New Backgrounds and New Ideas for
Sub-GeV Dark Matter Direct Detection

Peizhi Du
C.N. Yang Institute for Theoretical Physics

NHETC Seminar
Rutgers University
March 15, 2022

in collaboration with Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (PRX 12, 011009)
Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (in progress)
Daniel Egana-Ugrinovic, Rouven Essig, Miguel Sofo Haro, Mukul Sholapurkar and Javier Tiffenberg (in progress)
Dark Matter

- 80% of matter, 25% total energy density in the Universe
- Evidence for dark matter is currently only gravitational

Particle nature is unknown, a wide range of DM masses are allowed
Sub-GeV dark matter

- Fuzzy DM
- QCD Axion
- Sub-GeV DM
- WIMP
Sub-GeV dark matter

- Dark Photon model:
  \[ \mathcal{L} \supset -\frac{1}{4} F^{\mu \nu} F_{\mu \nu} - \frac{k}{2} F^{\mu \nu} F_{\mu \nu} + \frac{1}{2} m_A^2 A'^{\mu} A'^{\mu} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Detection method</th>
<th>Relic abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark photon as mediator</td>
<td>DM-electron scattering</td>
<td>freeze-in mechanism</td>
</tr>
<tr>
<td>Dark photon dark matter</td>
<td>DM absorption</td>
<td>gravitational production during inflation</td>
</tr>
</tbody>
</table>
Direct detection of sub-GeV DM

**Electron recoils**

Access to whole kinetic energy:

\[ E_{ER} \approx \frac{1}{2} m_X v^2 \approx 1 \text{ eV} \left( \frac{m_X}{0.5 \text{ MeV}} \right) \]

<table>
<thead>
<tr>
<th>Target</th>
<th>Signal</th>
<th>Threshold</th>
<th>DM Mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble Liquid</td>
<td>electron ionization</td>
<td>(~10 \text{ eV}) (atom ionization)</td>
<td>(&gt;10 \text{ MeV})</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>eh pairs</td>
<td>(~1 \text{ eV}) (bandgap)</td>
<td>(&gt;\text{MeV})</td>
</tr>
</tbody>
</table>
Direct detection of sub-GeV DM

![DM-electron scattering](image)

![Dark photon absorption](image)
Q1: Excess events are observed at current sub-GeV DM detectors. What is the origin of those events?

Q2: Can we probe sub-MeV (sub-eV) DM?
Outline of the talk

Part I   Unexplored low-energy backgrounds at sub-GeV DM detectors

Excesses at current sub-GeV DM detectors. Unexplored new backgrounds!

Part II   New targets for probing sub-MeV DM

Doped semiconductors as new targets with $O(10-100)$ meV threshold

Probing light DM: low threshold detectors and low backgrounds
Part I  Unexplored low-energy backgrounds at sub-GeV DM detectors
Excess in sub-GeV dark matter detectors

- Excess events are near the threshold
- Cannot be explained by known sources
- Limits the sensitivity for dark matter detection
Unexplored low energy backgrounds

Cherenkov radiation and radiative recombination photons are likely to explain the excess

Cherenkov radiation inside detector
Radiative recombination inside detector
Cherenkov radiation from holders

⇒ SENSEI excess
⇒ SuperCDMS HVeV excess

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020
Unexplored low energy backgrounds

Why these backgrounds haven’t been studied before?

- Not the usual high energy radioactivity backgrounds
- First generation of experiments of sub-eV resolution
- Challenging to identify them: events in the signal region
Cherenkov Radiation

Incident charge is moving faster than the speed of light inside the medium.

\[ \frac{d^2 N}{d\omega dx} = \alpha \left( 1 - \frac{\text{Re} \epsilon(\omega)}{v^2|\epsilon(\omega)|^2} \right) \]

Conditions:

\[ v^2 \text{Re} \epsilon(\omega) > 1 \]

\[ \epsilon = (n + ik)^2 \]

\[ \cos \theta_{Ch} = \frac{\sqrt{\text{Re} \epsilon(\omega)}}{v|\epsilon(\omega)|} \]
Cherenkov Radiation in semiconductors

