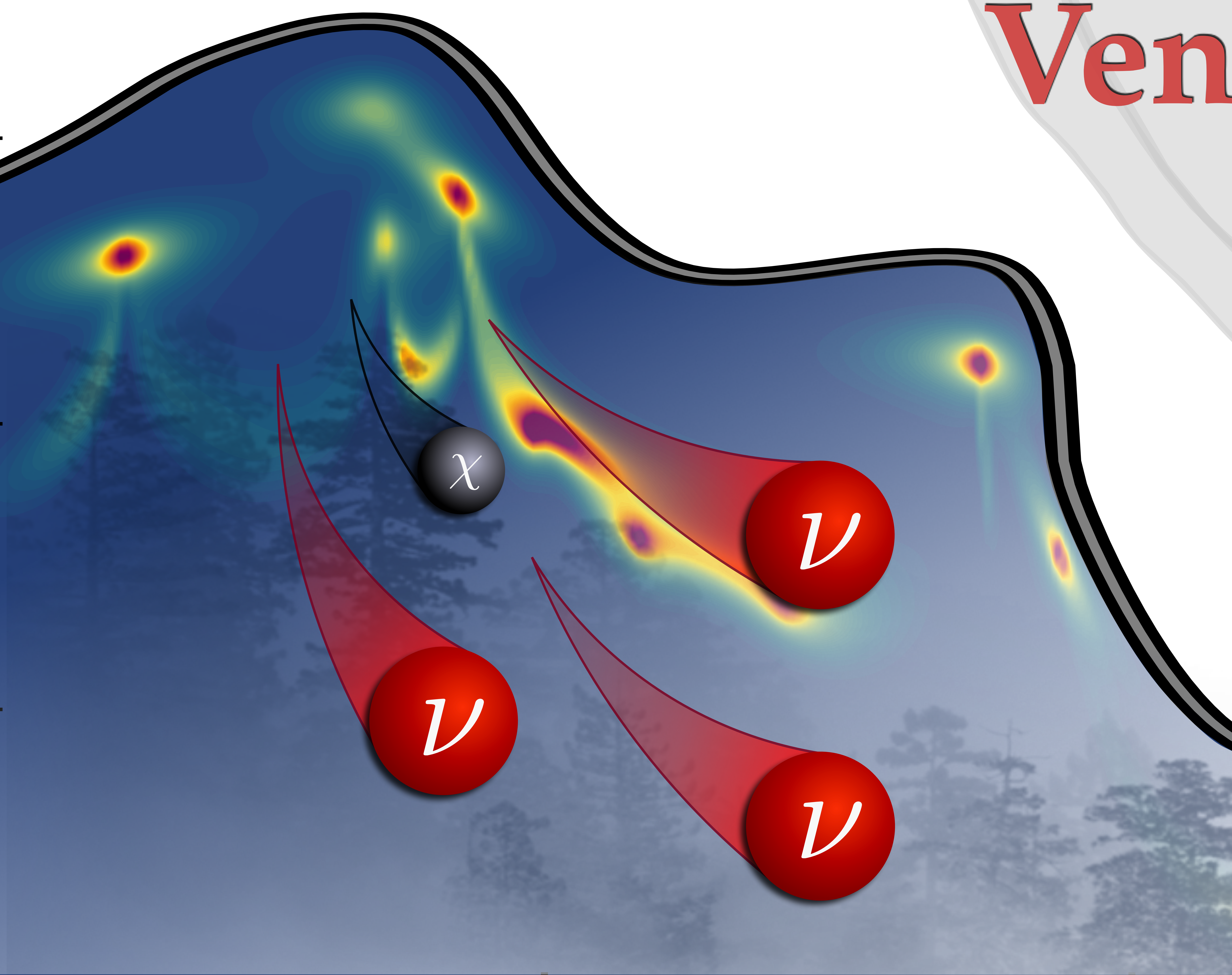
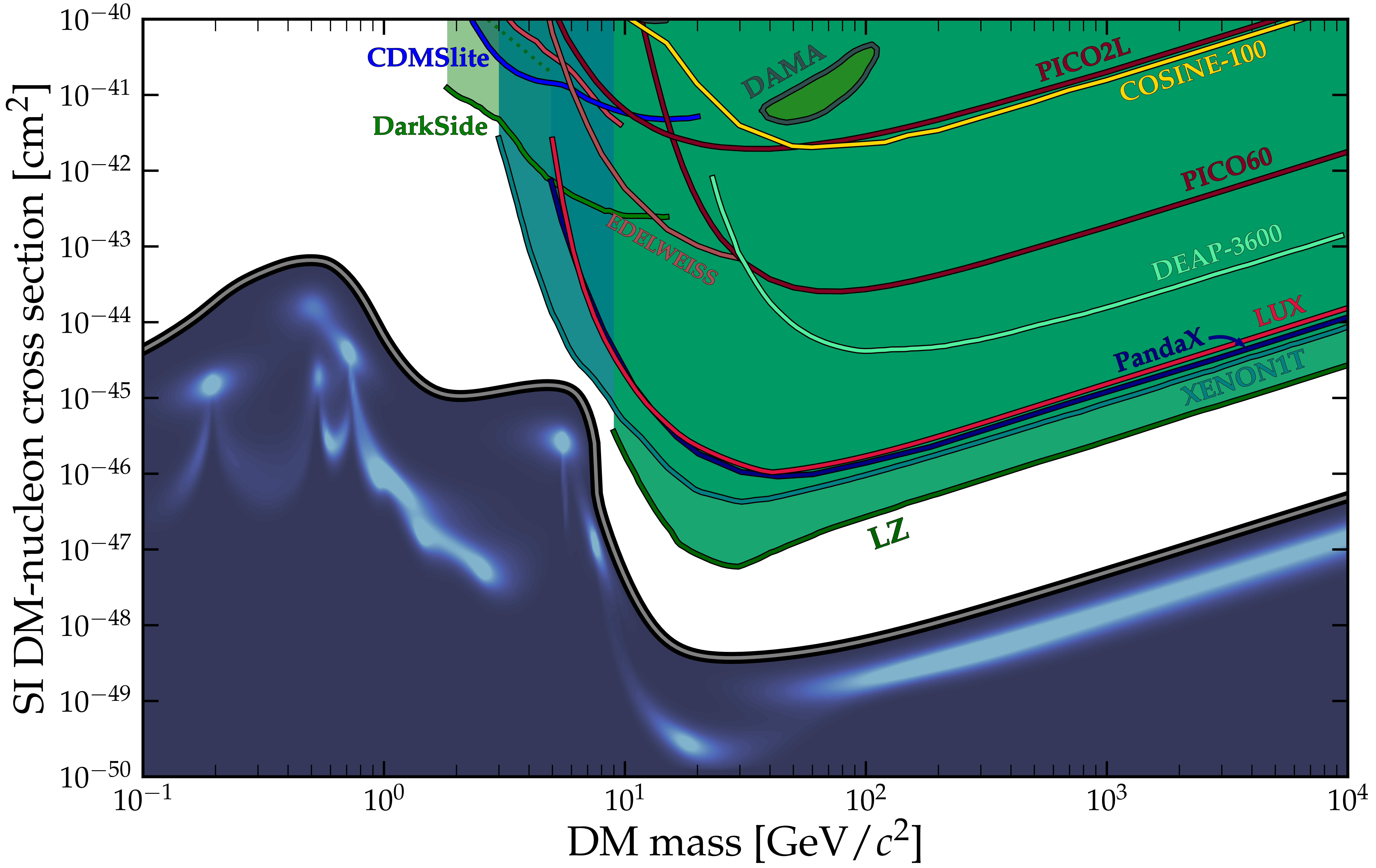
IDM 2022, Vienna

Venturing into the neutrino fog

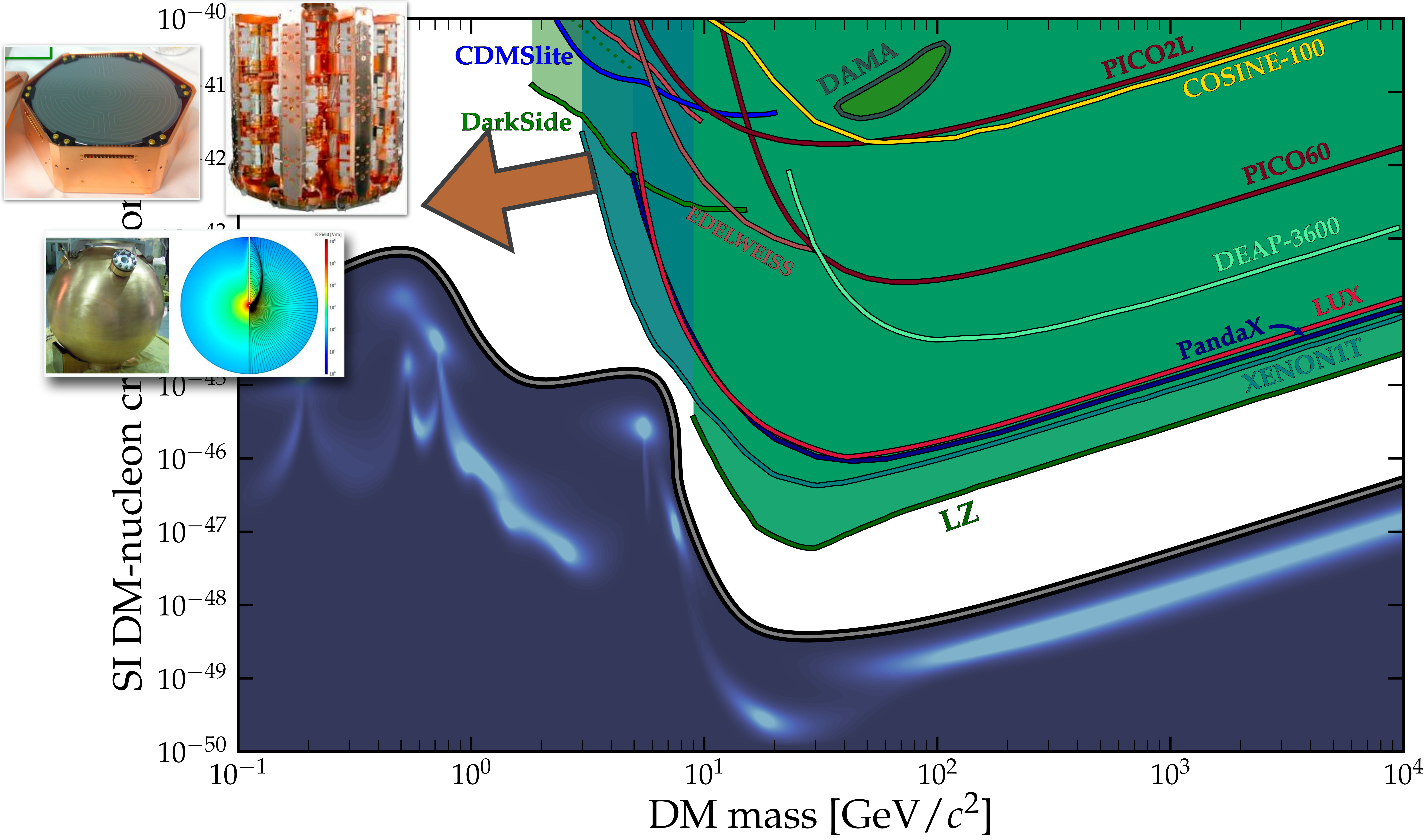
Ciaran O’Hare

University of Sydney





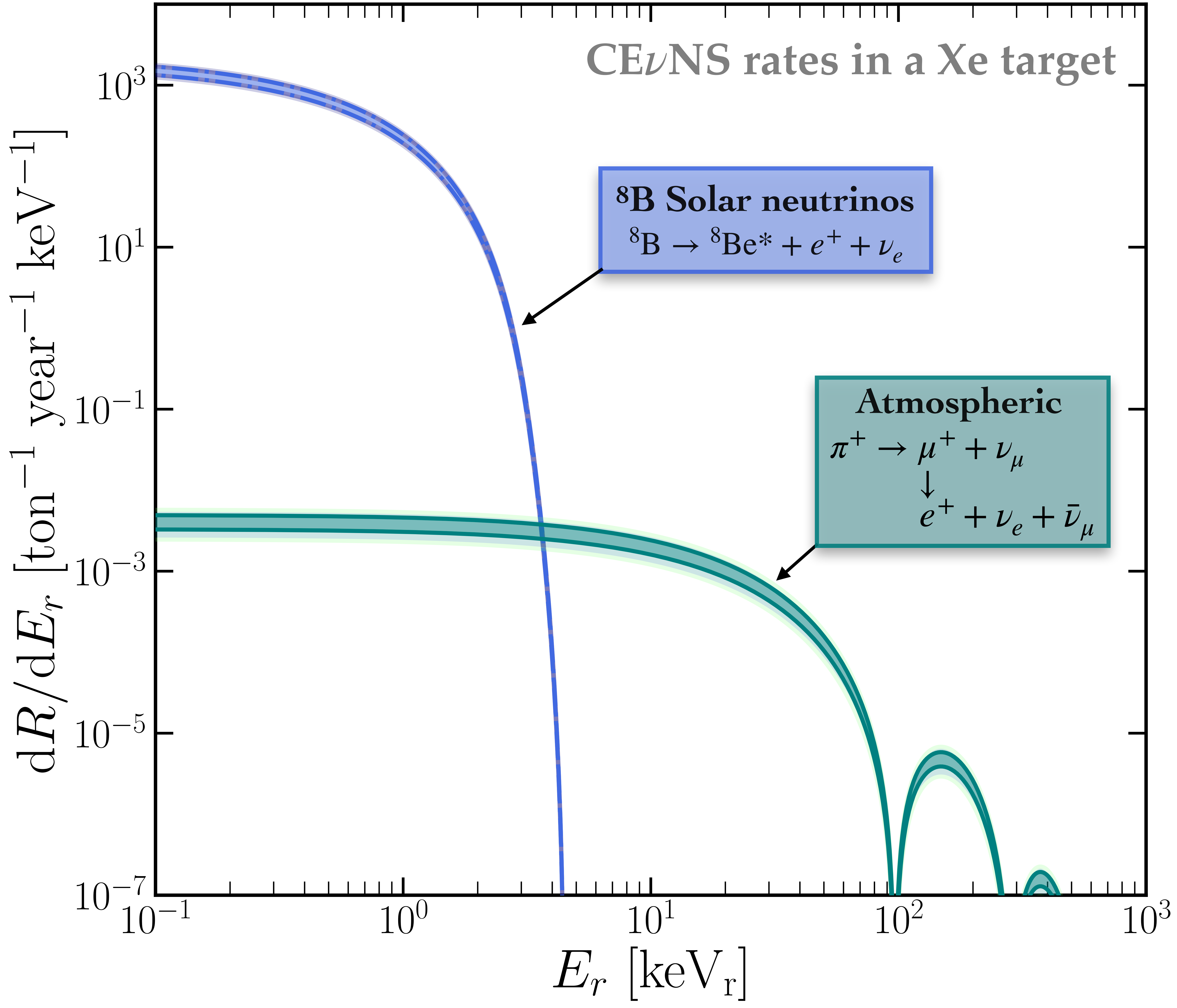
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
LZ
SI DM-nucleon cross section [cm^2]
DM mass [GeV/c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
DEAP-3600
EDELWEISS
LUX
PandaX
XENON1T
LZ
SI DM-nucleon cr
DM mass [GeV / c^2]
10^{-40}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

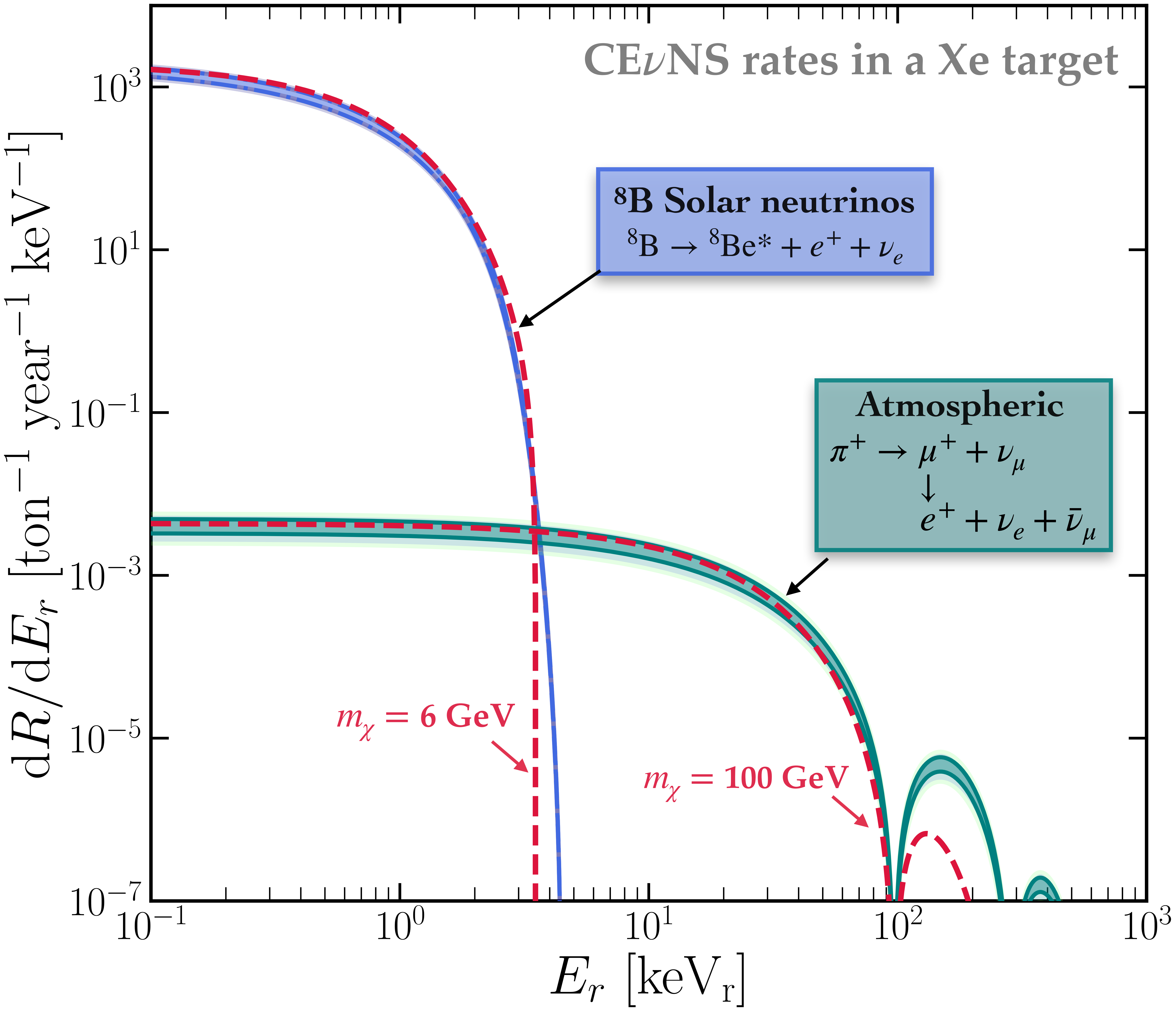
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
DEAP-3600
EDELWEISS
PandaX
XENO
LZ
SI DM-nucleon cr
DM mass [GeV/c^2]
10^{-40}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}


CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
PandaX
XENON
LZ
Neutrino fog
SI DM-nucleon cross section
DM mass [GeV/c^2]
10^{-40}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



CEvNS will be observed in DM experiments very soon!

^{8}B solar and atmospheric neutrinos are going to be the troublemakers, they look just like 6 GeV and 100 GeV WIMPs in Xenon



CEvNS will be observed in DM experiments very soon!

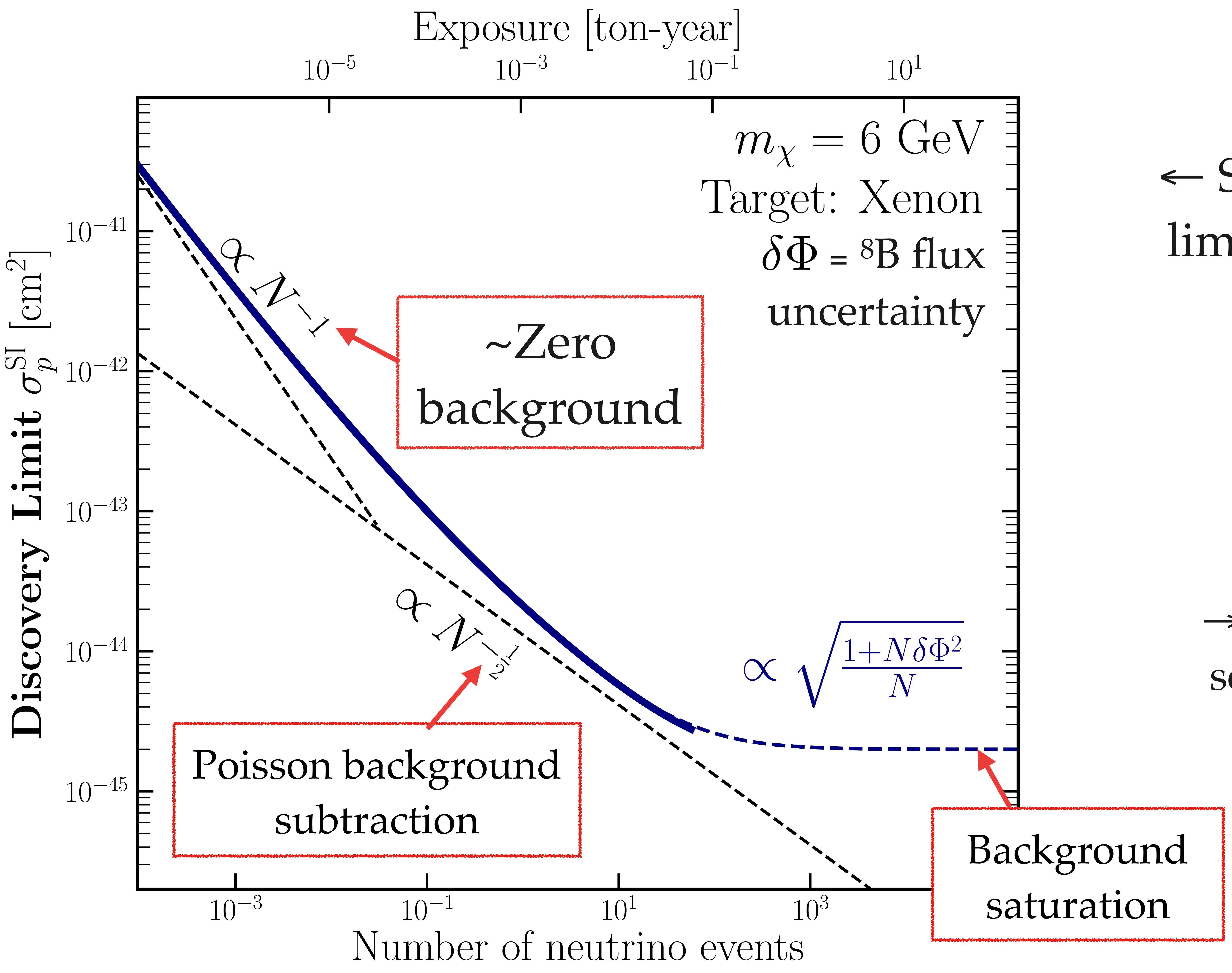
^{8}B solar and atmospheric neutrinos are going to be the troublemakers, they look just like 6 GeV and 100 GeV WIMPs in Xenon

The neutrino "floor" as it's usually presented

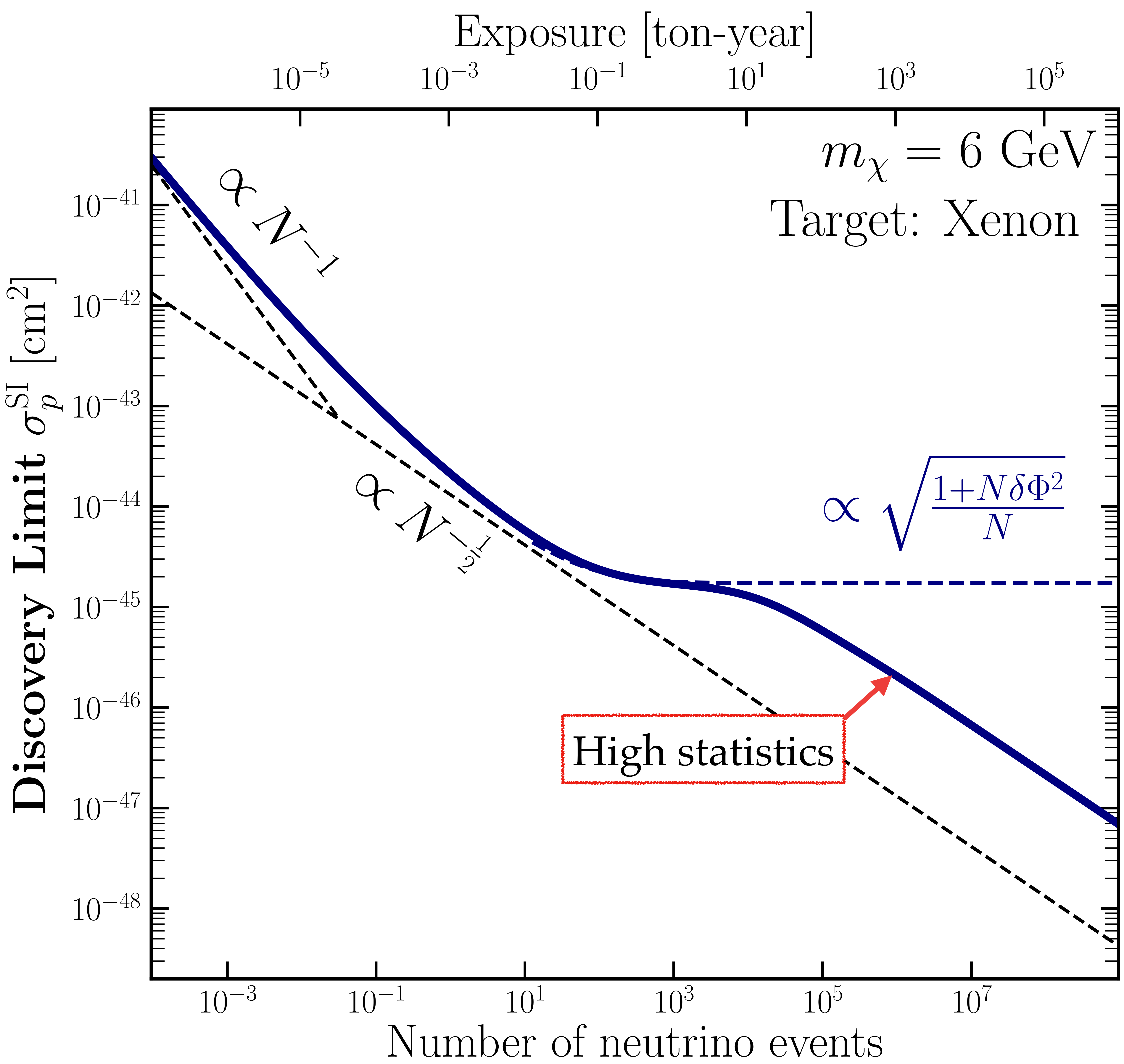
e.g. for LXe TPCs

The neutrino "floor"

