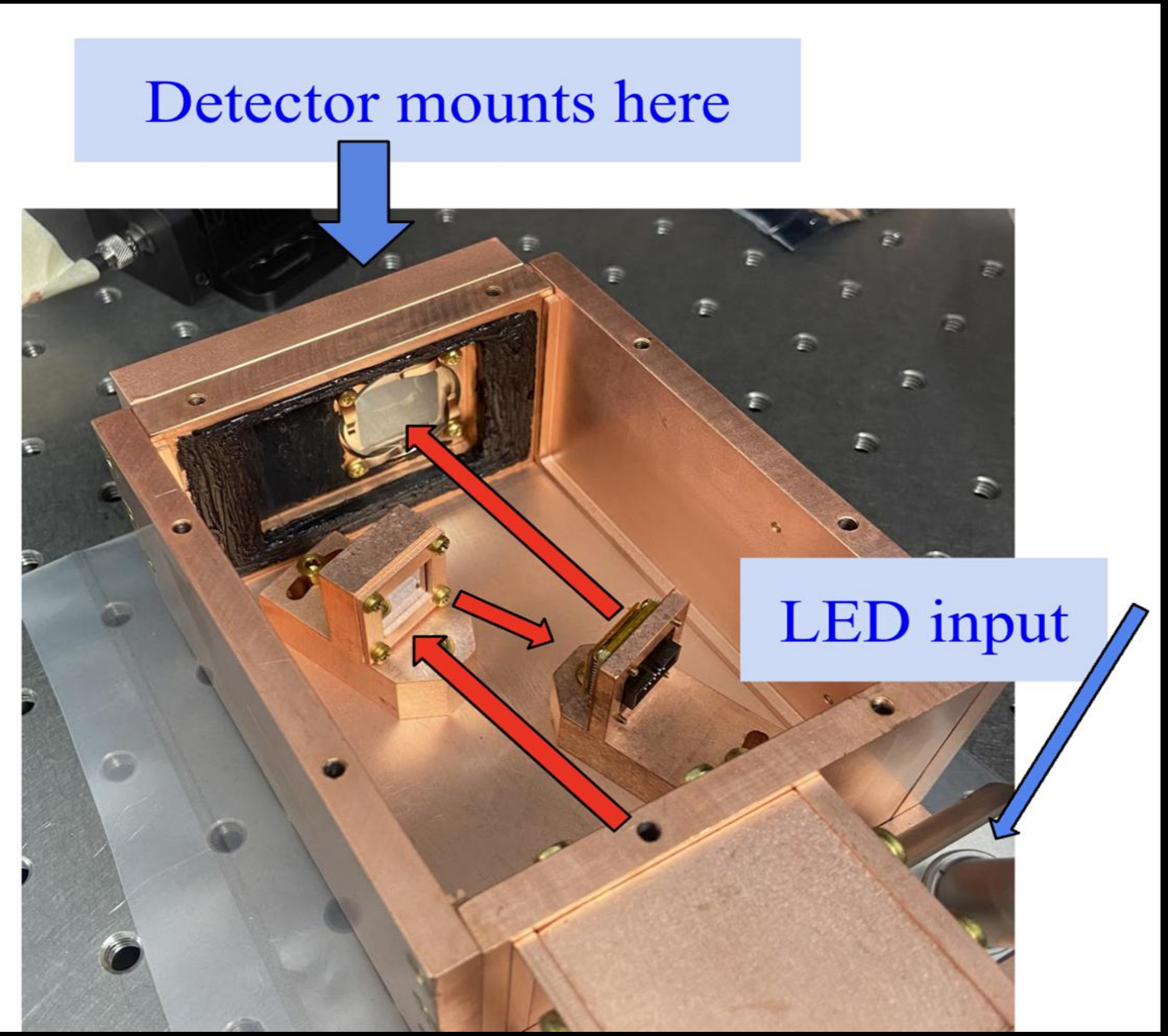
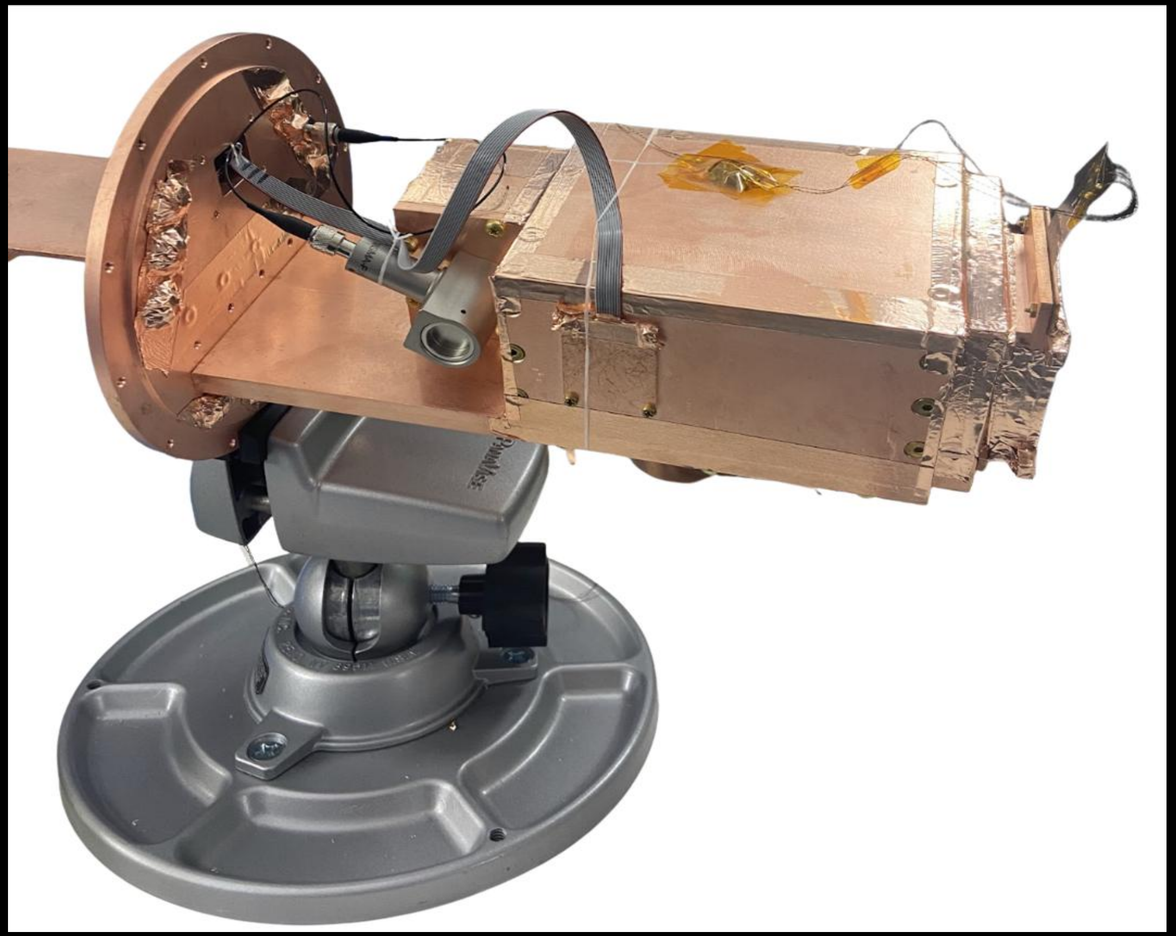


MEMS + HVeV Data





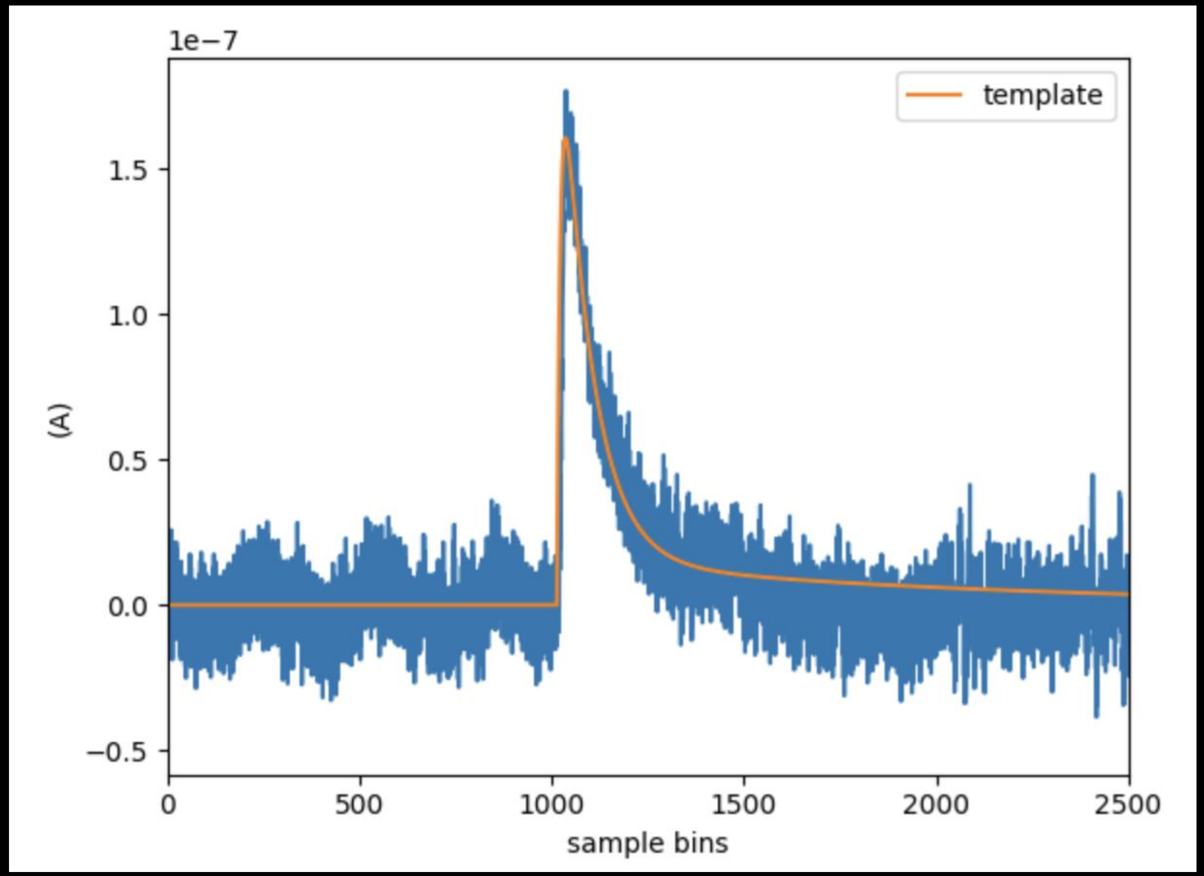
Data taken:

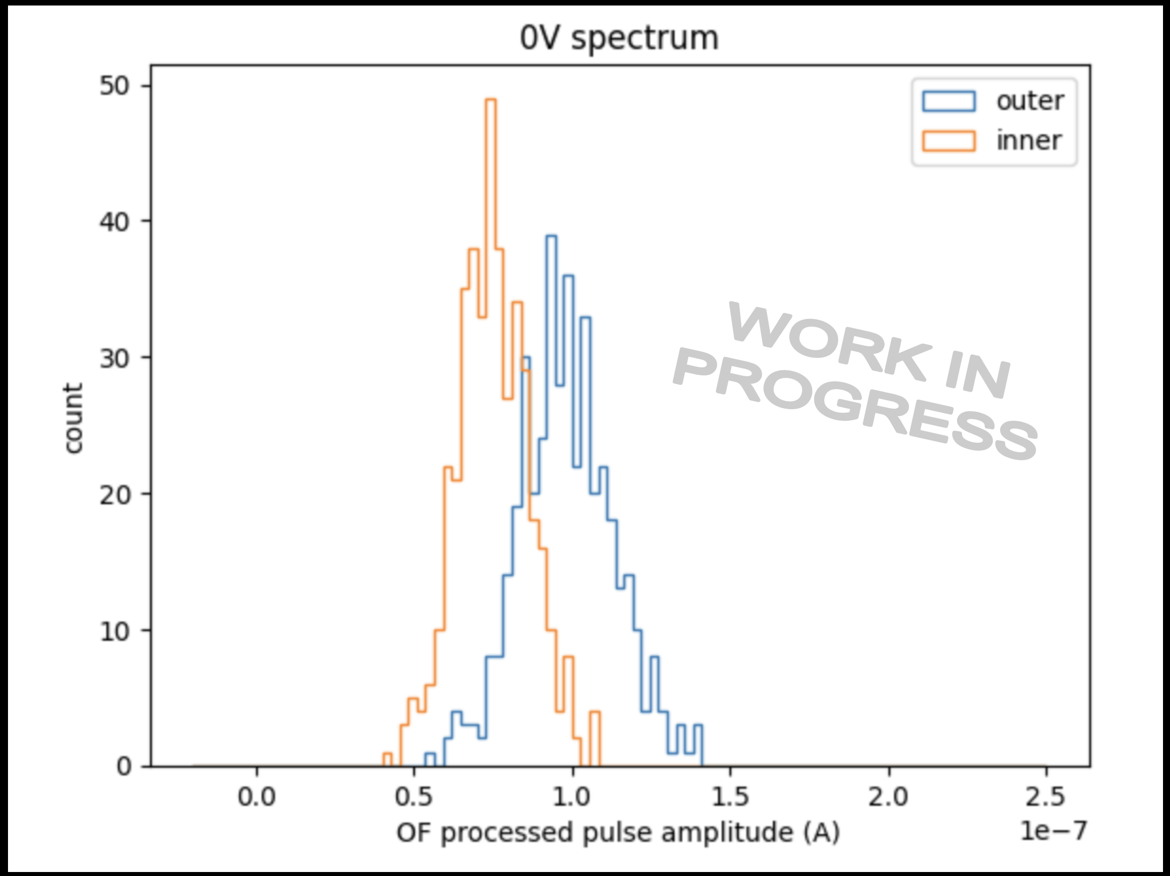
- Full detector: 1-2 minutes of data taken with LED pulsing at ~500/7000 points across detector
- HV bias: 0 / 50 / 90 / 100 V
- LED wavelength: 365/ 625 nm