Cherenkov spectrum:

\[ \omega \lesssim 4 \text{ eV} \]

Near bandgap/detection threshold

Typical rate:

\[ \frac{d^2 N}{d\omega dx} \sim \alpha \quad (\text{for } \epsilon(\omega) \gg 1) \]

\[ N \sim 40 \left[ \frac{\Delta \omega}{1 \text{ eV}} \right] \left[ \frac{\Delta x}{1 \text{ mm}} \right] \]

Significant rate for dark matter detection
Electron-hole recombination

Radiative recombination

\[ \Gamma_{\text{rec}}^e \propto n_e n_h \]

- Emitted spectrum near bandgap
- Significant for high carrier concentration (doped silicon)
- For 100 keV energy deposit and \( n_e = 10^{18} \text{ cm}^{-3} \)

\[ N_\gamma = N_e \frac{\tau_{\text{tot}}}{\tau_{\text{rad}}} \approx 200 \]

Ruff, Fick, Lindner, Rossler, Helbig, 1993
SENSEI experiment

- Look for electron-hole pairs in skipper CCD, ~0.1 e⁻ resolution
- **Location**: MINOS cavern at Fermilab, 104 m underground
- **CCD**: Excellent spatial resolution  Limited timing resolution
SENSEI experiment

SENSEI image (half of one quadrant)

- 1e events
- Electrons
- X ray
- Muons
SENSEI experiment

SENSEI image (half of one quadrant)

- Muons
- Electrons
- X ray
- 1e events
- Analysis cut: Halo mask
Single electron event excess

- The rate is correlated with high energy background event rate
- Has spatial correlation with high energy events
- Extends to 60 pixels away and the rate becomes flat: 450 events/g-day
Cherenkov radiation in SENSEI

Charged particles

\[ \theta_{\text{Ch}} \]

Cherenkov photons

CCD

1 e events
Cherenkov radiation in SENSEI

Cherenkov photons

\[ \omega \text{ [eV]} \]

135 K

10 cm
60 pixels
1 pixel

Rakanan, Sinhg, Shewchun, 1979

\[ E_k = 250 \text{ keV} \]
\[ E_k = 500 \text{ keV} \]

5 pixels
30 pixels
60 pixels

\[ N_\gamma (\text{per electron track}) \]

\[ \ell_r [\mu \text{m}] \]

Peizhi Du (Stony Brook) | Rutgers NHETC Seminar
Radiative recombination in SENSEI

- ~5 μm of highly doped region ($n_e \geq 10^{17}/cm^3$)
- Significant contribution to 1e events from radiative recombination
Simulation results (preliminary)

SENSEI image

High energy tracks

PD, Egana-Ugrinovic, Essig, Sholapurkar, (in prep)
Simulation results (preliminary)

SENSEI image

High energy tracks + Cherenkov + Radiative recombination

PD, Egana-Ugrinovic, Essig, Sholapurkar, (in prep)
Excess at SuperCDMS HVeV

- Independent of voltage
- Single electron events are likely to come from leakage current
- The origin of 2-6 electron events are unknown

<table>
<thead>
<tr>
<th>HVeV Rates (g-day)$^{-1}$</th>
<th>100 V</th>
<th>60 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>$(149 \pm 1)10^3$</td>
<td>$(165 \pm 2)10^3$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>$(1.1 \pm 0.1)10^3$</td>
<td>$(1.2 \pm 0.2)10^3$</td>
</tr>
<tr>
<td>$R_3$</td>
<td>$207 \pm 40$</td>
<td>$245 \pm 86$</td>
</tr>
<tr>
<td>$R_4$</td>
<td>$53 \pm 20$</td>
<td>$77 \pm 48$</td>
</tr>
<tr>
<td>$R_5$</td>
<td>$16 \pm 11$</td>
<td>$20 \pm 25$</td>
</tr>
<tr>
<td>$R_6$</td>
<td>$5 \pm 6$</td>
<td>$10 \pm 17$</td>
</tr>
</tbody>
</table>

