DIRECT DETECTION OF SUB-MEV DARK MATTER

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arXiv: 2212.04504
(See also Phys. Rev. X 12 (2022) 1, 011009)

In collaboration with

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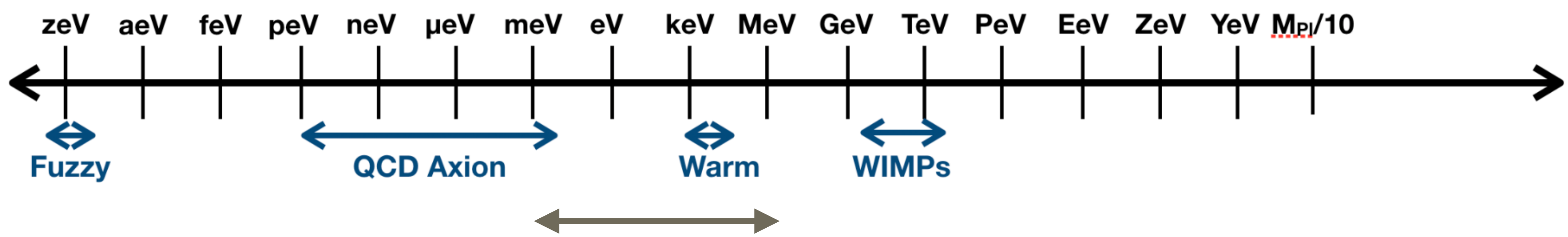
LIGHT DARK MATTER DETECTION



Here we focus on ***sub-MeV*** *DM scattering…*

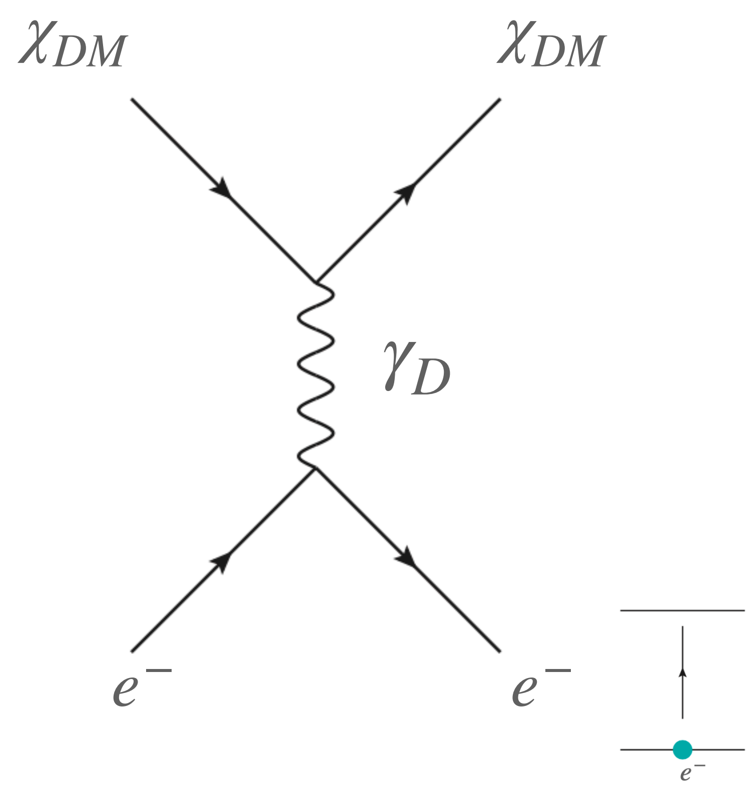
$$E_{det} \leq \frac{1}{2} m_{DM} v_{DM}^2 \sim \frac{1}{2}\mathrm{eV}\left[\frac{m_{DM}}{1\,\mathrm{MeV}}\right]$$

… and ***sub-eV*** *DM absorption.*

EXCELLENT THEORY TARGETS

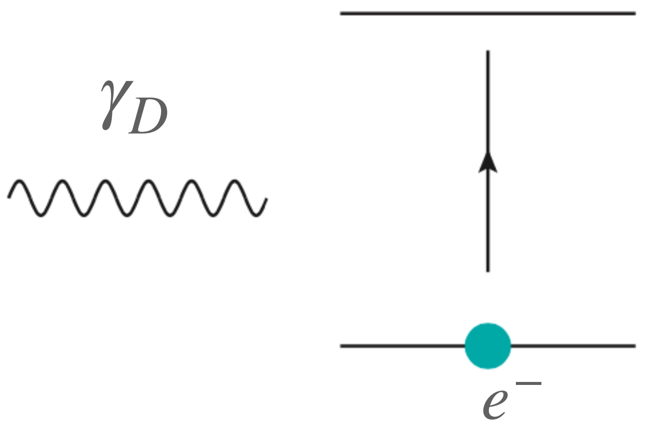
Scattering

Dark photon mediator



Absorption

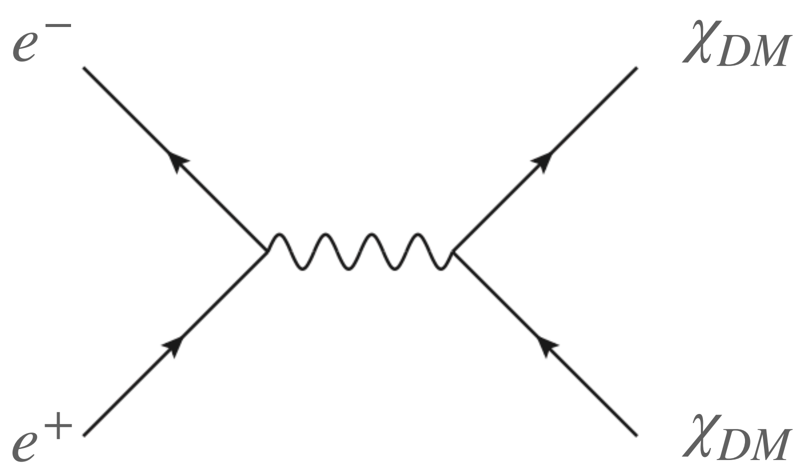
Dark photon DM



EXCELLENT THEORY TARGETS

Scattering

Freeze-in production



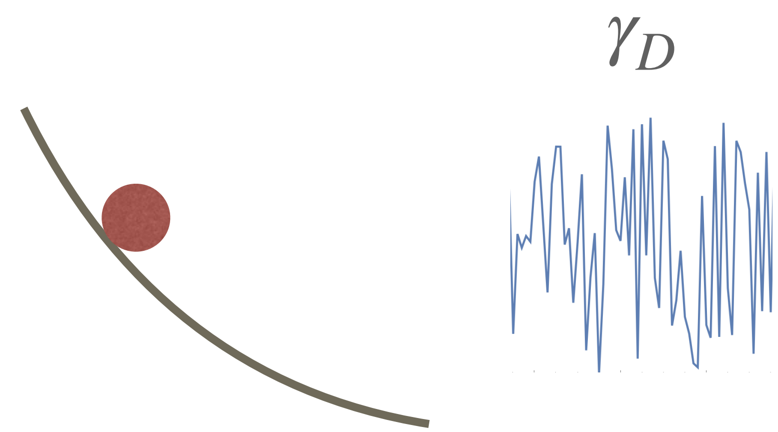
$$Y \approx \frac{n_{SM}\sigma v}{s} H^{-1}$$

$$g_e g_\chi \approx 10^{-12}$$

Hall et.al. 0911.1120

Absorption

Inflationary fluctuations



$$m_{\gamma_D} \approx 0.1\,\text{eV} \left(\frac{10^{13}\,\text{GeV}}{H_I}\right)^4$$

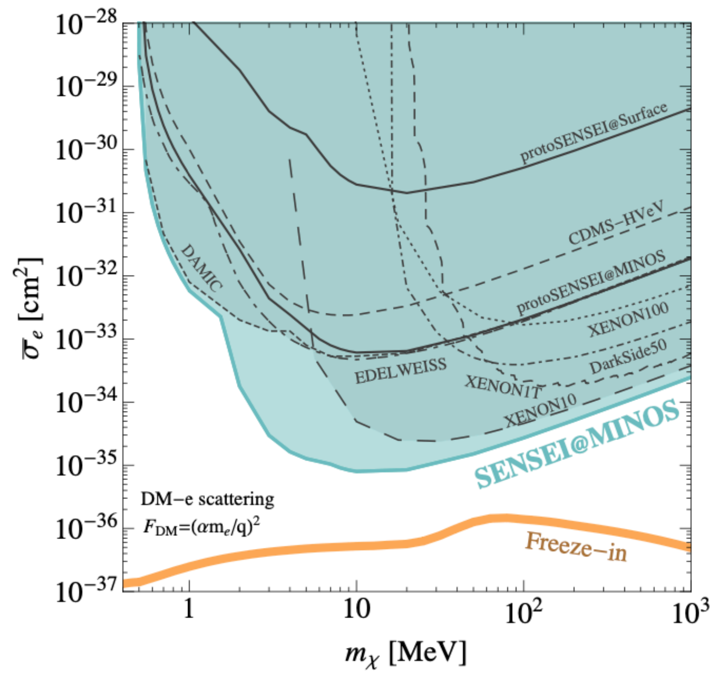
Graham et. al. 1504.02102

The state of the art
in light-DM detection

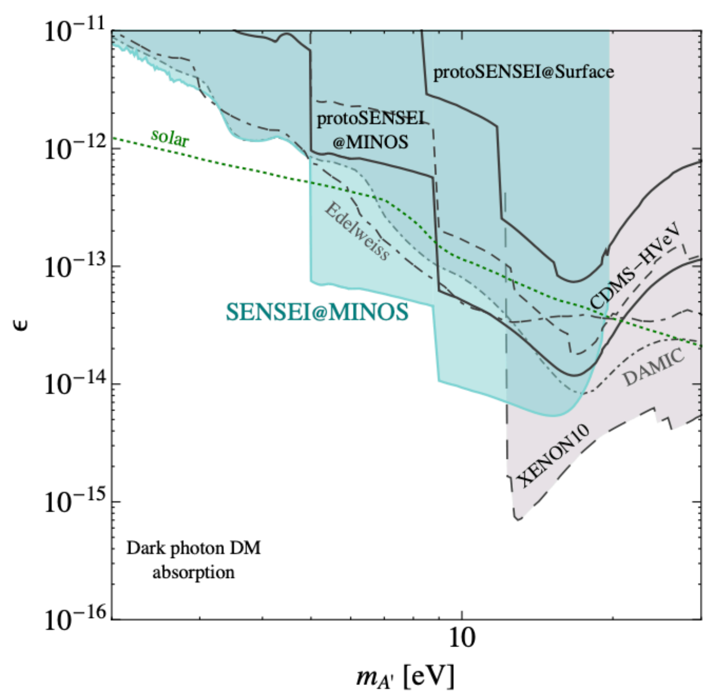
LIGHT-DARK MATTER DETECTORS

2004.11378 (SENSEI coll.)

Scattering



Absorption

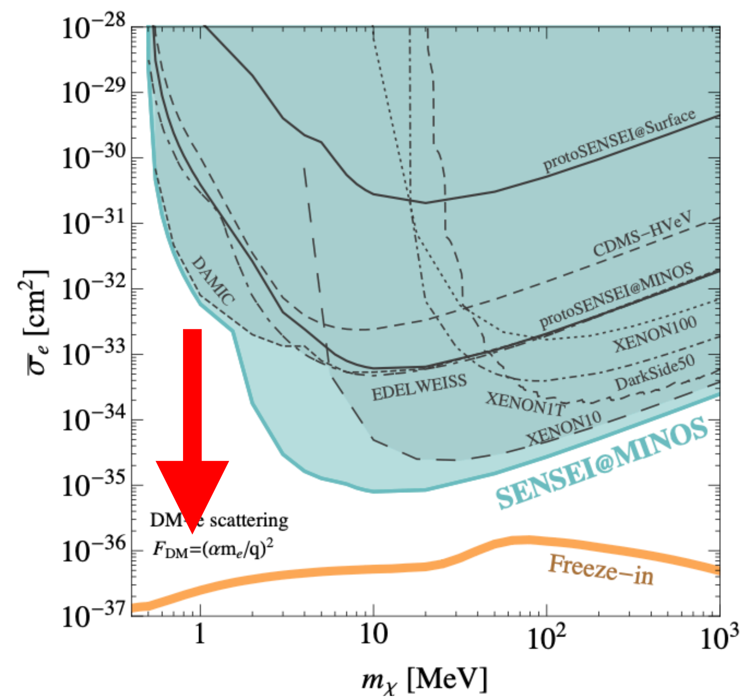


A plethora
of new experiments
are aiming for
sub-GeV DM:
SENSEI (2004.11378)
SuperCDMS (2005.14067)
EDELWEISS (2003.01046)
DAMIC (1907.12628)
LAMPOST (2110.01582),

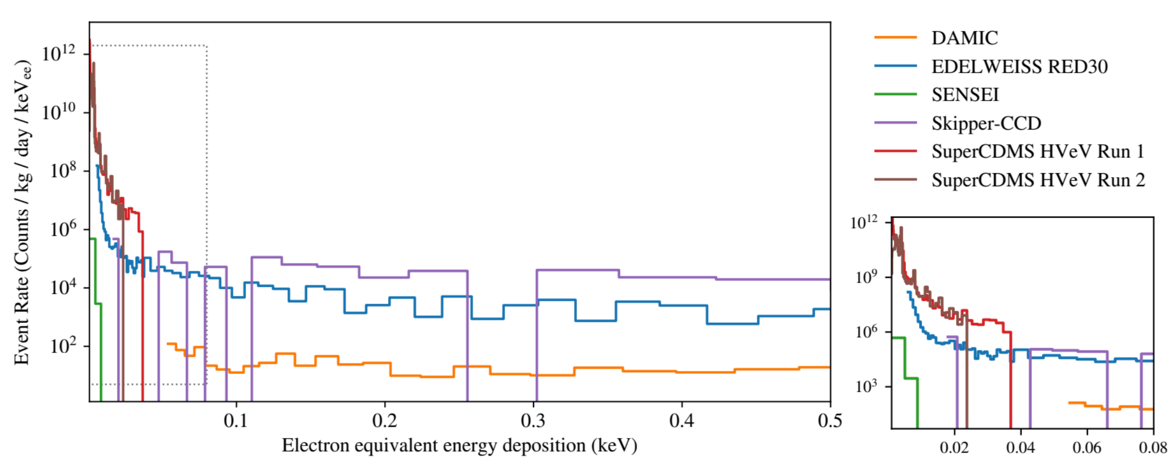
(plus many running and proposed
Ones:
SENSEI and SuperCDMS
at SNOLAB,
Damic-M,
Oscura, SPICE…)

LIGHT-DARK MATTER DETECTORS

2004.11378 (SENSEI coll.)



Better sensitivities require ***lower backgrounds***

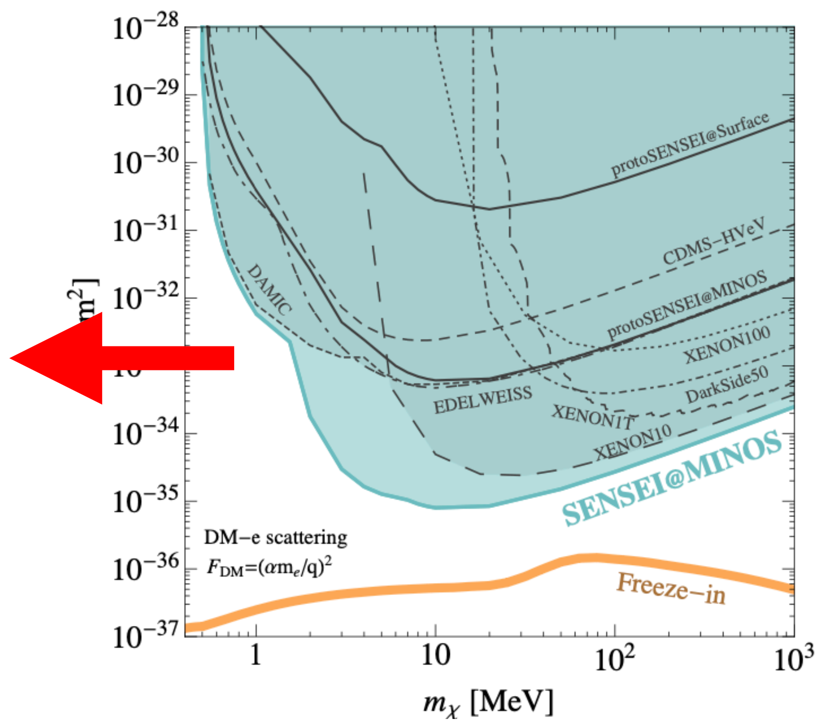


But ***all experiments*** *currently show a rise*
In backgrounds at low energies

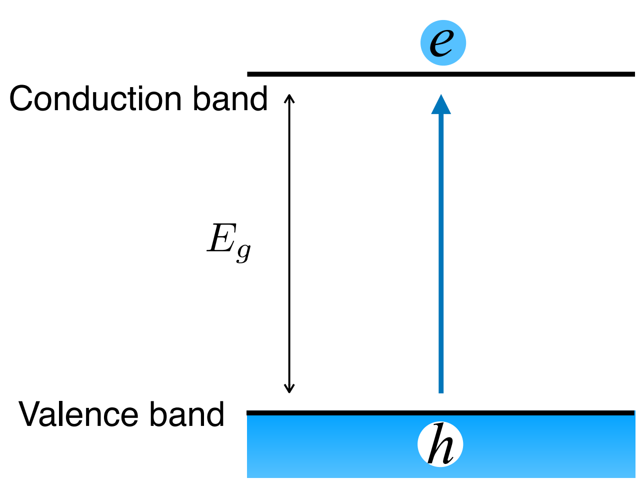
EXCESS workshop 2202.05097

LIGHT-DARK MATTER DETECTORS

2004.11378 (SENSEI coll.)