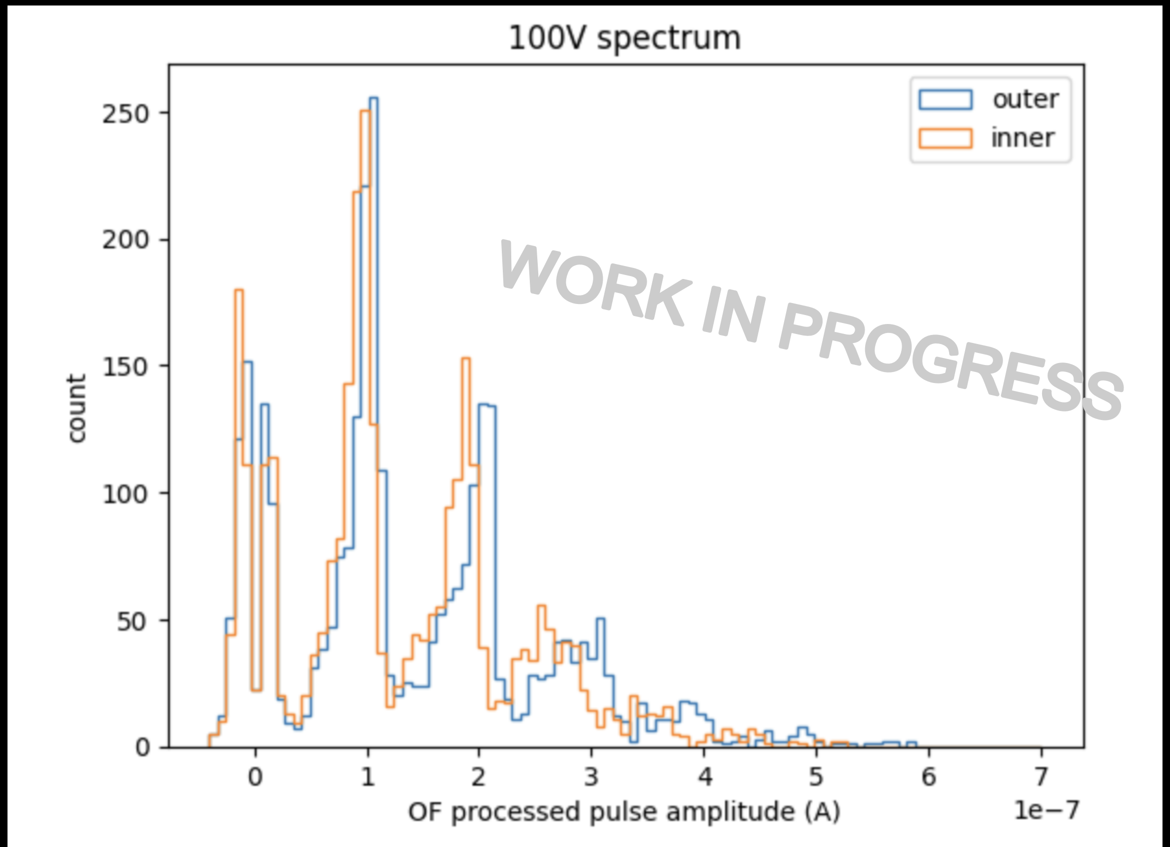
MEMS + HVeV Data

Data processing:

- Data recorded continuously and triggered offline with triggers in coincidence with LED pulses
- Events fitted with an optimal filter assuming a pulse template
- Data quality cuts

