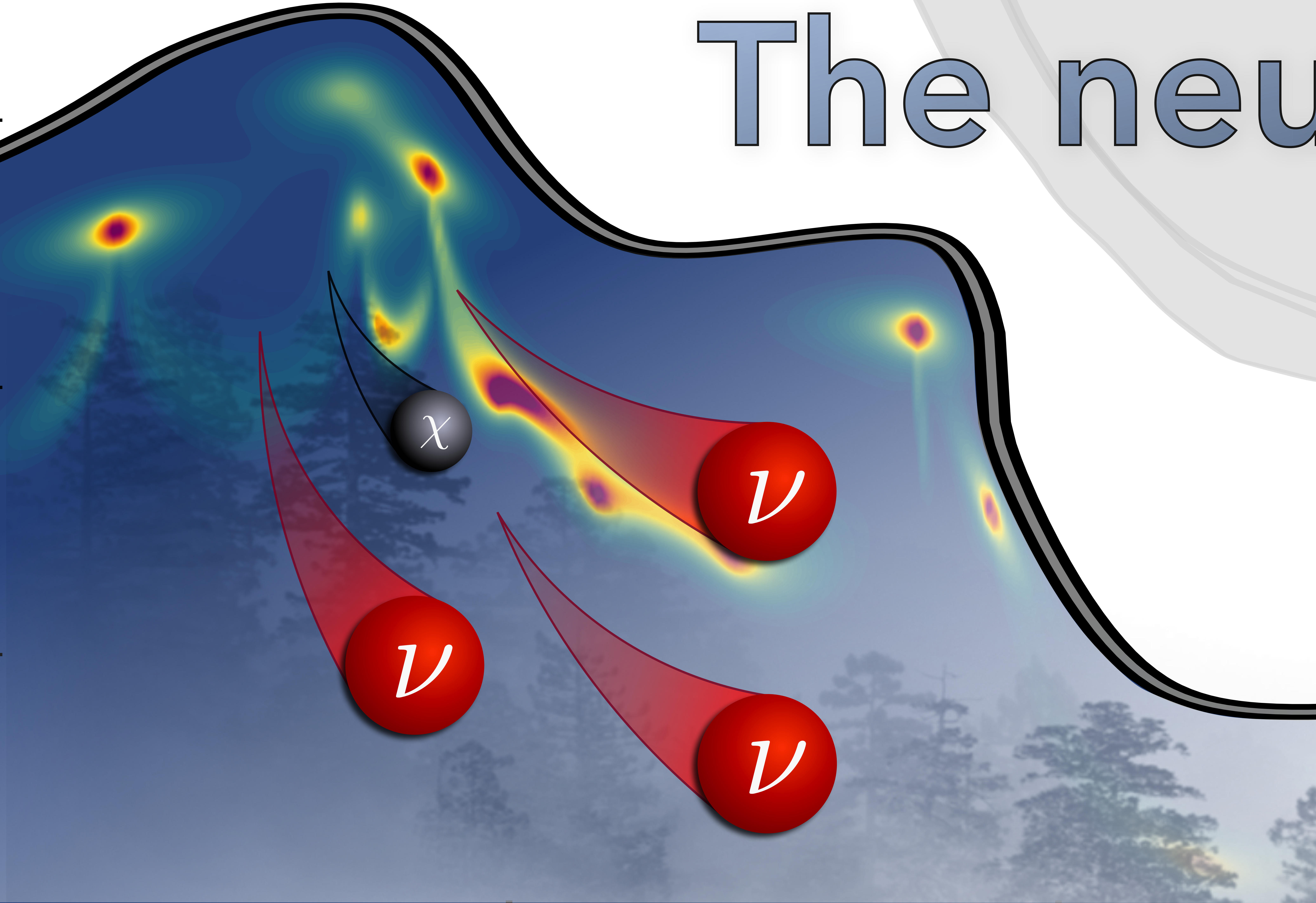
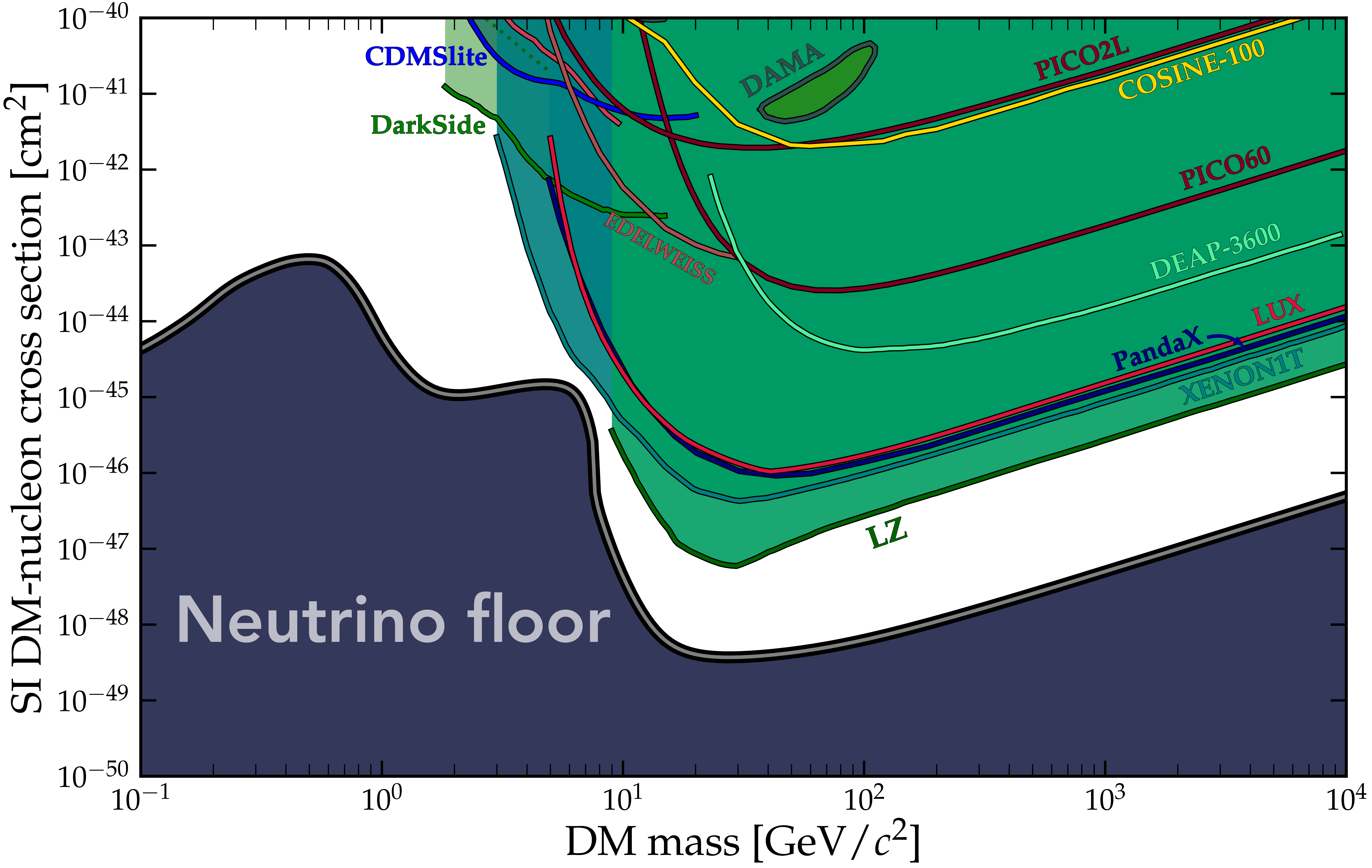
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

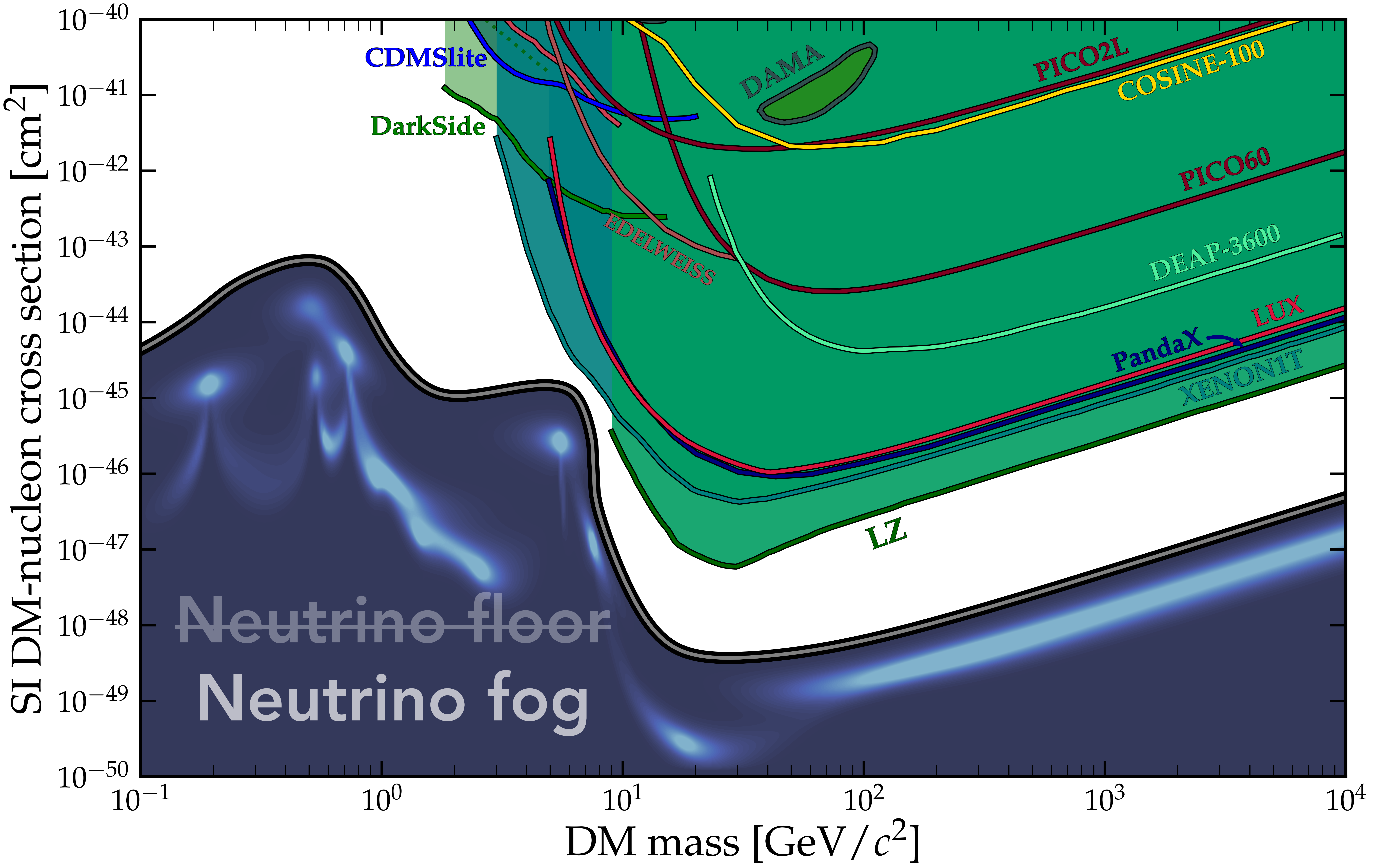
The neutrino fog



Ciaran O'Hare
University of Sydney



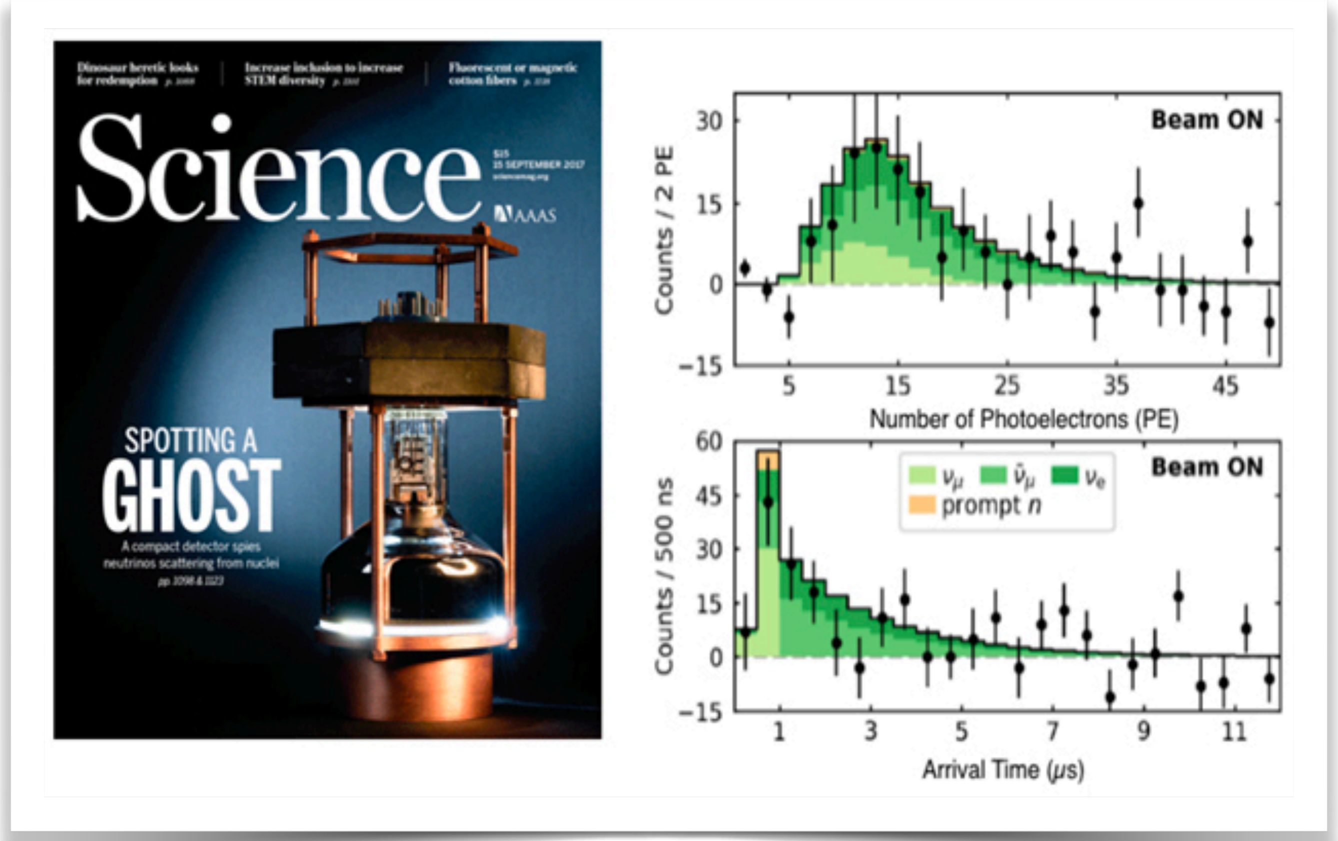
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
LZ
Neutrino floor
SI DM-nucleon cross section [cm^2]
DM mass [GeV / c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

