Direct Detection of Sub-GeV Dark Matter with Doped Semiconductors

Peizhi Du

C.N. Yang Institute for Theoretical Physics

Stony Brook University

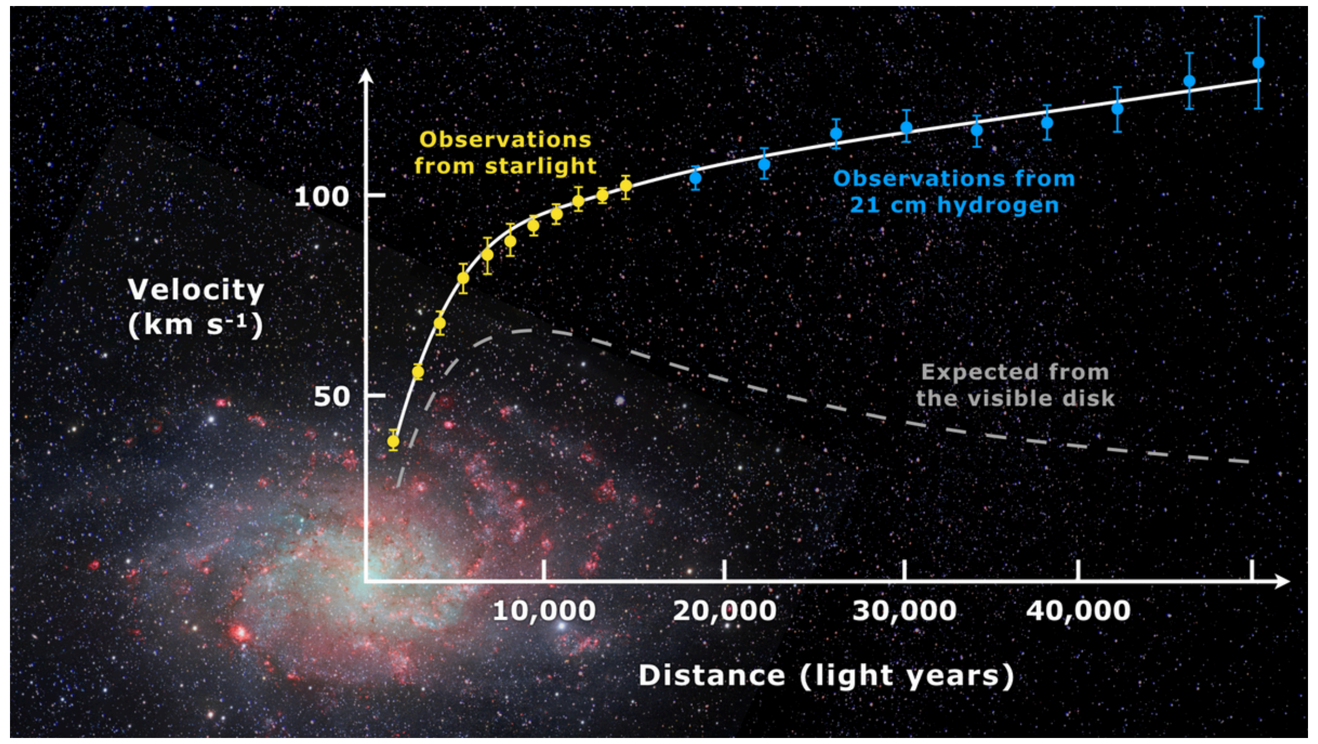
Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

Institute for Nuclear Theory, University of Washington

August 15, 2022

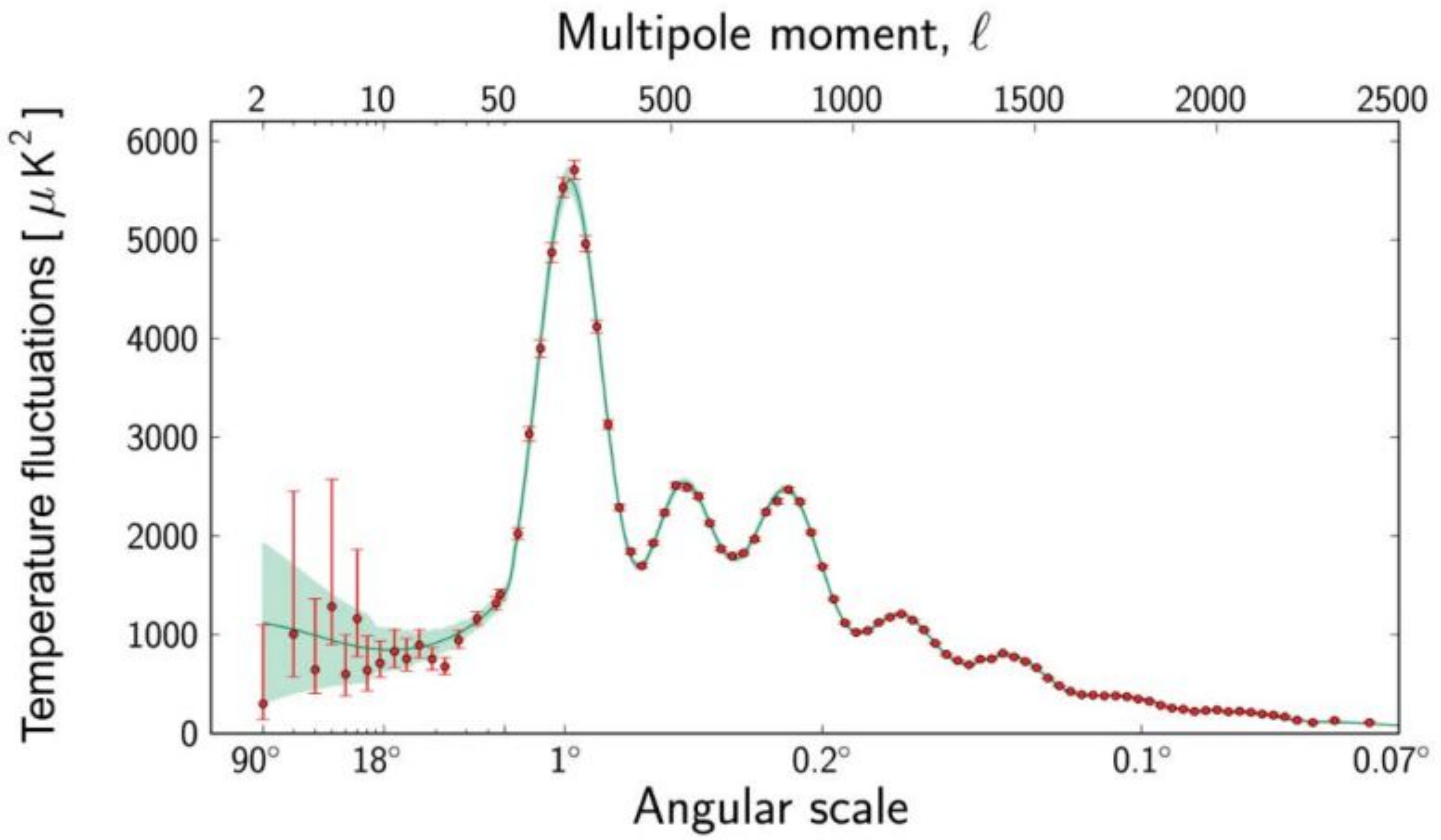
in collaboration with Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar (to appear)

Dark matter



Galaxy

Galaxy Cluster

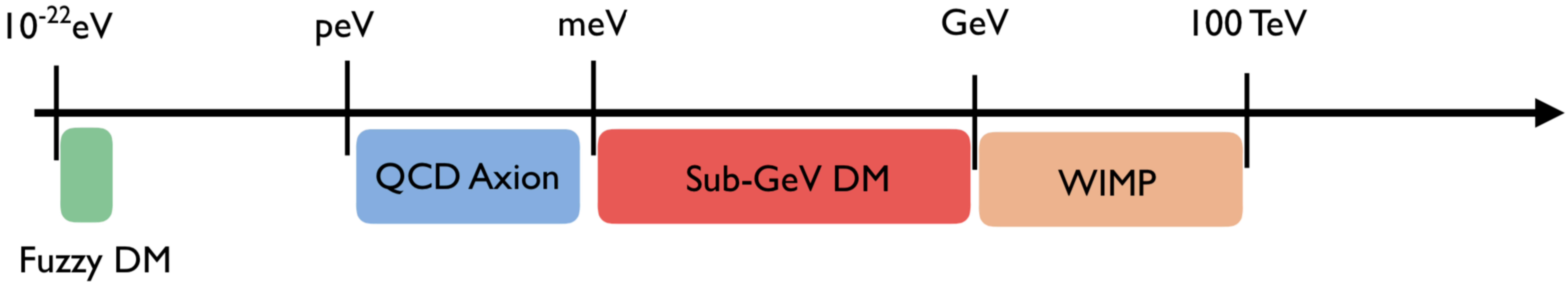


CMB

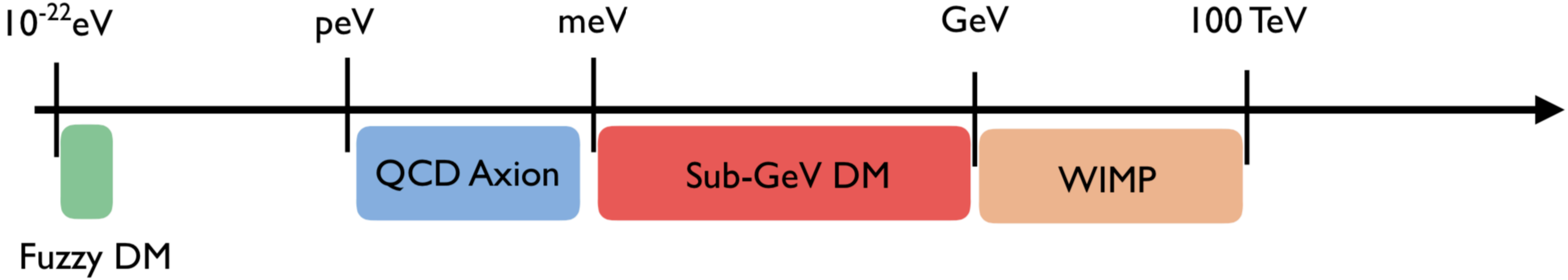
- 85% of matter, 27% total energy density in the Universe
- Evidence for dark matter is currently only gravitational

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

Dark matter

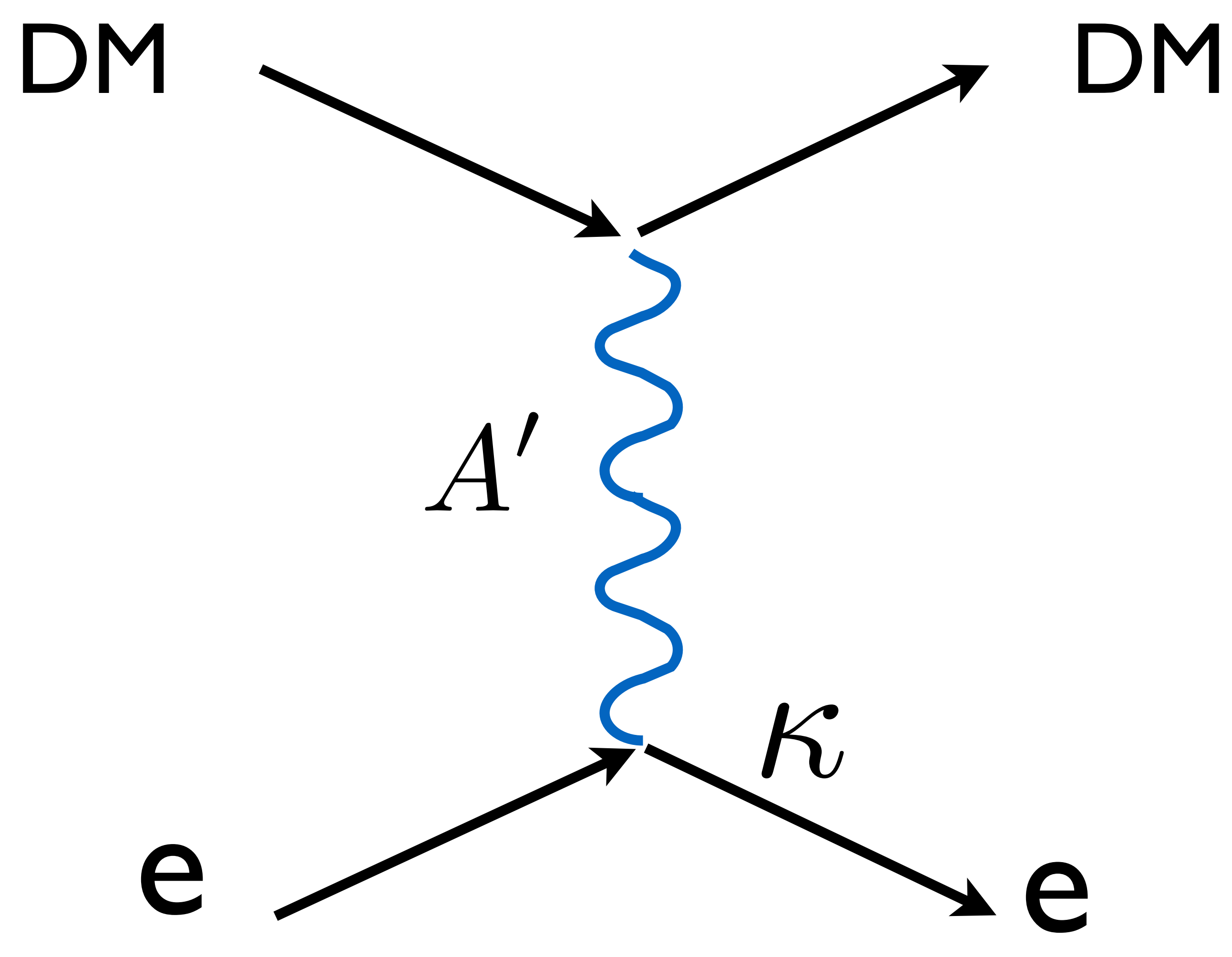


Sub-GeV dark matter

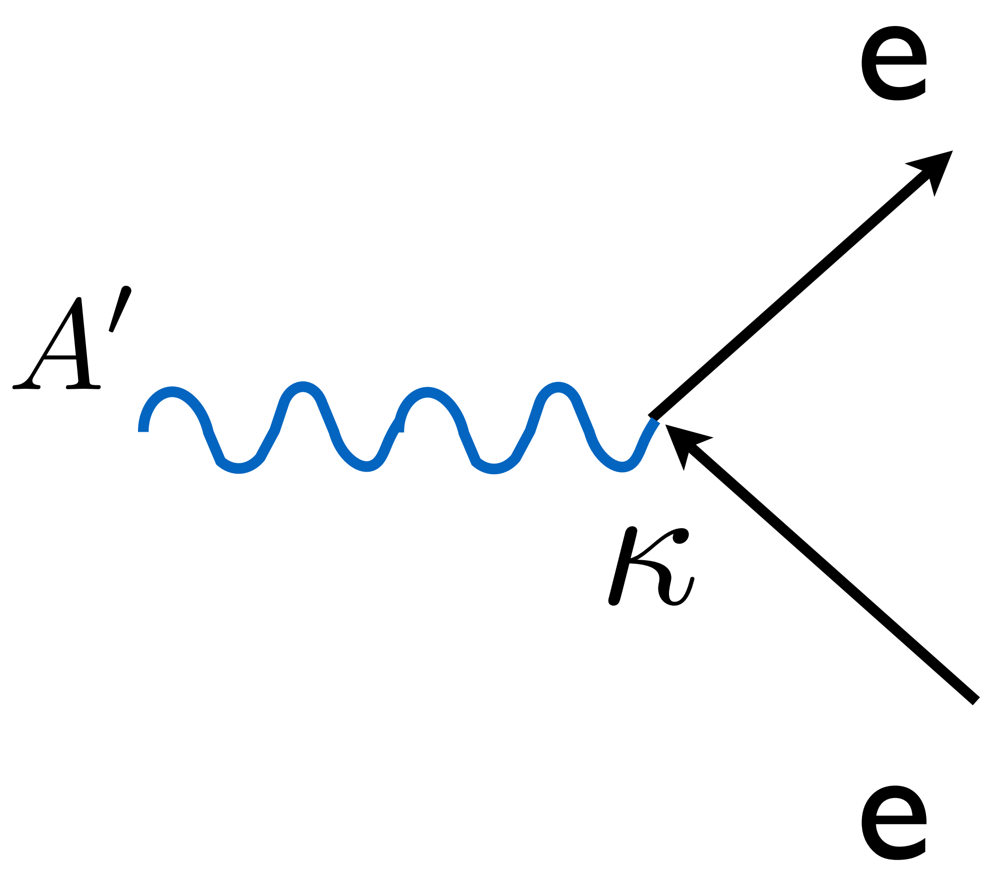


Dark photon model: $\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\kappa}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu}$

Other models, see talk by Robert McGehee

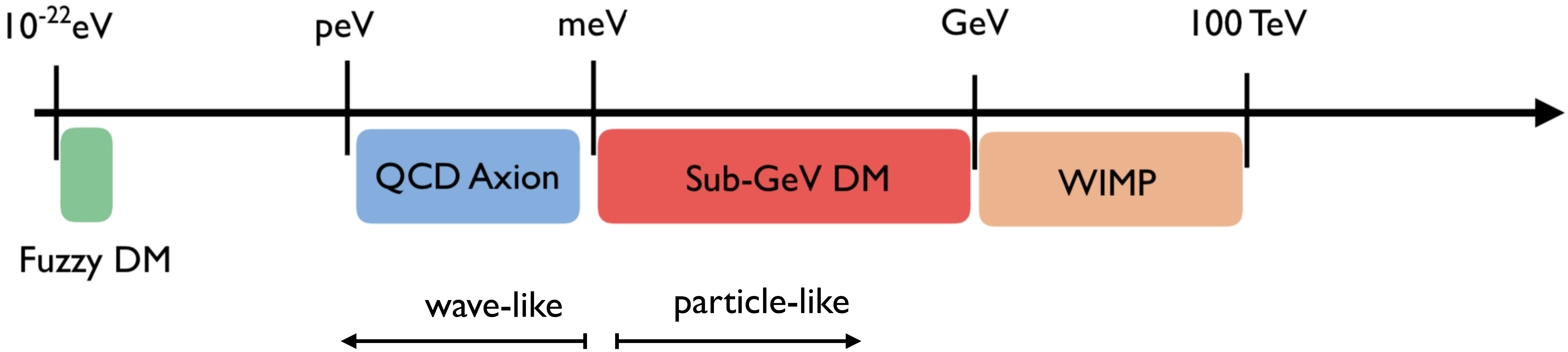


DM-electron scattering



Dark photon absorption

Direct Detection of DM



ADMX (talk by Gray Rybka)

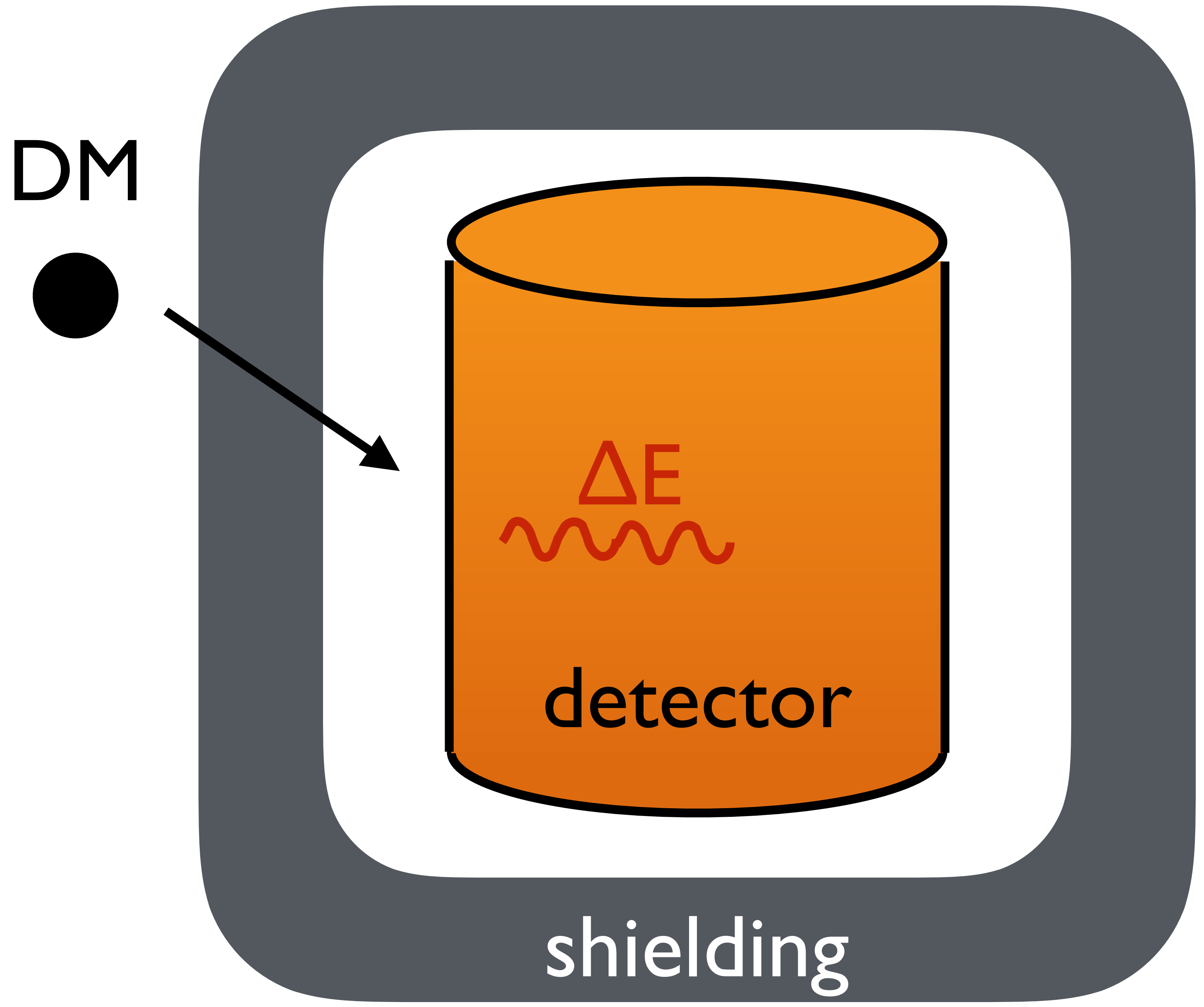
CAST, ABRACADABRA…

Xenon, LUX, PandaX…

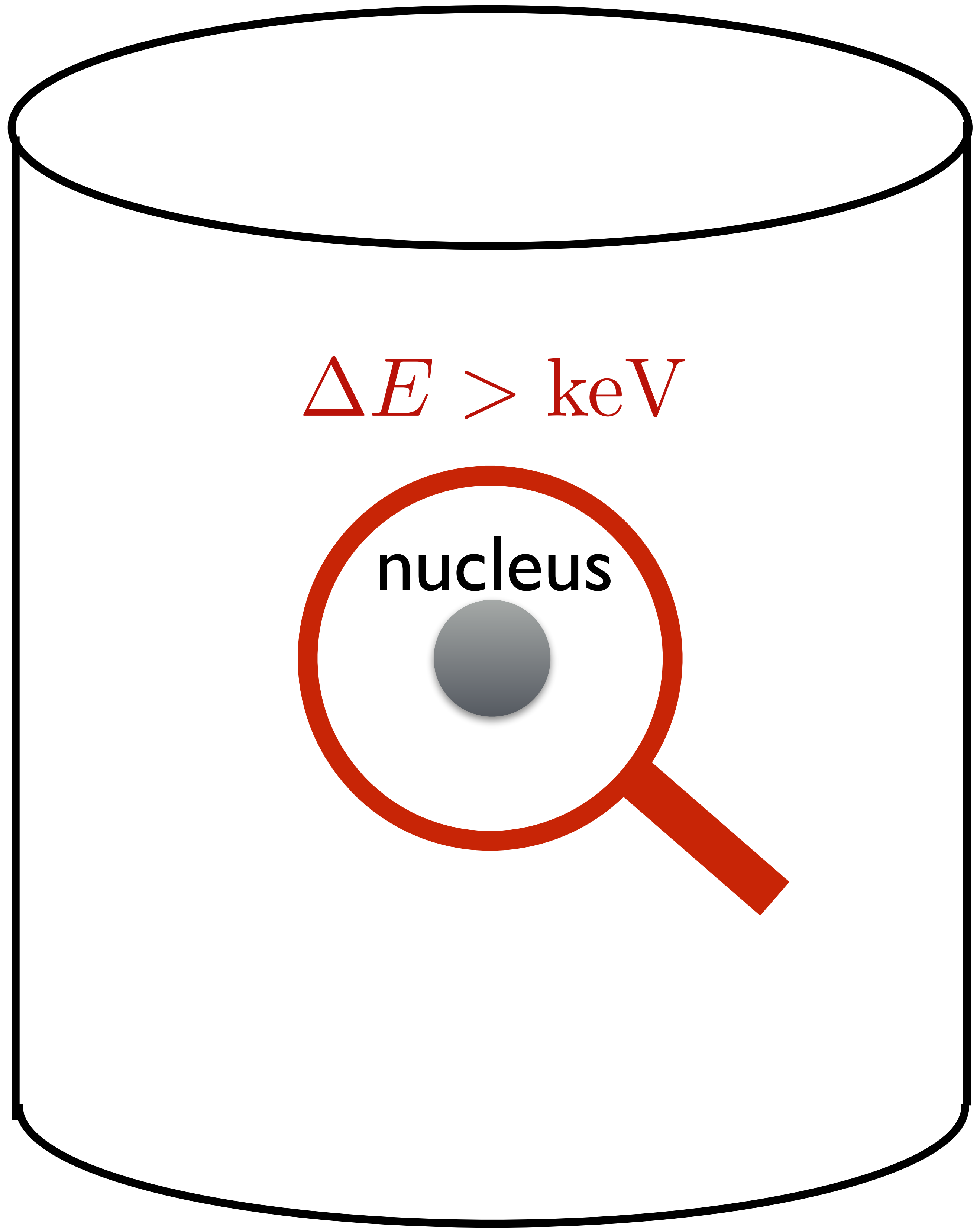
SENSEI, SuperCDMS, DAMIC (talk by Alvaro Chavarria)…

Direct Detection of DM

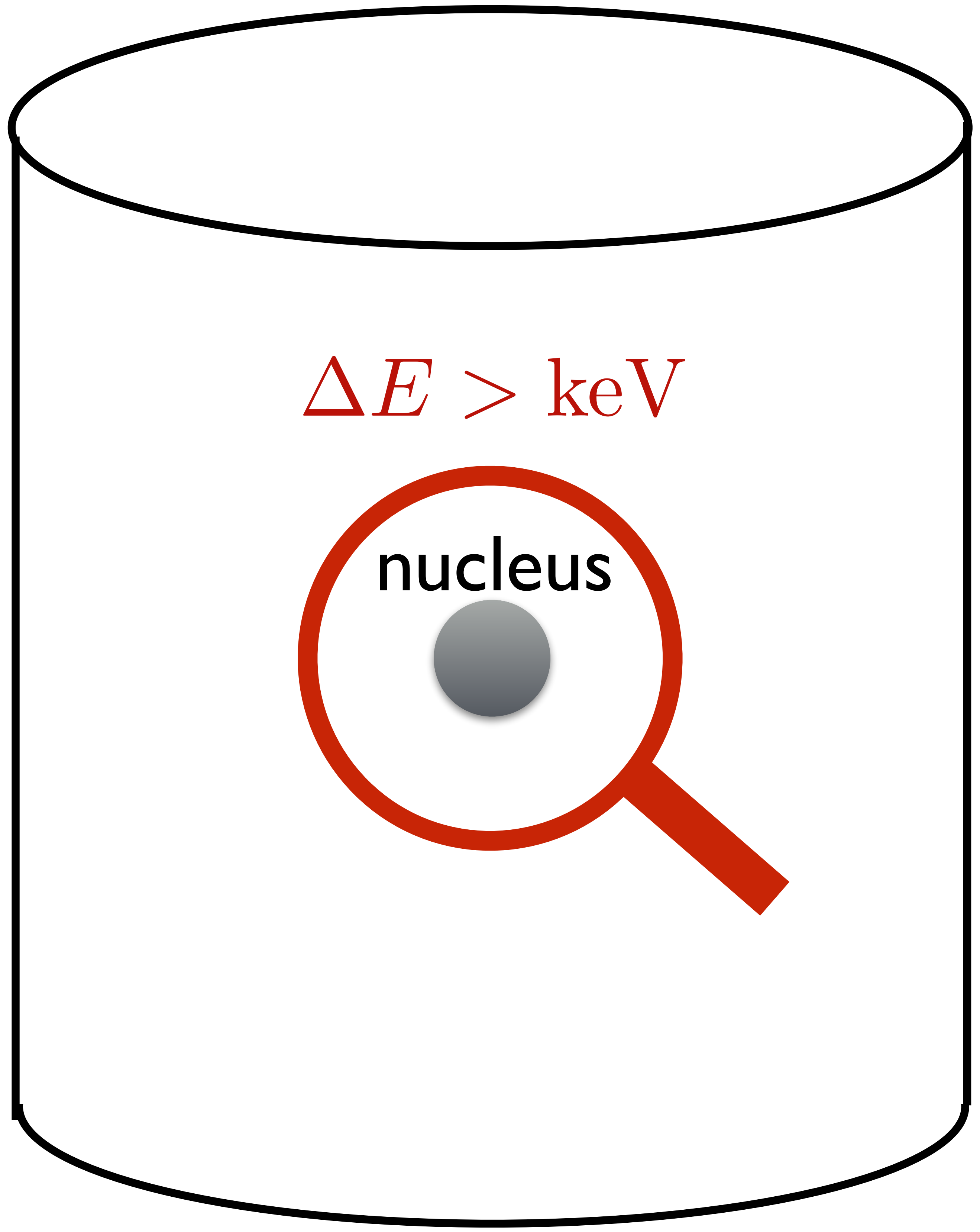
- Assuming DM has more than gravitational interactions with SM
- Clean environment, sensitive detector
- Wait for DM to come!