Going towards lower masses requires ***lower thresholds***



$$\approx 1\text{eV}$$

Leading ionization devices are limited by the bandgap

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

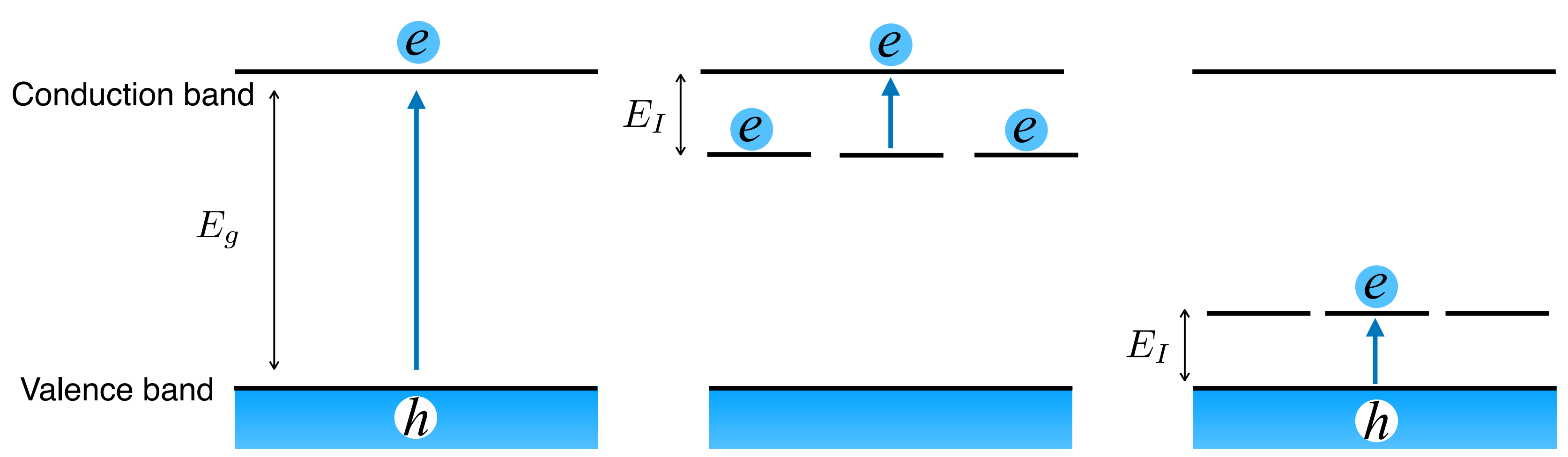
*How can we detect sub-**MeV** DM?*

DOPED SEMICONDUCTOR DETECTORS

Current ionization detectors
are fundamentally limited by the target bandgap

Solution: ***introduce doping in the target***

Egaña-Ugrinovic & Du, Essig, Sholapurkar
arXiv:2212.04504

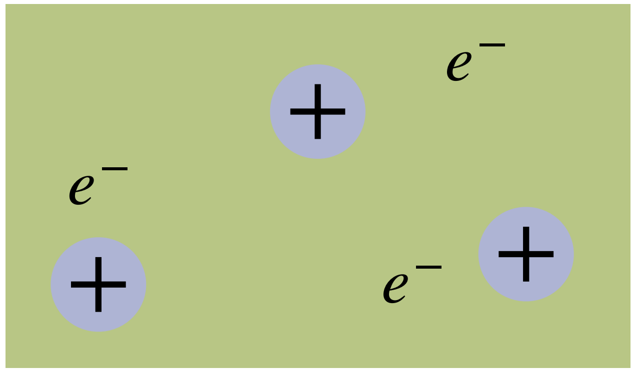


Old idea, doped IR light detectors already designed in the 80's!

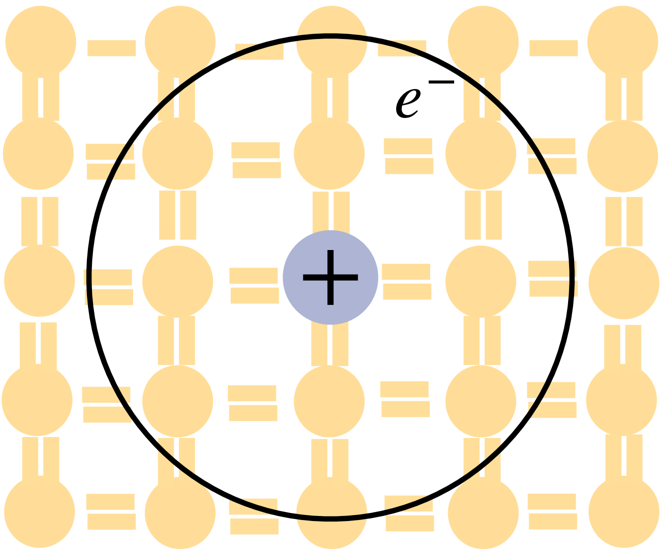
The reach of
doped semiconductor targets

MODELING DOPED SEMICONDUCTORS

- Focus on n-type dopants for concreteness



In Silicon bulk,
group 5 elements: P, As, Sb



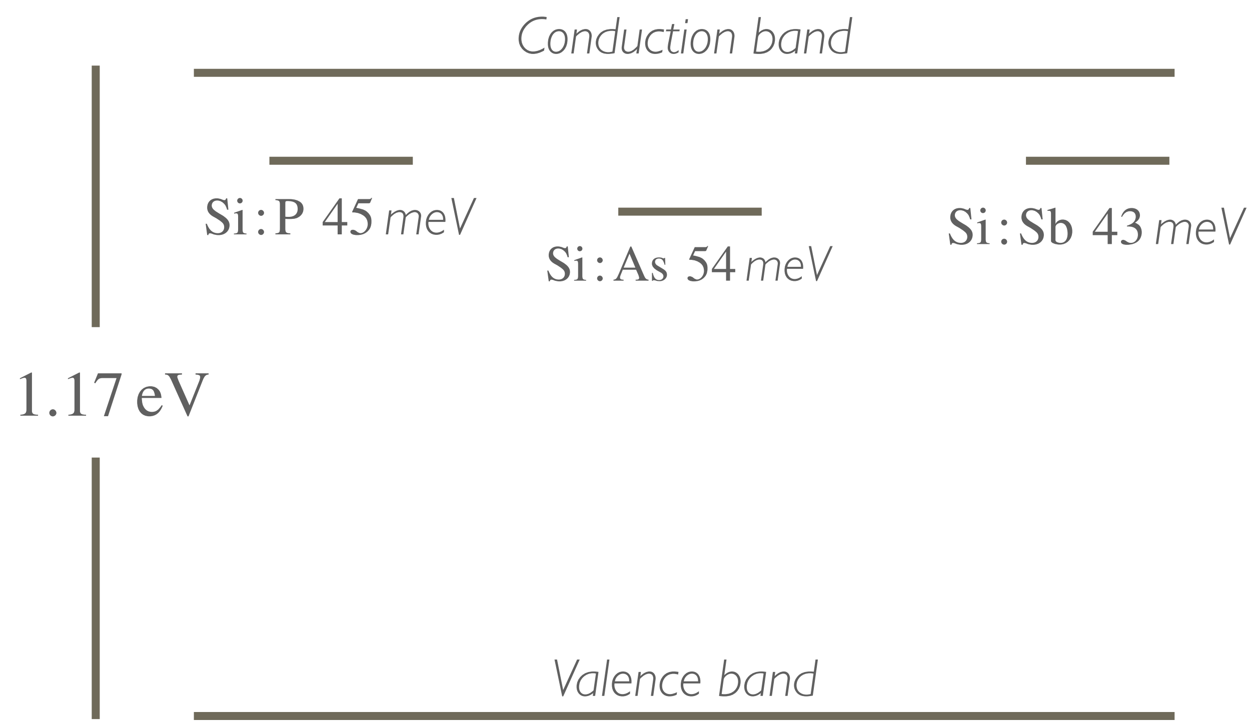
"Hydrogen" atom in dielectric background

$$E_I = \frac{1}{2}\left(\frac{\alpha}{\epsilon}\right) m_e^* \approx 50\,\text{meV}$$

$$r = \frac{\epsilon}{\alpha m_e^*} \approx 10 - 100\, a_*$$

CHOICE OF TARGET MATERIAL

Silicon



The particular dopant doesn't matter much.
We'll take ***Si:P***

REACH TO DM SCATTERING

Let's estimate first the reach to ***scattering***

DM velocity distribution *Interaction type* *Target response*

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q})\, S(\mathbf{q}, \omega_{\mathbf{q}})$$

REACH TO DM SCATTERING

Interaction type

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q})\, S(\mathbf{q}, \omega_{\mathbf{q}})$$

$$F(q) = \frac{1}{q^2 + m_{\gamma_D}^2} \approx \frac{1}{q^2}$$

"Light mediator"

REACH TO DM SCATTERING

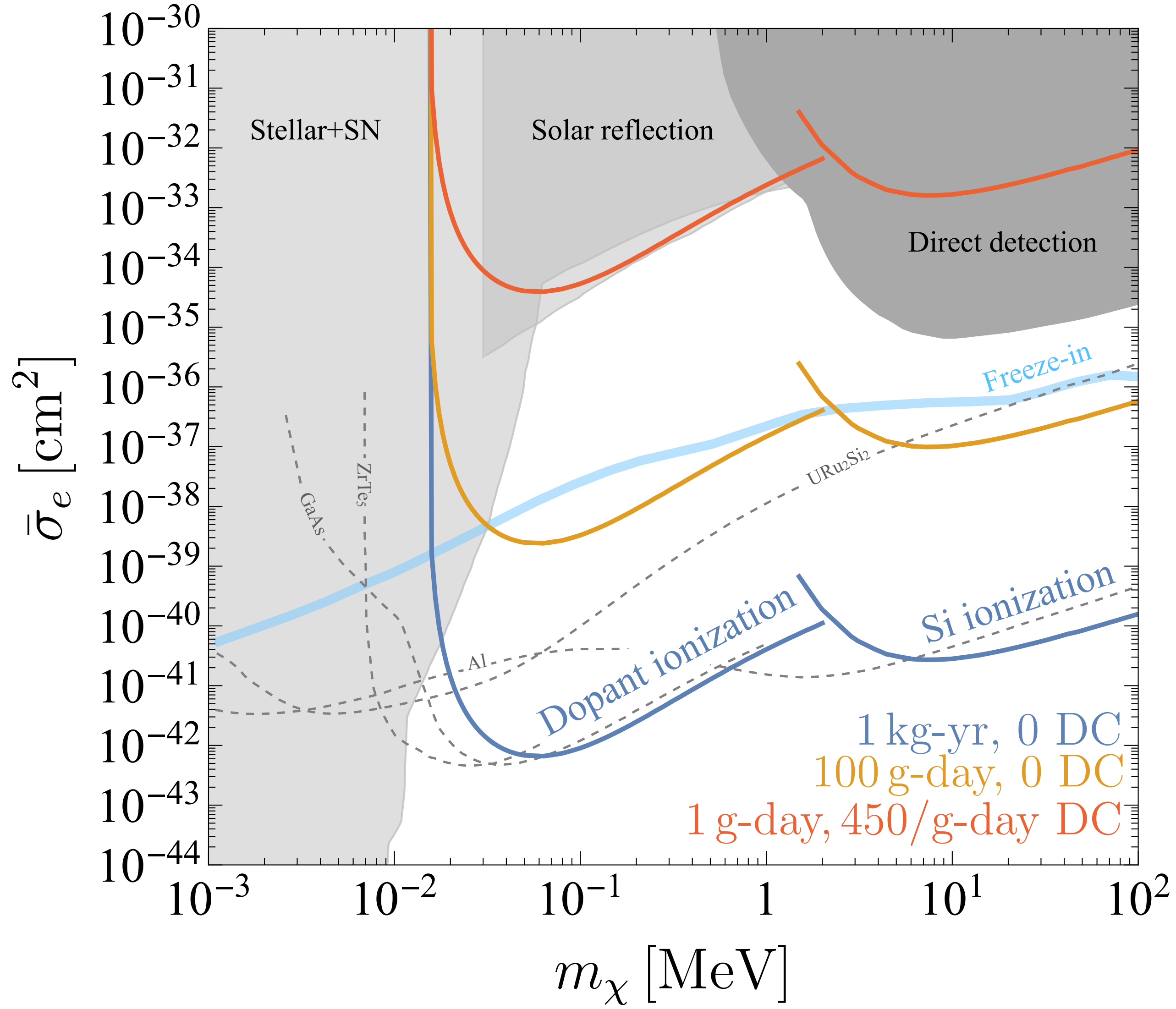
Target response

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q})\, S(\mathbf{q}, \omega_{\mathbf{q}})$$

Compute the target response simply as in a screened hydrogen atom

$$\mathcal{W}(\mathbf{q},\omega) = \left(\frac{E_{\rm eff}}{E_0}\right)^2 \frac{2^{10}\pi^2 \alpha m_* n_D a_*^4}{3|\epsilon(\mathbf{q},\omega)|^2} \frac{(3\tilde{q} + \tilde{k}^2 + 1)\exp\left[-\frac{2}{\tilde{k}}\tan^{-1}\left(\frac{2\tilde{k}}{\tilde{q}^2 - \tilde{k}^2 + 1}\right)\right]}{[(\tilde{q}+\tilde{k})^2+1]^3[(\tilde{q}-\tilde{k})^2+1]^3[1-\exp(-2\pi/\tilde{k})]}$$

REACH TO DM SCATTERING



$$n_D = 10^{18}/\mathrm{cm}^3$$

- A 1 gram-day detector would start probing new parameter space.
- A kg-year detector could probe freeze-in (no DC)

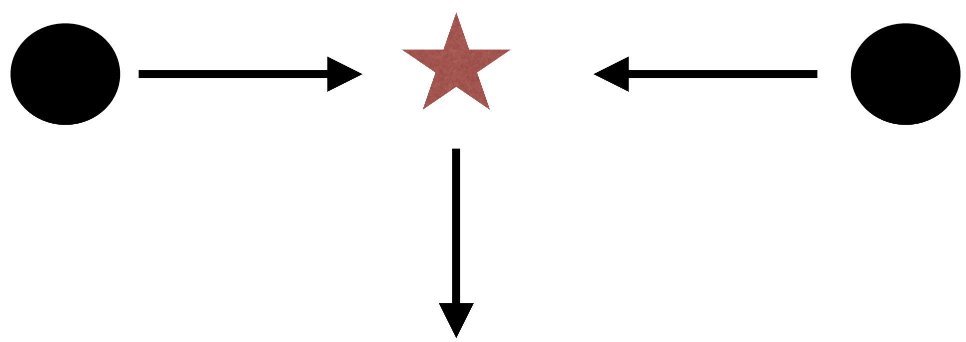
Egaña-Ugrinovic & Du, Essig, Sholapurkar arXiv:2212.04504

REACH TO DM SCATTERING

Target response

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q})\, S(\mathbf{q}, \omega_{\mathbf{q}})$$

$p_{\mathrm{DM}} \approx 100\,\mathrm{eV}\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{keV}}\right]$



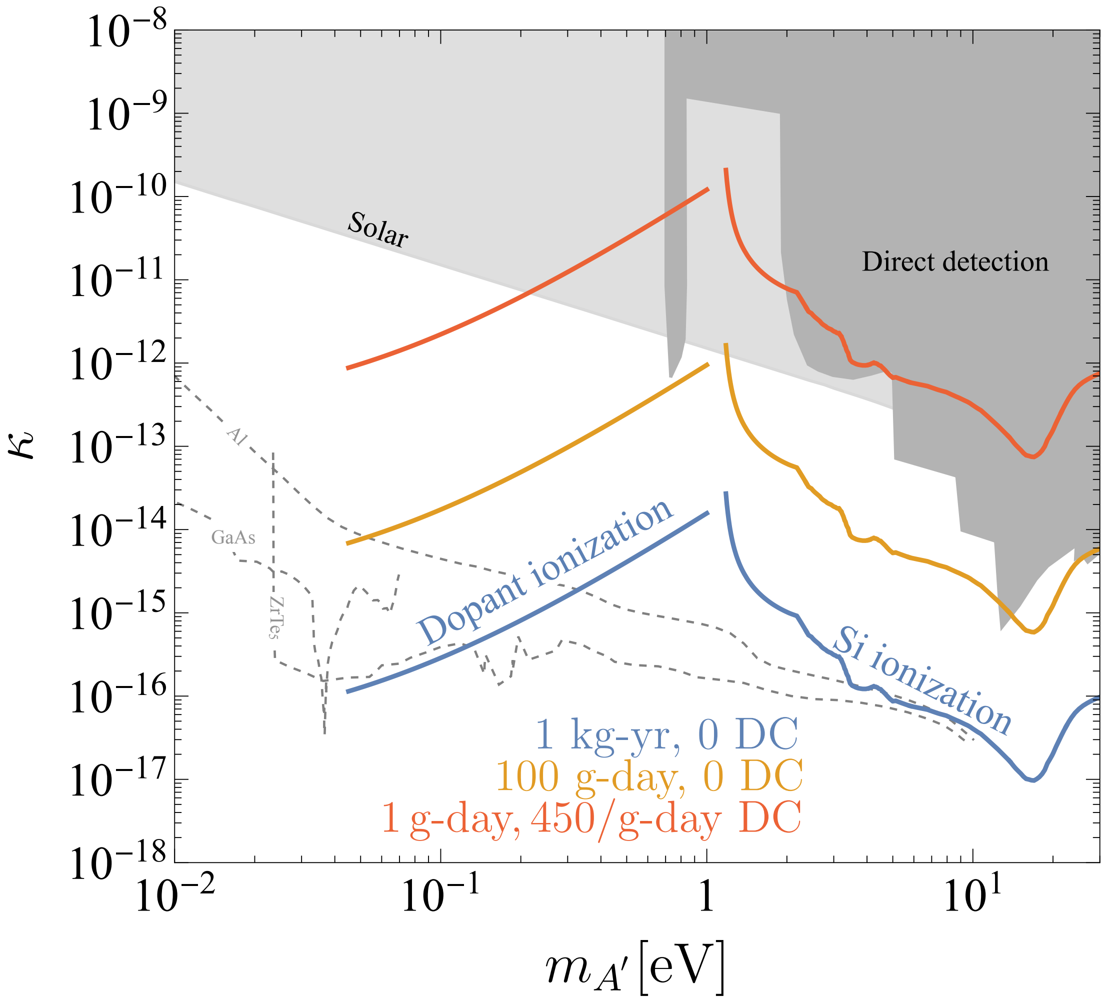
$p_e \approx \frac{1\mathrm{keV}}{\epsilon_{\mathrm{Si}}} \approx 100\,\mathrm{eV}$

$q \approx 100\mathrm{eV}$

$\omega = \frac{q^2}{2m_e} \approx 10\,\mathrm{meV}$

The kinematics is ***optimal***

REACH TO DM ABSORPTION



$$n_D = 10^{18}/\mathrm{cm}^3$$

- A 1 gram-day detector would improve bounds by two-orders of magnitude.

