Diamond Detector for Direct Detection of Sub-GeV Dark Matter

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Introduction

We propose the use of SuperCDMS-style diamond detectors for sub-GeV DM search. Diamond has several advantages:

1. Better mass matching to low mass DM
2. Excellent isotopic purity
3. Long-lived and fast phonon modes
4. Radiation hard
5. Large breakdown fields (≥20 MV/cm).
6. Absence of shallow impurity

Much of the current technology developed for Si and Ge substrates can be ported over to diamond with minimal modification, placing diamond detectors in an excellent position to broadly probe and detect DM in near future.

Detector Physics

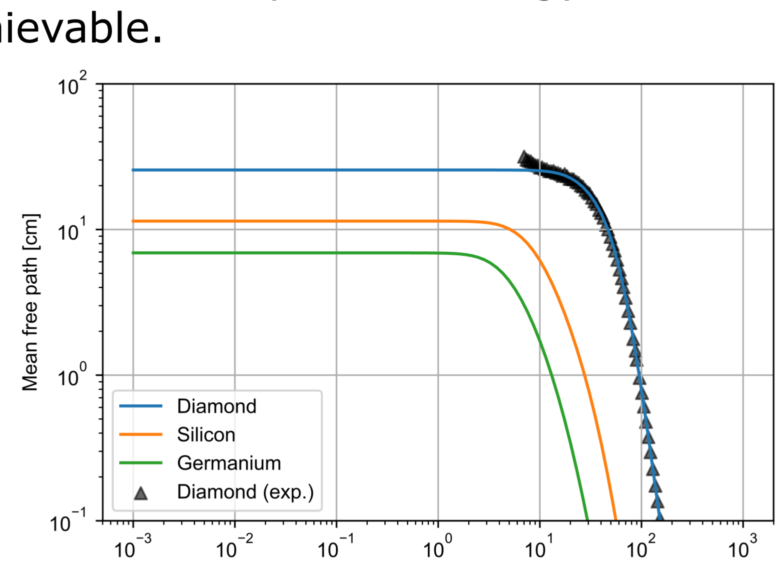
Charge Collection

Early demonstration of charge mobility in synthetic diamond showed a charge carrier lifetime in excess of 2μs **[1]**. For a field strength of 1-10 kV/cm, charge drift velocity is on the order of 10 cm/μs **[2]**. This corresponds to a mean free path, at room temperature, of 10 cm, which in fact is the maximum collection distance measured in **[1]** for high-quality chemical vapor deposition (CVD) diamonds at room temperature.

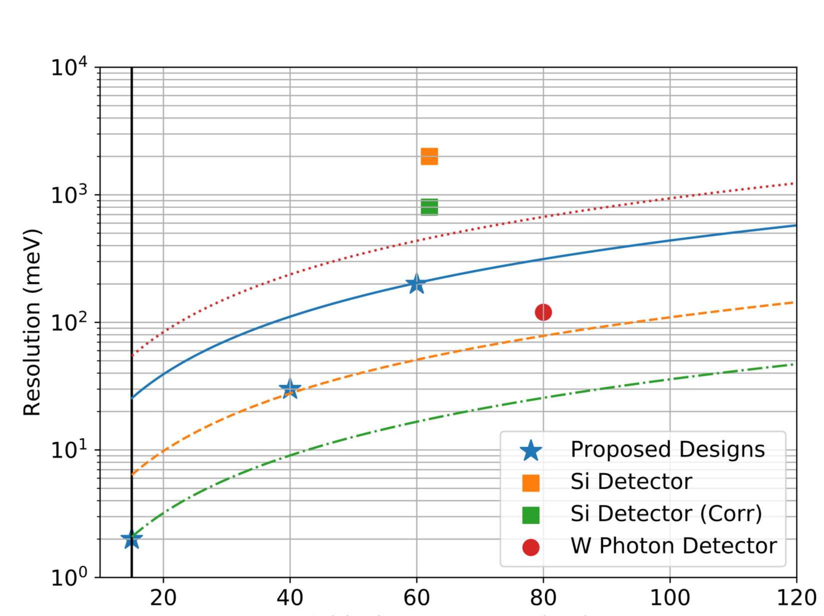
Phonon Collection

The high thermal conductivity of diamond translates into high phonon mean free path. An estimation using the Callaway model **[3,5]** shows that the phonon mean free path in high-purity CVD diamond is higher than in silicon or germanium with similar crystal size & surface quality. Combined with fast collection of phonons leads to a high phonon collection efficiency and thus good resolution

For small detectors, it is likely that sub-eV or even meV level phonon energy resolution is achievable.



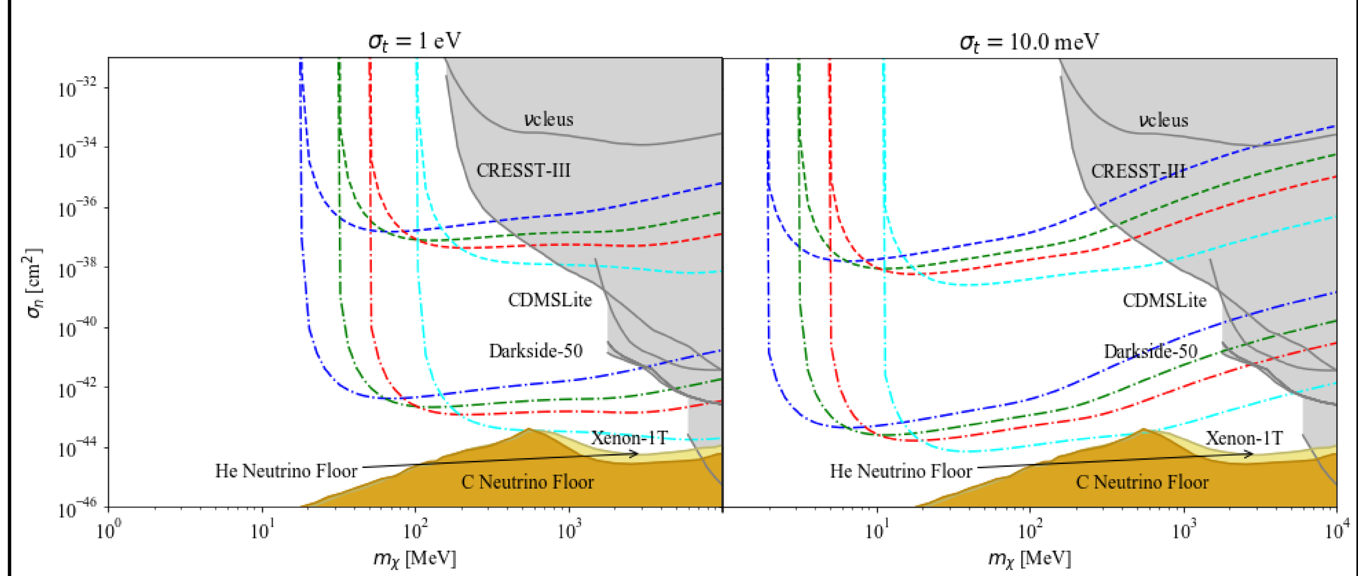
Estimated phonon mean free path for a cm-sized crystal using the Callaway model.



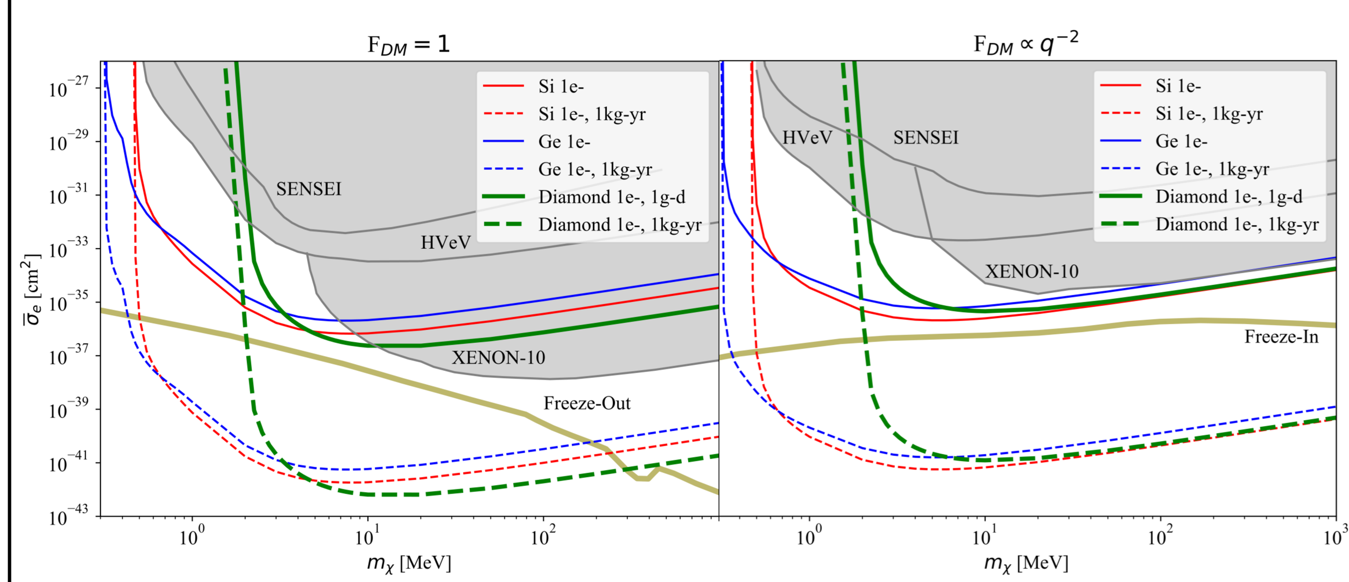
Resolution scaling of proposed designs for SuperCDMS-style diamond detectors. See **[5]**.

DM Sensitivity Limits

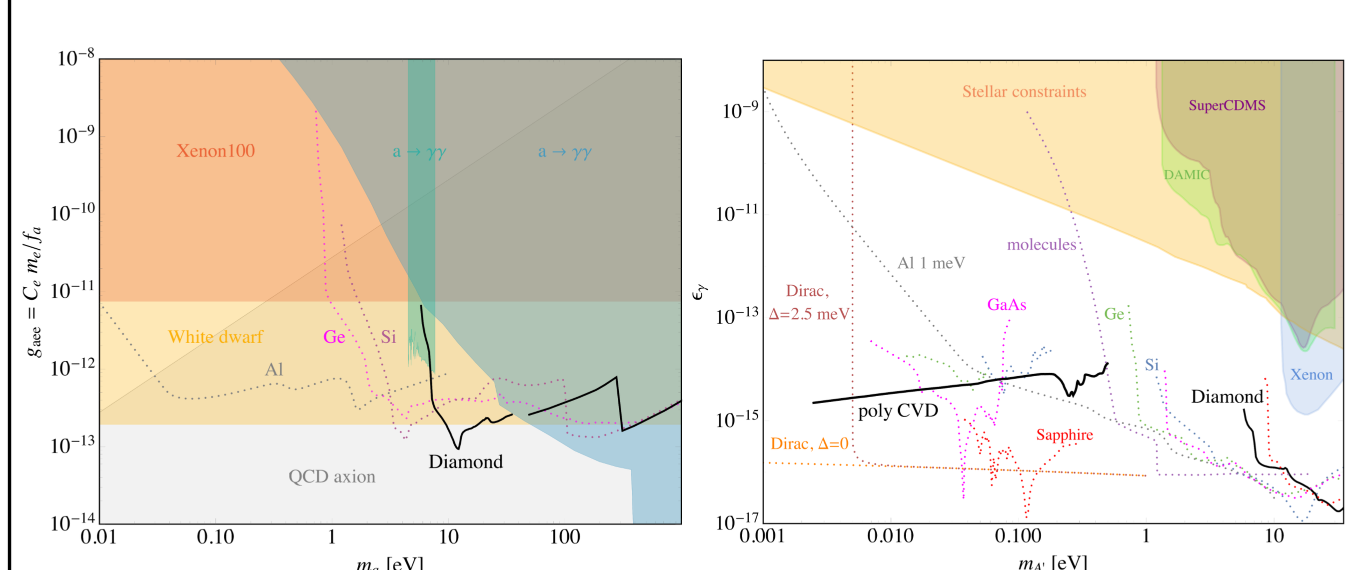
Below are the background-free limits of high-purity CVD diamond detector for various DM searches: **[5]**



Nuclear recoil limits for He (blue), diamond (green), Si (red), and Ge (cyan).



Electron recoil limits for heavy (left) and light (right) mediators.



Absorption limits for ALP (left) and heavy photons (right).

Backgrounds

Carbon-14 Impurity

Natural carbon contains 1 ppt of radioactive C14 which will be a main source of background. However, via isotopic purification of the methane gas used in the CVD process it is possible to achieve C14 ratio ~ 10^{-21} **[4]**, which corresponds to 10 ev/kg-yr.

Sub-gap excitations

Dark rates due to e.g. thermal excitation of shallow sites and crystal defects is another intrinsic background. However these are suppressed by the large bandgap and the deep impurity wells in diamond.

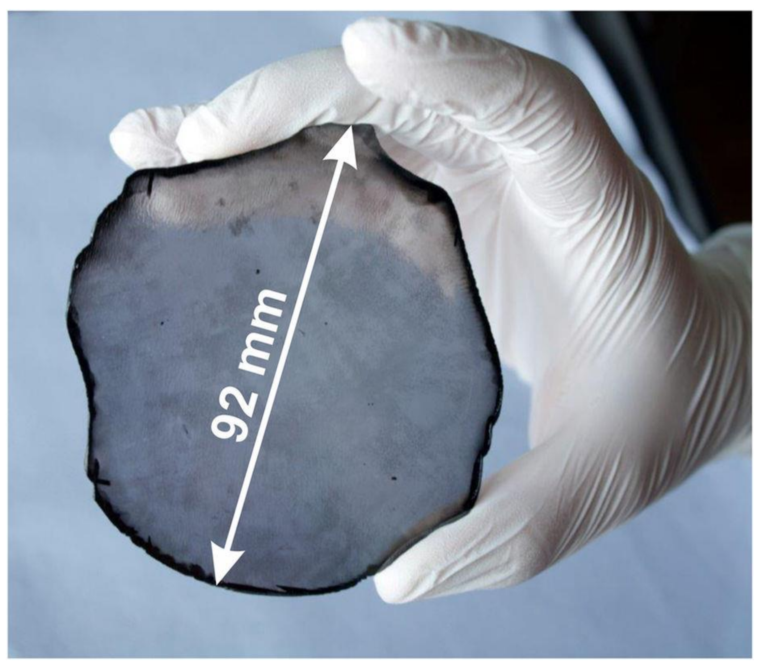
Compton Recoils

High energy radiation from environment can produce small energy deposits via Compton recoil off electrons. However due to the high bandgap of diamond such ER background has a high energy threshold and can be boosted beyond range of NR signal via high electric field to achieve separation of the NR signal and any ER background.

In addition, carbon has fewer electrons per nucleon. Thus the S/B ratio will also be higher than heavier elements.

All in all, we expect high-purity diamond substrates to have a relatively low background level.

Physical Properties	Diamond	Si	Ge
Debye Temp. (K)	2220	645	374
Bandgap (eV)	5.47	1.12	0.54
Pair creation energy (eV)	13	3.6	3
Speed of sound (m/s)	13360	5880	3550
Breakdown field (MV/cm)	20	0.3	0.1
Charge Impurities (Binding energy in meV)	N(1700) N(4000) P(500) Li(230) B(370)	N(15-50) P(45) Li(33) B(45)	P(12) Li(9.3) B(10)



Large CVD diamond wafer synthesized in **[6]**.

[1] Isberg, J. et al. *Science* 297.5587 (2002): 1670-1672.
[2] Nava, F., et al. *Solid State Communications*33.4 (1980): 475-477.
[3] Inyushkin, A. V., et al. *Physical Review B* 97.14 (2018): 144305.
[4] Litherland, A. E., et al. *AIP Conference Proceedings*. Vol. 785. No. 1. AIP, 2005.
[5] Kurinsky, N., et al. *Physical Review D* 99.12 (2019): 123005.
[6] Schreck, Matthias, et al. Scientific reports 7 (2017): 44462.

Conclusions

Diamond-based detectors have the potential to contribute to the next generation of dark matter experiments due to its various merits. Diamond offers exceptional phonon properties as well as better control over various backgrounds. Further details are in **[5]**.

One final practical concern is the cost of synthesizing high-purity CVD diamond at a kilogram level. As it stands the cost of 1 kg of jewelery-grade CVD diamond is roughly equal to the cost of the Xenon procured for LZ. However, in recent years we have seen major growth in CVD diamond industry driven by large inflow of investment from quantum computing initiatives and power electronics industry. It is believed the cost of high-quality diamond crystals will soon be cheap enough to allow kg-scale DM experiment using diamond substrate detector arrays.

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