UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Direct Dark Matter Searches: Part II

Principles of direct detection: electron recoil

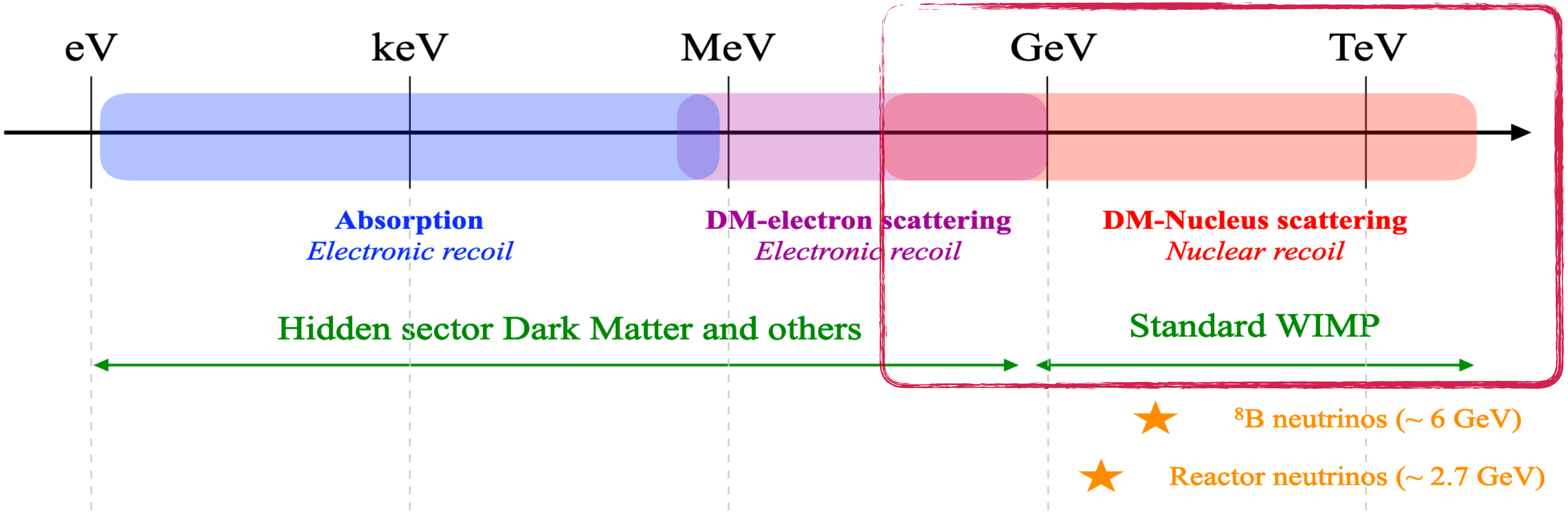
ISAPP School „Neutrinos and Dark Matter – in the lab and in the Universe“, 25.09.2024

Belina VON KROSIGK (bkrosigk@kip.uni-heidelberg.de)

Credit: Swinburne Astronomy Productions - J. Josephides

Reminder

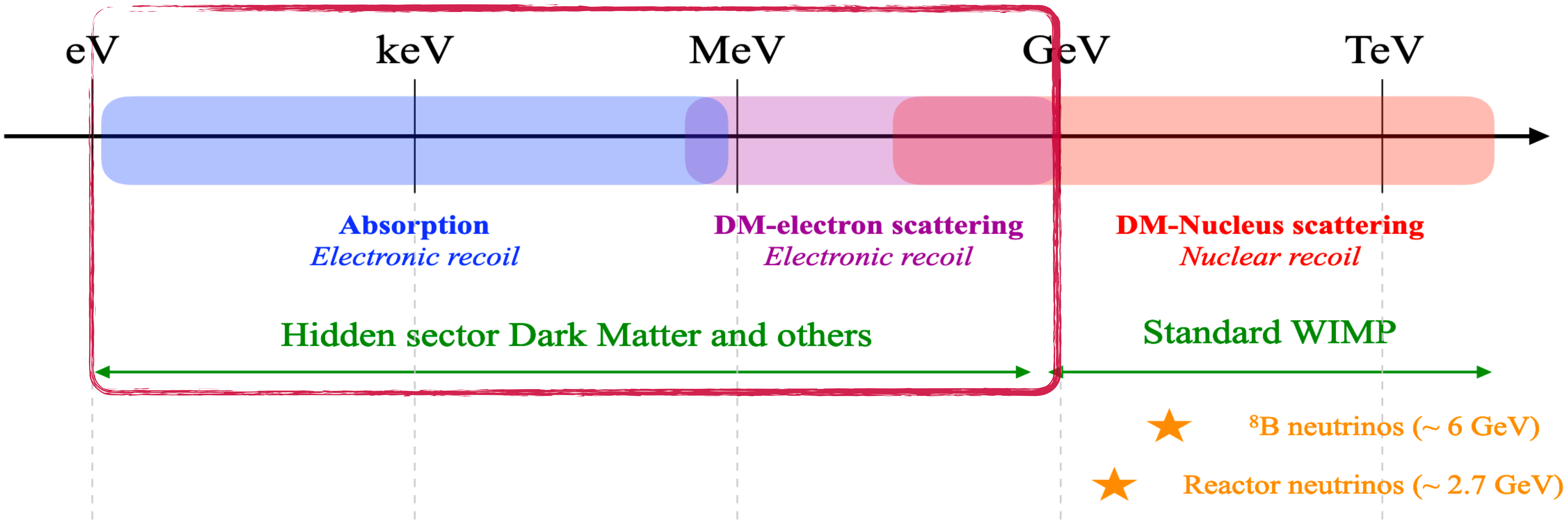
- Expected candidates, interactions, and rates



See **Marco Cirelli's** lectures

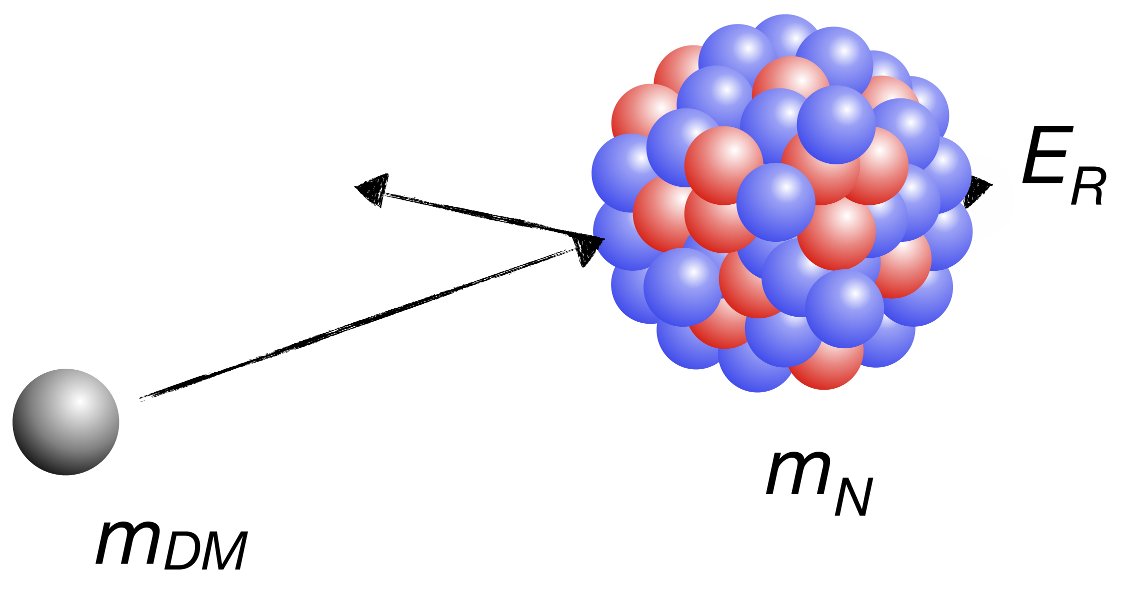
Today

- Expected candidates, interactions, and rates



See **Marco Cirelli's** lectures

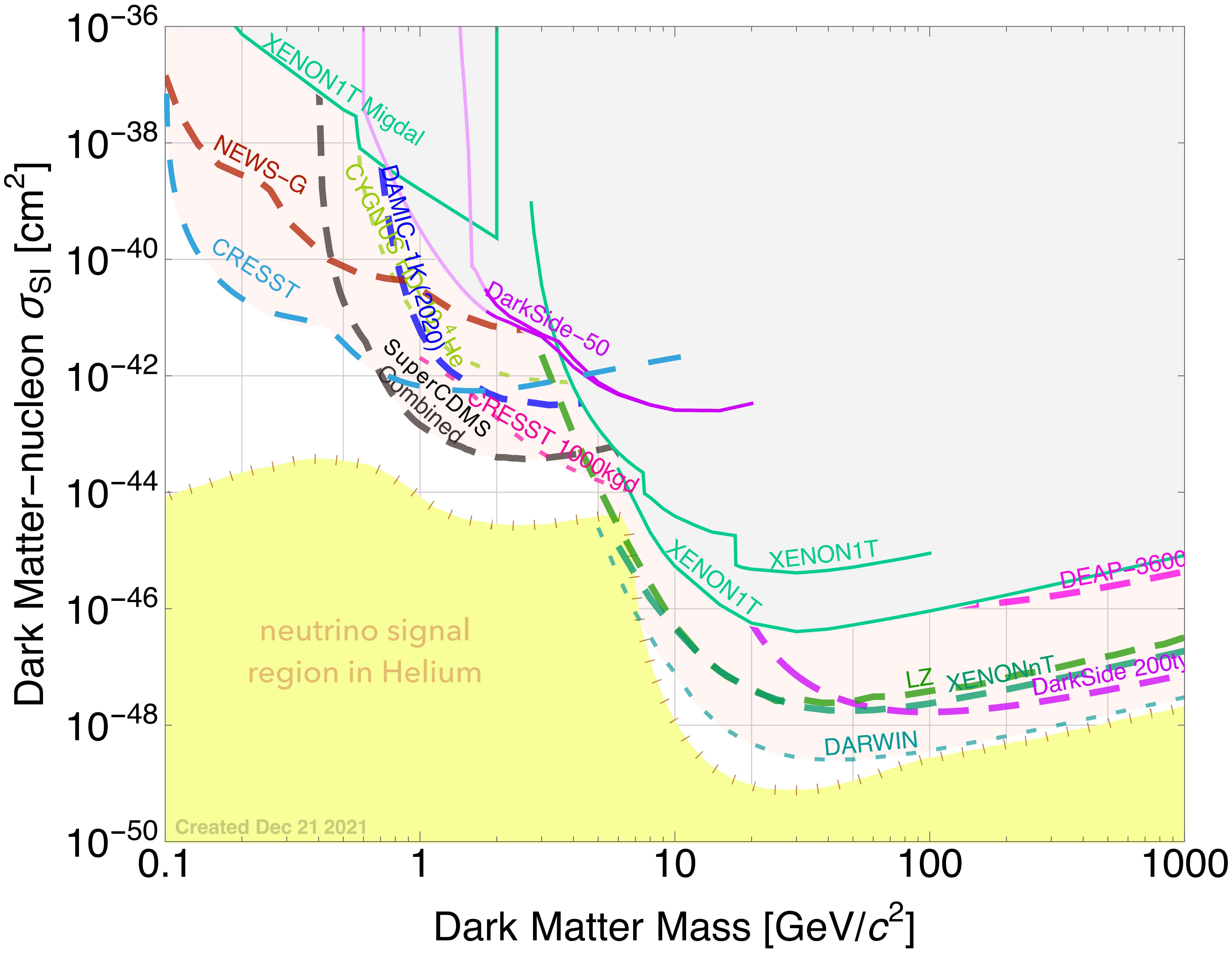
DM-nucleus scattering: reminder



Observable recoil energy:

$$E_R = \frac{1}{2}\frac{\Delta p^2}{m_N} \lesssim \frac{2\, m_{\mathrm{DM}}^2 v_{\mathrm{DM}}^2}{m_N}$$

$$\left(\frac{dR}{dE_R}\right)^{\mathrm{SI}}_{\chi N} = \frac{\sigma_0^{\mathrm{SI}}}{m_\chi} \cdot \frac{\rho_0 T(\vec{v})}{v\sqrt{\pi}} \cdot \frac{F_{\mathrm{SI}}^2(E_R)}{\mu^2}$$



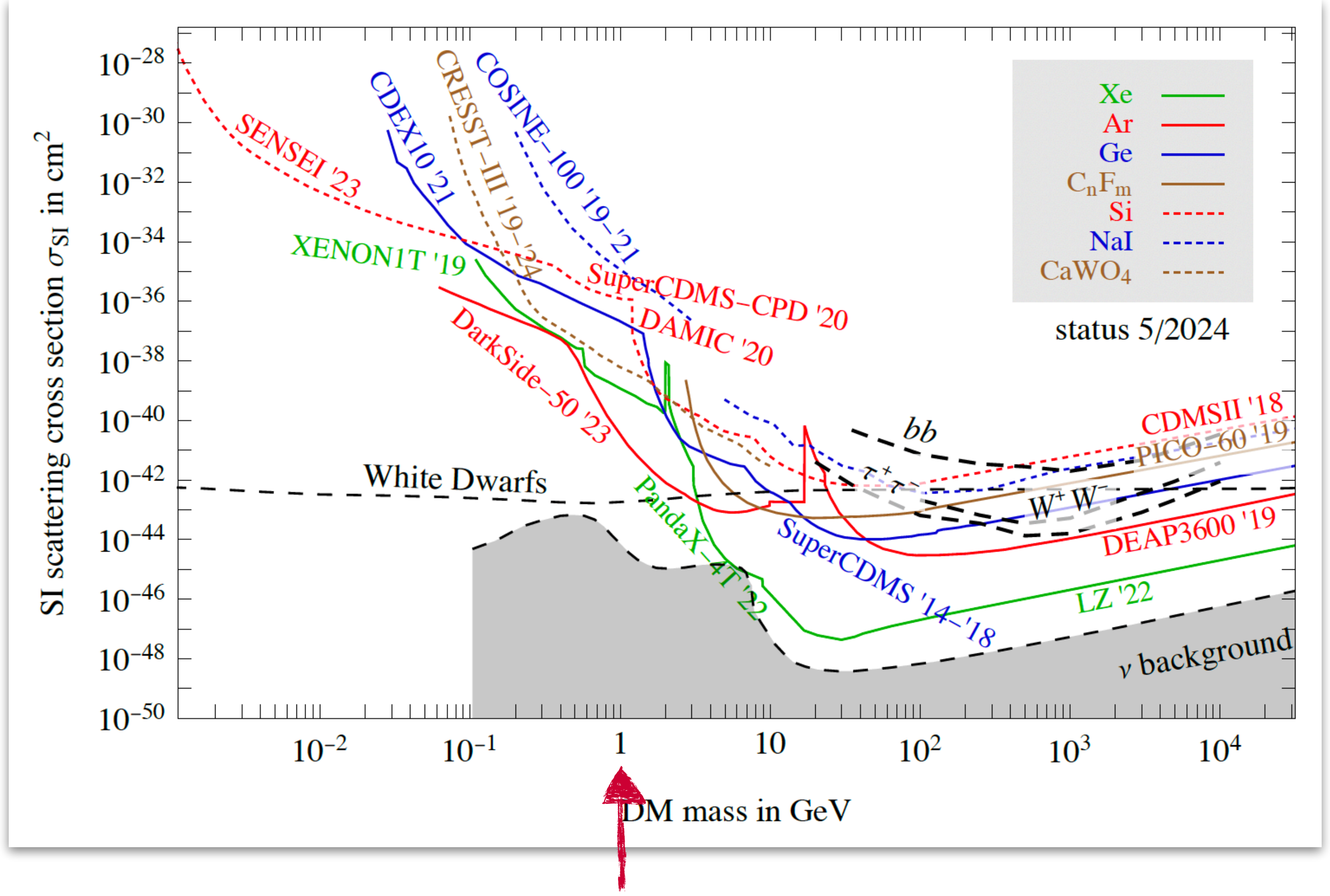
DM-nucleus scattering: experimental status

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

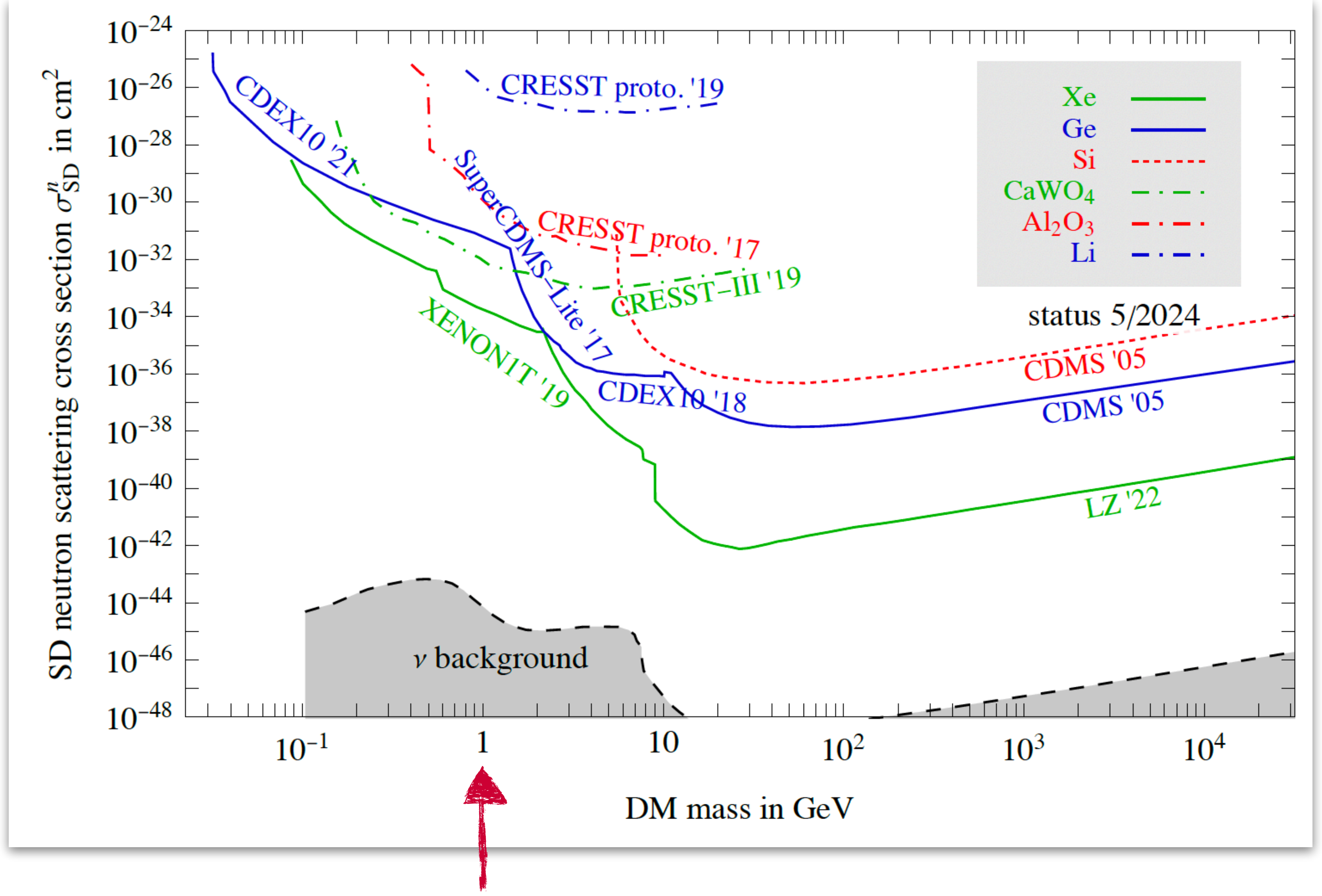
Many thanks to Marco Cirelli, Alessandro Strumia, Jure Zupan for a great, latest DM compilation!

arXiv:2406.01705

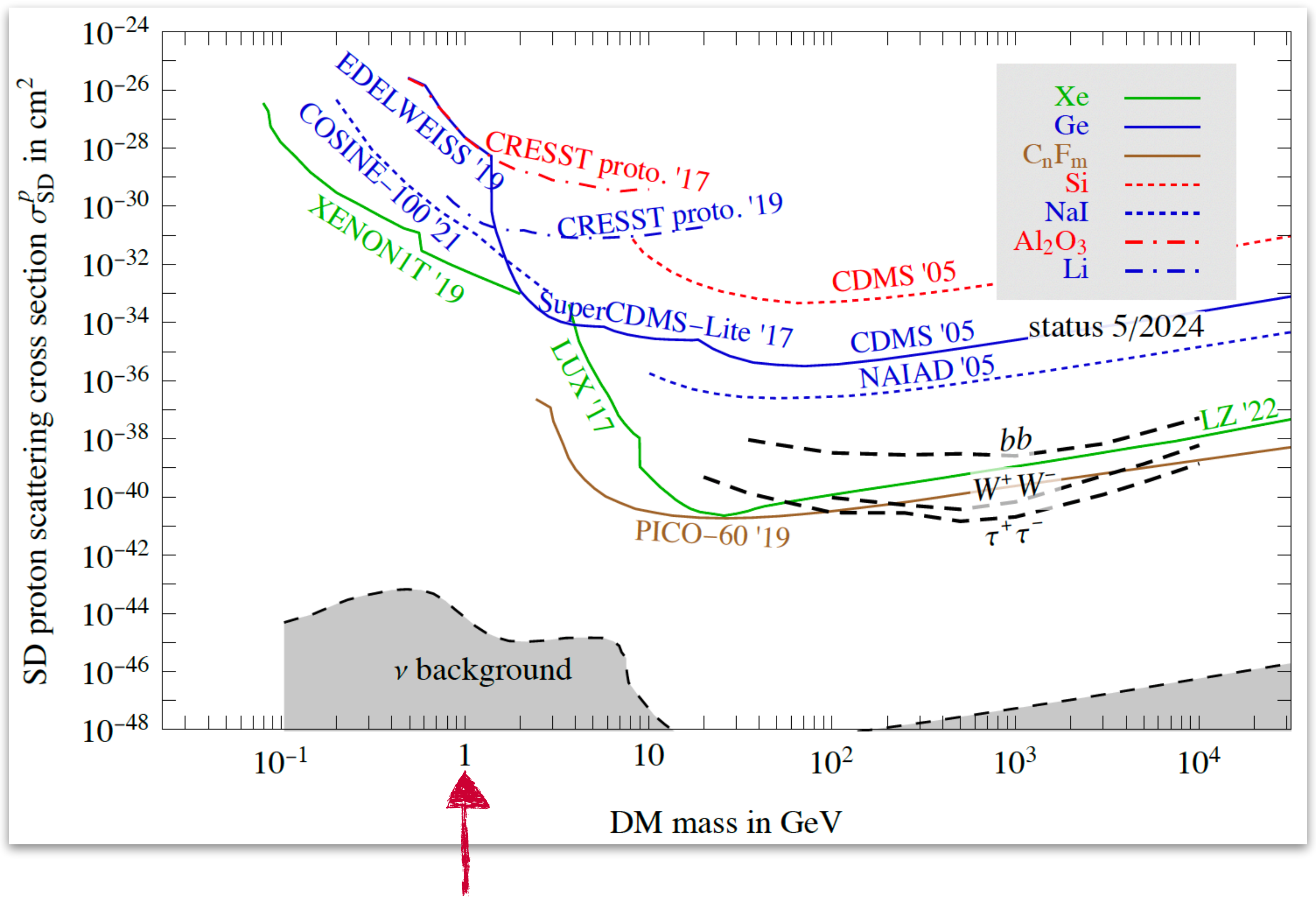
Spin-independent



Spin-dependent, neutron



Spin-dependent, proton



Quite some activity below 1 GeV!

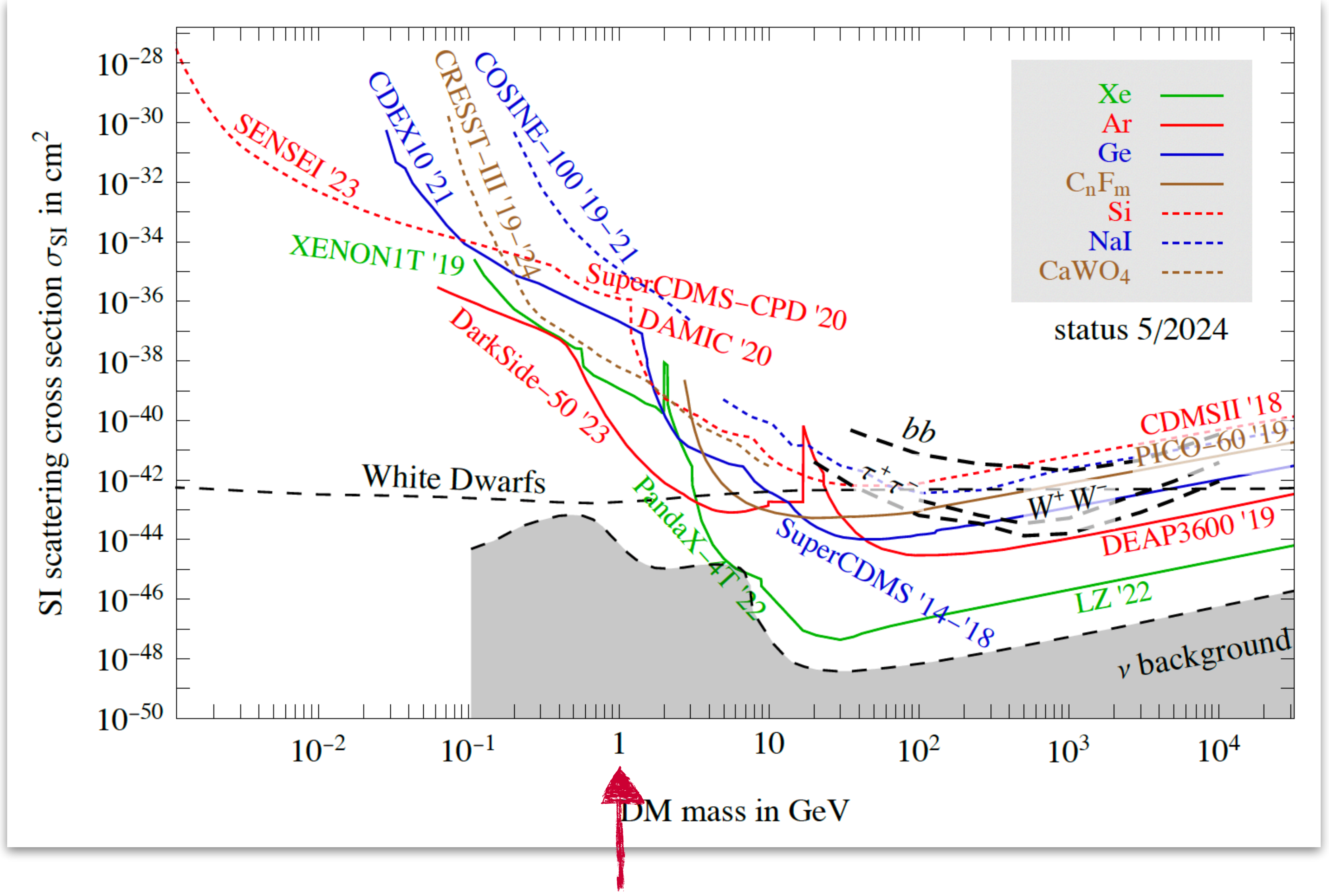
DM-nucleus scattering: experimental status

UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

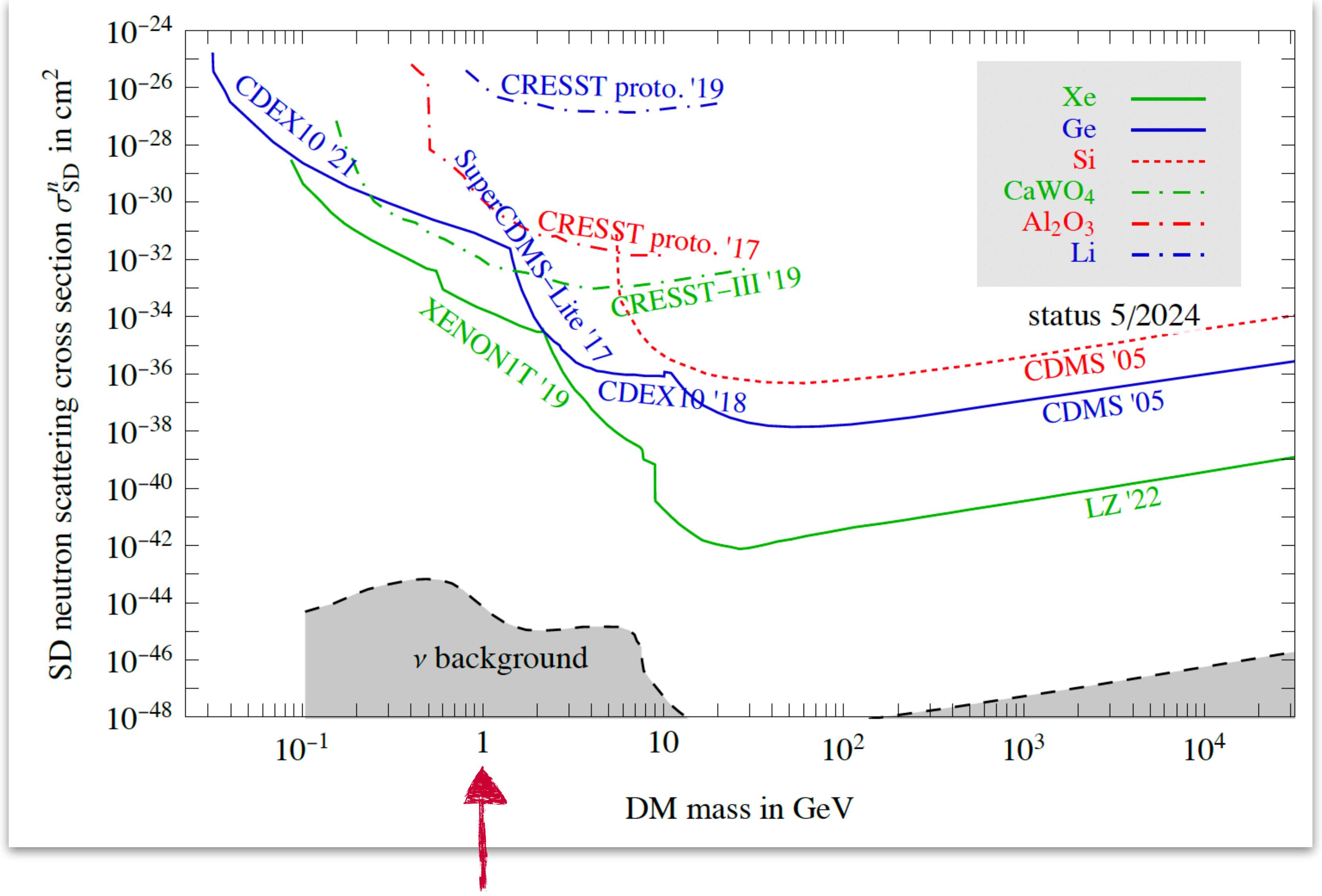
Many thanks to Marco Cirelli, Alessandro Strumia, Jure Zupan for a great, latest DM compilation!

arXiv:2406.01705

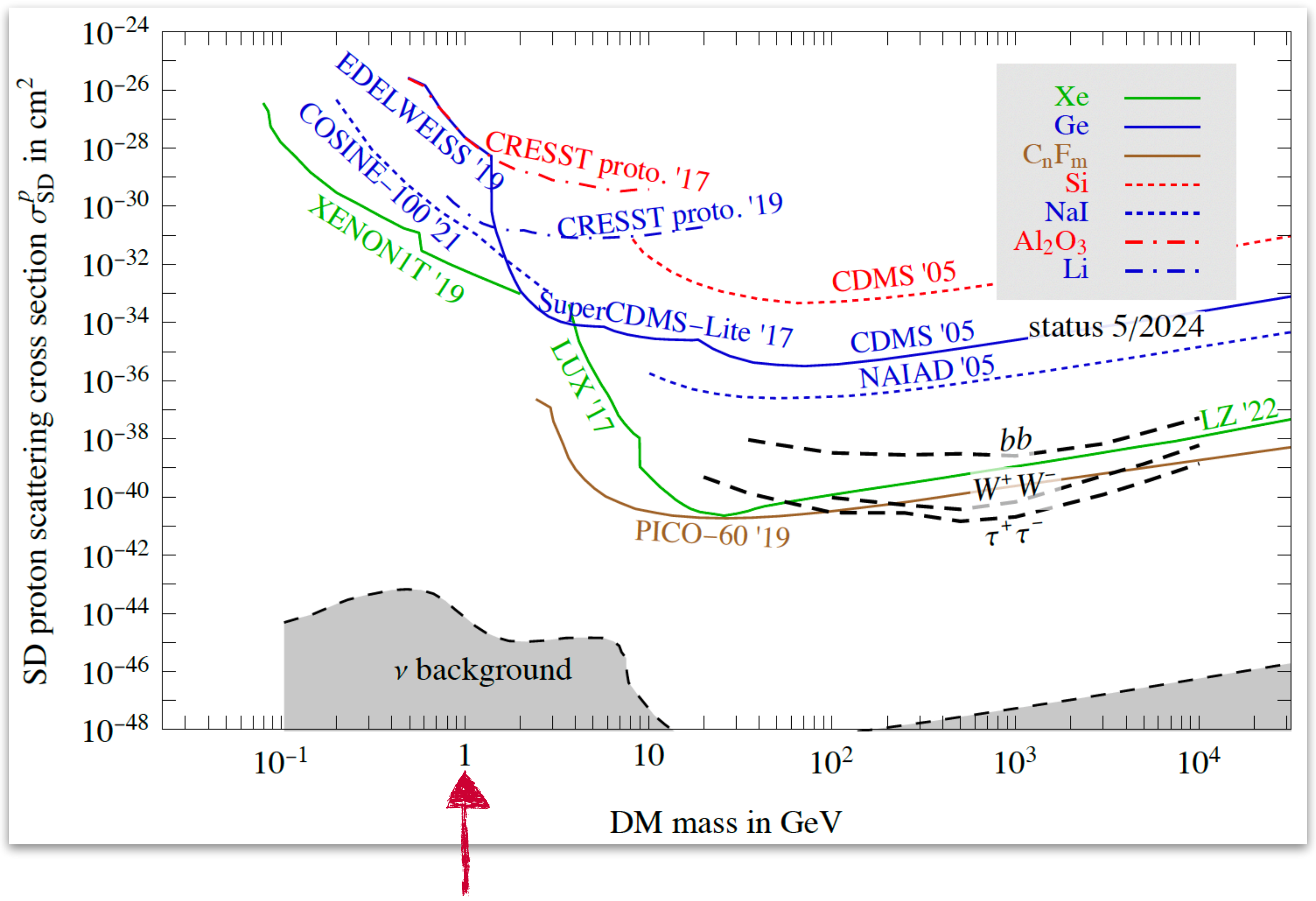
Spin-independent



Spin-dependent, neutron



Spin-dependent, proton

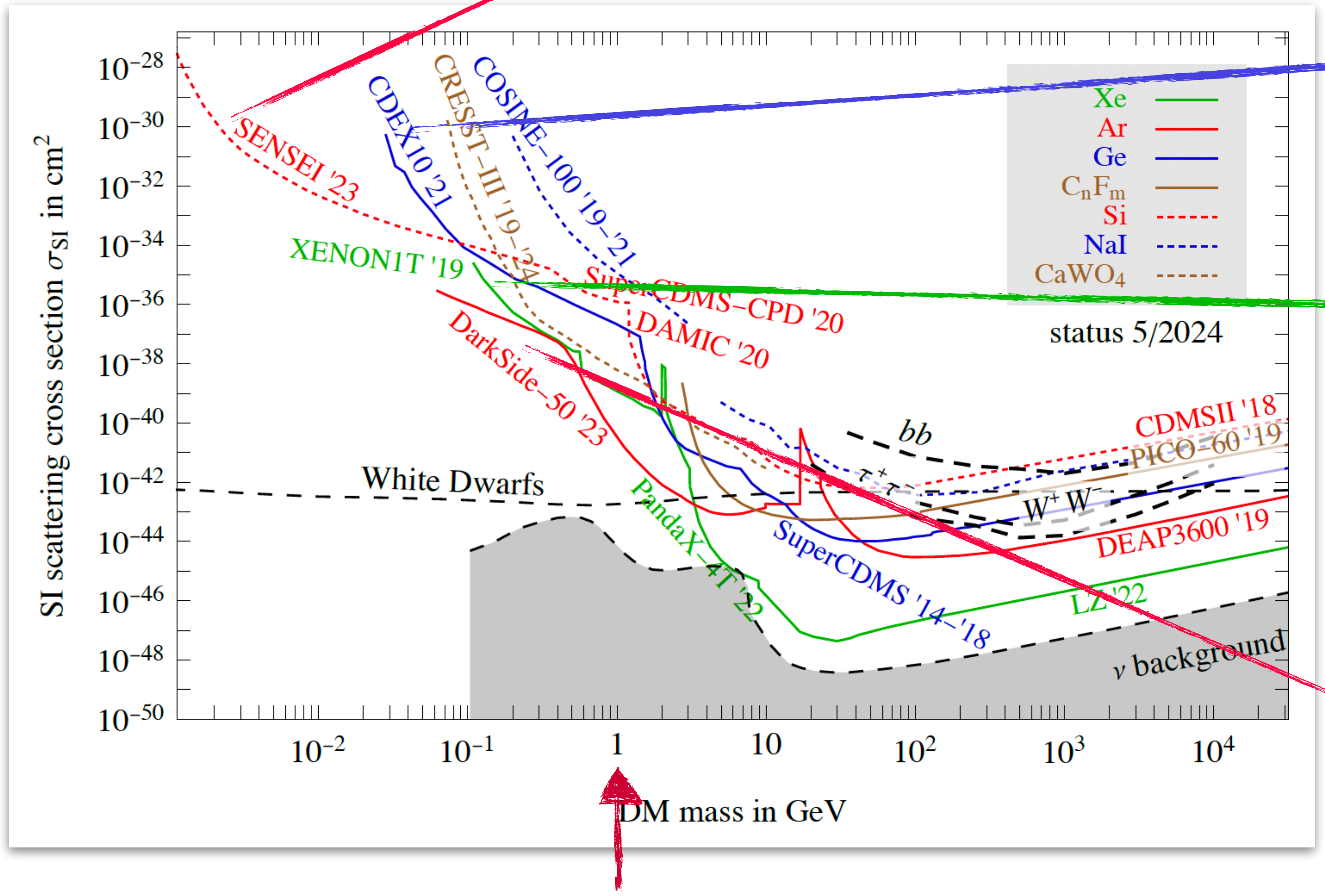


Quite some activity below 1 GeV!

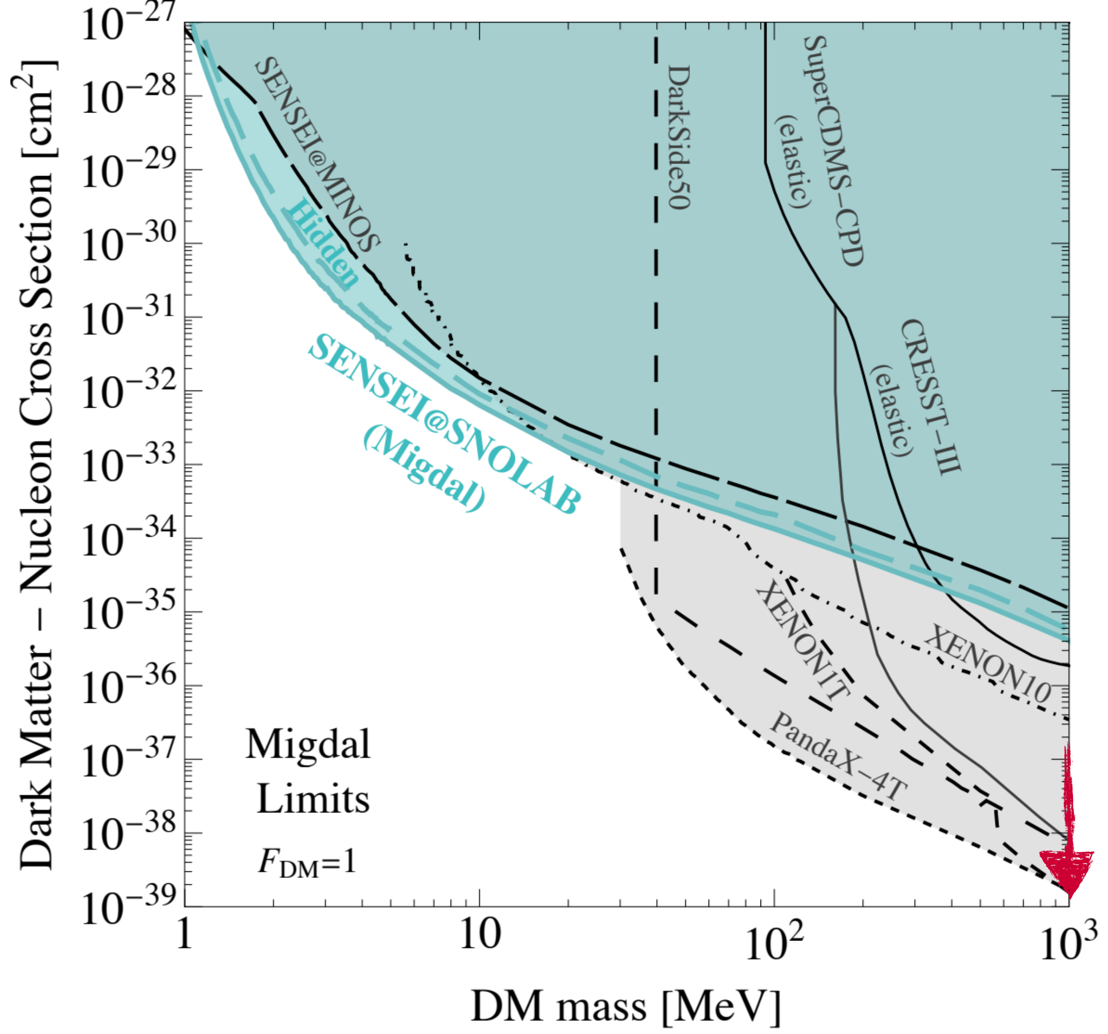
However, not all of it is **elastic** DM-nucleon scattering.

Principles of direct dark matter detection: electron recoil - Beli

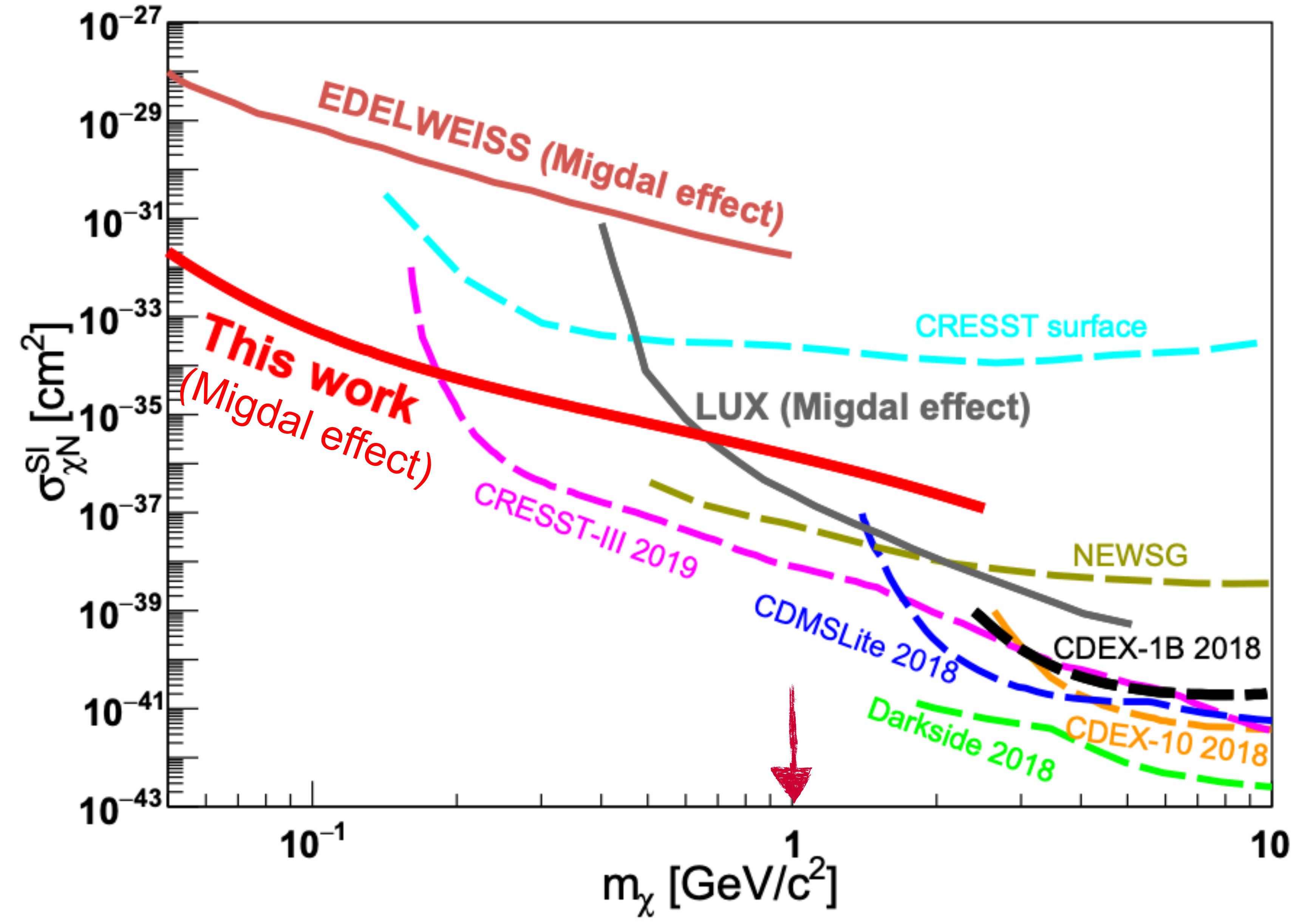
DM-nucleus scattering



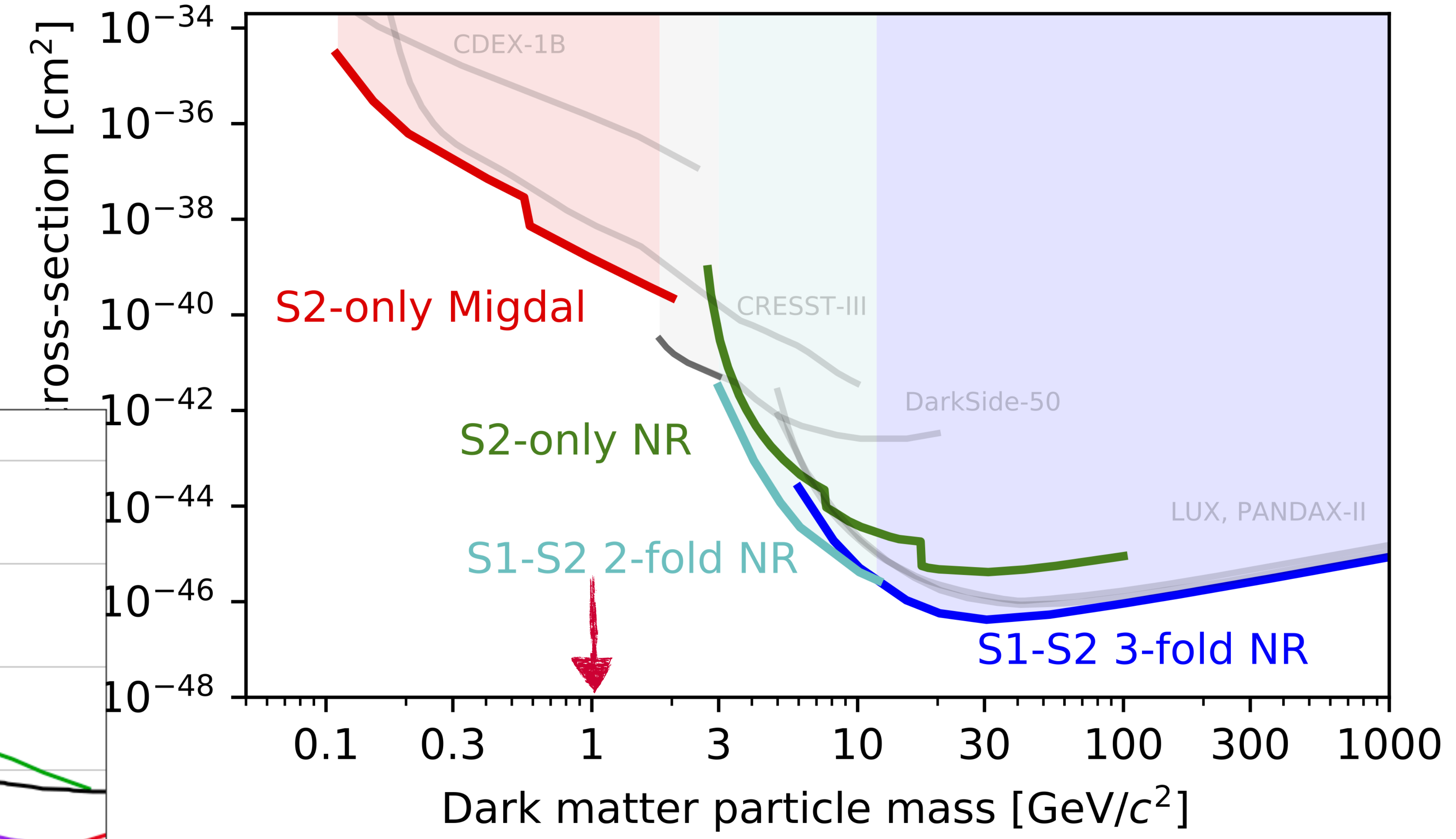
SENSEI, arXiv:2312.13342



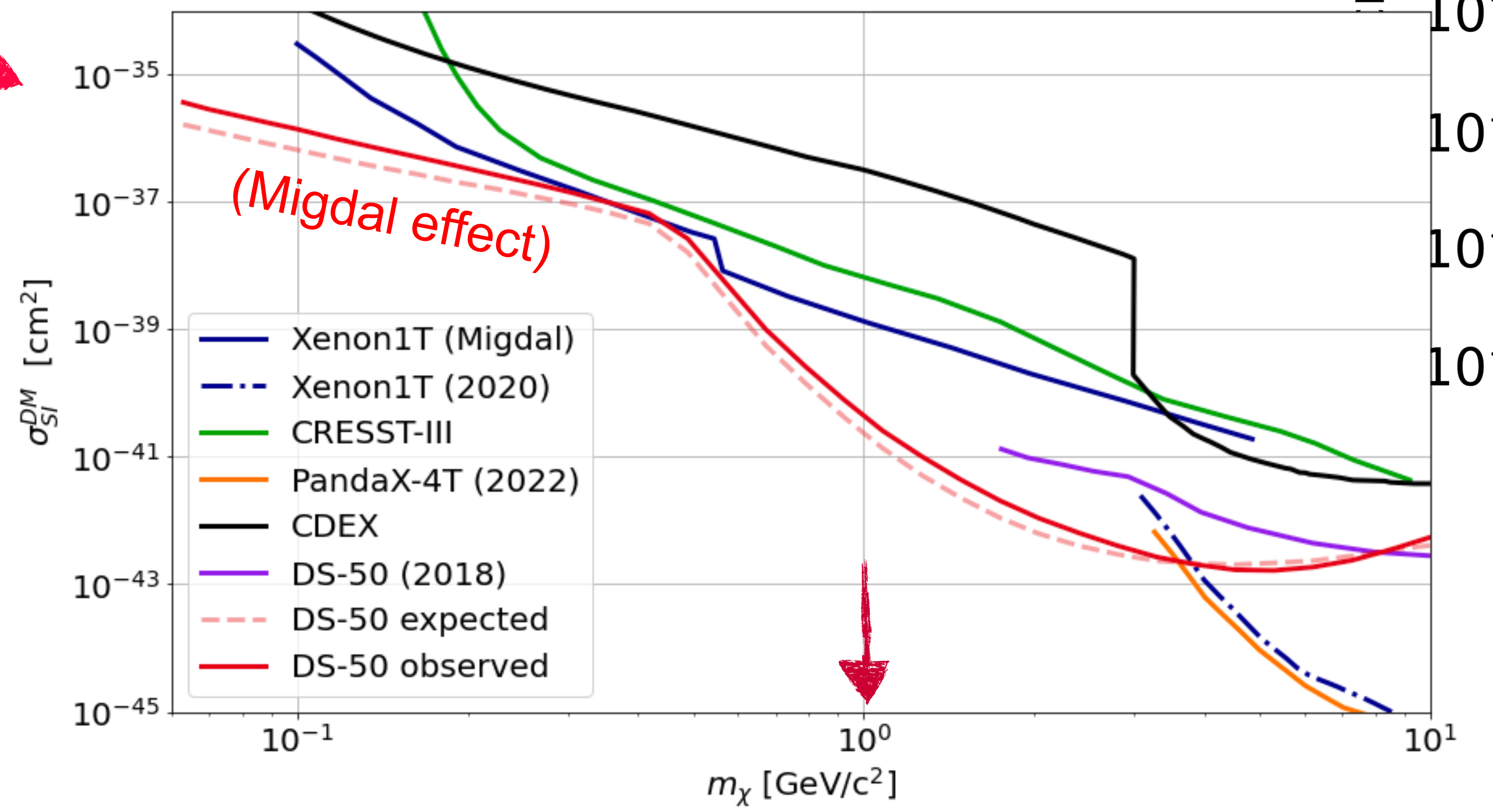
CDEX, Phys. Rev. Lett. 123, 161301



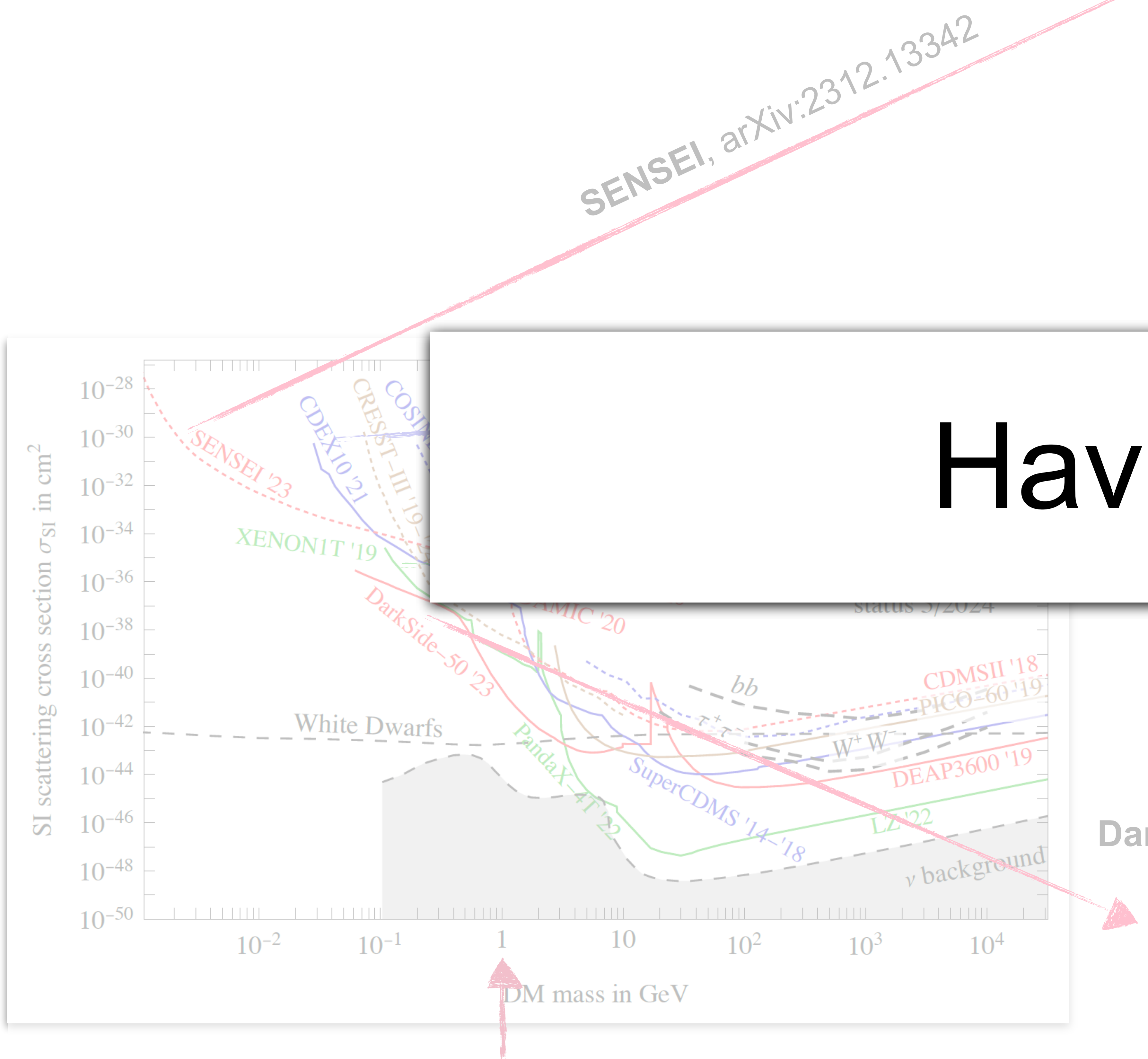
XENON1T, Phys. Rev. D 102, 072004

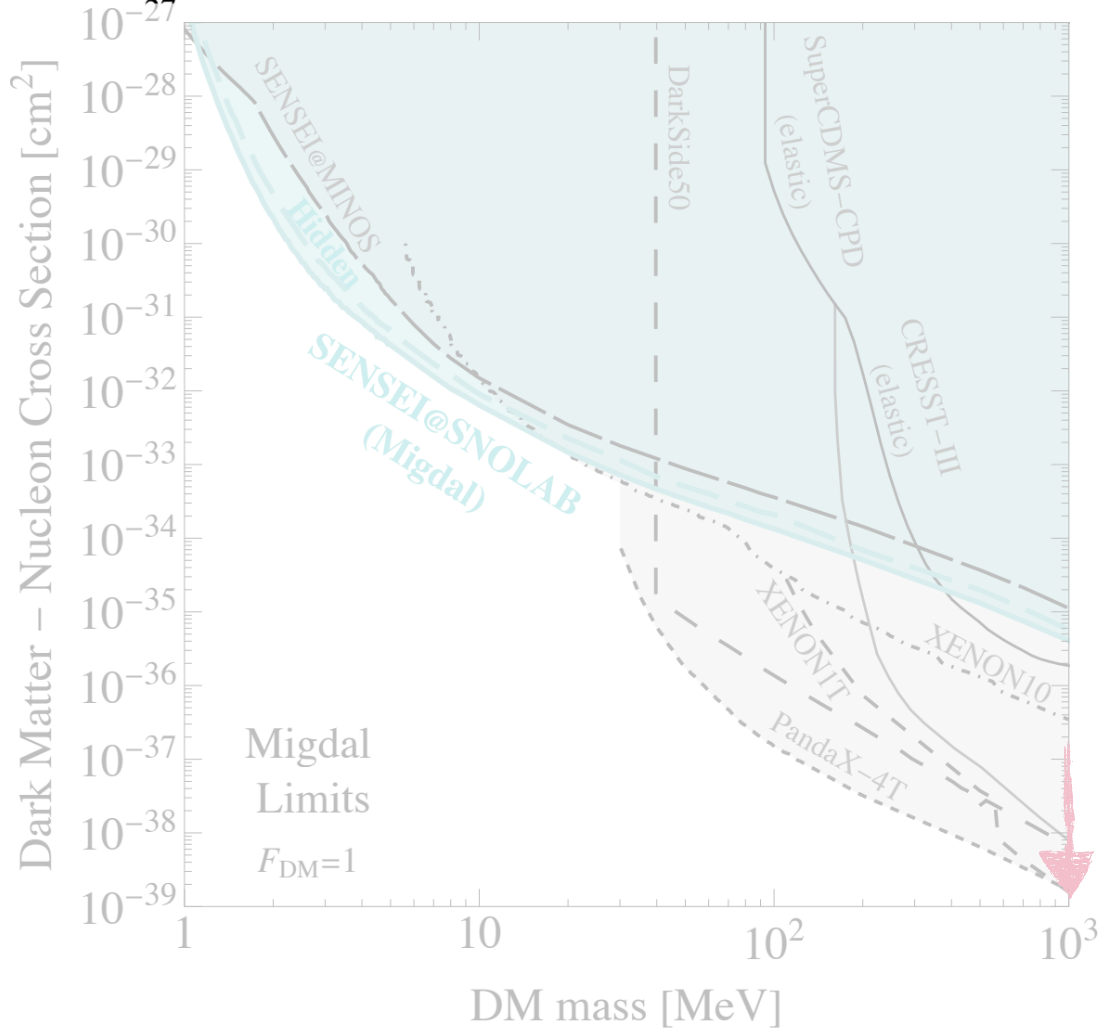


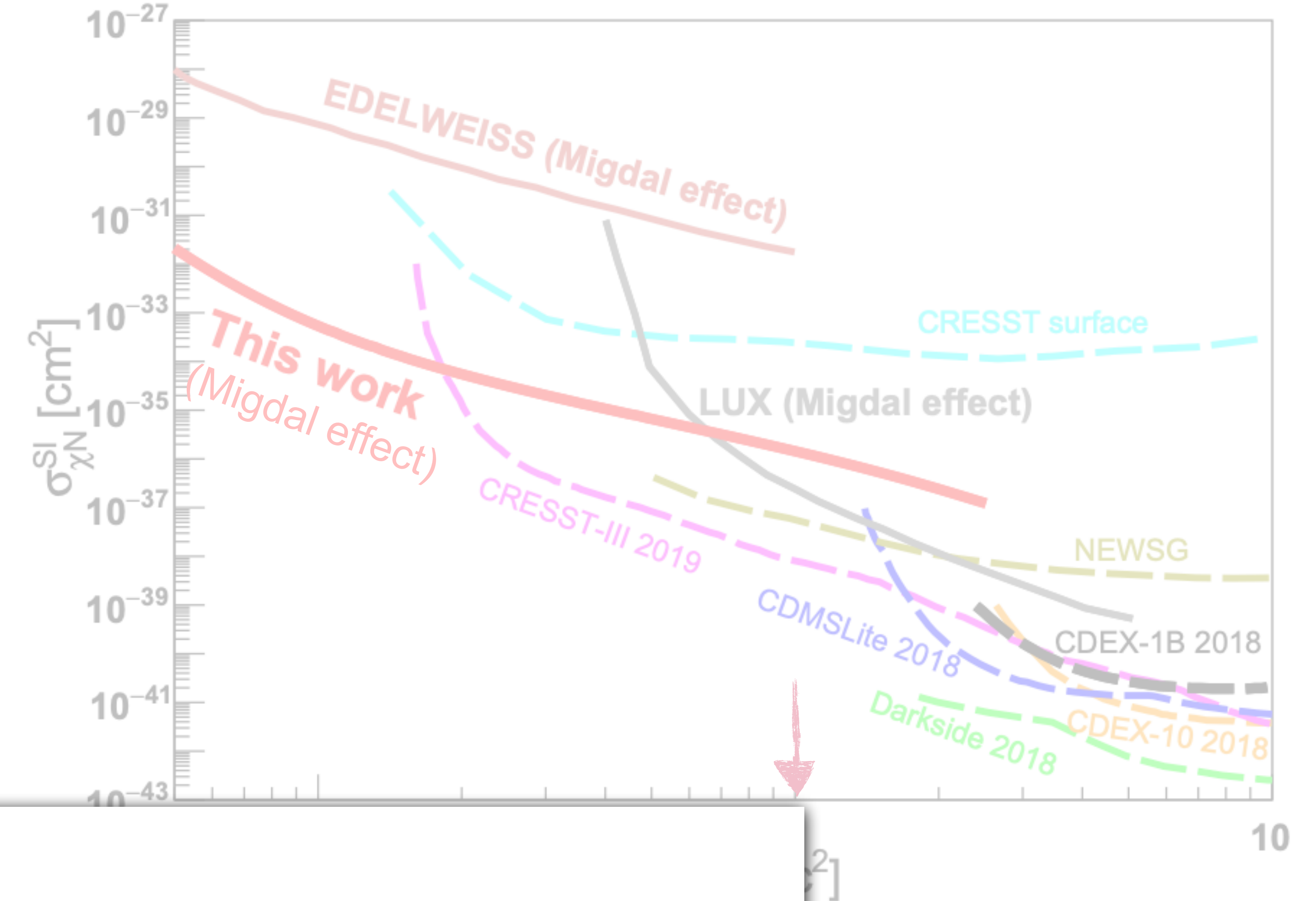
DarkSide-50, Eur. Phys. J. C 83, 322

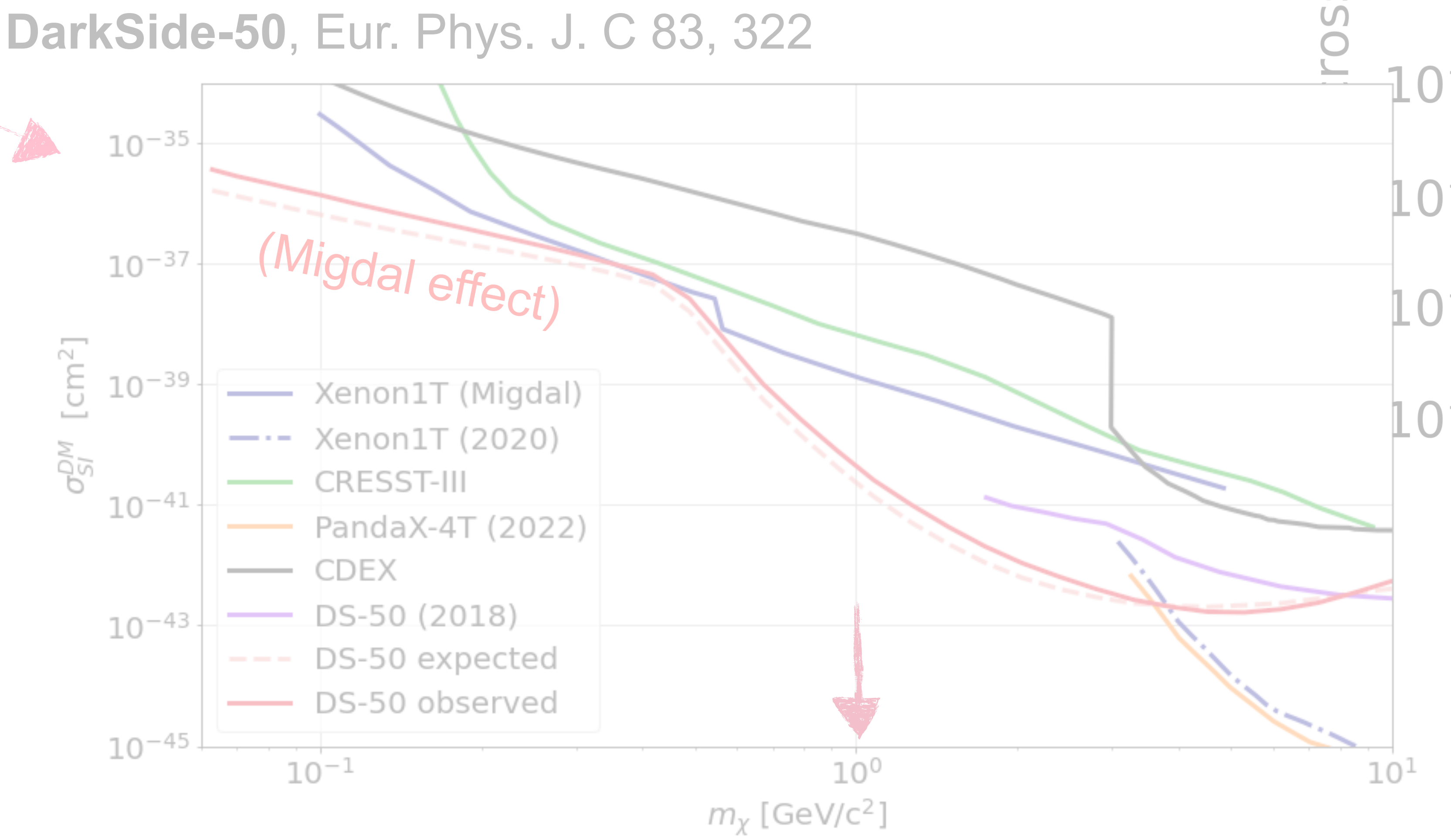


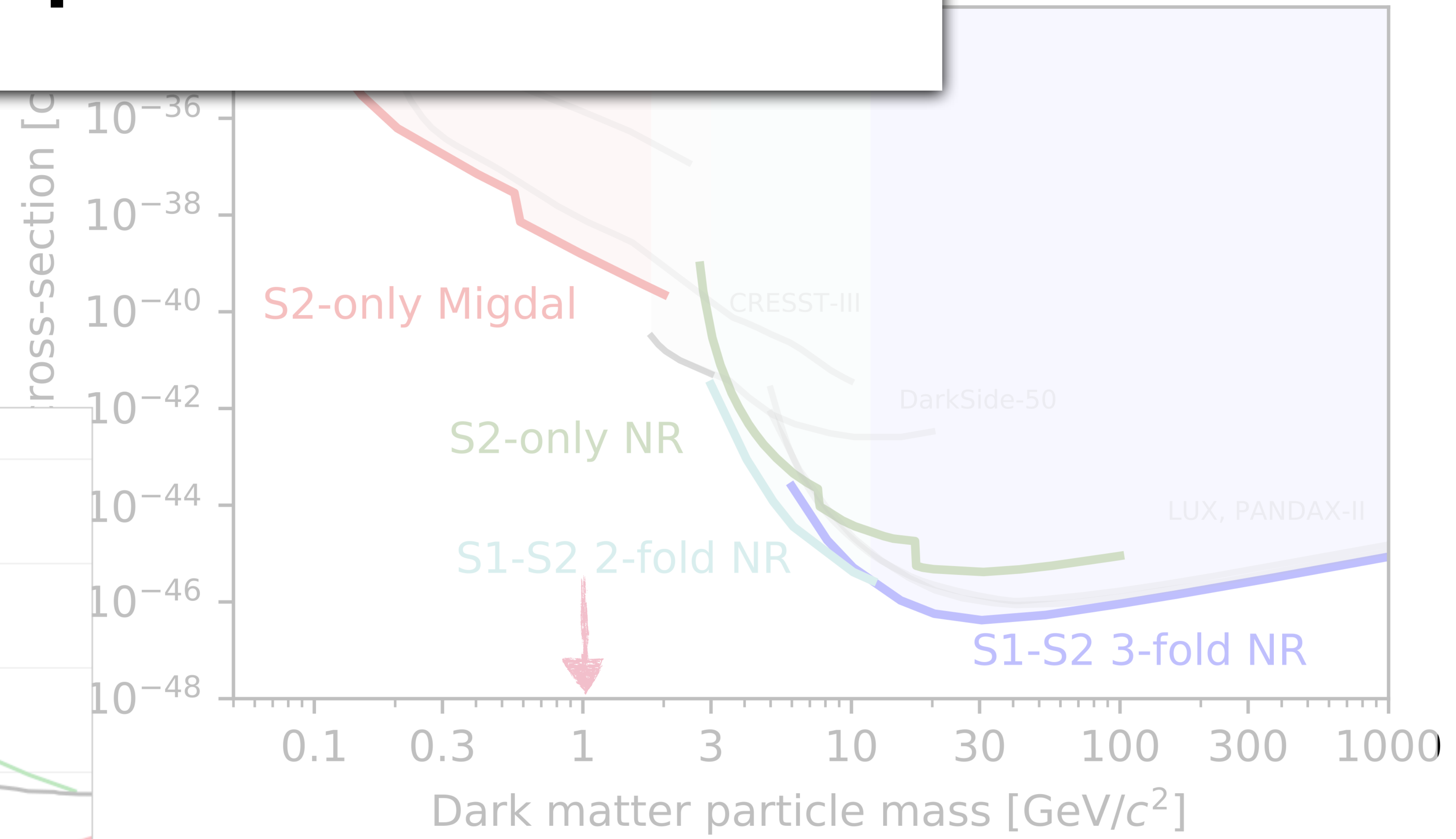
DM-nucleus scattering











Have to read the fine print!

