Semiconductors at the Single Electron Limit

Noah Kurinsky
Lederman Fellow, Fermi National Accelerator Laboratory

Neutrino-Electron Scattering at Low Energies, ACFI @ UMass Amherst

April 26, 2019

Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

~~Semiconductors~~ Solid State Crystals at the Single Electron Limit

Noah Kurinsky

Lederman Fellow, Fermi National Accelerator Laboratory

Neutrino-Electron Scattering at Low Energies, ACFI @ UMass Amherst

April 26, 2019

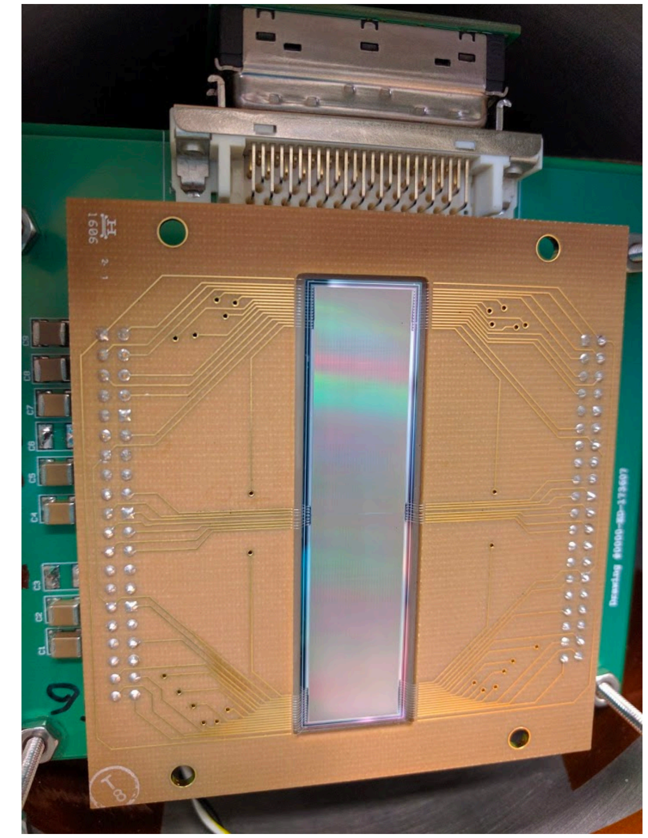
Overview

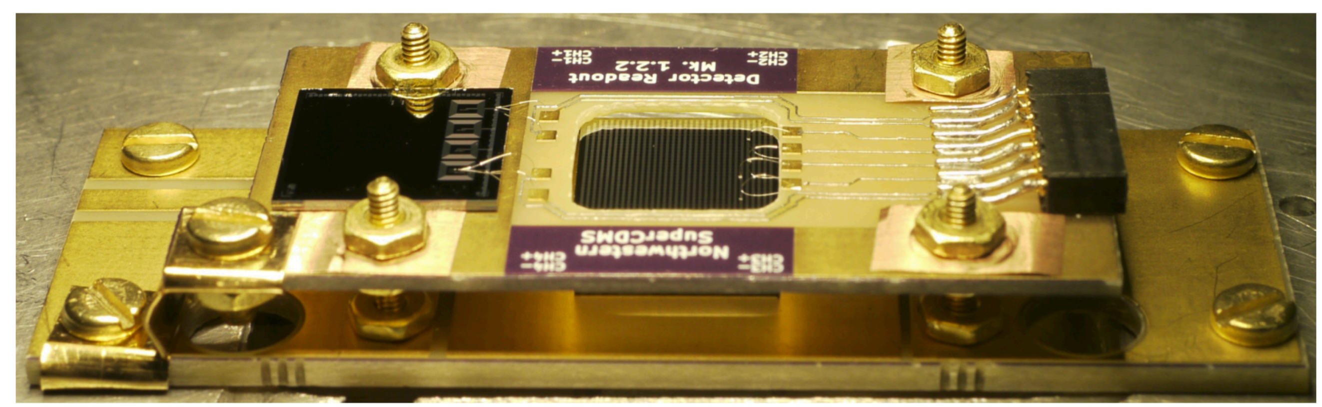
- What determines low-threshold performance?
  - Recoil kinematics
  - Charge yield and phenomenology

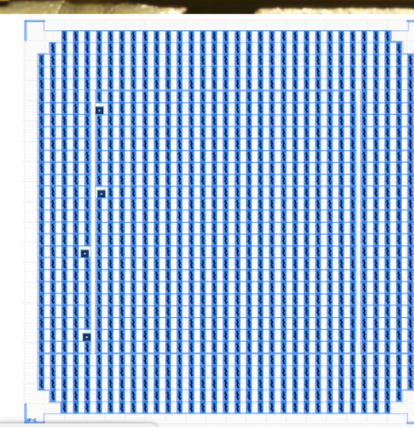
- What are the current technological challenges?
  - Charge readout resolution
  - Single photon detection
  - Low-threshold calorimetry
  - Dark rates are primary background challenge. Example: SuperCDMS HVeV

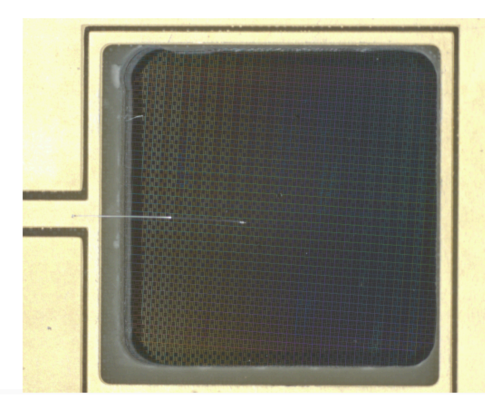
- New Low-Threshold Technologies
  - Low Z Calorimeters (e.g. Diamond)
  - Phonon resonance detectors
  - Superconducting Detectors

- Summary of Current R&D

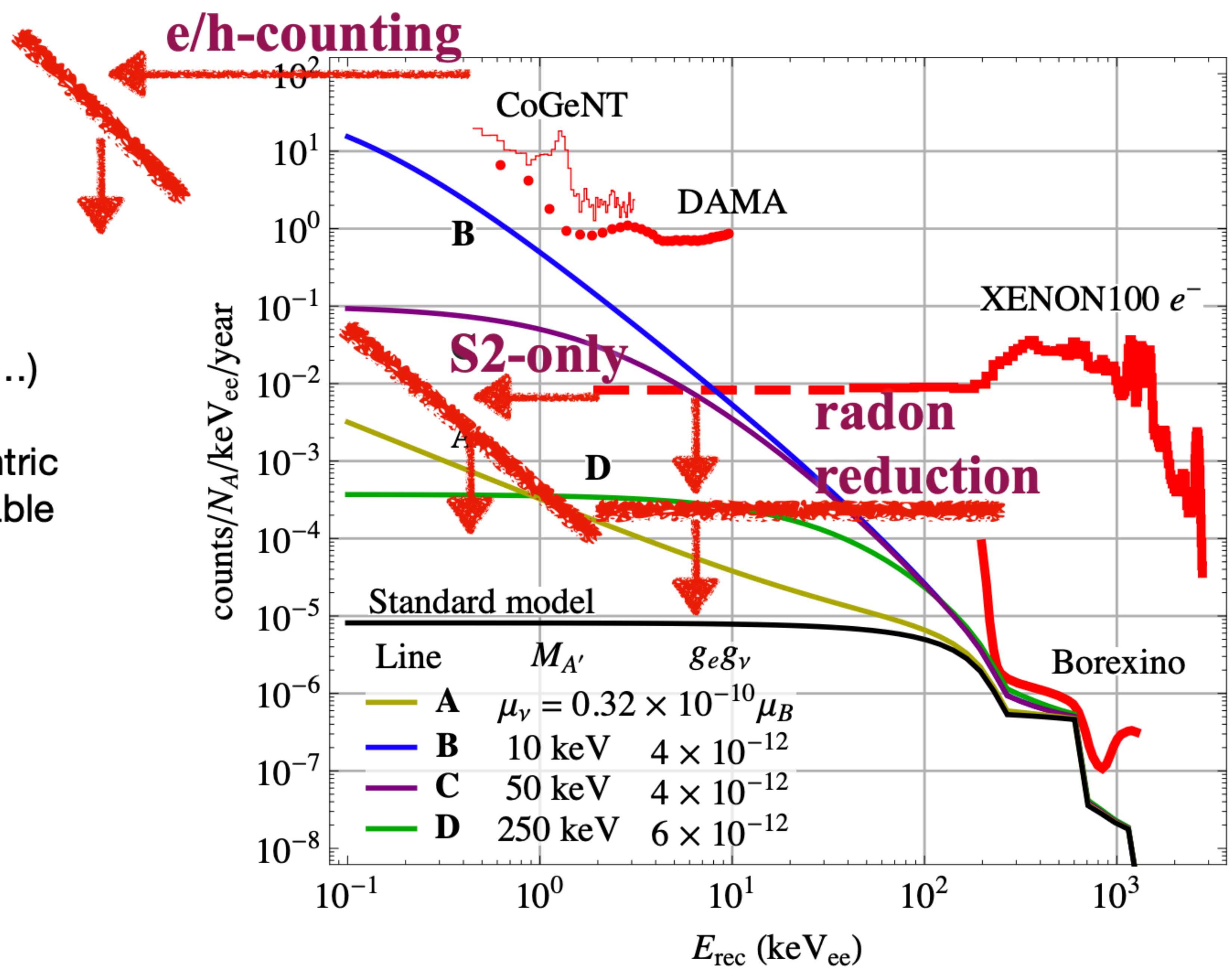








Single Electron Detectors in Context



(just rough sketches for now…)

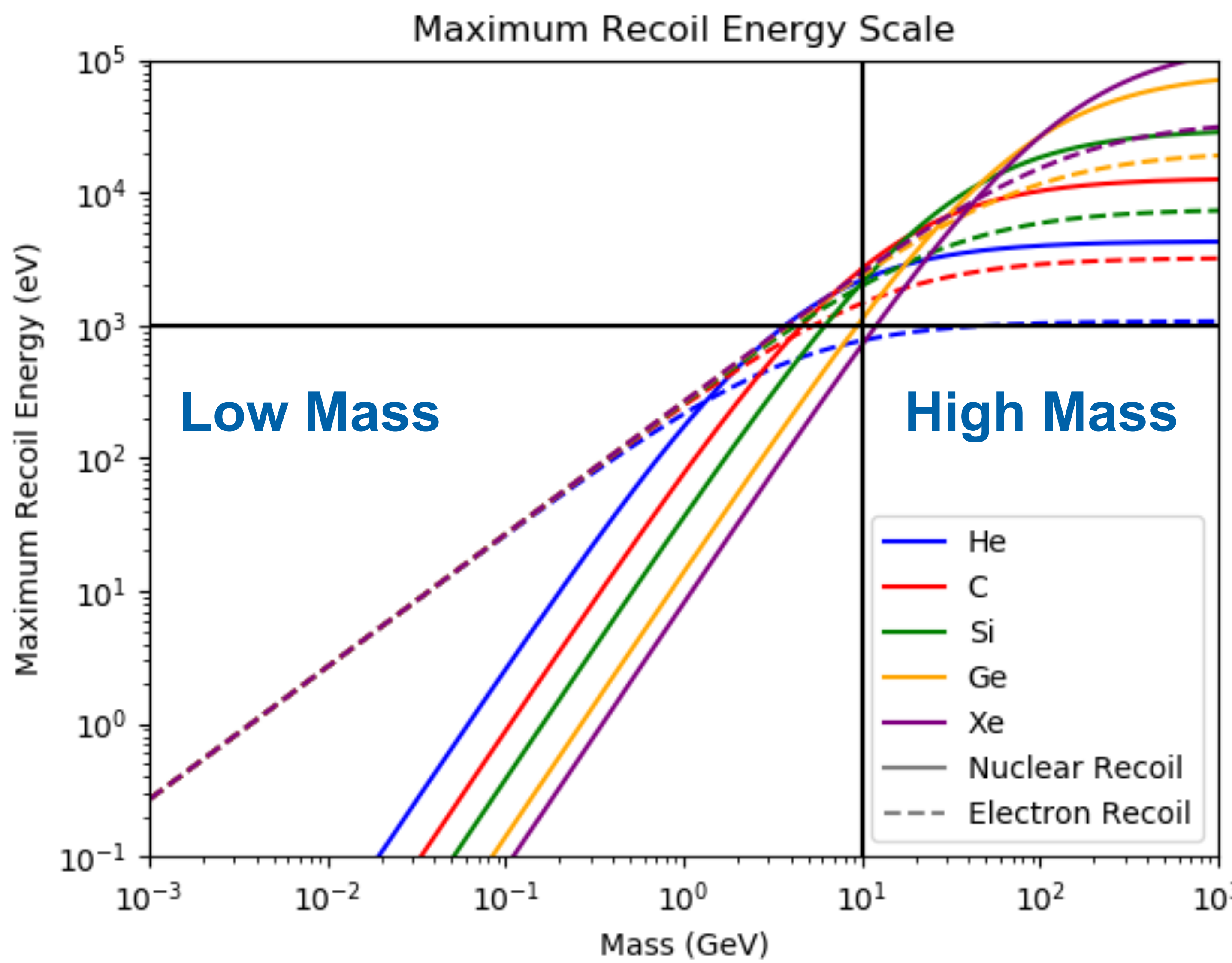
Point being: dark matter-centric R&D which is directly applicable

$$\frac{d\sigma_{EM}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

`Exploring nu signals in dark matter detectors'
Harnik, Kopp, Machado
arXiv:1201.6073

DM Collision Kinematics

- Recoil energy for a particle of a given mass and 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



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

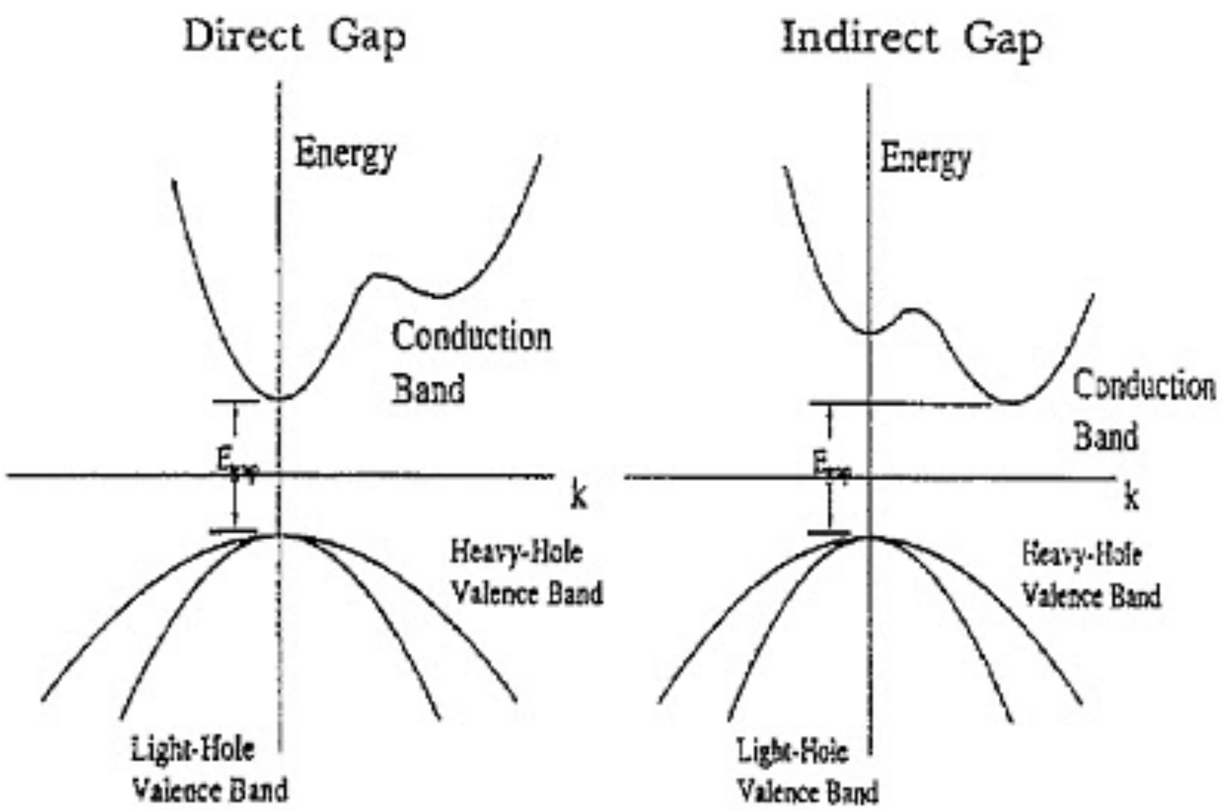
$$m_{\chi,ER} \geq \frac{2\sigma_E}{v^2}$$

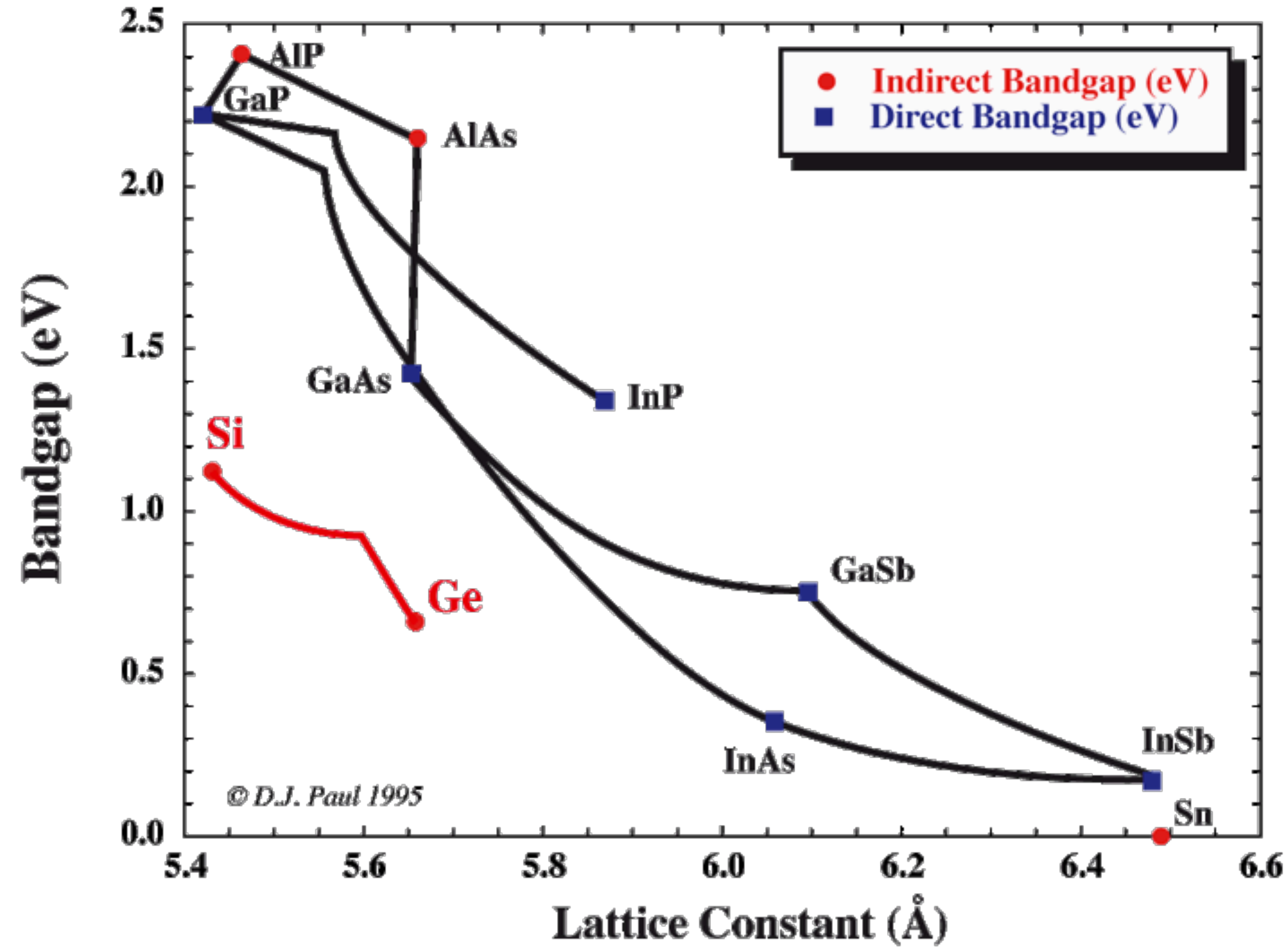
$$\Delta E_{NR} \leq \frac{1}{2m_N}q_{max}^2 = \frac{m_N v^2}{2}\left(\frac{2m_\chi}{m_\chi + m_N}\right)^2$$

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

Fermilab

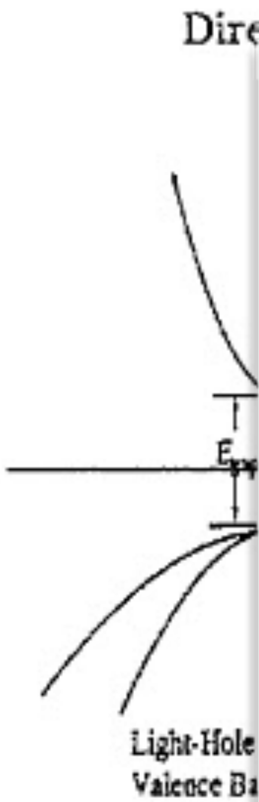
Charge Production: Semiconductors

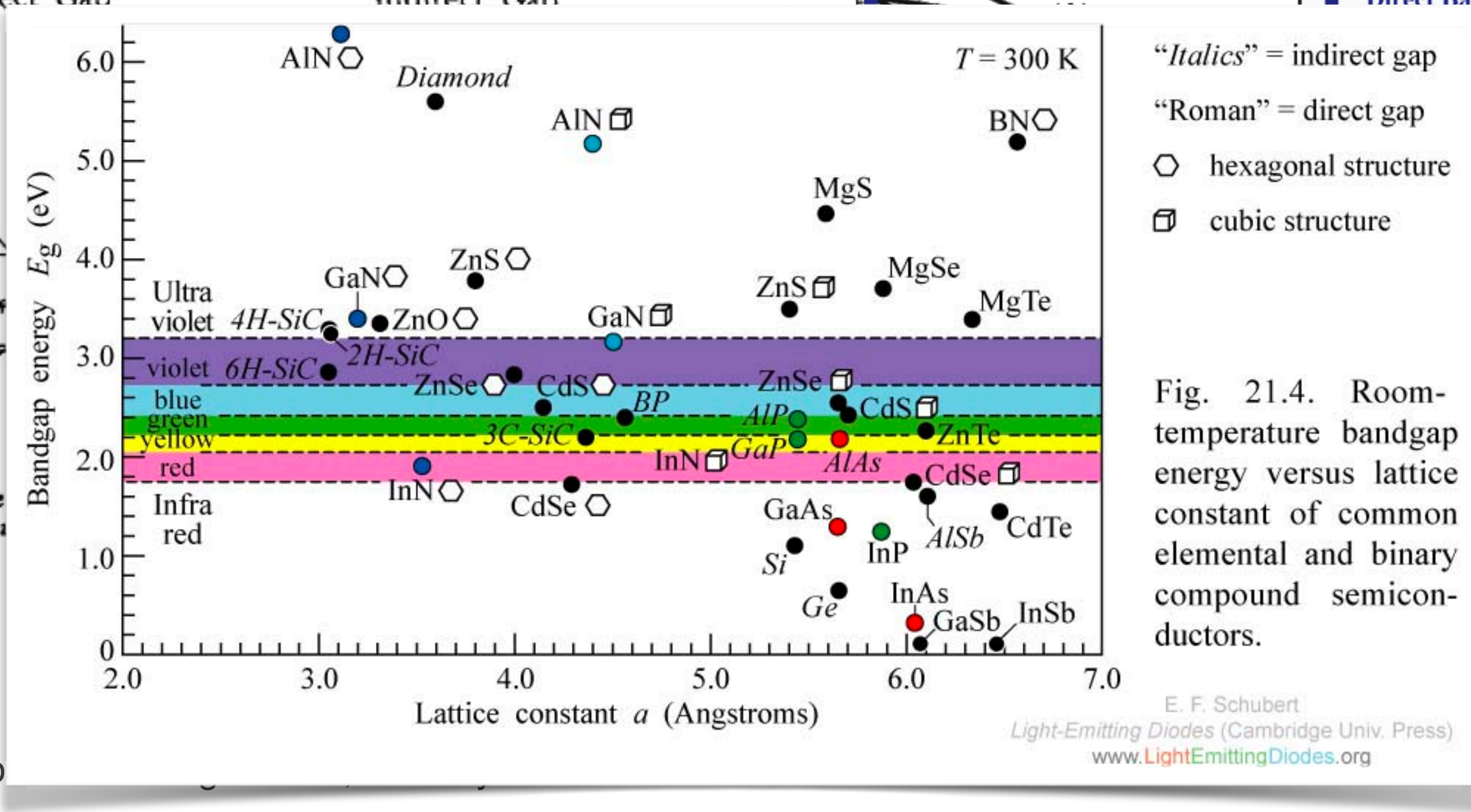




- Charges produced, and minimum photon energy, determined by material bandgap
- Bandgaps can be engineered, but only to some extent
- Indirect bandgaps require more energy to liberate electrons thermally, but are still sensitive radiation down to bandgap energies (though the efficiency is reduced)

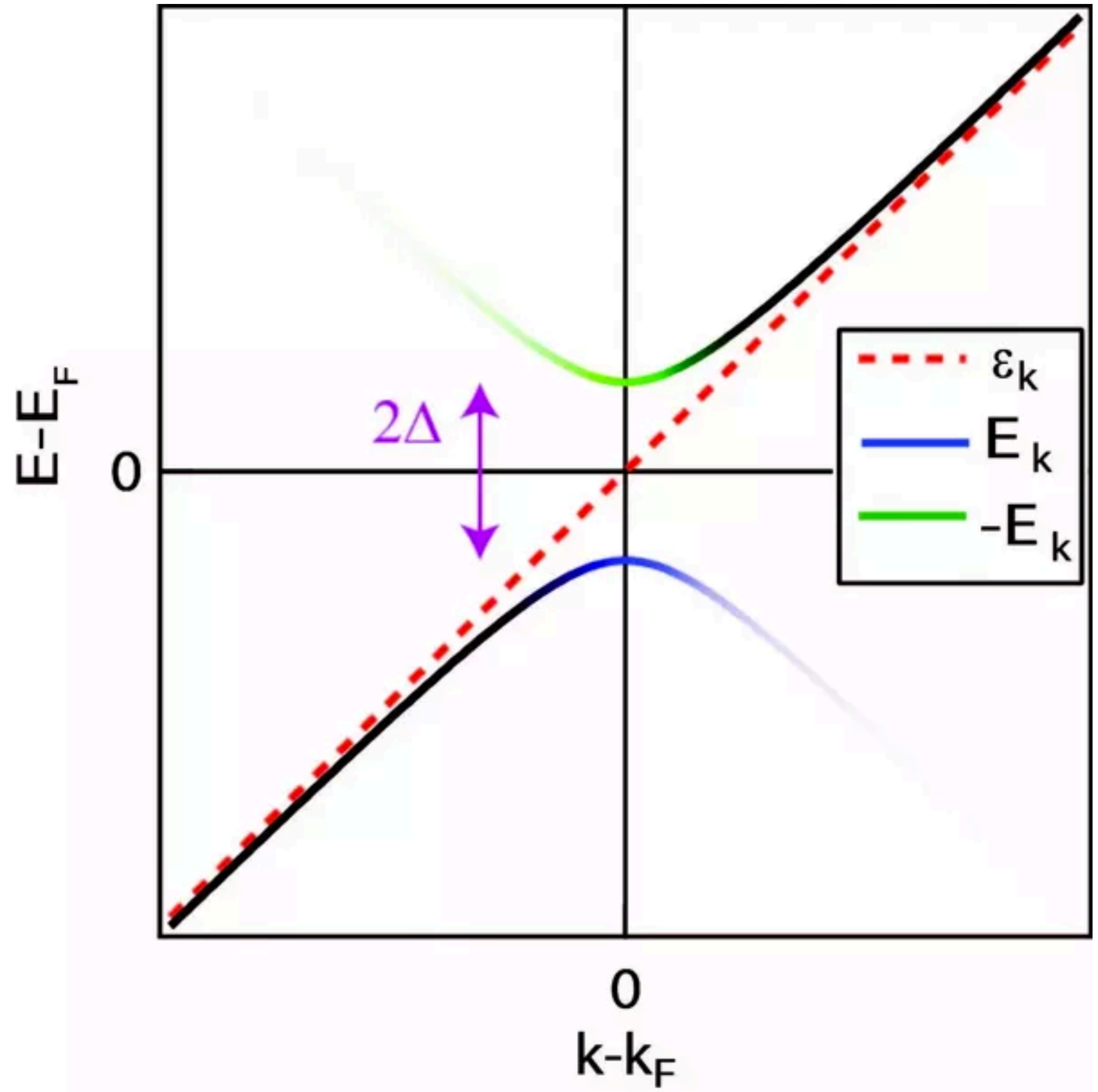
Charge Production: Semiconductors

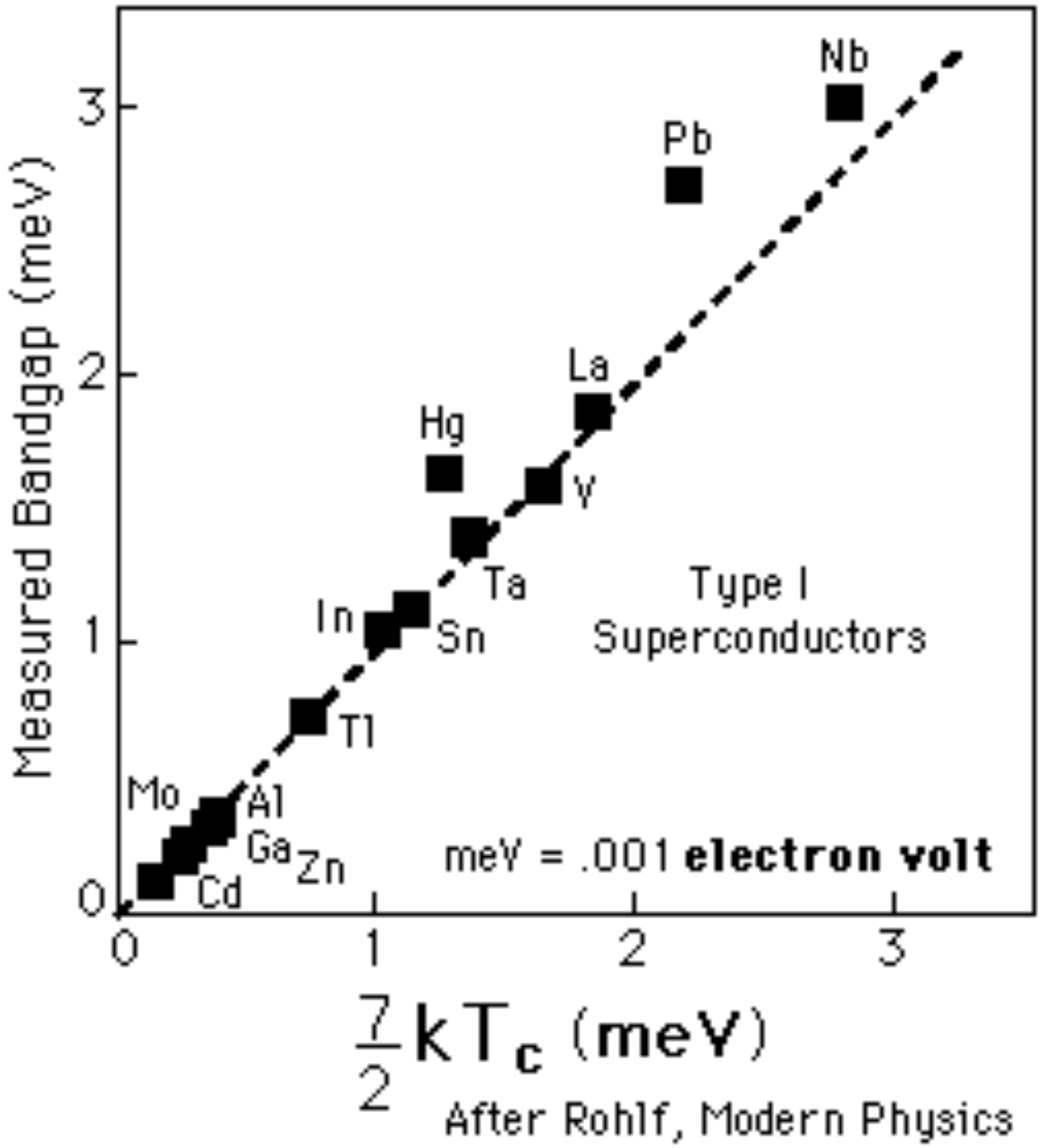




- Charges
- Bandgap
- Indirect bandgaps require more energy to liberate electrons thermally, but are still sensitive radiation down to bandgap energies (though the efficiency is reduced)

