PREPARING FOR DM DISCOVERY, GOTHENBURG, 2018

BELINA VON KROSIGK (bkrosigk@physics.ubc.ca)

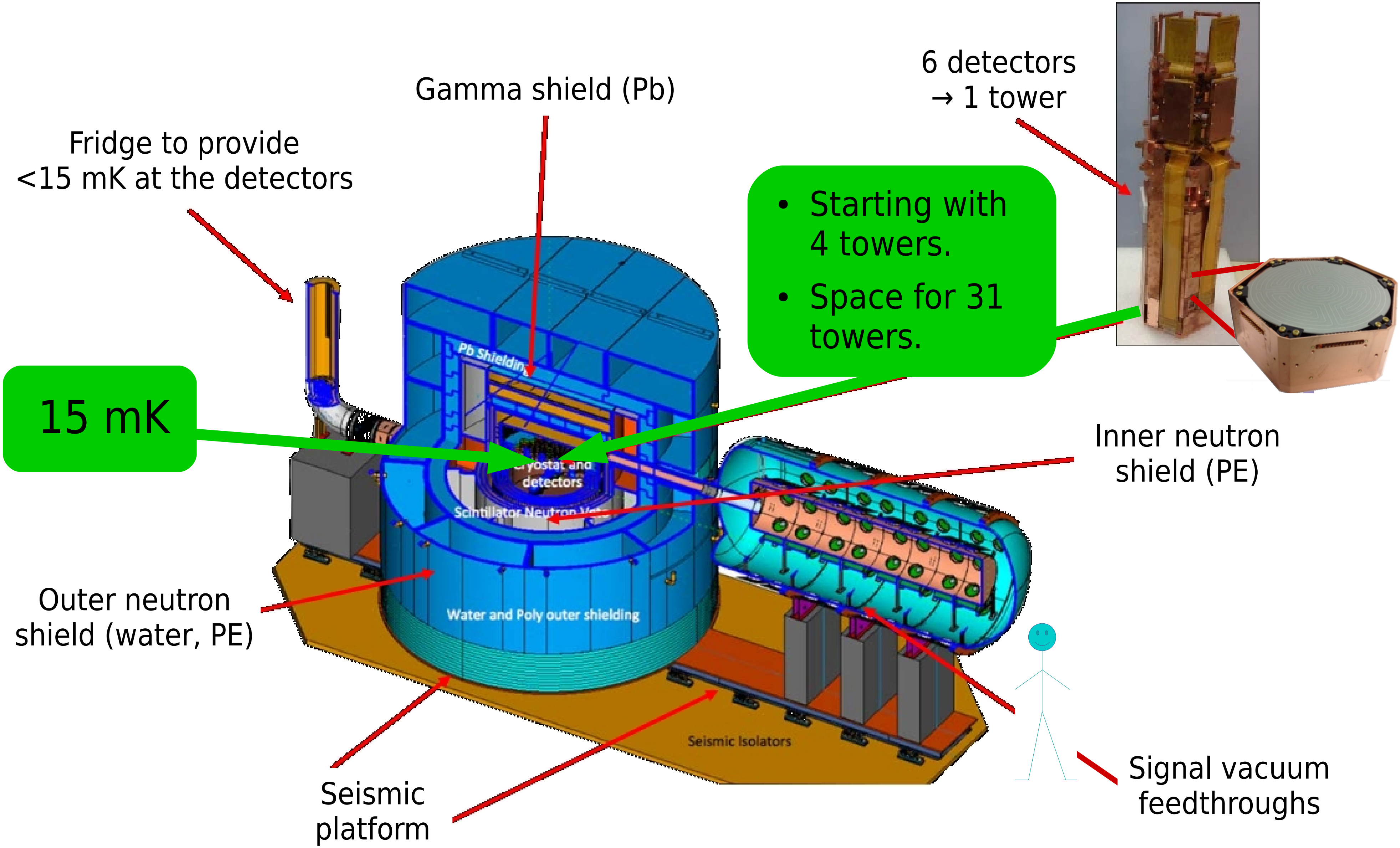
UNIVERSITY OF BRITISH COLUMBIA

First SuperCDMS DM Search Results using a Single e^-h^+ Pair Detector

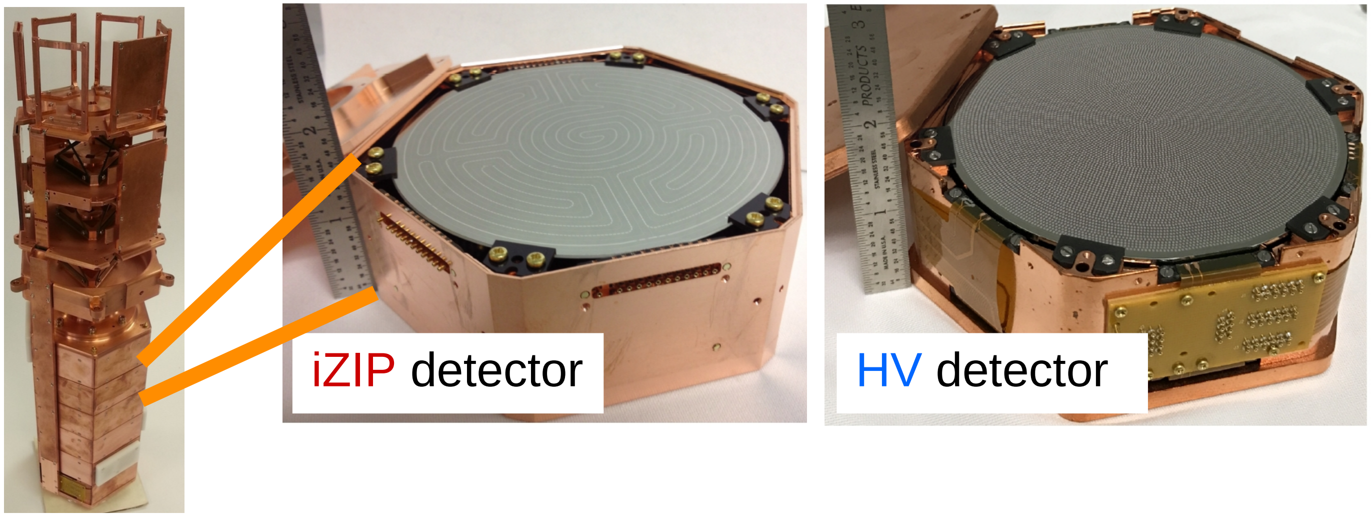
ON BEHALF OF THE SuperCDMS COLLABORATION

SuperCDMS DETECTOR TECHNOLOGY

THE SuperCDMS SNOLAB EXPERIMENT



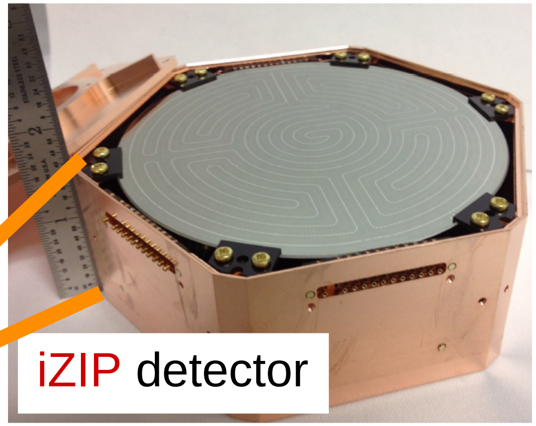
SuperCDMS DETECTORS

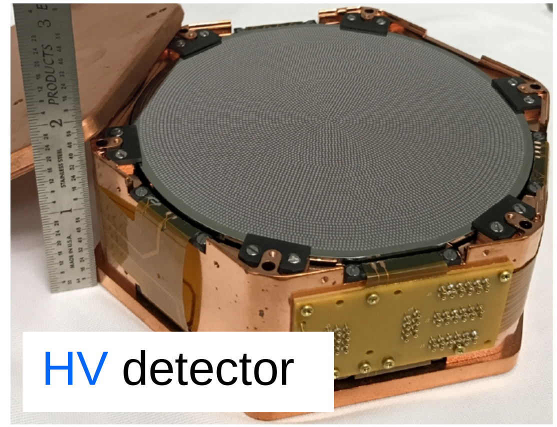


Ge detectors, 1.4 kg each.
Si detectors, 0.6 kg each.
Total: Ge: ~ 25 kg.
Total: Si: ~ 3.6 kg.

- High-purity Ge and Si crystals.
- Measurement of phonon signal via transition edge sensors.
- Bias voltage:
  - **iZIP**: < 10 V
    => Phonon + ionization signal
    => Nuclear / Electron Recoil discrimination.
  - **HV**: ~ 100 V
    => Phonon amplification of ionization signal
    => Very low threshold.

