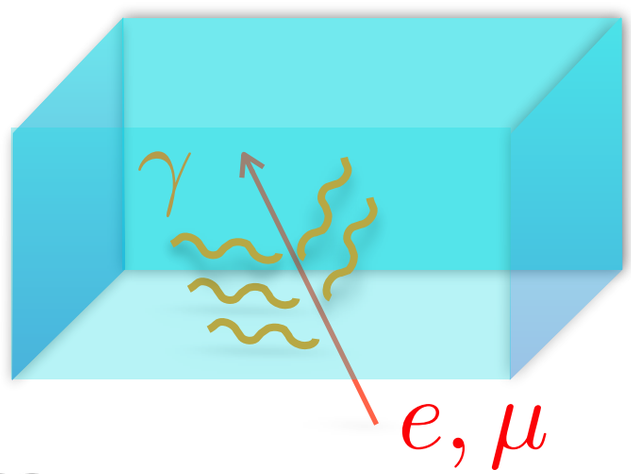
TRACK-INDUCED LOW ENERGY BACKGROUNDS

Daniel Egana-Ugrinovic
Simons Fellow
Perimeter Institute

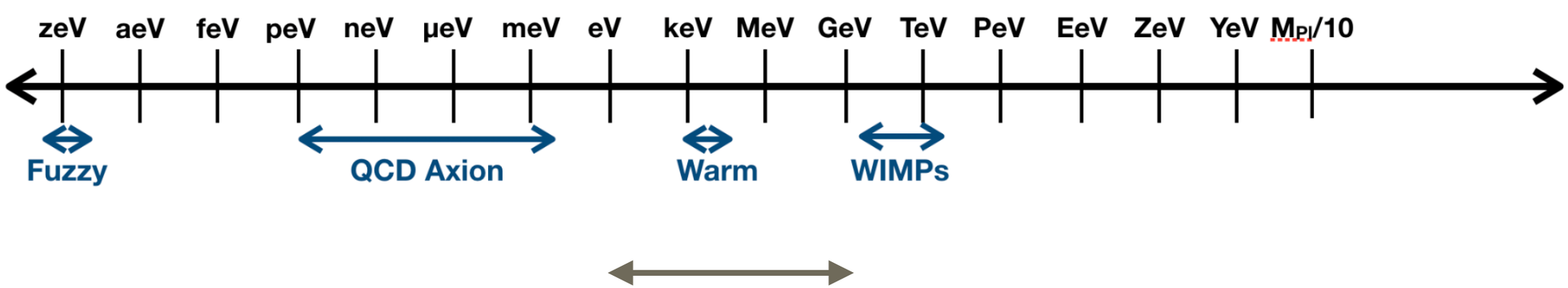
arXiv: 2011.13939 (PRX 12 (2022) 1, 011009)
and
arXiv: soon



In collaboration with
Peizhi Du
Rouven Essig
Mukul Sholapurkar

degana@perimeterinstitute.ca

DARK MATTER WITH SUB-GEV MASS

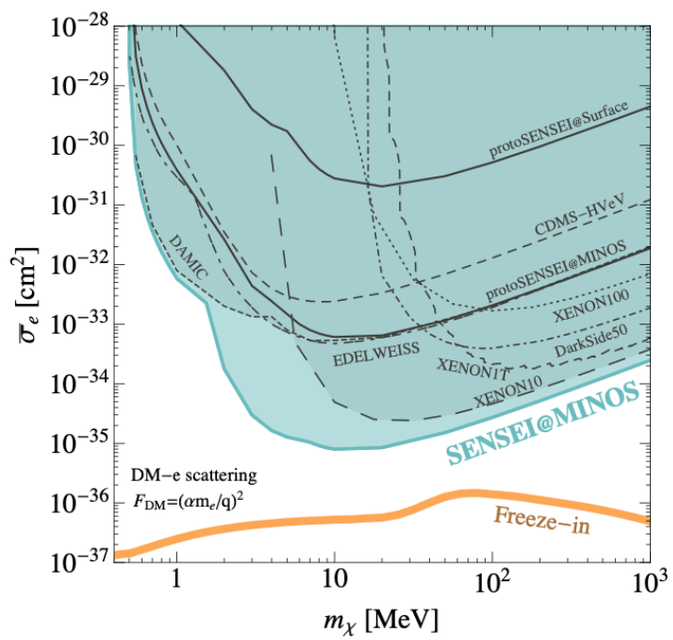


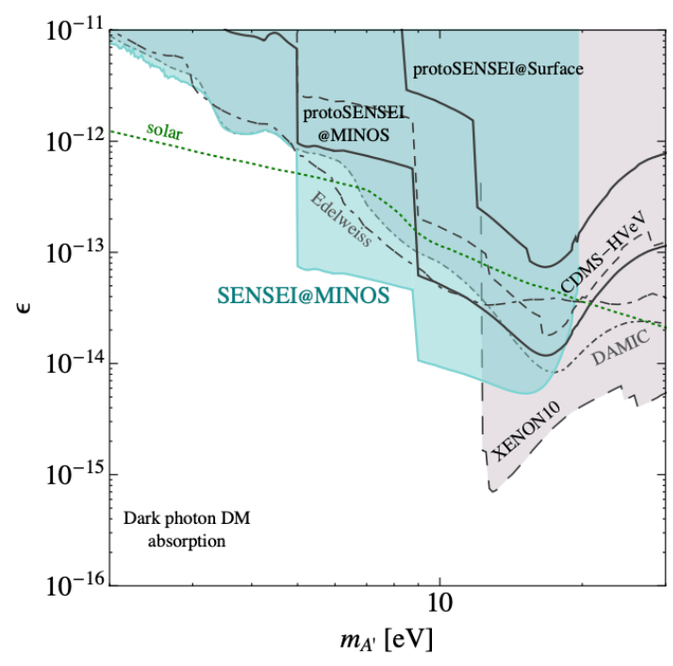
Here we concentrate on dark matter in the eV to GeV range

$$E_{det} \leq \frac{1}{2} m_{DM} v_{DM}^2 \sim \frac{1}{2} \mathrm{eV} \left[\frac{m_{DM}}{1\,\mathrm{MeV}} \right]$$

LIGHT-DARK MATTER DETECTORS

2004.11378 (SENSEI coll.)





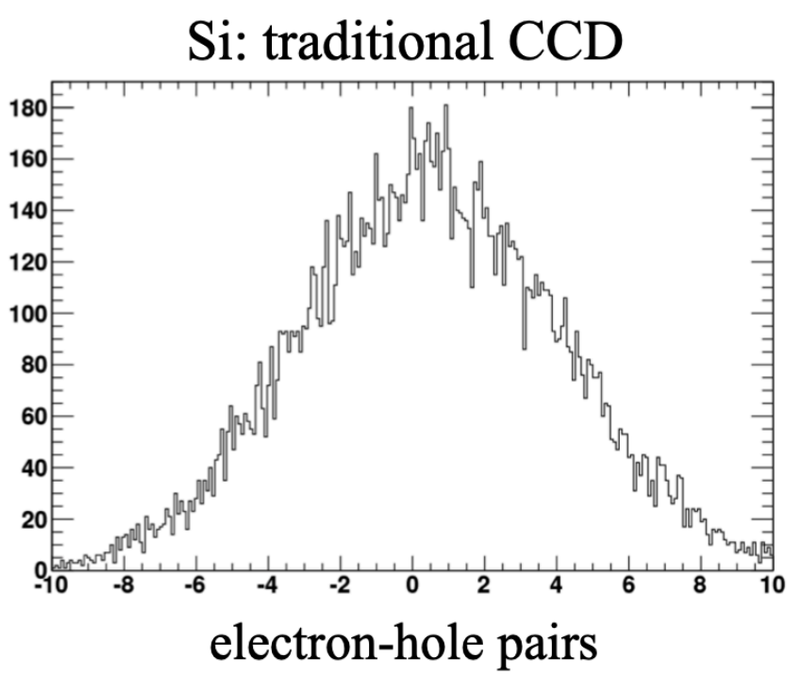
A plethora of new experiments are aiming for this mass range:
SENSEI
SuperCDMS (2005.14067)
EDELWEISS (2003.01046)
DAMIC (1907.12628)
LAMPOST,

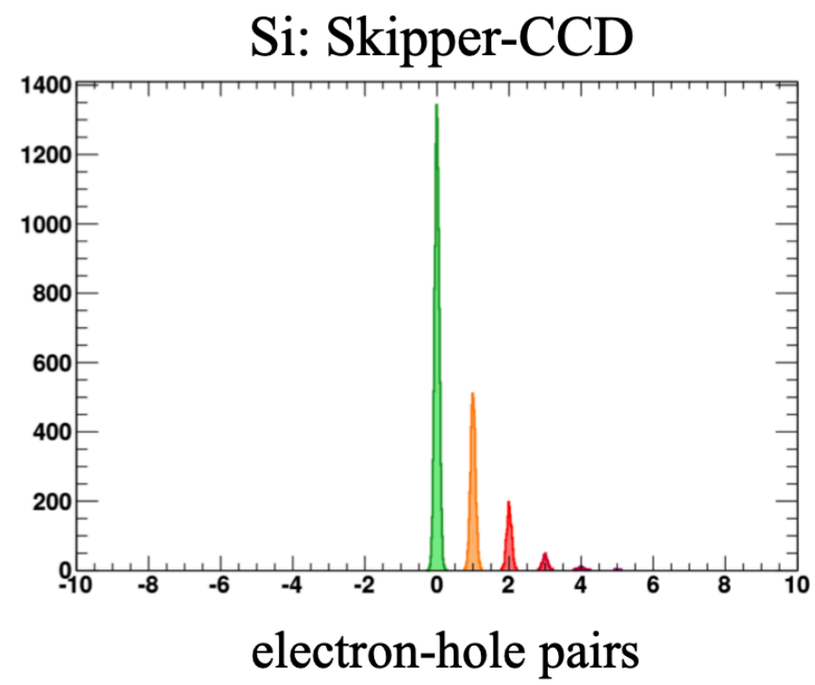
(plus many running and proposed Ones:
SENSEI and SuperCDMS at SNOLAB,
Damic-M,
Oscura, SPICE…)

See also Kurinsky, Li's talk on Wed. and Romani, Chavarría later today

DARK MATTER WITH SUB-GEV MASS

On the experimental side:





Essig, ICHEP 2020

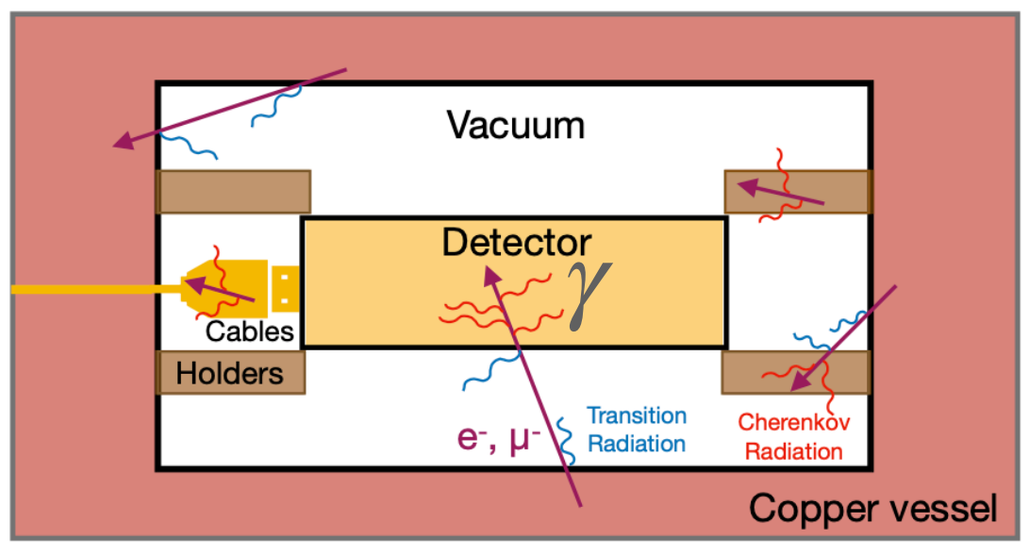
Energy depositions as low as an eV are now detectable in ~10 gram detectors

TRACK-INDUCED BACKGROUNDS

Cherenkov radiation

Luminescence

DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
PRX 12 (2022) 1, 011009



*~hundreds of tracks/g*day at SENSEI, ~10 thousand /g*day at SuperCDMS HVeV*

OUTLINE

1. Theory basics
    1. Cherenkov radiation
    2. Luminescence
2. Relevance at experiments
    1. SENSEI
    2. SuperCDMS HVeV
    3. LAMPOST
    4. Future: SuperCDMS SNOLAB
    5. Qubit decoherence?

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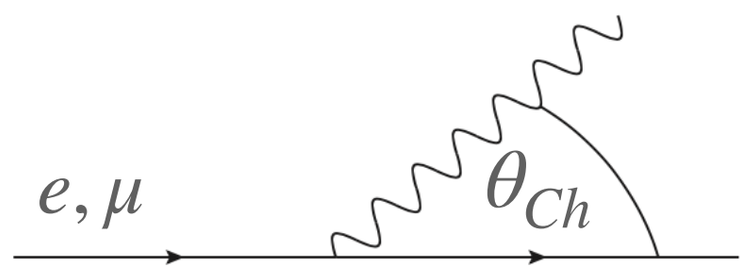
CHERENKOV RADIATION

- Is the spontaneous emission of radiation by tracks passing through non-conducting materials.



$$v^2 \varepsilon(\omega) > 1$$

Cherenkov condition

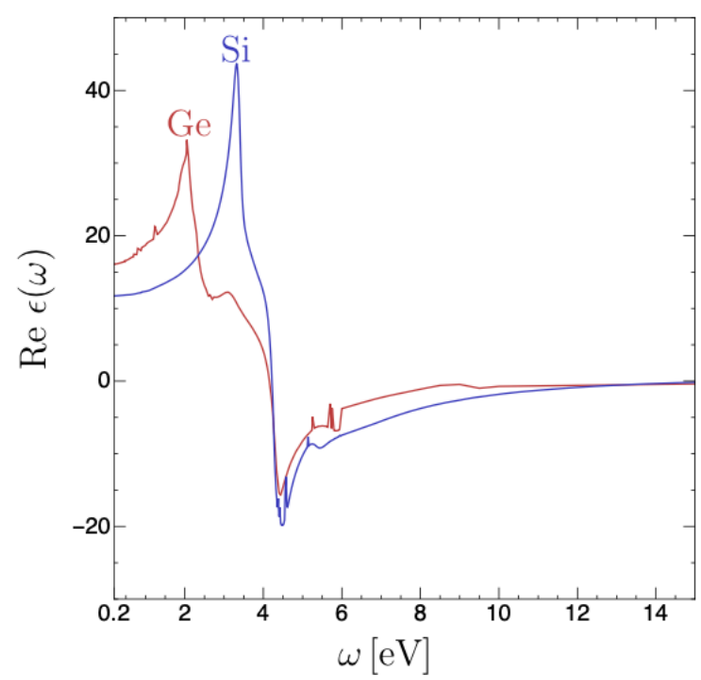
$$\frac{dN_\gamma}{d\omega dx} = \alpha \left(1 - \frac{1}{v^2 \varepsilon(\omega)} \right)$$

Rate

WHY IS CHERENKOV RADIATION RELEVANT?

