Cryogenic Charge and Phonon Detectors: SuperCDMS +

Noah Kurinsky

New Directions in the Search for Light Dark Matter Particles

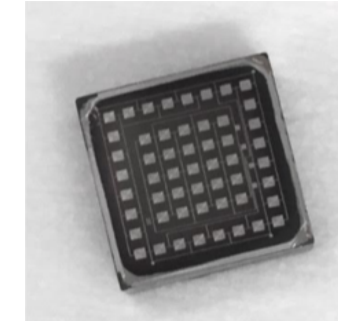
June 5, 2019

Athermal Sensors for NR and ER Dark Matter

- R&D has produced 3+ detectors with ~3-4 eV energy resolution
  - Large-area photodetector PD2, ~10g @ ~4 eV
  - Square-cm HV detectors, 0.25-1g @ ~3 eV
  - Fabricated 4g detectors designed for O(1 eV), yet to be tested

- Resolutions achieved by multiple routes; optimization is different
  - NR detectors minimize energy resolution, aim for low-Tc. R&D led by Matt Pyle at UC Berkeley (see talk yesterday)
  - HV detectors minimize charge resolution; aim for high efficiency at higher Tc for larger dynamic range
  - Both based on QET designs which achieve >20% energy efficiency; this is the largest single improvement

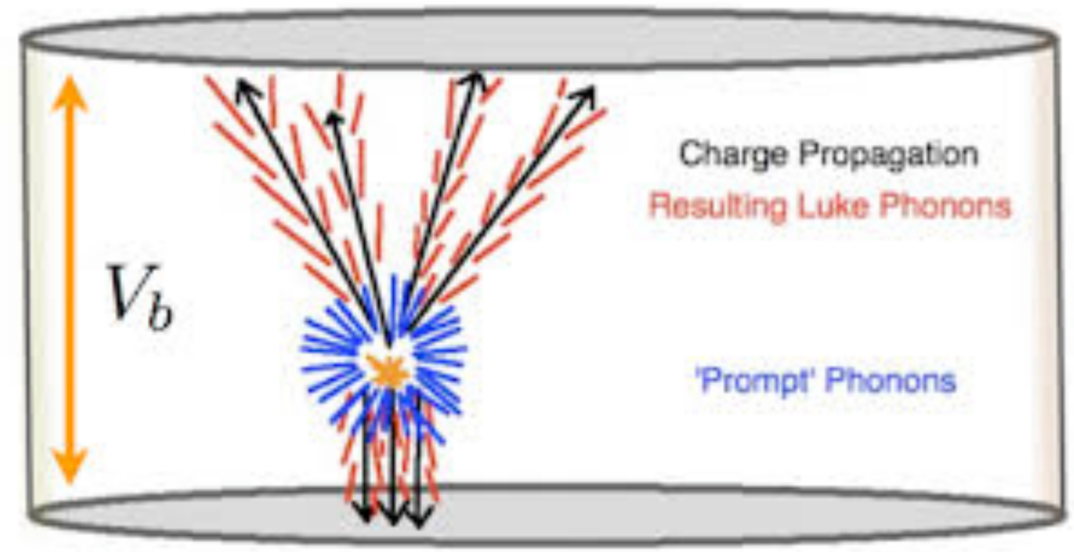
Charge Detection via NTL Effect

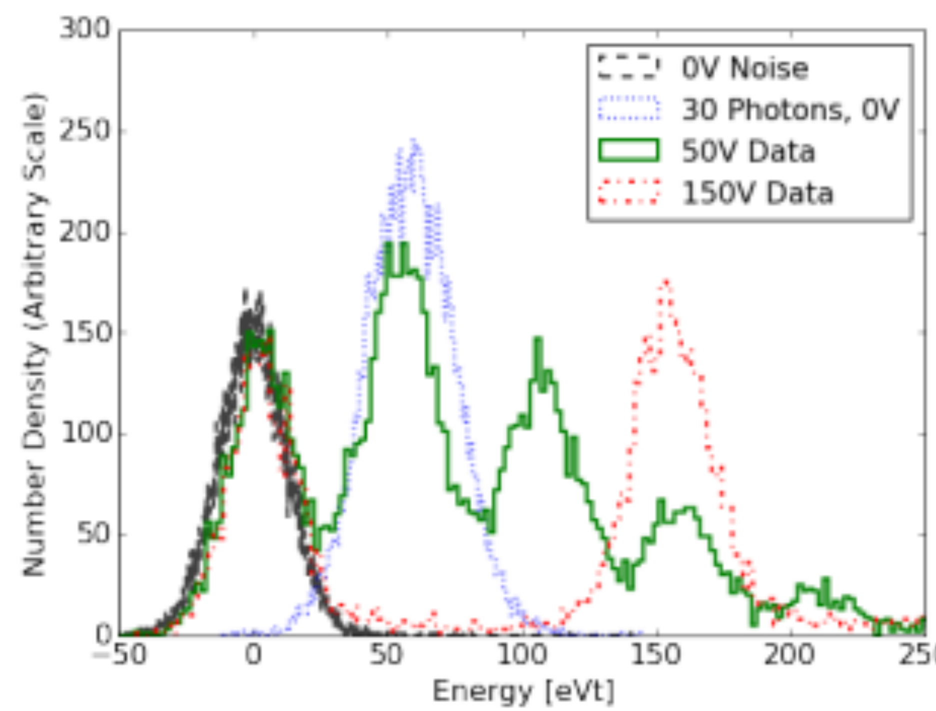


- In any recoil event, all energy eventually returns to the phonon system
  - Prompt phonons produced by interaction with nuclei
  - Indirect-gap phonons produced by charge carriers reaching band minima
  - Recombination phonons produced when charge carriers drop back below the band-gap
- Phonons are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

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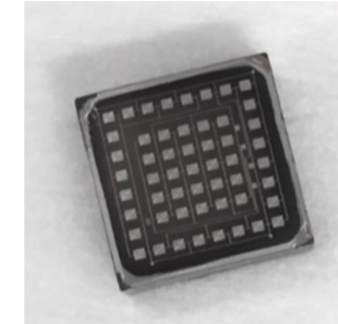

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  pho…
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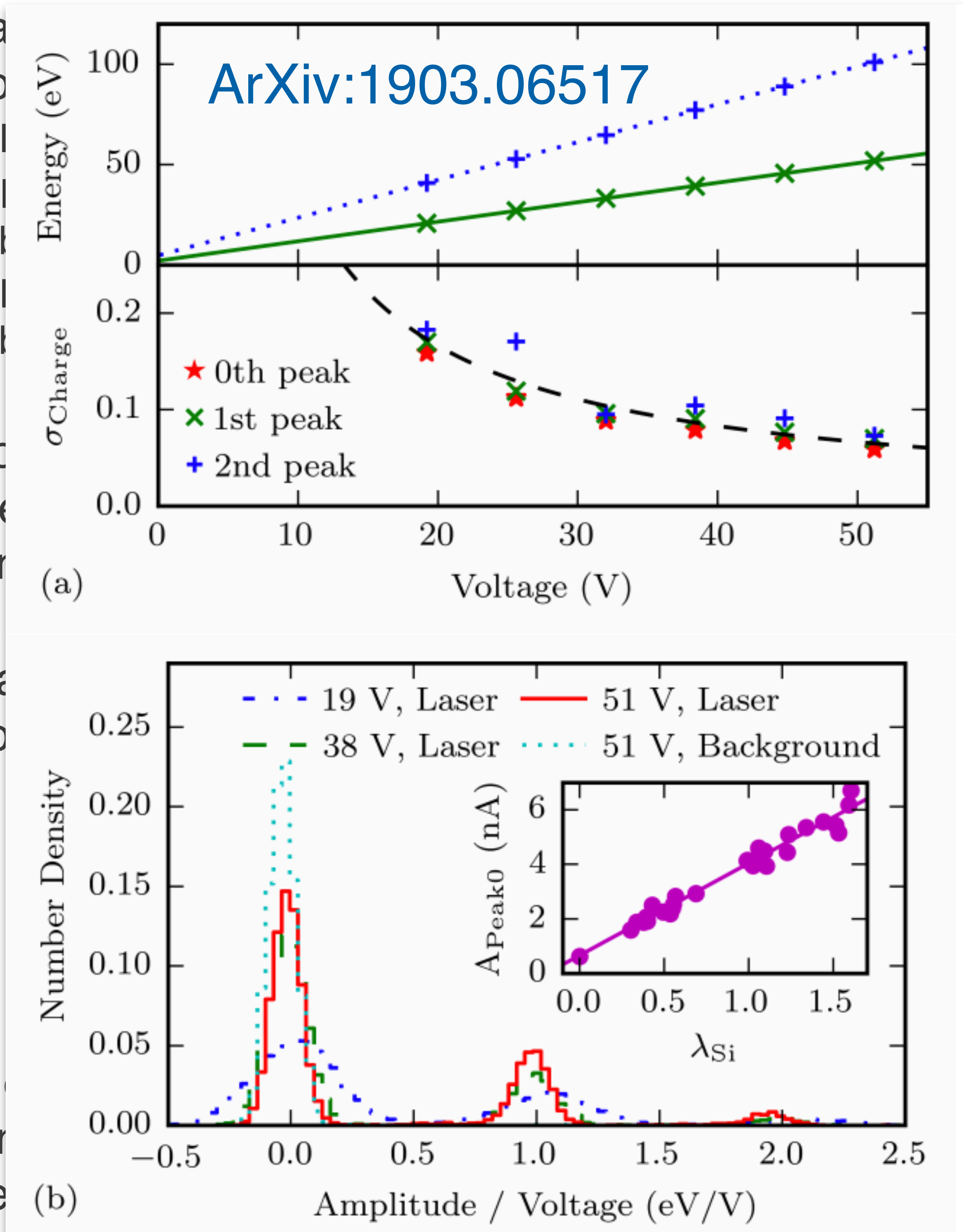