← Scaling of a DM discovery limit for increasing exposure



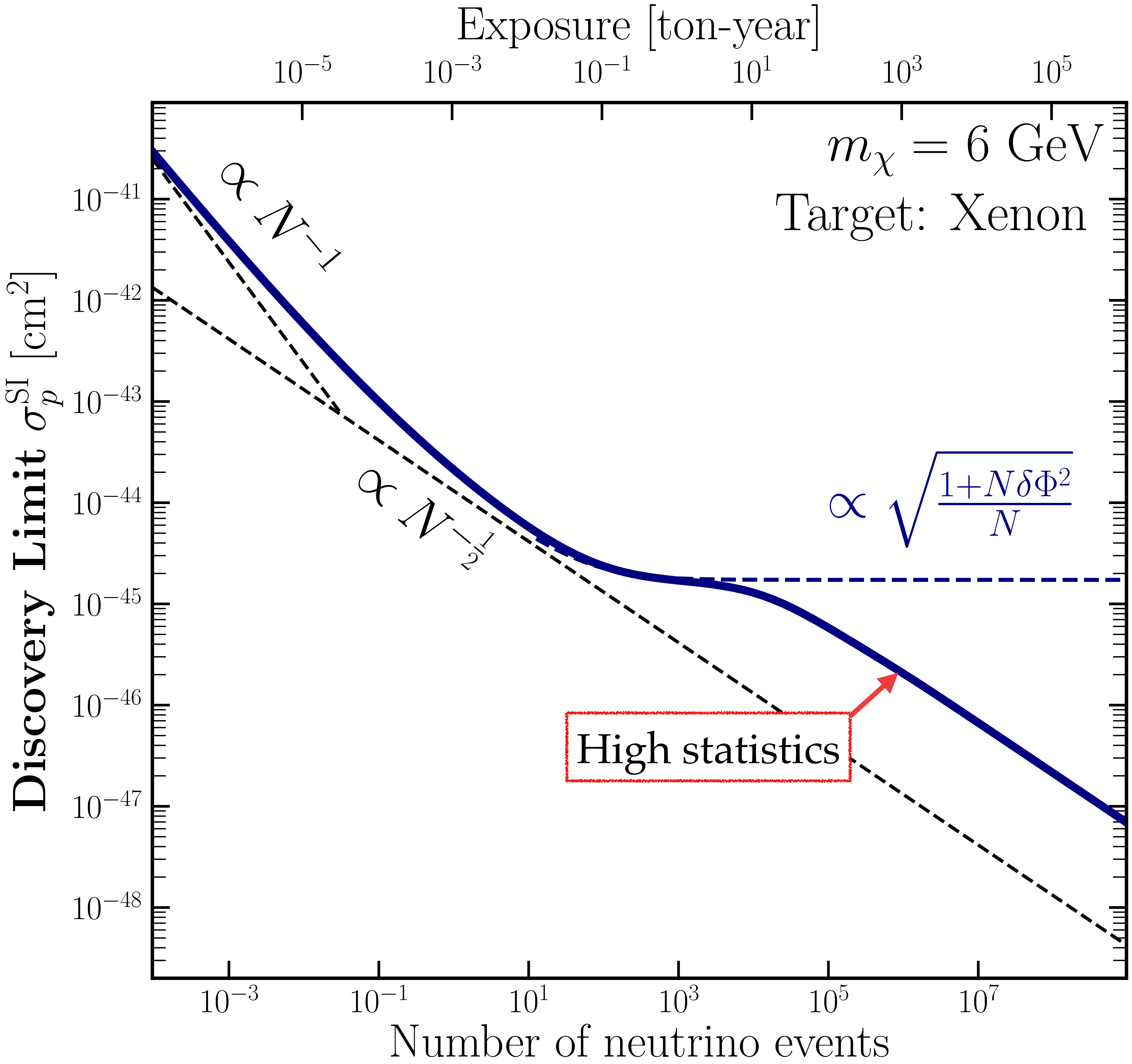
→ Experiment can't probe cross sections smaller than those that generate an excess in events smaller than estimated background fluctuations



The full story:

There is no neutrino "floor"

DM/CEvNS signals not **identical**
→ with high statistics, an experiment can bootstrap itself through the background uncertainty using spectral information (this is textbook statistics really, it's the limit when the likelihood dominates over the prior)

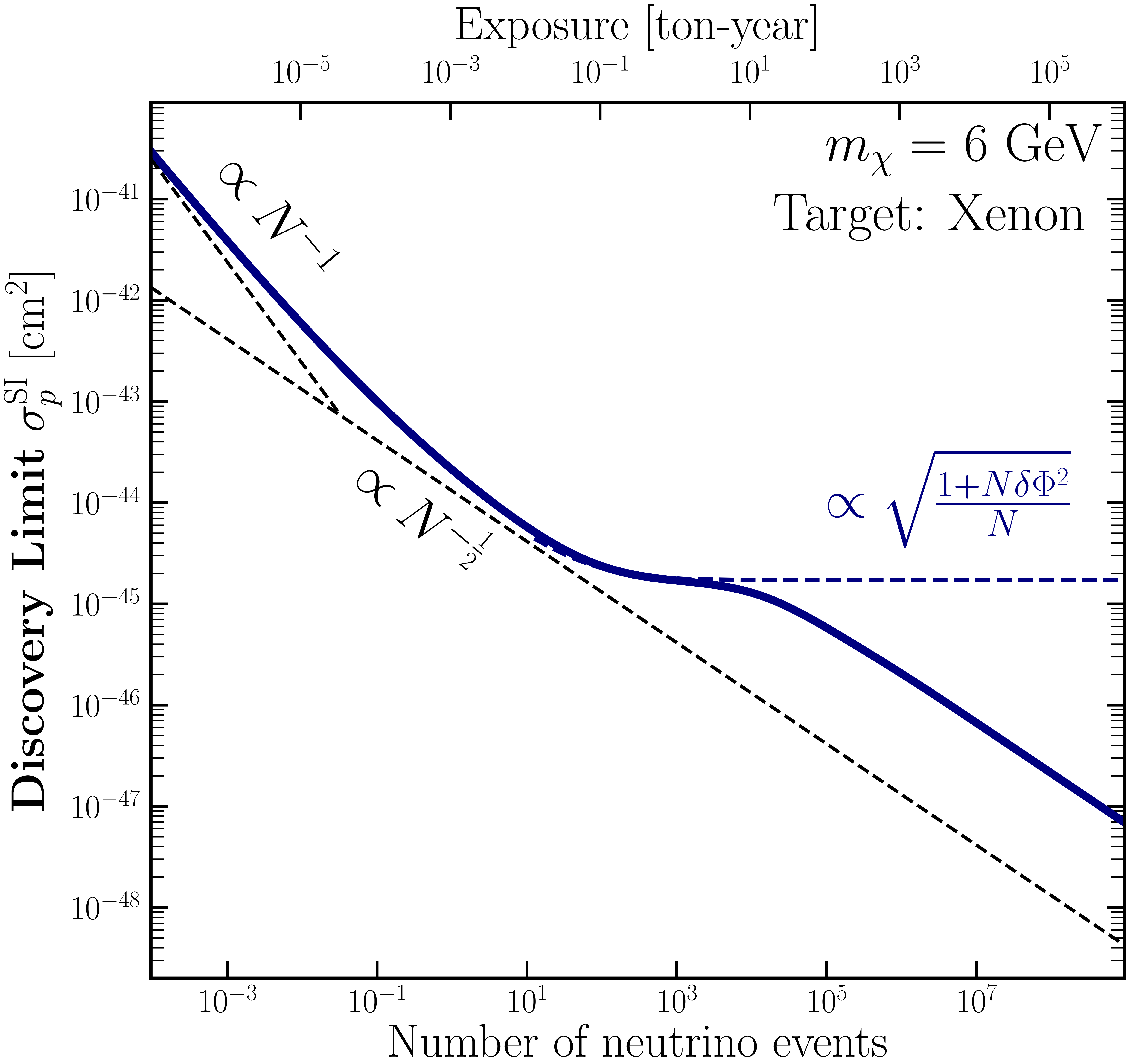


The full story:

<u>There is no neutrino "floor"</u>

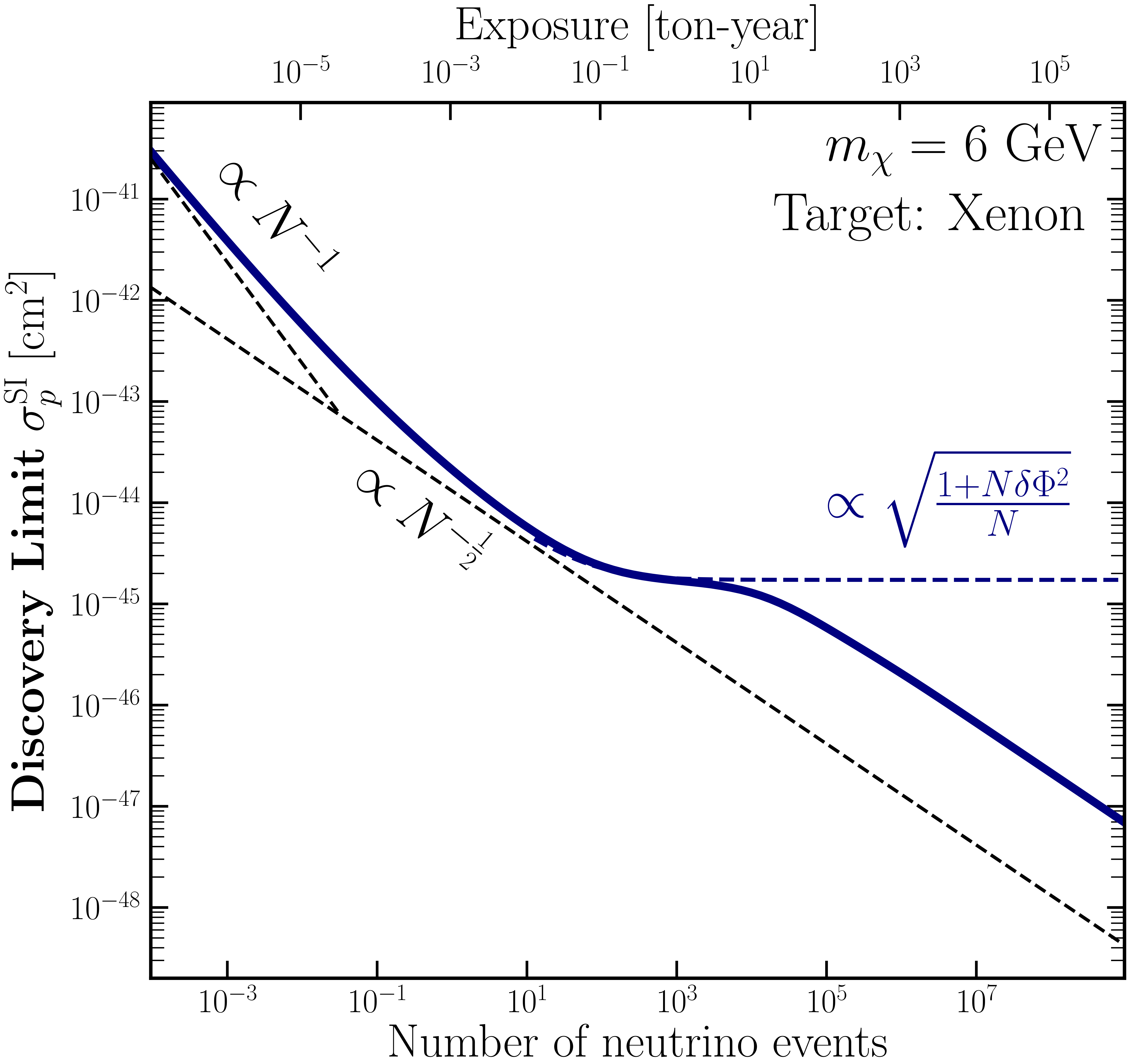
DM/CEvNS signals not **identical** → with high statistics, an experiment can bootstrap itself through the background uncertainty using spectral information (this is textbook statistics really, it's the limit when the likelihood dominates over the prior)

→ Required exposures are large yes, but there can never be a hard sensitivity floor unless the signal and background are *identical*



<u>How should we define it then?</u>

There is no “floor”, but we can quantity the neutrino “fog” by looking at the scaling



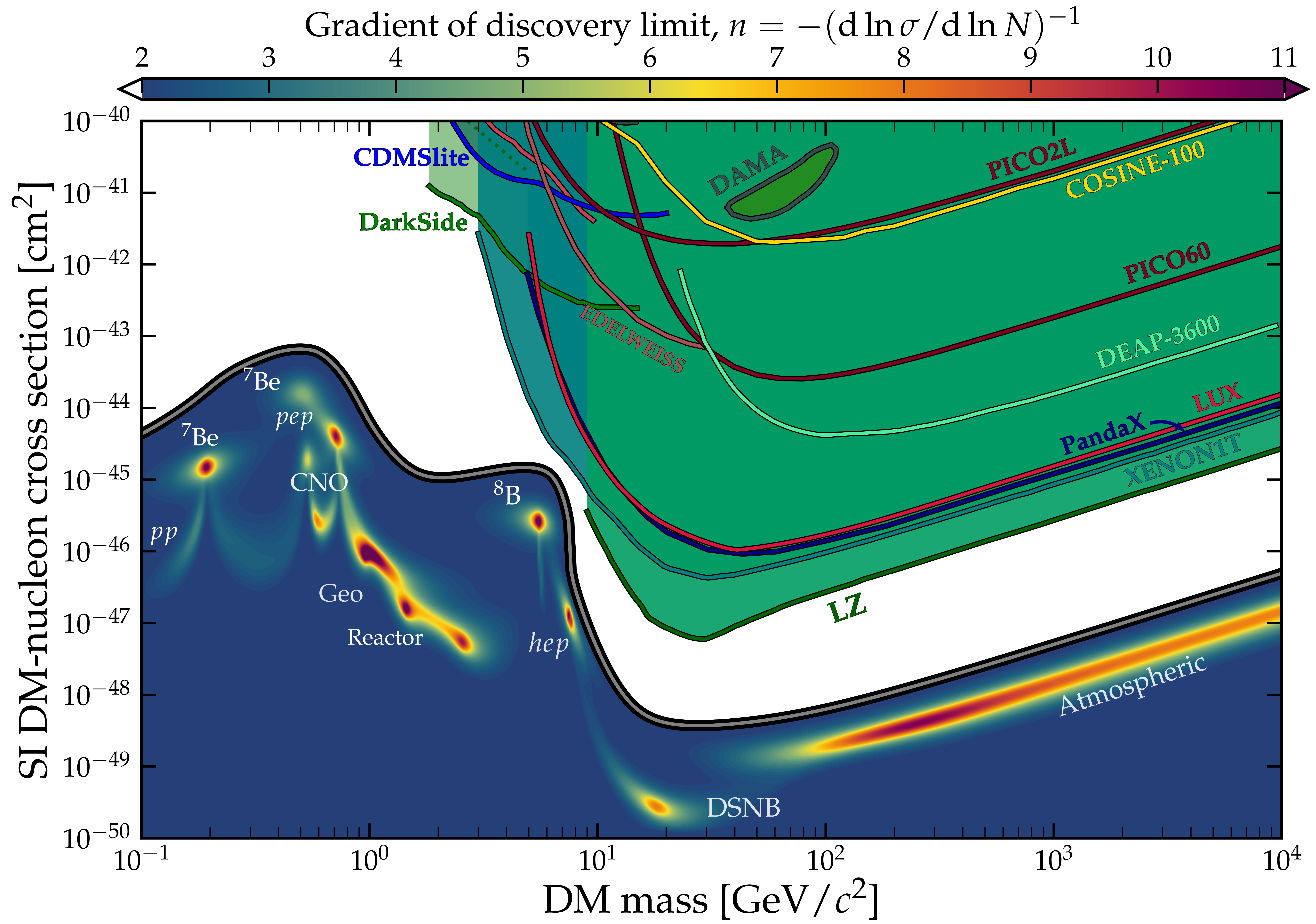
How should we define it then?

There is no "floor", but we can quantity the neutrino "fog" by looking at the scaling

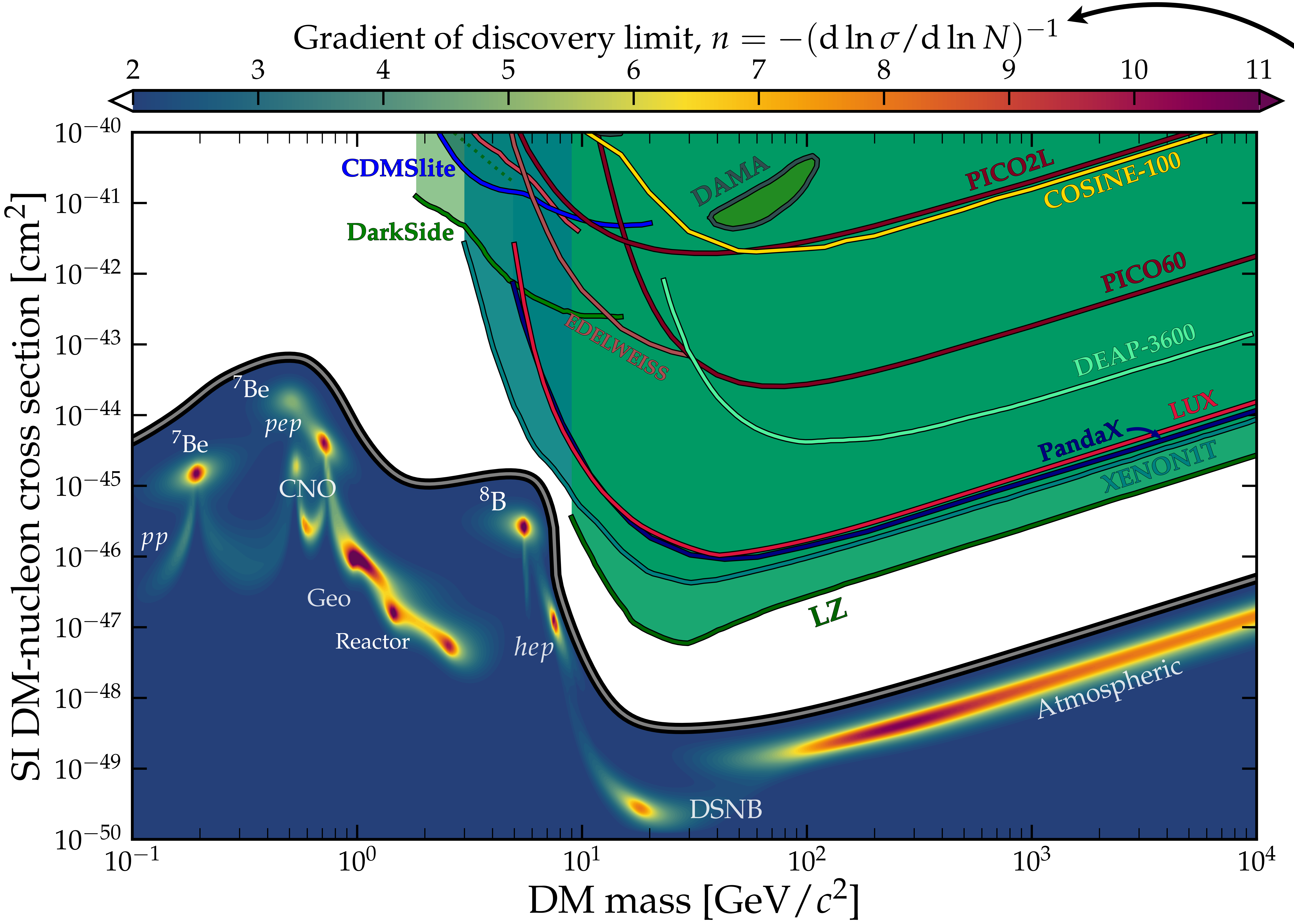
Define:

$$n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$$

So $n = 2$ for Poissonian background subtraction and $n > 2$ for worse than Poissonian

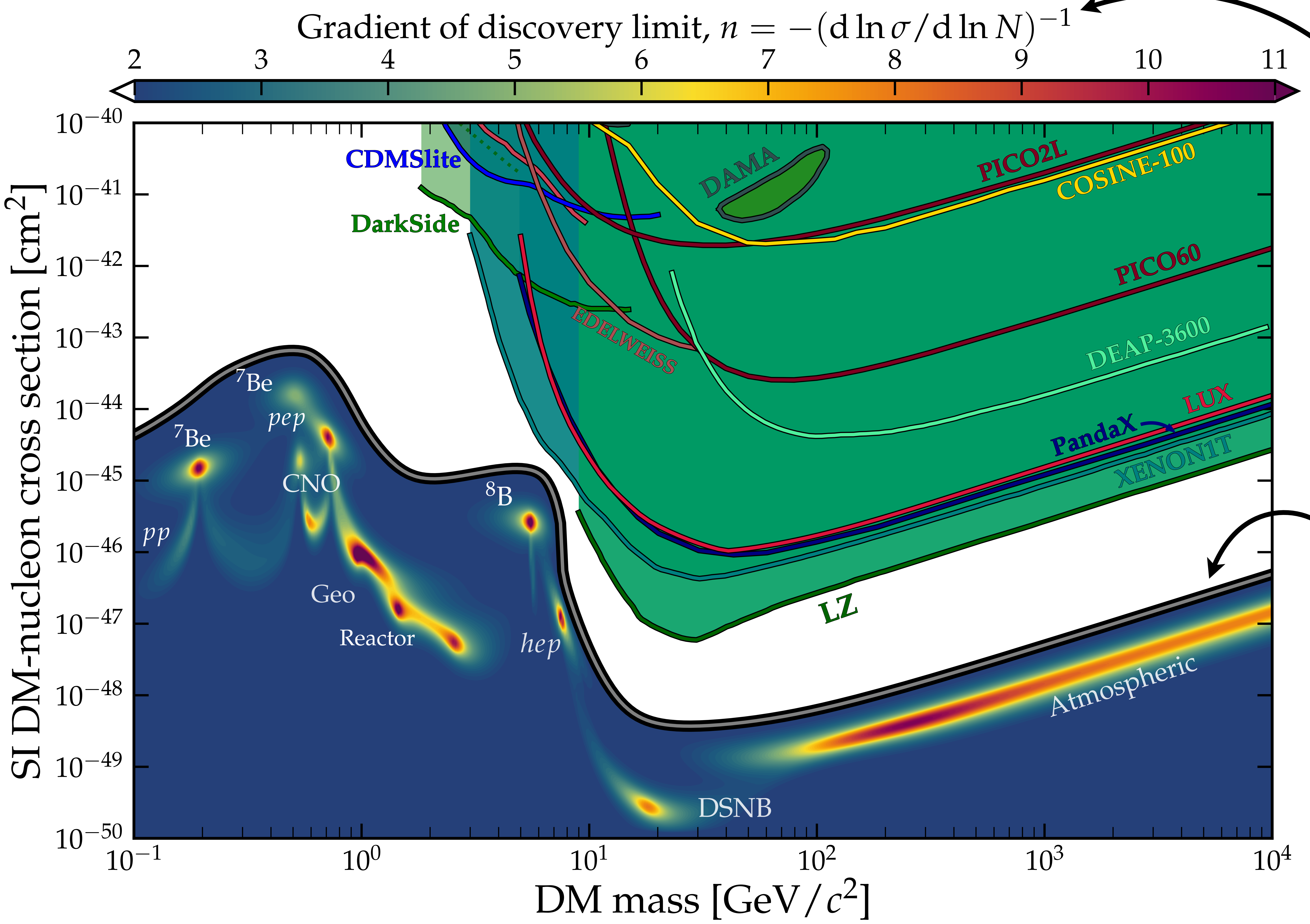


O'Hare [2109.03116]



n parameterises the "fogginess" of the neutrino fog
→ note that it's not uniformly foggy everywhere

O'Hare [2109.03116]



n parameterises the "fogginess" of the neutrino fog → note that it's not uniformly foggy everywhere

The "edge" of the fog (*n*>2), once you get past it, you can never do better than Poissonian again.

My 2¢: this is what should be shown on plots

O'Hare [2109.03116]

If we want to..