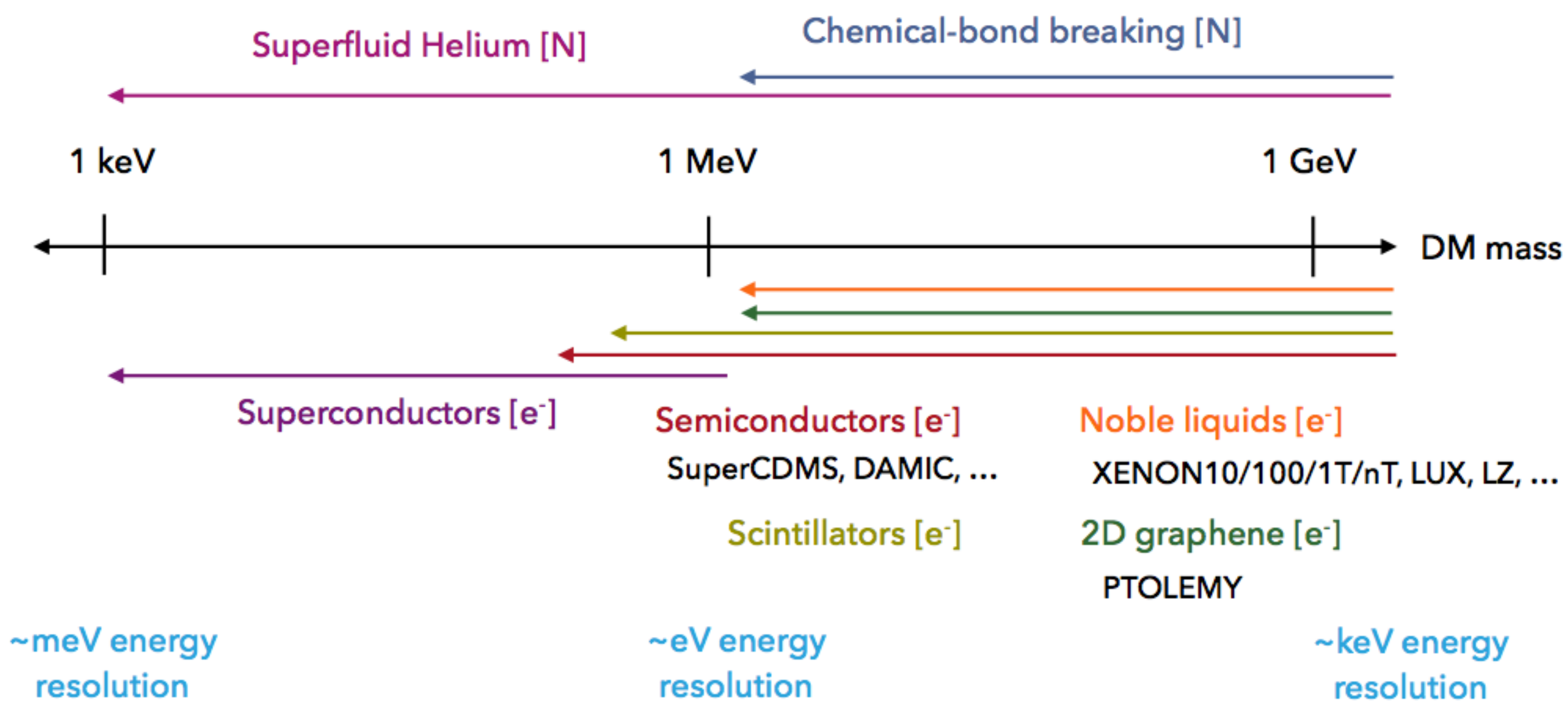
Quasiparticle Production: Superconductors





- Cooper pairs have a binding energy, which functions as a bandgap to turn pairs into quasiparticles
- Bandgaps can be engineered by Tc manipulation
- These are very low energies; experimentally this is challenging compared to existing CCD technology

Broad Picture: Detection Media for Lower Mass DM



- 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

US Cosmic Visions, arXiv:1707.04591

Broader Picture: Detection Media for Lower Mass

Chemical-bond breaking [N]

1 k

DM mass

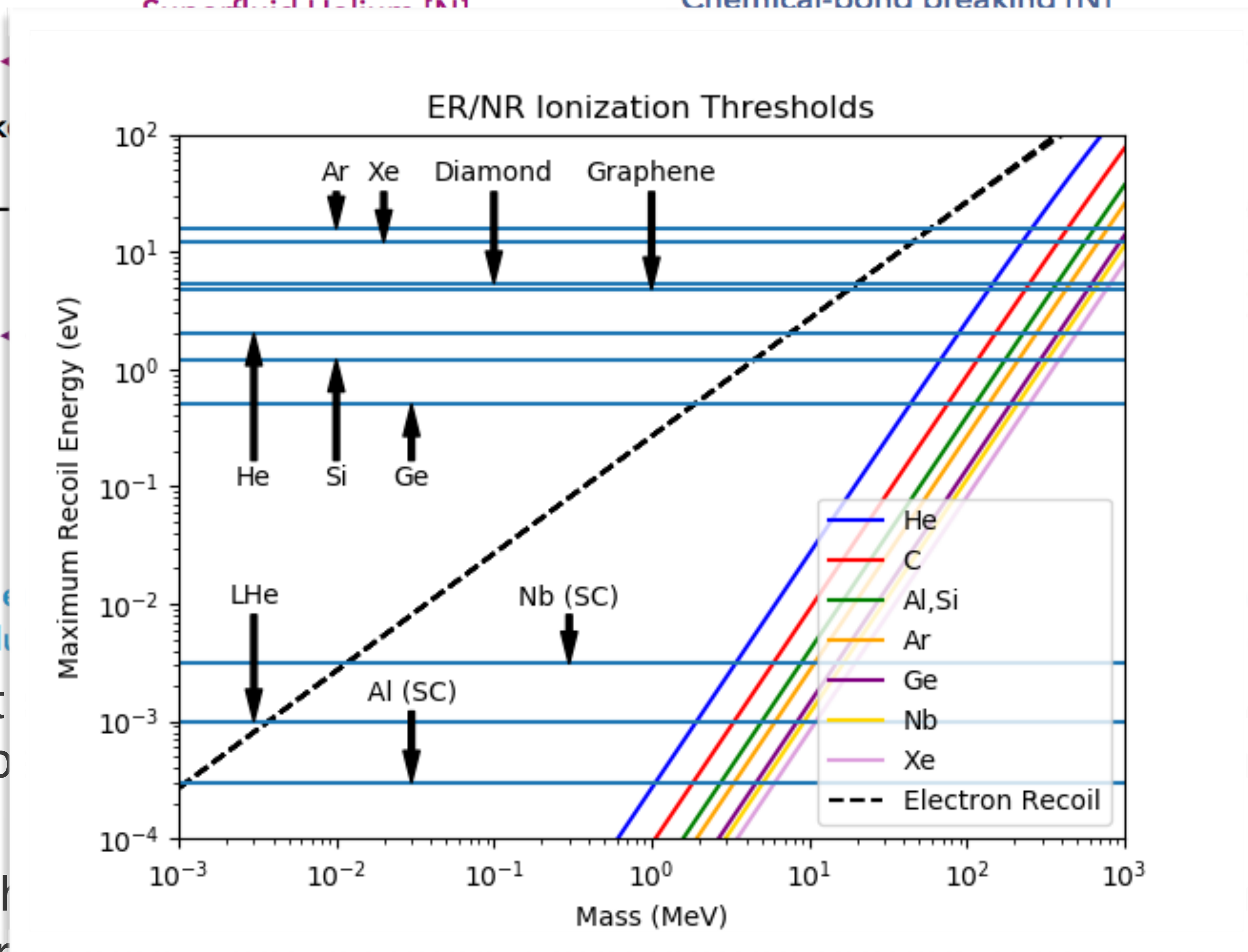
, LUX, LZ, …

~meV e

resol

energy

lution

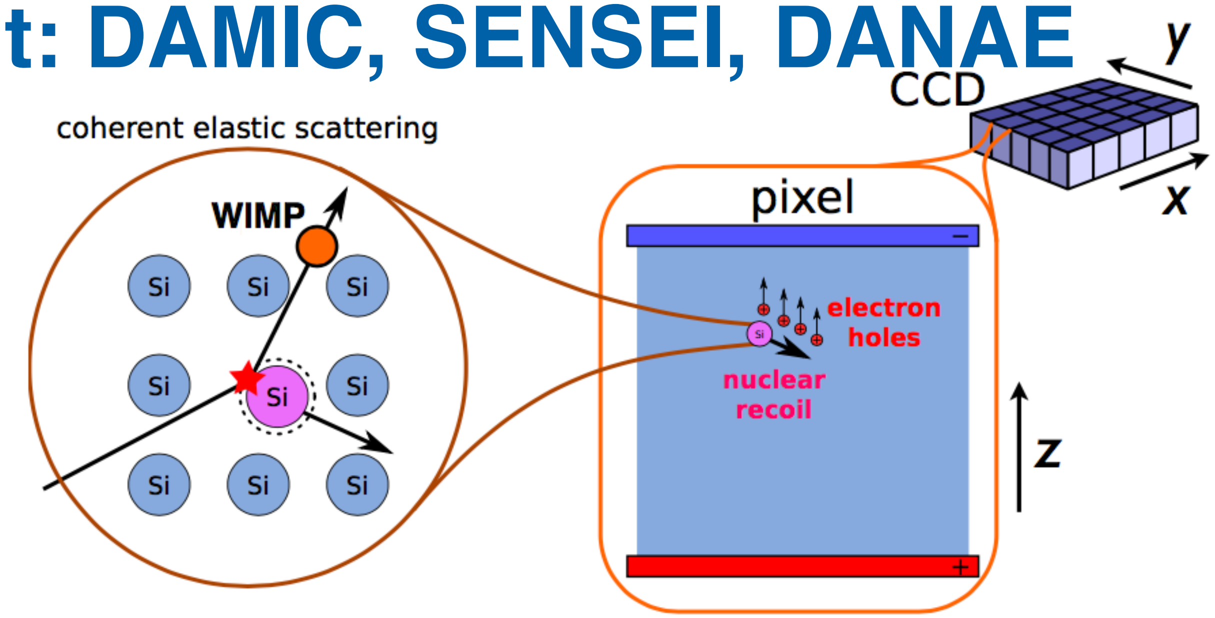


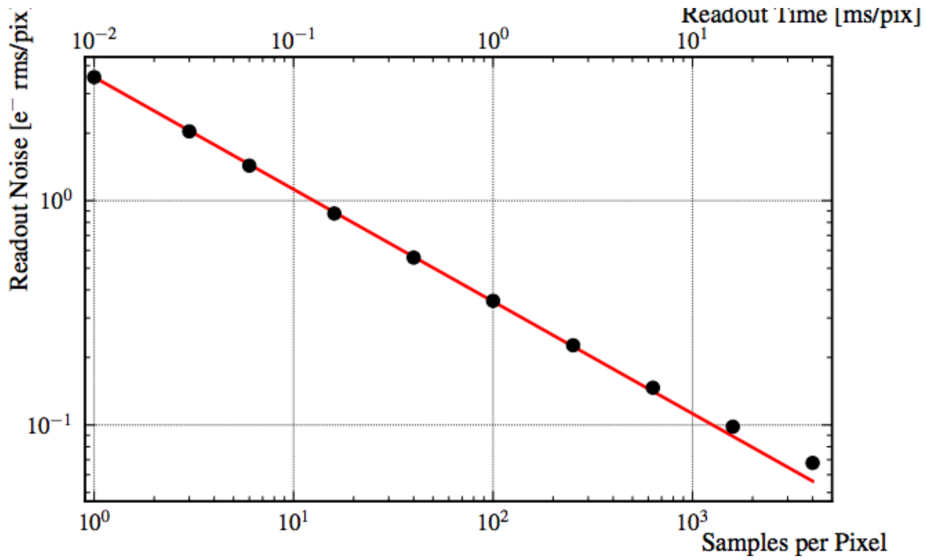
- Looking at … vith small but non-zero b … rier conversion
- Extent of th … atics and material properties, and assumes large current hurdles can be overcome in energy and charge noise across all experiments

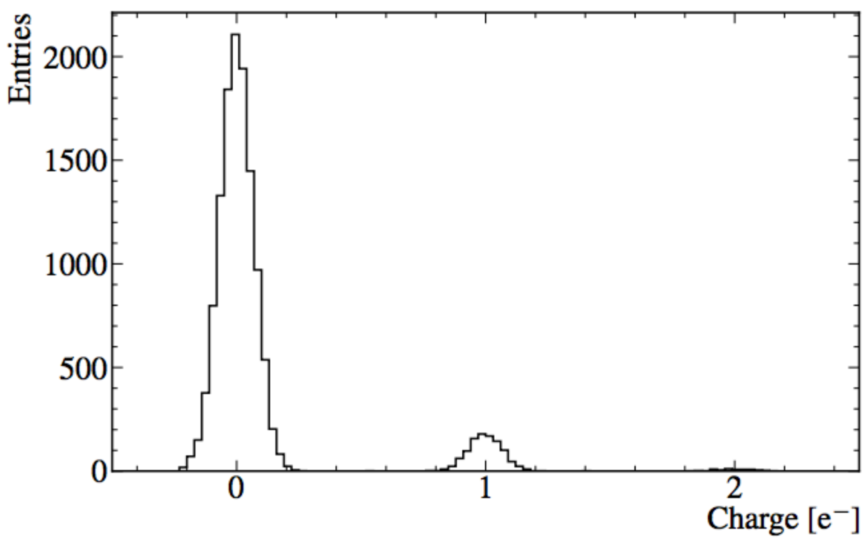
US Cosmic Visions, arXiv:1707.04591

High Resolution Charge Readout: DAMIC, SENSEI, DANAE

- Electron and nuclear recoils produce electron-hole pairs in Si, which are stored in pixels during the exposure
- Charges moved to set of charge amplifiers during readout
  - Single read noise limited by charge amplifier and electronics noise
  - Skipper CDDs capable of non-desctructive read; can re-sample the same pixel and arbitrary number of times
- Arbitrarily low resolution (in ideal case) at the expense of readout time. Very large dynamic range, excellent position resolution and event tracking
- No differentiation between paired and unpaired charge carrriers; operation at ~100K ensures some thermally generated carriers



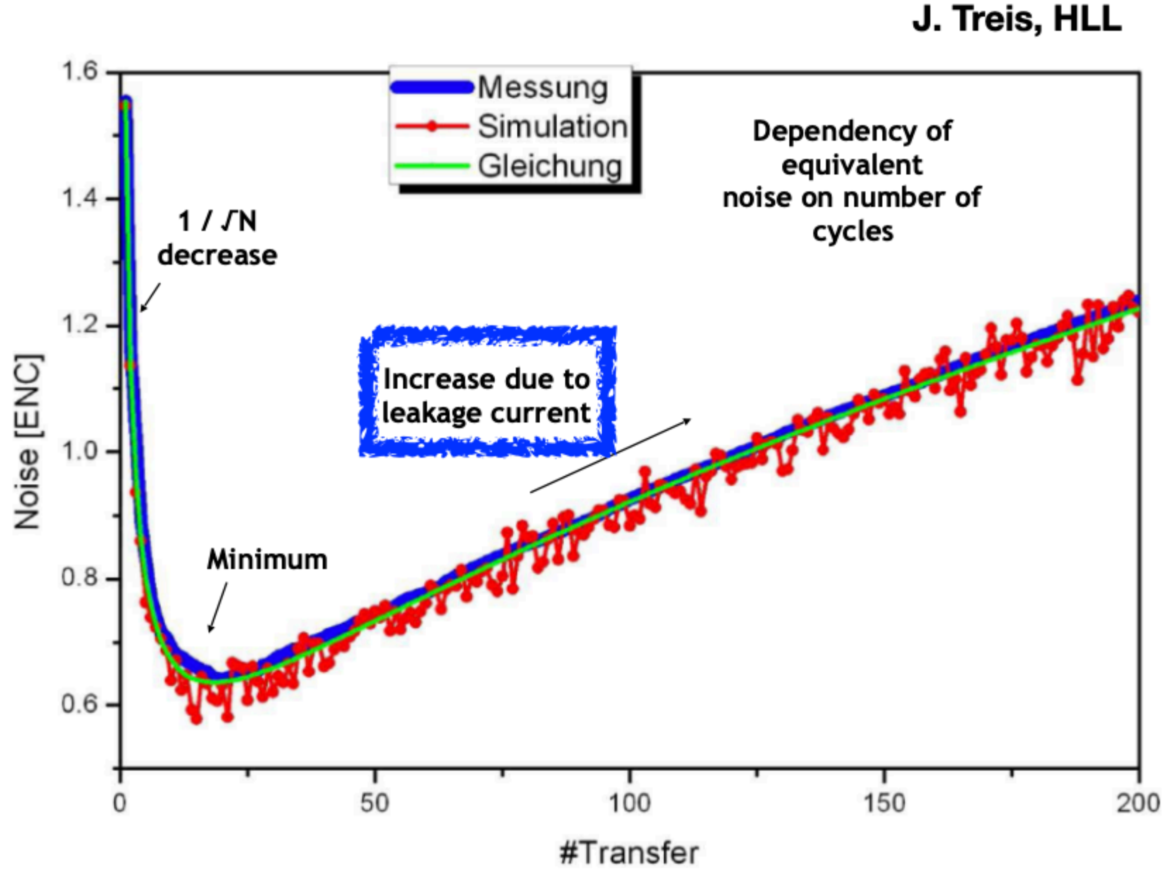


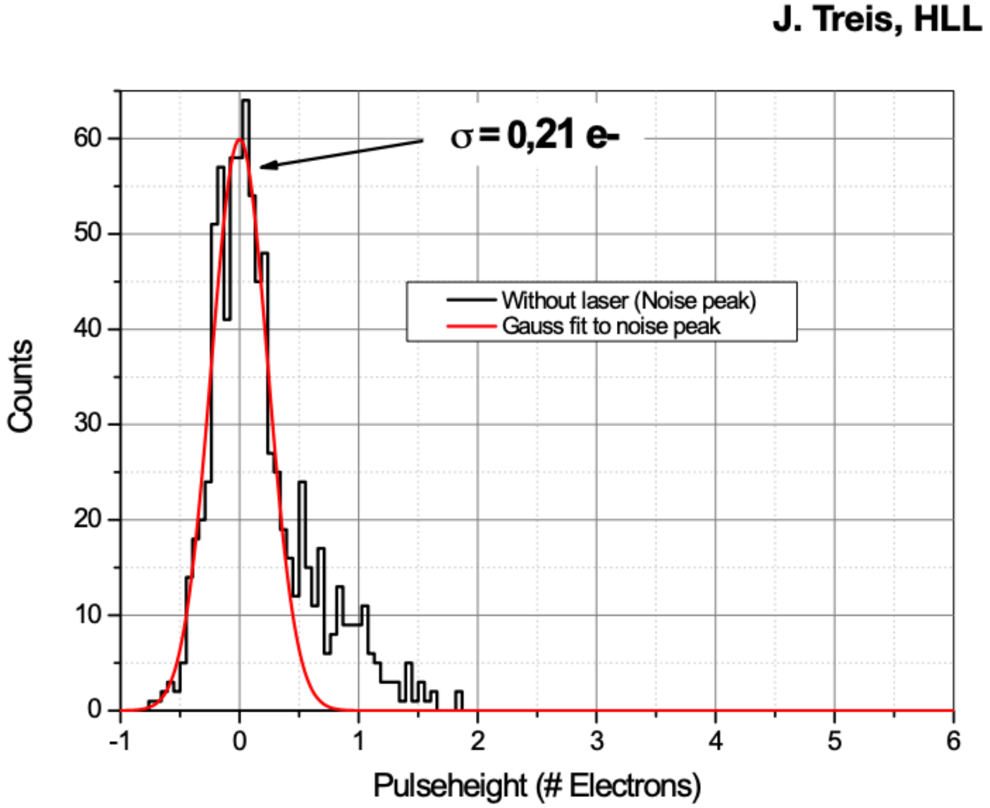


Tiffenberg et. al. 2017 (arXiv:1706.00028)

SENSEI vs. DANAE (CCD vs. CMOS)

Measured Performance for DEPFET-RNDR



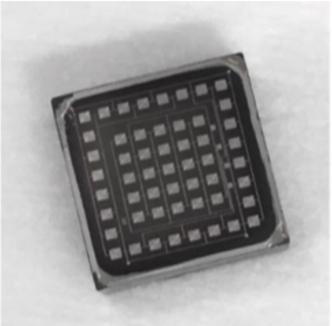


- noise performance as a function of readout cycles measured and reproduced by simulation

- **noise performance of σ=0,21 e⁻ achieved**

https://indico.desy.de/indico/event/18204/session/12/contribution/8/material/slides/0.pdf

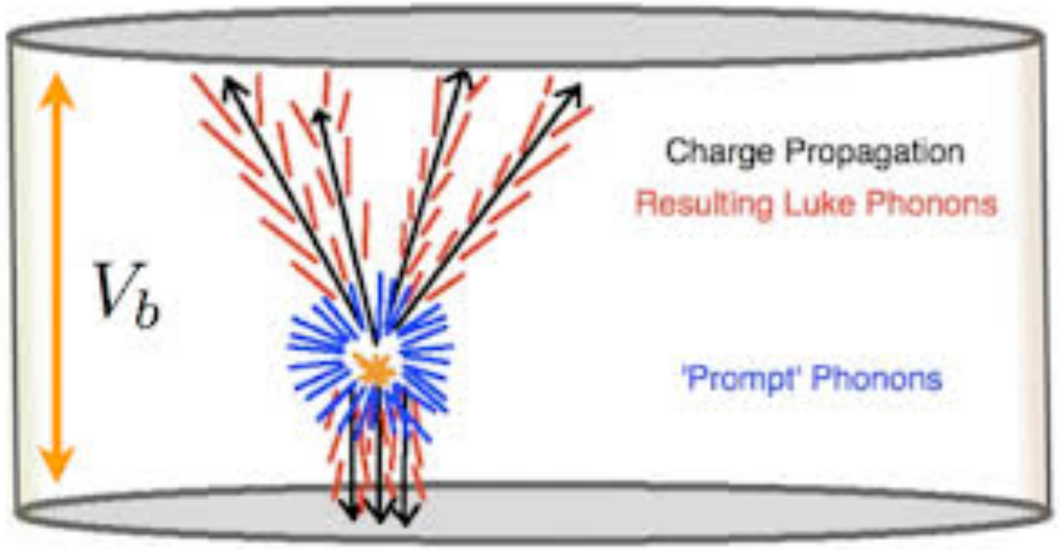
Athermal Phonon Sensors (SuperCDMS, EDELWEISS)

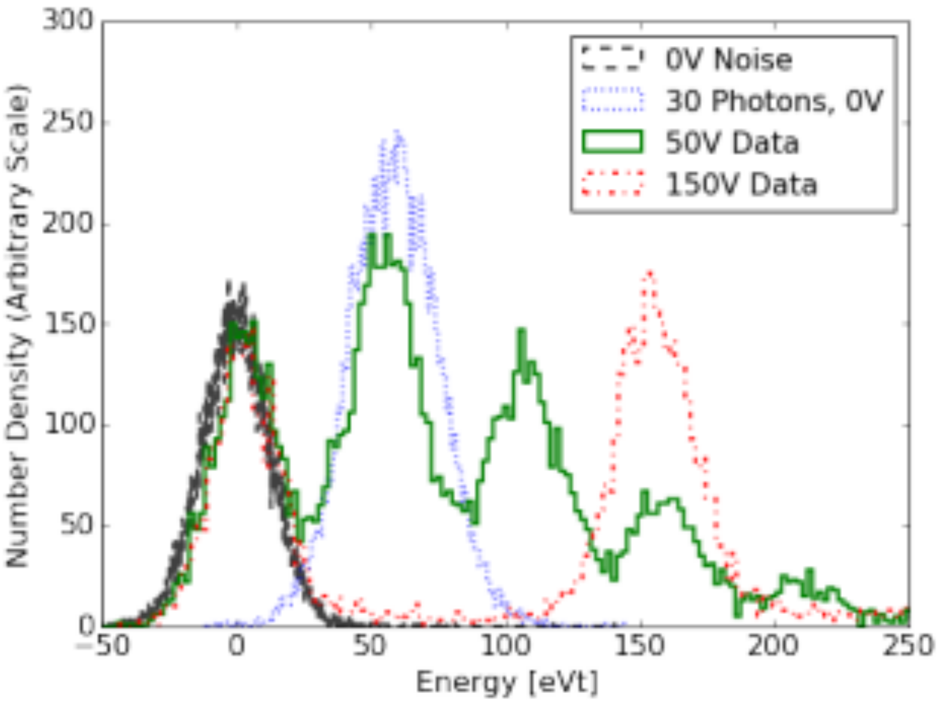


- In any recoil event, all energy eventually returns to the phonon system
  - Prompt phonons produced by interaction with nuclei
  - Indirect-gap phonons produced by charge carriers reaching band minima
  - Recombination phonons produced when charge carriers drop back below the band-gap
- Phonons are 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

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

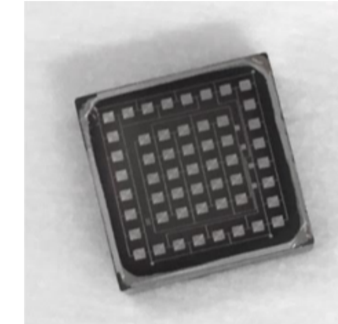
- Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity





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

Athermal Phonon Sensors (SuperCDMS, EDELWEISS)

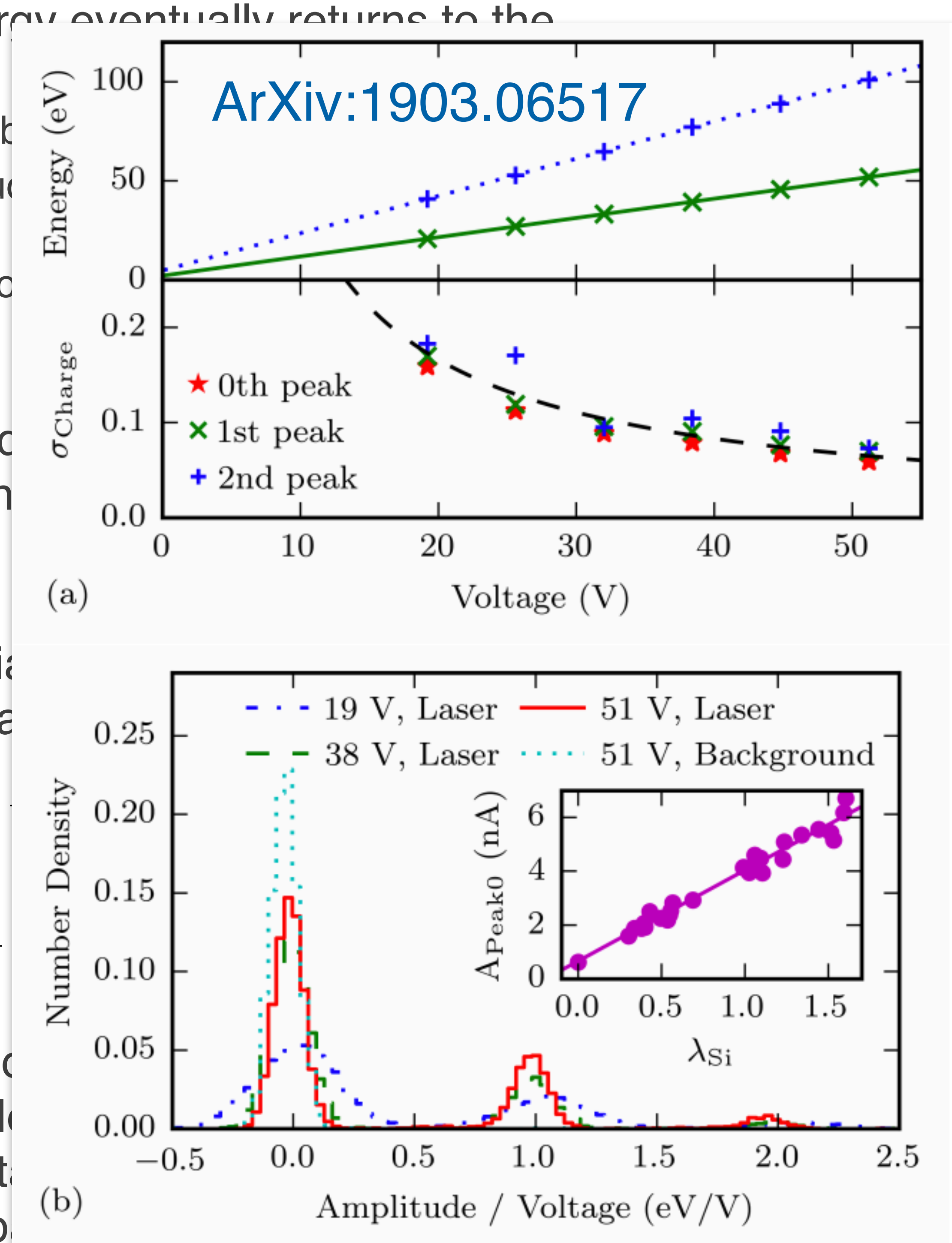


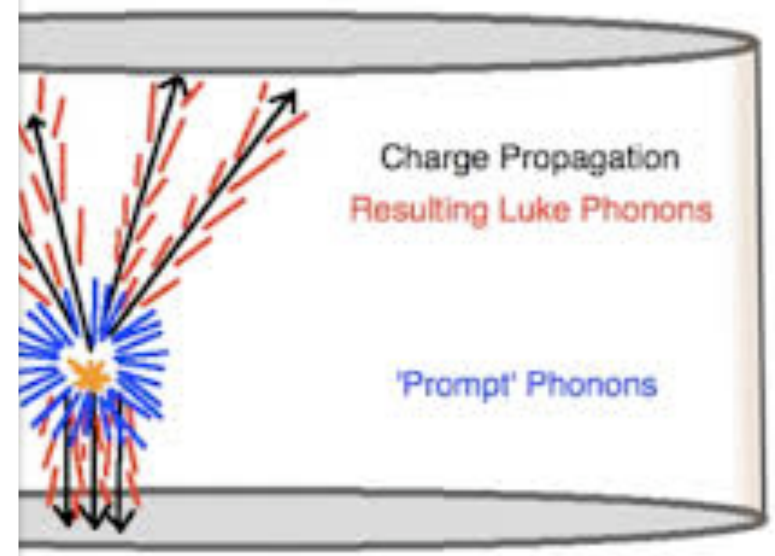
- In any recoil event, all energy eventually returns to the phonon system
    - Prompt phonons produced b
    - Indirect-gap phonons produ band minima
    - Recombination phonons pro back below the band-gap
- Phonons are also produced an electric field; makes sen alone
- Total phonon energy is initi phonon energy, as shown a

