New Backgrounds and New Ideas for Sub-GeV Dark Matter Direct Detection

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NHETC Seminar

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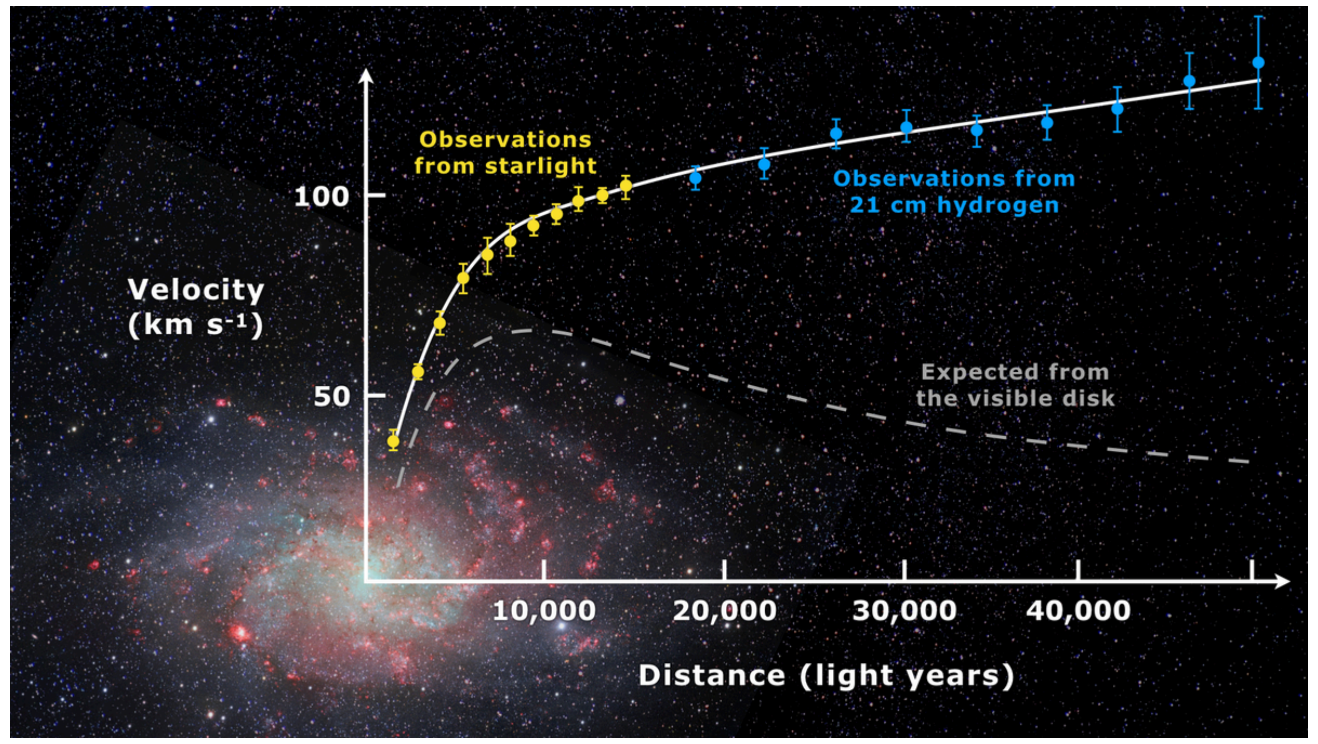
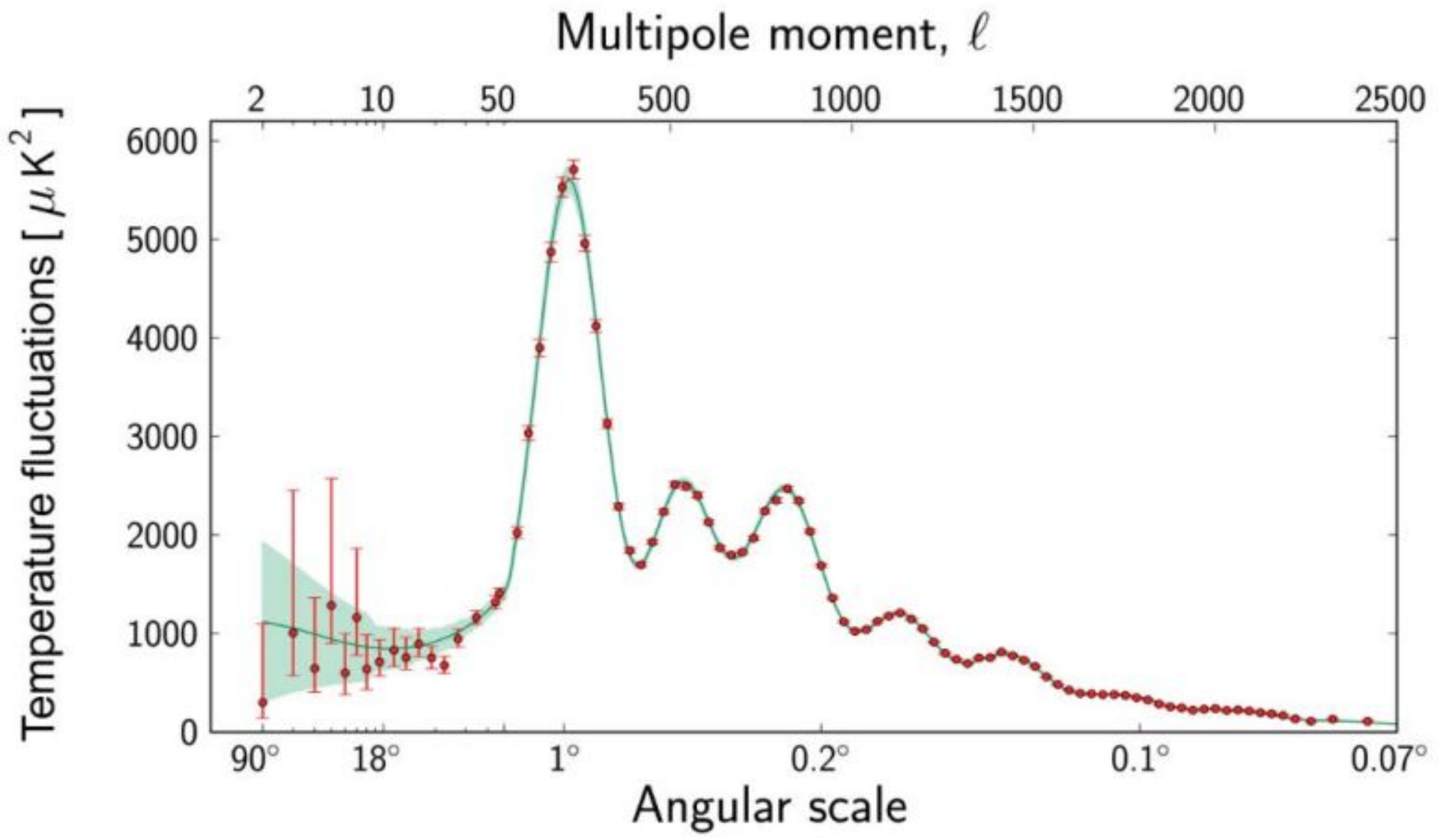
in collaboration with Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (PRX 12, 011009)
Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (in progress)
Daniel Egana-Ugrinovic, Rouven Essig, Miguel Sofo Haro, Mukul Sholapurkar and Javier Tiffenberg (in progress)

Dark Matter



Galaxy

Galaxy Cluster

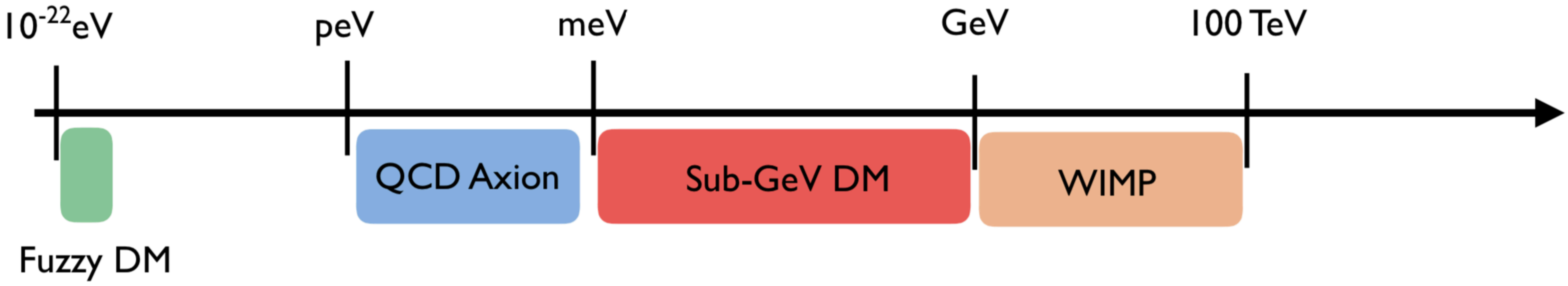


CMB

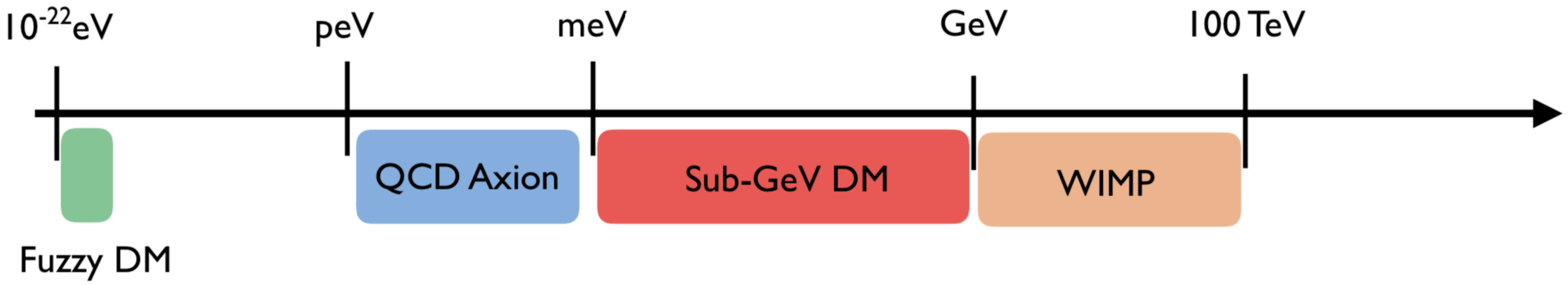
- 80% of matter, 25% total energy density in the Universe
- Evidence for dark matter is currently only gravitational

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

Sub-GeV dark matter



Sub-GeV dark matter

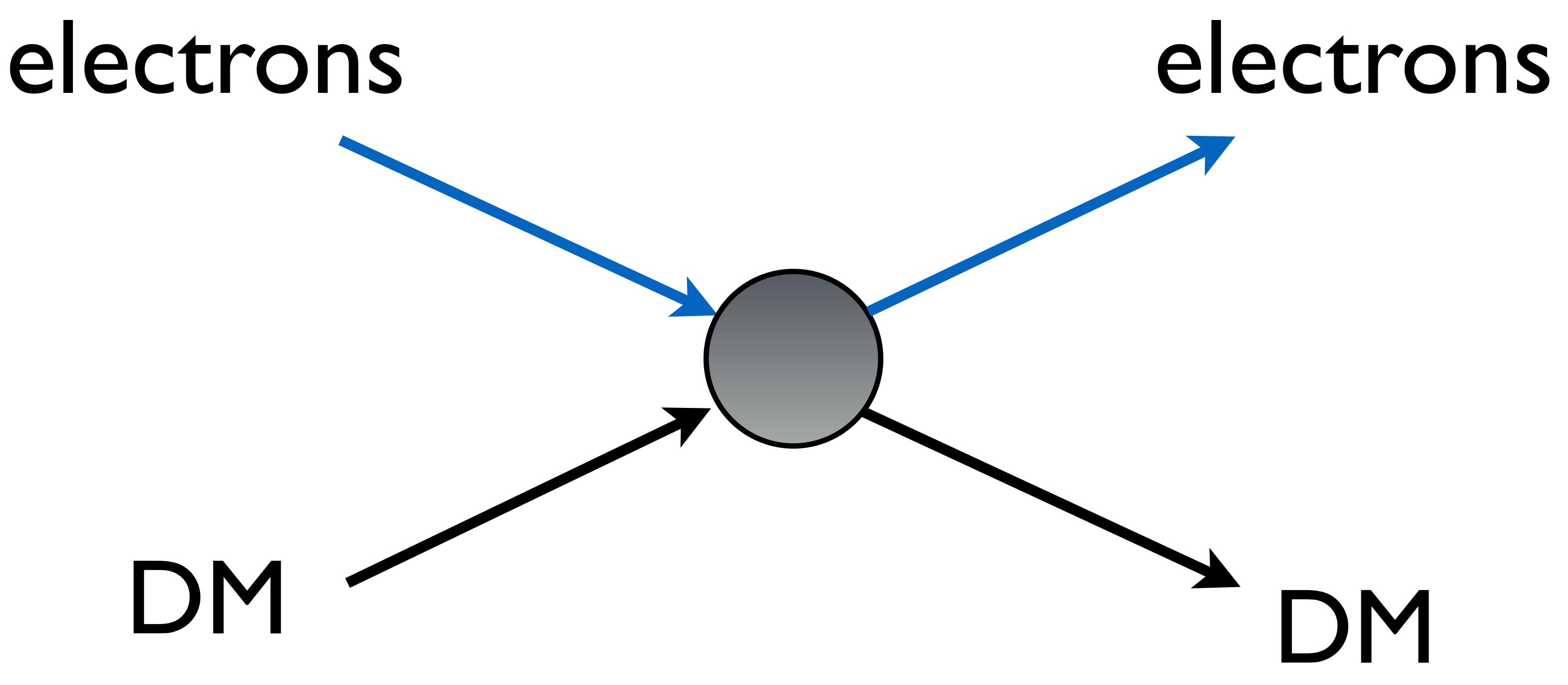


- Dark Photon model: $\mathcal{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\kappa}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_A^2 A'^{\mu} A'_{\mu}$

Model	Detection method	Relic abundance
Dark photon as mediator	DM-electron scattering	freeze-in mechanism
Dark photon dark matter	DM absorption	gravitational production during inflation

Direct detection of sub-GeV DM

Electron recoils



Access to whole kinetic energy:

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

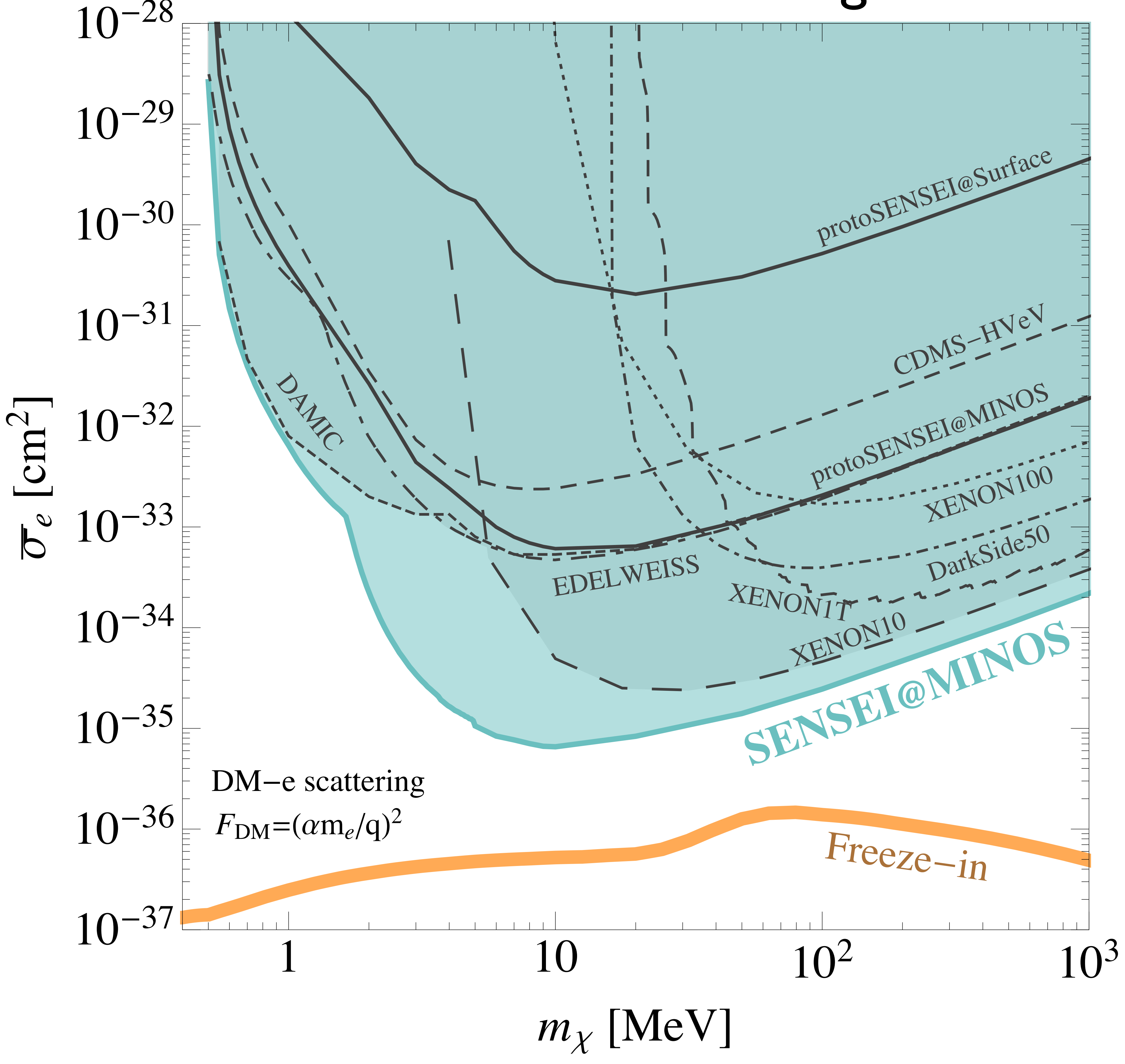
Current targets

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

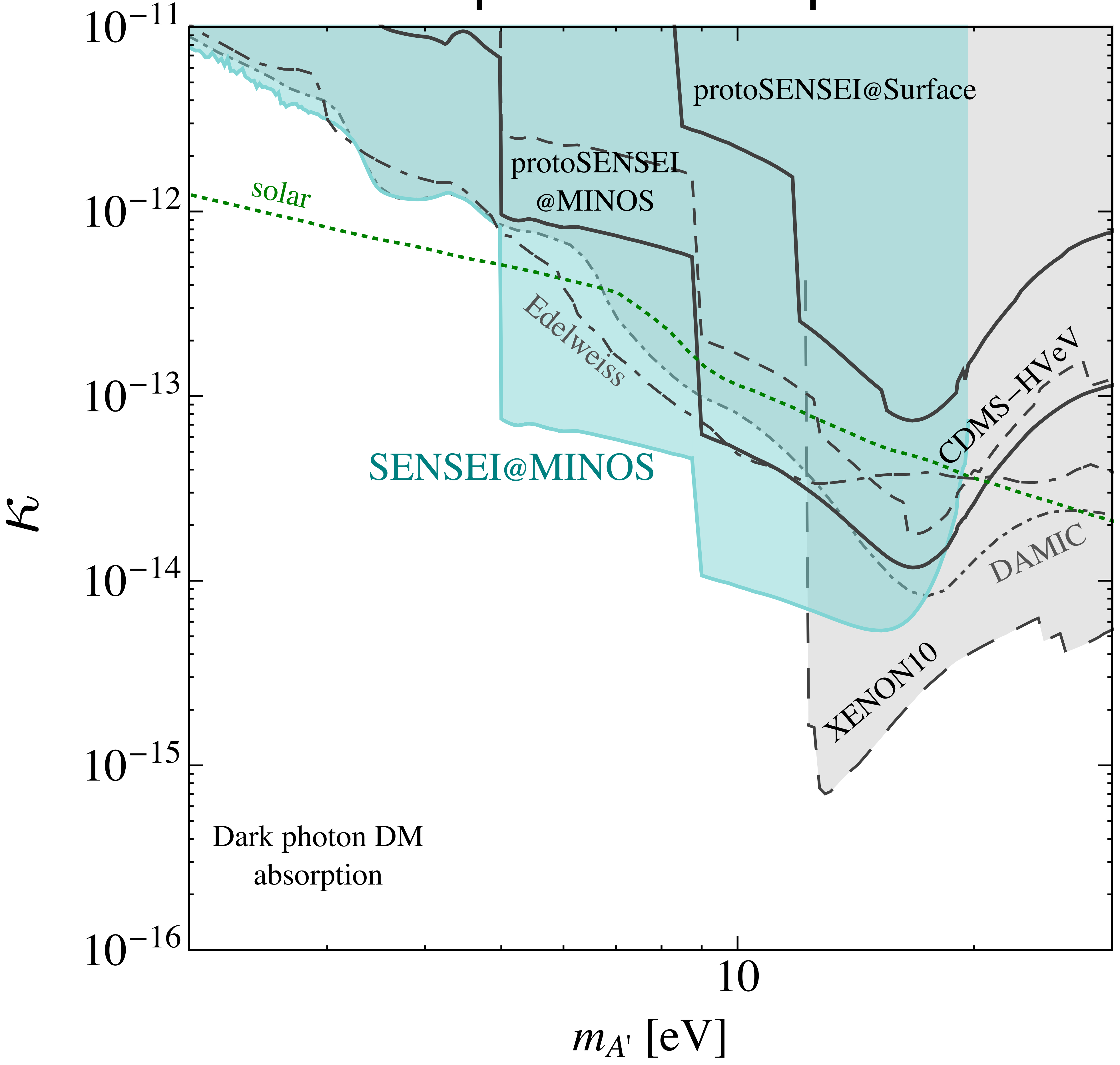
Direct detection of sub-GeV DM

SENSEI, 2020

DM-electron scattering



Dark photon absorption



Q1: Excess events are observed at current sub-GeV DM detectors.
What is the origin of those events?

Q2: Can we probe sub-MeV (sub-eV) DM?

Outline of the talk

Part I Unexplored low-energy backgrounds at sub-GeV DM detectors

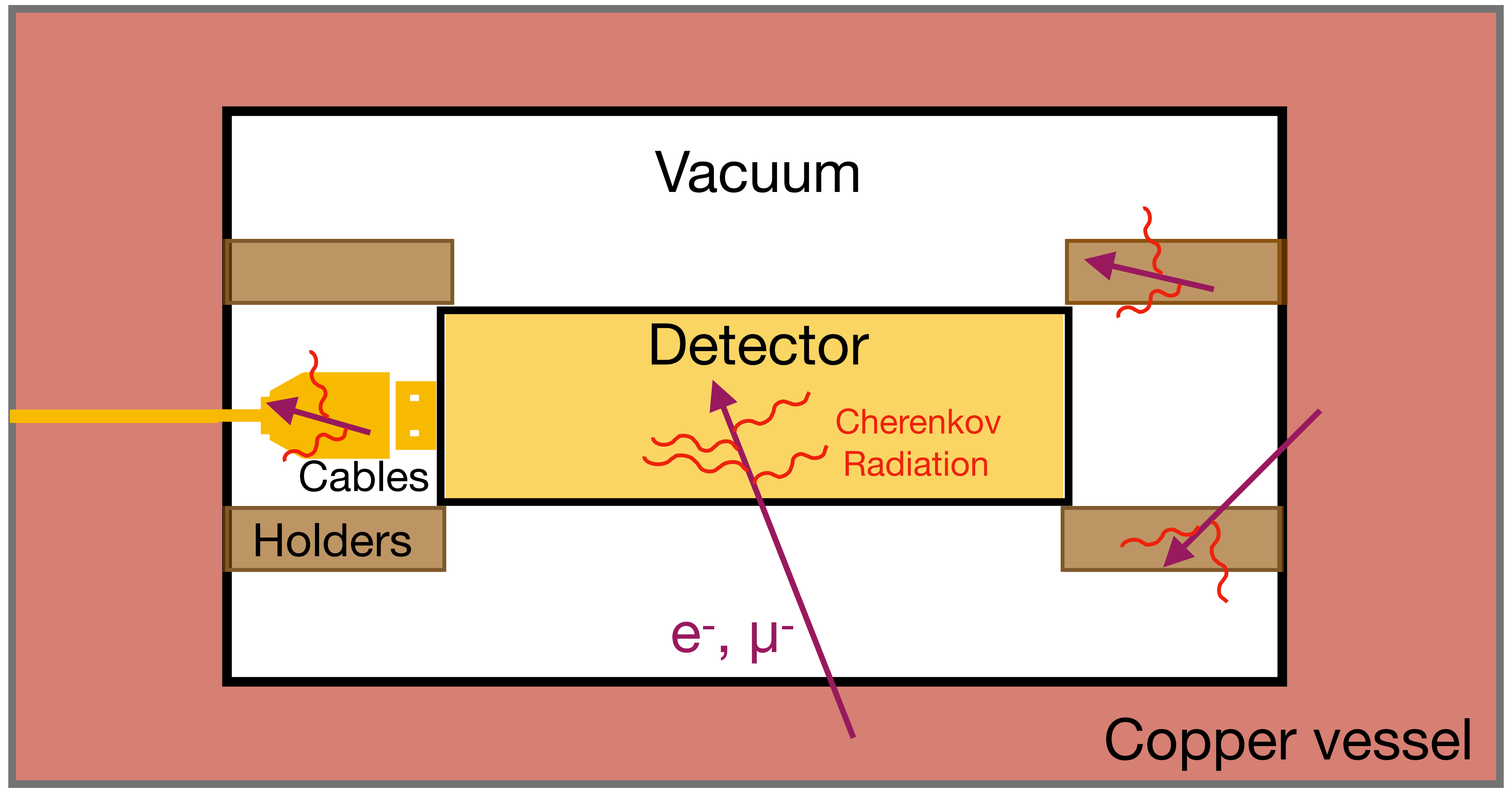
Excesses at current sub-GeV DM detectors. Unexplored new backgrounds!

Part II New targets for probing sub-MeV DM

Doped semiconductors as new targets with O(10-100) meV threshold

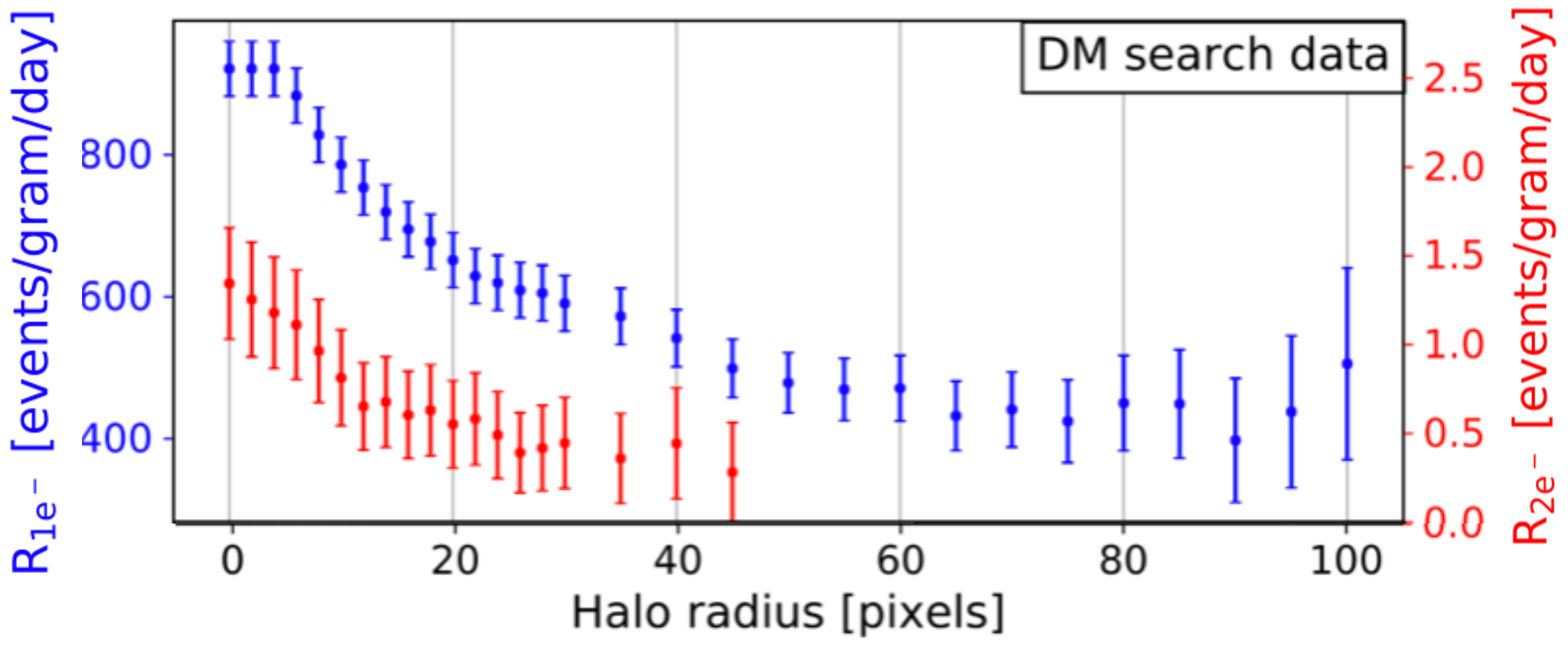
Probing light DM : low threshold detectors and low backgrounds

Part I Unexplored low-energy backgrounds at sub-GeV DM detectors

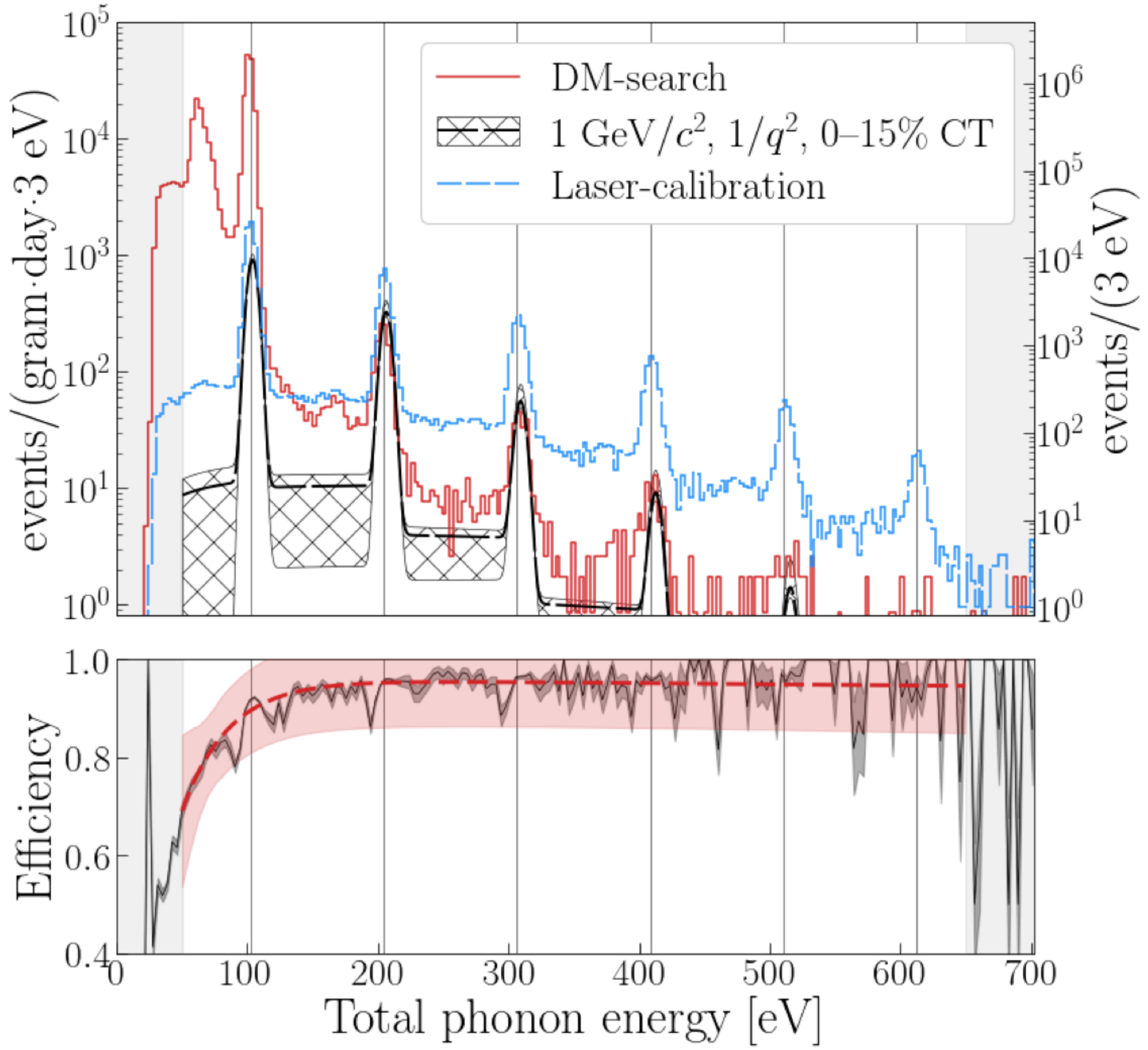


Excess in sub-GeV dark matter detectors

SENSEI SENSEI, 2020



SuperCDMS HVeV SuperCDMS, 2020

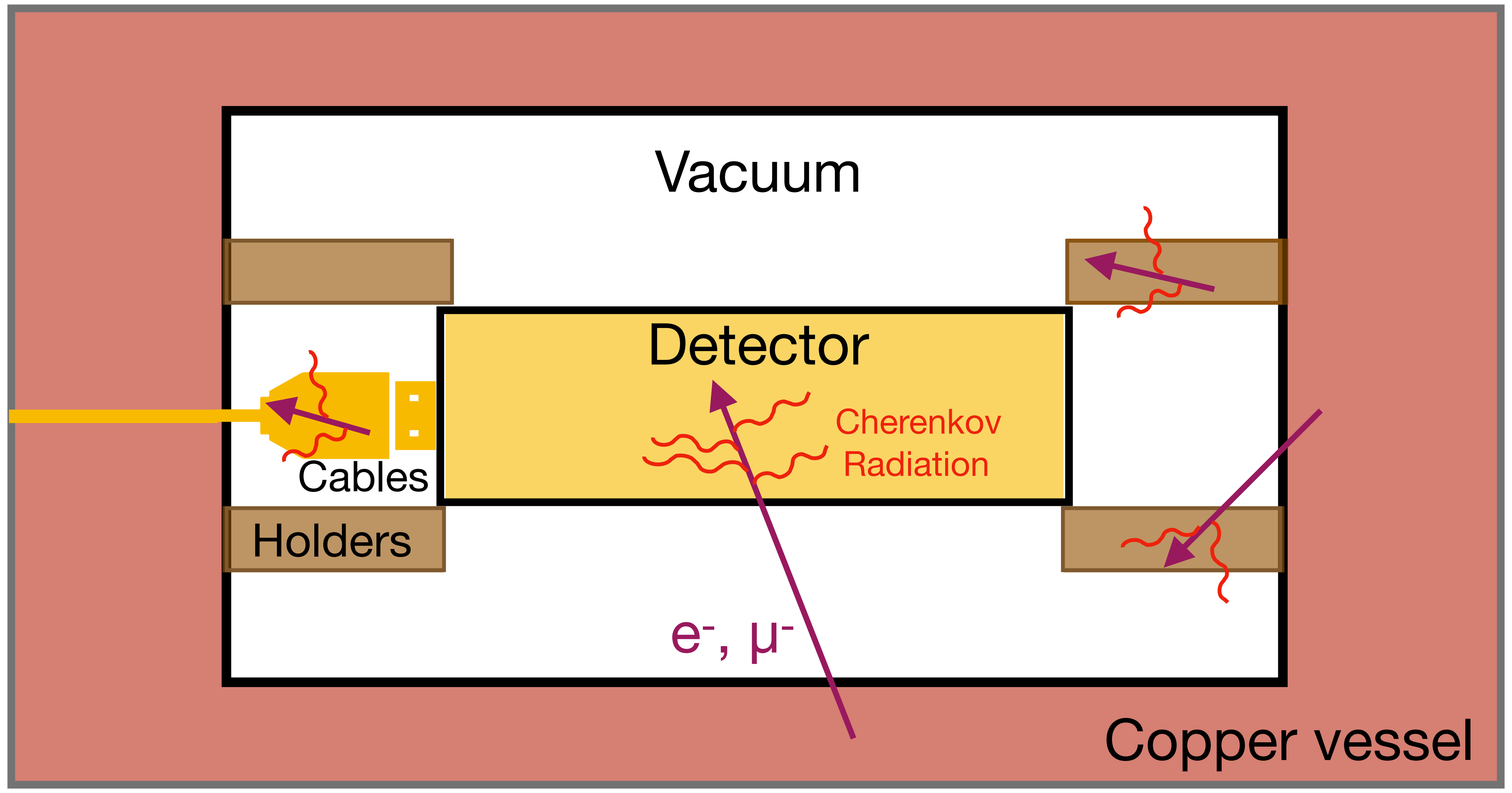


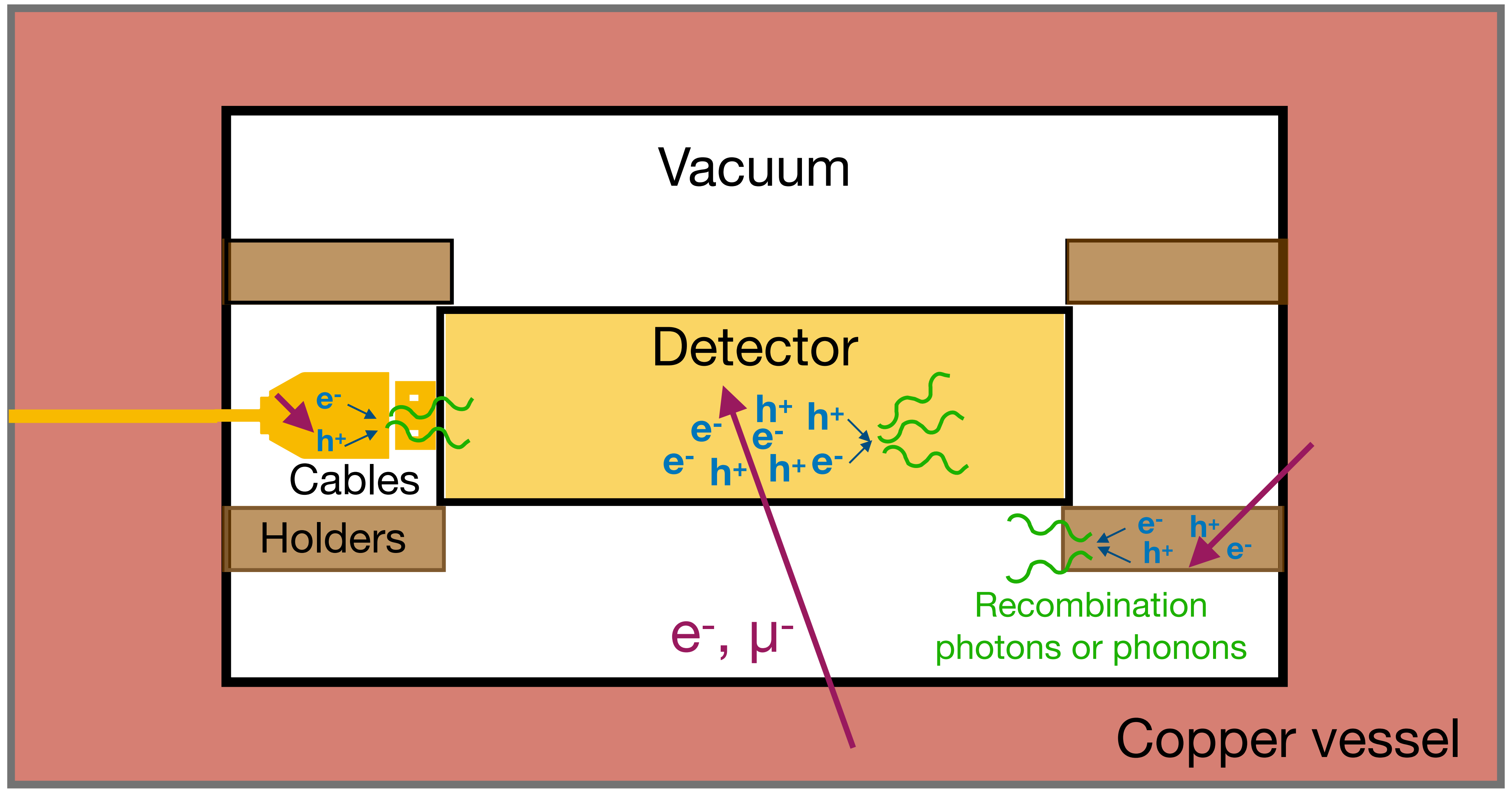
- Excess events are near the threshold
- Cannot be explained by known sources
- Limits the sensitivity for dark matter detection

