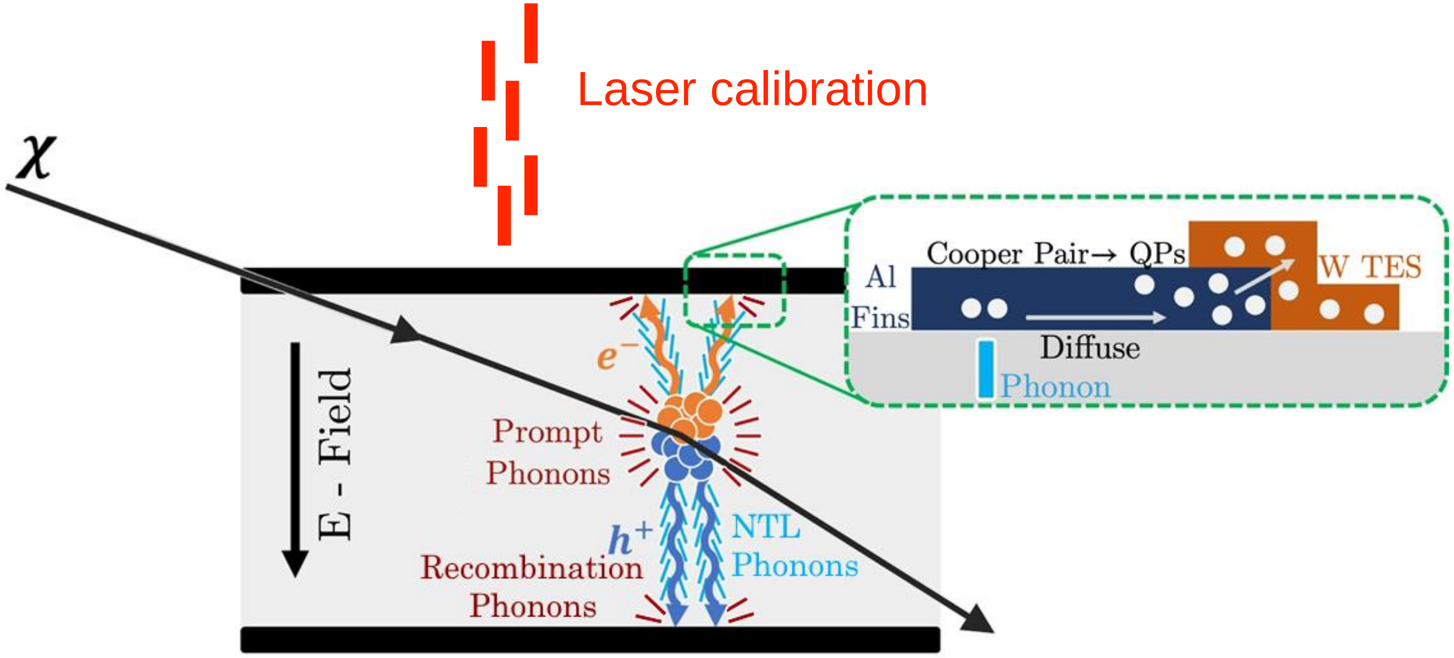
Improved Modeling of Charge Trapping and Impact Ionization in SuperCDMS HVeV detectors

Alexander Zaytsev, Matthew Wilson, Belina von Krosigk

SuperCDMS HVeV detector



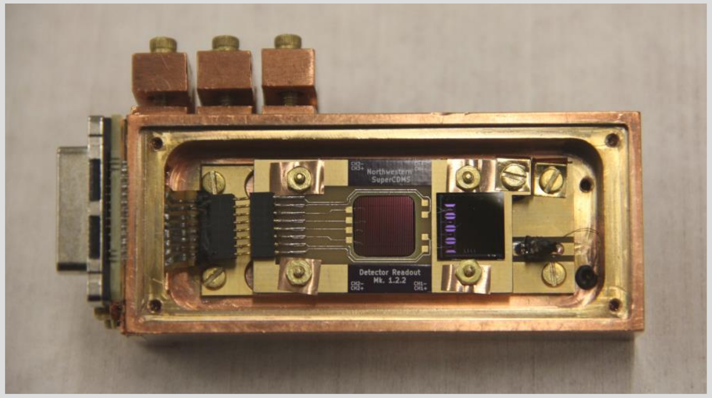
$$E_{\mathrm{phonon}} = E_{\mathrm{recoil}} + n_{\mathrm{eh}} e V_{\mathrm{bias}}$$

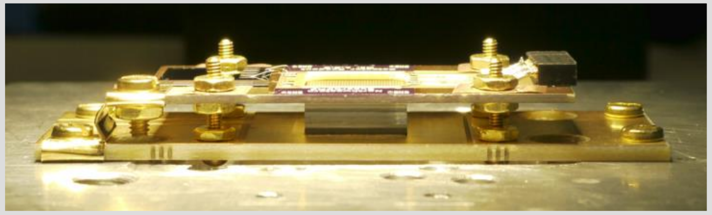
Neganov-Trofimov-Luke (NTL) gain

High-voltage eV-scale (HVeV)

10x10x4 mm^3, ~1g Si, 100 V bias

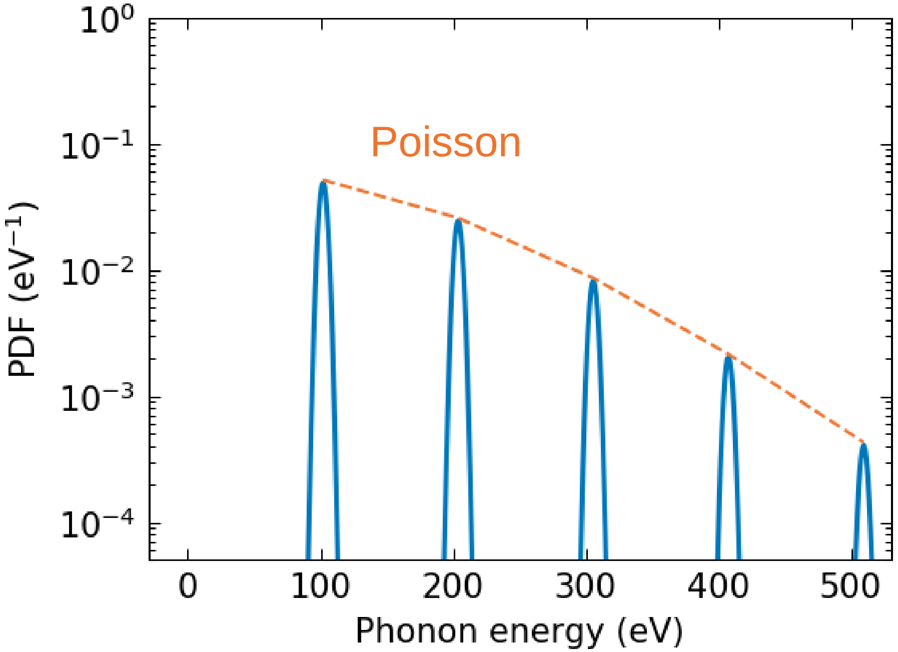
HVeV Run 2





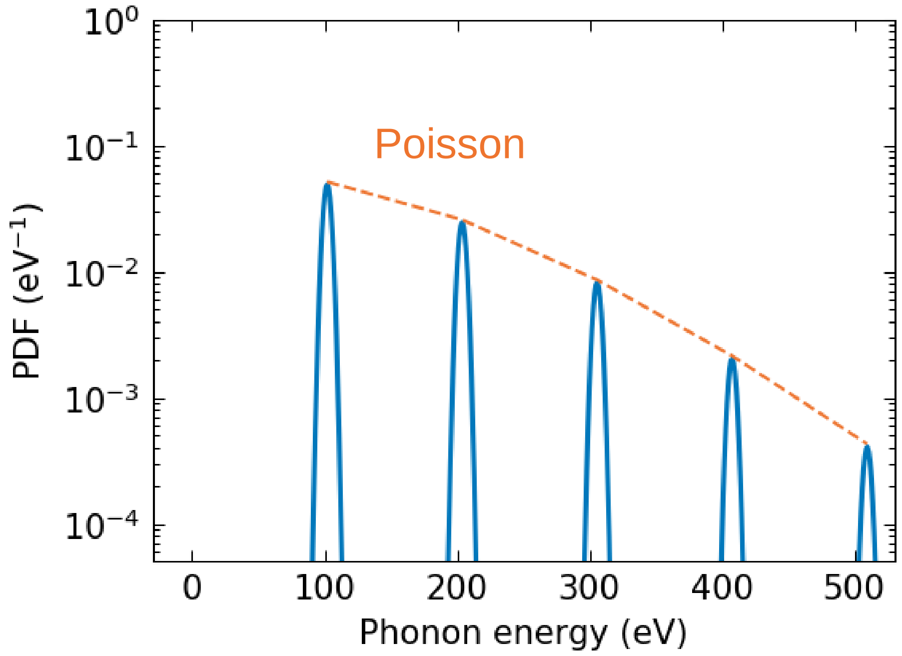
Phonon energy spectrum

- Laser photons, $E_\gamma = 1.95$ eV
- Poisson distribution of $n_\gamma = n_{\mathrm{eh}}$
- $E_{\mathrm{phonon}} = n_\gamma E_\gamma + n_\gamma e V_{\mathrm{bias}}$
- Resolution: 3 eV



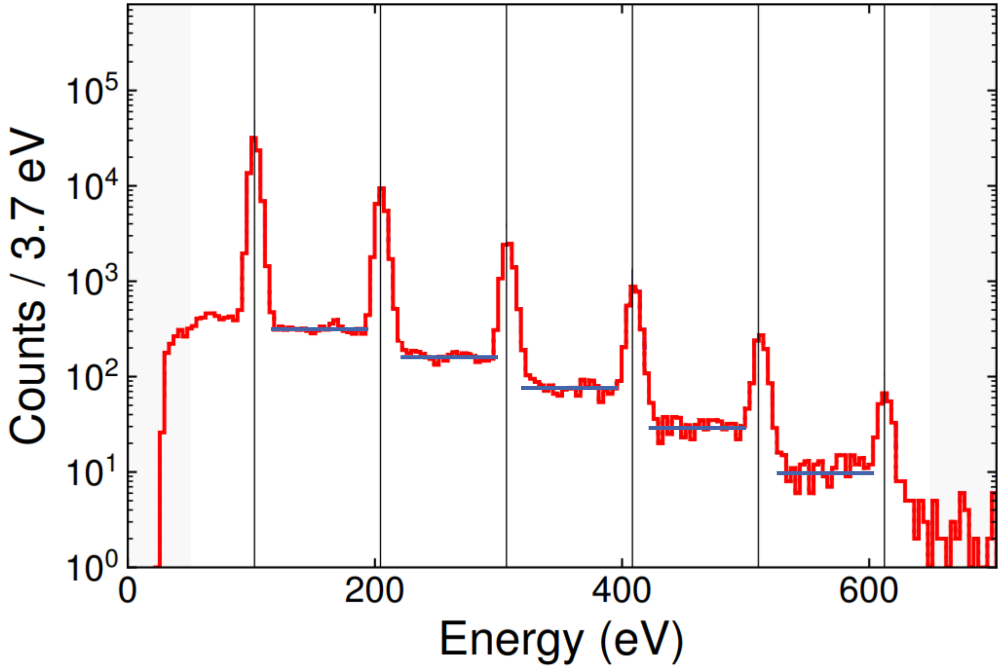
Phonon energy spectrum

- Laser photons, $E_\gamma = 1.95$ eV
- Poisson distribution of $n_\gamma = n_{\mathrm{eh}}$
- $E_{\mathrm{phonon}} = n_\gamma E_\gamma + n_\gamma e V_{\mathrm{bias}}$
- Resolution: 3 eV