1. Continue the search for DM *into* the neutrino fog

Reasons to want that: Athron+ [1705.07935], Beskidt+ [1703.01255], Roskowski+ [1411.5214] , Hisano+[1104.0228], Arcadi+[1711.02110], Baker+ [1912.02830], Arina+[1912.04008] …

2. Be able to study both DM and neutrino signals in experiments

Reasons to want that: Harnik+ [1202.6073], Pospelov+ [1103.3261], Franco+[1510.04196], Schumann+[1506.08309], Strigari [1604.00729], Dent+[1612.06350], Chen+[1610.04177], Cerdeño+[1604.01025], Dutta+[1901.08876], Lang+[1606.09243], Bertuzzo+[1701.07443], Dutta+[1705.00661], Aristizabal Sierra+[1712.09667] …

Then we need to clear the fog

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

1. Detect *a lot* of events

2. Use annual modulation

3. Have multiple target nuclei

4. Improve neutrino flux measurements

5. Use directional detectors

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

1. ~~Detect *a lot* of events~~

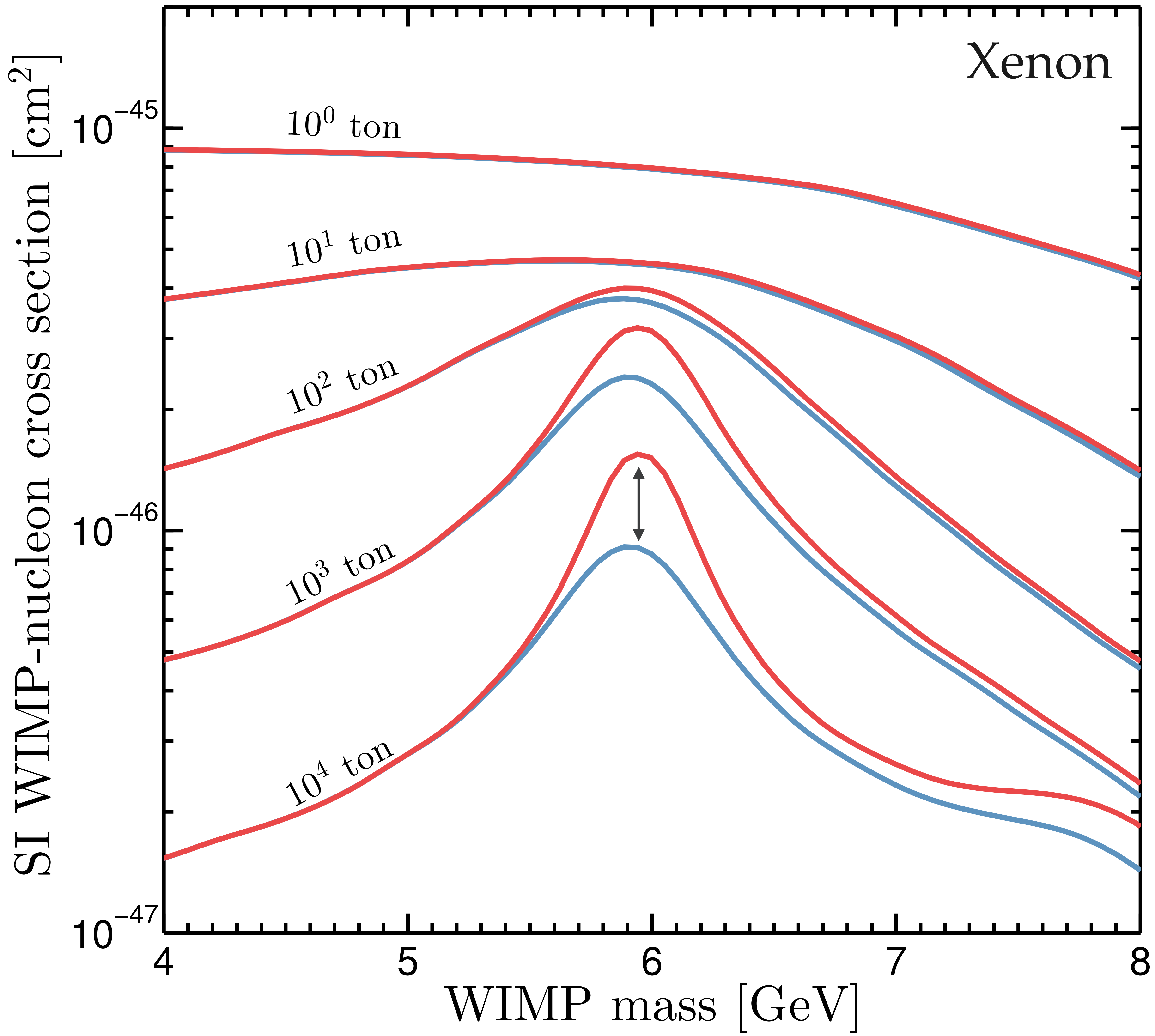
2. Use annual modulation

3. Have multiple target nuclei

4. Improve neutrino flux measurements

5. Use directional detectors

1. Annual modulation

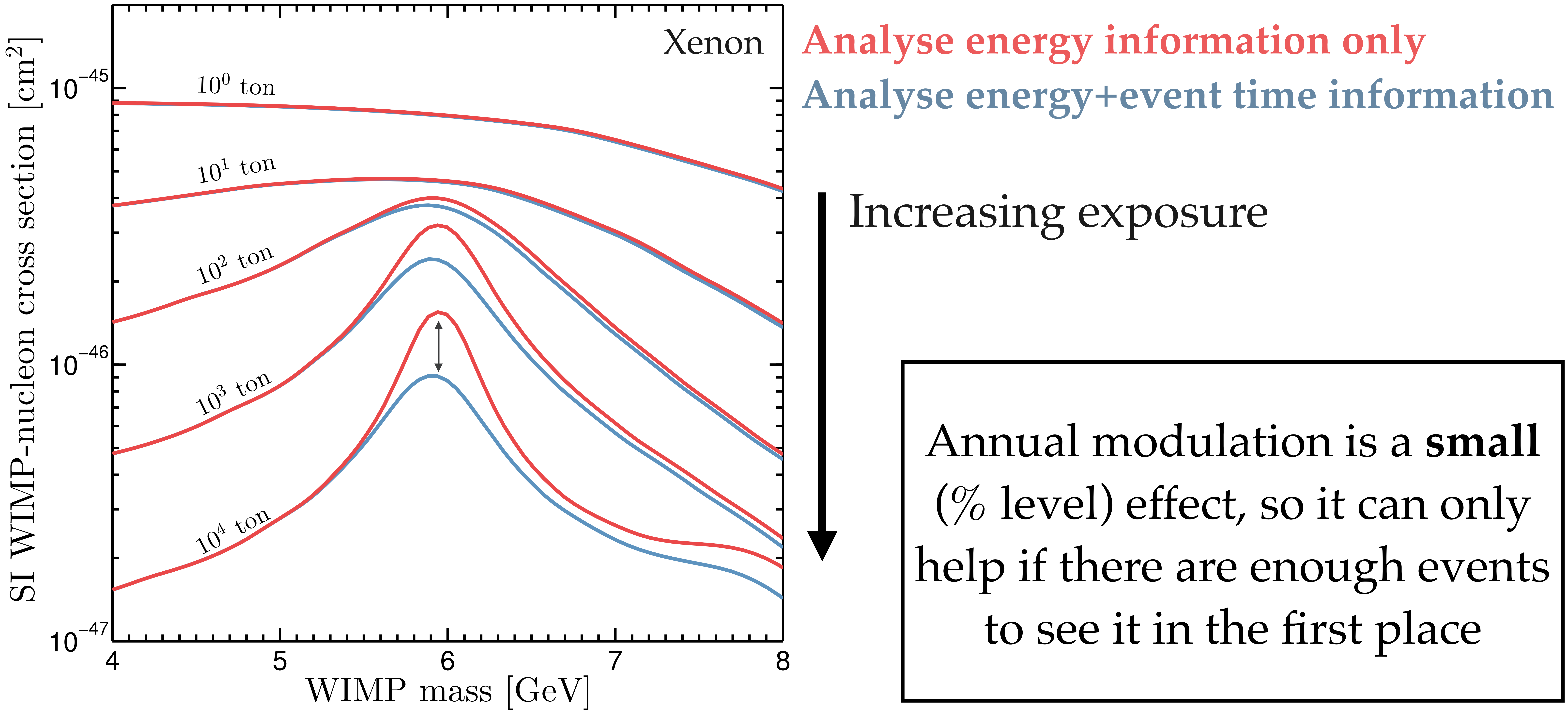


Analyse energy information only

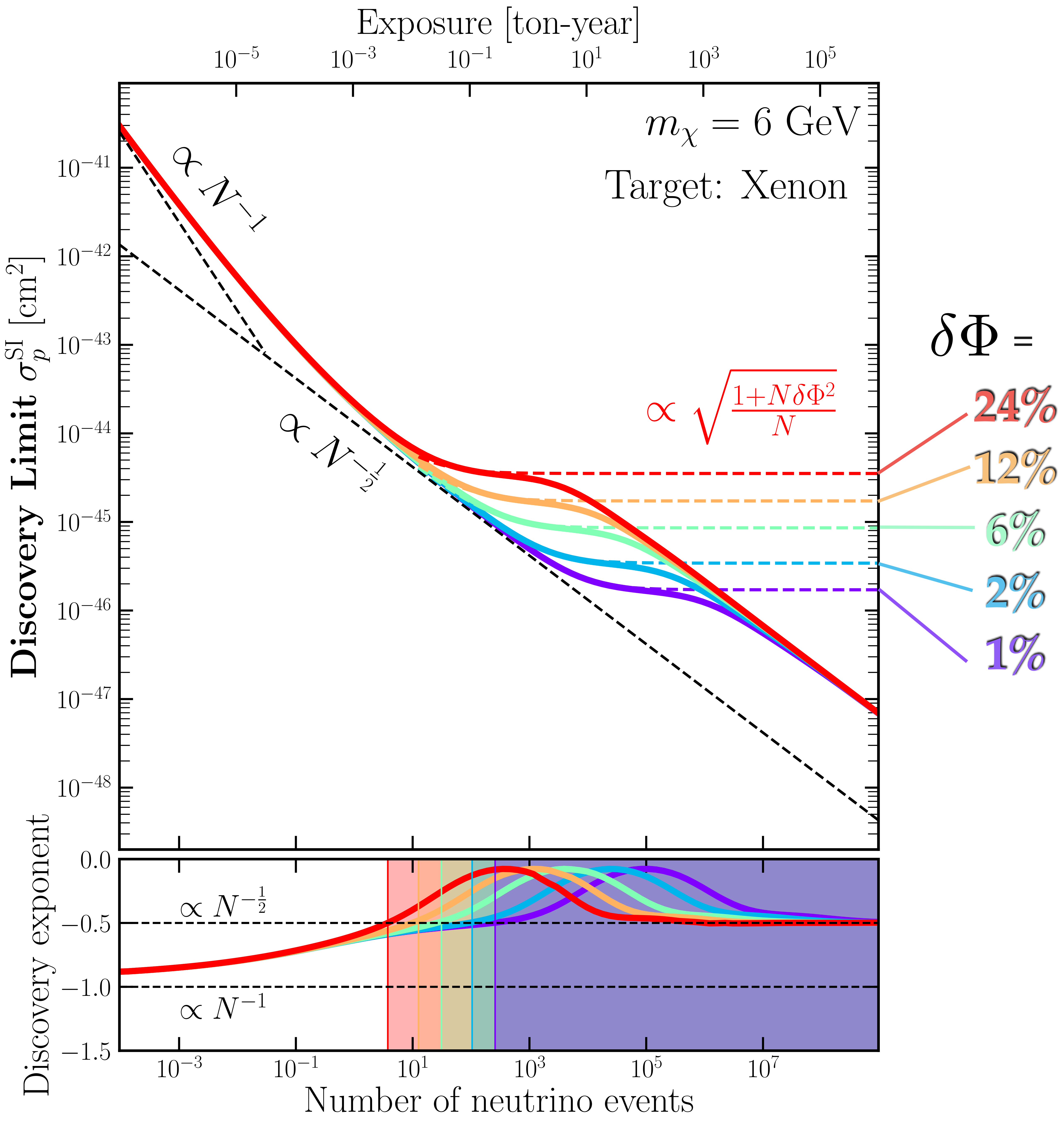
Analyse energy+event time information

Increasing exposure

1. Annual modulation



Annual modulation is a **small** (% level) effect, so it can only help if there are enough events to see it in the first place



2. Flux uncertainties

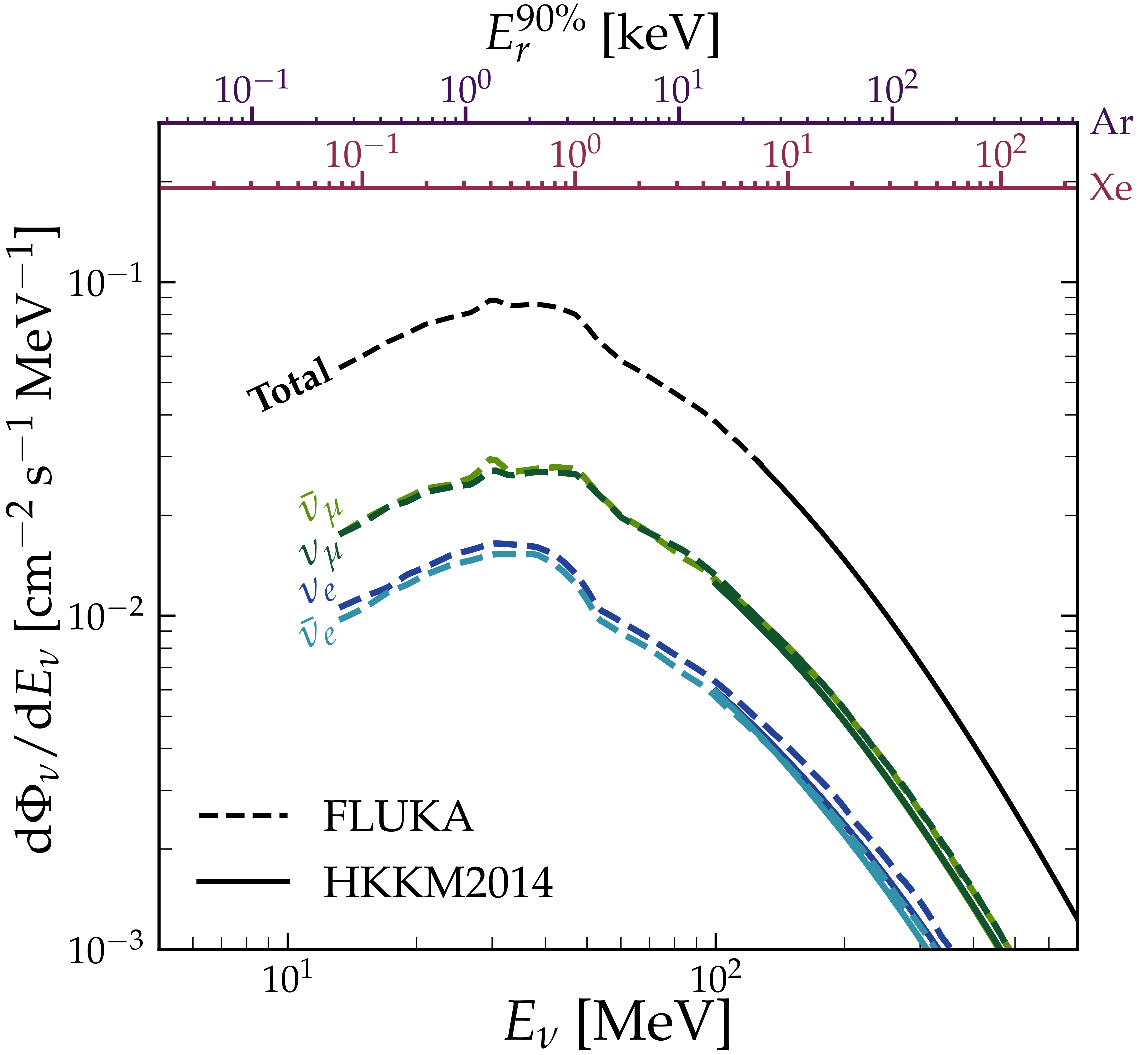
The better the neutrino flux prior is, the better you understand the background to begin with

→ onset of neutrino fog is pushed lower

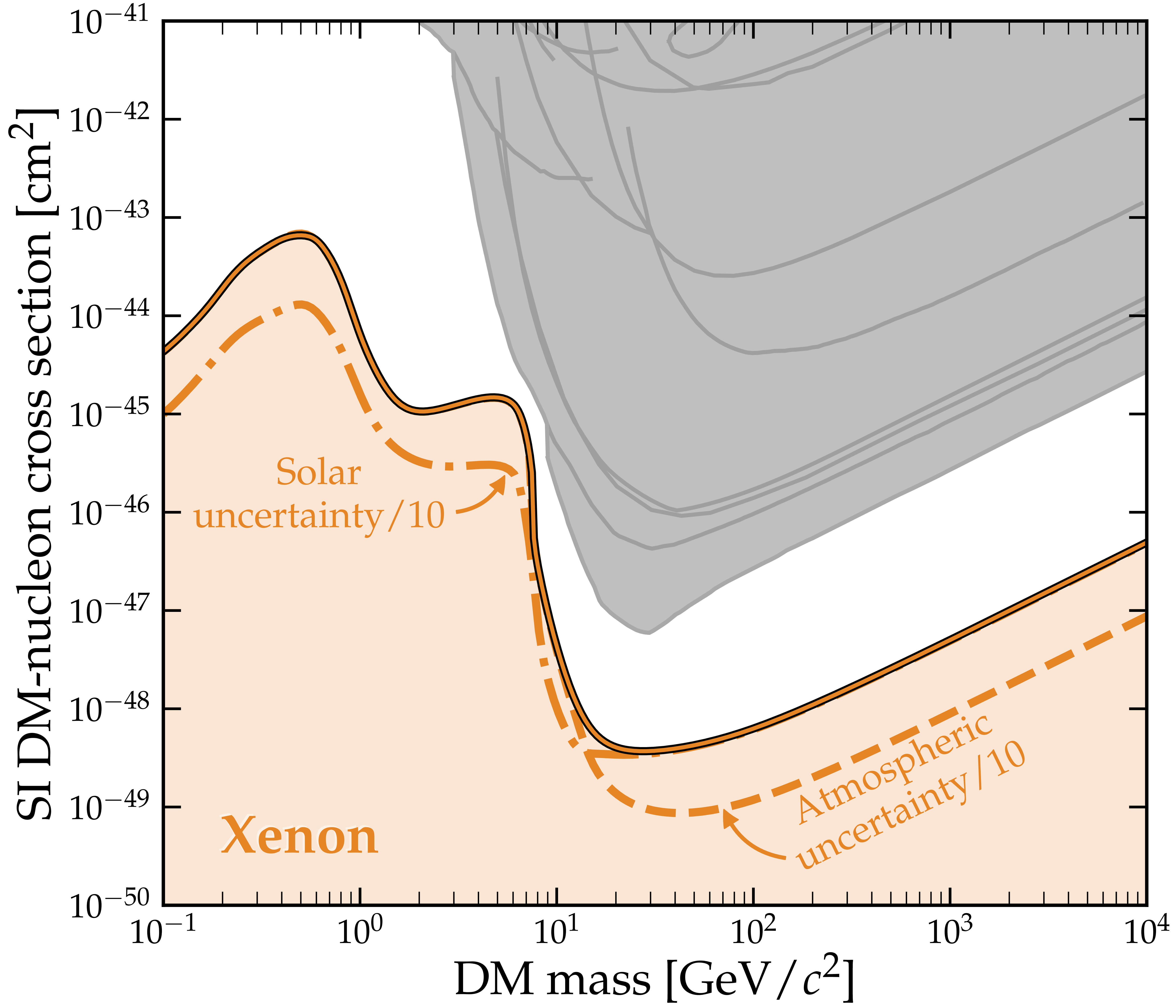
2. Flux uncertainties

ν **type**		$\Phi(1 \pm \delta\Phi/\Phi)$ $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	$\times 10^n$
Solar	*pp*	$5.98\,(1 \pm 0.006)$	10^{10}
	pep	$1.44\,(1 \pm 0.01)$	10^{8}
	hep	$7.98\,(1 \pm 0.30)$	10^{3}
	^{7}Be	$4.93\,(1 \pm 0.06)$	10^{8}
	^{7}Be	$4.50\,(1 \pm 0.06)$	10^{9}
	^{8}B	$5.16\,(1 \pm 0.02)$	10^{6}
	^{13}N	$2.78\,(1 \pm 0.15)$	10^{8}
	^{15}O	$2.05\,(1 \pm 0.17)$	10^{8}
	^{17}F	$5.29\,(1 \pm 0.20)$	10^{6}
Geo.	U	$4.34(1 \pm 0.20)$	10^{6}
	Th	$4.23(1 \pm 0.25)$	10^{6}
	K	$2.05(1 \pm 0.17)$	10^{7}
Reactor		$3.06(1 \pm 0.08)$	10^{6}
DSNB		$8.57(1 \pm 0.50)$	10^{1}
Atmospheric		$1.07(1 \pm 0.25)$	10^{1}

Low-E tail of **atmospheric flux** not yet measured at the relevant energies, 25% uncertainty is advisory from simulations. This is an important background for detecting DSNB so a measurement will happen in the future for sure



2. Effect of Flux uncertainties (for illustration only)



With smaller flux uncertainties the boundary of the neutrino fog is pushed to lower cross sections

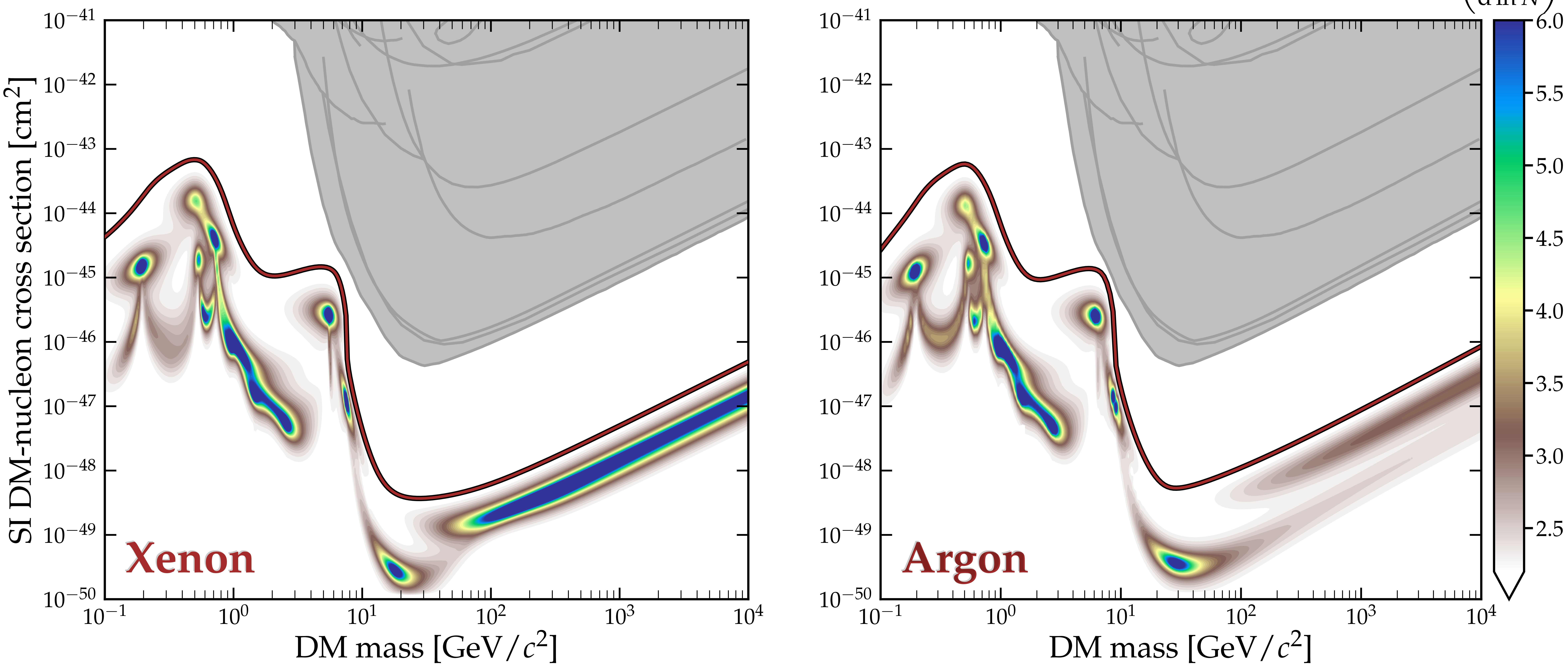
(This could make all the difference!)

