Progress Towards Sub-eV Thresholds with SuperCDMS Detectors

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CPAD, University of Wisconsin

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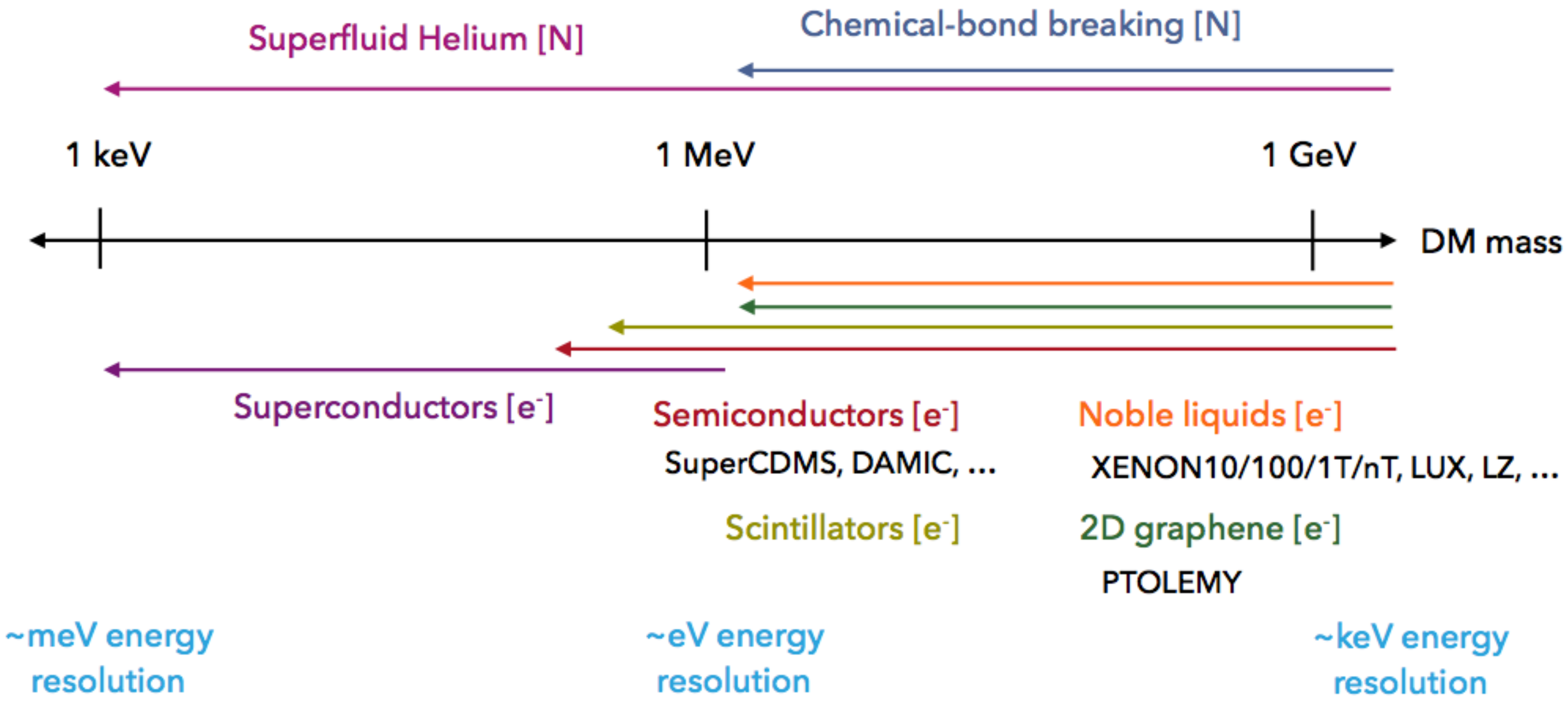
Broad Picture: Detection Media for Lower Mass

US Cosmic Visions, arXiv:1707.04591



Superfluid Helium [N]

Chemical-bond breaking [N]

1 keV

1 MeV

1 GeV

DM mass

Superconductors [e$^-$]

Semiconductors [e$^-$]

SuperCDMS, DAMIC, …

Noble liquids [e$^-$]

XENON10/100/1T/nT, LUX, LZ, …

Scintillators [e$^-$]

2D graphene [e$^-$]

PTOLEMY

~meV energy resolution

~eV energy resolution

~keV energy resolution

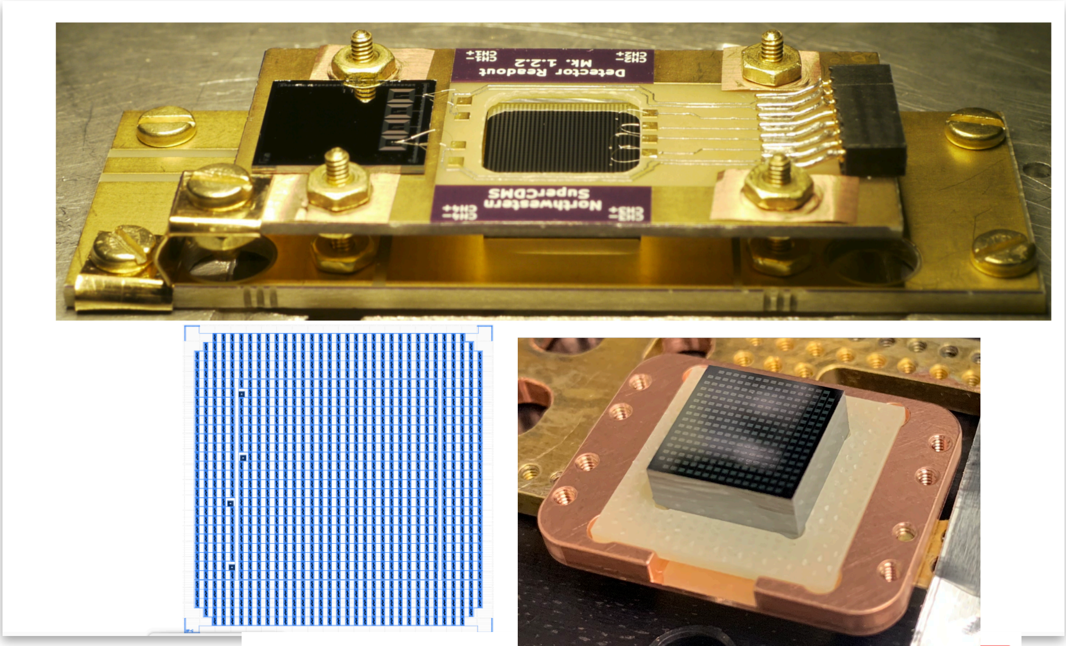
- Looking at current/future technologies, we have a mix of materials with small but non-zero bandgaps, to limit dark counts and maximize energy to carrier conversion

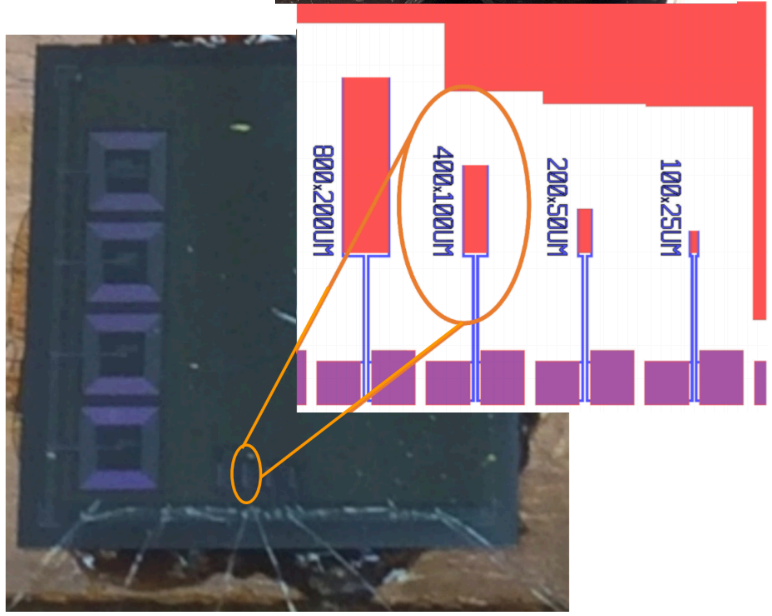
- Extent of these arrows driven by fundamental limitations from kinematics and material properties, and assumes large current hurdles can be overcome in energy and charge noise across all experiments

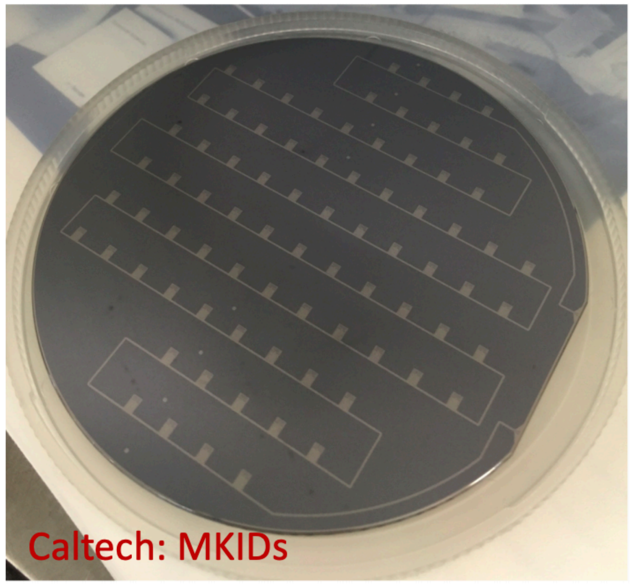
- Recent (June 2019) workshop exploring much more than cosmic visions: https://astro.fnal.gov/ldm/

Detector R&D Groups

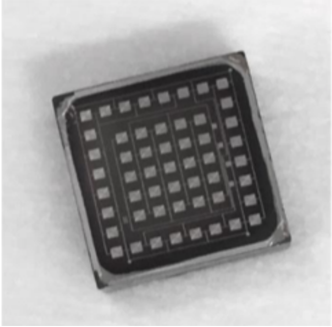
- HVeV (1g Detector Chips)
  - **Caltech**: Sunil Golwala, Yen-Yung Chang, Taylor Aralis, Osmond Wen
  - **Fermilab**: Noah Kurinsky, Dan Bauer
  - **Northwestern**: Enectali Figueroa-Feliciano, Ziqing Hong, Tom Ren, Ran Chen
  - **Stanford/SLAC**: Blas Cabrera, Betty Young, Francisco Ponce, Chris Stanford, To Chin Yu
  - **University of Minnesota**: Matt Fritts, Nick Mast
  - **University of Florida**: Tarek Saab, Corey Bathurst, Tyler Reynolds
- Large Area Photon Detectors
  - **UC Berkeley**: J. Camilleri, C. Fink, Y. Kolomensky, M. Pyle, B. Sadoulet, B. Serfass, S. Watkins
  - **Texas A&M**: Nader Mirabolfathi, Rupak Mahapatra, Fedja Kadribasic
- QET Fabrication R&D
  - Mark Platt (TAMU), Paul Brink (SLAC)






Caltech: MKIDs

SuperCDMS Athermal Phonon Sensors

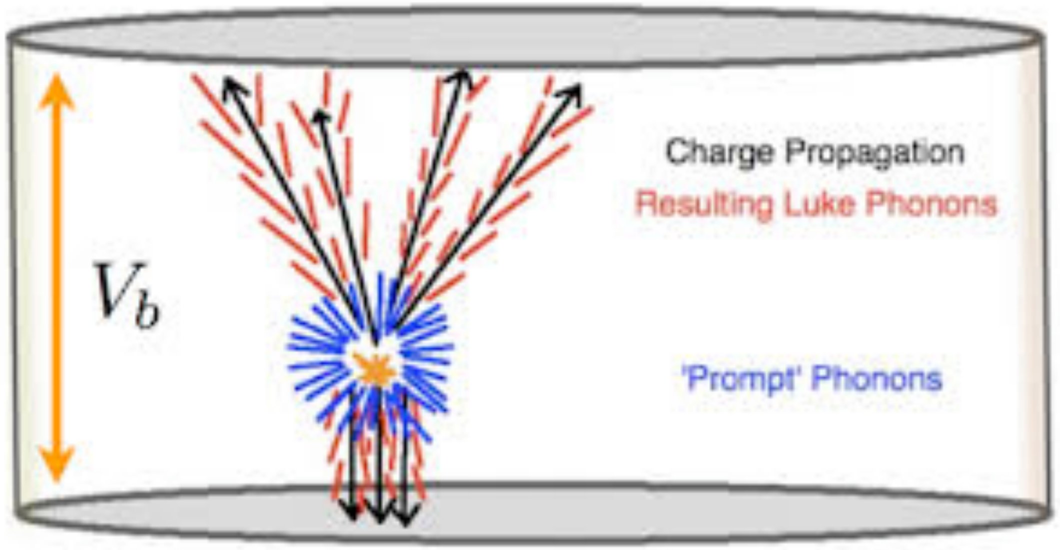


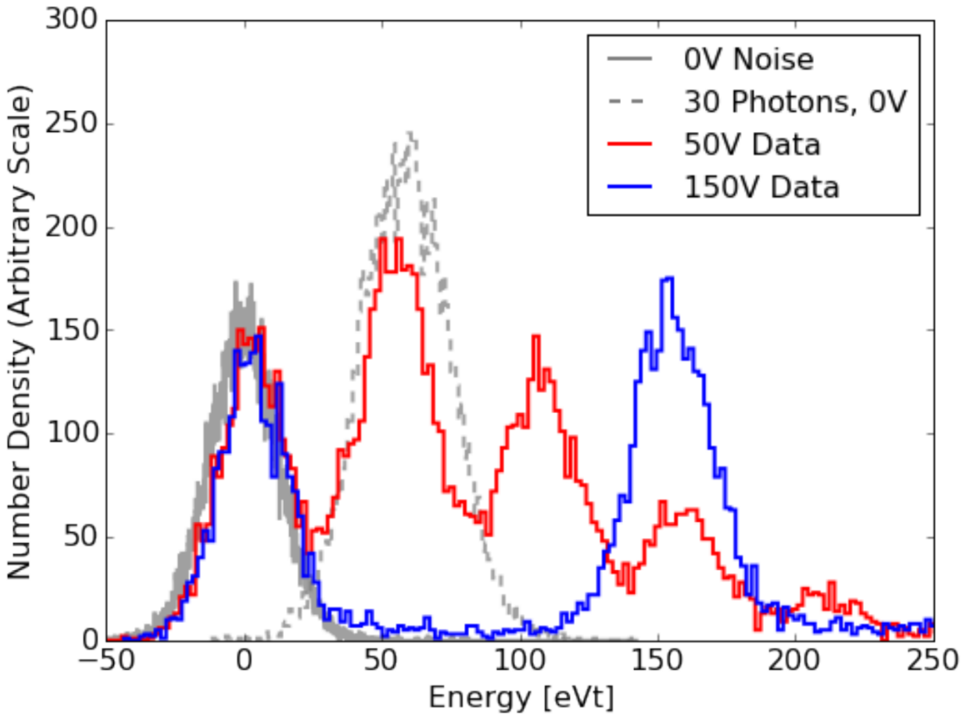
- In any recoil event, all energy eventually returns to the phonon system
  - Prompt phonons produced by interaction with nuclei
  - Indirect-gap phonons produced by charge carriers reaching band minima
  - Recombination phonons produced when charge carriers drop back below the band-gap
- Phonons are also produced when charges are drifted in an electric field; makes sense by energy conservation alone
- Total phonon energy is initial recoil energy plus Luke phonon energy, as shown at right

$$E_{phonon} = E_{recoil} + V * n_{eh}$$

$$= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]$$

- Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity

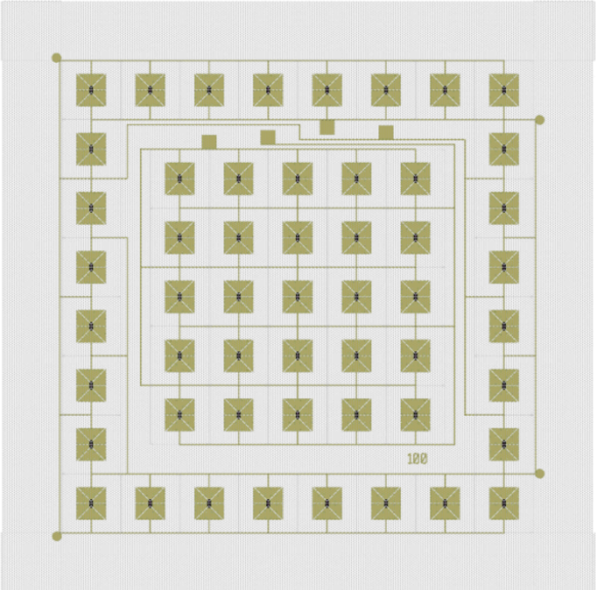




Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

R&D ‘HVeV’ Prototype Progress

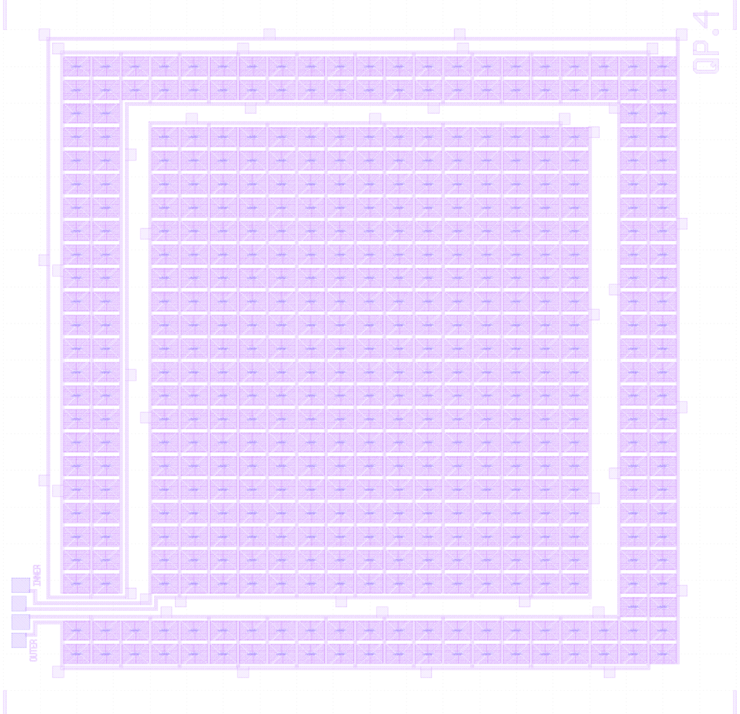
HVeV v1



Device: https://arxiv.org/abs/1710.09335
DM: https://arxiv.org/abs/1804.10697

- 10 eV Resolution
  - 0.07 electron-hole pairs (140V)
- 3-5% energy efficiency
- 1 gram mass
- No position resolution
- ~1.2 Ohm Resistance
- ~55 mK Tc
- Amorphous Layer

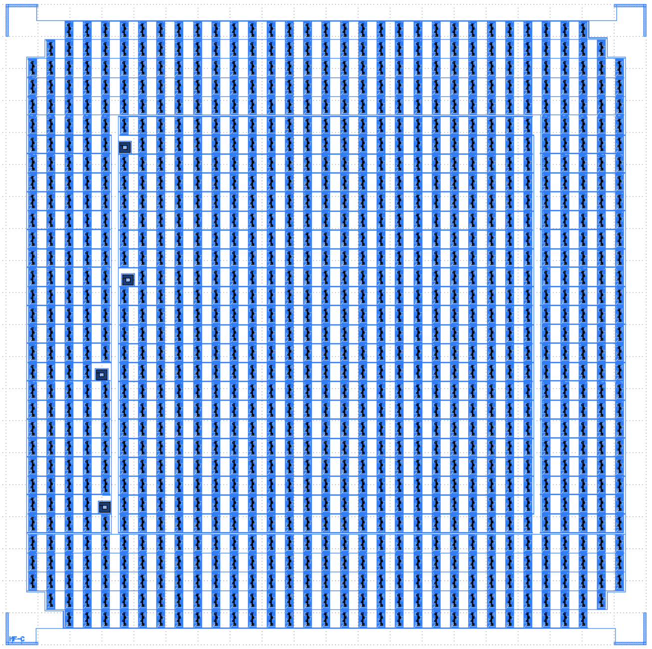
HVeV v1.5



Device: https://arxiv.org/abs/1903.06517

- 3 eV Resolution
  - 0.06 electron-hole pairs (50V)
- 25% energy efficiency
- 0.25 gram mass, contact-free design
- High position resolution
- ~400-900 mOhm Resistance
- 65 mK Tc
- No Amorphous Layer

HVeV v2 (NF-C)



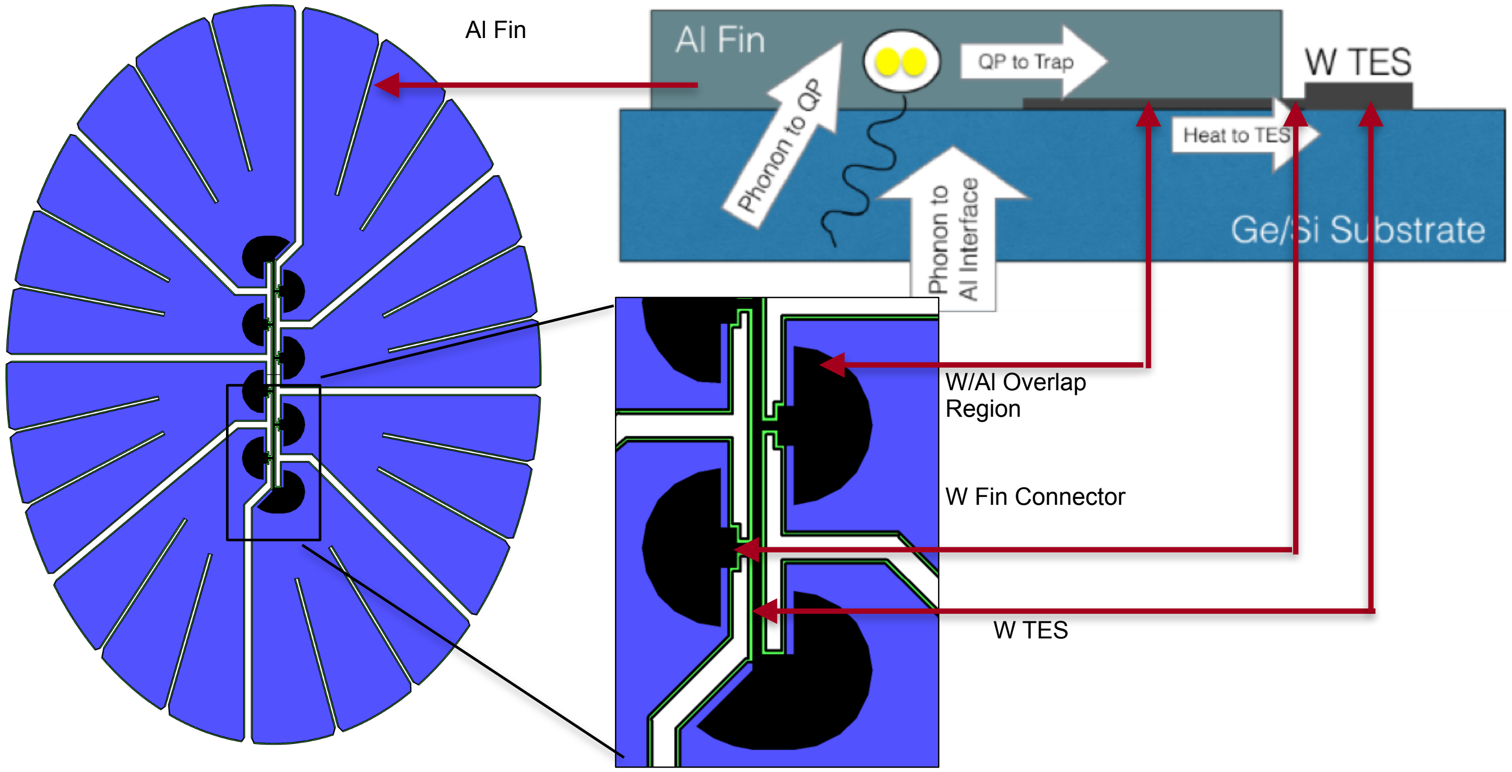
In Prep (TUNL, DM)