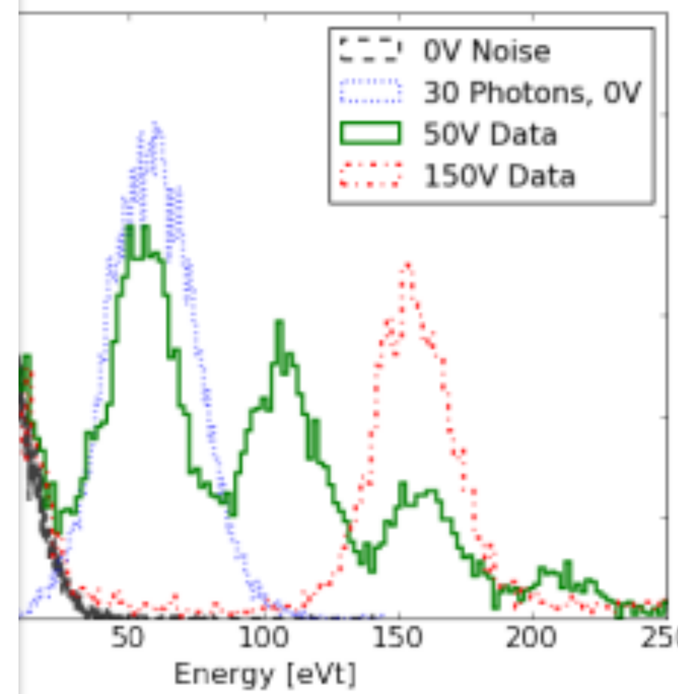
$$E_{phonon} = E_{recoil} +$$

$$= E_{recoil} \left[1 \right.$$

- Athermal phonons collected aluminum fins and channel effectively decoupling cryst calorimeter (TES) heat cap





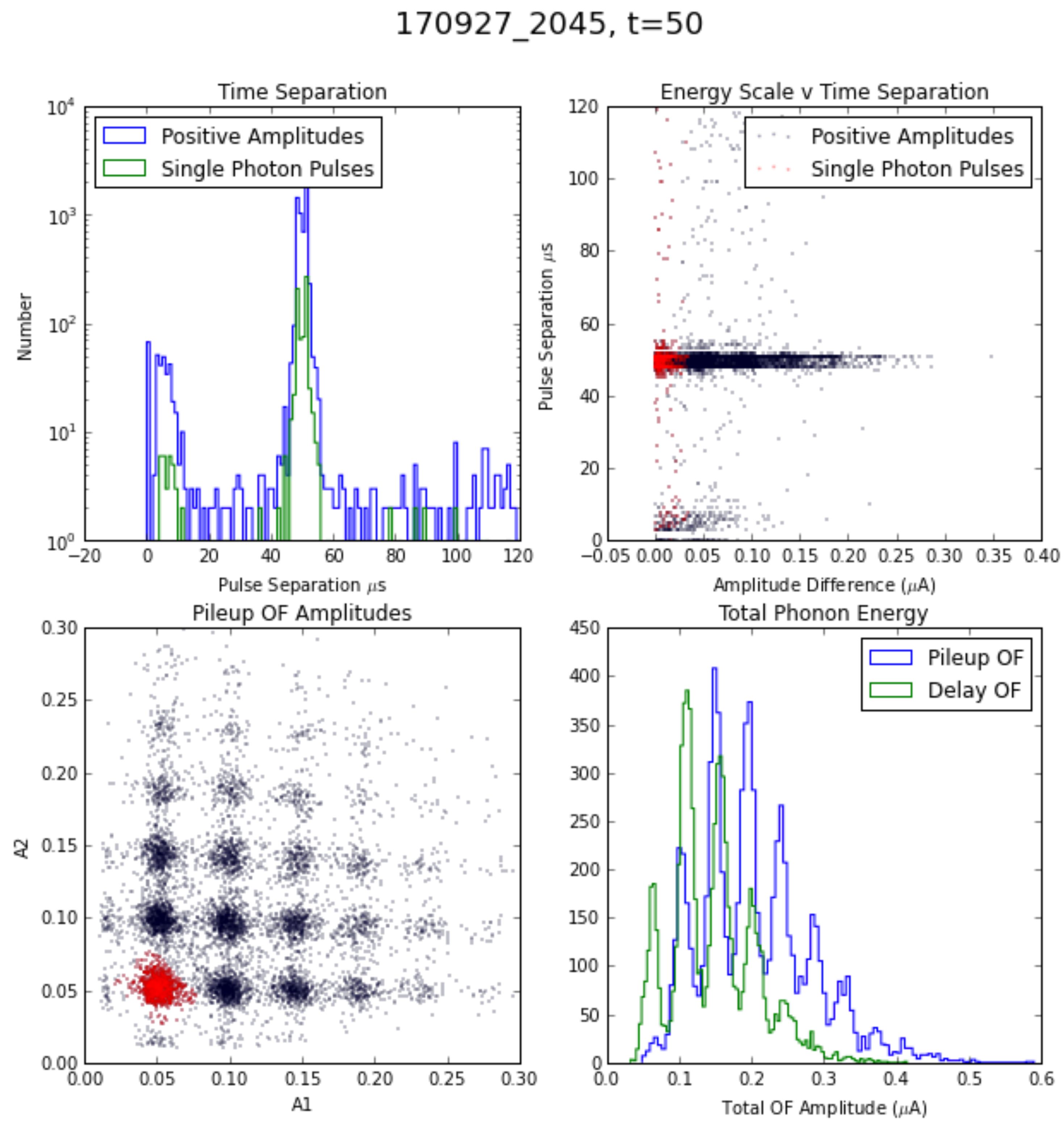


Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Fermilab

Background Rejection

- Small experiment using injected laser light to produce 2 pulses separated by variable amount of time
- We see both quantized amplitudes
- Timing resolution is ~3 microseconds, can separate pileup to better than 20 microsecond separations at 100% efficiency
  - Resolution is the result of a new pileup optimum filter technique, included in upcoming science paper
- Still need to estimate rate of dark counts…but that's great rejection



Fermilab

Non-Quantized Backgrounds

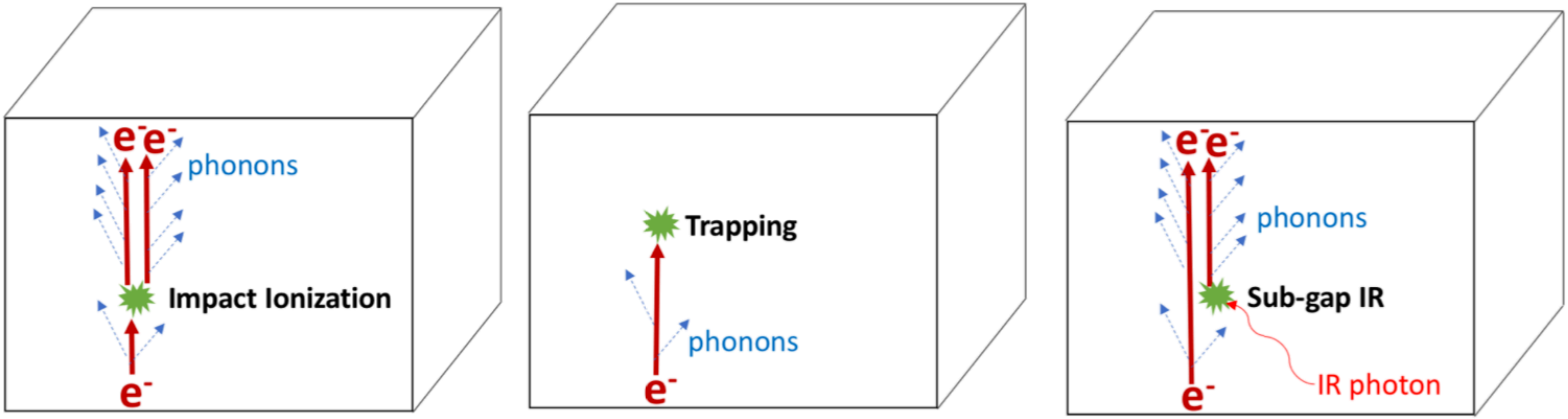


Figure Courtesy R.K. Romani

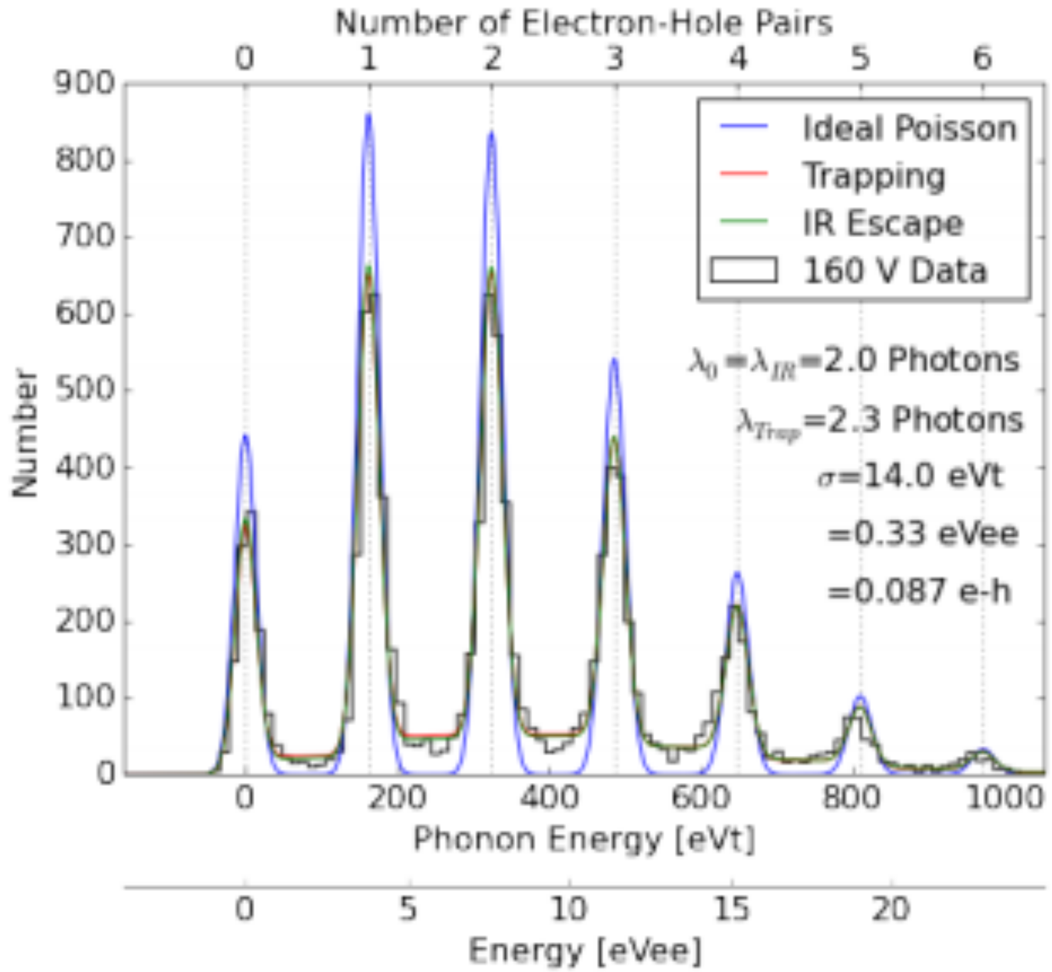
- During the initial experiment we saw that 15% of the events were non-quantized, which can be due to additional charge liberated from impurity states
  - Impact ionization: drifting charge ionizes an impurity
  - Trapping: drifting charge stopped by an impurity
  - IR: shallow impurity wells liberated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

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

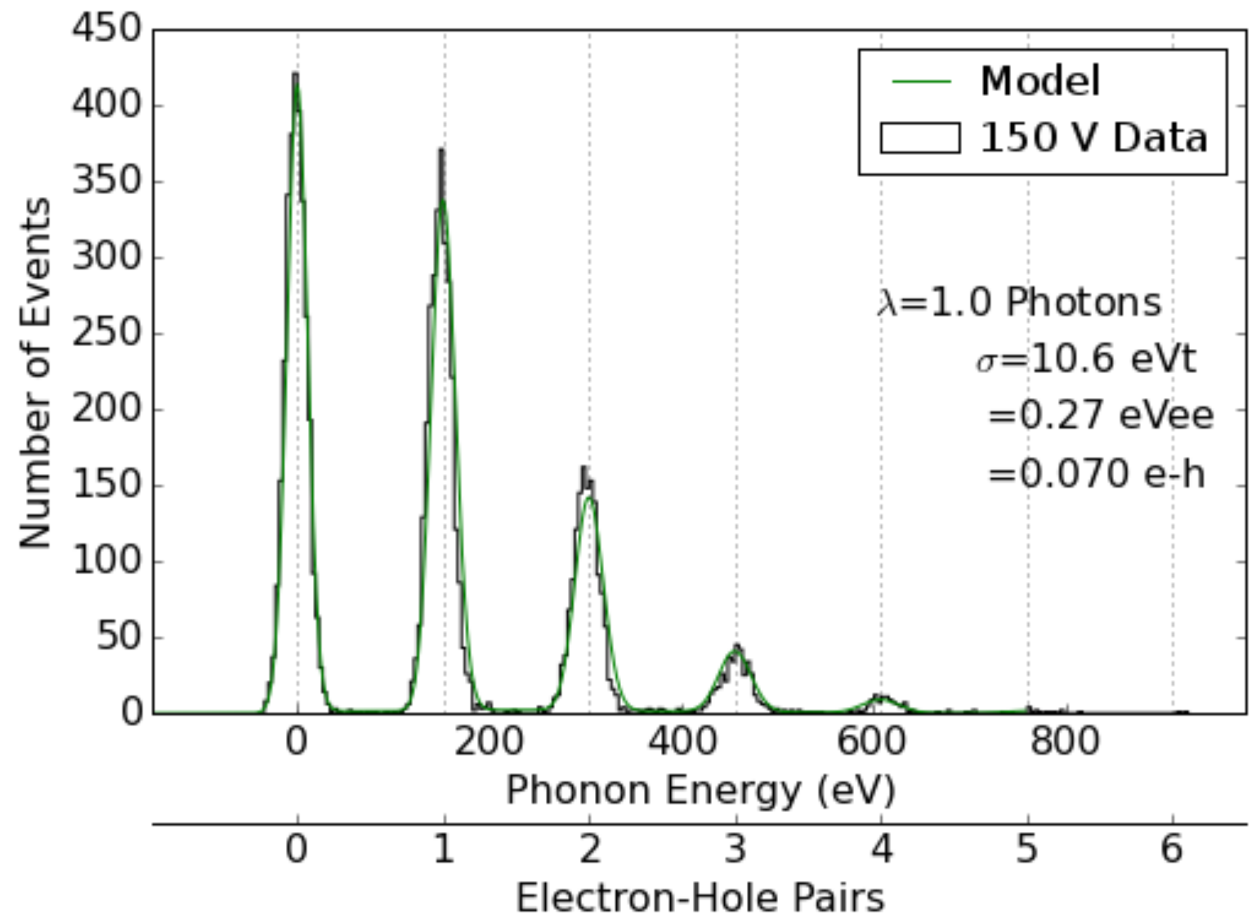
Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Effect of IR Filtering

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



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



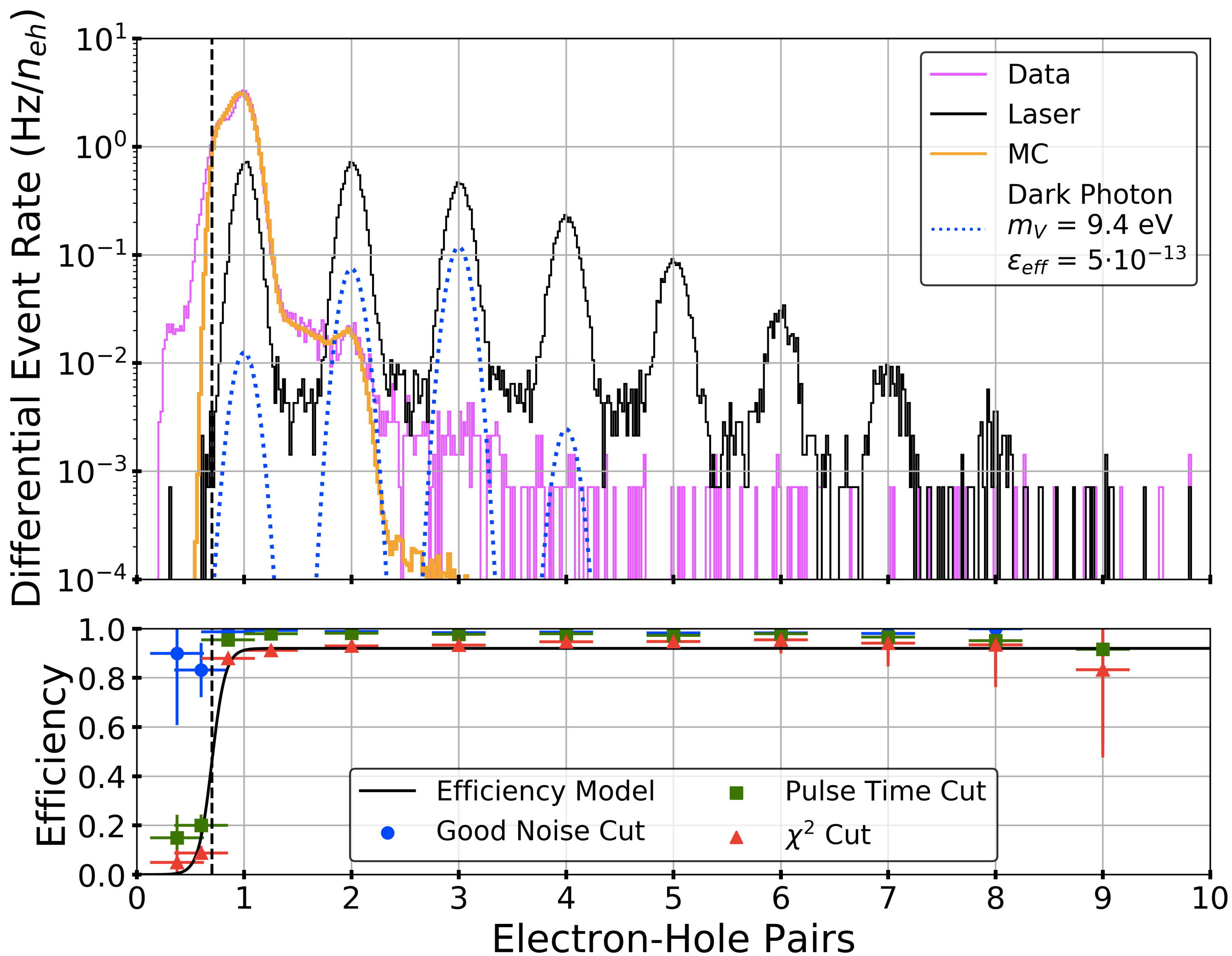
- Adding additional IR filtering improved fill-in regions between laser calibration peaks, validating the idea that our laser and background data was IR limited

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

0.5 Gram-Day Science Spectrum

- Ran the detector for ~12 hours with a 1 Hz laser calibration (black line)
- Non-quantized background likely unresolved outer sidewall events
- Device showed high charge 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)



Fermilab

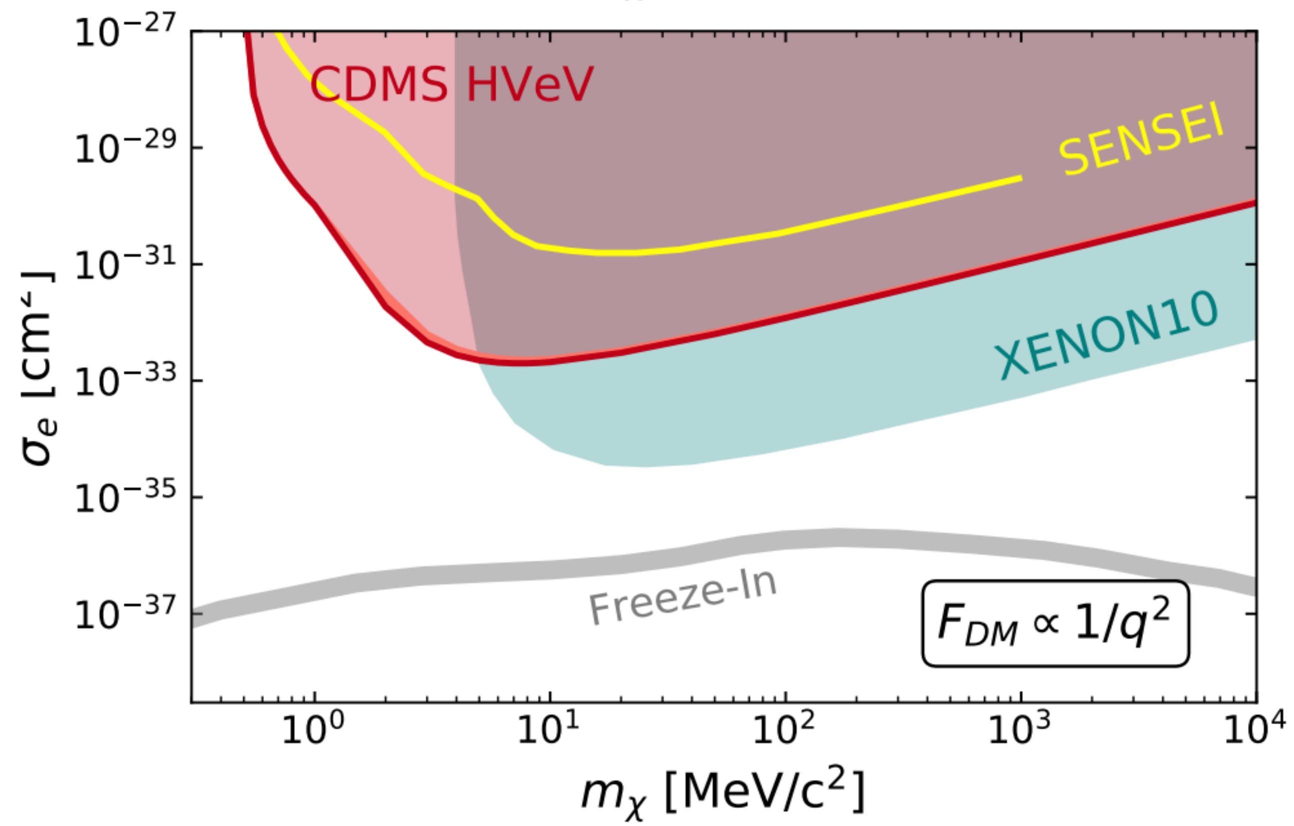
Surface Limits on Sub-GeV Dark Matter

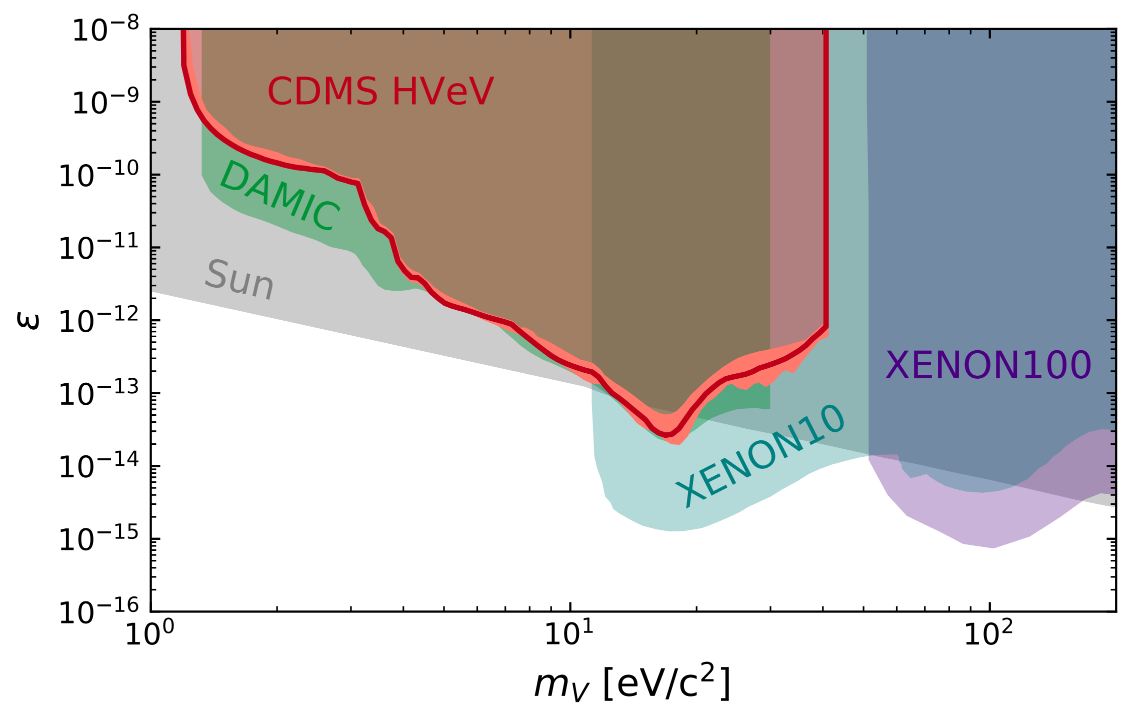
- Momentum dependent limits peak at low energy
  - Lowering energy threshold allows us to probe the same cross-section with ~1/10000 of the mass of Xenon10 at 4 MeV
  - Our prototype detector has world-leading limits for ~0.5-5 MeV

- Better pileup rejection and resolution allow us to probe the same dark-photon parameter space as DAMIC with 1/60 of the exposure (both searches are background limited)