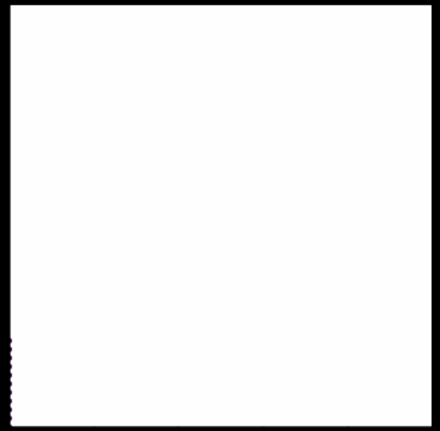


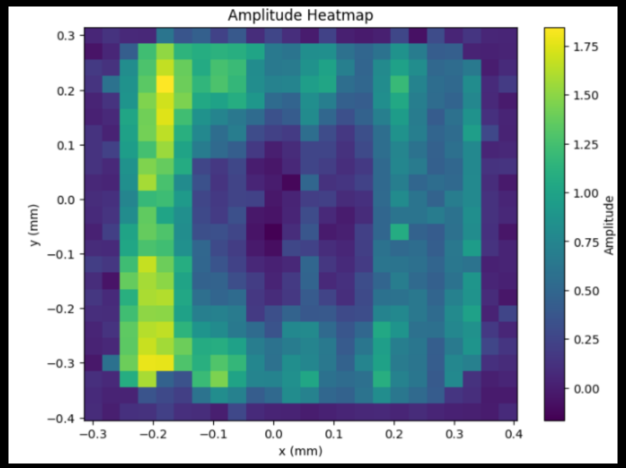




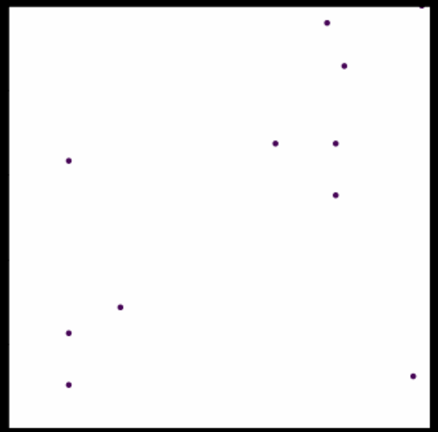
Scanning methods

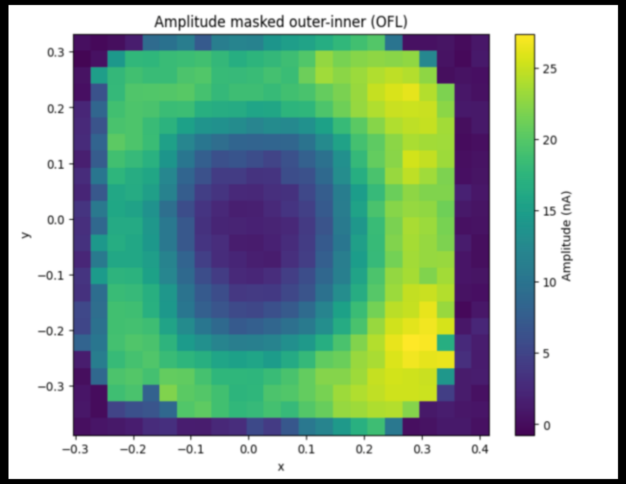
Regular raster



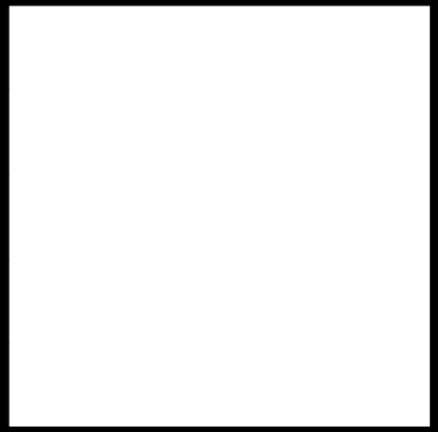


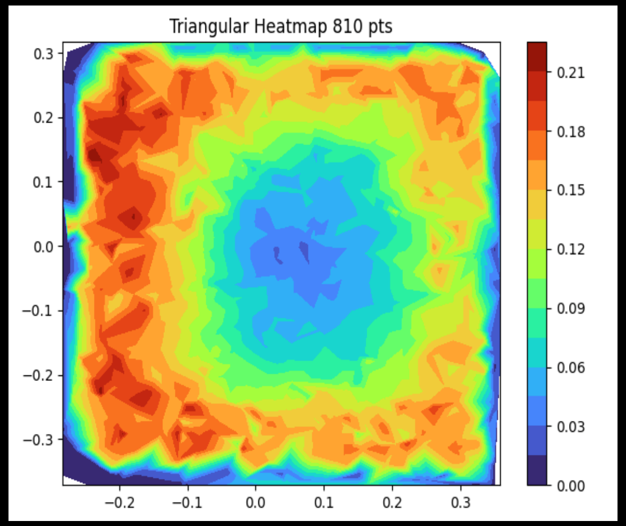
Random Raster





Poisson disk sampling





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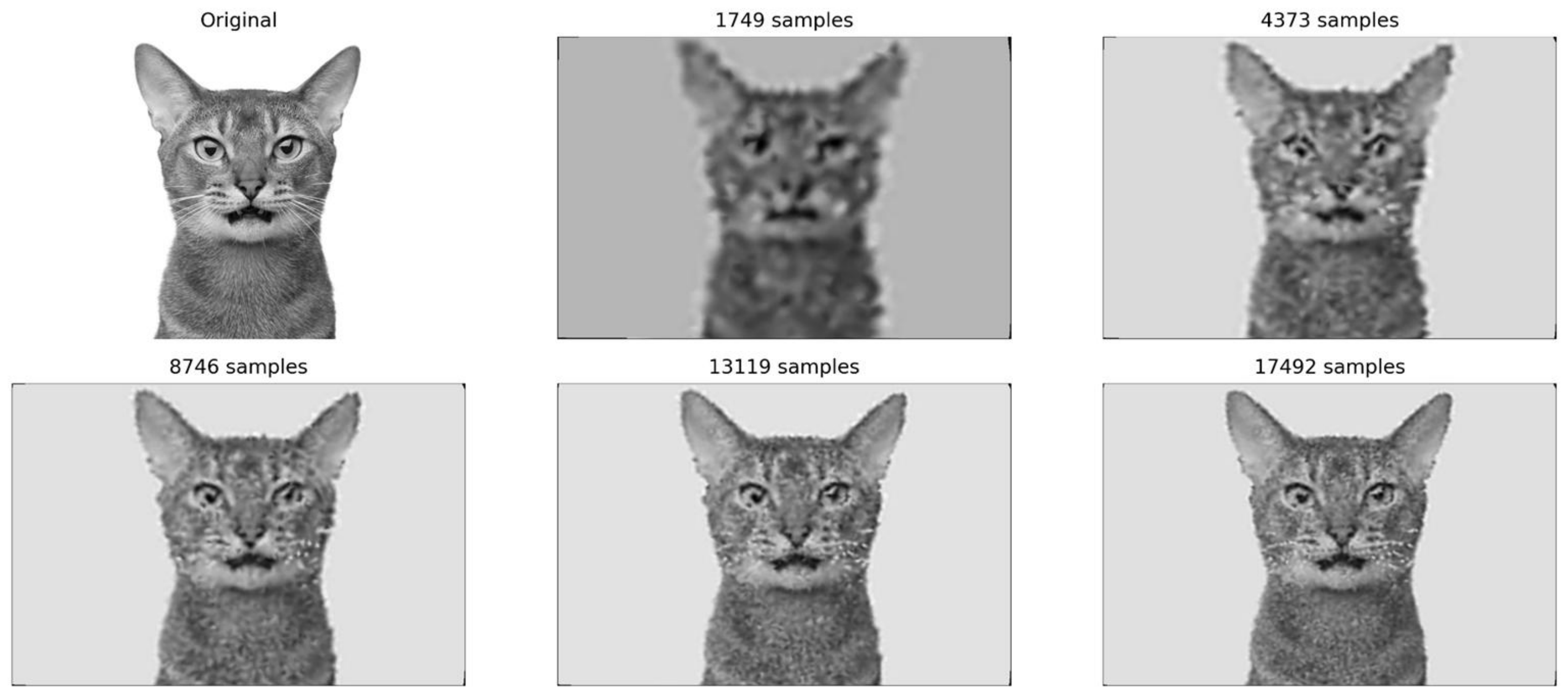
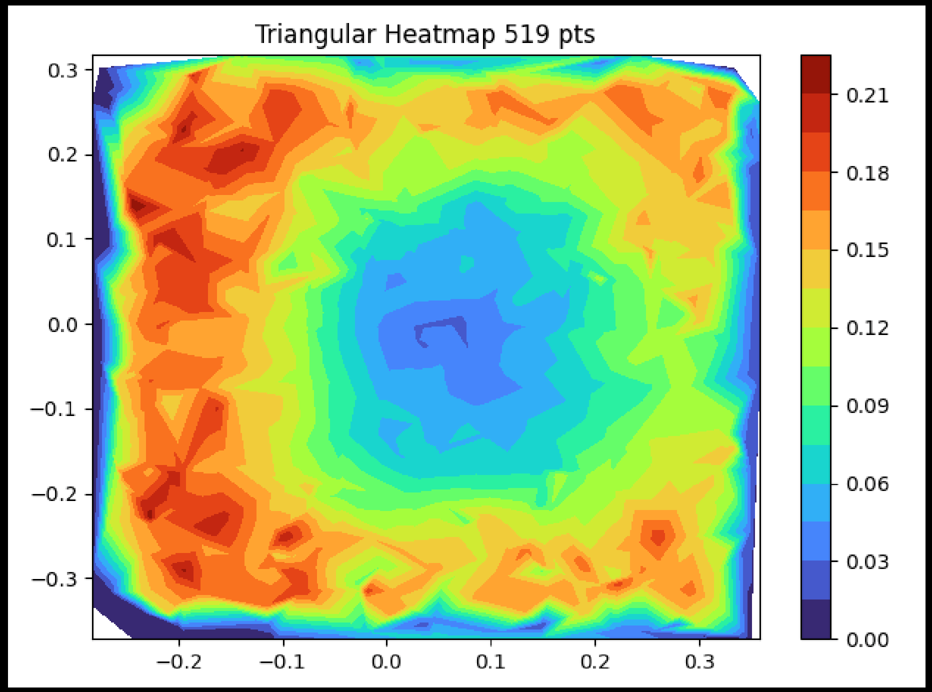
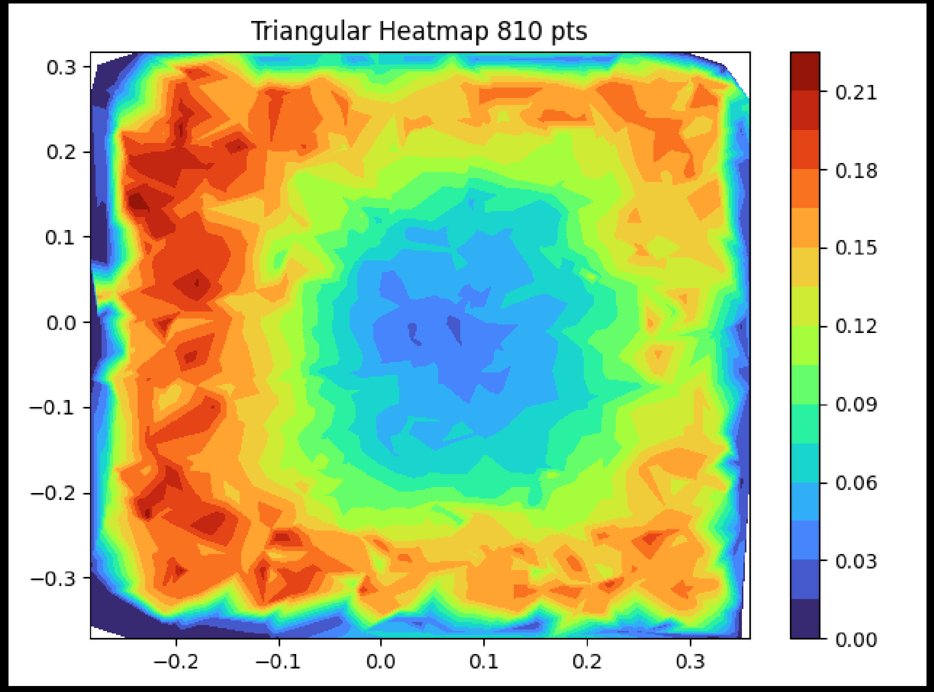
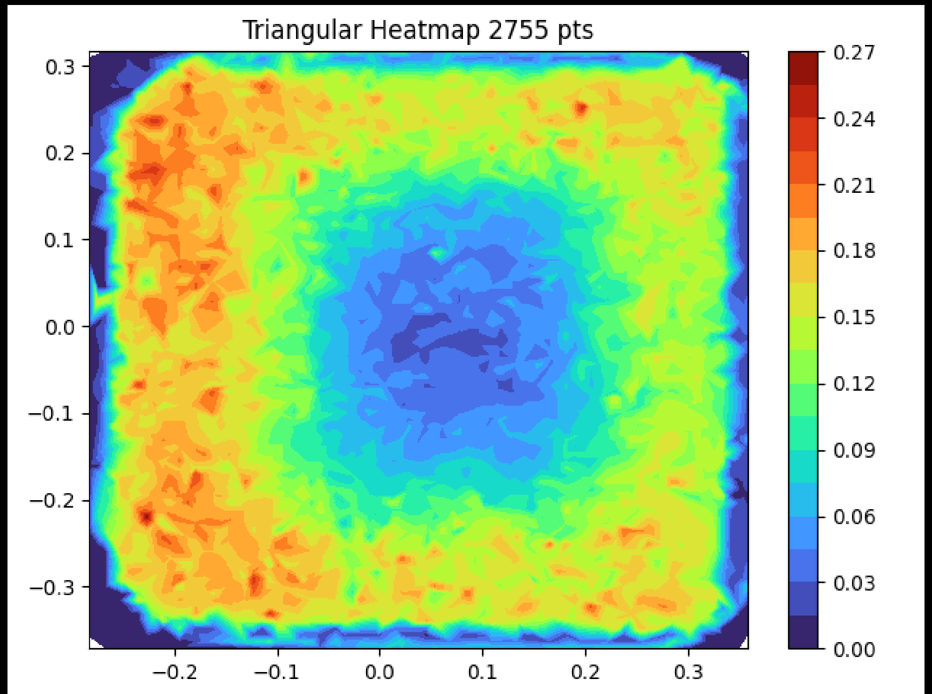
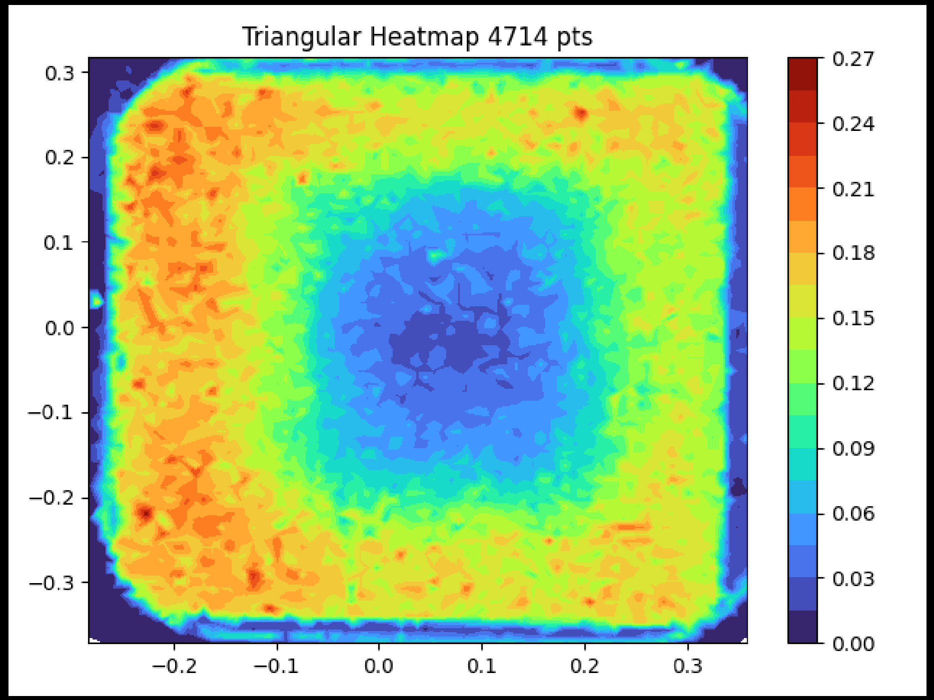






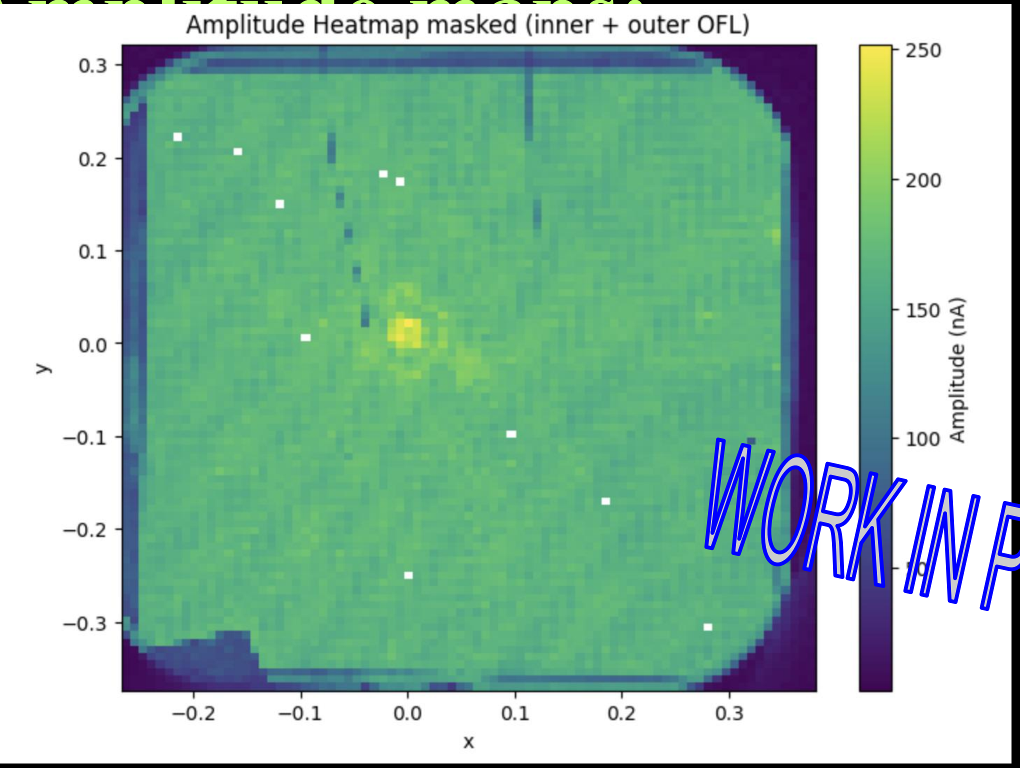




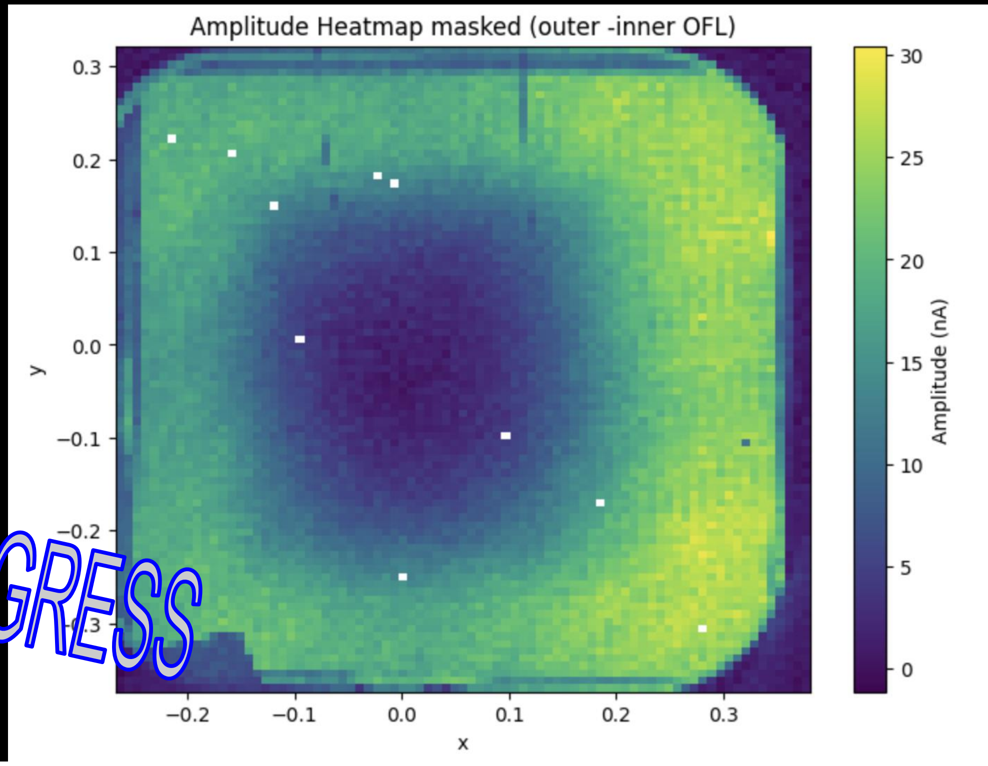
MEMS + HVeV Preliminary Analysis

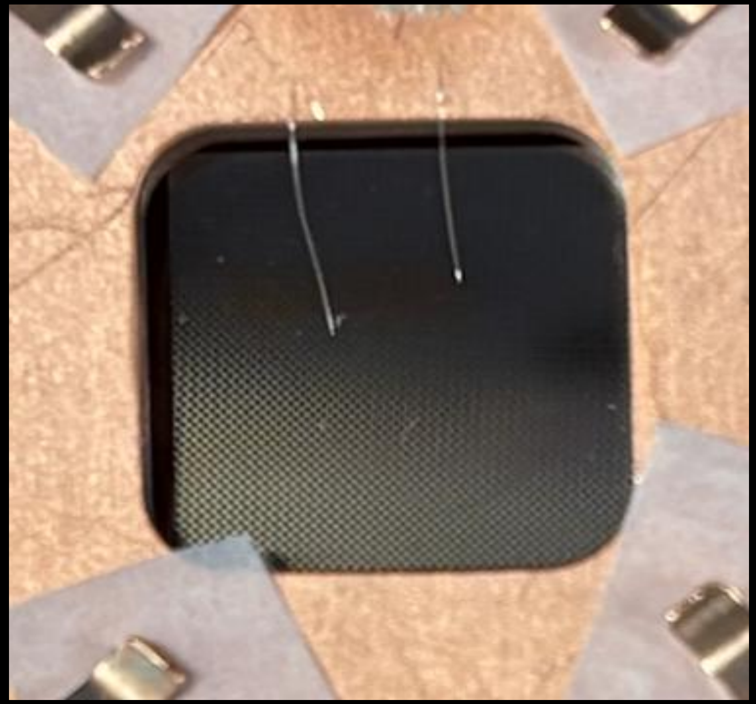
Pulse A

0V:

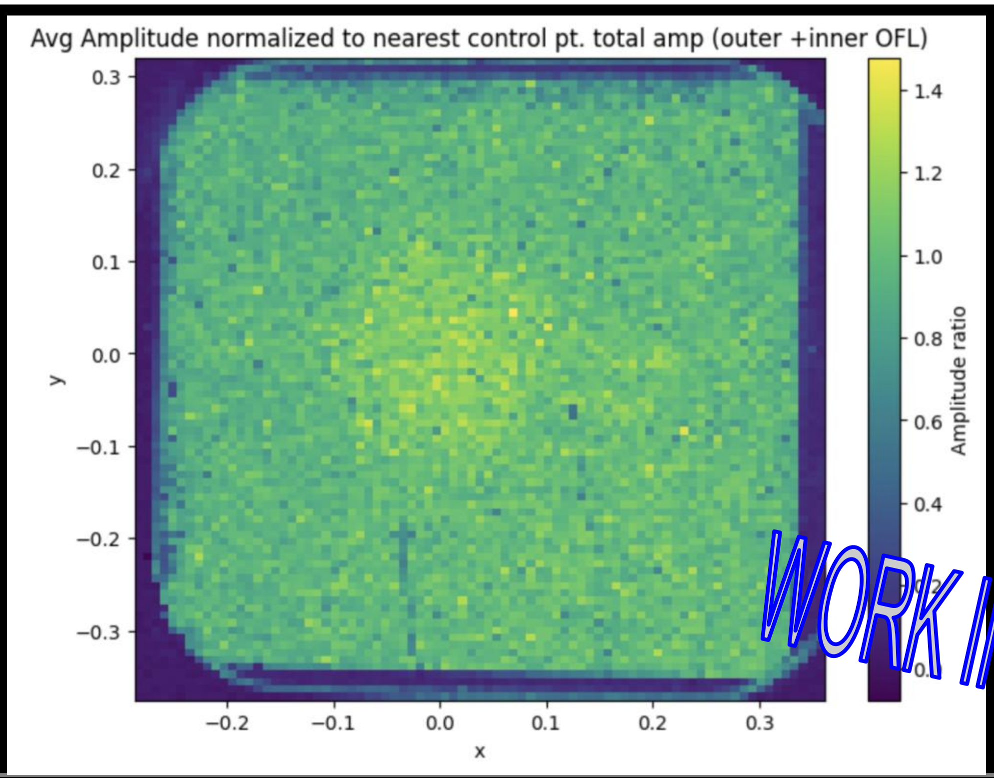


WORK IN PROGRESS





100V:



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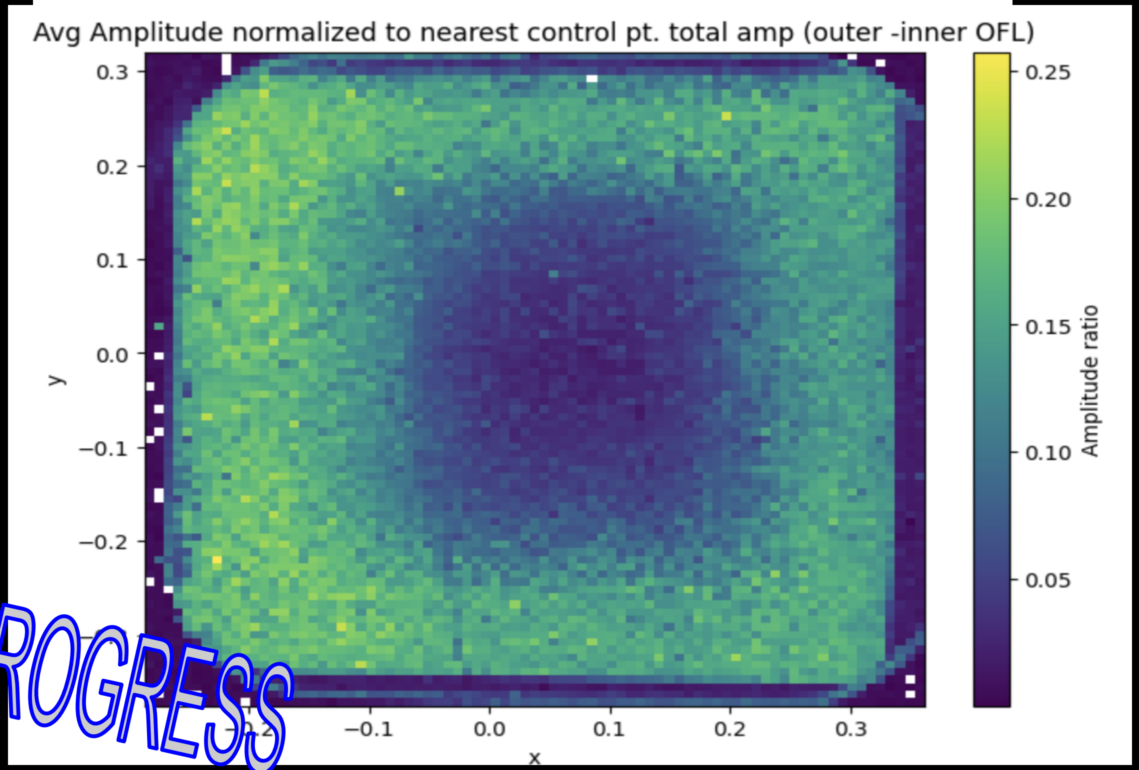
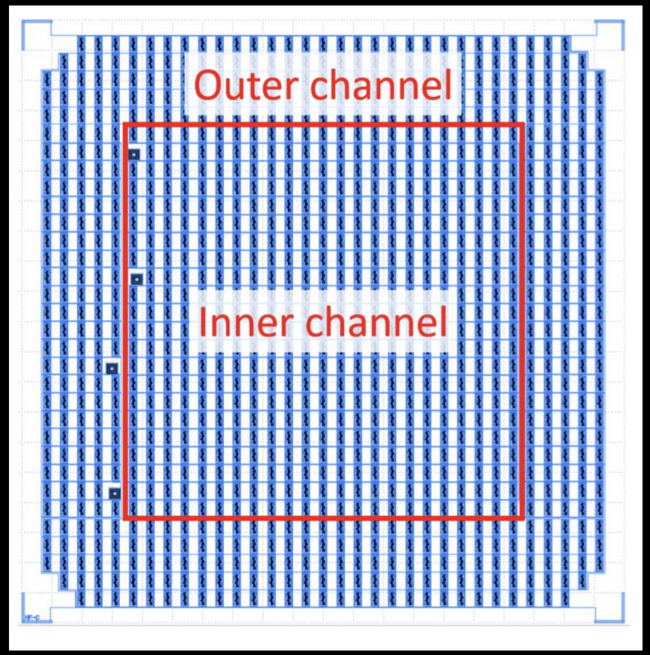
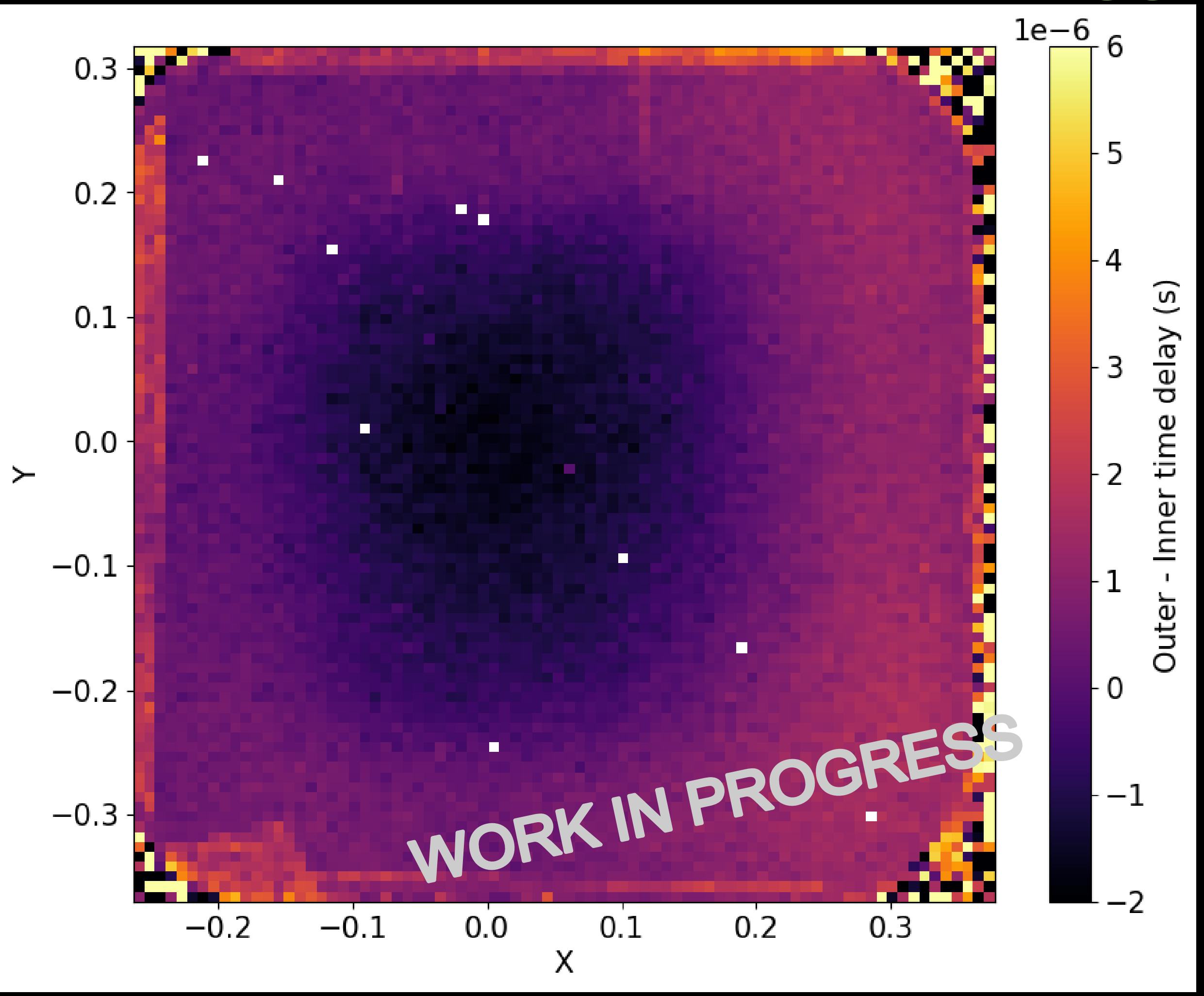