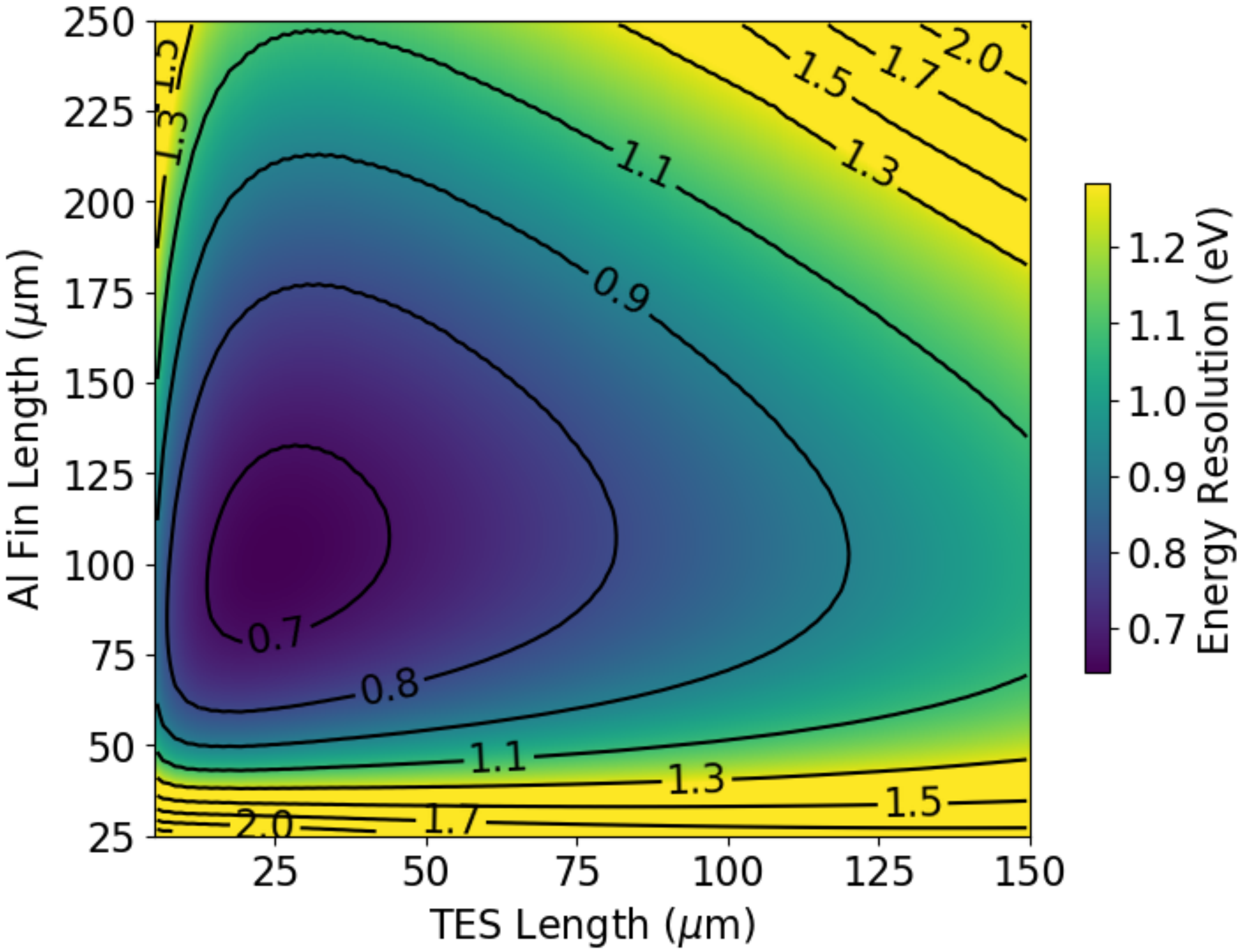
- 3 eV Resolution
  - <0.01 electron-hole pairs (100V)
- 25% energy efficiency
- 1 gram mass, backside contact
- High position resolution
- ~300 mOhm Resistance
- 65 mK Tc
- No Amorphous Layer

QET Optimization

- Longer, thicker Al films have longer QP diffusion lengths
  - Need to make slits or holes to prevent flux traps
- Larger TES overlaps have better energy efficiency
  - Contribute to TES noise budget!
- Shorter TES means lower TES volume, lower resolution
  - Long or low Tc TES at risk for phase separation
  - Bias rails dominate signal losses for very small TES volumes

$$\sigma_e \geq \frac{\sqrt{4k_bT_c^2C}}{\sqrt{5\epsilon}} \approx \frac{1}{\epsilon}\sqrt{\frac{2k_b\gamma T_c^3 V_{\mathrm{TES}}}{(\mathcal{L}-1)}}$$





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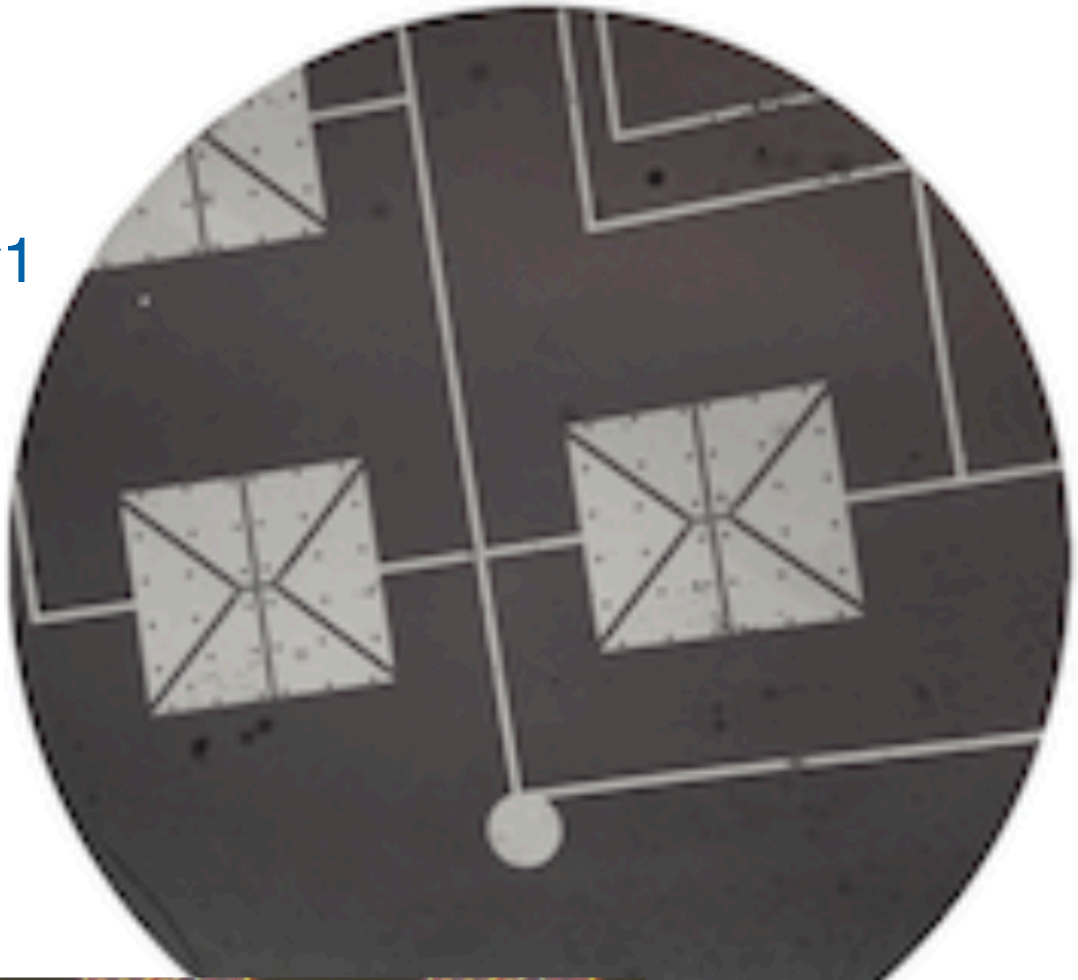
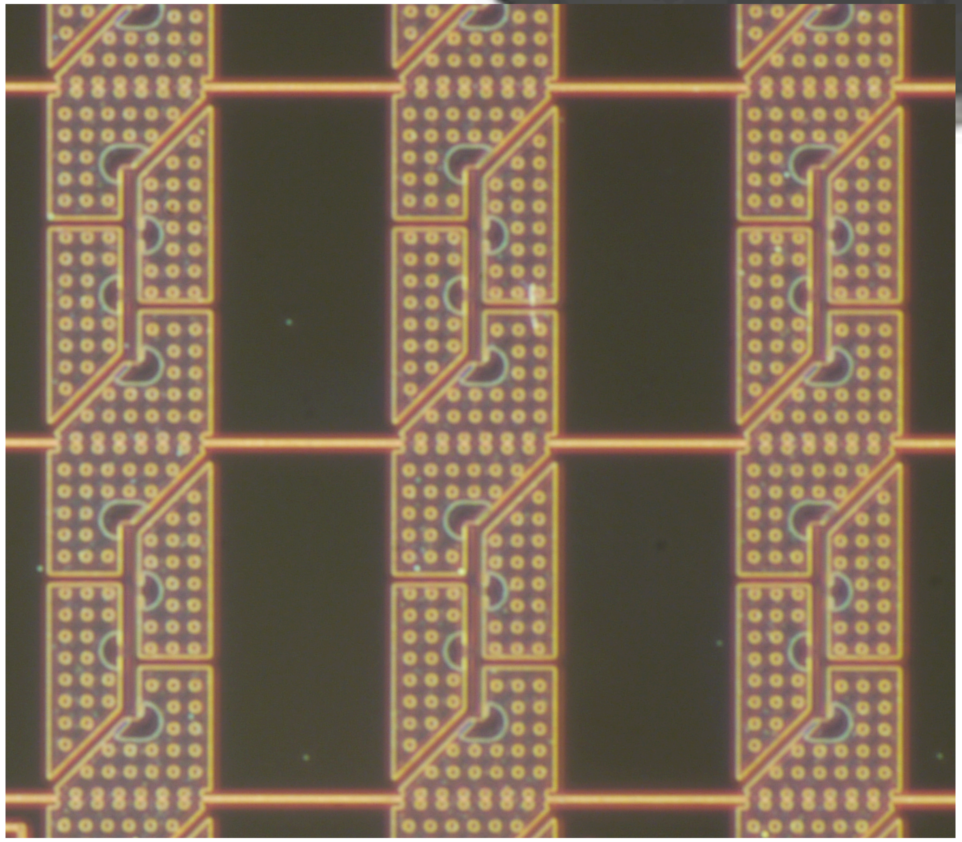
HVeV v1



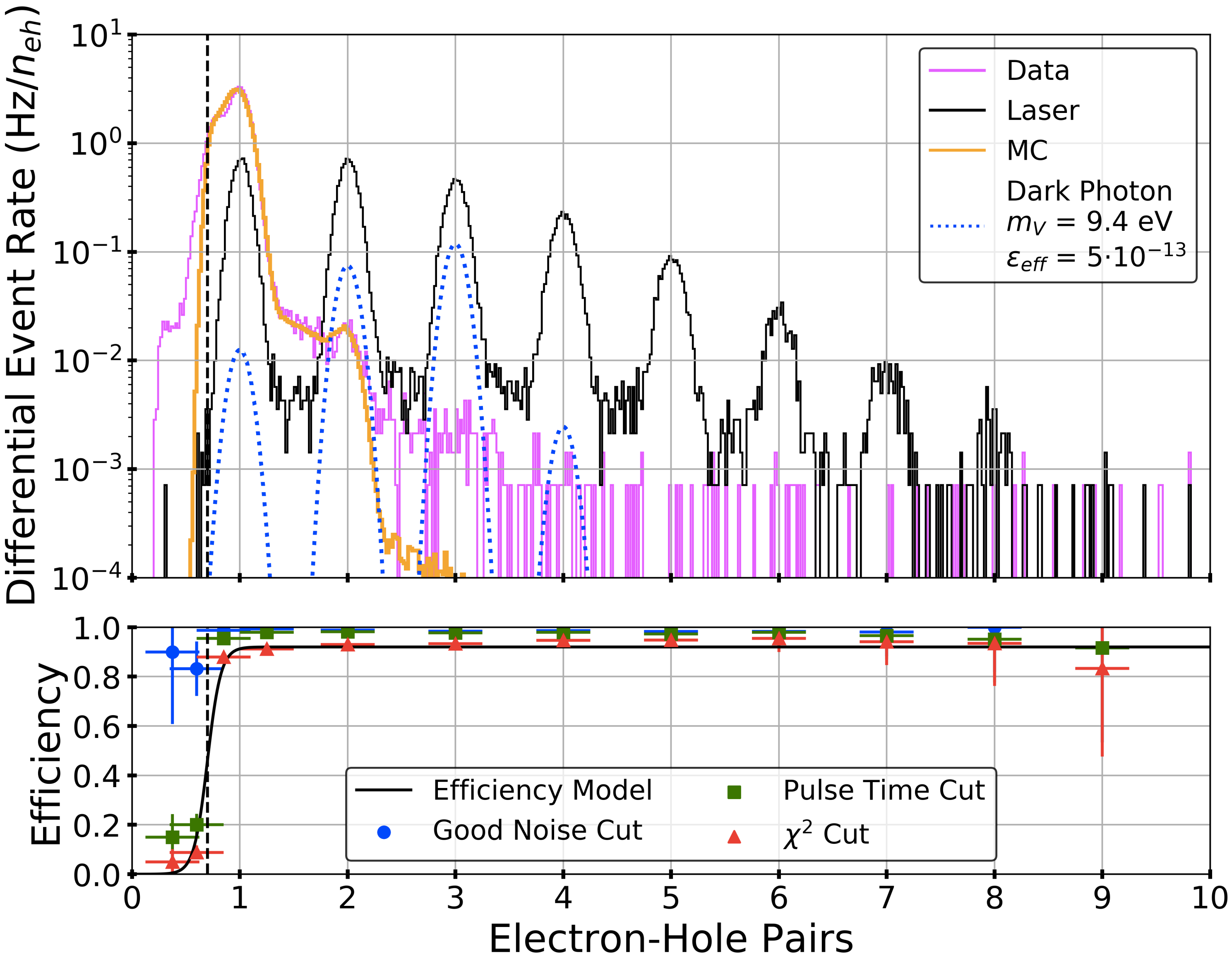


HVeV v2

HVeV v1 0.5 Gram-Day Science Spectrum

- Ran the detector for ~12 hours with a 1 Hz laser calibration (black line)
- Background consistent with IR at low energy, high-energy tail was not anticipated
  - Could be due to coherent scattering component or instrumental background
- Device shows high efficiency, excellent resolution, and the ability to distguish between ‘true’ events and impurity-mediated events (unlike CCDs which only measure electrons or holes)
- Very simple analysis; it’s easy to see how one rules out a quantized signal in light of this background

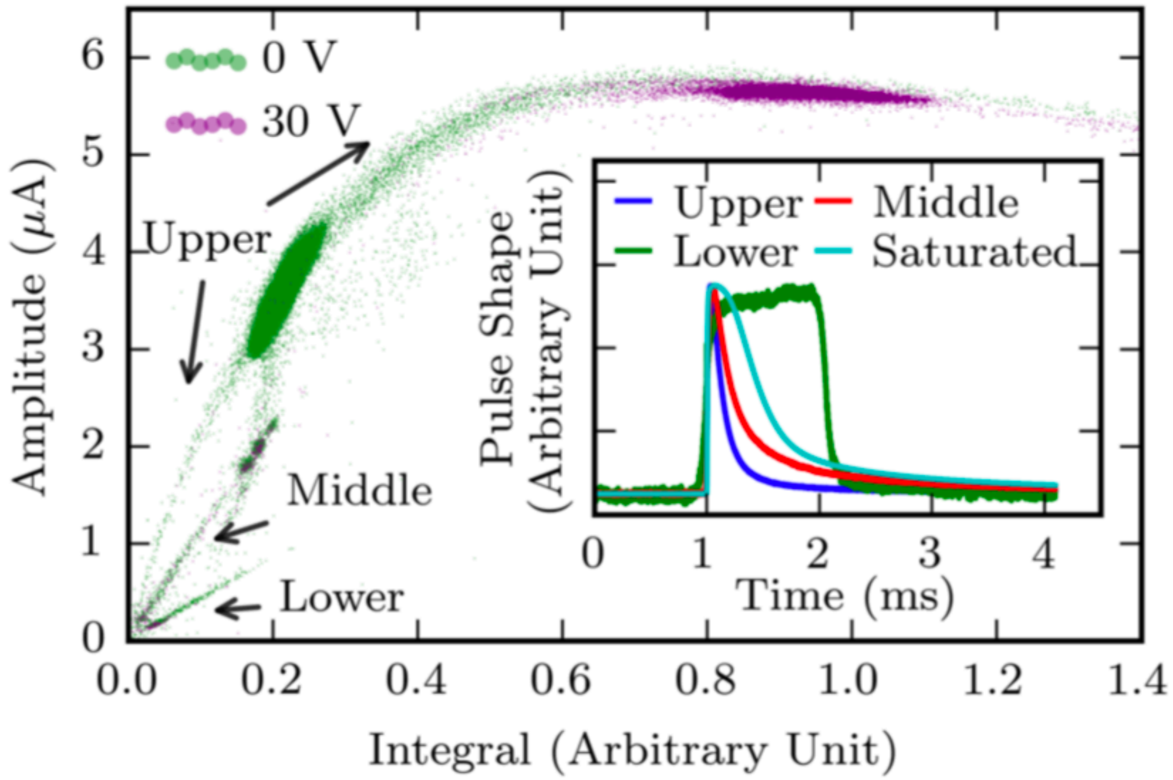
SuperCDMS Collaboration 2018 (https://arxiv.org/abs/1804.00088)

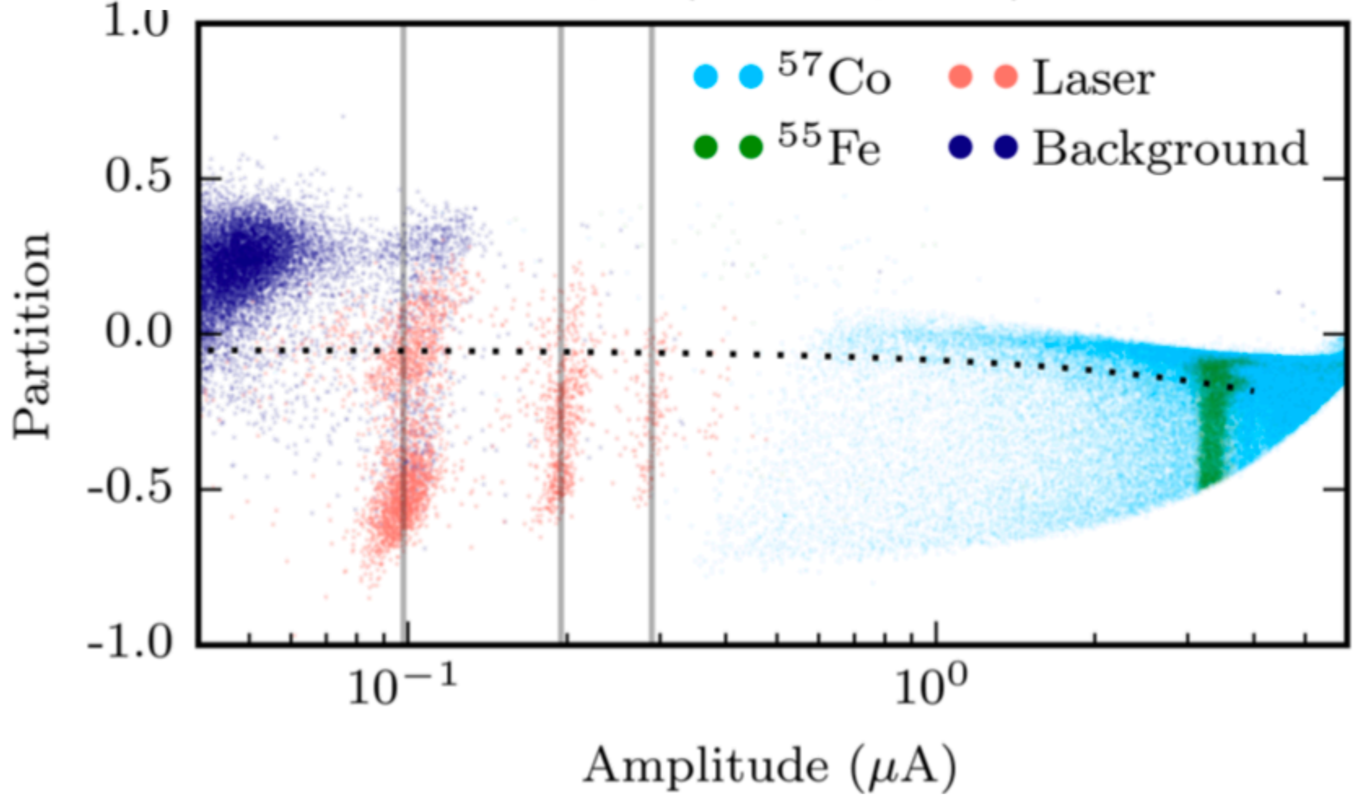


HVeV v1.5: Edge-Dominated Leakage

ArXiv:1903.06517

- Prototype demonstrated position dependence in the non-quantized data hinted at during HVeV Run 1
- Nearly contact-free biasing scheme isolates contact along the crystal edge, preventing charge tunneling through most of the high-voltage face
- Surface events have a distinct pulse shape and can be removed using a cut in the pulse-shape plane.
- Non-quantized leakage is dominant at high radius; 95% of non-quantized events removed by 50% radial cut efficiency. 80% of quantized events removed by the same cut