Unexplored low energy backgrounds

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

Cherenkov radiation and radiative recombination photons are likely to explain the excess





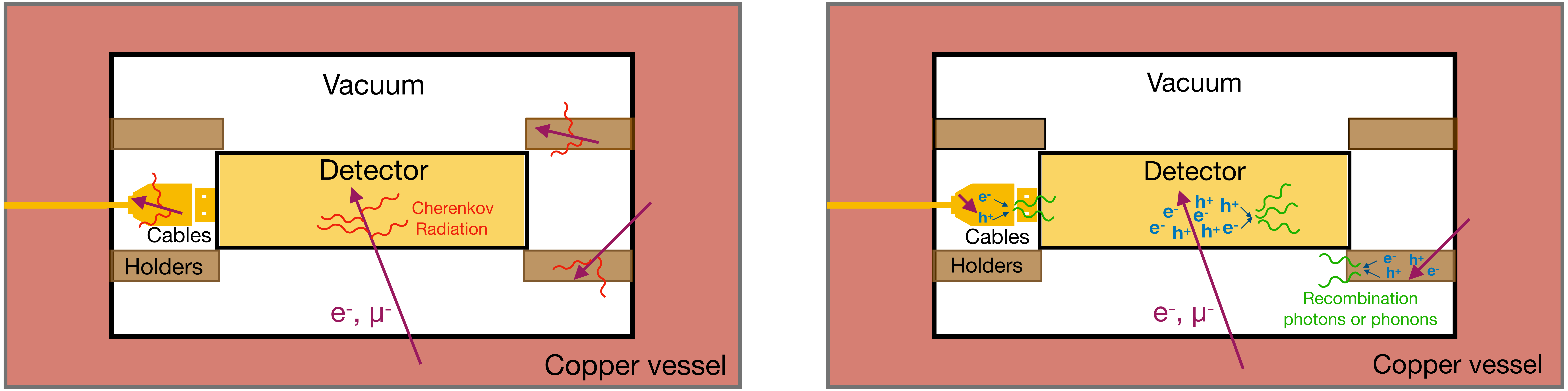
Cherenkov radiation inside detector

Radiative recombination inside detector } ⇒ SENSEI excess

Cherenkov radiation from holders ⇒ SuperCDMS HVeV excess

Unexplored low energy backgrounds

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020



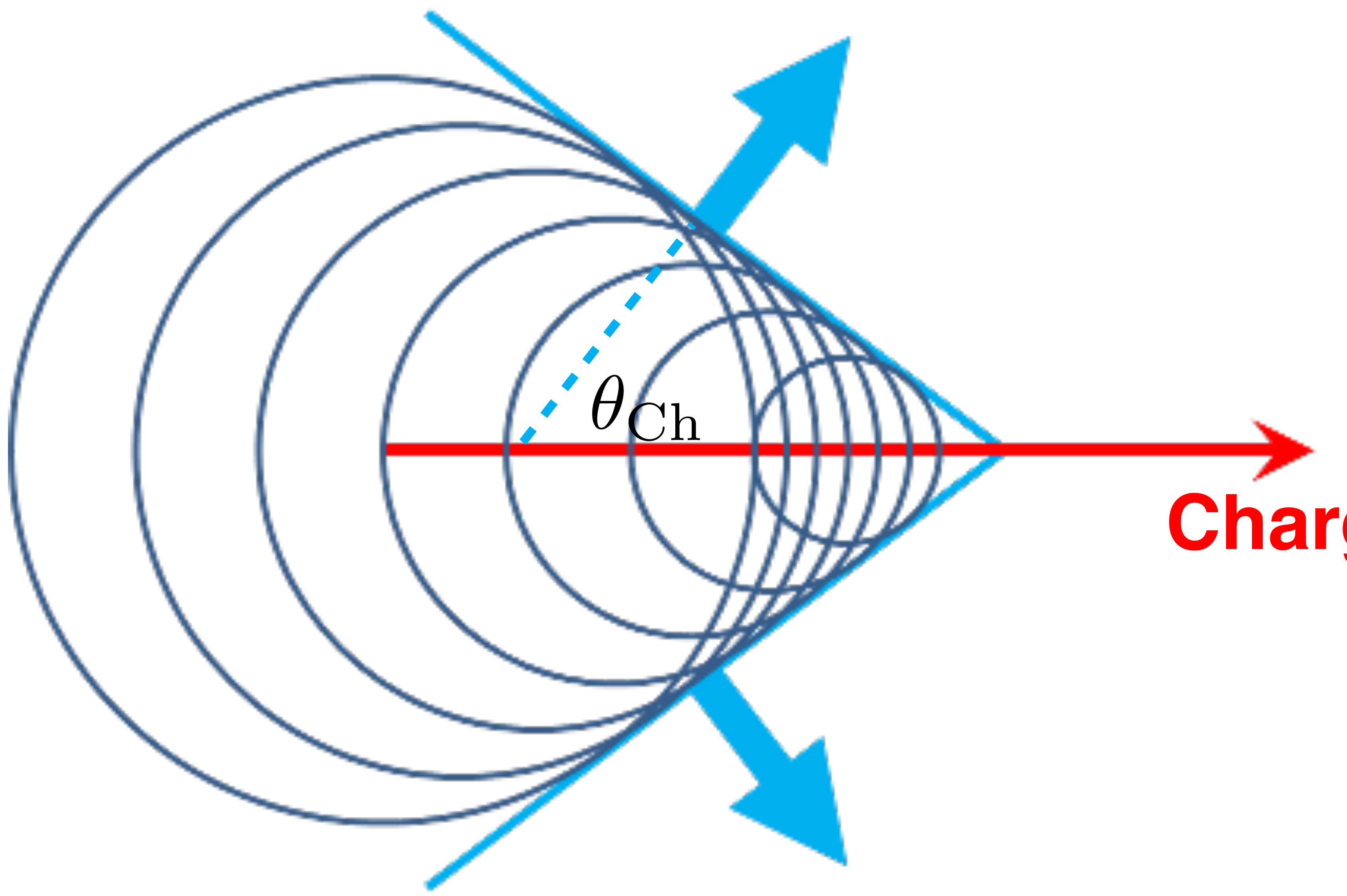
Why these backgrounds haven't been studied before?

- Not the usual high energy radioactivity backgrounds
- First generation of experiments of sub-eV resolution
- Challenging to identify them: events in the signal region

Cherenkov Radiation

Jackson, Classical Electrodynamics

Incident charge is moving faster than the speed of light inside the medium



Conditions:

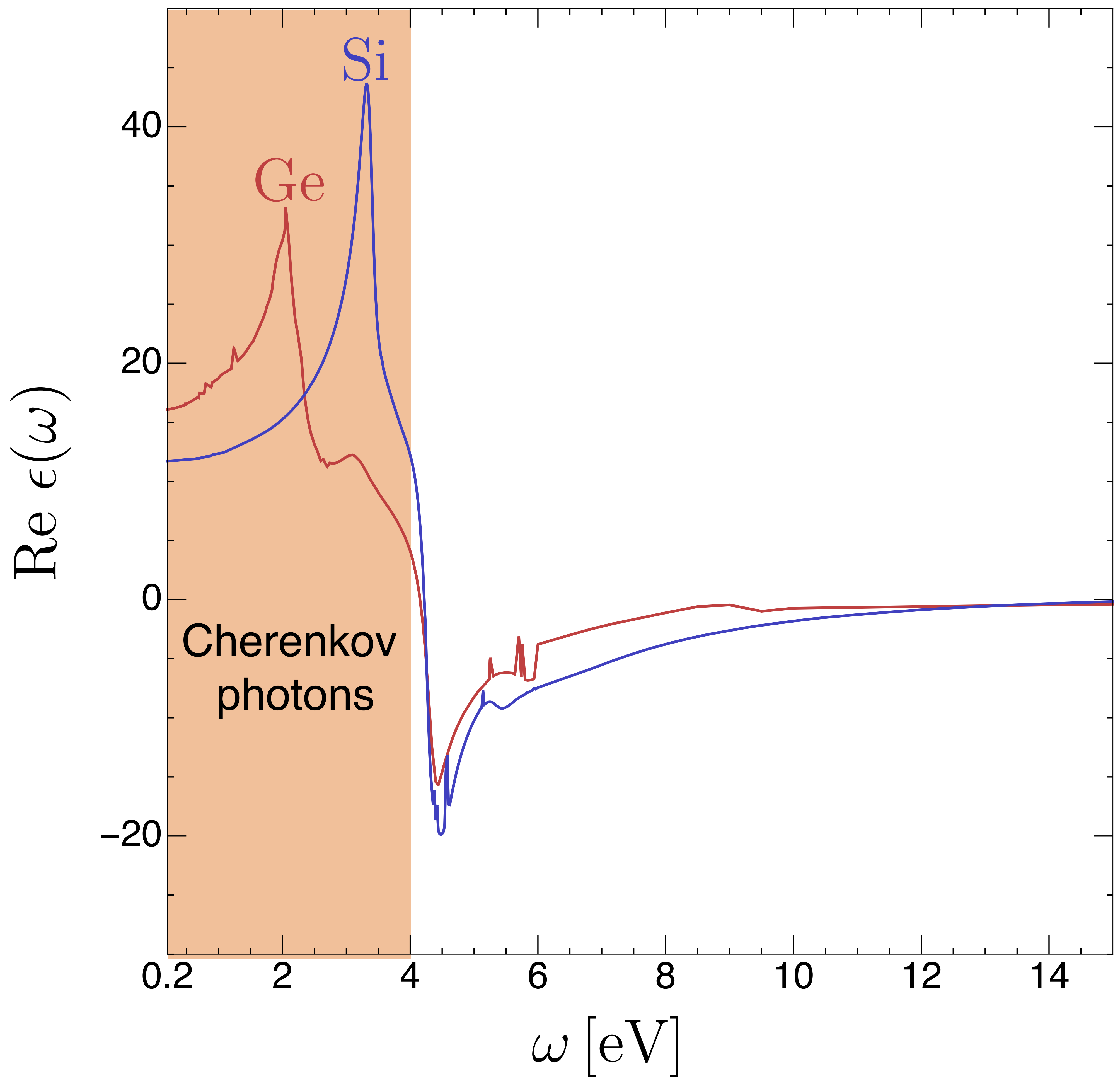
$$\boxed{v^2 \text{Re } \epsilon(\omega) > 1}$$

$$\epsilon = (n + ik)^2$$

$$\frac{d^2N}{d\omega dx} = \alpha \left(1 - \frac{\text{Re } \epsilon(\omega)}{v^2 |\epsilon(\omega)|^2}\right)$$

$$\cos\theta_{\text{Ch}} = \frac{\sqrt{\text{Re } \epsilon(\omega)}}{v|\epsilon(\omega)|}$$

Cherenkov Radiation in semiconductors



Cherenkov spectrum:

$$\omega \lesssim 4\,\mathrm{eV}$$

Near bandgap/detection threshold

Typical rate:

$$\frac{d^2N}{d\omega dx} \sim \alpha \quad (\text{for}\,\epsilon(\omega) \gg 1)$$

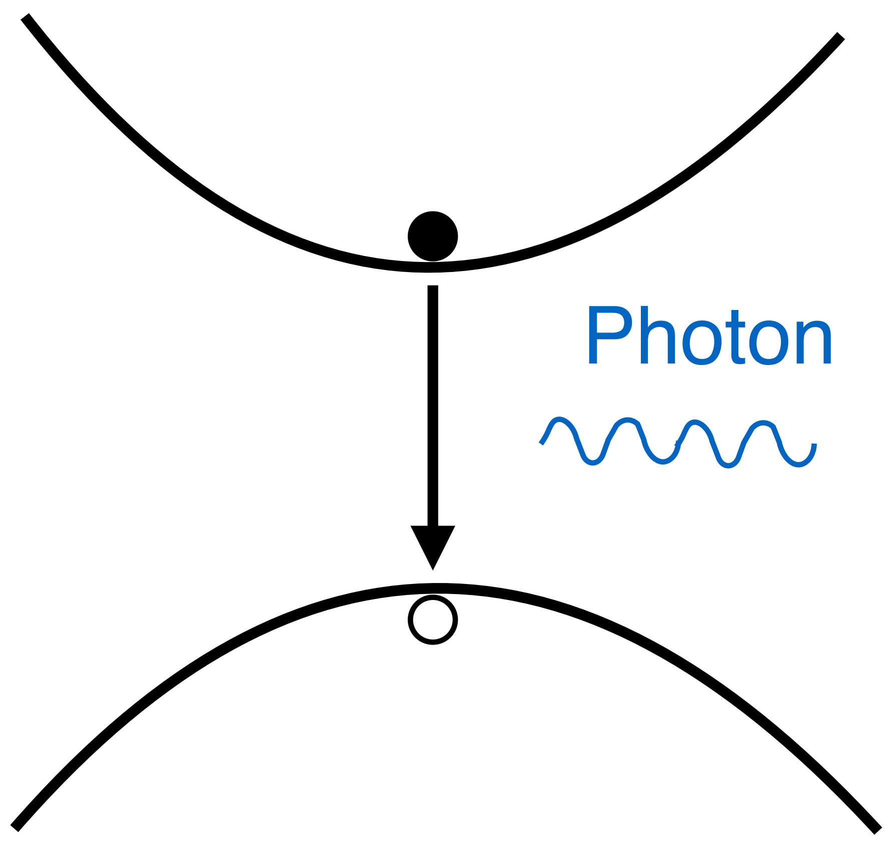
$$N \sim 40 \left[\frac{\Delta\omega}{1\,\mathrm{eV}}\right] \left[\frac{\Delta x}{1\,\mathrm{mm}}\right]$$

Significant rate for dark matter detection

Electron-hole recombination

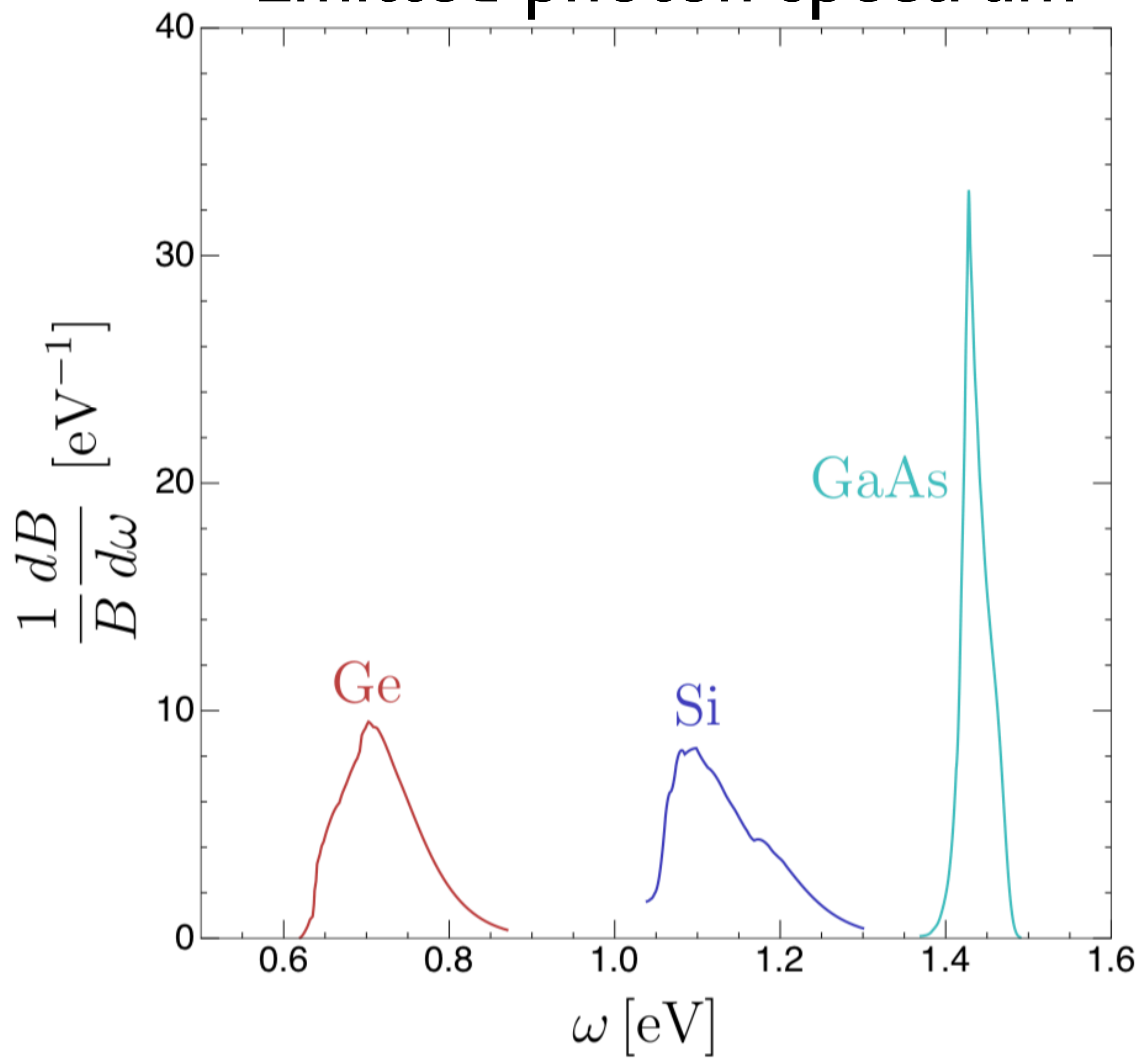
Ruff, Fick, Lindner, Rossler, Helbig, 1993

Radiative recombination



$$\Gamma^{e}_{\rm rec} \propto n_e n_h$$

Emitted photon spectrum



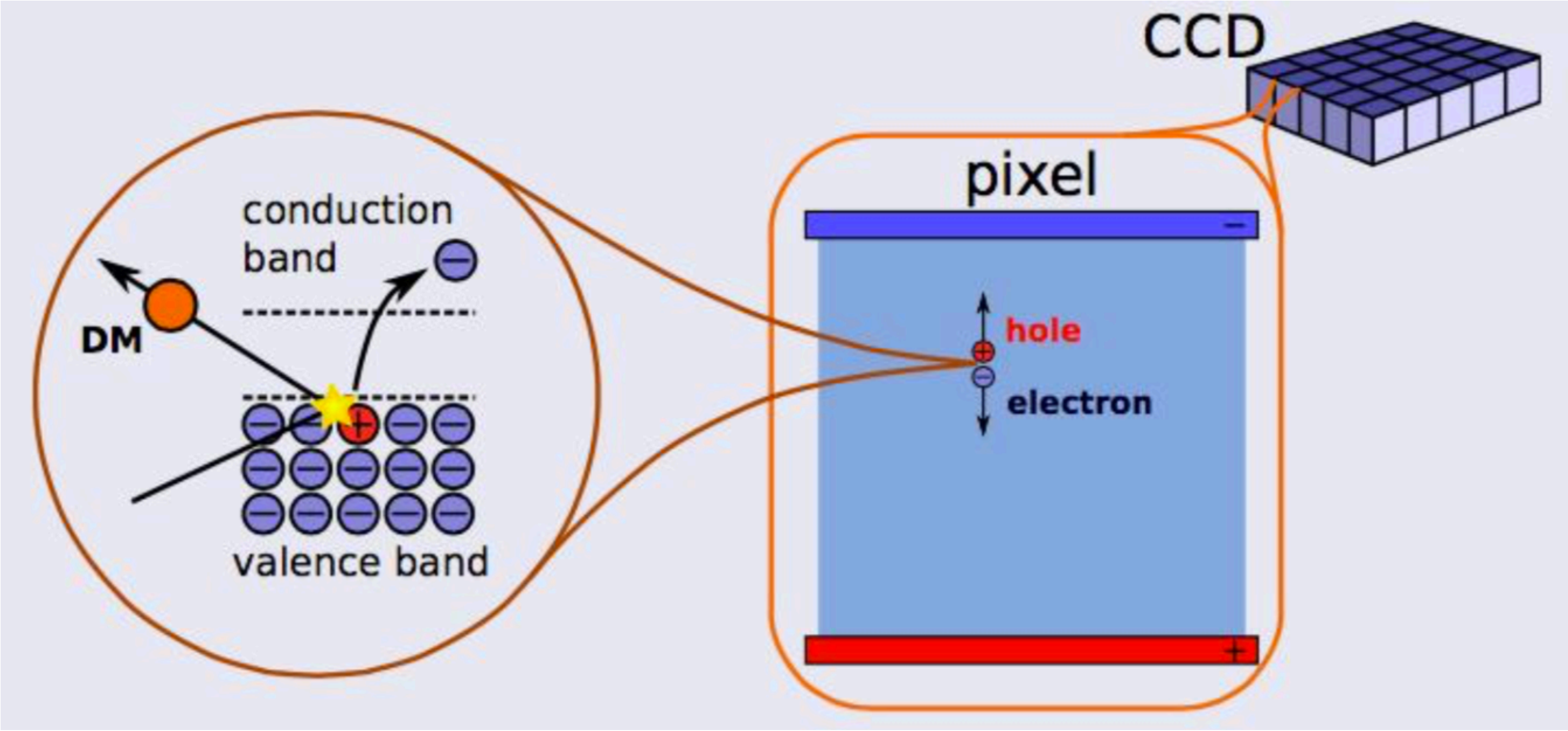
- Emitted spectrum near bandgap
- Significant for high carrier concentration (doped silicon)
- For 100 keV energy deposit and $n_e = 10^{18}$ cm^{-3}

$$N_\gamma = N_e \frac{\tau_{\rm tot}}{\tau_{\rm rad}} \approx 200$$

SENSEI experiment

SENSEI, 2020

- Look for electron-hole pairs in skipper CCD, ~0.1 e^- resolution
- Location: MINOS cavern at Fermilab, 104 m underground
- CCD: Excellent spatial resolution Limited timing resolution



SENSEI experiment

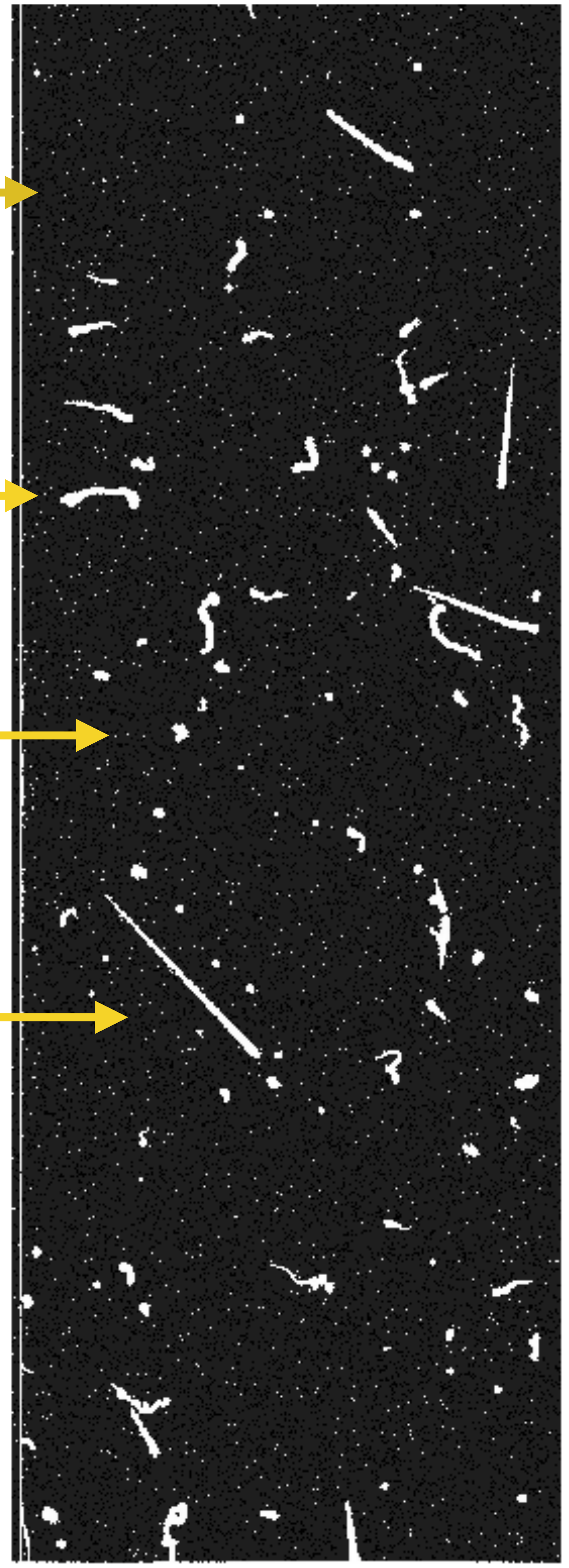
SENSEI image (half of one quadrant)

1e events

Electrons

X ray

Muons



SENSEI experiment

SENSEI image (half of one quadrant)