O'Hare [2109.03116]

3. Target complementarity: Xe & Ar

High mass (>100 GeV) **DM** (SI) versus **Atmospheric neutrinos**

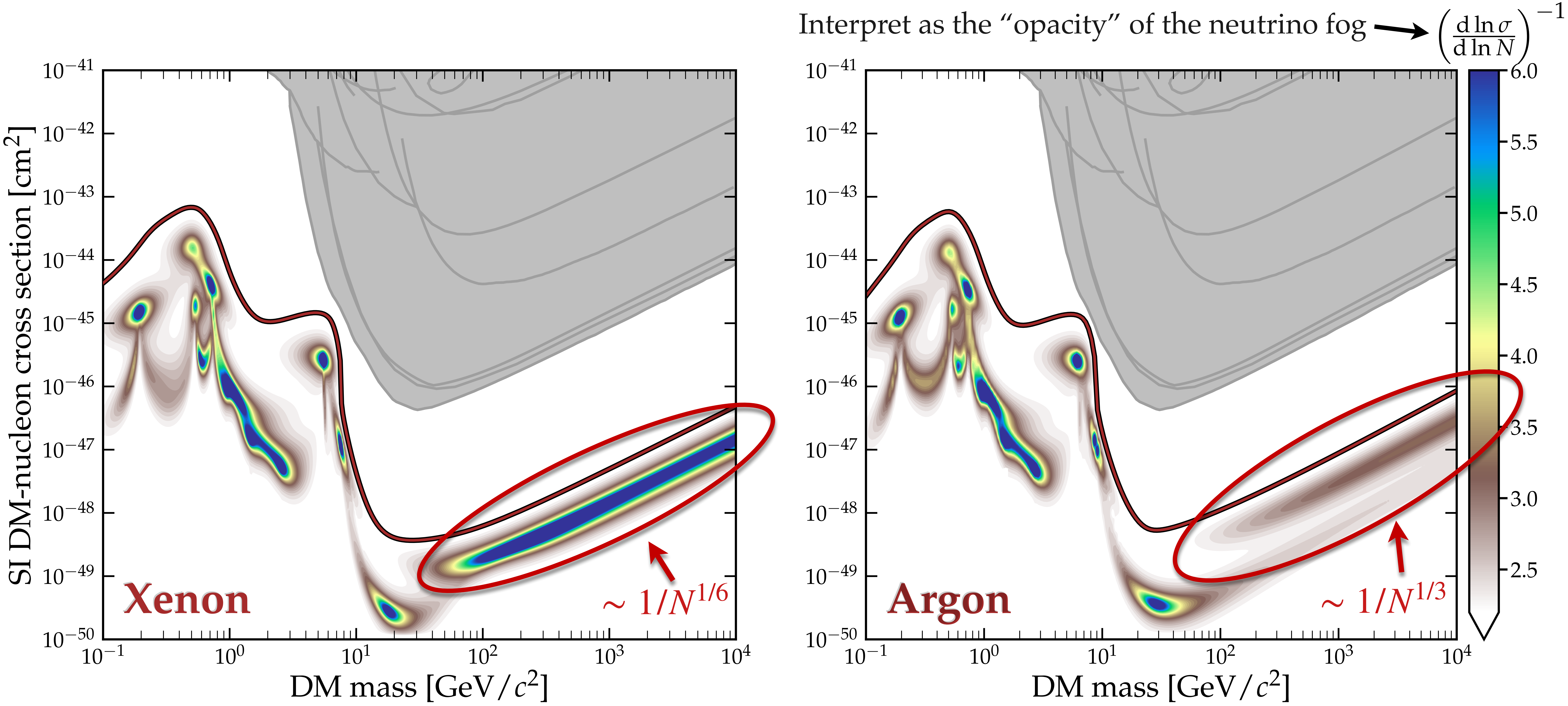
Interpret as the "opacity" of the neutrino fog → $\left(\frac{d \ln \sigma}{d \ln N}\right)^{-1}$



O'Hare [2109.03116]

3. Target complementarity: Xe & Ar

High mass (>100 GeV) **DM** (SI) versus **Atmospheric neutrinos**



O'Hare [2109.03116]

Taken to the extreme: Ultimate multi-ton Xe+Ar analysis

"Standard" strategy:

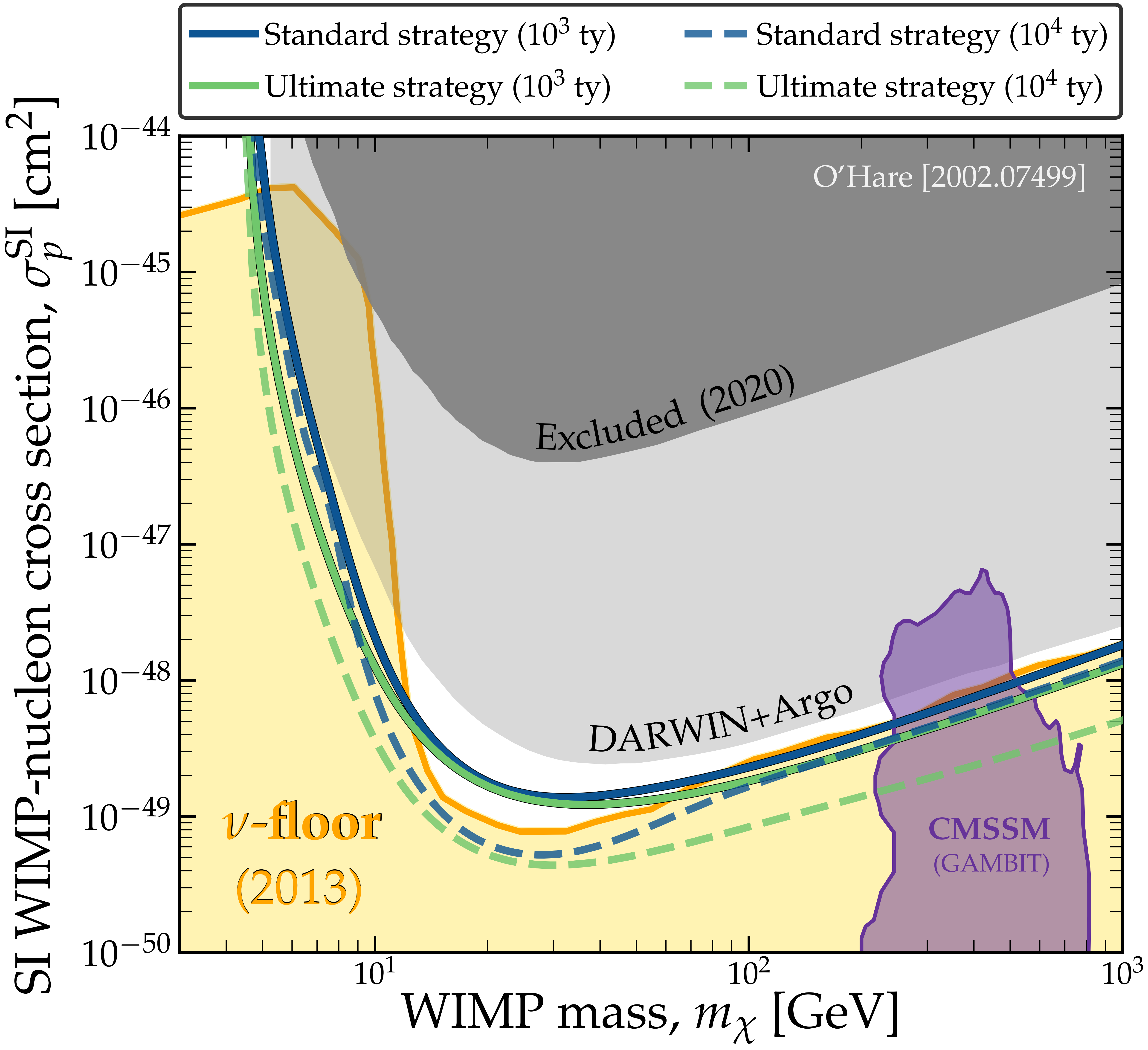
Xenon experiment only

"Ultimate" strategy:

+ Xenon / Argon combined analysis

+annual modulation

+Atmospheric flux uncertainty 25% → 10%



My 2¢: Most of this improvement is driven by neutrino flux improvement. Not clear to me if in practice the gain from having both Xe+Ar would outweigh the combined systematic uncertainties from two experiments

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

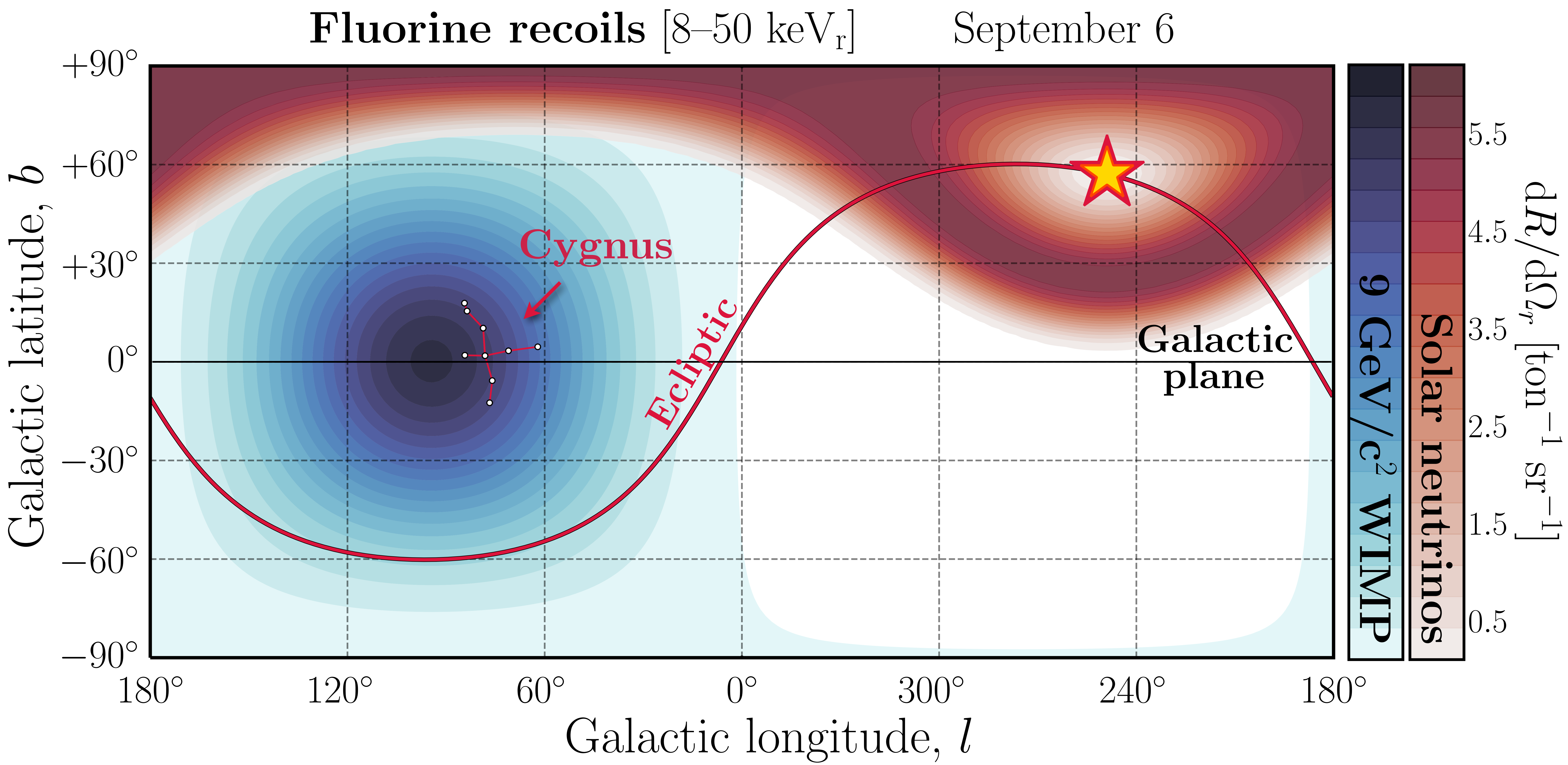
1. ~~Detect *a lot* of events~~
2. ~~Use annual modulation~~ ← Not good enough
3. ~~Have multiple target nuclei~~
4. Improve neutrino flux measurements ← Good, but not up to us
5. Use directional detectors

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

1. ~~Detect *a lot* of events~~
2. ~~Use annual modulation~~ ← Not good enough
3. ~~Have multiple target nuclei~~
4. Improve neutrino flux measurements ← Good, but not up to us
5. Use directional detectors

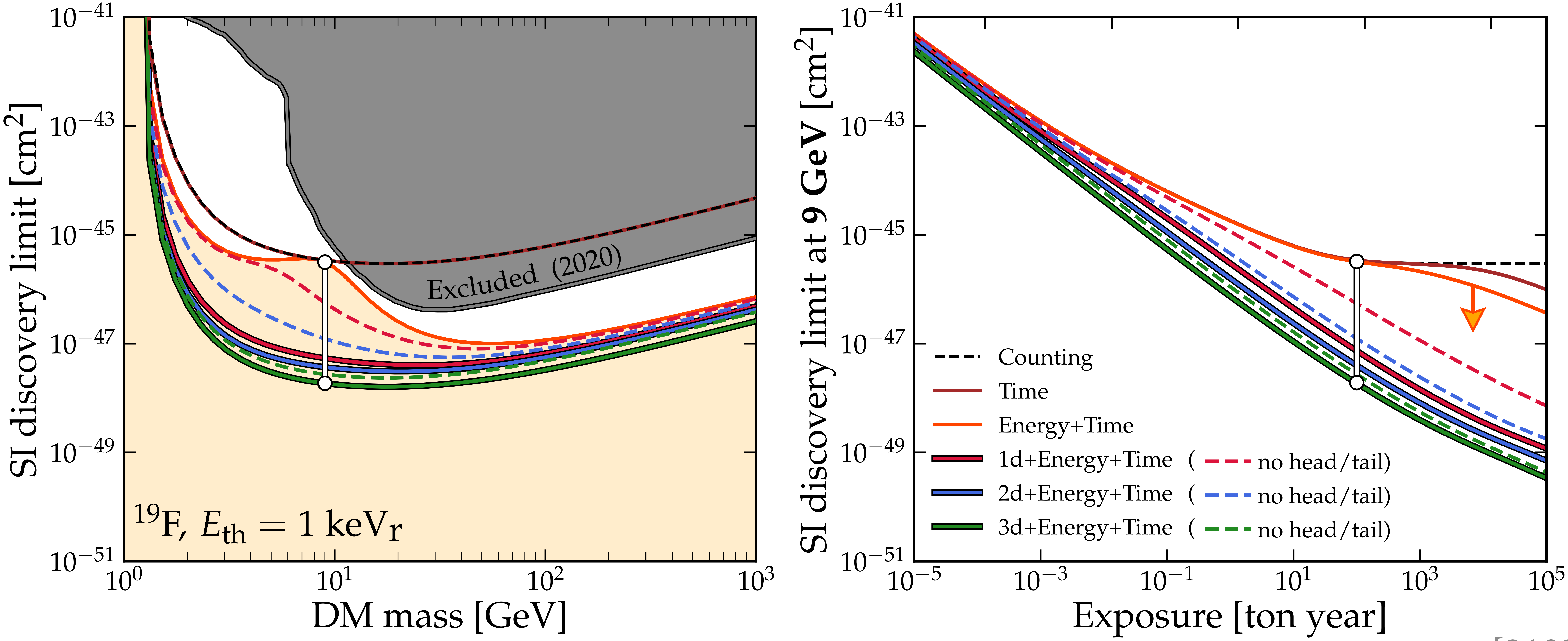
The DM flux on Earth is highly anisotropic and should align with our galactic rotation
→ highly characteristic signal that is not mimicked by any background, and is robust against particle-model and astrophysical uncertainties



A directional detector should be able to “see through” the neutrino fog

Subtracting the neutrino background with directionality

In an idealised case a directional experiment doesn't see the background at all, its sensitivity scales almost as $\sigma \propto (MT)^{-1}$, so how close can a real experiment get?



[2102.04596]

What is required of a directional experiment to clear the neutron fog?

(see our review [2102.04596] for reasoning)

- Angular resolution **<30°**
- Correct head/tail **>75%** of the time
- Fractional energy resolution $< 20\%$

If you don't achieve these then directionality adds nothing to the sensitivity (in the context of the ν background)

And achieved…

- At the level of individual events
- In as high a density target as possible (maximise target mass)
- Below <10 keVr (depends on nucleus, but usually CEvNS recoils are sub-10-keVr)
- With a timing resolution better than a few hours

Can this be done? → watch the talks in this session!

Takeaways

The neutrino floor is dead, long-live the neutrino fog

- The boundary of the neutrino fog can be defined when the scaling of an experiment's sensitivity drops below the Poissonian expectation ($\sigma \propto (MT)^{-1/2}$)
- The imminent CEvNS background will not halt any experiment's progress, just slow it
- We should look to our friends in the neutrino community to improve uncertainties on the fluxes (especially the sub-100 MeV atmospheric flux which is still unmeasured)
- Directional detection is the best way to get through the fog: a recoil imaging detector able to reconstruct sub-10 keV tracks in 3D with head/tail information will barely even see the neutrino fog.
- Forget daily/annual modulation, columnar recombination, target complementarity: They are not efficient until the >100 ton-scale.

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

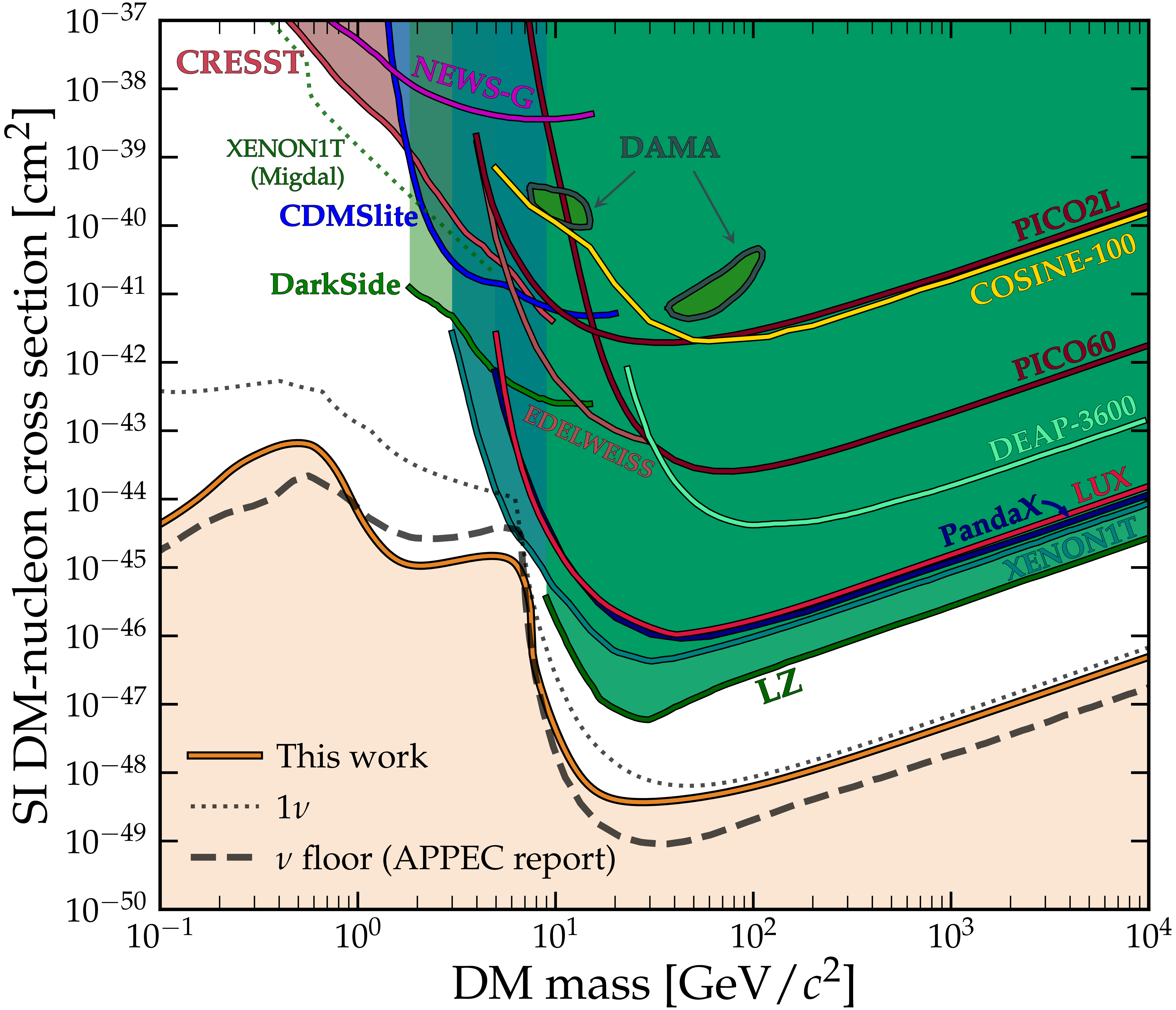
THE UNIVERSITY OF SYDNEY

Extra slides

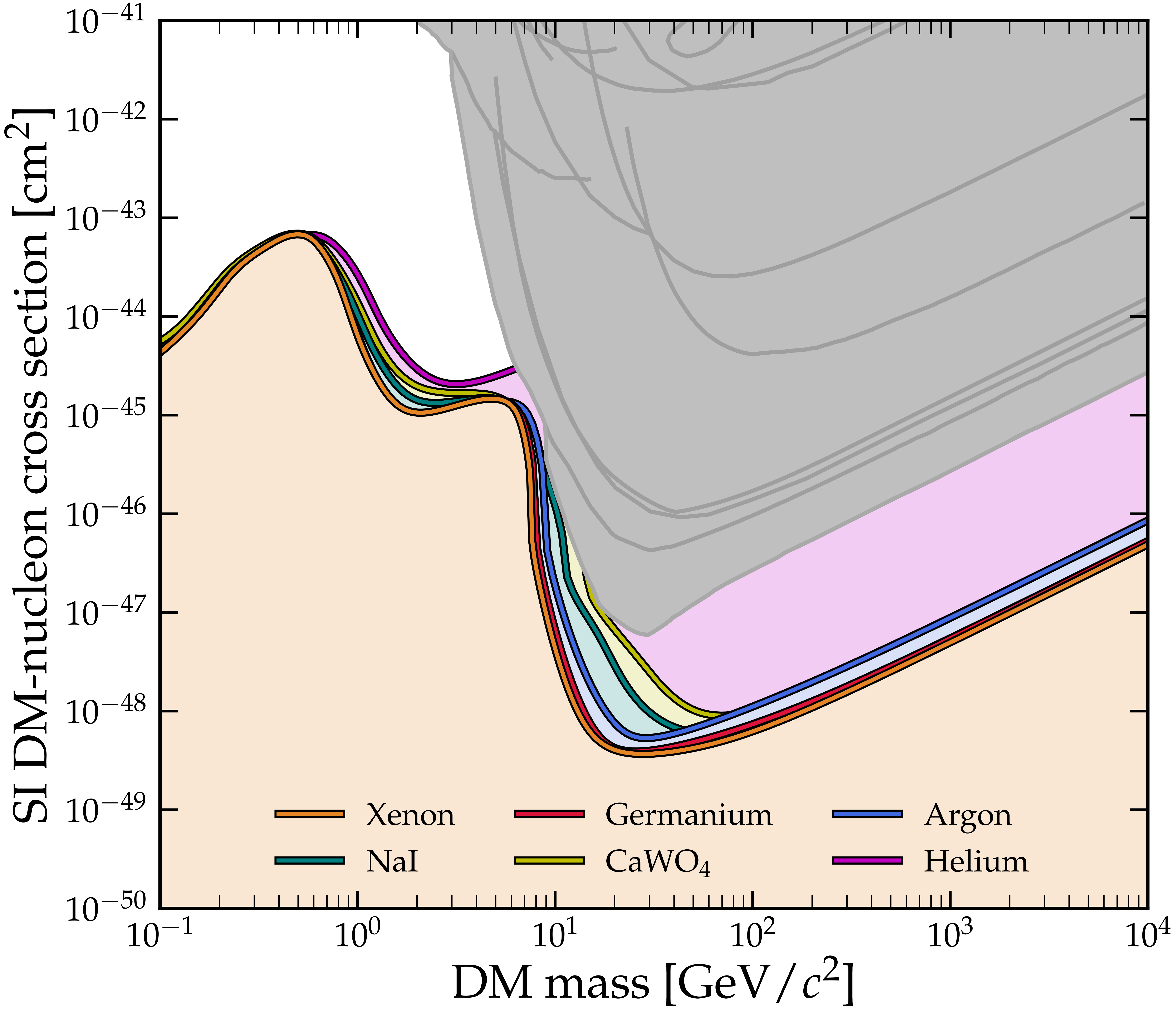
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

Comparison with other definitions

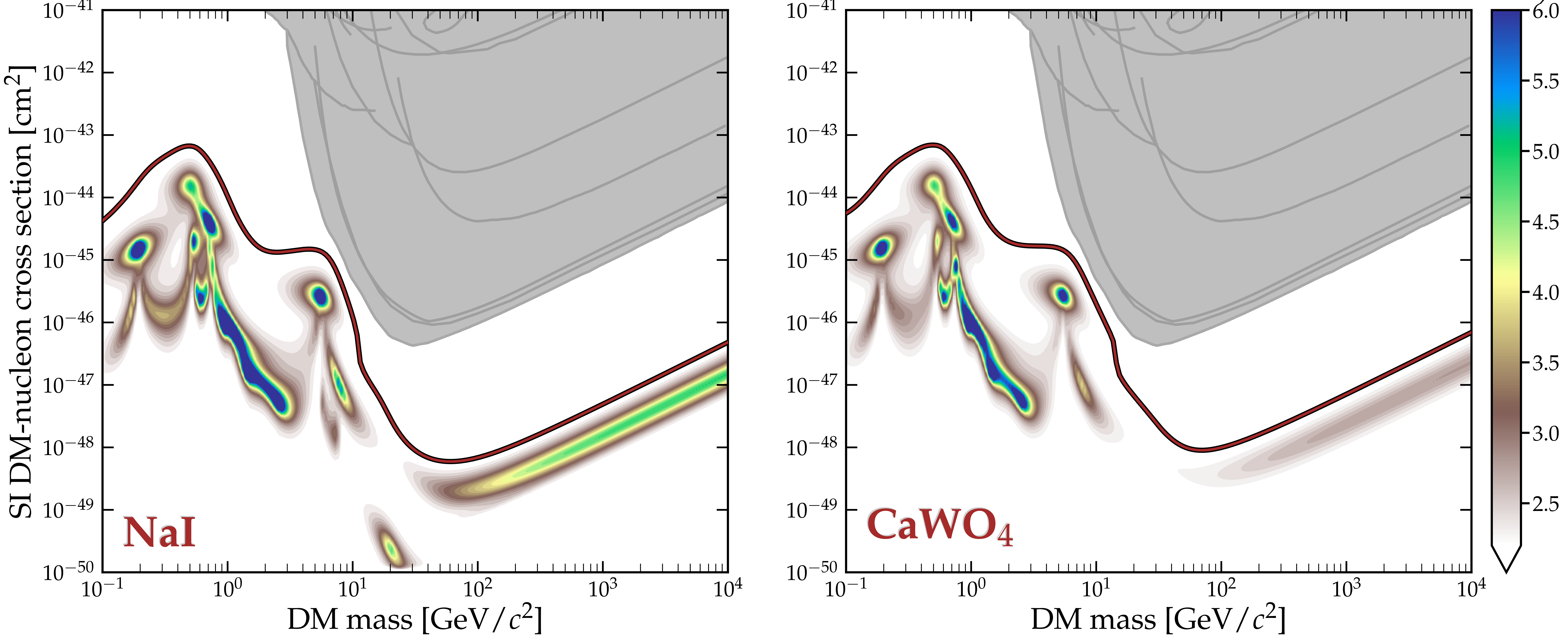


Target dependence



Molecular targets - neutrino fog is less foggy, but this doesn't help much

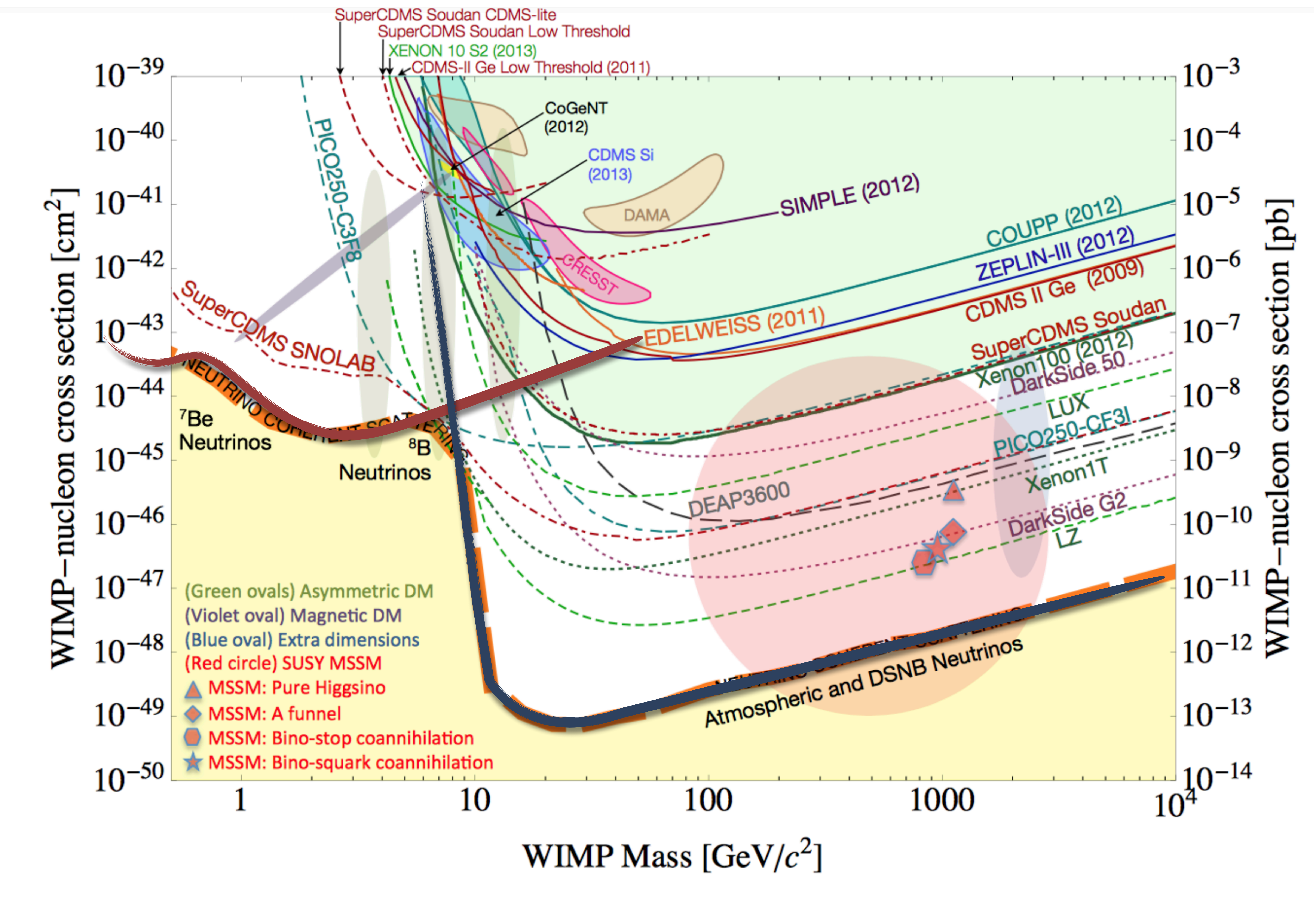
Interpret as the "opacity" of the neutrino fog → $\left(\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln N}\right)^{-1}$



