Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

SiC and Diamond Detectors for HEP

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Magnificent CEvNS
November 20, 2020

SNOWMASS Carbon-Based Detectors White Paper

Snowmass 2021 Letter of Interest
Cryogenic Carbon Detectors for Dark Matter Searches

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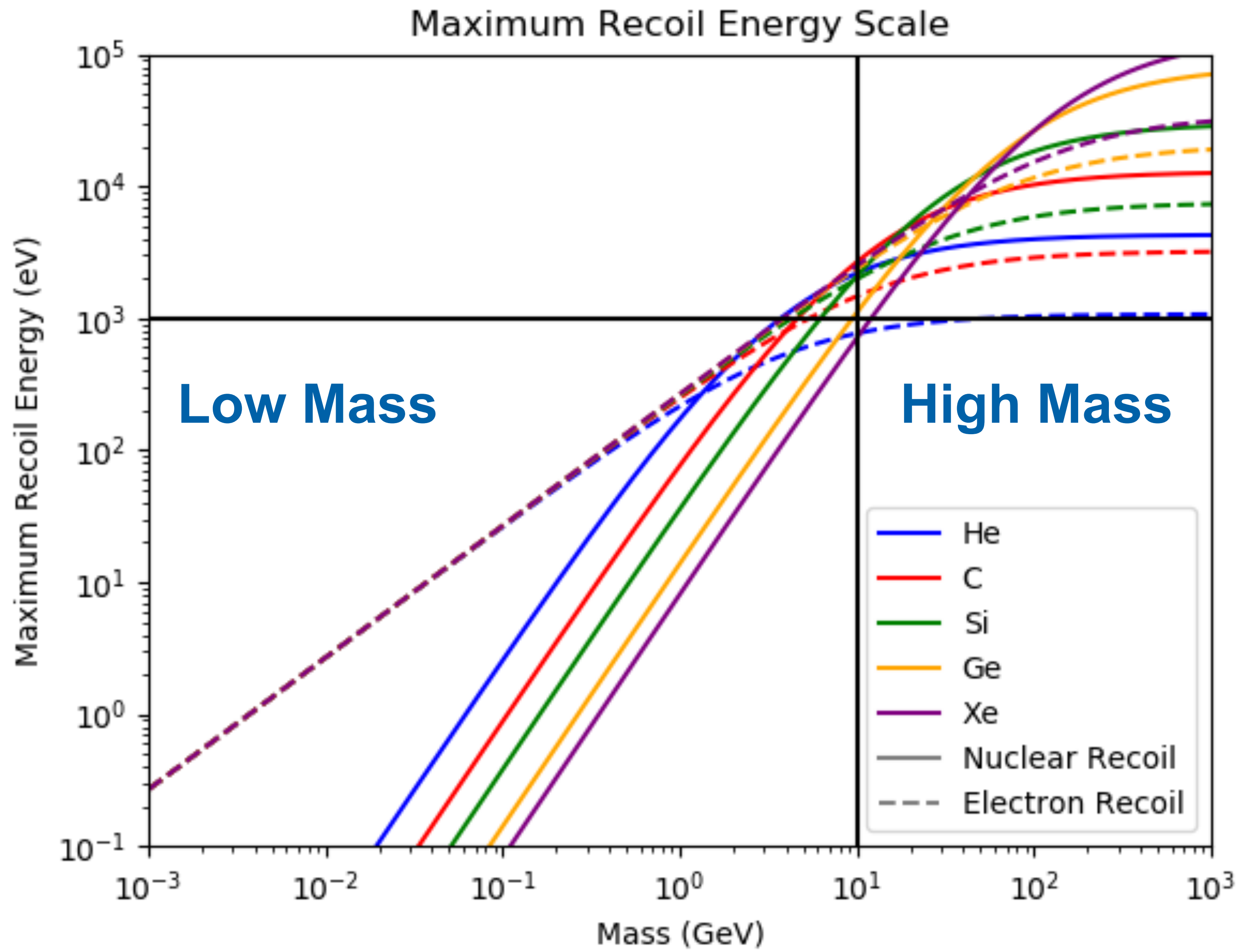
Yonit Hochberg	Hebrew University of Jerusalem
Danielle Braje	MIT Lincoln Laboratory
Harris Kagan & K.K. Gan	Ohio State University
Raymond Bunker	Pacific Northwest National Laboratory
Paul Brink & Richard Partridge	SLAC National Accelerator Laboratory
Blas Cabrera & To Chin Yu	Stanford University
Miriam Diamond & Ziqing Hong	University of Toronto

- Interest so far from dark matter, quantum science, and colliders; looking to gauge interest from CEvNS community

- Current collaboration includes diamond growth at MITLL, looking to expand to collaboration with other groups as well

Carbon for DM: Better Kinematic Matching

- Recoil energy for a typical DM particle 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



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

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

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

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

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Best Materials for keV-MeV DM (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, $CaWO_4$	SiC
Electron transitions	E_g^{-1} (Eq. (28))	depends on details of electron wavefunctions	InSb, Si	
Nuclear recoils	$(A\omega_{\rm min})^{-1}$ (Eq. (29))	$(Z/A)^2\,\omega_{\rm min}^{-1}$ (Eq. (31))	diamond, LiF	

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	$c_s/\omega_{\rm min}$ (Eq. (36))	Light mediator: $\omega_{\rm min}^{-1}$ (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	$(A\omega_{\rm min})^{-1}$ (Eq. (29))	Light mediator: $\omega_{\rm min}^{-1}$ (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)