SuperCDMS, 2020
Cherenkov radiation at SuperCDMS HVeV

Tracks hitting detectors

Can be vetoed by timing information

Tracks hitting PCBs, connectors

Cannot be vetoed

e, μ
Estimation of Cherenkov events

\( f \): efficiency of a Cherenkov photon being recorded at the detector

**Best fit:** \( f \approx 1.6 \times 10^{-3} \)

- Small \( f \) indicates a lot of Cherenkov photons generated
- One parameter fits the spectrum for 2-6 electron events

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020
Mitigation strategies

- Active and passive shielding
- Radio-pure materials
- Multiple detectors (remove coincident events)

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020
Mitigation strategies

- Active and passive shielding
- Radio-pure materials
- Multiple detectors (remove coincident events)
- Minimizing non-conductive/un-instrumented materials near detector
- Thinning the doped region of the CCD
- Reduce the reflectivity of inner copper wall

First proposed in our work

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020
Summary of part I

- Many sub-GeV dark matter experiments observe excess events
- **Cherenkov radiation** and **radiative recombination** are likely to explain the excess in SENSEI and SuperCDMS HVeV
- Several mitigation strategies can be applied to reduce these backgrounds
Part II  New targets for probing sub-MeV DM
Probing sub-MeV DM

<table>
<thead>
<tr>
<th>Target</th>
<th>Signal</th>
<th>Threshold</th>
<th>DM Mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nobel Liquid</td>
<td>electron ionization</td>
<td>~10 eV (atom ionization)</td>
<td>&gt;10 MeV</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>eh pairs</td>
<td>~1 eV (bandgap)</td>
<td>&gt;MeV</td>
</tr>
<tr>
<td>Polar materials</td>
<td>phonon</td>
<td>10-100meV</td>
<td>&gt;10-100 keV</td>
</tr>
<tr>
<td>Superconductor</td>
<td>phonon/quasiparticle</td>
<td>~1meV</td>
<td>&gt;1keV</td>
</tr>
</tbody>
</table>

Low threshold can probe low DM masses

Dirac materials, superfluid helium, Ge detector with charge amplification …

References:
- Hochberg, Zhao, Zurek, 2015
- Schutz, Zurek, 2016
- Knapen, Lin, Pyle, Zurek, 2017
- Hochberg, Kahn, Lisanti, Zurek, et.al, 2017
- D. M. Mei, et.al. 2017
## Probing sub-MeV DM

<table>
<thead>
<tr>
<th>Target</th>
<th>Signal</th>
<th>Threshold</th>
<th>DM Mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nobel Liquid</td>
<td>electron ionization</td>
<td>~10 eV (atom ionization)</td>
<td>&gt;10 MeV</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>eh pairs</td>
<td>~1eV (bandgap)</td>
<td>&gt;MeV</td>
</tr>
<tr>
<td>Polar materials</td>
<td>phonon</td>
<td>10-100meV</td>
<td>&gt;10-100 keV</td>
</tr>
<tr>
<td><strong>Doped Semiconductors</strong></td>
<td>phonon/ electron ionization/ eh pairs</td>
<td>10-100meV</td>
<td>&gt;10-100 keV</td>
</tr>
<tr>
<td>Superconductor</td>
<td>phonon/ quasiparticle</td>
<td>~1meV</td>
<td>&gt;1keV</td>
</tr>
</tbody>
</table>

**Doped semiconductors**

- Easy to get
- Rich signals
- Low threshold
- Good DM reach
Doped semiconductors

Donors in Silicon: P, As … (group V elements)
Acceptors in Silicon: B, Al … (group III elements)

Commonly used: p-n junction, diodes
Doped semiconductors

Donors in Silicon: P, As ...(group V elements)

Acceptors in Silicon: B, Al ...(group III elements)

Commonly used: p-n junction, diodes

Easy to get
Dopants in semiconductors

Dopants: “Hydrogen atoms” in a background with a large dielectric constant
Dopants in semiconductors