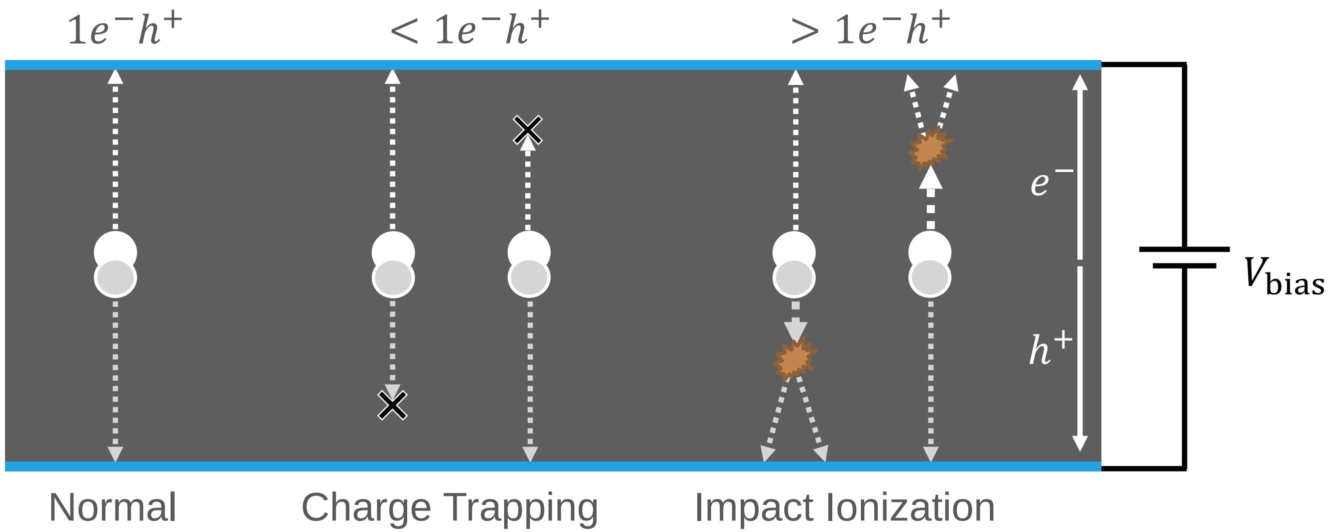
- Observed events with non-quantized energy
- Steps at quantized peaks
- Partial NTL amplification

HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102, 091101 (2020)



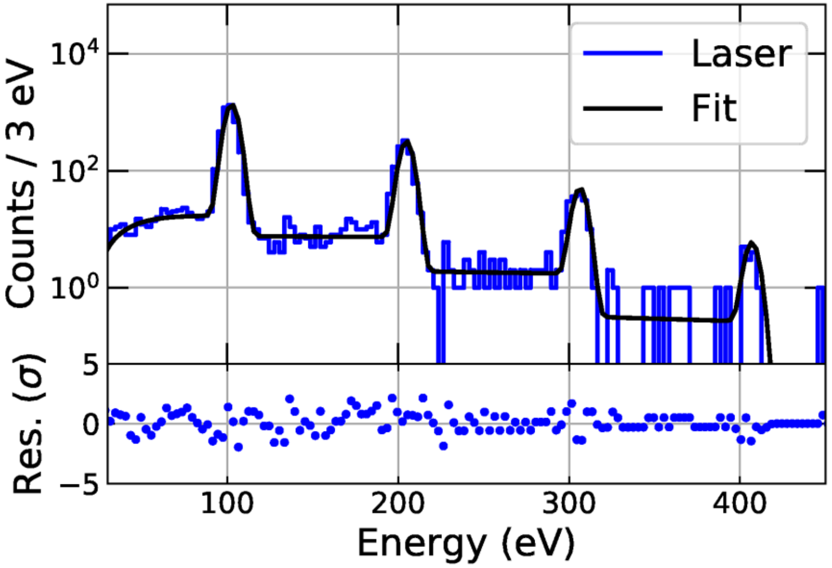
Charge Trapping and Impact Ionization

- Charges get trapped or ionize more charges on impurities
- Trapped or unpaired charges traverse only a part of the detector bulk
- Generate partial NTL amplification

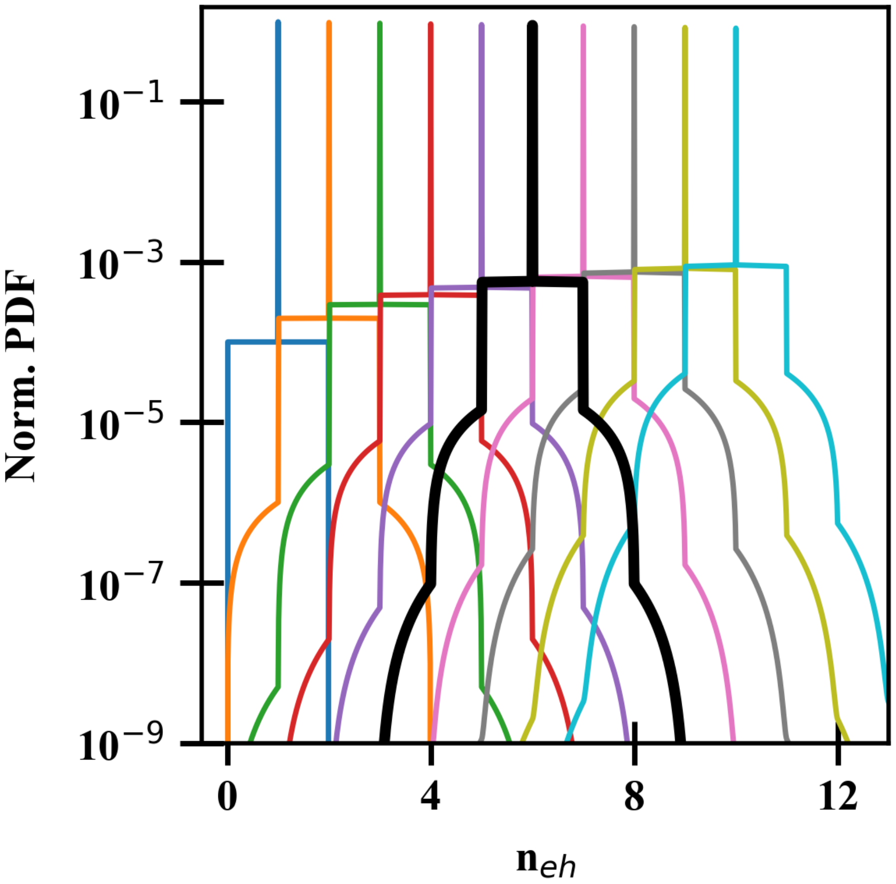


Simple CTII model

- Described analytically by Heaviside functions
- Used in HVeV Run 2 analysis



HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102, 091101 (2020)

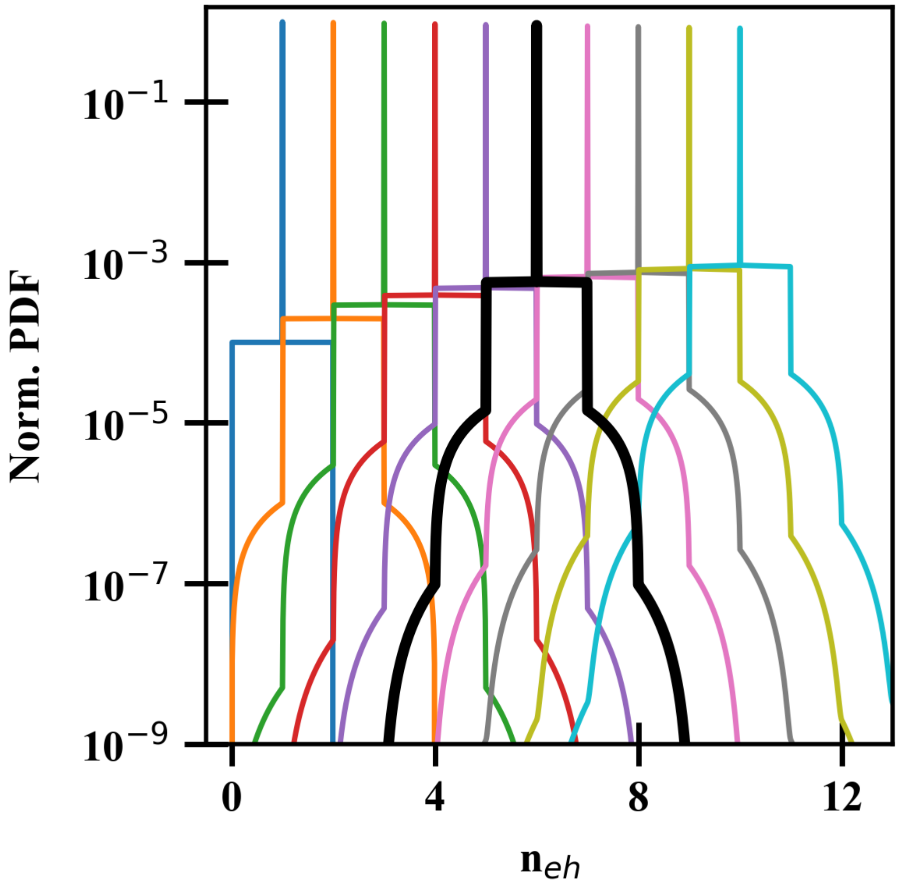


F. Ponce *et al*, J. Low Temp. Phys. 199, 598–605 (2020)

Simple CTII model

Limitations:

- Uniform probability distributions are not physically motivated
- No distinction between e^- and h^+
- Only models first-order effects



F. Ponce *et al*, J. Low Temp. Phys. 199, 598–605 (2020)

Improved CTII model

- Consider 6 processes (*e* and *h* trapping; *ee*, *eh*, *he*, *hh* ionization)
- Parametrize probability of each process by characteristic lengths τ_i
- Distance traveled along the E-filed before a CTII process occurs follows an exponential distribution

$$P_i(z) = \frac{1}{\tau_i} e^{-z/\tau_i}$$

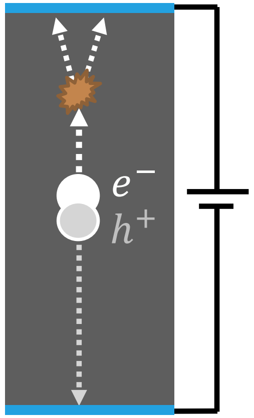
Improved CTII model: 1eh solutions

- Consider various combinations of processes
- Derive distribution of length traveled by charges for each combination
- Amount of NTL energy is proportional to the traveled path

$$T_e = \frac{1}{\tau_{\mathrm{CT}e}} + \frac{1}{\tau_{\mathrm{II}ee}} + \frac{1}{\tau_{\mathrm{II}eh}}$$

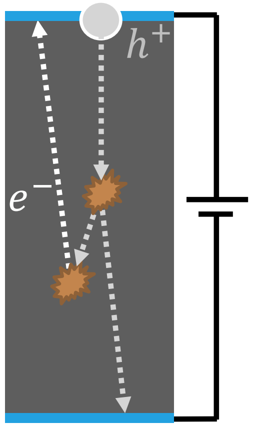
$$T_h = \frac{1}{\tau_{\mathrm{CT}h}} + \frac{1}{\tau_{\mathrm{II}he}} + \frac{1}{\tau_{\mathrm{II}hh}}$$