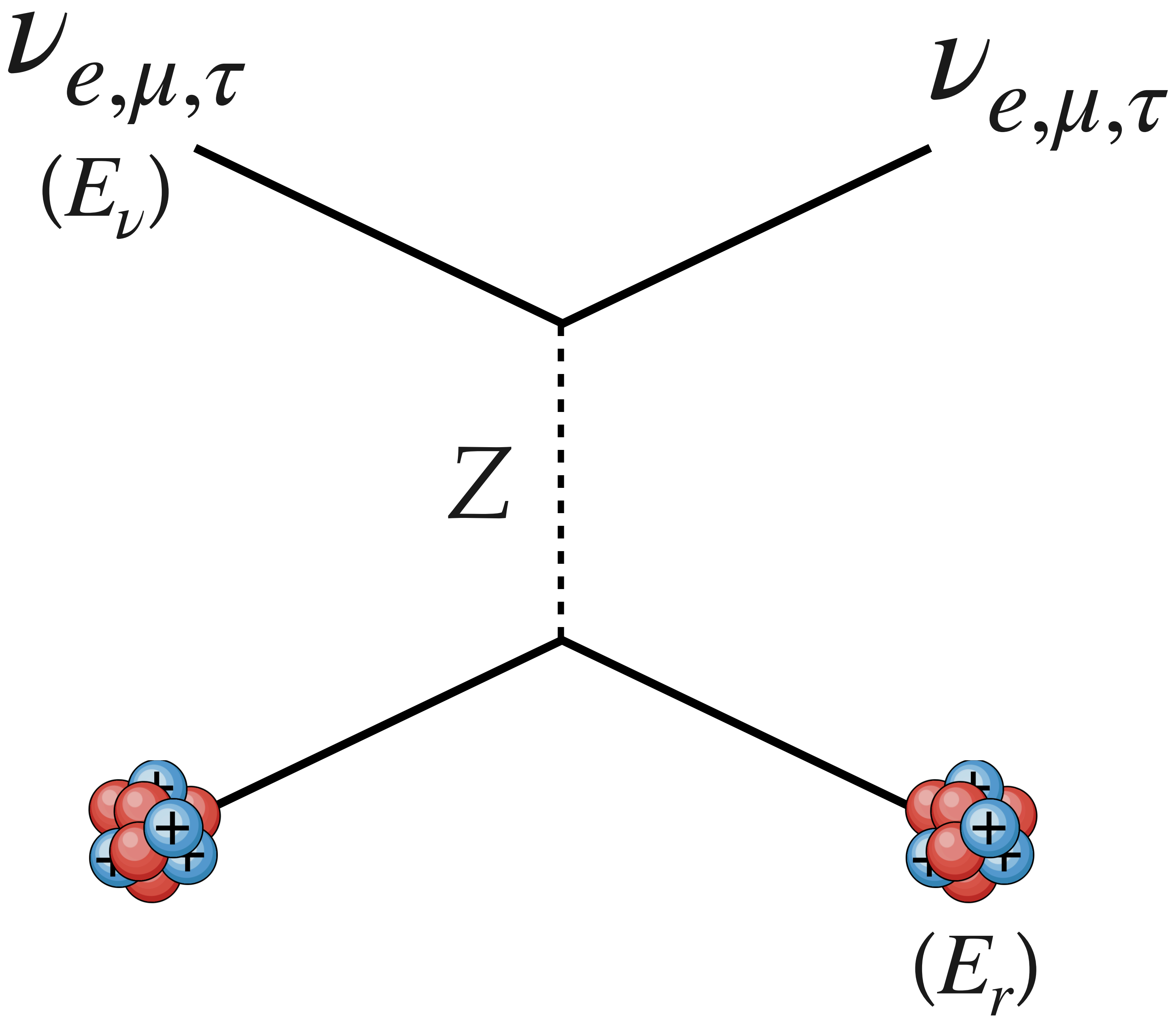


CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
DEAP-3600
EDELWEISS
LUX
PandaX
XENON1T
LZ
Neutrino floor
Neutrino fog
SI DM-nucleon cross section [cm^2]
DM mass [GeV/c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}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

Coherent elastic neutrino-nucleus scattering (CEνNS)

Freedman (1974), detected by COHERENT [2003.10630]





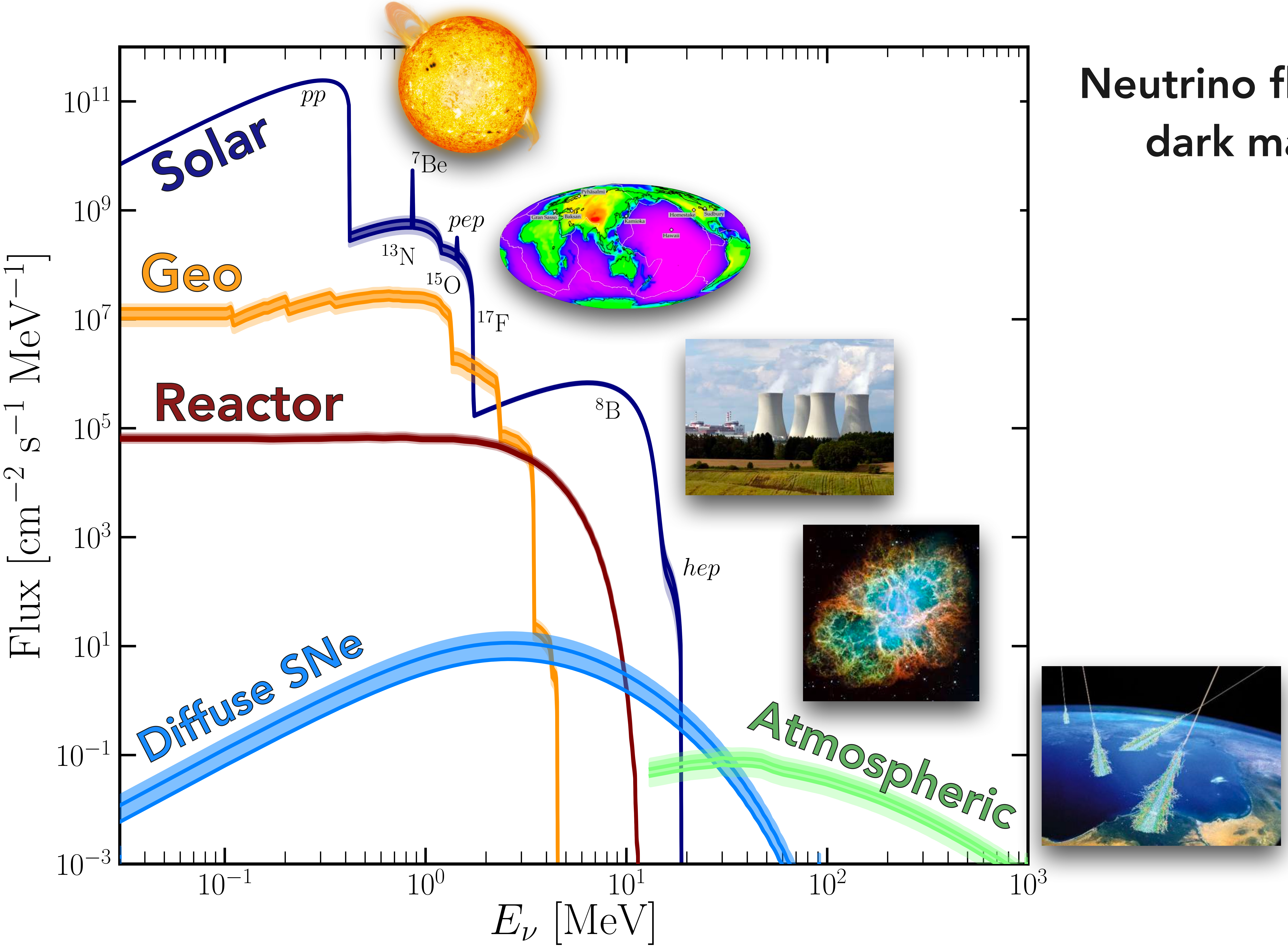
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{G_F^2}{4\pi} \underbrace{Q_W^2}_{\text{Weak hypercharge}} m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

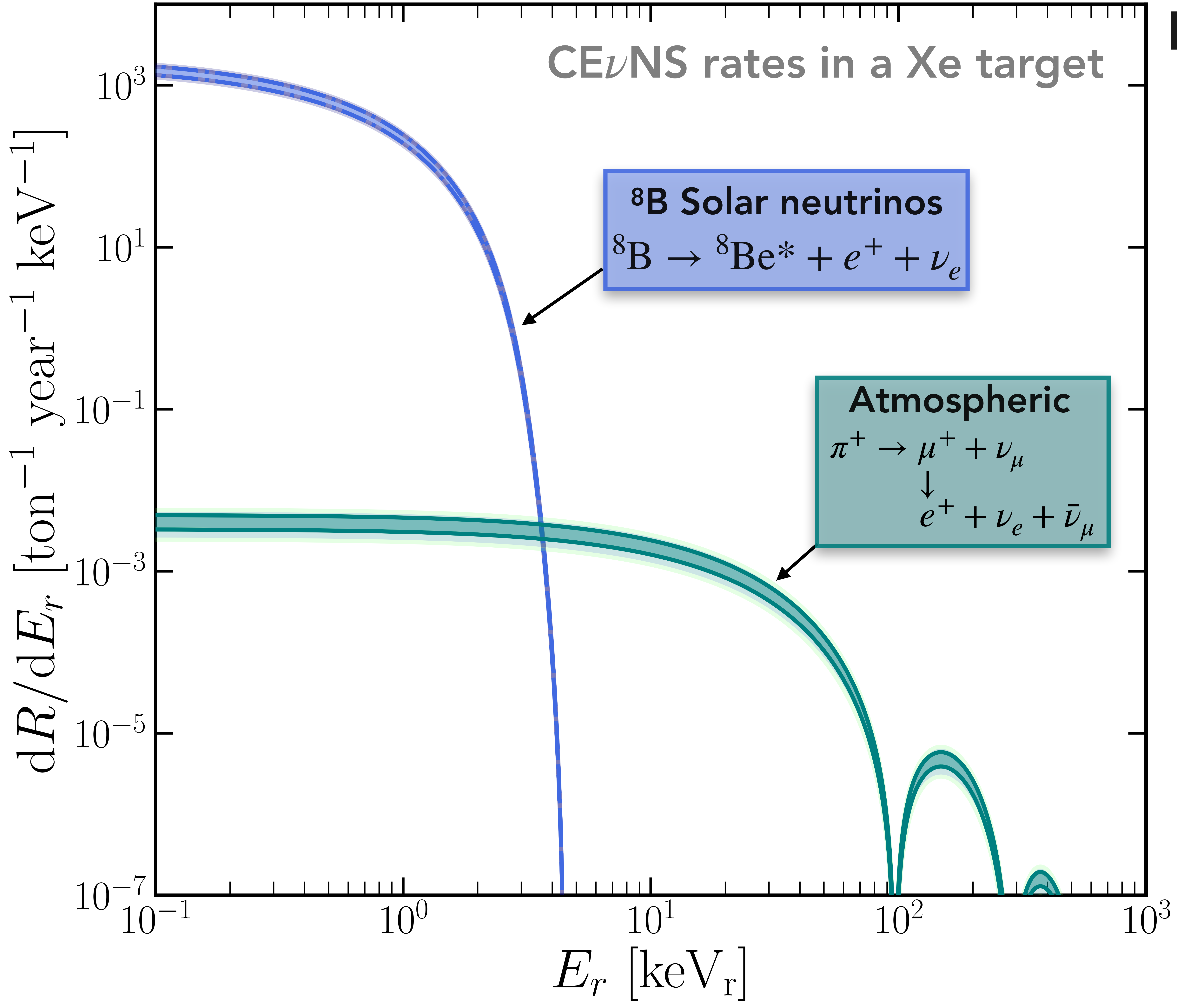
$$E_r \approx \mathcal{O}(10\,\mathrm{keV}) \Rightarrow E_\nu \lesssim \sqrt{\frac{m_N E_r}{2}} \approx 10\,\mathrm{MeV}$$

Neutral current
→ flavour blind

⇒ >10 MeV neutrinos will generate nuclear recoils in a similar energy range to $m_\chi \gtrsim$ GeV dark matter

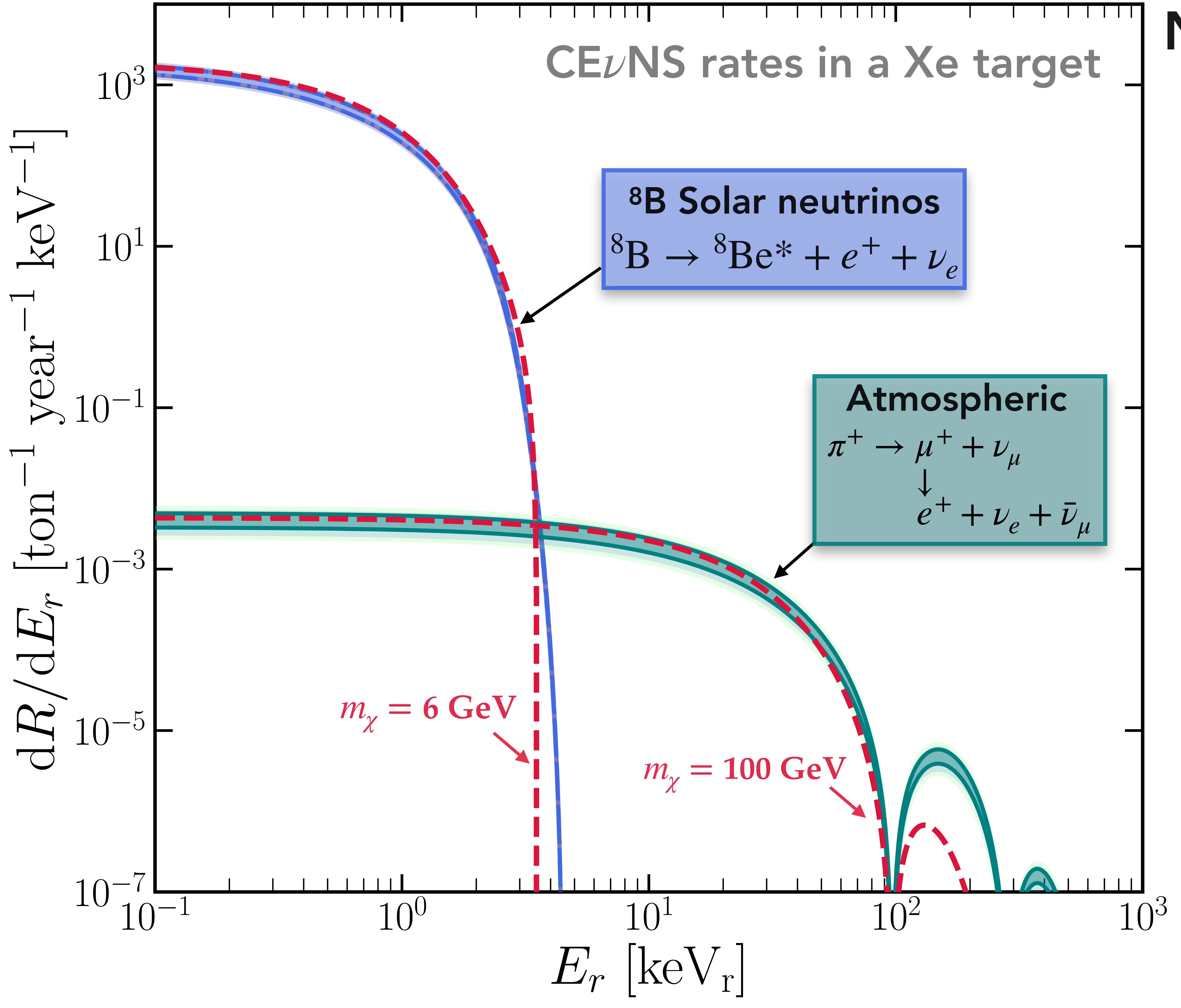
Neutrino fluxes relevant for dark matter searches





Neutrinos will be observed in LZ or XENONnT soon

$$\frac{\mathrm{d}R_\nu}{\mathrm{d}E_r} = \frac{1}{m_N}\int_{E_\nu^{\mathrm{min}}} \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu}\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\mathrm{d}E_\nu$$



Neutrinos will be observed in LZ or XENONnT soon

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N}\int_{E_\nu^{min}} \frac{d\Phi}{dE_\nu}\frac{d\sigma}{dE_r} dE_\nu$$