O'Hare [2109.03116]

The neutrino "floor"

Defined in Billard et al. [1307.5458] and popularised by Snowmass '13 Cosmic Frontier report [1401.6085]



Interpolation of two discovery limits

(3σ discovery in 90% of expts)

→ low mass / low threshold

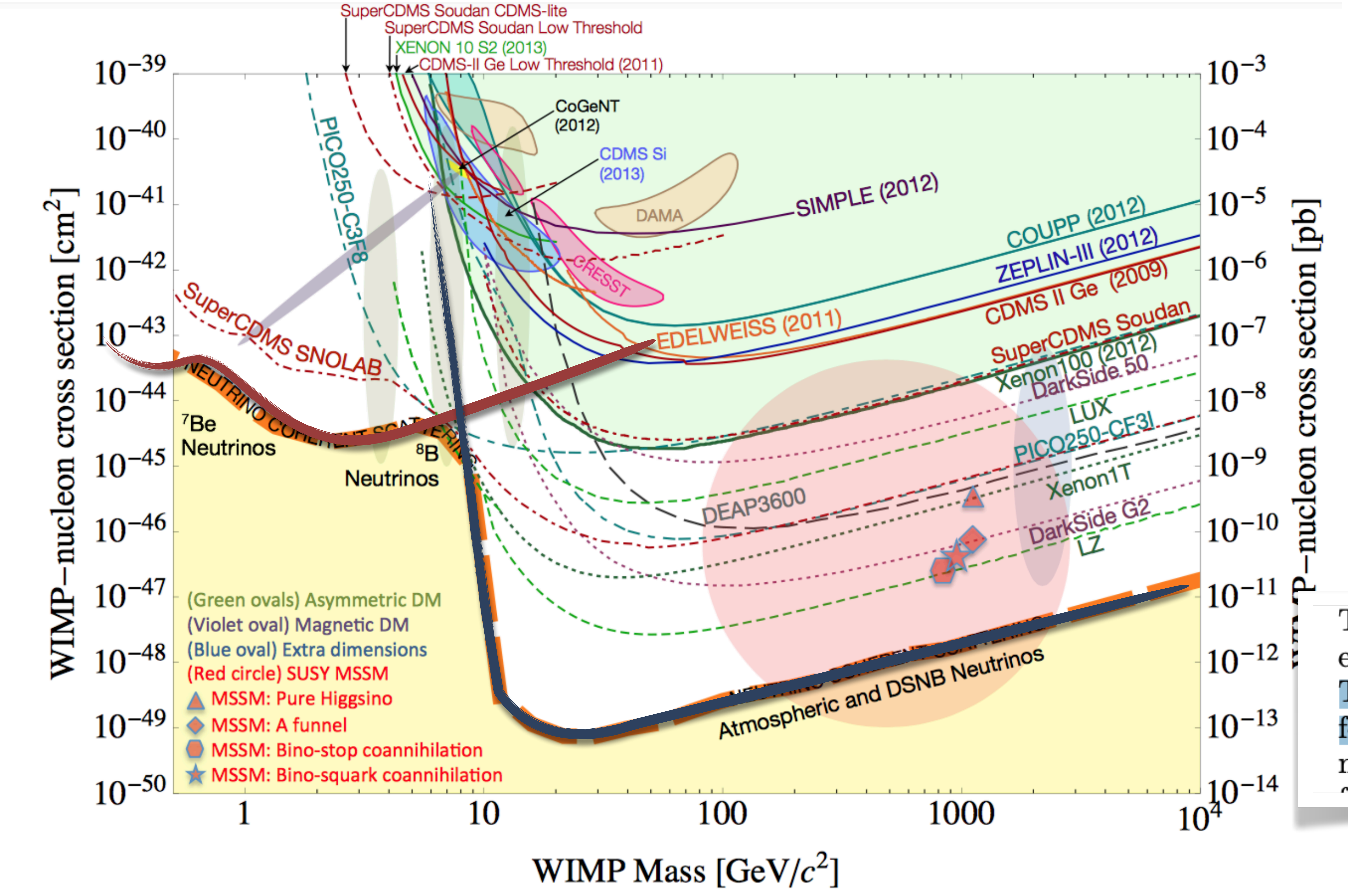
(500 solar neutrino events)

→ high mass / high threshold

(500 atmospheric events)

The neutrino "floor"

Defined in Billard et al. [1307.5458] and popularised by Snowmass '13 Cosmic Frontier report [1401.6085]



Interpolation of two discovery limits

(3σ discovery in 90% of expts)

→ low mass / low threshold (500 solar neutrino events)

→ high mass / high threshold (500 atmospheric events)

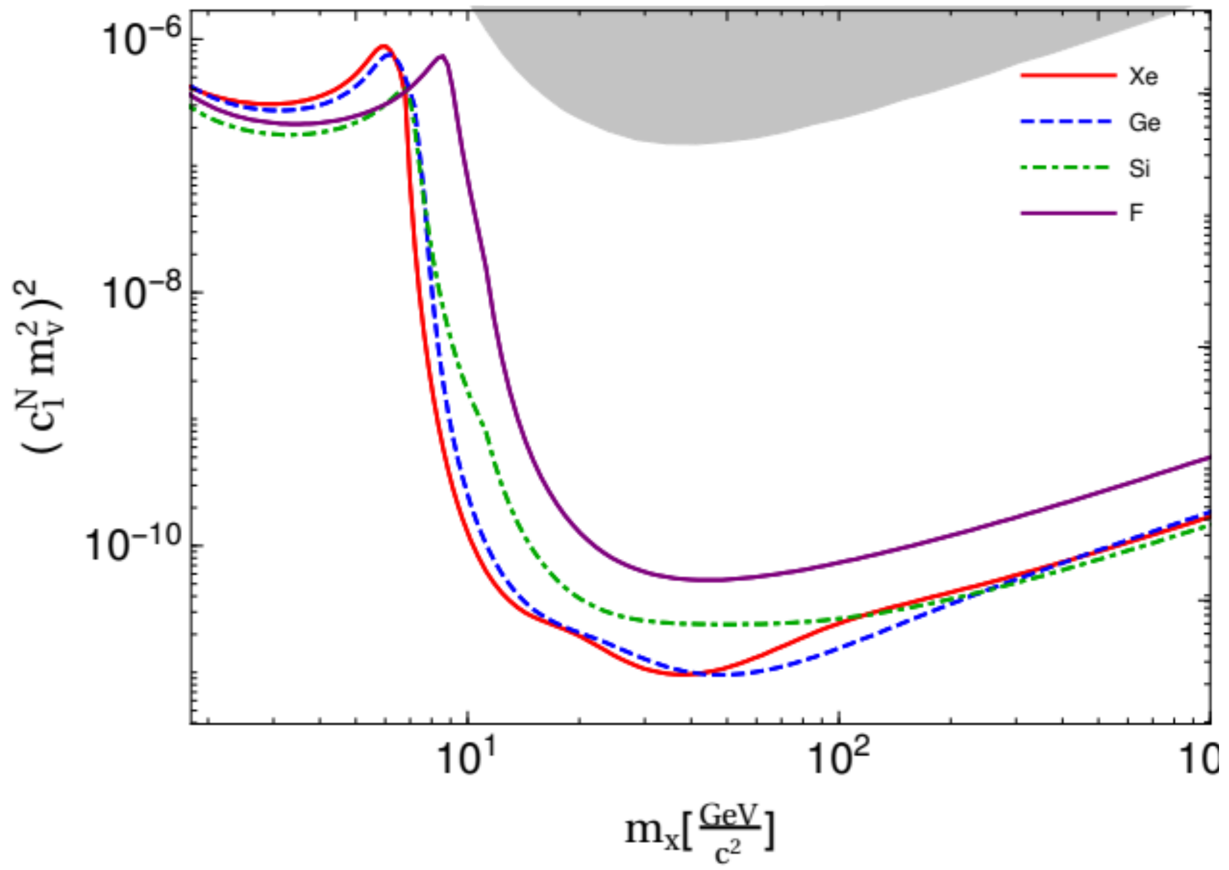
To ensure we are well into the systematics limited regime, exposures were increased to obtain 500 neutrino events. This line thus represents a hard lower discovery limit for dark matter experiments. Interestingly, we can denote three distinct features in the discovery limits coming

Neutrino “floors” beyond SI

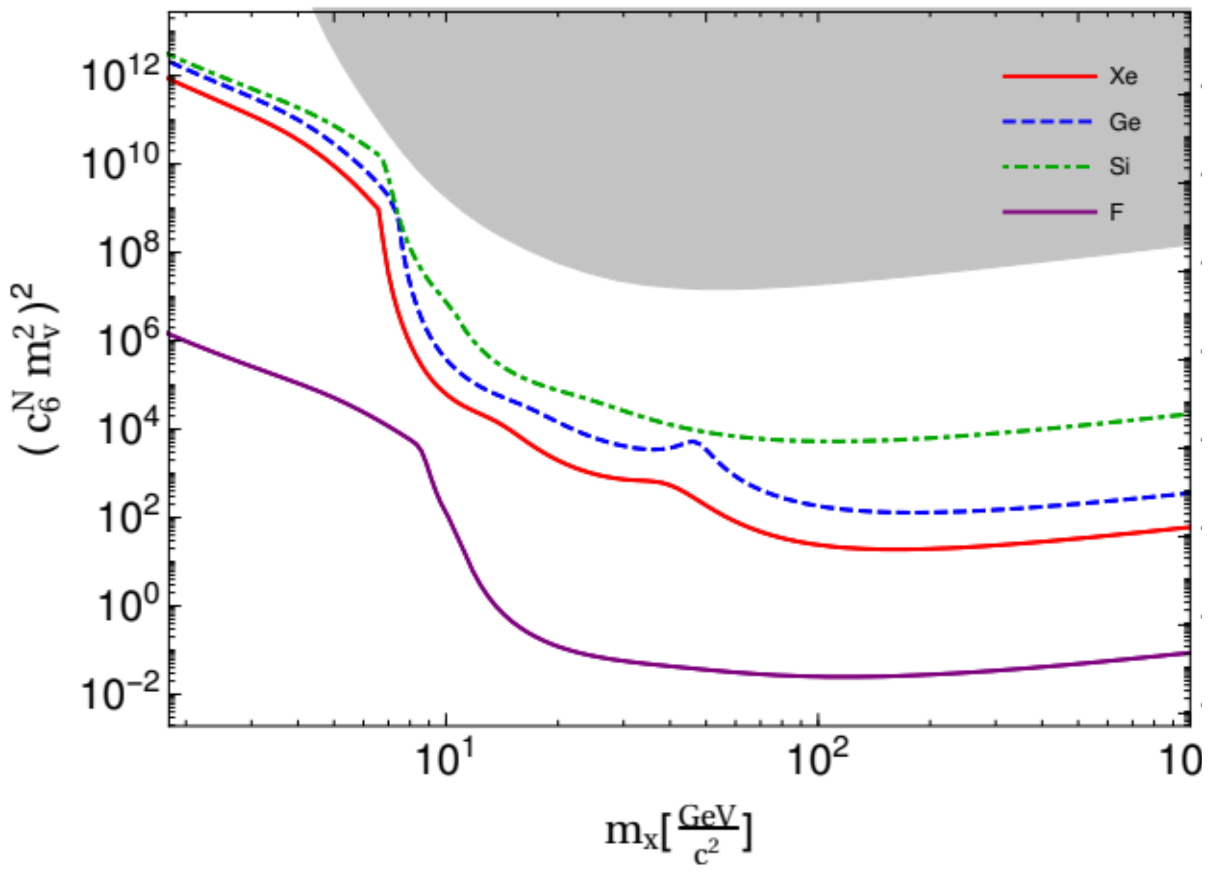
→ Not all possible DM-nucleon interactions suffer same saturation by CEvNS background

Newstead et al. [1602.05300]
→ Non-rel. EFT operators

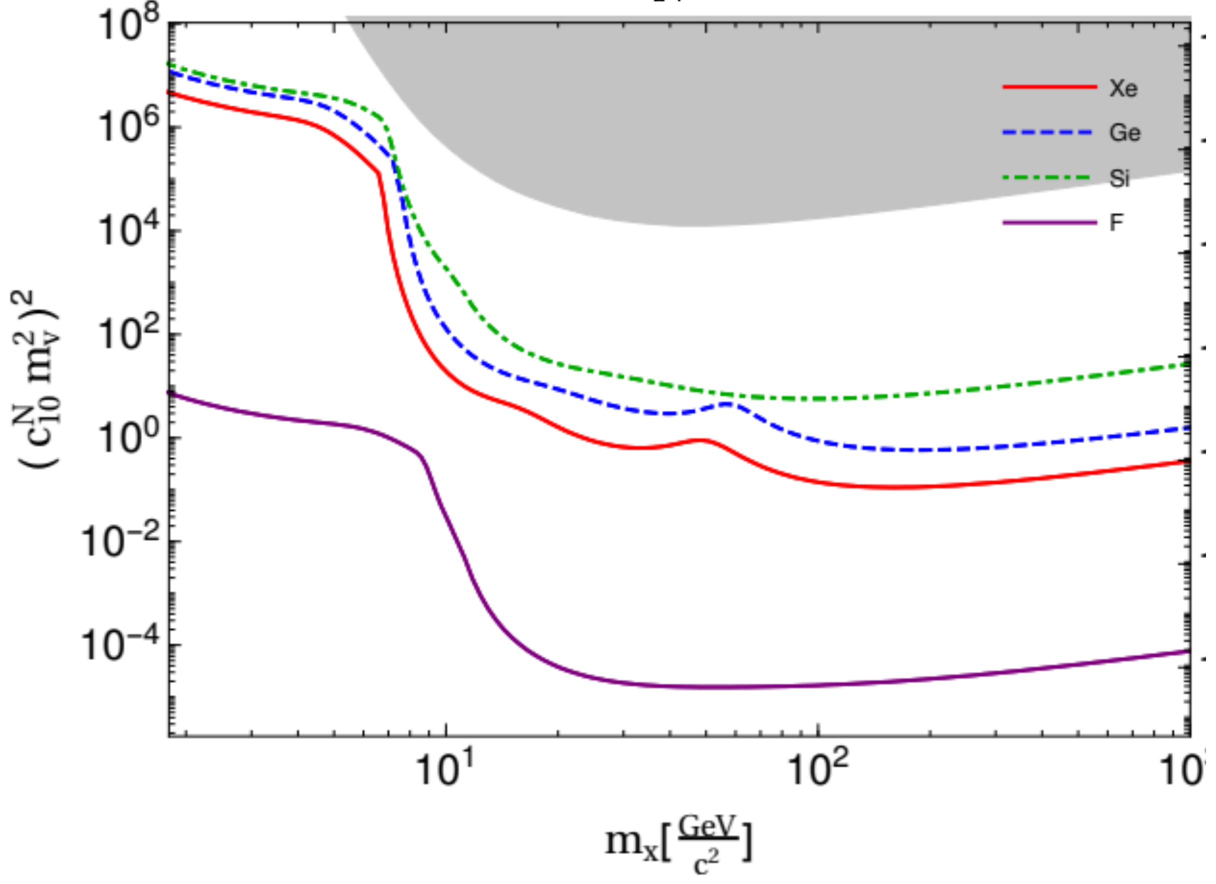
$1_\chi 1_N$



$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$



$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$

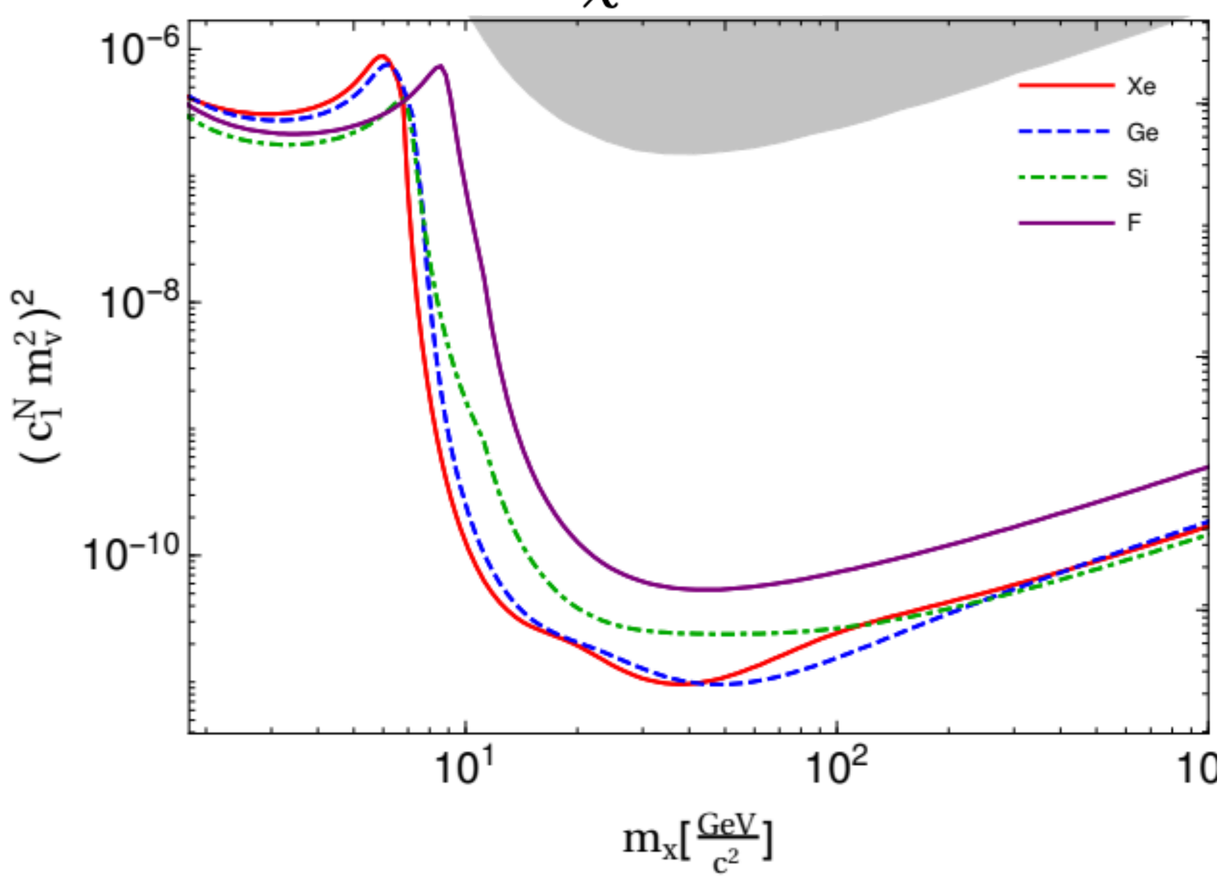


Neutrino “floors” beyond SI

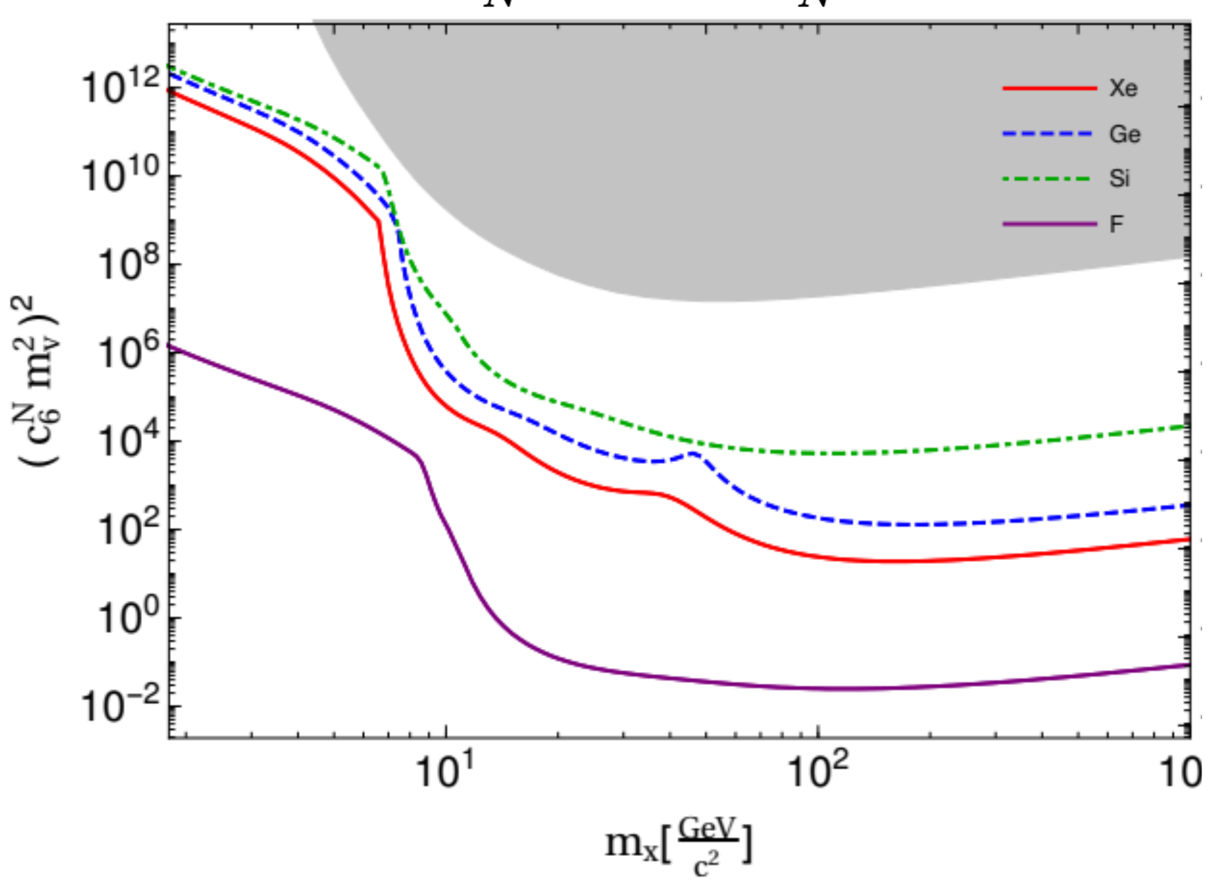
→ Not all possible DM-nucleon interactions suffer same saturation by CEvNS background