Bulk event; *e* ionizes *e*



$$P(E) = \begin{cases} \frac{-e^{T_{\mathrm{e}}(-2+E)}+e^{T_{\mathrm{h}}(-2+E)}}{\tau_{\mathrm{IIee}}(T_{\mathrm{e}}-T_{\mathrm{h}})} & 1 \leq E < 2 \\ 0 & \text{else} \end{cases}$$

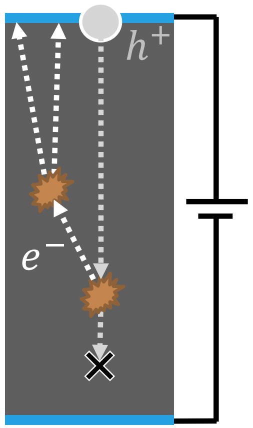
Surface event; *h* ionizes *h*, secondary *h* ionizes *e*



$$P(E) = \begin{cases} -\frac{2e^{T_{\mathrm{h}}-T_{\mathrm{h}}E}(-3+E)}{\tau_{\mathrm{IIhe}}\tau_{\mathrm{IIhh}}} & 2 \leq E < 3 \\ 0 & \text{else} \end{cases}$$

Improved CTII model: 1eh solutions

Surface event; *h* ionizes *e*, *h* traps, *e* ionizes *e*



$$P(E) = \begin{cases} \dfrac{e^{-T_\mathrm{h}E}\left(3T_\mathrm{e} - 3e^{\frac{2T_\mathrm{h}E}{3}}T_\mathrm{e} + T_\mathrm{h} - 4e^{-\frac{1}{2}(T_\mathrm{e}-T_\mathrm{h})E}T_\mathrm{h} + 3e^{\frac{2T_\mathrm{h}E}{3}}T_\mathrm{h}\right)}{2\tau_\mathrm{IIee}T_\mathrm{h}\left(-3T_\mathrm{e}^2 + 2T_\mathrm{e}T_\mathrm{h} + T_\mathrm{h}^2\right)\tau_\mathrm{IIhe}\tau_\mathrm{CTh}} & 0 \le E < 1 \\ \dfrac{e^{-T_\mathrm{e}E - \frac{1}{2}T_\mathrm{h}(2+E)}(\zeta_1(E) + \zeta_2(E))}{2T_\mathrm{e}\tau_\mathrm{IIee}T_\mathrm{h}(-T_\mathrm{e} + T_\mathrm{h})(3T_\mathrm{e} + T_\mathrm{h})\tau_\mathrm{IIhe}\tau_\mathrm{CTh}} & 1 \le E < 2 \\ -\dfrac{3e^{-T_\mathrm{h}}T_\mathrm{e} - 3e^{-\frac{T_\mathrm{h}E}{3}}T_\mathrm{e} + e^{-T_\mathrm{h}}T_\mathrm{h} - e^{-3T_\mathrm{e} - T_\mathrm{h} + T_\mathrm{e}E}T_\mathrm{h}}{6T_\mathrm{e}^2\tau_\mathrm{IIee}T_\mathrm{h}\tau_\mathrm{IIhe}\tau_\mathrm{CTh} + 2T_\mathrm{e}\tau_\mathrm{IIee}T_\mathrm{h}^2\tau_\mathrm{IIhe}\tau_\mathrm{CTh}} & 2 \le E < 3 \\ 0 & \text{else,} \end{cases}$$

where

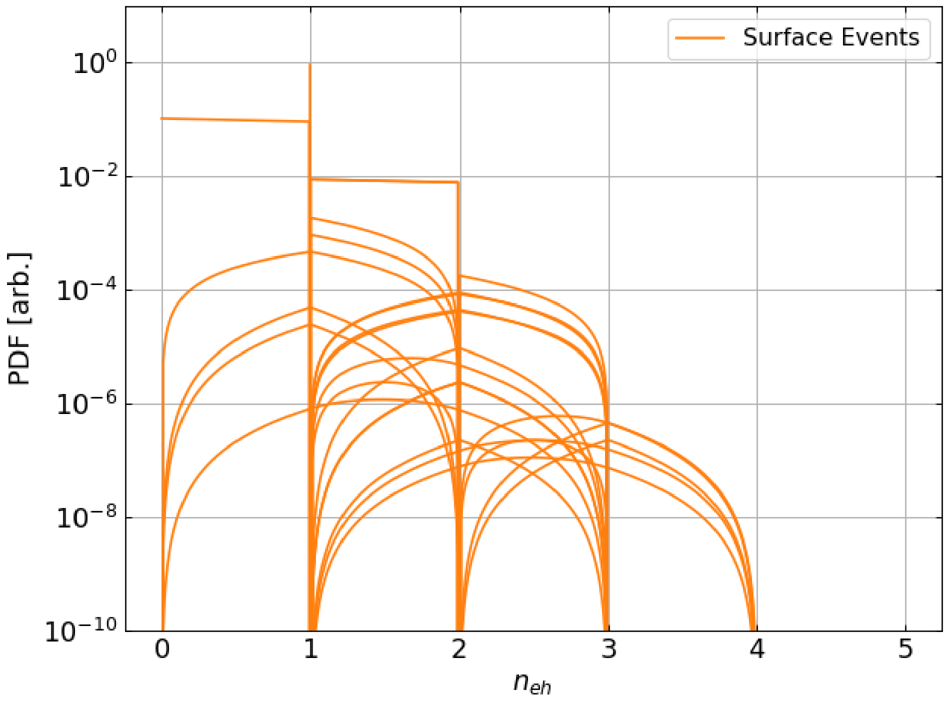
$$\zeta_1(E) = -4e^{T_\mathrm{h} + \frac{T_\mathrm{e}E}{2}}T_\mathrm{e}T_\mathrm{h} + 3e^{T_\mathrm{h} + T_\mathrm{e}E + \frac{T_\mathrm{h}E}{6}}T_\mathrm{e}(-T_\mathrm{e} + T_\mathrm{h})$$
$$\zeta_2(E) = e^{T_\mathrm{e} + \frac{T_\mathrm{h}E}{2}}T_\mathrm{h}(3T_\mathrm{e} + T_\mathrm{h}) + e^{T_\mathrm{e}E + \frac{T_\mathrm{h}E}{2}}\left(3T_\mathrm{e}^2 - 2T_\mathrm{e}T_\mathrm{h} - T_\mathrm{h}^2\right)$$

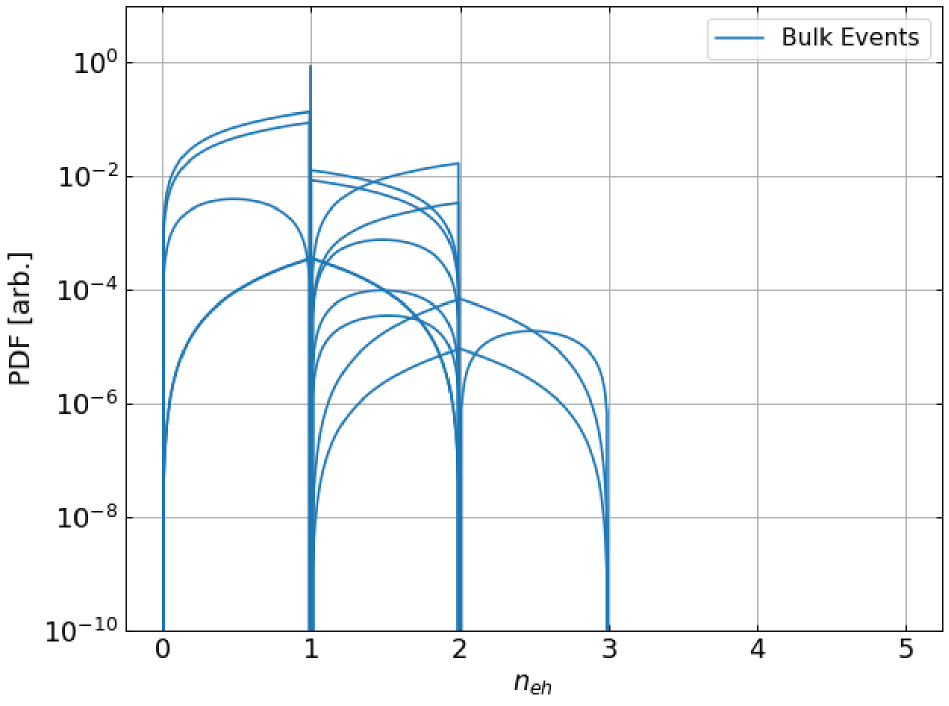
- It’s getting complicated!