Dopants: “Hydrogen atoms” in a background with a large dielectric constant

\[ a^* \sim \left( \frac{\alpha}{\epsilon} m^* \right)^{-1} \sim O(10) a_0 \]

\[ q^* \sim a^*_0 \sim O(100) \text{ eV} \]

\[ v^* = \frac{q^*}{m^*} \sim 10^{-3} \]

\[ E_{\text{ionization}} \sim \frac{1}{2} \left( \frac{\alpha}{\epsilon} \right)^2 m^* \sim 10 - 100 \text{ meV} \]
Dopants in semiconductors

Dopants: “Hydrogen atoms” in a background with a large dielectric constant

For $\epsilon \sim 10$, $a_* \sim \left( \frac{\alpha}{\epsilon} m_* \right)^{-1} \sim O(10) a_0$, $q_* \sim a_*^{-1} \sim O(100) \text{eV}$

$E_{\text{ionization}} \sim \frac{1}{2} \left( \frac{\alpha}{\epsilon} \right)^2 m_* \sim 10 - 100 \text{meV}$
Dopant energy levels in silicon

Undoped Si

Conduction band

Valence band

$E_g \approx 1.2 \text{ eV}$
Dopant energy levels in silicon

Undoped Si

Conduction band

\[ E_g \approx 1.2 \text{ eV} \]

Valence band

Doped Si

Conduction band

\[ \text{P} \quad 45\text{meV} \quad E_{\text{ionization}} \]

\[ \text{As} \quad 54\text{meV} \]

Valence band

\[ \text{B} \quad 45\text{meV} \]

\[ \text{Al} \quad 67\text{meV} \]

n-type dopants

p-type dopants
Dopant energy levels in silicon

<table>
<thead>
<tr>
<th>Conduction band</th>
<th>Valence band</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n=4 )</td>
<td>( P ) 45,meV</td>
</tr>
<tr>
<td>( n=3 )</td>
<td>( P ) 45,meV</td>
</tr>
<tr>
<td>( n=2 )</td>
<td>( \text{As} ) 54,meV</td>
</tr>
<tr>
<td>( n=1 )</td>
<td>( \text{As} ) 54,meV</td>
</tr>
</tbody>
</table>

\[ E_n \sim \frac{E_{\text{ionization}}}{n^2} \]
Signals in doped silicon

Phosphorus doped Si @10K

$n_d = 0.34 \times 10^{18} \text{cm}^{-3}$

Gaymann, Geserich, Lohenysen, 95

Ionization (theory)

Full data

CB

$n=1$  $\downarrow e^-$  phonon

$n=2$  $\downarrow e^-$

CB  $\uparrow e^-$

electron
Signals in doped silicon

Phosphorus doped Si @10K

$n_d = 0.34 \times 10^{18} \text{cm}^{-3}$

Gaymann, Geserich, Lohenysen, 95

Phosphorus doped Si @10K

$n_d = 0.34 \times 10^{18} \text{cm}^{-3}$

Gaymann, Geserich, Lohenysen, 95

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$

Out$[57]=50$

Out$[61]=50$
Signals in doped silicon

Phosphorus doped Si @10K

\[ n_d = 0.34 \times 10^{18} \text{ cm}^{-3} \]

Gaymann, Geserich, Lohenysen, 95

Out[57]=

Out[61]=

Printed by Wolfram Mathematica Student Edition

Full data

Ionization (theory)

\( \alpha (\text{cm}^{-1}) \)

\( \omega (\text{meV}) \)

\( \omega (\text{meV}) \)

\( \alpha (\text{cm}^{-1}) \)

Rich signals

Signals in doped silicon

CB

VB

\( n=2 \)

\( n=1 \)

\( e^- \)

\( e^- \)

\( h^+ \)

\( \text{phonon from de-excitation} \)

\( \text{electron from ionization} \)

\( \text{e-h pair} \)
What is the optimal $n_d$ for DM searches?

**Metal-insulator transition**

Electrons are localized on dopants

**Insulating**

$e^-$

$n_d < n_c$

Good for DM searches

Electrons are delocalized

**Metallic**

$+ e^- + e^- + e^- + e^-$

$n_d > n_c$

Metallic targets have no gap, hard to control noise

$n_d > n_c$
What is the optimal $n_d$ for DM searches?