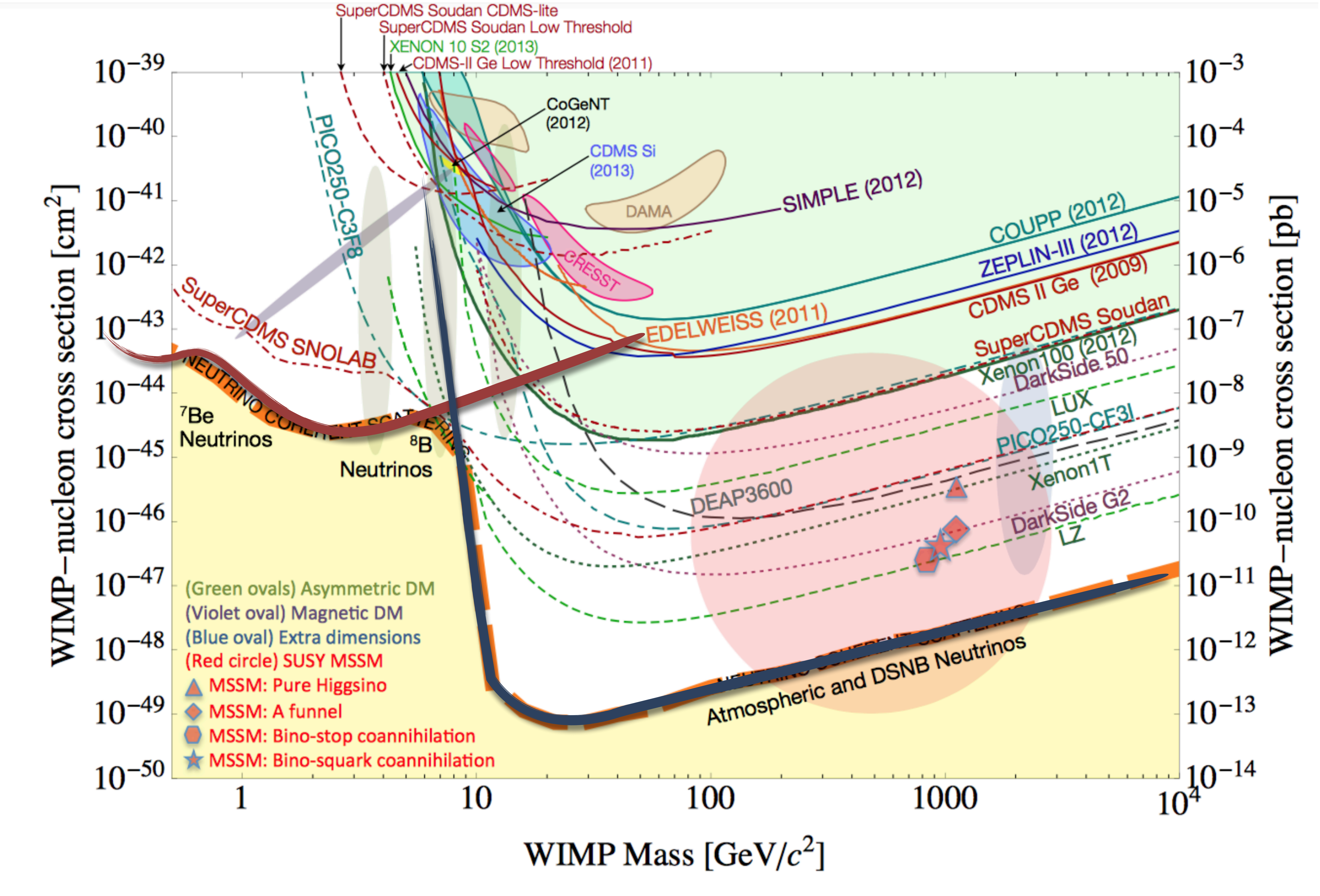
Atmospheric and ^{8}B solar neutrinos are going to be the troublemakers—their CEνNS rates look just like **6 GeV** and **100 GeV** WIMPs in Xenon

The neutrino "floor" as it's usually thought of

e.g. for LXe TPCs

The original neutrino floor

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



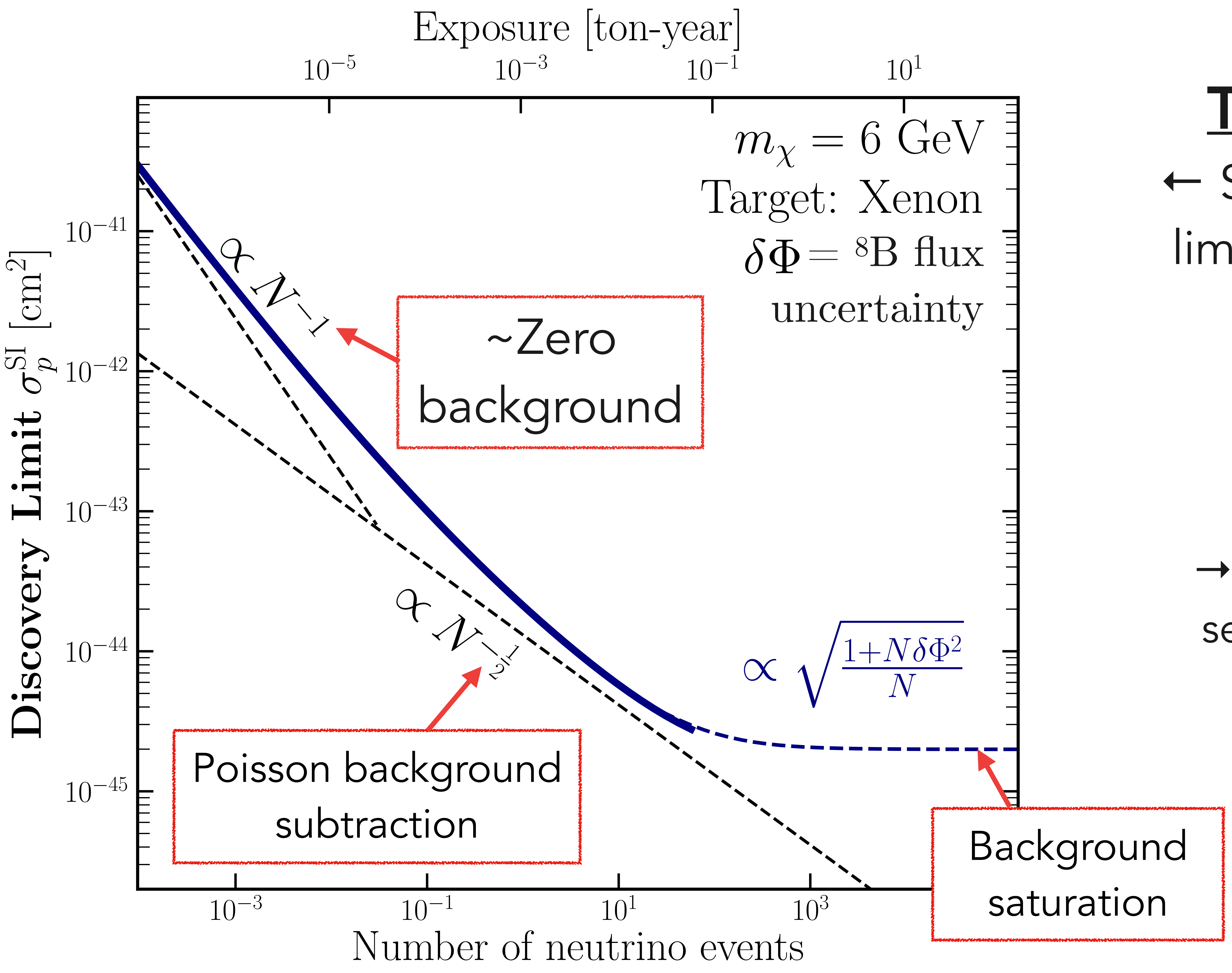
Interpolation of two discovery limits

(3σ discovery in 90% of expts)

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

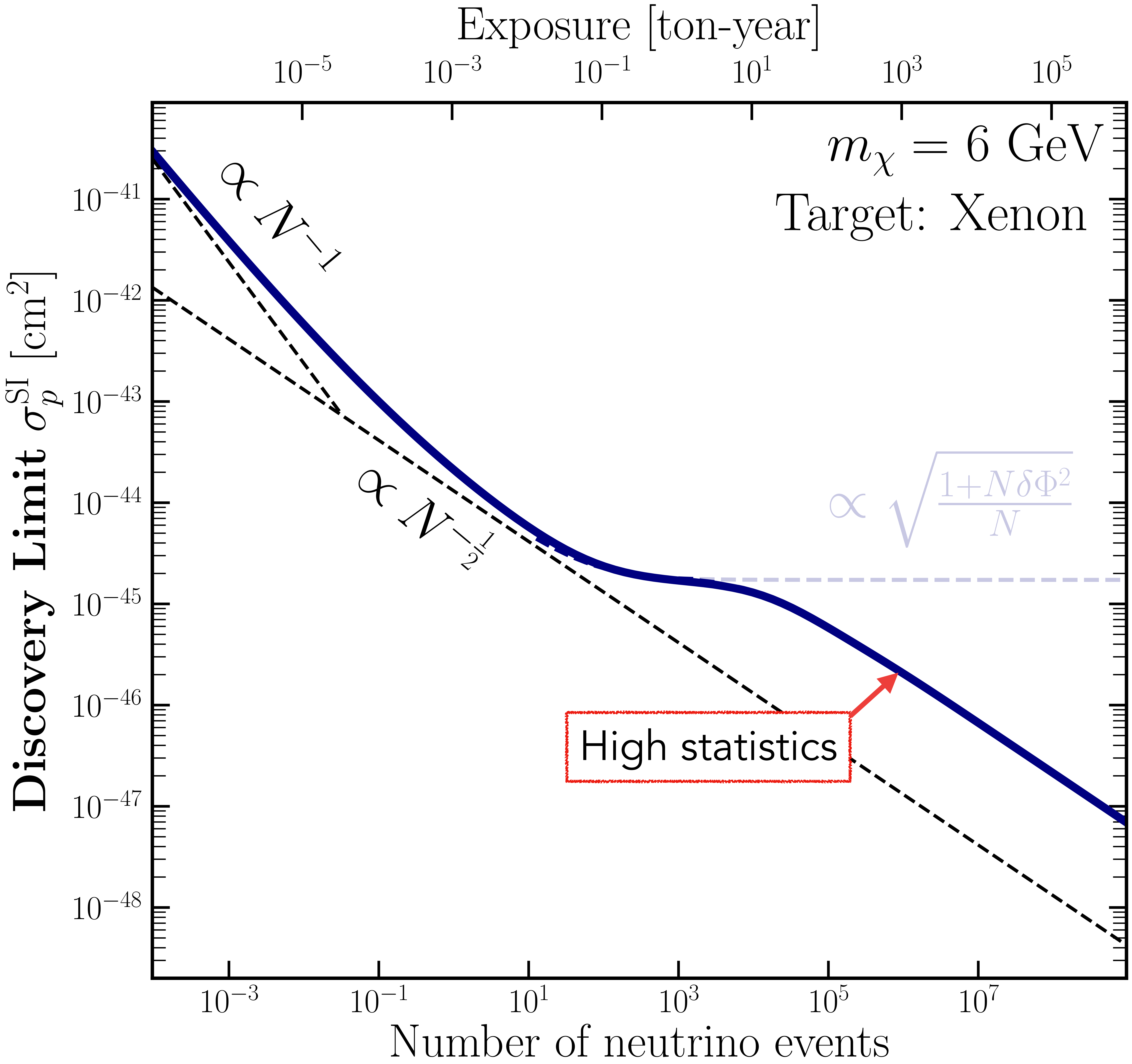
→ high mass/high threshold (500 atmospheric events)

The neutrino "floor"



← Scaling of a DM discovery limit for increasing exposure

→ Experiment can't probe cross sections smaller than those that generate an excess in events below the level of expected background fluctuations

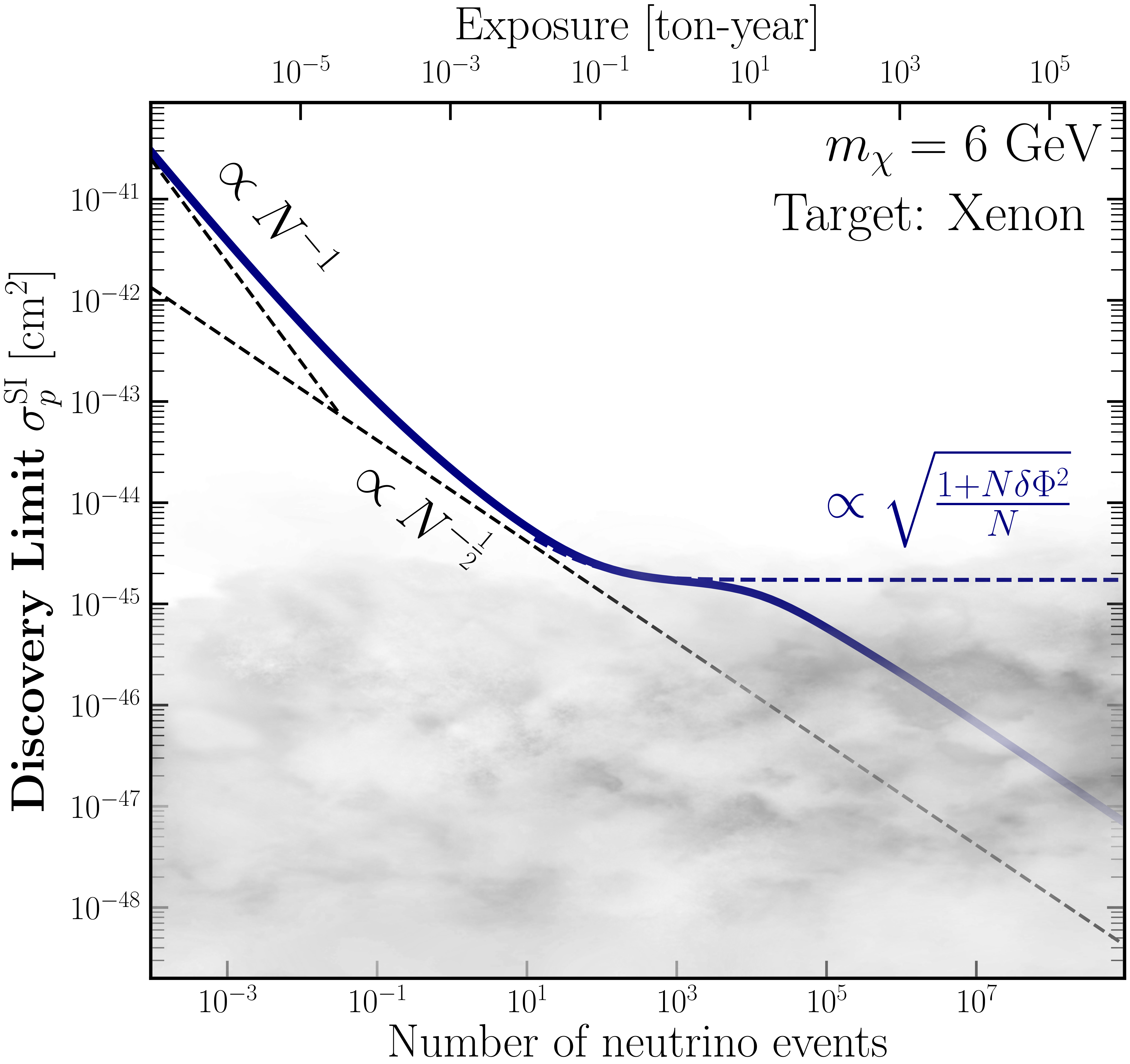


The full story:

<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 $\mathrm{d}R/\mathrm{d}E_r$ (this is textbook statistics really, it's the limit when the likelihood dominates over the prior)