- This is the opening shot in the next generation of light dark matter searches

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

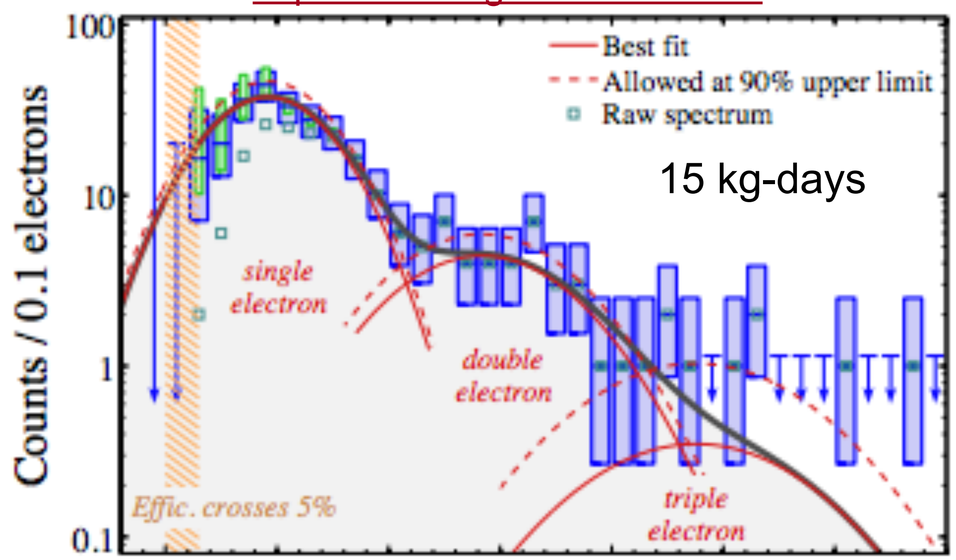


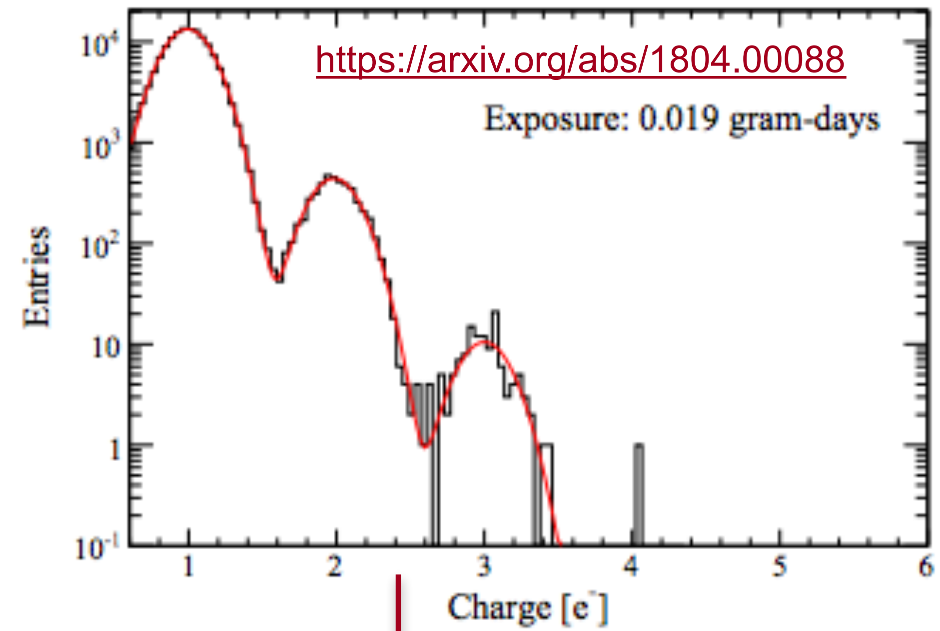


Fermilab

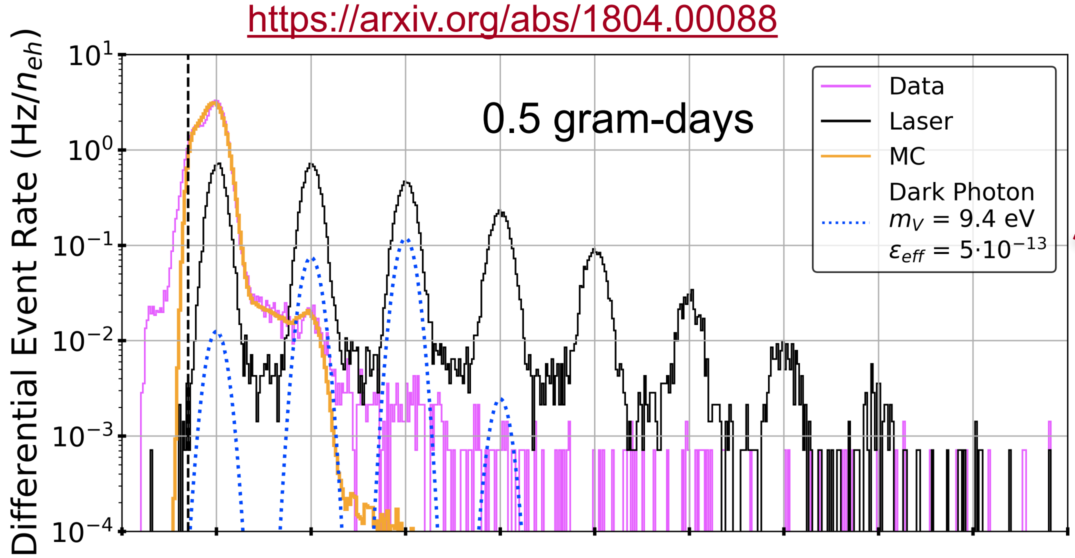
Comparison of ER Experiments

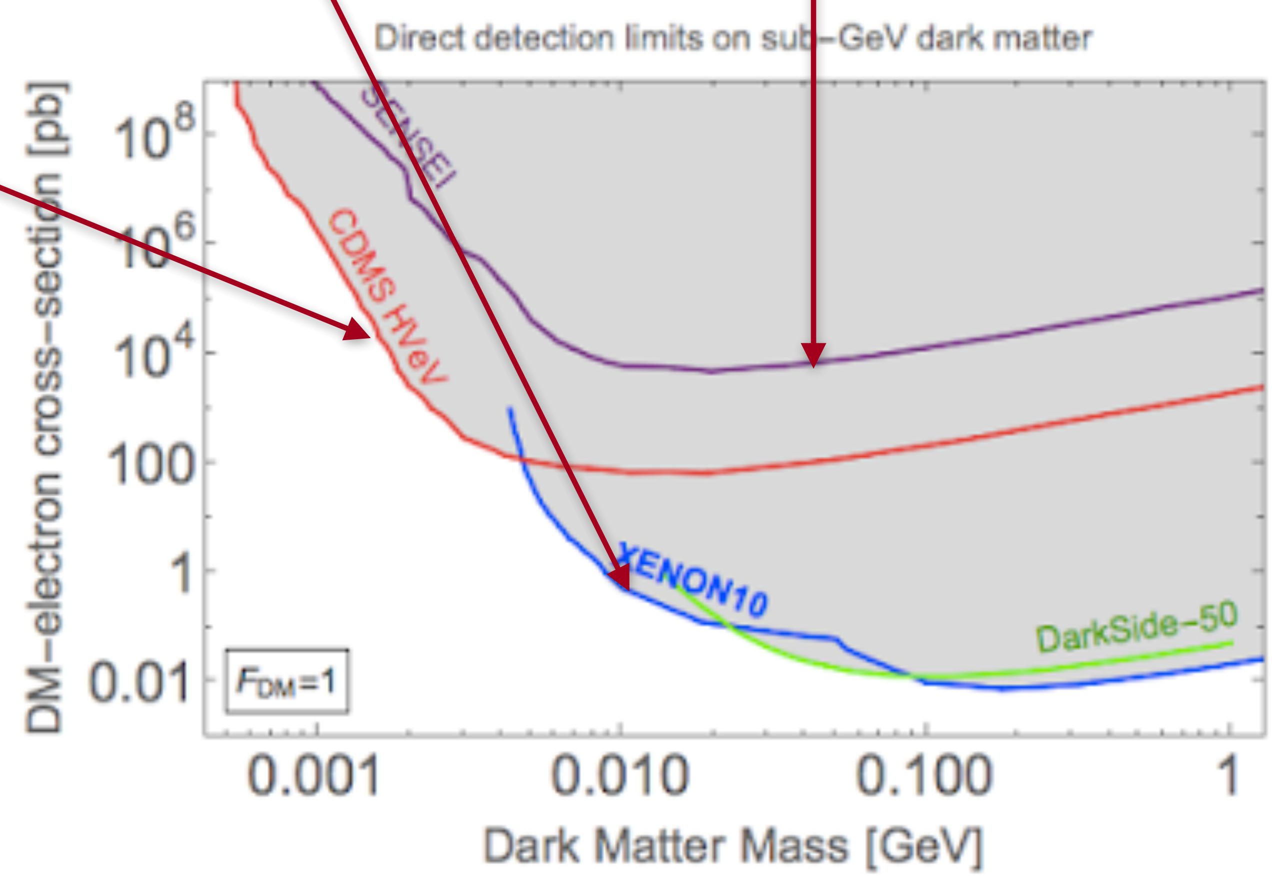
https://arxiv.org/abs/1206.2644





https://arxiv.org/abs/1804.00088



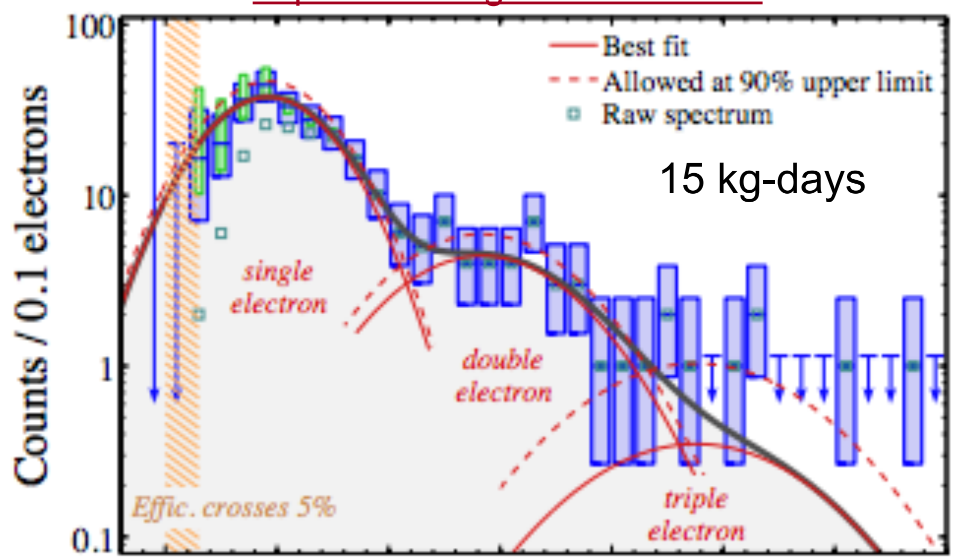


- Sensitivity determined by background, exposure, and resolution
- Pileup rejection important for IR-limited background

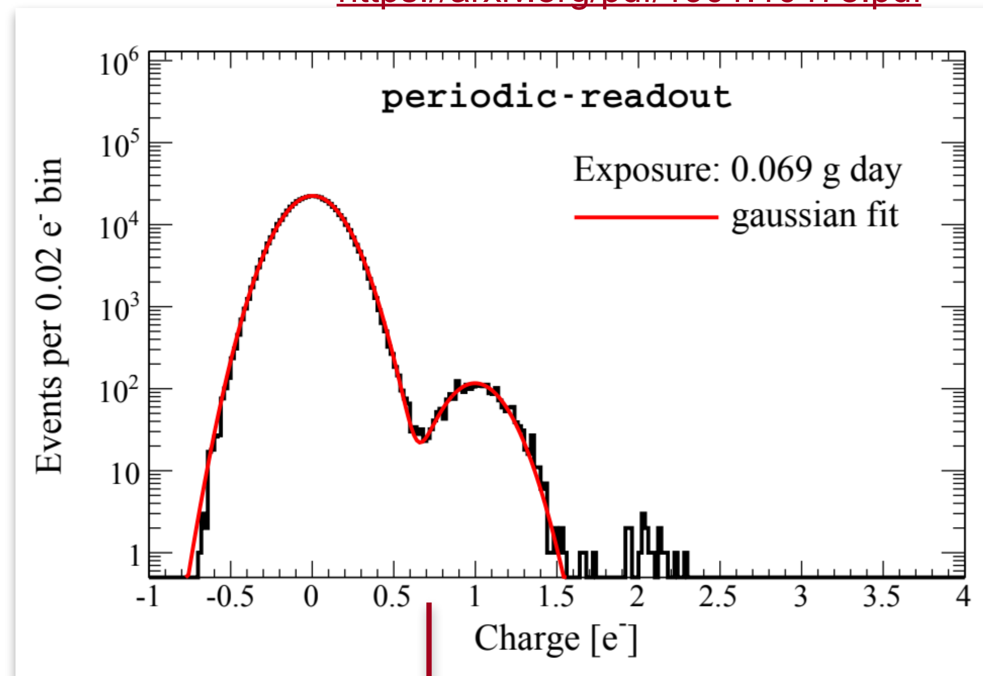
http://resonaances.blogspot.com/2018/05/dark-matter-goes-sub-gev.html

Comparison of ER Experiments

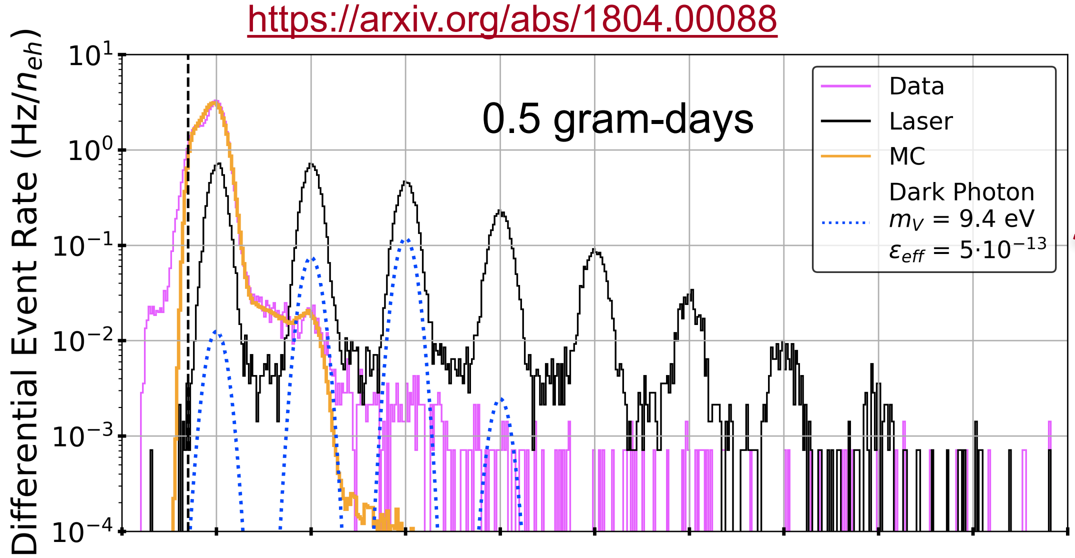
https://arxiv.org/abs/1206.2644

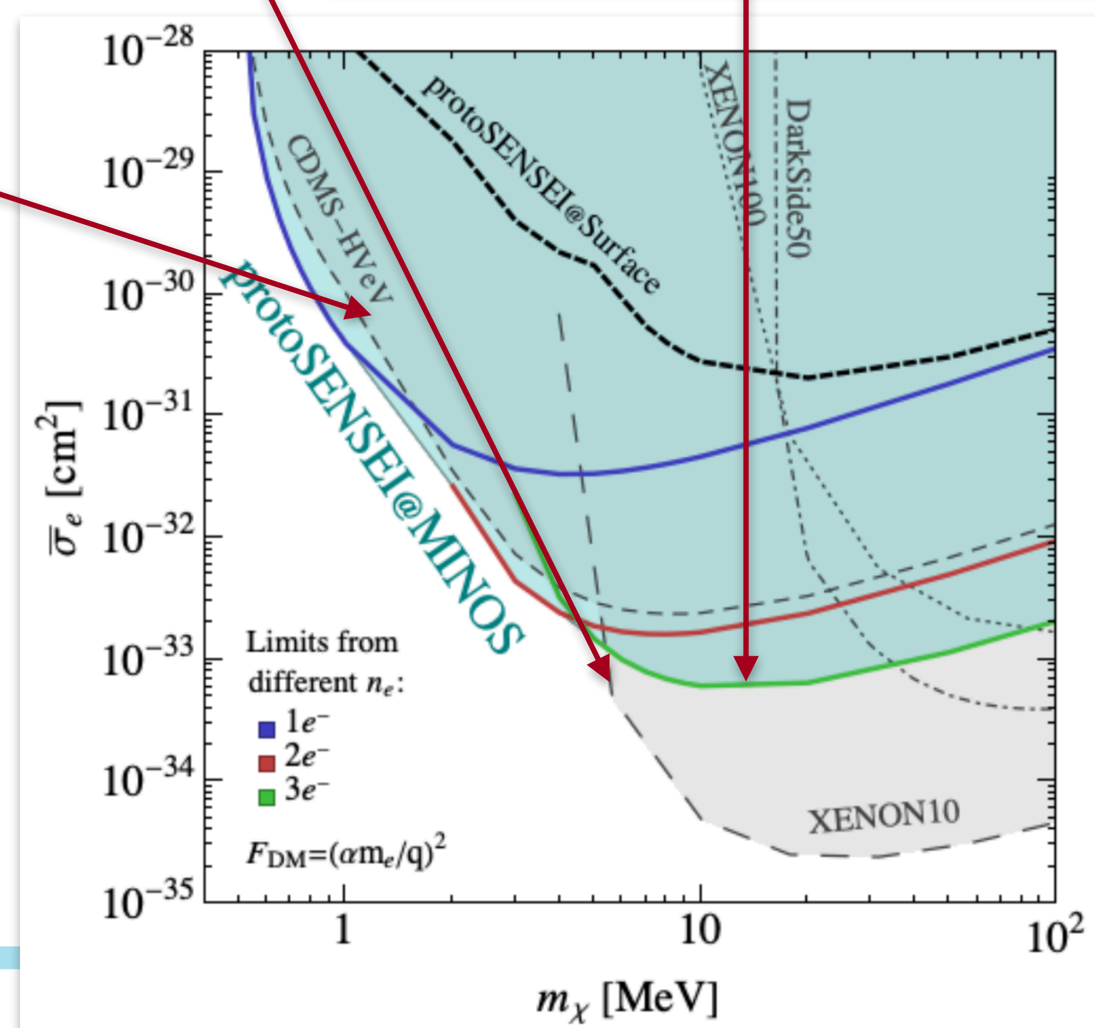


https://arxiv.org/pdf/1901.10478.pdf



https://arxiv.org/abs/1804.00088



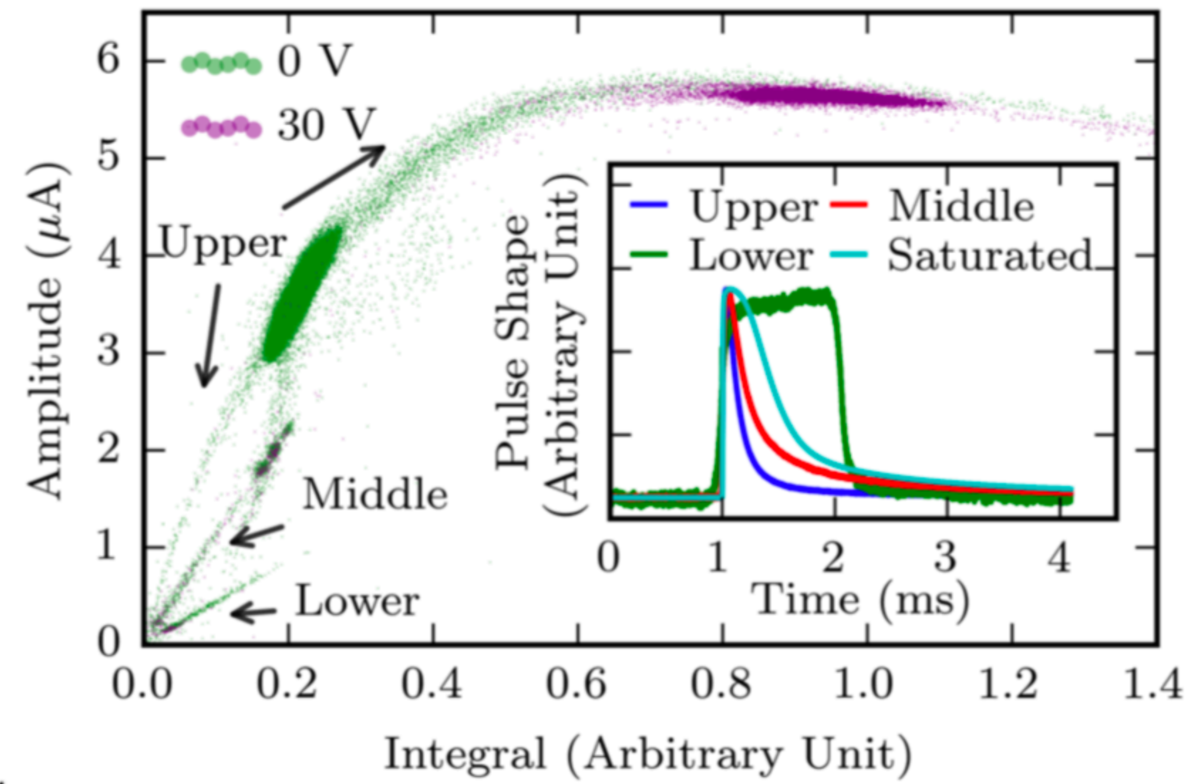


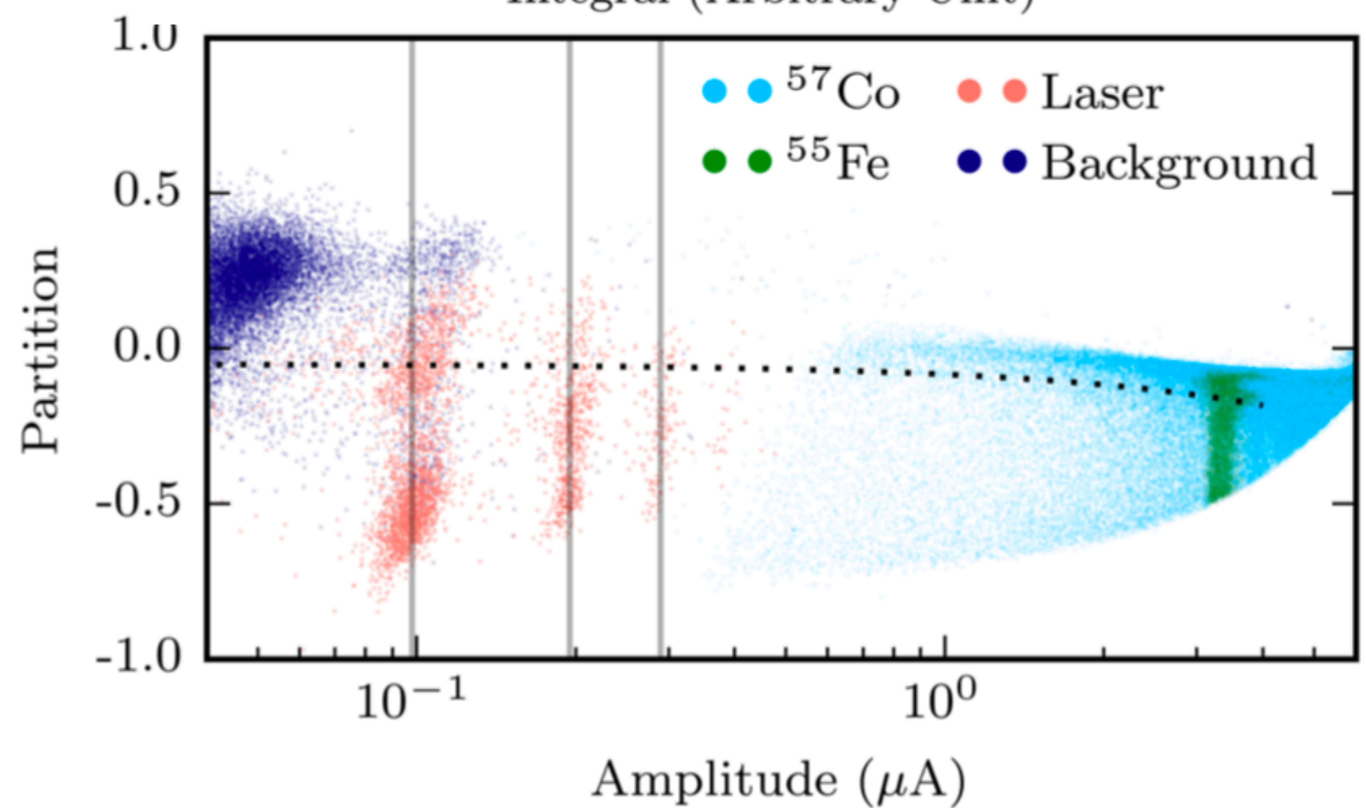
- Sensitivity determined by background, exposure, and resolution
- Pileup rejection important for IR-limited background

Recent Progress: Edge-Dominated Leakage

ArXiv:1903.06517

- New prototypes demonstrate 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



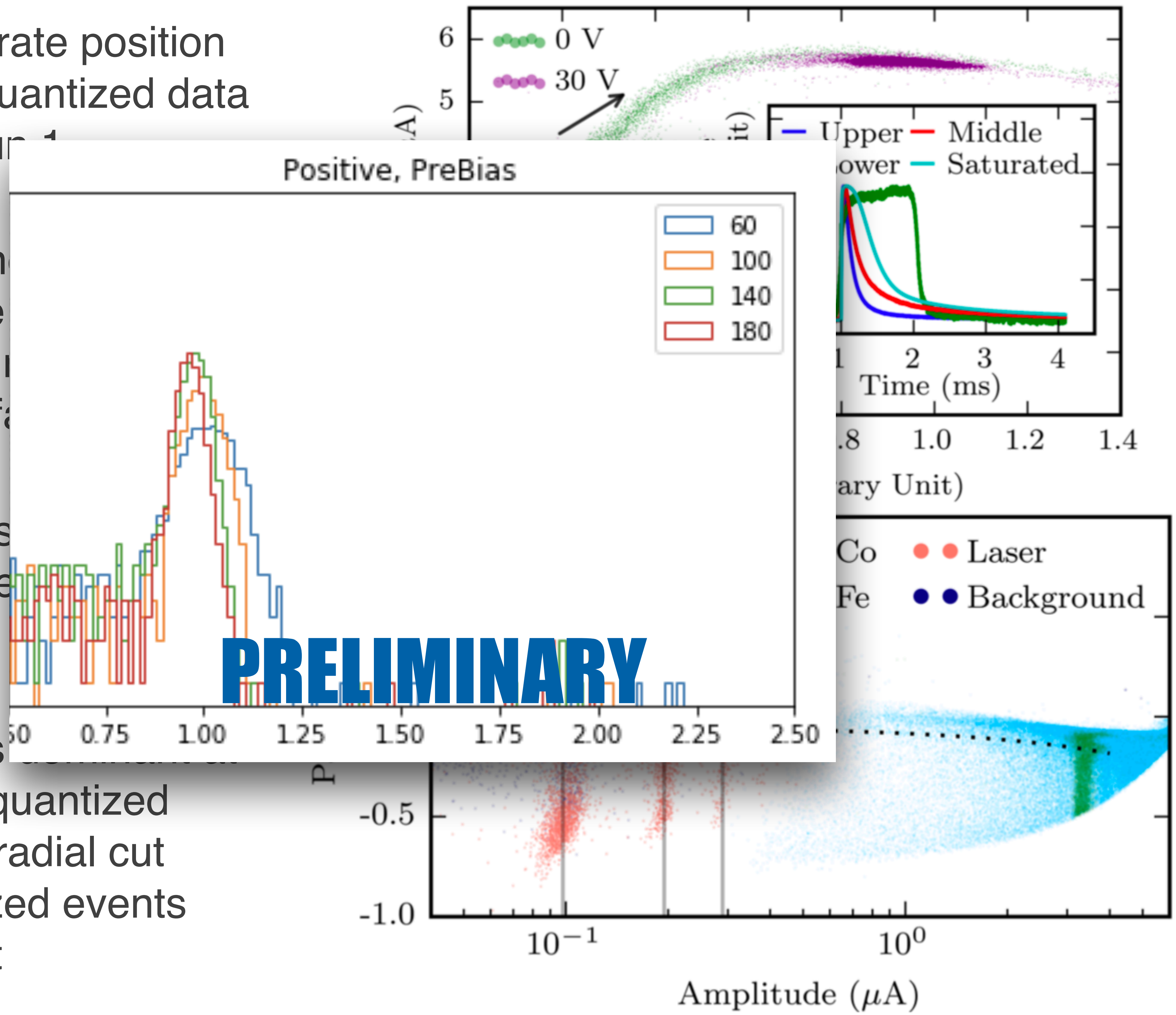


Fermilab

Recent Progress: Edge-Dominated Leakage

ArXiv:1903.06517

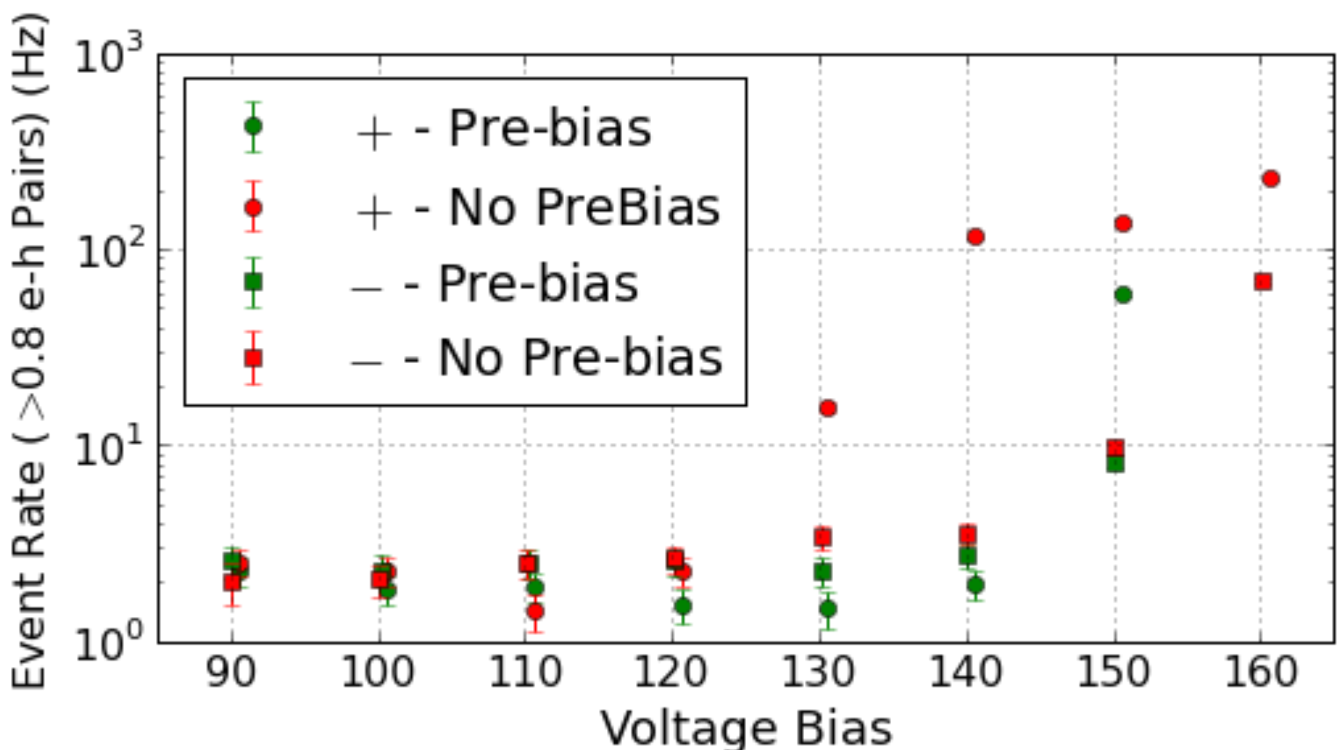
- New prototypes demonstrate position dependence in the non-quantized data hinted at during HVeV Run
- Nearly contact-free biasin
  isolates contact along the
  preventing charge tunneli
  most of the high-voltage f
- Surface events have a dis
  shape and can be remove
  in the pulse-shape plane.
- Non-quantized leakage is
  high radius; 95% of non-quantized events removed by 50% radial cut efficiency. 80% of quantized events removed by the same cut

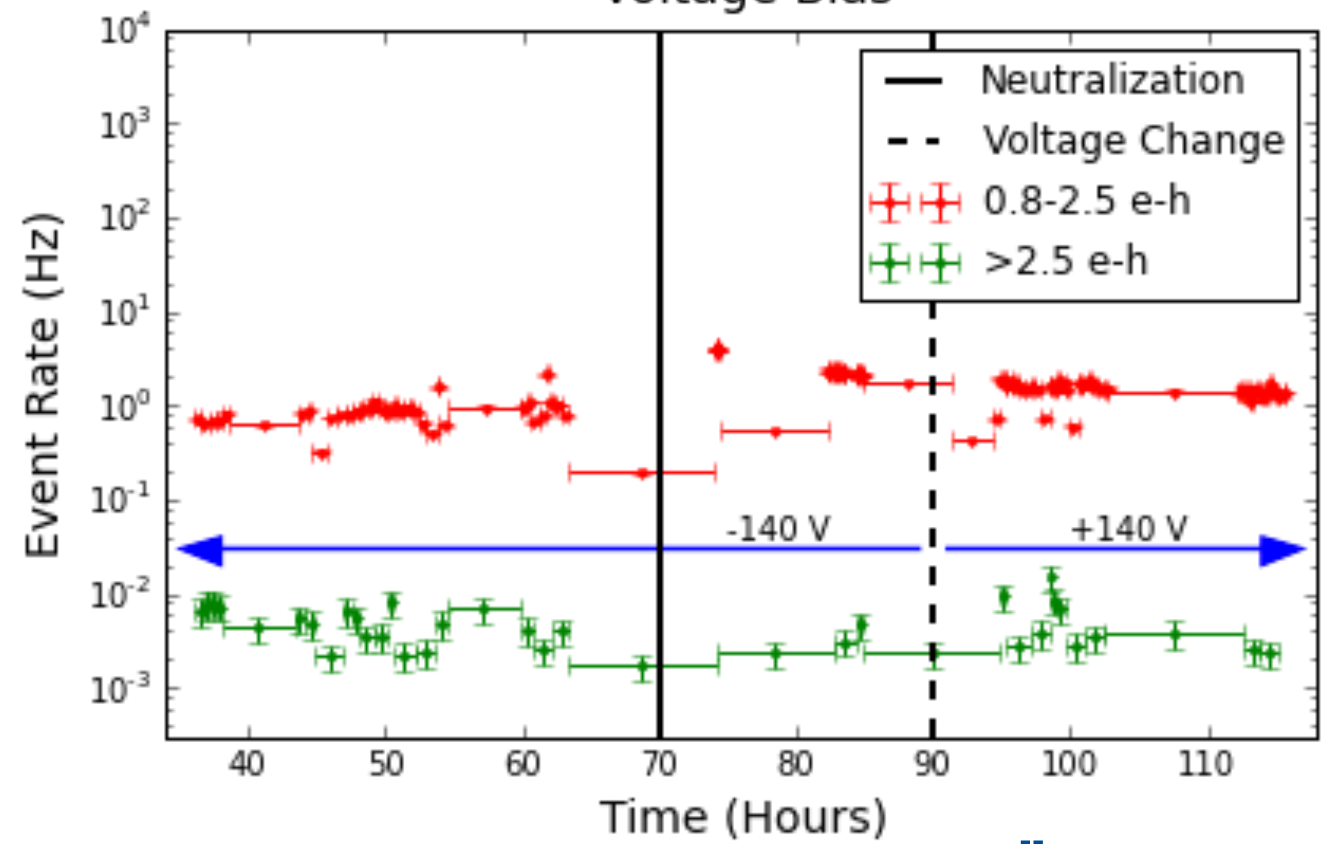


Fermilab

Understanding Leakage Rates

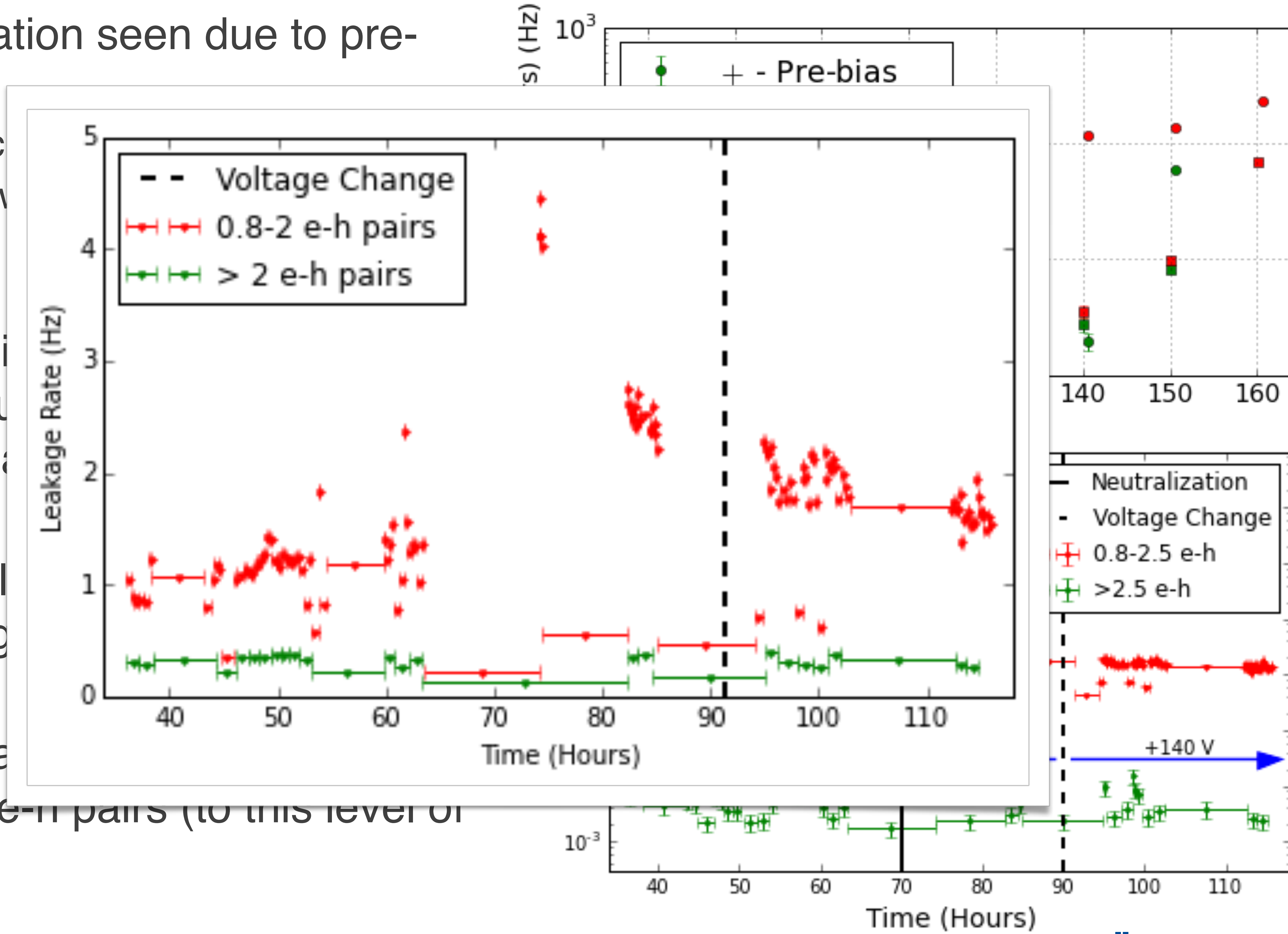
- Some variation seen due to pre-bias
  - Need to increase pre-bias voltage range
  - Determine what voltage empties traps reliably
- Neutralization seems to have elevated bulk leakage by ~3 for a matter of days
- Voltage polarity flip doesn't change bulk leakage rate
- Neither change impacts leakage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