**Metal-insulator transition**

- Electrons are localized on dopants
  - Insulating
  - Good for DM searches
  - $n_d < n_c$
  - Distance between two dopants

- Electrons are delocalized
  - Metallic
  - Metallic targets have no gap, hard to control noise
  - $n_d > n_c$
  - Radius of dopant “hydrogen atom”

For Phosphorus doped Si: $n_c = 3.5 \times 10^{18} \text{cm}^{-3}$

We choose $1.8 \times 10^{18} \text{cm}^{-3}$ for DM reach projection
DM-electron scattering rate

\[ R \sim \int d^3 v f(v) \int d^3 q F^2(q) S(q, \omega_q) \]
DM-electron scattering rate

\[
R \sim \int d^3v f(v) \int d^3q F^2(q) S(q, \omega_q)
\]

DM Kinematics

\[
\omega_q = \frac{p^2}{2m_\chi} - \frac{(p - q)^2}{2m_\chi} = q \cdot v - \frac{q^2}{2m_\chi}
\]
Target response

\[ R \sim \int d^3v f(v) \int d^3q \, F^2(q) \, S(q, \omega_q) \]

\[ S(q, \omega_q) = \frac{q^2}{2\pi \alpha} \text{Im} \left[ \frac{-1}{\epsilon(q, \omega_q)} \right] \]

Energy loss function (ELF)

ELF of hydrogen atom ionization (45 meV threshold)

\[ \omega = \frac{q^2}{2m_*} \]
Target response

\[ R \sim \int d^3v f(v) \int d^3q F^2(q) S(q, \omega_q) \]

\[ S(q, \omega_q) = \frac{q^2}{2\pi\alpha} \text{Im} \left[ \frac{-1}{\epsilon(q, \omega_q)} \right] \]

Energy loss function (ELF)

For \( q < q_* \) in “hydrogen atom” model

\[ \text{Im} \left[ \frac{-1}{\epsilon(q, \omega_q)} \right] \approx \text{Im} \left[ \frac{-1}{\epsilon(\omega_q)} \right] \]

\( \epsilon(\omega) \) can be obtained directly from optical data

ELF of hydrogen atom ionization (45 meV threshold)
Target response

\[ R \sim \int d^3v f(v) \int d^3q F^2(q) S(q, \omega_q) \]

\[ S(q, \omega_q) = \frac{q^2}{2\pi \alpha} \text{Im} \left[ \frac{-1}{\epsilon(q, \omega_q)} \right] \]

Energy loss function (ELF)

For \( q < q^* \) in “hydrogen atom” model

\[ \text{Im} \left[ \frac{-1}{\epsilon(q, \omega_q)} \right] \approx \text{Im} \left[ \frac{-1}{\epsilon(\omega_q)} \right] \]

\( \epsilon(\omega) \) can be obtained directly from optical data

We use \( S(q, \omega_q) \approx \frac{q^2}{2\pi \alpha} \text{Im} \left( \frac{-1}{\epsilon(\omega_q)} \right) \)

good approximation for low mass DM with light mediators

ELF of hydrogen atom ionization (45 meV threshold)

Knapen, Kozaczuk, Lin, 2021
Hochberg, Kahn, Kurinsky, Lehmann, Yu, Berggren, 2021
ELF for different targets

Doped silicon has large target response over a wide energy range

Phosphorus doped Si @10K with $n_d=1.8 \times 10^{18}$ cm$^{-3}$

Doped Si

GaAs

phonons in pure Si

Al extrapolated

Hochberg, Zhao, Zurek, 2015
Knapen, Lin, Pyle, Zurek, 2017
Knapen, Kozaczuk, Lin, 2021
Hochberg, Kahn, Kurinsky, Lehmann, Yu, Berggren, 2021
DM-electron scattering rate with doped silicon

