Neutrinos at direct detection: friend or foe?

Tarak Nath Maity
The University of Sydney, Australia

Based on:

B Carew, A Caddell, TNM, C O'Hare; 2312.04303

TNM, C Boehm; 2409.04385

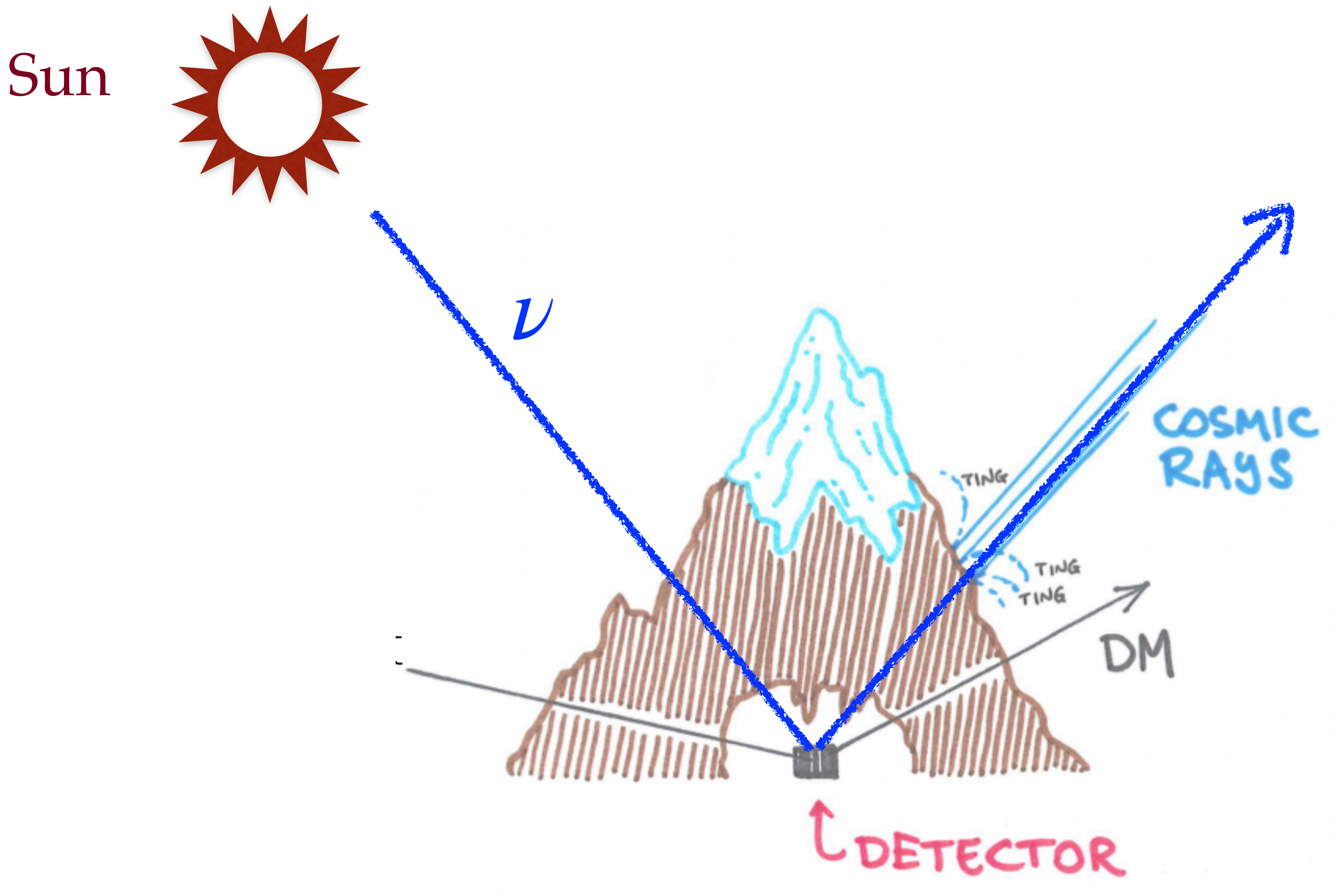
THE UNIVERSITY OF SYDNEY

SOTU Seminar

tifr

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Plan



XENONnT, SENSEI …

Foe

Slowed down the search of dark matter

Carew, Caddell, TNM, O'Hare; 2312.04303

Friend

Weak mixing angle at the lowest energy

TNM, Boehm; 2409.04385

Image modified from 2104.12785

Dark Matter exists!

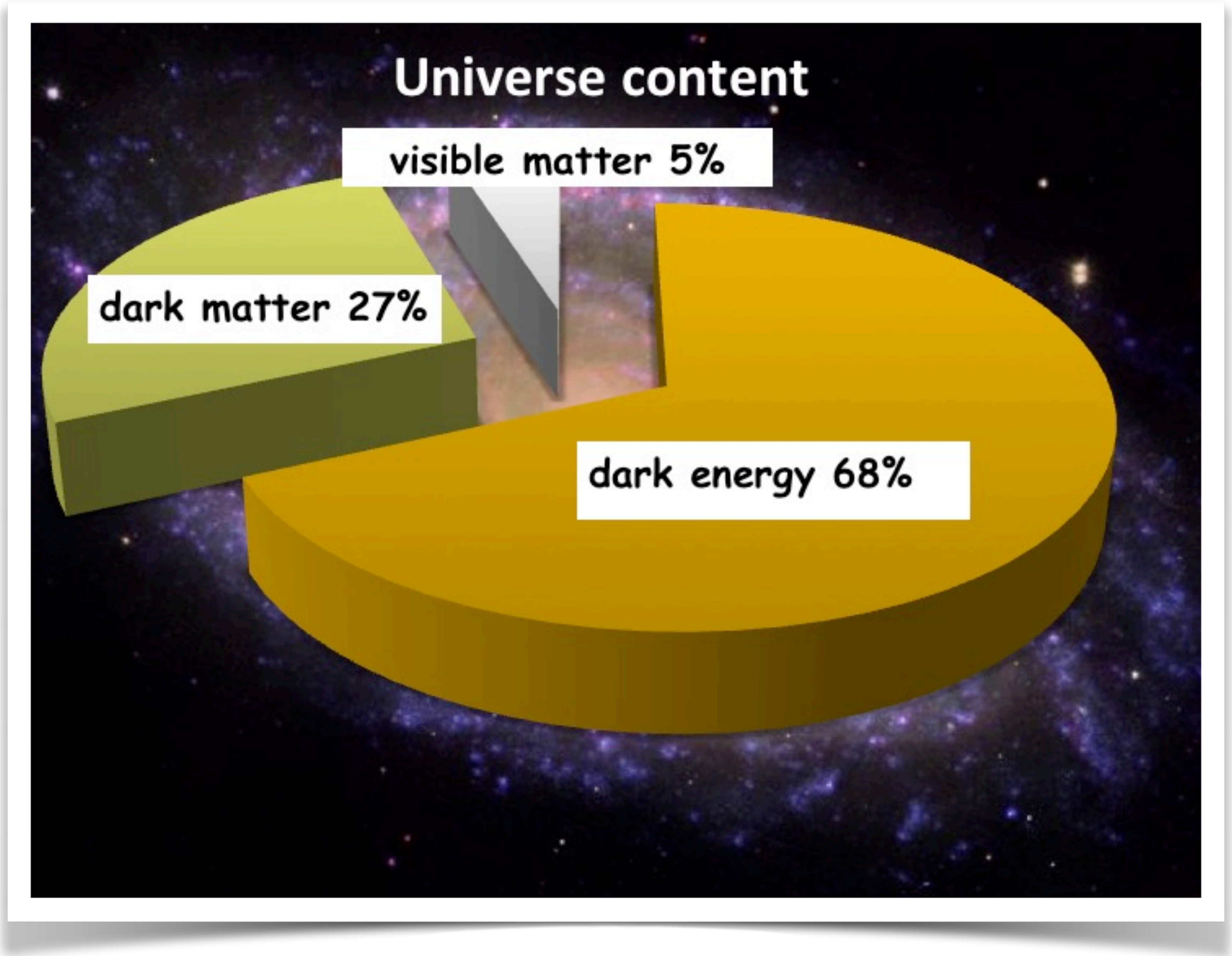


Image credit: QUANTUM DIARIES

- ☑ Stable: No decay, very long-lived
- ☑ Cold: Non-relativistic
- ☑ Massive: Wide range

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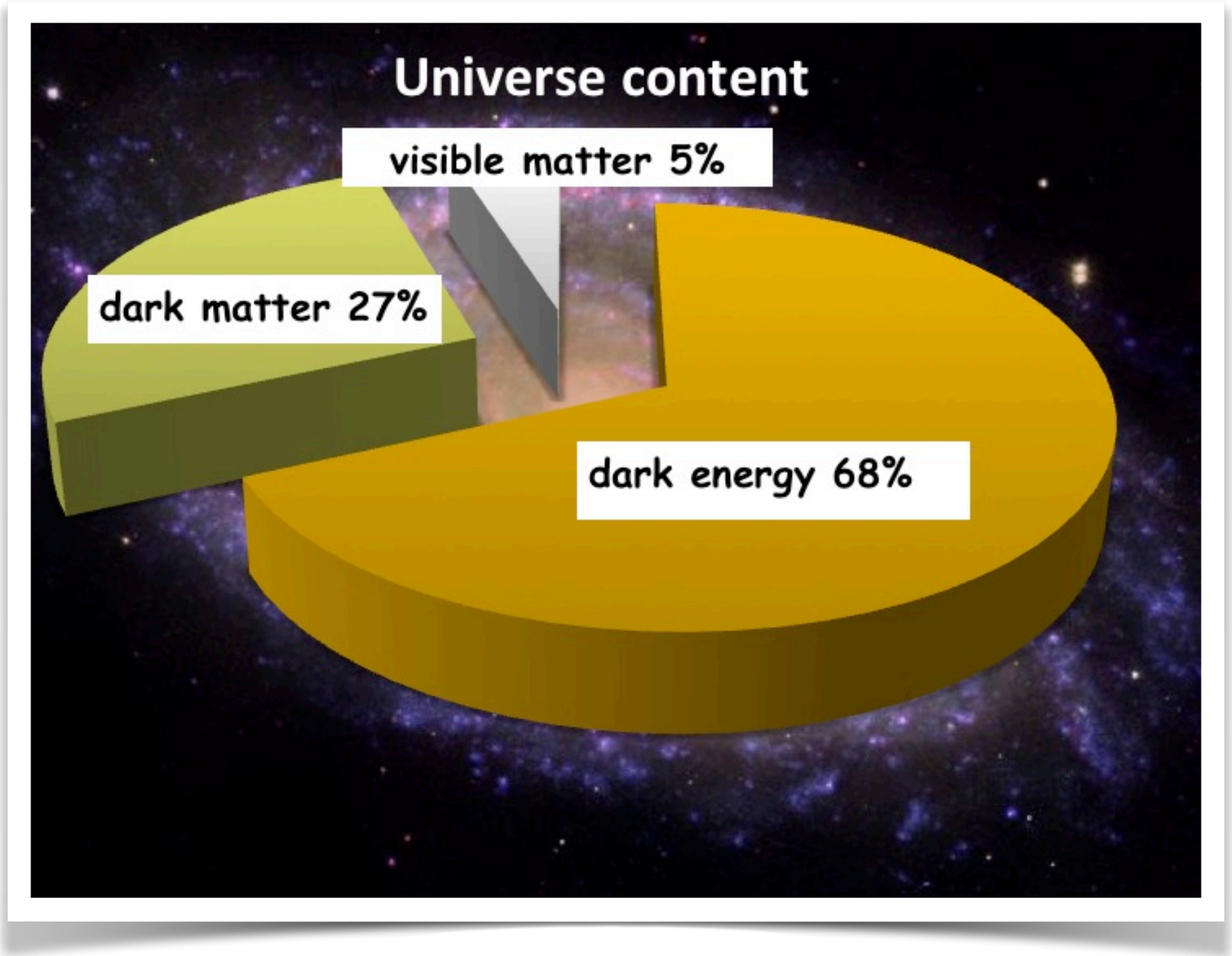

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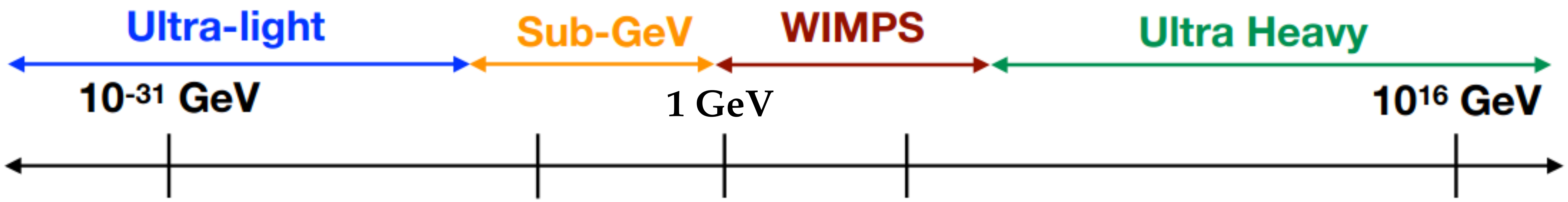
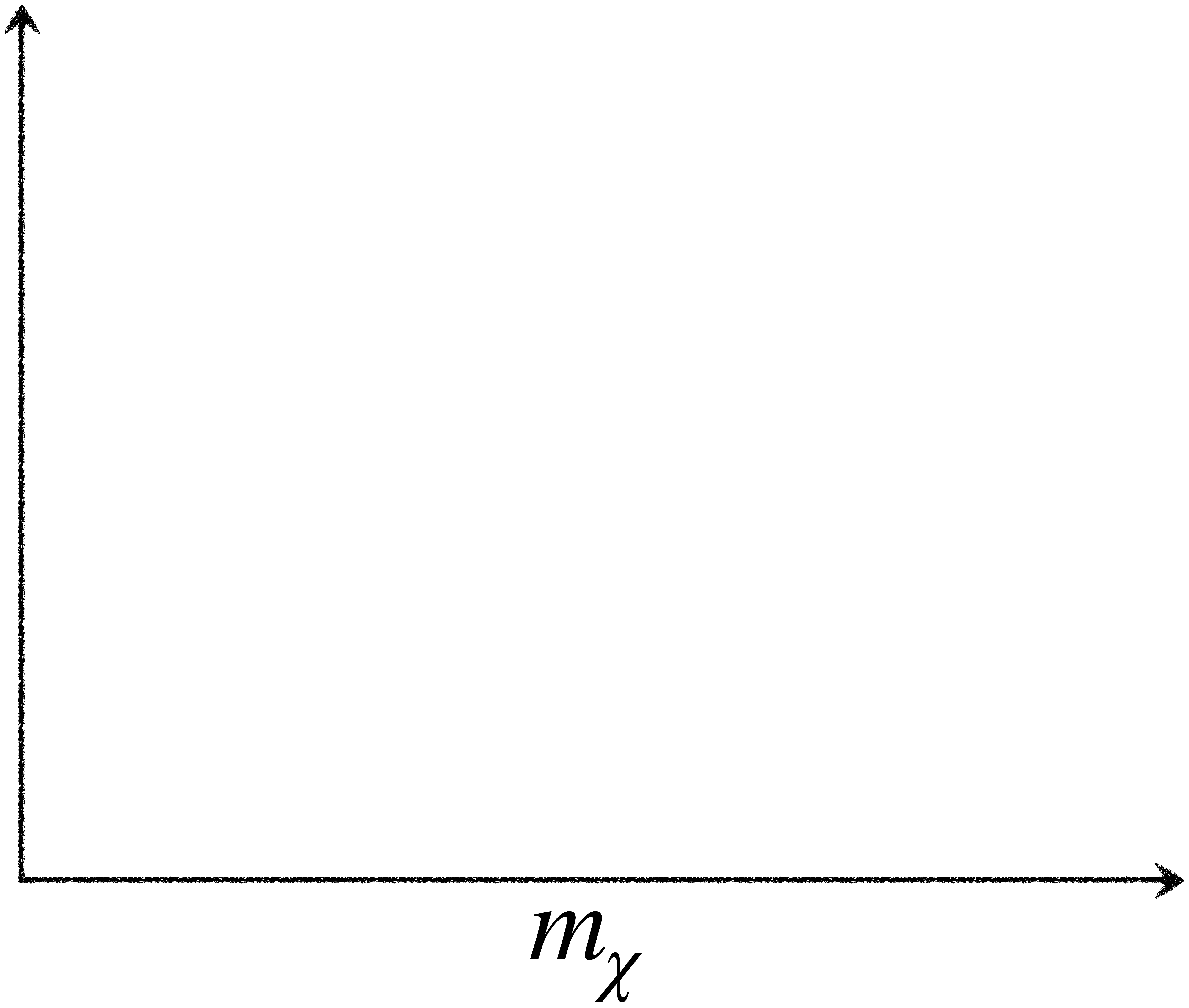


What else!

m_χ

What else!



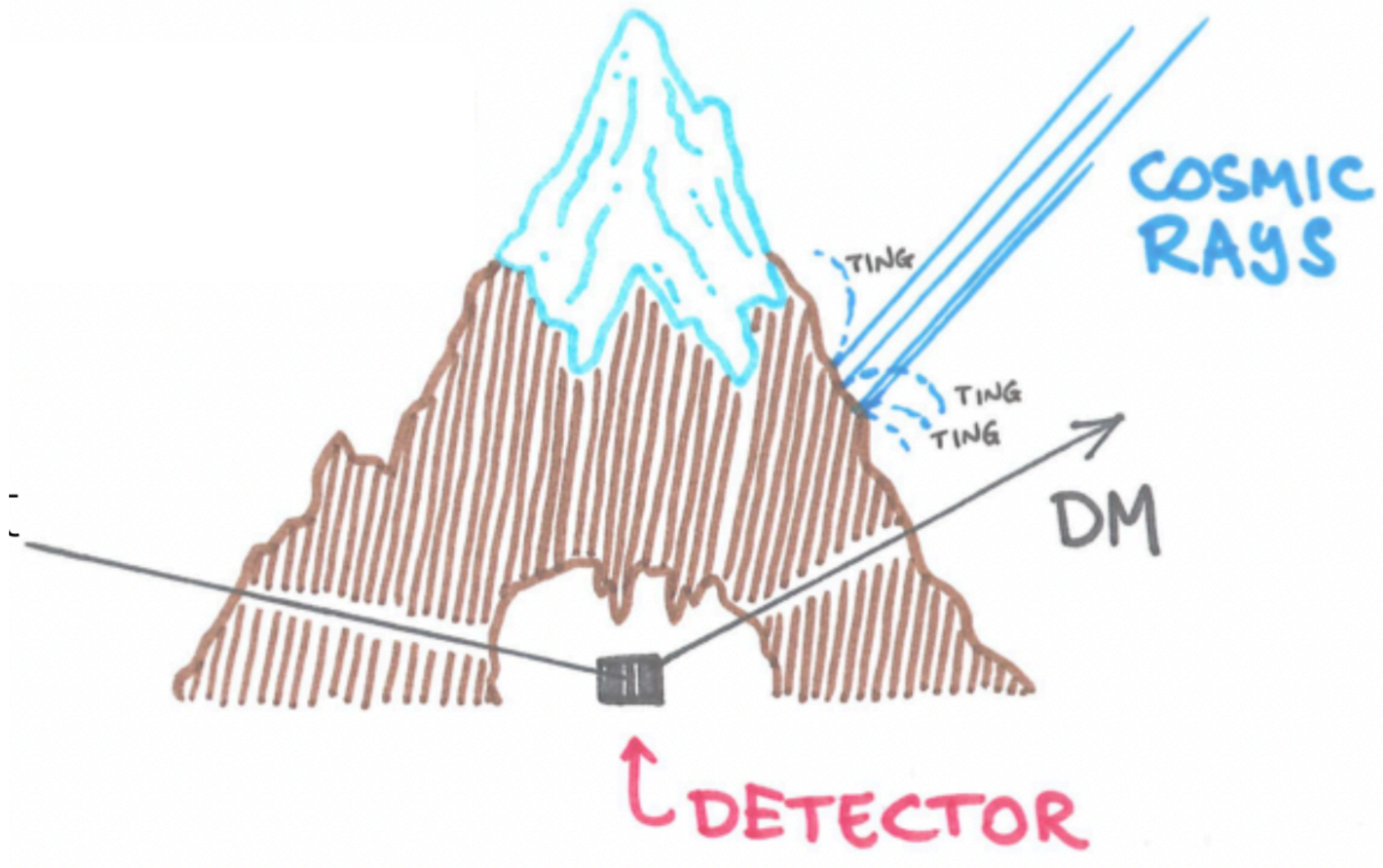
What else!

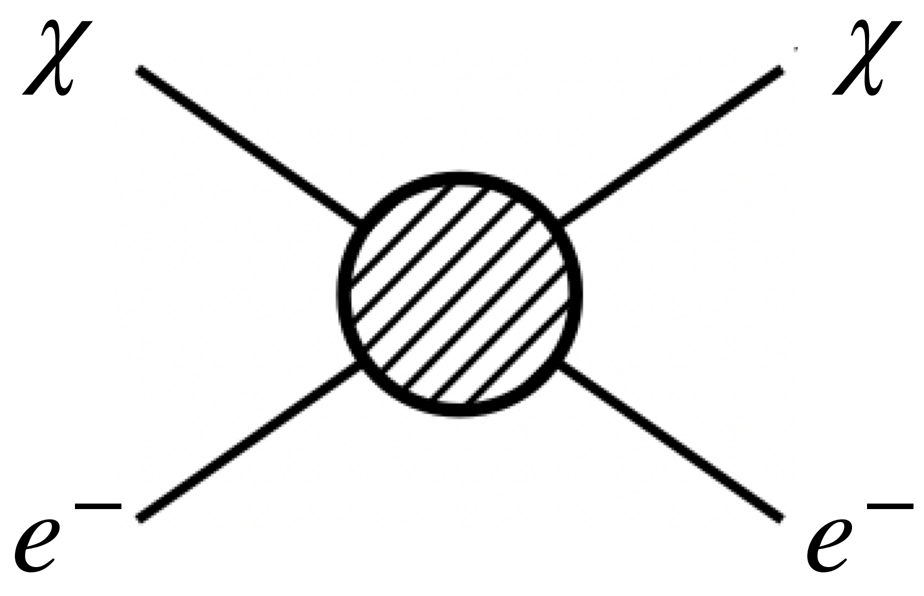
Test every possible interactions

- ✔ Discover DM 
- ⊖ Or set bounds

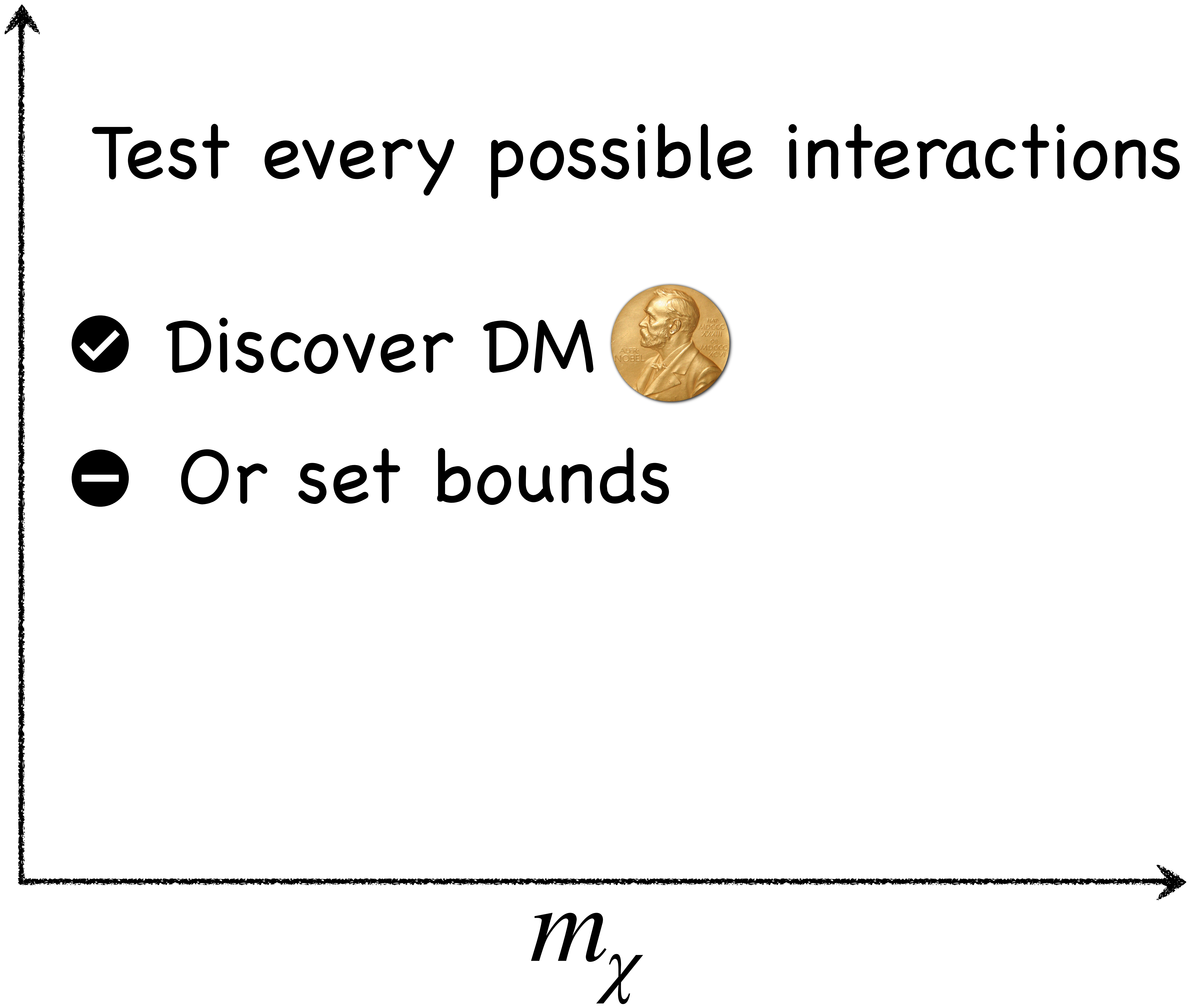
m_χ

What else!

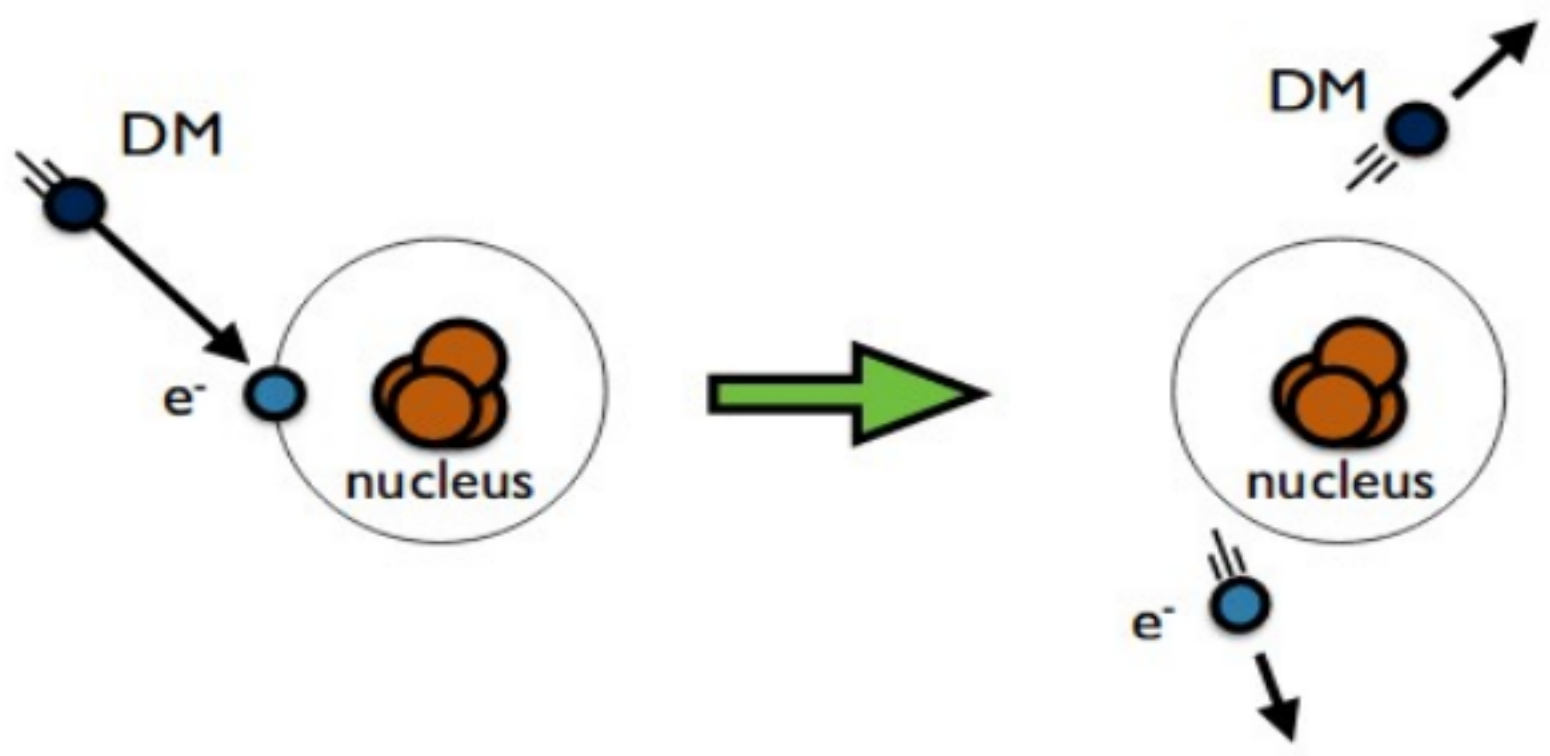




χ : DM



Sub-GeV DM-electron scattering



Essig+ 1108.5383, 1206.2644, 1509.01598, 1703.00910 …

Image credit: R Essig

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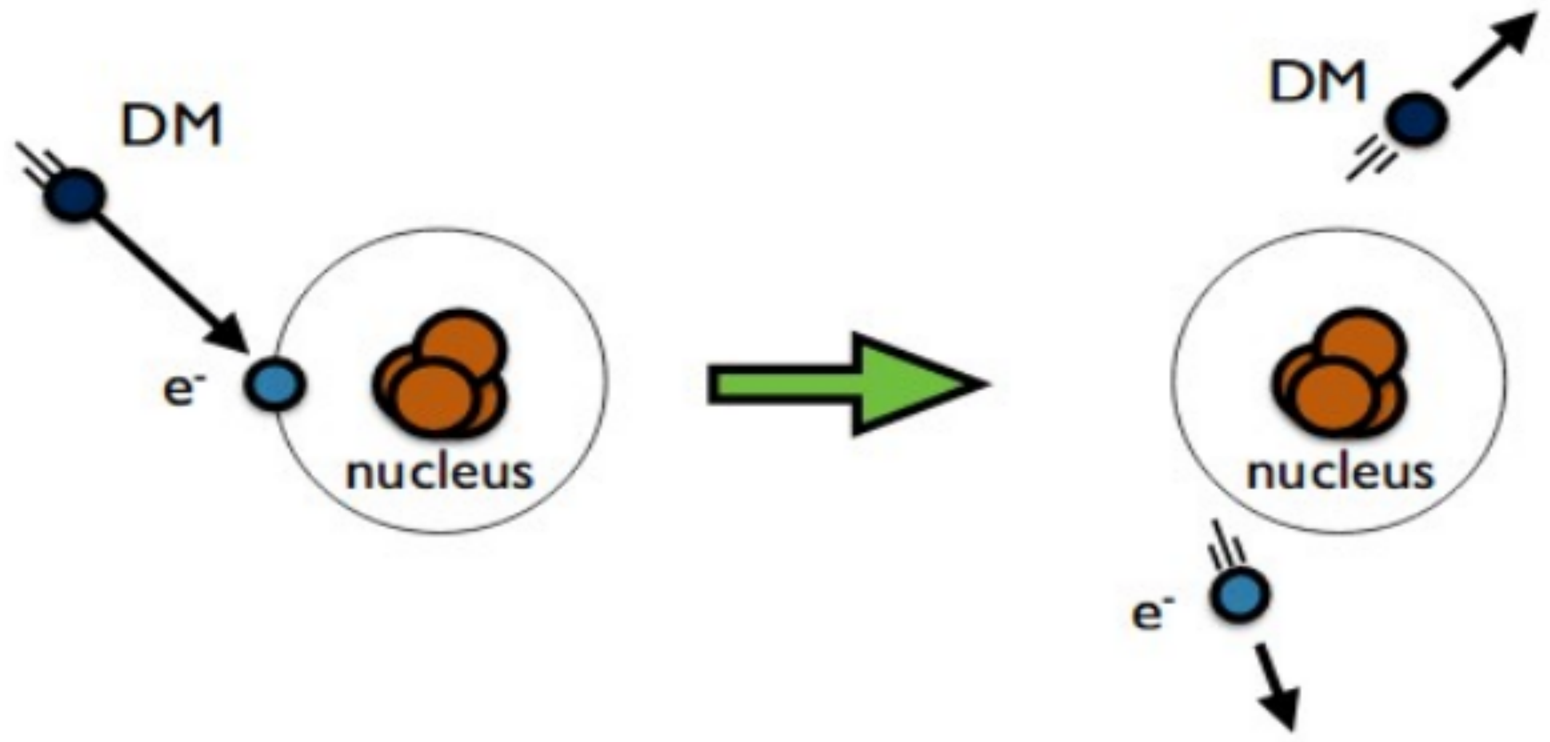

$$E_{\rm DM} \simeq 50\,{\rm eV}\frac{m_{\rm DM}}{100\,{\rm MeV}}\left(\frac{v}{10^{-3}}\right)^2$$

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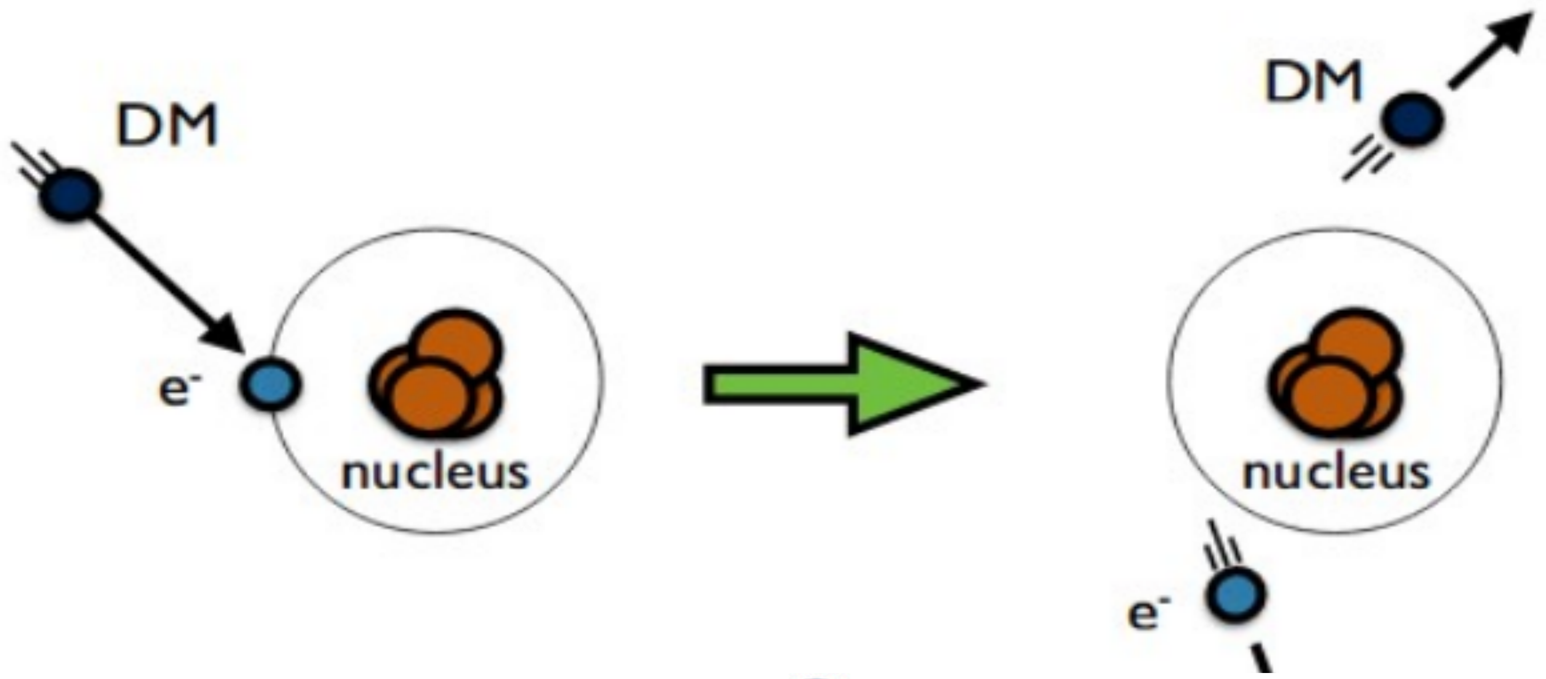

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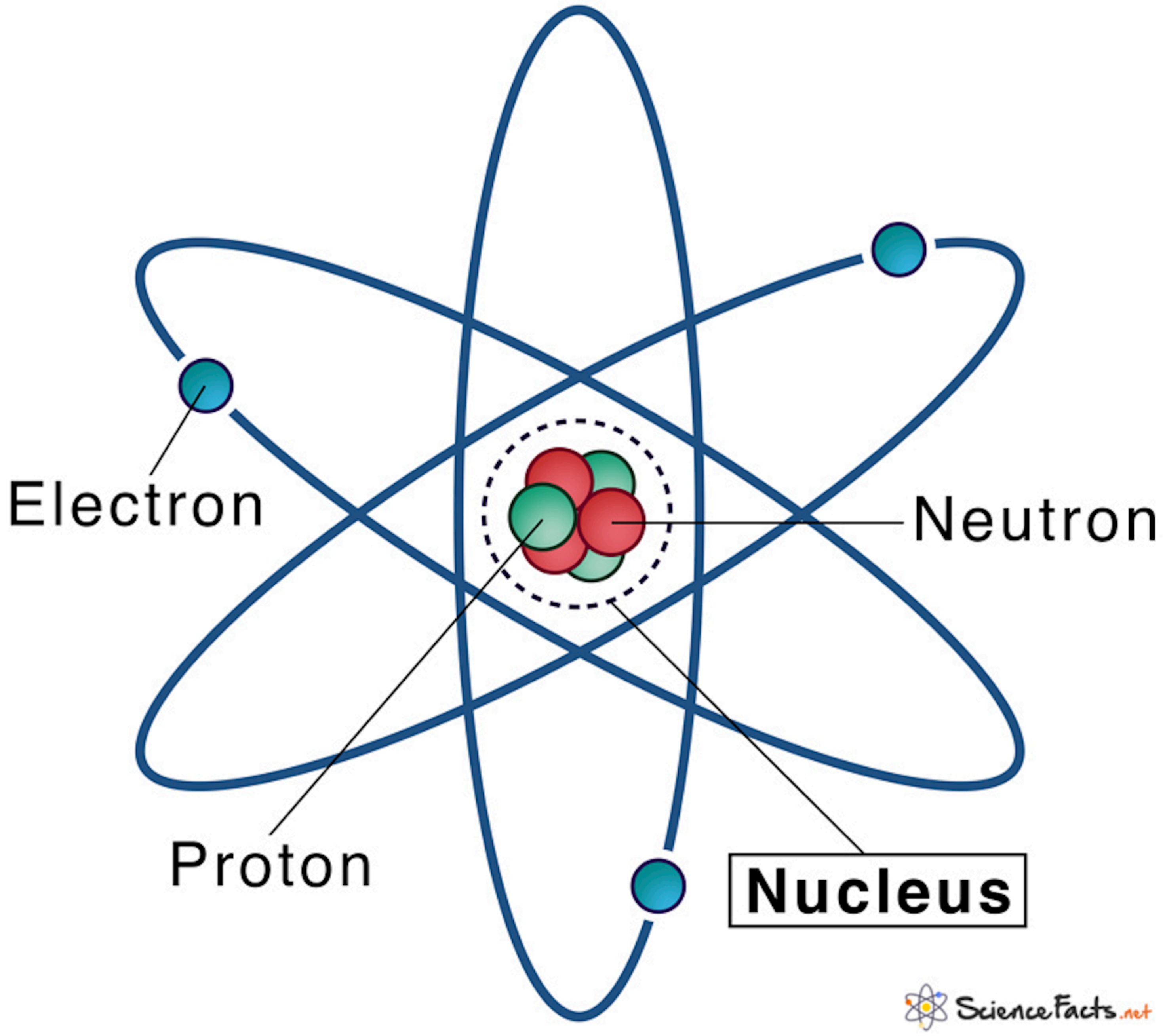
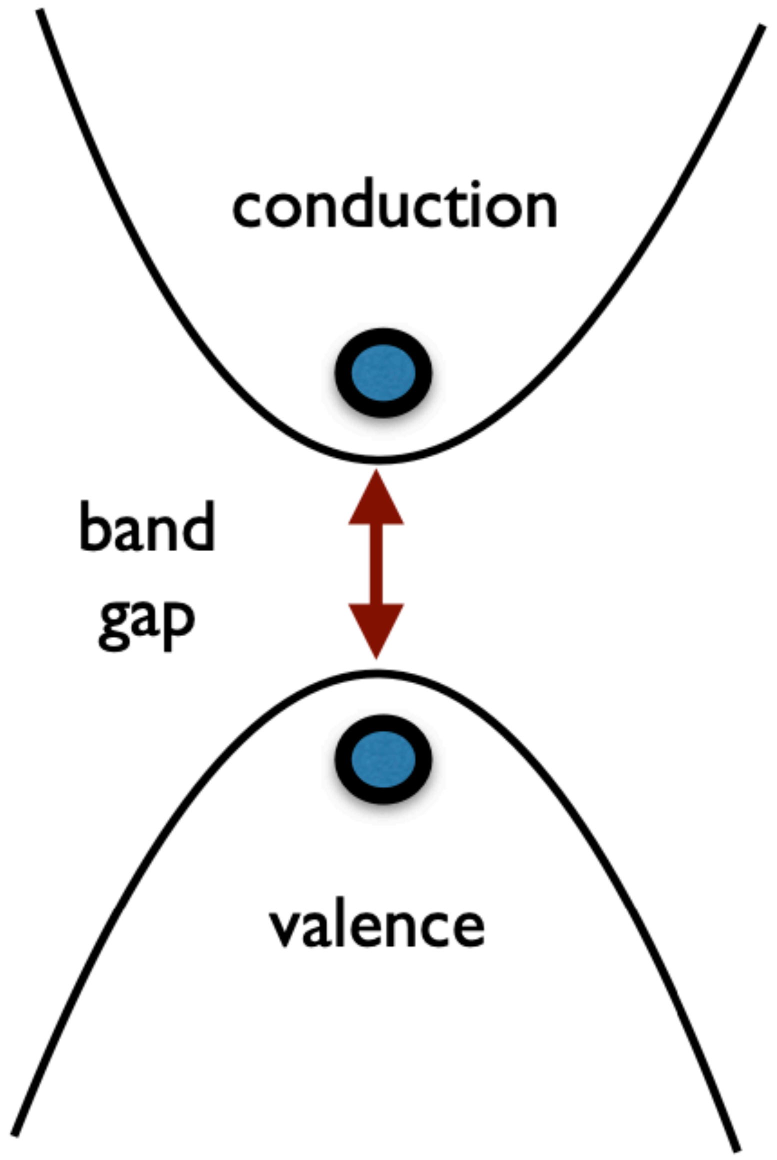




Atomic target

Atomic ionisation energy ~ 10 eV

Semiconductor target

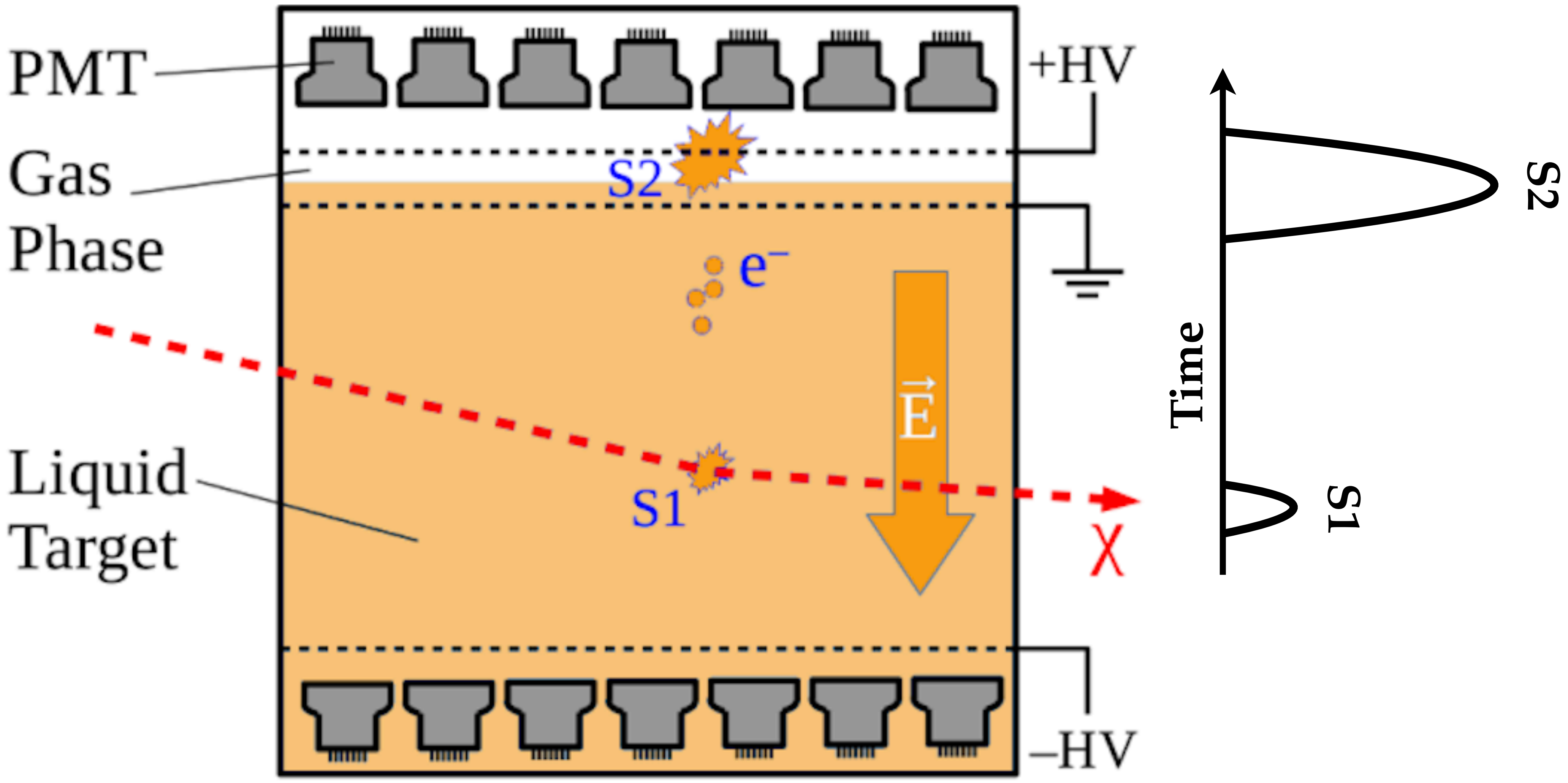
Band gap energy ~ 1 eV

Essig+ 1108.5383, 1206.2644, 1509.01598, 1703.00910 …

Image credit: R Essig

Signatures in experiments (Xe)

XENONnT, PandaX-4T, LZ ...



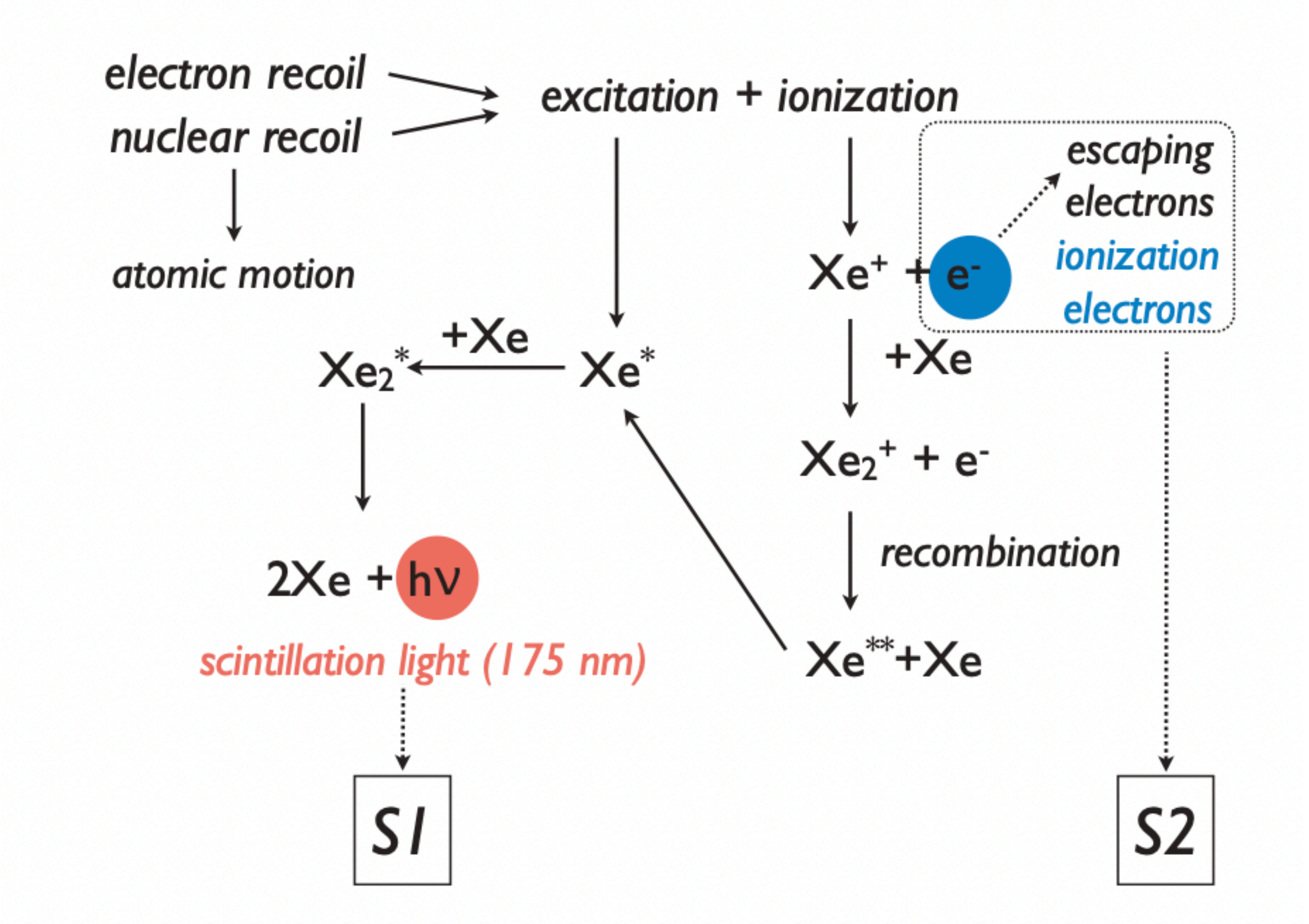


Image credit: 2110.02359, 1903.03026, 0909.1063

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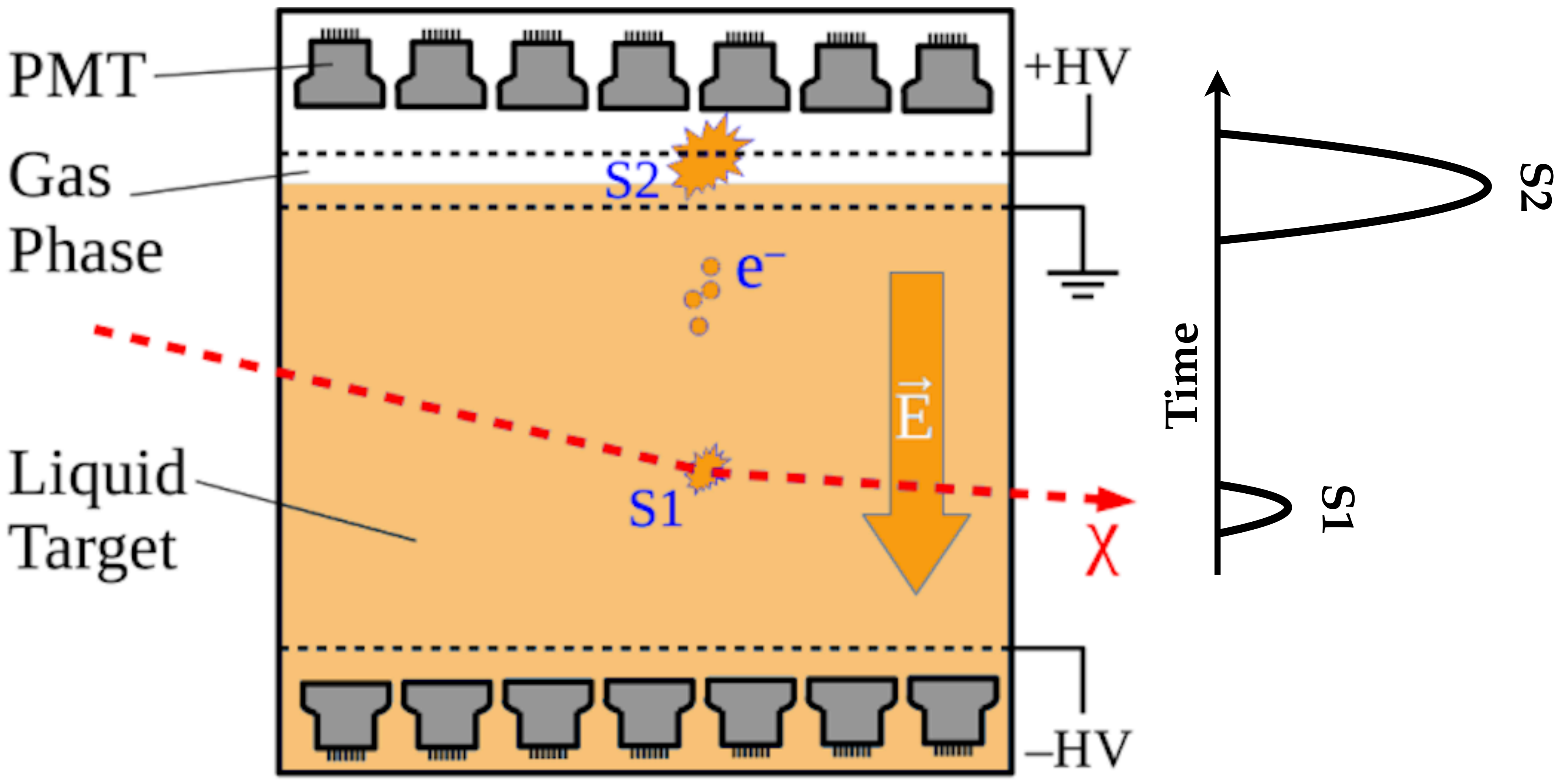
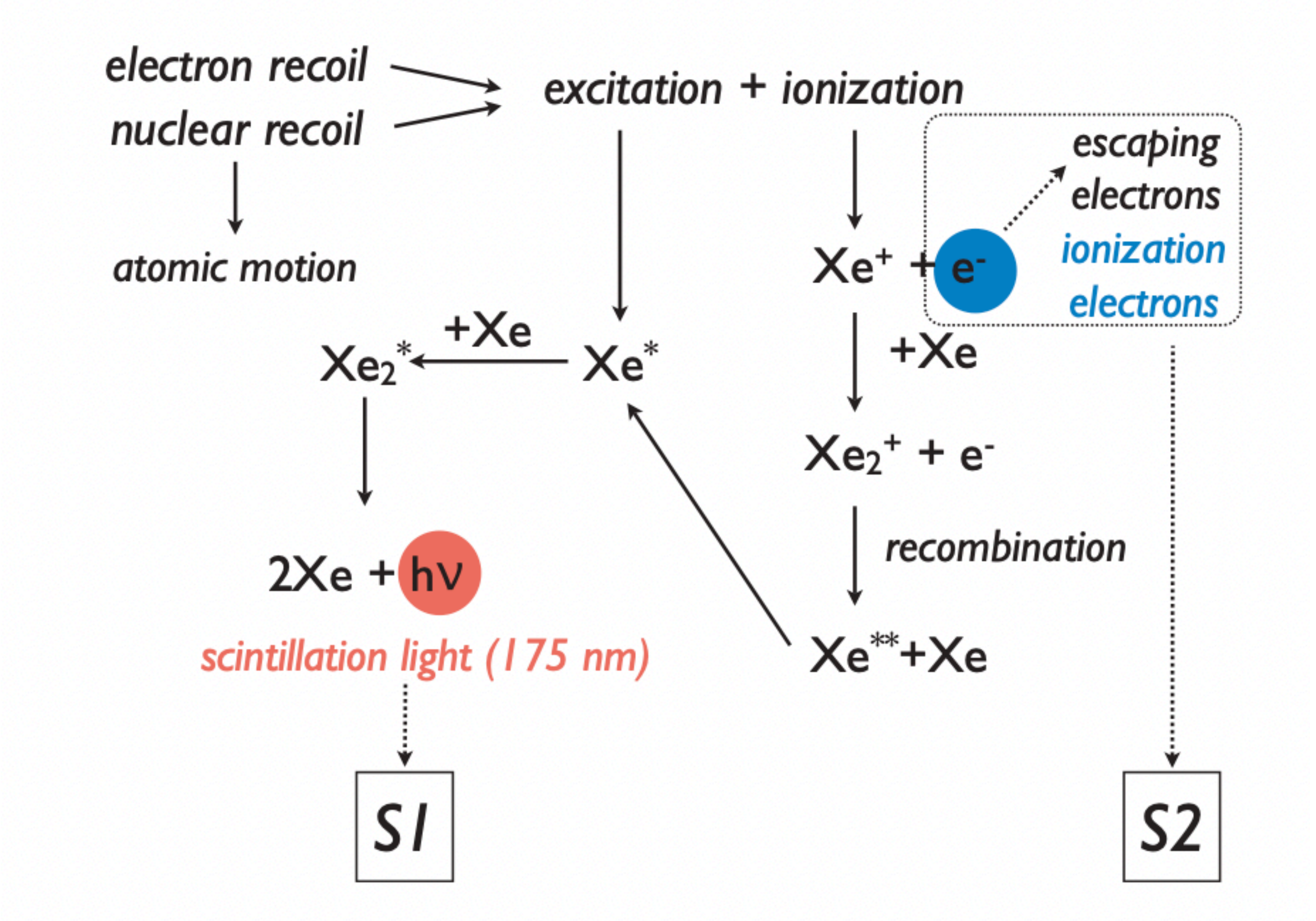
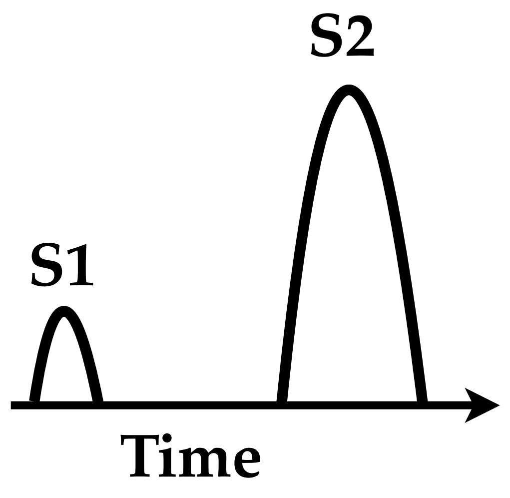


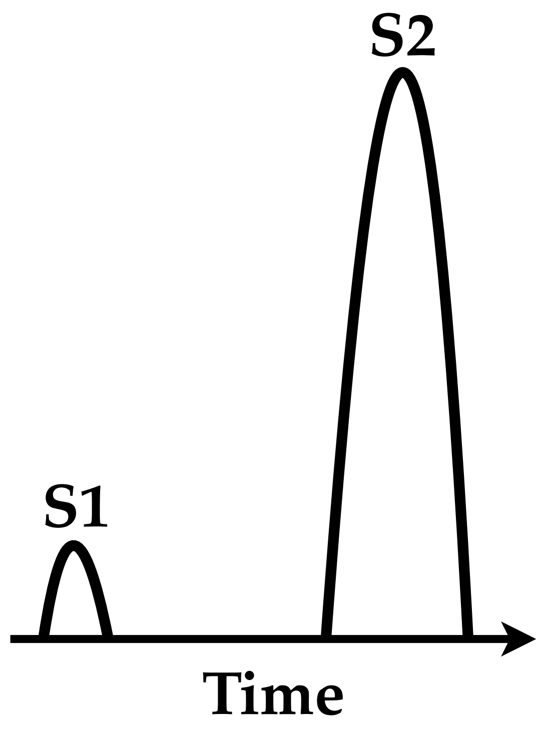


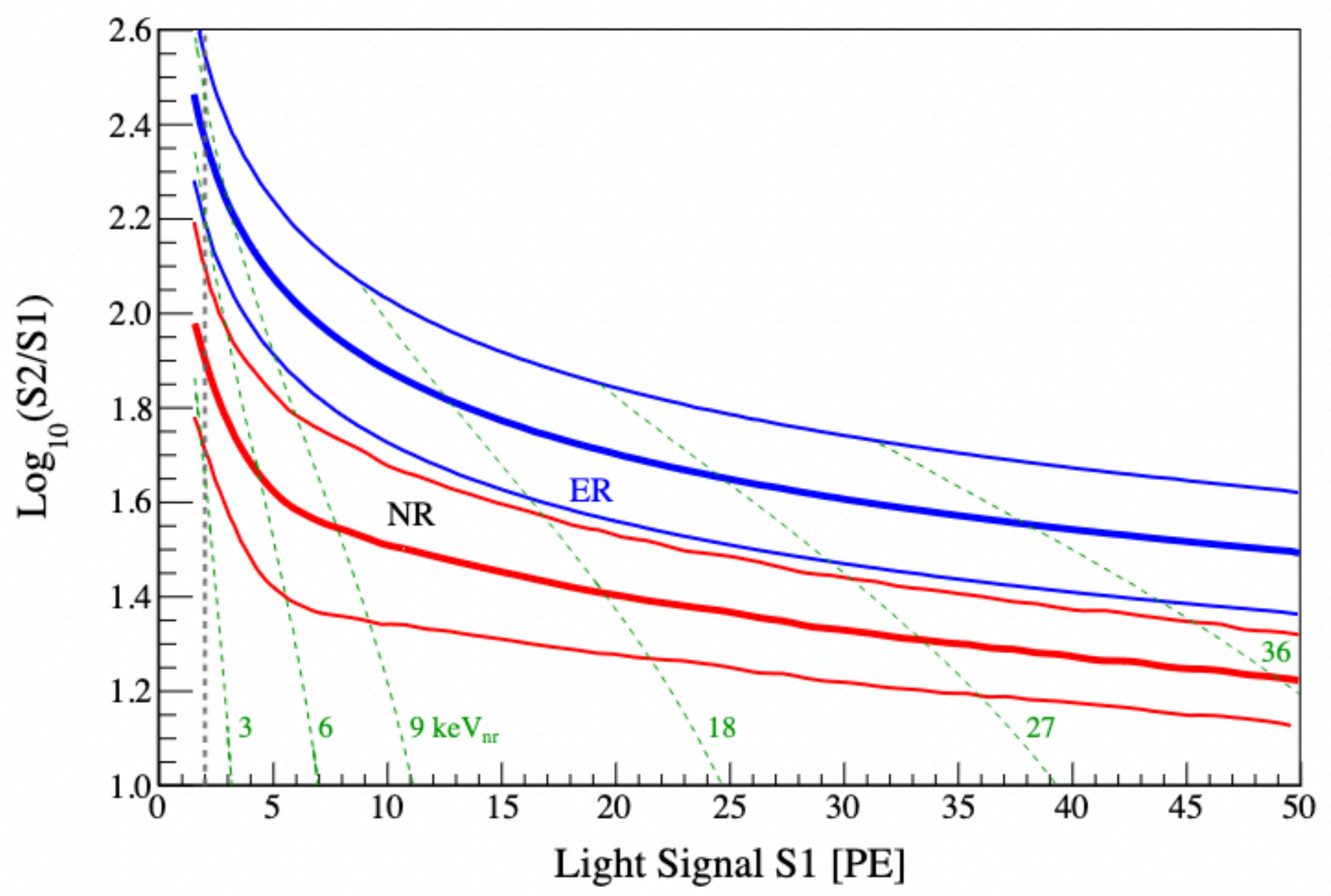
S1-S2 only analysis

Nuclear recoil



Electron recoil





S2/S1 ratio - can distinguish - nuclear and electron recoil

$$E_{\mathrm{recoil}} \gtrsim 0.5\,\mathrm{keV}$$

Image credit: 2110.02359, 1903.03026, 0909.1063

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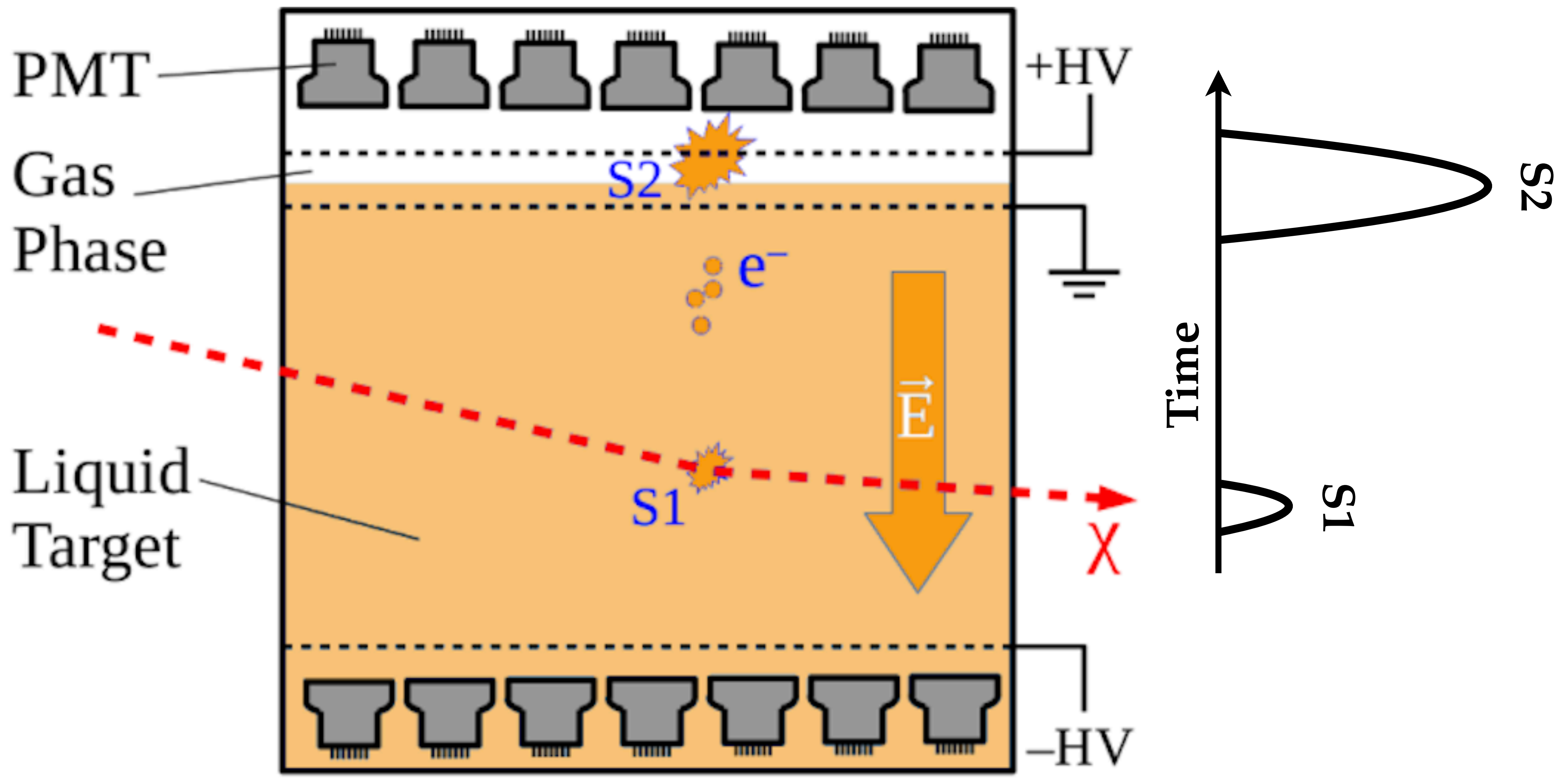

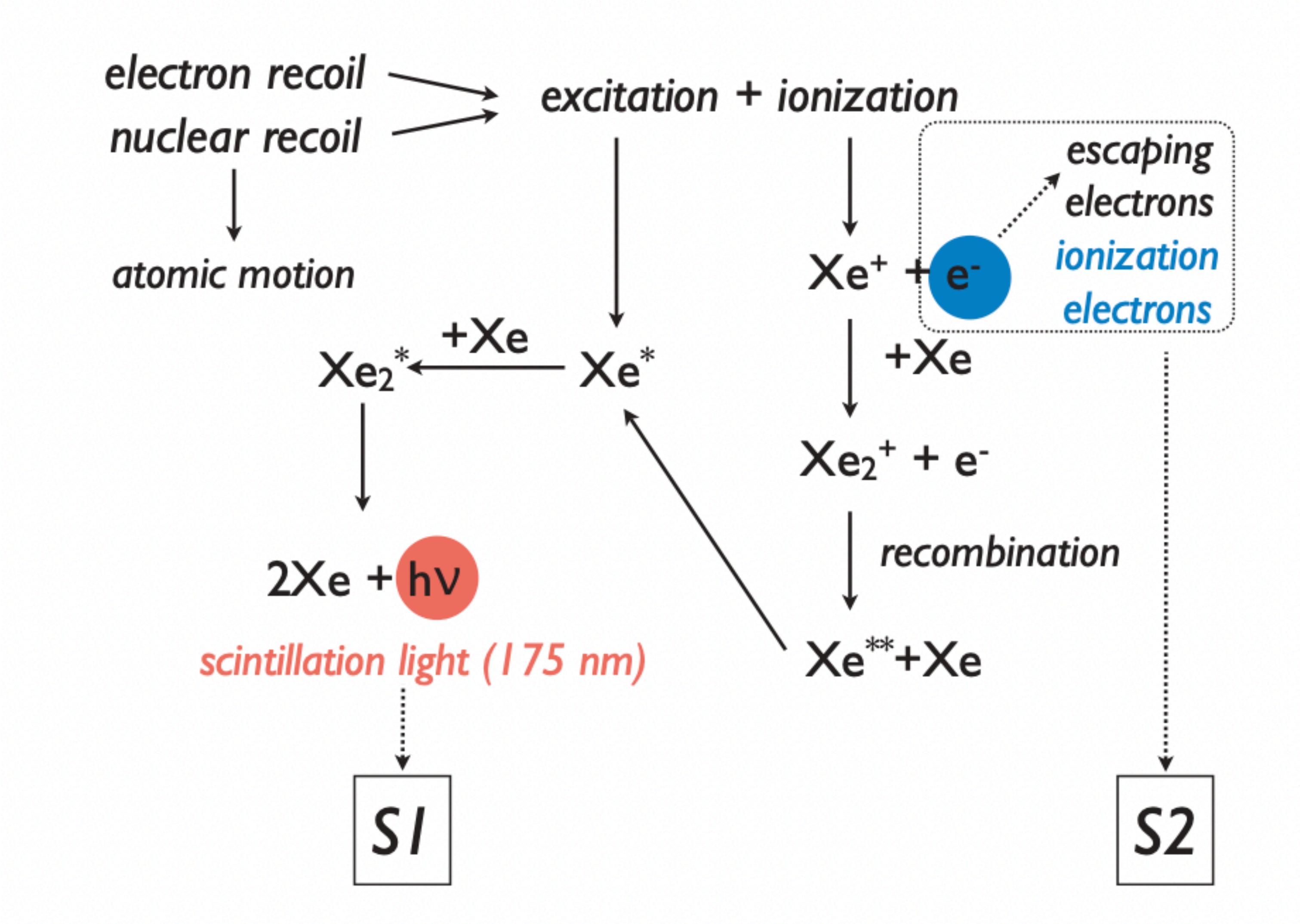

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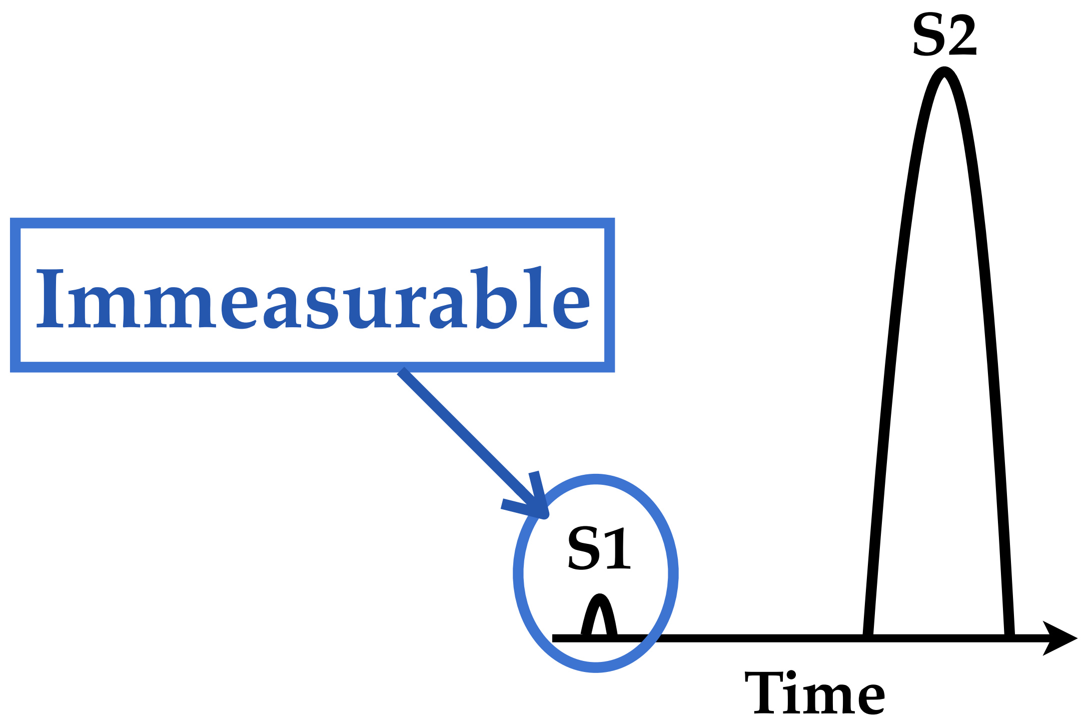
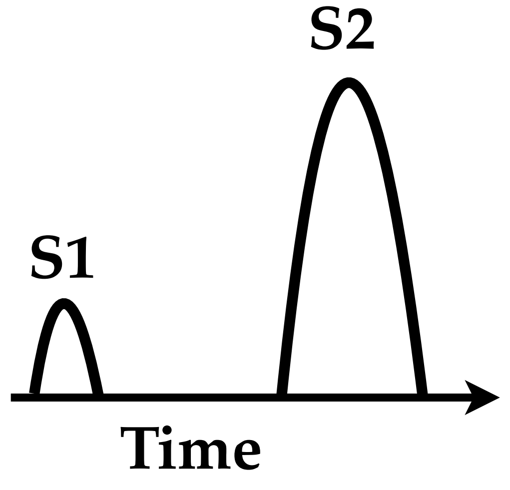
S2 only analysis



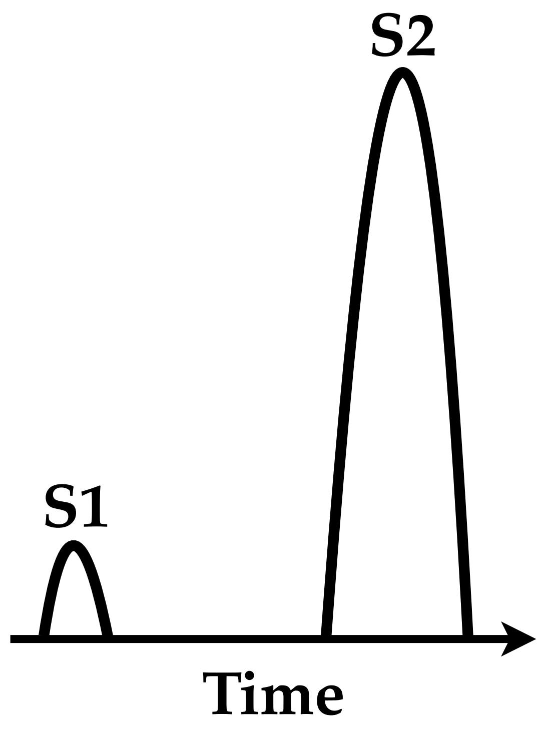
No S2/S1 ratio - can't distinguish - nuclear and electron recoil

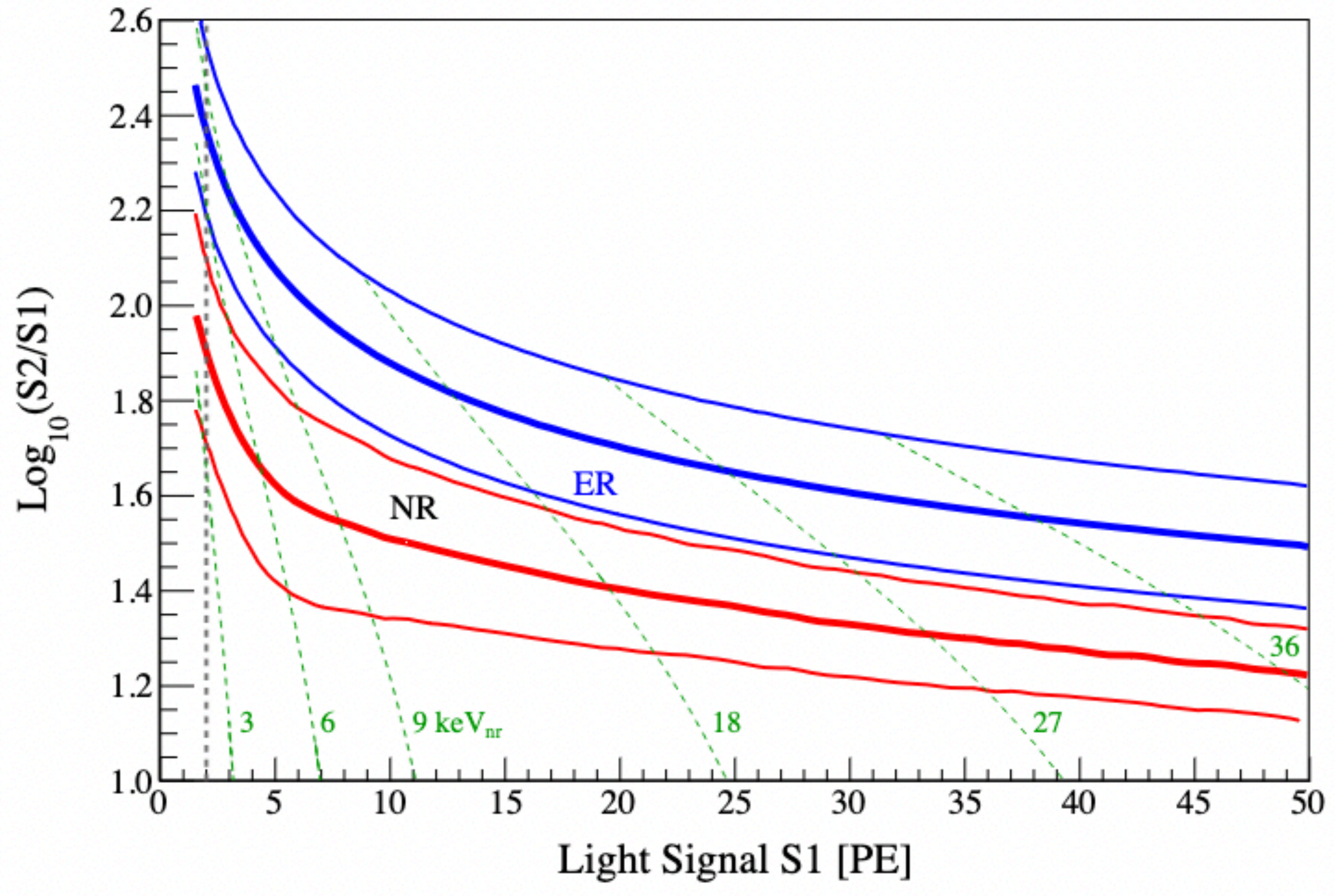
$E_{\rm recoil} \lesssim 0.5\,{\rm keV}$

Nuclear recoil



Electron recoil





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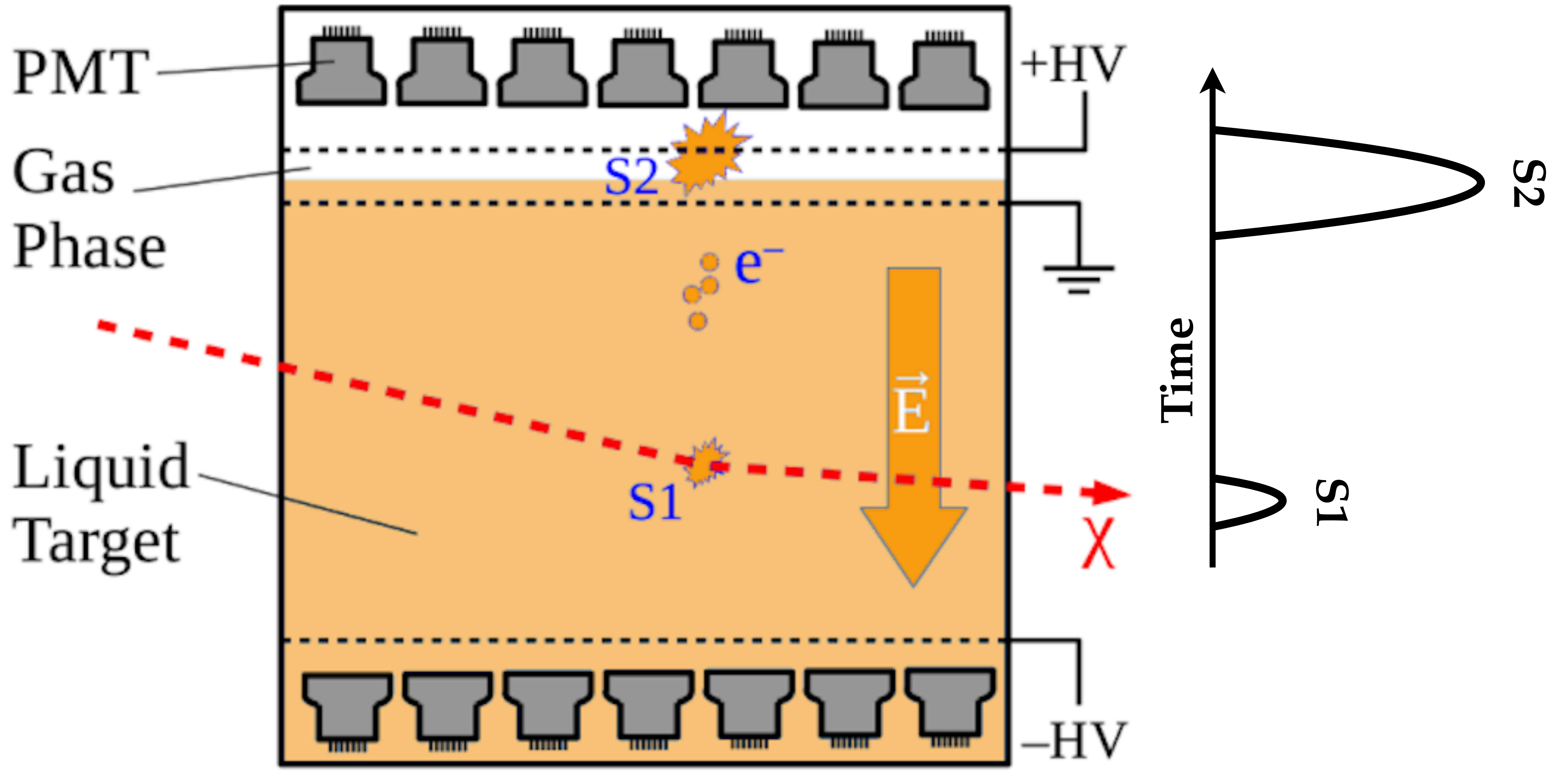
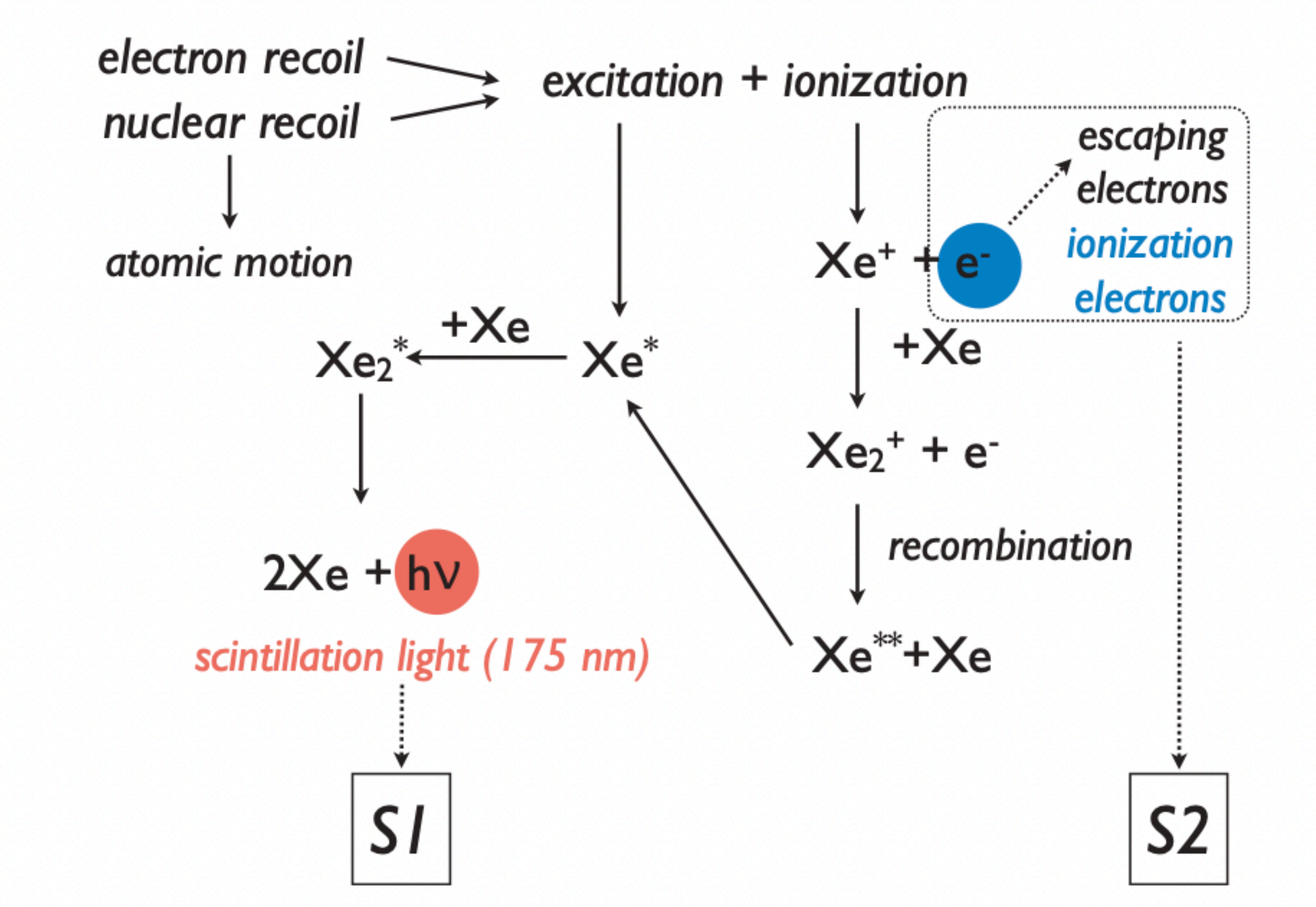
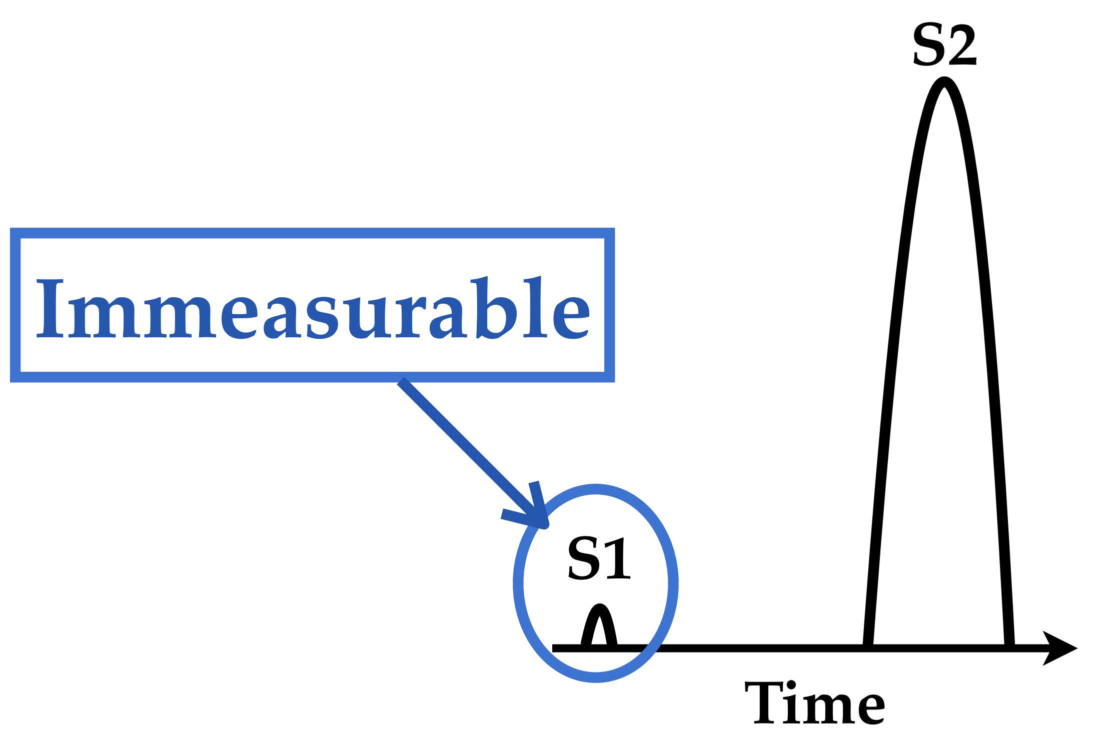




sub-GeV DM search

S2 only analysis



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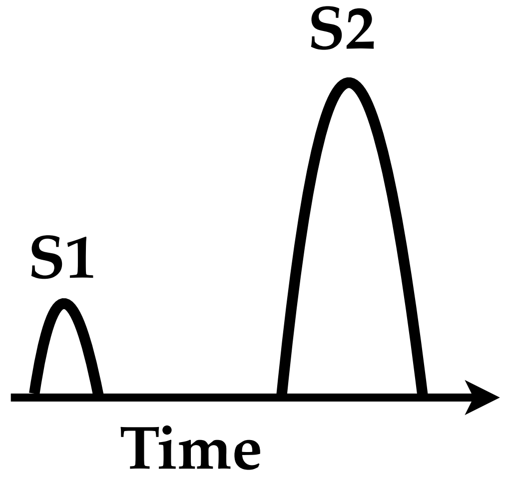

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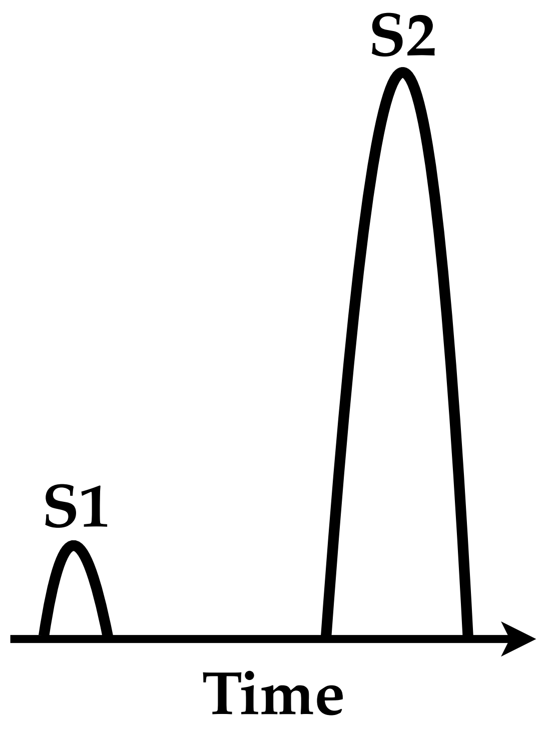

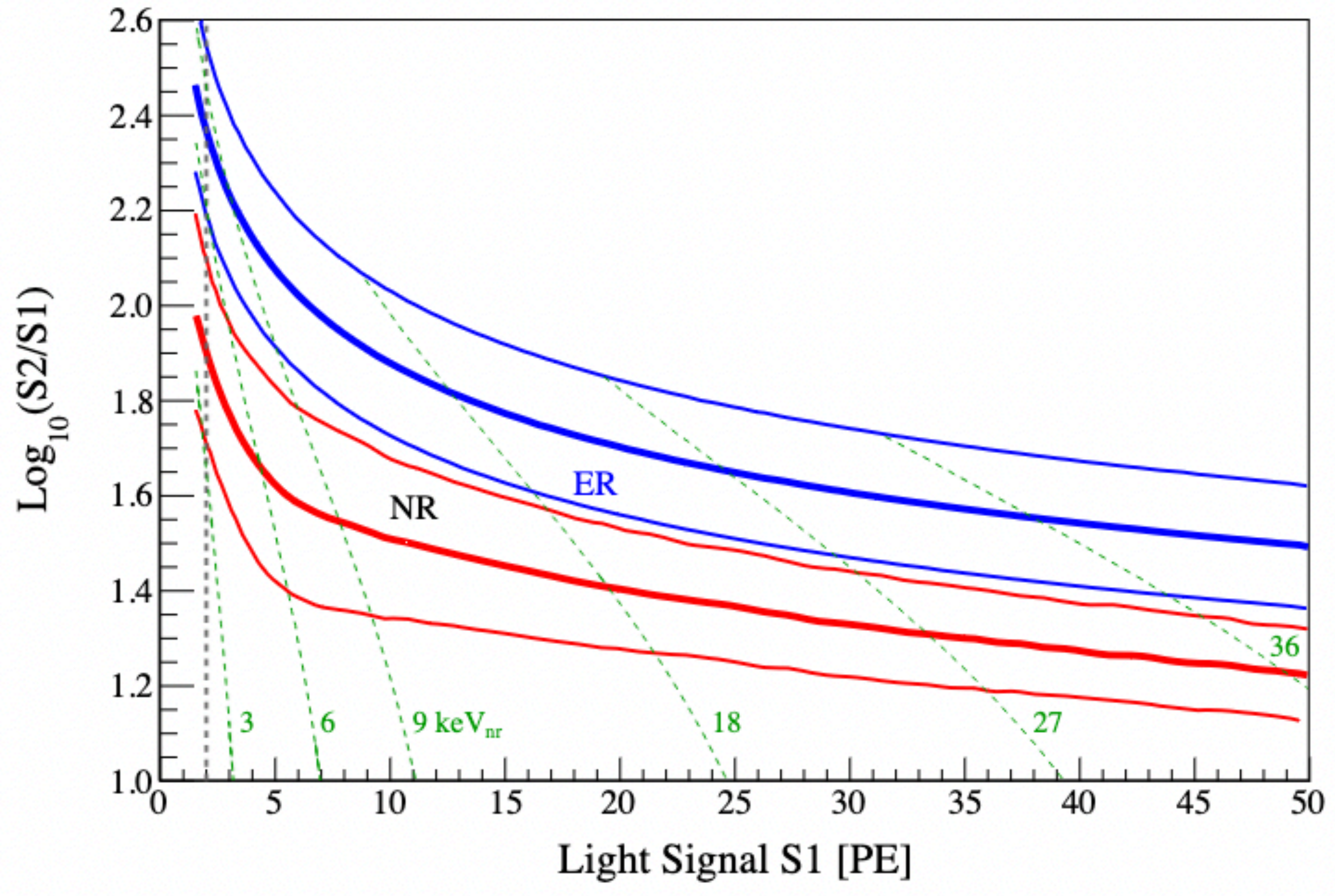

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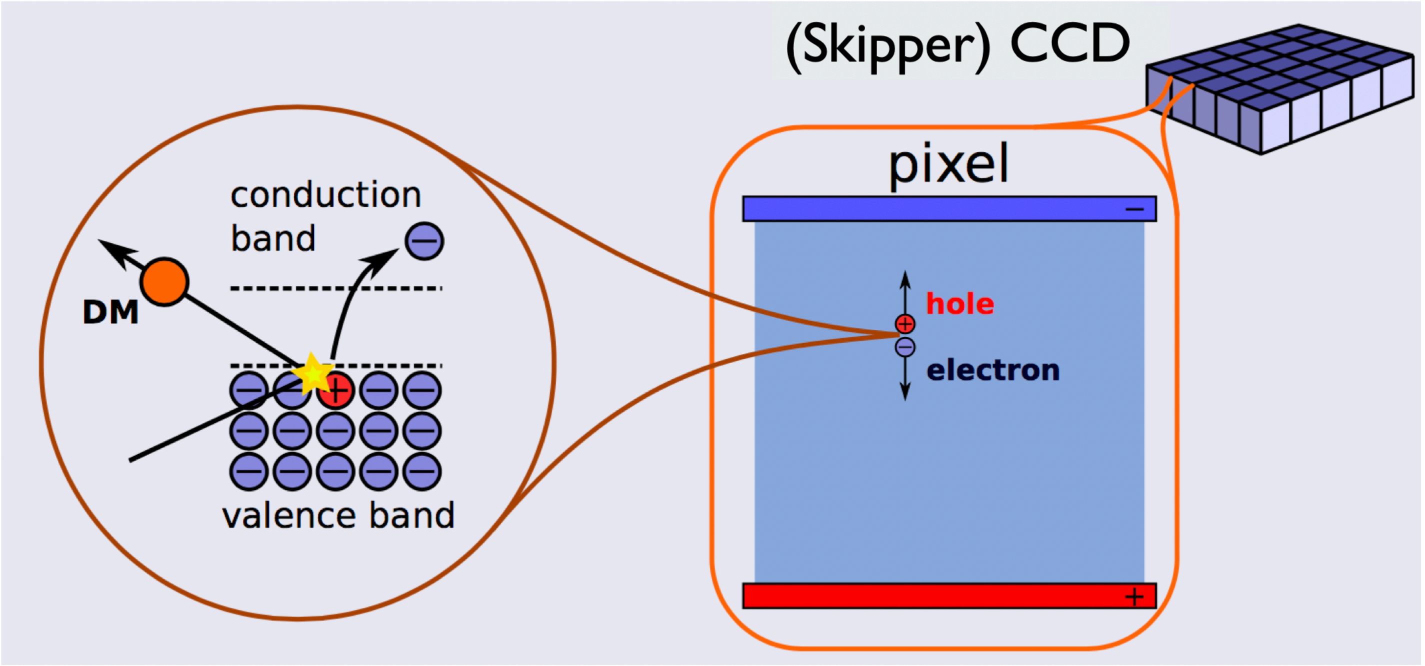
SENSEI, DAMIC-M ...



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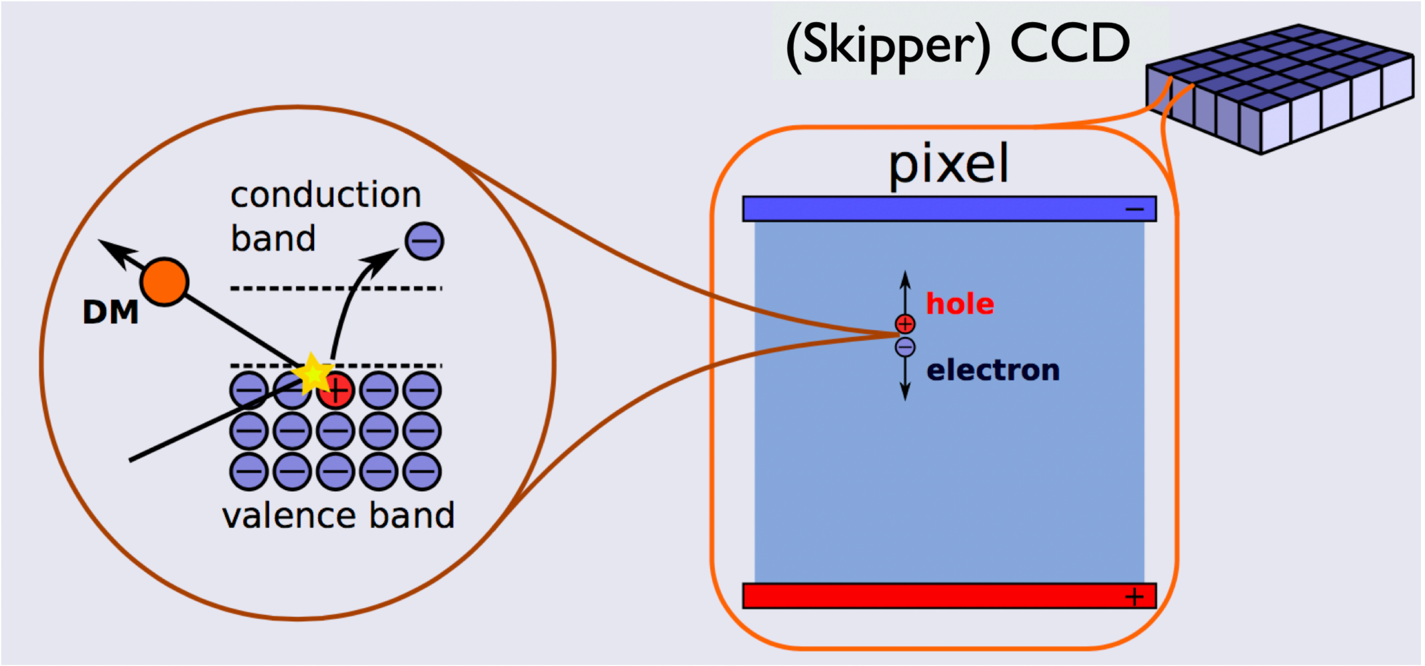

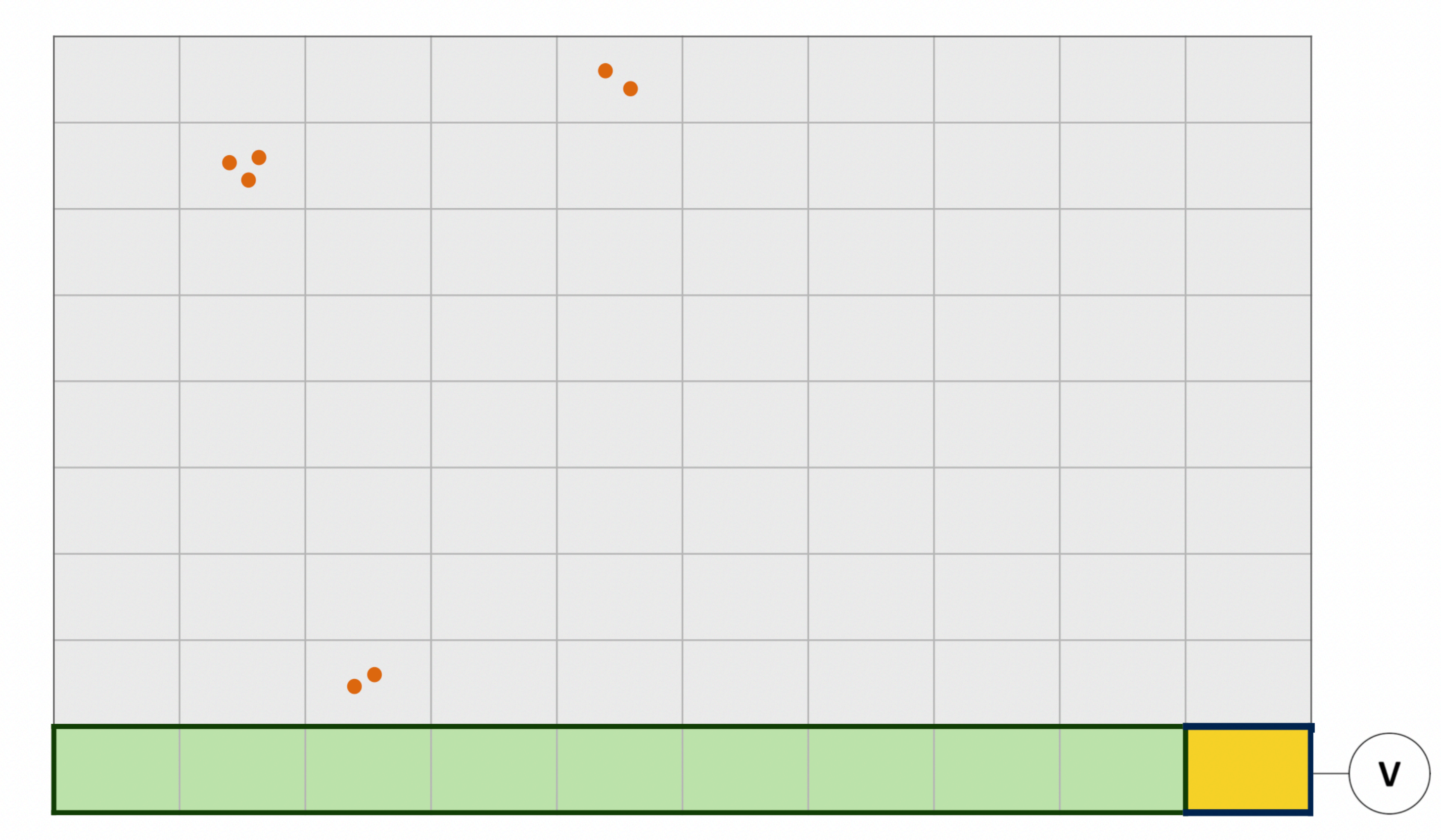

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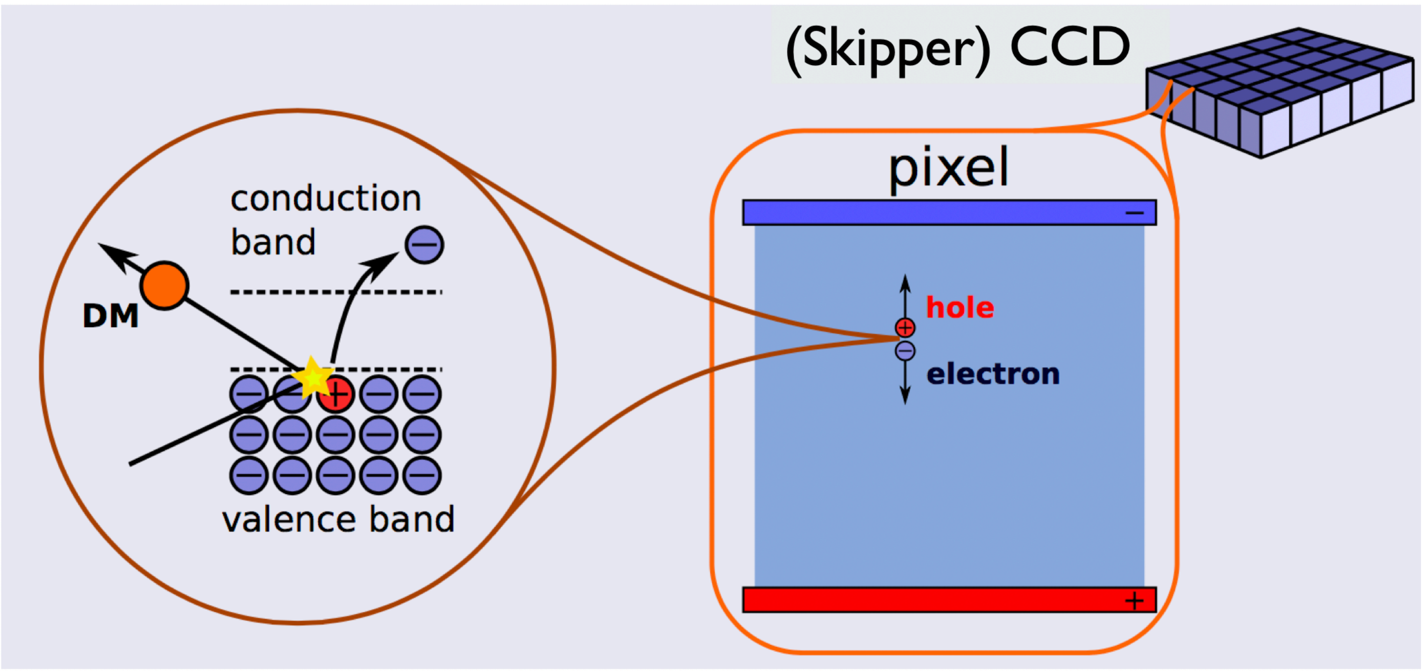

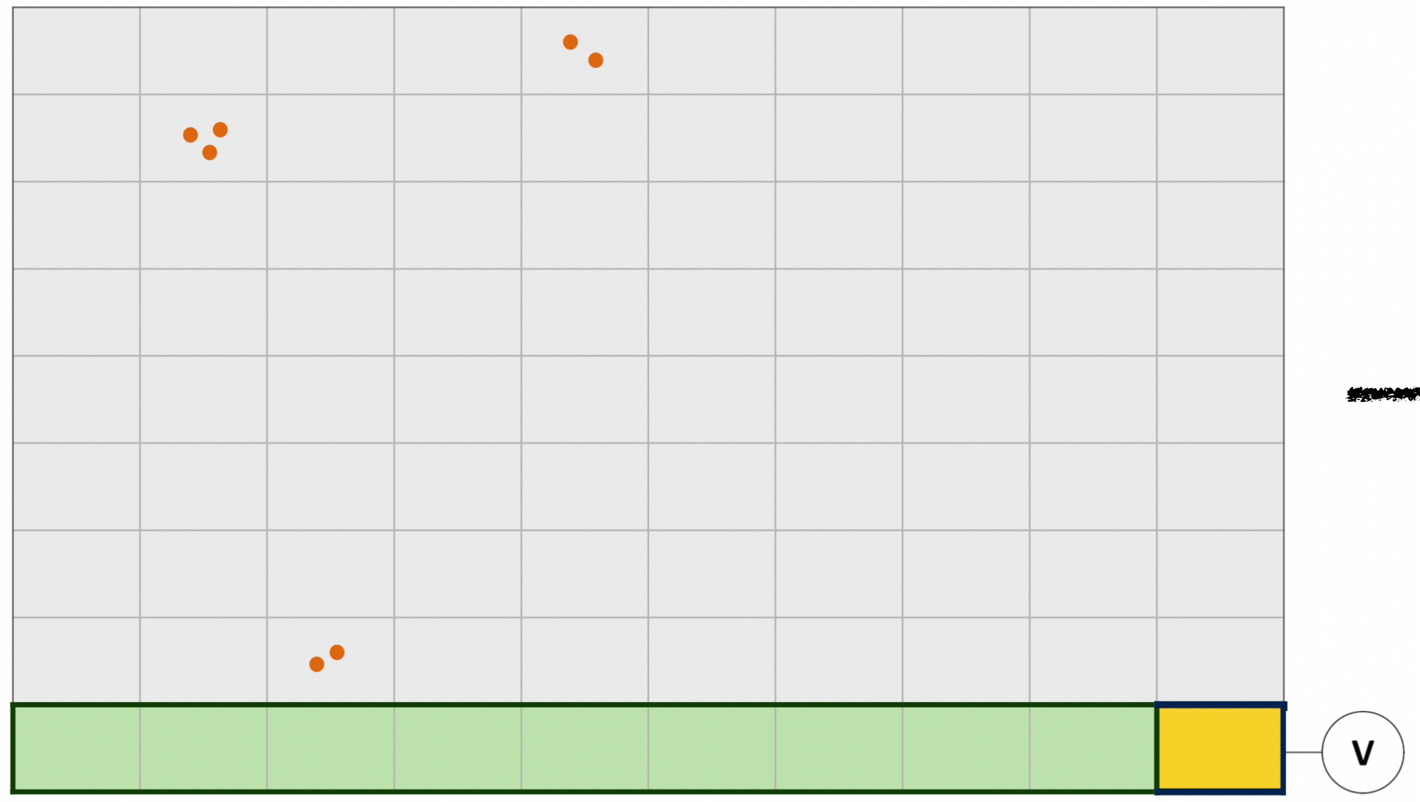

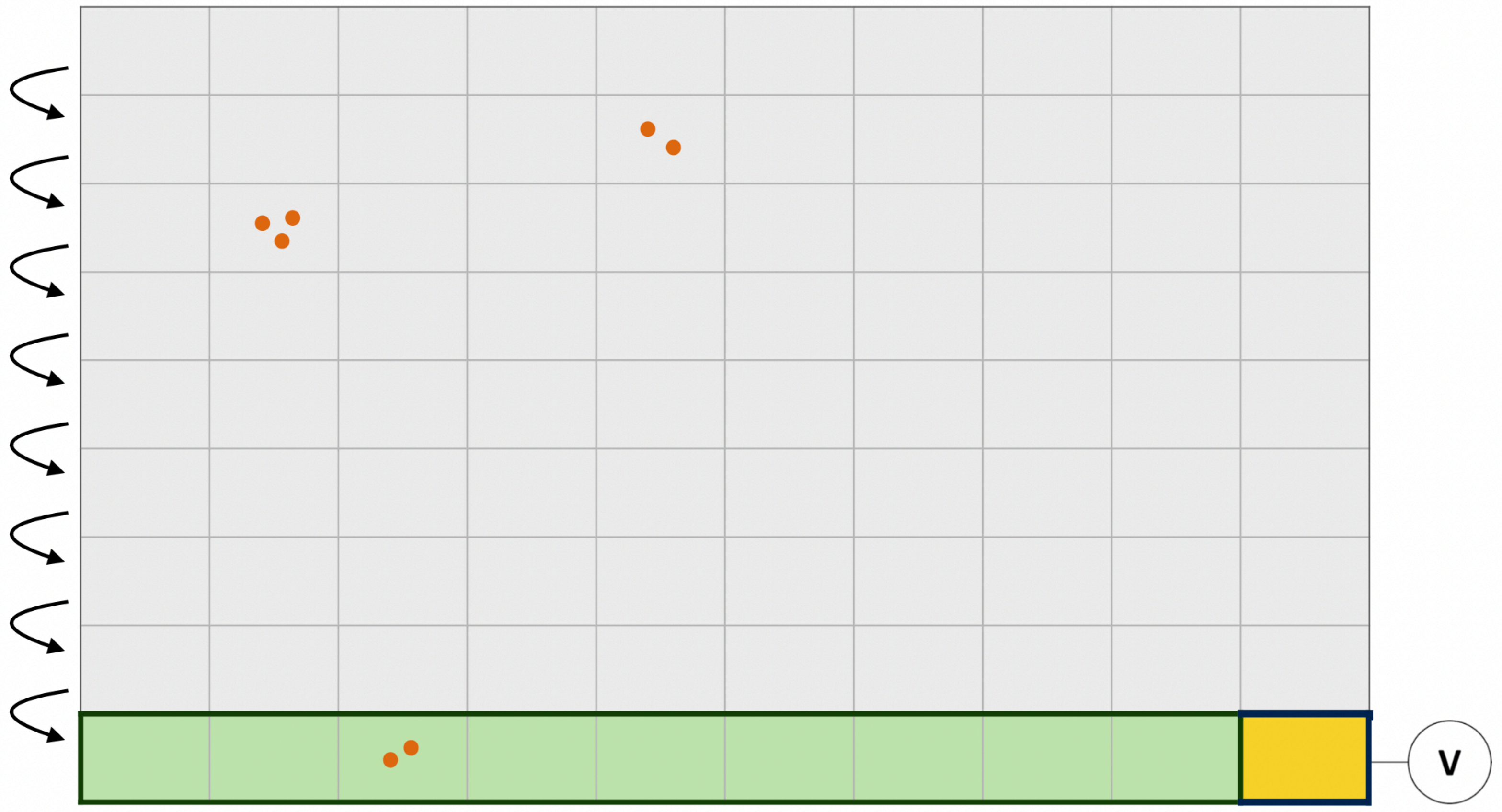

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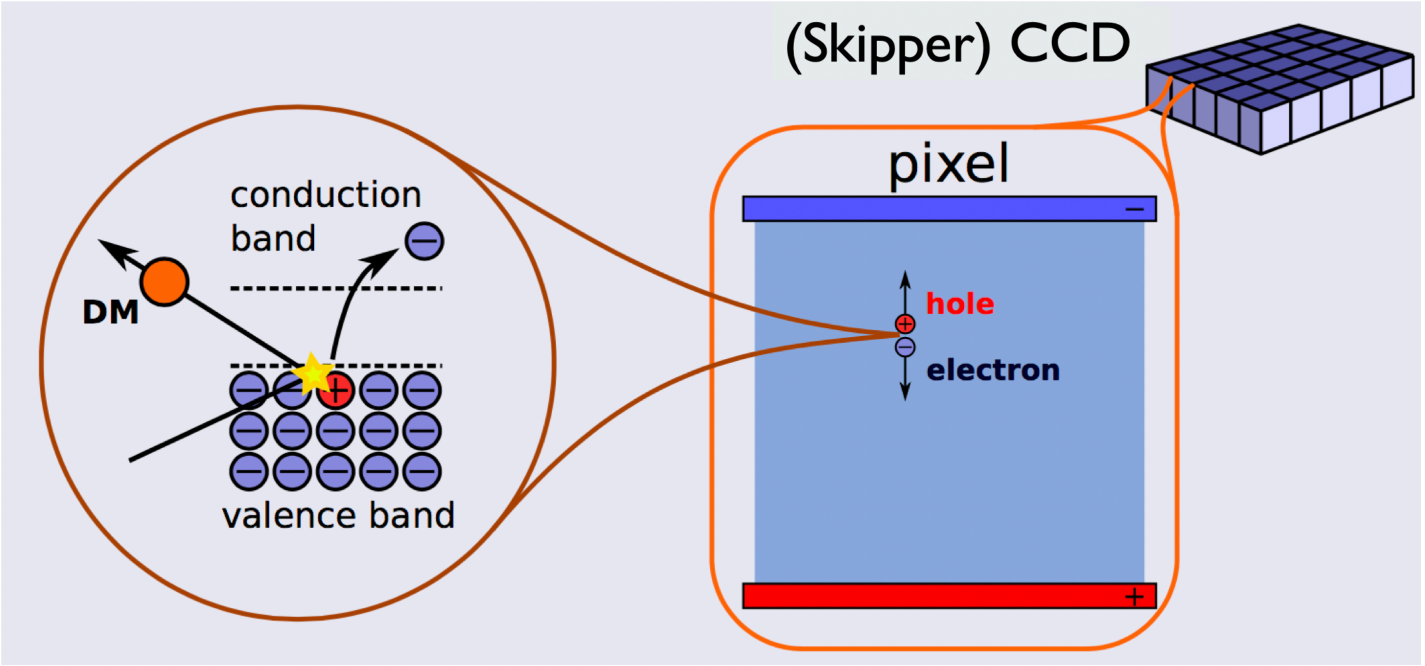

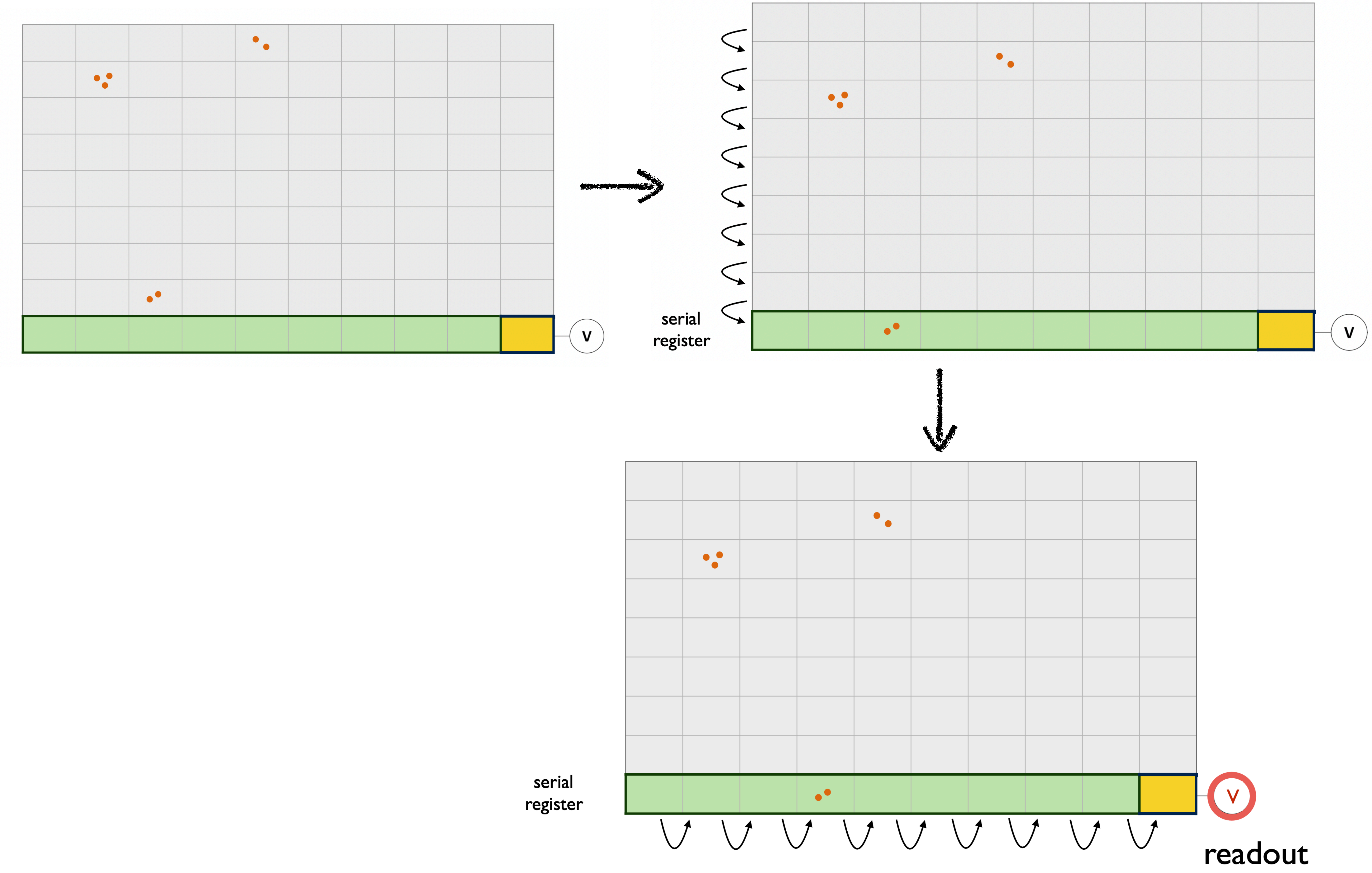

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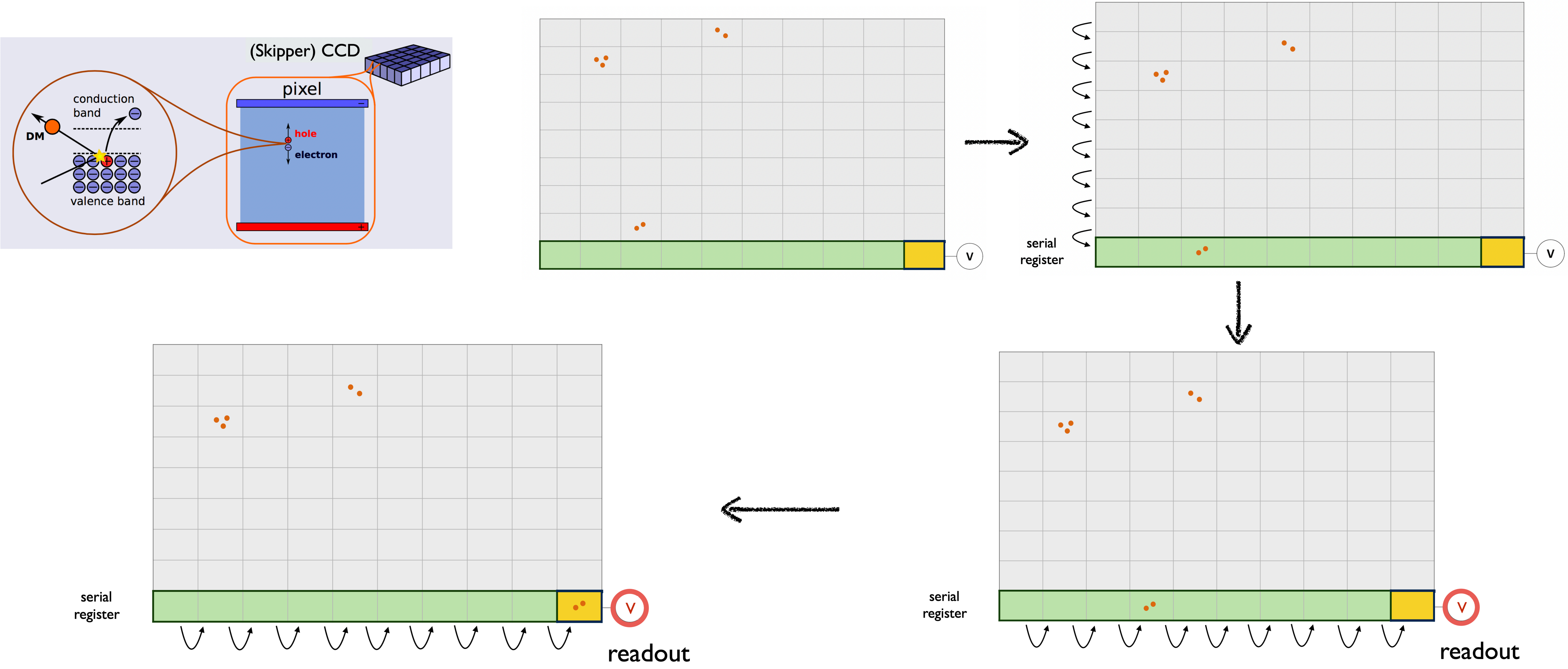
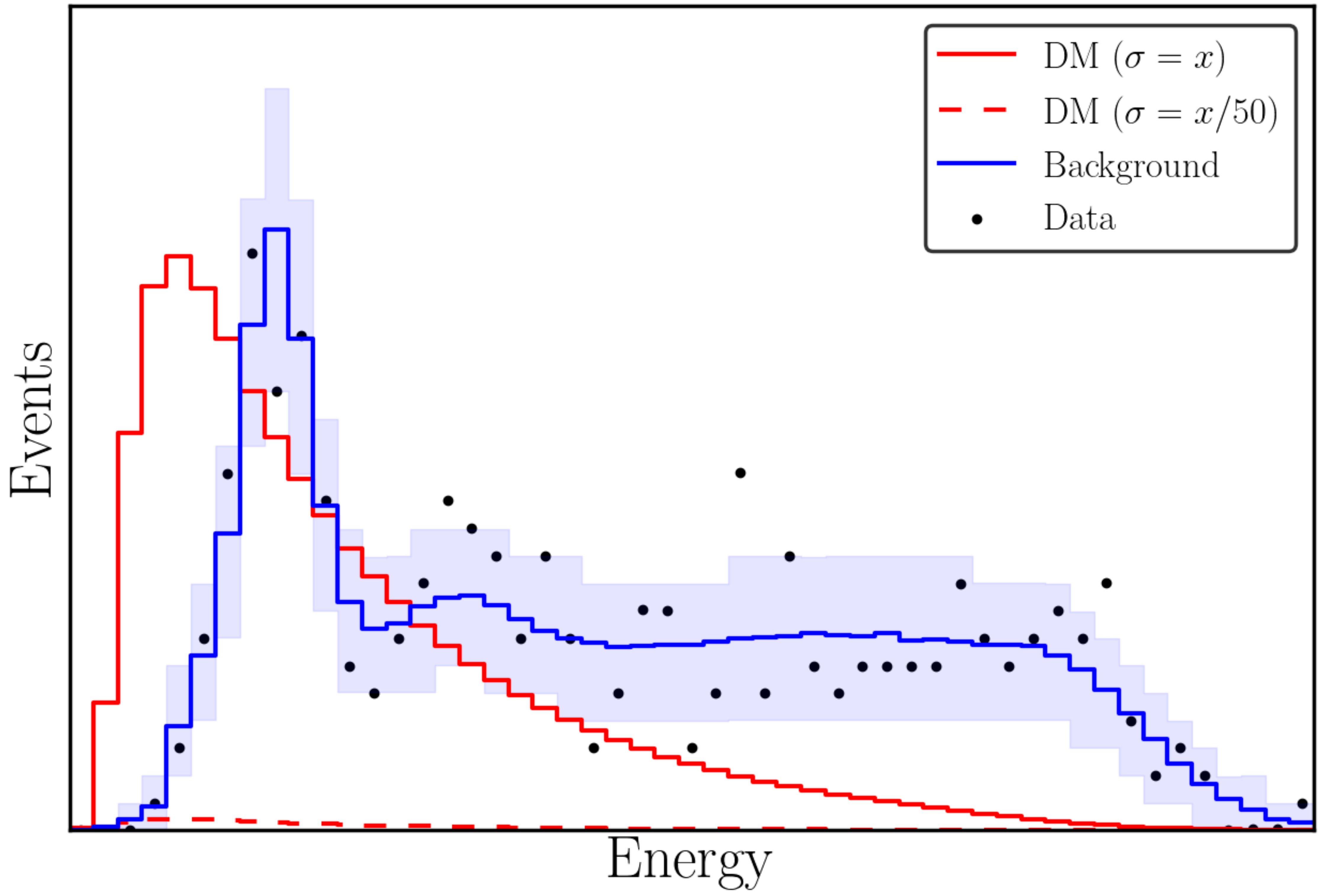


- ✤ Compared to typical CCD, in skipper-CCD one measure the charge multiple times : sub-electron readout noise
- ✤ Move the charge pixel by pixel and finally read it : typical CCD

Tiffenberg+ 1706.00028

Image credit: R Essig

No excess: bounds on DM



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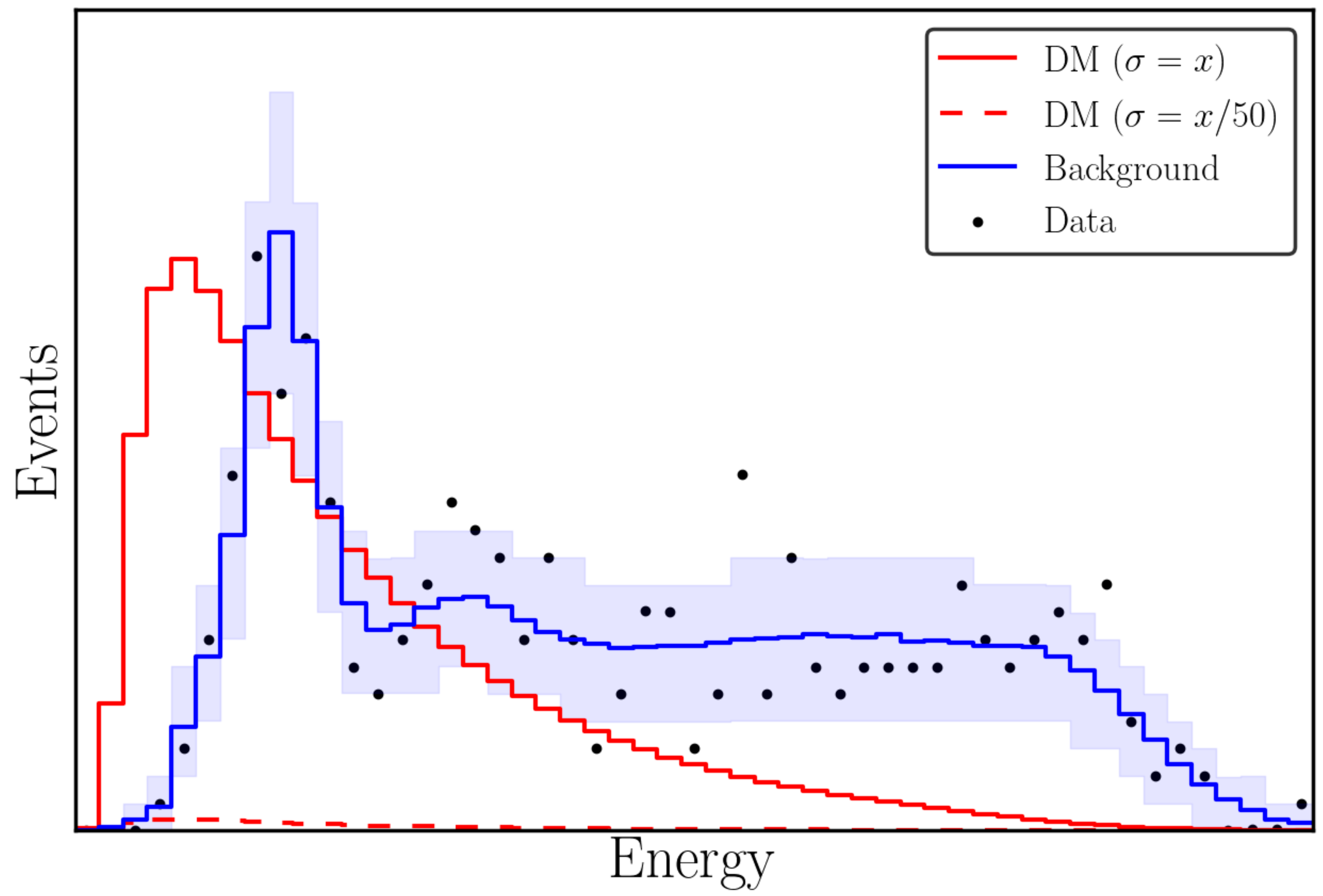

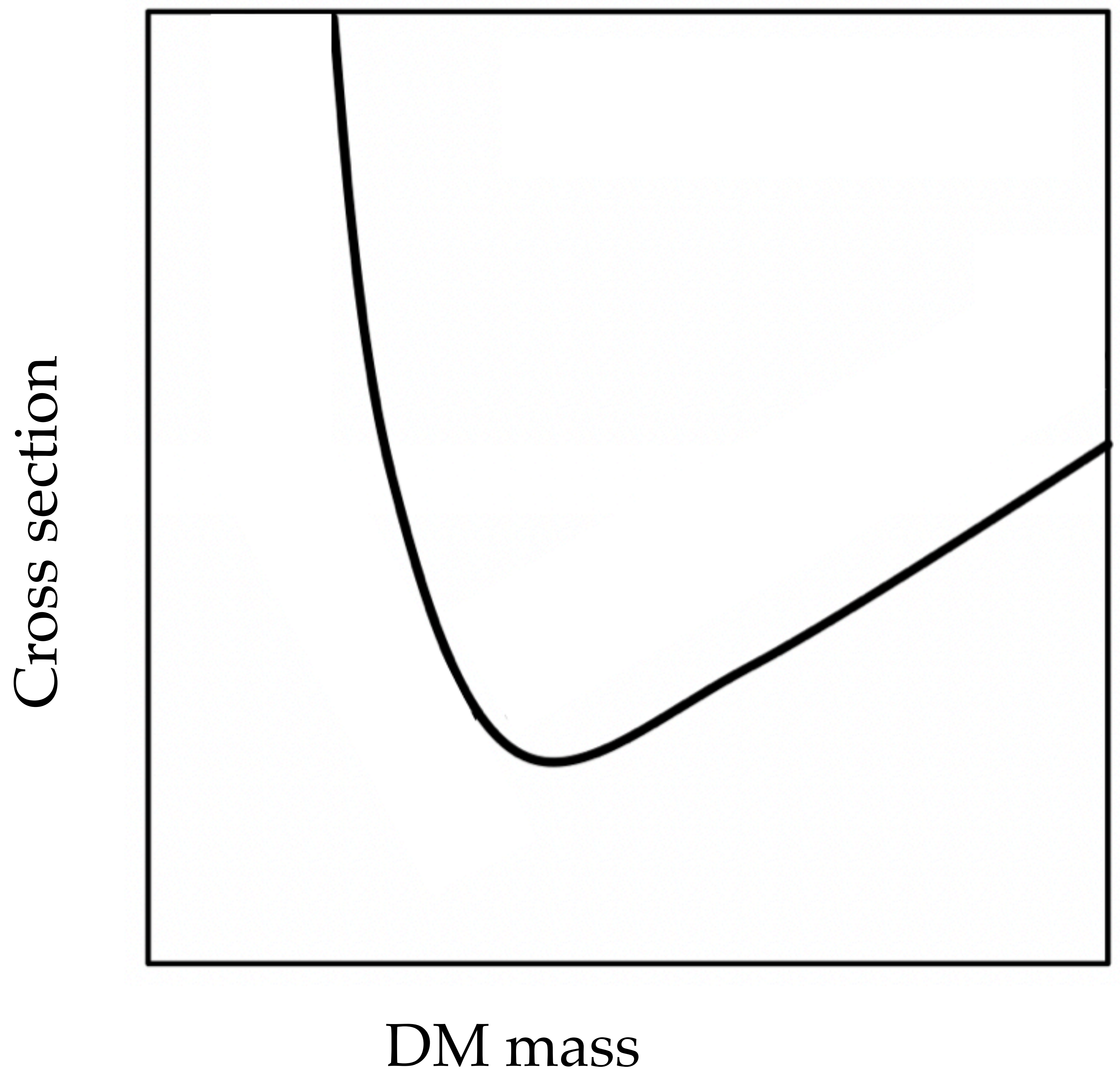

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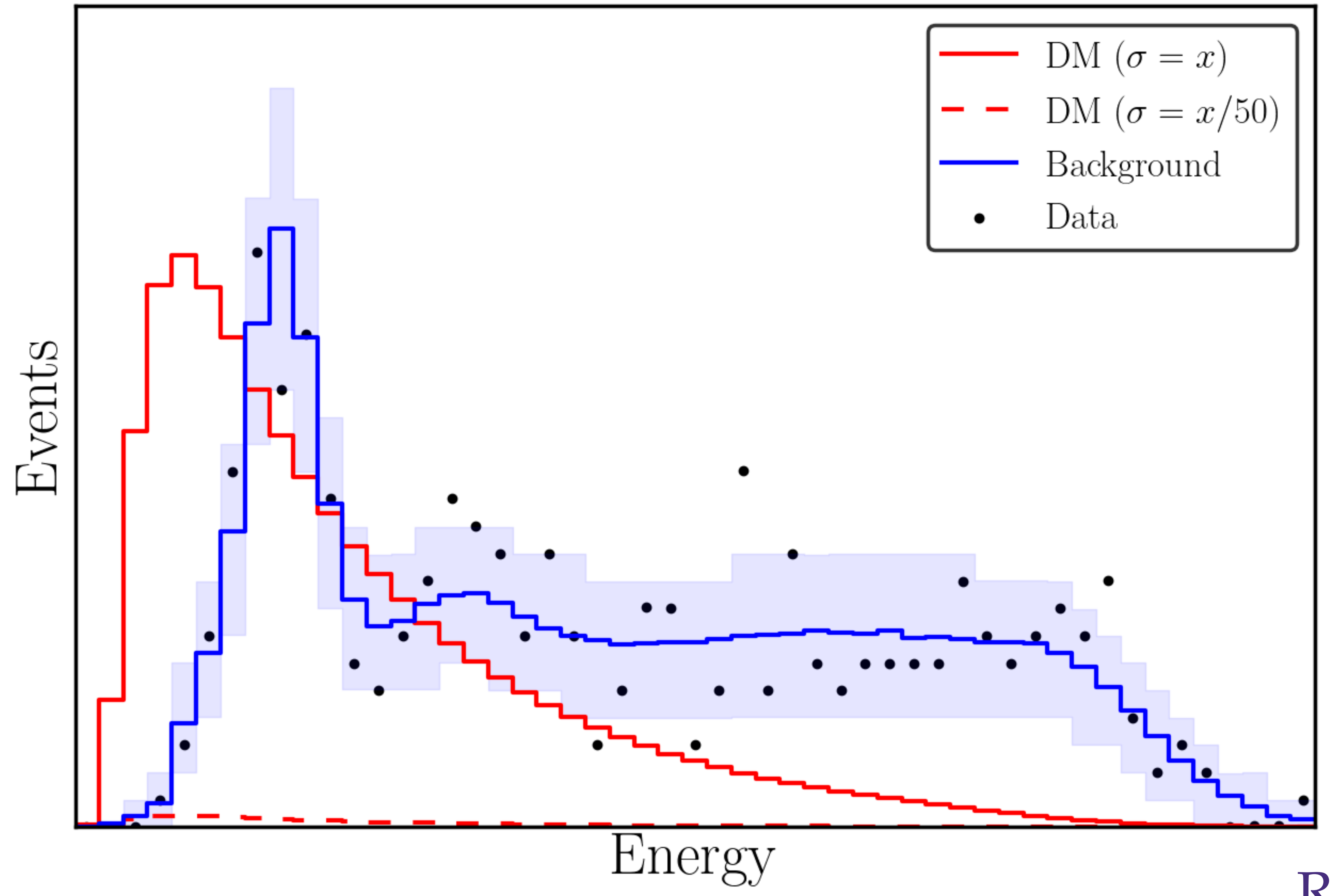

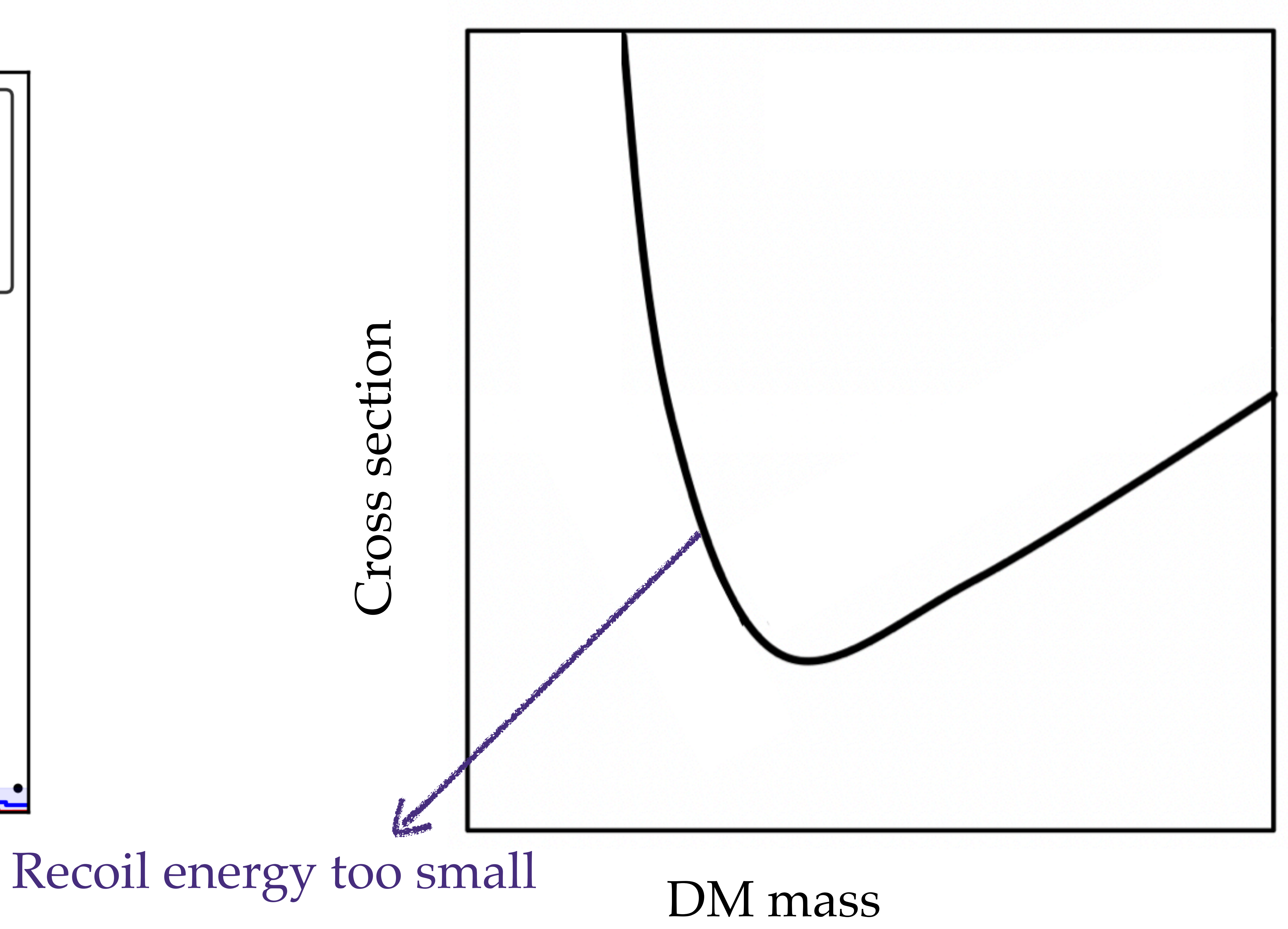

But see 2306.01717

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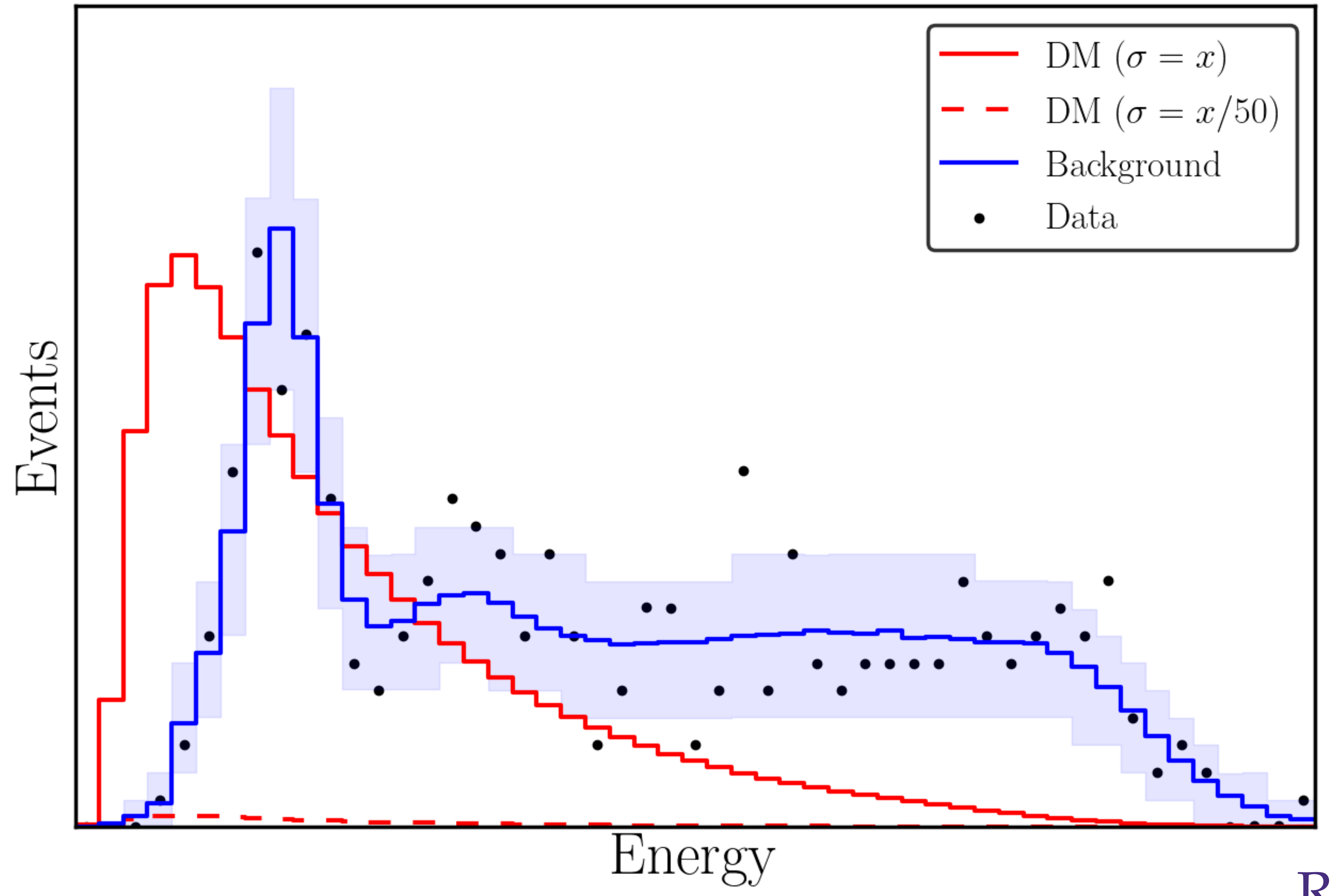
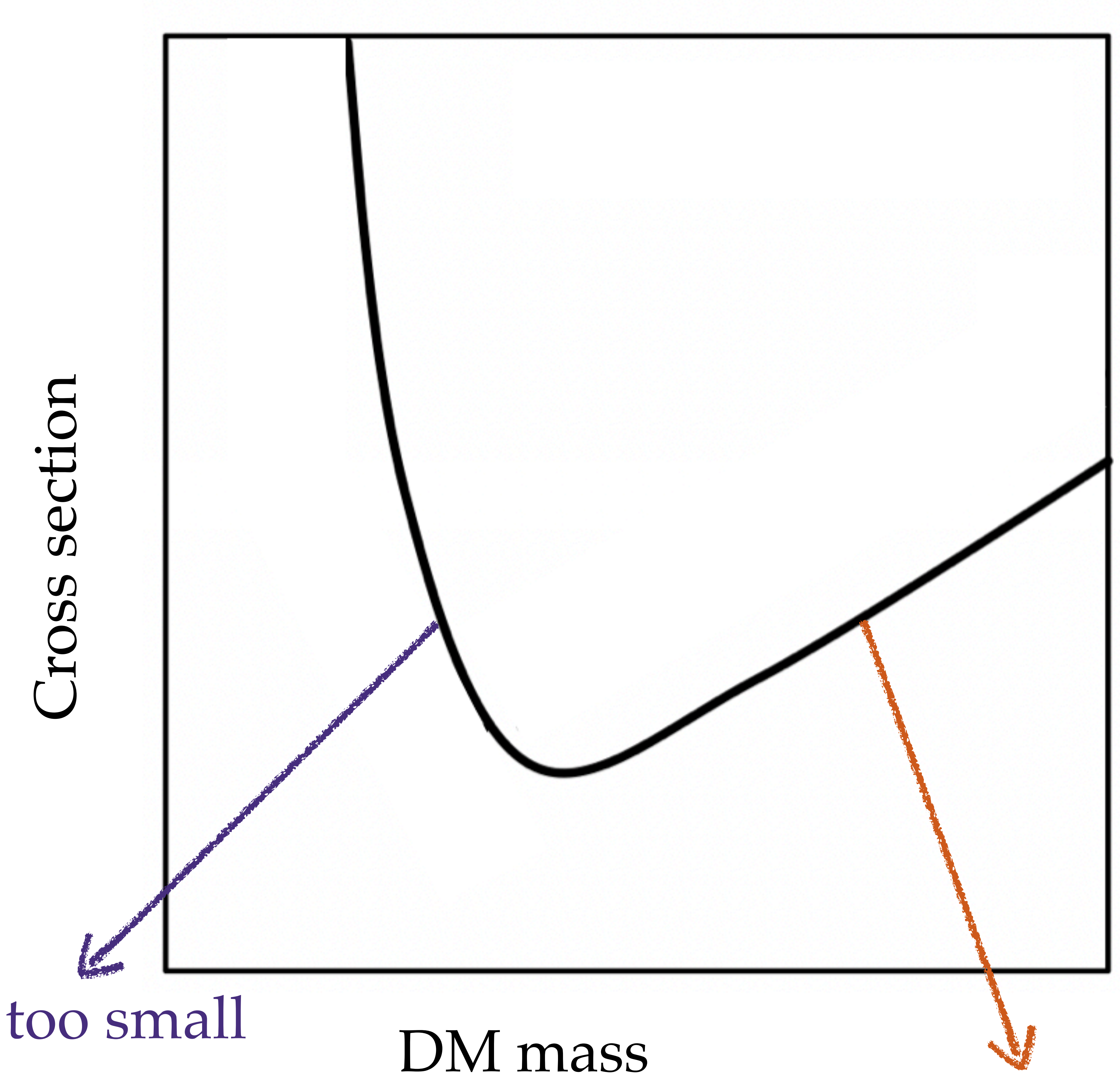




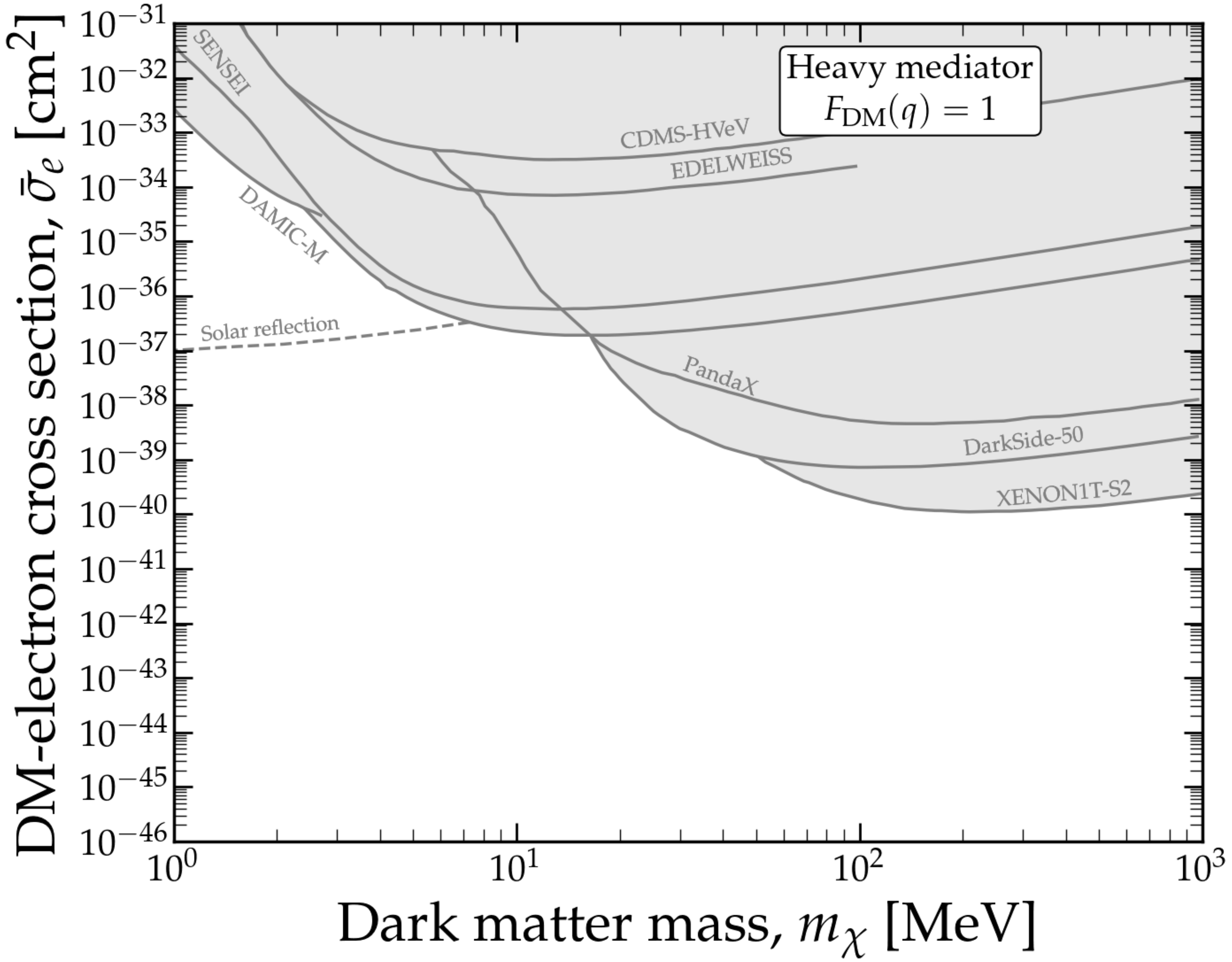
Recoil energy too small

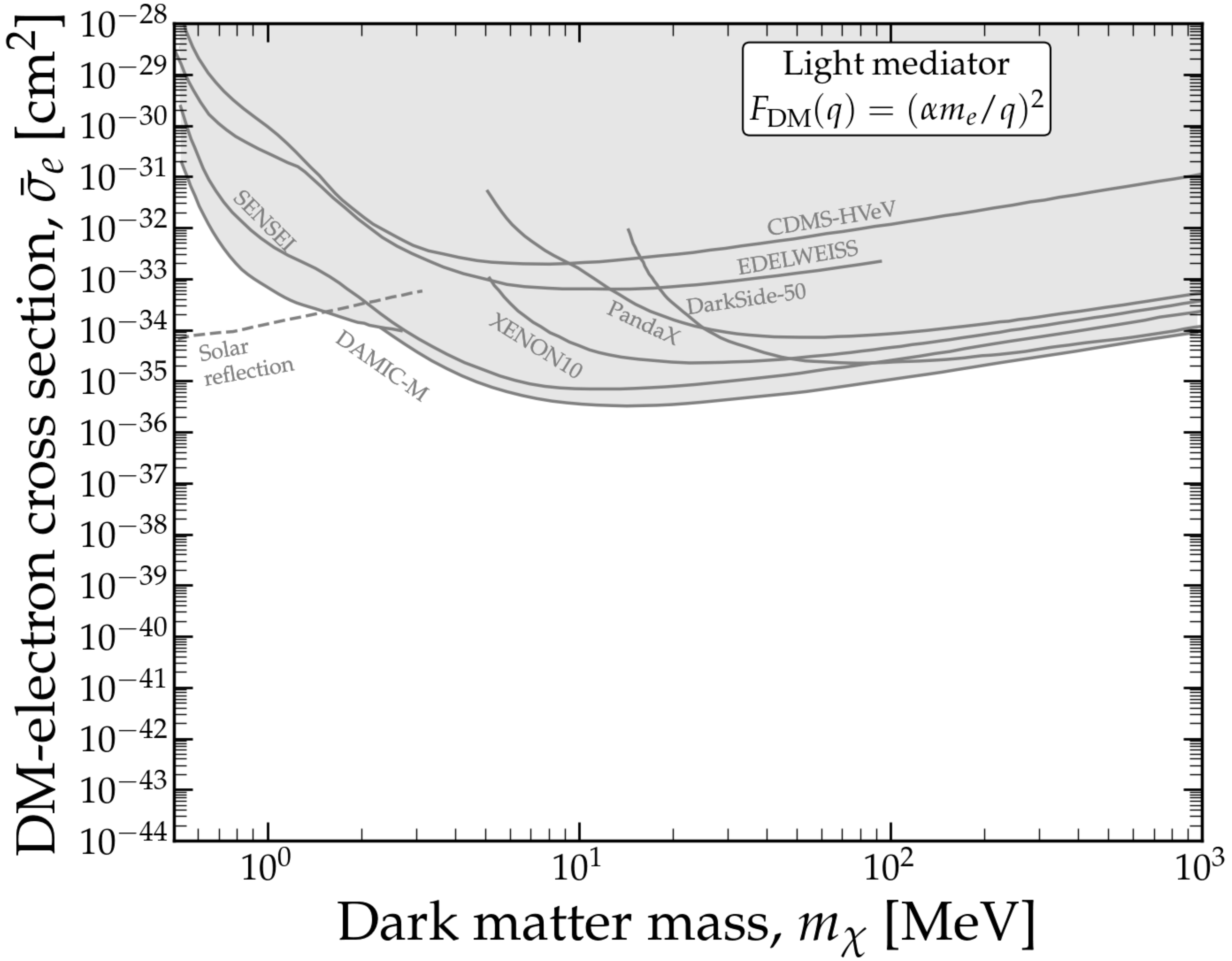
Linearly increasing, since

$$\text{Rate} \;\propto n_\chi \propto \frac{\rho_\chi}{m_\chi} \propto \frac{0.3\,\text{GeV/cm}^3}{m_\chi}$$

But see 2306.01717

DM-electron scattering: bounds





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XENON1T 1907.12771, 2112.12116
DAMIC-M 2302.02372, 2307.07251

An+ 1708.03642, 2108.10332
Emken 2102.12483
DarkSide-50 2207.11968

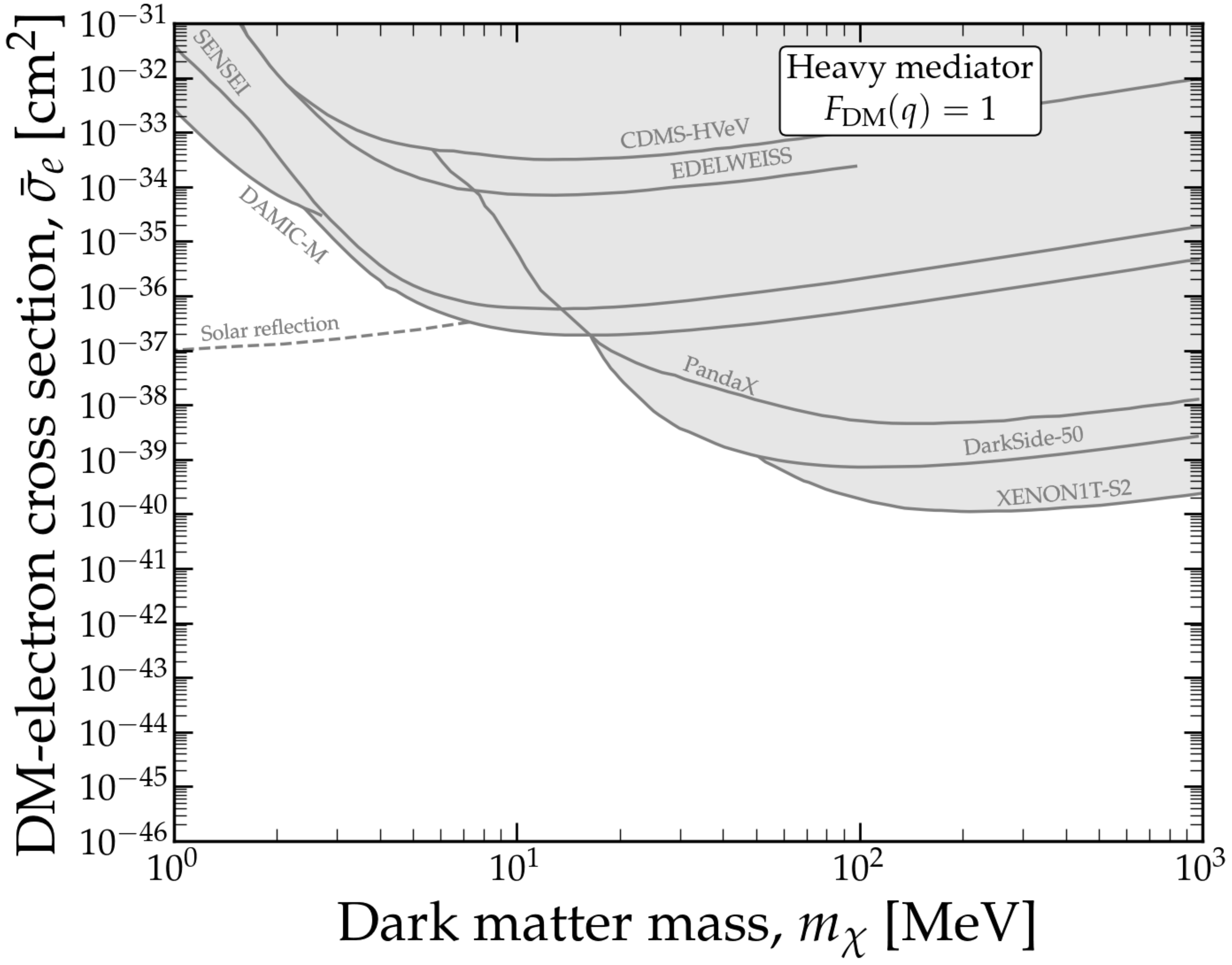
PandaX 2101.07479
CDMS 1804.10697
EDELWEISS 2003.01046

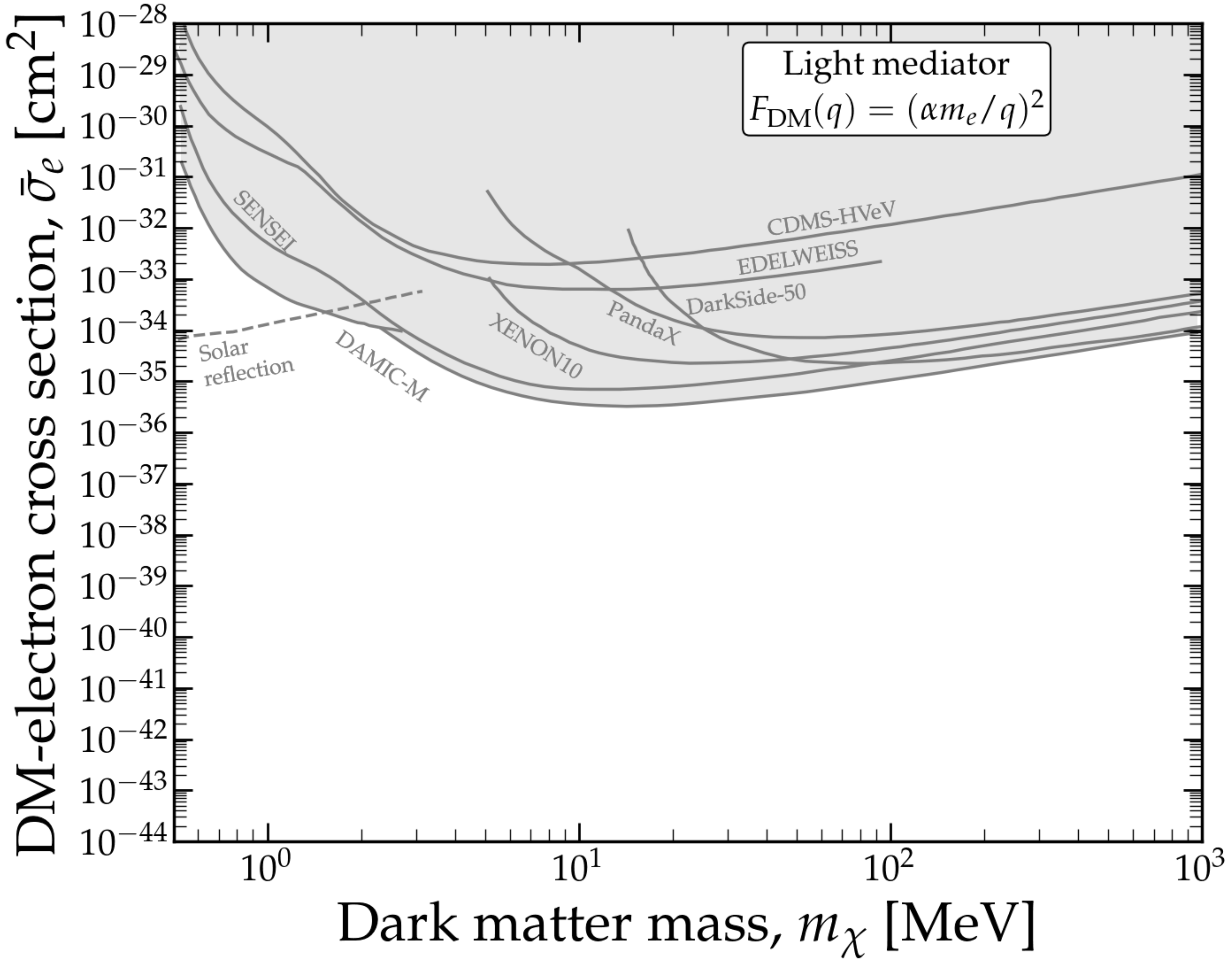
DM-electron scattering: bounds

There are ceiling

Defined by the cross section for which DM would not produce obs. recoil

Emken+ 1905.06348





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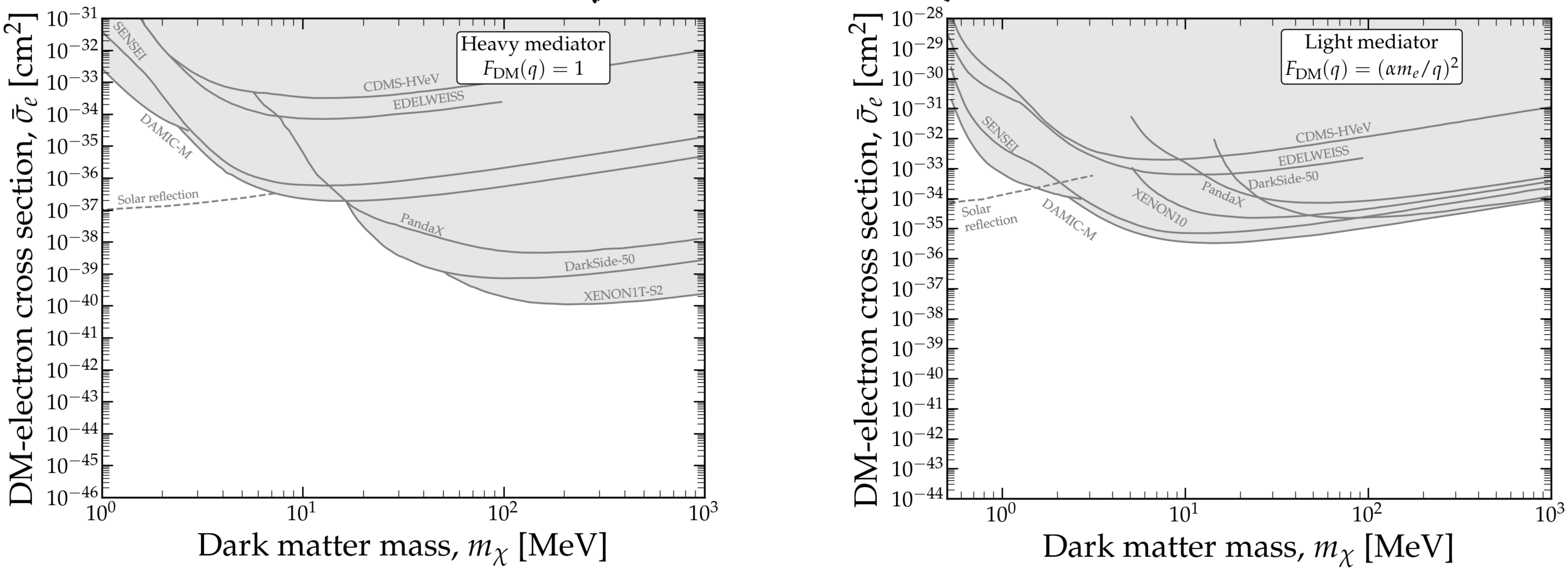

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For effect of non-SHM distributions →

Radick+ 2011.02493
TNM+ 2011.12896
Buch+ 2007.13750
TNM+ 2208.14471

Where do neutrinos show up?

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Source of neutrinos?

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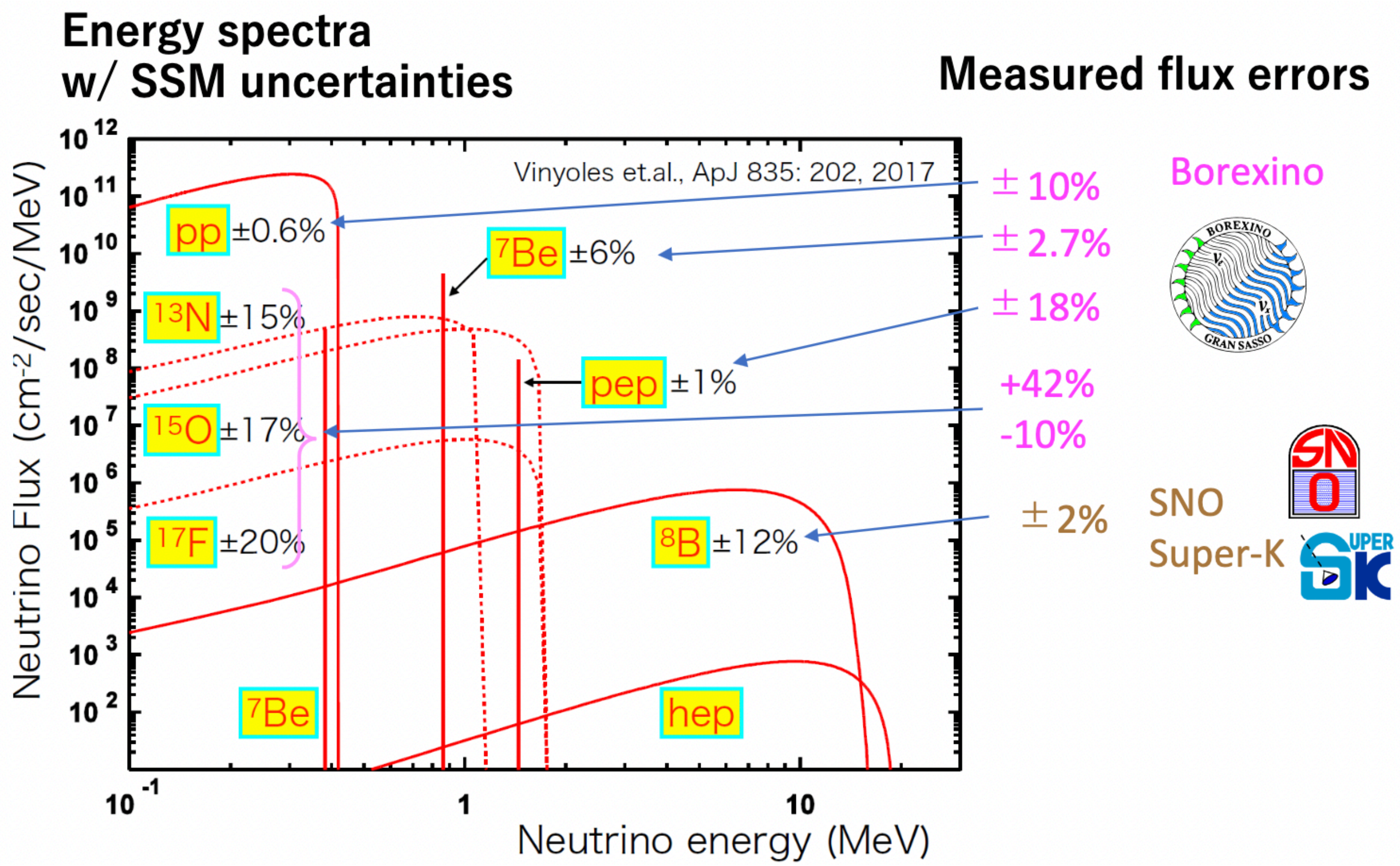
Source of neutrinos?

Mainly the Solar neutrinos



Atmospheric and DSNB are subdominant

Sekiya TAUP 2023
Borexino Nature (2018)
SNO nucl-ex/0204008
Bergstrom+ 1601.00972

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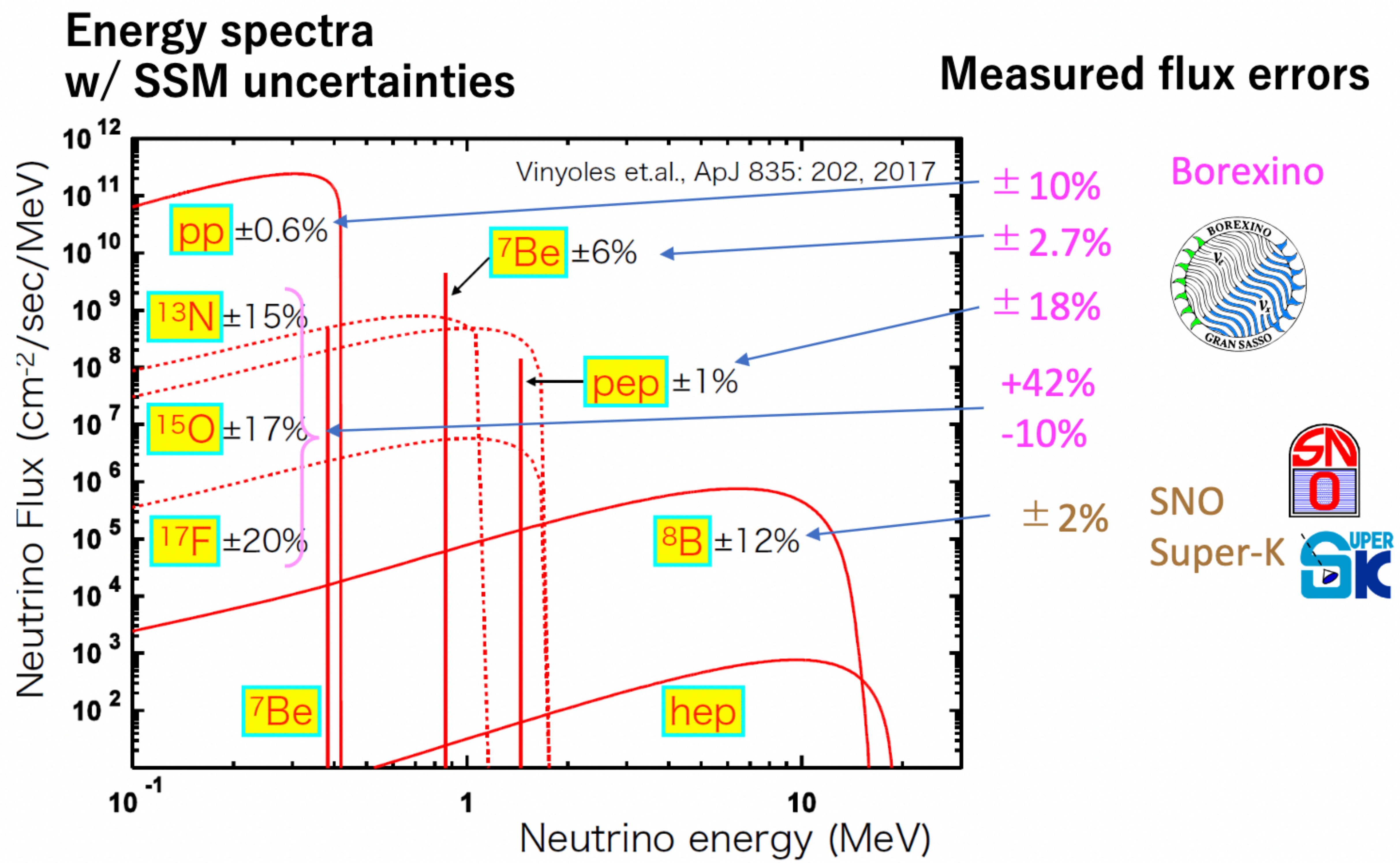

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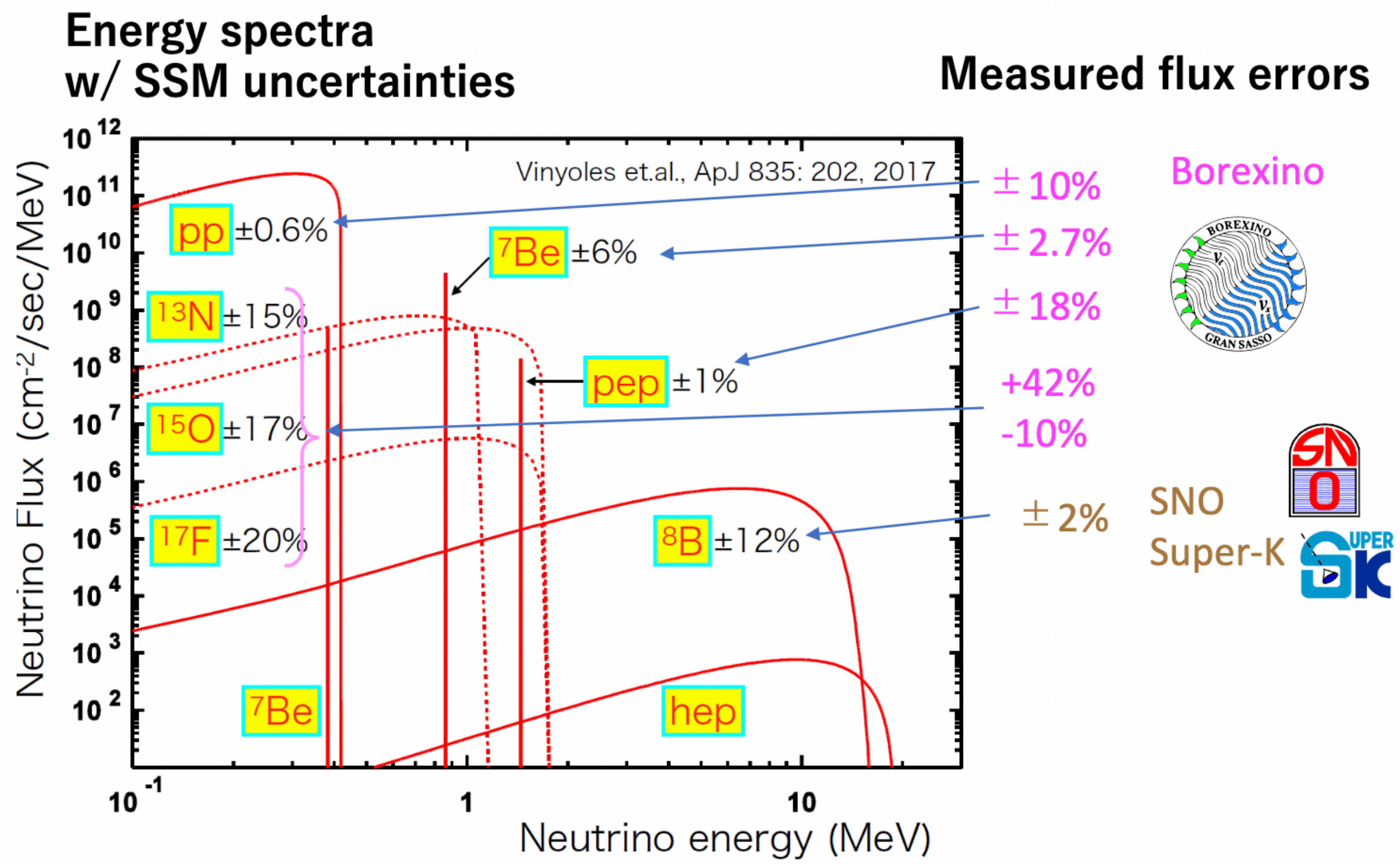

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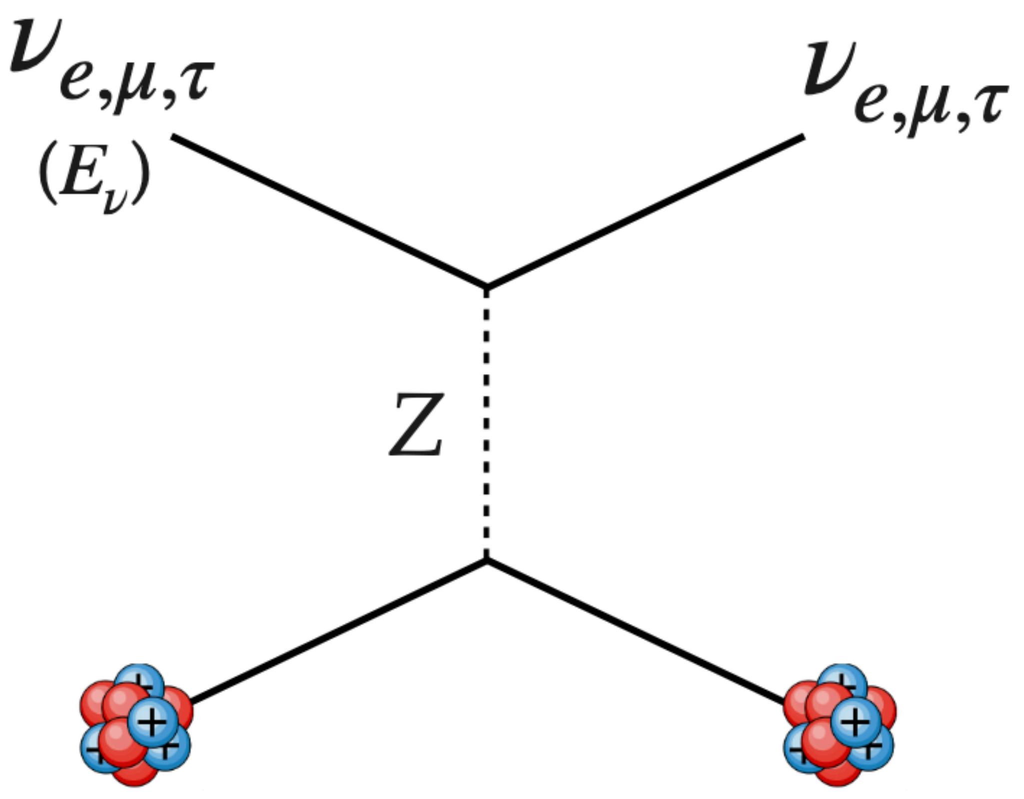
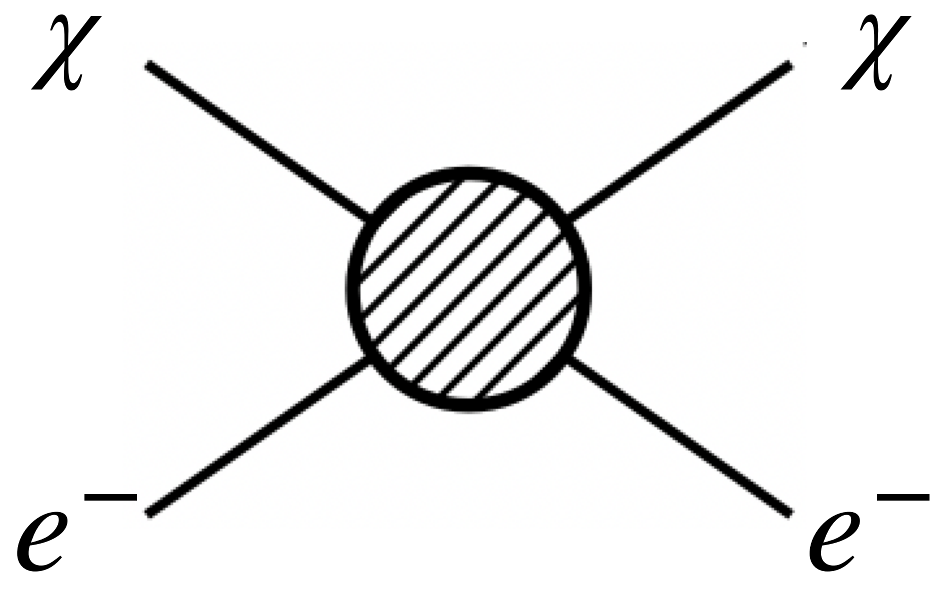


Coherent elastic neutrino -nucleus scattering (CEvNS)



χ : DM

DM-electron scattering

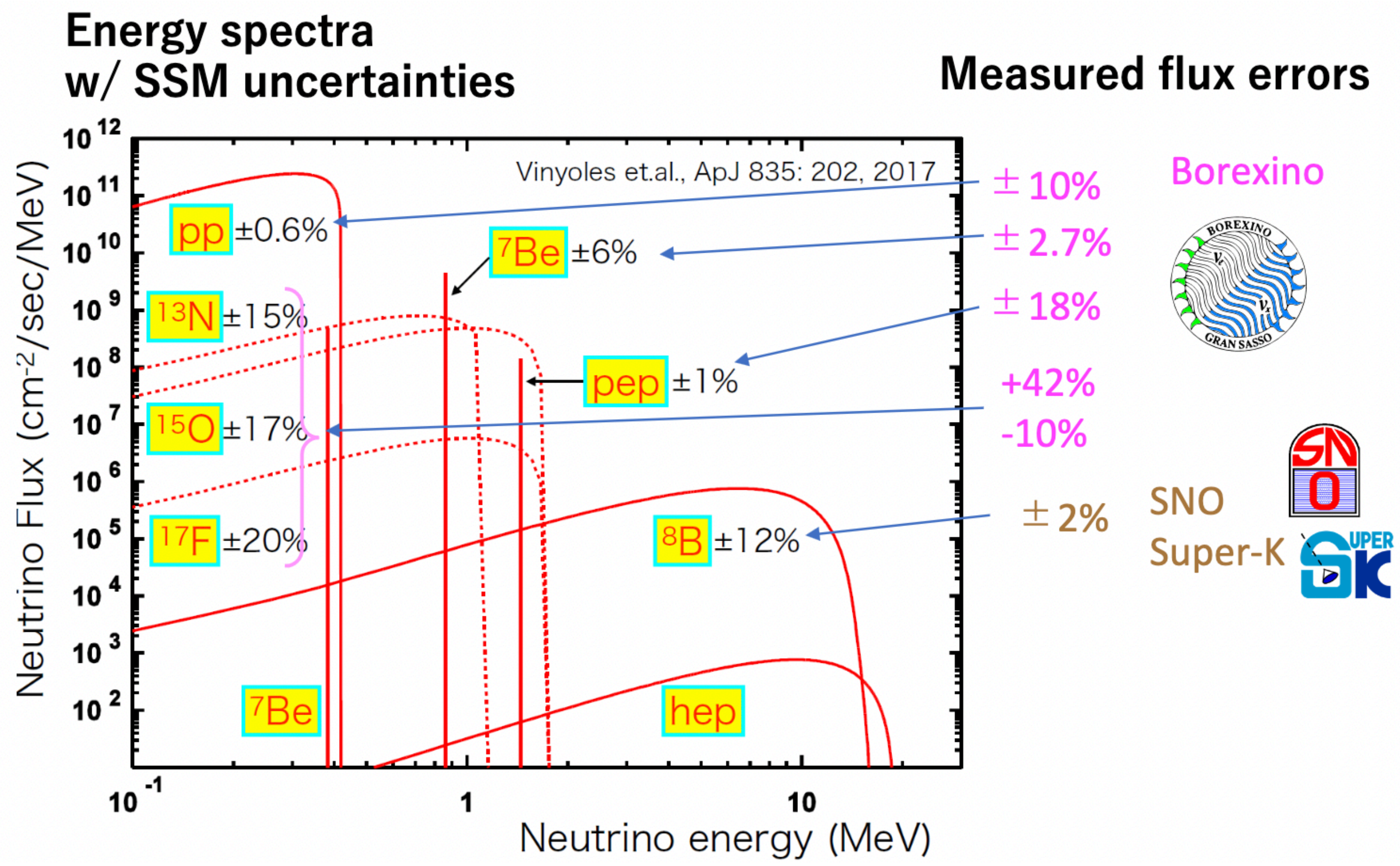
Neutrinos may mimic DM-like signal

Sekiya TAUP 2023
Borexino Nature (2018)
SNO nucl-ex/0204008
Bergstrom+ 1601.00972

Where do neutrinos show up?

Source of neutrinos?

Mainly the Solar neutrinos



Atmospheric and DSNB are subdominant

Sekiya TAUP 2023
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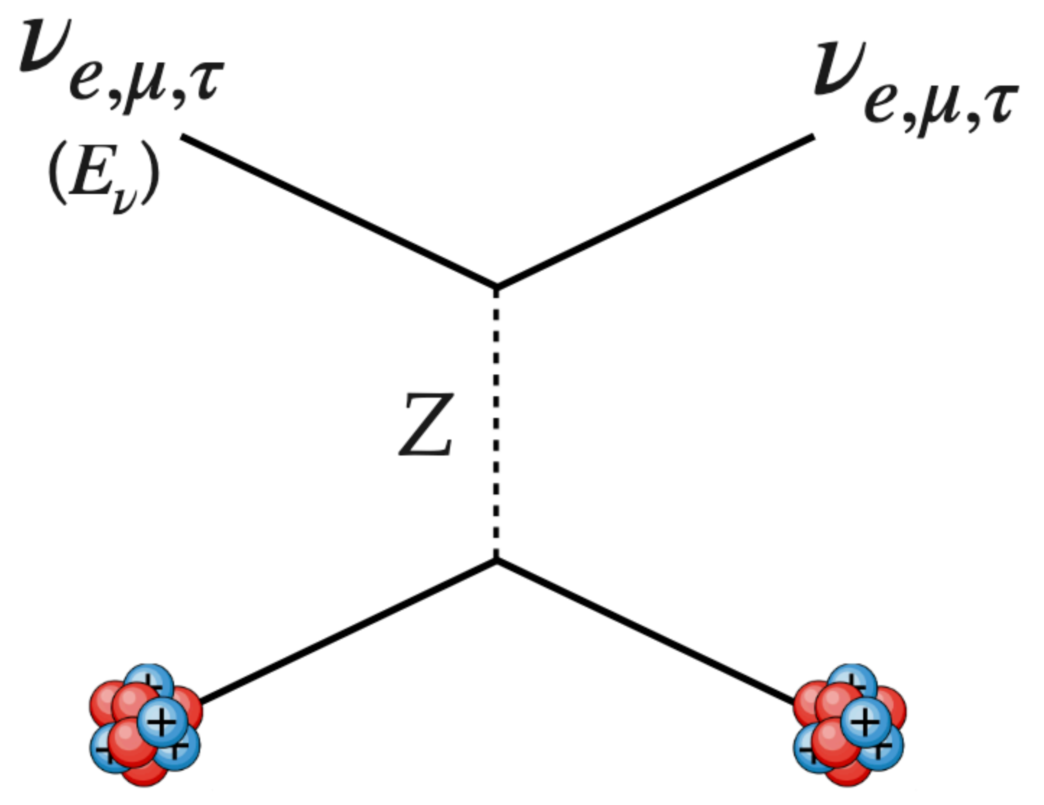
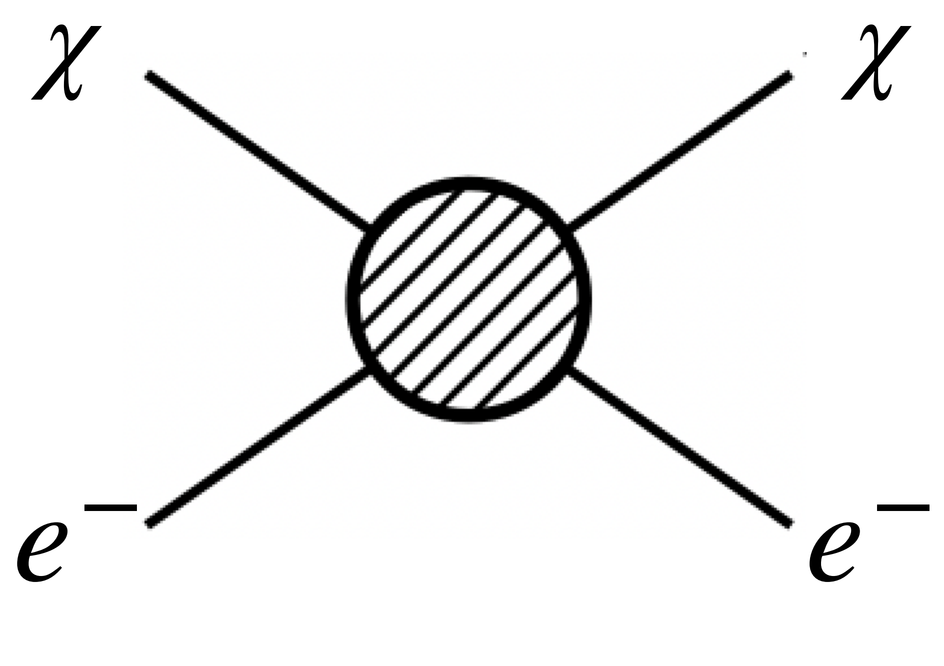
Why are they problematic?



Coherent elastic neutrino -nucleus scattering (CEvNS)

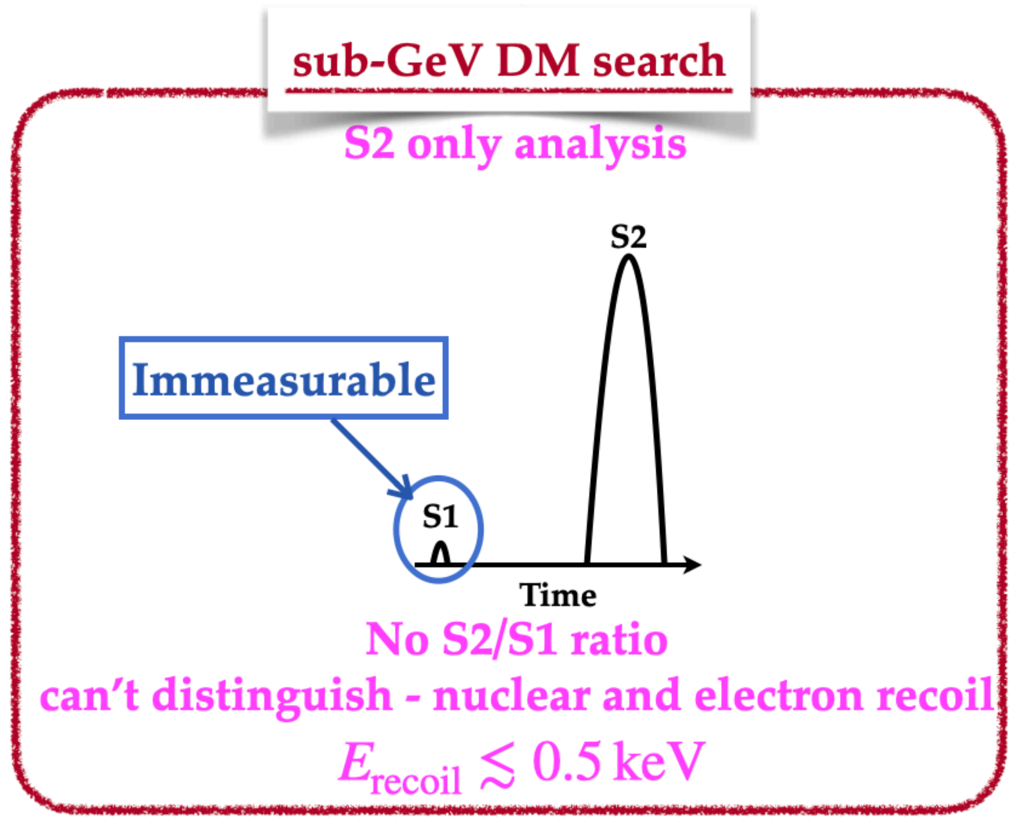


χ : DM

DM-electron scattering

Neutrinos may mimic DM-like signal

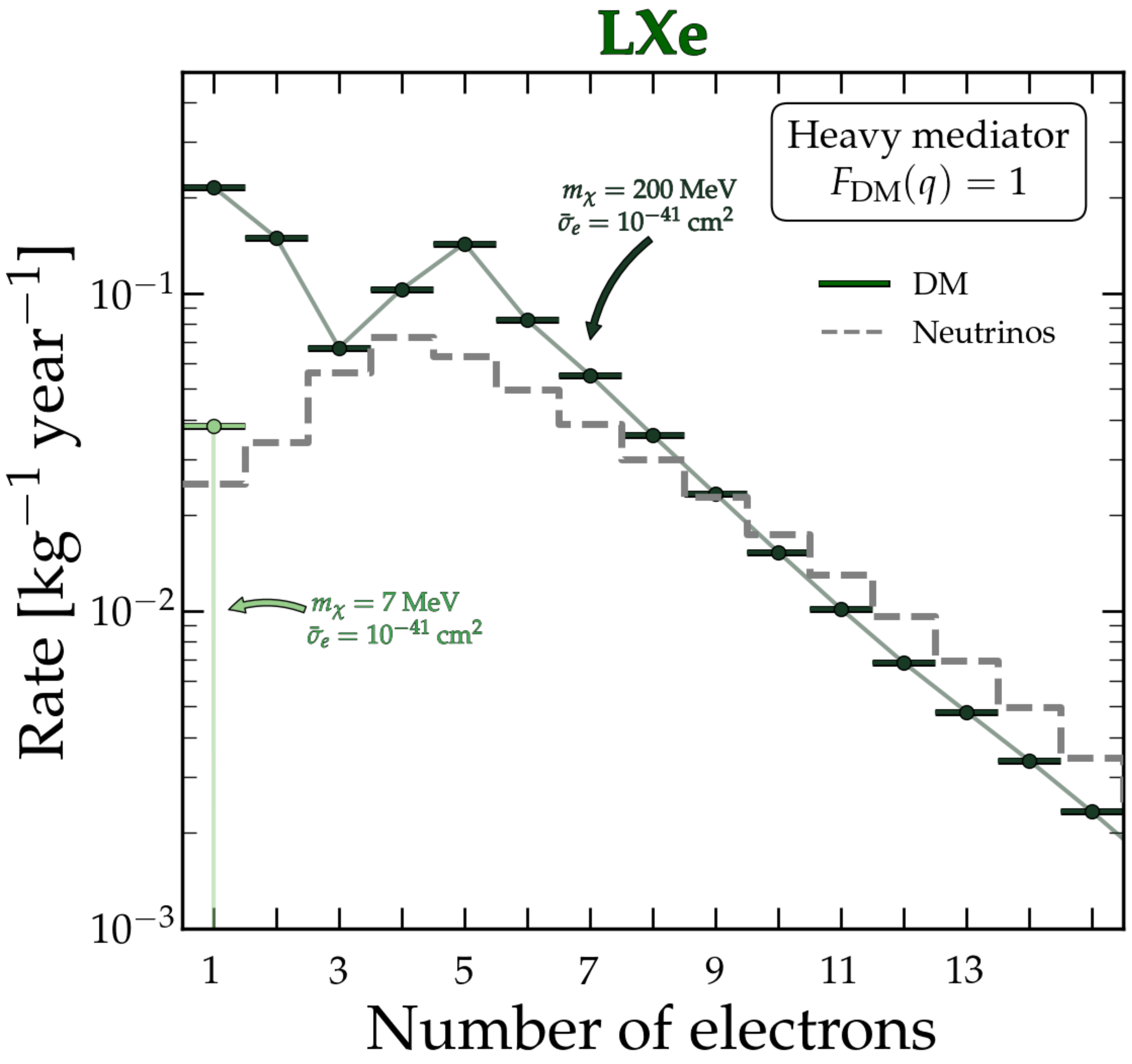
✳ Ionisation produce from nuclear recoil can be misidentified as electron recoil

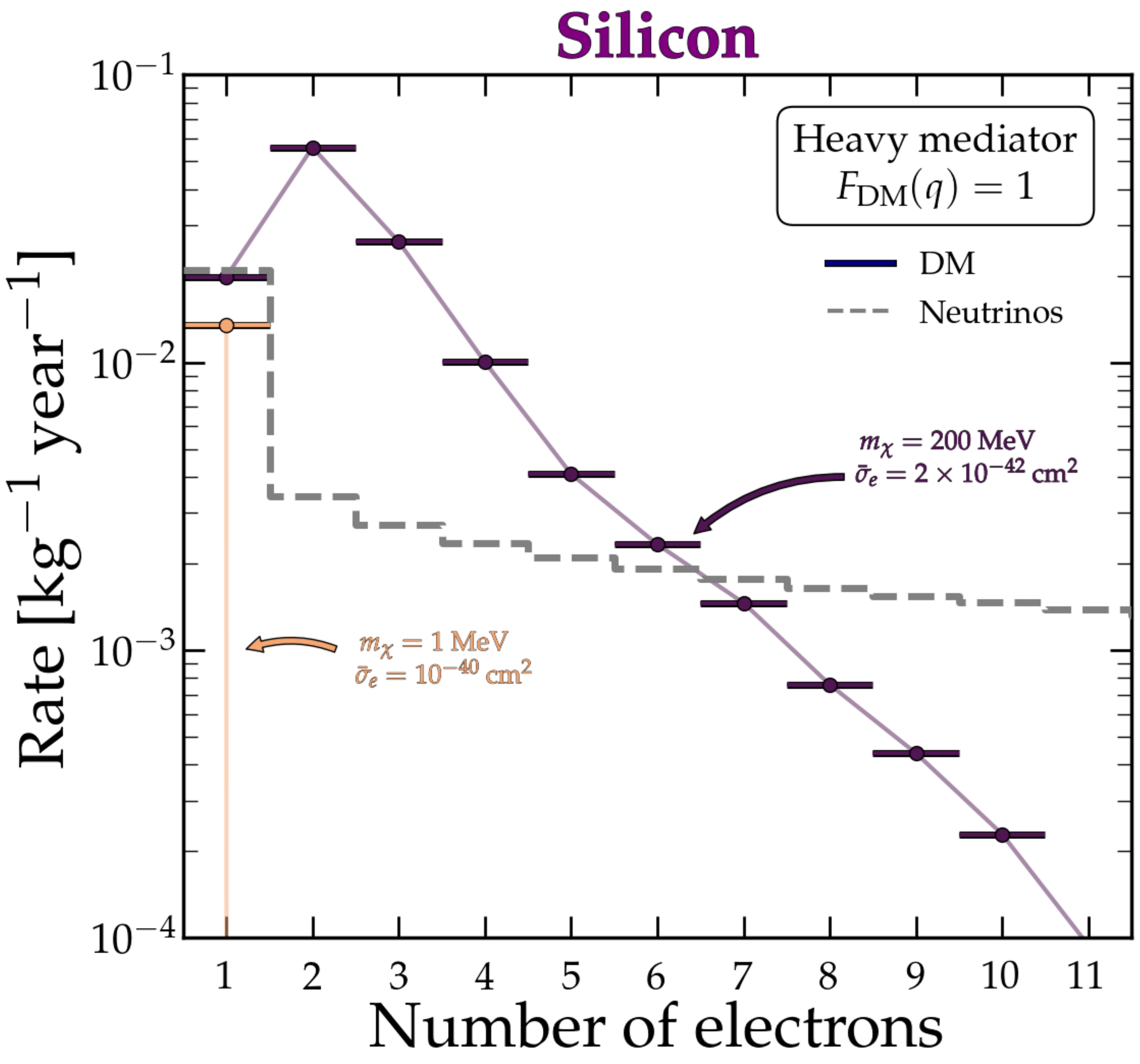


Essig+ 1801.10159
Wyenberg+ 1803.08146

Where do neutrinos show up?

Event rate





Knapen+, *DarKEFL*, 2104.12786
Essig+, *QEdark*, 1509.01598
Canddell+, 2305.05125

Carew, Caddell, TNM, O'Hare; 2312.04303

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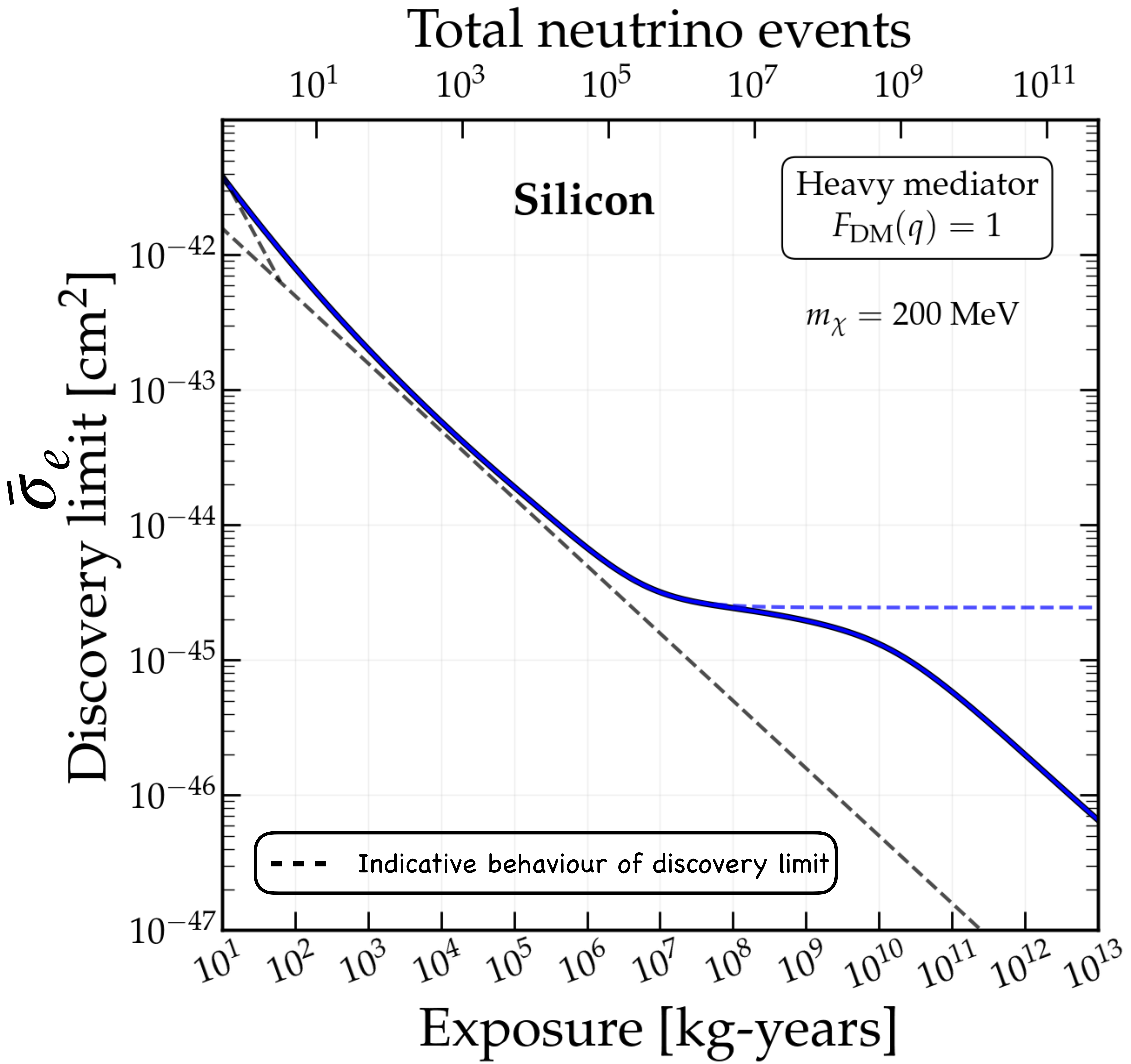

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$\delta\phi$: Uncertainty in the neutrino flux

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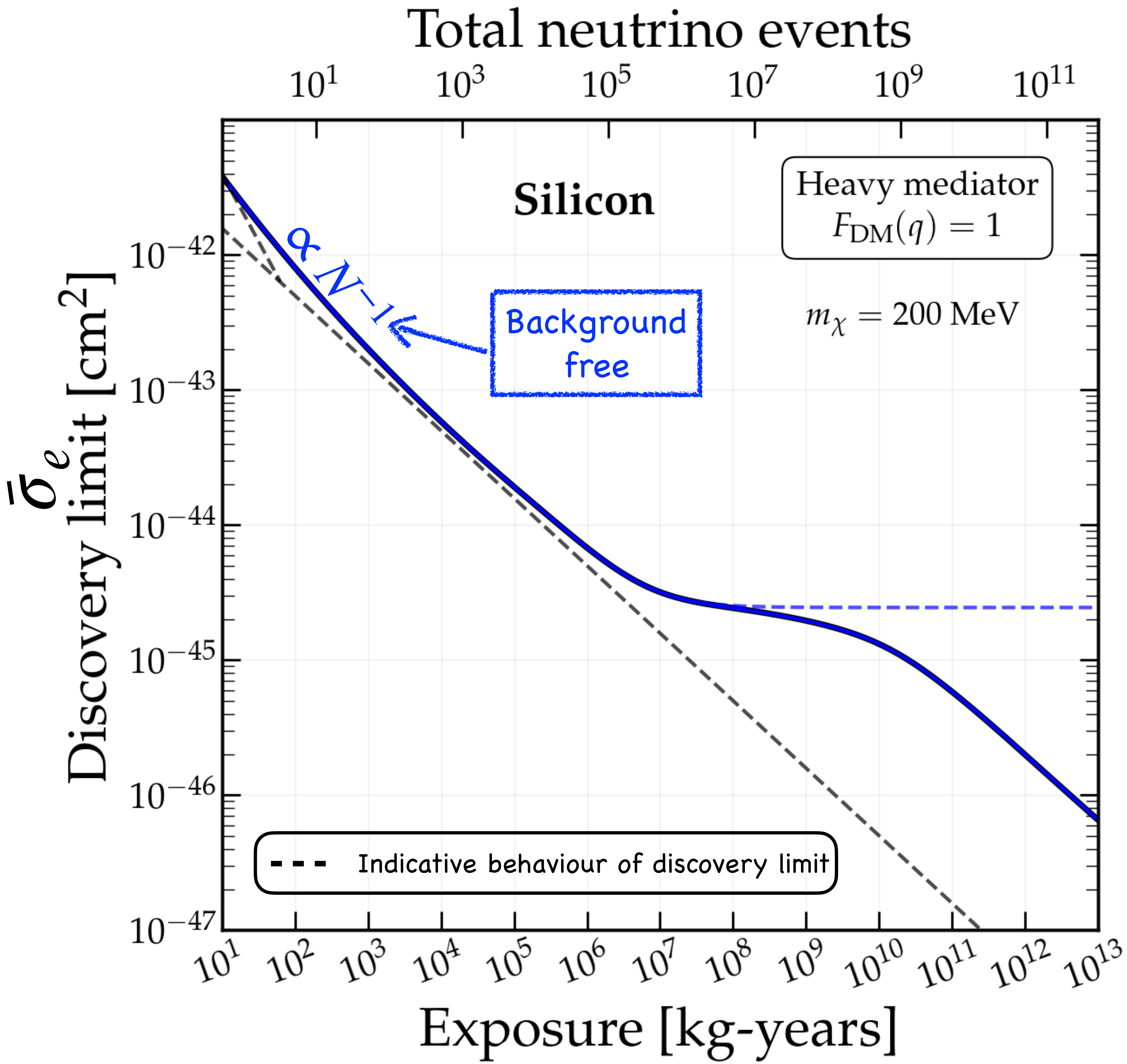

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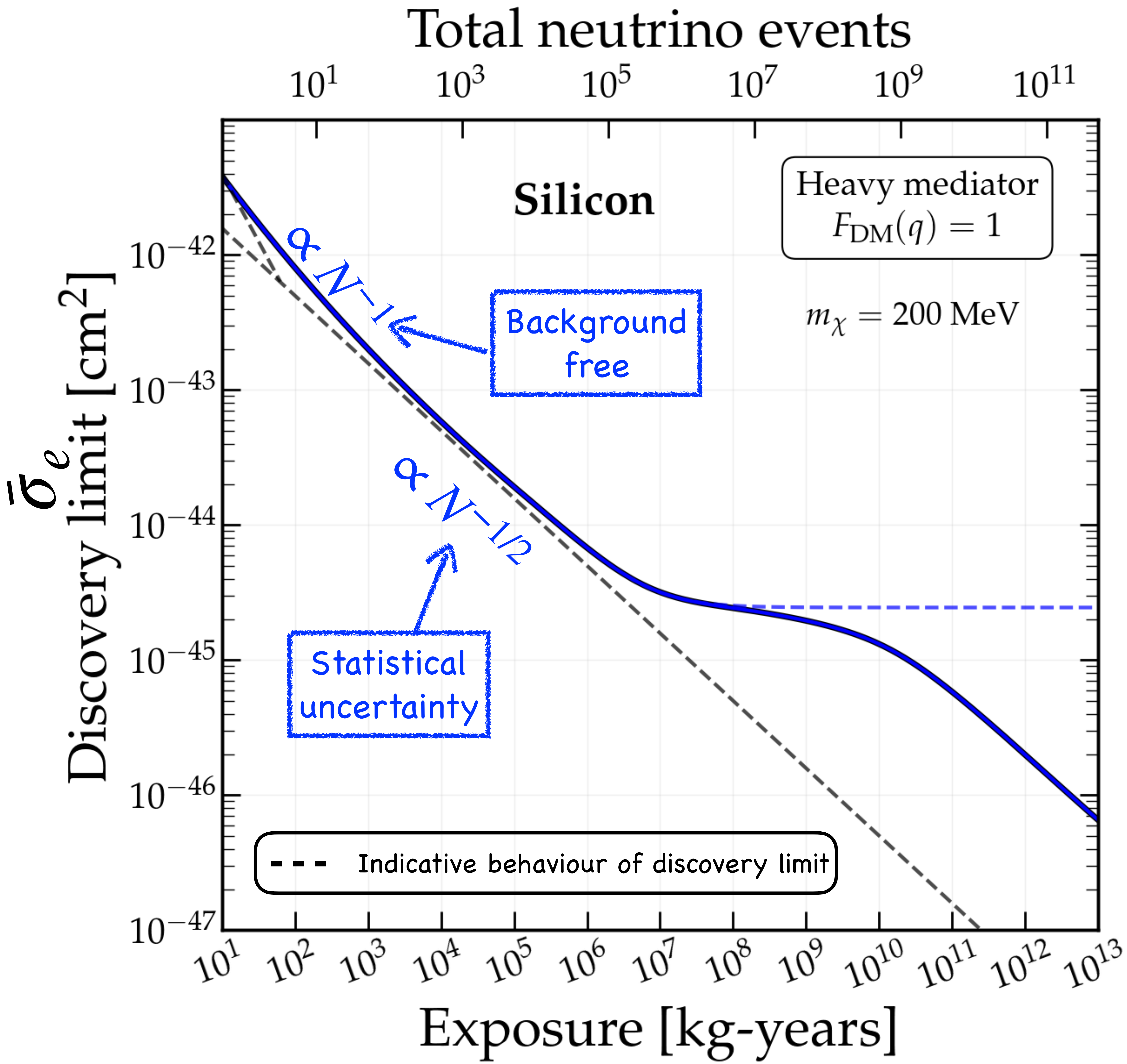

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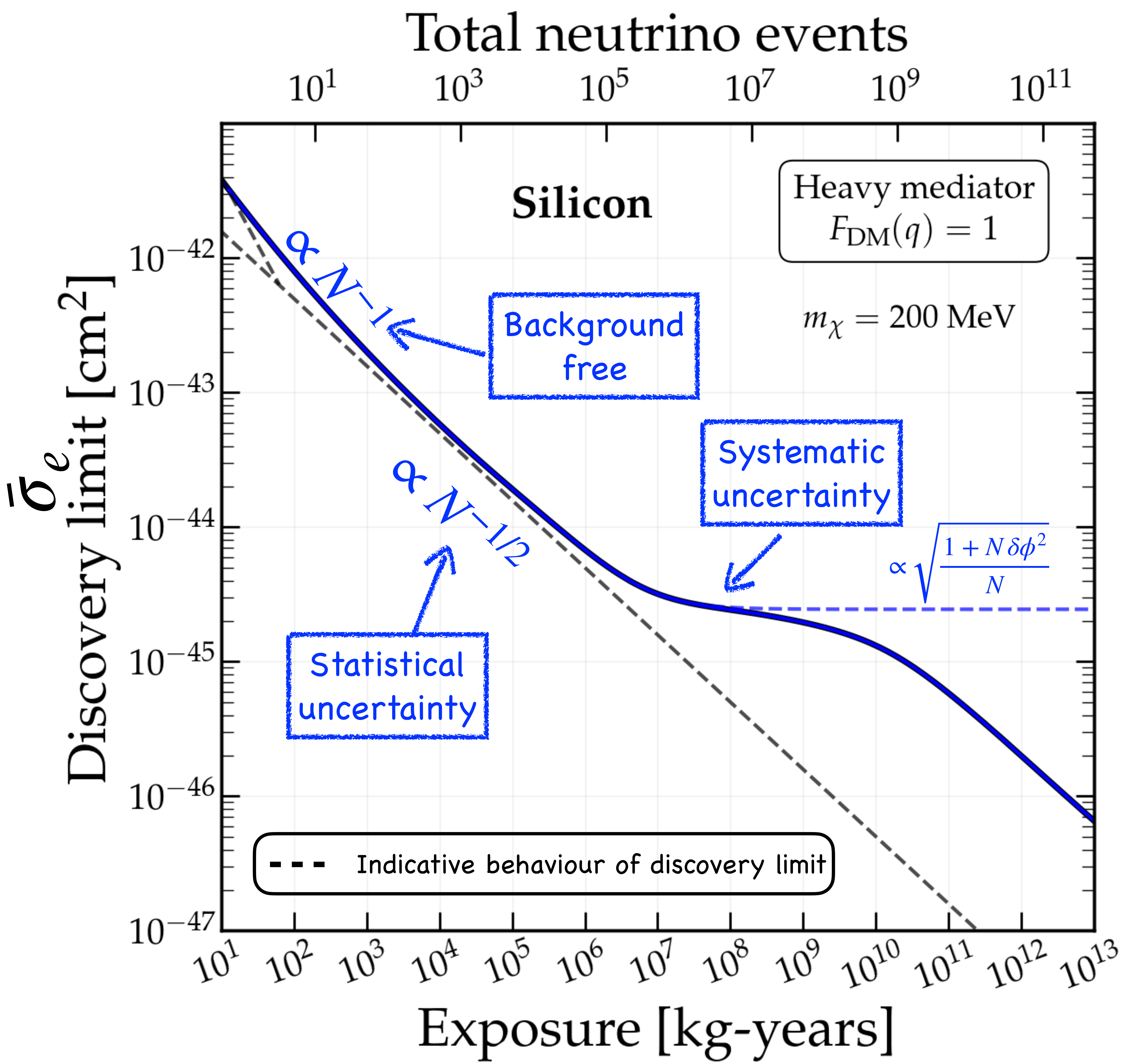

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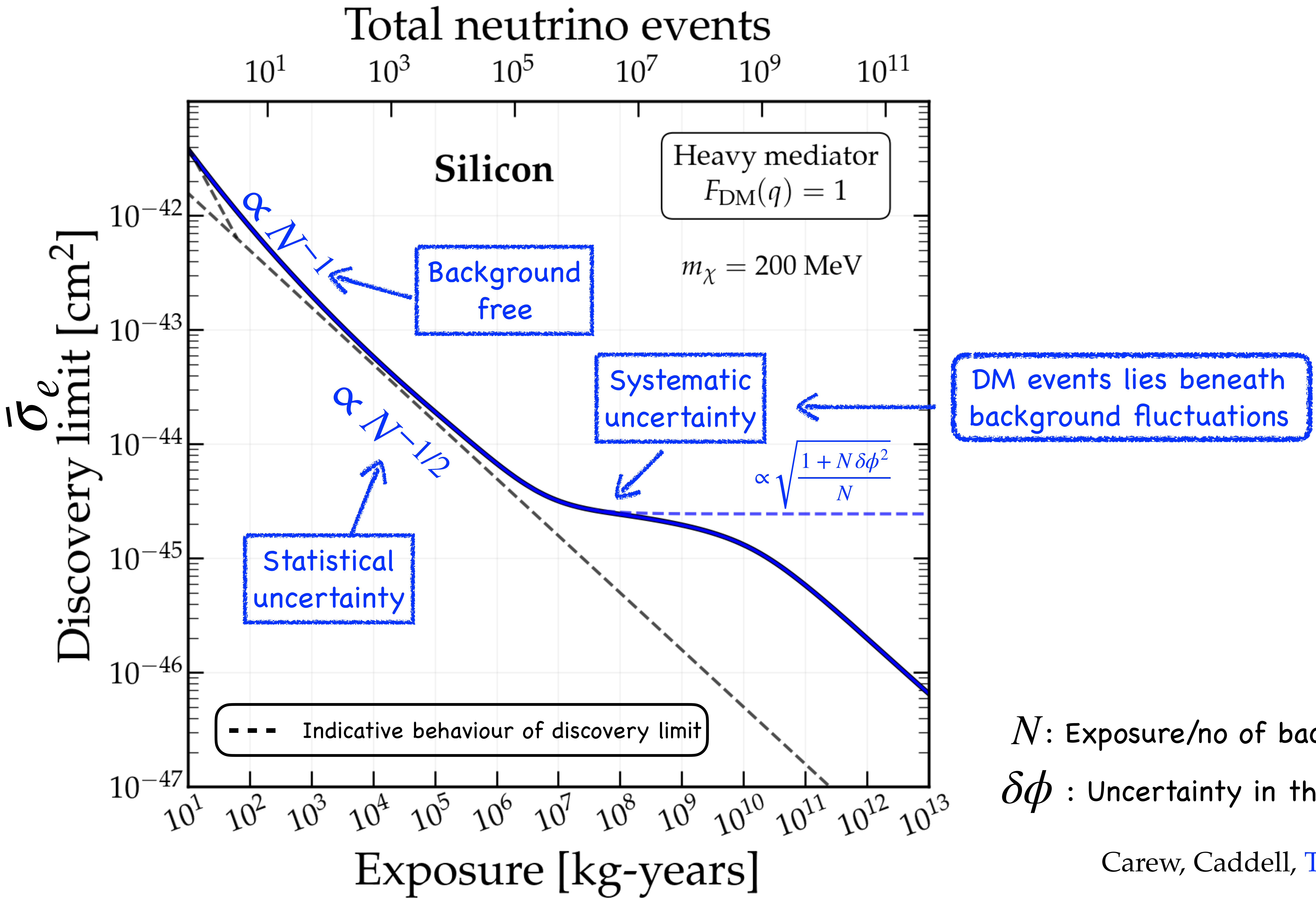

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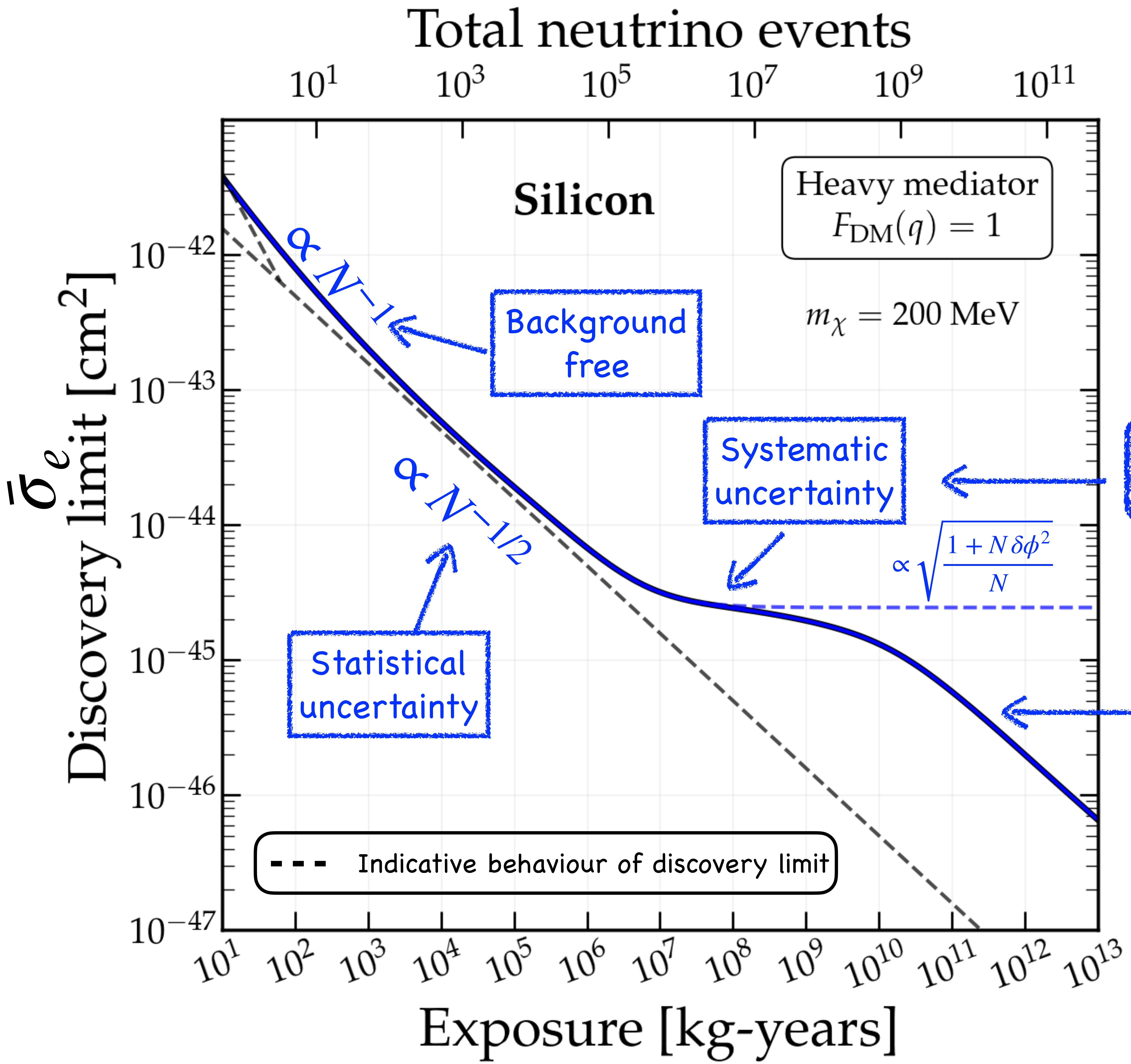

DM events lies beneath background fluctuations

✓ There no hard floor if spectrum are not identical

✓ With huge exposure, it is in principle possible to distinguish between DM and neutrinos

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Tarak Nath Maity

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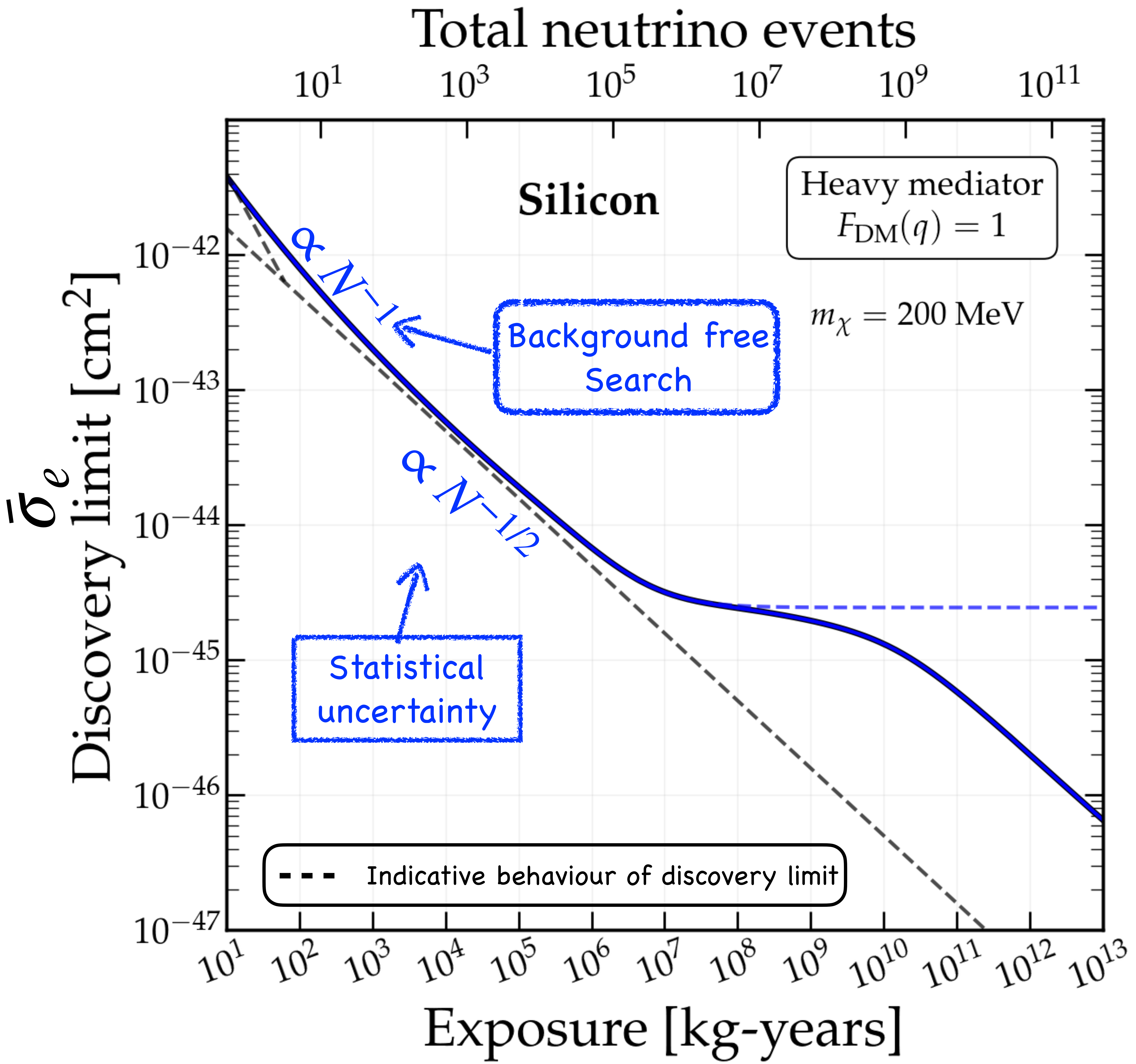

How to calculate the neutrino "floor"?

Note: "floor" may not be hard

Carew, Caddell, TNM, O'Hare; 2312.04303

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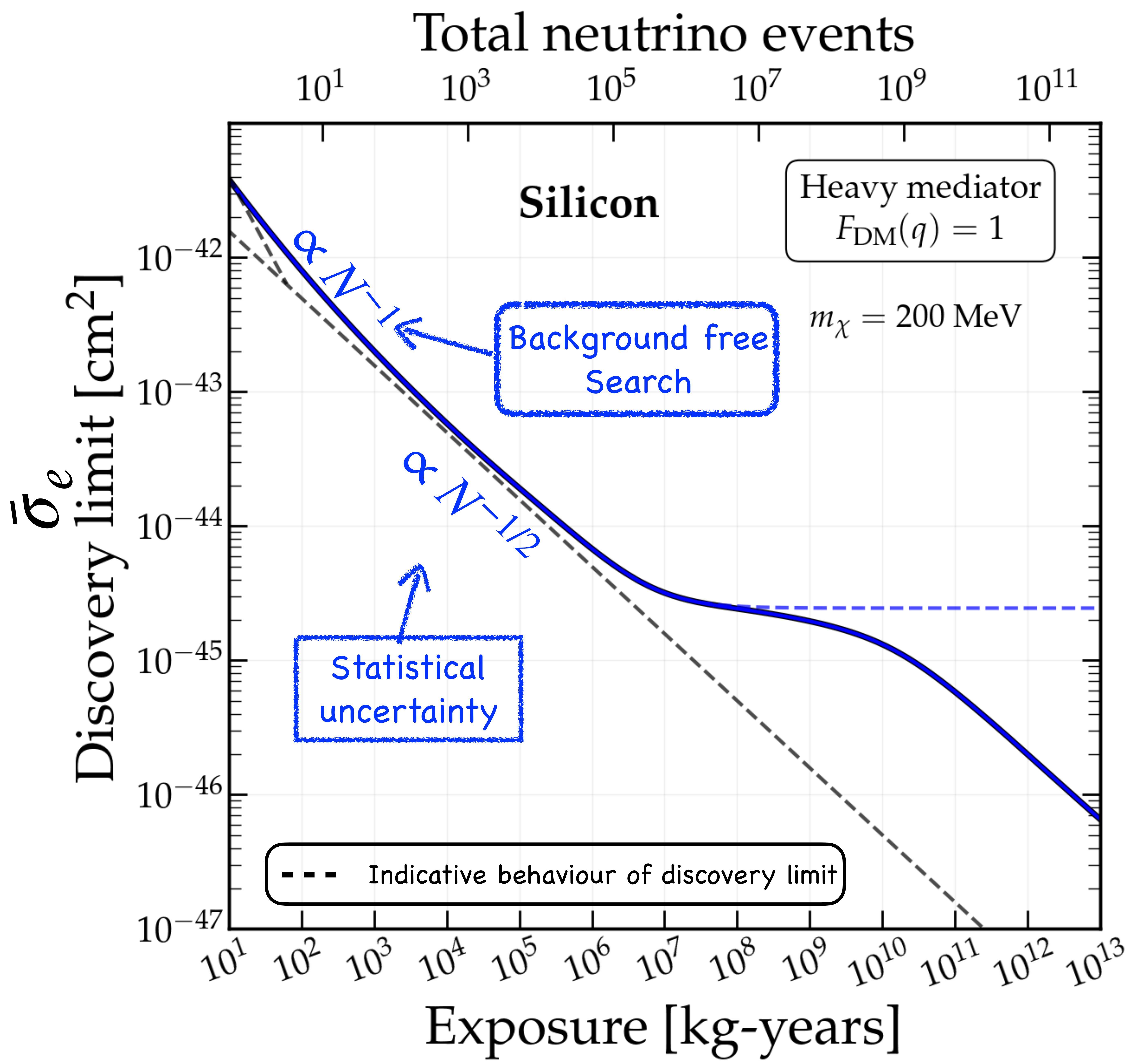

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Define: Gradient of the discovery limit

O'Hare 2109.03116

$$n = -\left(\frac{\mathrm{d}\ln\bar{\sigma}_e}{\mathrm{d}\ln N}\right)^{-1}$$

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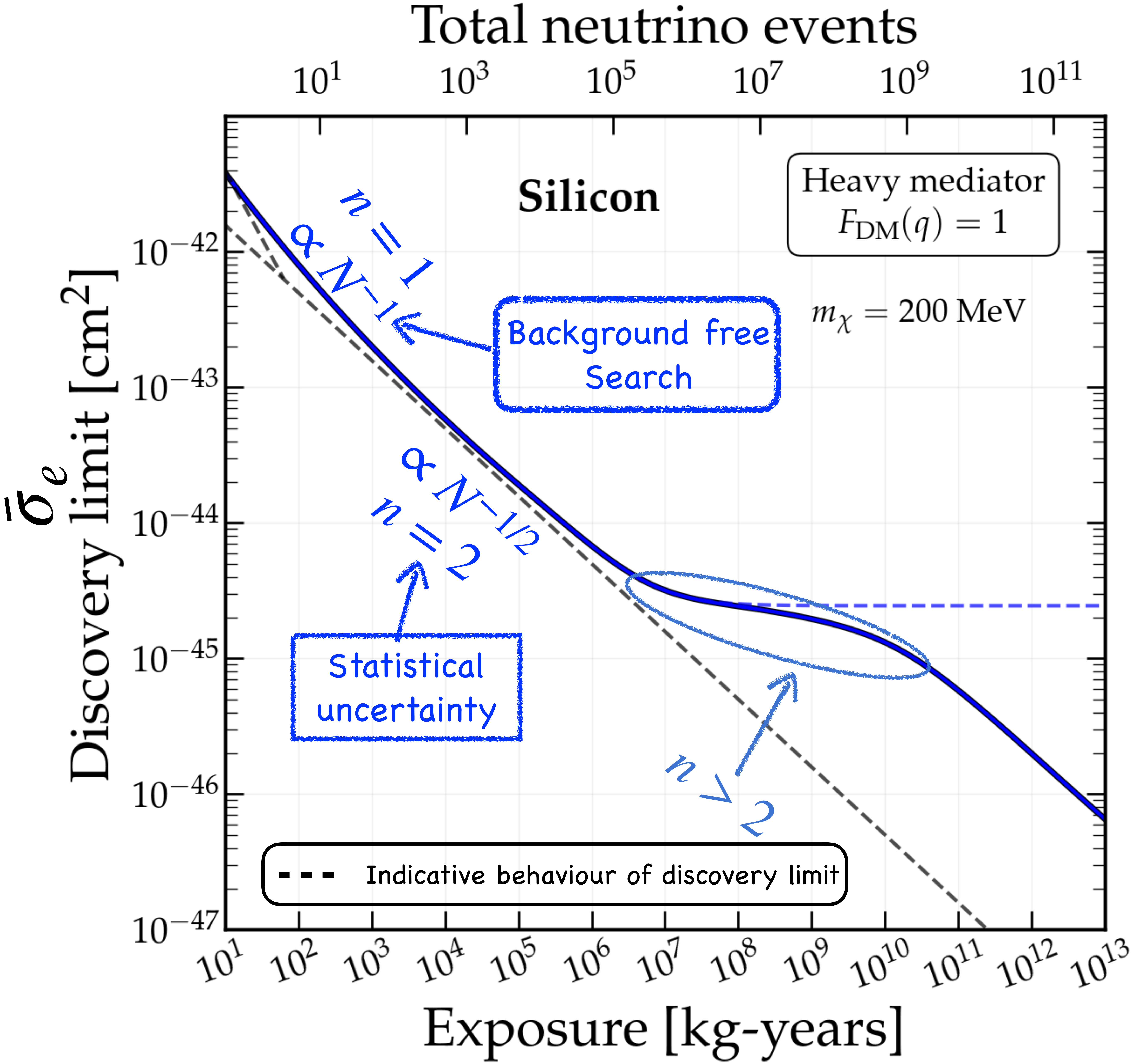

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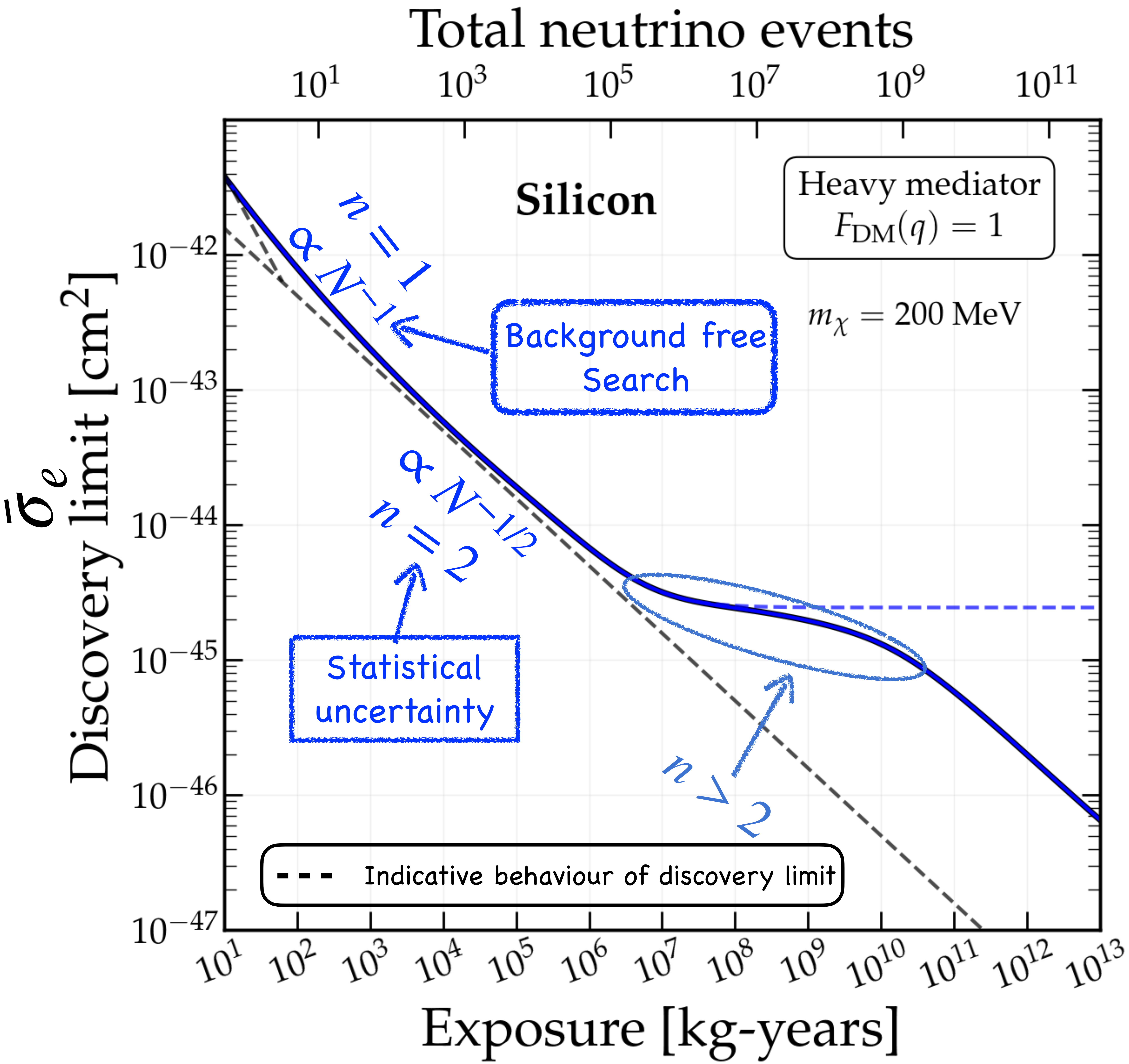

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✤ For each DM mass, the cross section at which n crosses 2 (i.e., departs from Poisson regime) can be the visual guide to neutrino "floor"

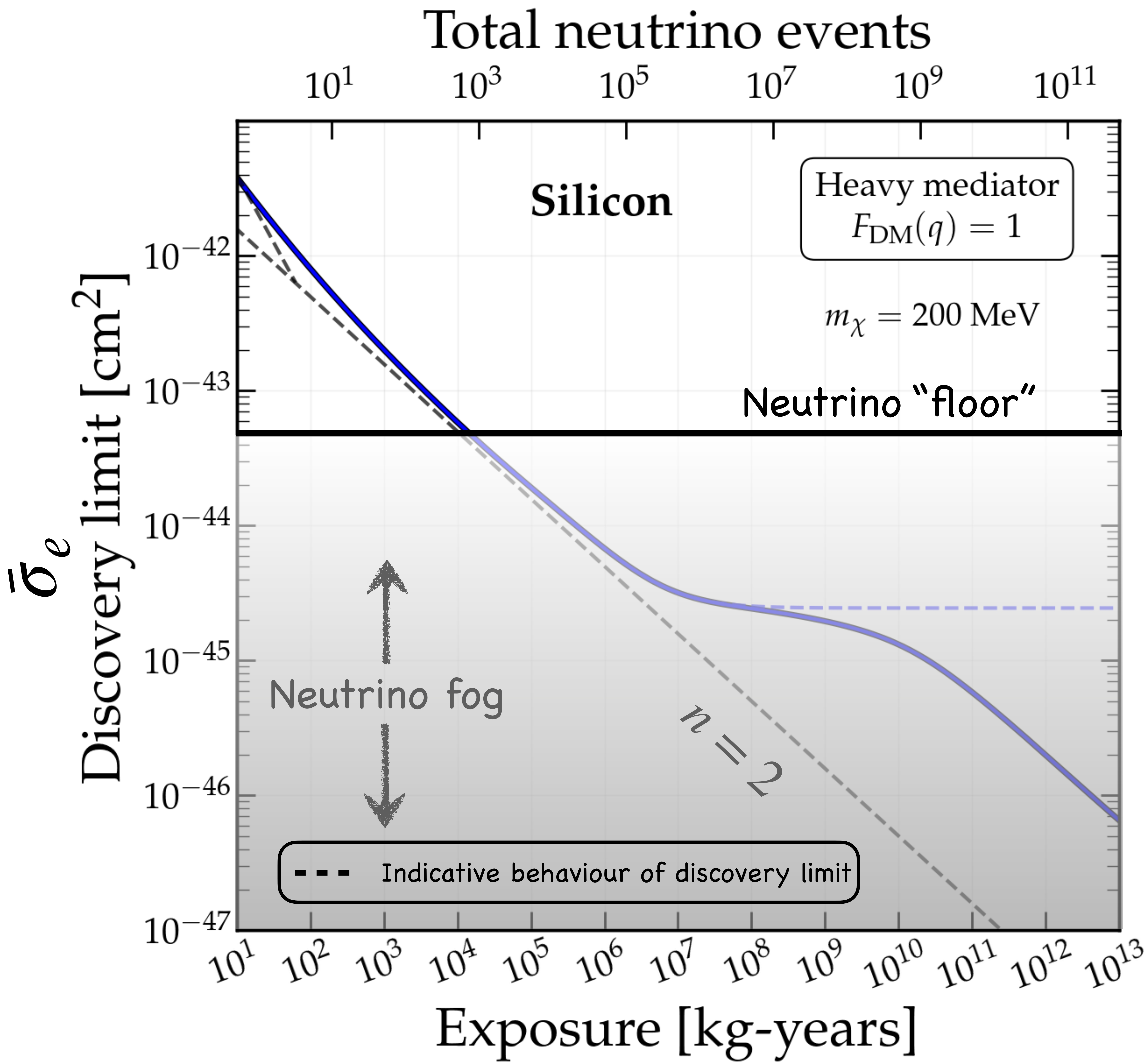
↓

✤ As below that cross section, the discovery limit never scales better than the Poisson

Carew, Caddell, TNM, O'Hare; 2312.04303

Tarak Nath Maity

Neutrino fog for DM-electron scattering



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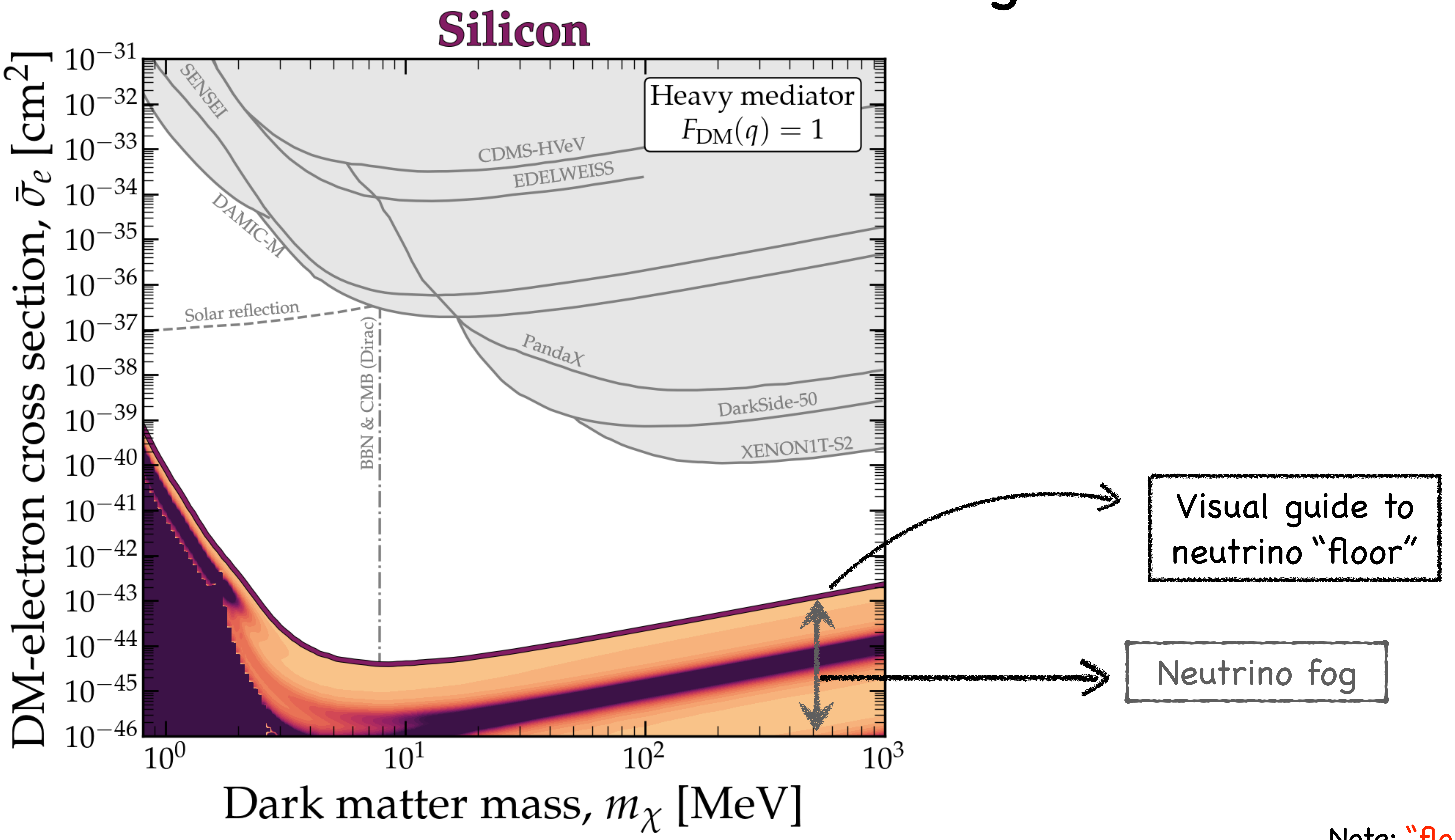

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Darker colour : more spectral degeneracy between DM and neutrinos

Carew, Caddell, TNM, O'Hare; 2312.04303

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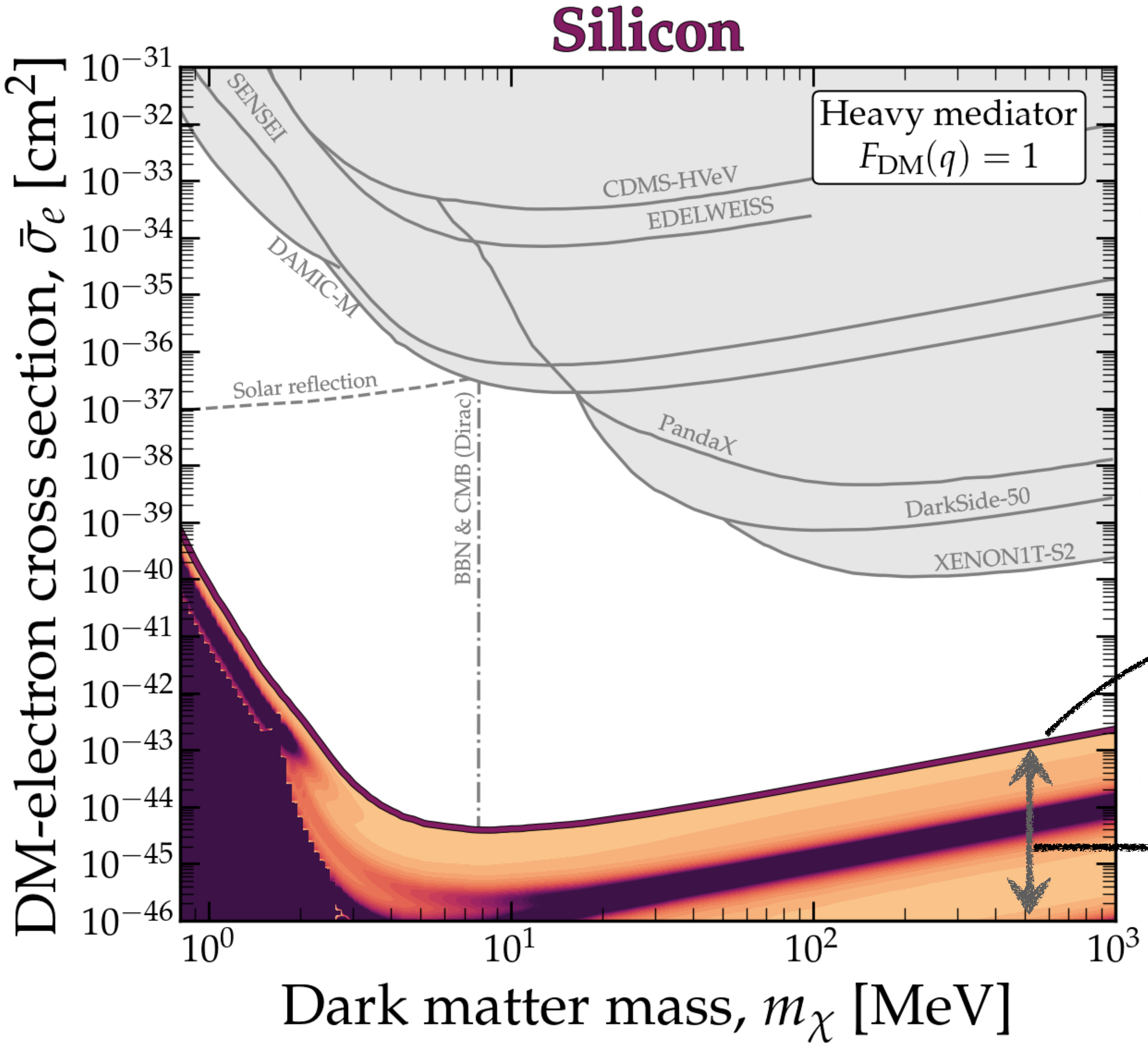

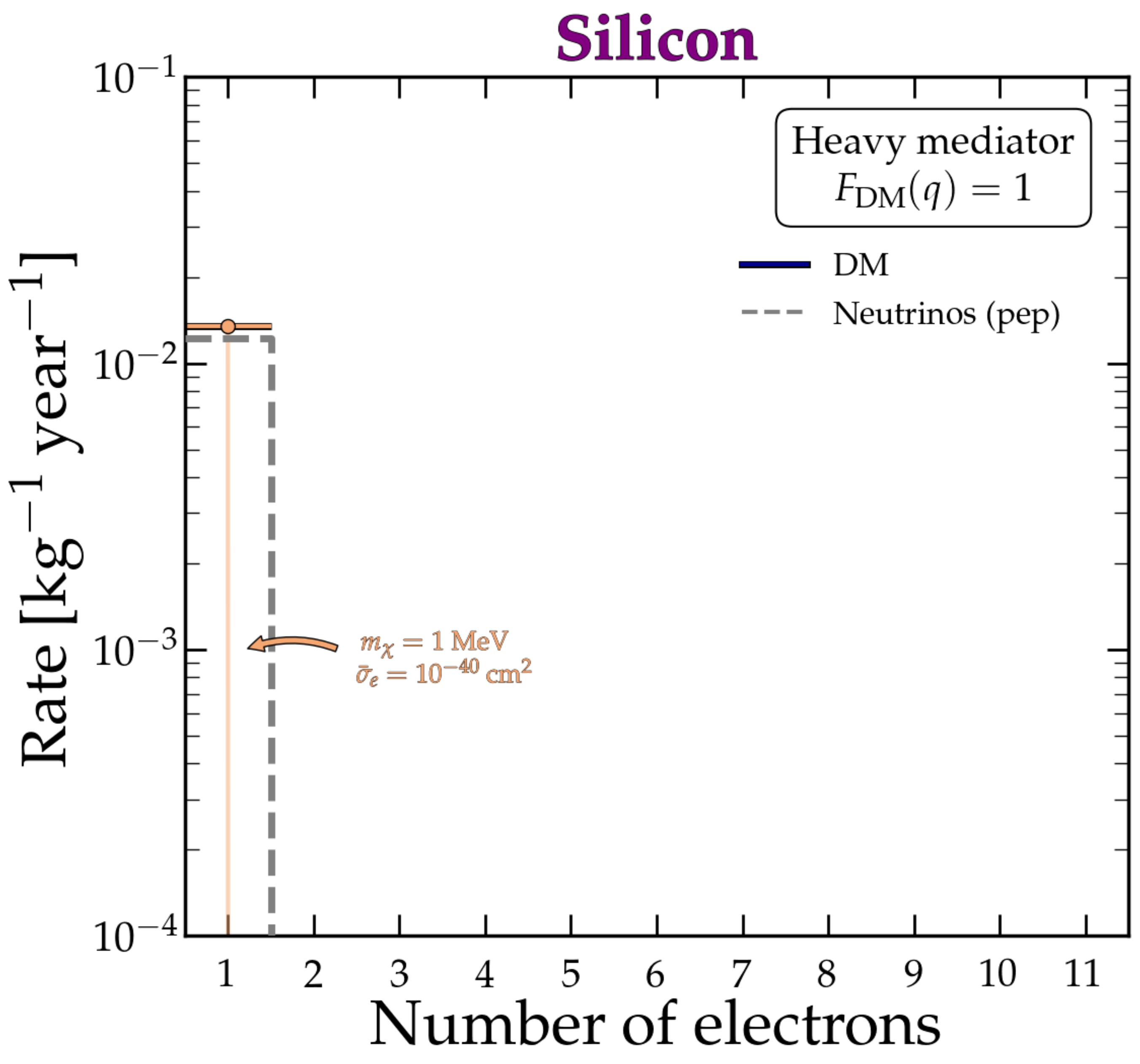

Visual guide to neutrino "floor"

Neutrino fog

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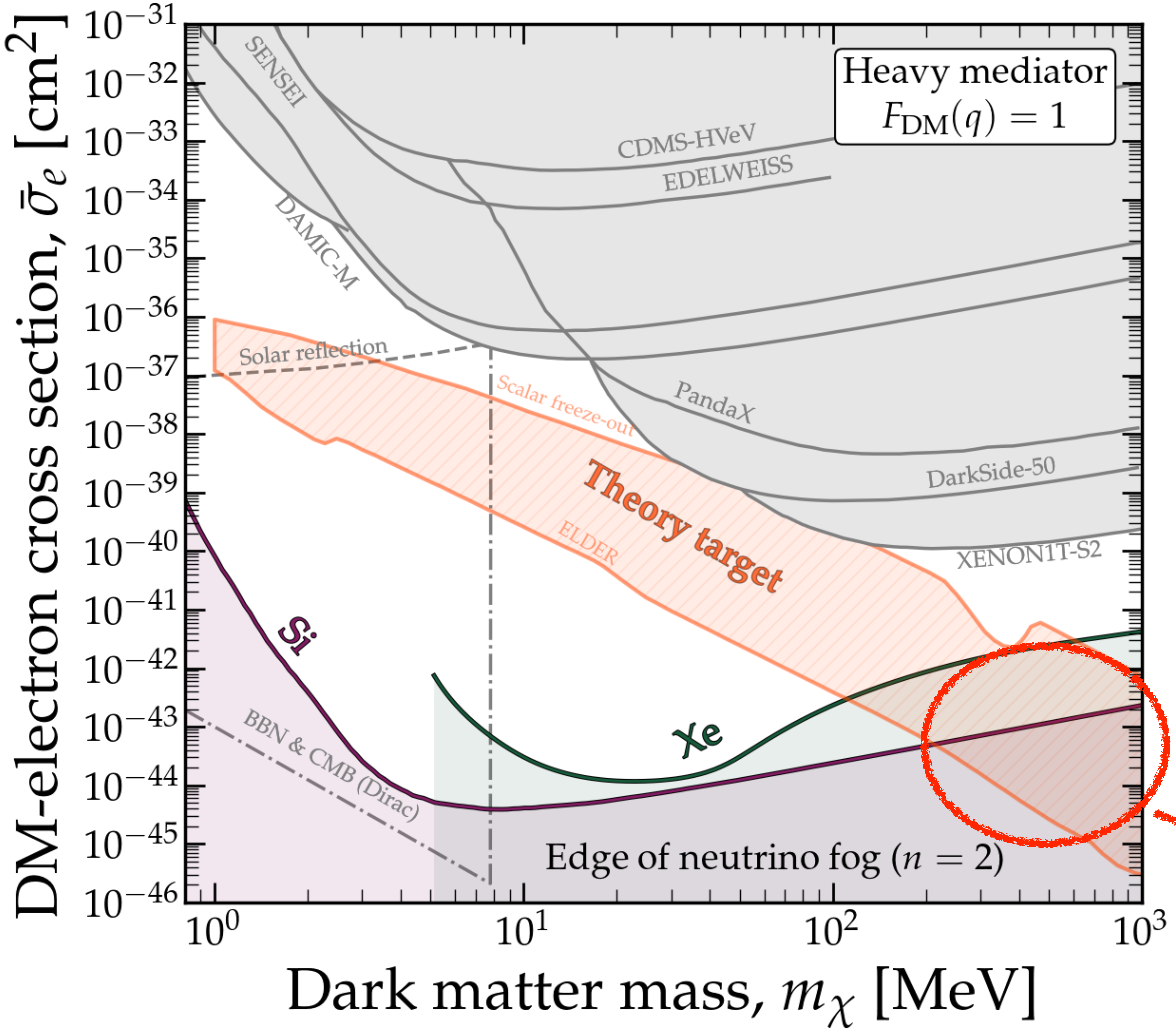

Theory target: regions where different DM freeze-out mechanism satisfy relic density

Kuflik+ 1512.04545
Snowmass 2203.08297
Essig+ 1509.01598

❖ For DM masses < 100 MeV neutrino floor is orders magnitude away from current bound

For probing this region neutrino would be an important background to tackle

Note: "floor" may not be hard

Carew, Caddell, TNM, O'Hare; 2312.04303

What can we infer from these neutrinos?

Test Standard Model in sub-MeV energy regime with current neutrino events

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Weak mixing angle

$$A^\mu = B_0^\mu \cos\theta_W + W_0^\mu \cos\theta_W$$

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$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2}$$

g : $SU(2)_L$ gauge coupling

g' : $U(1)_Y$ gauge coupling

Quantum correction

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Running of weak mixing angle

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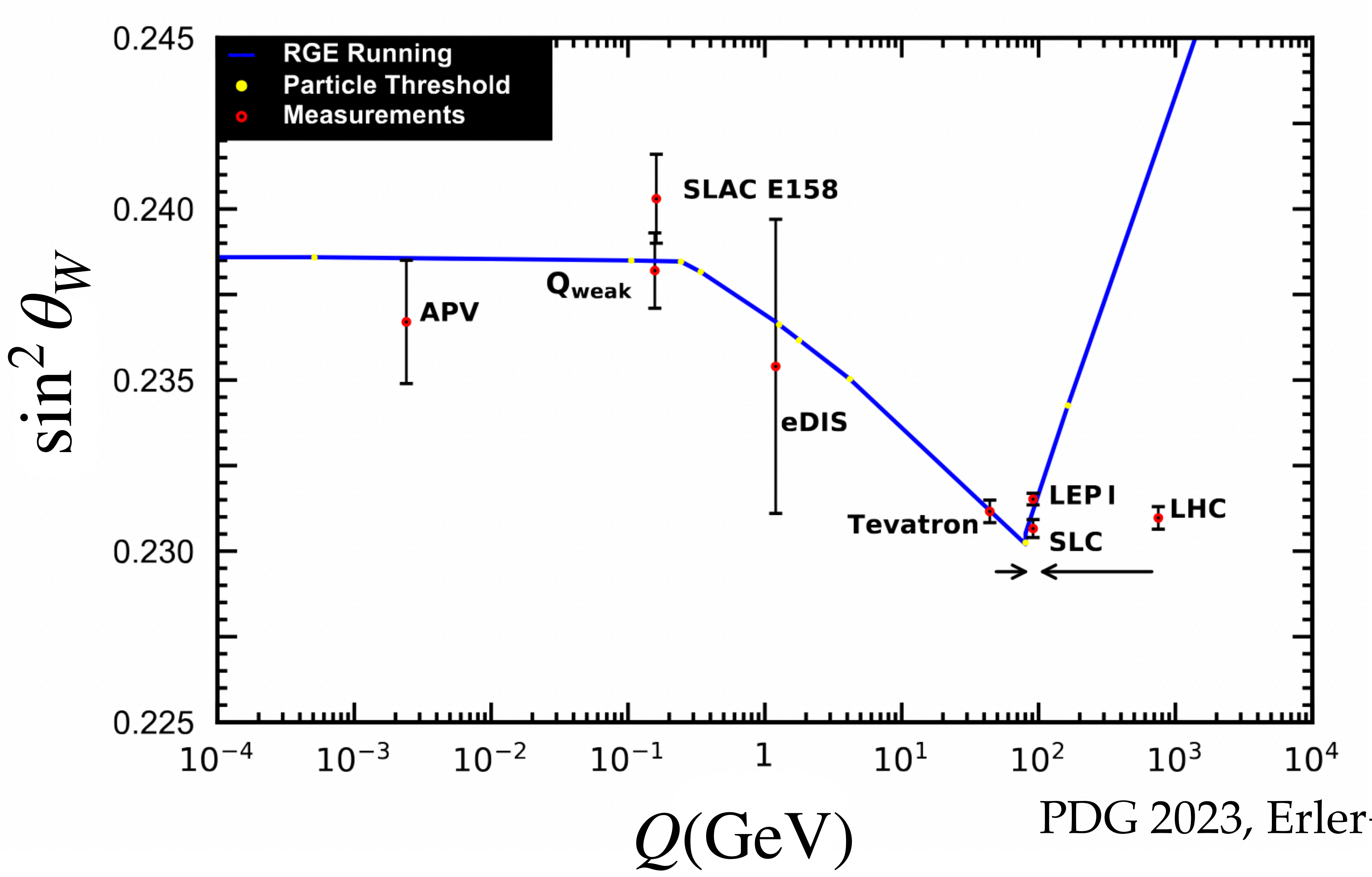

PDG 2023, Erler+ 1712.09146

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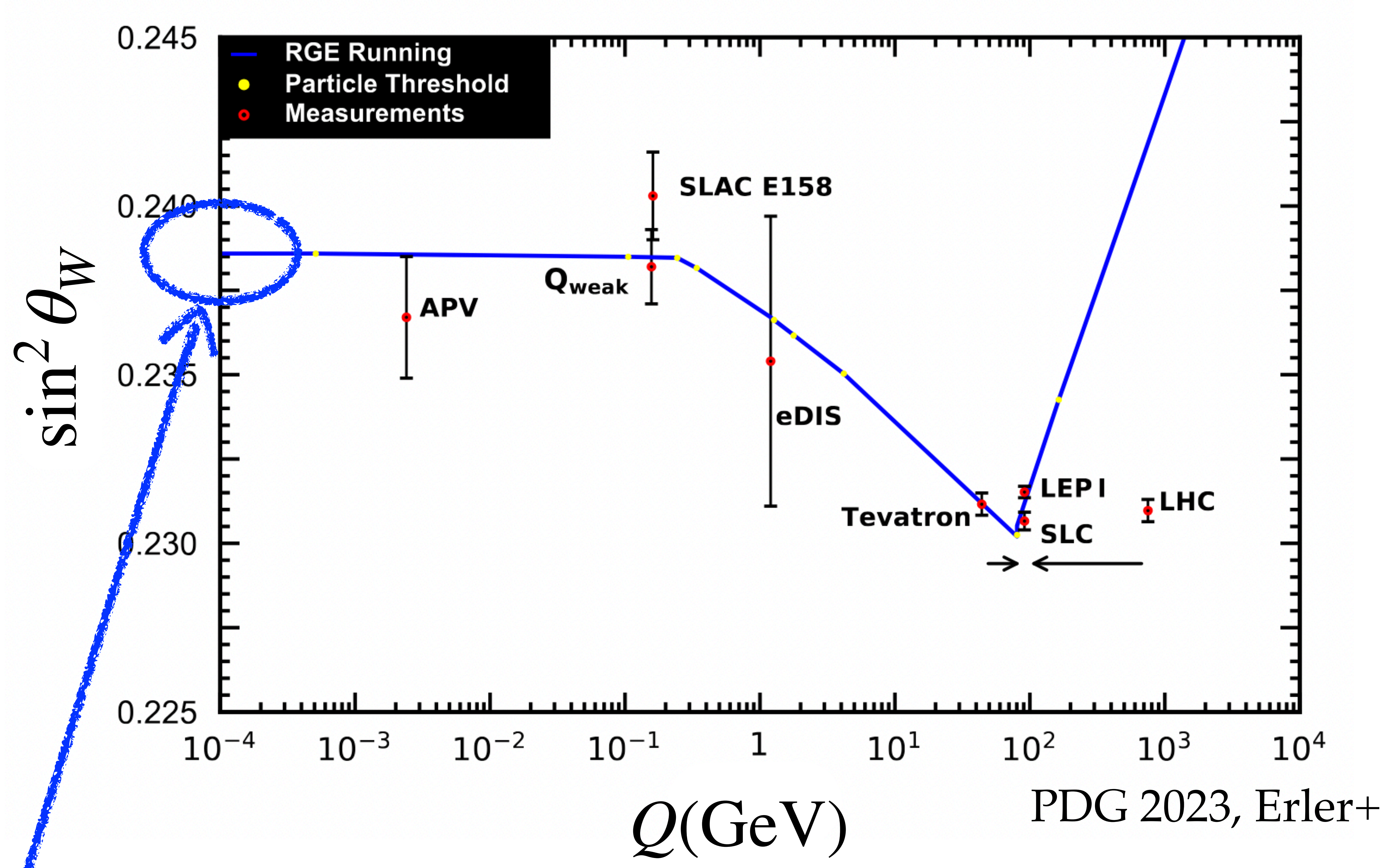

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direct detection experiments can measure here

TNM, Boehm; 2409.04385

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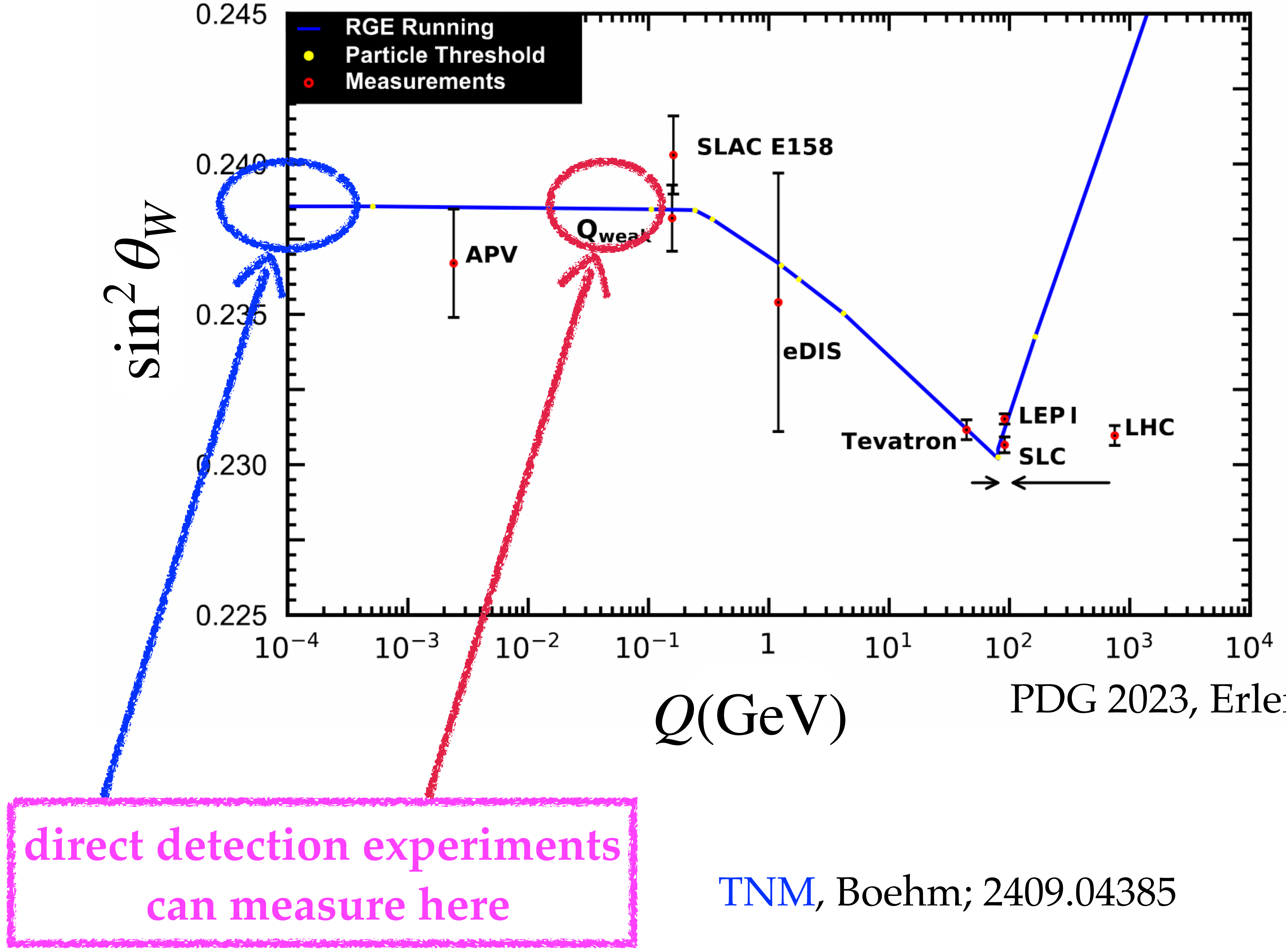

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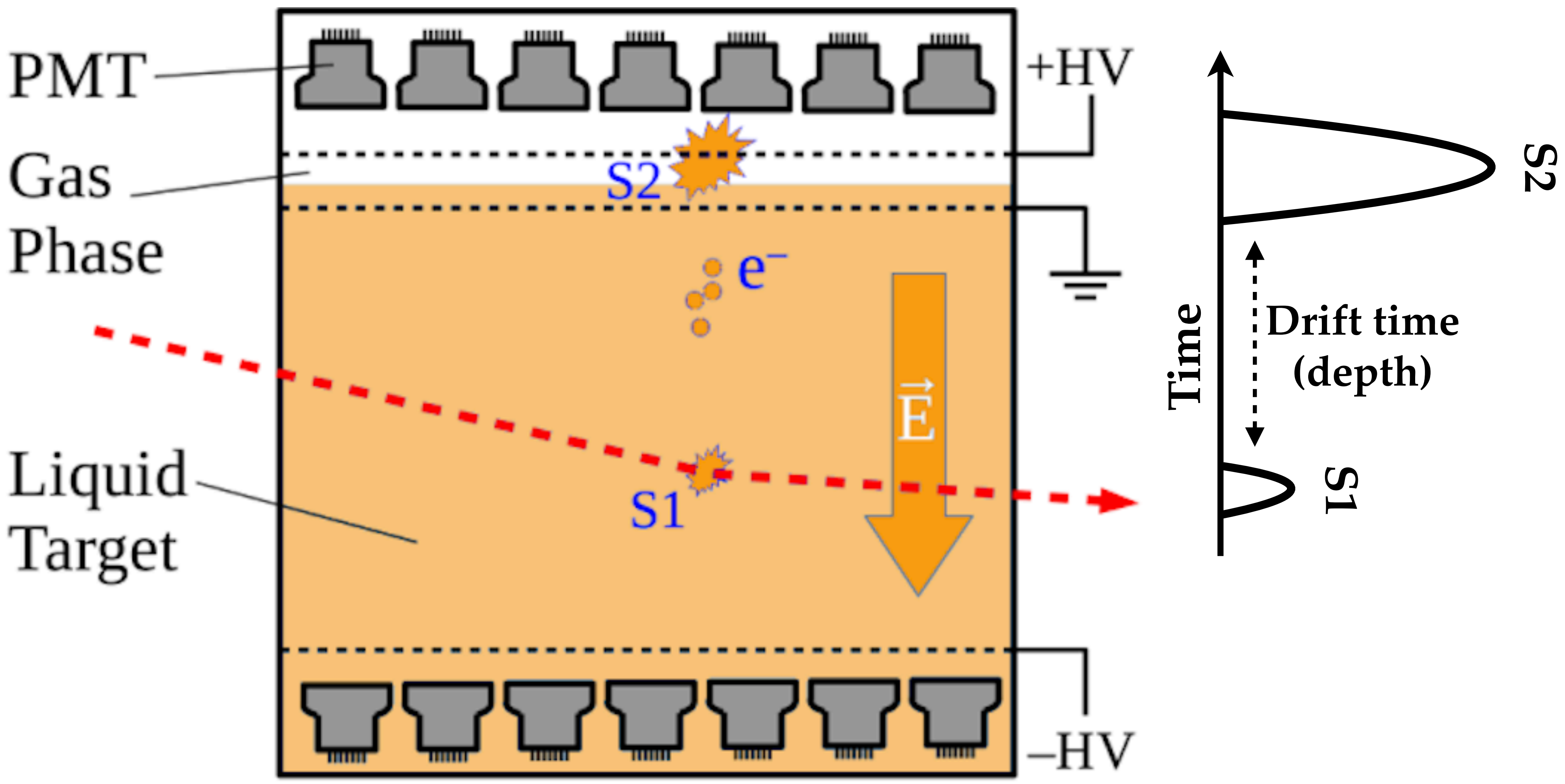
Observing neutrinos in DD(Xe)

XENONnT, PandaX-4T, LZ …



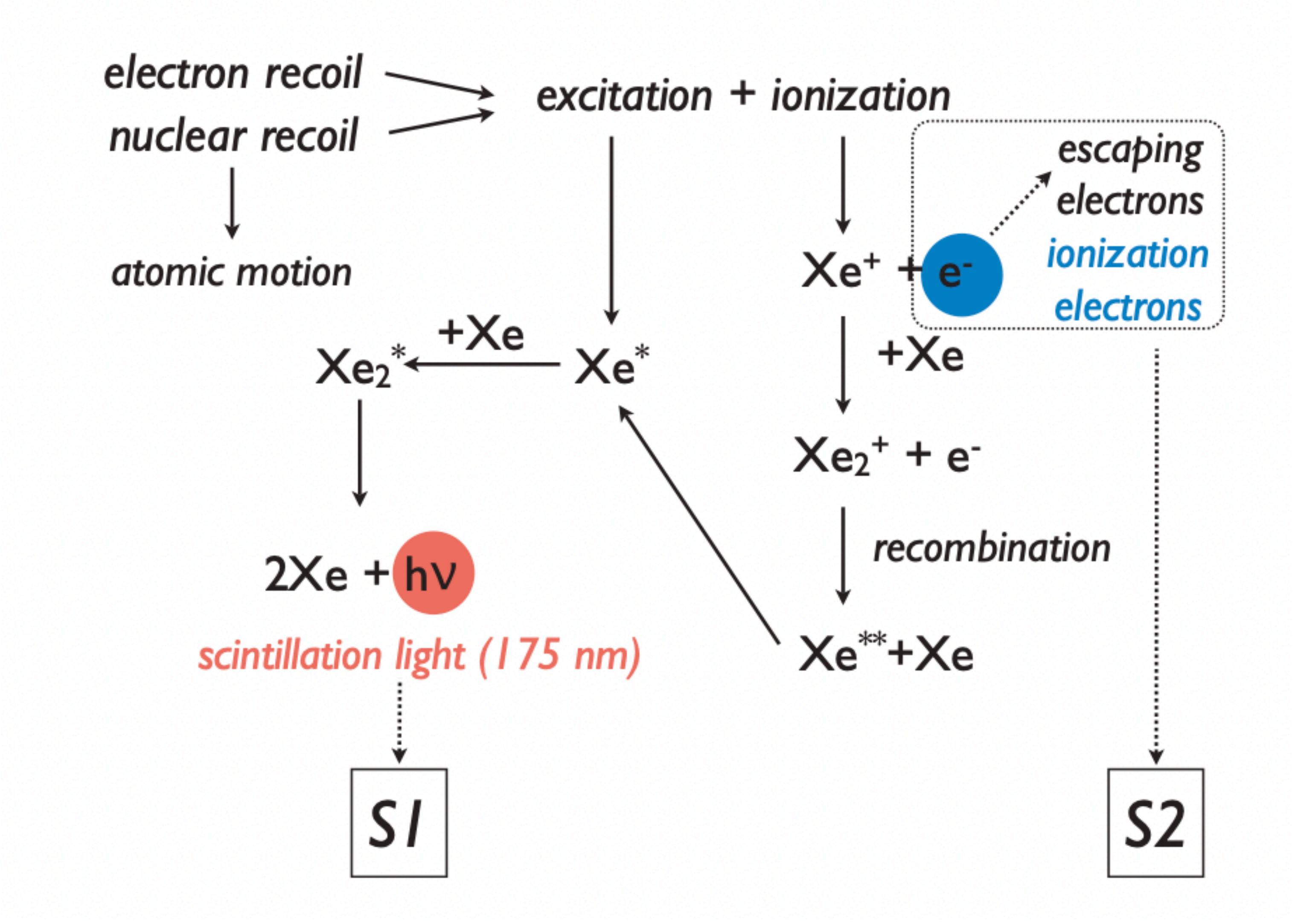


Image credit: 2110.02359, 1903.03026, 0909.1063

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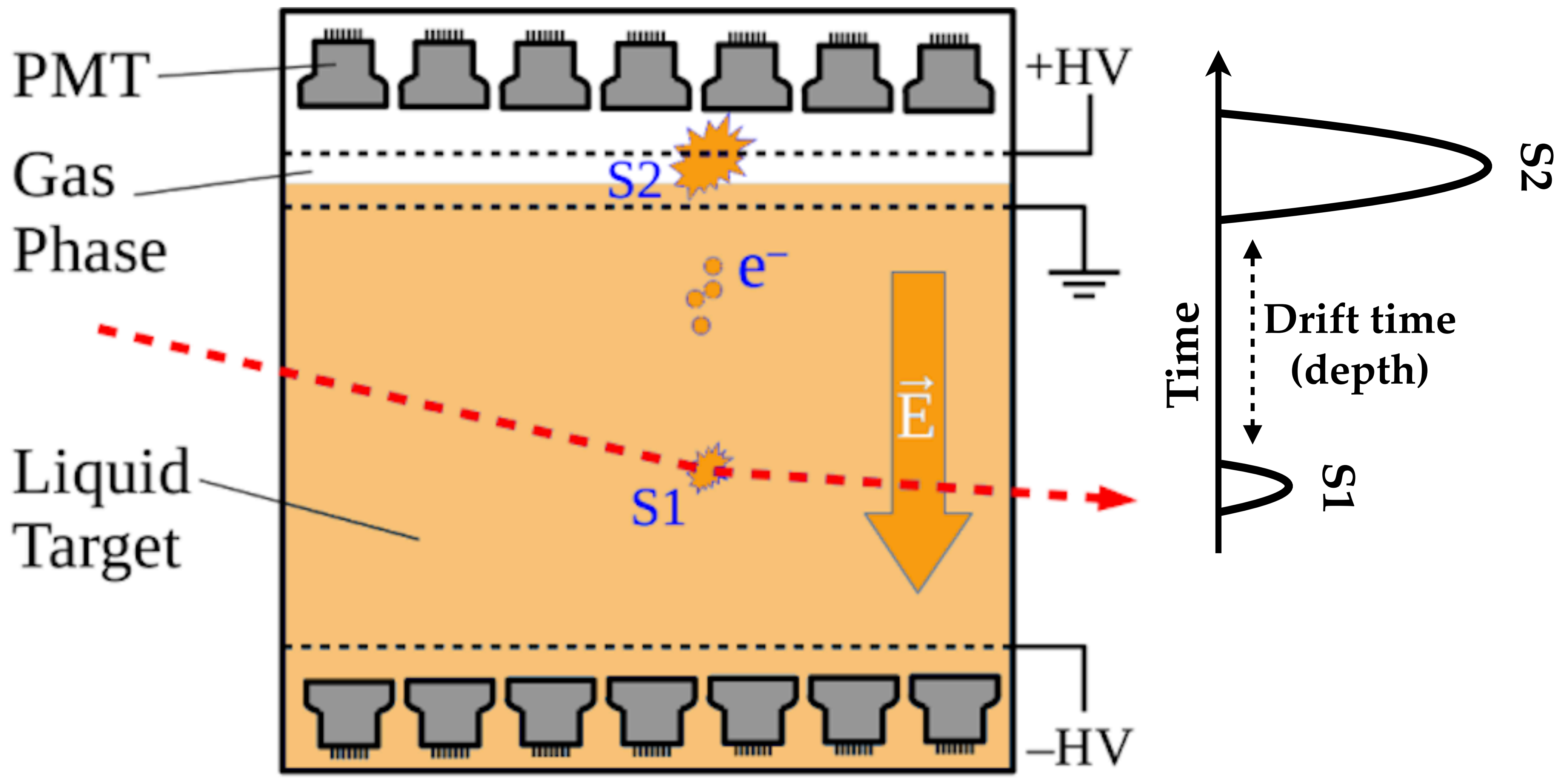
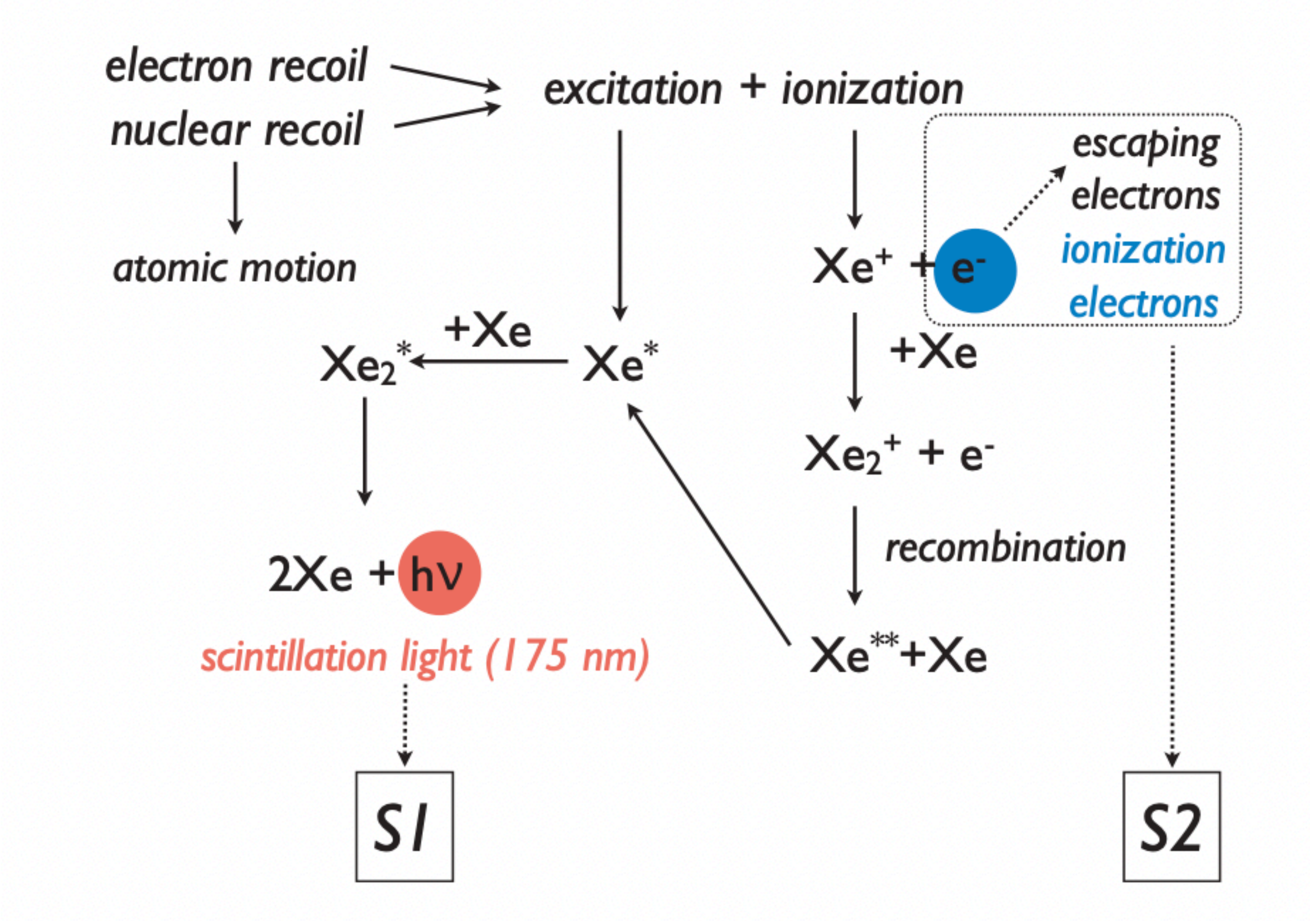
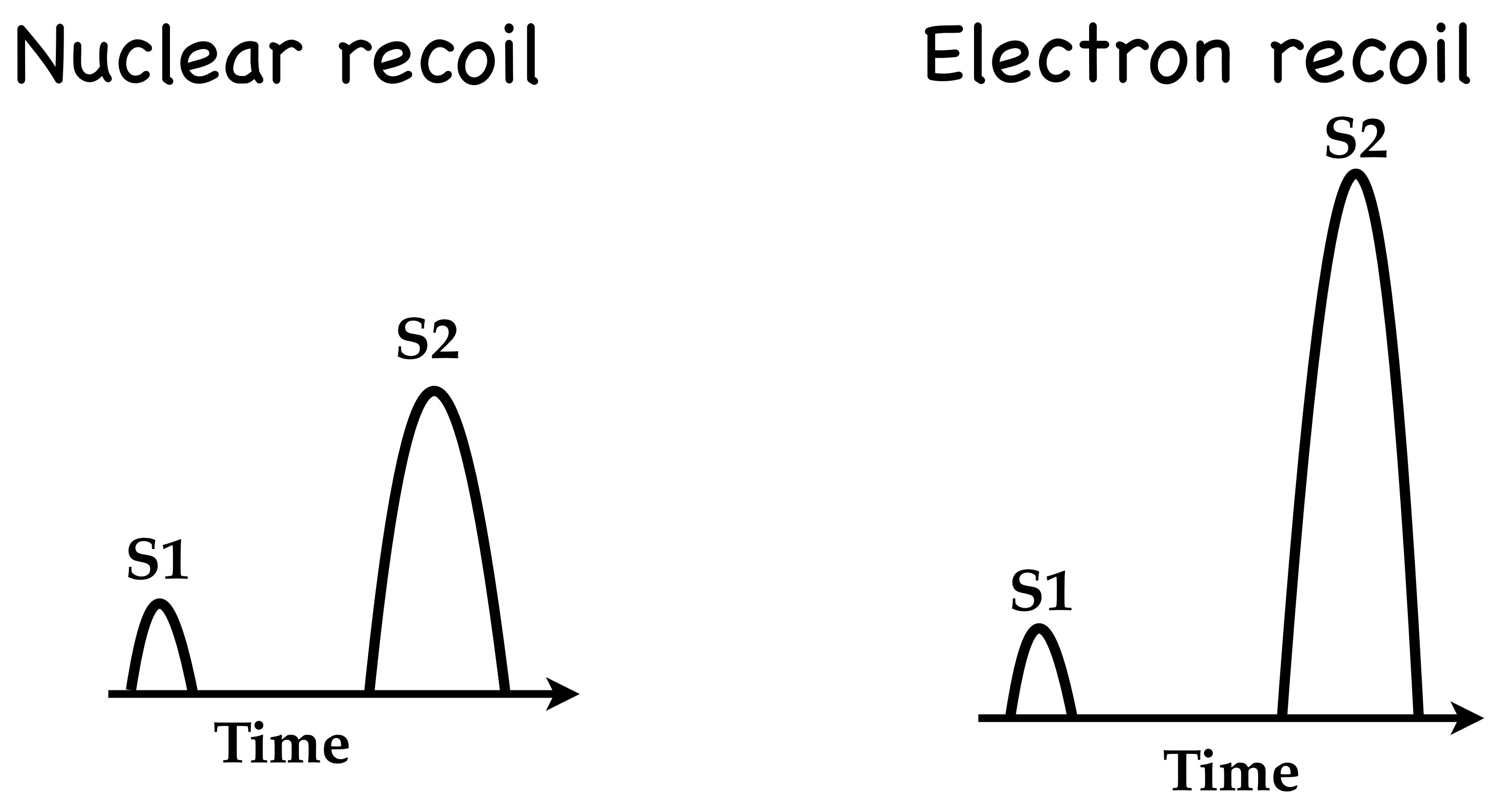




S1-S2 analysis



S2/S1 << S2/S1

S2/S1 ratio - can distinguish - nuclear and electron recoil

$$E_{\rm recoil} \gtrsim 0.5\,{\rm keV}$$

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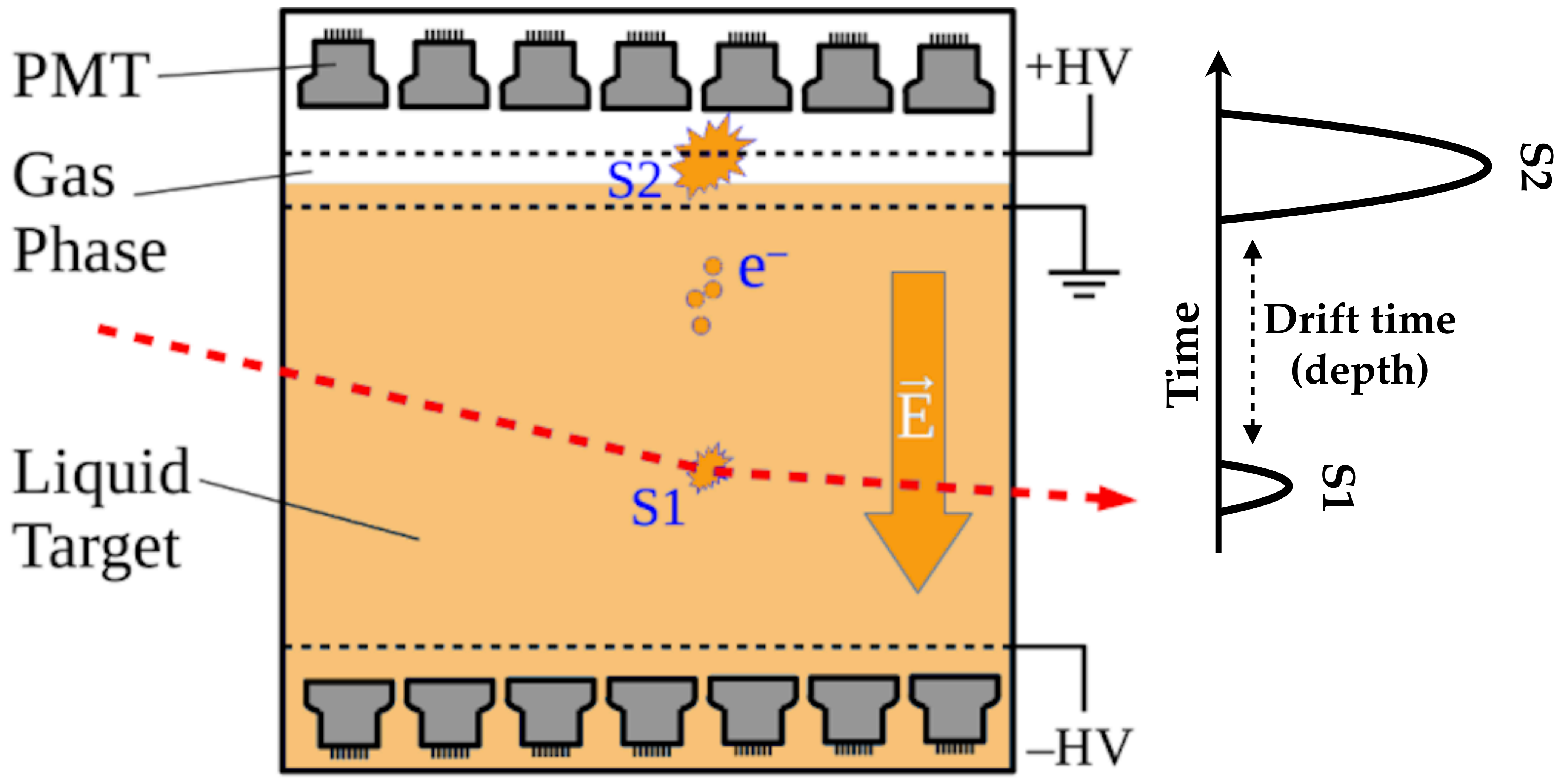

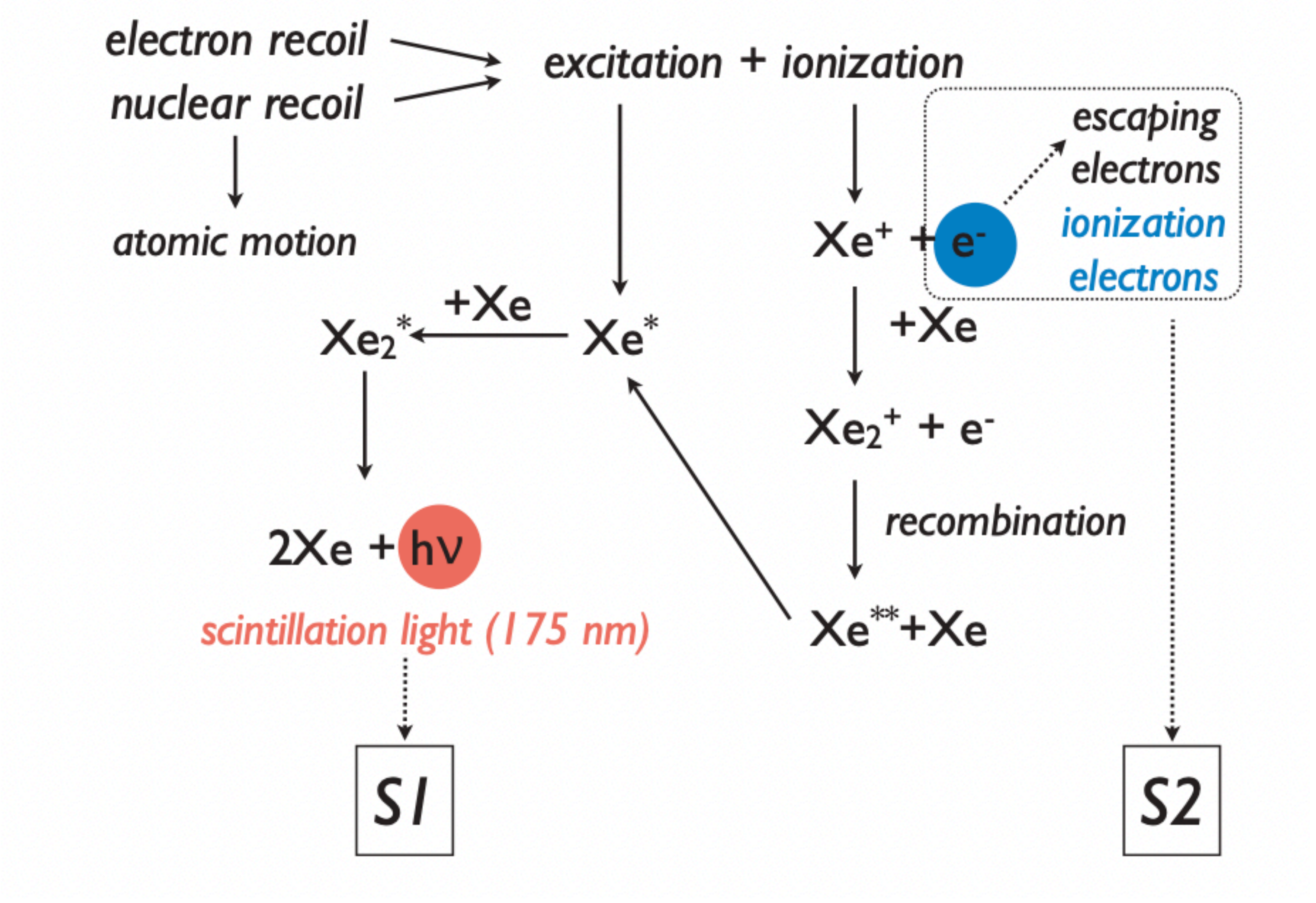

S2 only analysis

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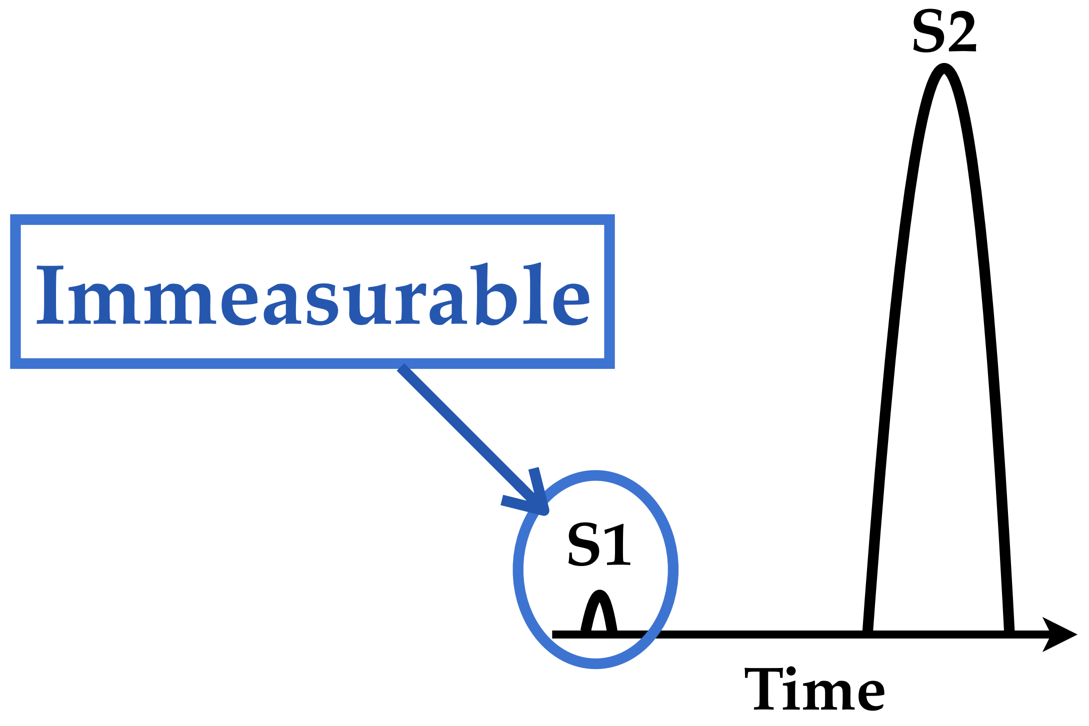
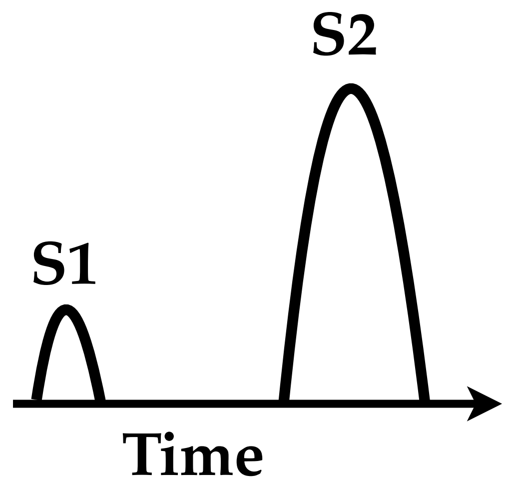
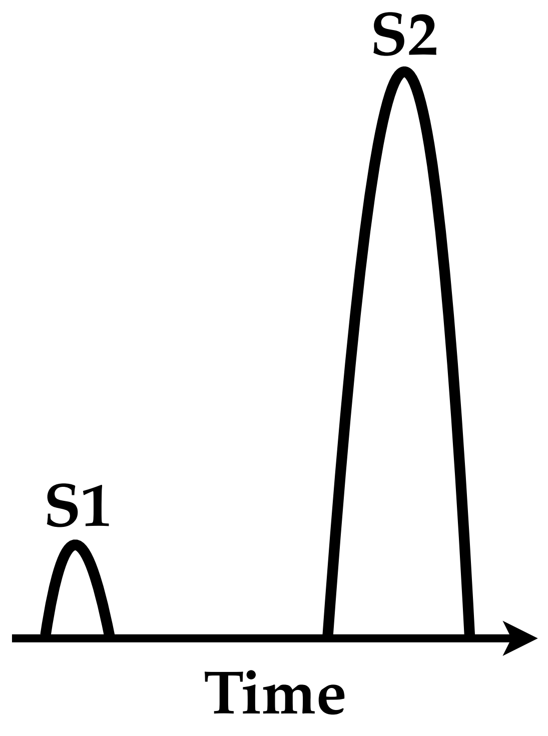


Nuclear recoil



Electron recoil



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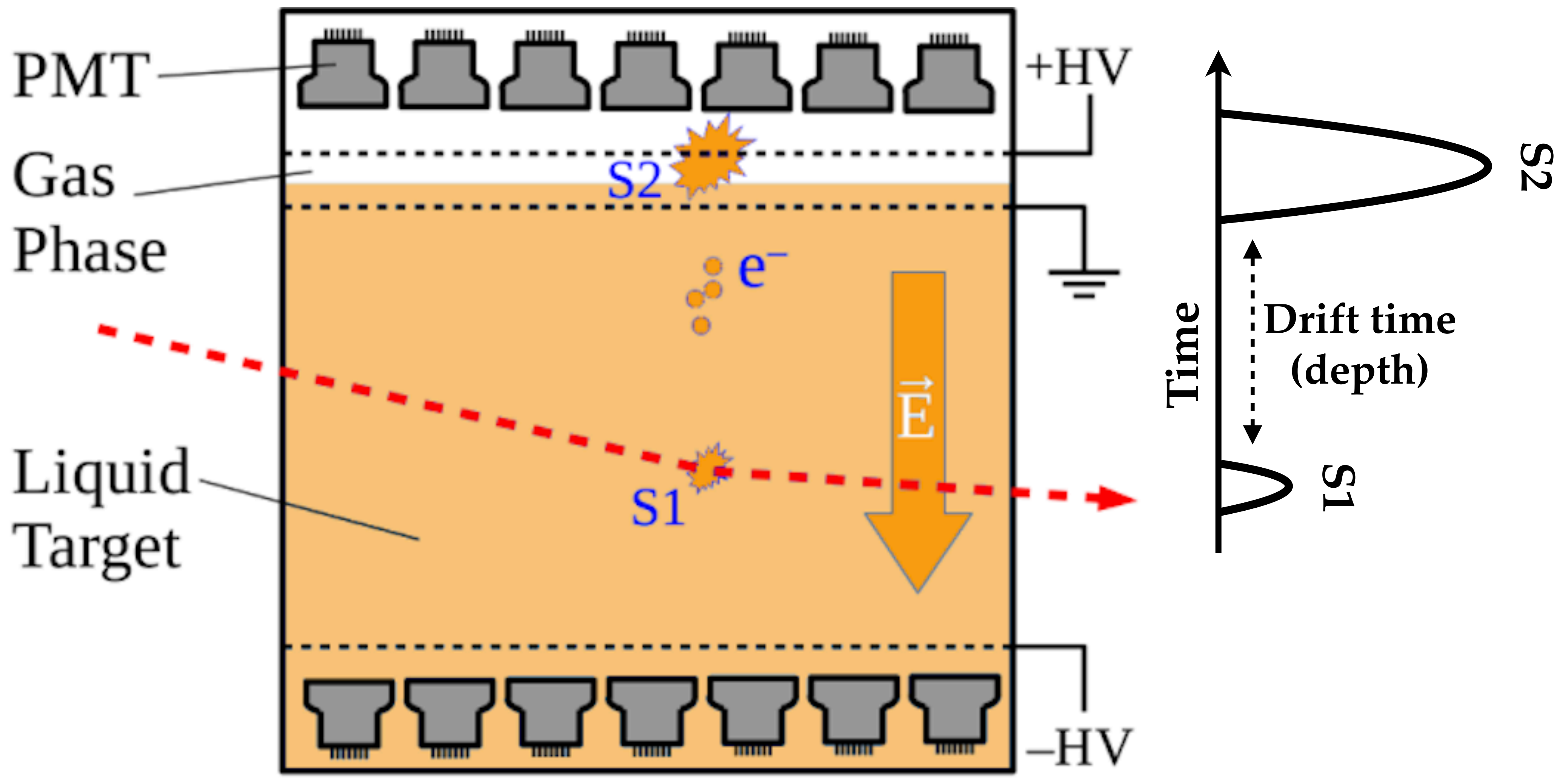

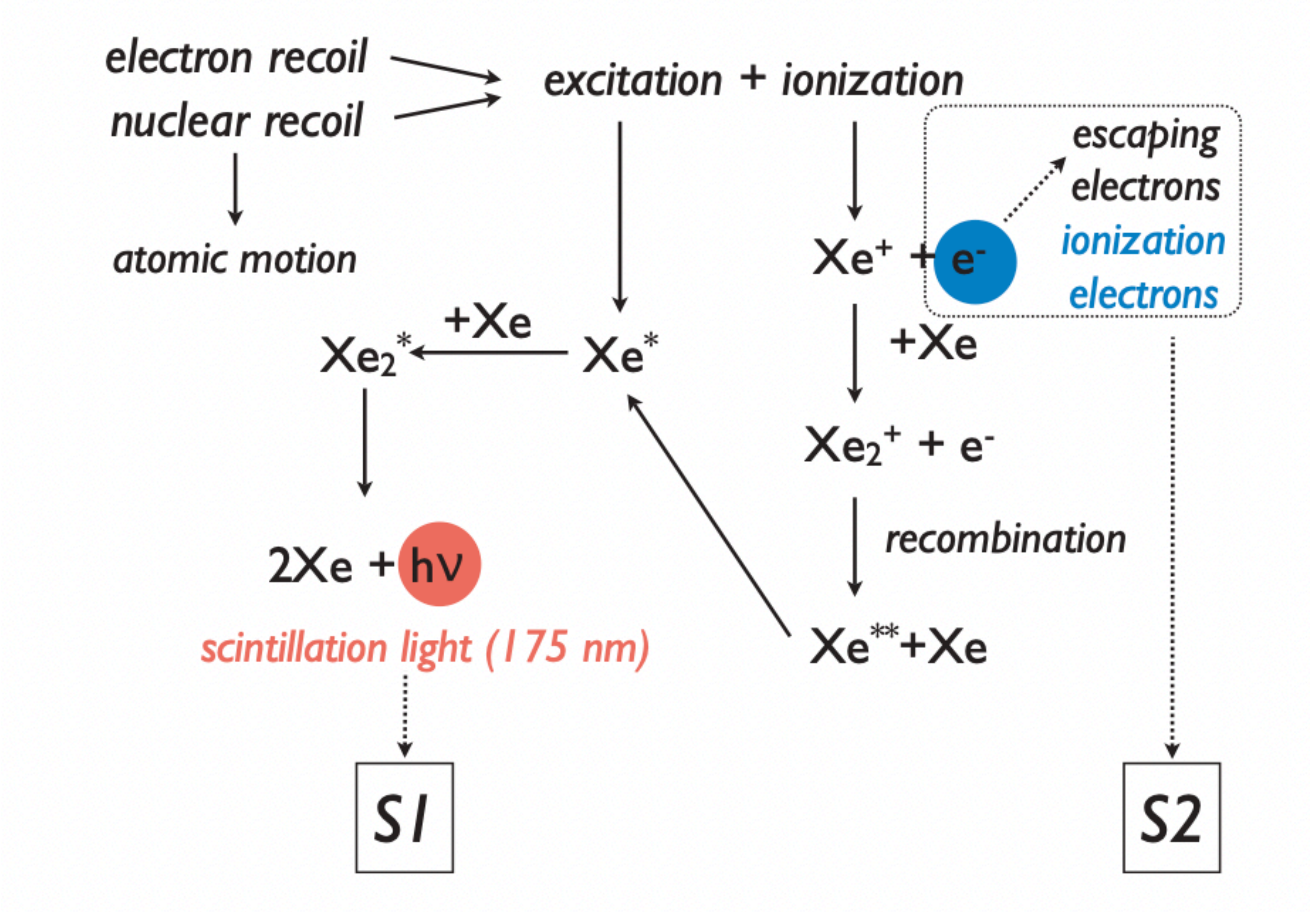

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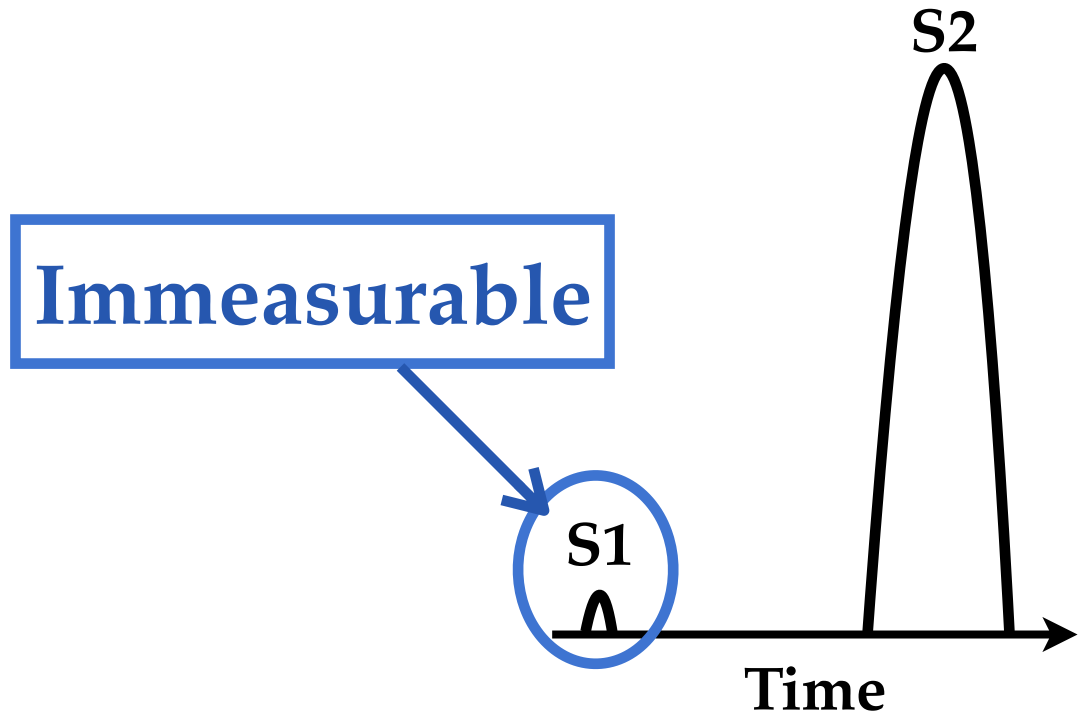

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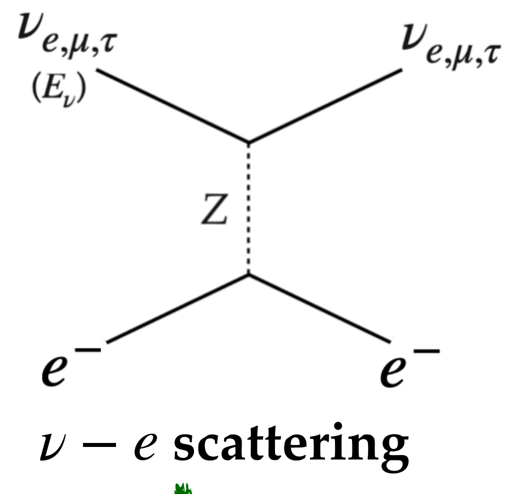

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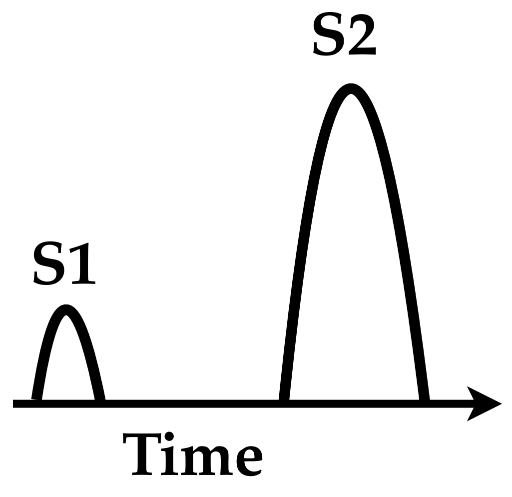

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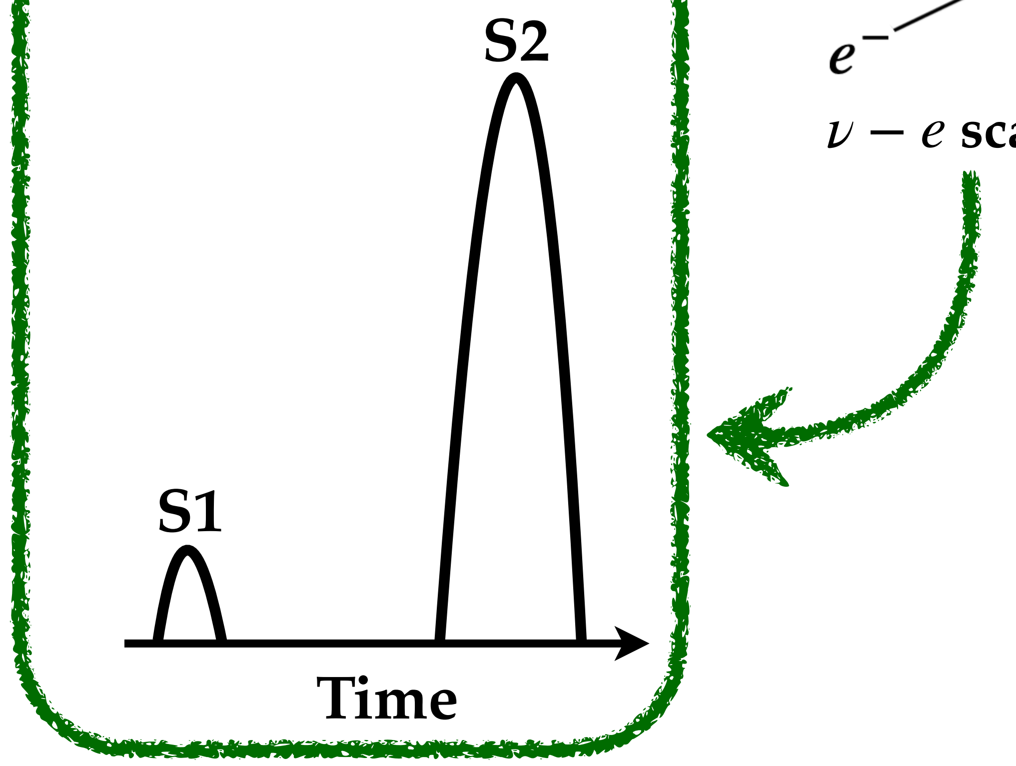

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Image credit: 2110.02359, 1903.03026, 0909.1063

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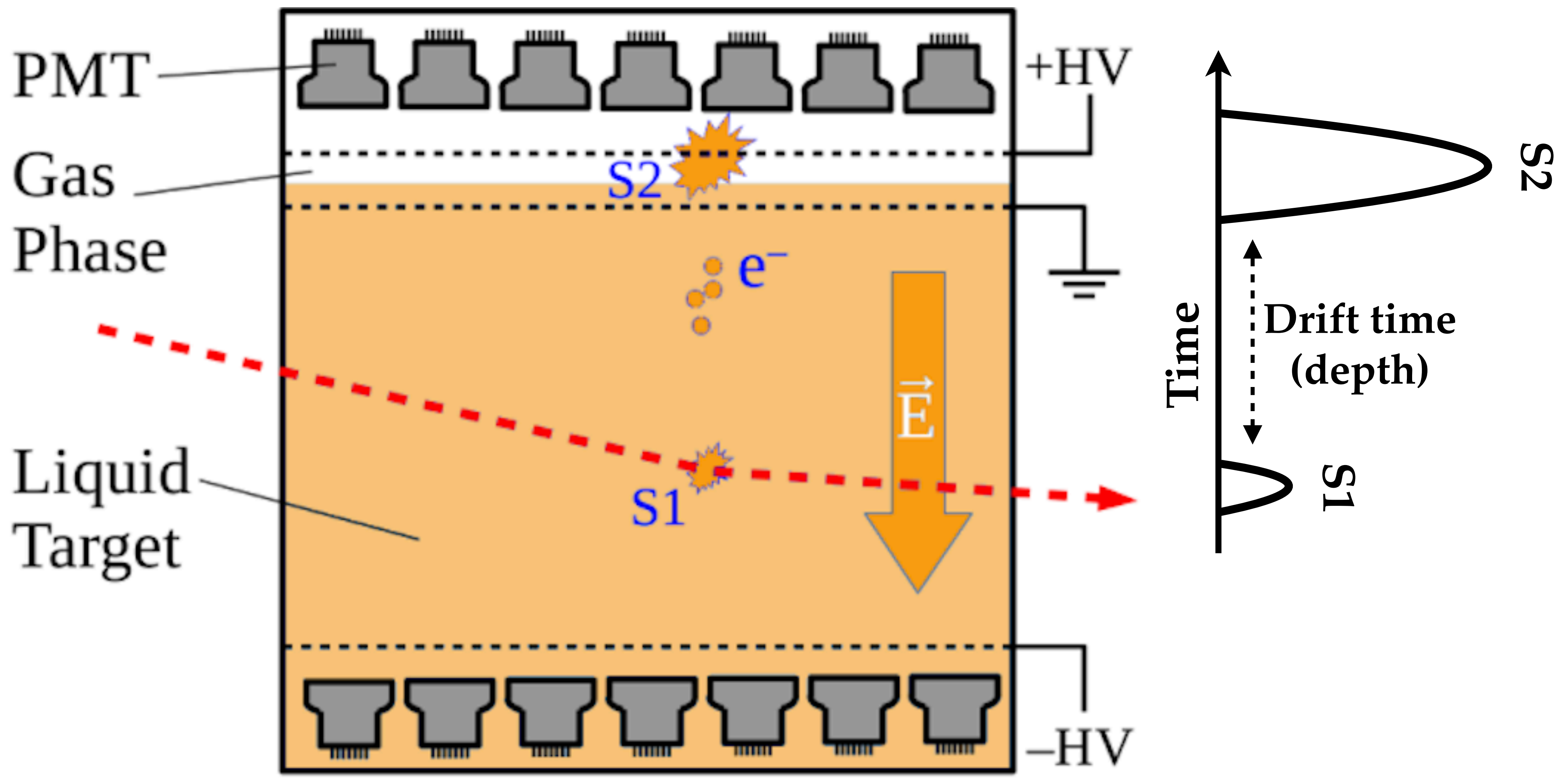

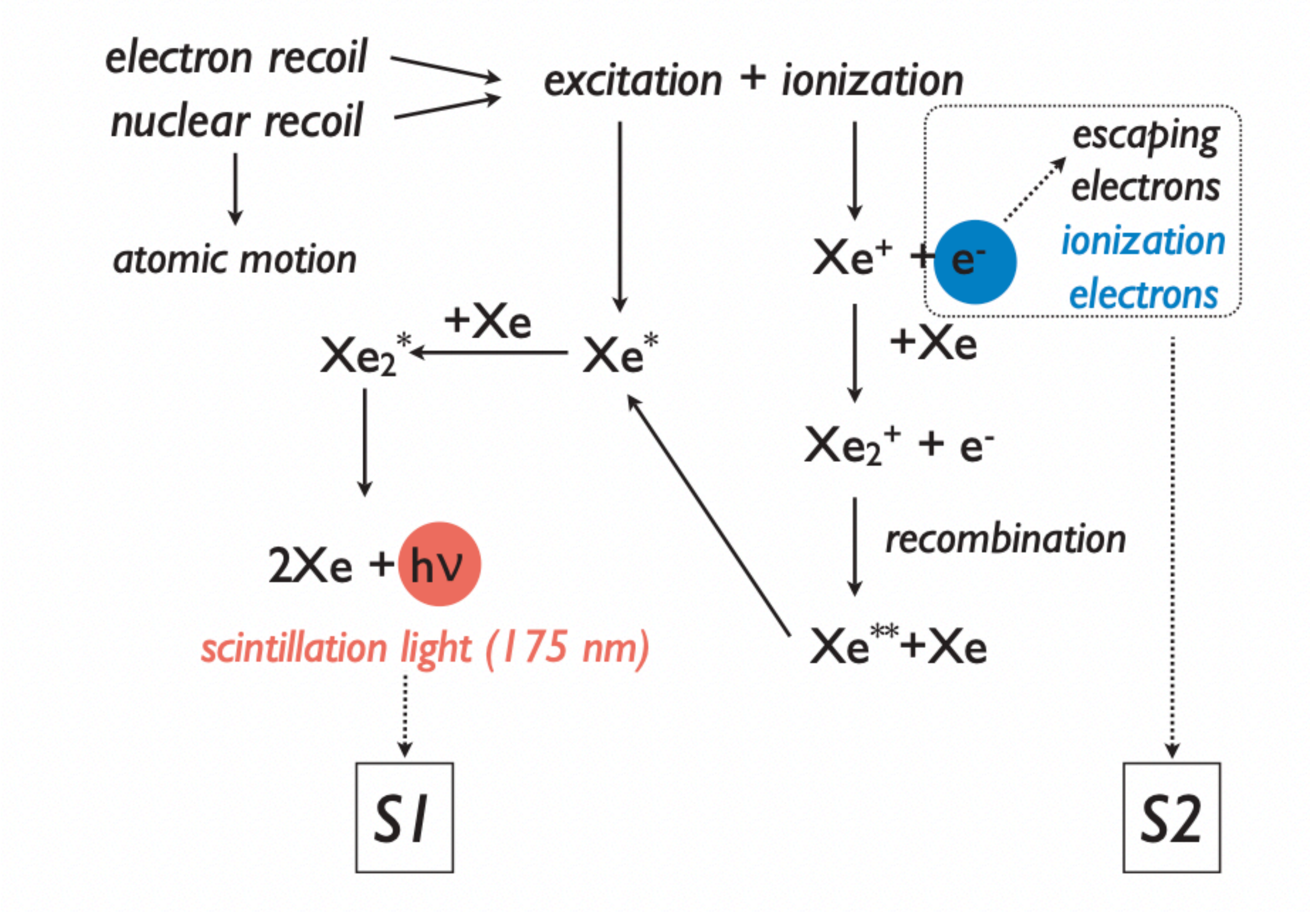

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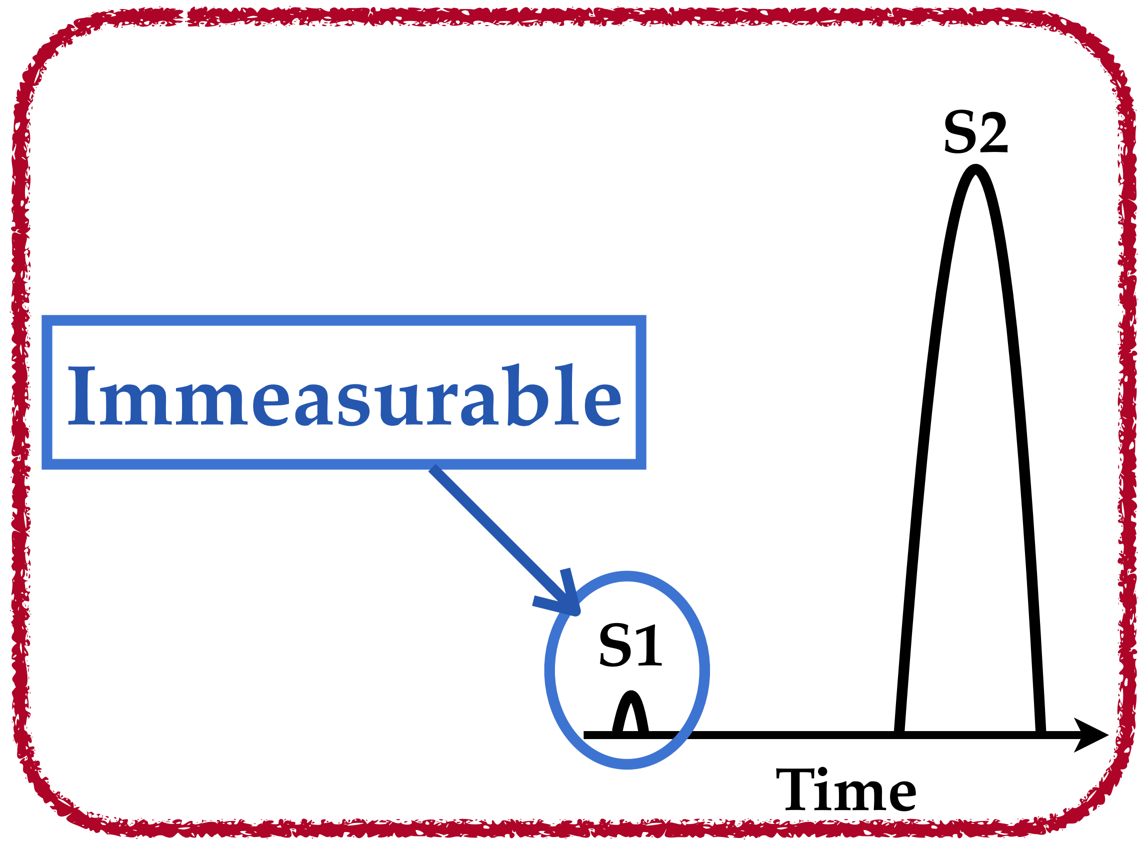

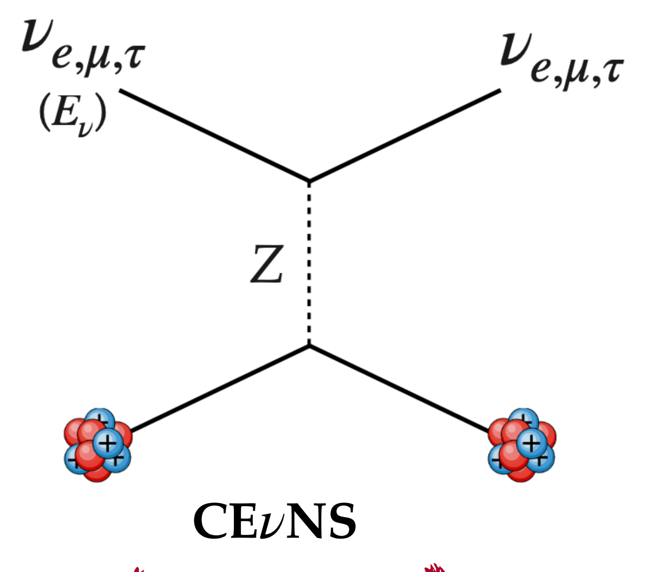

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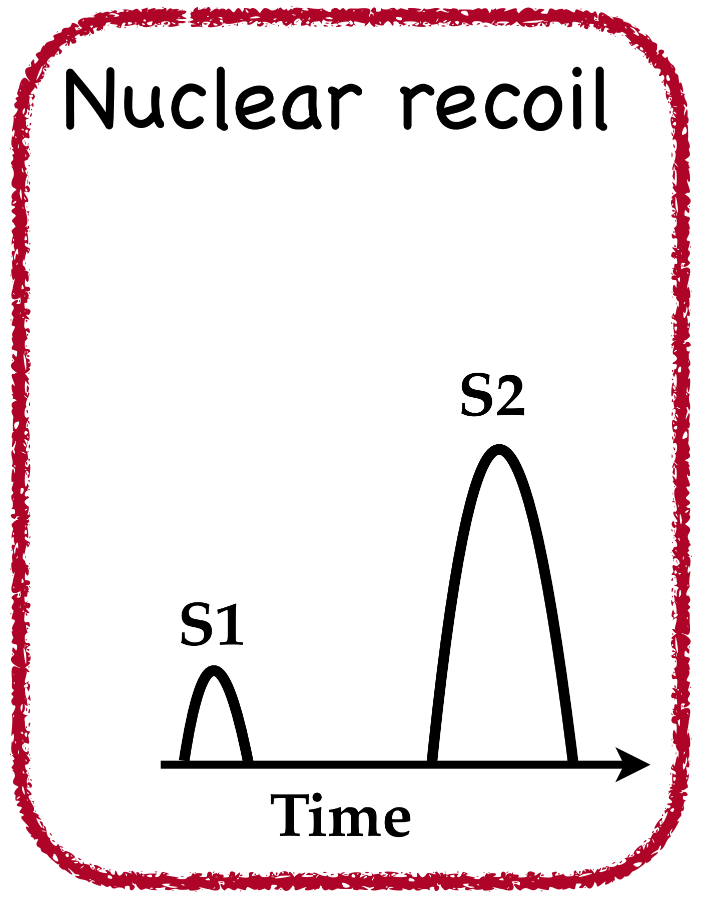

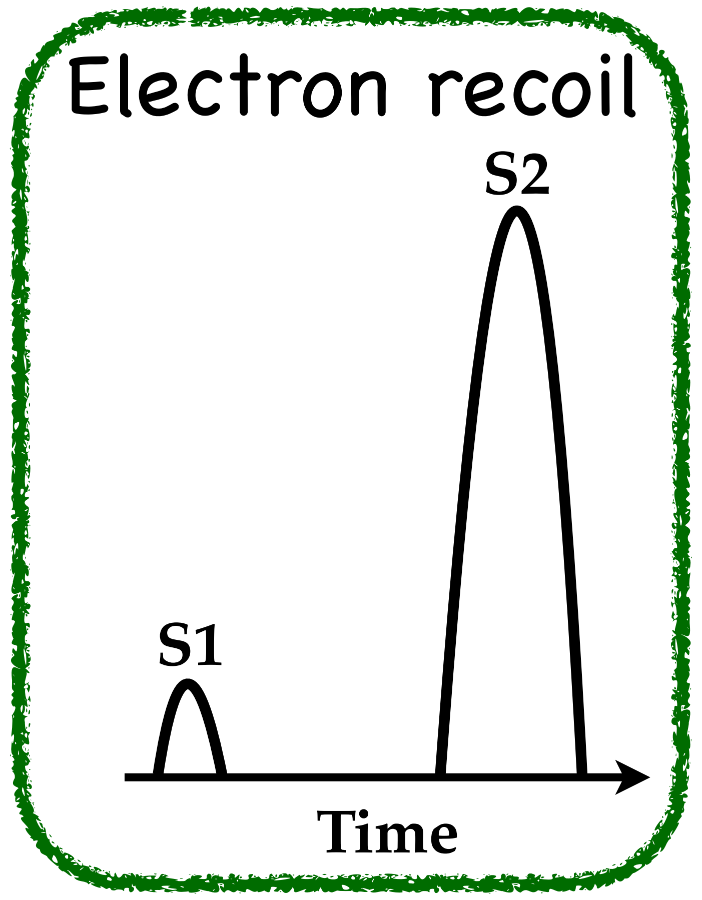

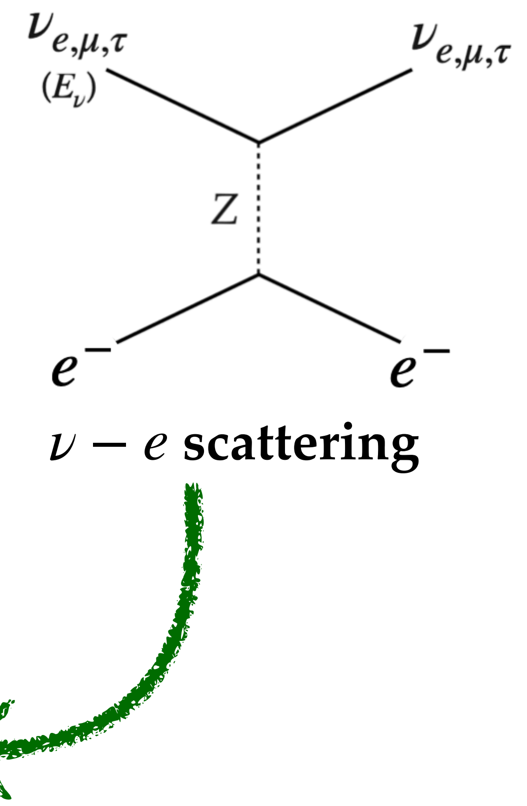

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Image credit: 2110.02359, 1903.03026, 0909.1063

Neutrino events at DD? nuclear recoil

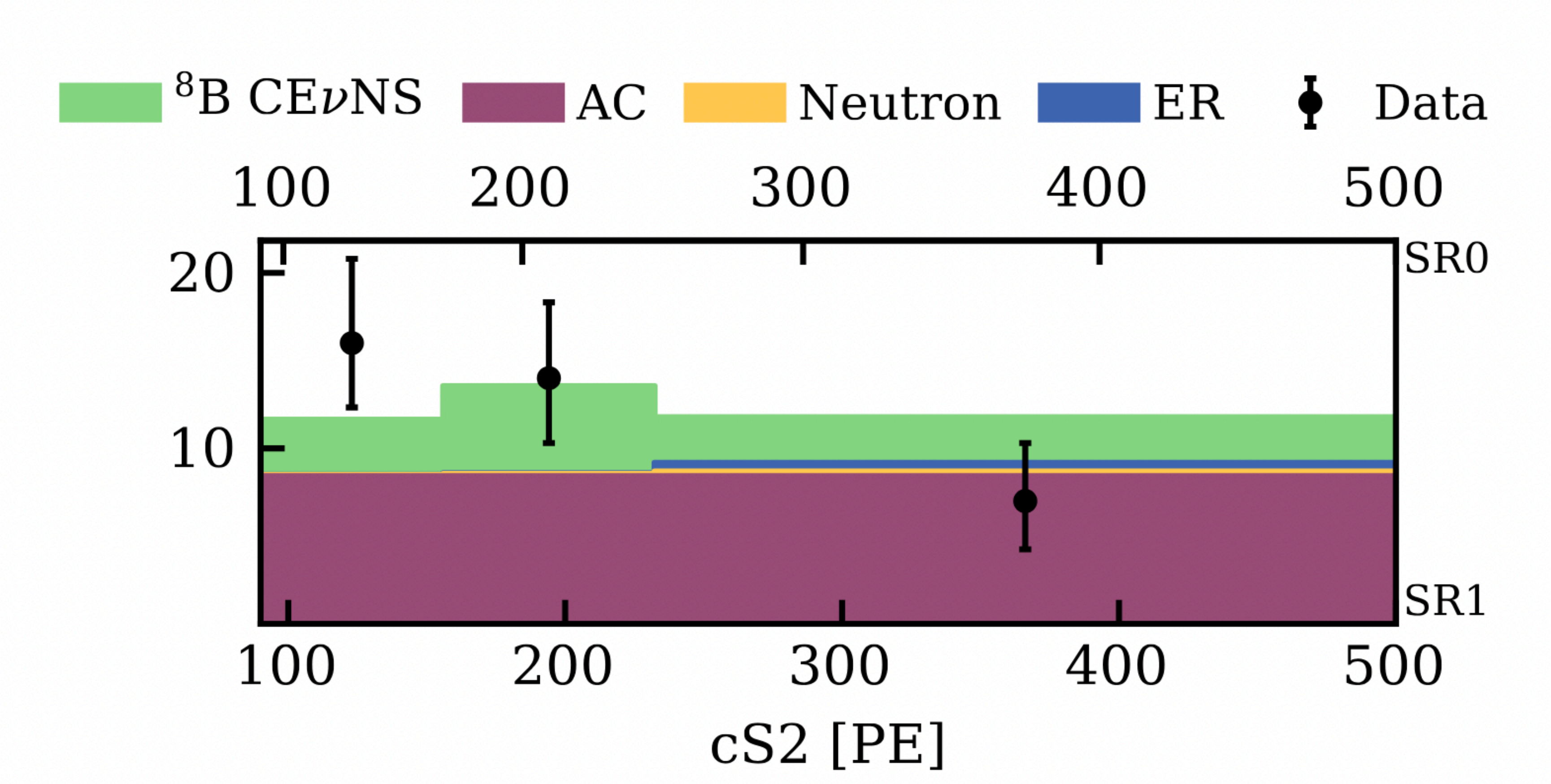
XENONnT

arXiv > nucl-ex > arXiv:2408.02877

Nuclear Experiment

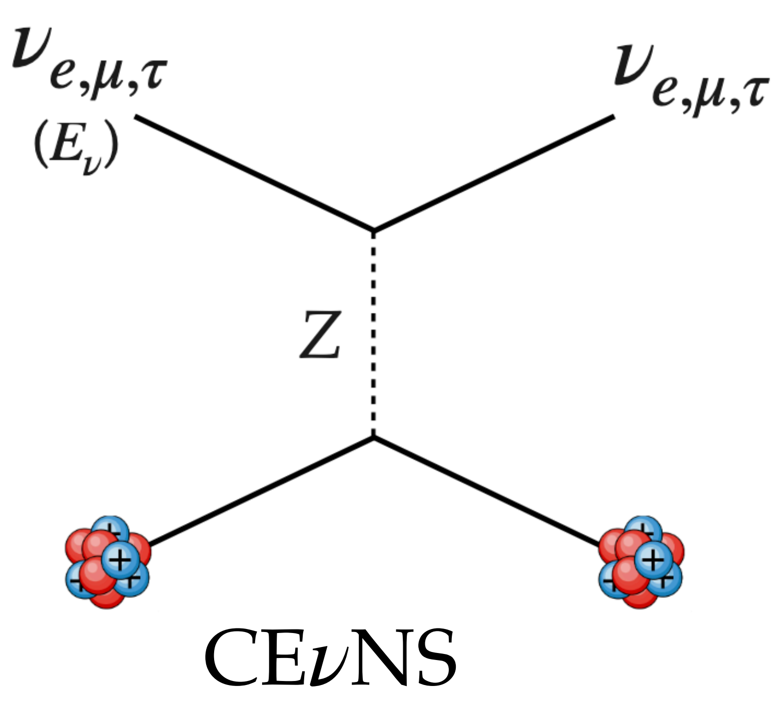
[Submitted on 6 Aug 2024]

First Measurement of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT



Observed events: $10.7^{+3.7}_{-4.2}$ **(S1-S2 analysis)**

Statistical significance: 2.73 σ



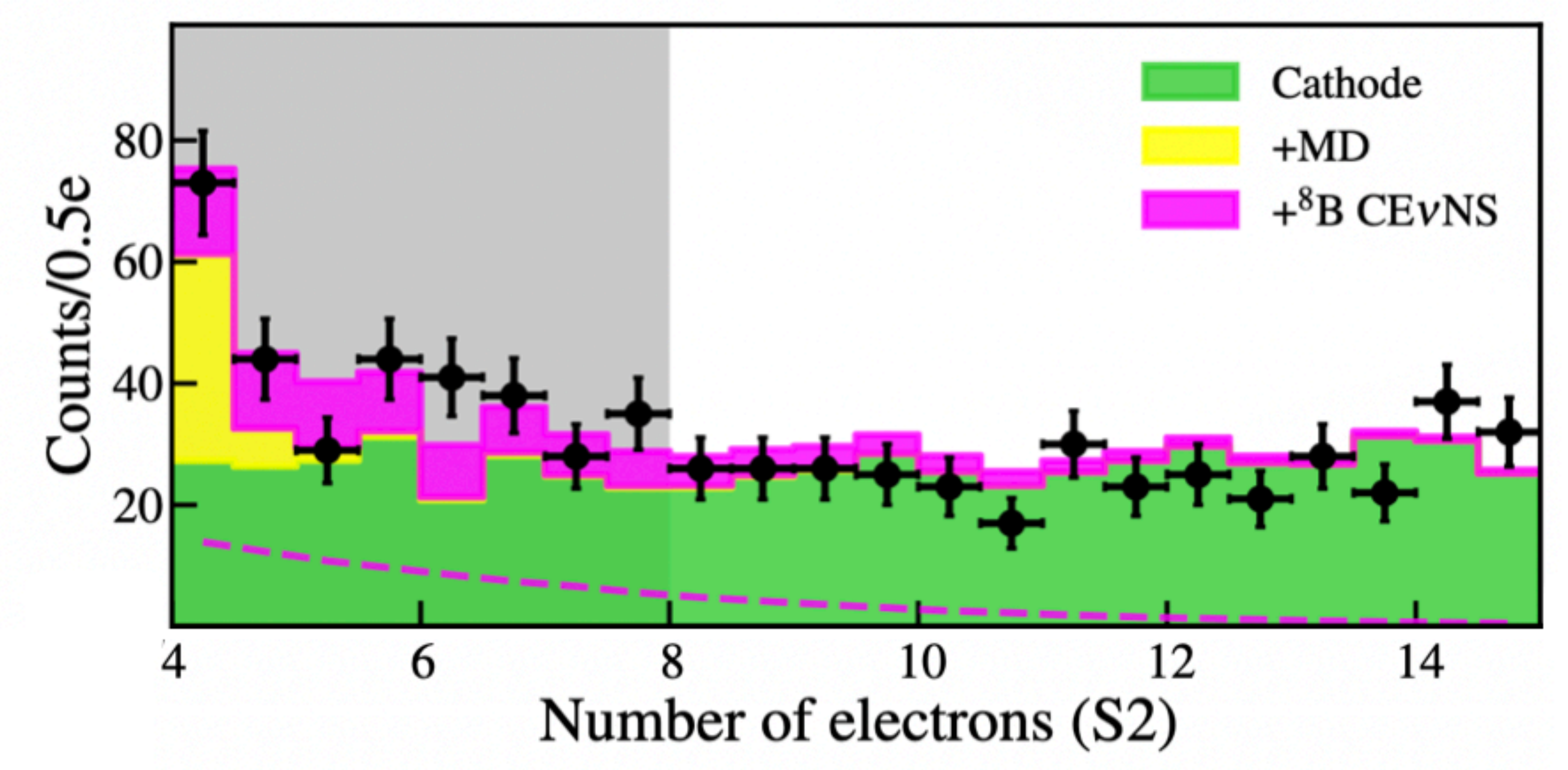
PandaX-4T

arXiv > hep-ex > arXiv:2407.10892

High Energy Physics - Experiment

[Submitted on 15 Jul 2024 (v1), last revised 13 Sep 2024 (this version, v3)]

First Indication of Solar ^{8}B Neutrino Flux through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T



Observed events: 3.5 ± 1.3 **(S1-S2 analysis)**

Observed events: 78 ± 28 **(S2-only analysis)**

Statistical significance: 2.64 σ

Neutrino events at DD? nuclear recoil

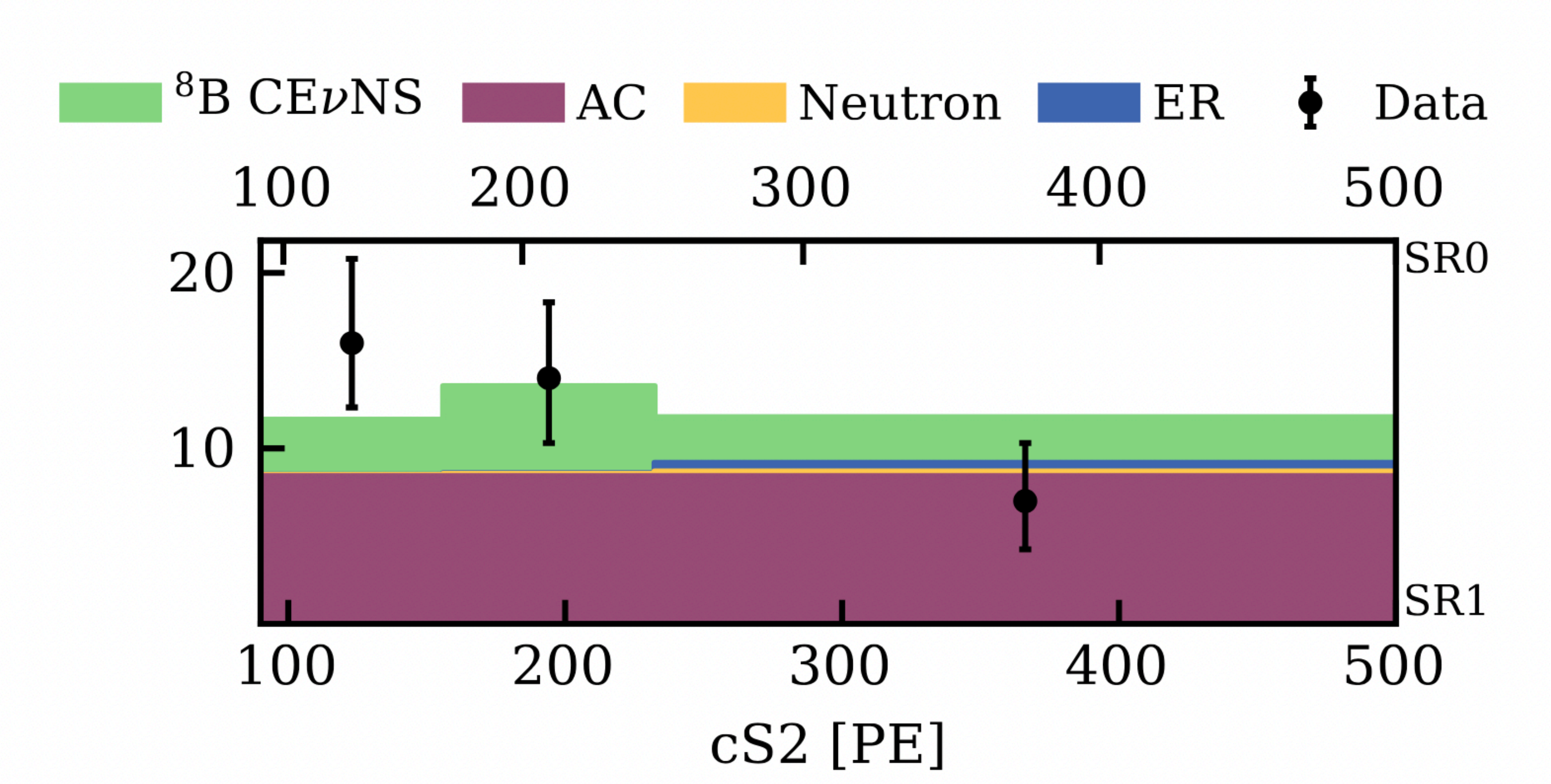
XENONnT

arXiv > nucl-ex > arXiv:2408.02877

Nuclear Experiment

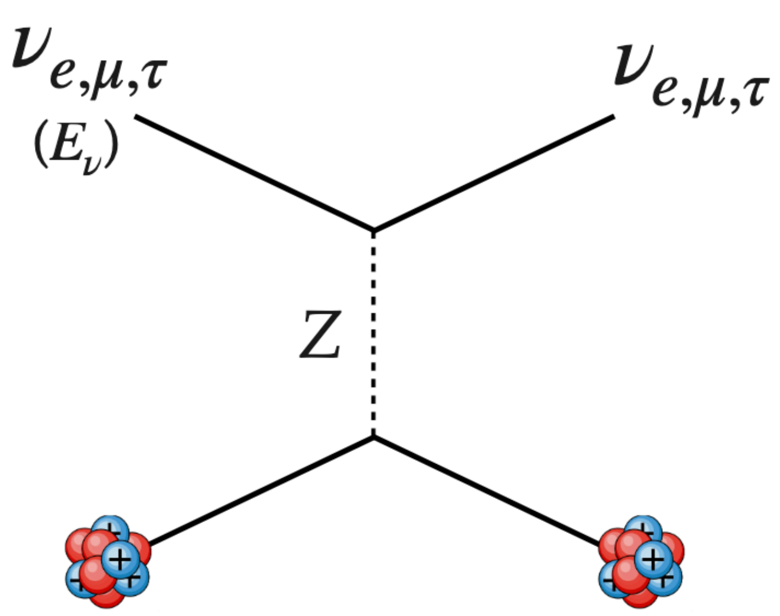
[Submitted on 6 Aug 2024]

First Measurement of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT



Observed events: $10.7^{+3.7}_{-4.2}$ **(S1-S2 analysis)**

Statistical significance: 2.73 σ



CEνNS

PandaX-4T

arXiv > hep-ex > arXiv:2407.10892

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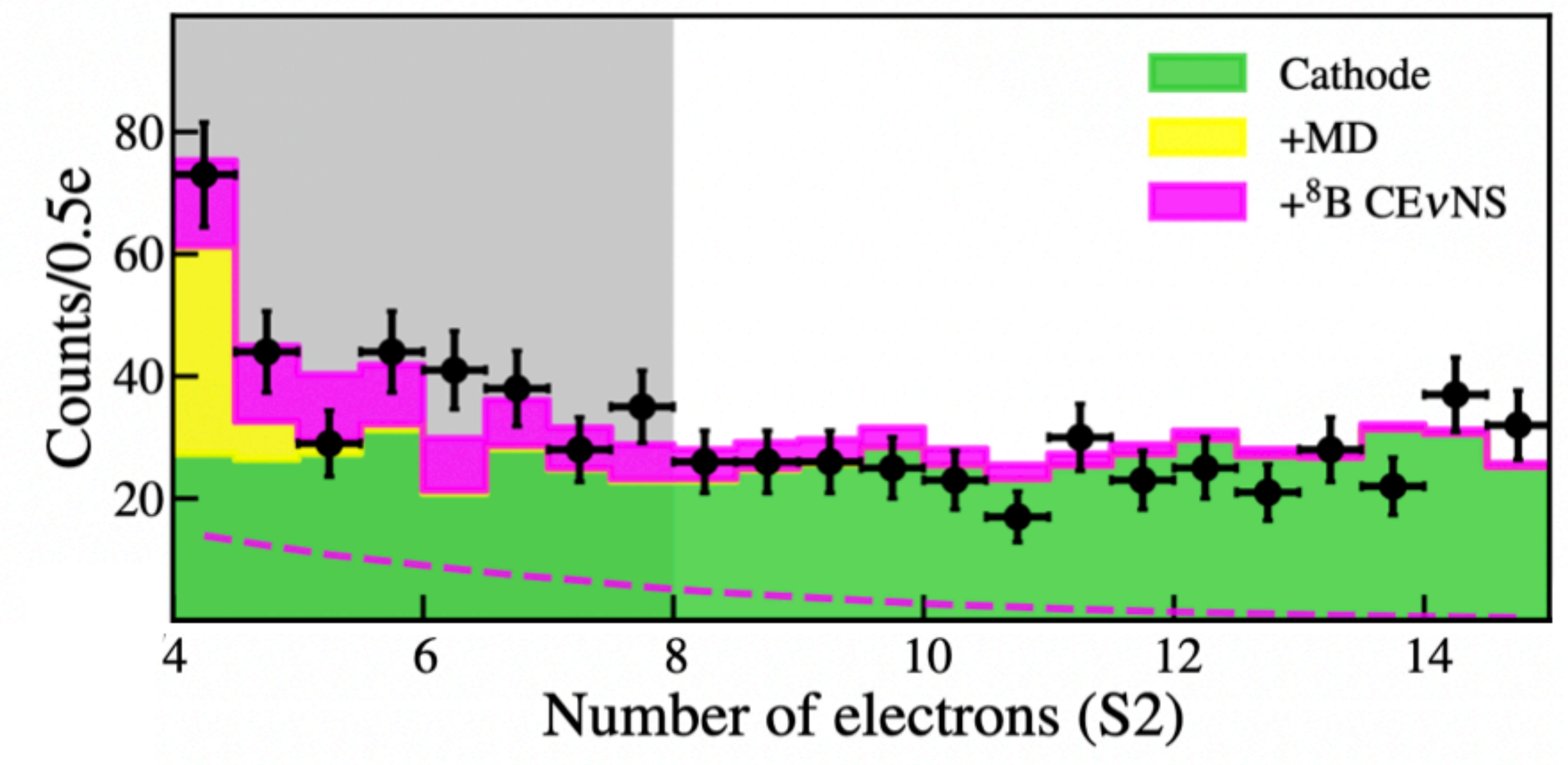

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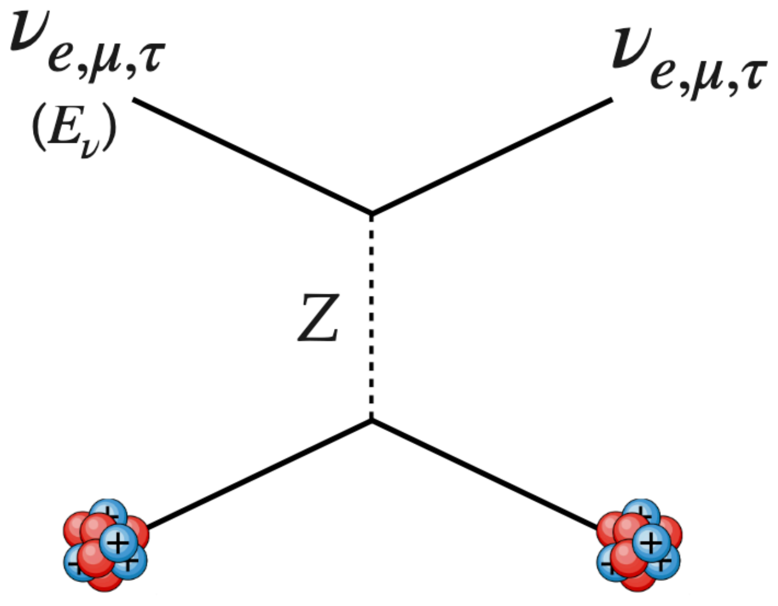
Observing essentially the Standard Model process, can we say something new?

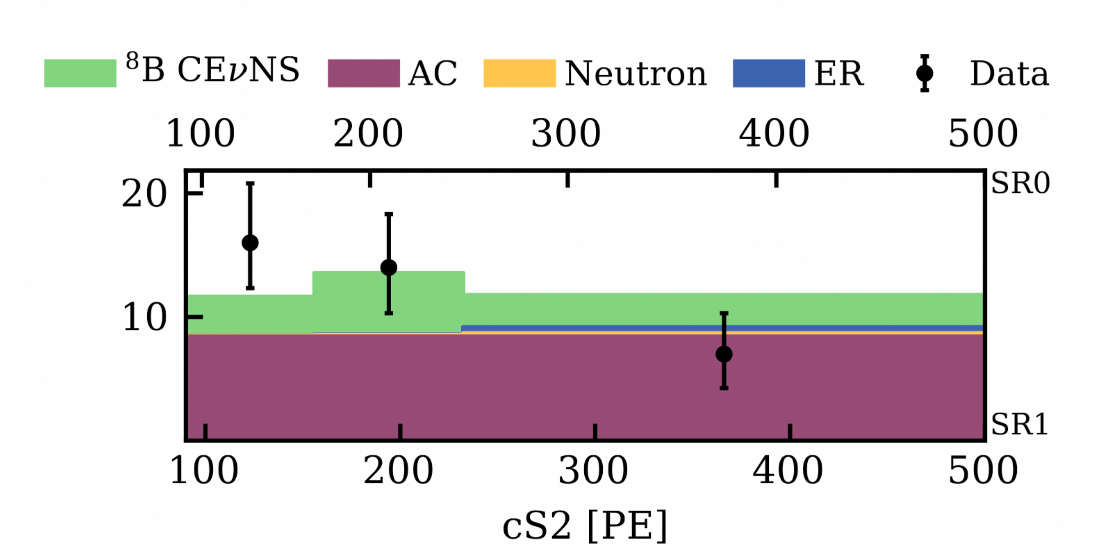
Our results: nuclear recoil



CEνNS

$$\frac{d\sigma}{dE_N} \propto f(\sin^2\theta_W)$$

XENONnT



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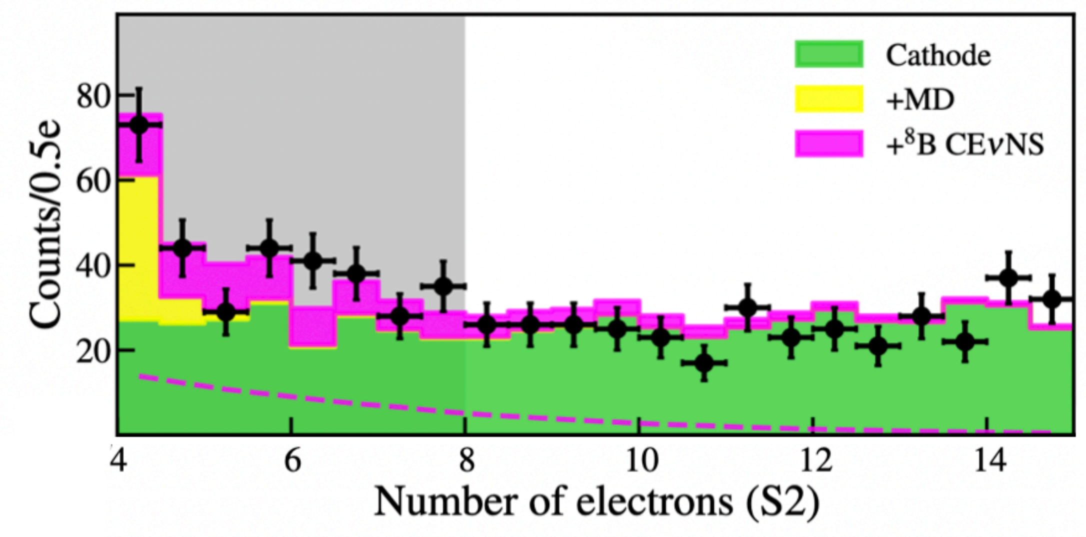

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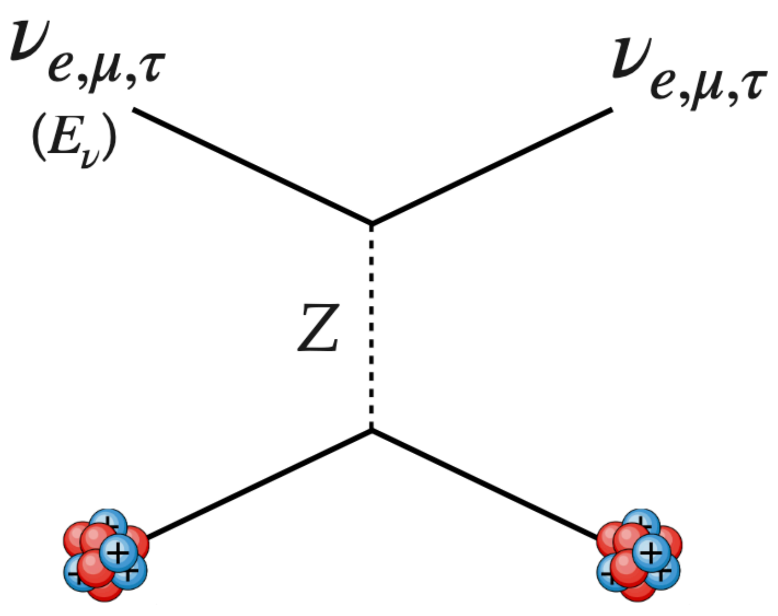

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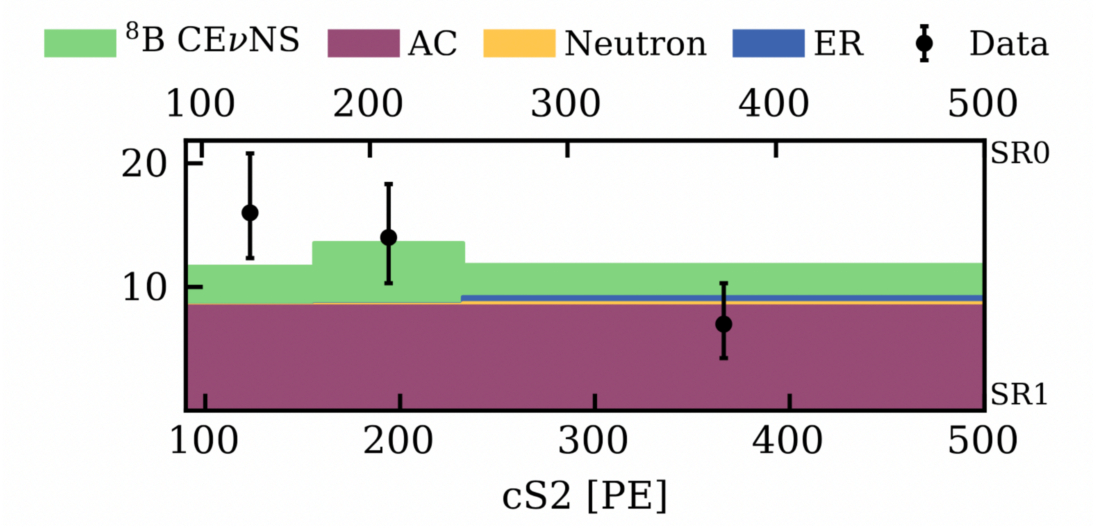

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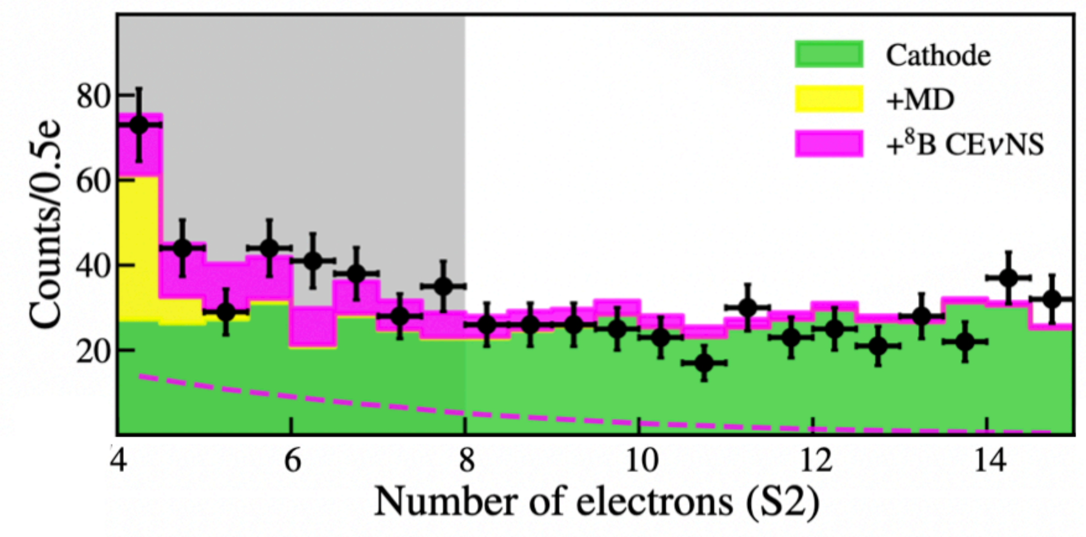

Observed solar ^{8}B events depends on $\sin^2\theta_W$ → One can measure $\sin^2\theta_W$ using these data

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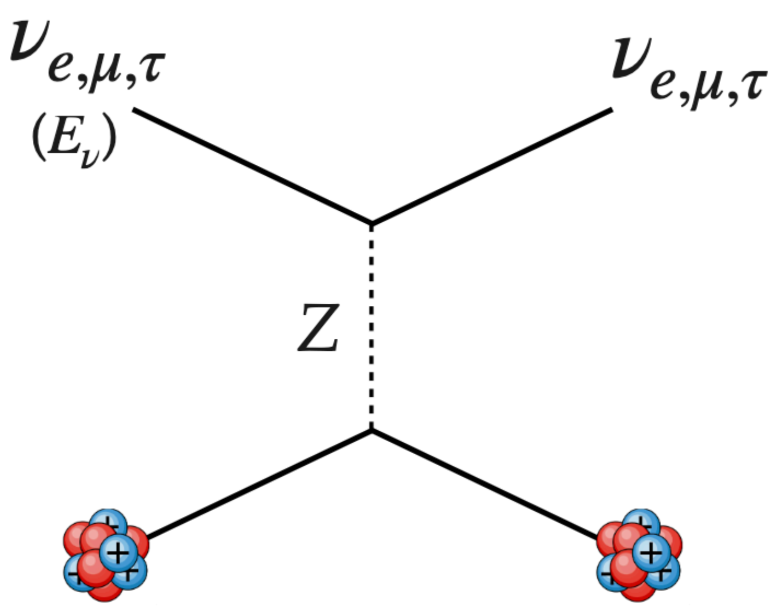

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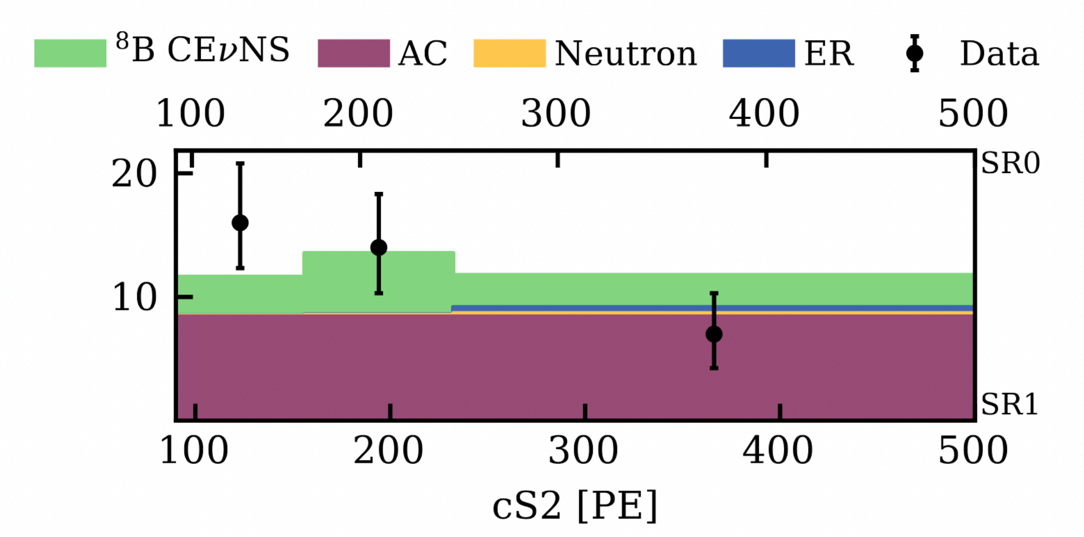

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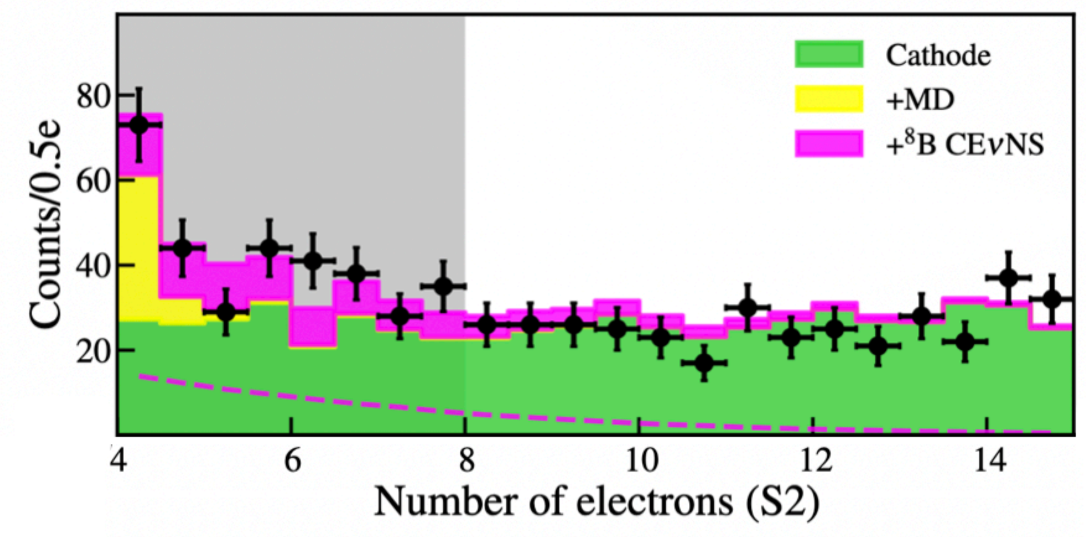

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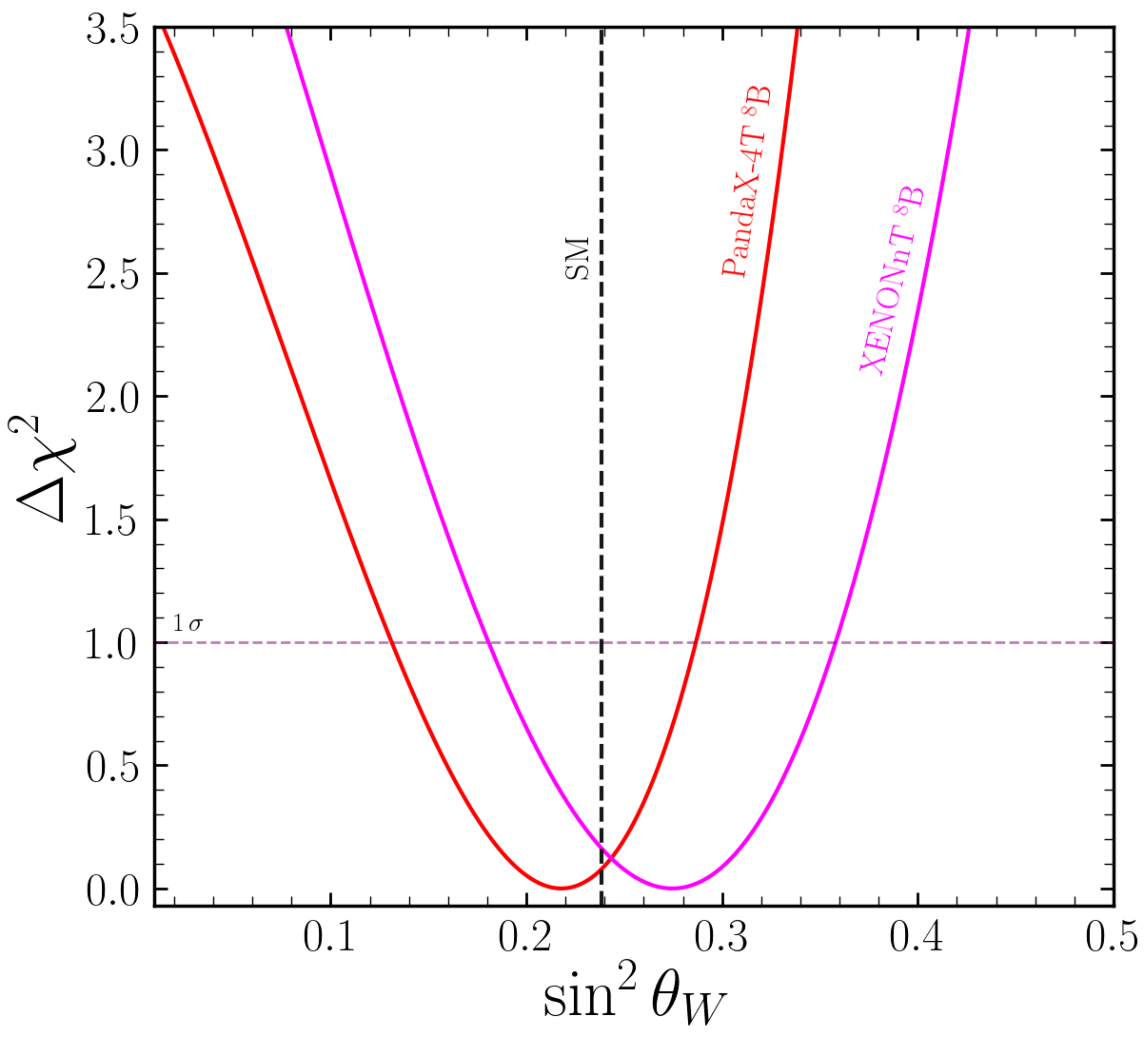

TNM, Boehm; 2409.04385

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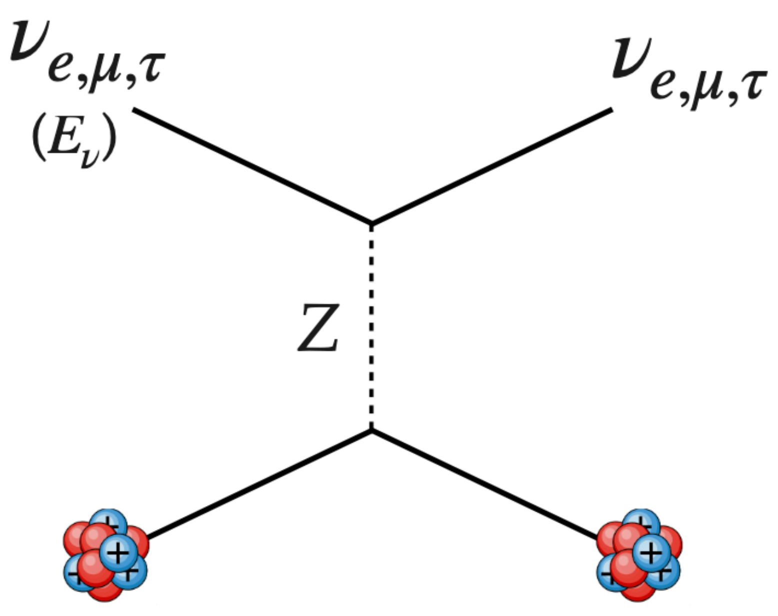

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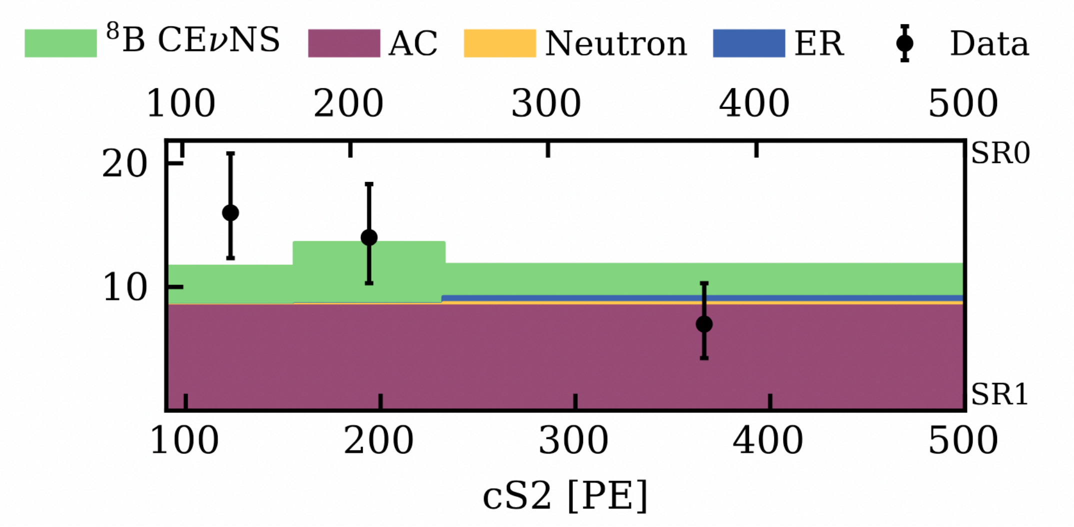

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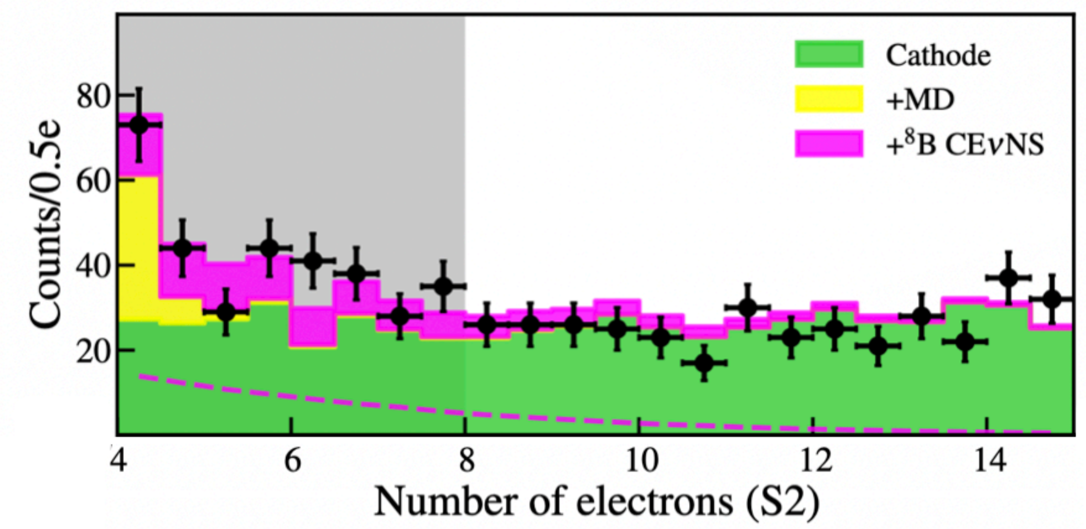

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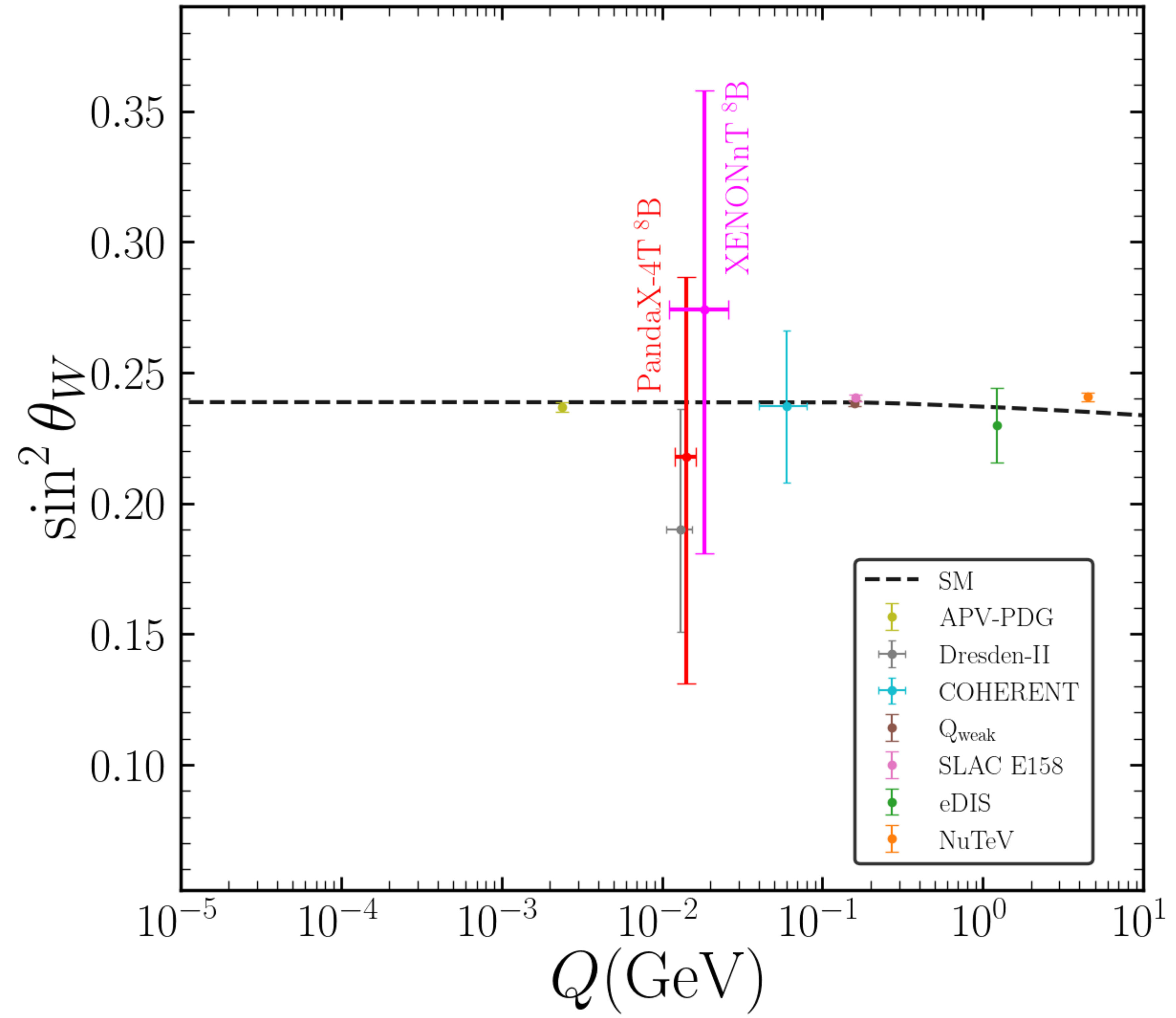
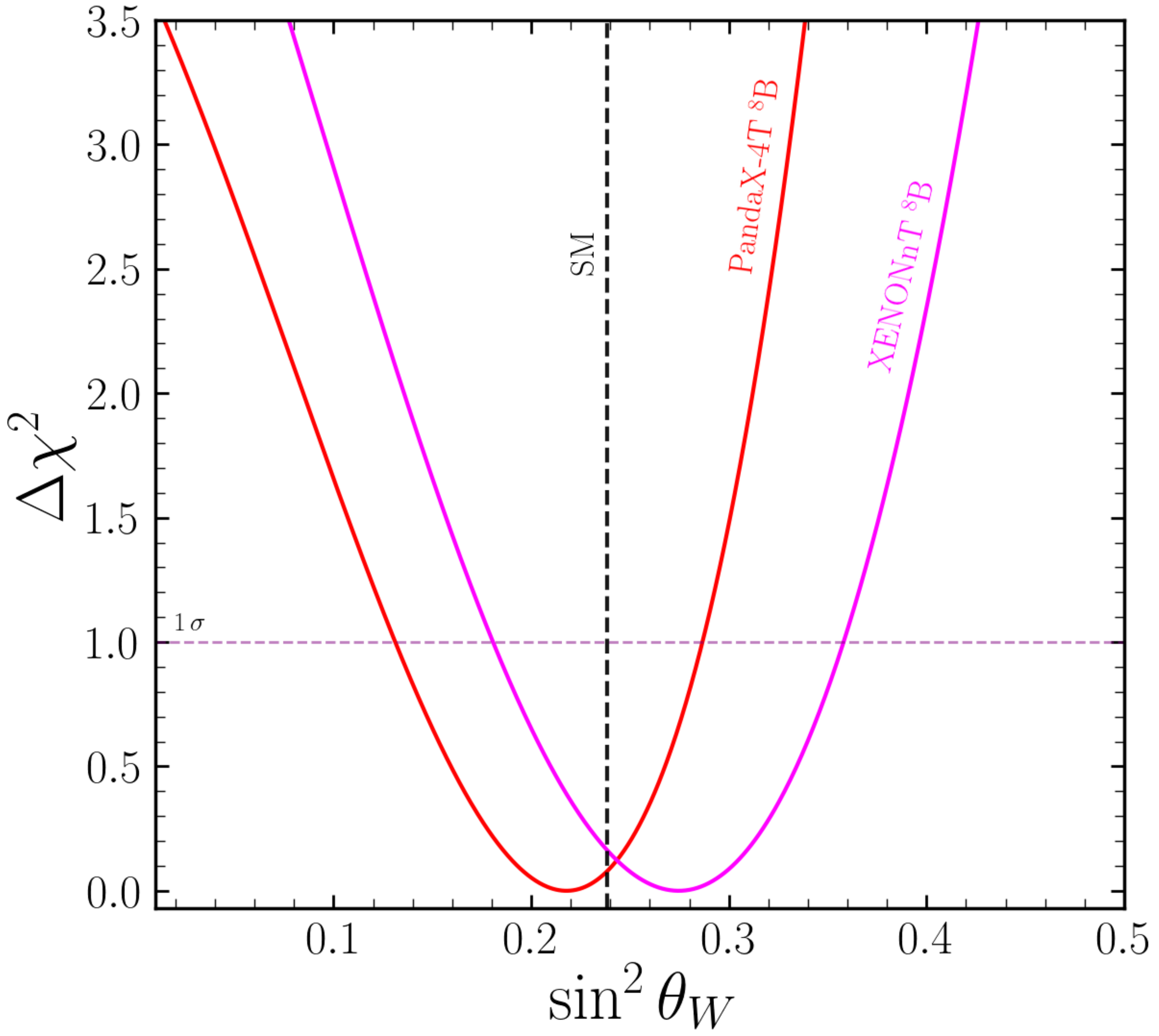


Energy scale determined from recoil energy regime



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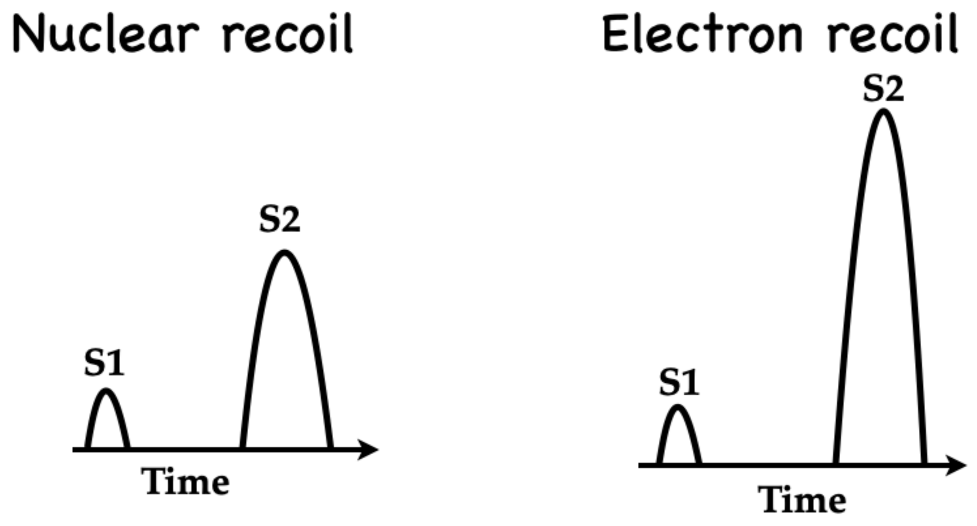

S2/S1 ratio - can distinguish - nuclear and electron recoil

$$E_{\rm recoil} \gtrsim 0.5\,{\rm keV}$$

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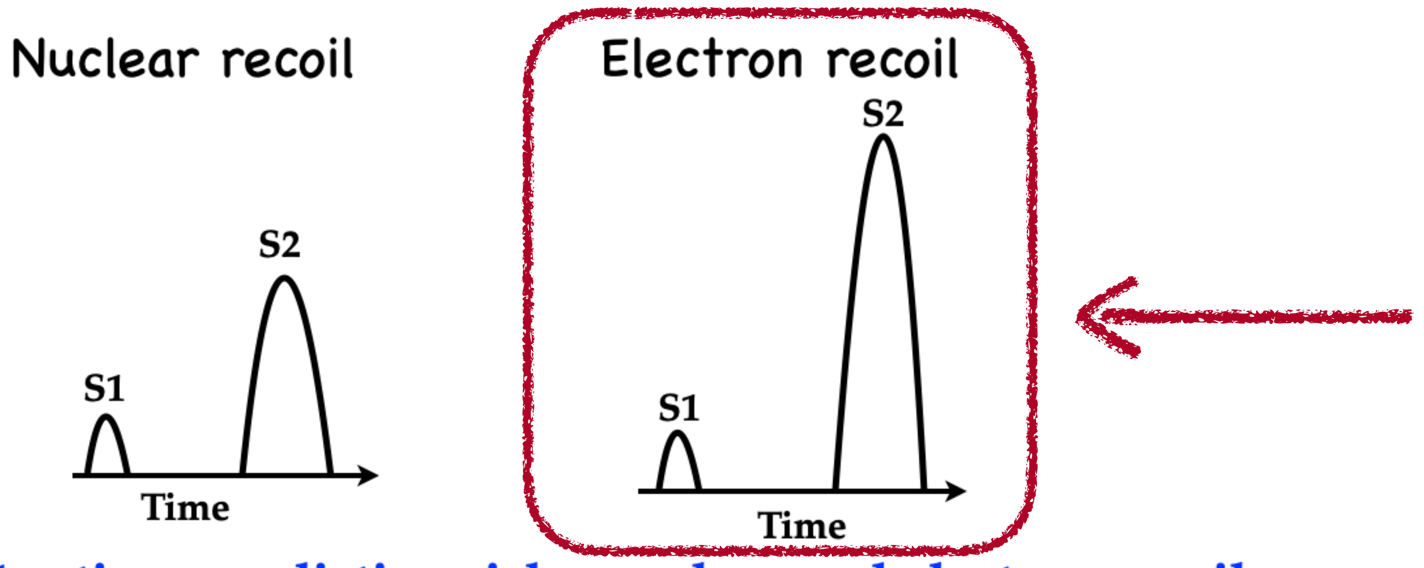

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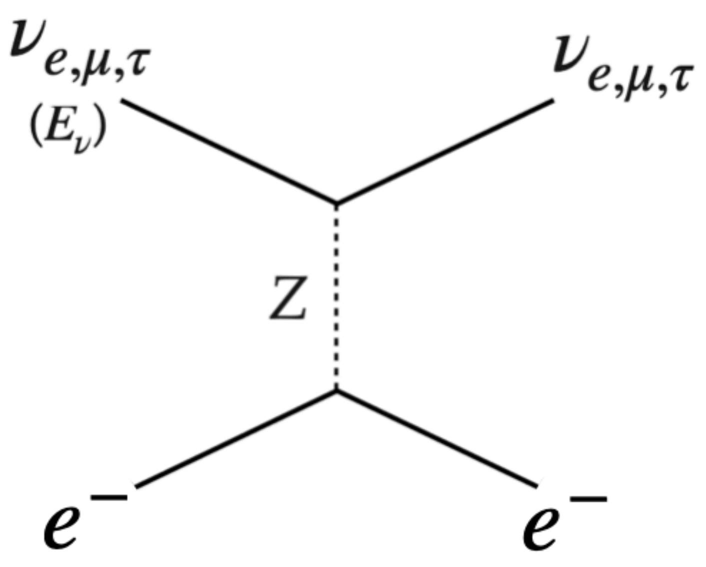

Neutrino-electron scattering

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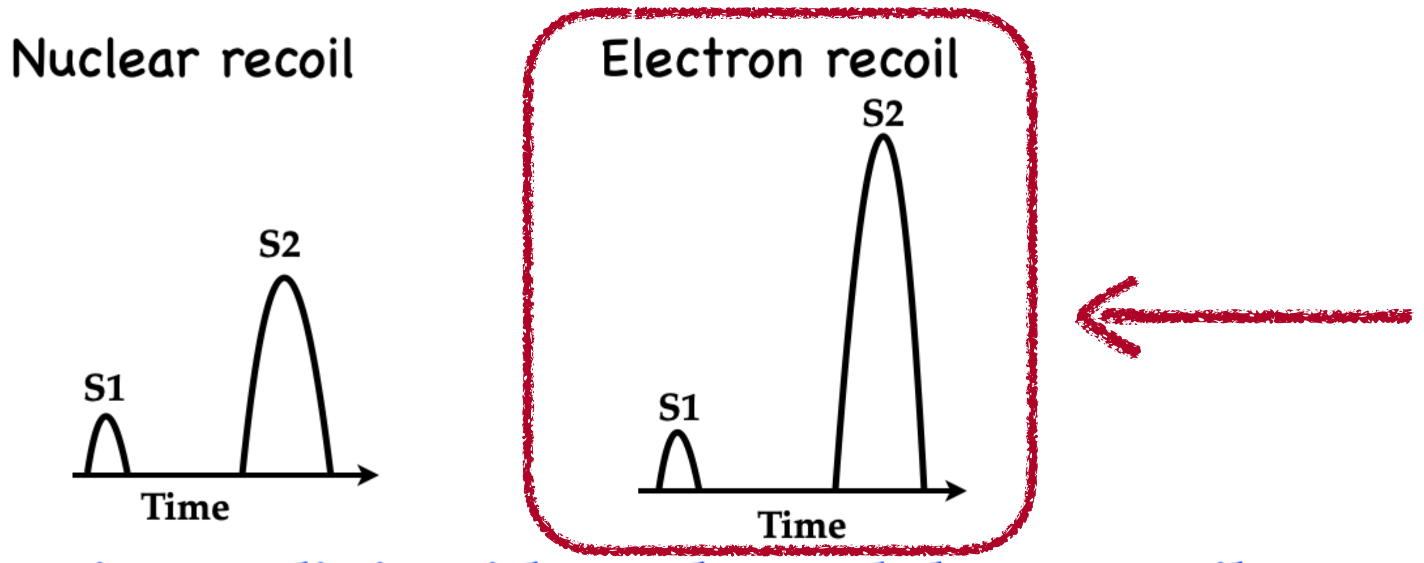

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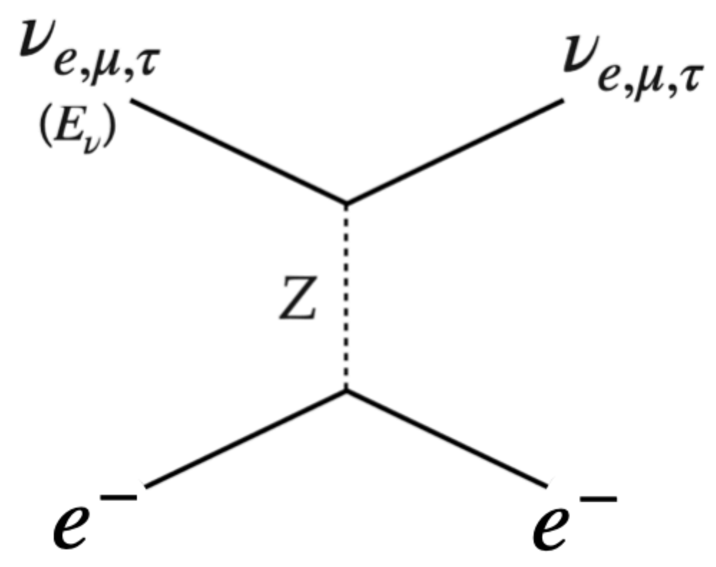

Neutrino-electron scattering

Observed $\nu - e$ events: ~ 60

But statistically not significant due to huge background

XENONnT 2207.11330
LZ 2307.15753
PandaX-4T 2408.07641

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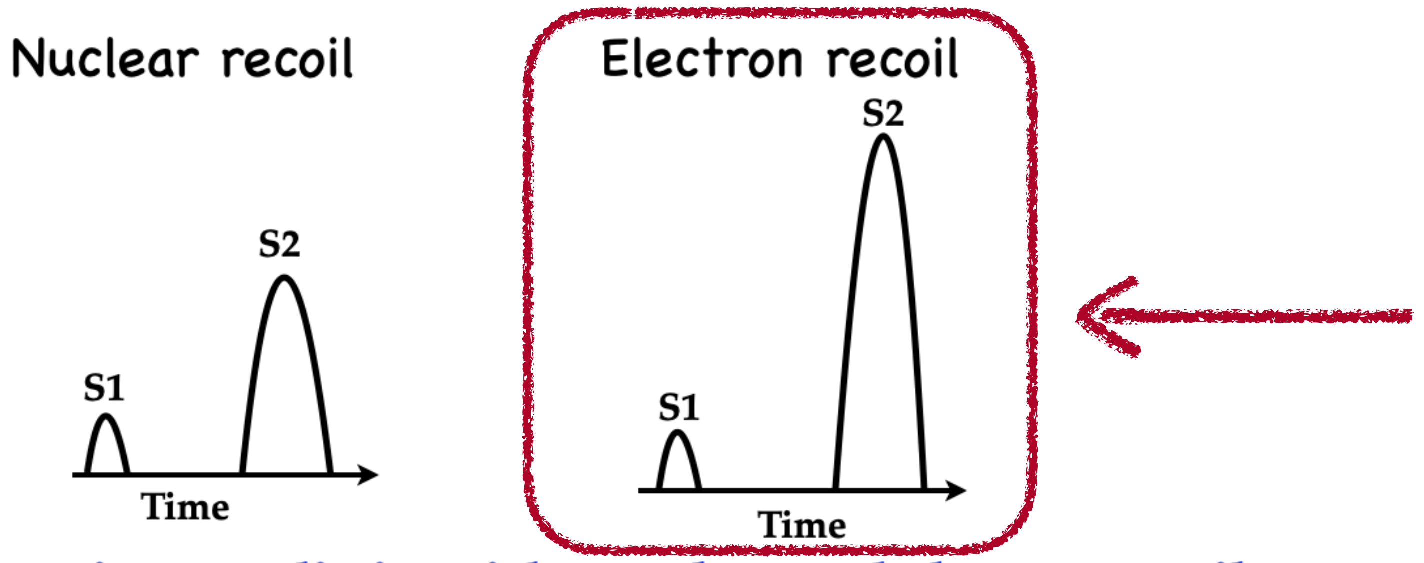

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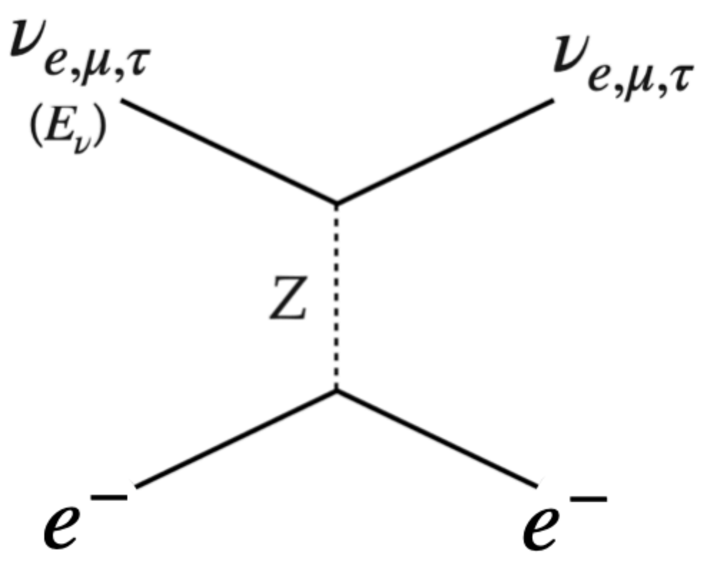

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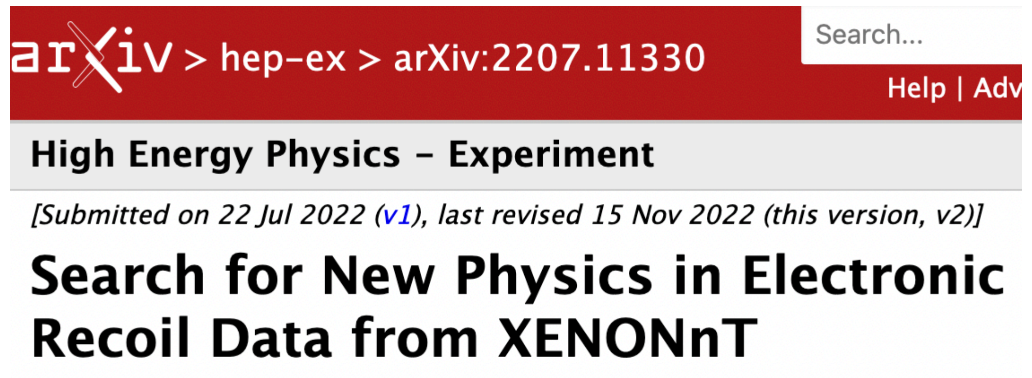
arXiv > hep-ex > arXiv:2207.11330

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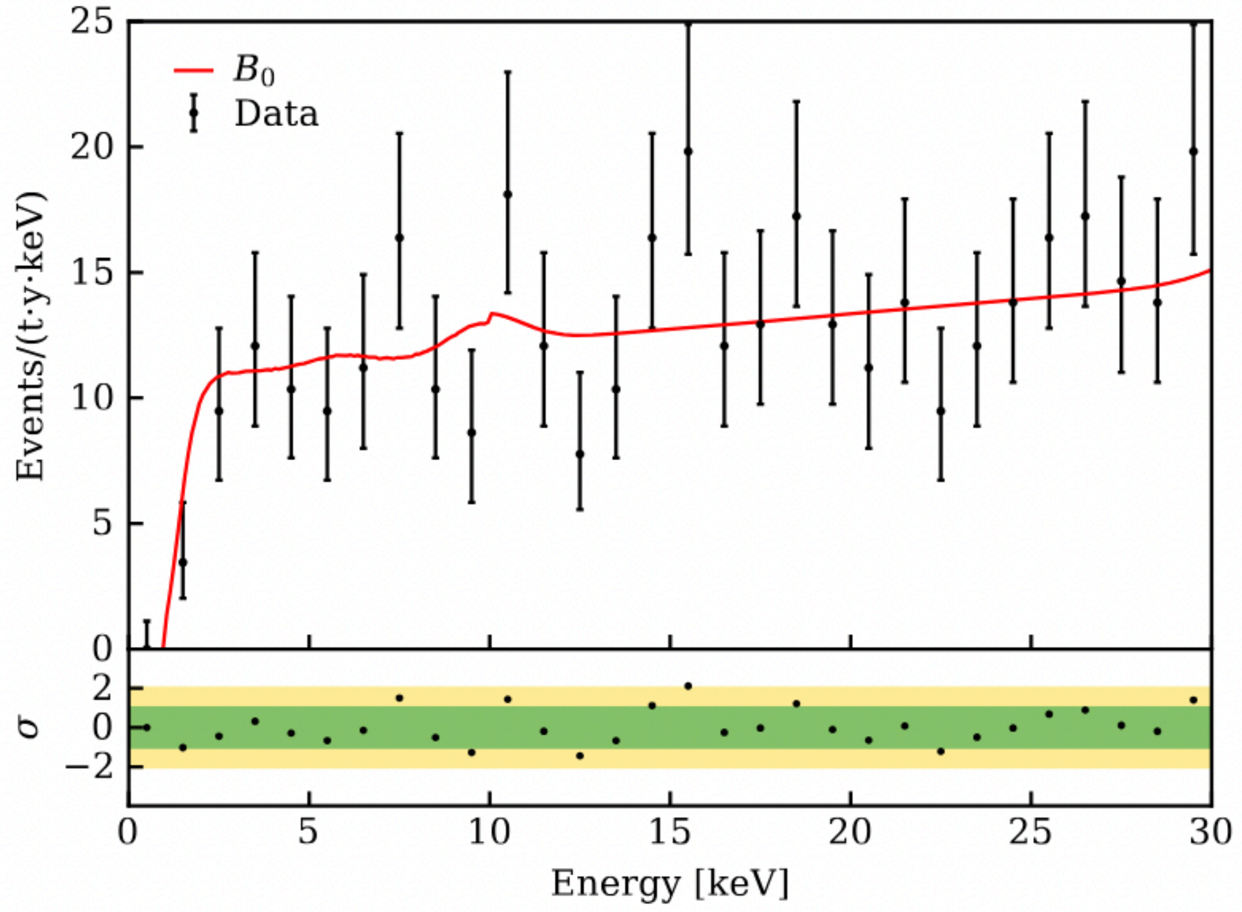
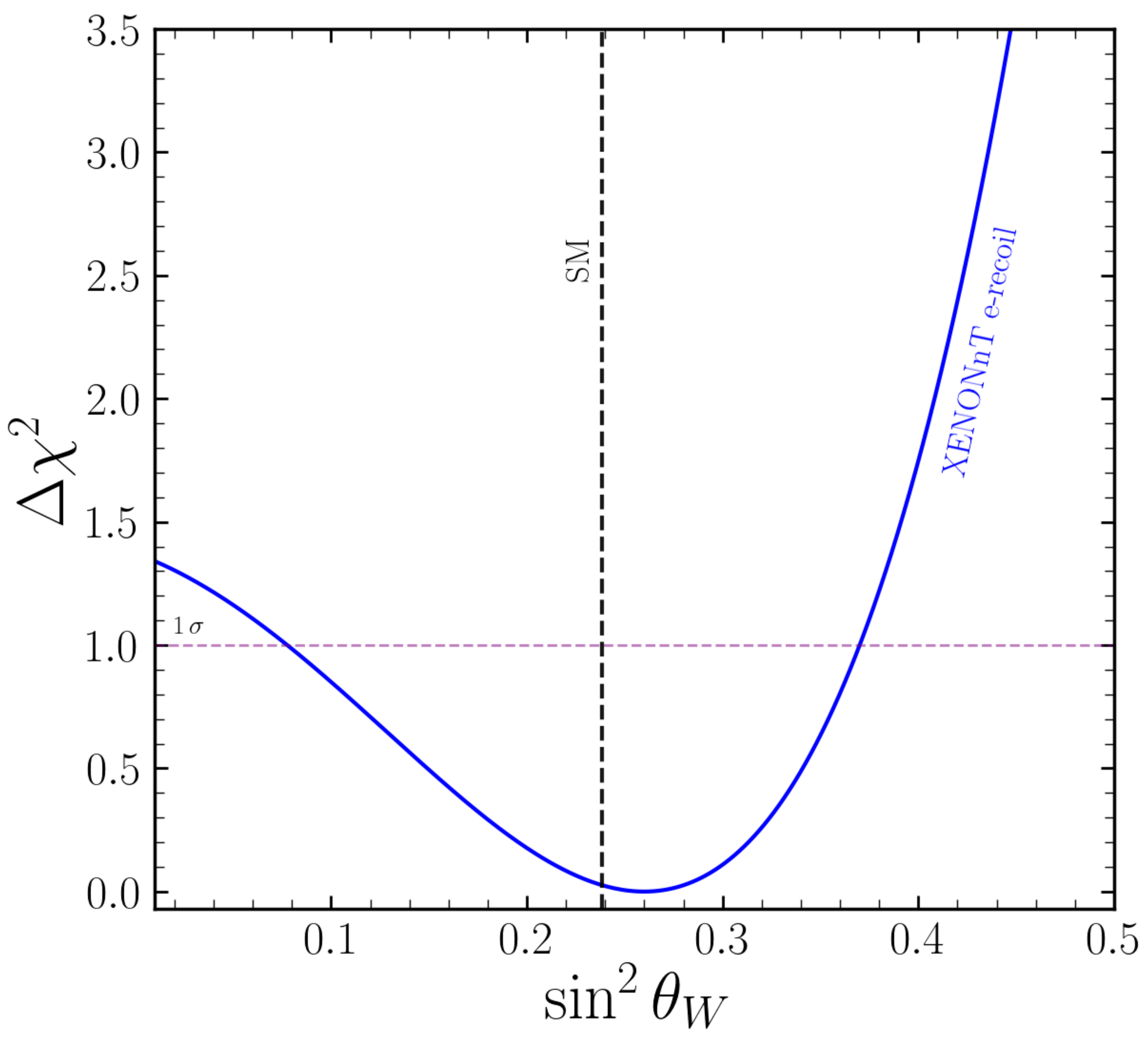
High Energy Physics – Experiment

[Submitted on 22 Jul 2022 (v1), last revised 15 Nov 2022 (this version, v2)]

Search for New Physics in Electronic Recoil Data from XENONnT





Only upper limits above 1.16 σ

TNM, Boehm; 2409.04385

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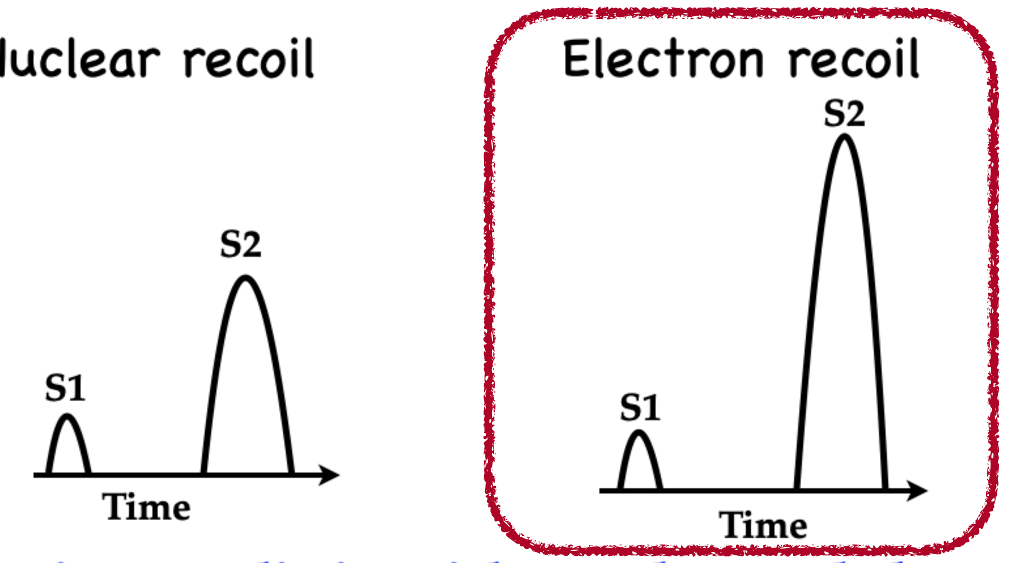

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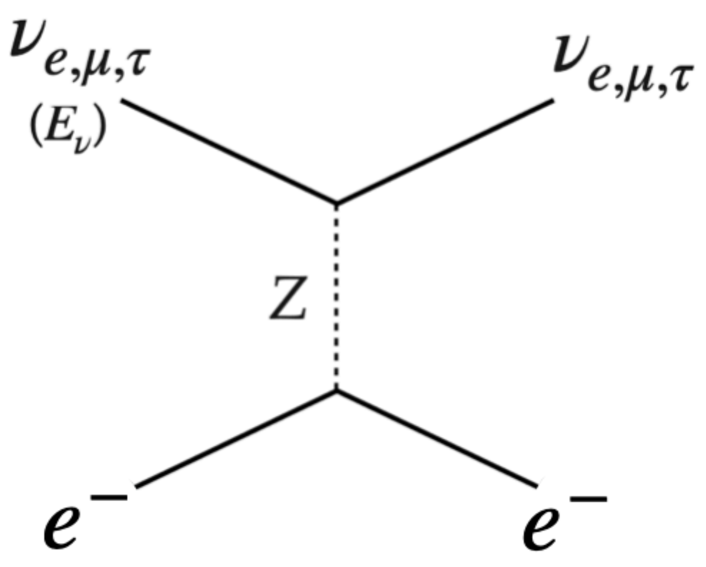

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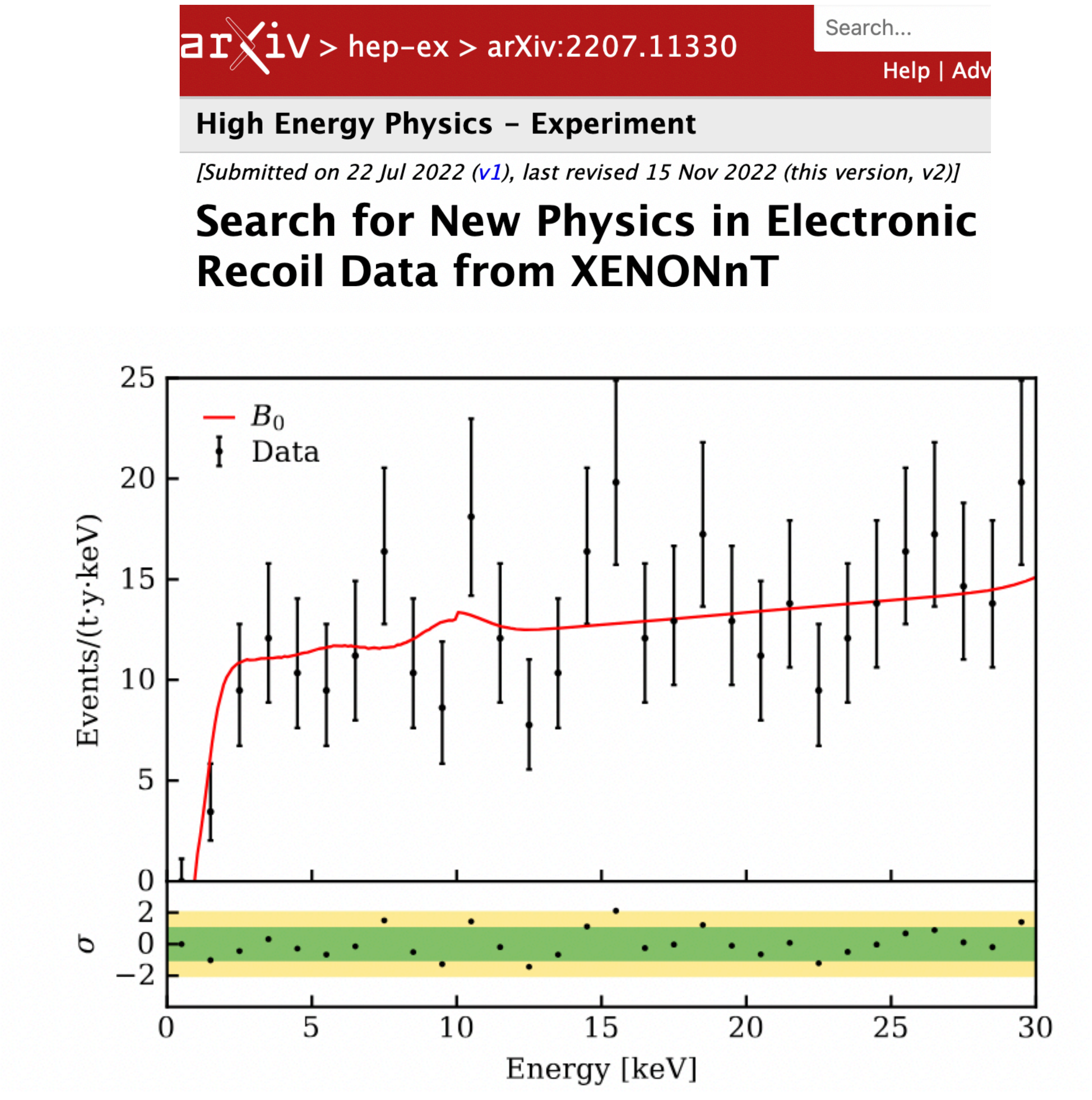

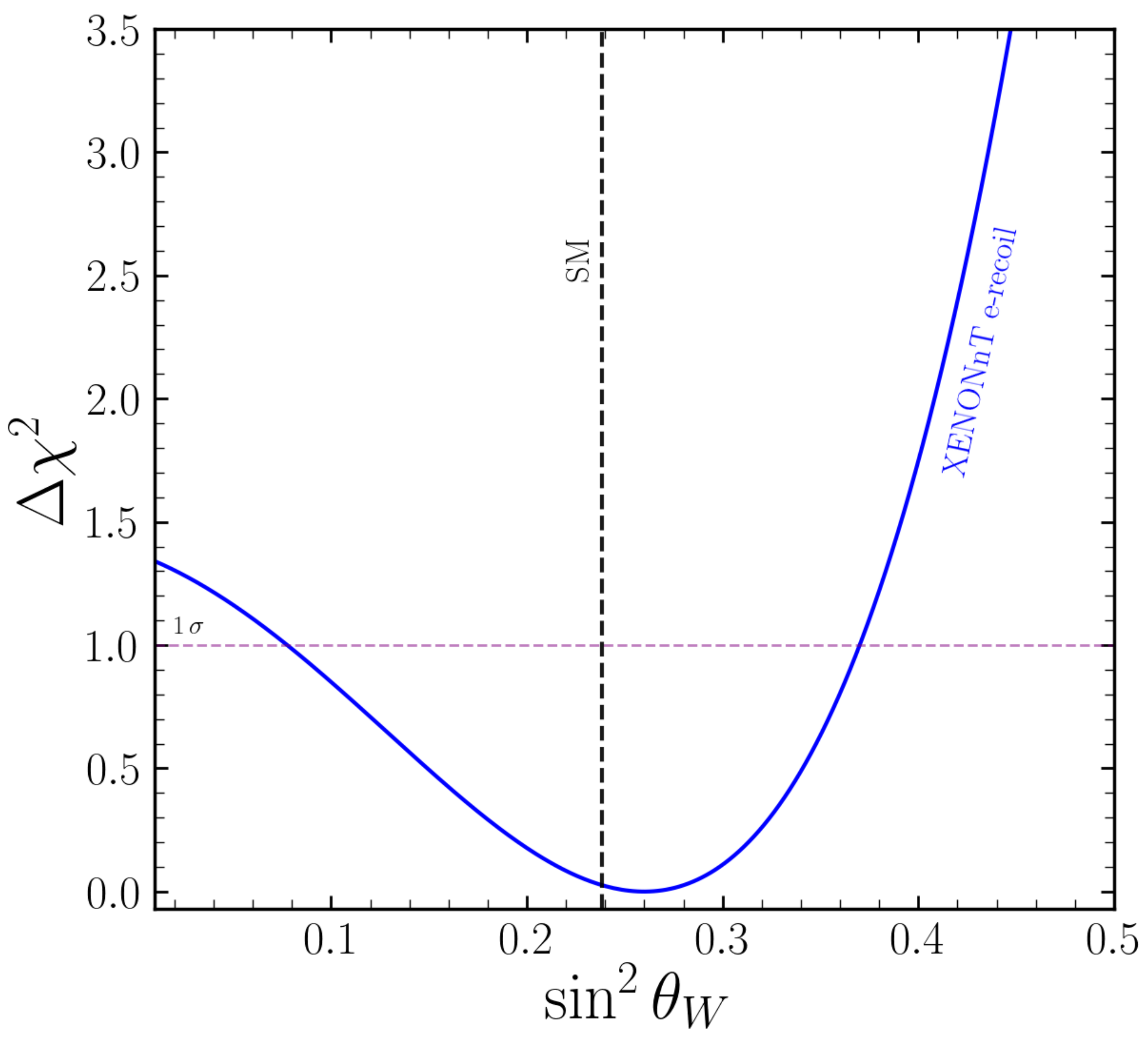

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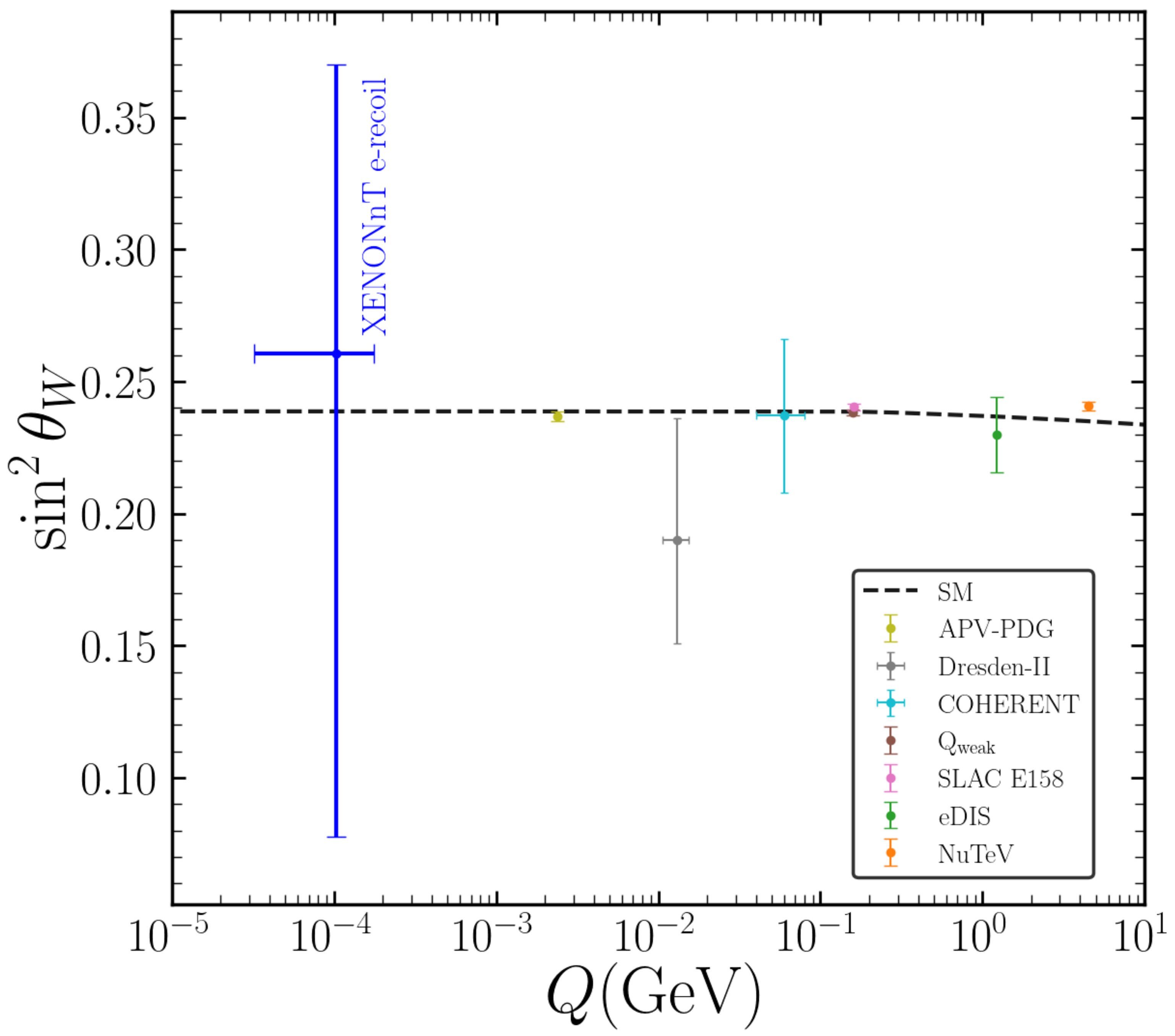


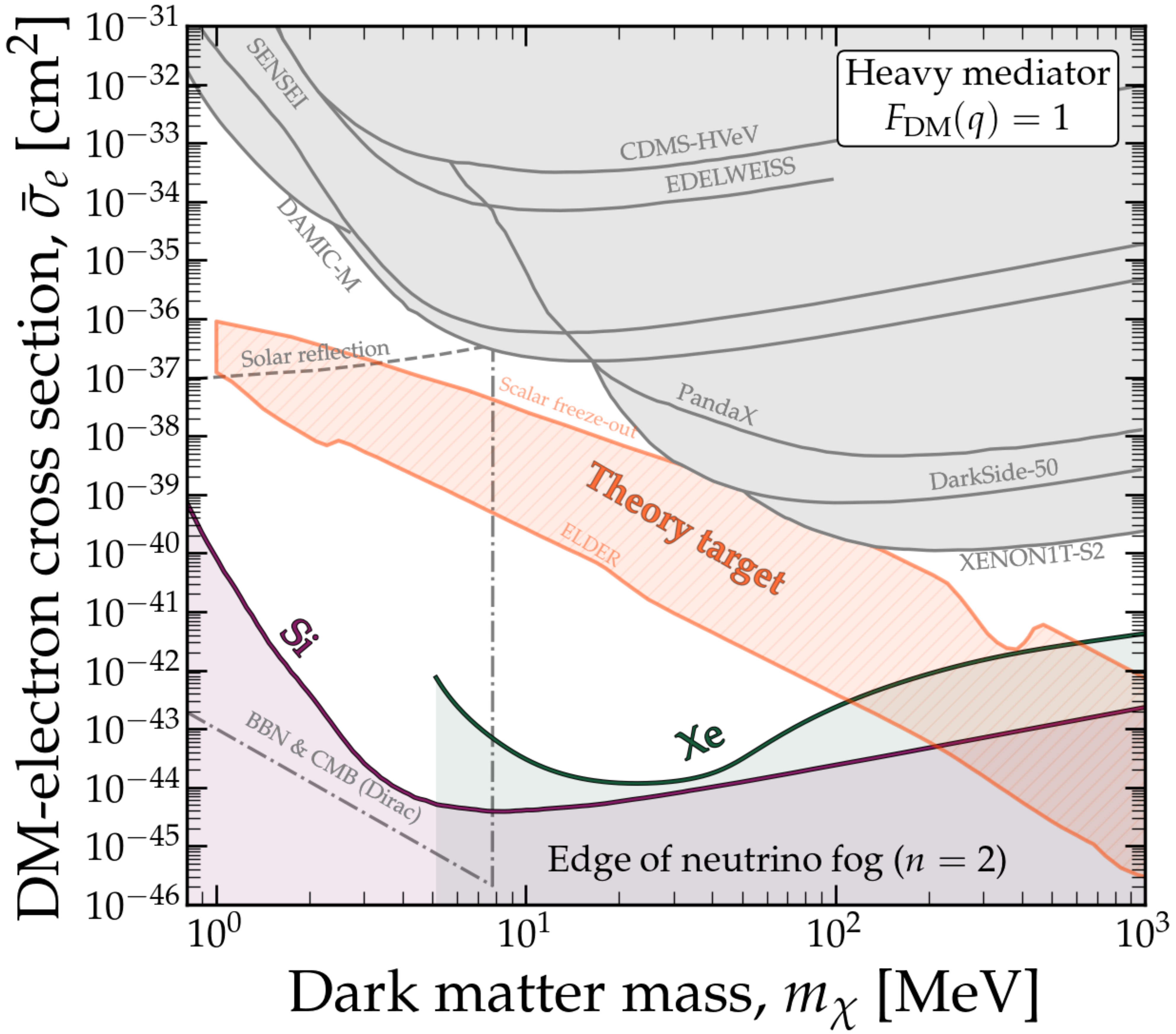
Probing a SM parameter in an entirely new regime

TNM, Boehm; 2409.04385

Summary

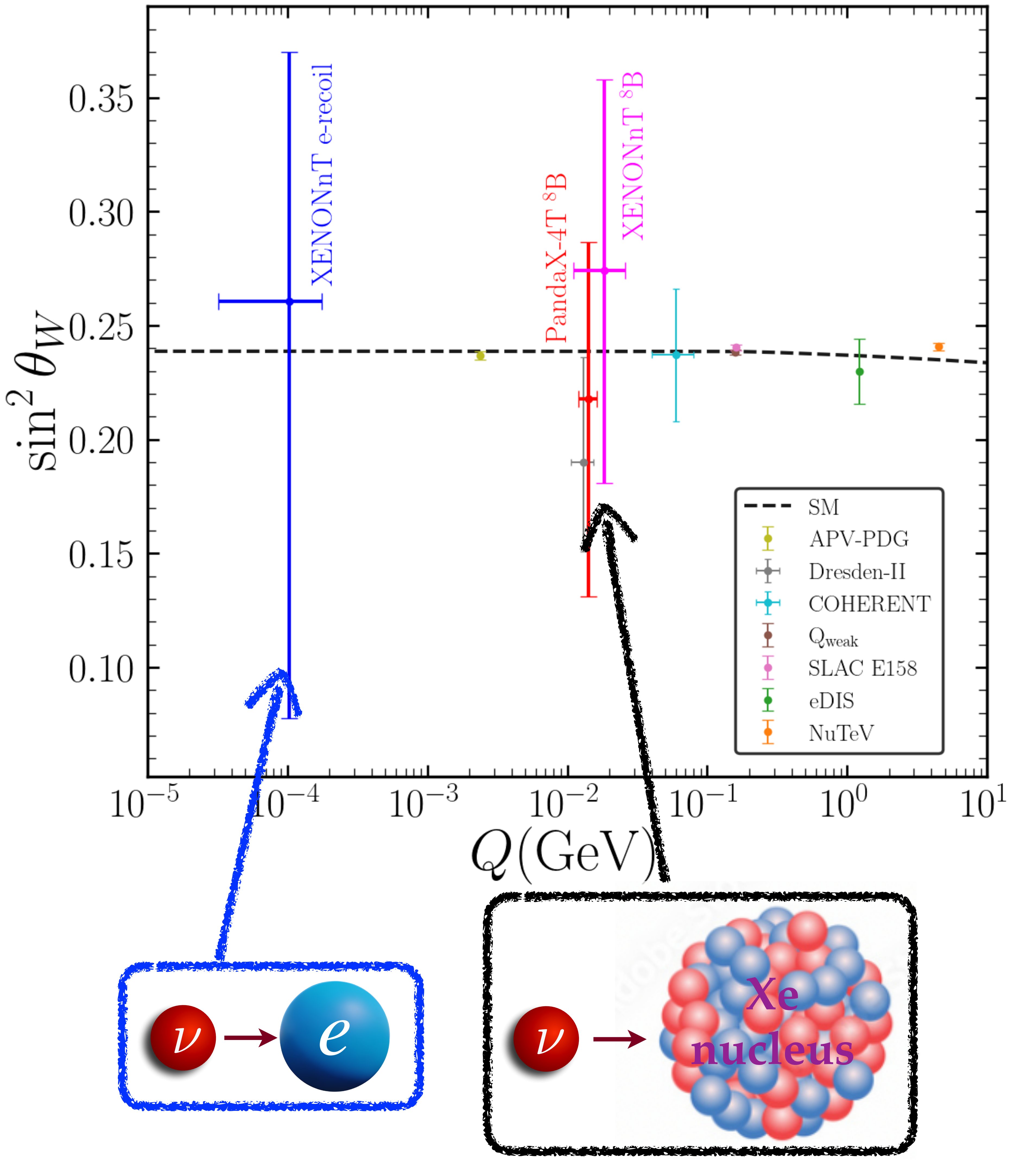
Neutrinos at direct detection

Foe: Slowing down the search of DM



Carew, Caddell, TNM, O'Hare; 2312.04303

Friend: probing SM in an uncharted territory



Huge scope of improvement with XLZD, DarkSide-20

TNM, Boehm; 2409.04385

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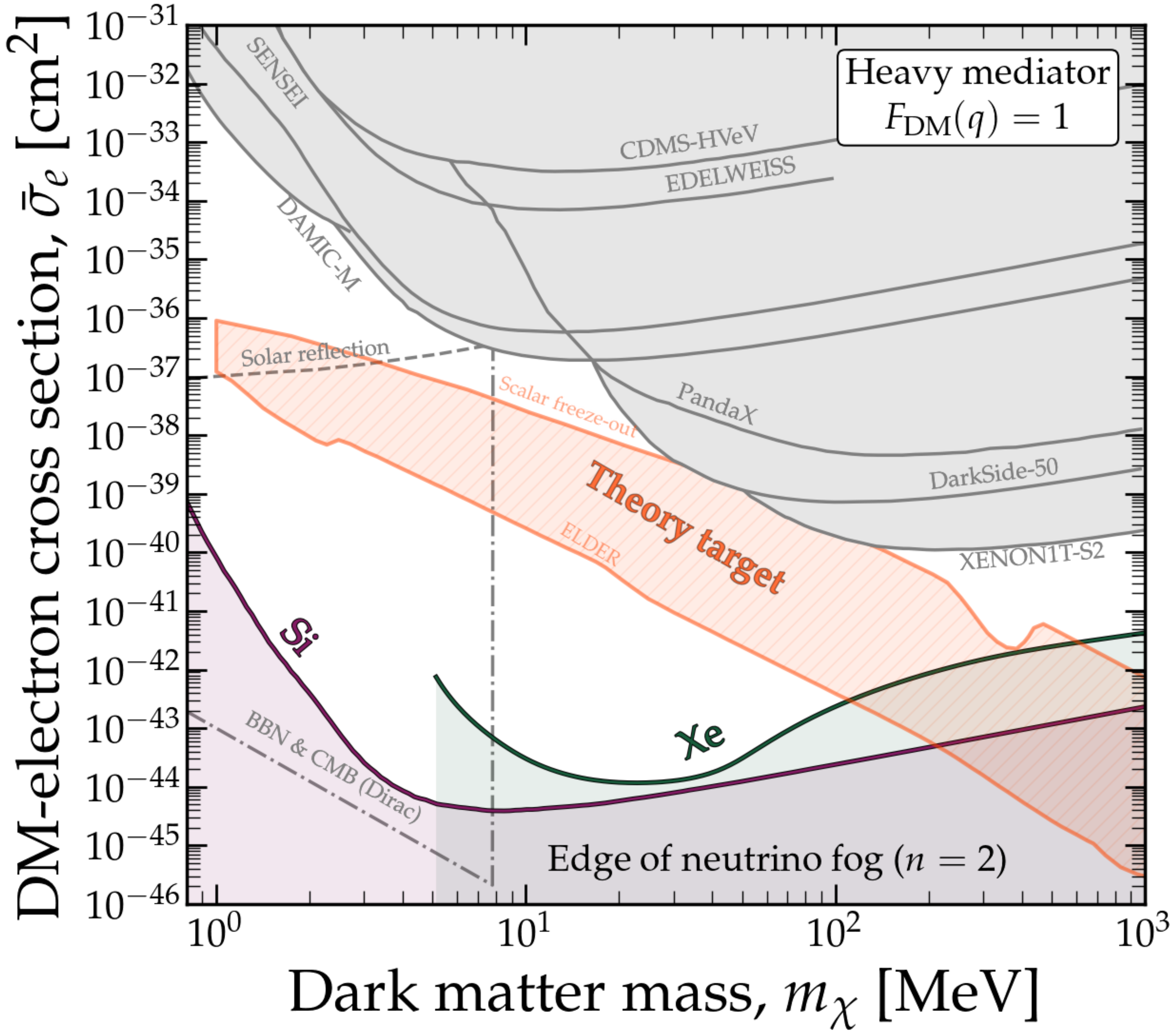

Carew, Caddell, TNM, O'Hare; 2312.04303

email: tarak.maity.physics@gmail.com

Thank you

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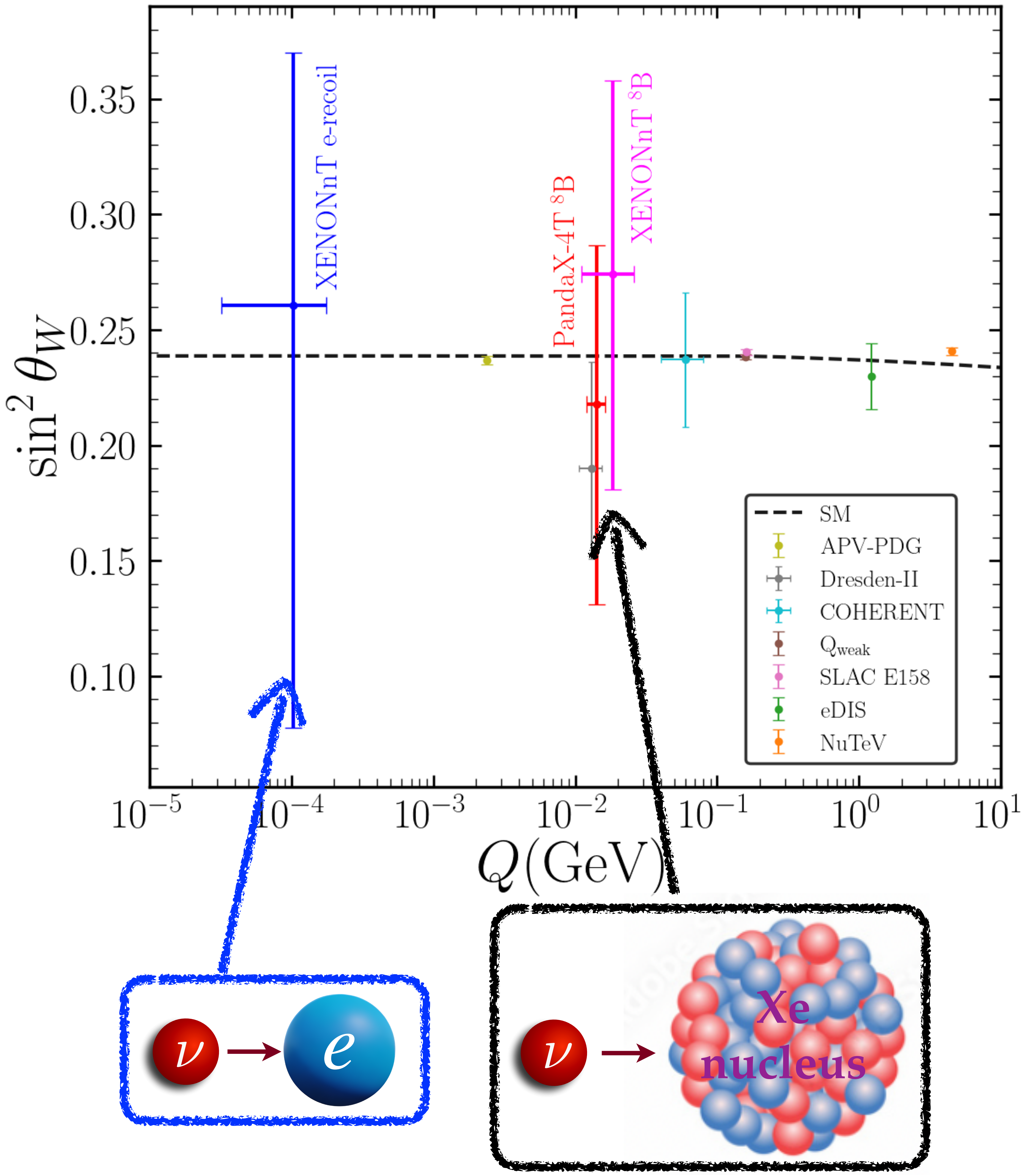


Huge scope of improvement with XLZD, DarkSide-20

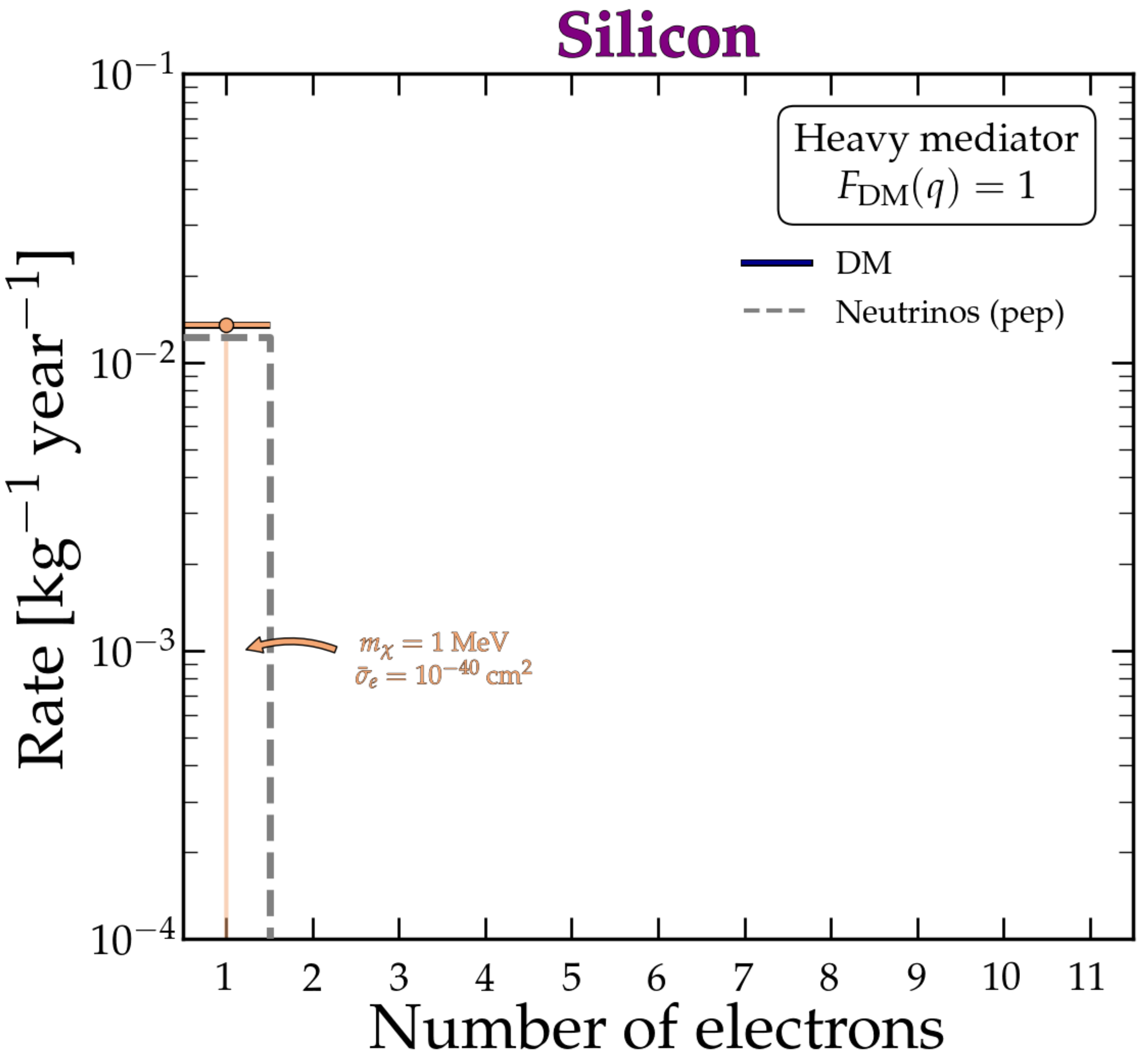
TNM, Boehm; 2409.04385

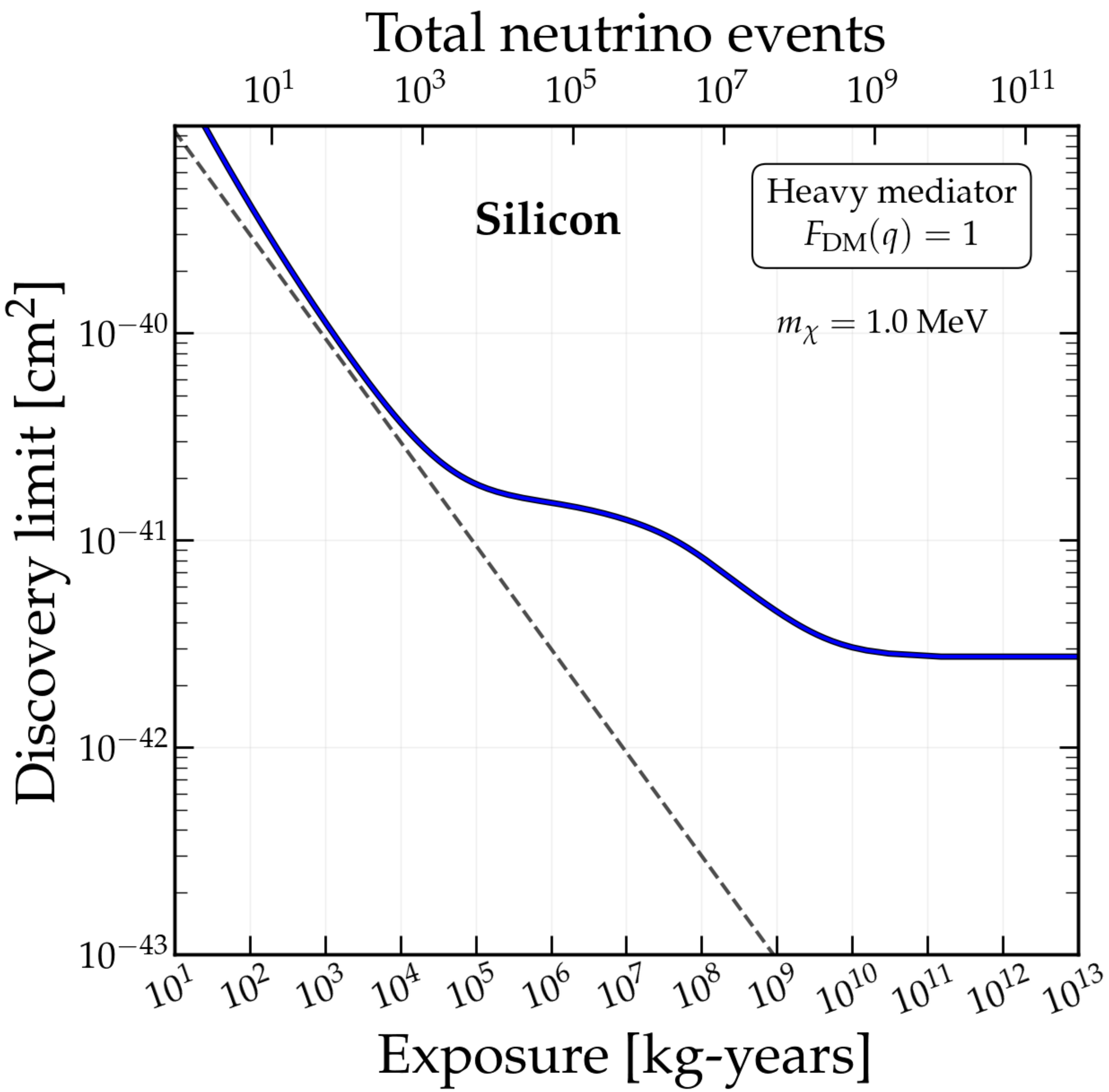
Backup

Neutrino flux

ν **Source**	$\mathbf{\Phi(1 \pm \delta\Phi/\Phi)}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
pp	$5.98(1 \pm 0.006) \times 10^{10}$
pep	$1.44(1 \pm 0.01) \times 10^{8}$
hep	$7.98(1 \pm 0.30) \times 10^{3}$
^{7}Be	$4.93(1 \pm 0.06) \times 10^{8}$
^{7}Be	$4.50(1 \pm 0.06) \times 10^{9}$
^{8}B	$5.16(1 \pm 0.02) \times 10^{6}$
^{13}N	$2.78(1 \pm 0.15) \times 10^{8}$
^{15}O	$2.05(1 \pm 0.17) \times 10^{8}$
^{17}F	$5.28(1 \pm 0.20) \times 10^{6}$

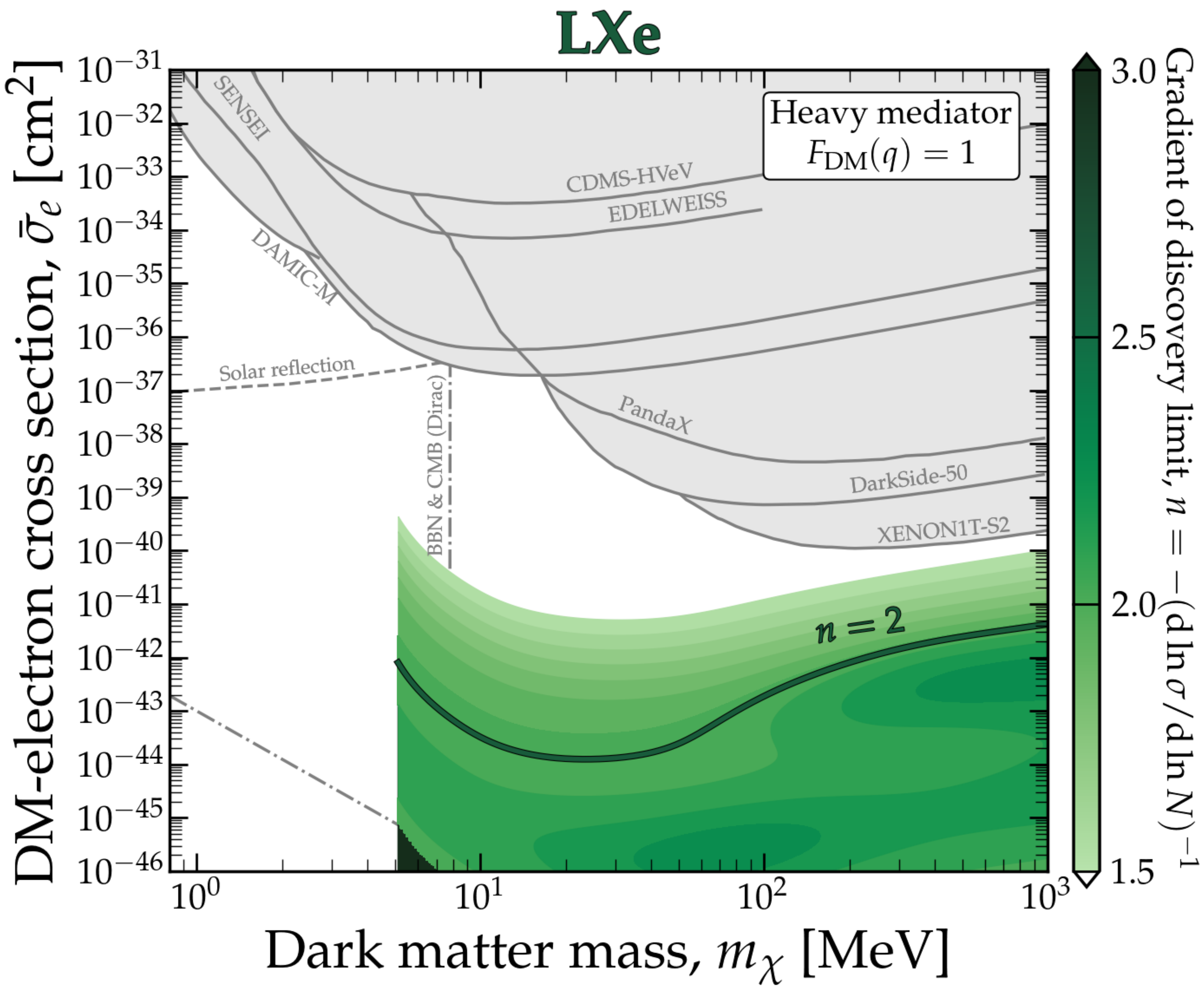
Low mass Si





Tarak Nath Maity

Neutrino fog Xe



Carew, Caddell, TNM, O'Hare; 2312.04303

Neutrino "floor" and future projections