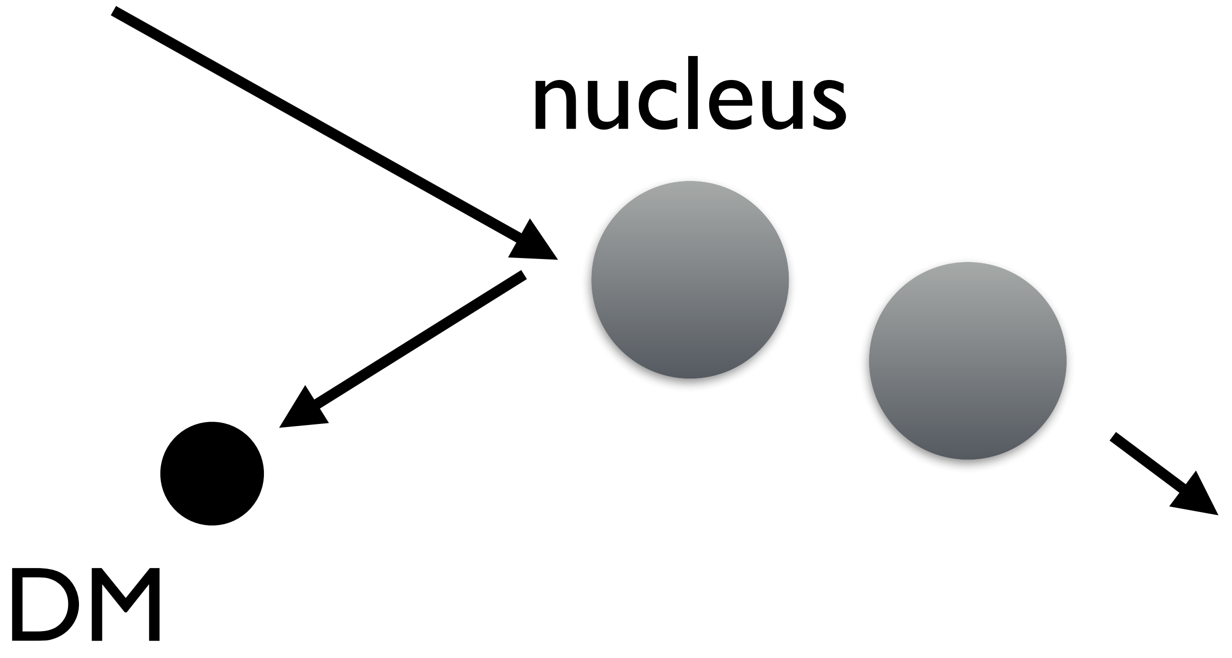
Direct Detection: ΔE>keV



Direct Detection: ΔE>keV

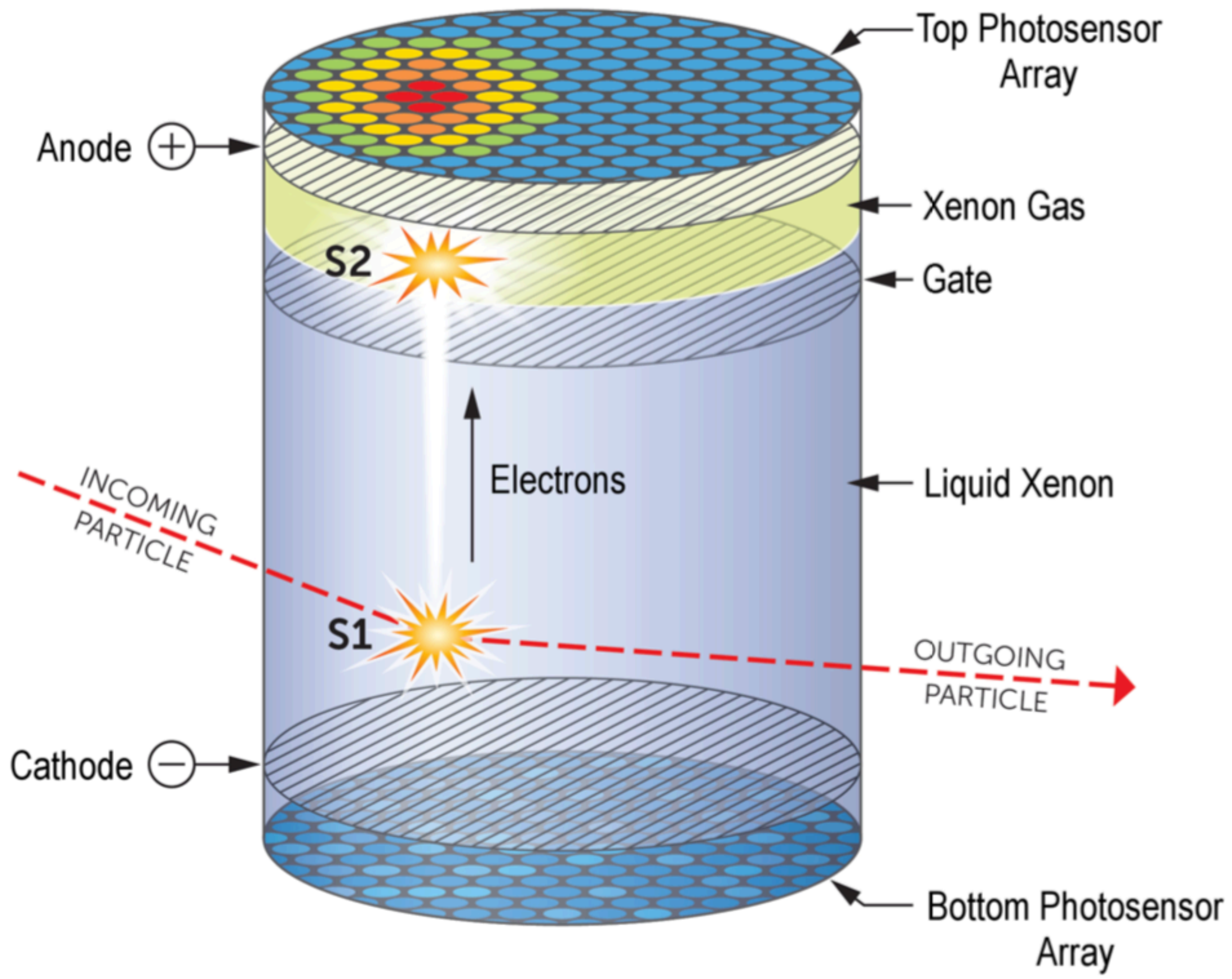


Elastic DM-nuclear scattering



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

Figure from J. Aalbers et.al. , 2022

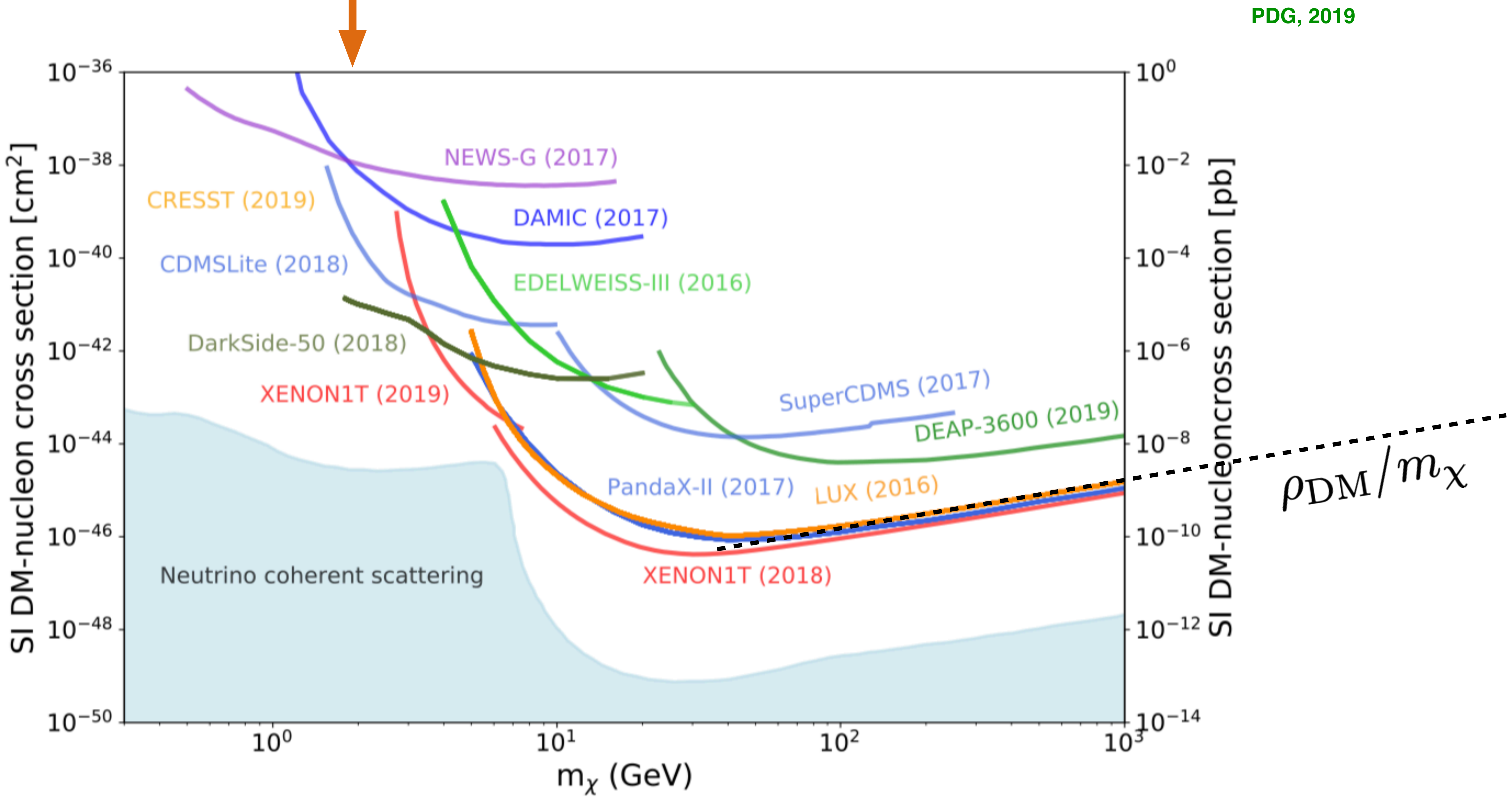


Signals: S1+S2

Threshold: ~keV

Nuclear recoil constraints

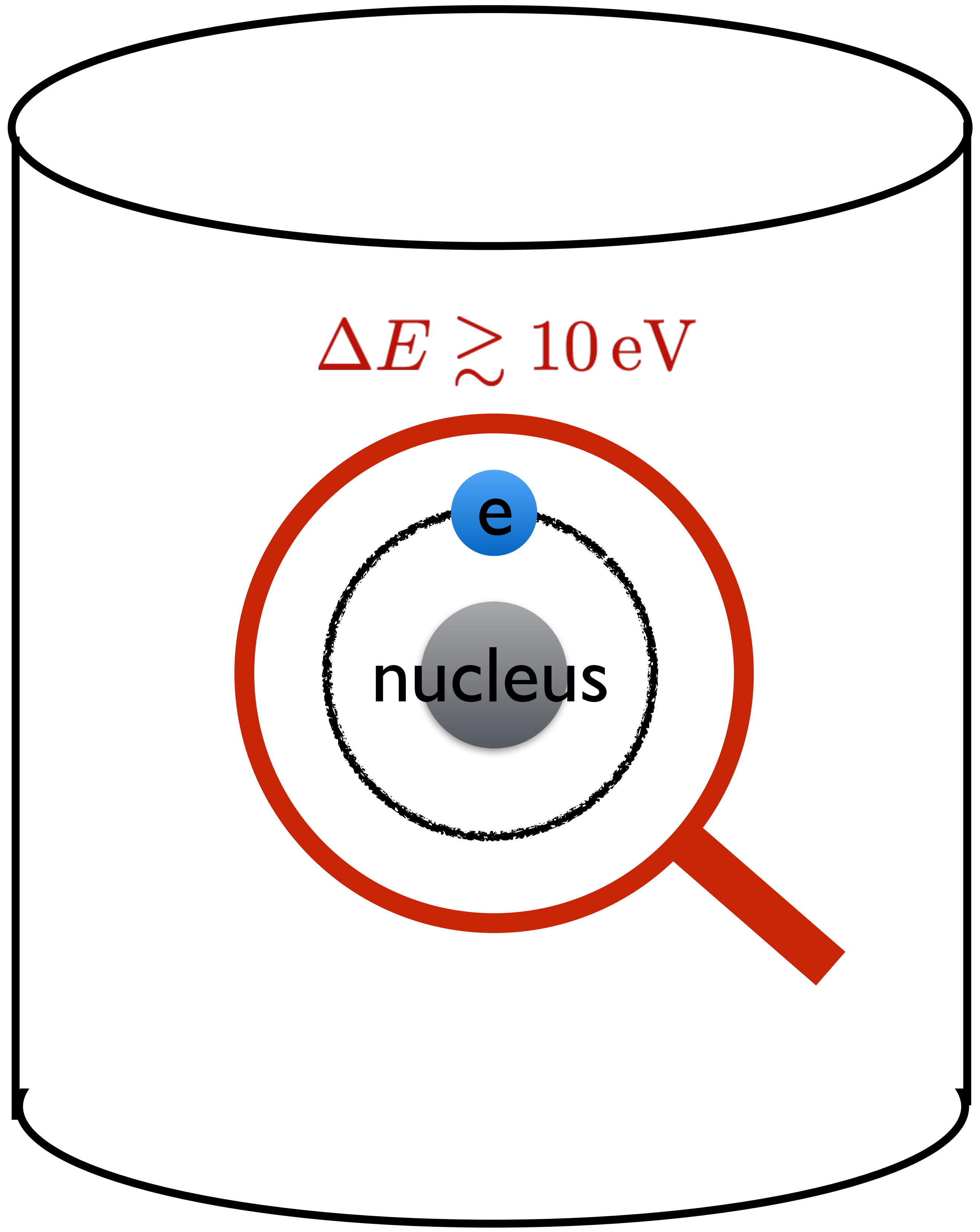
Limited by ~keV threshold



Insufficient energy transfer

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

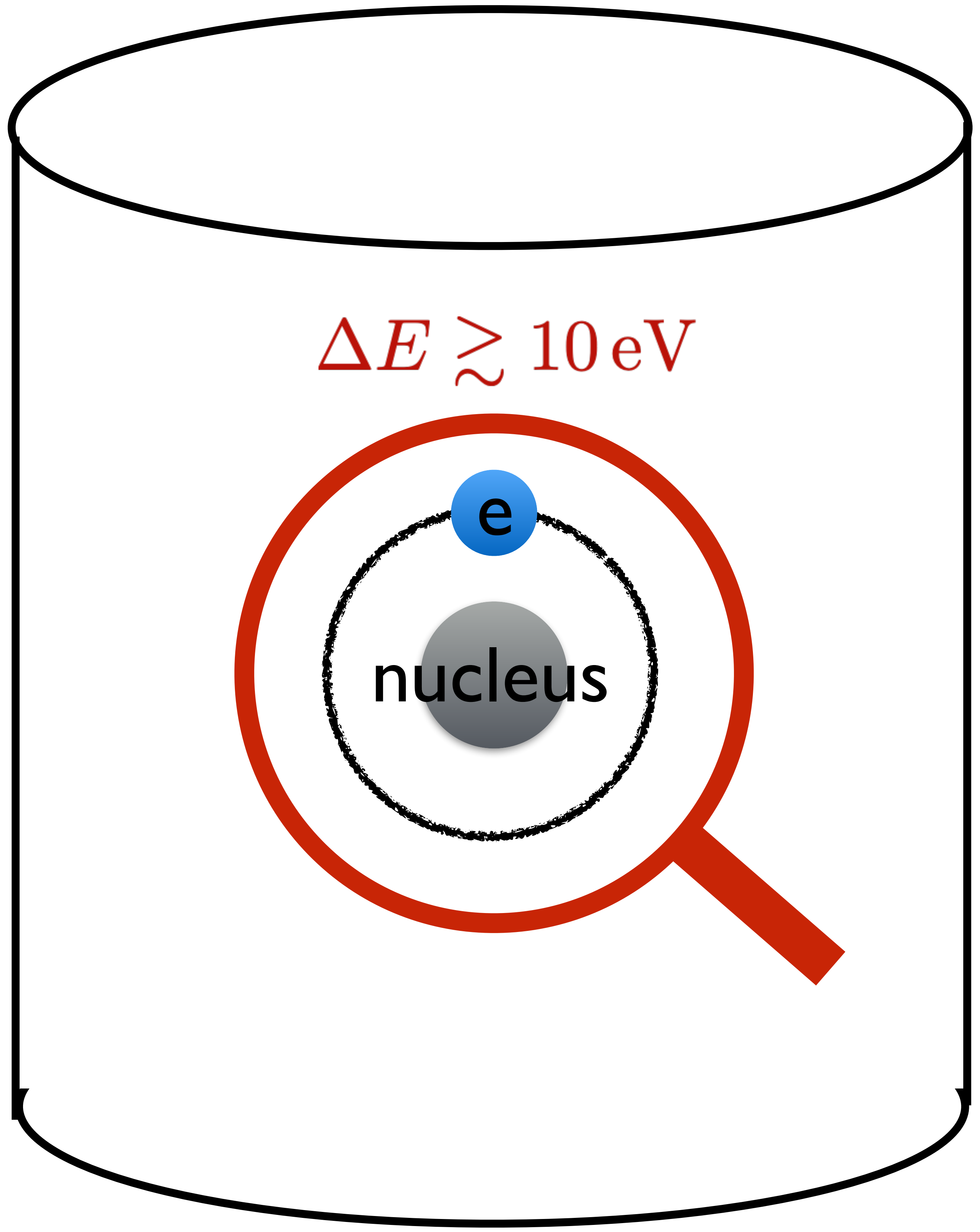
Direct Detection: ΔE>O(10)eV

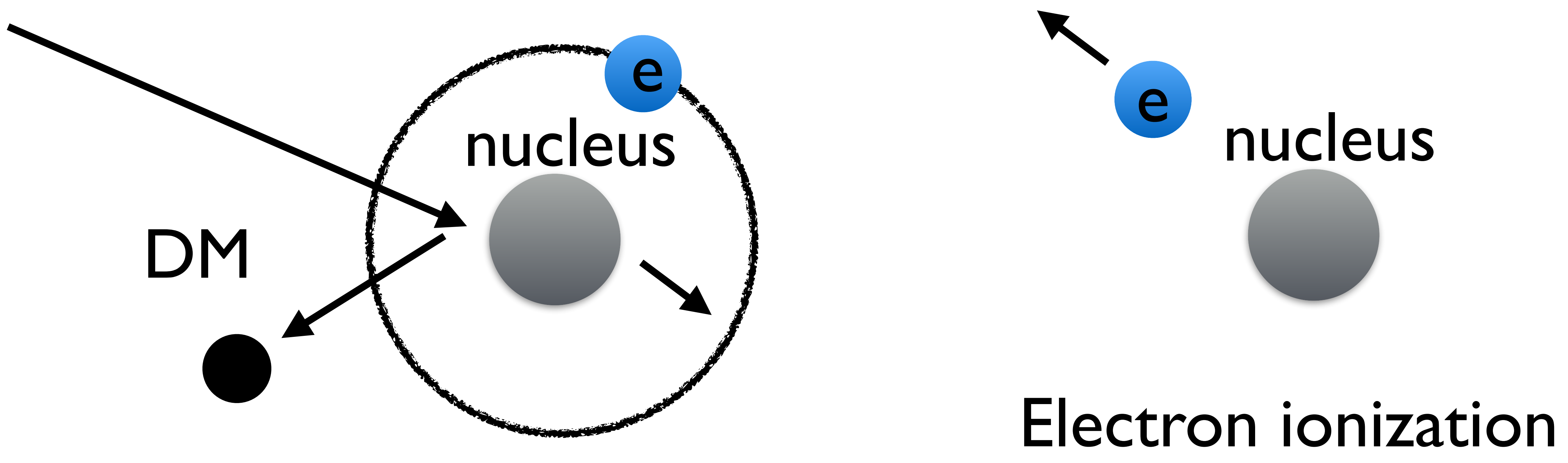


Direct Detection: ΔE>O(10)eV

Vergados, Ejiri , 2004
Ive, Nakano, Shoji, Suzuki, 2017

Migdal effect (See also talks by Nicole Bell and Kim Berghaus)



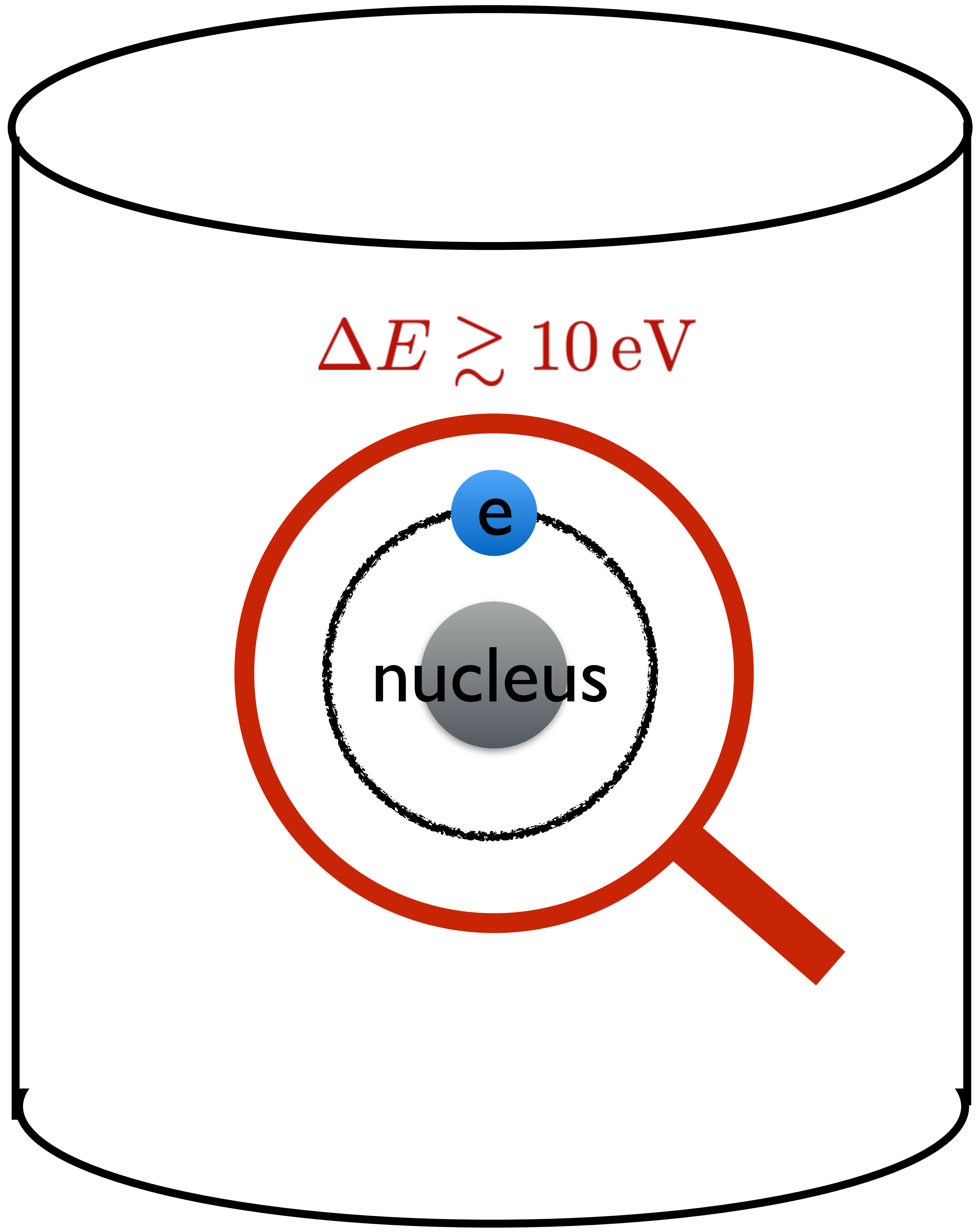


Signal: electron ionization (S2)

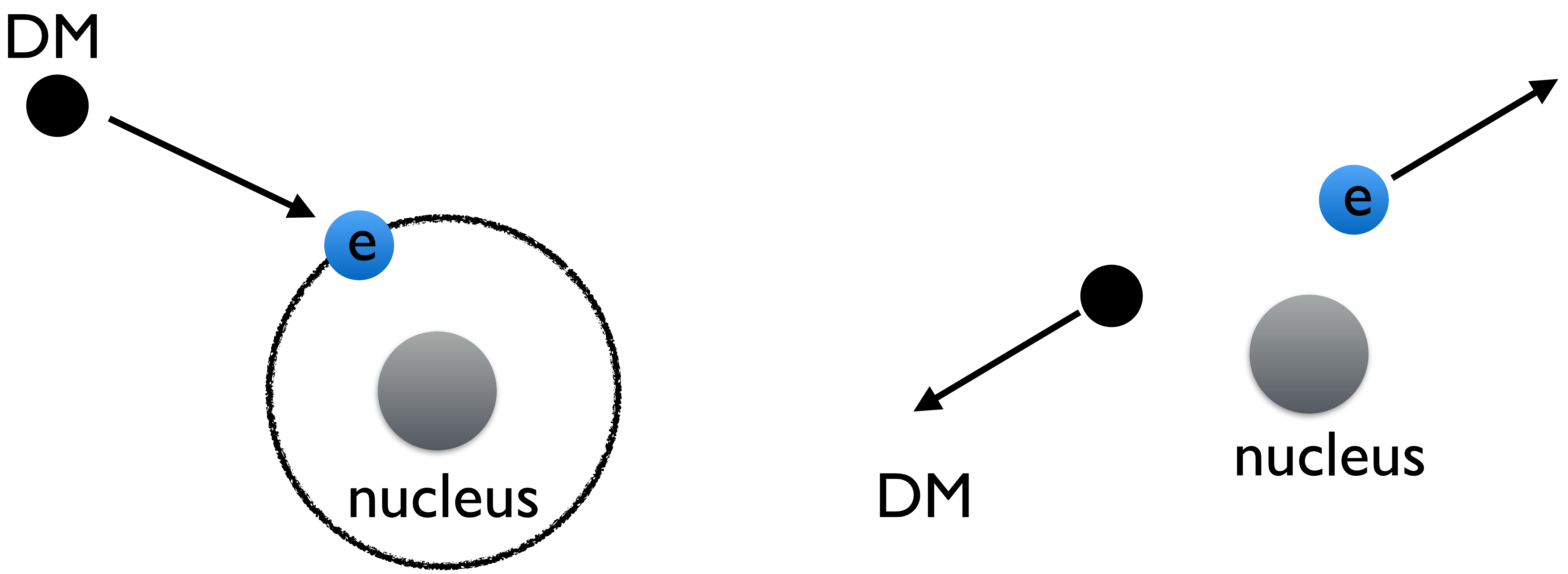
Threshold: ~10 eV

Direct Detection: ΔE>O(10)eV

Essig, Mardon, Volansky, 2011



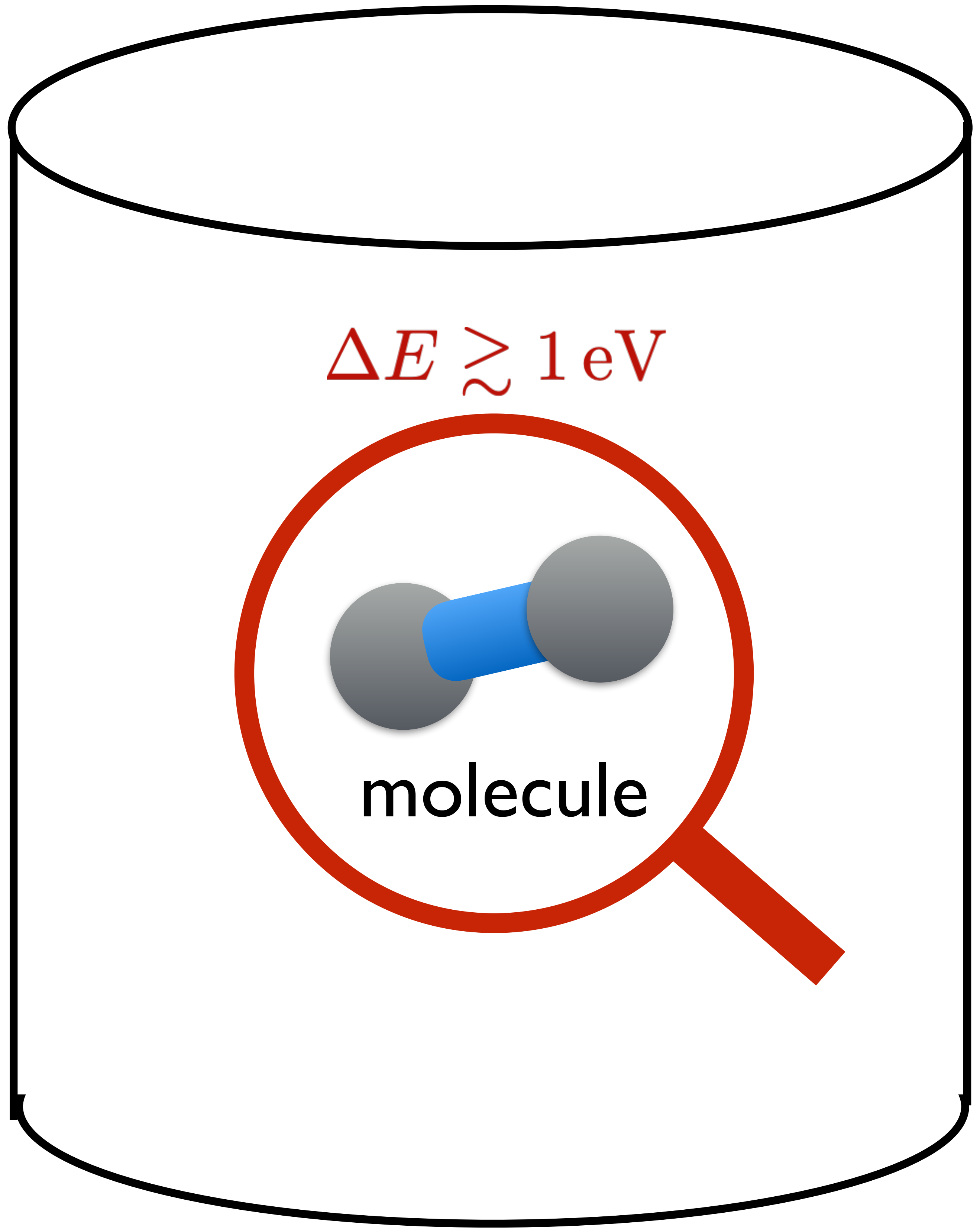
DM-electron scattering



Efficient energy transfer for light DM $E_{\mathrm{ER}} \lesssim \frac{1}{2} m_\chi v^2$ >> $E_{\mathrm{NR}} \lesssim \frac{2(m_\chi v)^2}{m_N}$