What's the Migdal effect?

Why not using the regular elastic scattering interaction?

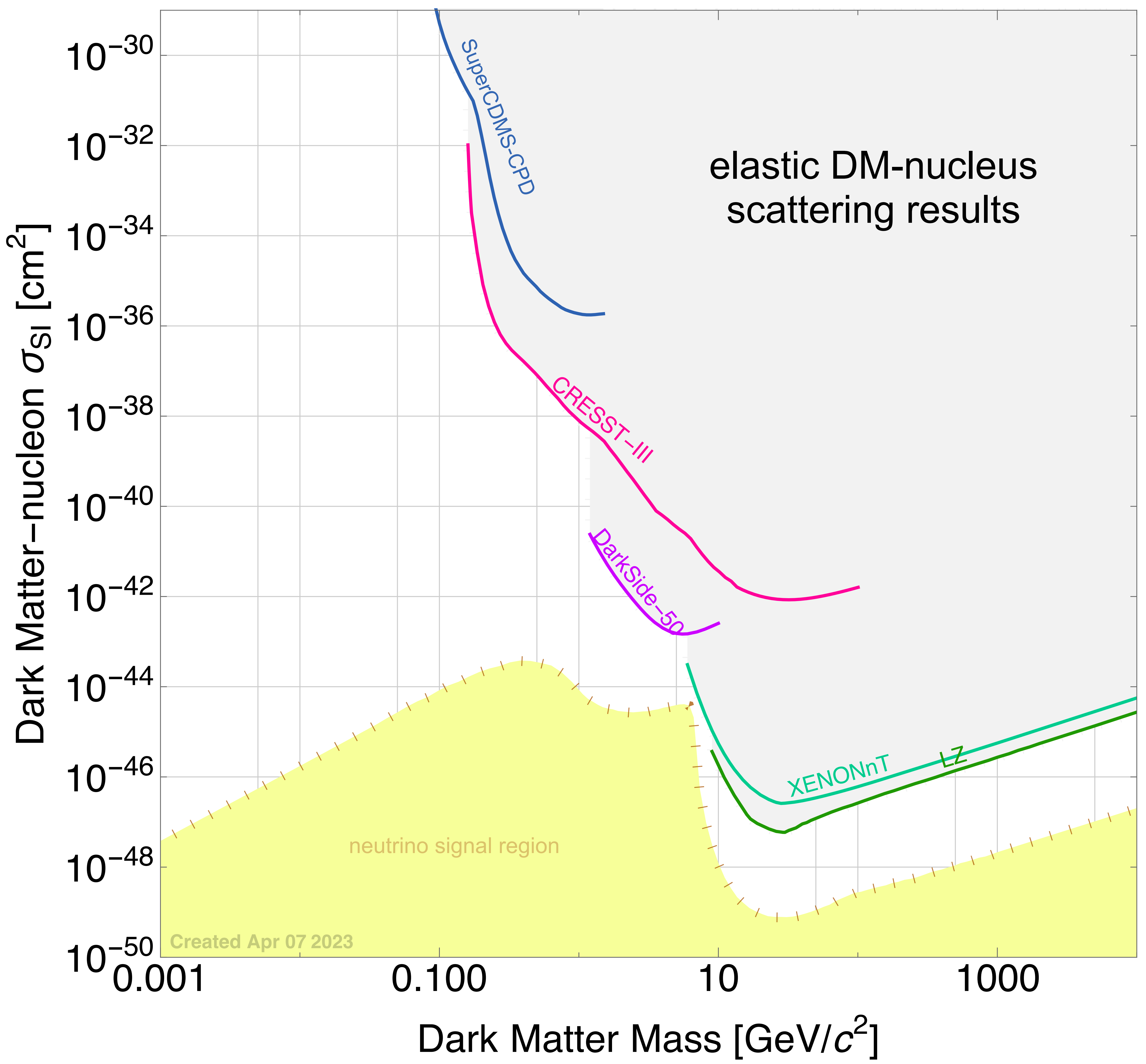
And why the effort in the first place?

What’s the Migdal effect ?

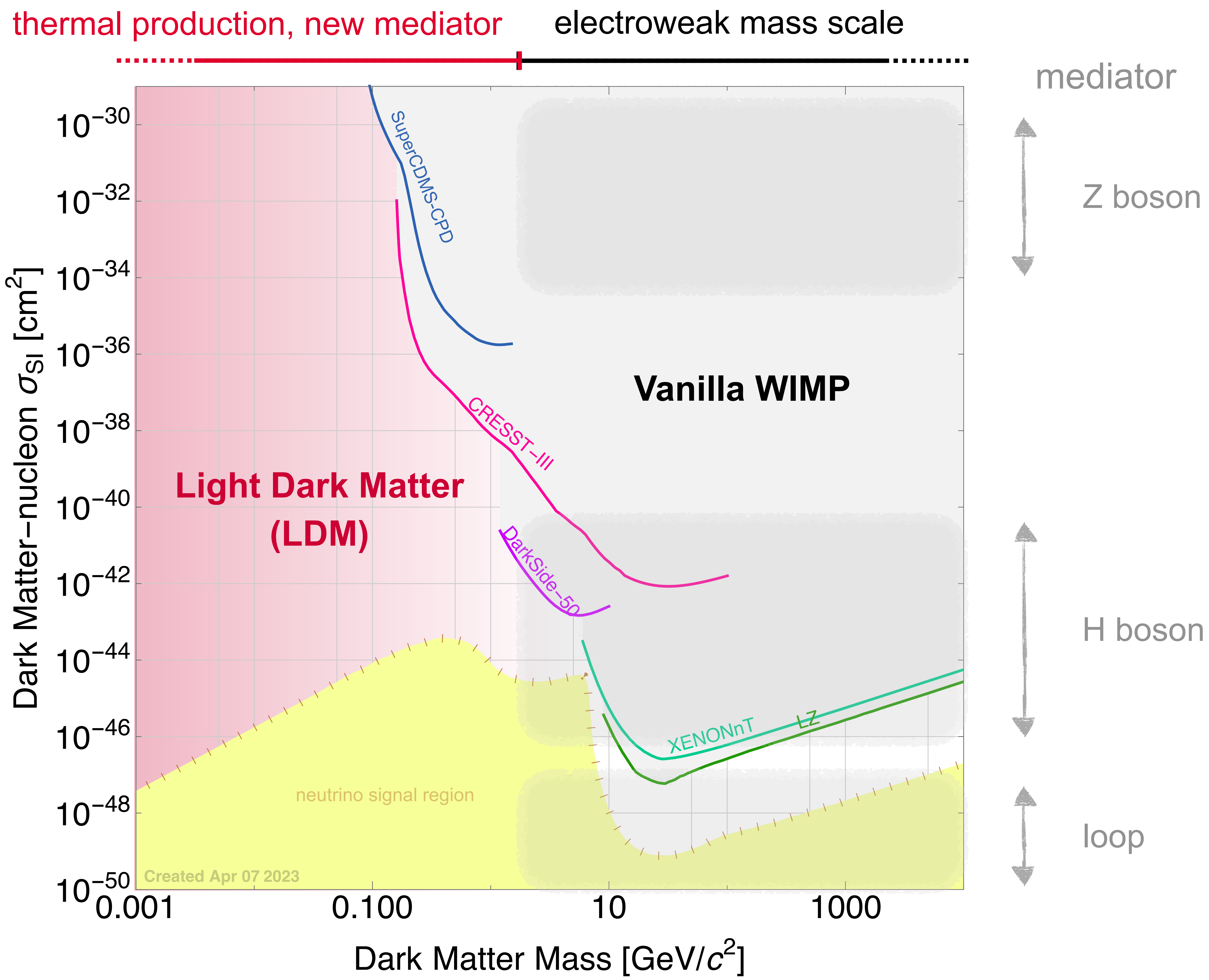
Why not using the regular elastic scattering interaction ?

And why the effort in the first place ?

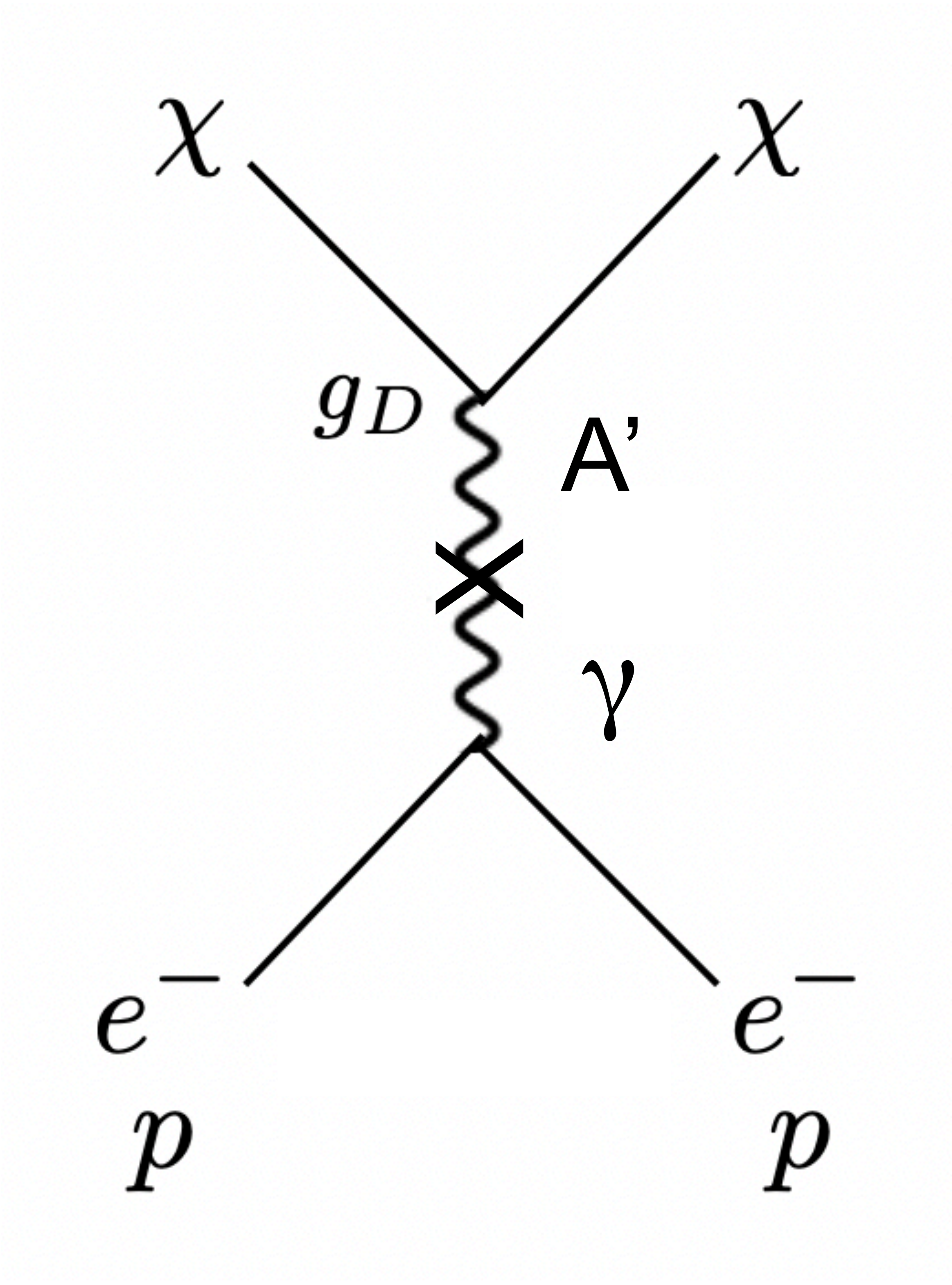
The sub-GeV parameter space



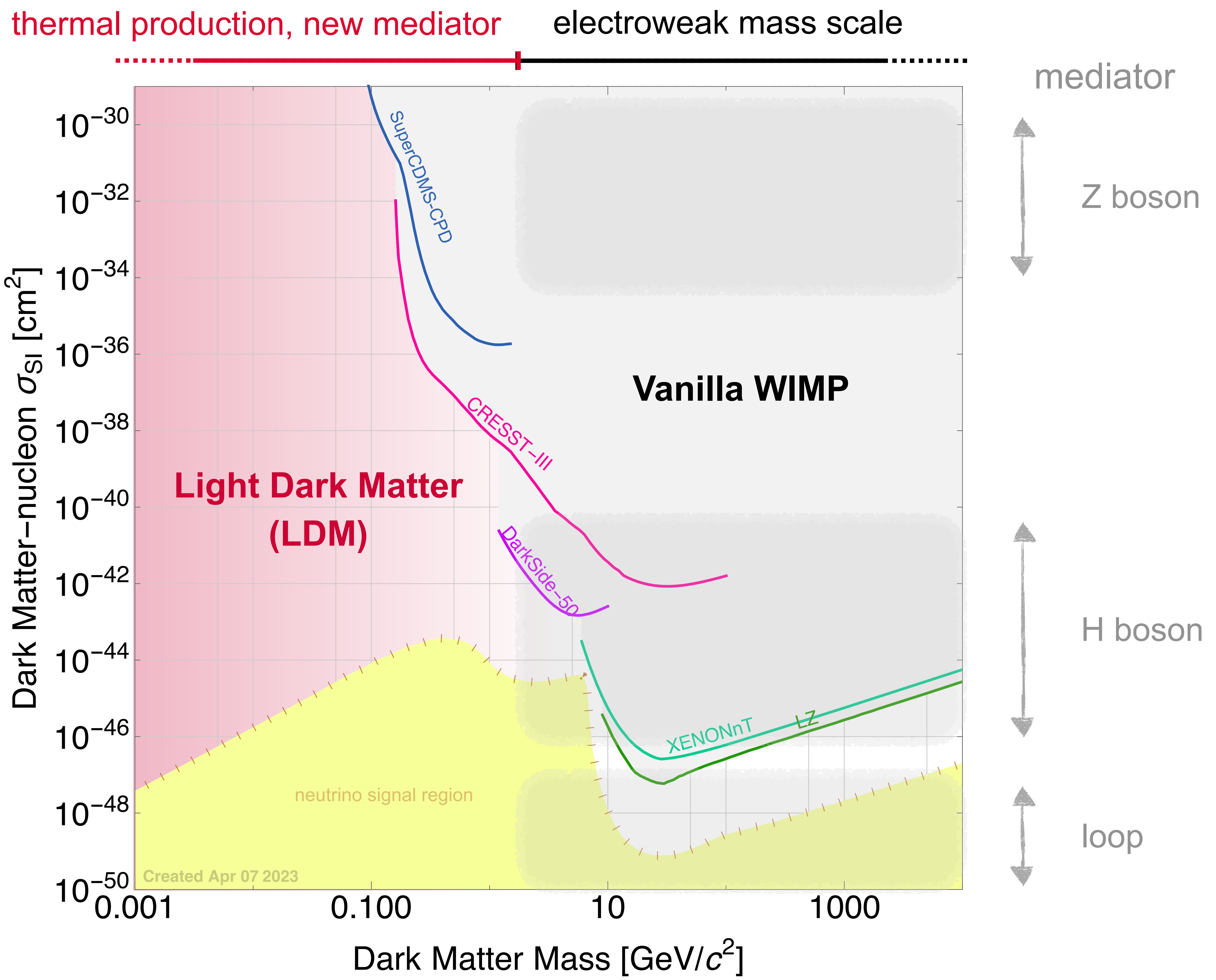
The sub-GeV parameter space



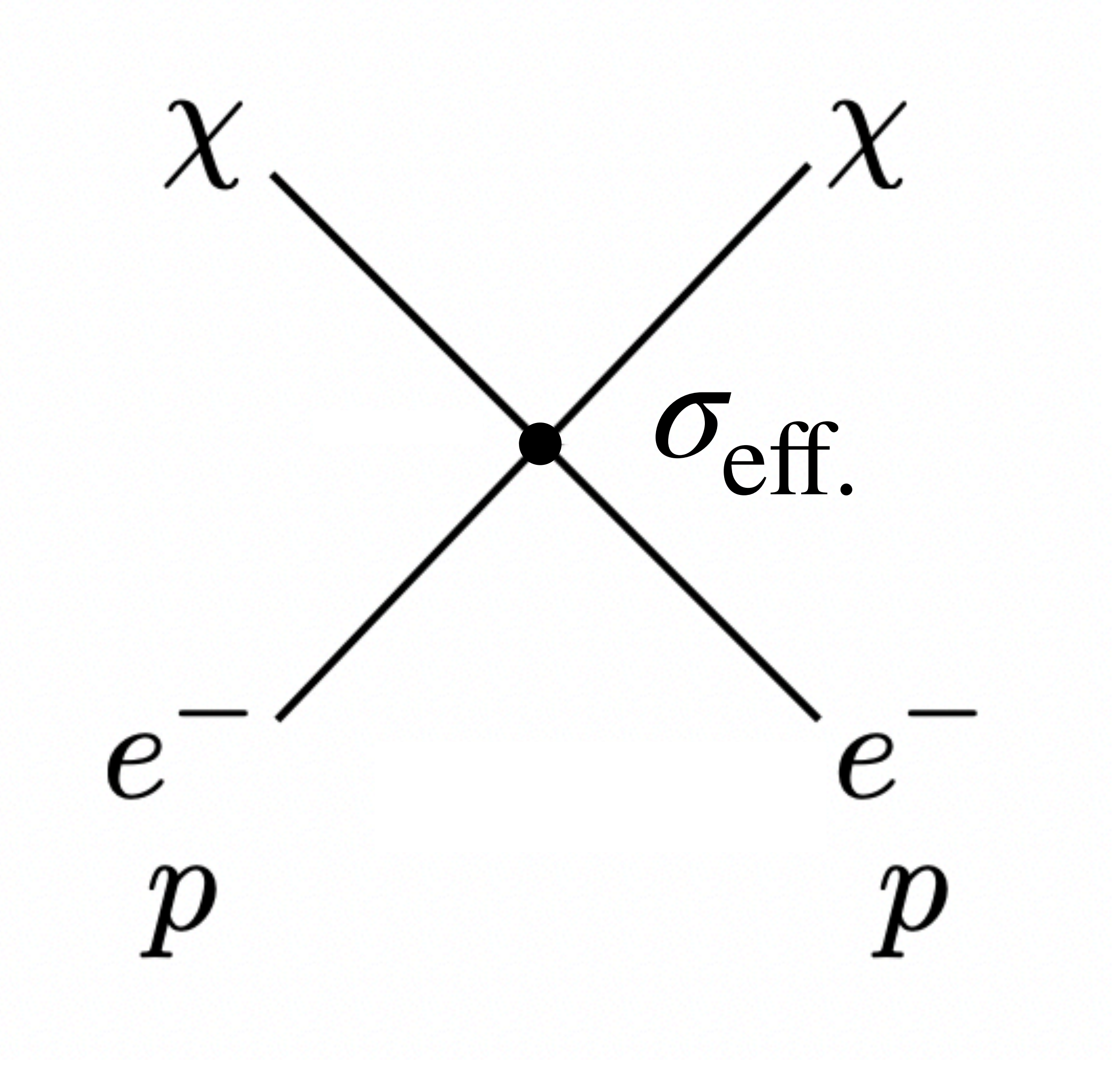
The sub-GeV parameter space



- New mediator, e.g. dark photon A'.
- Coupling to electrons and nuclei via kinetic mixing with SM photon.

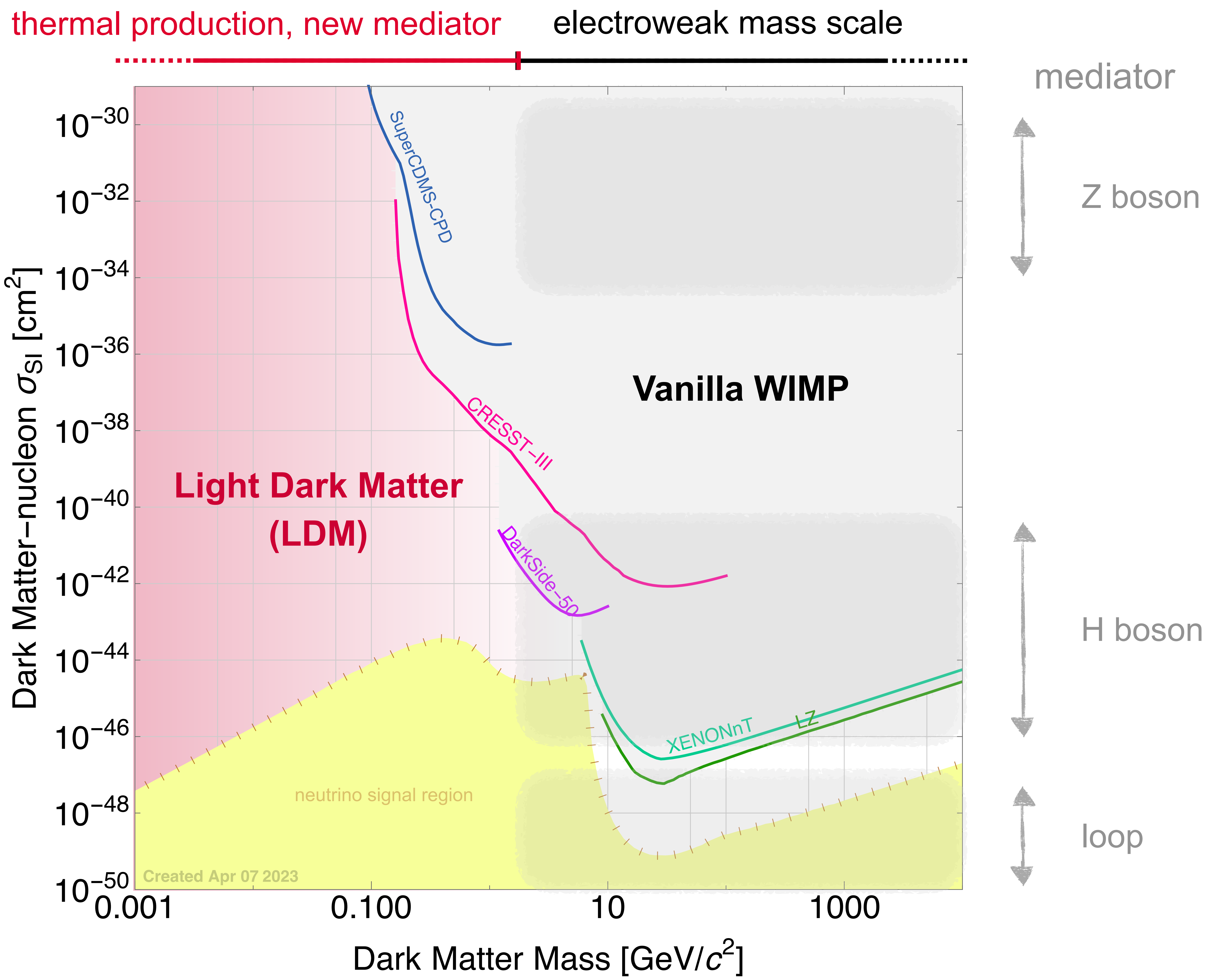


The sub-GeV parameter space



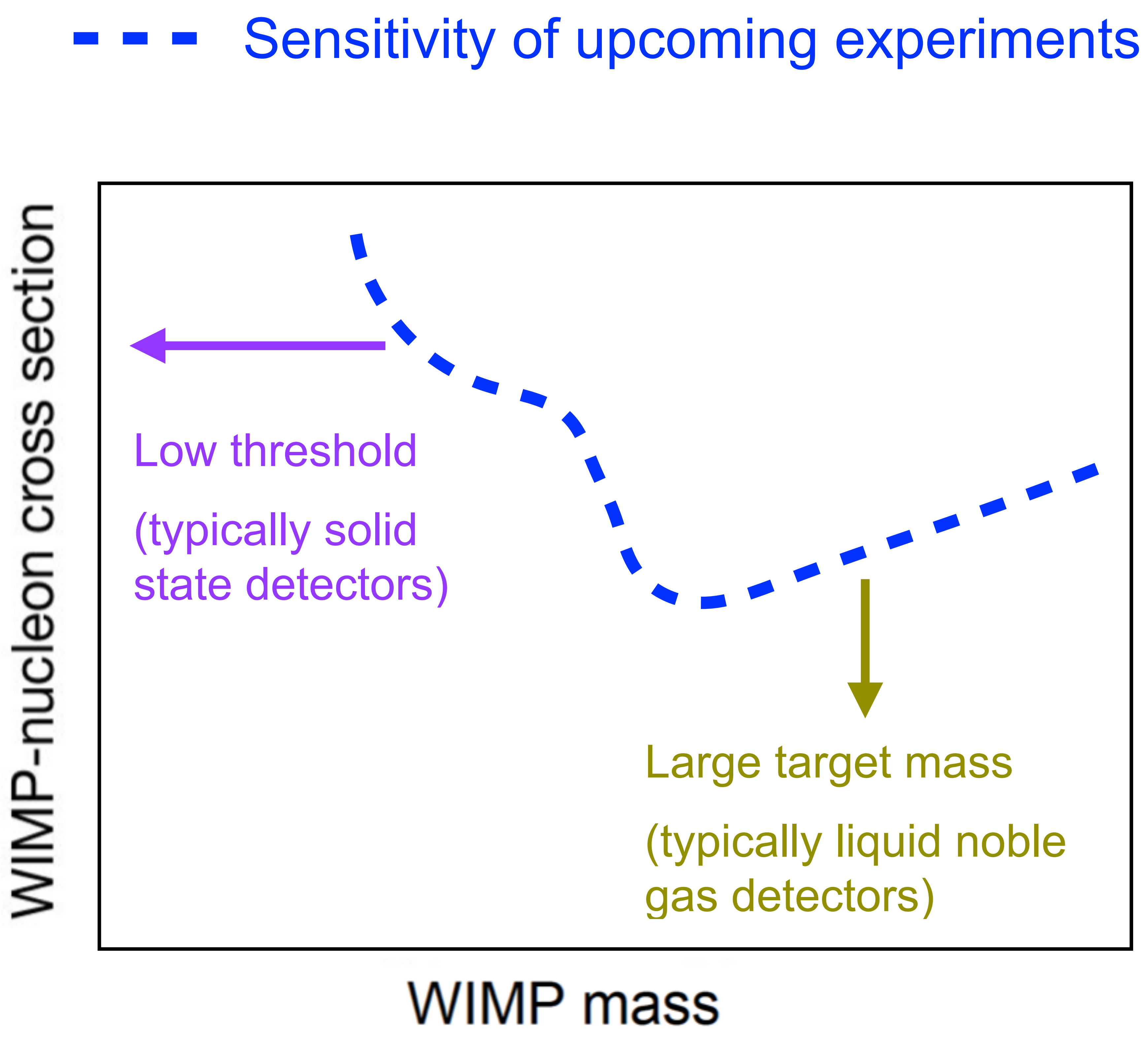
Observable:

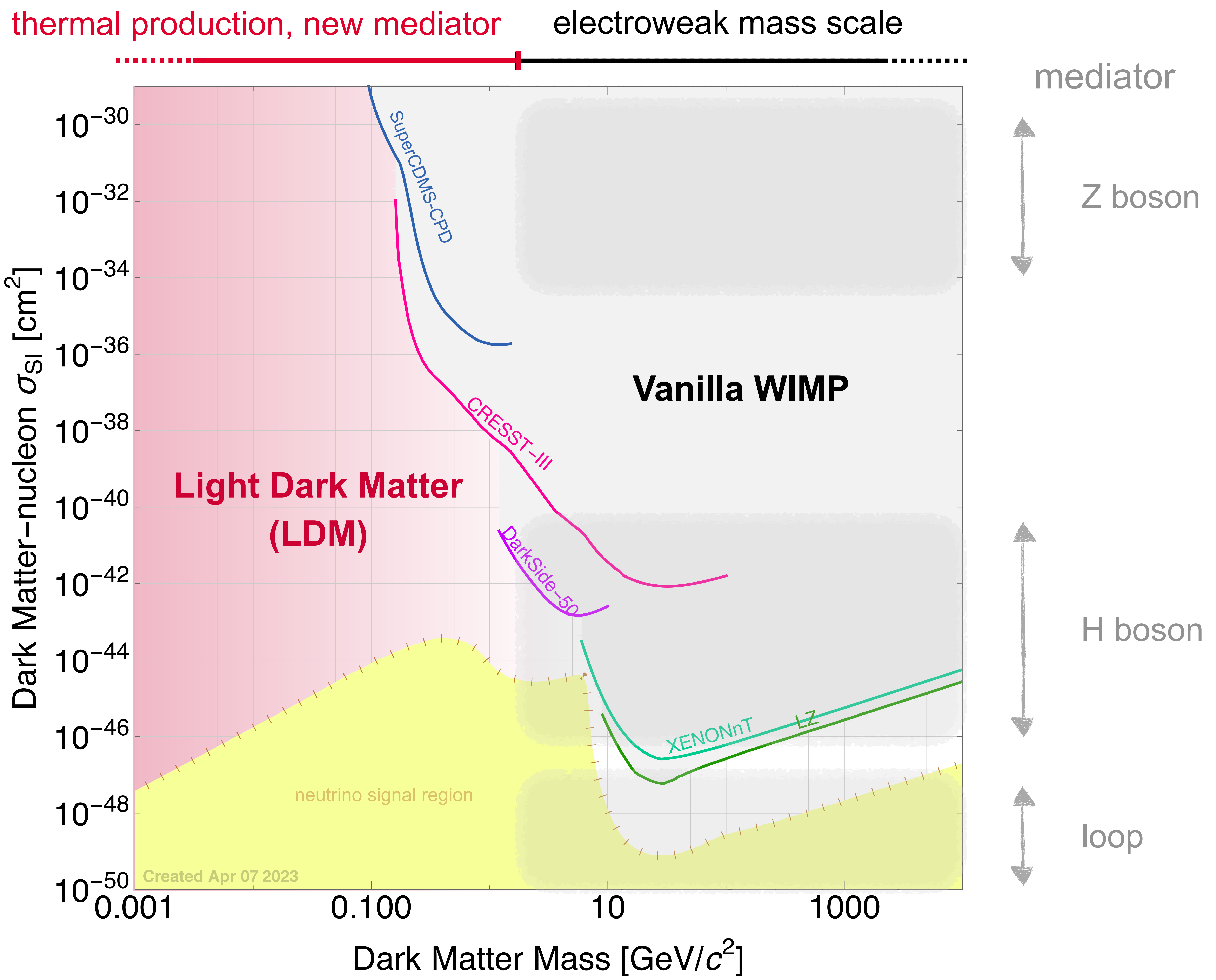
effective interaction cross section.



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

The sub-GeV parameter space



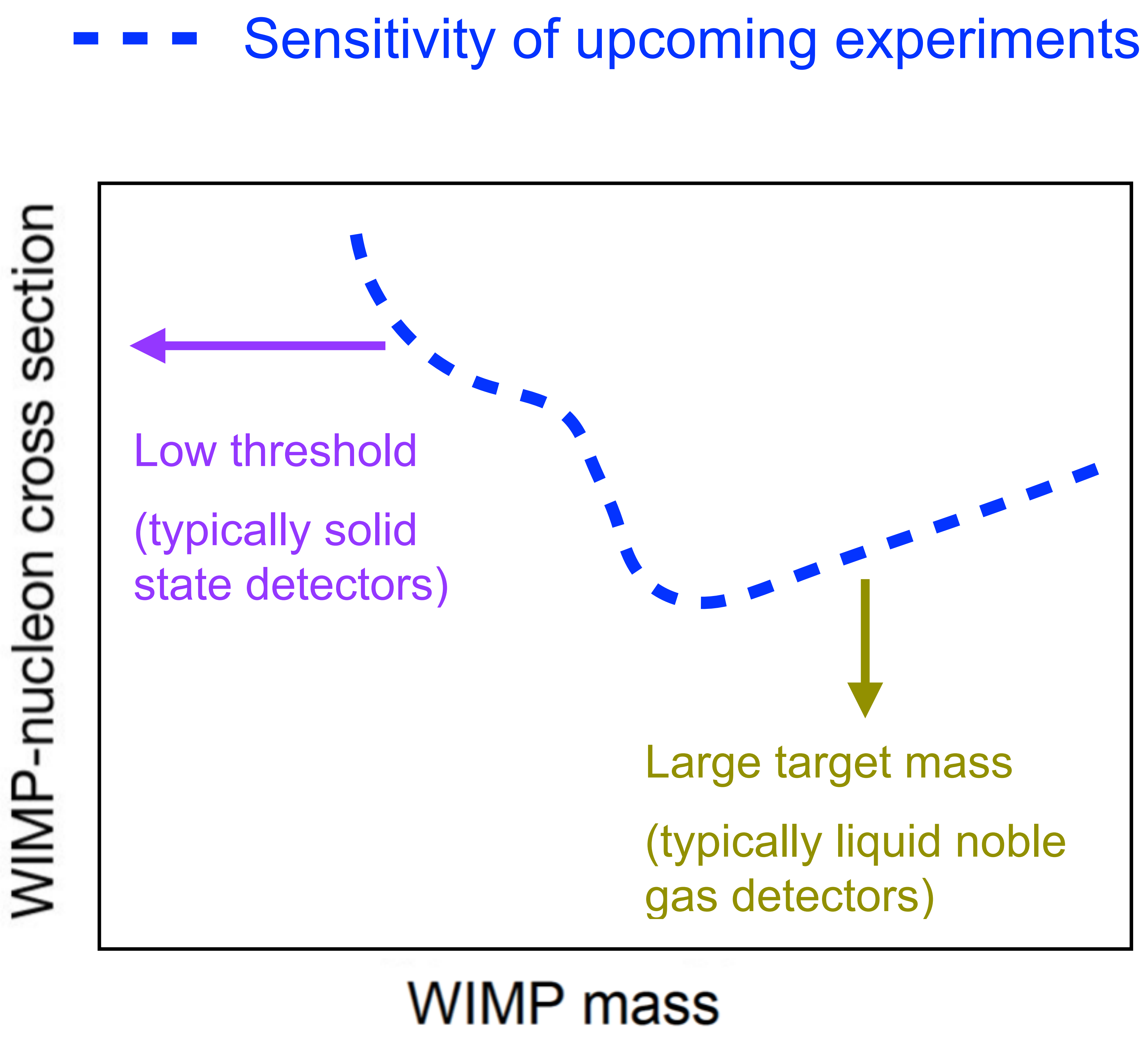


What's the Migdal effect ?

Why not using the regular elastic scattering interaction ?

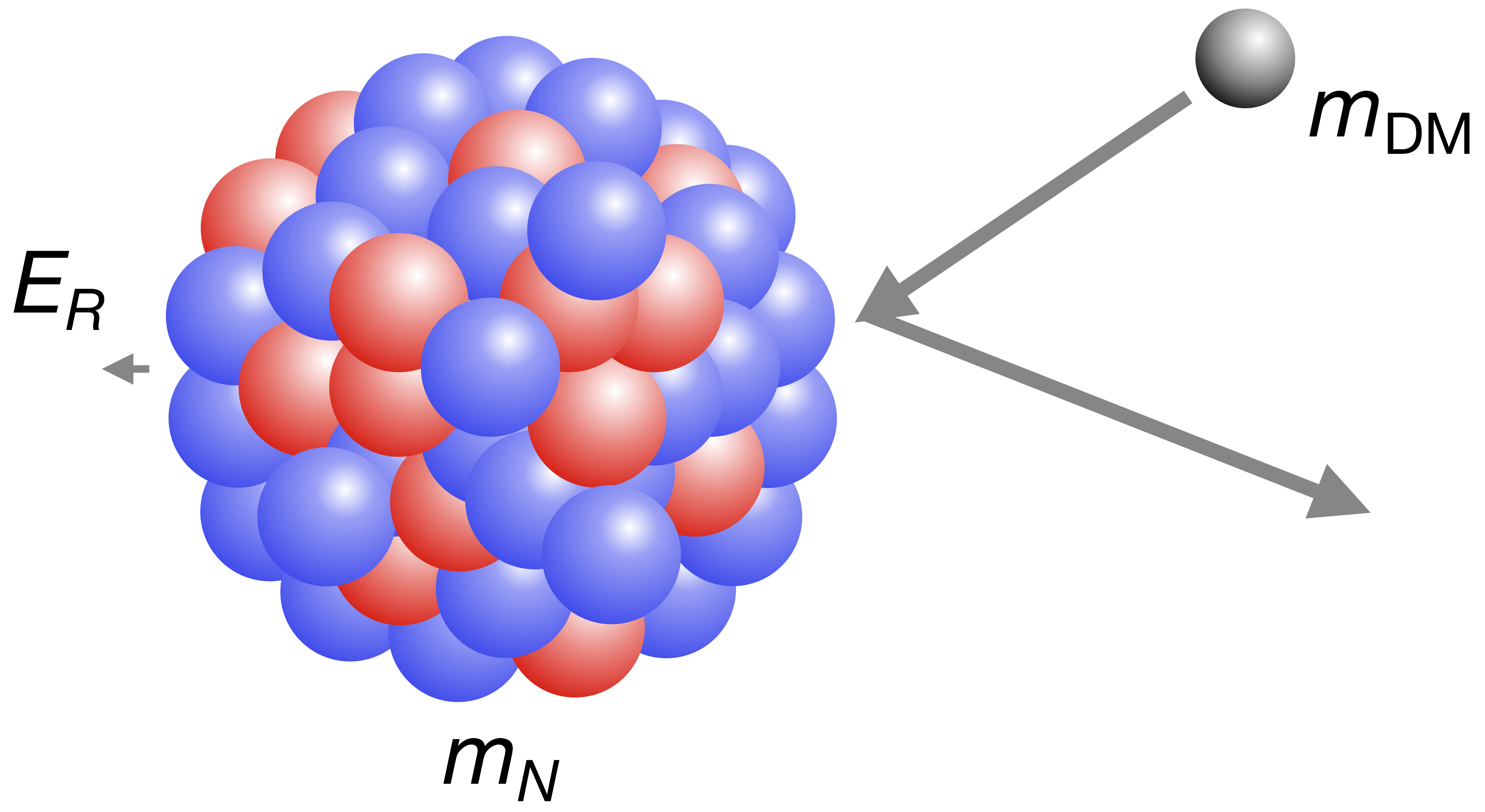
And why the effort in the first place ?

The sub-GeV parameter space



Typical target nuclei:

Xe (54, ~131u), Ge (32, ~73u), Ar (18, ~40u), Si (14, ~28u)



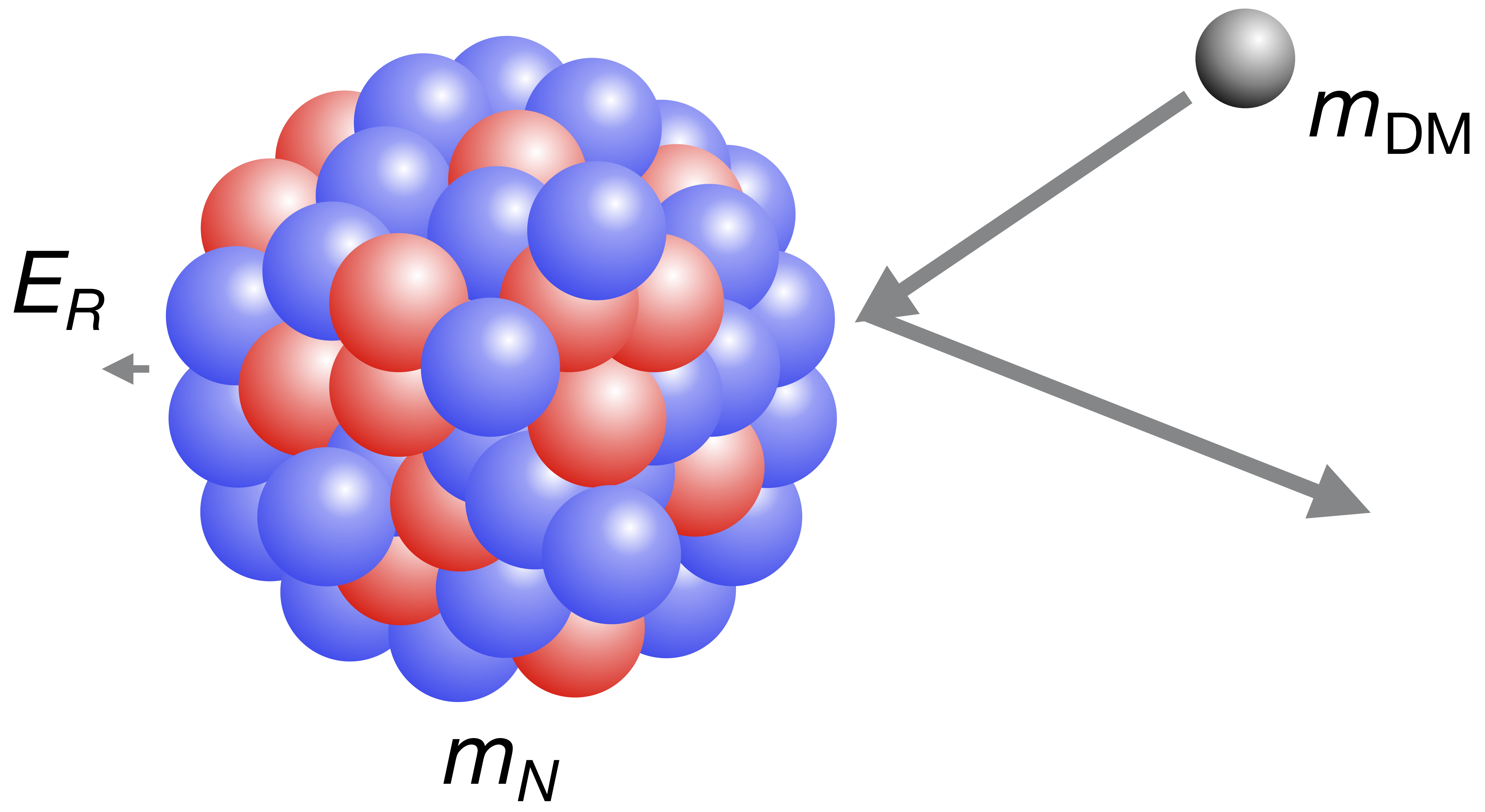
At some point, the nuclear recoil is just way too small… even for ultra-low threshold detectors…

The sub-GeV parameter space

Typical target nuclei:

Xe (54, ~131u), Ge (32, ~73u), Ar (18, ~40u), Si (14, ~28u)

- Possible approaches
  - Alternate interaction channels in existing and upcoming experiments.
  - Alternate target materials in new experiments.
  - A combination of both.



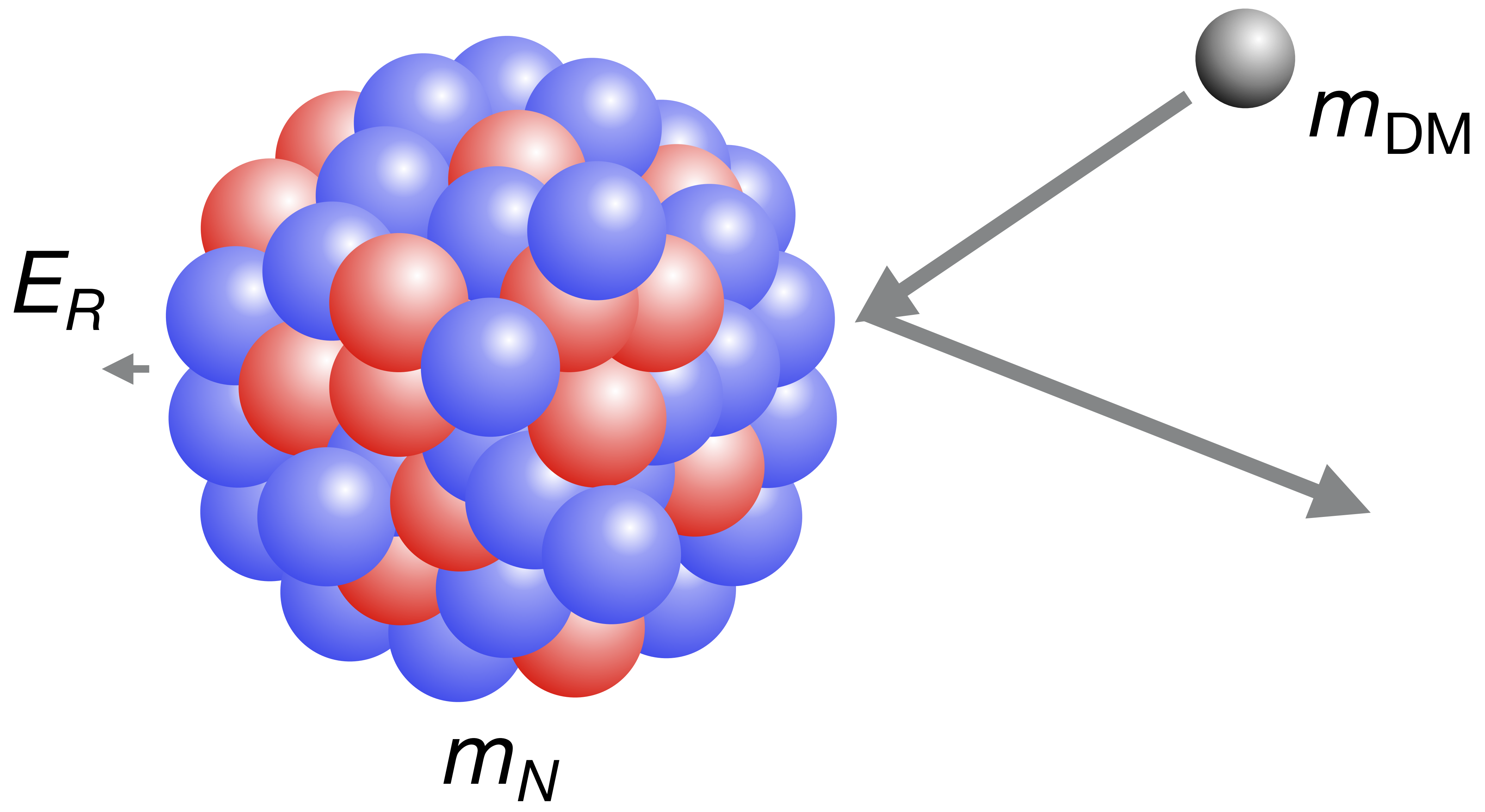
At some point, the nuclear recoil is just way too small… even for ultra-low threshold detectors…

The sub-GeV parameter space

Typical target nuclei:

Xe (54, ~131u), Ge (32, ~73u), Ar (18, ~40u), Si (14, ~28u)

- Possible approaches
  - Alternate interaction channels in existing and upcoming experiments.
  - Alternate target materials in new experiments.
  - A combination of both.



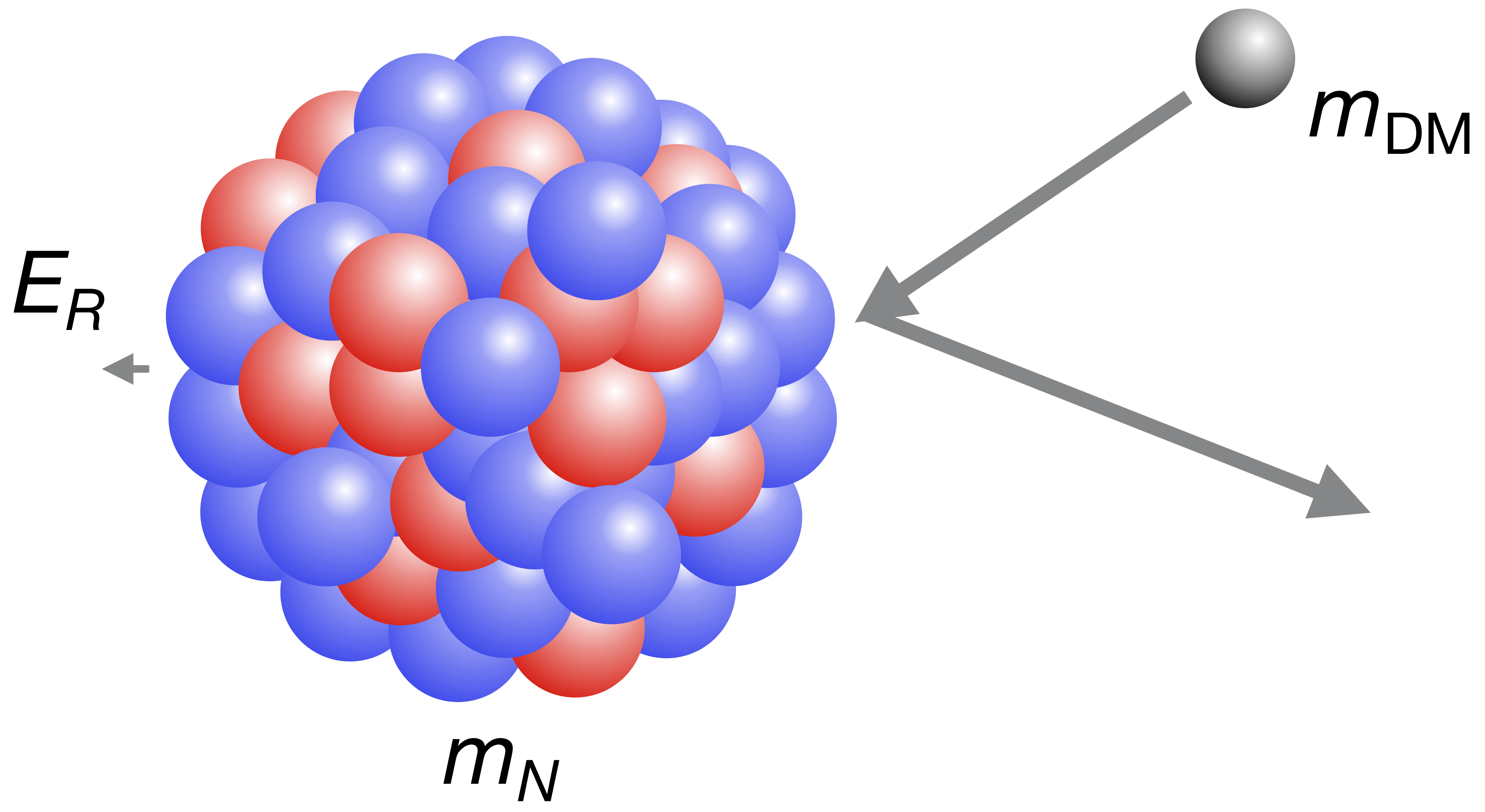
At some point, the nuclear recoil is just way too small… even for ultra-low threshold detectors…

The sub-GeV parameter space

Typical target nuclei:

Xe (54, ~131u), Ge (32, ~73u), Ar (18, ~40u), Si (14, ~28u)

- Possible approaches *this lecture*
  - Alternate interaction channels in existing and upcoming experiments.
  - Alternate target materials in new experiments. DELight
  - A combination of both.



At some point, the nuclear recoil is just way too small… even for ultra-low threshold detectors…

The sub-GeV parameter space

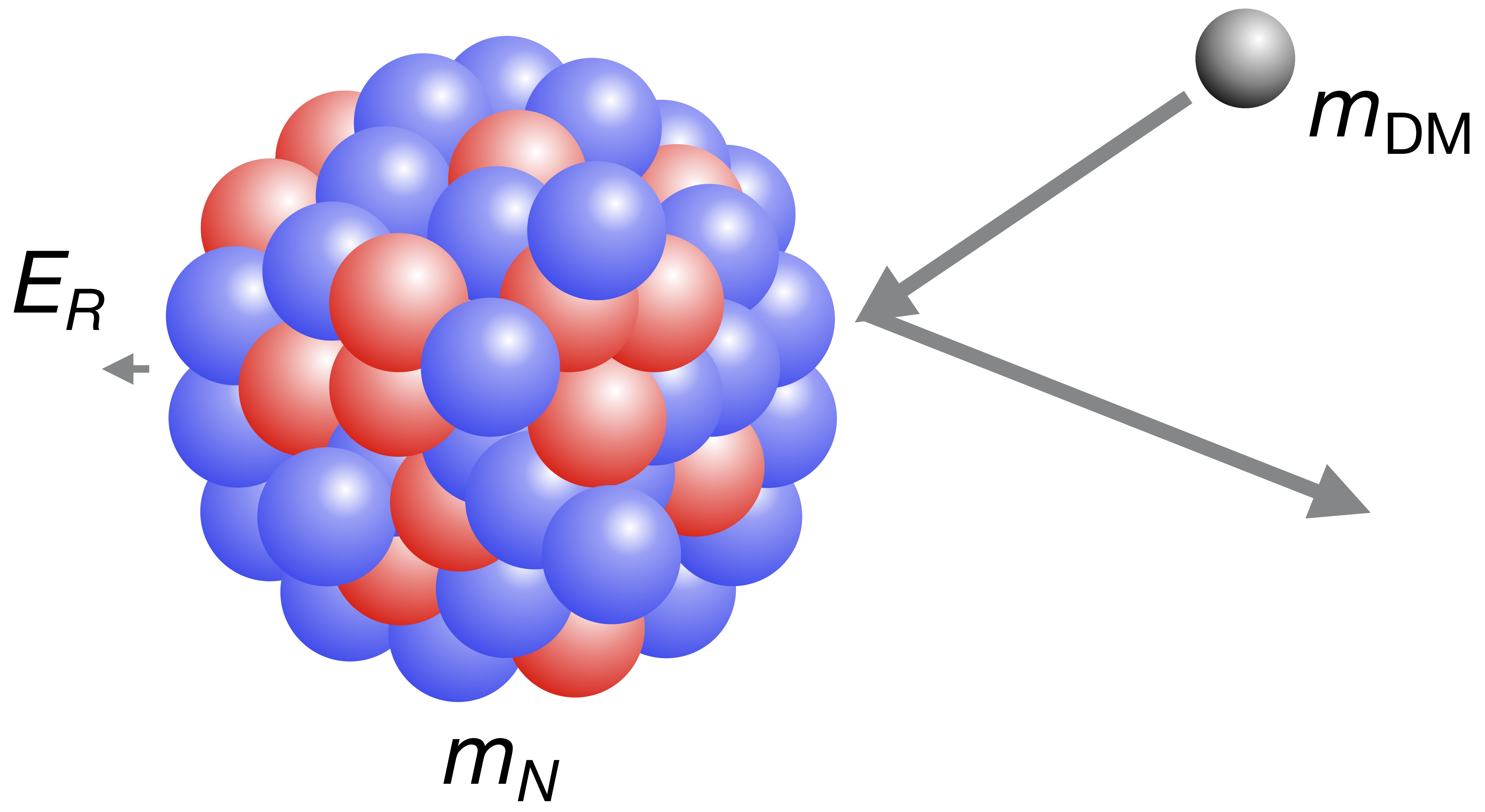
Typical target nuclei:

Xe (54, ~131u), Ge (32, ~73u), Ar (18, ~40u), Si (14, ~28u)

- Possible approaches
  - Alternate interaction channels in existing and upcoming experiments.

this lecture

    - "Bremsstrahlung"
    - Migdal effect
    - DM-electron scattering
    - (Bosonic absorption)



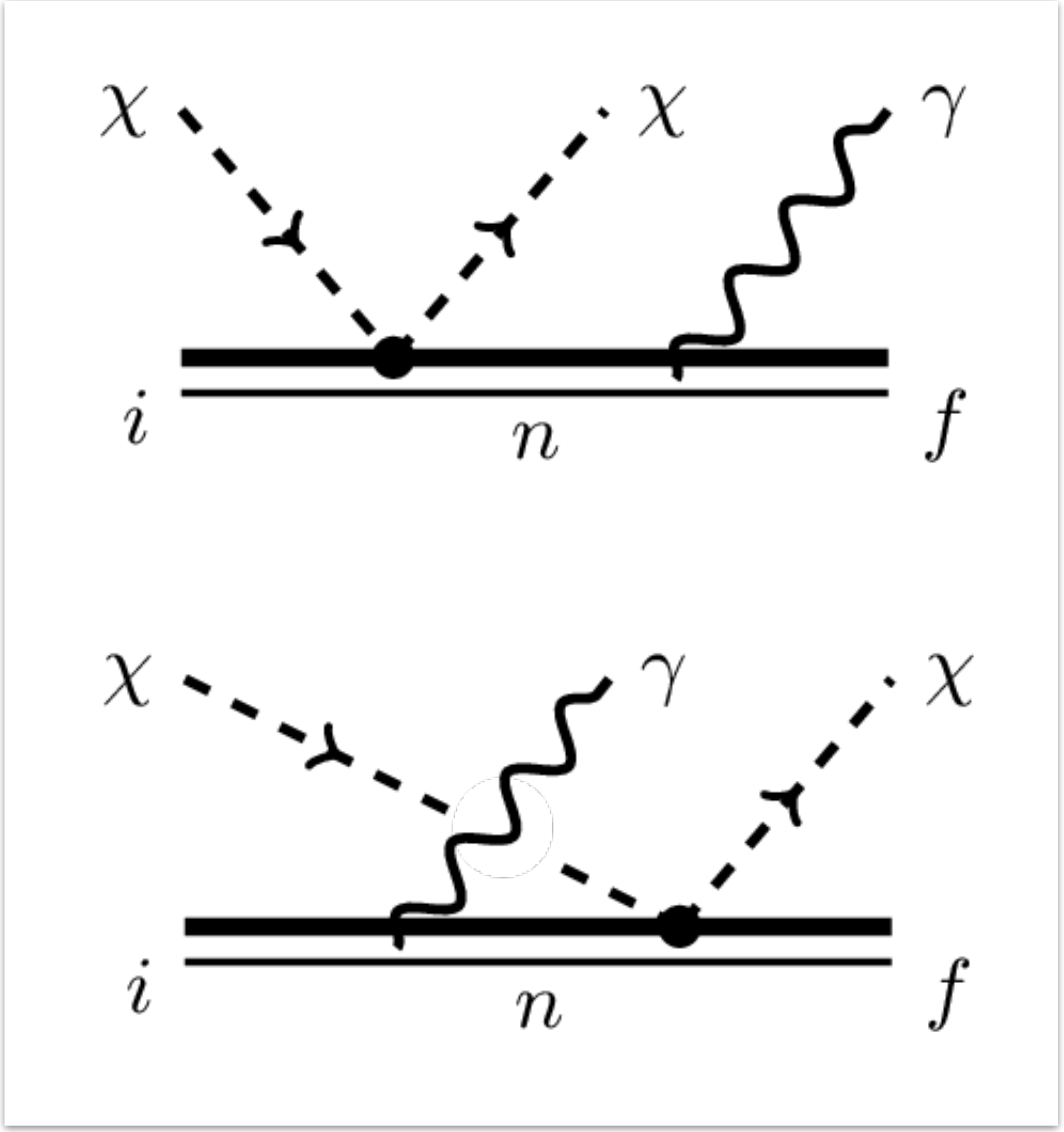
At some point, the nuclear recoil is just way too small… even for ultra-low threshold detectors…

The sub-GeV parameter space

“Bremsstrahlung”
(inelastic DM-n scattering)

Initial state radiation, final state radiation

C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)

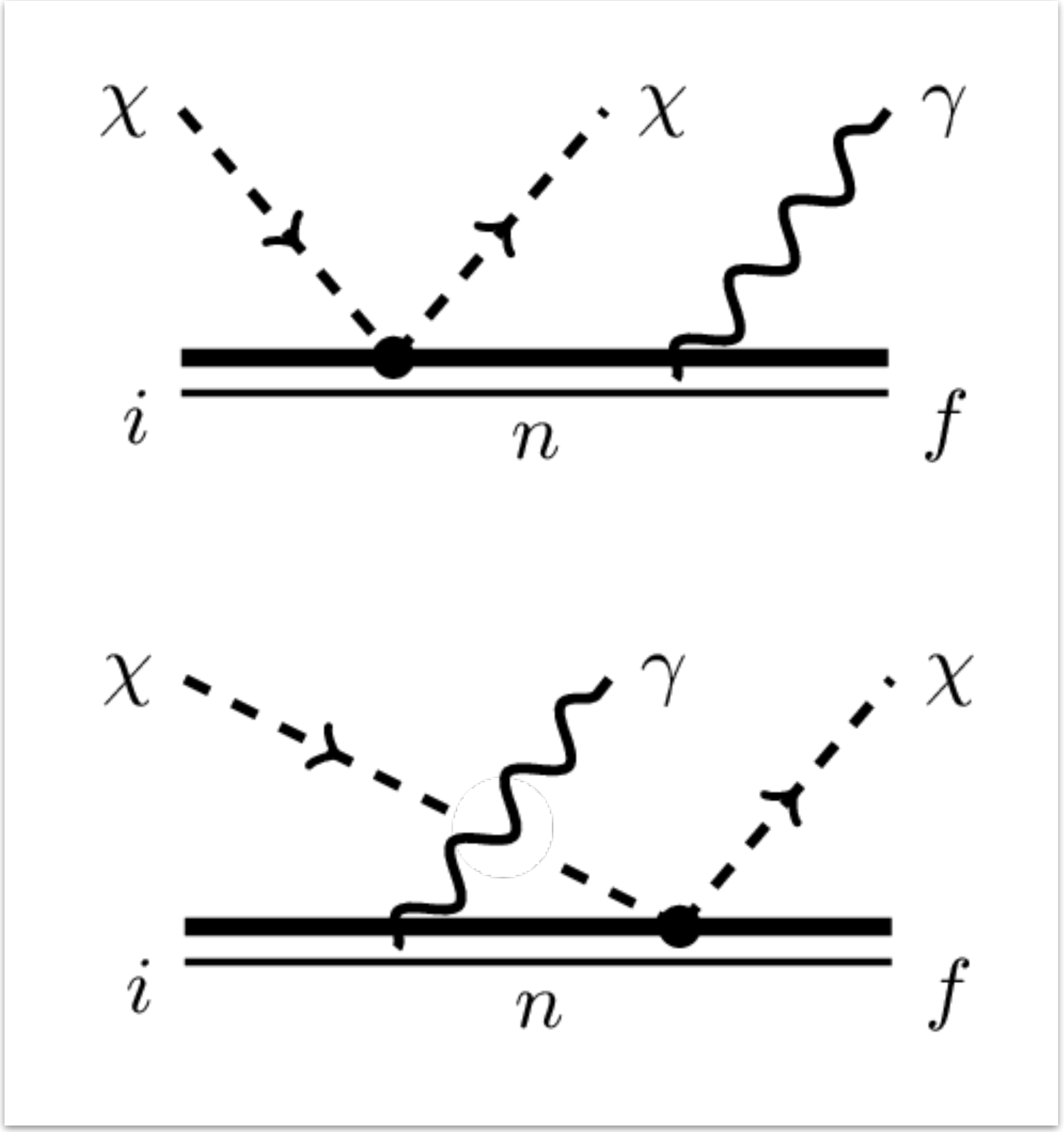


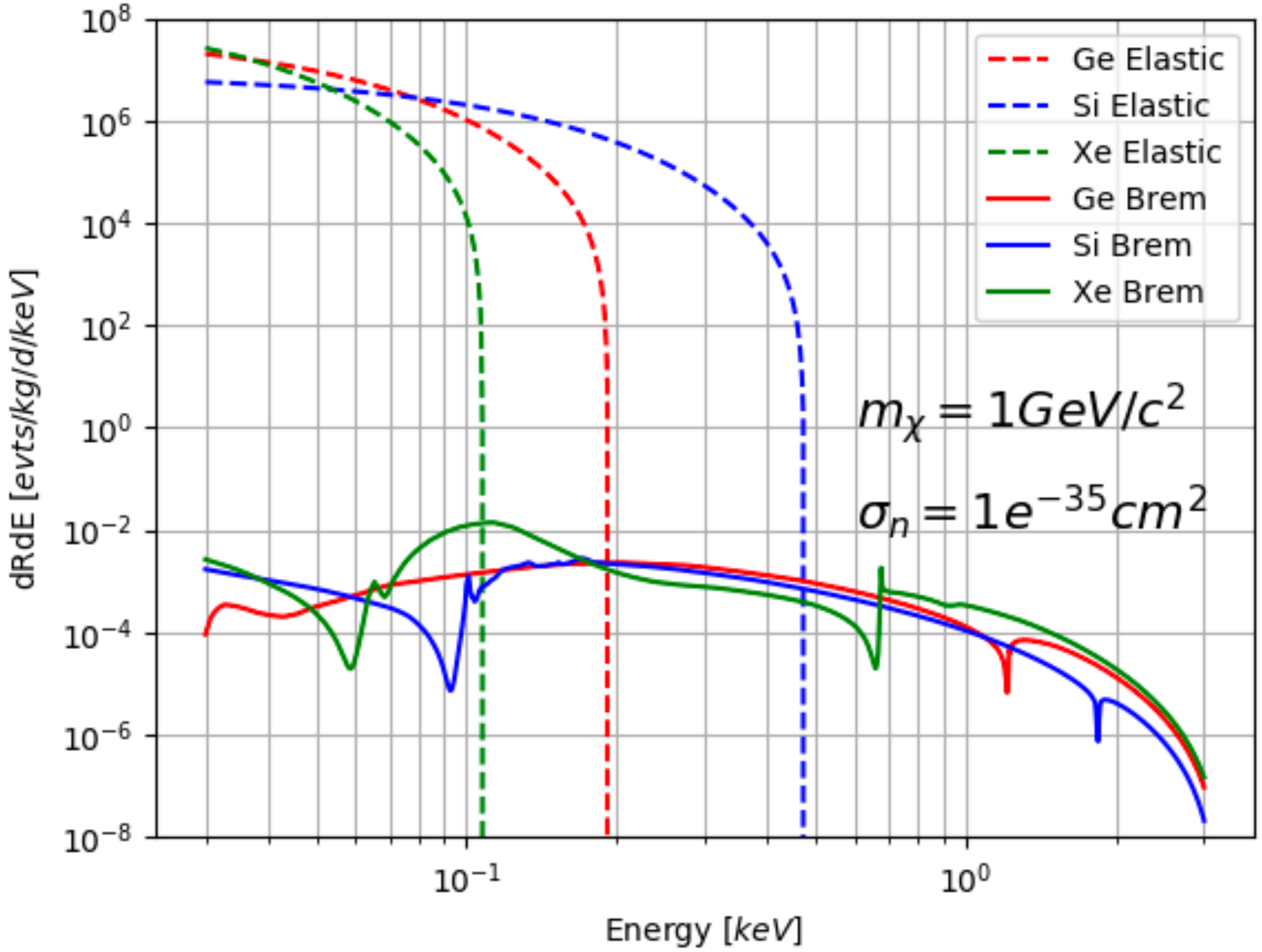
Target nuclei are not isolated!

They are part of an atom.

Initial state radiation, final state radiation

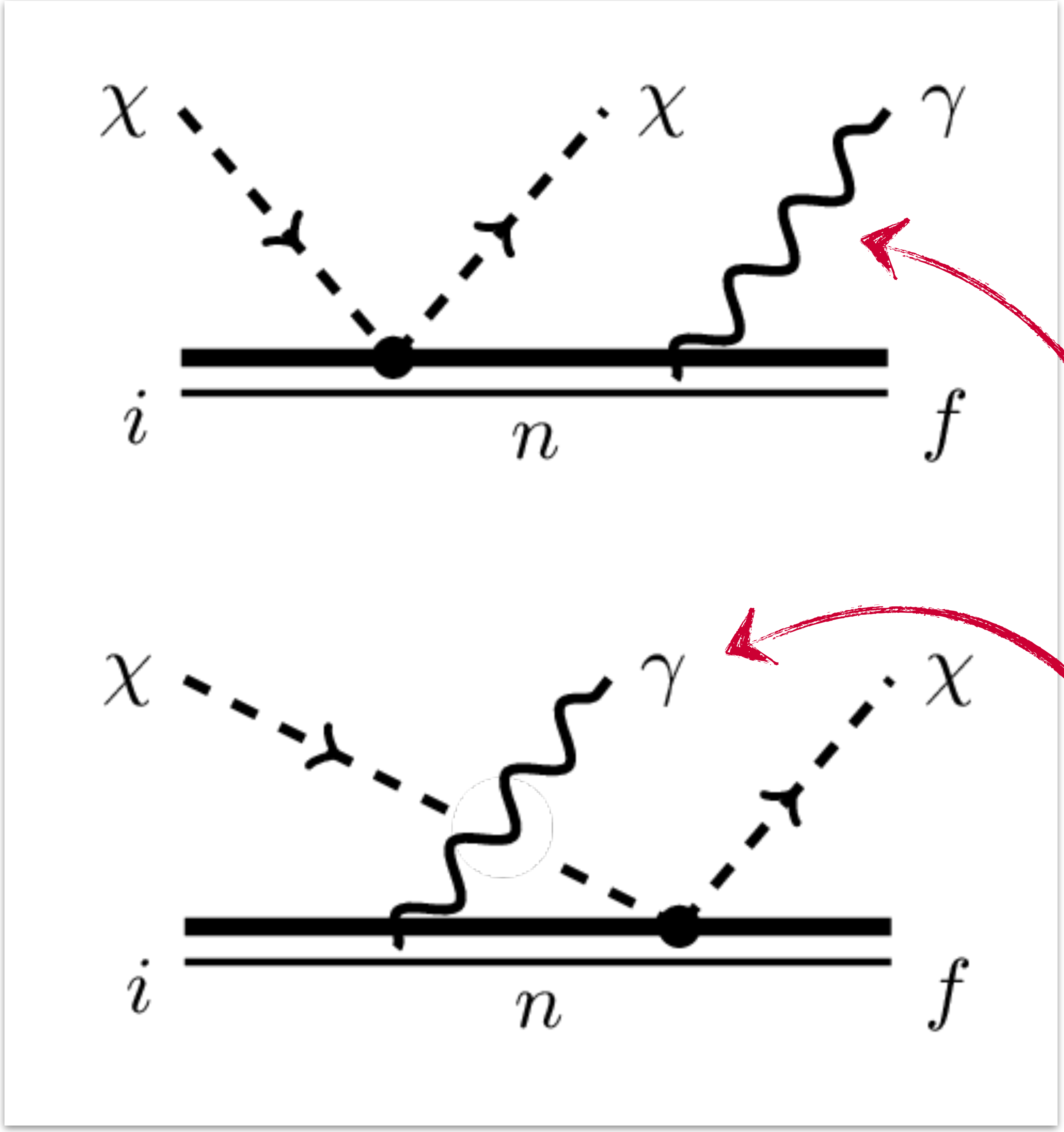
C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)

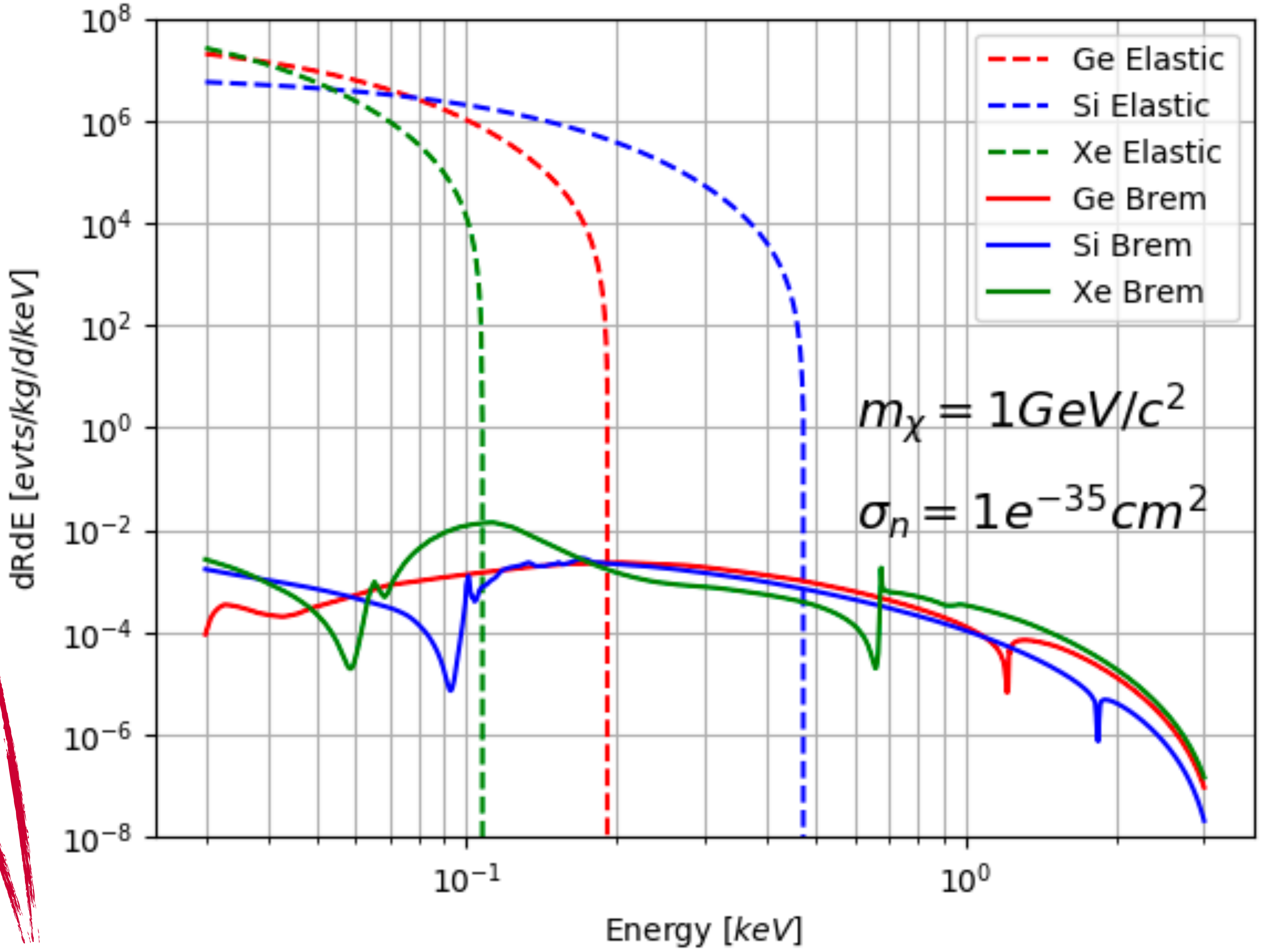




Initial state radiation, final state radiation

C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)



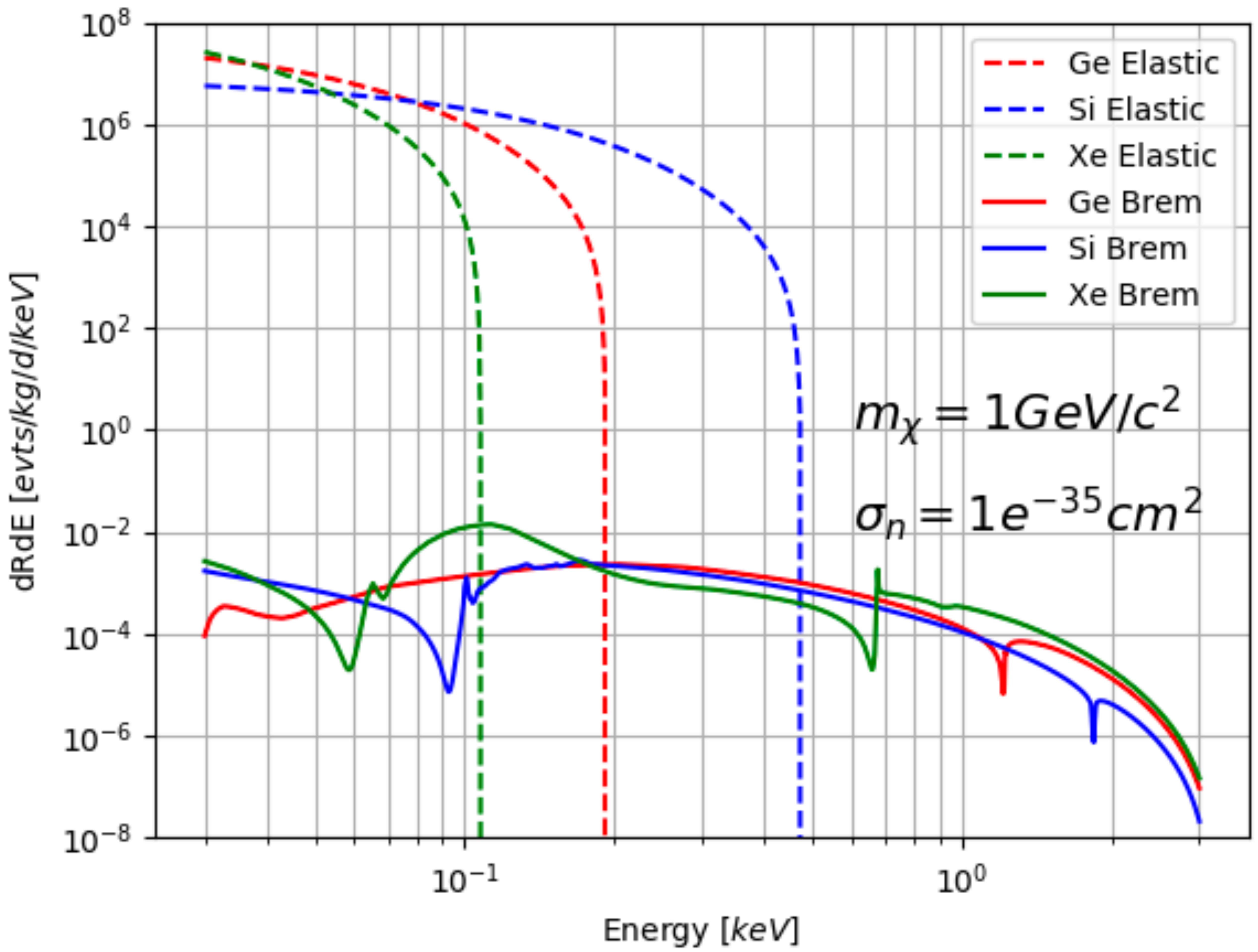


observe this

Initial state radiation, final state radiation

C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)

$$\frac{d\sigma}{dE_\gamma} = \frac{4\alpha\,|f(E_\gamma)|^2}{3\pi E_\gamma}\frac{\mu^2 v^2 \sigma_0^{\mathrm{SI}}}{m_N^2}\sqrt{1-\frac{2E_\gamma}{\mu v^2}}\left(1-\frac{E_\gamma}{\mu v^2}\right)$$



Initial state radiation, final state radiation

C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)

$$\frac{d\sigma}{dE_\gamma} = \frac{4\alpha\,|f(E_\gamma)|^2}{3\pi E_\gamma} \frac{\mu^2 v^2 \sigma_0^{\mathrm{SI}}}{m_N^2} \sqrt{1 - \frac{2E_\gamma}{\mu v^2}} \left(1 - \frac{E_\gamma}{\mu v^2}\right)$$

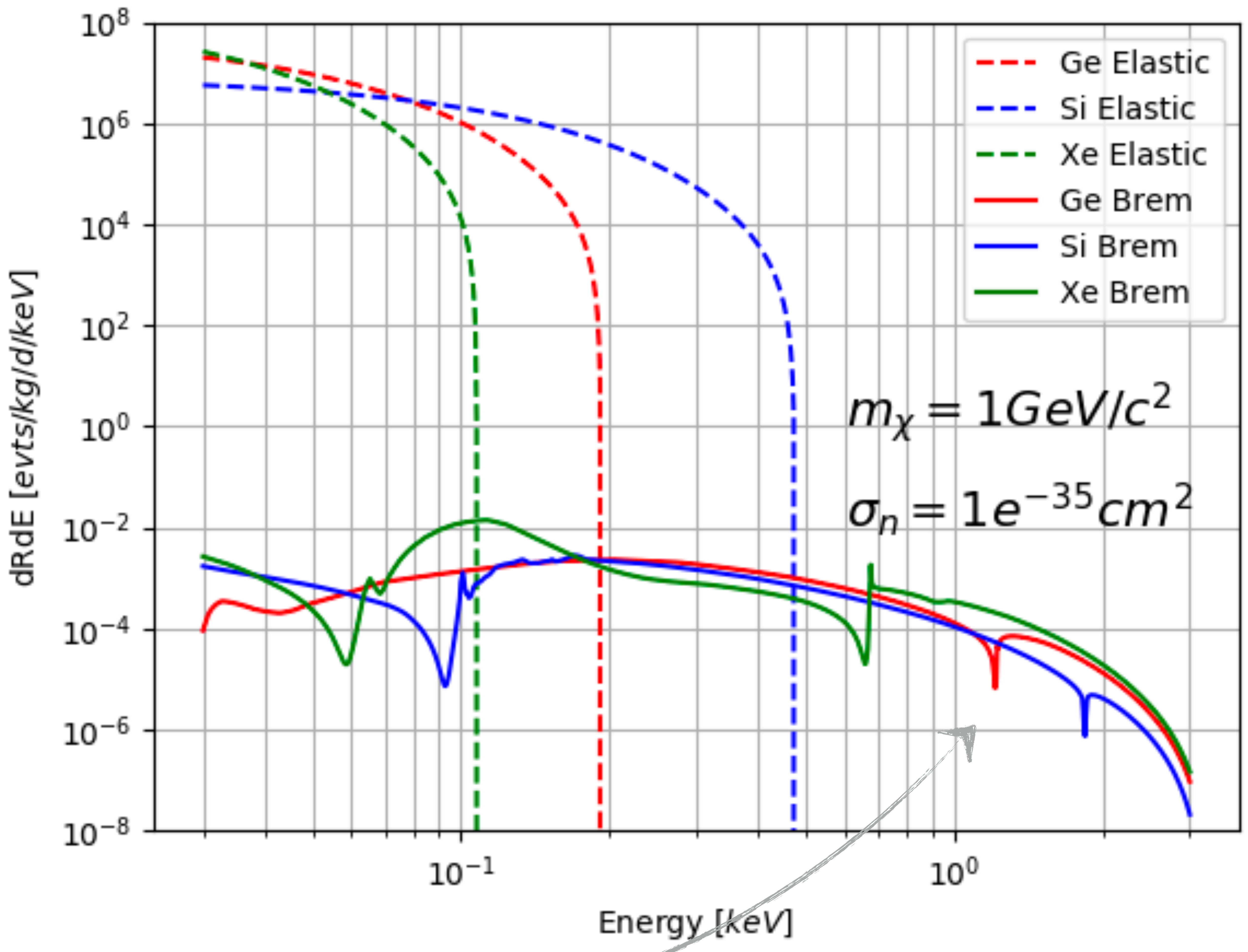
Atomic scattering function *f* :

$$|f|^2 = |f_1 + i f_2|^2 = f_1^2 + f_2^2$$

$$f_2(E_\gamma) = \frac{\sigma_{\mathrm{p.e.}}(E_\gamma)}{2 r_e \lambda}$$

$$f_1(E_\gamma) = Z^* + \frac{1}{\pi r_e h c} \mathscr{P} \int_0^\infty \frac{E_\gamma'^2 \sigma_{\mathrm{p.e.}}(E_\gamma')}{E_\gamma^2 - E_\gamma'^2} dE_\gamma' .$$

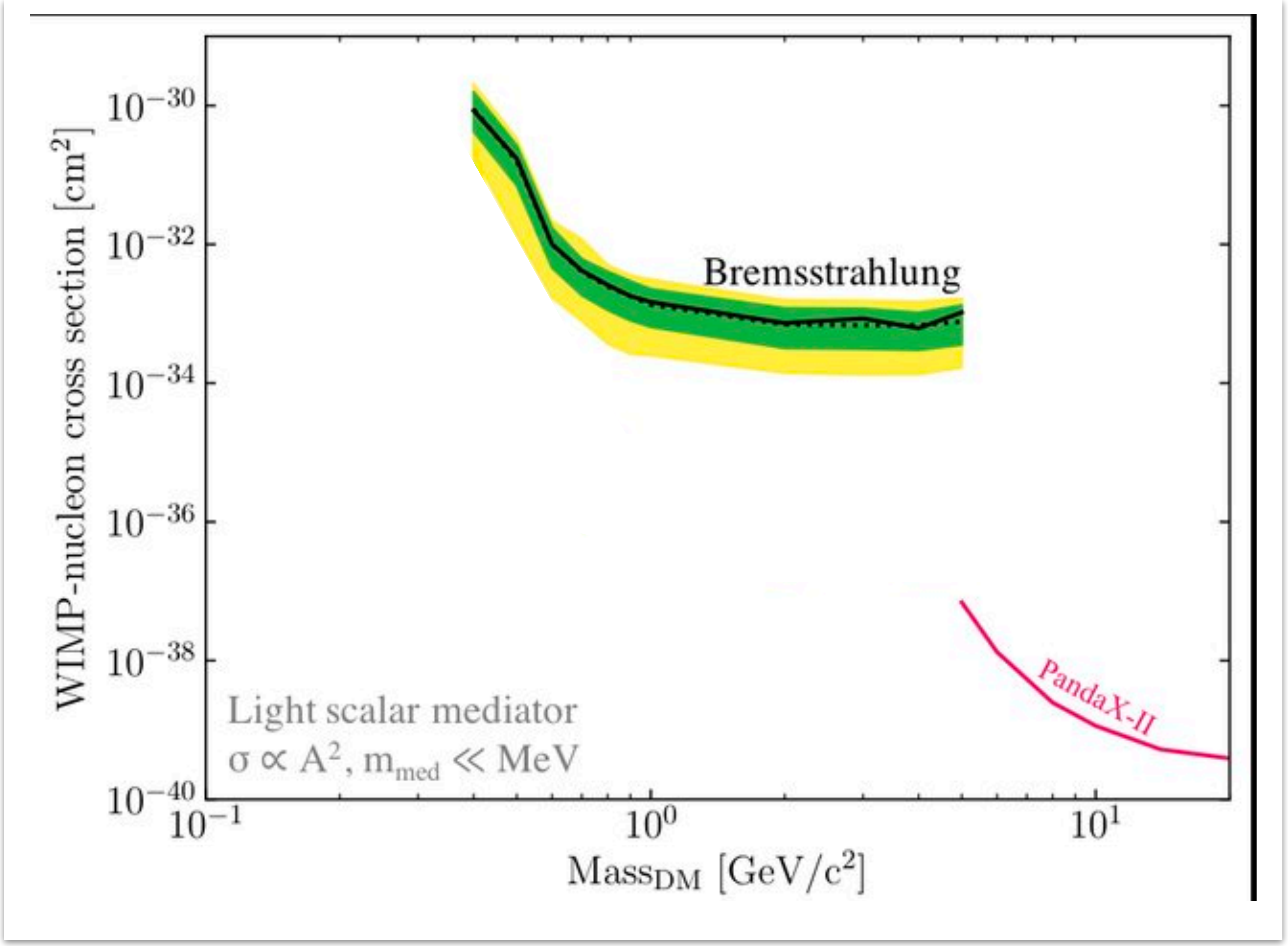
with photoelectric absorption cross section $\sigma_{\mathrm{p.e.}}$.



causes sub-structure (FYI)

Extended sensitivity due to Bremsstrahlung

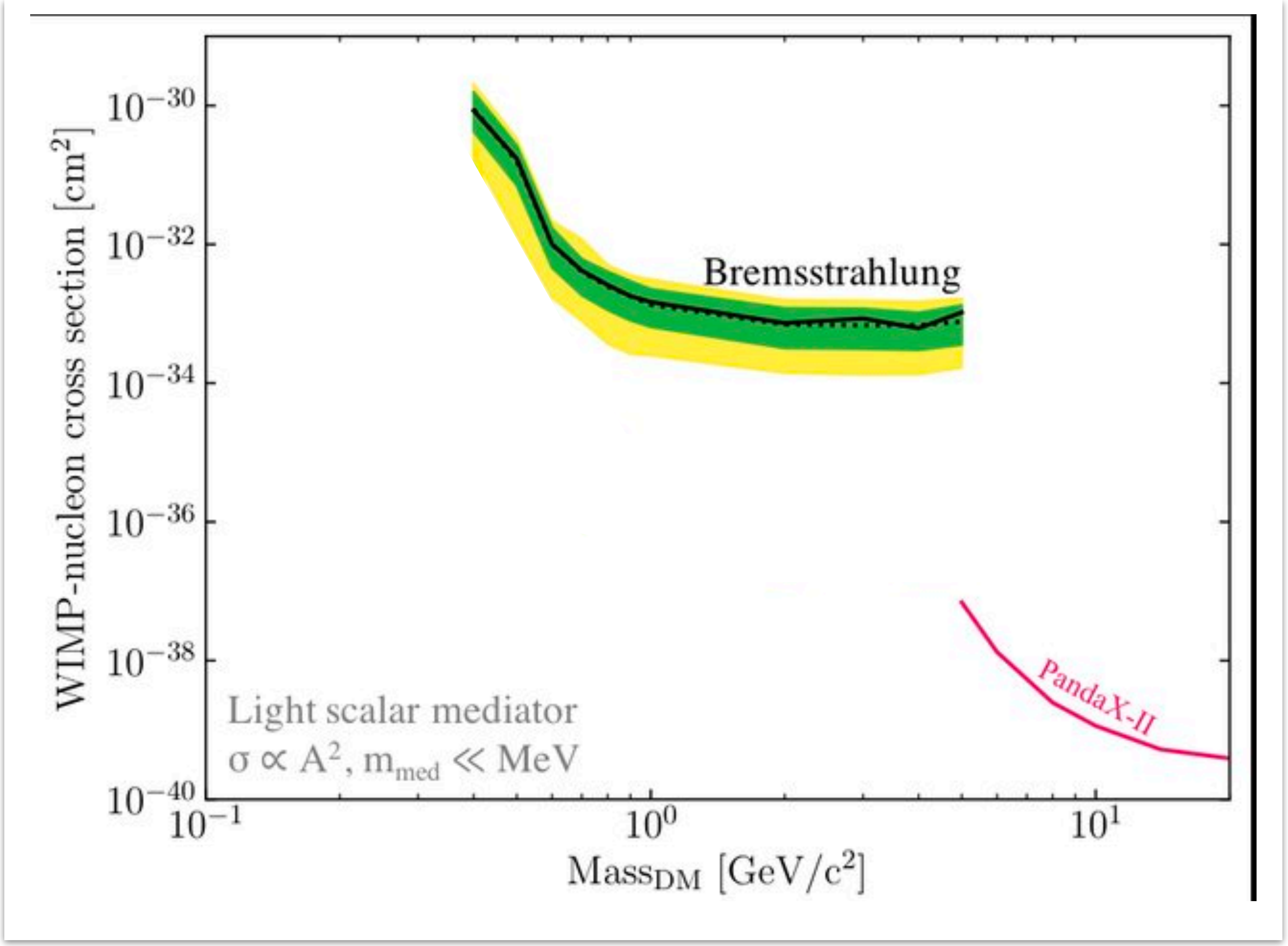
V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073



Extended sensitivity due to Bremsstrahlung

V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073

$$\frac{d\sigma}{dE_R} = \frac{m_N \sigma_0^{SI}}{2\mu^2 v^2} F_{SI}(E_R)\, F_\chi(E_R, m_\phi)$$



Extended sensitivity due to Bremsstrahlung

V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073

$$\frac{d\sigma}{dE_R} = \frac{m_N \sigma_0^{SI}}{2\mu^2 v^2} F_{SI}(E_R)\, F_\chi(E_R, m_\phi)$$

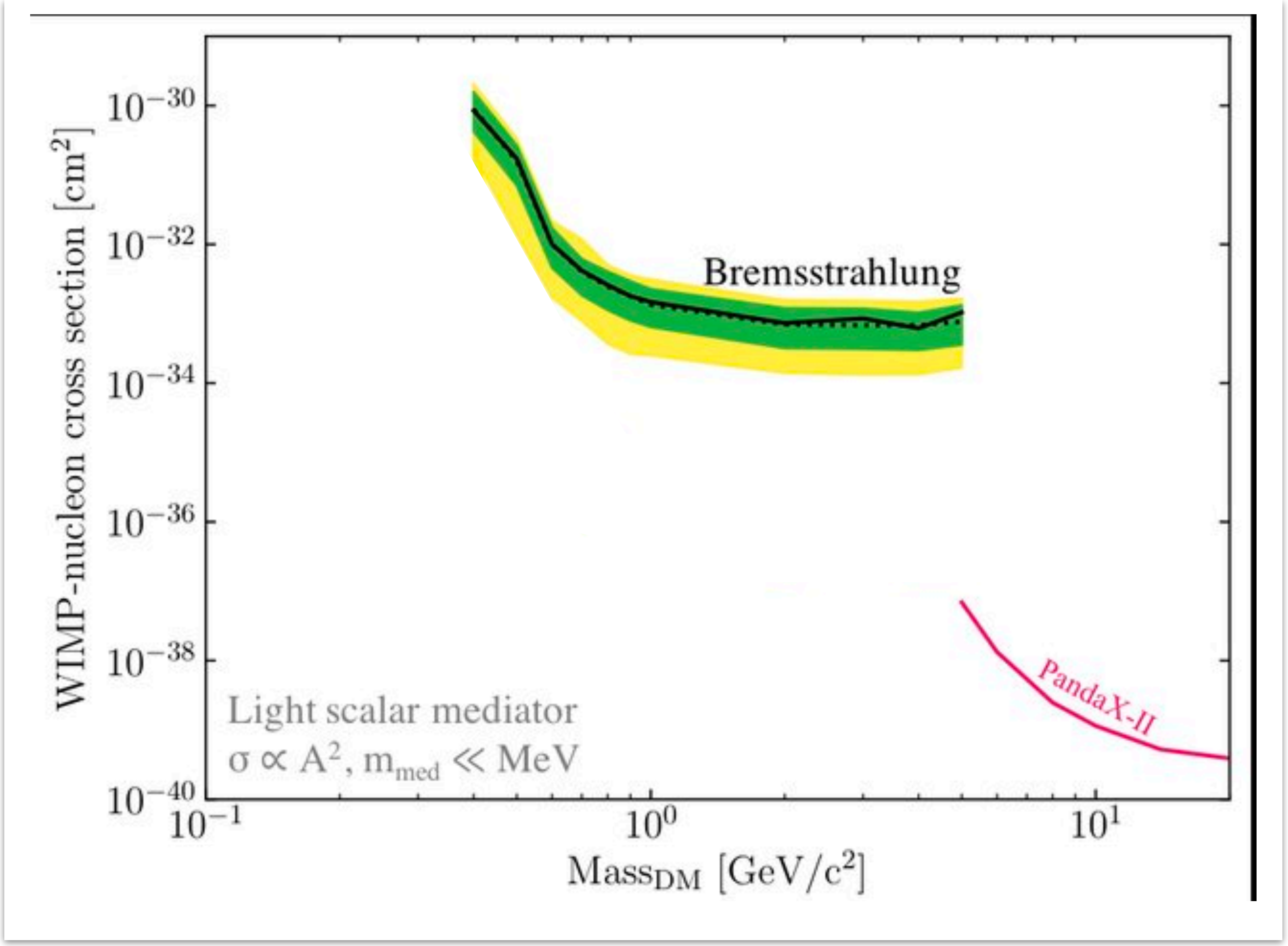
DM form factor for

heavy mediator Φ:

$$F_\chi(E_R, m_\phi) \approx 1$$

ultra-light mediator Φ:

$$F_\chi(E_R, m_\phi) \propto \frac{1}{q^2 + m_\phi^2}$$



UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

What’s the Migdal effect ?

Why not using the regular elastic scattering interaction ?

And why the effort in the first place ?

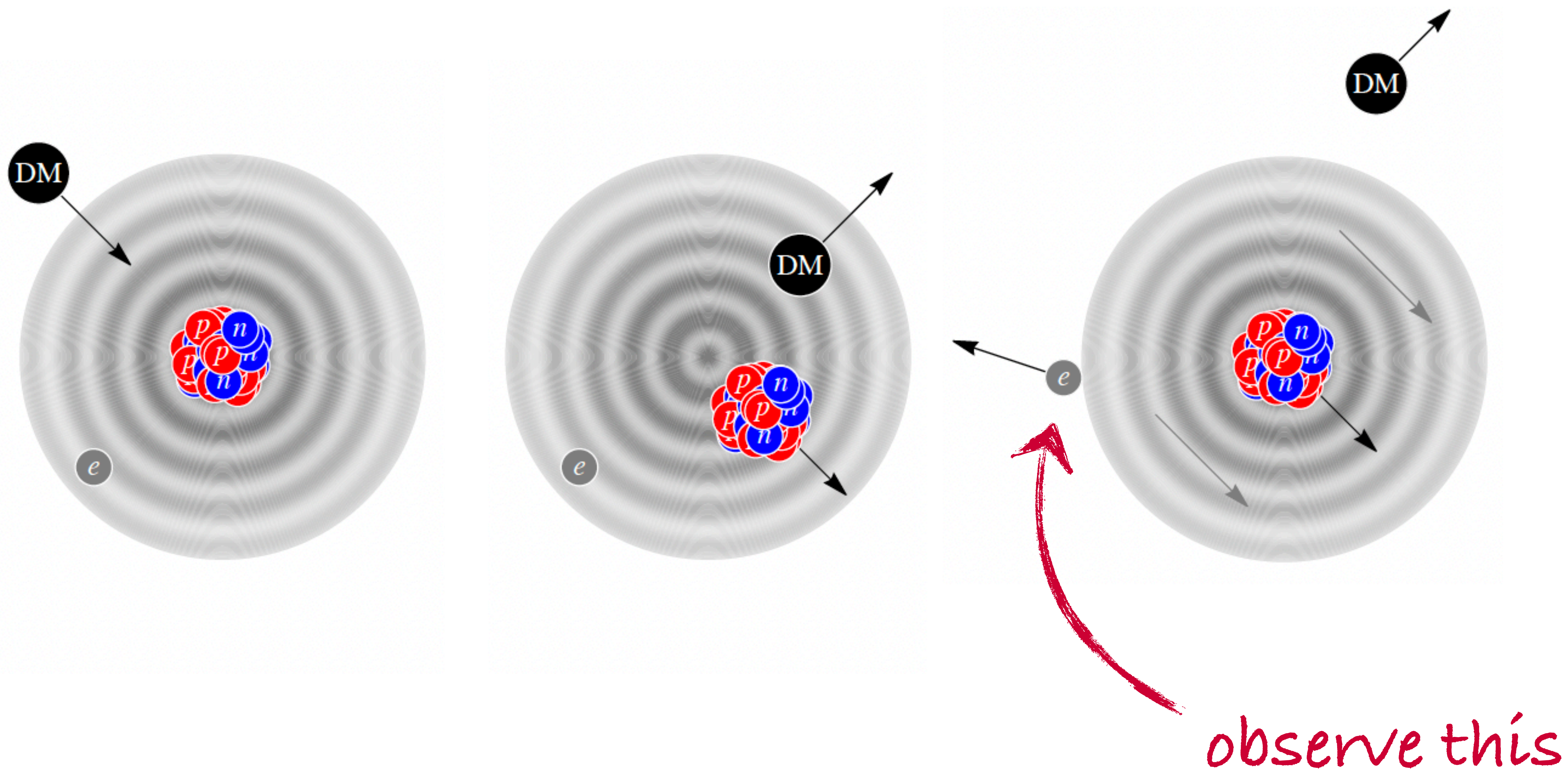
The sub-GeV parameter space

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

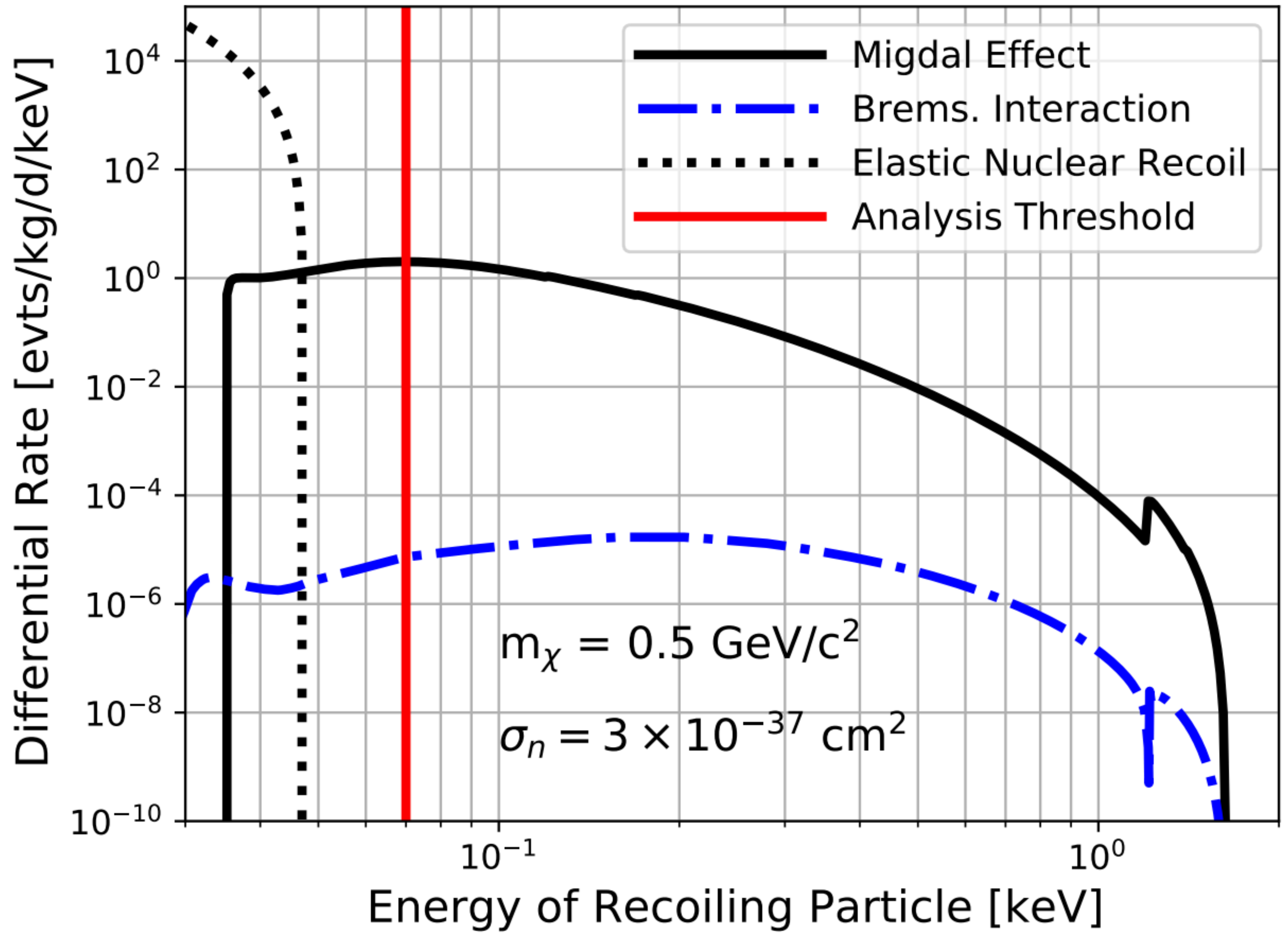
The Migdal effect
(inelastic DM-n scattering)

Inelastic DM-nucleus scattering and the Migdal effect

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705

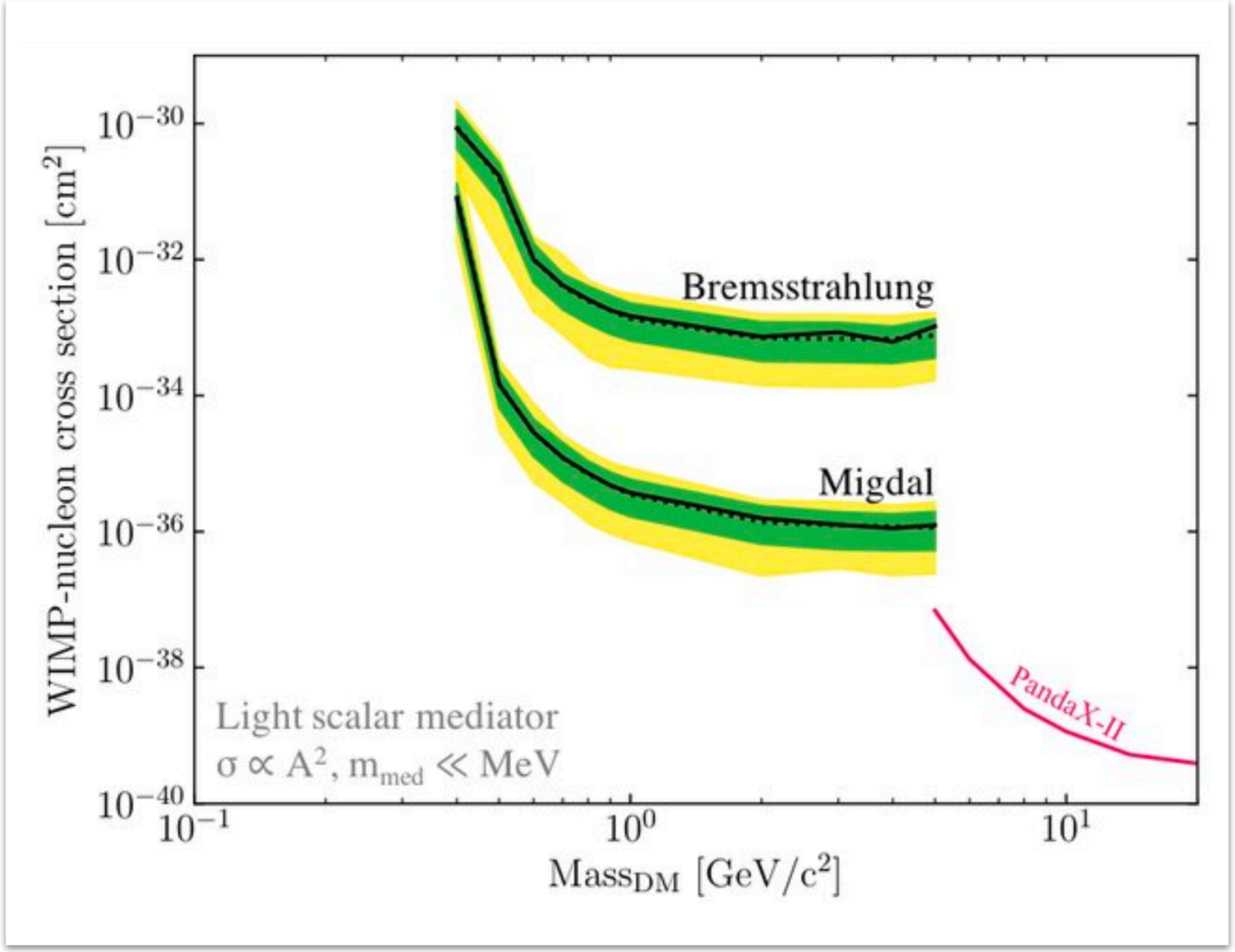


SuperCDMS, Phys. Rev. D 107



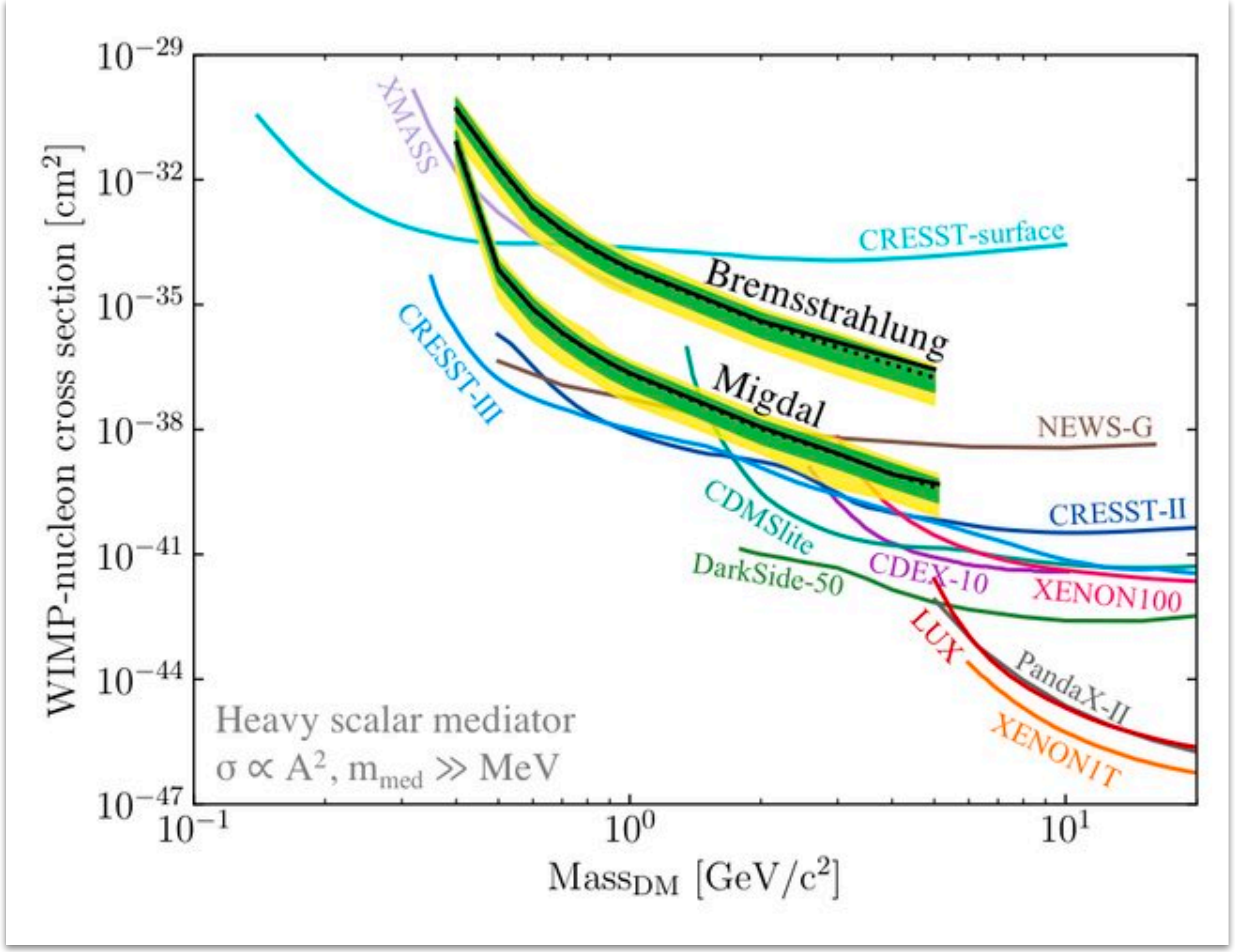
Migdal atomic relaxation can lead to keV electron recoil energy for sub-keV nuclear recoils.

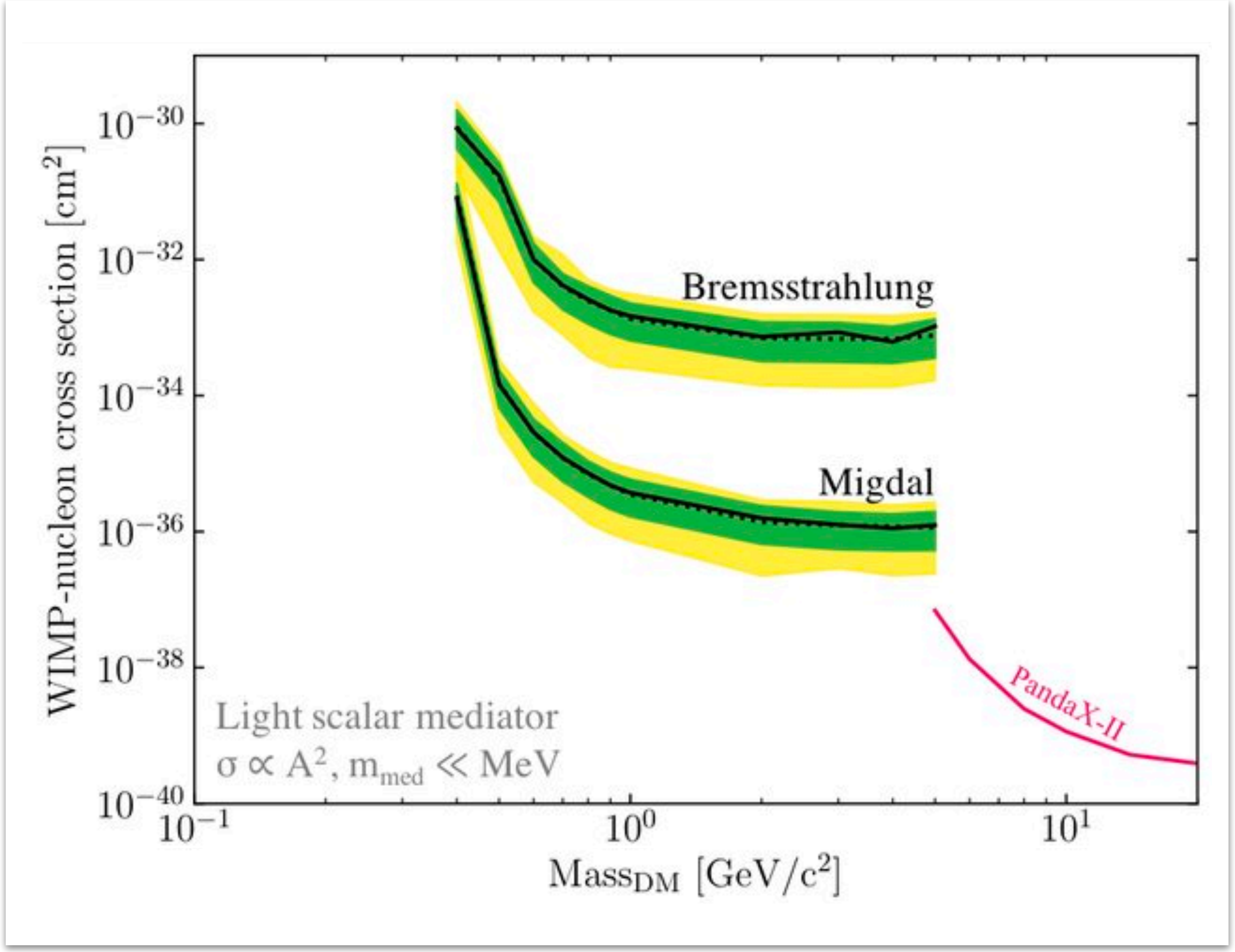
Extended sensitivity due to the Migdal effect



V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073

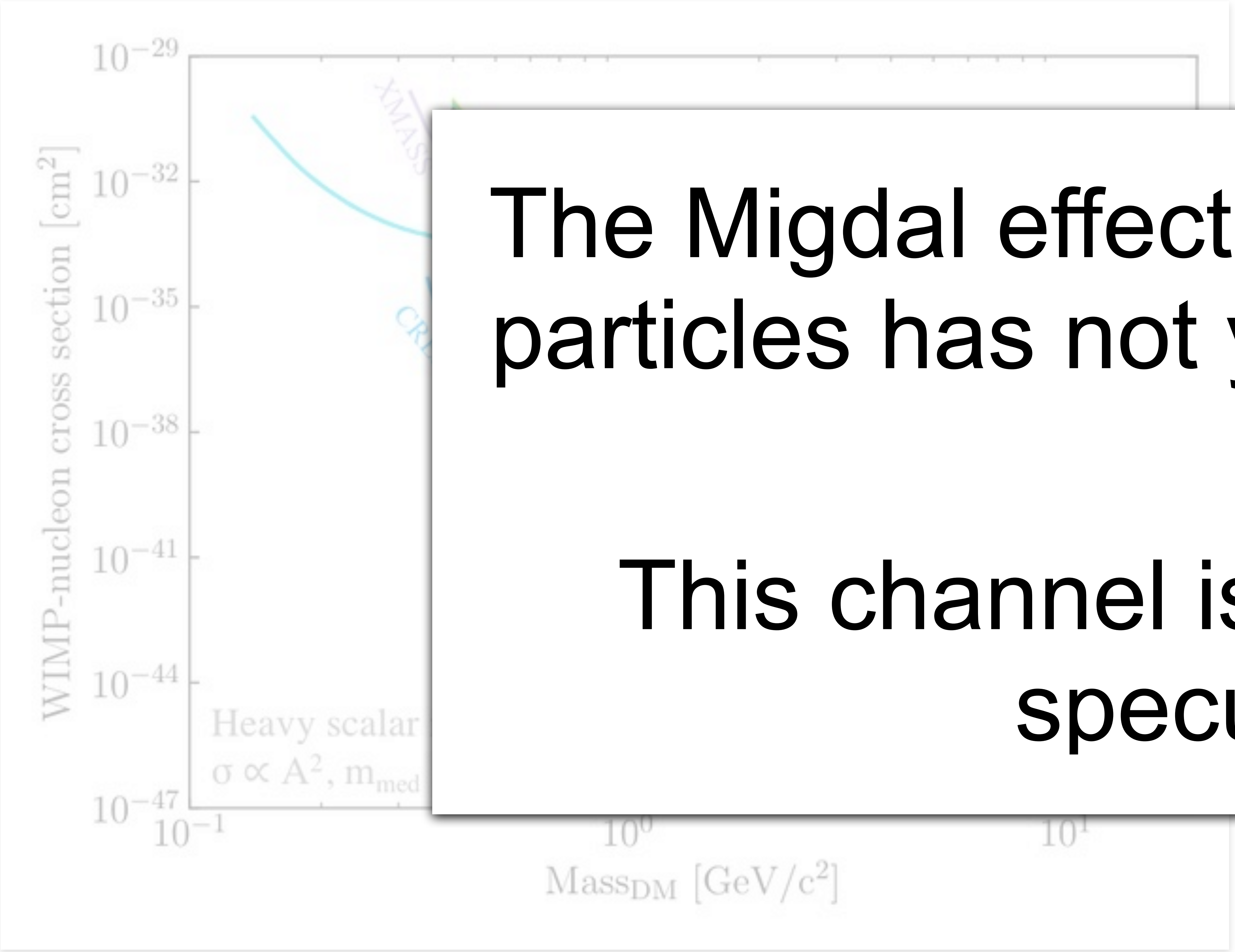
Extended sensitivity due to the Migdal effect

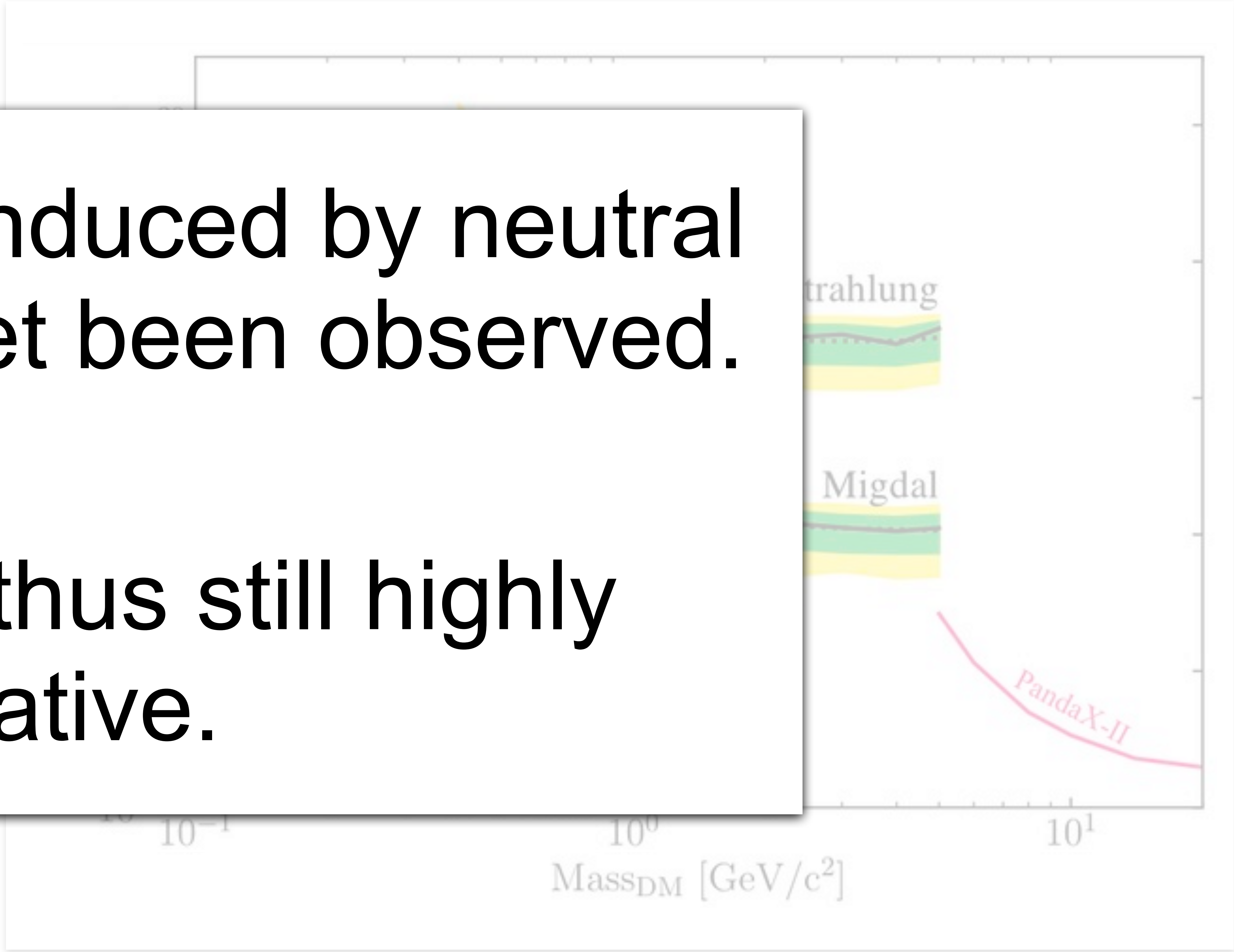




V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073

Extended sensitivity due to the Migdal effect





The Migdal effect induced by neutral particles has not yet been observed.

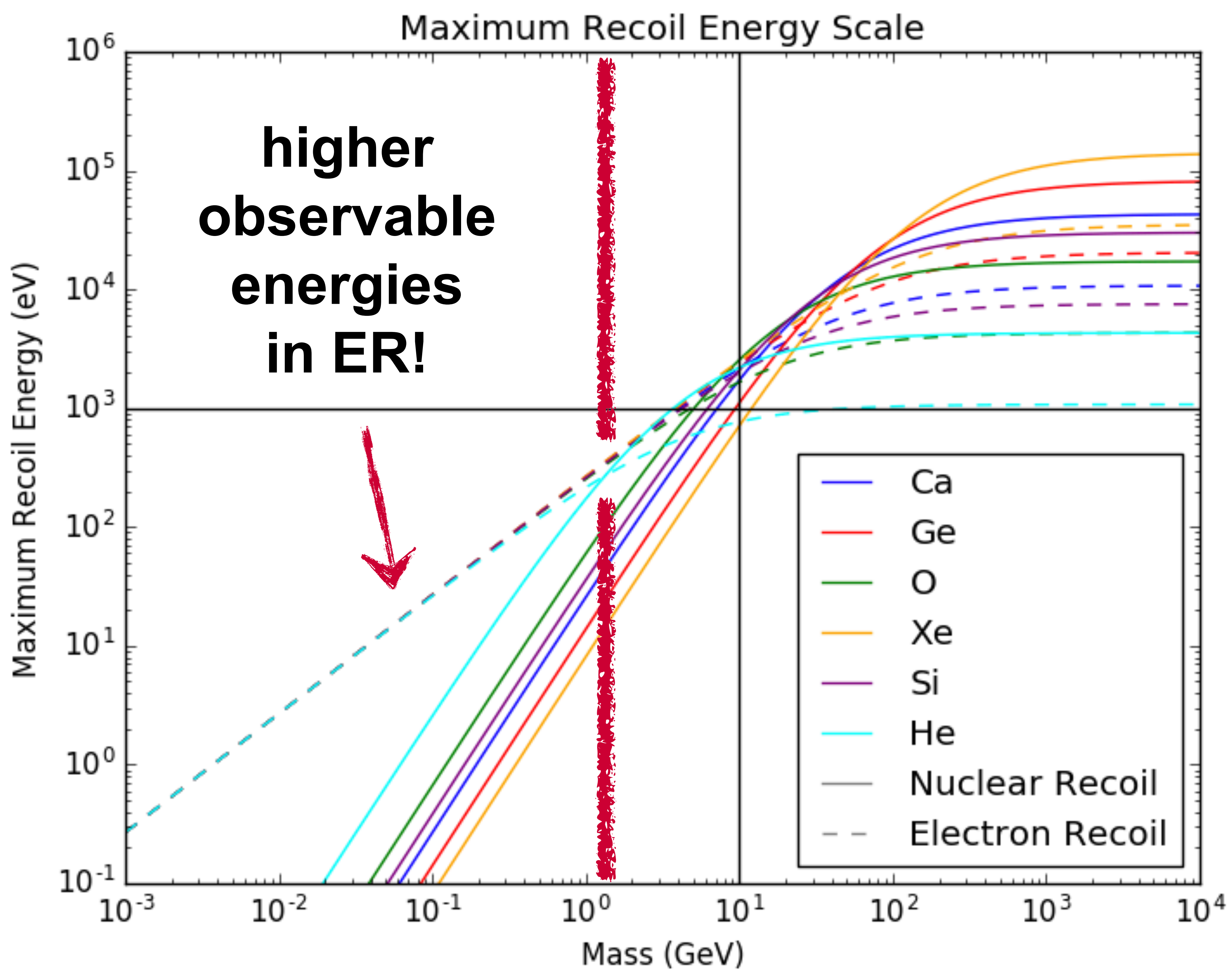
This channel is thus still highly speculative.

V. Kudryavstev, Universe 2019, 5(3), 73; https://doi.org/10.3390/universe5030073

The sub-GeV parameter space

DM-electron scattering

Nuclear Recoil (NR) vs. Electron Recoil (ER)

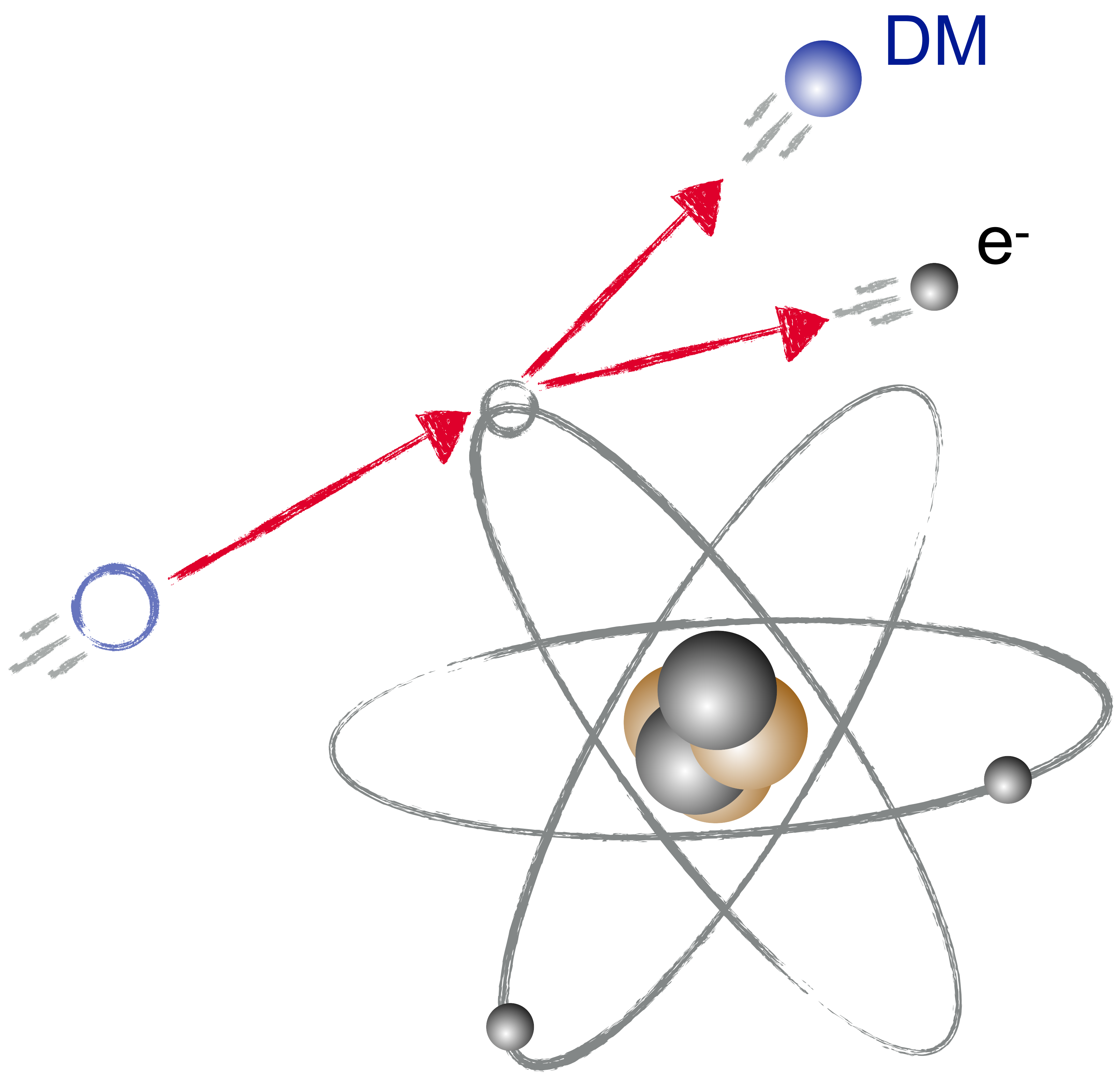


- Nuclear Recoils (elastic):
  - Inefficient energy transfer unless $m_N \lesssim m_\chi$
- Electron Recoils (largely inelastic):
  - Energy transfer depends on e$^-$ orbital and kinematics within bound e$^-$-atom system.
  - e$^-$ determines typical momentum transfer.

Dark matter - electron scattering

Need to overcome binding energy:

$$E_\chi \sim \frac{1}{2} m_\chi v > E_{\mathrm{bind.}}$$



$$\Rightarrow m_\chi \gtrsim 300\,\mathrm{keV/c^2} \left(\frac{E_{\mathrm{bind.}}}{1\,\mathrm{eV}}\right)$$

for $v \lesssim 800\,\mathrm{km/s}$

$m_\chi \ll \mathrm{GeV/c^2}$ accessible!

with $E_{\mathrm{bind.}} \mathcal{O}(1 - 100\,\mathrm{eV})$

Dark matter - electron scattering

Need to overcome binding energy:

$$E_\chi \sim \frac{1}{2} m_\chi v > E_{\text{bind.}}$$

Small binding / ionization / band gap energies are favorable!