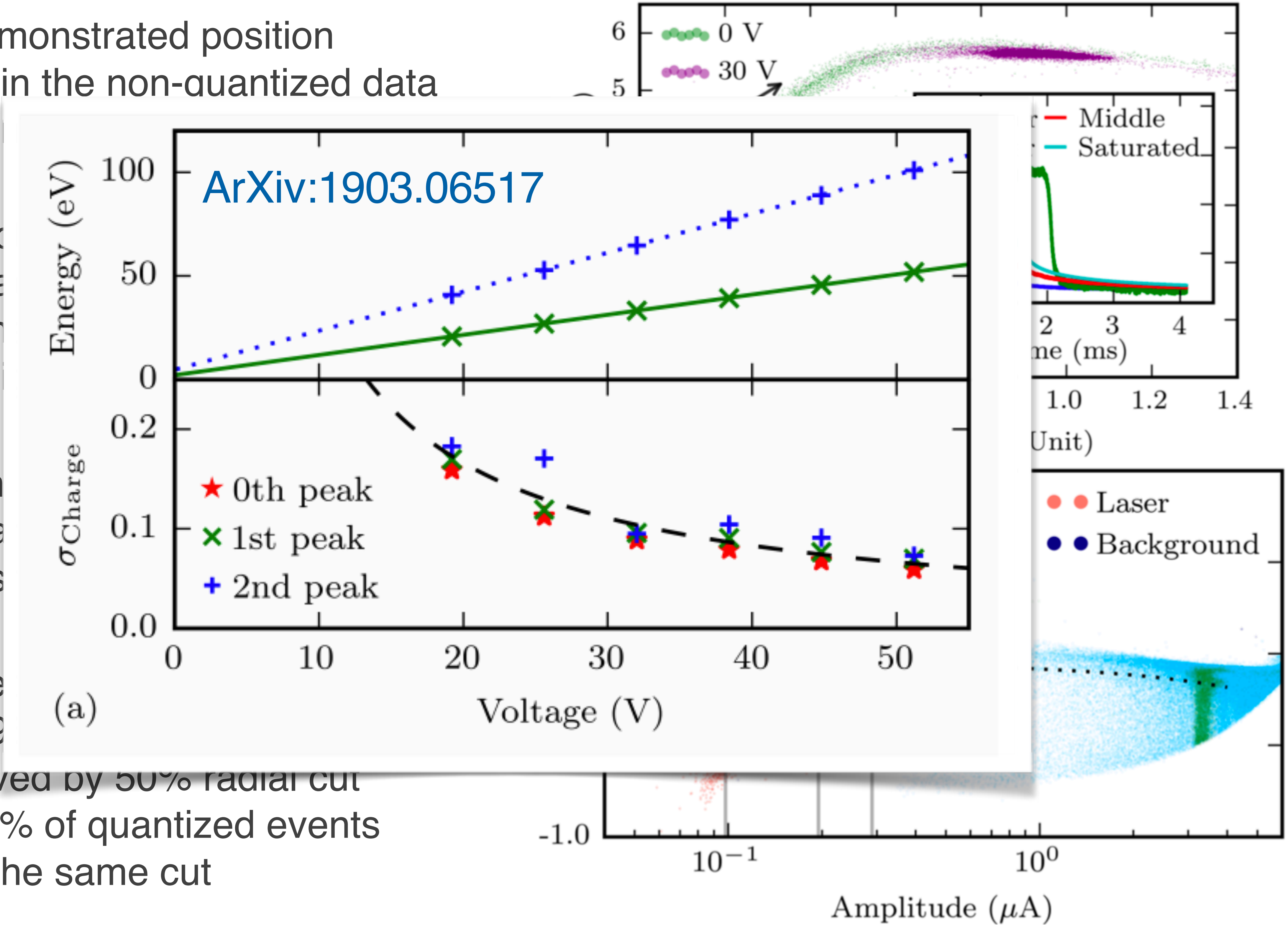




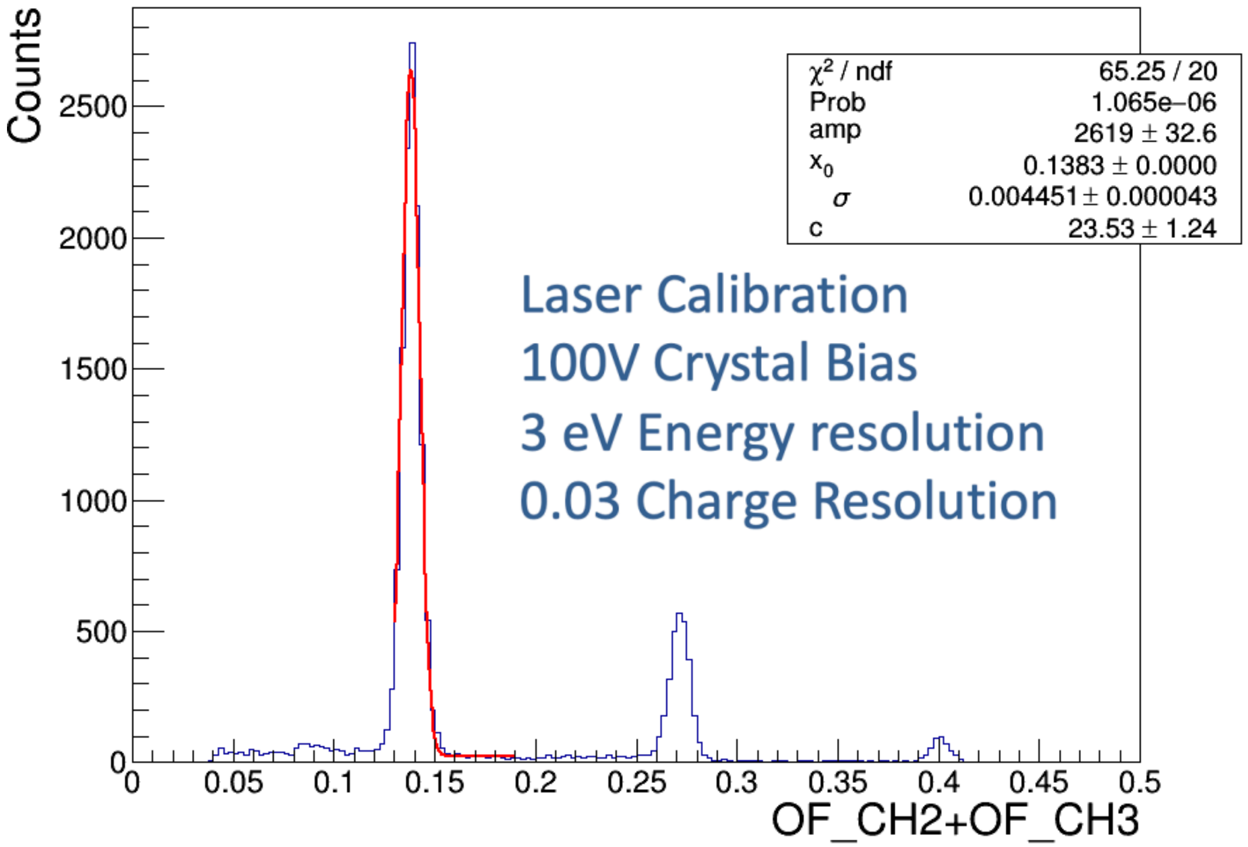
HVeV v1.5: Edge-Dominated Leakage

- Prototype demonstrated position dependence in the non-quantized data hinted at duri
- Nearly contac isolates conta preventing ch most of the hi
- Surface even shape and ca in the pulse-s
- Non-quantize high radius; 9 events removed by 50% radial cut efficiency. 80% of quantized events removed by the same cut

ArXiv:1903.06517

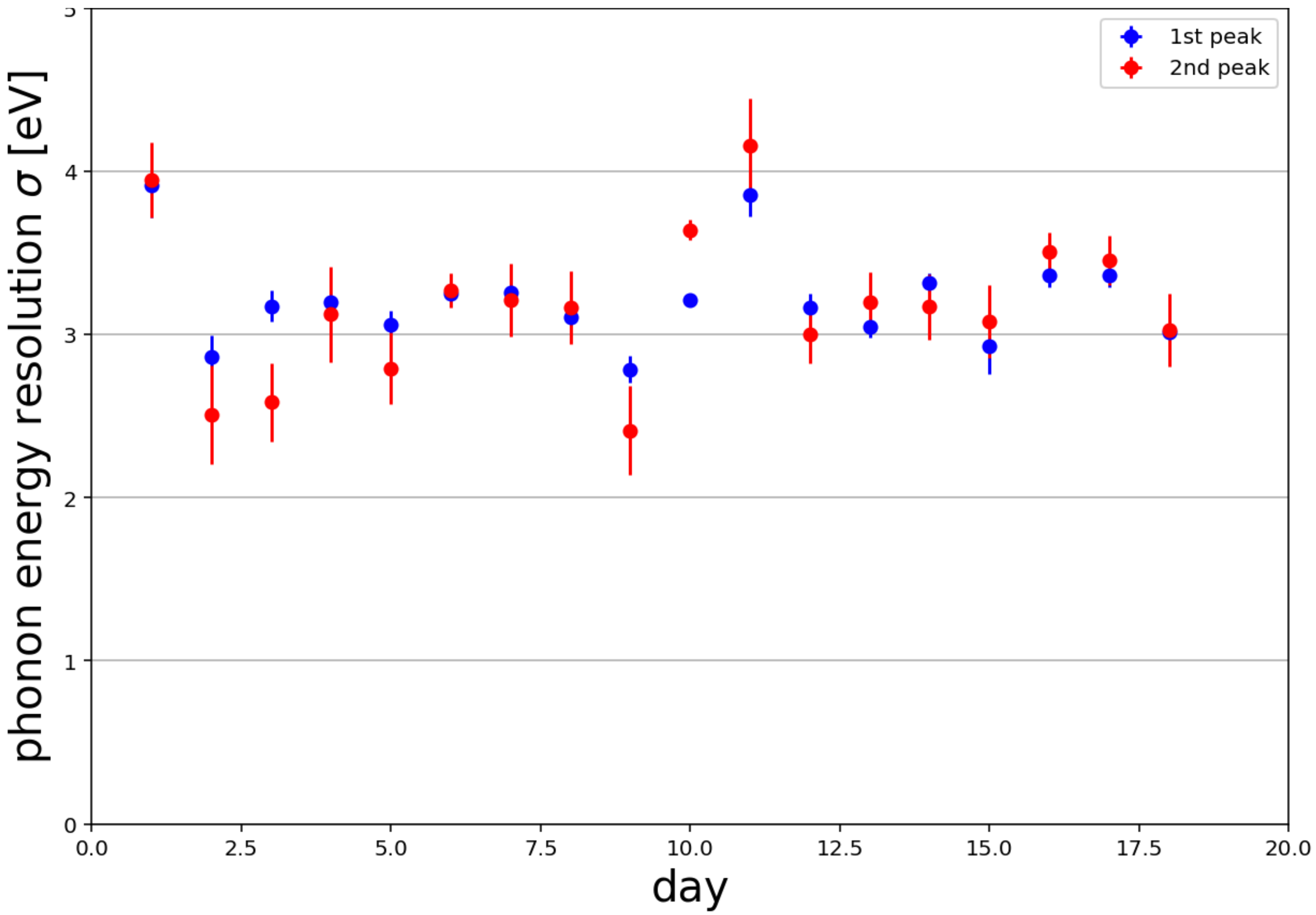


HVeV v2: Combining Lessons



Laser Calibration
100V Crystal Bias
3 eV Energy resolution
0.03 Charge Resolution

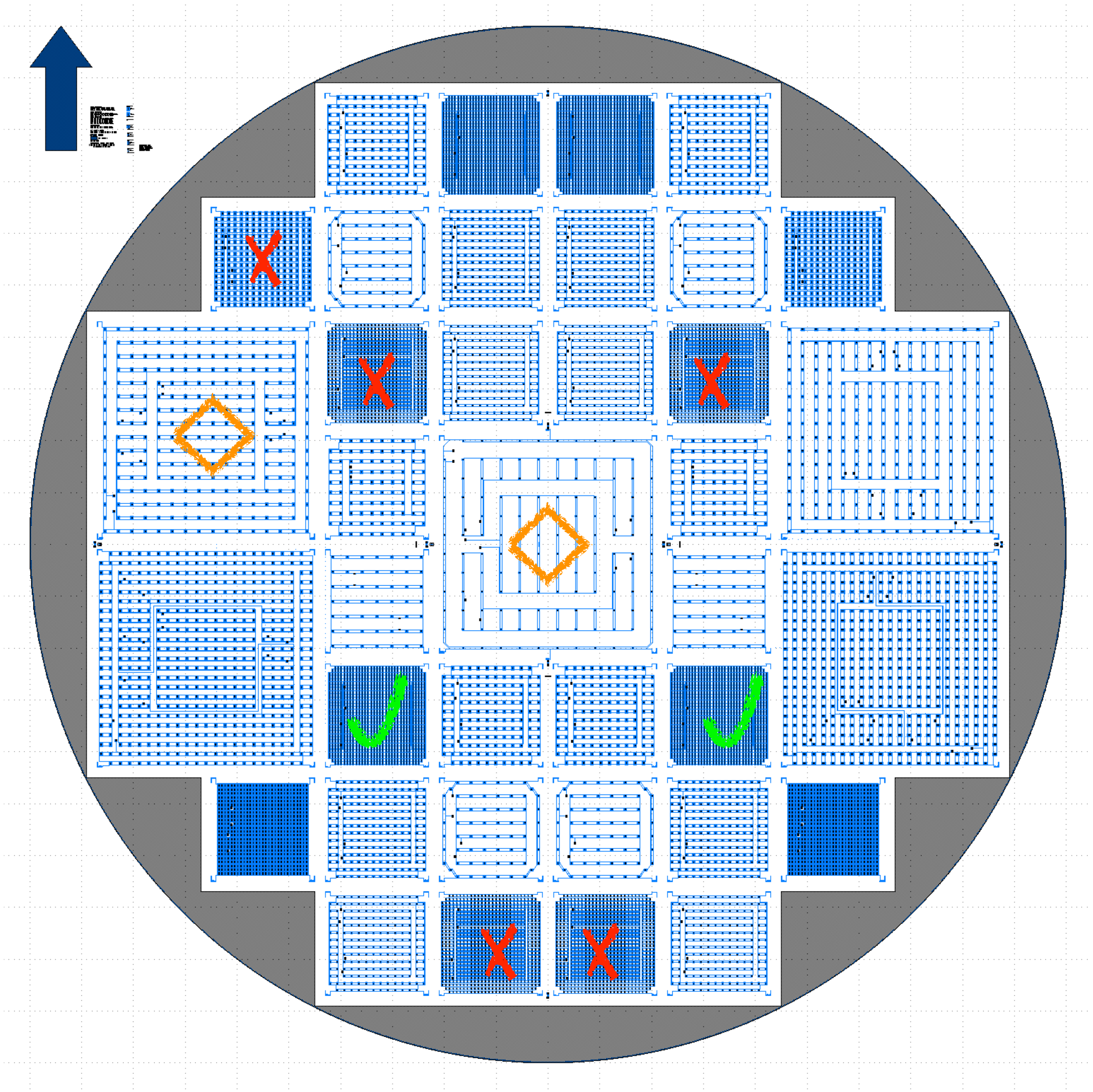
https://agenda.infn.it/event/15448/contributions/95710/



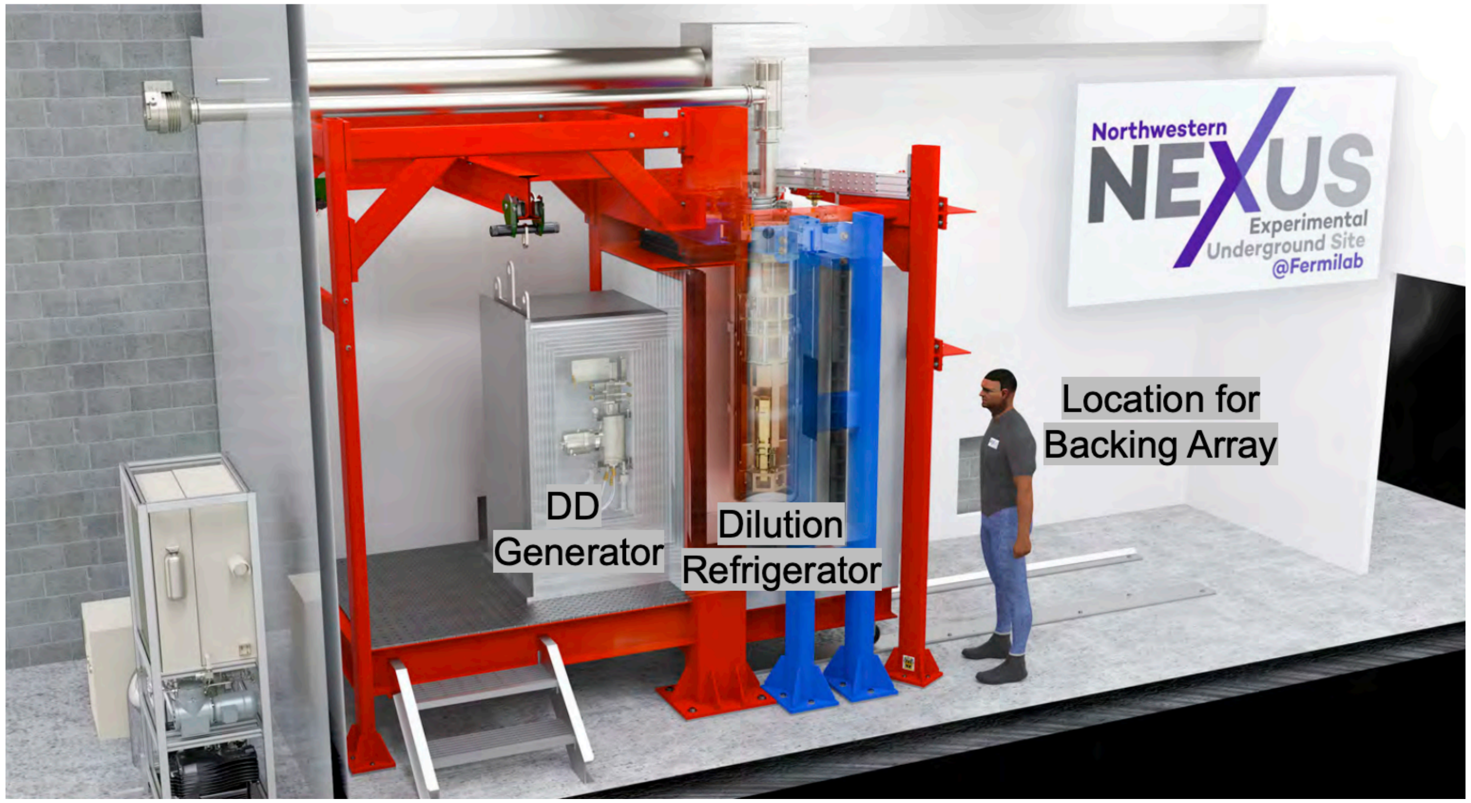
- Used very thin Al backside grid, HVeV 1.5 QET design, no amorphous layer
  - High efficiency, high electric fields; world record charge resolution (achieved 0.01 in short run)
- Still seeing some issues with sidewall trapping and incomplete neutralization
  - We observe ~15% trapping
- Physics results from Nuclear Recoil calibration at TUNL and DM search at Northwestern coming soon!

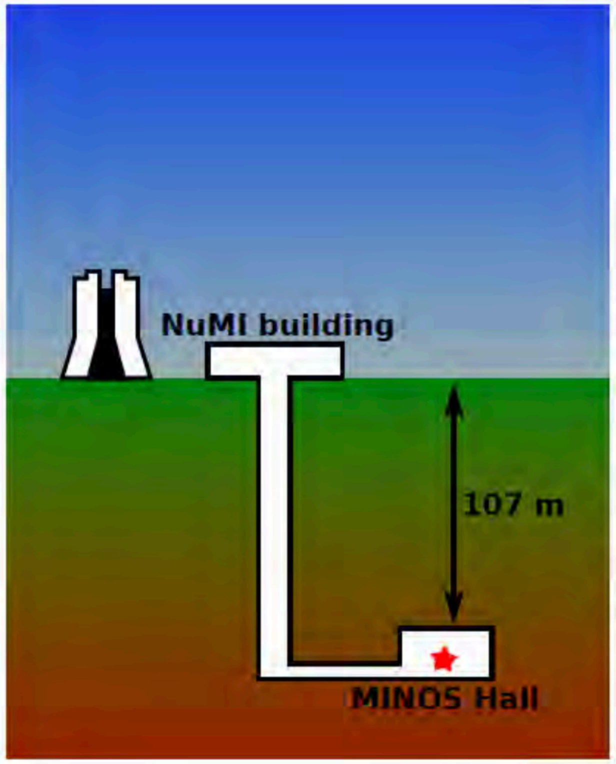
Future for HVeV Program

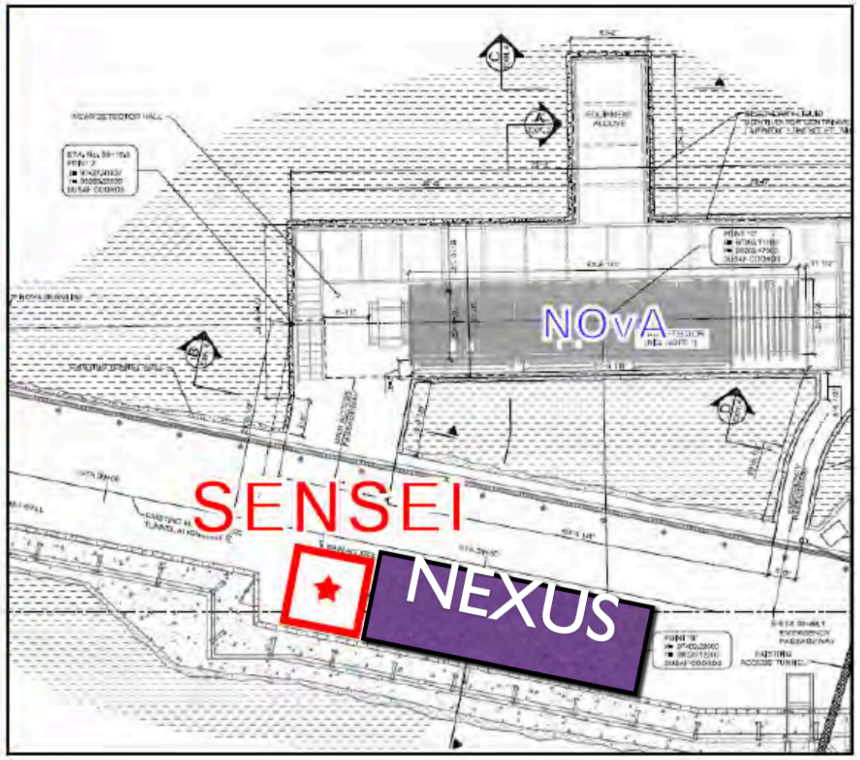
- Mounting issues damaged some prototypes (X’s)
- 2 1g v2 detectors, optimized for dynamic range, now successfully operated
- 2 4g detectors currently being mounted (both optimized for low energy resolution)
- *Many more* prototypes to help test the resolution and efficiency models that go into this detector design
  - Multiple designs with sub-eV projected resolutions



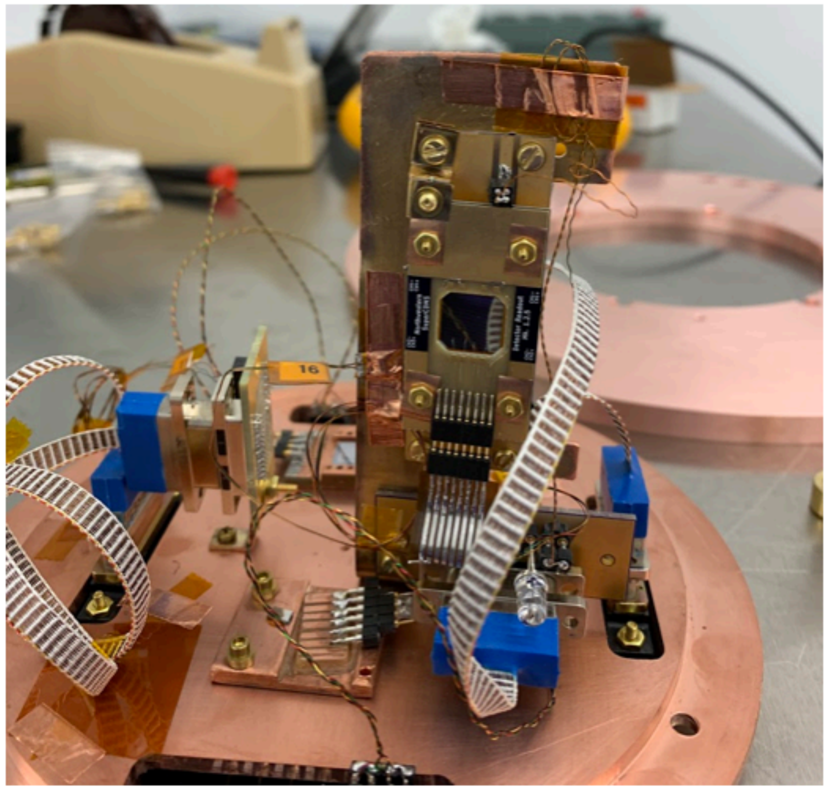
NEXUS: Underground Experimental Site for R&D