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



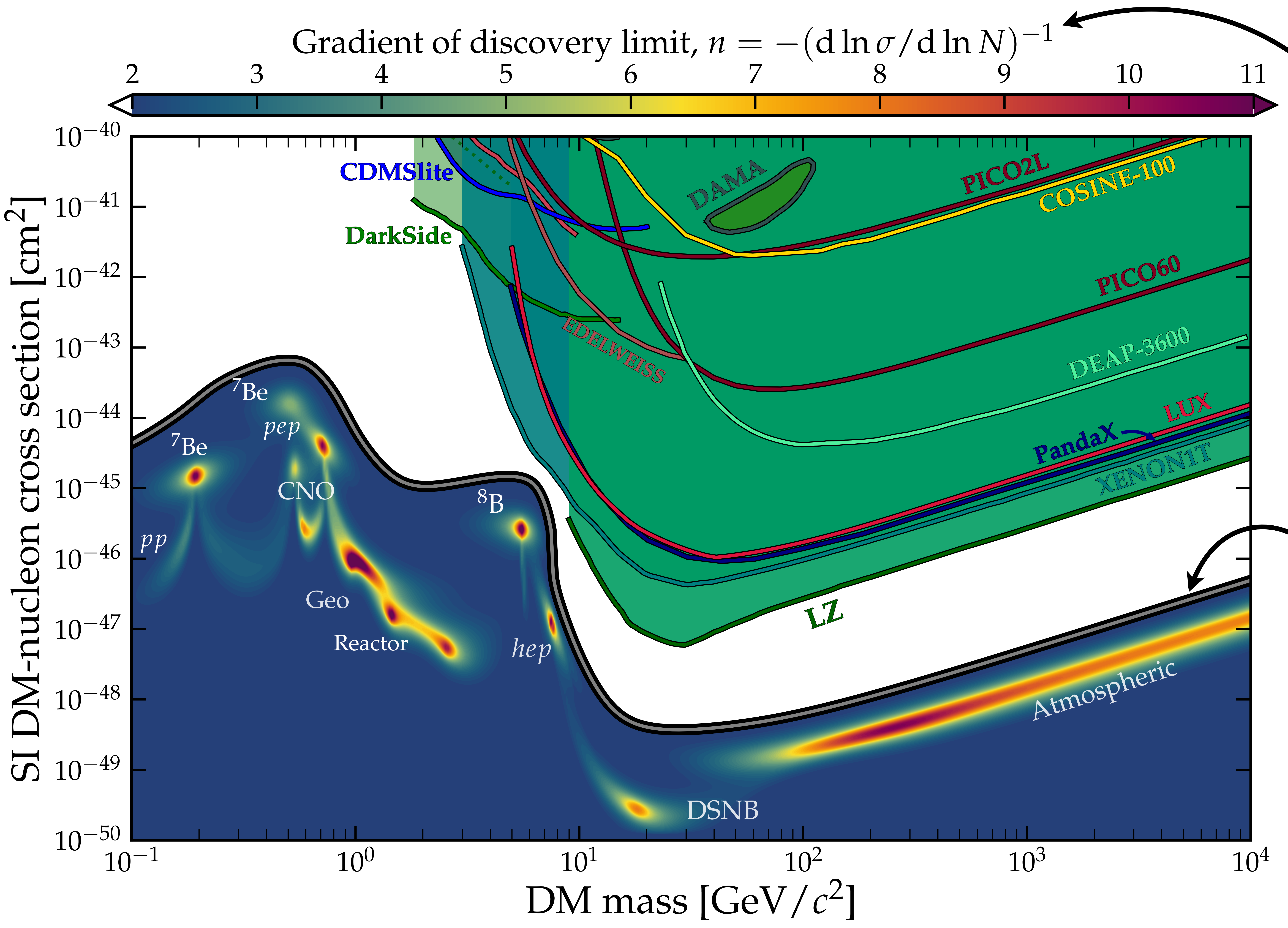
How should we define it then?

There is no "floor", but we can quantify 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



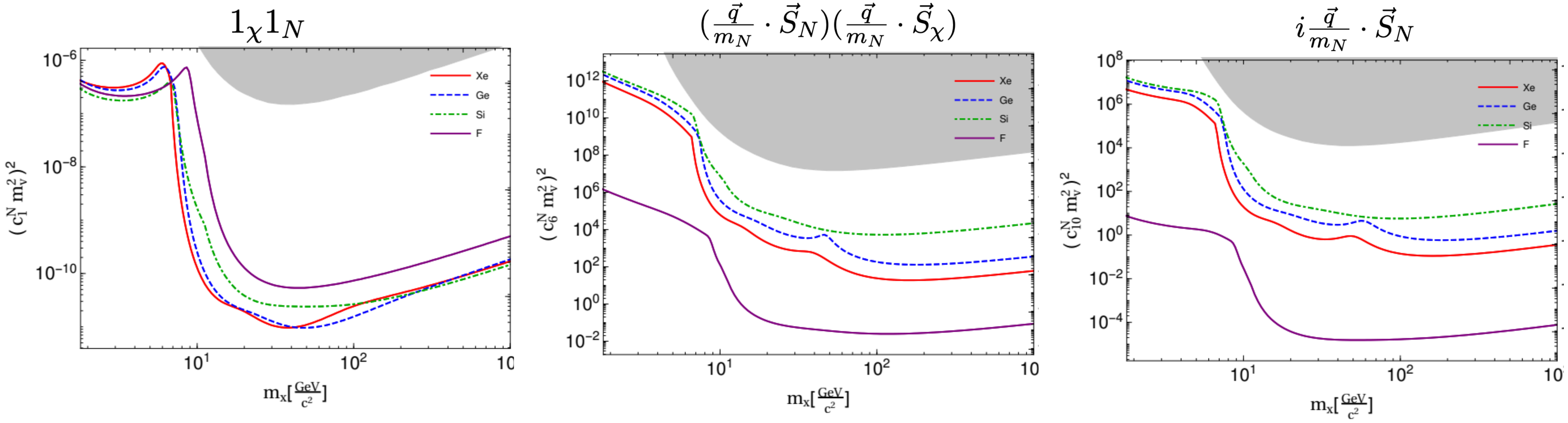
n parameterises the "fogginess" of the neutrino fog
→ note that it's not uniformly foggy everywhere

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

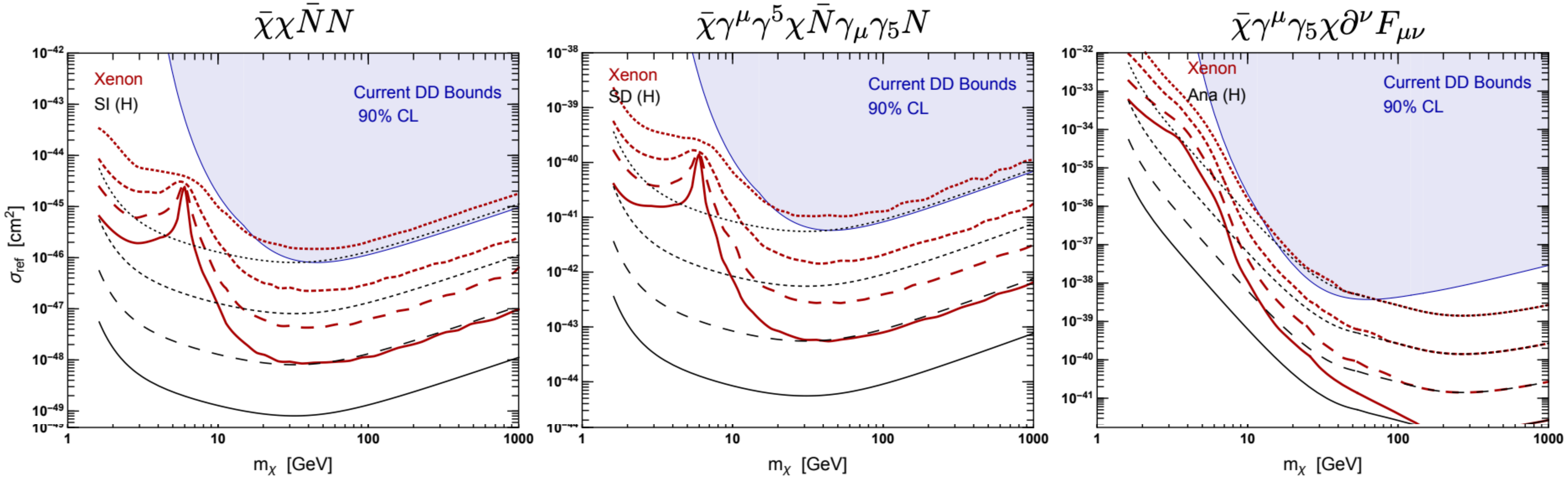
Neutrino "floors" beyond SI

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

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

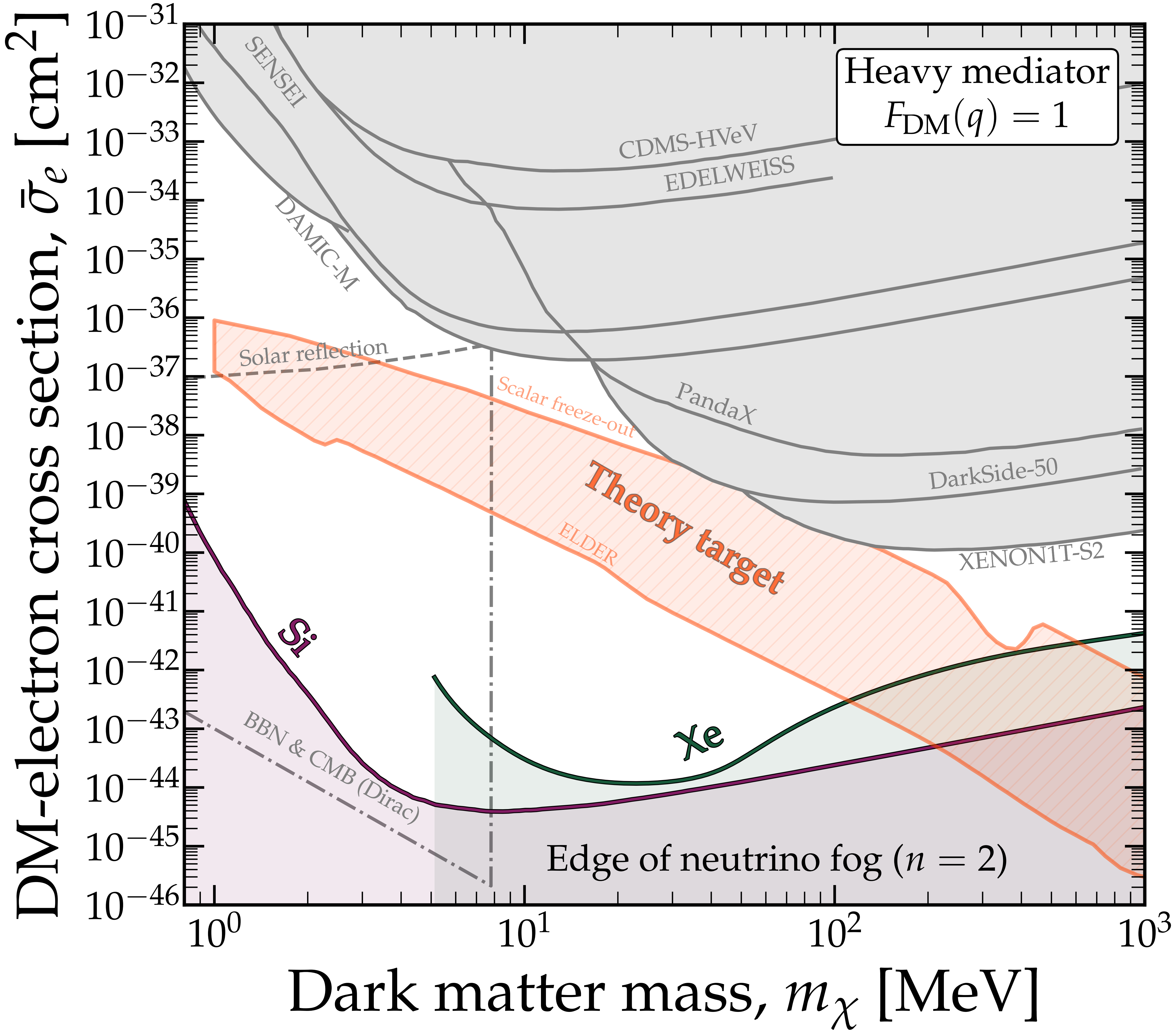


Gelmini et al. [1804.01638] → Various DM Interaction models



Neutrino “floors” beyond vanilla WIMP DM

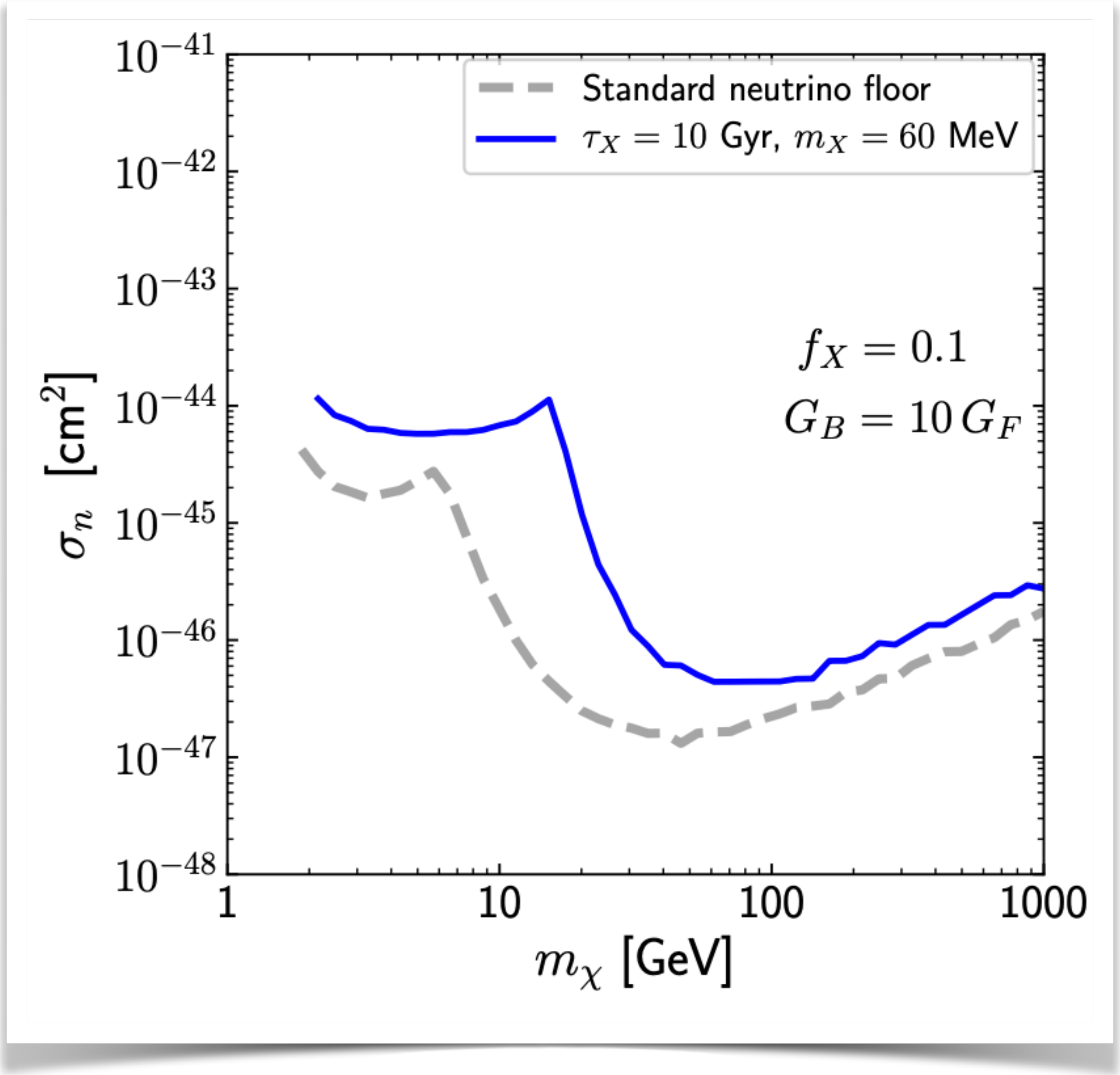
DM-electron scattering



More complicated DM models

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

Nikolic et al. [2008.13557]