Light dark photon mediator (3 events/kg-yr)

\[ \sigma_\text{e} \text{[cm}^2\text{]} = 10^{-38} \text{ to } 10^{-44} \]

- Freeze-in
- Ionization
- Full
- Stellar
- ZrTe$_5$
- URu$_2$Si$_2$
- G$_2$As
- Al
- Electron
- Eh pair
- Phonon

PD, Egana-Ugrinovic, Essig, Sholapurkar, (in prep)
DM-electron scattering rate with doped silicon

Light dark photon mediator (3 events /kg-yr)

\[ \sigma_{\text{eff}} [\text{cm}^2] \]

- \( M_x [\text{MeV}] \)

- Stellar
- Freeze-in
- URu$_2$Si$_2$
- GaAs
- G$_2$As
- ZrTe$_5$
- Al

**Ionization**

**Full**

**Good DM reach**

PD, Egana-Ugrinovic, Essig, Sholapurkar, (in prep)
DM absorption rate with doped silicon

Dark photon absorption (3 events /kg-yr)

$$R \sim \kappa^2 m_{DM} \text{Im} \left[ \frac{-1}{\epsilon(m_{DM})} \right]$$

Peizhi Du (Stony Brook) | Rutgers NHETC Seminar
DM reach including backgrounds

Need a “background free” exposure of \(\sim\text{g-month} (1\text{e})\) or \(\sim\text{g-yr} (2\text{e})\) to probe freeze-in benchmark

Backgrounds maybe reduced by modeling Cherenkov/radiative recombination events

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020
Thoughts on experimental designs

PD, Egana-Ugrinovic, Essig, Sofo Haro, Sholapurkar, Tiffenberg (in prep)

For phonon signals:

- Doped semiconductor + TES

For charge signals:

- New CCD design with doped bulk material
- Single charge resolution, like Skipper CCD
- Two detectors may distinguish between electron ionization from dopants to eh pair creation
Summary of Part II

- Dopants in semiconductors can be thought as “Hydrogen atom” in a background with a large dielectric constant.
- Doped semiconductors can be detector targets with $O(10-100)$ meV threshold and have sensitivity over a wide range of DM masses: $>10$ keV for DM scattering and $>10$ meV for DM absorption.
Thank you
## Summary of current experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>Cherenkov contribution</th>
<th>Dominant Source of Cherenkov</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSEI</td>
<td>~100m underground</td>
<td>likely dominant with radiative recombination</td>
<td>ambient high energy particles hitting detector</td>
</tr>
<tr>
<td>SuperCDMS HVeV</td>
<td>surface</td>
<td>likely dominant</td>
<td>ambient high energy particles hitting holders</td>
</tr>
<tr>
<td>EDELWEISS</td>
<td>~1800m underground</td>
<td>subdominant</td>
<td>radioactivity from impurities in holders</td>
</tr>
<tr>
<td>CRESST</td>
<td>~1400m underground</td>
<td>vetoed, everything near the detector is instrumented</td>
<td>-</td>
</tr>
</tbody>
</table>

- Good spatial resolution
- Good timing resolution
- High ambient backgrounds
- Low ambient backgrounds

EDELWEISS and CRESST excess may dominantly come from crystal cracking/microfracture
Cherenkov radiation in SENSEI

- Cherenkov photons are generated inside CCD, pitch adapter and epoxy
- Cherenkov photons may be absorbed after several bounces at surfaces

↓

1e events far from the original track
SuperCDMS HVeV experiment

- HVeV detector measures electron-hole pairs via phonons (NTL effect)
- **Location**: on surface in Northwestern University
- HVeV detector has **0.03 e- resolution**, excellent time resolution
SuperCDMS @ SNOLAB

Well shielded, deep underground, clean environment

Cherenkov radiation from beta decays of impurities in holders (Cirlex clamps)

Potential events:

\[ N_{\text{Cirlex}} \sim 130/\text{day/tower} \]

much larger than previously estimated <100 eV backgrounds \(~0.1/\text{day/tower}\)

Figure from Ben Loer, DM 2018

Cirlex clamps

SuperCDMS SNOLAB, 2016