- Pho…
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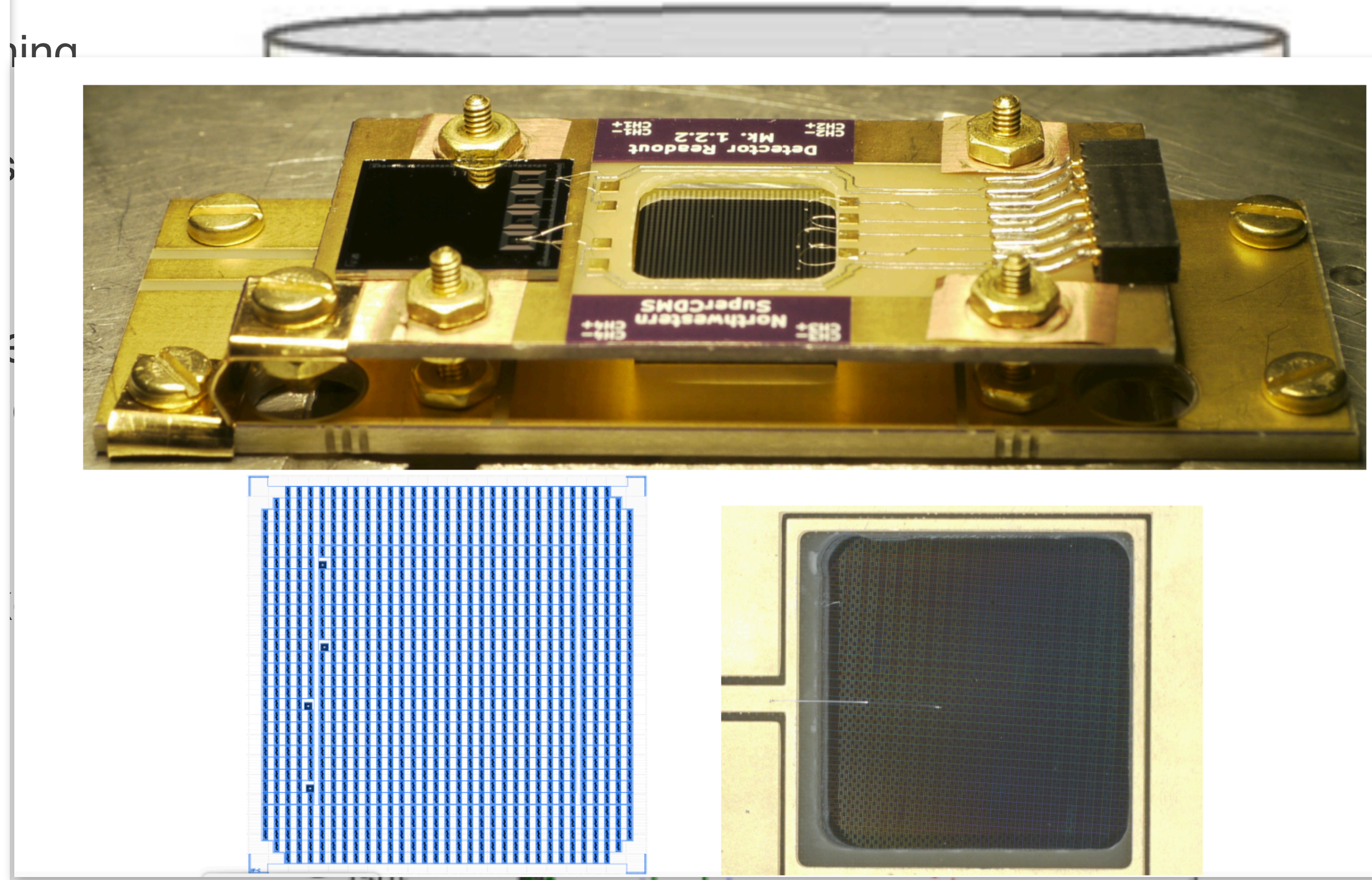
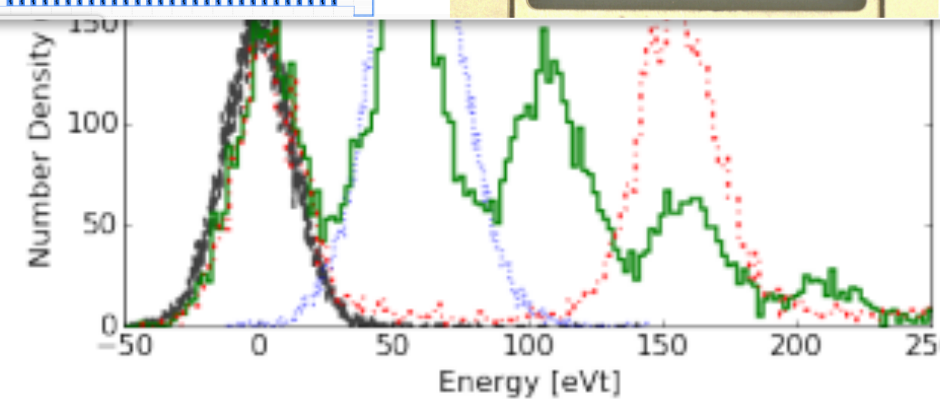
  calorimeter (TES) heat capacity





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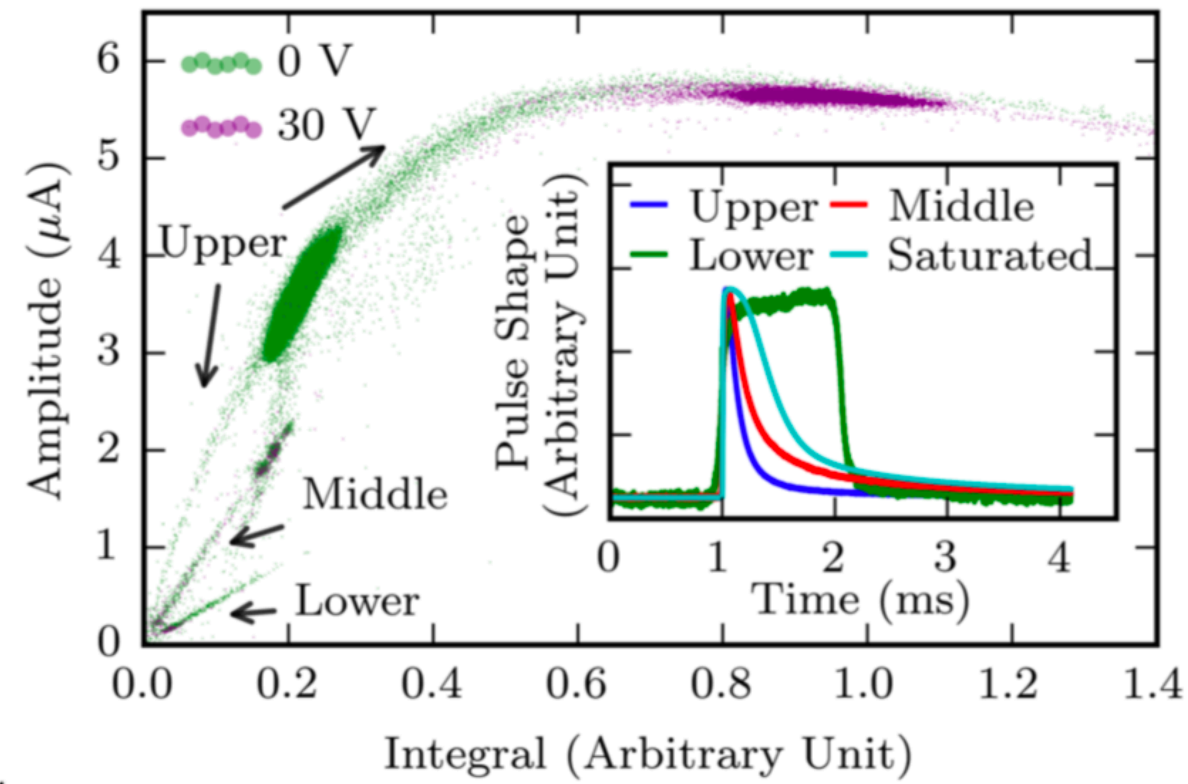
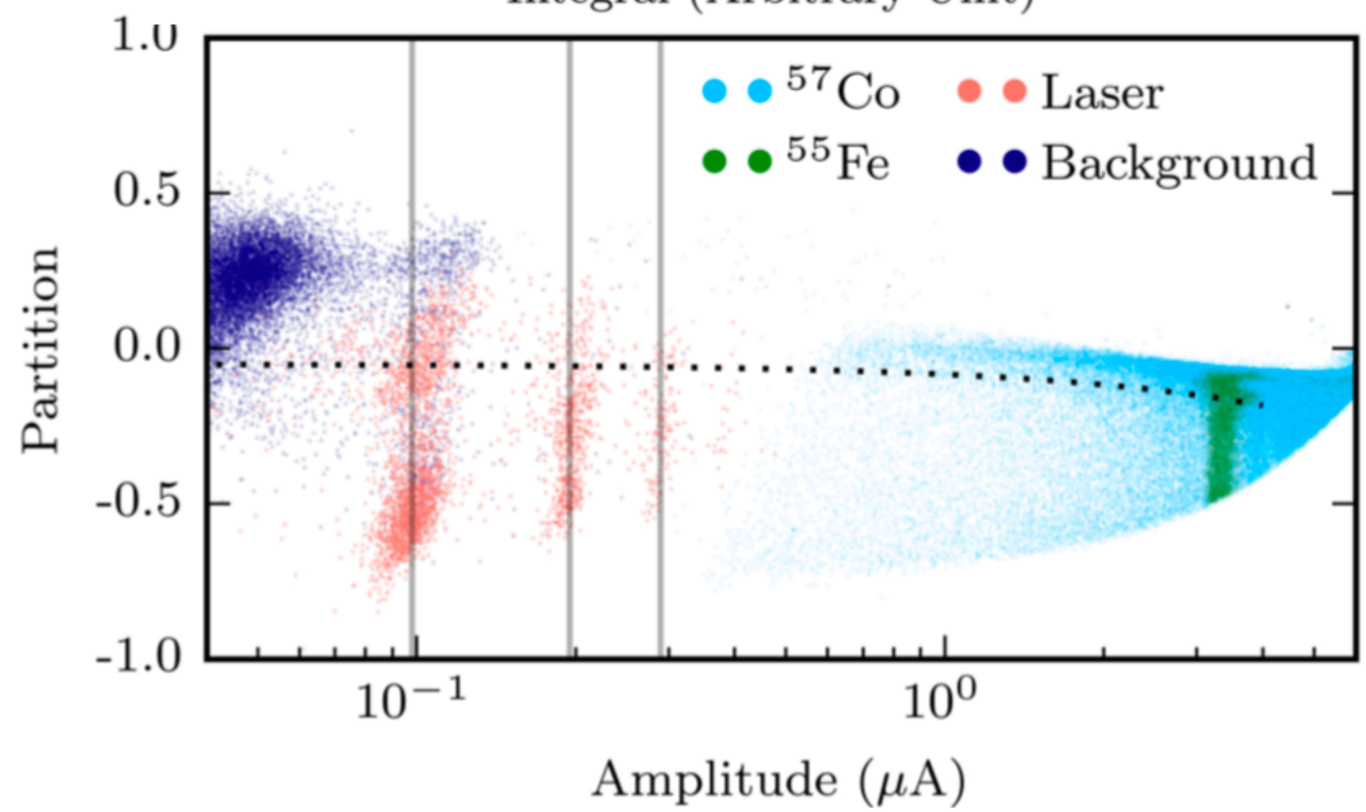
Recent Progress: Edge-Dominated Leakage