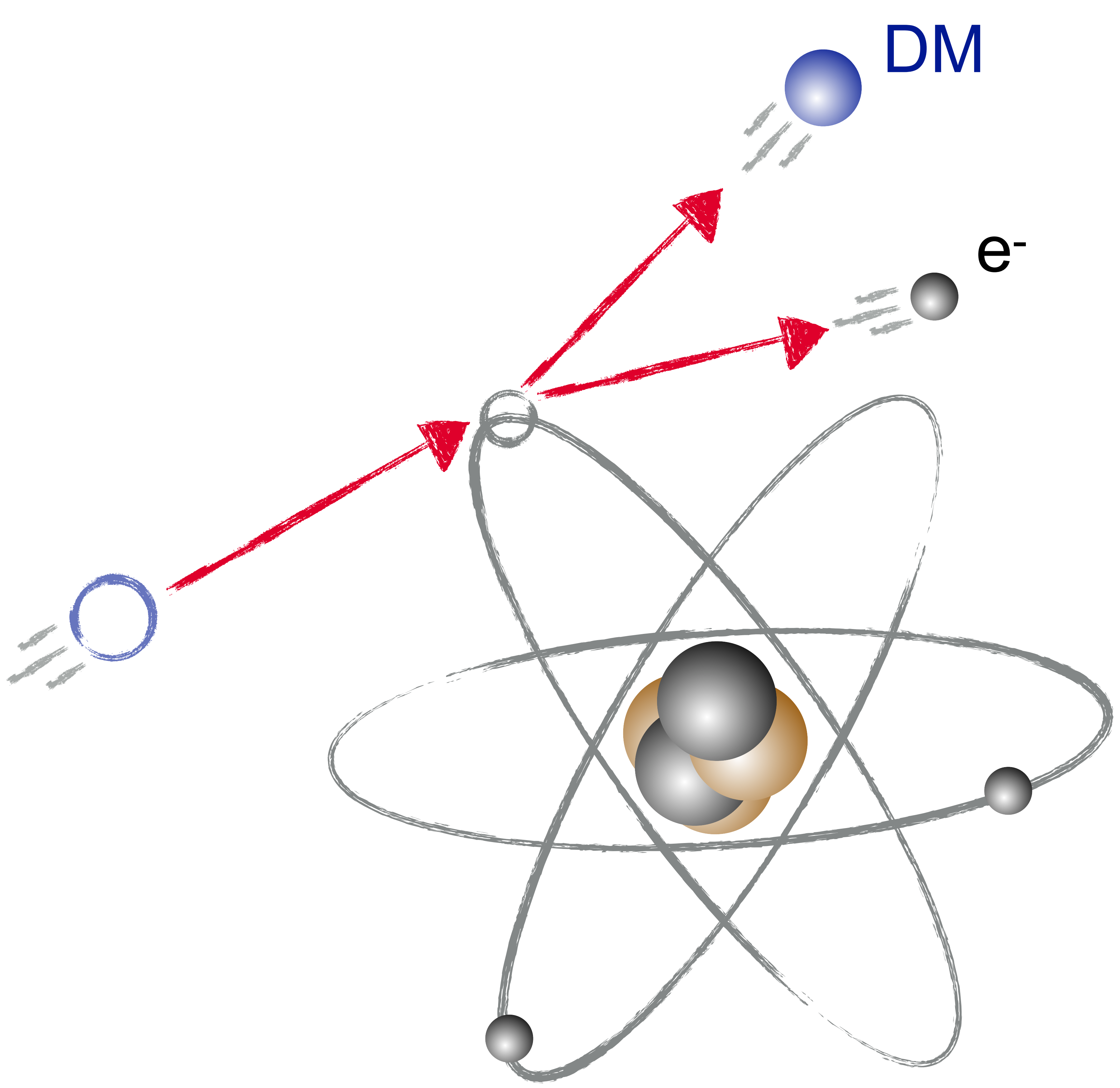
$$\Rightarrow m_\chi \gtrsim 300\,\text{keV/c}^2 \left(\frac{E_{\text{bind.}}}{1\,\text{eV}}\right)$$

for $v \lesssim 800\,\text{km/s}$

$$m_\chi \ll \text{GeV/c}^2 \quad \text{accessible!}$$

with $E_{\text{bind.}} \mathcal{O}(1 - 100\,\text{eV})$

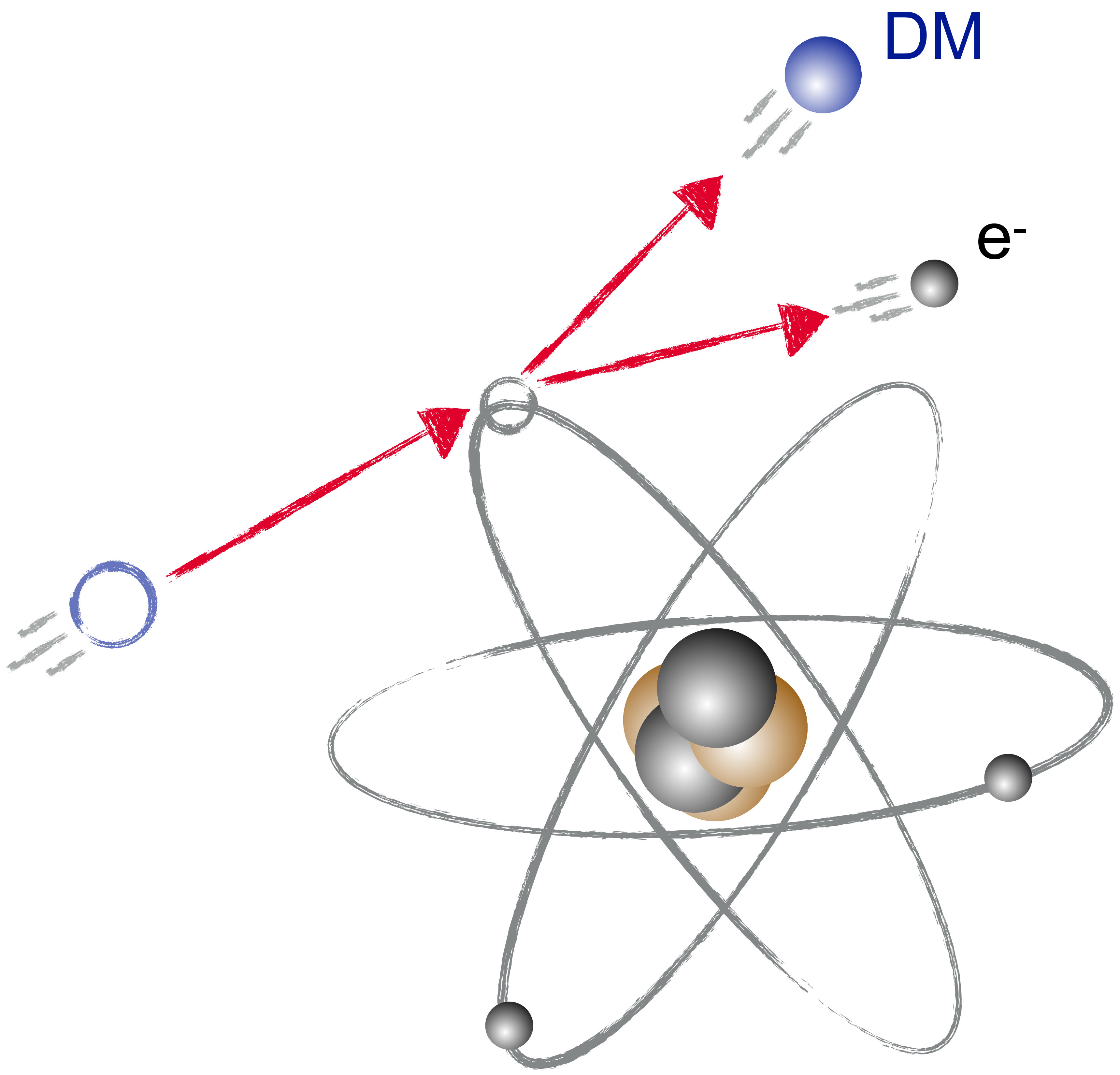
The dark matter - electron scattering master formula



Expected interaction rate | Particle theory | Local properties of DM halo etc. | Crystal and mediator properties

$$\frac{dR}{d\ln E_R} = \frac{\bar{\sigma}_e}{m_\chi} \; \rho_0 \, \alpha \frac{m_e^2}{\mu^2} \; V_{\rm det} \frac{\rho_{\rm target}}{2m_{\rm target}} I_{\rm crystal}(E_e; F_\chi)$$

The dark matter - electron scattering master formula



Expected interaction rate | Particle theory | Local properties of DM halo etc. | Crystal and mediator properties

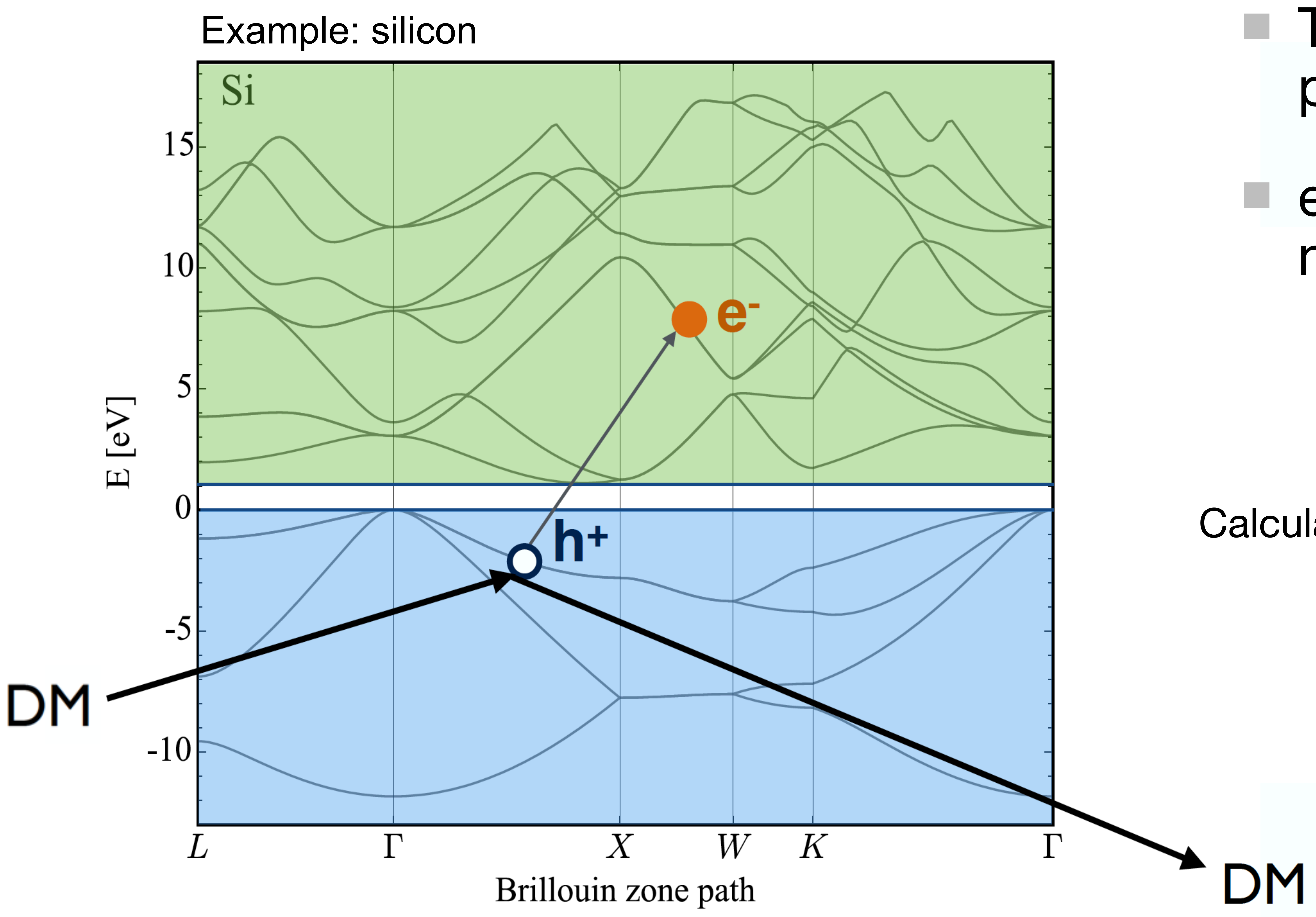
$$\frac{dR}{d\ln E_R} = \frac{\bar{\sigma}_e}{m_\chi}\;\rho_0\,\alpha\frac{m_e^2}{\mu^2}\;V_{\text{det}}\frac{\rho_{\text{target}}}{2m_{\text{target}}}I_{\text{crystal}}(E_e;F_\chi)$$

DM form factor for

- heavy mediator: $F_\chi \approx 1$
- ultra-light mediator: $F_\chi = \frac{(\alpha m_\text{e})^2}{q^2}$

q: momentum transfer between the DM and electron

Dark matter - electron scattering: silicon as example



- This is condensed matter physics!
- e^- are not free but part of many-body system

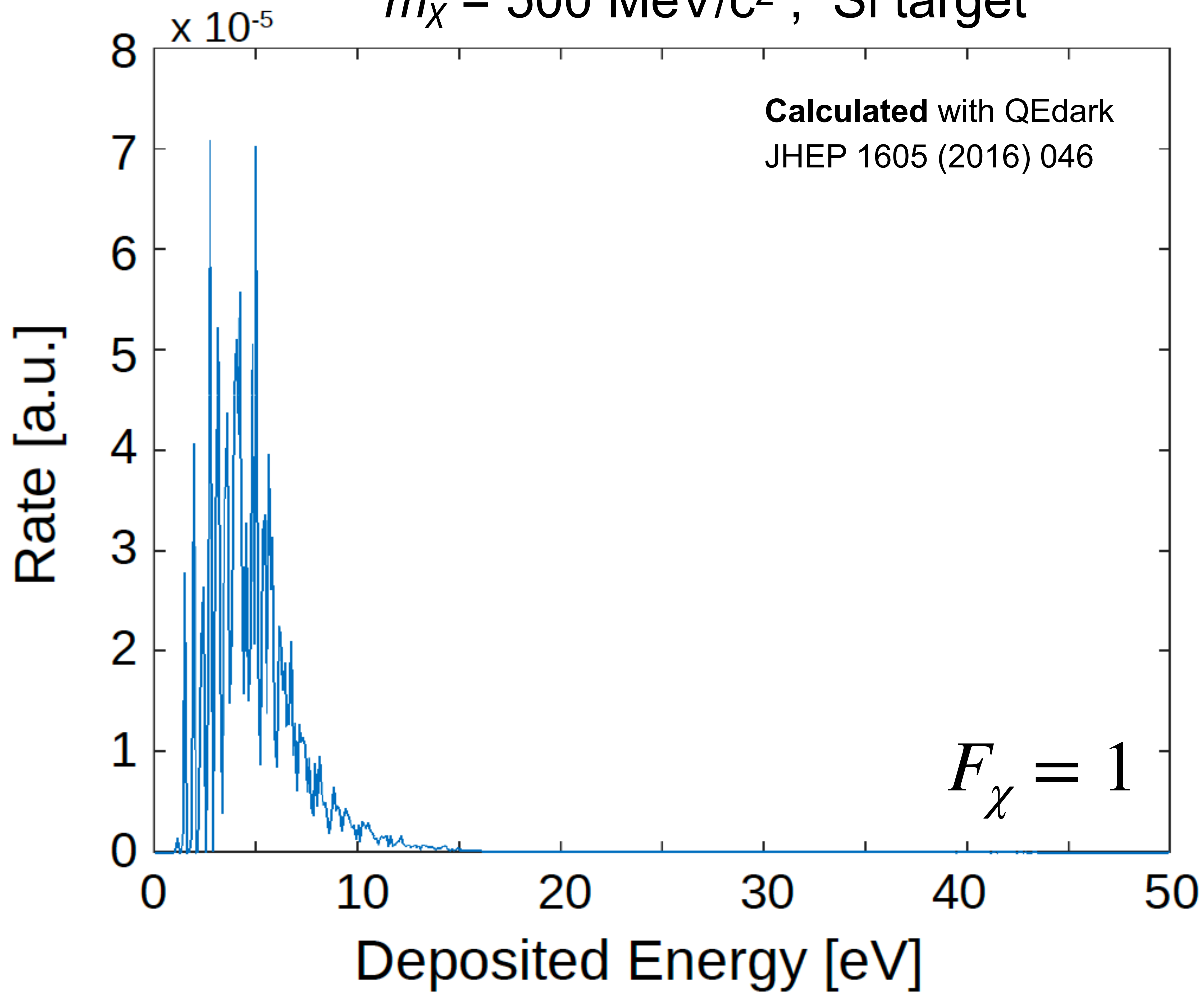
Calculating the differential rates is challenging

QEdark

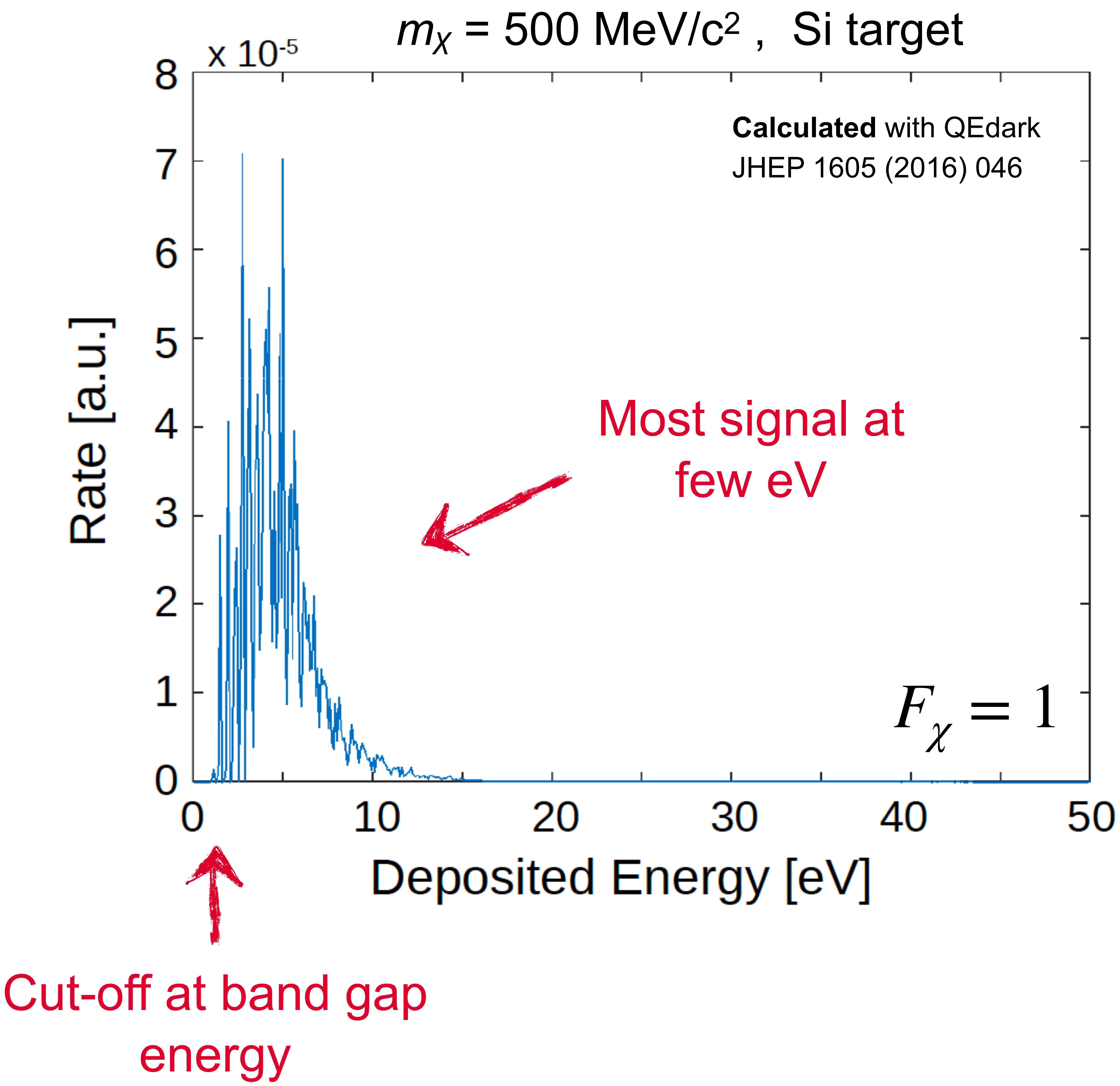
http://ddldm.physics.sunysb.edu/ddlDM/

Dark matter - electron scattering: silicon as example

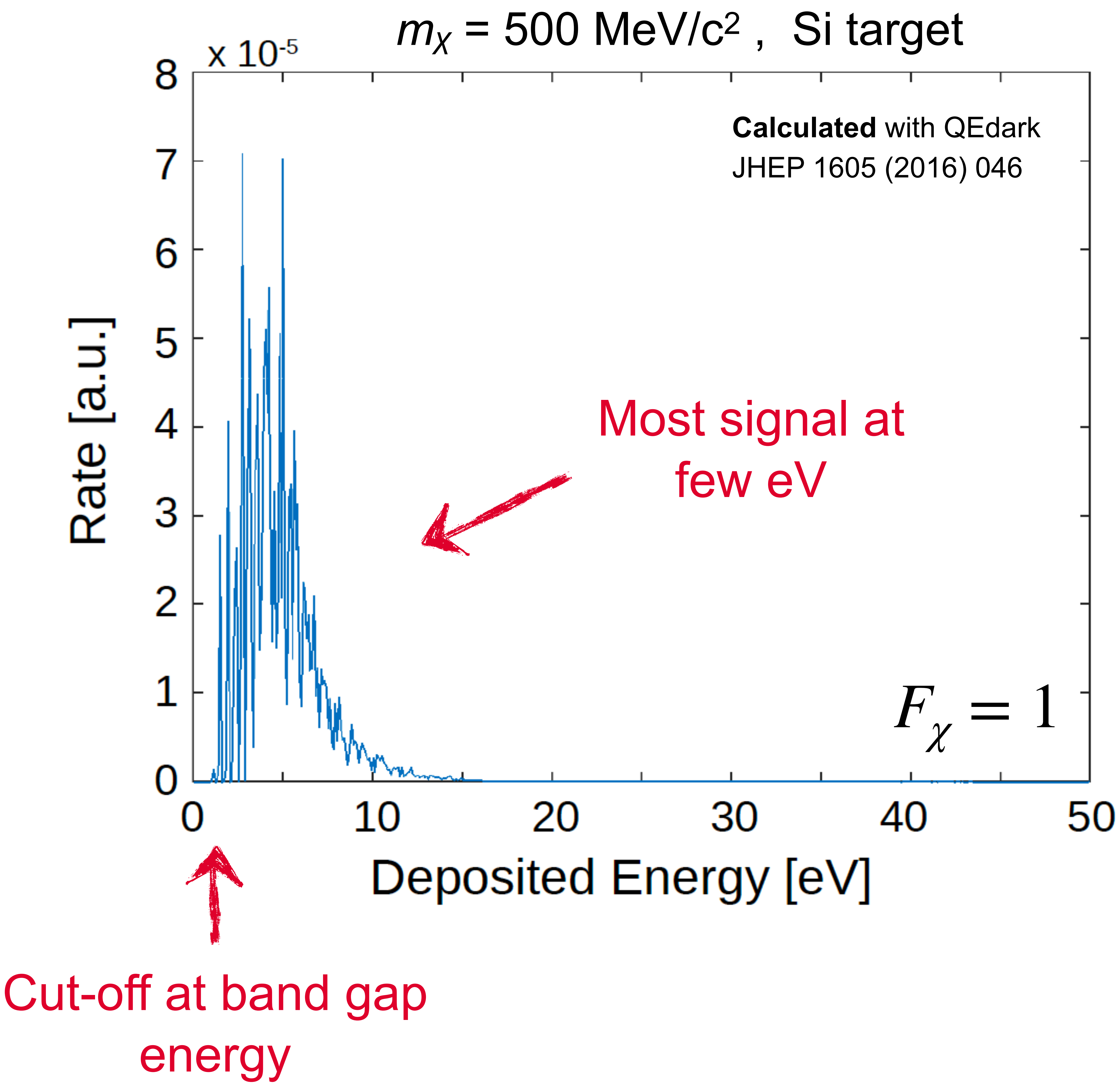
$m_\chi = 500\ \mathrm{MeV}/c^2$, Si target



Dark matter - electron scattering: silicon as example



Dark matter - electron scattering: silicon as example



- e⁻, not DM, sets typical momentum transfer:

$$q_{\mathrm{typ}} \sim \alpha m_{\mathrm{e}} \sim 4\,\mathrm{keV}$$

- Transferred energy:

$$\Delta E_{\mathrm{e}} \sim \vec{q} \cdot \vec{v}$$

- Typical recoil energy:

$$\Delta E_{\mathrm{typ}} \approx 4\,\mathrm{eV}$$

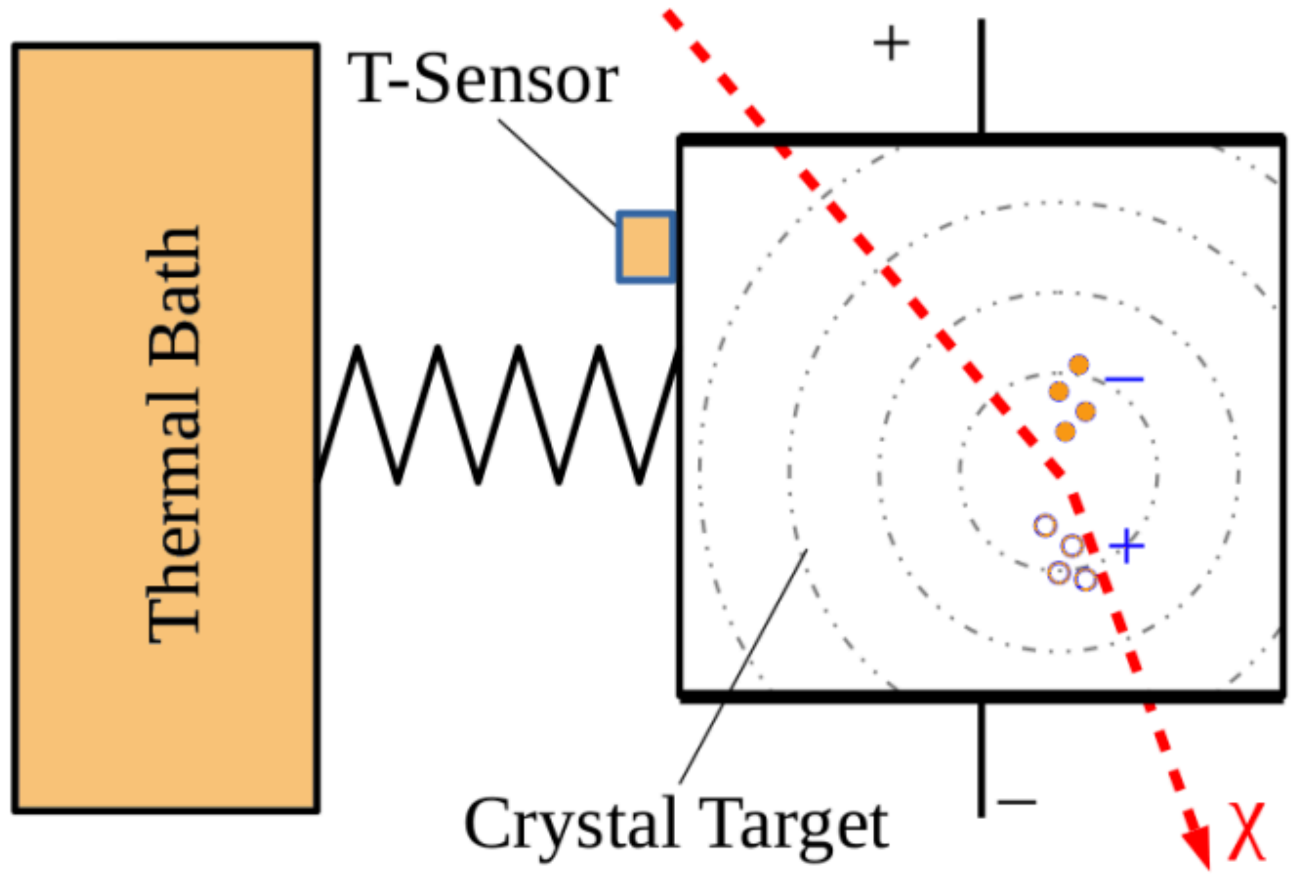
State-of-the-art DM-e Scattering Detectors

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Credit: WorldAtlas.com

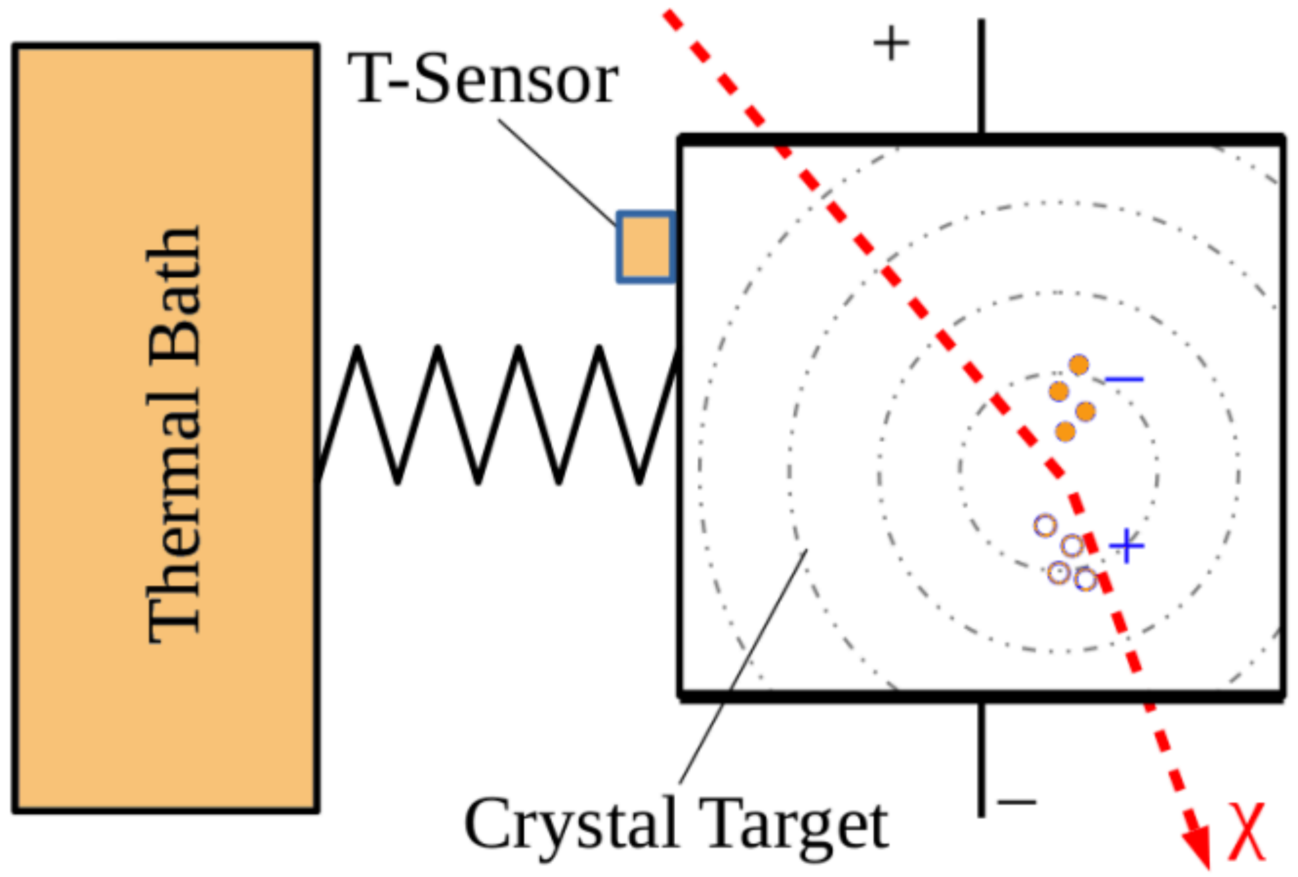
Cryogenic calorimeters / bolometers

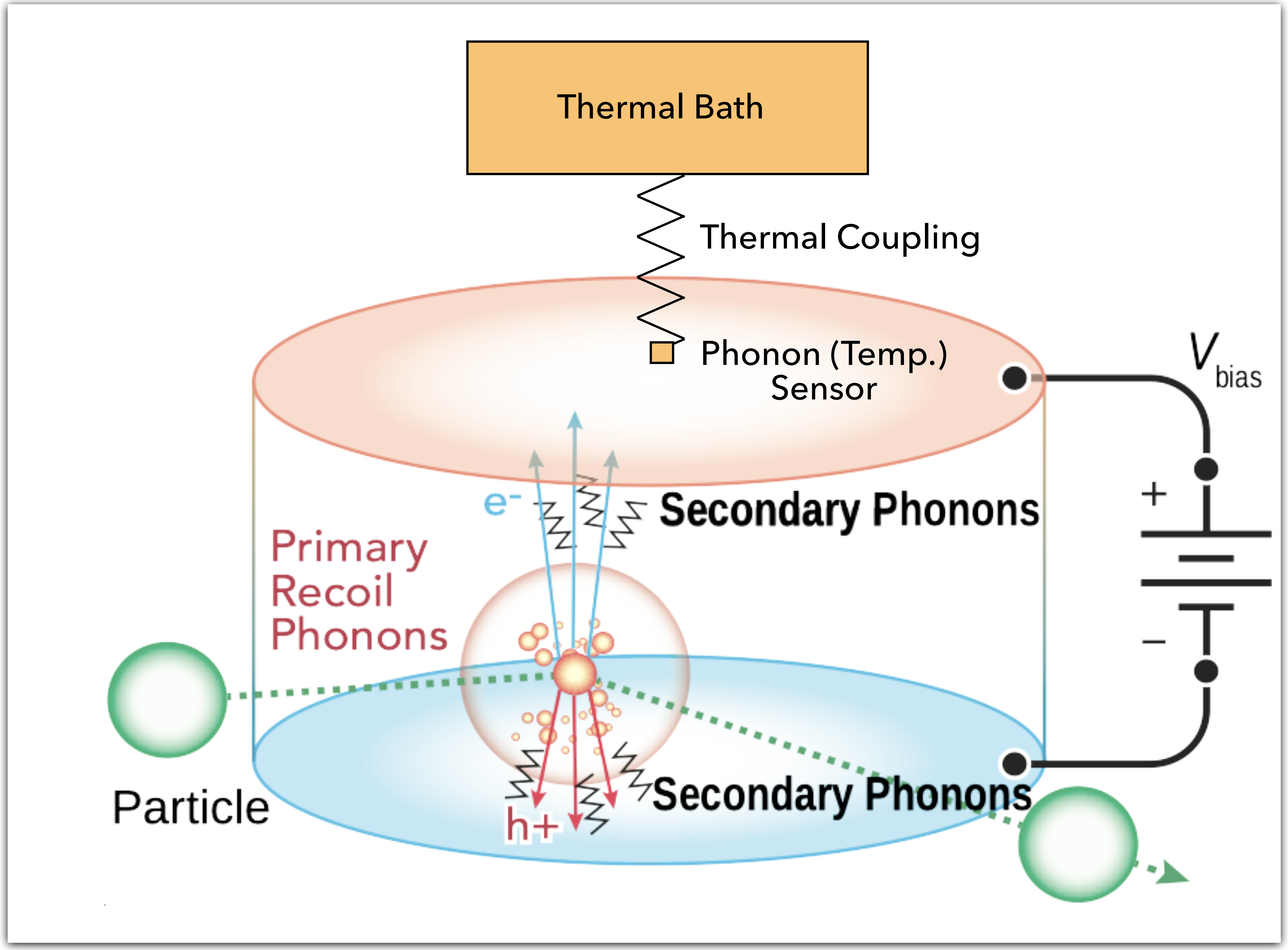
Example: measurement of PHONON / HEAT and IONIZATION signals



Cryogenic calorimeters / bolometers

Example: measurement of PHONON / HEAT and IONIZATION signals



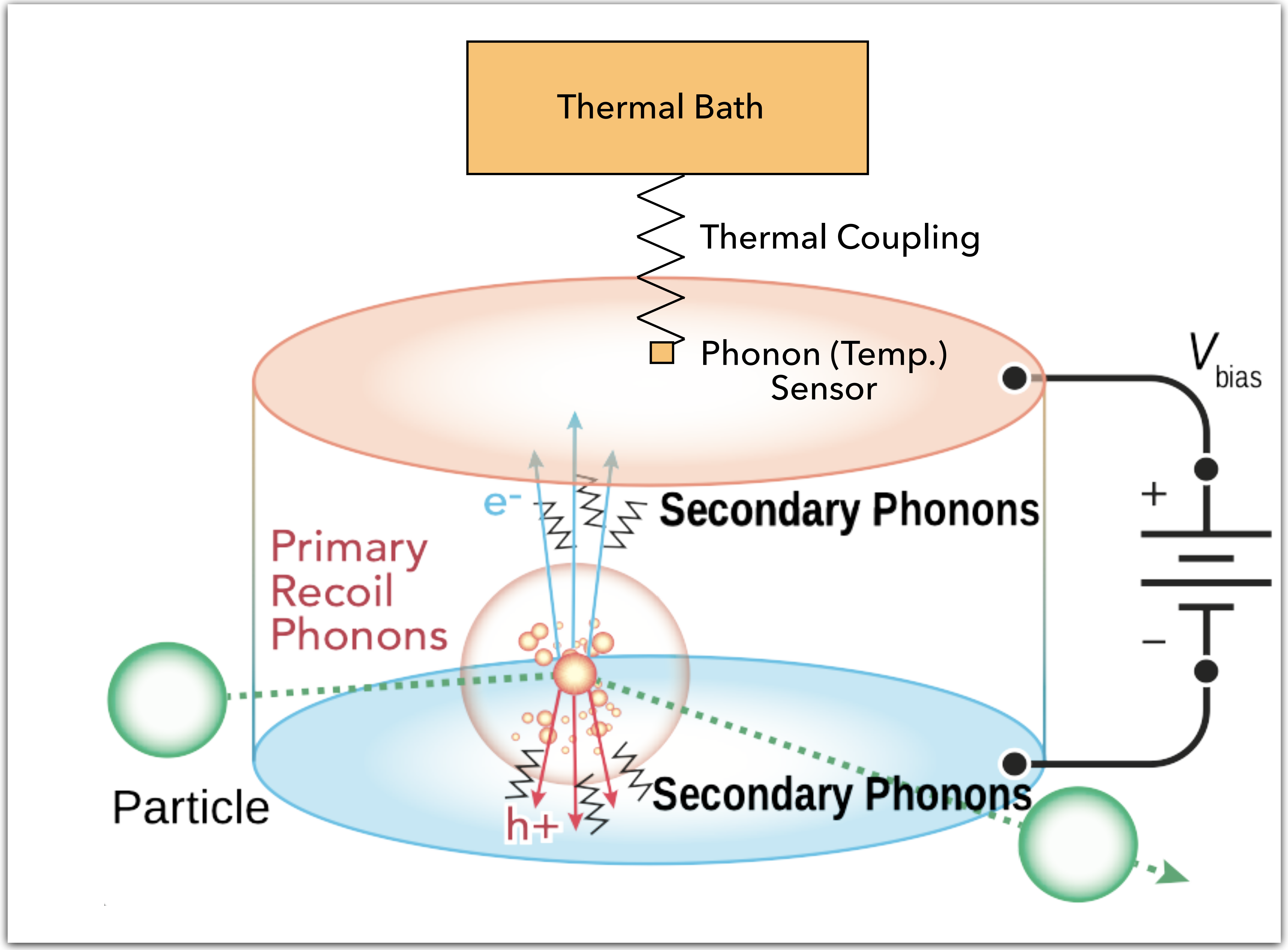


Cryogenic calorimeters / bolometers

Amplification of the charge signal via the Neganov-Trofimov-Luke effect

$$E_{\text{phonon}} = E_{\text{dep.}} + n_{eh}\, e\, V_{\text{bias}}$$

$$= E_{\text{prompt}} + E_{\text{recomb.}} + E_{\text{NTL}}$$

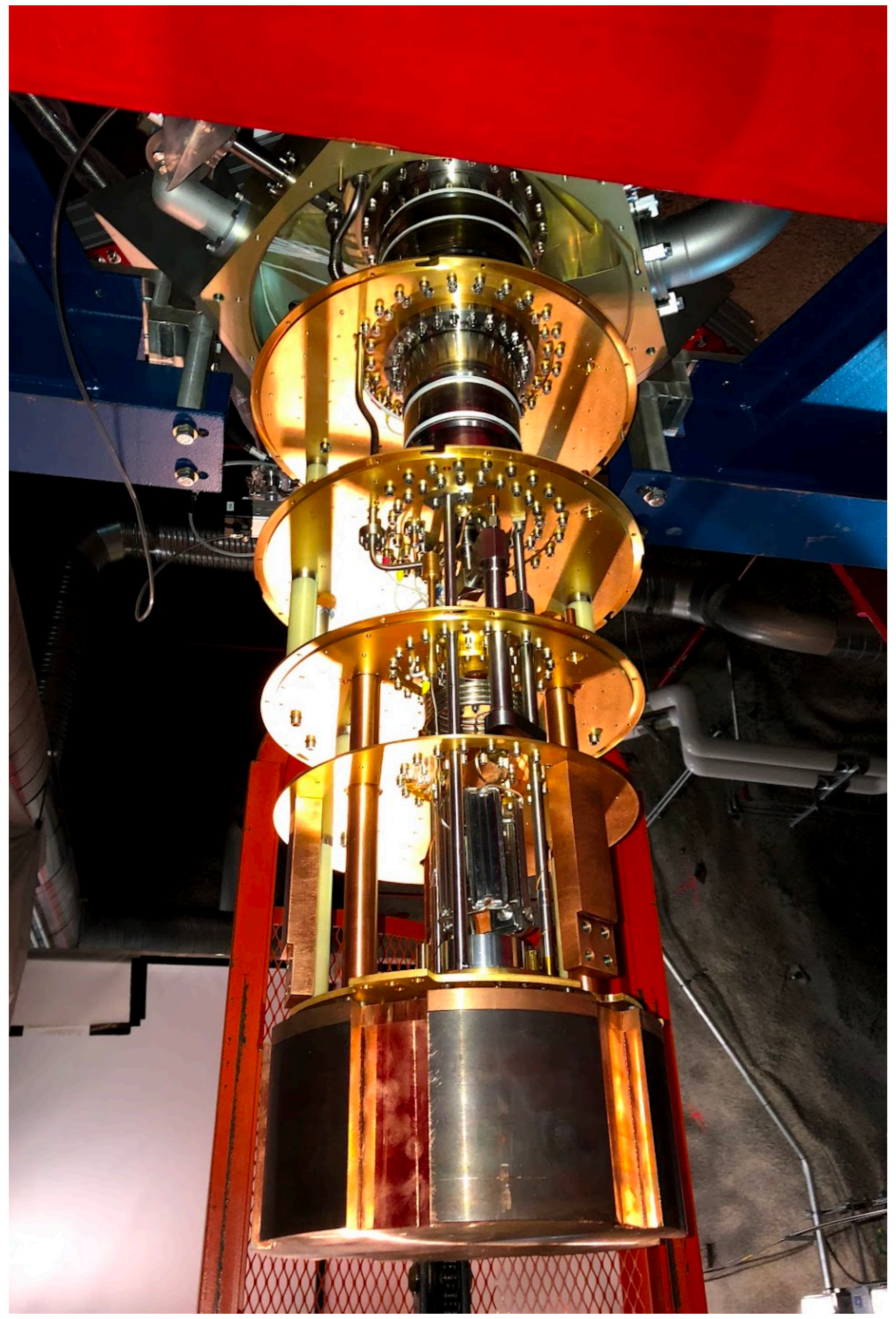


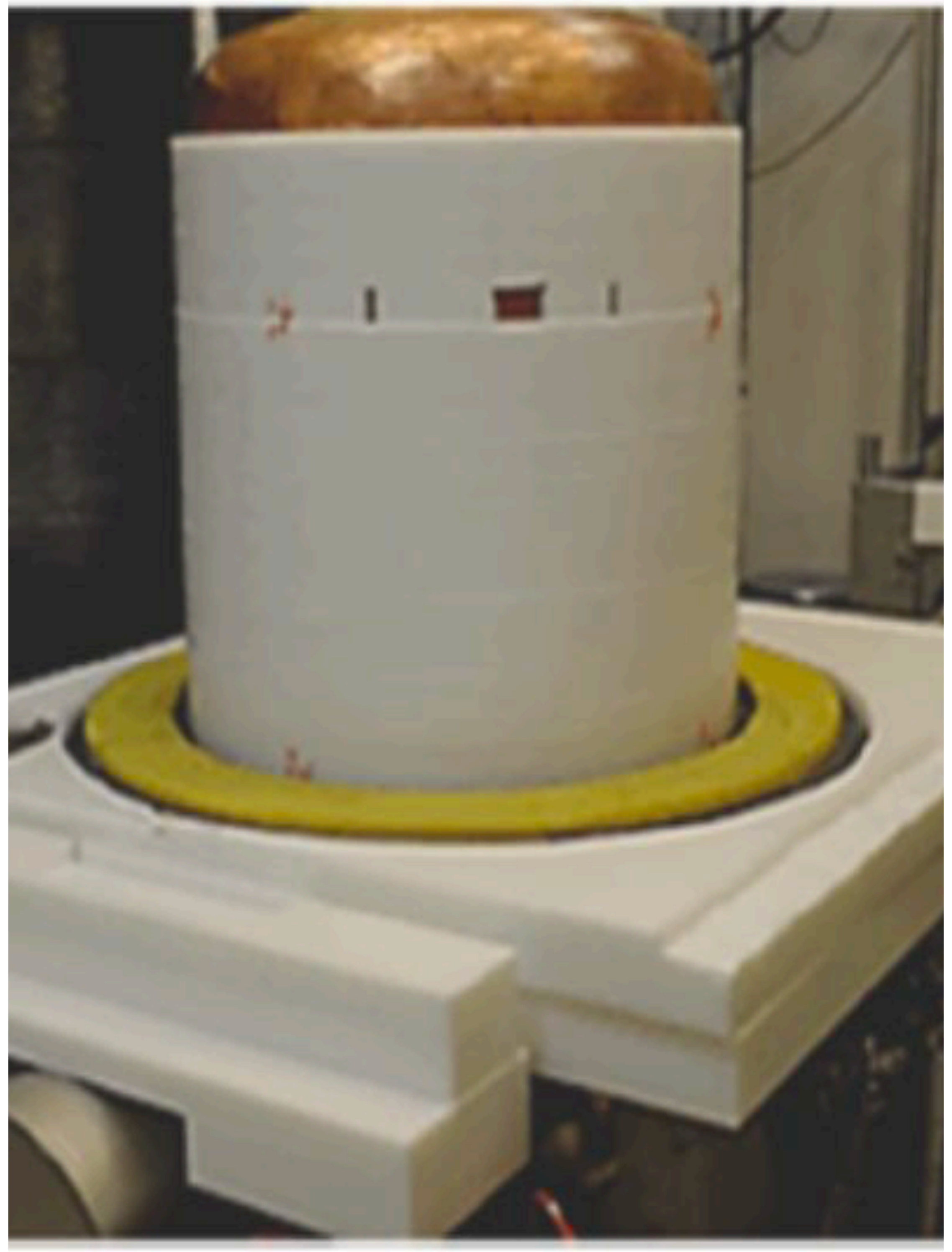
Cryogenic calorimeters / bolometers

SuperCDMS-HVeV

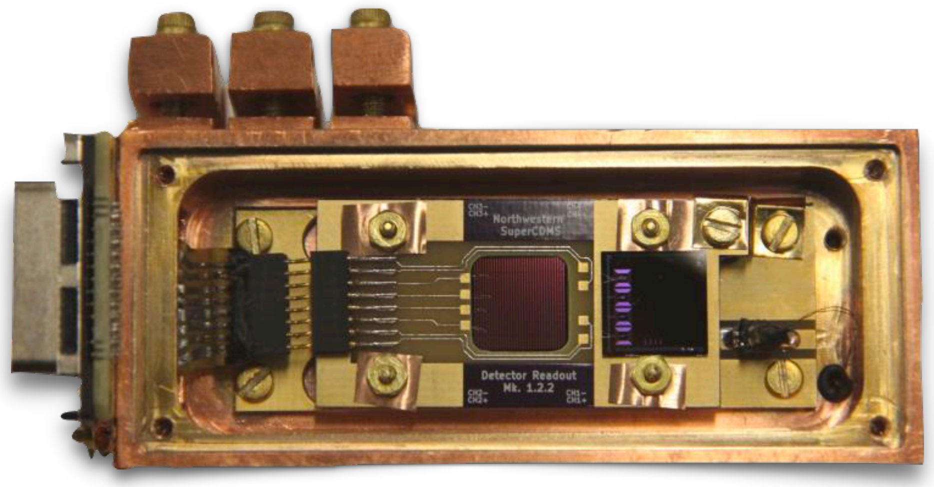
EDELWEISS

Pictures courtesy: SuperCDMS collaboration



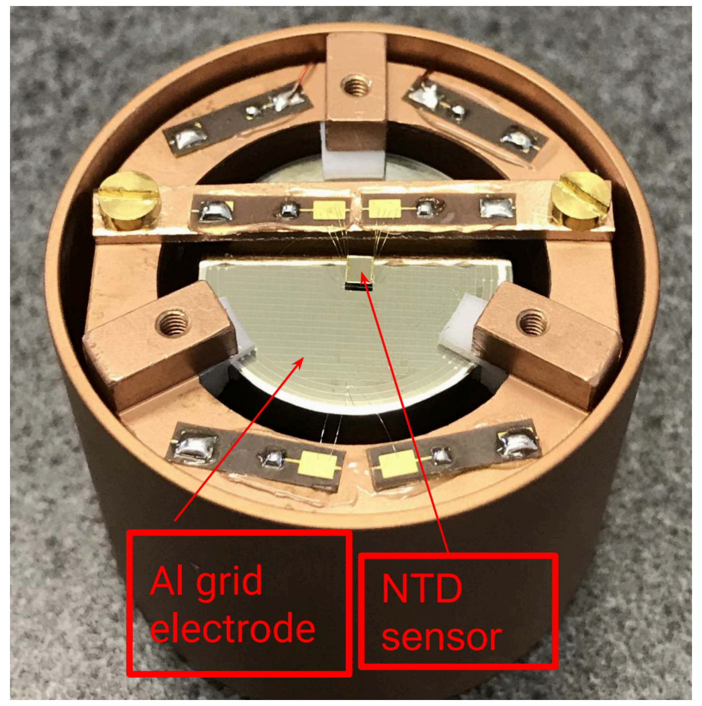


Pictures courtesy: EDELWEISS collaboration



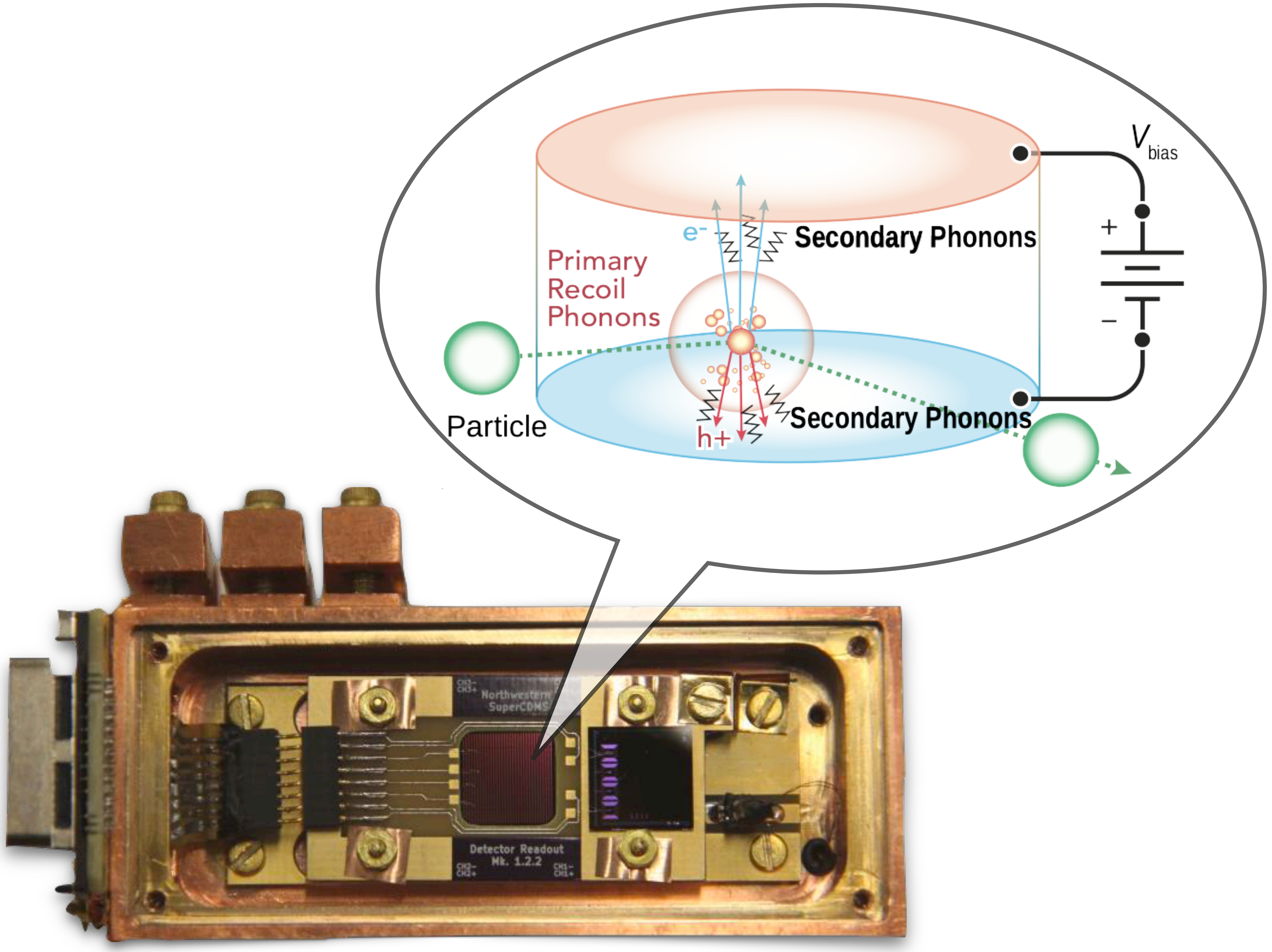
silicon target

- High time and energy resolution but poor spatial resolution



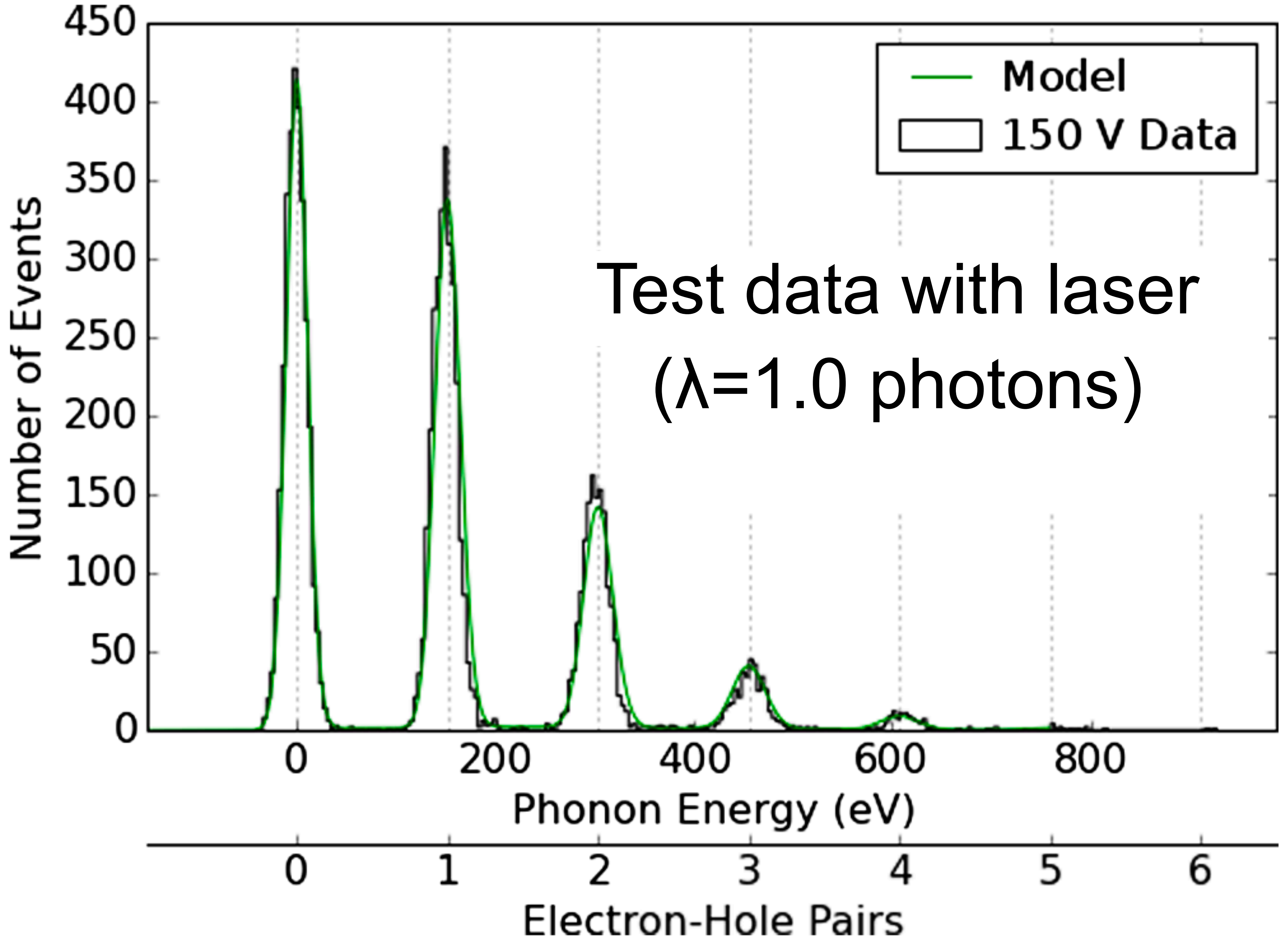
germanium target

Cryogenic calorimeters: SuperCDMS-HVeV



Si chip with bias voltage around ~ 100 V.

(1 cm² x 4 mm, 0.93 g)



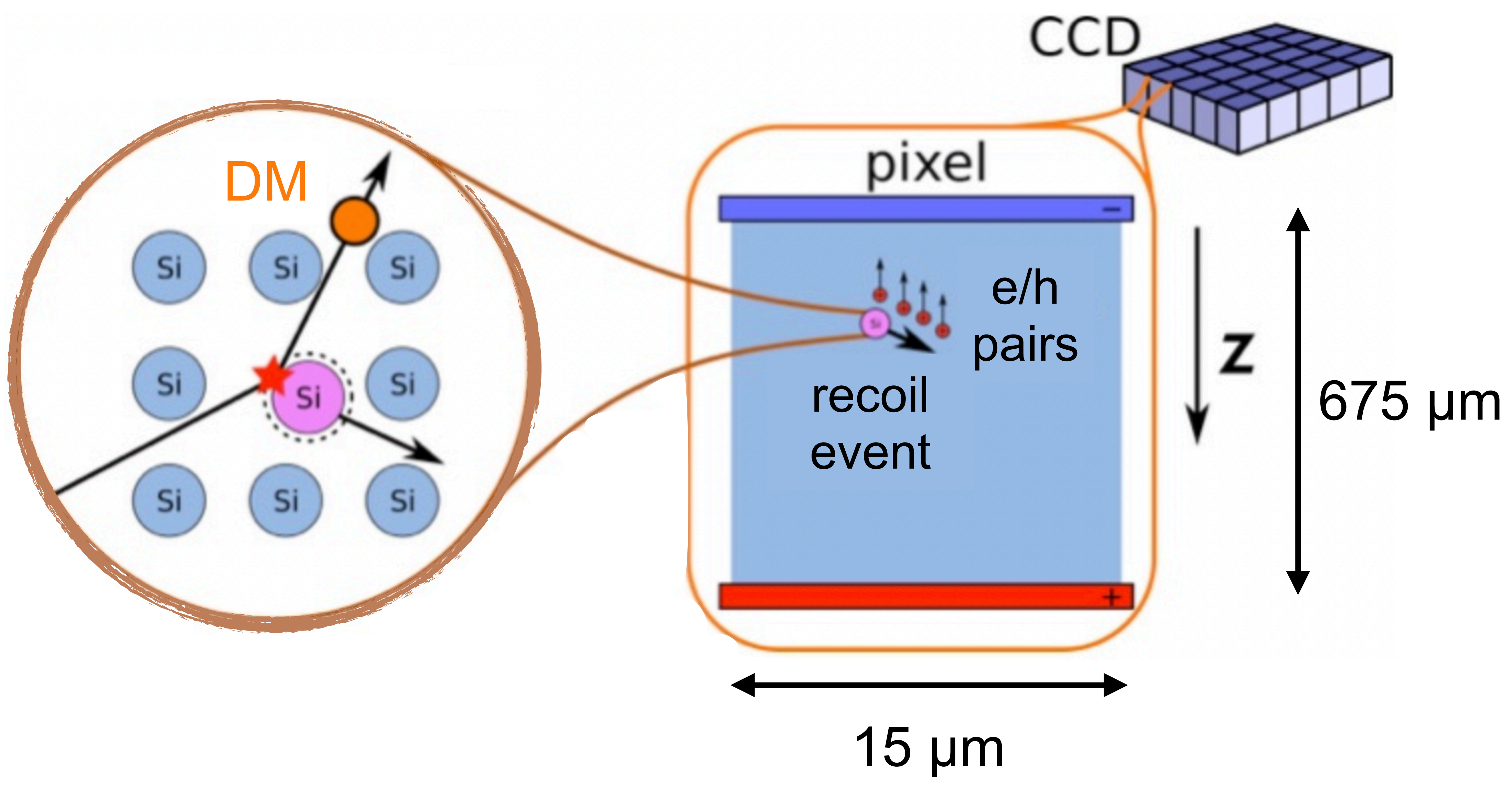
- Single electron-hole pair resolution
- Ultra-low threshold at ~1 eV (band-gap)

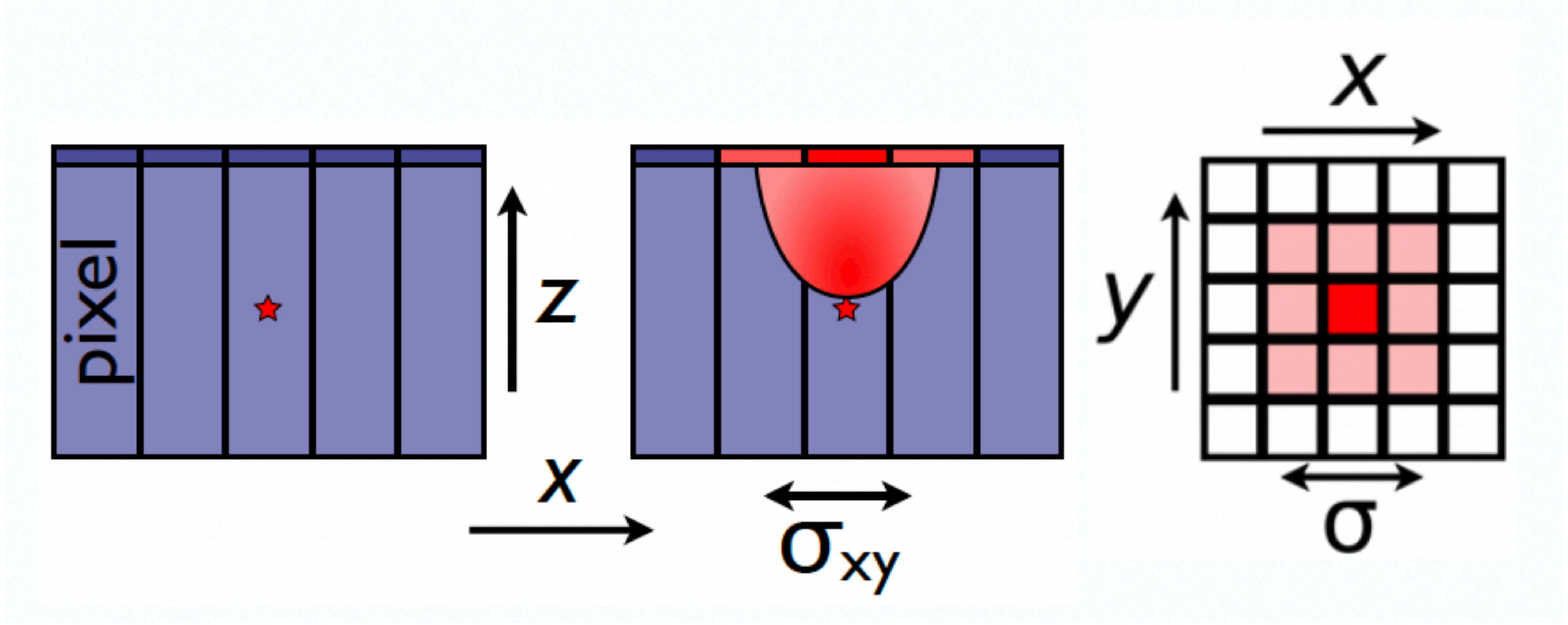
Credit: SuperCDMS Collaboration

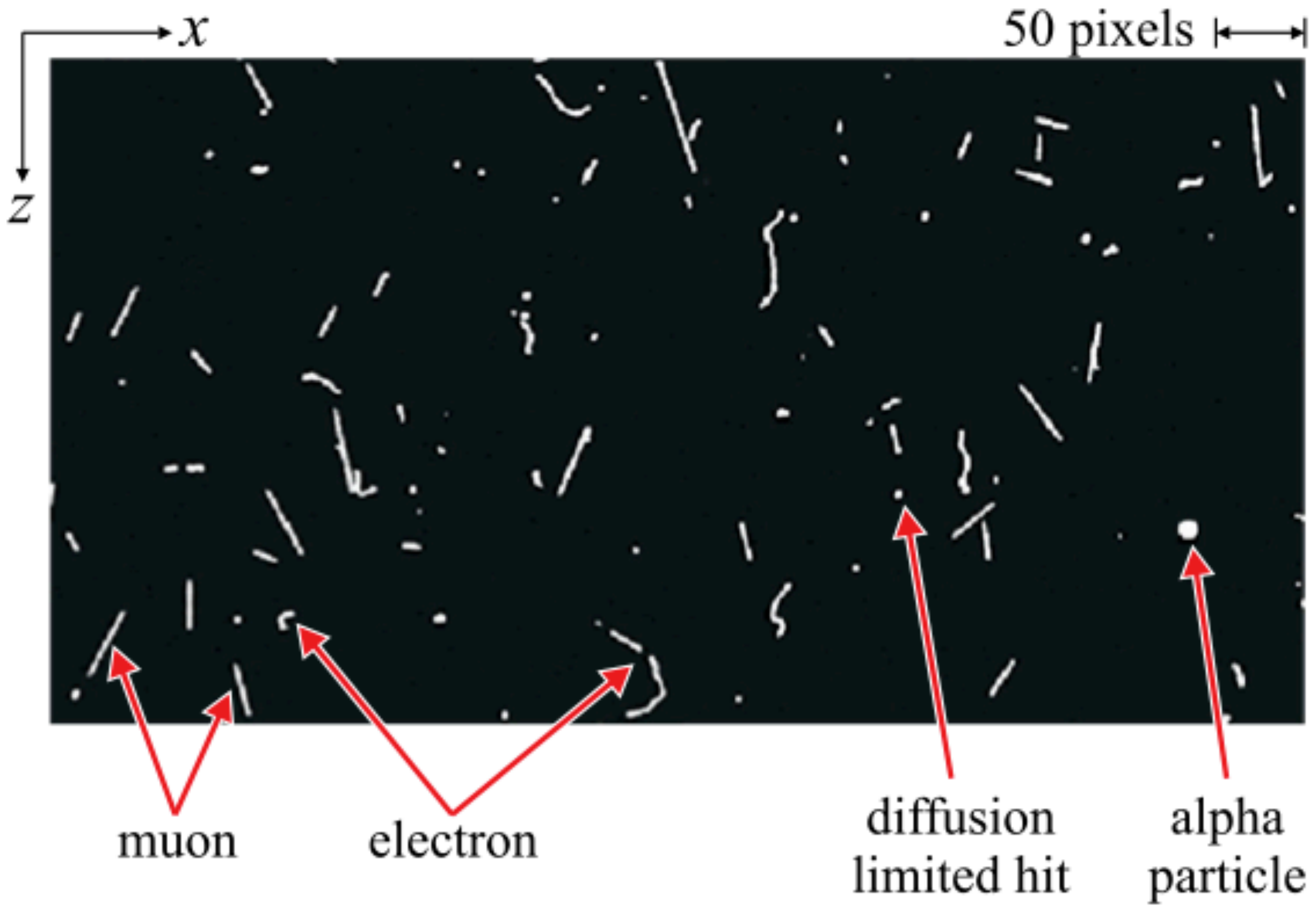
Credit: Jack Price's 1932 News Photography

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

CCD-based detectors: DAMIC



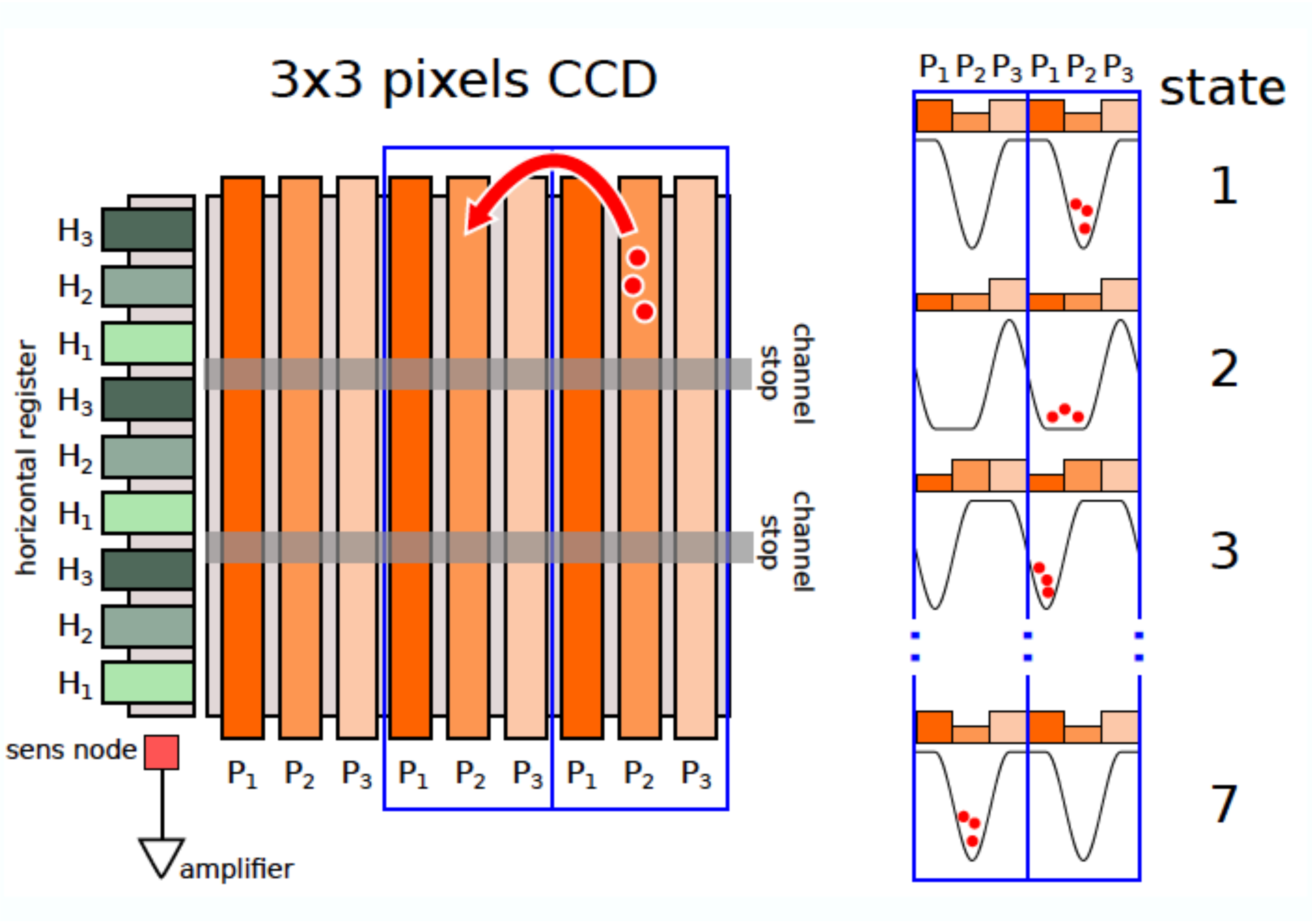




Pictures courtesy: DAMIC collaboration

CCD-based detectors: DAMIC

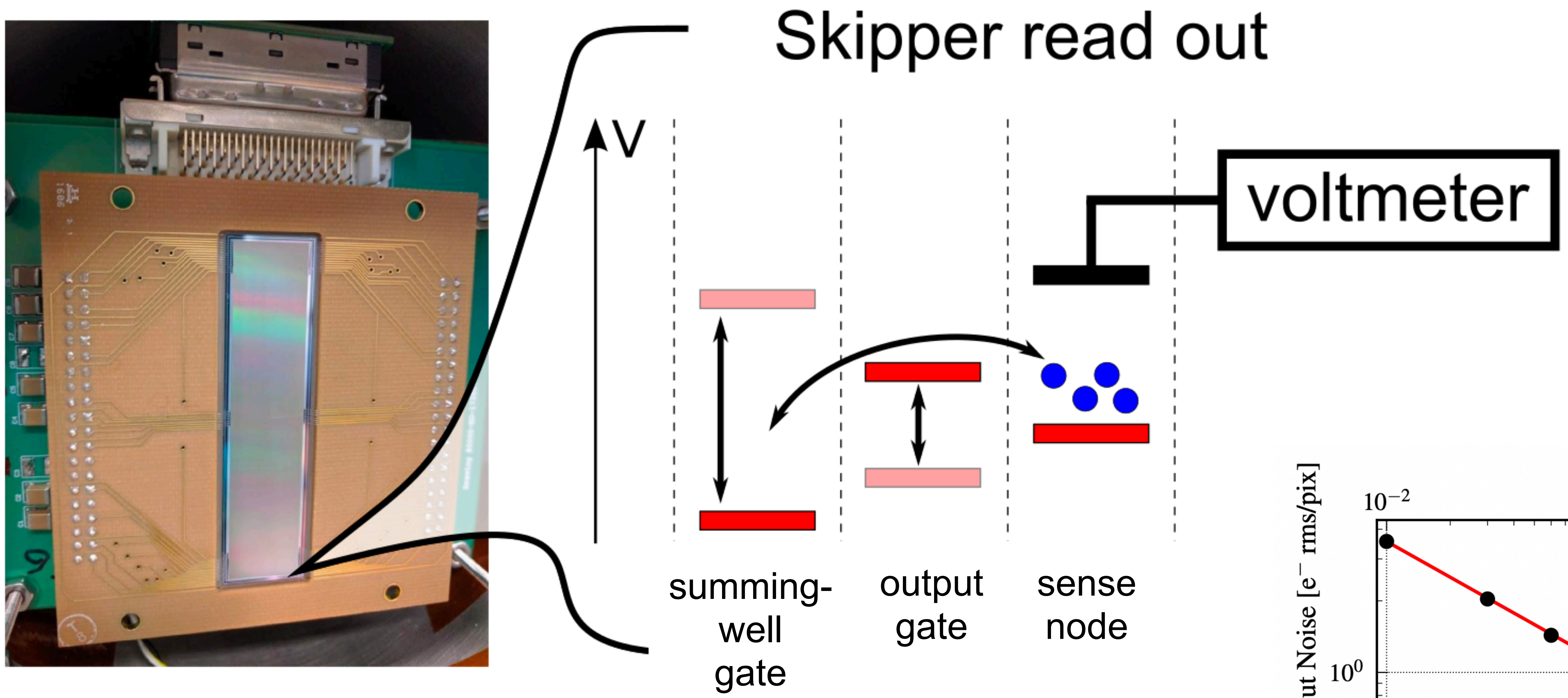
Serial readout

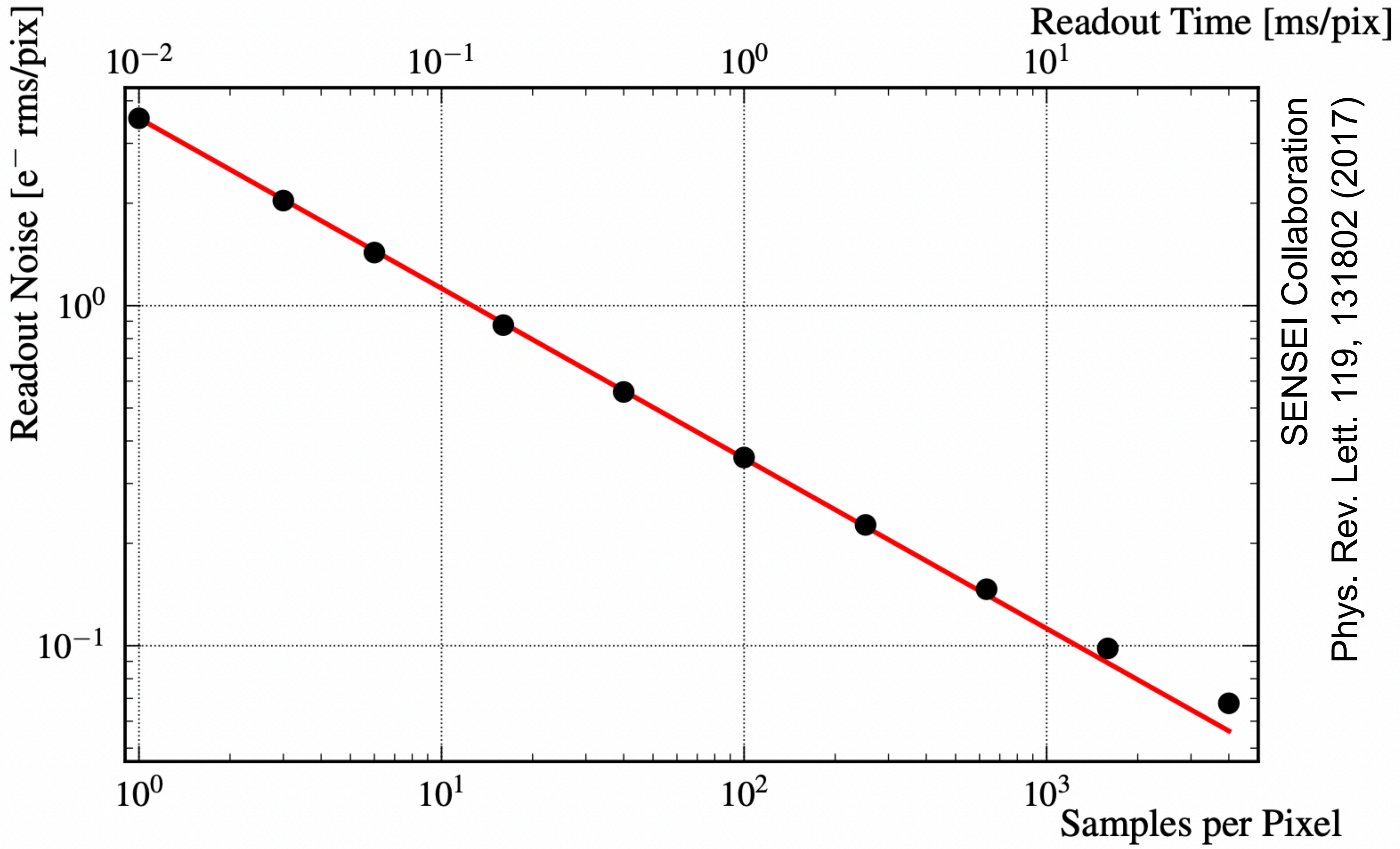


- Dark current negligible
- Each pixel readout induces 7.2 eV (2e$^-$) noise
- Number of readouts drives total noise

CCD-based detectors: SENSEI

Pictures courtesy: SENSEI collaboration

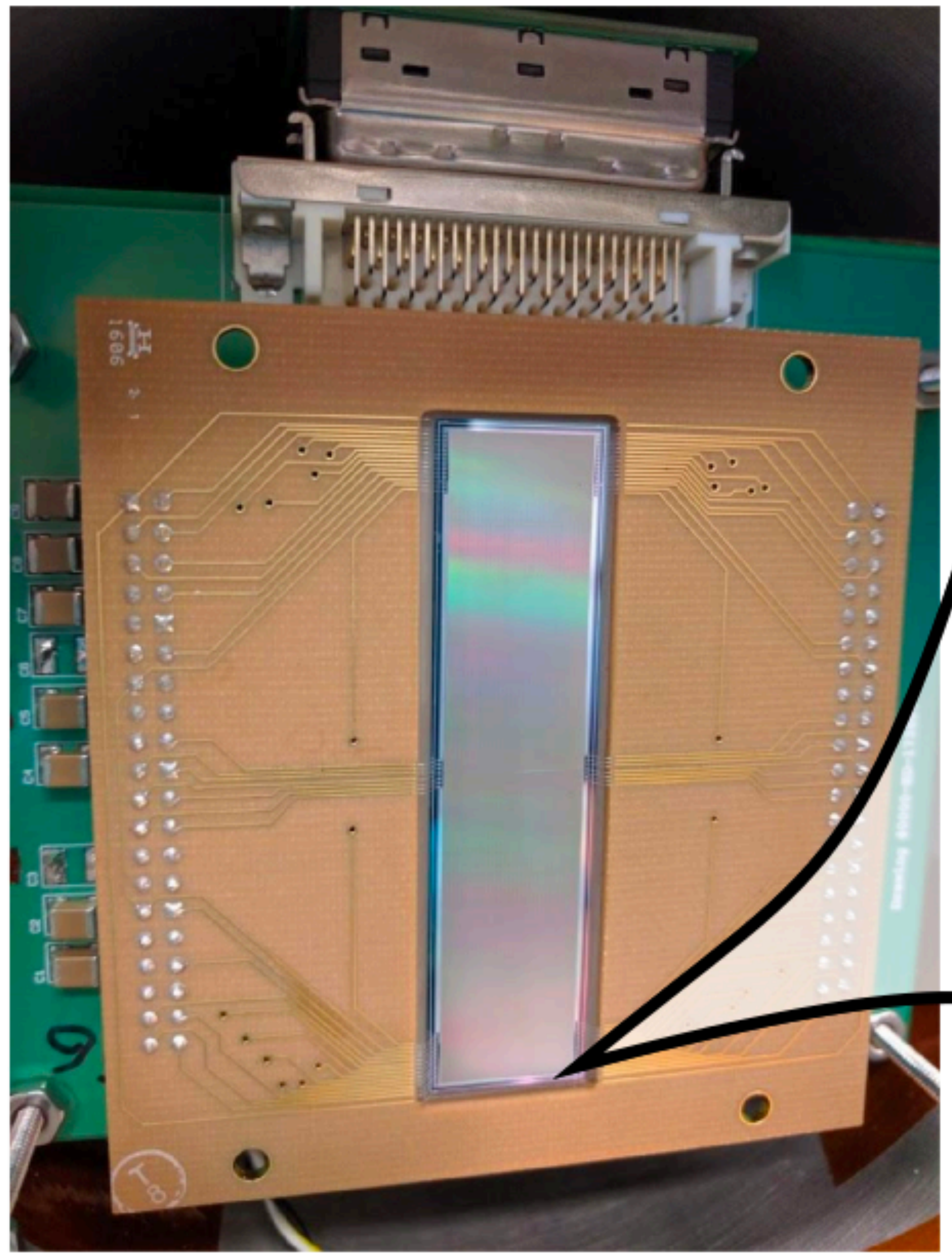


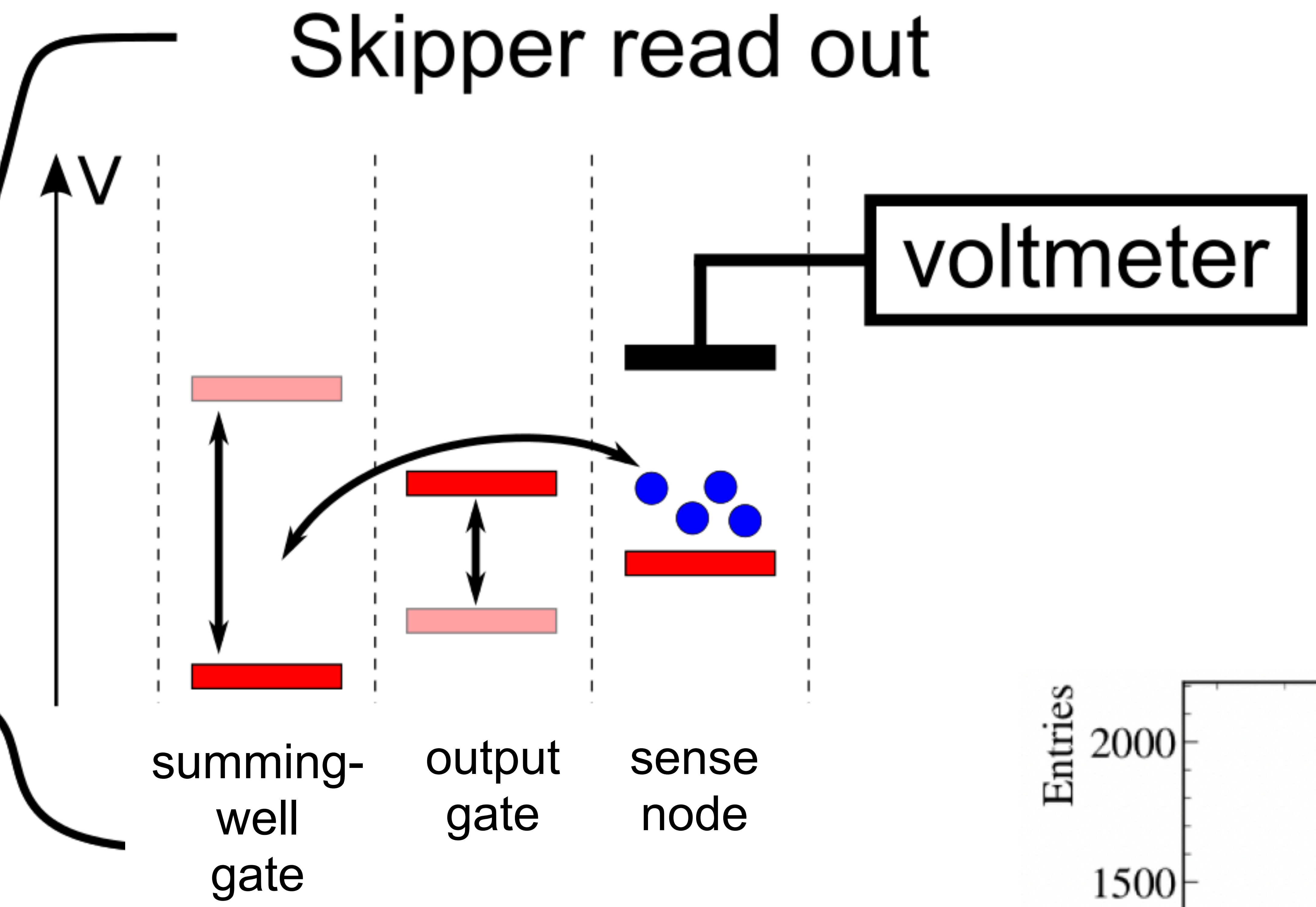


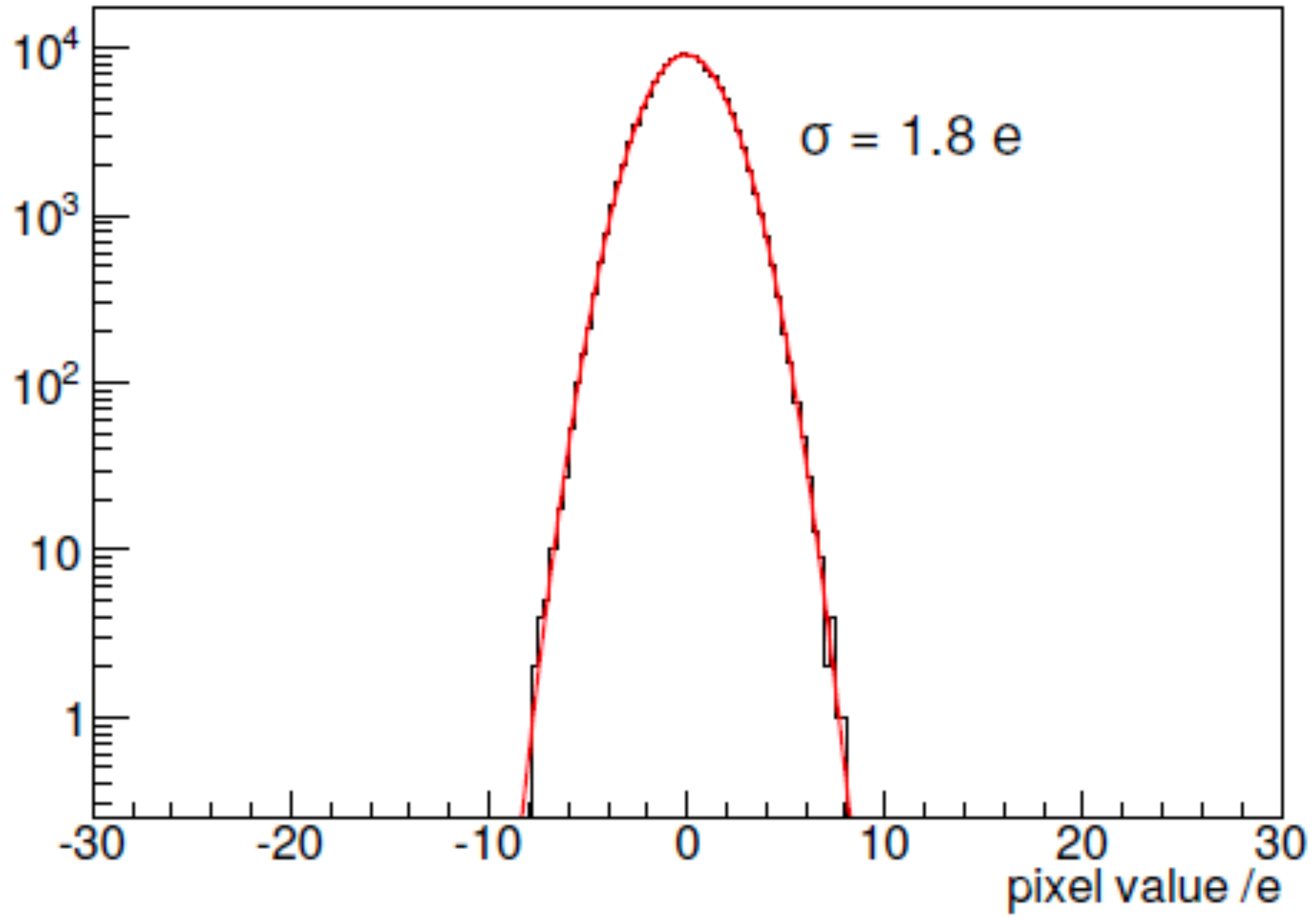
SENSEI Collaboration
Phys. Rev. Lett. 119, 131802 (2017)

- Sampling the same charge packet multiple times strongly reduces the observed readout noise

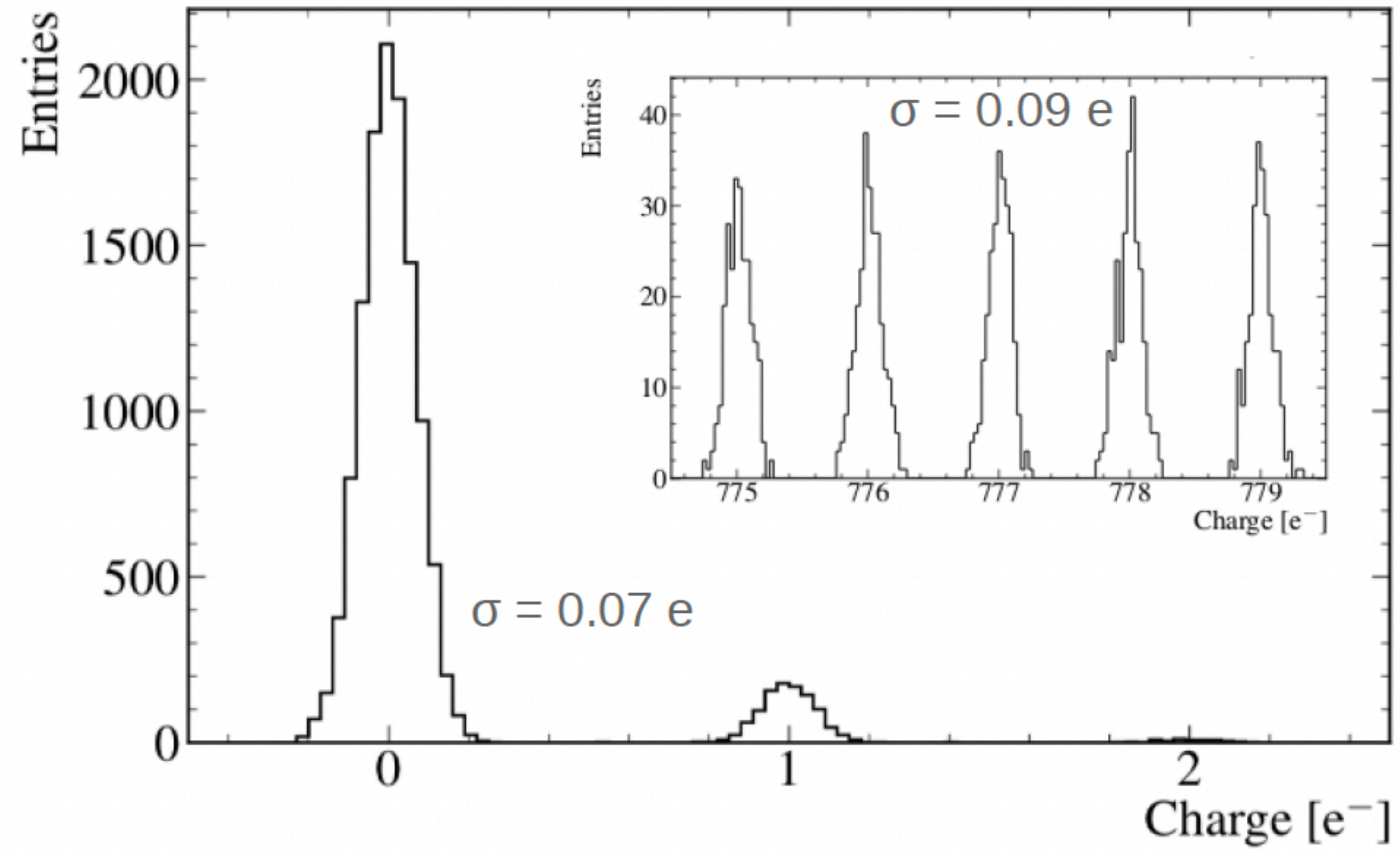
CCD-based detectors: SENSEI (and DAMIC-M)


Pictures courtesy: SENSEI collaboration





skipper CCD



SENSEI Collaboration, PRL 119, 131802 (2017)

- Sampling the same charge packet multiple times strongly reduces the observed readout noise

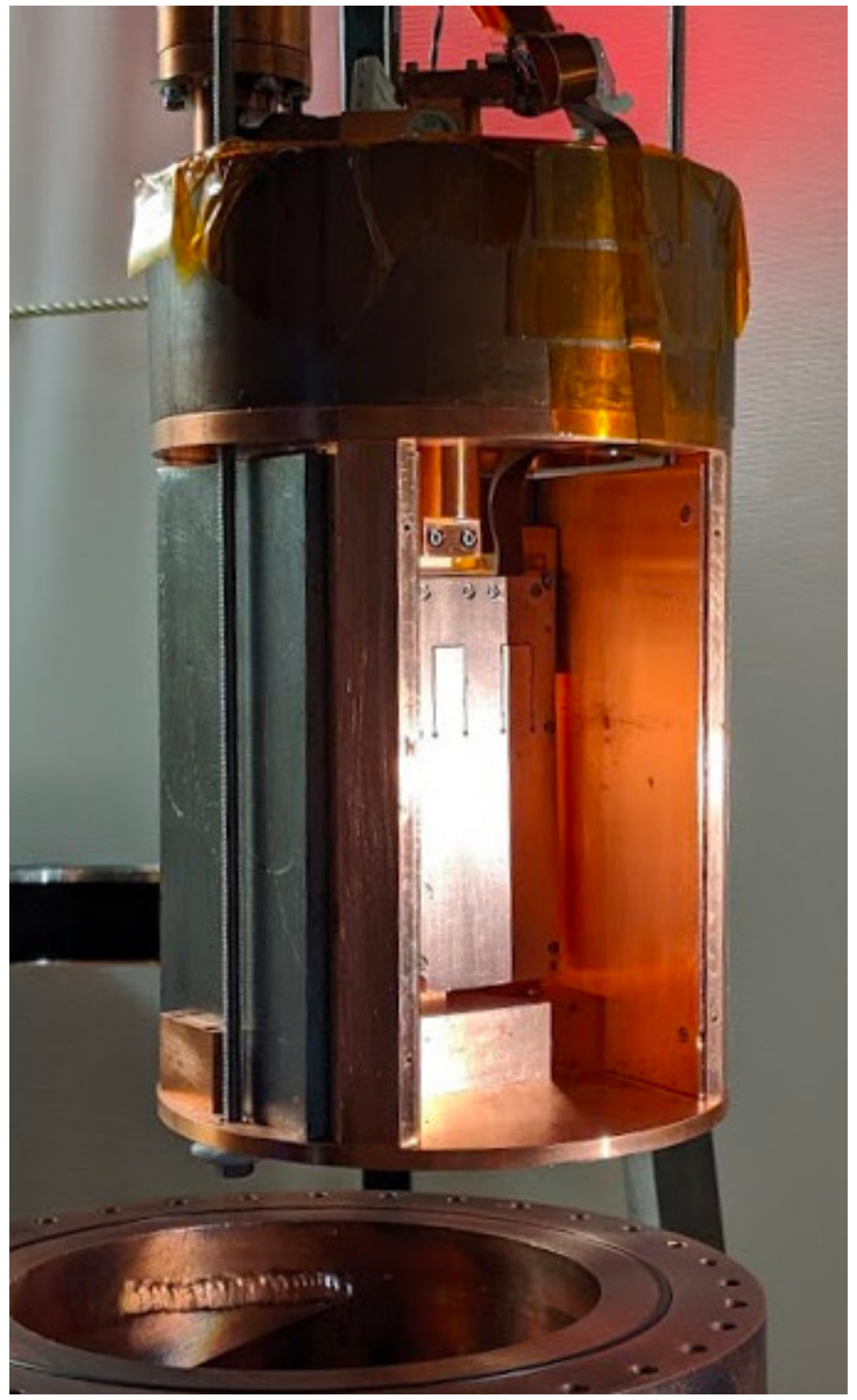
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

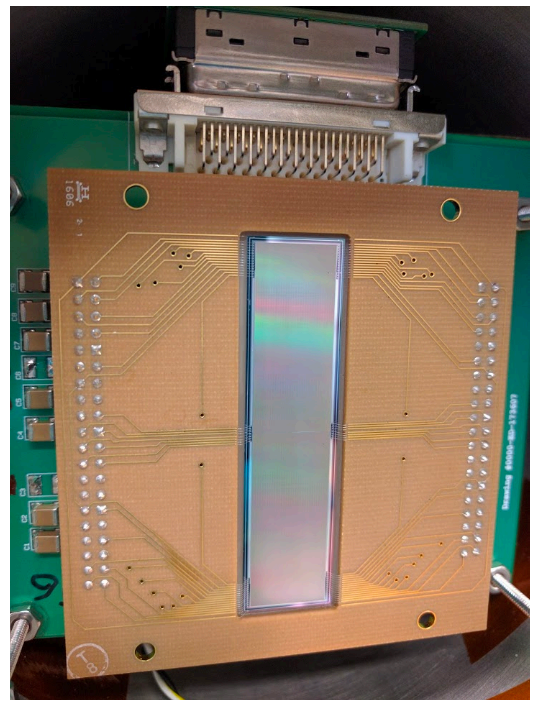
CCD-based: SENSEI & DAMIC

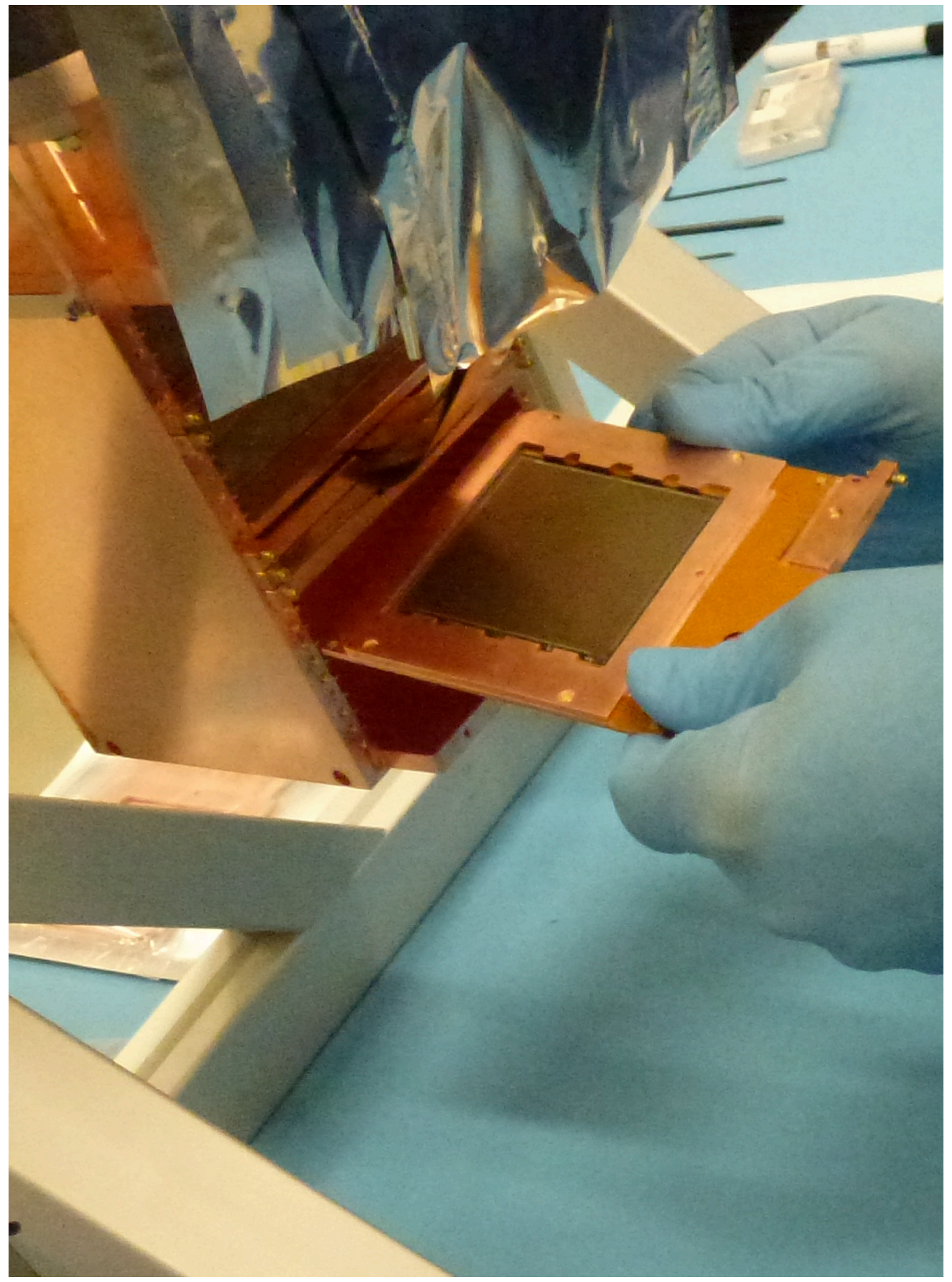
SENSEI

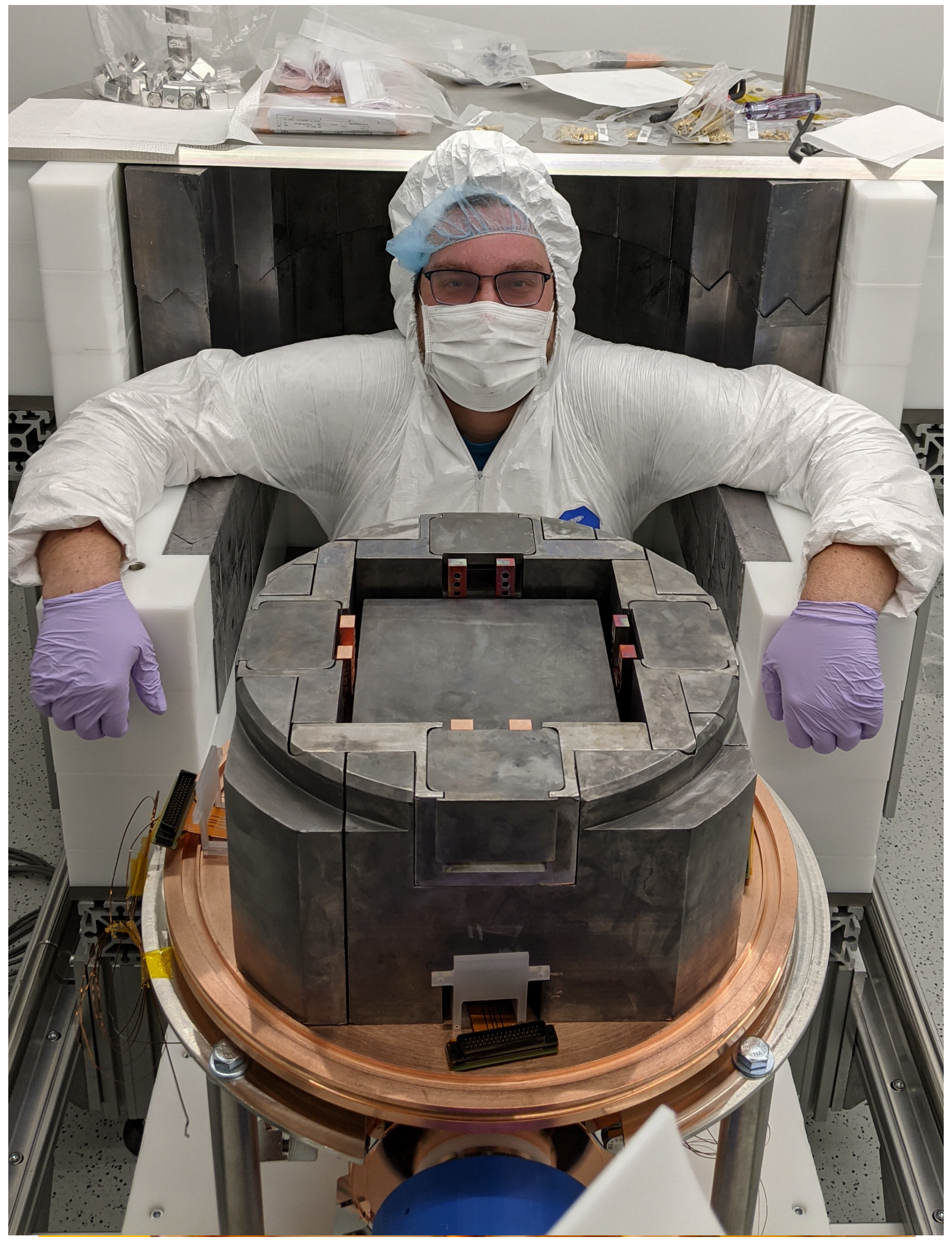
DAMIC / DAMIC-M

Pictures courtesy: SENSEI collaboration



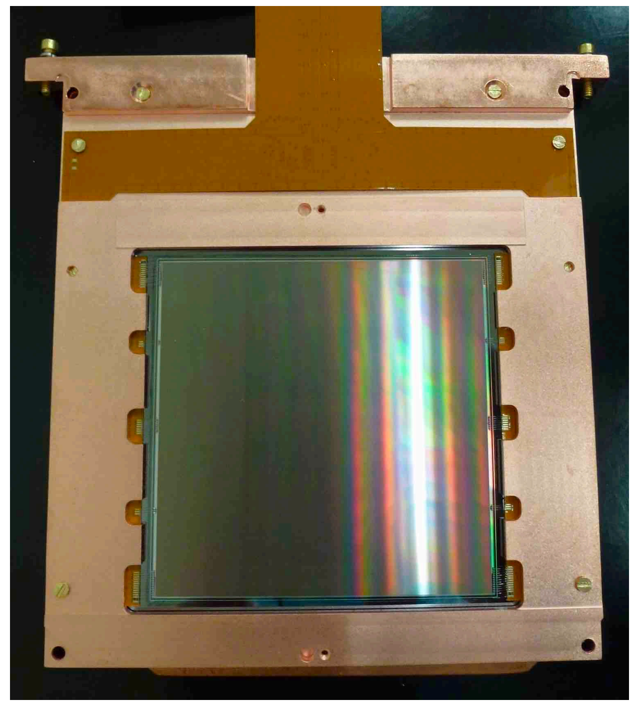






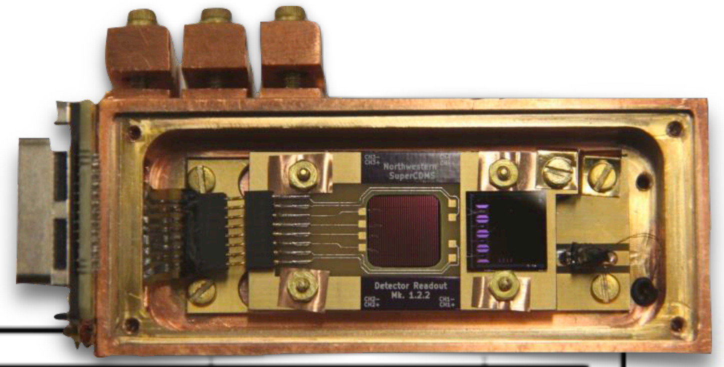
Pictures courtesy: DAMIC collaboration

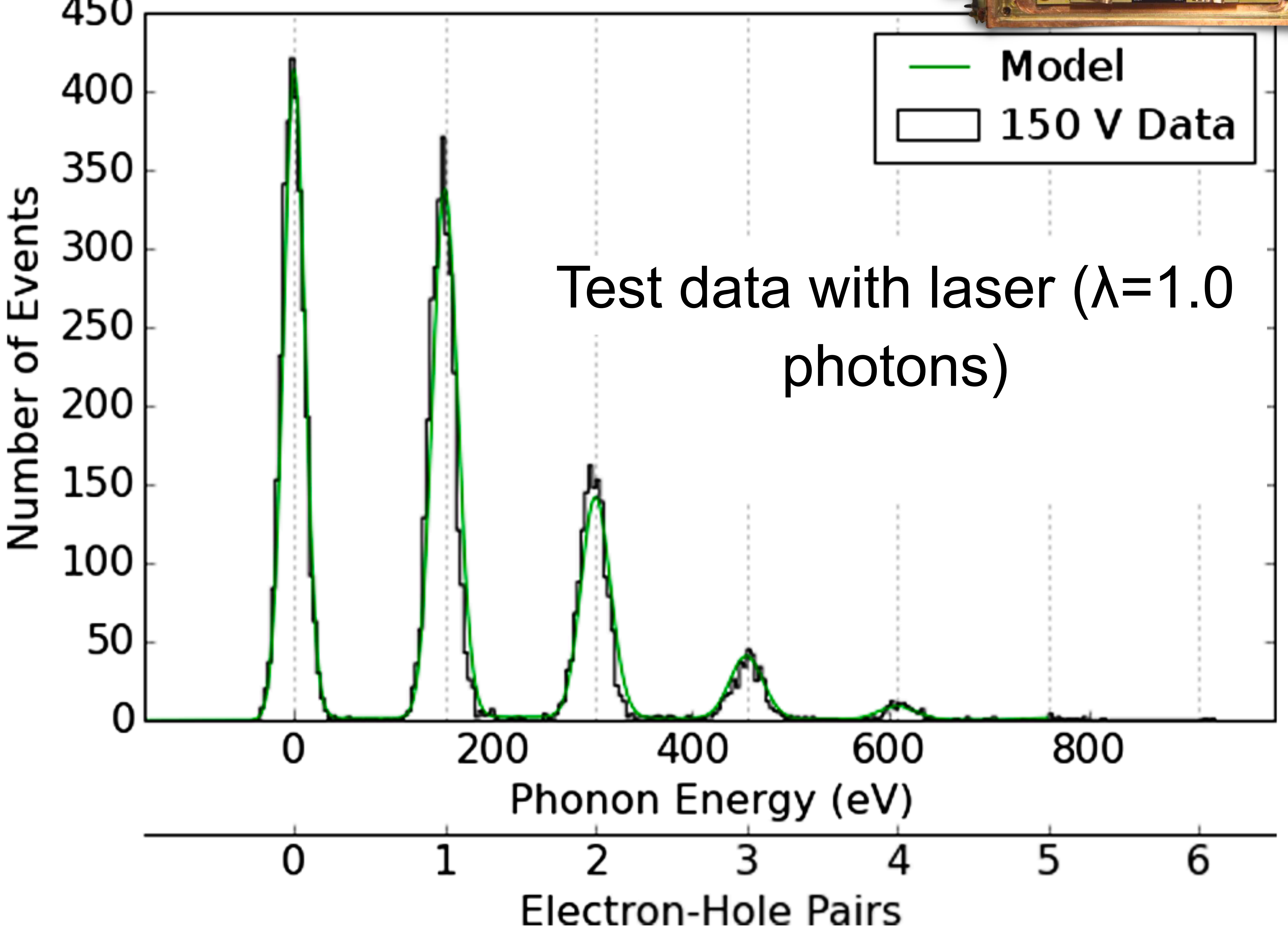
- High spatial and energy resolution but poor time resolution



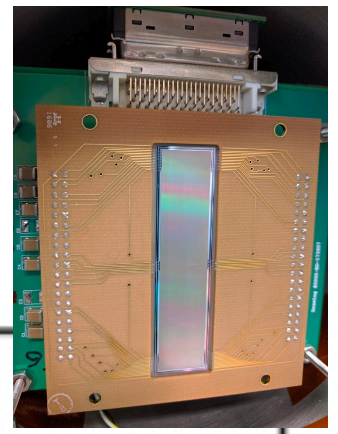
Single-charge sensitivities

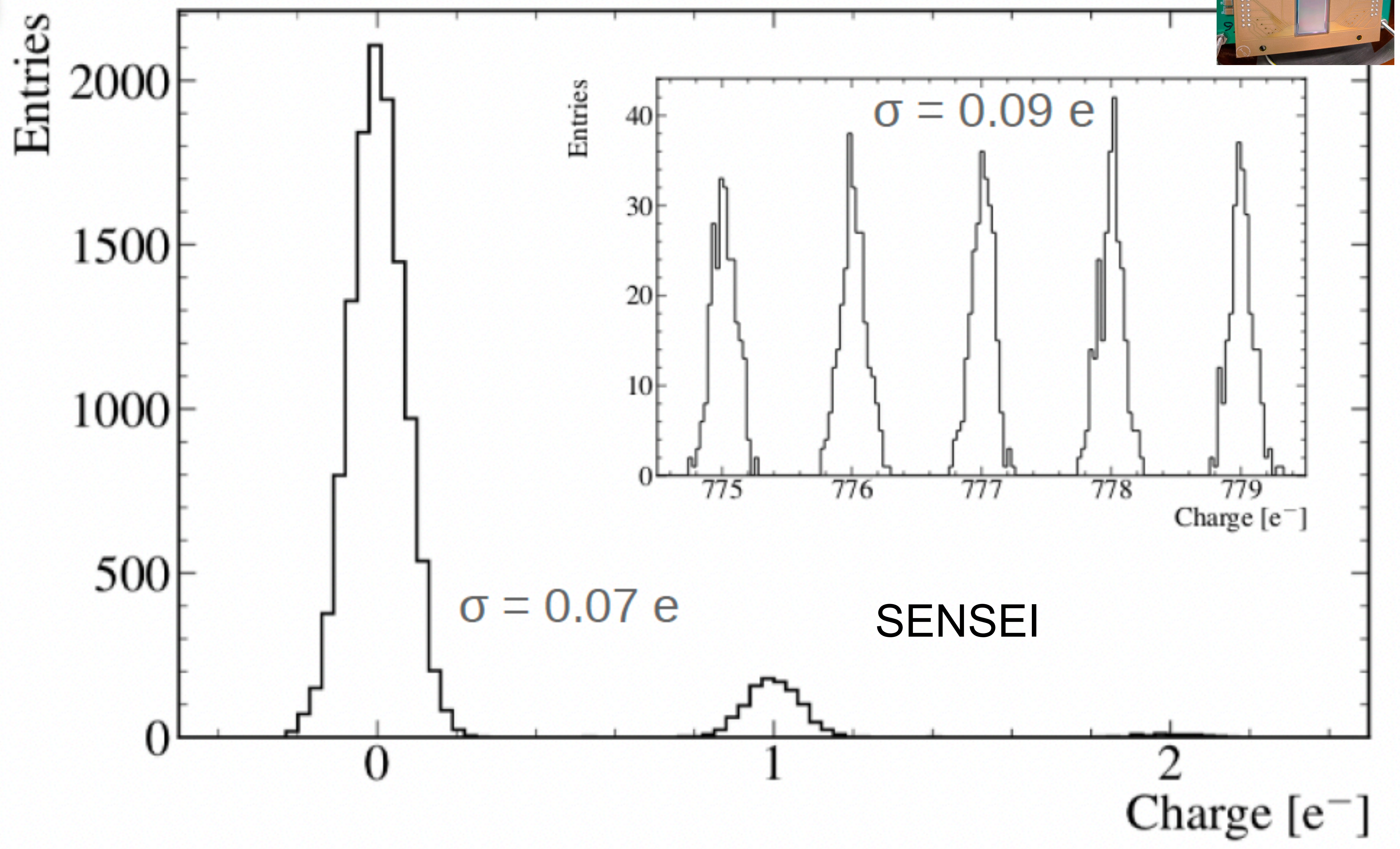
SuperCDMS





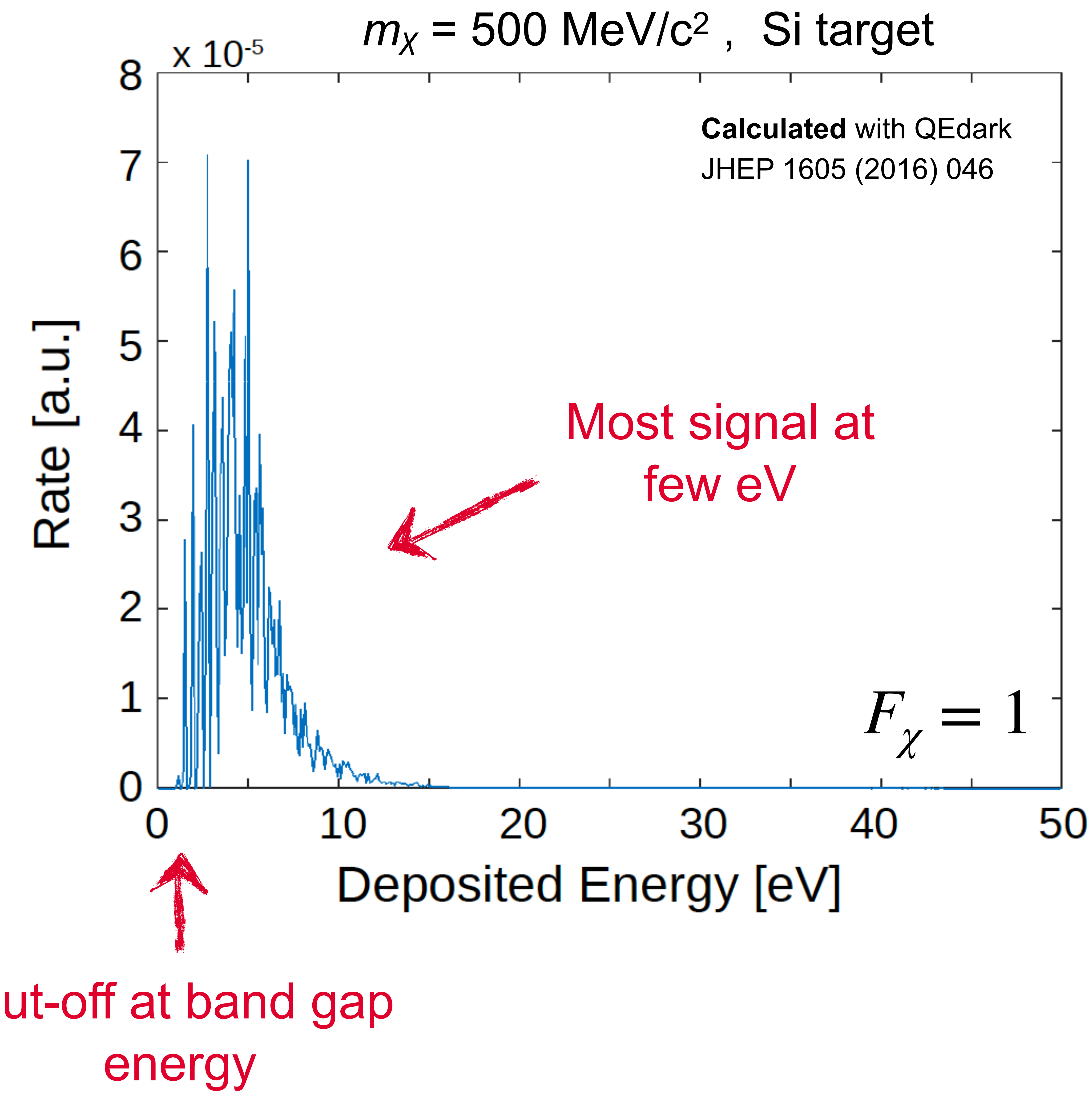
SENSEI





The signal is quantized!

Dark matter - electron scattering: signal model



- e⁻, not DM, sets typical momentum transfer:

$$q_{\mathrm{typ}} \sim \alpha m_{\mathrm{e}} \sim 4\,\mathrm{keV}$$

- Transferred energy:

$$\Delta E_{\mathrm{e}} \sim \vec{q} \cdot \vec{v}$$

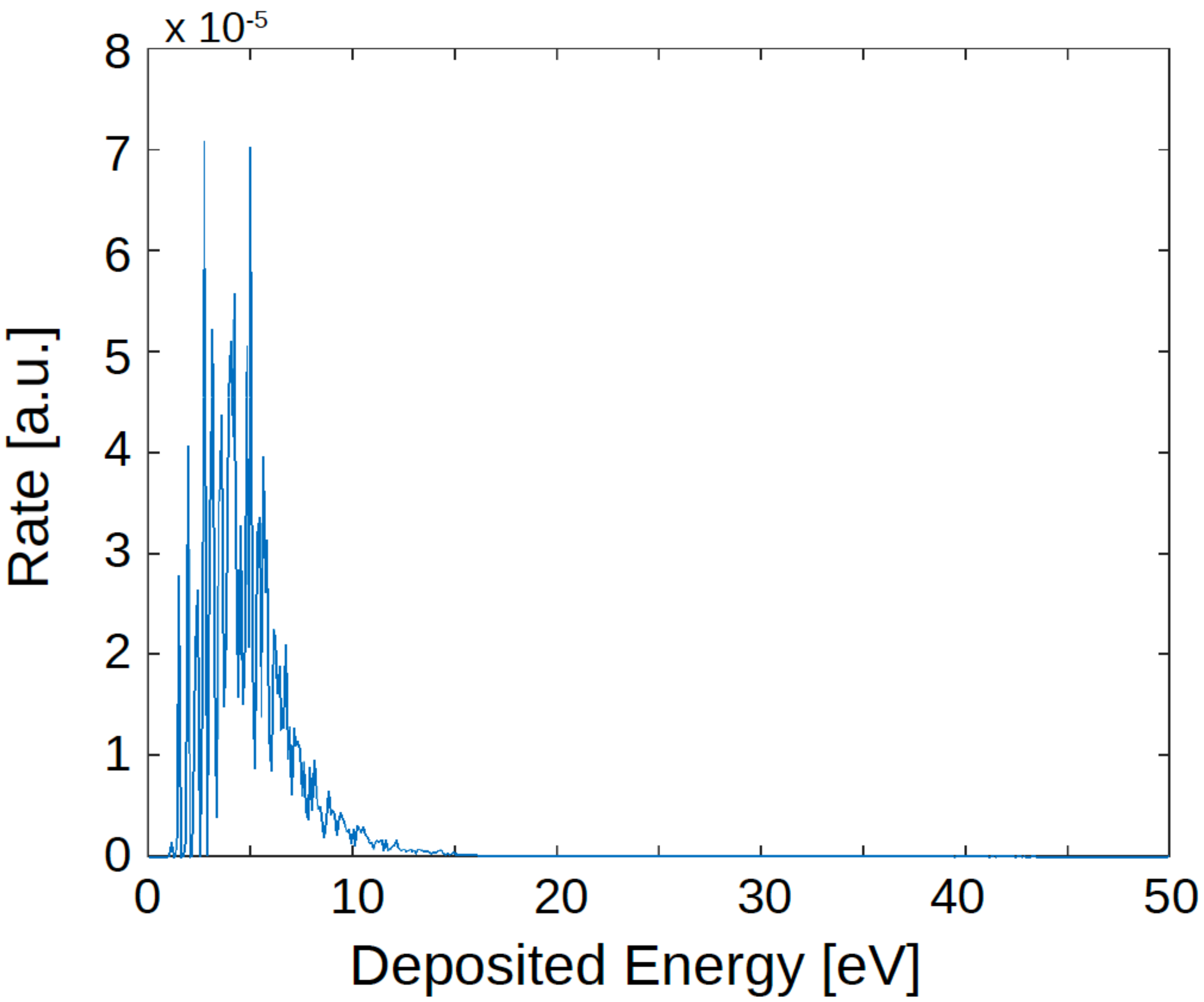
- Typical recoil energy:

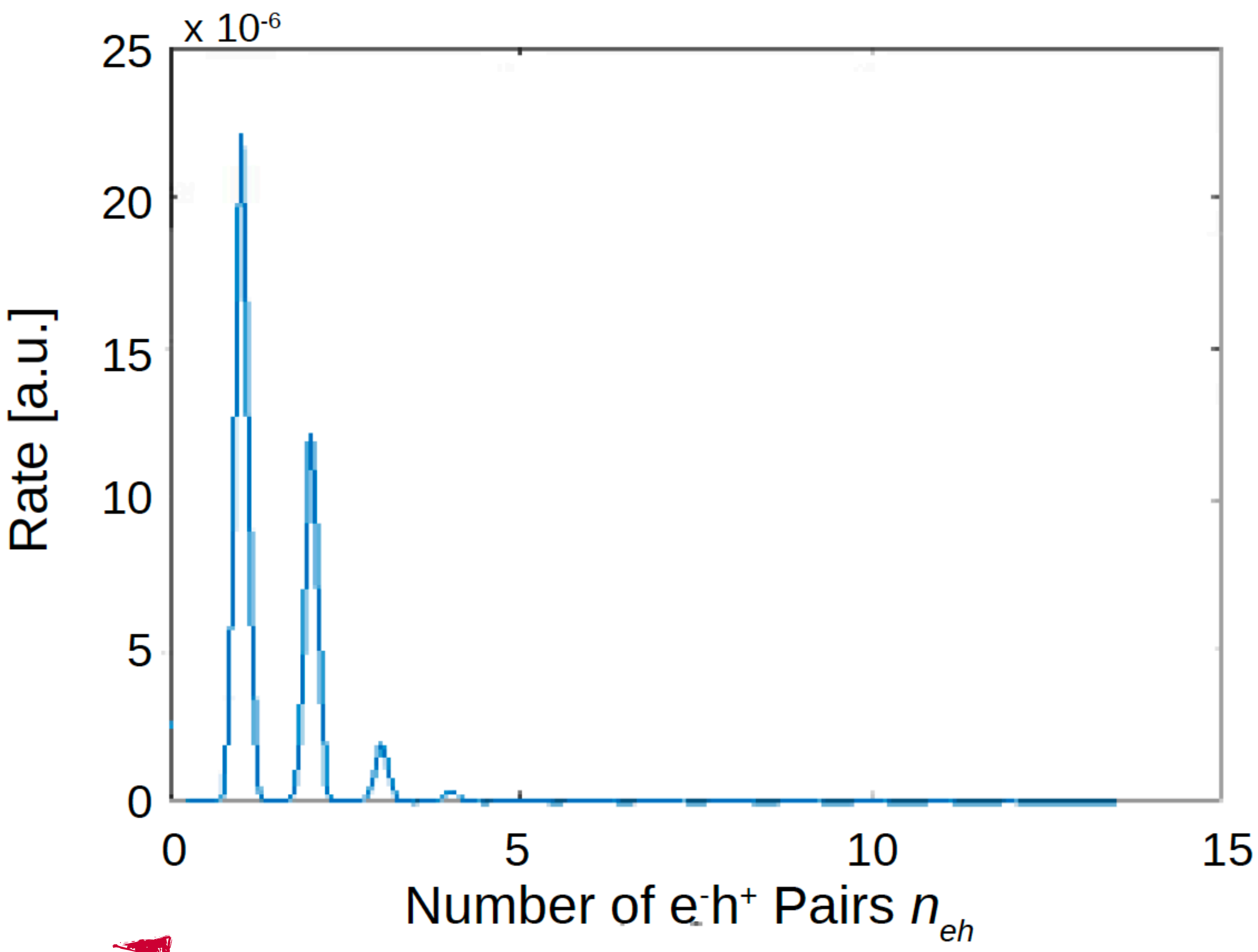
$$\Delta E_{\mathrm{typ}} \approx 4\,\mathrm{eV}$$

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

From continuous to quantized signal

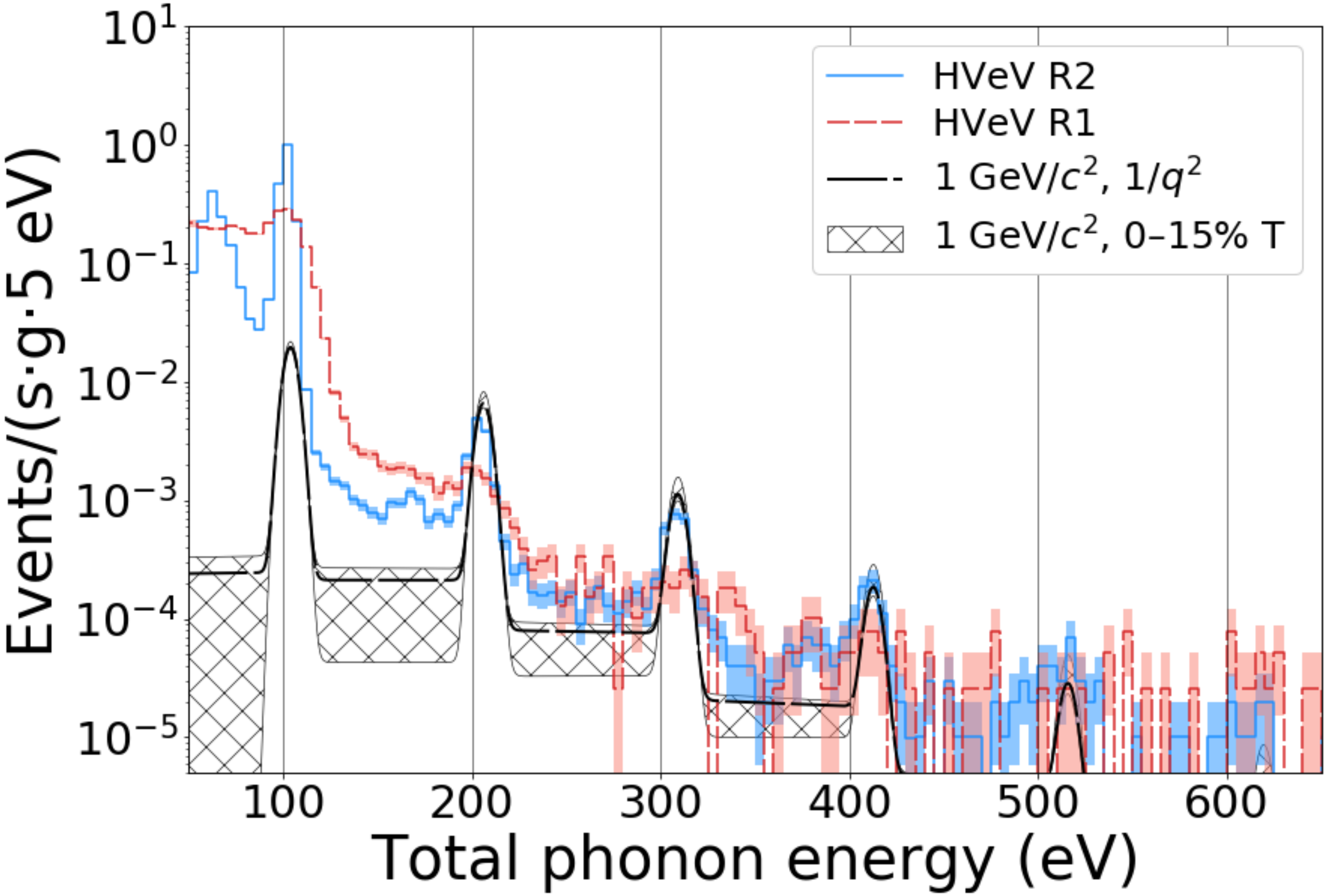
m_χ = 500 MeV/c^2 , Si target





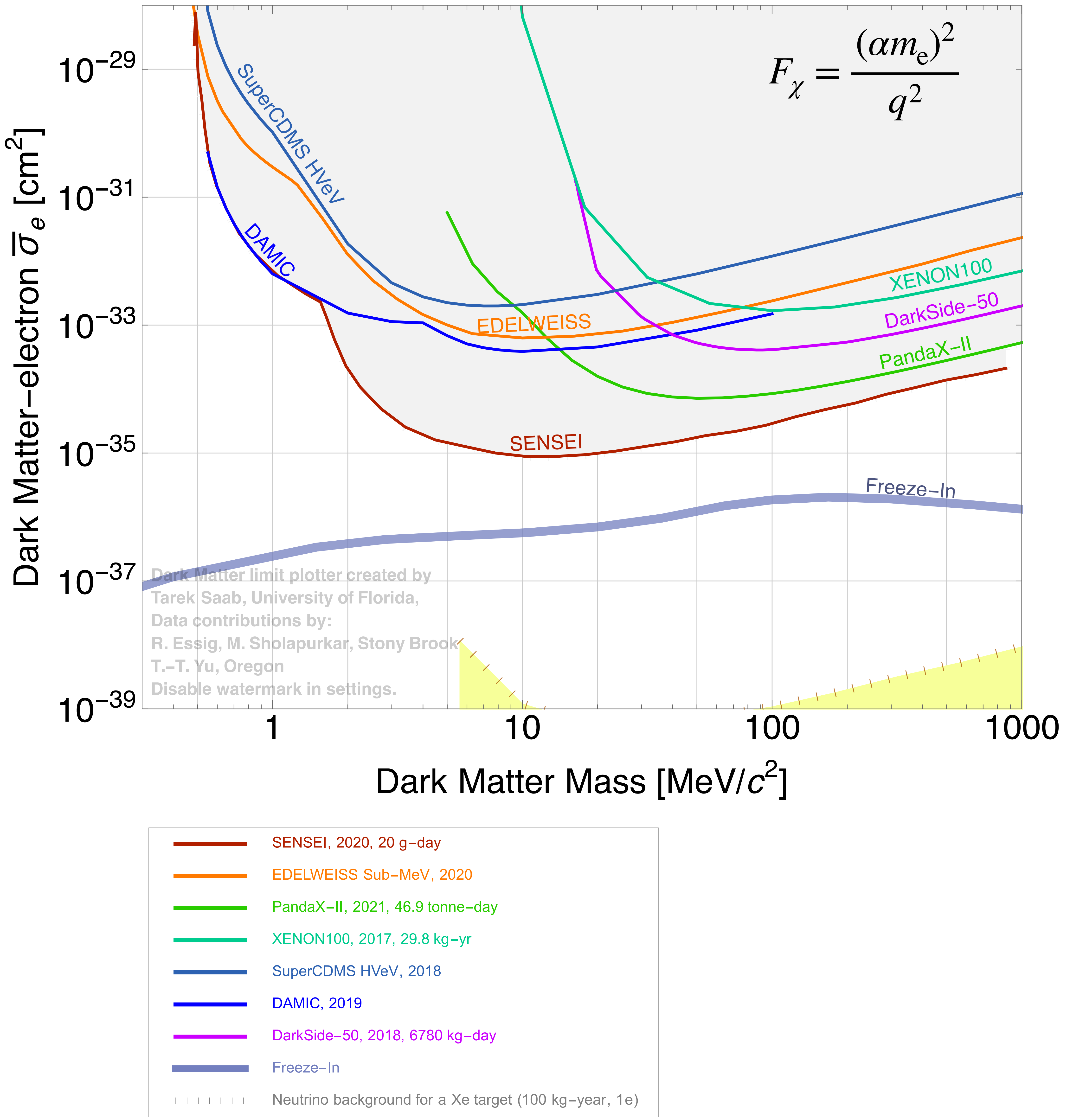
Ionization model

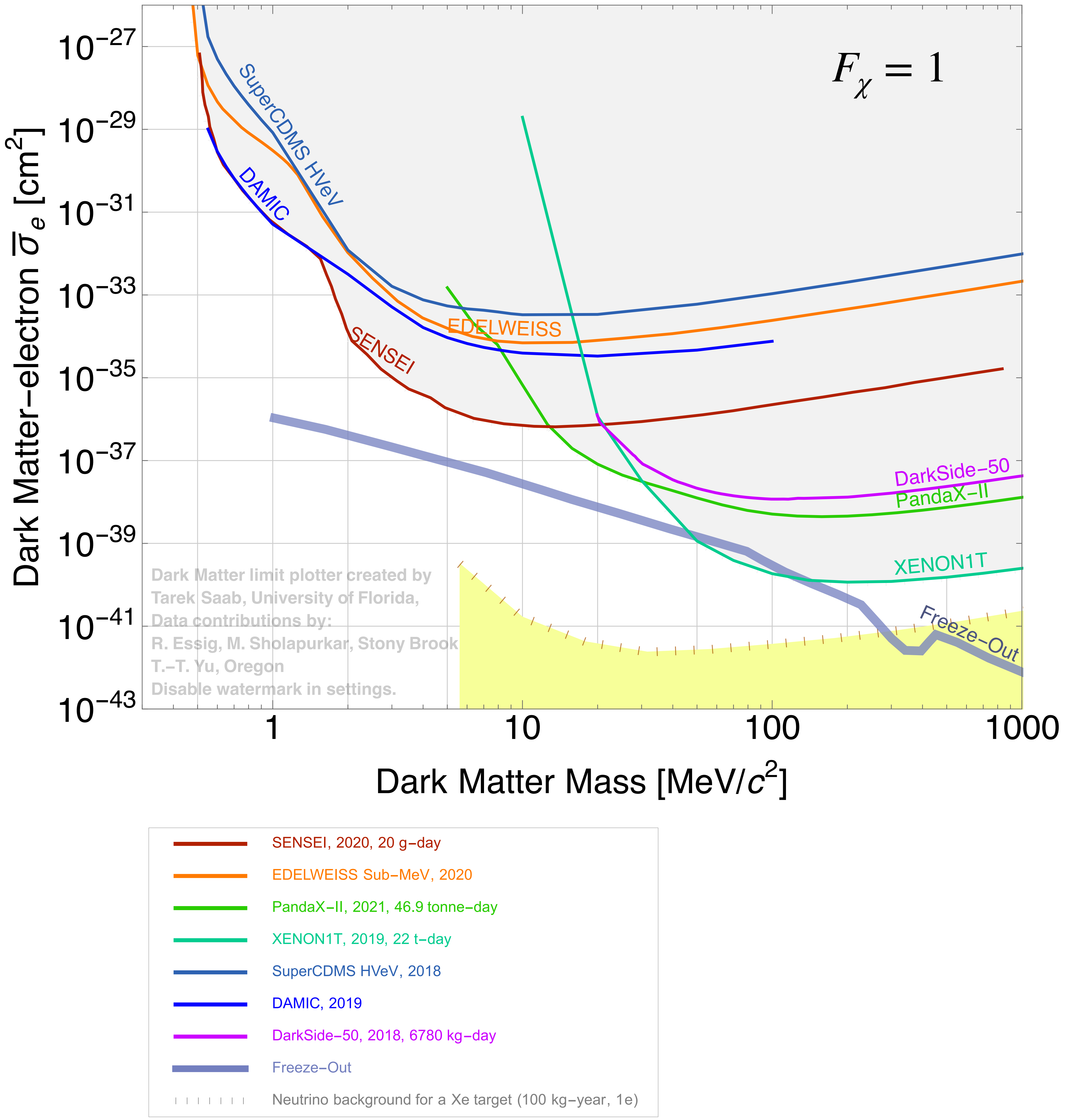
SuperCDMS dark matter - electron scattering search



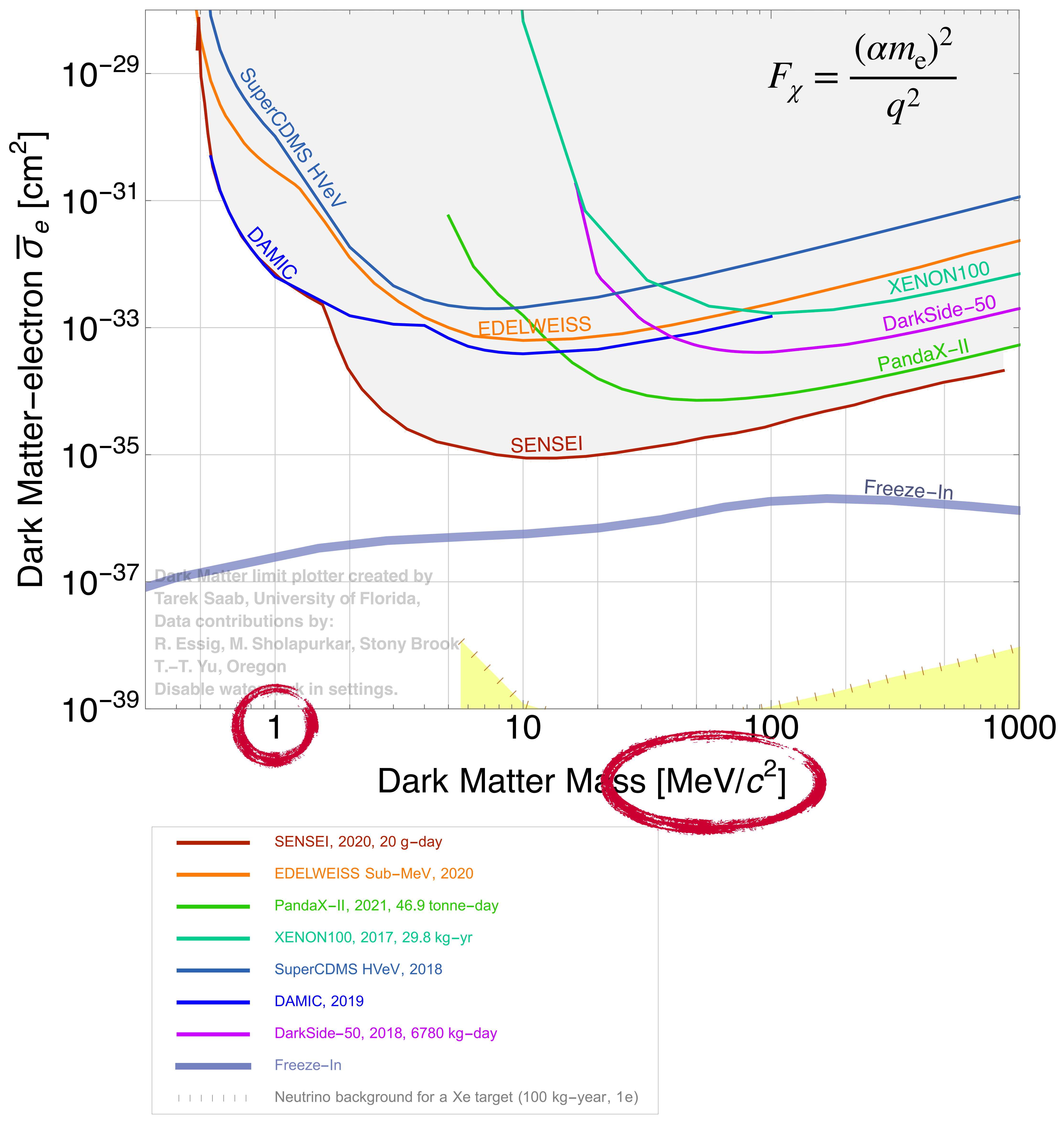
Credit: SuperCDMS Collaboration

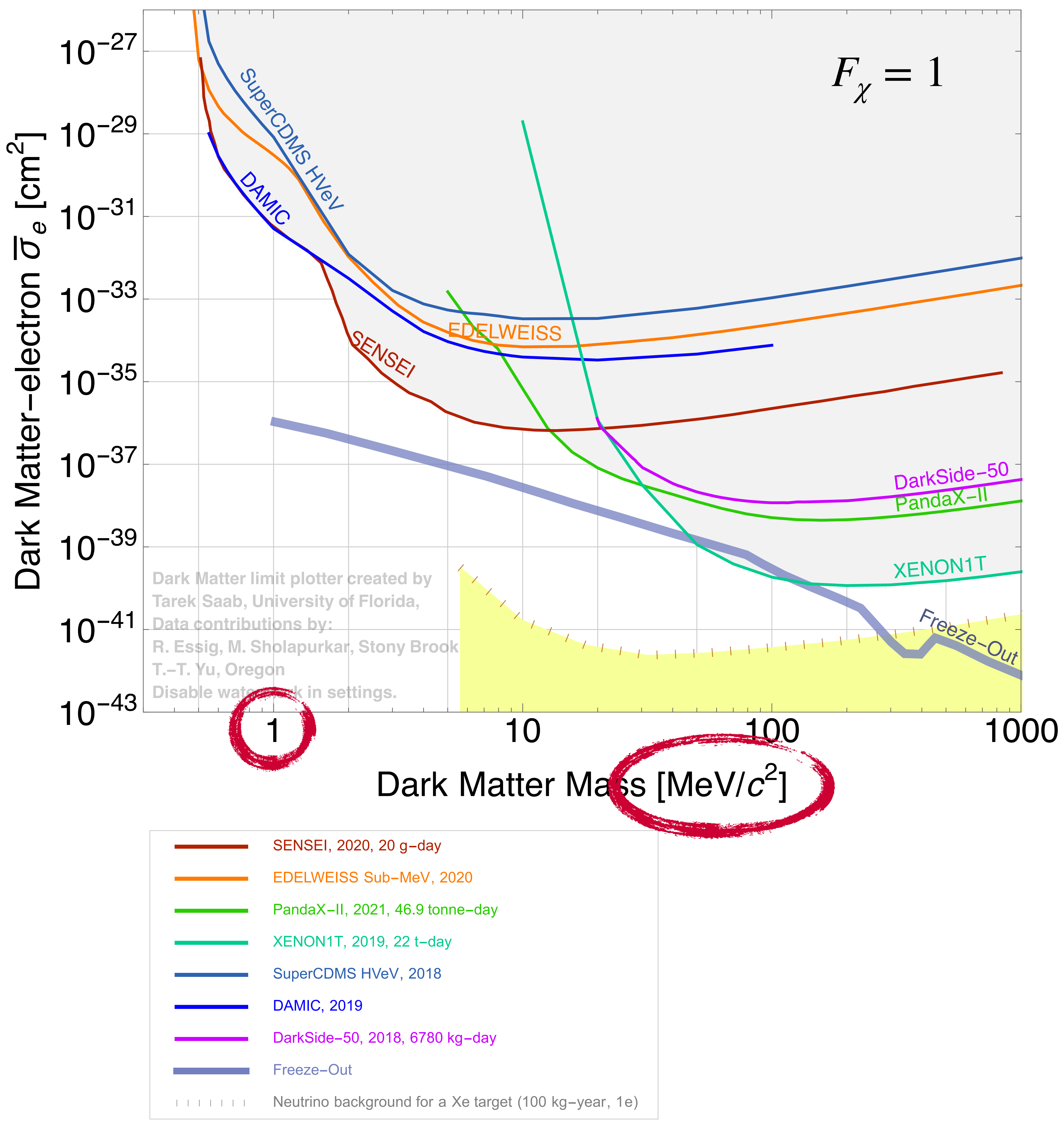
Dark matter - electron scattering parameter space





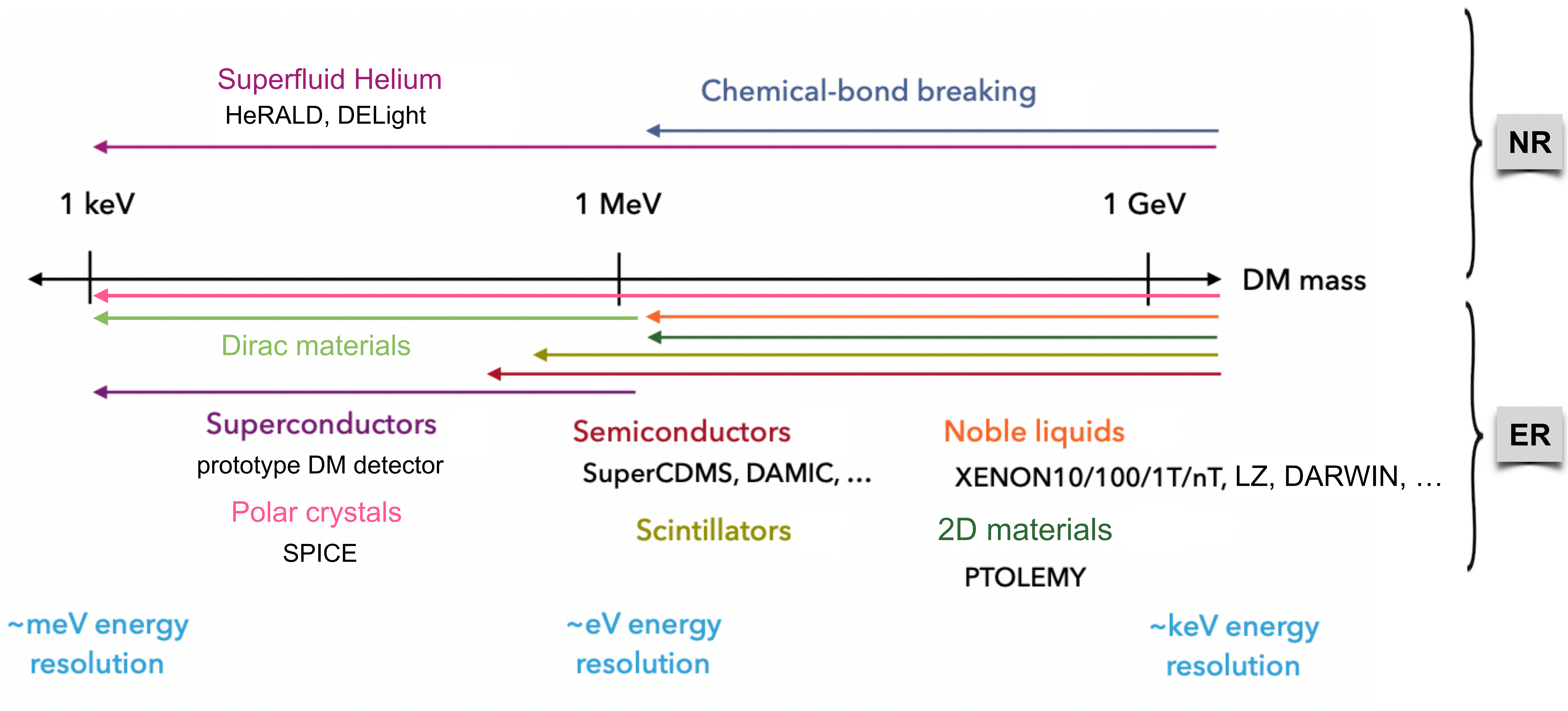
Dark matter - electron scattering parameter space





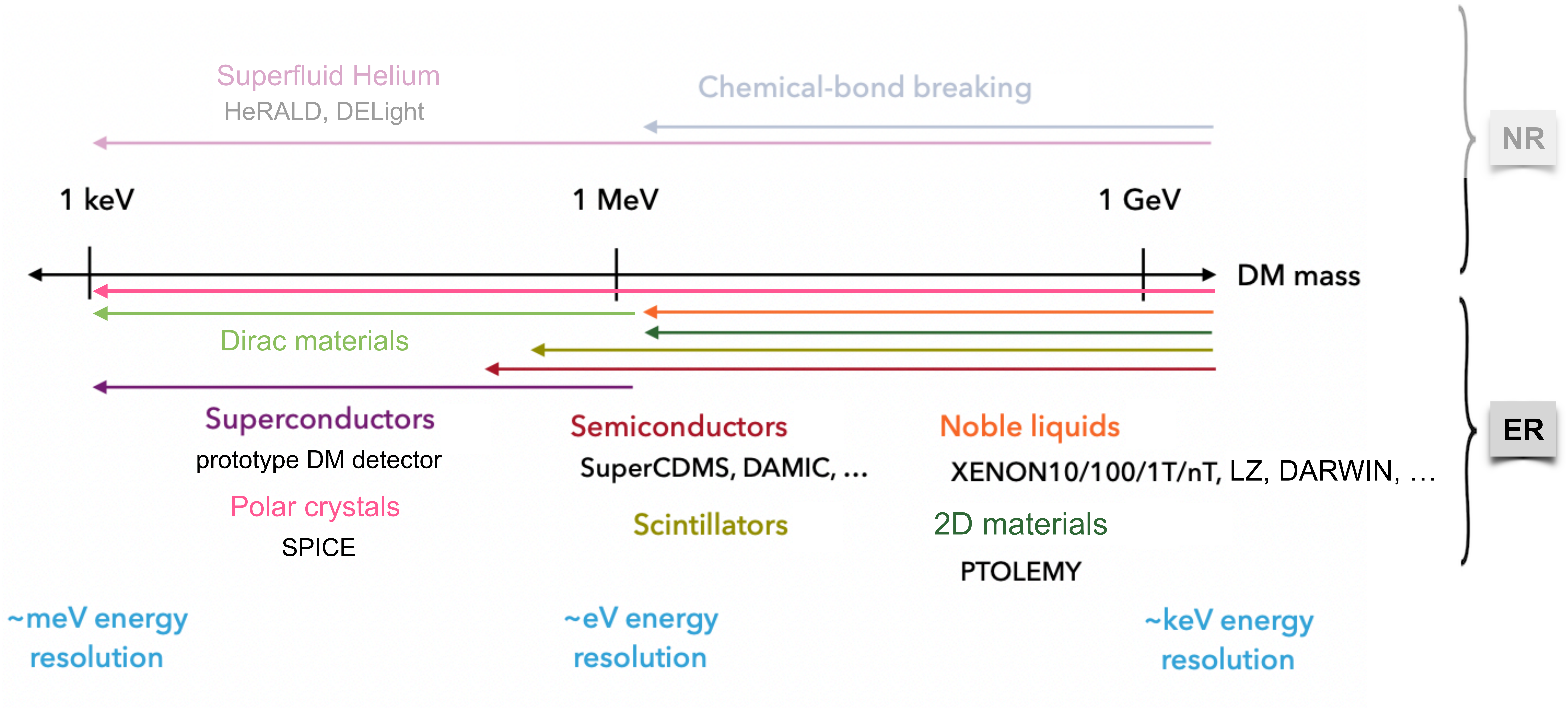
New avenues

New Avenues for LDM Direct Detection



Dark Sectors 2016 Workshop: Community Report
arXiv:1608.08632 [hep-ph], (2016)

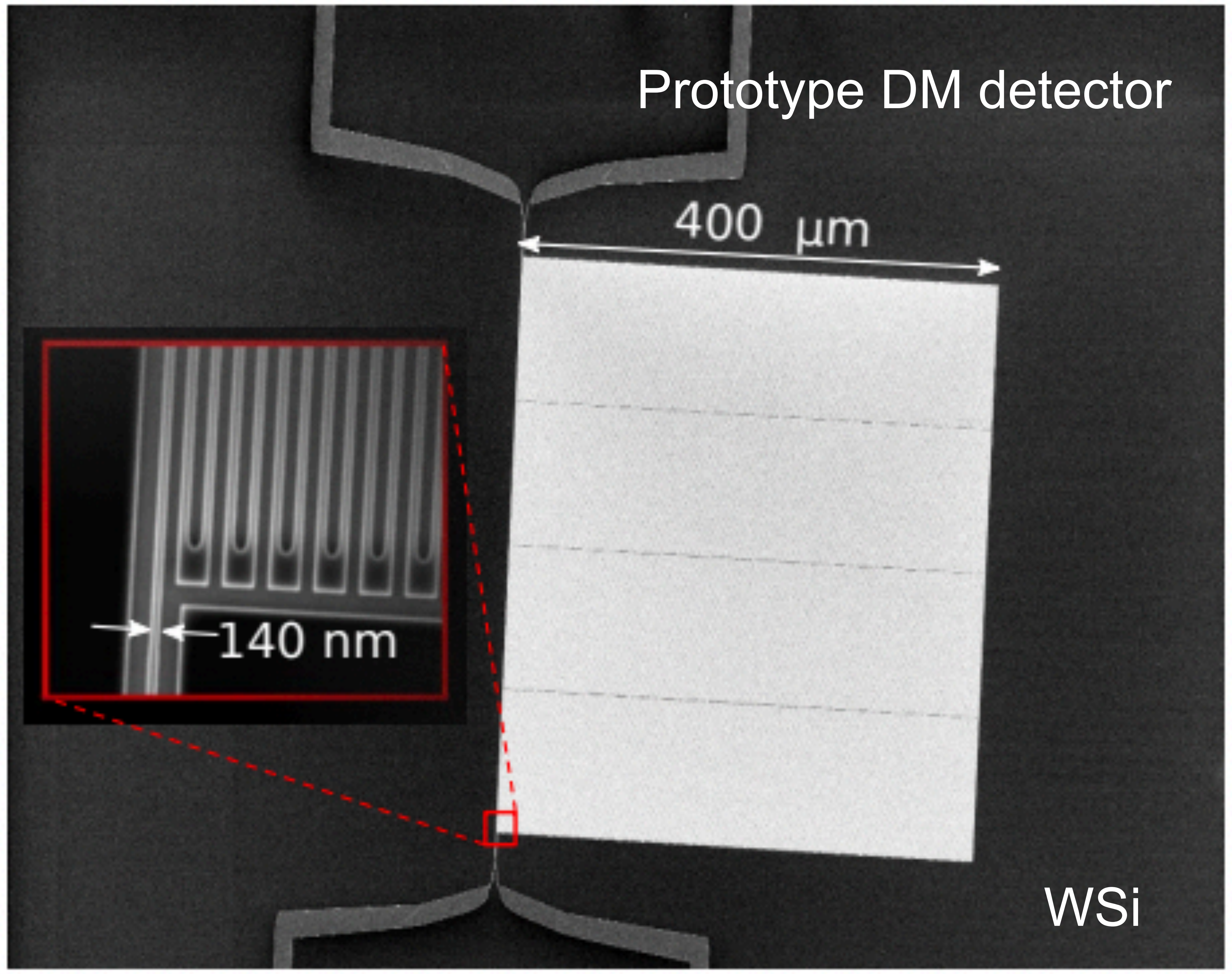
New Avenues for LDM Direct Detection

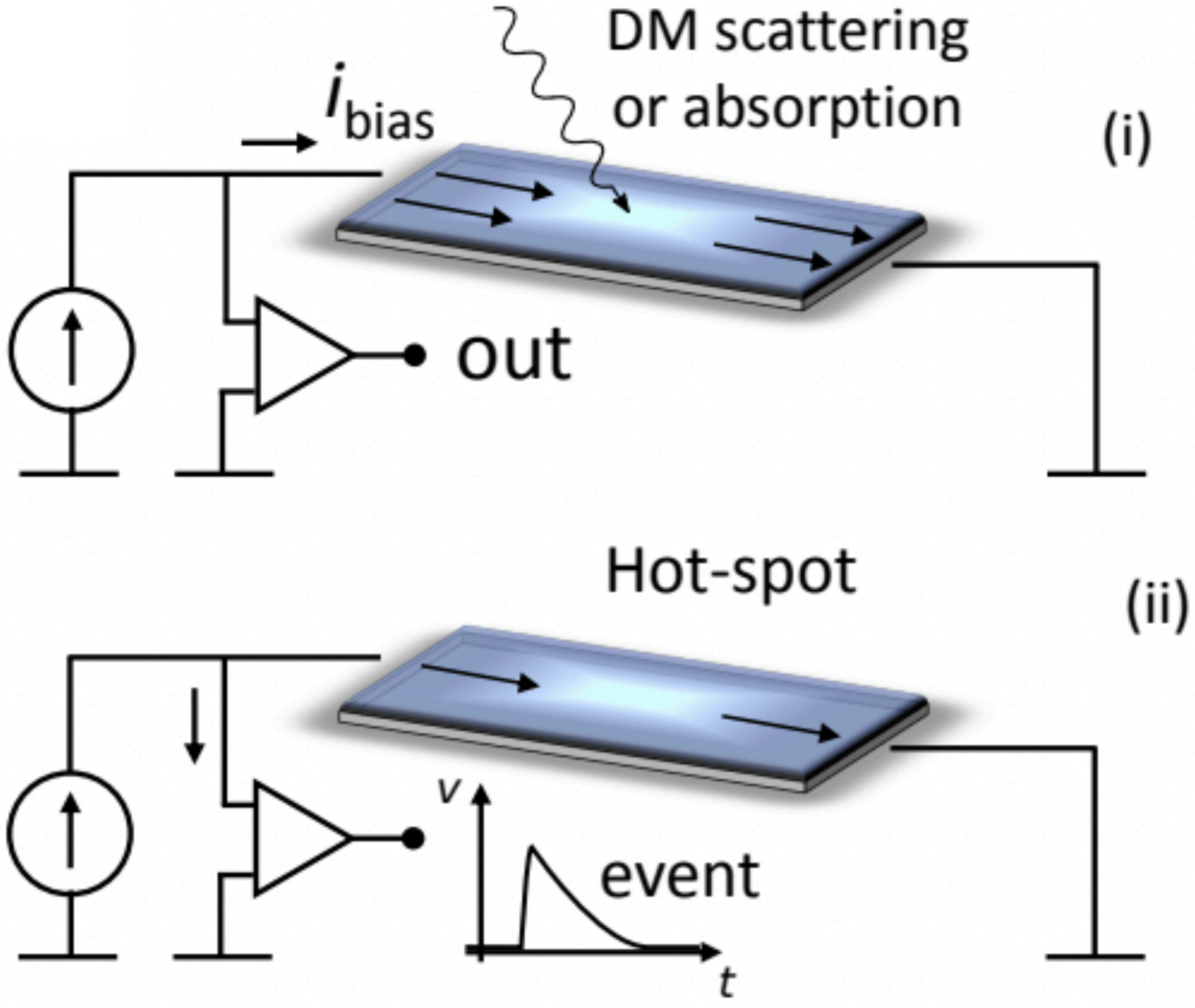


Dark Sectors 2016 Workshop: Community Report
arXiv:1608.08632 [hep-ph], (2016)

Superconducting Nanowire Single Photon Detector (SNSPD)

Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M Colangelo, K.K. Berggren
Phys. Rev. Lett. 123, 151802, (2019)

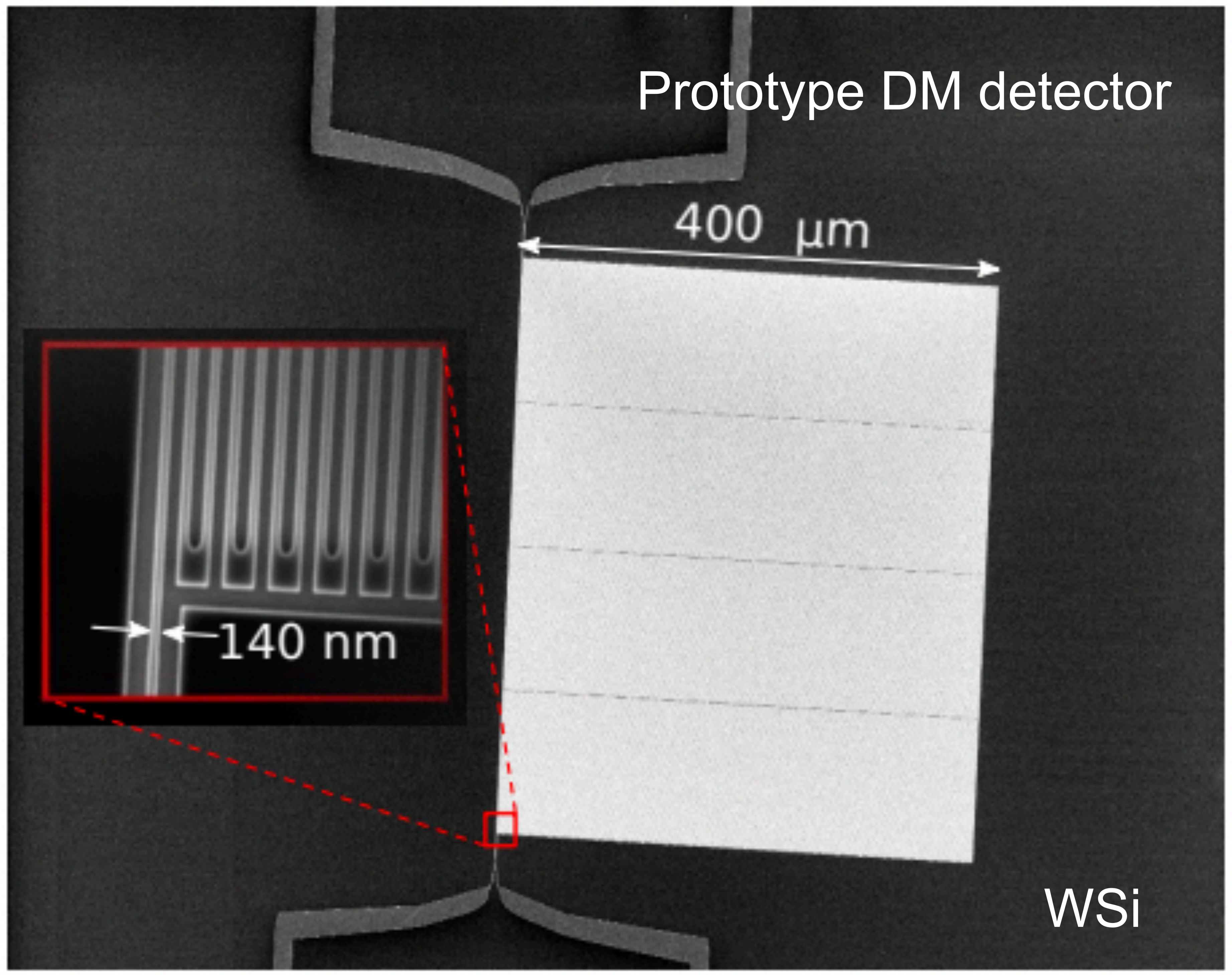


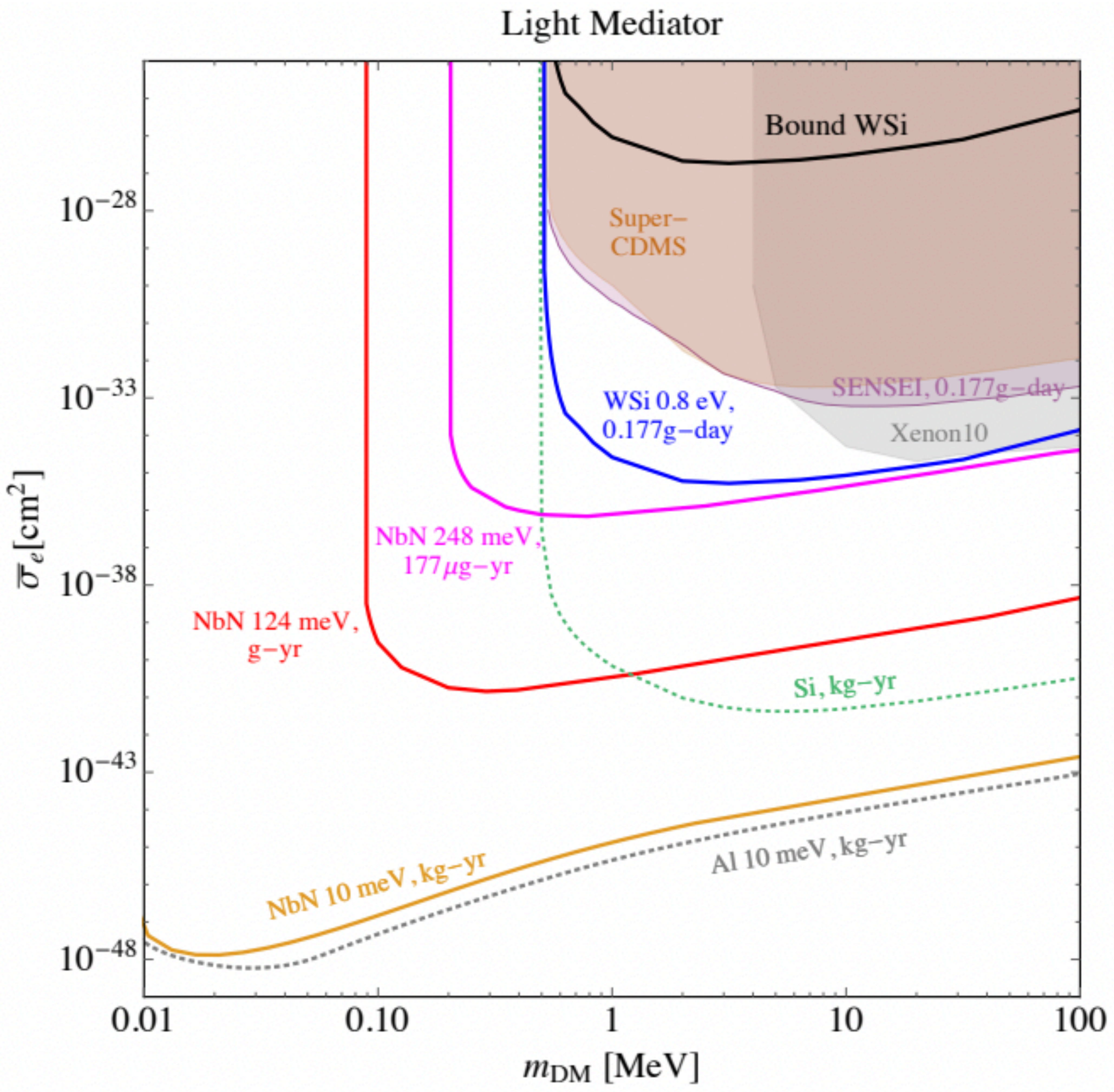


- Superconducting gap of O(meV)

Superconducting Nanowire Single Photon Detector (SNSPD)

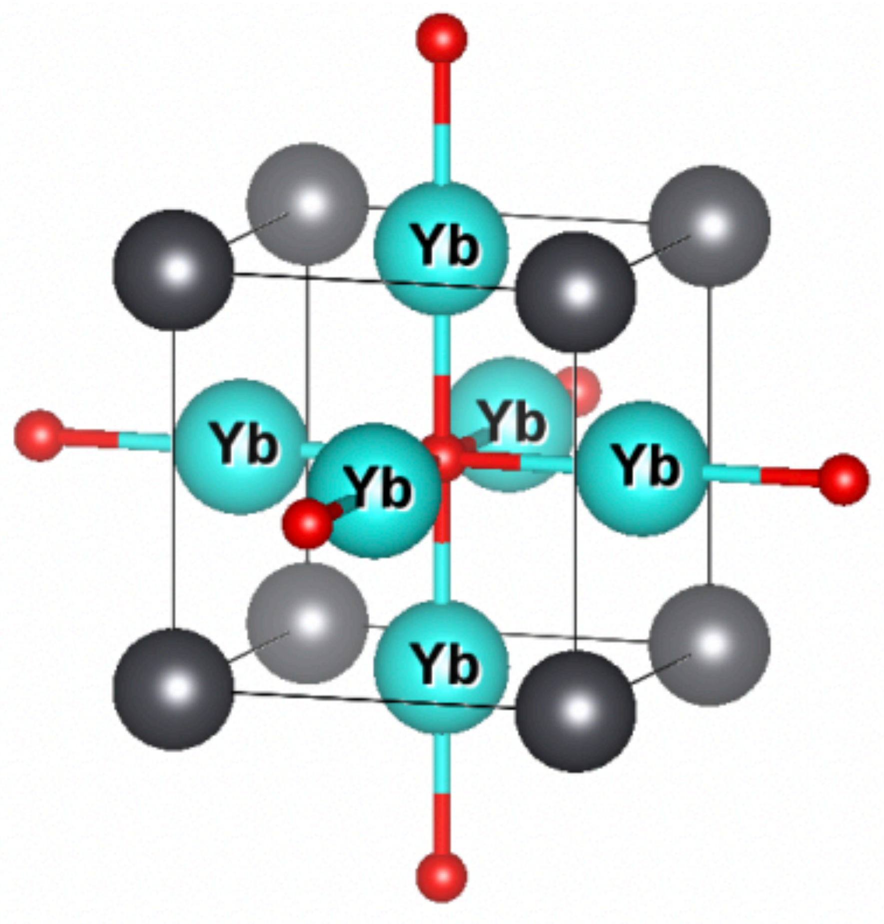
Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M Colangelo, K.K. Berggren
Phys. Rev. Lett. 123, 151802, (2019)

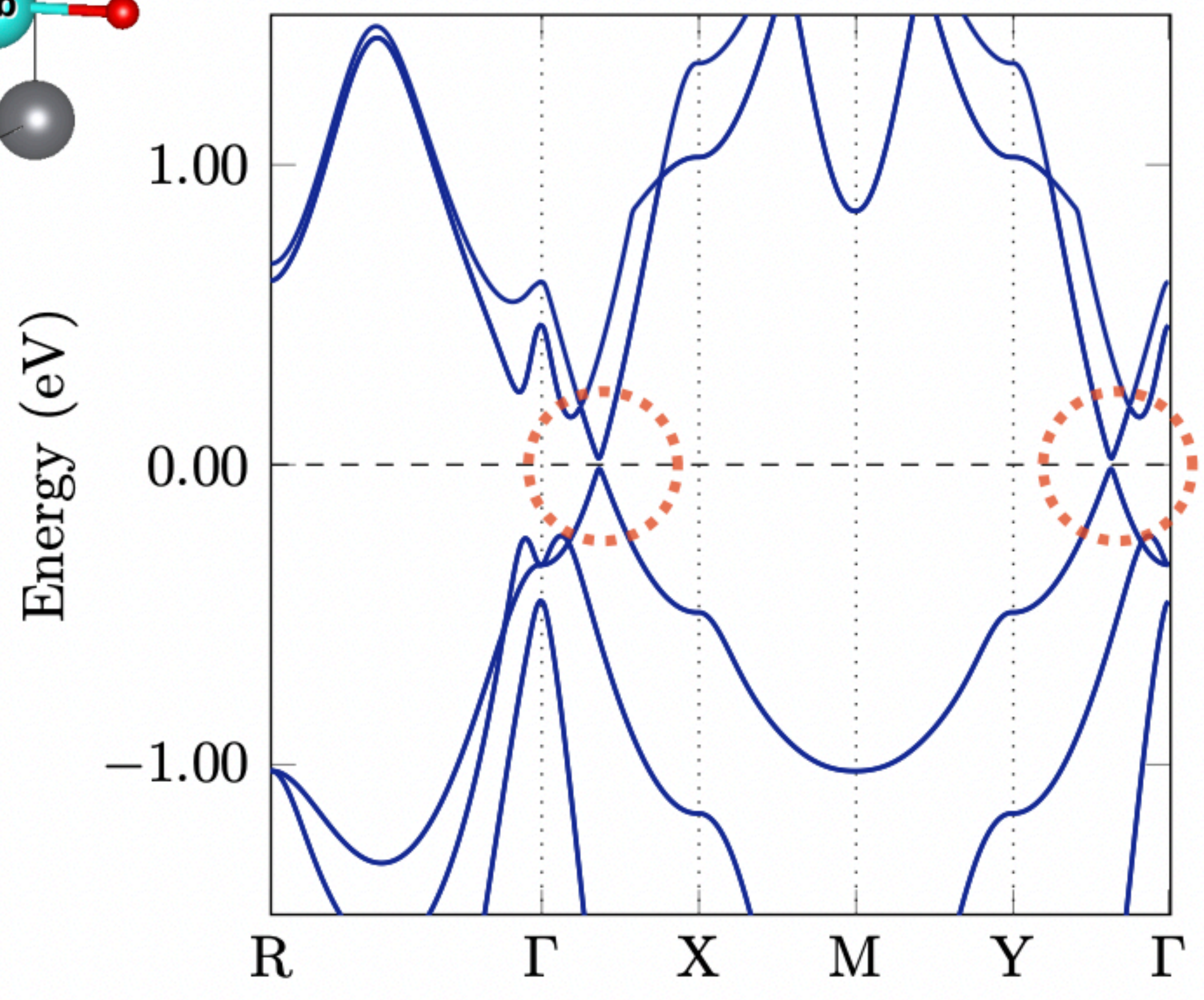




- Superconducting gap of O(meV)

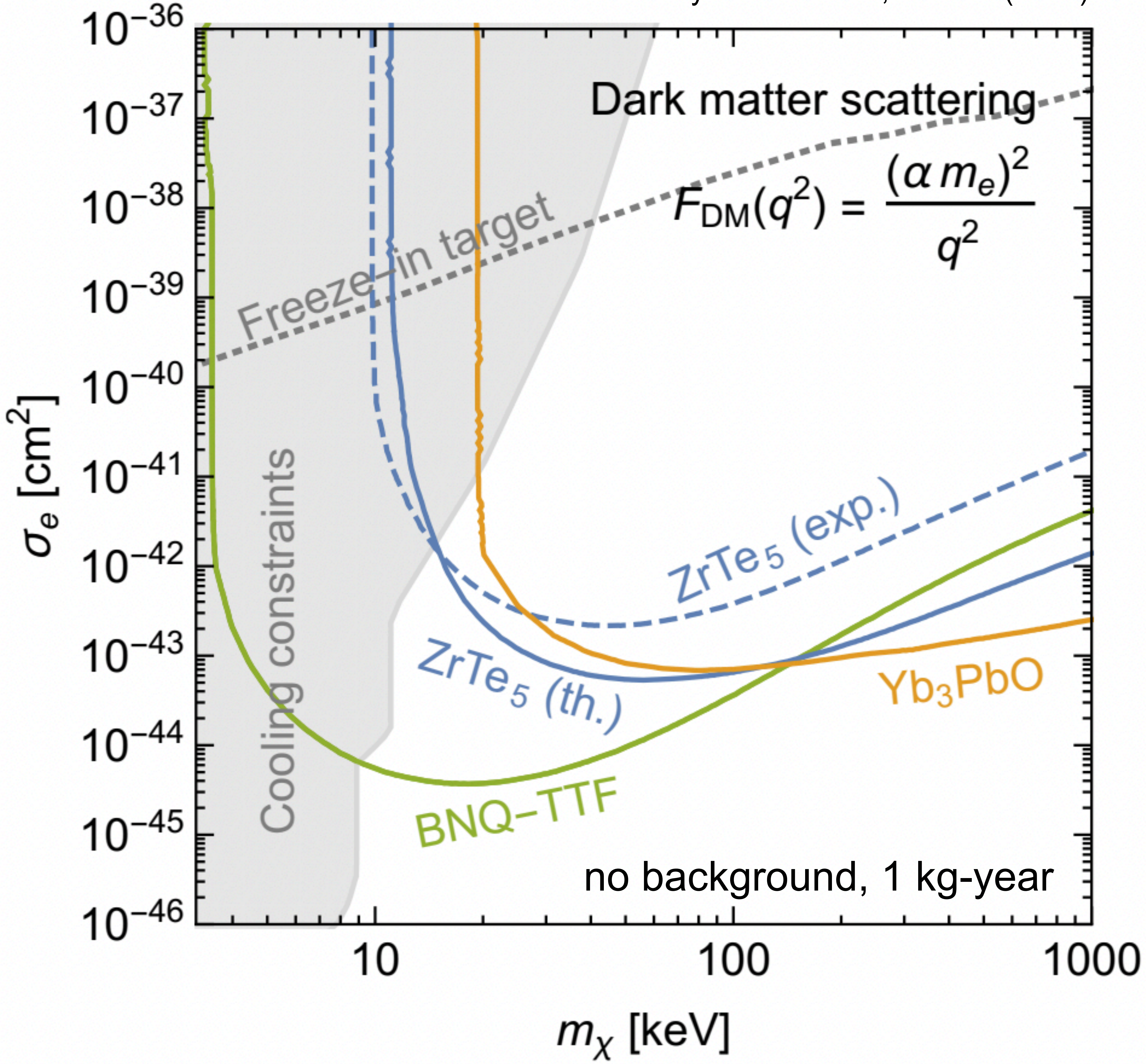
Dirac materials: example Yb3PbO



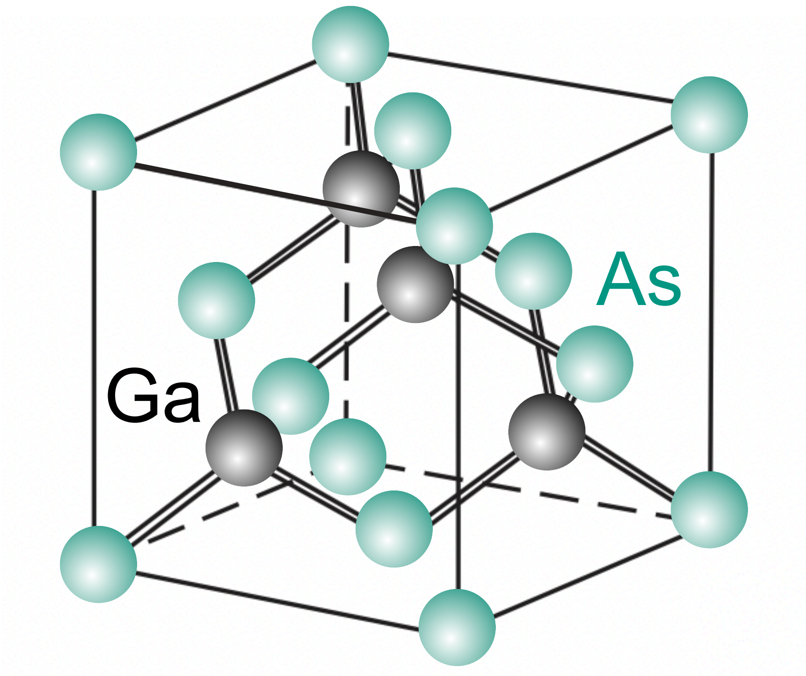


- Band gap: ~17 - 19 meV

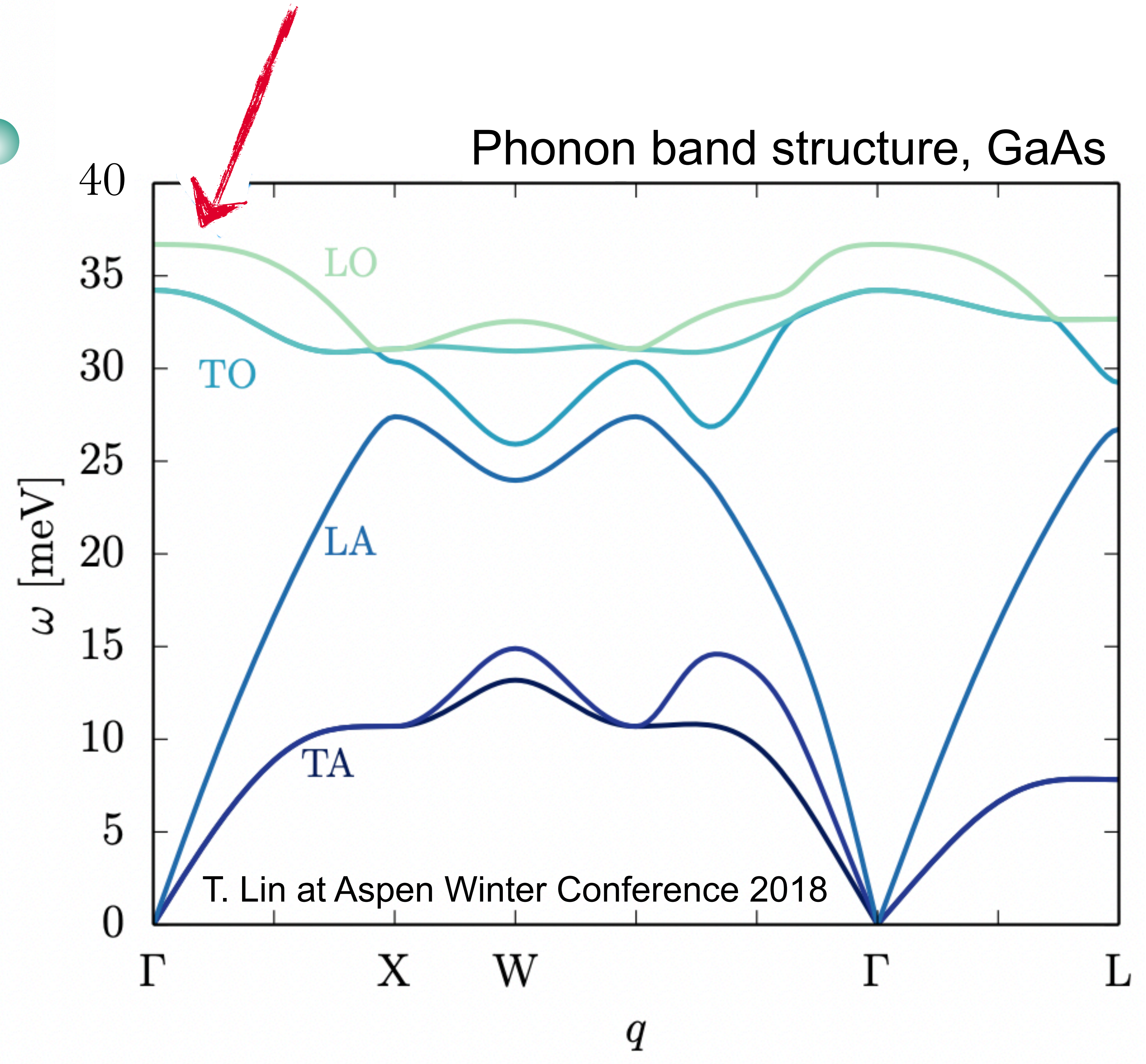
R. M. Geilhufe, F. Kahlhoefer, M. W. Winkler
Phys. Rev. D 101, 055005 (2020)



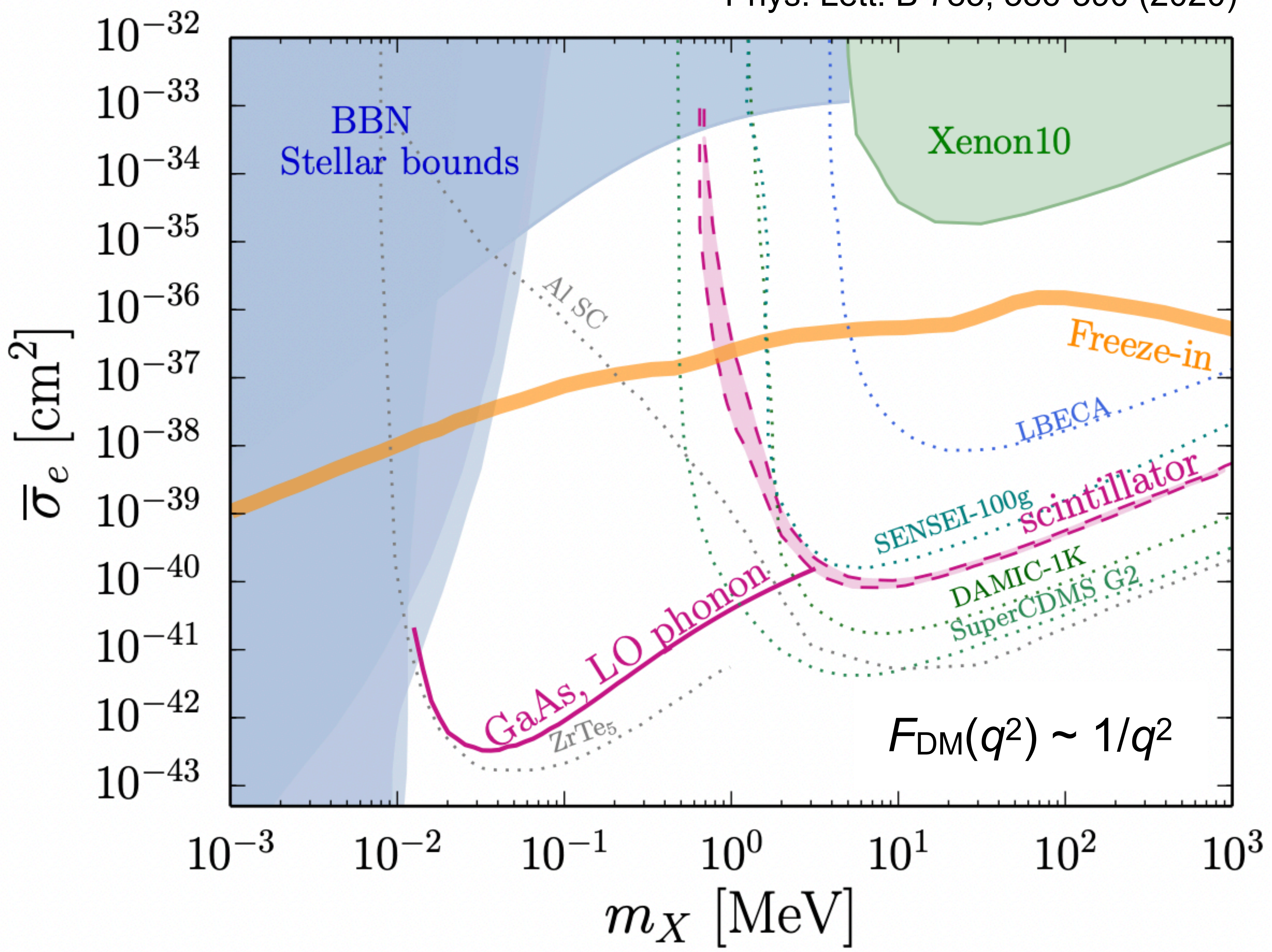
Polar crystals: example GaAs



Gapped optical phonons

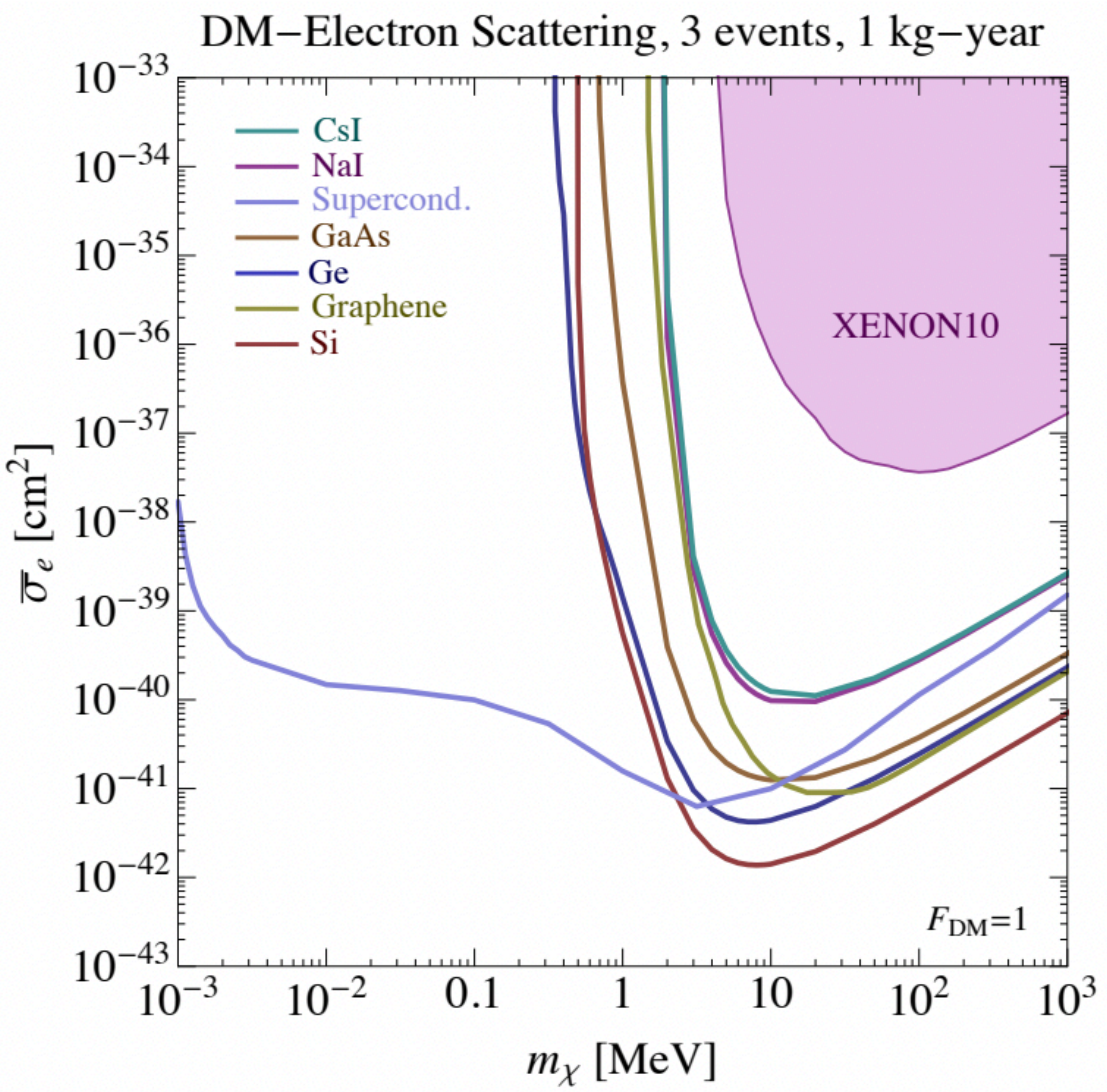


S. Knapen, T. Lin, M. Pyle, K. M. Zurek, Phys. Lett. B 785, 386-390 (2020)



Upcoming experiment: SPICE (TESSERACT Collaboration)

New avenues for Light DM direct detection



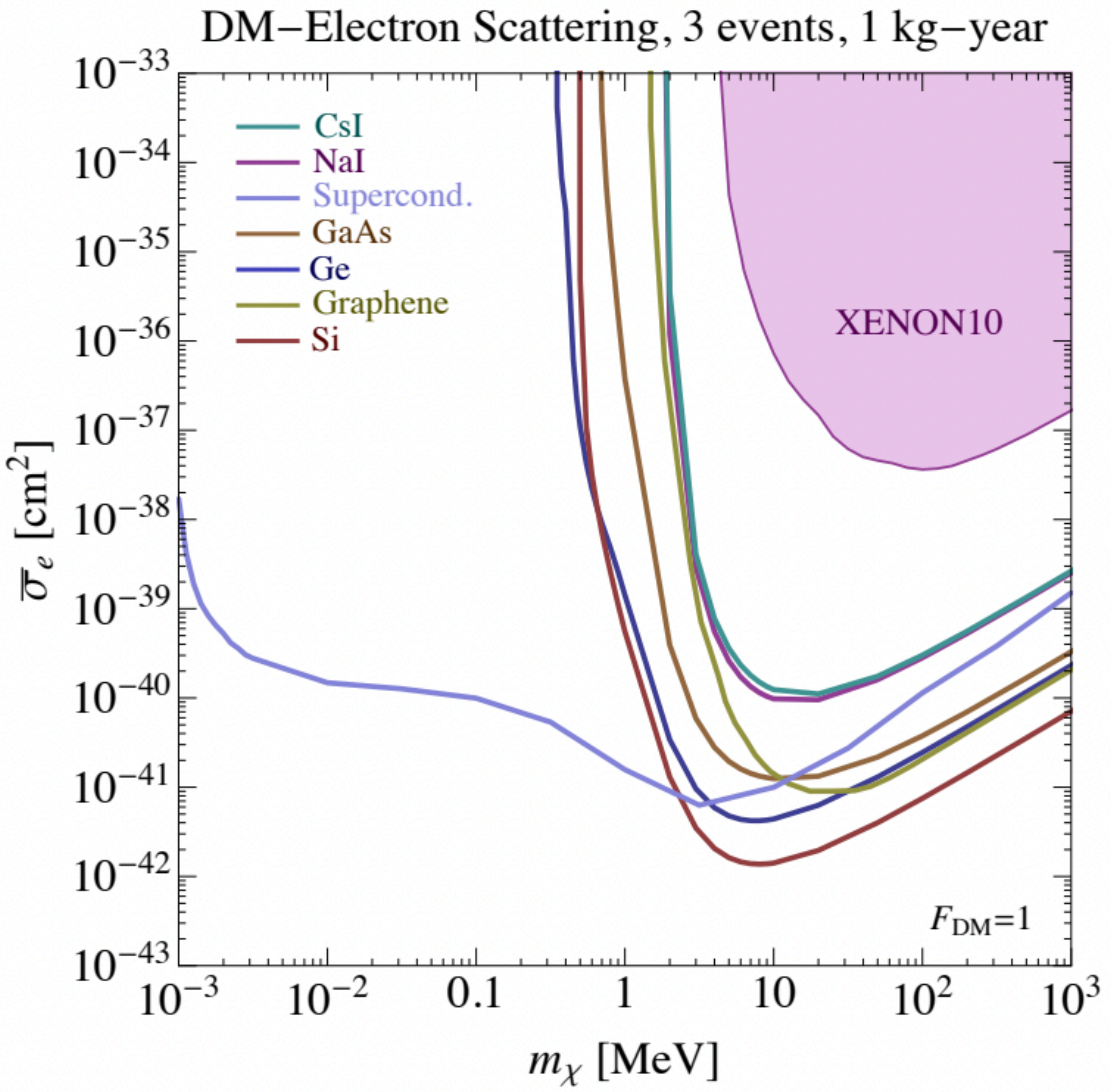
New avenues for Light DM direct detection

Let's assume you want to build your own experiment…

… which material would you pick?

… why?

NB: It's not black or white. Different people have different well-motivated reasons to pick different materials.

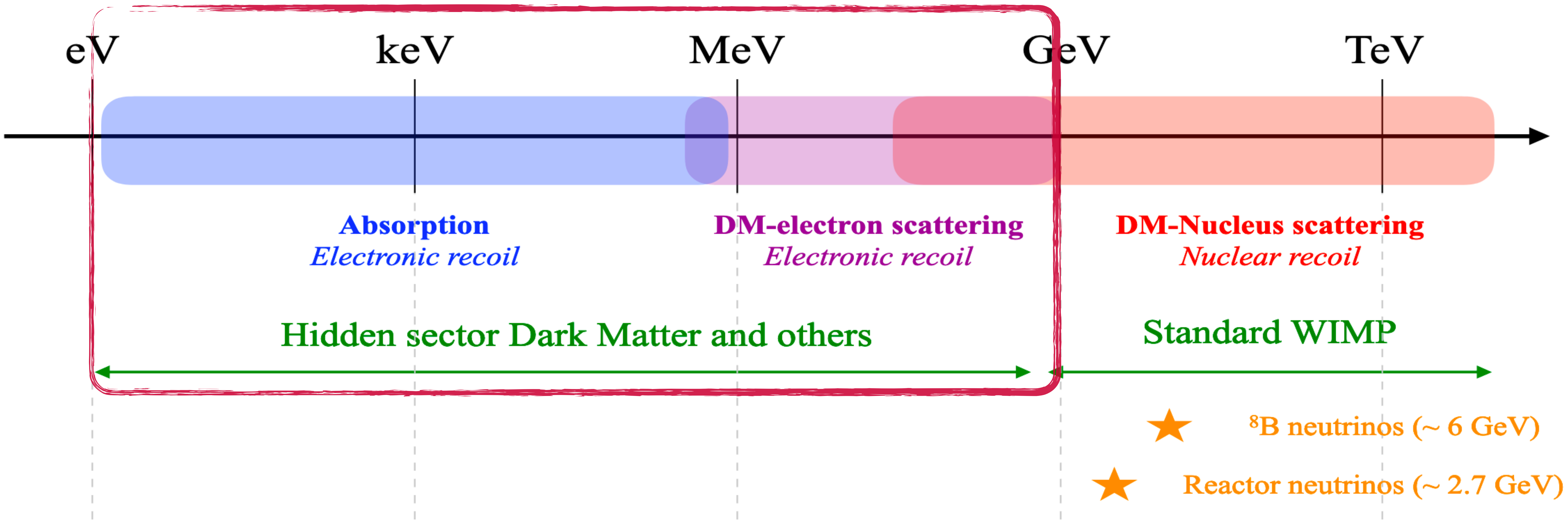


UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Bosonic dark matter searches

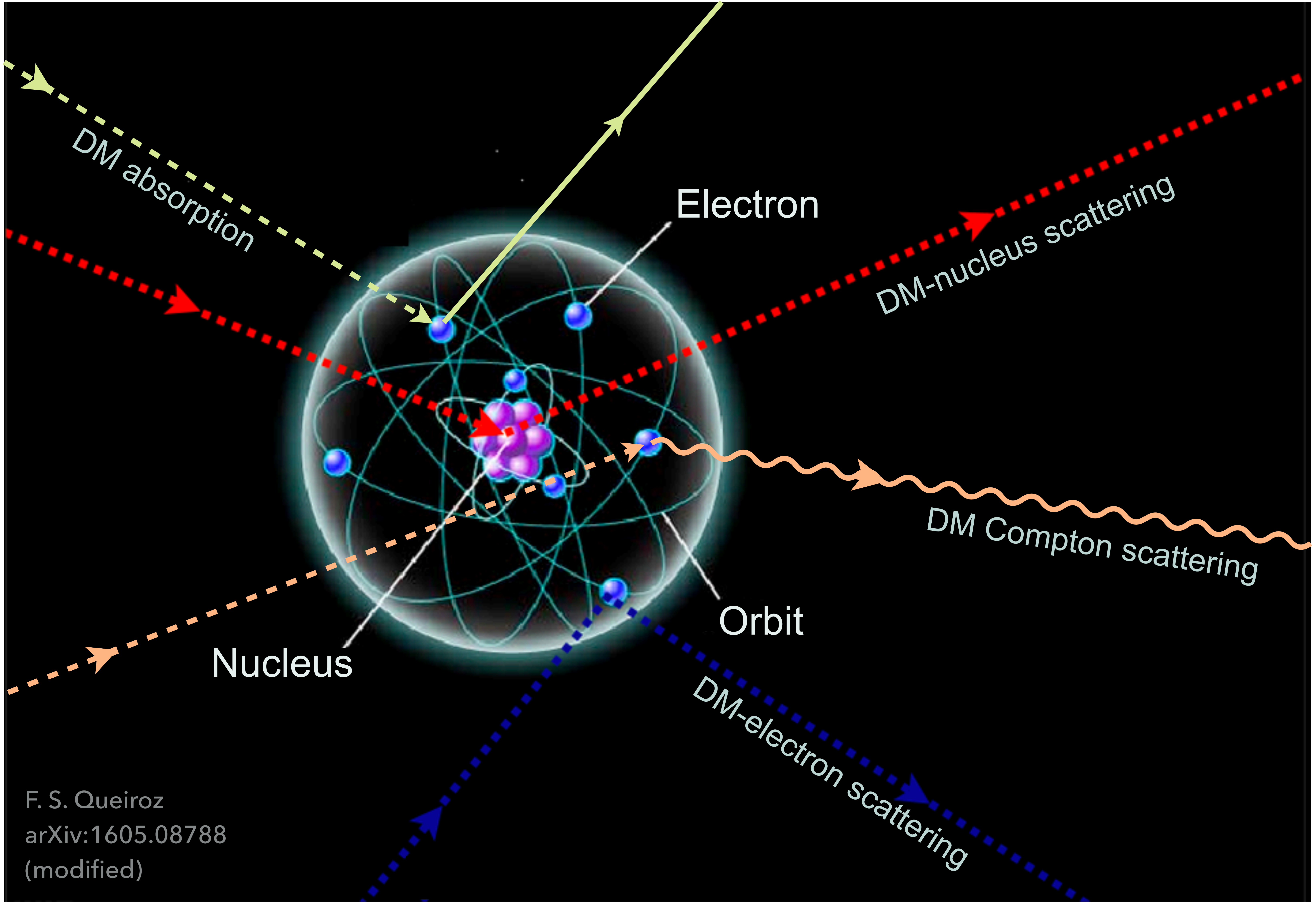
Mass range accessible via electron recoil searches

- Expected candidates, interactions, and rates



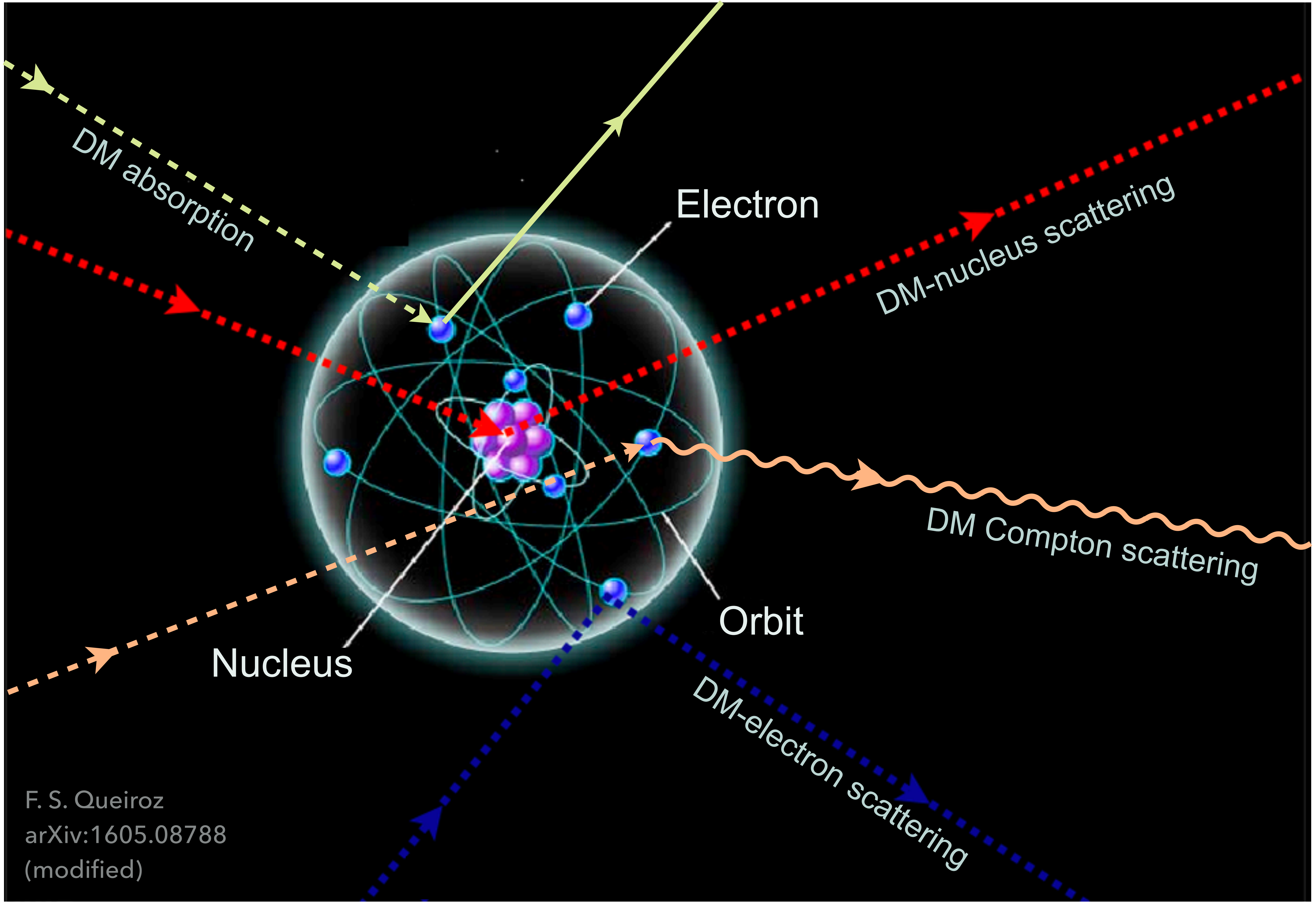
See **Marco Cirelli's** lectures

Reminder



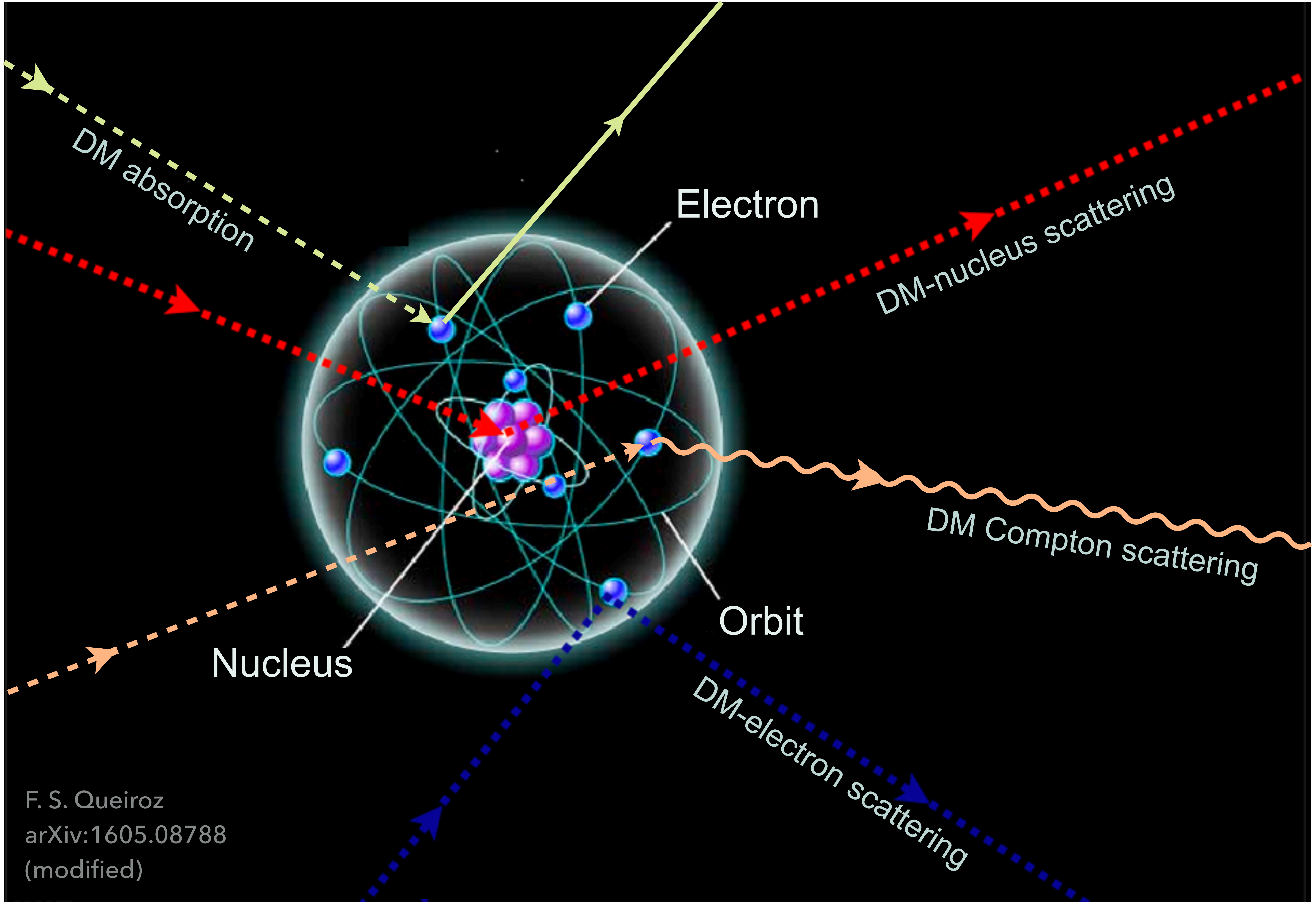
- Basic idea:
  - Dark Matter is made of particles which directly interact with the atoms of the detector material.
  - **Any** observable interaction counts!

Reminder



- Elastic DM-nucleon **scattering**
  - Spin-independent (SI)
  - Spin-dependent (SD)
- Inelastic DM-nucleon **scattering**
  - Migdal effect
  - Bremsstrahlung
- DM-electron **scattering**

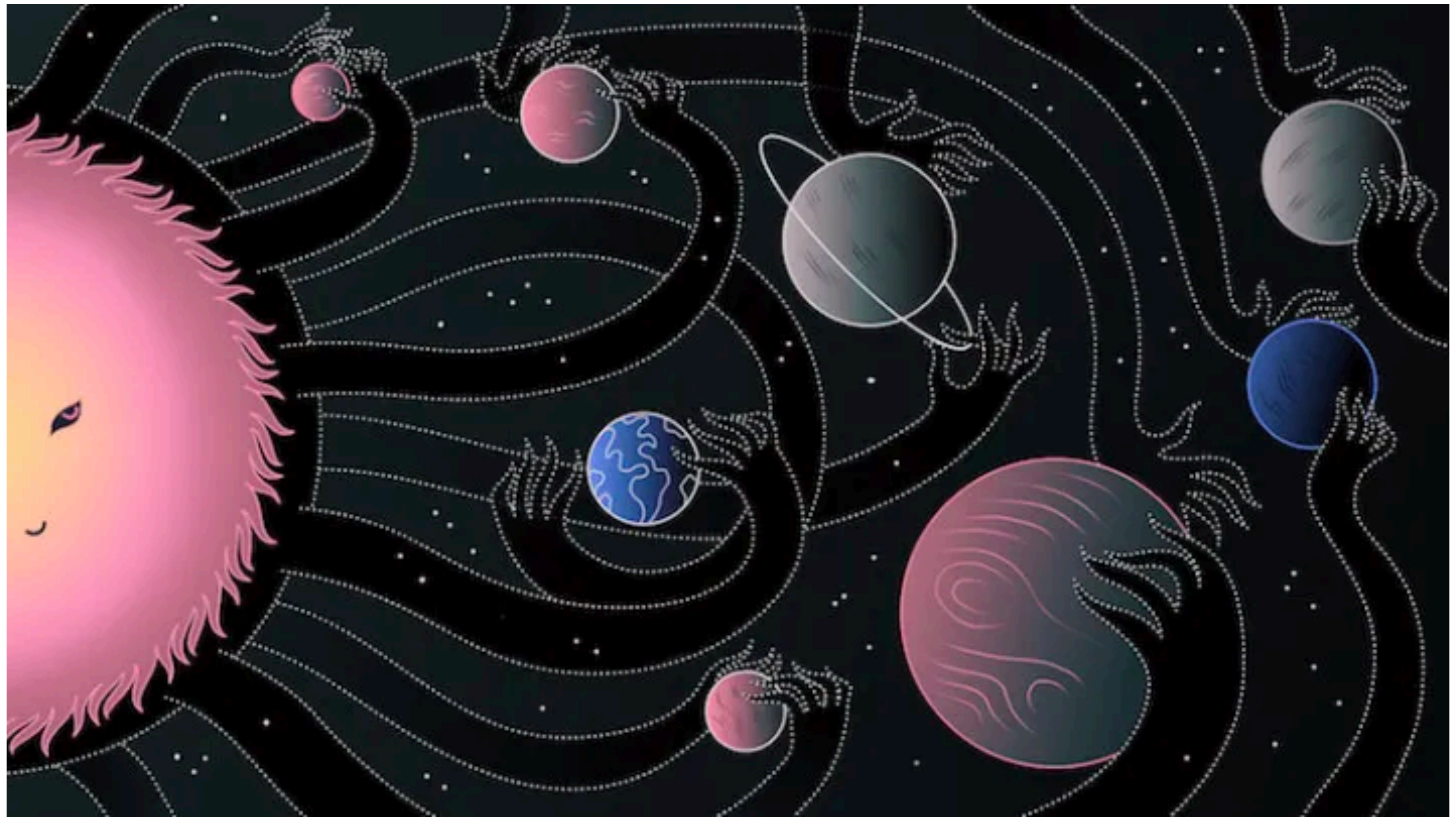
Reminder



- Elastic DM-nucleon **scattering**
  - Spin-independent (SI)
  - Spin-dependent (SD)
- Inelastic DM-nucleon **scattering**
  - Migdal effect
  - Bremsstrahlung
- DM-electron **scattering**
- Dark **absorption** of
  - ALPs
  - Dark photons
- Dark **Compton scattering** of
  - ALPs
  - Dark photons
- **Bragg scattering** of axions / ALPs

Bosonic cold dark matter candidates

Dark photons *A'*

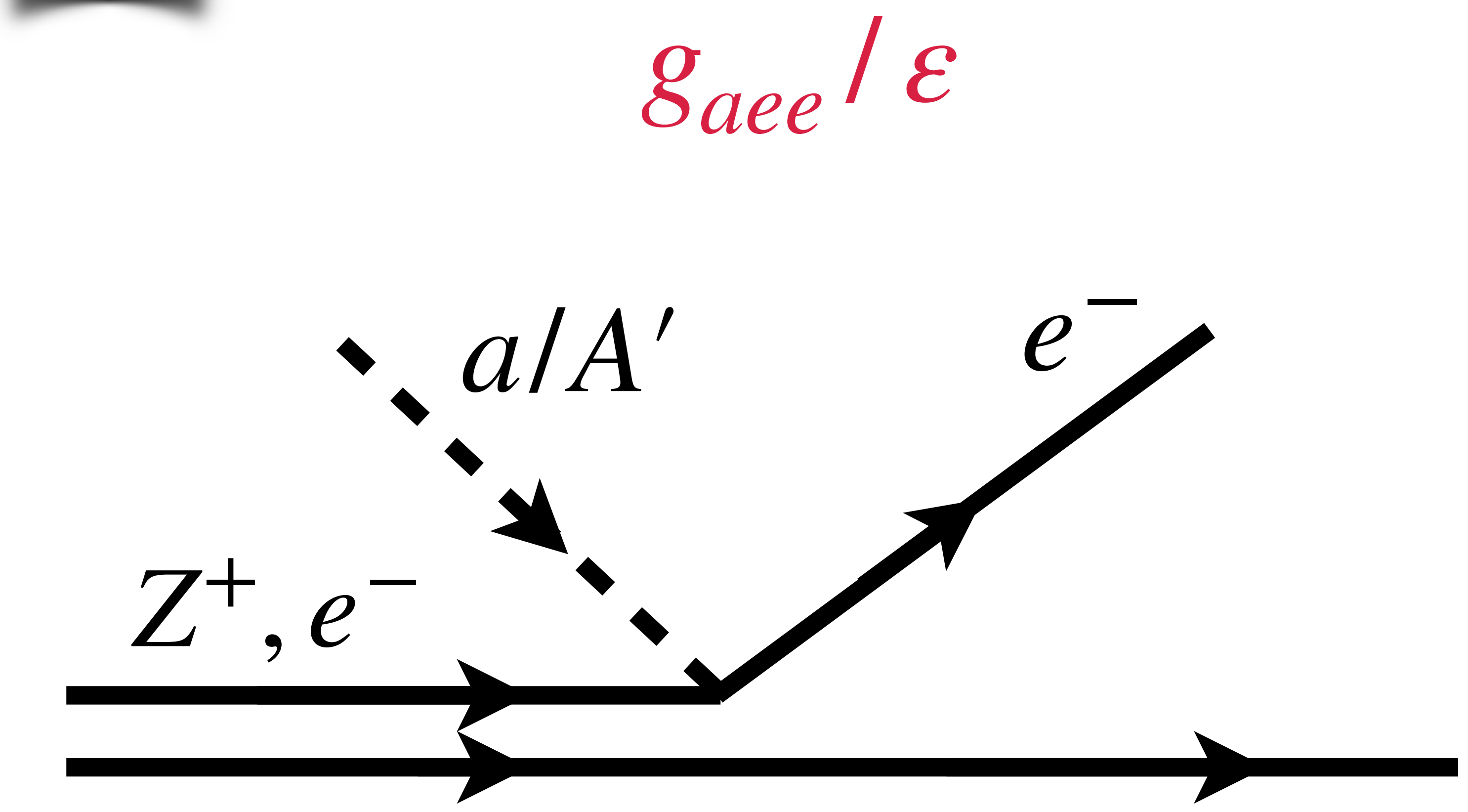


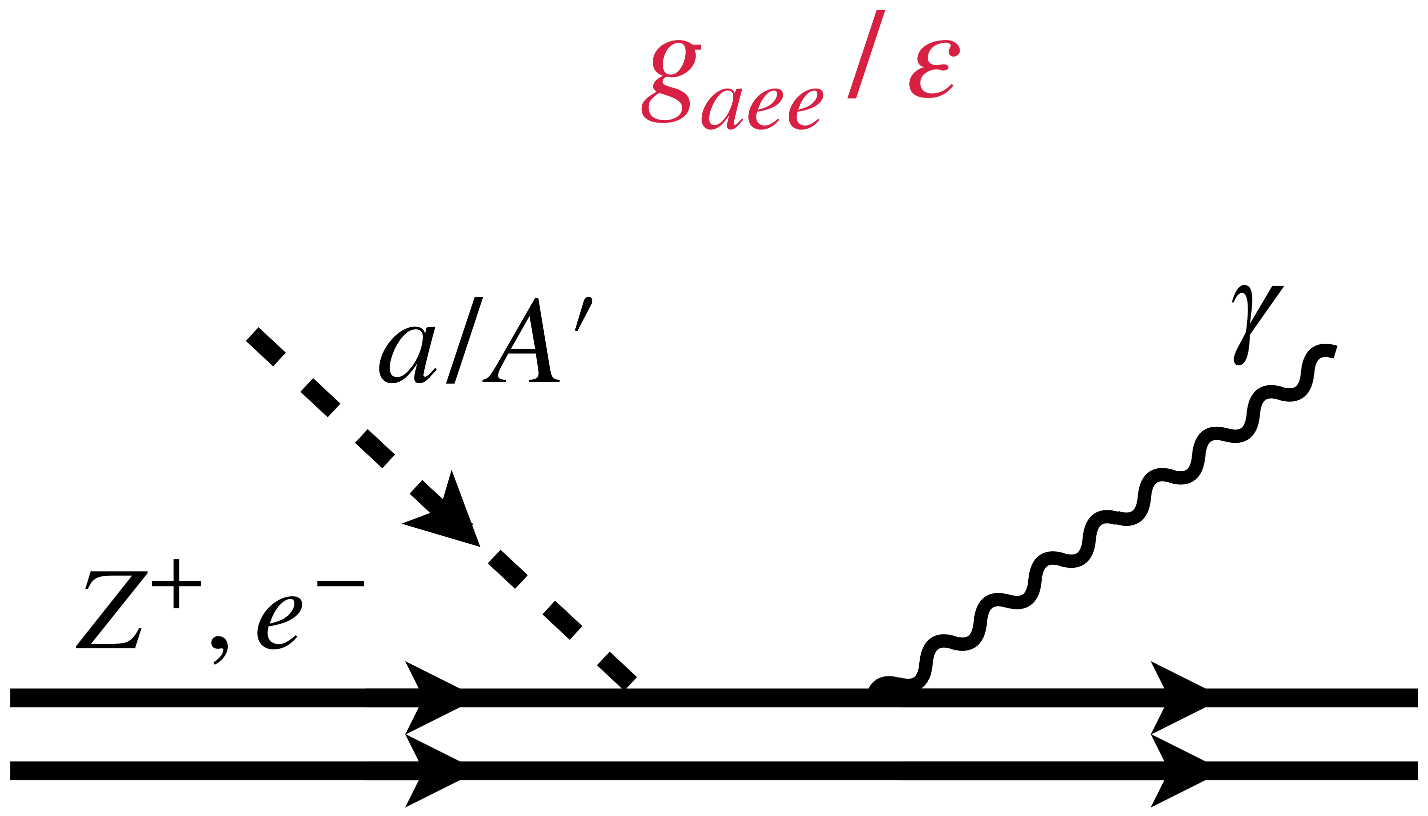
Artwork by Sandbox Studio, Chicago with Ana Kova

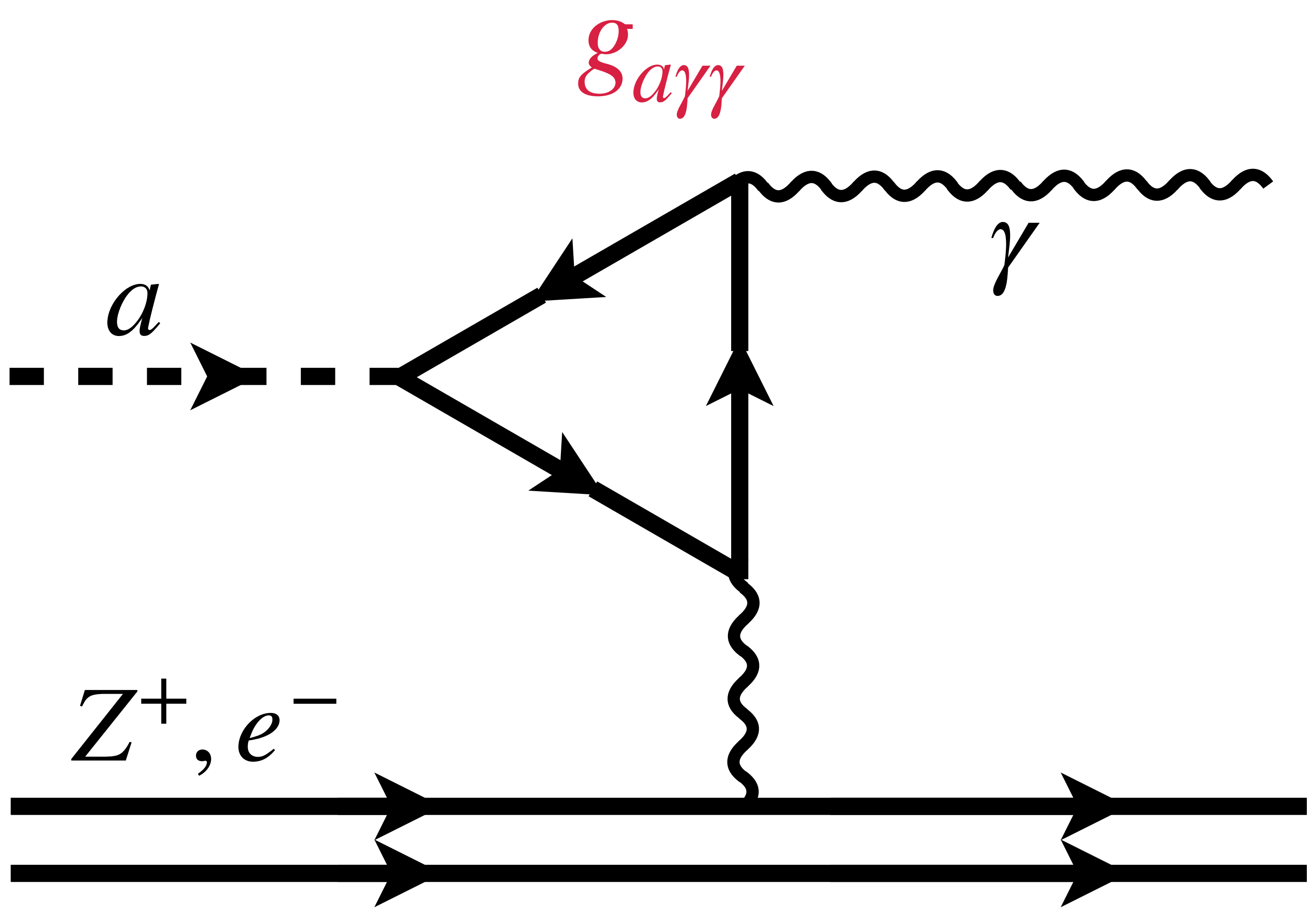
Axion and Axionlike Particle (ALP) *a*

Currently Considered Channels

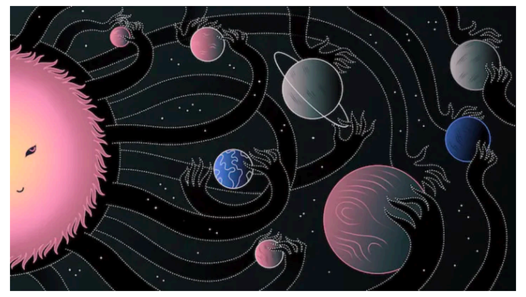
ER



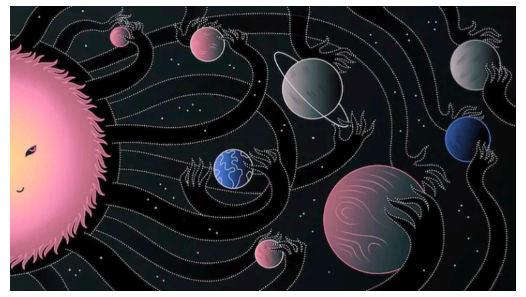




Dark absorption



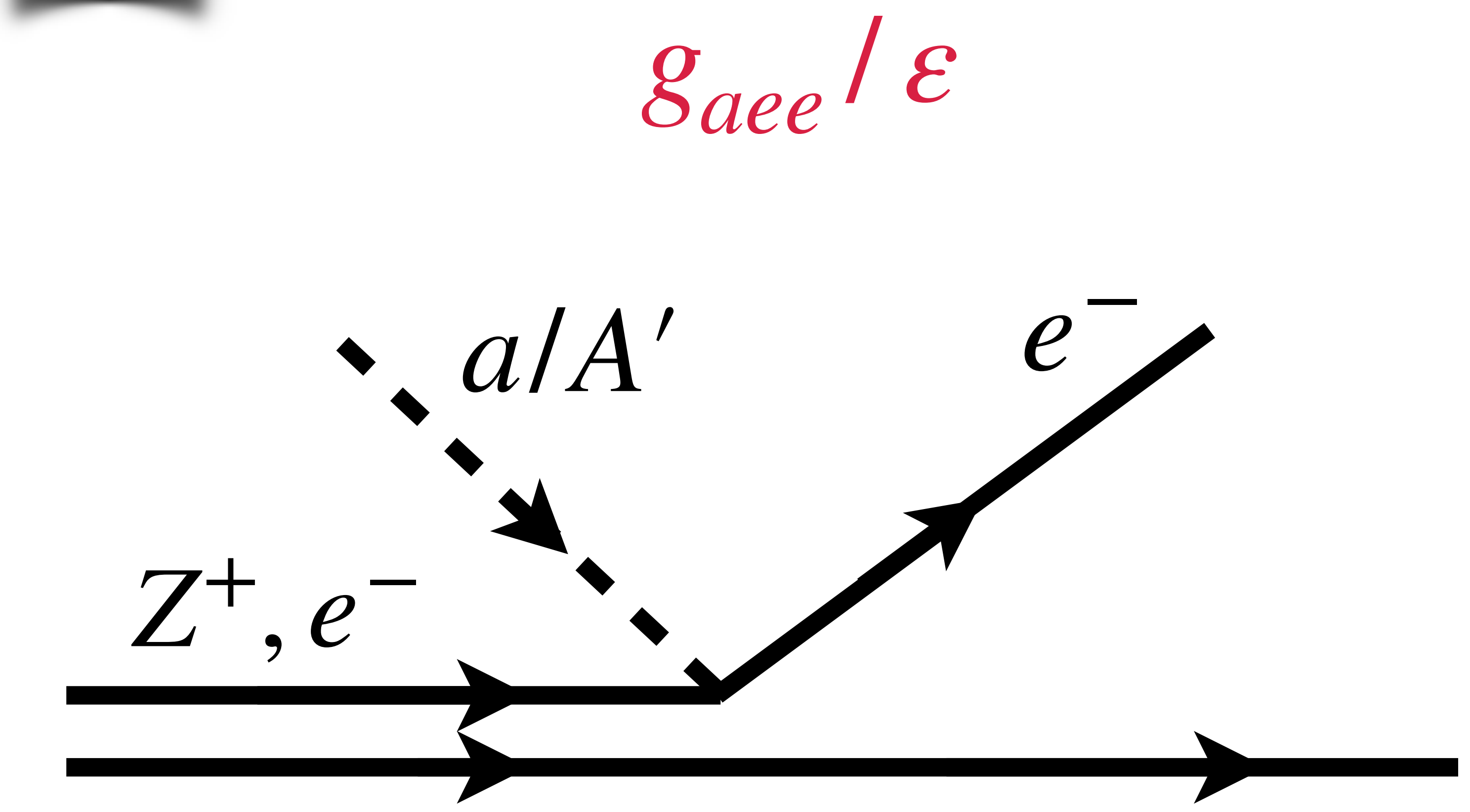
Dark Compton scattering



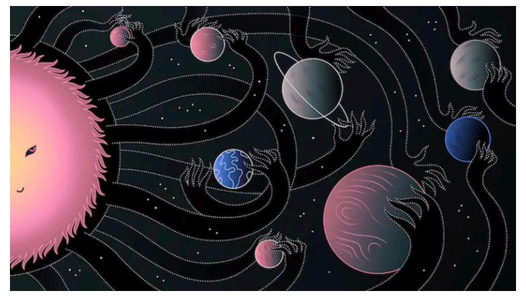
Dark Bragg scattering (Primakoff-like effect)

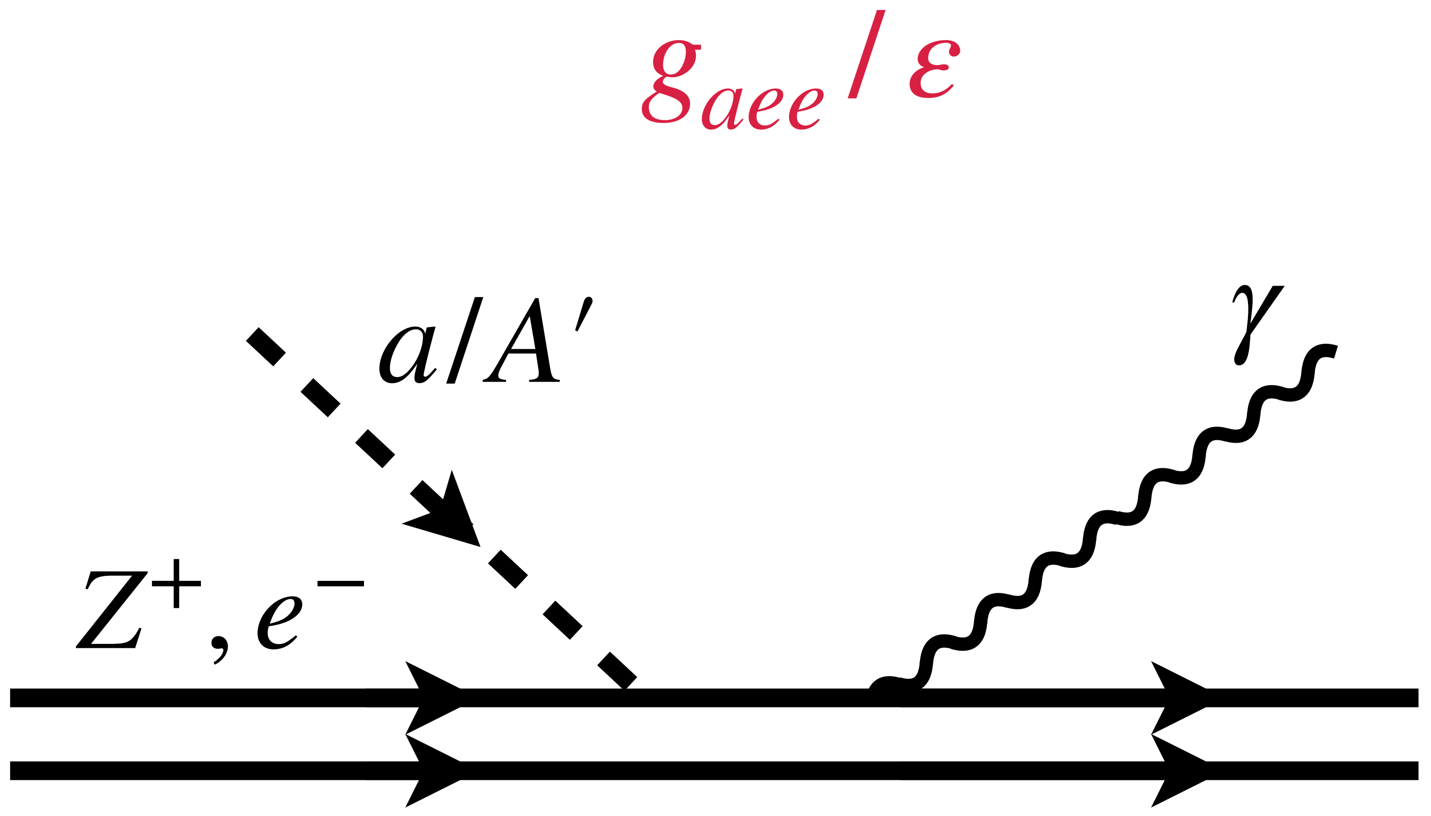
Currently Considered Channels

ER

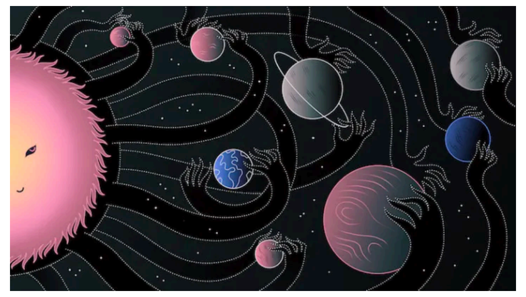


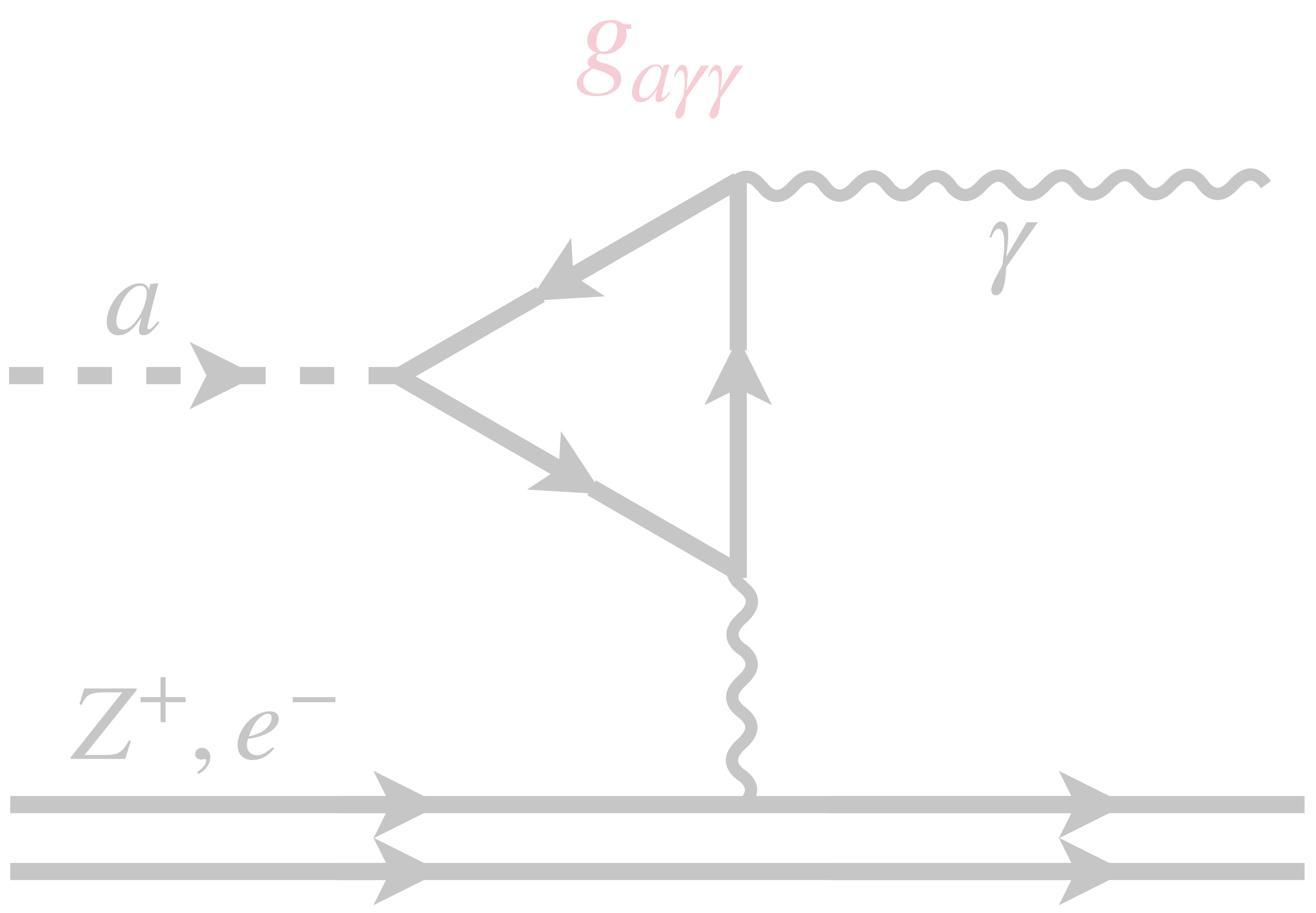
Dark absorption





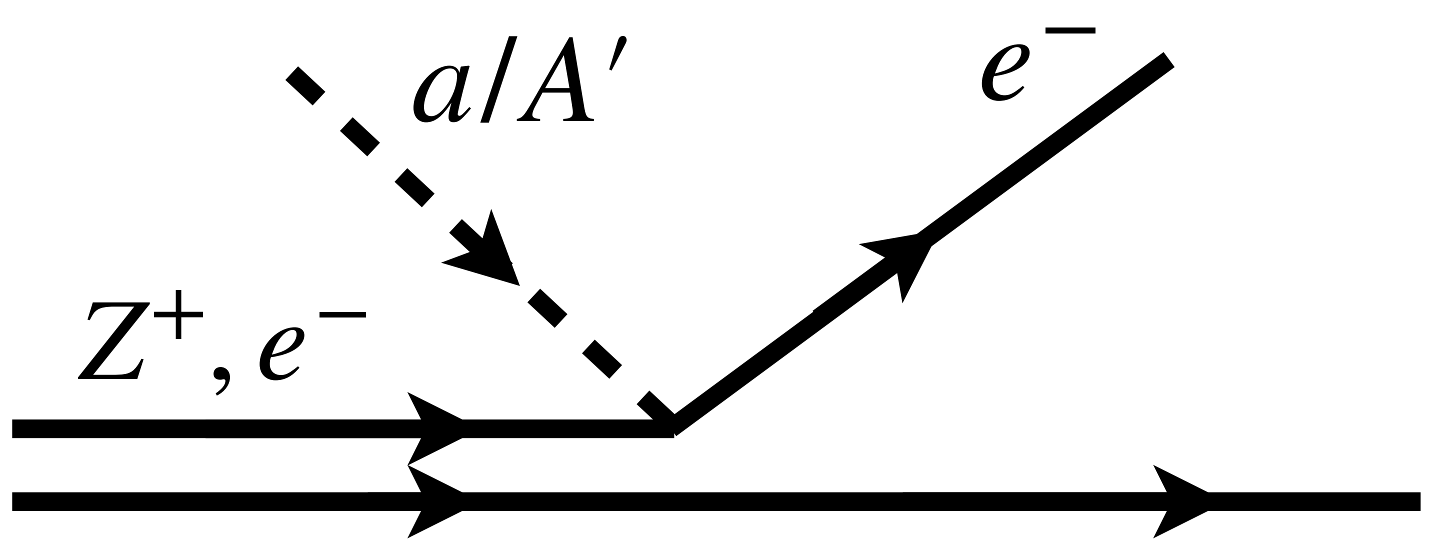
Dark Compton scattering

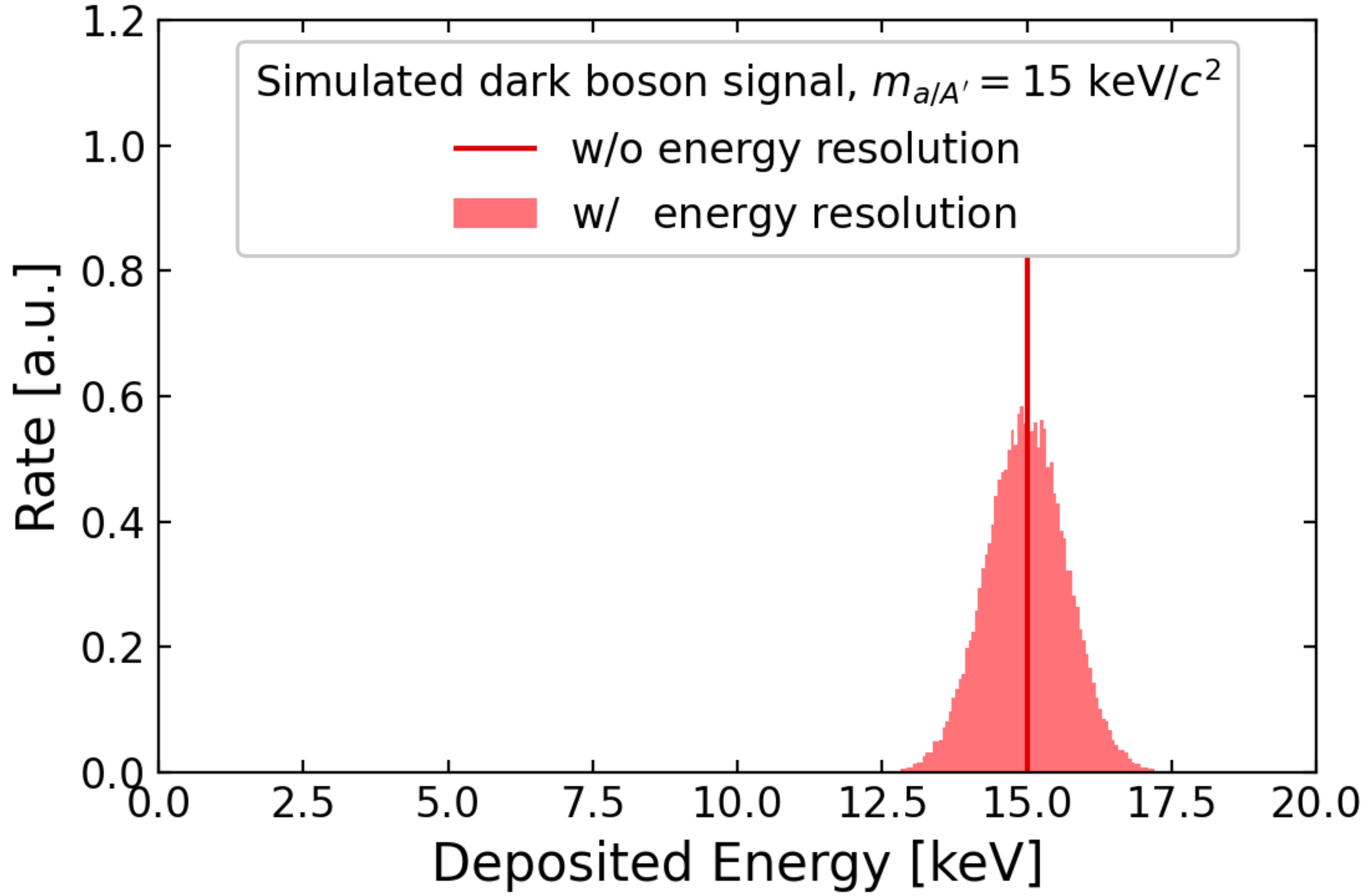




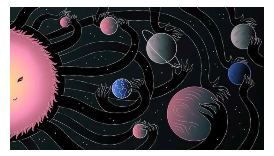
Dark Bragg scattering (Primakoff-like effect)

Dark Absorption: Signal Model





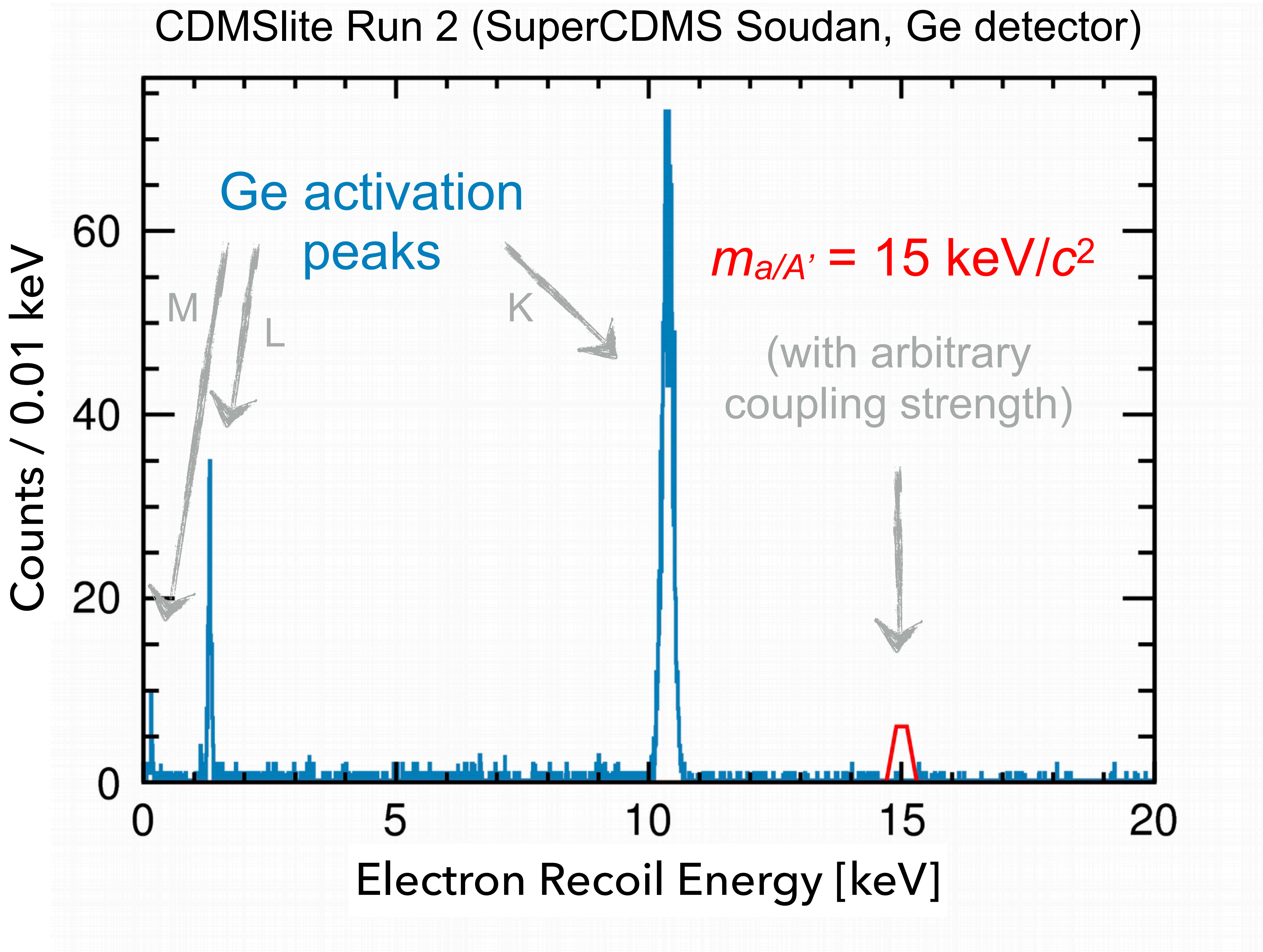
$$R \propto \rho_{\mathrm{DM}}\, g_{aee}^2\, m_a\, \sigma_{\mathrm{p.e.}}(\omega = m_a)$$



$$R \propto \rho_{\mathrm{DM}}\, \varepsilon^2\, m_{A'}^{-1}\, \sigma_{\mathrm{p.e.}}(\omega = m_{A'})$$

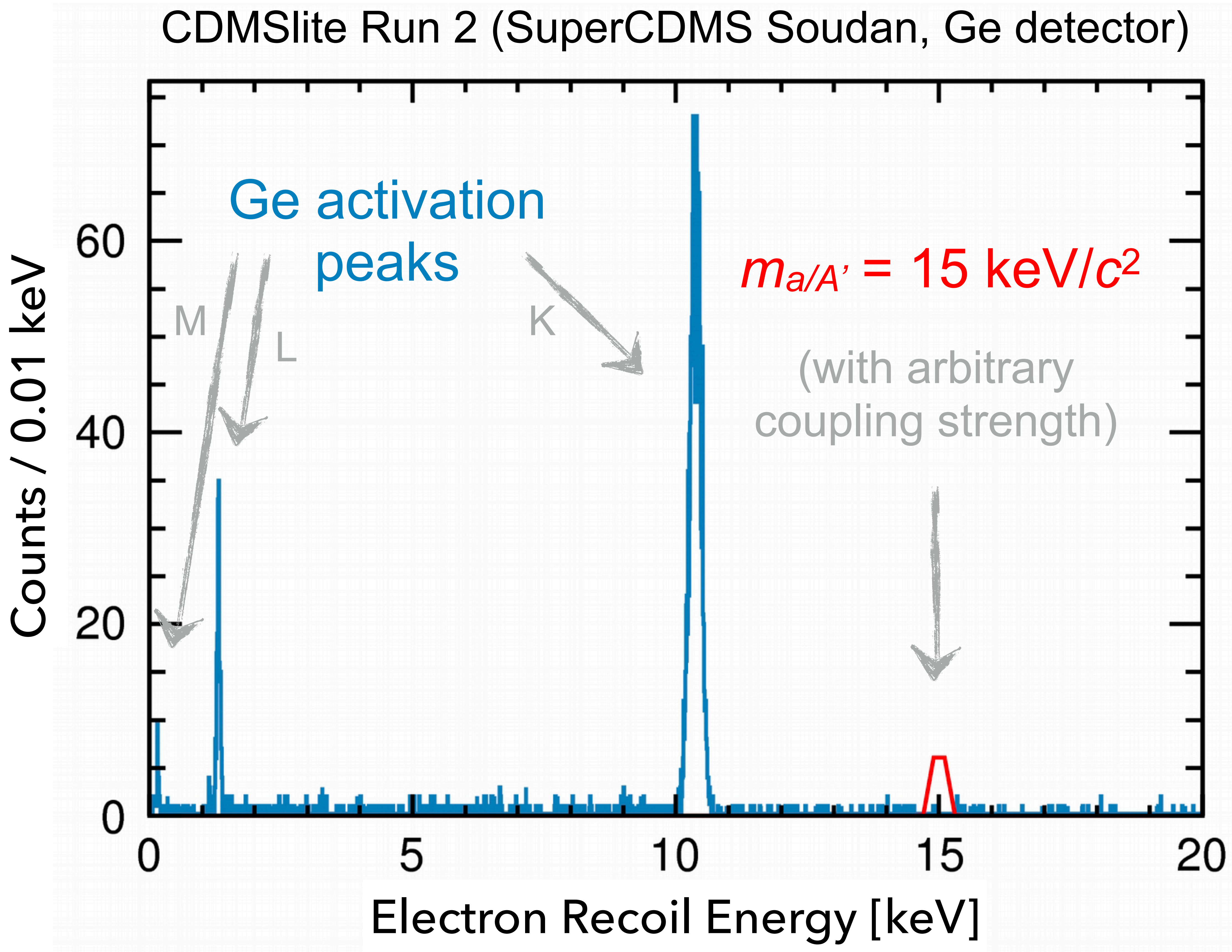
- Expected signal: $E_{\mathrm{R}} = m_{a/A'}$
  - Peak at electron recoil energy E_{R} corresponding to $m_{A'}$ or m_a.

Dark Absorption in germanium



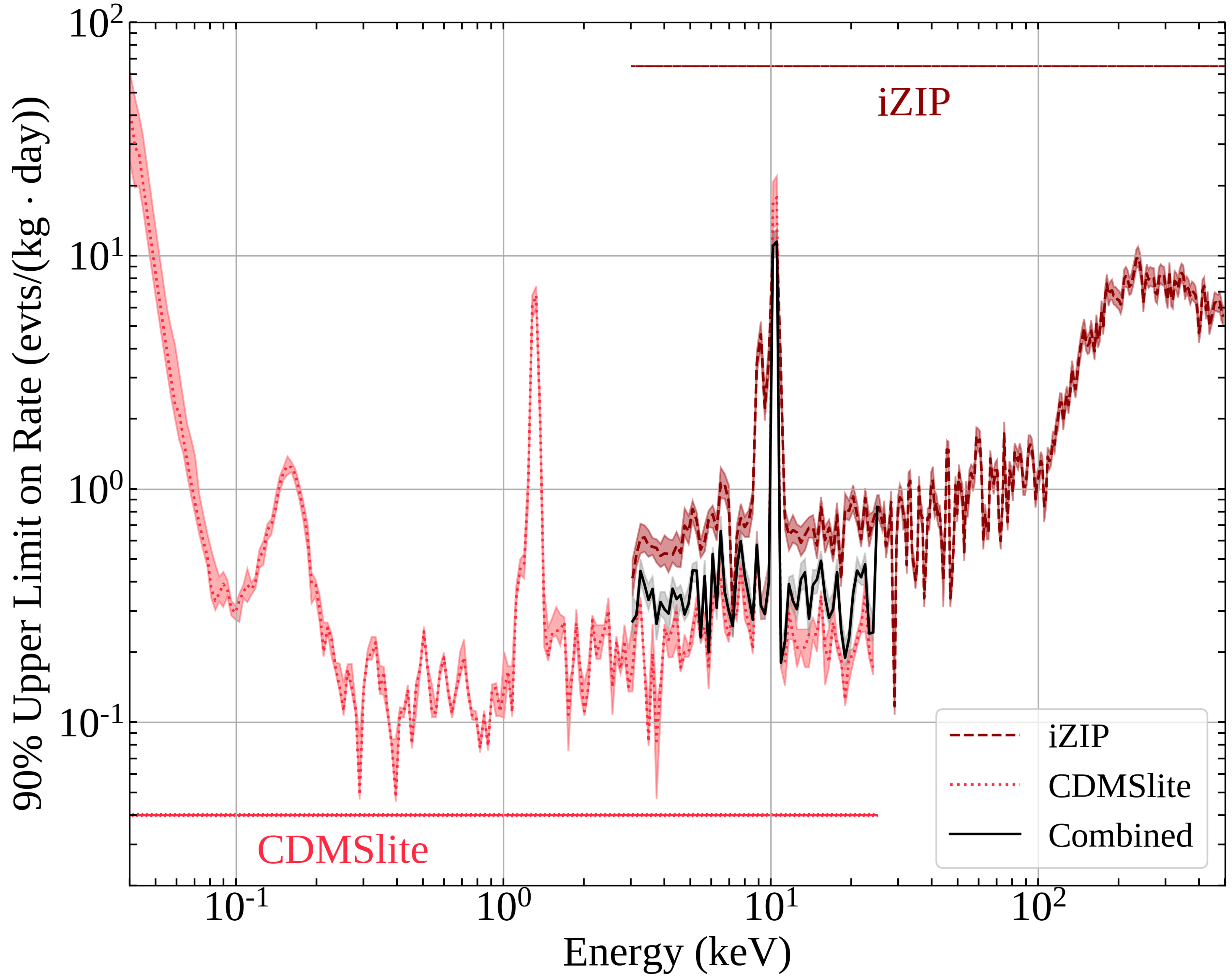
Dark Absorption in germanium

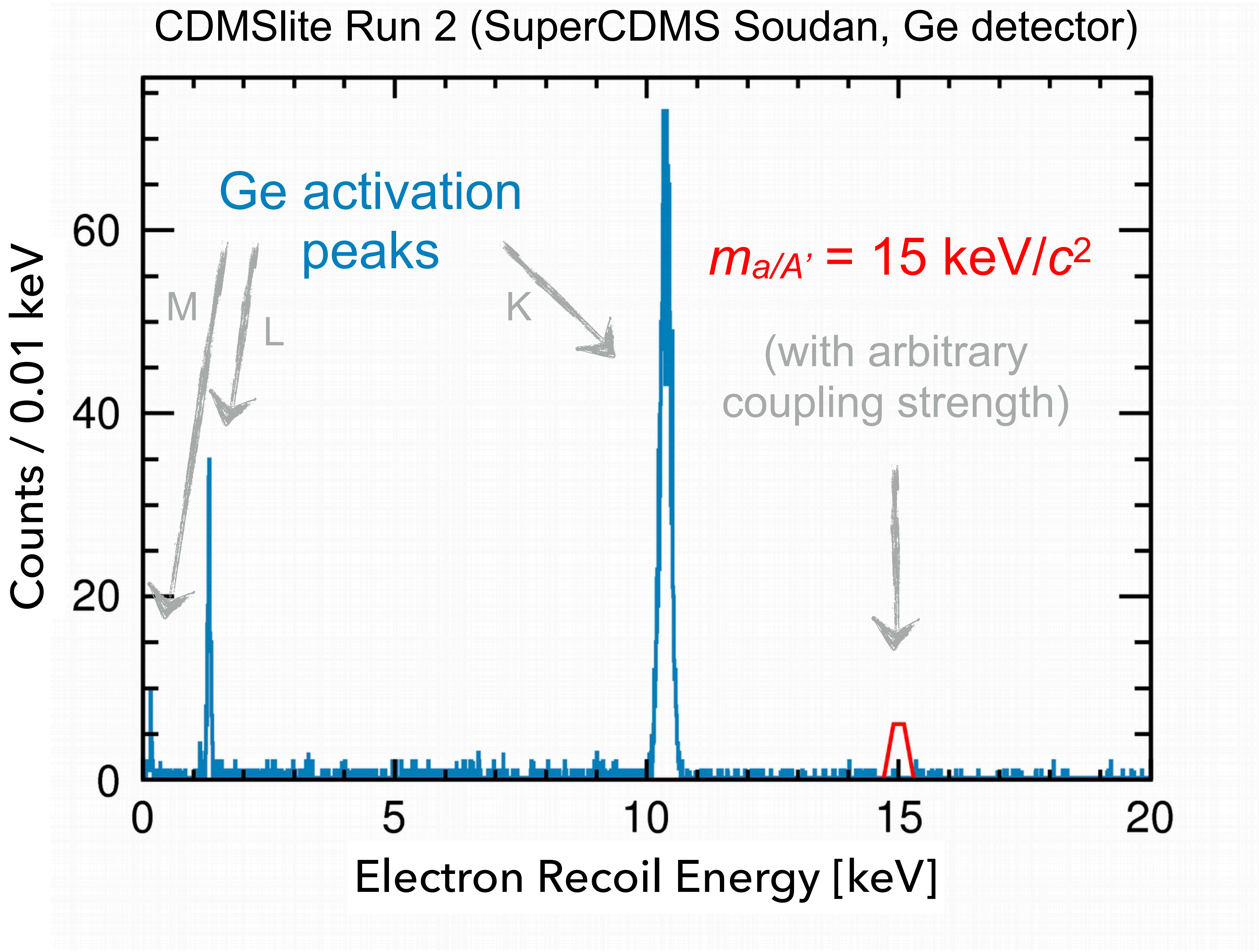
- ^{252}Cf neutron source:
  - ^{70}Ge + n → ^{71}Ge.
  - ^{71}Ge decays via electron-capture.
  - Well-known energy released in K-, L- and M-shell captures:
    - K-shell (BR ≲88%): 10.37 keV,
    - L-shell (BR ≲11%): 1.30 keV,
    - M-shell (BR ≲2%): 0.16 keV.
- High-statistics K-shell capture used for calibration.



Setting a limit

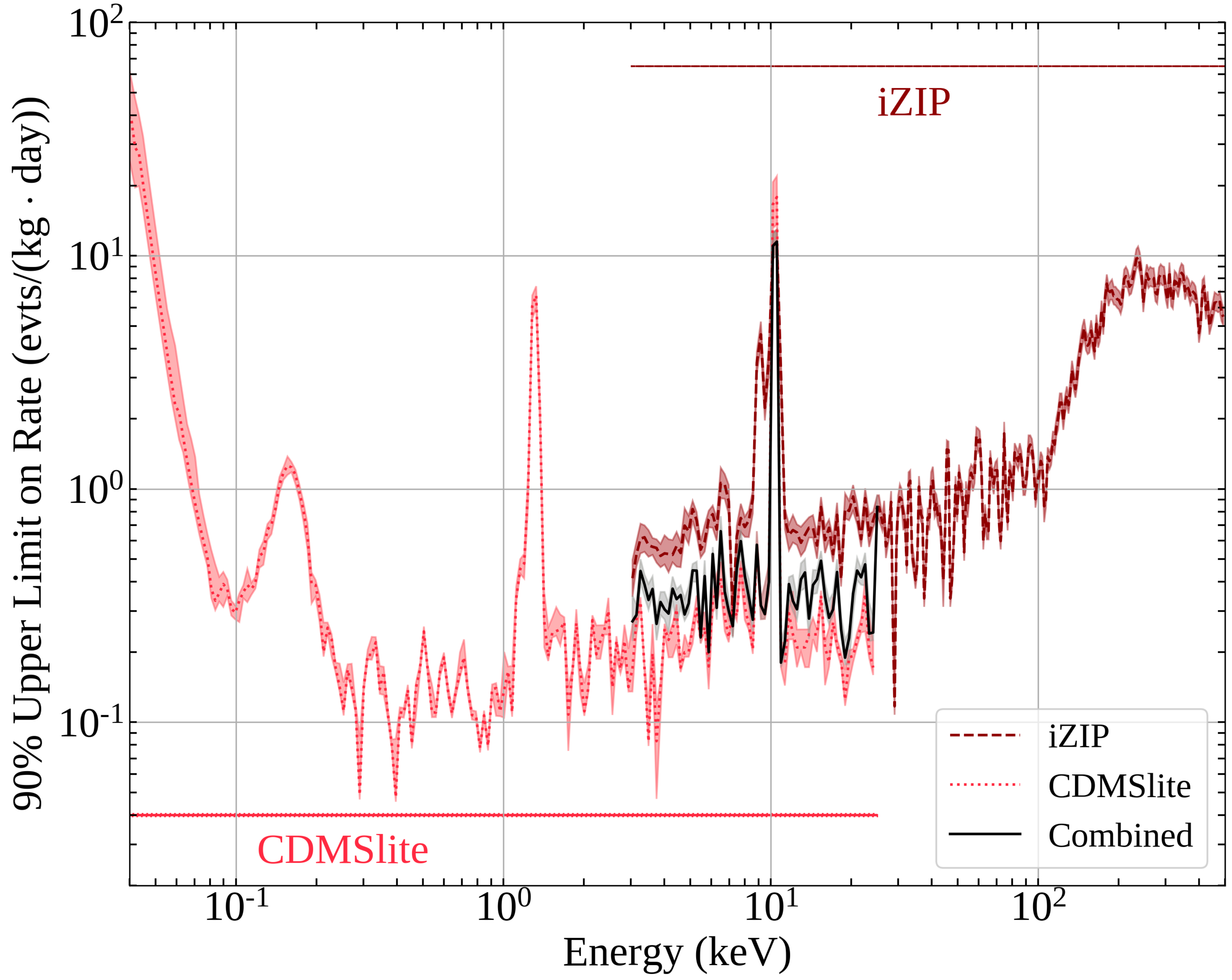
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386





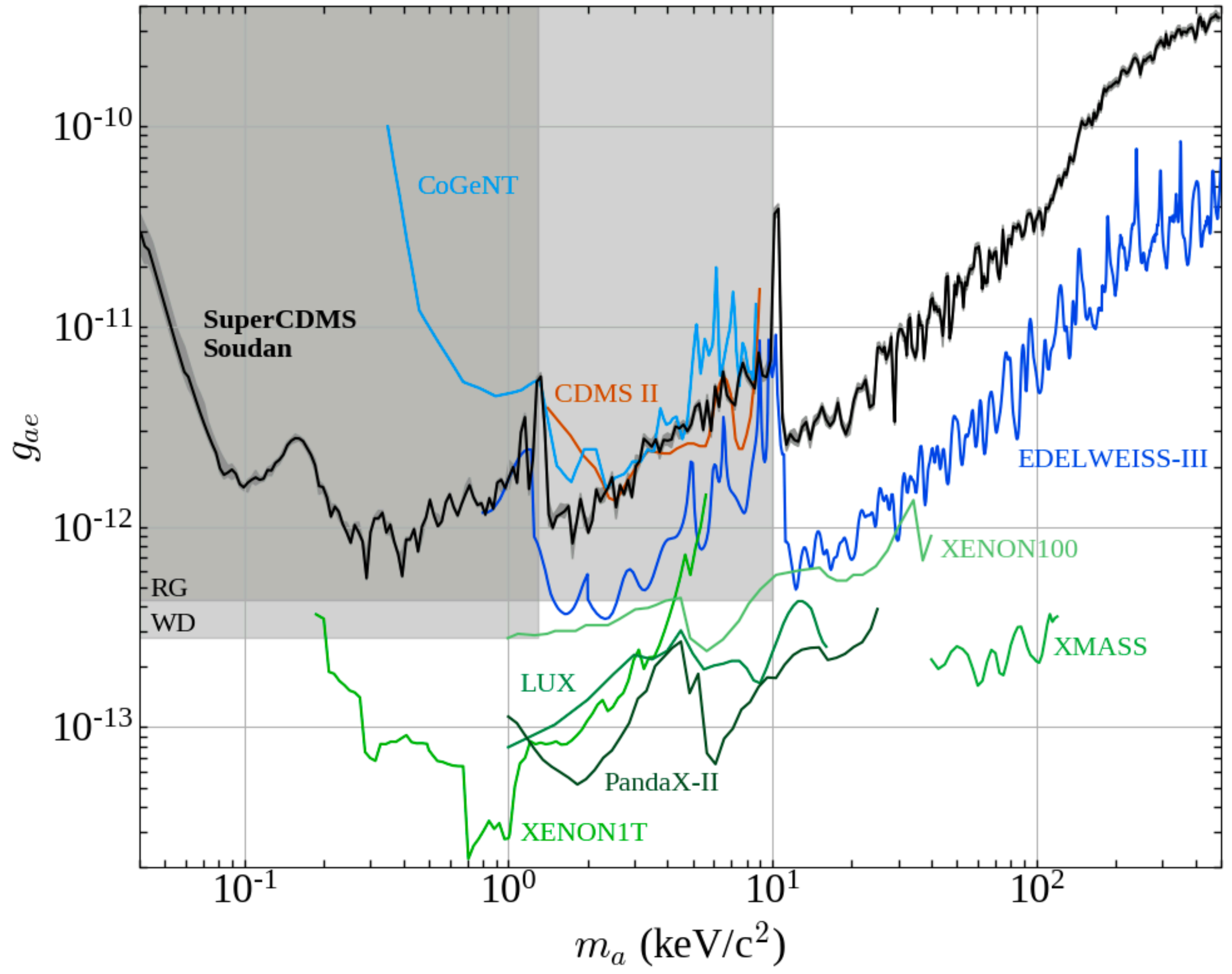
SuperCDMS Collaboration, Phys. Rev. D 101 (2020)

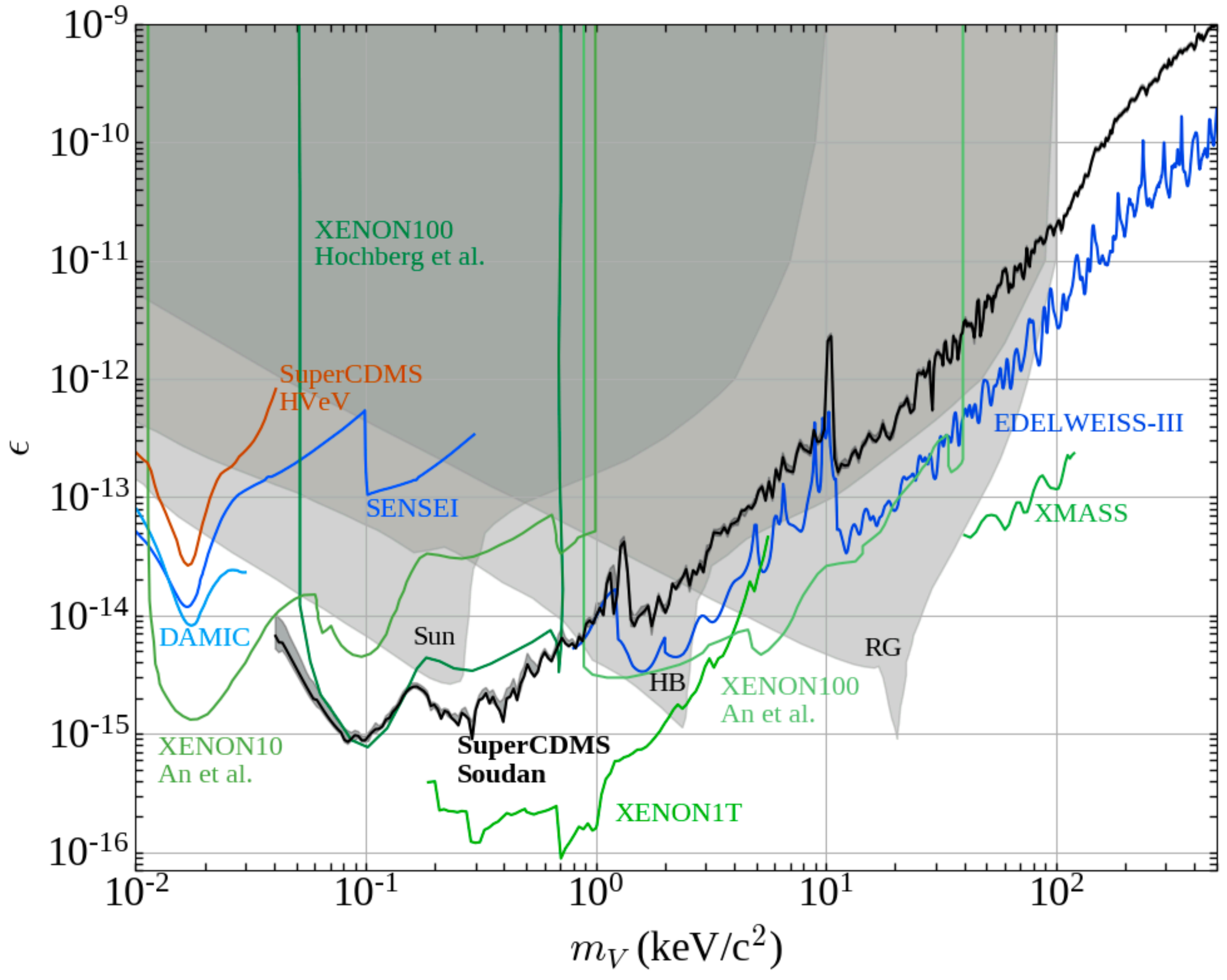
Setting a limit



$$R \propto \rho_{DM}\, g_{aee}^2\, m_a\, \sigma_{p.e.}$$

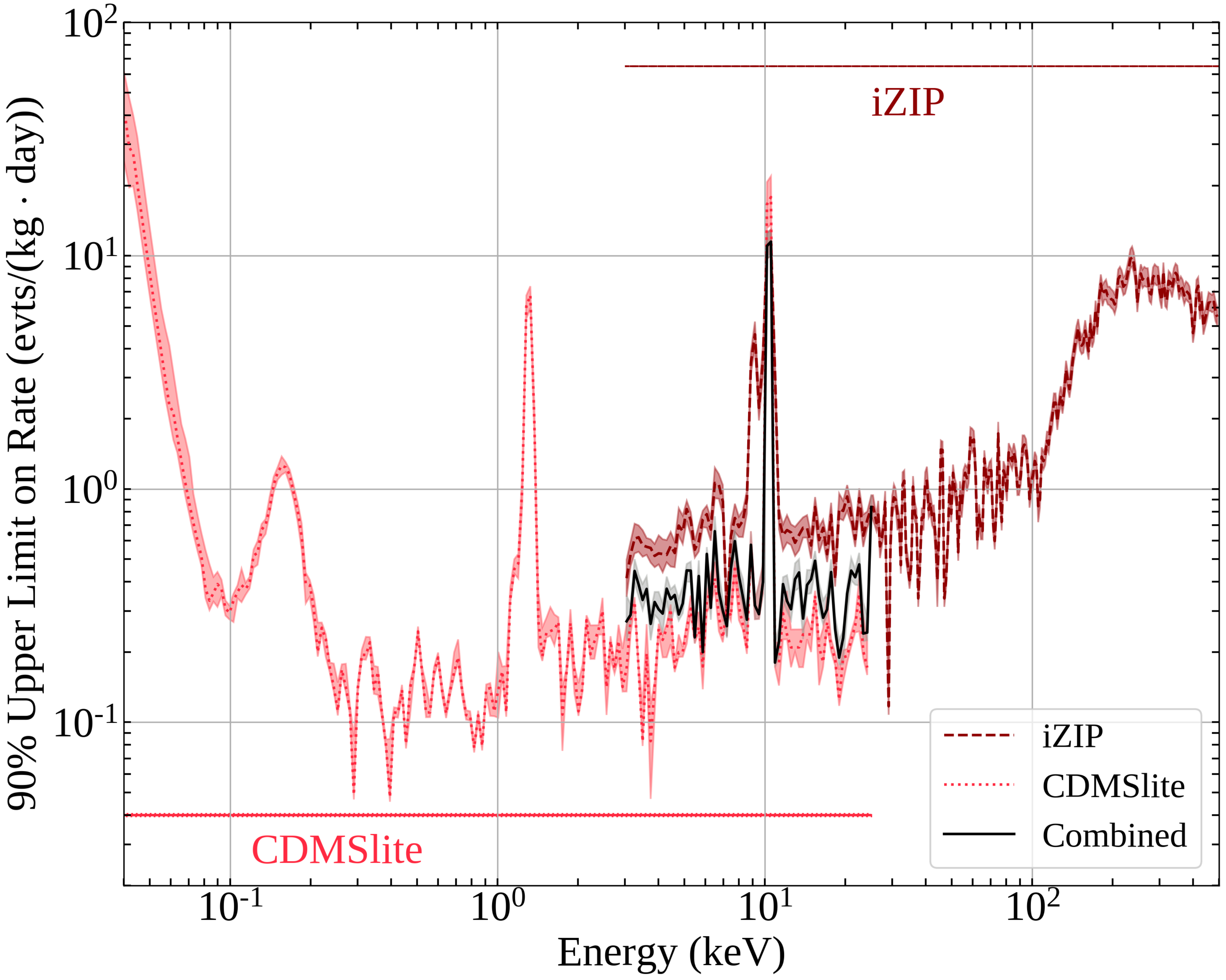
$$R \propto \rho_{DM}\, \varepsilon^2\, m_{A'}^{-1}\, \sigma_{p.e.}$$





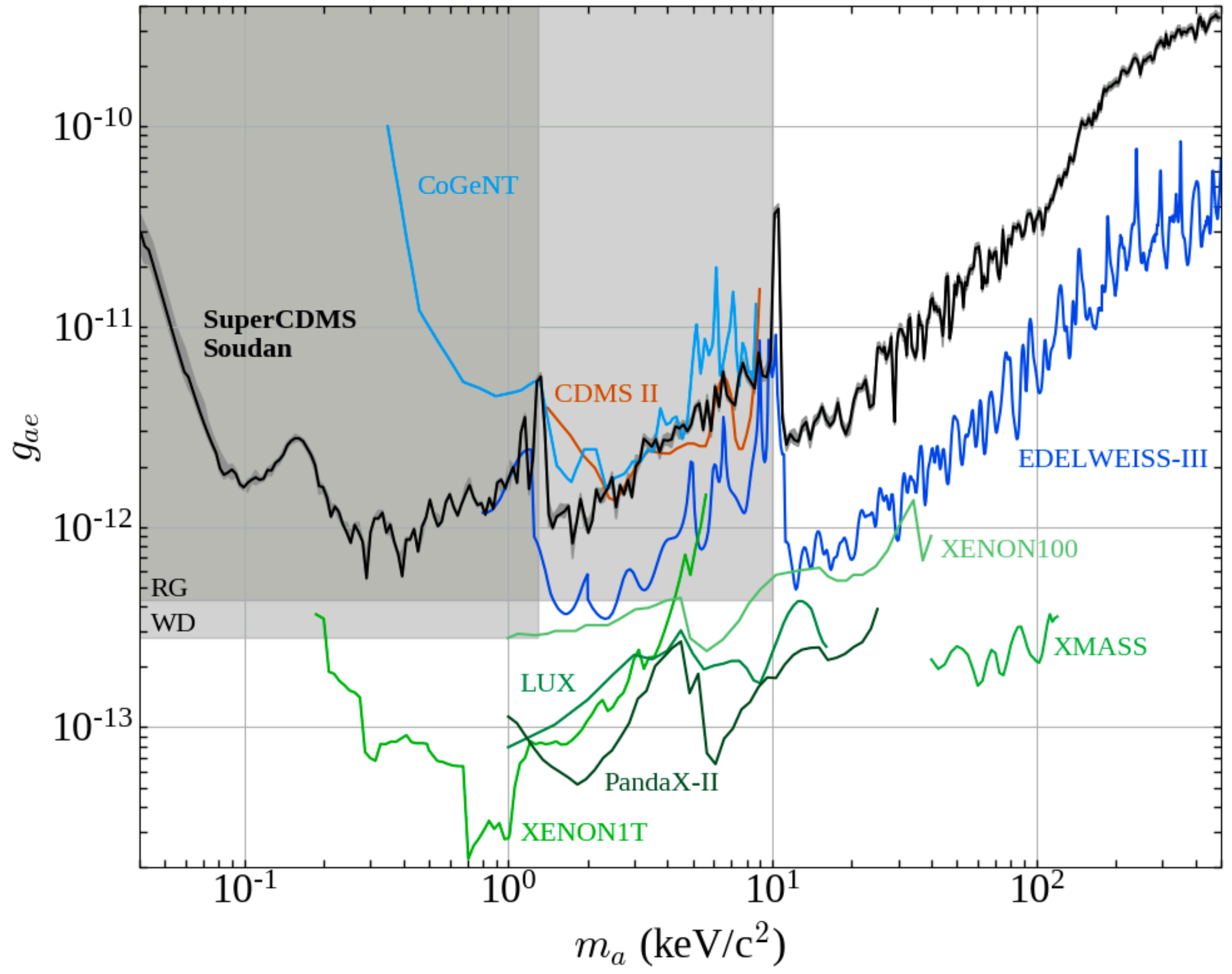
SuperCDMS Collaboration, Phys. Rev. D 101 (2020)