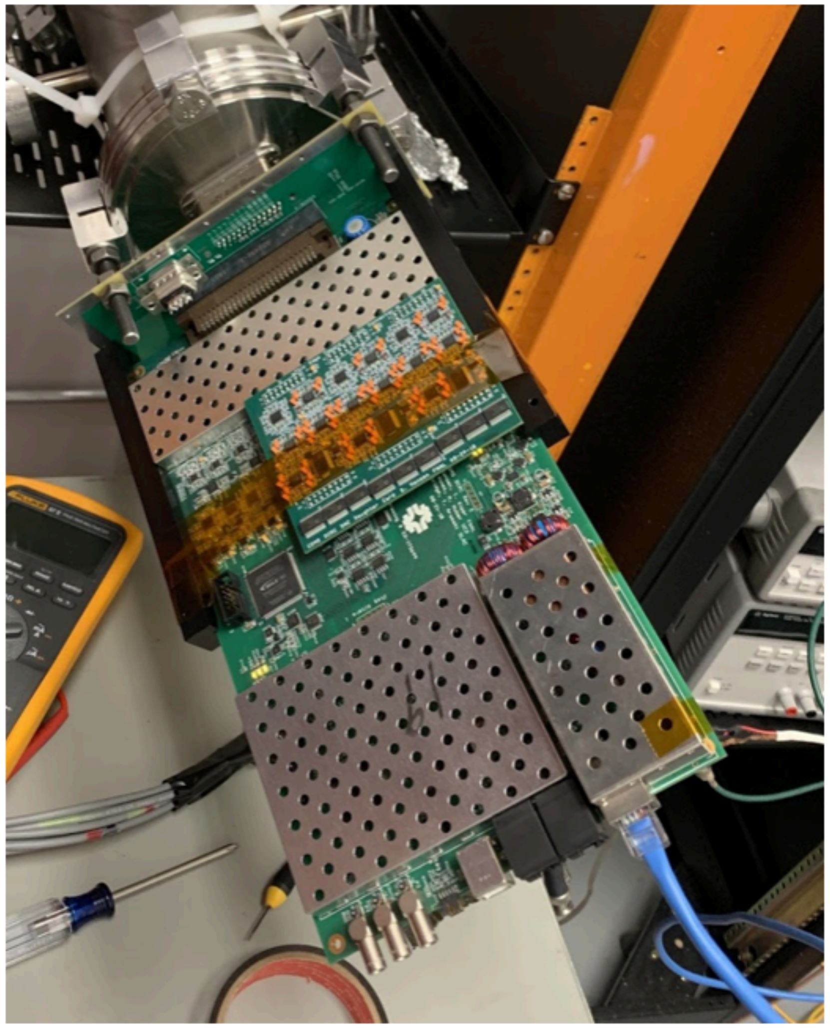


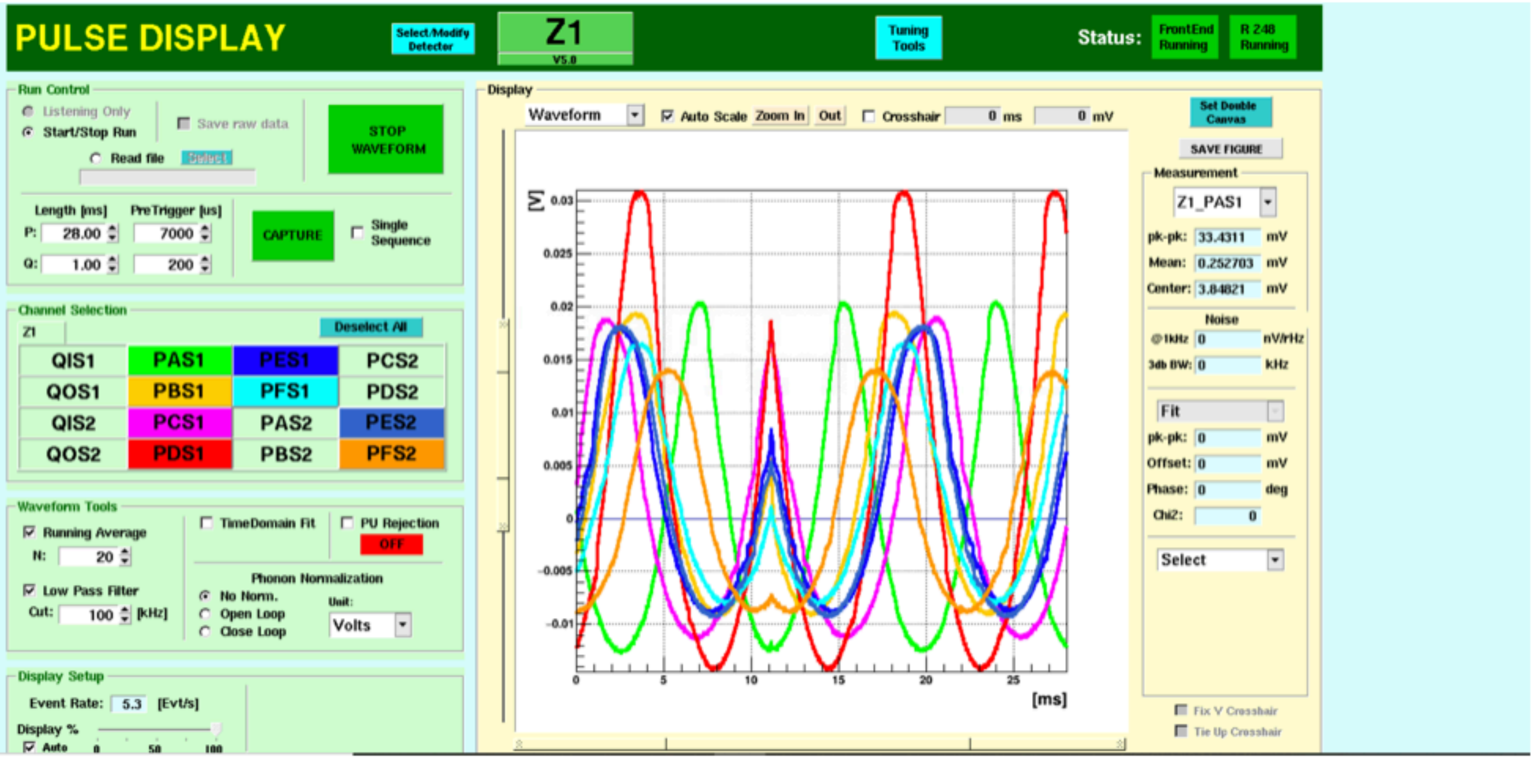




NEXUS Right Now







○ Listening Only
● Start/Stop Run
○ Read file
☐ Save raw data

Length [ms] / PreTrigger [us]
P: 28.00 / 7000
Q: 1.00 / 200
☐ Single Sequence

Channel Selection

Z1

QIS1	PAS1	PES1	PCS2
QOS1	PBS1	PFS1	PDS2
QIS2	PCS1	PAS2	PES2
QOS2	PDS1	PBS2	PFS2

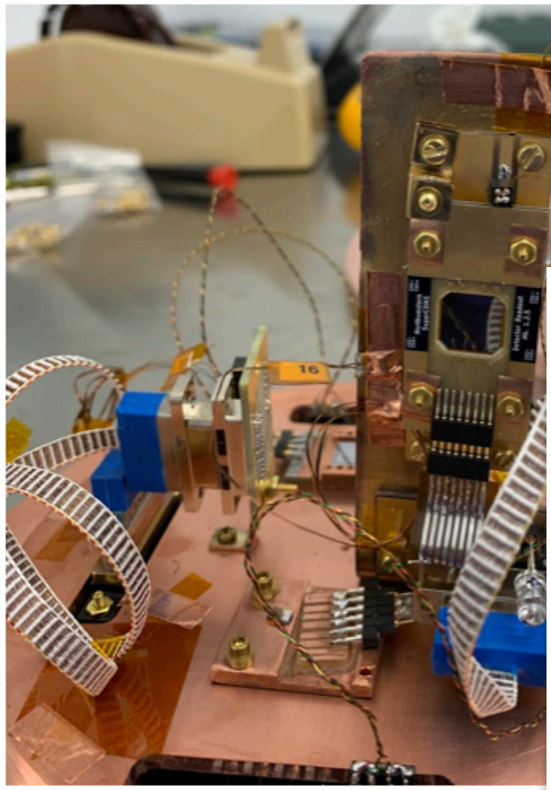
Waveform Tools
☑ Running Average
N: 20
☑ Low Pass Filter
Cut: 100 [kHz]
☐ TimeDomain Fit
☐ PU Rejection
Phonon Normalization
● No Norm.
○ Open Loop
○ Close Loop
Unit: Volts

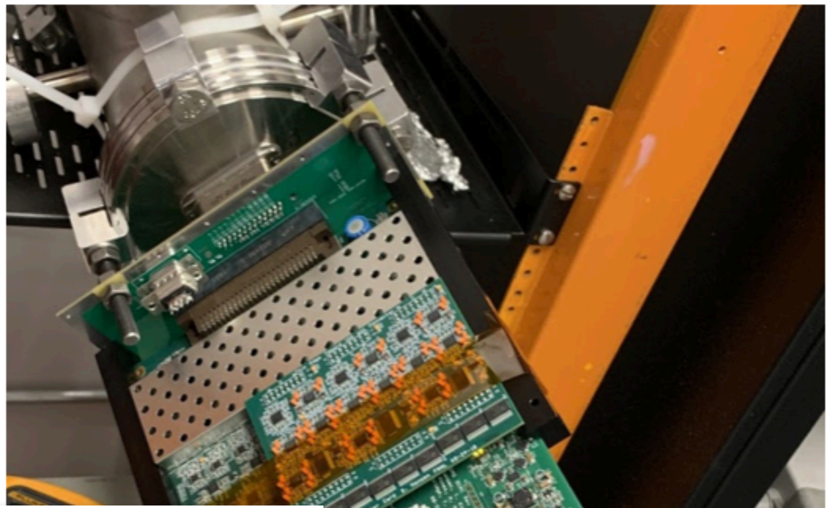
Display Setup
Event Rate: 5.3 [Evt/s]
Display %
☑ Auto 0 50 100

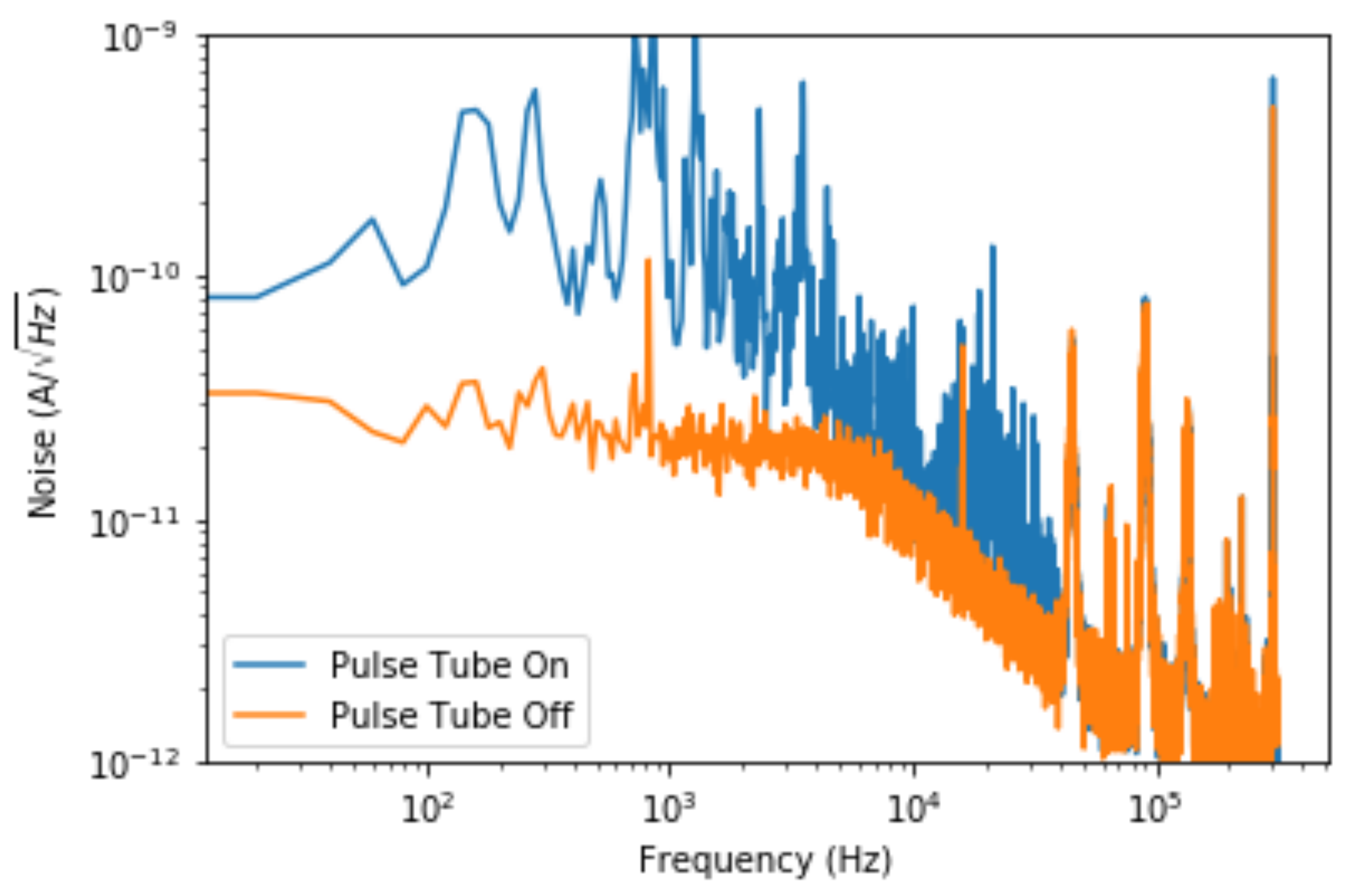
Waveform
☑ Auto Scale
☐ Crosshair 0 ms 0 mV

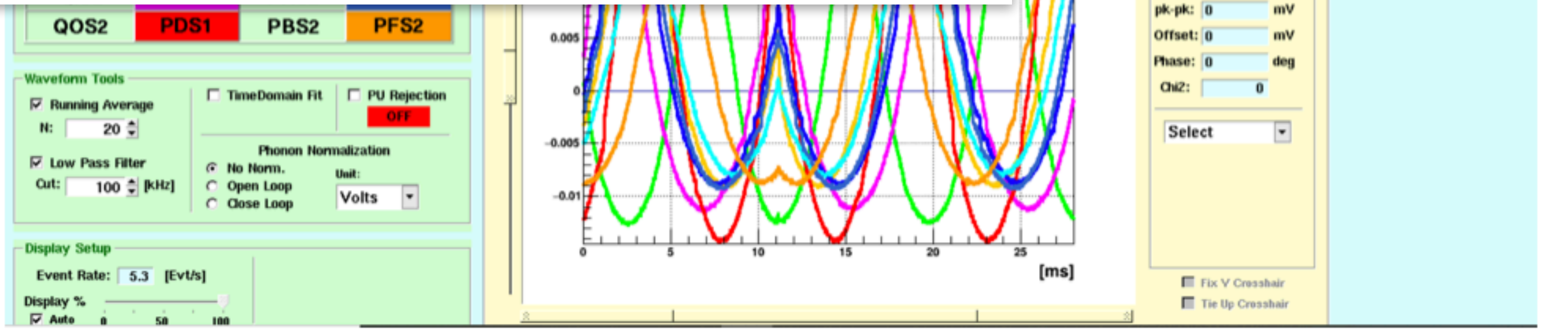
Measurement
Z1_PAS1
pk-pk: 33.4311 mV
Mean: 0.252703 mV
Center: 3.84821 mV
Noise
@1kHz 0 nV/rHz
3db BW: 0 kHz
Fit
pk-pk: 0 mV
Offset: 0 mV
Phase: 0 deg
Chi2: 0
Select
☐ Fix V Crosshair
☐ Tie Up Crosshair

NEXUS Right Now









ms 0 mV

Measurement
Z1_PAS1
pk-pk: 33.4311 mV
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Noise
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Phase: 0 deg
Chi2: 0

Waveform Tools
☑ Running Average
N: 20
☑ Low Pass Filter
Cut: 100 [kHz]
☐ TimeDomain Fit
☐ PU Rejection OFF

Phonon Normalization
● No Norm.
○ Open Loop
○ Close Loop
Unit: Volts

Display Setup
Event Rate: 5.3 [Evt/s]
Display % 0 50 100
☑ Auto

Fermilab

NEXUS Projects (Current and Proposed)

- HVeV Dark Matter Science (Ongoing)
  - Including HVeV/QET R&D outlined here
  - Installation of UV, Visible, and BB IR sources

- Nuclear Recoil Charge Yield in Si/Ge (In Prep w/ Enectali Figueroa-Feliciano at Northwestern)
  - Also exploring using DD generator for non-cryogenic detectors

- KIDs on Si (In Prep w/ Sunil Golwala at Caltech)
  - Installation of RF readout

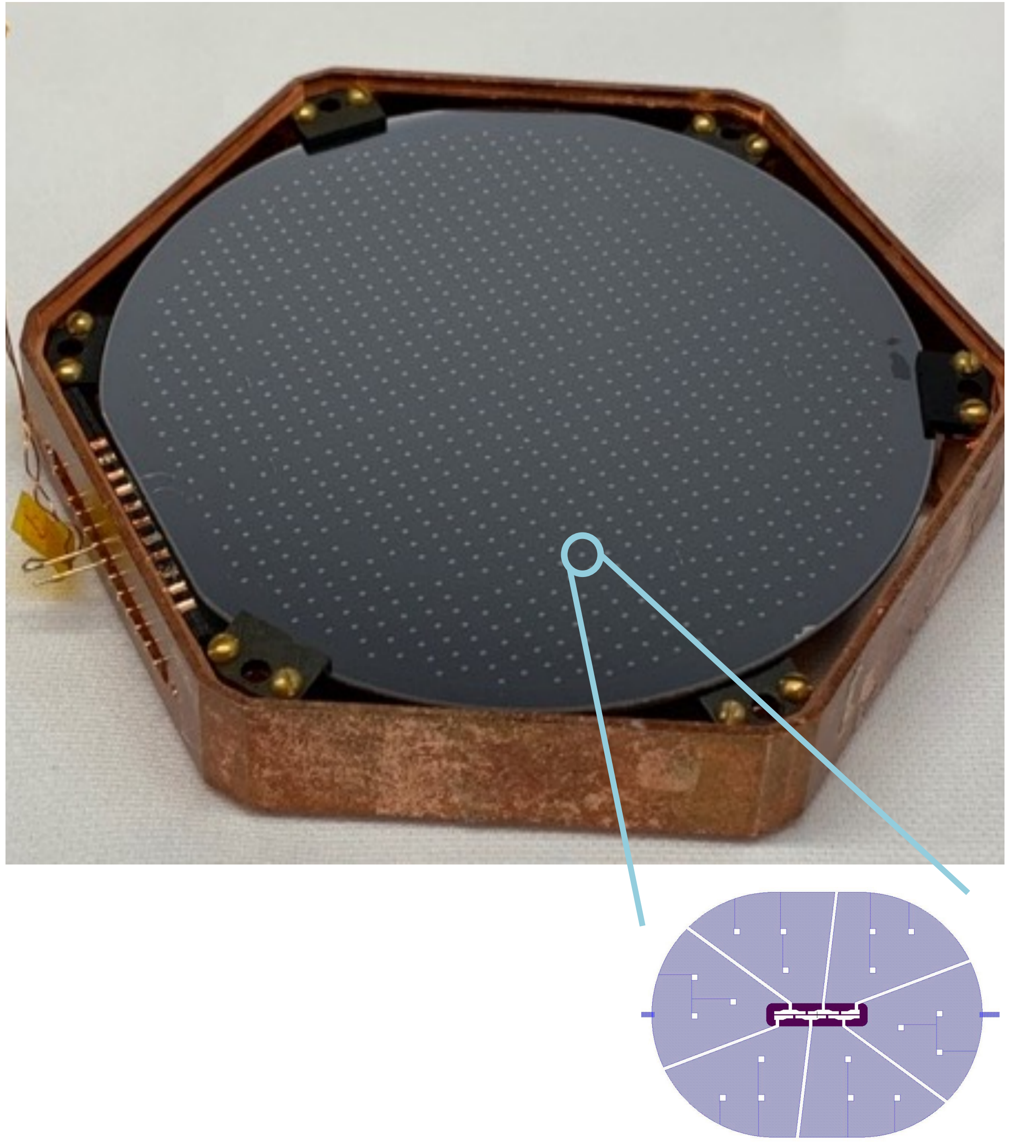
- Testing Athermal Phonon Effects on QuBits (In Prep w/ D. Bowring at FNAL)
  - Uses KID RF readout with minor modifications

- meV-Gap Photodetectors as DM Detectors (Proposed w/ Y. Kahn at UIUC)
  - Possible multi-lab collaboration

- **Your proposal?**

Design of a Large Area Photon Detector

- The detector is a CDMS-style athermal phonon sensor
  - 1 mm thick silicon wafer, 45.6 cm^2 surface area
  - Mass of 10.6 grams
- The device has been optimized for photon detection
  - Distributed athermal sensor array read out by TESs
  - Single distributed channel gives a fast collection time of athermal phonons
  - This reduces efficiency penalties due to athermal phonon down conversion
  - T_c=41.5 mK, lowering the expected energy resolution
- Designed originally for degraded alpha rejection in neutrinoless double beta decay and for an active photon veto for dark matter experiments



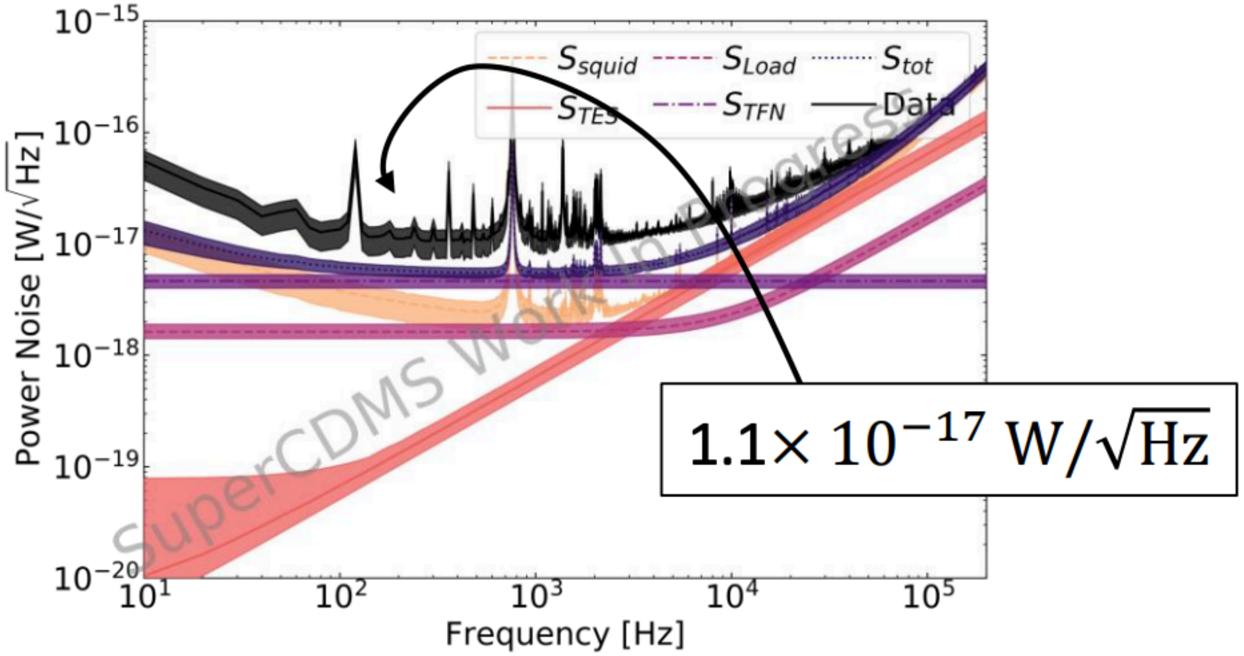
https://agenda.infn.it/event/15448/contributions/95785/

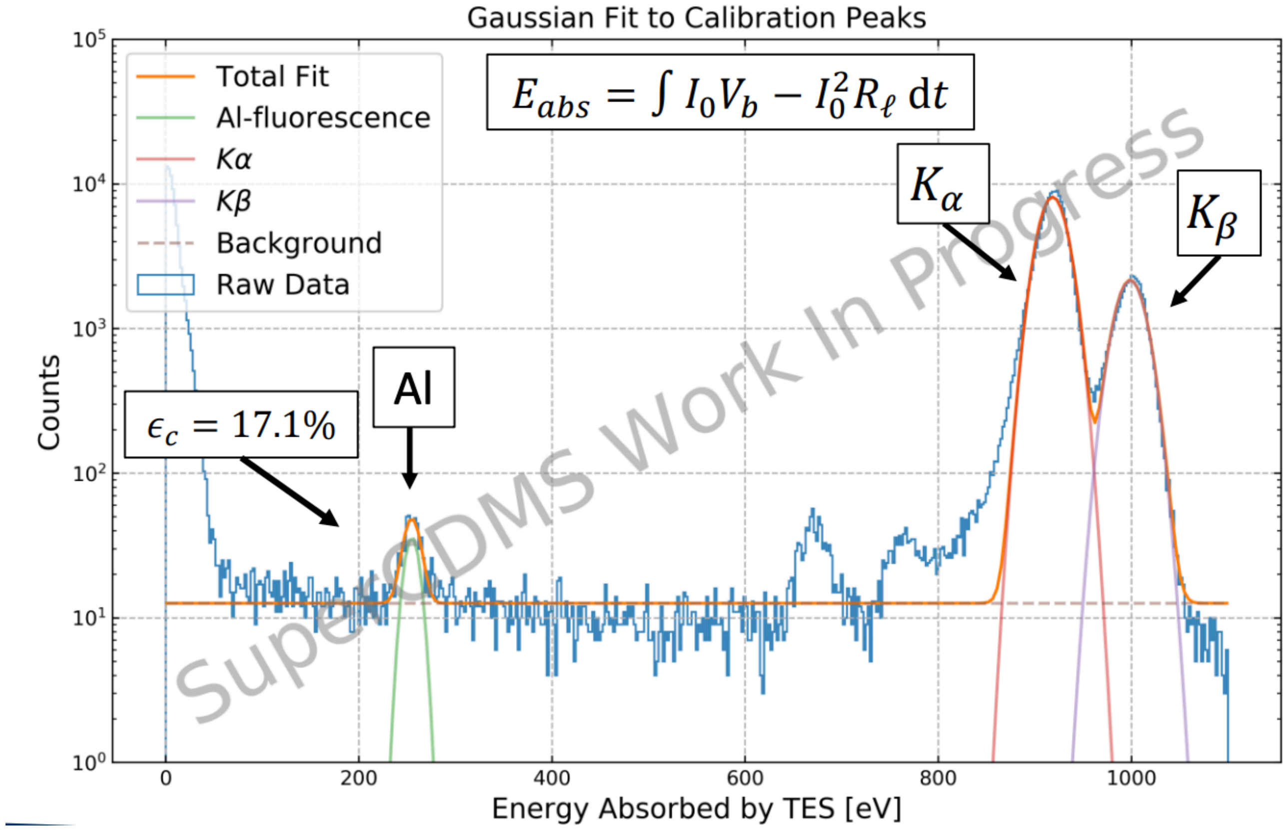
Reducing Readout Noise

- Readout noise limited by thermal fluctuation shot noise between sensor and crystal
  - Can reduce this only by weakening the link between the sensor and absorber, or dropping the sensor temperature
  - Power noise at the level of 1e-18 aW/sqrt(Hz)
  - Hitting readout limitations