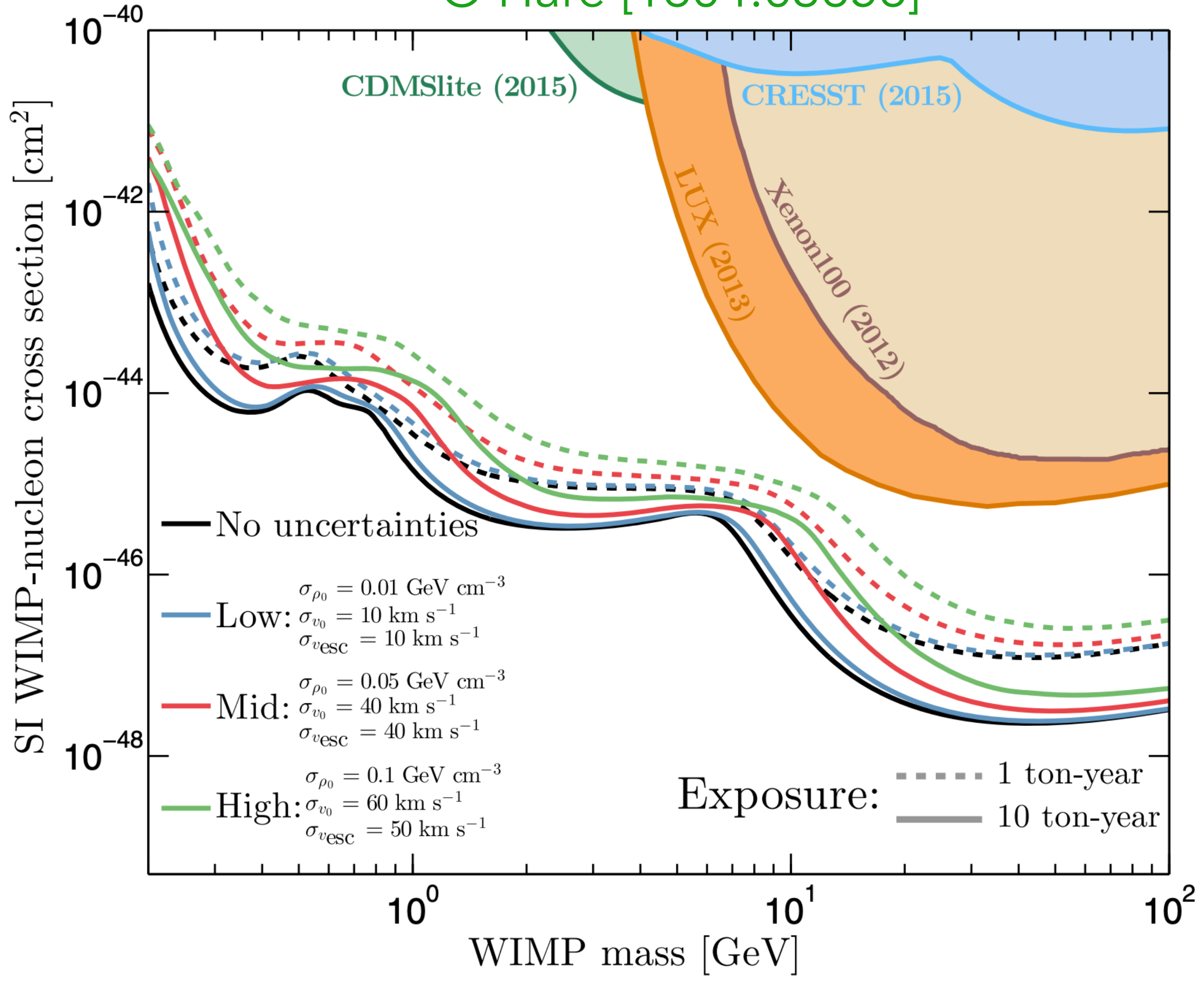


Uncertainties…

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

Astrophysical uncertainties

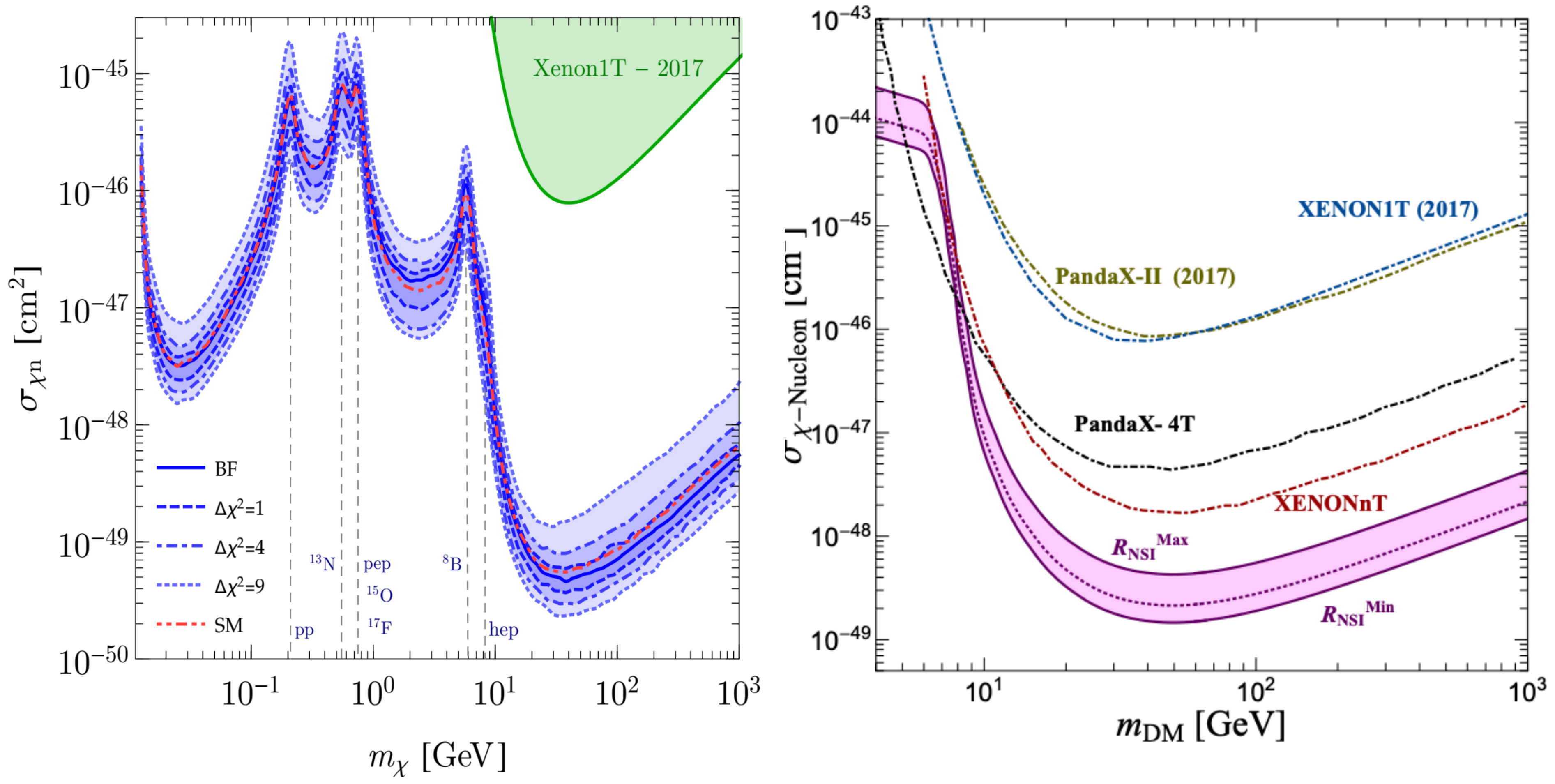
O'Hare [1604.03858]



Neutrino non-standard interactions

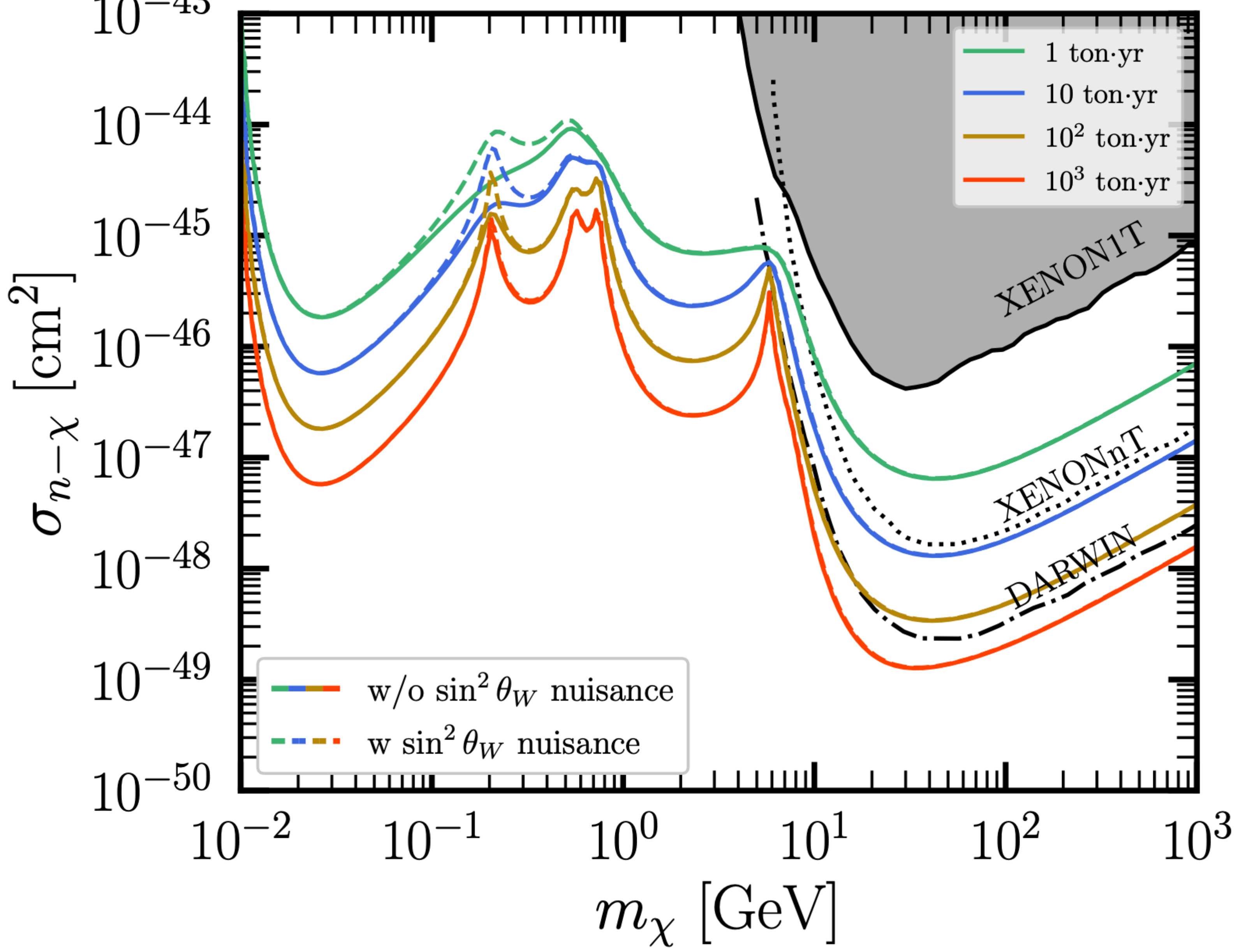
Aristizabal Sierra et al. [1712.09667]

Gonzalez-Garcia et al. [1803.03650]



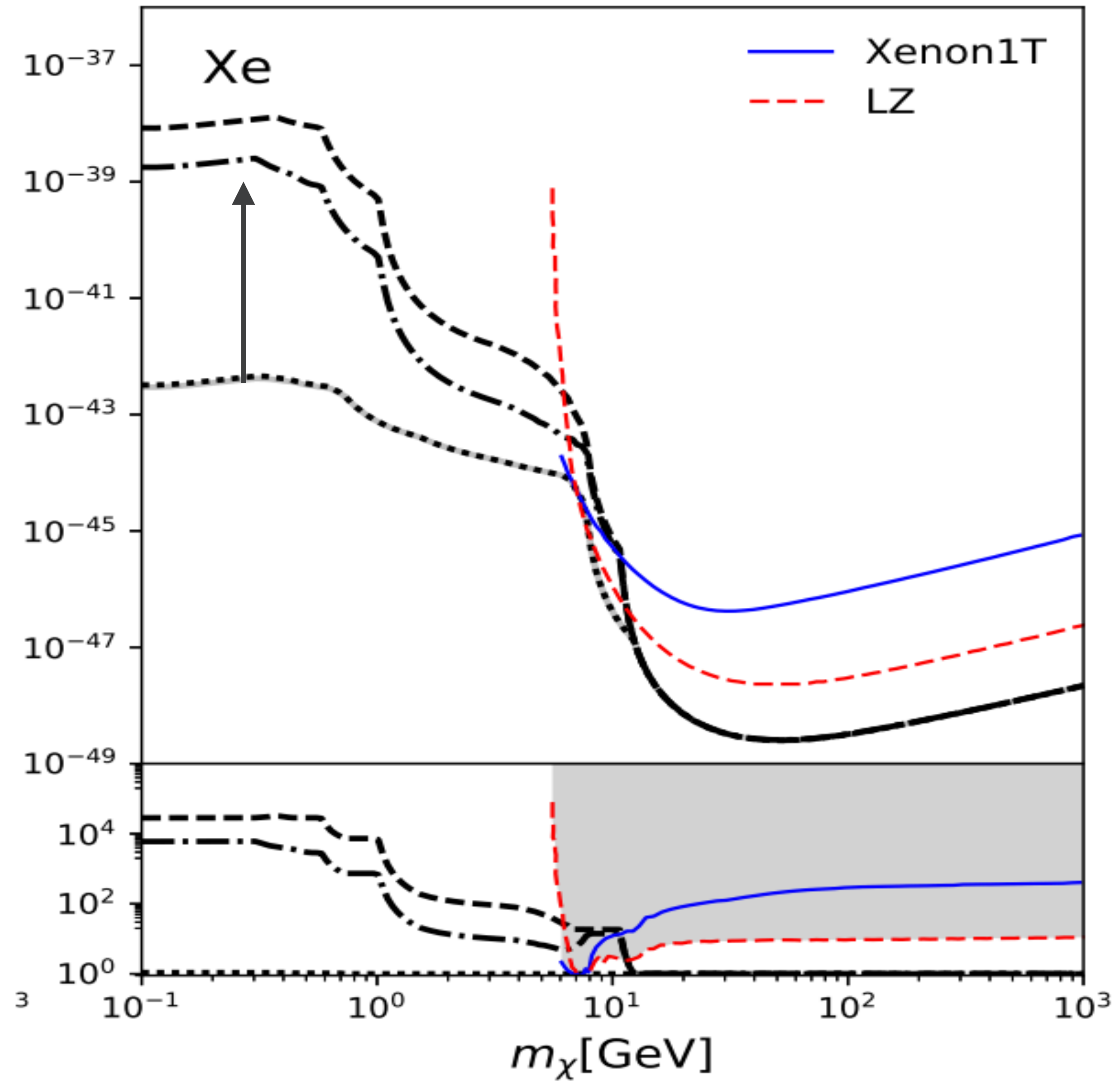
CEvNS uncertainties

Aristizabal Sierra et al. [2109.03247]



New mediators involved in CEvNS

Boehm et al. [1809.06385]



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:

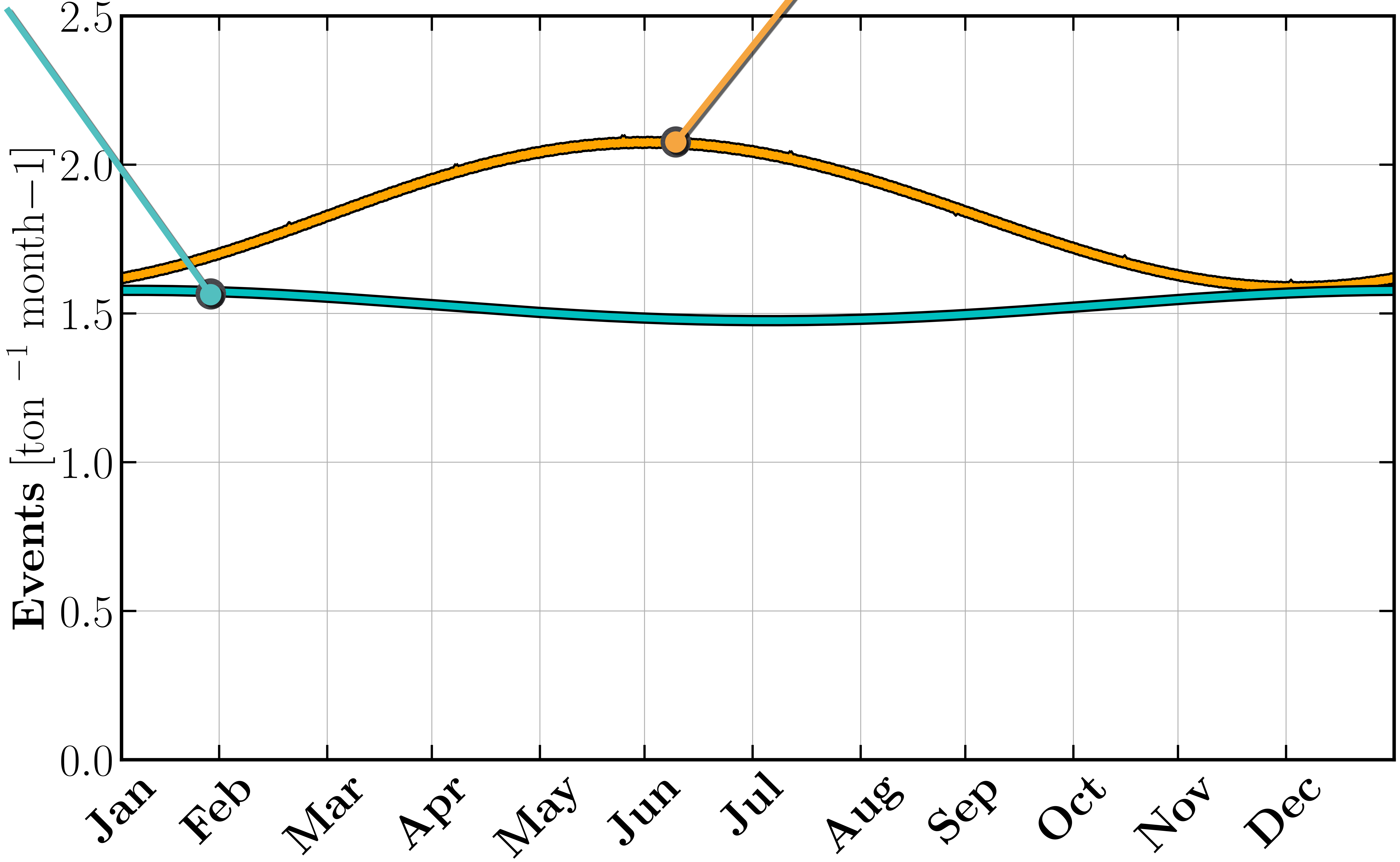
5 methods, ordered (sort of) in increasing effectiveness

1. ~~Detect *a lot* of events~~
2. Use annual modulation
3. Have multiple target nuclei
4. Improve neutrino flux measurements
5. Use directional detectors

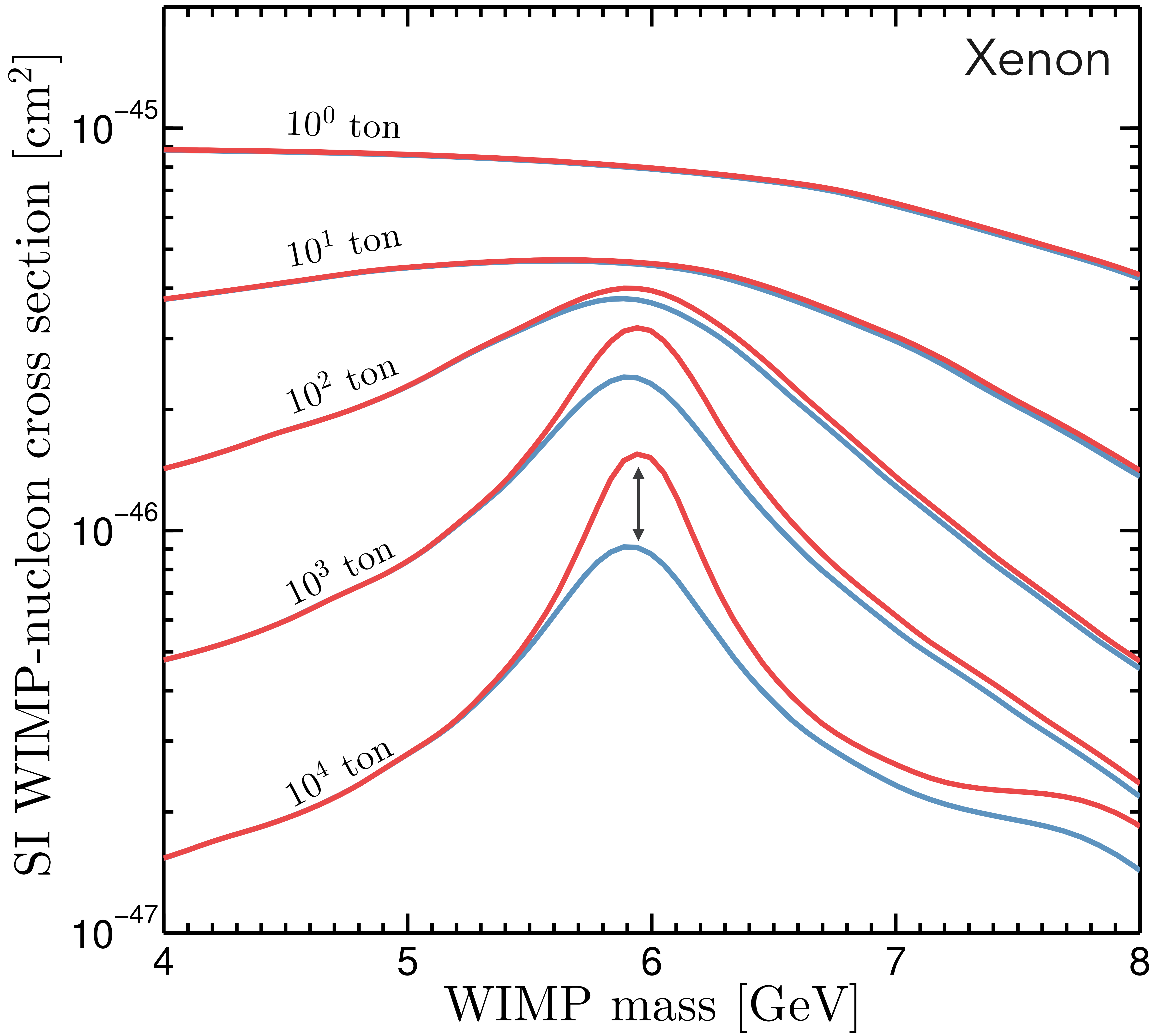
1. Annual modulation

Neutrinos peak in January when Earth is closest to the Sun

DM peaks in June when Earth is facing the DM wind



1. Annual modulation



Analyse energy information only

Analyse energy+event time information

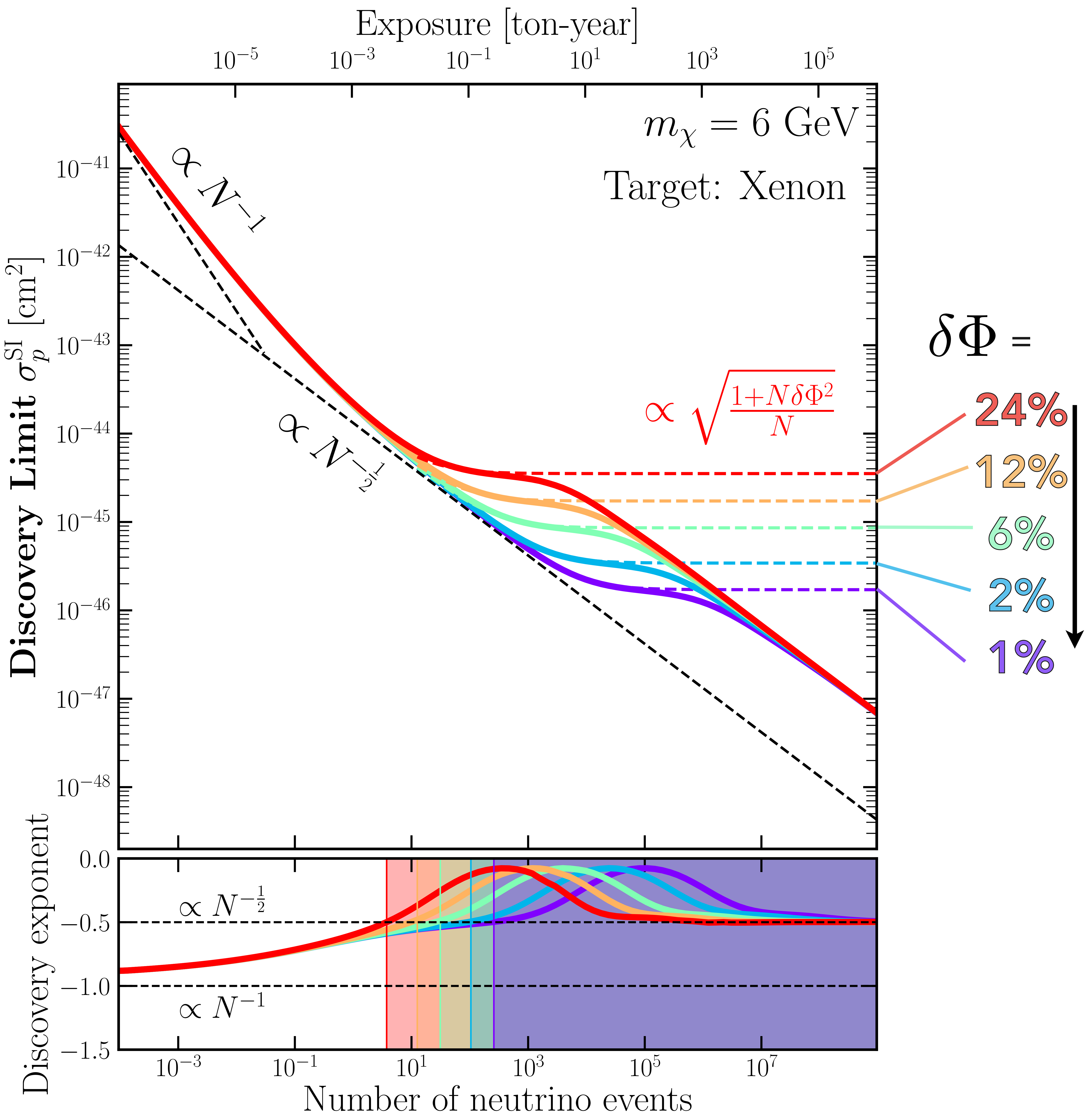
Increasing exposure

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

With a smaller neutrino flux uncertainty, the onset of the neutrino fog is pushed to lower cross sections

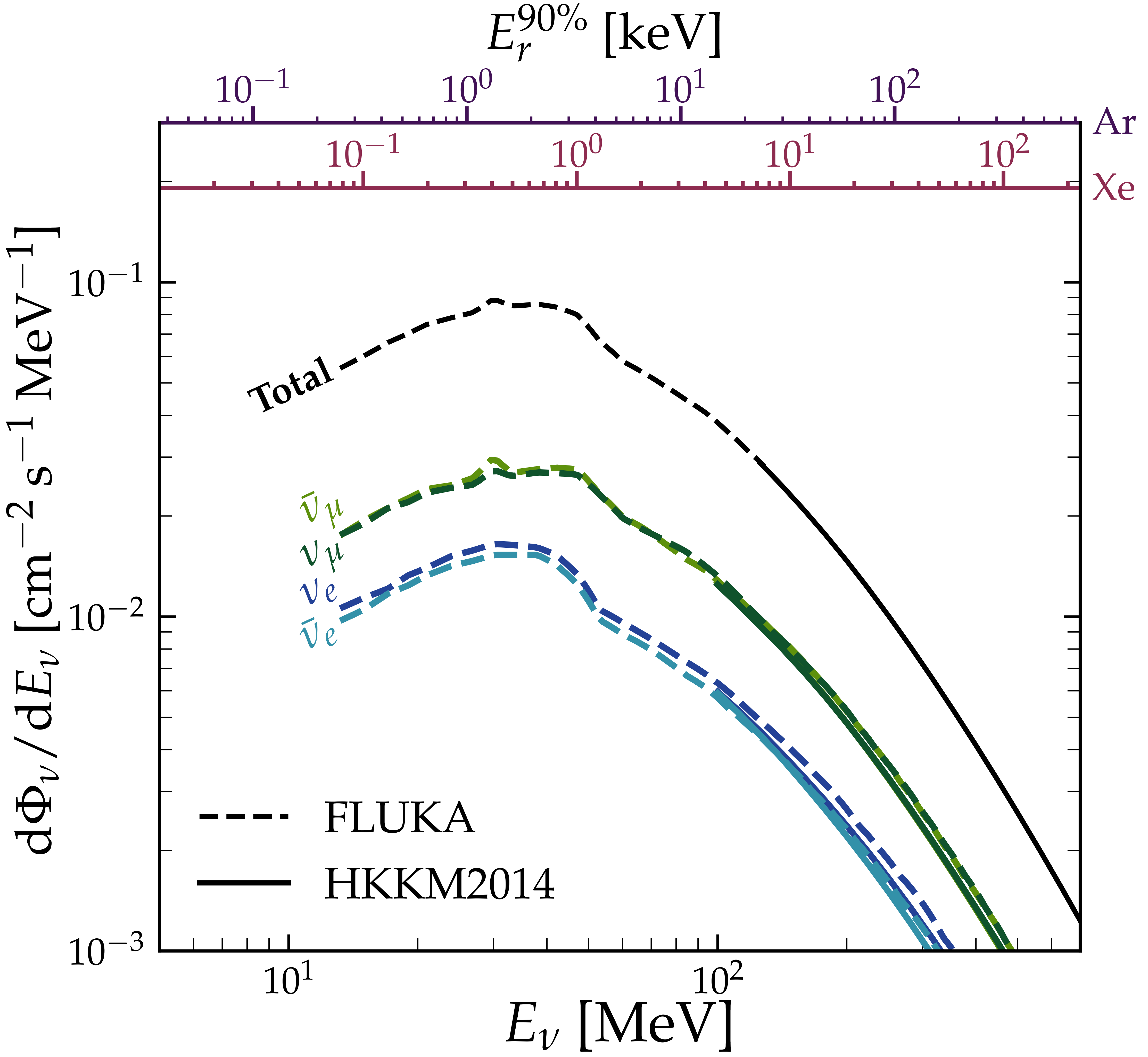
i.e. if you have better prior knowledge of the background, you can tolerate more of it before it starts to impact sensitivity



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}

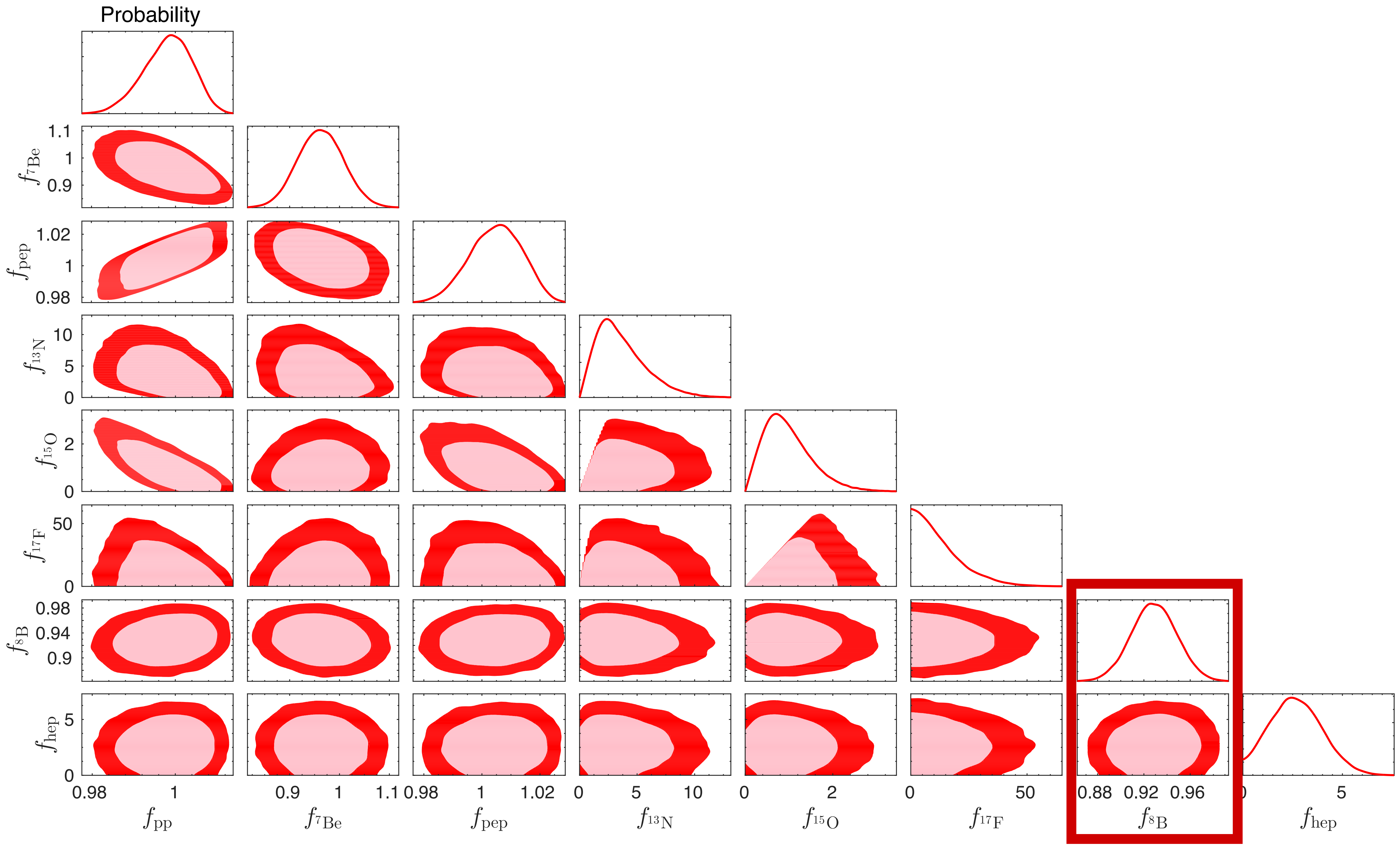
Low-E tail of **atmospheric flux** not yet measured at the relevant energies—25% uncertainty is advisory from simulations. This is an important background for detecting DSNB, so a measurement will happen in the future for sure



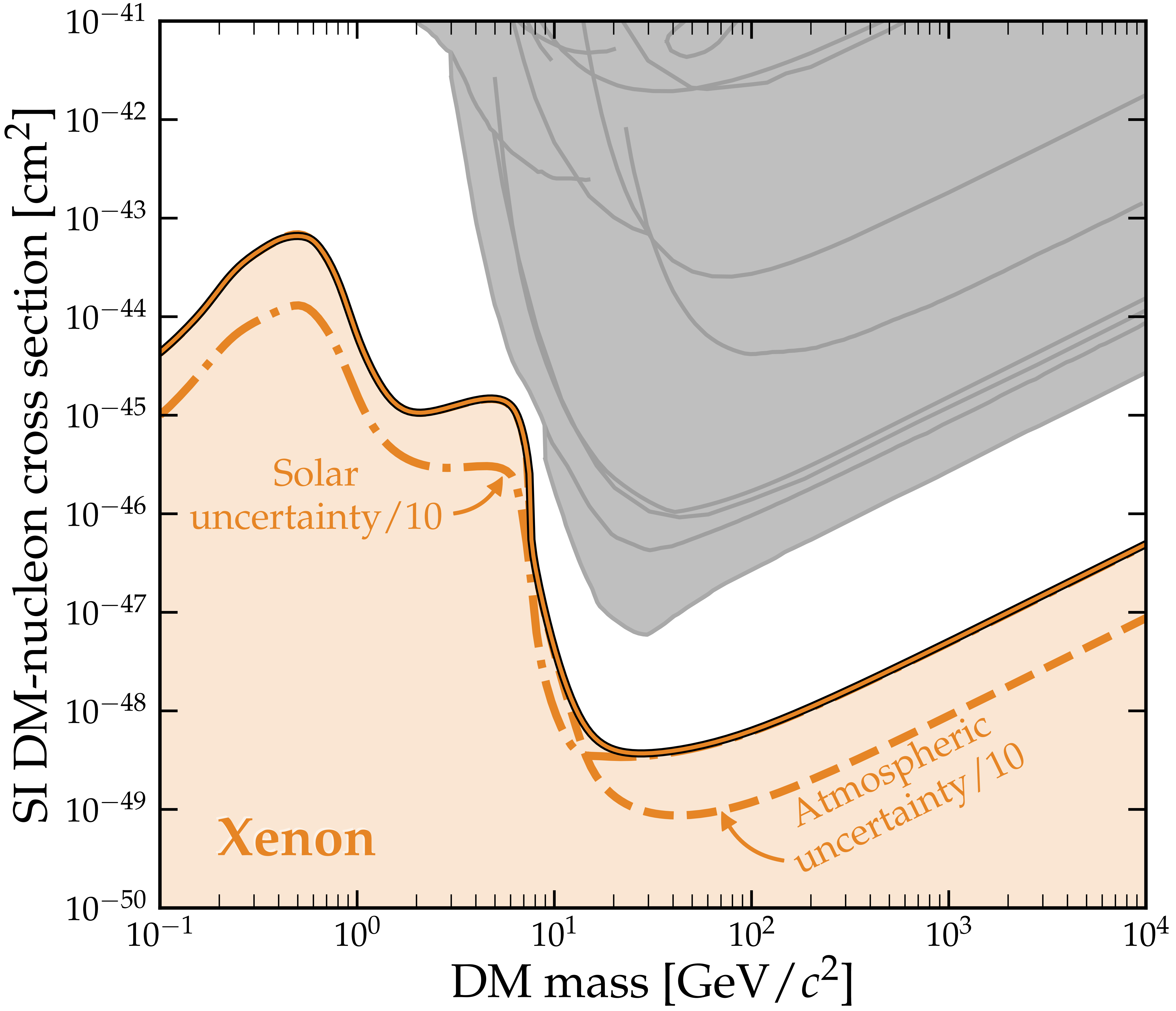
2. Flux uncertainties

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}

^{8}B flux at ~2% (from global fit 1601.00972), so already well-measured. Could improve further with experiments like DUNE, JUNO, Hyper-K, all of which will observe massive numbers of solar neutrinos



2. Effect of reducing flux uncertainties

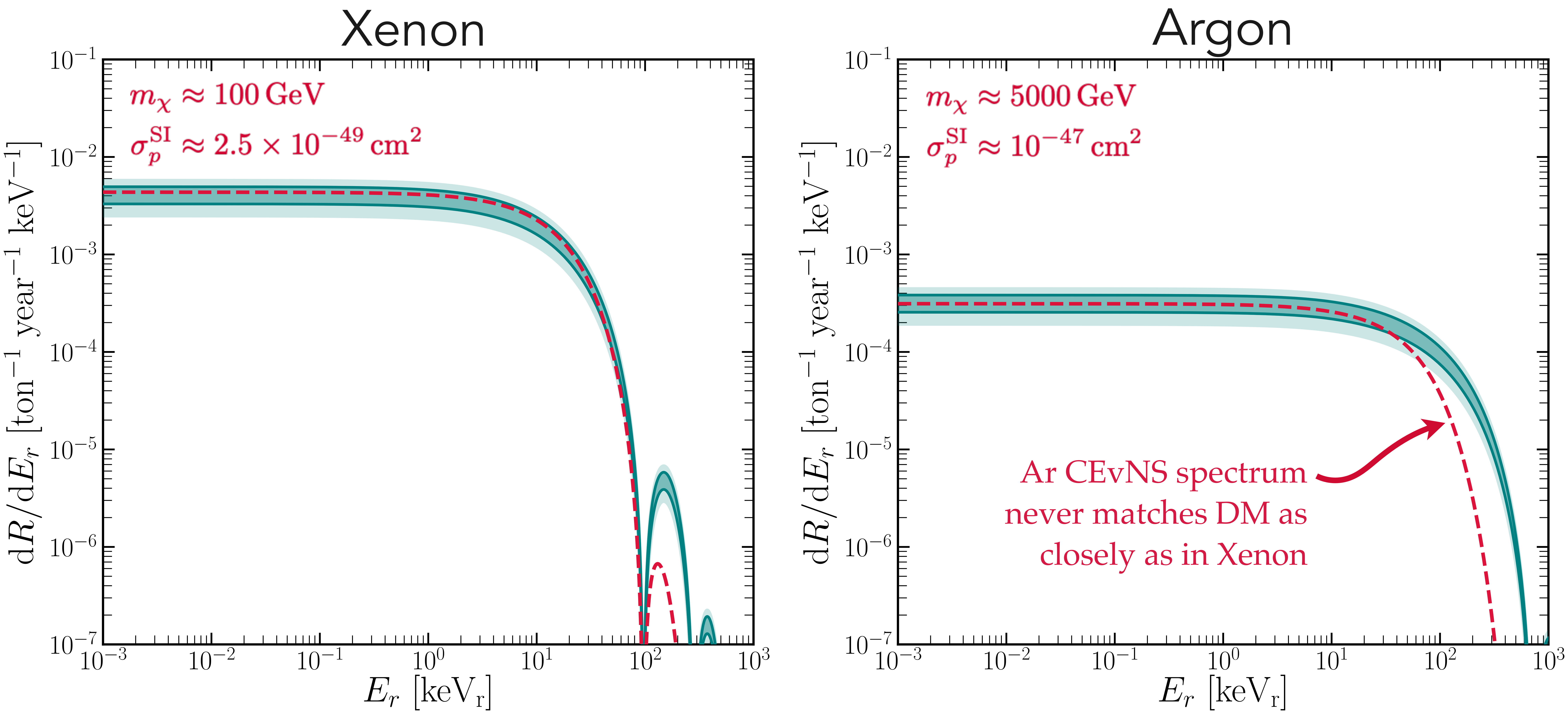


With smaller flux uncertainties the boundary of the neutrino fog is pushed lower

(This could make all the difference! But ultimately relies on neutrino experiments)

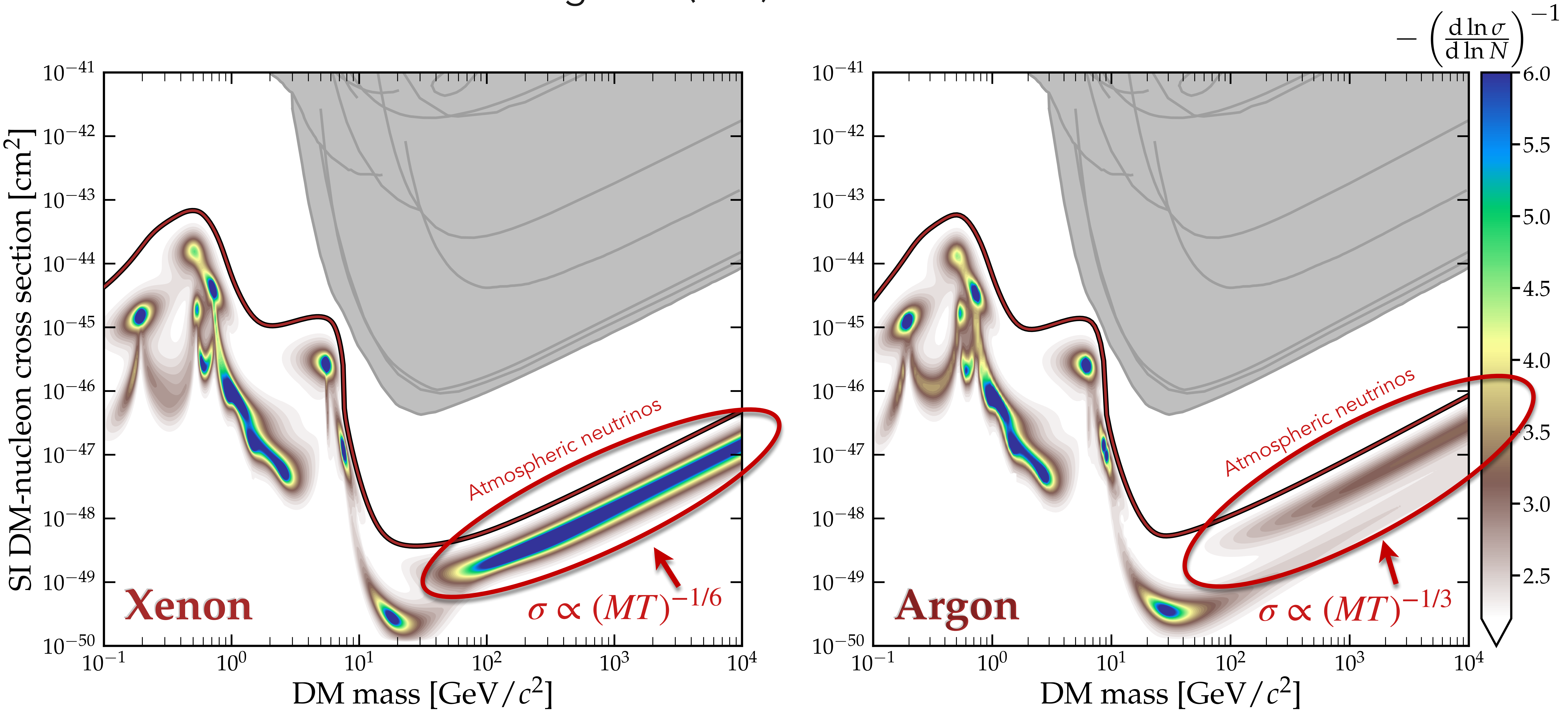
3. Target complementarity: Xe & Ar

100 GeV DM versus Atmospheric neutrinos



3. Target complementarity: the fogginess is target-dependent

e.g. at $\mathcal{O}$(TeV) for **Xe** versus **Ar**



O'Hare [2109.03116]