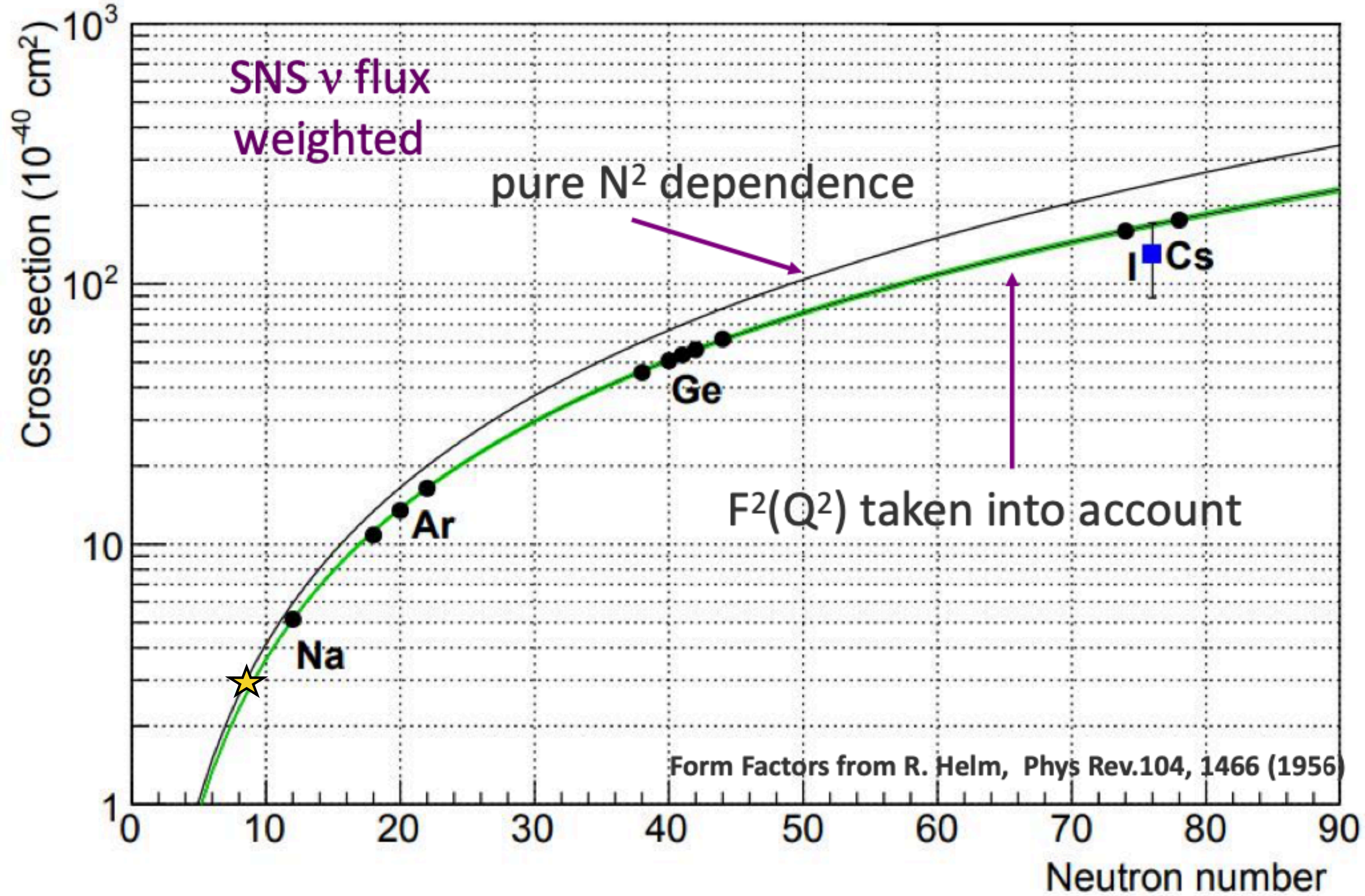
Carbon for CEvNS

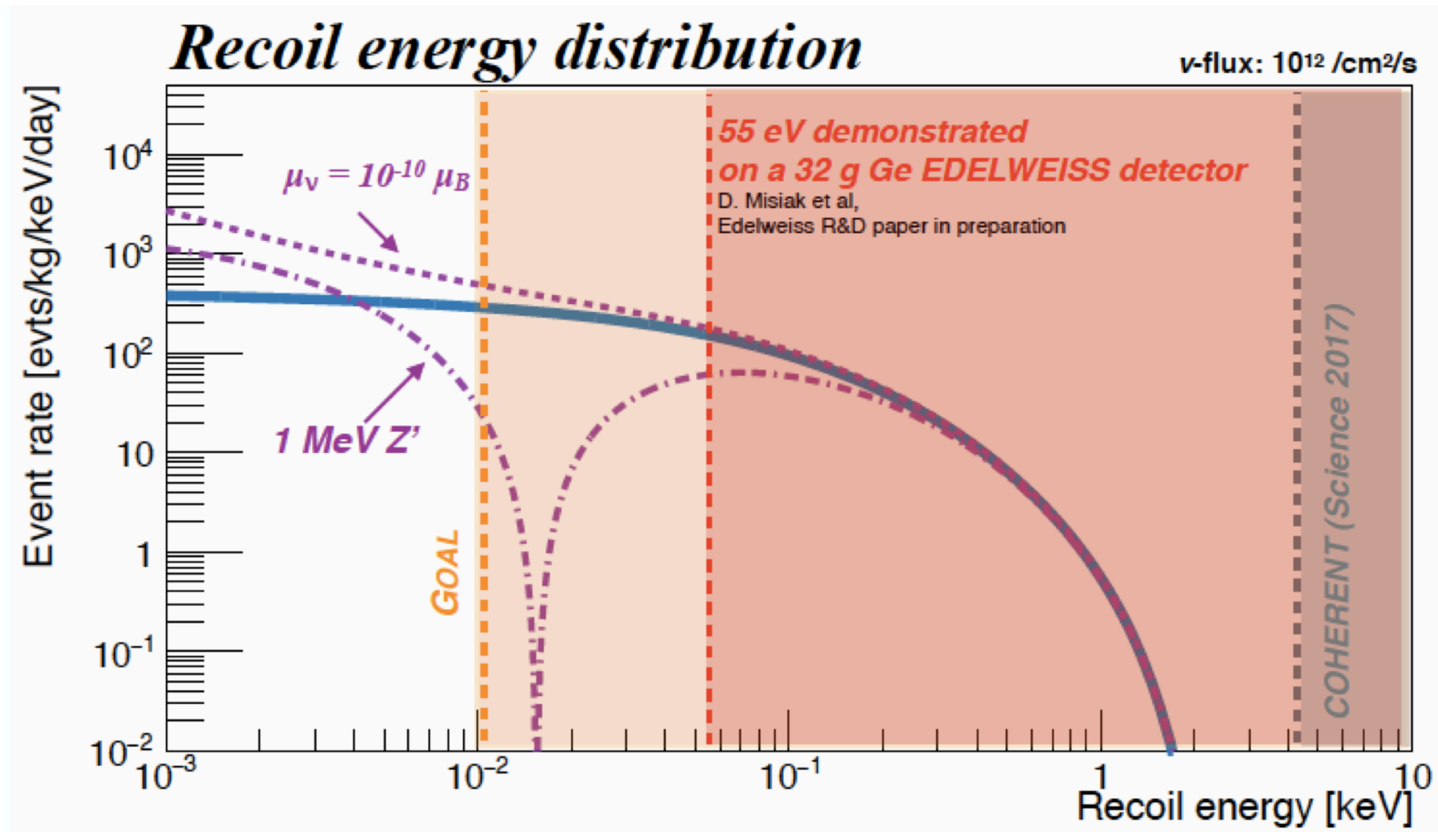
- Lighter nuclei are not necessarily beneficial for a SM measurement in a beam, and diamond/SiC aren't as easy to scale to large masses as e.g. Ar.
  - SiC detectors would provide two more points on the neutron dependence curve
  - Higher resolution allows for study of spectral shape to search for BSM physics

- For low-energy beams, or for precise spectrum measurement, much lower resolutions are needed.

- Definitely interesting for neutrino magnetic moment measurement

- I'm not a neutrino person, but I am interested in how these detectors could benefit the field. Making a 1 keV SiC detector at kg-scale is easier than a 1 eV, 1g SiC detector, if there is interest.





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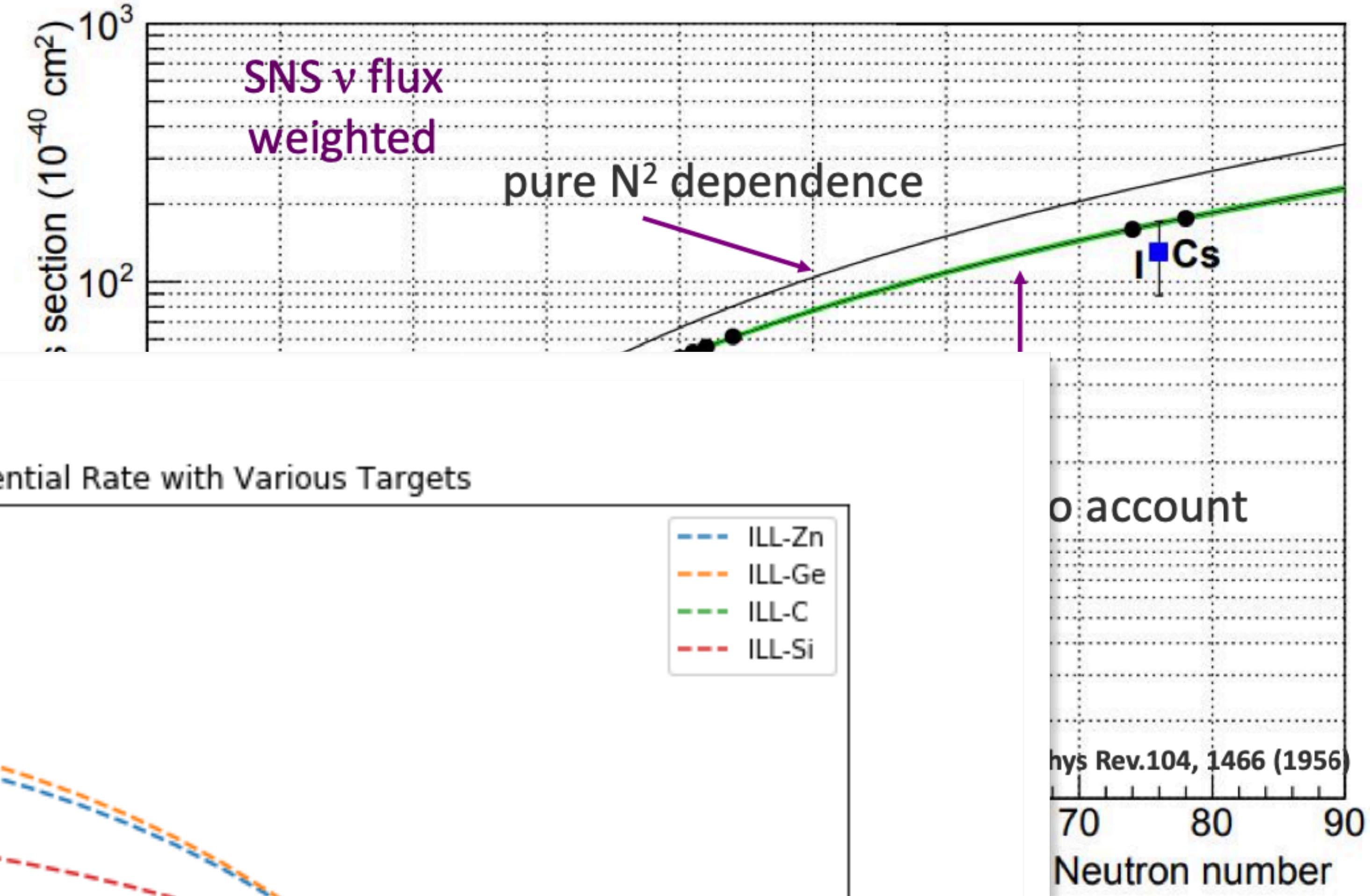