Understanding Leakage Rates

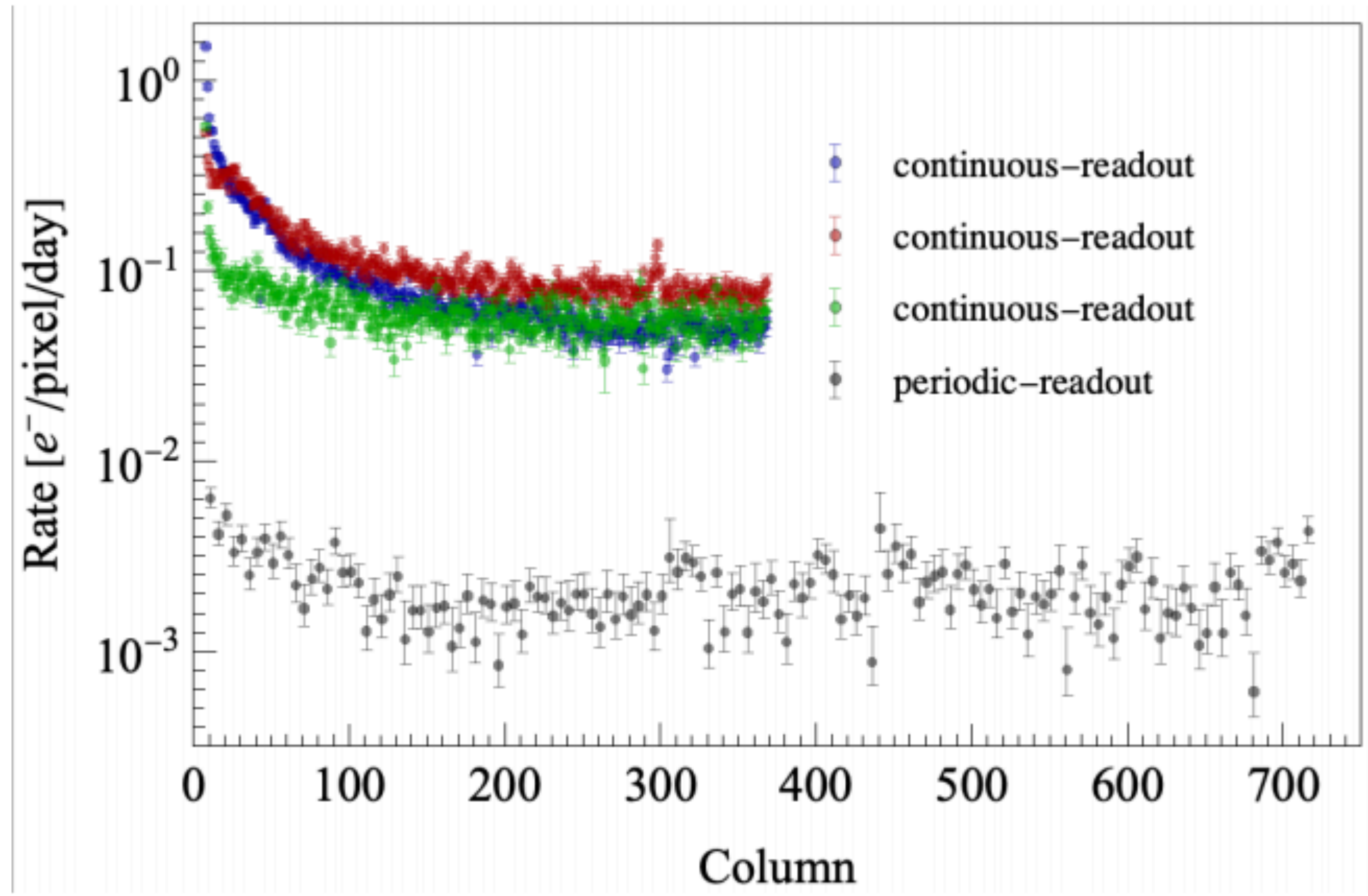
- Some variation seen due to pre-bias
  - Need to inc
  - Determine v reliably
- Neutralizati elevated bu matter of da
- Voltage pol bulk leakag
- Neither cha above 2.5 e-h pairs (to this level of statistics)

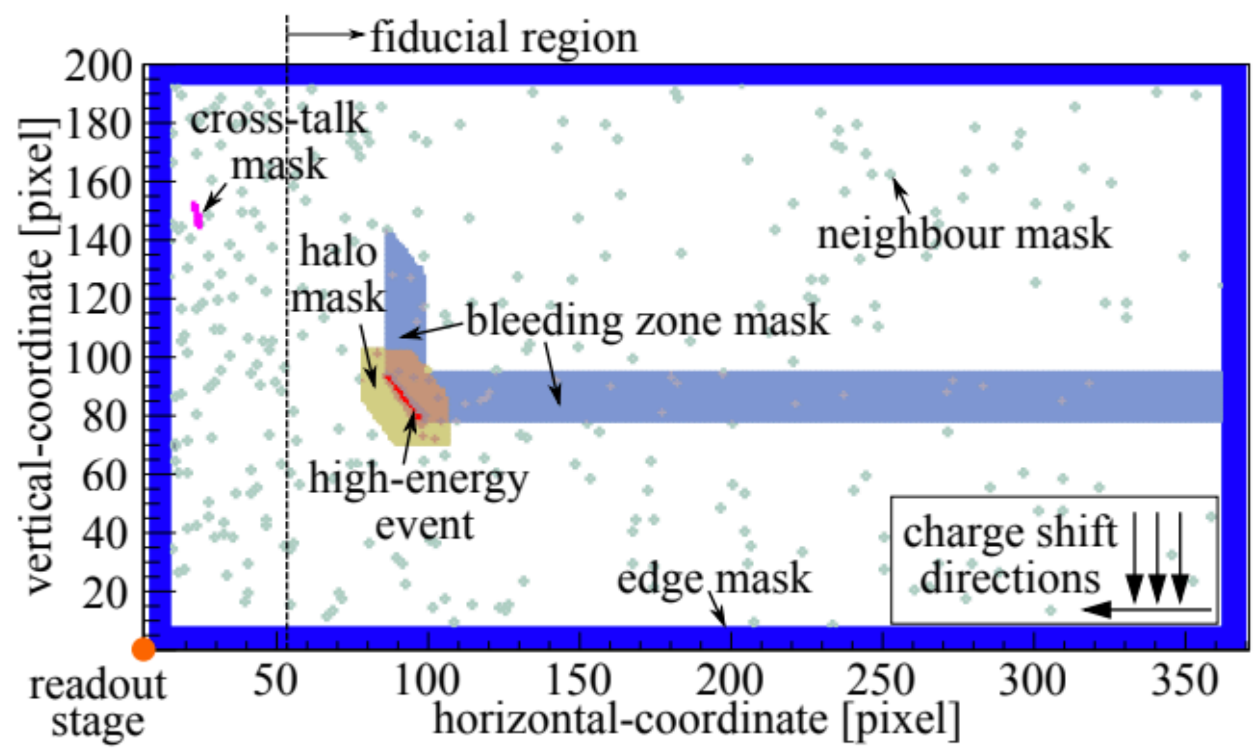


Fermilab

CCD Leakage Studies

- Leakage vastly reduced by turning amplifiers off during run; seems that amplifiers are a source of IR-induced leakage
  - Also means loss of timing information
- Edge effects and readout-adjacent effects also seen, and removed, from signal search
- Bleeding zone from charge transfer inefficiency, which looks like an elevated leakage current





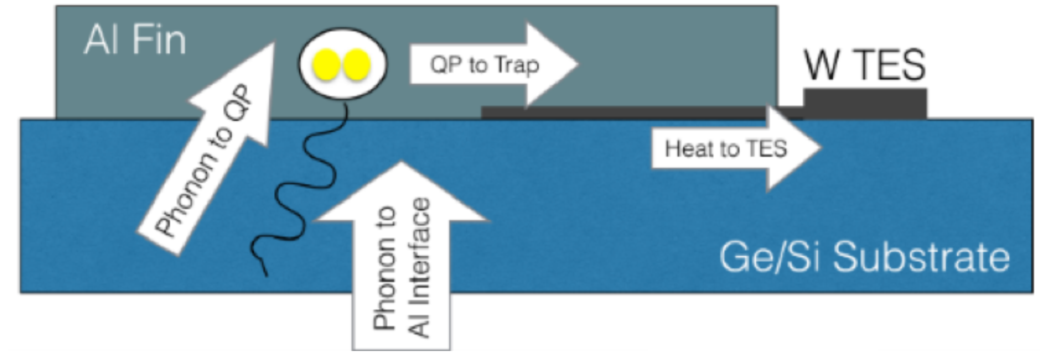
https://arxiv.org/pdf/1901.10478

Fermilab

How do we Overcome Charge Leakage?

- Determine mechanisms in existing technologies, and reduce leakage through dedicated R&D - in progress
  - Claims have been made that for sufficiently IR-tight designs, 1 mHz/g has been achieved in DAMIC at SNOLAB; will limit most experiments to 2e- thresholds for > 1kg-day
- Make detectors which are less susceptible to charge leakage
  - If surface physics, can reduce leakage through surface passivation, cleaning, and event rejection
  - If IR, detectors which have more tightly bound impurity states - Insulators and high-gap semiconductors satisfy this criterion (here I consider the example of diamond)
- Make detectors which have much lower ionization quanta, such that the signal is at a much higher energy than the leakage current
  - Superconductors
  - Exotic Semiconductors
  - Highly-doped insulators

Calorimeter Resolution

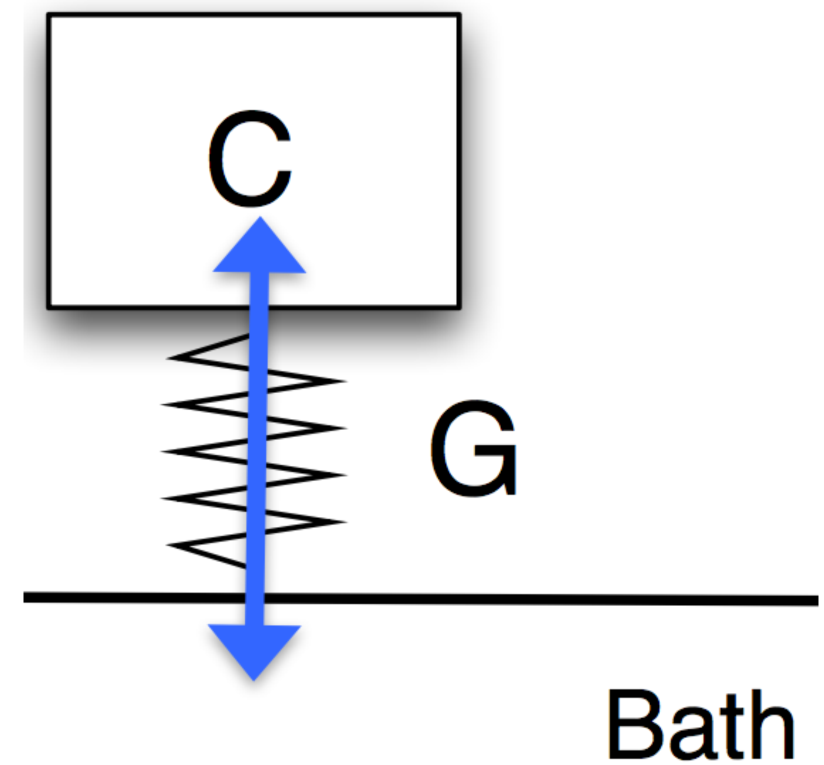


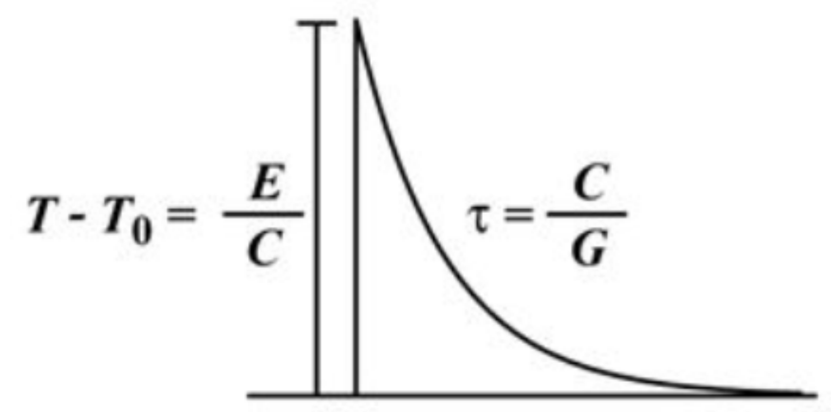
- Calorimeter energy resolution is fundamentally limited by thermal fluctuations between the sensing volume and the bath regardless of detector geometry; this minimum resolution follows

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

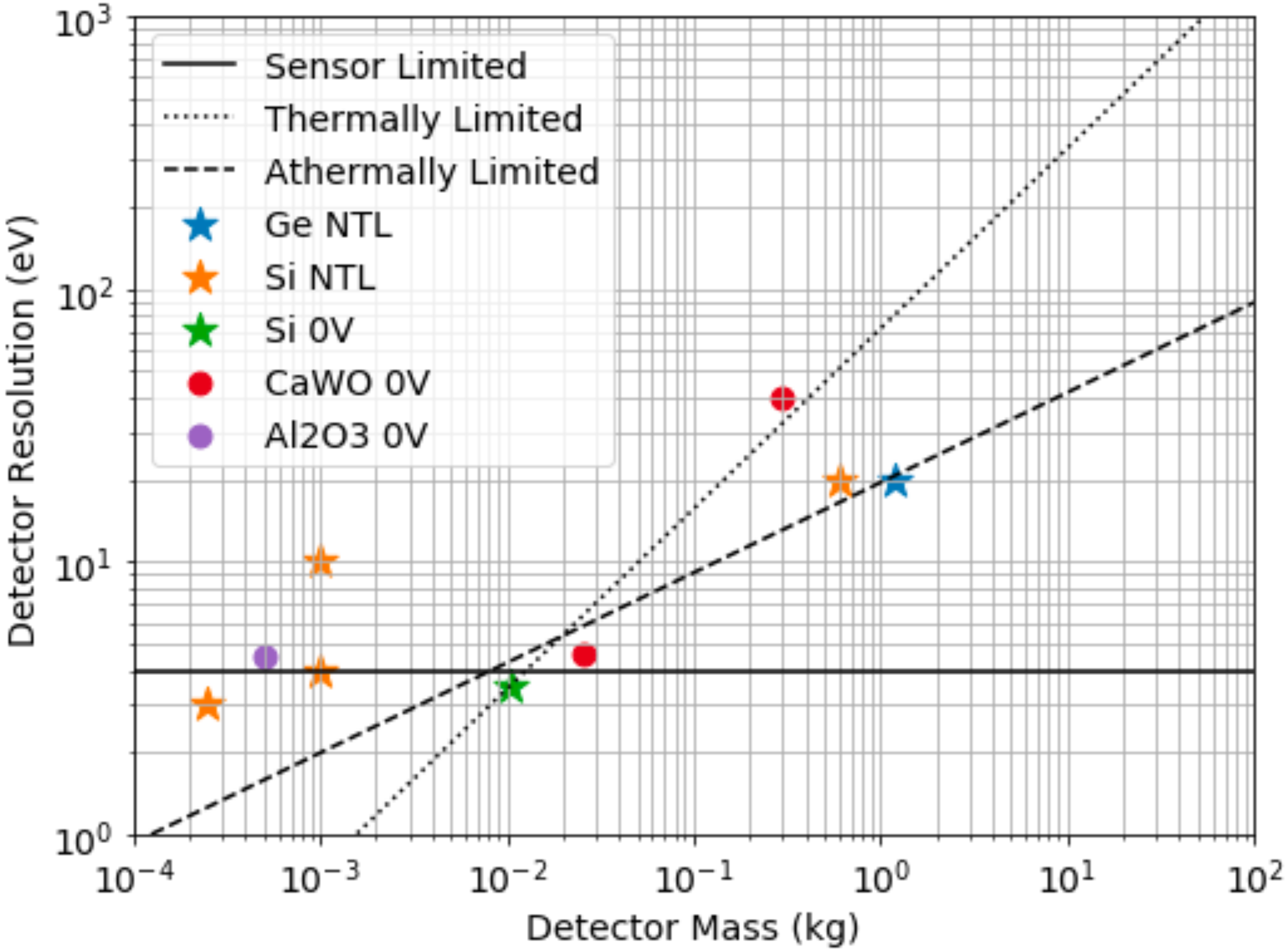
- One way around the volume limitation is by collecting the energy before thermalization; the volume is thus the sensor volume, not the target volume