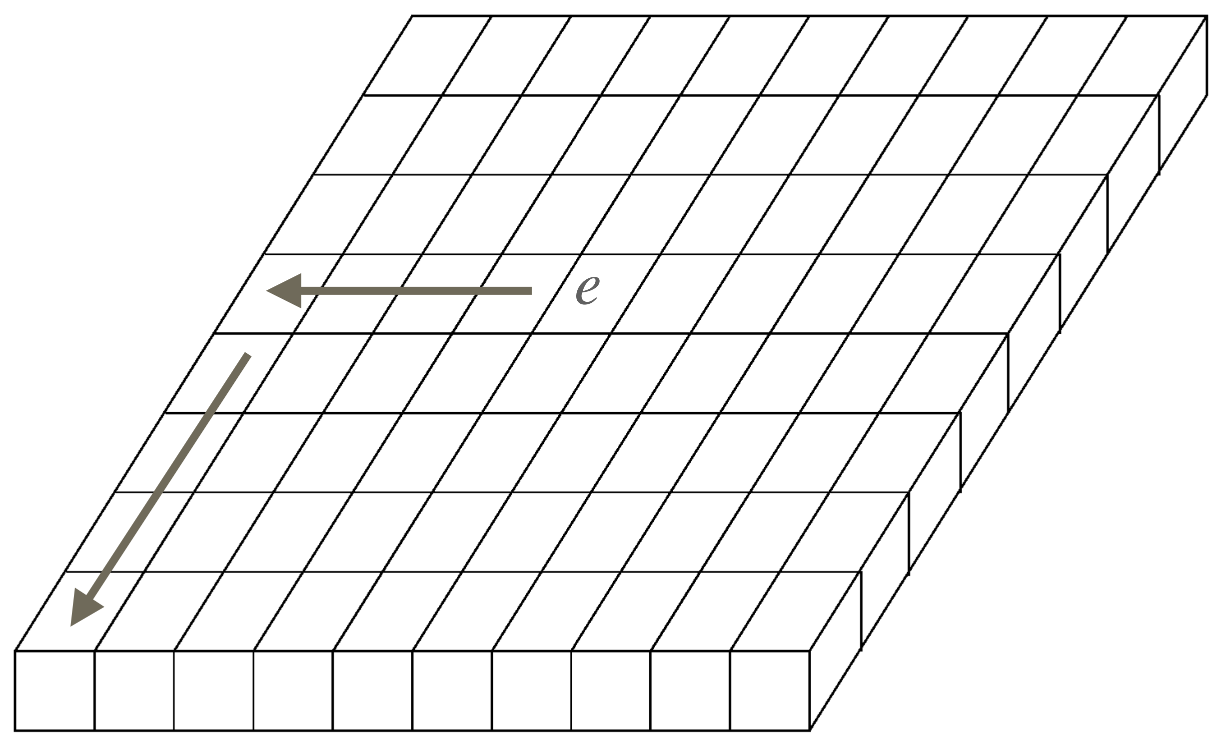
Egaña-Ugrinovic & Du, Essig, Sholapurkar
arXiv:2212.04504

Backgrounds

BACKGROUNDS

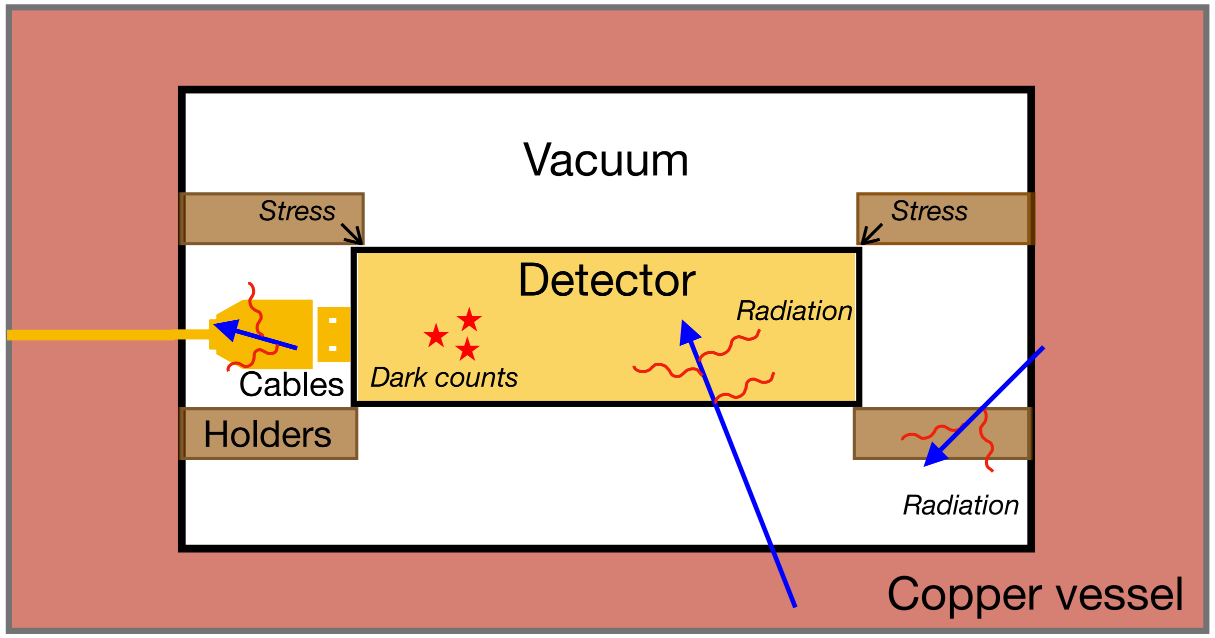
- Can't say much without a concrete detector design, besides an **educated guess**
- Our proposal could be implemented by modifying existing pure-semiconductor detectors.
- Assume that detector is akin to a CCD, but with a doped bulk.

Skipper CCD readout



BACKGROUNDS

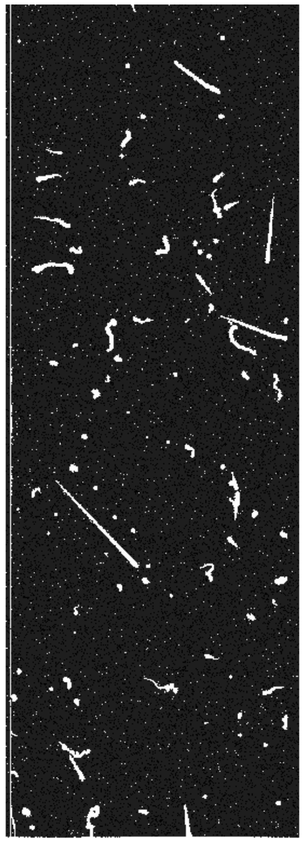
- Two main types: radiative and intrinsic (“dark currents”).

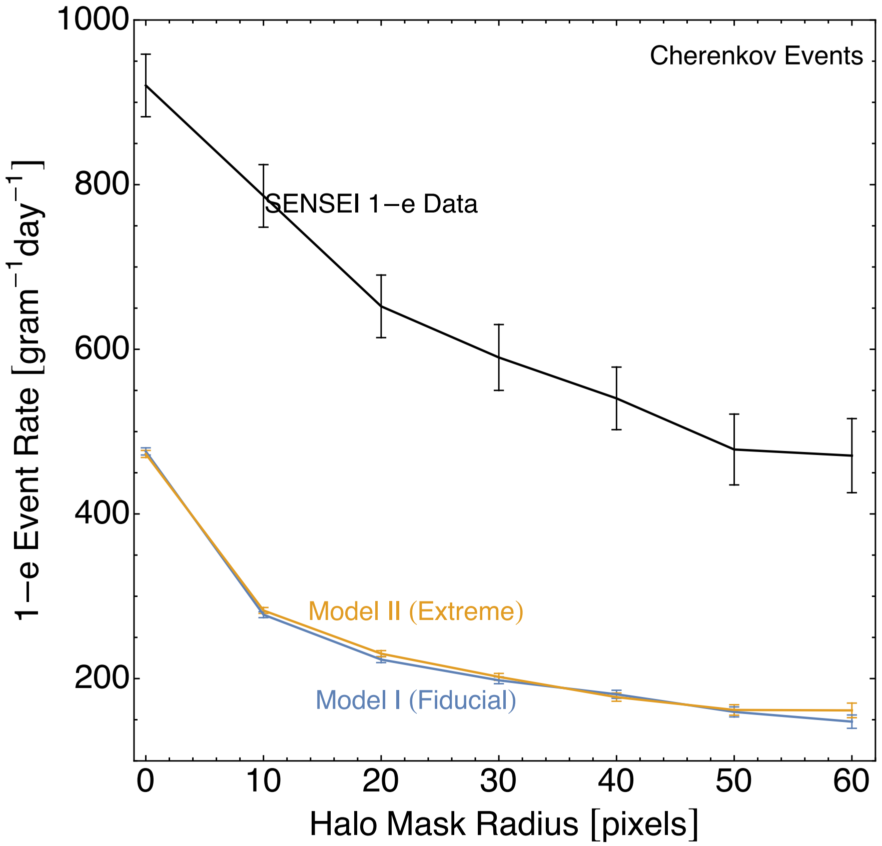


Egaña-Ugrinovic & Du, Essig, Sholapurkar
PRX 12 (2022) 1,1

BACKGROUNDS AT SIMILAR DETECTORS

- The 500 events/g-day are likely 30% radiative, 70% true dark counts.





Radiative backgrounds at SENSEI

Egaña-Ugrinovic & Du, Essig, Sholapurkar To appear

- A possibility is that the 70% comes from "charge leakage".

What are the next steps?

REQUIRED STEPS

1. Evaluate the relevance for DM detection. *Done*.

2. Design the detector readout. *In preparation for a similar device* (*Egaña-Ugrinovic*+Du,Essig, Fernandez, Sofo-Haro,Tiffenberg, Uemura).

3. Merge with a full detector architecture. Modifications are needed with respect to usual CCDs, ask me why offline.

4. Study backgrounds, especially charge leakage, ask me why offline.

5. Get money.

6. Build.

Likely ~5-10 year timeframe.

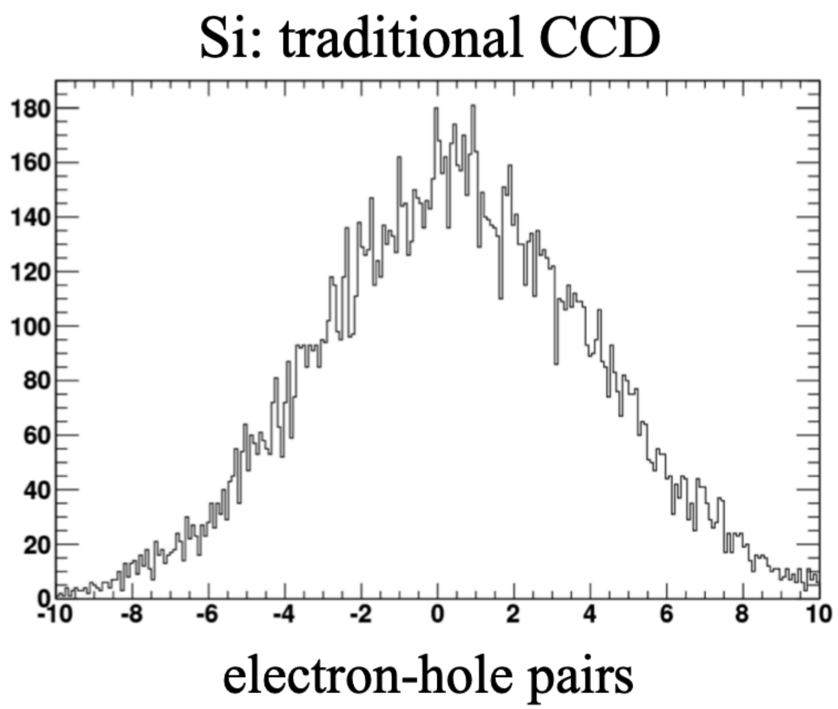
CONCLUSIONS

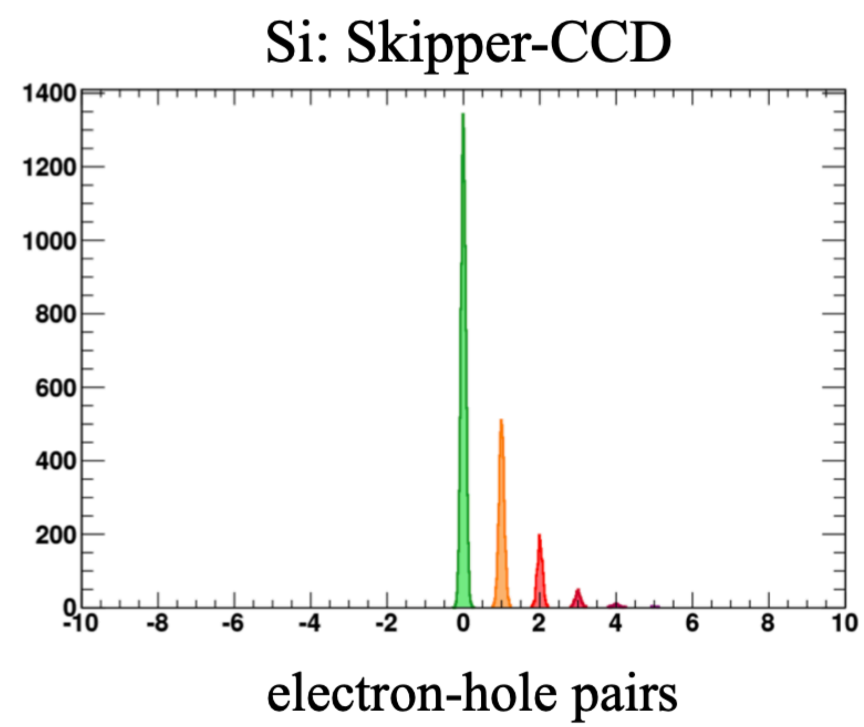
- Doped-semiconductor detectors have a *significant potential* to discover **sub-MeV DM**.
- They could be designed around existing architectures. In fact, doped devices for IR light detection *already exist ("BIBs").*
- The main challenge, as with any light-DM detector, is to design a low-DC detector.
- The competition are SNSPDs, TESs looking for athermal phonons (SPICE-HERALD), others. None of these technologies can at present test sub-MeV DM (ask me offline why).
- The theory motivations are there, *now the challenge is experimental.*

Backup

DARK MATTER WITH SUB-GEV MASS

On the experimental side:



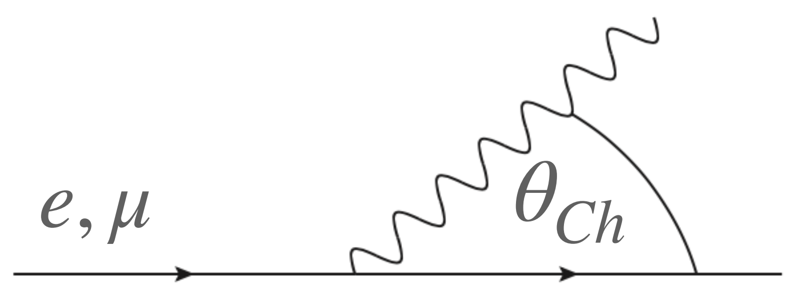


Essig, ICHEP 2020

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

CHERENKOV RADIATION

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



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

Cherenkov condition

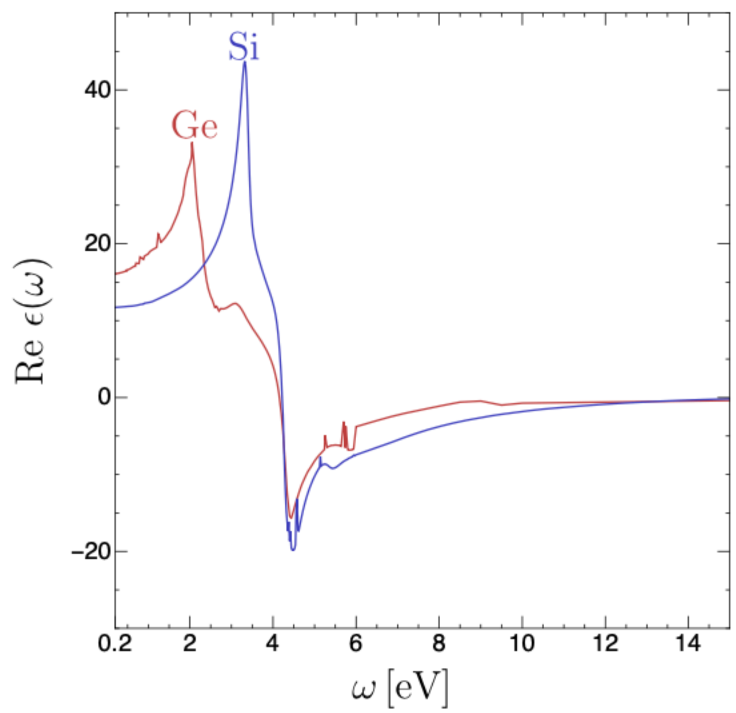
$$\frac{dN_\gamma}{d\omega dx} = \alpha \left(1 - \frac{1}{v^2 \varepsilon(\omega)} \right)$$

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

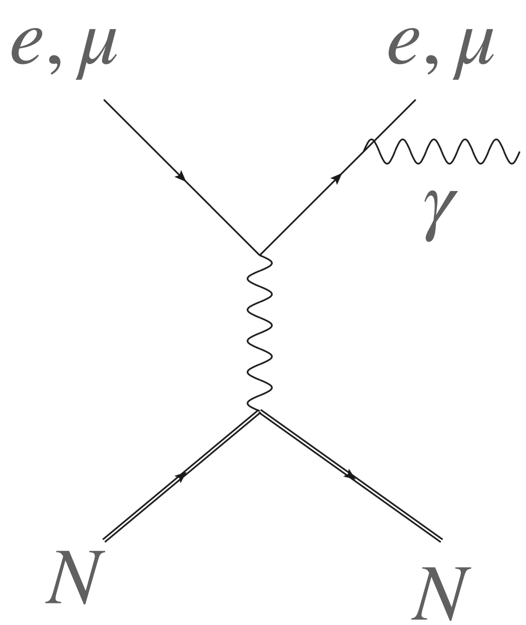
Cherenkov photons have energies $\omega \lesssim 4\,\mathrm{eV}$

WHY IS CHERENKOV RADIATION RELEVANT?