- Power to current gain impacted by total heat capacity of the sensor
  - Make smaller sensors

- Massive on-sensor multiplexing
  - Readout smaller sections of the detector
  - Use MKIDs or other naturally multiplexed sensors rather than DC TES




Gaussian Fit to Calibration Peaks

https://agenda.infn.it/event/15448/contributions/95785/

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  - Can reduce between th dropping th
  - Power nois
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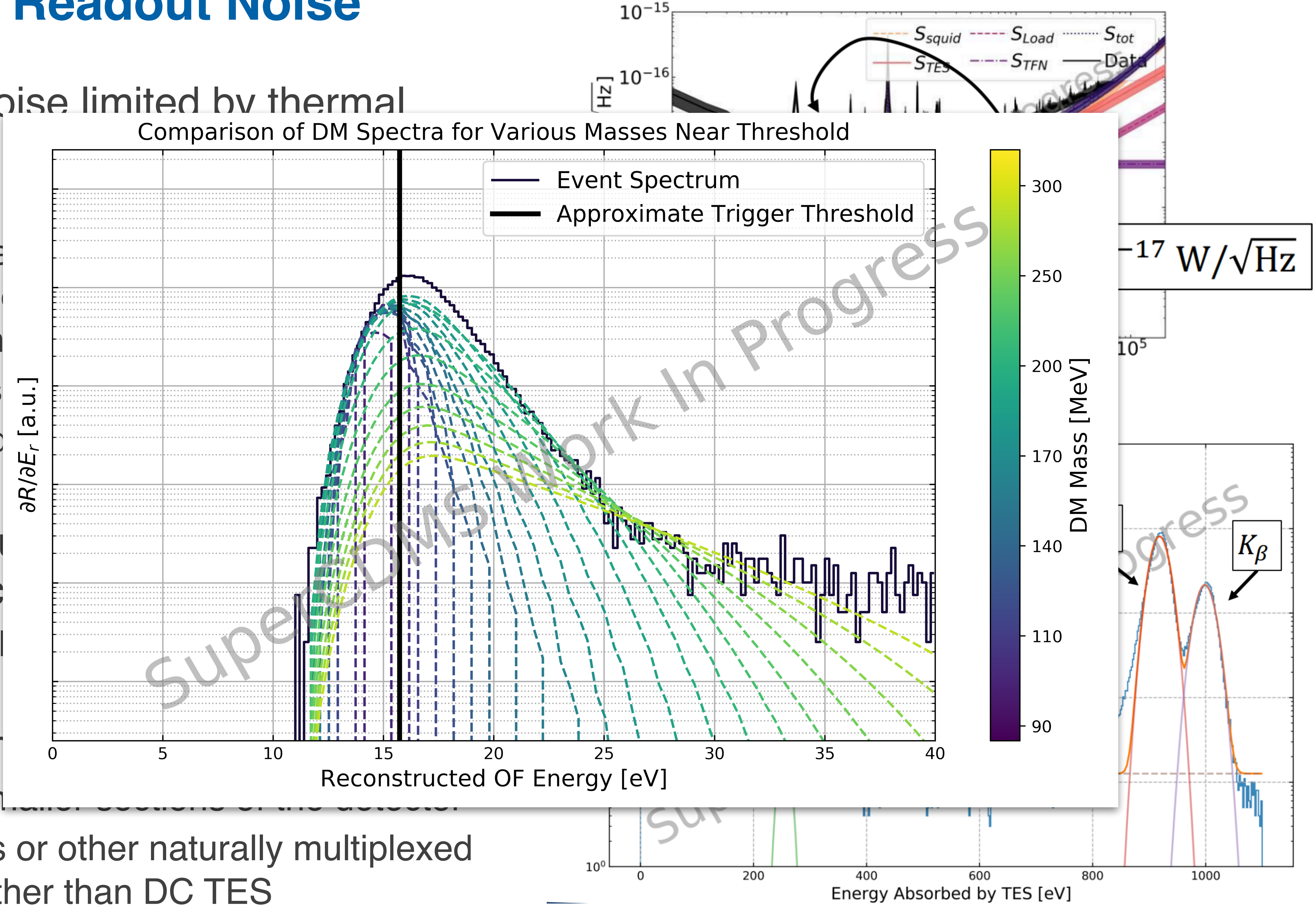

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Detector Performance

- From the good randoms after cuts, the energy resolution is now directly calculable

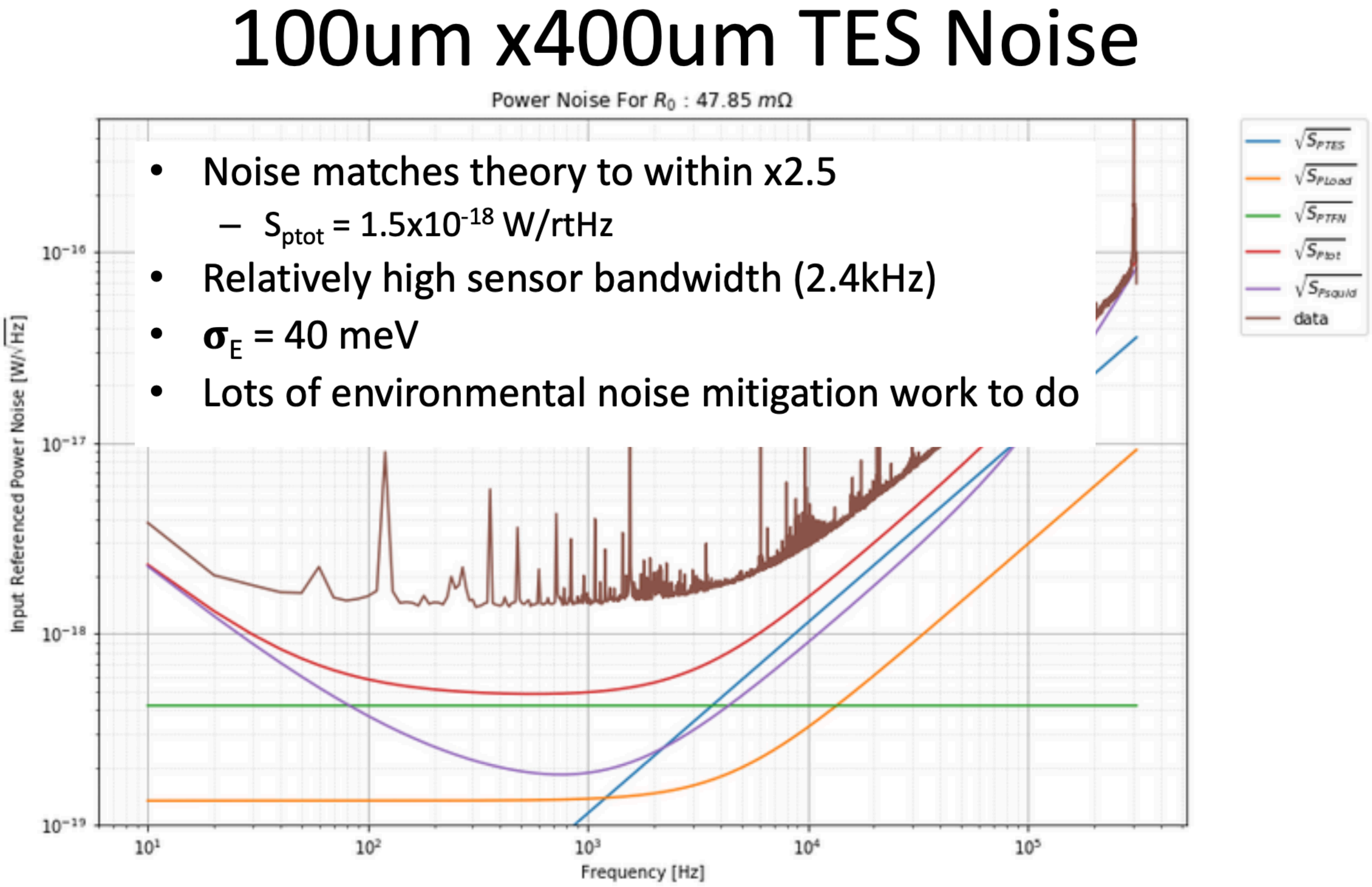
- We find that this detector has an energy resolution of σ_E=3.9±0.1(stat.) ±0.18(sys.) eV
  - This detector is a world-leading device for detecting photons given its size!

- We have therefore demonstrated O(3) eV resolution across 2 orders of magnitude in mass!

	Sensor	Area (cm^2)	σ_E [eV]	$\frac{\sigma_E}{\sqrt{\mathrm{Area}}}$ $[\frac{\mathrm{eV}}{\mathrm{cm}}]$
CRESST 2 LD Rothe et al JLTP 193,1160 (2018)	W TES	12.5	4-7	1.1-2.0
LMO-3 LD E. Armengaud et al, Eur. Phys. J. C (2017) 77 :785	NTD	5	7.7	3.4
CALDER 1801.08403	Al/Ti/Al MKID	4	26	13
This Detector	**W TES**	**45.6**	**3.9**	**0.58**

TES Noise Power Developments

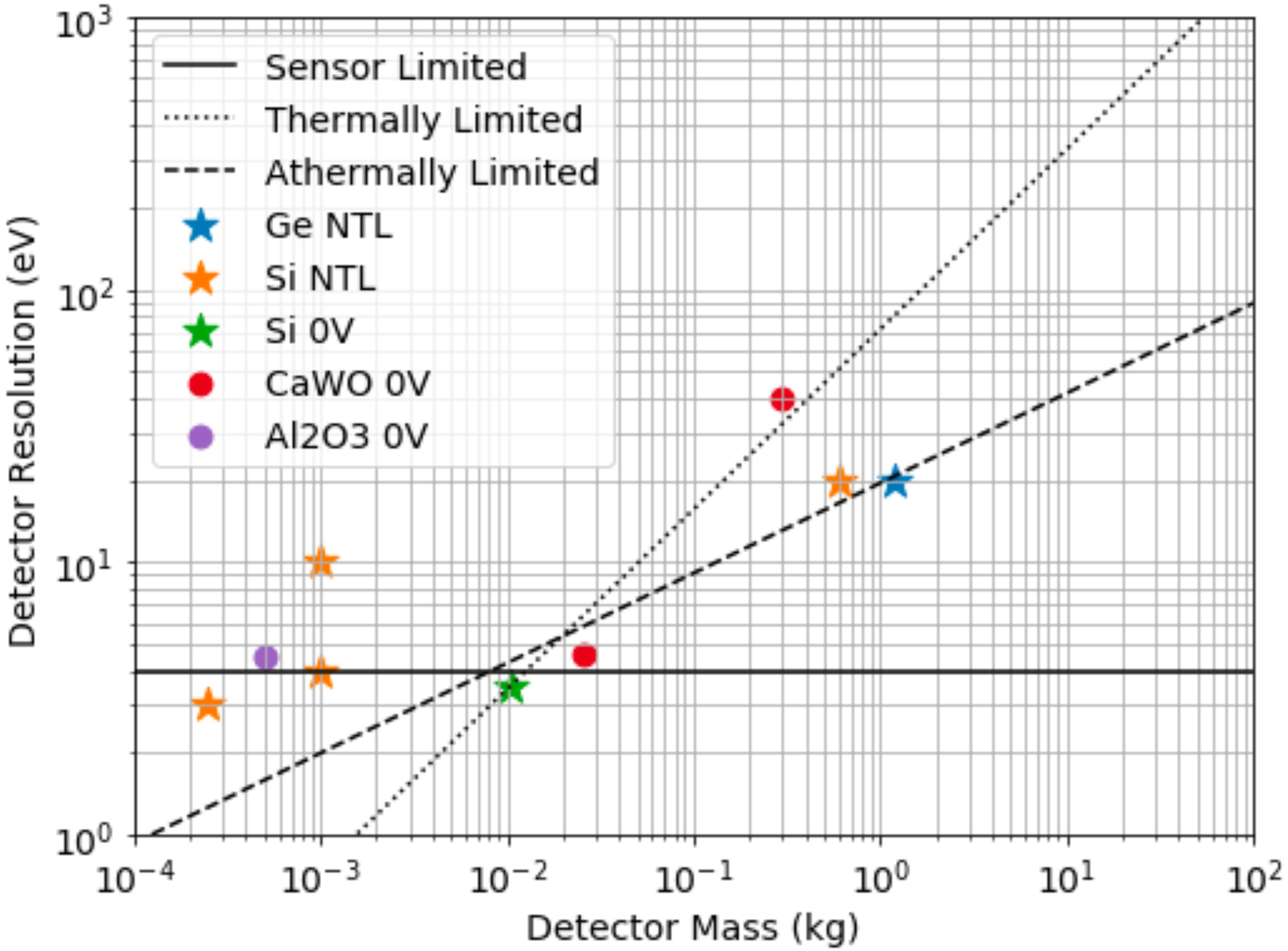
https://indico.fnal.gov/event/20385/session/47/contribution/4/material/slides/0.pdf



100um x400um TES Noise

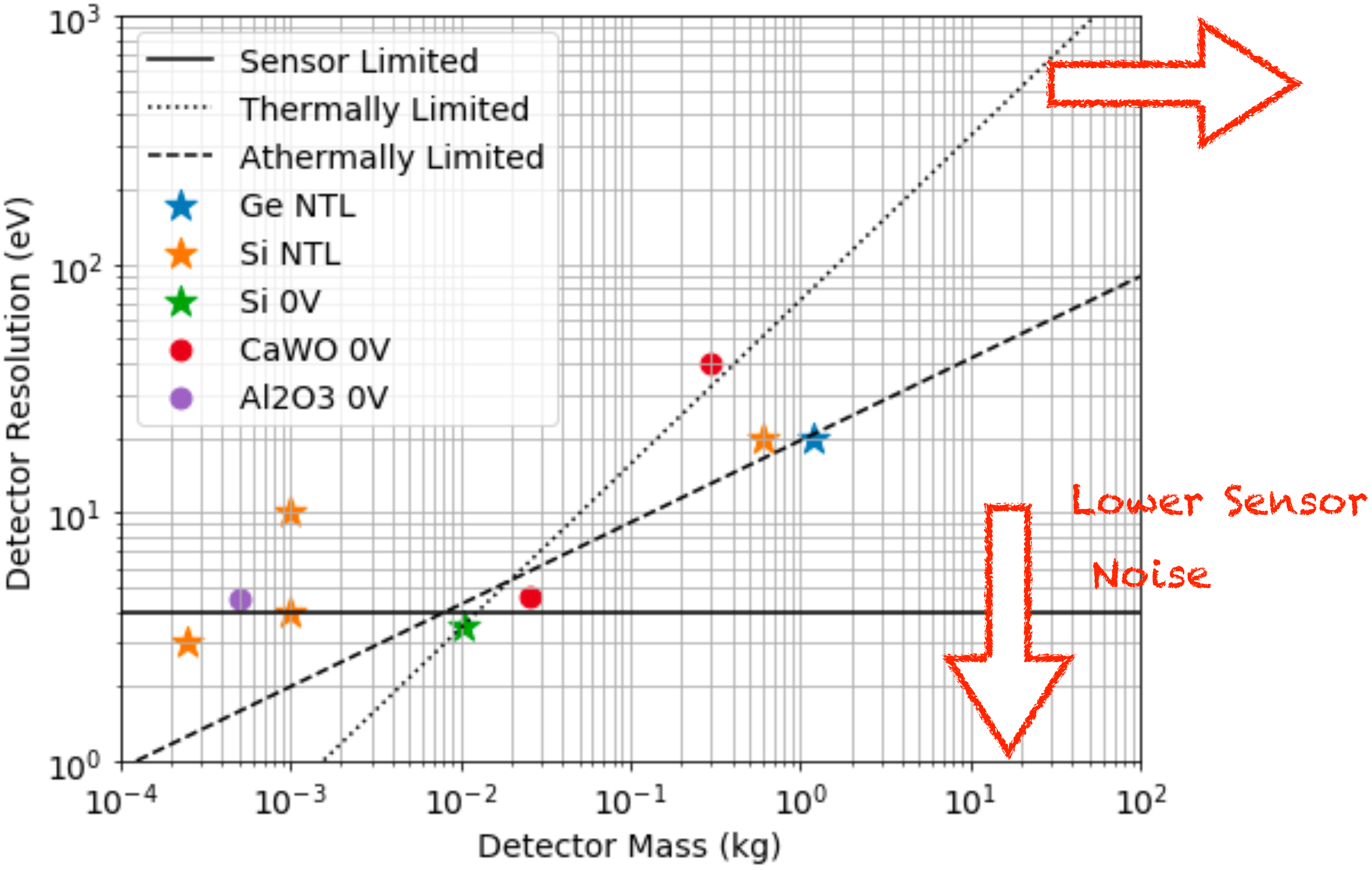
- Noise matches theory to within x2.5
  - $S_{ptot} = 1.5\times10^{-18}$ W/rtHz
- Relatively high sensor bandwidth (2.4kHz)
- σ_E = 40 meV
- Lots of environmental noise mitigation work to do

Scaling Up in Mass



Scaling Up in Mass

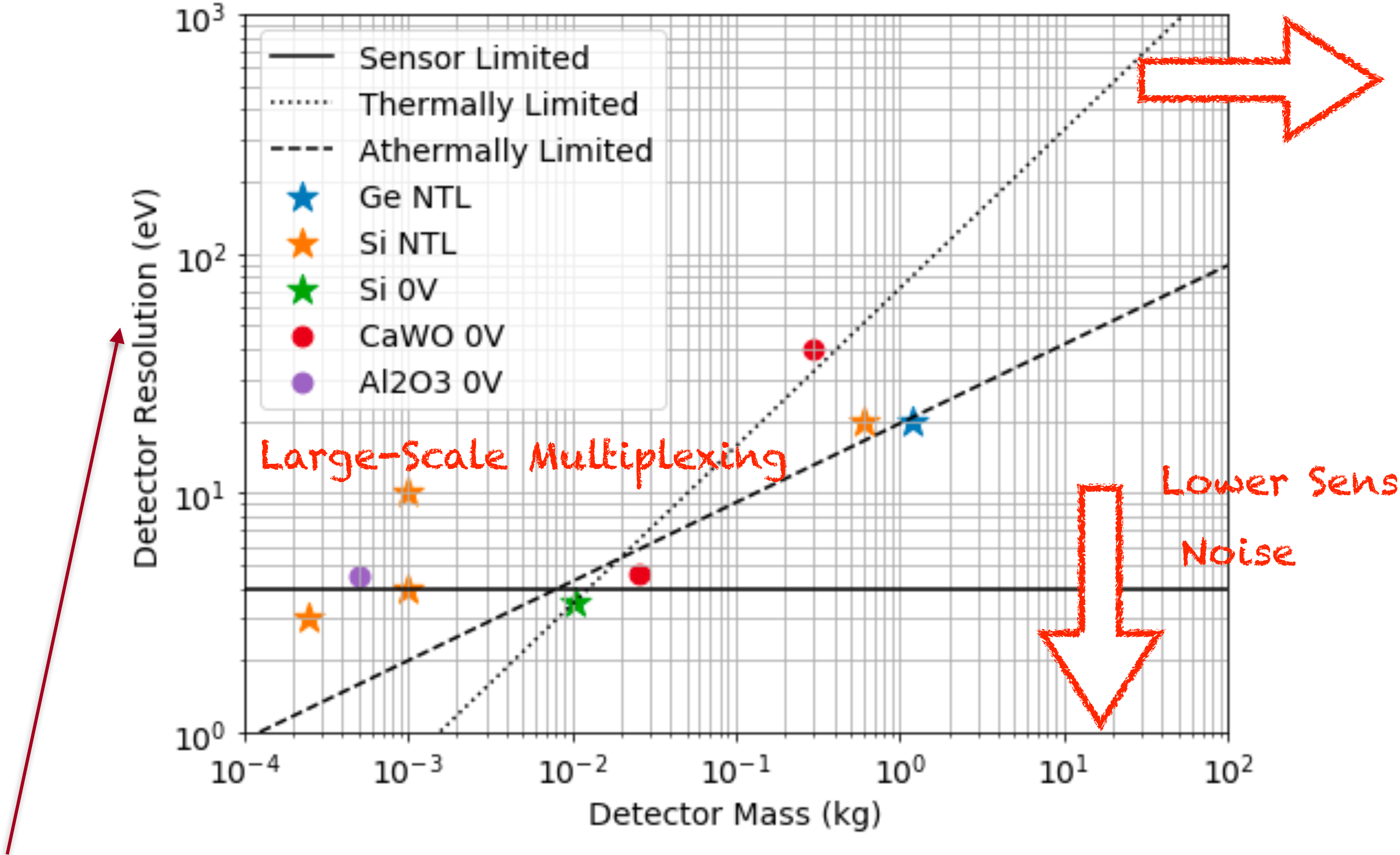
Faster Signal



Lower Sensor Noise

Scaling Up in Mass

Faster Signal



Large-Scale Multiplexing

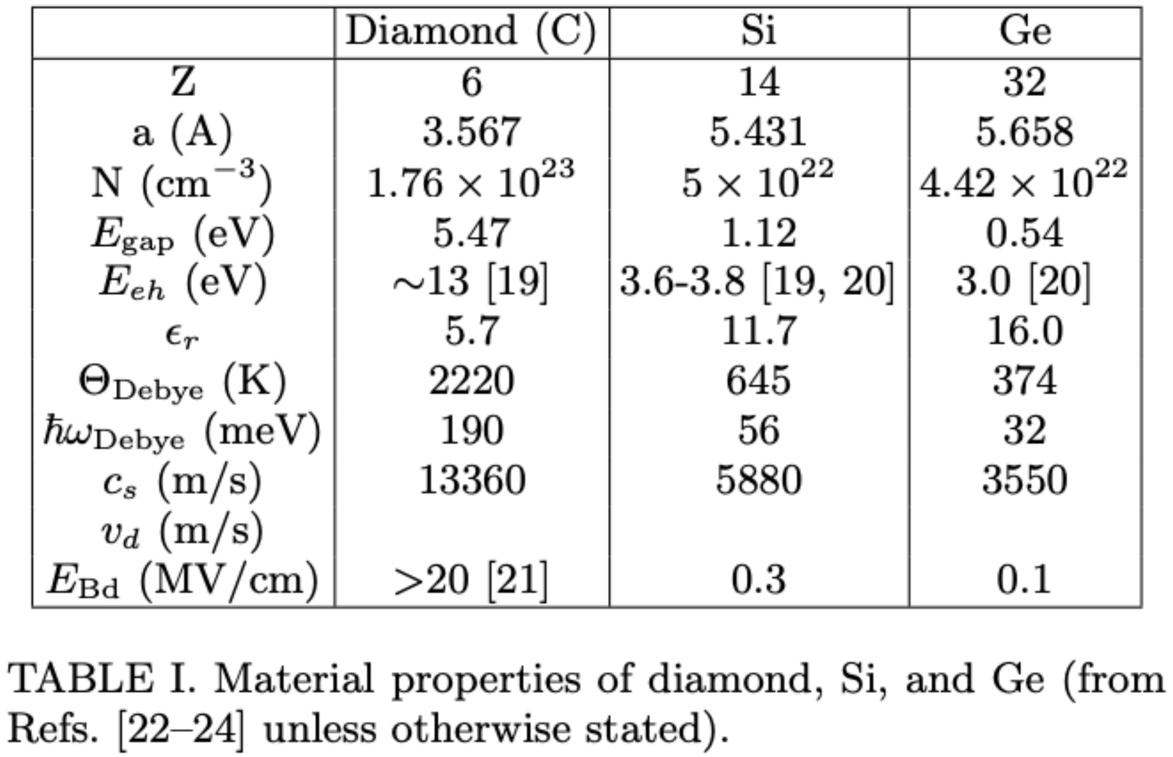
Lower Sensor Noise

Sets Operating Voltage for NTL Single-Charge Readout

Carbon-Based Detectors

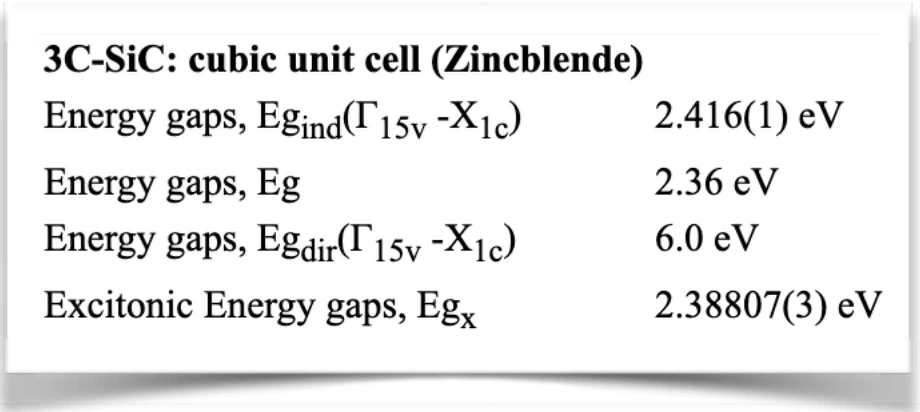
- SiC/Diamond are semiconductors with long-lived charge excitations
- Carbon has a lighter nucleus than either Si or Ge, giving it a kinematic advantage for low-mass Nuclear recoils
- Can withstand >10x larger electric fields than Si or Ge, and has many orders of magnitude lower leakage current even at room temperature
- Radiation hard; ~10x larger displacement energies (studied by RD42)
- SiC has many of the same properties, *and* is strongly polar
  - In many ways intermediate between Si and diamond
- You get similar benefits from Sapphire (Al2O3) but with a more complex crystal structure

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)



	Diamond (C)	Si	Ge
Z	6	14	32
a (A)	3.567	5.431	5.658
N (cm^{-3})	1.76×10^{23}	5×10^{22}	4.42×10^{22}
E_{gap} (eV)	5.47	1.12	0.54
E_{eh} (eV)	~13 [19]	3.6-3.8 [19, 20]	3.0 [20]
ϵ_r	5.7	11.7	16.0
Θ_{Debye} (K)	2220	645	374
$\hbar\omega_{\mathrm{Debye}}$ (meV)	190	56	32
c_s (m/s)	13360	5880	3550
v_d (m/s)			
E_{Bd} (MV/cm)	>20 [21]	0.3	0.1

TABLE I. Material properties of diamond, Si, and Ge (from Refs. [22–24] unless otherwise stated).