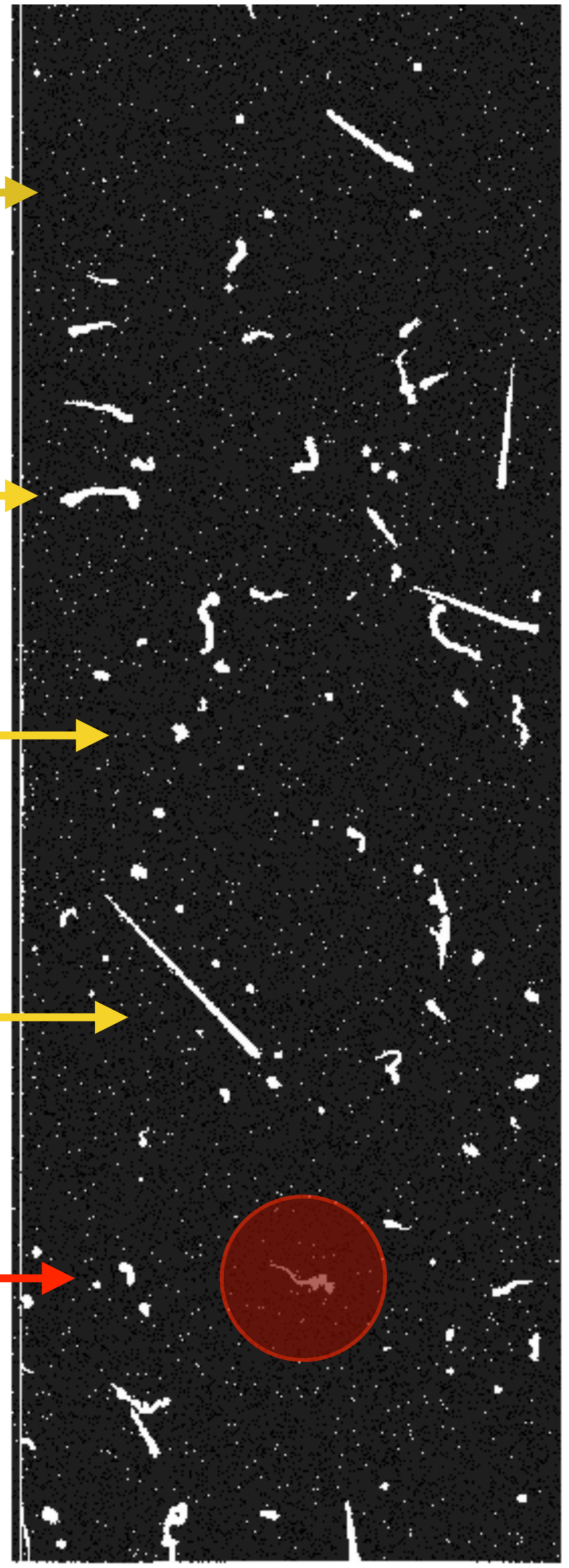
1e events

Electrons

X ray

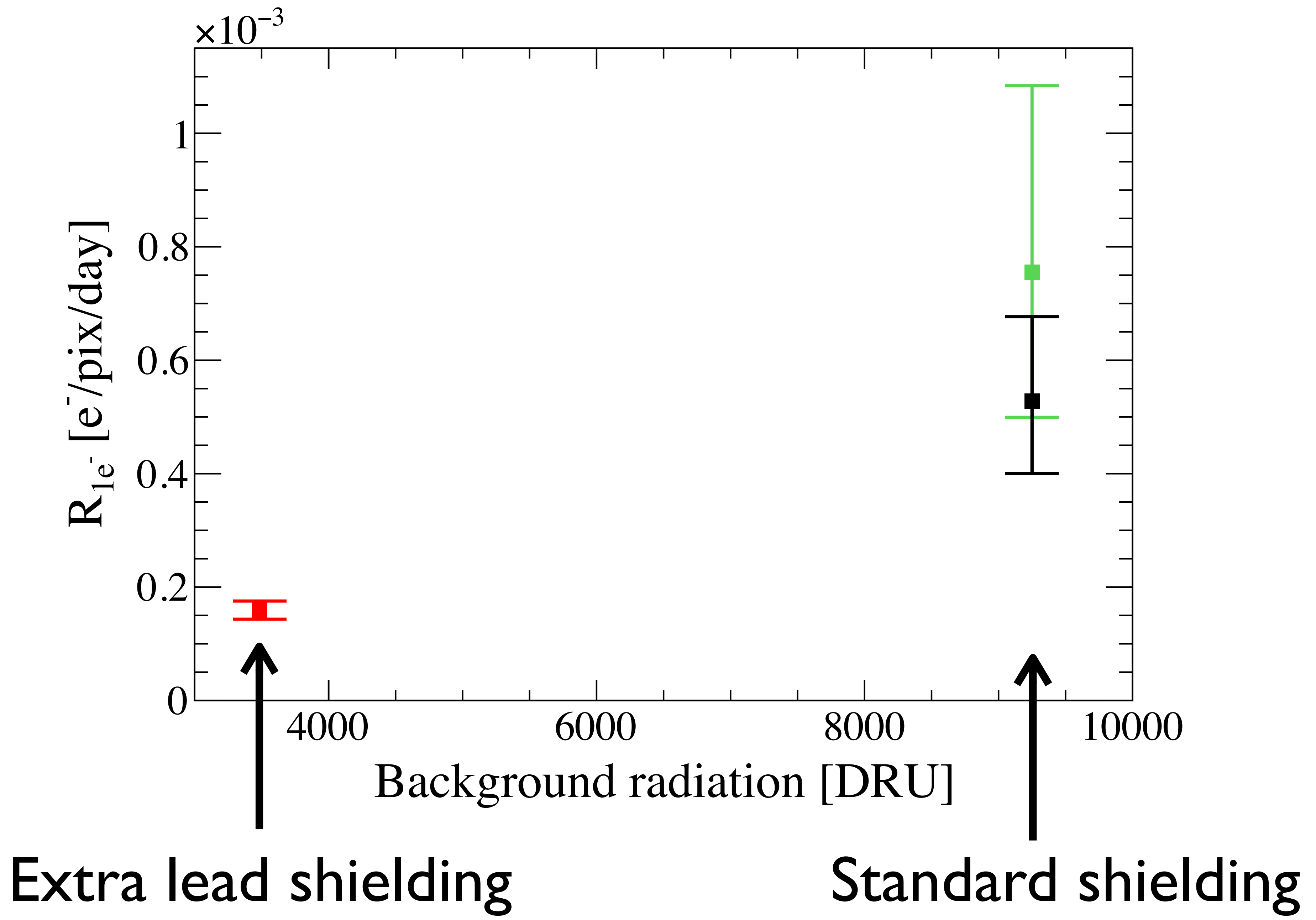
Muons

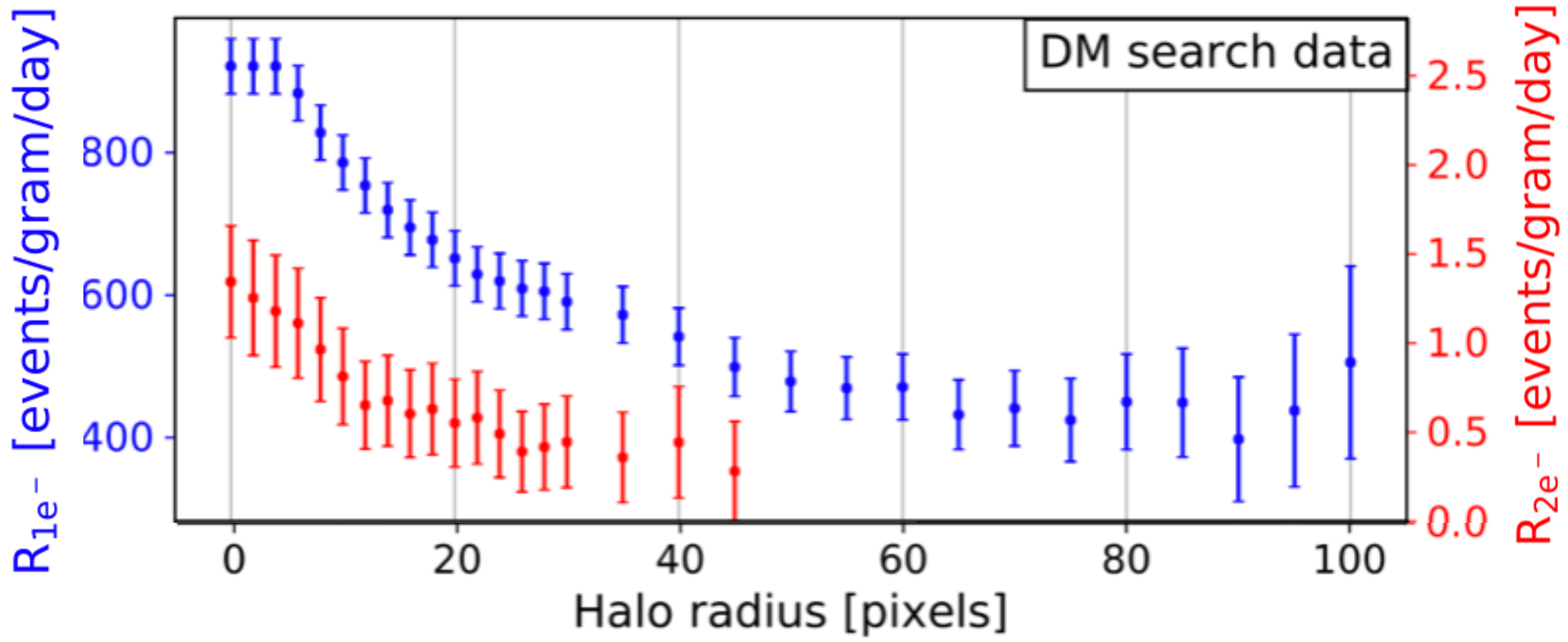
Analysis cut: Halo mask



Single electron event excess

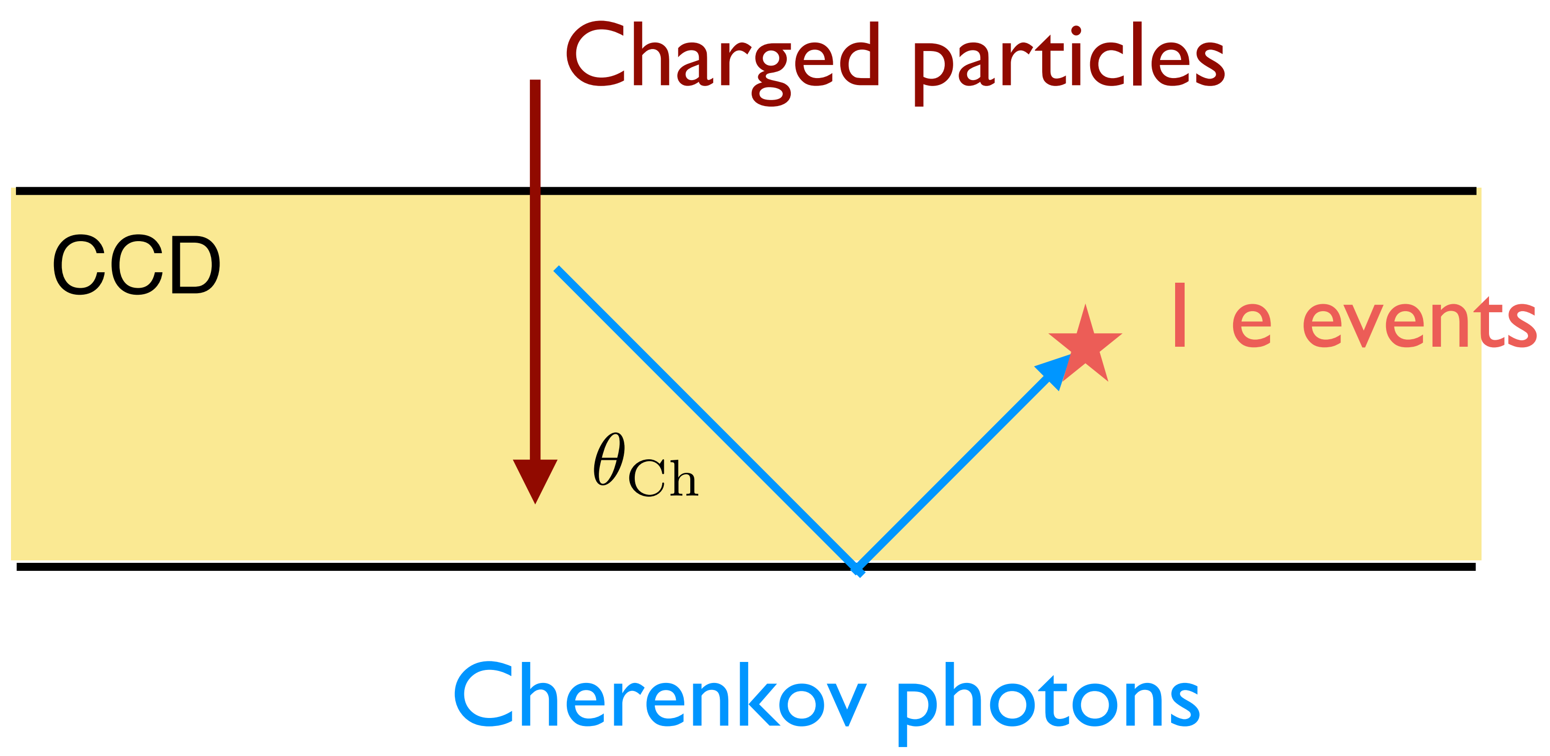
SENSEI, 2020



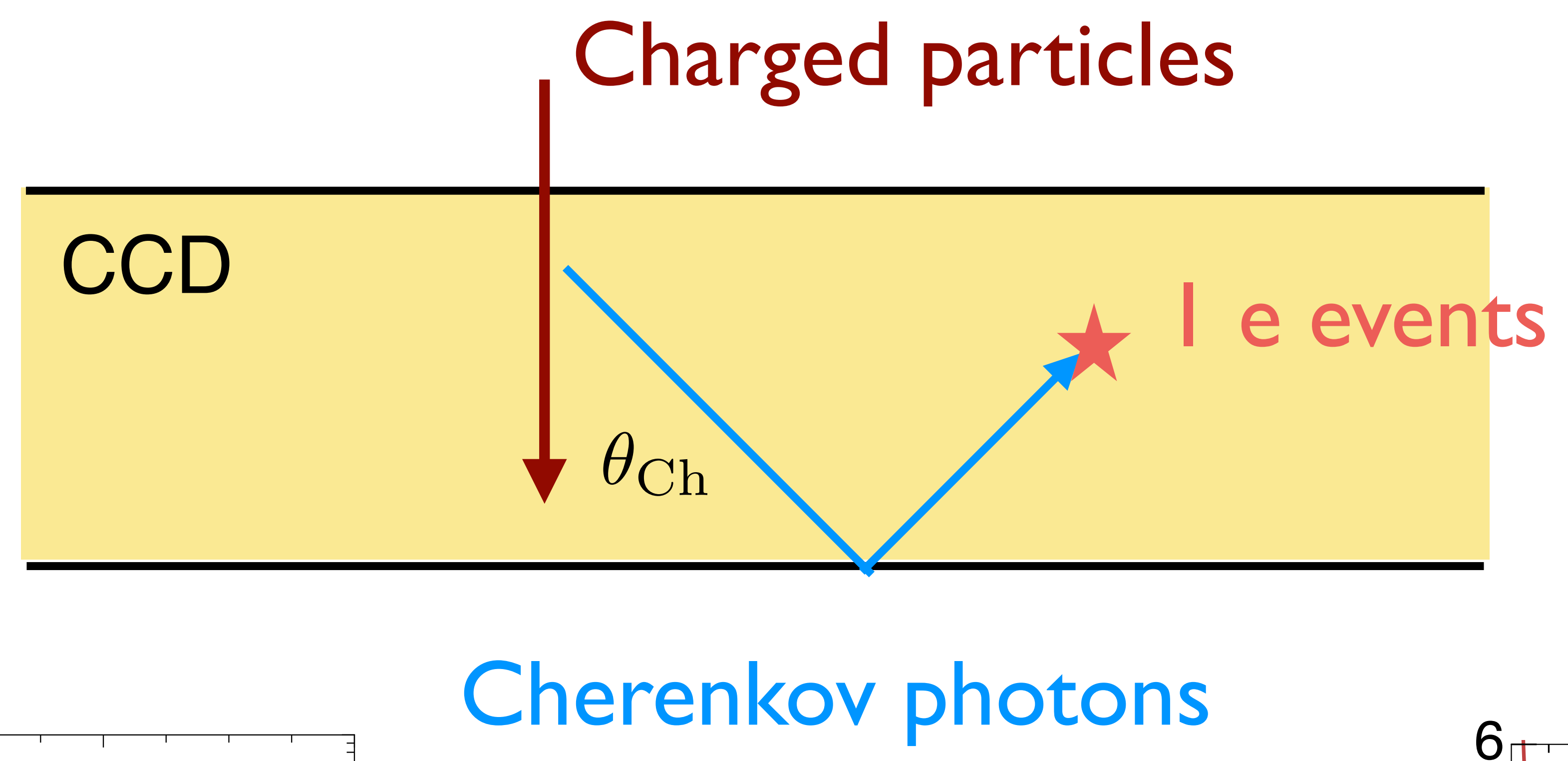


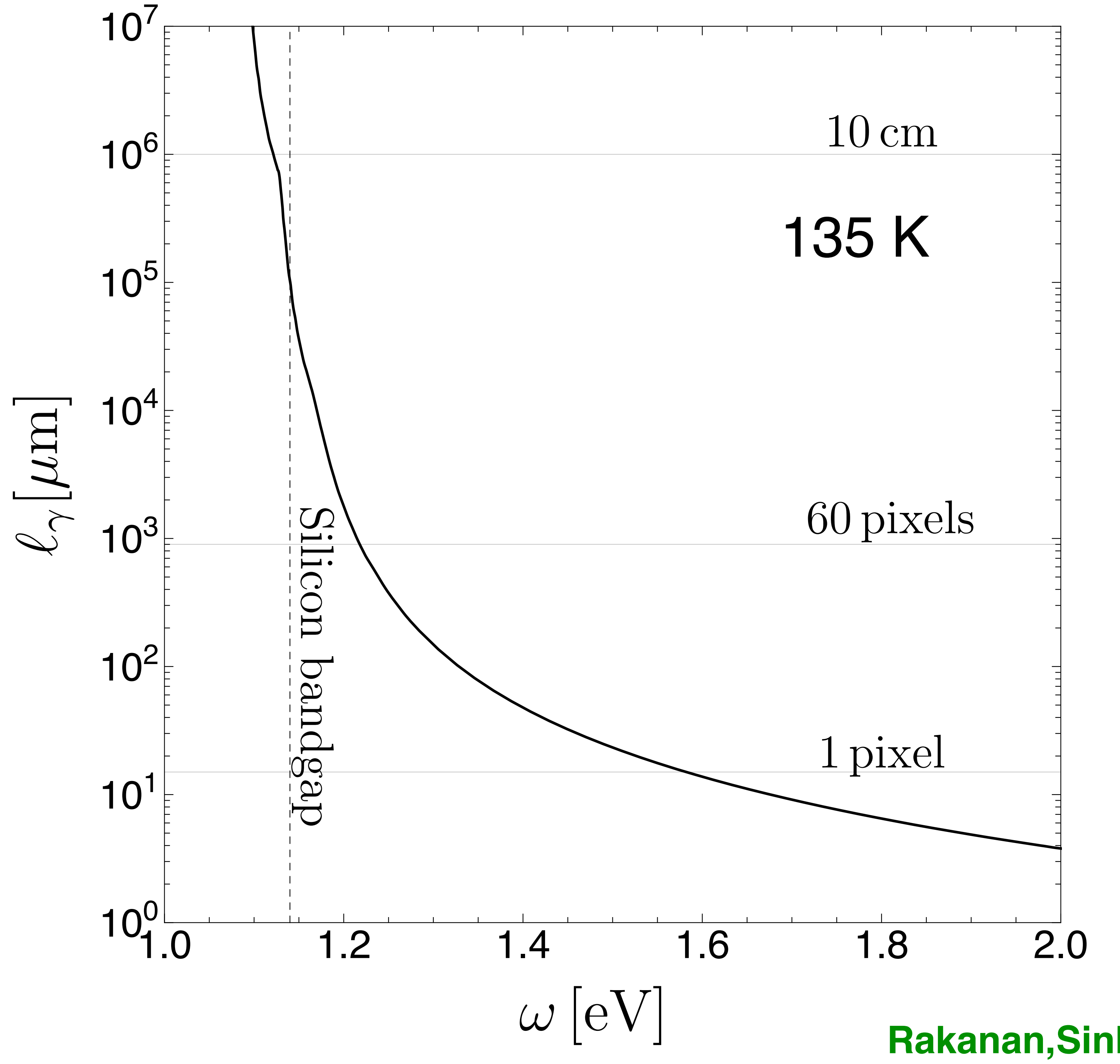
- The rate is correlated with high energy background event rate
- Has spatial correlation with high energy events
- Extends to 60 pixels away and the rate becomes flat: 450 events/g-day

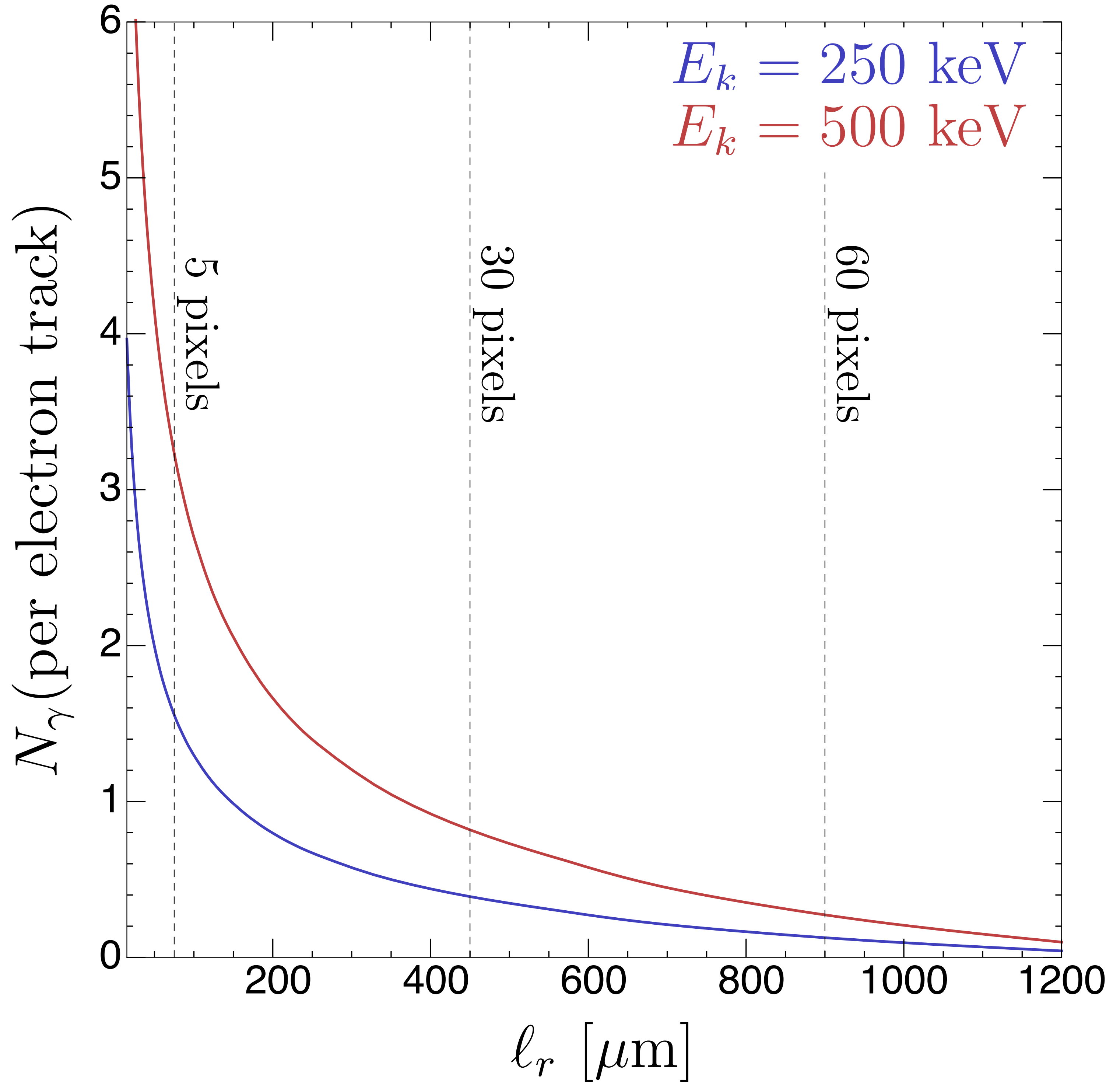
Cherenkov radiation in SENSEI



Cherenkov radiation in SENSEI

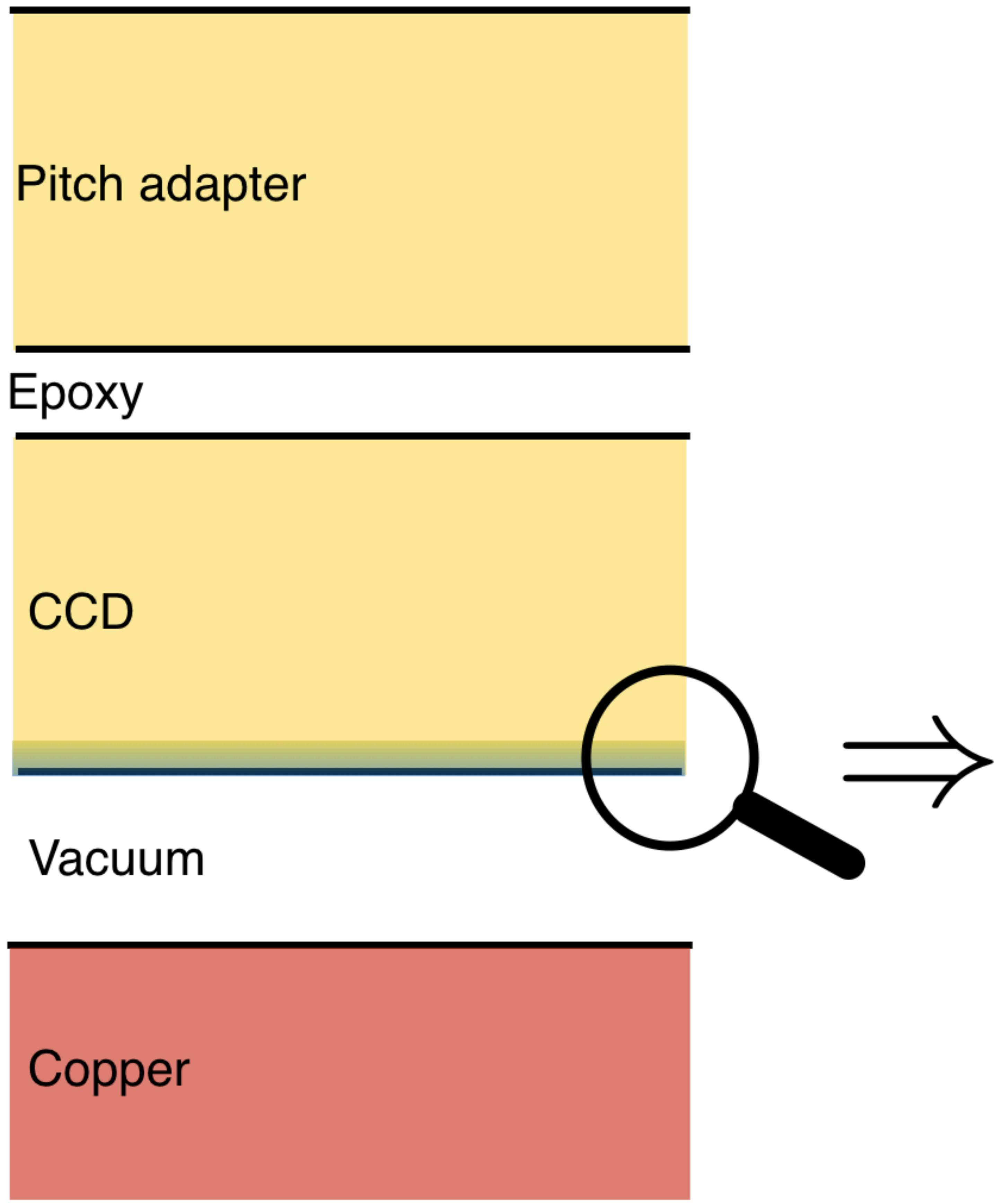




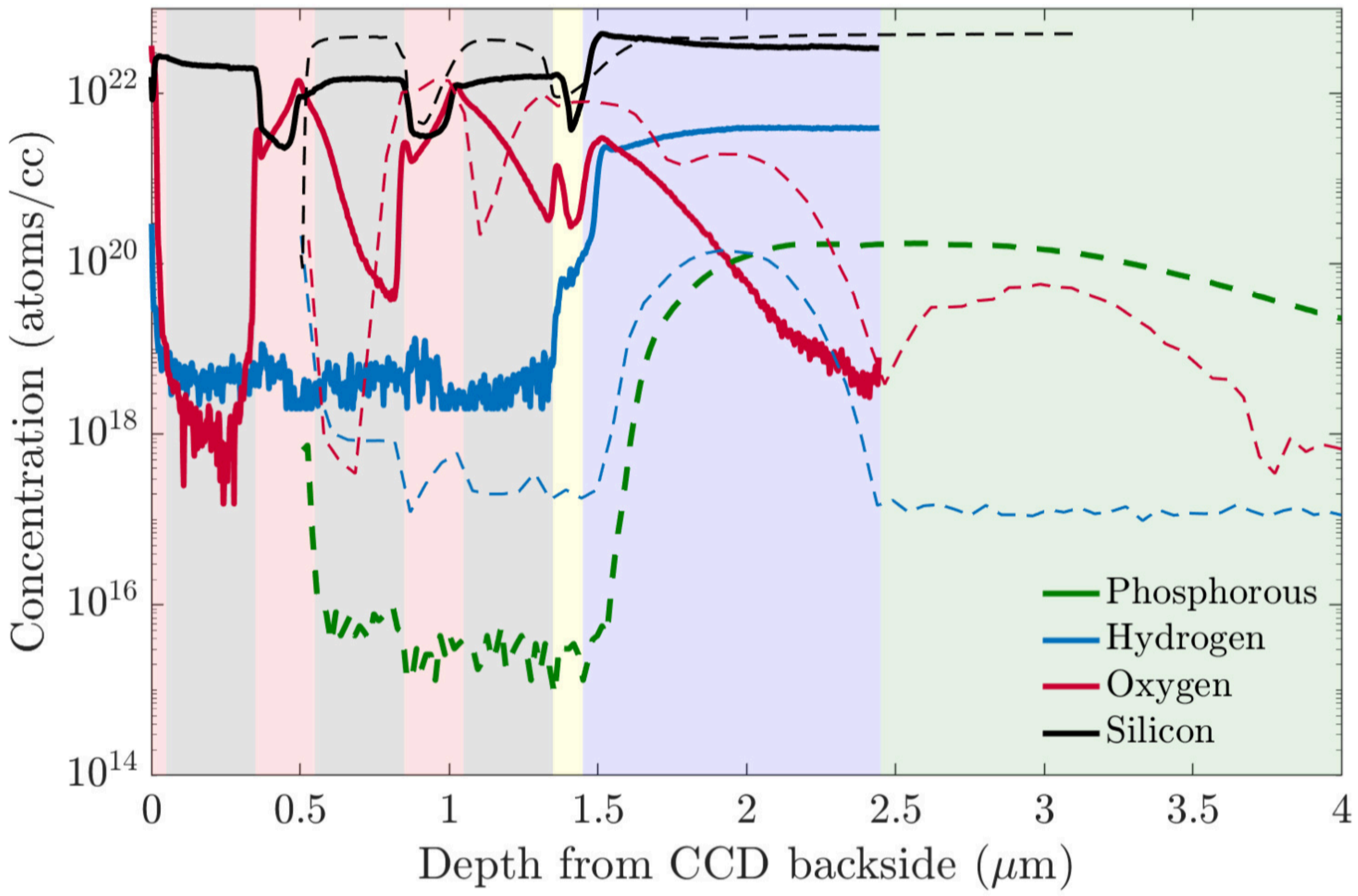


Rakanan,Sinhg,Shewchun, 1979

Radiative recombination in SENSEI



Backside of the CCD



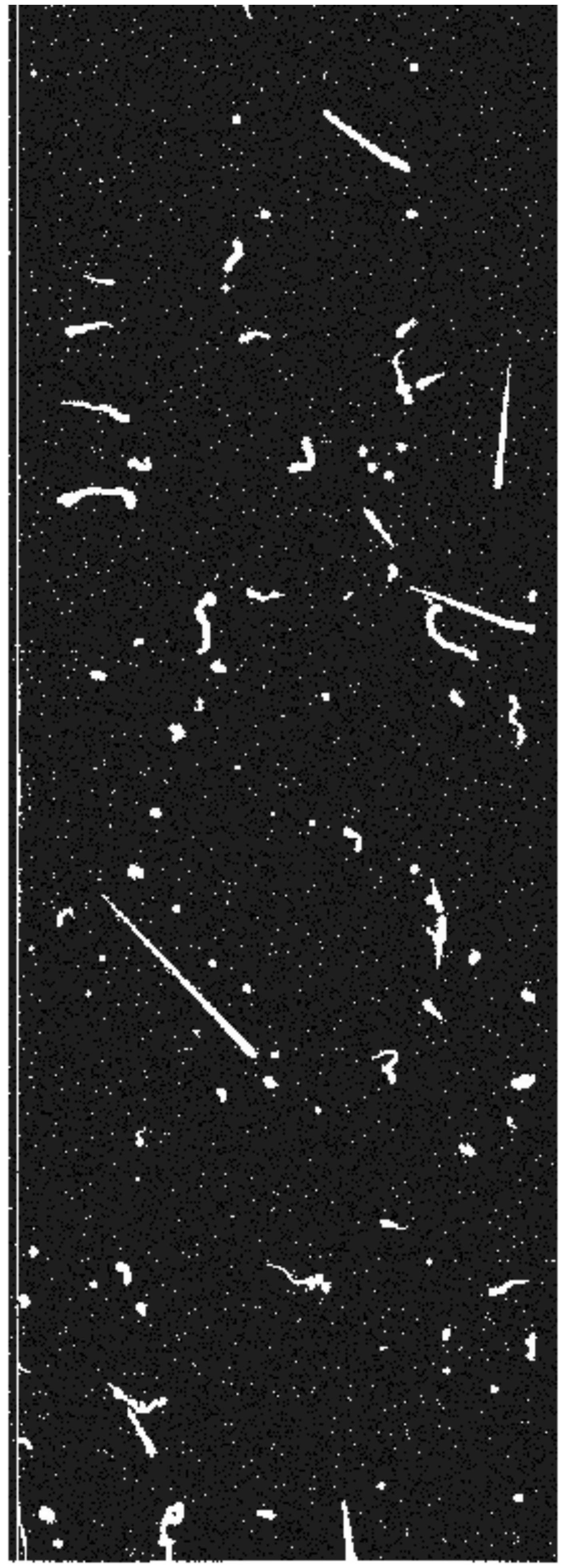
DAMIC, 2021

- ~5 μm of highly doped region ($n_e \geq 10^{17}$ /cm^3)
- Significant contribution to 1e events from radiative recombination

Simulation results (preliminary)

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

SENSEI image

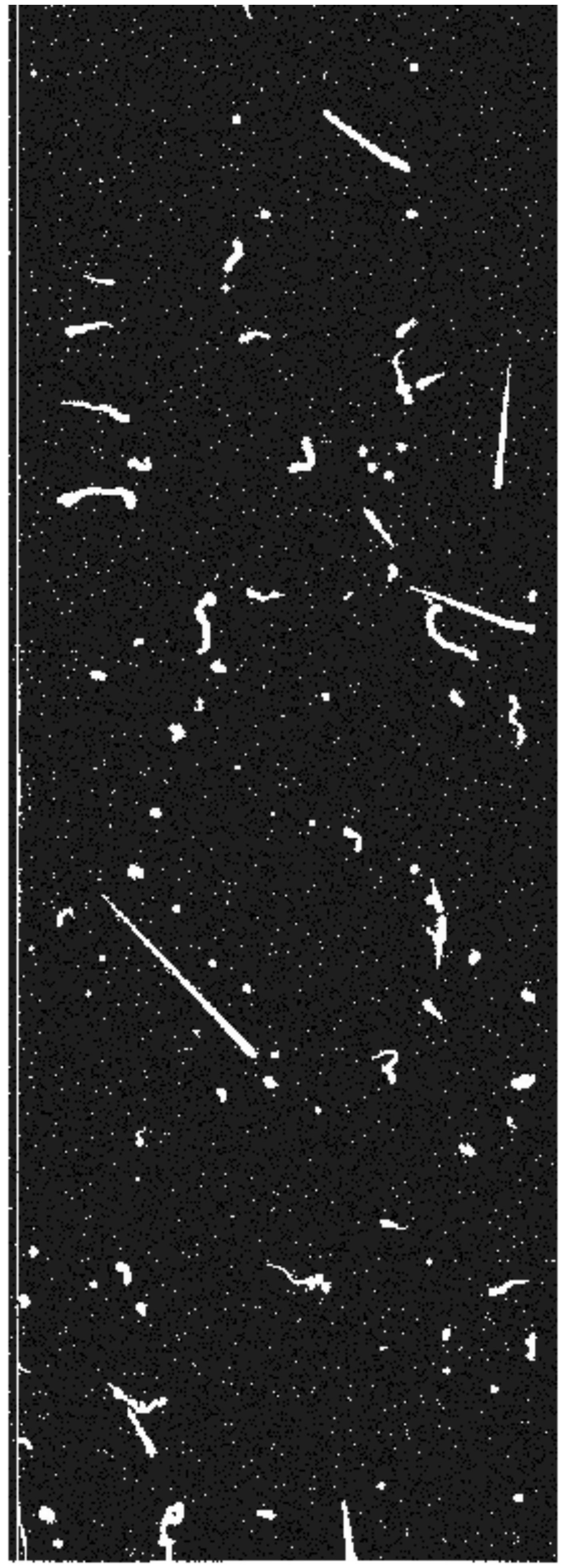


High energy tracks

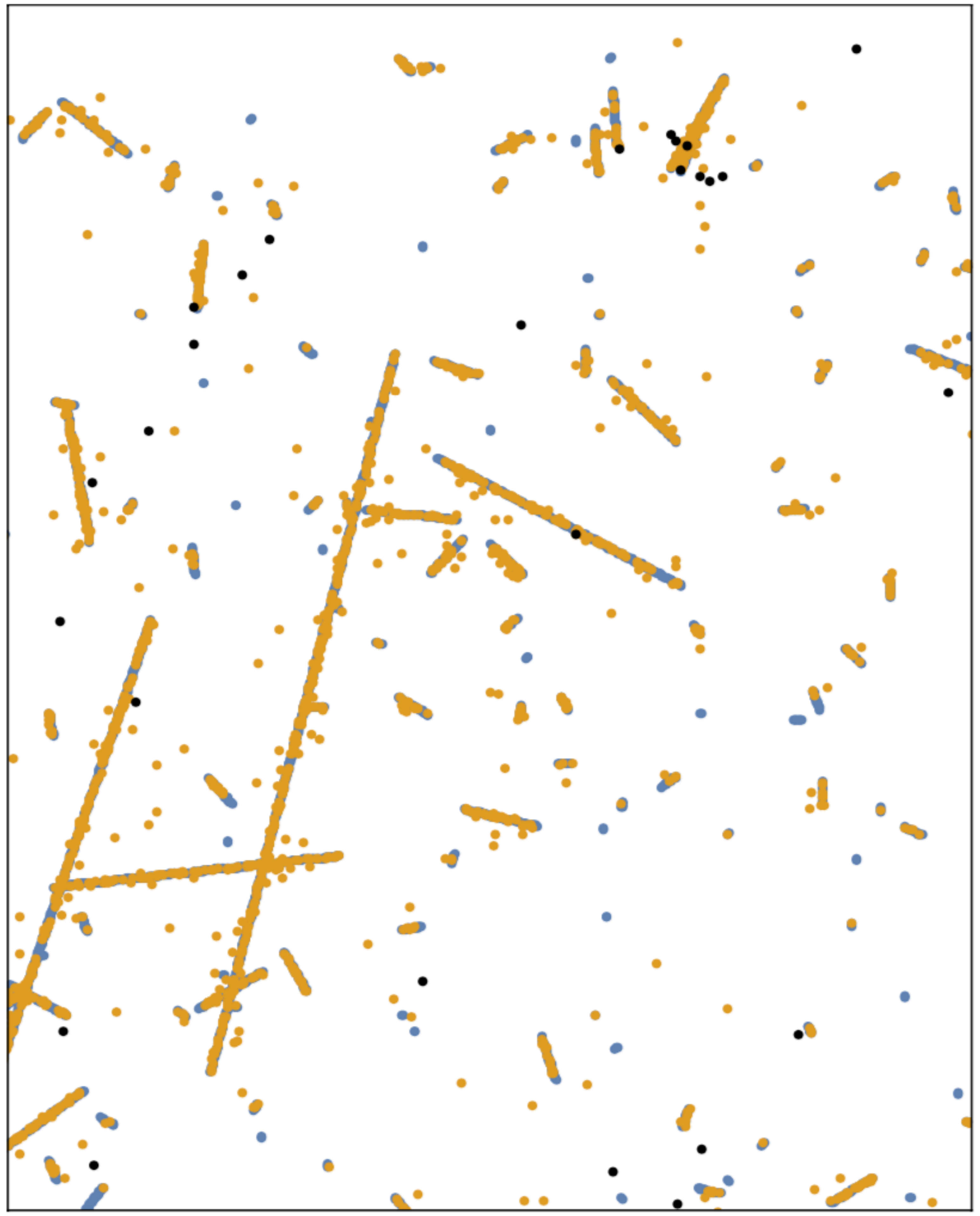
Simulation results (preliminary)

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

SENSEI image

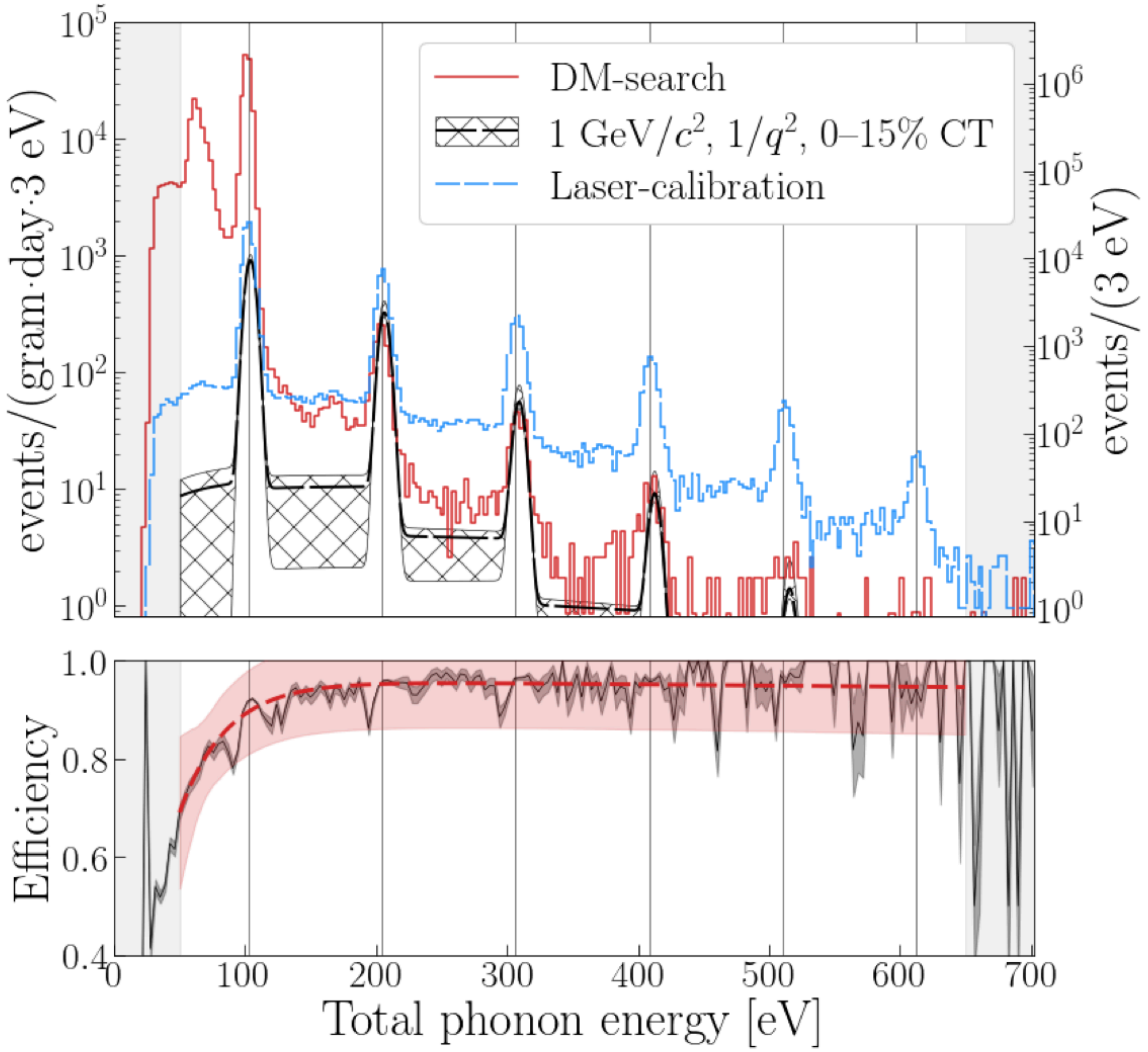


High energy tracks+Cherenkov+Radiative recombination



Excess at SuperCDMS HVeV

SuperCDMS, 2020

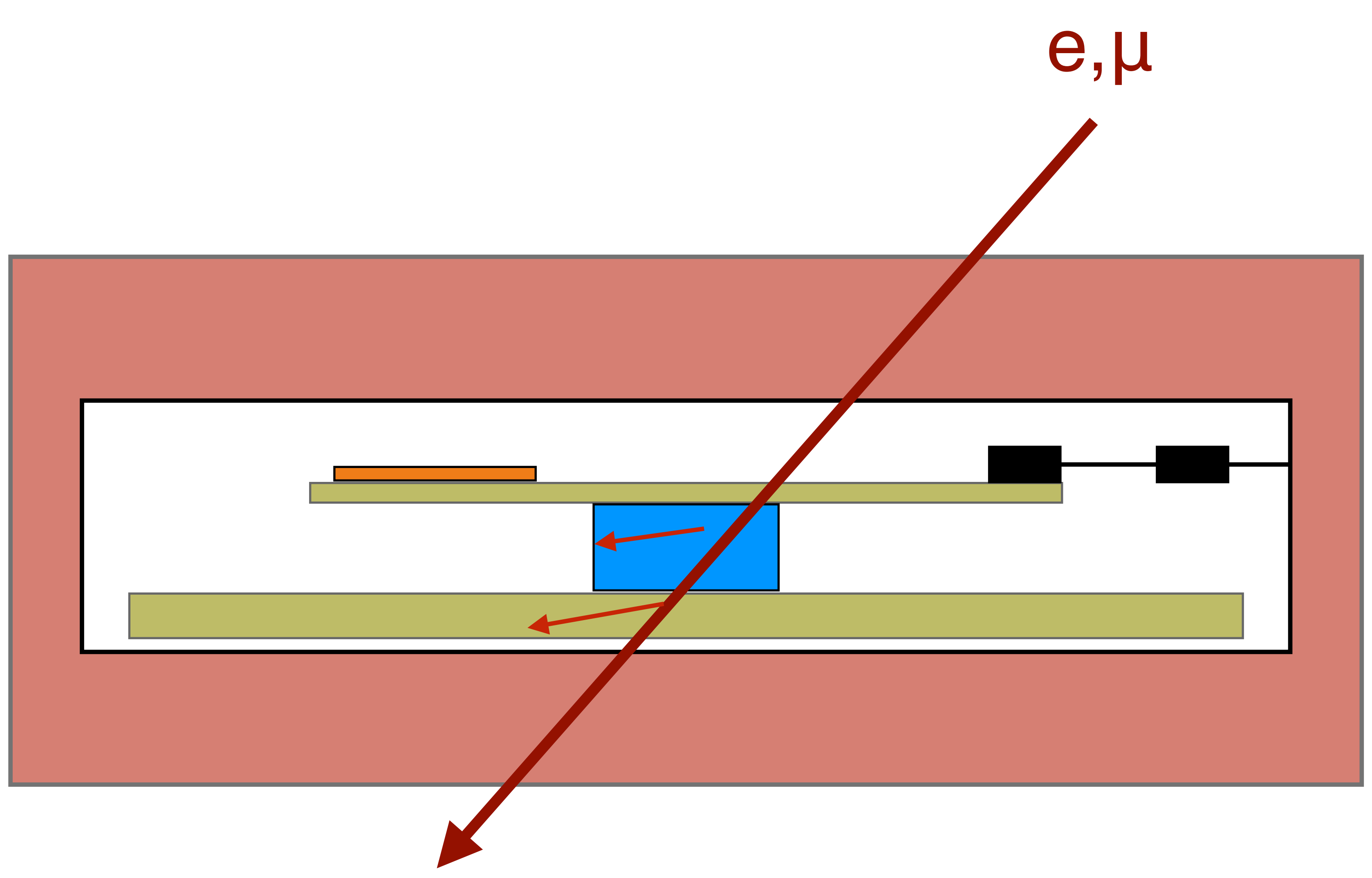


	HVeV Rates $(\text{g-day})^{-1}$	
	100 V	60 V
R_1	$(149 \pm 1)10^3$	$(165 \pm 2)10^3$
R_2	$(1.1 \pm 0.1)10^3$	$(1.2 \pm 0.2)10^3$
R_3	207 ± 40	245 ± 86
R_4	53 ± 20	77 ± 48
R_5	16 ± 11	20 ± 25
R_6	5 ± 6	10 ± 17

- Independent of voltage
- Single electron events are likely to come from leakage current
- The origin of 2-6 electron events are unknown