SuperCDMS DETECTORS





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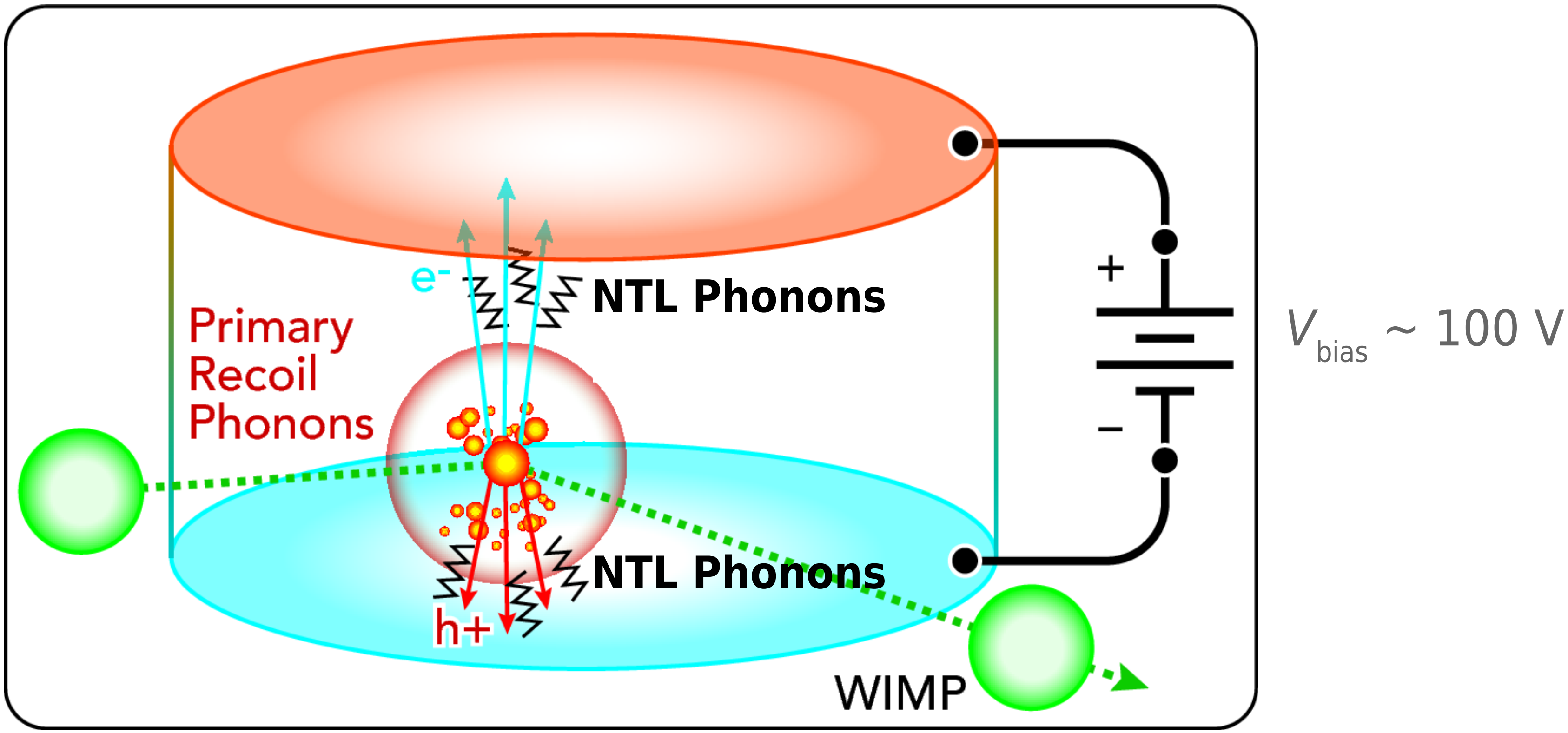
Neganov-Trofimov-Luke Effect

NEGANOV-TROFIMOV-LUKE AMPLIFICATION

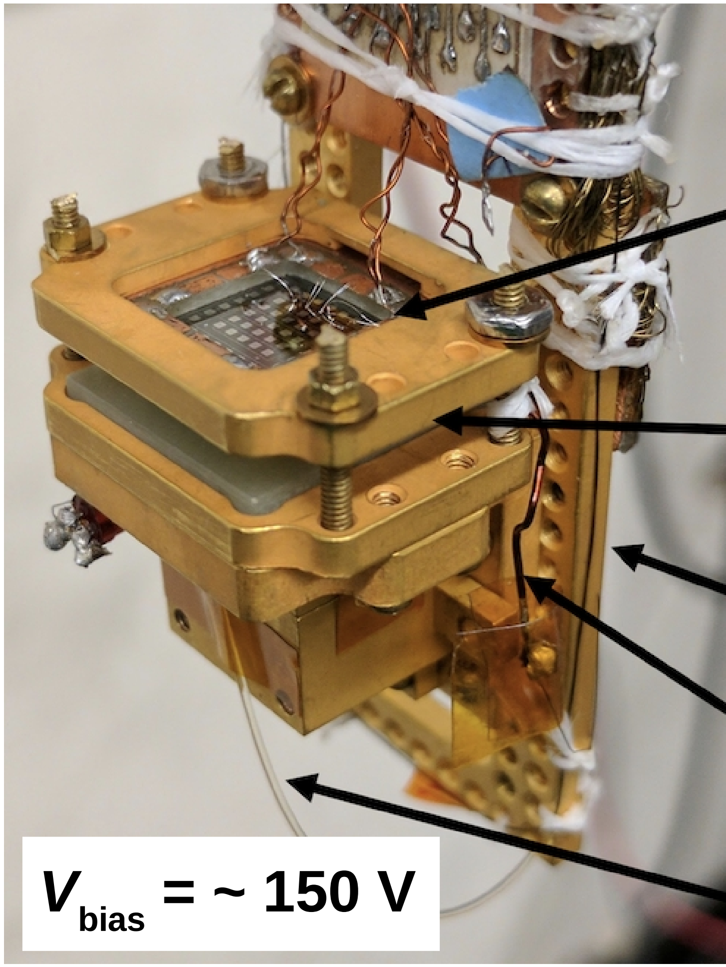
NTL: Neganov-Trofimov-Luke



Observed Phonon Energy = E_{Recoil} + $\mathbf{E_{NTL}}$

PROTOTYPE SINGLE e^-h^+ PAIR DETECTOR

R.K. Romani et al., Appl.Phys.Lett. 112 (2018) 043501



Si crystal (1cm^2 x 4mm, 0.93 g), Phonon sensors

Crystal holder

Dilution refrigerator sample stage (30 mK)

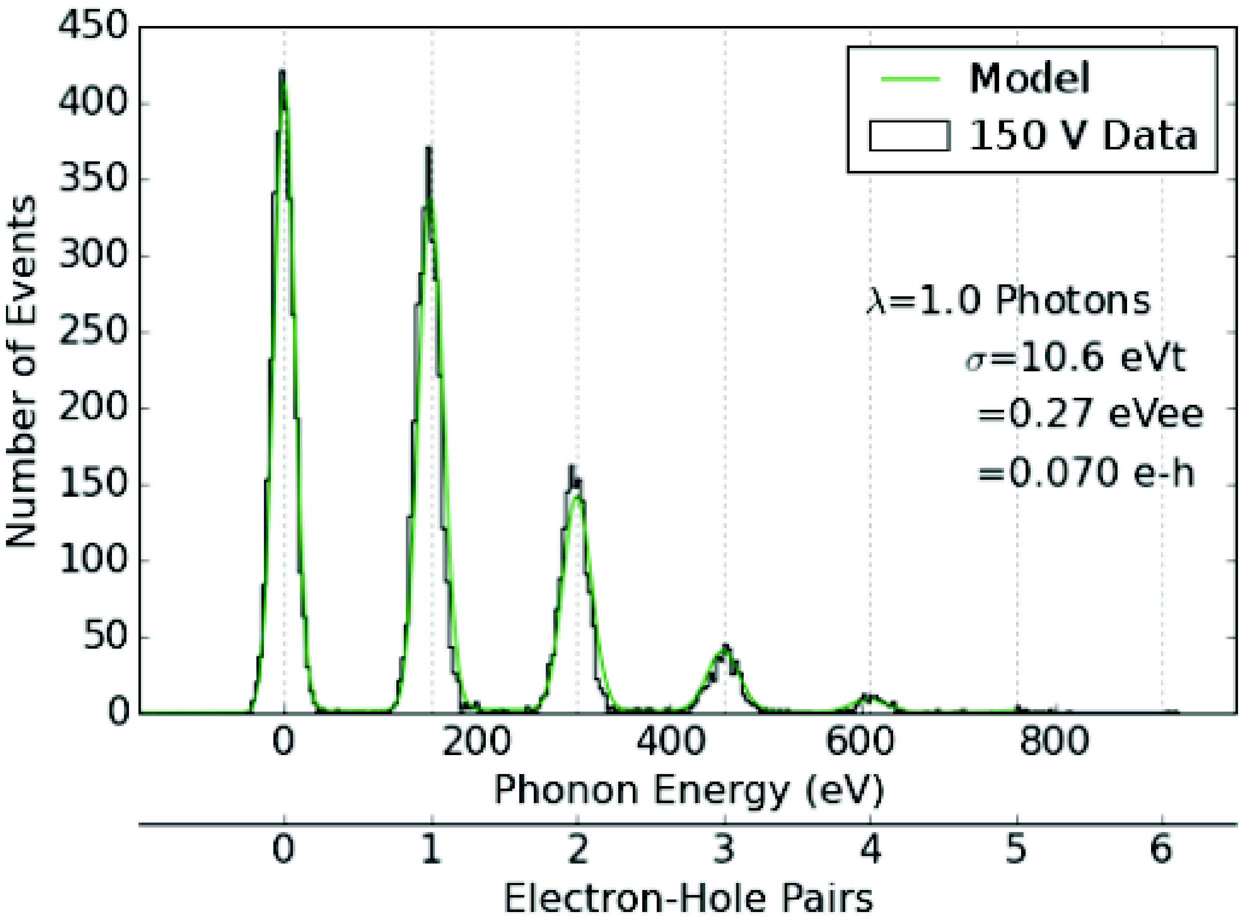
Bias voltage line

Fiber optic

- Strong NTL amplification of e^-h^+ pairs.
- Detector operated on surface at Stanford.