3C-SiC: cubic unit cell (Zincblende)	
Energy gaps, $Eg_{\mathrm{ind}}(\Gamma_{15v}$ -$X_{1c})$	2.416(1) eV
Energy gaps, Eg	2.36 eV
Energy gaps, $Eg_{\mathrm{dir}}(\Gamma_{15v}$ -$X_{1c})$	6.0 eV
Excitonic Energy gaps, Eg_x	2.38807(3) eV

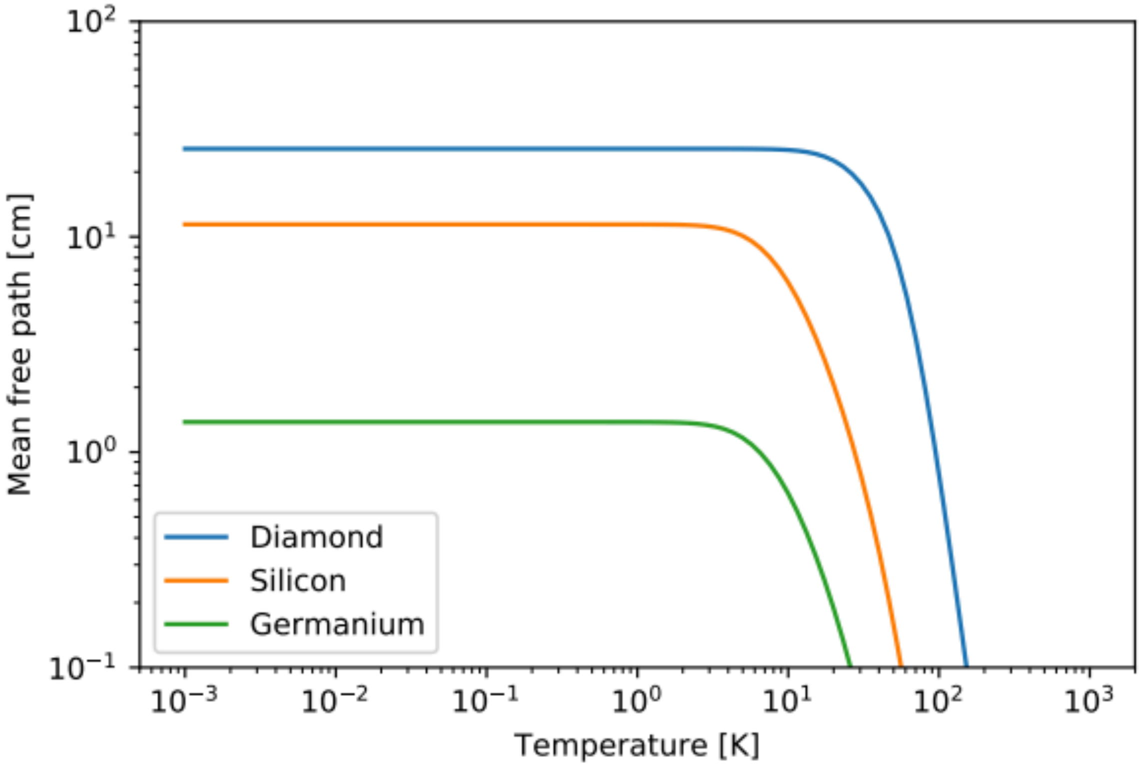
Optical photon energy	*3C*-SiC	102.8 meV
	4H-SiC	104.2 meV
	6H-SiC	104.2 meV

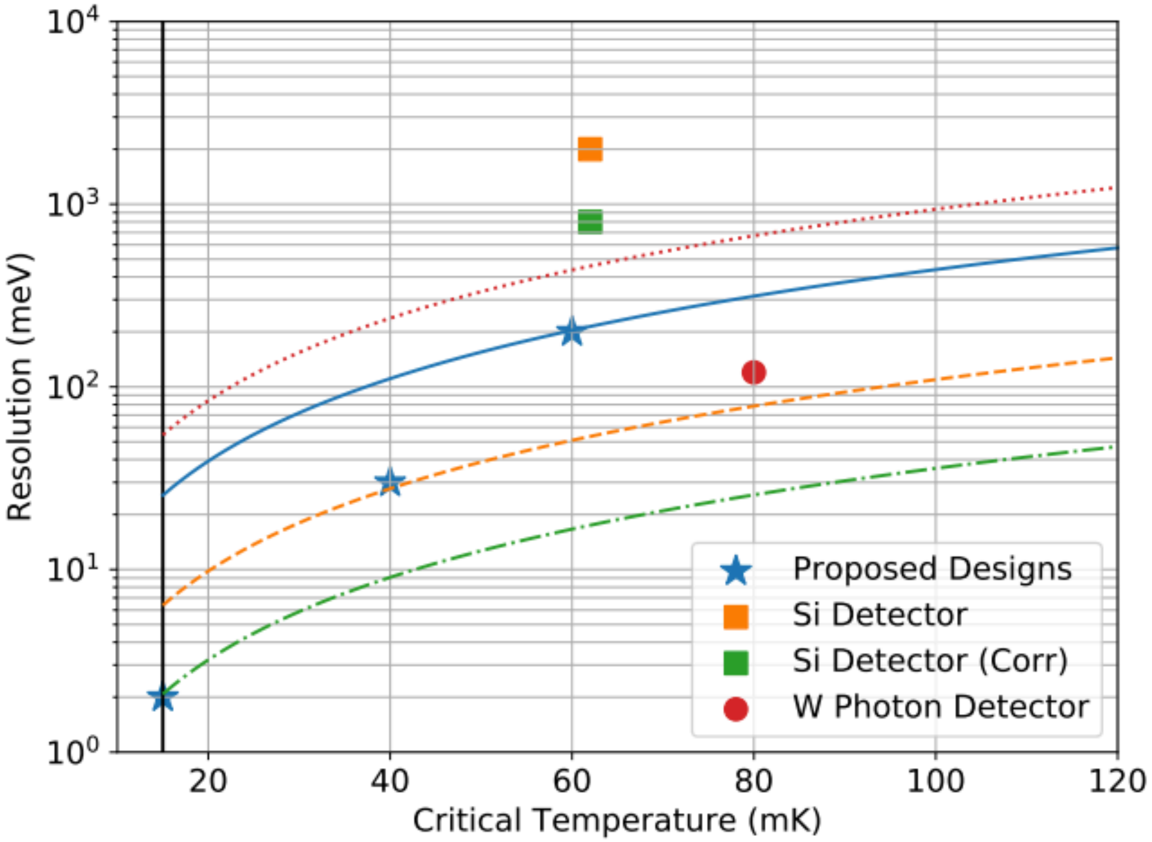
Example: Diamond Calorimeter

- Diamond, Ge, and Si have similar phonon characteristics, but diamond has higher energy, longer-lived phonon modes
- Phonons are 3x faster than in Si, 4x faster than in Ge
- Phonon lifetime is limited by crystal size to much higher temperatures - larger crystals have less phonon down-conversion
- It is easier to improve resolution by simply making the TES volume smaller, since the phonons can be allowed to bounce around the crystal more without down-conversion
- Here we consider ~30-300 mg crystals in order to minimize phonon collection time, such that the readout in TES dominated at all critical temperatures and phonon sensor geometries

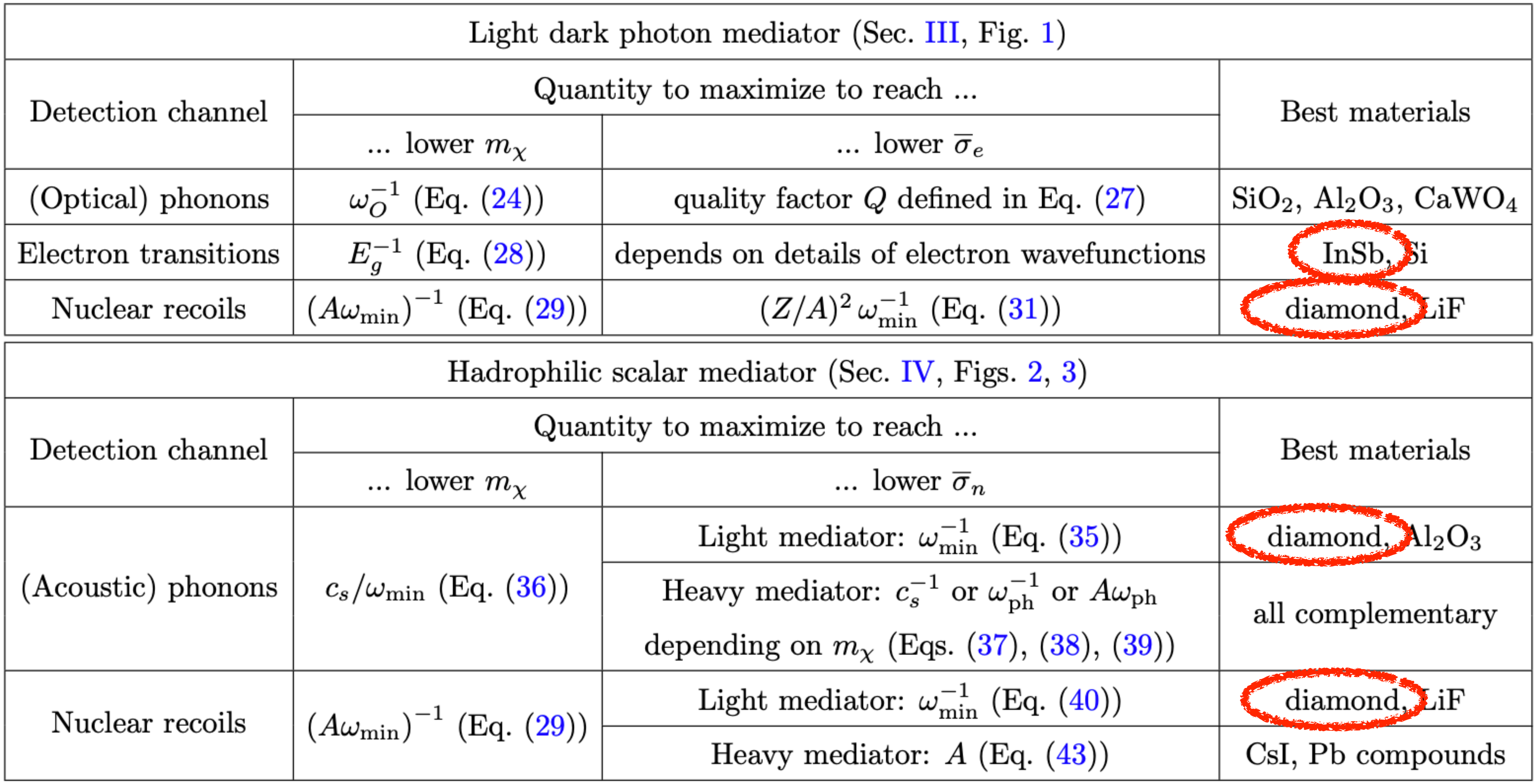
$$\sigma_e \geq \frac{\sqrt{4k_b T_c^2 C}}{\sqrt{5}\epsilon} \approx \frac{1}{\epsilon}\sqrt{\frac{2k_b \gamma T_c^3 V_{\mathrm{TES}}}{(\mathcal{L}-1)}}$$

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)





Best Materials (of Crystals)



Light dark photon mediator (Sec. III, Fig. 1)

Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_e$	
(Optical) phonons	ω_O^{-1} (Eq. (24))	quality factor Q defined in Eq. (27)	SiO_2, Al_2O_3, $CaWO_4$
Electron transitions	E_g^{-1} (Eq. (28))	depends on details of electron wavefunctions	InSb, Si
Nuclear recoils	$(A\omega_{\min})^{-1}$ (Eq. (29))	$(Z/A)^2\,\omega_{\min}^{-1}$ (Eq. (31))	diamond, LiF

SiC

Hadrophilic scalar mediator (Sec. IV, Figs. 2, 3)

Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_n$	
(Acoustic) phonons	$c_s/\omega_{\min}$ (Eq. (36))	Light mediator: $\omega_{\min}^{-1}$ (Eq. (35))	diamond, Al_2O_3
		Heavy mediator: c_s^{-1} or $\omega_{\rm ph}^{-1}$ or $A\omega_{\rm ph}$ depending on m_χ (Eqs. (37), (38), (39))	all complementary
Nuclear recoils	$(A\omega_{\min})^{-1}$ (Eq. (29))	Light mediator: $\omega_{\min}^{-1}$ (Eq. (40))	diamond, LiF
		Heavy mediator: A (Eq. (43))	CsI, Pb compounds

- Easy to make a case for Diamond/SiC + Sapphire + low gap (InSb, etc) to carve out next round of low-mass (keV - GeV) dark matter parameter space (from https://arxiv.org/pdf/1910.10716.pdf, Griffin et. al. 2019)

Summary of Future Work

- Continuing QET R&D
  - Still can improve efficiency by 2x
  - Find ways to move to small TES (photolithography, etc) at same Tc, reduce impact of wiring (e.g. Nb wires)
  - Push to lower Tc
  - Need to mitigate extant source of environmental noise, which is a large challenge with current electronics
  - Explore new TES films (IrPt, AlMn)

- Mitigate Leakage in HV devices
  - Blocking layers or new materials
  - Contact-free design being pioneered by Mirabolfathi group at TAMU

- Explore KID readout
  - Al and AlMn KIDs being studied by Caltech/FNAL
  - Implicit advantage for massive multiplexing

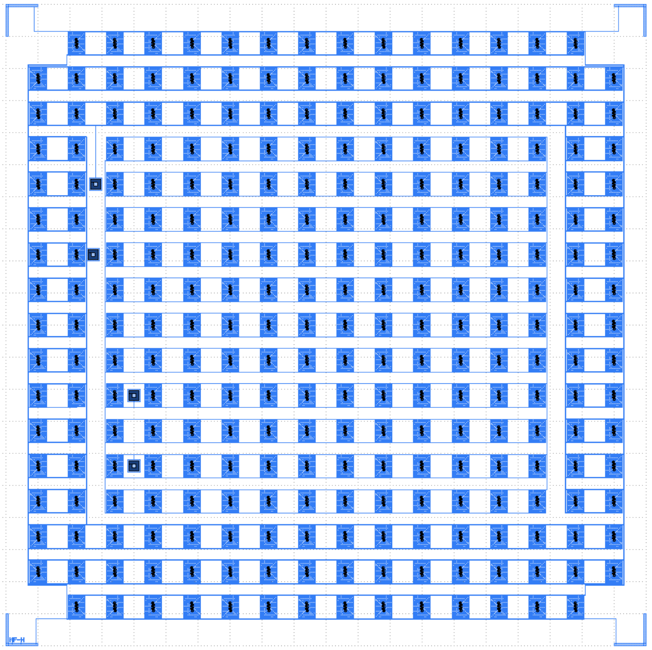
- Moving to new materials
  - Making devices from Sapphire, Diamond, SiC
  - Demonstrating HVeV performance on Ge
  - Use superior material properties to scale in mass and threshold over Si performance

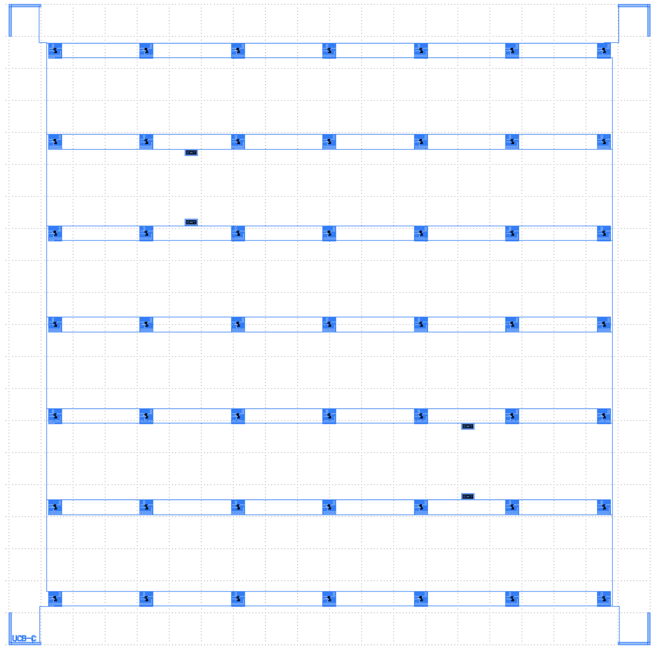
Backup

HVeV v2 1cm Designs

- Best for NR
  - UCB A/C - low coverage, single channel
  - 600 mOhm normal state resistance
- Best for ERDM
  - Optimized for baseline resolution with varying levels of Al coverage
  - 900 mOhm Rn - NF F, G, H
  - 300 mOhm Rn - NF A, D, E
    - NF-A is roughly the same as QP.4, i.e. AR64
- Best for Calibrations
  - Sacrifice baseline resolution for higher dynamic range
  - 300 mOhm normal state - NF-B/C

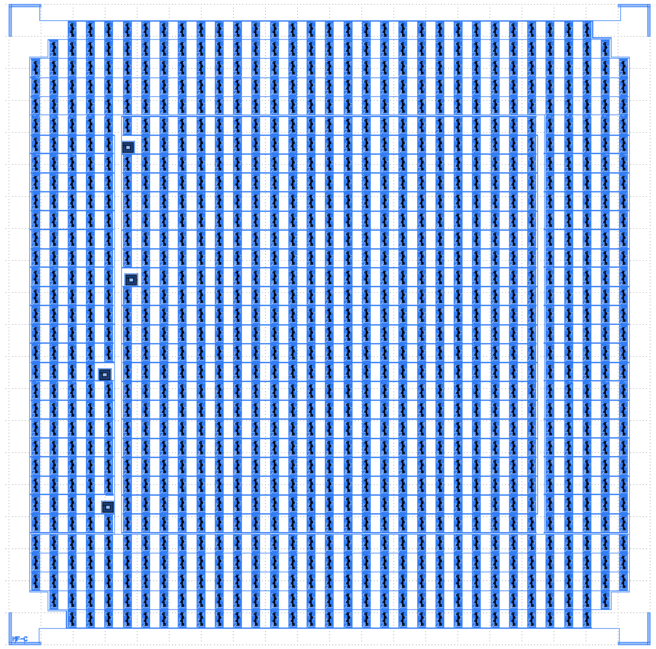
NF-H





UCB-C

NF-C



https://confluence.slac.stanford.edu/display/CDMS/HVeV+v2+Design

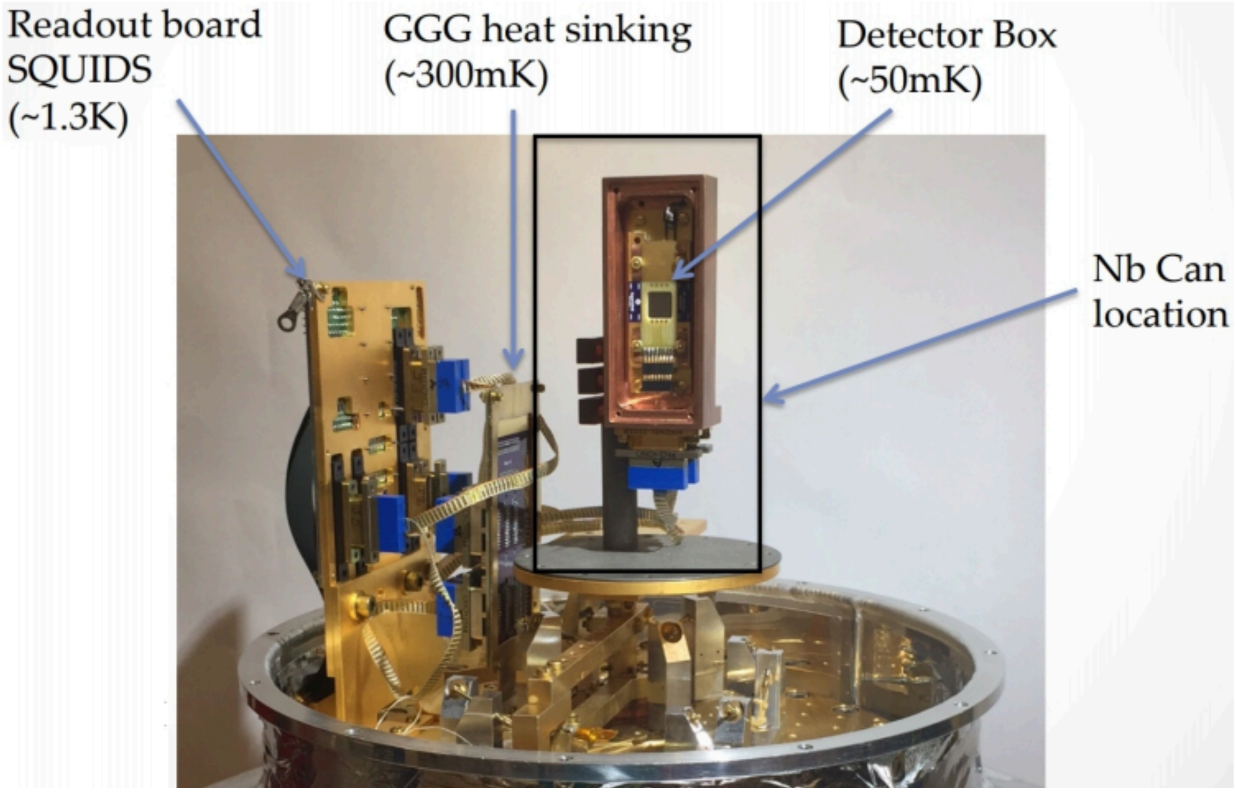
NEXUS Si/Ge Dark Matter Search Timeline

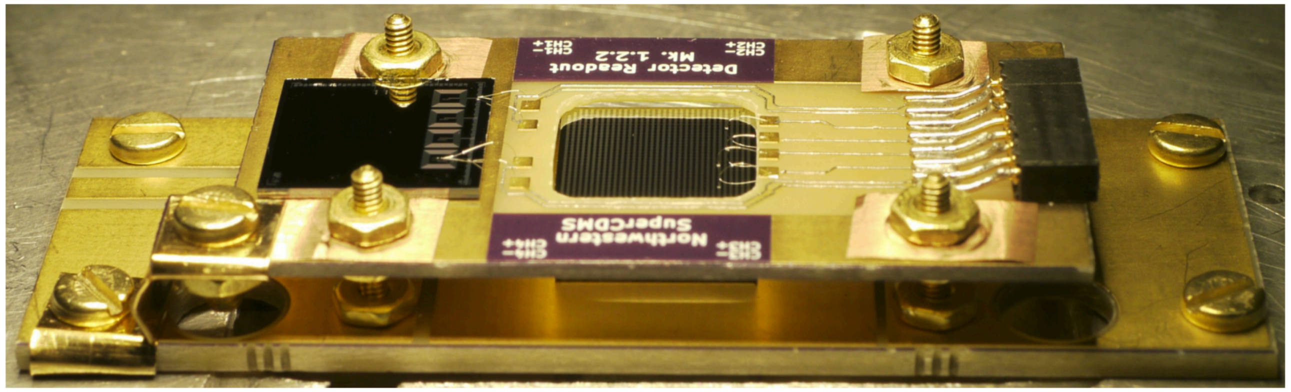
- Spring-Fall 2019 (ADR Demonstrator): 1 gram
  - 1 gram, 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 4 keV in energy
  - DM search with 1 gram-week