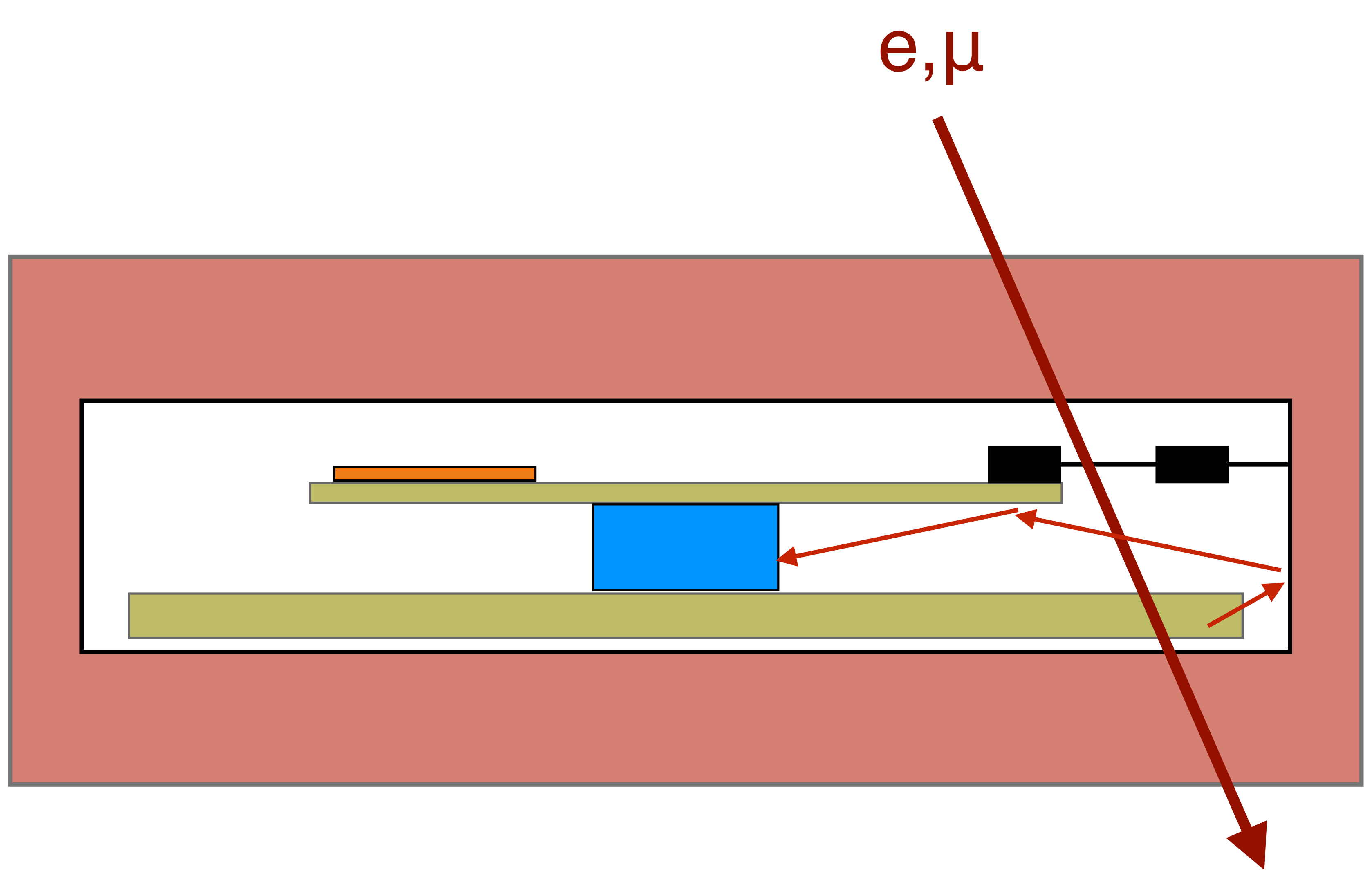
Cherenkov radiation at SuperCDMS HVeV

Tracks hitting detectors



Can be vetoed by timing information

Tracks hitting PCBs, connectors



Cannot be vetoed

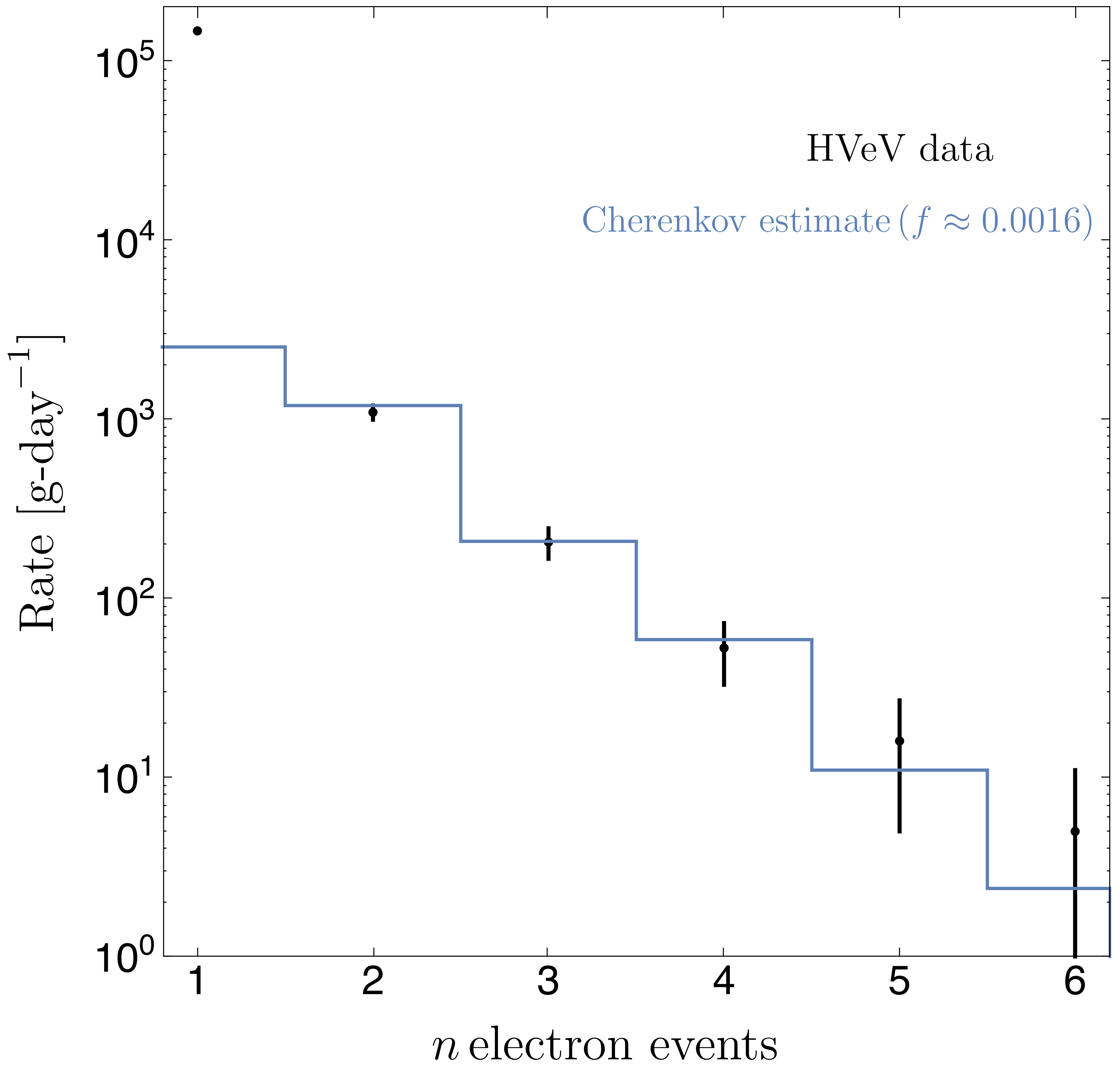
Estimation of Cherenkov events

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

f : efficiency of a Cherenkov photon being recorded at the detector

Best fit: $f \approx 1.6\times10^{-3}$

- Small f indicates a lot of Cherenkov photons generated
- One parameter fits the spectrum for 2-6 electron events



Mitigation strategies

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

- Active and passive shielding
- Radio-pure materials
- Multiple detectors (remove coincident events)

Mitigation strategies

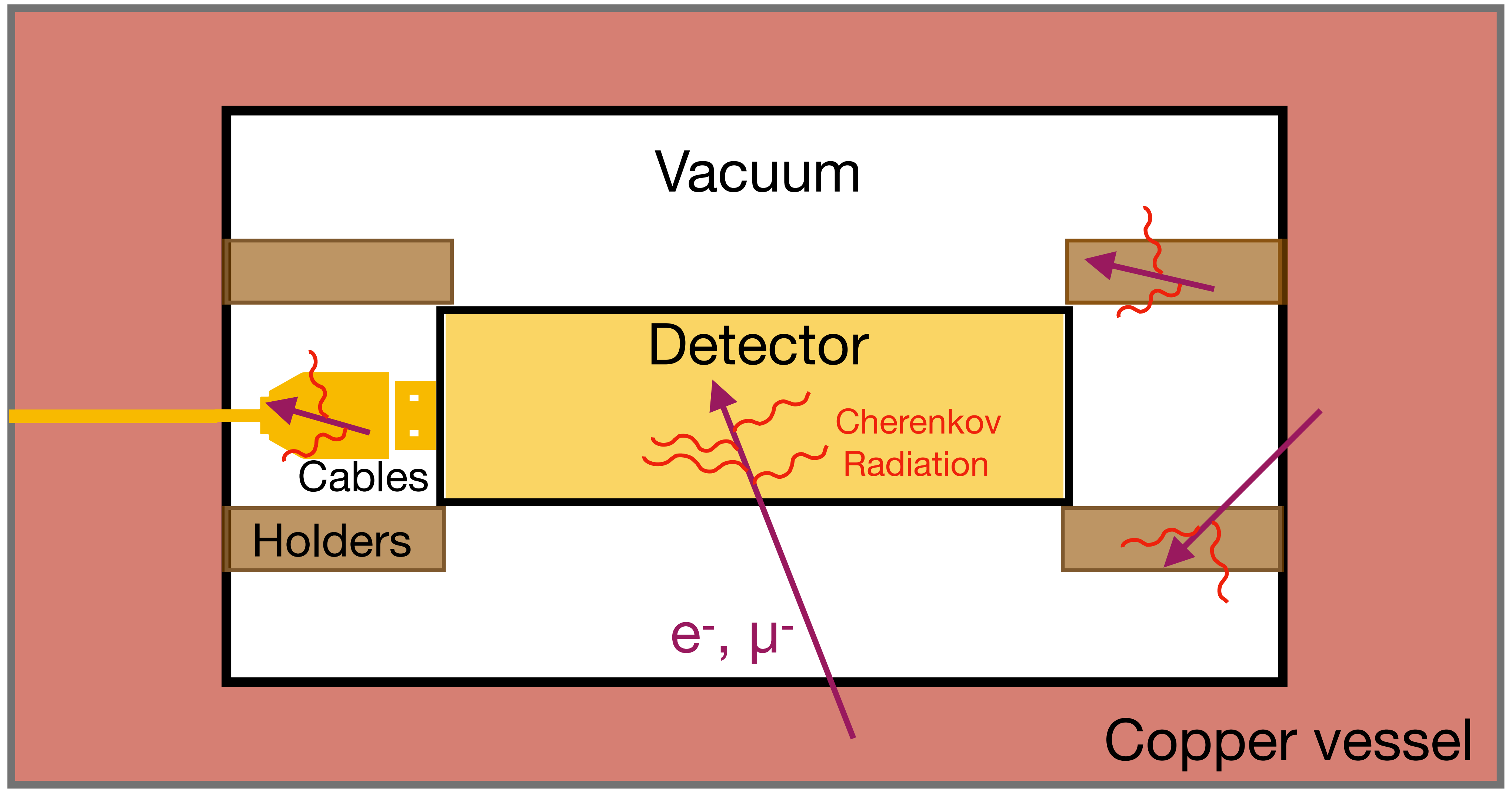
PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

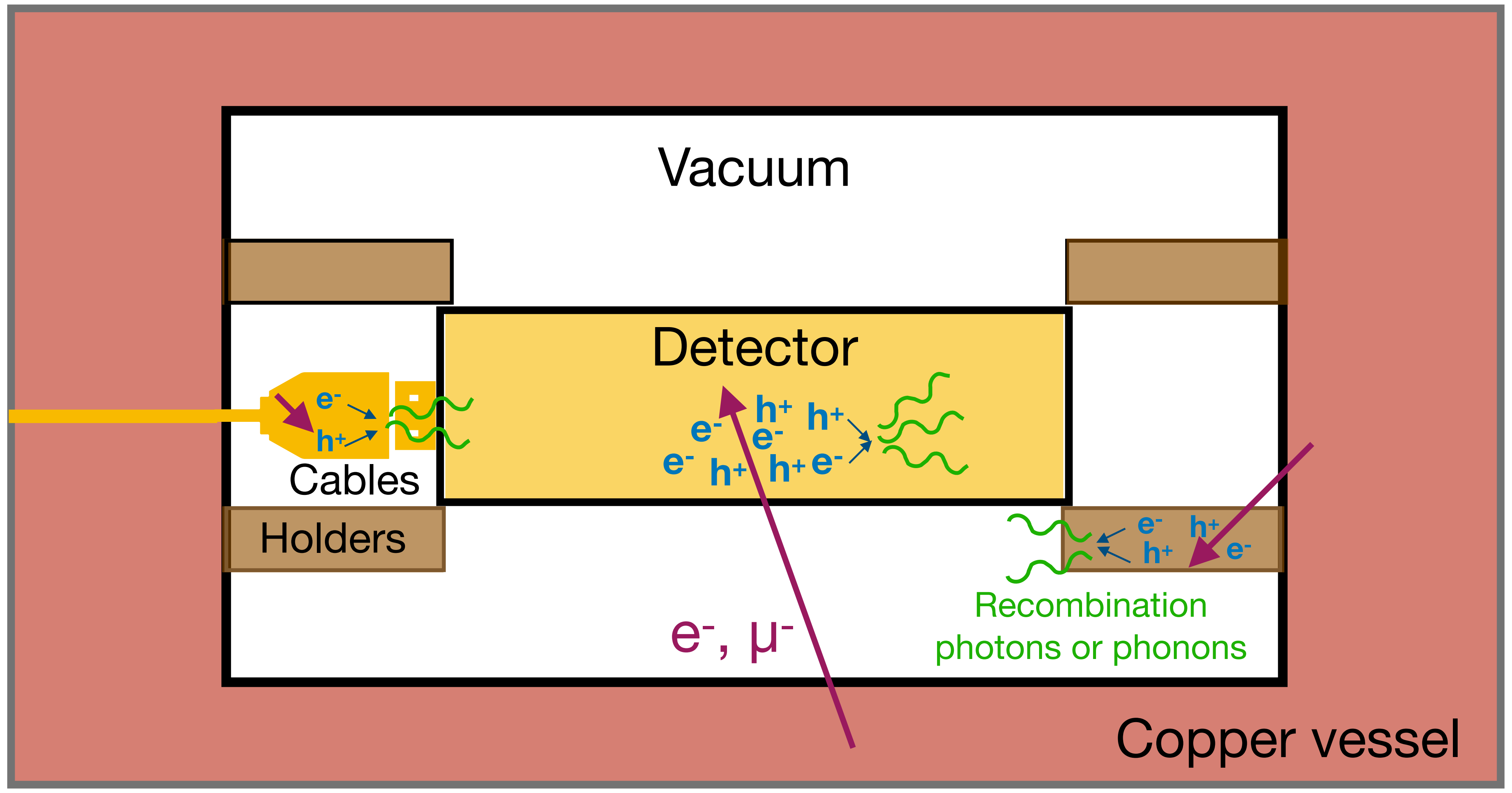
- Active and passive shielding
- Radio-pure materials
- Multiple detectors (remove coincident events)
- Minimizing non-conductive/un-instrumented materials near detector
- Thinning the doped region of the CCD
- Reduce the reflectivity of inner copper wall

First proposed in our work

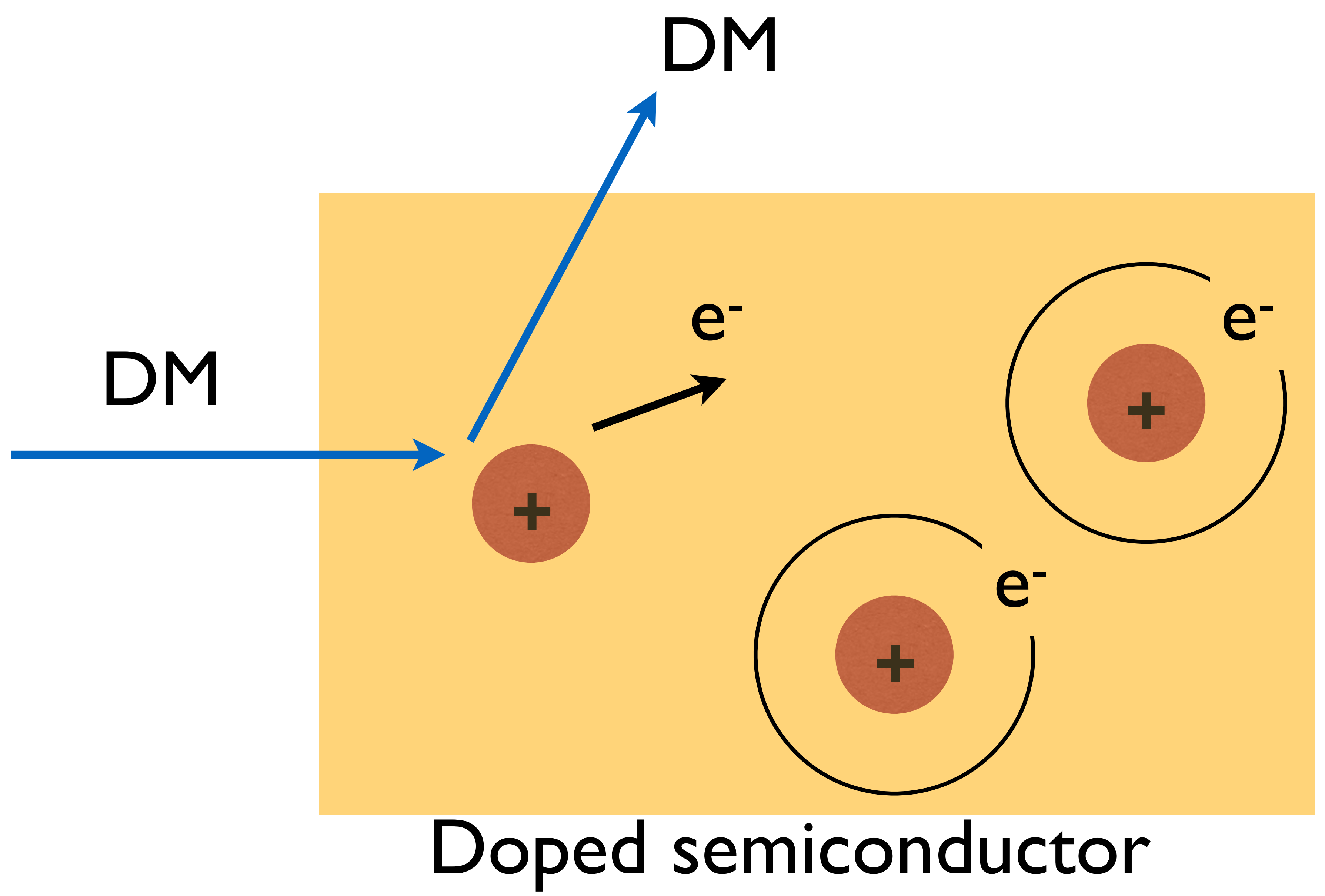
Summary of part I

- Many sub-GeV dark matter experiments observe excess events
- Cherenkov radiation and radiative recombination are likely to explain the excess in SENSEI and SuperCDMS HVeV
- Several mitigation strategies can be applied to reduce these backgrounds





Part II New targets for probing sub-MeV DM



Probing sub-MeV DM

Hochberg, Zhao, Zurek, 2015
Schutz, Zurek, 2016
Knapen, Lin, Pyle, Zurek, 2017
Hochberg, Kahn, Lisanti, Zurek, et.al, 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

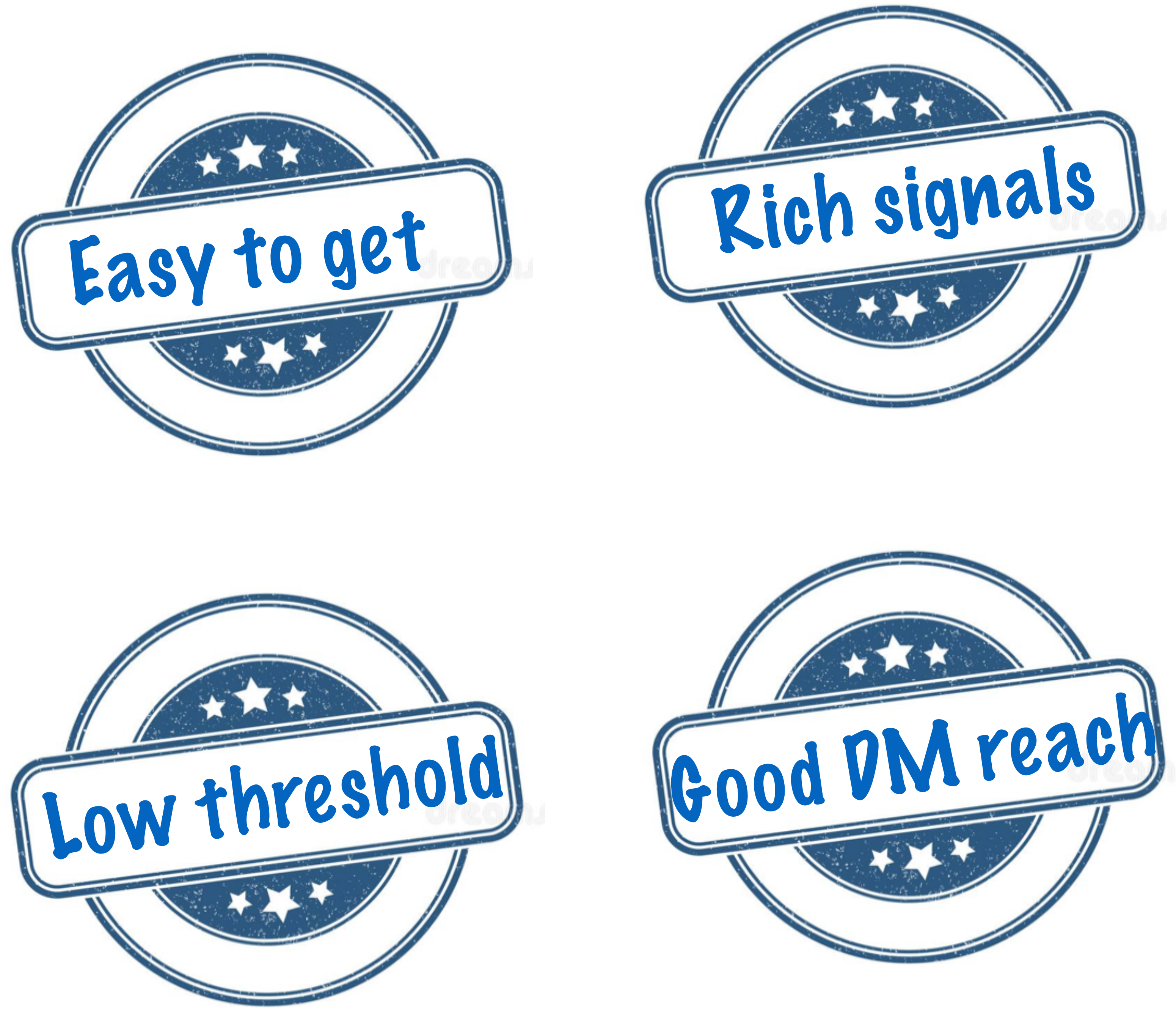
Low threshold can probe low DM masses

Dirac materials, superfluid helium, Ge detector with charge amplification …

Probing sub-MeV DM

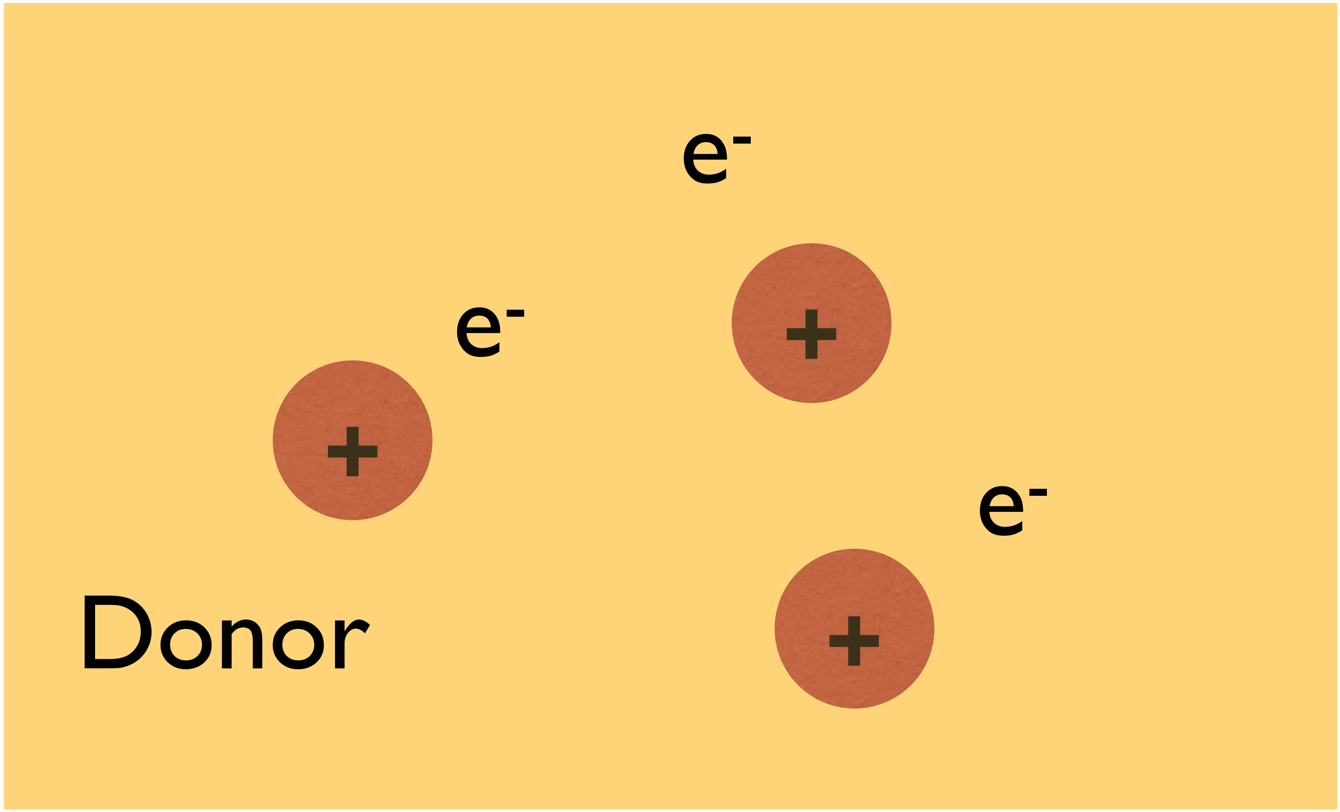
Target	Signal	Threshold	DM Mass range
Nobel Liquid	electron ionization	~10 eV (atom ionization)	>10 MeV
Semiconductors	eh pairs	~1eV (bandgap)	>MeV
Polar materials	phonon	10-100meV	>10-100 keV
Doped Semiconductors	phonon/ electron ionization/ eh pairs	10-100meV	>10-100 keV
Superconductor	phonon/ quasiparticle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

Doped semiconductors

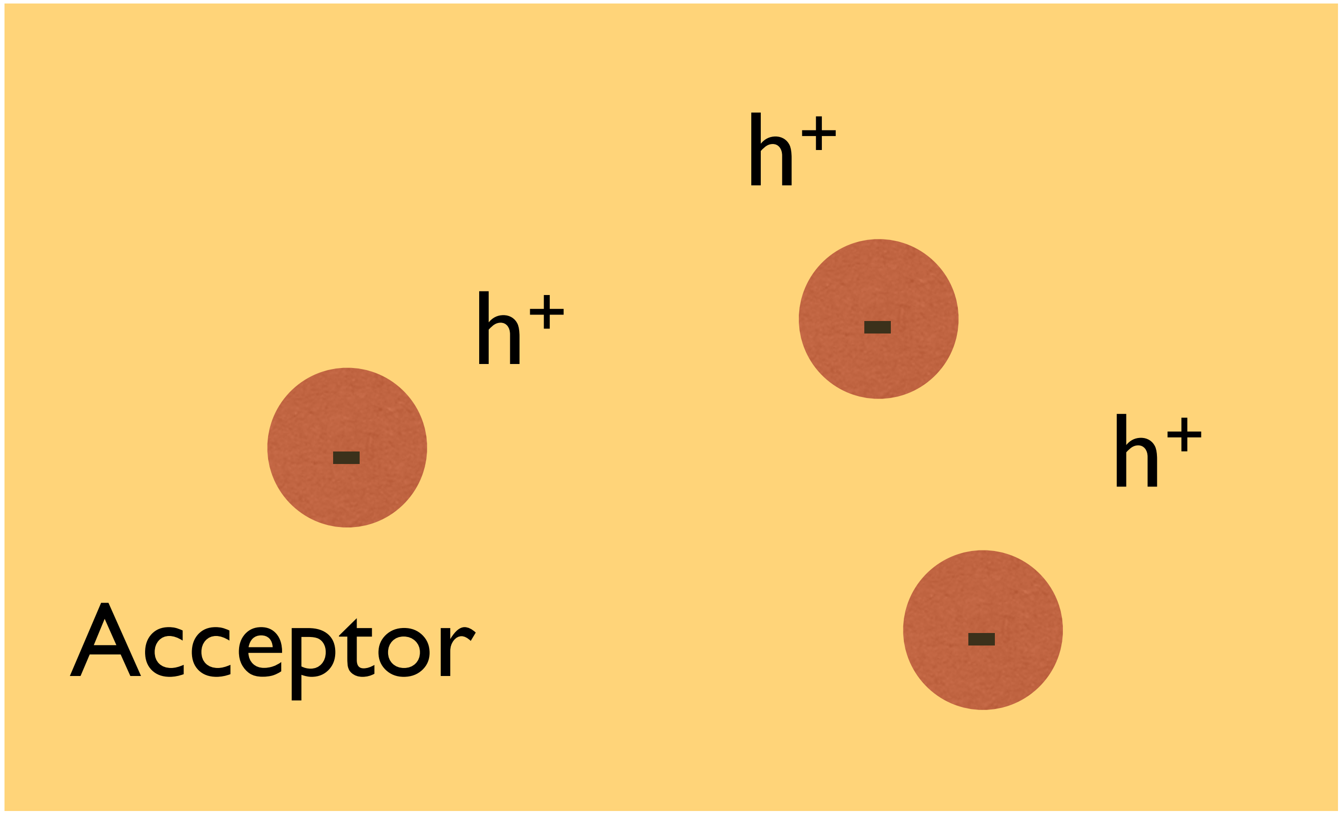


Doped semiconductors

n-type semiconductor



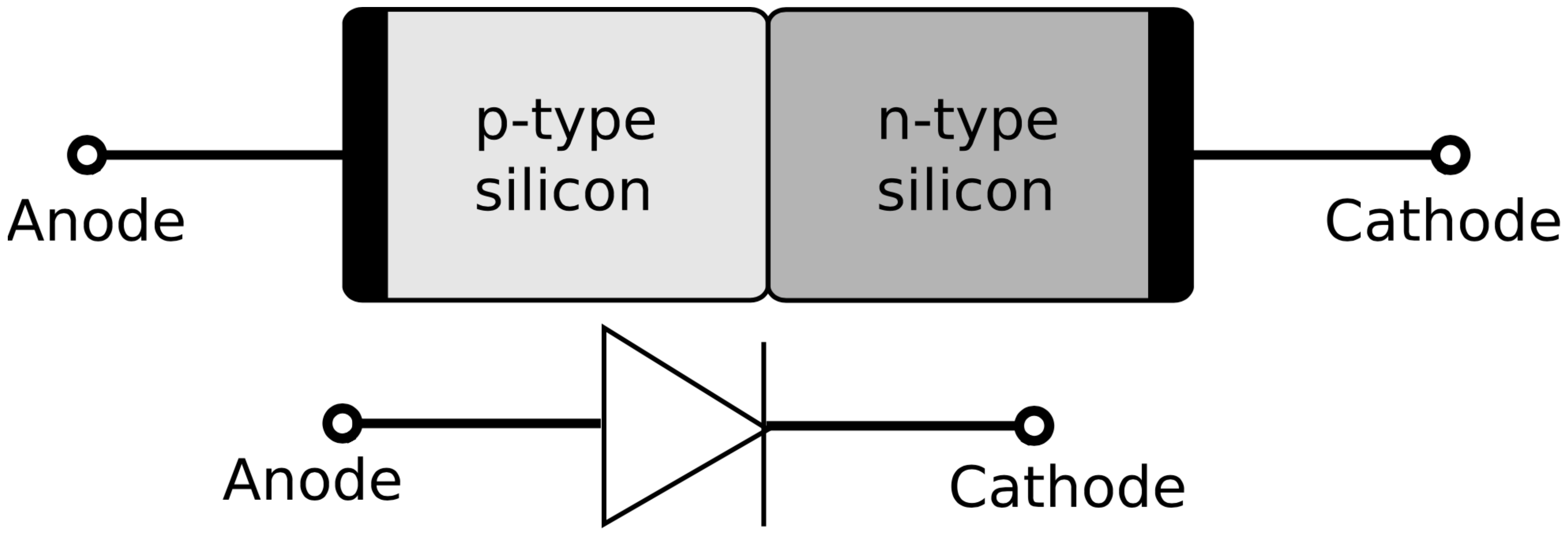
p-type semiconductor



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

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

Commonly used: p-n junction, diodes



Doped semiconductors

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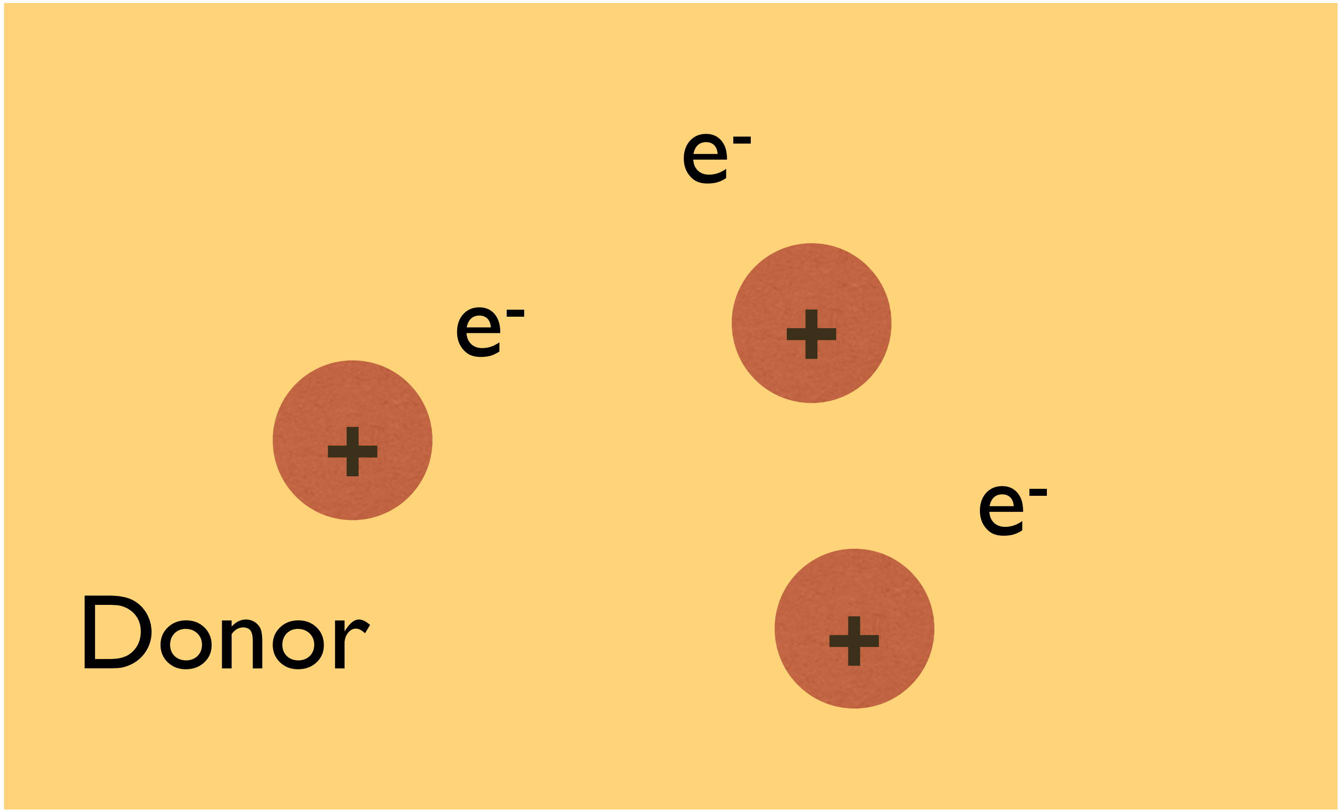

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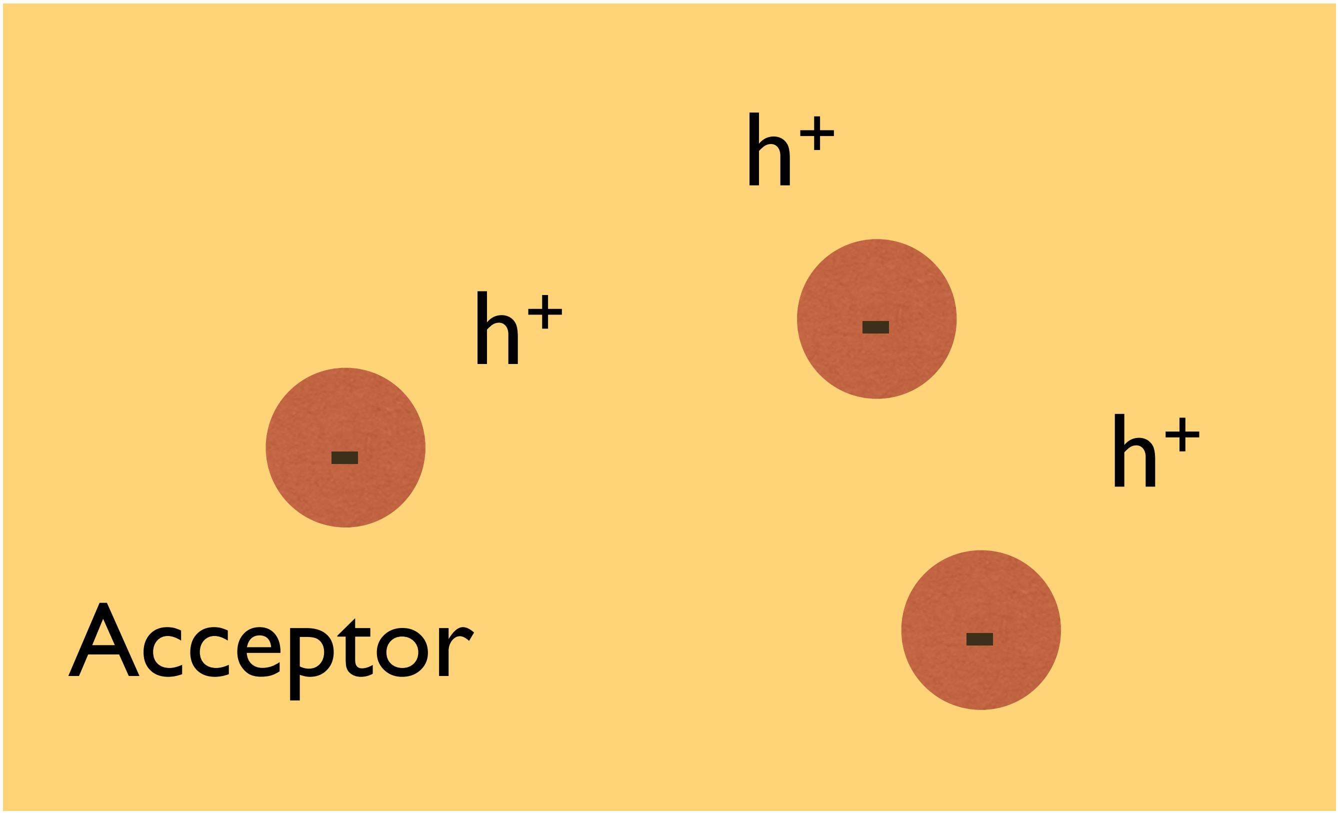