1. It leads to photons with energies matching the detector thresholds

$$v^2\varepsilon(\omega) > 1 \longrightarrow \varepsilon(\omega) > 1$$ *necessary condition*



DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
PRX 12 (2022) 1, 011009

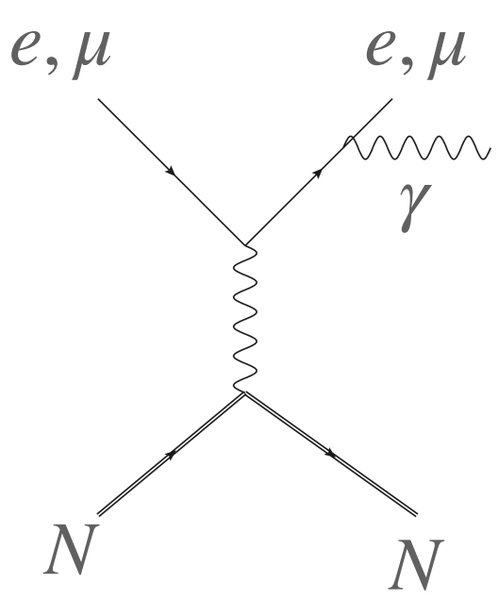
Cherenkov photons have energies $\omega \lesssim 4\,\mathrm{eV}$

WHY IS CHERENKOV RADIATION RELEVANT?

2. It arises at leading order in electrodynamics

$$\frac{dN_\gamma}{d\omega dx} \sim \alpha \qquad \textit{(for } \varepsilon(\omega) \gg 1\textit{)}$$

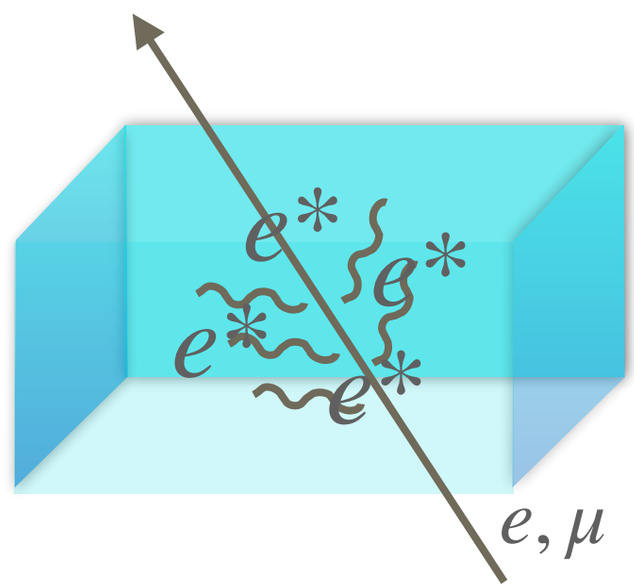
$$N_\gamma \sim 4\left[\frac{\Delta\omega}{1\,\mathrm{eV}}\right]\left[\frac{\Delta x}{100\,\mu\mathrm{m}}\right]$$



As opposed to bremsstrahlung, $\sim \alpha^3$

LUMINESCENCE

- Results in the emission of photons/phonons as excited electrons in a material return to the ground state



LUMINESCENCE

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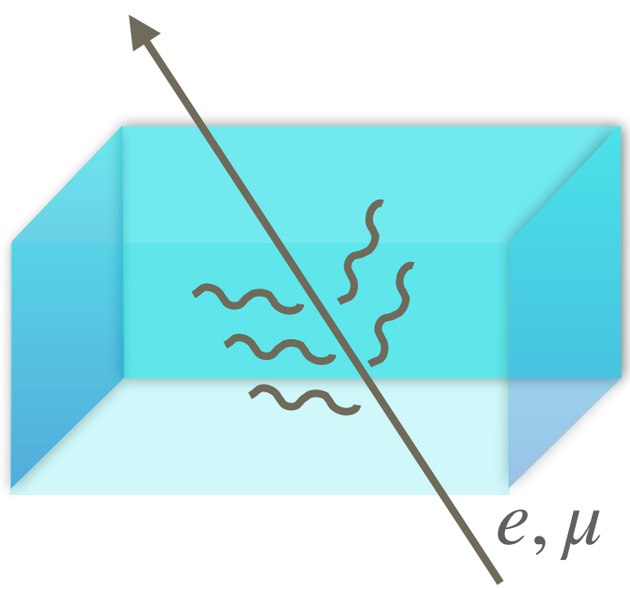
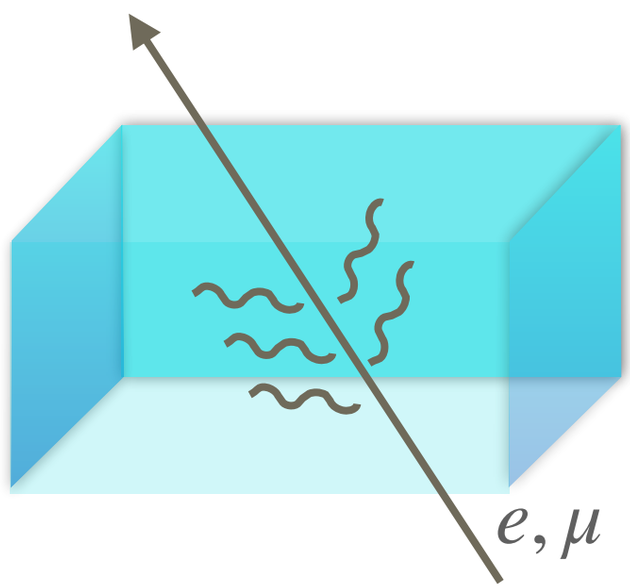


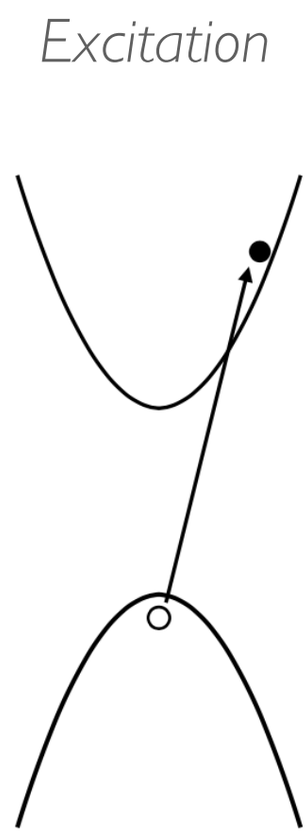
Luminescence or scintillation

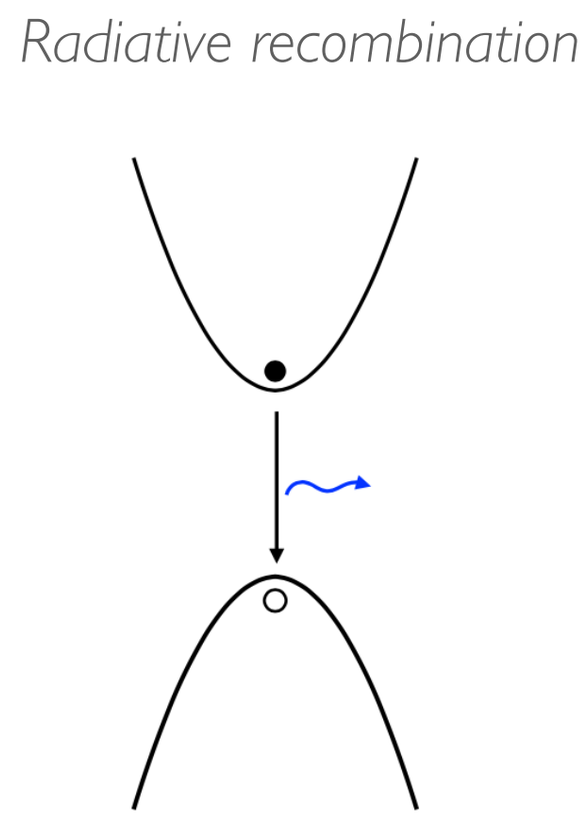
Slow: phosphorescence, afterglow

LUMINESCENCE FROM RADIATIVE RECOMBINATION

- Results in the emission of photons/phonons as excited electrons in a material return to the ground state



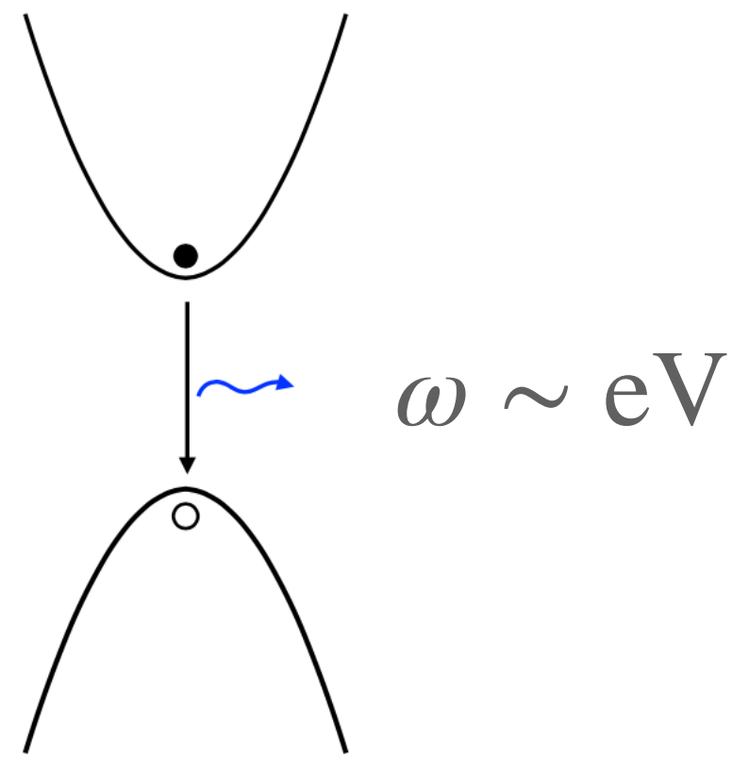




WHY IS LUMINESCENCE RELEVANT?

1. It leads to photons with energies matching the detector thresholds

Energy gaps in semiconductors are typically of order $\sim \mathrm{eV}$



WHY IS LUMINESCENCE RELEVANT?

2. Tracks leave most of their energy in materials by exciting electron-hole pairs ("ionization")

DEU, Du, Essig, Sholarpurkar
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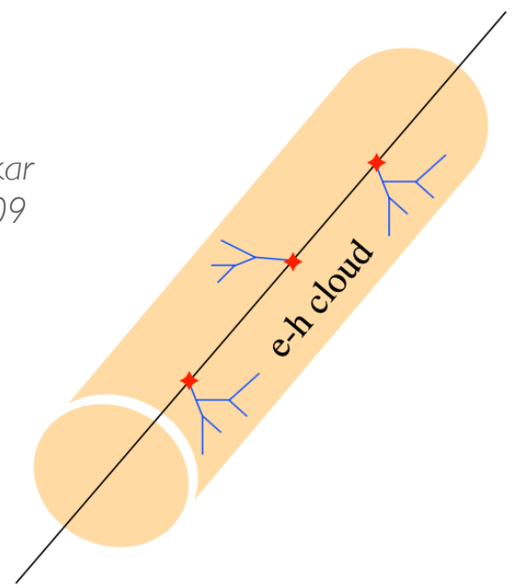

A single $200\,\mathrm{keV}$ *electron track leaves*

$$N_{eh} \sim 6 \times 10^4 \quad !!$$

$$\frac{\partial n_h}{\partial t} = -\nabla . \vec{j}_h - \Gamma_h^{\mathrm{Auger}} - \Gamma_h^{\mathrm{radiative}}$$

Radiative rates are <u>highly material dependent</u>

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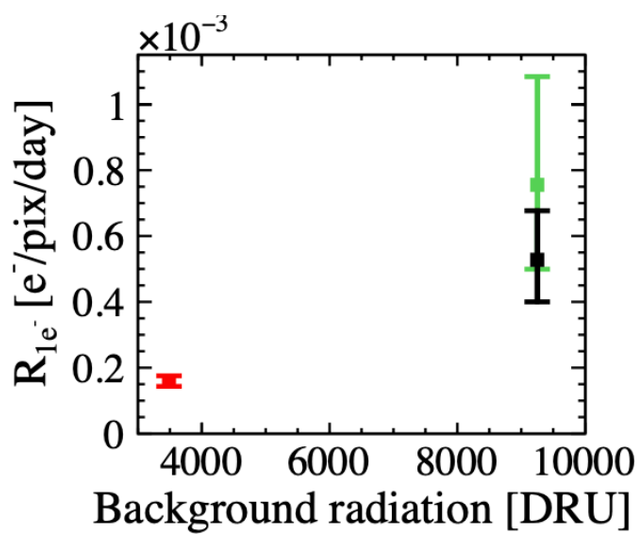
SENSEI

SENSEI (2020 DATA)

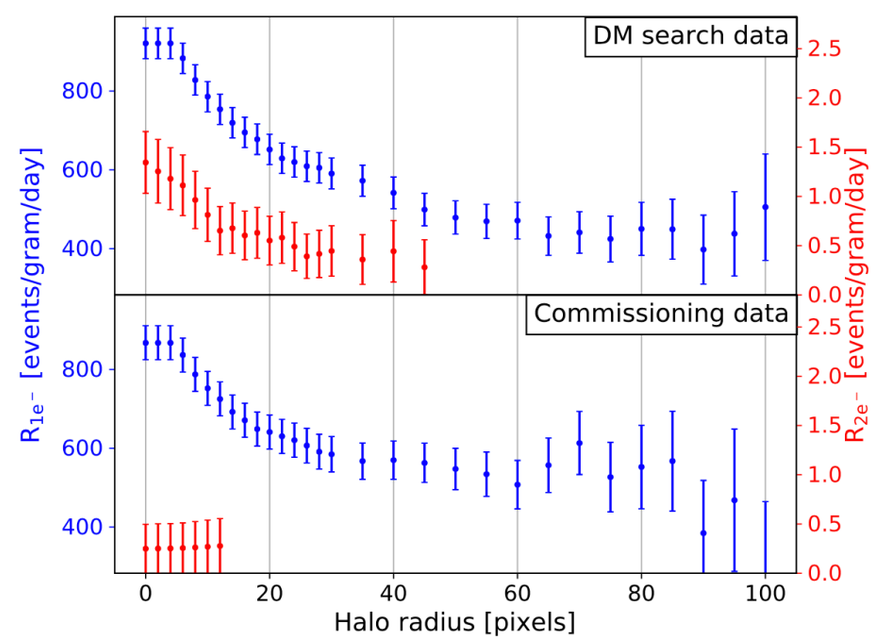
2004.11378 (SENSEI coll.)