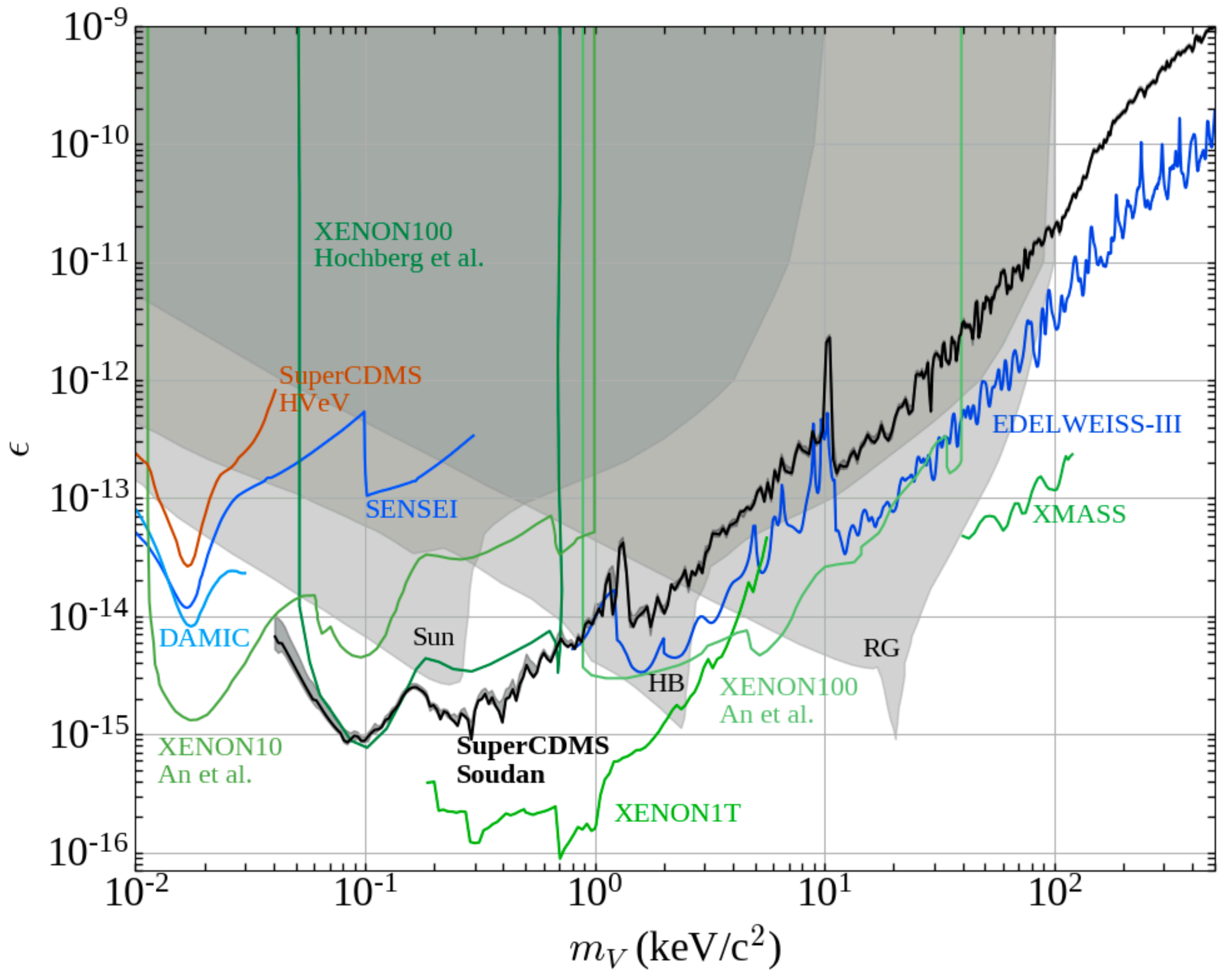
Setting a limit



$$R \propto \rho_{DM}\, g_{aee}^2\, m_a\, \sigma_{p.e.}$$

$$R \propto \rho_{DM}\, \varepsilon^2\, m_A^{-1}\, \sigma_{p.e.}$$



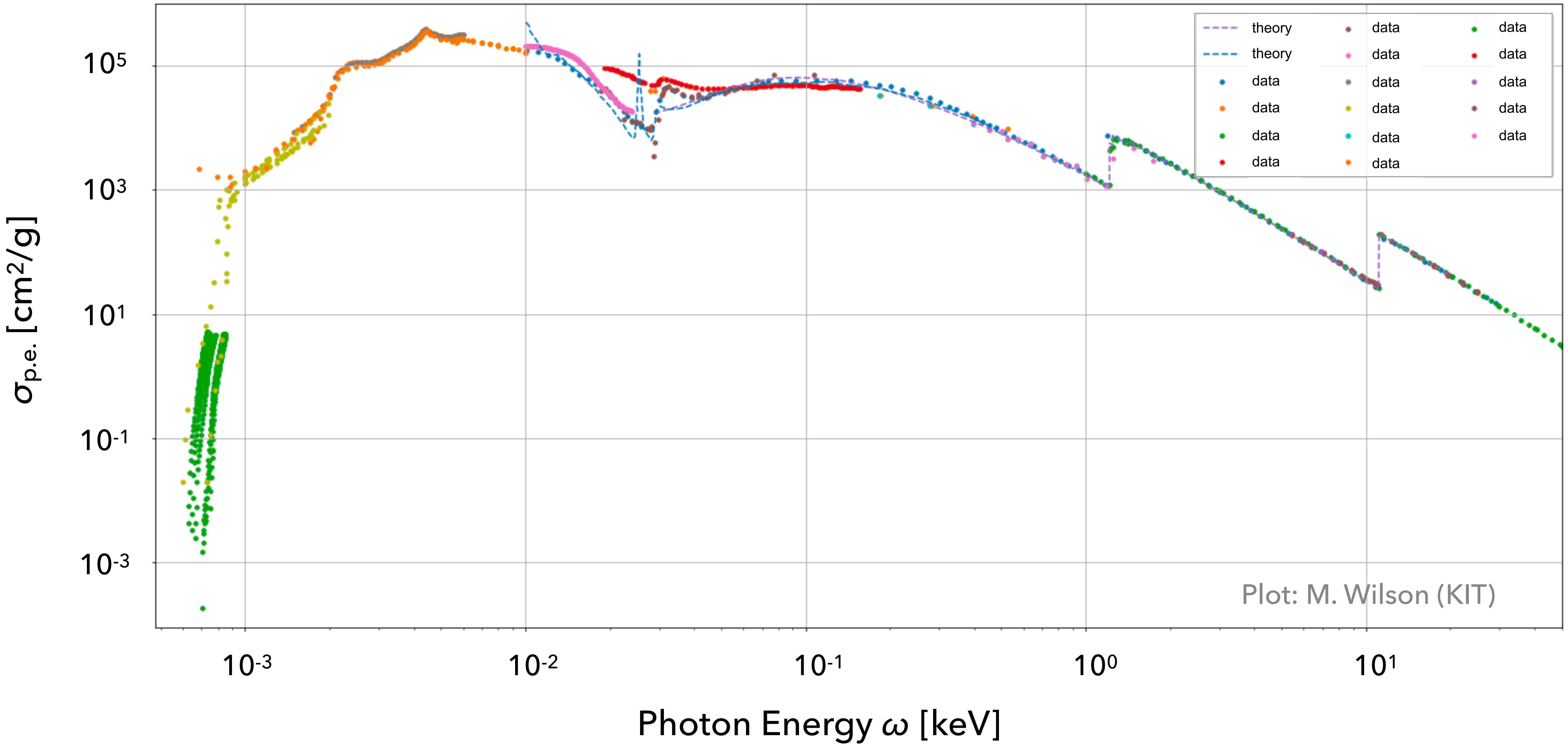


SuperCDMS Collaboration, Phys. Rev. D 101 (2020)

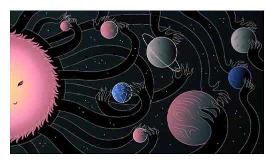
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Dark Absorption in germanium

Ge Photoelectric cross section

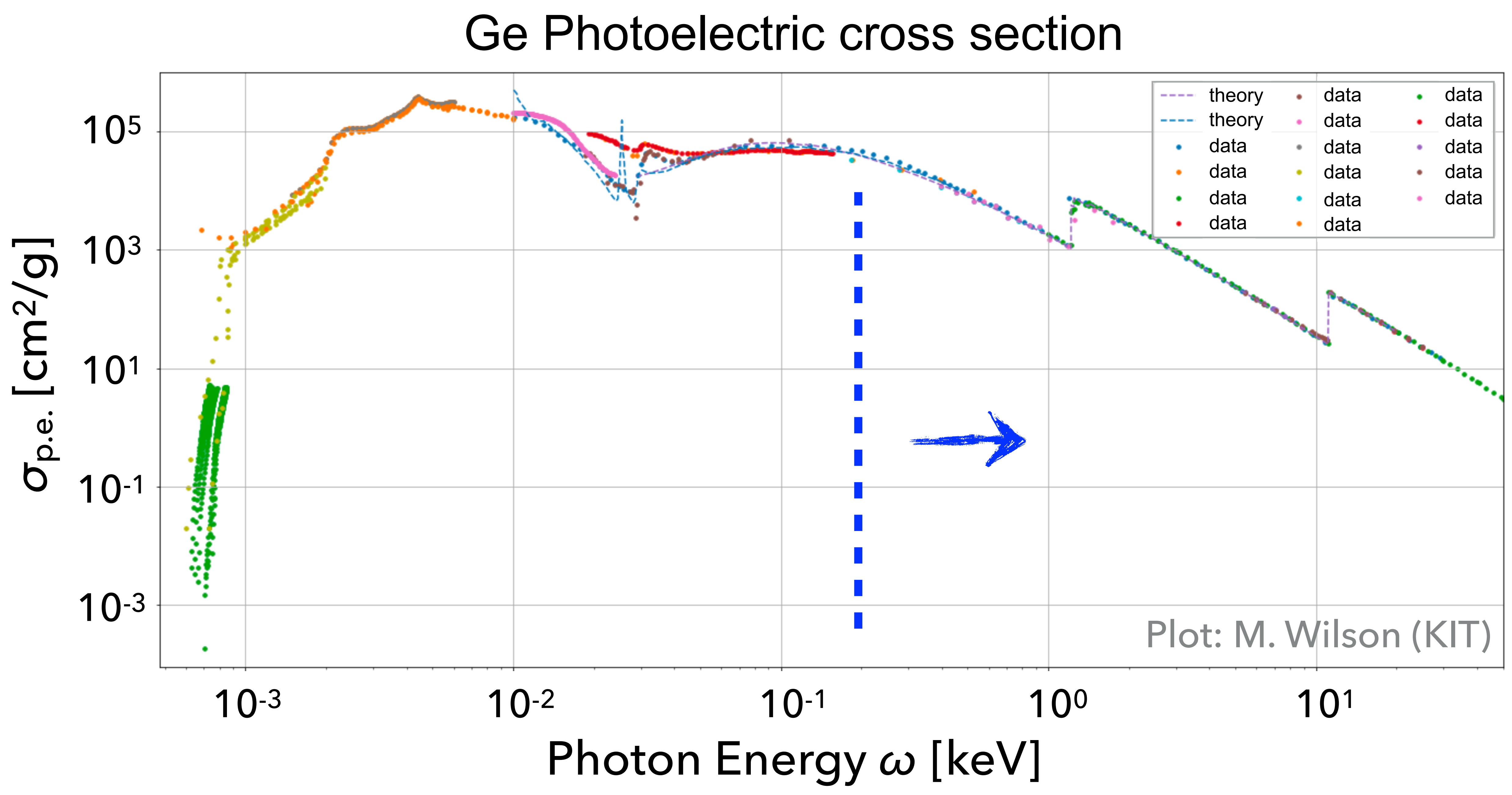


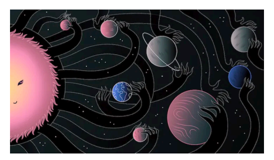
$$R \propto \rho_{\text{DM}}\, g_{aee}^2\, m_a\, \sigma_{\text{p.e.}}(\omega = m_a)$$



$$R \propto \rho_{\text{DM}}\, \varepsilon^2\, m_{A'}^{-1}\, \sigma_{\text{p.e.}}(\omega = m_{A'})$$

Photoelectric Absorption vs. Compton Scattering





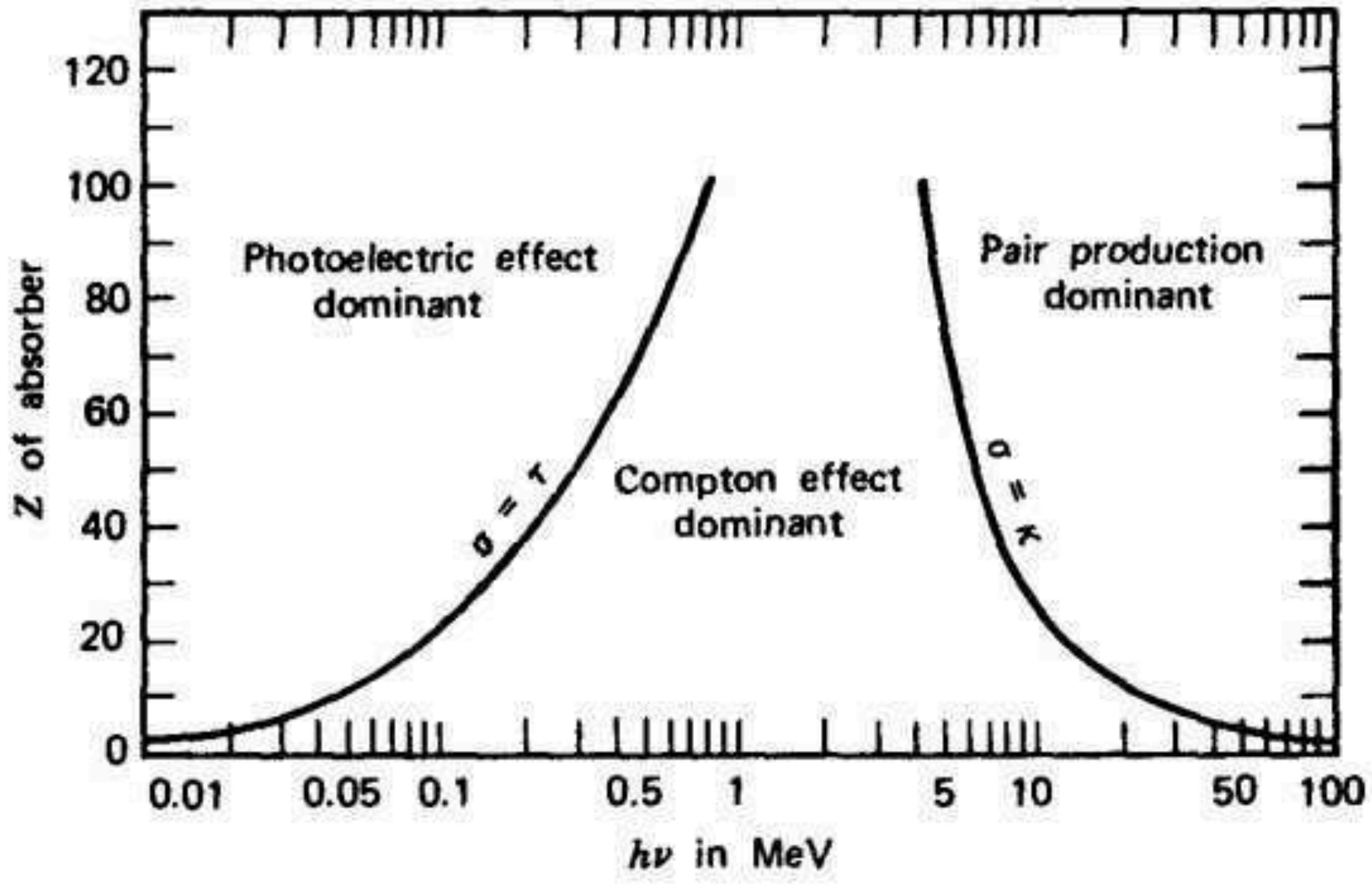
$R \propto g_{aee}^2 \, \sigma_{\text{p.e.}}$ $\qquad$ $R \propto \varepsilon^2 \, \sigma_{\text{p.e.}}$

$$\sigma_{\text{p.e.}} \propto \frac{Z^n}{\omega^3} \quad \text{with} \quad n = 4 - 5$$

Sensitivity to dark boson coupling quickly drops with increasing mass.

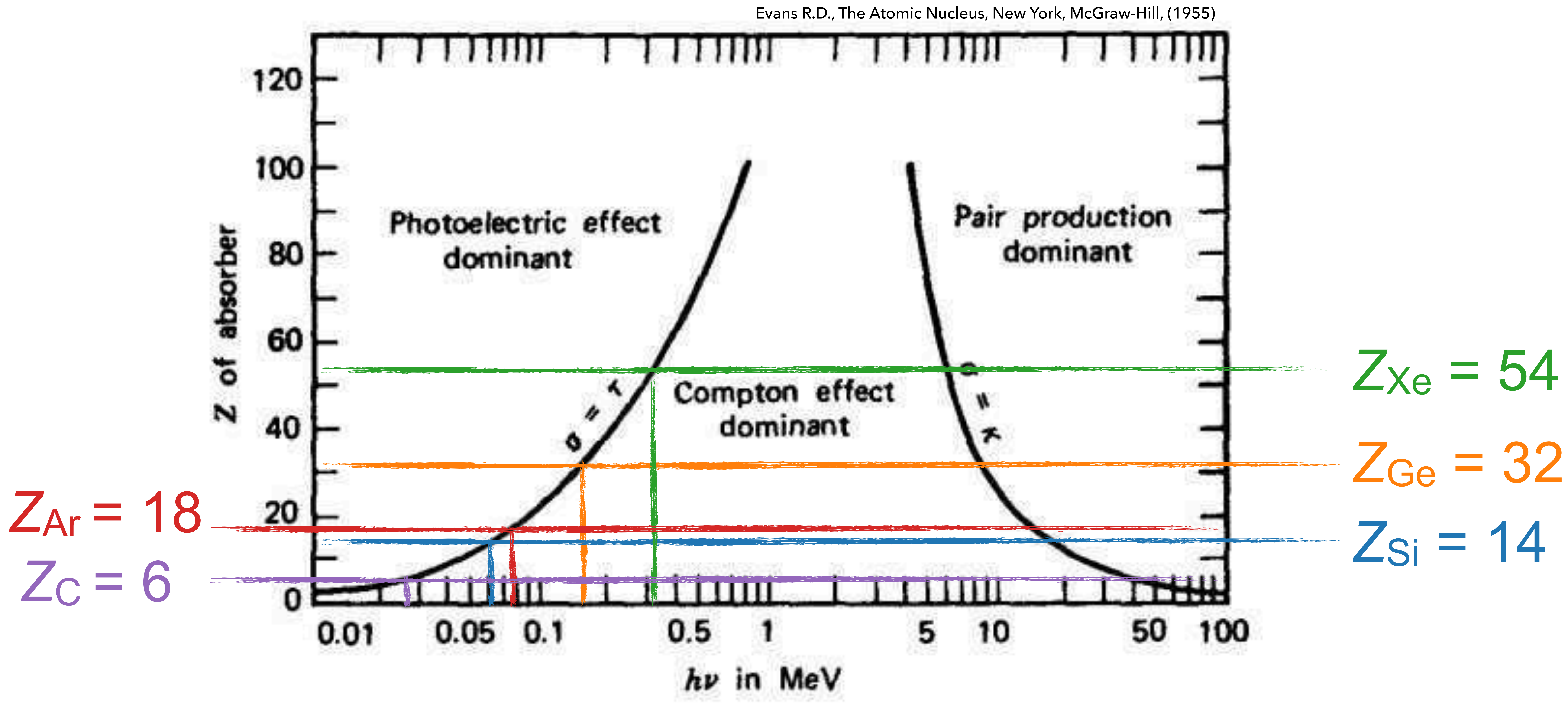
Photoelectric Absorption vs. Compton Scattering

Evans R.D., The Atomic Nucleus, New York, McGraw-Hill, (1955)



- SM photon interactions 101:
  - Compton scattering dominates over photoelectric effect after certain photon energy.

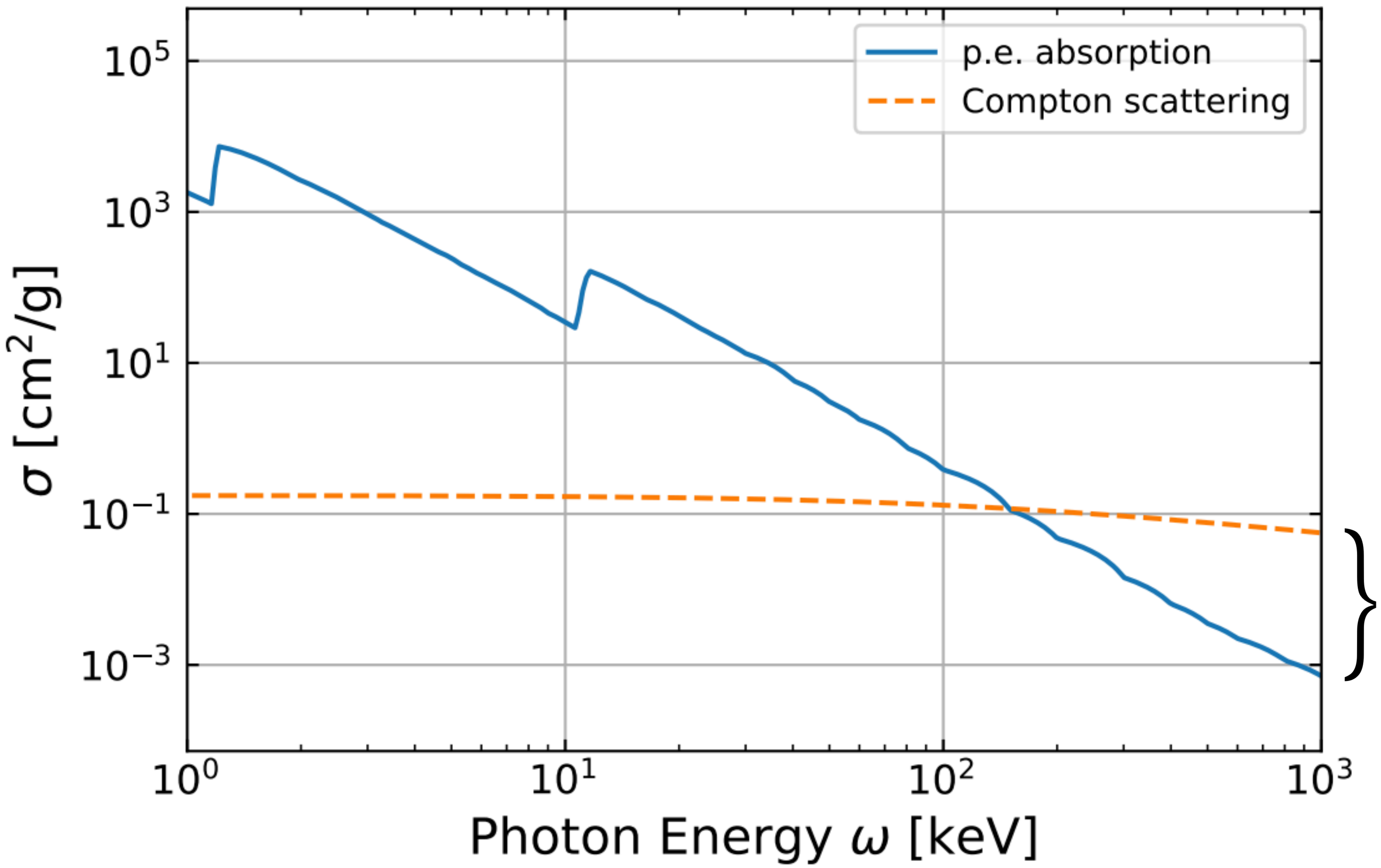
Photoelectric Absorption vs. Compton Scattering



- SM photon interactions 101:
  - Compton scattering dominates over photoelectric effect after certain photon energy.

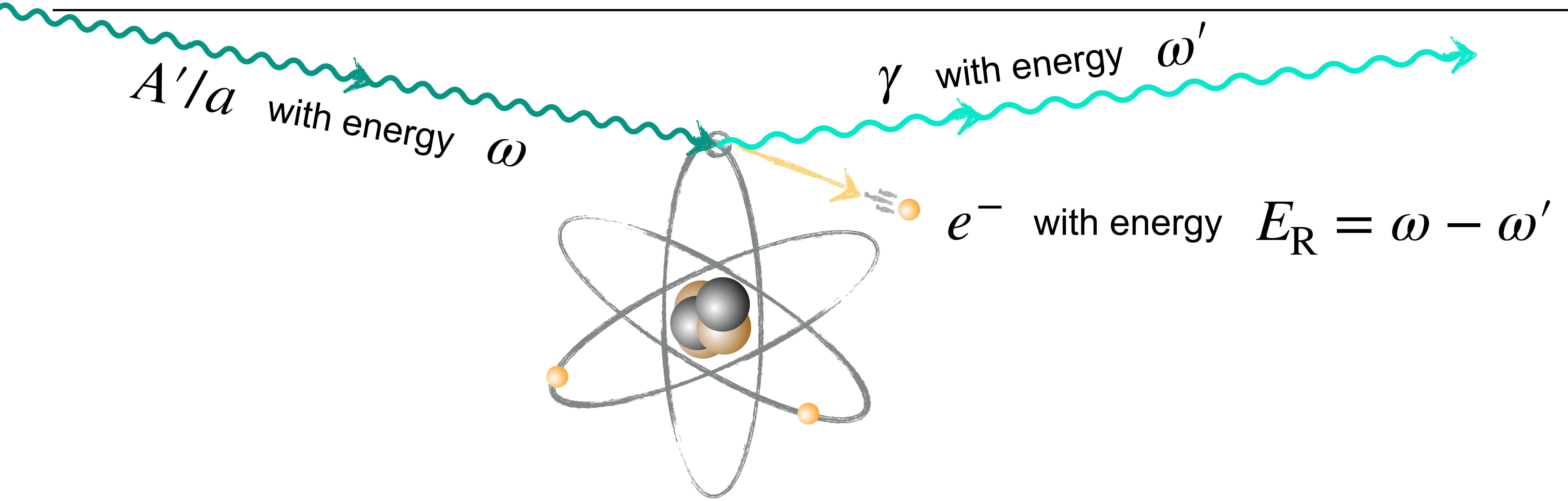
Photoelectric Absorption vs. Compton Scattering

Germanium



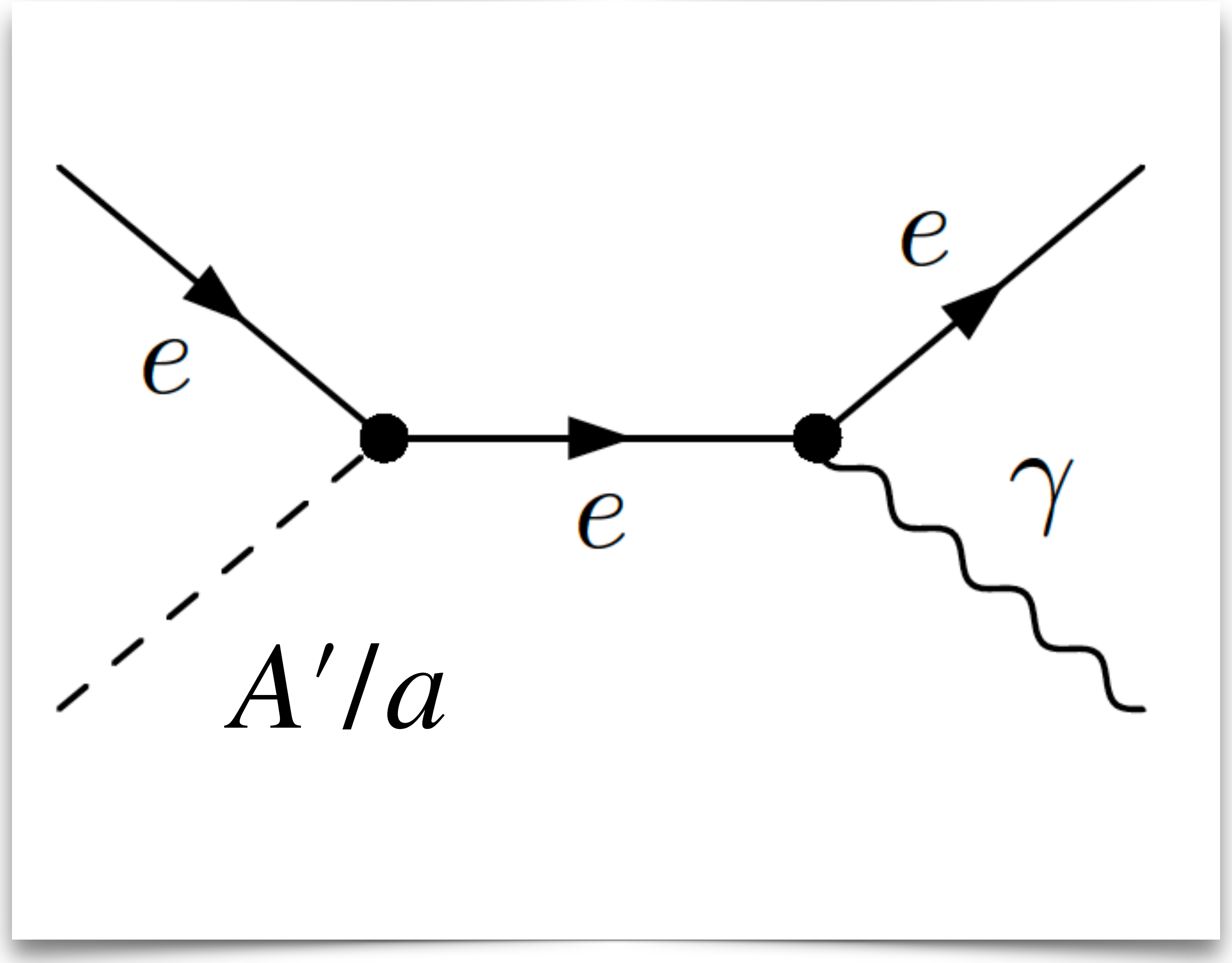
Up to ~2 orders of magnitude higher cross section in Ge.

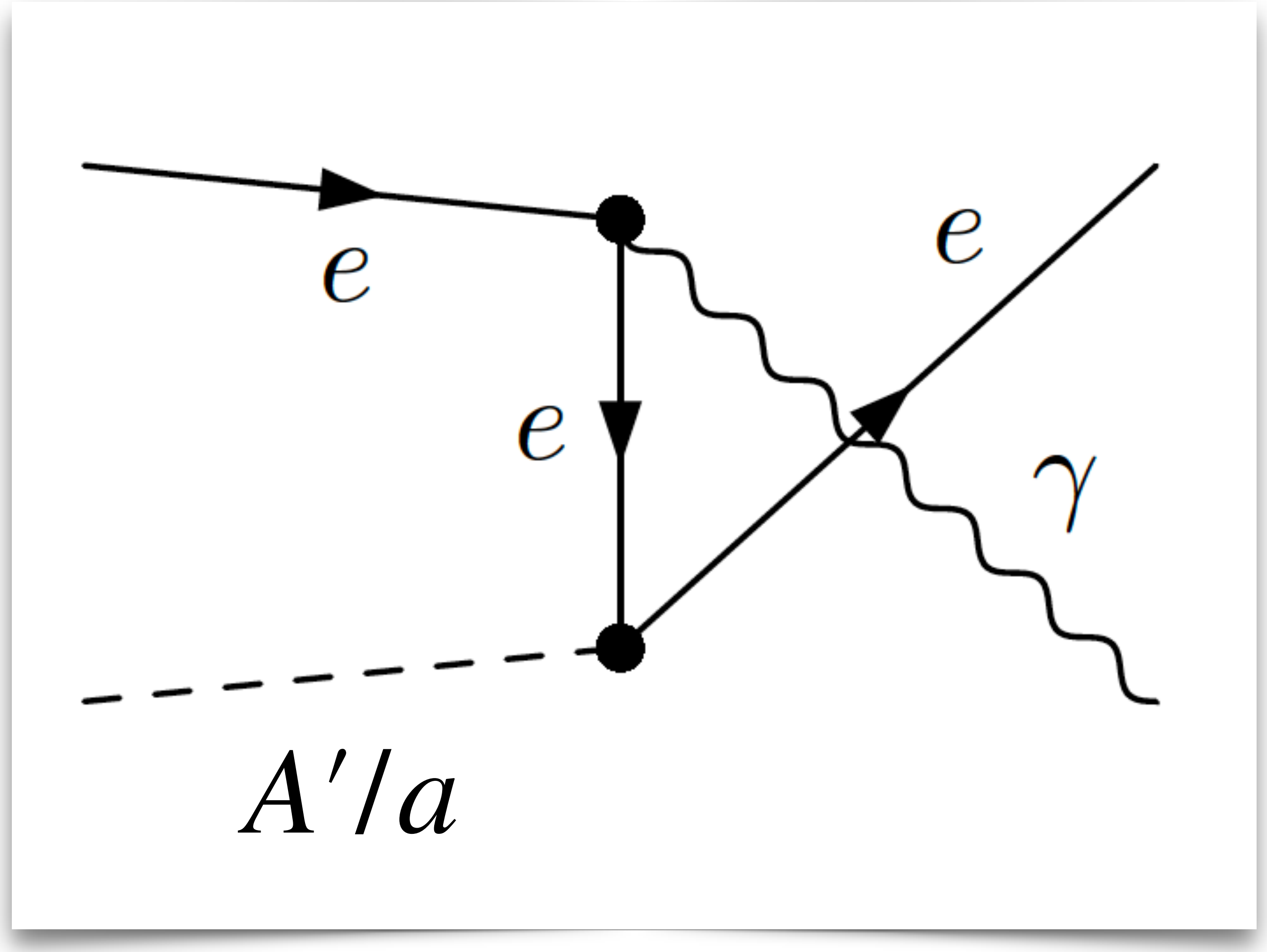
Dark Compton Scattering



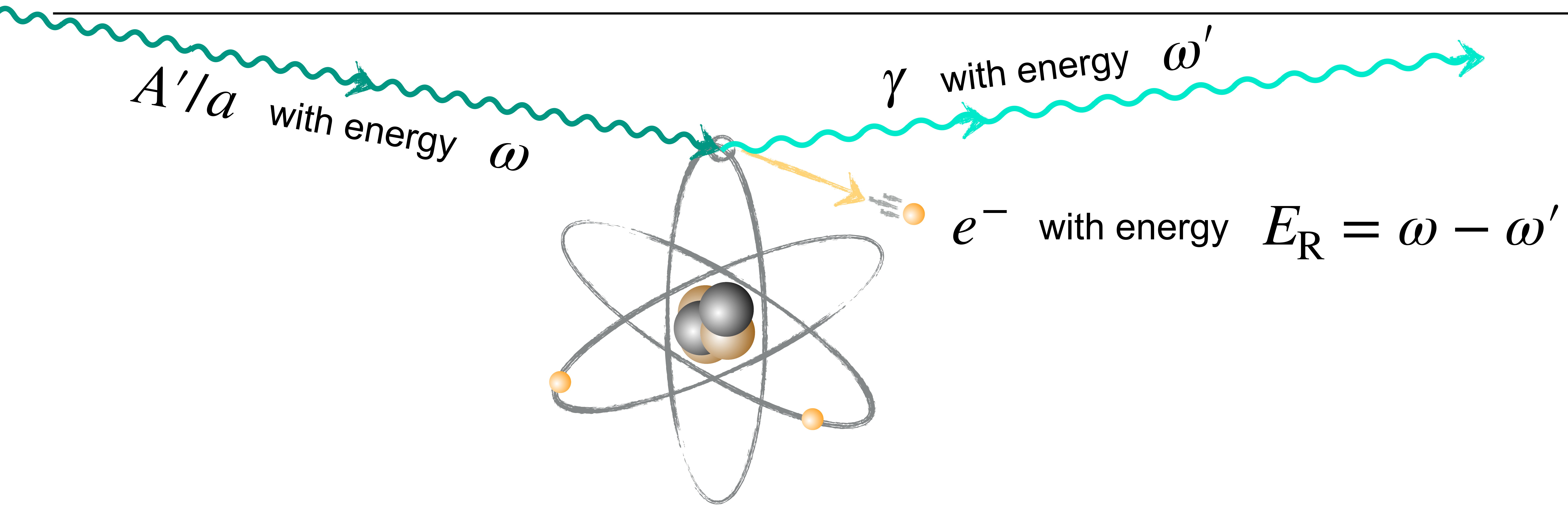
Dark boson is converted to a photon via electron scattering.

$$e^- + A'/a \rightarrow e^- + \gamma$$





Dark Compton Scattering: Signal Model



Dark boson is converted to a photon via electron scattering.

$$e^- + A'/a \rightarrow e^- + \gamma$$

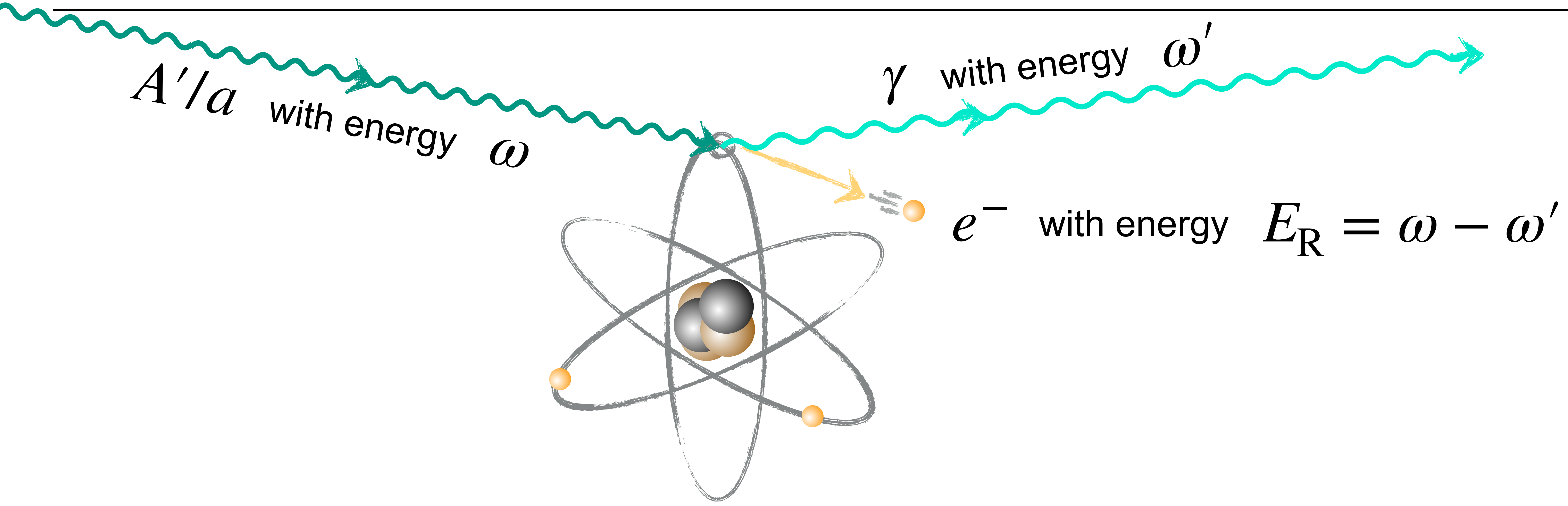
Dark Photons:

$$R_{\text{Com.}} = \rho_{\text{DM}} \frac{n_e}{\rho_T} \frac{e^4 \varepsilon^2}{24\pi} \frac{(m_{A'} + 2m_e)(m_{A'}^2 + 2m_e m_{A'} + 2m_e^2)}{m_e^2 m_{A'} (m_{A'} + m_e)^3}$$

ALPs:

$$R_{\text{Com.}} = \rho_{\text{DM}} \frac{n_e}{\rho_T} \frac{e^2 g_{aee}^2}{16\pi} \frac{m_a (m_a + 2m_e)^2}{m_e^2 (m_a + m_e)^4}$$

Dark Compton Scattering: Signal Model



Dark boson is converted to a photon via electron scattering.

$$e^- + A'/a \rightarrow e^- + \gamma$$

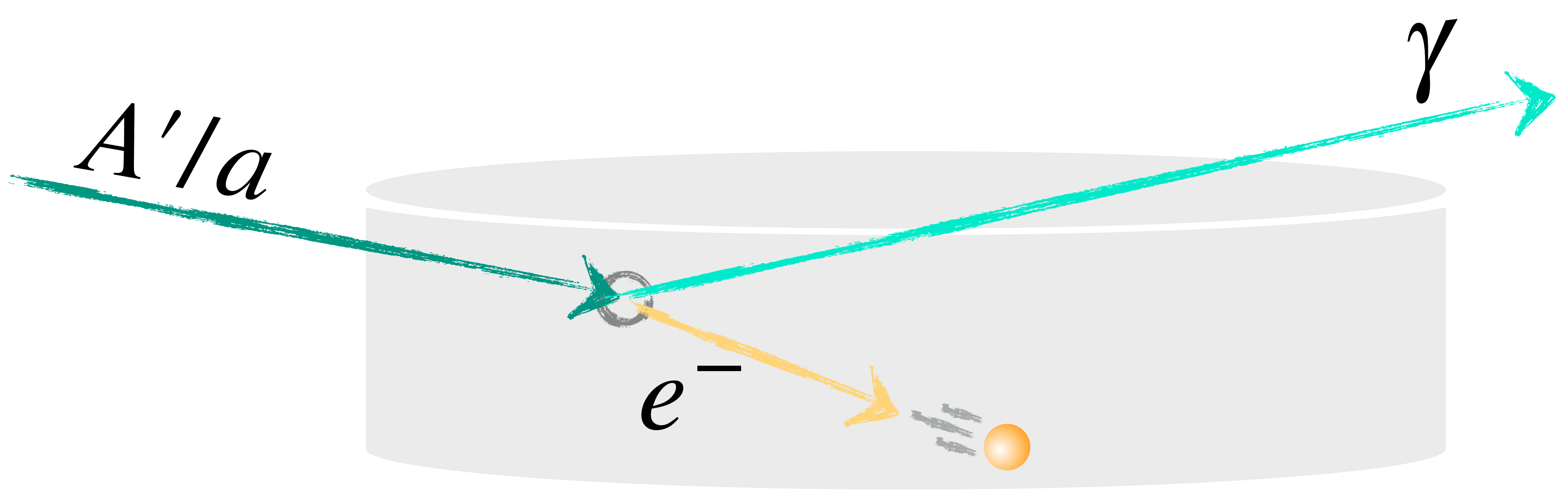
$$R_{\text{Com.}} \propto \frac{n_e}{\rho_T} \varepsilon^2 / g_{aee}^2$$

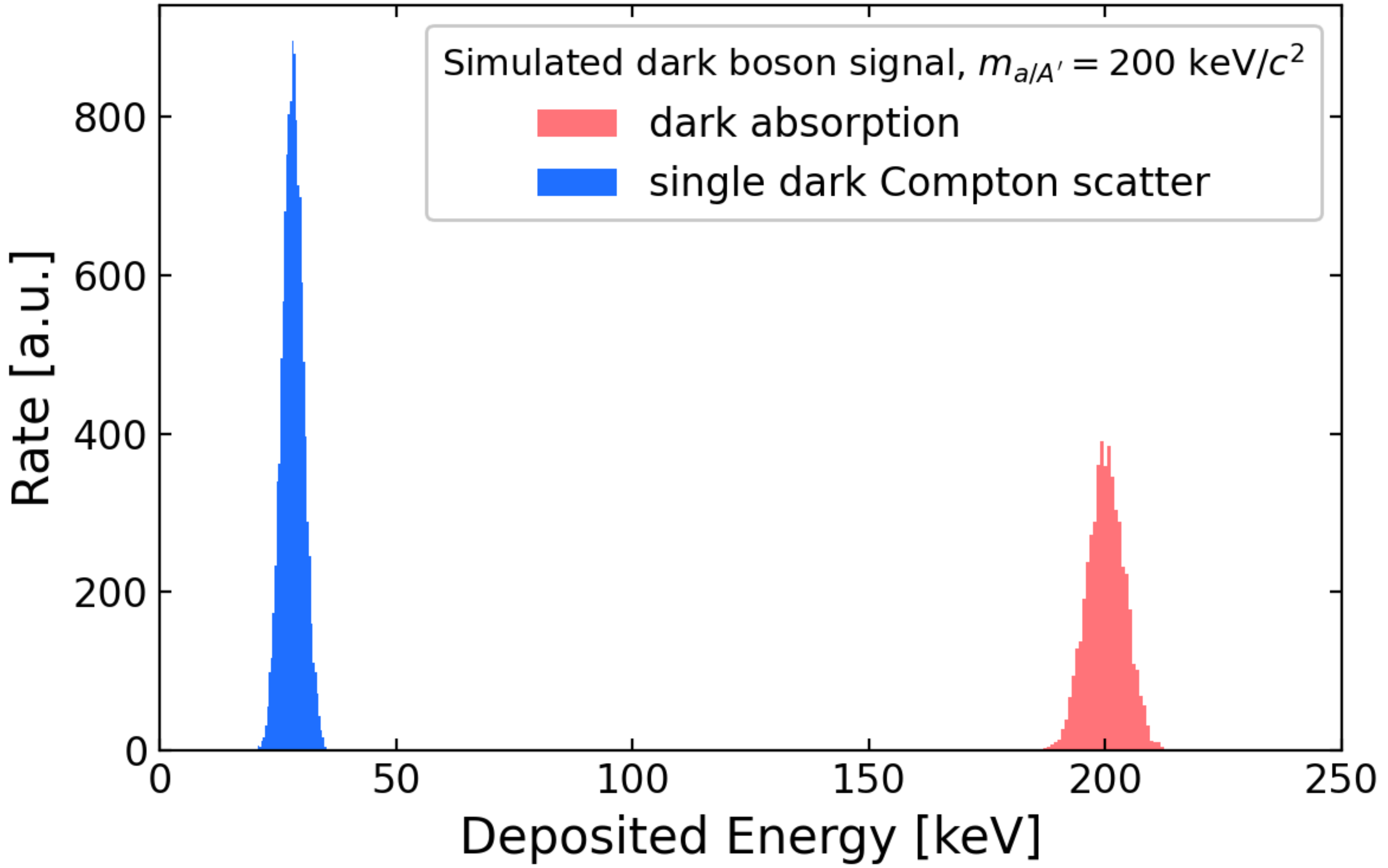
n_e: electron density

ρ_T: target density

Reminder: $R_{\text{Abs.}} \propto \sigma_{\text{p.e.}} \varepsilon^2 / g_{aee}^2$

Dark Compton Scattering: Signal Model





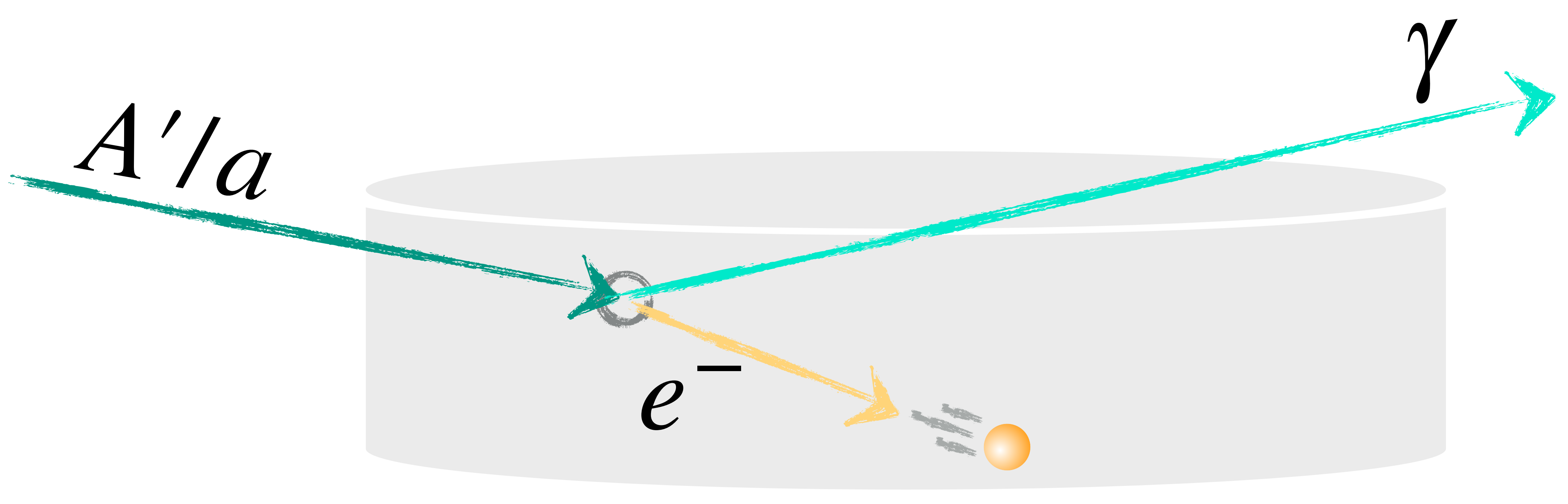
$$E_{\mathrm{R,Com.}} = \omega - \omega' = \frac{m_{a/A'}^2}{2(m_e + m_{a/A'})}$$

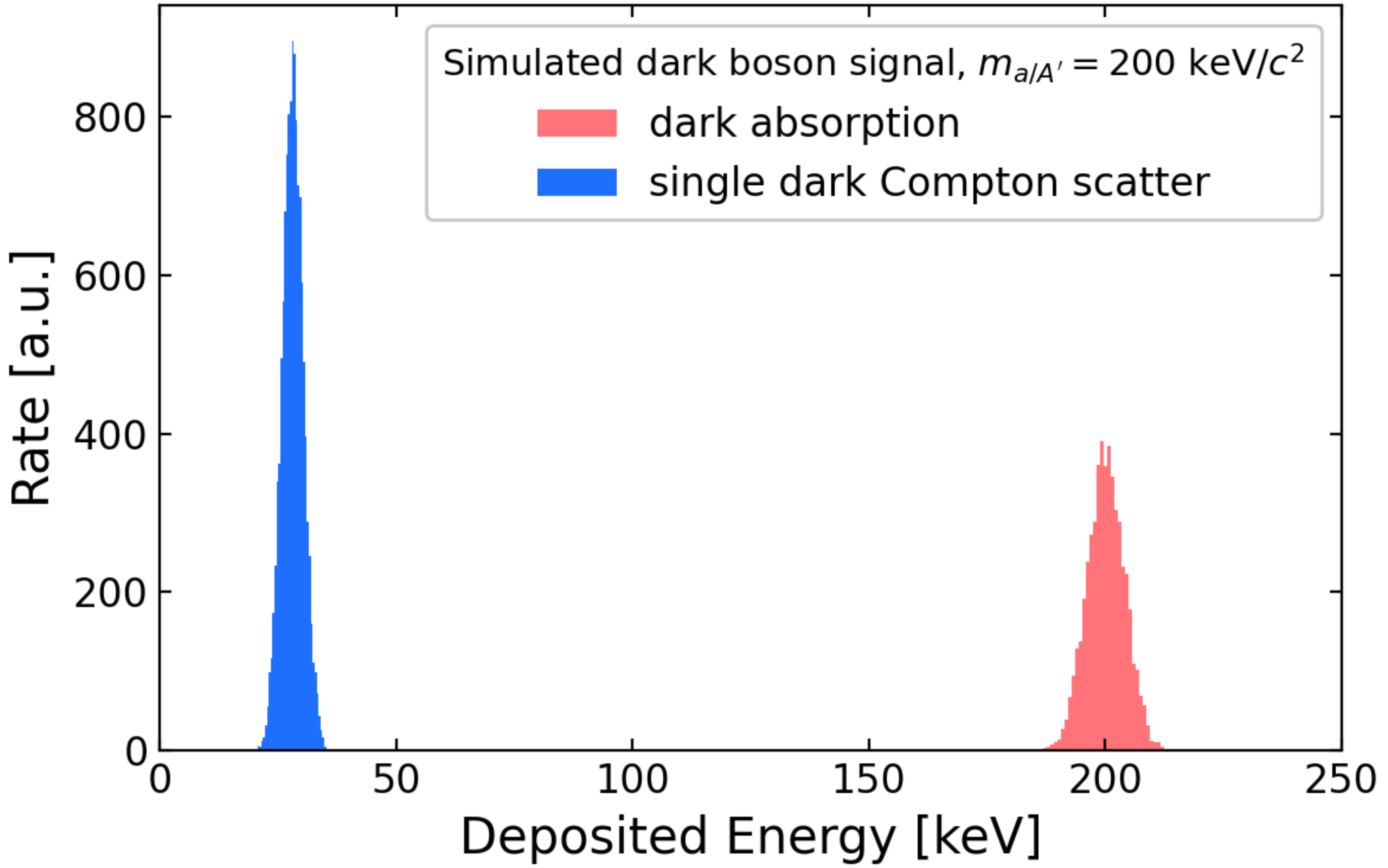
$$E_{\mathrm{R,Abs.}} = m_{a/A'}$$

Dark Compton scattering

Detector considerations

Dark Compton signature

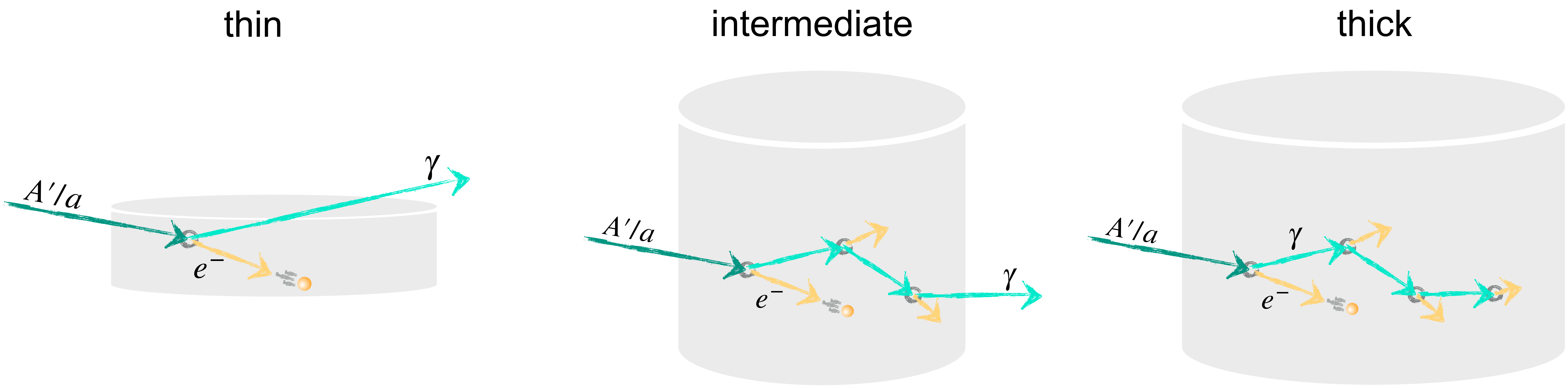




$$E_{R,\text{Com.}} = \omega - \omega' = \frac{m_{a/A'}^2}{2(m_e + m_{a/A'})}$$

$$E_{R,\text{Abs.}} = m_{a/A'}$$

Detector target size



$$E_{R,\mathrm{tot.}} = E_{R,\mathrm{Com.}}$$

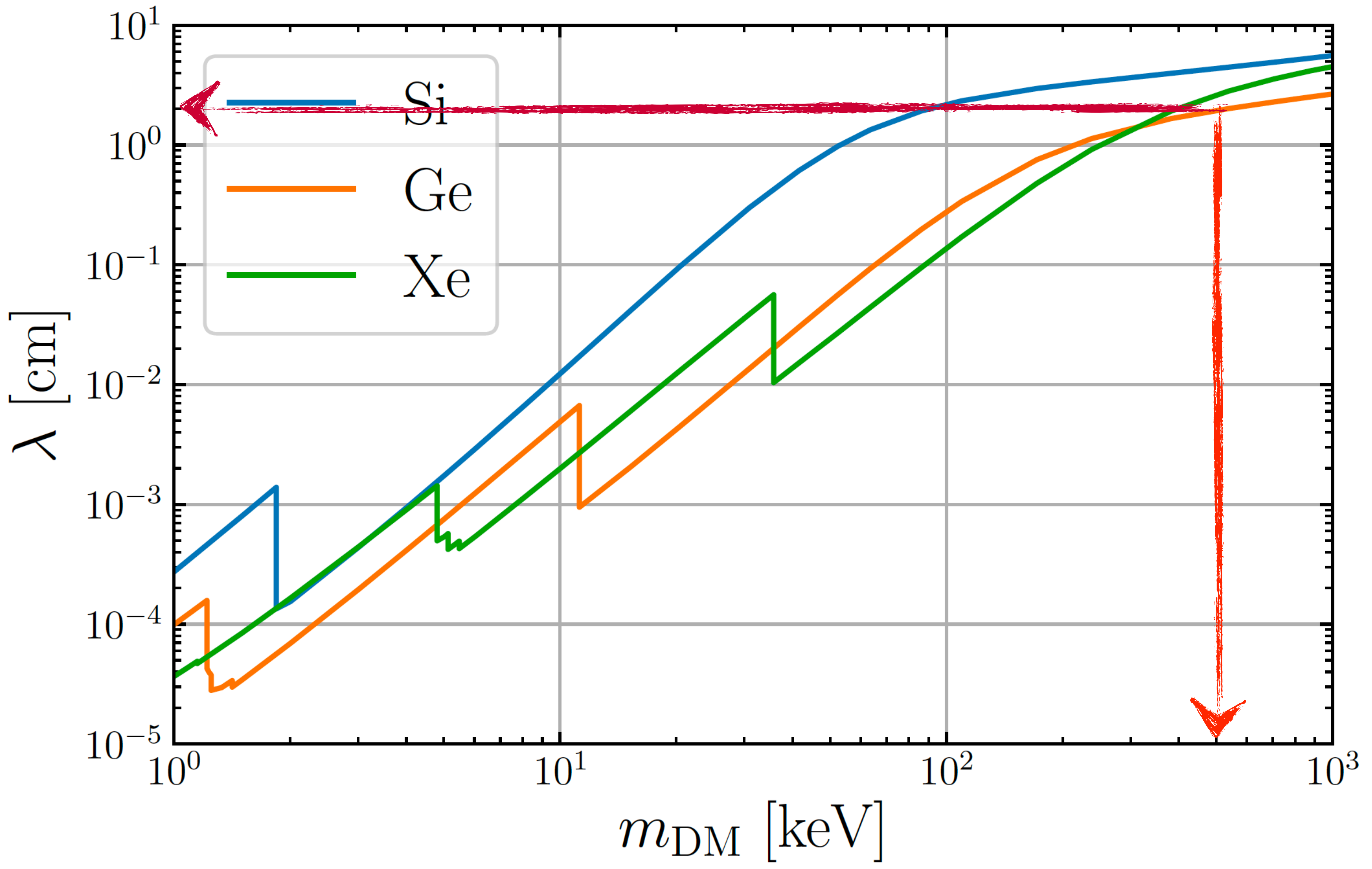
$$E_{R,\mathrm{Com.}} \leq E_{R,\mathrm{tot.}} \leq E_{R,\mathrm{Abs.}}$$

$$E_{R,\mathrm{tot.}} = E_{R,\mathrm{Abs.}}$$

Compton-peak “walks” towards absorption-peak if outgoing photon further interacts in target.

Selection of relevant experiments

Experiment	Material	Dimensions [cm]	λ_{max} [cm]	m_{DM} cutoff [keV]
Past and current experiments				
EDELWEISS III [62]	Ge	H: 4, ⌀: 7	2.2	500
SuperCDMS Soudan [63]	Ge	H: 2.5, ⌀: 7.6	2.2	500
GERDA (HPGe) [64]	Ge	H: 7–11, ⌀: 6–8†	2.6	1000
GERDA (BEGe) [64]	Ge	H: 2.5–5, ⌀: 6.5–8	2.6	1000
XENON1T [65]	Xe	H: 97, ⌀: 96	0.88	200
PandaX-4T [66]	Xe	H: 130, ⌀: 100	4.2	1000
Upcoming experiments				
SuperCDMS SNOLAB [60, 67]	Si	H: 3.3, ⌀: 10	2.1	100*
SuperCDMS SNOLAB [60, 67]	Ge	H: 3.3, ⌀: 10	0.3	100*
LZ [68]	Xe	H: 150, ⌀: 150	0.09	85
DARWIN [69, 70]	Xe	H: 260, ⌀: 260	4.2	1000



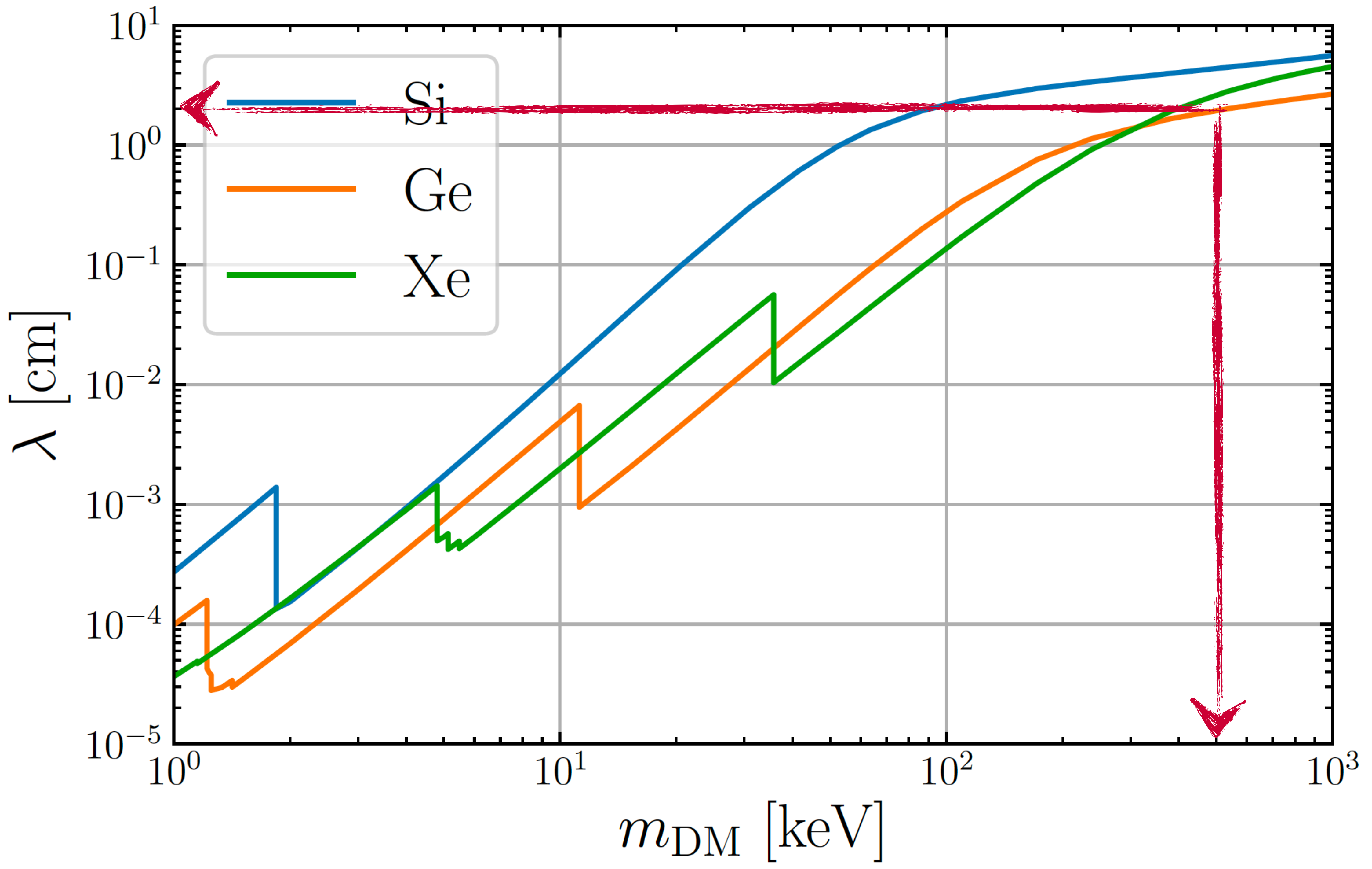
- Thin: $d \ll \lambda$
- Intermediate: $d \approx \lambda$
- Thick: $d \gg \lambda$

λ: attenuation length

d: diameter / thickness of detector

Selection of relevant experiments

Experiment	Material	Dimensions [cm]	λ_{max} [cm]	m_{DM} cutoff [keV]
Past and current experiments				
EDELWEISS III [62]	Ge	H: 4, ∅: 7	2.2	500
SuperCDMS Soudan [63]	Ge	H: 2.5, ∅: 7.6	2.2	500
GERDA (HPGe) [64]	Ge	H: 7–11, ∅: 6–8†	2.6	1000
GERDA (BEGe) [64]	Ge	H: 2.5–5, ∅: 6.5–8	2.6	1000
XENON1T [65]	Xe	H: 97, ∅: 96	0.88	200
PandaX-4T [66]	Xe	H: 130, ∅: 100	4.2	1000
Upcoming experiments				
SuperCDMS SNOLAB [60, 67]	Si	H: 3.3, ∅: 10	2.1	100*
SuperCDMS SNOLAB [60, 67]	Ge	H: 3.3, ∅: 10	0.3	100*
LZ [68]	Xe	H: 150, ∅: 150	0.09	85
DARWIN [69, 70]	Xe	H: 260, ∅: 260	4.2	1000

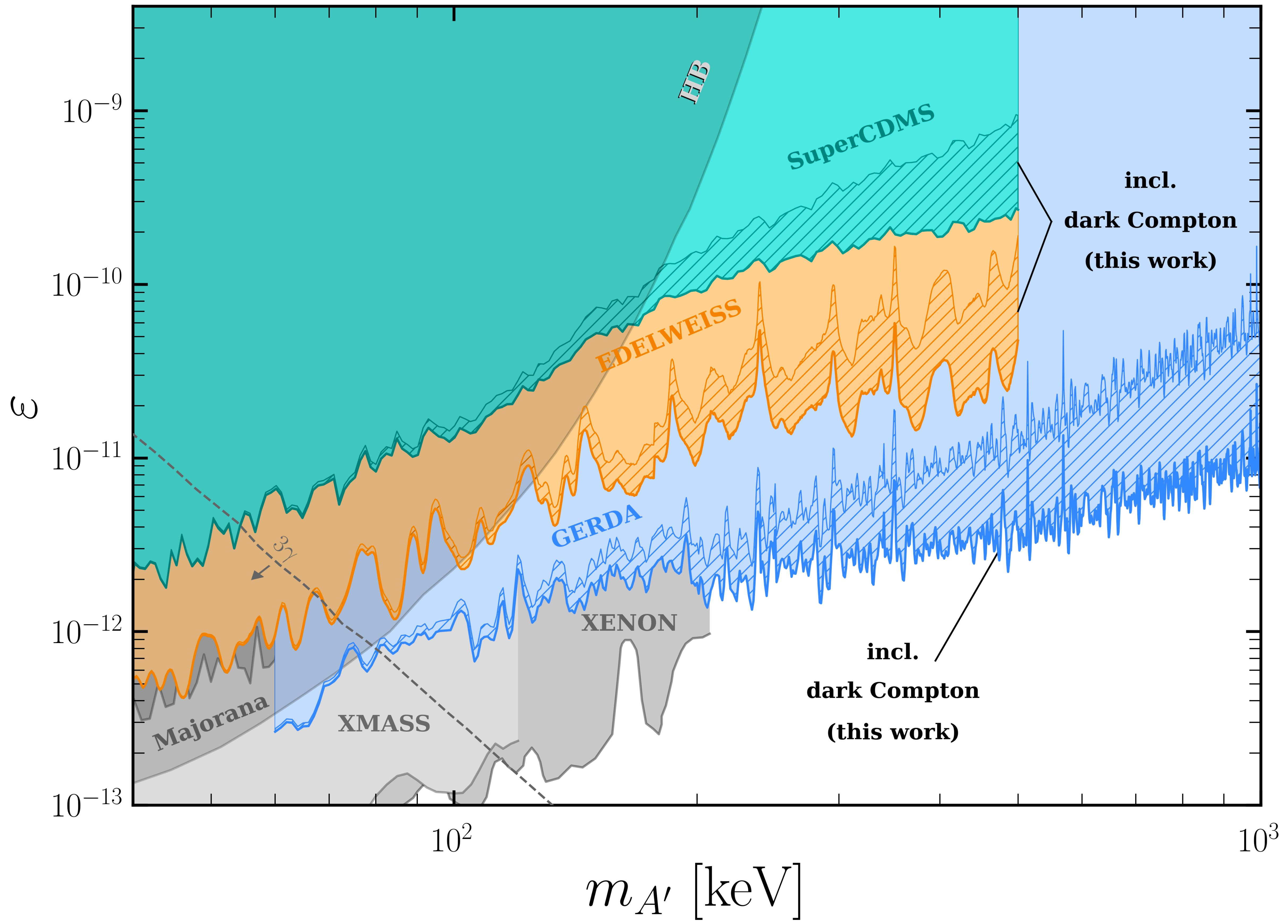


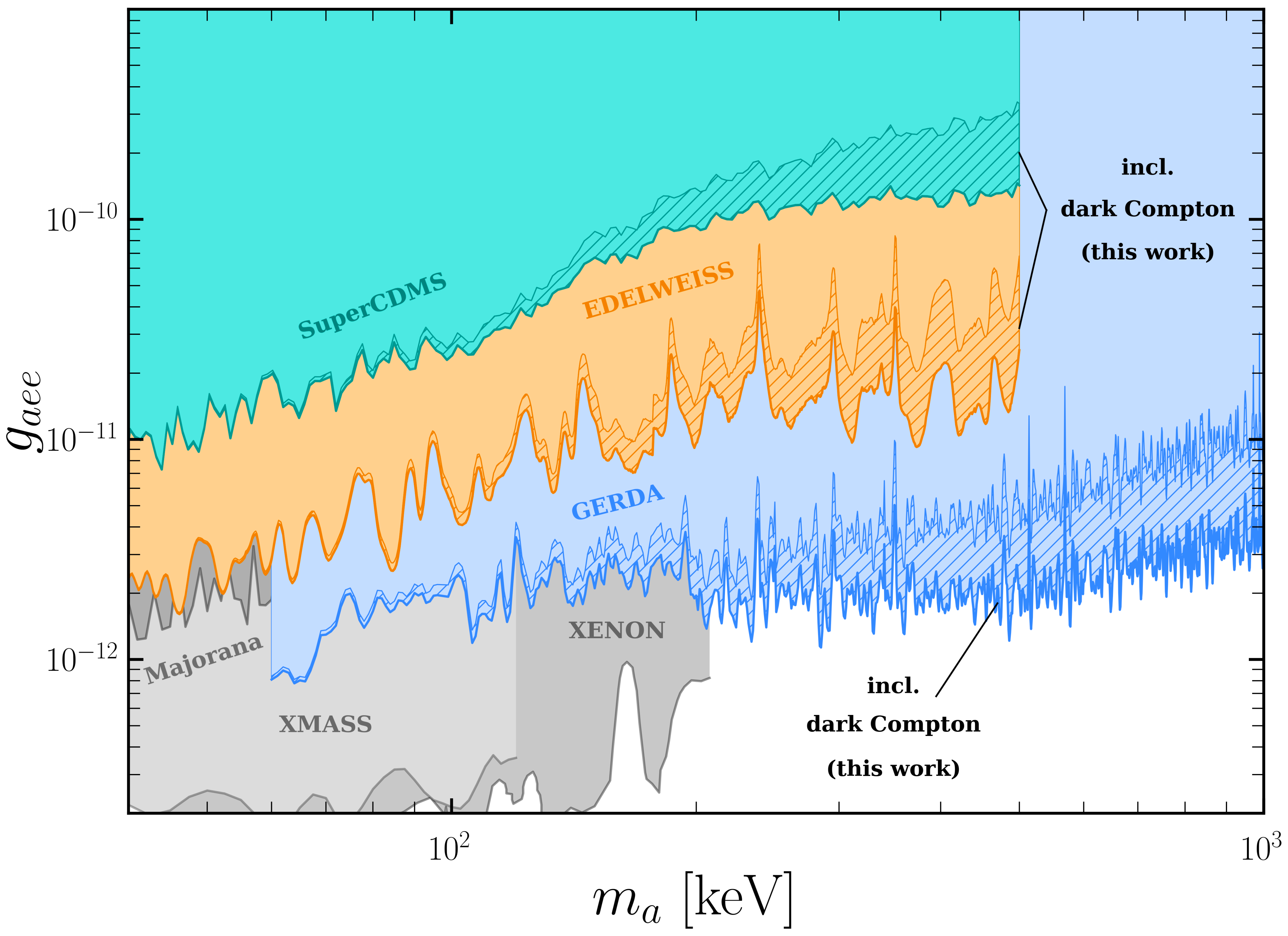
- Thin: $d \ll \lambda$
- Intermediate: $d \approx \lambda$ ⟶ typical Ge detectors
- Thick: $d \gg \lambda$ ⟶ typical Xe detectors

λ: attenuation length
d: diameter / thickness of detector

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Dark Compton Scattering





New parameter space accessible with existing data!

Y. Hochberg, BvK, E. Kuflik, T.C. Yu, Phys. Rev. Lett. 128, 191801, (2022)

Take-home messages

- Understanding the nature of DM is one of the biggest challenges in science today.
- Today's direct DM experiments can probe a sensationally wide range of DM masses.
- Advances in direct DM will allow to notably expand the accessible parameter space.
- **This is an extremely variate and rich field (experiment and theory) that welcomes the next generation of creative minds!**