2. It arises at leading order in electrodynamics

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

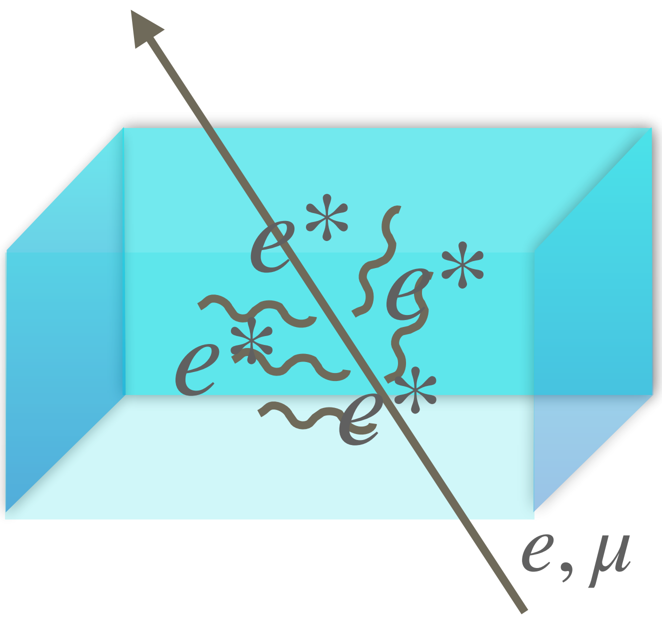
$$N_\gamma \sim 4\left[\frac{\Delta\omega}{1\,\mathrm{eV}}\right]\left[\frac{\Delta x}{100\,\mu\mathrm{m}}\right]$$



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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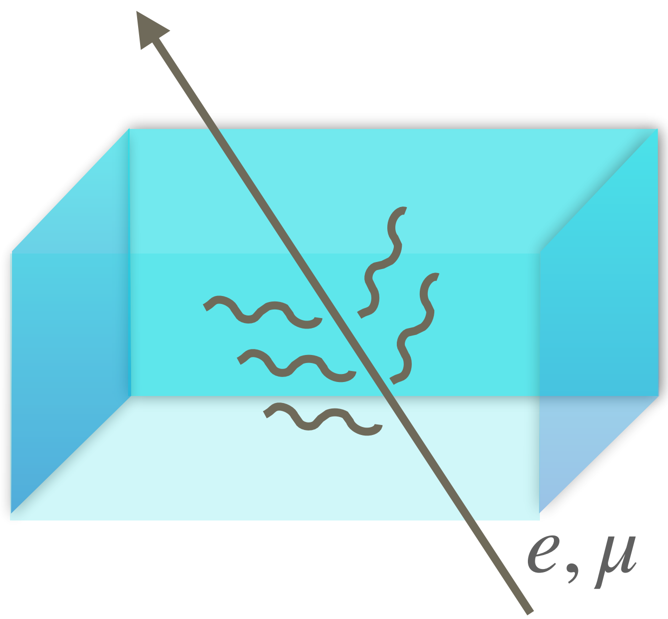
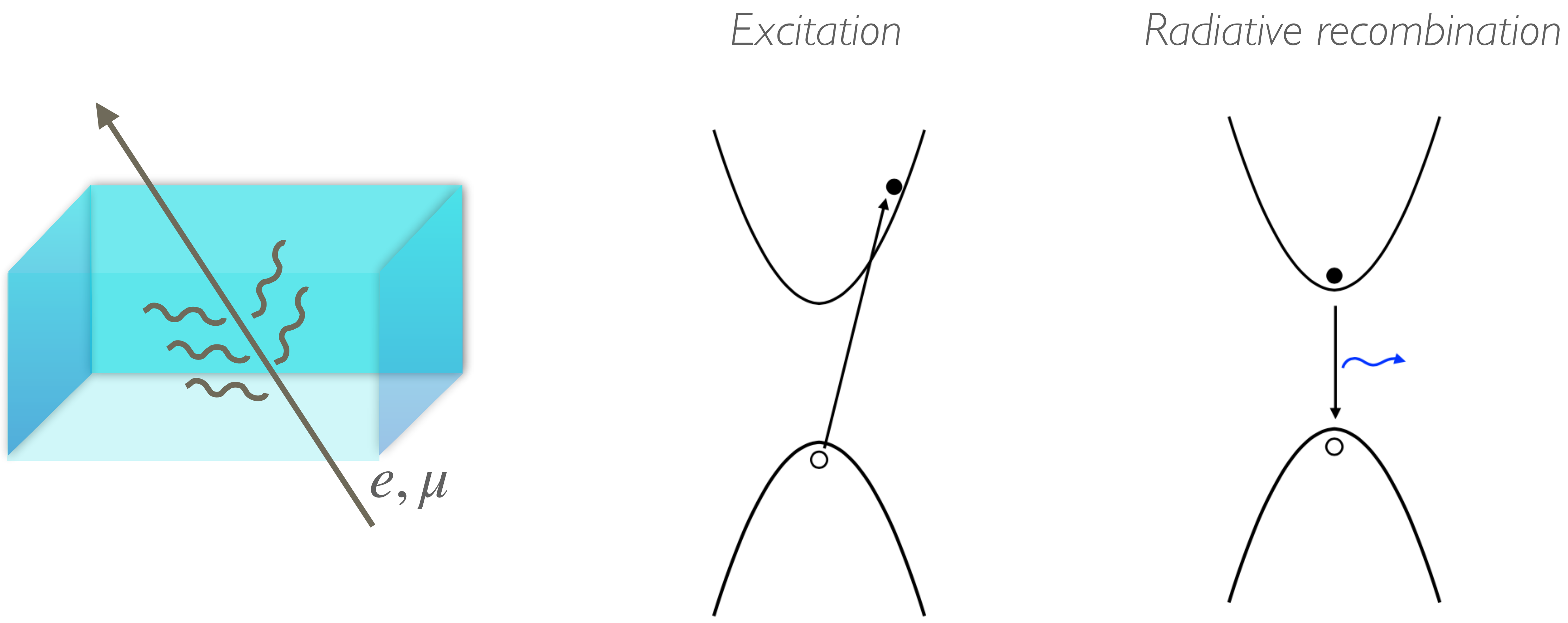


Luminescence or scintillation

Slow: phosphorescence, afterglow

LUMINESCENCE FROM RADIATIVE RECOMBINATION

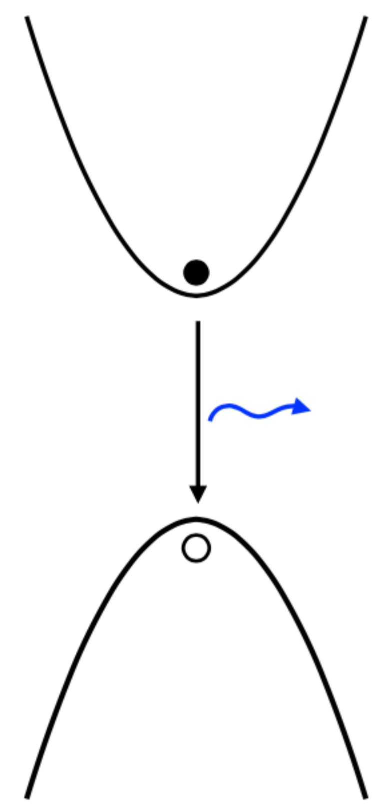
- Results in the emission of photons/phonons as excited electrons in a material return to the ground state



WHY IS LUMINESCENCE RELEVANT?

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

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

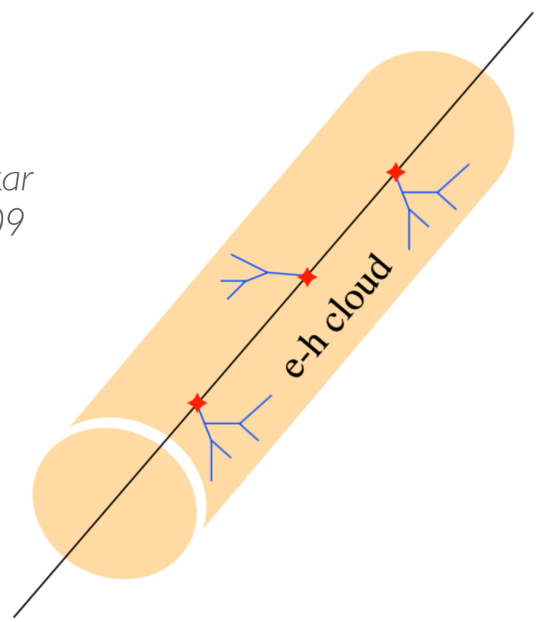


$\omega \sim \mathrm{eV}$

WHY IS LUMINESCENCE RELEVANT?

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

DEU, Du, Essig, Sholarpurkar
PRX 12 (2022) 1, 011009



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

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

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

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

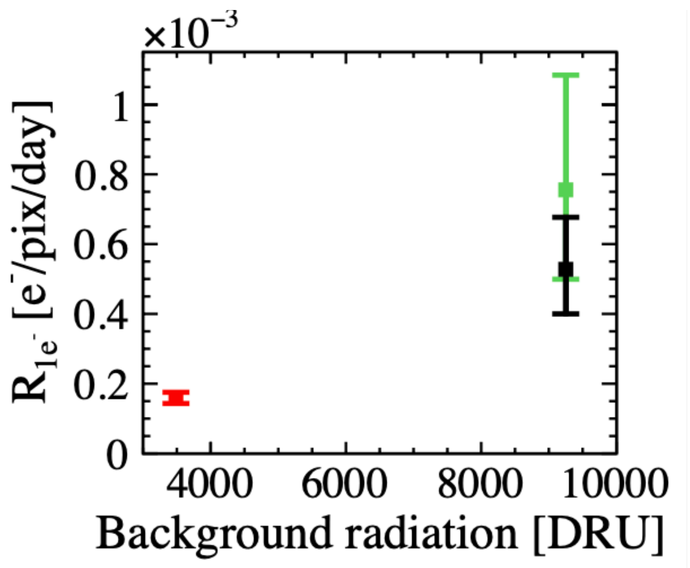
SENSEI

SENSEI (2020 DATA)

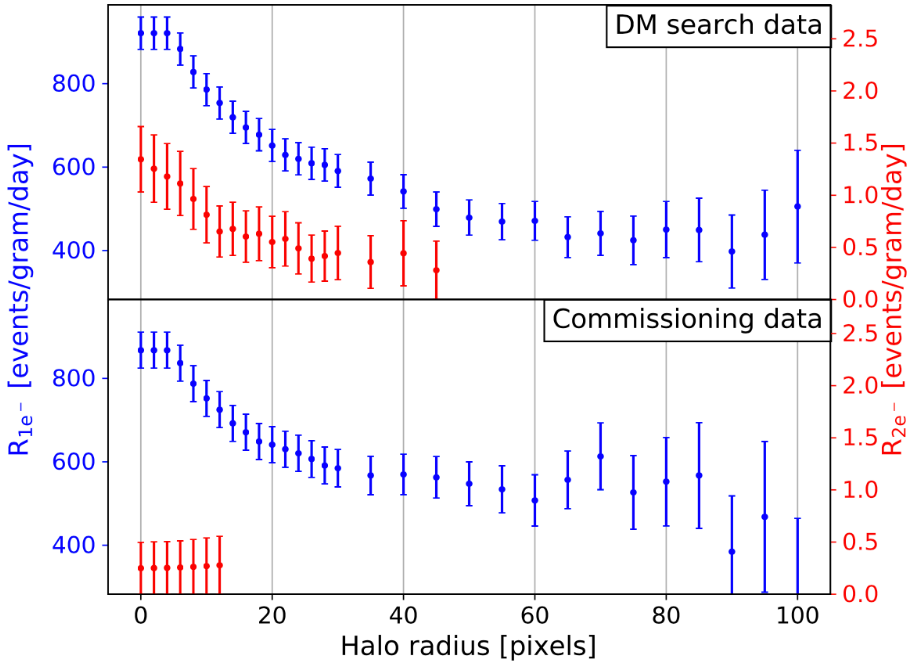
2004.11378 (SENSEI coll.)

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

Depends on track rate



Depends on halo mask



CHERENKOV RADIATION

DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
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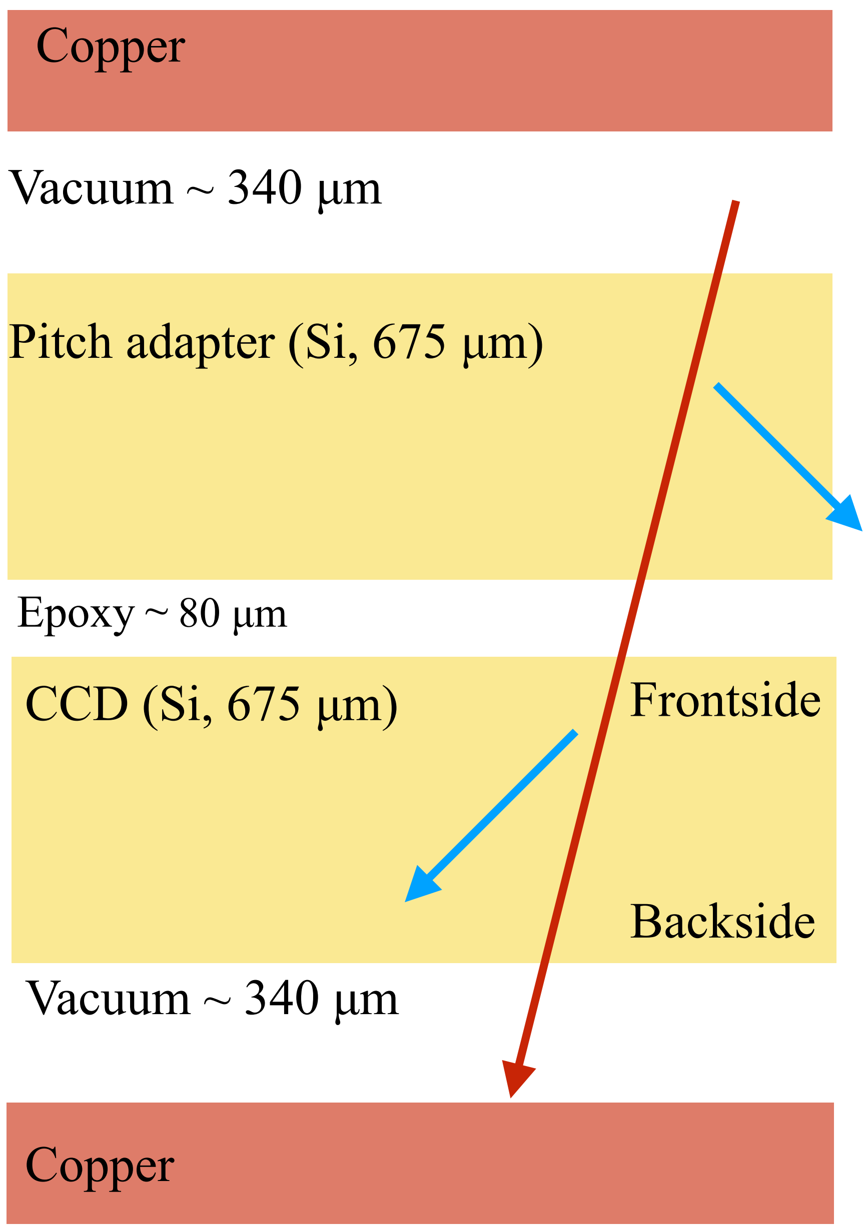
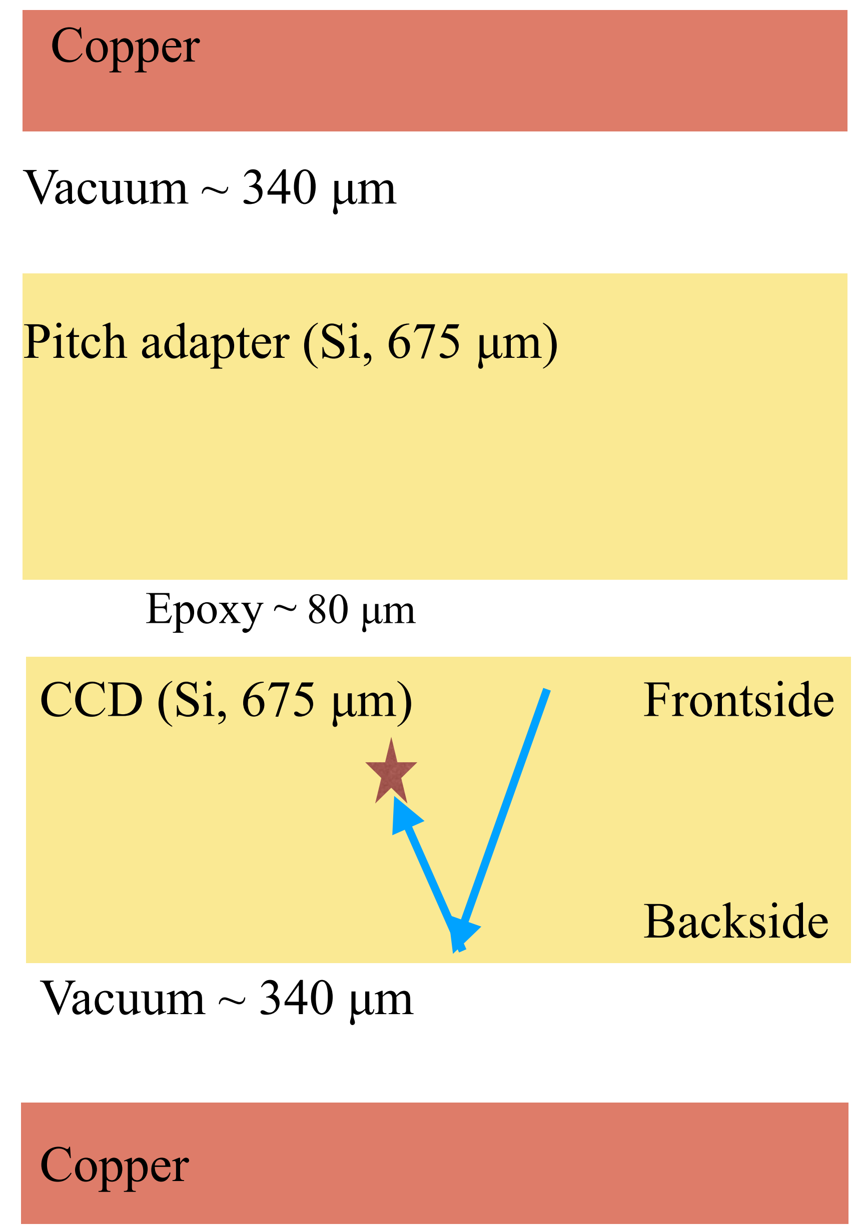
Track passage and radiation



Photons bounce around until absorbed



LUMINESCENCE (RADIATIVE RECOMBINATION)