$$R_{1e} = 450/\mathrm{g} - \mathrm{day}$$

Depends on track rate



Depends on halo mask

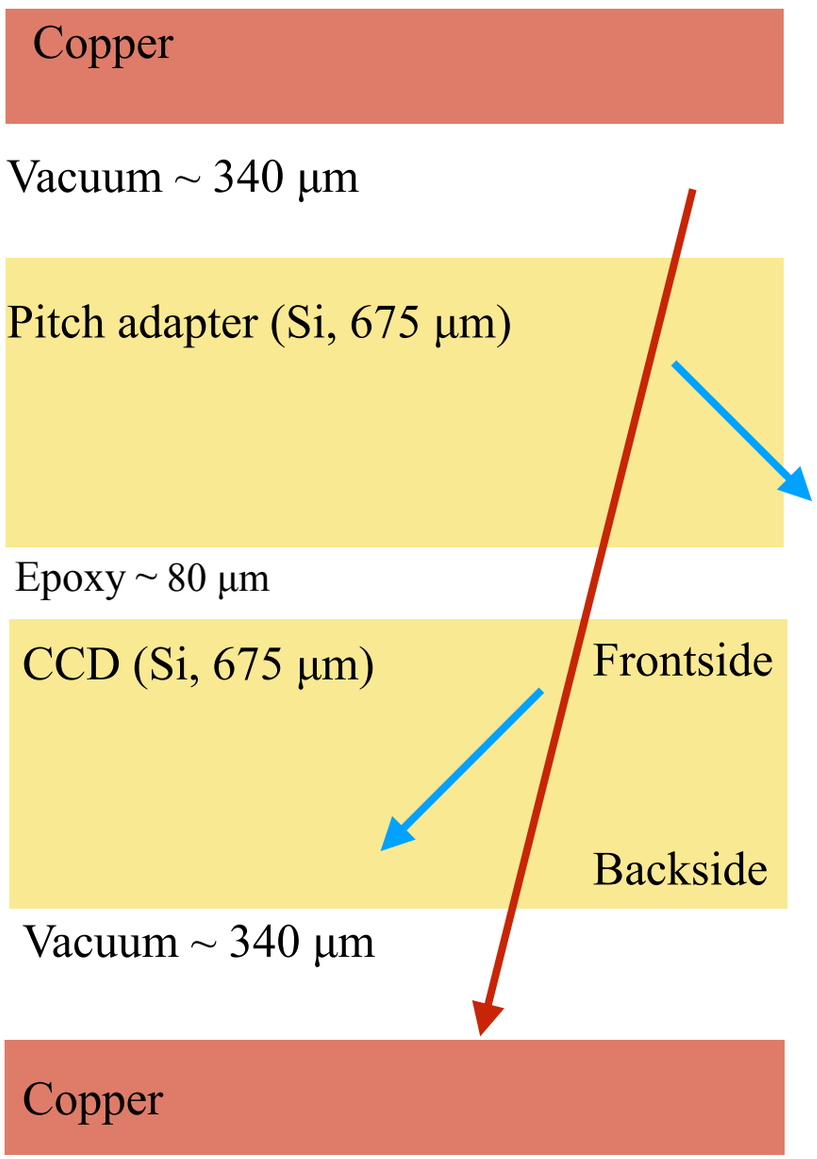


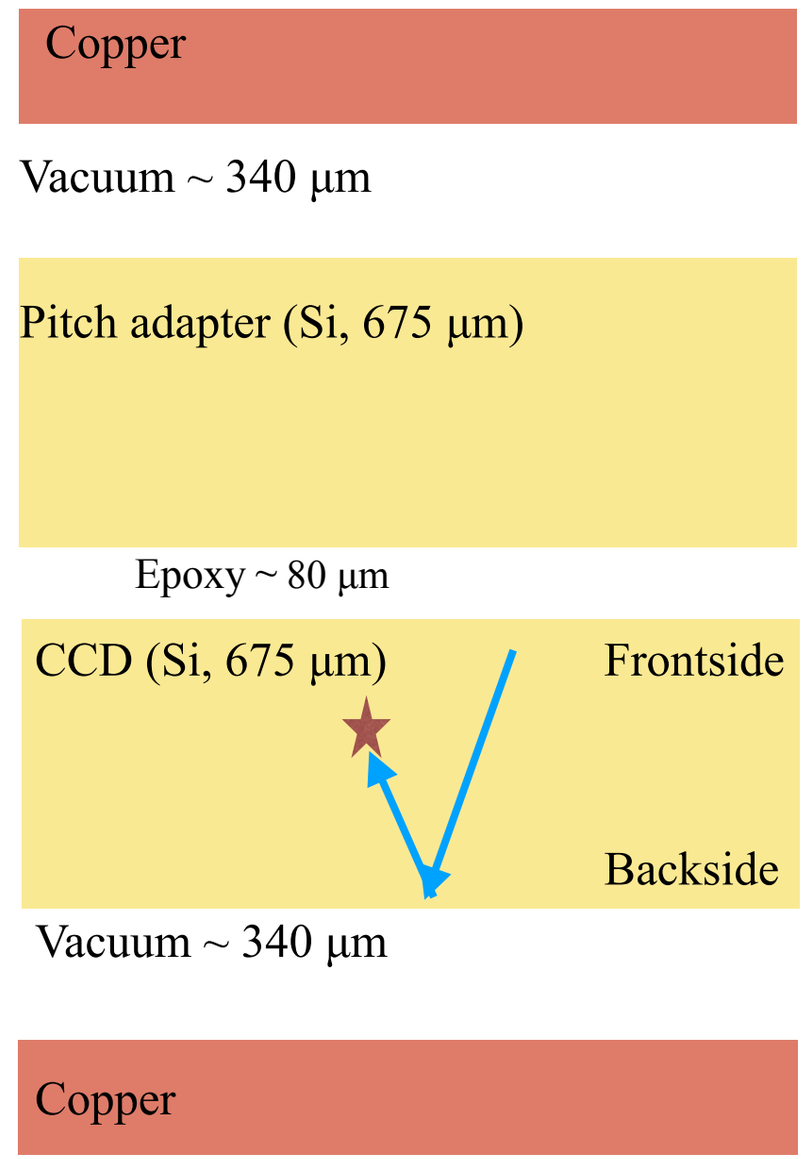
CHERENKOV RADIATION

Track passage and radiation

DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
PRX 12 (2022) 1, 011009

Photons bounce around until absorbed





LUMINESCENCE (RADIATIVE RECOMBINATION)

Track passage and radiation

DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
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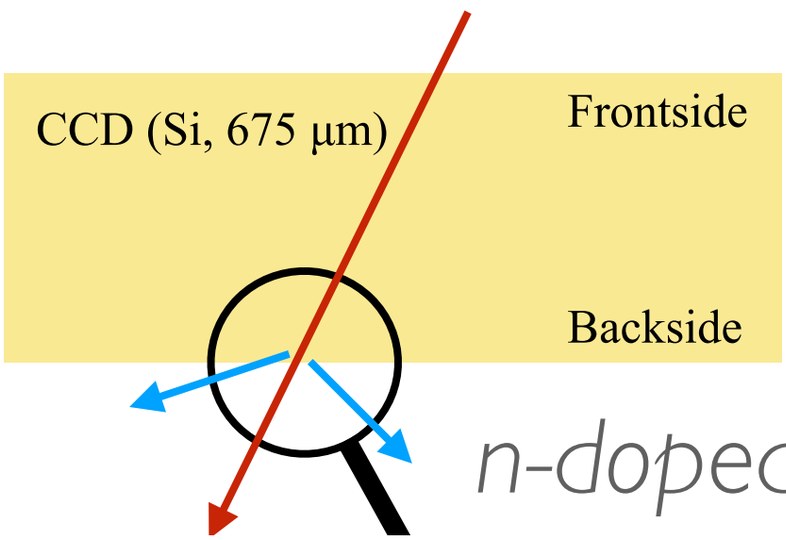
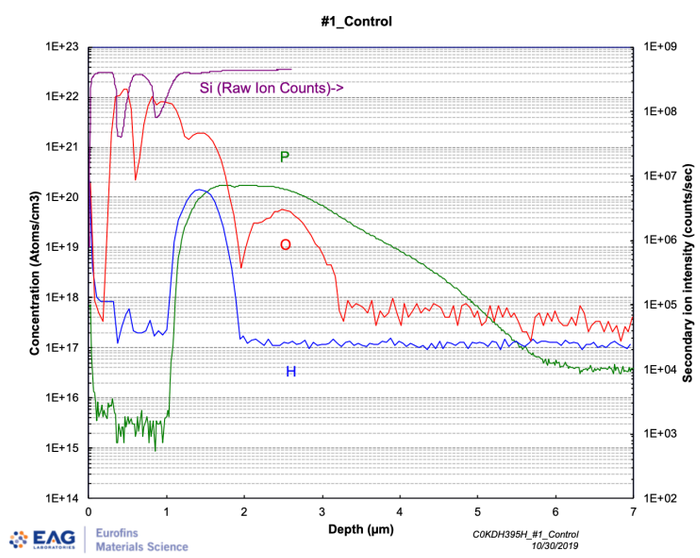
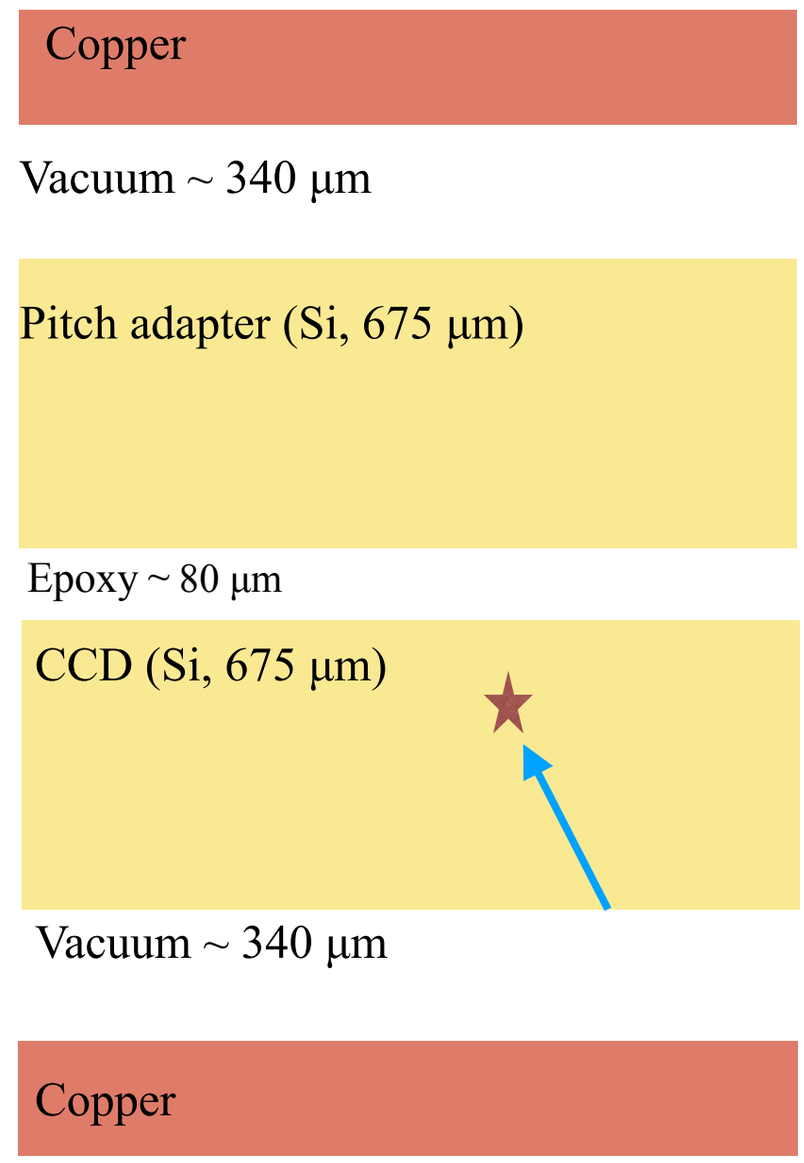
Photons bounce around until absorbed



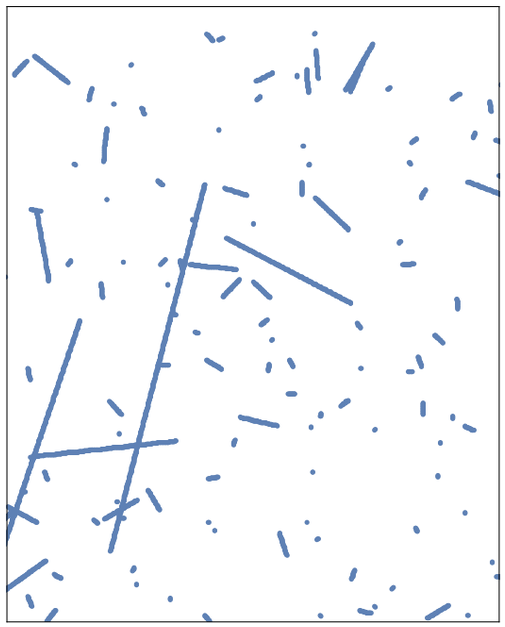
n-doped layer!