Signal: electron ionization (S2)
Threshold: ~10 eV

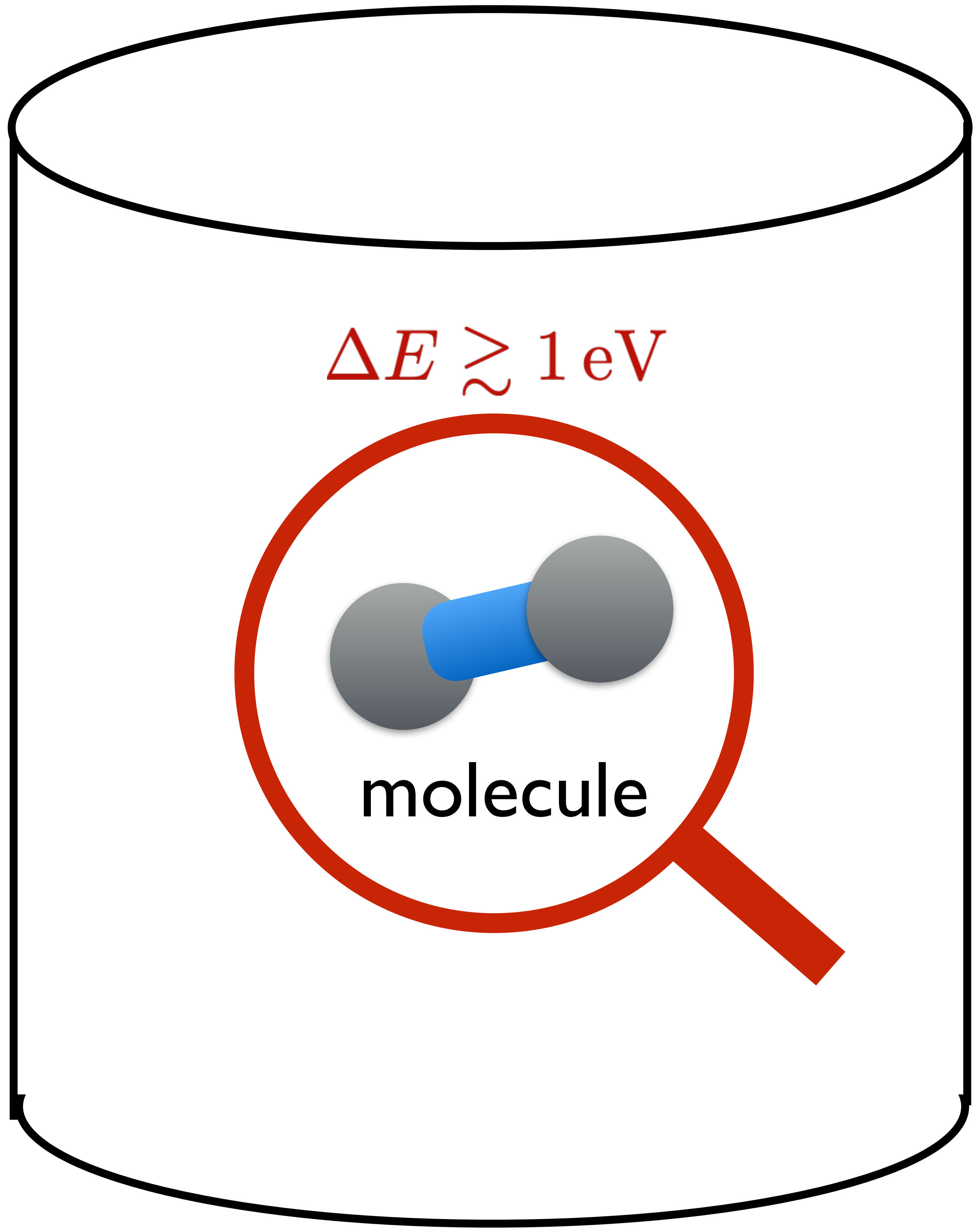
Direct Detection: ΔE>O(1)eV



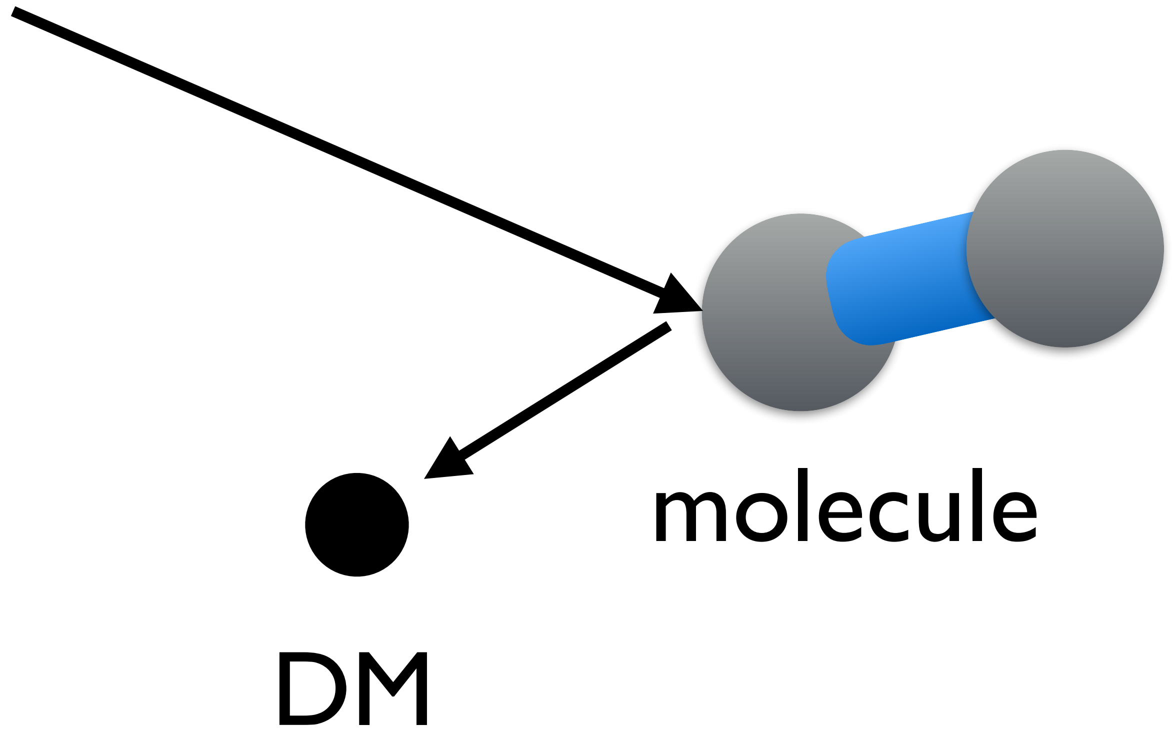
Direct Detection: ΔE>O(1)eV

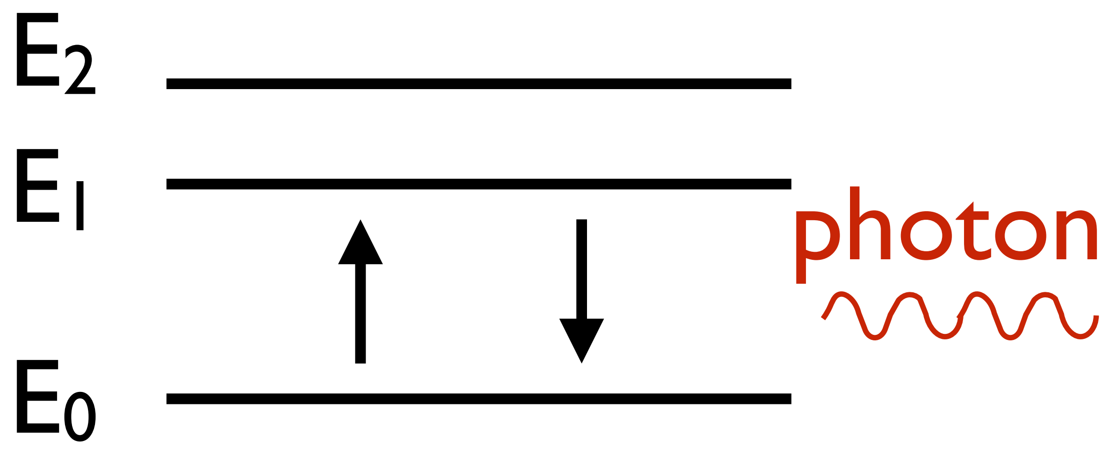
Blanco, Collar, Kahn, Lillard, 2019

Essig, Perez-Rios, Ramani, Slone, 2019



Excitation in molecules



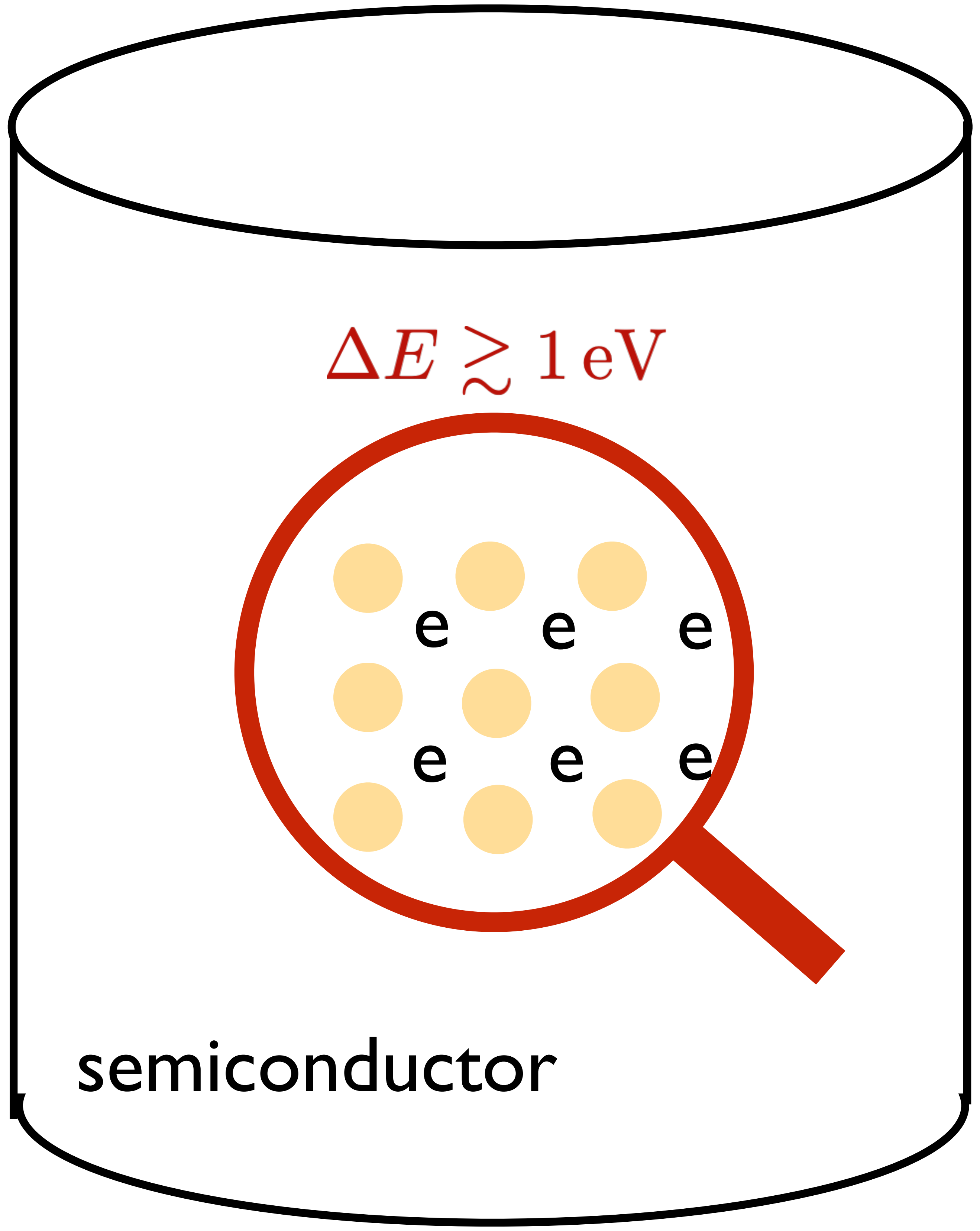


Signal: photons

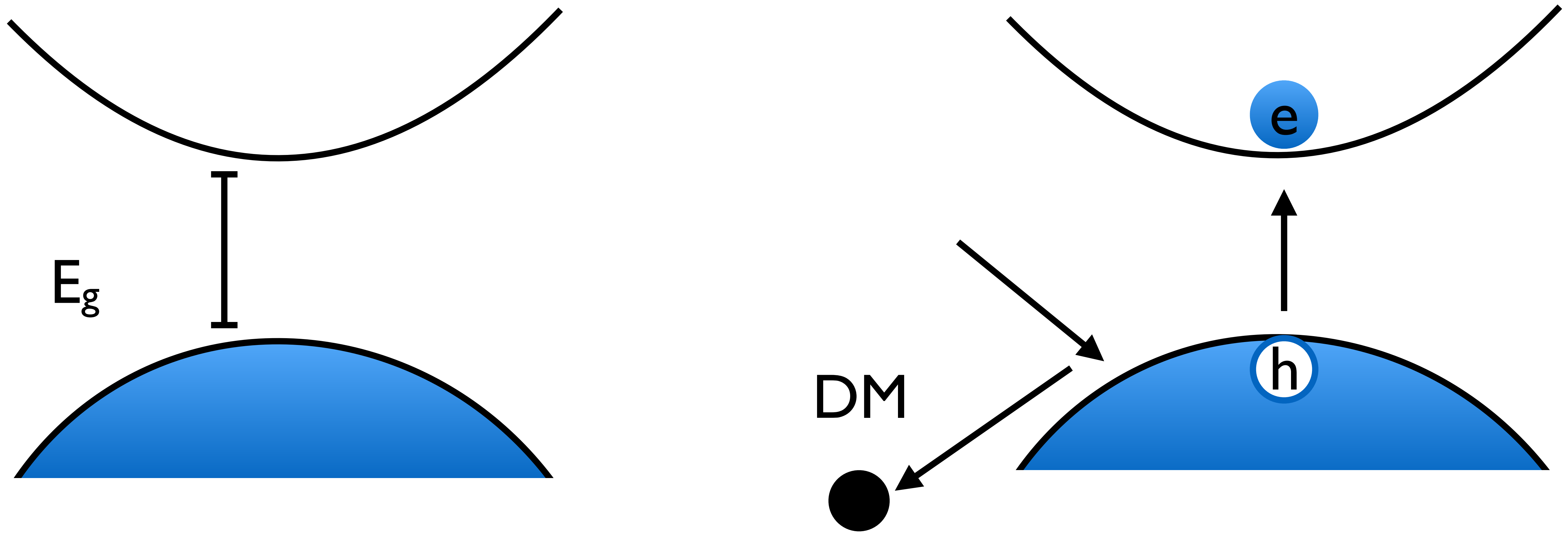
Threshold: O(1) eV

Direct Detection: ΔE>O(1)eV

Essig, Mardon, Volansky, 2011



Electron ionization in semiconductors

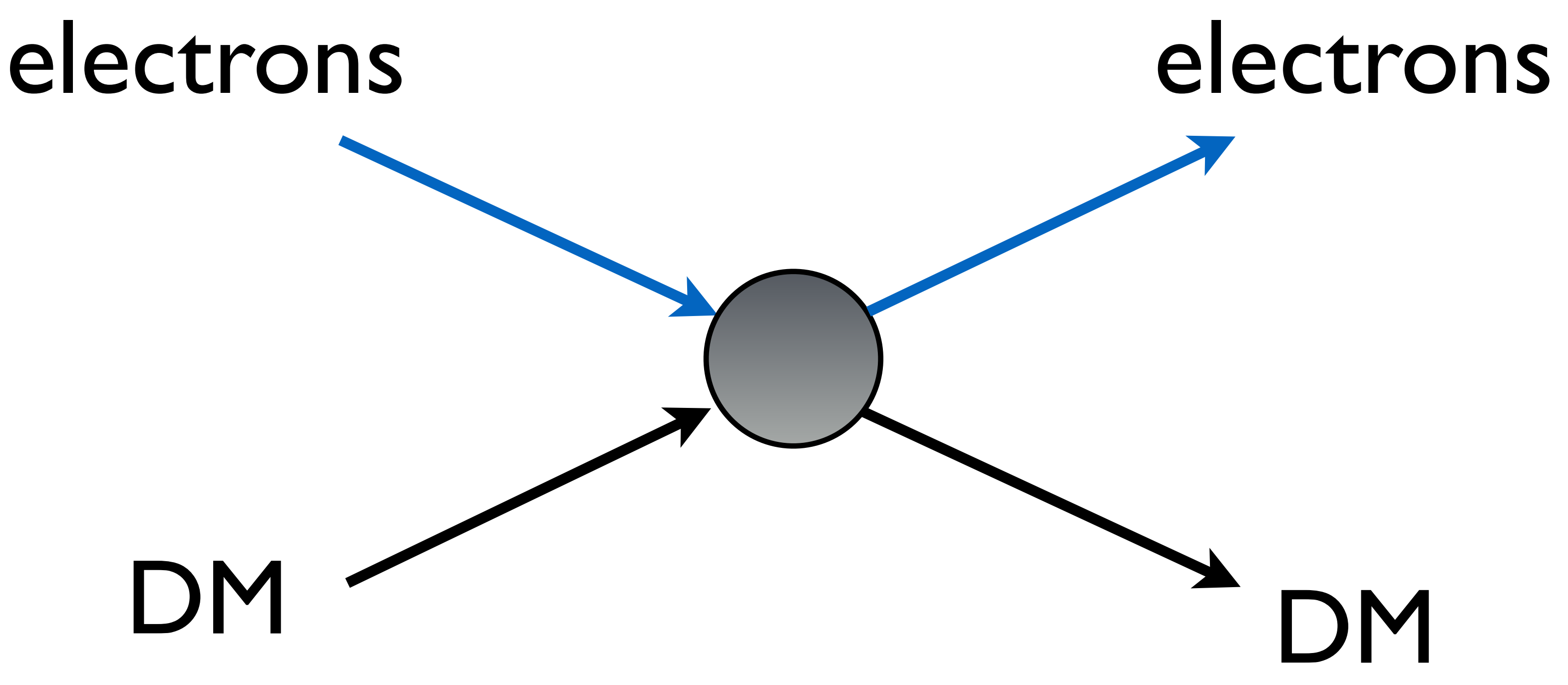


Signals: eh pairs

Threshold: E_g~1 eV

Direct detection of sub-GeV DM

Electron recoils



Access to whole kinetic energy:

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

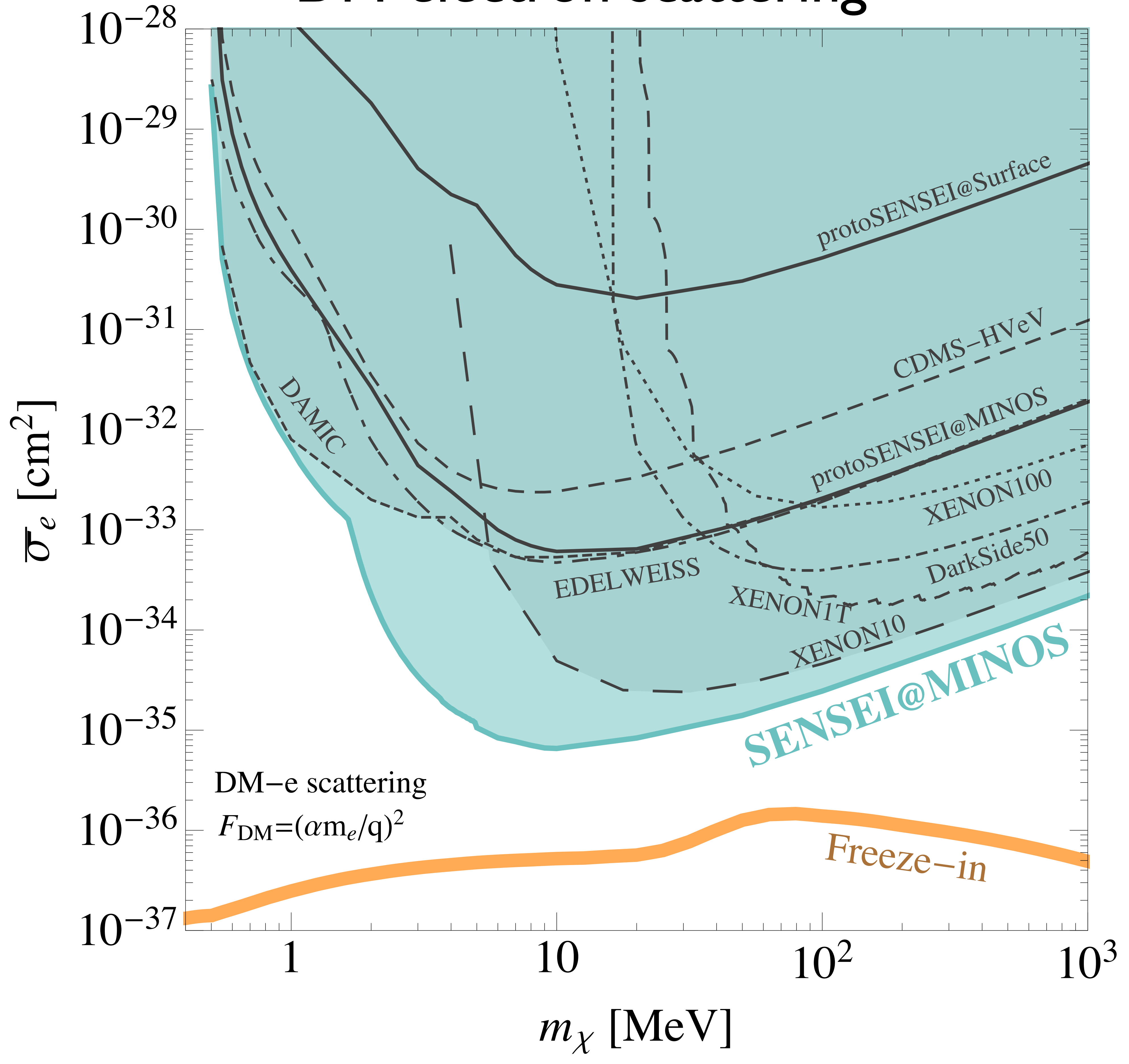
Current targets

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

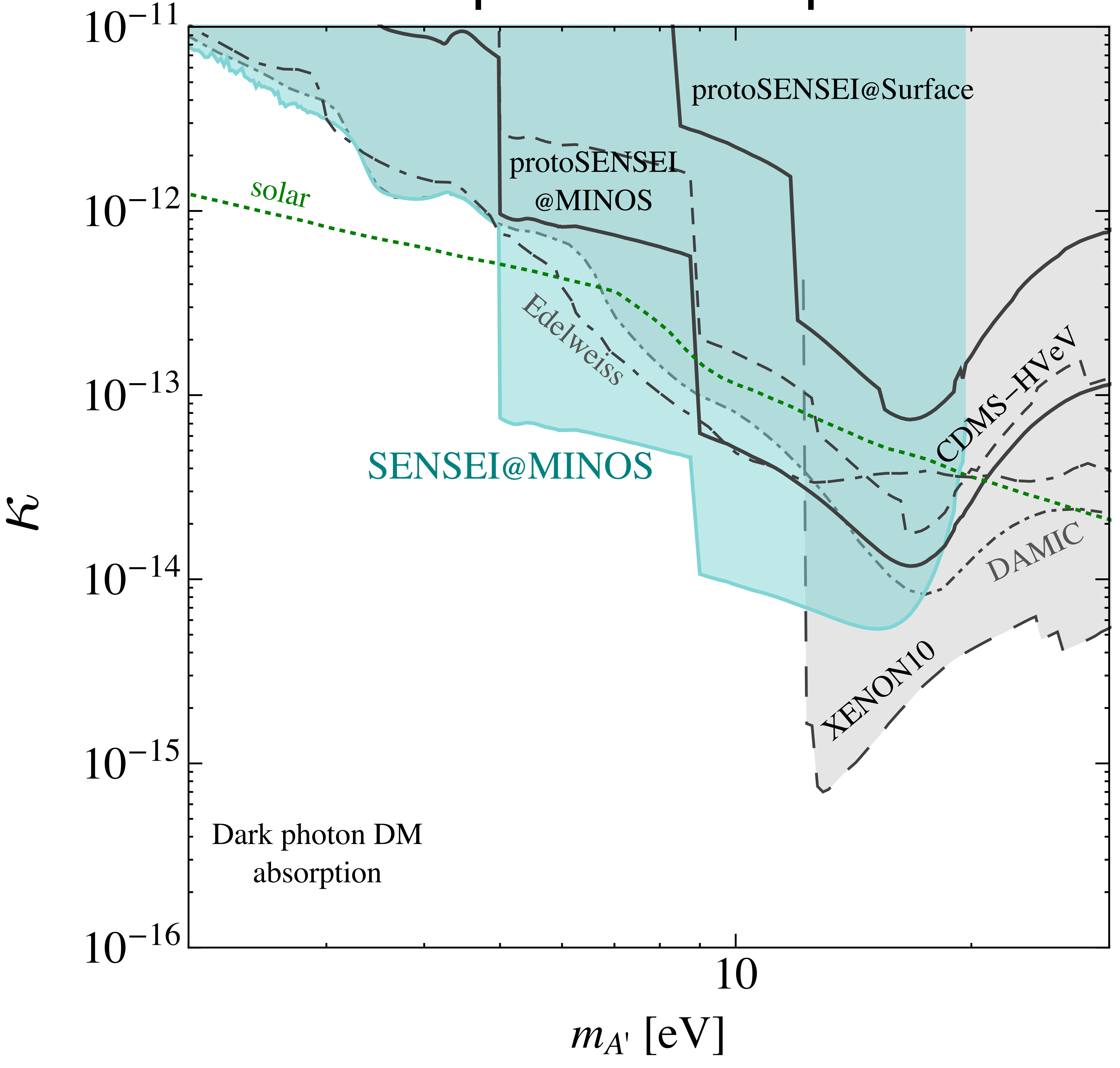
Direct detection of sub-GeV DM

Figure from SENSEI, 2020

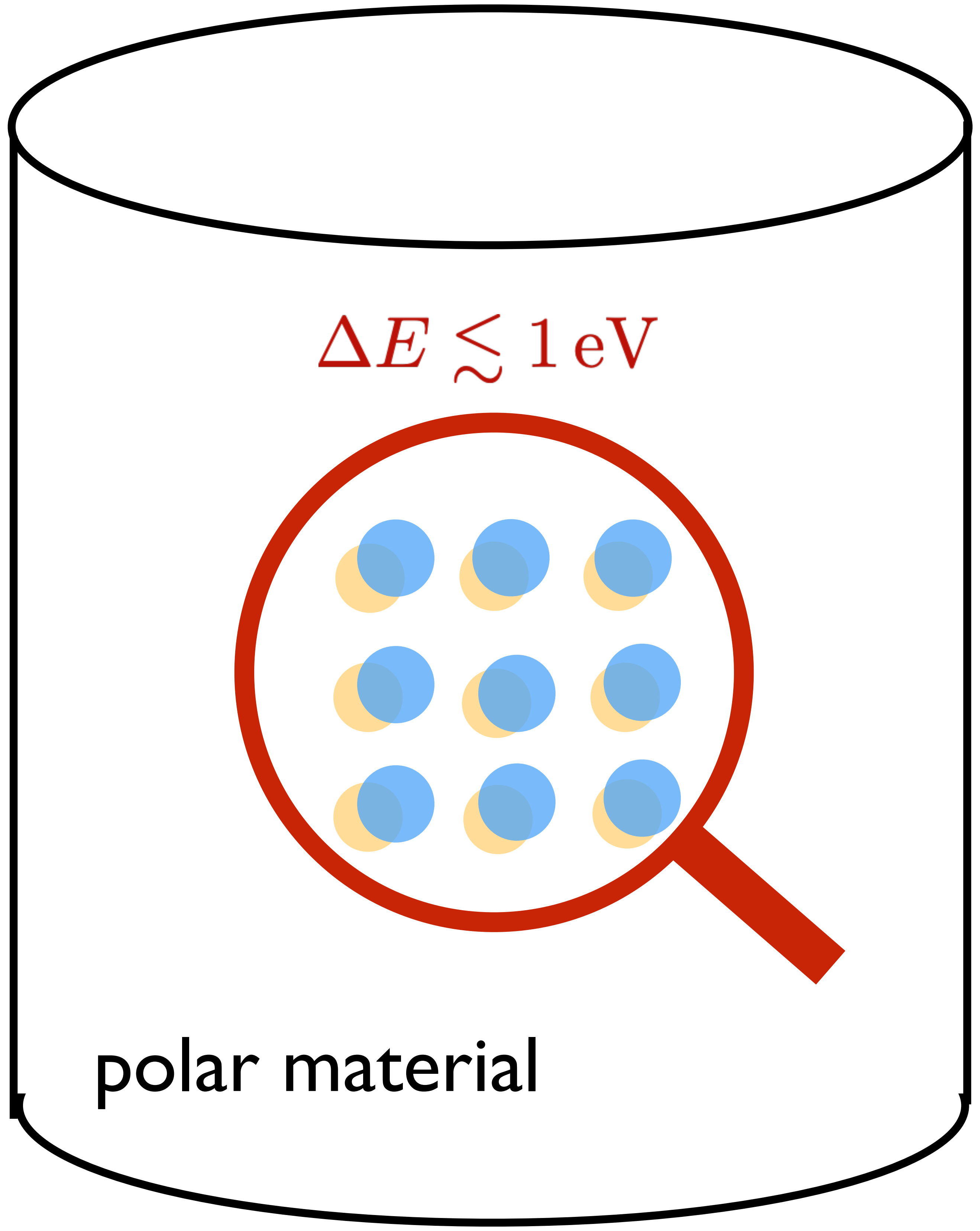
DM-electron scattering



Dark photon absorption

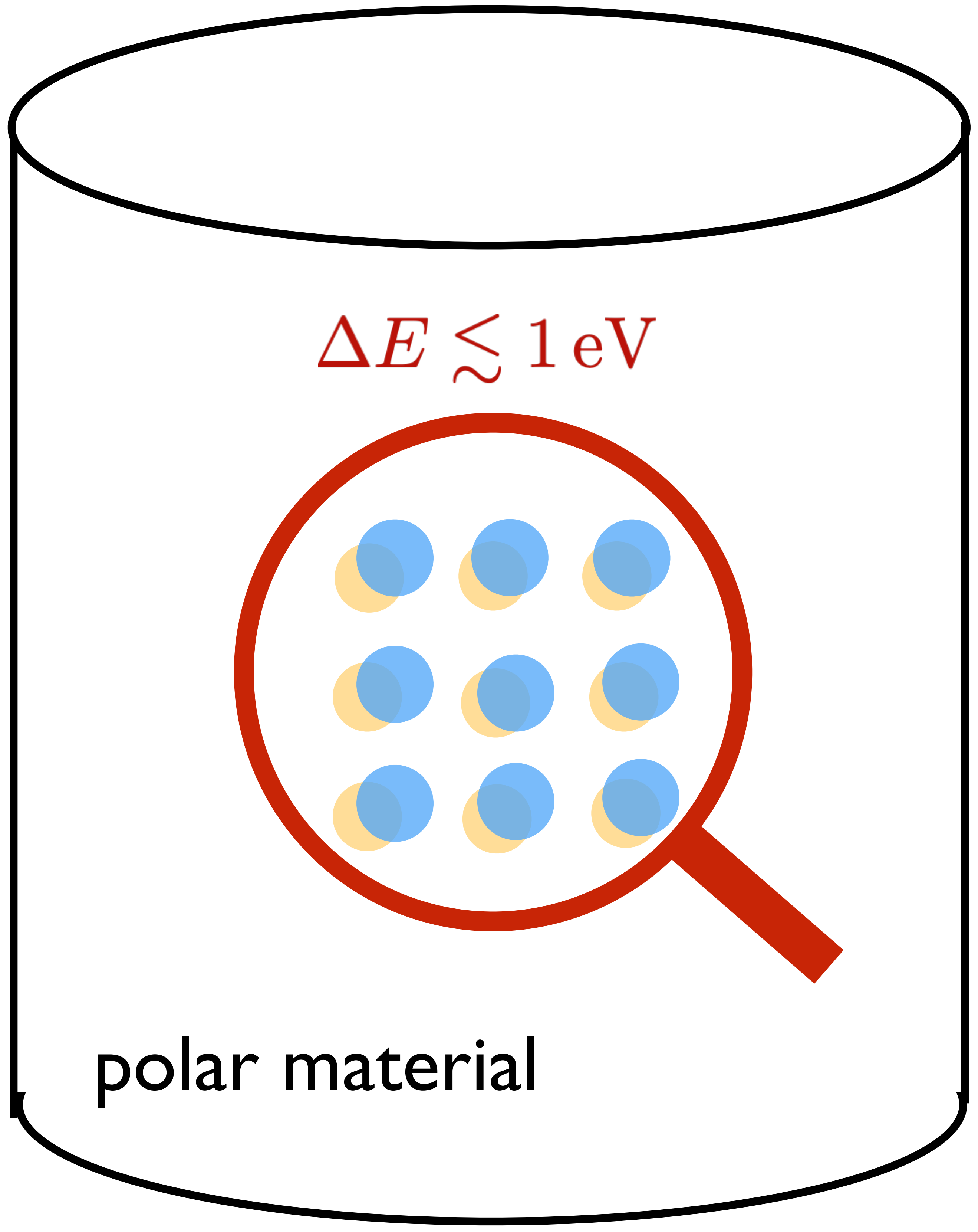


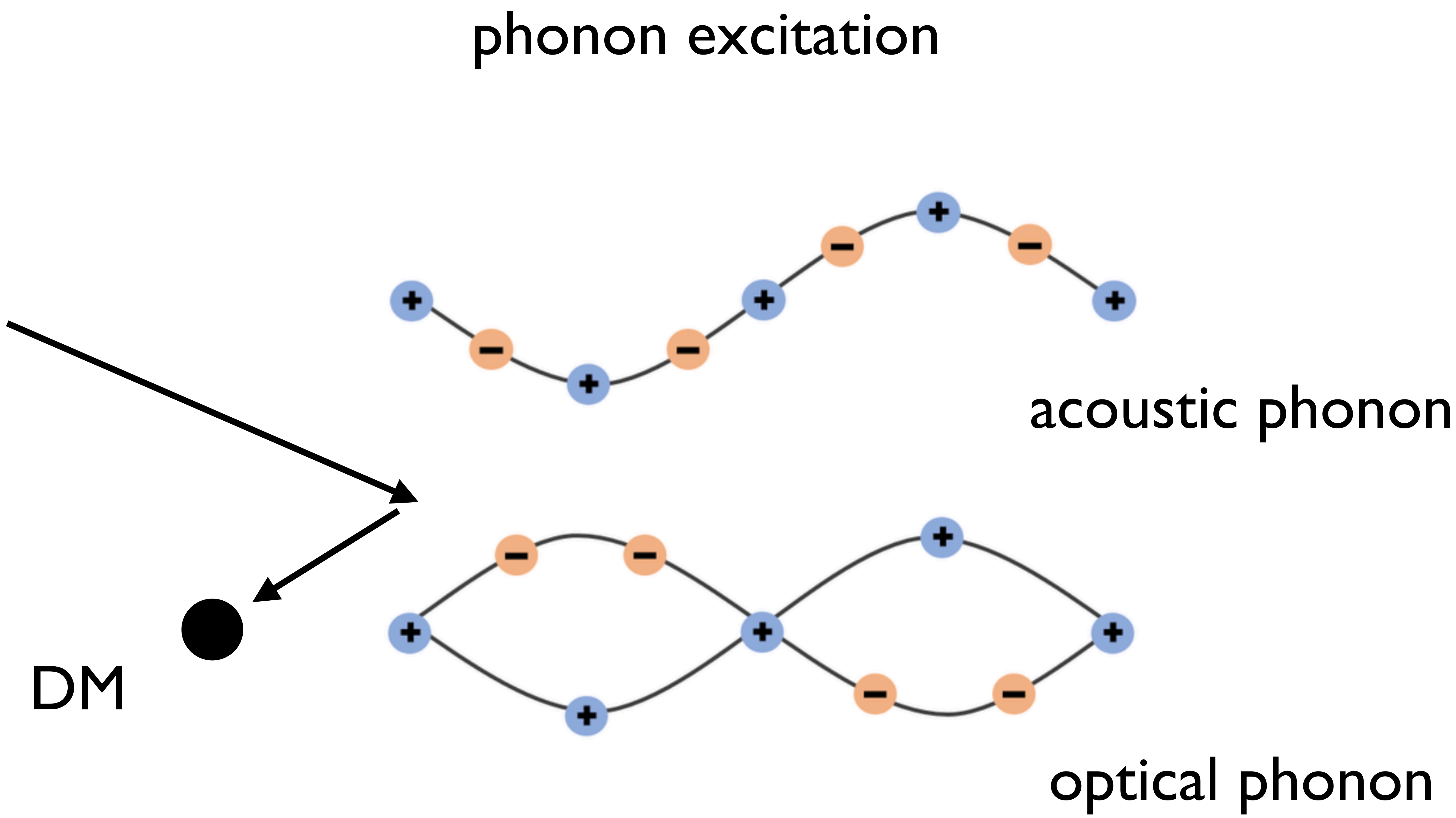
Direct Detection: ΔE<1eV



Direct Detection: ΔE<1eV

Knapen, Lin, Pyle, Zurek, 2017





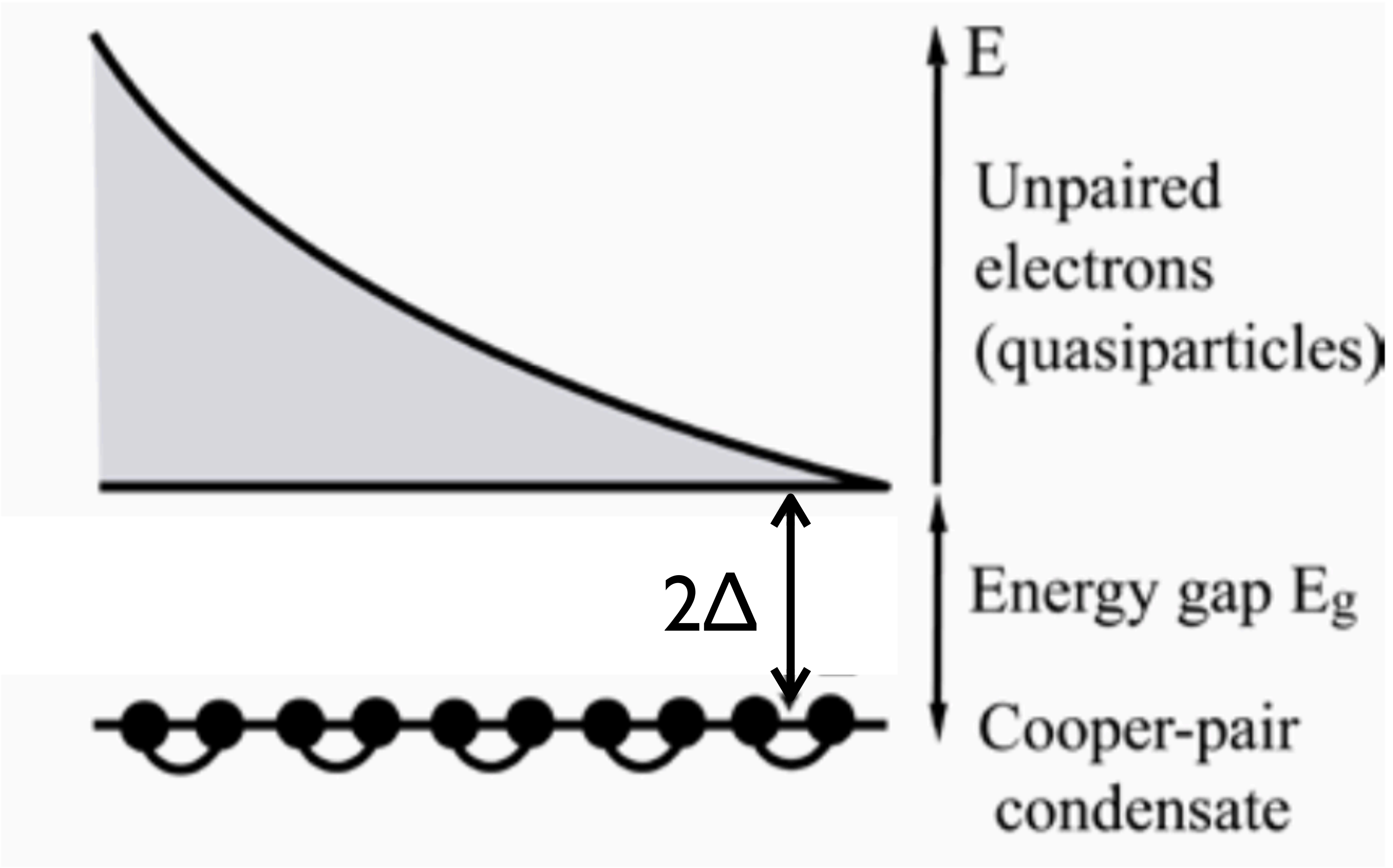
Signals: optical phonons

Threshold: ~10-100 meV

Direct Detection: ΔE<1eV

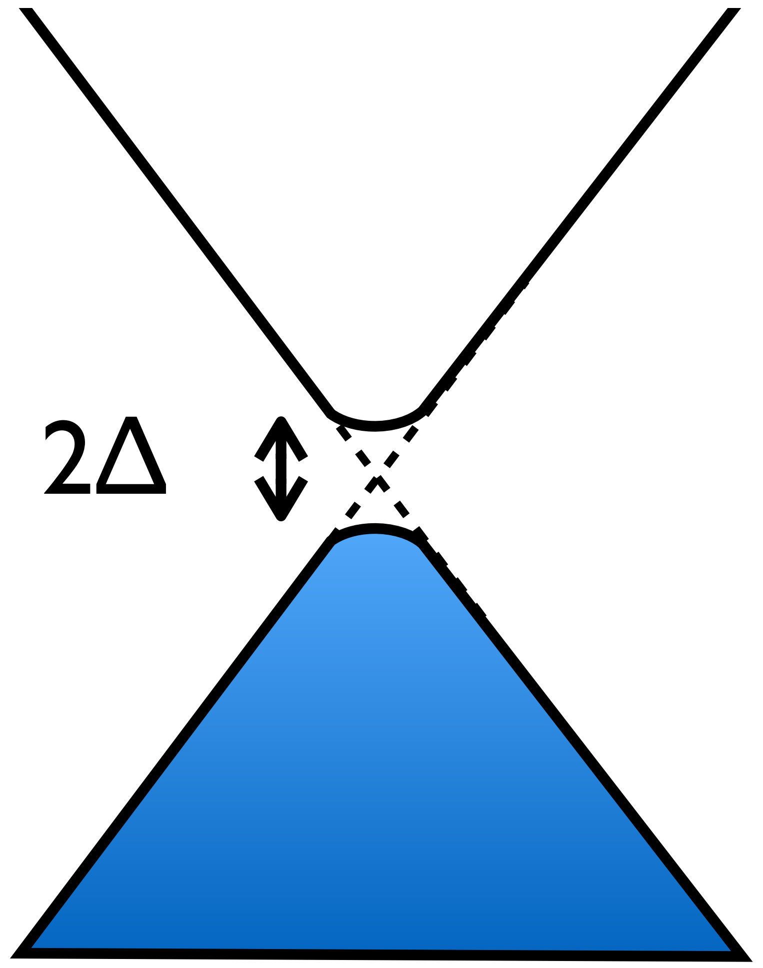
Hochberg, Zhao, Zurek, 2015
Hochberg, Kahn, Lisanti, Zurek, et.al, 2017

Superconductor



Δ=O(1) meV

Dirac material



Δ=O(1) meV

Signals: quasiparticles/phonons

Threshold: ~1 meV

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

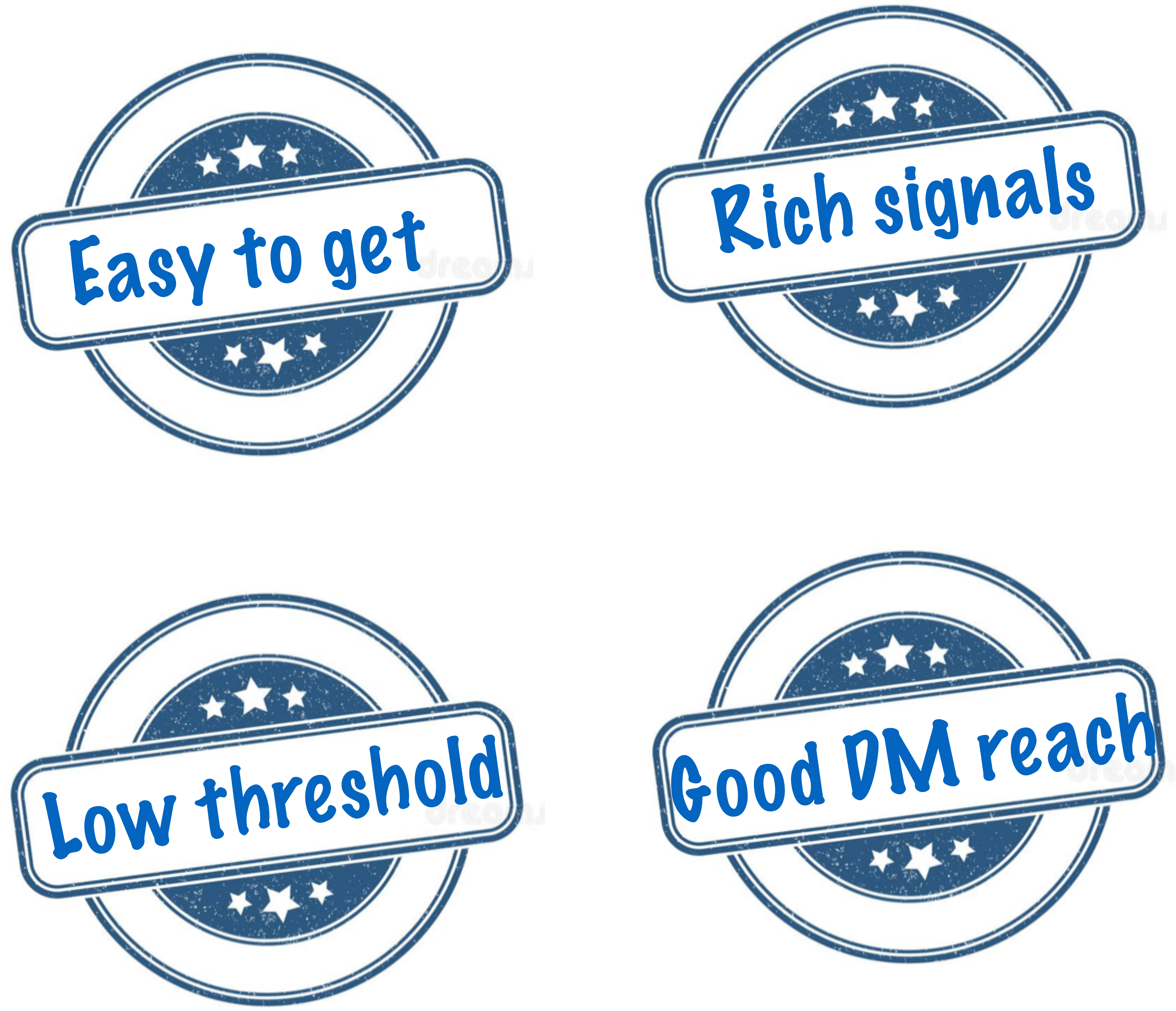
Low threshold can probe low DM masses

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

Probing sub-MeV (sub-eV) DM

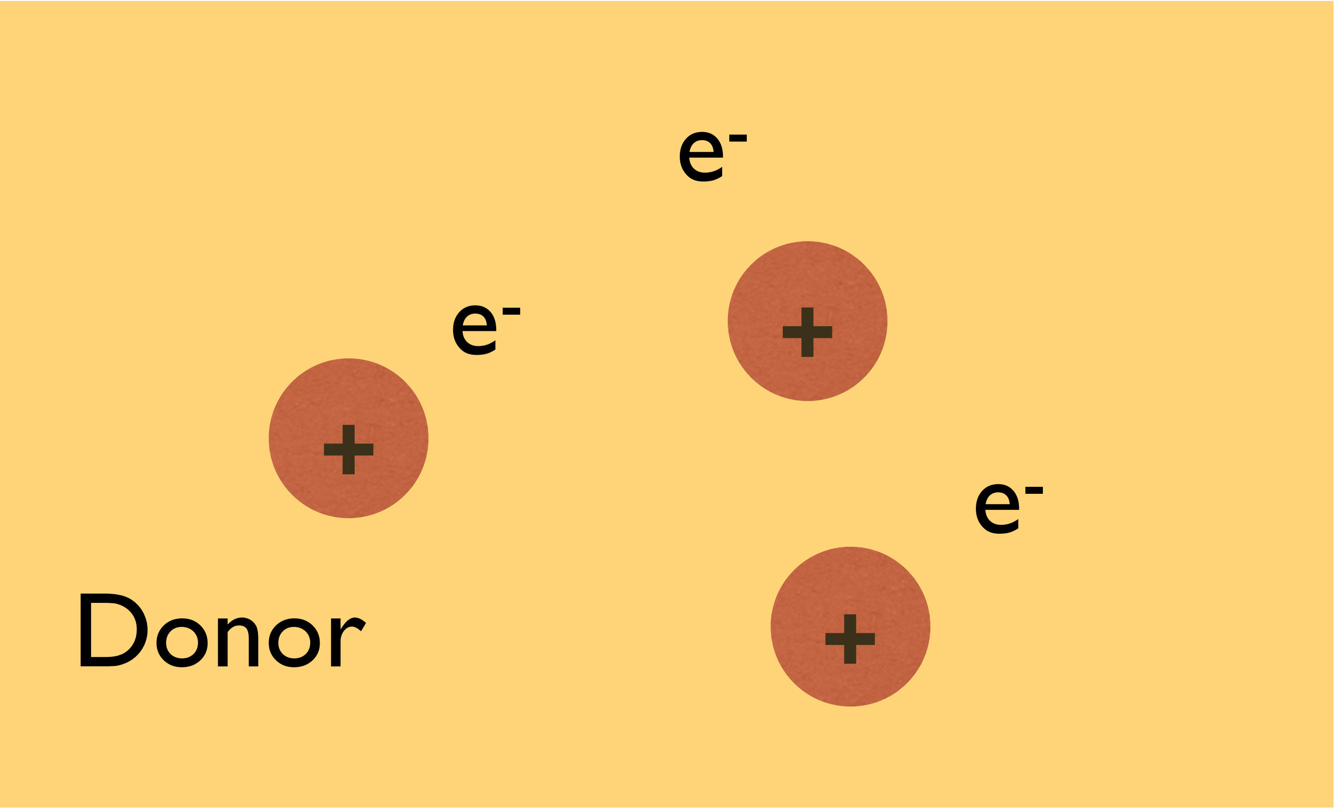
Target	Signal	Threshold	DM Mass range
Nobel Liquid	electron ionization	~10 eV (atom ionization)	>10 MeV
Semiconductors	eh pairs	~1eV (bandgap)	>MeV
Polar materials	phonon	10-100meV	>10-100 keV
Doped Semiconductors	phonon/ electron ionization/ eh pairs	10-100meV	>10-100 keV
Superconductor	phonon/ quasiparticle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

Doped semiconductors

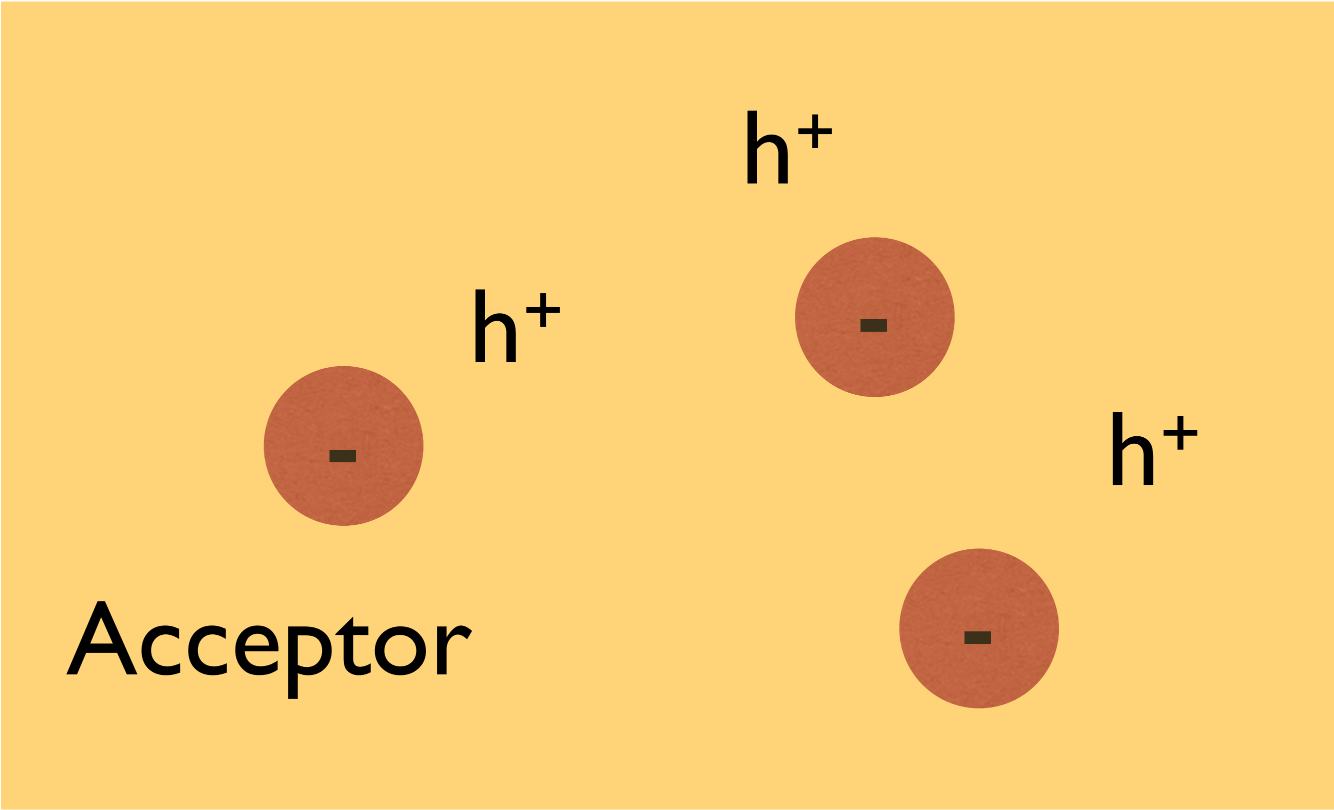


Doped semiconductors

n-type semiconductor



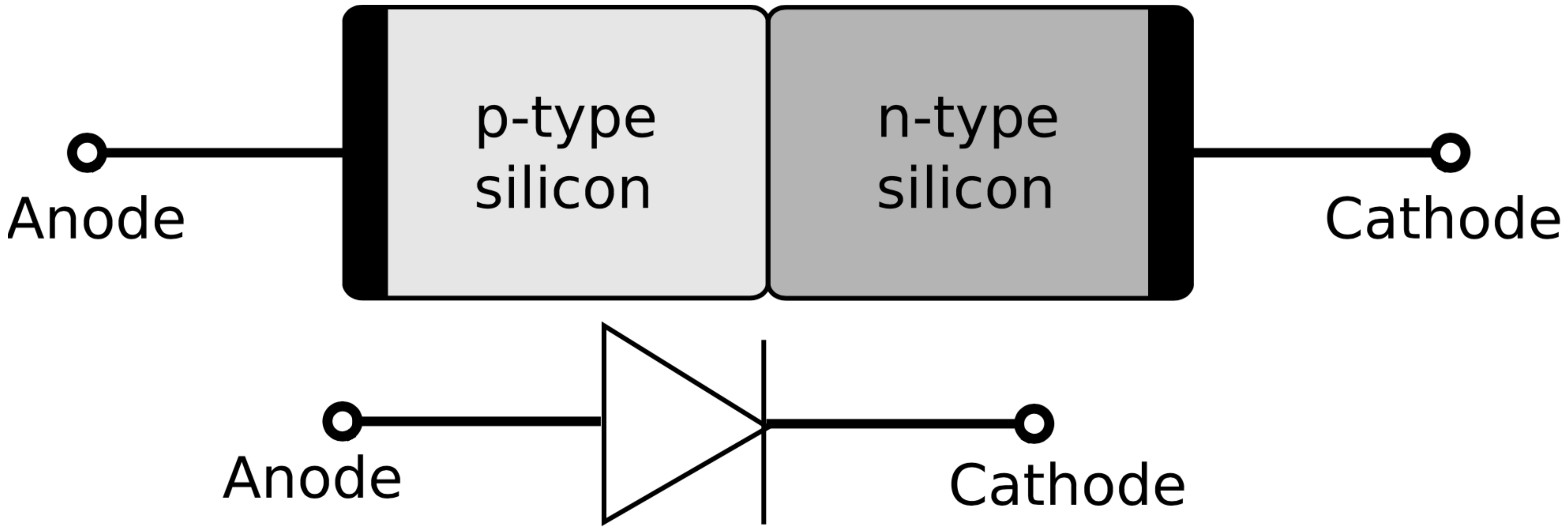
p-type semiconductor



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

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

Commonly used: p-n junction, diodes



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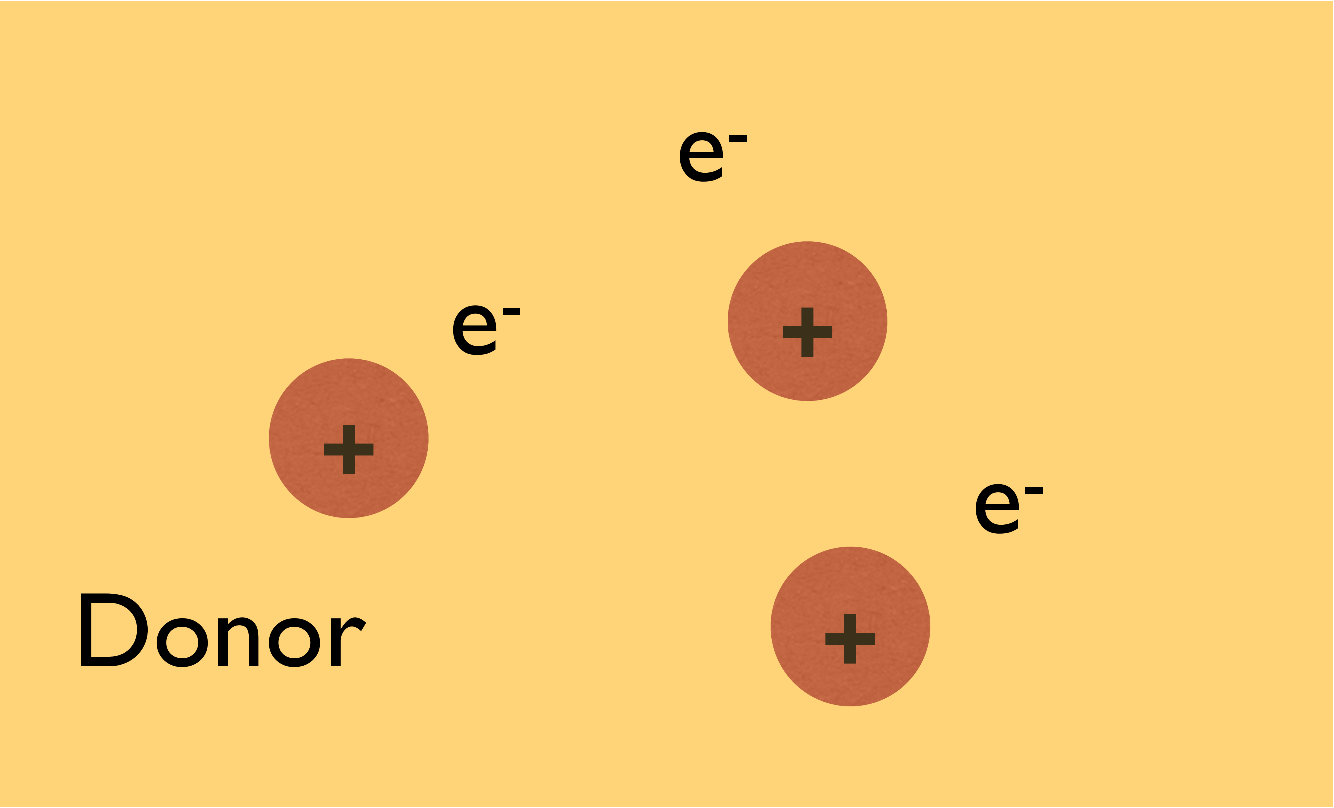
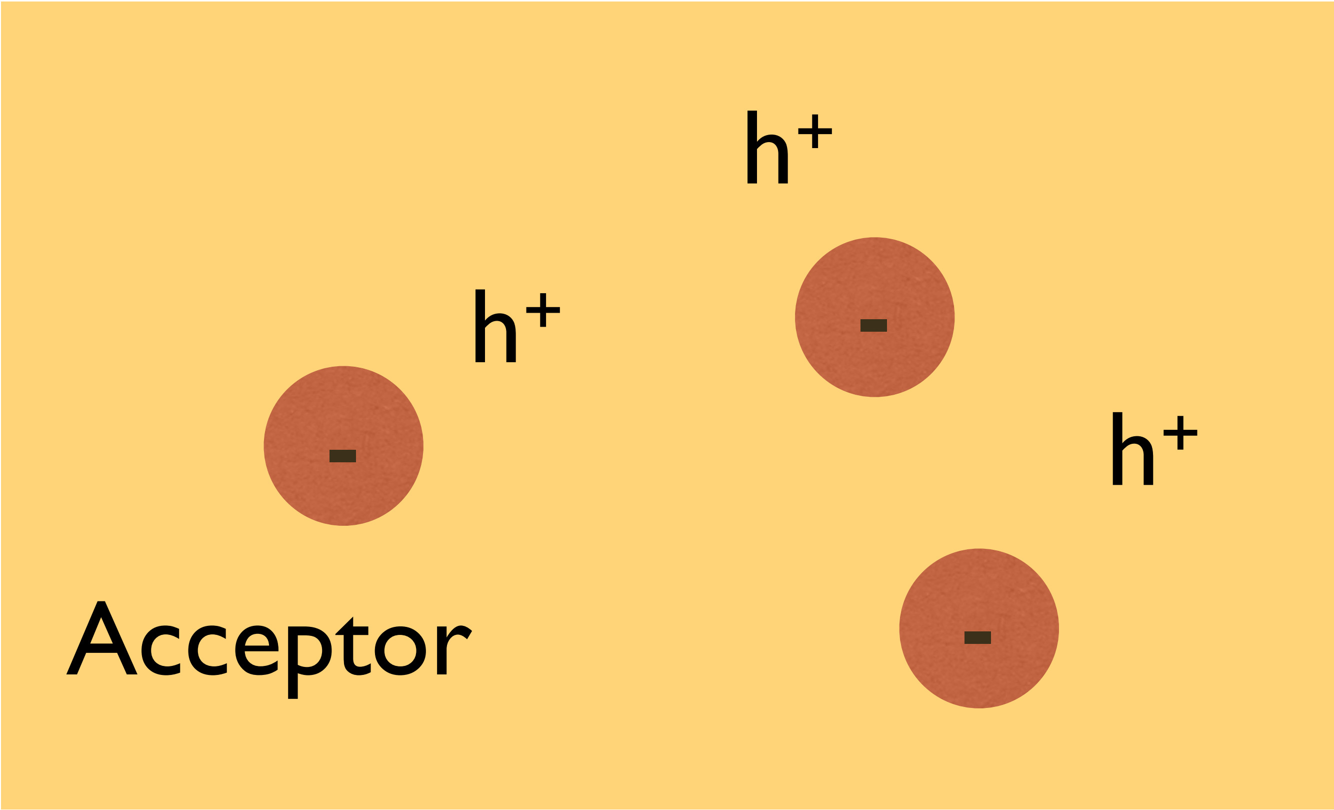