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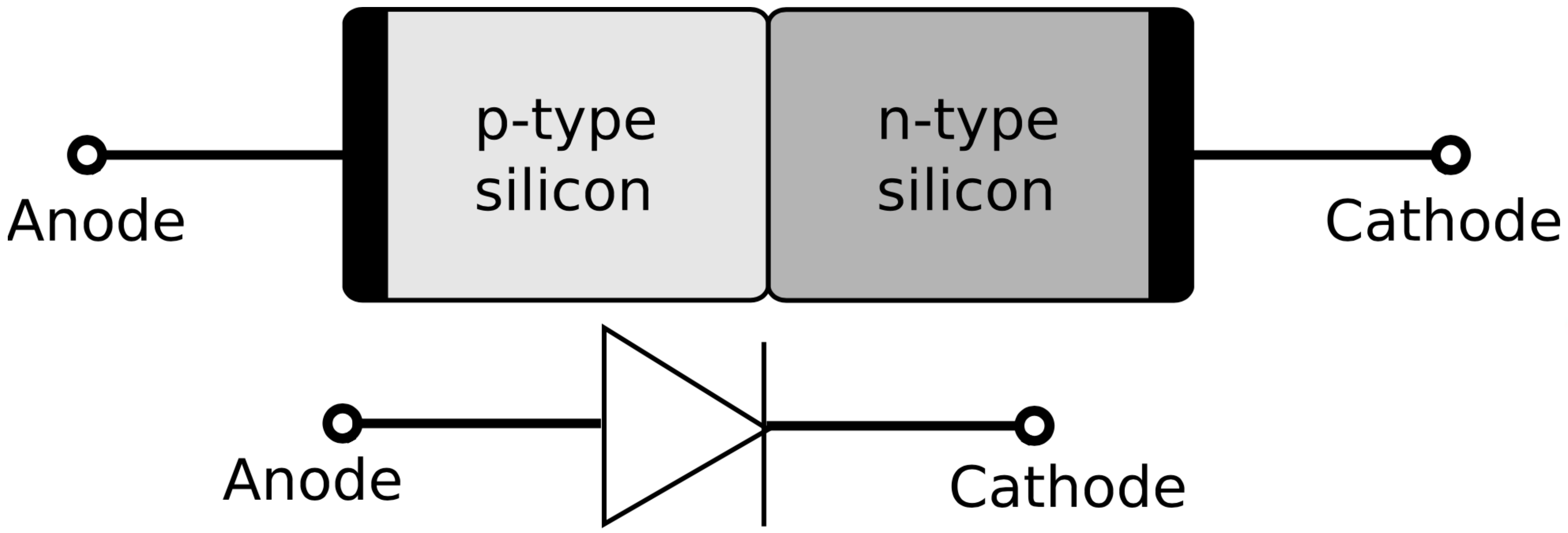
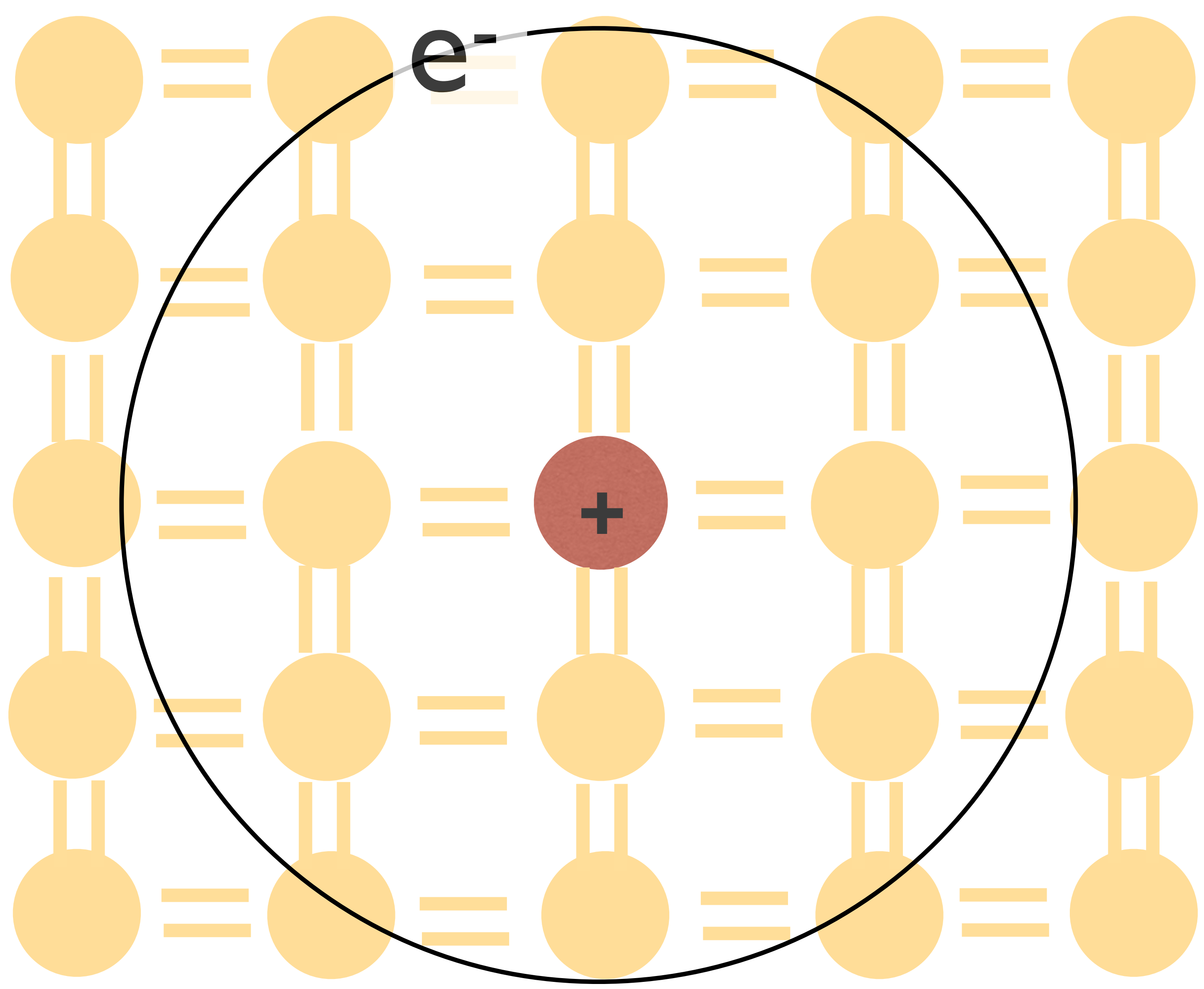
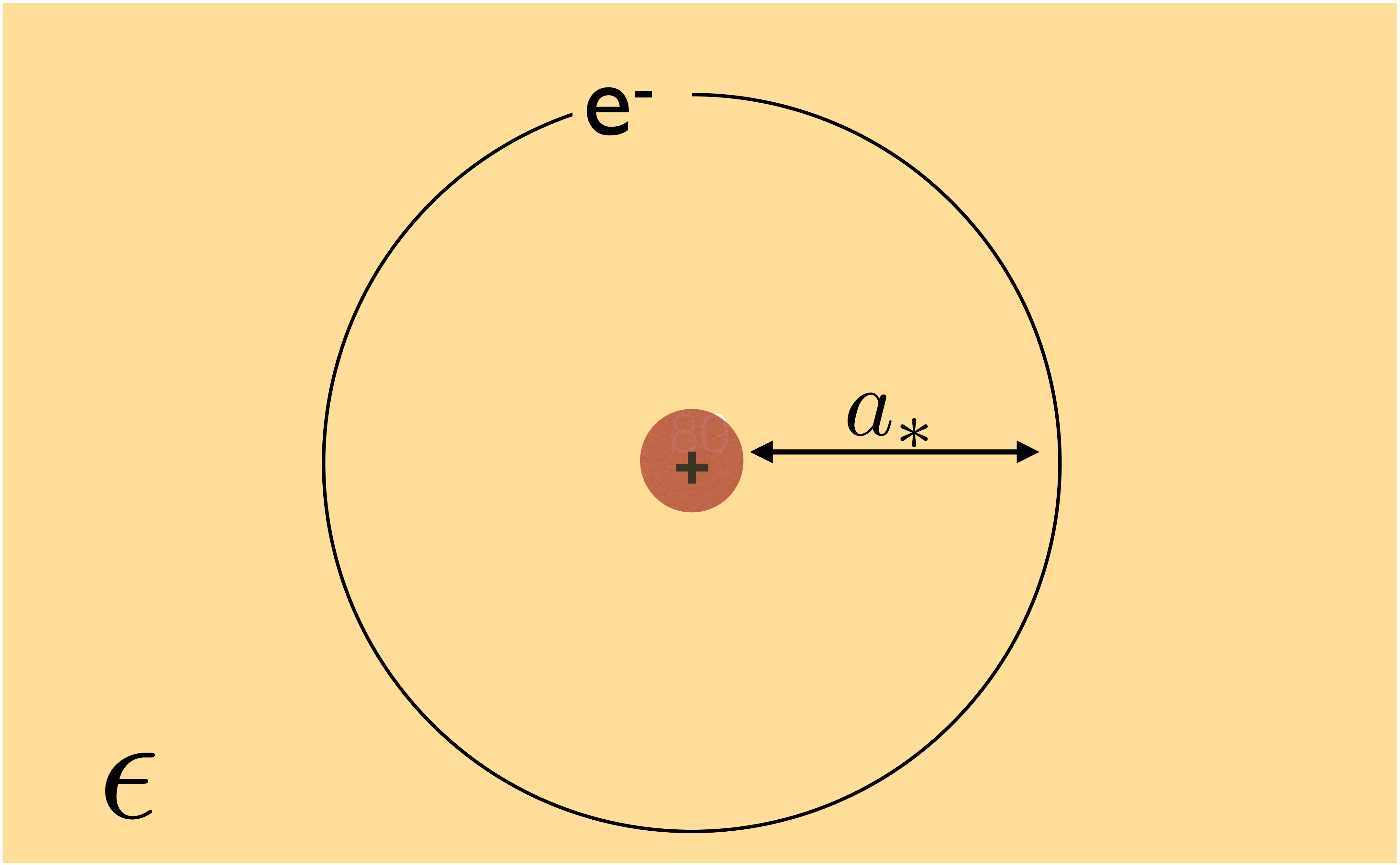


Dopants in semiconductors

Dopants: "Hydrogen atoms" in a background with a large dielectric constant





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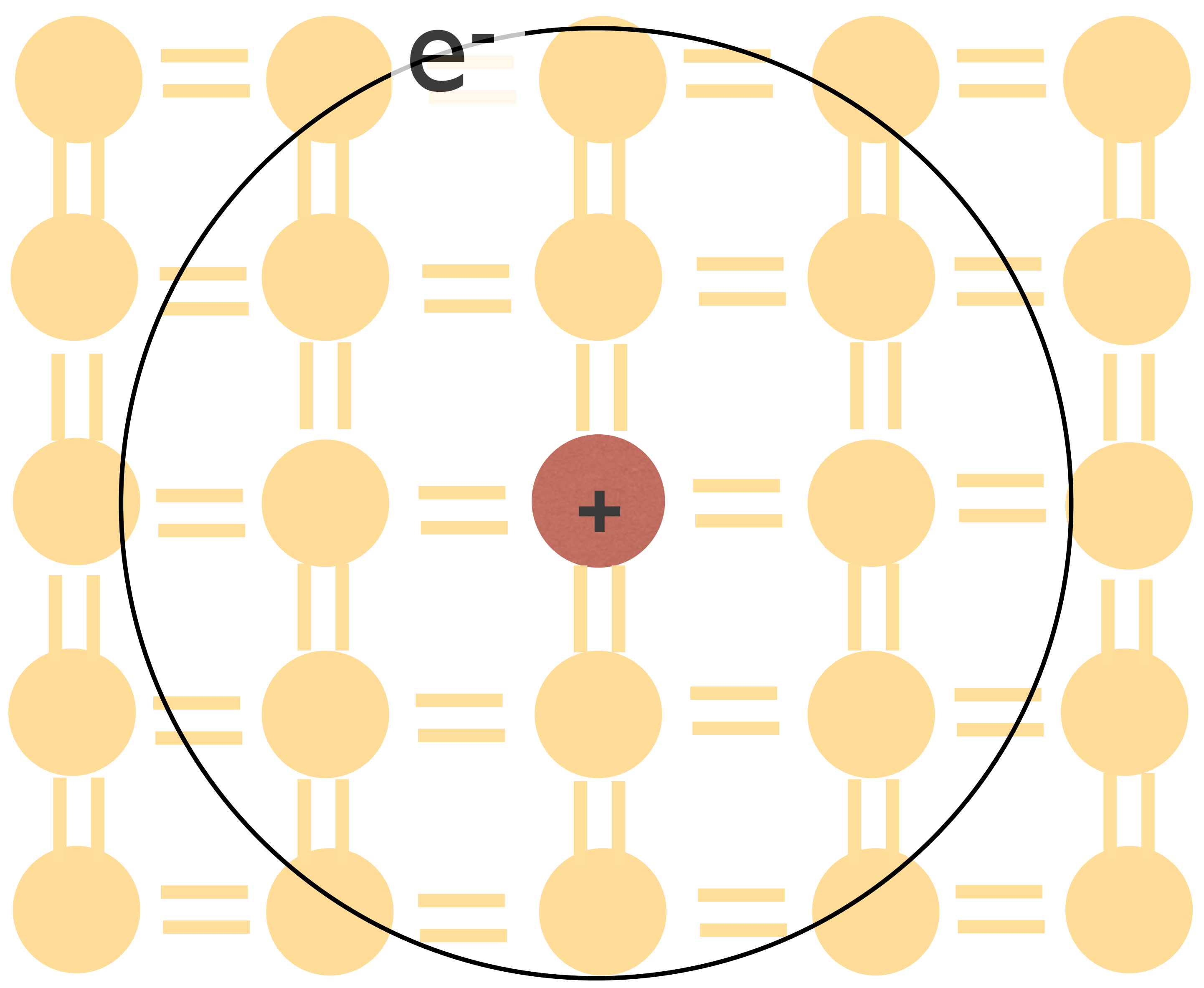
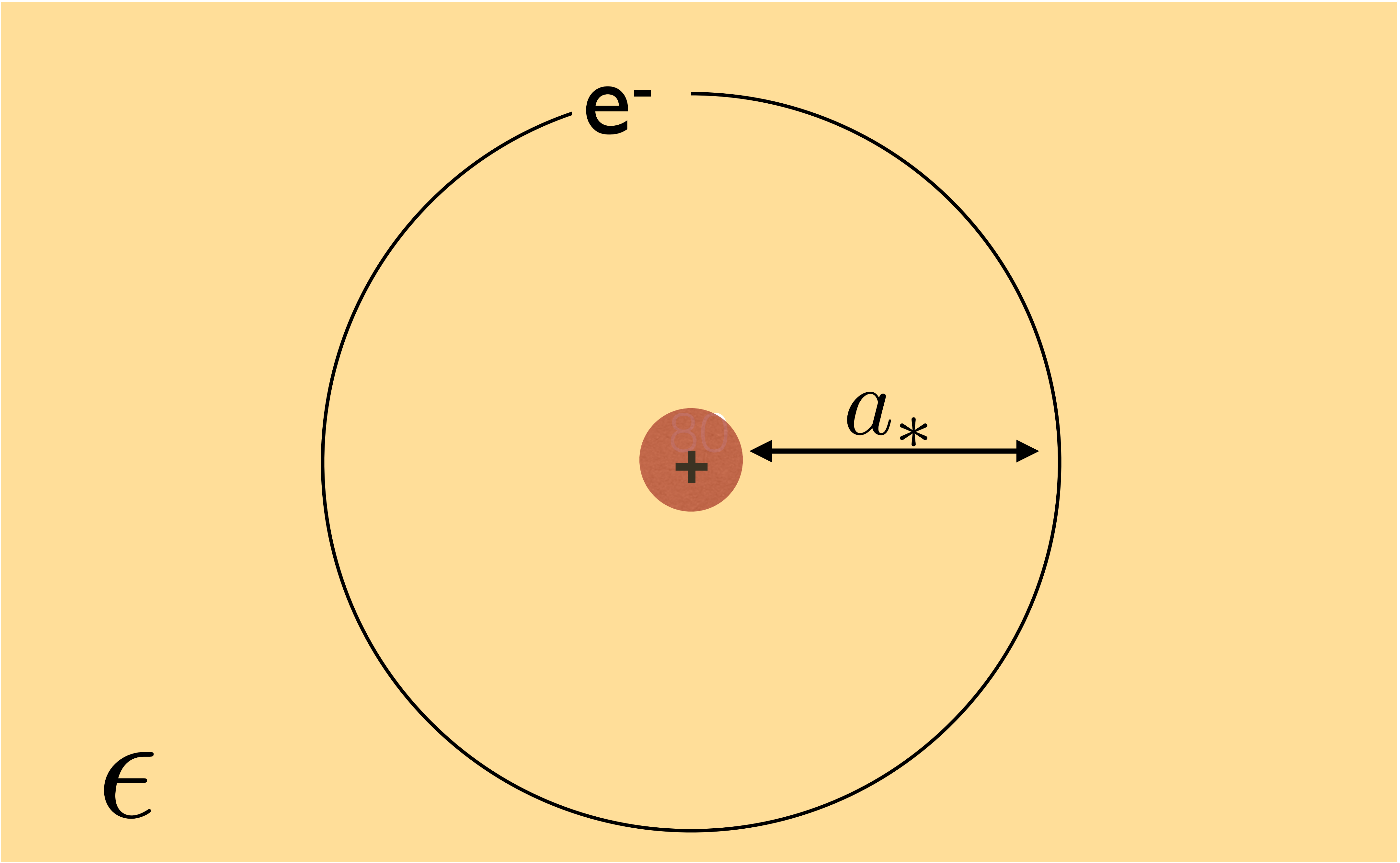




electron effective mass

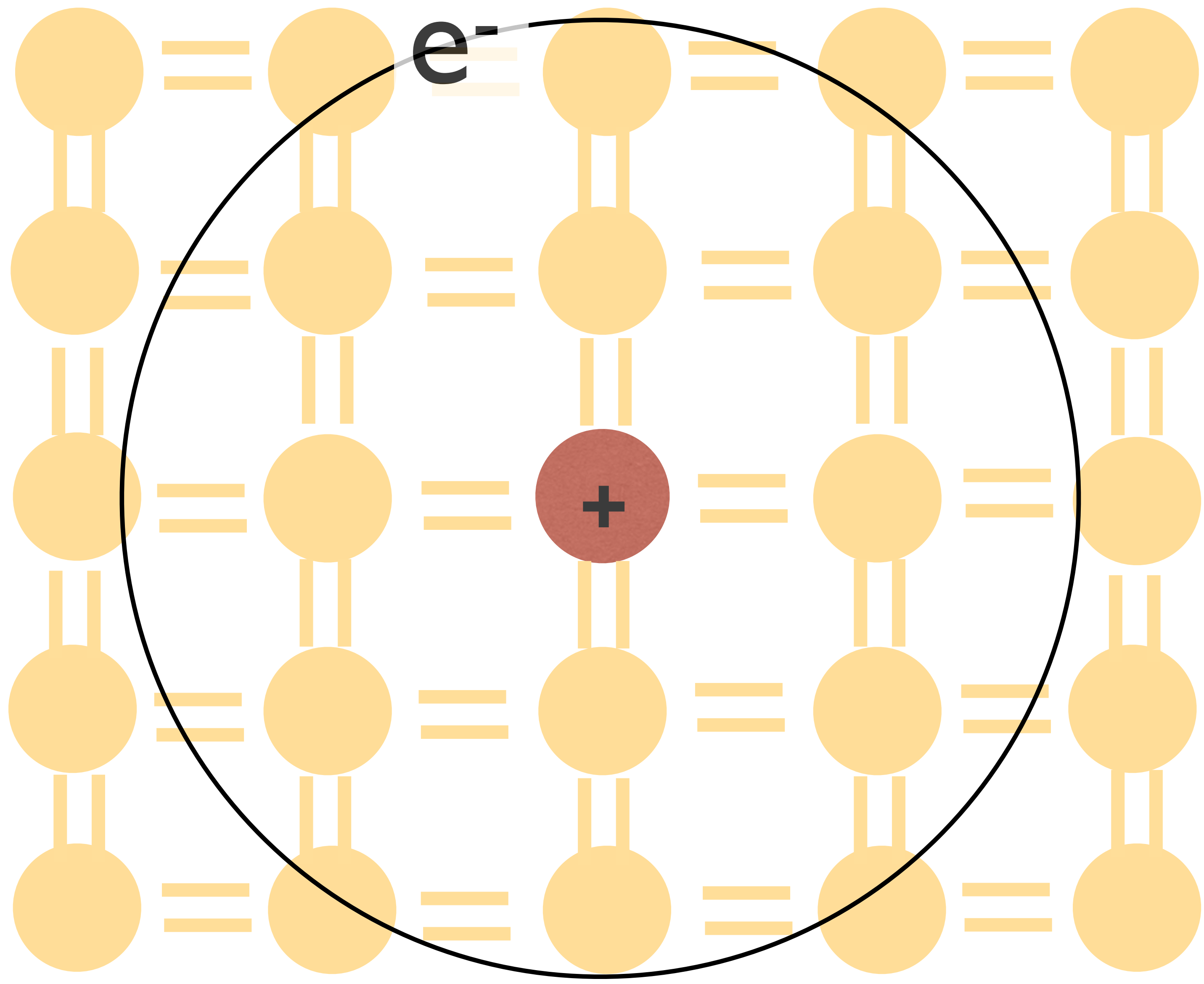
Bohr radius

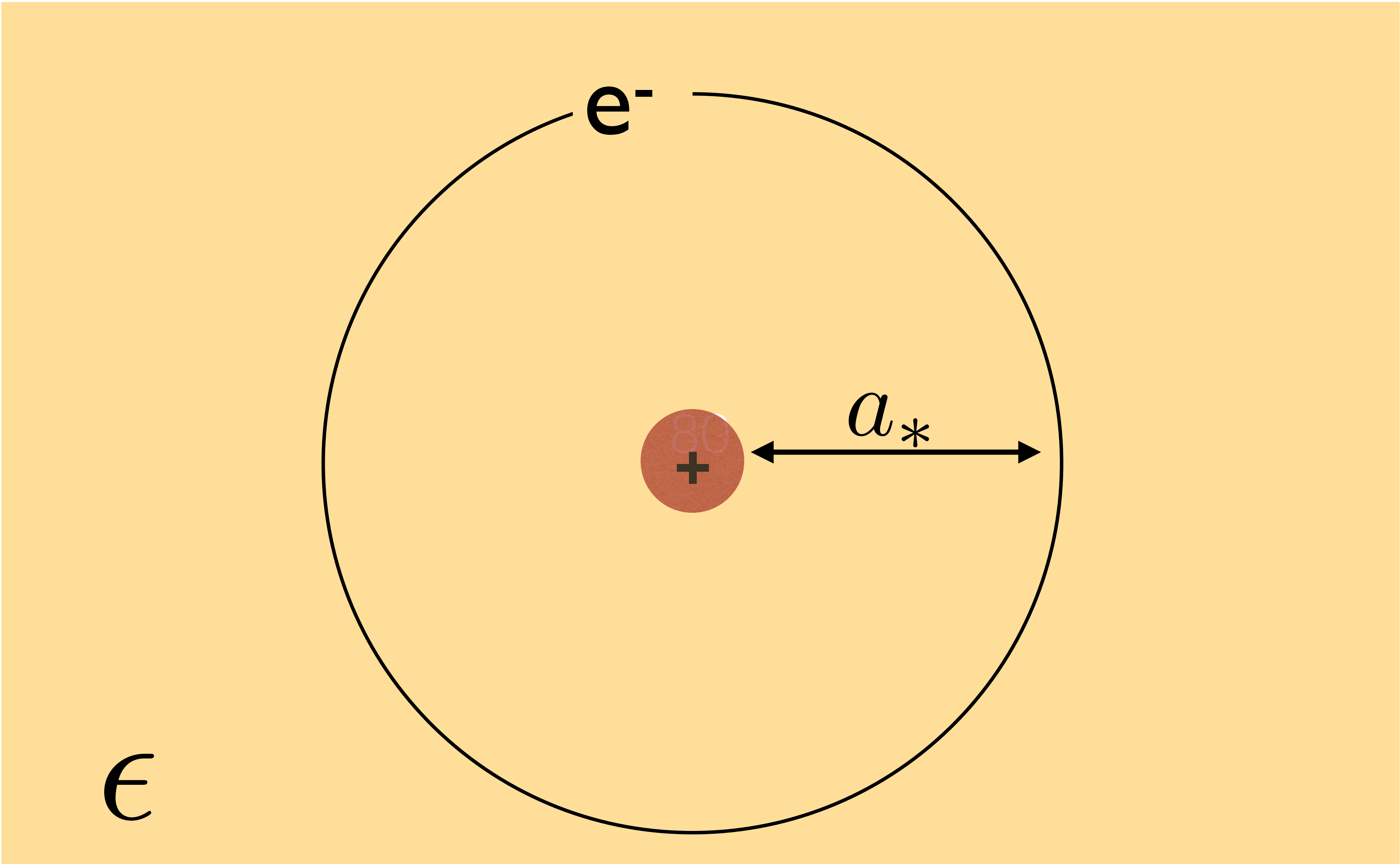
For $\epsilon \sim 10$ $\quad a_* \sim (\frac{\alpha}{\epsilon} m_*)^{-1} \sim O(10)\, a_0 \quad q_* \sim a_*^{-1} \sim O(100)\,\mathrm{eV} \quad v_* = \frac{q_*}{m_*} \sim 10^{-3}$

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

Dopants in semiconductors

Dopants: "Hydrogen atoms" in a background with a large dielectric constant



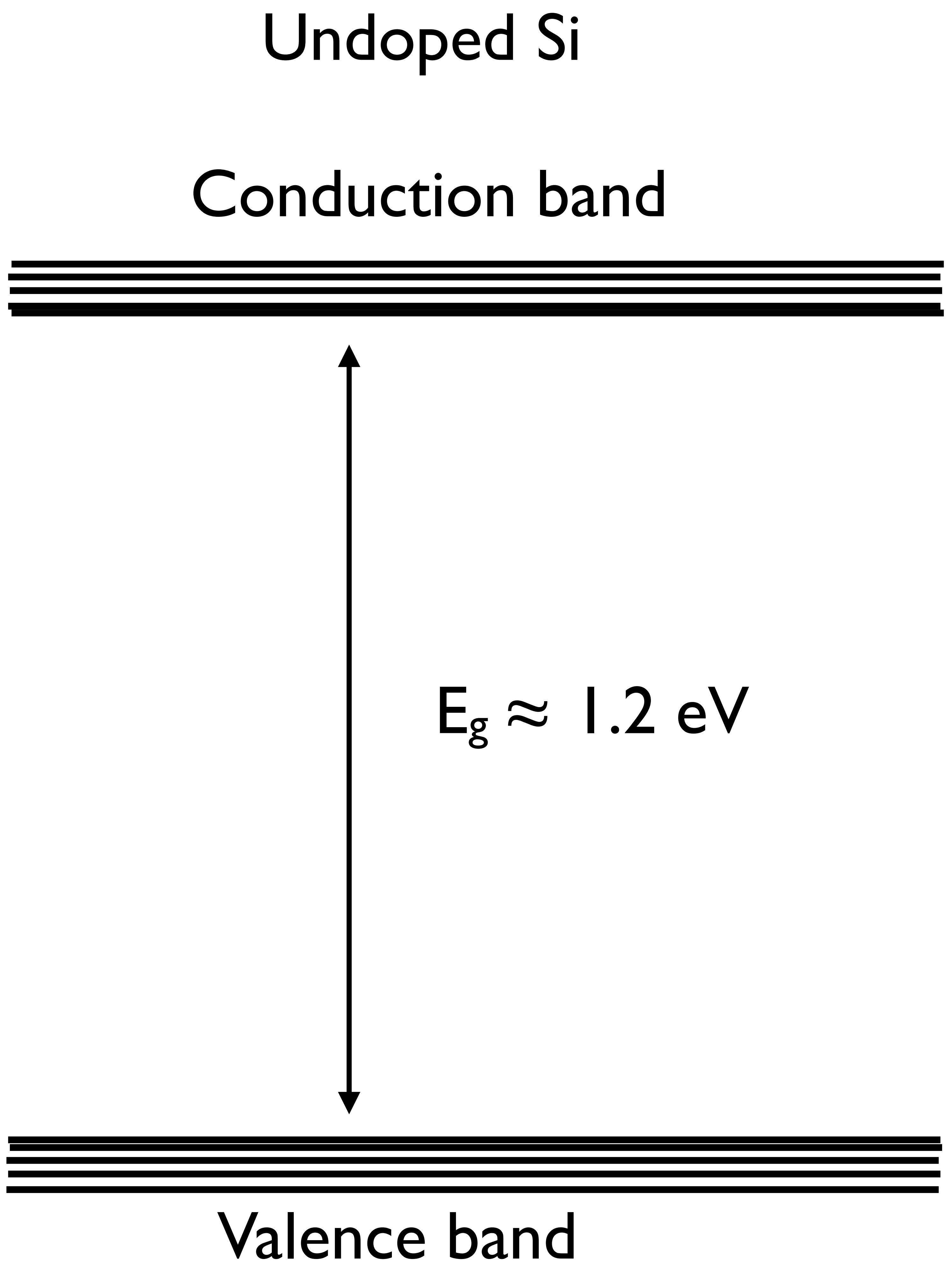


electron effective mass   Bohr radius

For $\epsilon \sim 10$ $\quad a_* \sim (\frac{\alpha}{\epsilon} m_*)^{-1} \sim O(10)\, a_0 \quad q_* \sim a_*^{-1} \sim O(100)\,\mathrm{eV}$

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

Dopant energy levels in silicon



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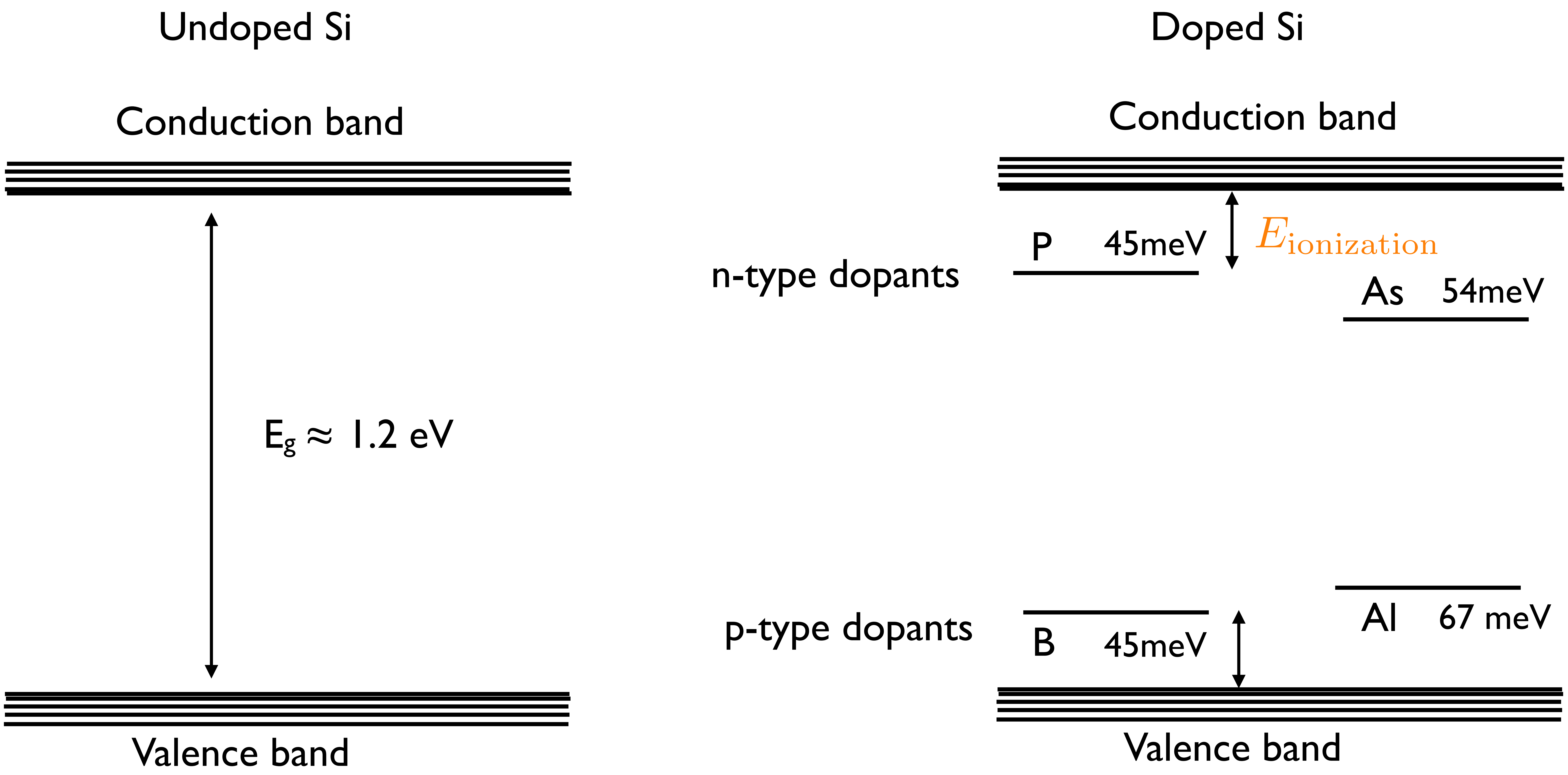
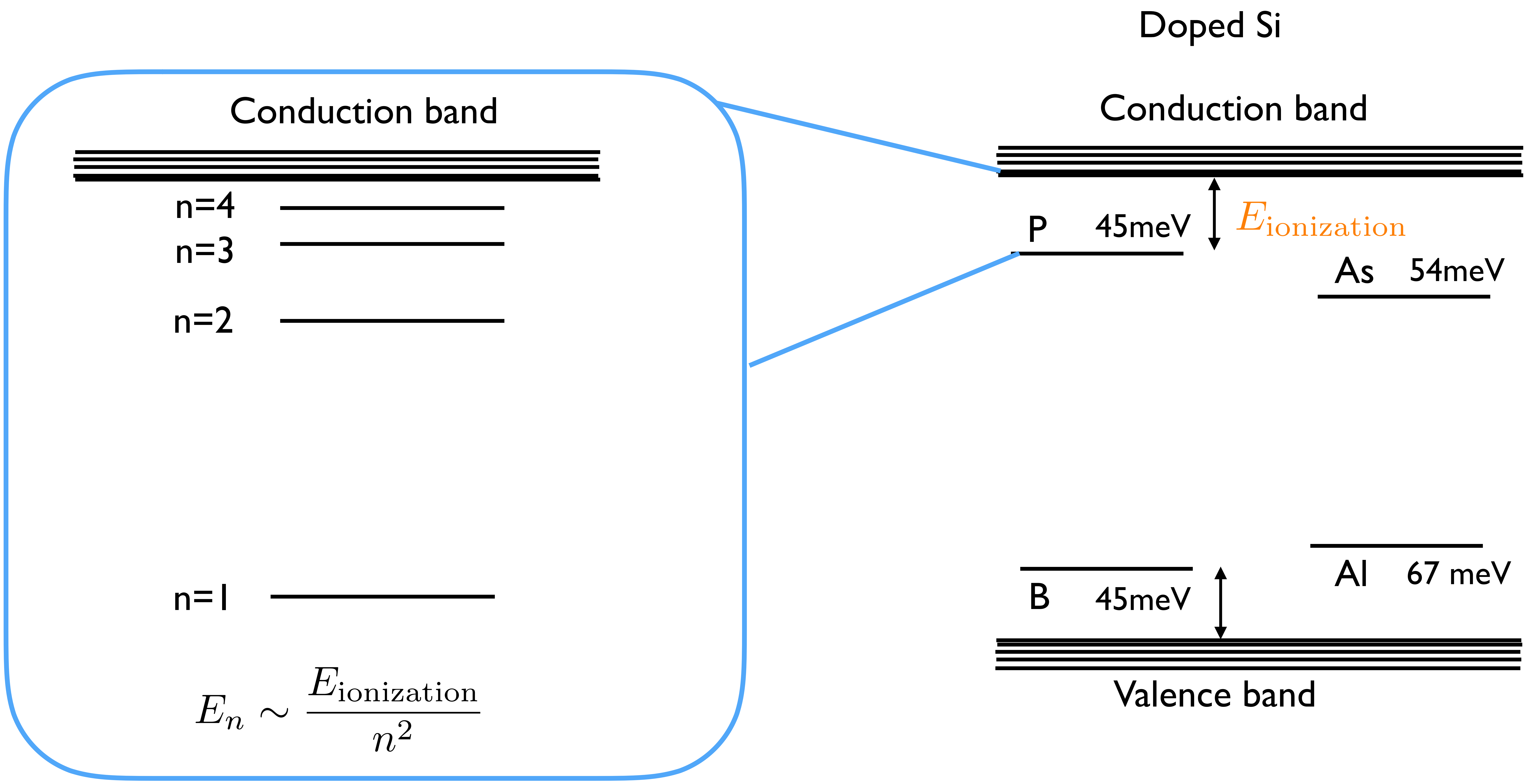