Improved CTII model: 1eh solutions

Surface events: up to second-order processes

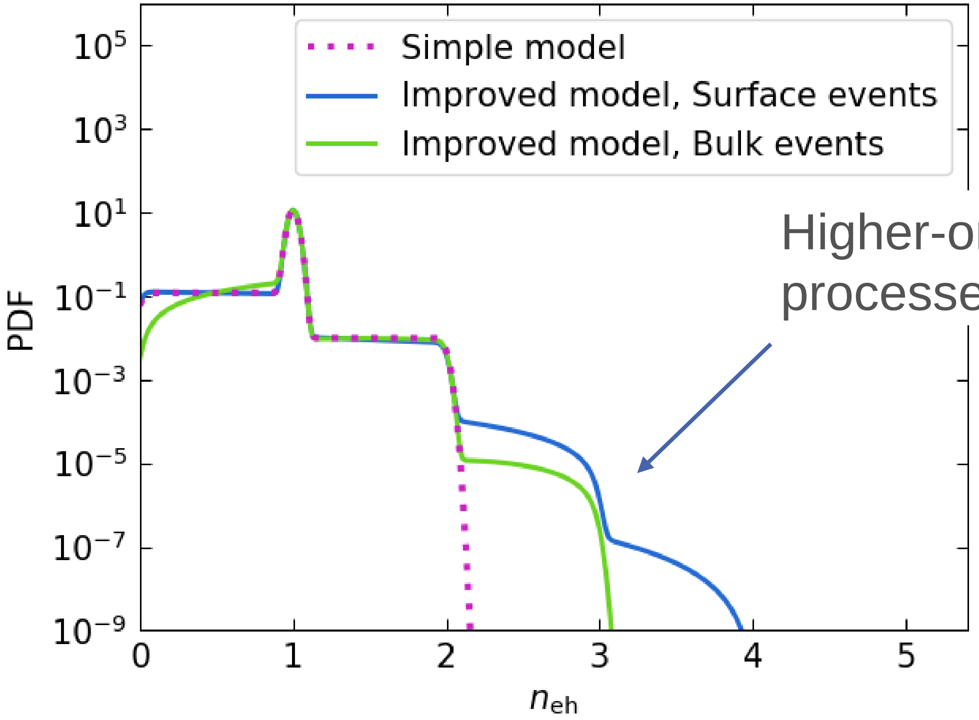
Bulk events: only first-order processes





Simple vs Improved CTII model

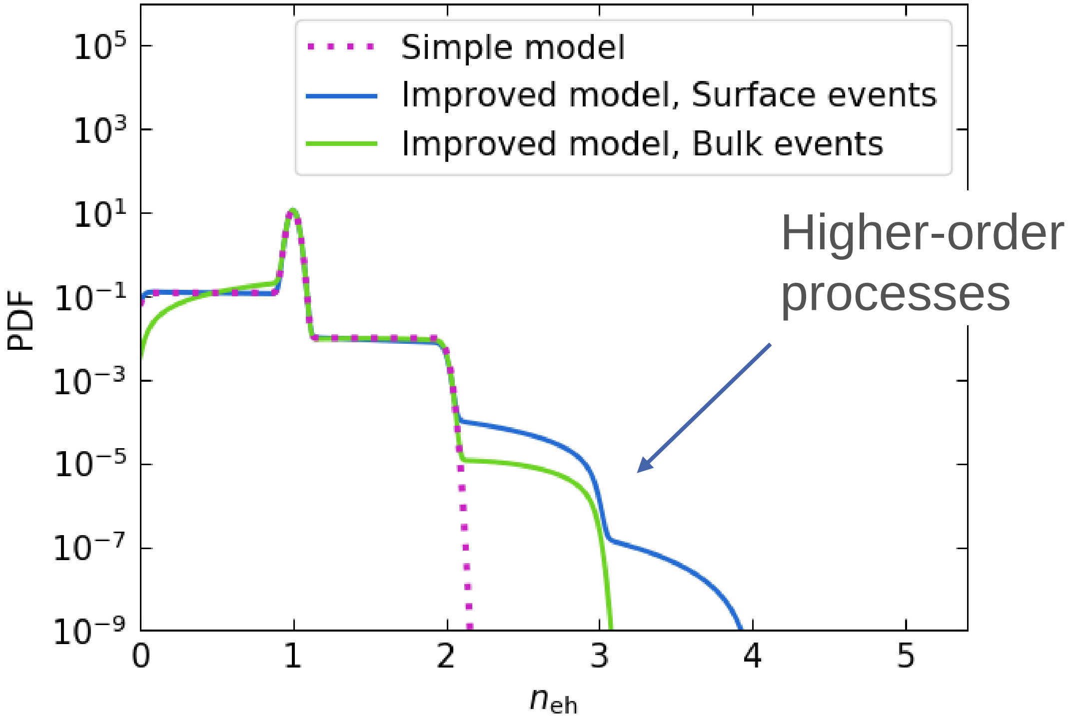
- Adding resolution, comparing to the flat model



Higher-order processes

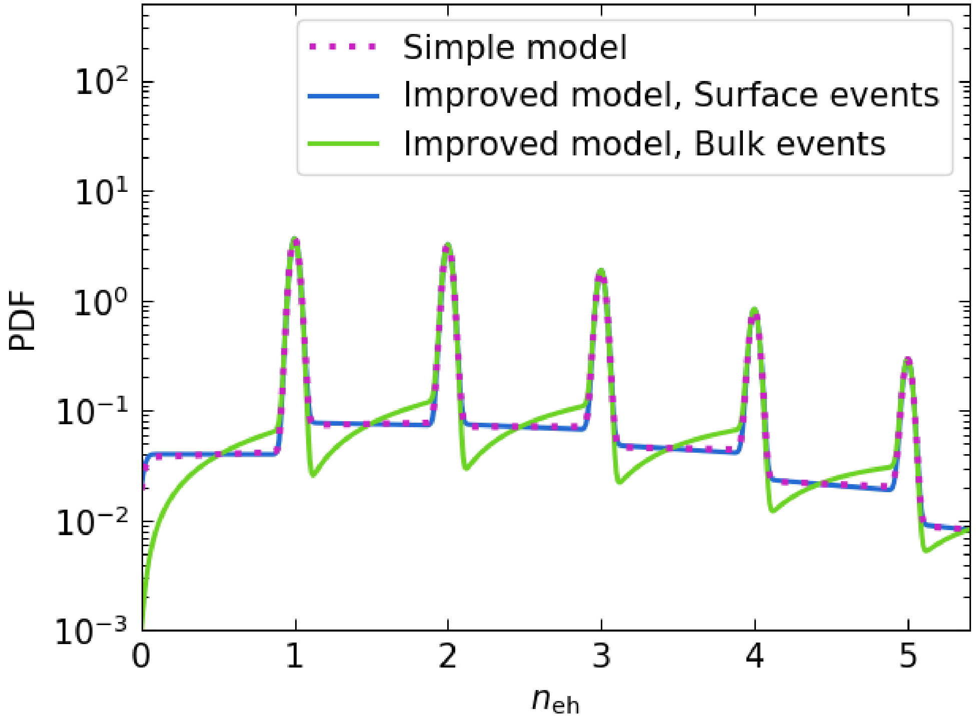
Simple vs Improved CTII model

- Adding resolution, comparing to the flat model



Higher-order processes

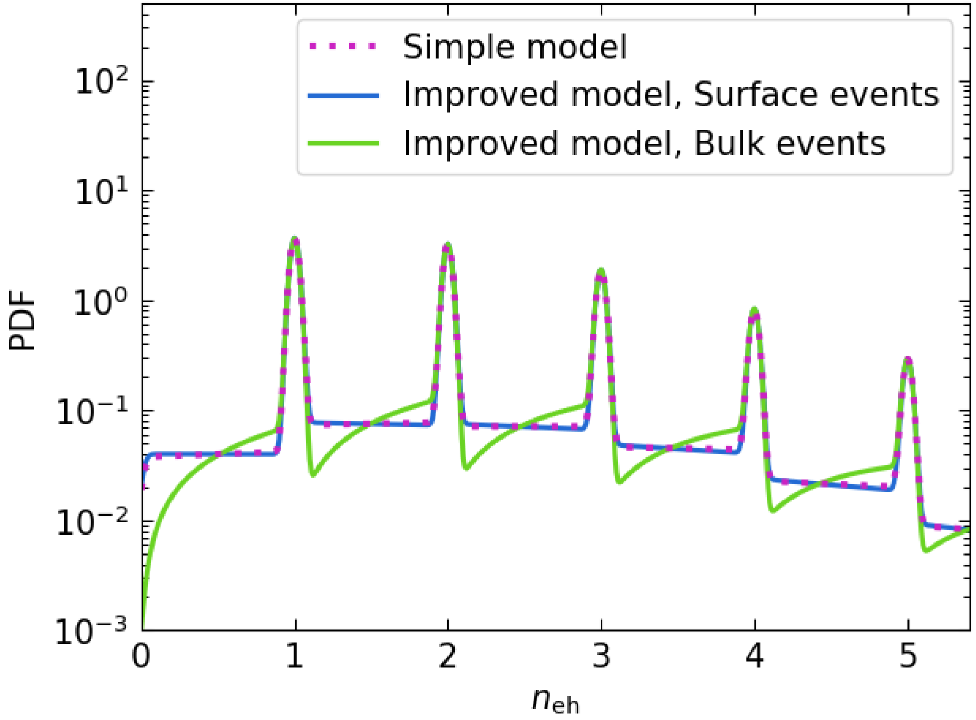
- Getting multi-eh solution by convolving 1eh solutions



Simple vs Improved CTII model

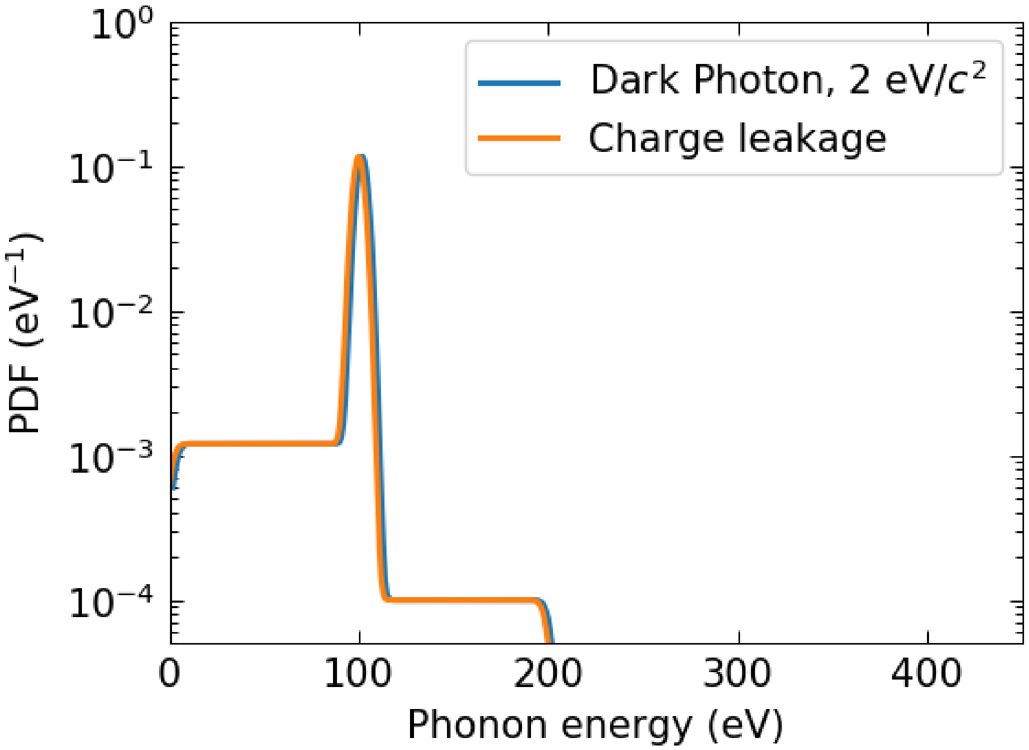
- Getting multi-eh solution by convolving 1eh solutions

- Simple model and Improved model for surface events look very similar
- Significant difference between surface and bulk events!
- Intuitive explanation: combinatorial effect from having 2 charge carriers