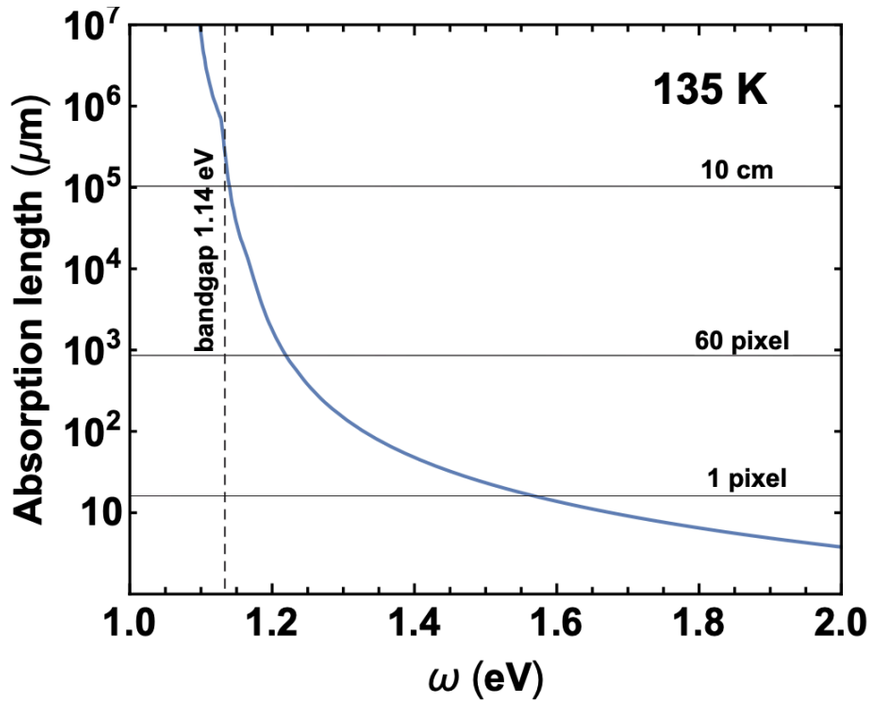
From A. Chavarria et al. 2110.13133



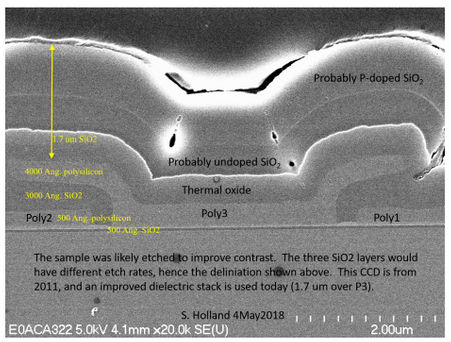
Simulated tracks



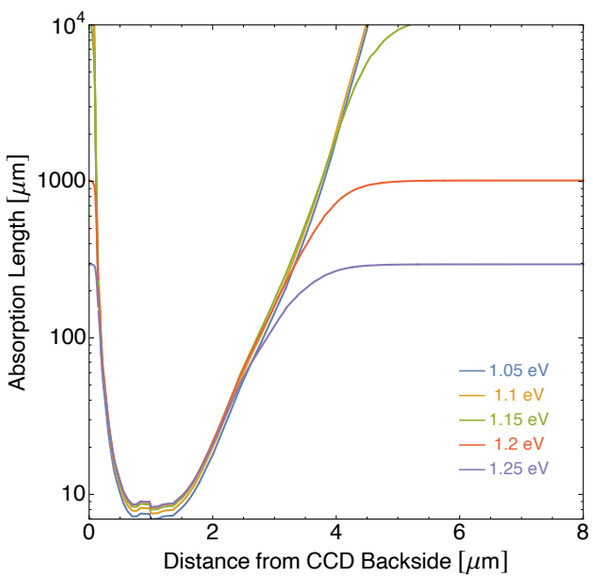
Photon absorption



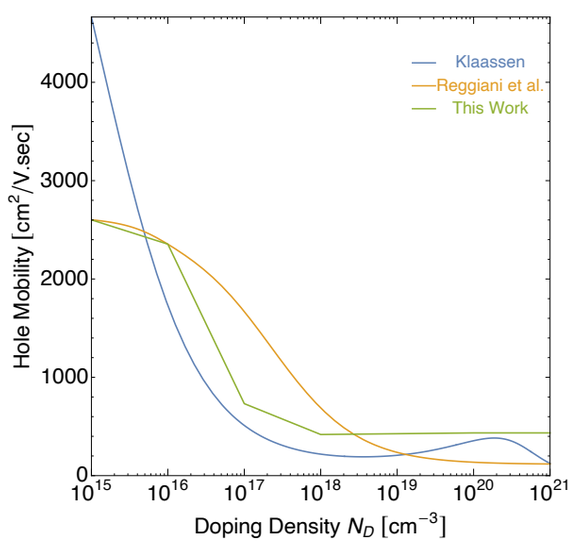
Reflection/refraction, thin-film interference



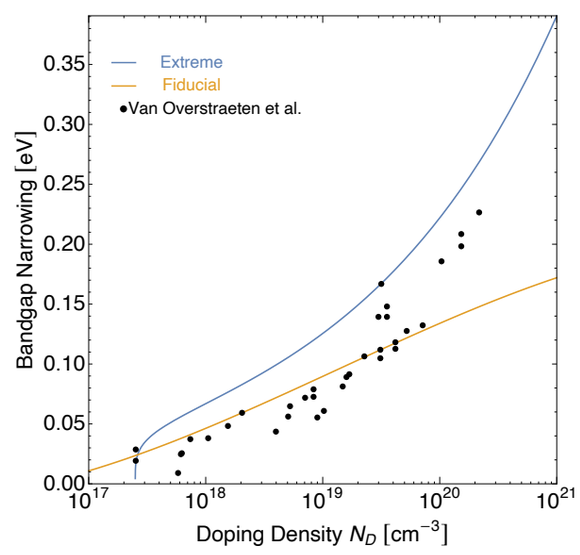
Backside absorption



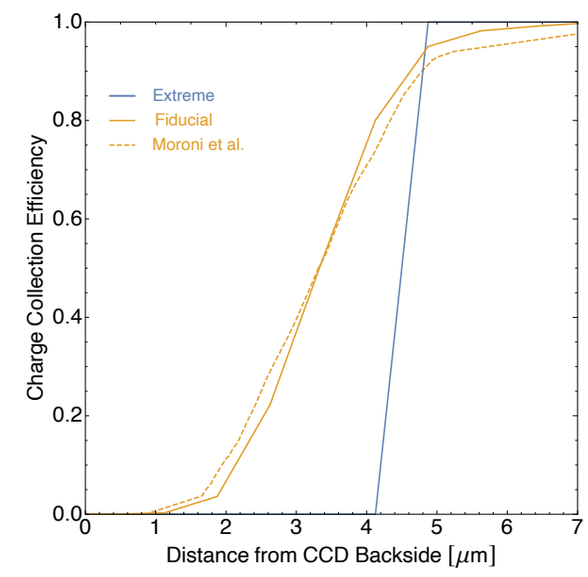
Mobility models



Bandgap gradients



Partial charge collection



etc. etc. etc.

RESULTS

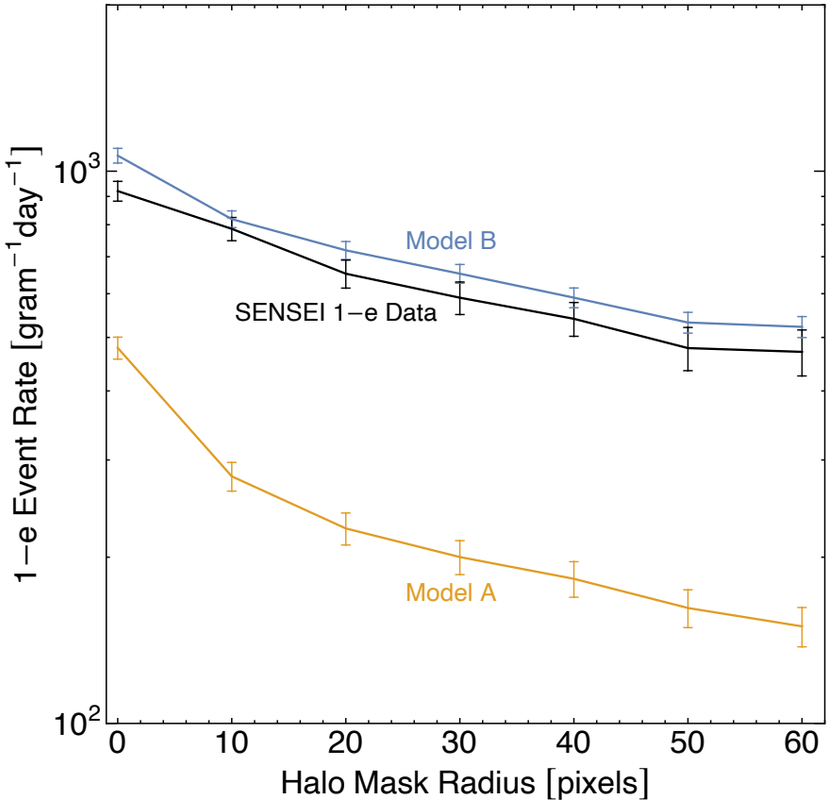
Latest simulation

$$R_{1e}^{Cherenkov} = 150/\mathrm{g-day}$$

$$R_{1e}^{Reco} = (few - 360)/\mathrm{g-day}$$

(to be published)

(v/s 450 observed)

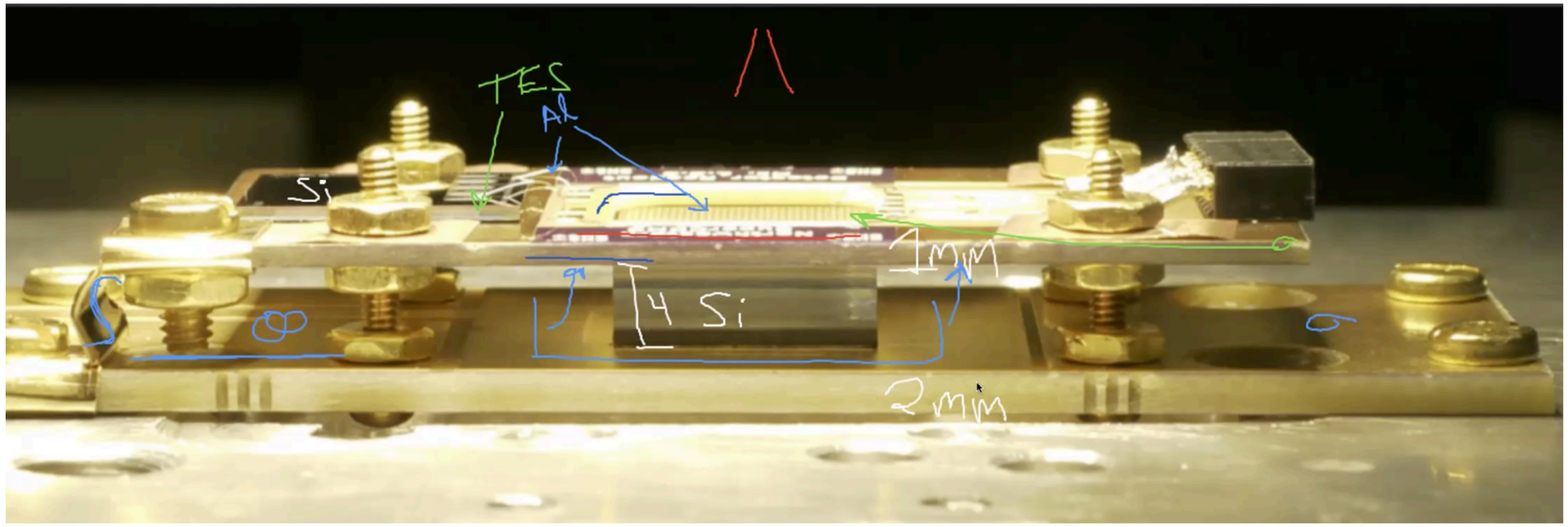


DEU, Du, Essig, Sholapurkar
to be published

SUPERCDMS HVEV

THE SUPERCDMS HVEV EXPERIMENT

- The SuperCDMS HVeV experiment, uses a TES to detect phonons created by drifted electron-hole pairs (Neganov-Luke effect).
- Located on surface @ Northwestern.



SUPERCDMS HVEV (2019 DATA)

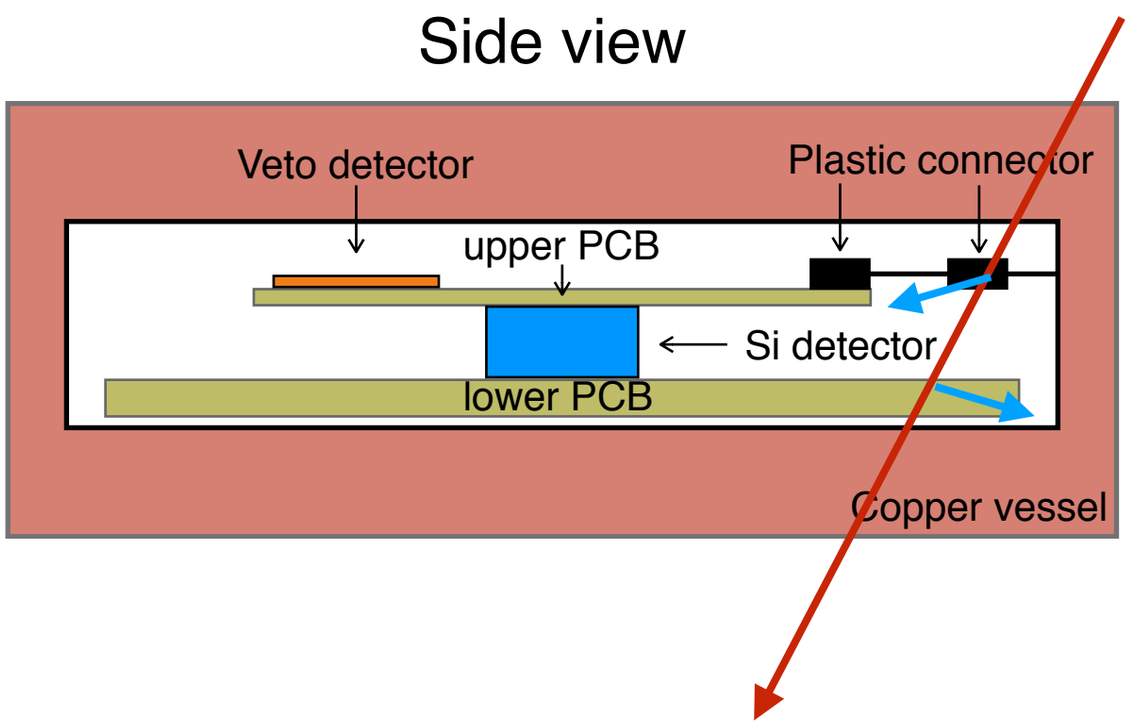
The one-electron rate is likely generated by charge leakage *(*private communications)*

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

2005.14067 (SuperCDMS coll.)

SUPERCDMS HVEV

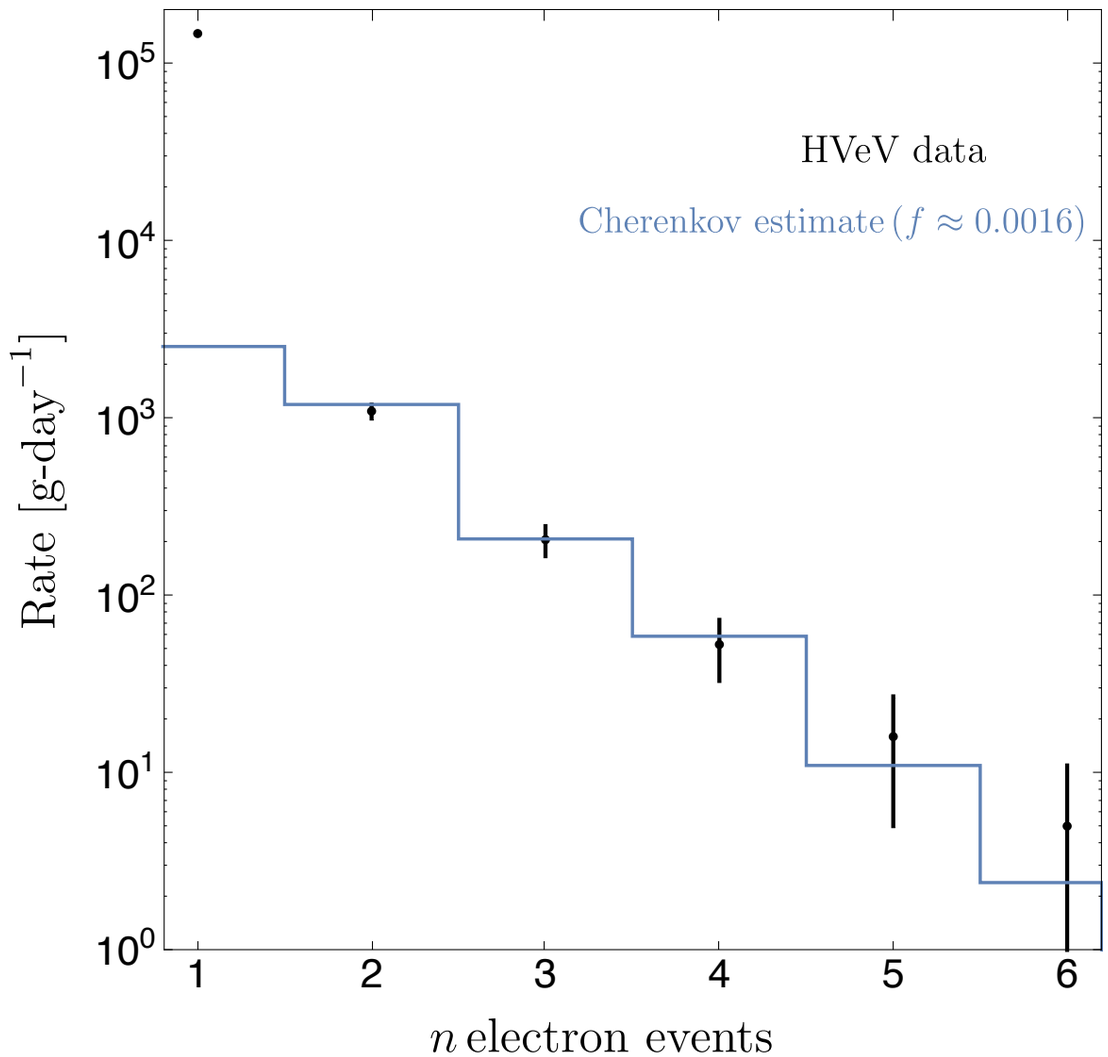
- But tracks passing through auxiliary materials are not vetoed.



