Semiconductor Targets for Direct Detection Experiments

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Physics 290e

Searching for Light Dark Matter

- New paradigm: Search everywhere, not just for WIMPS!
- **Plenty of sub-GeV DM Models to Probe**: MeV dark matter, WIMPless miracle DM, bosonic super-WIMP, GeV hidden sector dark matter, asymmetric DM, freeze-in DM, Strongly Interacting Massive Particles....
- *Light* Dark Matter (LDM) ~ keV to GeV mass range
- A time for new ideas, experiments, detection technologies!

Nuclear Recoils (Traditional)

CDMS, CRESST, DAMA/LIBRA, DAMIC, LUX, SABRE....

Elastic Nuclear Recoil Energy Transferred:

$$\Delta E \leq \frac{\Delta P^2}{2M_N} \longrightarrow \Delta E \leq \frac{2m_{DM}^2 v_{DM}^2}{M_N}$$

100 MeV DM – He Nucleus scattering → ~ 1 eV detectable energy (below current detector thresholds)

Total energy is much larger → Elastic nuclear scattering inefficient for LDM

$$E_{tot} = \frac{1}{2} m_{DM} v^2 \simeq 50eV \times \frac{m_{DM}}{100MeV}$$

New Ways to do Direct Detection

- Superconductors
- Dirac materials

order meV gaps

- Multi-excitation production in superfluid helium
- Single phonon and magnon excitations in crystals
- **Electron transitions in atoms and semiconductors**

Target Comparison Study of 24 Crystal Materials (arXiv:1910.10716)

- What types of **excitations** can be used as efficient detection paths?
- What **materials** have the strongest response to DM scattering?

Three Main Detection Channels

- Nuclear Recoils
  - Best for > 100 MeV mass DM
- **Electron Transitions across band gaps in crystals**
  - **Best for < ~ 100 MeV down to ~ 100 keV**
- Single phonon excitations in crystals
  - Reaches lower masses ~ keV mass DM

Small Band Gap → Low Mass Reach

- Low bandgaps of order 1 eV → Low threshold for ionization/excitation to conduction band
  - Silicon 1.1 eV
  - Germanium 0.67 eV
  - Diamond 5.47 eV
  - Gallium Arsenide 1.42 eV
  - **Indium Antimonide** 0.17 eV (**0.24 eV** at “low temperature”)
- Lowest DM masses possible set by

$$m_\chi v_{max}^2/2 > E_g \longrightarrow m_\chi \sim 0.3 MeV \frac{E_g}{eV}$$

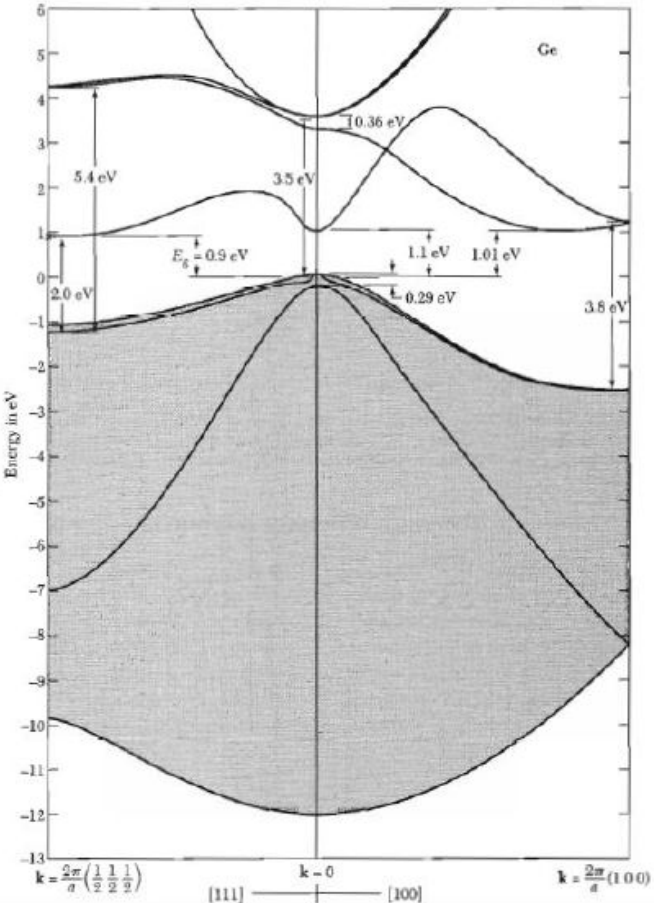
→ Lightest DM mass sensitivity possible for Germanium ~ 200 keV