PROTOTYPE SINGLE e^-h^+ PAIR DETECTOR

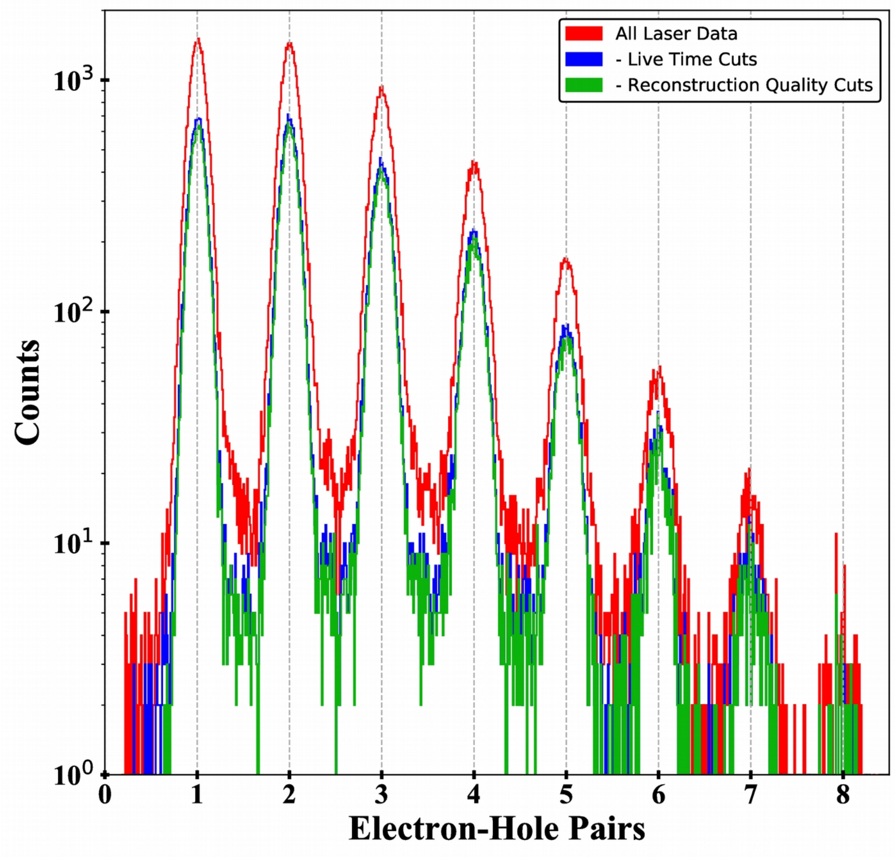
- Si band gap: ~ 1.2 eV.
- Calibration data with pulsed 650 nm laser => 1.91 eV photons.



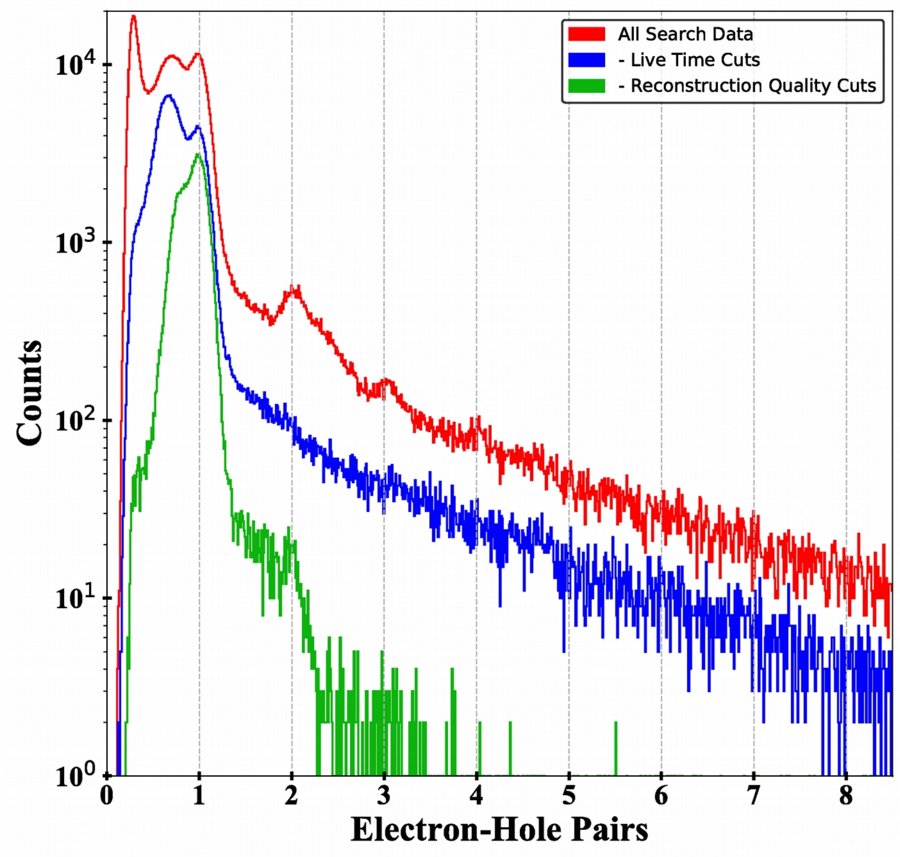
Sensitivity to single e^-h^+ pairs in Si crystal with a phonon sensor!

0.49 GRAM-DAYS OF SCIENCE DATA

Calibration Laser Data



DM Search Data



- Live Time Cuts:
  - Low-frequency noise, surface leakage, system stability.
- Reconstruction Quality Cuts:
  - Pre-trigger noise, reconstructed pulse start time, pulse shape.

DARK MATTER SEARCHES

DARK MATTER SIGNATURES

Nuclear Recoil

↓

$$\frac{\text{Number of } e^-h^+ \text{ pairs}}{\text{Primary Phonons}} = \textbf{small}$$

↓

Primary SuperCDMS DM search event class for default detectors.

↓

- Elastic WIMP-nucleon scattering.

Electron Recoil

↓

$$\frac{\text{Number of } e^-h^+ \text{ pairs}}{\text{Primary Phonons}} = \textbf{large}$$

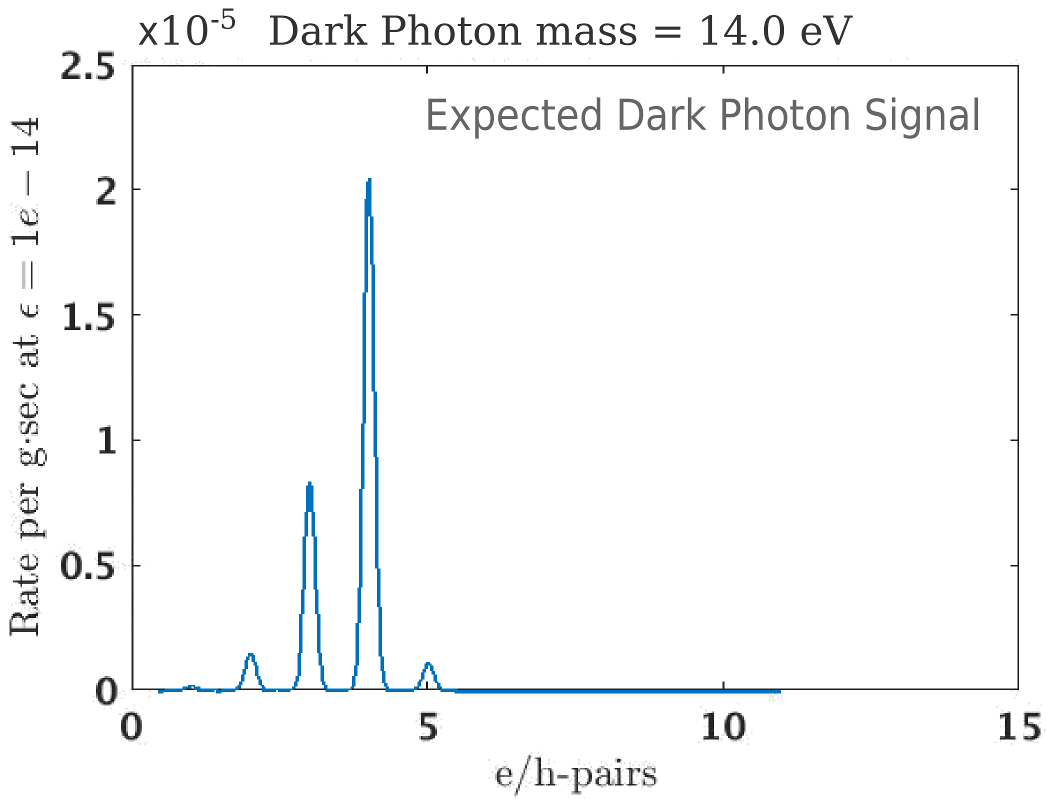
↓

Particularly interesting for single e^-h^+ pair detector!

↓

- Absorption of relic dark photons.
- Light DM-electron scattering.
- …

DARK PHOTON ABSORPTION IN QUANTIZATION LIMIT



Ionization model:

$$\langle n_{eh}(E_\gamma)\rangle = \begin{cases} 0 & E_\gamma < E_{gap} \\ 1 & E_{gap} < E_\gamma < \epsilon_{eh} \\ E_\gamma/\epsilon_{eh} & \epsilon_{eh} < E_\gamma \end{cases}$$

Absorption rate:

$$R \sim \rho_{DM}\, \varepsilon_{eff}^{2}\, m_V^{-1}\, \sigma_{p.e.}(E=m_V)$$

m_V: dark photon mass.

ε_{eff}: effective kinetic mixing parameter.

$\sigma_{p.e.}$: photoelectric absorption.

ρ_{DM}: relic DM energy density.

DARK PHOTONS: IN-MEDIUM EFFECTS

Absorption rate:

$R \sim \rho_{DM}\, \varepsilon_{eff}^{\,2}\, m_V^{-1}\, \sigma_{p.e.}(E=m_V)$

with:
$$\varepsilon_{\rm eff}^2 = \varepsilon^2 \cdot \frac{m_V^4}{[m_{V'}^2 - {\rm Re}\Pi]^2 + [{\rm Im}\Pi]^2}$$

≠1

for

$m_V <$ ~100 eV

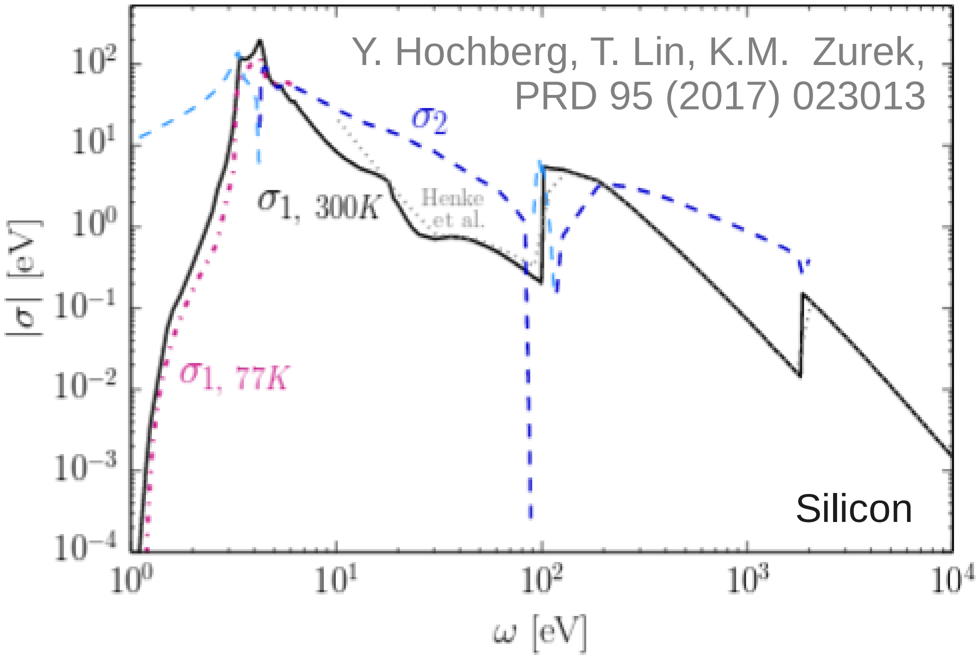
≈1

for

$m_V >$ ~ 100 eV

Π: In-medium polarization tensor. Depends on $\sigma_{p.e.}$ as well.

PHOTOELECTRIC ABSORPTION



- $\sigma_1 \hat{=} \sigma_{p.e.}$ always needed.
- σ_2 needed for in-medium correction.

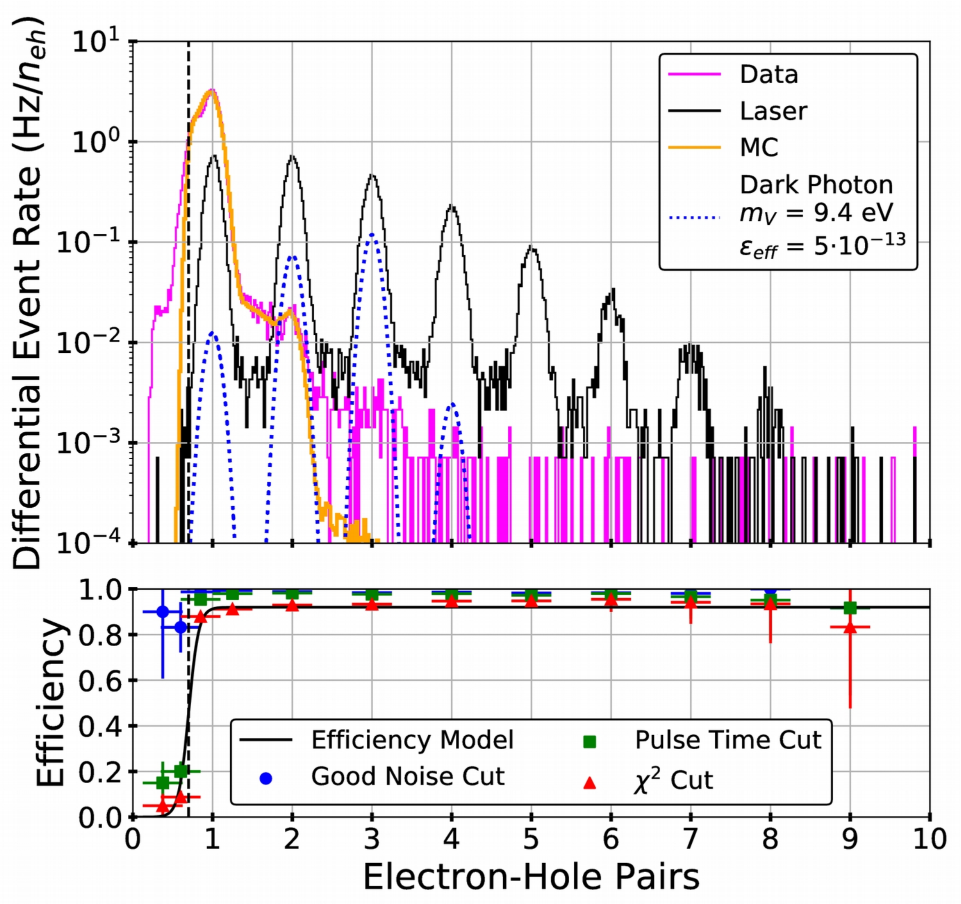
Dedicated study in
Ancillary file to arXiv:1804.10697,
SuperCDMS Collaboration

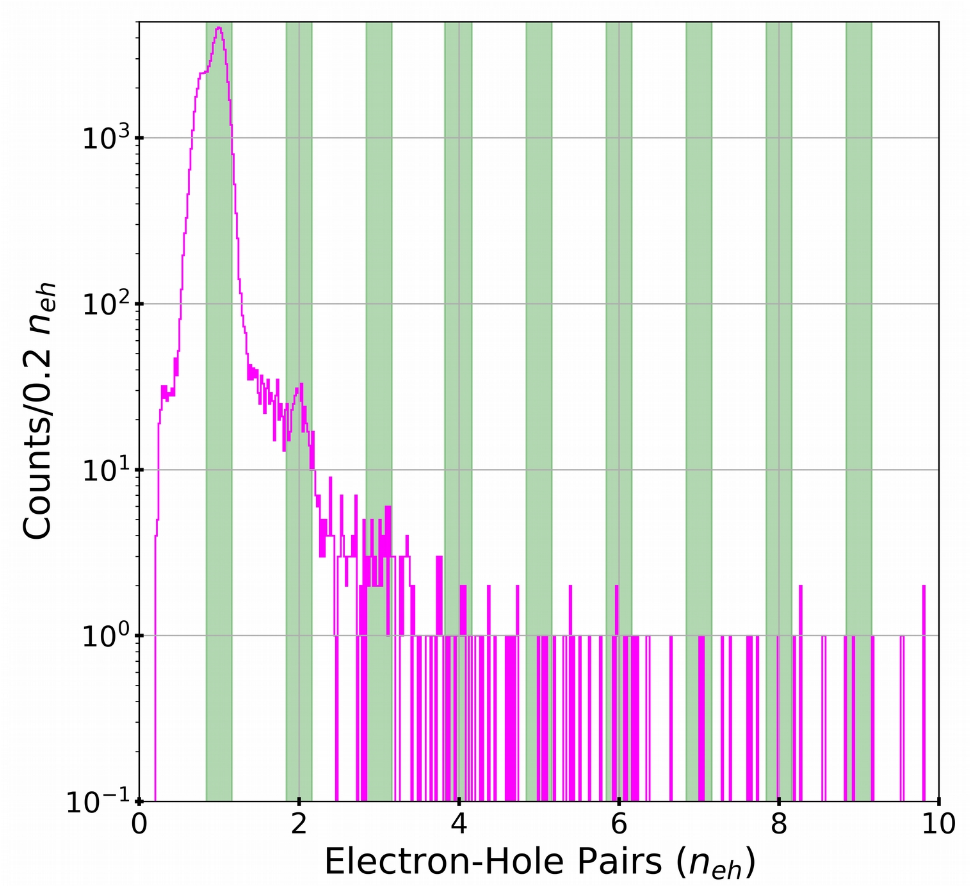
- Depends on:
  - **Temperature** (SuperCDMS at ≤ 30 mK),
  - **E-field strength** (detectors are biased),
    - Franz-Keldysh Effect [B.O. Seraphin, N. Bottka, PR 139 A 560],
  - **Charge carrier density**,
    - Zero free charge carriers at SuperCDMS (O(mK); biased),
    - σ_1 often measured in transmission experiments.
- Effects particularly prominent near band gap.

DARK PHOTON SEARCH

SuperCDMS Collaboration, arXiv:1804.10697
submitted to PRL

0.49 g-day exposure after data selection cuts.

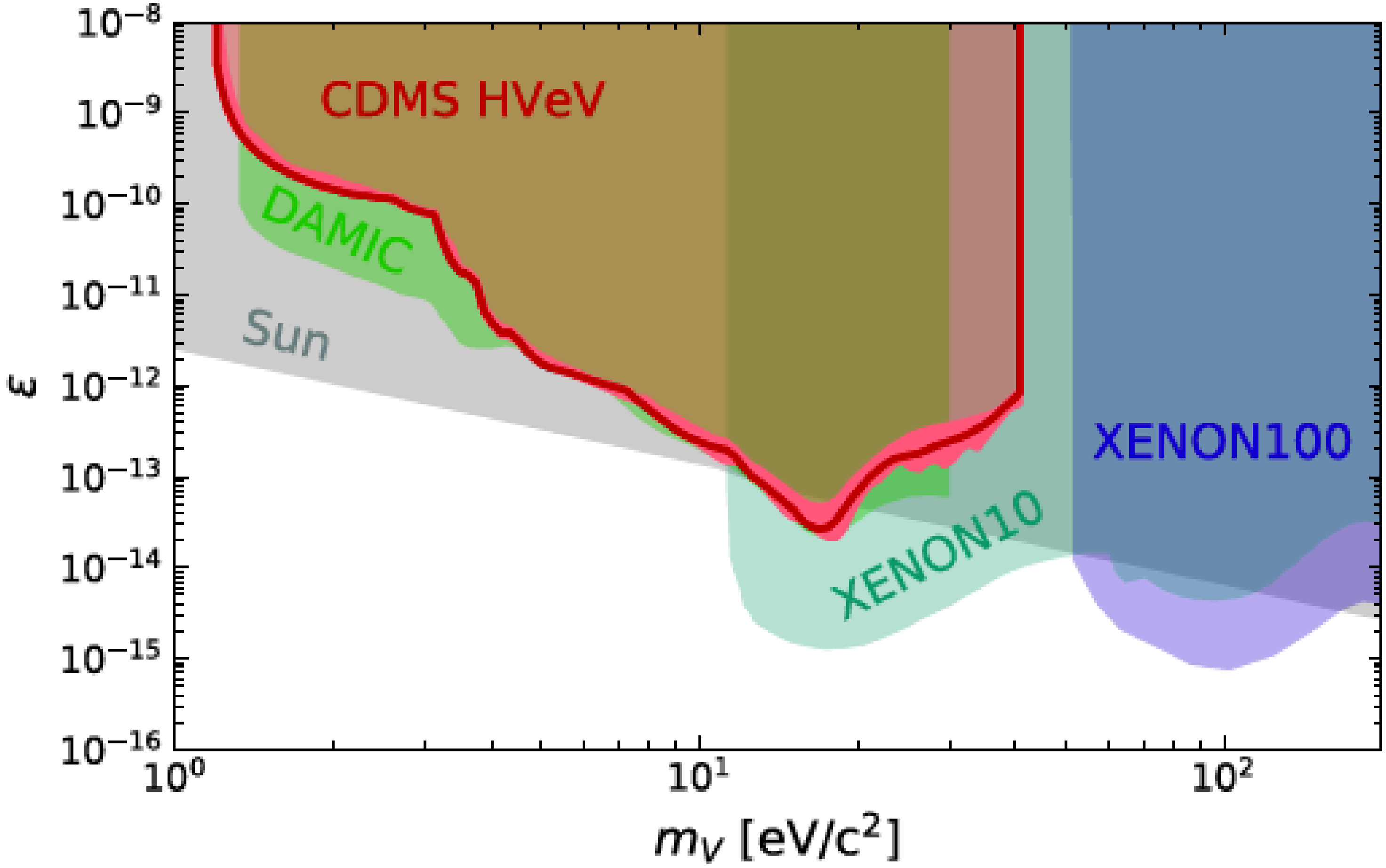




Region of Interest: +/- 2 σ quantization peak regions.

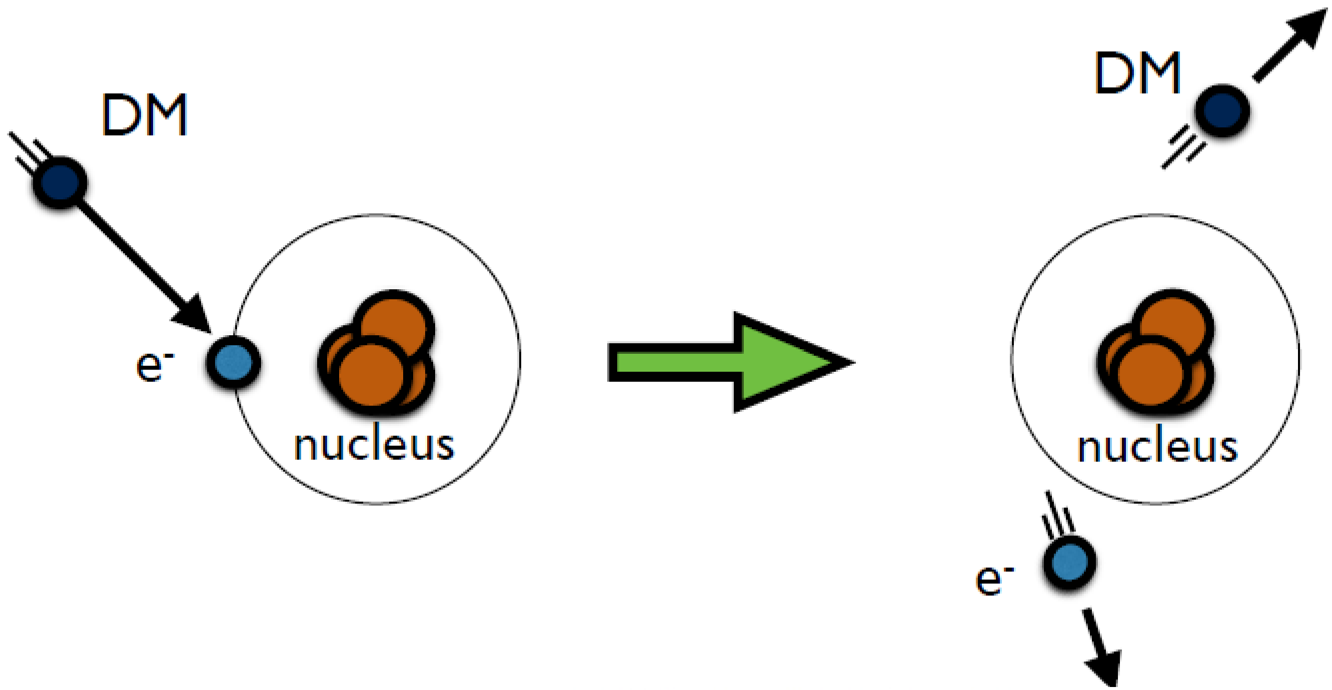
90% C.L. KINETIC MIXING LIMIT

SuperCDMS Collaboration, arXiv:1804.10697
submitted to PRL



Reaching existing limit despite order of magnitude smaller exposure.

DARK MATTER - ELECTRON SCATTERING



From R. Essig

DM model parameters solid state physics

$$\frac{d\langle\sigma v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2} \int q\, dq\, |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

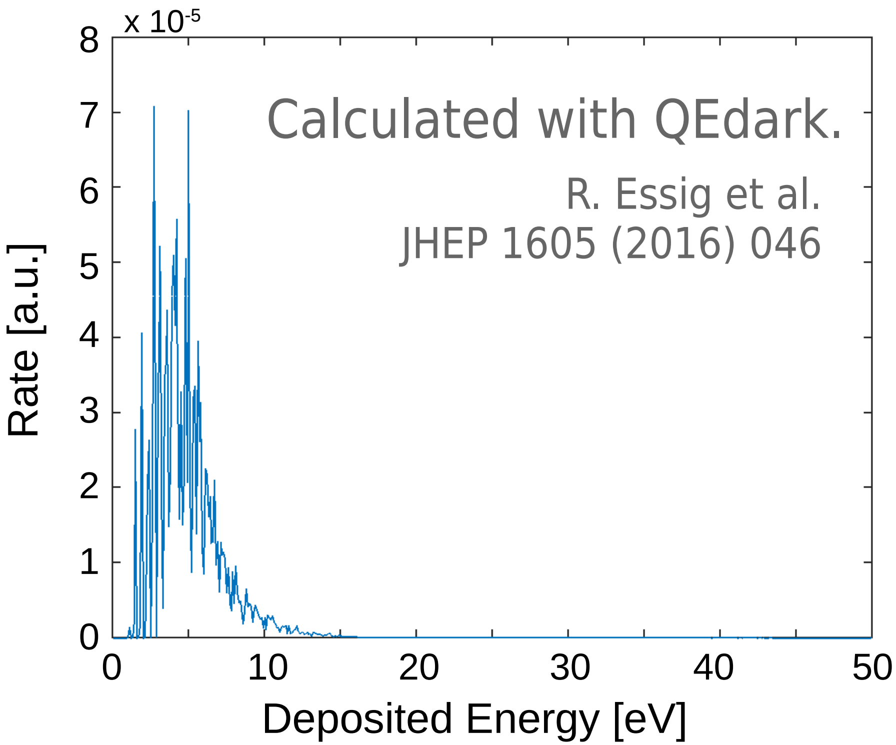
DM form factor

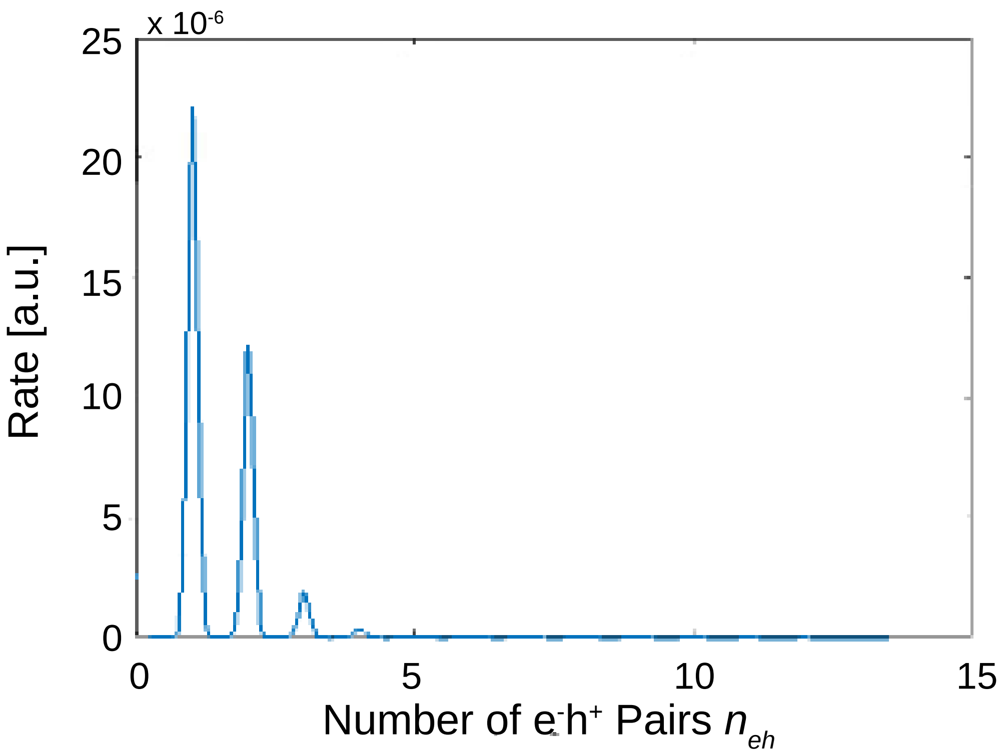
Heavy mediator: $F_{DM} = 1$

Light mediator: $F_{DM} \propto 1/q^2$

LIGHT DM ELECTRON RECOIL SPECTRUM

500 MeV/c² DM particle on Si Target (F_{DM} = 1).





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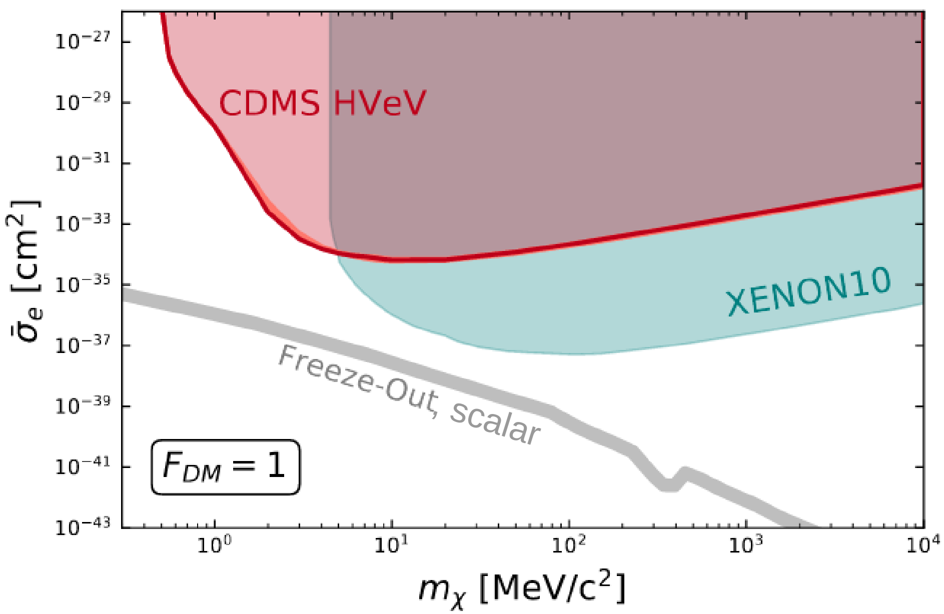
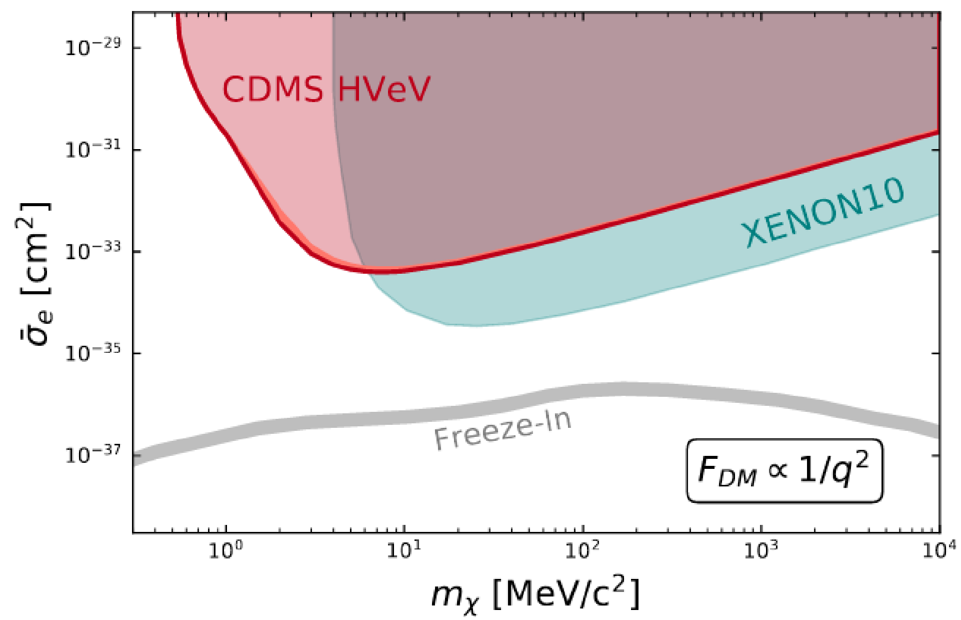
90% C.L. DM-ELECTRON SCATTERING LIMIT

SuperCDMS Collaboration, arXiv:1804.10697
submitted to PRL

Heavy dark photon mediator.



Ultra-light dark photon mediator.



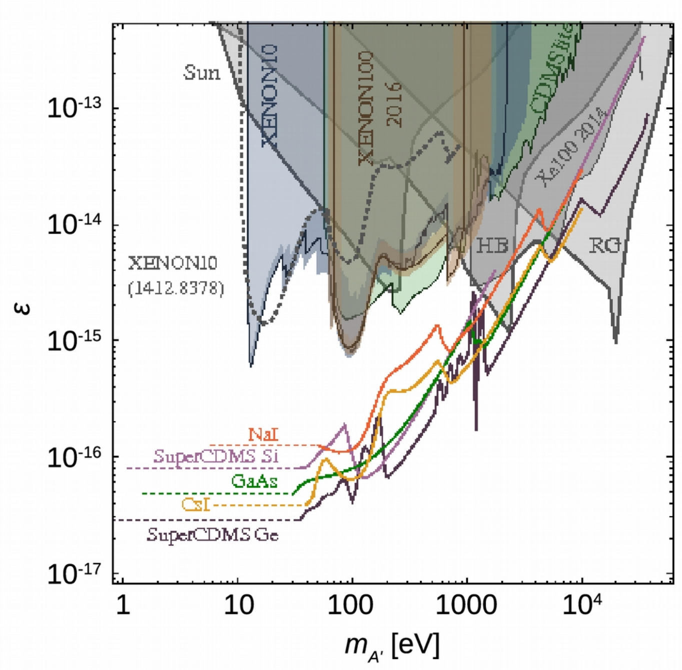
Improving over existing direct detection limits below 4 MeV/c^2.

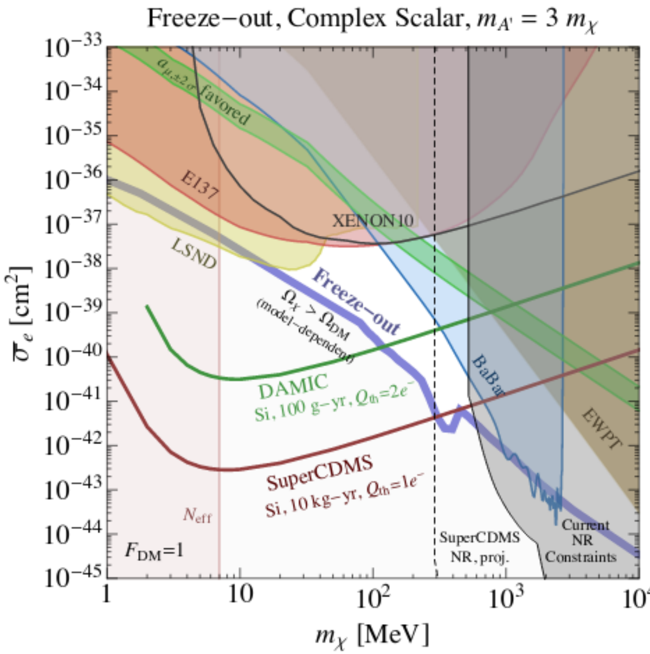
POTENTIAL OF SuperCDMS SNOLAB

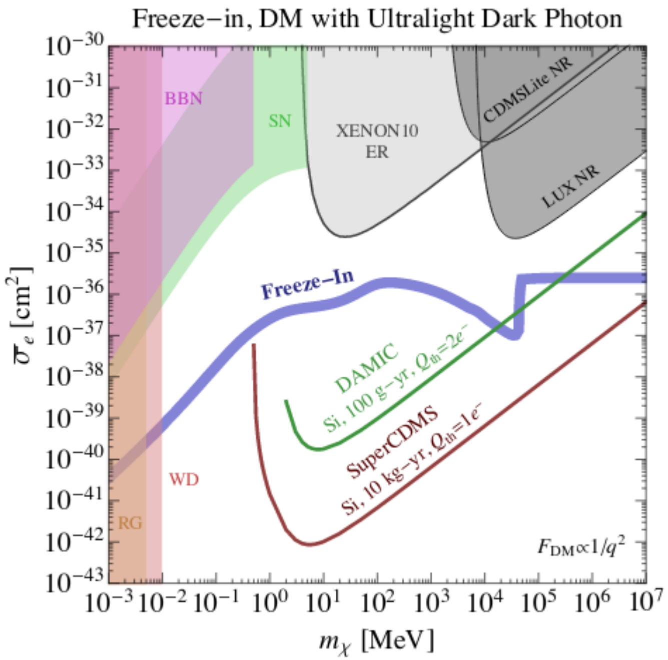
- ε: Projections for state-of-the-art SuperCDMS HV detectors.
- $\bar{\sigma}_e$: Projections for SuperCDMS HV detectors with ~1 eV threshold.

I. Bloch et al., JHEP 1706 (2017) 087

R. Essig et al., JHEP 1605 (2016) 046







- Commissioning of SuperCDMS SNOLAB in 2020.
- Starting to take data end of 2020!
- Potential future upgrade:
  Upscaled single $e^- h^+$ pair detectors for SuperCDMS SNOLAB.

THE SuperCDMS COLLABORATION

California Inst. of Tech.
CNRS-LPN*
Durham University
FNAL
NISER
NIST*
Northwestern
PNNL
Queen's University
Santa Clara University
SLAC
South Dakota SM&T
SMU
SNOLAB
Stanford University
Texas A&M University
TRIUMF
U. British Columbia
U. California, Berkeley
U. Colorado Denver
U. Evansville
U. Florida
U. Montréal
U. Minnesota
U. South Dakota
U. Toronto

* Associate members

SUPPLEMENTARY MATERIAL

DARK PHOTONS: IN-MEDIUM EFFECTS

Absorption rate:

$R \sim \rho_{DM}\, \varepsilon_{eff}^{\,2}\, m_V^{\,-1}\, \sigma_{p.e.}(E=m_V)$

with:
$$\varepsilon_{\rm eff}^2 = \varepsilon^2 \cdot \frac{m_V^4}{[m_{V'}^2 - {\rm Re}\Pi]^2 + [{\rm Im}\Pi]^2}$$

In-medium polarization tensor:

$$\Pi(E_\gamma = m_{V'}c^2) \approx -i \cdot \hat{\sigma} \cdot m_{V'}c^2$$

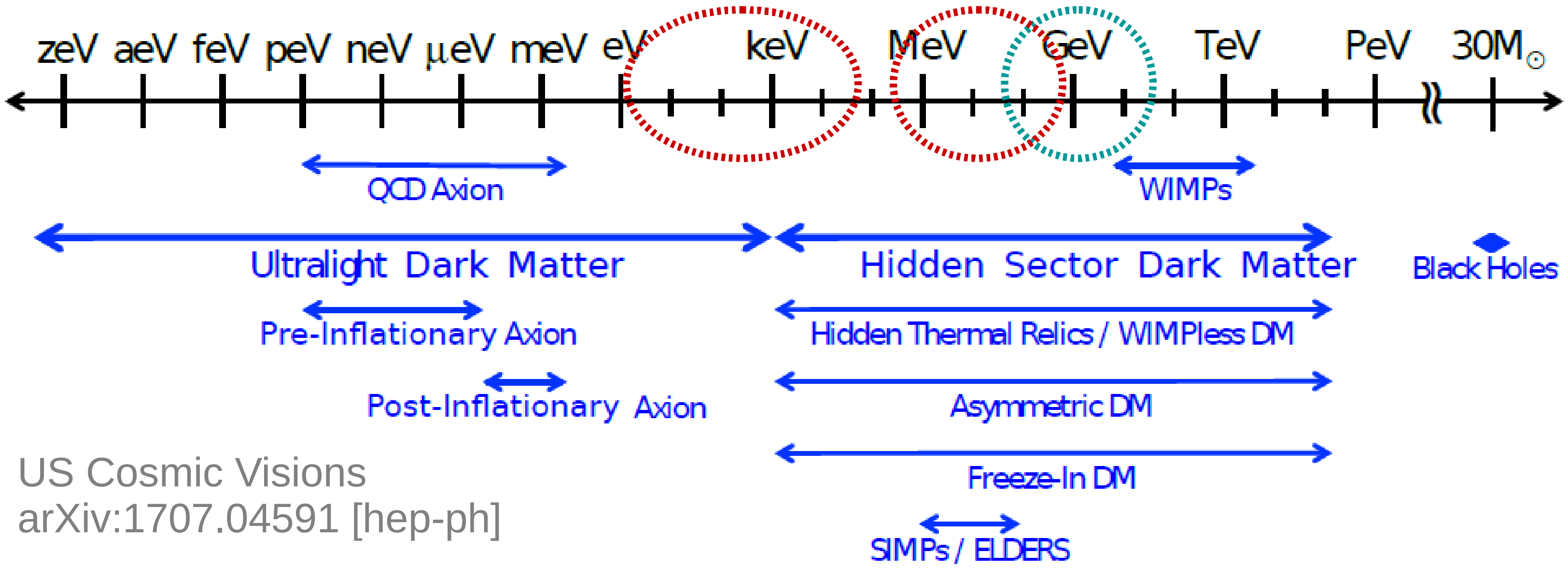
Conductivity:

$$\hat{\sigma} \equiv \sigma_1 + i\sigma_2$$

DM DETECTION CHANNELS - Electron Recoil

SuperCDMS DM Search
(Electron Recoil)

SuperCDMS WIMP Search
(Nuclear Recoil)

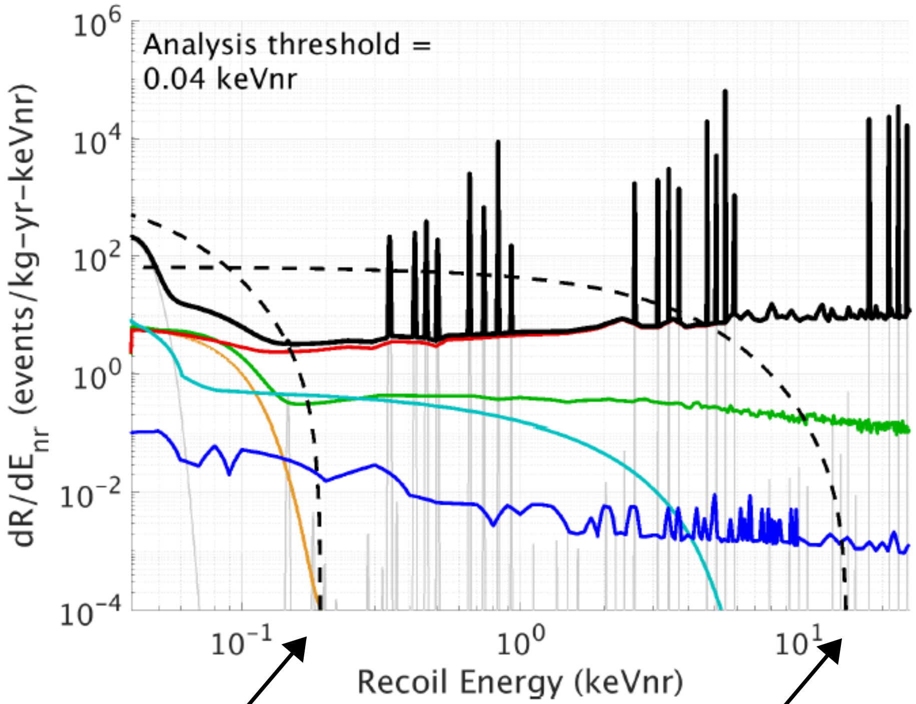


US Cosmic Visions
arXiv:1707.04591 [hep-ph]

WIMP-NUCLEON SCATTERING

- **Spin-independent (SI) elastic WIMP-nucleon scattering.**
  - **Primary Dark Matter search.**
- Spin-dependent (SD) elastic WIMP-nucleon scattering.
- Dominant backgrounds have Electron Recoil signature.

Prediction in
Ge HV detectors
after fiducial cuts:



Total
^{3}H and Comptons
Ge activation
Surface betas
Surface ^{206}Pb
Coherent neutrinos
Neutrons

1 GeV WIMP   10 GeV WIMP   with $\sigma = 10^{-42}$ cm^2.

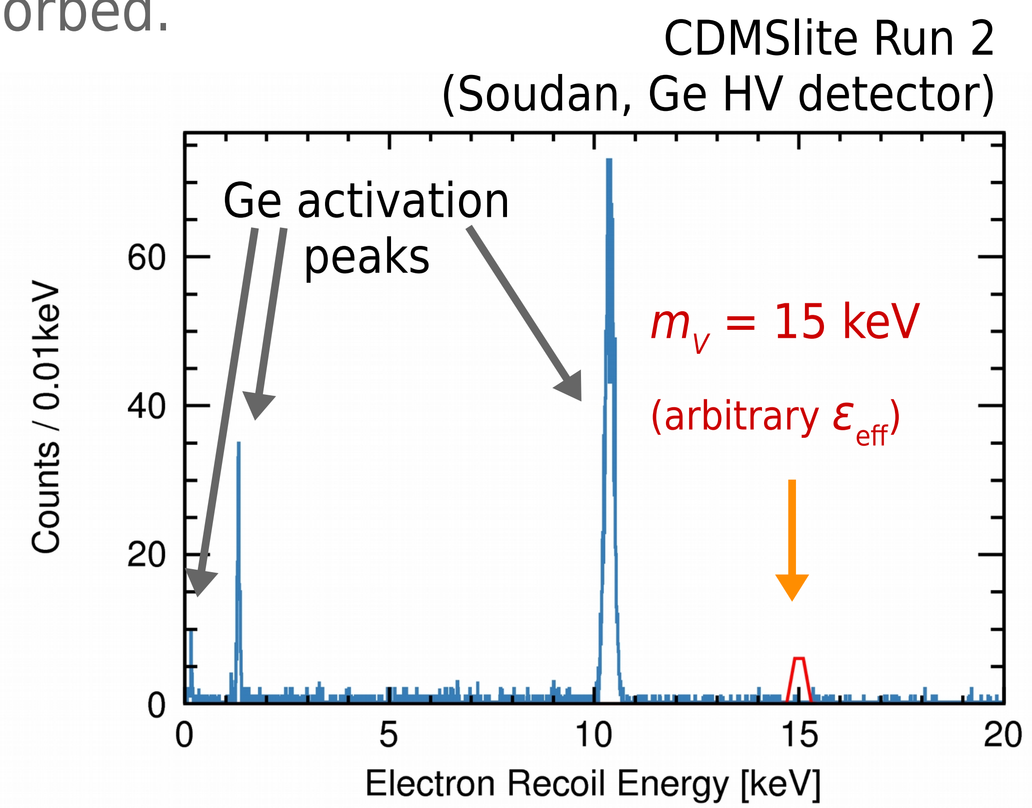
DARK PHOTON ABSORPTION

- Analogous to photoelectric absorption, but with a dark photon V being absorbed.