p-type semiconductor



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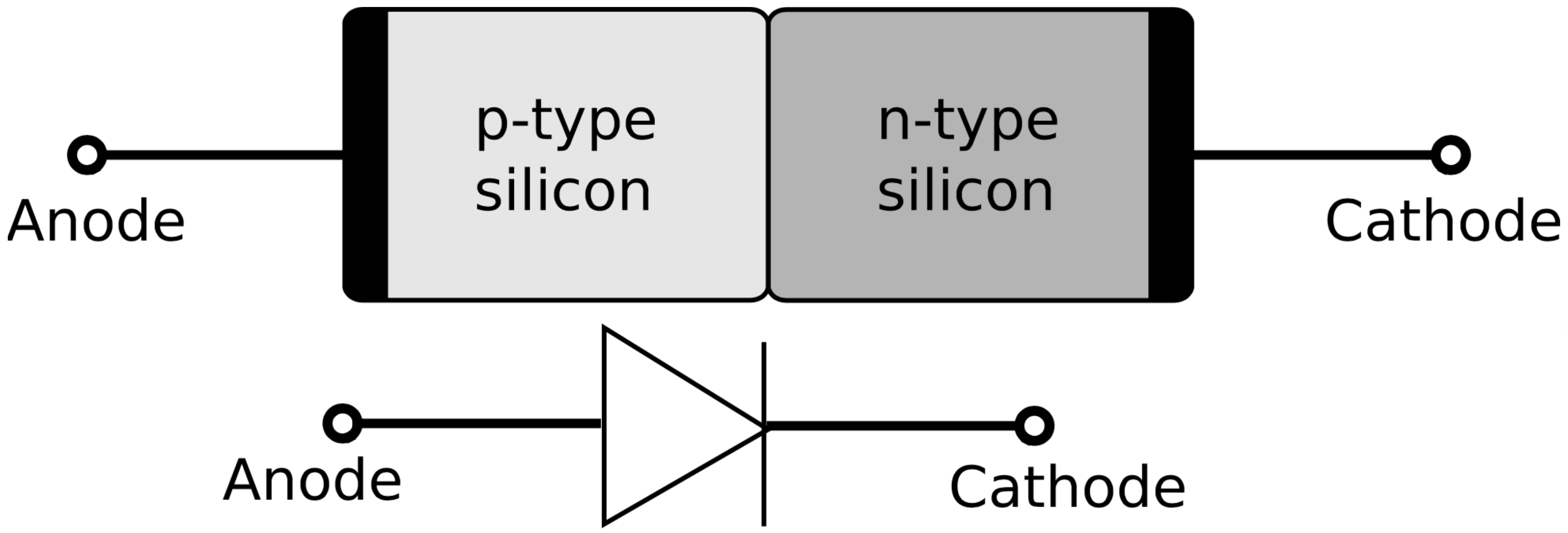
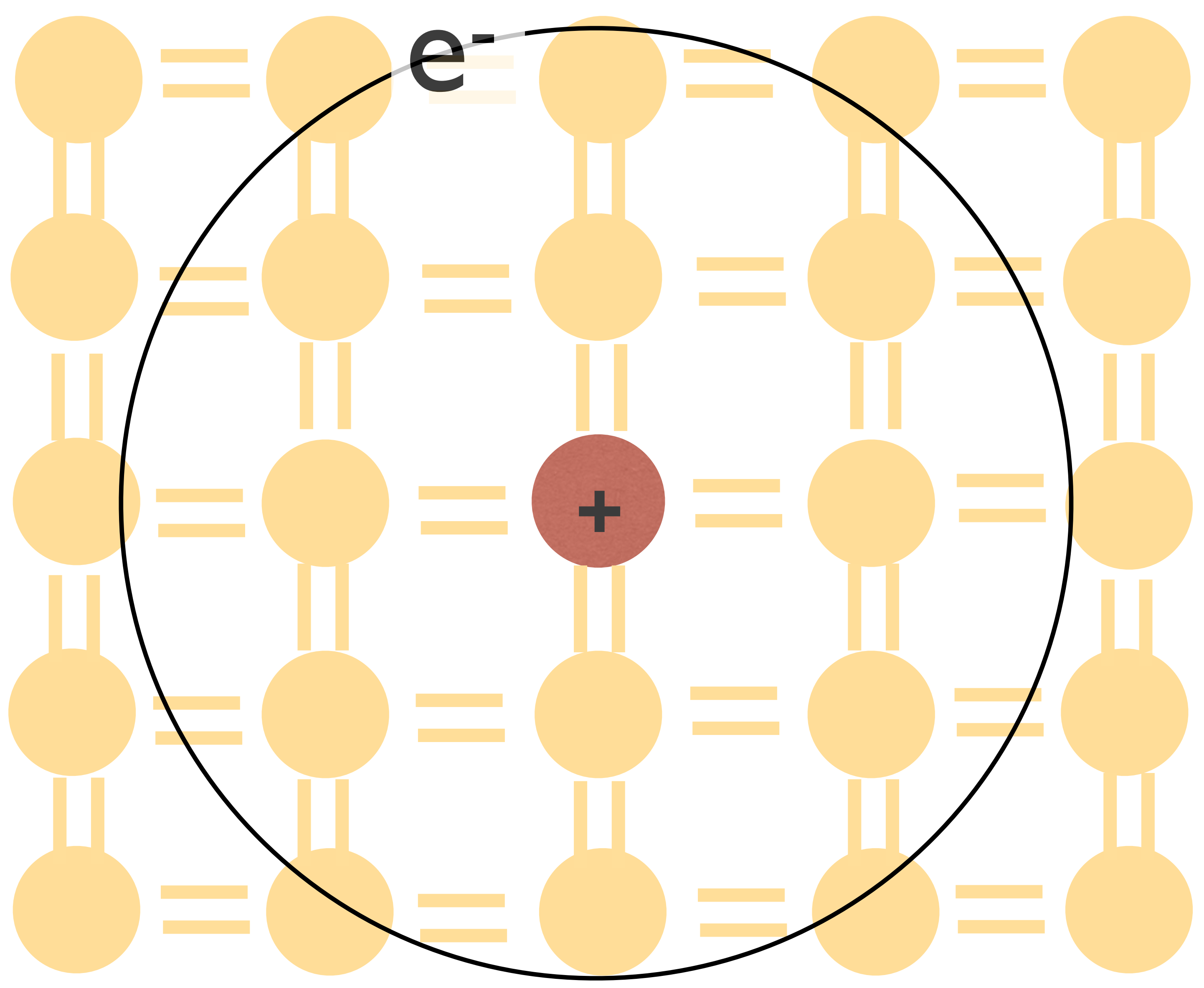
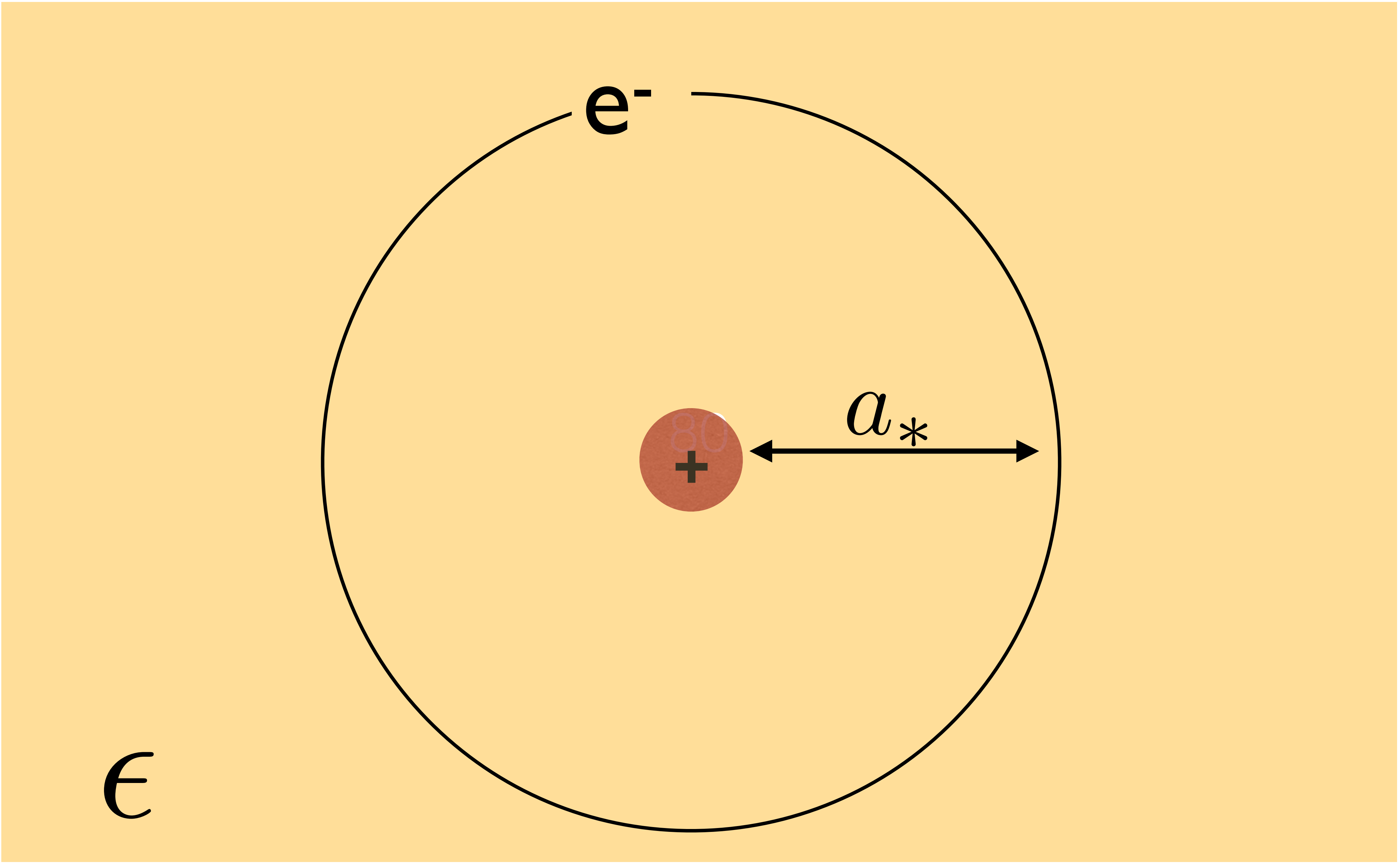


Dopants in semiconductors

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





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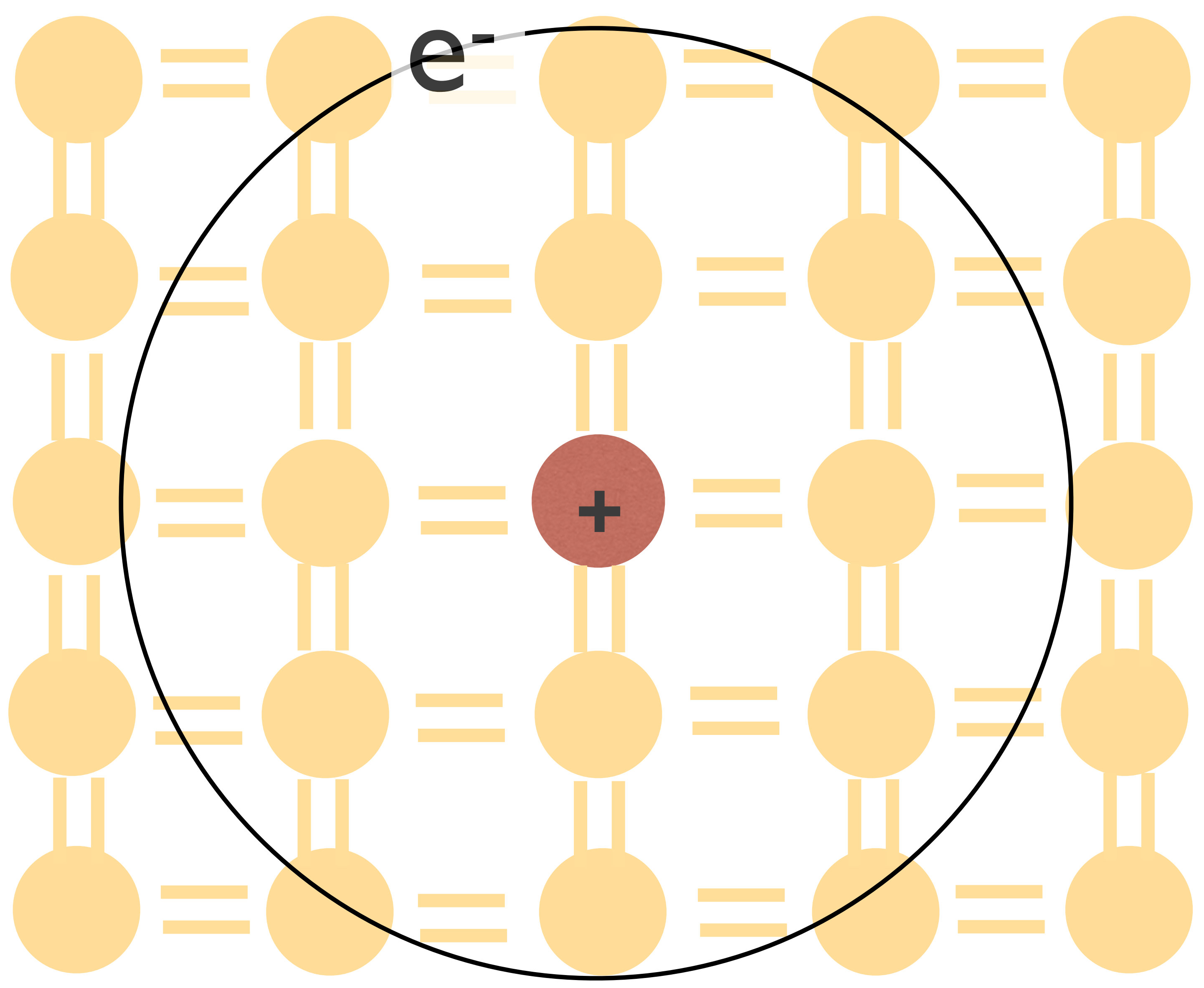
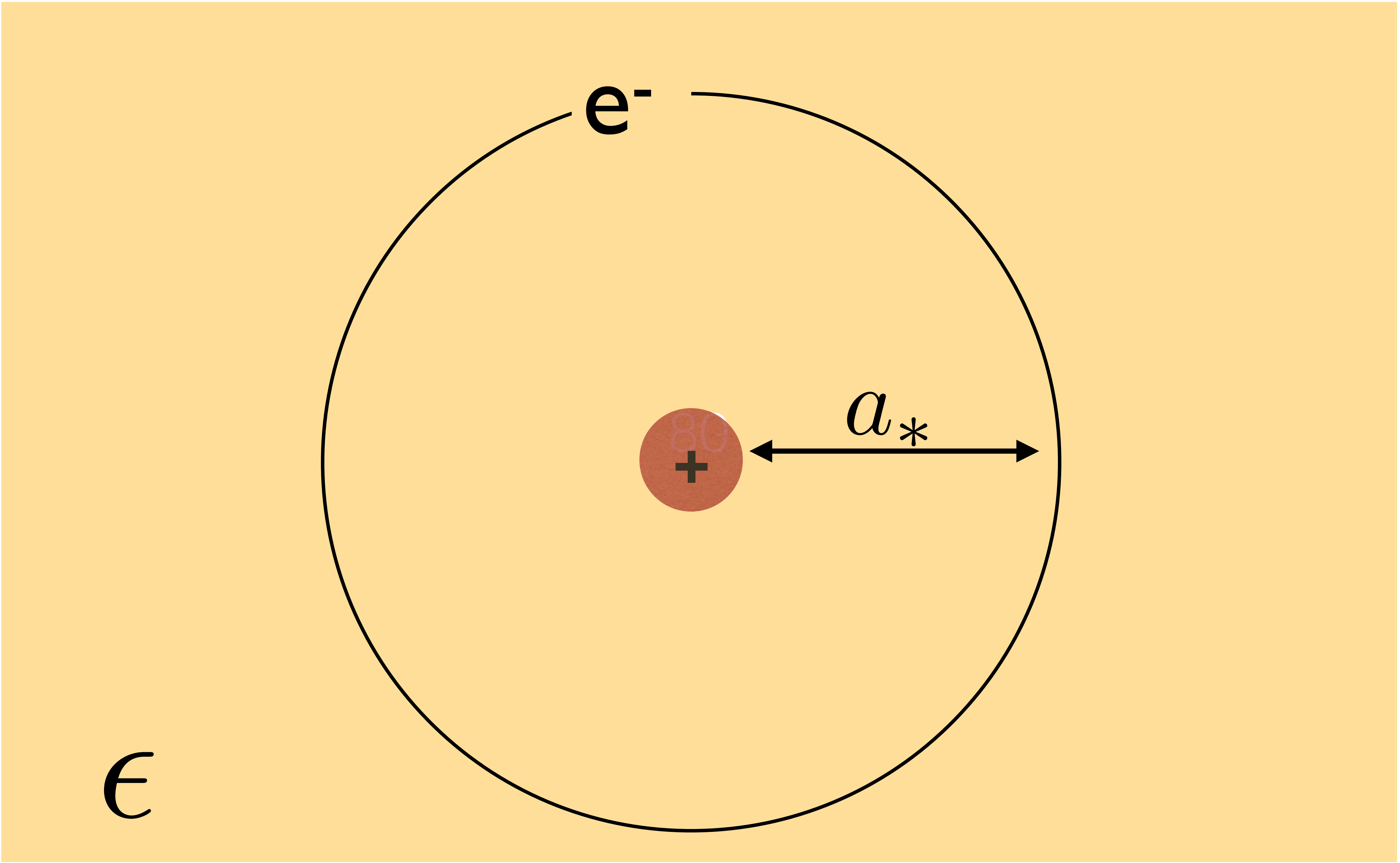




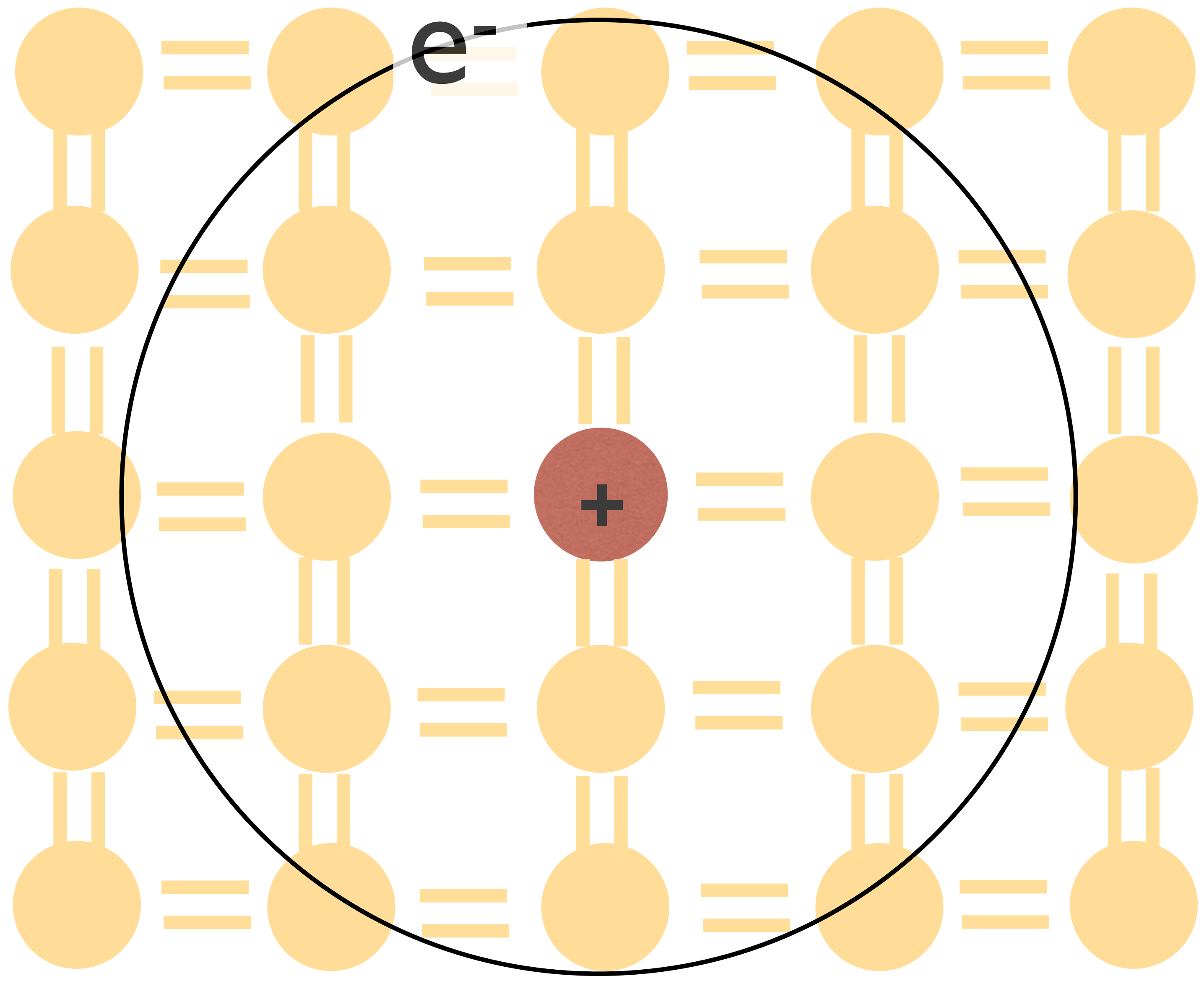
electron effective mass Bohr radius

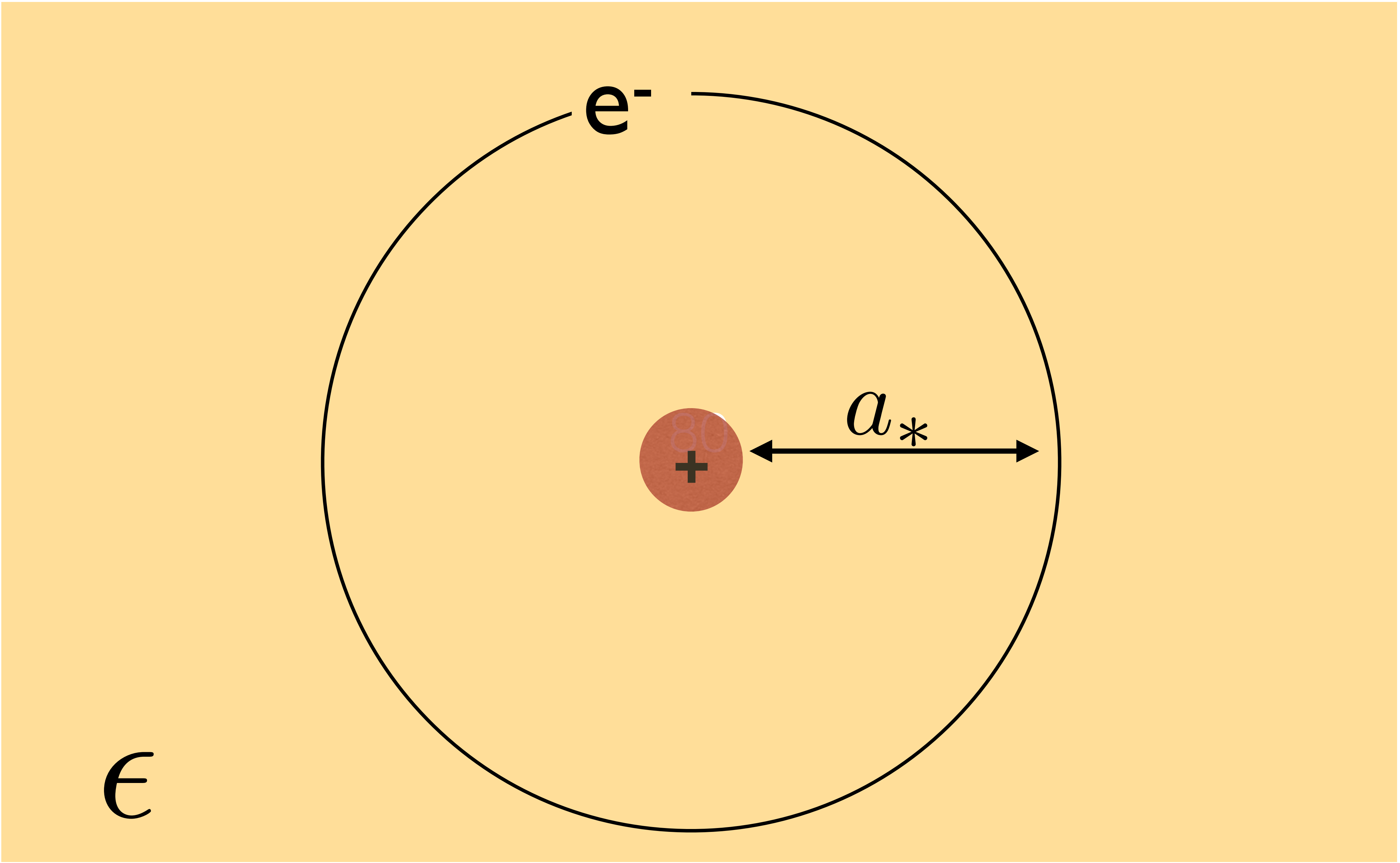
For $\epsilon \sim 10$ $\quad a_* \sim (\frac{\alpha}{\epsilon} m_*)^{-1} \sim O(10)\, a_0 \quad q_* \sim a_*^{-1} \sim O(100)\,\mathrm{eV} \quad v_* = \frac{q_*}{m_*} \sim 10^{-3}$

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

Dopants in semiconductors

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





electron effective mass   Bohr radius

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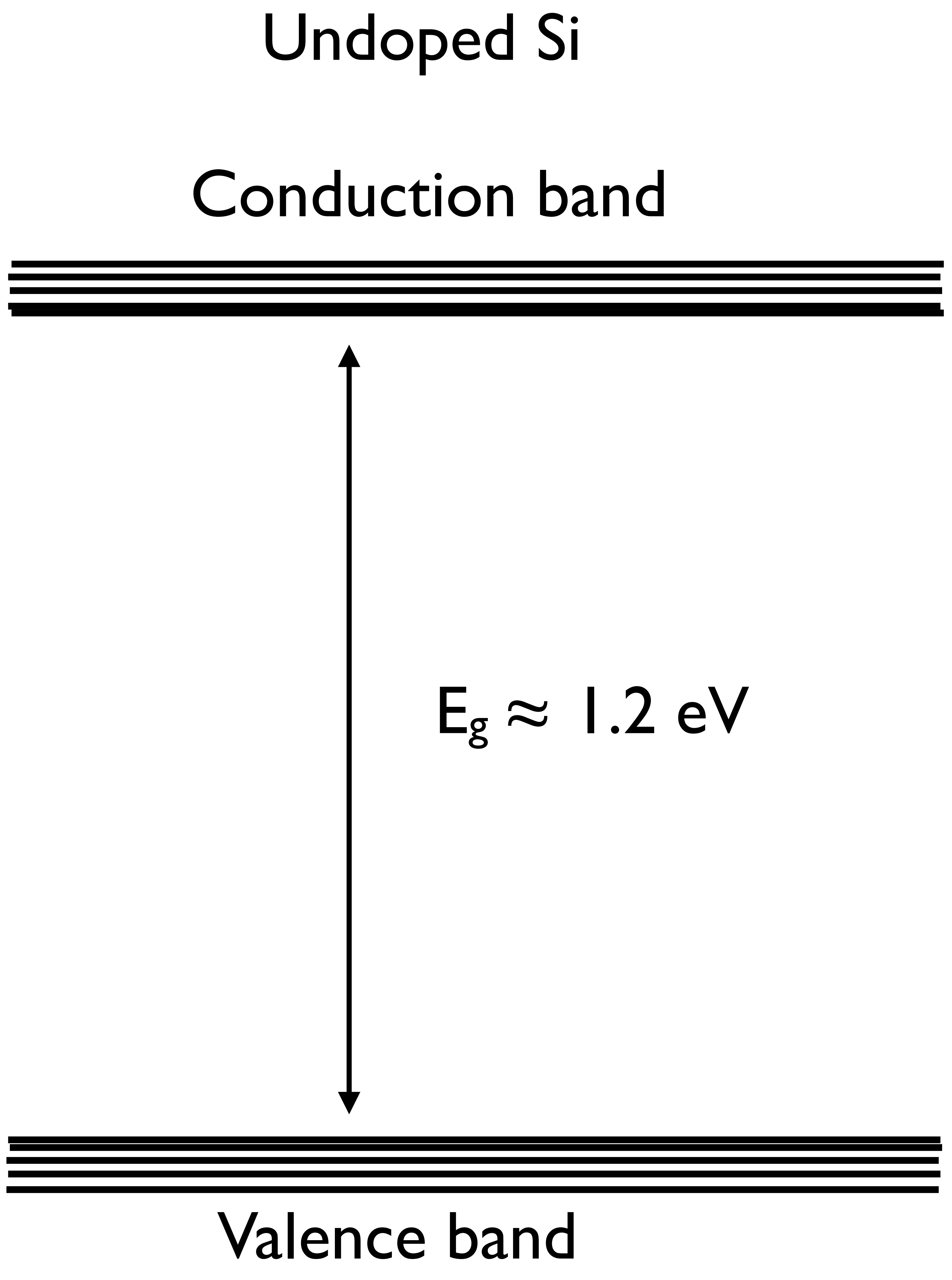
Dopant energy levels in silicon



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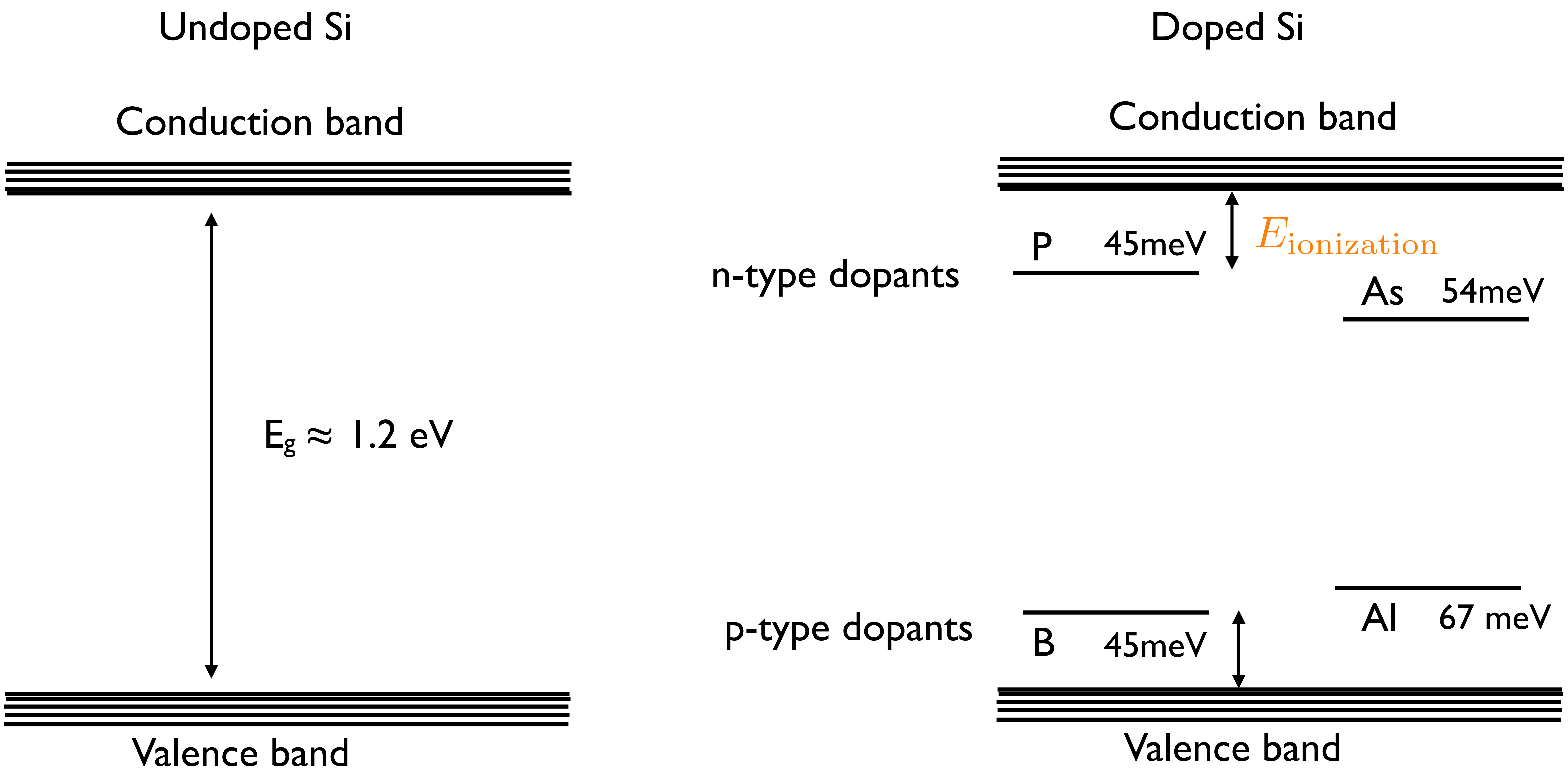