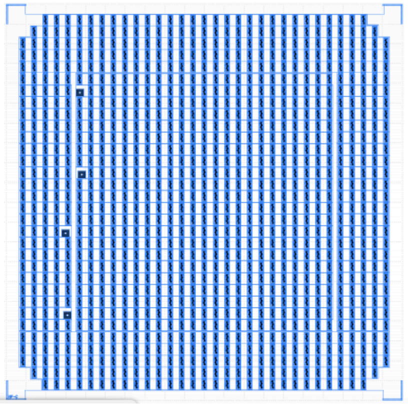
- Winter 2019 - Spring 2020: 10 grams,
  - 2-4 ~4g detectors
  - 4 eV resolution (20 eV threshold),
  - 0.01 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 40 keV in energy
  - DM search with 1 gram-month

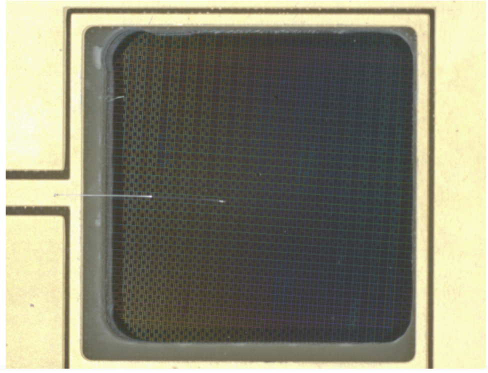
- Late 2020 - 2021: 30-100 grams,
  - 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution
  - 4 eV to 40 keV in energy
  - DM search with 1-10 gram-year (~kg day)

- 2021+: 10 kg payload
  - <20 eV threshold
  - Up to 60 keV in energy
  - 0.01 electron-hole pair resolution
  - DM search/***neutrino physics*** with 1 kg-year of exposure









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Leakage R&D

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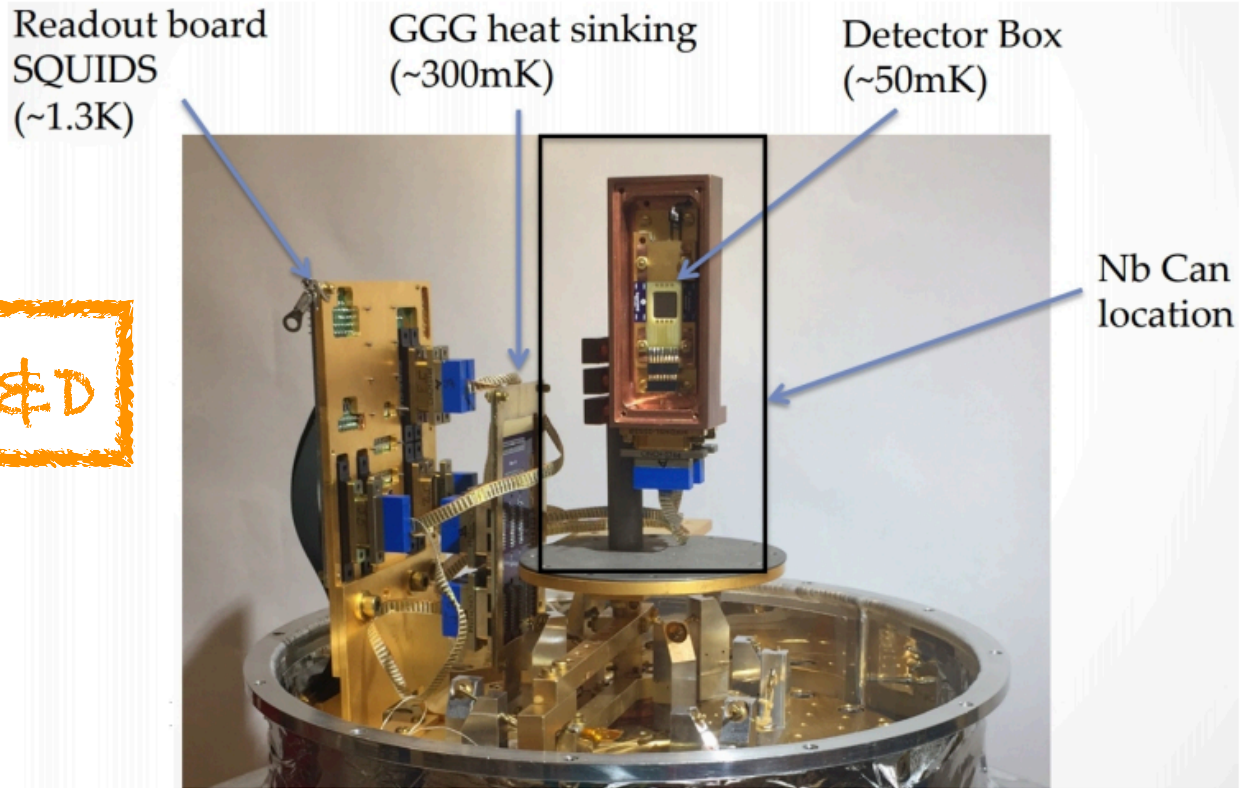
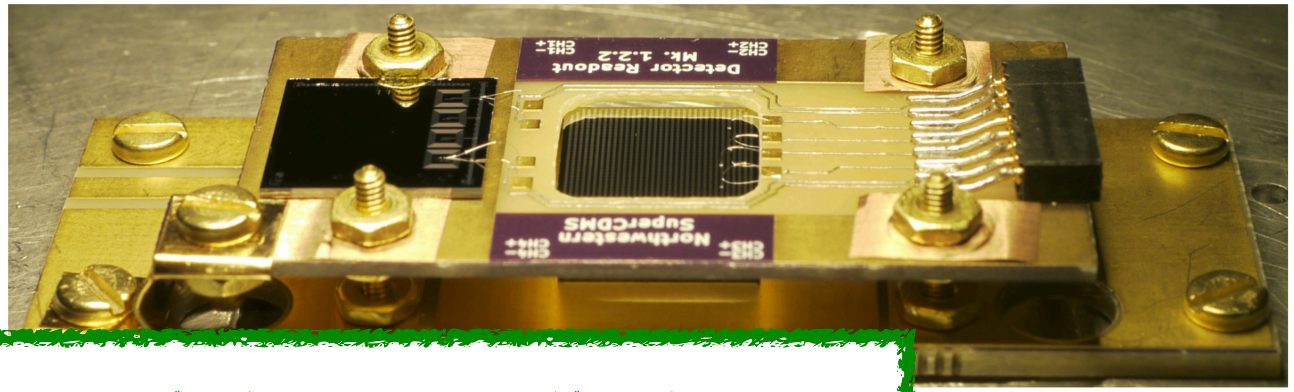
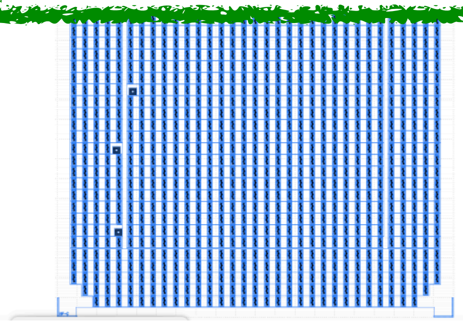
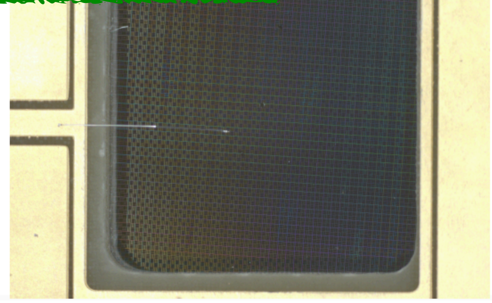
  - <20 eV threshold
  - Up to 60 keV in energy
  - 0.01 electron-hole pair resolution
  - DM search/***neutrino physics*** with 1 kg-year of exposure





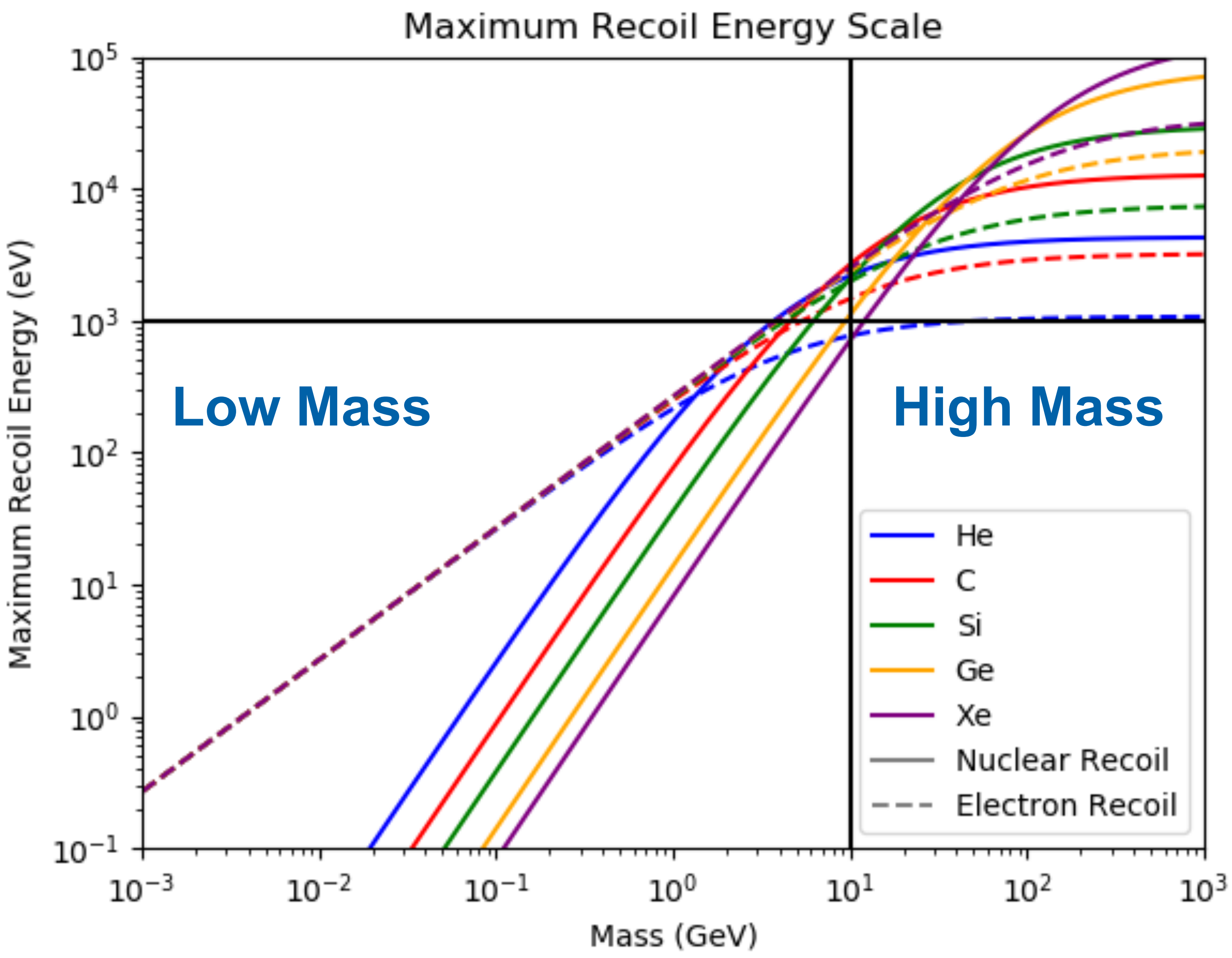
Larger Crystals or Multiplexing





Collision Kinematics

- Recoil energy for a typical WIMP velocity depends on target mass and recoil type
- Electron and nuclear recoils have different kinematics; nuclear recoils are simple elastic collisions, electron recoils are largely inelastic and depend on electron orbital and kinematics within the bound electron-atom system
- In addition to momentum transfer for a fixed velocity, using a velocity and angular distribution yields an expected energy spectrum



$$m_{\chi,NR} \geq \frac{\sqrt{2m_T\sigma_E}}{v}$$

$$m_{\chi,ER} \geq \frac{2\sigma_E}{v^2}$$

$$\Delta E_{NR} \leq \frac{1}{2m_N}q^2_{max} = \frac{m_N v^2}{2}\left(\frac{2m_\chi}{m_\chi + m_N}\right)^2$$

$$\Delta E_{ER} \leq \frac{1}{2}\mu_{N\chi}v^2 = \frac{m_N v^2}{2}\left(\frac{m_\chi}{m_\chi + m_N}\right)$$

Collision Kinematics

- Recoil energy for a typical WIMP
  velocity depe
  recoil type

- Electron and
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  recoils are la
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- In addition to
  fixed velocity
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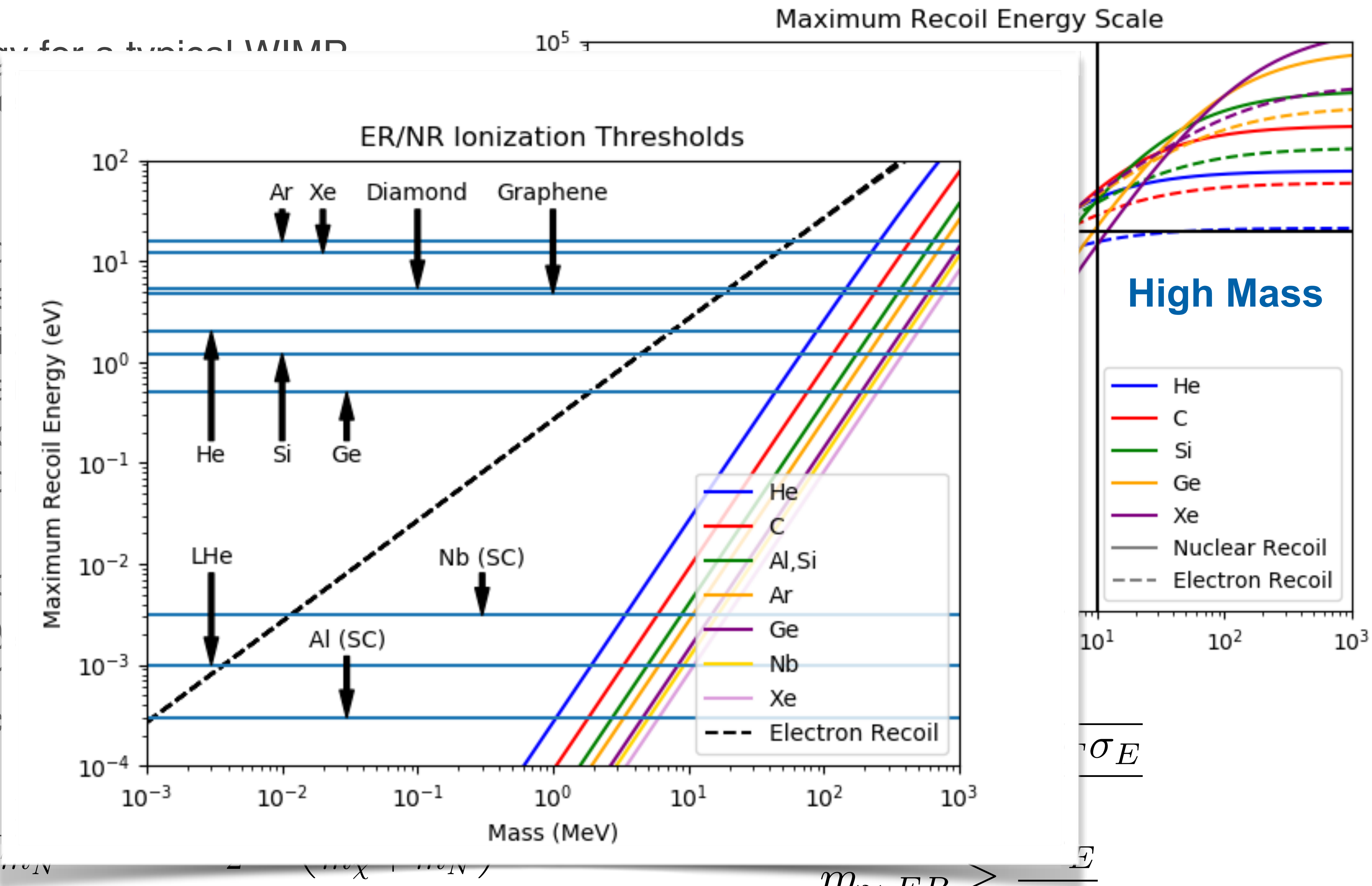


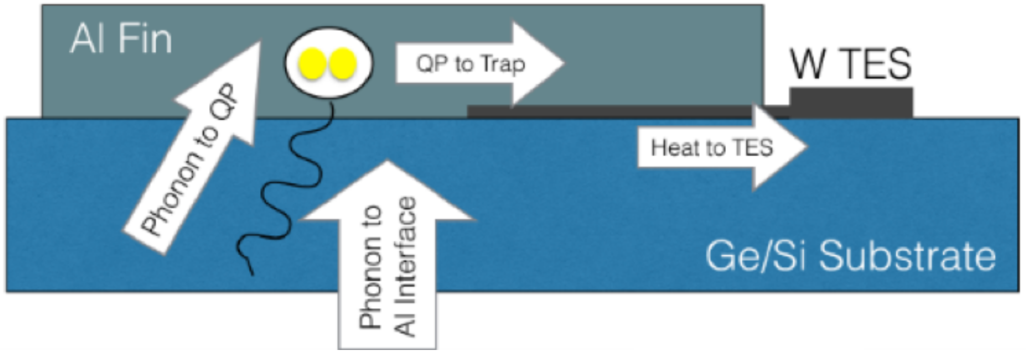
σ_E

$\Delta E_{NR} \le$

$$m_{\chi,ER} \ge \frac{E}{v^2}$$

$$\Delta E_{ER} \le \frac{1}{2}\mu_{N\chi}v^2 = \frac{m_N v^2}{2}\left(\frac{m_\chi}{m_\chi + m_N}\right)$$

Calorimeter Resolution

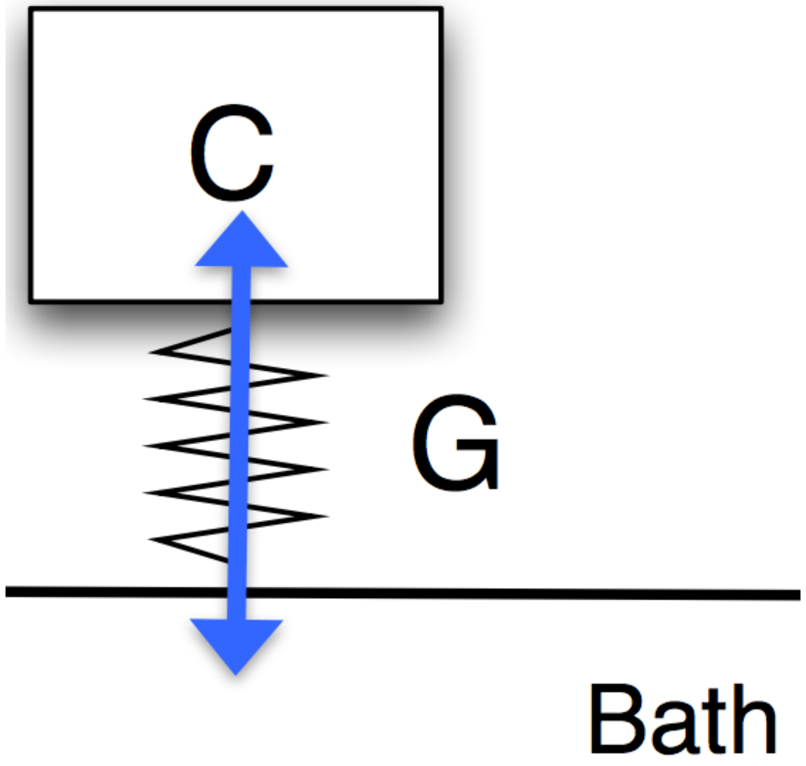


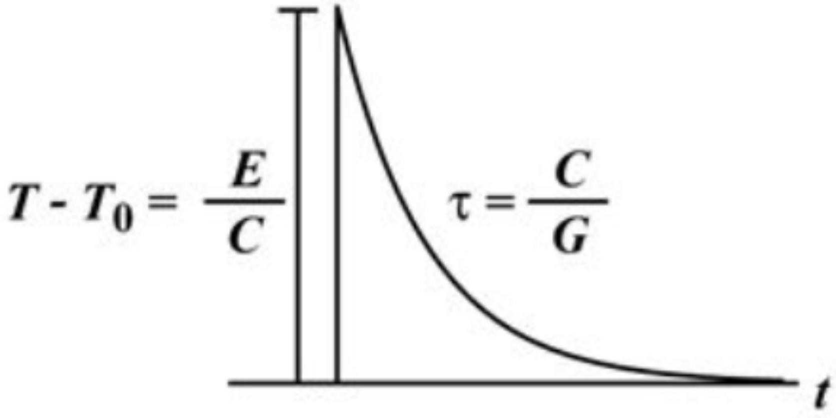
- Calorimeter energy resolution is fundamentally limited by thermal fluctuations between the sensing volume and the bath regardless of detector geometry; this minimum resolution follows

$$\sigma_E^2 = \frac{G k_b T^2}{\epsilon^2}\tau = \frac{C k_b T^2}{\epsilon^2} \approx cV\frac{k_b T^3}{\epsilon^2}$$

- One way around the volume limitation is by collecting the energy before thermalization; the volume is thus the sensor volume, not the target volume

- Even with target decoupling, the tradeoff between sensor volume and energy efficiency requires temperatures below ~50 mK for sub-GeV dark matter





Aside: History and Economics

- Diamond have been used as ionization-chamber style charge detectors since the 70's
- The main barrier historically was cost, purity, and form factor
  - The lack of man-made diamonds meant groups normally had to rely on a source with access to natural diamond, and select the few diamonds with the best performance
- In the last 5 years, the cost of high-quality lab-grown diamond has dropped from ~$6000/carat to $2000/carat, and recently gem-gem-quality diamonds could be purchased by consumers for $800/carat
- This is driven by the electronics industry, which is aiming to use diamond both as a heat sink and as a semiconductor for high-high-power, high-temperature transistors
- Diamonds have also come into use as a potential storage medium for quantum computing

elementsix™ a De Beers Group Company

EL SC Plate 4.5x4.5mm, 0.50mm thick

Quantum / Radiation Detectors

Single Crystal

145-500-0390

$2,150.00

30 mg

A Battle Over Diamonds: Made by Nature or in a Lab?