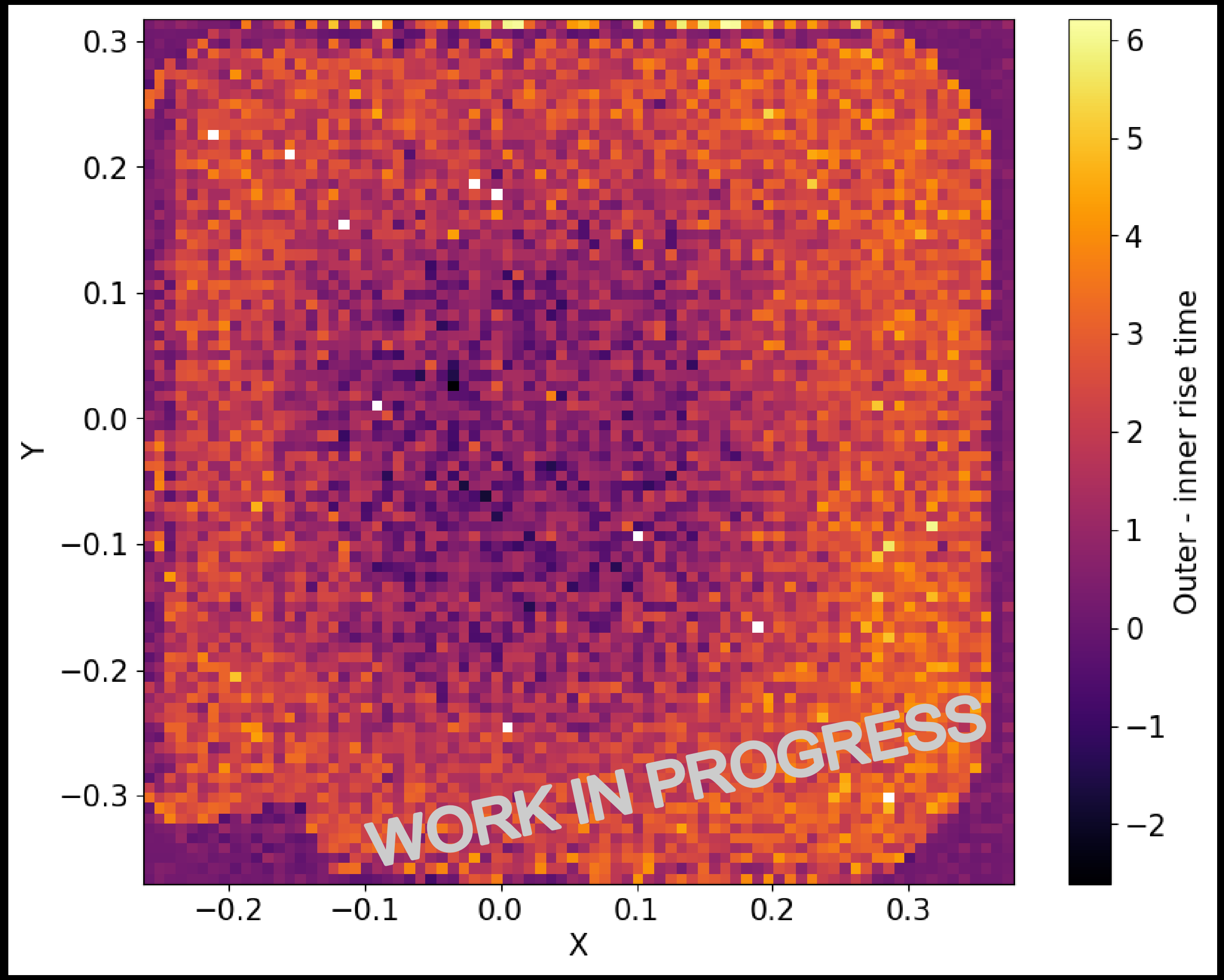
Credit: A. Pradeep

MEMS + HVeV Preliminary Analysis

Pulse arrival times w.r.t trigger



Pulse rise times



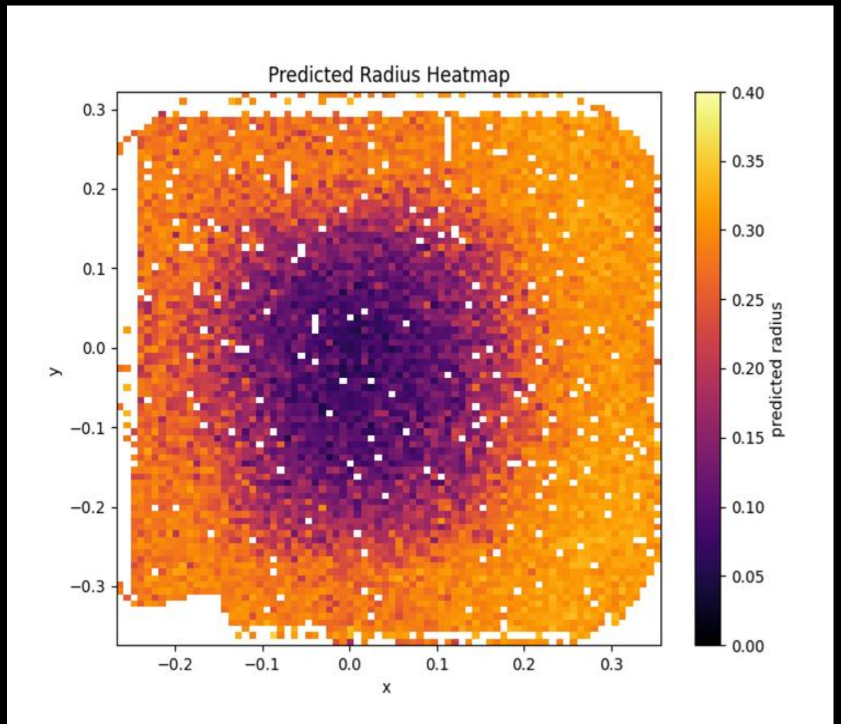
Pulse integral, phonon collection efficiencies, energy calibration…

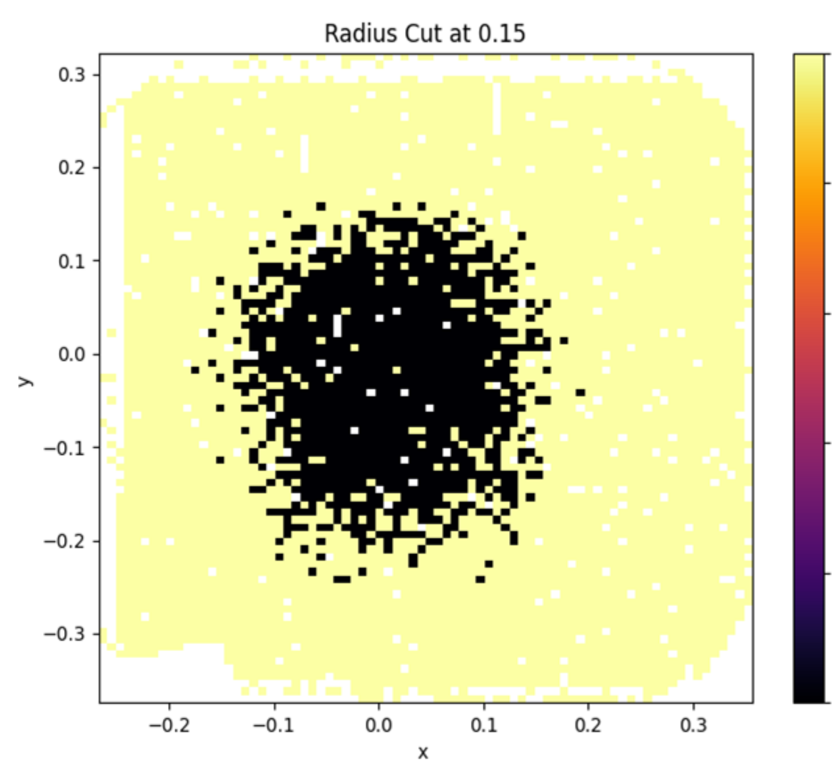
Position reconstruction

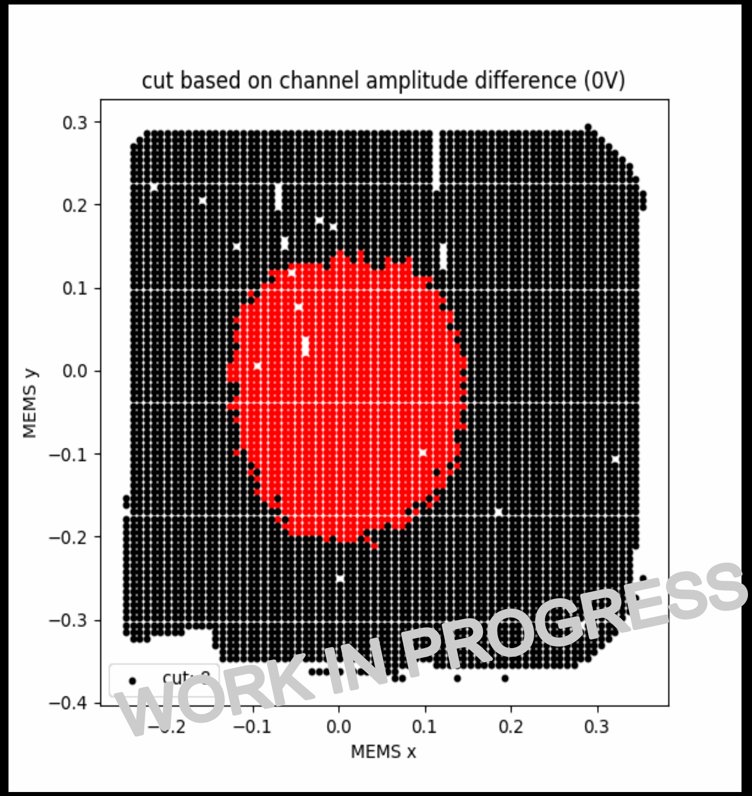
Amplitude difference between inner and outer channel provides a reasonably good sense of the distance of the source of the pulse from the center of the detector, allowing us to make cuts

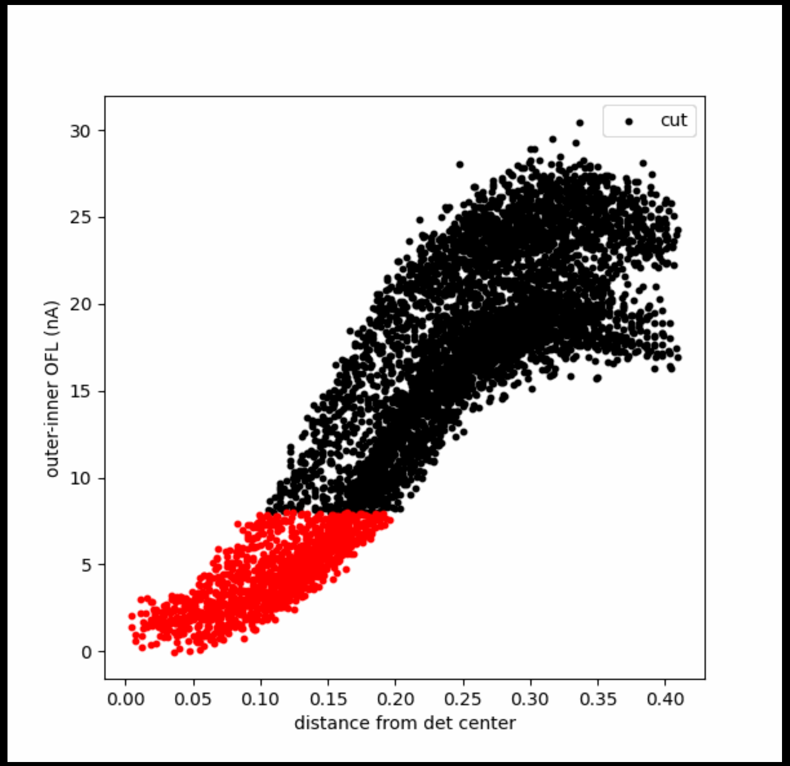
ML techniques provide slightly enhanced radius estimation

Results appear to be Random Rin agreement with G4CMP simulations









Hope Fu
DMQIS grad student

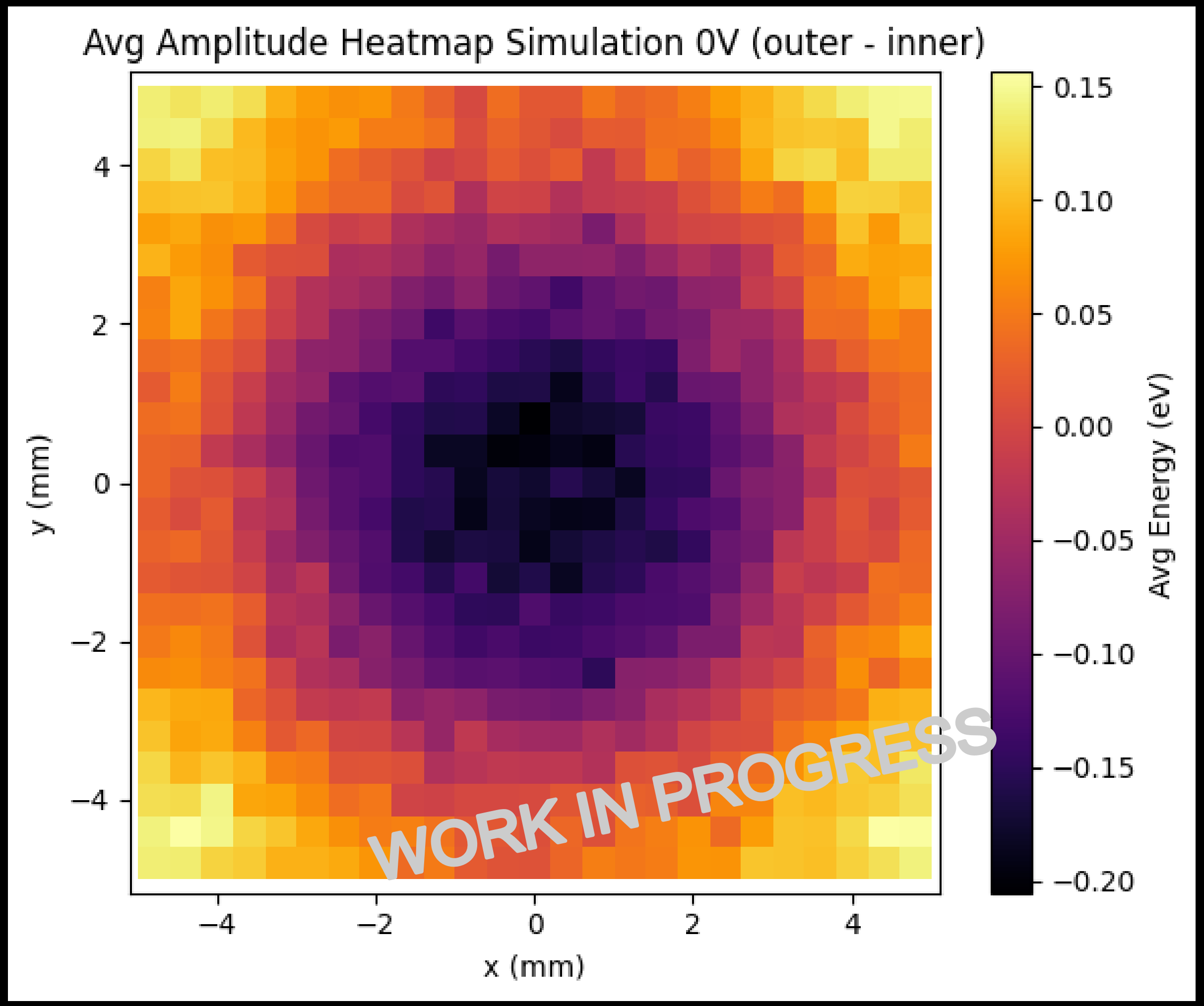
Qihua Wang
DMQIS grad student

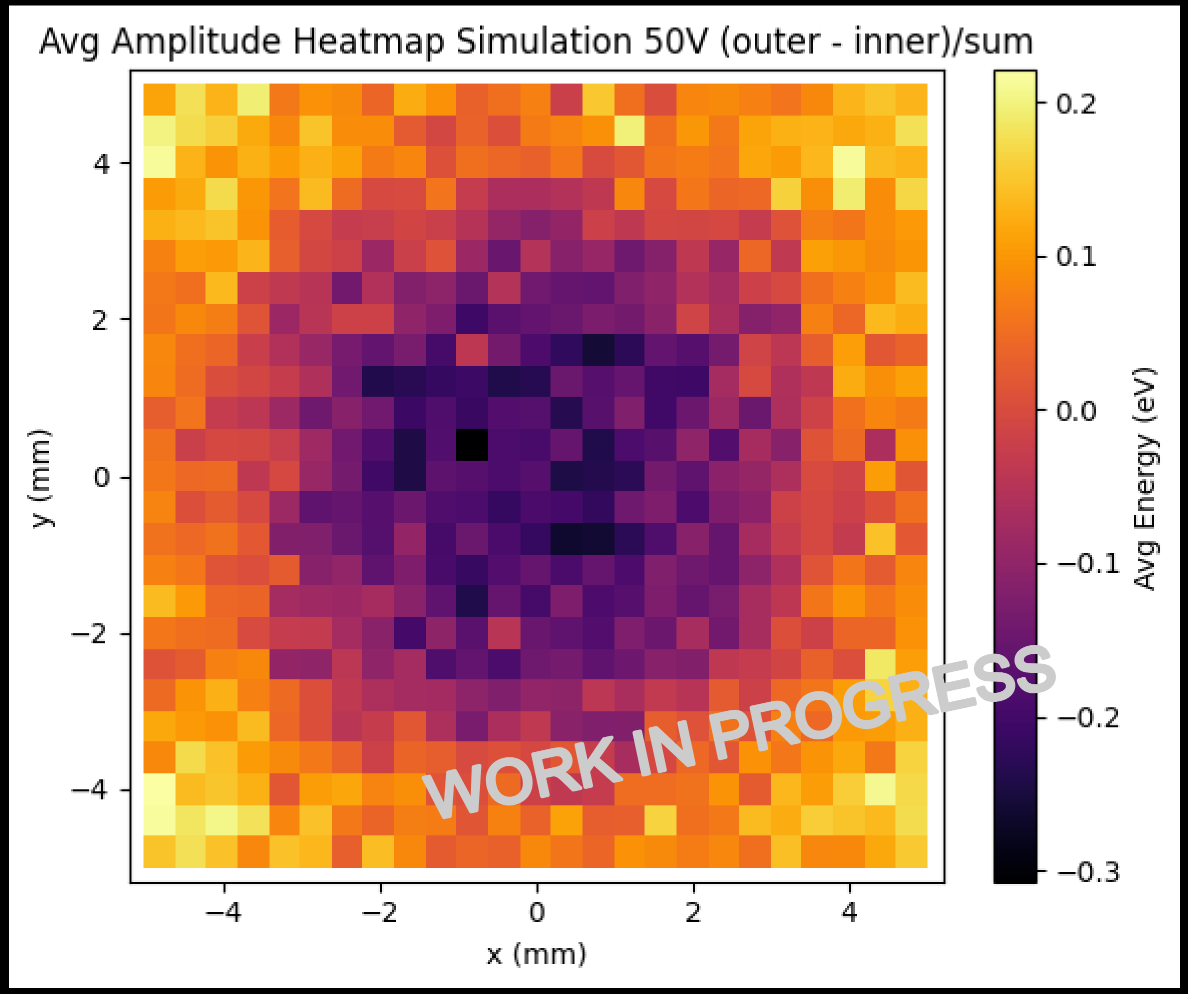
Credit: Q. Wang

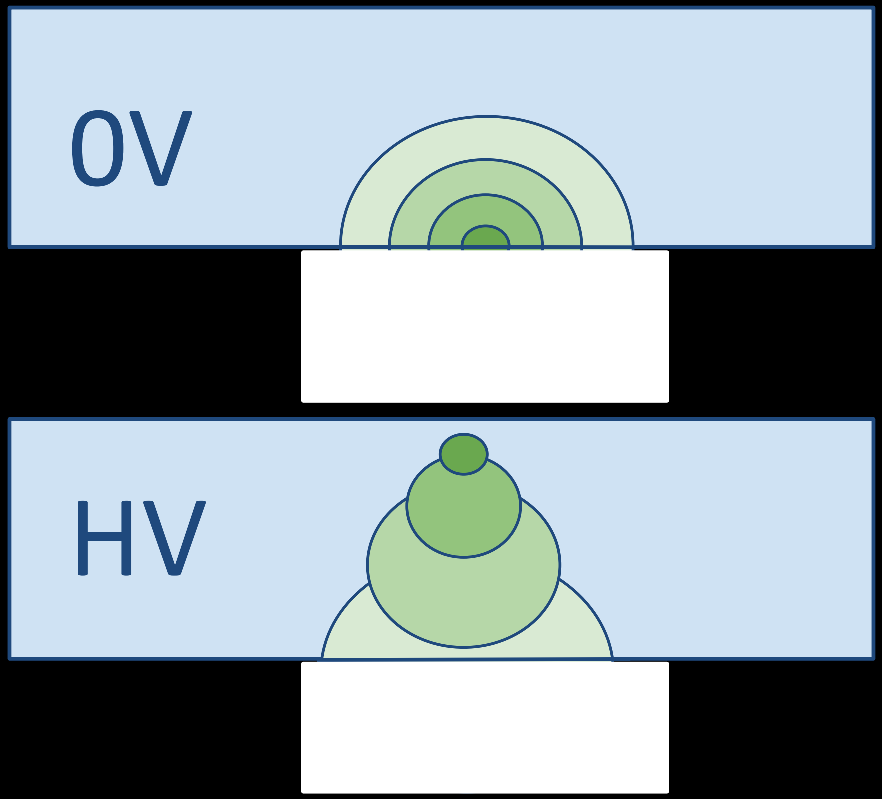
Credit: C. Stone-Whitehead

G4CMP Simulations

- Single 2.0 eV photon per event
- Lumped outer and inner channel geometry
- 4 x 10 x 10 mm Si crystal (1,0,0)
- R=1 (0.1% loss) at side walls, Pabs=1 at channels
- Phonon can reflect 1000 times before being killed

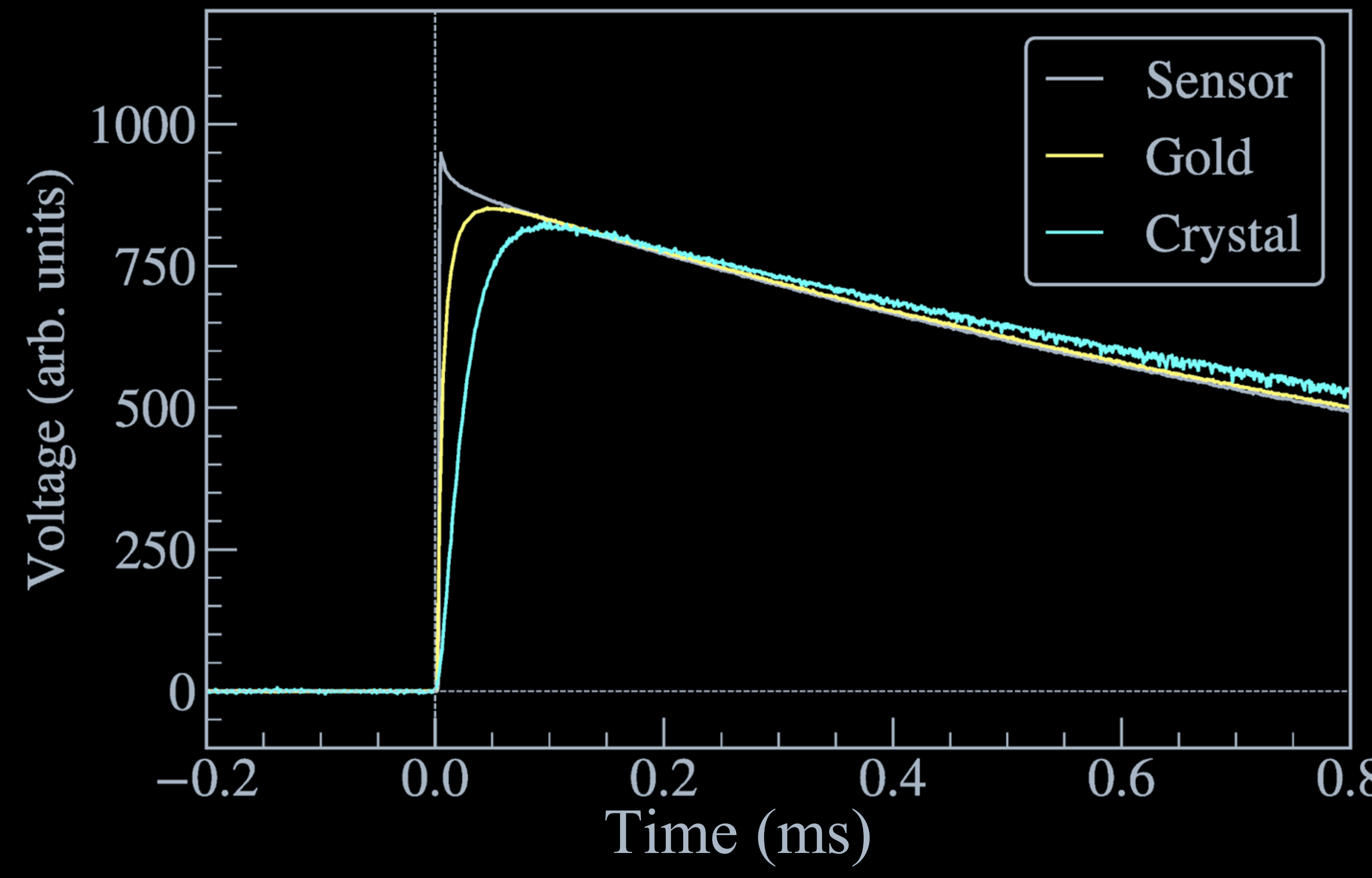






Carbon Based Substrates

- Light carbon nuclei provide better kinematic match for sub-GeV dark matter candidates
- Polar structure and different polytypes of SiC could enable directional searches *arxiv:1807.10291*
- High energy long-lived phonon modes shown in diamond promise excellent phonon collection efficiency and increased sensitivity
- High band gap allows for higher voltage bias with minimal leakage current