ArXiv:1903.06517

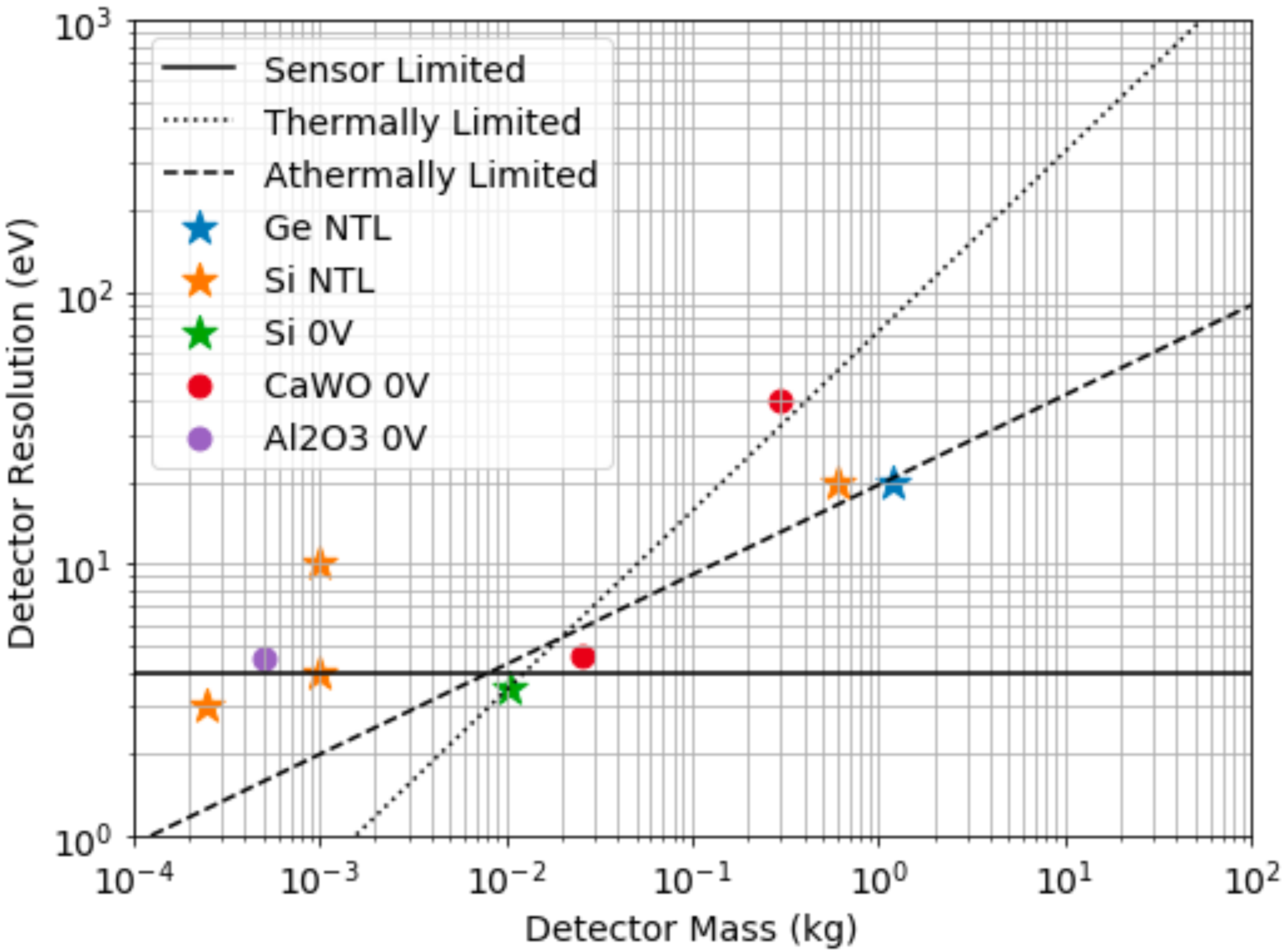
- New prototypes demonstrate position dependence in the non-quantized data hinted at during HVeV Run 1
- Nearly contact-free biasing scheme isolates contact along the crystal edge, preventing charge tunneling through most of the high-voltage face
- Surface events have a distinct pulse shape and can be 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

Scaling Up in Mass



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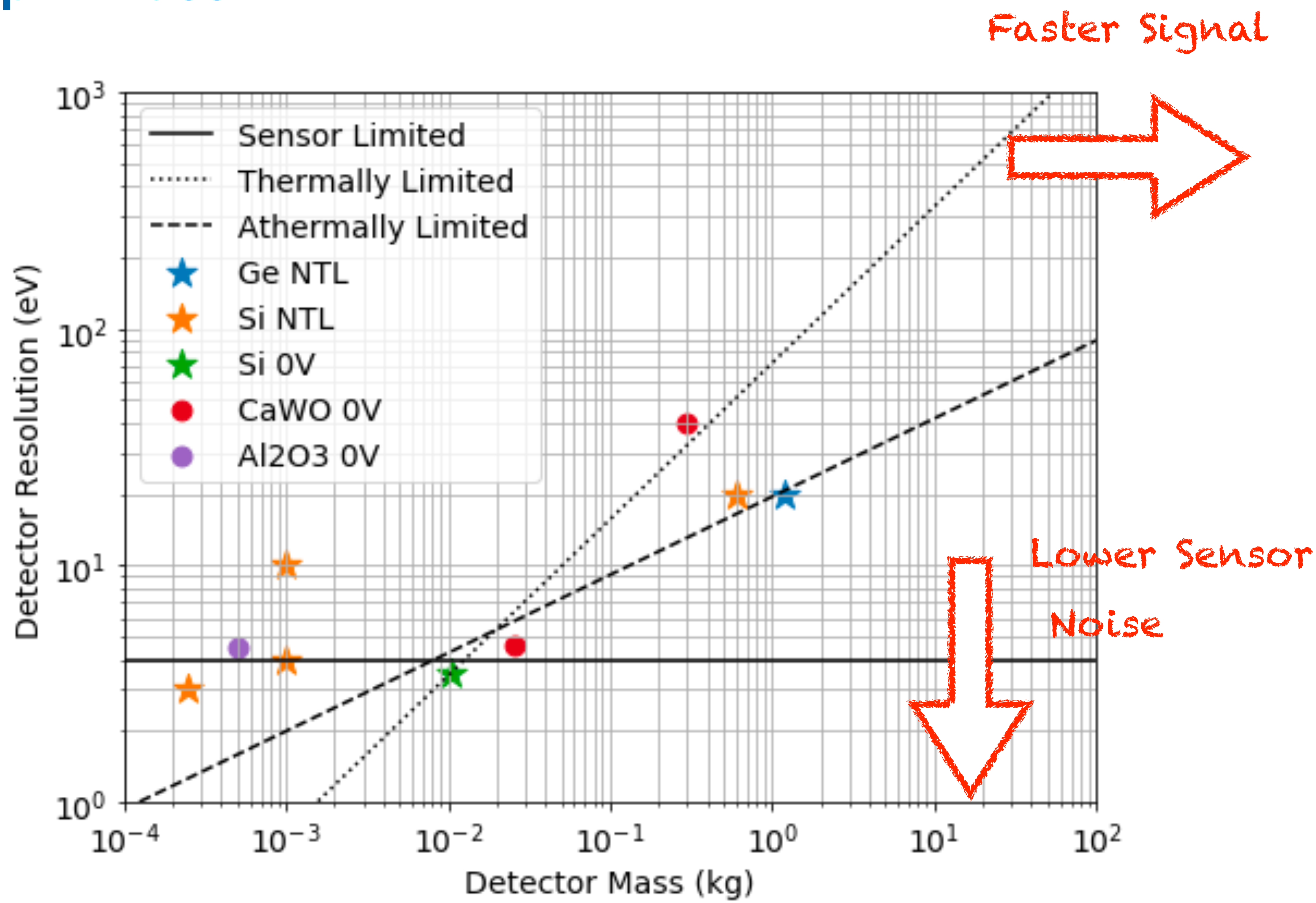

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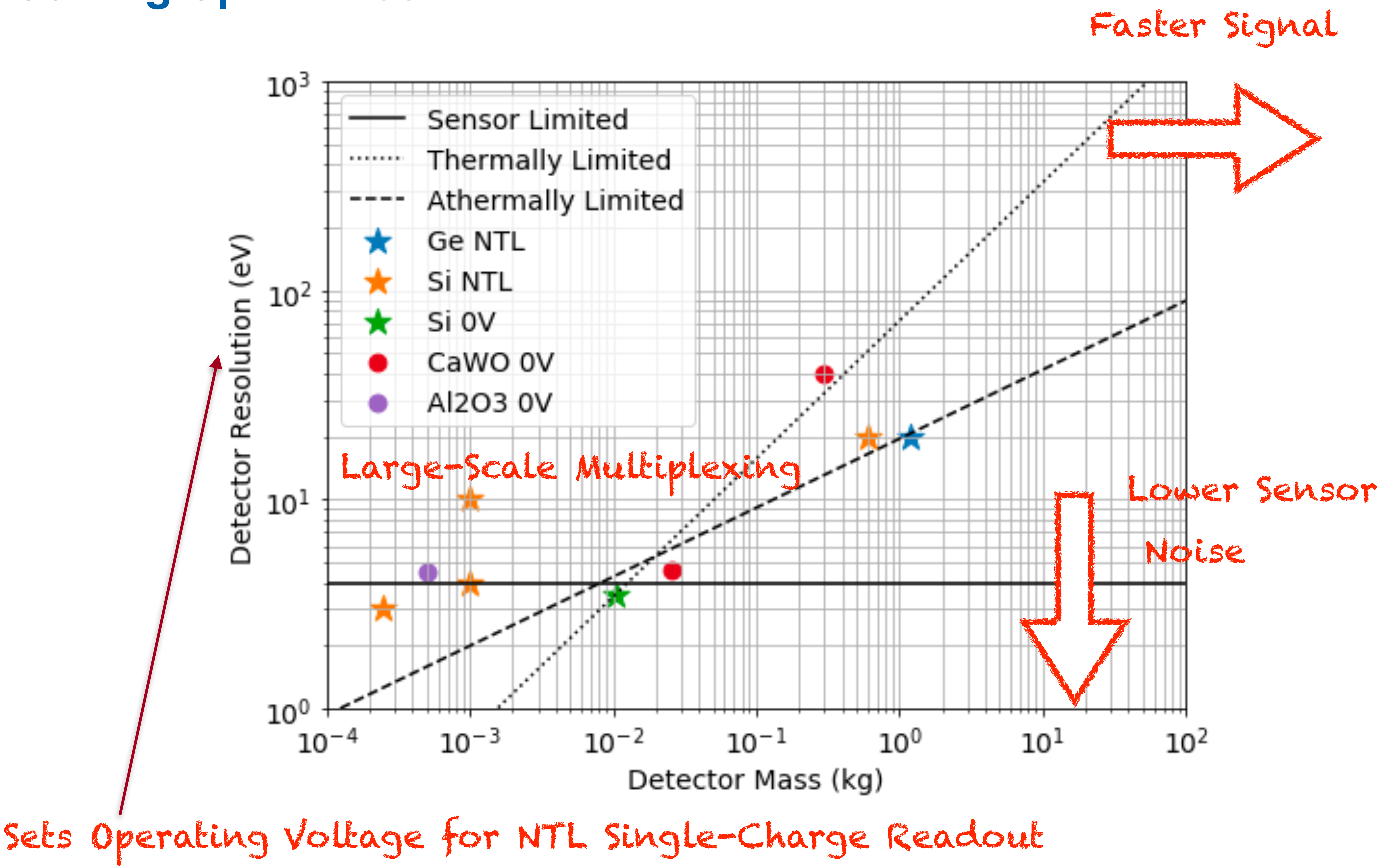
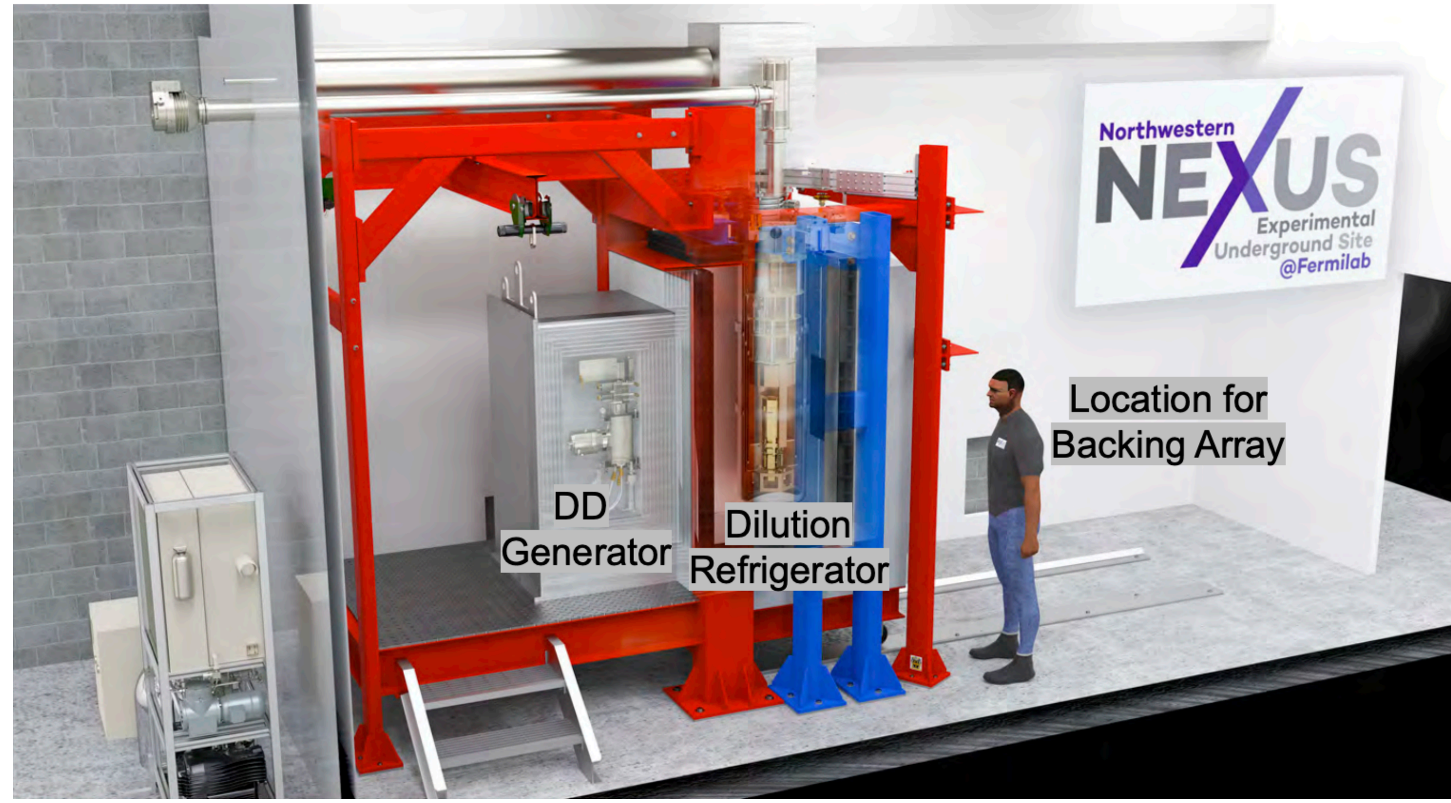
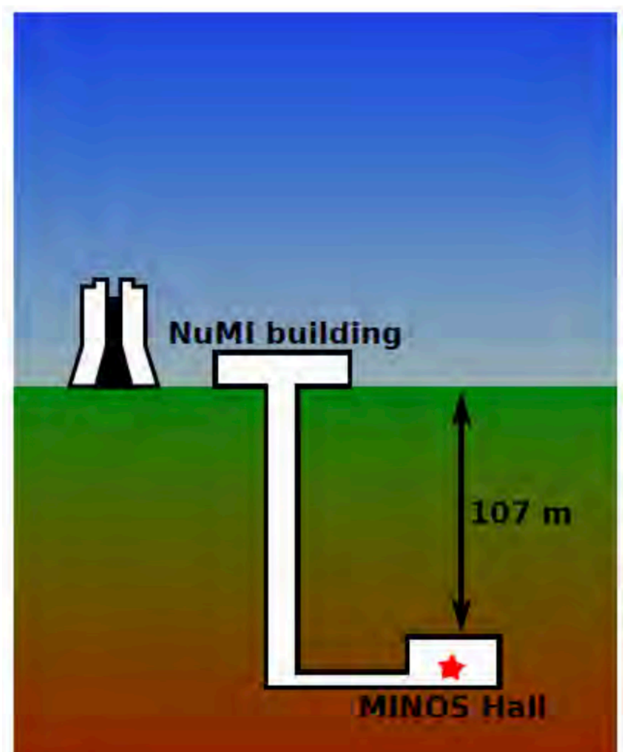
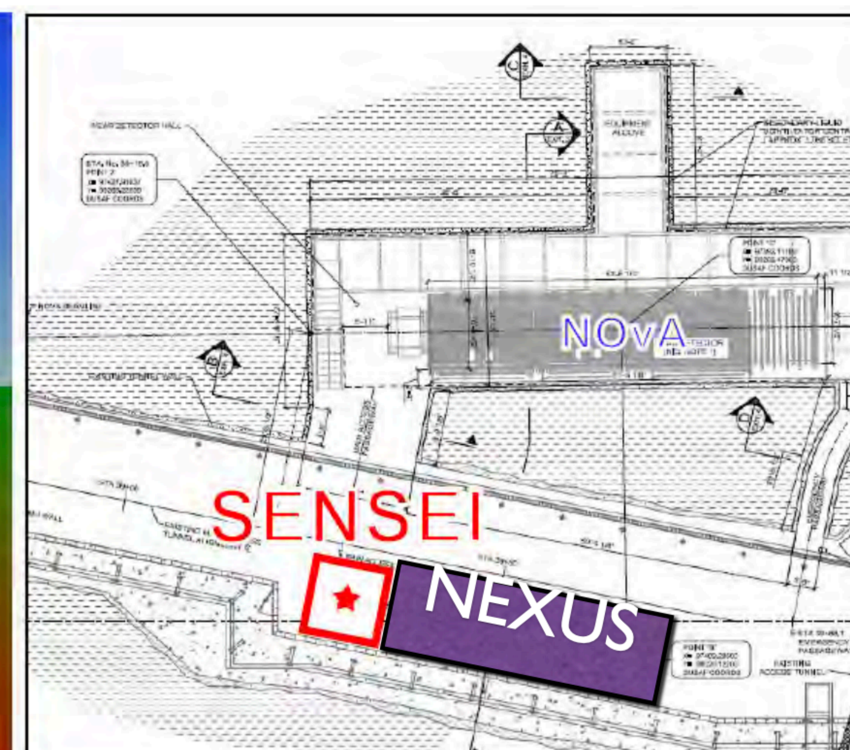


NEXUS: Underground Experimental Site for R&D







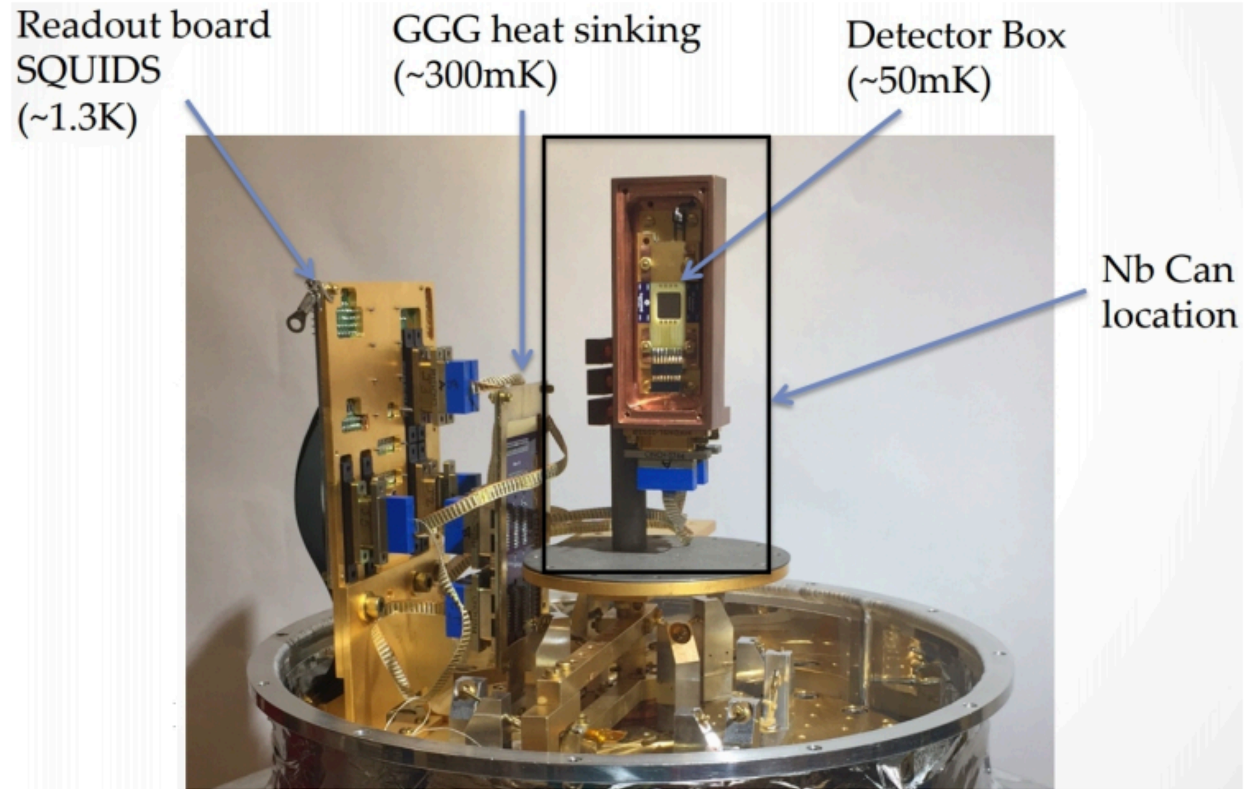
NEXUS Si/Ge Experimental Timeline

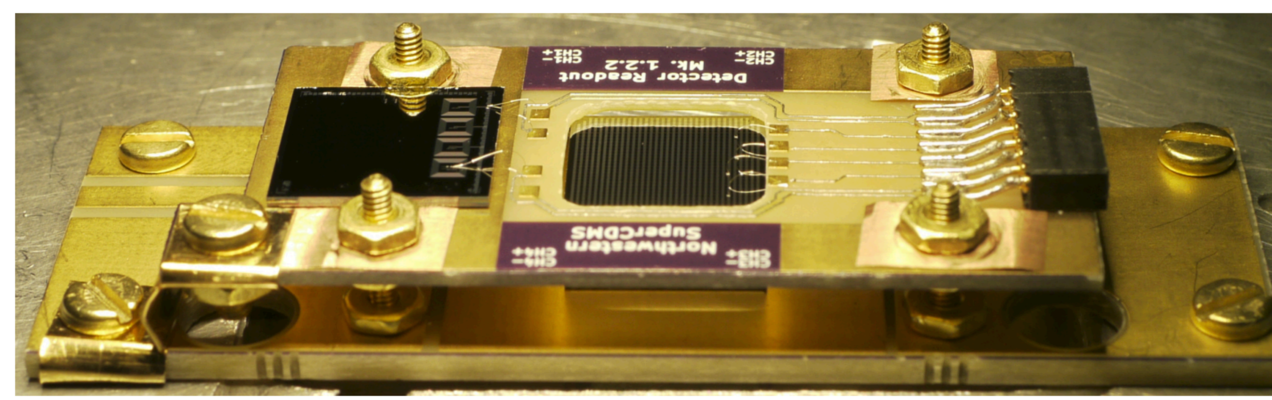
- Now (Animal ADR Demonstrator): 1 gram
  - 1 gram, 4 eV resolution (20 eV threshold)
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 4 keV in energy
  - DM search with 1 gram-week

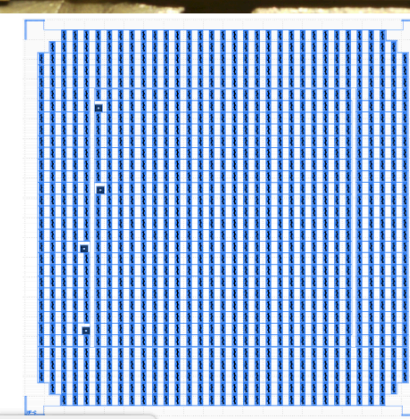
- Late Summer 2019: 10 grams,
  - 2-4 ~4g detectors
  - 4 eV resolution (20 eV threshold),
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 40 keV in energy
  - DM search with 1 gram-month

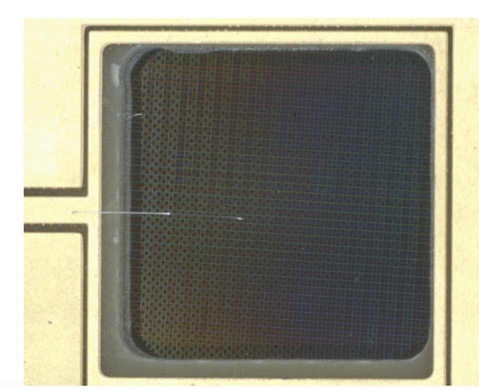
- Fall 2019-Winter 2020: 30-100 grams,
  - 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution
  - 4 eV to 40 keV in energy
  - DM search with 1-10 gram-year (~kg day)

- 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









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Leakage R&D

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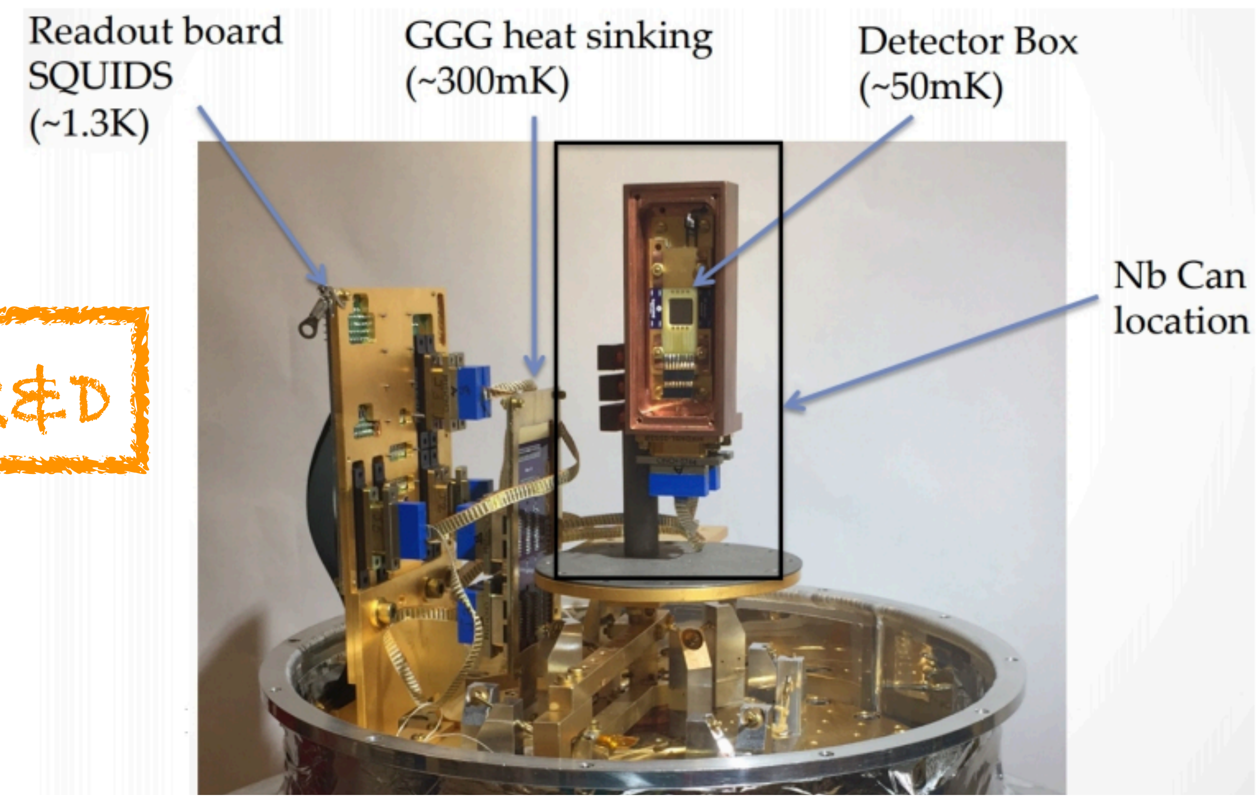
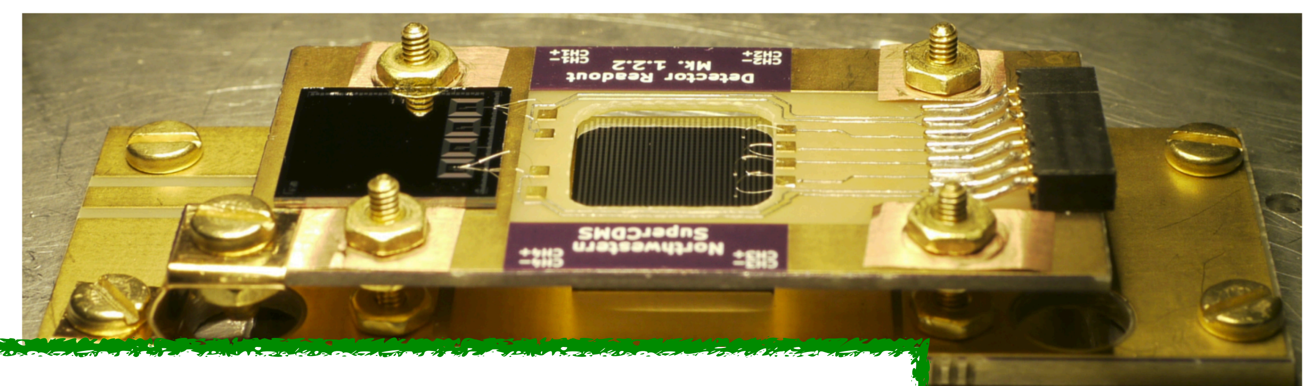
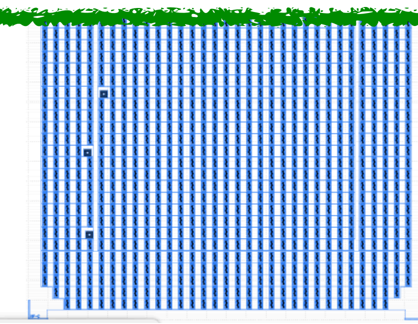
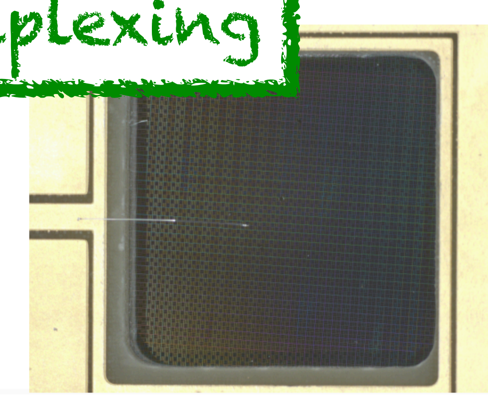




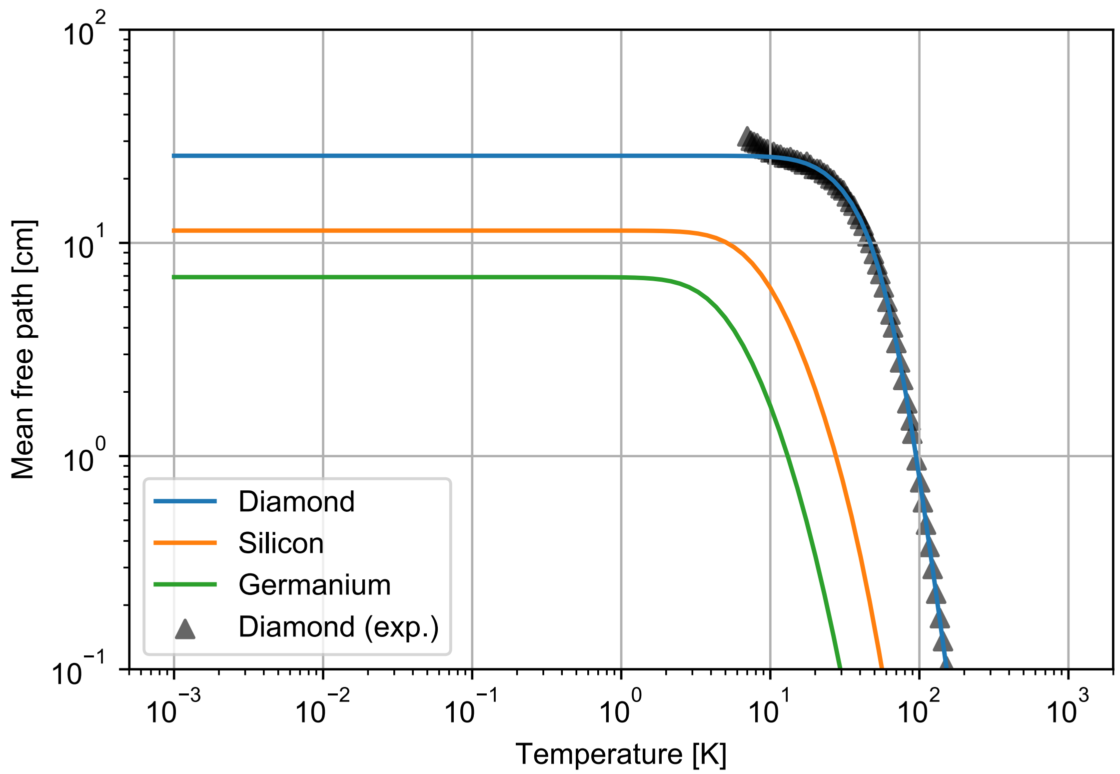
Larger Crystals or Multiplexing





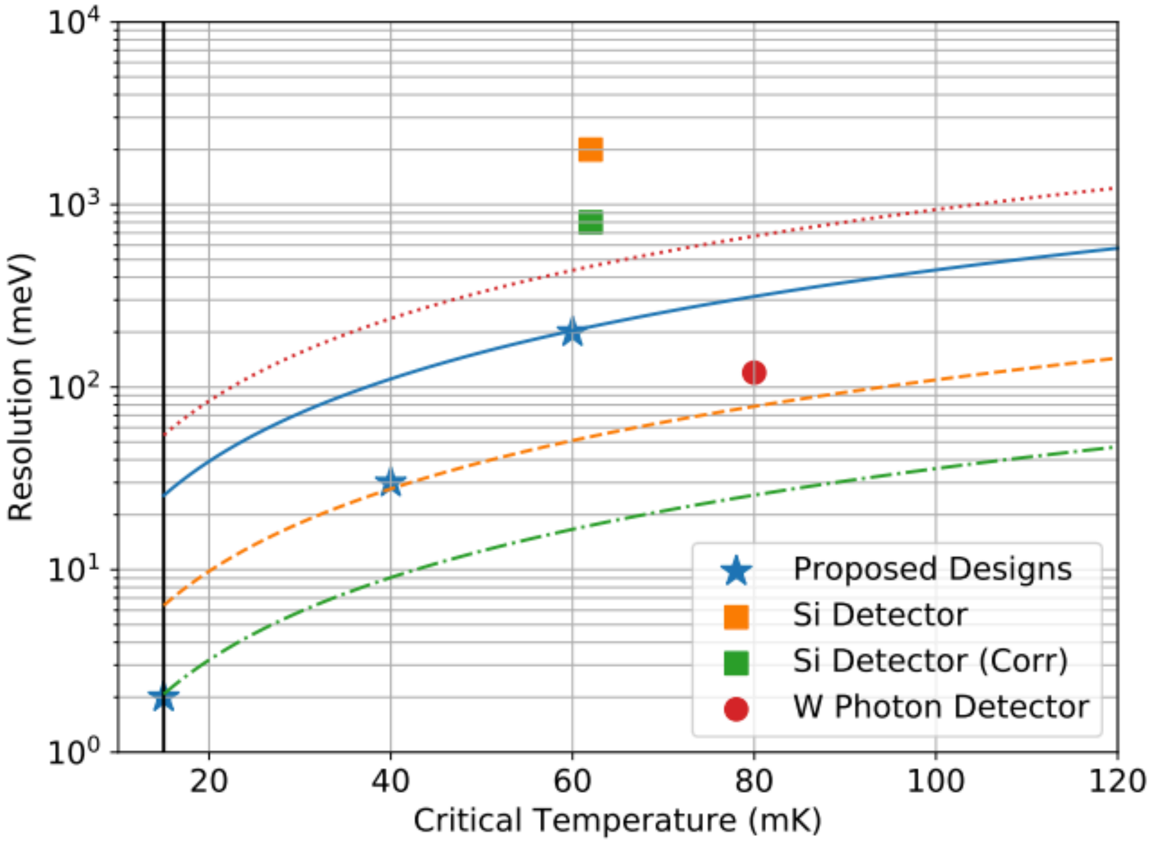
Diamond Targets

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)



- 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

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



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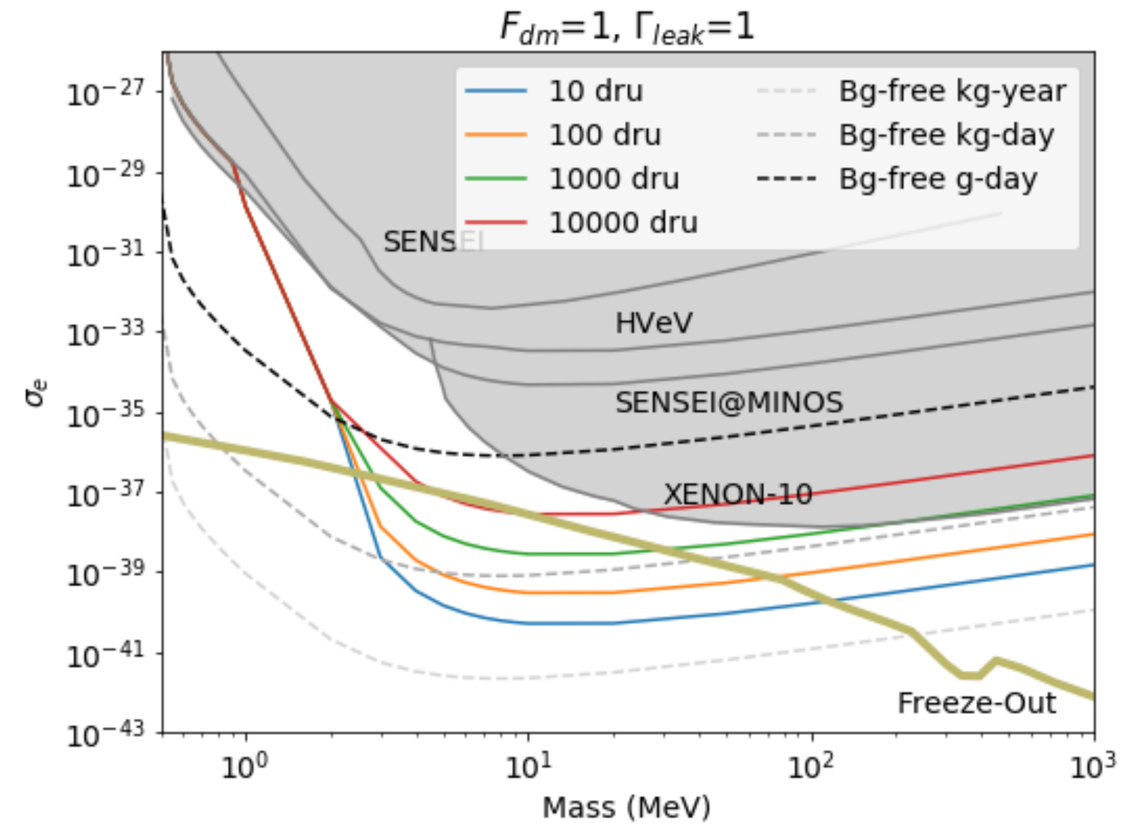
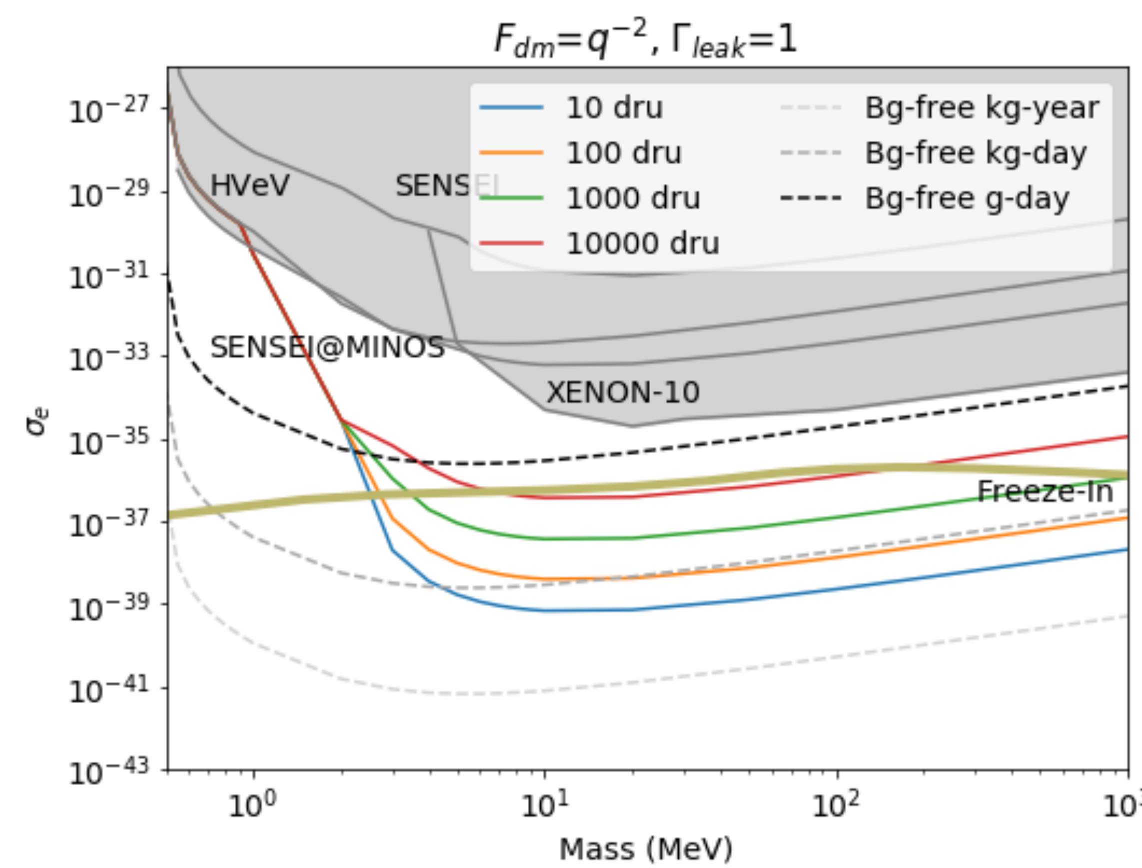
Near-Term ERDM Scattering Reach

- With measured leakage current and better light tightness, relic density can be probed at NEXUS (~100 dru) with ~100g payload
  - gram-month begins to probe relic density at current levels





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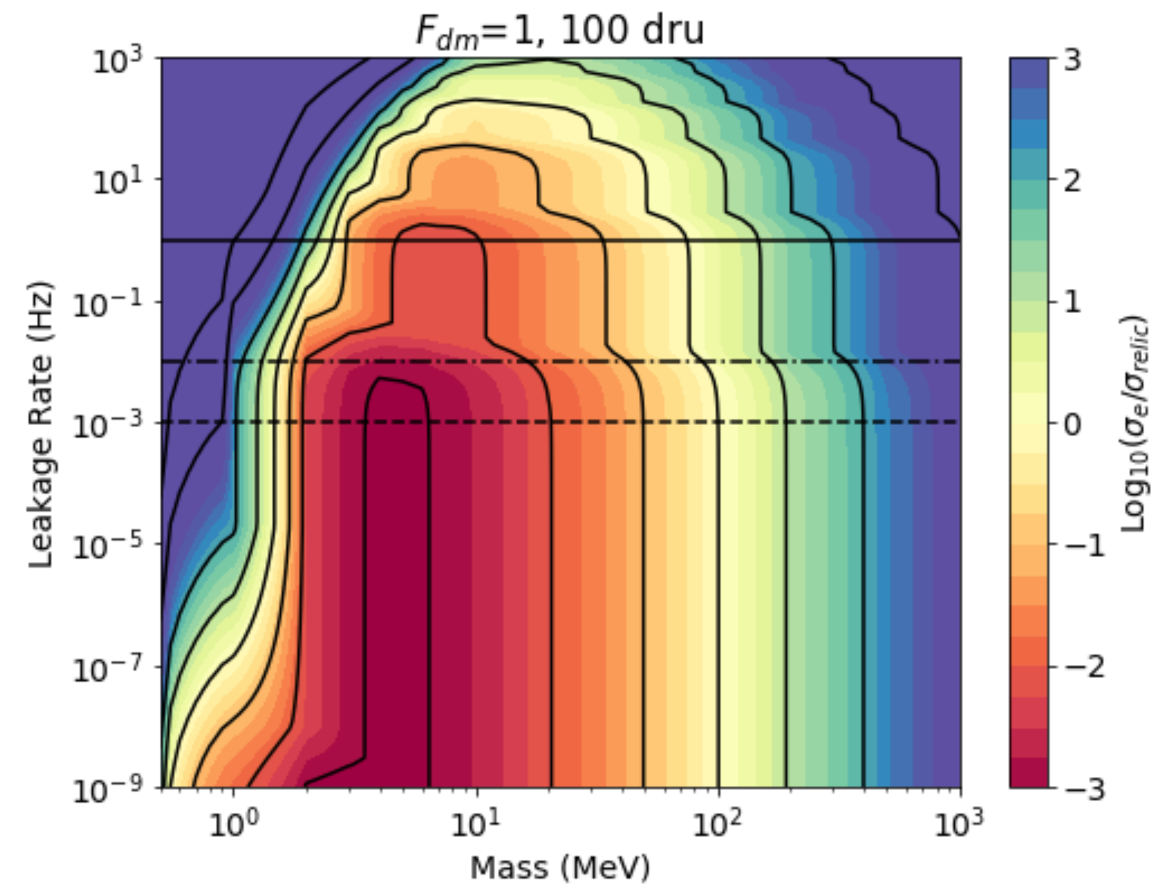

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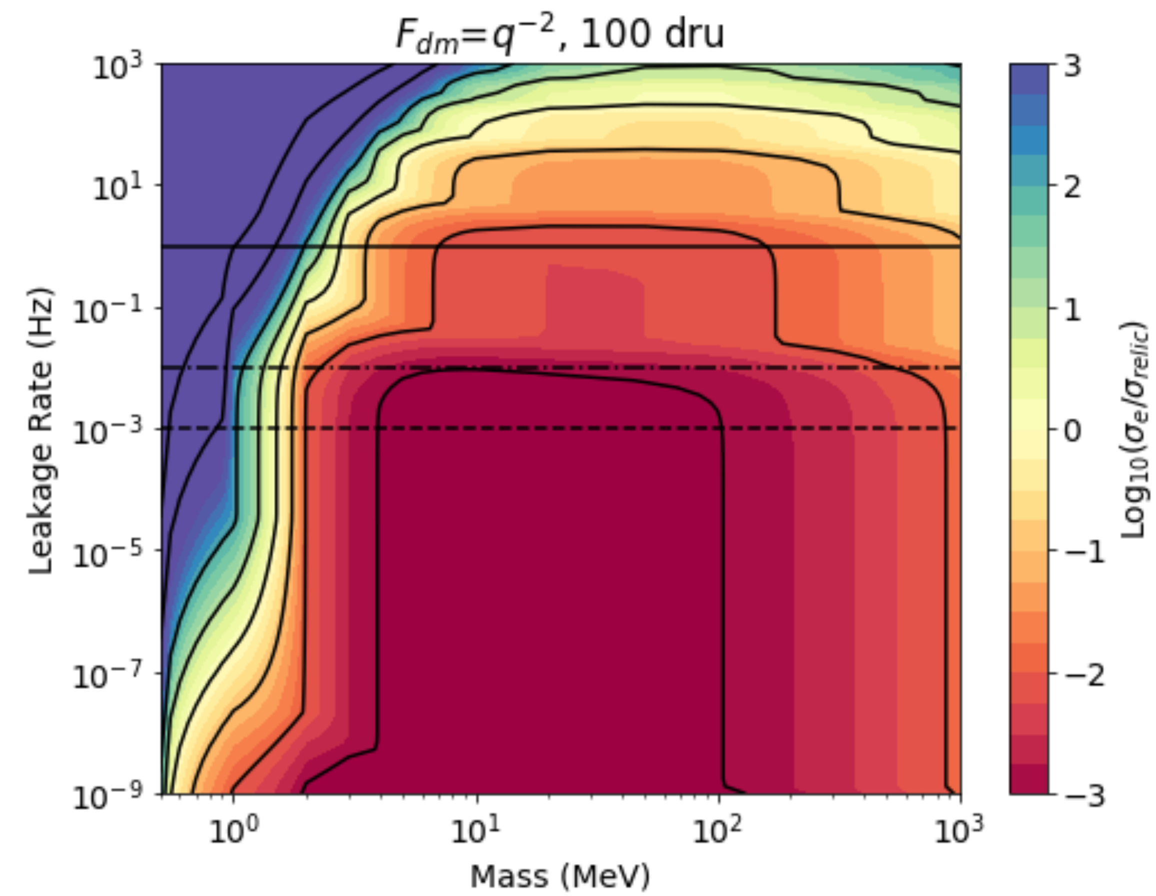
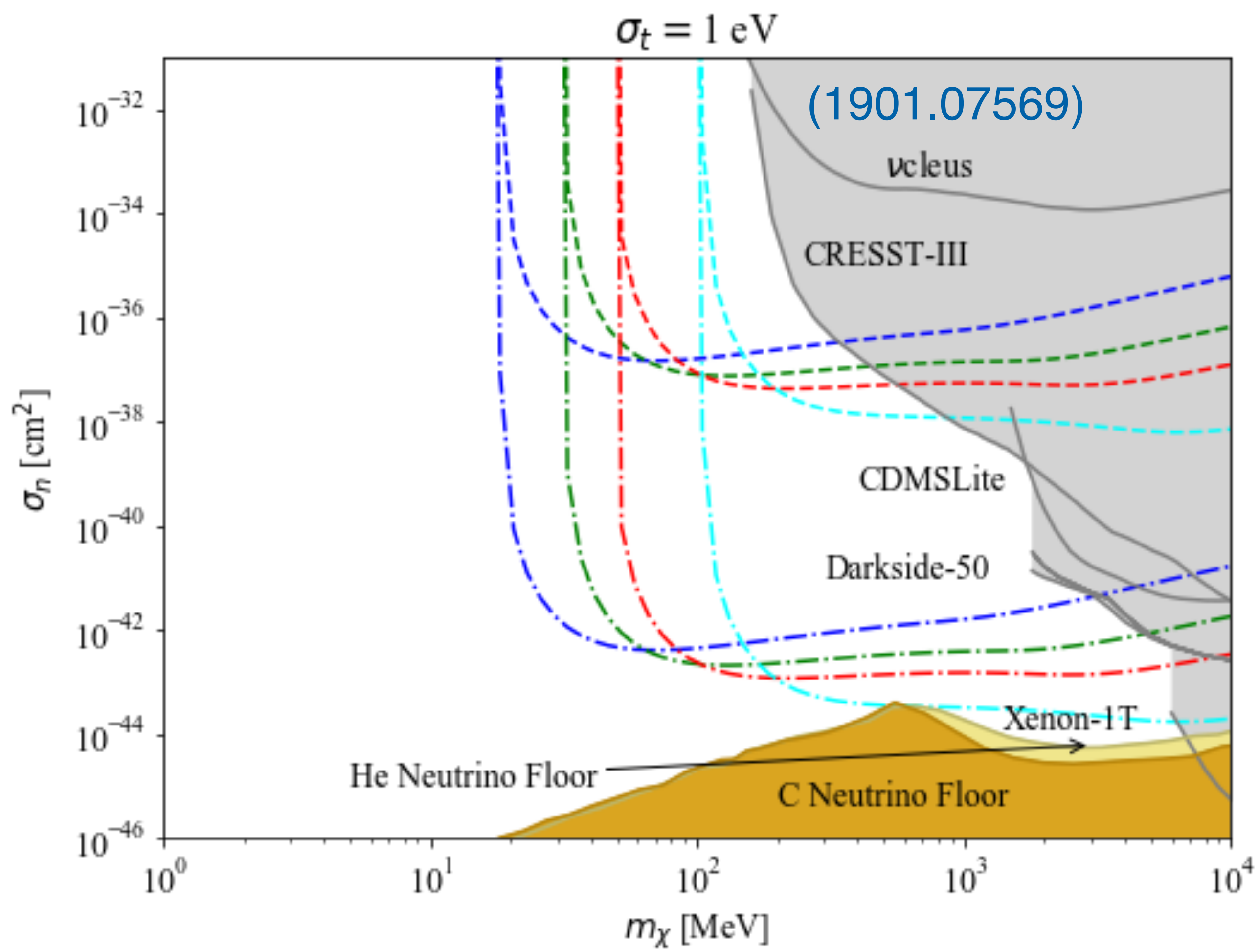
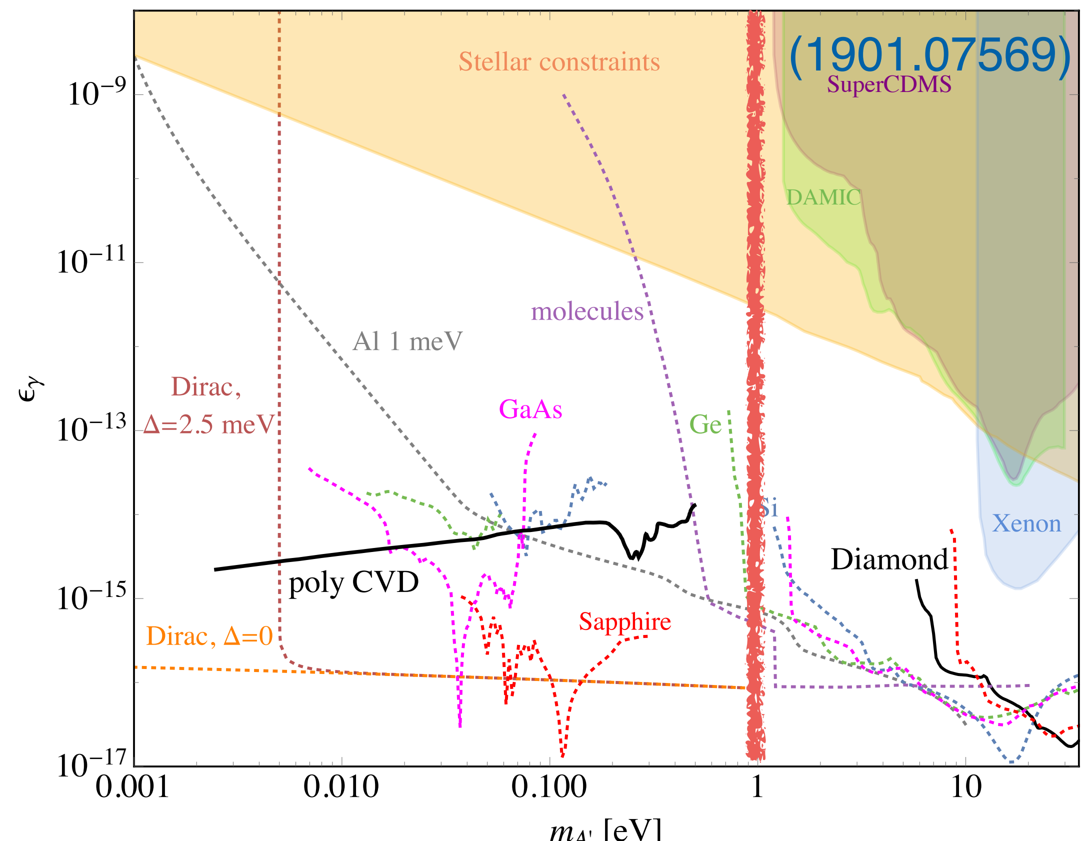


- Leakage current improvement improves reach across mass range
  - 100x improvement significantly improves overall exposure reach
  - Various ways to improve surface leakage, work already ongoing to experiment with new insulating layers

NR & Absorption Reach (ST)

- Short-term: gram-day exposure at 1 eV threshold (about 10x improvement over current) probes large uncovered parameter space
  - Absorption down to band-gap also probed, depending on backgrounds
  - Lighter targets provide lower mass reach but lower exposure; diamond more competitive with He than Si for NR





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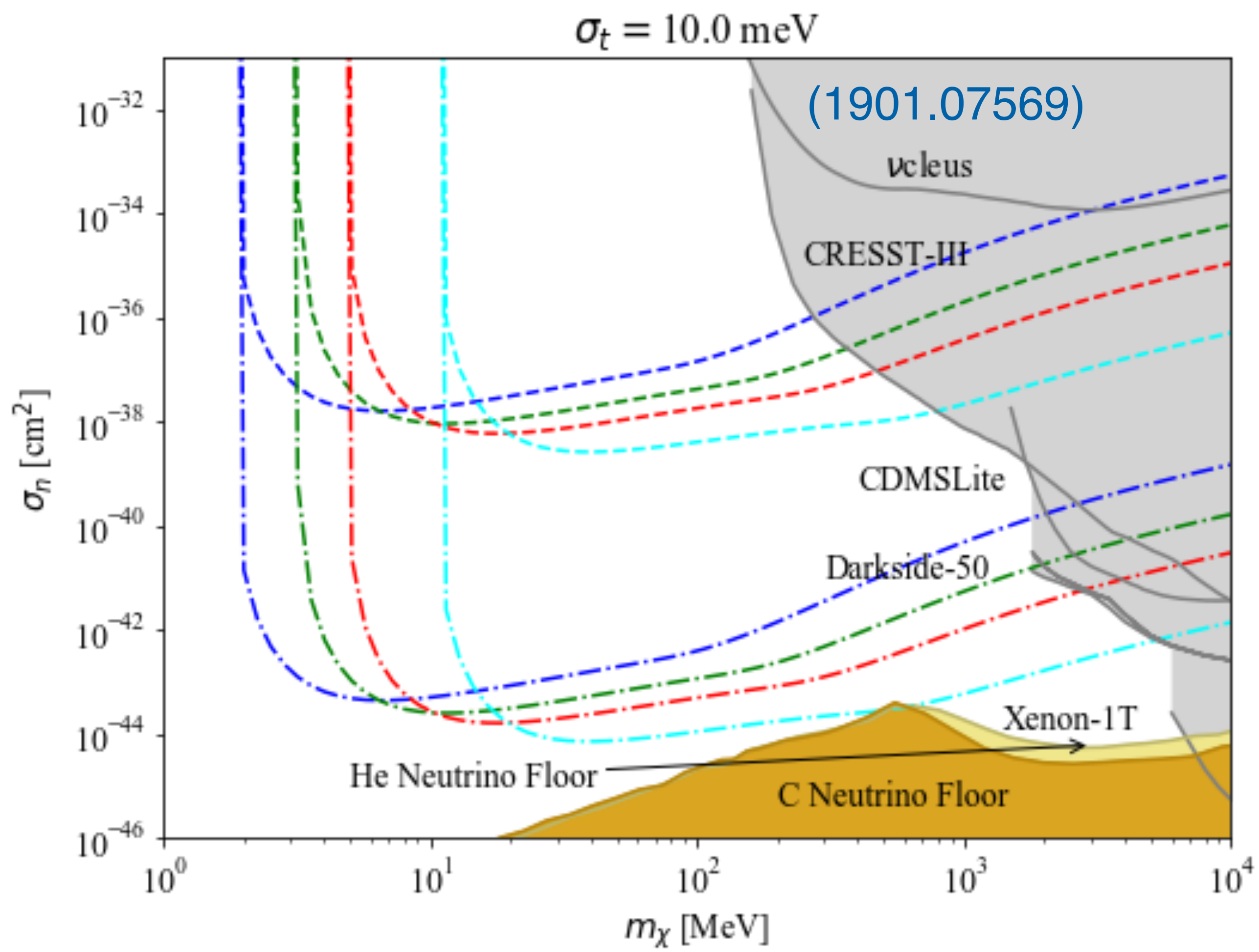
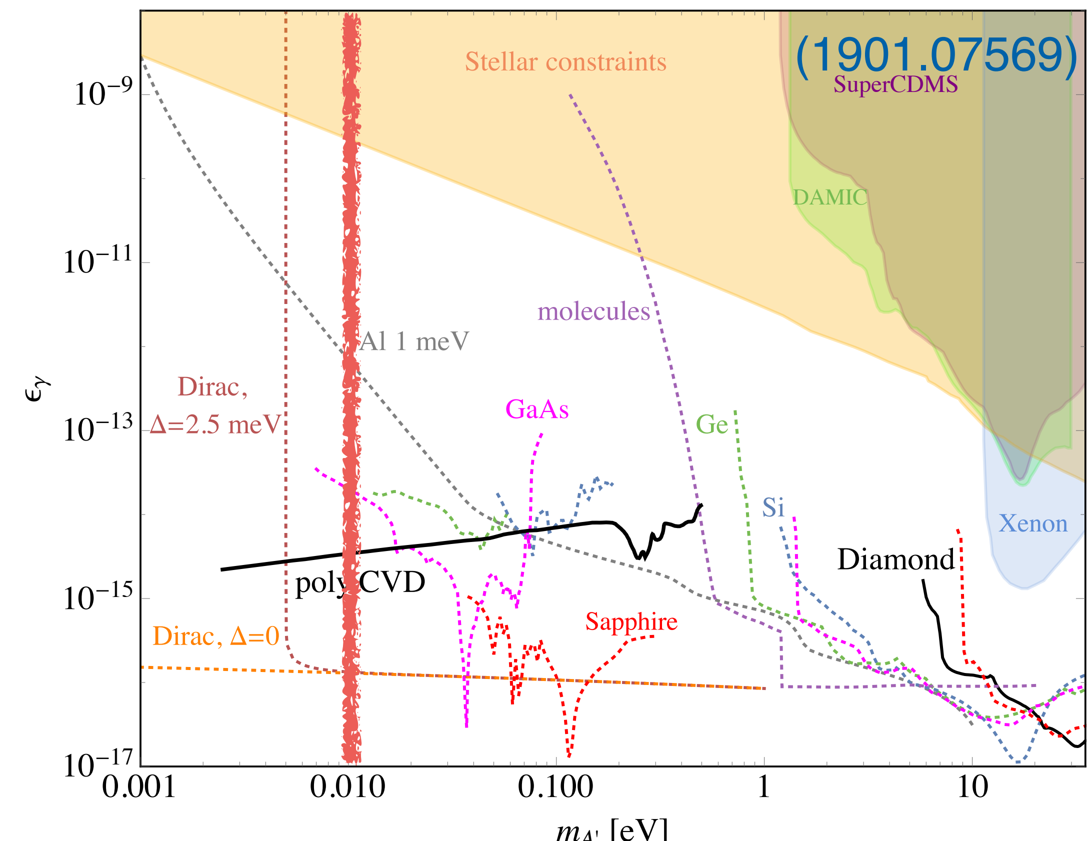
NR & Absorption Reach (LT)

- Short-term: gram-day exposure at 1 eV threshold (about 10x improvement over current) probes large uncovered parameter space
  - Absorption down to band-gap also probed, depending on backgrounds
  - Lighter targets provide lower mass reach but lower exposure; diamond more competitive with He than Si

- Significant R&D needed to achieve ‘ultimate’ limit of cryogenic readout
  - Compare to ~40 meV resolution in yesterday’s slides from MP
  - SuperCDMS has a path to ultra-low resolution, but this is still speculative





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Backup

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

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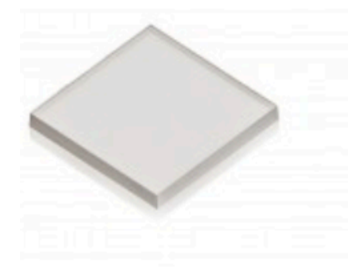
a De Beers Group Company



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