By Paul Sullivan

Feb. 9, 2018

The New York Times

LIGHTBOX

LABORATORY-GROWN DIAMONDS

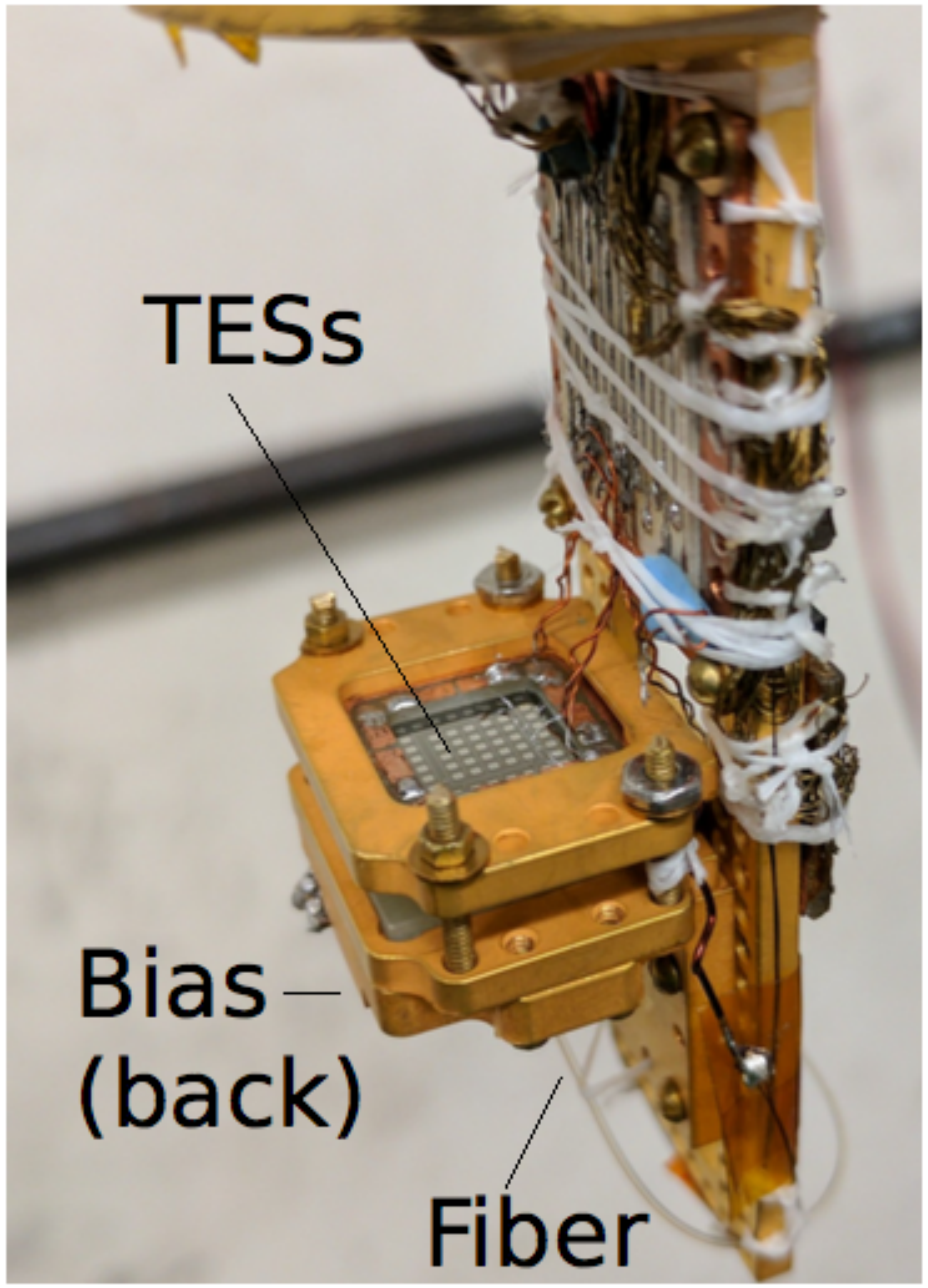
200 mg

1 CARAT
$800

Experimental Setup

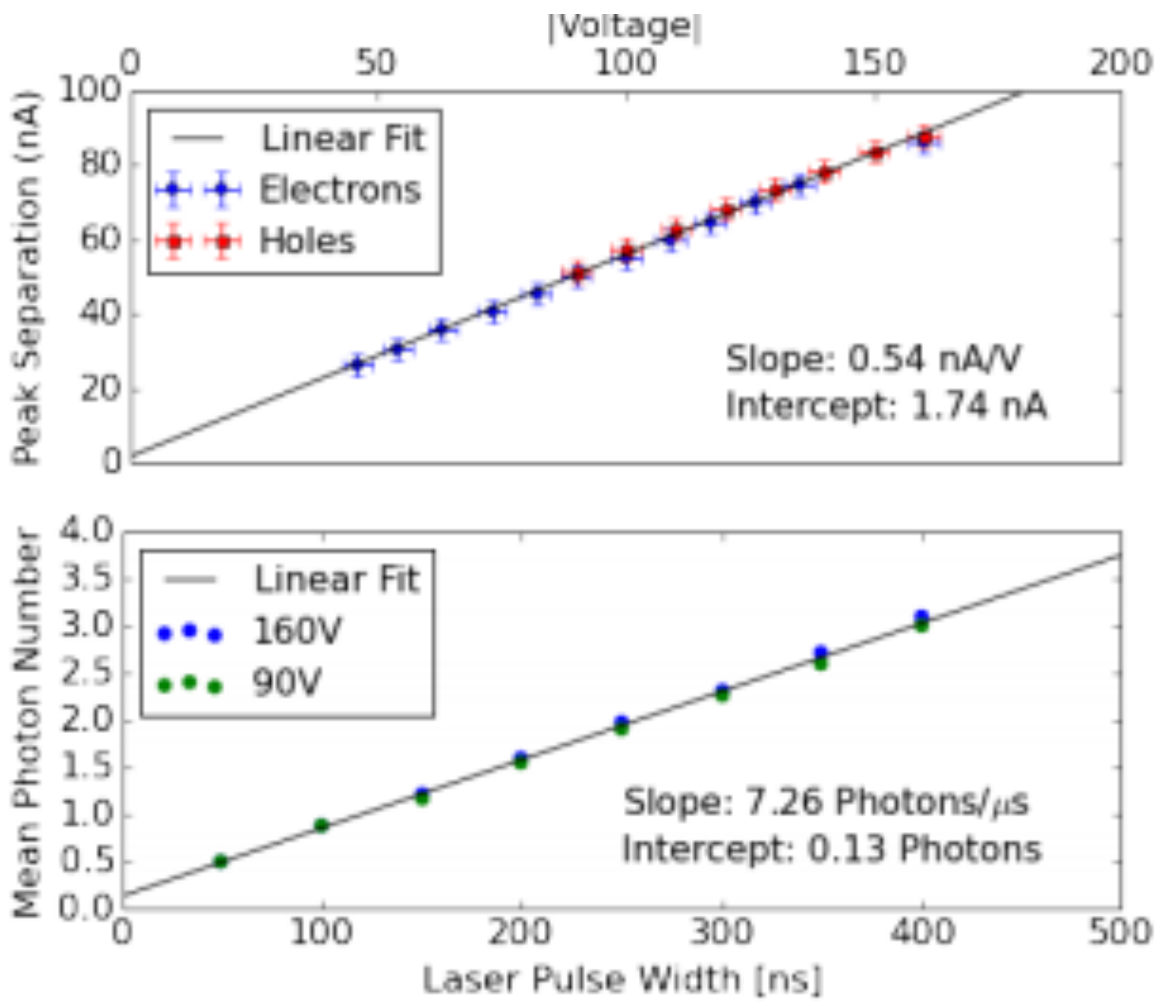
Laser Excitation System:

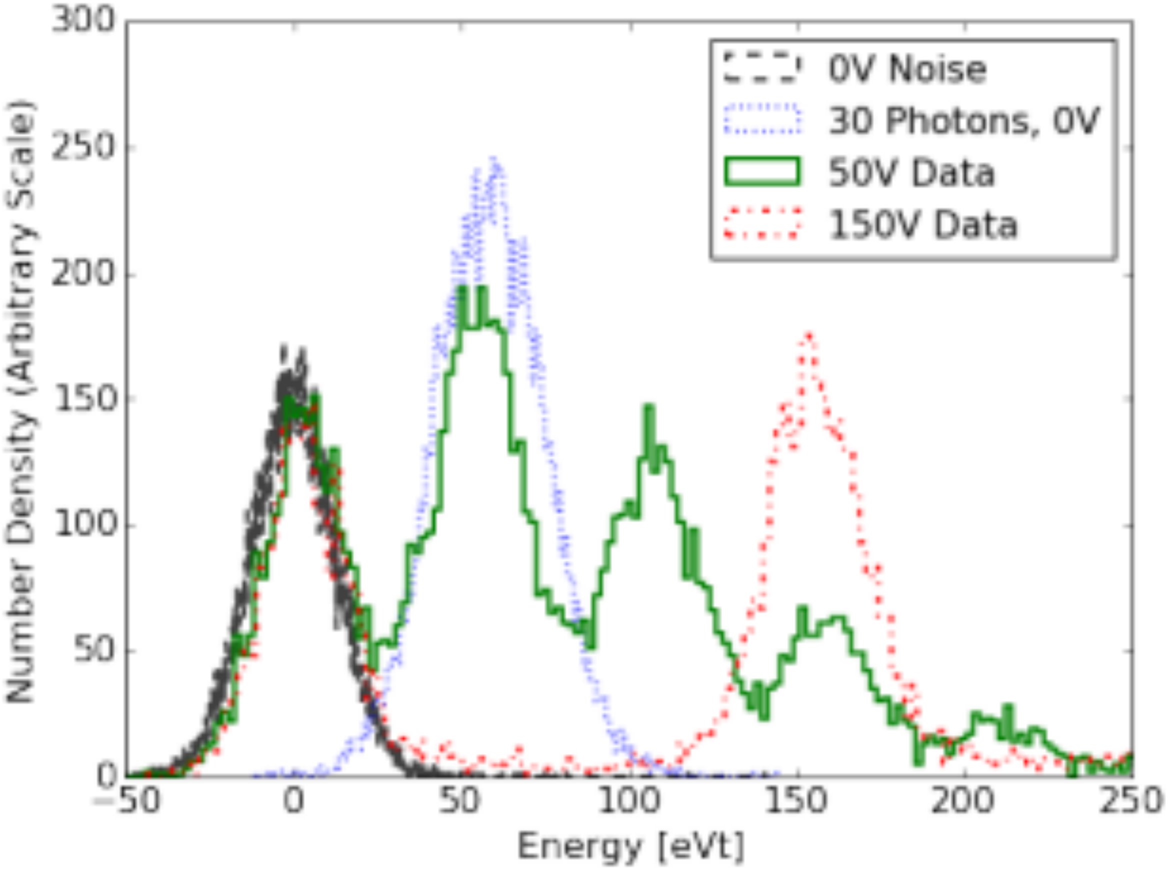
- Ran fiber from 300 K to sample stage, illuminates crystal backside
- Berkeley Nucleonics laser pulse system, 650 nm photons, pulse widths > 10 ns
- Trigger on the laser pulse
- Standard Si physics:
  - 1.9 eV per photon
  - 1.2 eV to e-h pair
  - 0.7 eV prompt phonons
  - Get full 1.9 eV of phonons back at sensor
- Studied Luke gain under a variety of bias conditions



Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Results from Stanford Test Detector: Linearity





- Energy gain is linear in voltage up 160V - highest voltage testable within safety limits of our electronics
- Clear separation seen between 0 and 1 photon peaks!
- Noise does not increase with voltage; we achieve the best signal/noise scaling possible for this technique

Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Non-Quantized Backgrounds

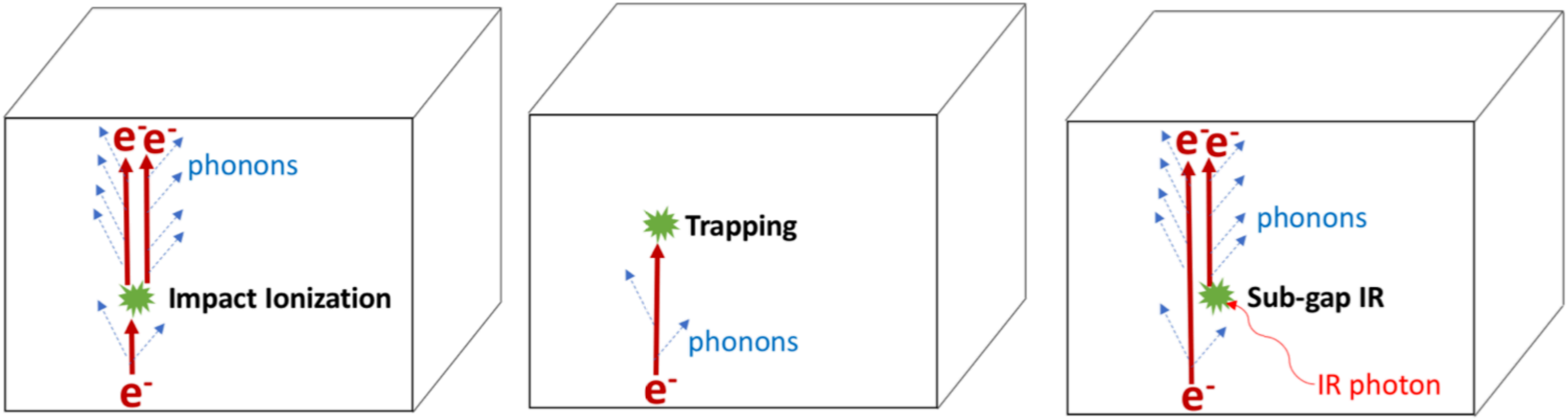


Figure Courtesy R.K. Romani

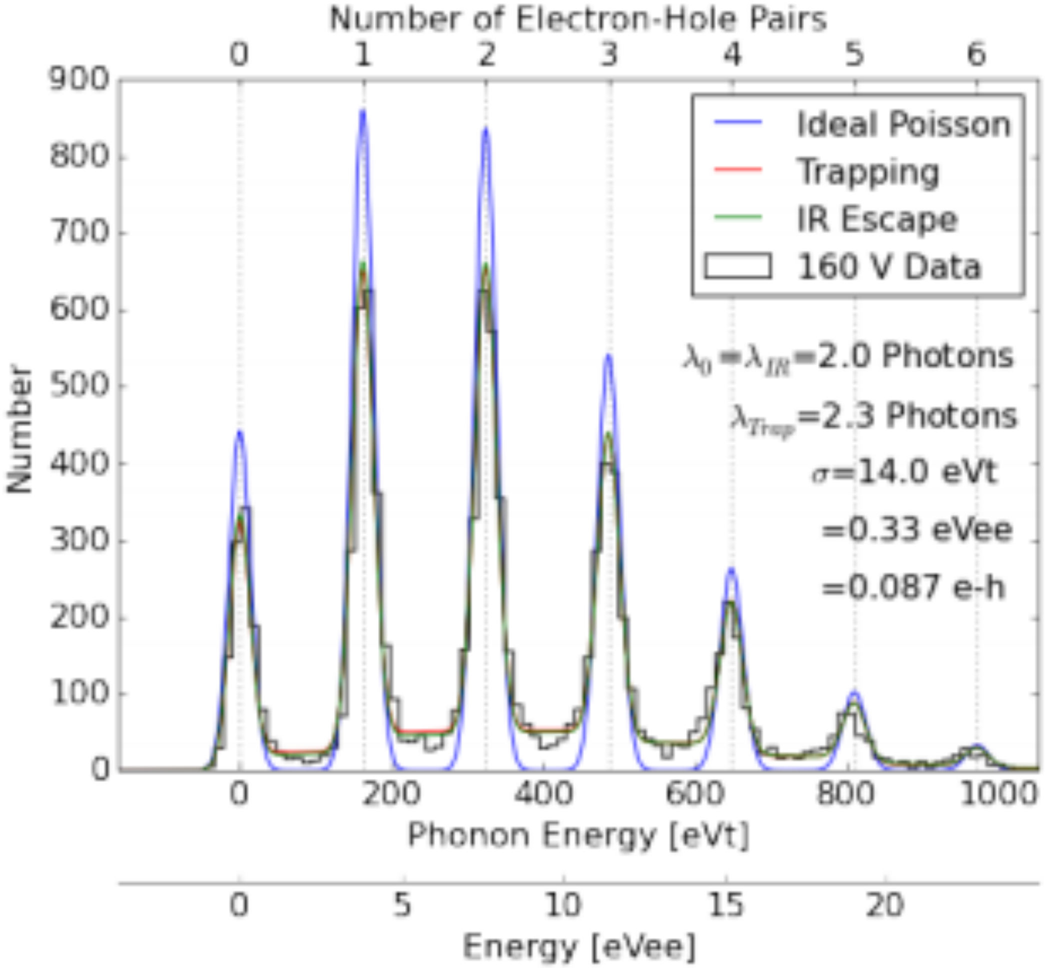
- During the initial experiment we saw that 15% of the events were non-quantized, which can be due to additional charge liberated from impurity states
  - Impact ionization: drifting charge ionizes an impurity
  - Trapping: drifting charge stopped by an impurity
  - IR: shallow impurity wells liberated by IR leaking in from warmer stages

- Hypothesis pointed to IR as the dominant cause due to high correlation with laser activity

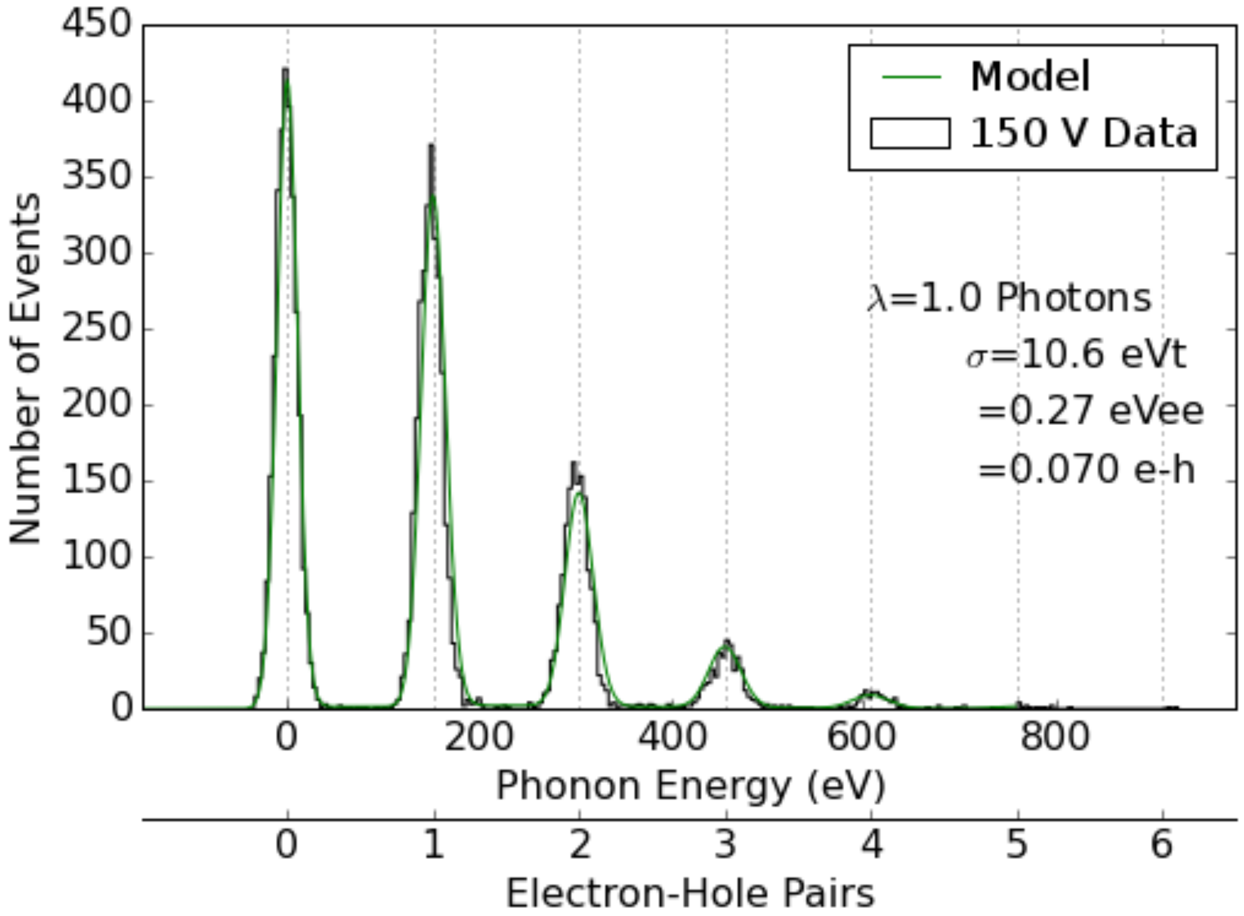
Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Effect of IR Filtering

Romani et. al. 2018 (https://arxiv.org/abs/1710.09335)



SuperCDMS Collaboration 2018 (https://arxiv.org/abs/1804.00088)



- Adding additional IR filtering improved fill-in regions between laser calibration peaks, validating the idea that our laser and background data was IR limited

- The calibration data after IR filtering is consistent with impact ionization/trapping at the 2-3% level

Impurity Binding Energies

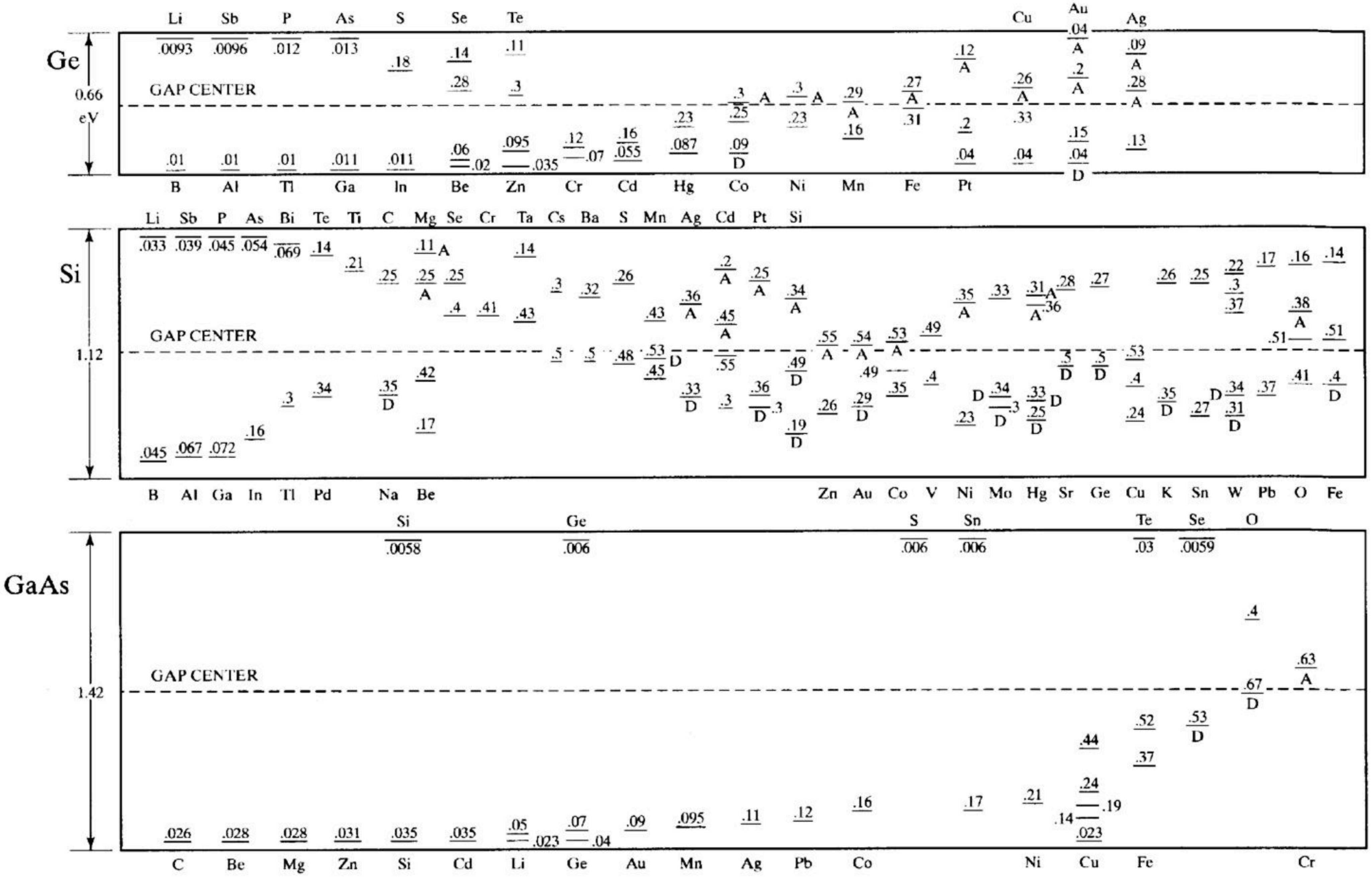


Figure 4.14 Measured ionization energies for the most commonly encountered impurities in Ge, Si, and GaAs. The levels above midgap are referenced to E_c and are donor-like or multiply charged donors, unless marked with an A which identifies an acceptor level. The levels below midgap are referenced to E_v and are acceptor-like or multiply charged acceptors, unless marked with a D for donor level. (From Sze.[3] Reprinted with permission.)

~10^{11} cm^{-3}

~10^{13} cm^{-3}

Understanding Volume Leakage Backgrounds

- Some variation seen due to pre-bias
    - Need to increase pre-bias voltage range
    - Determine what voltage empties traps reliably
- Neutralization seems to have elevated bulk leakage by ~3 for a matter of days
- Voltage polarity flip doesn't change bulk leakage rate
- Neither change impacts leakage above 2.5 e-h pairs (to this level of statistics)