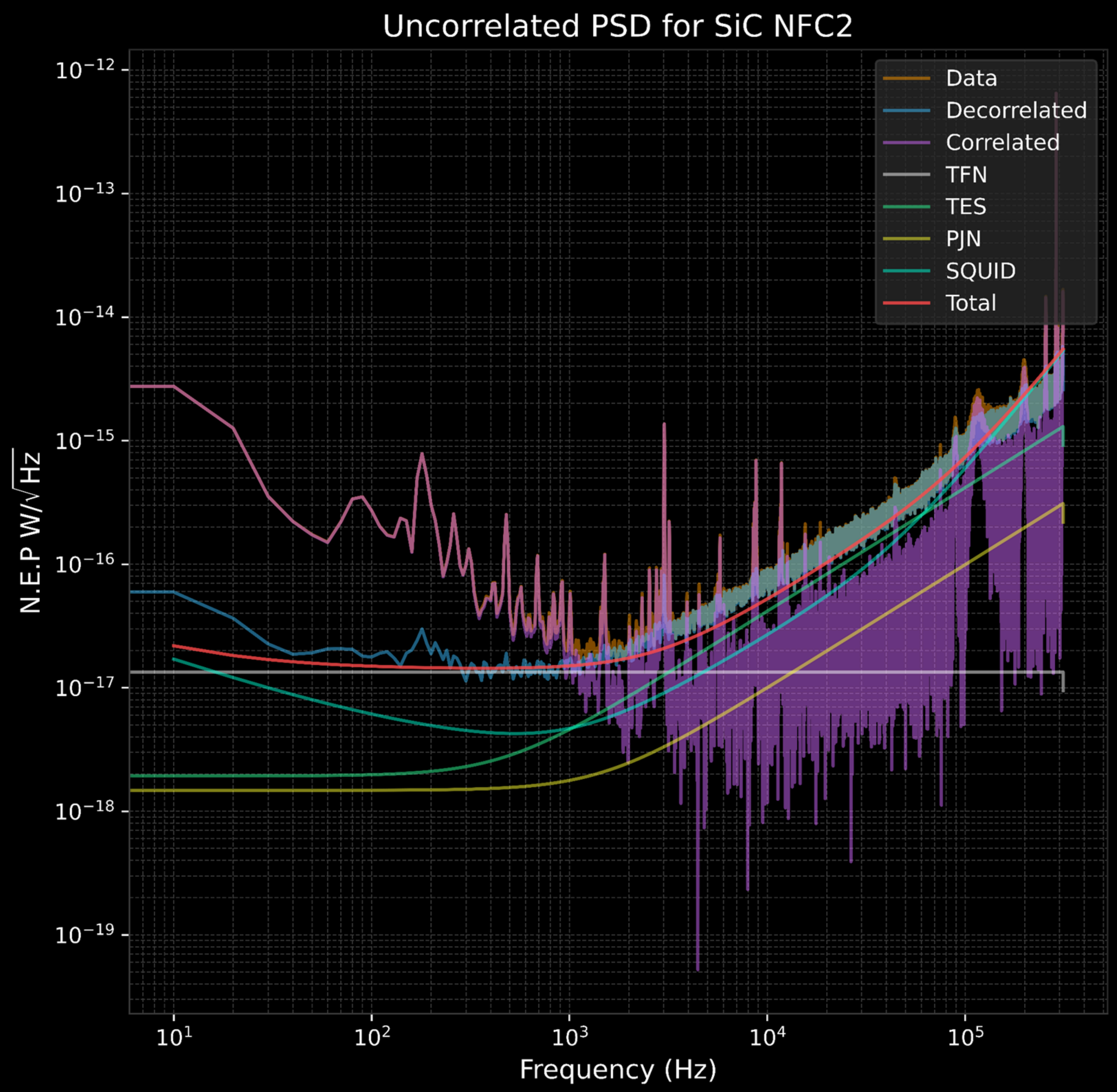


	pCVD	sCVD	Sapphire
Dimension (mm^3)	$10 \times 10 \times 0.5$	$5 \times 5 \times 0.3$	$5 \times 5 \times 0.5$
$\mathcal{E}_{athermal}$ (%)	99.8±2.3	39.3±2.7	73.1±2.7
$\mathcal{E}_{height}$ (%)	95.4±0.5	45.6±3.2	76.2±1.7
$\mathcal{E}_{area}$ (%)	99.6±0.6	45.6±4.8	83.8±2.2

arxiv:2409.19238

TES Performance

- Decorrelated noise fits well to ideal TES, and indicates ~5eV resolution assuming 30% phonon collection efficiency

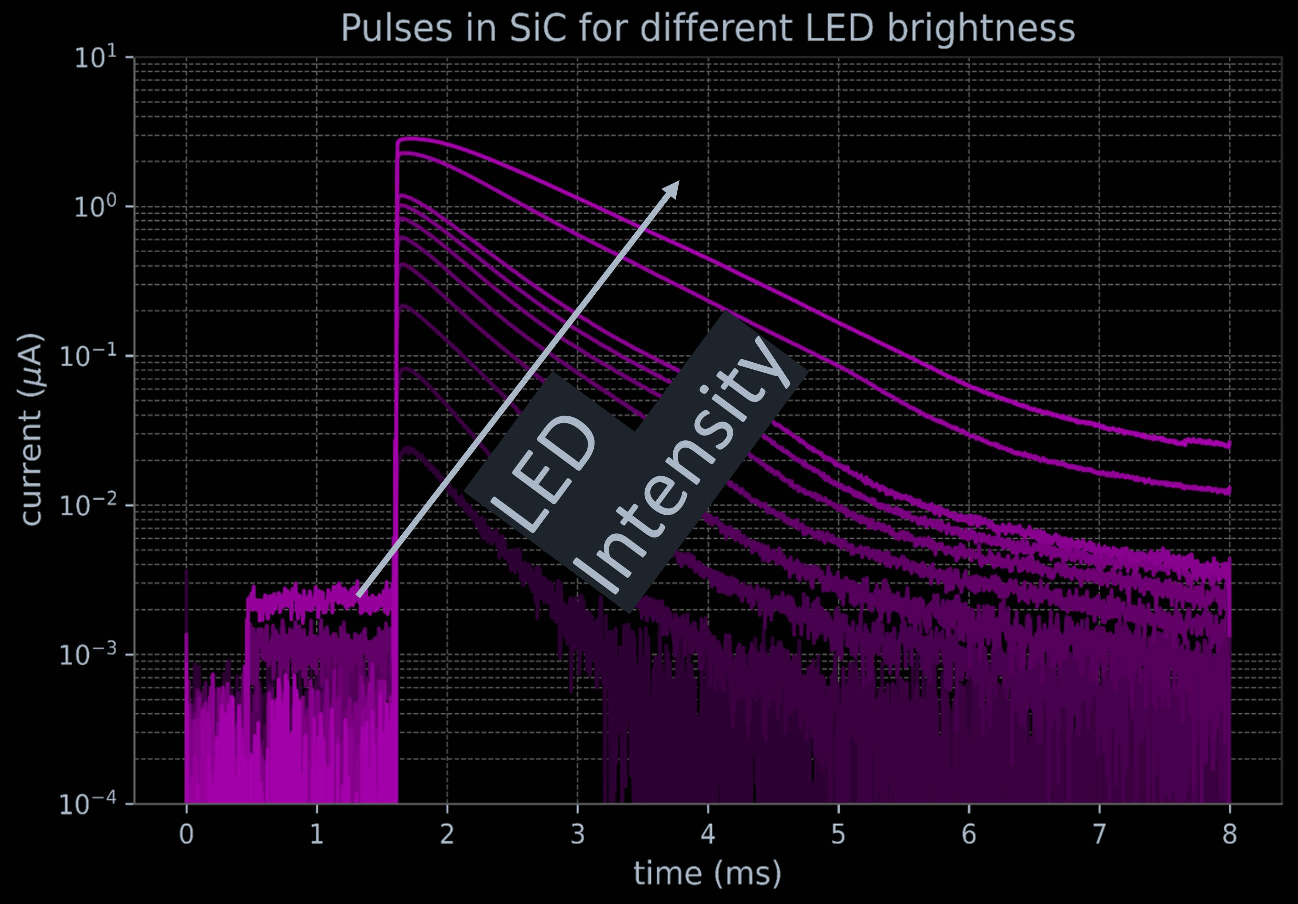


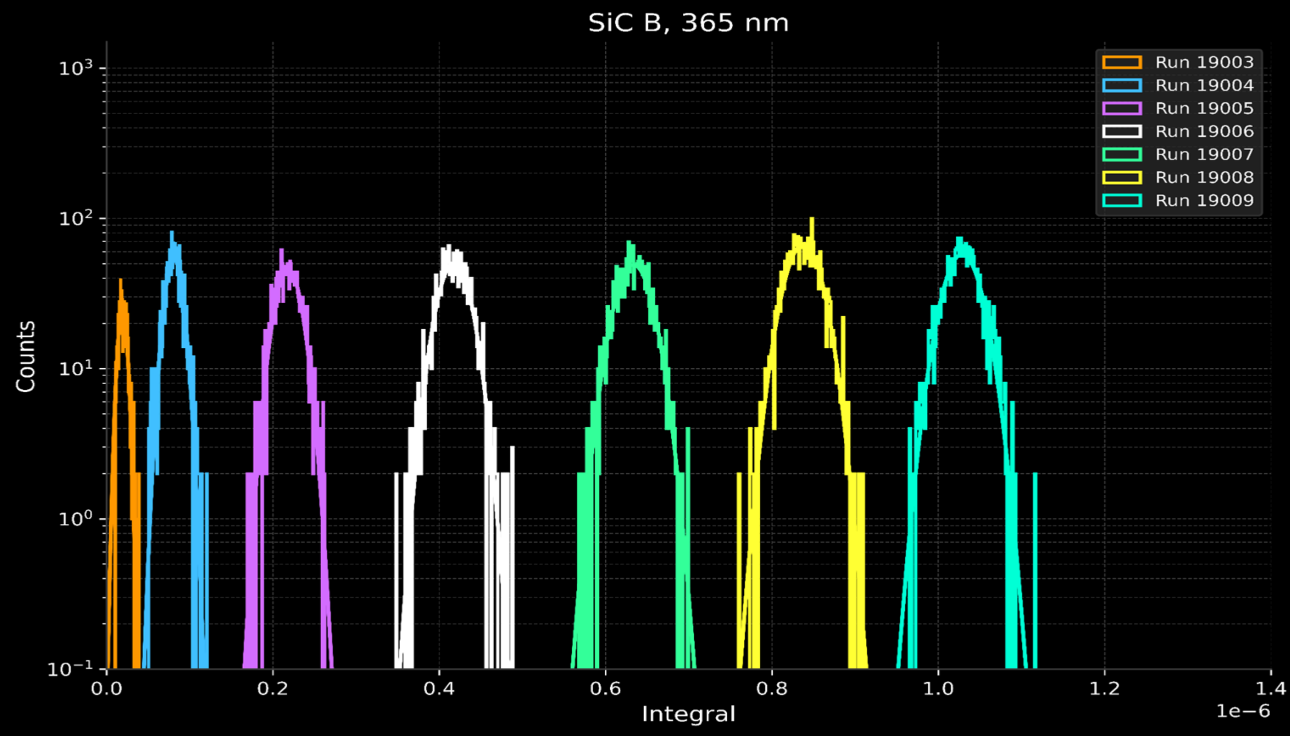
Shot Noise Calibration

- LED was pulsed at different intensities and wavelength
- Pulse's amplitude estimated with offline optimal filter
- Energy resolution is calculated by fitting the variance of resulting peaks -

$$\sigma_A^2 = a * (1 - \exp(\frac{-\mu_A}{b})) + c - (1)$$

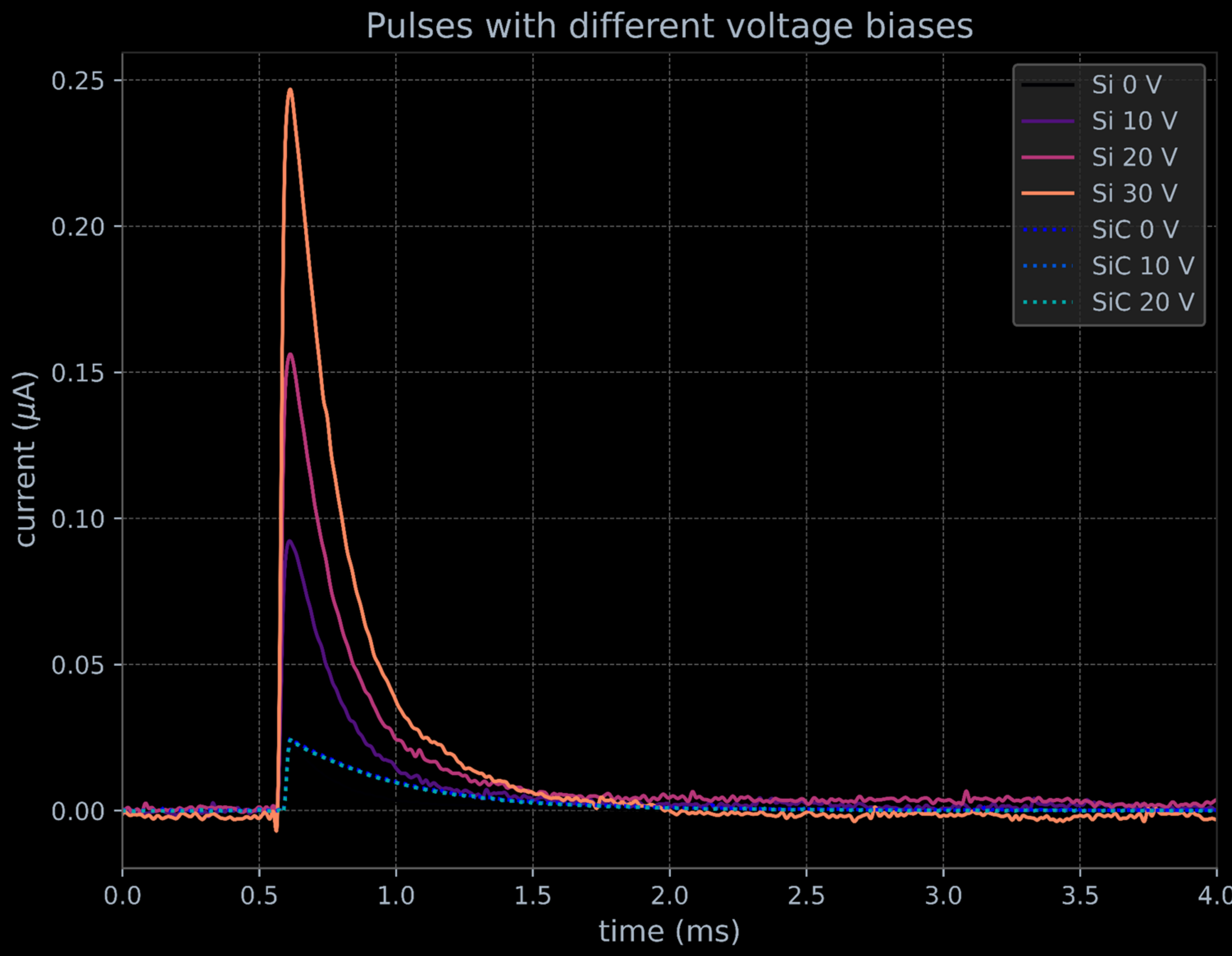
$$\sigma_A^2 \sim a\frac{\mu_A}{b} + c - (2)$$





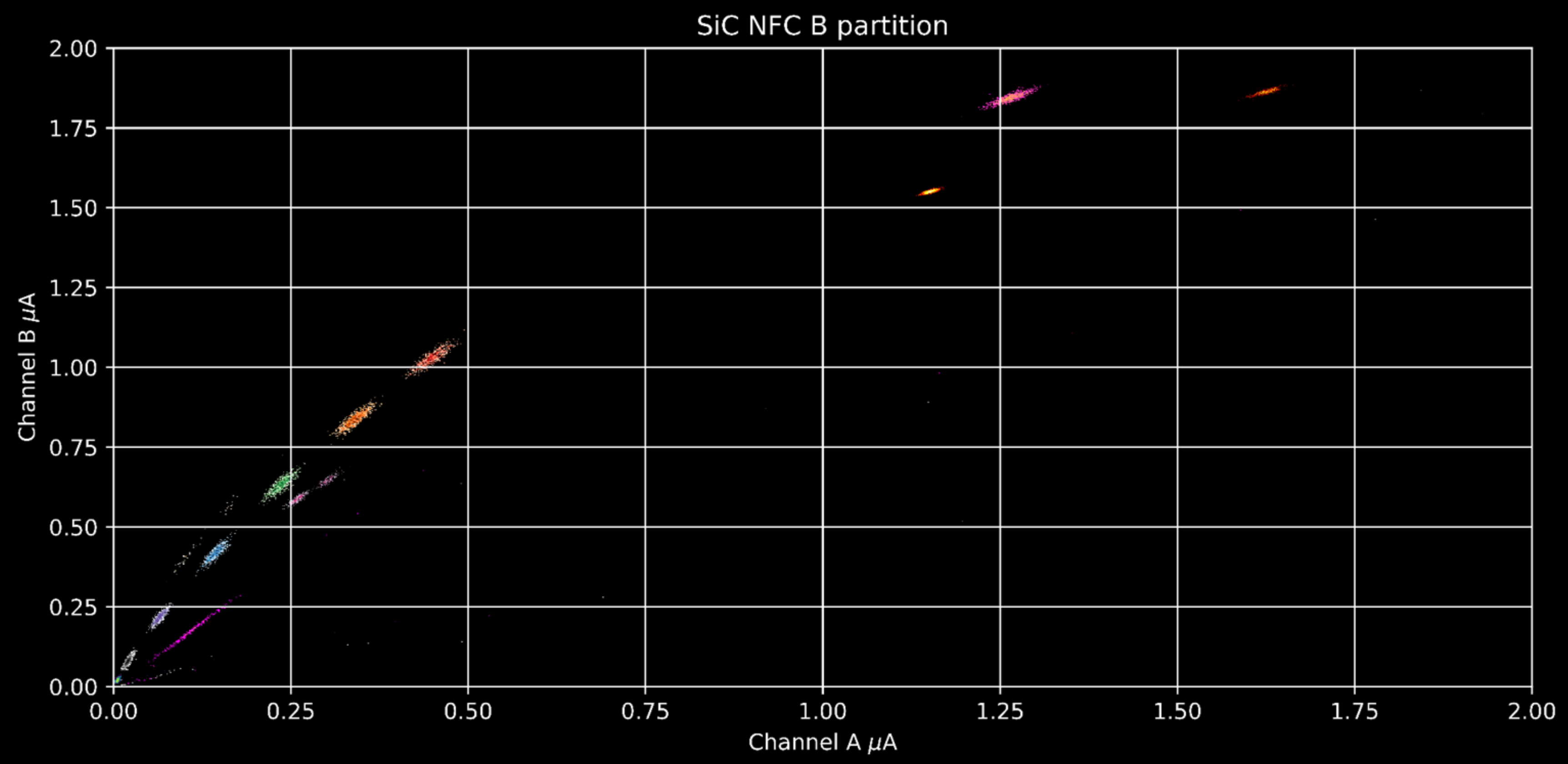
NTL effect (or lack thereof)

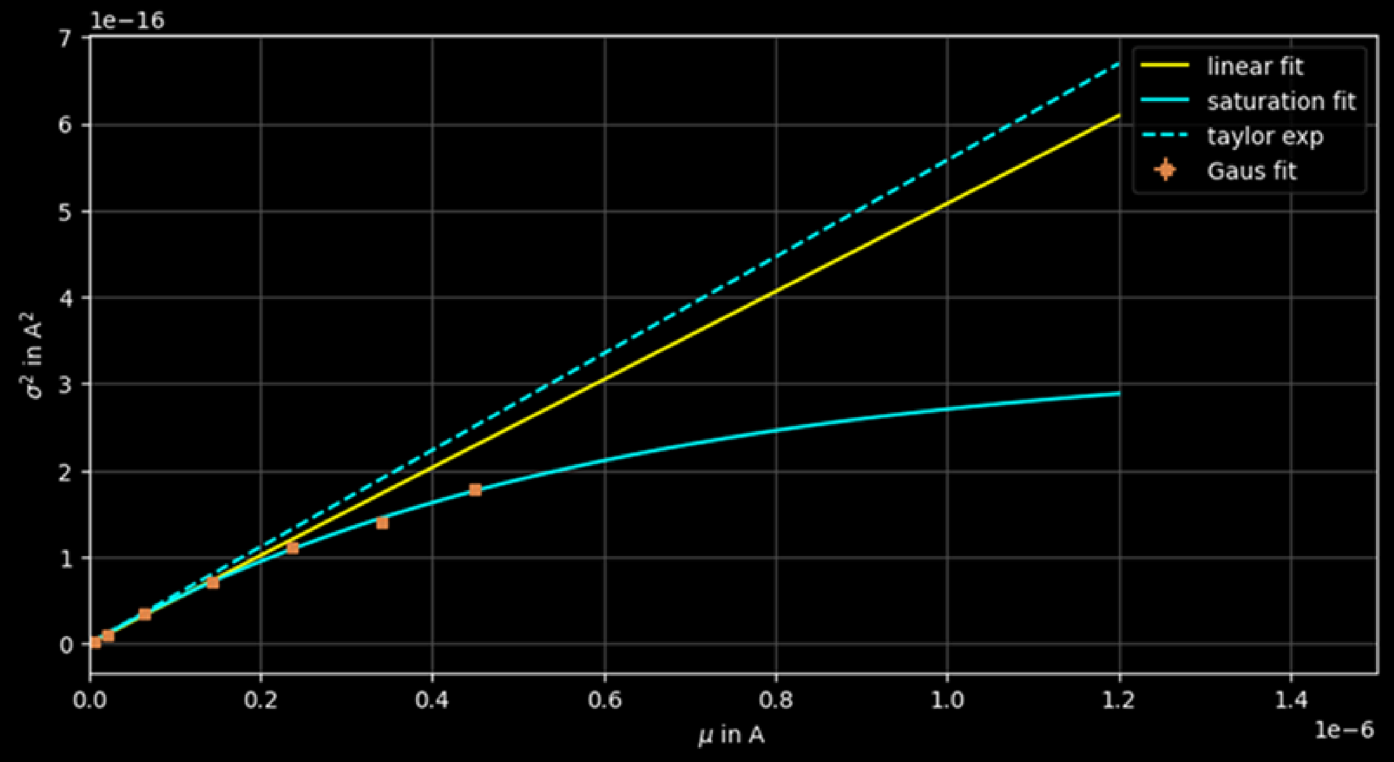
- In most measurements, SiC detectors don't seem to show NTL effect
- Substrate polarization and surface defects could explain poor charge mobility
- Si detectors on same system show expected amplification of charge events
- Higher grade SiC and RIE pre-cleaning showed no improvement



Shot Noise Calibration - results

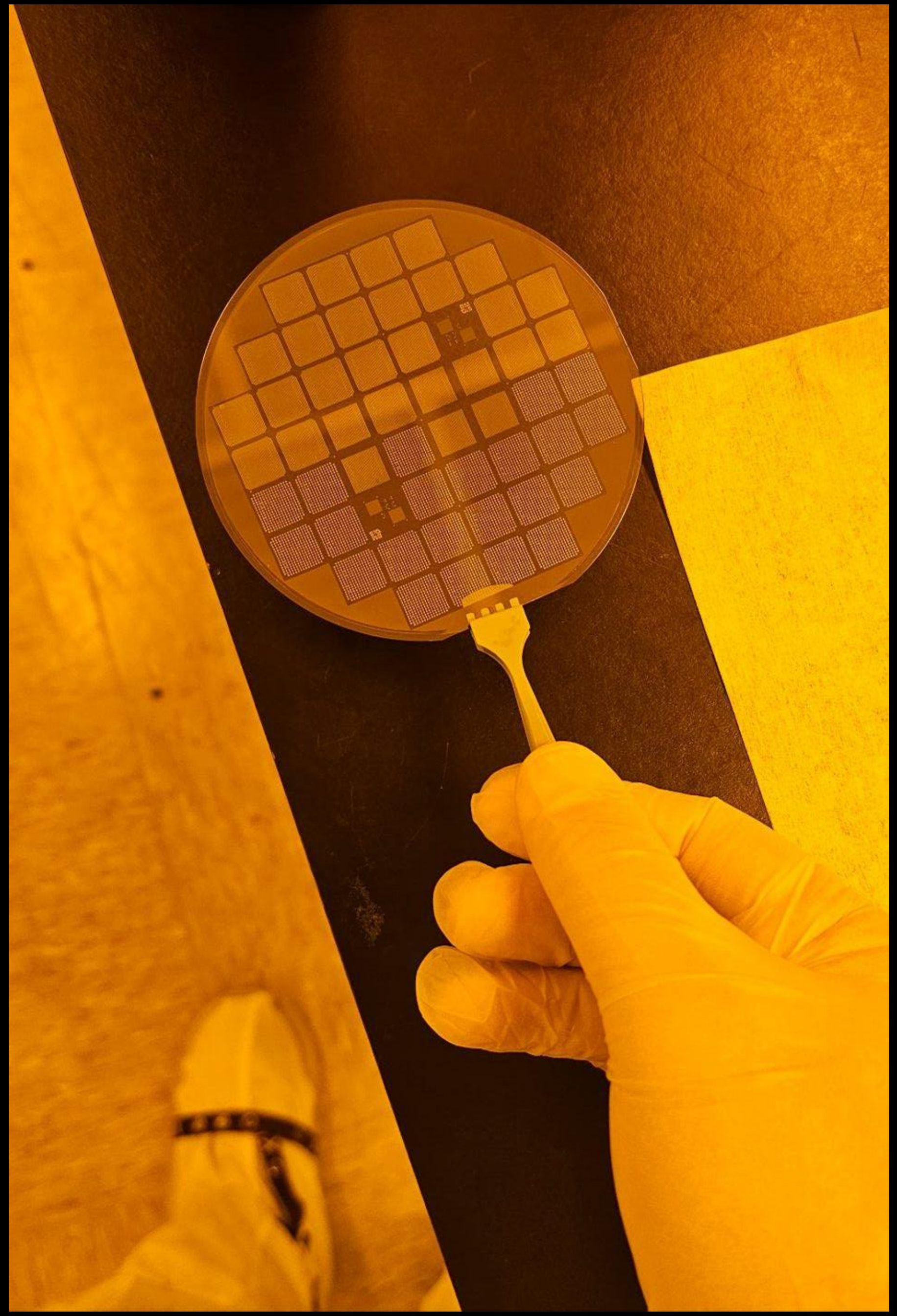
- Net detector resolution measured at 5.1eV
- Phonon collection efficiency is ~30%





Next steps

- Fabrication of lower Tc SiC detectors could enable a competitive dark matter search
- Diamonds have been acquired and r&d has begun on chip scale fabrication on them
- Higher channel count detectors for better position reconstruction and potential LEE probing, 2cm 4 channel detectors already fabricated and calibrated, expect MEMs results soon
- Careful Analysis of MEMs results could illuminate phonon loss channels



Thank You!

DMQiS

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SUPER CDMS

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Measurement Setup

- Detectors are mounted in light-tight enclosures and stacked in a tower mounted on a vibration-isolation stage
- The tower is placed in a light-tight cryoperm shield, providing magnetic shielding and additional EM radiation shielding
- External LED attached to fiber feedthrough shines on back of detectors
- Current through TES is read out with SQUID amplifiers