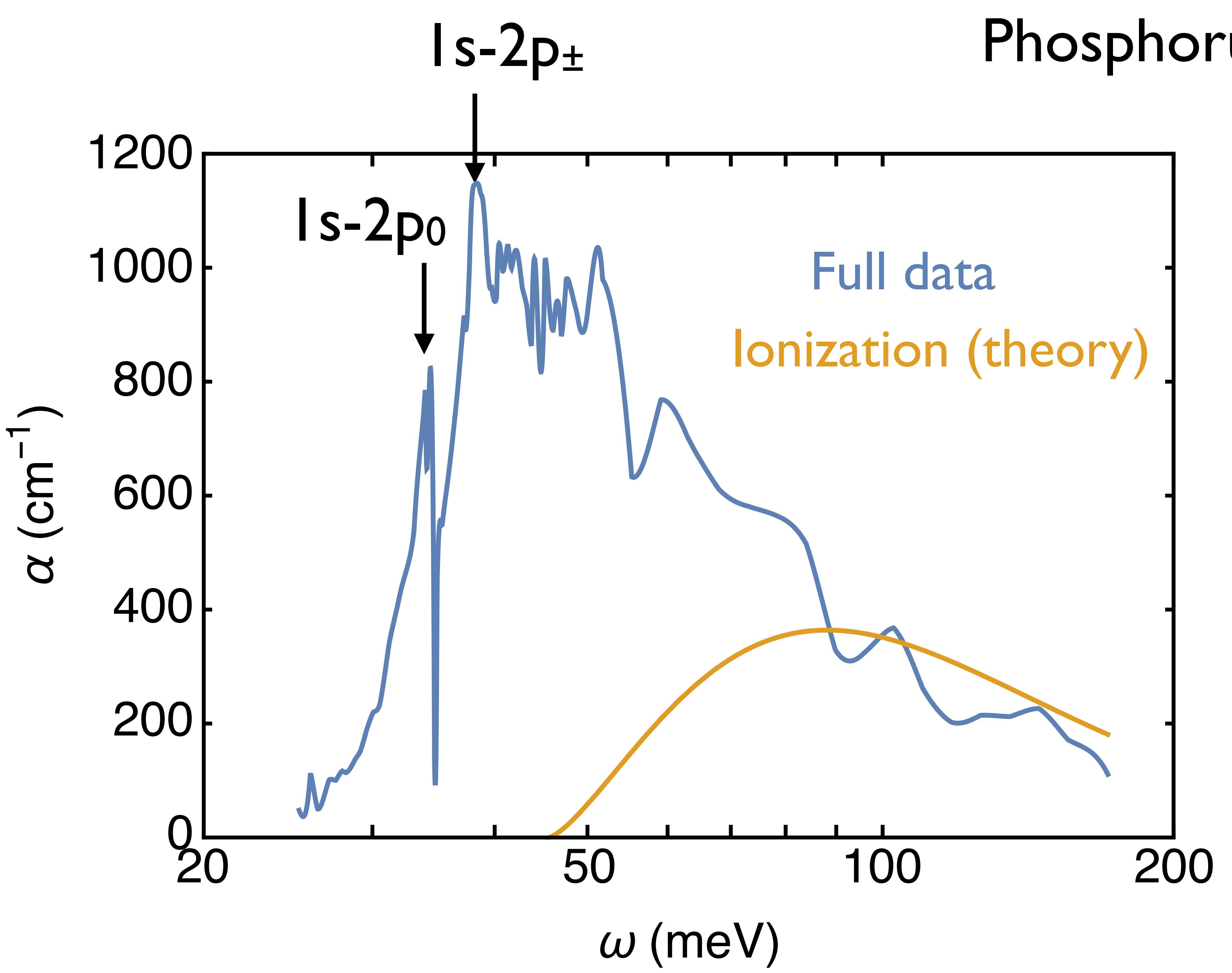
Dopant energy levels in silicon

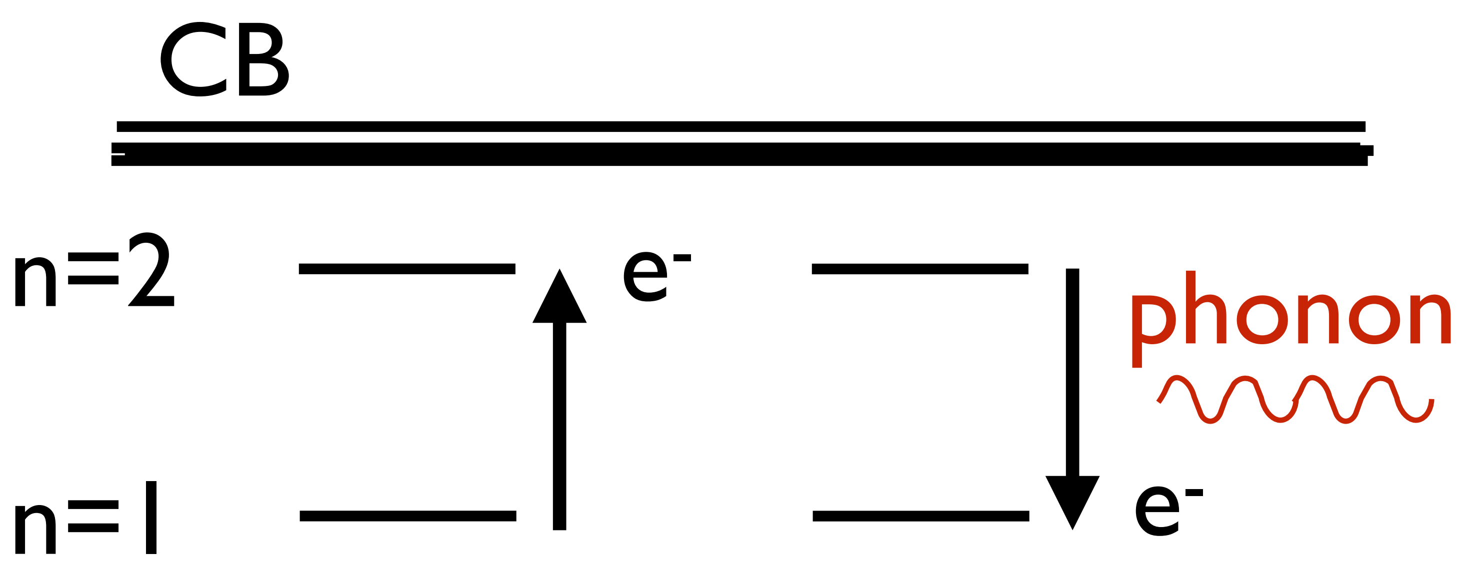


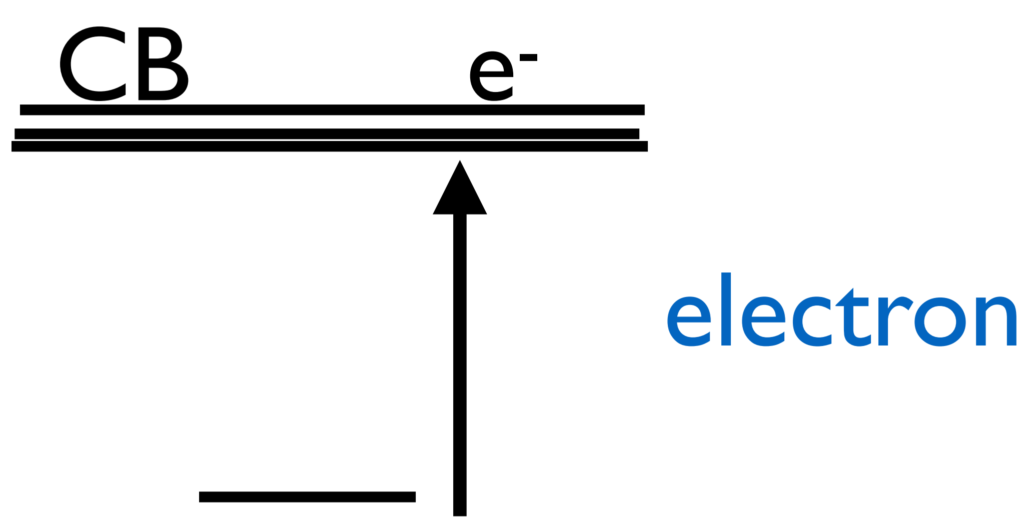
Signals in doped silicon

Gaymann, Geserich, Lohenysen, 95

Phosphorus doped Si @10K n_d=0.34×10^{18}cm^{-3}







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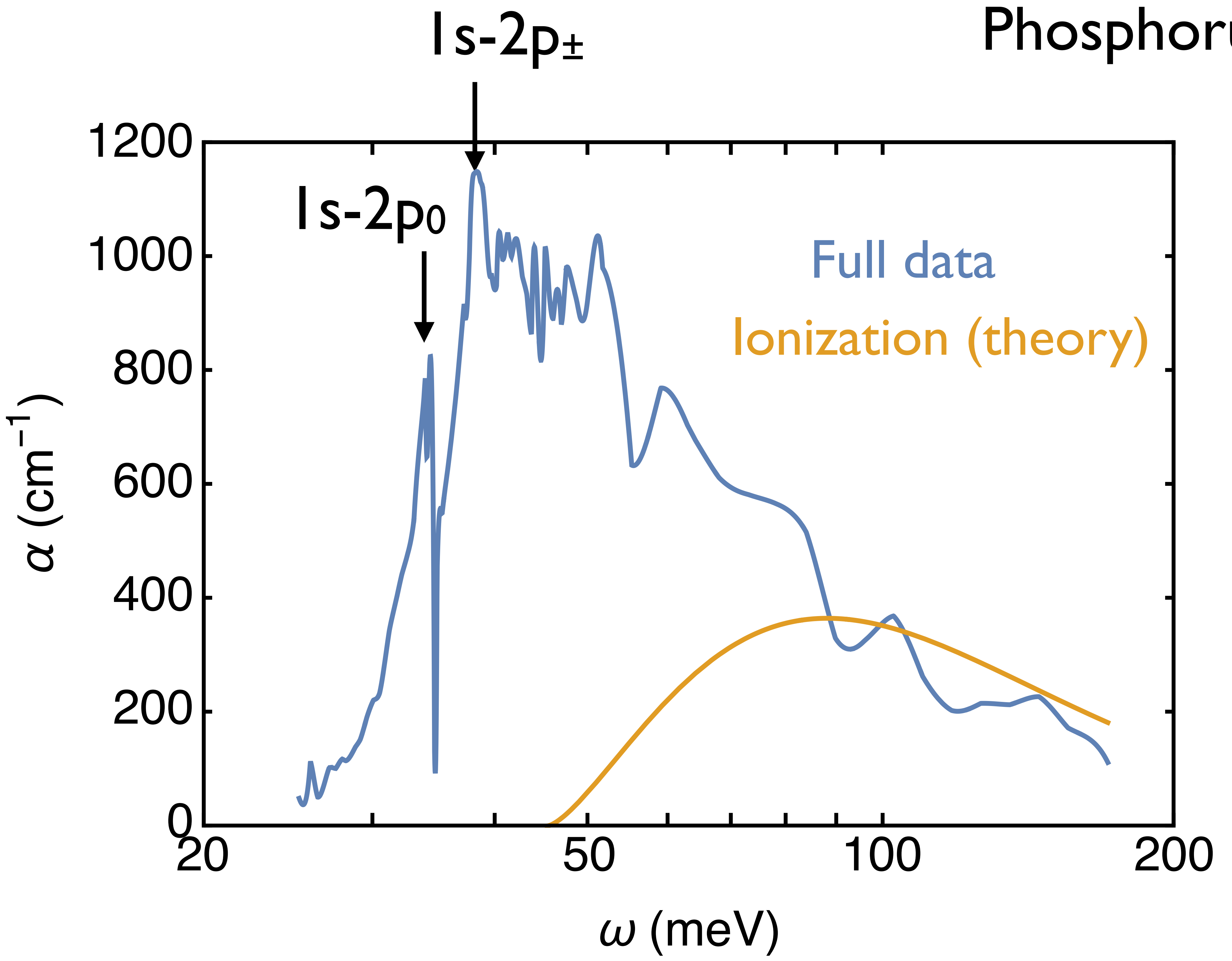

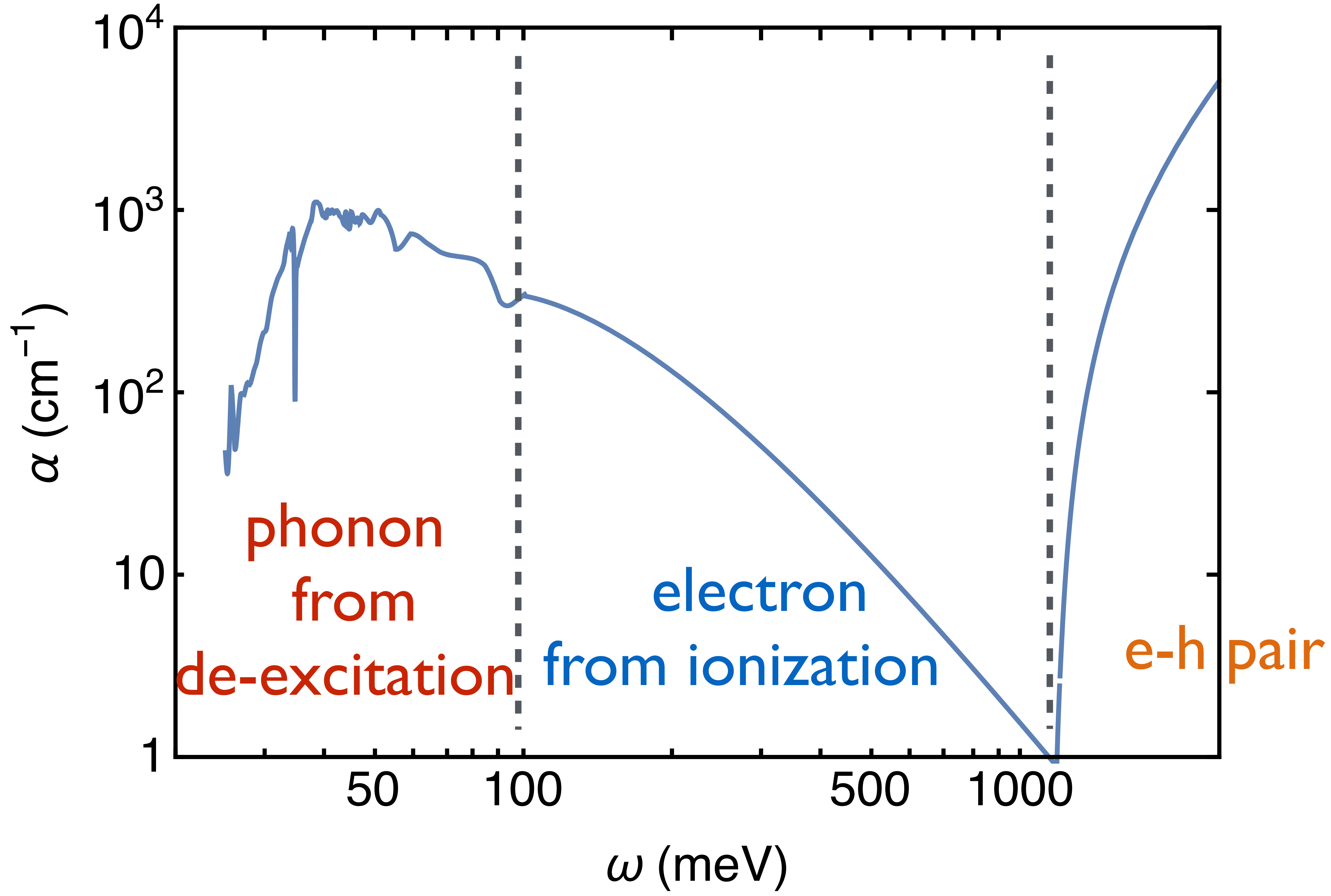

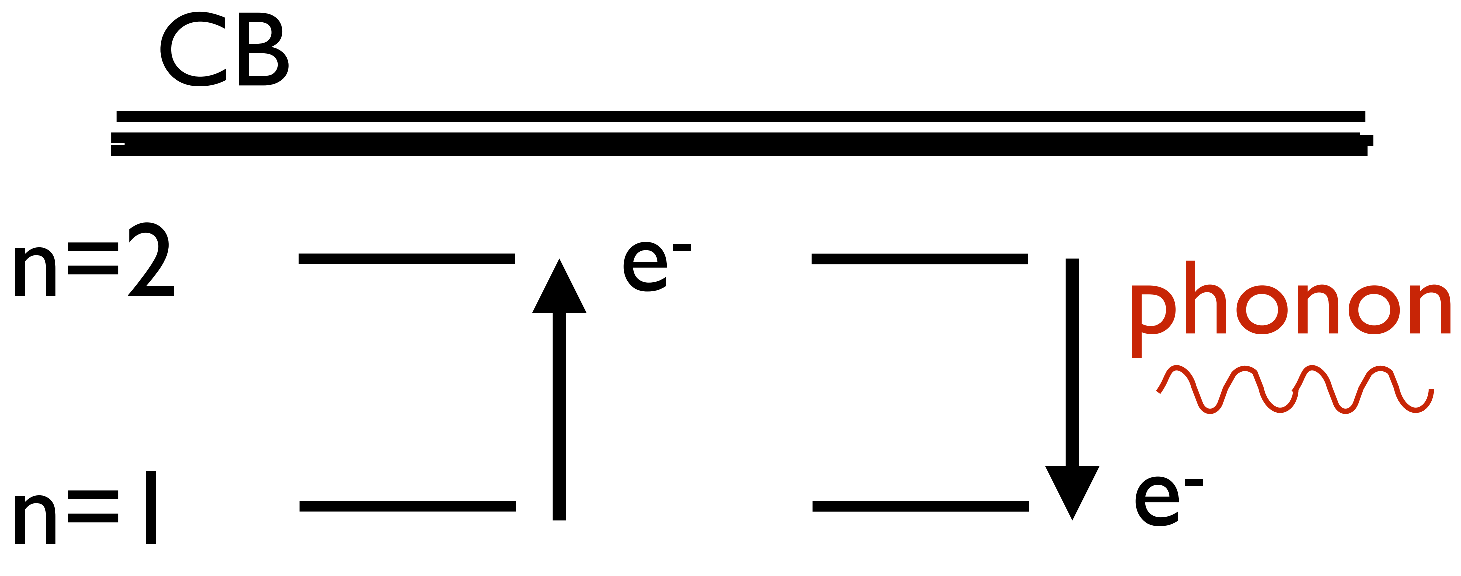

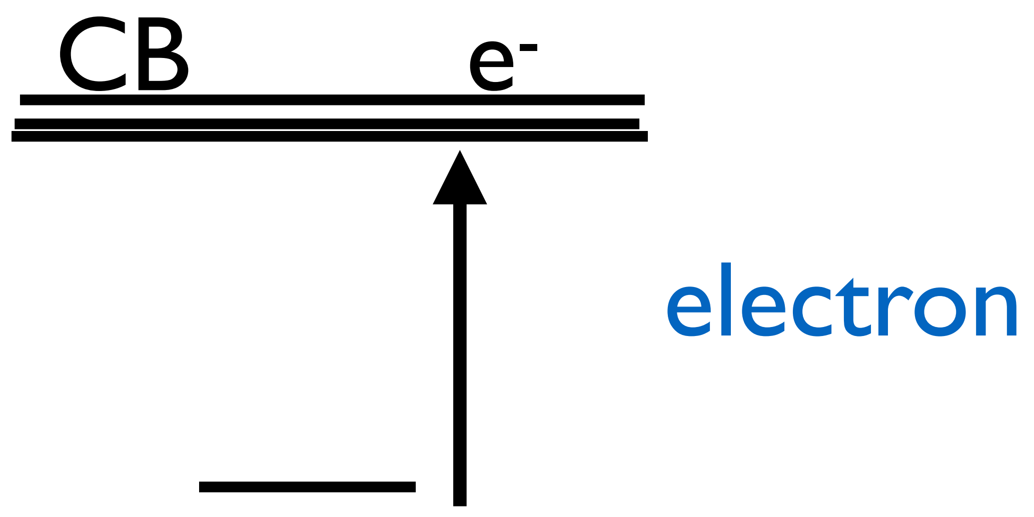

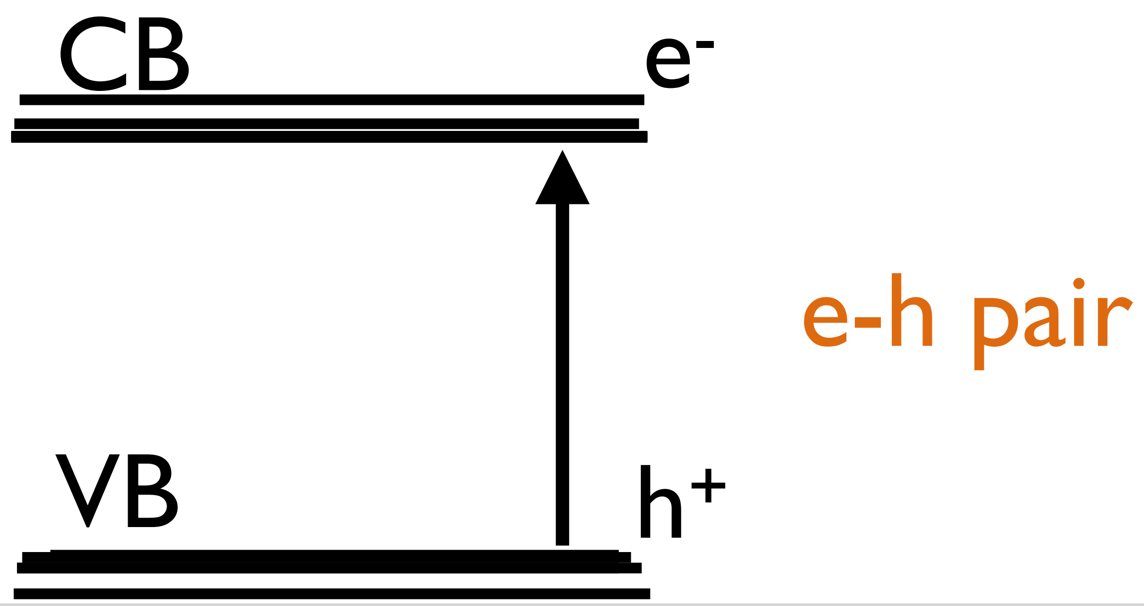

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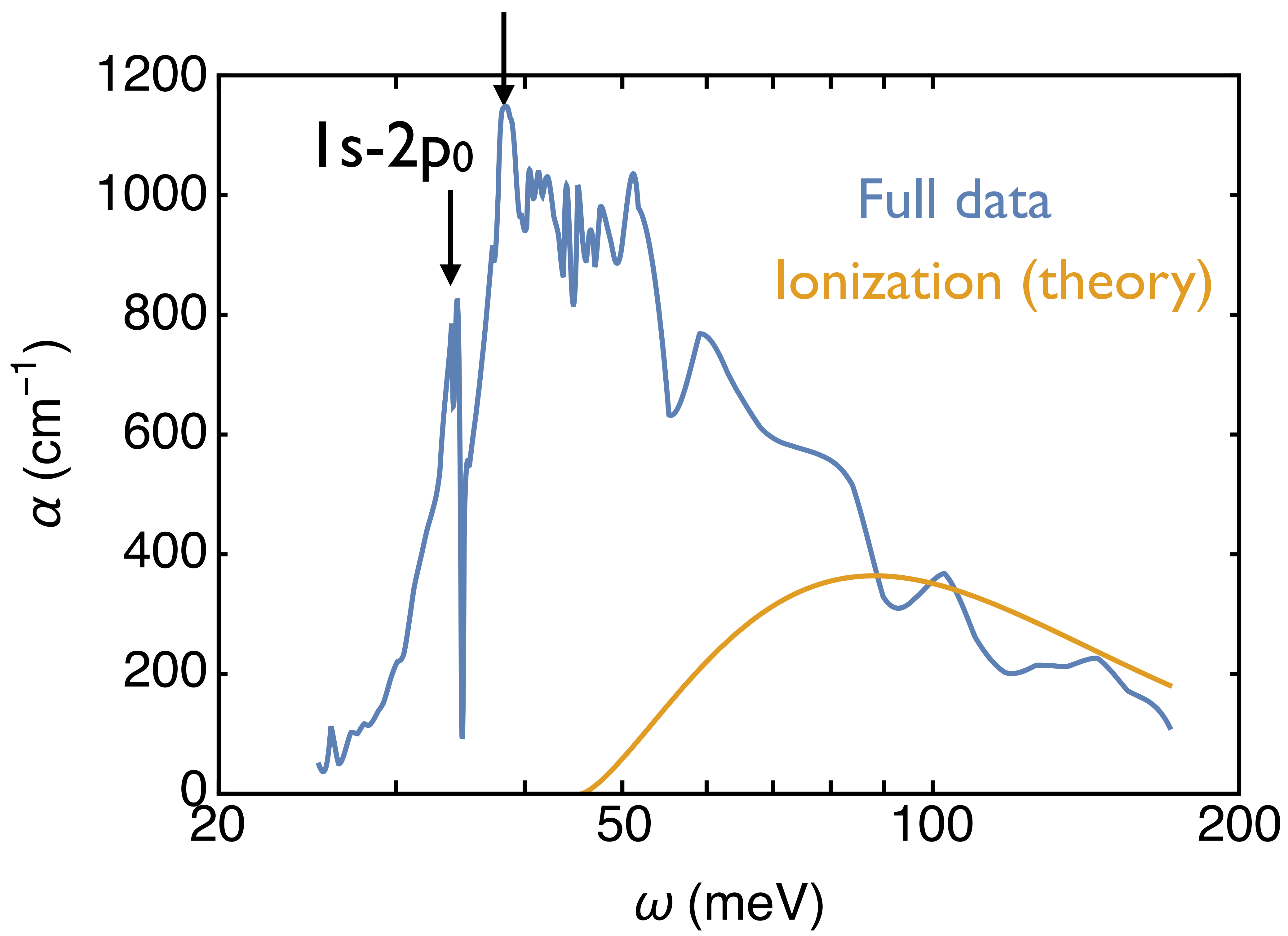
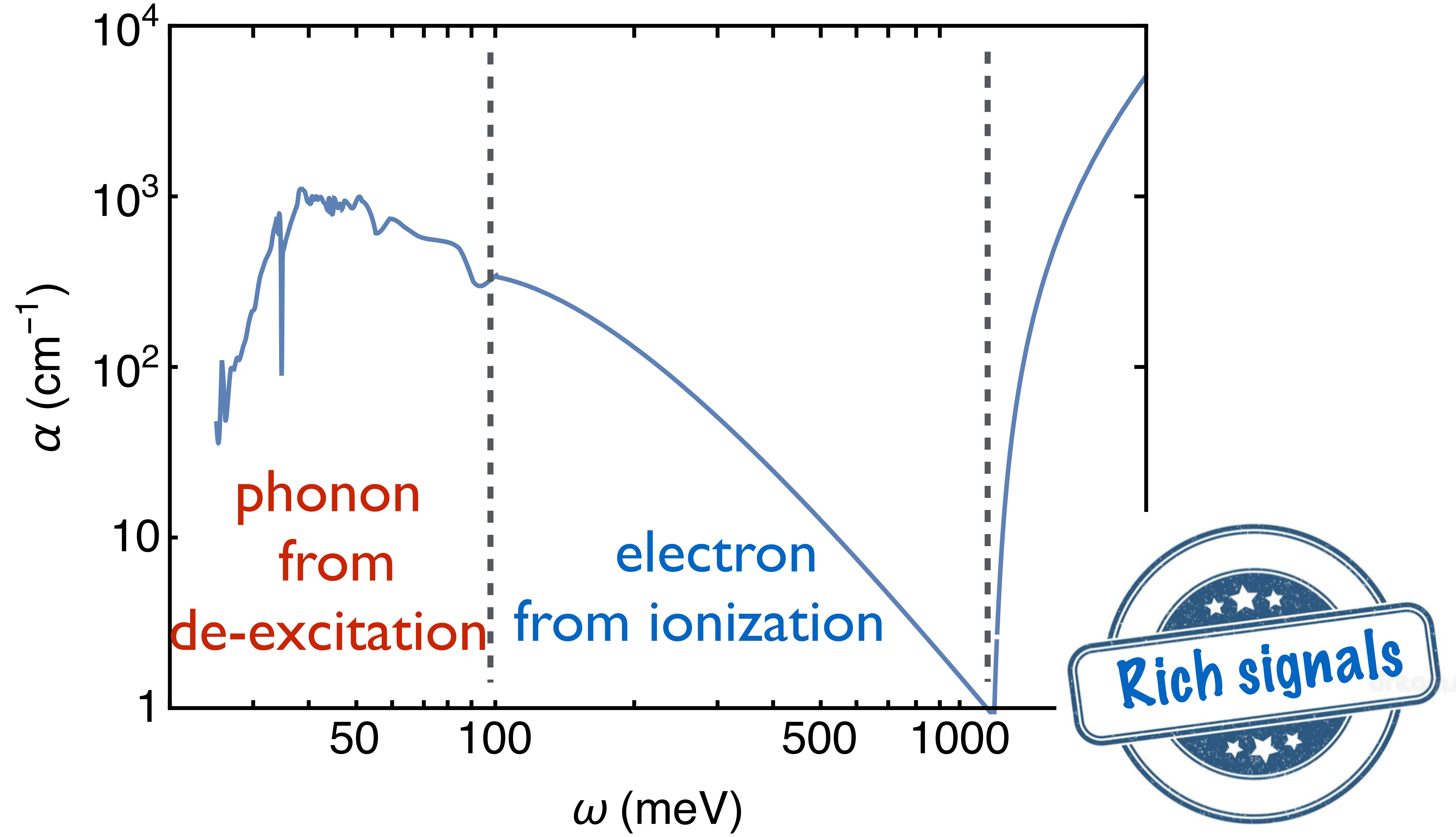
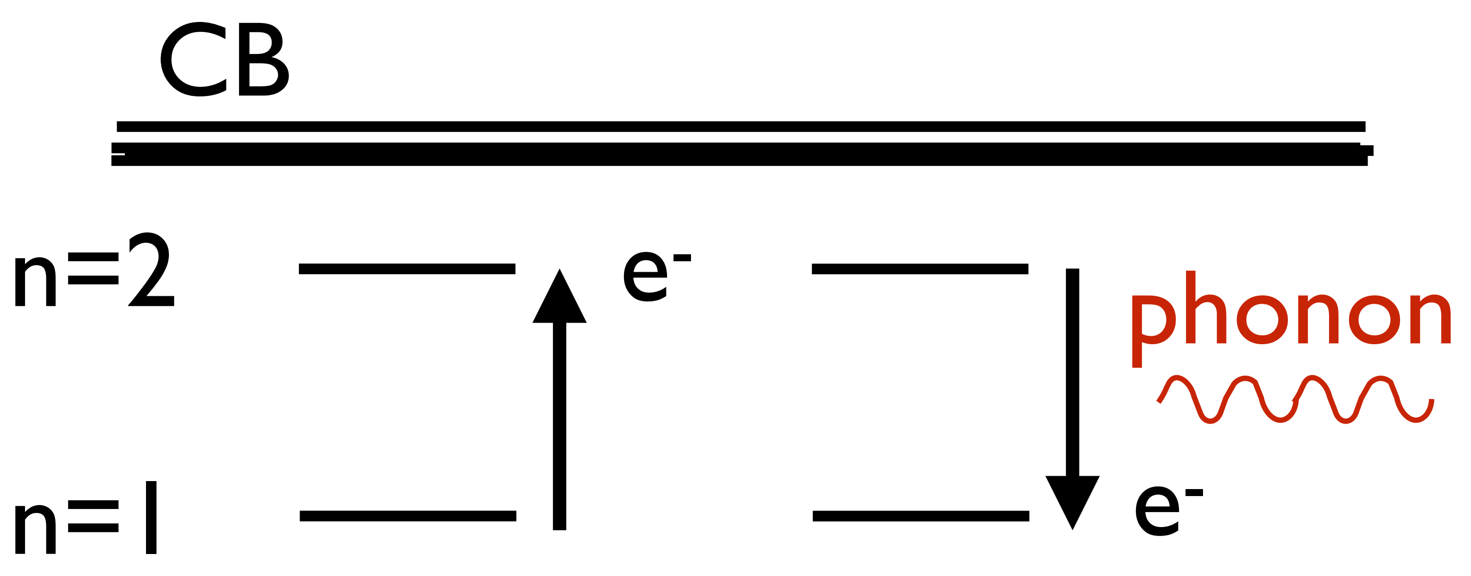
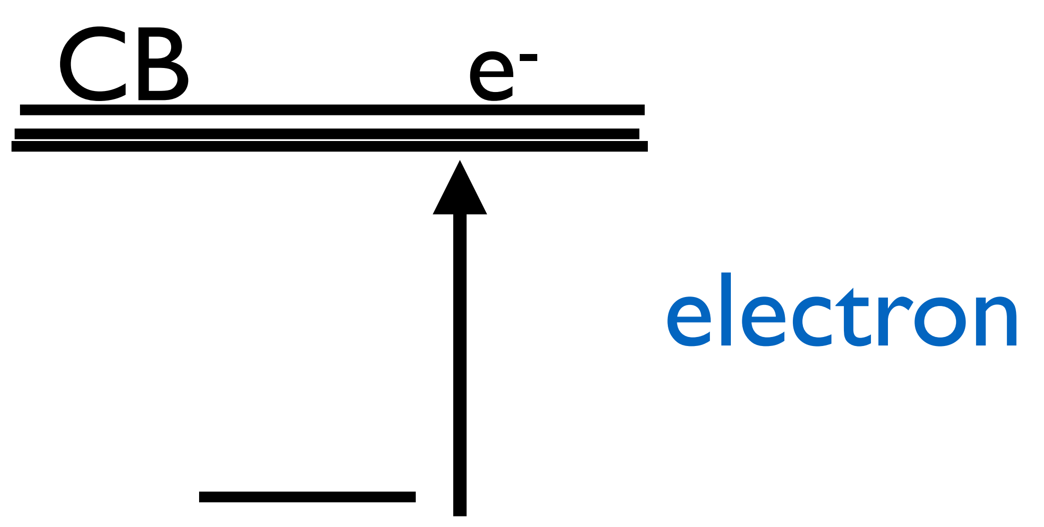
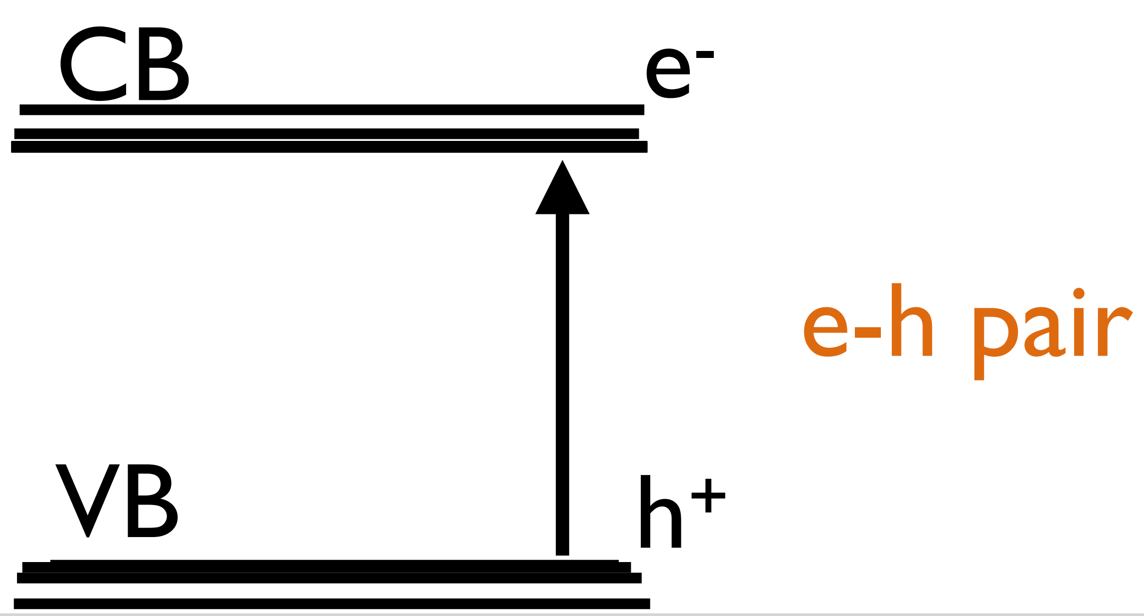






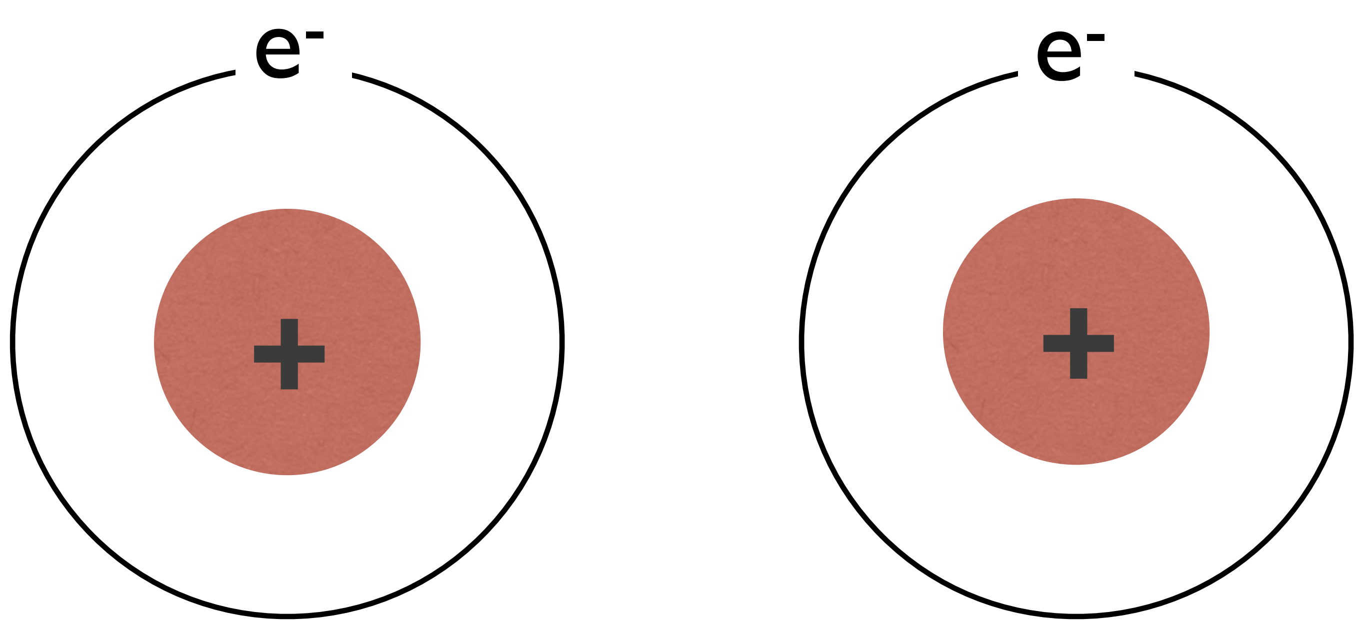




What is the optimal n_d for DM searches?

Metal-insulator transition

Electrons are localized on dopants

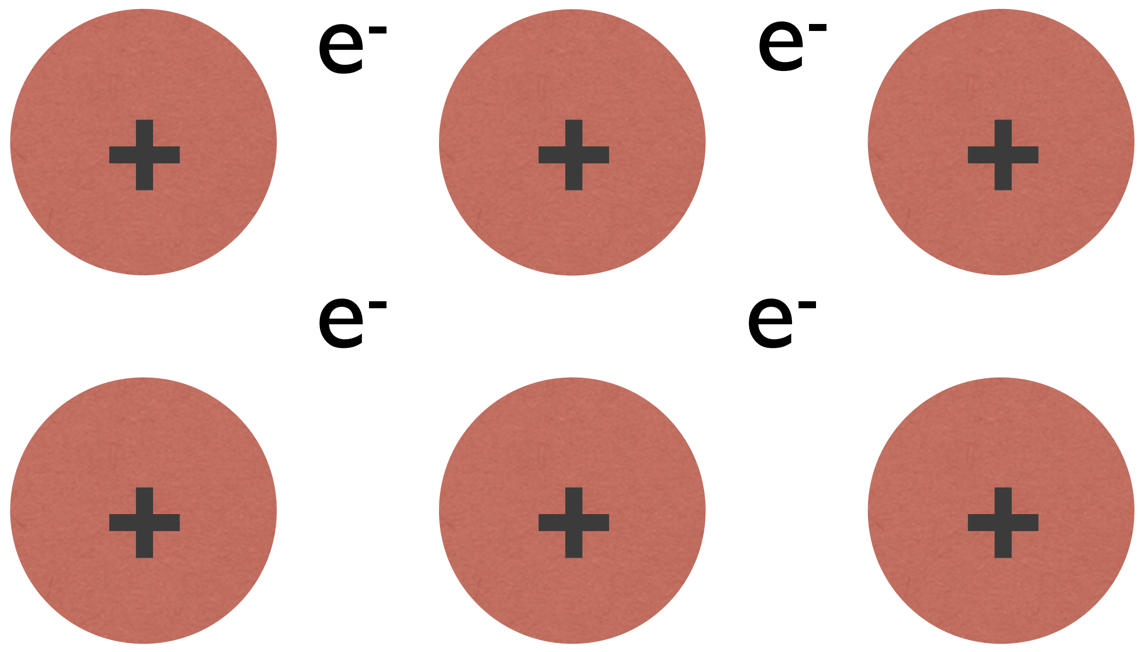


Insulating

$n_{\mathrm{d}} < n_c$

Good for DM searches

Electrons are delocalized



Metallic

$n_{\mathrm{d}} > n_c$

Metallic targets have no gap, hard to control noise

What is the optimal n_d for DM searches?