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



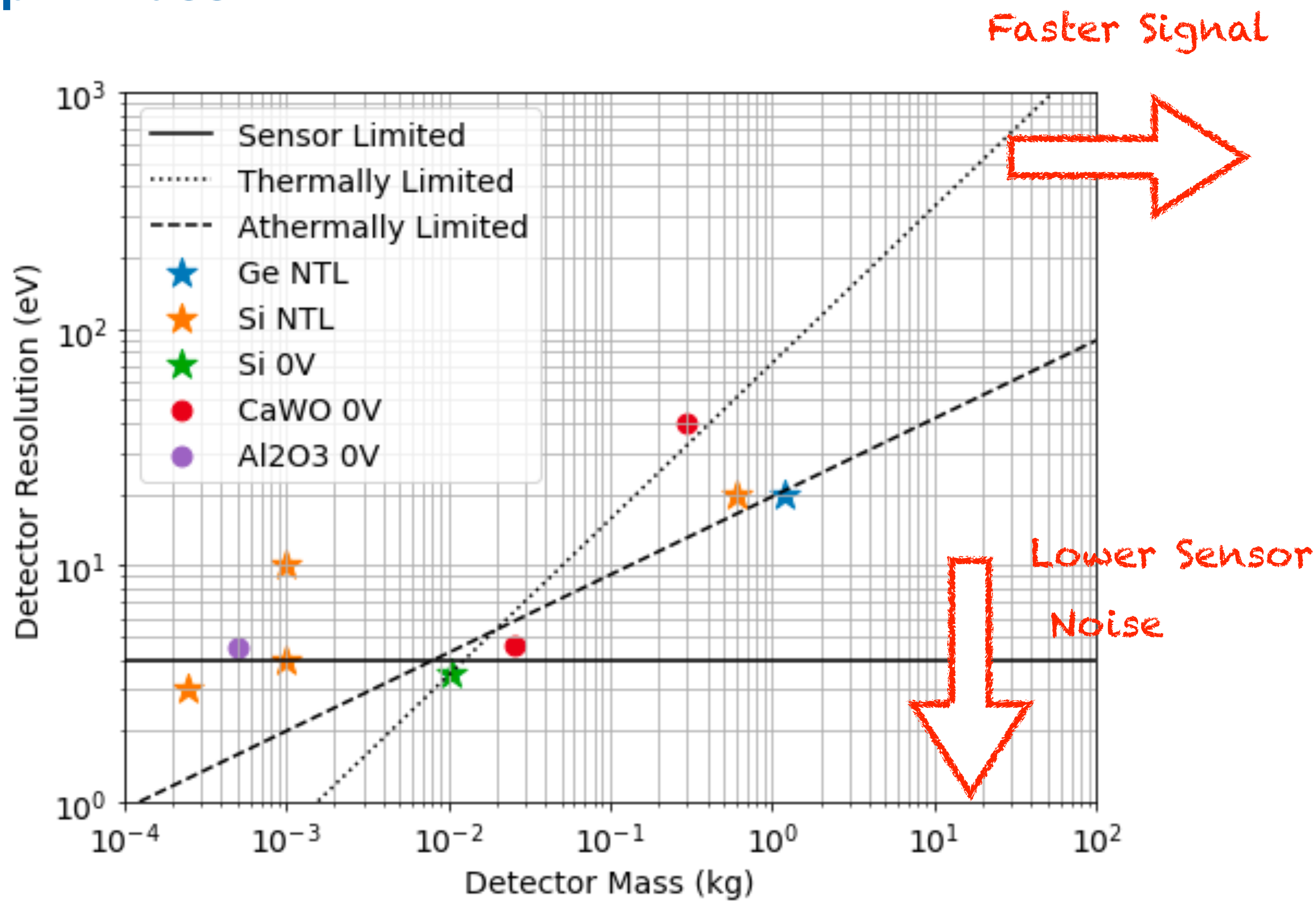


Scaling Up in Mass

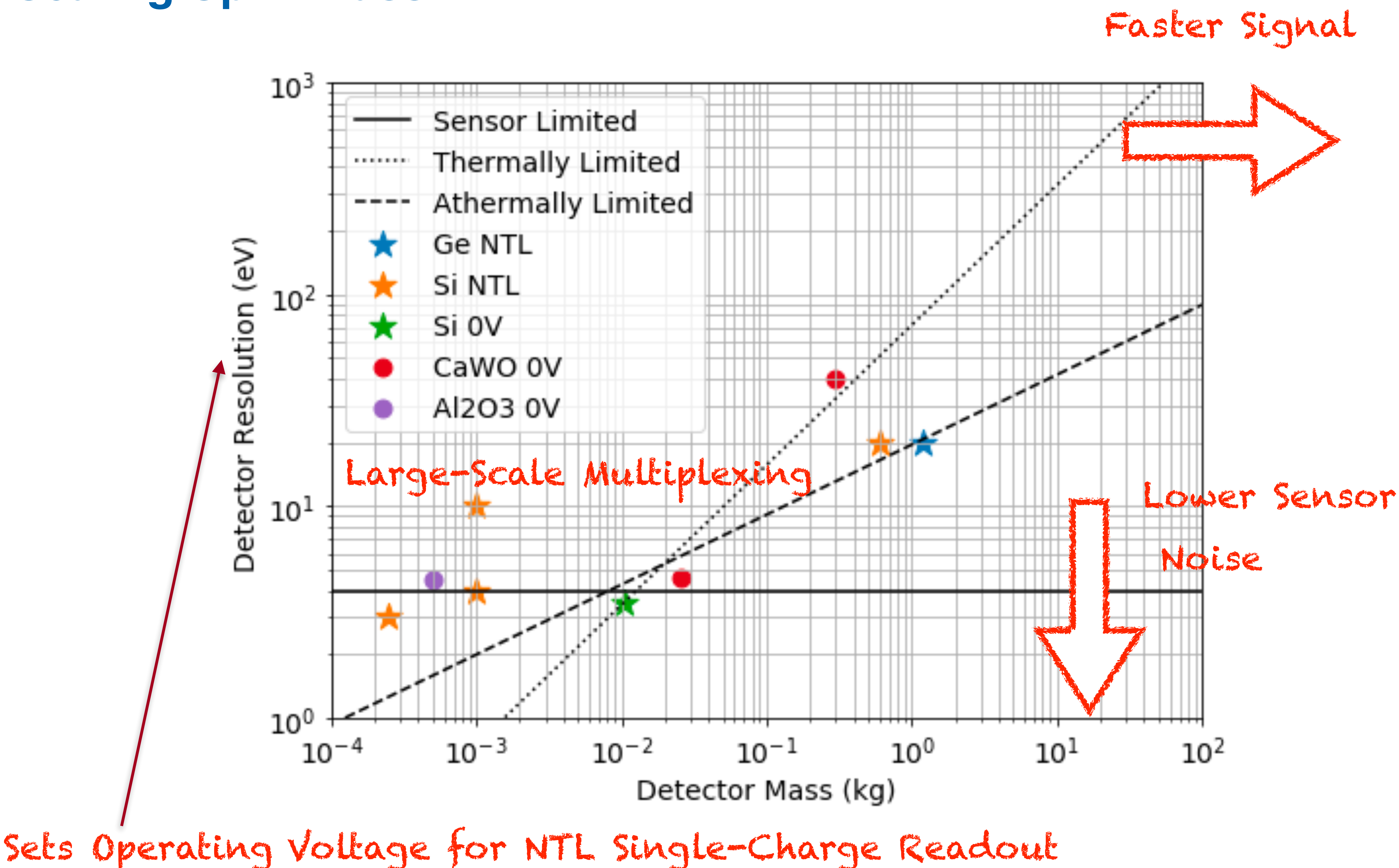


Fermilab

Scaling Up in Mass

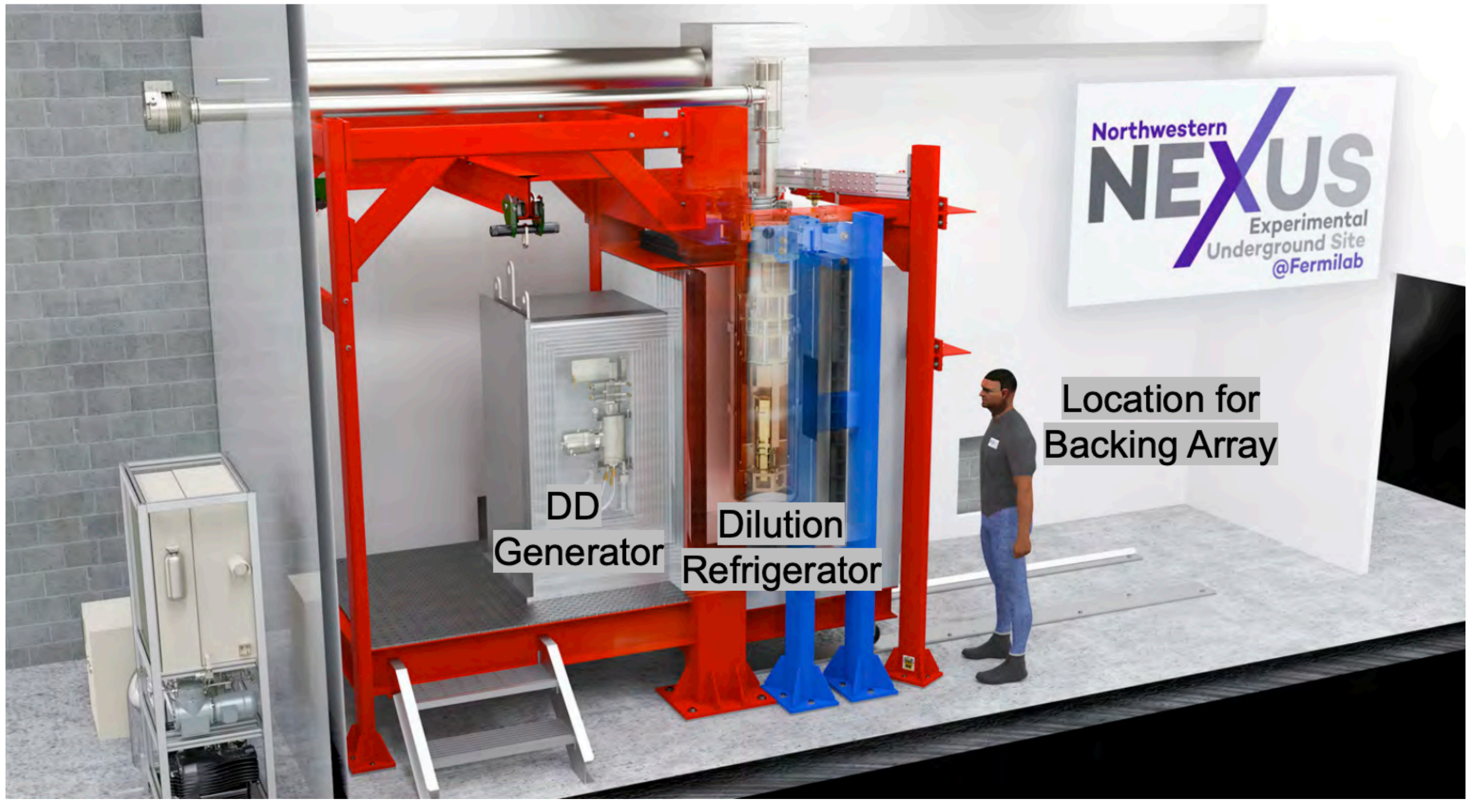


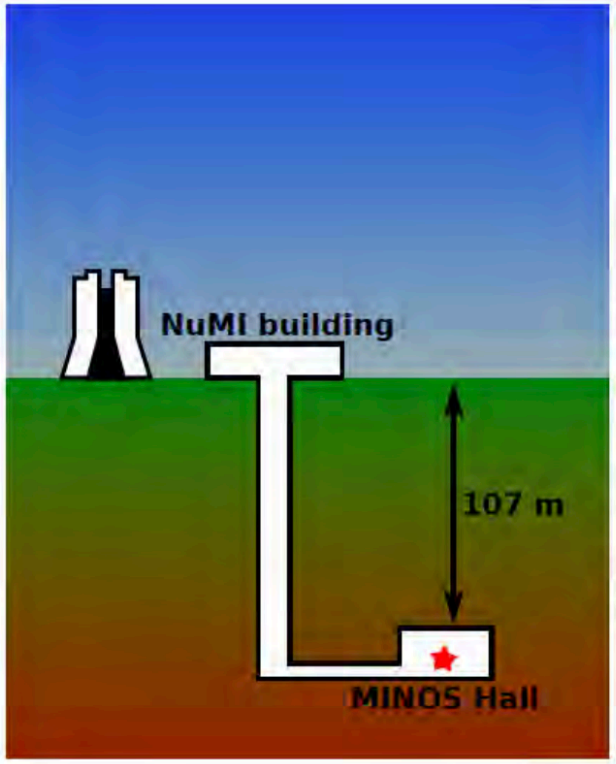
Scaling Up in Mass

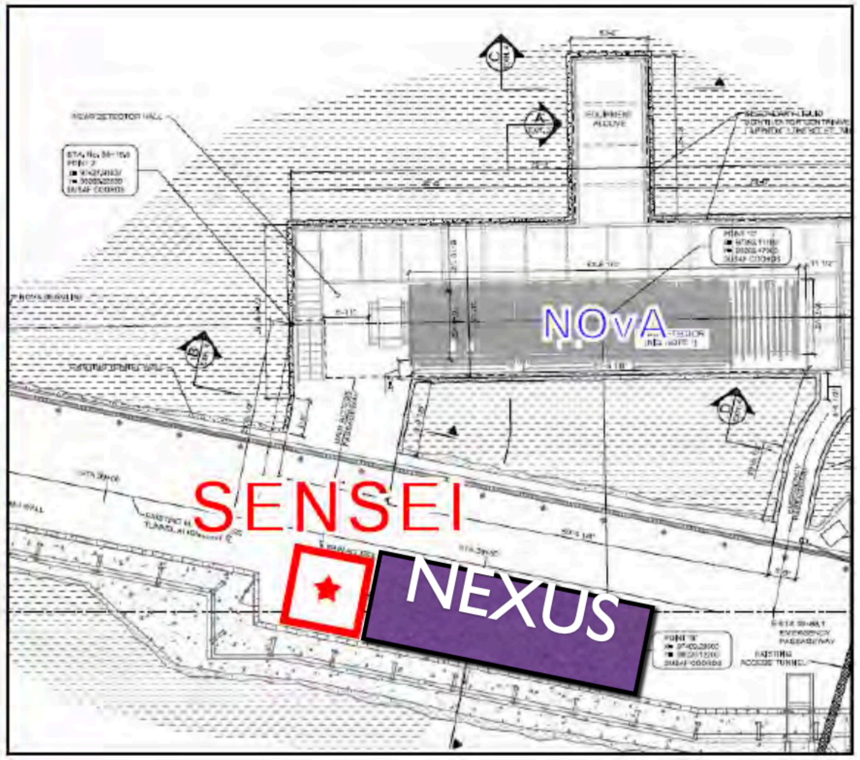


Fermilab

NEXUS: Underground Experimental Site for R&D







Fermilab

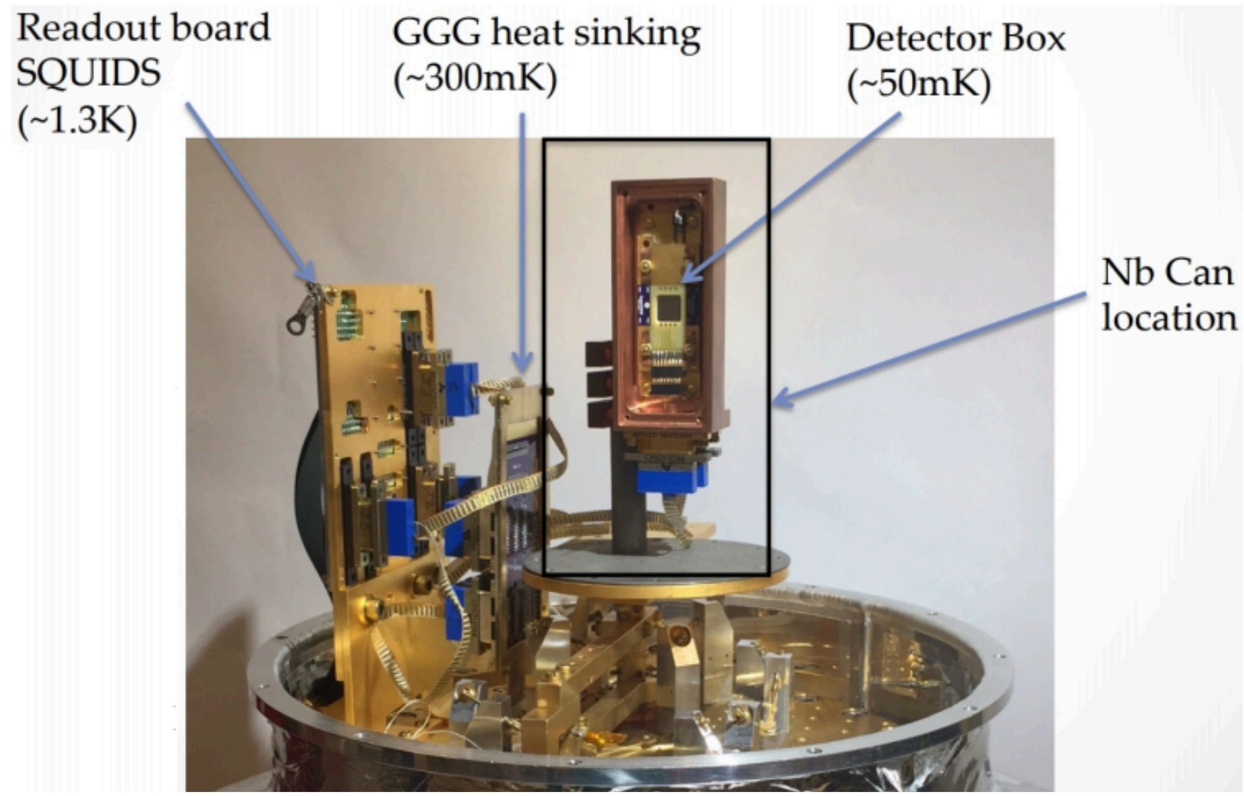
NEXUS Si/Ge Experimental Timeline

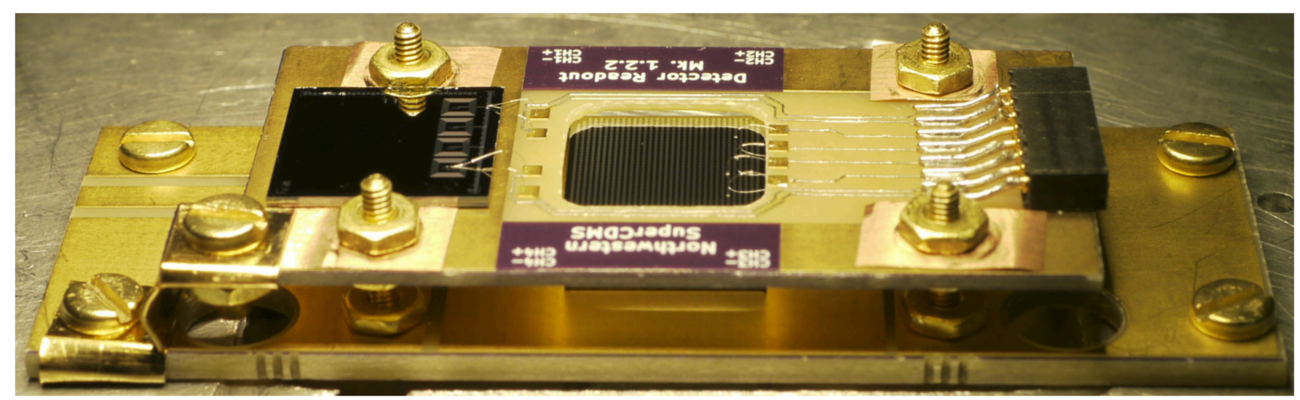
- Now (Animal ADR Demonstrator): 1 gram
  - 1 gram, 4 eV resolution (20 eV threshold)
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 4 keV in energy
  - DM search with 1 gram-week

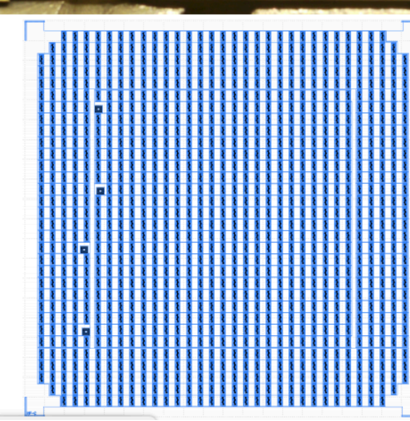
- Late Summer 2019: 10 grams,
  - 2-4 ~4g detectors
  - 4 eV resolution (20 eV threshold),
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 40 keV in energy
  - DM search with 1 gram-month

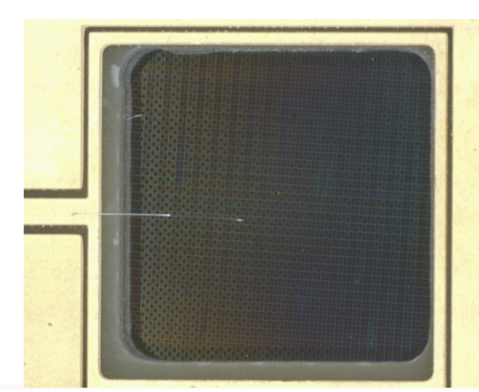
- Fall 2019-Winter 2020: 30-100 grams,
  - 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution
  - 4 eV to 40 keV in energy
  - DM search with 1-10 gram-year (~kg day)

- Late 2020 - Early 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









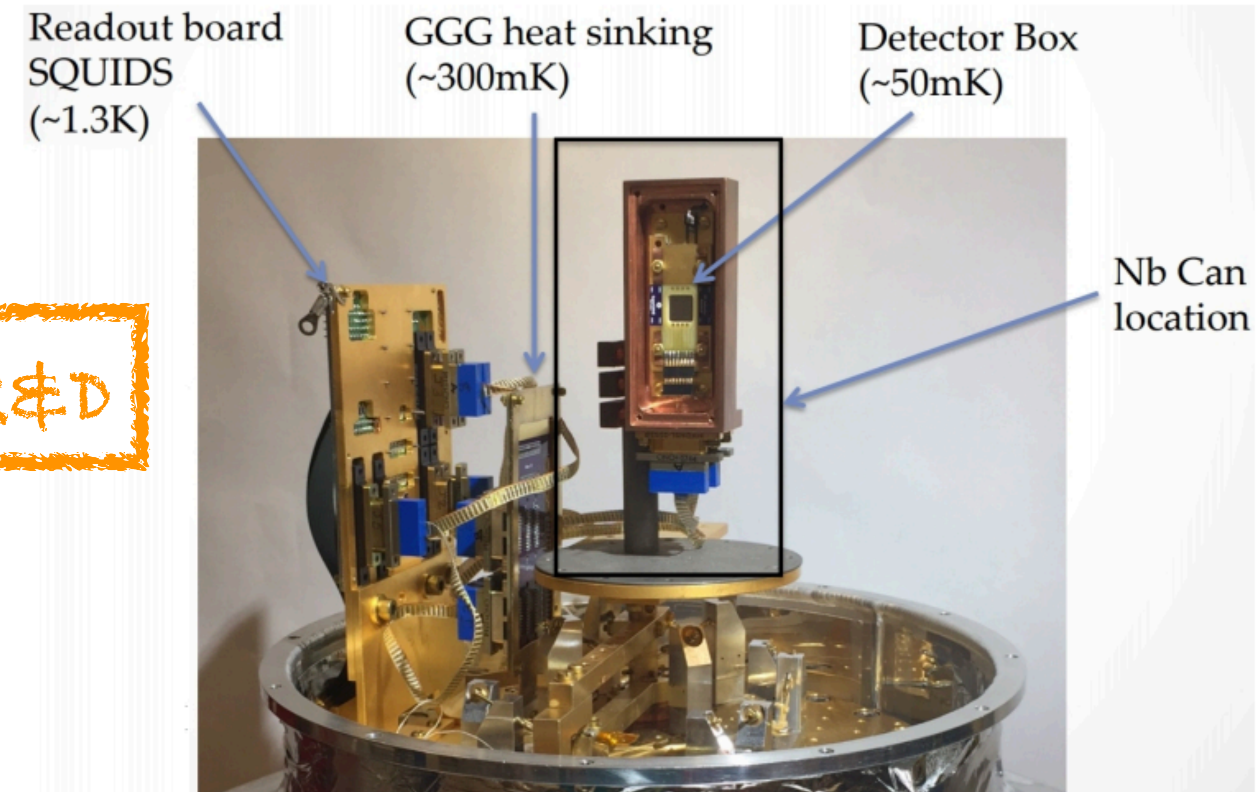
NEXUS Si/Ge Experimental Timeline

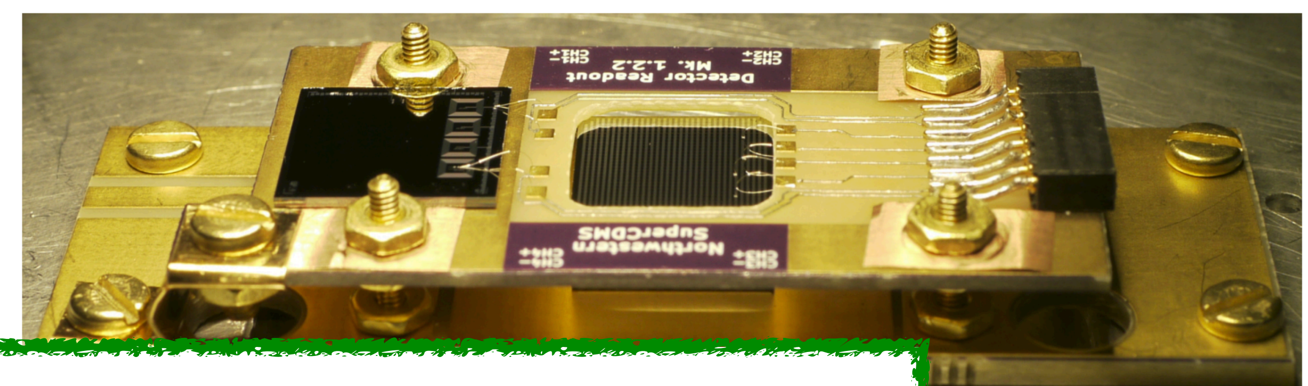
- Now (Animal ADR Demonstrator): 1 gram
  - 1 gram, 4 eV resolution (20 eV threshold)
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 4 keV in energy
  - DM search with 1 gram-week
- Late Summer 2019: 10 grams,
  - 2-4 ~4g detectors
  - 4 eV resolution (20 eV threshold),
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 40 keV in energy
  - DM search with 1 gram-month

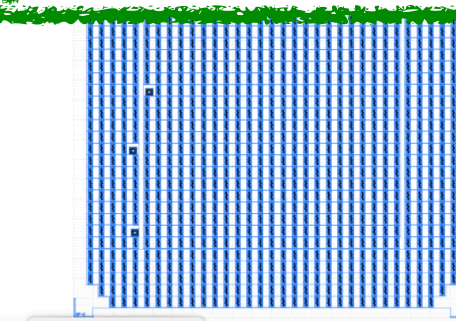
Leakage R&D

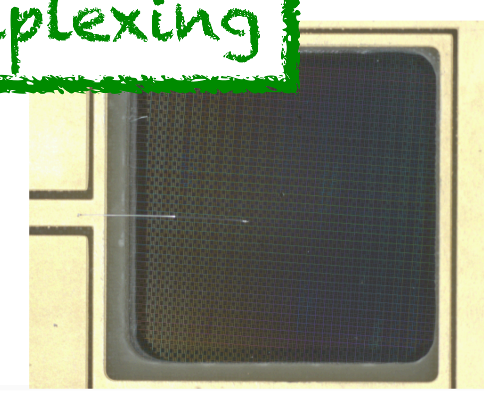
- Fall 2019-Winter 2020: 30-100 grams,
  - 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution
  - 4 eV to 40 keV in energy
  - DM search with 1-10 gram-year (~kg day)
- Late 2020 - Early 2021: 10 kg payload
  - <20 eV threshold
  - Up to 60 keV in energy
  - 0.01 electron-hole pair resolution
  - DM search/***neutrino physics*** with 1 kg-year of exposure

Larger Crystals or Multiplexing









Low-Z: Diamond Detectors

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

- Diamond is a semiconductor with long-lived charge excitations
- It 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
- Impurity states have higher energies, making it less susceptible to 1-4 K blackbody radiation by orders of magnitude

	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
$\hbar\omega_{Debye}$ (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).

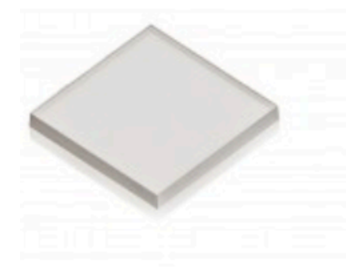
	Diamond	Si	Ge
Donors			
N	1700, 4000	15–50	
P	500	45	12
Li	230	33	9.3
Acceptors			
B	370	45	10
Neutral	∼10	2	0.5

TABLE V. Energies of common residual impurities in diamond, Si and Ge in units of meV [23, 66]. Given the difficulty to controllably dope Si and Ge with nitrogen, the impurity energy is not well-determined for Si and essentially unmeasured for Ge, though it should be on the order of the other shallow impurities.

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

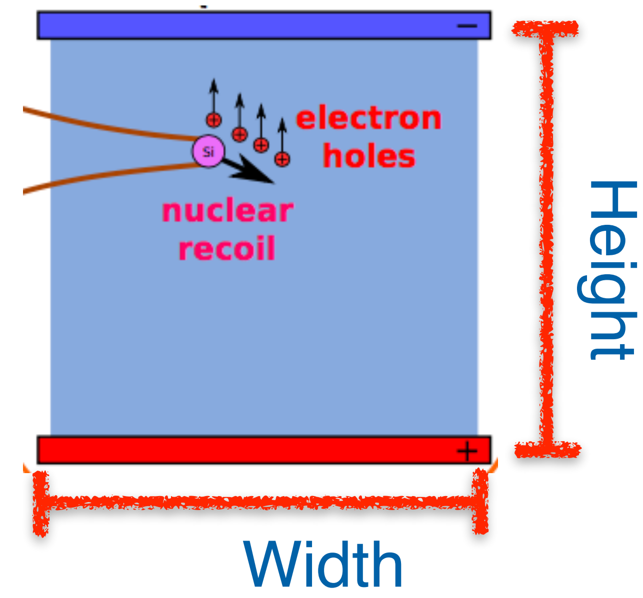
200 mg

1 CARAT
$800

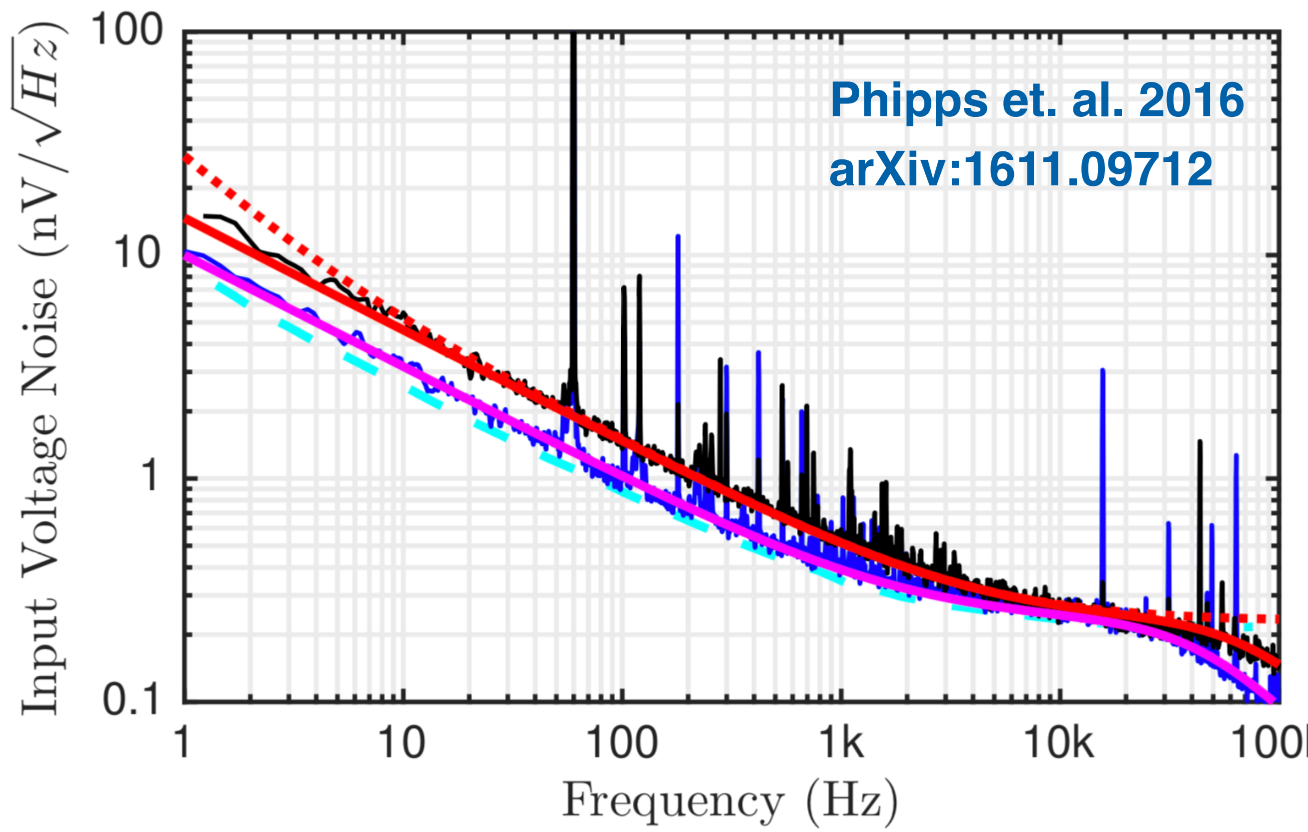
Diamond Charge Detector

$$\sigma_q \geq \frac{N_v(C_{\rm det}+C_{\rm in})}{\epsilon_q\sqrt{\tau}}$$

$$\sigma_q \approx 35\frac{(C_{\rm det}+C_{\rm in})/(250\ \rm{pF})}{(C_{\rm in}/100\ \rm{pF})^{1/4}}$$



- Full charge collection has been demonstrated many times in CVD diamond crystals
- Charge resolution is determined by detector+readout capacitance, voltage noise, and 1/f cutoff
- Capacitance in diamond is 2x lower than in Si and 3x lower than in Ge for the same geometry, allowing for larger pixels to have the same charge resolution, or lower resolution in pixels of the same size
- Recent HEMT amplifiers have achieved performance at 4.2K sufficient for single-charge ionization-chamber style diamond detectors for low-rate signals



Design	Dimensions	Mass (mg)	Temp. (K)	V_{Bias}	σ_E	σ_q
Single Cell	16 mm^2 × 0.5 mm	28	4.2 K	10 V	13–39 eVee	1–3e^-
Segmented	1 mm^2 × 0.5 mm	1.8			1.3–3.9 eVee	0.1–0.3e^-/segment

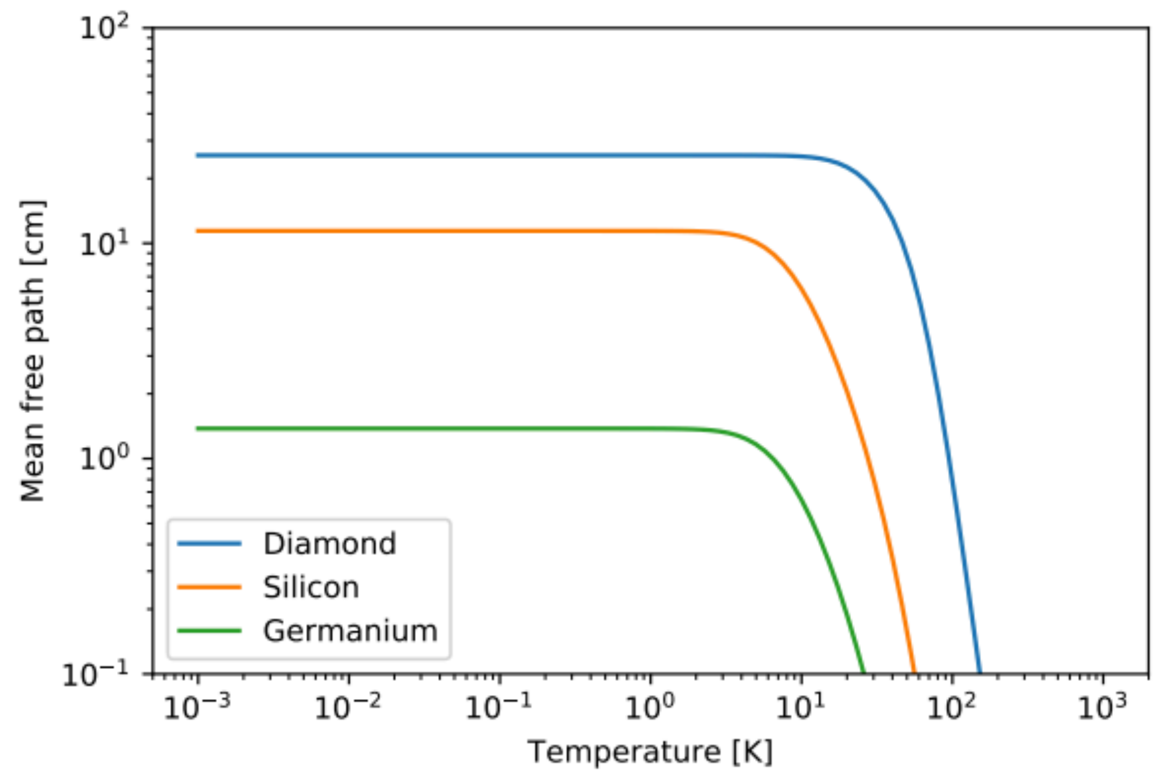
Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

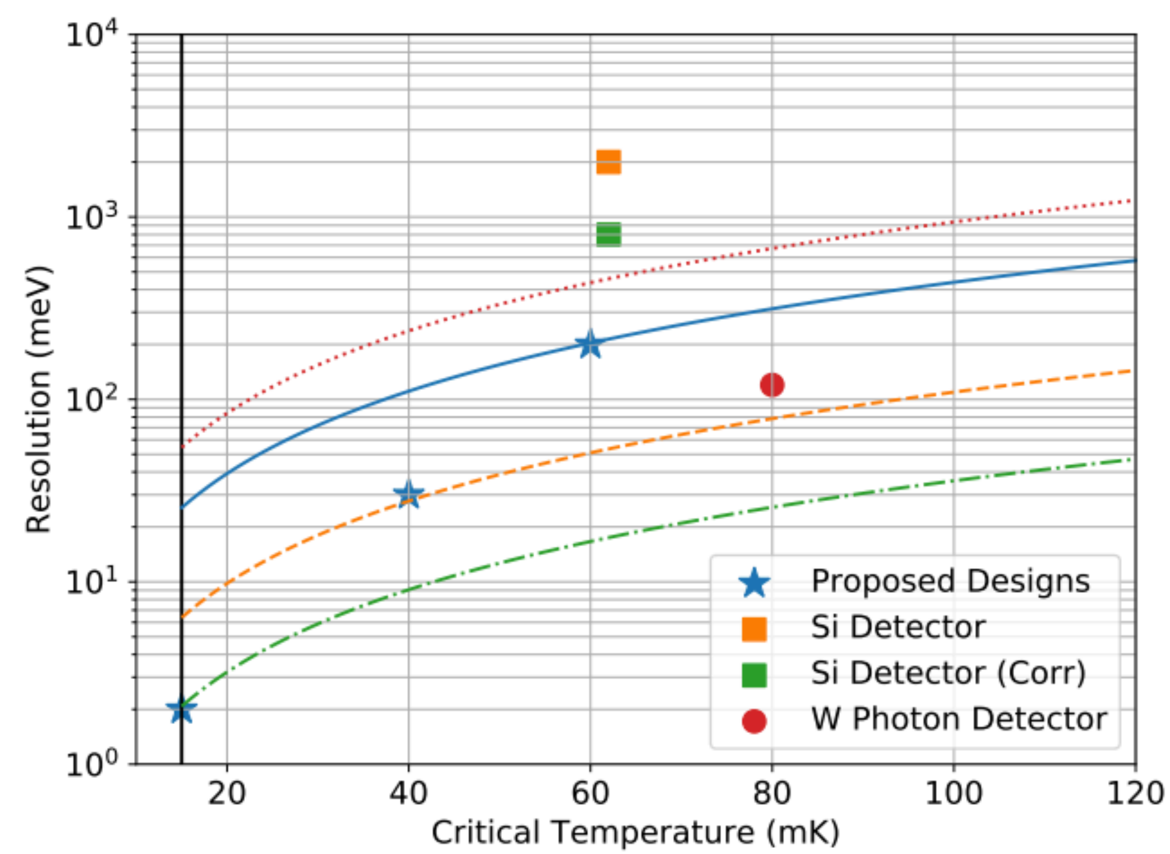
Diamond Calorimeter

- 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

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

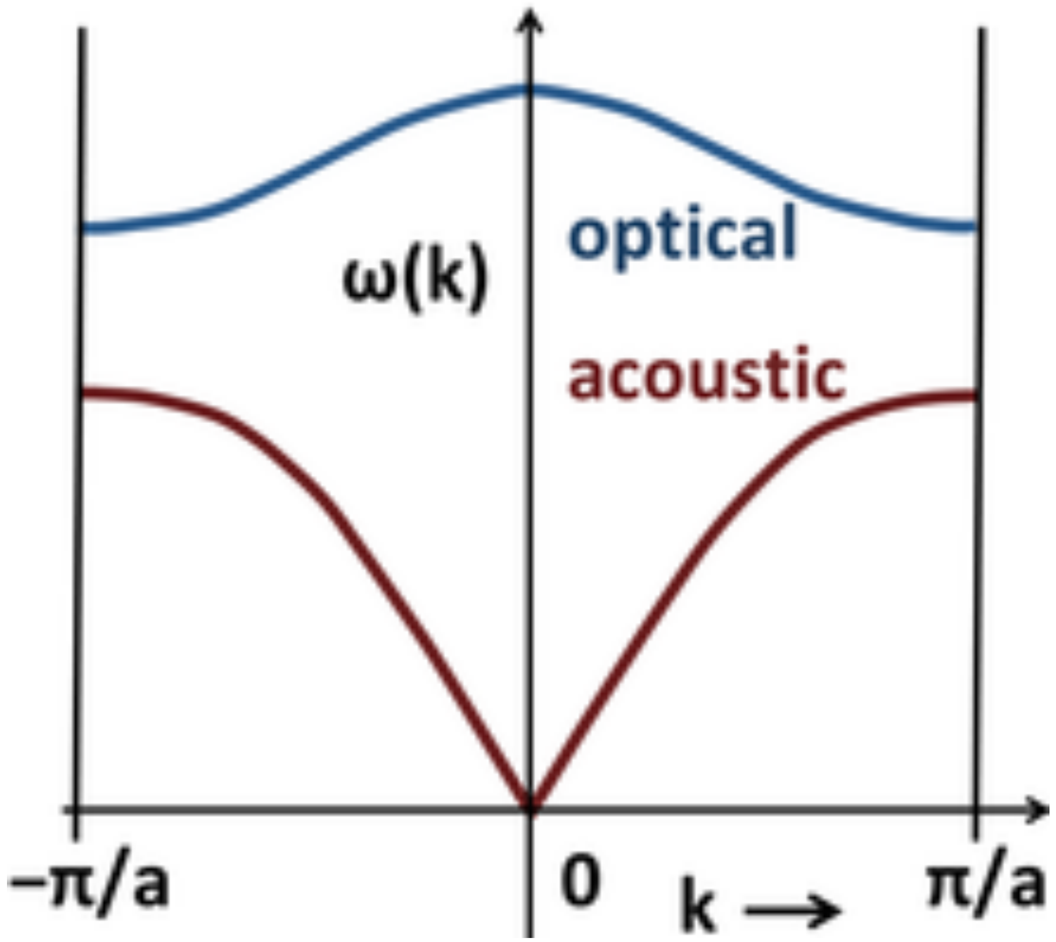
Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

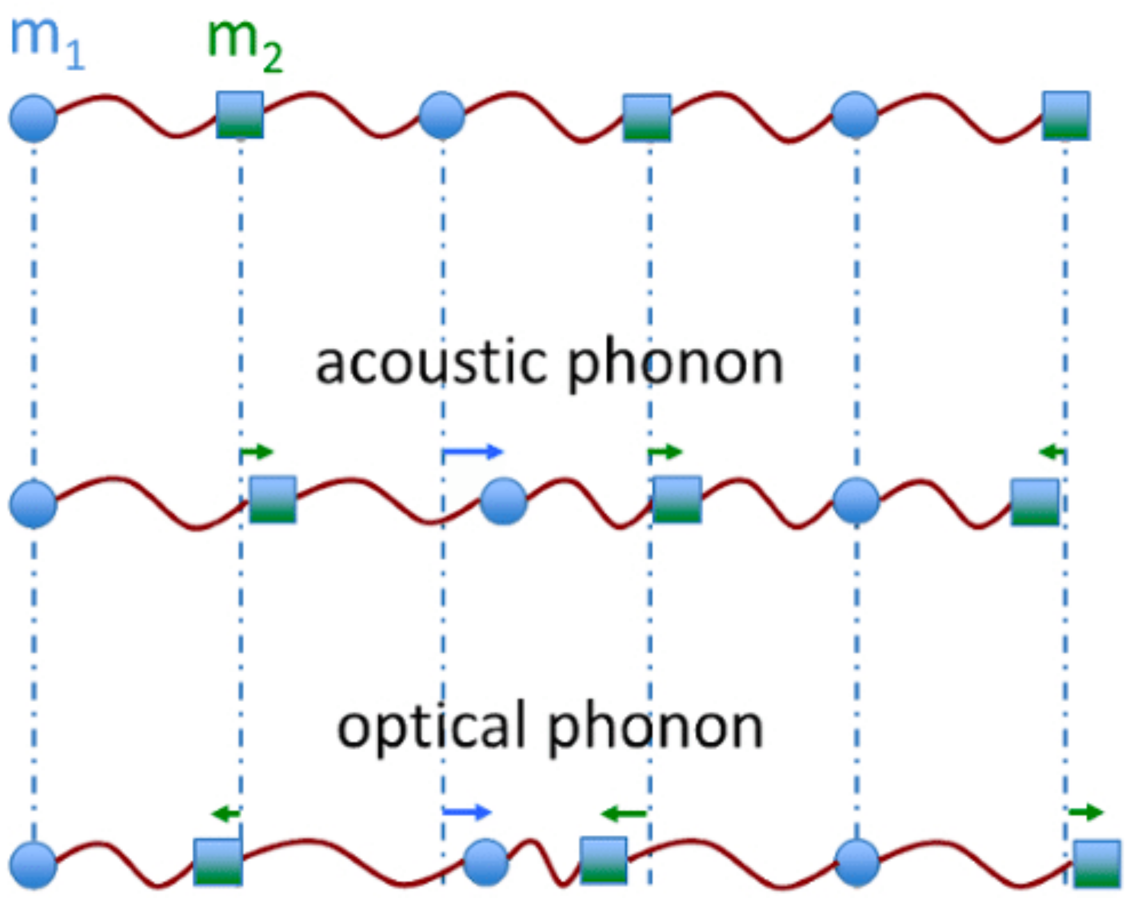




Fermilab

Quantized Lattice Vibrations: Optical Phonons





- Lattice vibrations at low temperature also have a band-like structure, with one or multiple mono-energetic optical phonons separated from an acoustic band.
  - In non-polar crystals, photons can stimulate pair-production of optical phonons
  - Diamond, Si, and Ge all have sensitivity to photons in the range 2-3 times that of their optical phonon modes

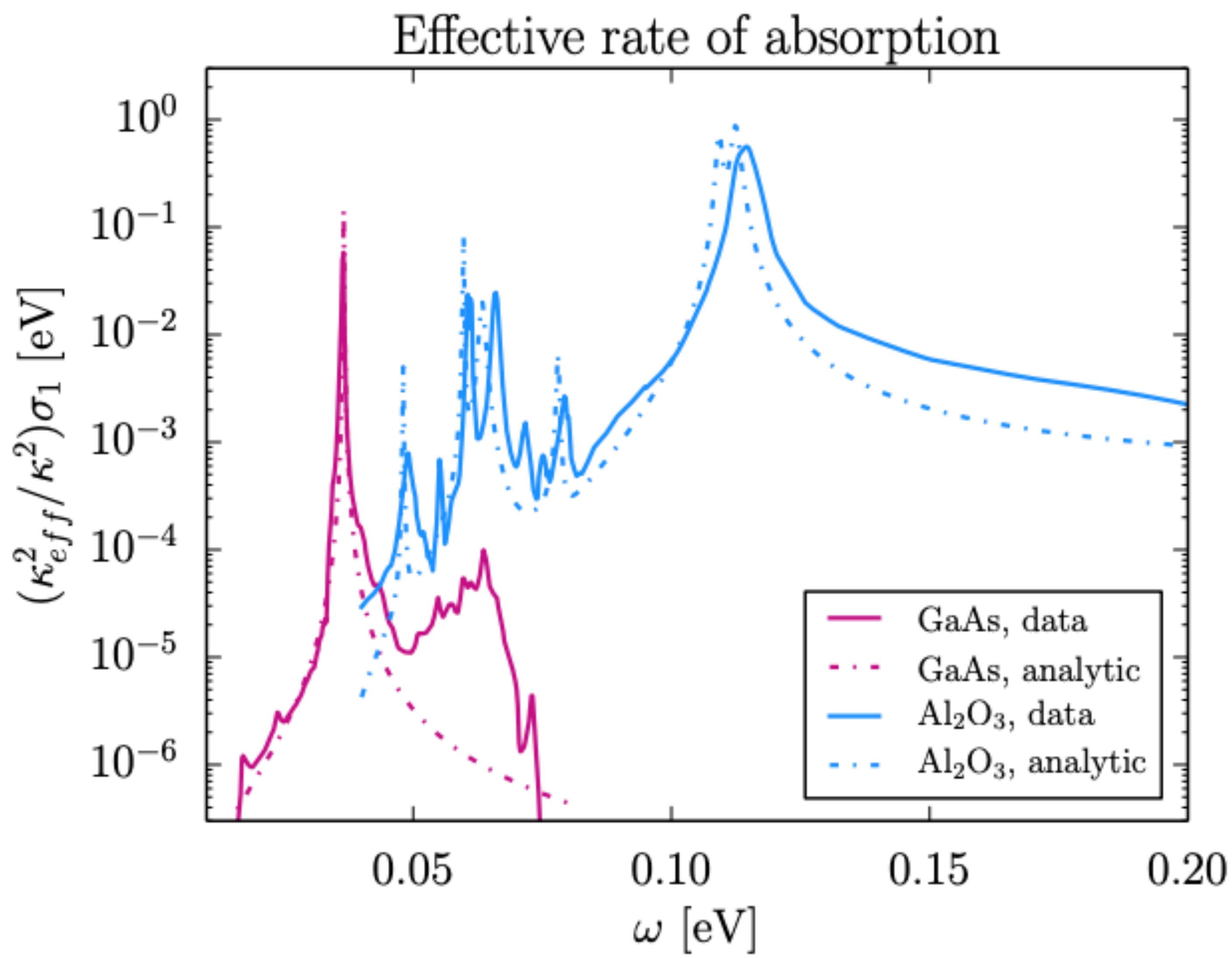
Phonon Scattering in Polar Materials

- Polar materials can use the virtual photon produced by polarizing the material to produce single phonons, allowing for a much more strongly coupled process

- GaAs and sapphire both have significant event rates in the 10 meV - 1 eV energy range

- If DM scattering is mediated by a dark photon, this can also be used to couple keV-scale DM to electrons, producing phonons rather than electron-hole pairs

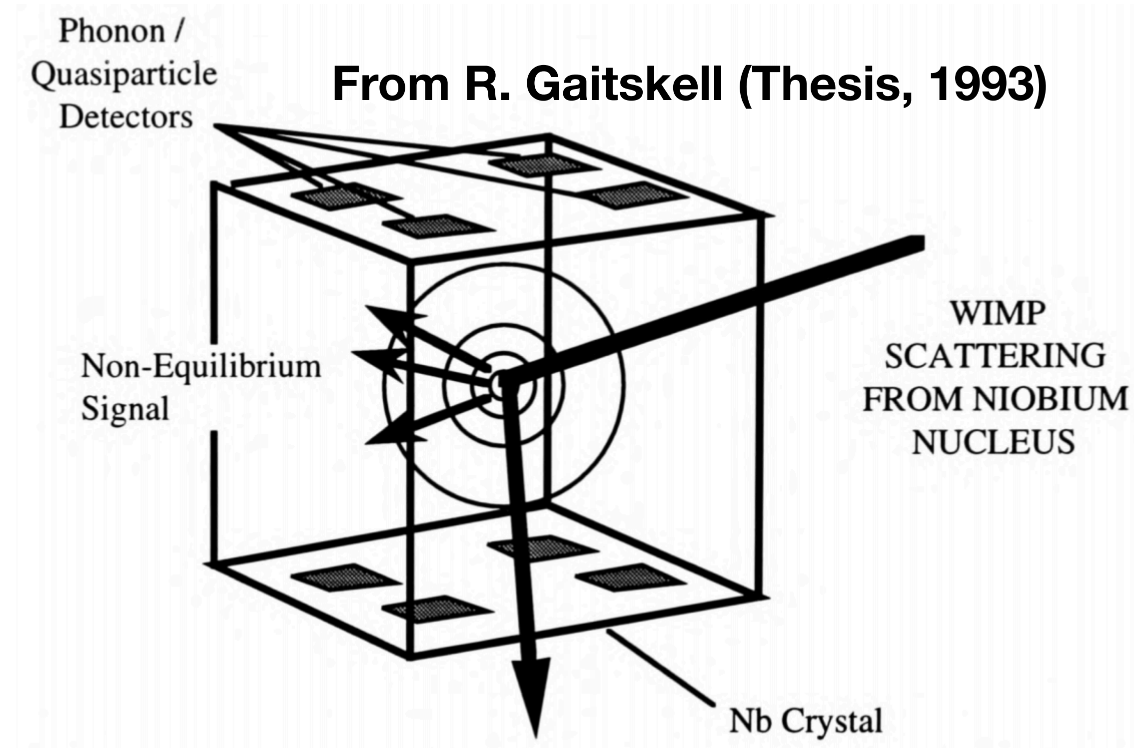
https://arxiv.org/abs/1807.10291

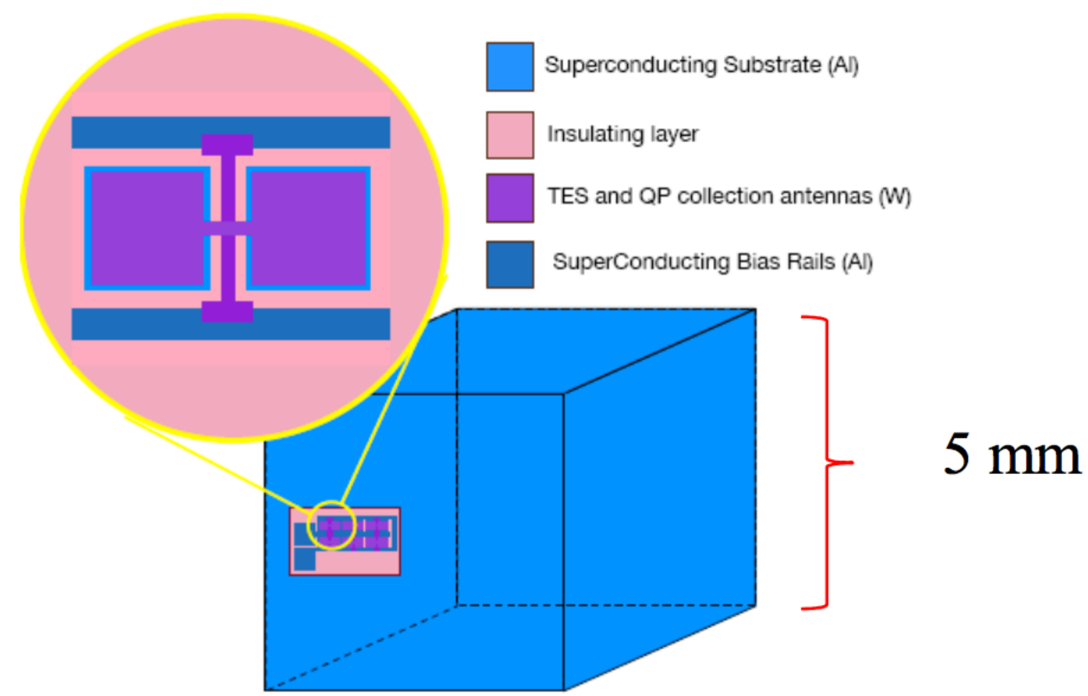


$$\Gamma^{\text{iso}}(v_i) = \frac{|e'|^2}{4\pi}\frac{\omega_{LO}}{v_i}\left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_0}\right)\log\frac{1+\sqrt{1-2\omega_{\text{LO}}/m_X v_i^2}}{1-\sqrt{1-2\omega_{\text{LO}}/m_X v_i^2}}\Theta\left(m_X v_i^2/2 - \omega_{\text{LO}}\right)$$

meV-scale Scattering: Superconducting Detectors

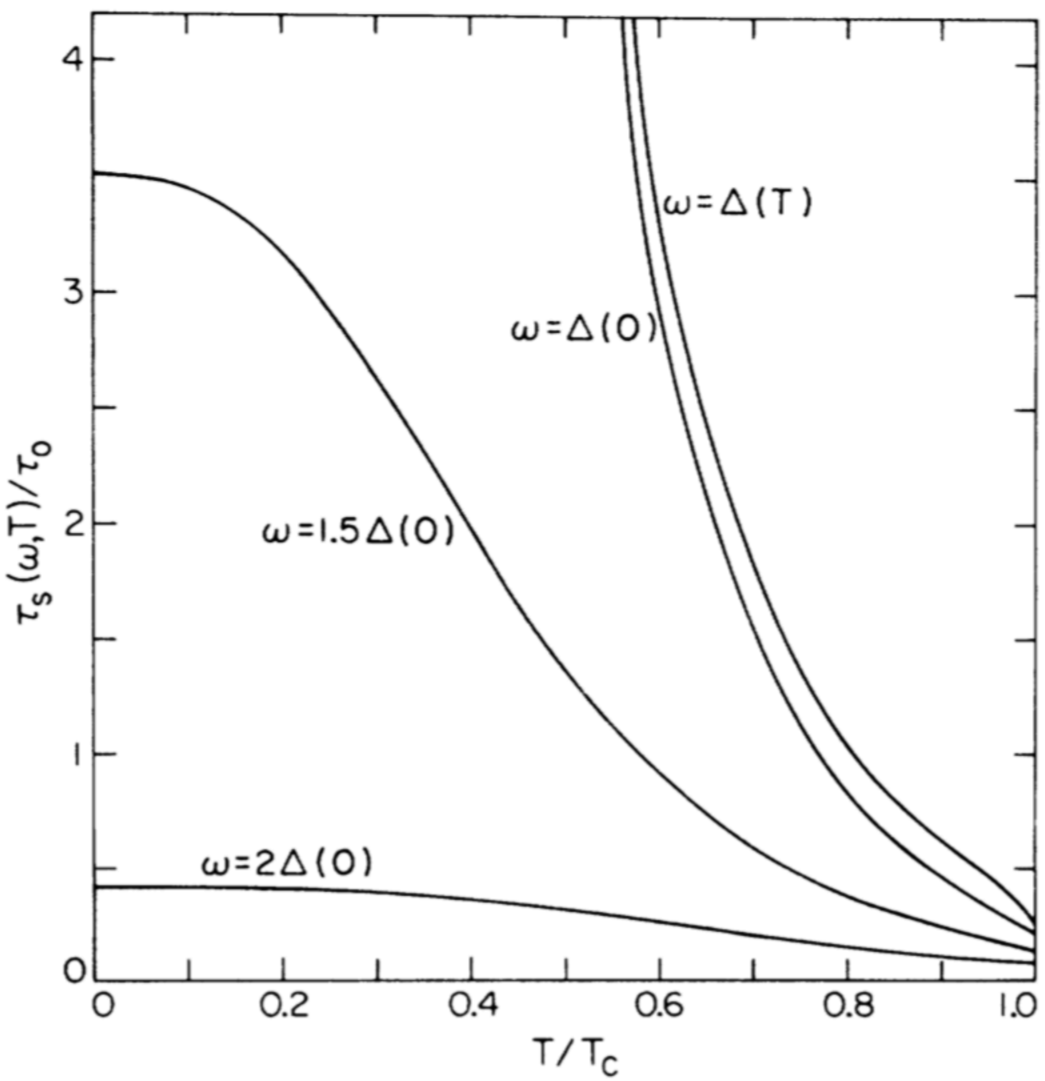
- Superconducting detectors for dark matter were being worked on actively 20 years ago, but the success of Ge/Si/Xe put their development on hold
- For energy deposits below the ~0.5 eV bandgap of Ge, they're one of the few remaining model-independent options, and can probe DM masses down to the keV scale
- Backgrounds largely untested, and IR requirements very stringent. Need dedicated R&D setup to test a variety of designs to build a theory of operation, and narrow down best target and design.

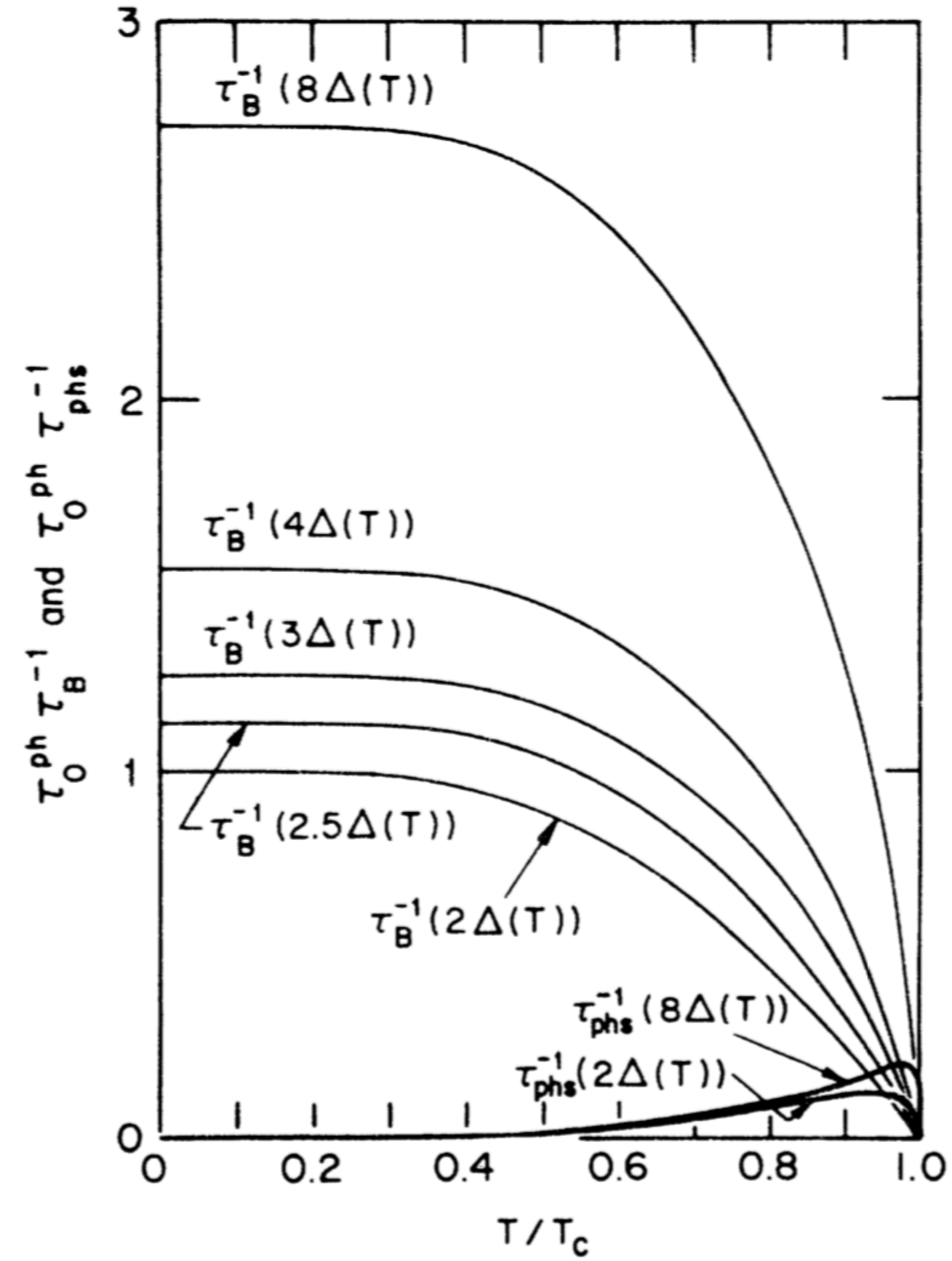




https://arxiv.org/pdf/1512.04533.pdf

Quasiparticle and Phonon Lifetimes





- Quasiparticles quickly reach the gap energy, and at zero temperature, phonons below the gap propagate freely

- Sufficiently pure crystals, well below the superconducting bandgap, have very long lived excitations limited by surface and impurity scattering (as in semiconductors)

Quasiparticle and phonon lifetimes in superconductors, Kaplan et. al. 1976

Superconducting Detector R&D

- The design drivers for superconducting (SC) detectors are less obvious (as described in ArXiv.1512.04533)
  - Should we focus on collecting quasiparticles (Al, Zn) or phonons (Ta, Nb)? The preferable method depends on Tc (known) and quasiparticle lifetime (largely unknown for pure, large crystals)
  - How well do film and bulk properties of SCs correlate?

- It's non-trivial to read out but electrically isolate a bulk superconductor. We can use higher Tc trapping regions, but we need to try different combinations of sensor materials and geometries to optimize energy transport efficiency.

From R. Gaitskell (Thesis, 1993)

	T_c (K)	Θ_D (K)	Δ (meV)	τ_0^{qp} (ns)	τ_0^{ph} (ps)
Nb	9.2	275	1.515	0.149	4.17
Pb	7.19	105	1.350	0.196	34.0
Sn	3.75	200	0.590	2.30	110
In	3.4	108	0.540	0.799	169
Al	1.19	428	0.180	110 [27]	242

Table 3.3.1. Parameters for a number superconductors. Taken from Ref. **[36]** unless otherwise indicated.

Effective quasiparticle and phonon lifetimes are a rate balance:

$$\tau_{eff} = \frac{\tau_r}{2}\left(1 + \frac{\tau_{\phi\phi}}{\tau_{pb}}\right)$$

	Energy (μeV)	Decay Time (Klemens Model)	Decay Time (Tamura Model)
$2\Delta_{\mathrm{Al\ film}}$	400	1.8 ms	24.2 ms
$2\Delta_{\mathrm{Sn\ film}}$	1150	6.6 μs	123 μs
Δ_{Nb}	1515	2.1 μs	31.1 μs
$2\Delta_{\mathrm{Pb\ film}}$	2730	110 ns	1.63 μs
$2\Delta_{\mathrm{Nb}}$	3030	64 ns	970 ns

Table 3.3.3 Decay times of L phonons at various energies of interest calculated using the models of Klemens and Tamura. We will use the times from Tamura in this paper unless otherwise specified.

Fermilab

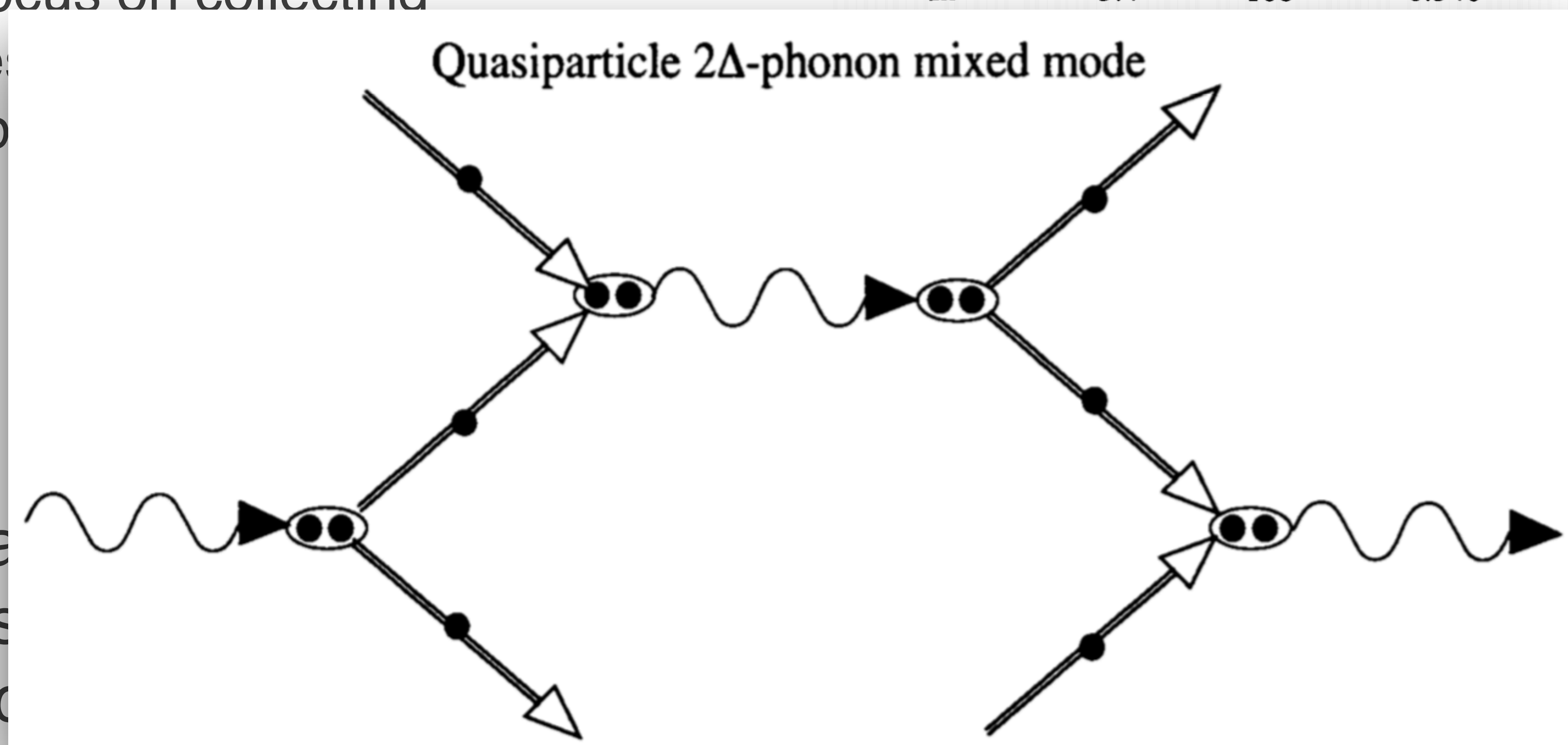
Superconducting Detector R&D

From R. Gaitskell (Thesis, 1993)

	T_c (K)	Θ_D (K)	Δ (meV)	τ_0^{qp} (ns)	τ_0^{ph} (ps)
Nb	9.2	275	1.515	0.149	4.17
Pb	7.19	105	1.350	0.196	34.0
Sn	3.75	200	0.590	2.30	110
In	3.4	108	0.540	0.799	169
				110 [27]	242

from Ref. [36] unless otherwise

- The design drivers for superconducting (SC) detectors are less obvious (as described in ArXiv.1512.04533)
  - Should we focus on collecting quasiparticle… The preferab… (known) and… unknown for… and phonon …balance:
  - How well do… correlate?
- It's non-trivia… electrically is… supercondu… trapping regions, but we need to try different combinations of sensor materials and geometries to optimize energy transport efficiency.



		…l)	Decay Time (Tamura Model)
			24.2 ms
$2\Delta_{Sn\ film}$	1150	6.6 µs	123 µs
Δ_{Nb}	1515	2.1 µs	31.1 µs
$2\Delta_{Pb\ film}$	2730	110 ns	1.63 µs
$2\Delta_{Nb}$	3030	64 ns	970 ns

Table 3.3.3 Decay times of L phonons at various energies of interest calculated using the models of Klemens and Tamura. We will use the times from Tamura in this paper unless otherwise specified.

Fermilab

(Some) Ongoing R&D Efforts

- Charge detectors
  - Silicon - SENSEI, DAMIC, DANAE, SuperCDMS
  - Graphene - PTOLEMY-G3

- Phonon Detectors
  - Si/Ge - SuperCDMS, EDELWEISS
  - Diamond - Stanford/FNAL
  - Superfluid Helium - LBL/UMass (arXiv:1810.06283)

- Photon Detectors:
  - GaAs - LBL (arXiv:1802.09171)
  - Sapphire - nuCLEUS (ArXiv:1704.04317), LBL

(Some) Ongoing R&D Efforts

- Charge detectors
  - Silicon - SENSEI, DAMIC, DANAE, SuperCDMS
  - Graphene - PTOLEMY-G3

- Phonon Detectors
  - Si/Ge - SuperCDMS
  - Diamond - Stanford/
  - Superfluid Helium - L

- Photon Detectors:
  - GaAs - LBL (arXiv:18
  - Sapphire - nuCLEUS

- Conceptual Stage
  - Superconductors - Caltech, LBL, FNAL
  - Germanium CCDs
  - Dirac Materials
  - Molecular Detectors
  - Magnetic Bubble Chambers
  - Magnetic Phonons
  - Lots of Exotic Ideas

Take Aways

- Next generation of low-mass dark matter experiments should cover much of the interesting MeV-scale electron-recoil dark matter space
  - Need to get dark rates under control; no single charge sensitive detector has demonstrated rates comparable to the low dark rate claimed by DAMIC
  - Current technologies all achieve higher resolution by sacrificing other event information; room for improvement

- Really fun R&D to do in this space over the next few years, will also be useful for neutrino physics
  - If you give us targets to aim for, we have the tools to go after them

- Low energy ER backgrounds largely unknown below 100 eV; lots of interesting effects starting to pop up that make for fun particle physics

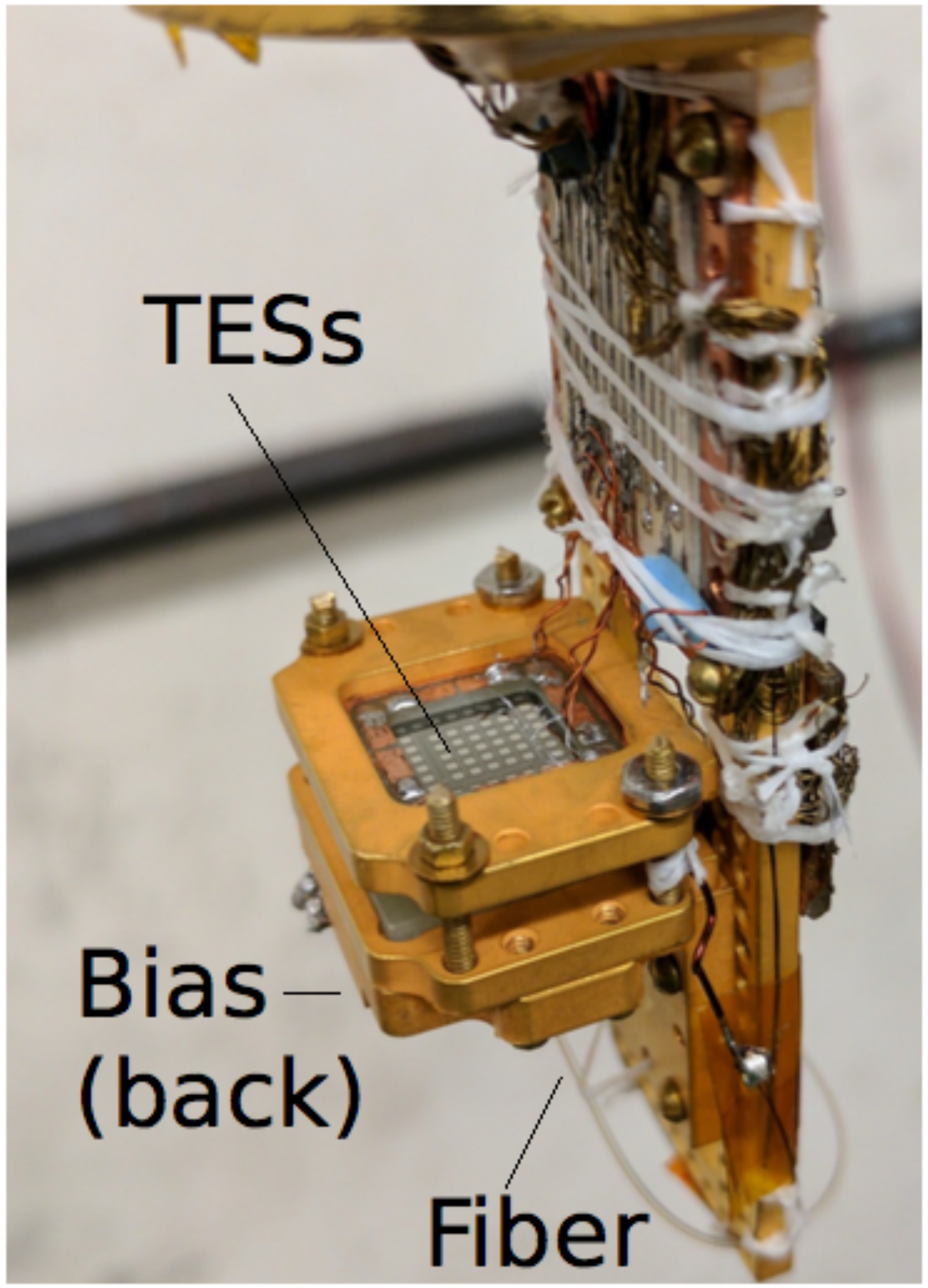
- Lots of new investment in this space given the high potential of inexpensive experiments in contrast to massive liquid noble high-mass searches

Backup

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

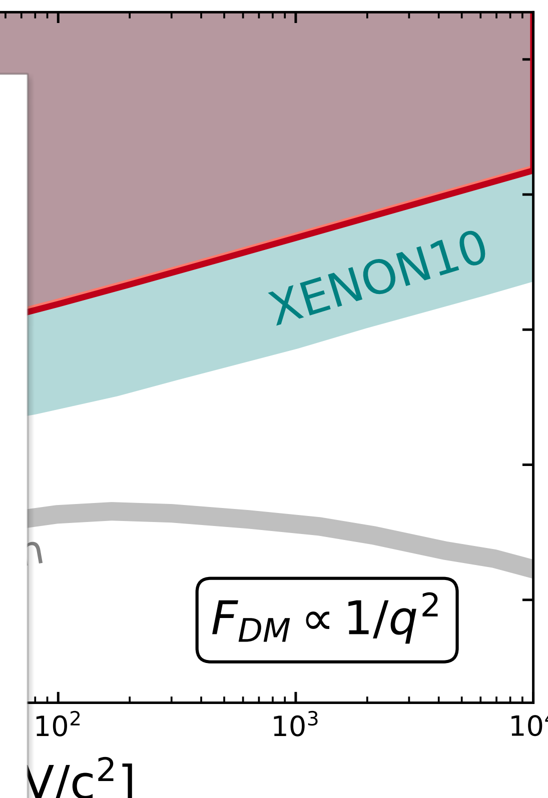


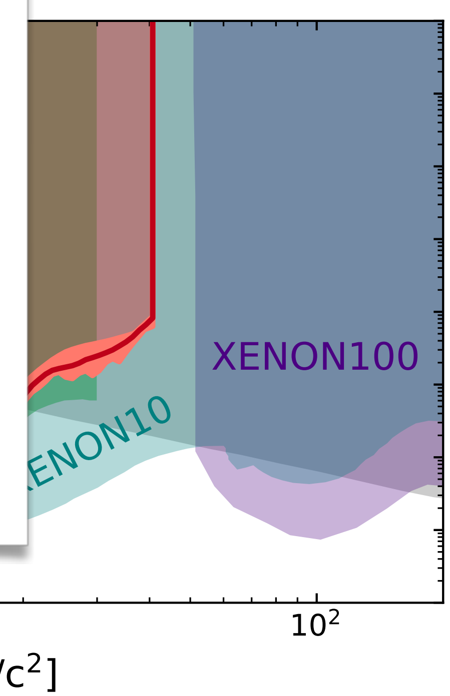
Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

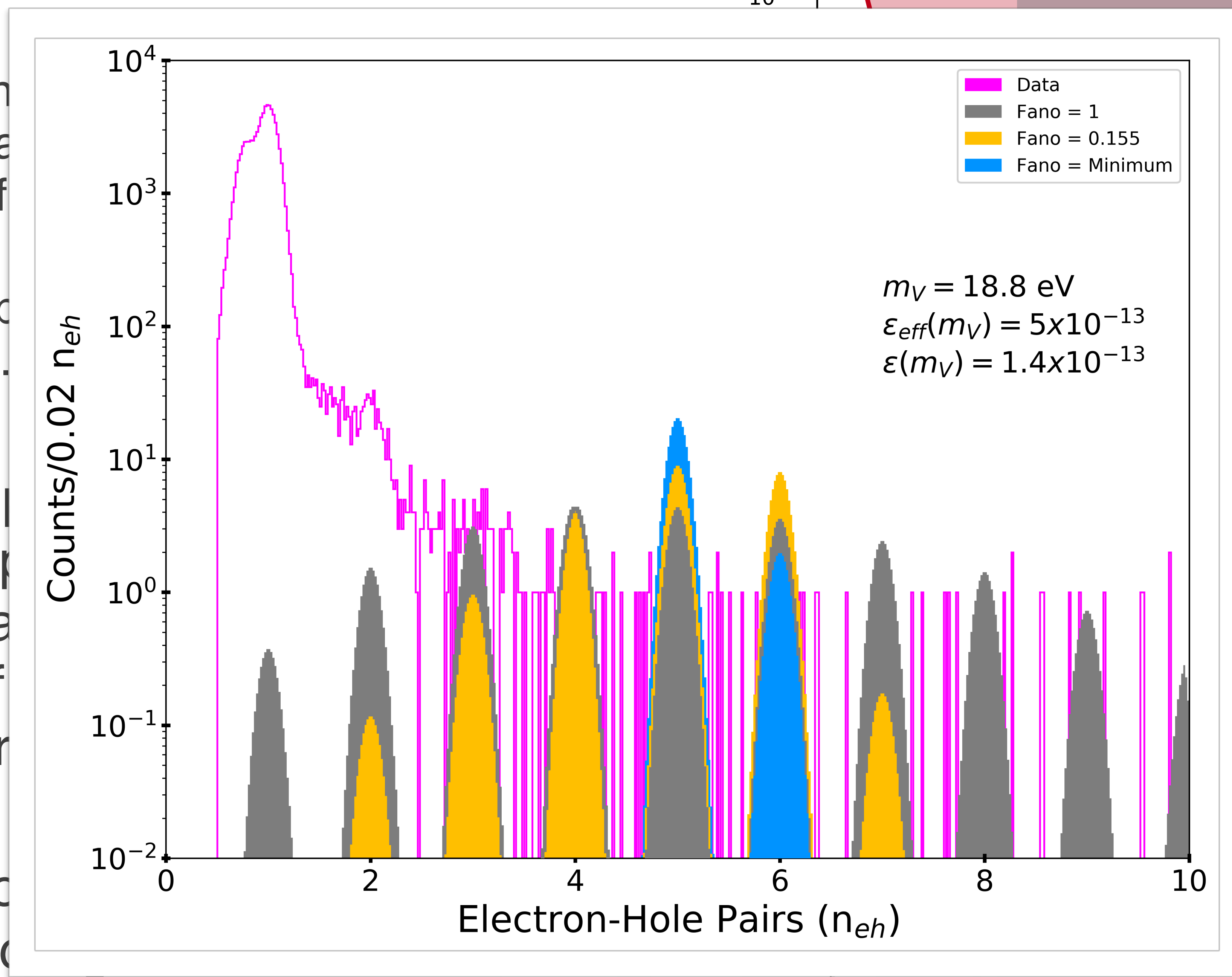
New Limits on Sub-GeV Dark Matter

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

- Momentum dependent limits peak at low energy
  - Lowering en probe the sa ~1/10000 of 4 MeV
  - Our prototyp limits for ~0.
- Better pileu allow us to photon para with 1/60 of searches ar
- This is the generation searches

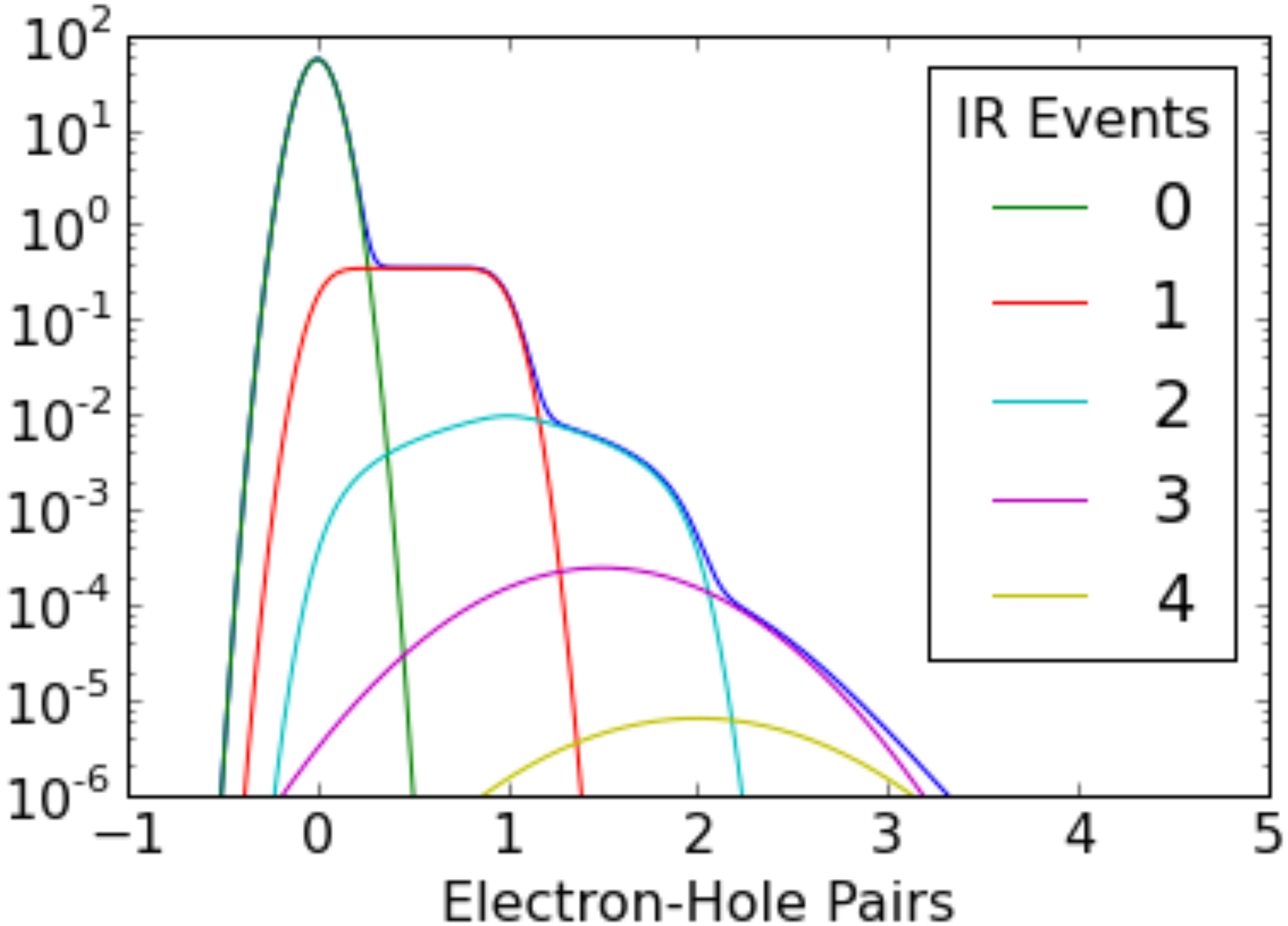


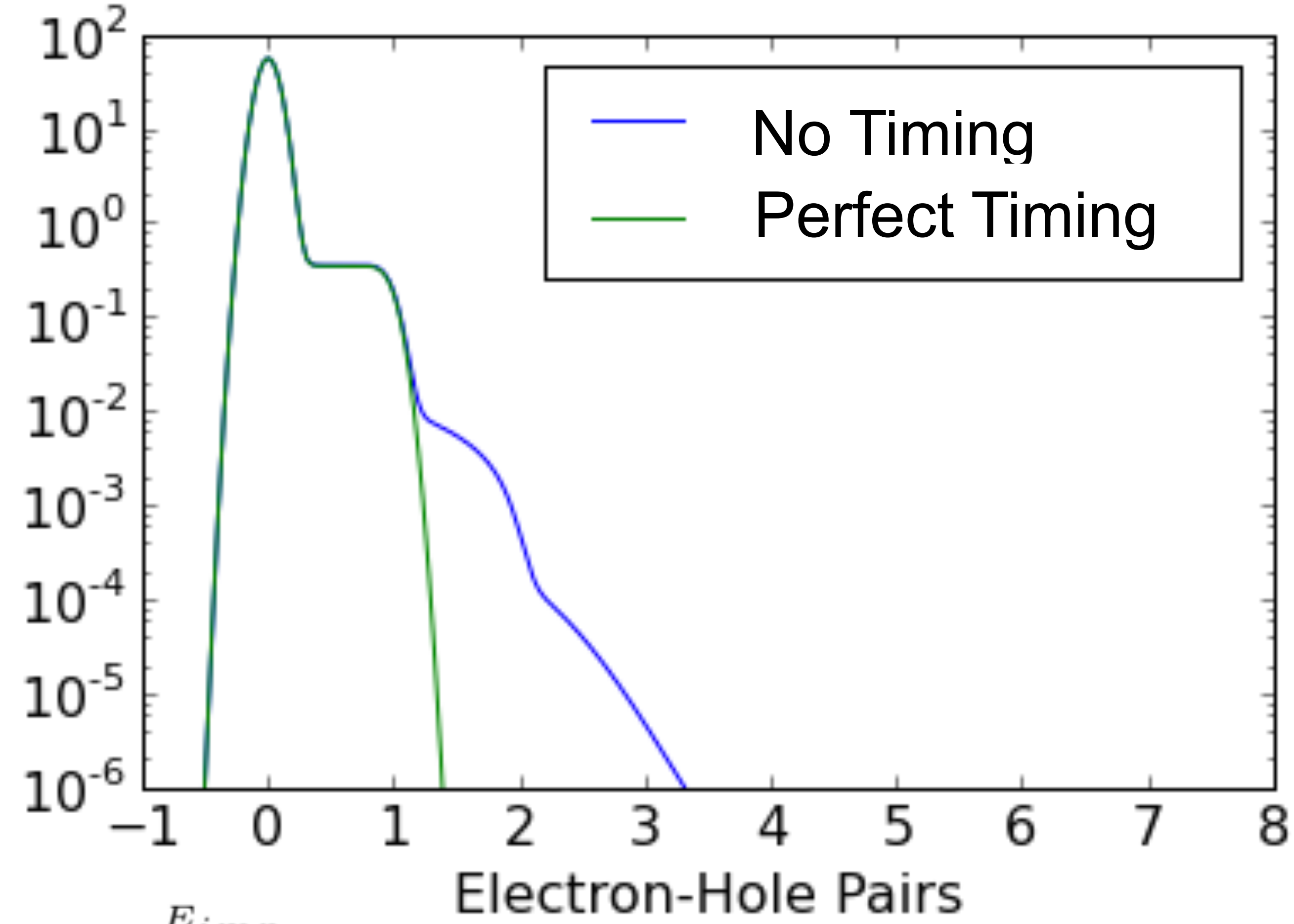




Fermilab

IR (Volume) Leakage





$$\Gamma \propto n_{imp} E_{imp}^3 e^{-\frac{E_{imp}}{k_b T}}$$

- Left is the trend for a no-photon event given a small IR probability without timing information, showing distributions due to various numbers of coincident (within the same acquisition window) photons
- Right compares the background with/without timing information. With perfect timing we have 0 background above 1 electron-hole pair. With real timing it's still an immense improvement over the no-timing scenario (cut down the coincidence rate by orders of magnitude)

Kurinsky, PhD Thesis, FERMILAB-THESIS-2018-15

Impurity Binding Energies

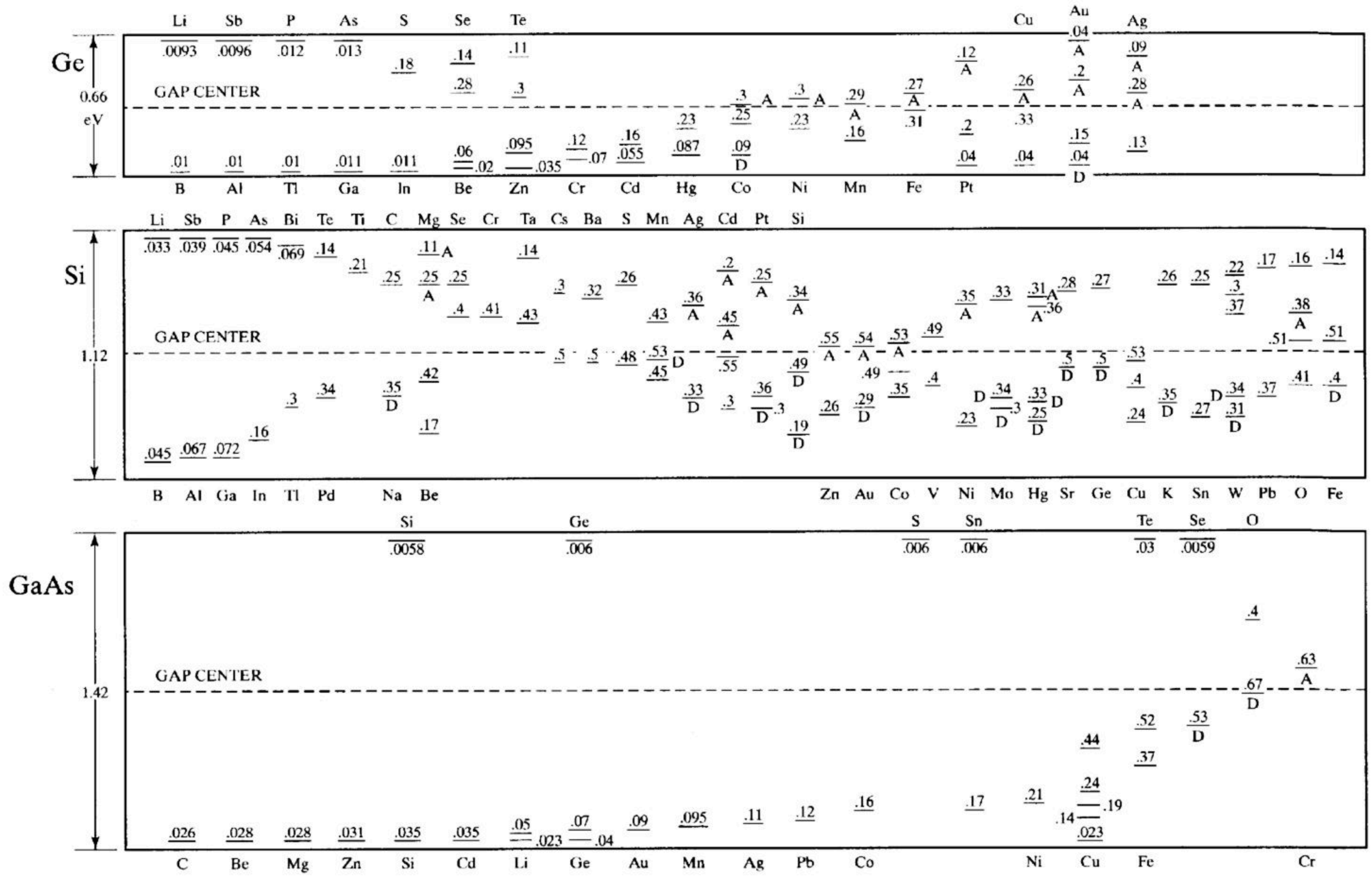
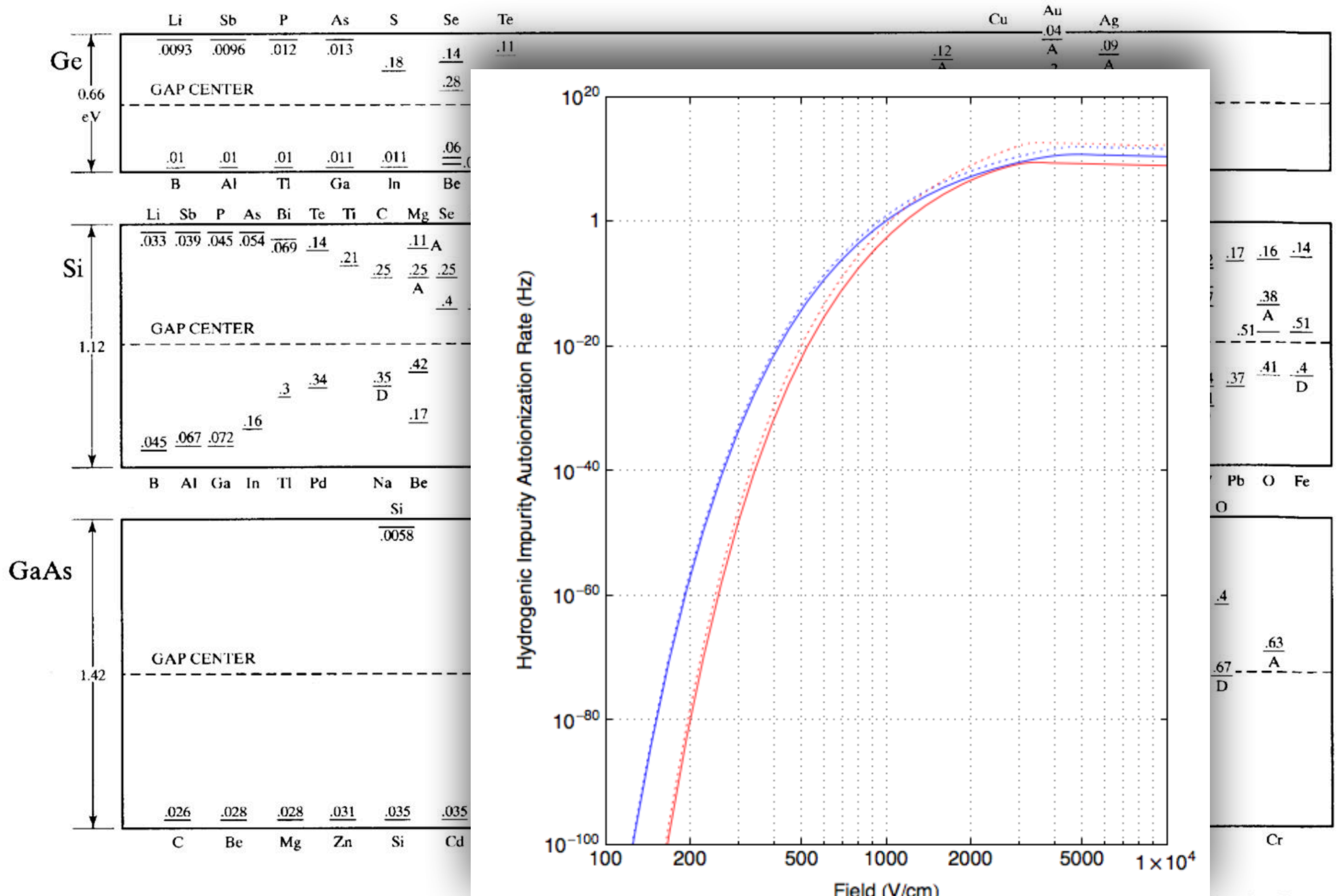


Figure 4.14 Measured ionization energies for the most commonly encountered impurities in Ge, Si, and GaAs. The levels above midgap are referenced to E_c and are donor-like or multiply charged donors, unless marked with an A which identifies an acceptor level. The levels below midgap are referenced to 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}

Impurity Binding Energies



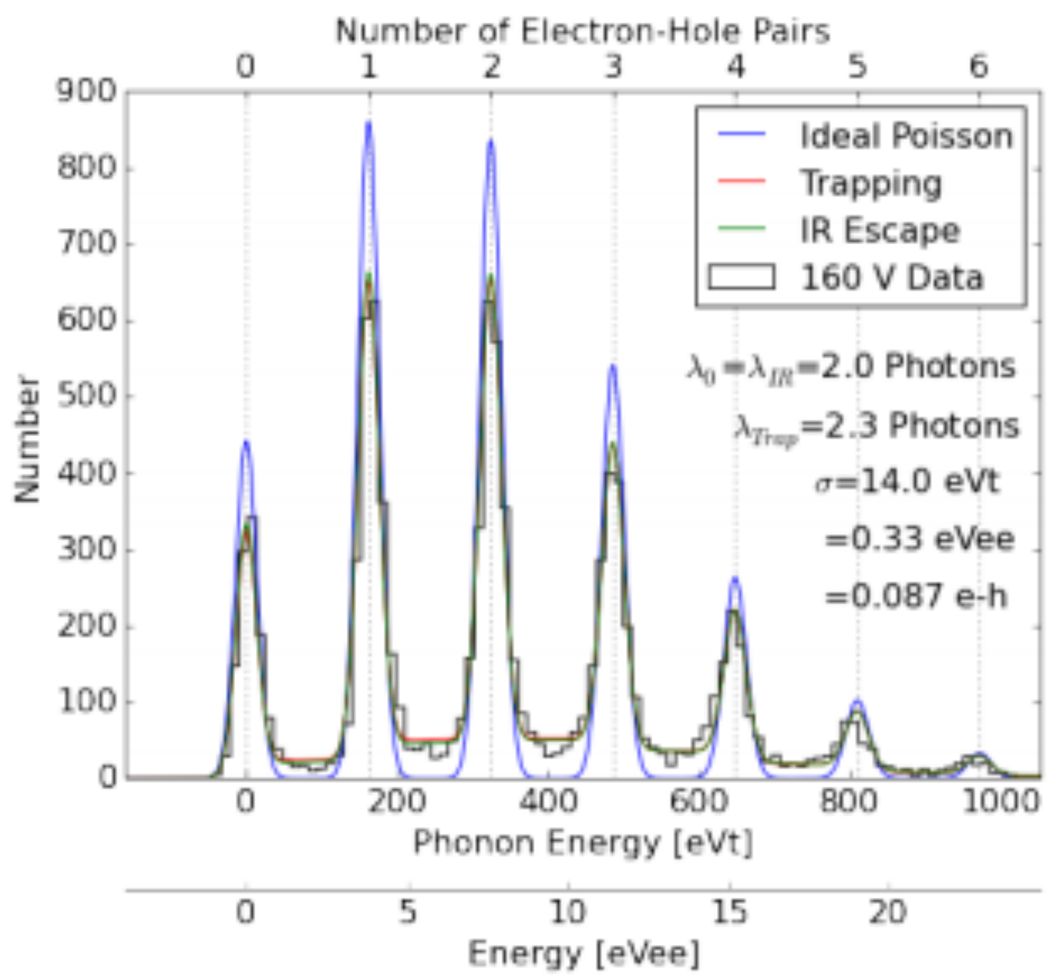
~10^{11} cm^{-3}

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

Figure 4.14 Measured ionization energies f[illegible] 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.)

Fermilab

Gram-Scale DM Detectors for Sub-GeV Masses



Romani et. al. 2018

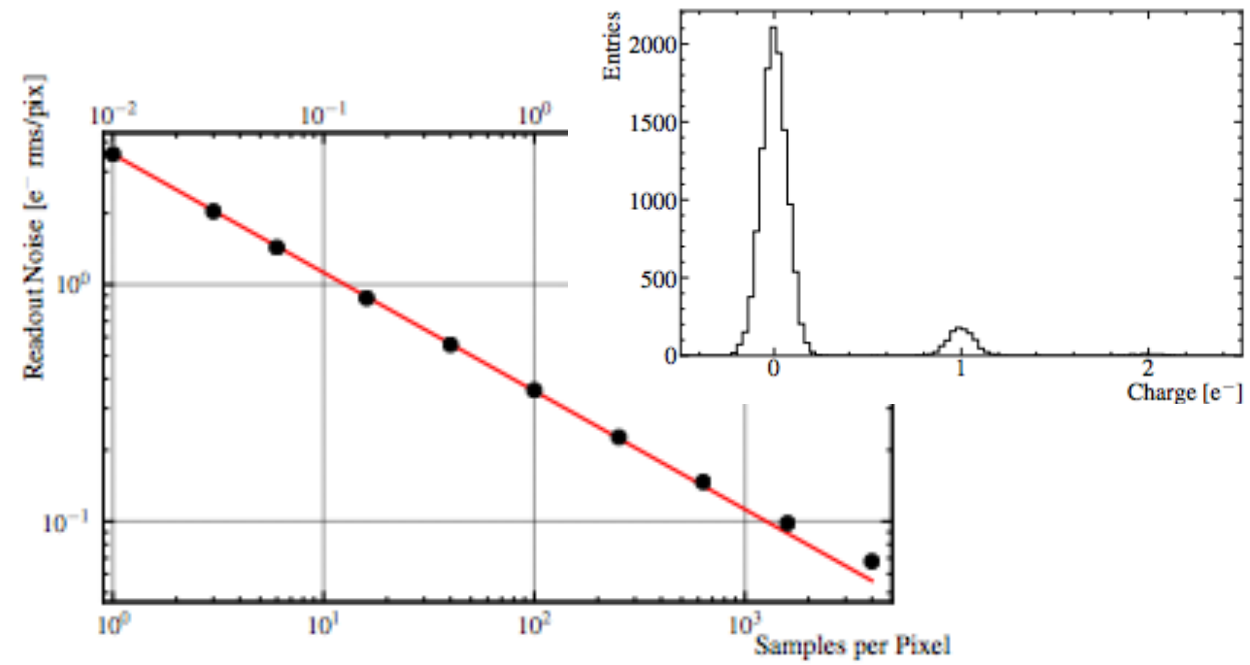


FIG. 3. Measured readout noise as a function of the number of non-destructive readout samples per pixel for the Skipper CCD. Black points show the standard deviation of the empty pixels distribution as a function of the number of averaged samples. The red line is the theoretical expectation assuming independent, uncorrelated samples (Eq. (1)). The number of readout samples can be dynamically configured on a per pixel basis.

Tiffenberg et. al. 2017

- This is an active area of R&D for CDMS and competitors; on the left is a new result (posted to ArXiv today) and the right is a result from earlier this year where we see single electron-hole pair resolution
  - CDMS device has less dynamic range but better pileup rejection
  - DAMIC device has excellent linearity but long read time
  - Excellent complementarity between experiments - the same background will look very different in each detector