Aside: Direct versus Indirect Gap Semiconductors

- **Direct gap:** Electron transition from valence band to conduction band changed **potential energy**
- **Indirect gap:** Electron transition from valence band to conduction band changes **potential energy** and **momentum**

- E_g should be replaced with the minimum kinematically allowed energy difference

- Germanium (indirect gap) actually has worse reach than Silicon



Theoretical Framework

- Calculate scattering rates (complicated)
  - Electrons moving fast
  - Have Indefinite momentum
  - Complicated Energy Level Structure

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int dv^3 f_\chi(v)\Gamma(v) \qquad \Gamma(v) = \frac{\pi\bar{\sigma}}{\mu^2}\int \frac{d^3q}{(2\pi)^3}\mathcal{F}^2_{med}(q)S(q,\omega_q)$$

$$S(q,\omega_q) = \frac{1}{V}\sum_f |\langle f|\mathcal{F}_T(q)|i\rangle|^2 2\pi\delta(E_f - E_i - \omega)$$

Evaluate S for each detection channel

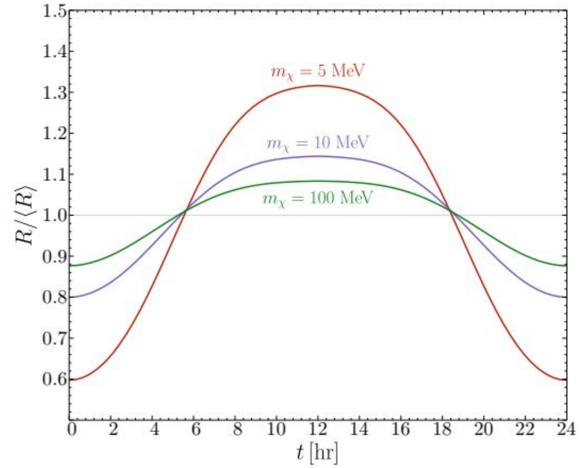
- Electron Transitions:
  - Found by calculating a whole bunch of Bloch wavefunctions using density functional theory
  - Generally not isotropic in q

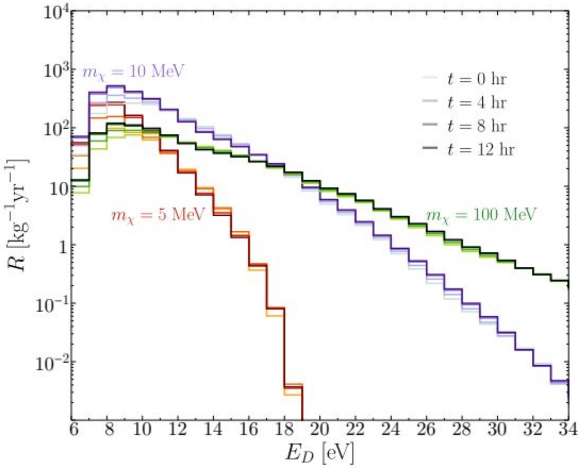
Dark Matter “Wind”

- Simplest crystal targets (Si, Ge) quite isotropic
  - Rate independent of incoming DM velocity

- As the target rotates with Earth, the DM wind incoming velocity comes from different directions
  - Daily modulation of the rate
  - Distinct modulation from backgrounds!

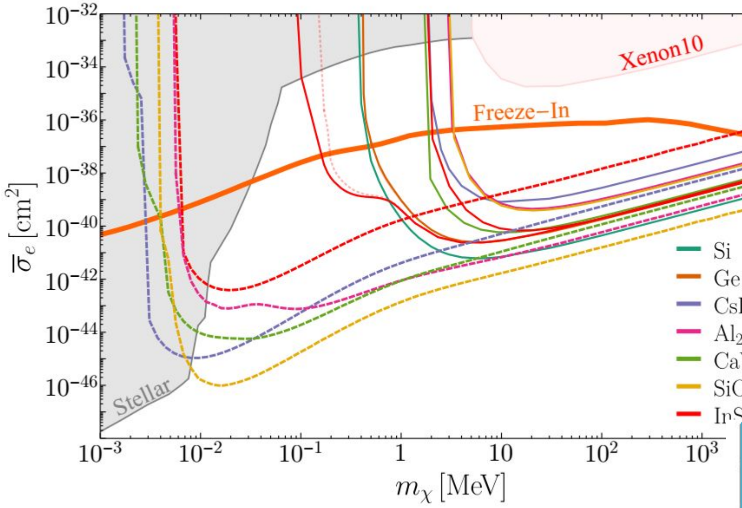
- Example: Boron Nitride has layered crystal structure → highly anisotropic
  - 10-40% rate modulation
  - Greater modulation for smaller energy depositions, greater anisotropies near the band gap