Absorption rate:

$$R \sim \rho_{DM}\, \varepsilon_{eff}^{2}\, m_V^{-1}\, \sigma_{p.e.}(E=m_V)$$

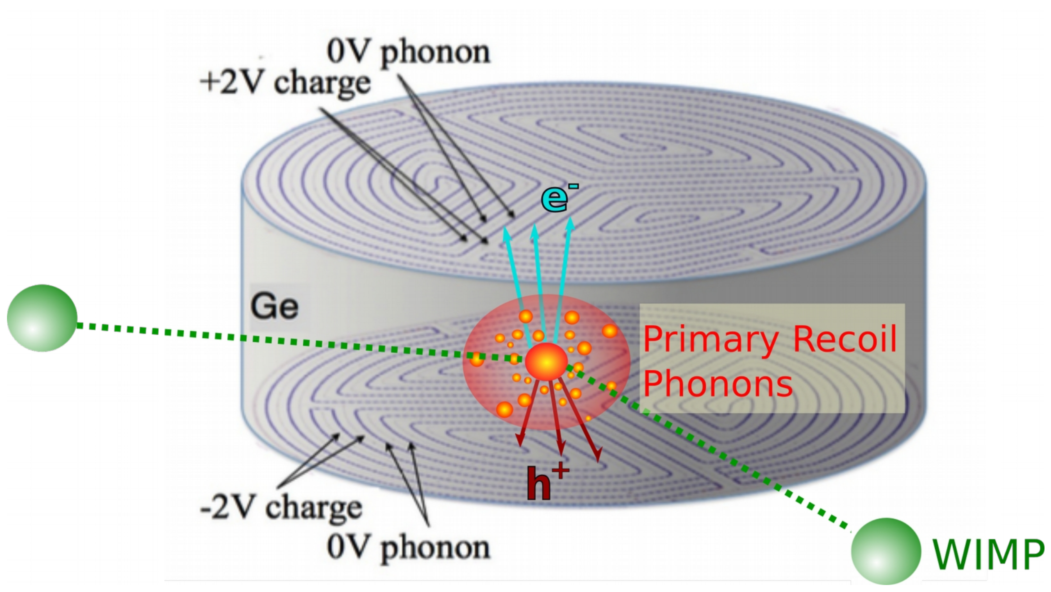
m_V: dark photon mass.
ε_{eff}: effective kinetic mixing parameter.
$\sigma_{p.e.}$: photoelectric absorption.
ρ_{DM}: relic DM energy density.

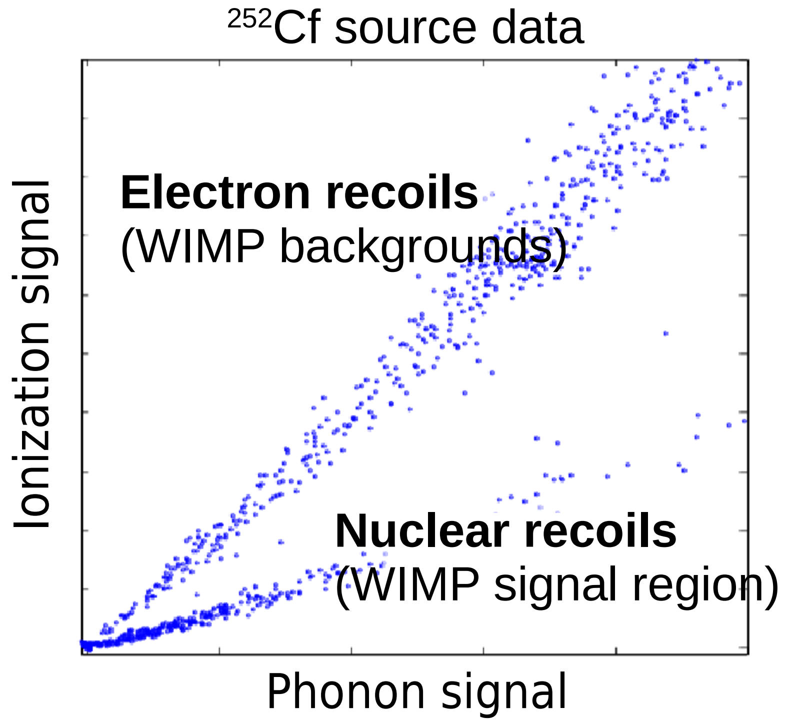


Expected signal: **Peak at electron recoil energy corresponding to m_V**

DETECTION PRINCIPLE – iZIP MODE

interleaved **Z**-Sensitive **I**onization and **P**honon detectors.





- **Phonon signal**: Heat / energy deposition.
- **Ionization signal**: e^-/h^+ pair production.
  - Reduced for nuclear recoil.
- **Combination**: Efficient discrimination between nuclear and electron recoil events.

PRODUCTION RATE

DM model parameters **solid state physics**

$$\frac{d\langle\sigma v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\, dq\, |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

Dark Matter form factor

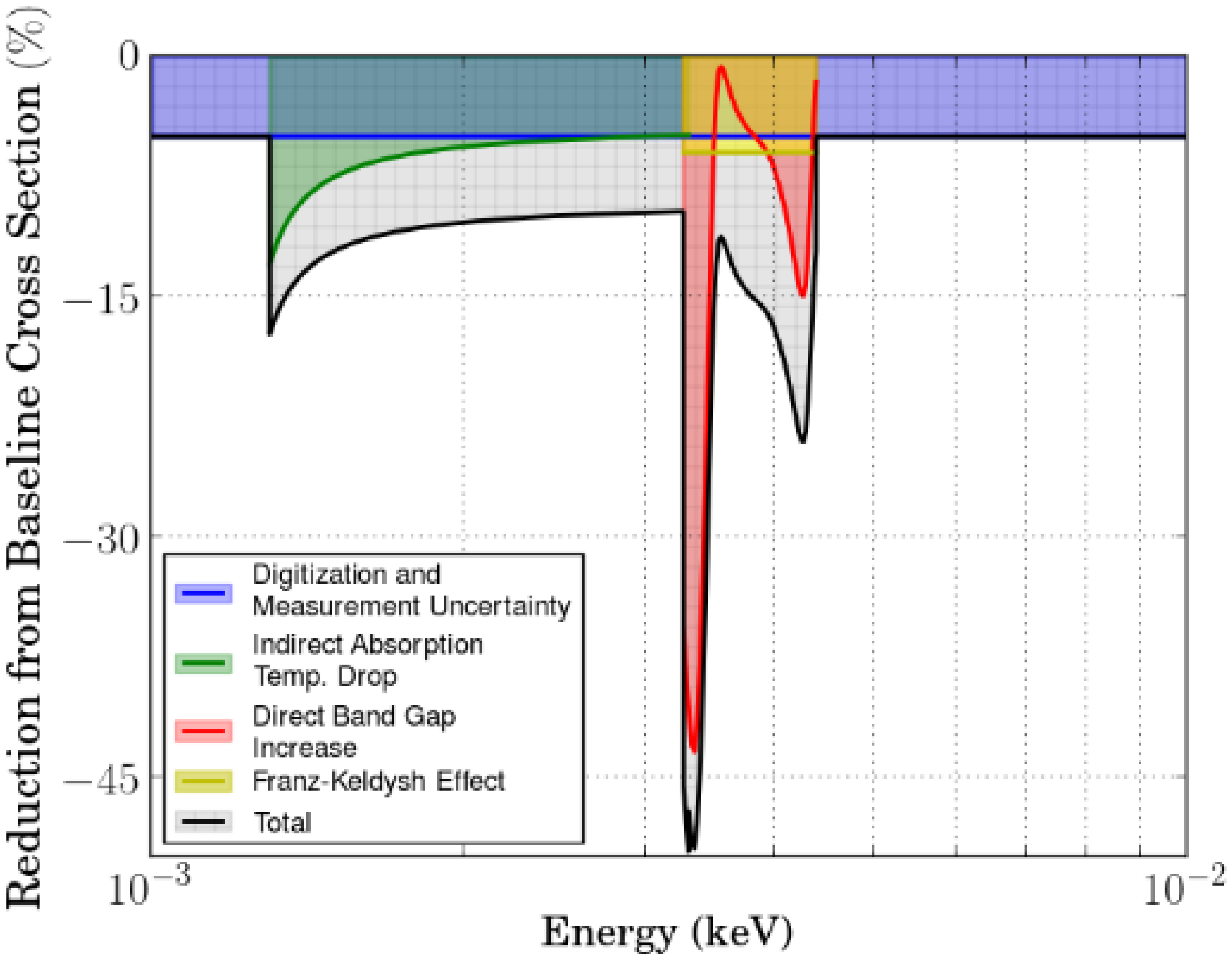
$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2}$$

- "Heavy" A' (>> αm_e).
  - $m_{A'} \sim m_{DM}$
  - $F_{DM}(q) \approx 1$.
- Generates relic DM density via freeze-out.

- "Ultra-Light" A' (<< αm_e).
  - $m_{A'}$ << keV.
  - $F_{DM}(q) \sim 1/q^2$.
- Generates relic DM density via freeze-in.

PHOTOELECTRIC CROSS SECTION SYSTEMATICS

SuperCDMS Collaboration, arXiv:1804.10697
Ancillary file



SYSTEMATIC EFFECT OF FANO TERM