Track passage and radiation

DEU, Du, Essig, Sholapurkar
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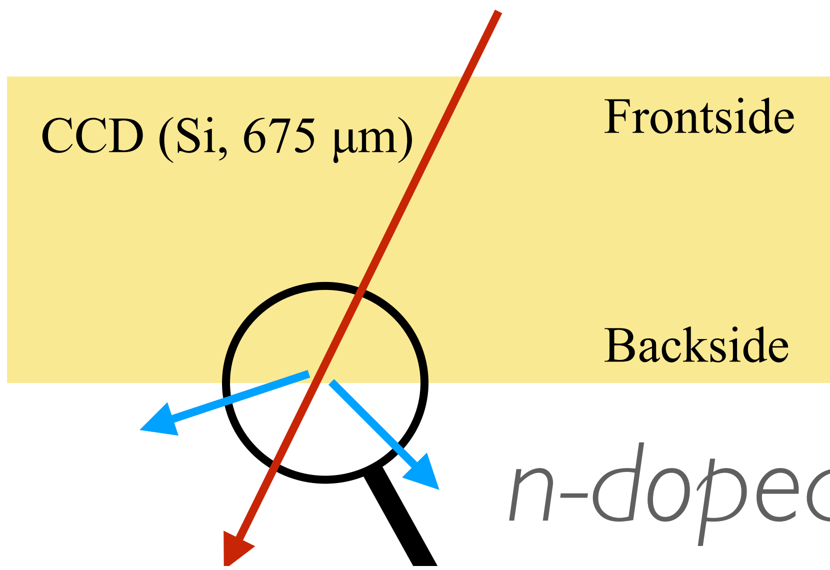
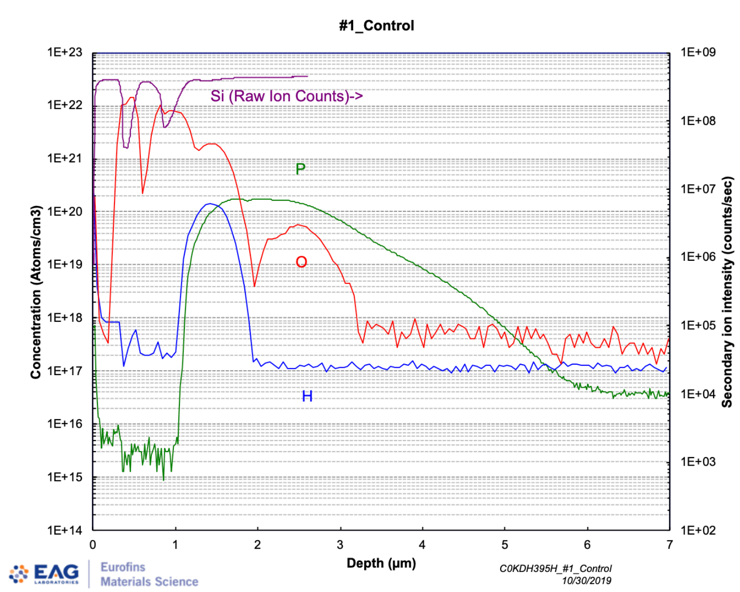
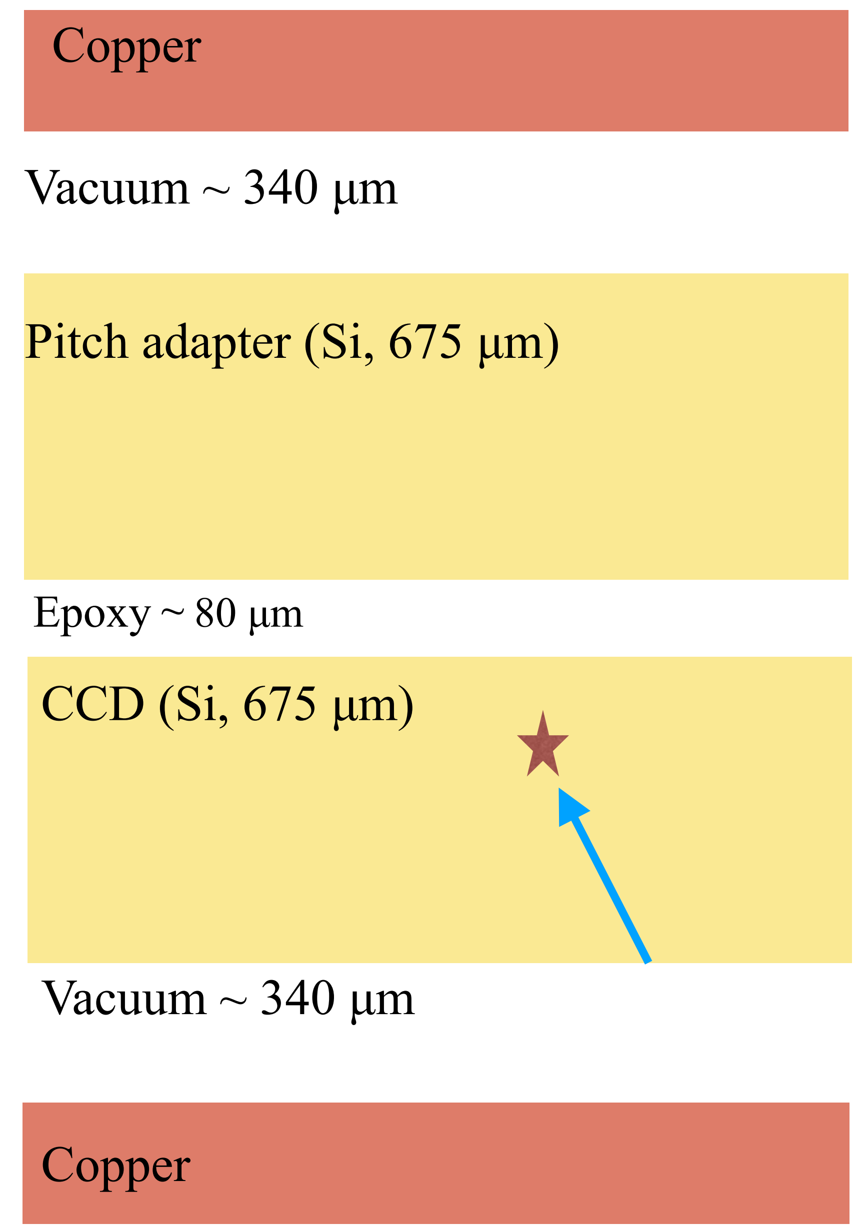
Photons bounce around until absorbed



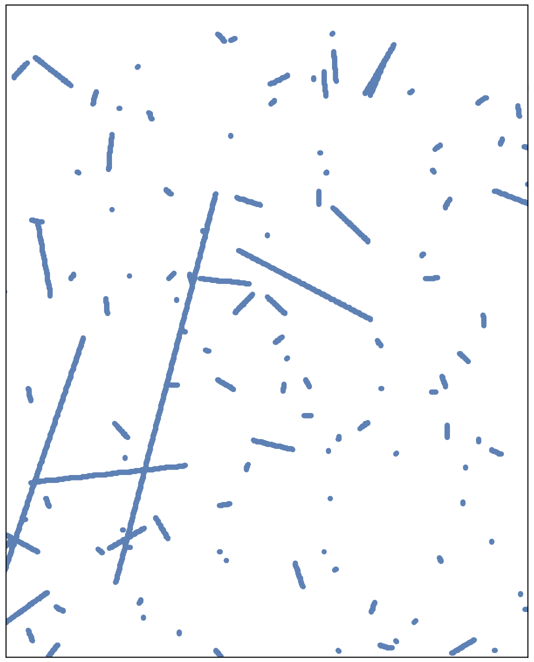
n-doped layer!



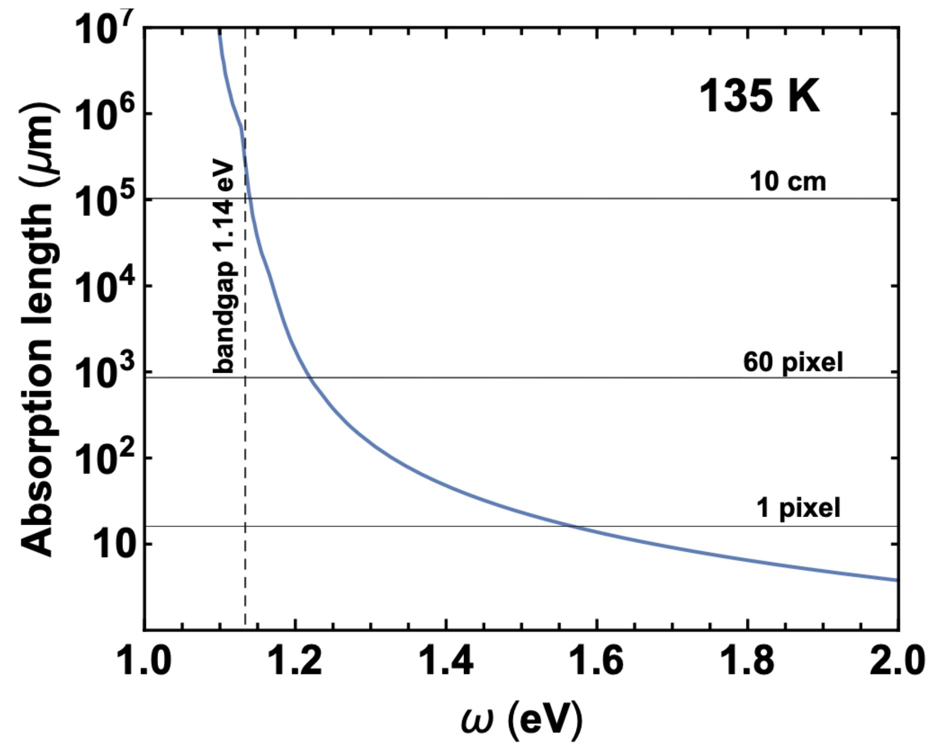
From A. Chavarria et al. 2110.13133



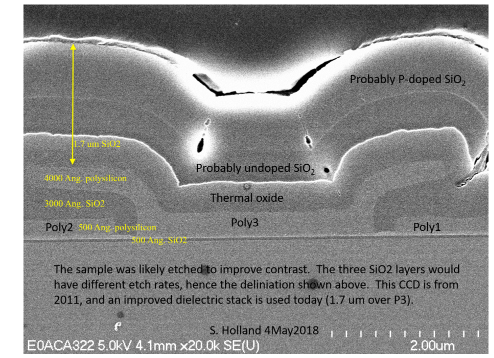
Simulated tracks



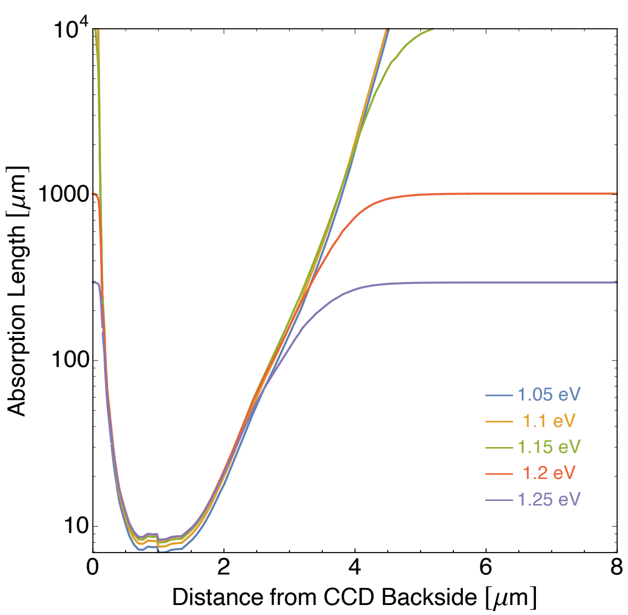
Photon absorption



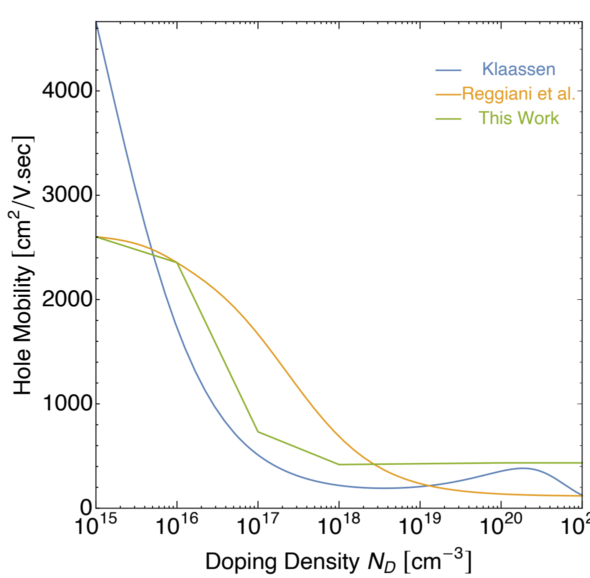
Reflection/refraction, thin-film interference



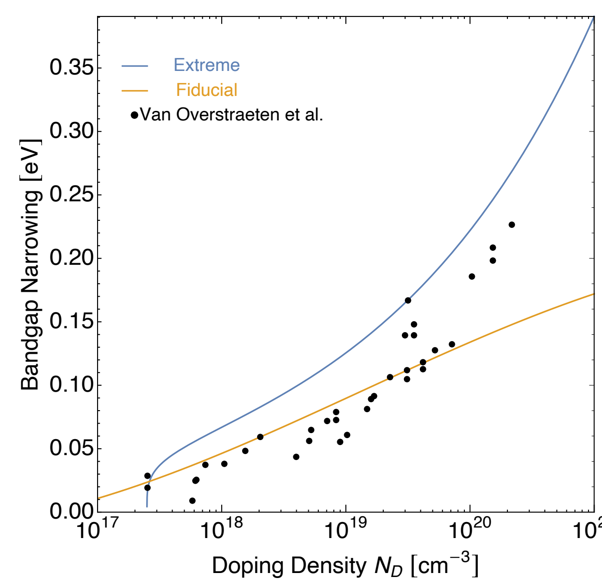
Backside absorption



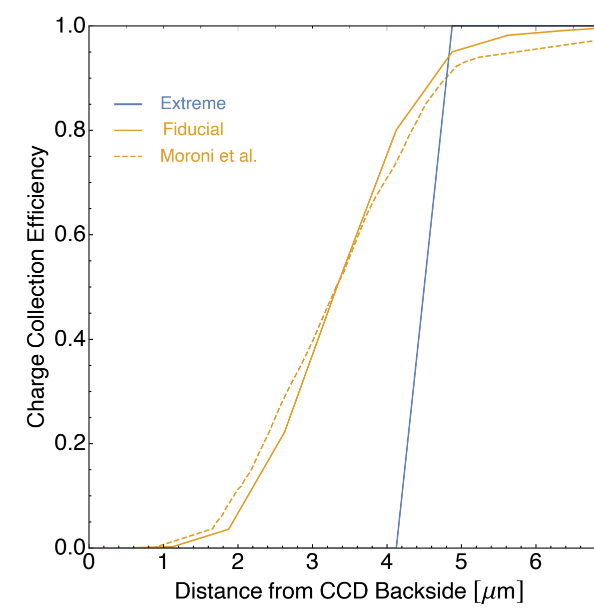
Mobility models



Bandgap gradients



Partial charge collection



etc. etc. etc.

RESULTS

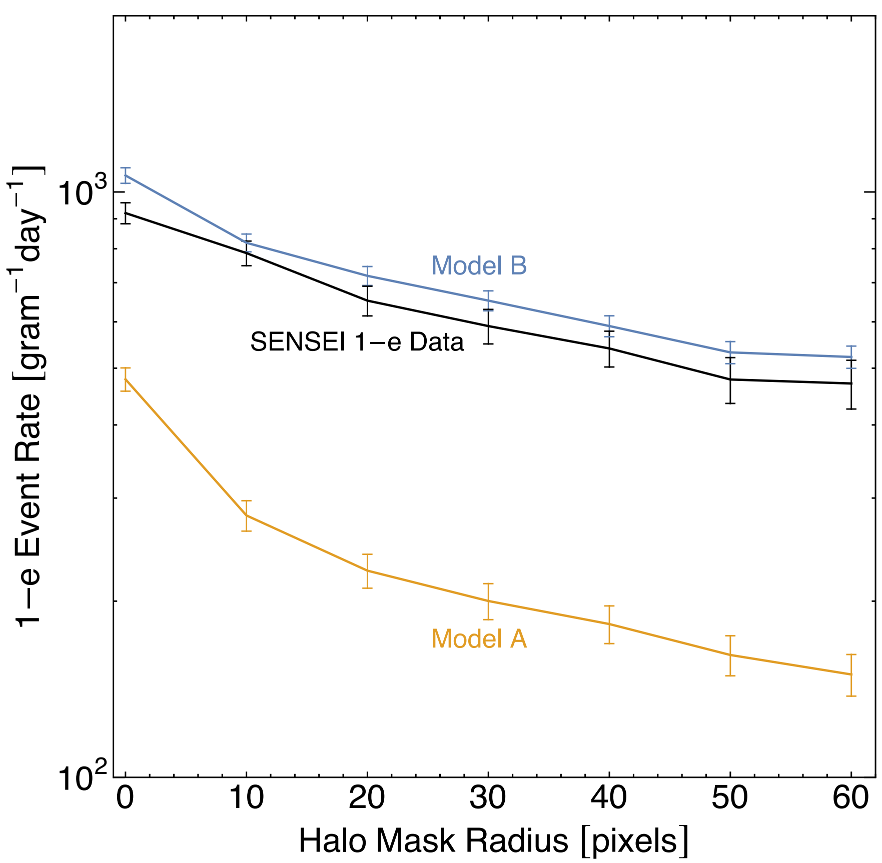
Latest simulation

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

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

(to be published)

(v/s 450 observed)

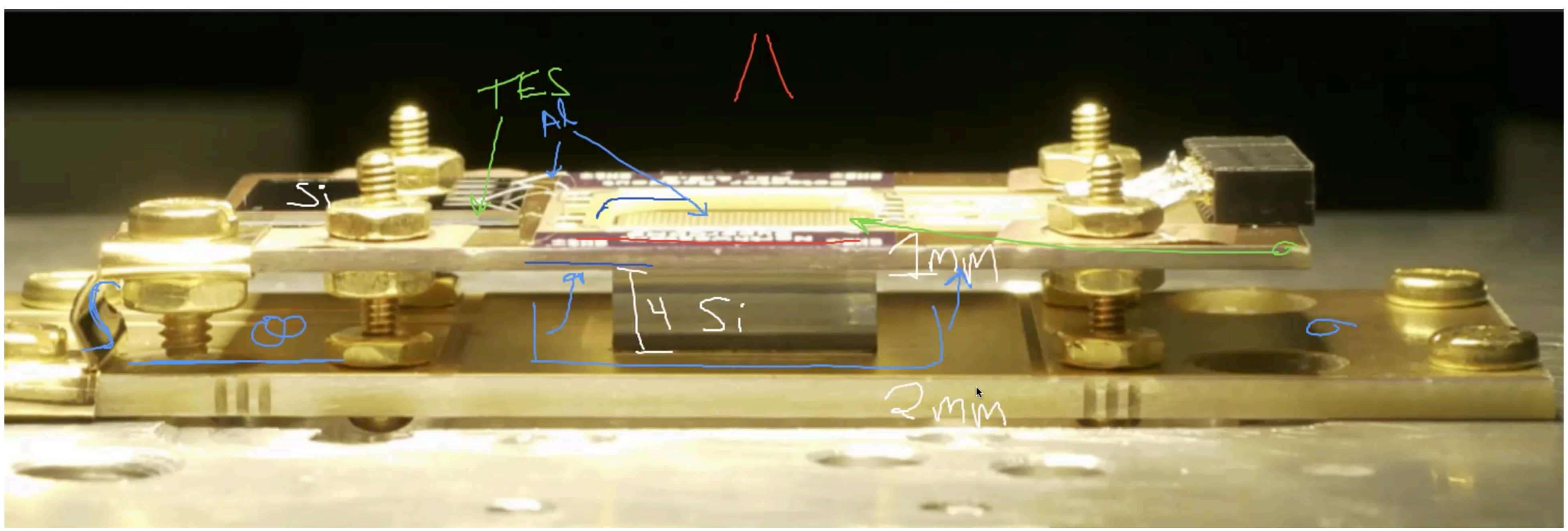


DEU, Du, Essig, Sholapurkar to be published

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)

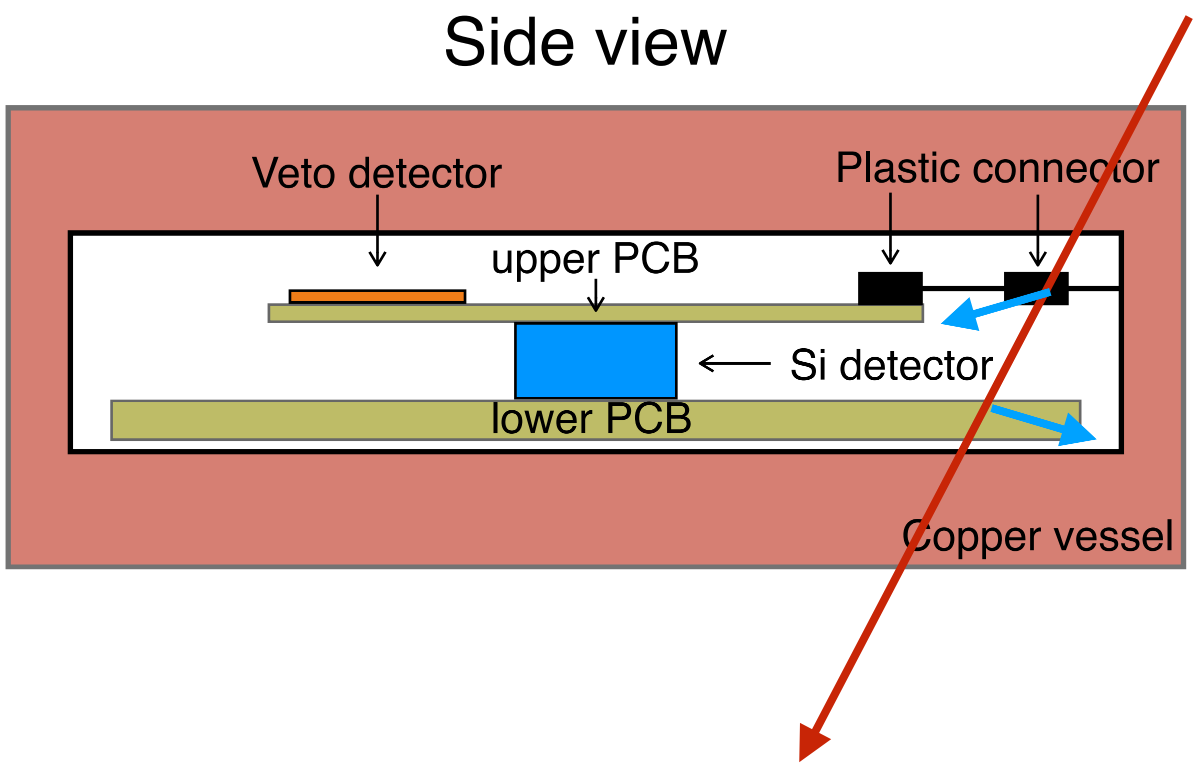
The one-electron rate is
likely generated by charge leakage *(*private communications)*

	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.



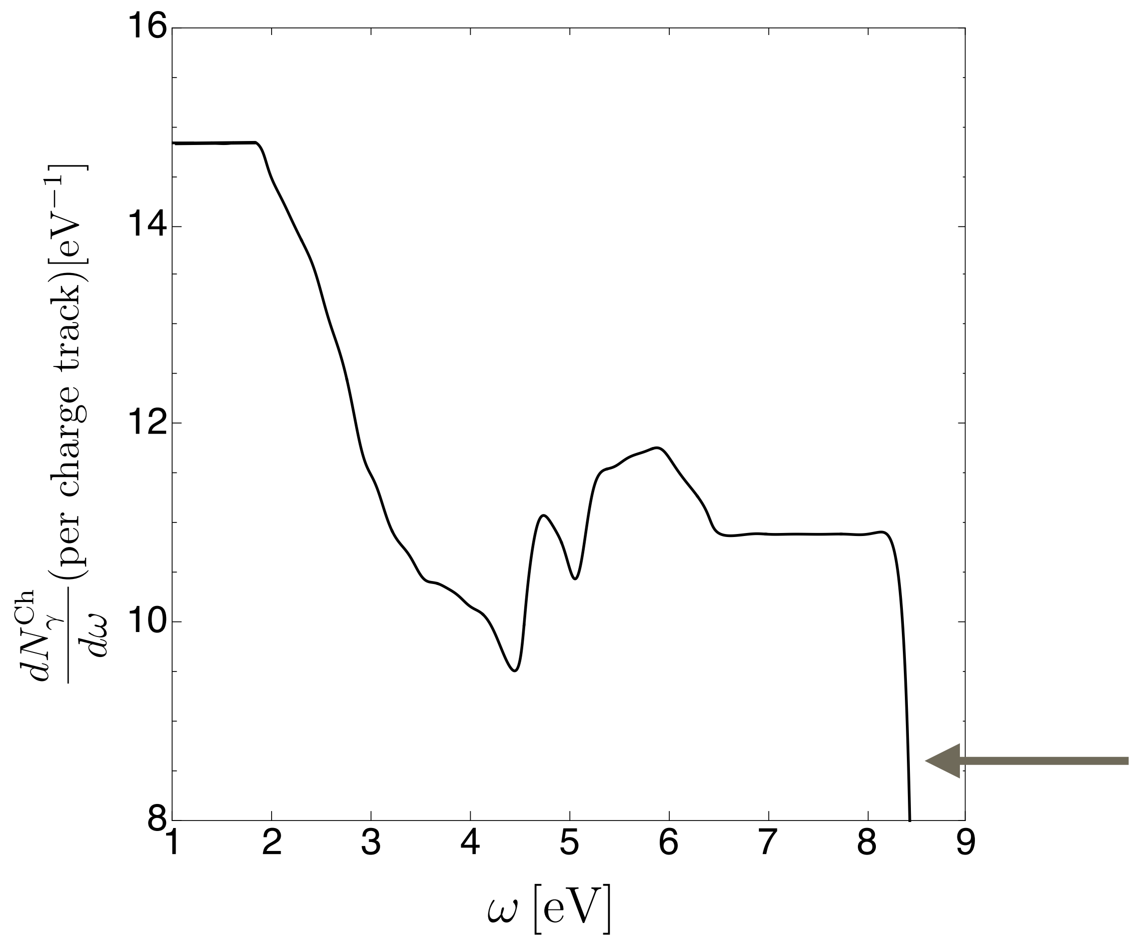
Not vetoed

Most of them from the PCBs

Cherenkovs and possibly Luminescence

RATE ESTIMATE

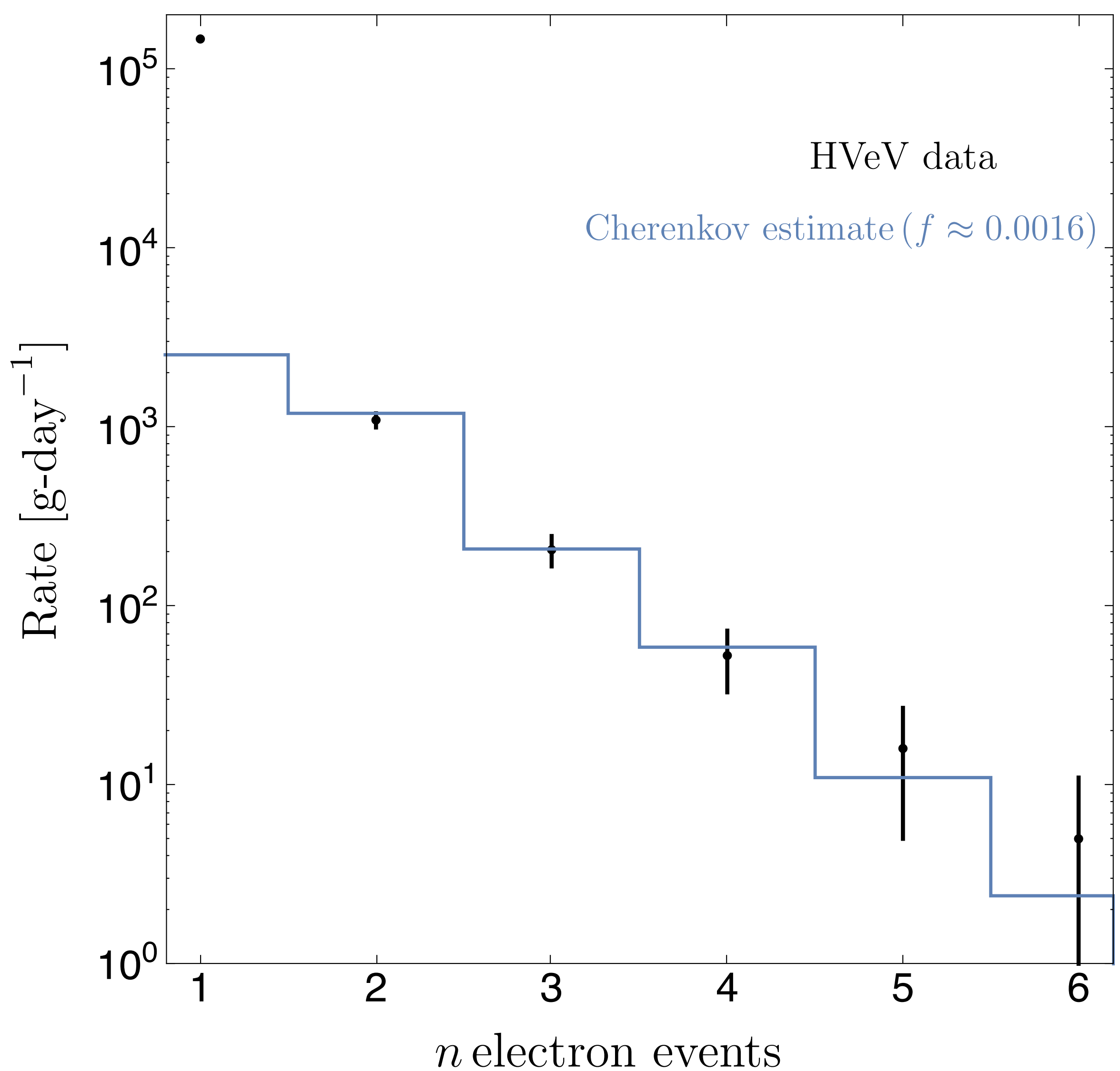
- A spectrum is inherited from the PCB absorption coefficient



PCB becomes absorptive so spectrum is cutoff

SUPERCDMS HVEV

See also
2204.08038
(new! SuperCDMS coll.)



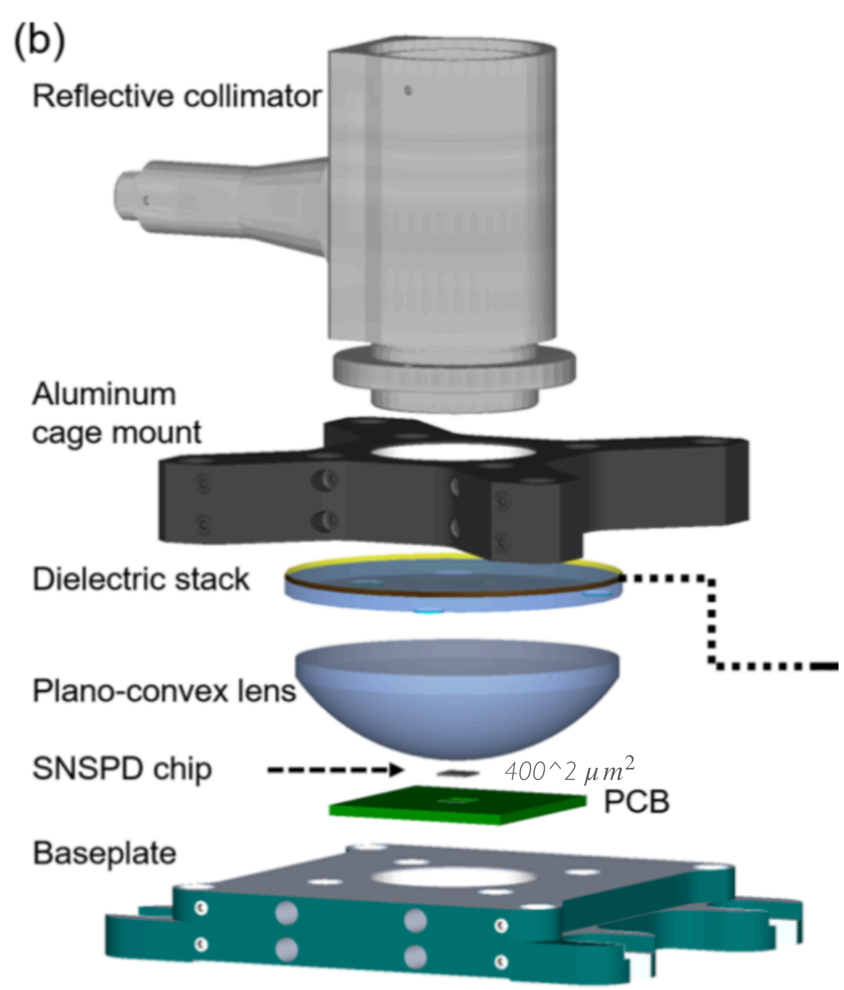
DEU, Du, Essig, Sholapurkar
arXiv:2011.13939
PRX 12 (2022) 1, 011009

Excellent agreement of the Cherenkov hypothesis with the observed spectrum

LAMPOST

LAMPOST

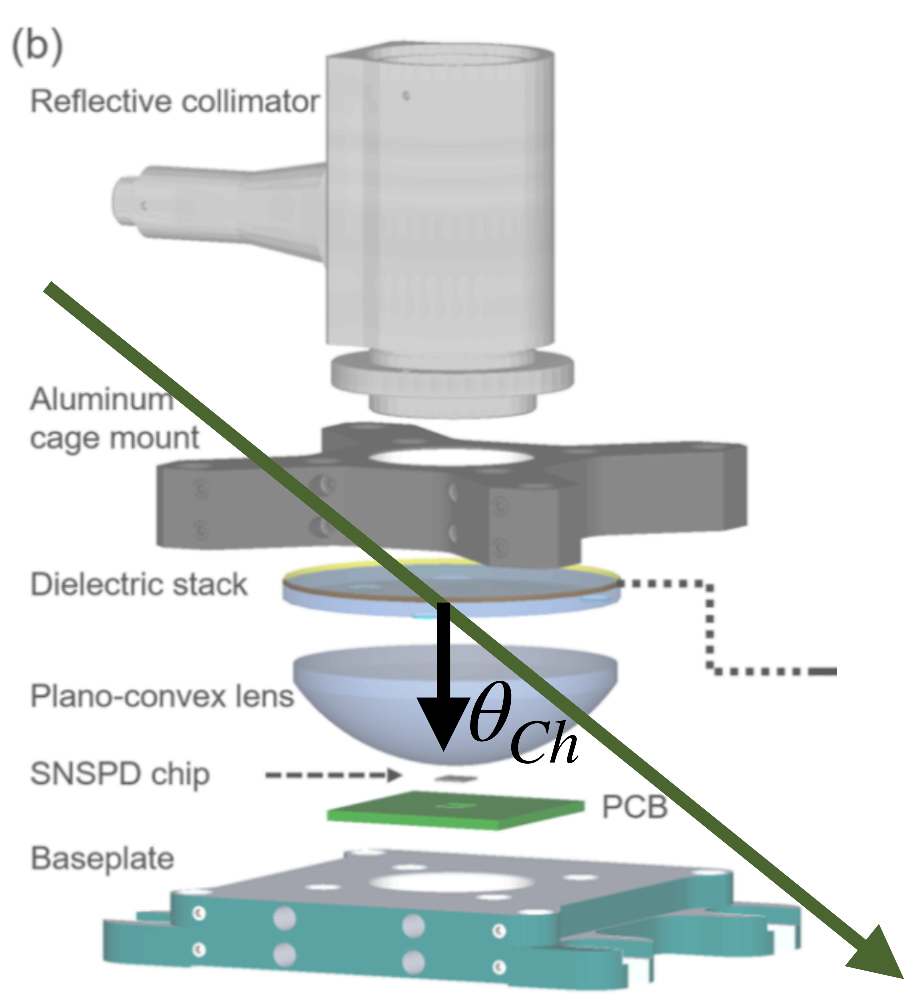
- Observes 6×10^{-6} counts/s in SNSPD detector.



2110.01582 (LAMPOST coll.)

LAMPOST

- Tracks passing through the lens generate Cherenkov photons.



From muons only

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

(~100 per track!)

SUPERCDMS SNOLAB

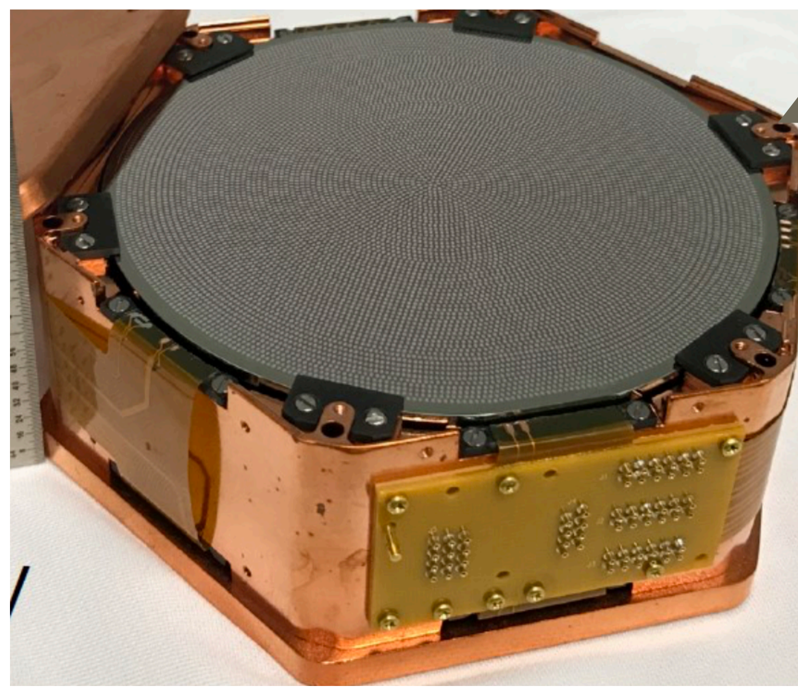
SUPERCDMS SNOLAB

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

Cirlex clamps

SuperCDMS coll. 1610.00006

Figure from Loer, DM 2018



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

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

Qubit decoherence?

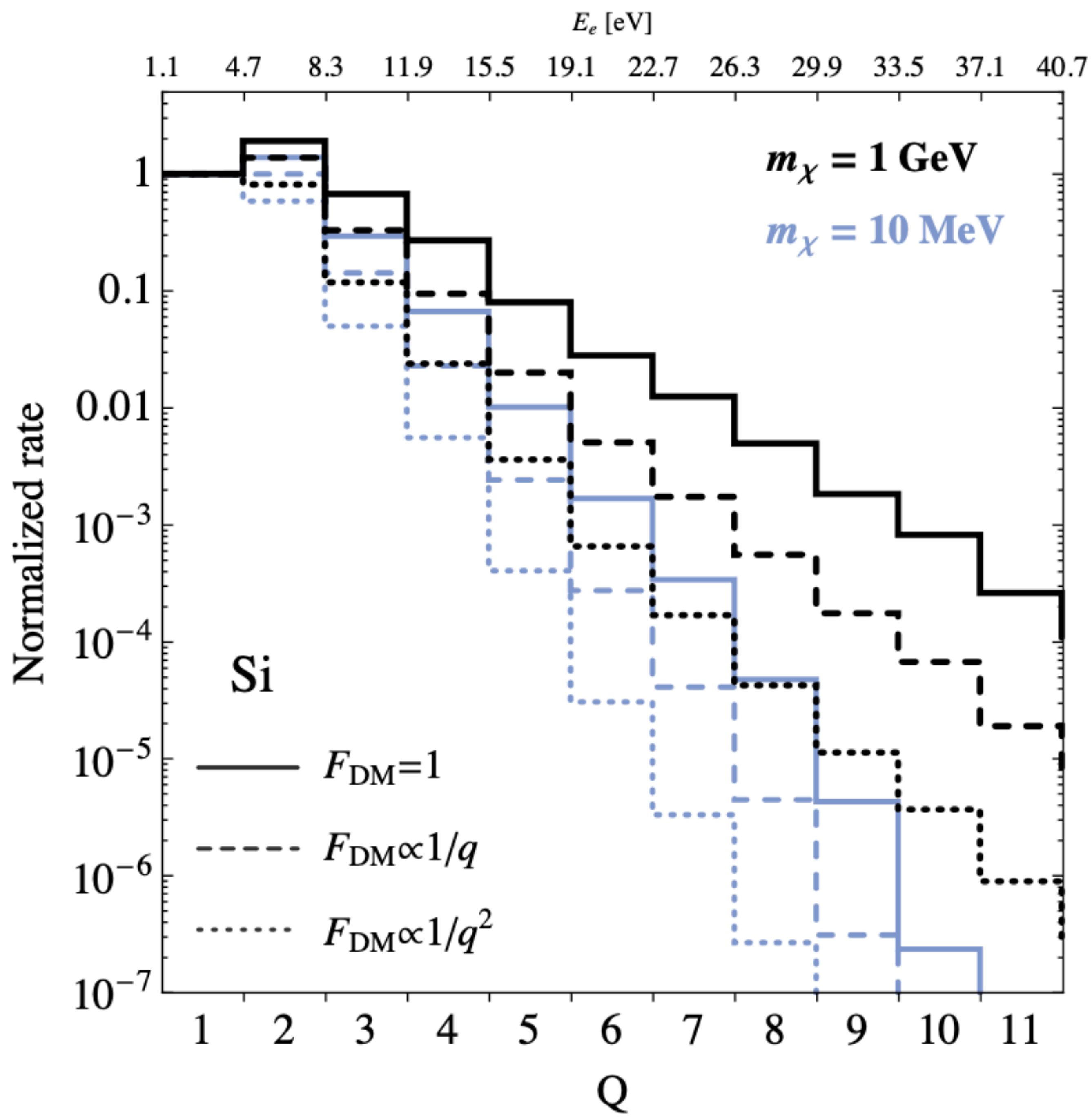
QUBIT DECOHERENCE

- 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

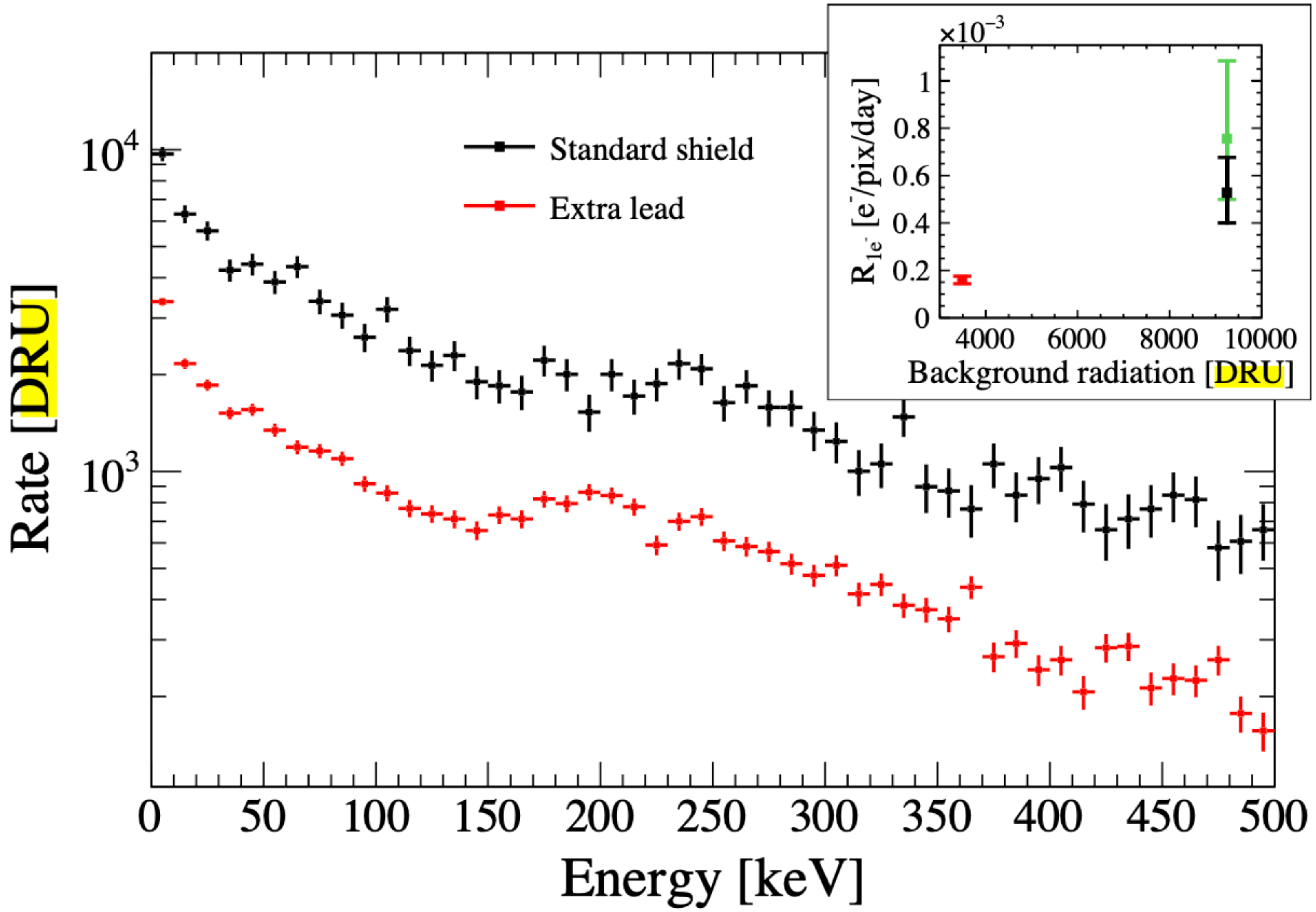
→ 10^3 *quasiparticles/track!*

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

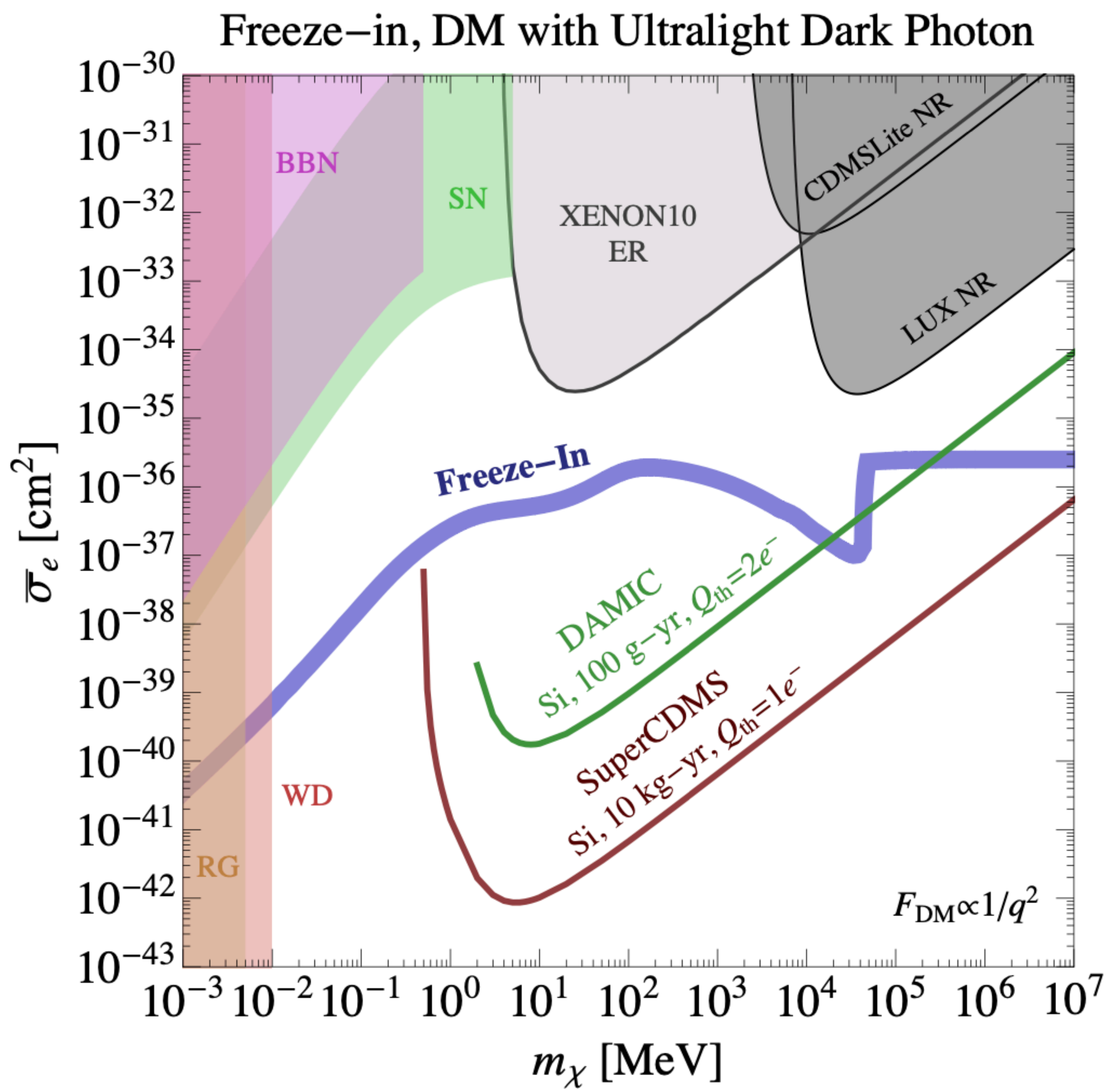
See also Formaggio, Hall, Li, and D'Imperio's talks on Wednesday



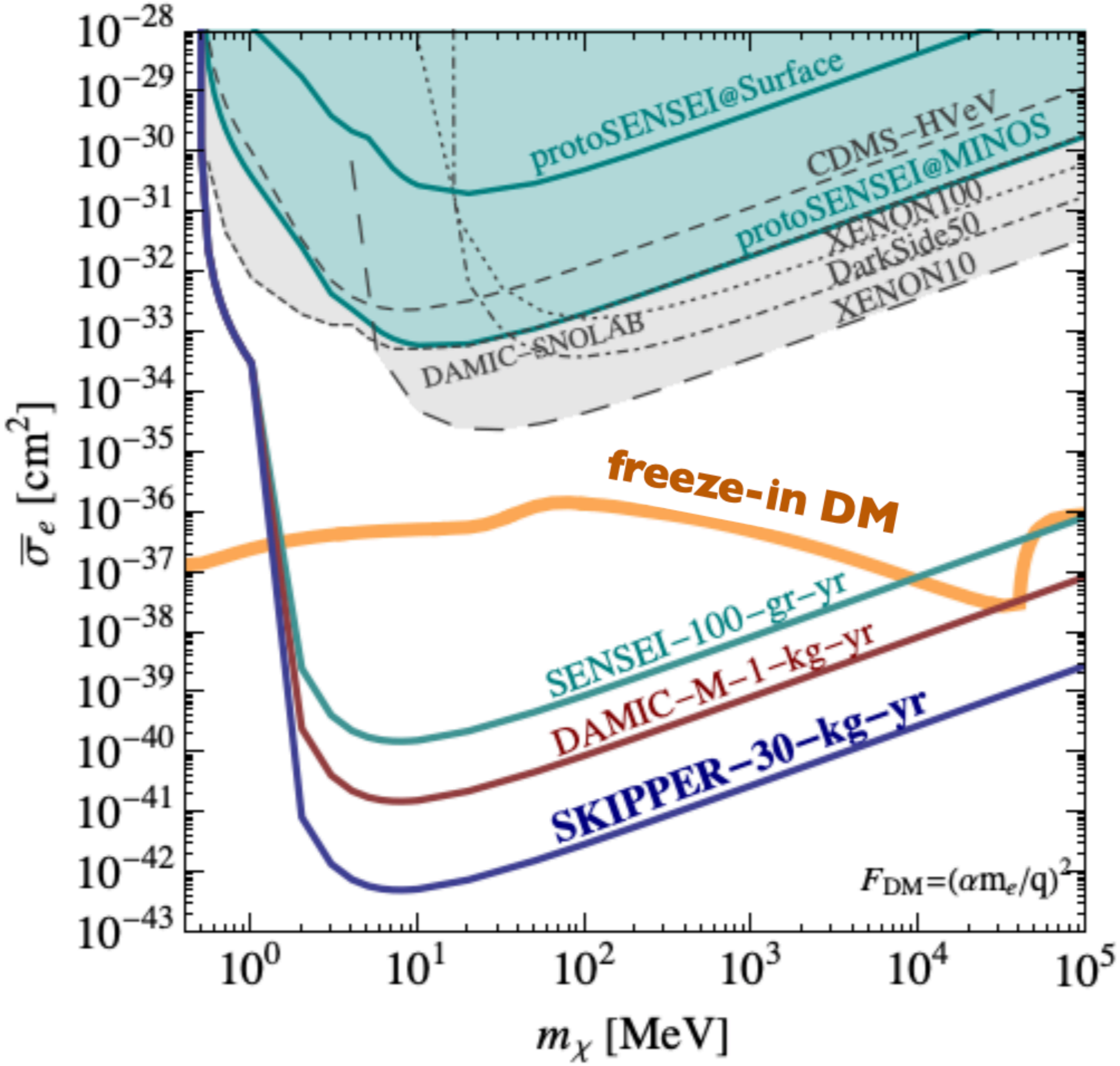
Essig et.al.
1509.01598


Standard shield
Extra lead
Rate [DRU]
Energy [keV]
10^4
10^3
0
50
100
150
200
250
300
350
400
450
500
$\times10^{-3}$
R_{1e^-} [e^-/pix/day]
Background radiation [DRU]
4000
6000
8000
10000
0
0.2
0.4
0.6
0.8
1

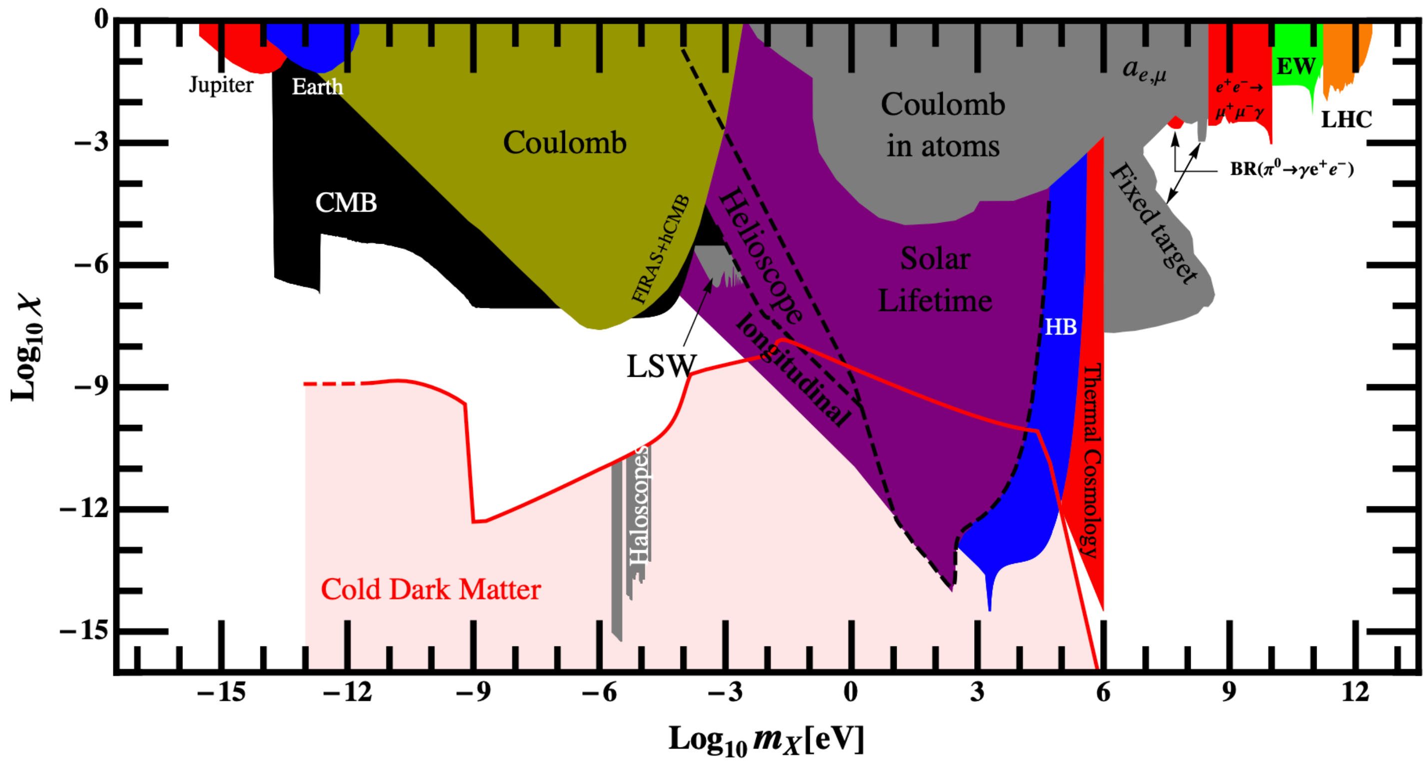
SENSEI coll.



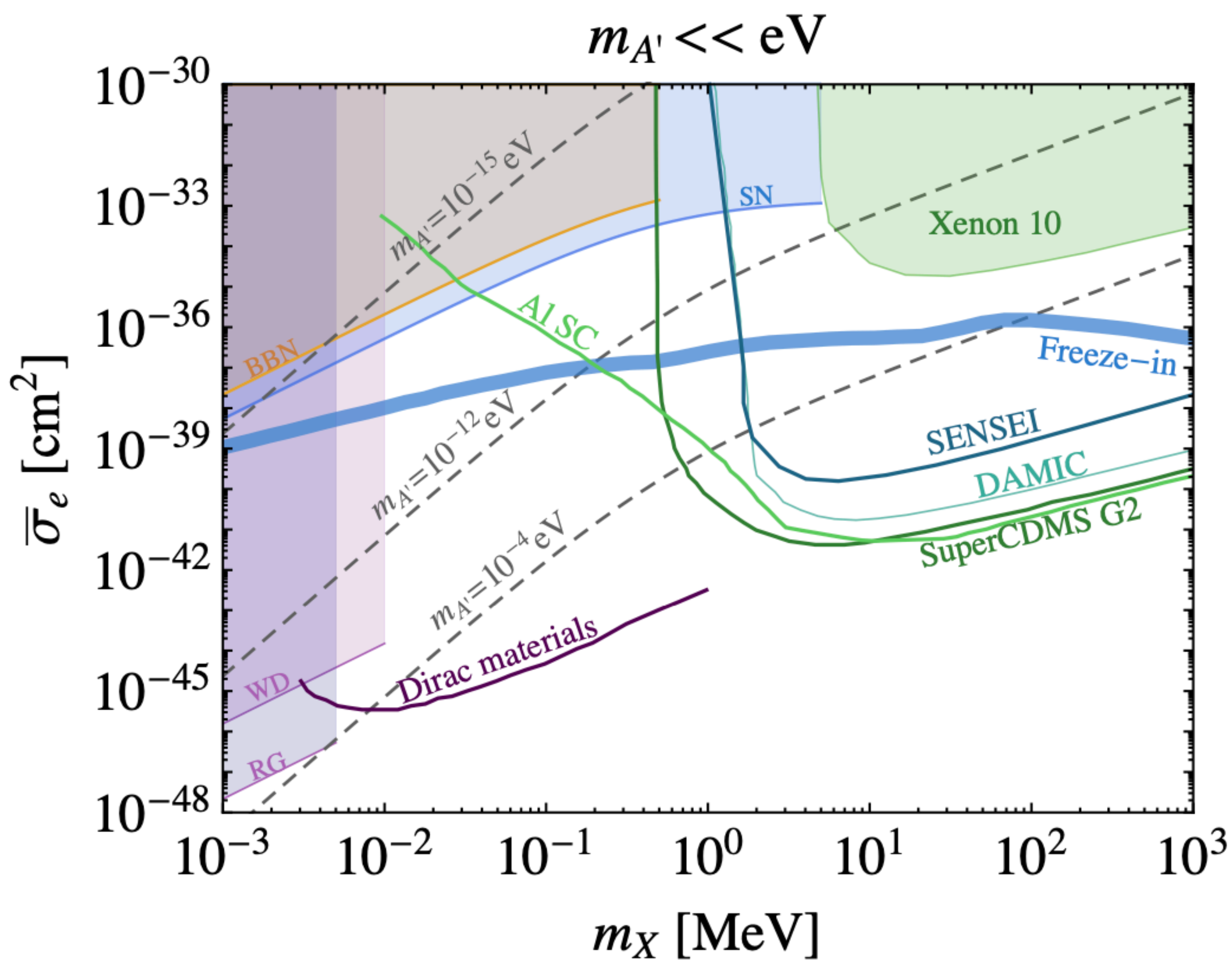
Essig et.al.
1509.01598



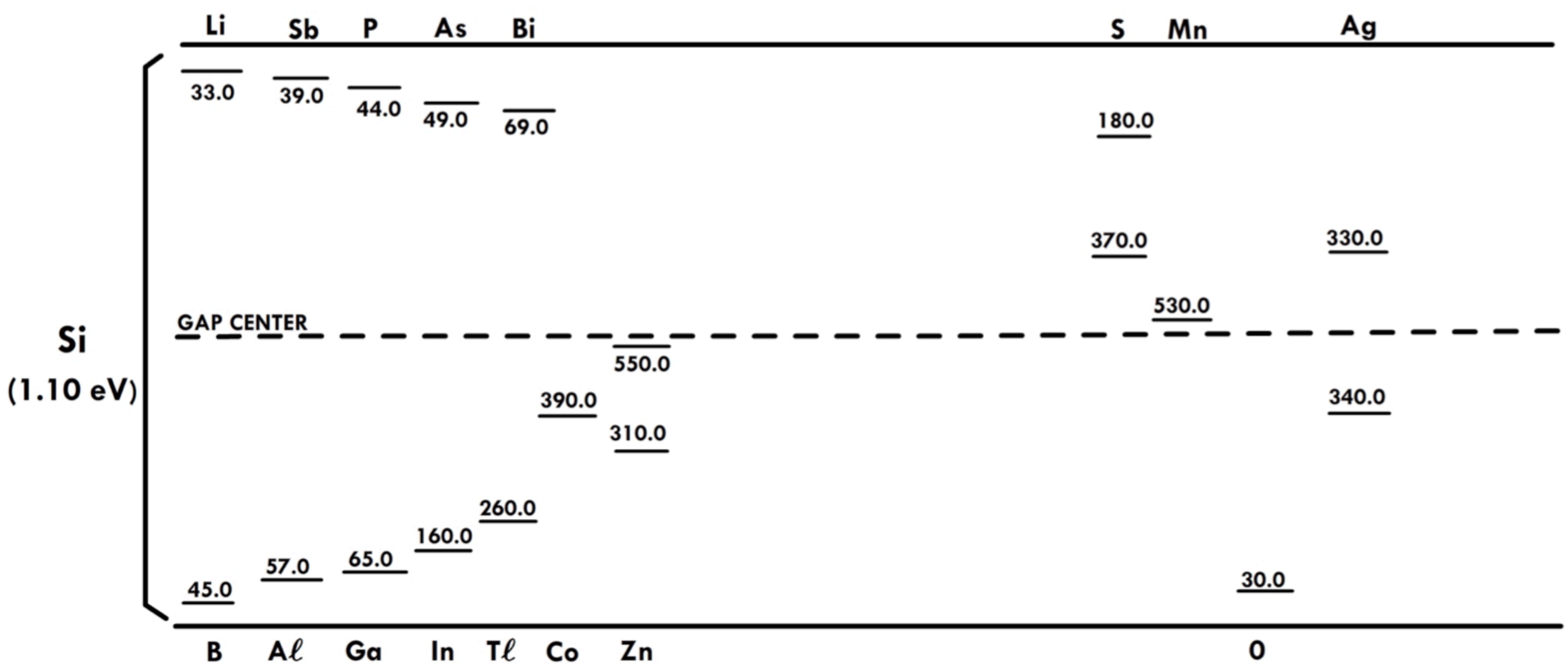
Essig, ICHEP 2020



Jaeckel 1303.1821



Zurek et. al.
1709.07882


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
Si
(1.10 eV)
GAP CENTER
550.0
390.0
340.0
310.0
260.0
160.0
65.0
57.0
45.0
30.0
B
Aℓ
Ga
In
Tℓ
Co
Zn
0

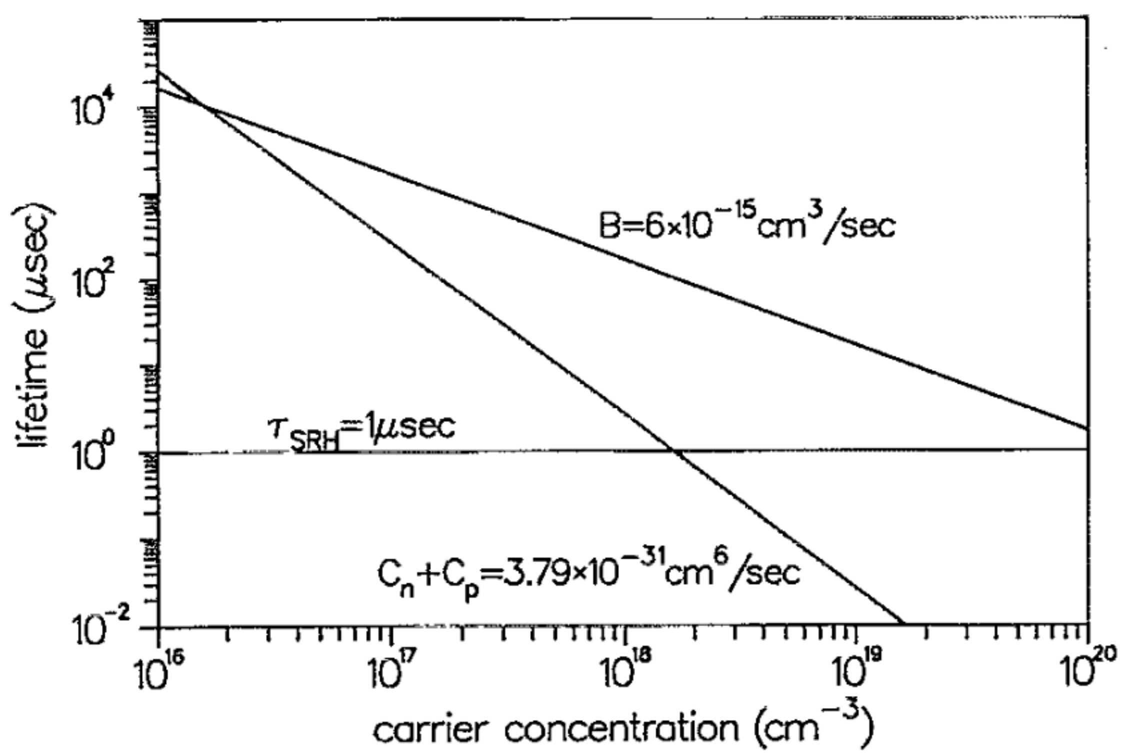
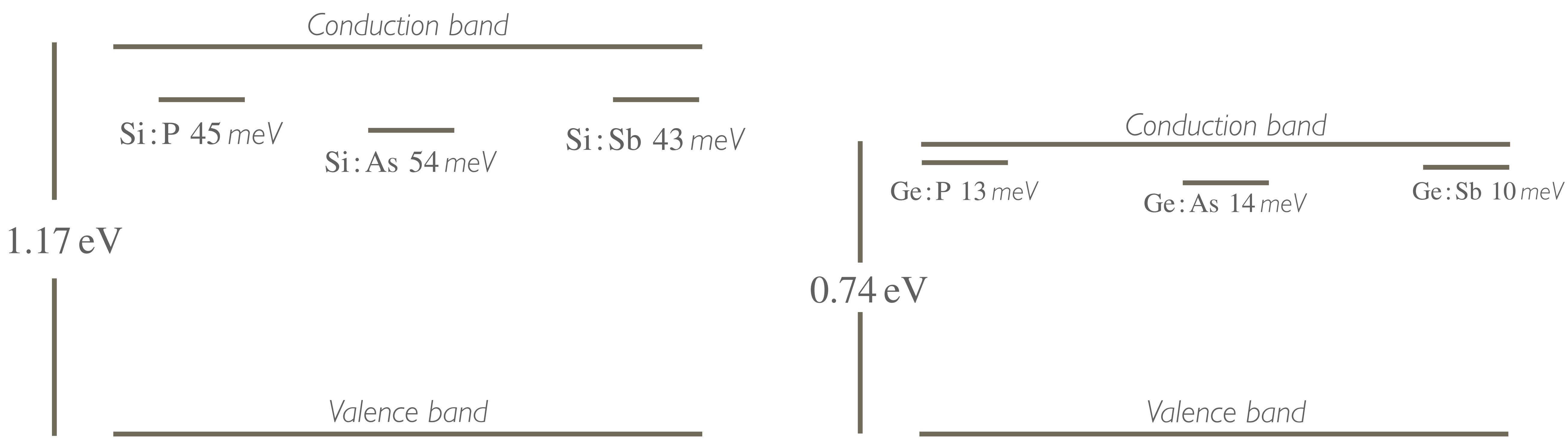


FIG. 1. Lifetime of carriers in Si caused by different recombination mechanism: Shockley–Read–Hall recombination τ_{SRH}, intrinsic band-band recombination B, Auger recombination C_n+C_p.

CHOICE OF TARGET MATERIAL

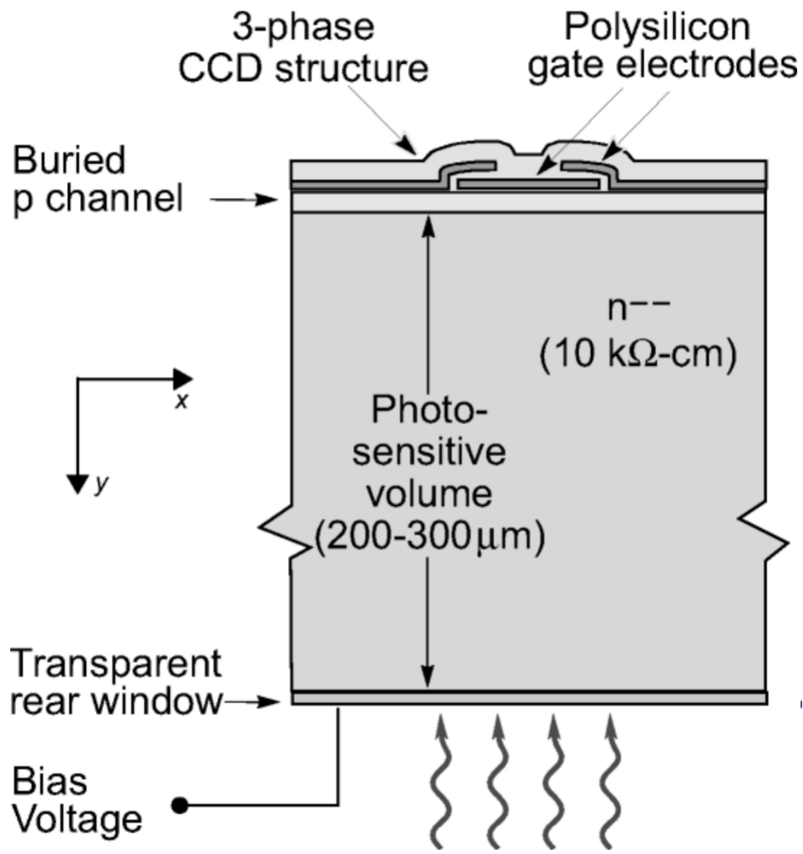
Silicon ***Germanium***

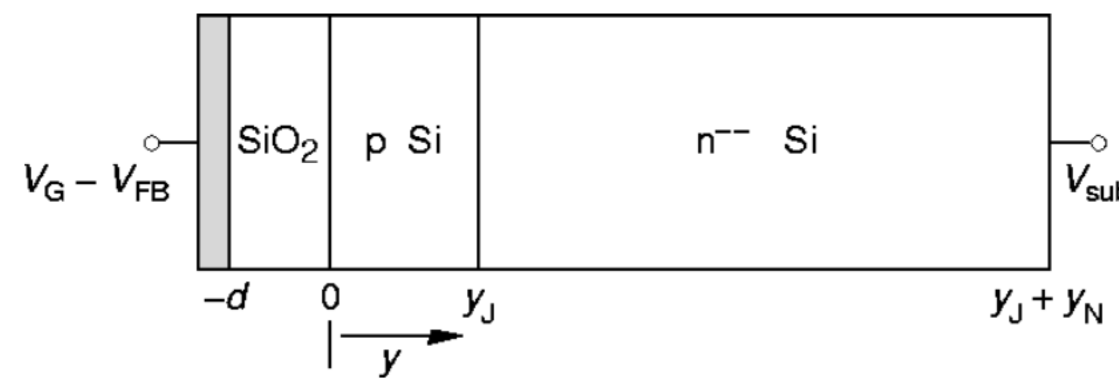


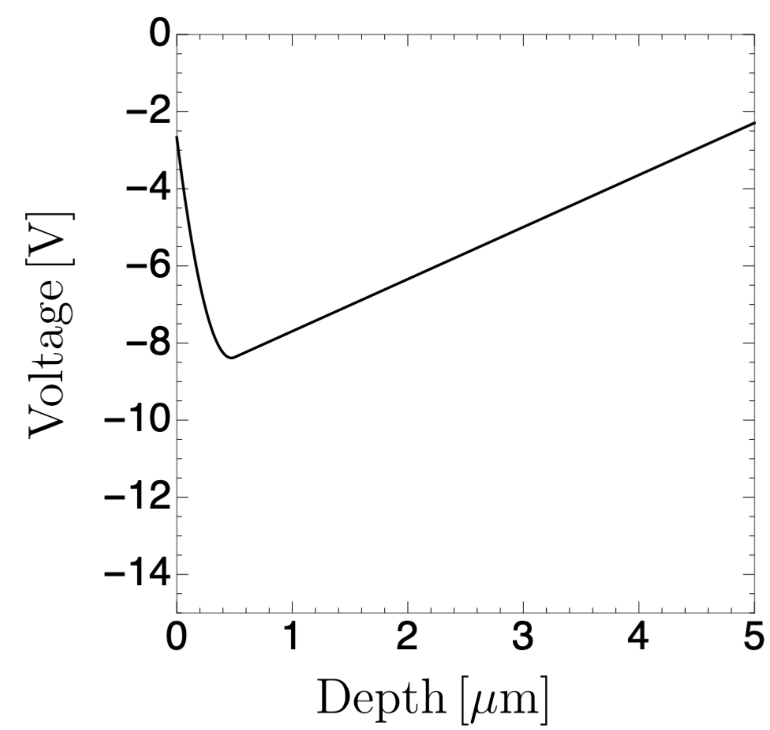
The particular dopant doesn't matter much.
We'll take ***Si:P***

	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].

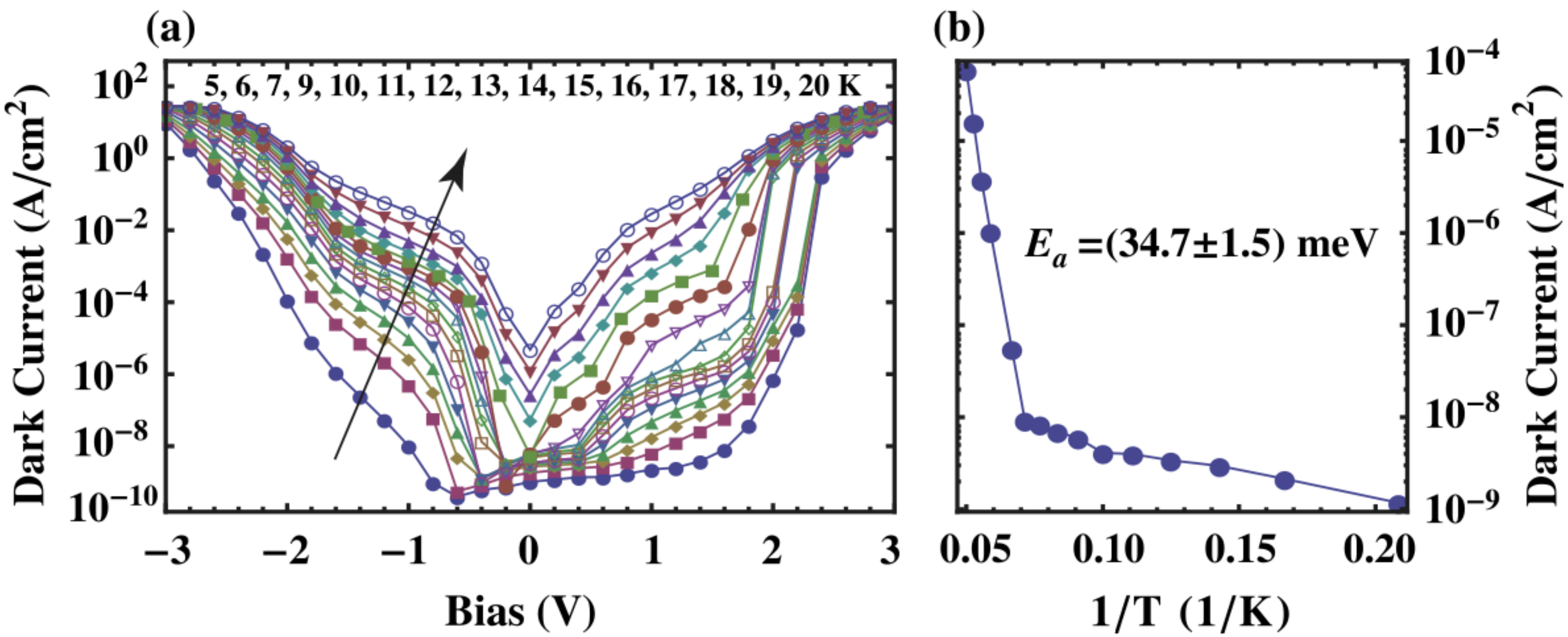






$$E_{SiO_2} \approx 10^6\,\mathrm{V/cm}$$

DCS IN BIBS



Liao et.al. Applied, Physics Letters 105, 143501 (2014)