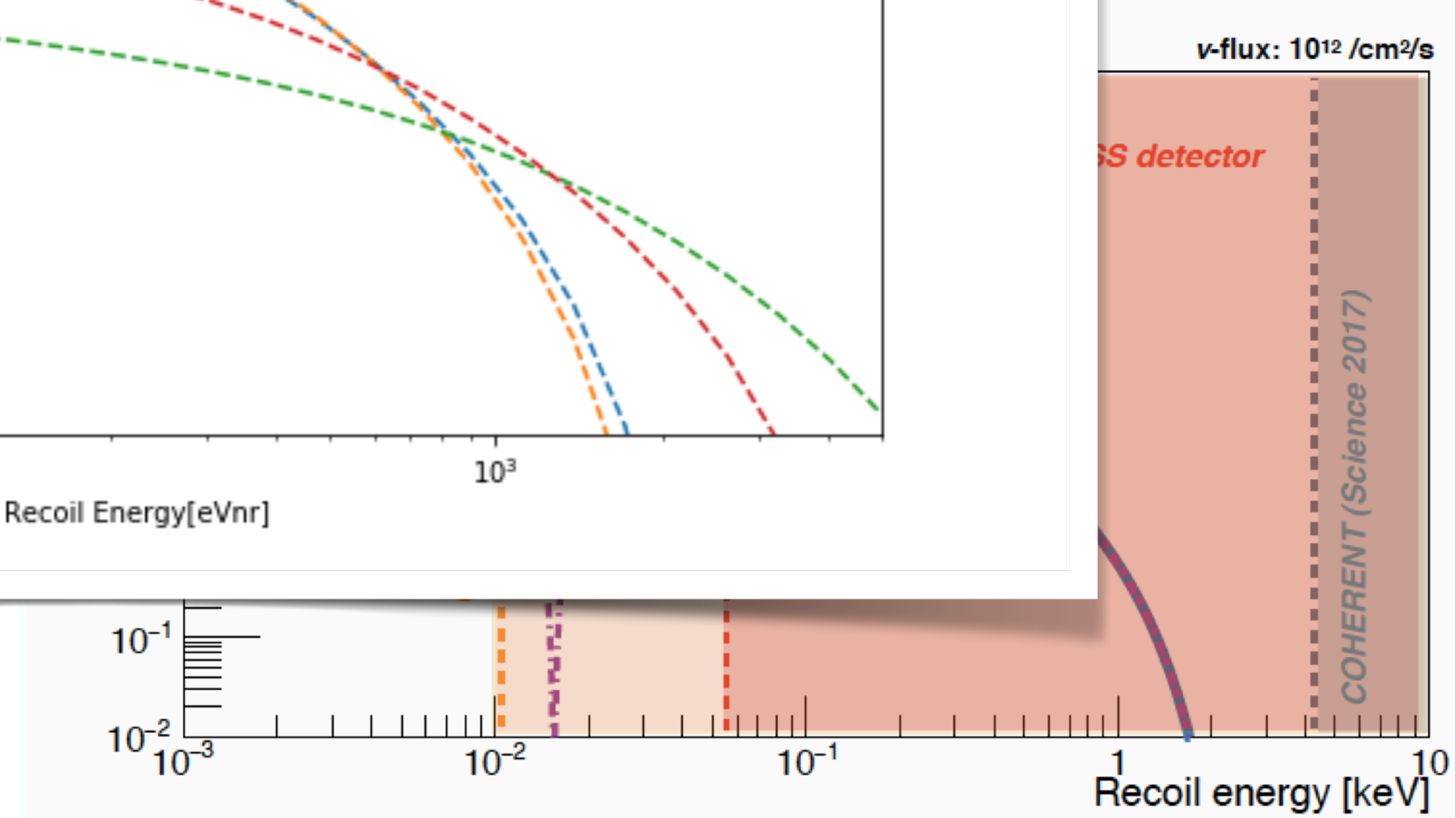
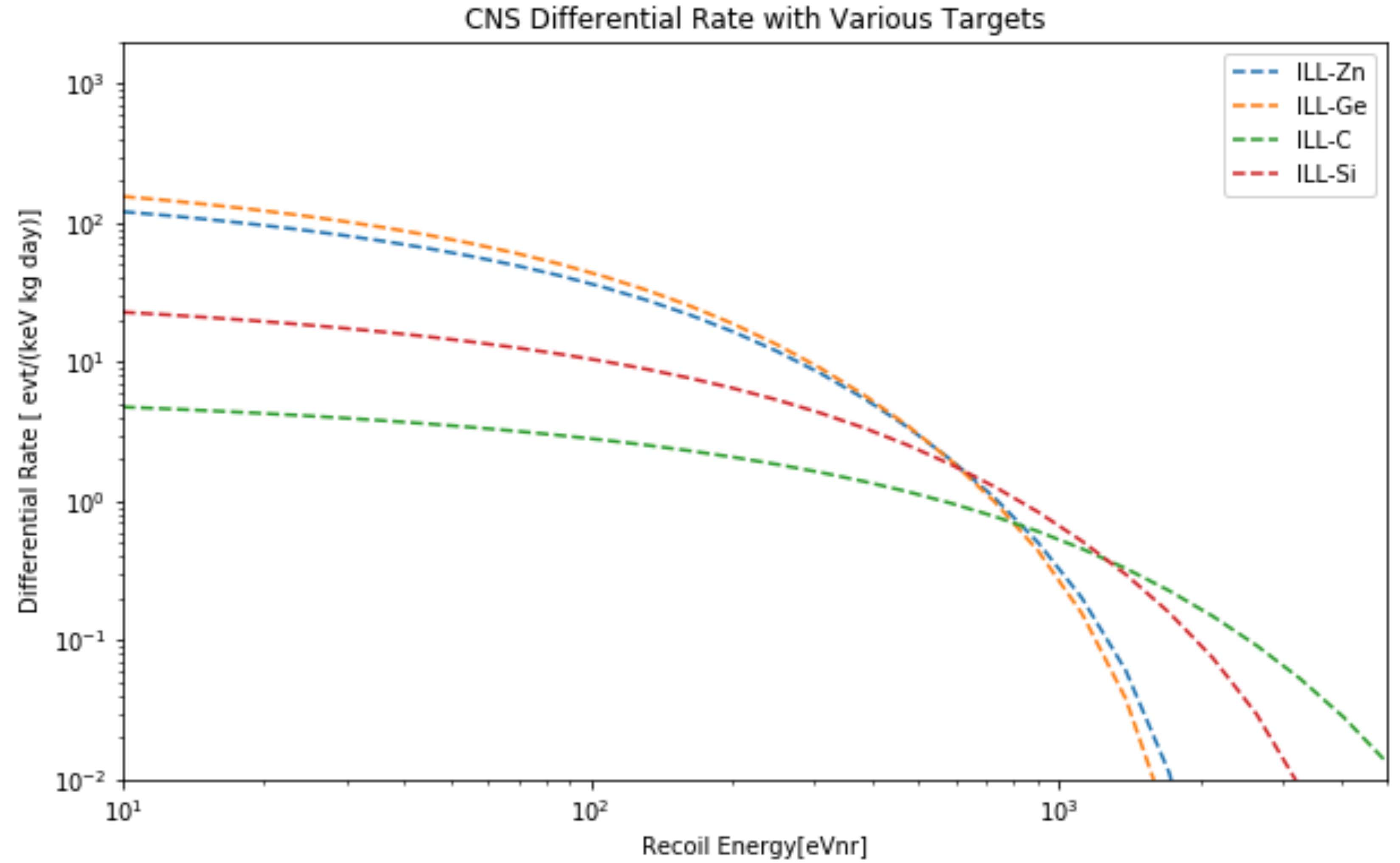


Figure Courtesy R. Chen



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 DM or CEvNS 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
- MPI group demonstrated 70 eV thermal W TES detector on diamond substrate this year (https://link.springer.com/article/10.1007/s10909-020-02350-4)

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

Diamond DM Prospects

Griffin et. al. 2019 (1910.10716)

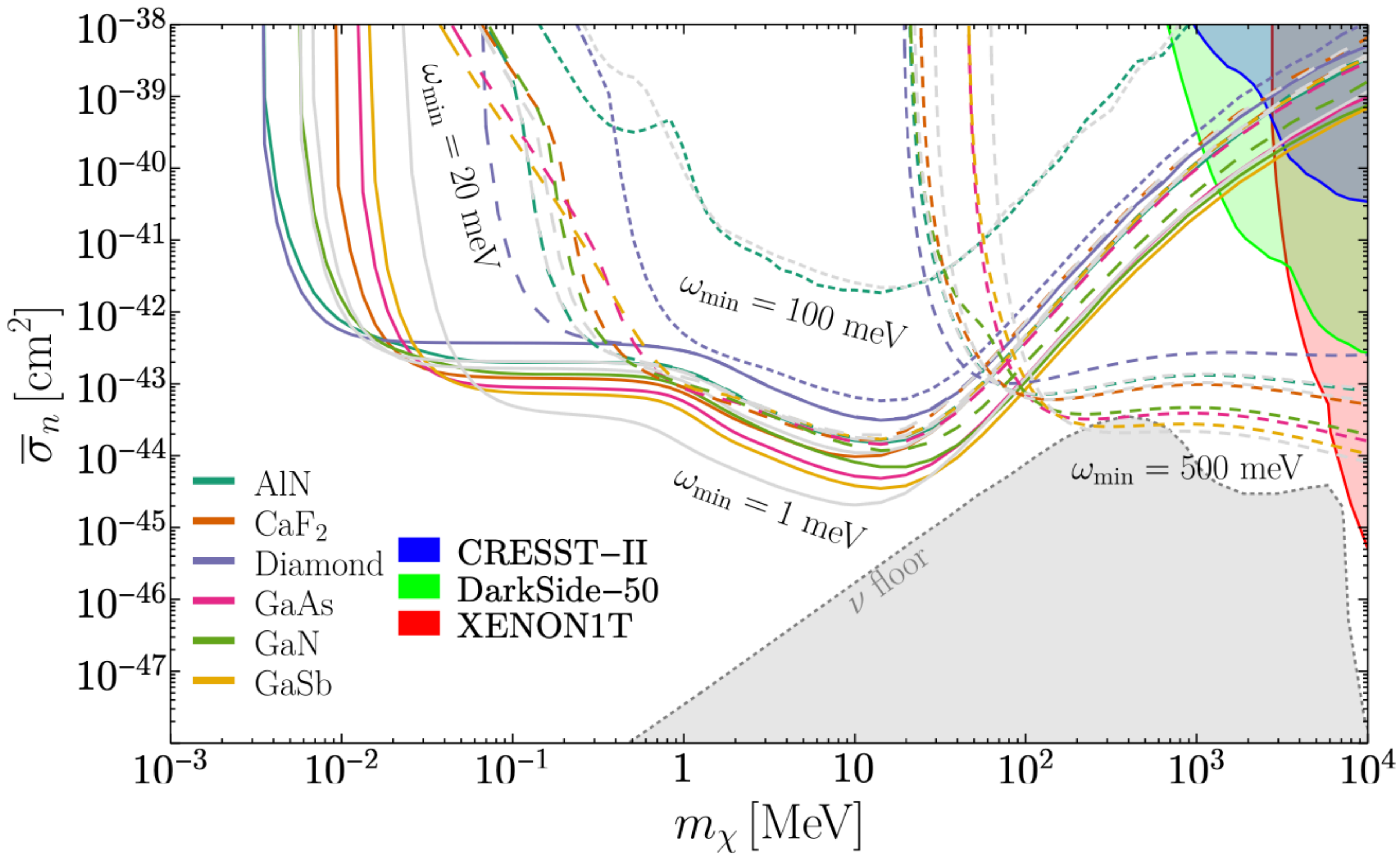


Figure 16. Same as Fig. 3, but with different materials. For reference, gray lines are CsI, Si, and Al_2O_3 taken from Fig. 3.

- Diamond's high-energy, long-lived phonons are unparalleled. A 100 meV threshold detector has ten times the reach per gram of any other target.
- The long-lived, high-energy phonons also make it more conducive to use as a single-phonon detector; there is a well-motivated path to achieving 100 meV threshold

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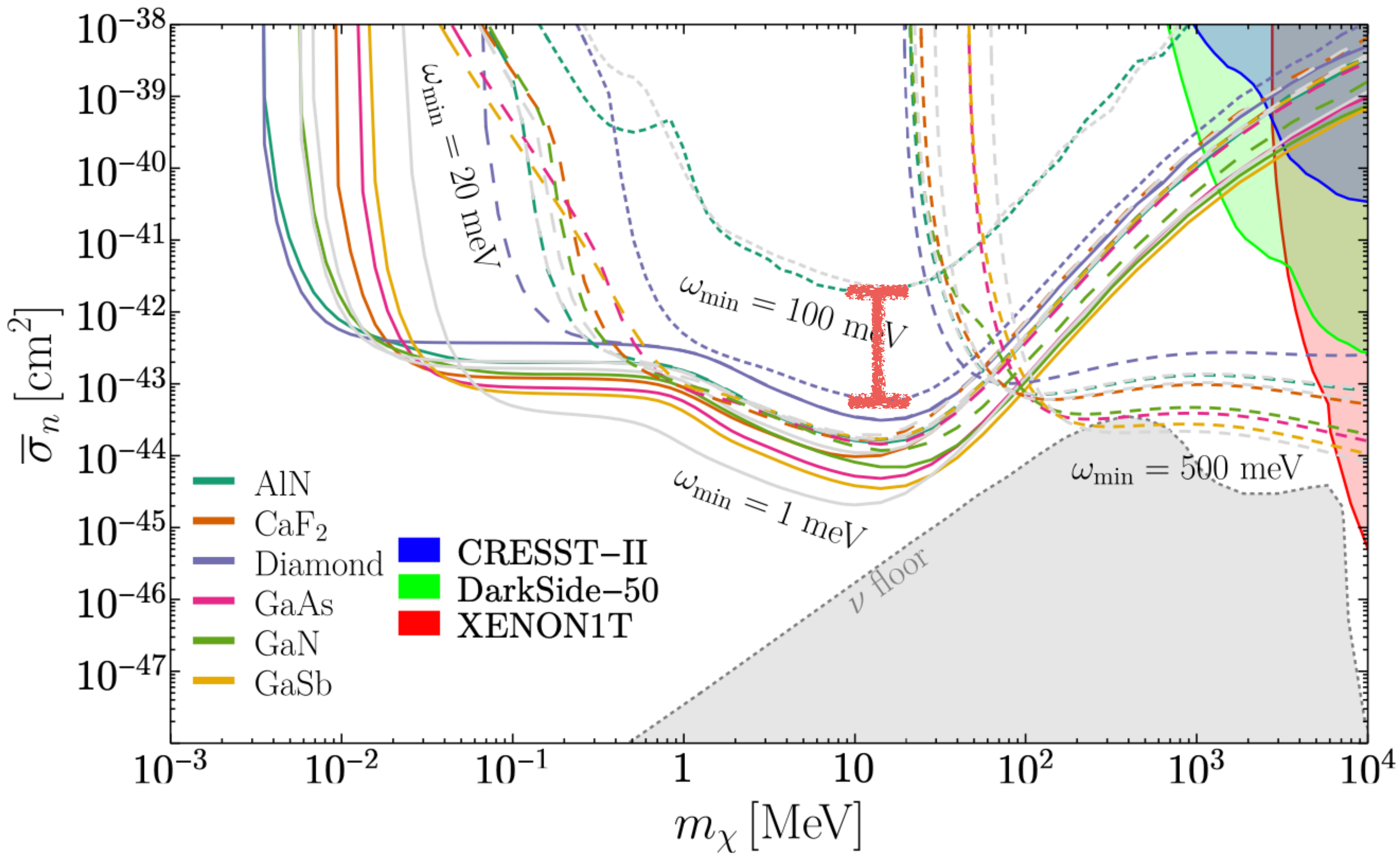

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Challenge: Sourcing Diamond Substrates

- 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-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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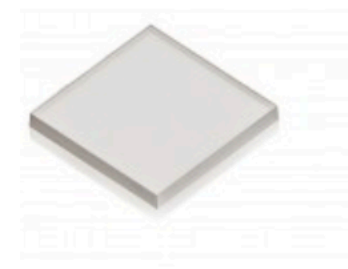

EL SC Plate 4.5x4.5mm, 0.50mm thick

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

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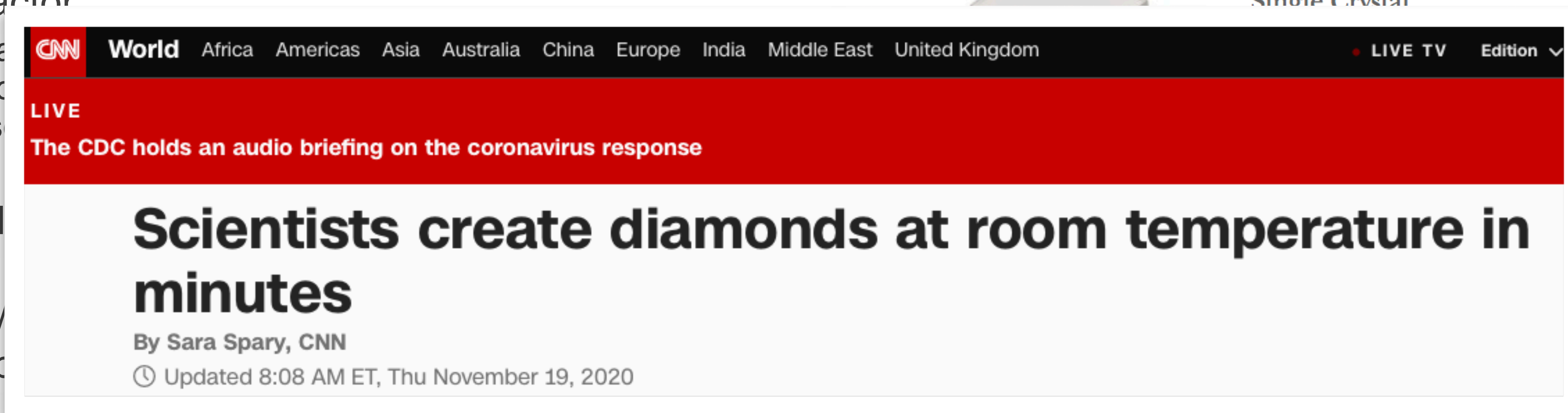

200 mg

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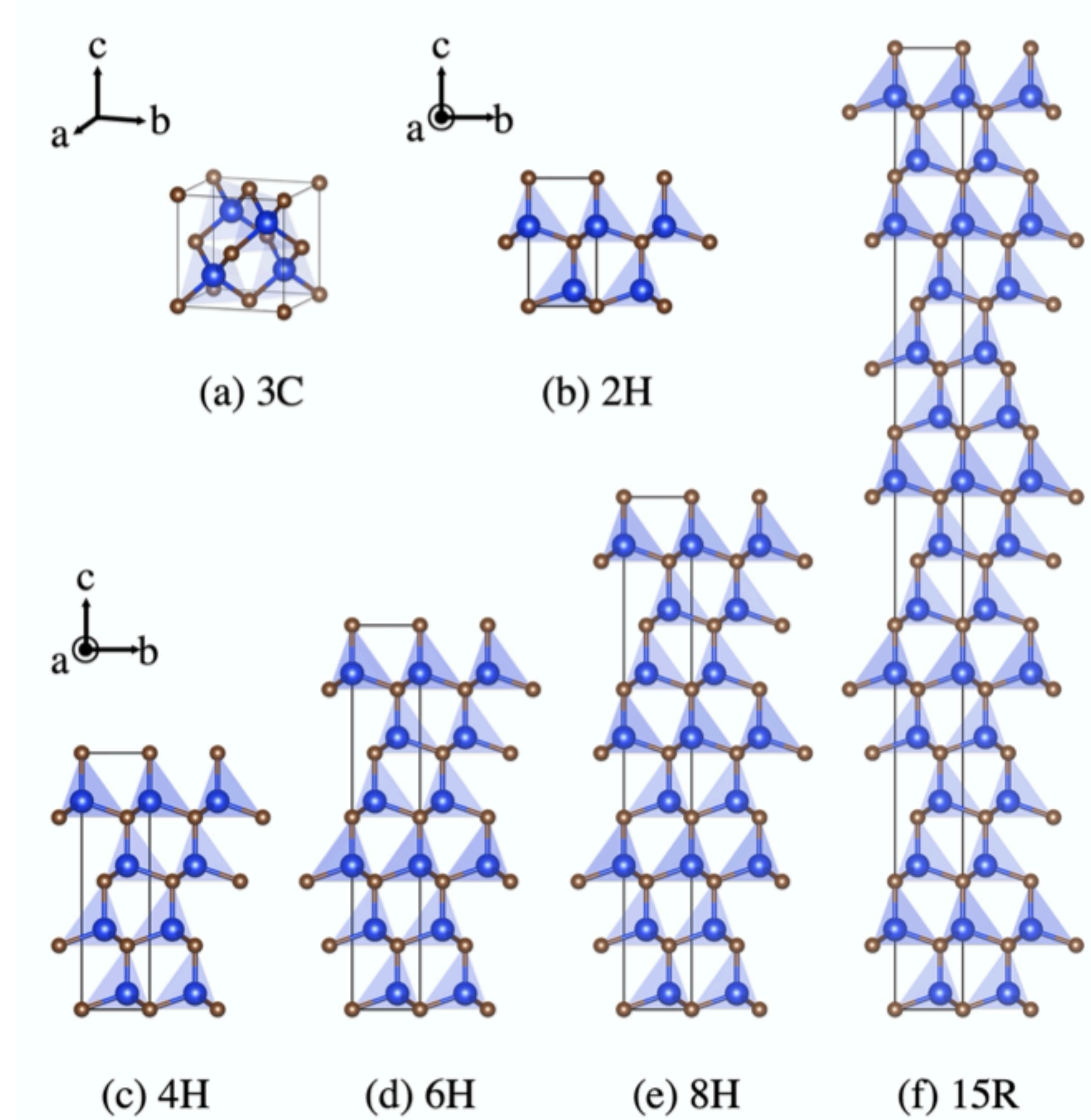
SiC Polytypism

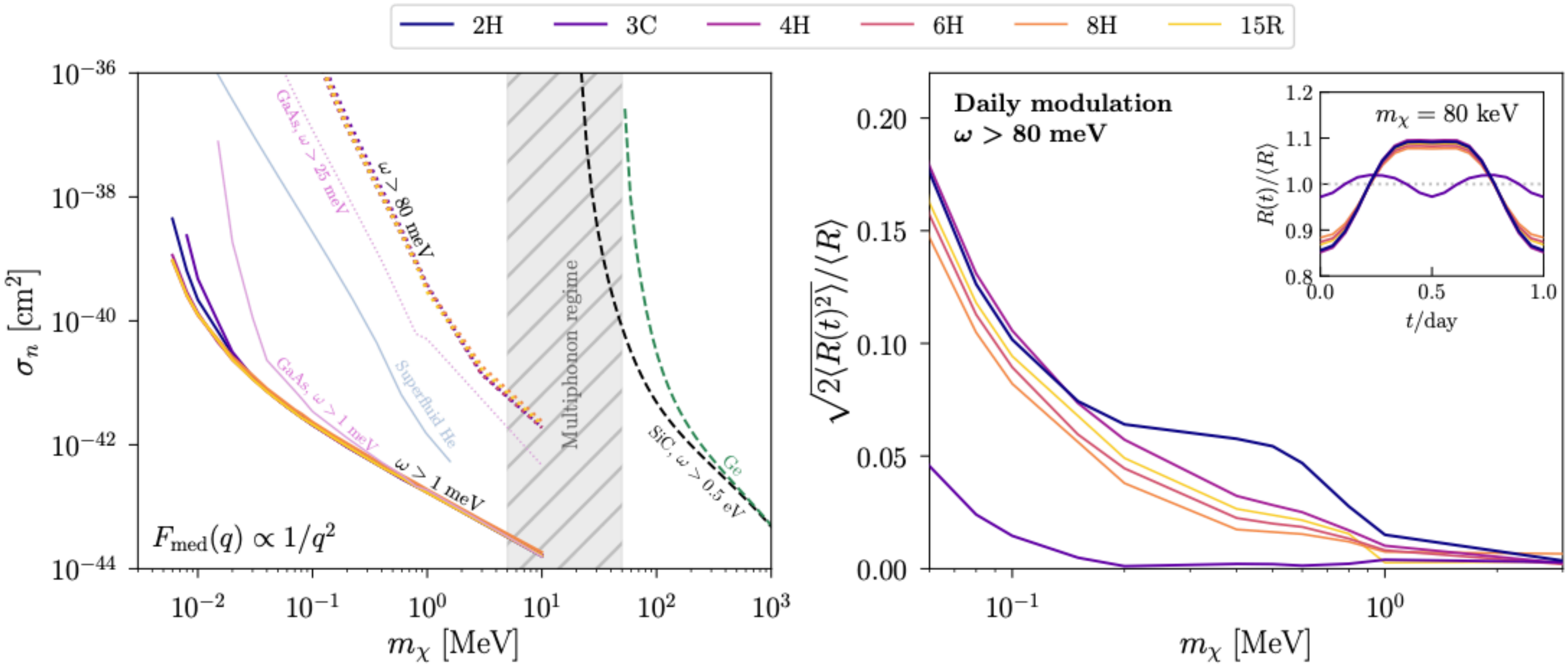
- SiC has over 200 stable crystal polytypes
- The ~6 most common types have identical bonds but vary by a geometric twist; this leads to a polytype-dependent gap but constant phonon properties
- Same technology in the same environment can provide discovery potential by changing ionization yield
- 4H/6H widely available from commercial wafer vendors, grown by same process as Si/Ge



Parameter	Diamond (C)	Si	SiC					
Polymorph	-	-	3C (β)	8H	6H (α)	4H	2H	15R
Crystal Structure	cubic			hexagonal				rhombohedral
ρ (g cm^{-3})	3.51	2.33	~3.2 [31, 32]					
N (10^{23}cm^{-3})	1.76	0.5	0.96					
n_e (10^{23}cm^{-3})	3.54	1	1.95					
$\hbar\omega_p$ (eV)	22	16.6	22.1[33]					
a (c) (Å)	3.567	5.431	4.36	3.07 (20.15)	3.08 (15.12)	3.07 (10.05)	3.07 (5.04)	3.07 (37.80)
f_H	0.0	0.0	0.0	0.25	0.33	0.5	1.0	0.4
$E_{\rm gap}$ (eV)	5.47	1.12	2.39	2.7	3.02	3.26	3.33	3.0
$E_{\rm gap}$ (eV)$^{[calc]}$			2.24	2.66	2.92	3.15	3.17	2.86

Griffin et. al. (2008.08560)

SiC DM Prospects



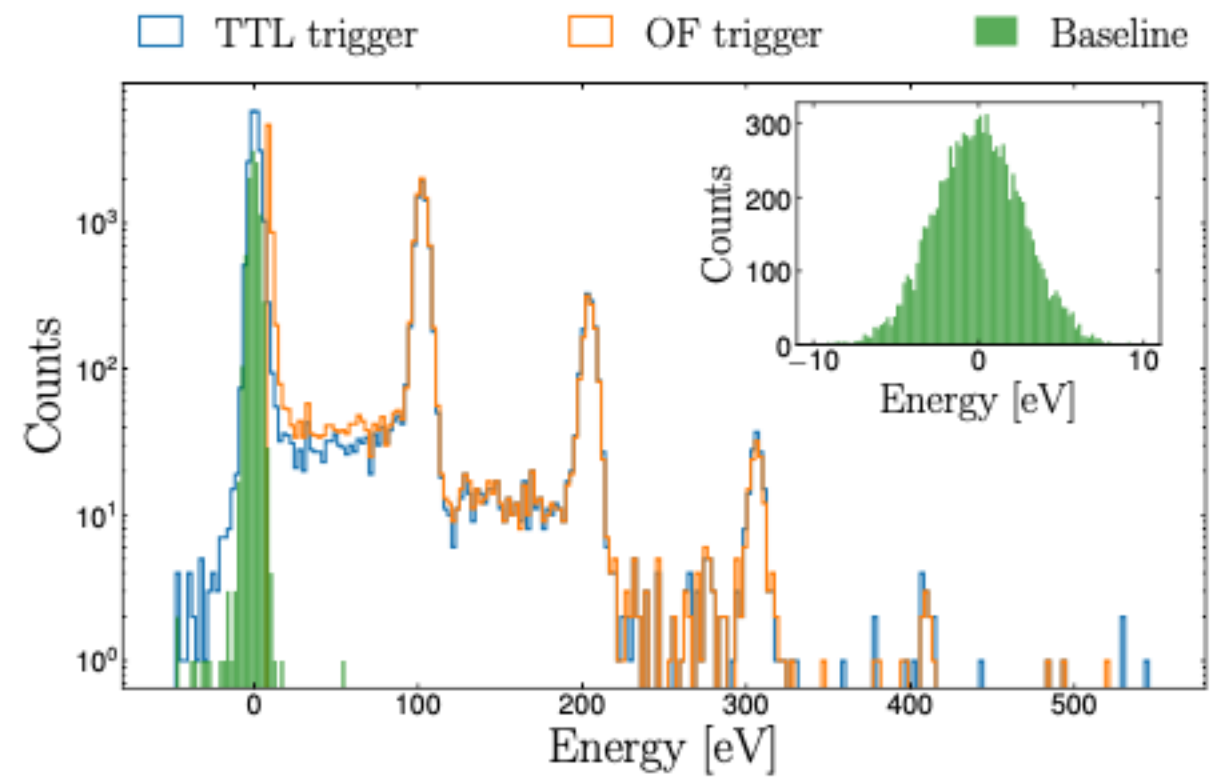
- Significant reach into single-phonon DM regime at higher threshold than GaAs, Sapphire
  - Best reach of polar materials for single-phonon thresholds
  - Single material complementarity in daily modulation signal

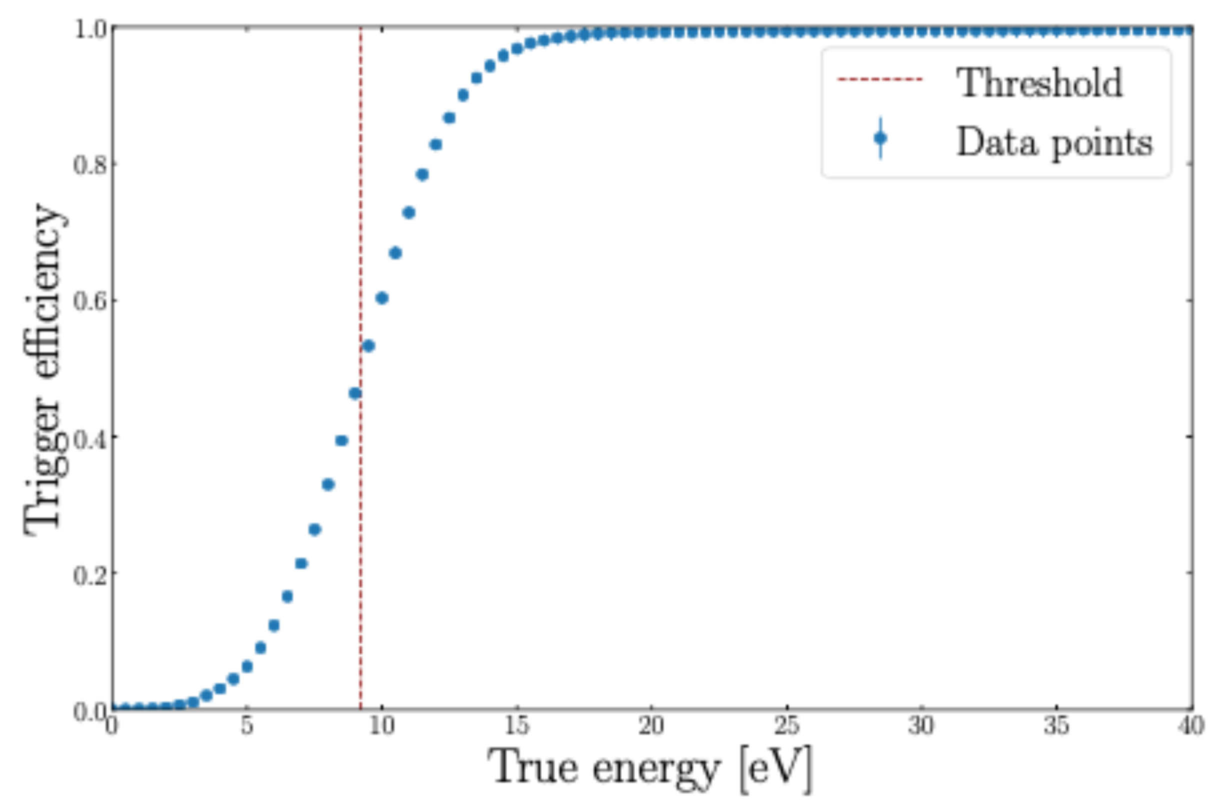
- Same material properties with different electronic gap; allows for same-target statistical characterization of signals. Nuclear recoils and electron recoil will appear at different energy scales in charge readout.

Griffin et. al. (2008.08560)

Making Low-Threshold SiC/Diamond Detectors

- HVeV (gram-scale Si detectors) have repeatedly achieved 3 eV resolution, and <10 eV threshold, with the TES-based SuperCDMS sensors.
  - This detector was run as a DM detector at NW and NEXUS, and in the TUNL neutron beam
- Fabrication easily ported to SiC/diamond as long as the carbon doesn't spoil Tc
- Even with degradation in efficiency, first designs comparable to this resolution should be achievable
  - Much of the uncertainty put to rest by the MPI group, who has now made a diamond detector with TES technology at 70 eV resolution





Ren et. al. in prep (2020)

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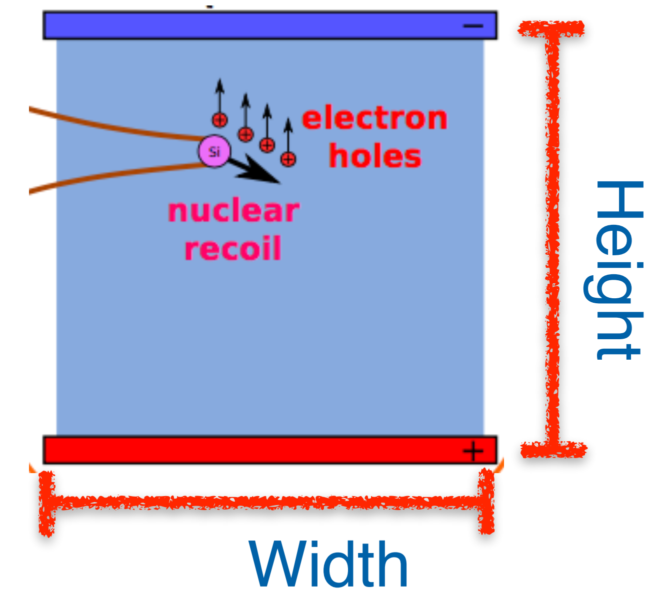
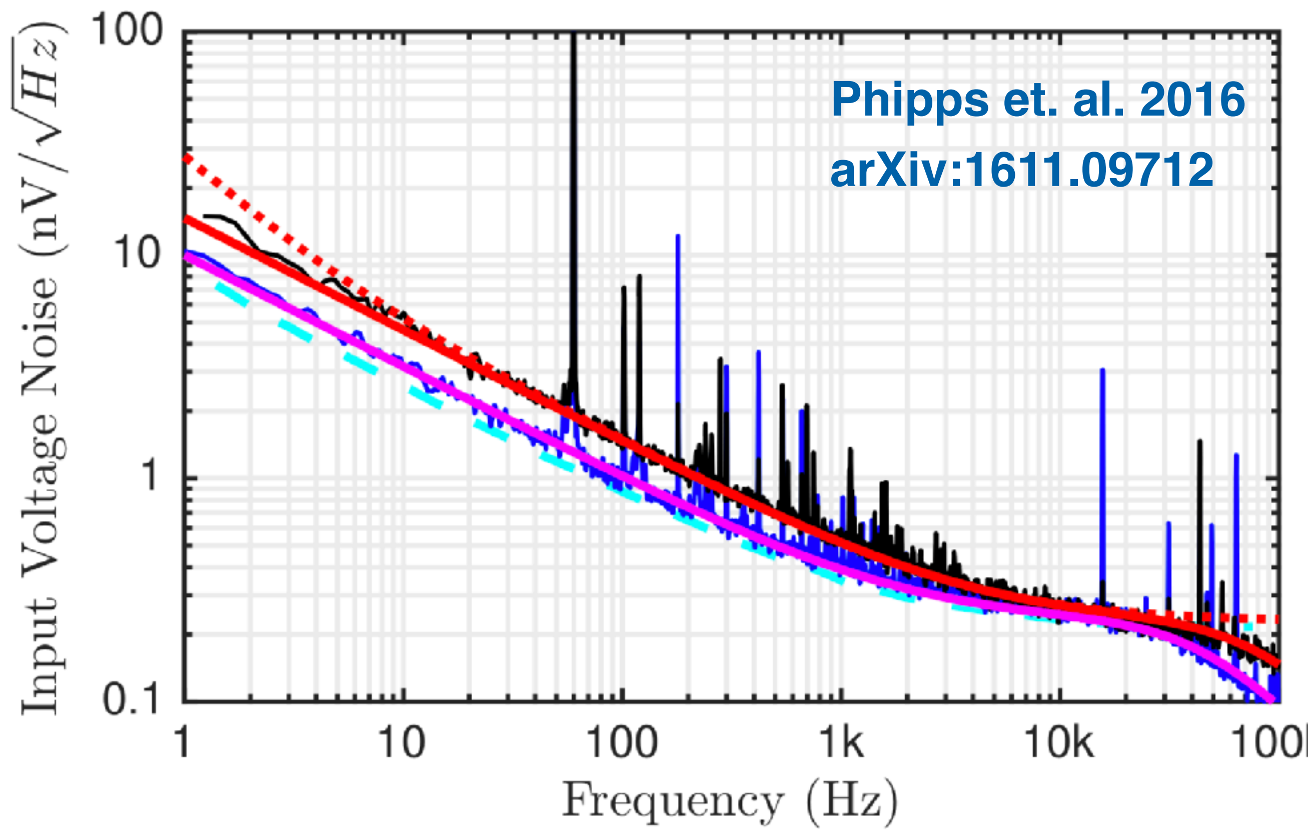
Diamond Charge Detector

- 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
  - ASICS group at FNAL and HEMT group at CNRS both working on this device topology

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

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





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)

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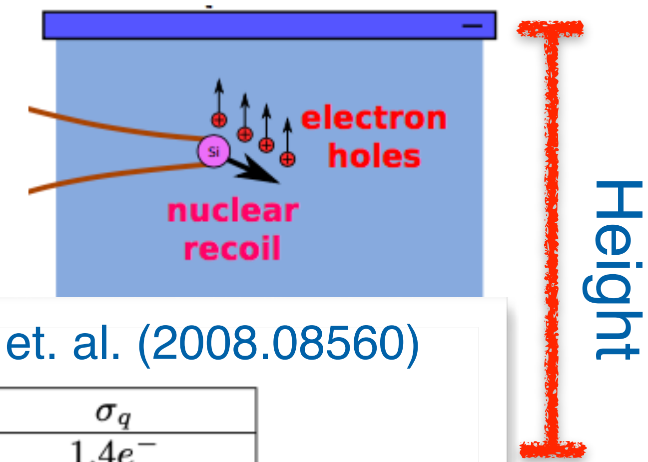


- Full charge collection has been demonstrated many times in CVD diamond crystals
- Charge detector and 1/f
- Capacita and 3x l geometr sam pixe

Griffin et. al. (2008.08560)

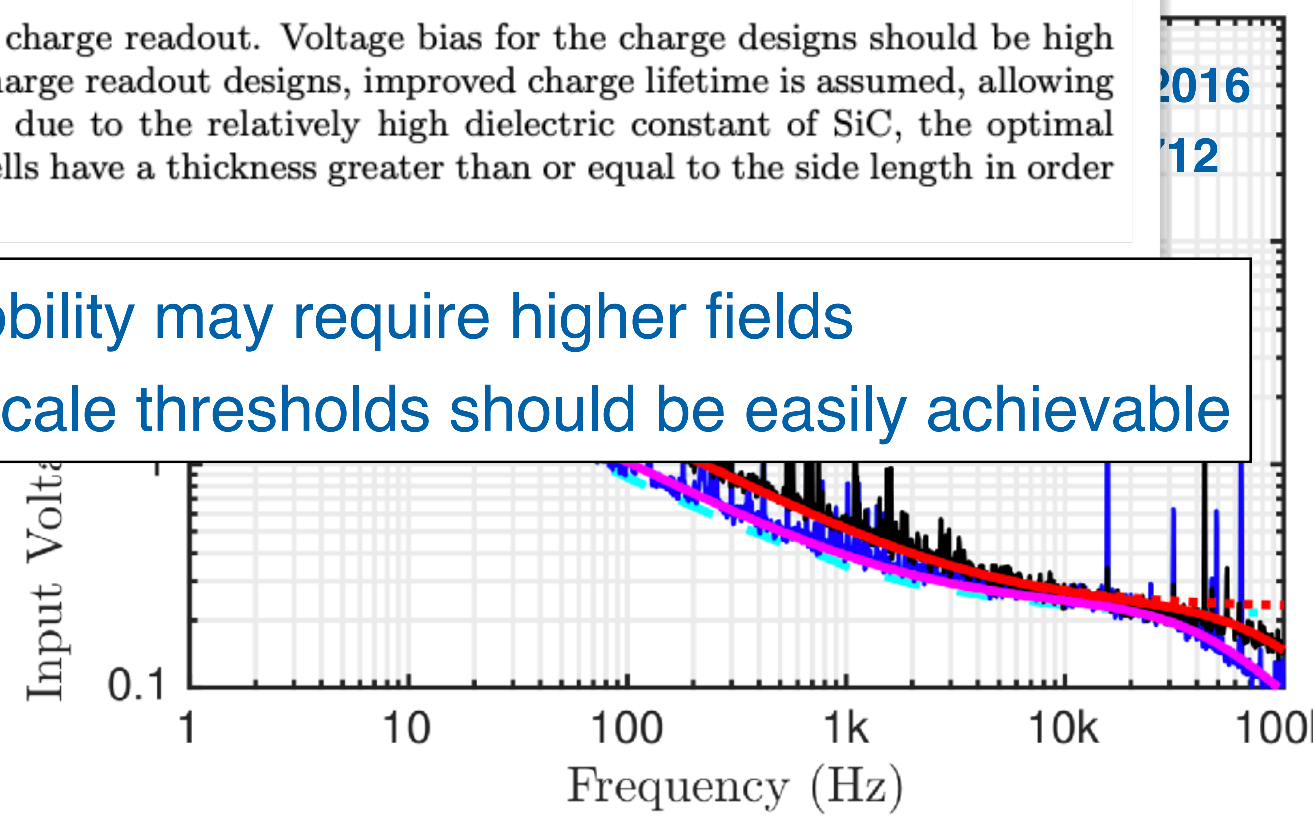
Readout	Design	Dimensions	Mass (g)	Temp. (K)	V_{bias}	σ_q
Charge	Single Cell	1.0 cm side length × 0.5 cm thick	1.6	4.2 K	4 kV	$1.4e^-$
	Single Cell	0.5 cm side length × 0.5 cm thick	0.4		4 kV	$0.5e^-$
	Single Cell	1.0 cm diameter × 1.5 cm thick	4.8		500 V	$0.5e^-$
	Segmented	0.2 cm side length × 0.2 cm thick	0.025		50 V	$0.25e^-$/segment

TABLE II. Summary of the detector designs discussion for charge readout. Voltage bias for the charge designs should be high enough to ensure full charge collection. For the lower two charge readout designs, improved charge lifetime is assumed, allowing for lower voltage bias and thicker crystals. We note that, due to the relatively high dielectric constant of SiC, the optimal geometry (given current readout constraints) is such that cells have a thickness greater than or equal to the side length in order to minimize capacitance per unit mass.

Also possible for SiC; Lower charge mobility may require higher fields

This is for *single charge* sensors. keV-scale thresholds should be easily achievable

- Recent HEMT amplifiers have achieved performance at 4.2K sufficient for single-charge ionization-chamber style diamond detectors for low-rate signals
  - ASICS group at FNAL and HEMT group at CNRS both working on this device topology



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Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

Further Development Paths

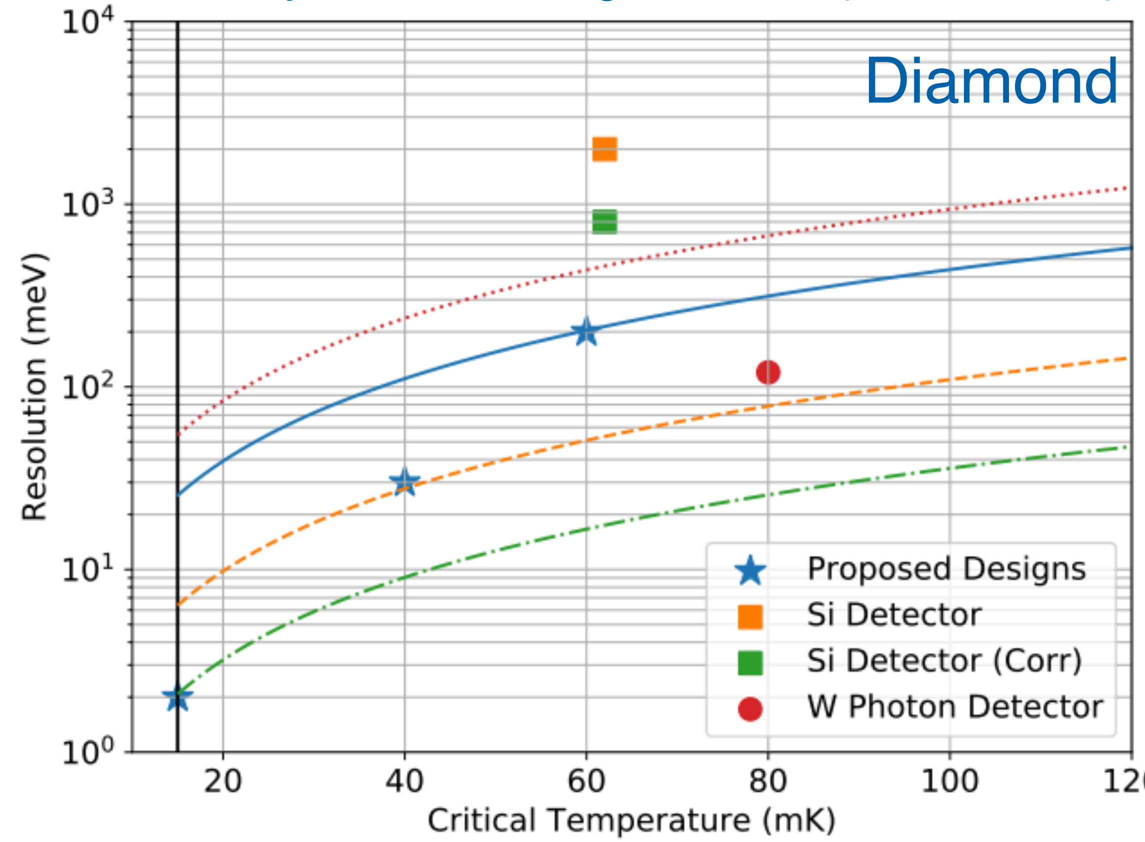
- Multiple ways to achieve eV-scale or single quantum resolution with carbon-based crystals; these are already substrates used in QIS

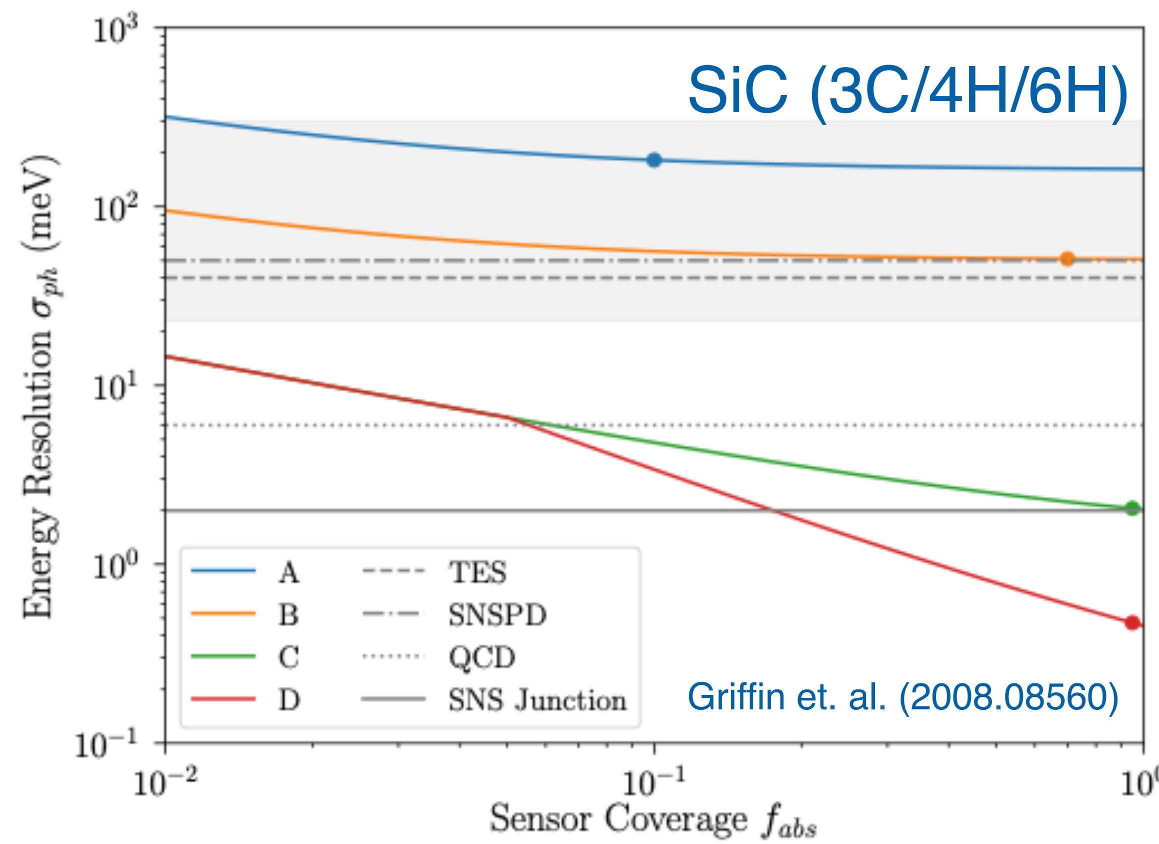
- Charge readout
  - Contact-free cryogenic charge readout (FNAL, CNRS)
  - Charge-sensitive qubits (FNAL, JPL)

- Athermal Phonon Readout
  - TES (SuperCDMS + others)
  - MKIDs (Caltech-led, see S. Golwala's talk)
  - Nanowires/QCDs

- Thermal Phonon Readout
  - TES thermometry— CRESST/MPI
  - Ricochet-style readout - MIT/NW/others

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)





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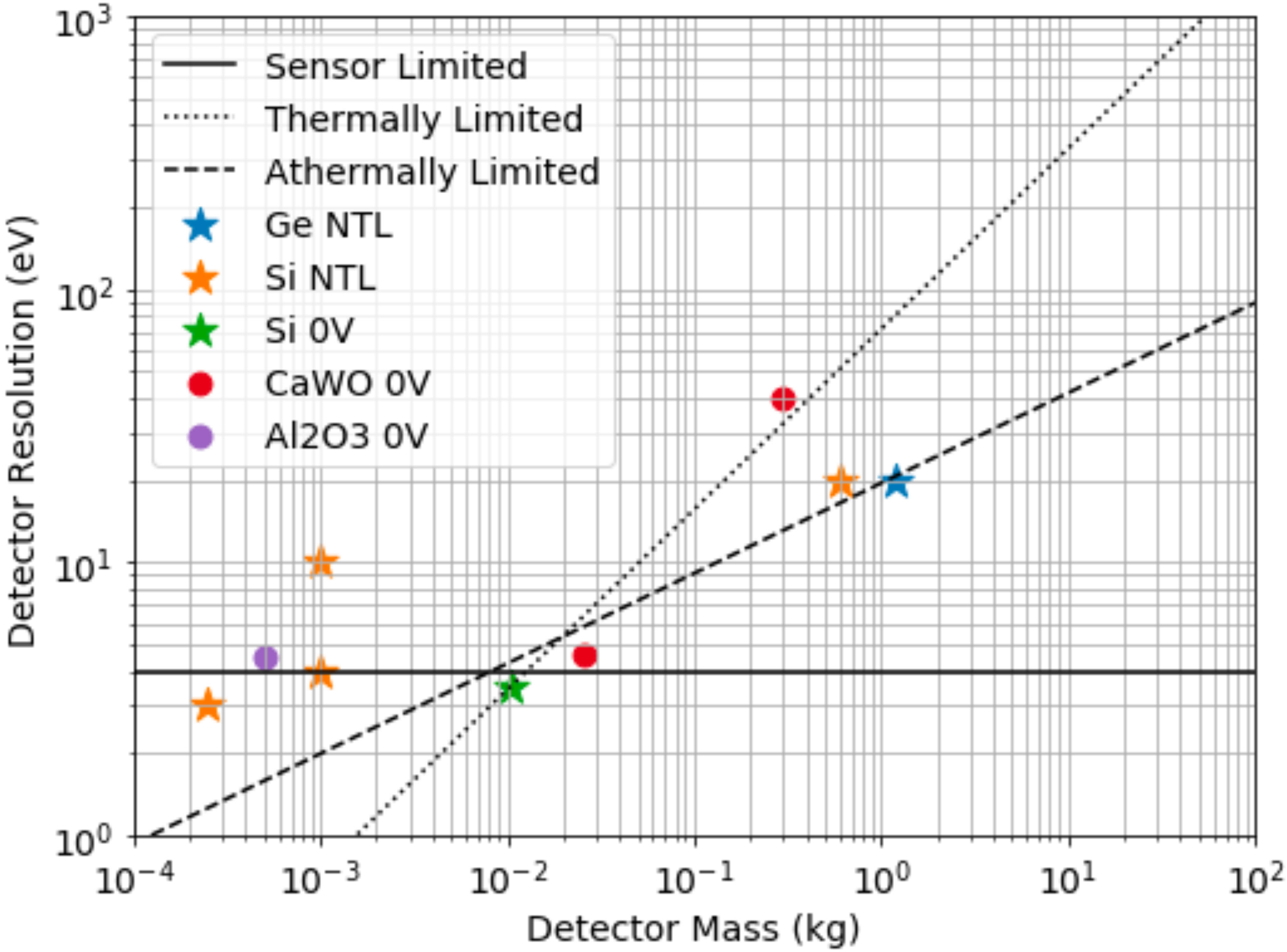
Scaling Up in Mass



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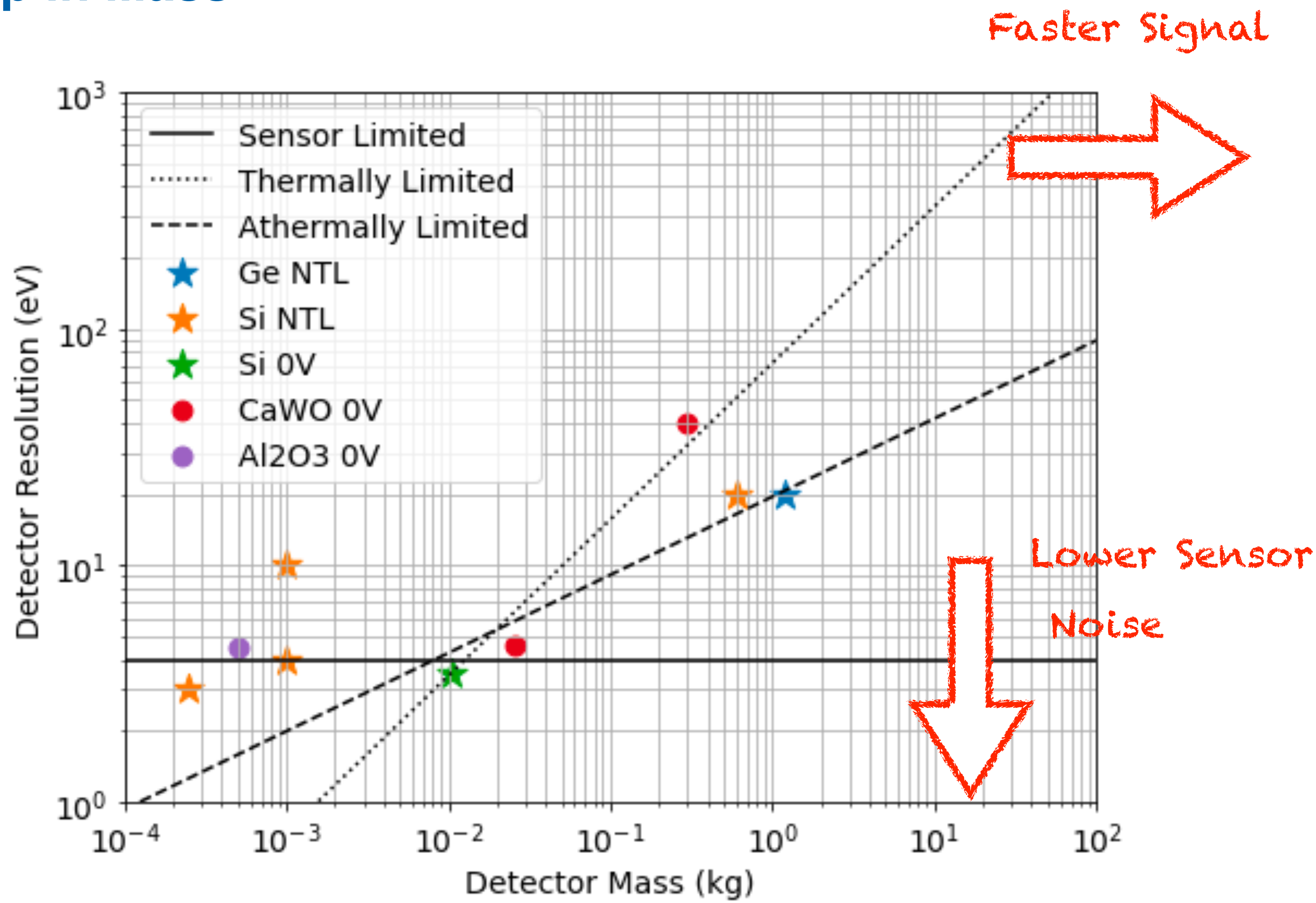

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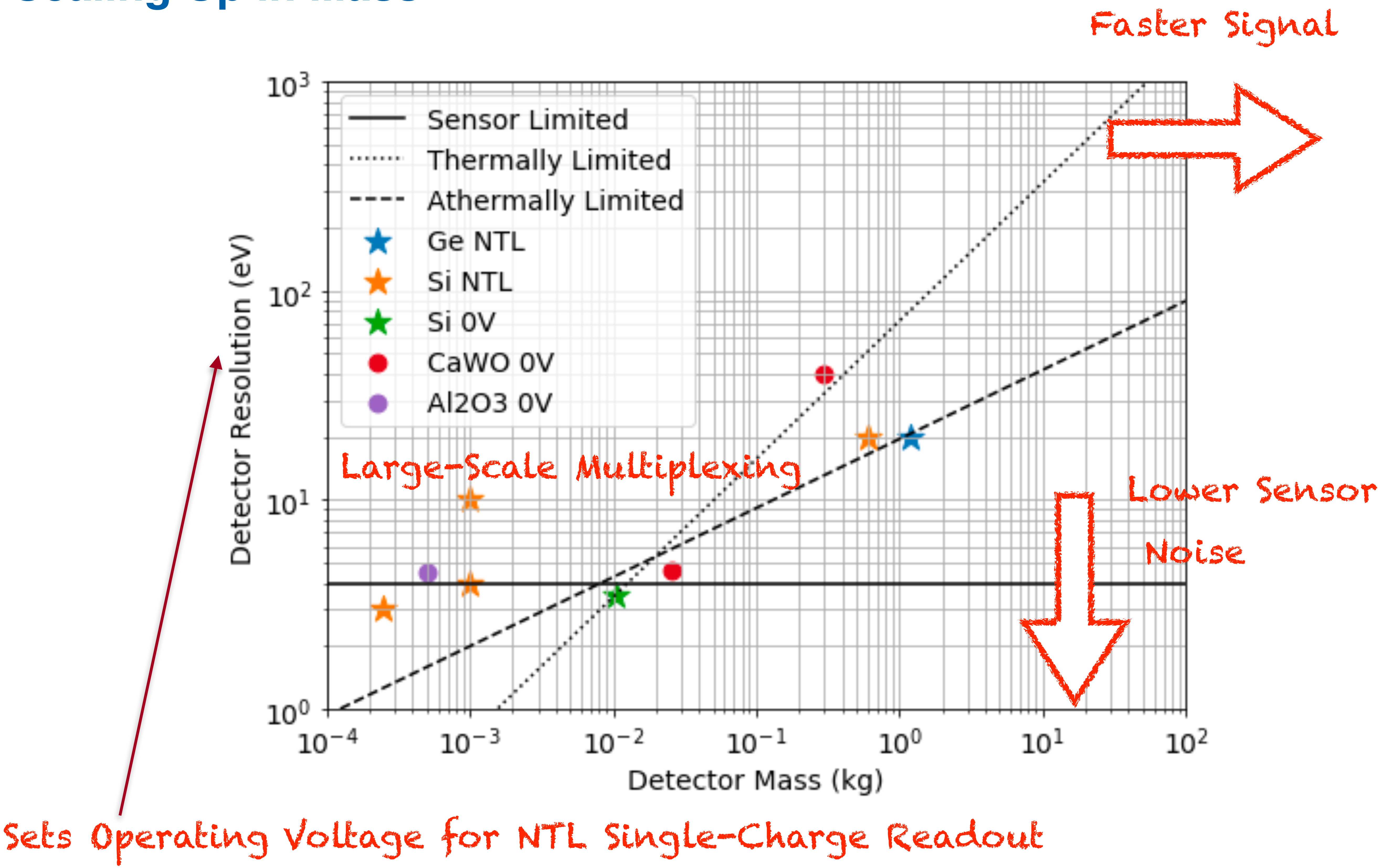

Conclusions and Future Plans

- Gram-scale diamond and kg-scale SiC detectors are viable and will be made over the next few years
  - Trying to gauge interest beyond the DM community
  - This interest can help inform R&D plans

- Advances being developed in Si technology should be easily portable to these new substrates

- Polytypism of SiC makes for interesting discovery science, using varying gap and crystal symmetry to differentiate between types of signals

- Will develop phonon-based detectors for DM science and charge-readout detectors for imaging science and beam monitoring
  - The latter will also help scale growth of CVD diamond crystals