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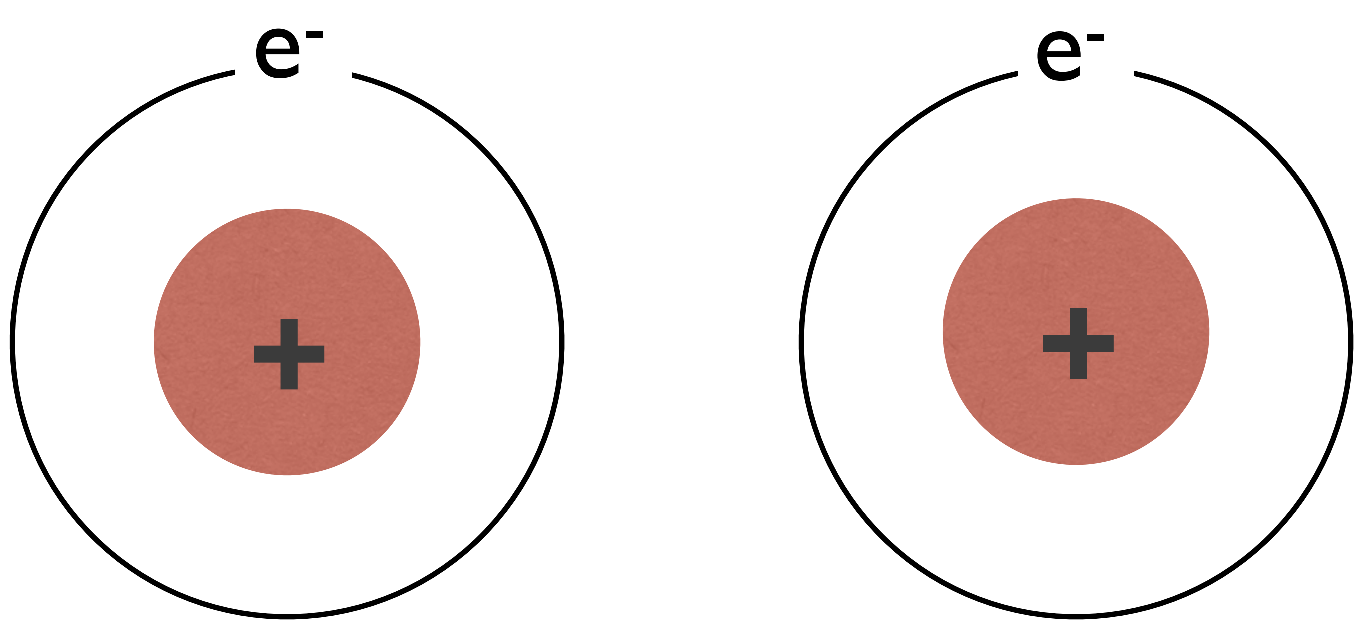

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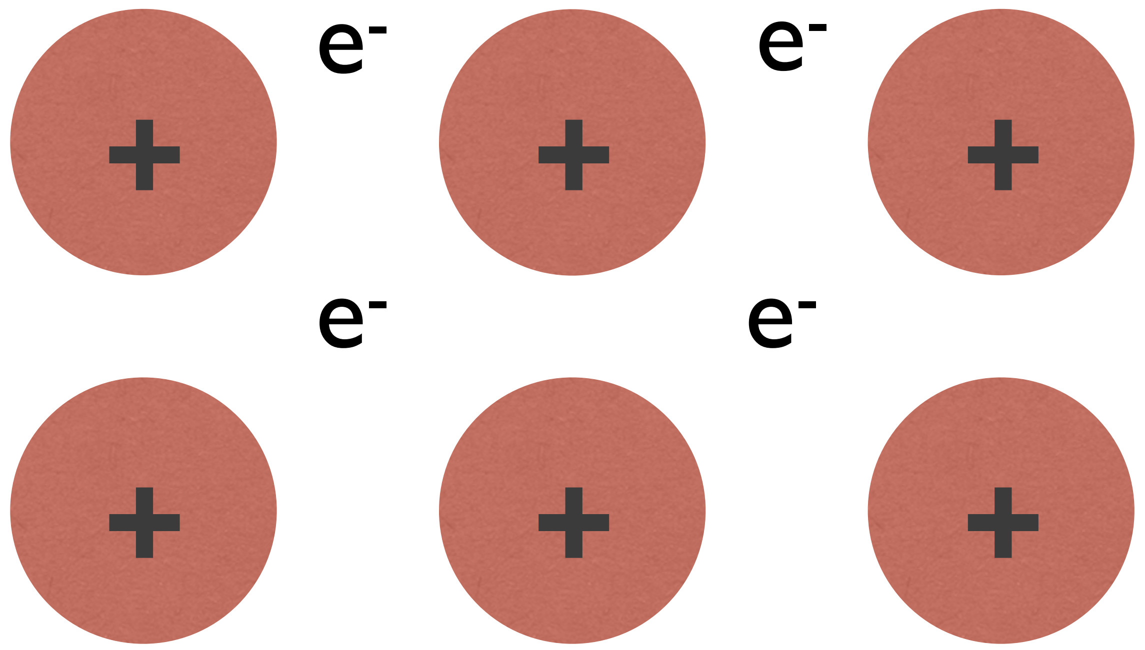

Metallic

$n_\mathrm{d} > n_c$

Metallic targets have no gap, hard to control noise

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

Distance between two dopants

Radius of dopant "hydrogen atom"

For Phosphorus doped Si: $n_c = 3.5 \times 10^{18}\mathrm{cm}^{-3}$ We choose $1.8\times10^{18}\mathrm{cm}^{-3}$ for DM reach projection

DM-electron scattering rate

DM velocity distribution   Interaction type   Target response

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

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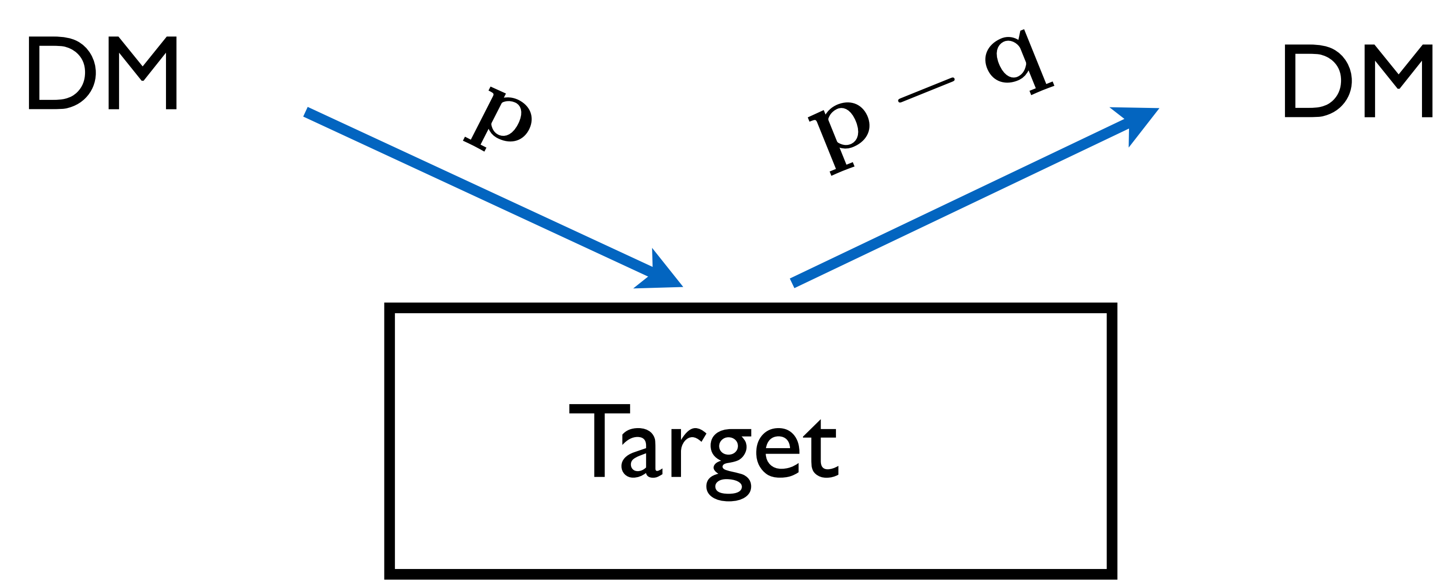
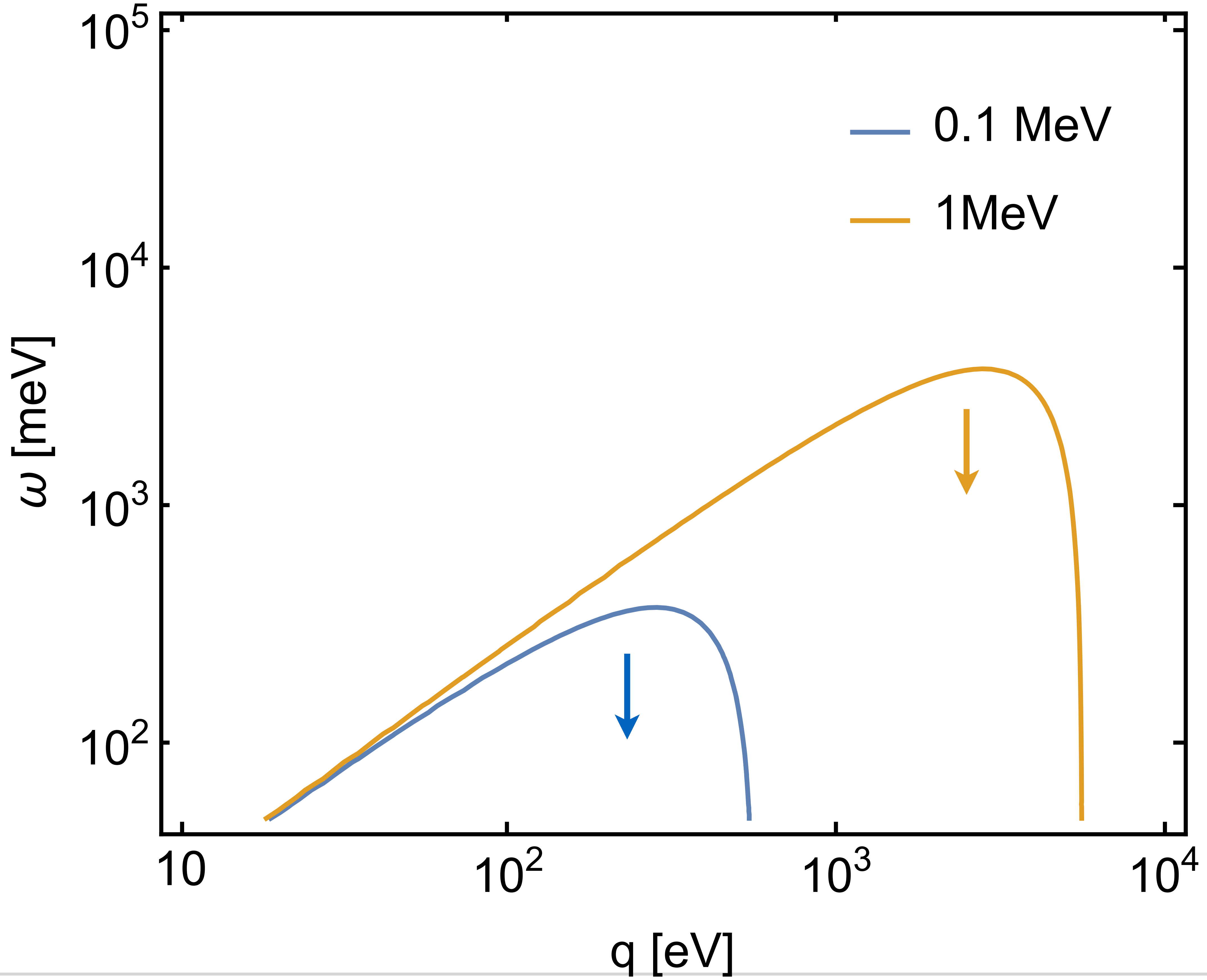
DM Kinematics



$$\omega_{\mathbf{q}} = \frac{\mathbf{p}^2}{2m_\chi} - \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} = \mathbf{q}\cdot\mathbf{v} - \frac{q^2}{2m_\chi}$$



Target response

Knapen, Kozaczuk, Lin, 2021

Hochberg, Kahn, Kurinsky, Lehmann, Yu, Berggren, 2021

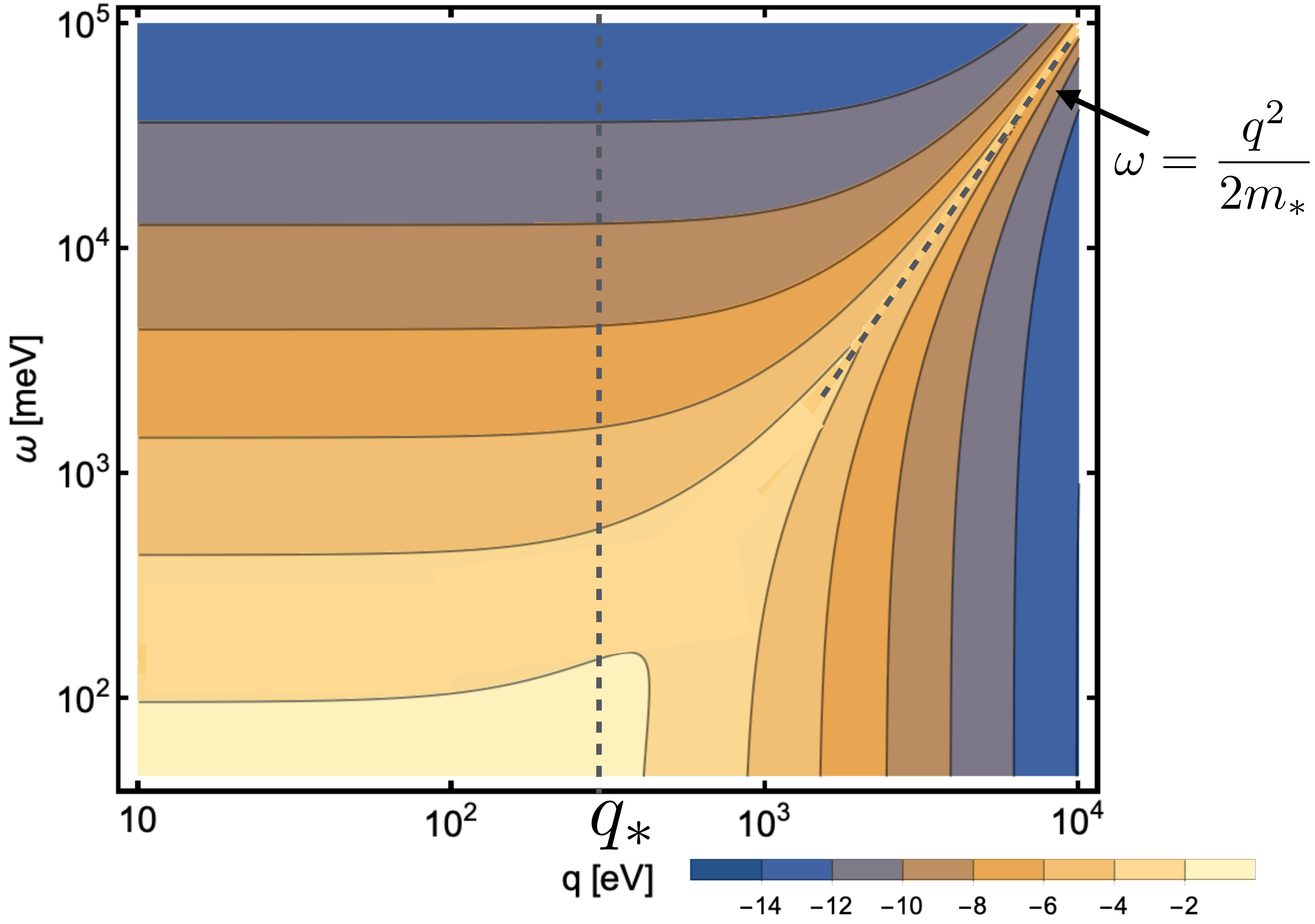
Target response

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

$$S(\mathbf{q}, \omega_\mathbf{q}) = \frac{q^2}{2\pi\alpha} \boxed{\mathrm{Im}\left[\frac{-1}{\epsilon(\mathbf{q}, \omega_\mathbf{q})}\right]}$$

Energy loss function (ELF)

ELF of hydrogen atom ionization (45 meV threshold)



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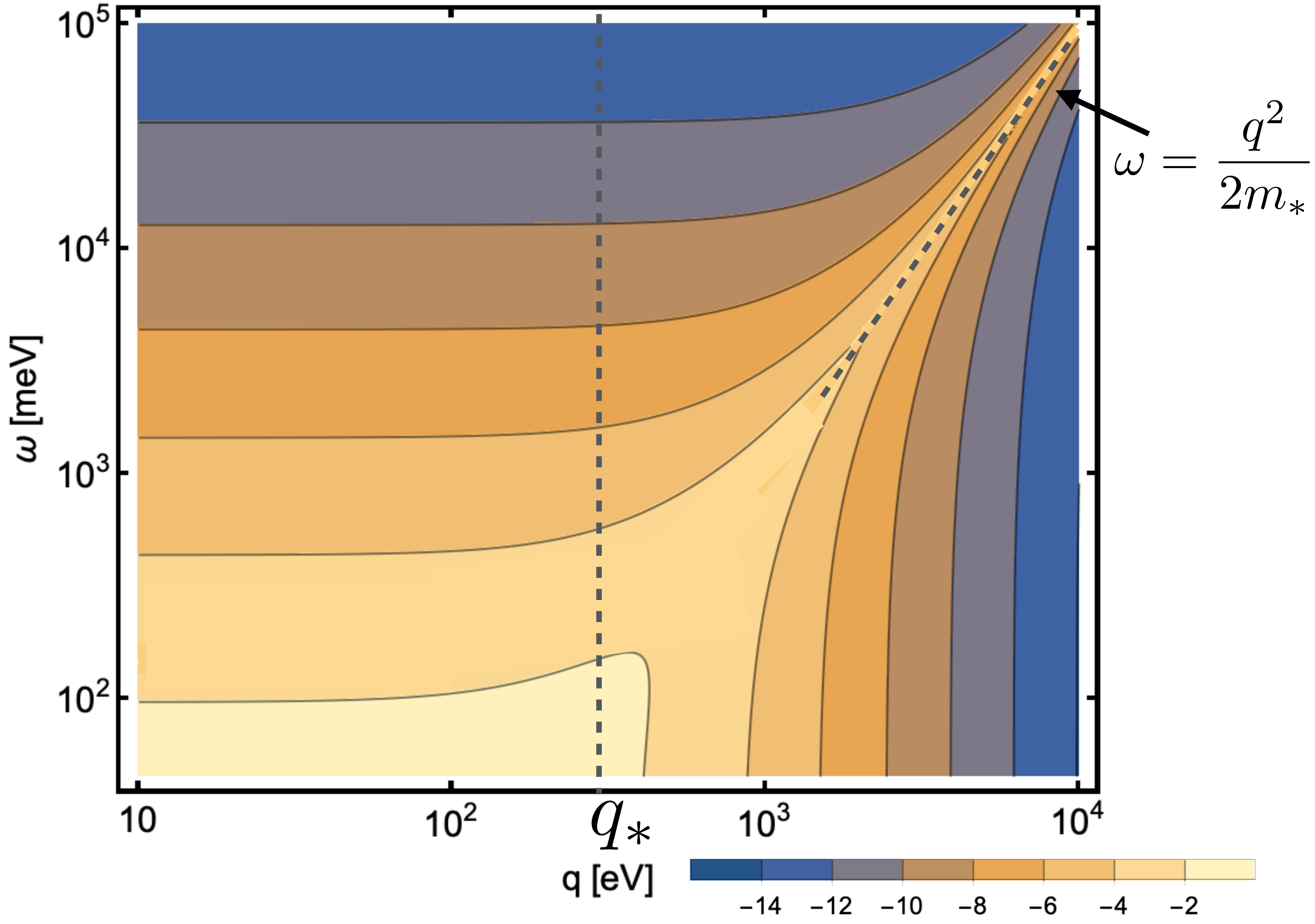
Energy loss function (ELF)

For $q < q_*$ in "hydrogen atom" model

$$\mathrm{Im}\left[\frac{-1}{\epsilon(\mathbf{q}, \omega_{\mathbf{q}})}\right] \approx \mathrm{Im}\left[\frac{-1}{\epsilon(\omega_{\mathbf{q}})}\right]$$

$\epsilon(\omega)$ can be obtained directly from optical data

ELF of hydrogen atom ionization (45 meV threshold)



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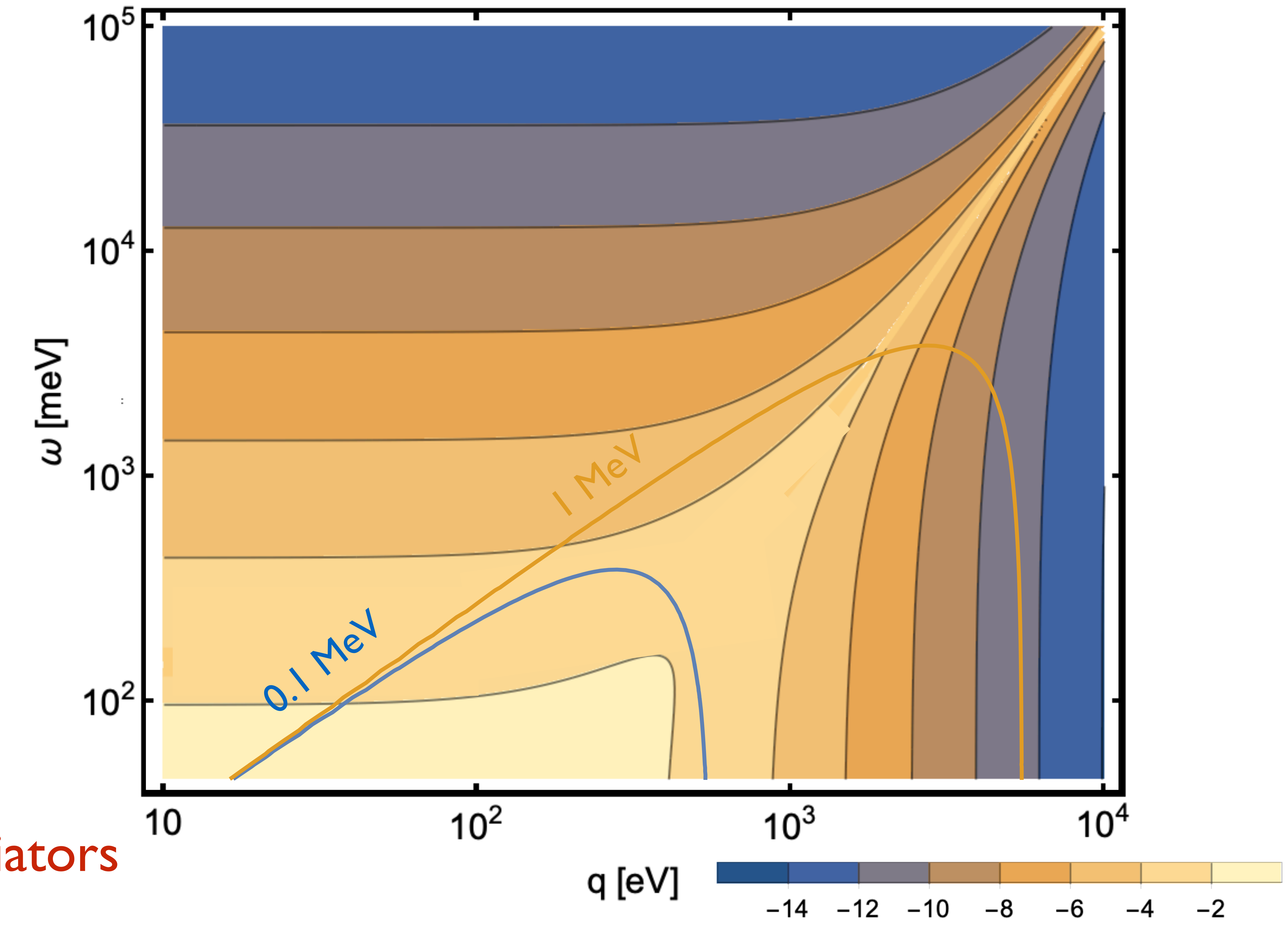
$\epsilon(\omega)$ can be obtained directly from optical data

We use $S(\mathbf{q}, \omega_{\mathbf{q}}) \approx \frac{q^2}{2\pi\alpha} \mathrm{Im}\left(\frac{-1}{\epsilon(\omega_{\mathbf{q}})}\right)$

good approximation for low mass DM with light mediators

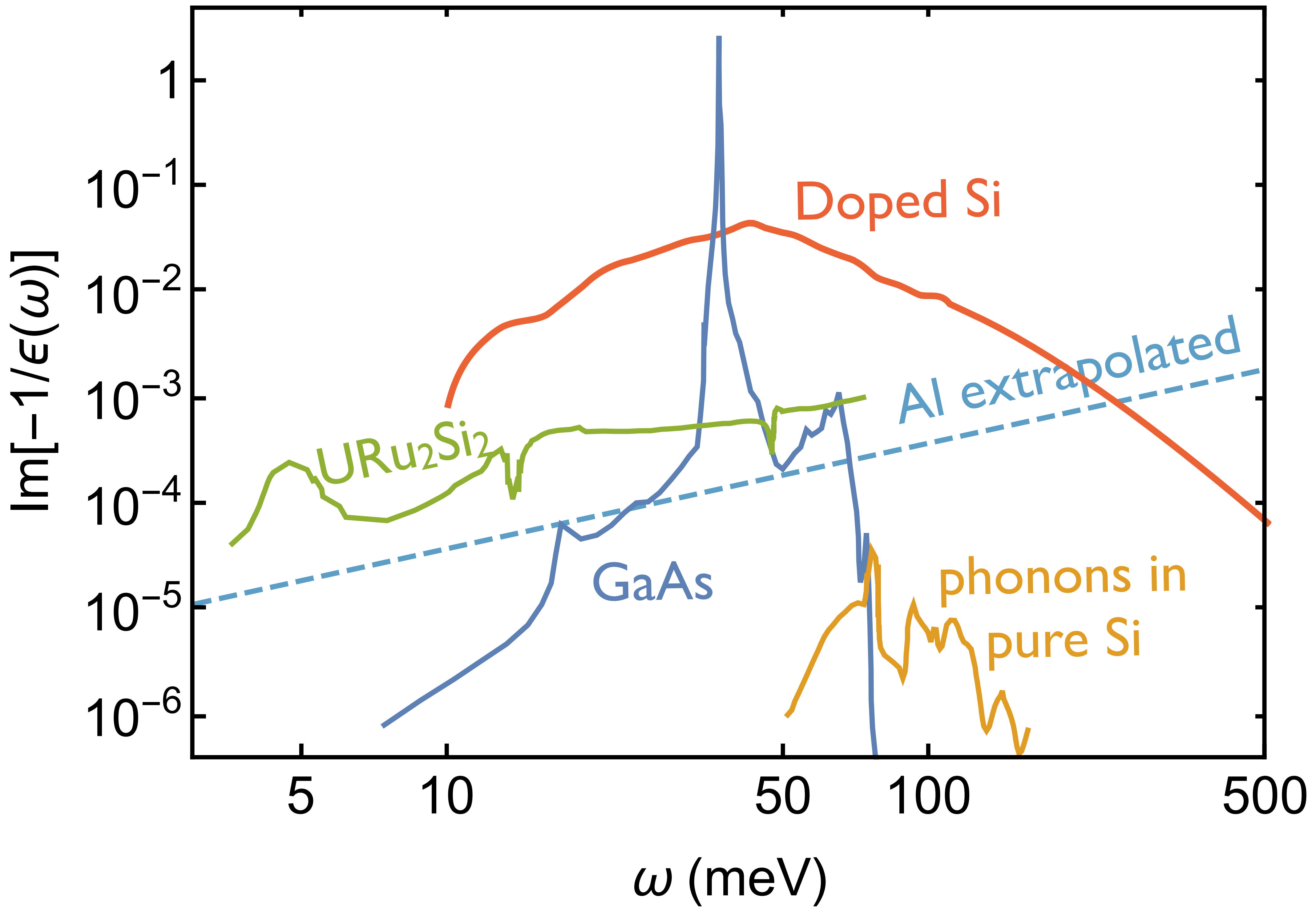
ELF of hydrogen atom ionization (45 meV threshold)



ELF for different targets

Hochberg, Zhao, Zurek, 2015
Knapen, Lin, Pyle, Zurek, 2017
Knapen, Kozaczuk, Lin, 2021
Hochberg, Kahn, Kurinsky, Lehmann, Yu, Berggren, 2021

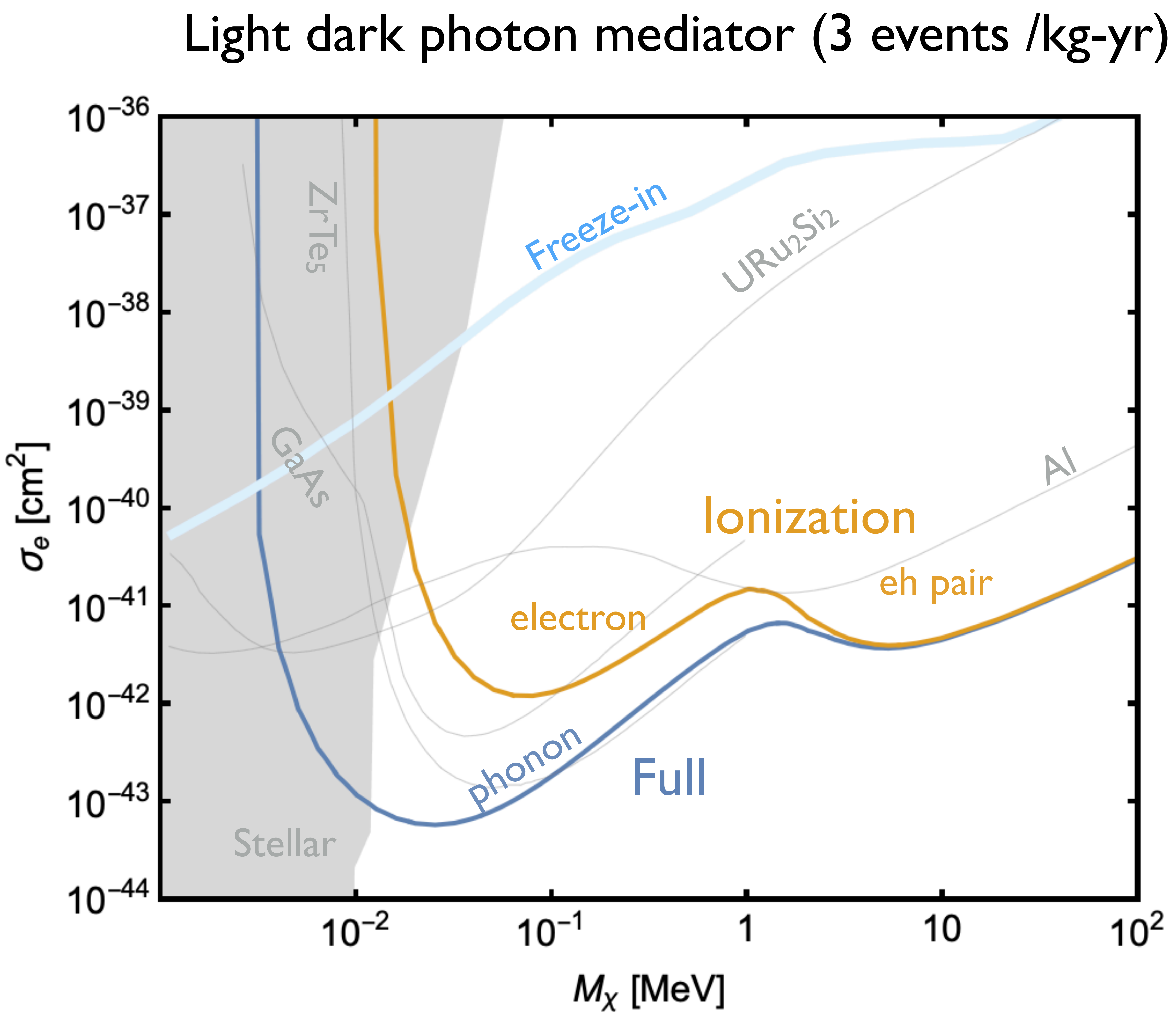
Phosphorus doped Si @10K with $n_d = 1.8\times10^{18} cm^{-3}$

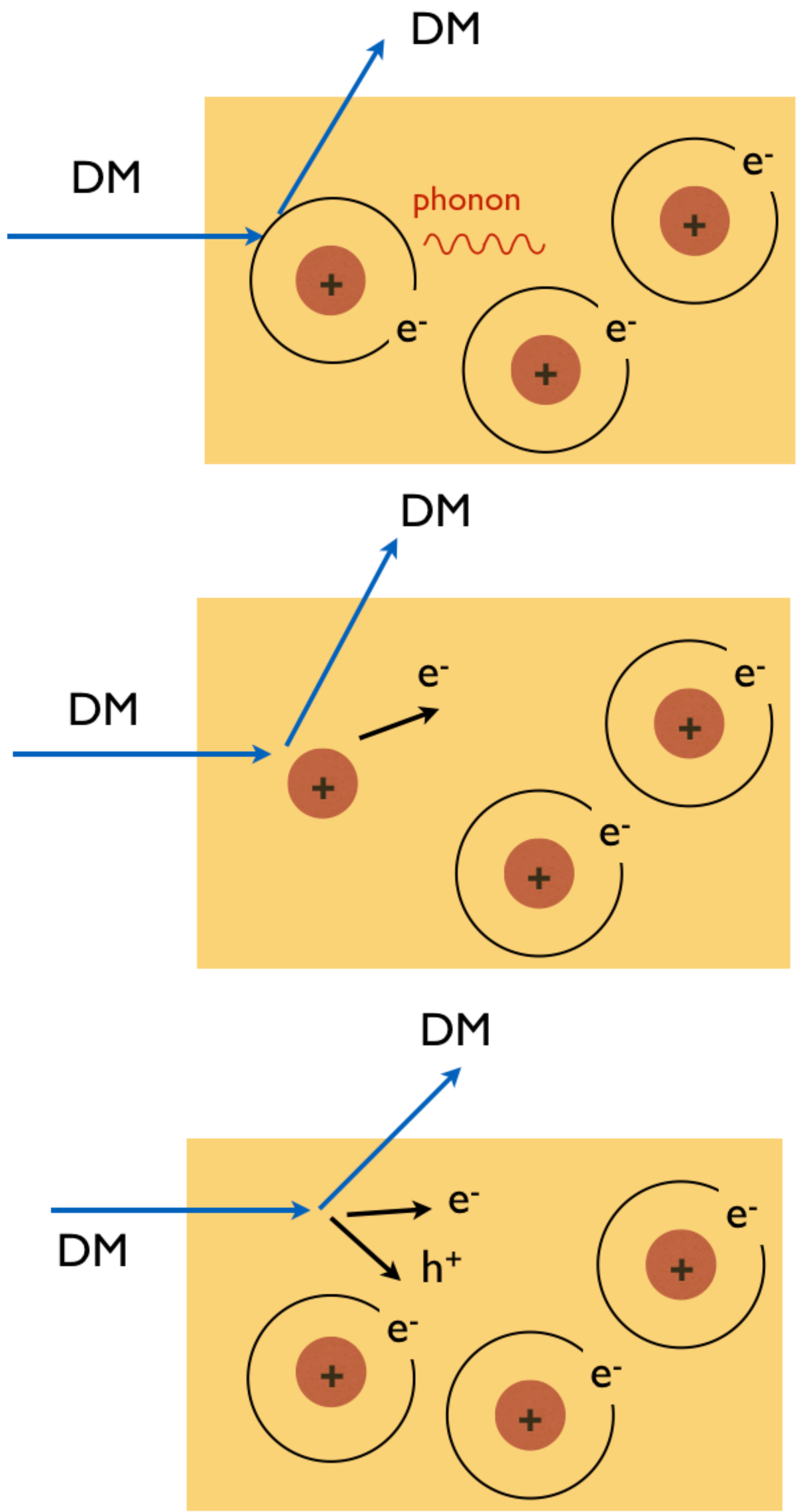


Doped silicon has large target response over a wide energy range

DM-electron scattering rate with doped silicon

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





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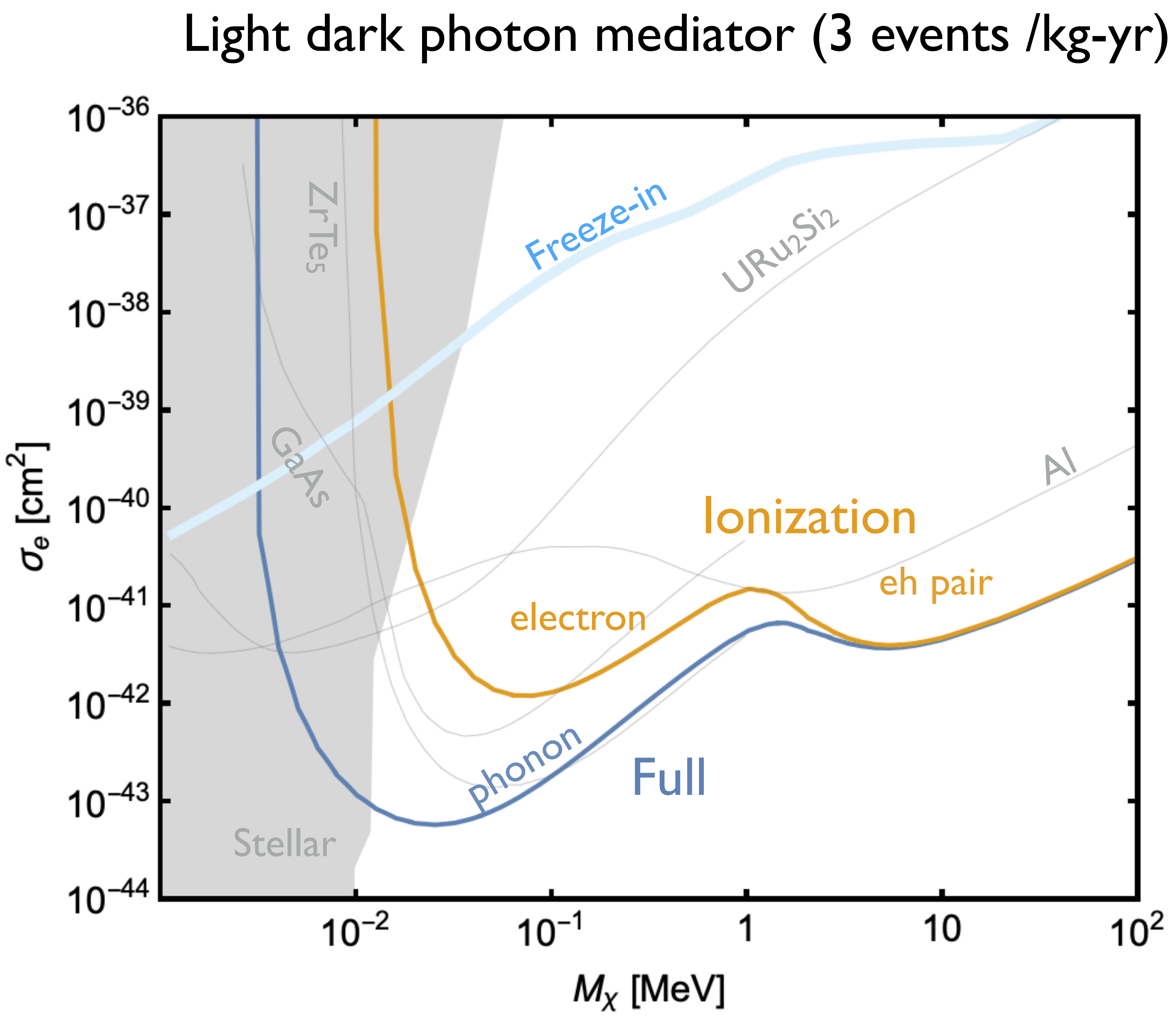
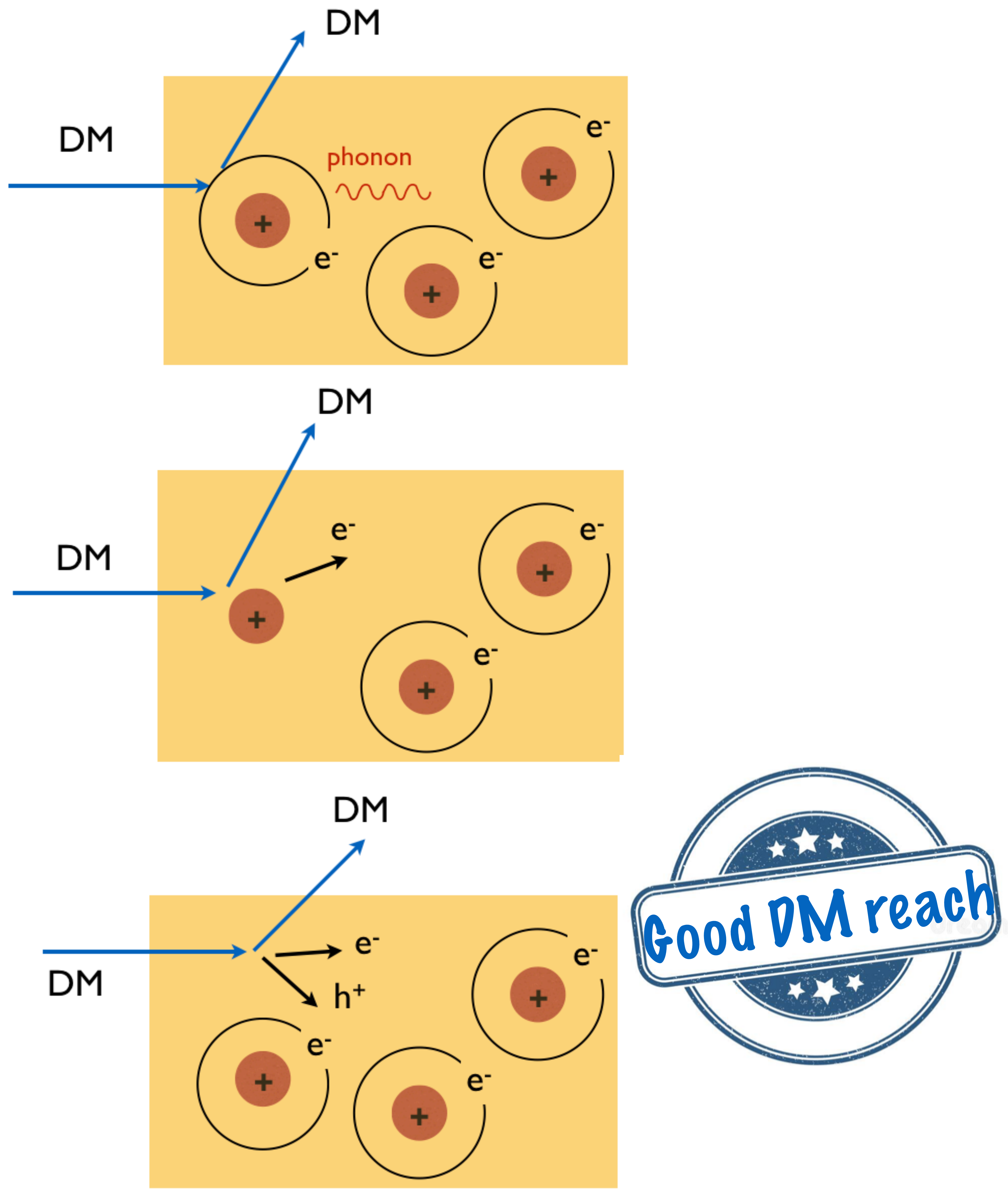
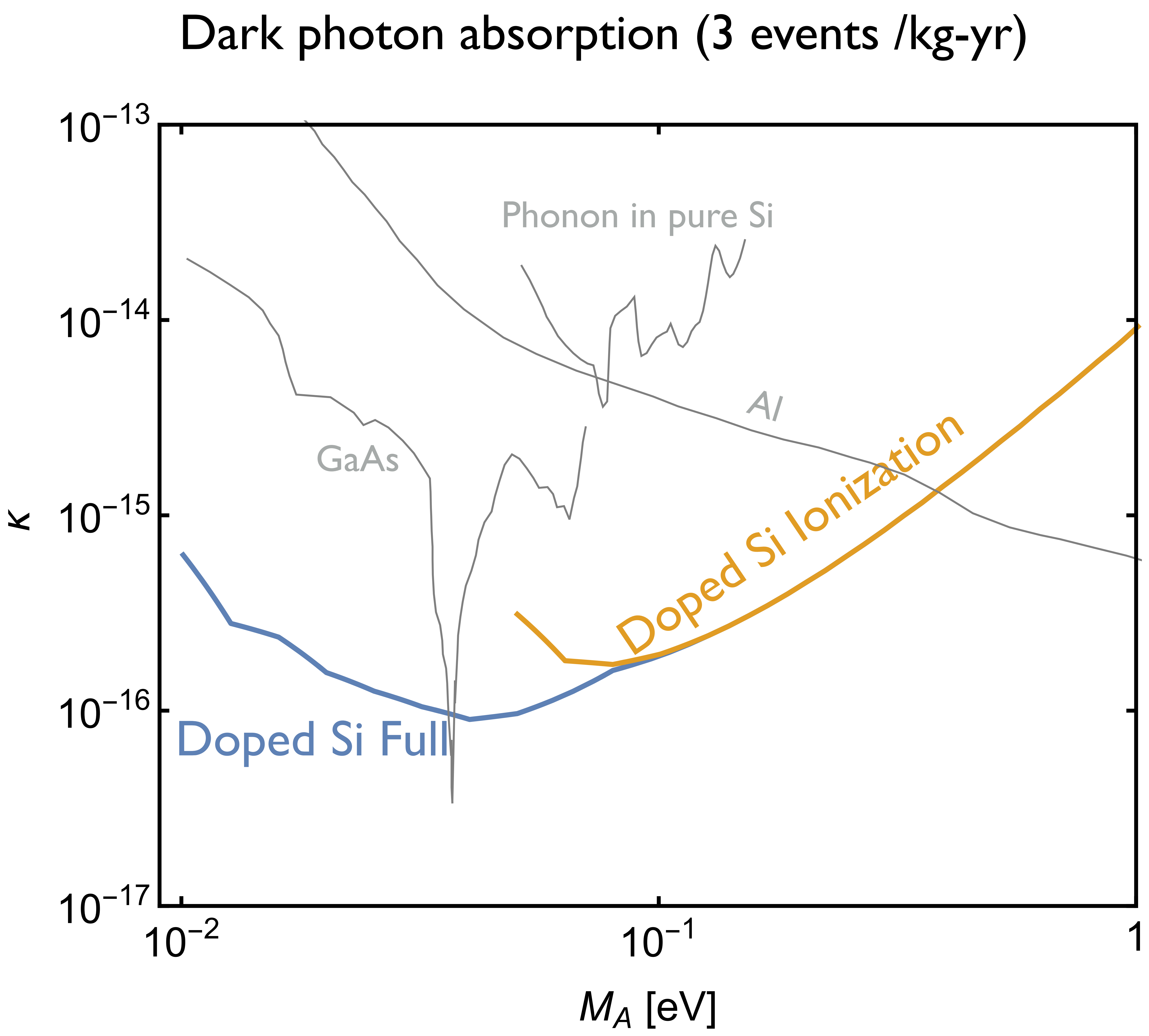




DM absorption rate with doped silicon

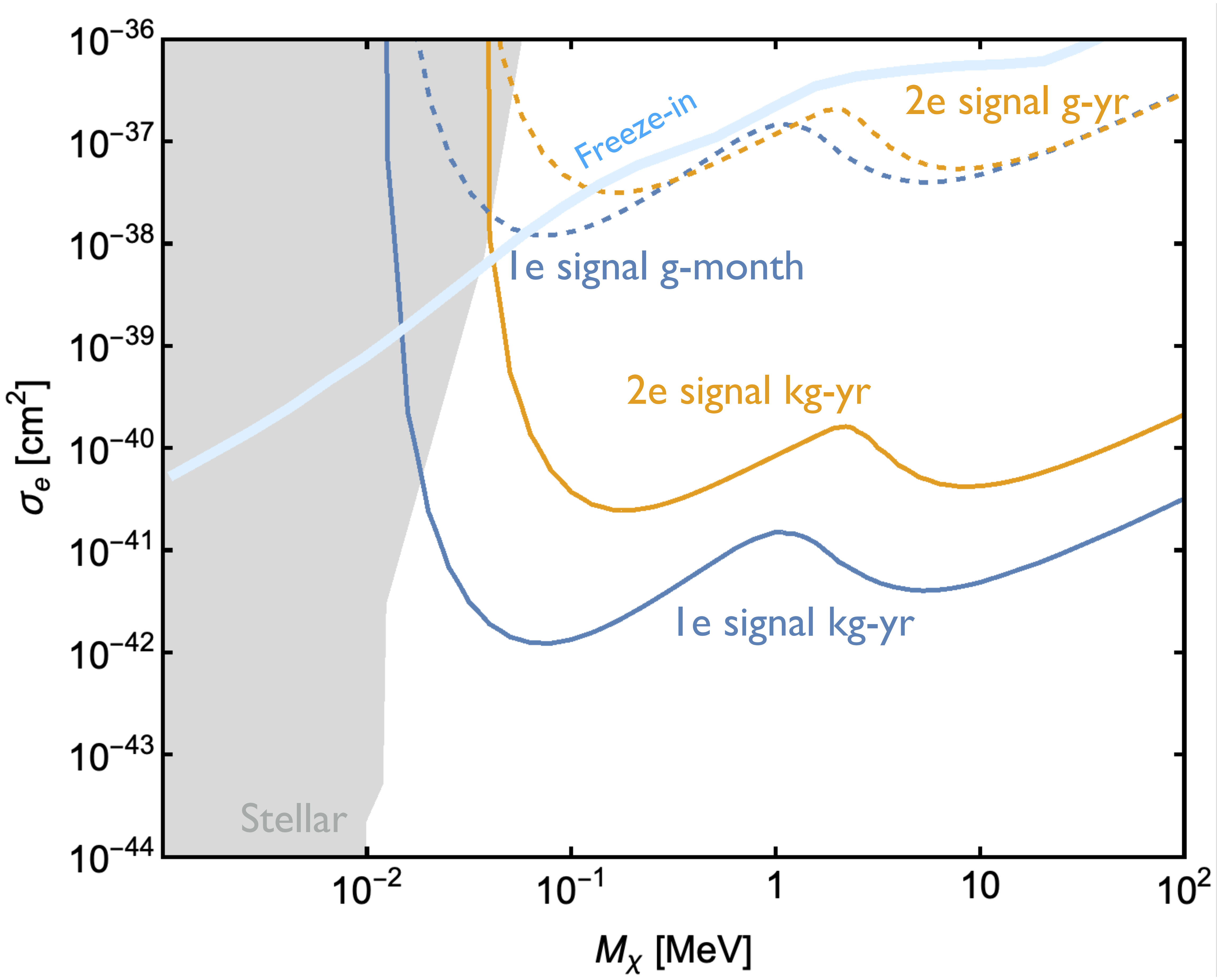
PD, Egana-Ugrinovic, Essig, Sholapurkar, (in prep)



$$R \sim \kappa^2 m_{\rm DM} \mathrm{Im}\left[\frac{-1}{\epsilon(m_{\rm DM})}\right]$$

DM reach including backgrounds

Need a "background free" exposure of ~g-month (1e) or ~g-yr (2e) to probe freeze-in benchmark



Backgrounds maybe reduced by modeling Cherenkov/radiative recombination events

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

Thoughts on experimental designs

PD, Egana-Ugrinovic, Essig, Sofo Haro, Sholapurkar, Tiffenberg (in prep)

For phonon signals:

- Doped semiconductor + TES

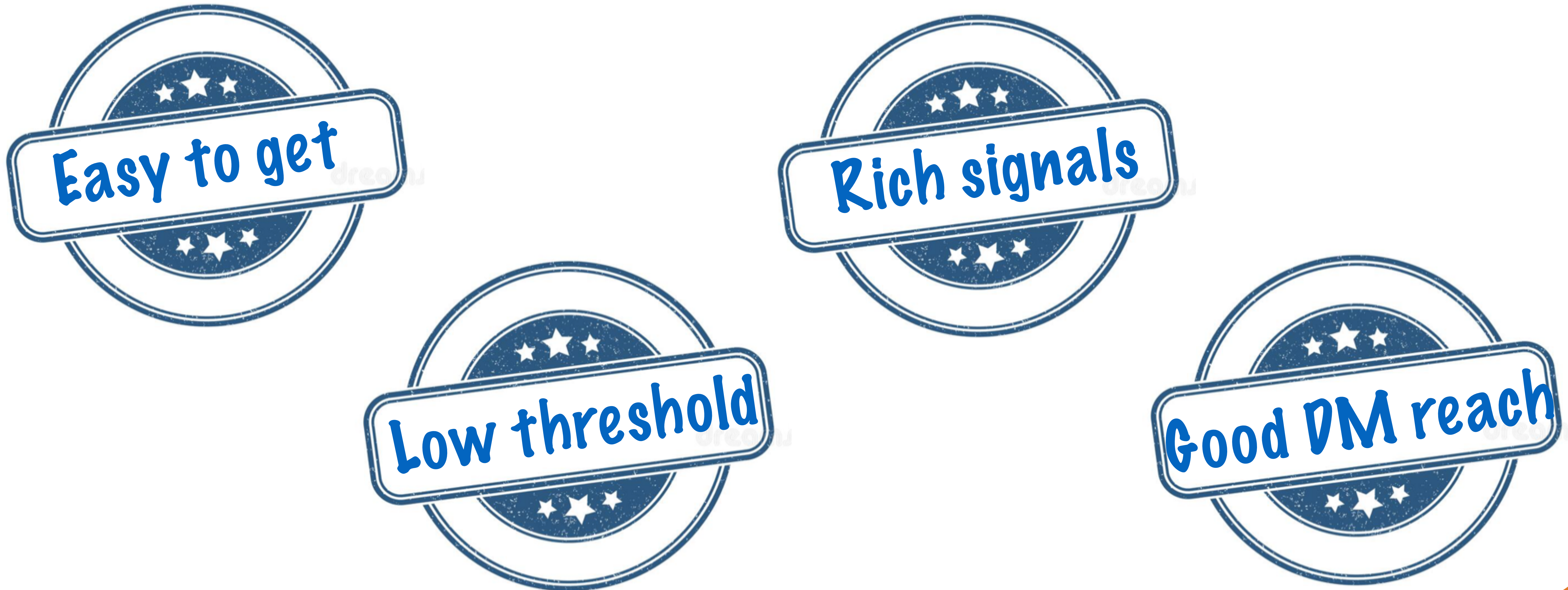
For charge signals:

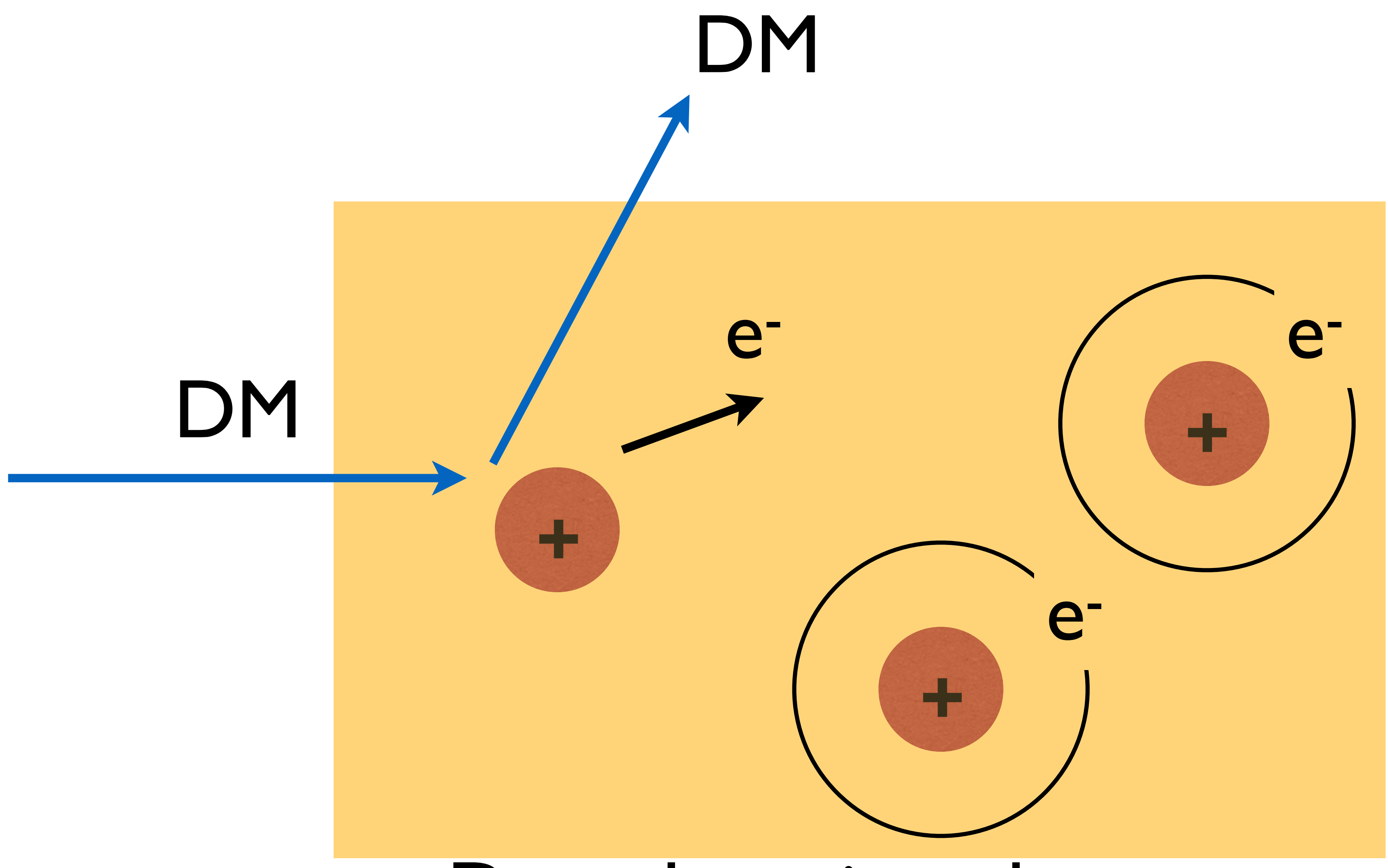
- New CCD design with doped bulk material
- Single charge resolution, like Skipper CCD
- Two detectors may distinguish between electron ionization from dopants to eh pair creation

Summary of Part II

- Dopants in semiconductors can be thought as “Hydrogen atom” in a background with a large dielectric constant
- Doped semiconductors can be detector targets with O(10-100) meV threshold and have sensitivity over a wide range of DM masses: >10 keV for DM scattering and >10 meV for DM absorption

Doped semiconductors





Doped semiconductor

Thank you

Summary of current experiments

Good spatial resolution

Good timing resolution

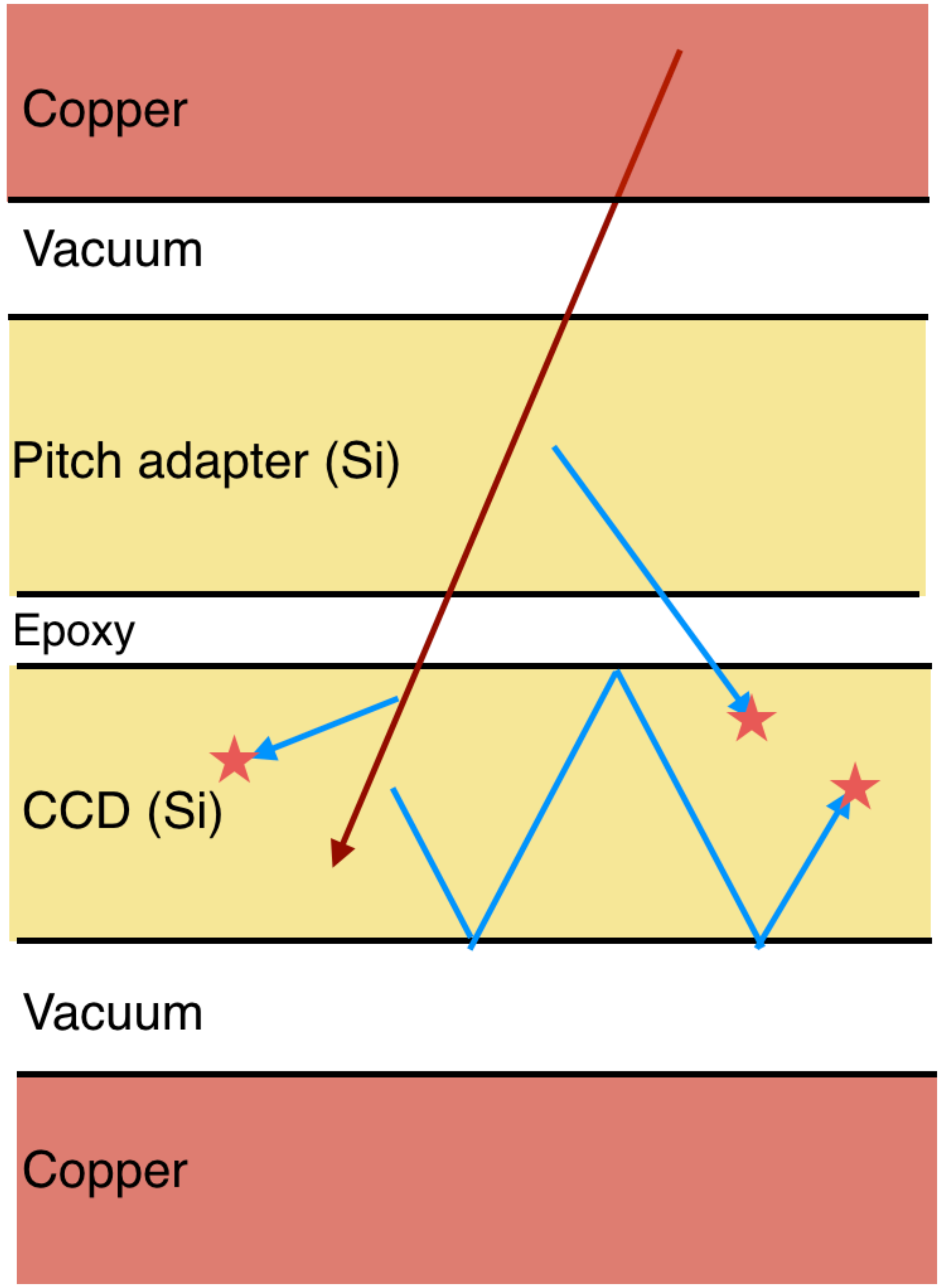
High ambient backgrounds

Low ambient backgrounds

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	-

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

Cherenkov radiation in SENSEI



- Cherenkov photons are generated inside CCD, pitch adapter and epoxy
- Cherenkov photons maybe absorbed after several bounces at surfaces

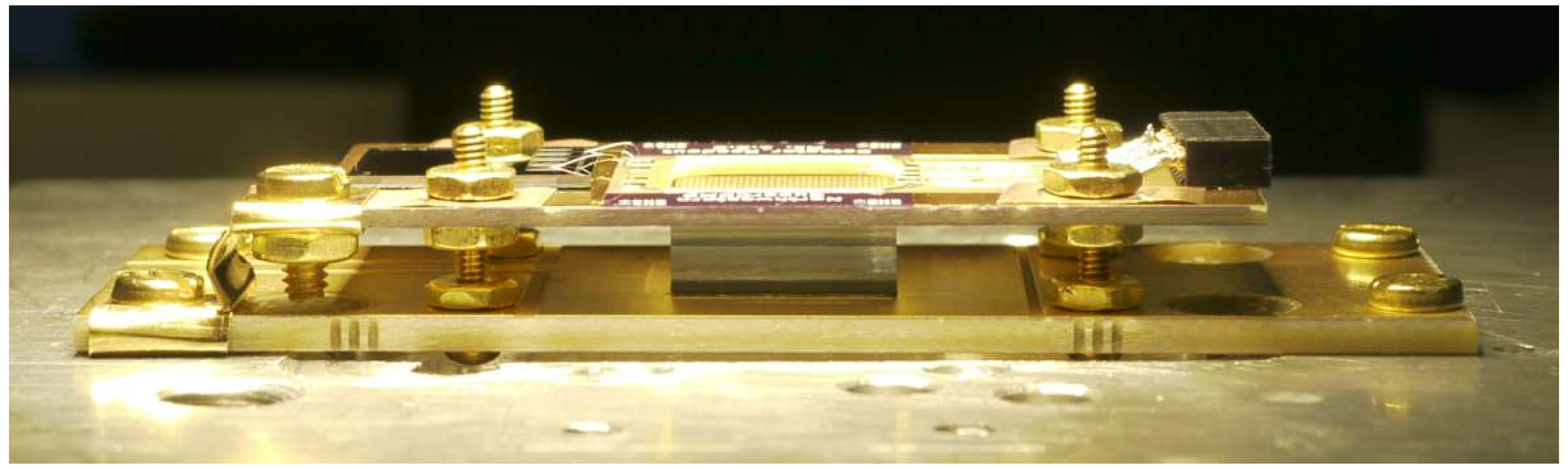
$$\Downarrow$$

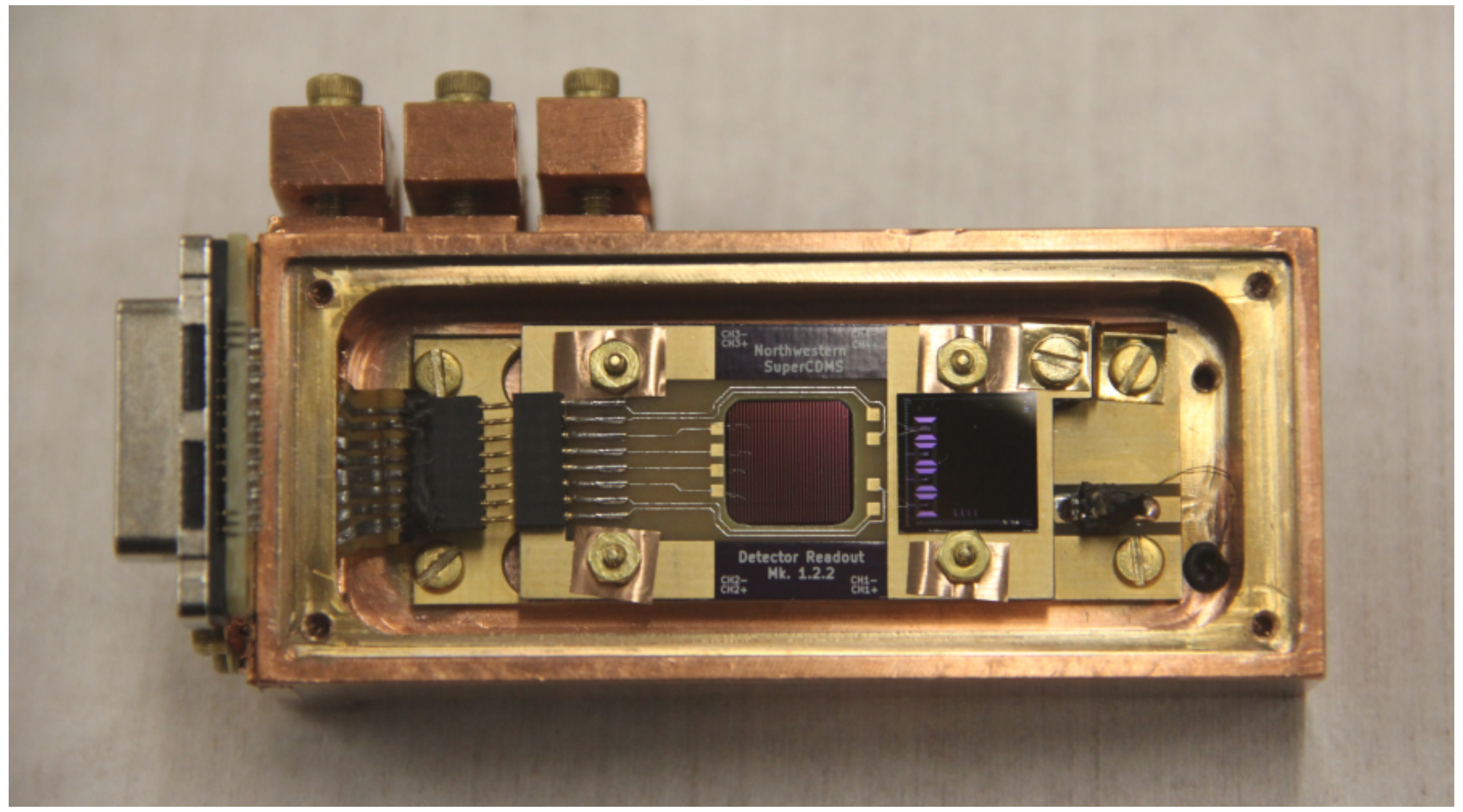
1e events far from the original track

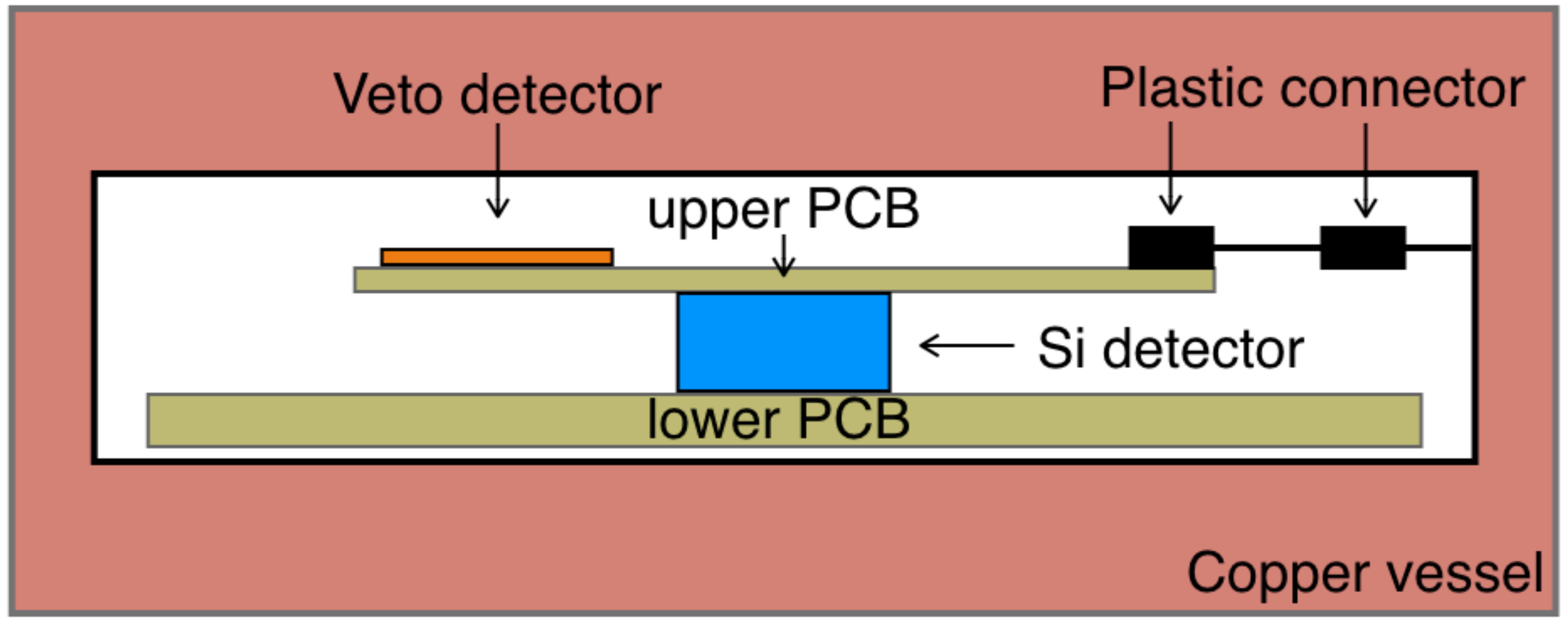
SuperCDMS HVeV experiment

SuperCDMS, 2020

- HVeV detector measures electron-hole pairs via phonons (NTL effect)
- Location: on surface in Northwestern University
- HVeV detector has 0.03 e- resolution, excellent time resolution



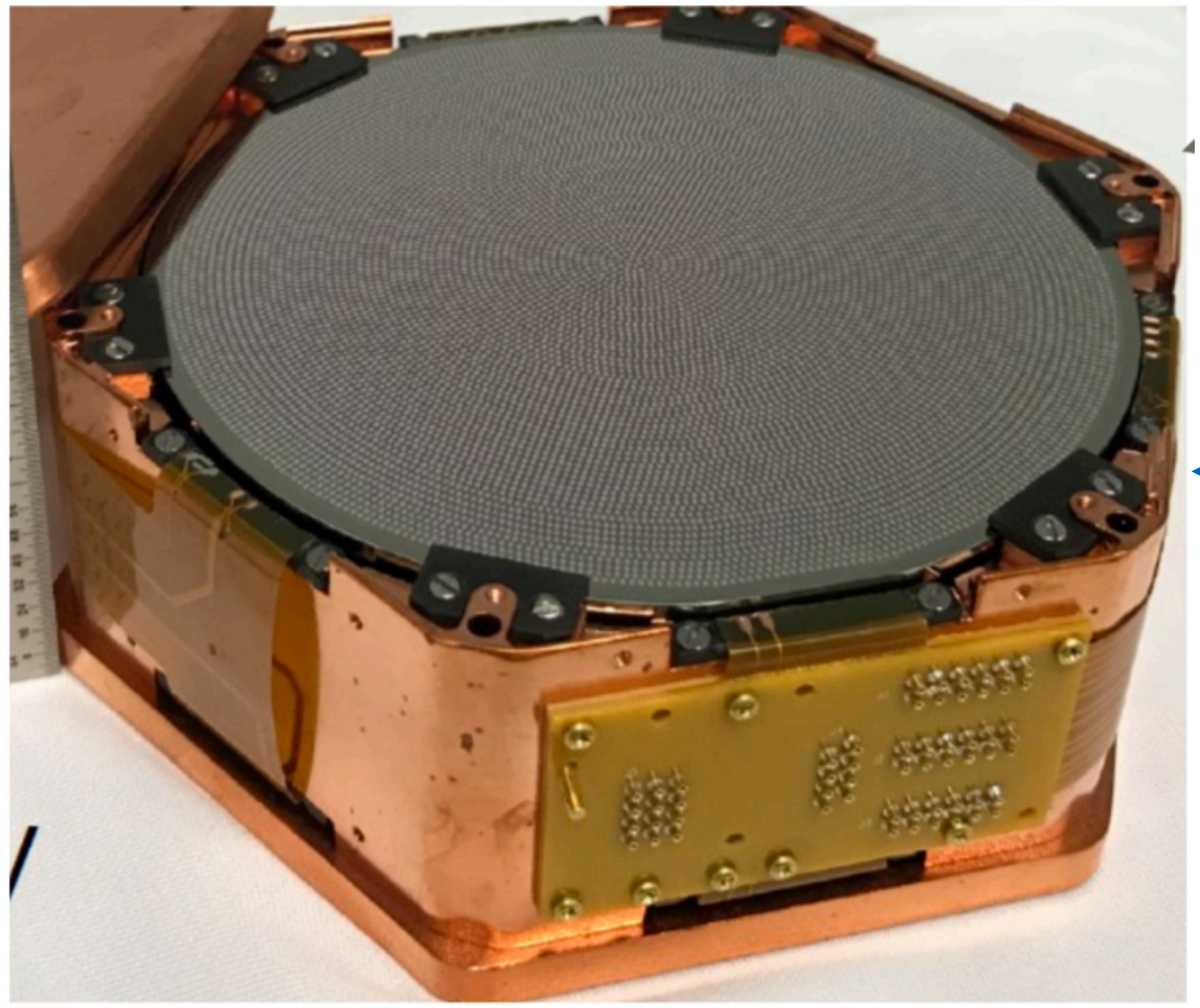




SuperCDMS @ SNOLAB

Well shielded, deep underground, clean environment

Cherenkov radiation from beta decays of impurities in holders (Cirlex clamps)



Cirlex clamps

Figure from Ben Loer, DM 2018

Potential events: $$N^{\text{Cirlex}}_{\text{events}} \sim 130/\text{day}/\text{tower}$$

much larger than previously estimated <100 eV backgrounds **~0.1/day/tower**

SuperCDMS SNOLAB, 2016