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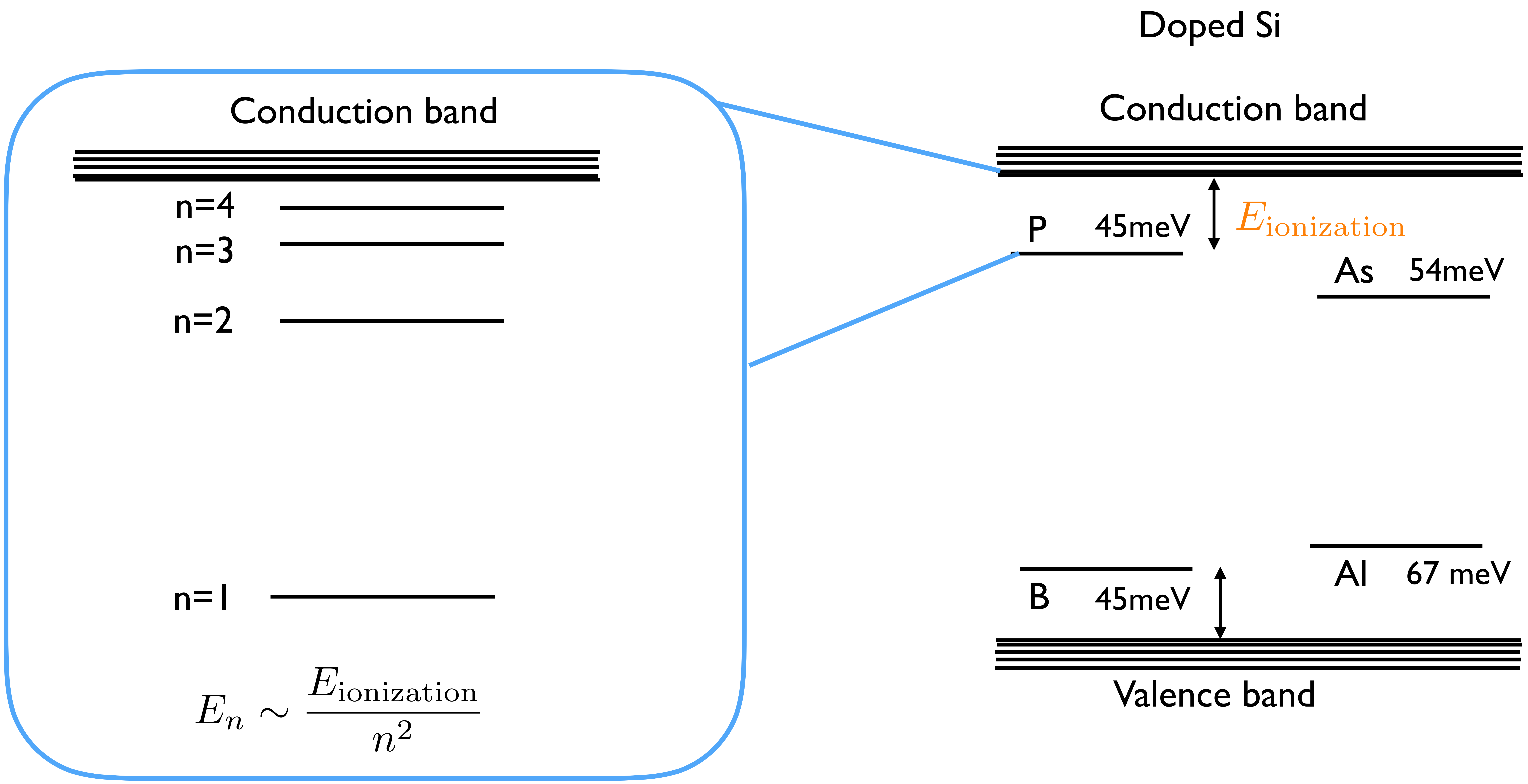
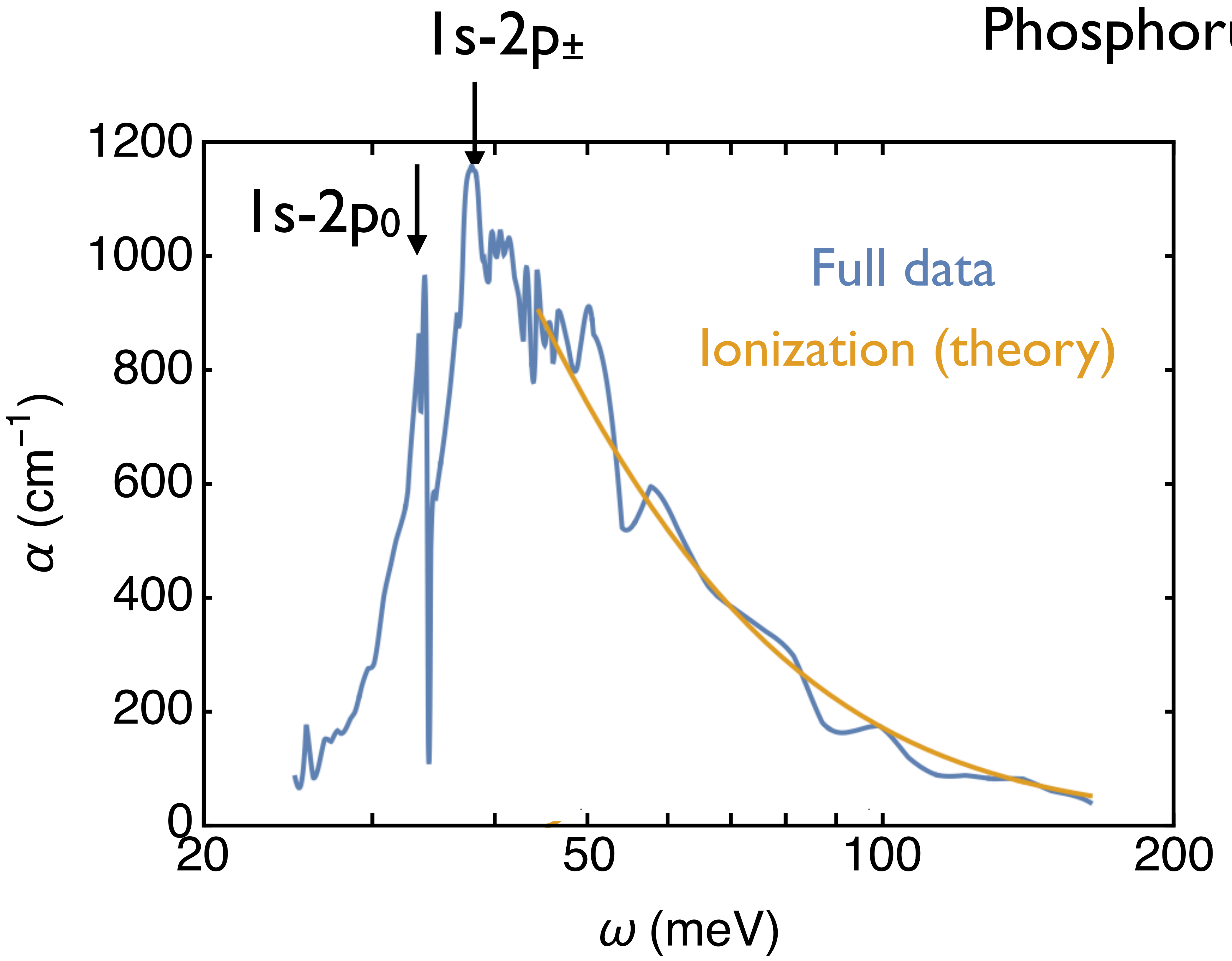
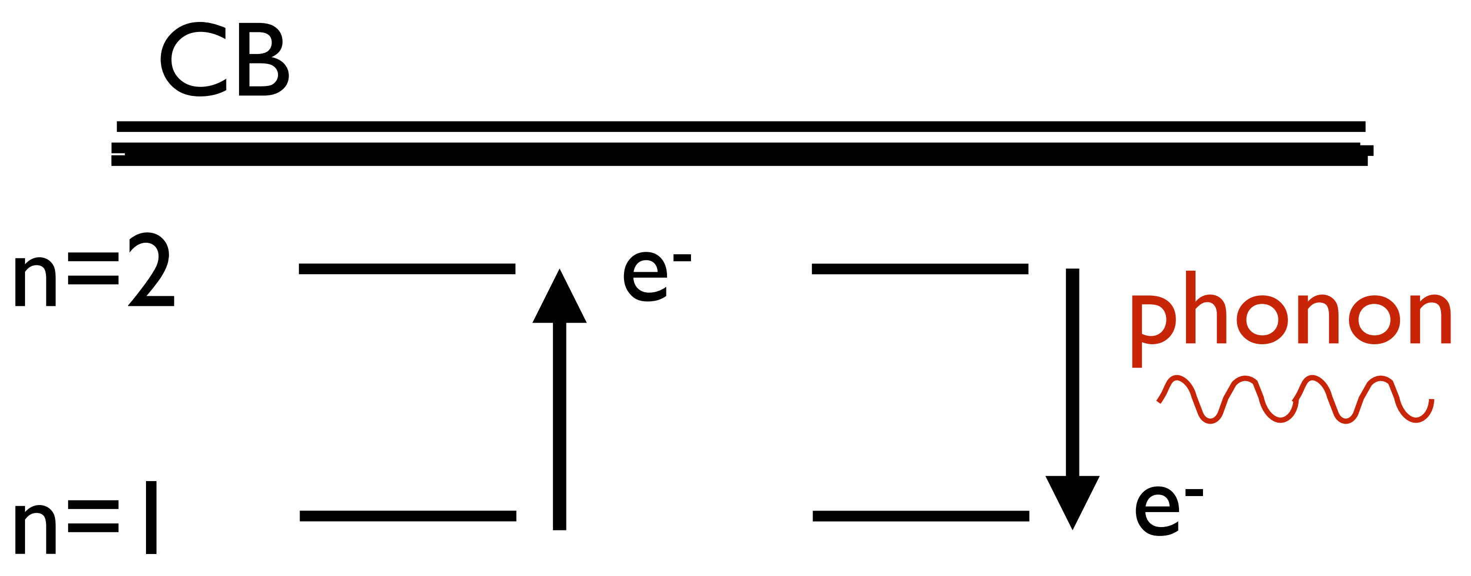


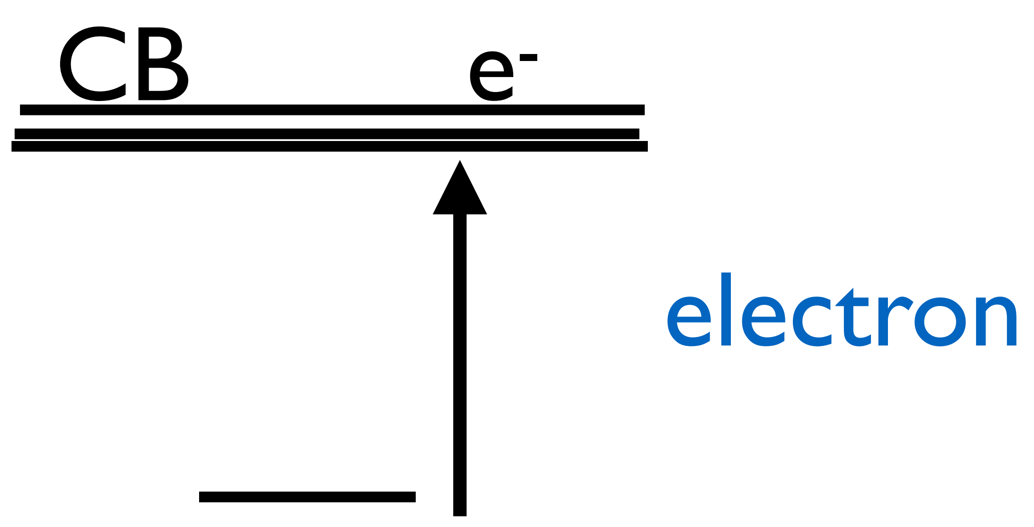
Signals in doped silicon

Gaymann, Geserich, Lohenysen, 95

Phosphorus doped Si @10K $n_d=0.34\times10^{18}\mathrm{cm}^{-3}$







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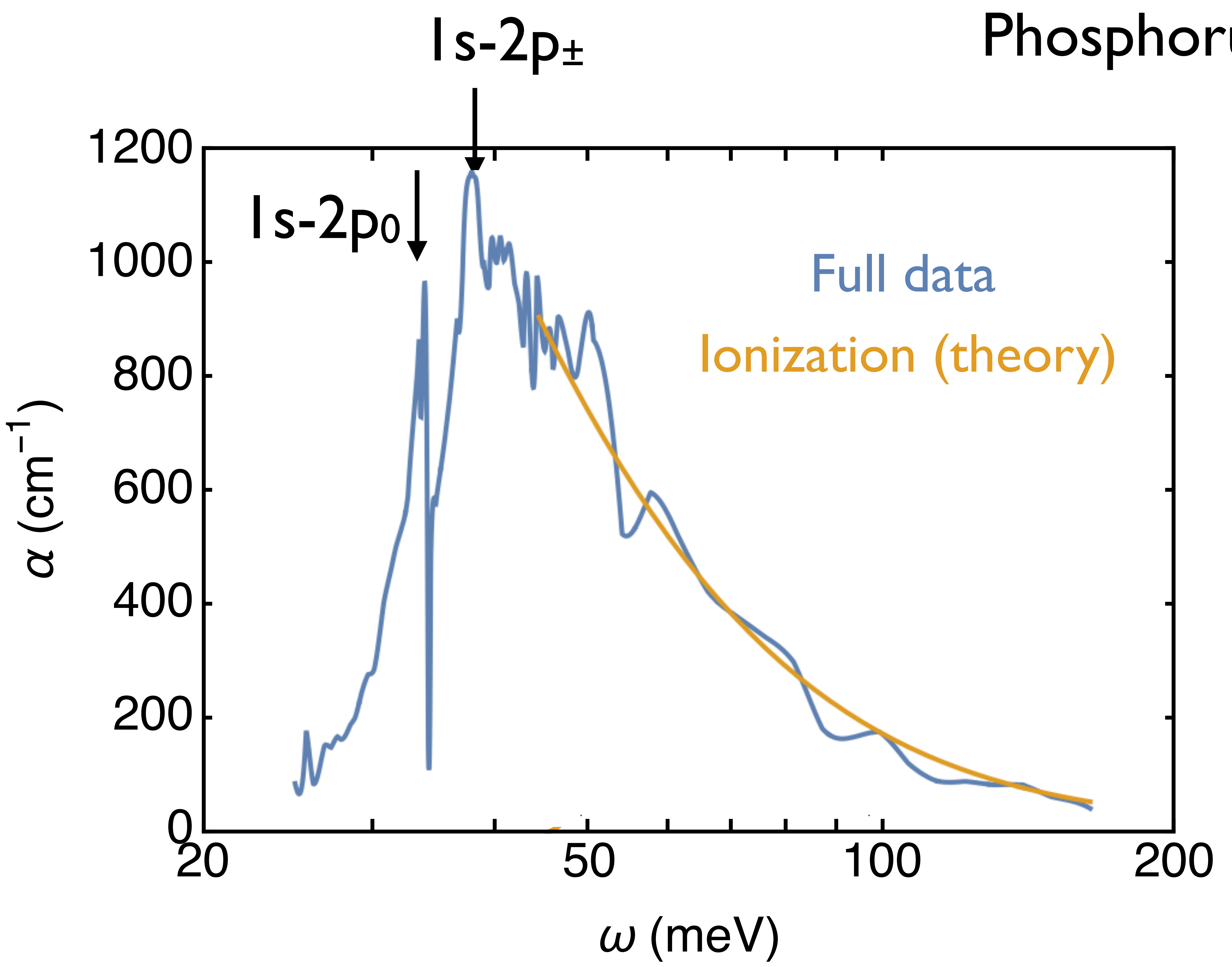

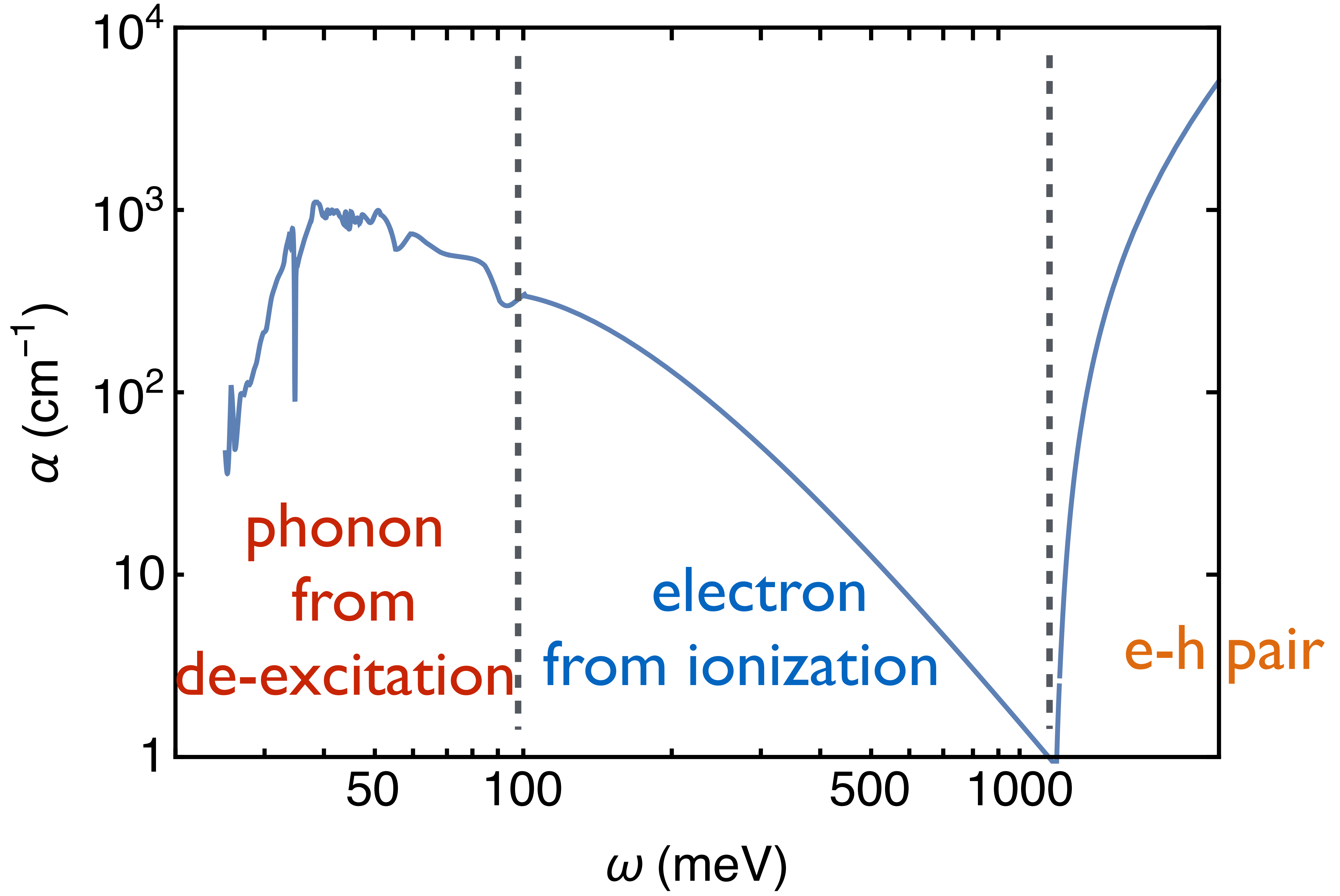

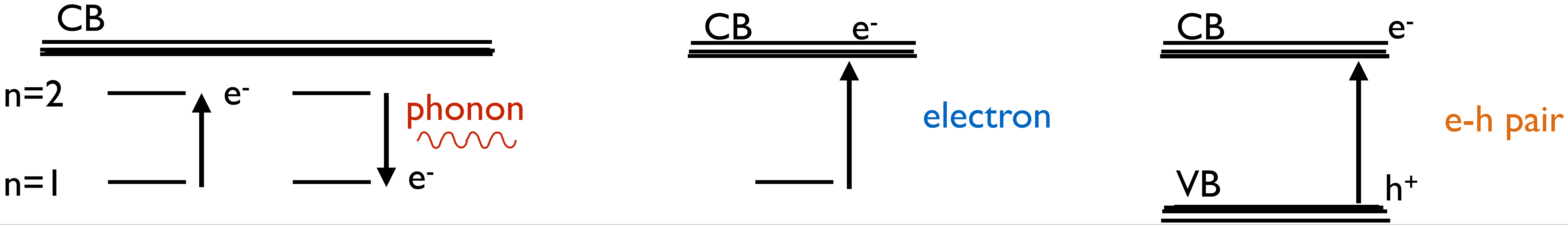

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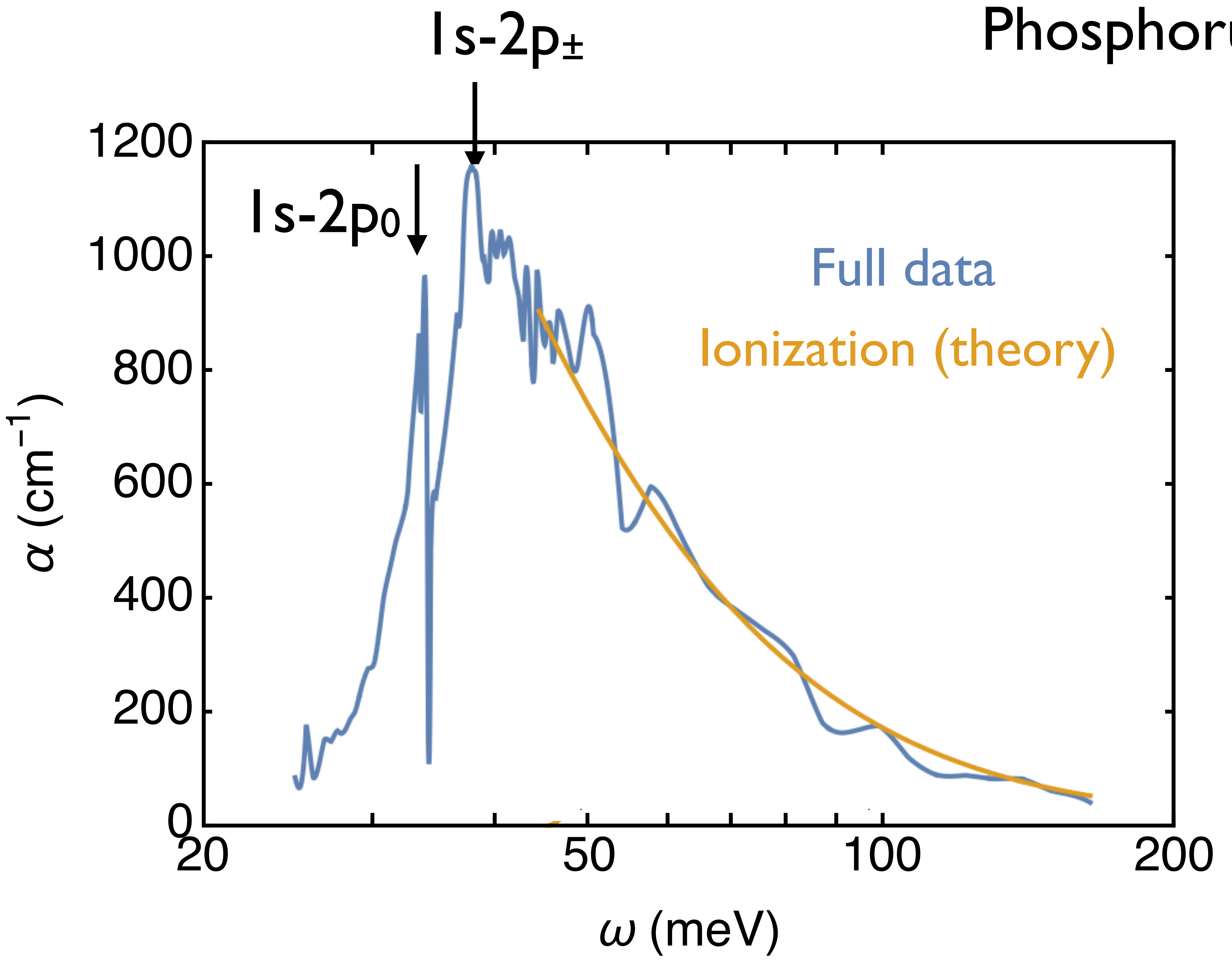
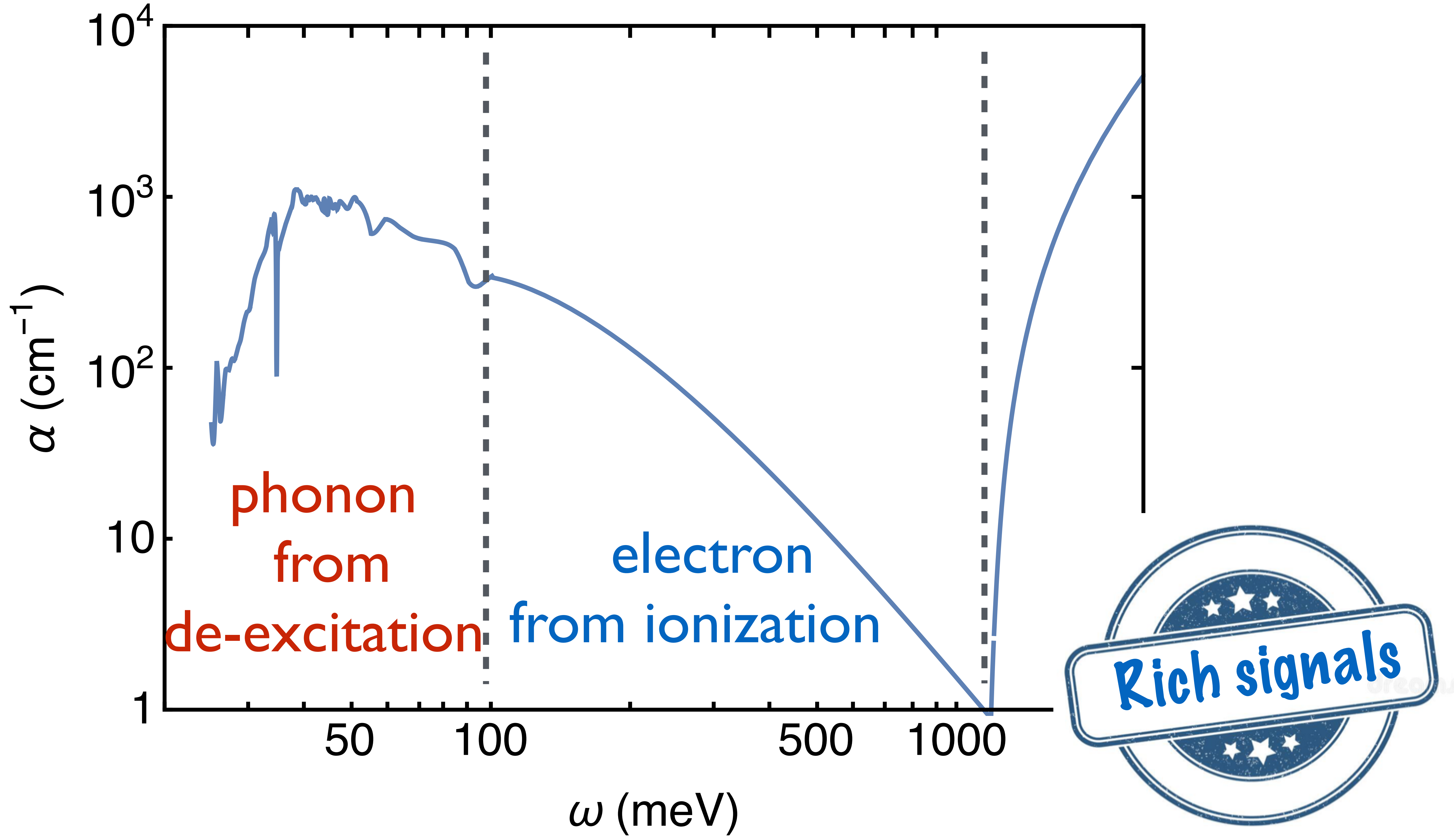
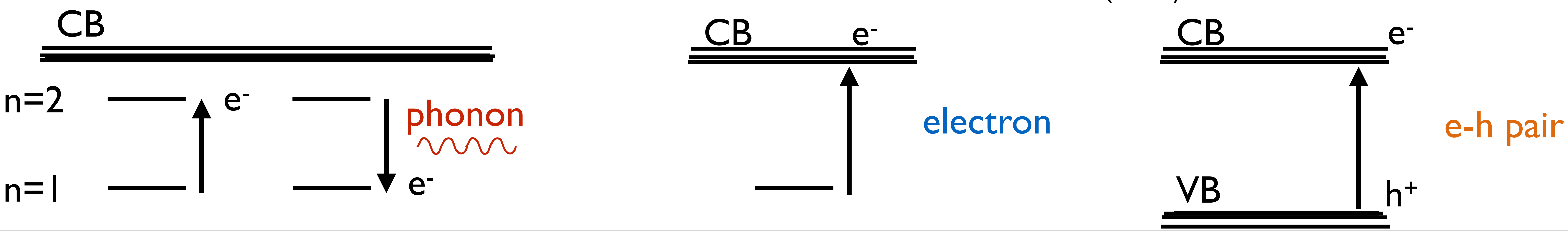


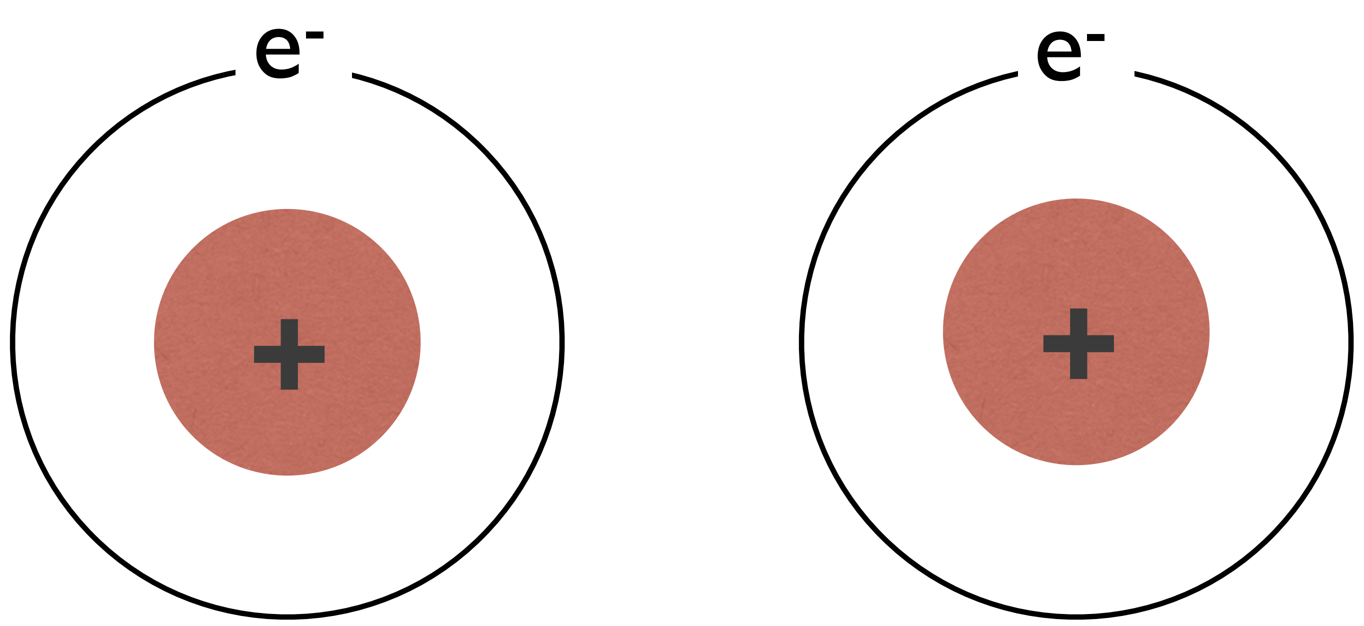




What is the optimal n_d for DM searches?

Metal-insulator transition

Electrons are localized on dopants

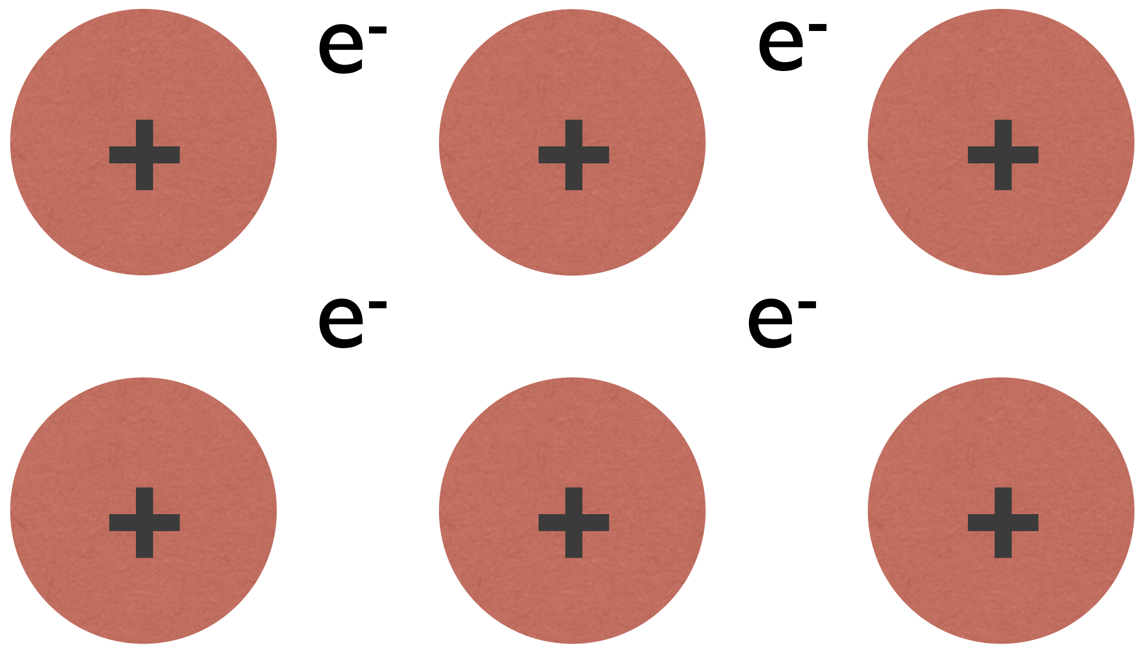


Insulating

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

Good for DM searches

Electrons are delocalized



Metallic

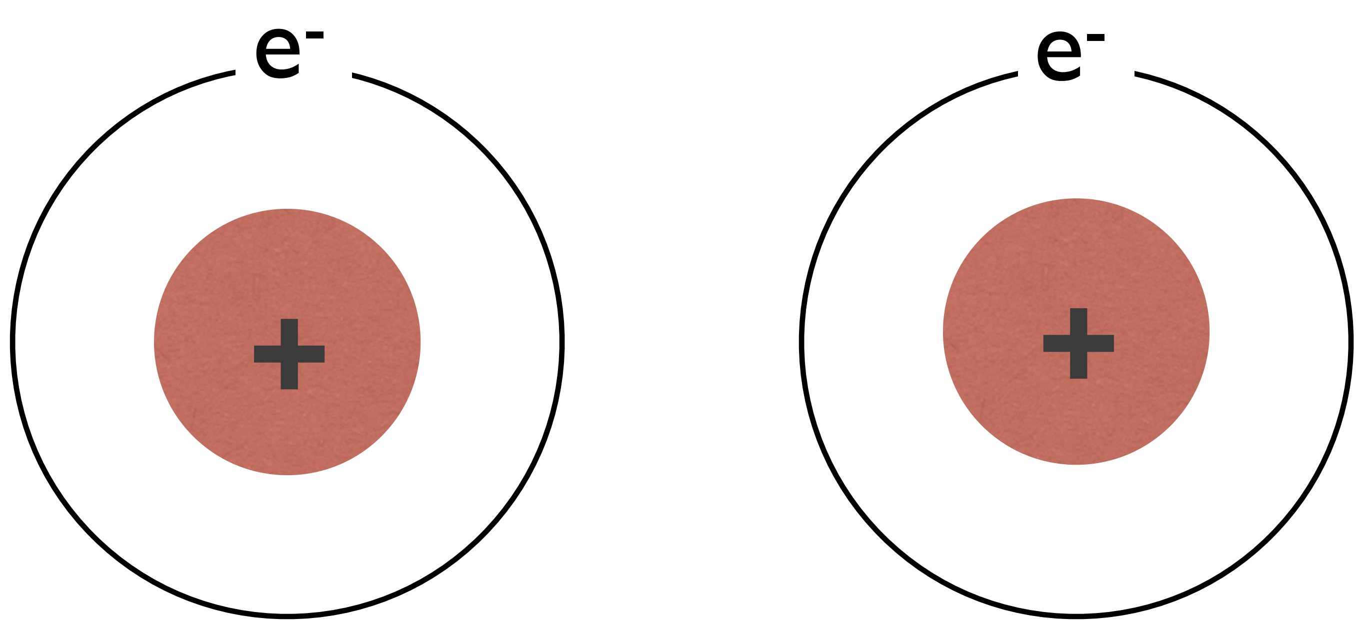
$n_{\mathrm{d}} > n_c$

Metallic targets have no gap, hard to control noise

What is the optimal n_d for DM searches?

Metal-insulator transition

Electrons are localized on dopants



Insulating

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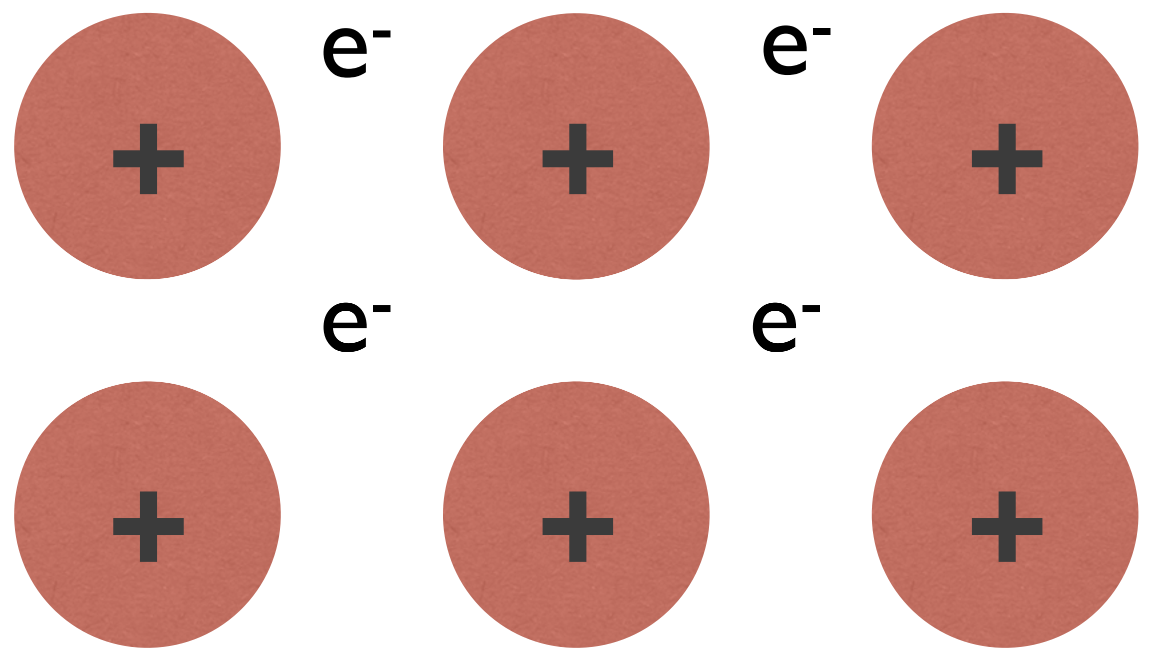

Metallic

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

Metallic targets have no gap, hard to control noise

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

For Phosphorus doped Si: $n_c = 3.5 \times 10^{18}\mathrm{cm}^{-3}$ We choose $1\times10^{18}\mathrm{cm}^{-3}$ for DM reach projection

DM-electron scattering rate

DM velocity distribution Particle interaction 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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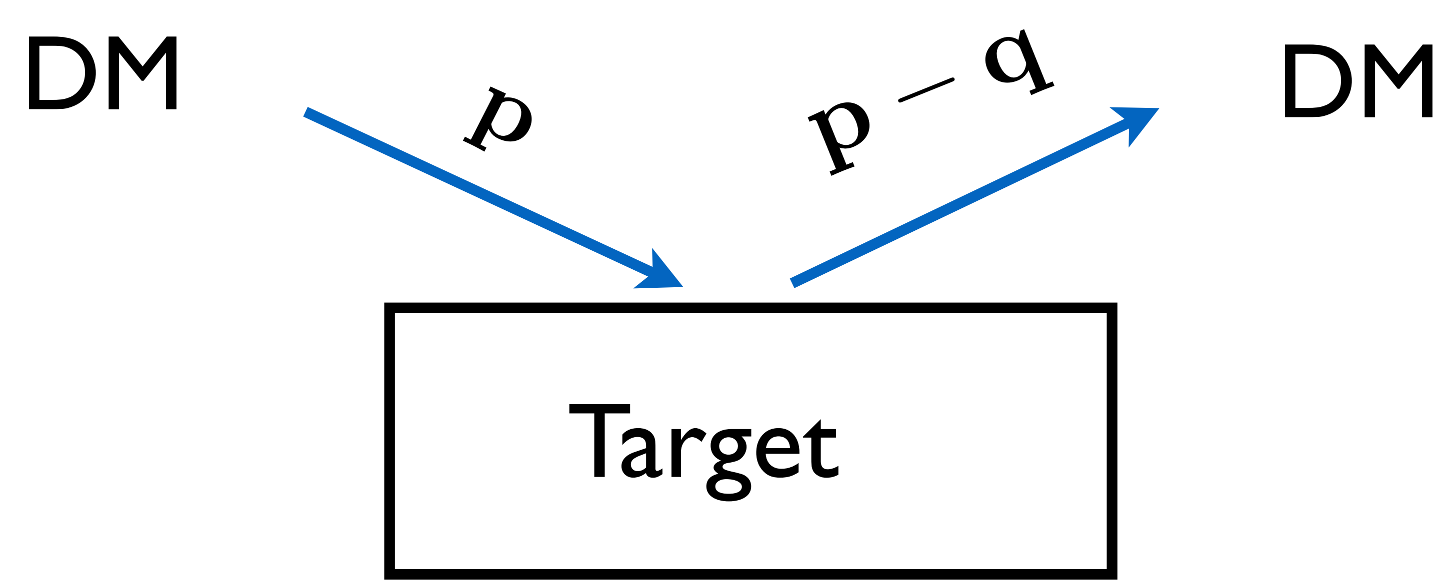
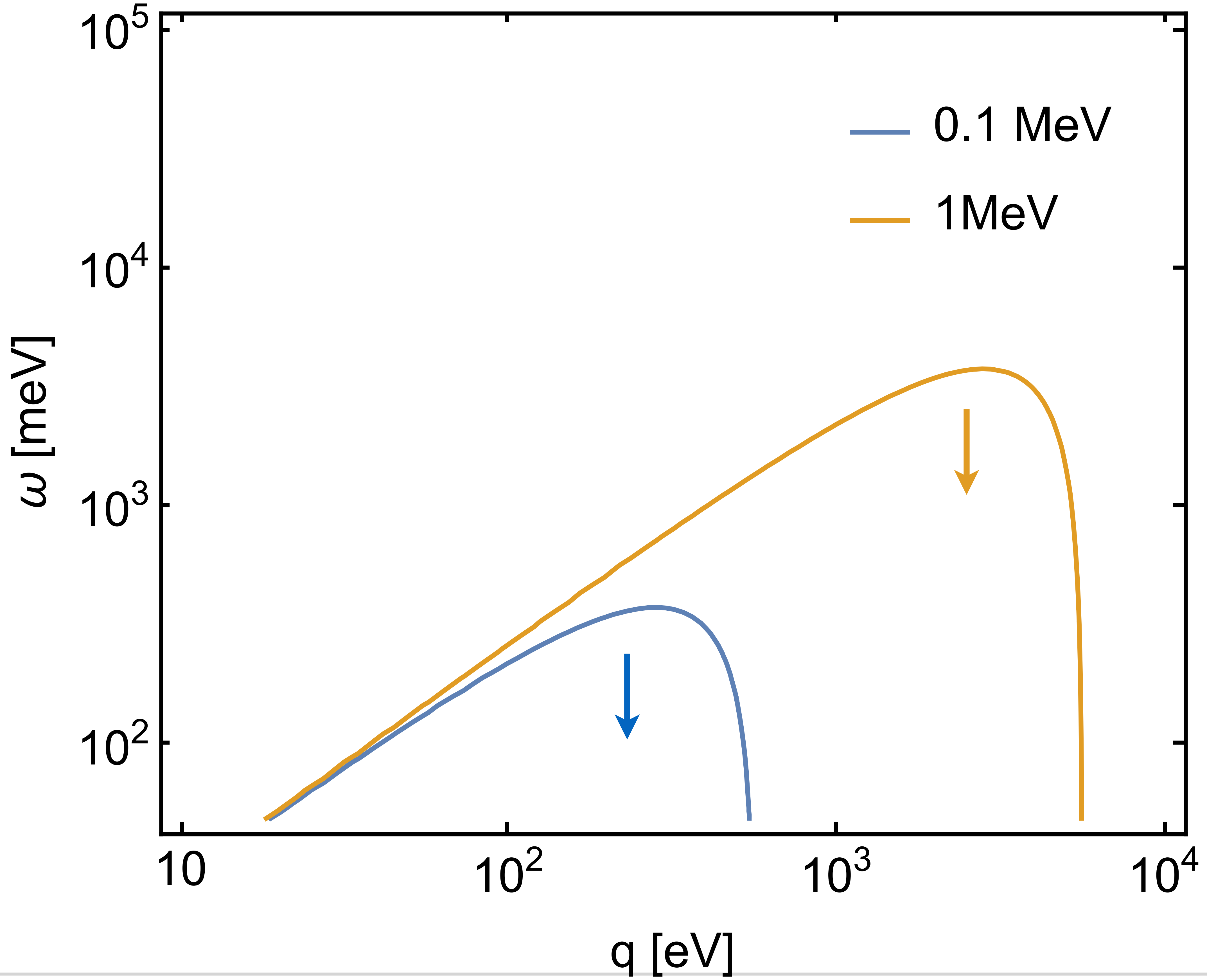
DM Kinematics



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



Target response

Knapen, Kozaczuk, Lin, 2021

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

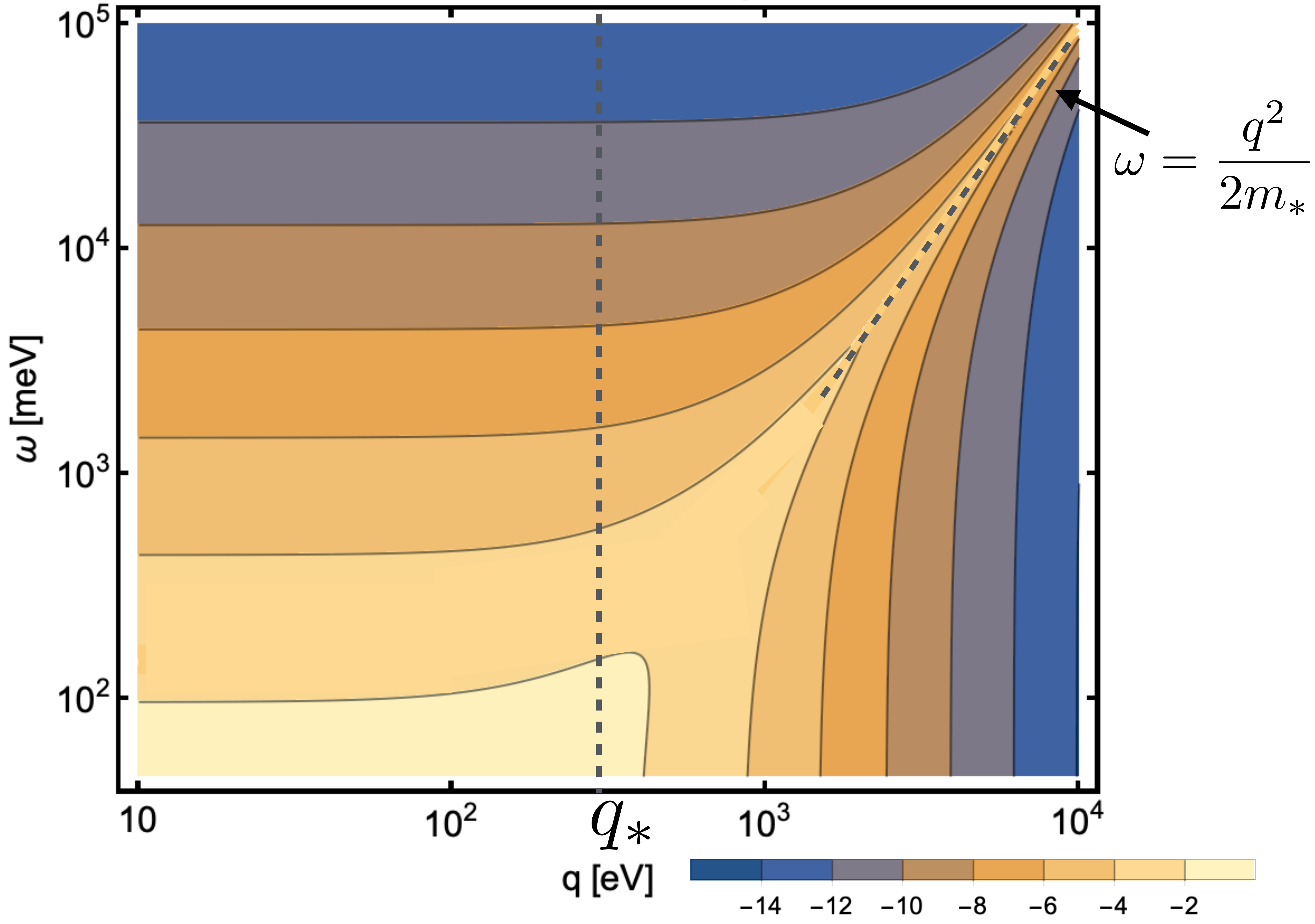
Target response

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

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

Energy loss function (ELF)

ELF for ionization of P dopants in Si



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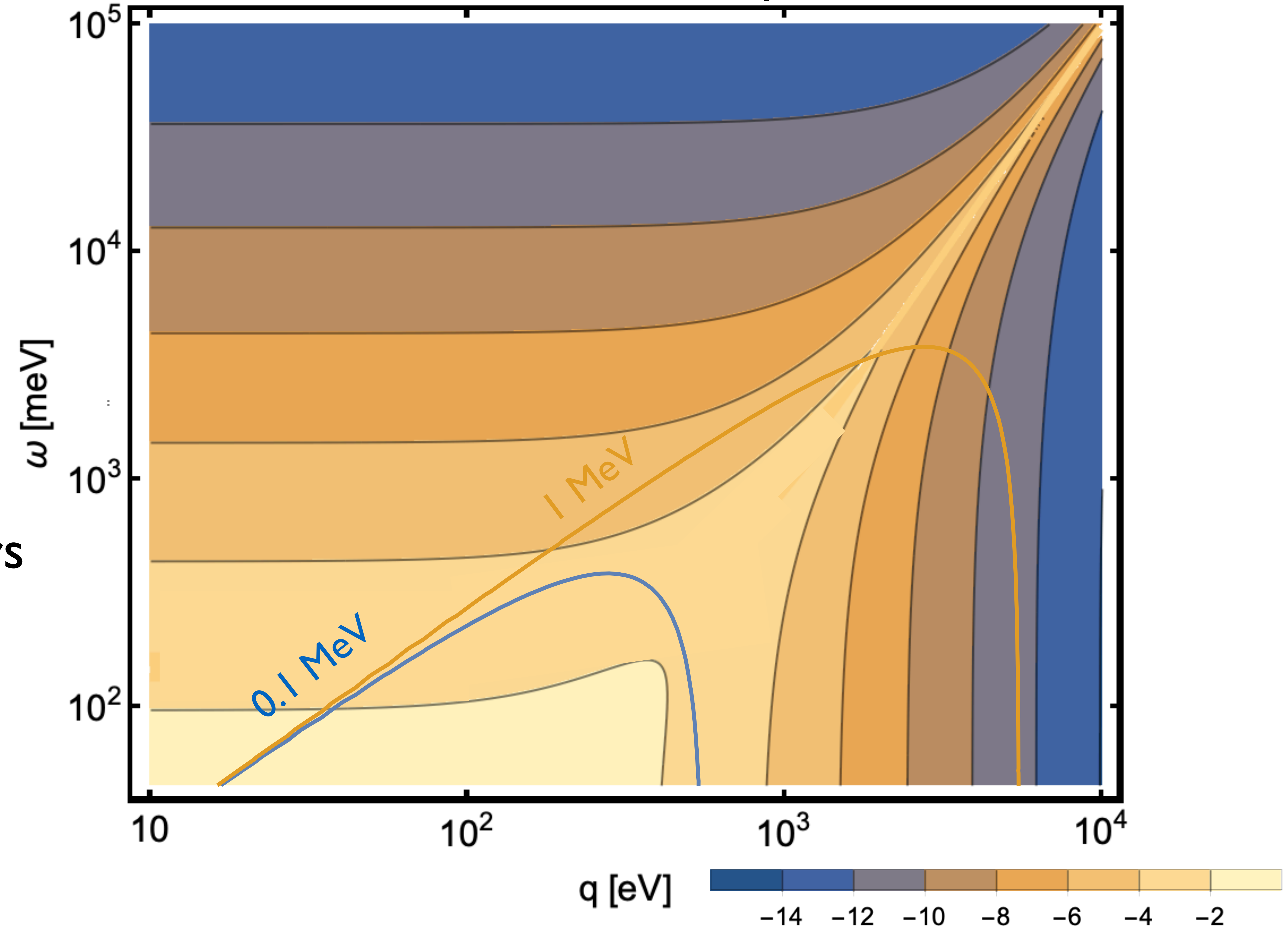
Energy loss function (ELF)

good reach for low mass DM with light mediators

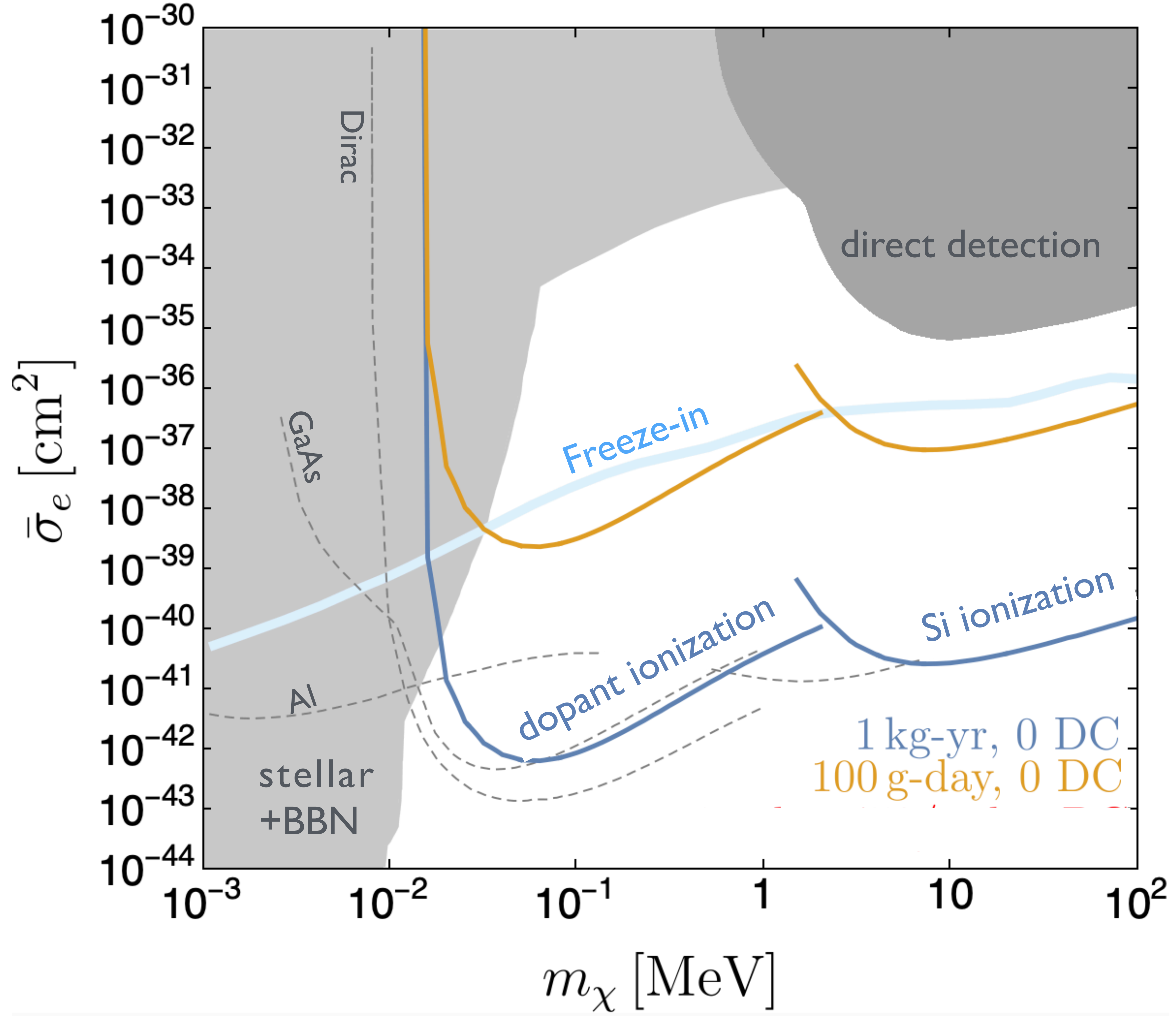
ELF for ionization of P dopants in Si



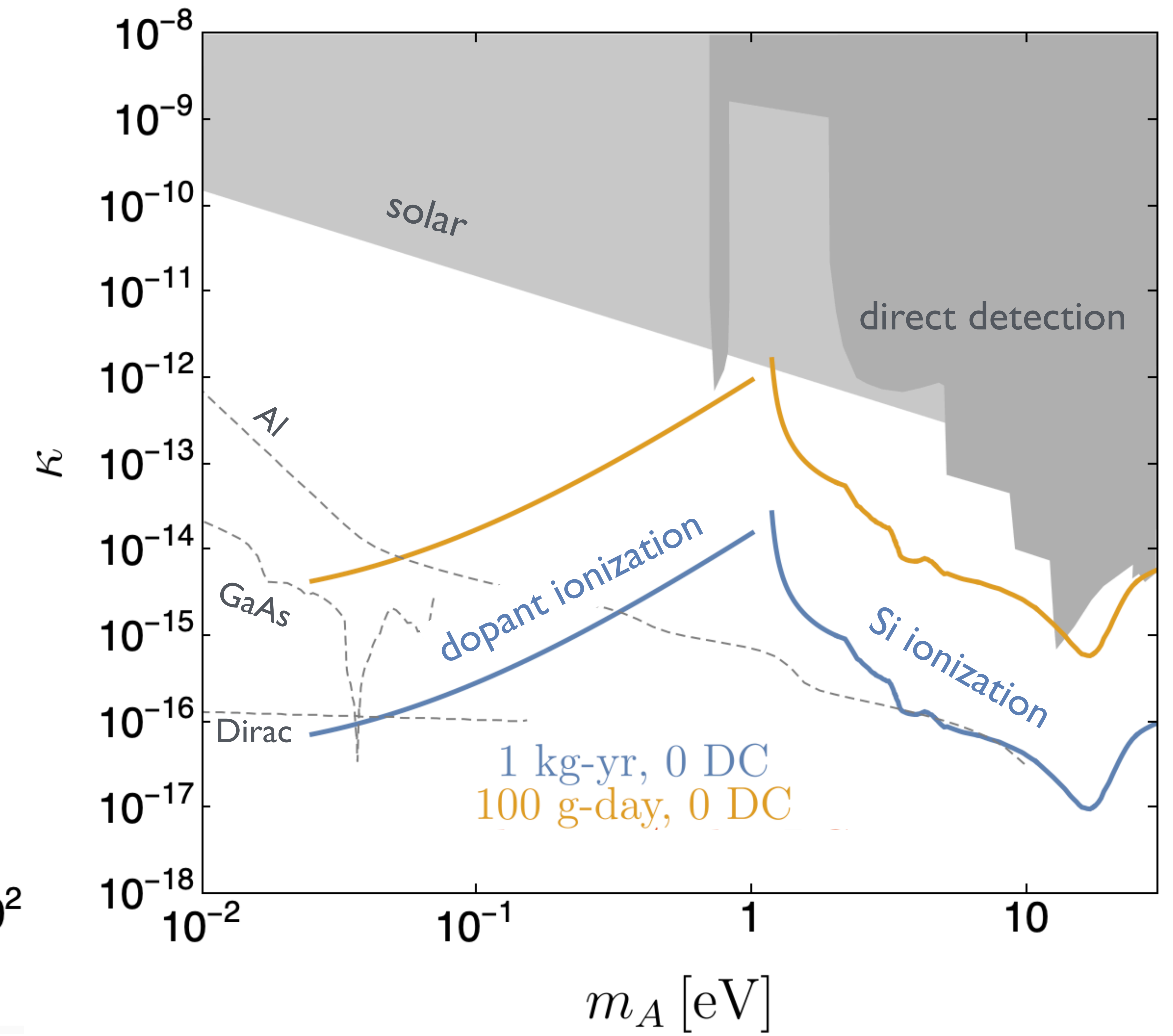
DM-electron scattering rate with doped silicon

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

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



Dark photon dark matter



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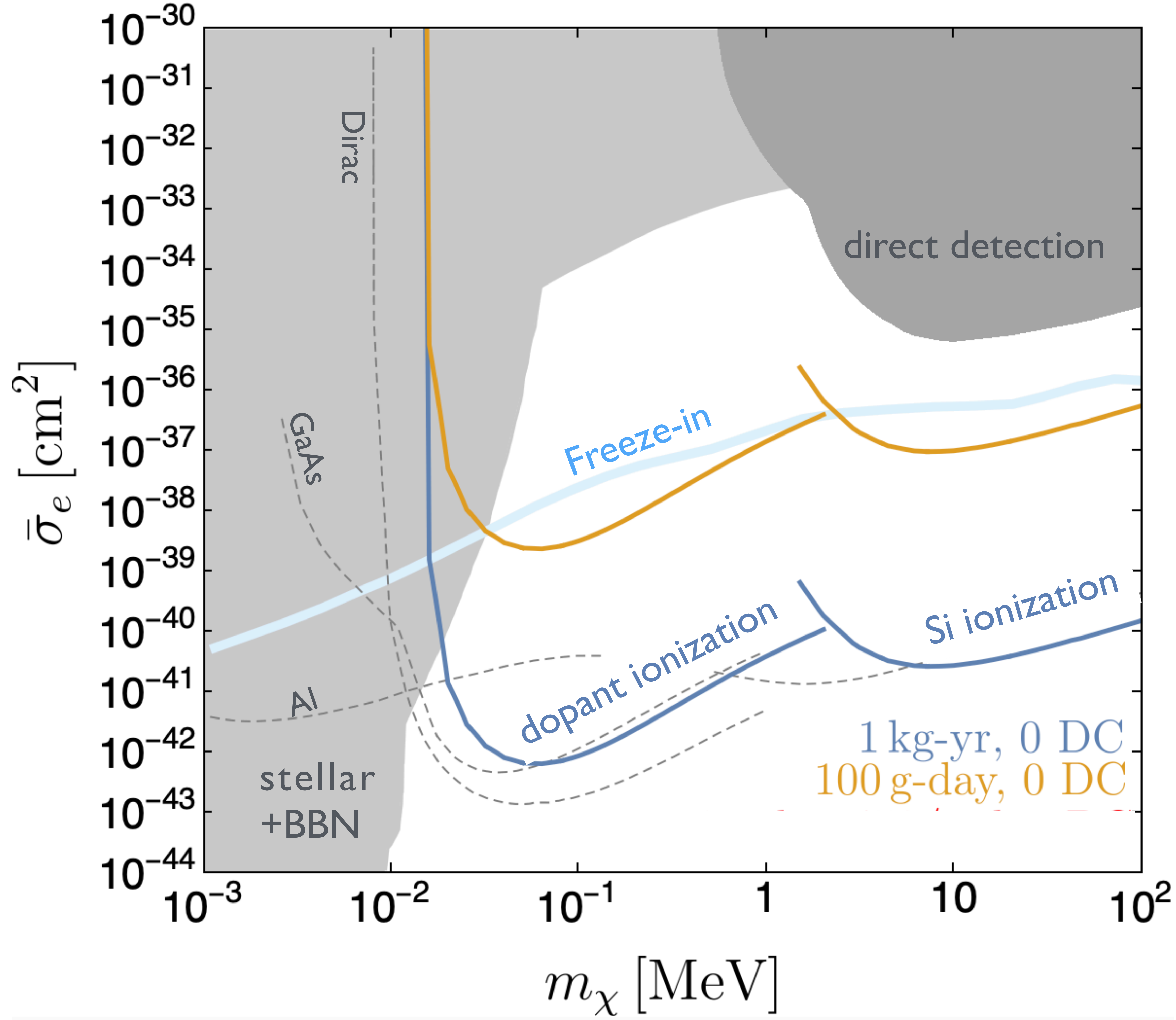
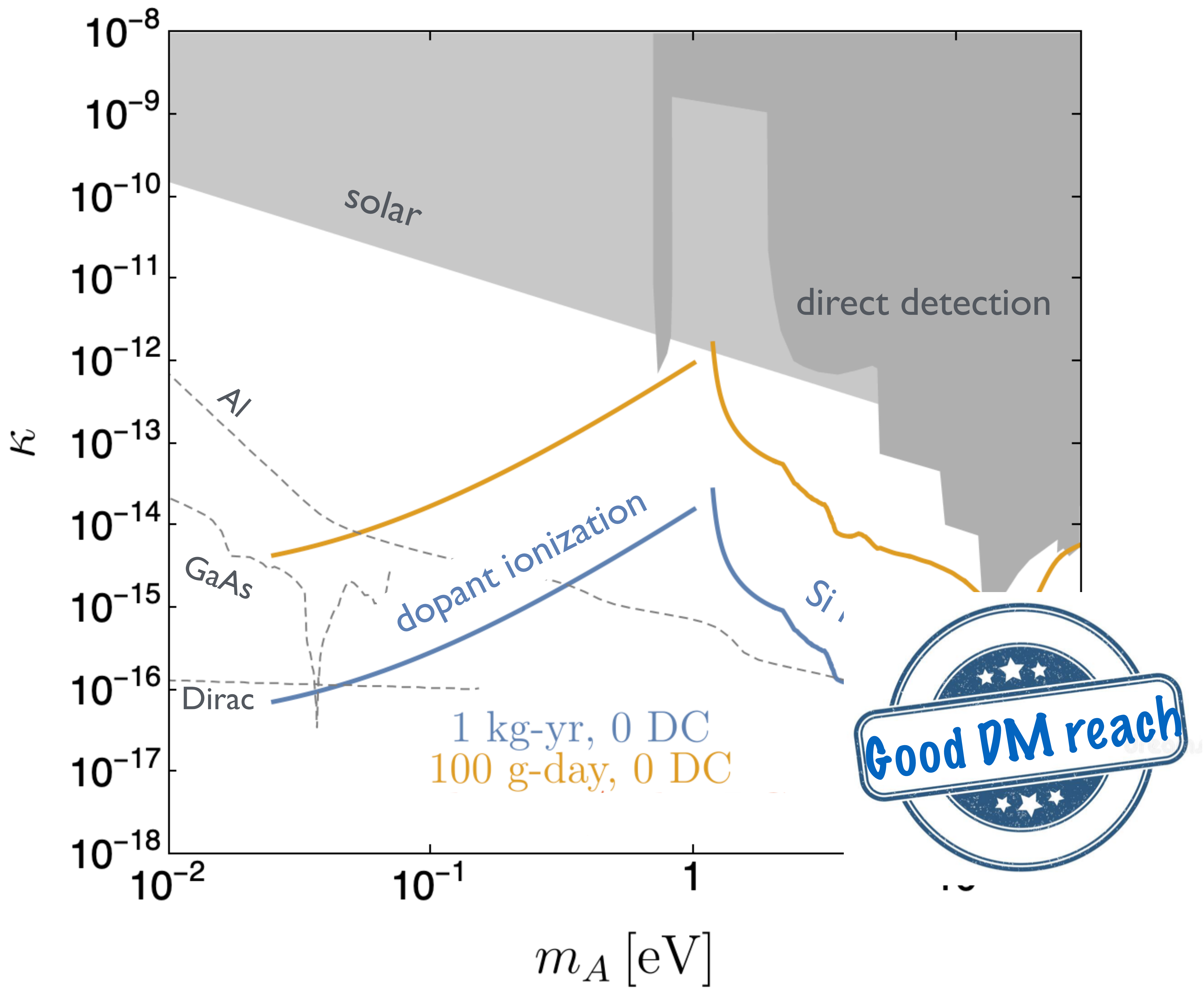
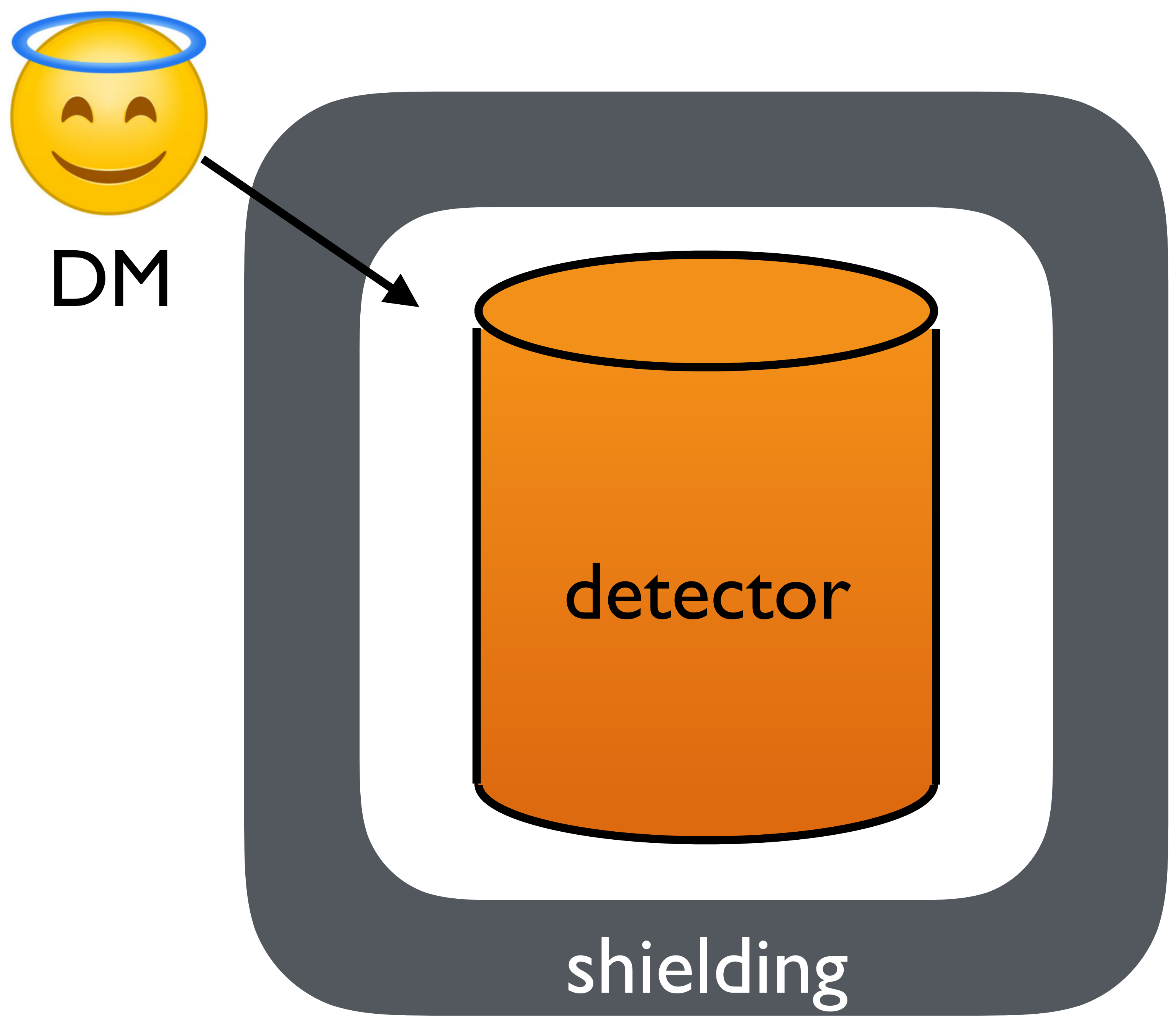


Dark photon dark matter



What about backgrounds?



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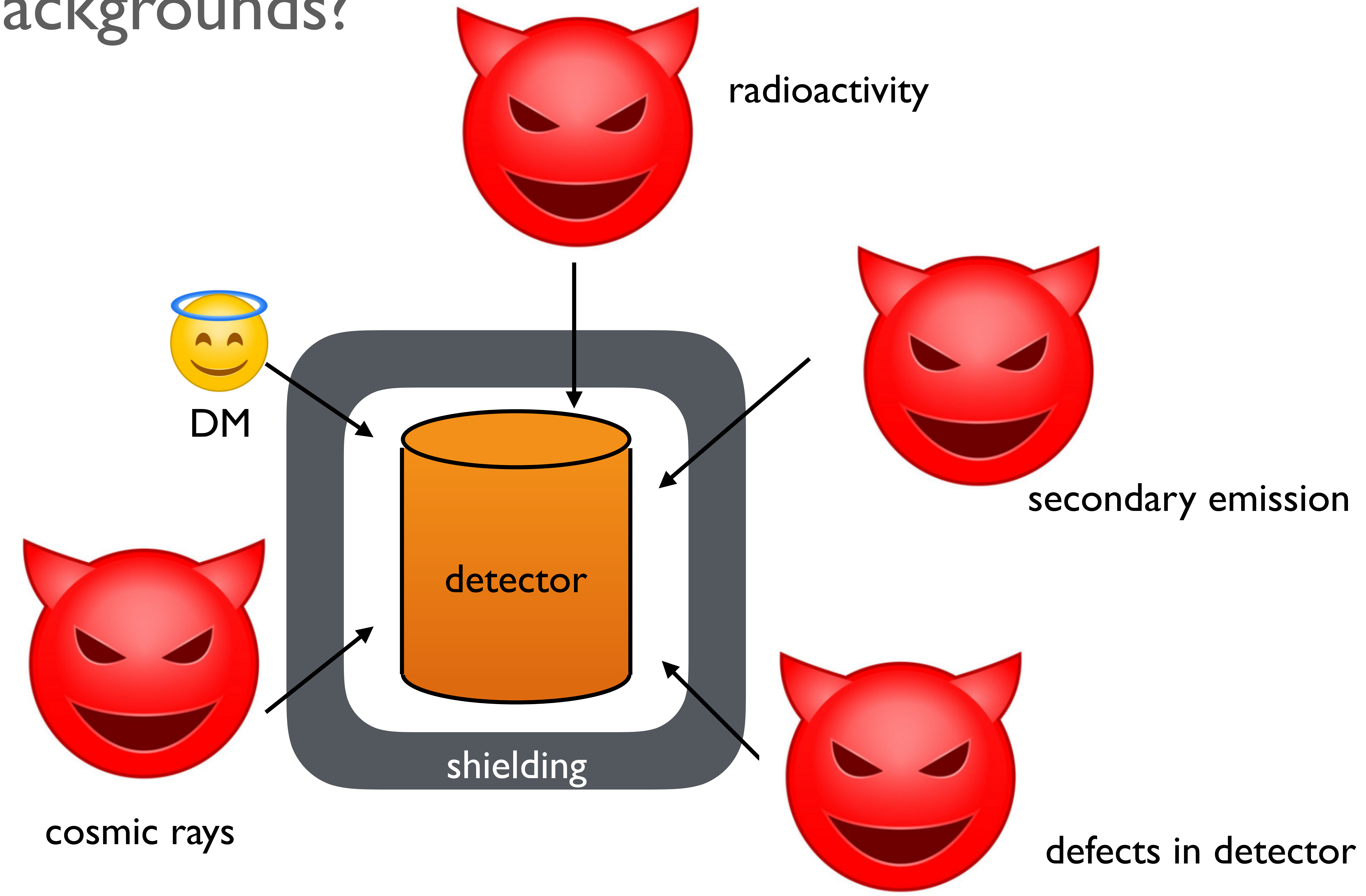
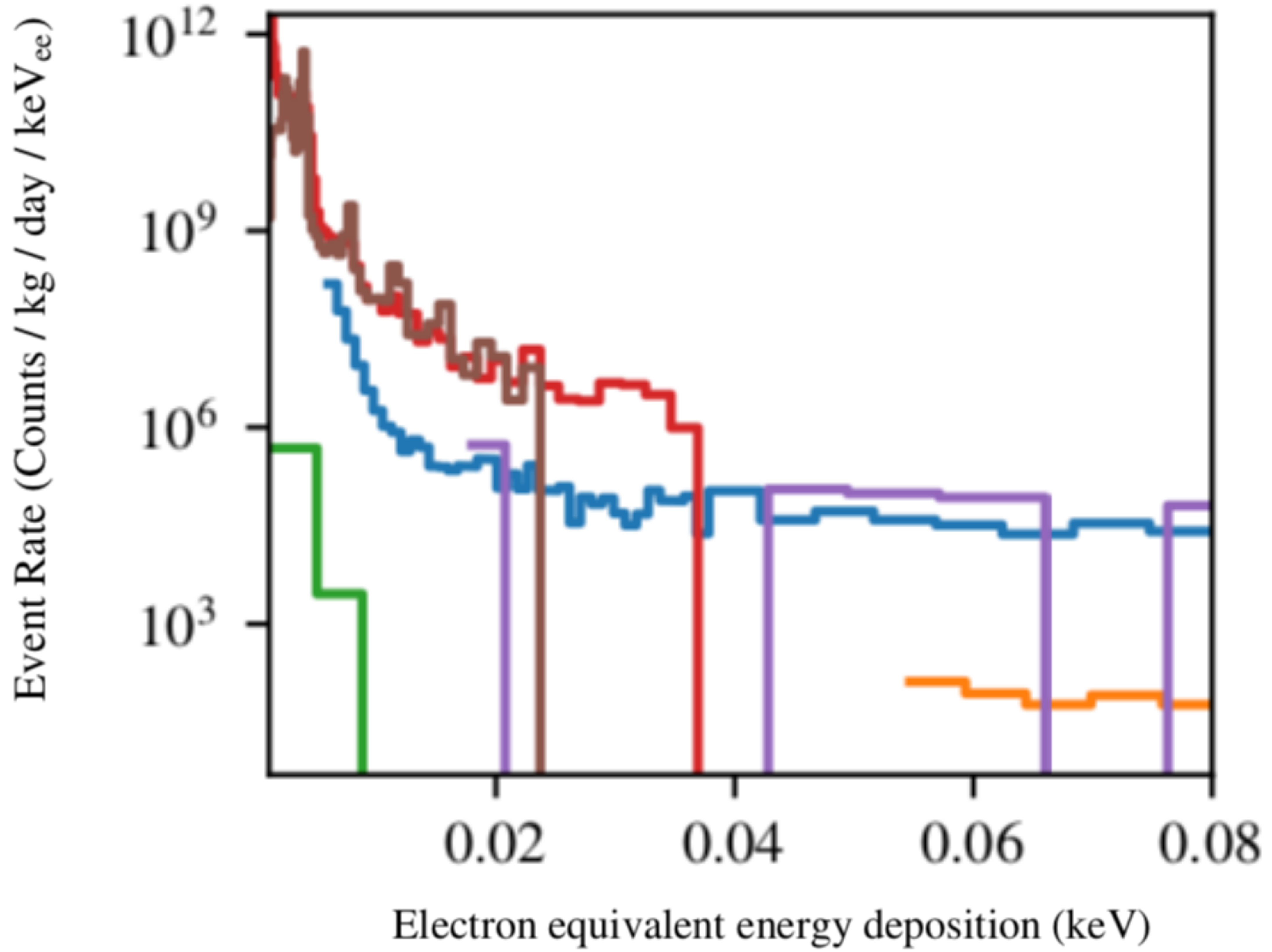


Low energy backgrounds at current detectors



- Cherenkov radiation and radiative recombination may explain SENSEI and superCDMS excess

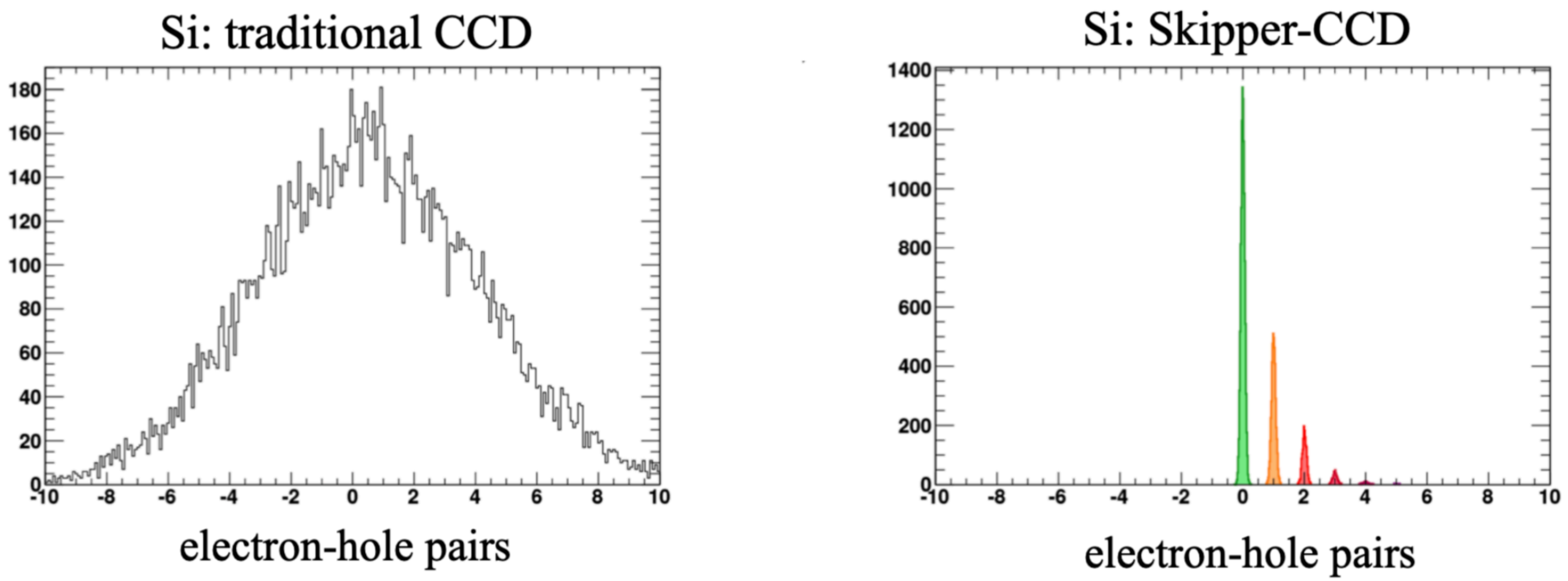
PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

See talk by Mukul Sholapurkar

- There are likely more sources of excess: crystal cracking/microfracture…

Skipper CCD

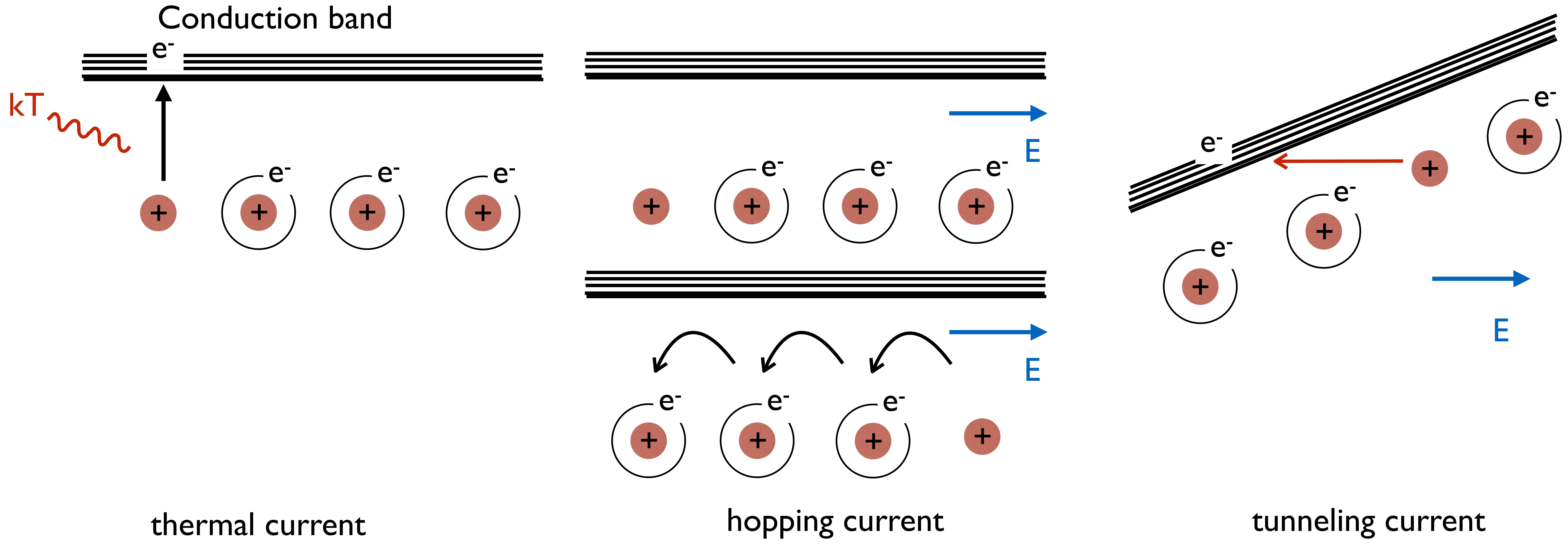
- Fully depleted and excellent spatial resolution
- Skipper readout: noise $\sim 1/\sqrt{N}$



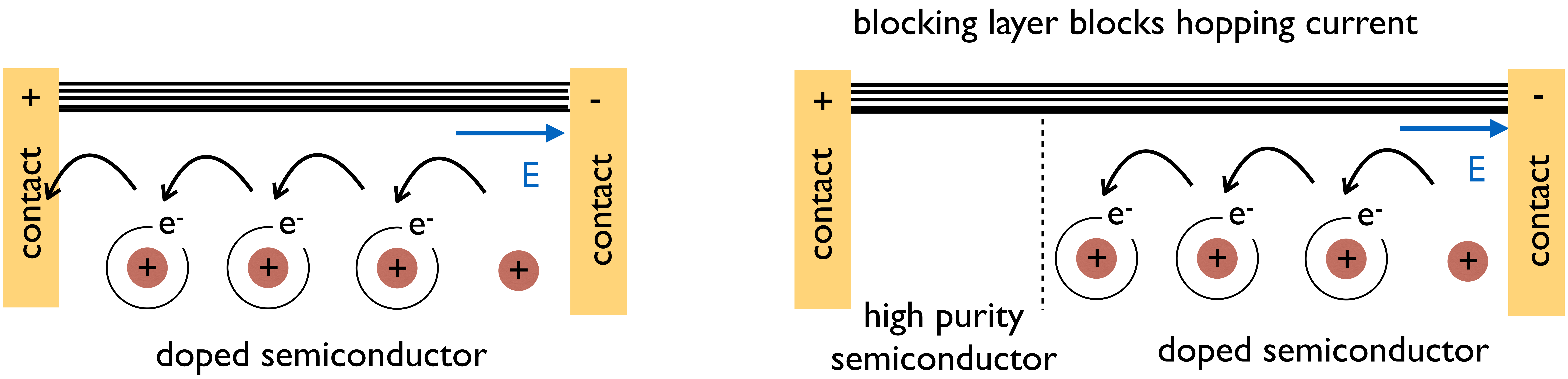
Essig, ICHEP 2020

- Single electron resolution and ultra-low dark current: $O(10^{-4})$ e/pixel/day

Dark current in doped semiconductor



Dark current in doped semiconductor

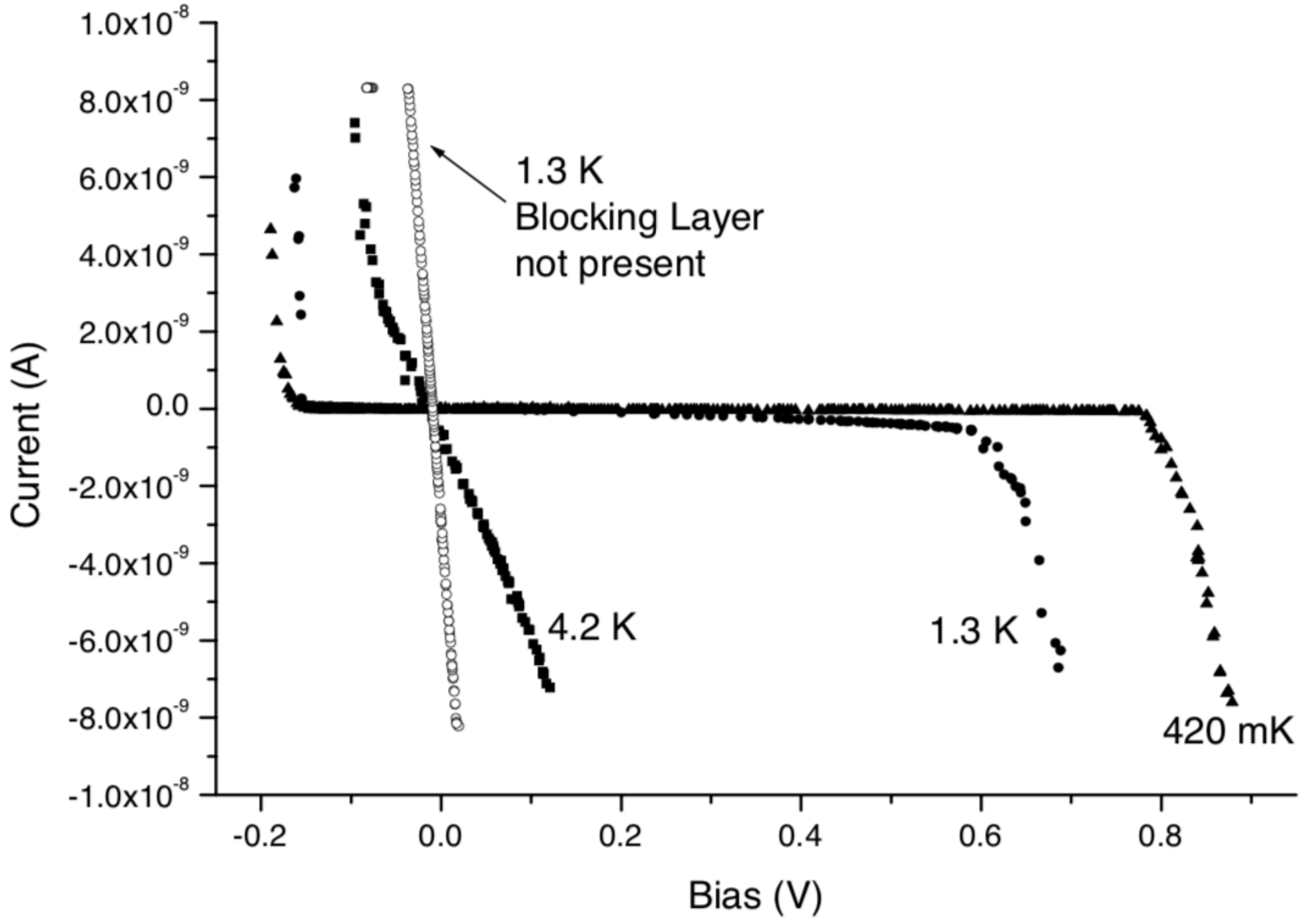


blocked impurity band detector: low dark current at low temperature with a blocking layer

Petroff, Stapelbroek, 1980

Dark current in BIB detector

GaAs:Te BIB detector



Benjamin Lewin Cardozo, 2004

- JWST uses Si:As BIB detector with

  dark current: $O(10^{-2})$ e/pixel/s

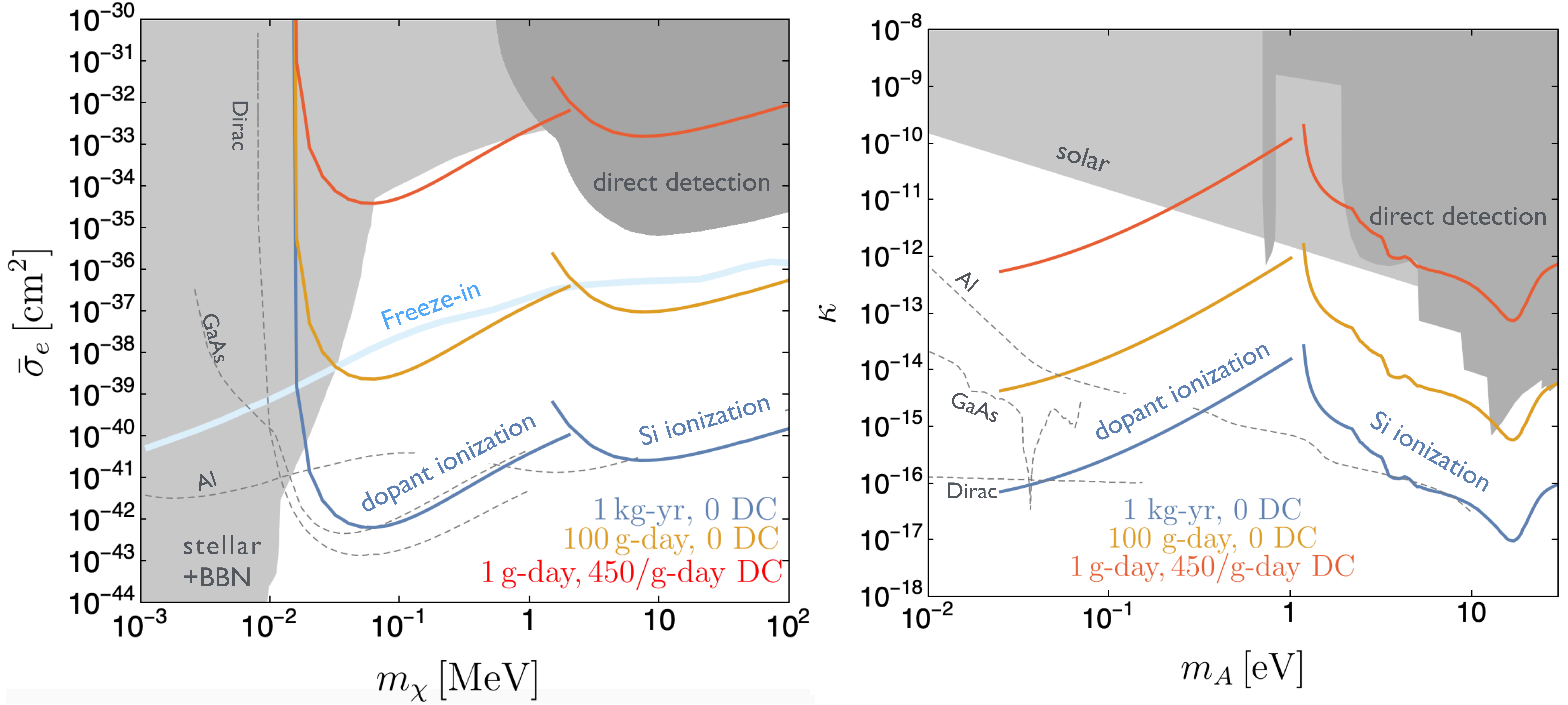
  Rieke et.al. , The Mid-Infrared Instrument for JWST

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

- Skipper CCD with doped Si and blocking layers may achieve low dark current

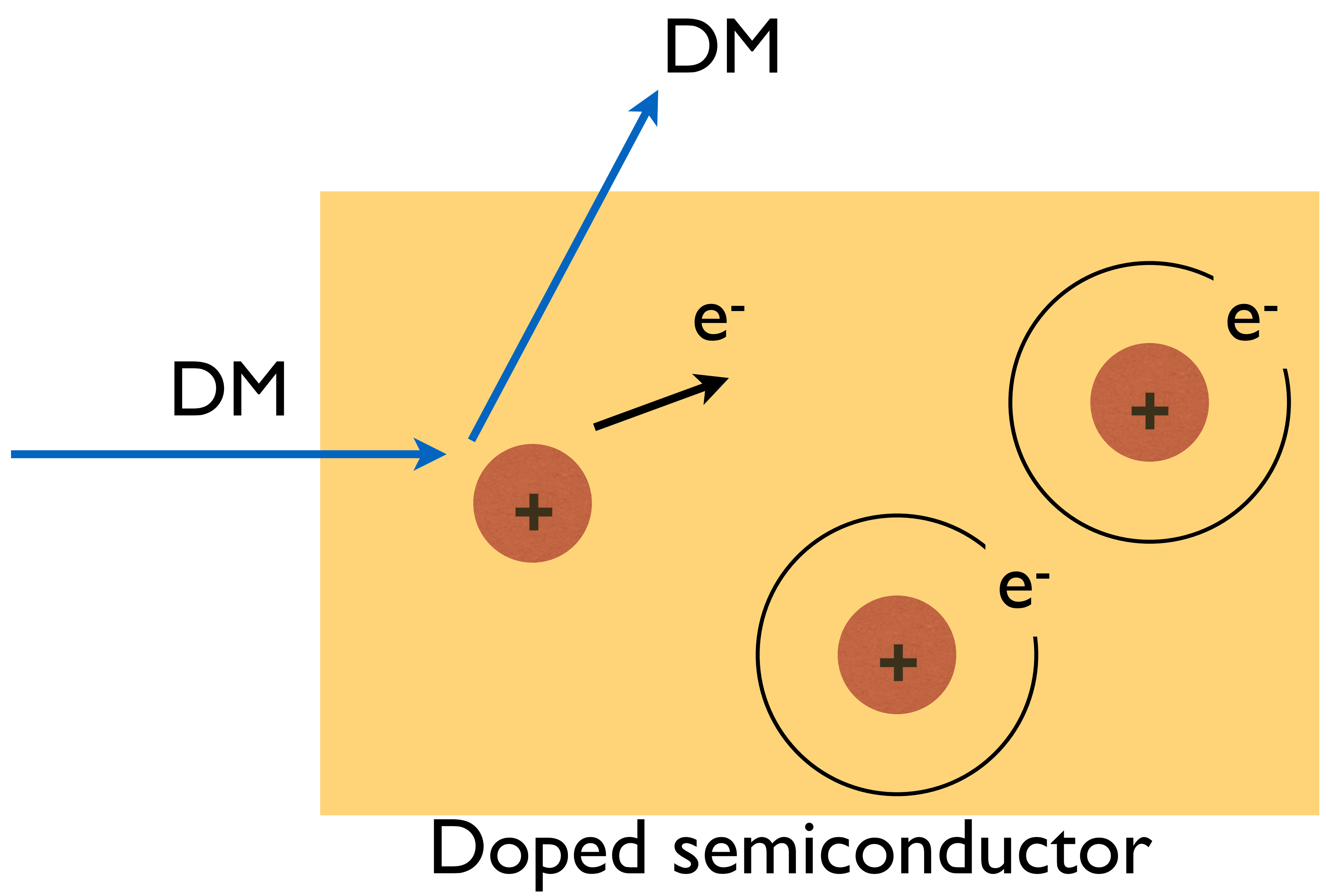
DM reach with backgrounds

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



Conclusions

- 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
- Skipper CCD with doped Si and blocking layers may achieve low dark current



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

Good timing resolution

High ambient backgrounds

Low ambient backgrounds

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