Newstead et al. [1602.05300]
→ Non-rel. EFT operators

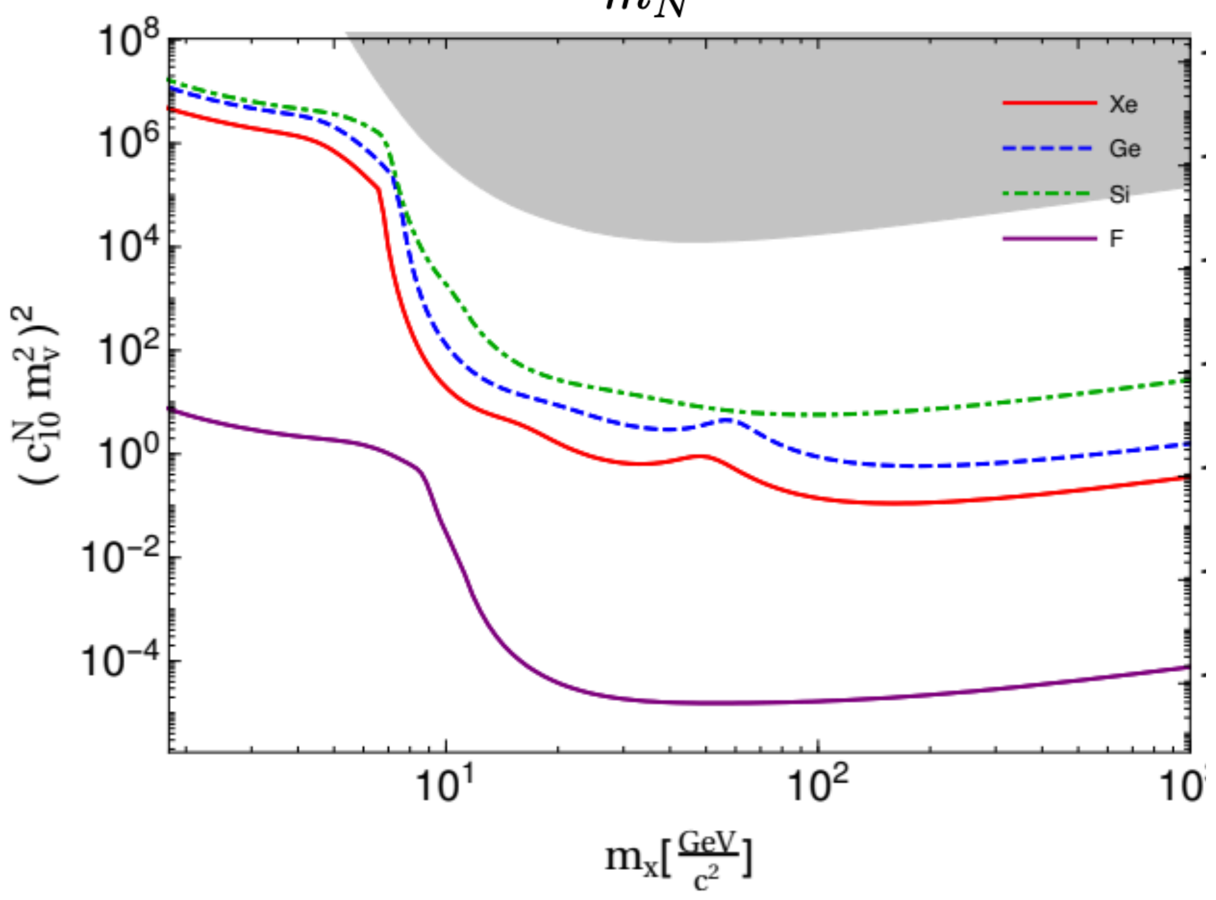
$1_\chi 1_N$



$(\frac{\vec{q}}{m_N}\cdot\vec{S}_N)(\frac{\vec{q}}{m_N}\cdot\vec{S}_\chi)$

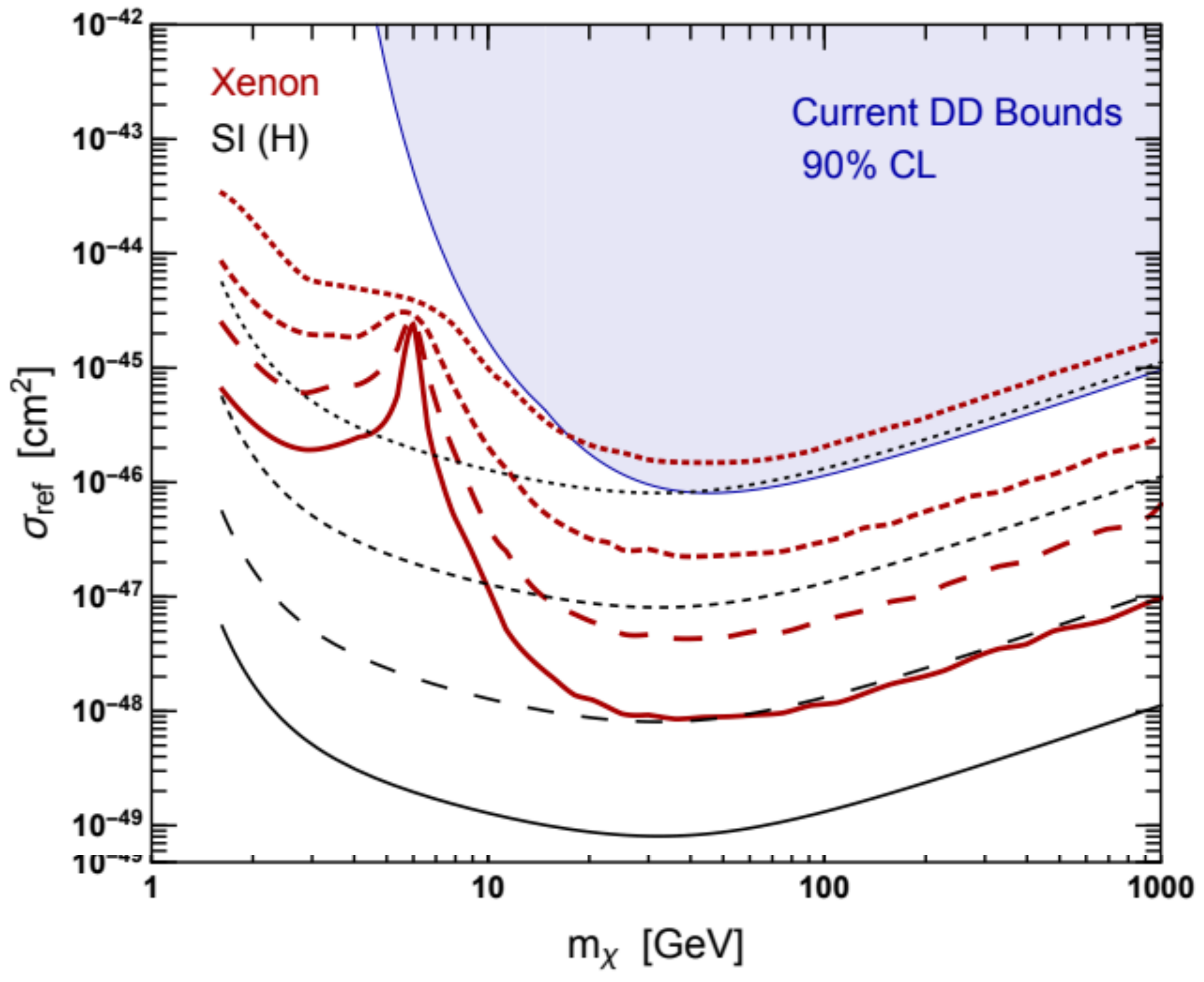


$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$

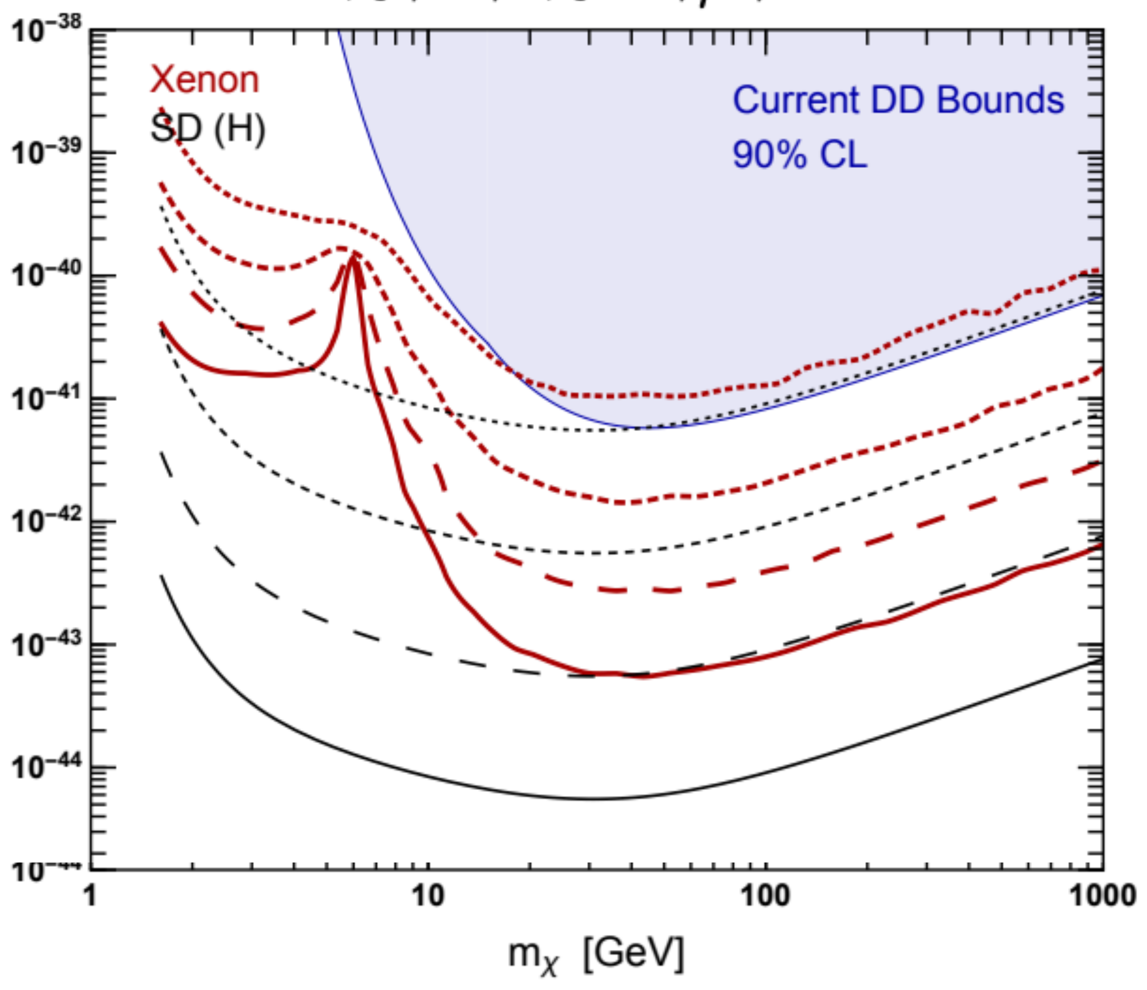


Gelmini et al. [1804.01638]
→ Various DM Interaction models

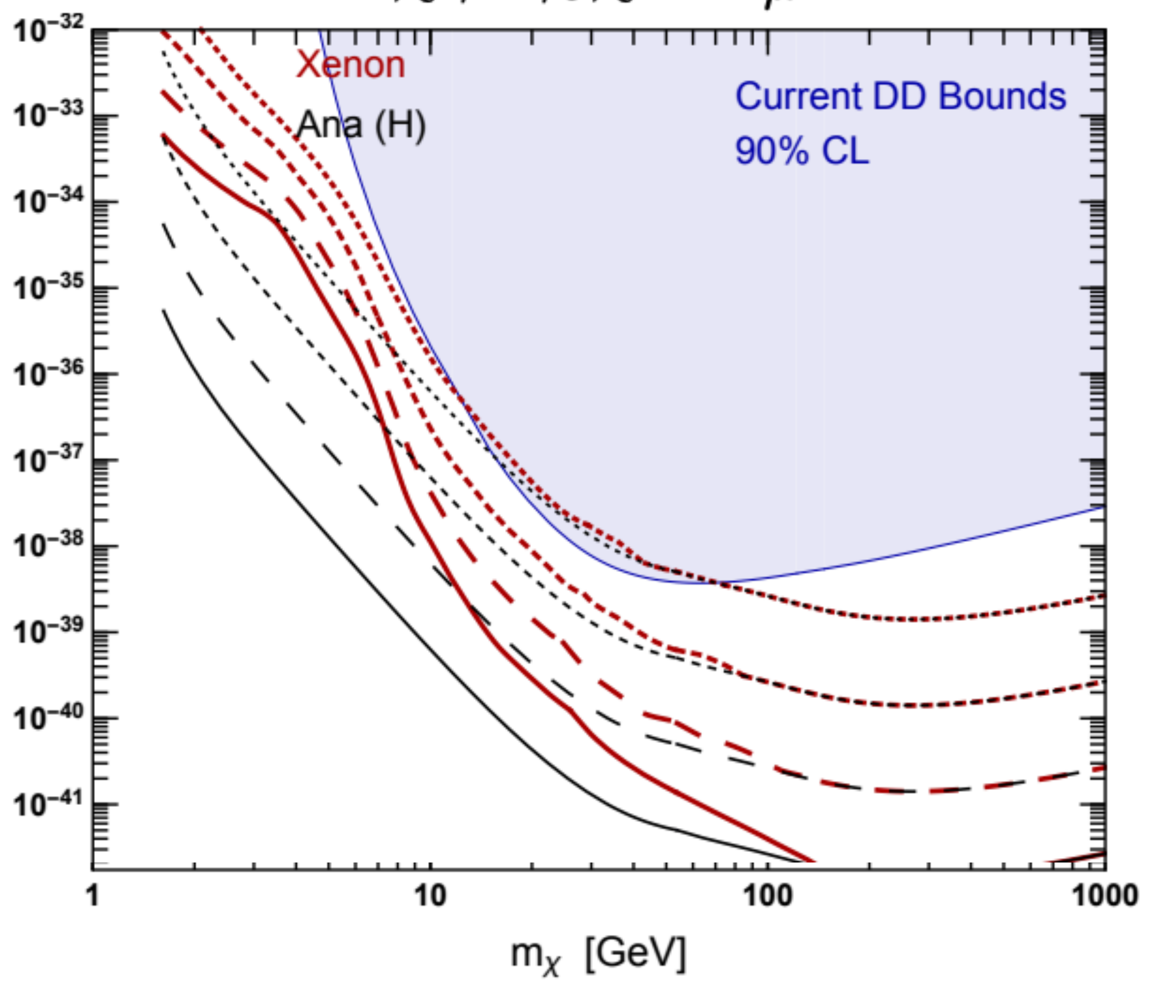
$\bar{\chi}\chi\bar{N}N$



$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma_5 N$



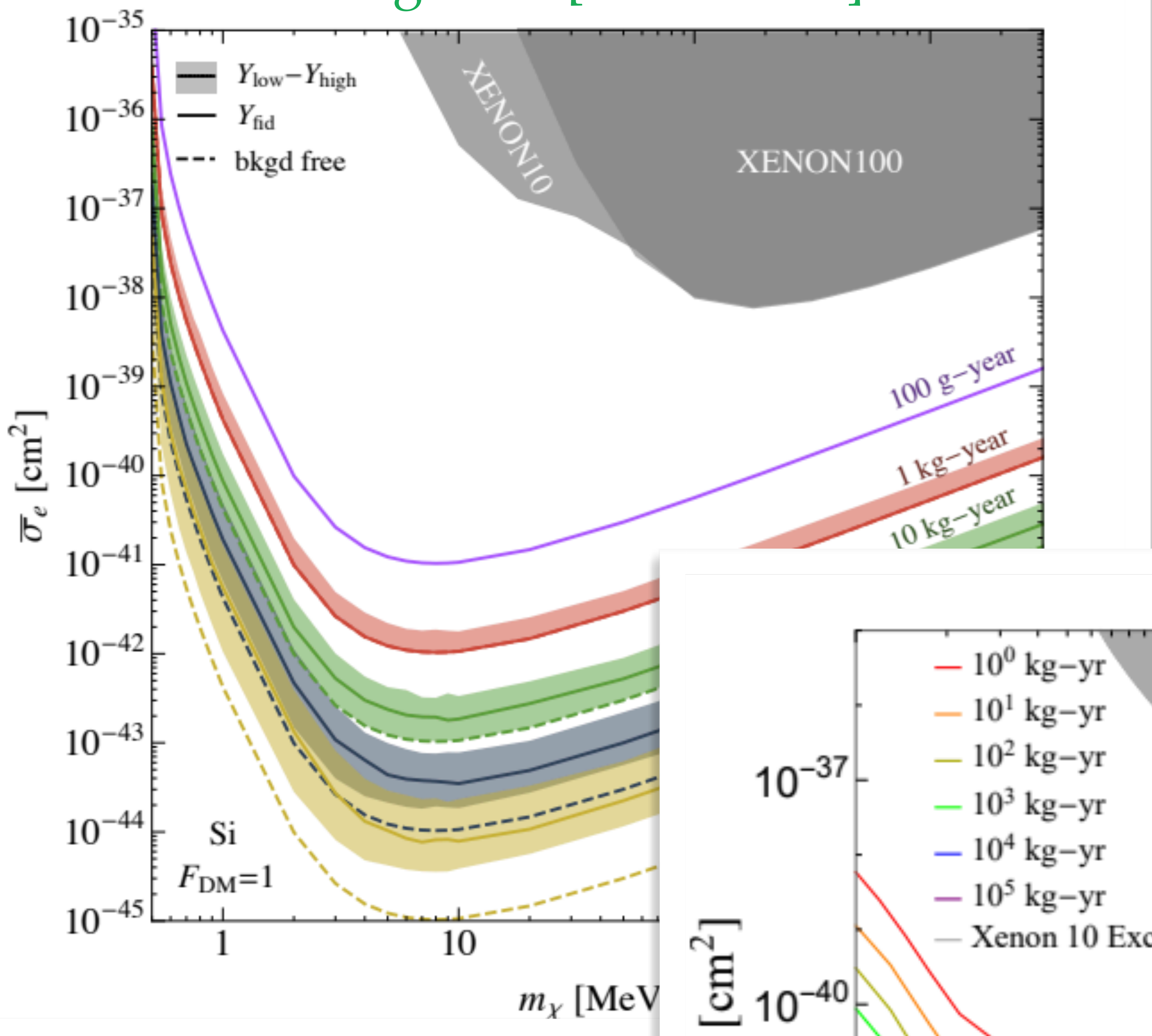
$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$



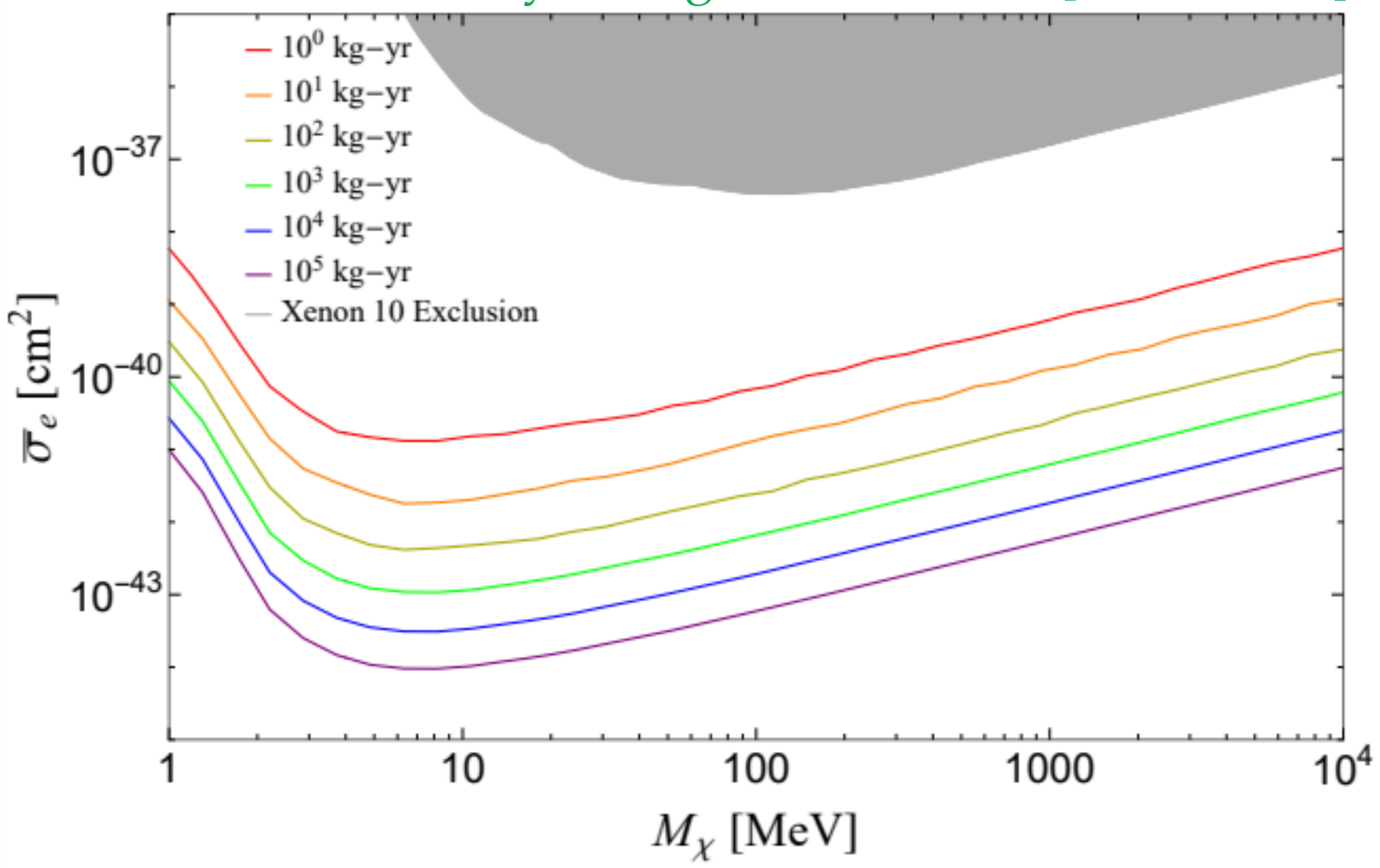
Neutrino "floors" beyond vanilla WIMP DM

DM-electron scattering

Essig et al. [1801.10159]



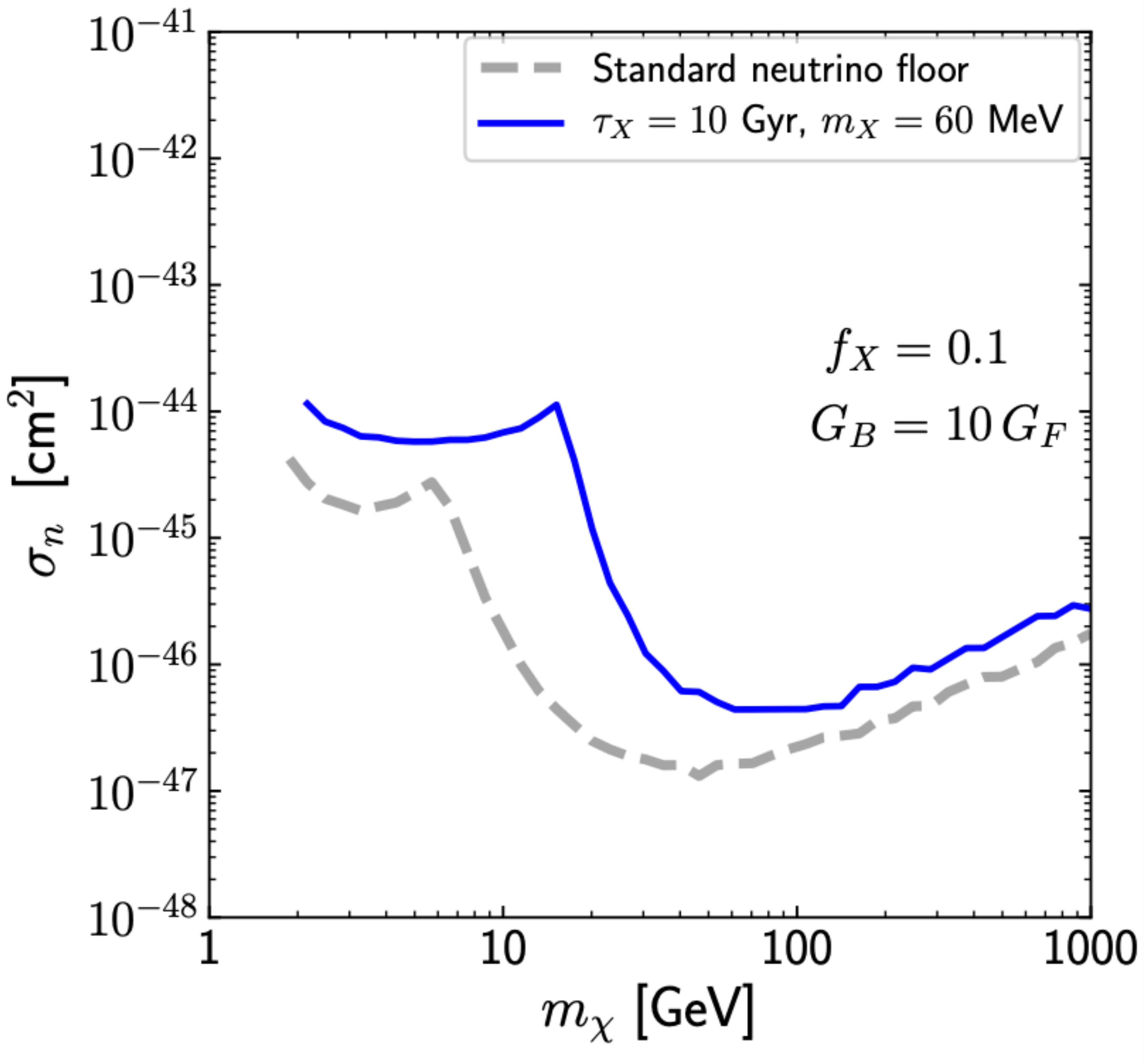
Wyenberg & Shoemaker [1803.08146]



More complicated DM models

DM + dark radiation from DM decay in the form of SM-v/sterile-v

Nikolic et al. [2008.13557]