Not vetoed
Most of them from the PCBs
<u>Cherenkovs and possibly Luminescence</u>

SUPERCDMS HVEV

See also
2204.08038
(new! SuperCDMS coll.)



DEU, Du, Essig, Sholapurkar
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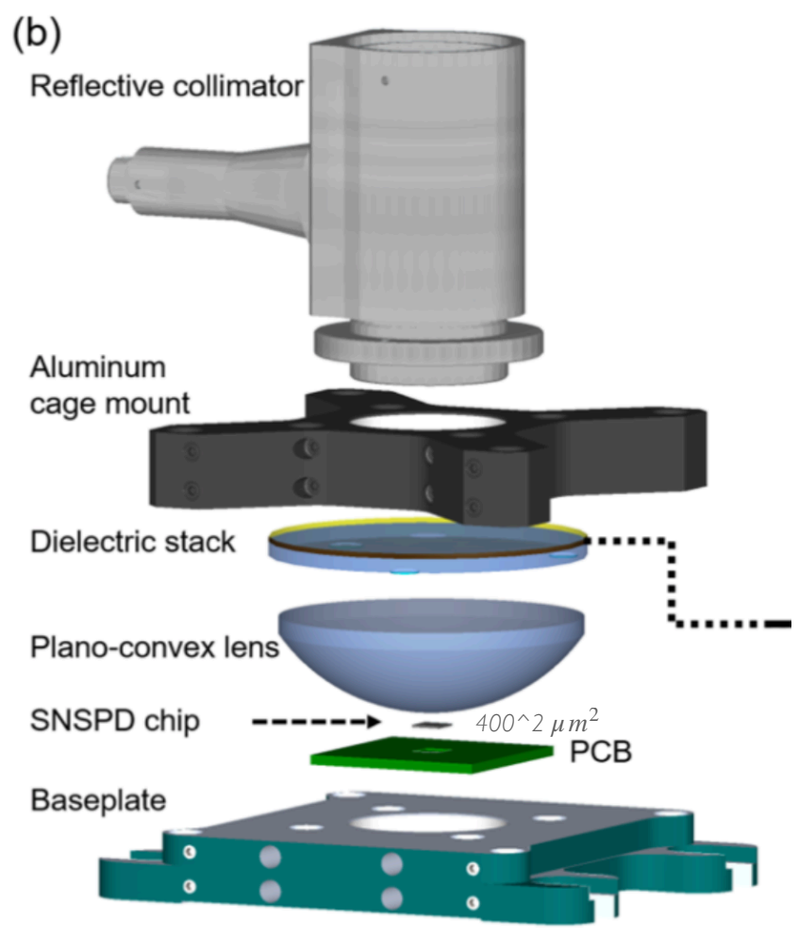
Excellent agreement of the Cherenkov hypothesis with the observed spectrum

LAMPOST

LAMPOST

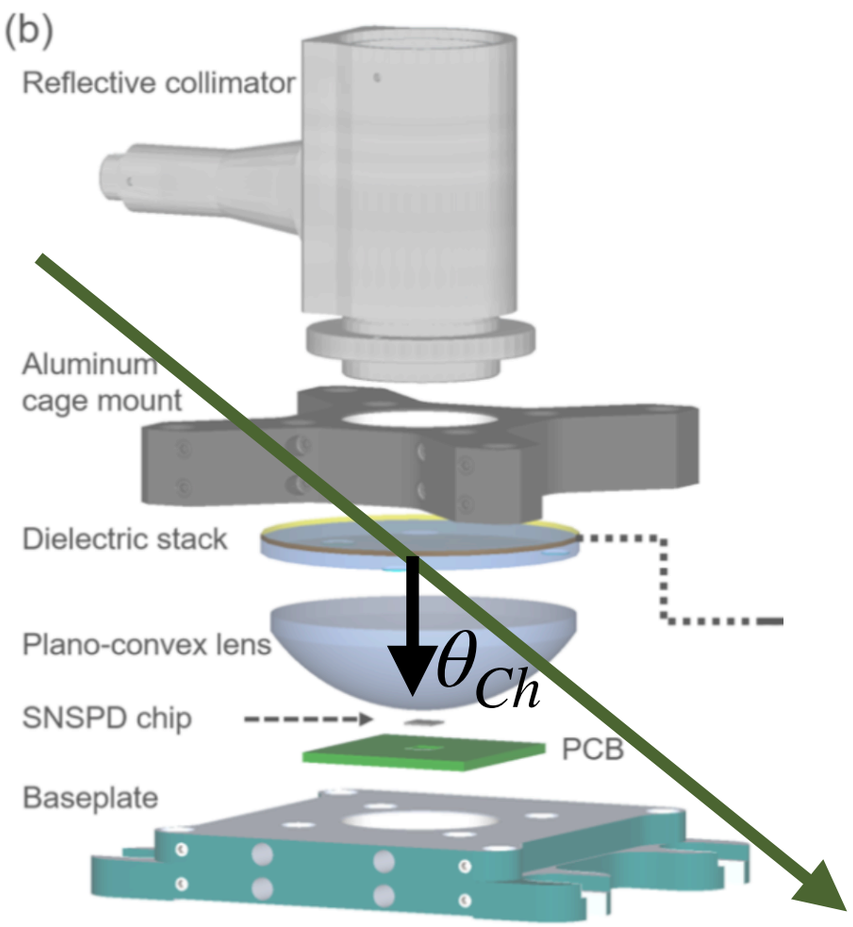
- Observes 6×10^{-6} counts/s in SNSPD detector.



2110.01582
(LAMPOST coll.)

LAMPOST

- Tracks passing through the lens generate Cherenkov photons.



From muons only

$$N_{Cherenkov} \sim 10^5 / day / eV$$

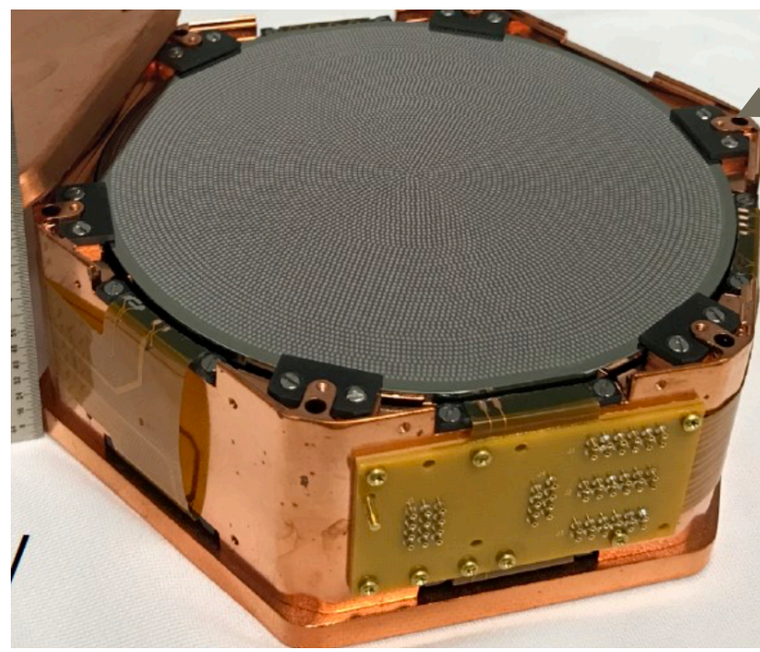
(~100 per track!)

SUPERCDMS SNOLAB

SUPERCDMS SNOLAB

- High-voltage detectors are held by Cirlex clamps. Radioactive tracks from the Cirlex generate Cherenkovs.

Figure from Loer, DM 2018



Cirlex clamps

SuperCDMS coll. 1610.00006

$$N_{\text{events}}^{\text{Cirlex}} \sim 130/\text{day/tower}$$

DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
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Qubit decoherence?

QUBIT DECOHERENCE

- Tracks passing through substrates create Cherenkov light and eh pairs.
- Cherenkov light and luminescence generate long-lived photons that can break Cooper pairs.
- As an example, a track going over 300 μm of Sapphire substrate leads to ~10^2 eV in energy of sub-gap Cherenkov photons

DEU, Du, Essig, Sholapurkar
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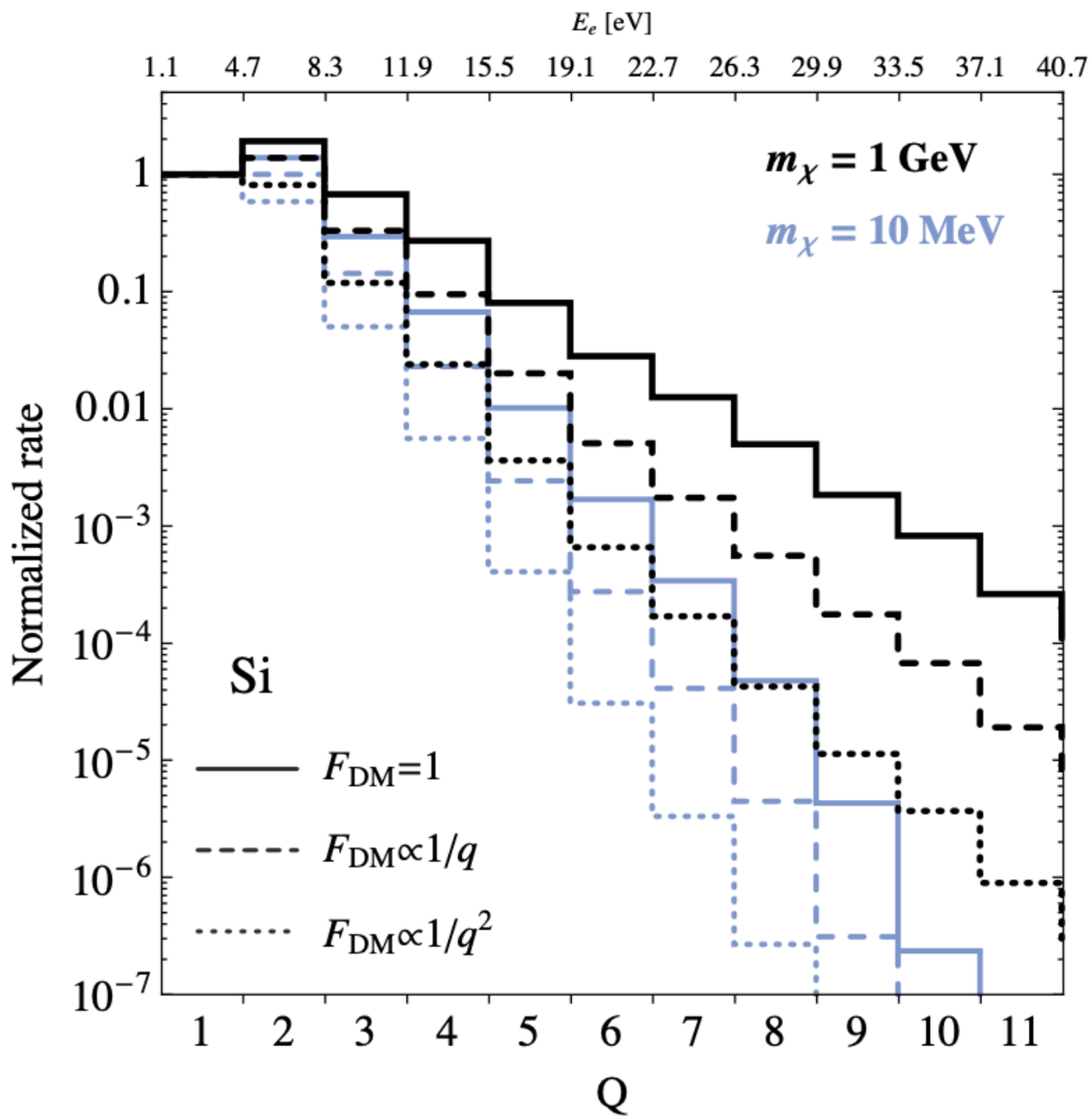
→ 10^3 *quasiparticles/track!*

See also Formaggio, Hall, Li, and D'Imperio's talks on Wednesday

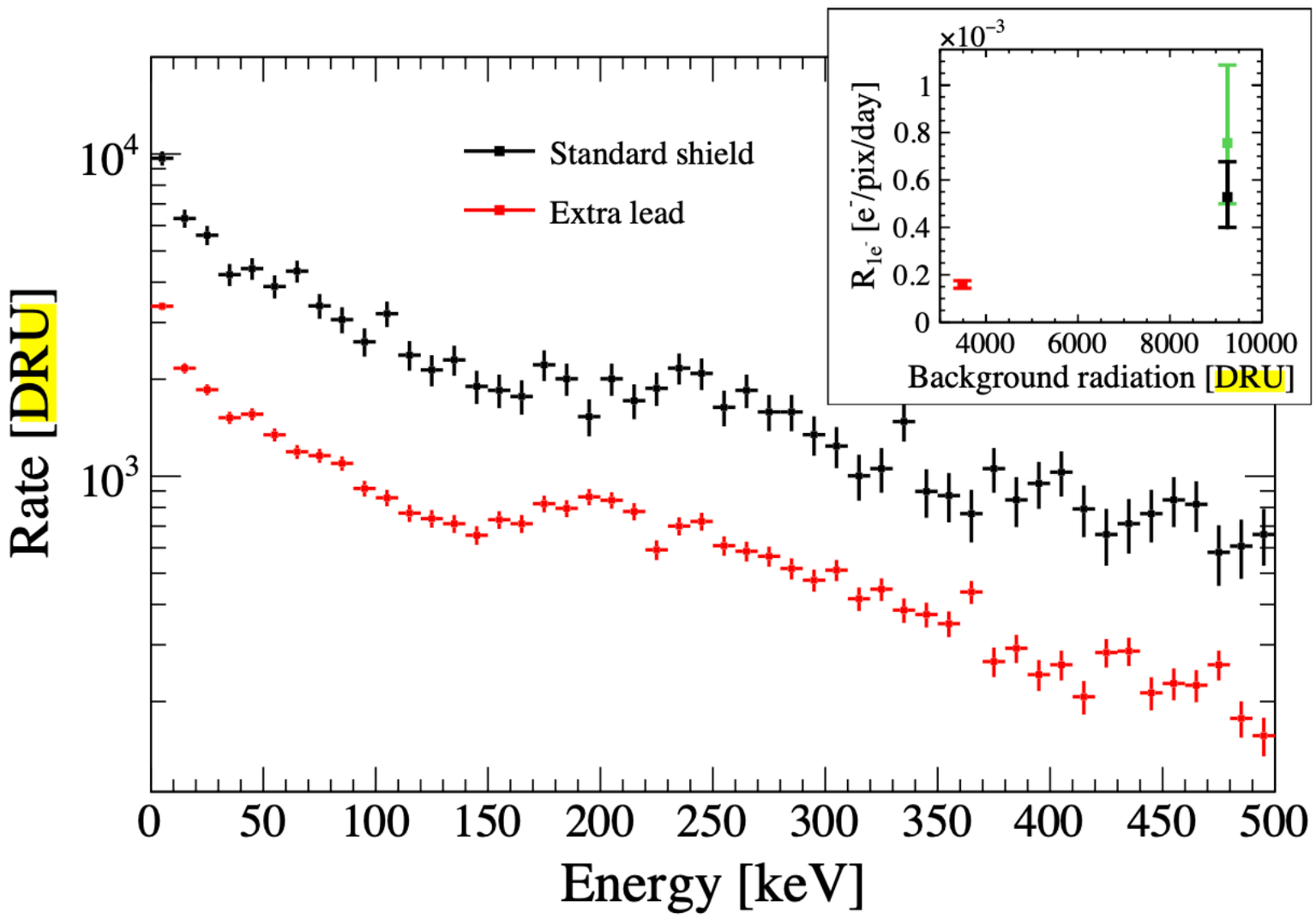
CONCLUSIONS

- We discussed important backgrounds that affect a variety of low-energy threshold dark-matter detectors: Cherenkov radiation and luminescence.
- We showed that these are possible explanations for the excess events at SENSEI, SuperCDMS HVeV and LAMPOST.
- Concrete mitigation strategies can be taken towards the future: these can *significantly* improve the reach to detect dark matter.

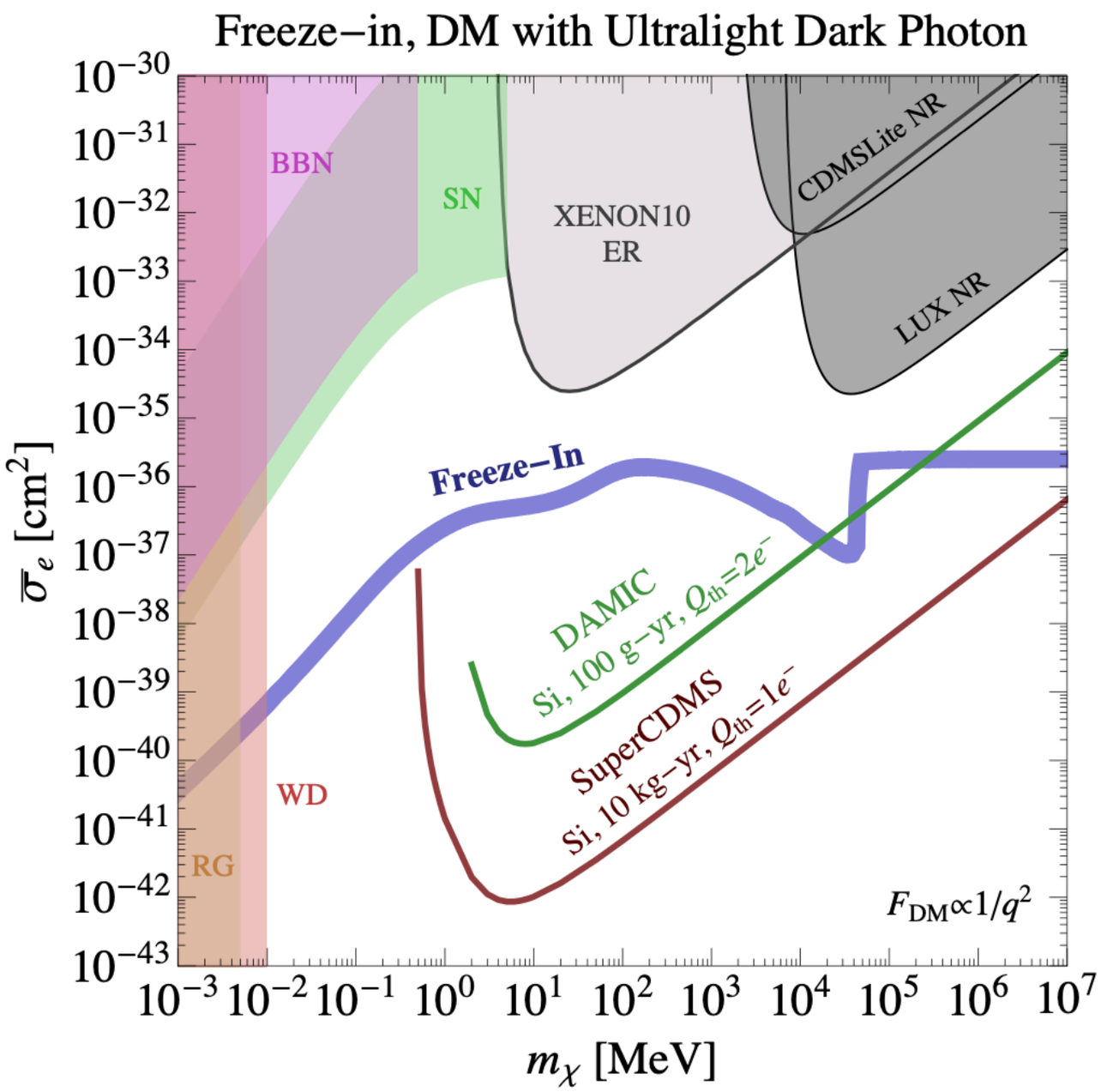
Thanks!



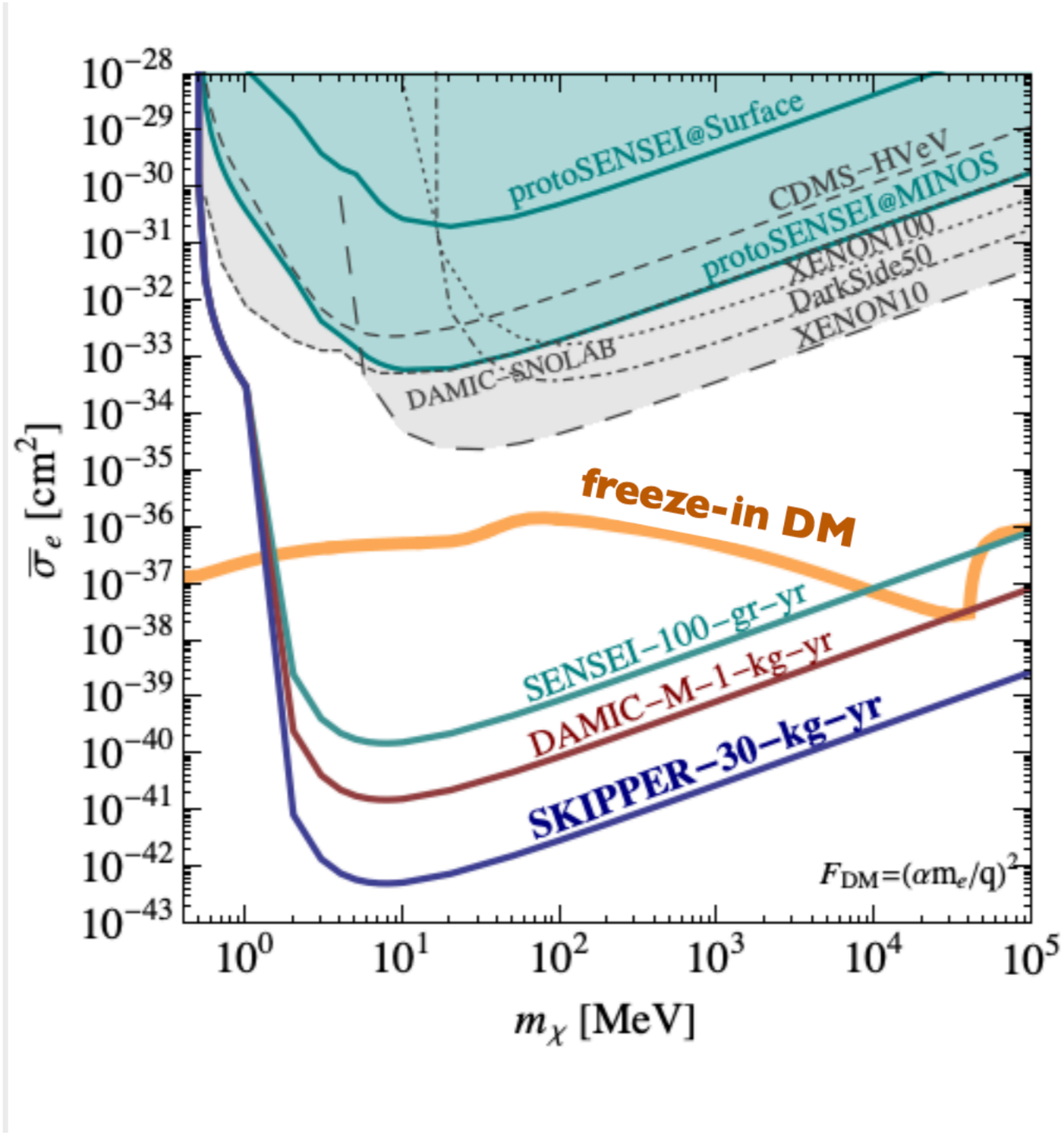
Essig et.al. 1509.01598


Standard shield
Extra lead
Rate [DRU]
Energy [keV]
10^4
10^3
0
50
100
150
200
250
300
350
400
450
500
$\times 10^{-3}$
R_{1e^-} [e^-/pix/day]
Background radiation [DRU]
1
0.8
0.6
0.4
0.2
0
4000
6000
8000
10000

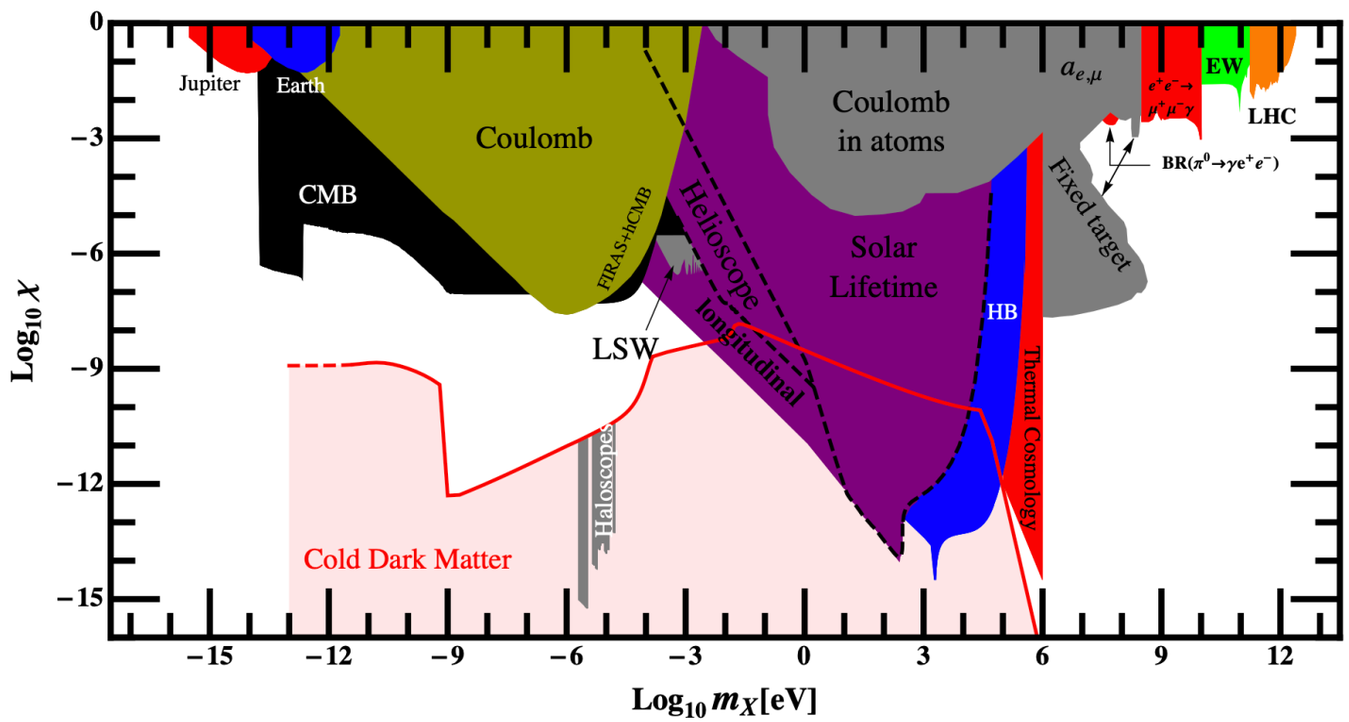
SENSEI coll.



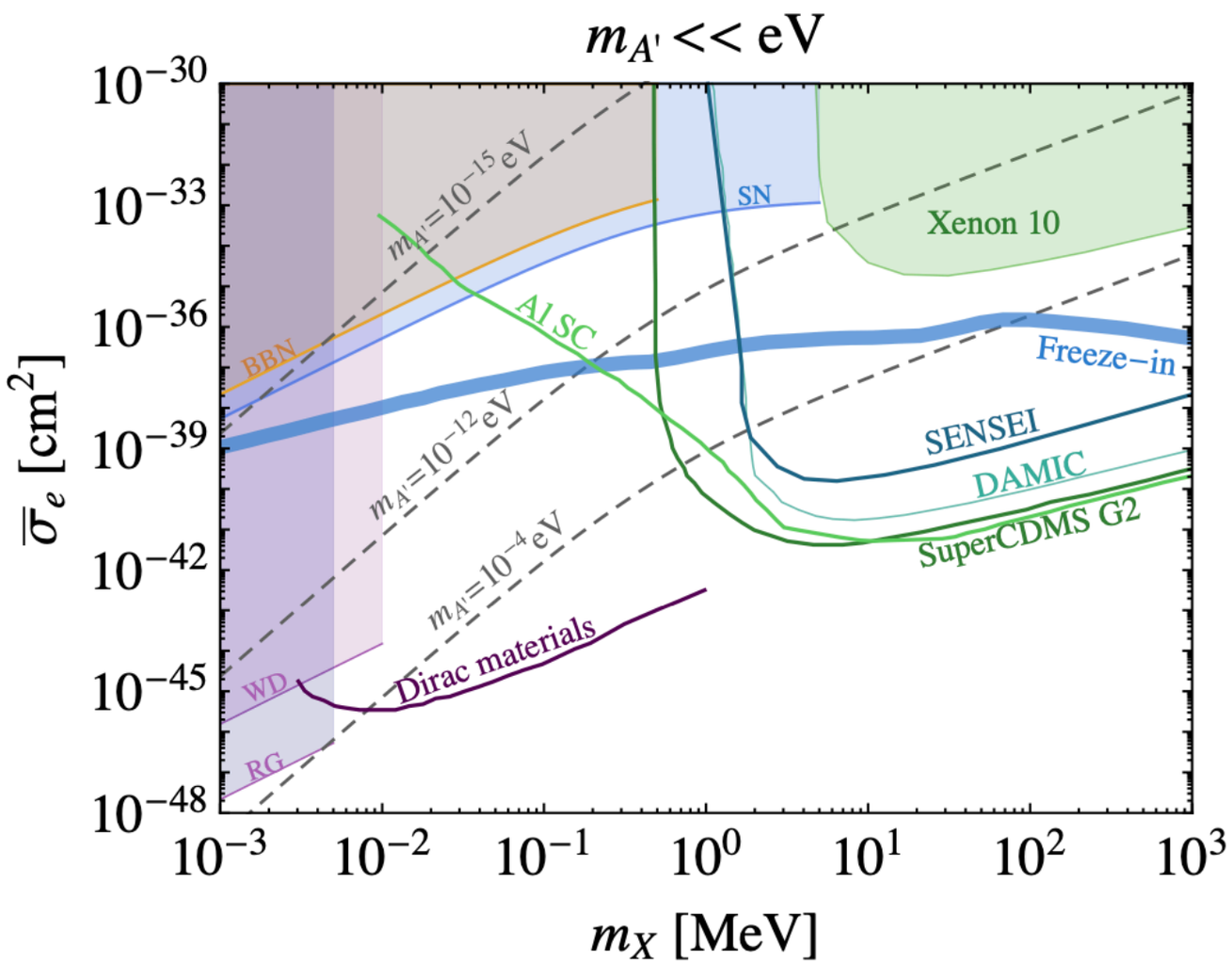
Essig et.al. 1509.01598



Essig, ICHEP 2020



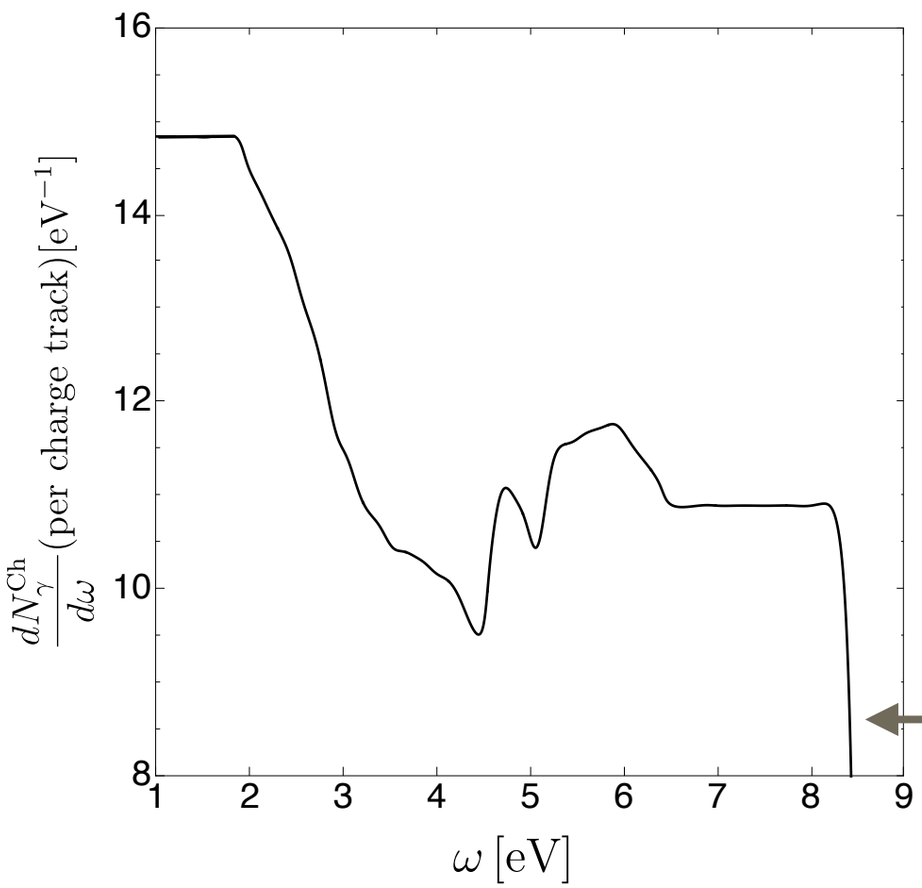
Jaeckel 1303.1821



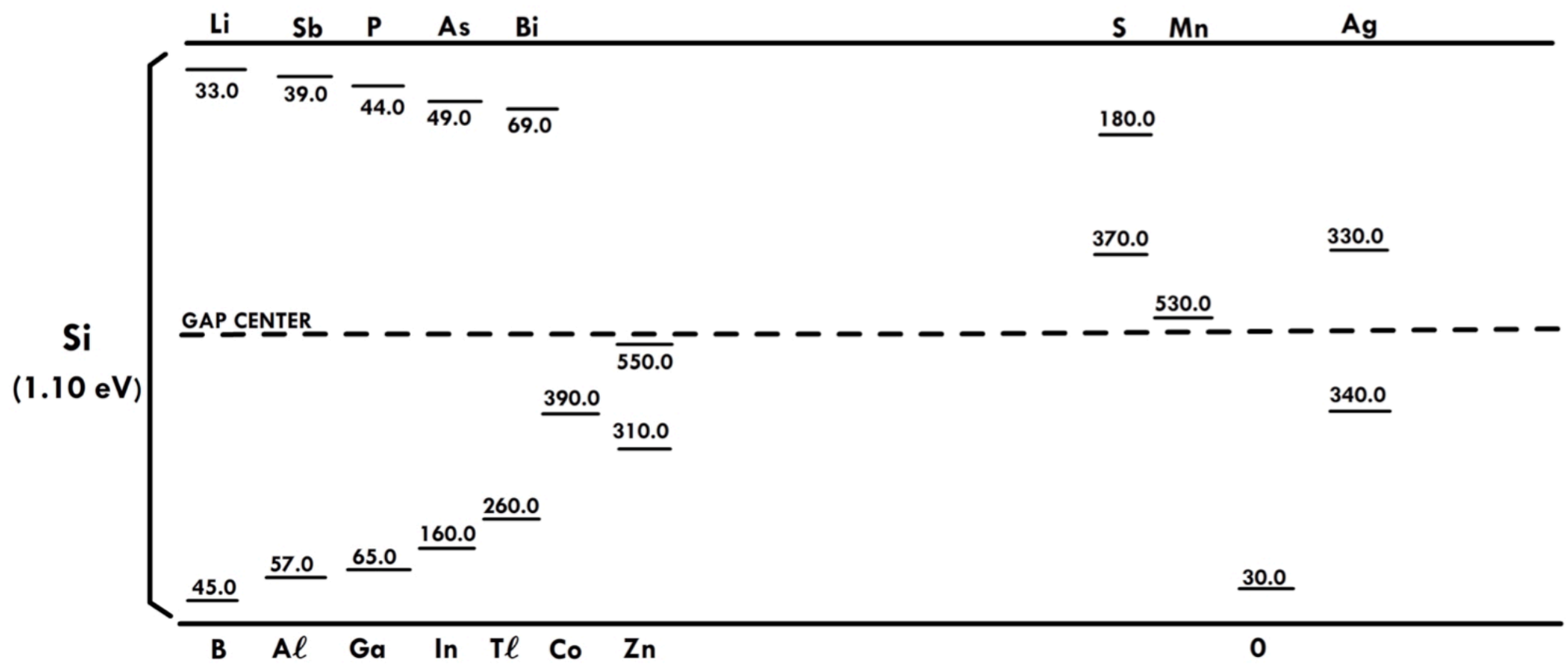
Zurek et. al. 1709.07882

RATE ESTIMATE

- A spectrum is inherited from the PCB absorption coefficient



PCB becomes absorptive so spectrum is cutoff


Li
Sb
P
As
Bi
S
Mn
Ag
33.0
39.0
44.0
49.0
69.0
180.0
370.0
330.0
530.0
GAP CENTER
Si
(1.10 eV)
550.0
390.0
340.0
310.0
260.0
160.0
57.0
65.0
45.0
30.0
B
Aℓ
Ga
In
Tℓ
Co
Zn
O

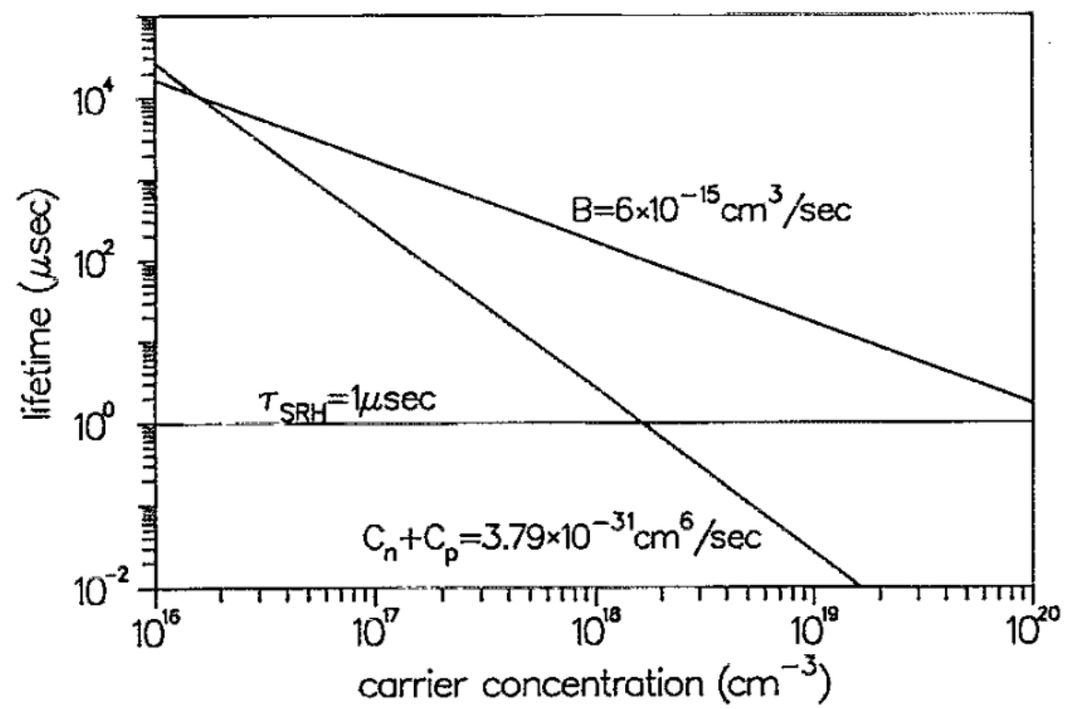
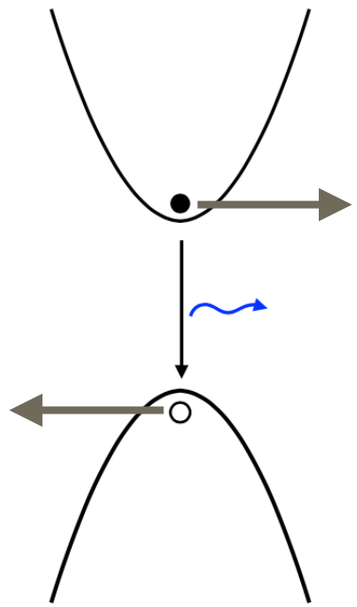


FIG. 1. Lifetime of carriers in Si caused by different recombination mechanism: Shockley–Read–Hall recombination τ_{SRH}, intrinsic band-band recombination B, Auger recombination $C_n + C_p$.

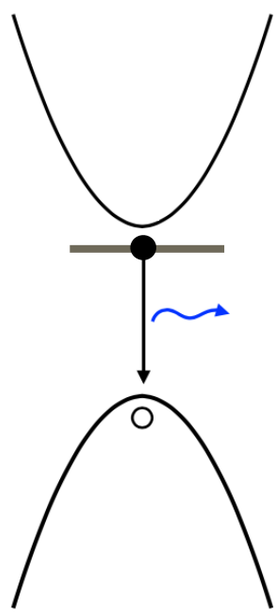
	Si	Ge	GaAs
E_g [eV] [102]	1.11	0.66	1.43
ε [eV] [127, 129–131]	3.63	2.8	4.57
μ_e [cm^2/V/s] [132]	1400	3900	8500
μ_h [cm^2/V/s] [132]	470	1900	400
B [cm^3/s] [133–135]	10^{-14}	3.4×10^{-14}	7.2×10^{-10}
a_e [cm^6/s] [136–138]	2.8×10^{-32}	2×10^{-32}	1.7×10^{-31}
a_h [cm^6/s] [136–138]	9.9×10^{-32}	1.1×10^{-31}	2.4×10^{-30}

TABLE I: Electronic properties of Si, Ge and GaAs at room-temperature and low doping levels. E_g is the bandgap, ε the mean ionization energy, $\mu_{e,h}$ the electron and hole mobilities, B the radiative recombination coefficient, and $a_{e,h}$ the electron and hole Auger coefficients. For our estimates in SENSEI's Si Skipper-CCDs (see Sec. V A), which operate at 135 K, we will use $\varepsilon = 3.75$ eV [139].

CALCULATING THE RADIATIVE RATE

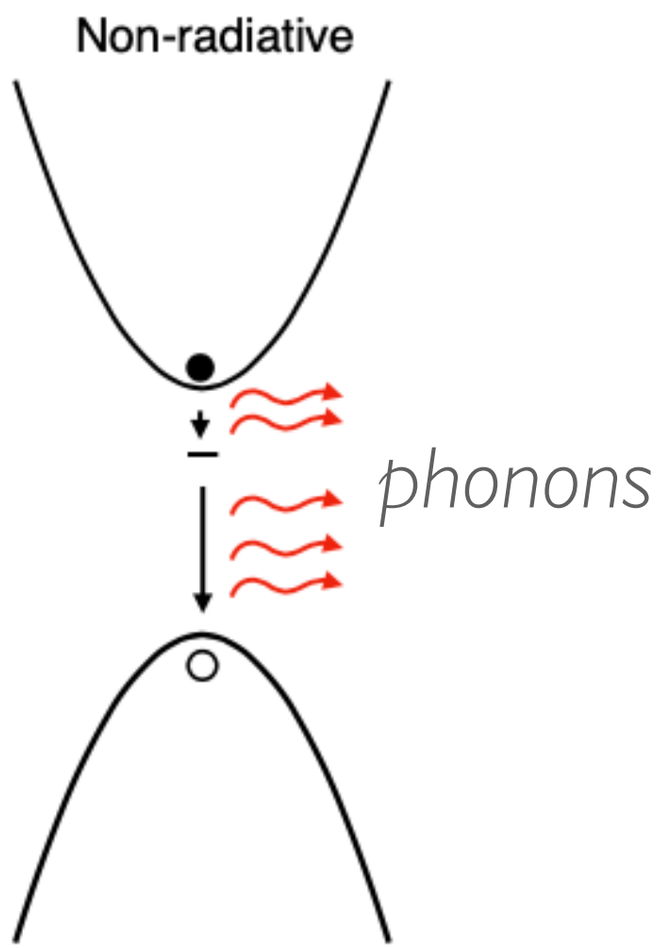


Diffusion will suppress radiative recombination in undoped semiconductors …



but it will not do it in doped semiconductors

CALCULATING THE RADIATIVE RATE



Non-radiative (trap-assisted) recombination also suppresses radiative rate

RATE ESTIMATE AT SNOLAB

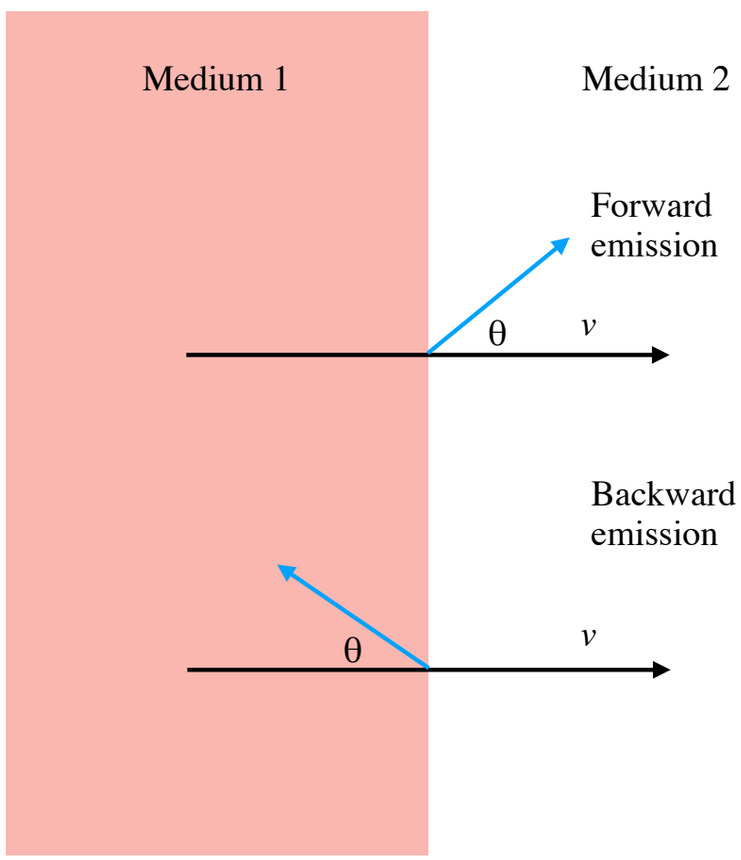
- Cirlex has a radioactivity rate of ~few mBq/kg ($^{238}\mathrm{U}, ^{232}\mathrm{Th}\ldots$).
- Radioactive β's generate Cherenkov radiation (may also generate luminescence, we don't know).
- Given the mass in Cirlex with direct view to the HV detector, we estimate that tracks will generate several Cherenkovs.

$$N_{\mathrm{events}}^{\mathrm{Cirlex}} \sim 130/\mathrm{day/tower}$$

- These events are mostly low-energy, likely below ~100 eV energy depositions. Previous bkgs are at the level of $0.1/\mathrm{day/tower}$

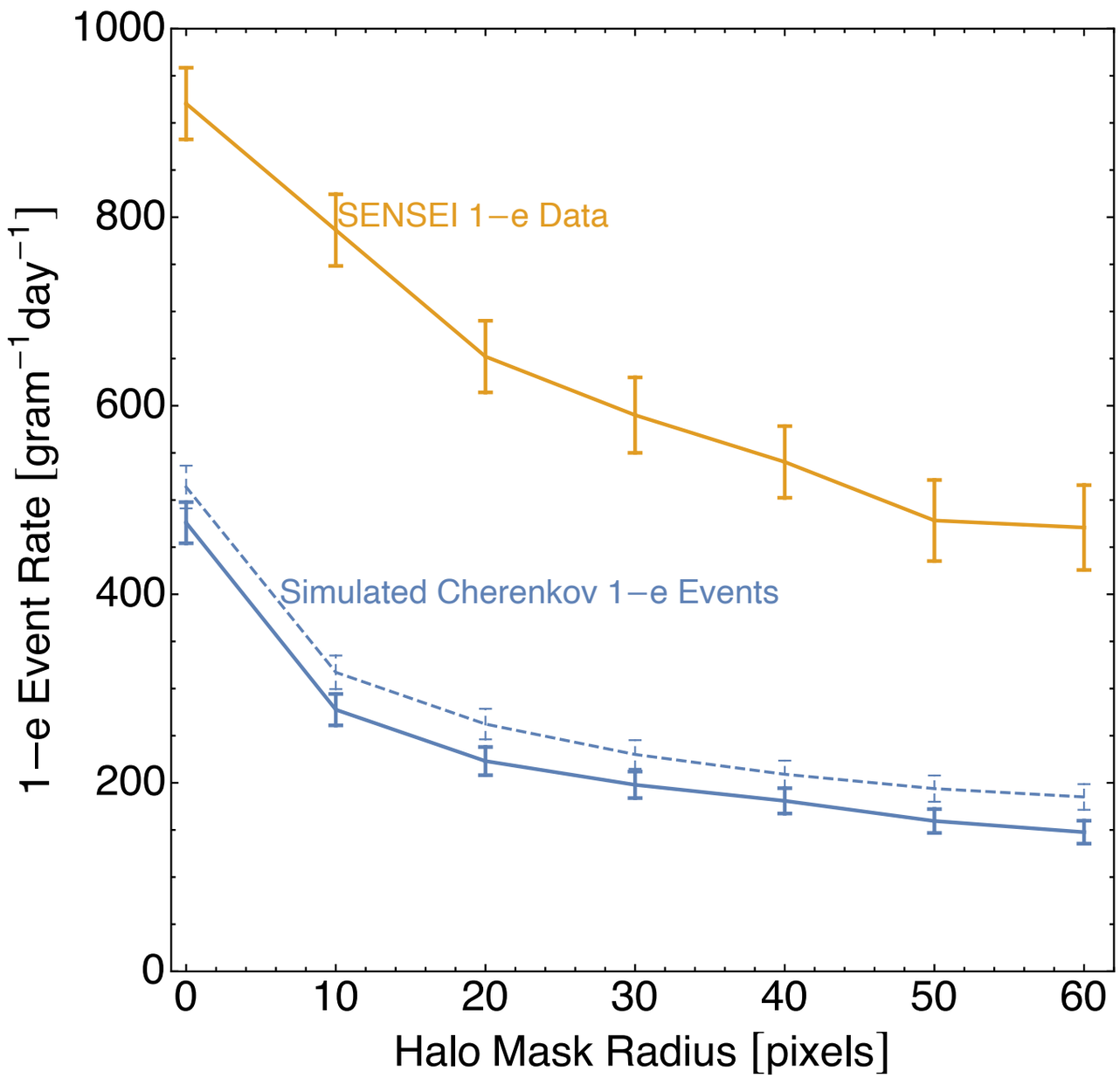
TRANSITION RADIATION

- Is the spontaneous emission of radiation by tracks passing through material interfaces

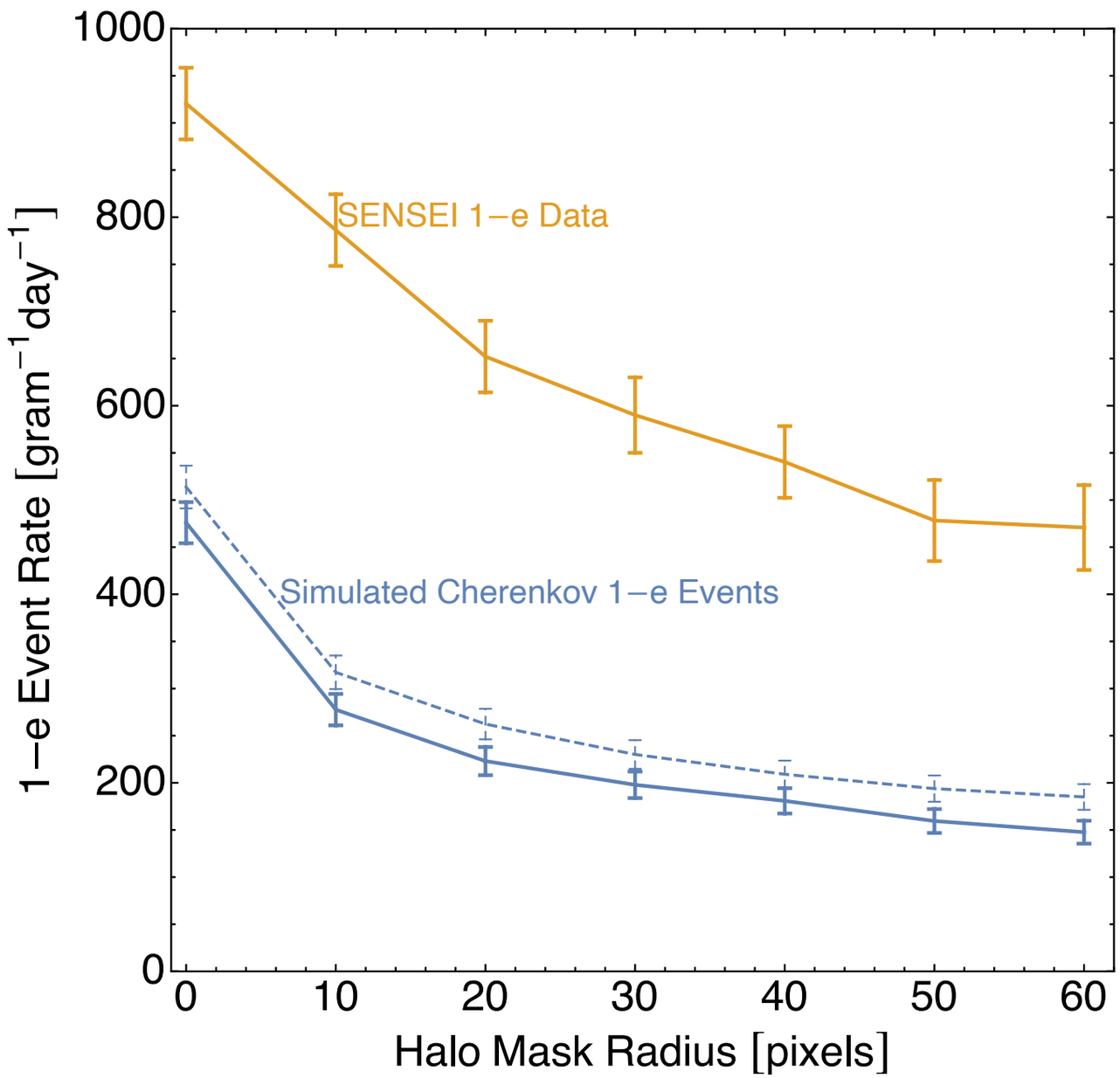


$$N_\gamma(\omega = 1\text{eV}) \sim \alpha v^2/\textit{interface} \sim 10^{-2}$$

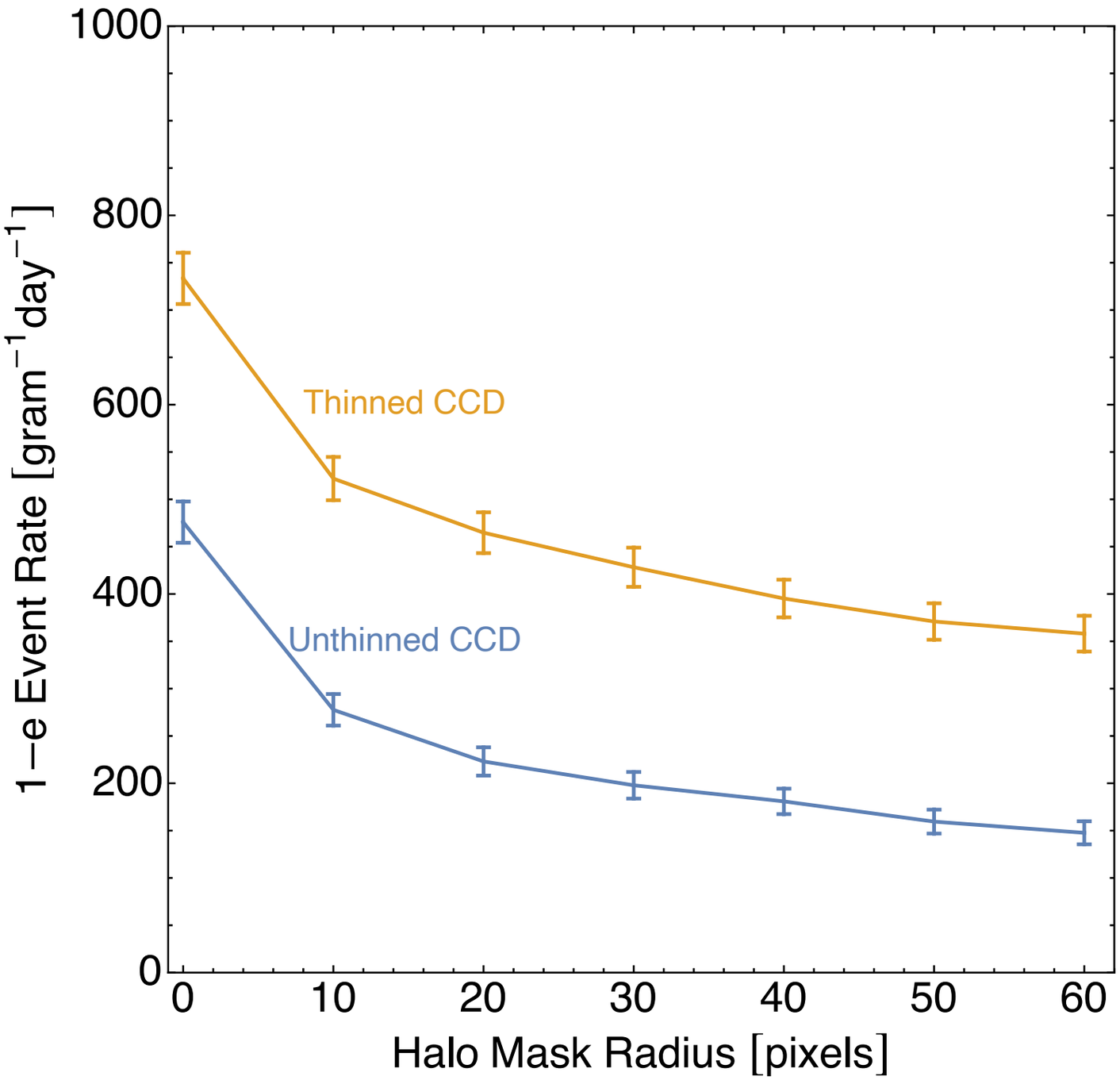
SYSTEMATICS OF CHERENKOV



SYSTEMATICS OF CHERENKOV



THINNED BACK SIDE



SYSTEMATICS RECO EFFICIENCY