Breaking signal-background degeneracy

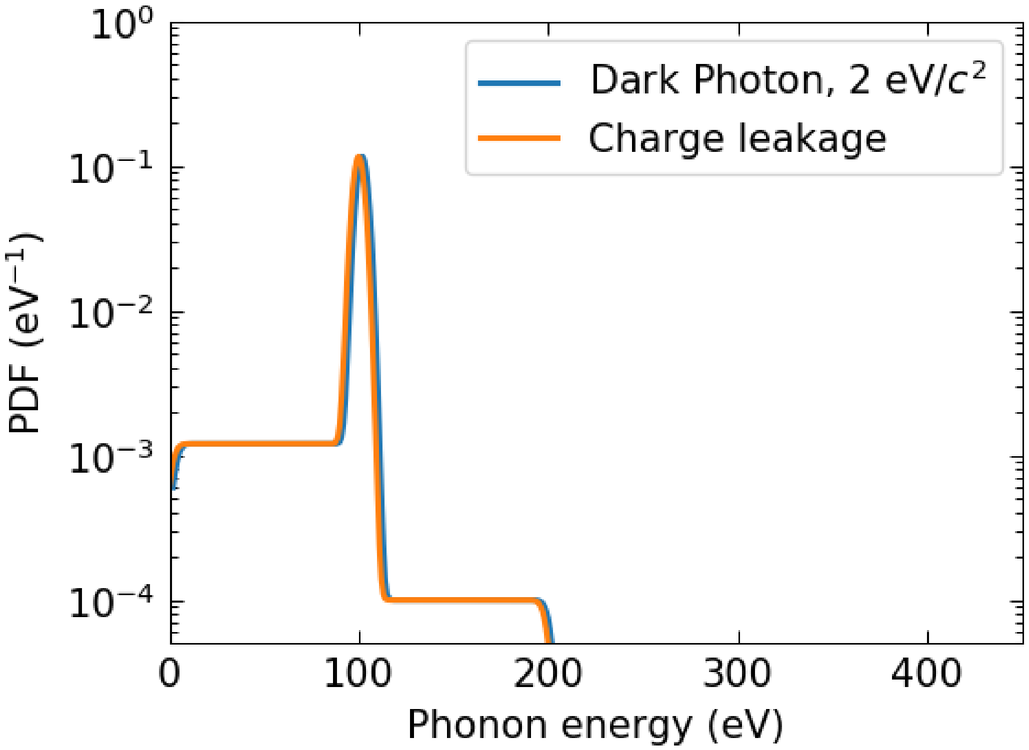
- Simple CTII model



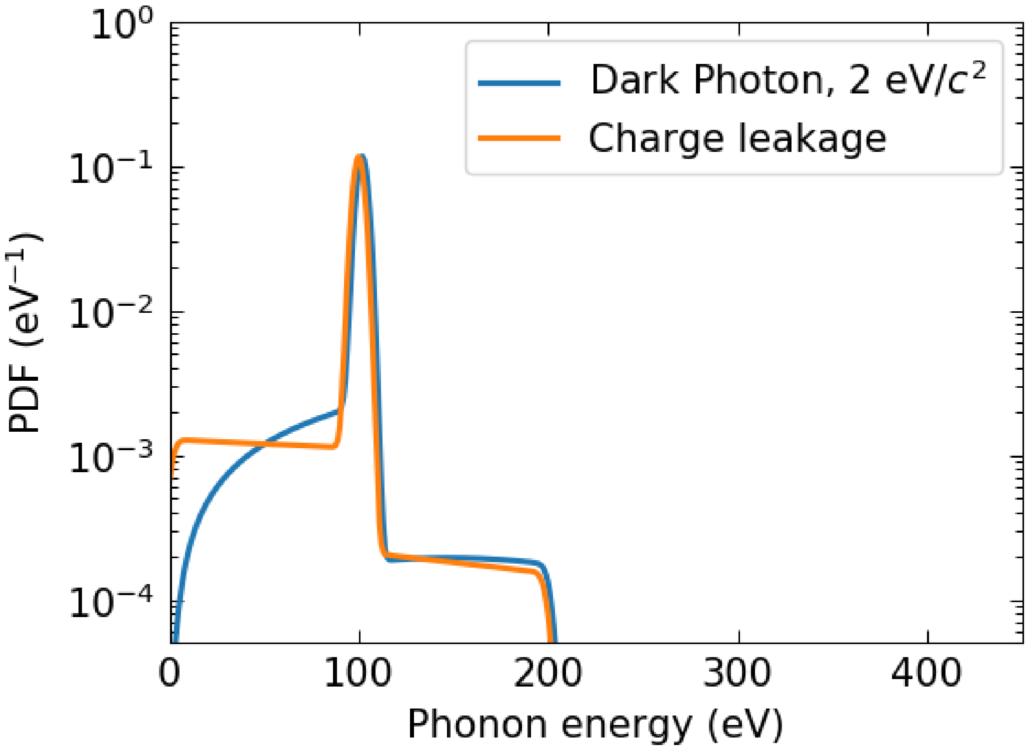
- Light DM is indistinguishable from leakage and surface backgrounds

Breaking signal-background degeneracy

- Simple CTII model

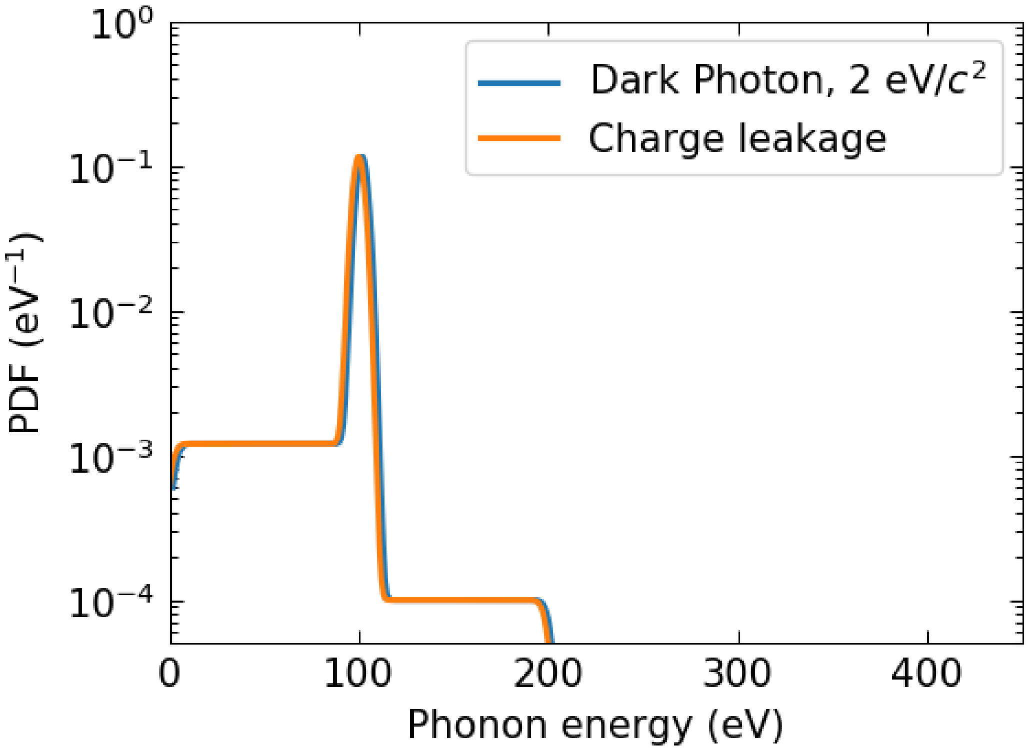


- Improved CTII model

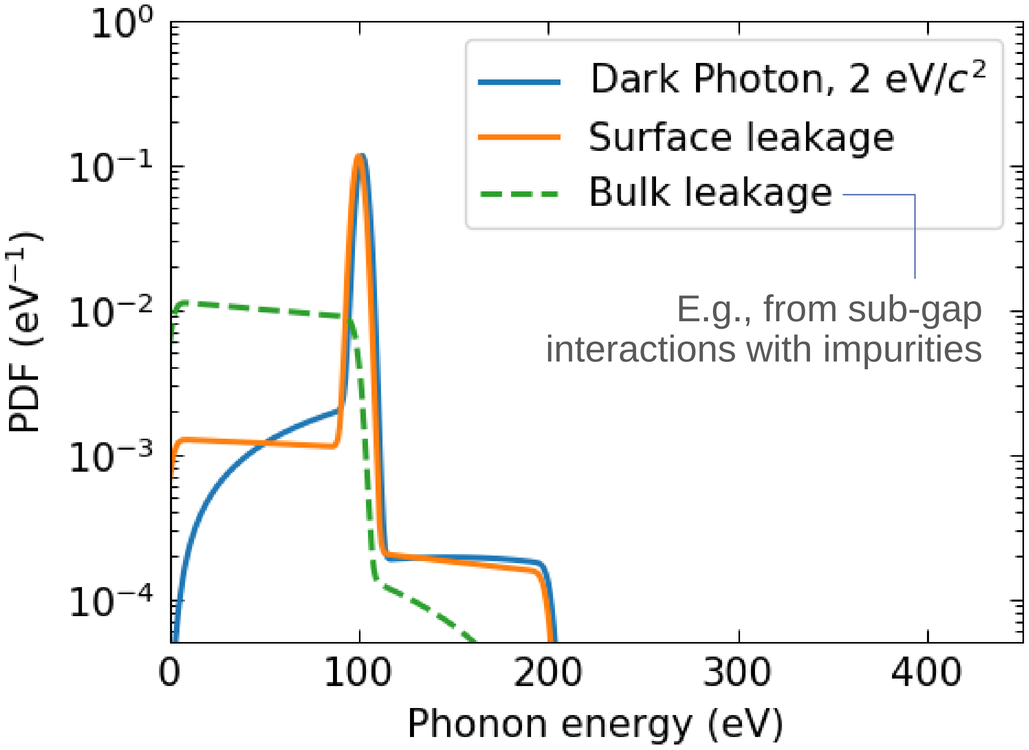


Breaking signal-background degeneracy

- Simple CTII model



- Improved CTII model



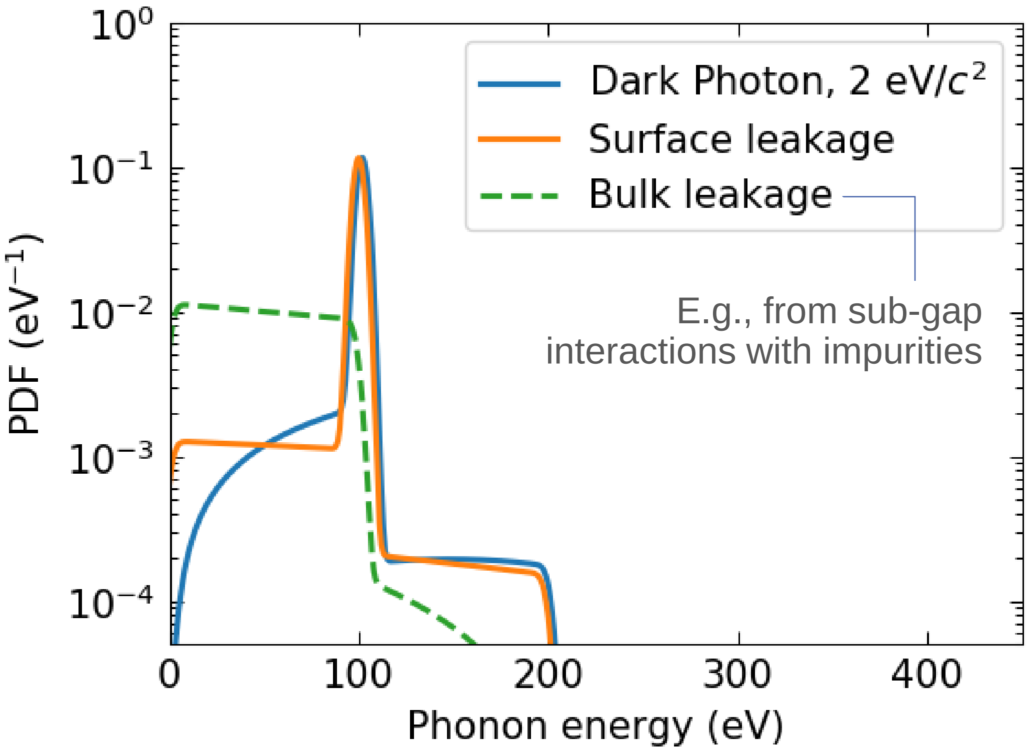
E.g., from sub-gap
interactions with impurities

Breaking signal-background degeneracy

- Bulk events producing eh pairs have a distinct signature in their spectrum
- This can be used in likelihood DM search analyses
- The difference can help us understand the nature of low-energy excess events

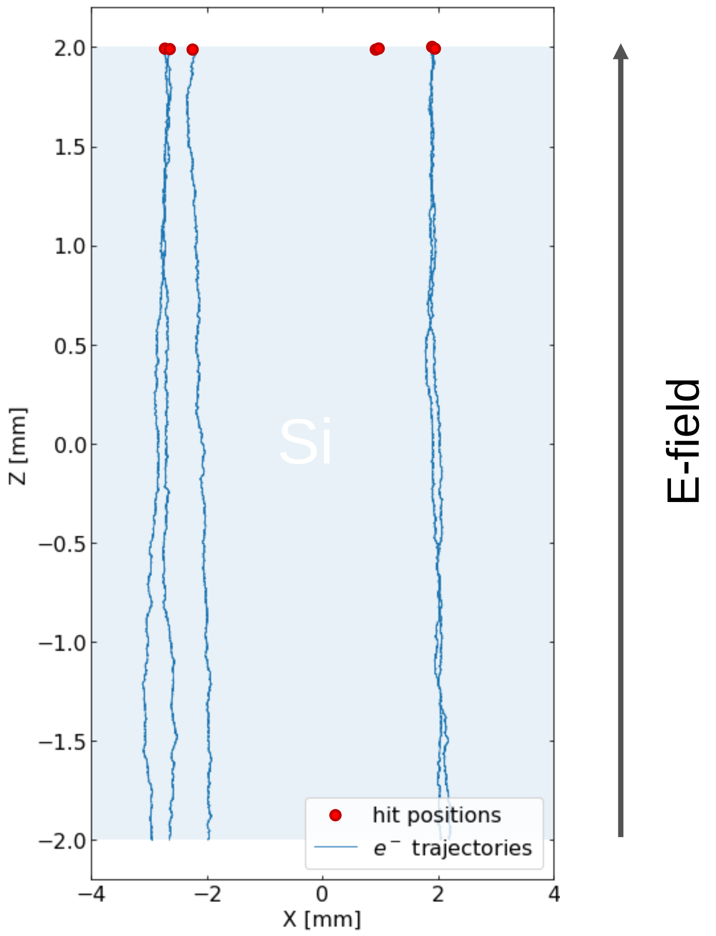
HVeVs are coming to CUTE@SNOLAB early 2024

- Improved CTII model



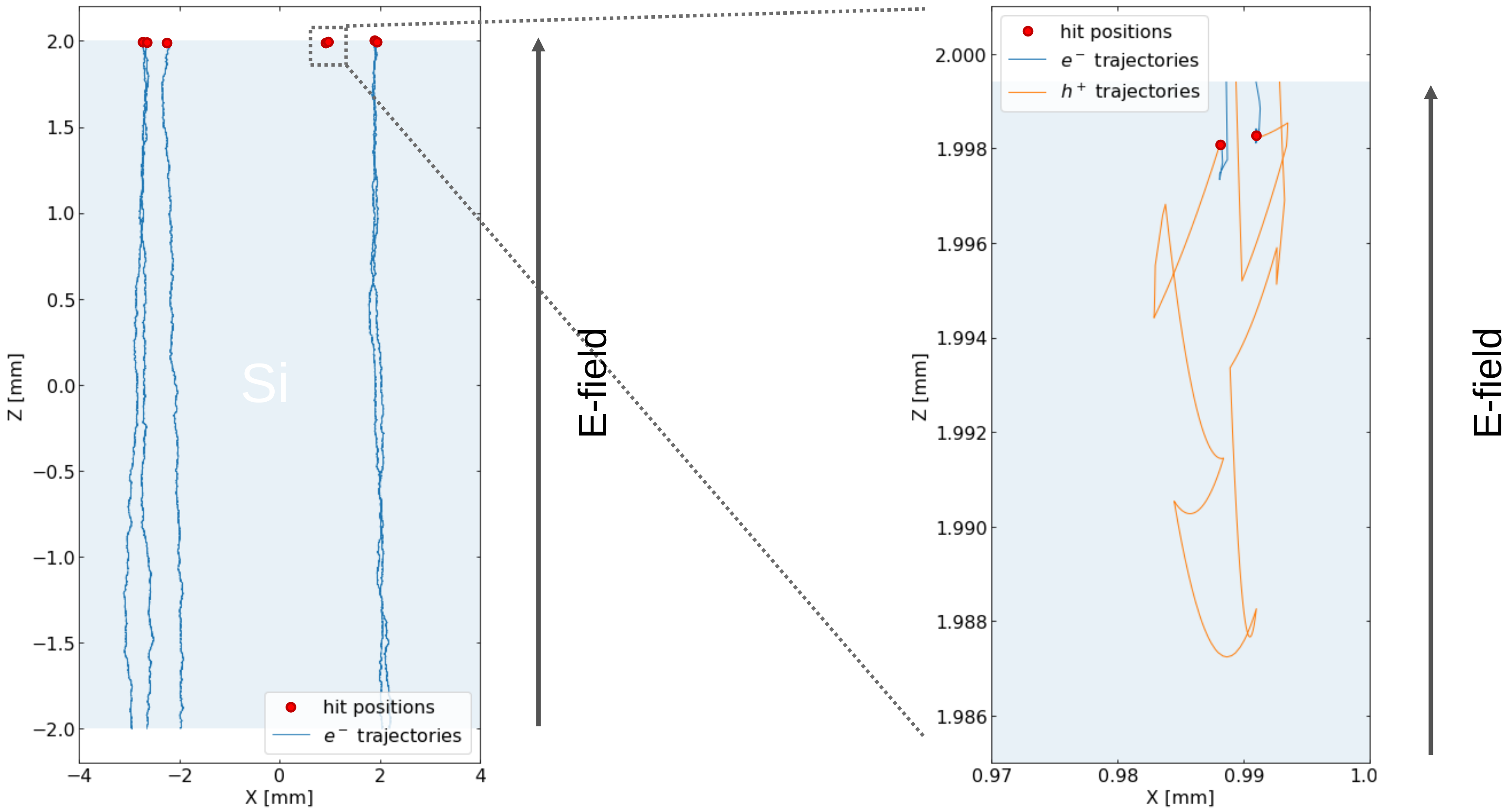
E.g., from sub-gap interactions with impurities

Surface trapping



- G4CMP: Geant4 Condensed Matter Physics
- Production and transport of charges and athermal phonons in cryogenic semiconductors
- M. H. Kelsey *et al*, Nucl. Instrum. Methods Phys. Res. 1055, 168473 (2023)
- G4CMP on GitHub

Surface trapping

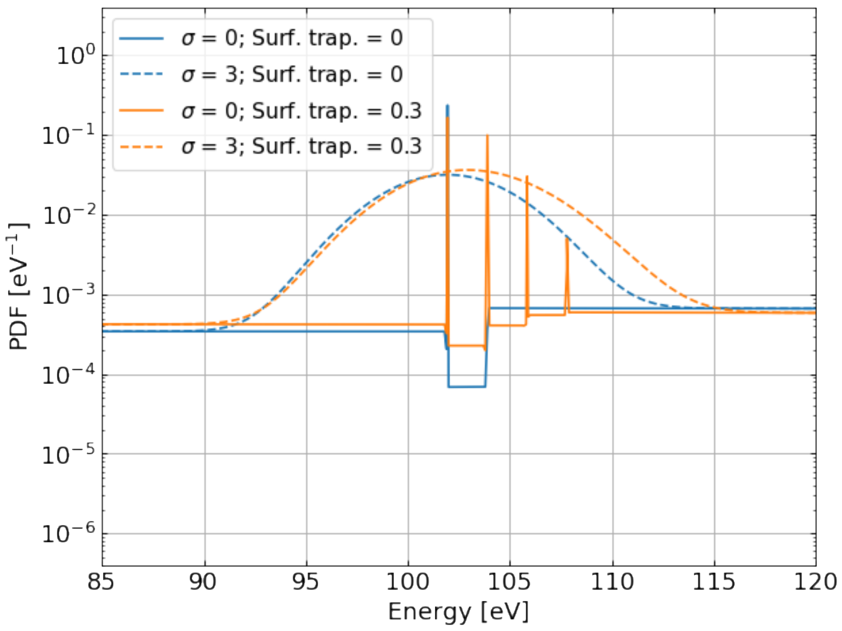


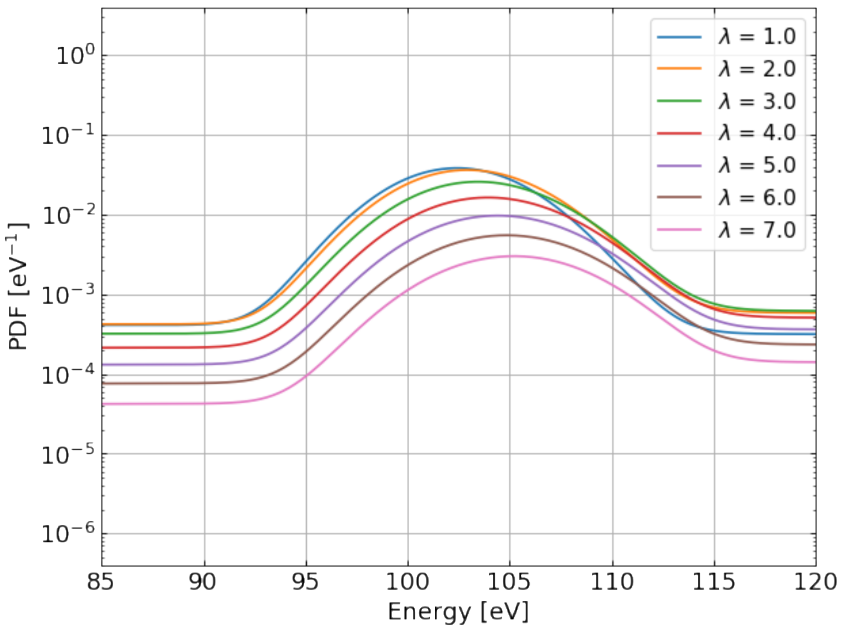
- Both charges trapped on the same surface
- No NTL amplification

Surface trapping: laser events

- Extra peaks from trapped eh pairs

- Peak shift dependent on mean number of photons λ

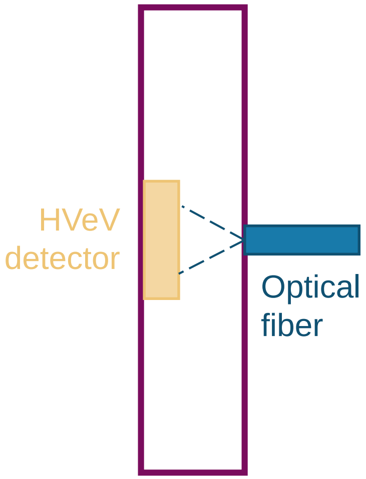


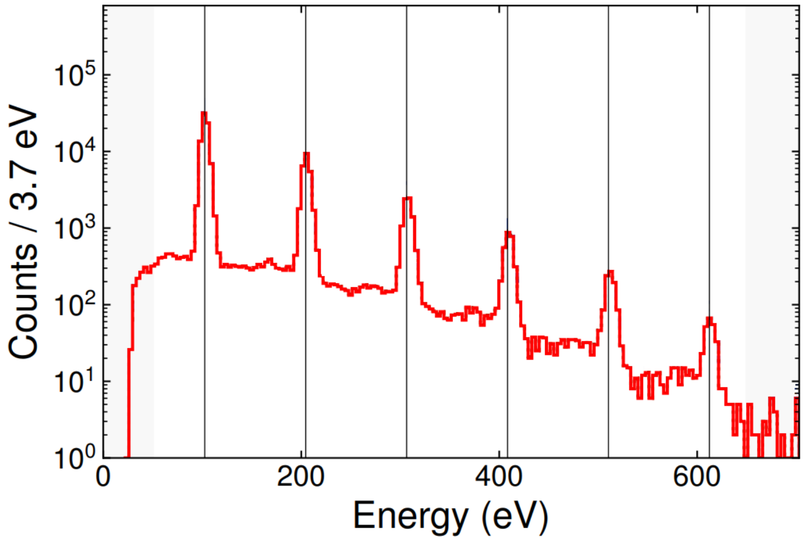


- This effect is observed in HVeV laser data!

Sidewall trapping

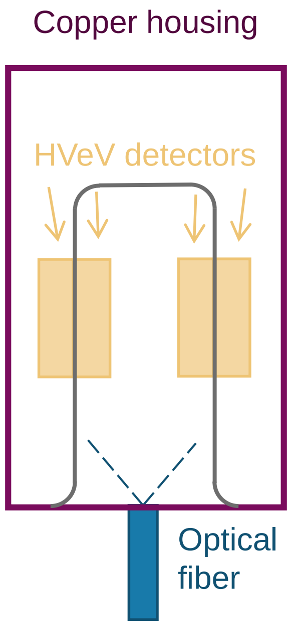
- HVeV Run 2: laser shining onto the crystal’s top surface

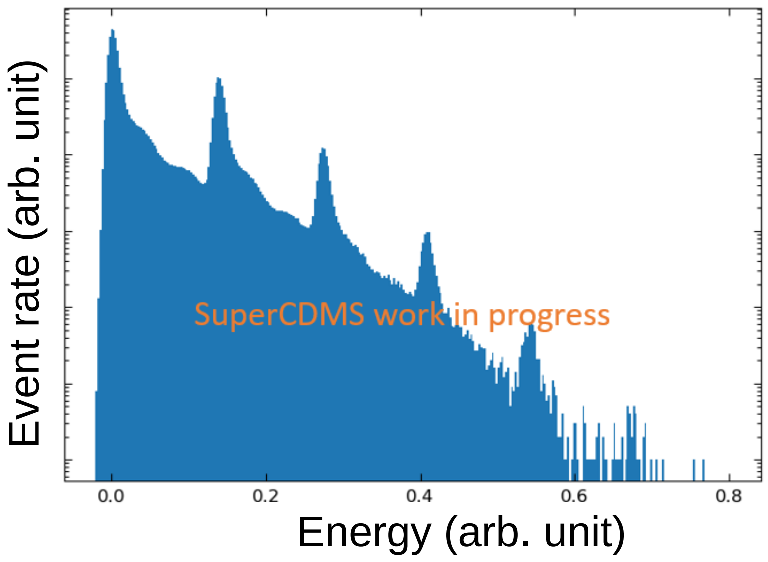




SuperCDMS, Phys.Rev.D 102, 091101 (2020)

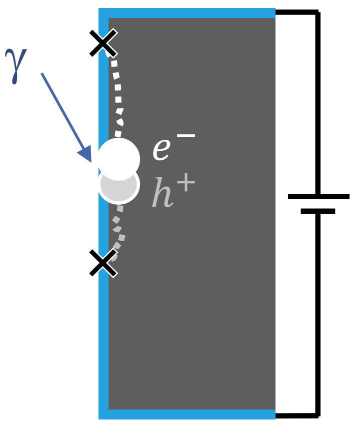
- HVeV Run 3: laser shining into the housing, photons hitting detectors’ sidewalls

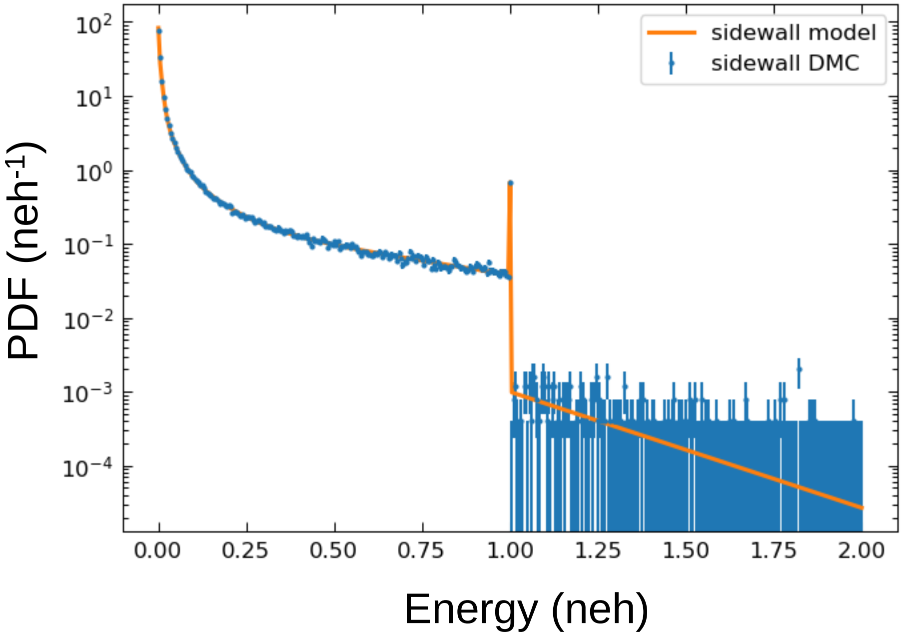




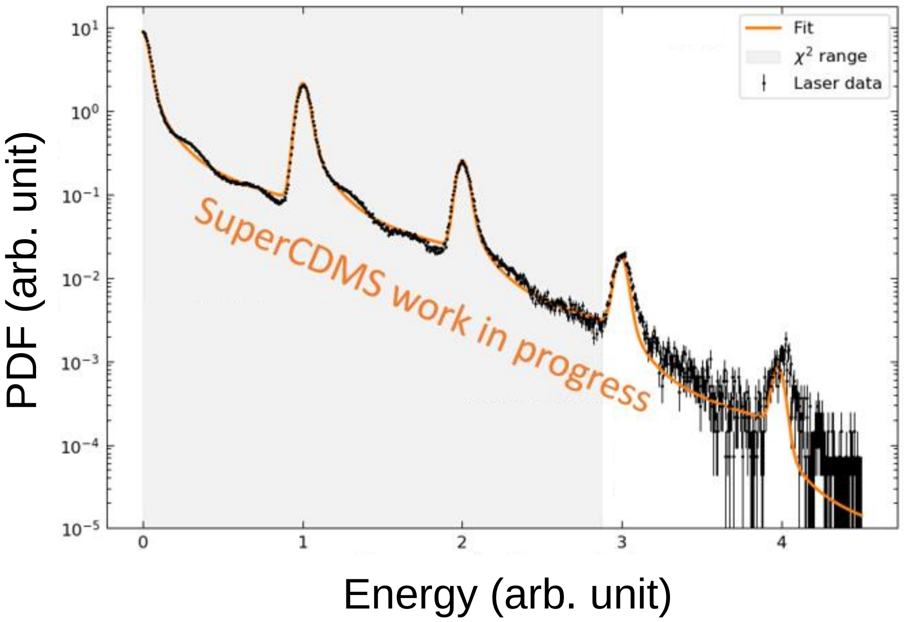
Sidewall trapping

- Simulating sidewall events in G4CMP





- Fitting HVeV Run 3 laser data with CTII + sidewall model



- Further work is required

Summary

- An improved model is developed for bulk CTII and surface trapping effects
- Bulk, top/bottom surface and sidewall events have different NTL energy pdfs
- Correctly accounting for these effects is important for calibration and for modeling DM signals
- The difference can be used for signal-background discrimination and for helping understand the nature of events in the low-energy excess

supercdms.slac.stanford.edu

Follow us on twitter:

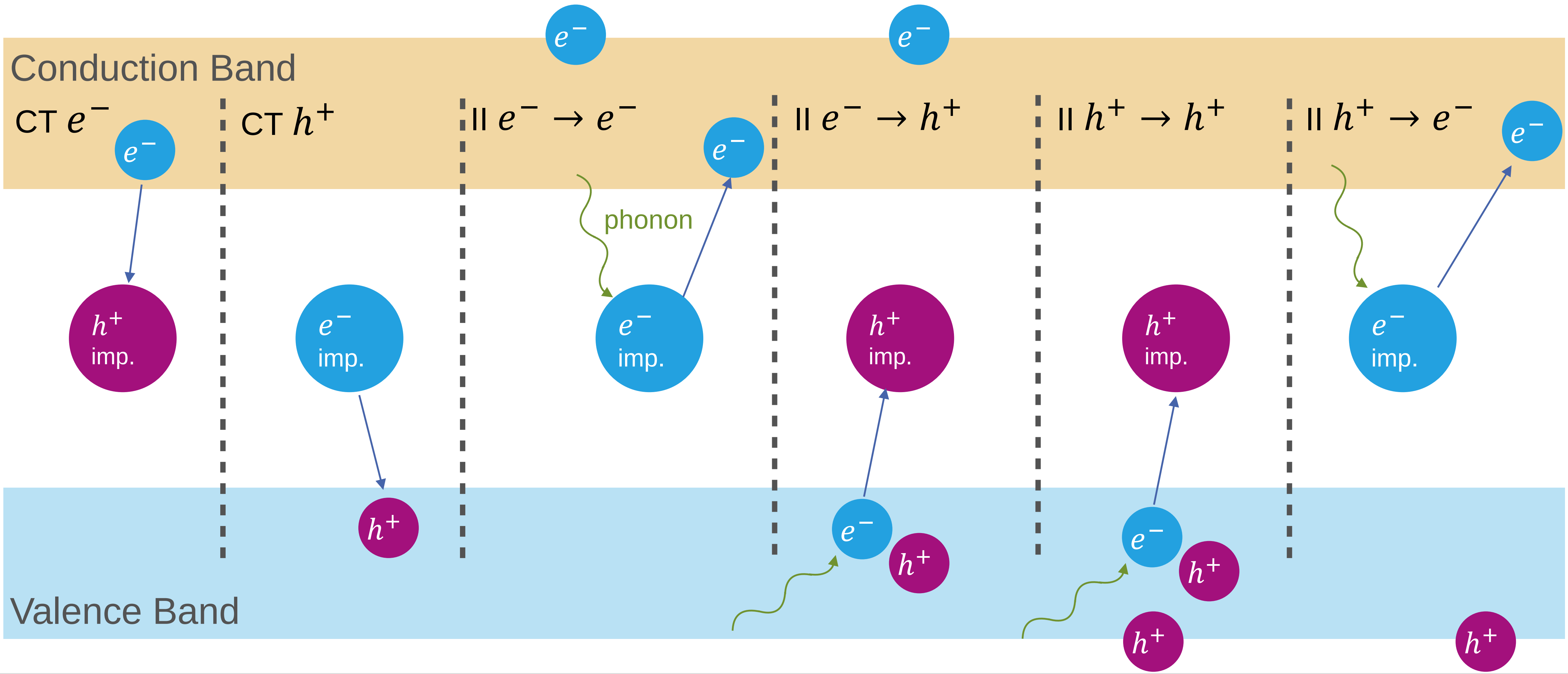
𝕏 @SuperCDMS

CTII paper is coming soon!

Stay tuned for HVeV@CUTE (SNOLAB)

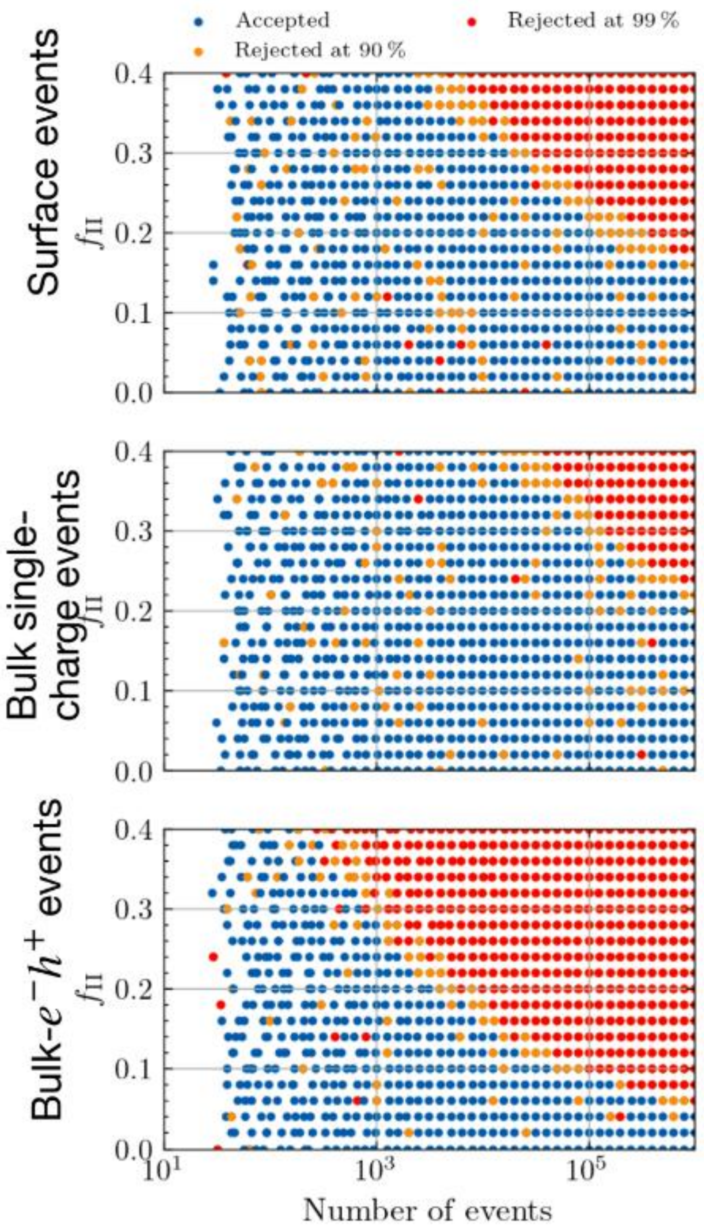
Backup slides

Possible CTII mechanisms



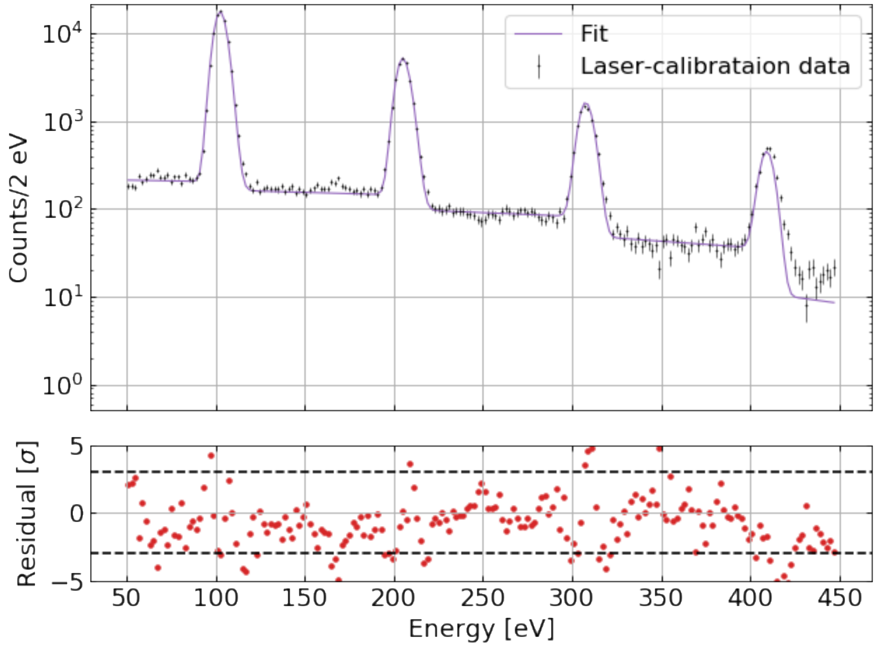
Applicability test

- Kolmogorov-Smirnov test: analytical model vs MC simulation
- At high II probabilities the higher order effects become more important



Improved vs Simple CTII model

Improved model



$\langle \mathrm{pCT} \rangle = 0.118 \pm 0.001$

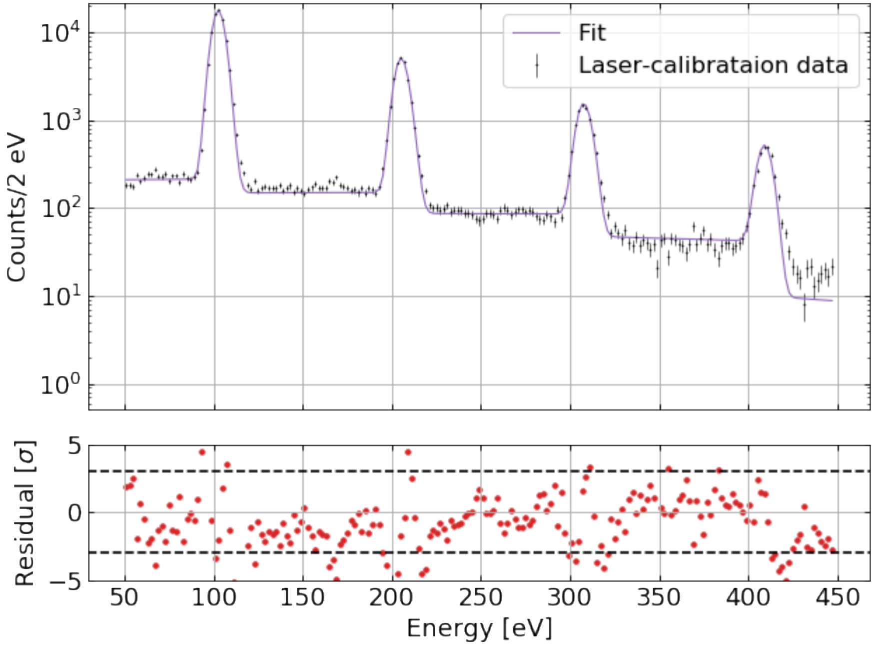
$\langle \mathrm{pII} \rangle = 0.011 \pm 0.005$

$\langle \mathrm{PoissonMean} \rangle = 1.13 \pm 0.03$

$\langle \mathrm{Resolution} \rangle = 3.26 \pm 0.02$ eV

$\langle \mathrm{Reduced}\chi^2 \rangle = 1.50$

Simple model



$\langle \mathrm{pCT} \rangle = 0.119 \pm 0.001$

$\langle \mathrm{pII} \rangle = 0.001 \pm 0.001$

$\langle \mathrm{PoissonMean} \rangle = 0.701 \pm 0.004$

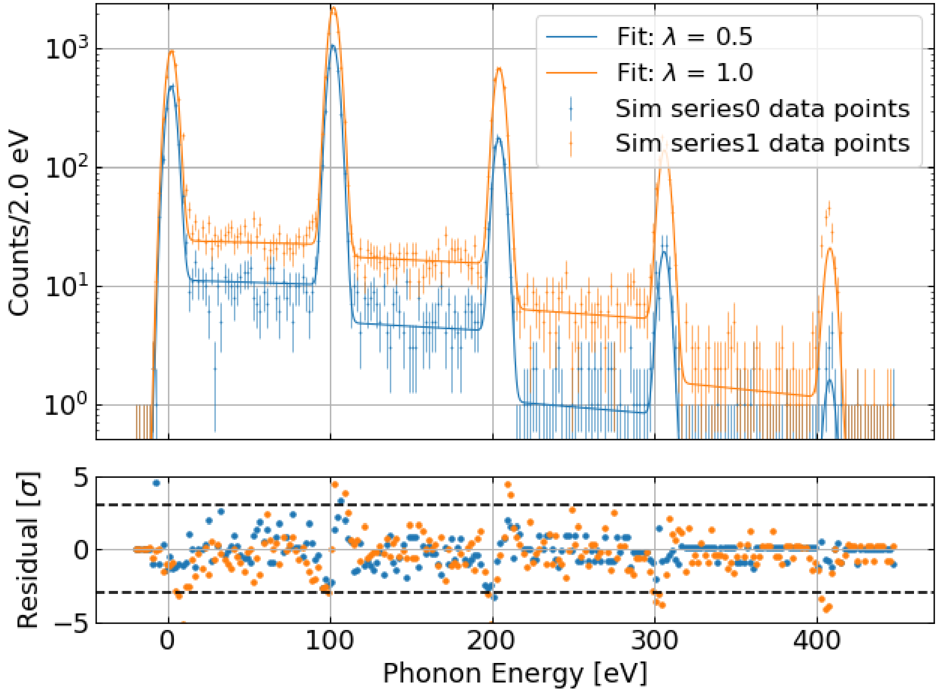
$\langle \mathrm{Resolution} \rangle = 3.382 \pm 0.009$ eV

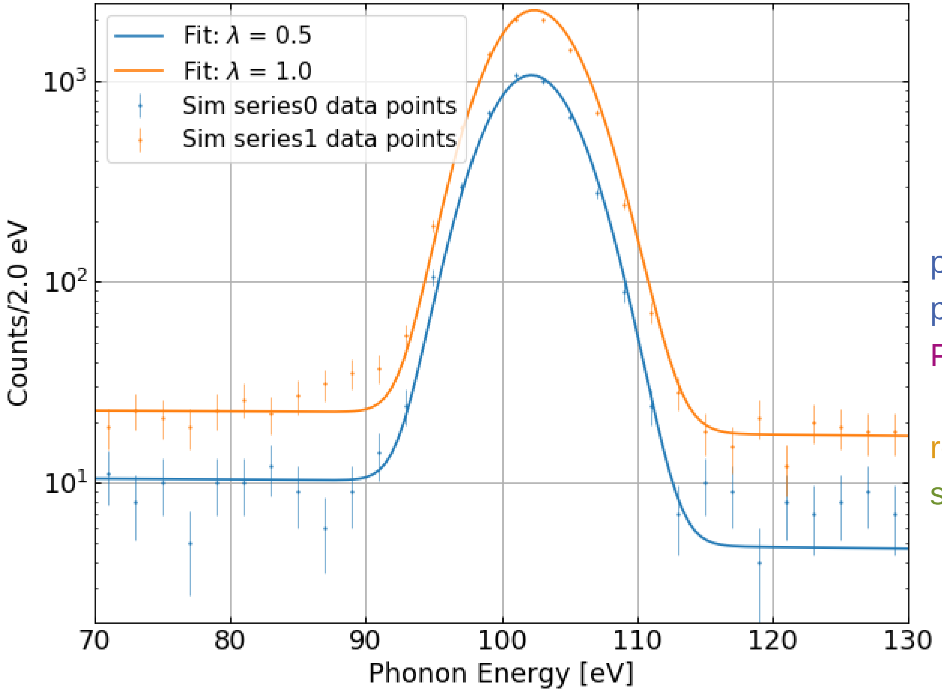
Reduced $\chi^2 = 1.70$

HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102, 091101 (2020)

Surface trapping probability measurement

- Fitting to multiple laser-calibration data series to obtain CT/II probabilities, Poisson means λ, resolution, and surface trapping probability





$p_{CT} = 0.113 \pm 0.003$

$p_{II} = 0.010 \pm 0.002$

Poisson means $\lambda = 0.532 \pm 0.017,$

0.980 ± 0.015

resolution = 3.018 ± 0.017 eV

surf. trap. prob = 0.297 ± 0.004

Bulk events example: dark matter models

- Simulation of DM-electron scattering at various masses with $\overline{\sigma}_e = 10^{-33}$ and ~3 g-days exposure