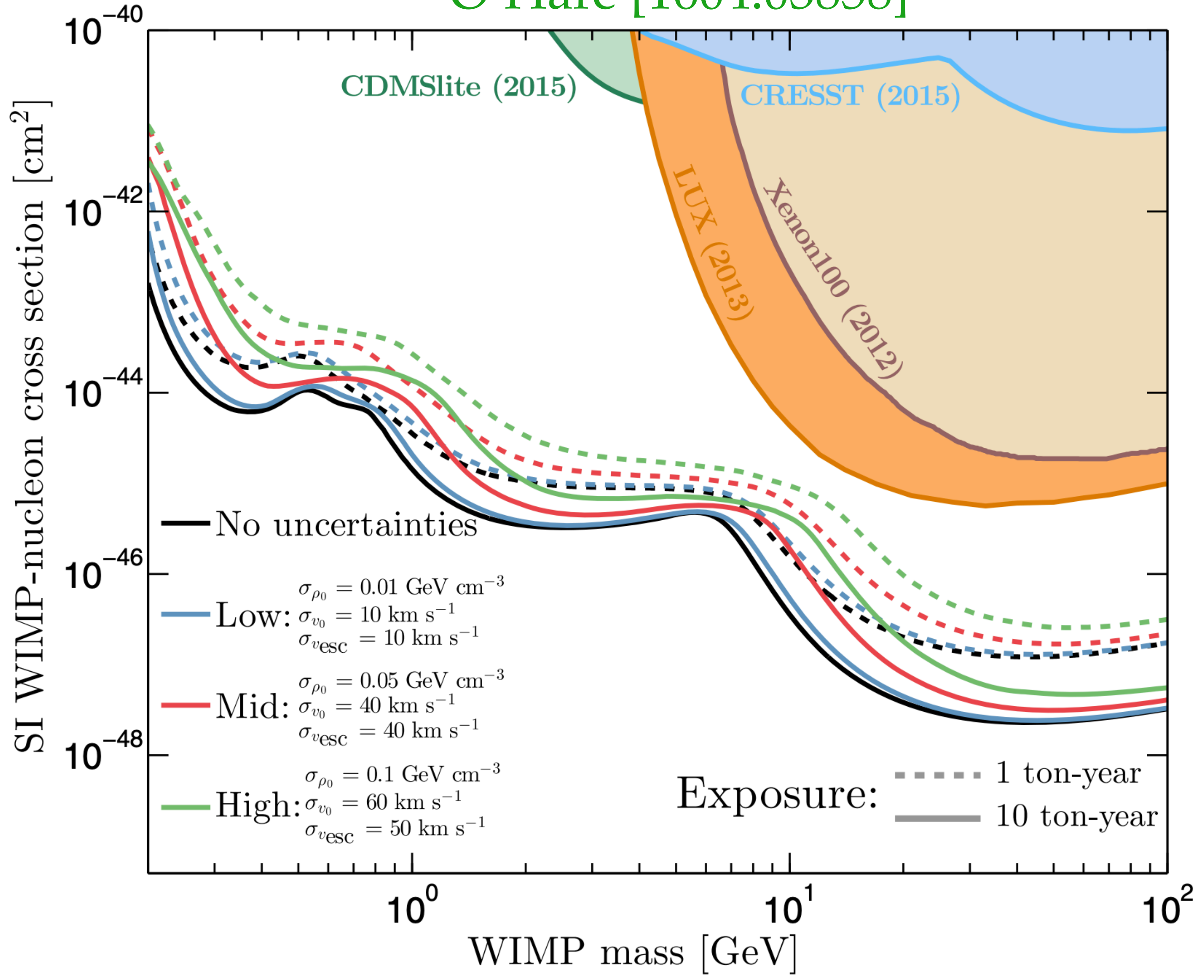


Uncertainties…

Some of these are things we would like to study in DD experiments

Astrophysical uncertainties

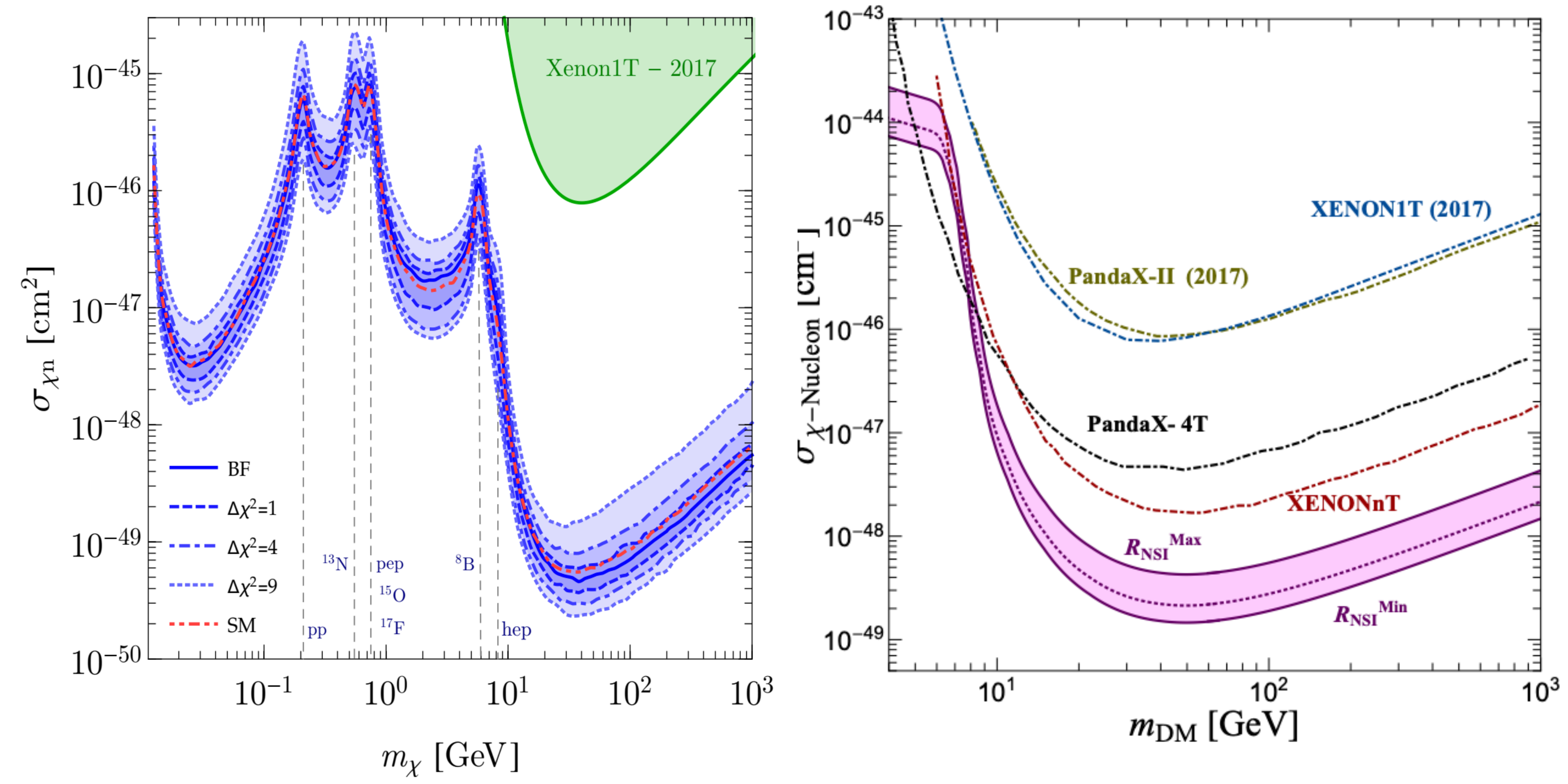
O'Hare [1604.03858]



Neutrino non-standard interactions

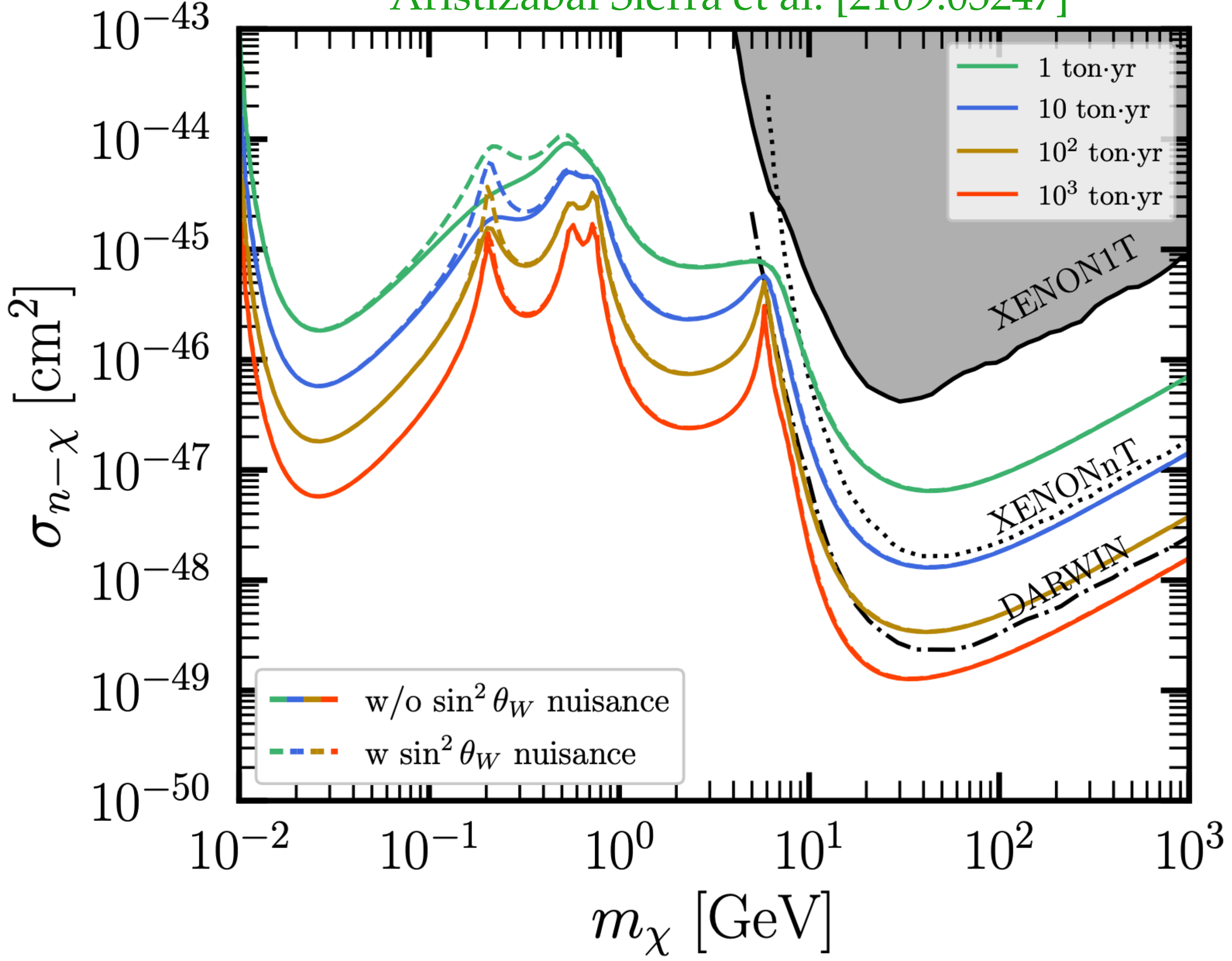
Aristizabal Sierra et al. [1712.09667]

Gonzalez-Garcia et al. [1803.03650]



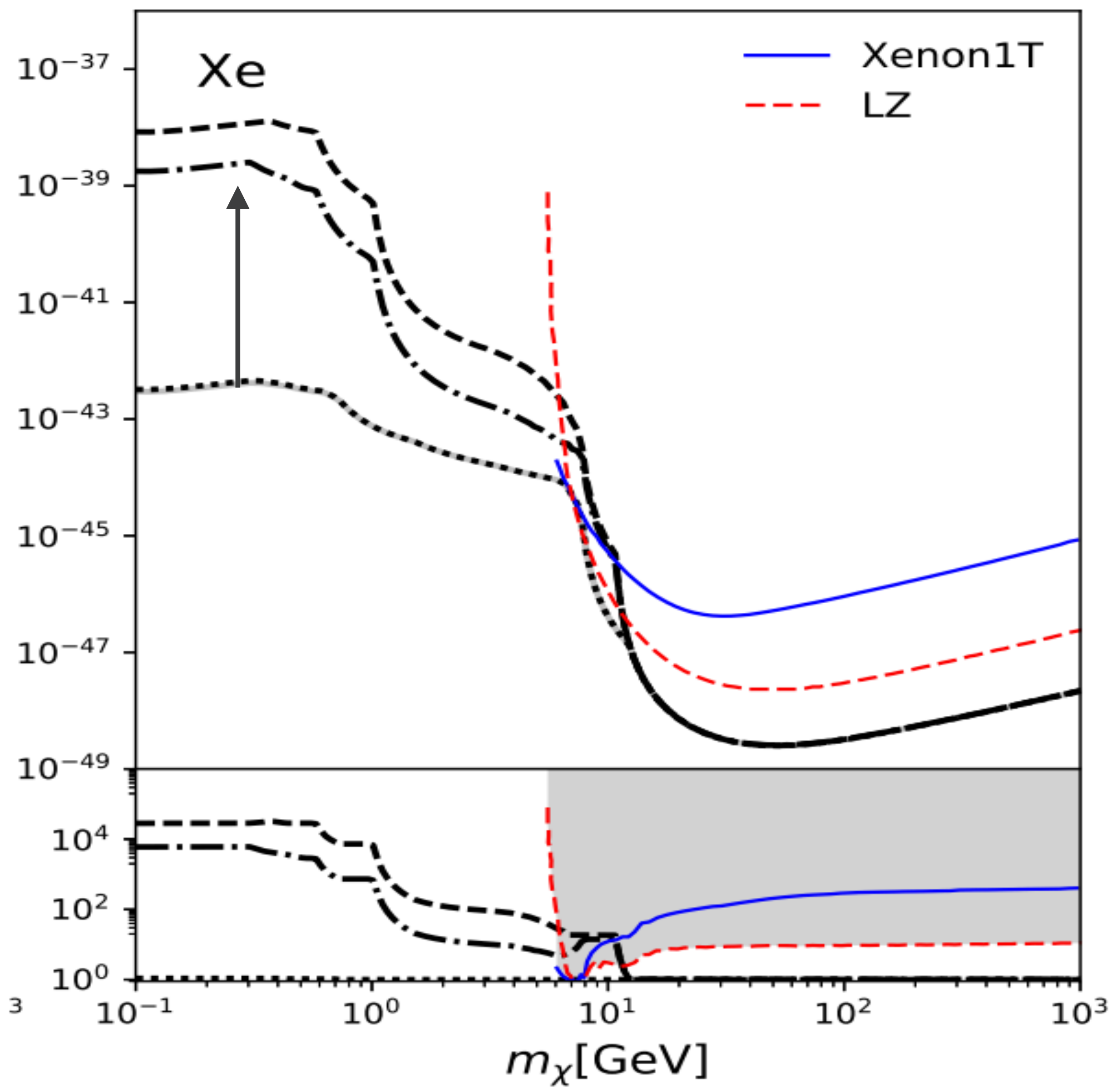
CEvNS uncertainties

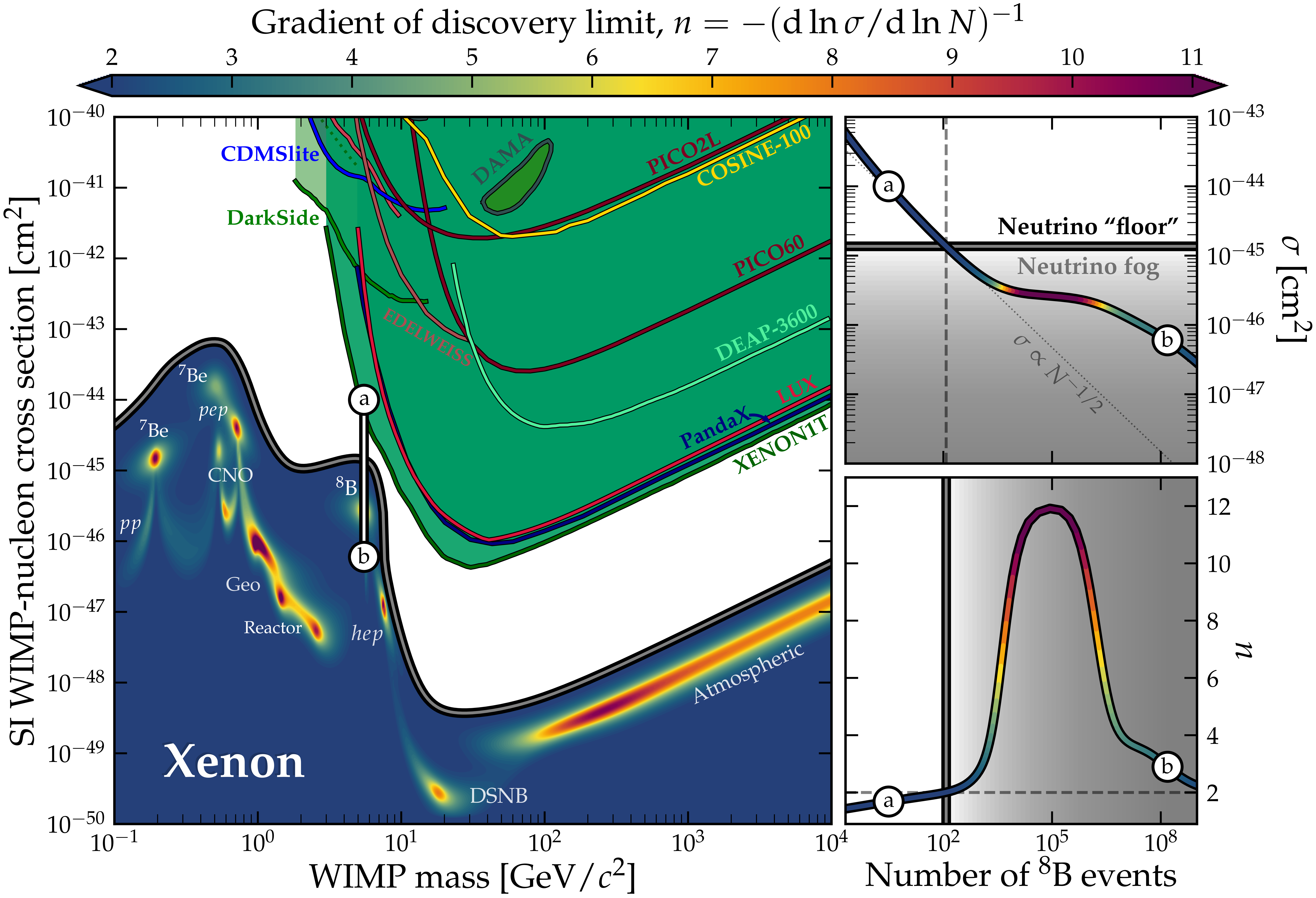
Aristizabal Sierra et al. [2109.03247]



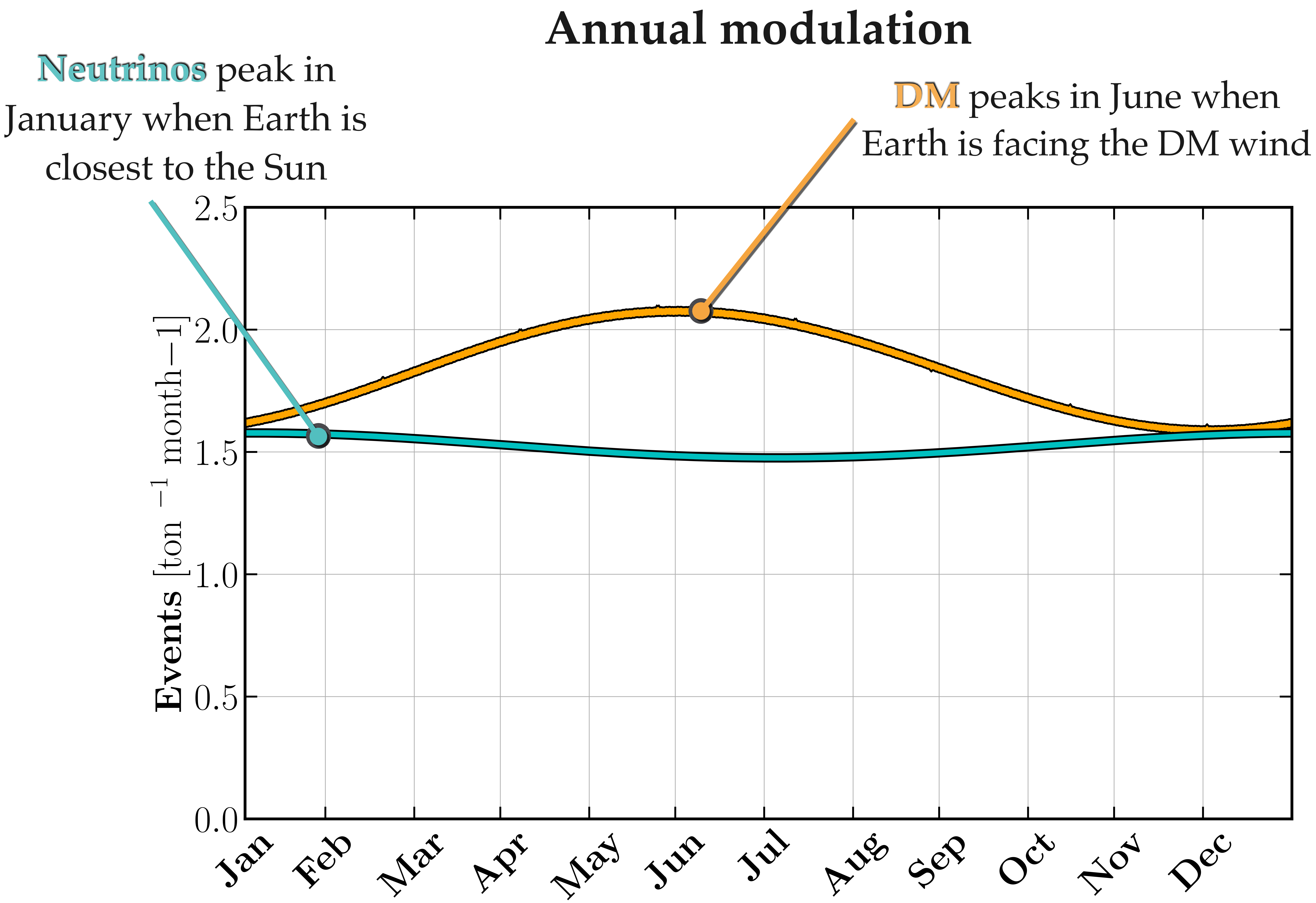
New mediators involved in CEvNS

Boehm et al. [1809.06385]





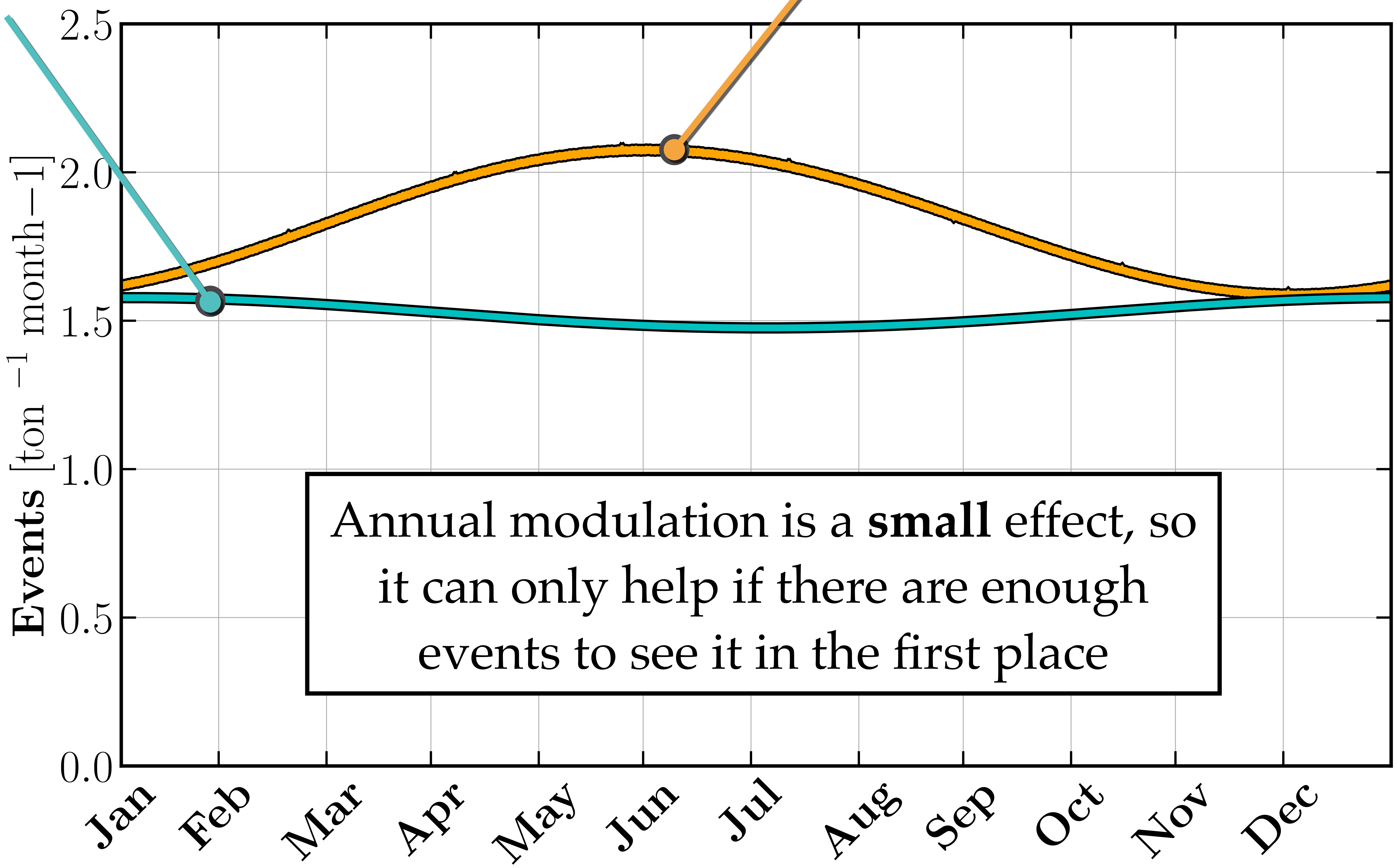
Gradient of discovery limit, $n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$
2 3 4 5 6 7 8 9 10 11
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
^{7}Be
^{7}Be
pep
CNO
pp
^{8}B
Geo
Reactor
hep
Atmospheric
DSNB
Xenon
a
b
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
Neutrino "floor"
Neutrino fog
$\sigma \propto N^{-1/2}$
σ [cm^2]
n
Number of ^{8}B events


Annual modulation
Neutrinos peak in January when Earth is closest to the Sun
DM peaks in June when Earth is facing the DM wind
2.5
2.0
1.5
1.0
0.5
0.0
Events [ton −1 month−1]
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Annual modulation

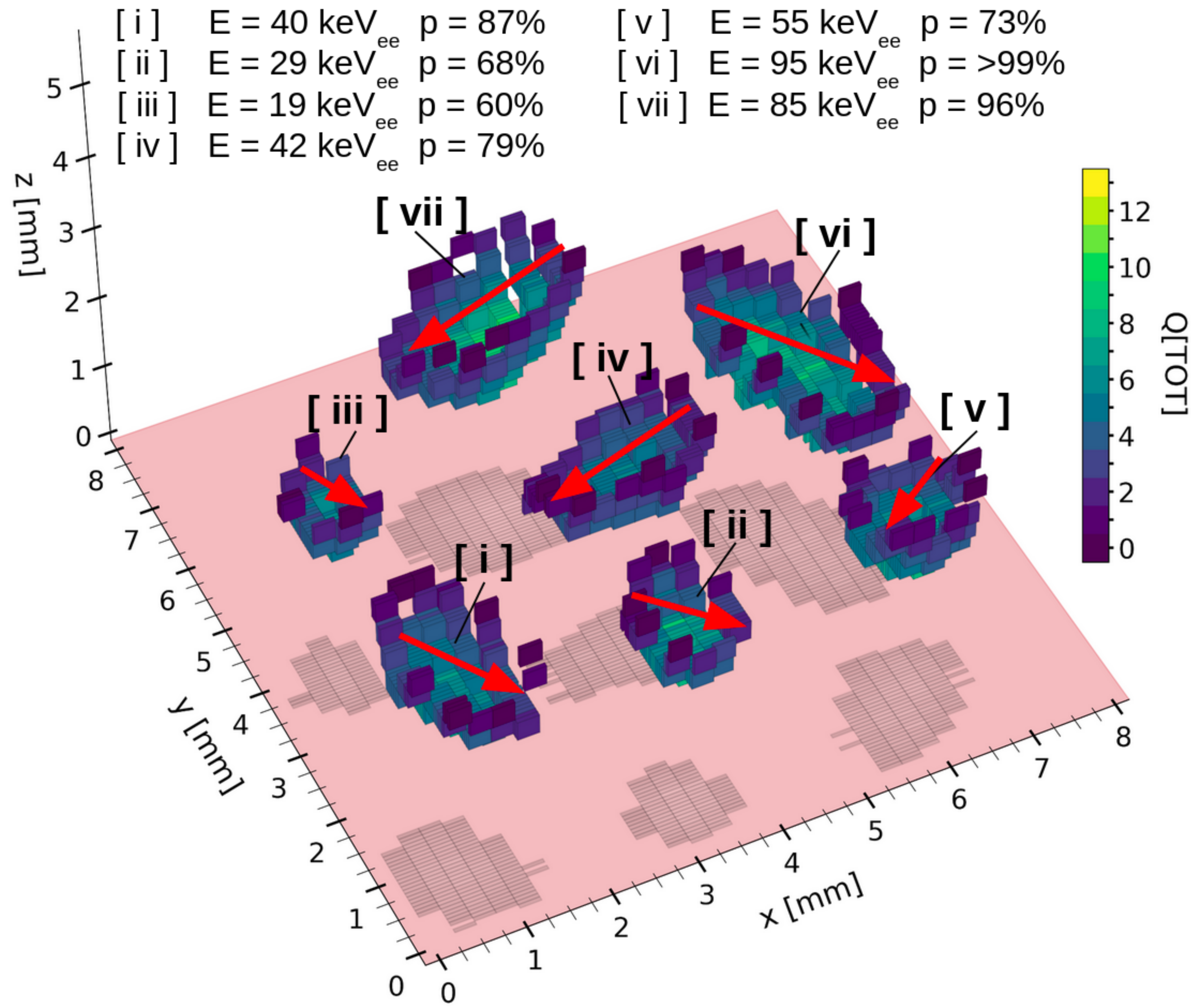
Neutrinos peak in January when Earth is closest to the Sun