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

~~0. Detect *a lot* of events~~

~~1. Use annual modulation~~ ← Not really good enough

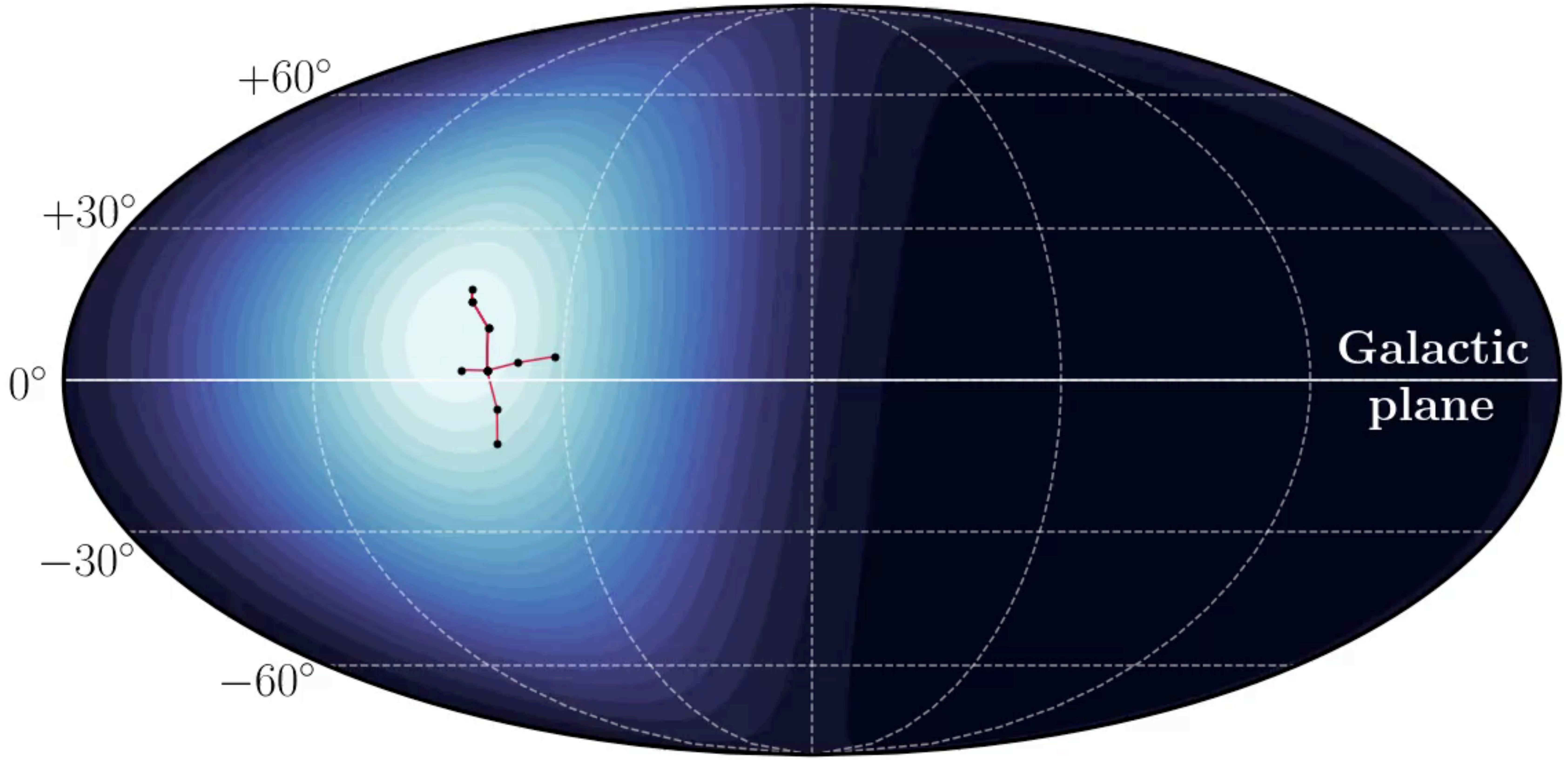
~~2. Have multiple target nuclei~~

↓

3. Improve neutrino flux measurements ← Good, but not up to us

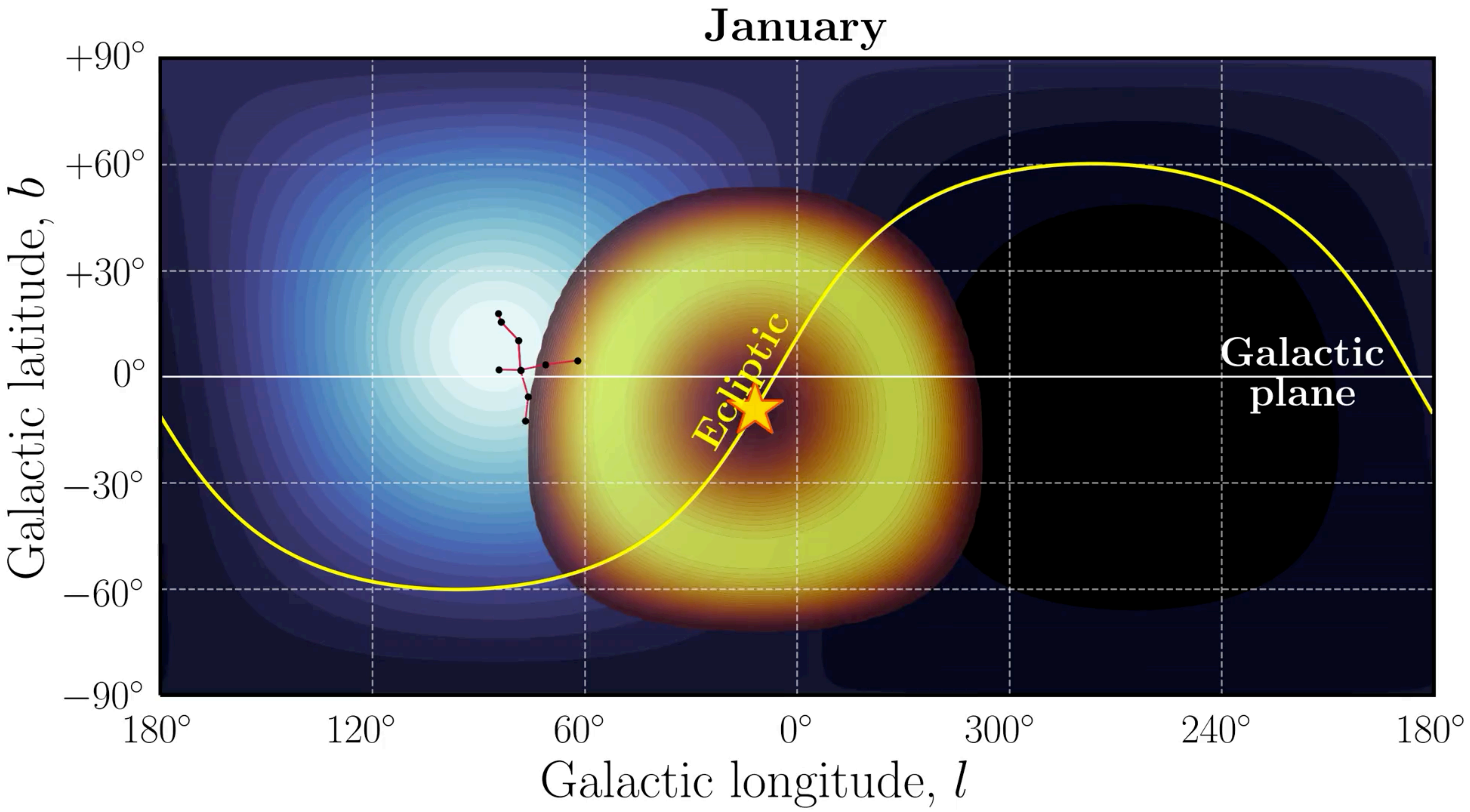
4. Use directional detectors


Cygnus
Jun
Dec

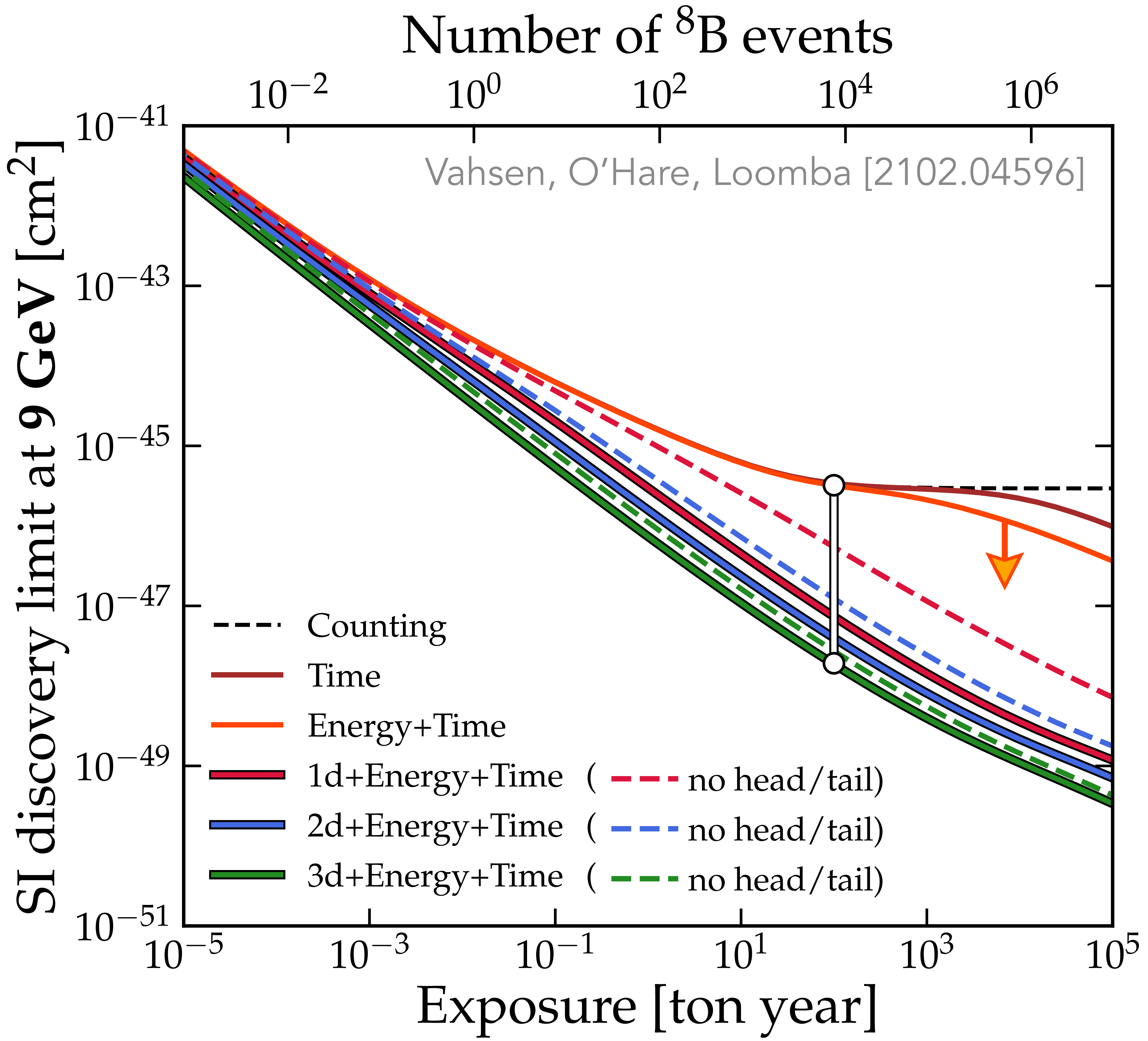


The dark matter flux on Earth is anisotropic and should align with the direction of galactic rotation → a highly characteristic signal that is robust against theoretical and astrophysical uncertainties

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



Seeing through the neutrino fog with directionality



In an idealised case a directional experiment doesn't see the background at all—its sensitivity scales almost as $\sigma \propto (MT)^{-1}$

How close can a real experiment get?

What is required to clear the neutrino fog?

(see our review [2102.04596] and Snowmass WP [2203.05914] 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 fog)

And achieved…

- At the level of individual events
- In as high a density target as possible
- Below <10 keVr
- With a timing resolution better than a few hours

Can this be done? Maybe, but the way to go seems to be "recoil imaging"

Distance through the neutrino fog

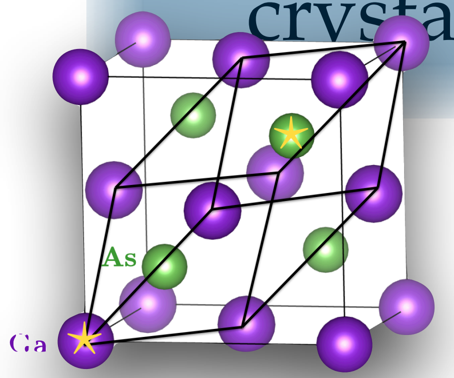
Least directionality → Most directionality

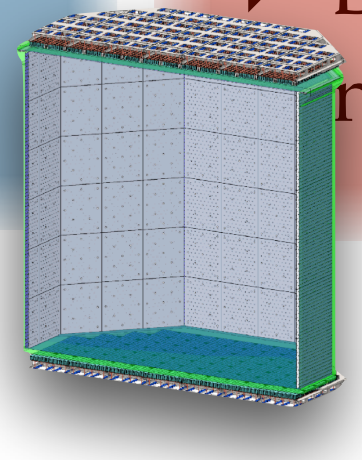
Indirect | **Recoil imaging**

Statistical | **Event-level**

Modulation-based directionality — Indirect recoil event directionality — Time-integrated recoil imaging — Time-resolved recoil imaging

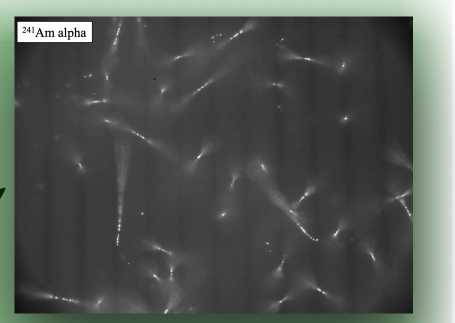
Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes



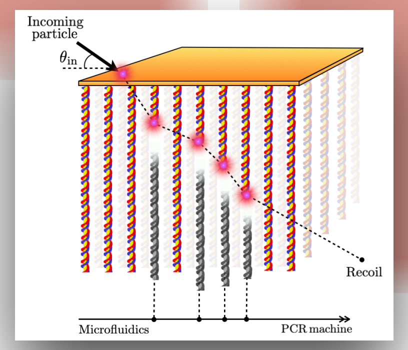


Columnar recombination
- Event-level 1d directions
- No head/tail
- Direction and energy are not independent

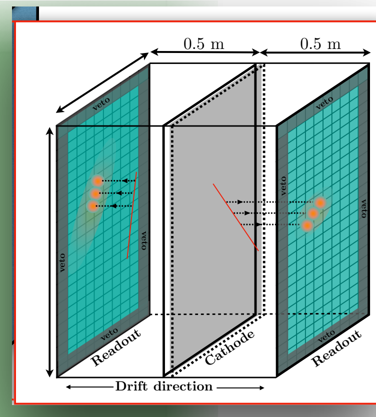
Nuclear emulsions
- 2d recoil tracks, head/tail
- No event times information recorded



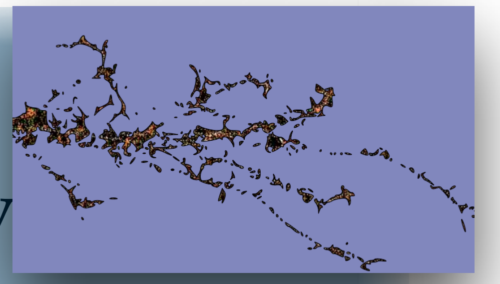
DNA detector
- 3d recoils without head/tail
- No event times recorded



Gas TPC
- Head/tail measurable
- 1d, 2d or 3d
- Independent energy/direction measurement



Crystal defects
- 3d track topology
- Head/tail measurable



Demonstrated
R&D
Proposed

Vahsen, CAJO, Loomba [2102.04596]

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Takeaways

THE UNIVERSITY OF SYDNEY

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 precisely reconstruct sub-10 keV tracks in 3D will be ideal → CYGNUS collab. is working towards this + detection of solar neutrinos via electron and nuclear recoils

Download neutrino fog data for various targets here:
https://github.com/cajohare/NeutrinoFog/tree/main/data/floors