arxiv:1910.08092

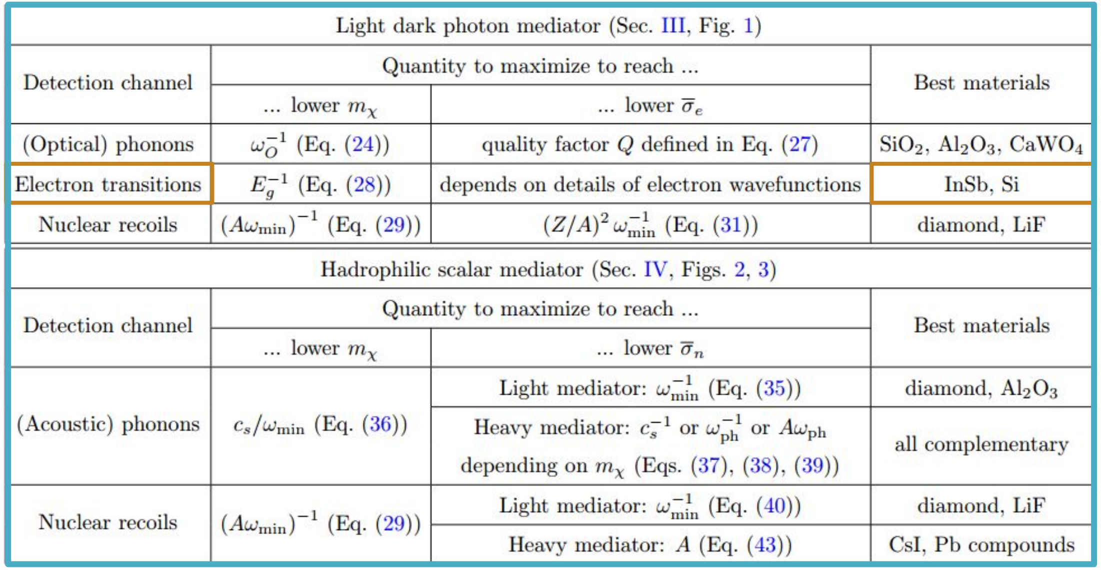
Best Materials for Electron Signal Path



DM scattering mediated by a kinetically mixed light dark photon

Dashed: Single phonon excitations
Solid: Electron transitions

They highlight SiO_2 and InSb as particularly sensitive to this benchmark model



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	$(A\omega_{\rm min})^{-1}$ (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

Table II. Summary of our results. The material properties relevant for the optimization of target are: atomic mass number A, proton number Z, electronic band gap E_g, speed of sound c_s, optical phonon energy ω_O, average phonon energy $\omega_{\rm ph}$, as well as Born effective charges and the high-frequency dielectric constant that enter the quality factor Q. Achieving lower detector energy thresholds $\omega_{\rm min}$ is also crucial in several cases.

Single Electron Hole Pair Detection

In order to achieve these low-mass thresholds, need to detect single electron-hole pairs

ZEPLIN-II and XENON10: Amplification by drifting electrons through gas-phase xenon producing scintillation light

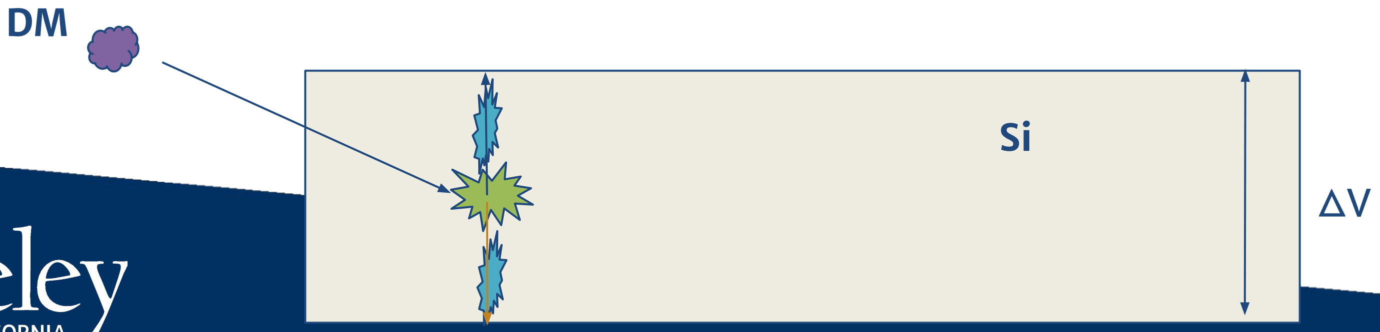
Semiconductor Targets: Amplification by drifting electrons across crystal producing phonons **OR** really accurate charge measurement

All Experiments: Apply an electric field across detector to drift electrons to readout

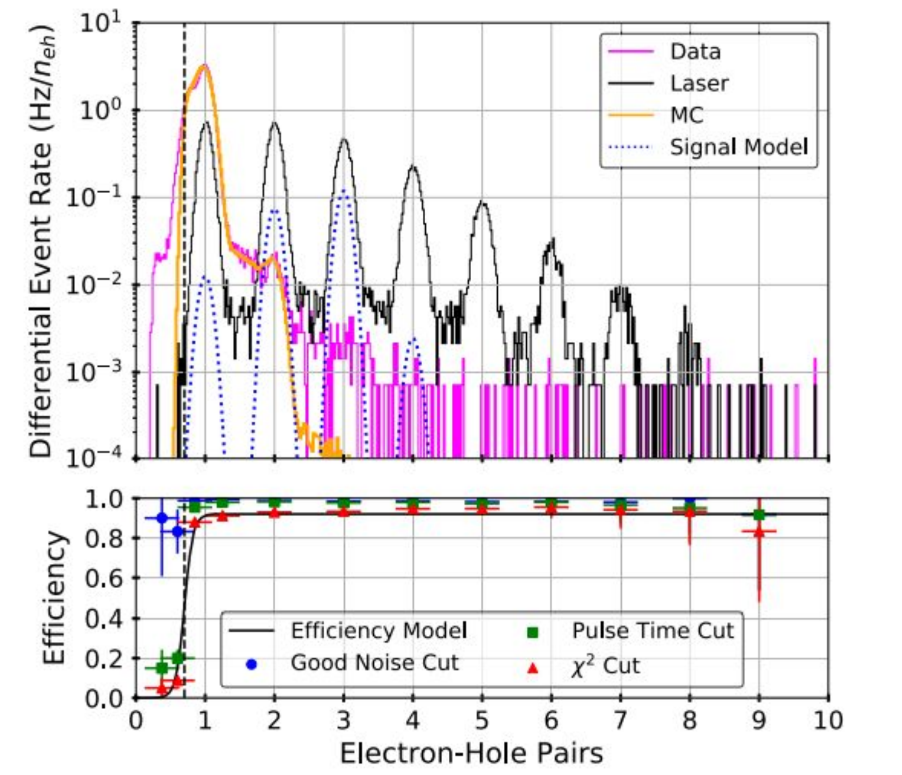
SuperCDMS HVeV Detector: Luke-Neganov Gain

- 0.93 gram **Silicon** target
- Luke-Neganov Gain:
  - total phonon energy: $E_{total} = E_{recoil} + N_{eh} e \Delta V$

- Instrumented with phonon sensors and electrodes
- Phonon sensors have thermal noise → Operated at ~40mK temperatures



SuperCDMS HVeV Detector: Energy Spectrum and Charge Leakage

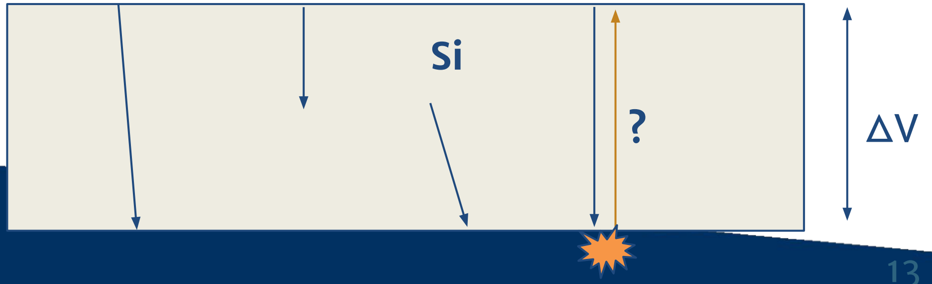


Simple background model of bulk and surface charge leakage with impact ionization fits data below 2eh pairs

But the amount of 2eh pairs is non-Poissonian

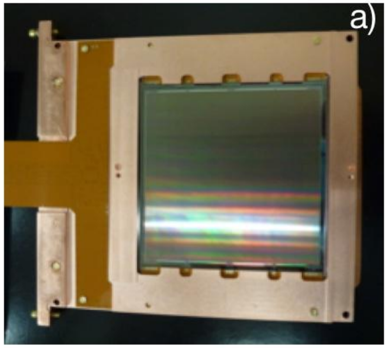
- Impact ionization?
- Transport Physics?
- Scintillation of surrounding materials?

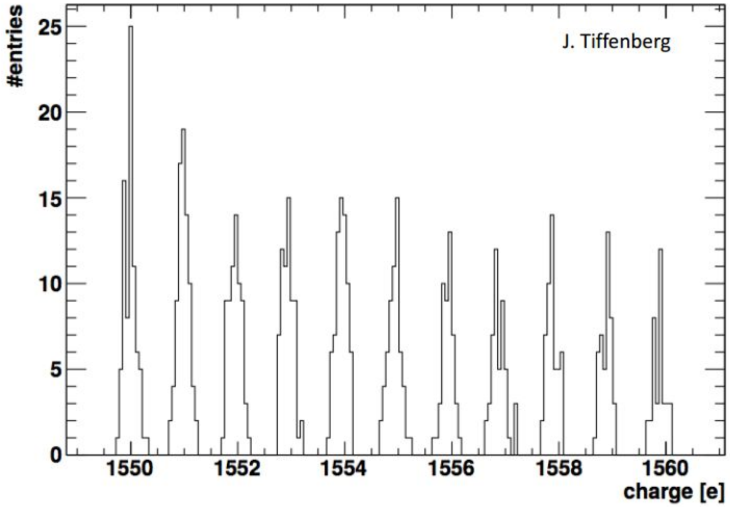
Charge leakage mostly near outer radius



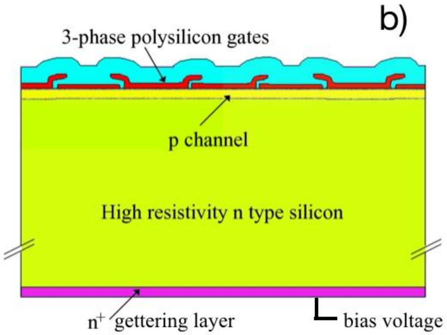
DAMIC/SENSEI

- Typical CCD sensors use photoelectric effect to absorb incident photons in a Si substrate and generate eh pairs
- Uses Skipper CCDs to detect nuclear + electron recoils in **Silicon**





- Operated at 140 K
- 675 um thick
- 70V applied

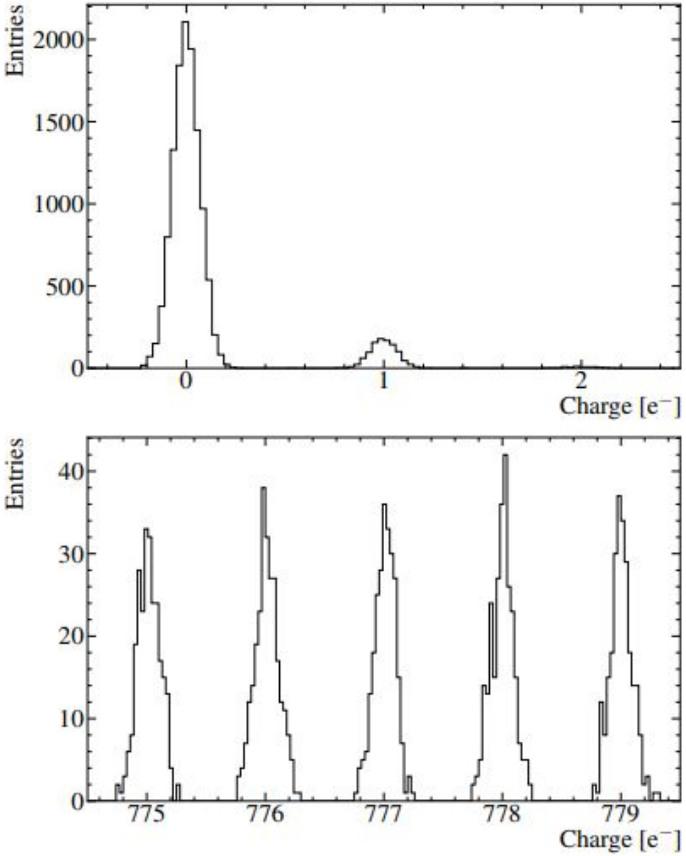


DAMIC/SENSEI: Electronic Recoils in CCDs

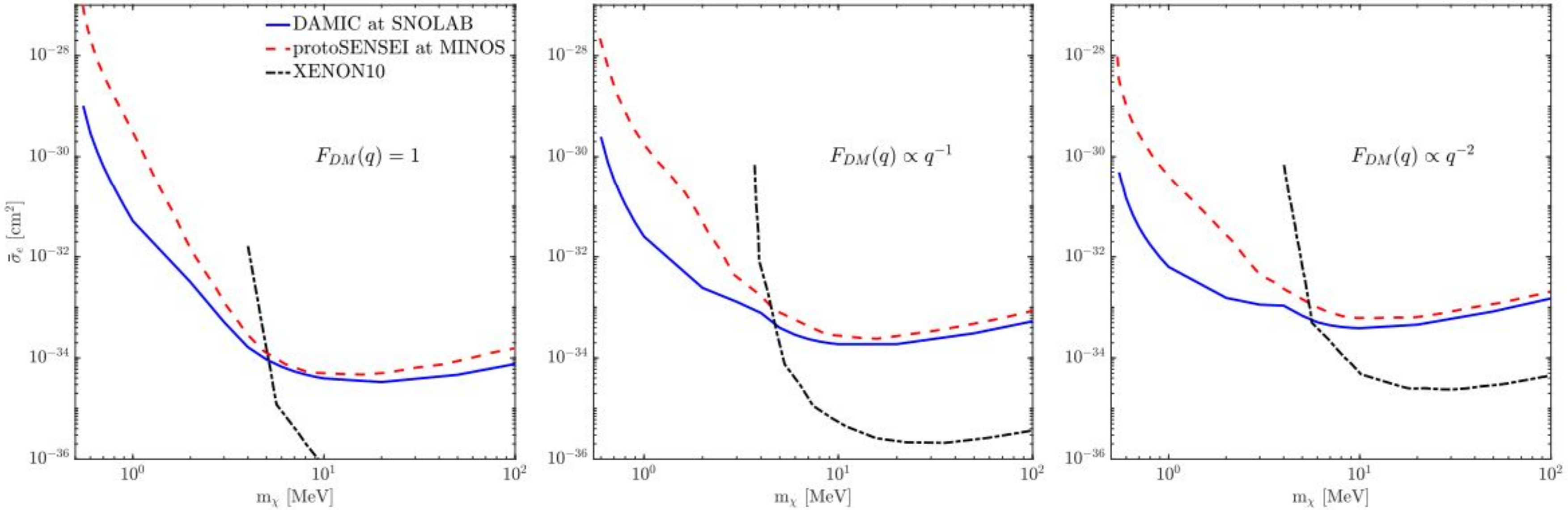
- Low-frequency readout noise has been a fundamental limit on single-electron counting
- → "Skipper" CCD Readout Technology
  - N-samples:

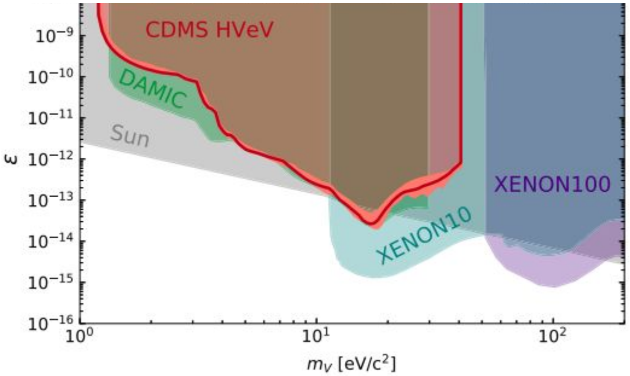
$$\sigma \rightarrow \frac{\sigma}{\sqrt{N}}$$

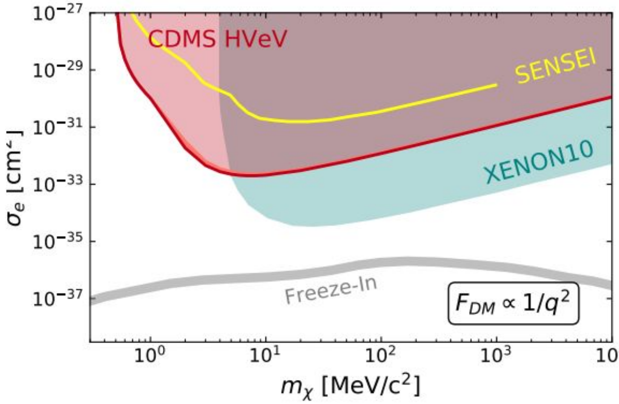
- **Constraints on hidden-photon DM with masses 1.2-30eV**
- **Constraints on DM masses of ~500 keV - 4 MeV**

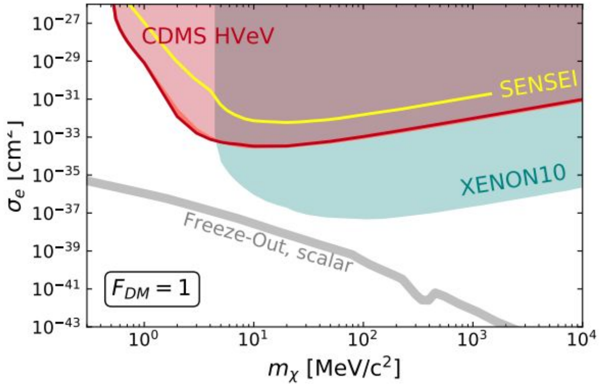


Limits


DAMIC at SNOLAB
protoSENSEI at MINOS
XENON10
$F_{DM}(q) = 1$
$F_{DM}(q) \propto q^{-1}$
$F_{DM}(q) \propto q^{-2}$
$\bar{\sigma}_e$ [cm^2]
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{0}
10^{1}
10^{2}
m_χ [MeV]


CDMS HVeV
DAMIC
Sun
XENON100
XENON10
ε
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{0}
10^{1}
10^{2}
m_V [eV/c^2]


CDMS HVeV
SENSEI
XENON10
Freeze-In
$F_{DM} \propto 1/q^2$
σ_e [cm^2]
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
m_χ [MeV/c^2]


CDMS HVeV
SENSEI
XENON10
Freeze-Out, scalar
$F_{DM} = 1$
σ_e [cm^2]
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
m_χ [MeV/c^2]

Papers

arxiv:1910.10716 (Target Comparison)
arxiv:1911.11905 (SuperCDMS axion+dark photon search)
arXiv:1804.10697 (SuperCDMS Electron scattering and dark photon absorption CDMS HVeV)
arXiv:1203.2531 (Semiconductors Proposed)
arxiv:1108.5383 (Semiconductors Proposed)
arxiv:1509.01598 (Numerical Calculation of Scattering Rates – Expands on arXiv:1108.5383)
arxiv:1910.08092 (Theoretical Framework for Direct Detection Rates)
arxiv:1607.01009 (Scintillating Targets)

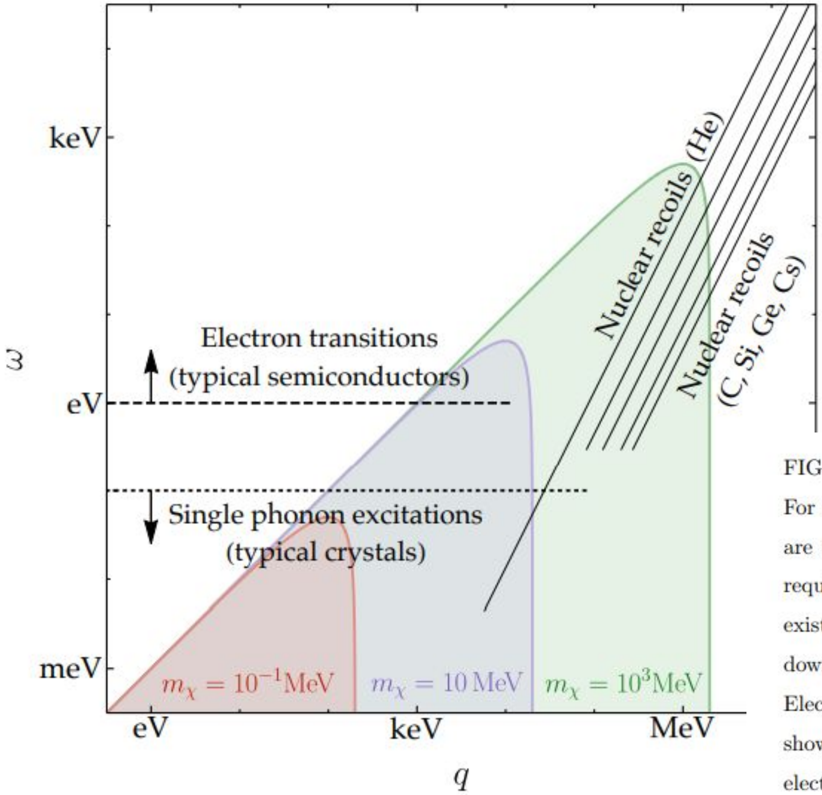
Other Experiments

DarkSide-50: DM Electron Scattering in Liquid Argon target. Readout: 38 3 inch PMTs.

Dedicated LDM searches in other dual-phase noble liquid experiments such as XENON100 and LUX

XENON10

Kinematic Regimes



arxiv.org:1910.08092 Fig 1

FIG. 1. Illustration of kinematic regimes probed via the three detection channels considered in this paper. For an incoming DM particle with velocity $v = 10^{-3}$, the momentum transfer q and energy deposition ω are bounded by $\omega \leq qv - q^2/2m_\chi$, shown by the shaded regions for three DM masses. Nuclear recoils require $\omega = q^2/2m_N$ for a given type of nucleus, shown by the solid lines for helium and several elements in existing or proposed crystal targets. Standard calculations assuming scattering off individual nuclei break down below a few meV (a few hundred meV) for superfluid He (crystal targets), where we truncate the lines. Electron transitions can be triggered for ω above the band gap, which is $\mathcal{O}(\text{eV})$ for typical semiconductors, as shown by the dashed line. The end point at $q \sim 10\,\text{keV}$ corresponds to a few times αm_e, above which valence electron wavefunctions are suppressed, and only (semi-)core electrons can contribute (which requires ω to be much higher than the band gap). Single phonon excitations are relevant for $\omega \lesssim \mathcal{O}(100\,\text{meV})$ in typical crystals, as shown by the dotted line. The momentum transfer can be up to $q \sim \sqrt{m_N \omega_{\text{ph}}} \sim \mathcal{O}(100\,\text{keV})$ with ω_{ph} the phonon energies, above which the rate is suppressed by the Debye-Waller factor. We see that a GeV-mass DM can be probed by all three channels; a 10 MeV DM is out of reach in conventional nuclear recoil searches, but can be searched for via electron transitions in semiconductors and single phonon excitations in crystals; a sub-MeV DM cannot even trigger electron transitions in eV-gap materials, but can still be detected via single phonon excitations.

SuperCDMS Axion and Dark Photon Search

Electron recoils in germanium “dark absorption”

Used CDMSlite data for lower masses and iZIP dater for higher masses

Constraints on axioelectric coupling of axion–like particles and the kinetic mixing parameter of dark photons

Signal: peak in the recoil spectrum at the rest mass of the particle

Did not model or subtract the background → only set upper limits on dark absorption rates

Covers the mass range 40 eV – 500 keV

Backgrounds

- Low-energy electron recoils from small-angle Compton scattering of external gamma rays
- Fast neutrons
- High Voltage: charge leakage

Future Experiments: Scintillating Targets

Proposal to use GaAs and a scintillation signal

No electric field required to detect the photons → no charge leakage