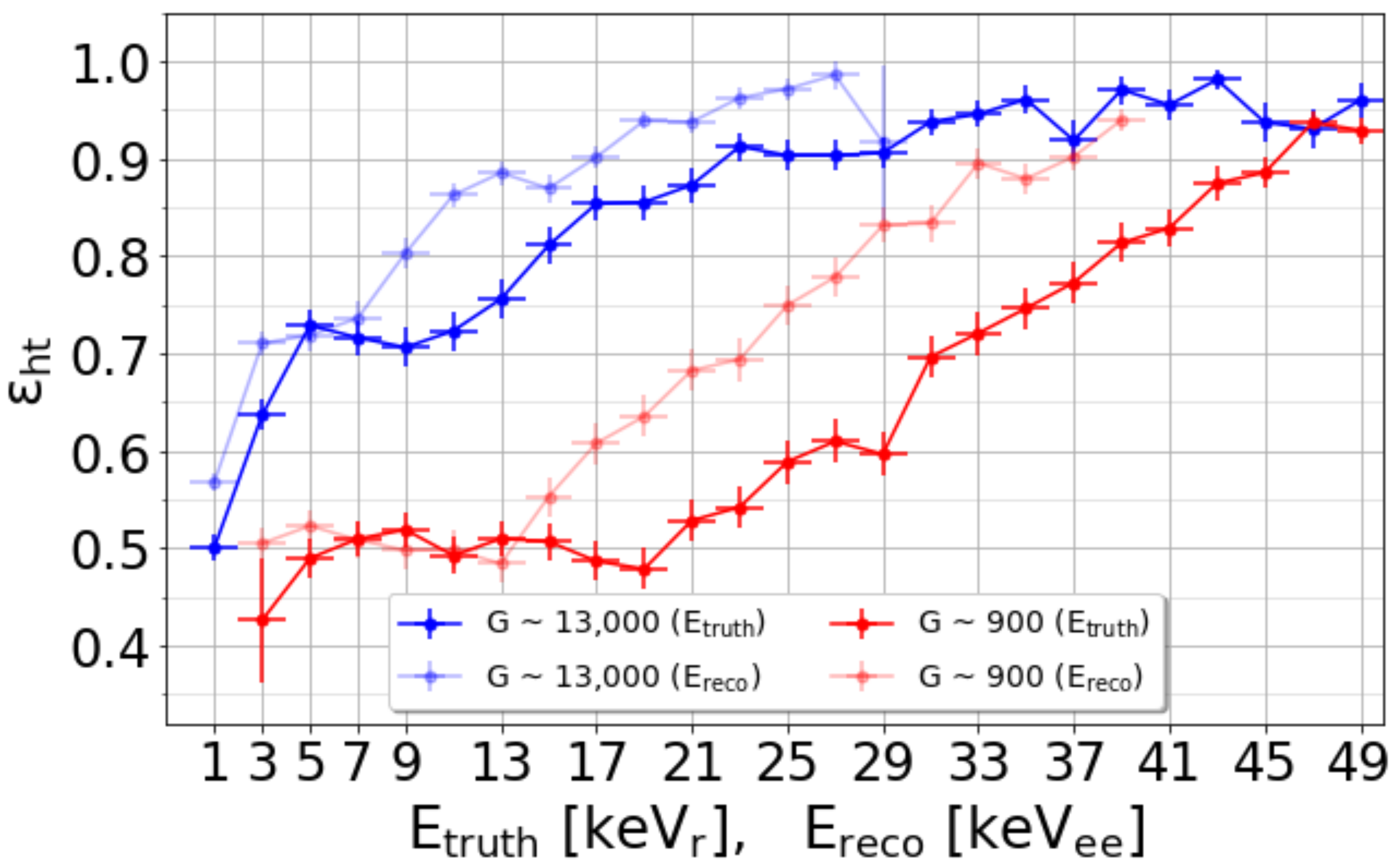
DM peaks in June when Earth is facing the DM wind



HD TPC performance studies

Final goal for high-definition imaging of recoils in 3D, meeting low-energy performance goals may not be so far away…





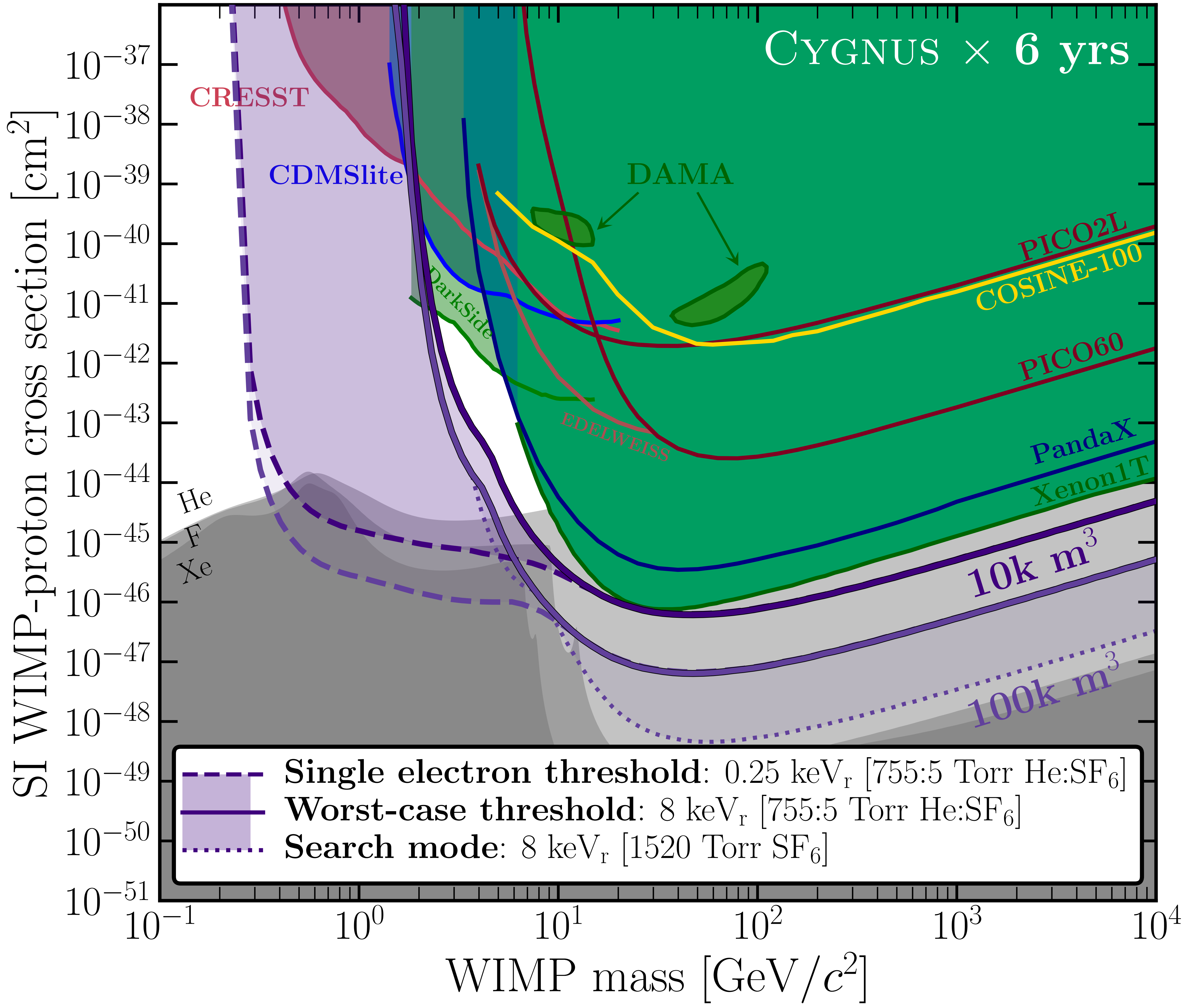
CNN reconstruction of neutron-induced He recoils in BEAST TPC

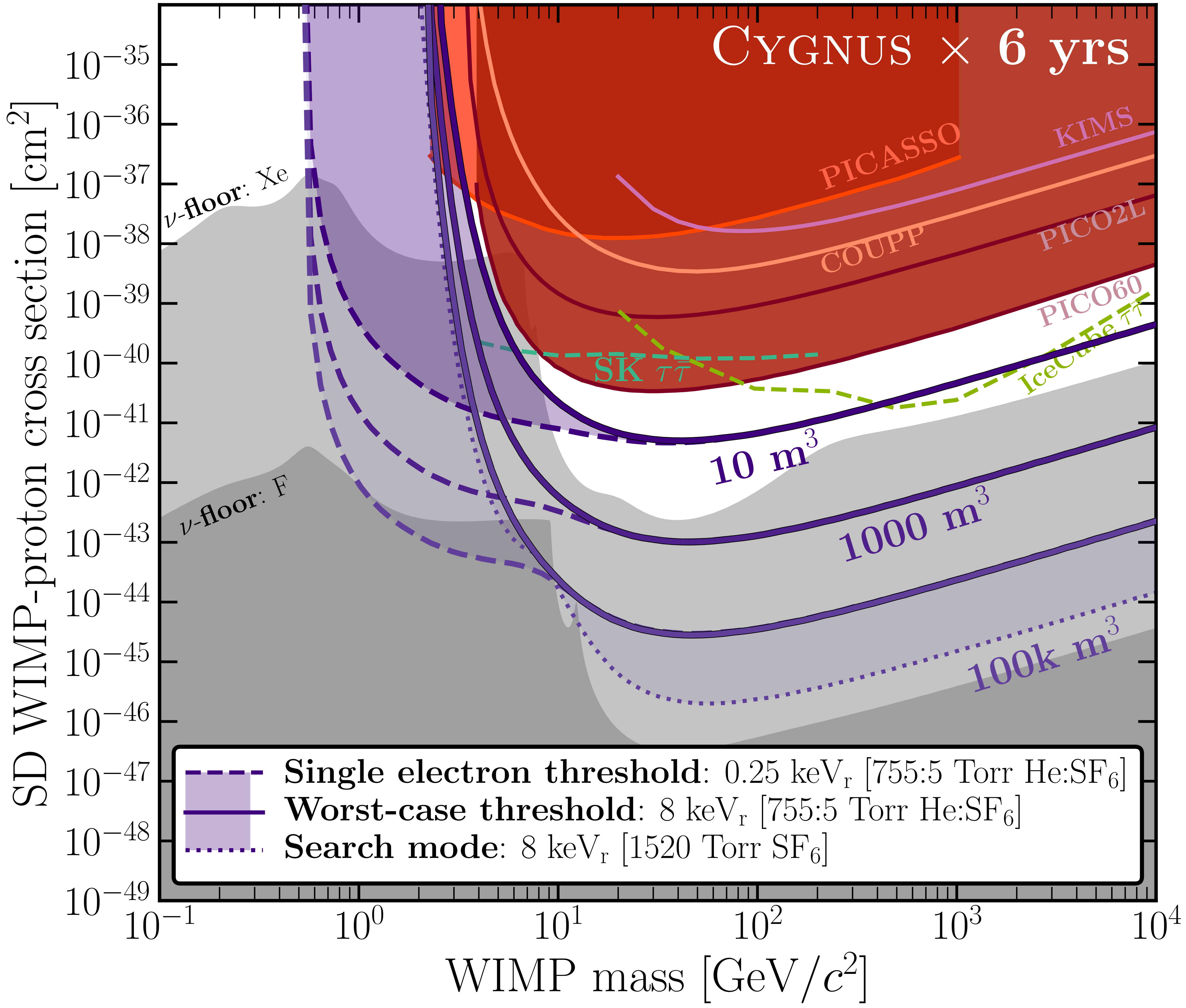
J. Schueler, S. Vahsen (U. Hawaii)

Vahsen, CAJO+ [2008.12587]

Cygnus: projected sensitivity

Target gas, volume, and threshold are still under investigation, but there is scope for world-leading (SD) limits even with a 10 m³ scale experiment (~2025–2030)



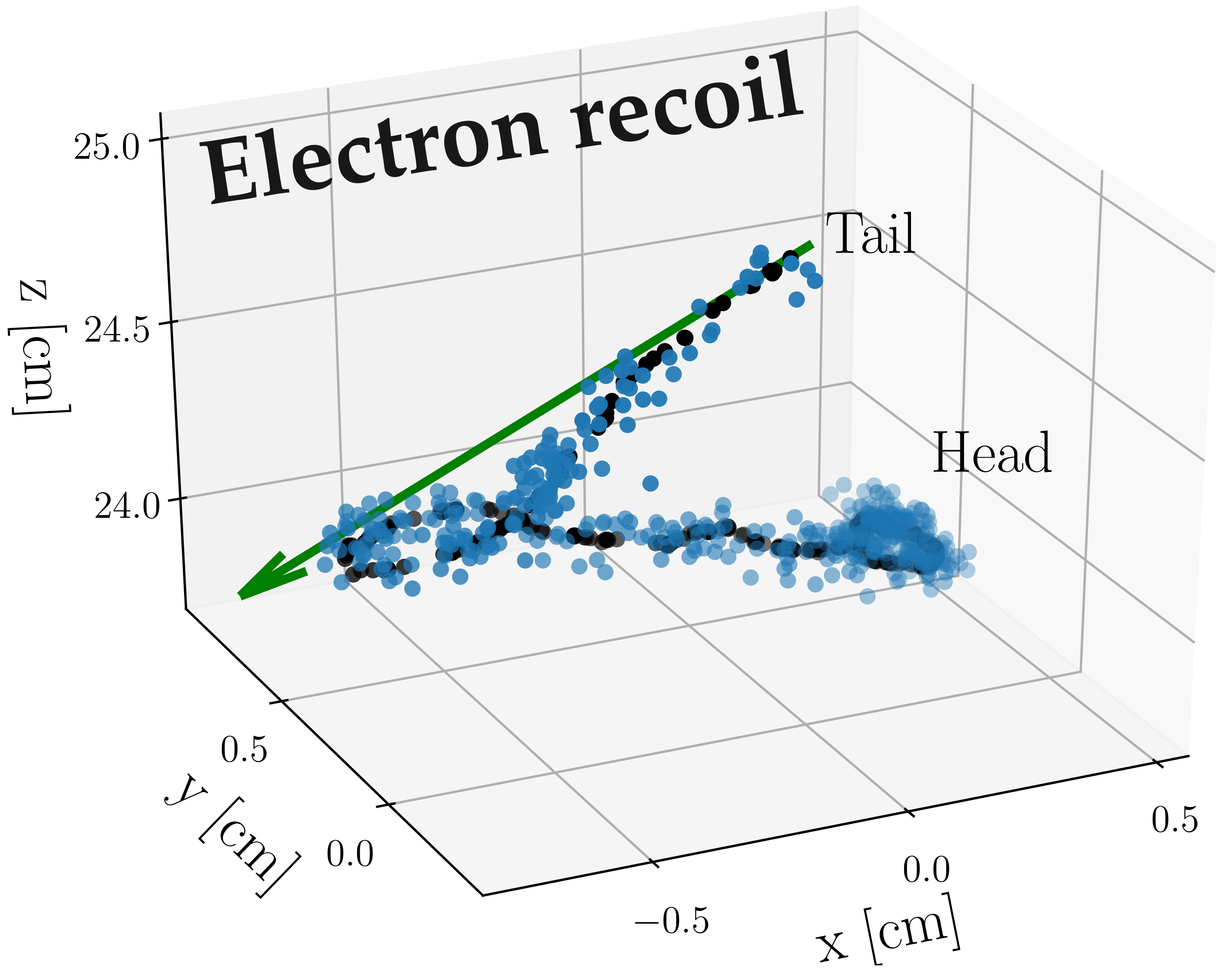


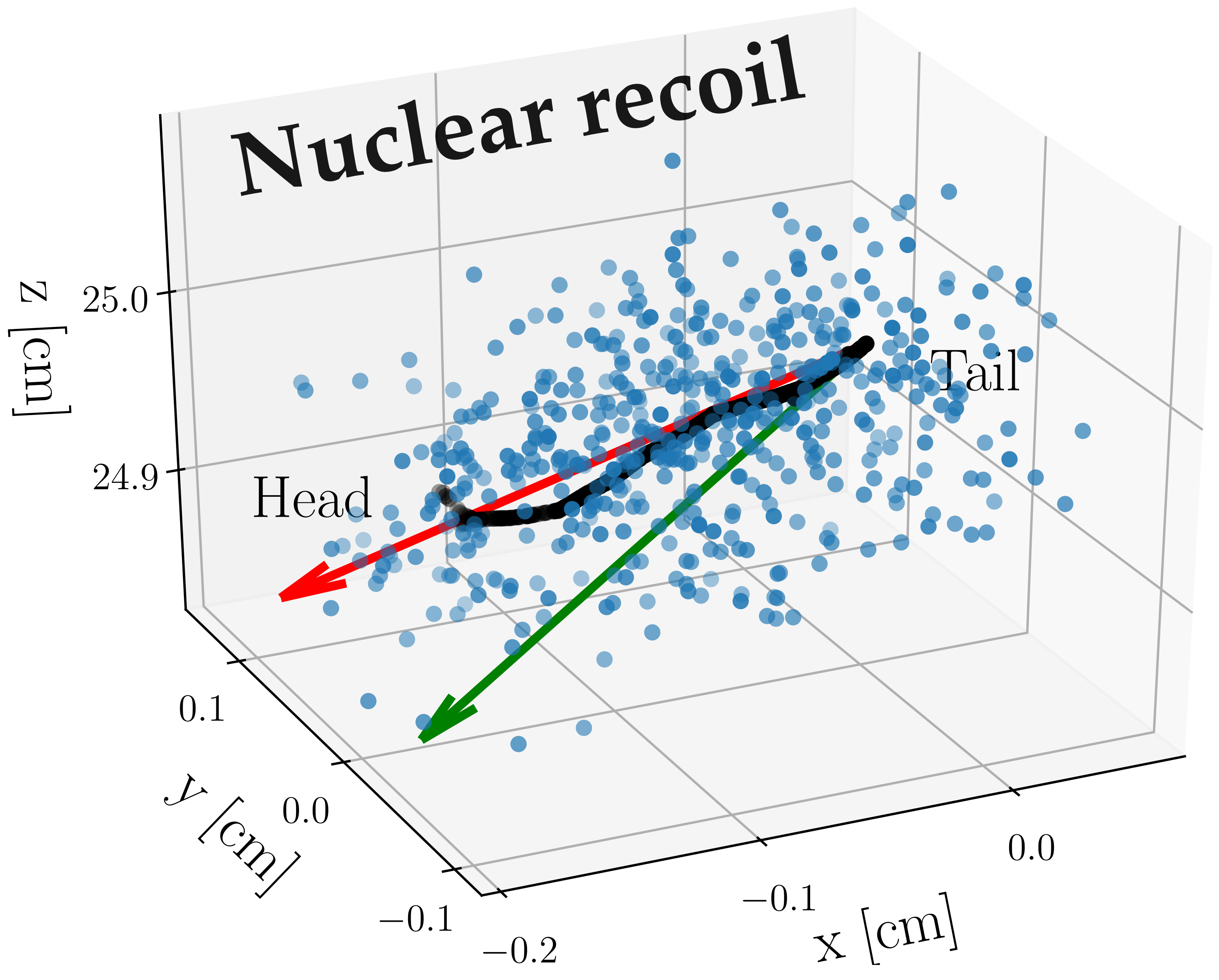
…Angular performance

Everything gets worse at lower energies:

- Decreasing quenching factor, means recoils are harder to detect
- Tracks get shorter → harder to measure directions
- Contrast in dE/dx is lower, harder to measure head-tail
- All this makes it harder to distinguish ER/NRs, so worse background rejection

→ Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals





2102.04596

Directional Recoil Detection

Sven E. Vahsen,[1] Ciaran A. J. O'Hare,[2] and Dinesh Loomba[3]

[1]Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA; email: sevahsen@hawaii.edu
[2]ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, School of Physics, NSW 2006, Australia; email: ciaran.ohare@sydney.edu.au
[3]Department of Physics and Astronomy, University of New Mexico, NM 87131, USA, email: dloomba@unm.edu

Annual Review of Nuclear and Particle Science 2021. XX:1–45

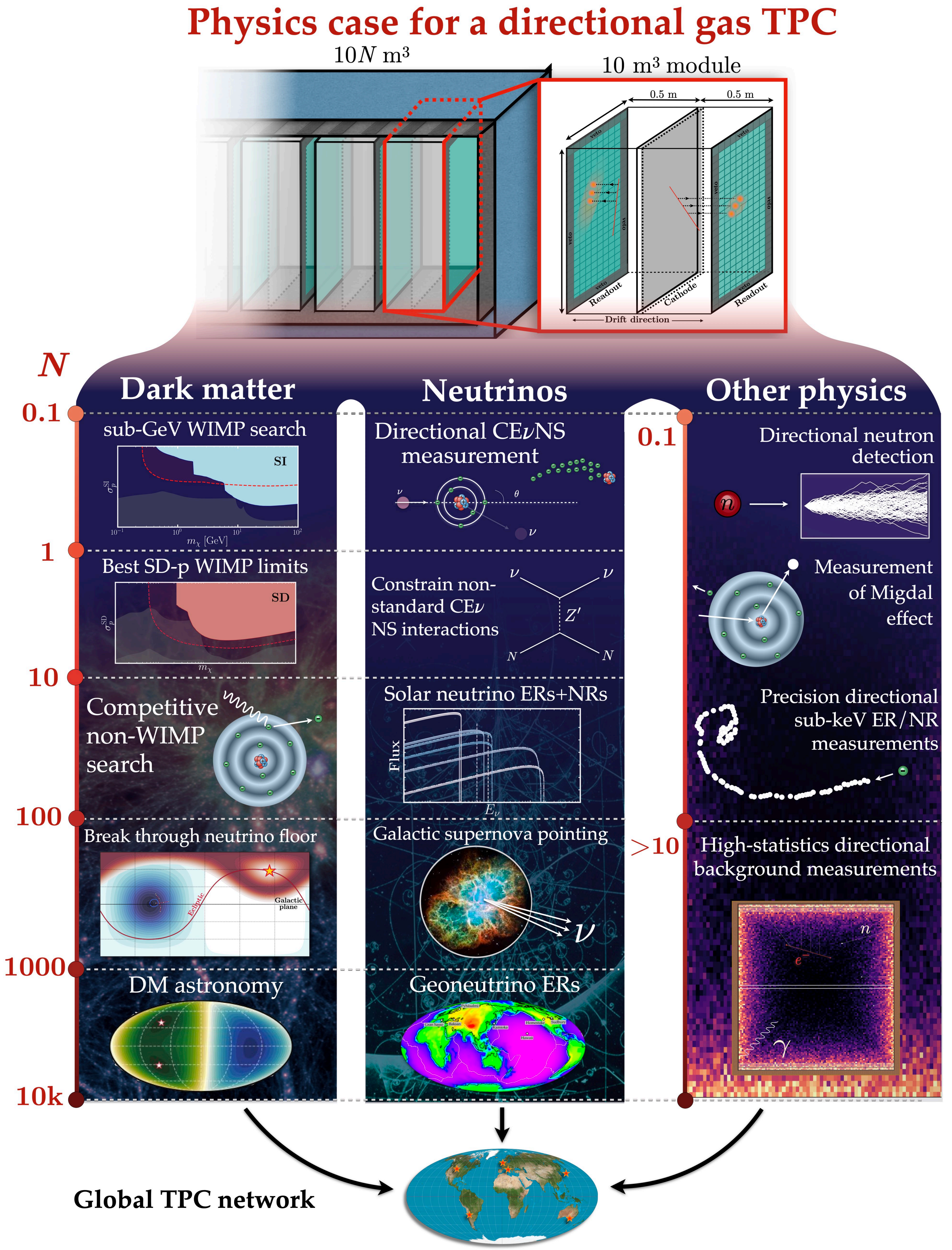
This article's doi: 10.1146/annurev-nucl-020821-035016

Keywords

nuclear recoils, electron recoils, dark matter, neutrinos, gas time projection chambers, Migdal effect

Abstract

Searches for dark matter-induced recoils have made impressive advances in the last few years. Yet the field is confronted by several outstanding problems. First, the inevitable background of solar neutrinos will soon inhibit the conclusive identification of many dark matter models. Second, and more fundamentally, current experiments have no practical way of confirming a detected signal's galactic origin. The concept of directional detection addresses both of these issues while offering opportunities to study novel dark matter and neutrino-related physics. The concept remains experimentally challenging, but gas time projection chambers are an increasingly attractive option, and when properly configured, would allow directional measurements of both nuclear and electron recoils. In this review, we reassess the required detector performance and survey relevant technologies. Fortuitously, the highly-segmented detectors required to achieve good directionality also enable several fundamental and applied physics measurements. We comment on near-term challenges and how the field could be advanced.



Further reading (of my own papers…)

[2203.05914] - Snowmass white paper on recoil imaging
[2102.04596] - a review of directional detection
[2002.07499] - directional detection in Xe/Ar
[2008.12587] - directional detection with gas TPCs
[2105.11949] - directional detection with DNA
[2109.03116] - the neutrino fog

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY