New Semiconductor Devices for Dark Matter Detection

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Particle Physics Seminar
University of Science and Technology of China
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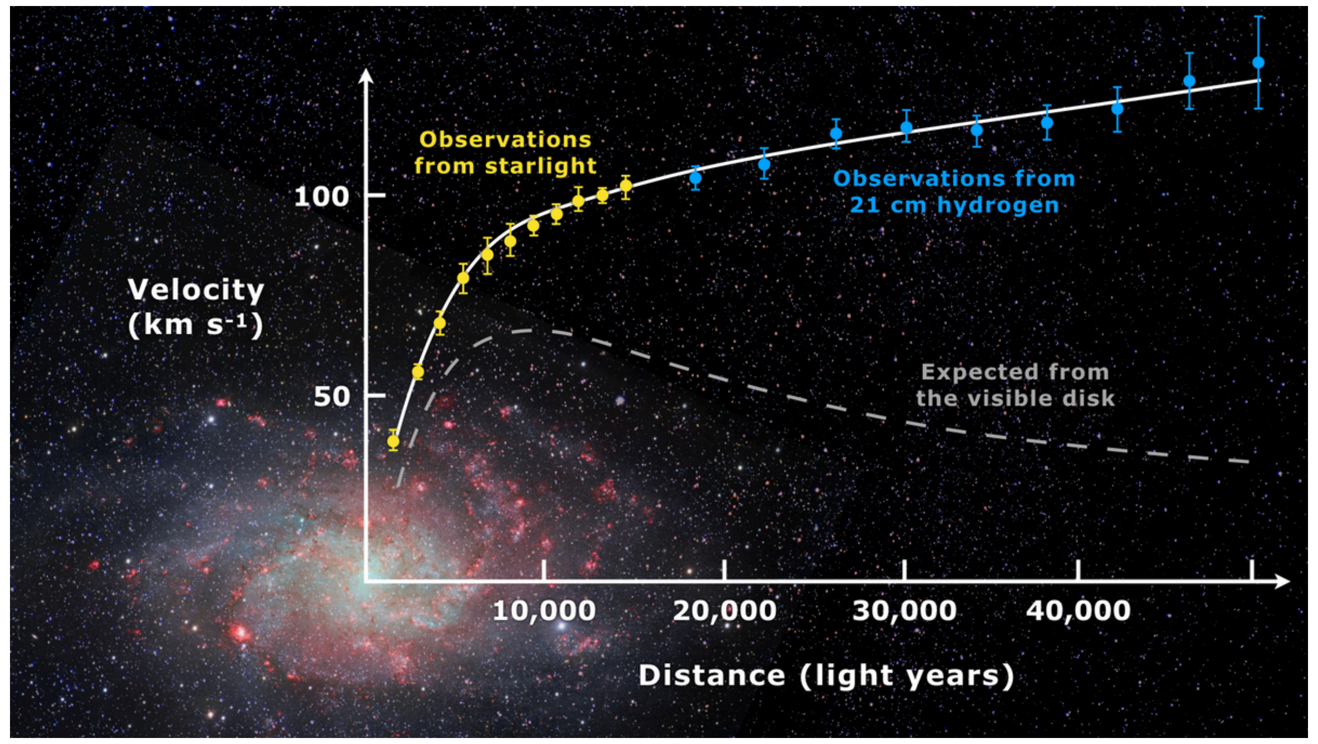
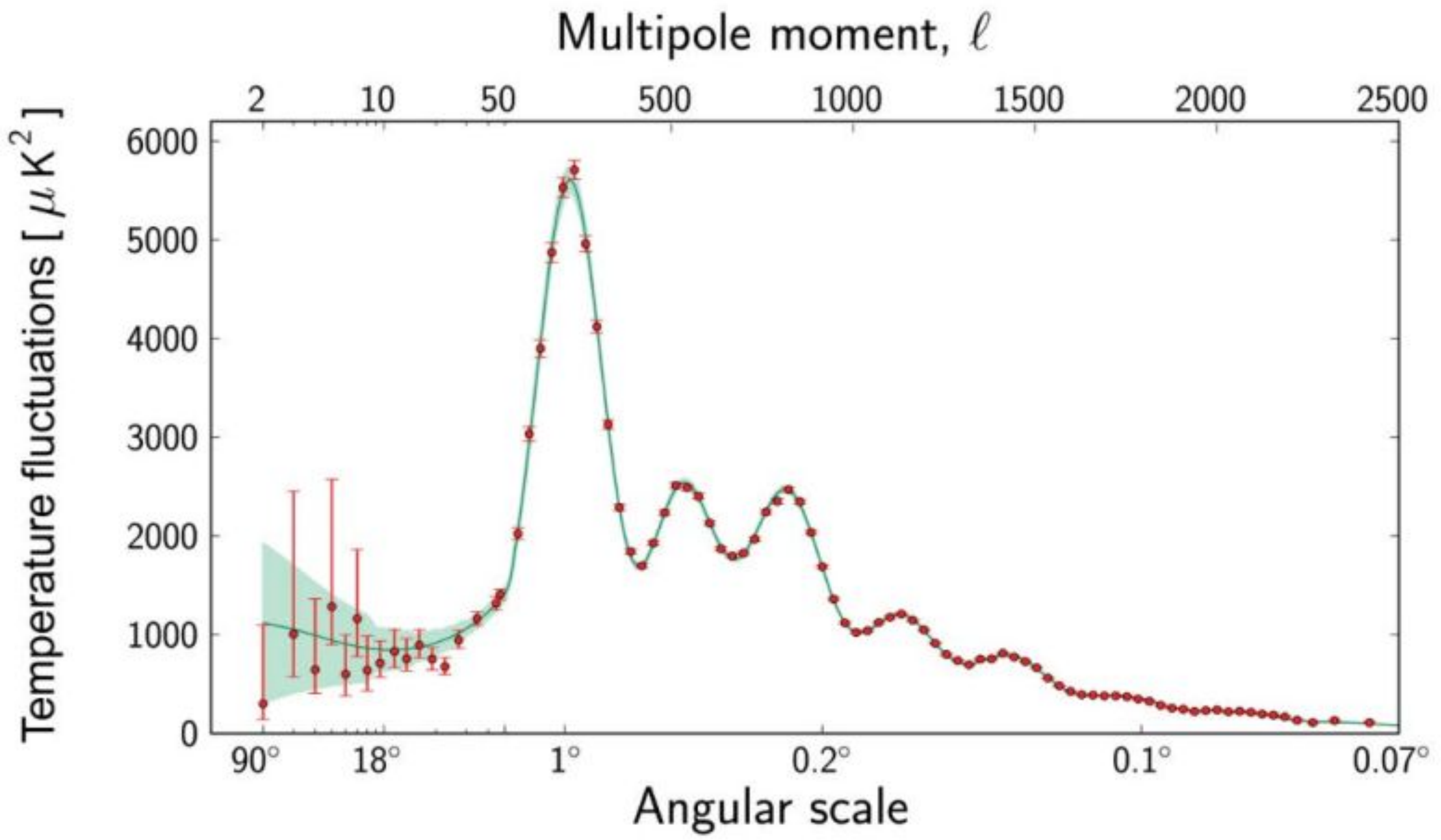
in collaboration with Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (PRX **12**, 011009)
Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (arXiv:2212.04504)
Javier Tiffenberg, Daniel Egana-Ugrinovic, Rouven Essig, Guillermo Fernandez-Moroni, Miguel Sofo Haro, Sho Uemura (arXiv:2307.13723)

Dark matter



Galaxy

Galaxy Cluster

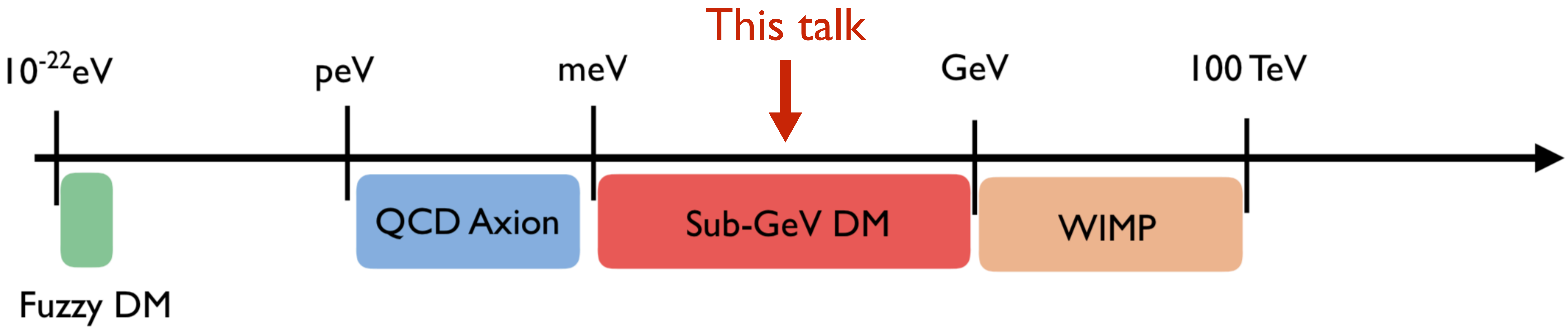


CMB

- 85% of matter, 27% total energy density in the Universe
- Evidence for dark matter is currently only gravitational

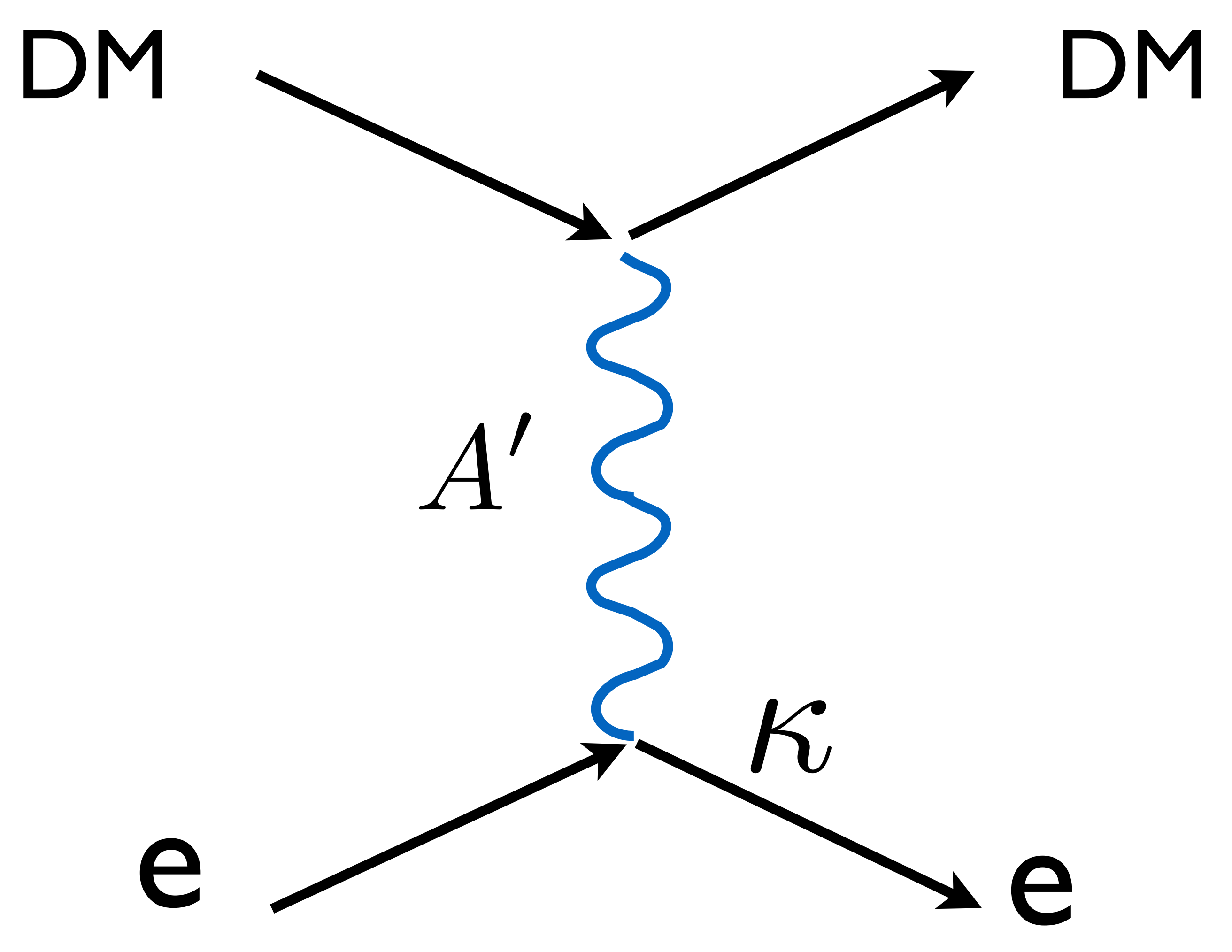
Particle nature is unknown, a wide range of DM masses are allowed

Dark matter


This talk
10^{-22}eV
peV
meV
GeV
100 TeV
QCD Axion
Sub-GeV DM
WIMP
Fuzzy DM

Sub-GeV dark matter

Dark photon model: $\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\kappa}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu} - g_D A'_{\mu}\bar{\chi}\gamma^{\mu}\chi$



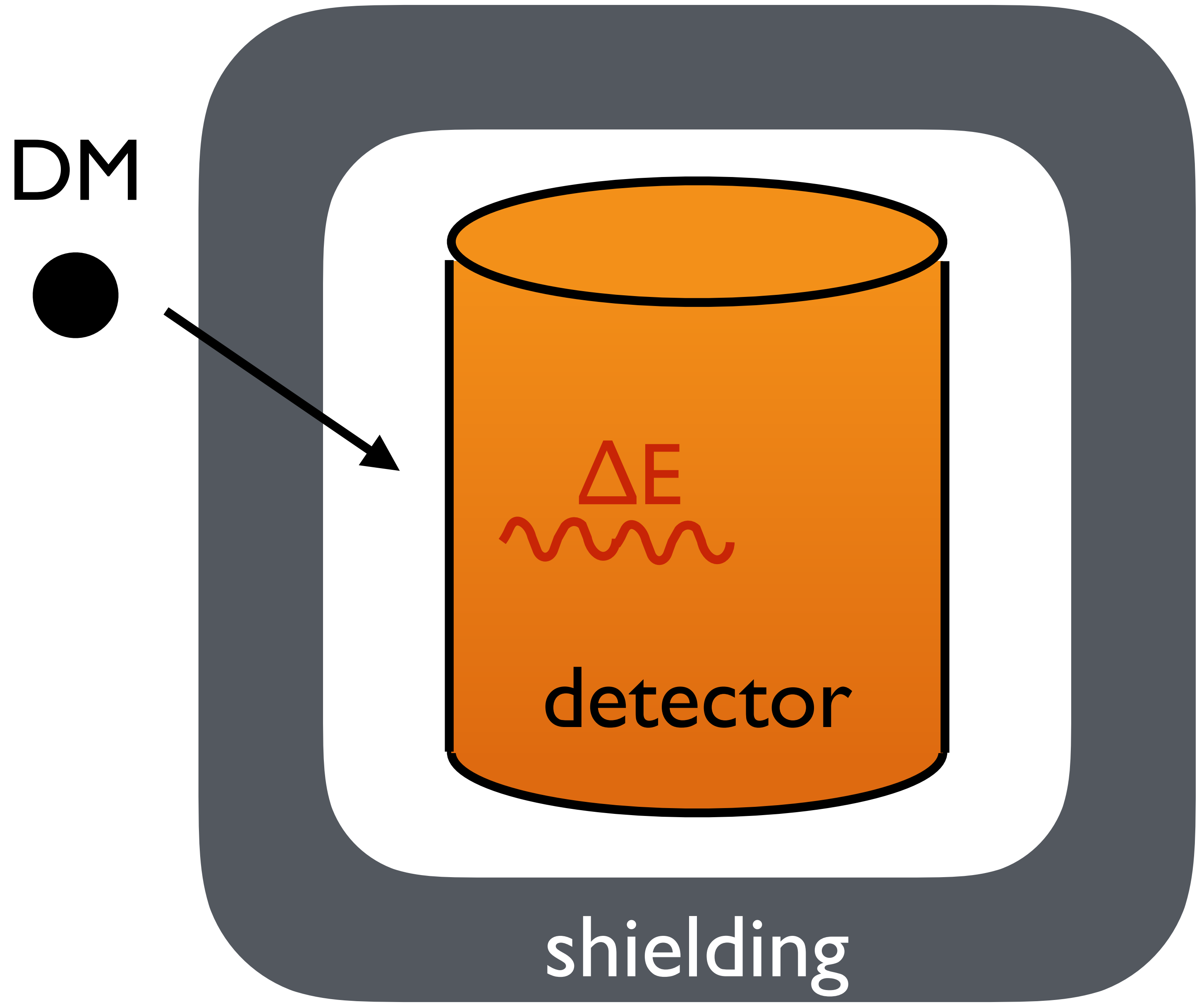
DM-electron scattering

DM χ + (light) Dark photon A' mediator

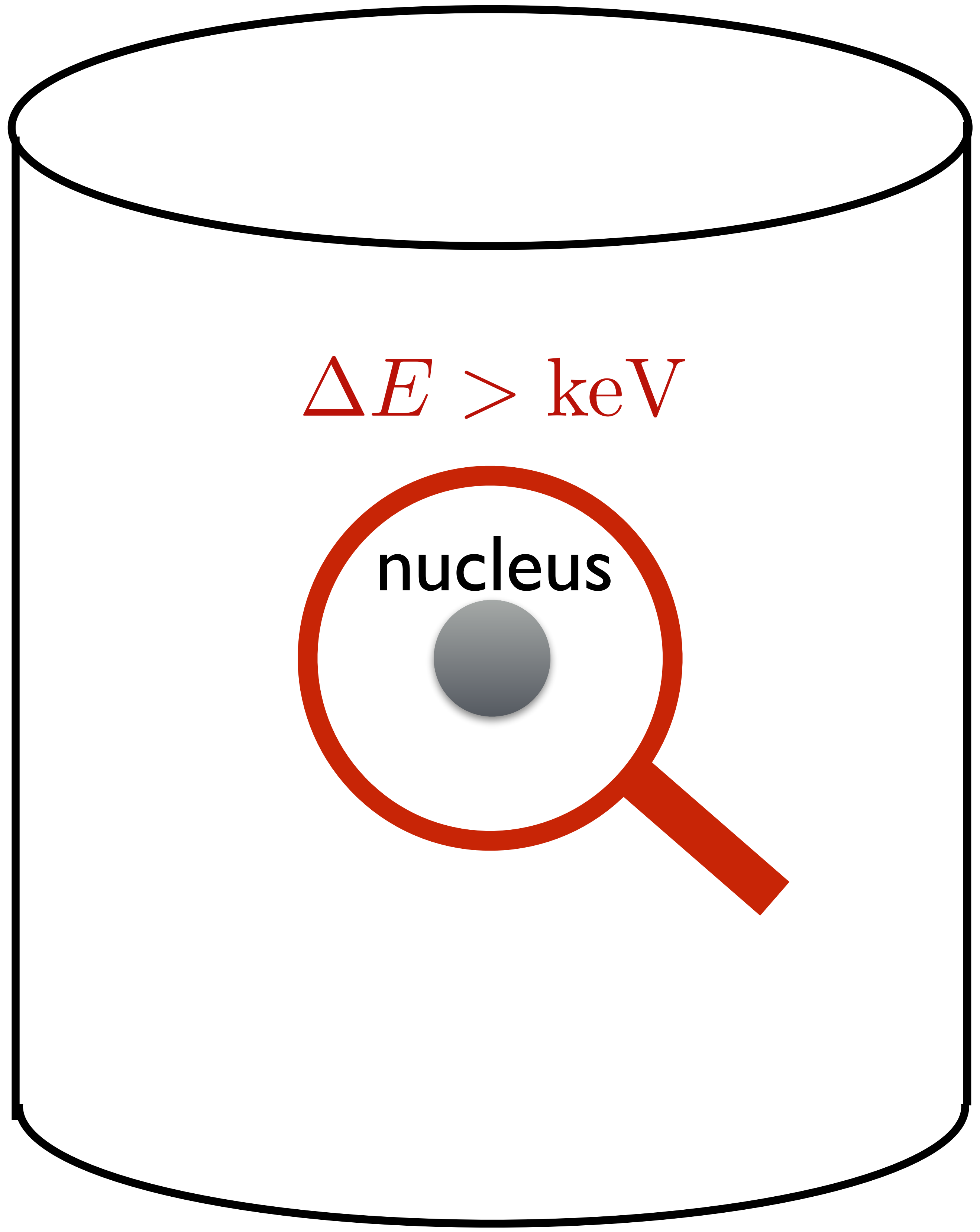
Relic abundance: Freeze-in mechanism

Direct Detection of DM

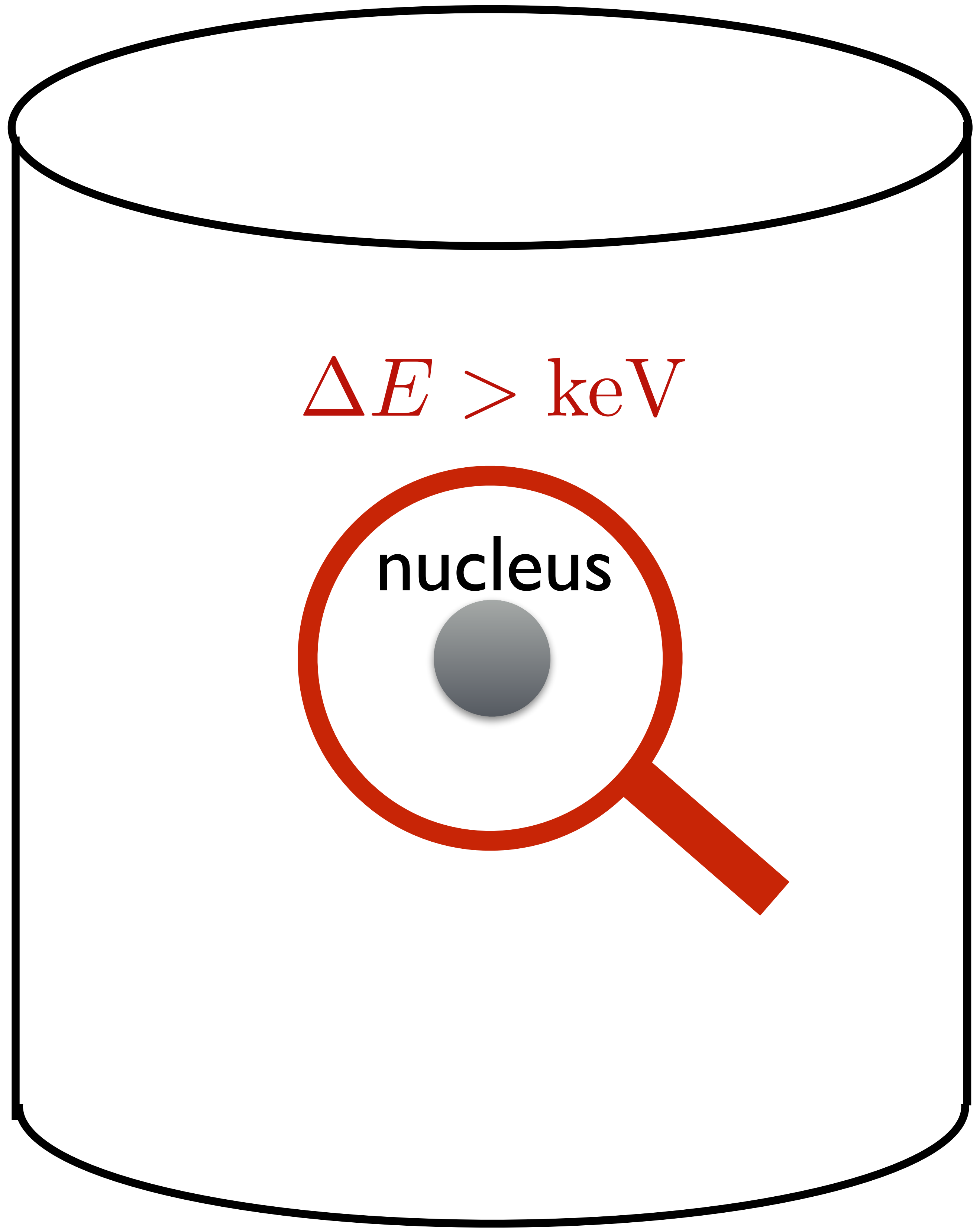
- Assuming DM has more than gravitational interactions with SM
- Clean environment, sensitive detector
- Wait for DM to come!



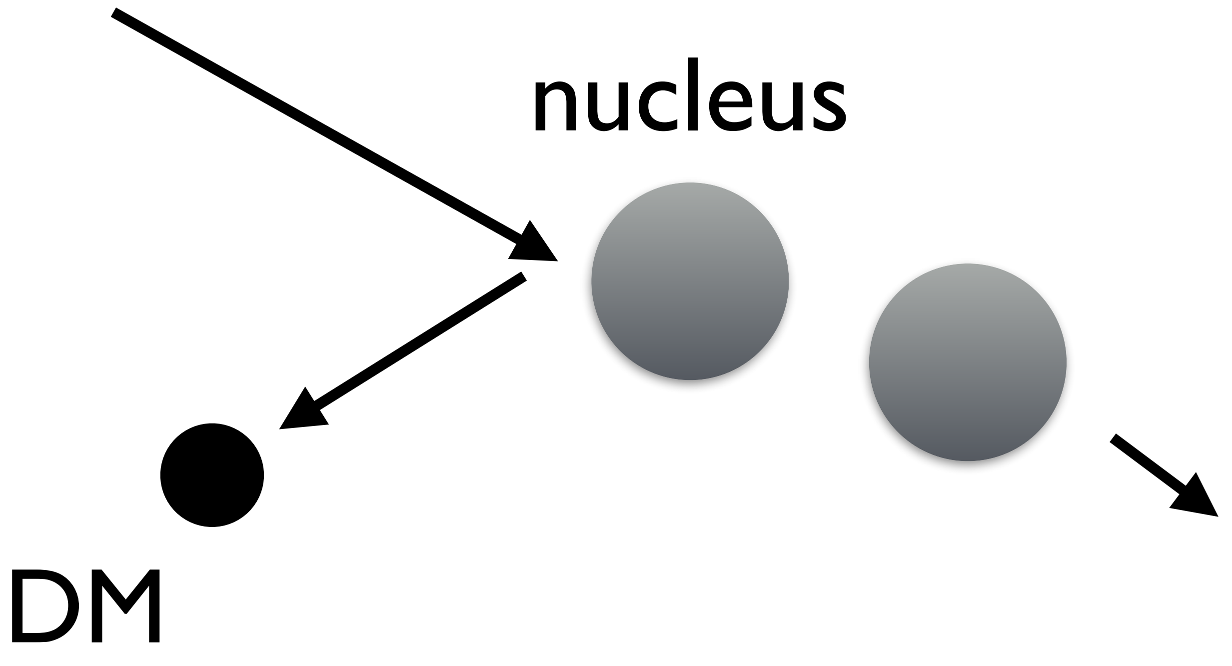
Direct Detection: ΔE>keV



Direct Detection: ΔE>keV

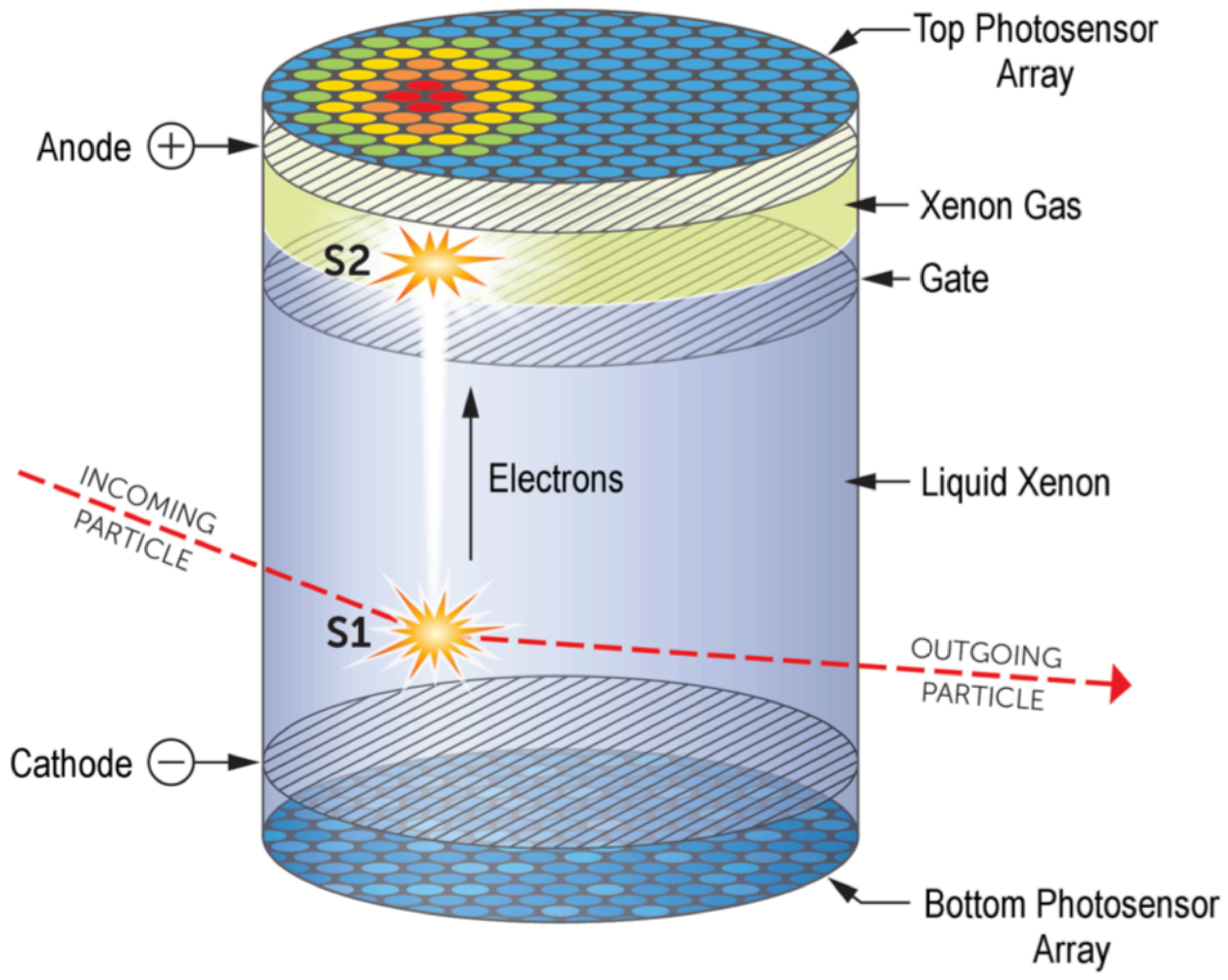


Elastic DM-nuclear scattering



$$E_{\mathrm{NR}} \lesssim \frac{2(m_\chi v)^2}{m_N}$$

Figure from J. Aalbers et.al. , 2022

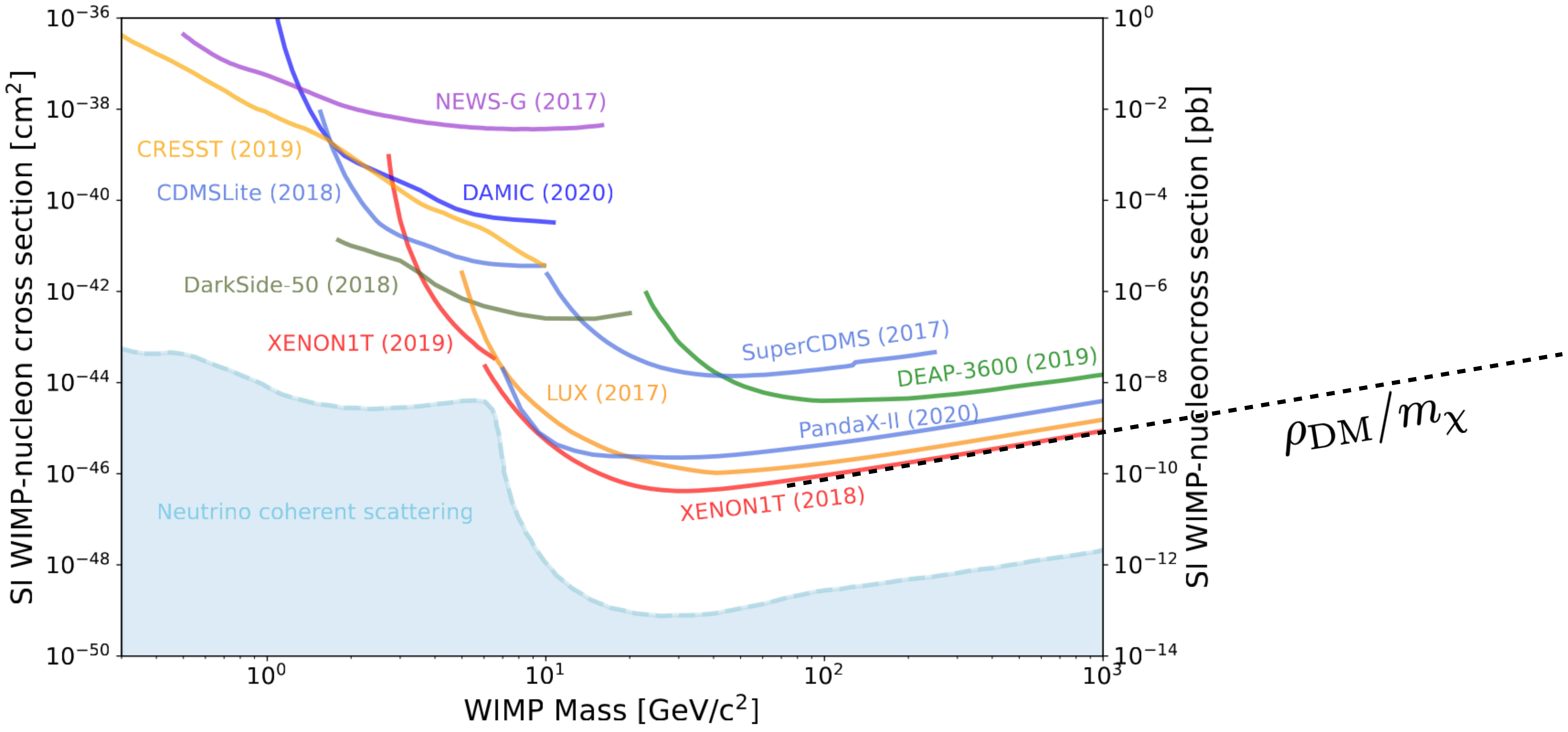


Signals: S1+S2

Threshold: ~keV

Nuclear recoil constraints

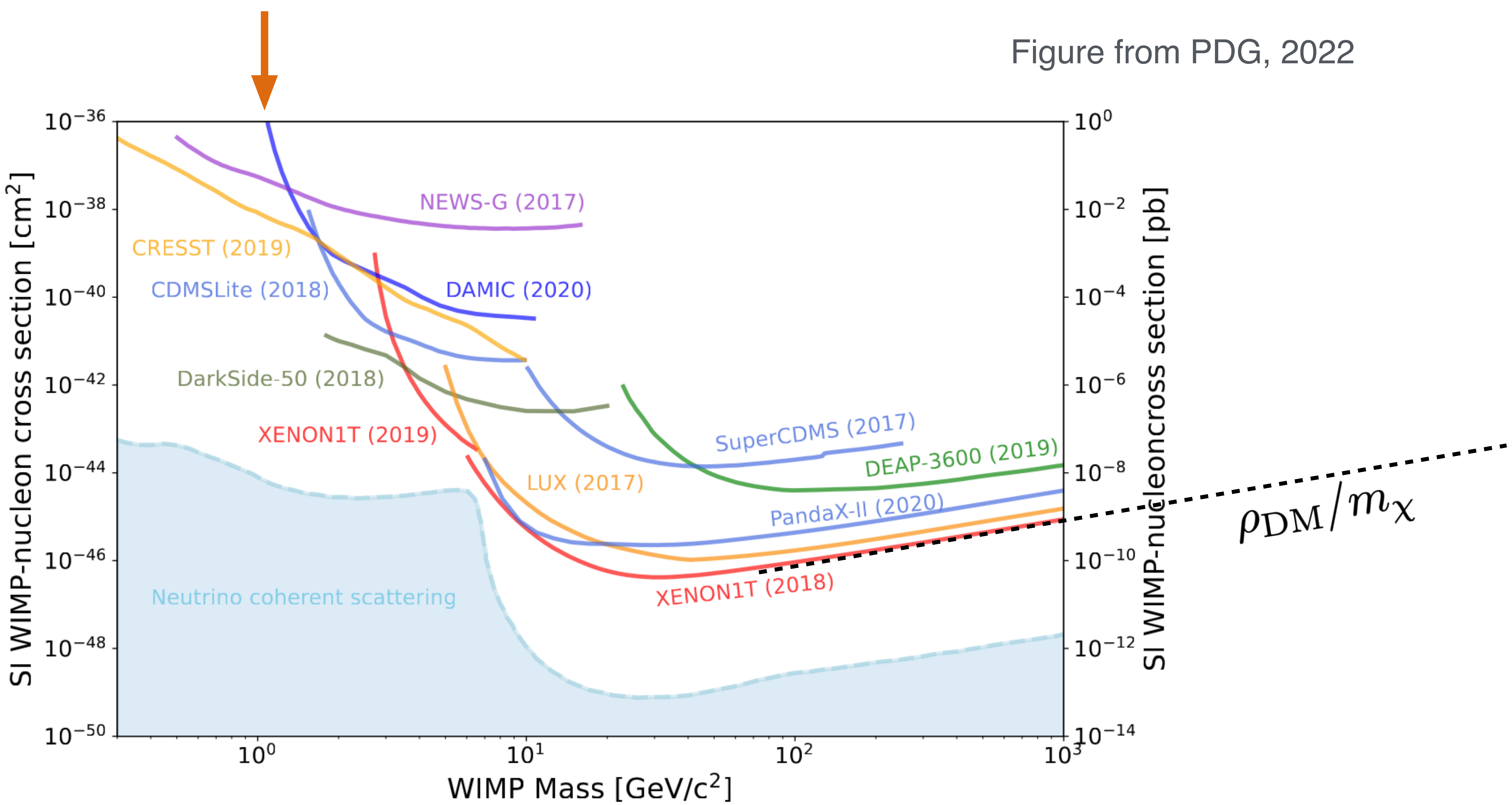
Figure from PDG, 2022



Nuclear recoil constraints

Limited by ~keV threshold

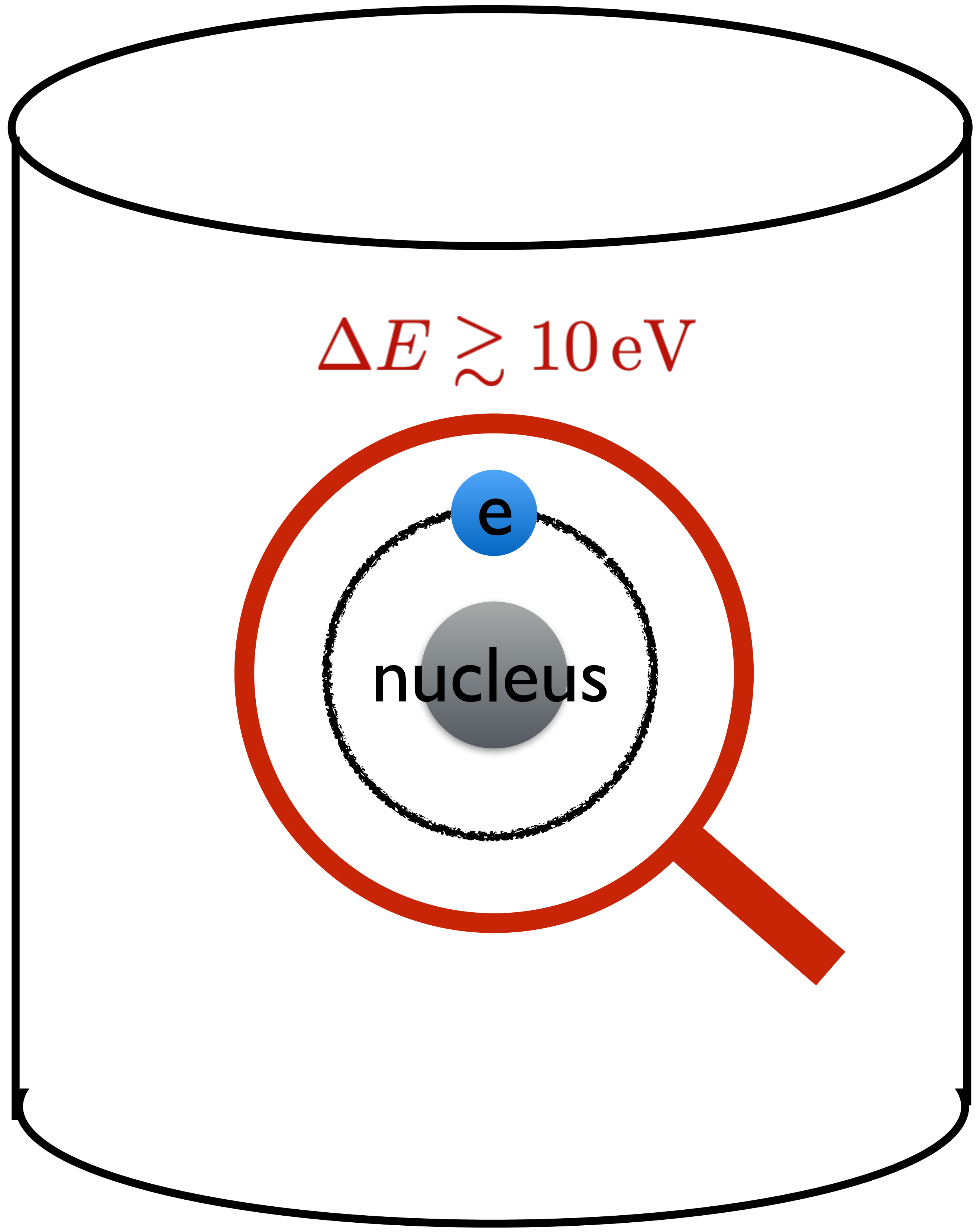
Figure from PDG, 2022



Insufficient energy transfer

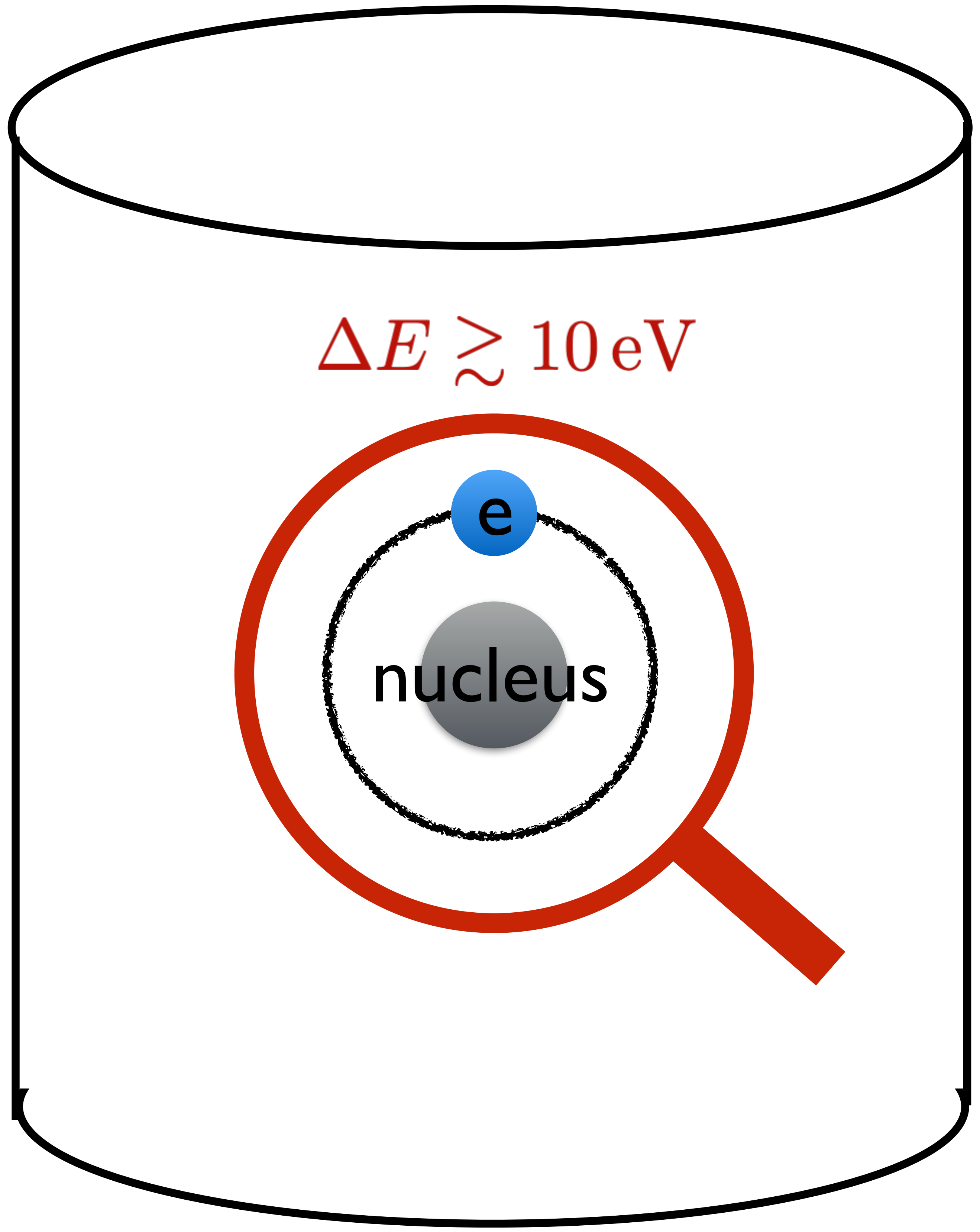
$$E_{\rm NR} \lesssim 1\,{\rm keV}\left[\frac{m_\chi}{4\,{\rm GeV}}\right]^2\left[\frac{100\,{\rm GeV}}{M_N}\right]$$

Direct Detection: ΔE>O(10)eV

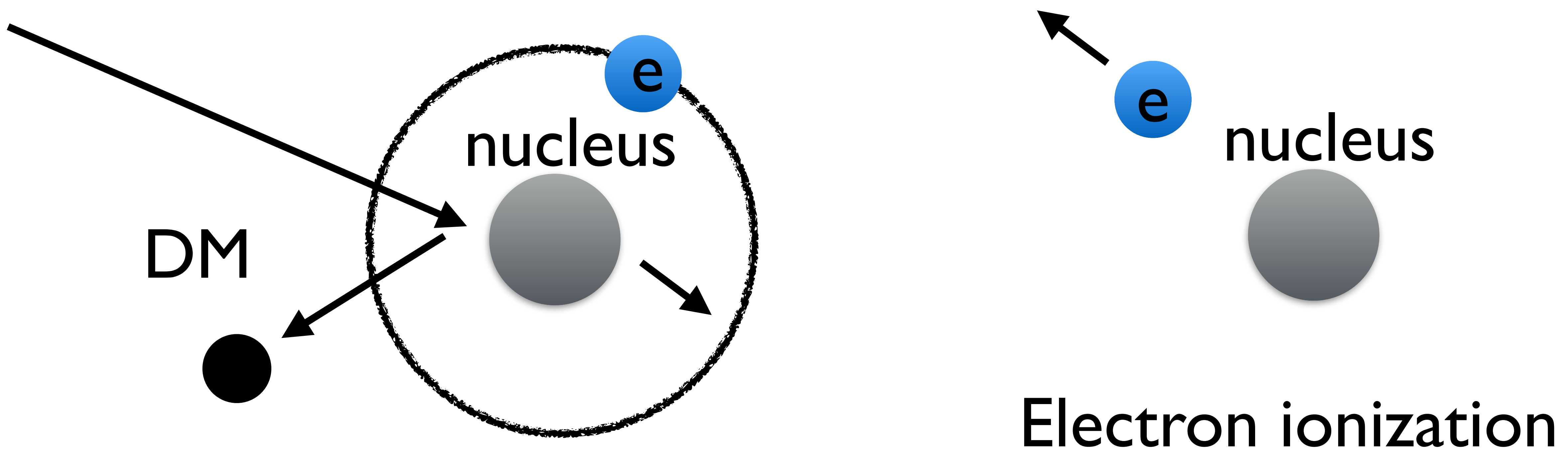


Direct Detection: ΔE>O(10)eV

Vergados, Ejiri , *PLB* 2004
Ibe, Nakano, Shoji, Suzuki, *JHEP* 2018



Migdal effect

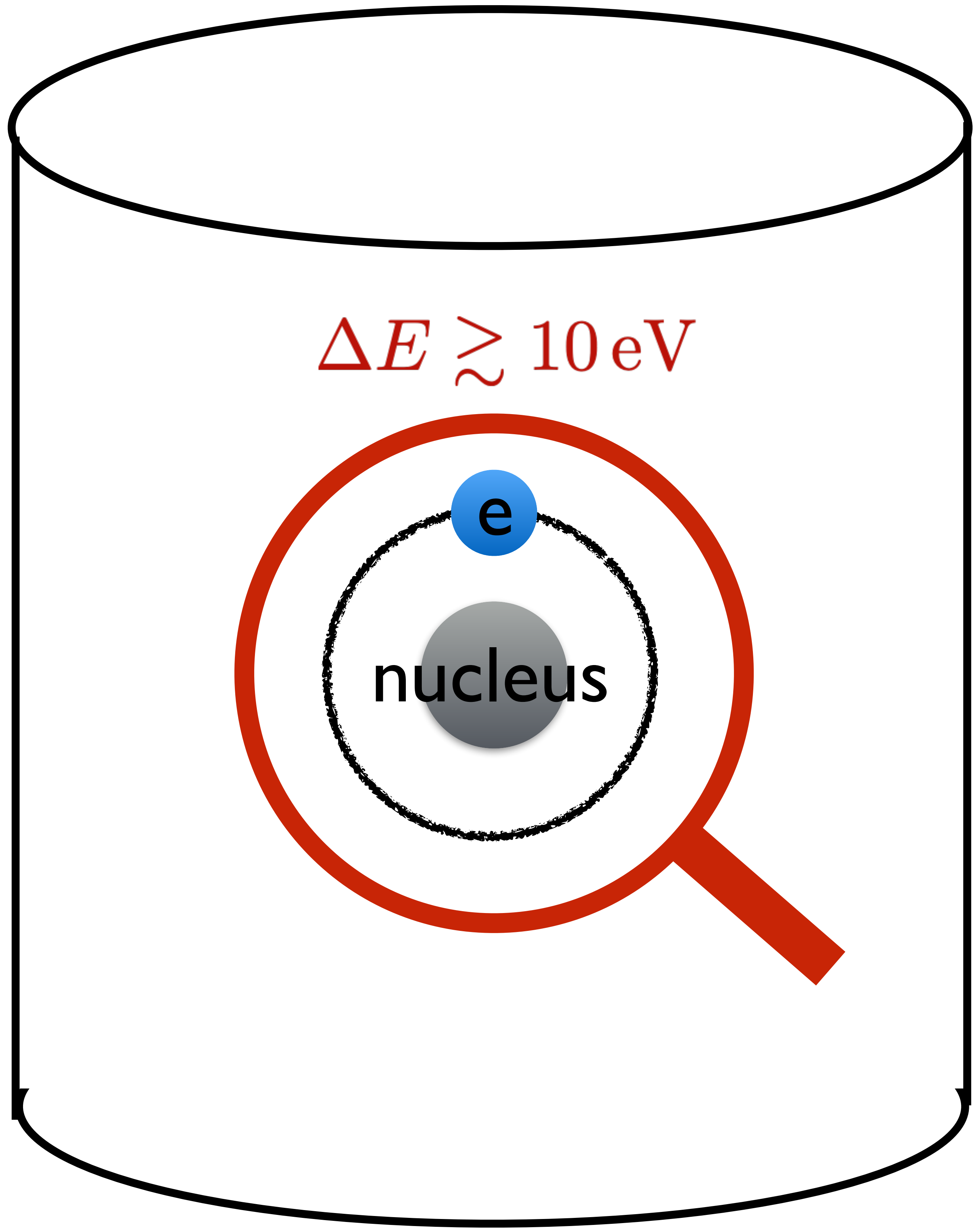


Signal: electron ionization

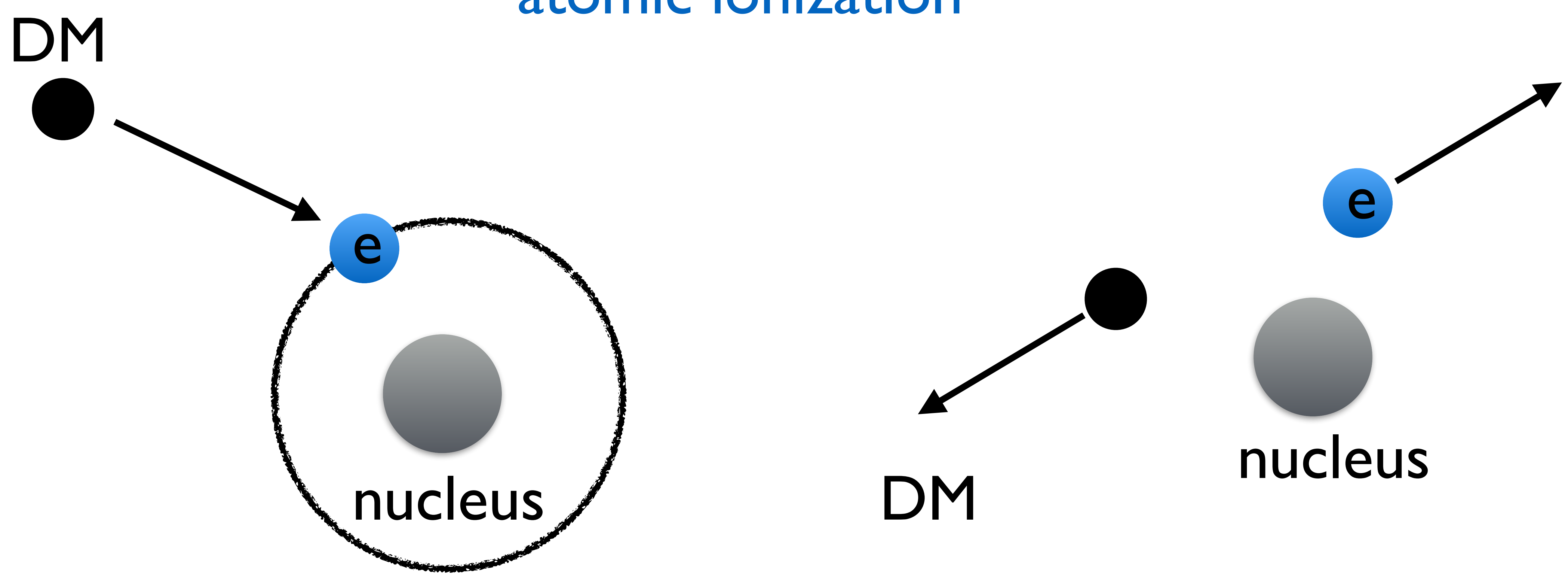
Threshold: ~10 eV

Direct Detection: ΔE>O(10)eV

Essig, Mardon, Volansky, *PRD* 2012



DM-electron scattering
atomic ionization

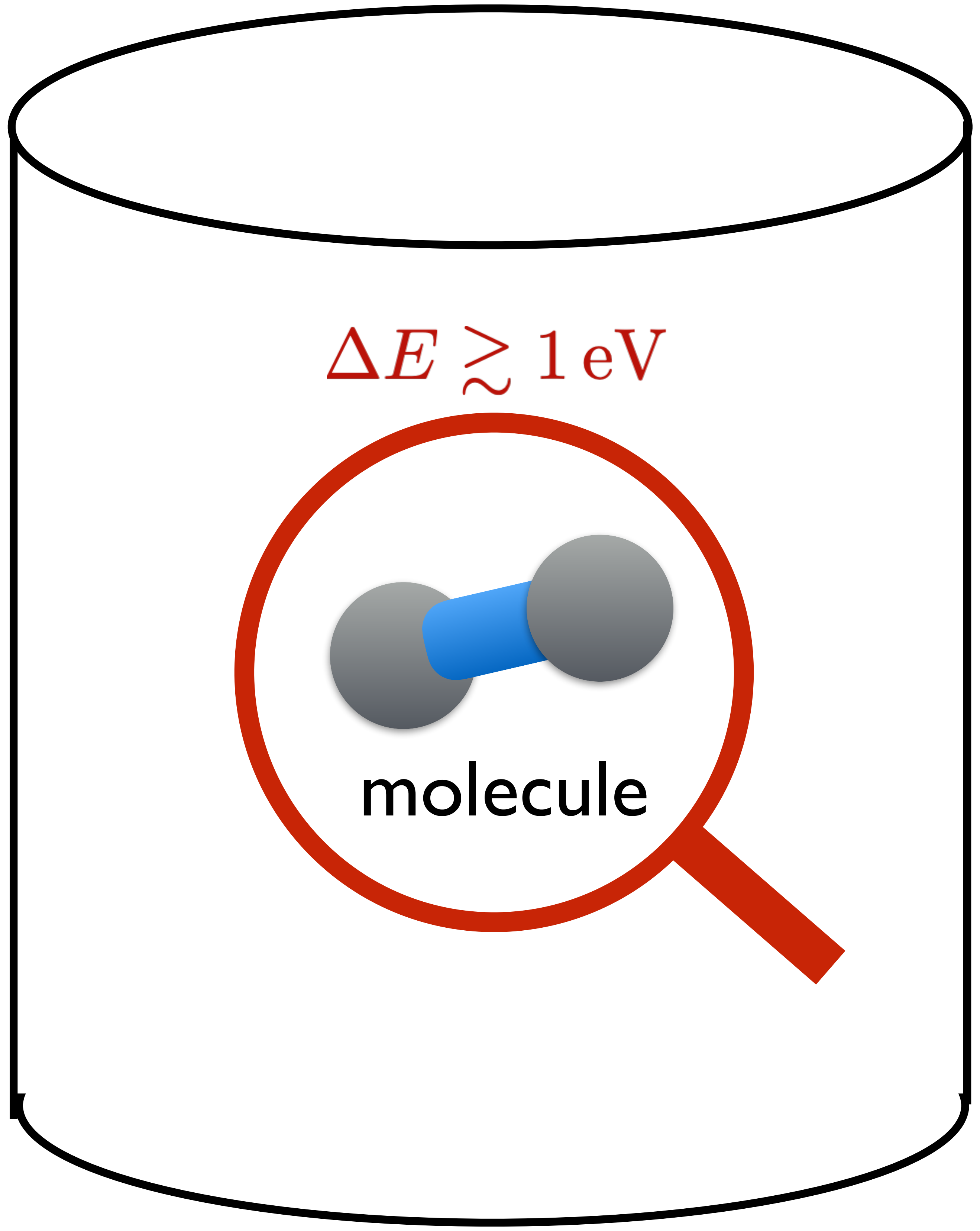


Efficient energy transfer for light DM

$$E_{\mathrm{ER}} \lesssim \frac{1}{2} m_\chi v^2 \quad >> \quad E_{\mathrm{NR}} \lesssim \frac{2(m_\chi v)^2}{m_N}$$

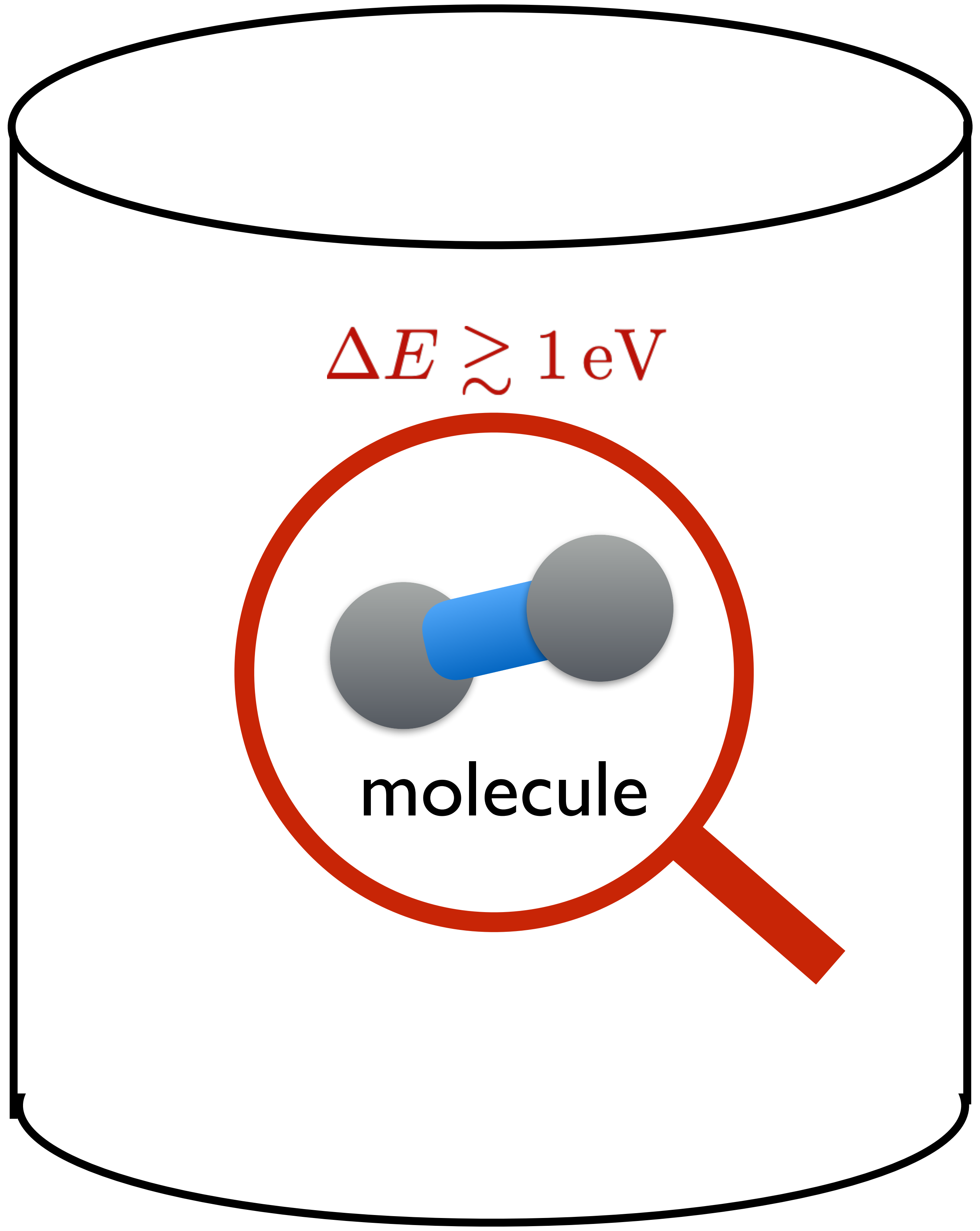
Signal: electron ionization
Threshold: ~10 eV

Direct Detection: ΔE>O(1)eV

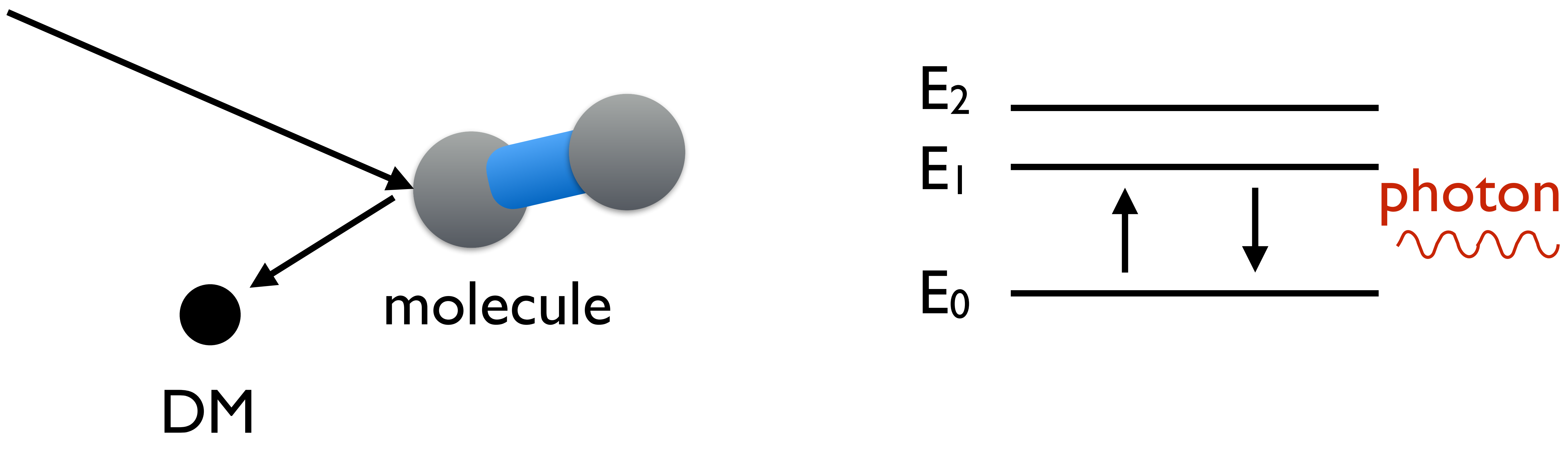


Direct Detection: ΔE>O(1)eV

Essig, Perez-Rios, Ramani, Slone, *PR Research* 2019
Blanco, Collar, Kahn, Lillard, *PRD* 2020



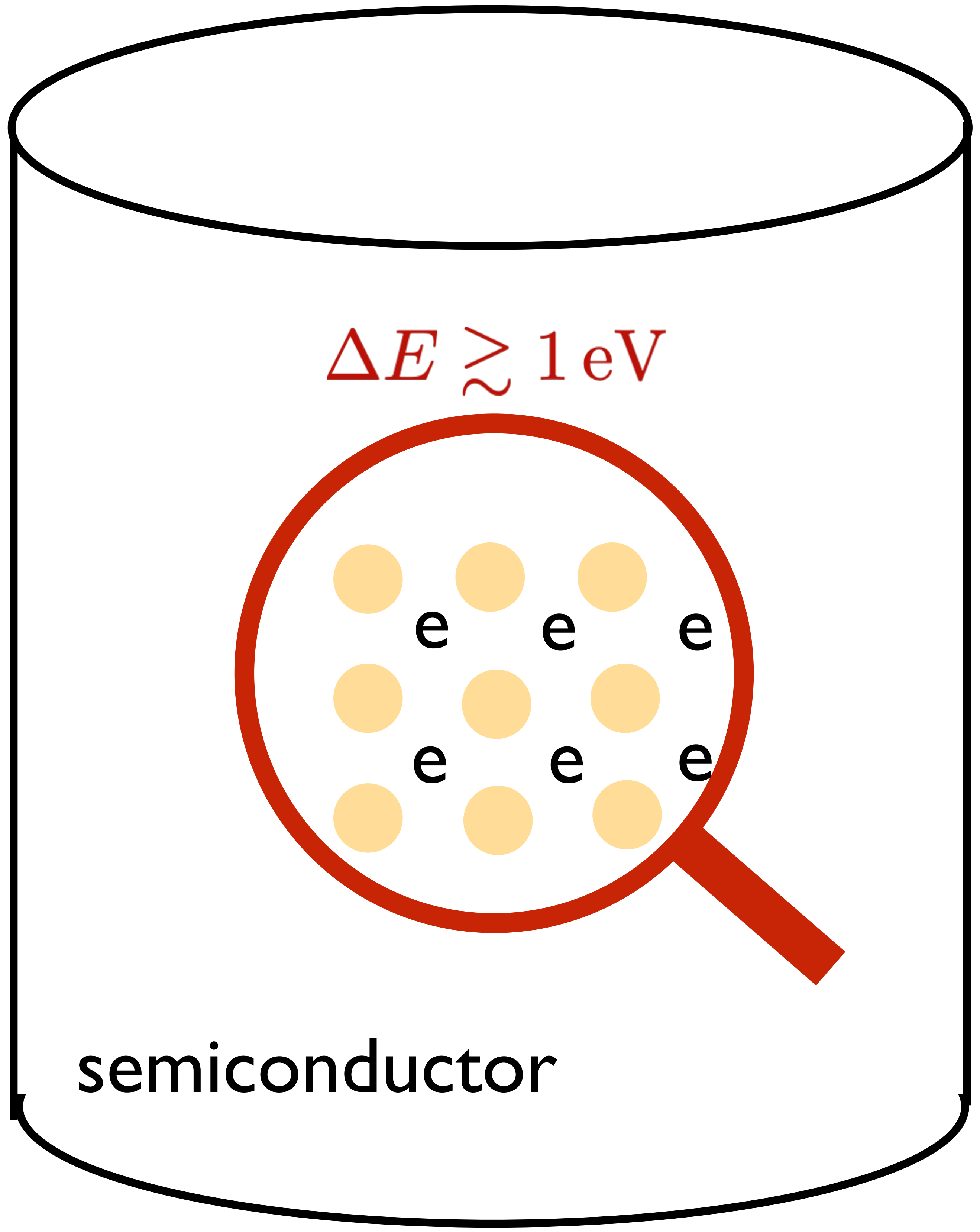
Excitation in molecules



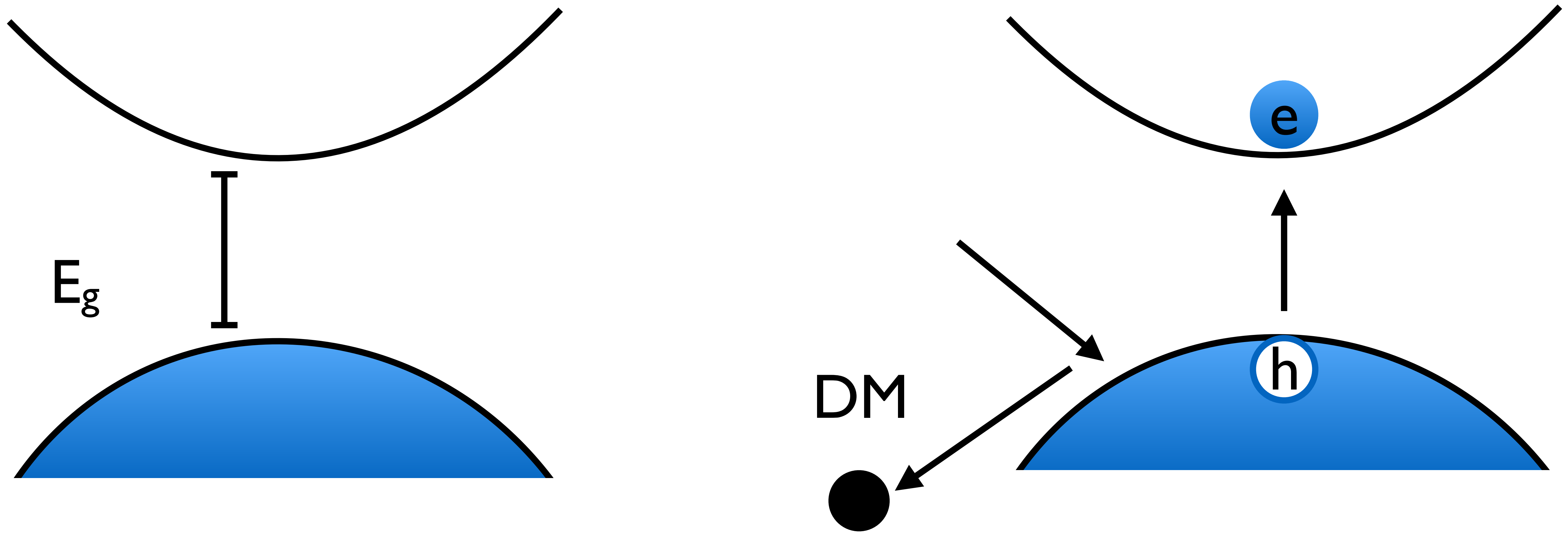
Signal: photons
Threshold: O(1) eV

Direct Detection: ΔE>O(1)eV

Essig, Mardon, Volansky, *PRD* 2012



Electron ionization in semiconductors

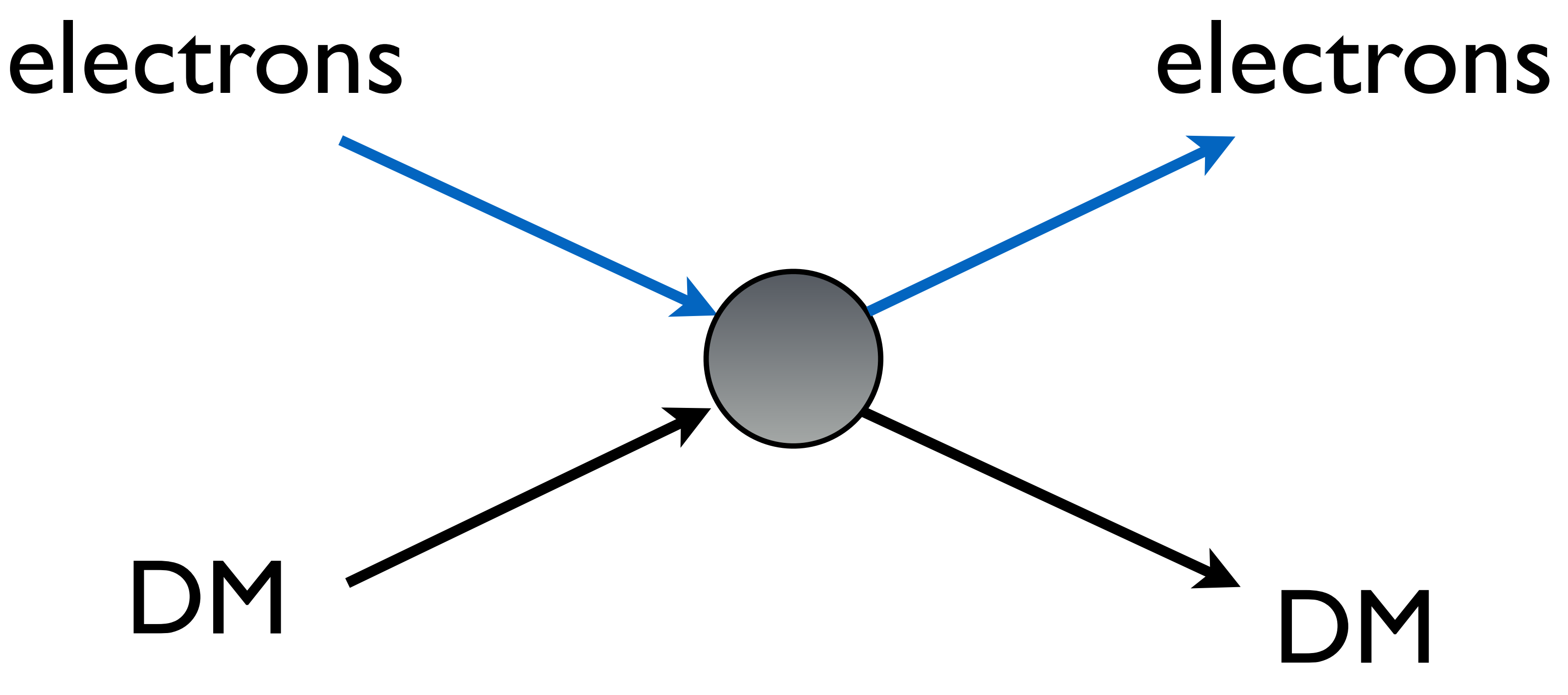


Signals: eh pairs

Threshold: E_g~1 eV

Direct Detection of Sub-GeV DM

Electron recoils



Access to whole kinetic energy:

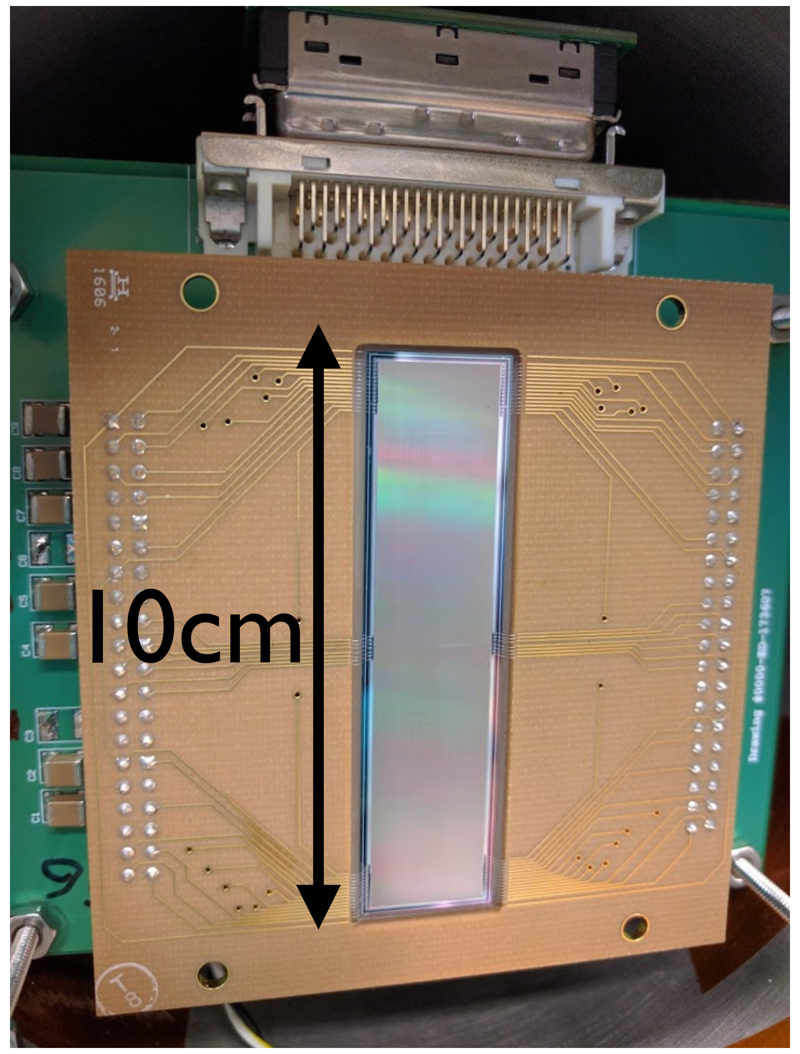
$$E_{\rm ER} \lesssim \frac{1}{2} m_\chi v^2 \approx 1\,{\rm eV}\left[\frac{m_\chi}{0.5\,{\rm MeV}}\right]$$

Current targets

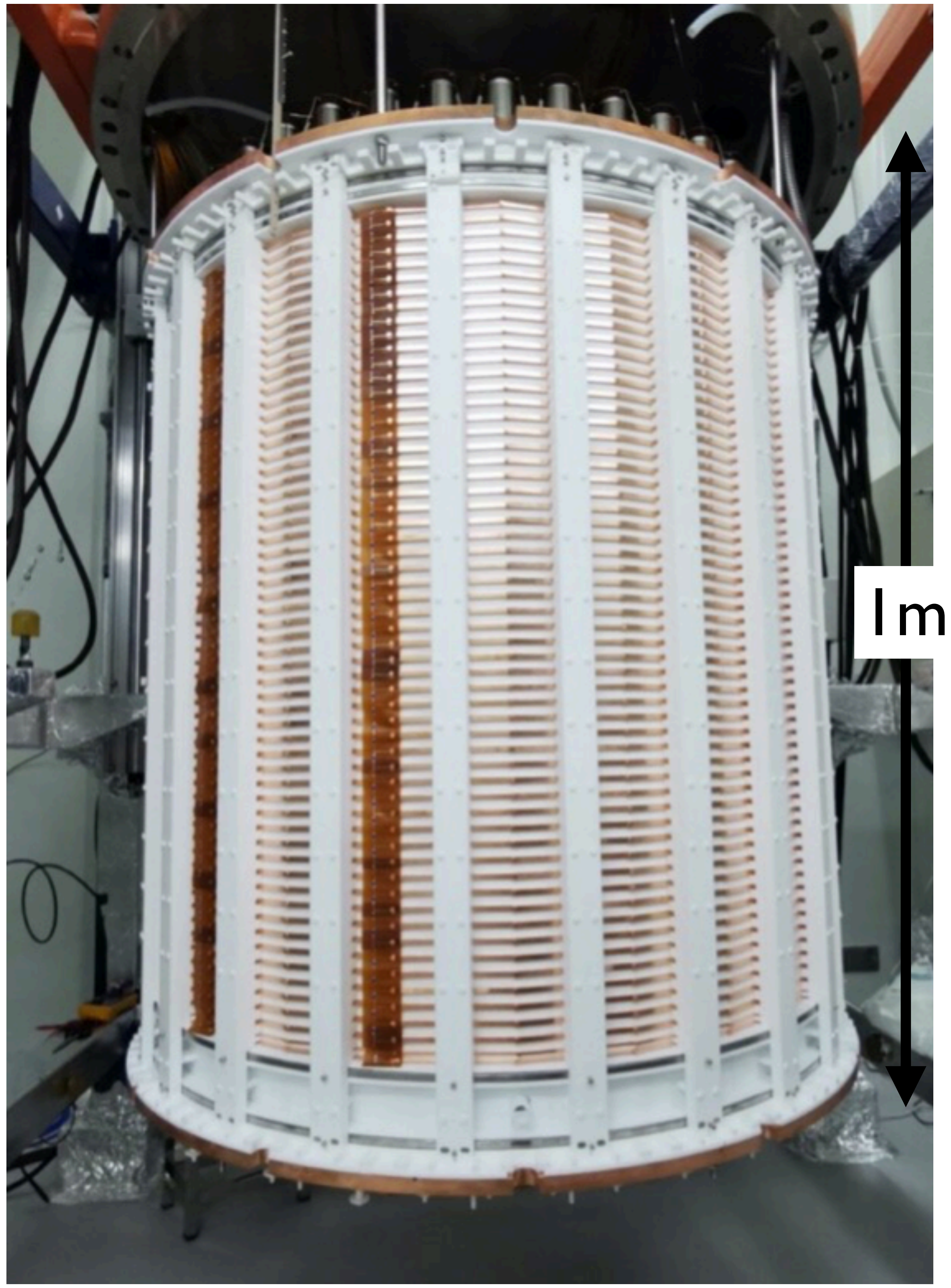
Target	Signal	Threshold	DM Mass range
Noble Liquid	electron ionization	~10 eV (atom ionization)	>10 MeV
Semiconductors	eh pairs	~1eV (bandgap)	>MeV

Sub-GeV DM detection: tabletop experiments

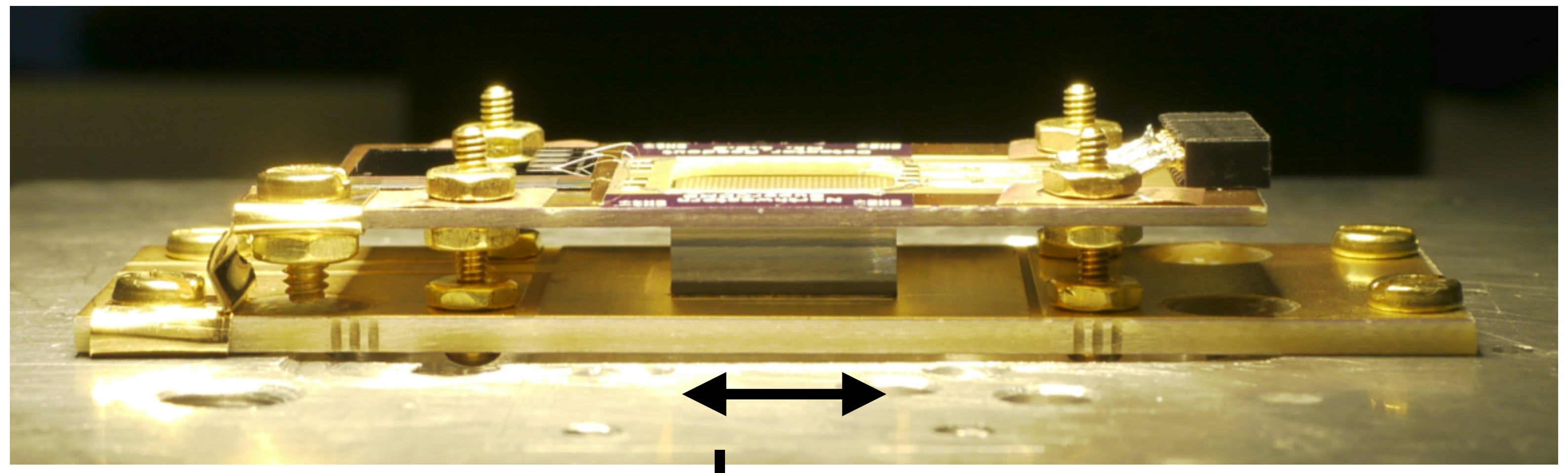
SENSEI



PandaX (WIMP)



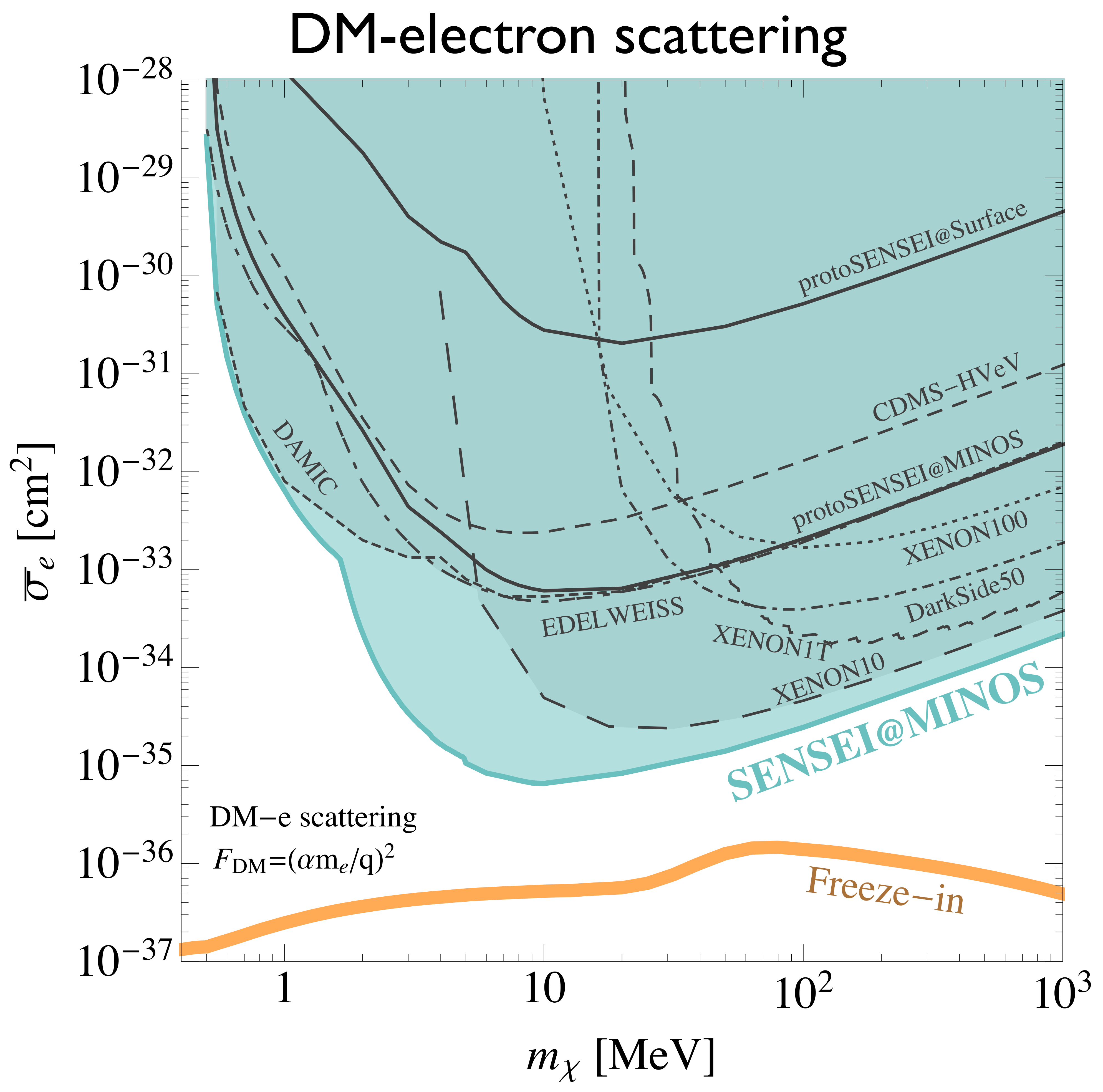
SuperCDMS HVeV



1cm

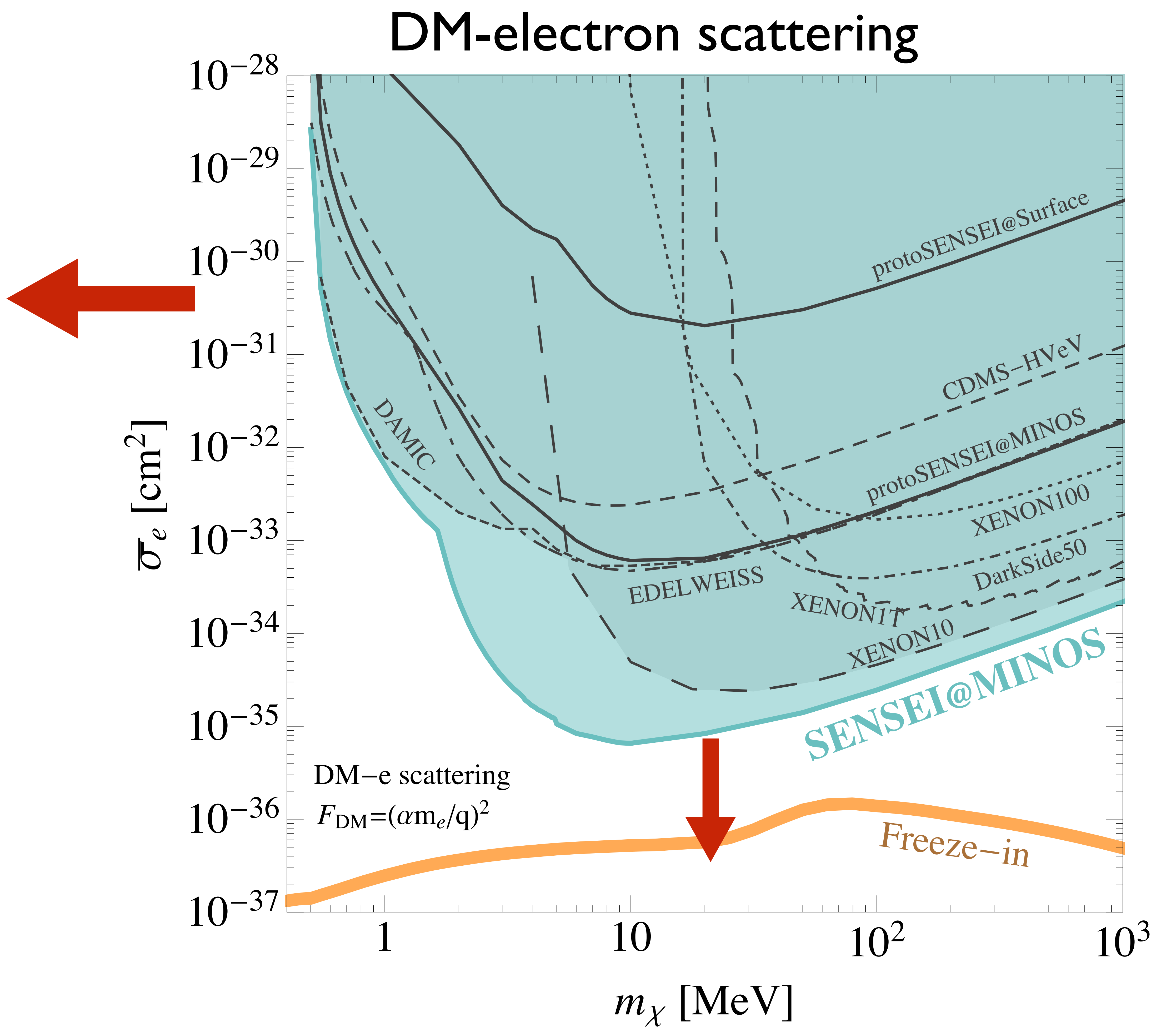
Direct Detection of Sub-GeV DM

Figure from SENSEI, *PRL* 2020



Direct Detection of Sub-GeV DM

Figure from SENSEI, *PRL* 2020

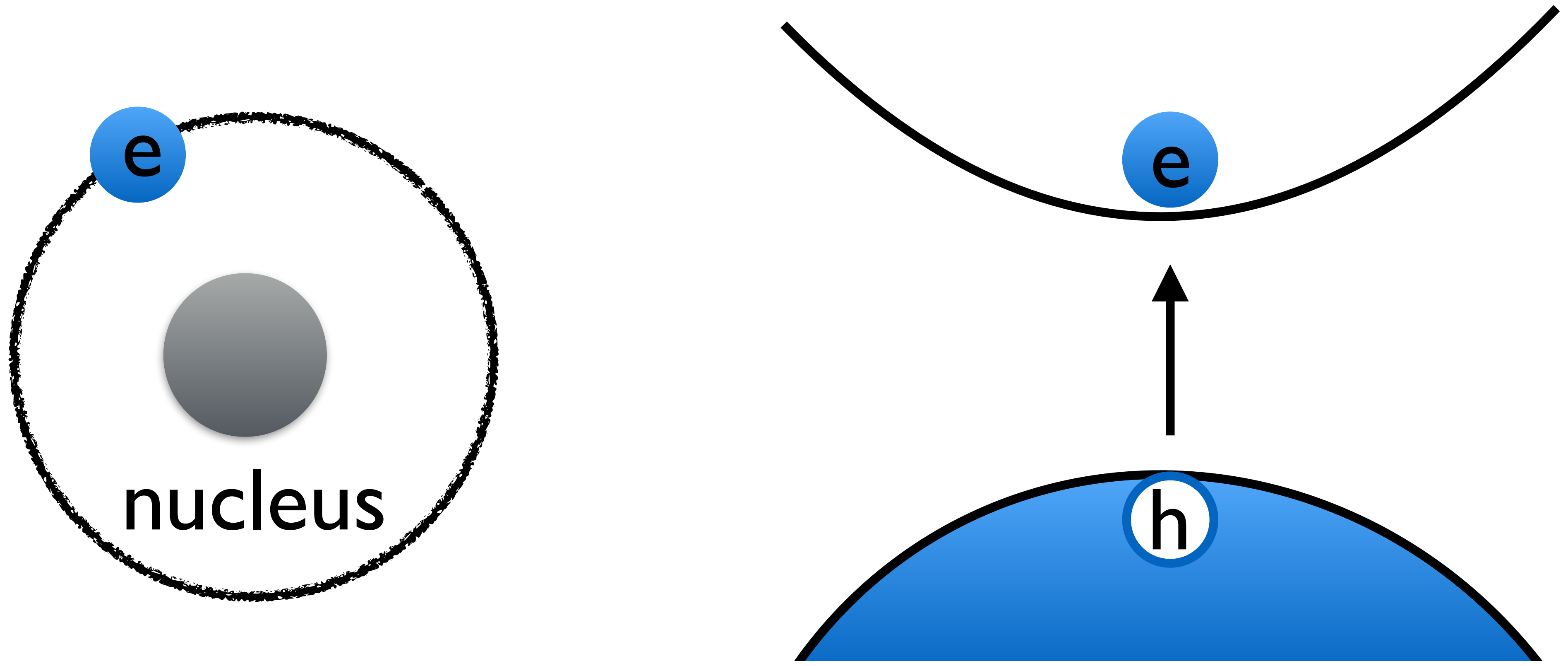


Questions:

how to probe sub-MeV DM?

how to probe Freeze-in theory target?

Probing Sub-MeV DM

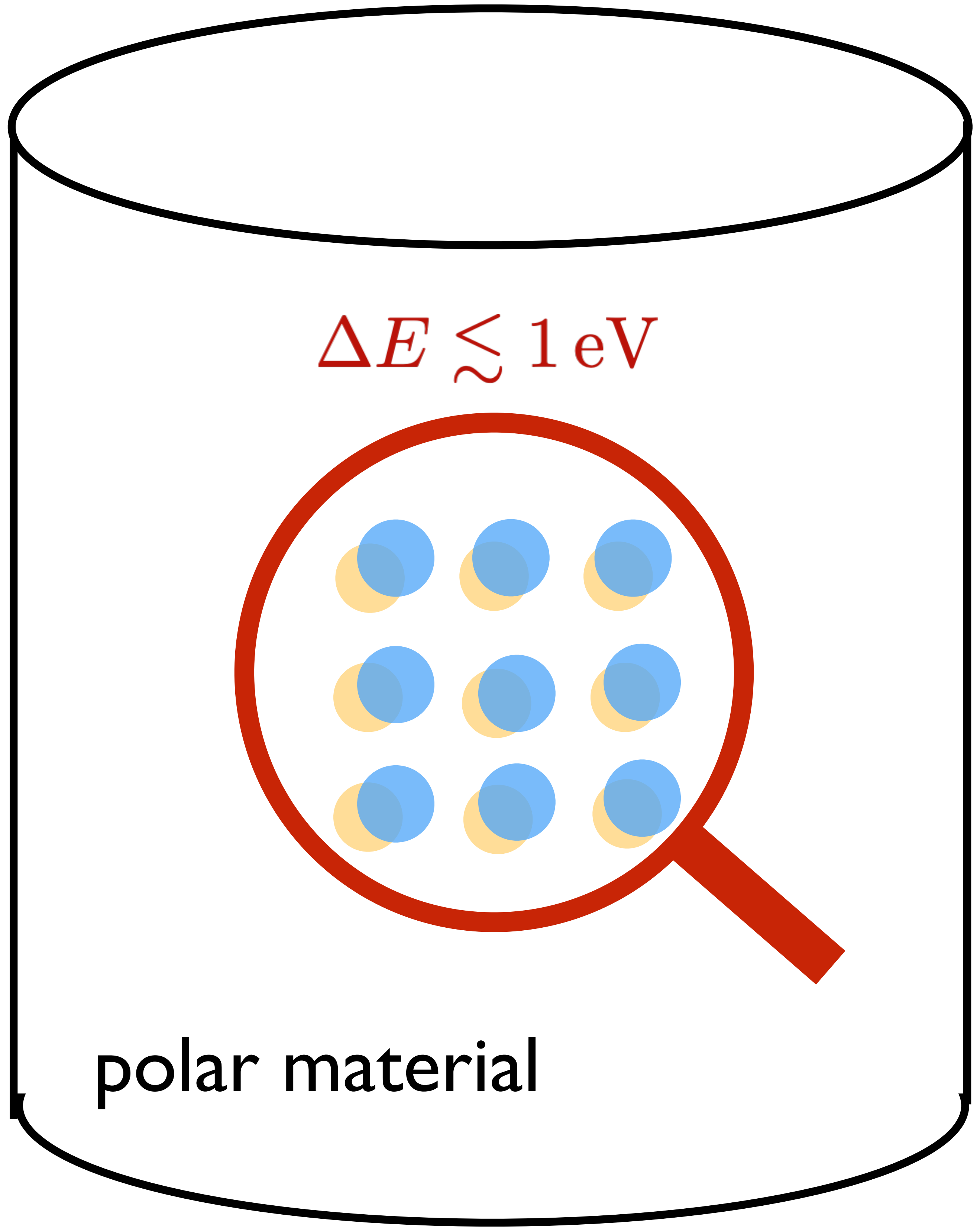


sub-eV threshold detector

Threshold	10 eV	1eV	100meV	10meV	1meV
DM Mass	10 MeV	1MeV	100keV	10keV	1keV

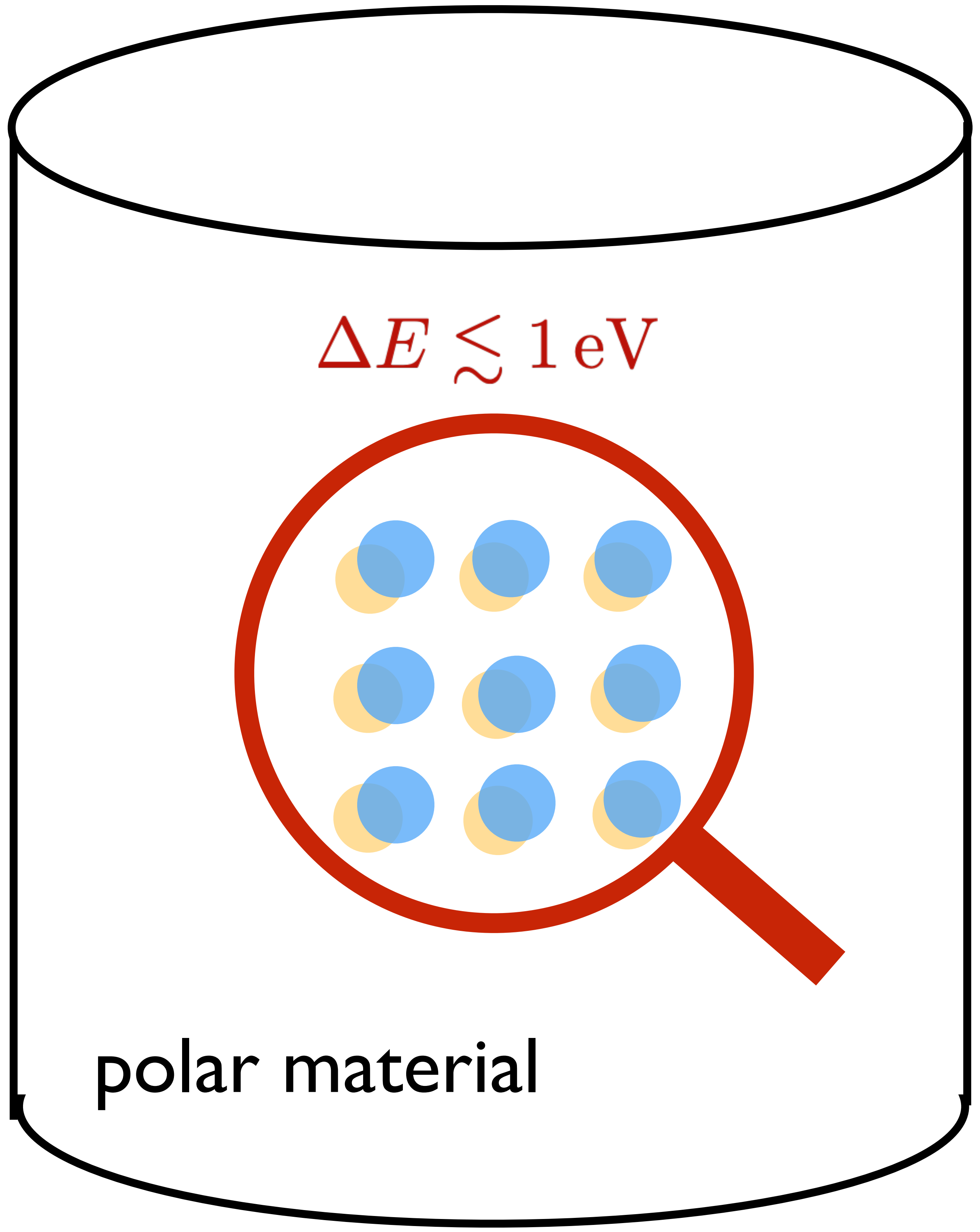
Low threshold detector can probe low mass DM

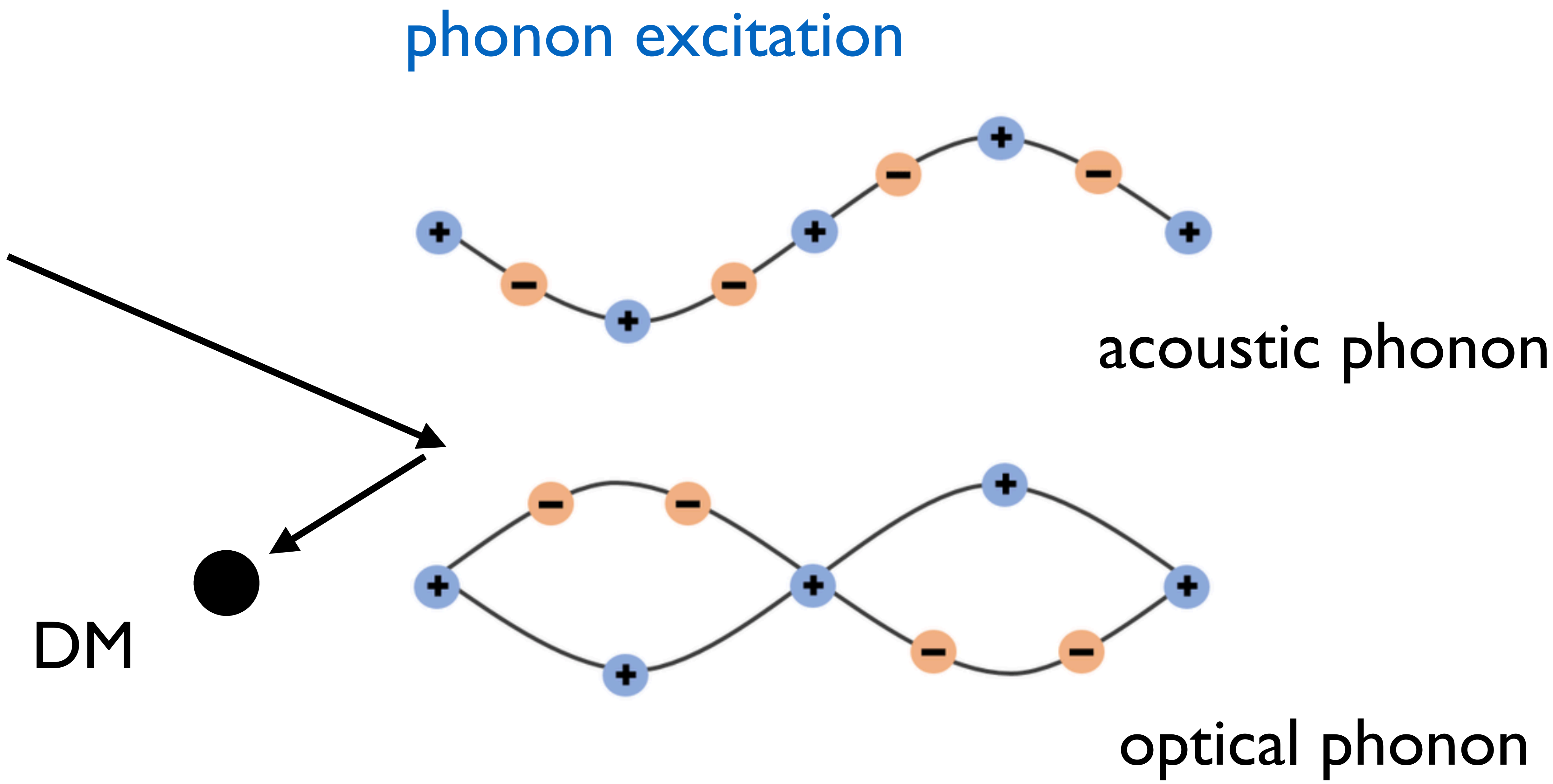
Direct Detection: ΔE<1eV



Direct Detection: ΔE<1eV

Knapen, Lin, Pyle, Zurek, *PLB* 2018





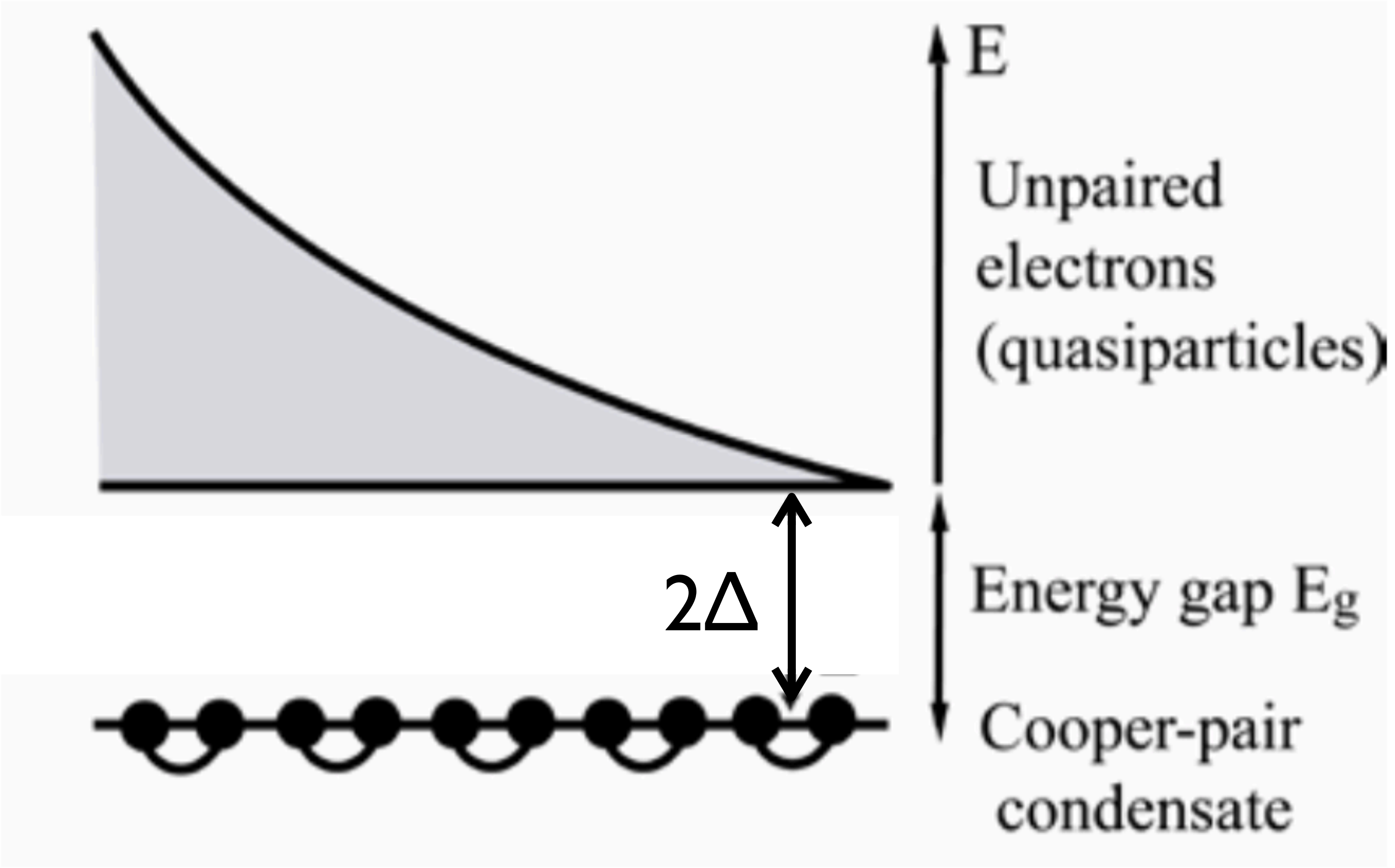
Signals: optical phonons

Threshold: ~10-100 meV

Direct Detection: ΔE<1eV

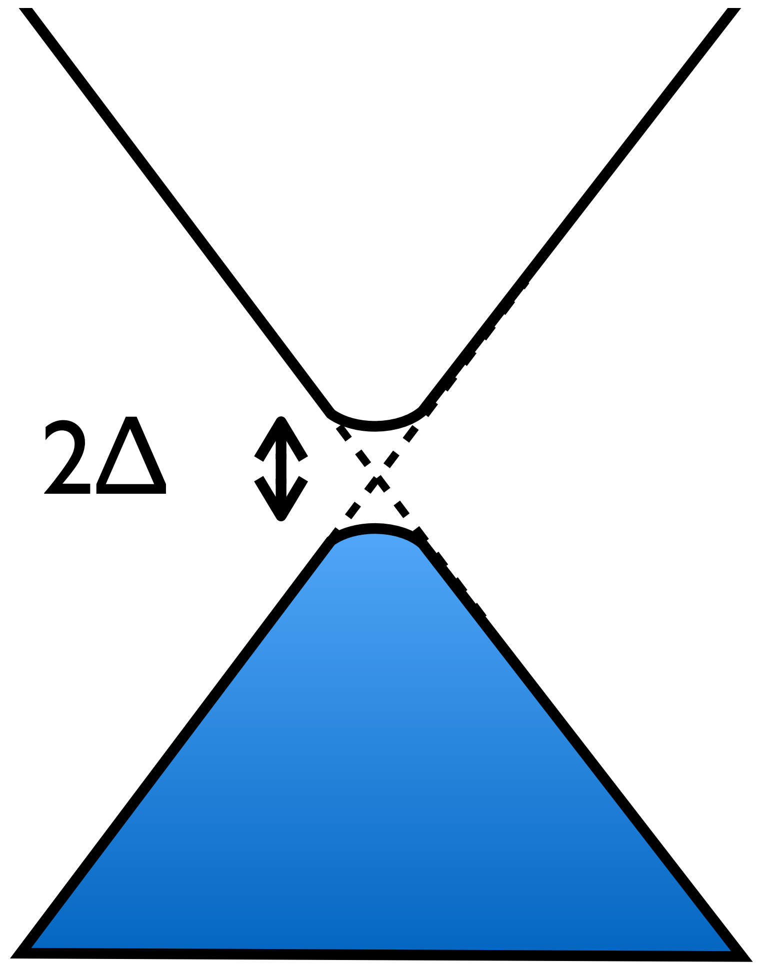
Hochberg, Zhao, Zurek, *PRL* 2015
Hochberg, Kahn, Lisanti, Zurek, et.al, *PRD* 2017

Superconductor



Δ=O(1) meV

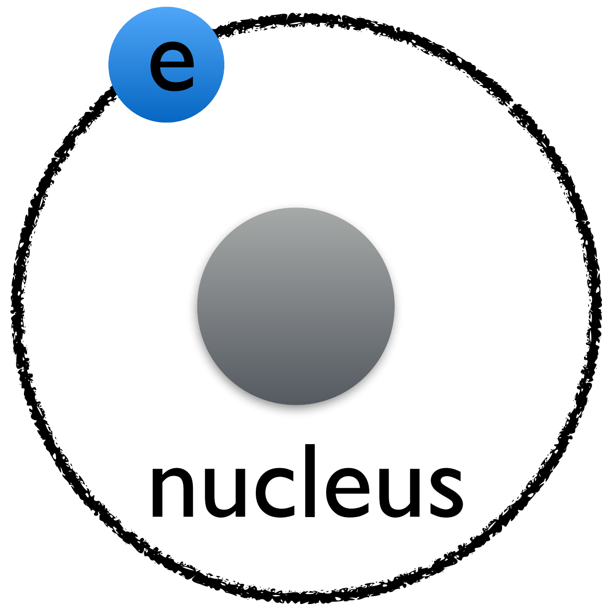
Dirac material

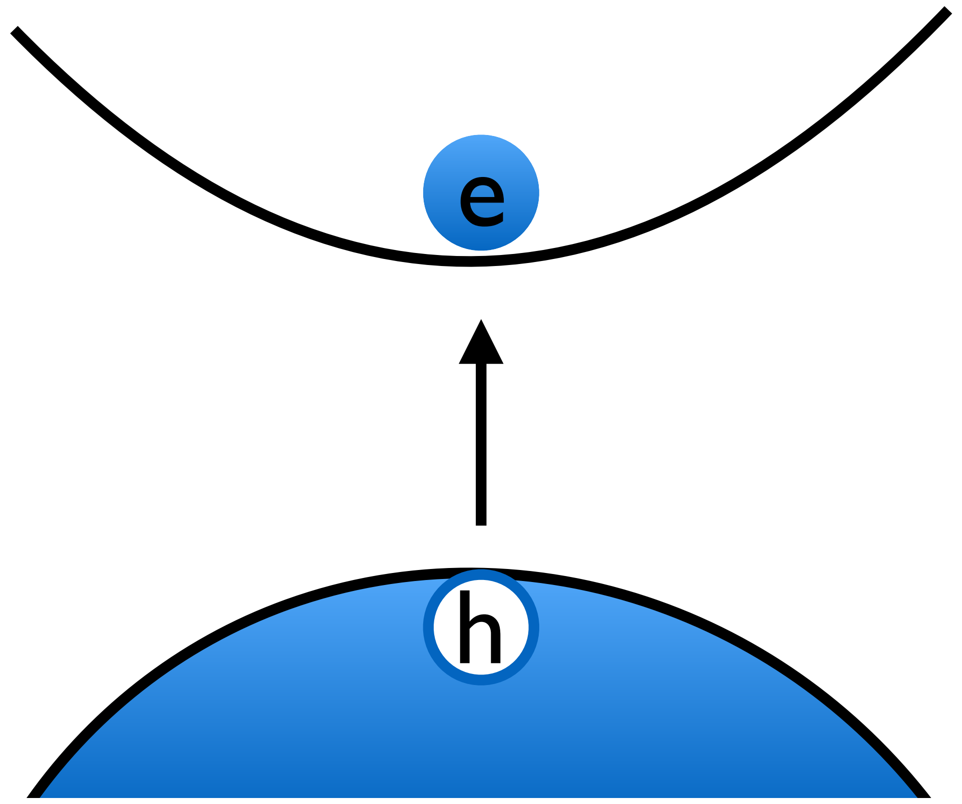


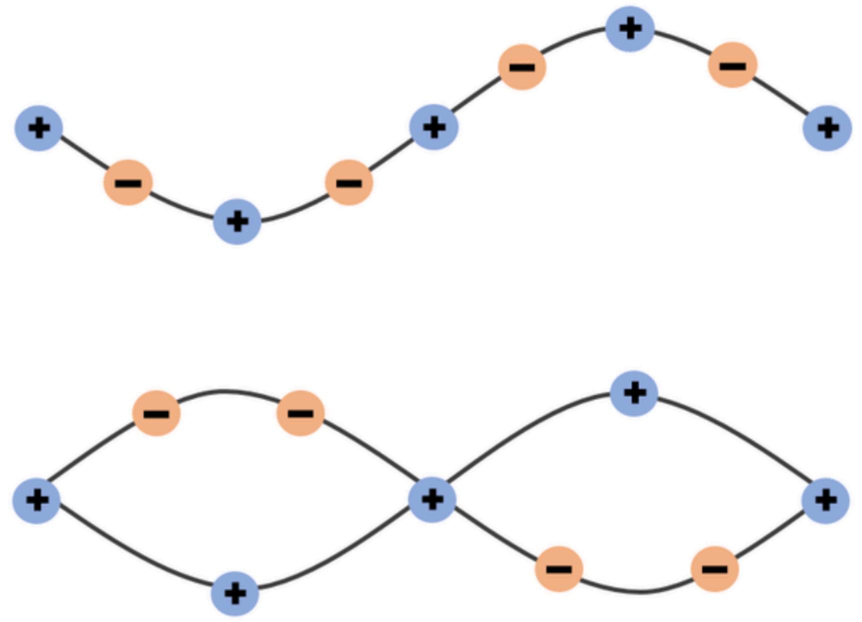
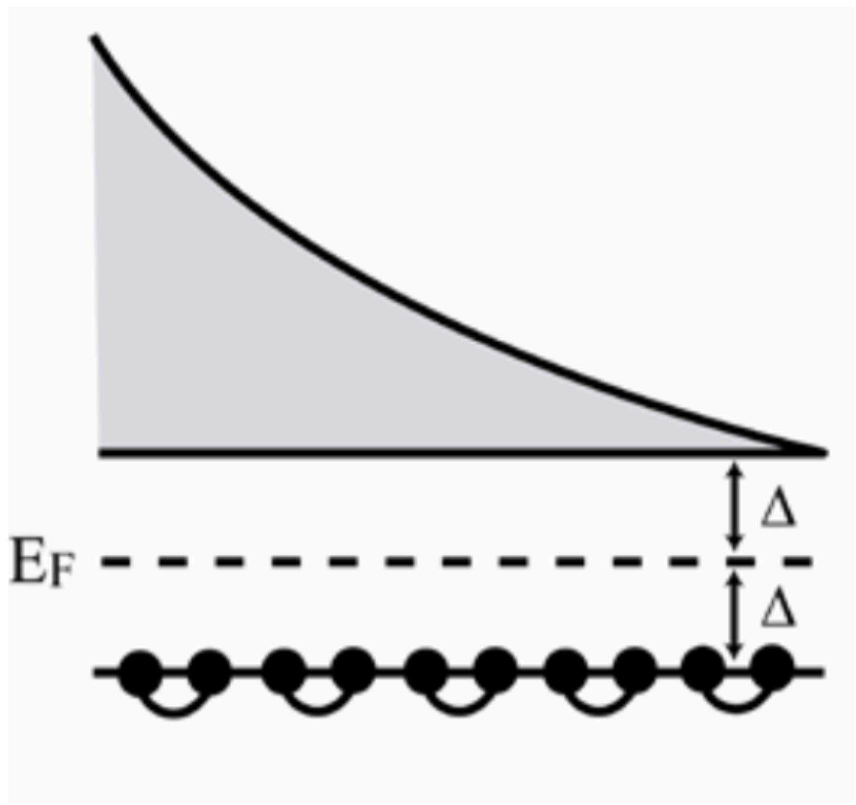
Δ=O(1) meV

Signals: quasiparticles/phonons
Threshold: ~1 meV

Probing Sub-MeV DM





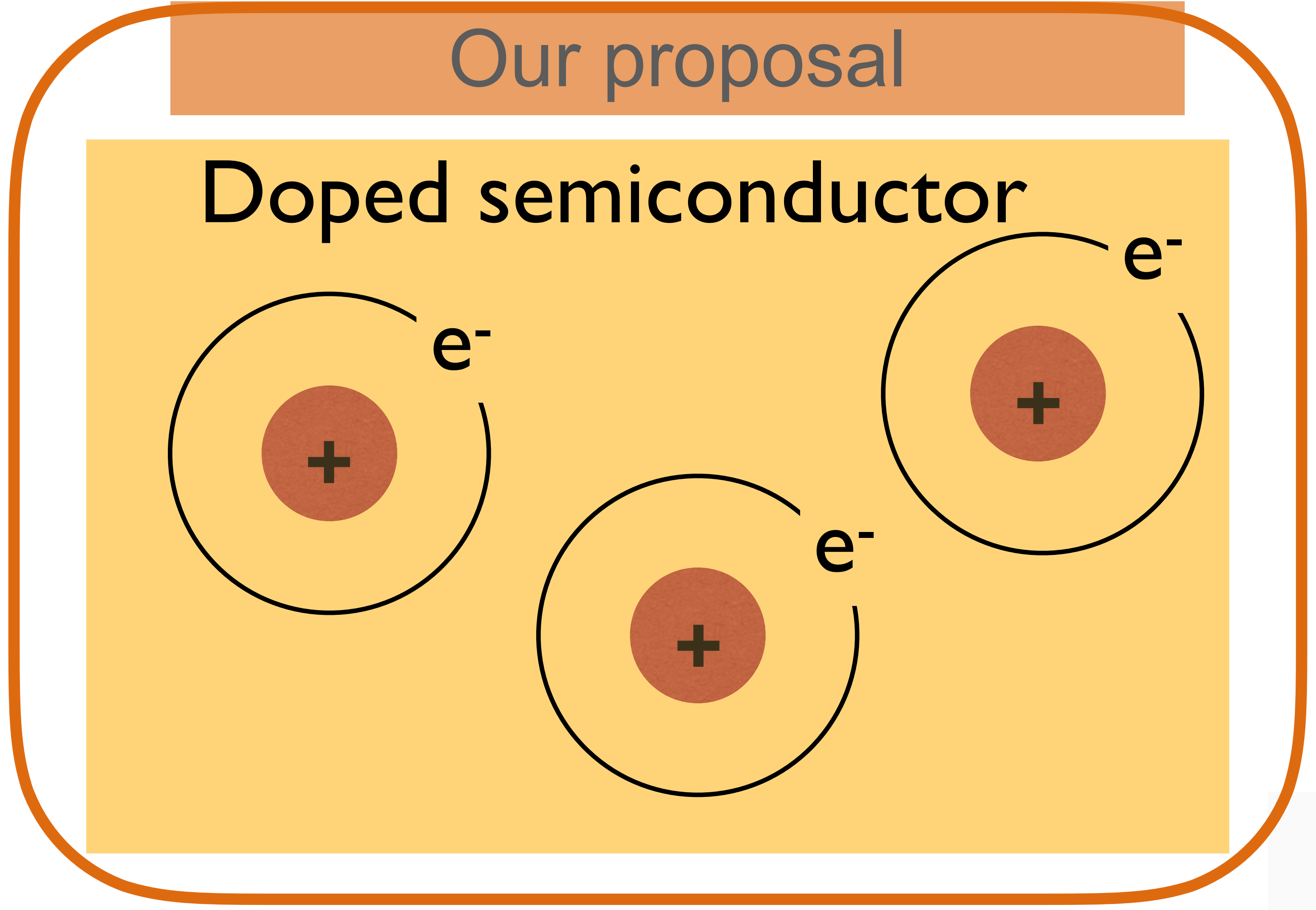



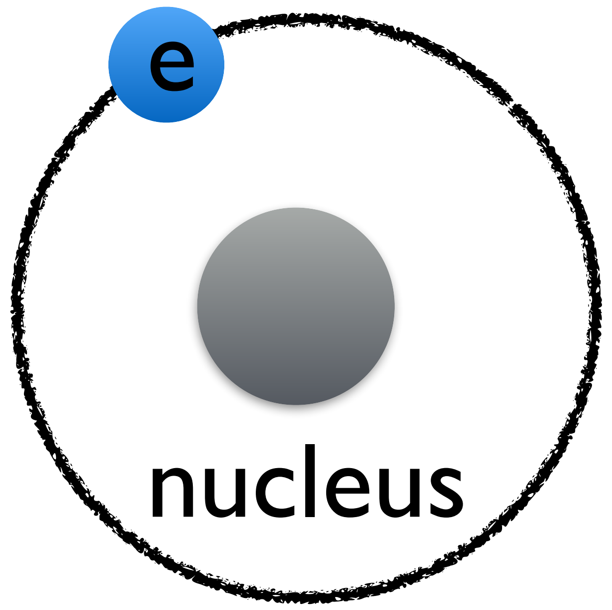
Threshold: 10 eV — 1eV — 100meV — 10meV — 1meV

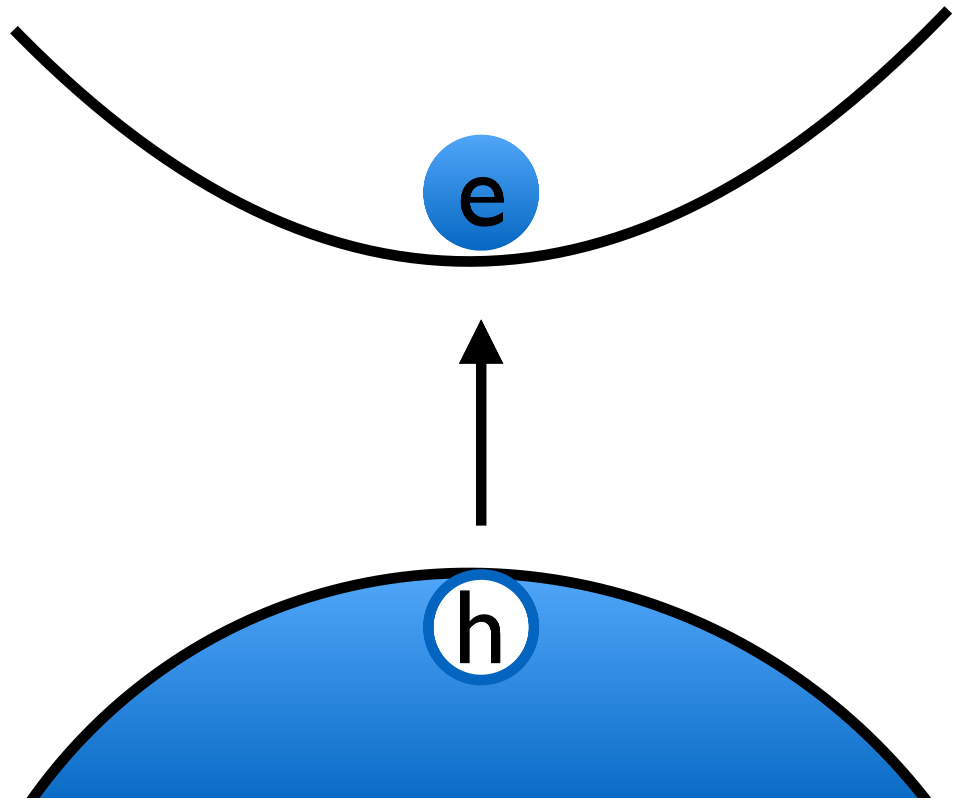
DM Mass: 10 MeV — 1MeV — 100keV — 10keV — 1keV

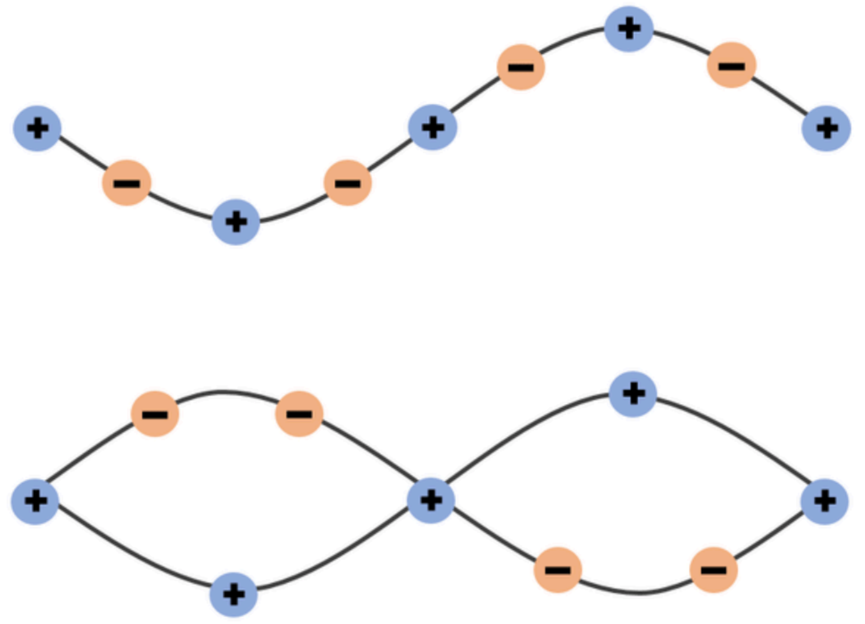
Low threshold detector can probe low mass DM

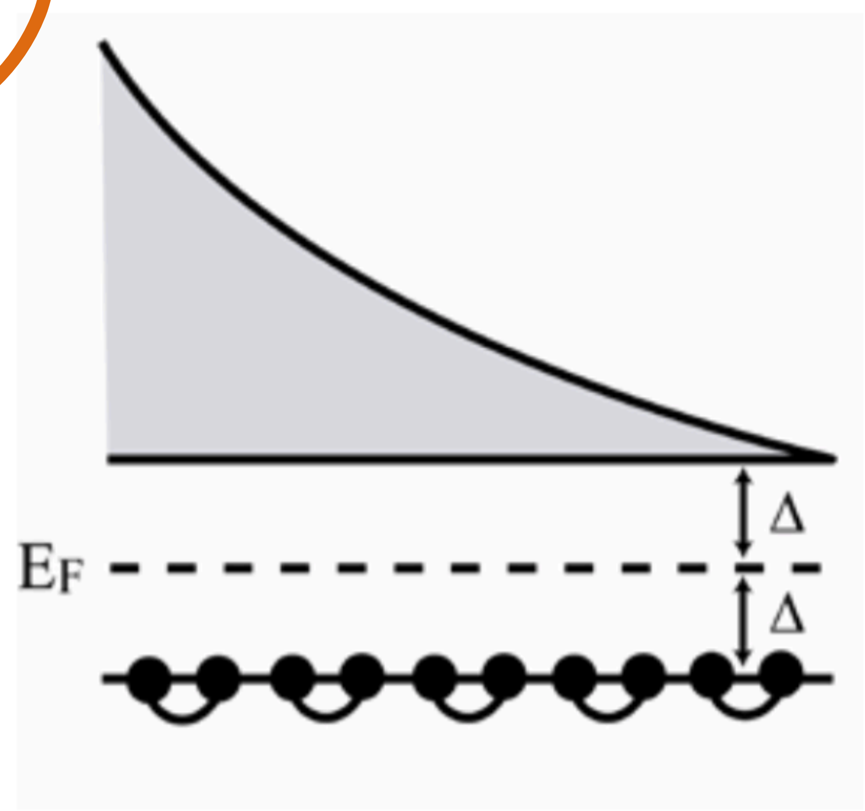
Probing Sub-MeV DM











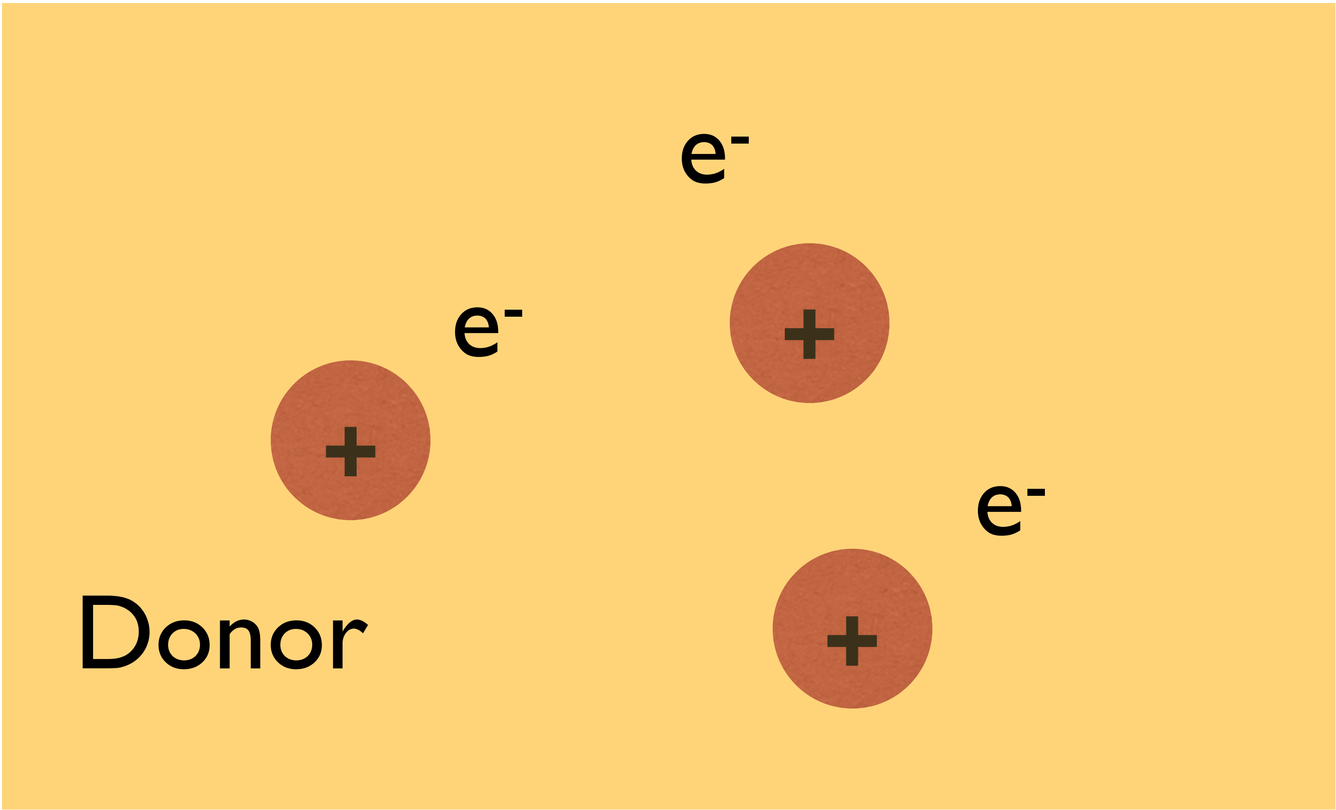
Threshold: 10 eV → 1eV → 100meV → 10meV → 1meV

DM Mass: 10 MeV → 1MeV → 100keV → 10keV → 1keV

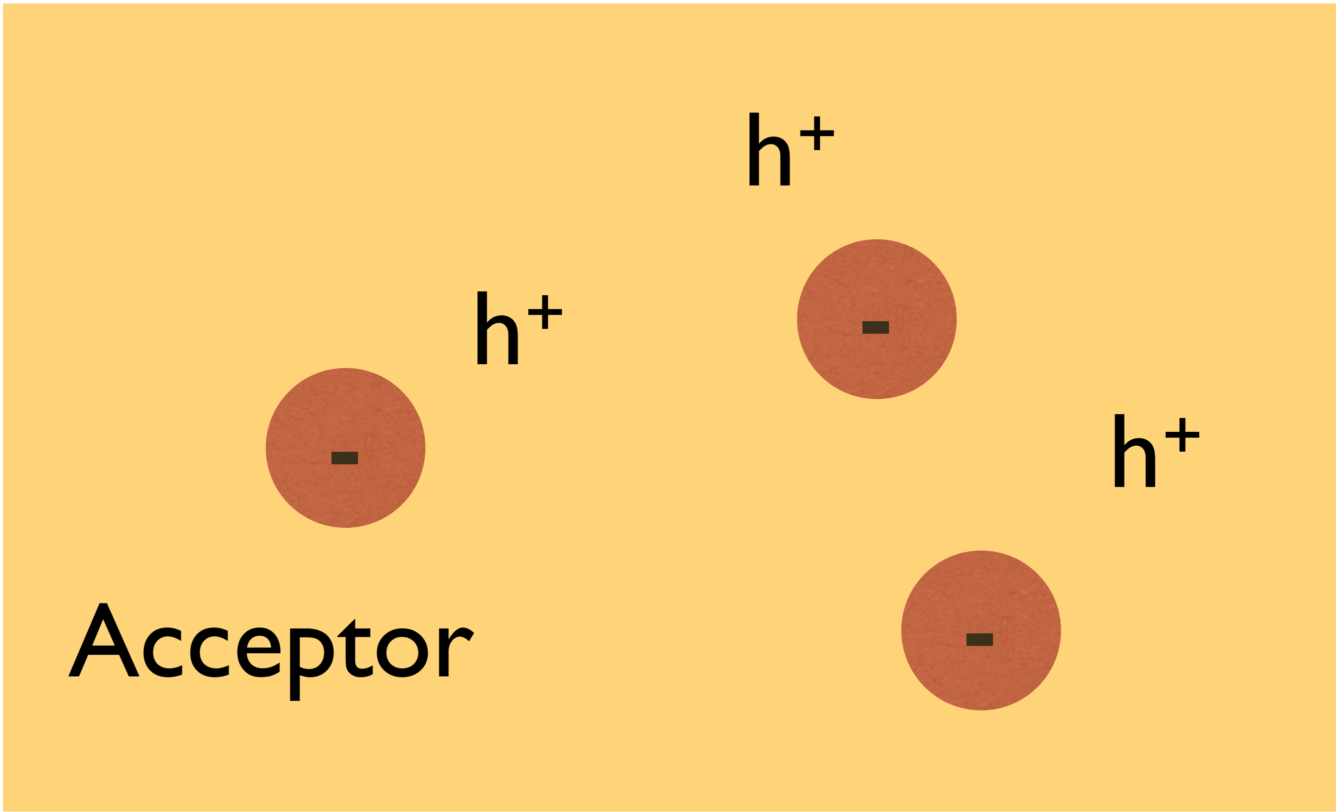
Low threshold detector can probe low mass DM

Doped semiconductors

n-type semiconductor



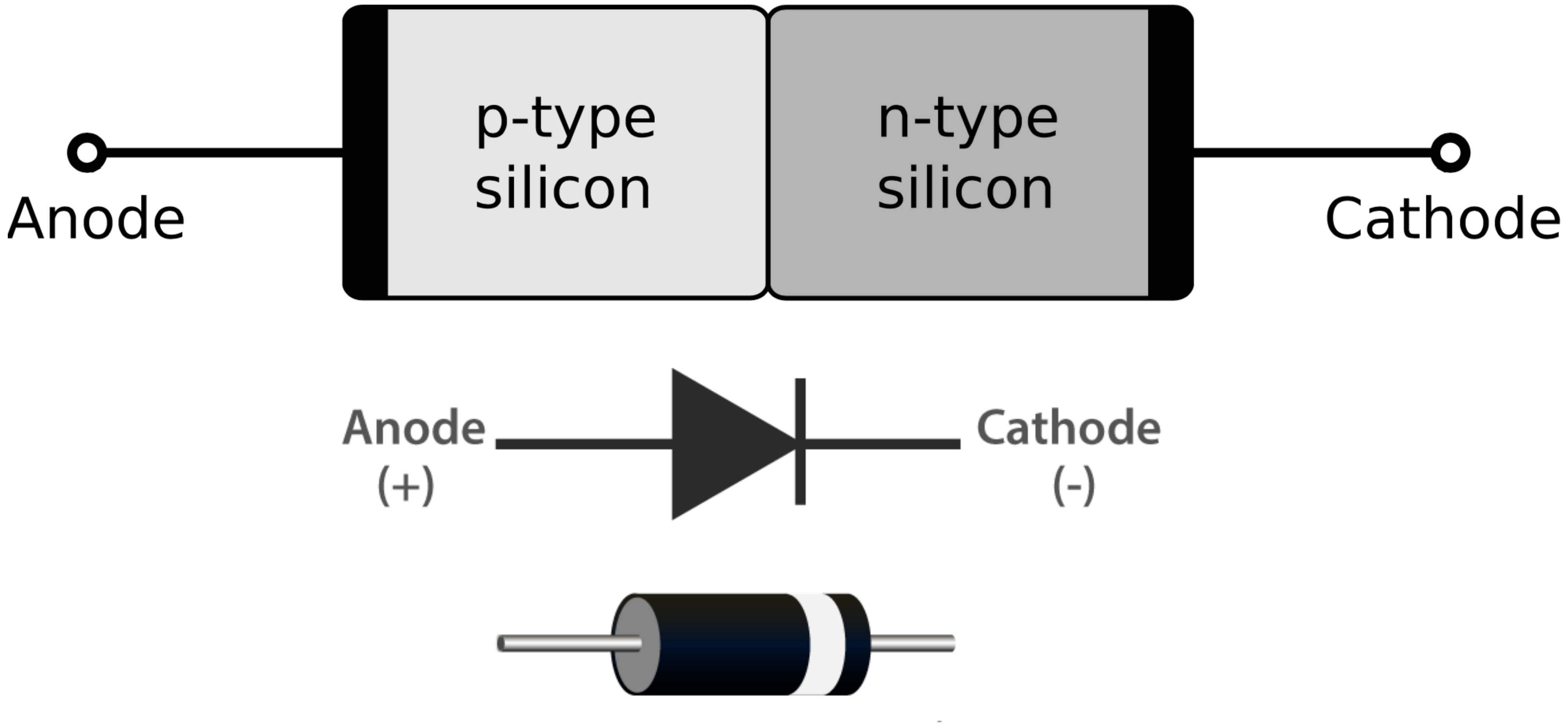
p-type semiconductor



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

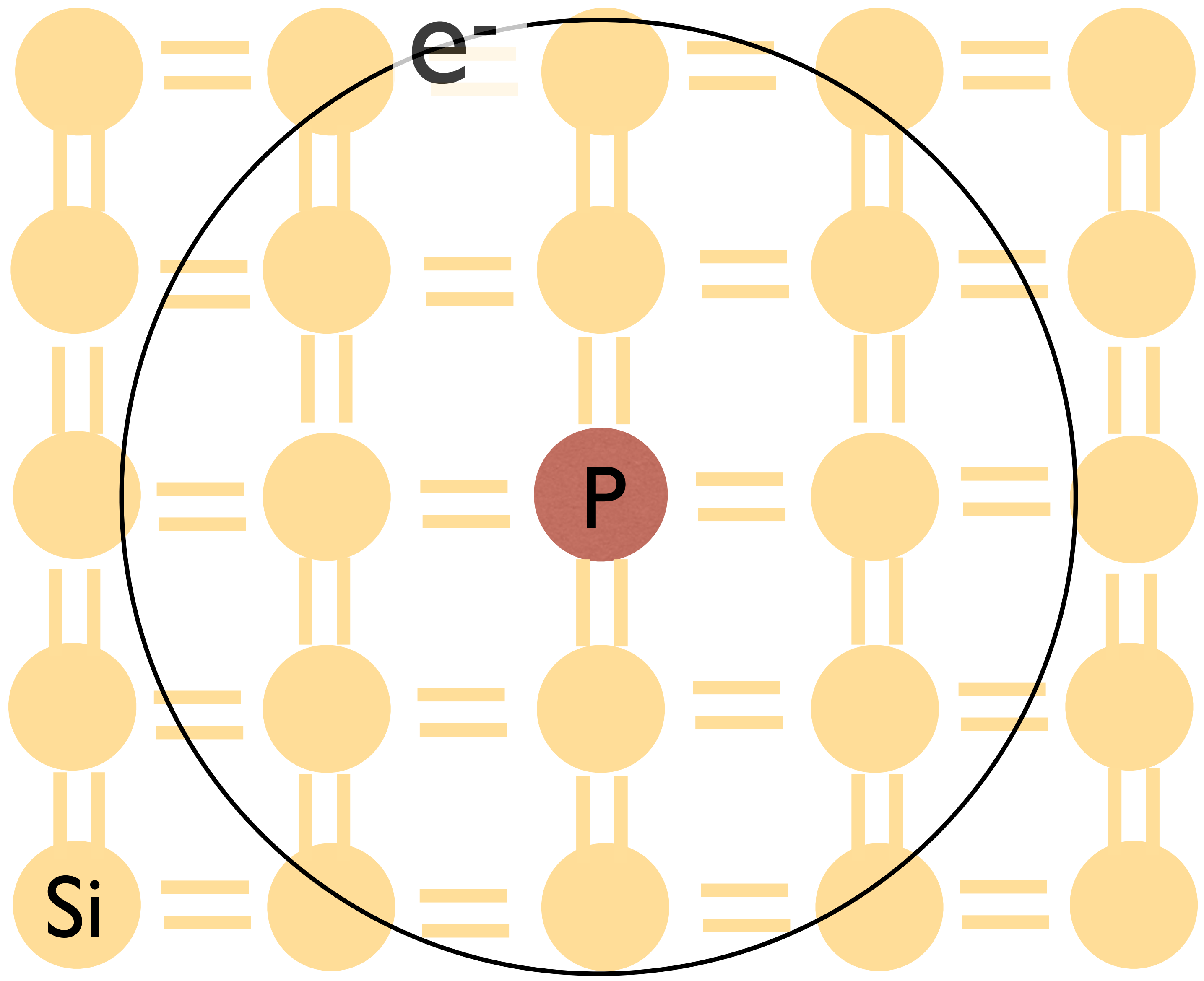
Acceptors in Silicon: B , Al …(group III elements)

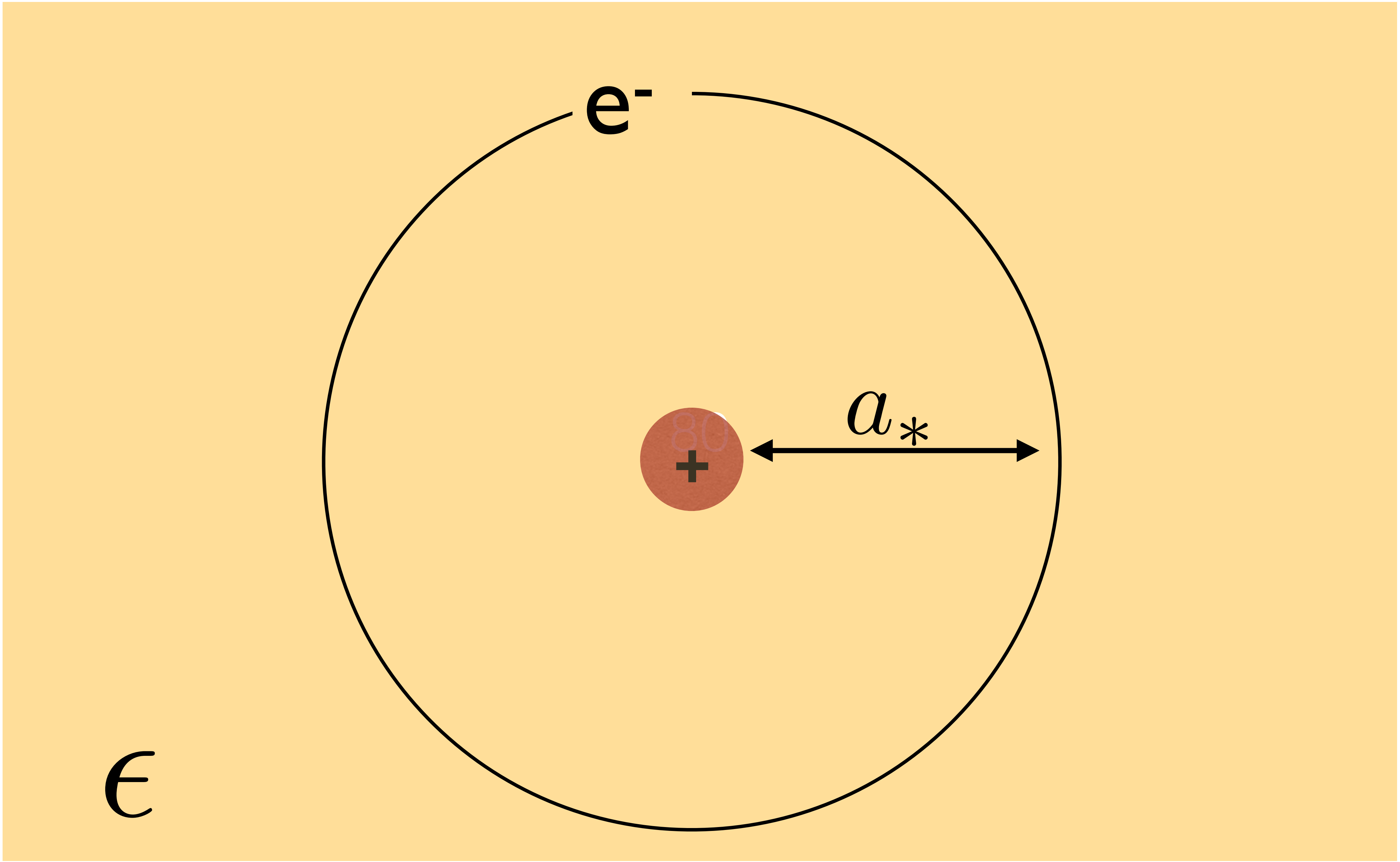
Commonly used: p-n junction, diodes



Dopants in semiconductors

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





Dopants in semiconductors

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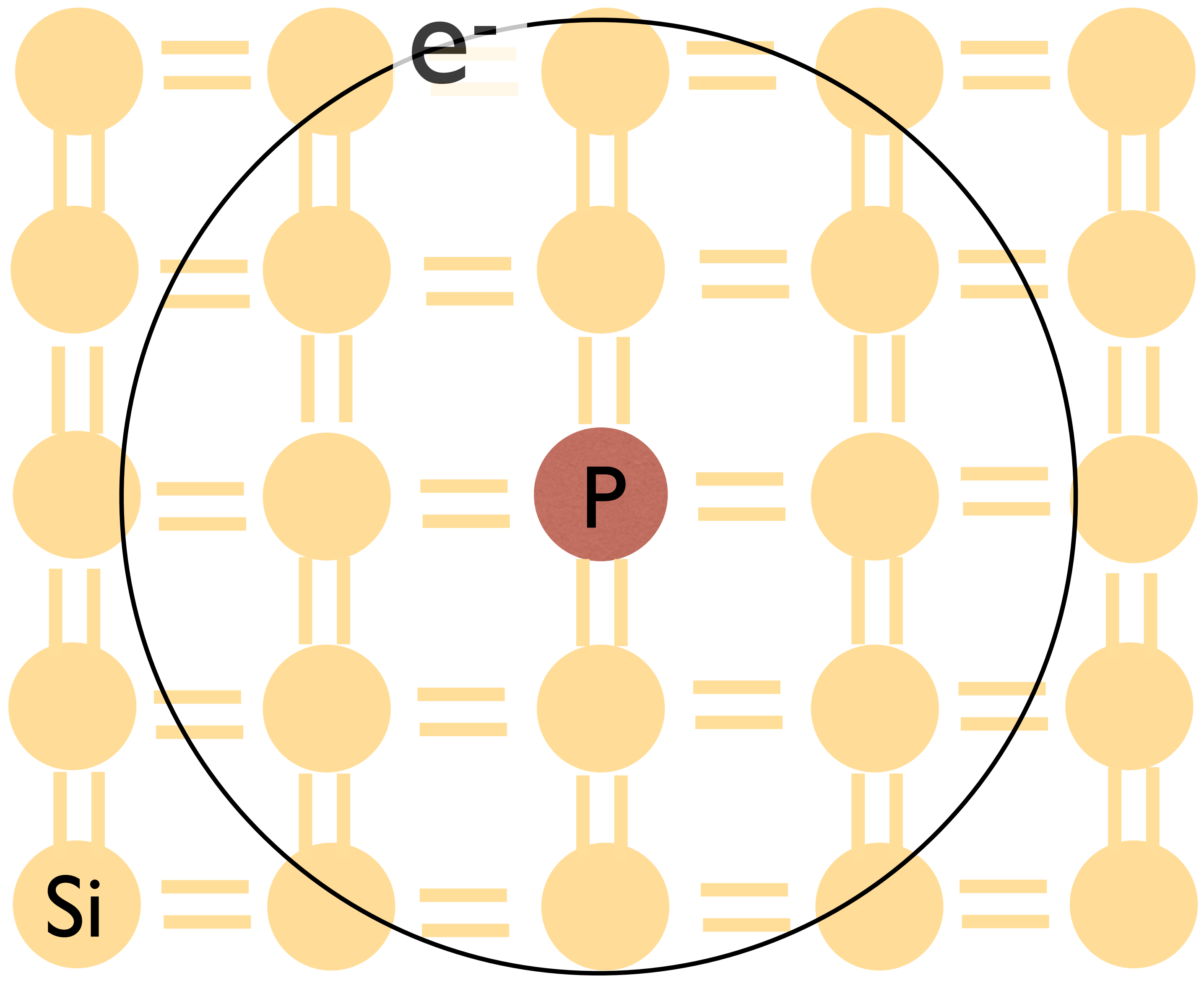
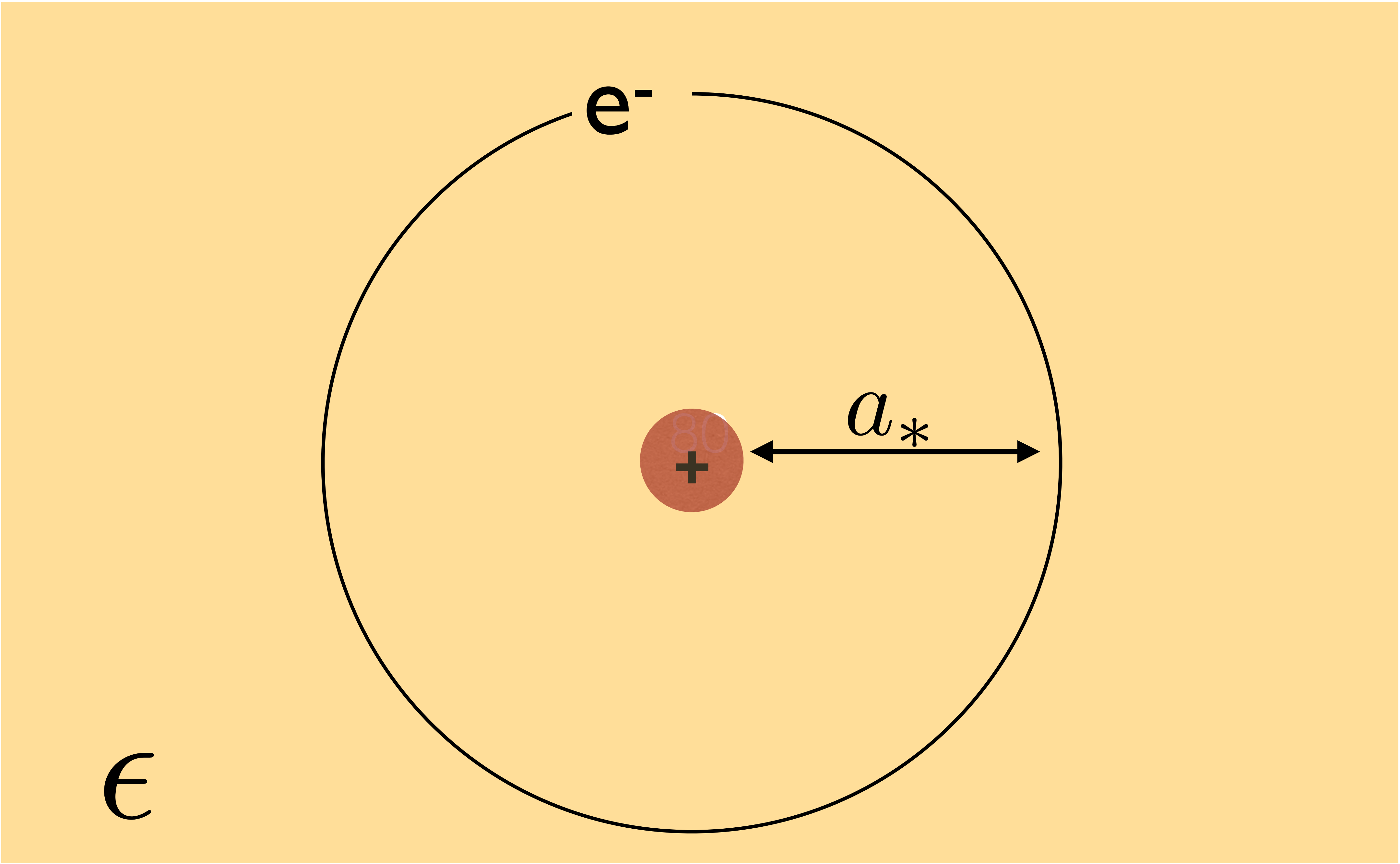
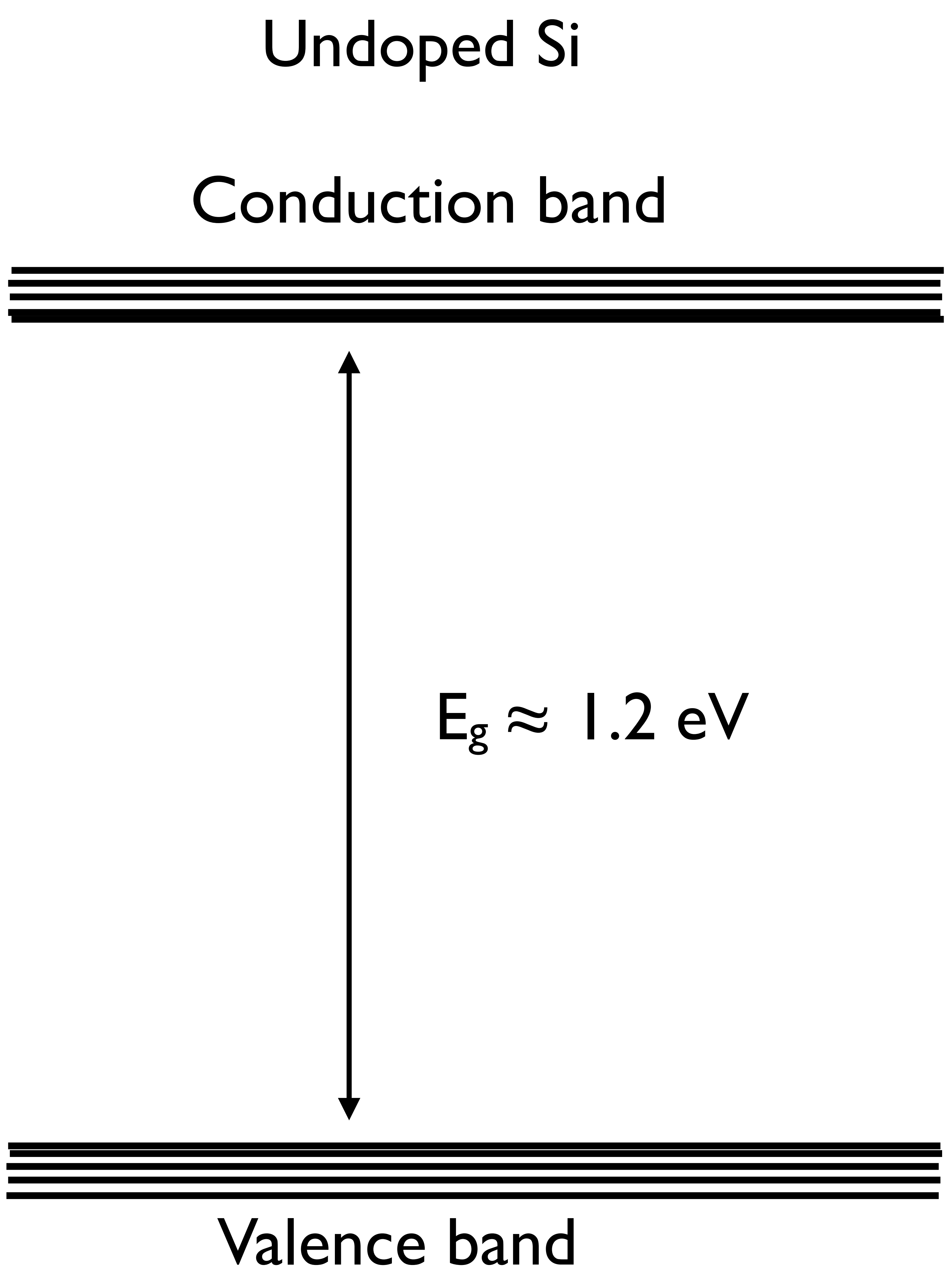




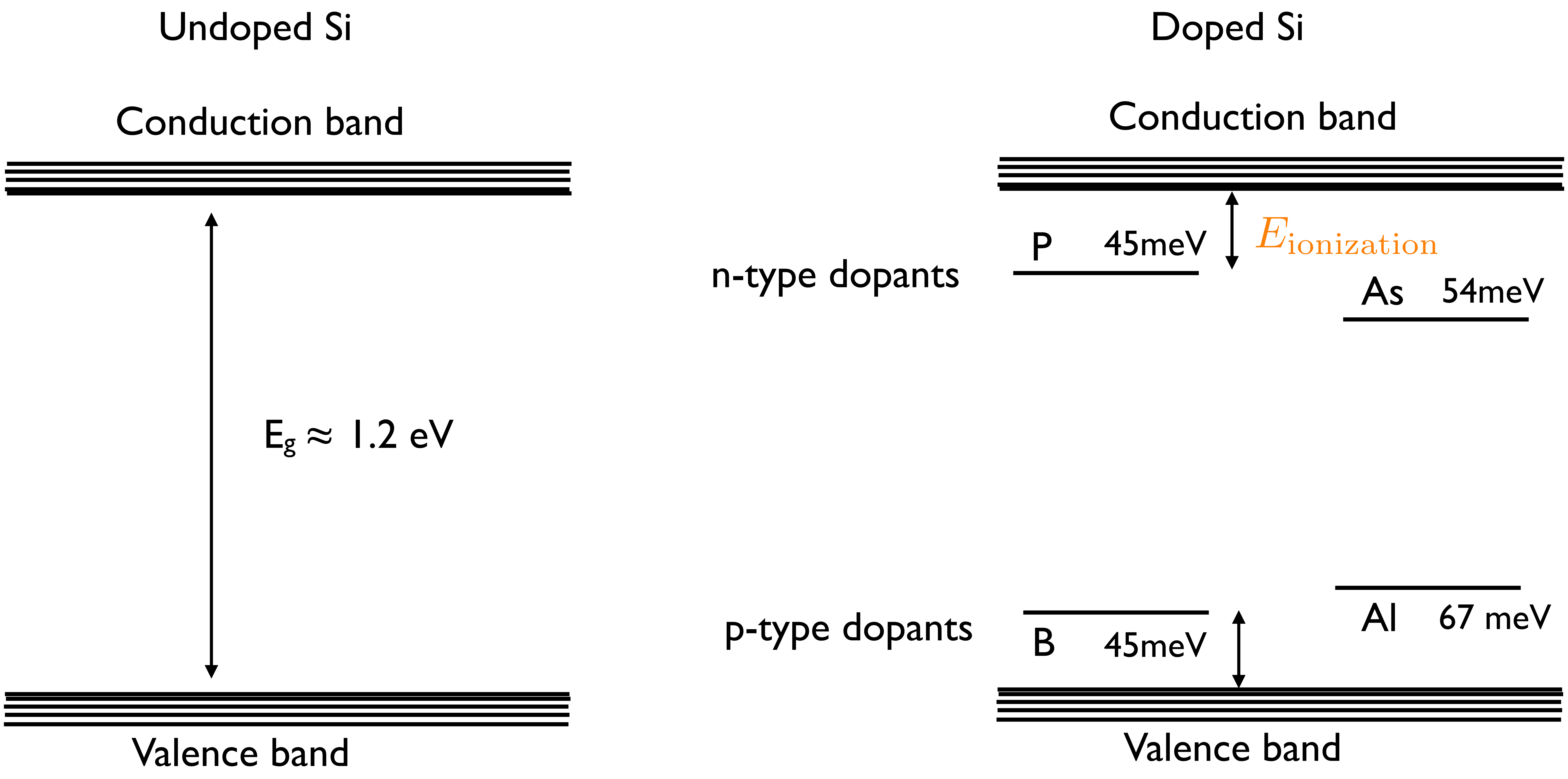
electron effective mass   Bohr radius

For $\epsilon \sim 10$ $a_* \sim (\frac{\alpha}{\epsilon} m_*)^{-1} \sim O(10)\, a_0$ $E_{\text{ionization}} \sim \frac{1}{2}\left(\frac{\alpha}{\epsilon}\right)^2 m_* \sim 10 - 100\,\text{meV}$

Dopant energy levels in silicon

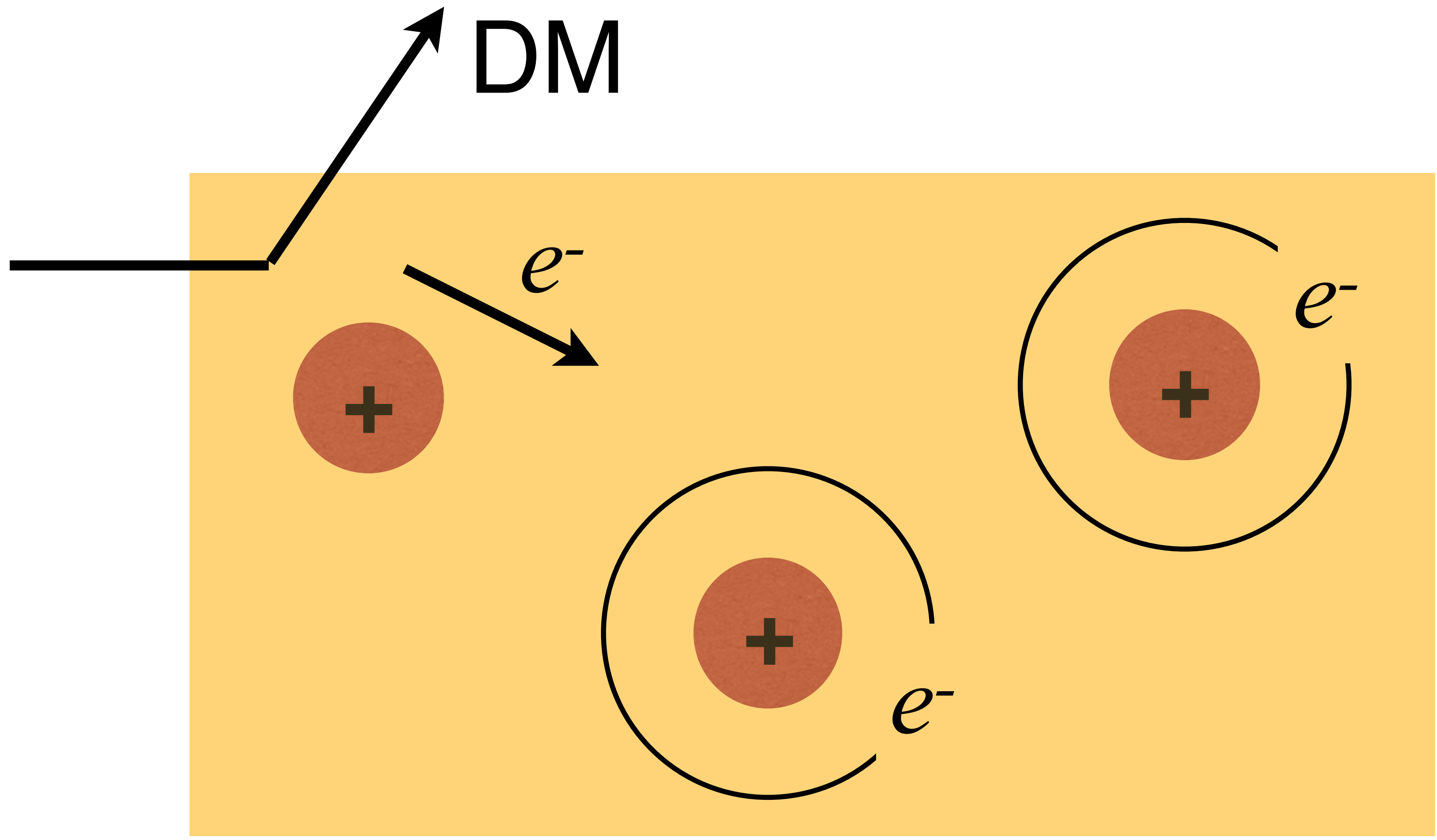


Dopant energy levels in silicon



DM reach with doped silicon

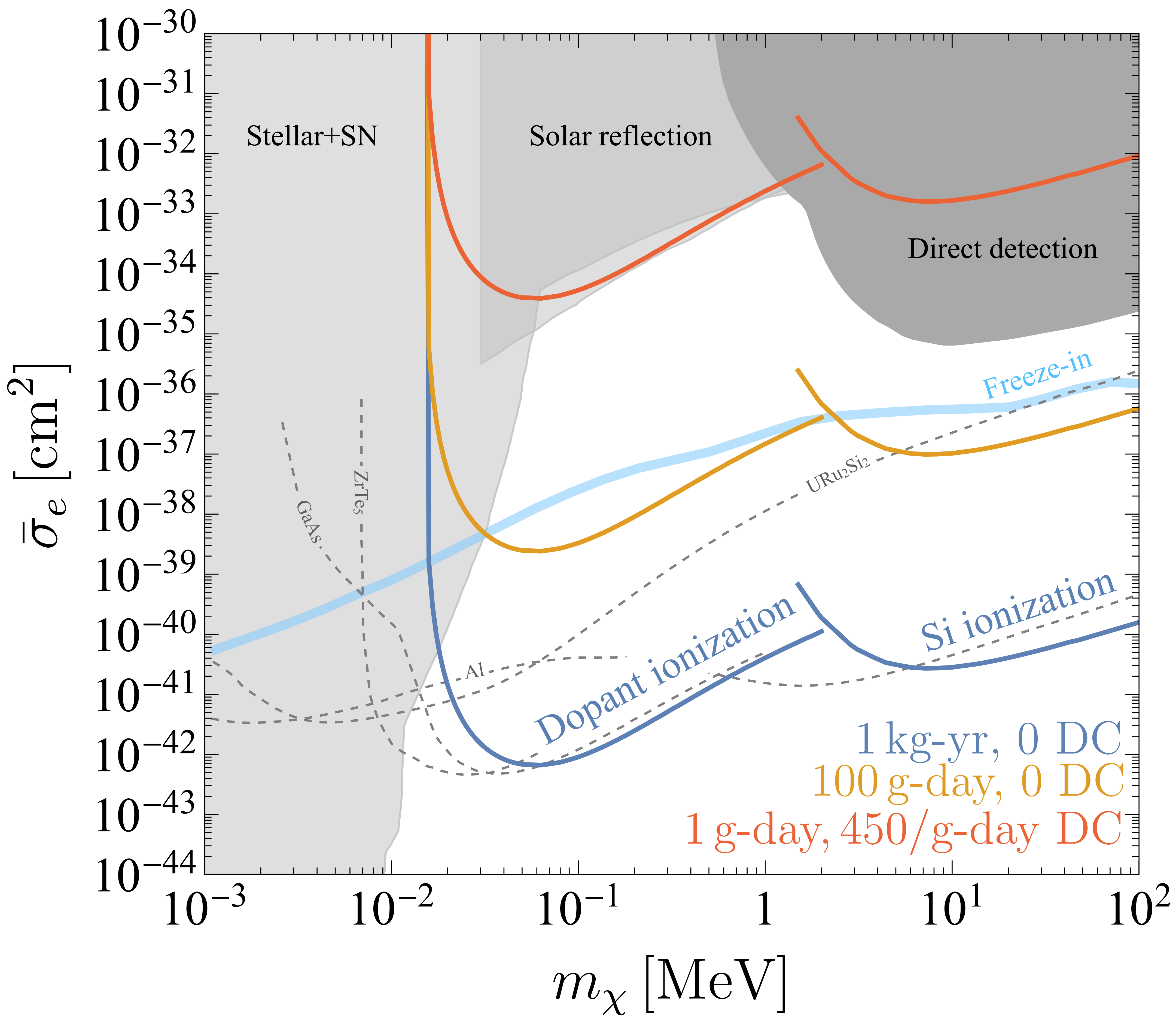
PD, Egana-Ugrinovic, Essig, Sholapurkar, arXiv:2212.04504



Signals: dopant ionization

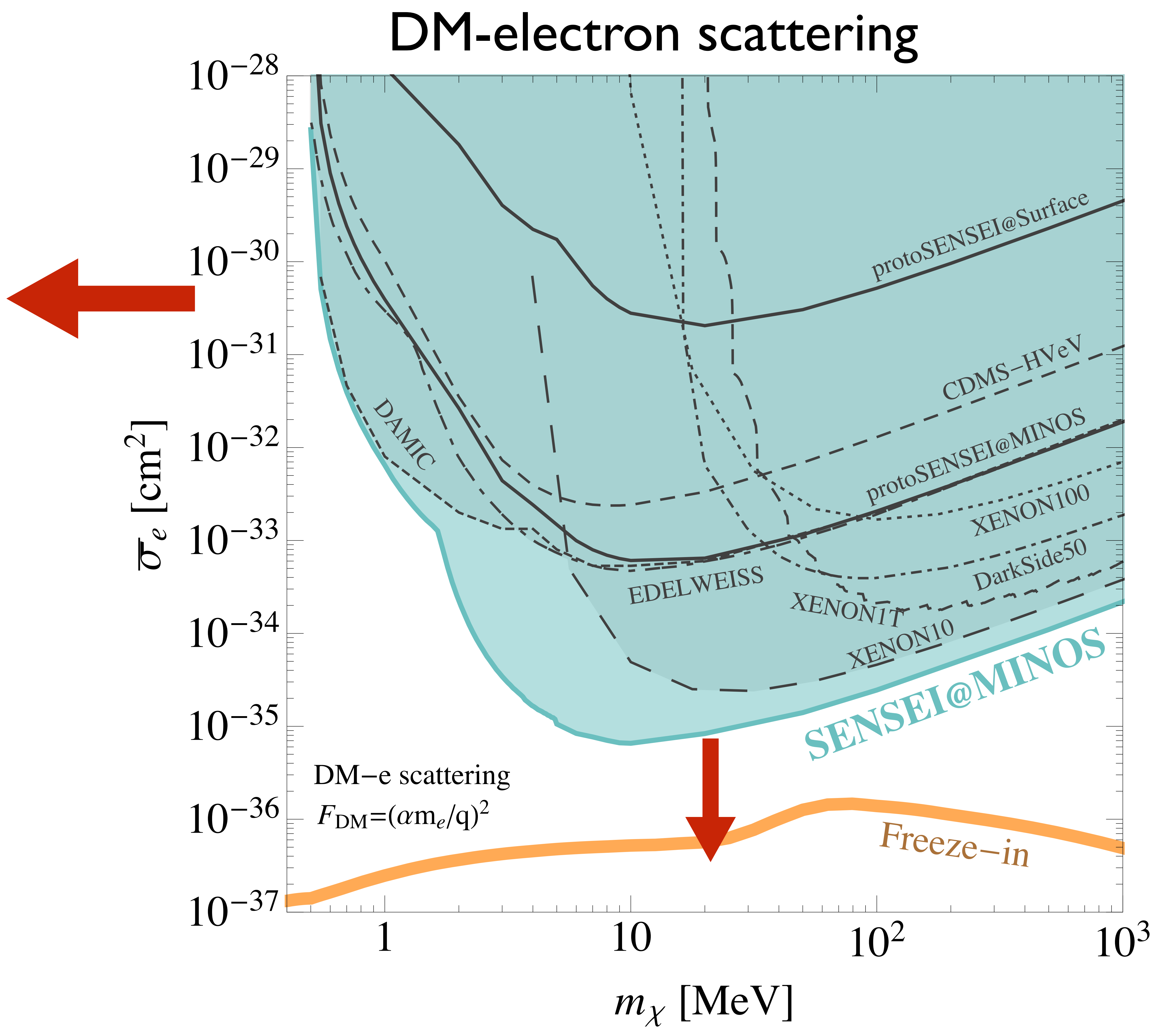
Threshold: E_I~10-100 meV

Light dark photon mediator (Si:P, $n_d = 1\times10^{18}$cm^{-3})



Direct Detection of Sub-GeV DM

Figure from SENSEI, *PRL* 2020



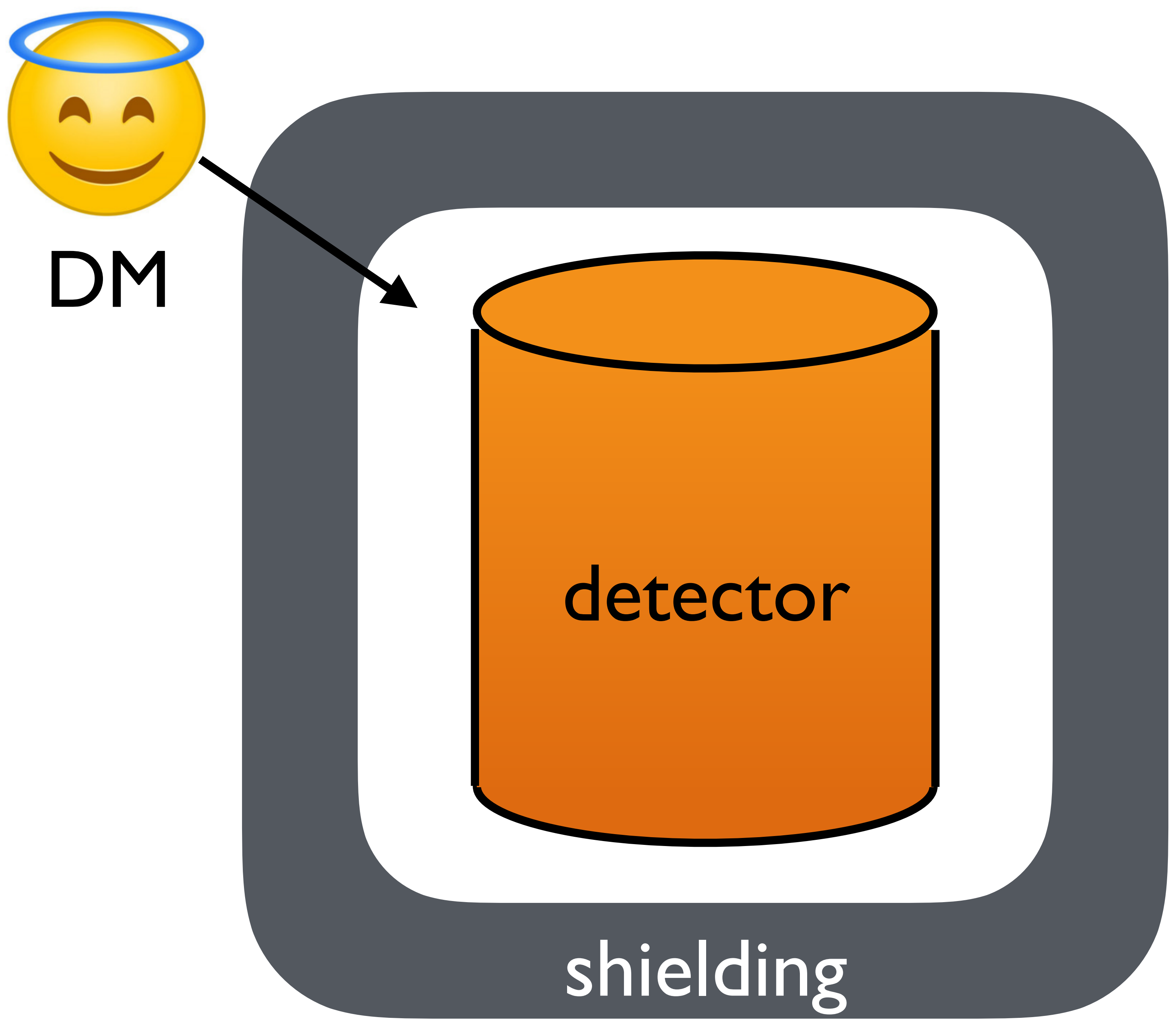
Questions:

how to probe sub-MeV DM?

doped semiconductors

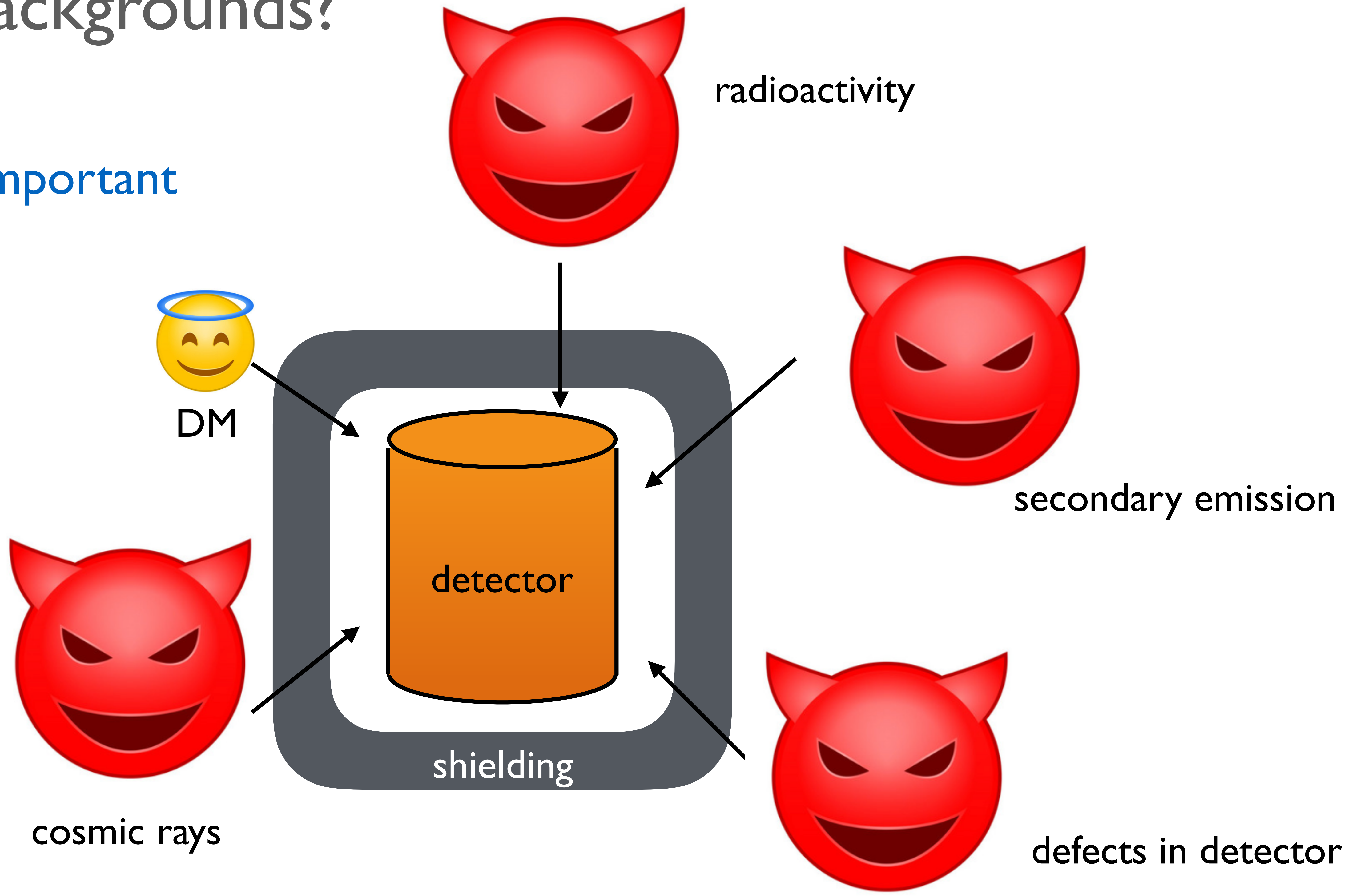
how to probe Freeze-in theory target?

What about backgrounds?

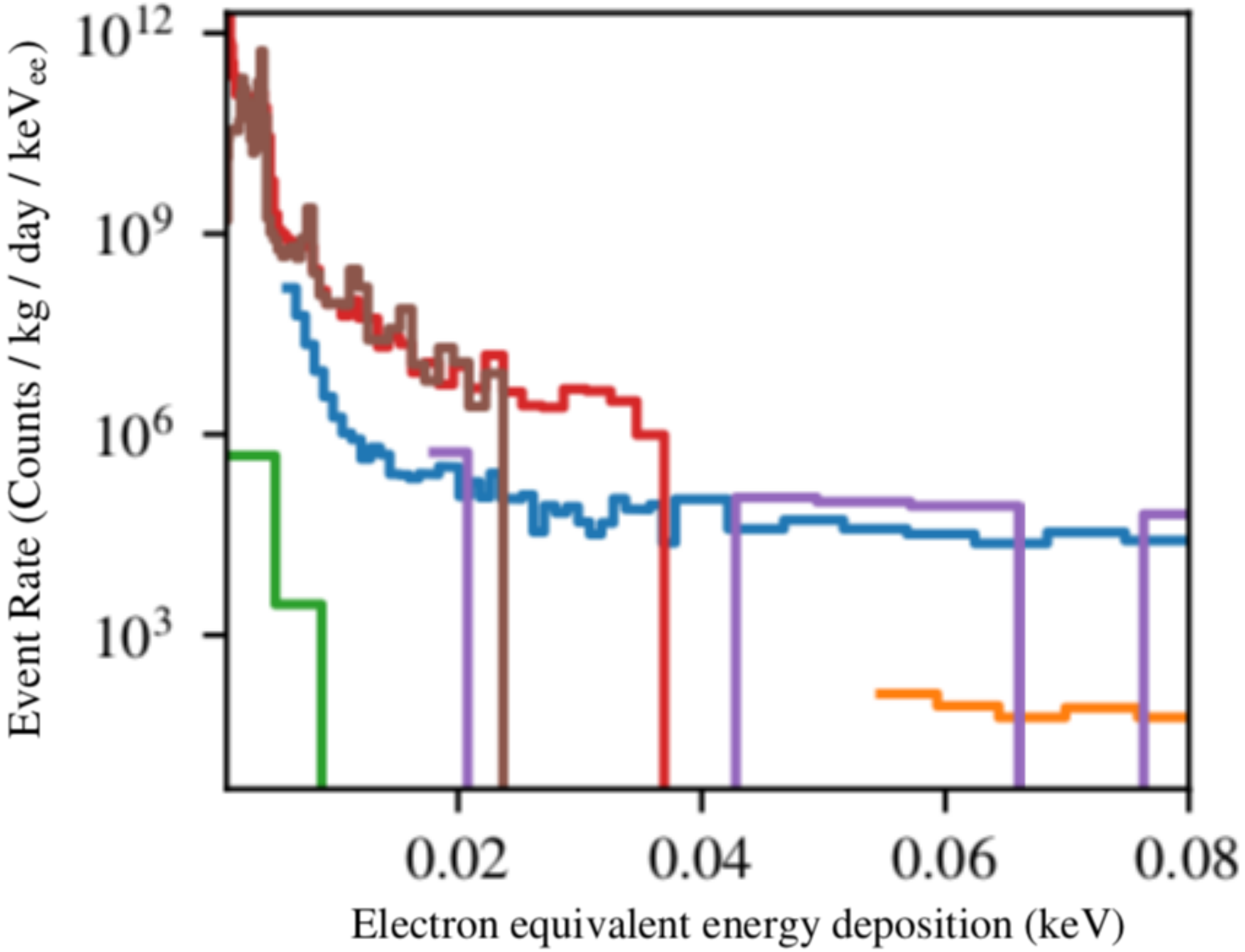


What about backgrounds?

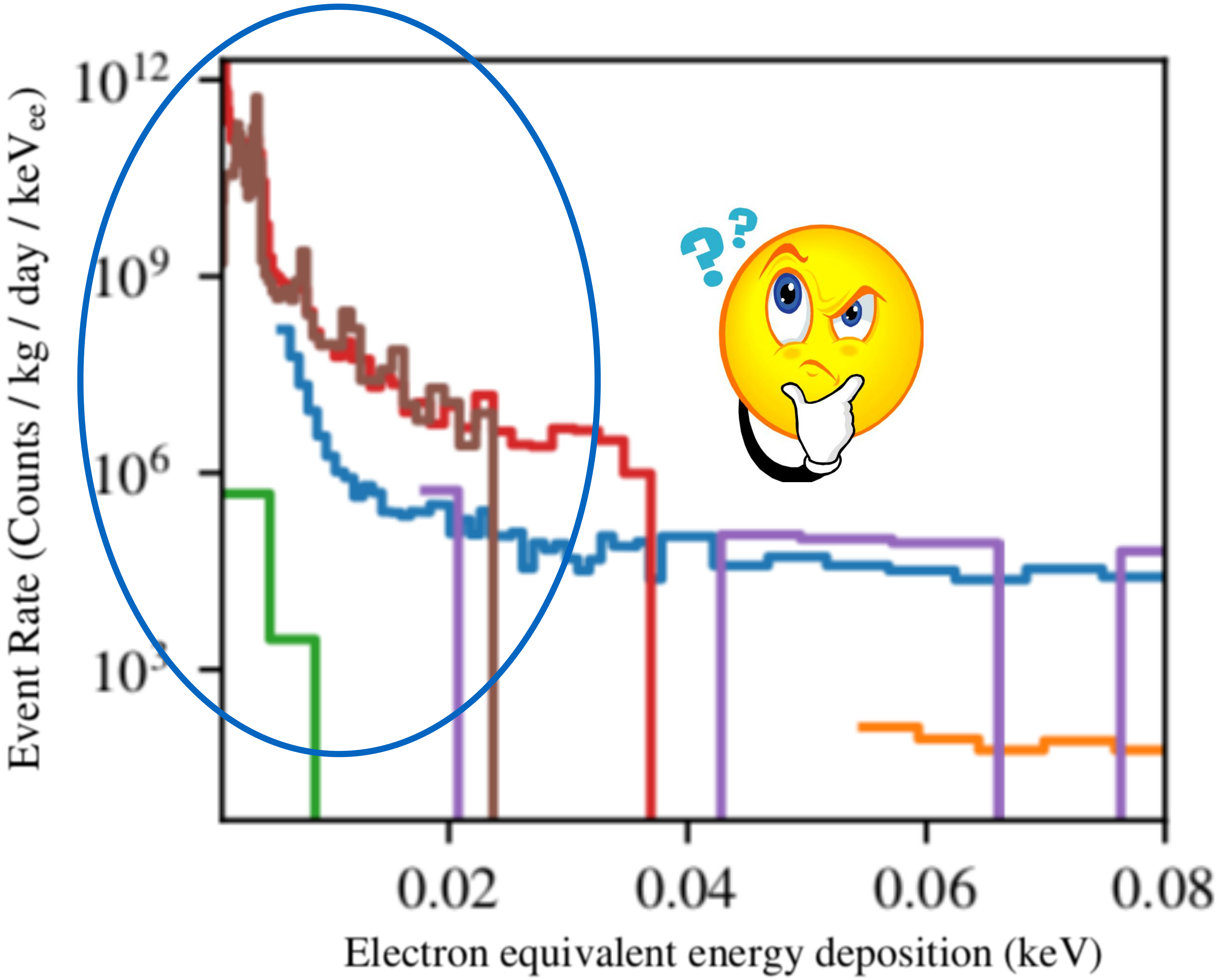
Backgrounds are important and interesting!



Anomalous events in low-threshold dark matter detectors

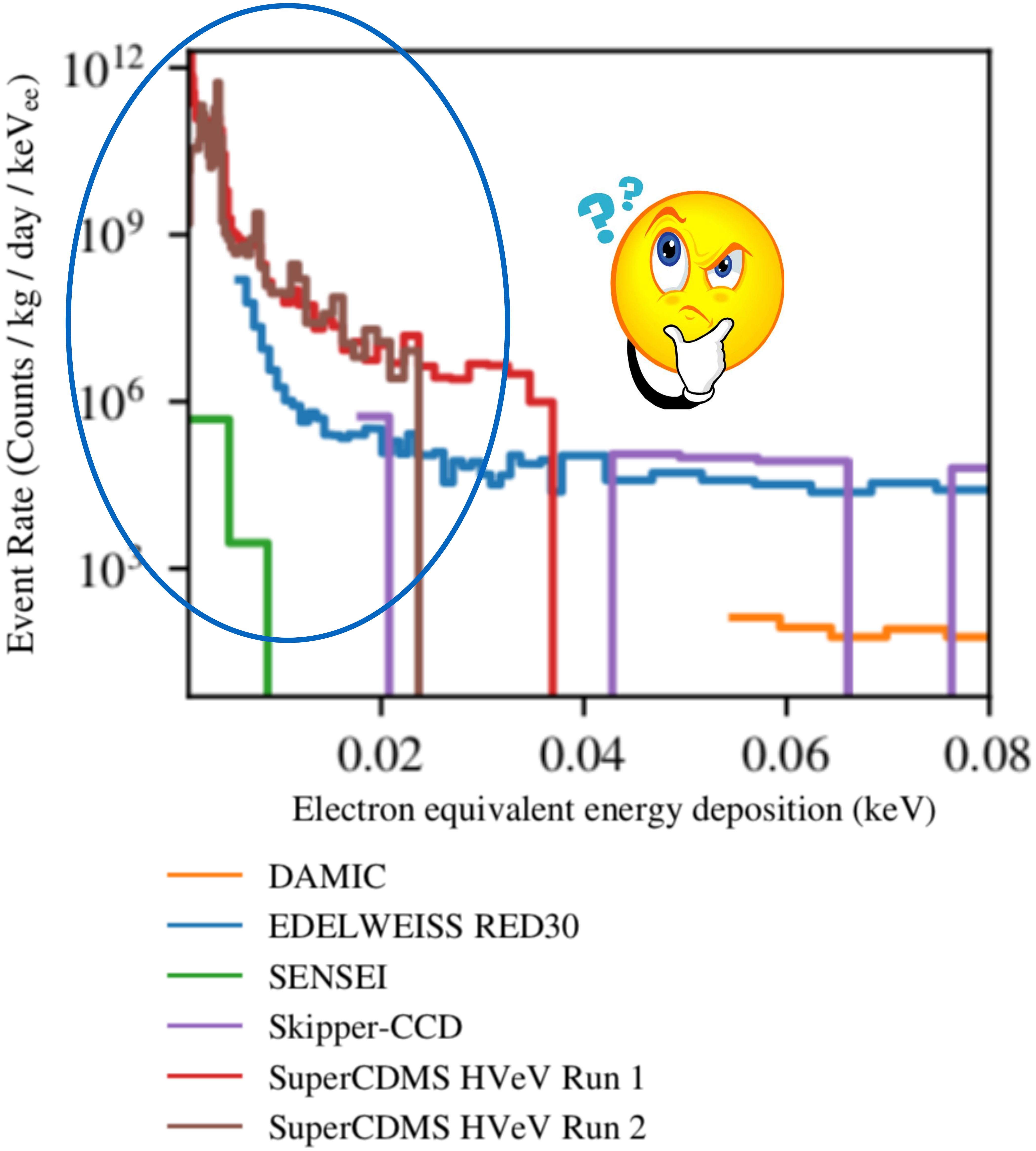


Anomalous events in low-threshold dark matter detectors



- Excess events are near the threshold
- Cannot be explained by known sources

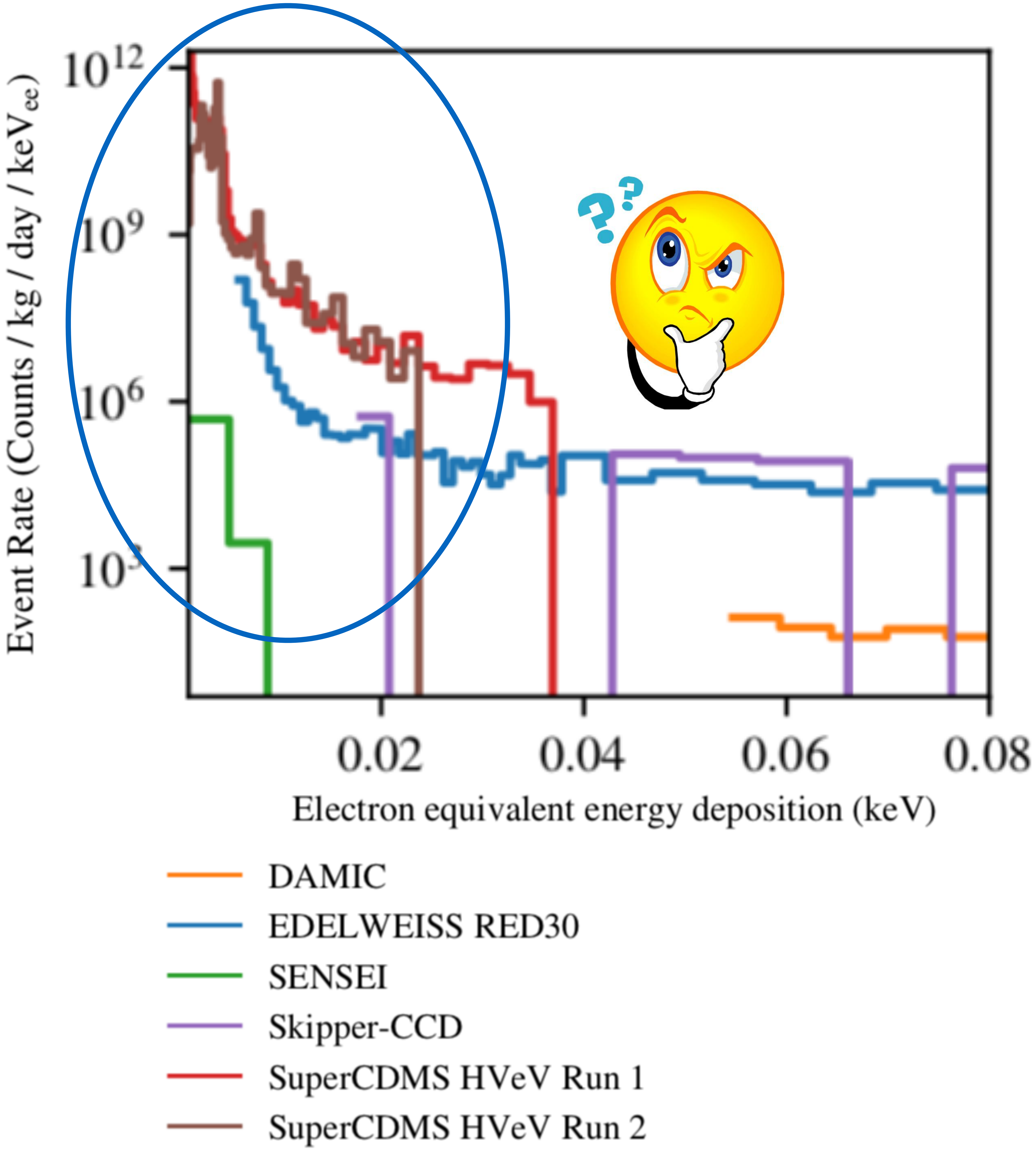
Anomalous events in low-threshold dark matter detectors



Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Anomalous events in low-threshold dark matter detectors



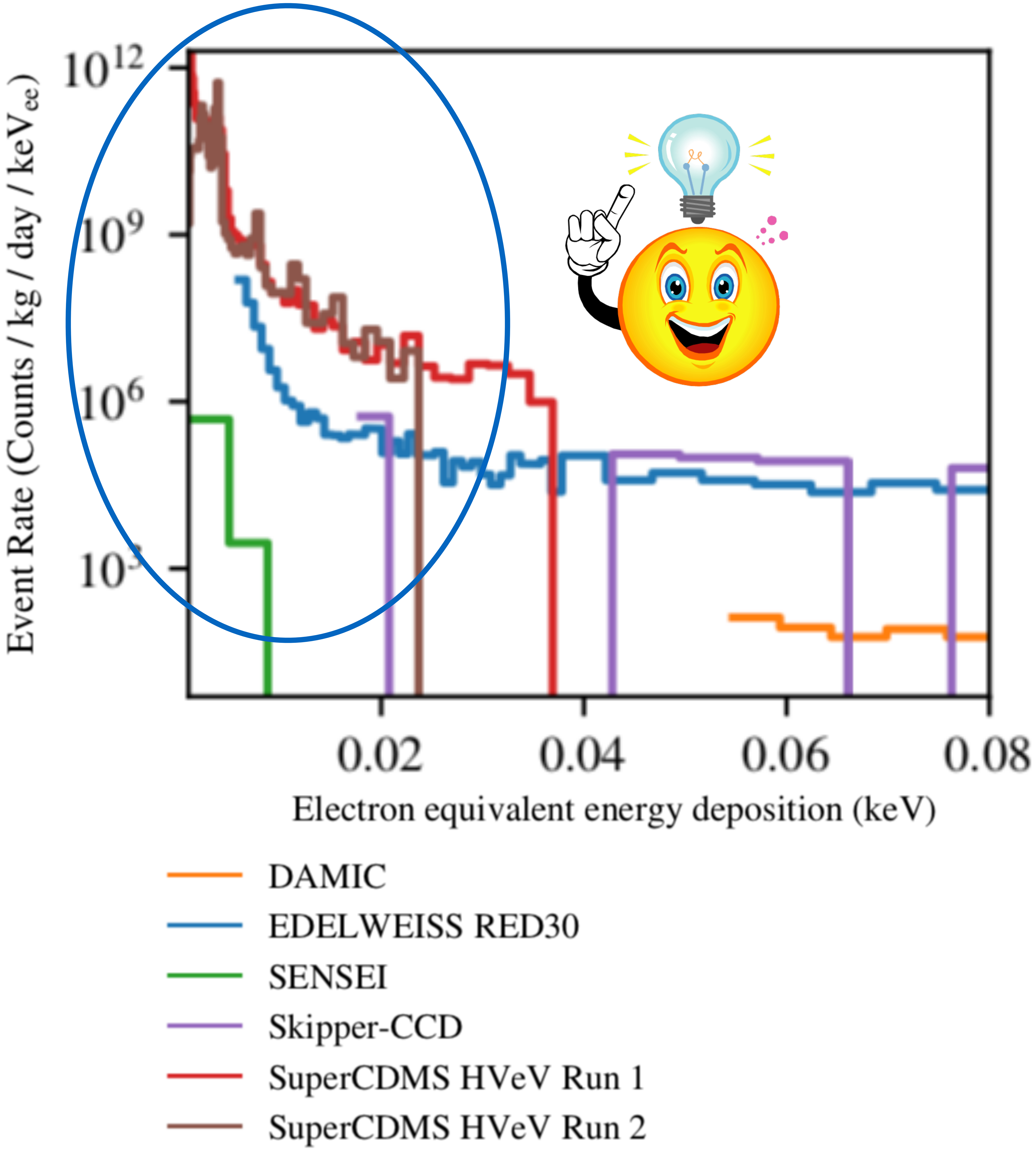
Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Probably not DM

Kozaczuk, Lin, *PRD*, 2020

Anomalous events in low-threshold dark matter detectors



Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Probably not DM

Kozaczuk, Lin, *PRD*, 2020

Those are likely unexplored backgrounds!

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRX*, 2022

Abbamonte, Baxter, Kahn, Krnjaic, Kurinsky, Mandava, Wagner *PRD*, 2022

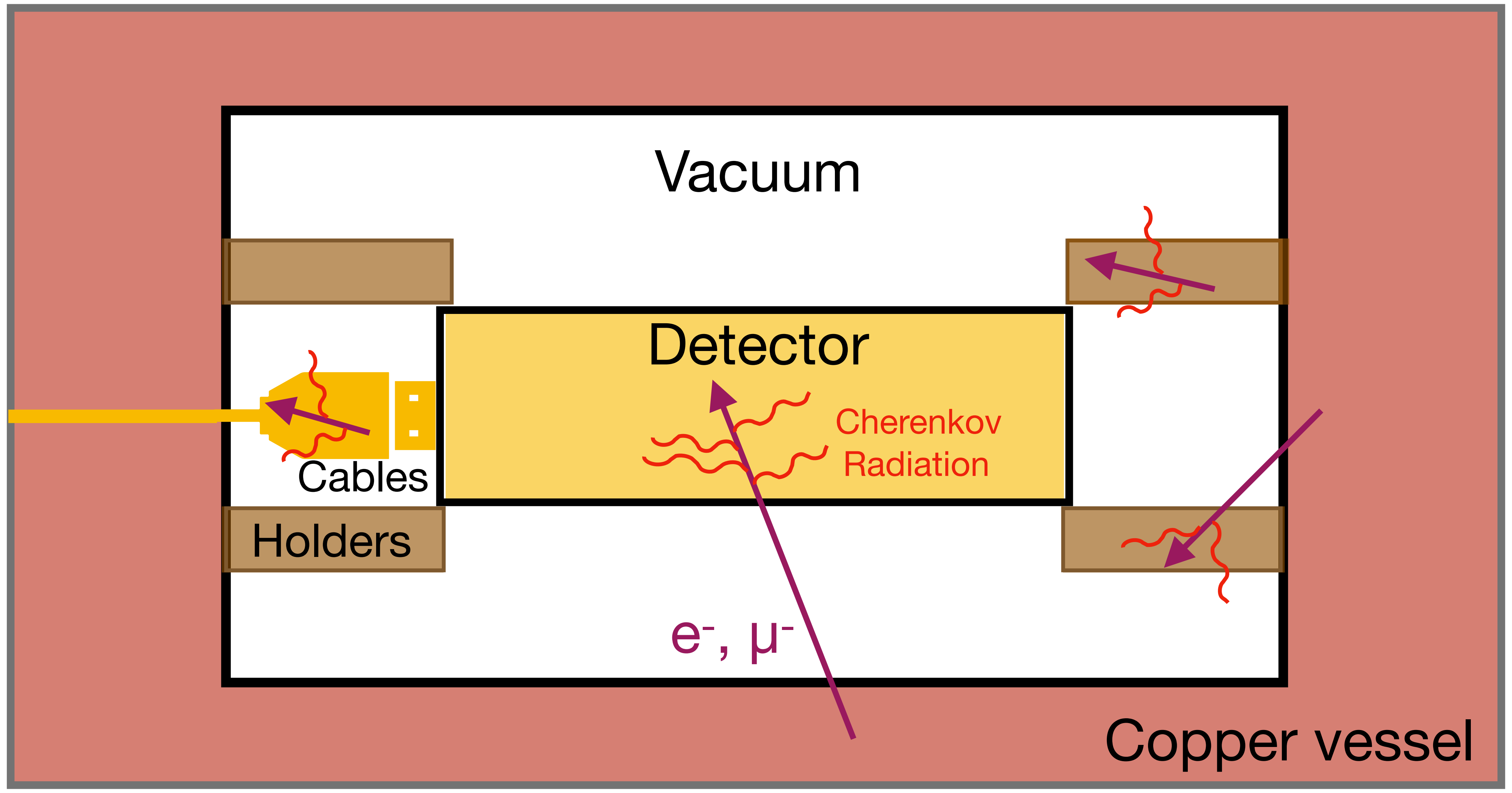
SuperCDMS, *PRD* 2022

EXCESS Workshop Report, 2022

Unexplored low energy backgrounds

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRX*, 2022

Cherenkov radiation can mimic dark matter signals!

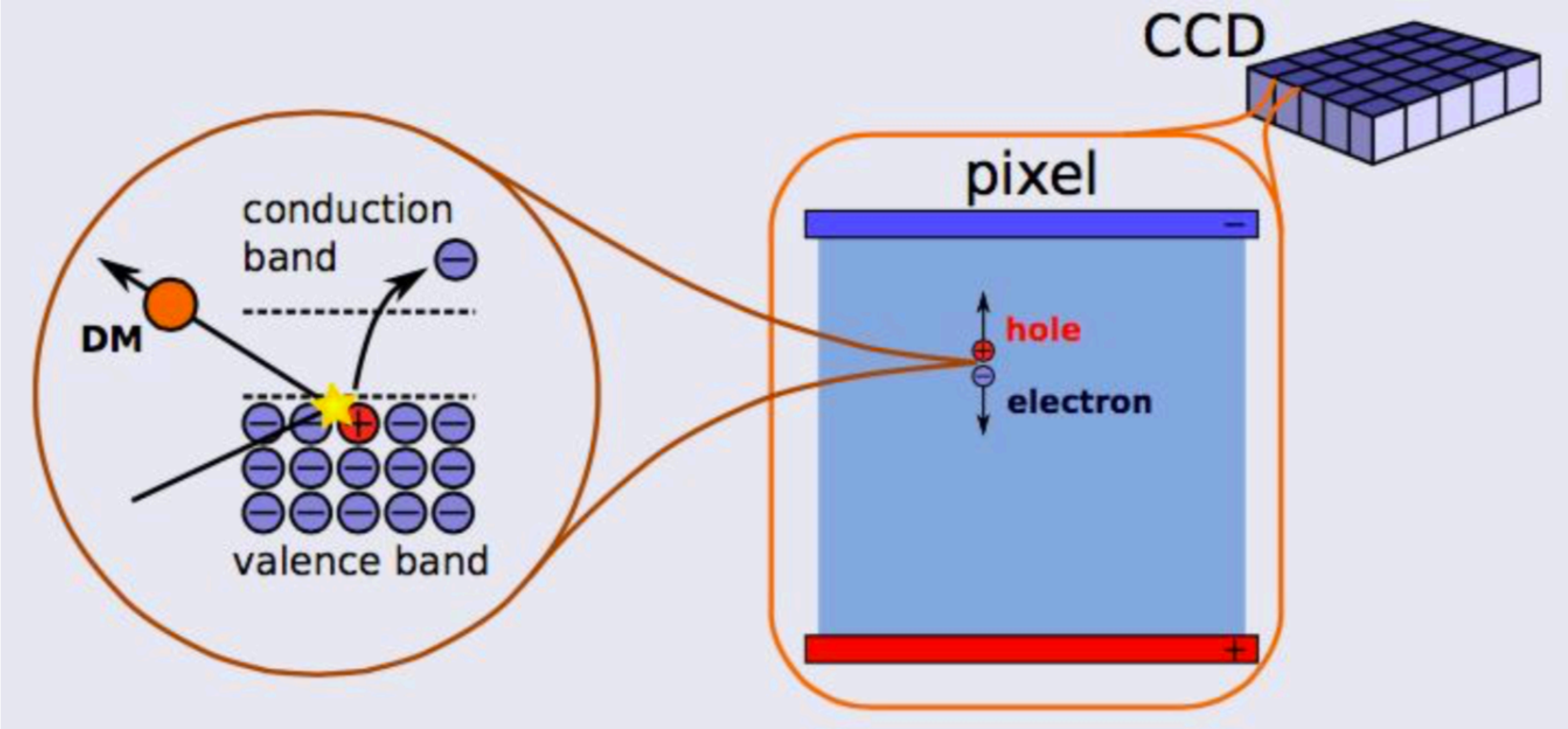


Cherenkov radiation inside detector ⇒ SENSEI excess

Cherenkov radiation from holders ⇒ SuperCDMS HVeV excess

SENSEI experiment

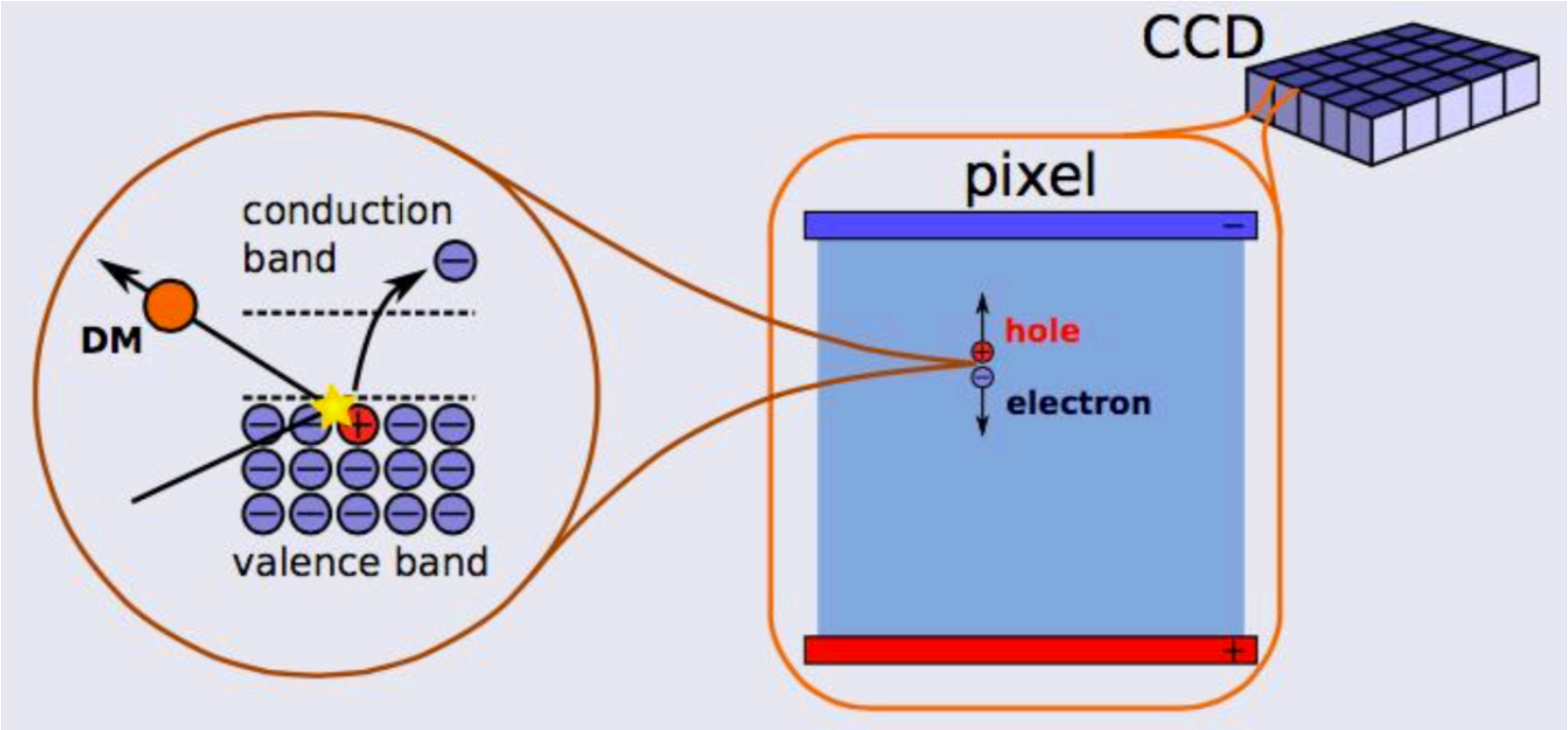
Look for electron-hole pairs in skipper CCD



Expected DM signal: one or few electrons per pixel

SENSEI experiment

Look for electron-hole pairs in skipper CCD



Expected DM signal: one or few electrons per pixel

SENSEI image (half of one quadrant)

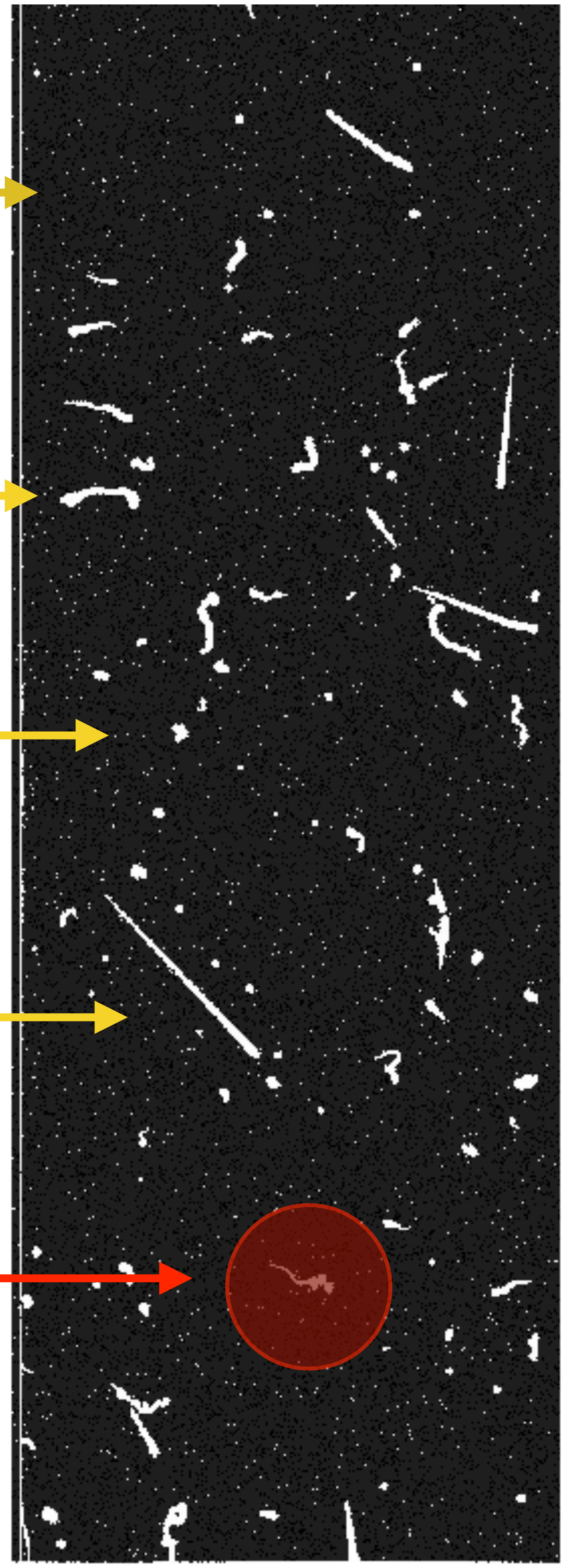
1e events

High energy electrons

X ray

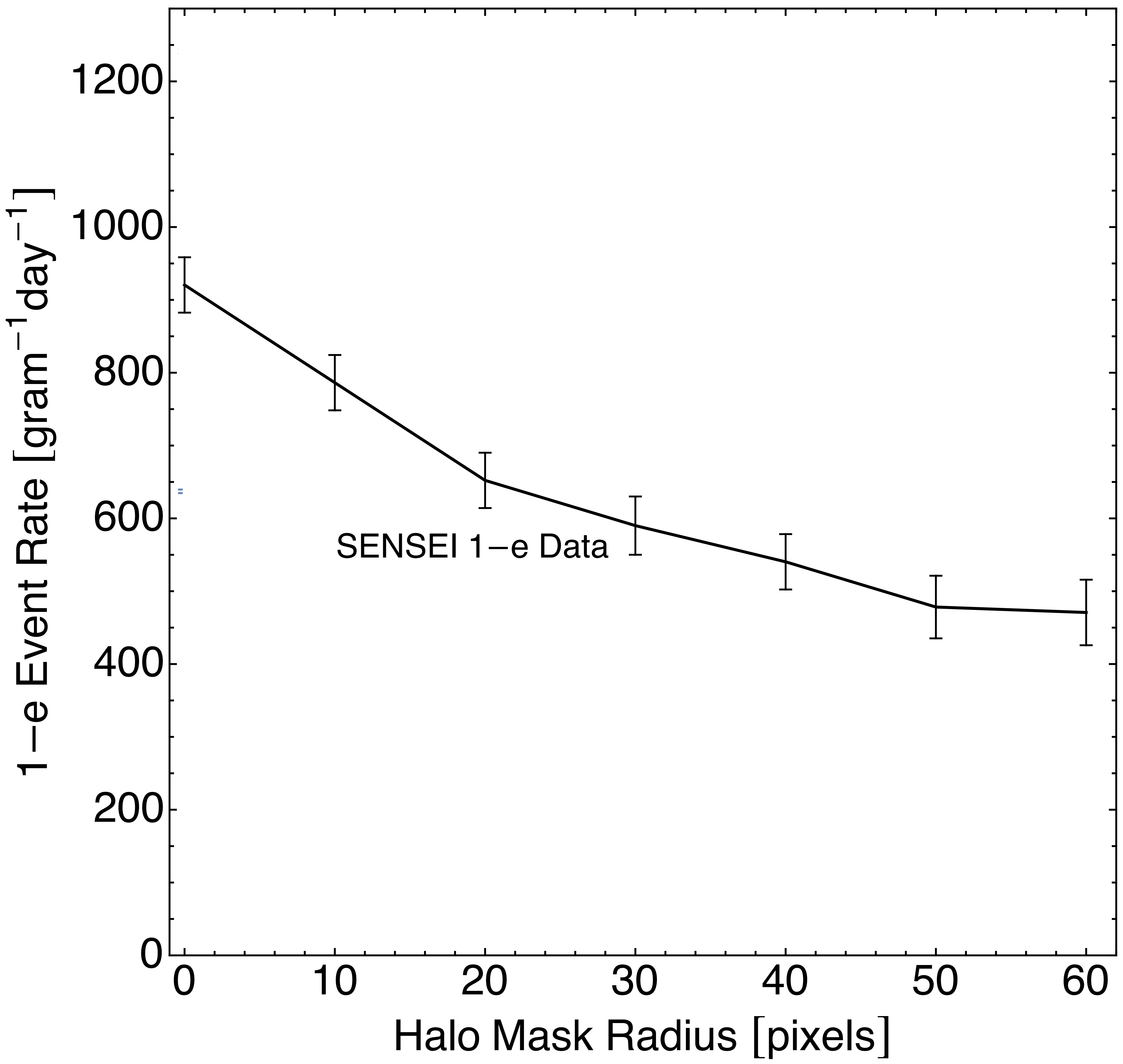
Muons

Analysis cut: Halo mask



Simulation results

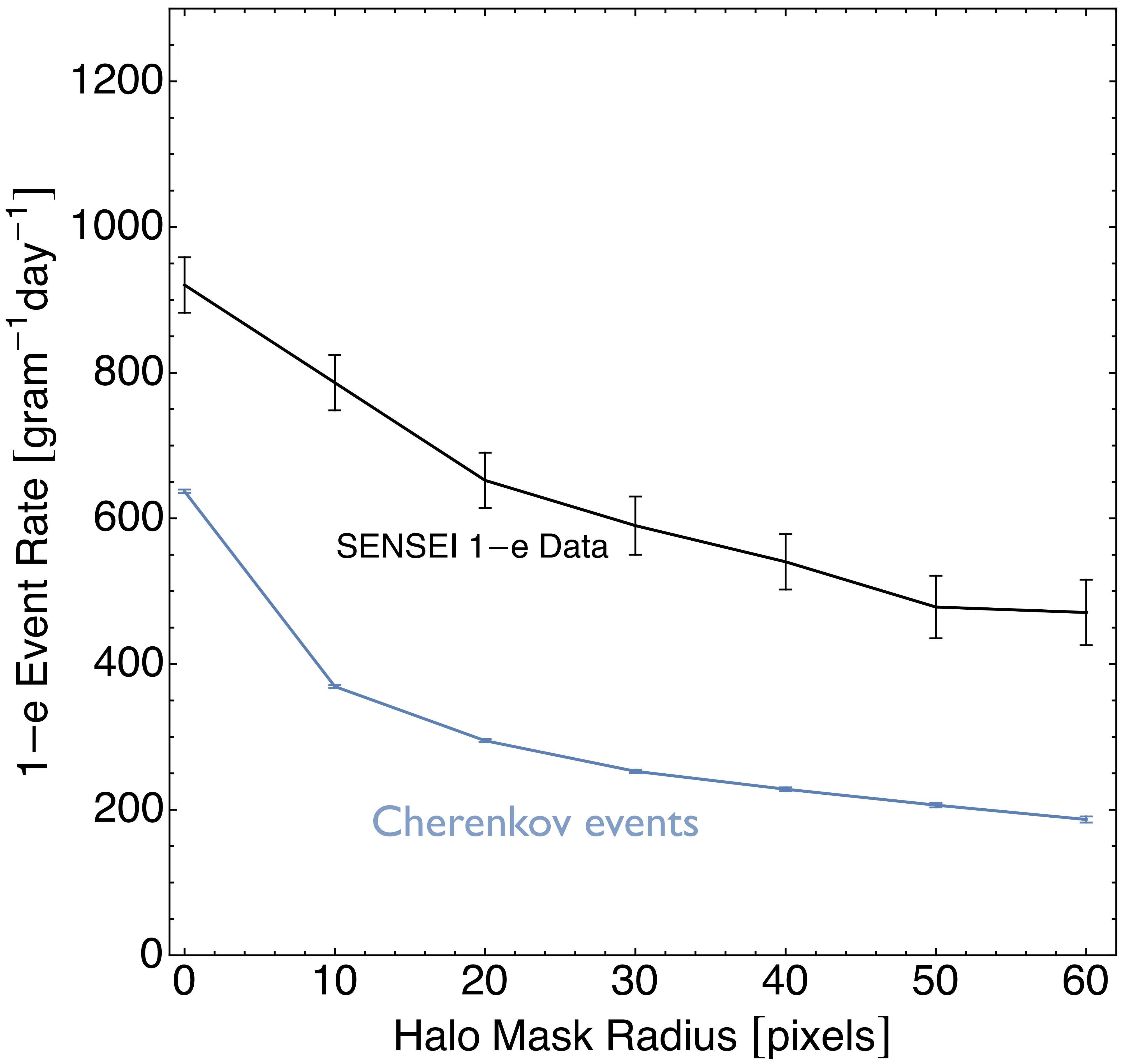
PD, Egana-Ugrinovic, Essig, Sholapurkar, (*in prep)*



SENSEI 1e events:

Simulation results

PD, Egana-Ugrinovic, Essig, Sholapurkar, (*in prep)*



SENSEI 1e events:

- Cherenkov events contribute 1/3 of total,

  explain the observed shape of the spectrum

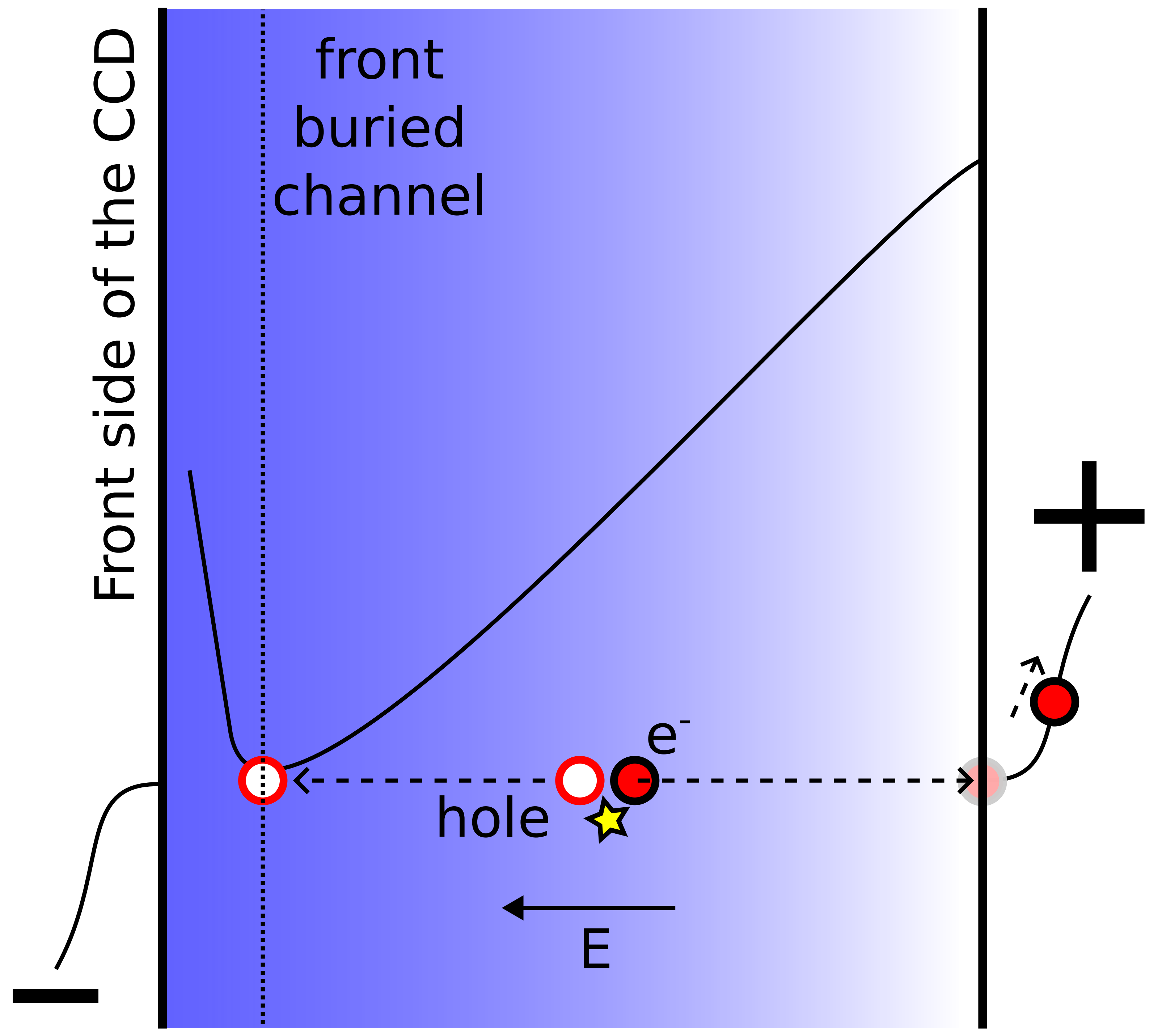
- The remaining 2/3 is spatially uniform

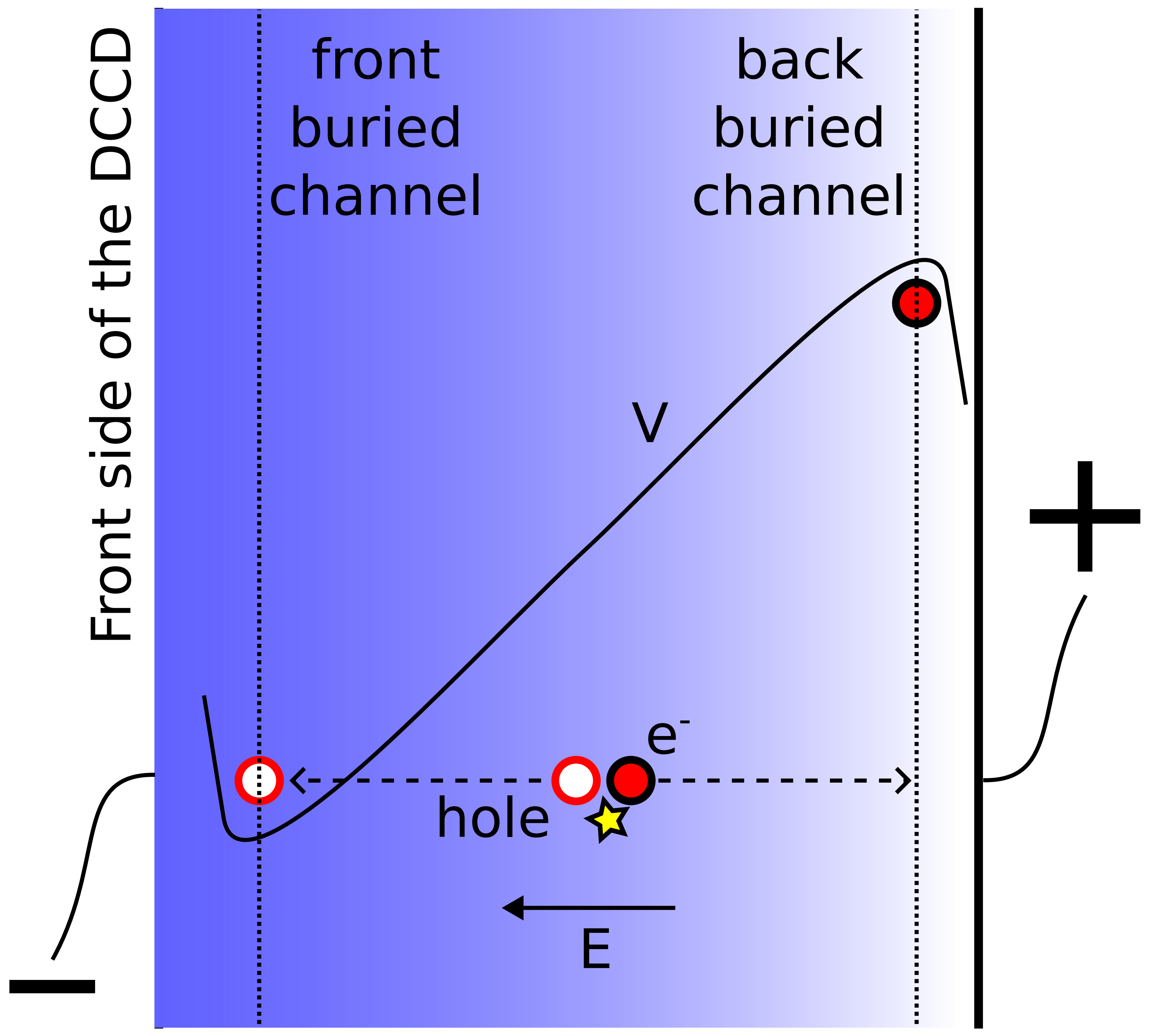
  possible sources:
  surface dark current from defects, charge leakage…

How to reduce surface dark current ?

Dual-Sided CCD

Tiffenberg, **PD**, Egana-Ugrinovic, Essig, Fernandez-Moroni, Sofo Haro, Uemura (arXiv:2307.13723)



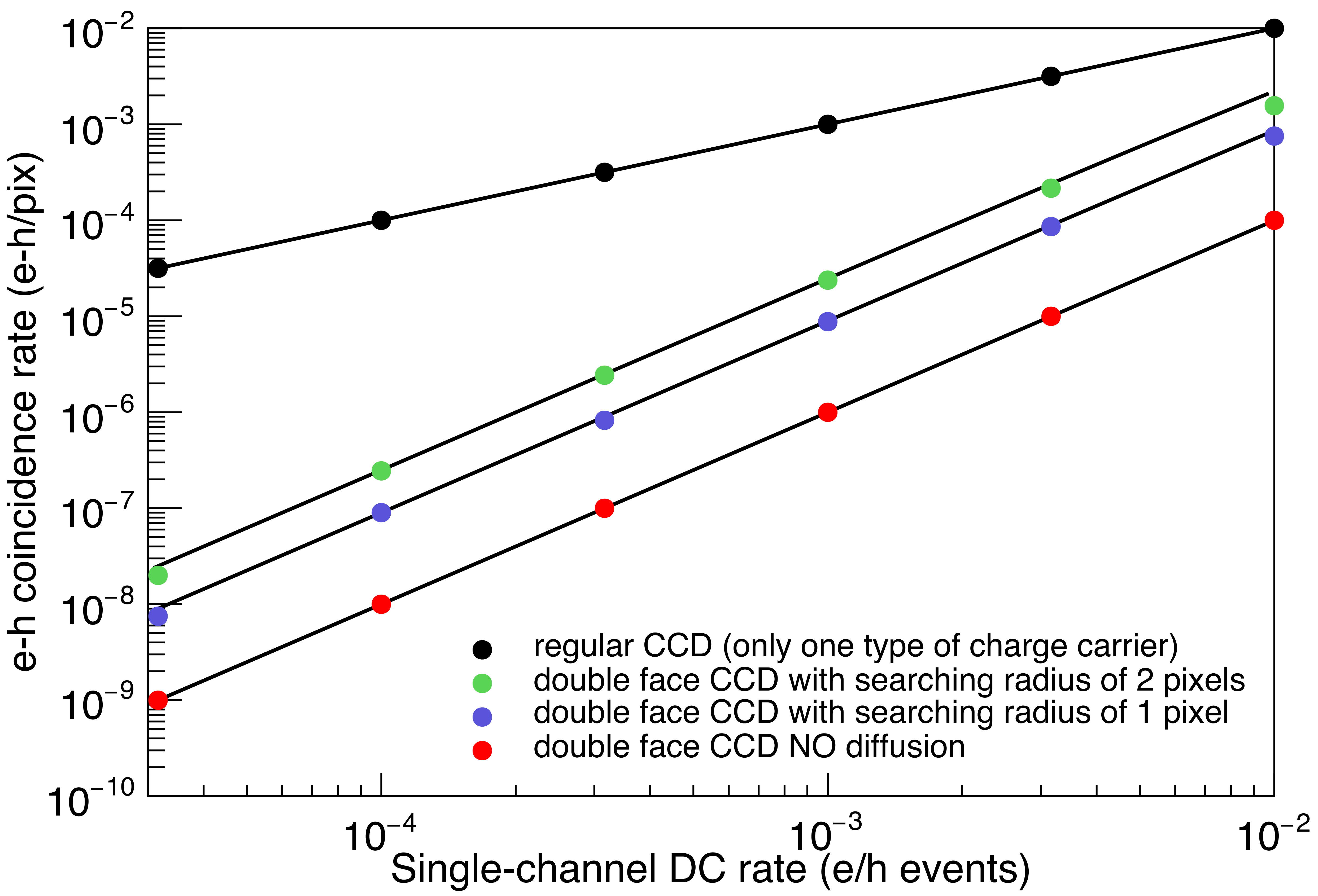


Regular CCD collects only one charge

DCCD collects both charges at two sides

Surface DC are only collected in one side of the image

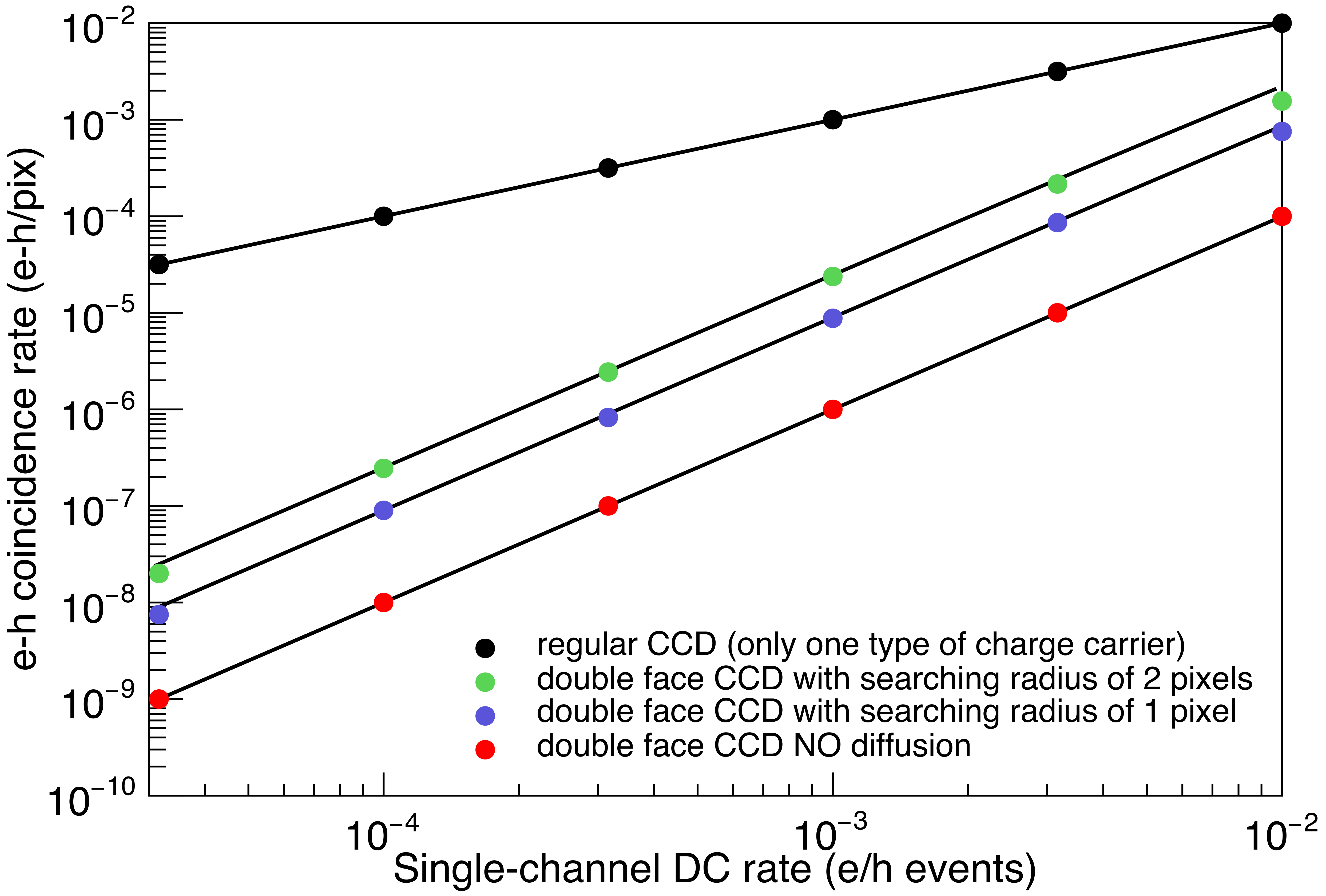
Surface DC rejection in timed-exposure mode

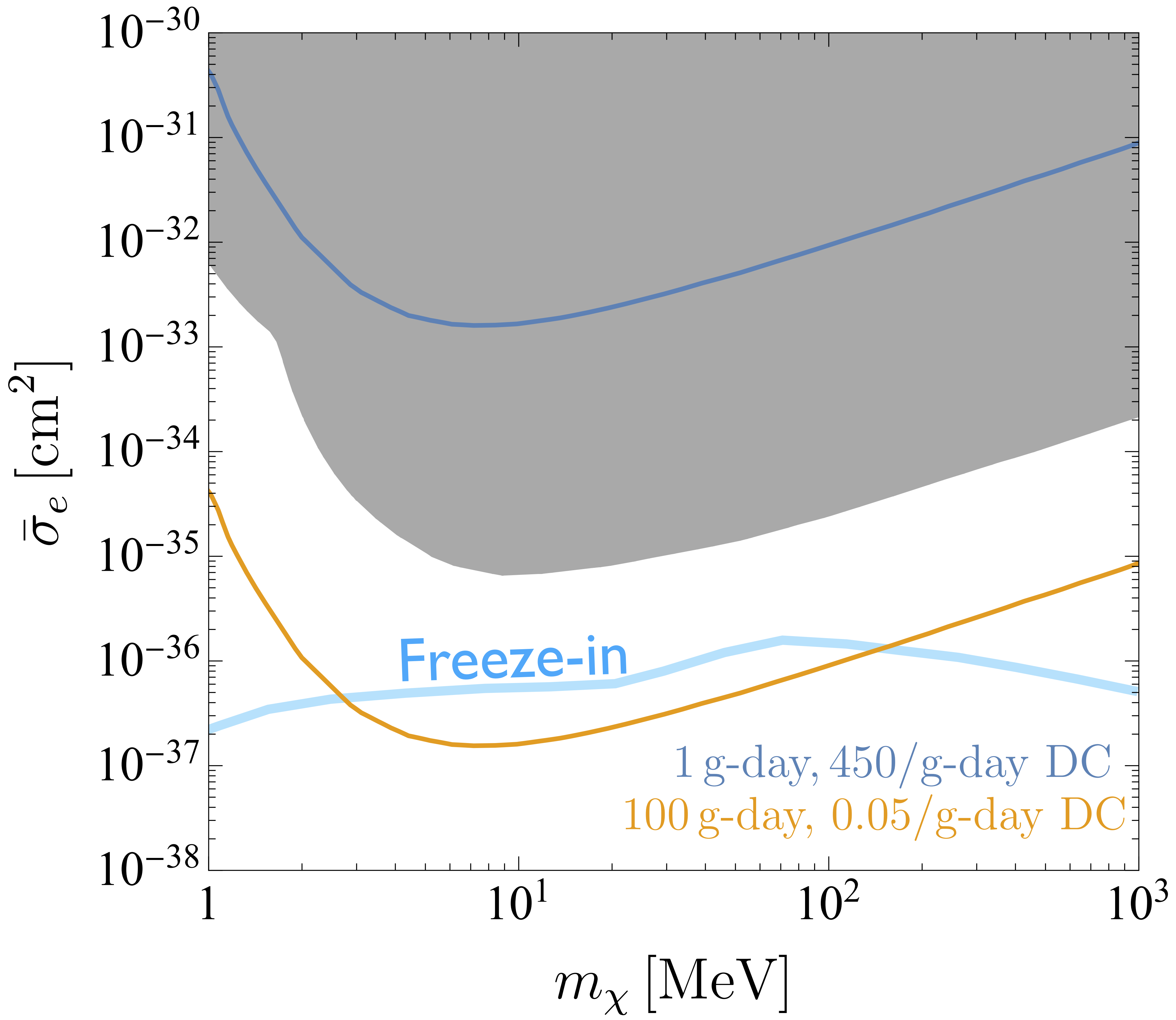


SENSEI 1e dark current: $O(10^{-4})$ e/pixel/day

dark current rejection: $O(10^{-3})$-$O(10^{-4})$

Surface DC rejection in timed-exposure mode

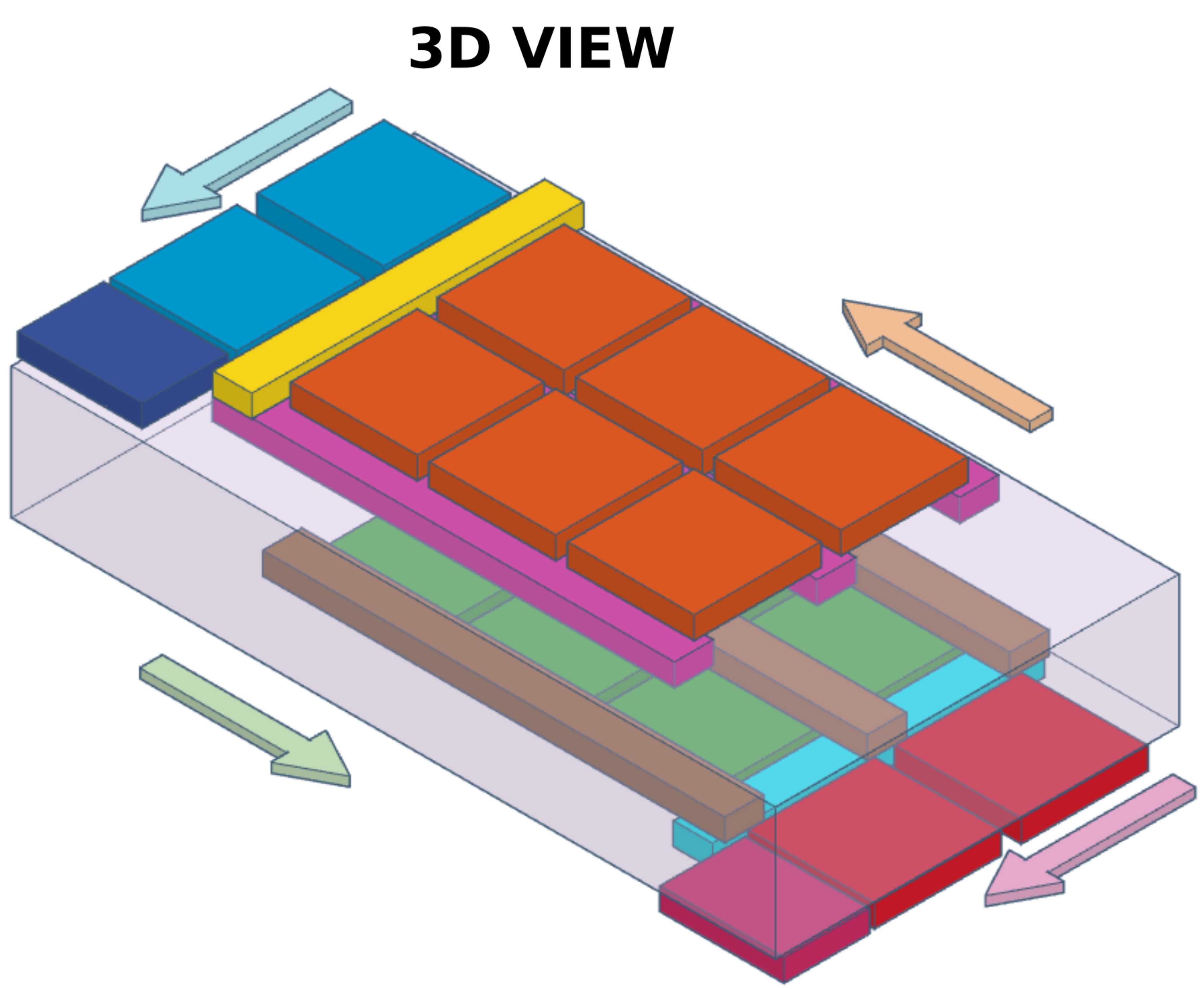


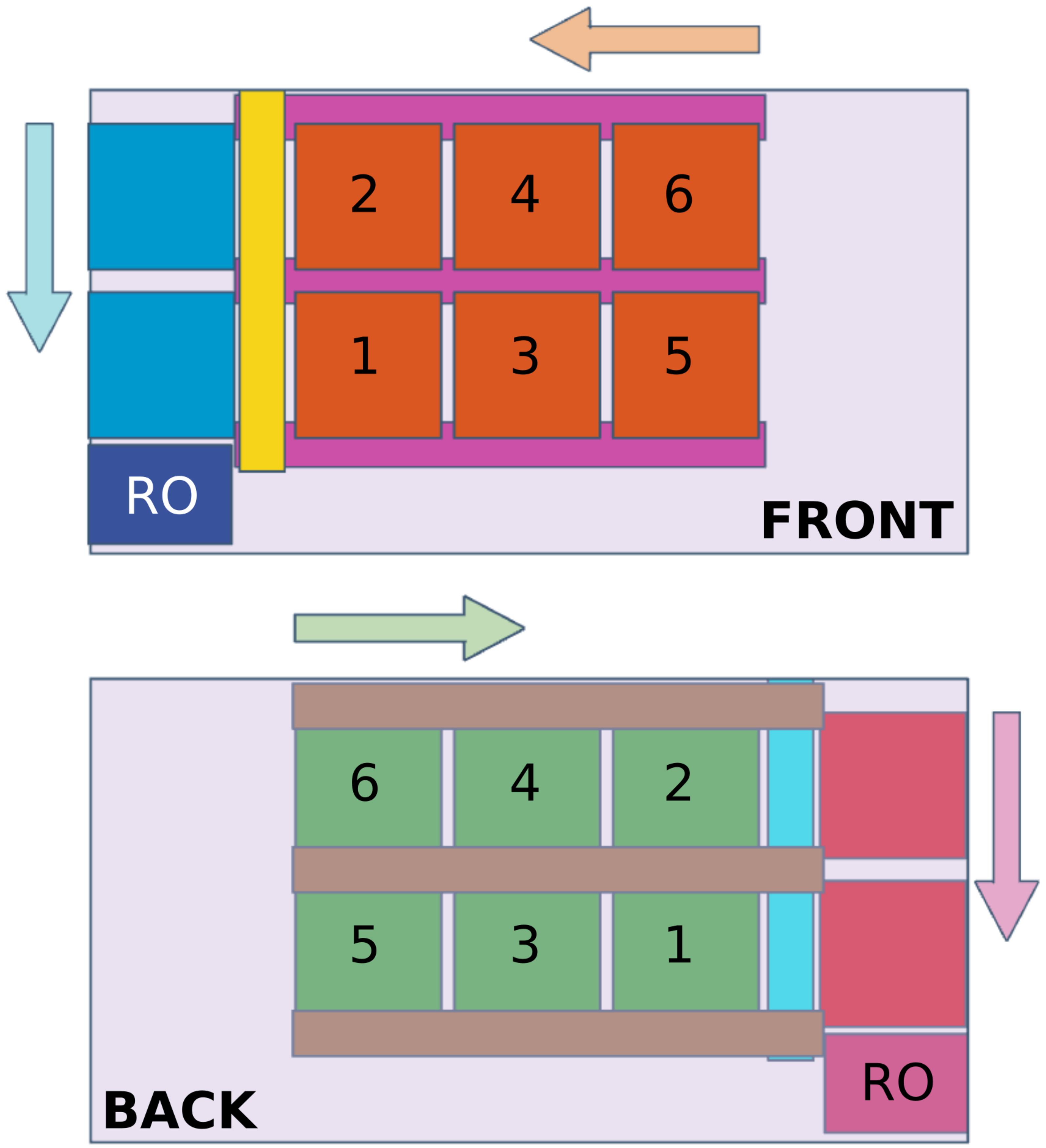


SENSEI 1e dark current: O(10^{-4}) e/pixel/day

dark current rejection: O(10^{-3})-O(10^{-4})

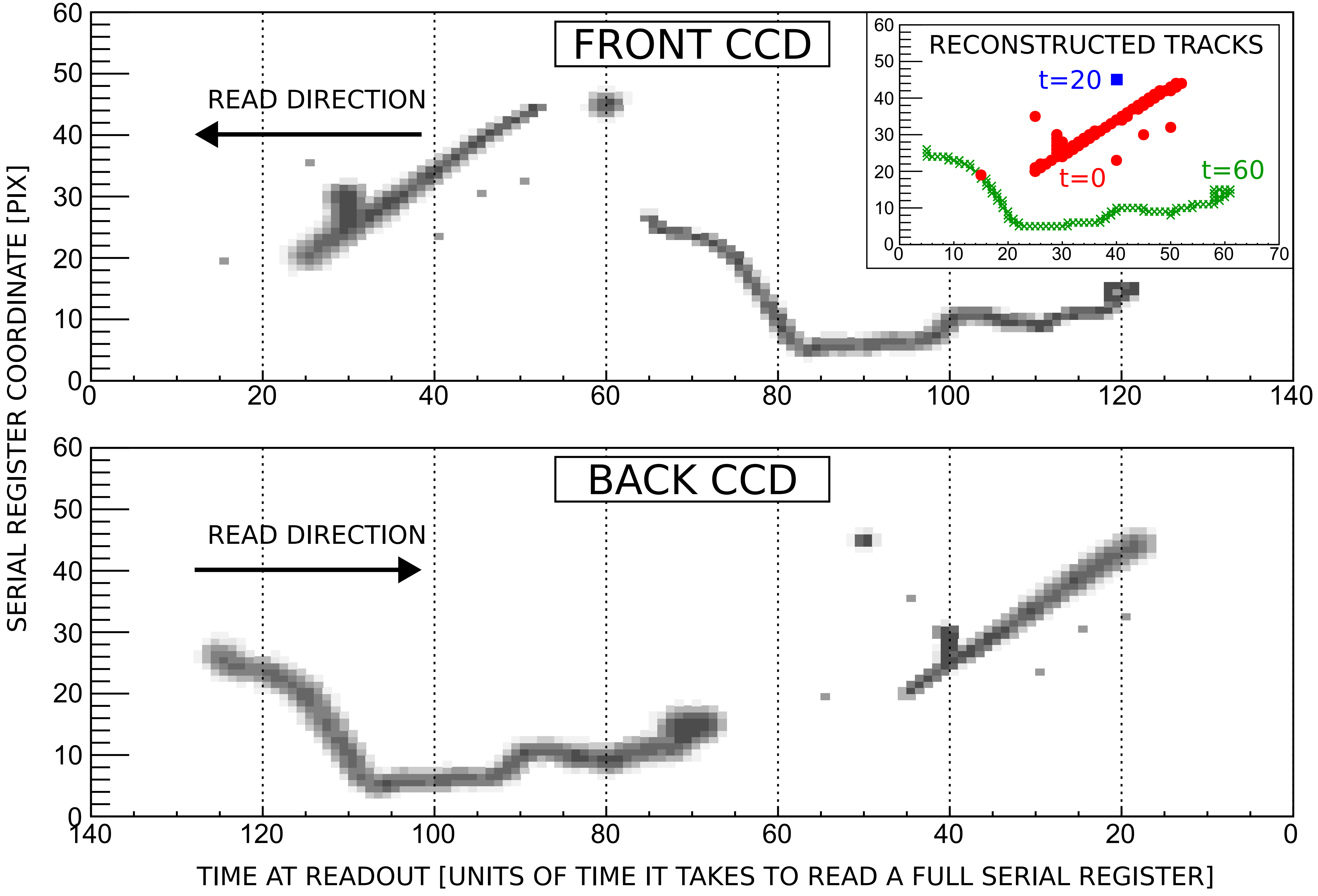
Improved timing resolution: continuous readout mode



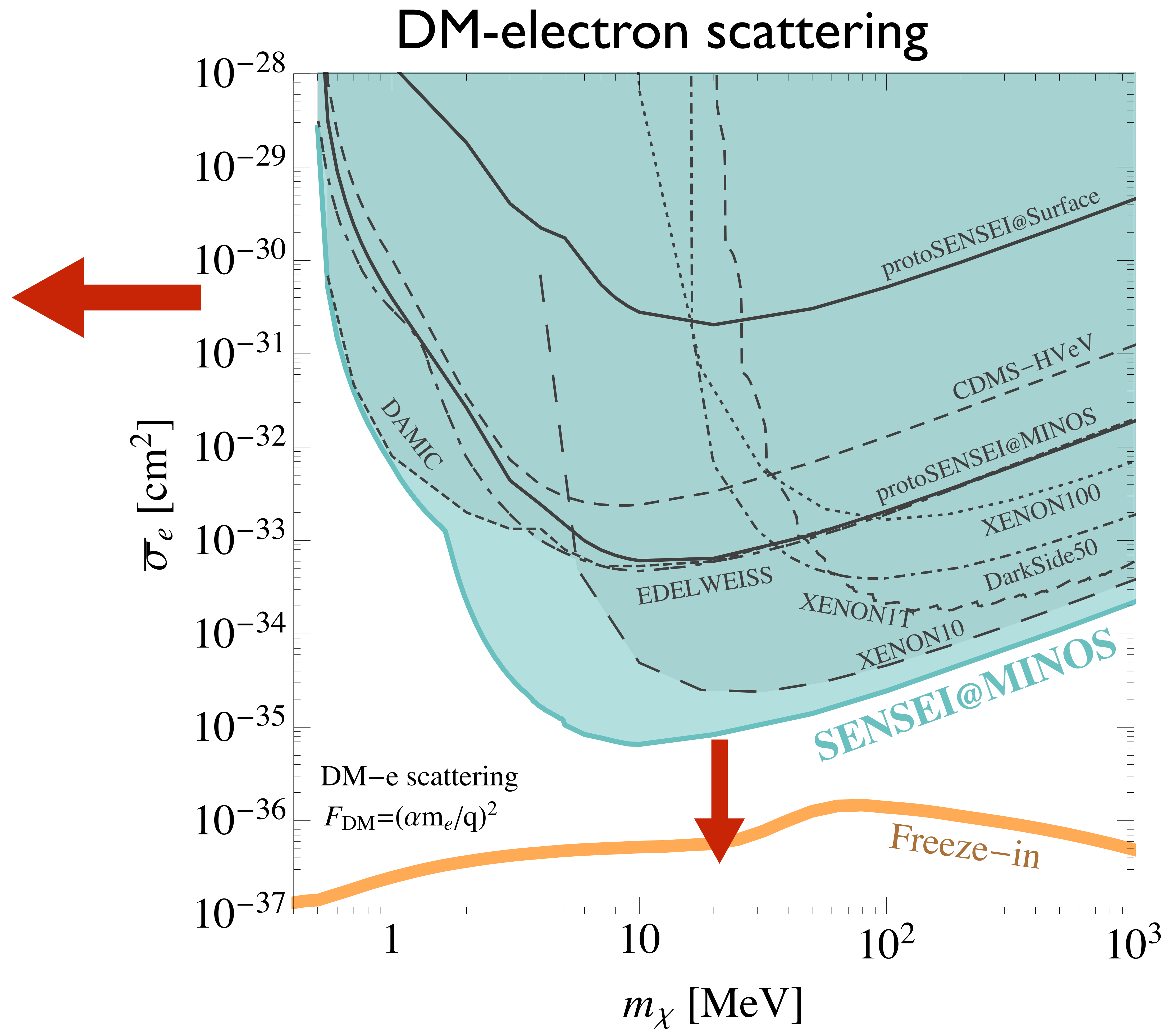


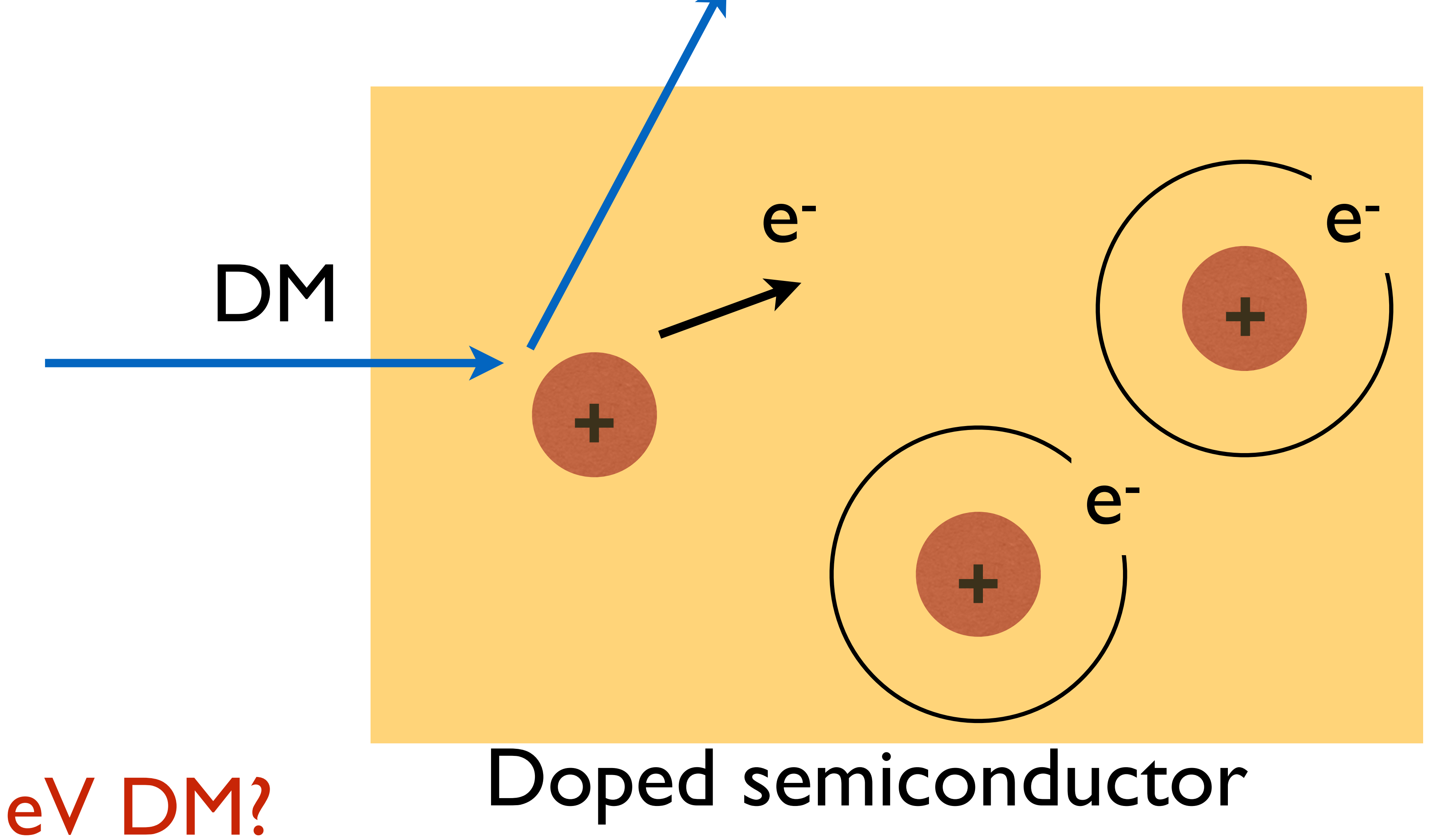
	Regular CCD	DCCD
Timing resolution	T_{CCD} ~1s	$T_{CCD}/N_{\rm row}$ ~ms

Improved timing resolution: continuous readout mode



Conclusions





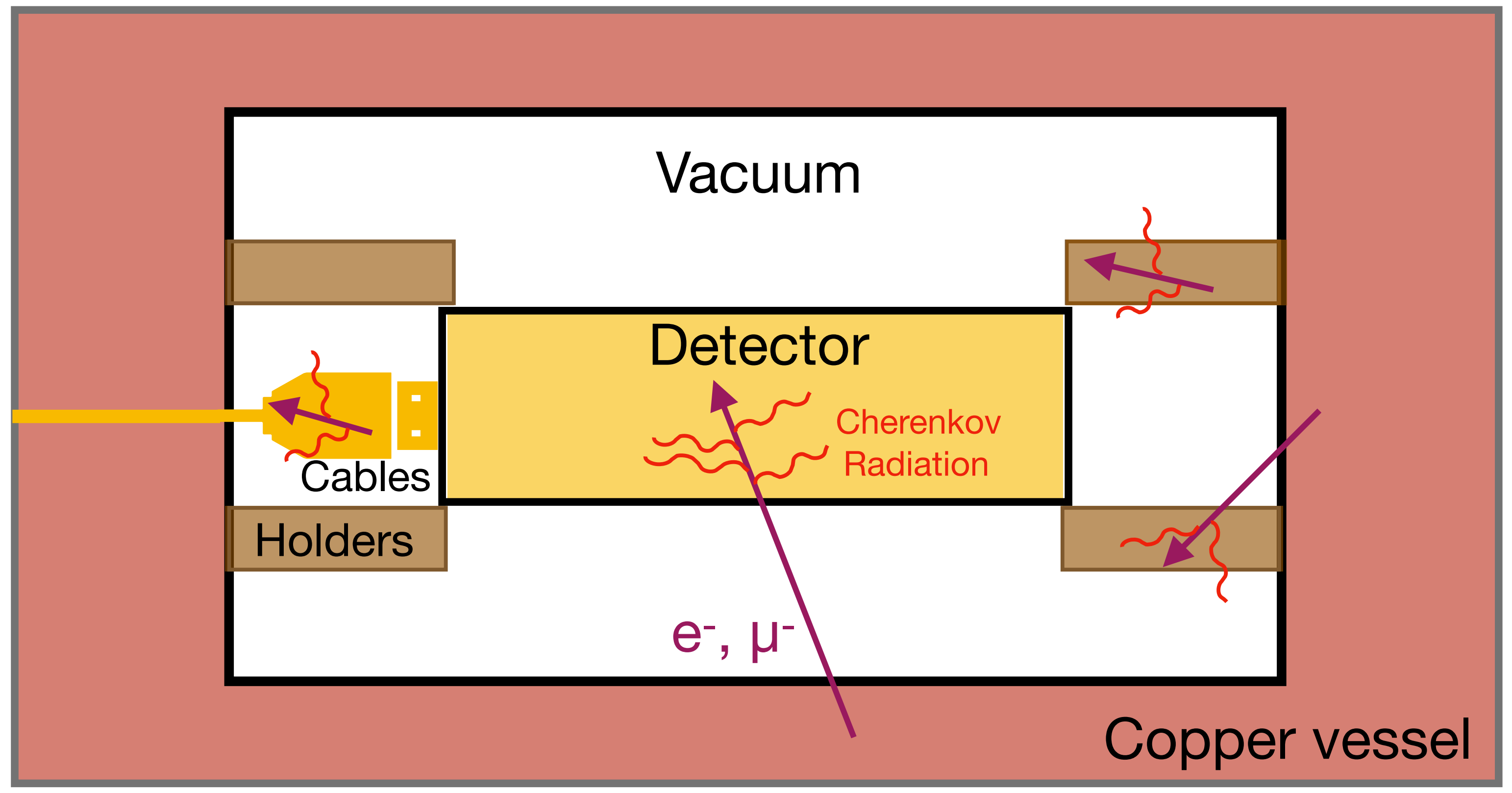
how to probe sub-MeV DM?

doped semiconductors

how to probe Freeze-in theory target?

need to understand backgrounds

DCCD can reduce some of backgrounds



Thank you

Summary of current experiments

Experiment	Location	Cherenkov contribution	Domiant Source of Cherenkov
SENSEI	~100m underground	likely dominant with radiative recombination	ambient high energy particles hitting detector
SuperCDMS HVeV	surface	likely dominant	ambient high energy particles hitting holders
EDELWEISS	~1800m underground	subdominant	radioactivity from impurities in holders
CRESST	~1400m underground	vetoed everything near the detector is instrumented	-

Good spatial resolution: SENSEI

Good timing resolution: SuperCDMS HVeV, EDELWEISS, CRESST

High ambient backgrounds: SENSEI, SuperCDMS HVeV

Low ambient backgrounds: EDELWEISS, CRESST

EDELWEISS and CRESST excess may dominantly come from crystal cracking/microfracture

Probing sub-MeV (sub-eV) DM

Hochberg, Zhao, Zurek, 2015
Schutz, Zurek, 2016
Knapen, Lin, Pyle, Zurek, 2017
Hochberg, Kahn, Lisanti, Zurek, et.al, 2017
Bunting, Gratta, Melia, Rajendran, 2017
D. M. Mei, et,al. 2017
⋮

Target	Signal	Threshold	DM Mass range
Nobel Liquid	electron ionization	~10 eV (atom ionization)	>10 MeV
Semiconductors	eh pairs	~1eV (bandgap)	>MeV
Polar materials	phonon	10-100meV	>10-100 keV
Superconductor	phonon/ quasiparticle	~1meV	>1keV

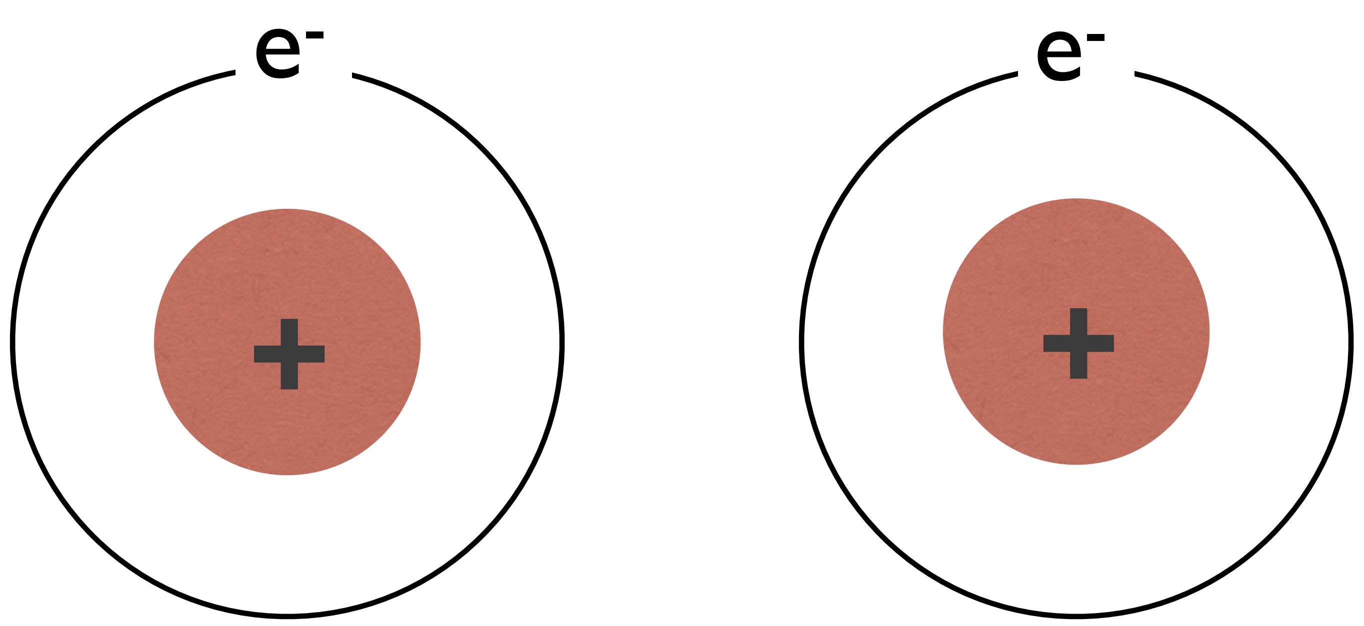
Low threshold can probe low DM masses

Dirac materials, superfluid helium, magnetic bubble chamber, Ge detector with charge amplification …

What is the optimal n_d for DM searches?

Metal-insulator transition

Electrons are localized on dopants

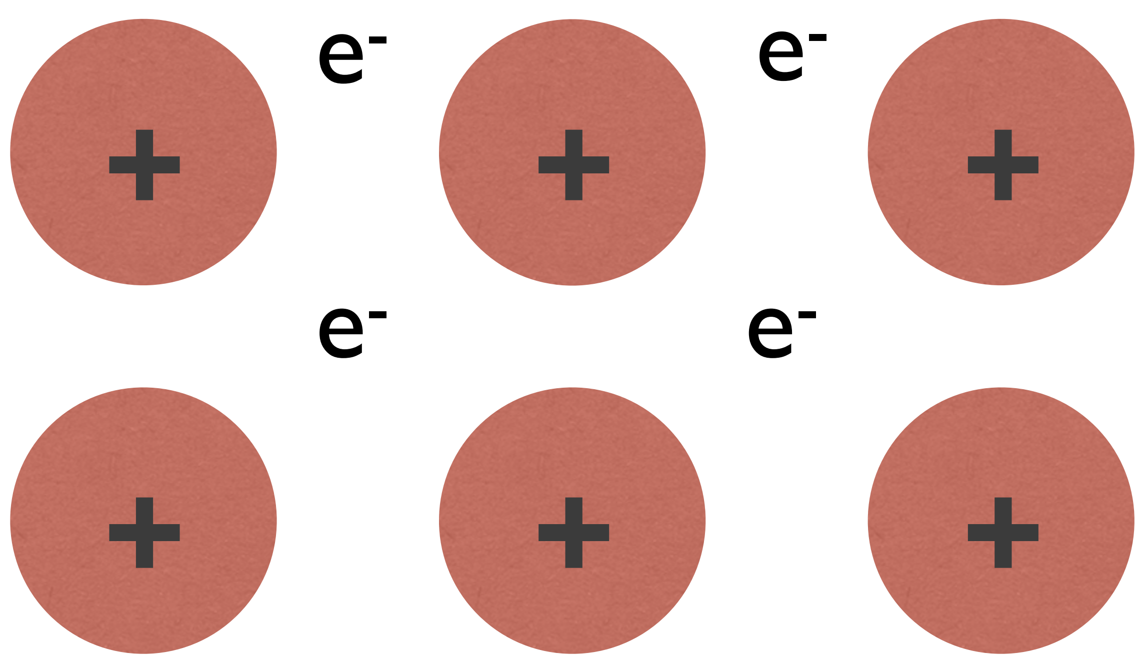


Insulating

$n_{\rm d} < n_c$

Good for DM searches

Electrons are delocalized



Metallic

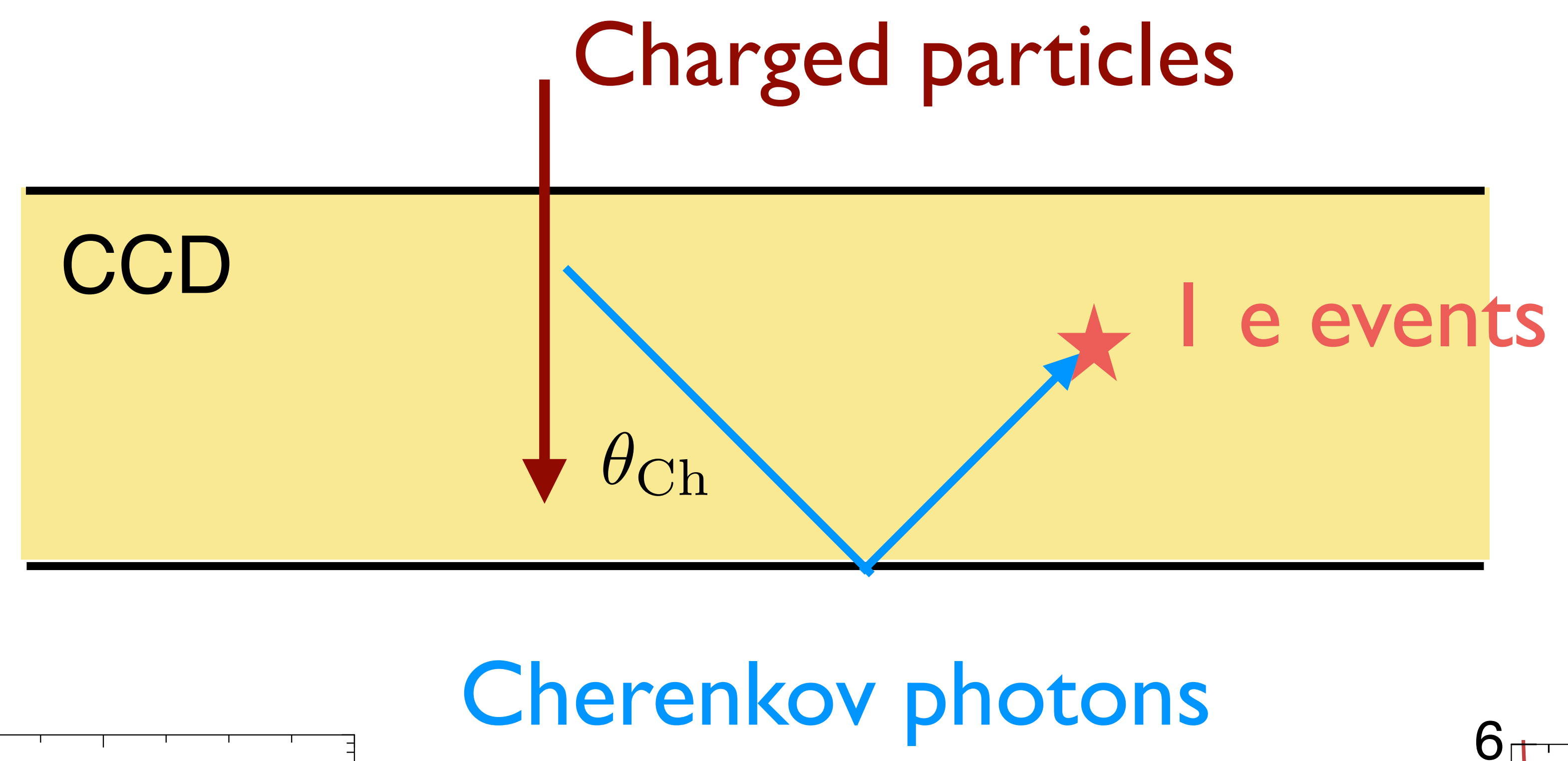
$n_{\rm d} > n_c$

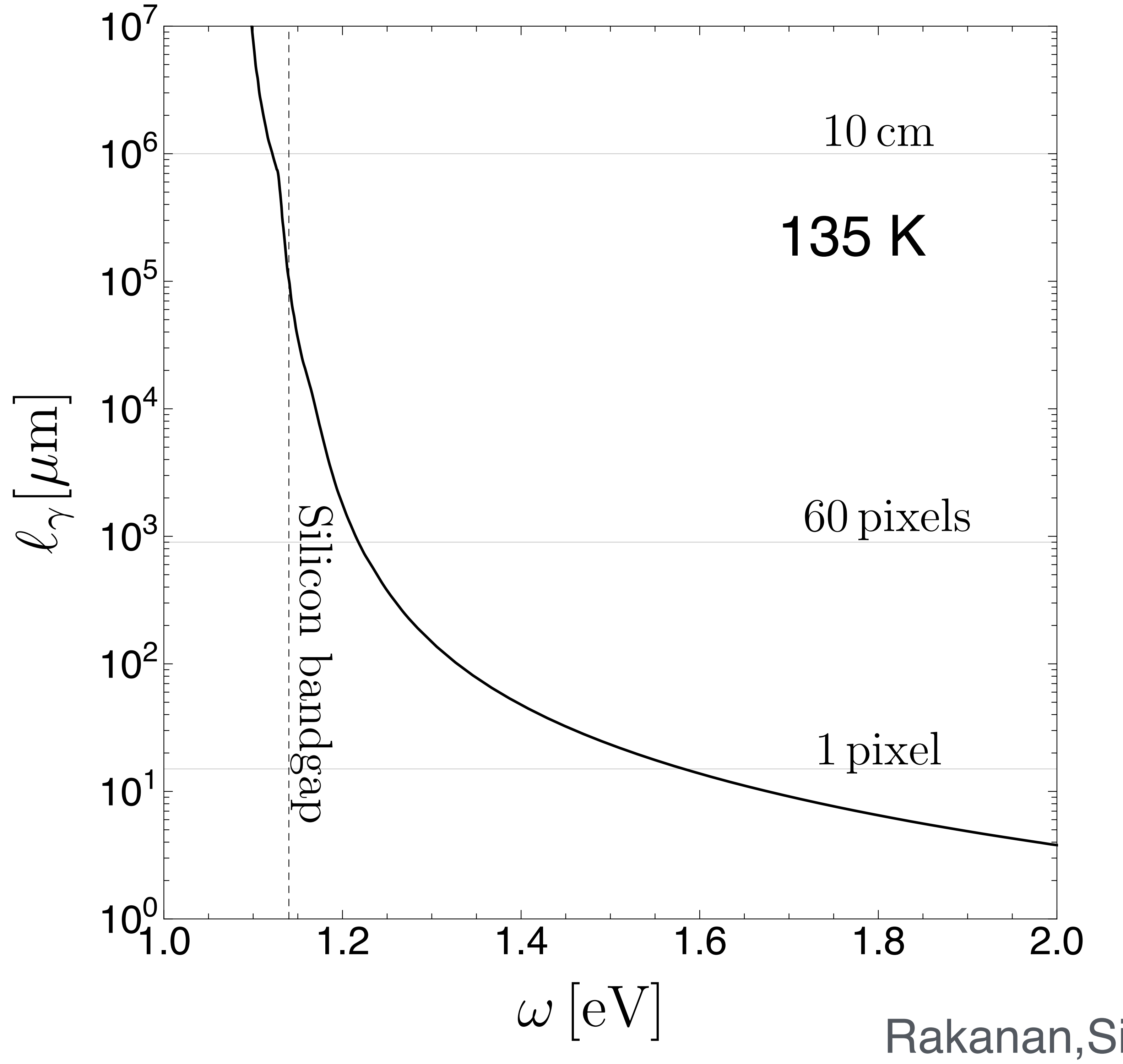
Metallic targets have no gap, hard to control noise

$$(n_c)^{-1/3} \sim a_*$$

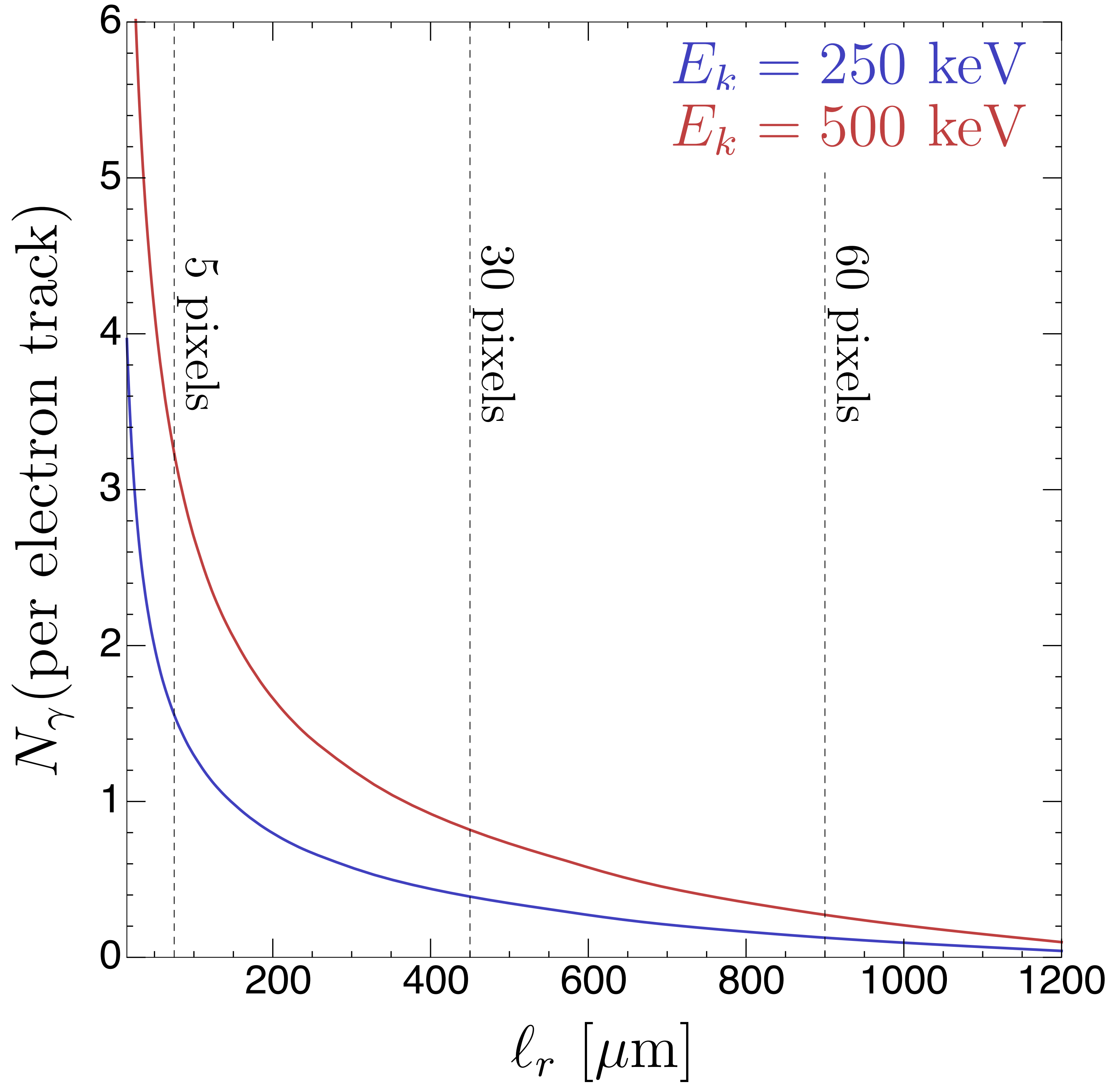
For Phosphorus doped Si: $n_c = 3.5 \times 10^{18} \mathrm{cm}^{-3}$ We choose $1 \times 10^{18} \mathrm{cm}^{-3}$ for DM reach projection

Cherenkov radiation in SENSEI





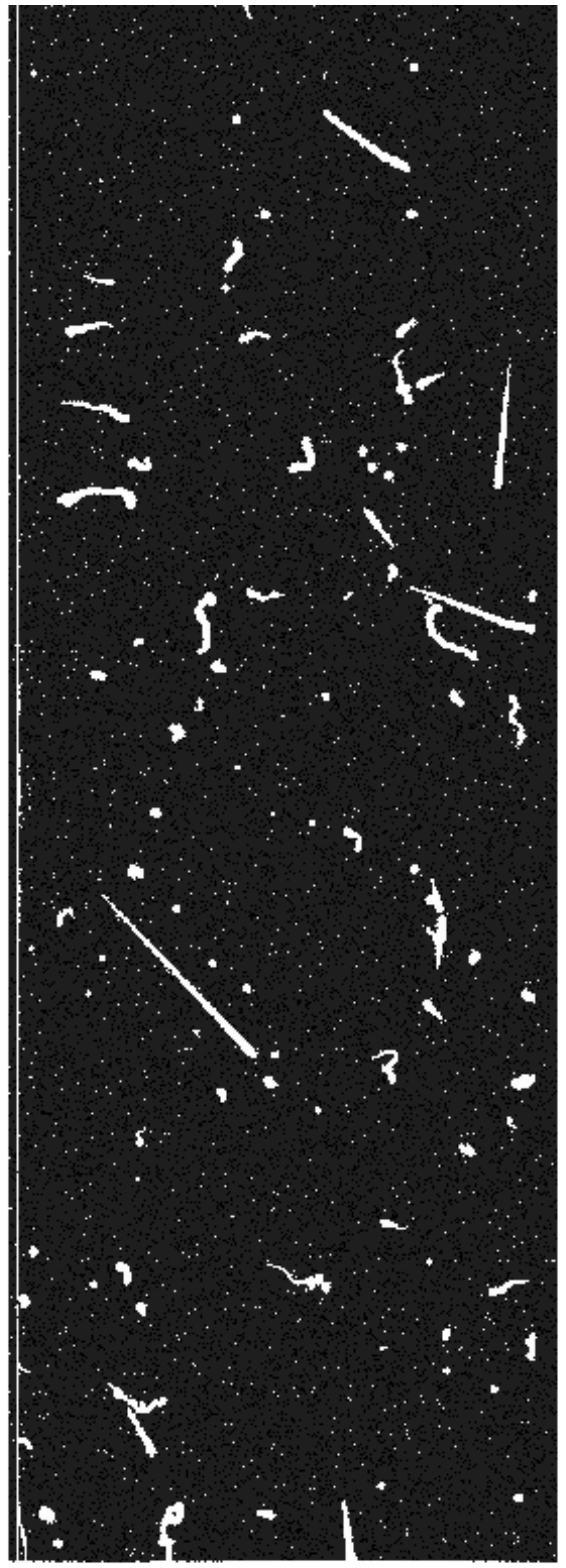
Rakanan,Sinhg,Shewchun, 1979



Simulation results (preliminary)

PD, Egana-Ugrinovic, Essig, Sholapurkar, (*in prep*)

SENSEI image

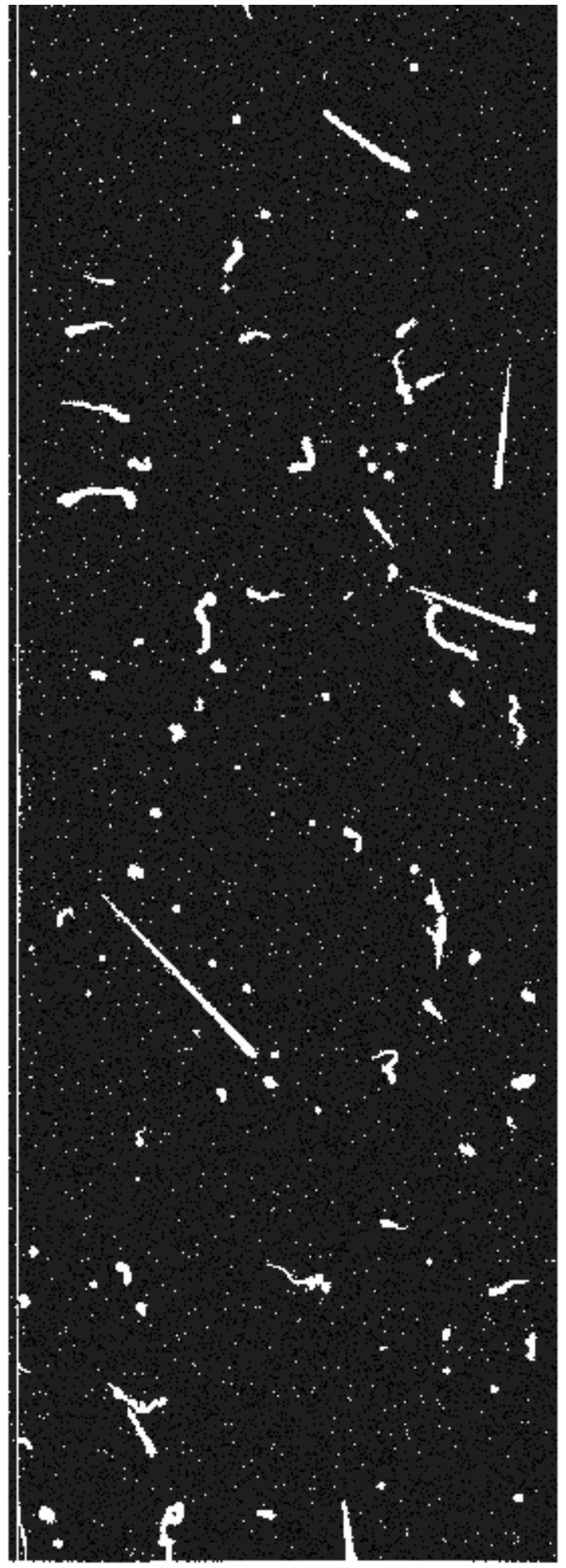


High energy tracks

Simulation results (preliminary)

PD, Egana-Ugrinovic, Essig, Sholapurkar, (*in prep)*

SENSEI image



High energy tracks+Cherenkov+Radiative recombination