ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

The neutrino fog

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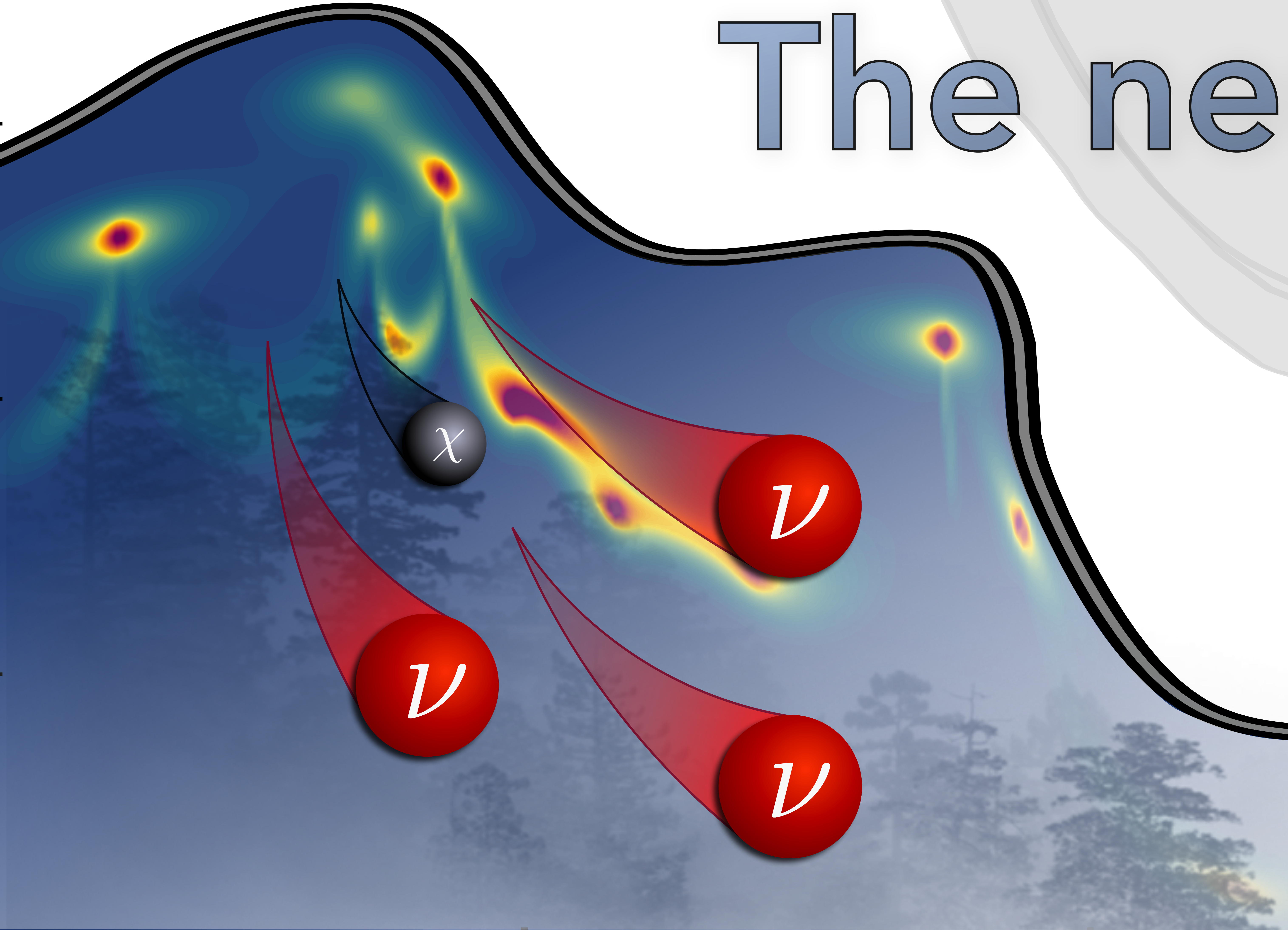
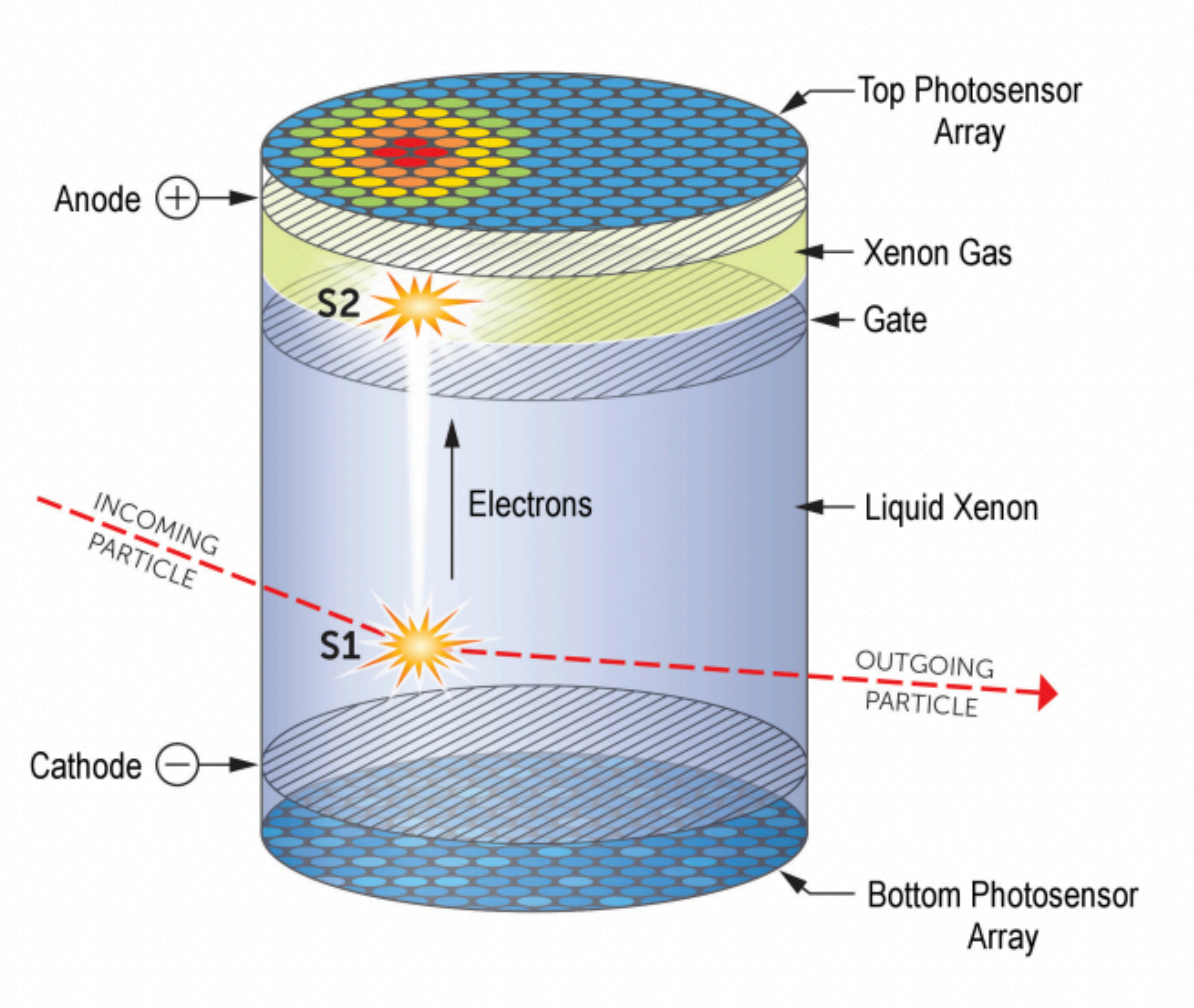
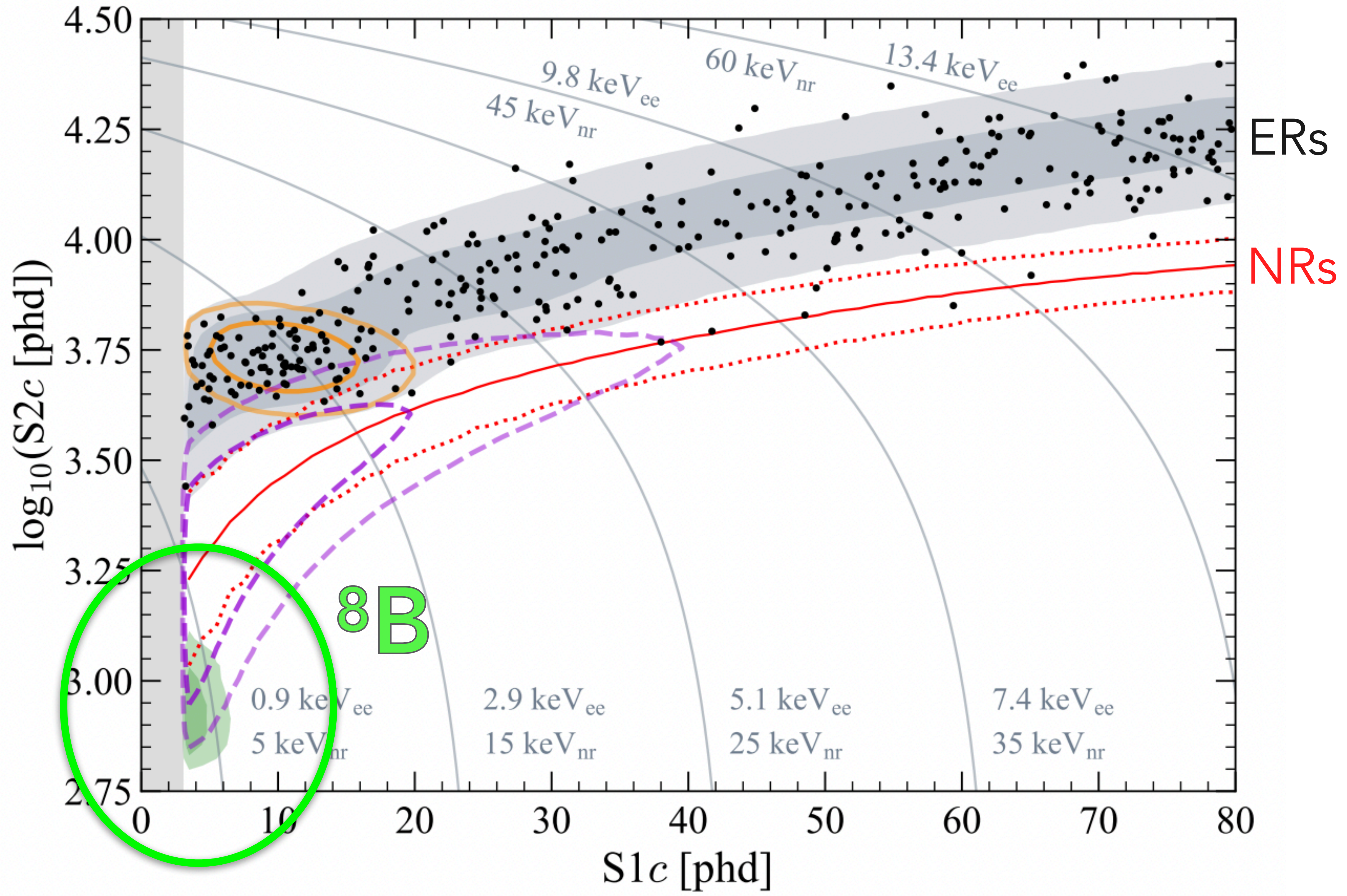


Searching for astrophysical CEνNS with Liquid-noble-gas detectors

^{8}B solar neutrinos scattering in LXe: Recoil energies ($\lesssim$ 5 keVr) are close to threshold so a hard measurement, but this will be the first detection of CEvNS with a natural neutrino source (see e.g. L.D. Garcia talk)



LZ, 2207.03764



“CEνNS-like” dark matter models

Turns out these detectors can also look for dark matter (fancy that!)

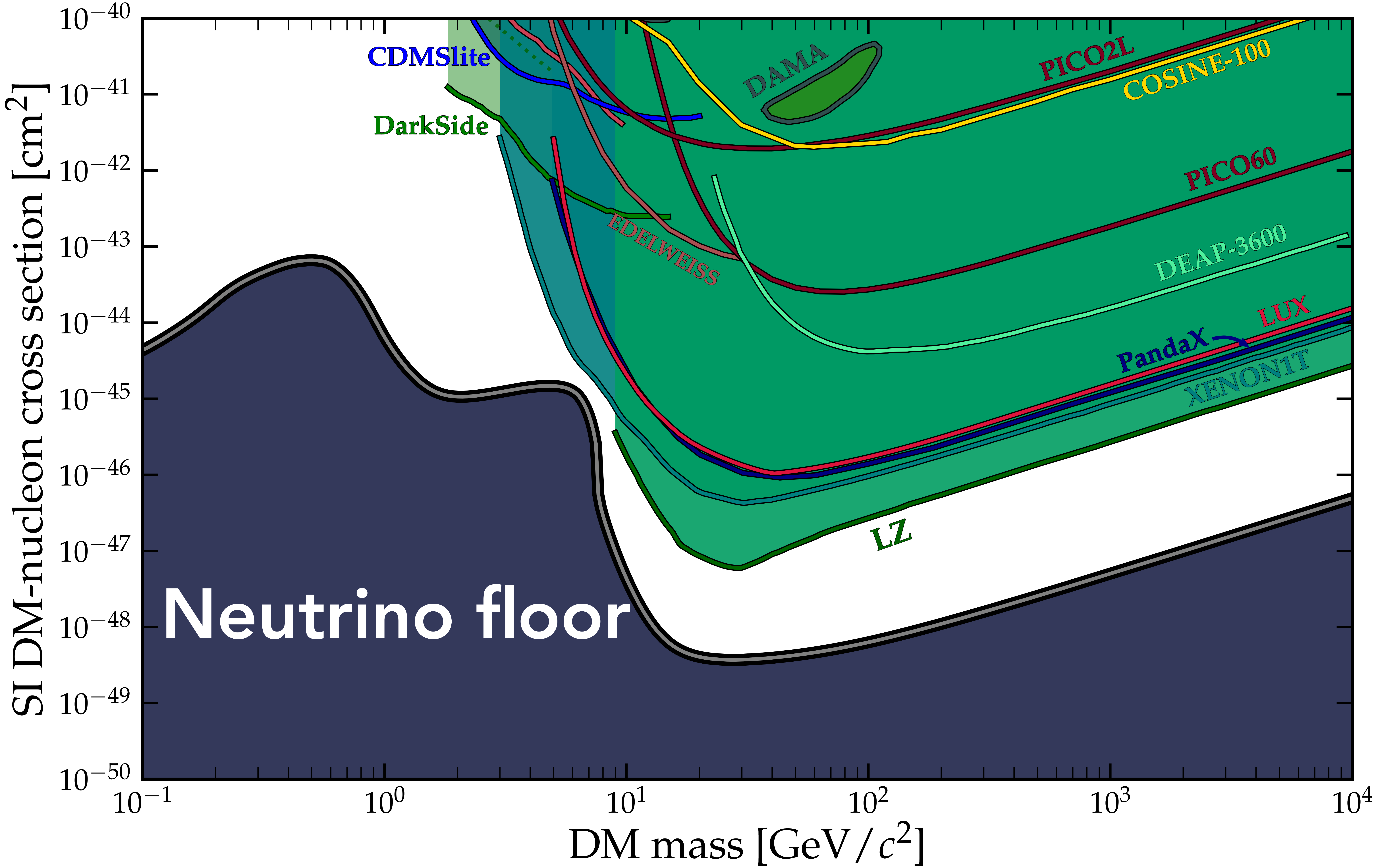
Observable: >keV-scale nuclear recoils. Generic signal for any DM model with the following:

- Mass: $m_\chi \sim$ GeV—TeV
- Scattering cross-section with nucleons
- Non-relativistic incoming velocities (e.g. in our galaxy $v_{\rm max} \sim v_\odot + v_{\rm esc} \sim 800\,{\rm km/s}$)

This is a neutrino workshop, why should you care?

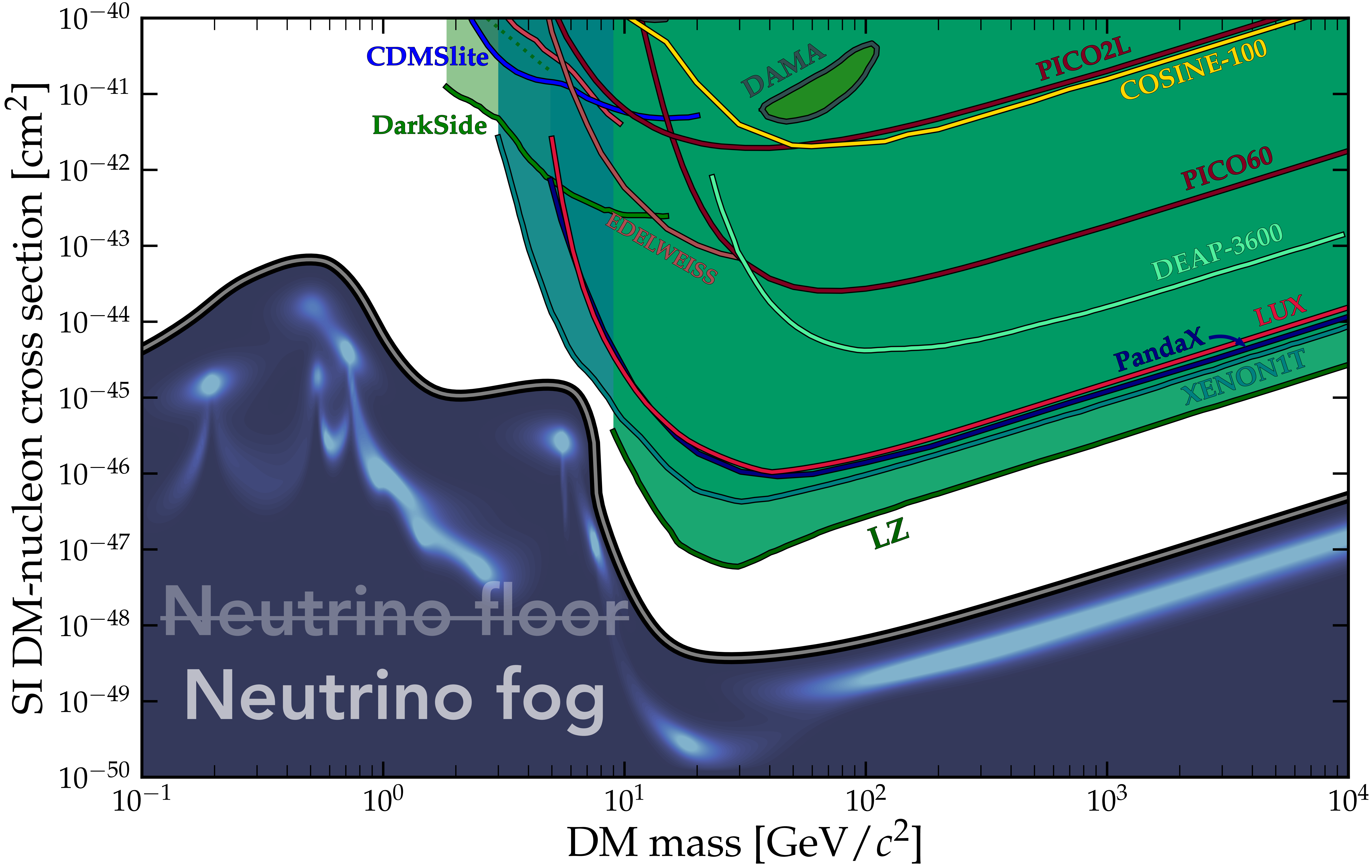
- Many theoretically attractive and *unexplored* DM models generate “CEvNS-like” signals
- Swathes of models have event rates well below CEvNS background, e.g. many classic susy WIMPs, asymmetric DM, thermal higgsino DM, list goes on…
- There are big planned experiments poised to test this paradigm to its limits while simultaneously measuring CEvNS (see e.g. LZ, XENONnT, PandaX, XLZD)

Parameter space for CEνNS-like dark matter

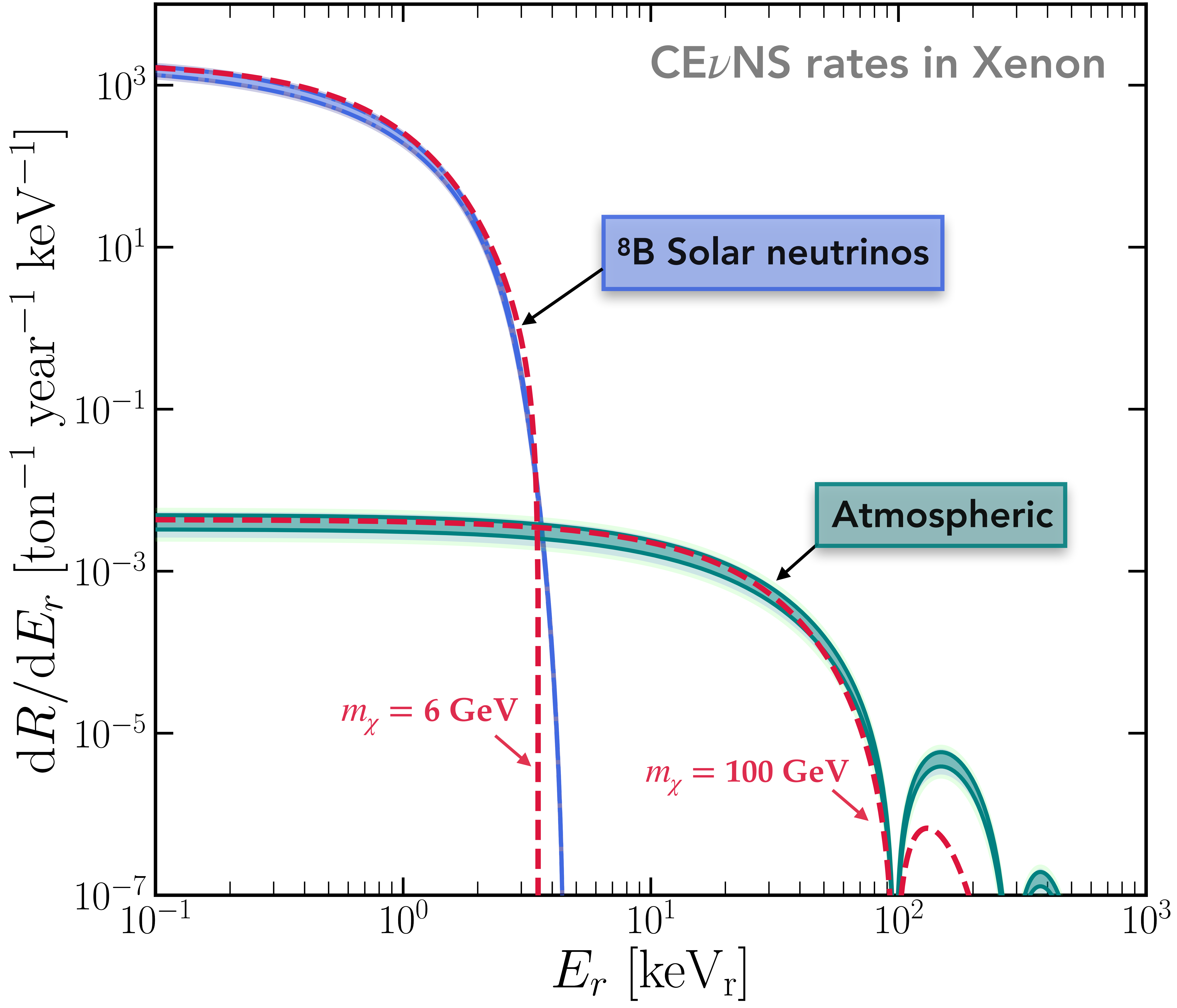


Models where CEνNS dominates over DM signal

Parameter space for CEνNS-like dark matter

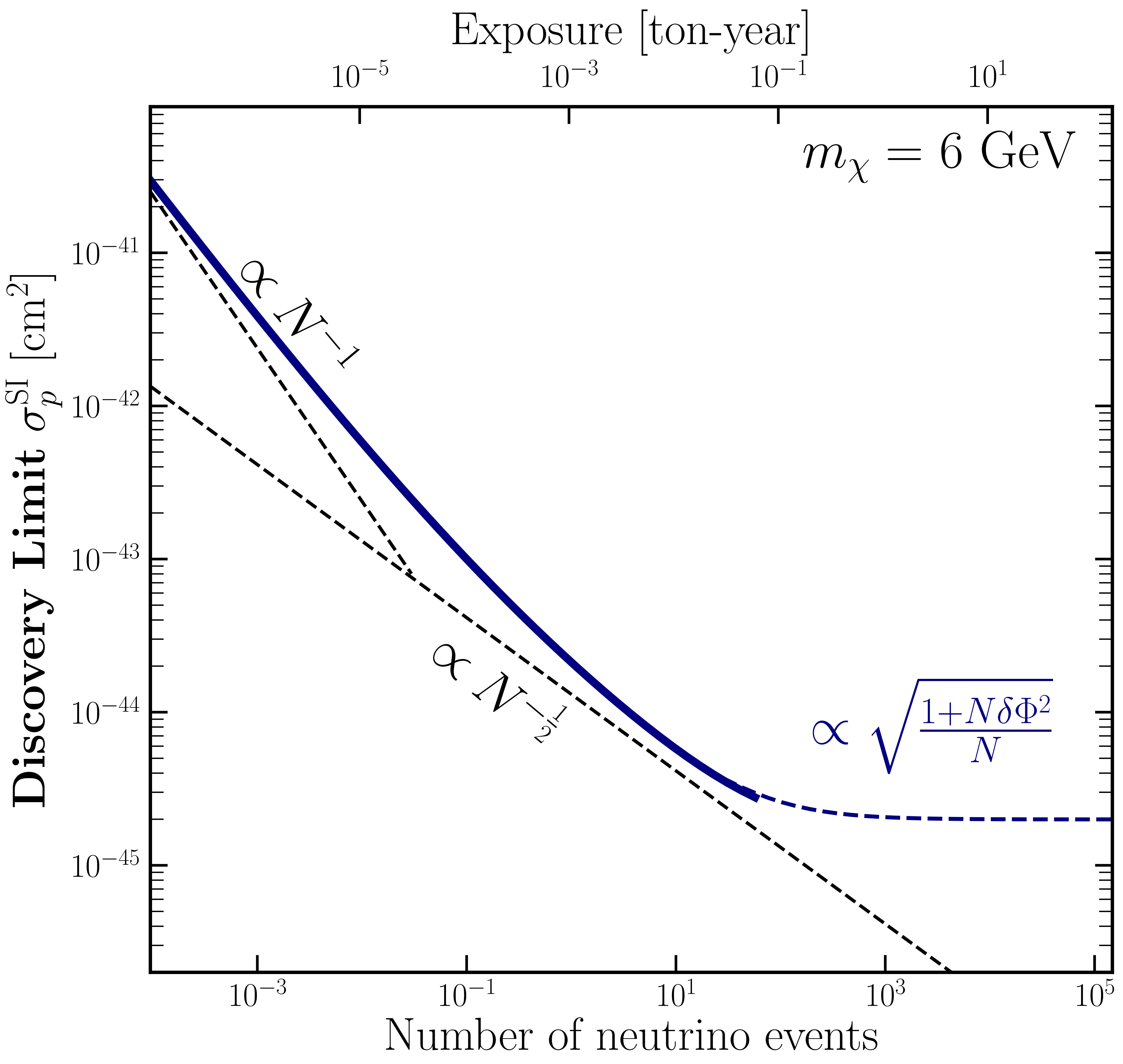


Models where CEνNS *prevents* DM discovery



Why is there a neutrino "floor"?

^{8}B solar and atmospheric neutrinos generate NR spectra through CEνNS that look near-identical to **O(1) GeV** and **O(100) GeV** mass DM respectively

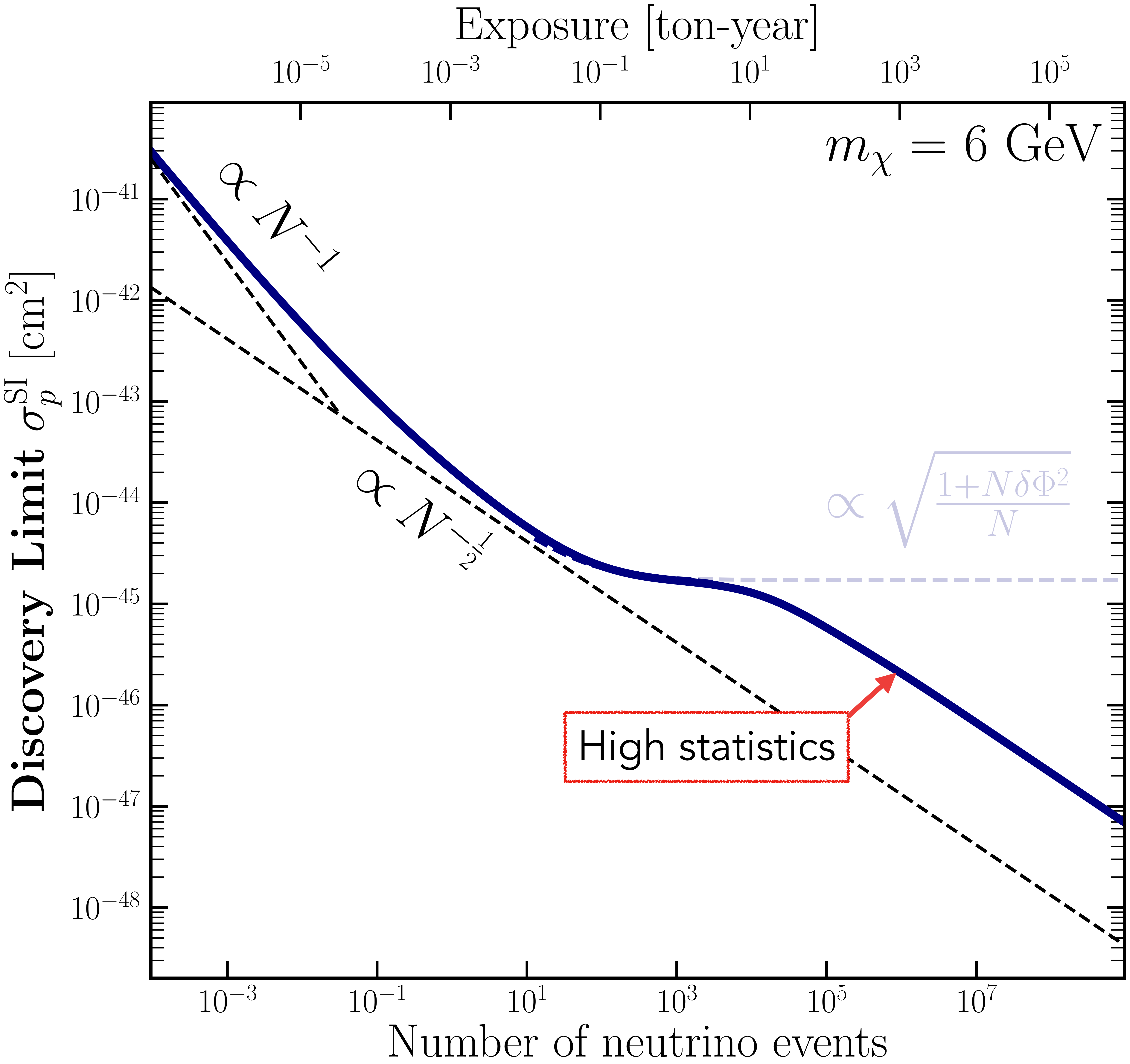


The neutrino "floor"

← Scaling of sensitivity as experiment's exposure increases. If there are no problematic backgrounds this should go like $\sigma \sim 1/\sqrt{N}$ for $N \gtrsim 1$ background events

→ Experiment can't claim discovery of a DM model that creates an excess in events smaller than the expected level of systematic background fluctuations

(Billard et al. 2013)

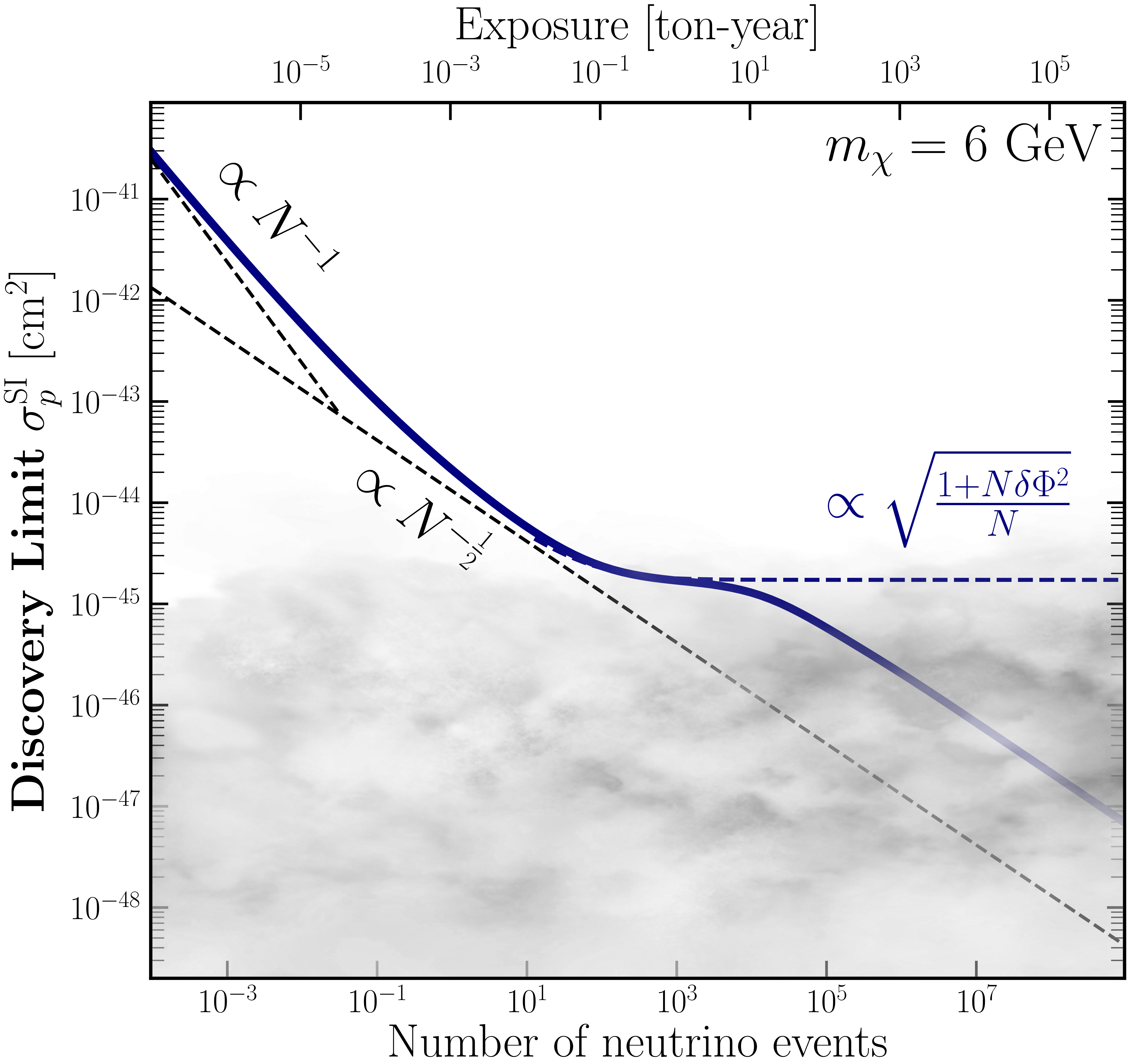


The full story:

There is no neutrino "floor"

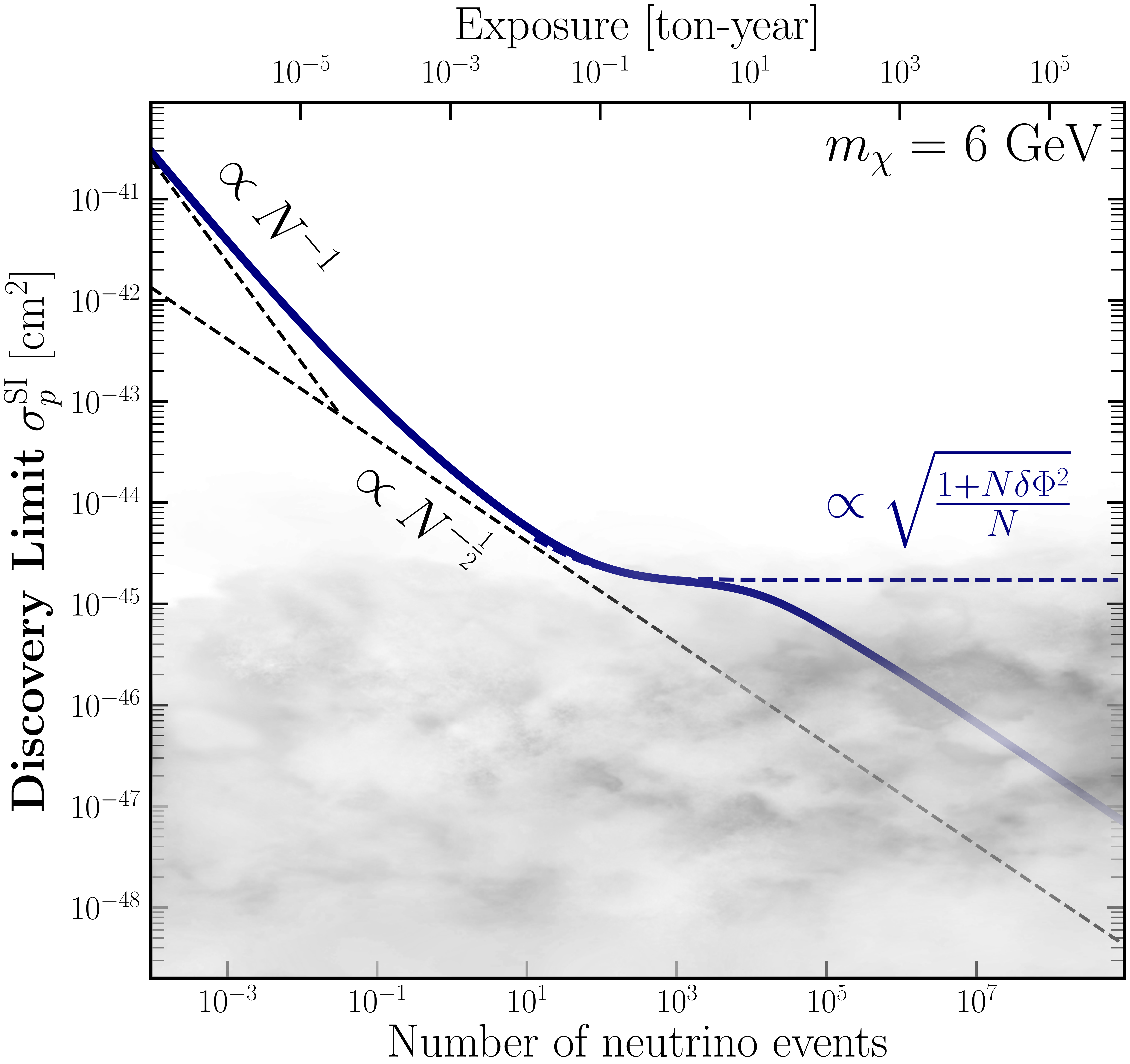
DM/CEvNS signals not **identical**
→ with high statistics, an experiment can bootstrap itself through the systematic background uncertainty and claim a discovery using differences in $\mathrm{d}R/\mathrm{d}E_r$ (*Ruppin et al. 2014*)

Required exposures to do this are absurdly large, but the point is that there can never be a hard sensitivity floor unless the signal and background are truly *identical* (which they are not in this case).



How should we define it then?

There is no “floor”, but we can quantify the neutrino “fog” by looking at the scaling of σ sensitivity



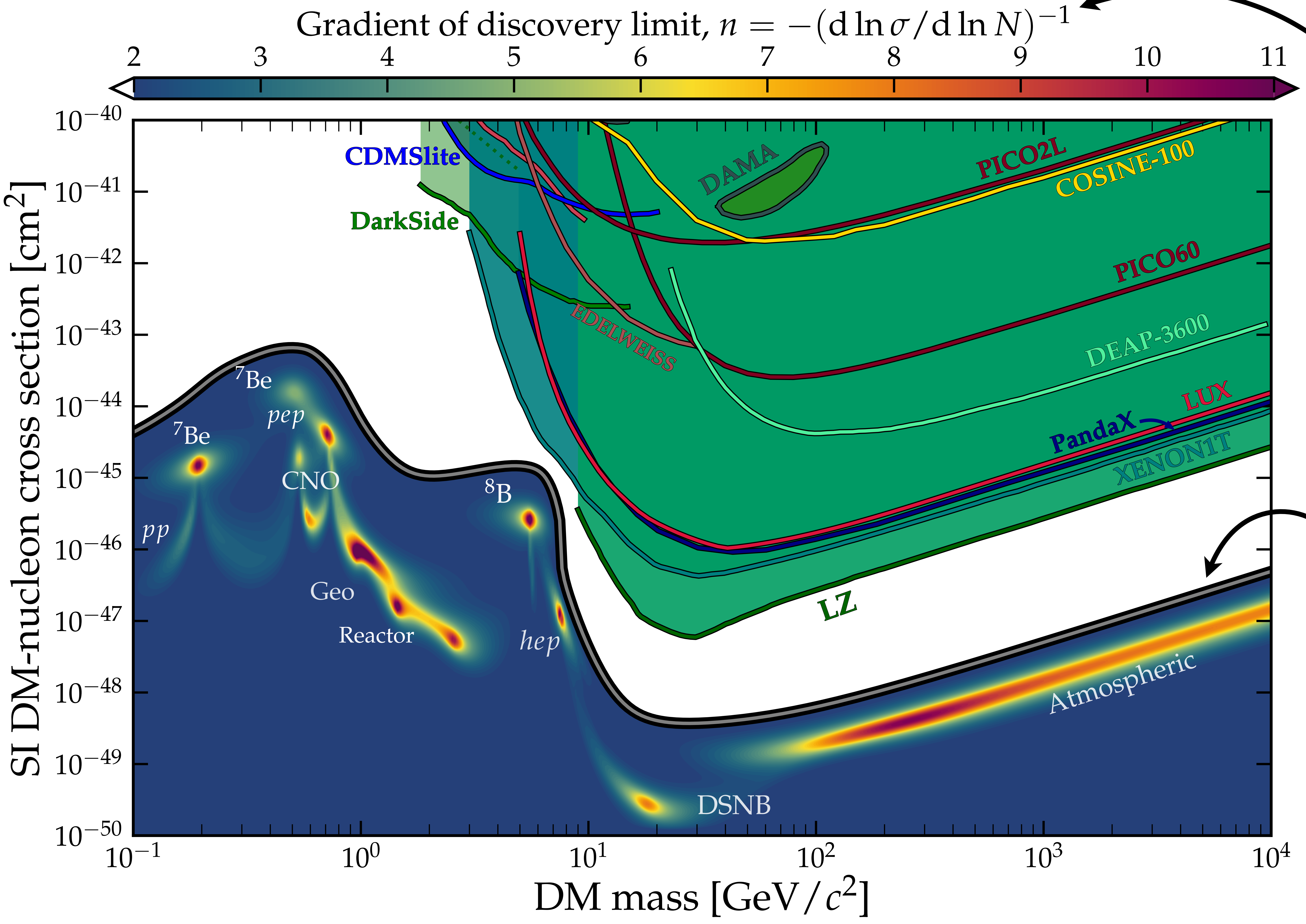
How should we define it then?

There is no "floor", but we can quantify the neutrino "fog" by looking at the scaling of σ sensitivity

Define neutrino fog "opacity":

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

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



n parameterises the "fogginess" of the neutrino fog → this shows that the parameter space is not uniformly foggy everywhere

The "edge" of the fog (n>2), once you get past it, you can never do better than Poissonian again (because N_{bg}>1).

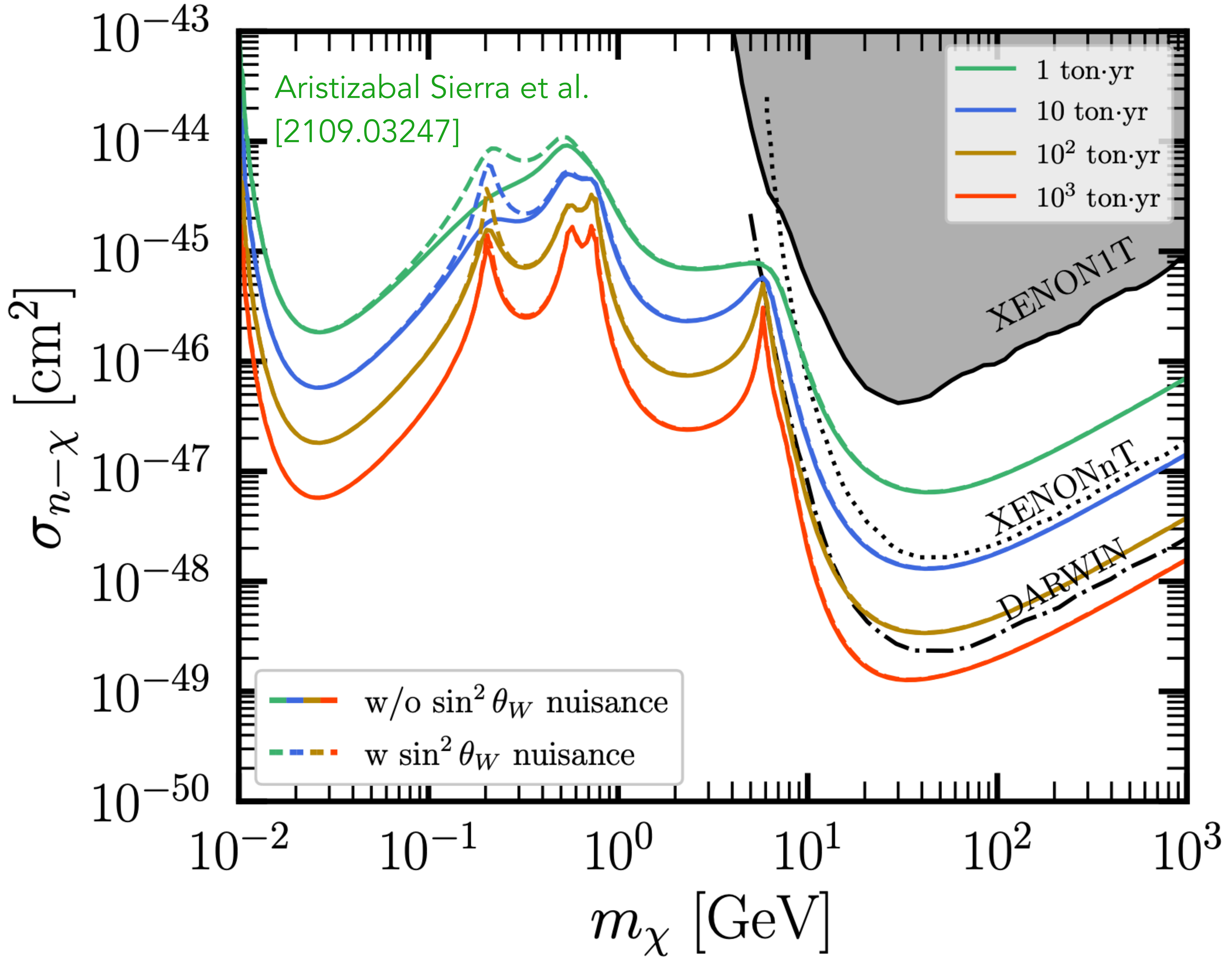
There is not one "neutrino fog"

Depends on interplay of parameters+uncertainties going into both DM and neutrino signals, e.g. target nucleus:

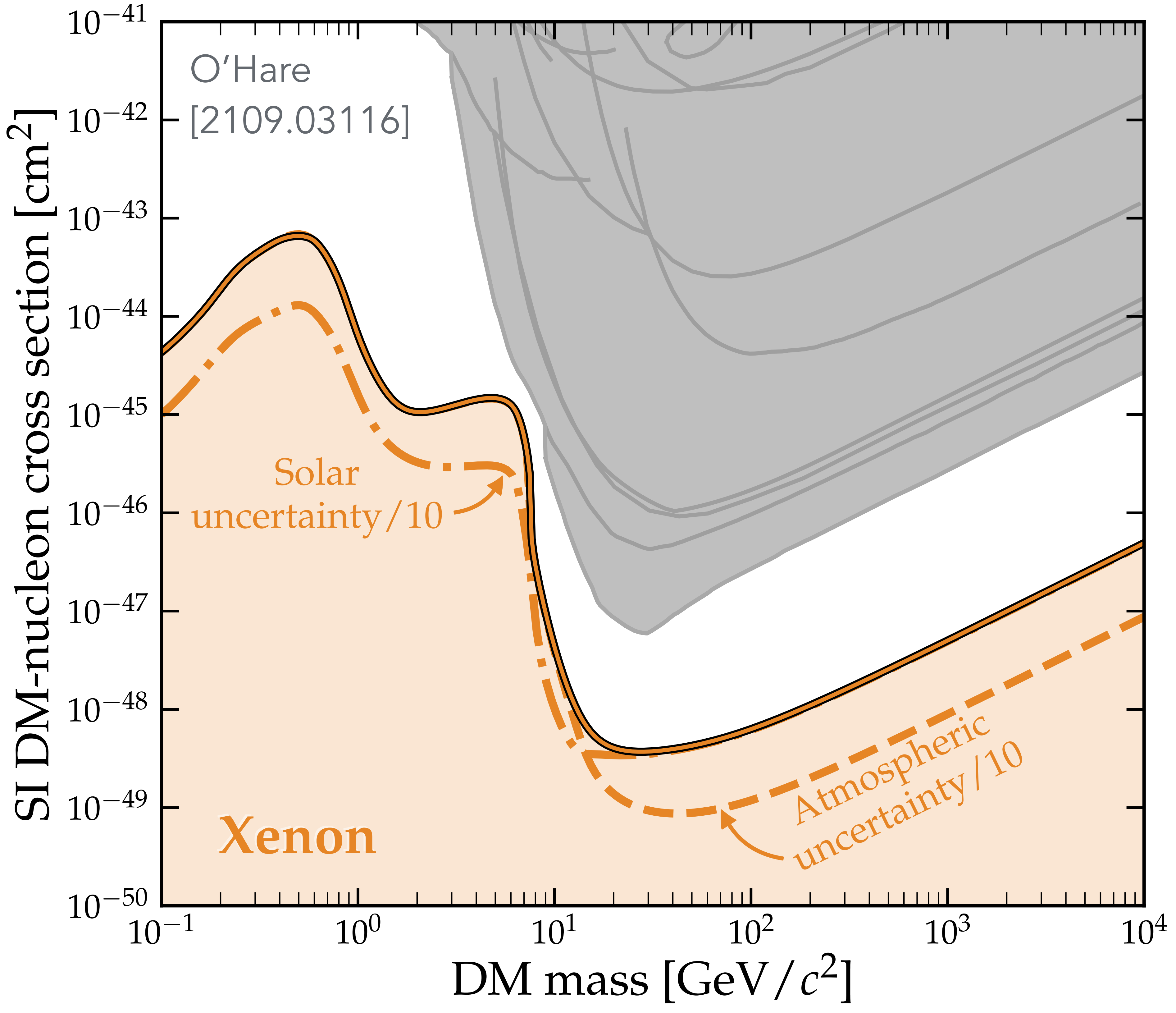
A = 4 | 40 | ~73 | ~131

Dependence on systematic uncertainties

Additional uncertainties
→ Neutrino fog moves up

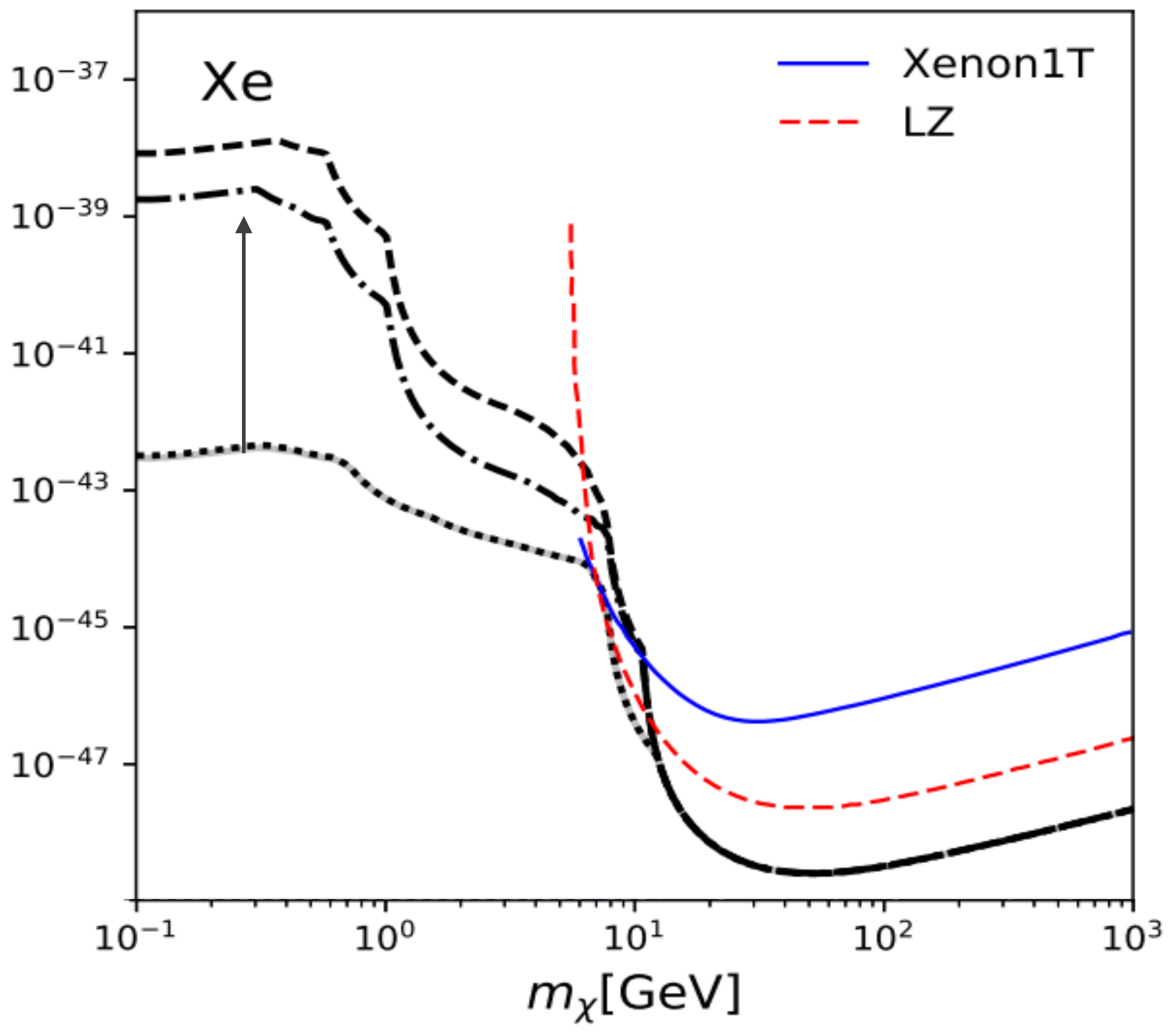


Reduced uncertainties
→ Neutrino fog moves down



Dependence on neutrino/DM model

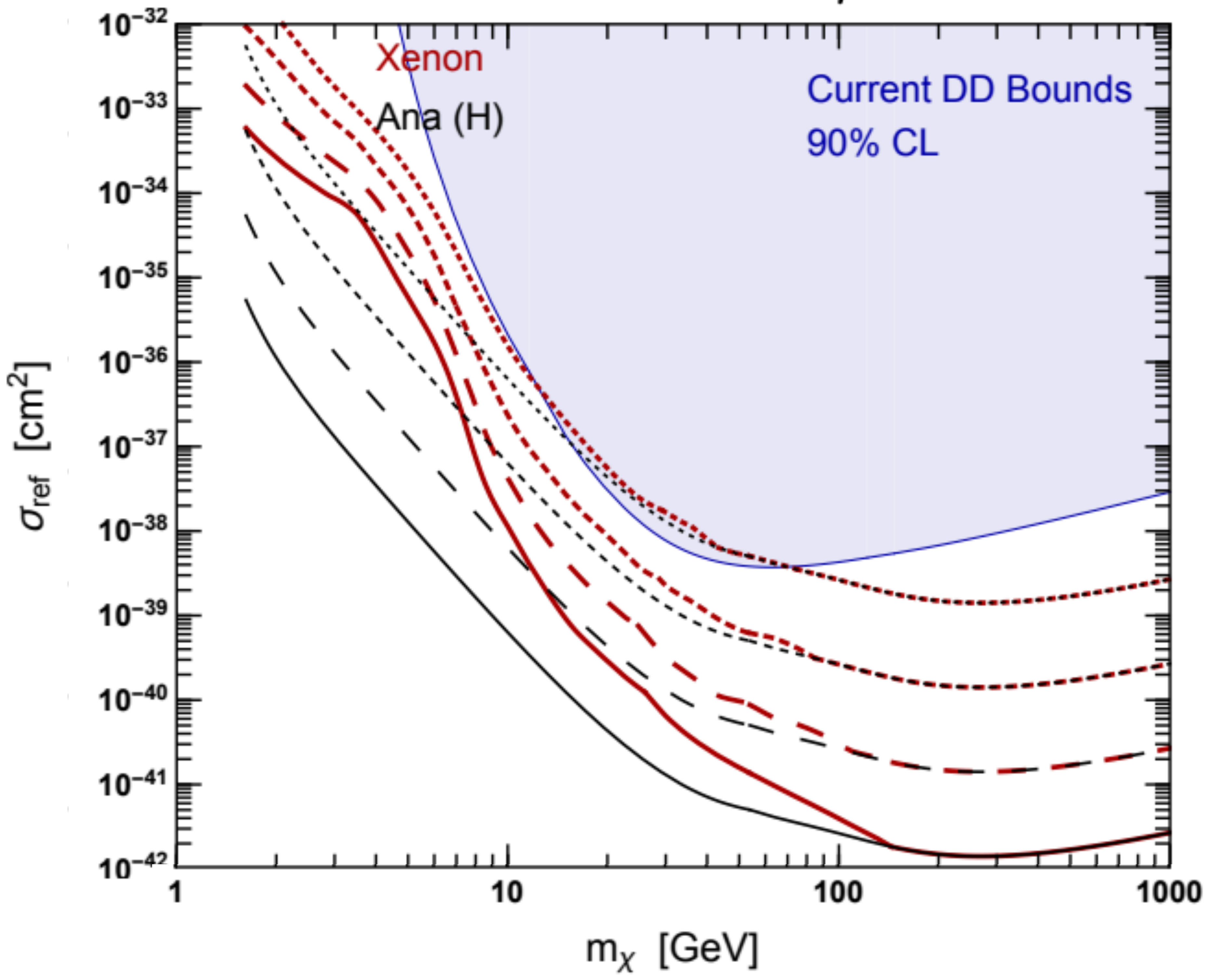
- Neutrino fog changes if there are new interactions hiding in CEvNS cross section



e.g. Boehm+ [1809.06385], Cerdeño talk at this workshop

- Neutrino fog changes if you consider different DM models

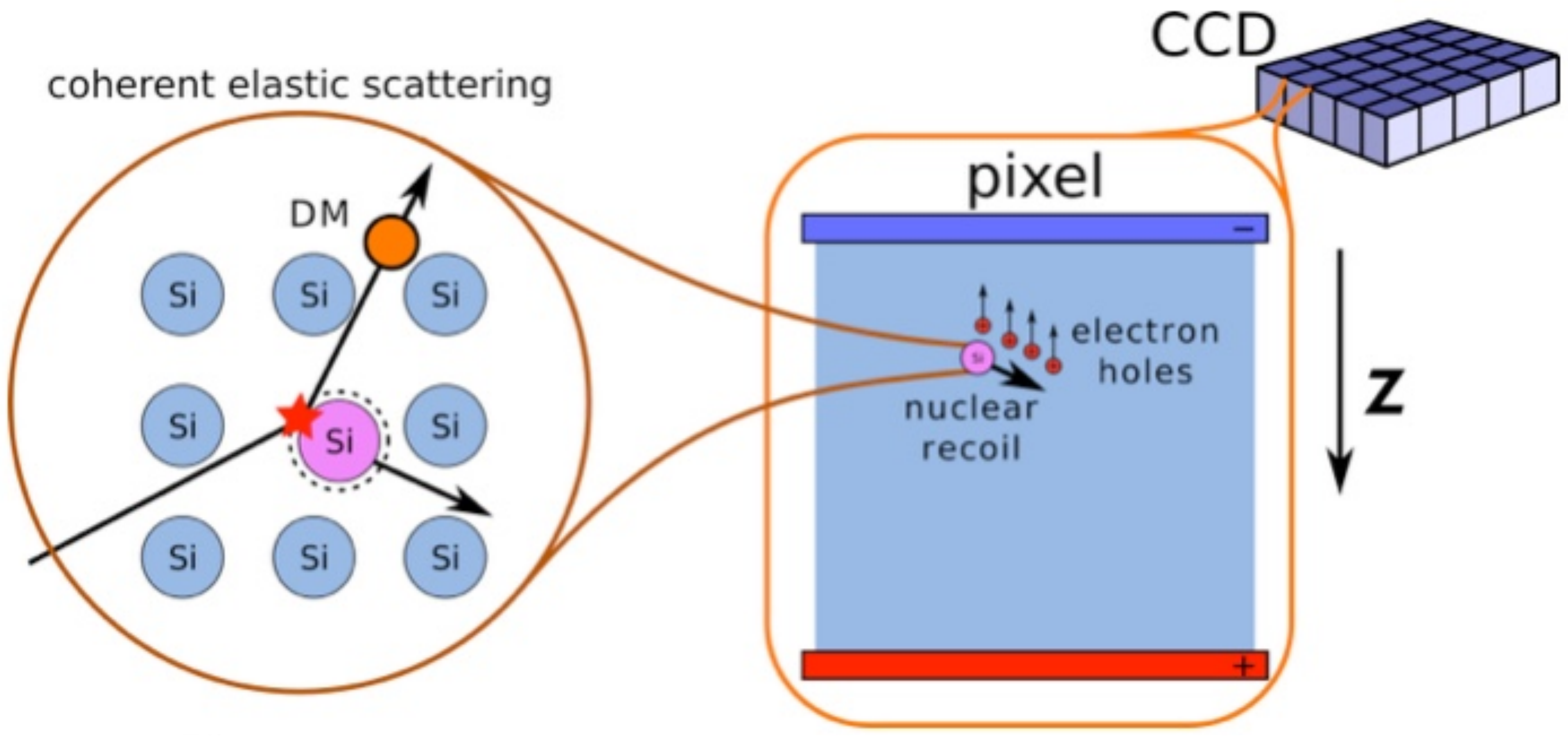
$$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$$

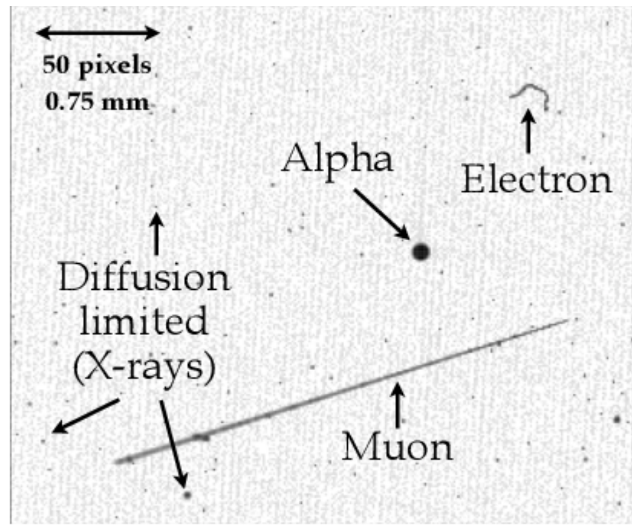


e.g. Newstead+ [1602.05300], Gelmini+ [1804.01638]

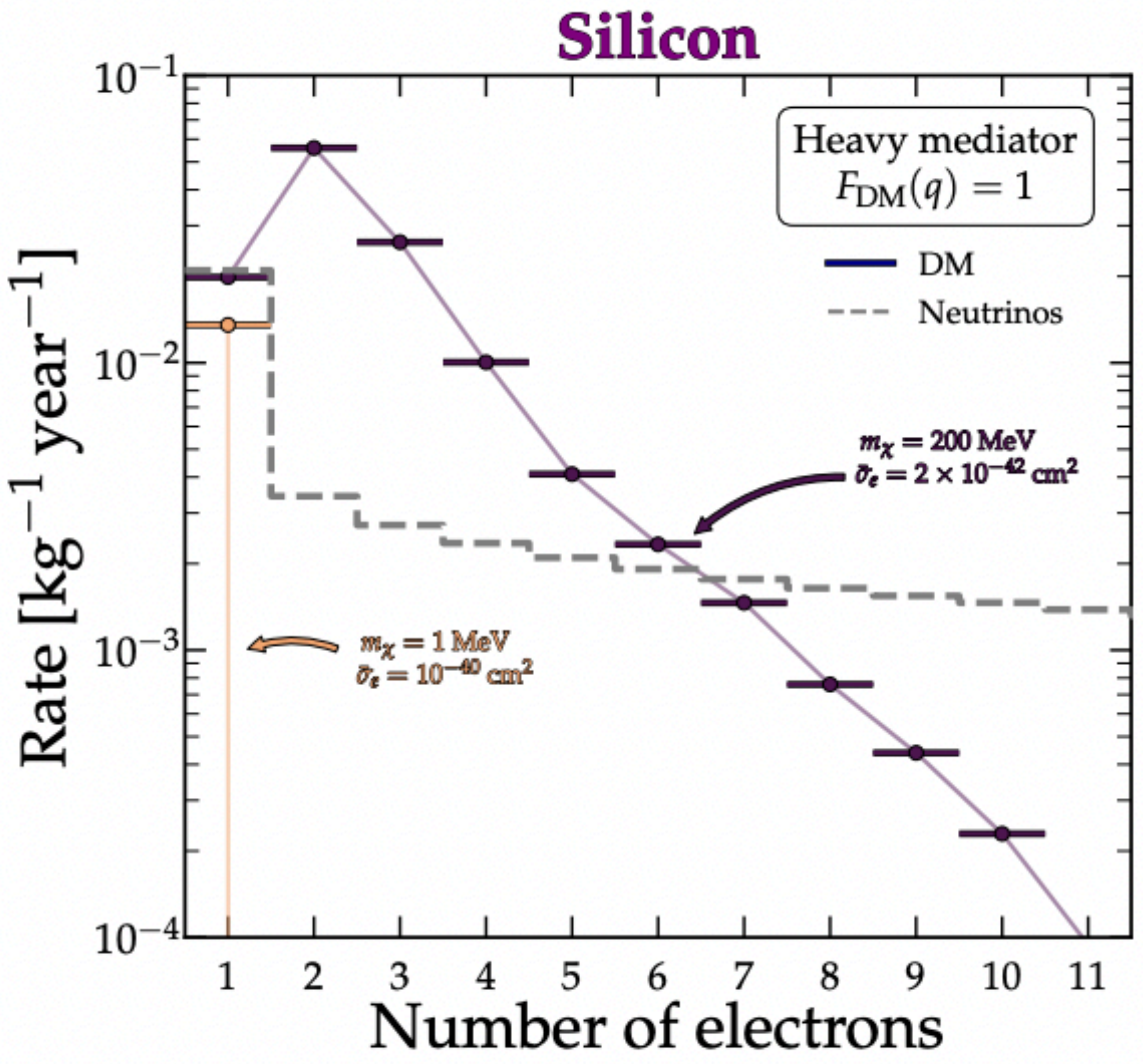
Neutrino fog for DM-electron scattering expts.

Neutrinos may show up in low-threshold ionisation detectors looking for light ($m_\chi \gtrsim$ MeV) DM using *electron* recoils. No NR/ER discrimination, so low-energy CEvNS is an irreducible background here too (pp $\nu e^- \to \nu e^-$ rate negligible at these energies and exposures)





e.g. DAMIC-M, SENSEI

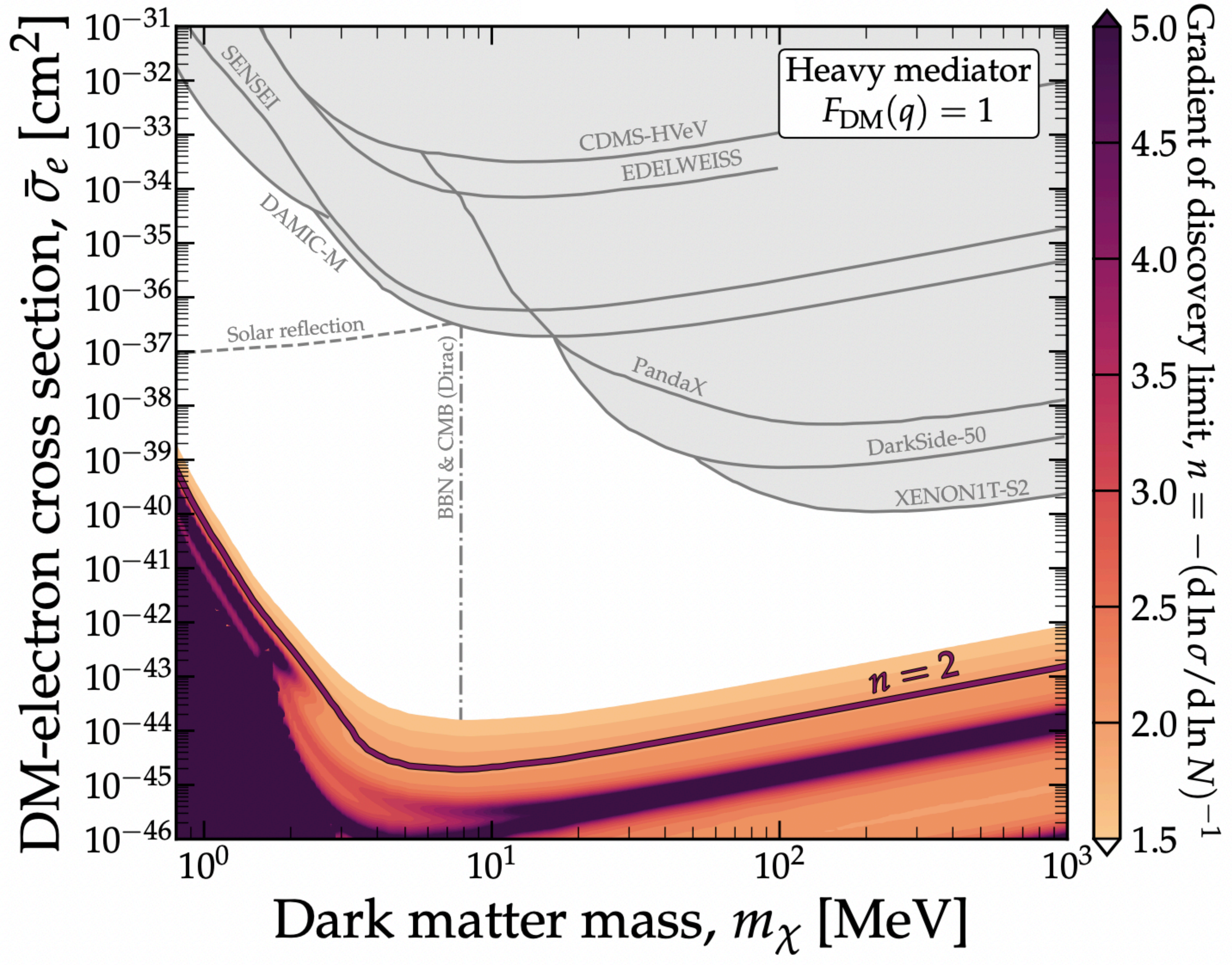


Carew, O'Hare+ [2312.04303]

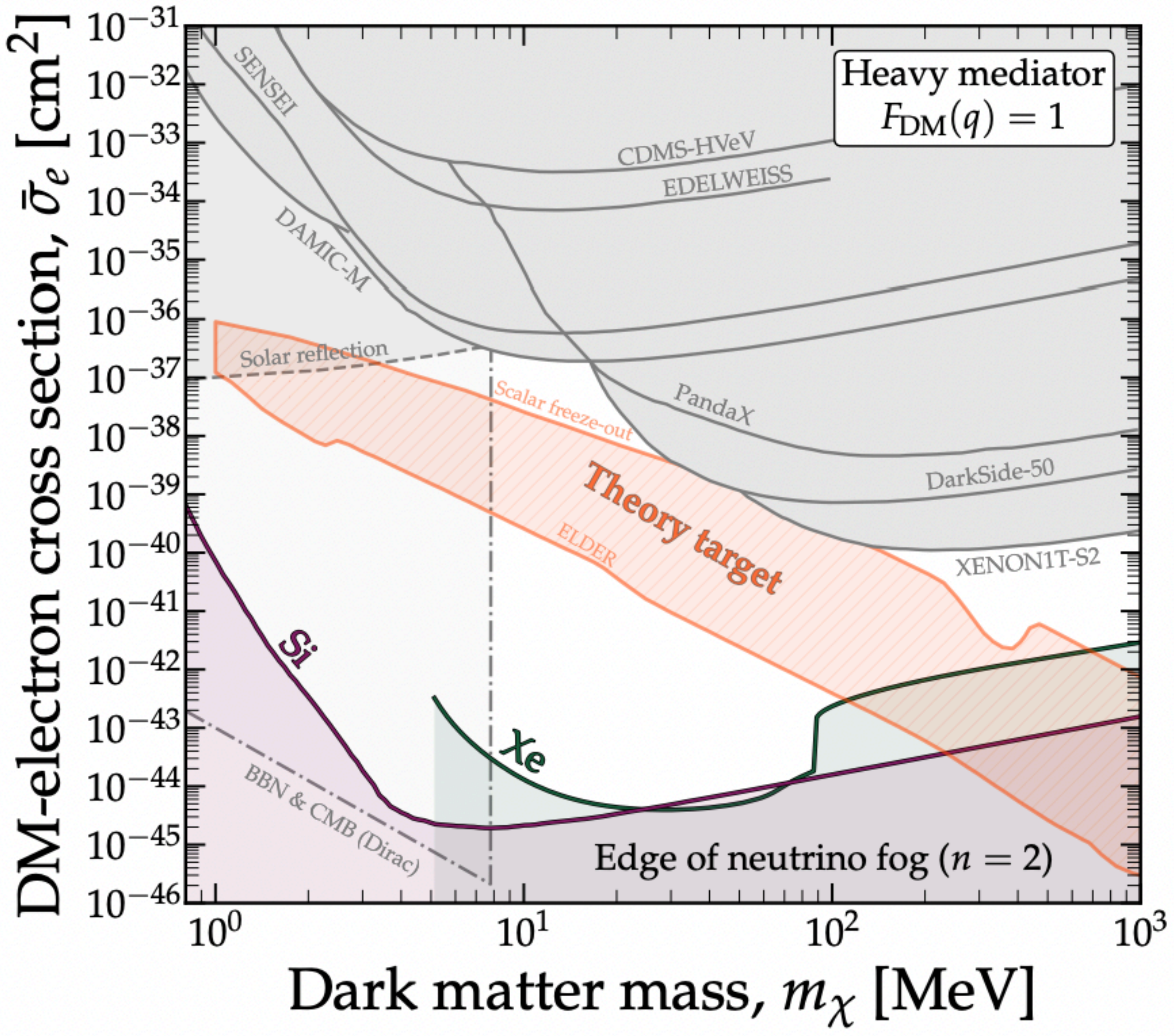
Neutrino fog for DM-electron scattering expts.

Carew, O'Hare+ [2312.04303]

Neutrino fog for silicon



Neutrino fog "boundaries"

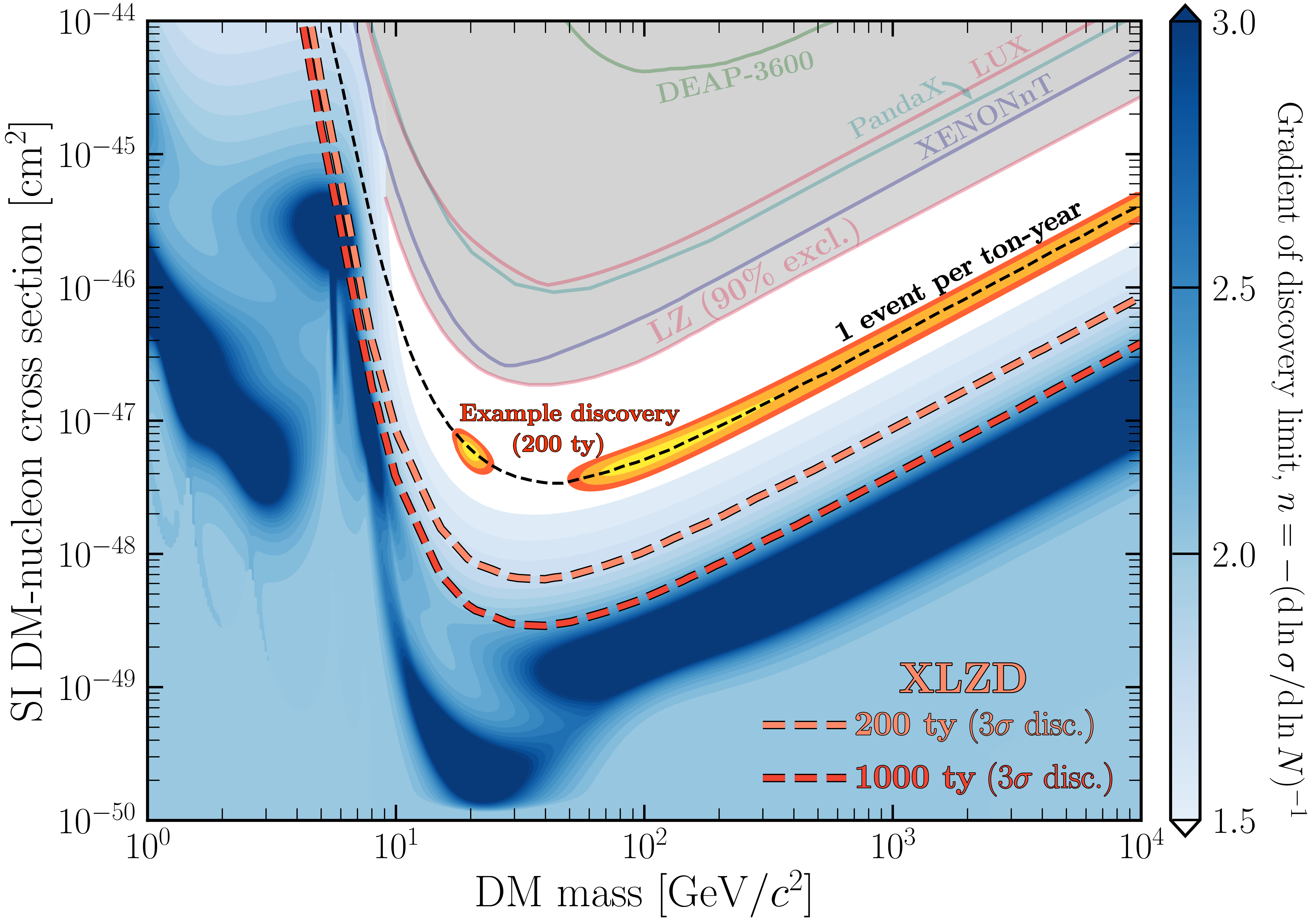


XLZD: the ultimate (?) DM direct detection experiment

Neutrino fog marks the endpoint of conventional direct detection

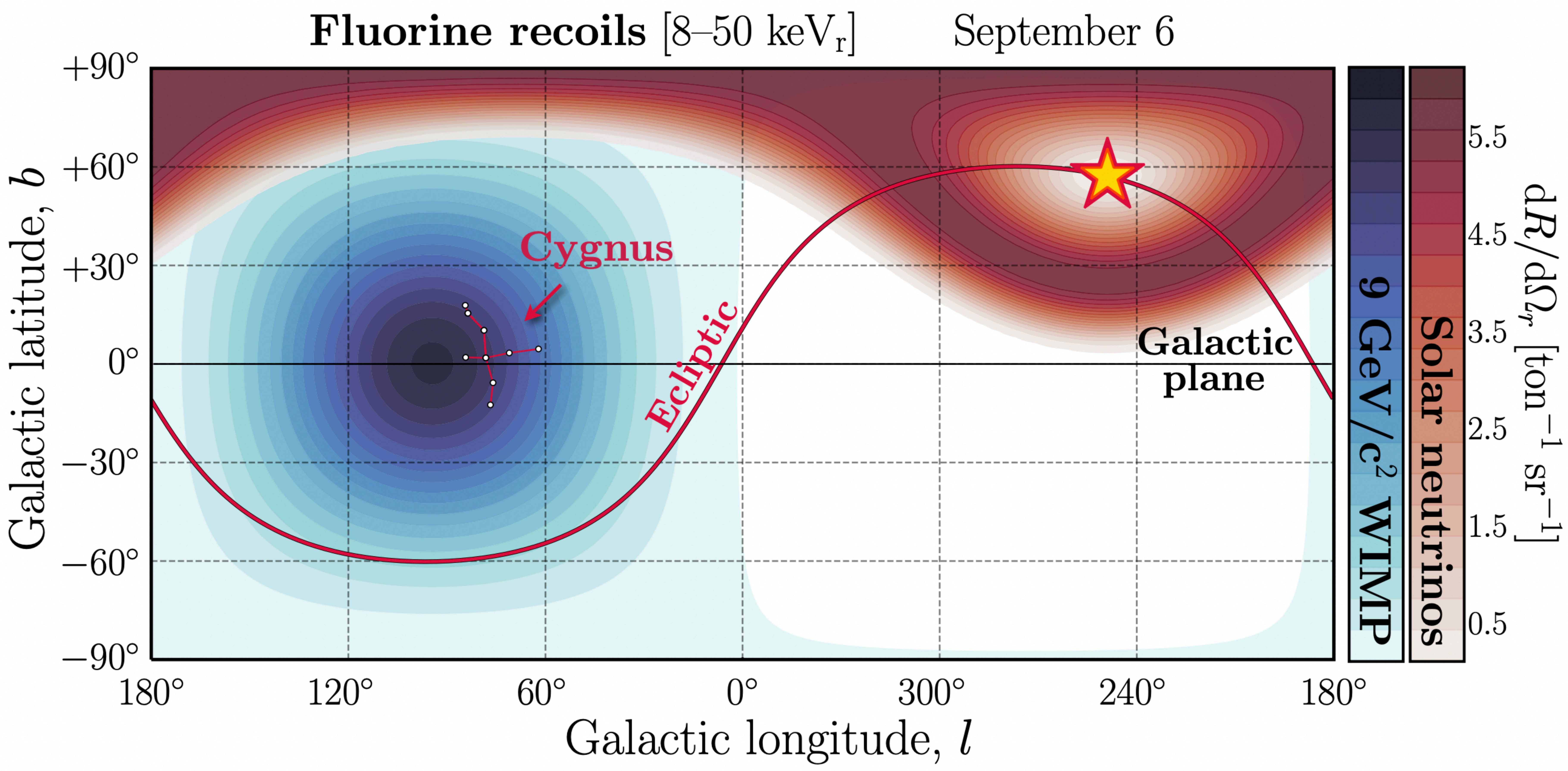
The floor/fog distinction is somewhat academic. Rather, this is about the message we send to the community—recent rebranding during last Snowmass process.

Is this the end? Do we want to have a strategy in place to get past the neutrino fog?

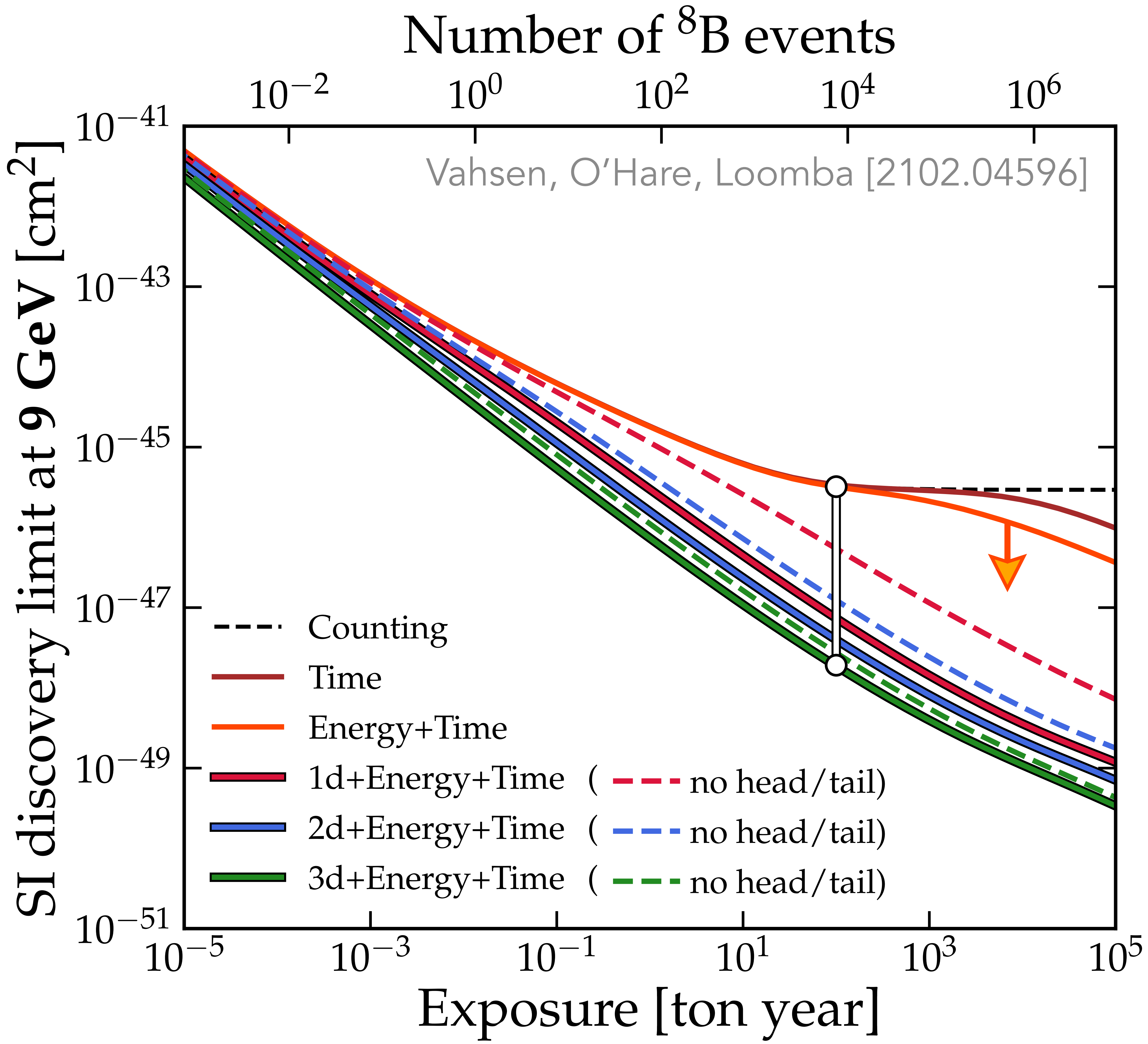


A <u>directional</u> detector should be able to "see through" the neutrino fog

Sun and Cygnus separated by between 60—120° on the sky depending on the time of year. Mostly non-overlapping angular distributions—only need small amount of direction sensitivity to tell them apart.



Seeing through the neutrino fog with directionality



- Using even limited levels of directional information (1d/2d projection of tracks, no head-tail etc.) the CEvNS background can be subtracted
- Best case scenario (full 3D tracks), sensitivity scales almost as $\sigma \propto N^{-1}$, i.e. <u>there is no neutrino fog at all</u>

How close can a real experiment get?

What is required to clear the neutrino fog?

(see our review [2102.04596] and recoil imaging WP [2203.05914] for reasoning)

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

Achieve this and you clear ν-fog by order of magnitude compared to non-directional detector

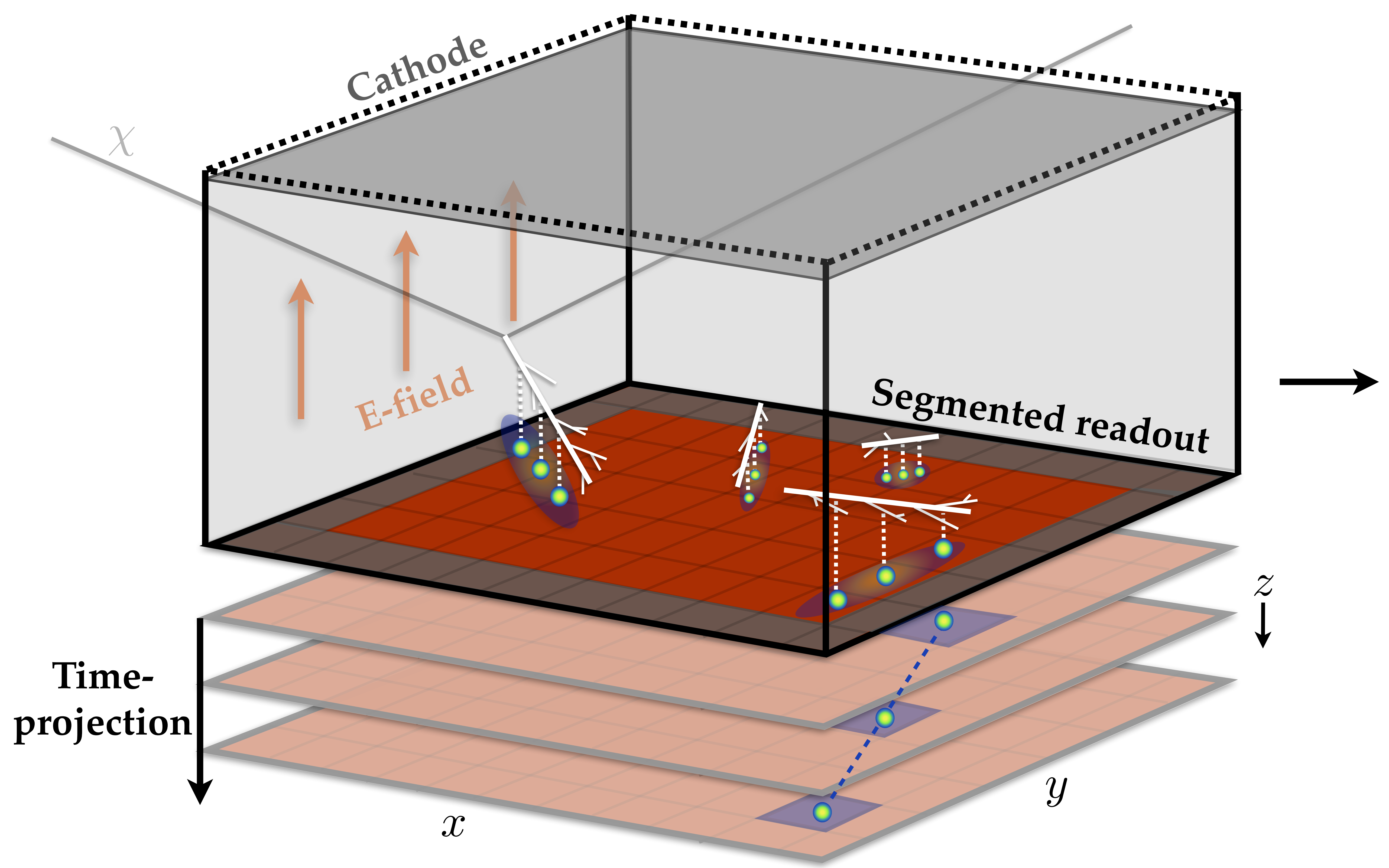
And achieved…

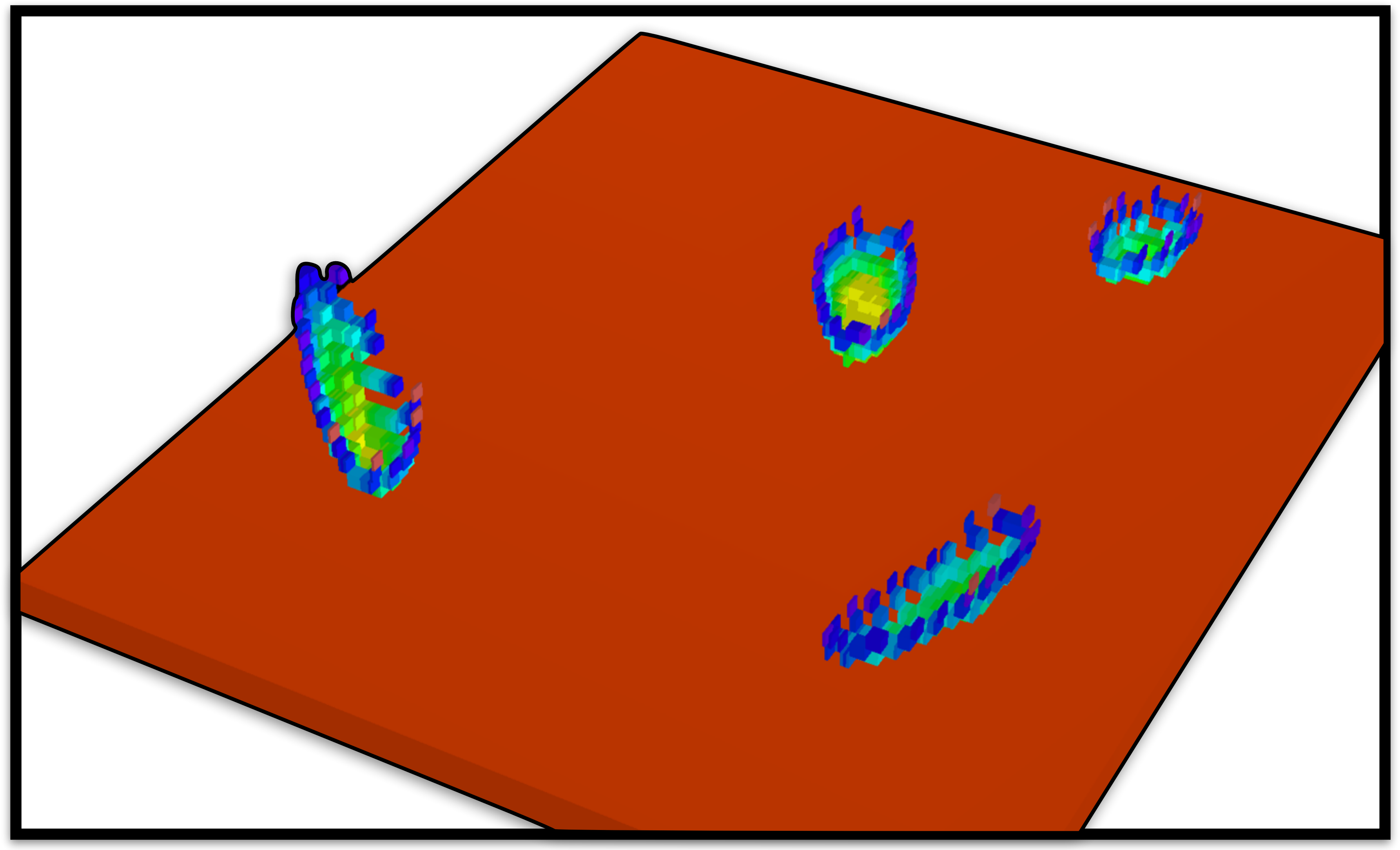
- At the level of individual events
- In as high a density target as possible
- Below <10 keVr
- With a timing resolution better than a few hours

Combination only possible through "recoil imaging": the event-by-event measurement of recoil tracks

Micro-pattern gaseous detectors

MPGD technology promises to provide high signal-to-noise reconstruction of nuclear and electronic recoil tracks in gas at O(100) μm^3-voxel size. Sufficient to reach ν-fog performance goals, but needs to be implemented at scale, and come with low-enough backgrounds. See also talks by Majd Ghrear, Dinesh Loomba in this workshop for more on this technology.





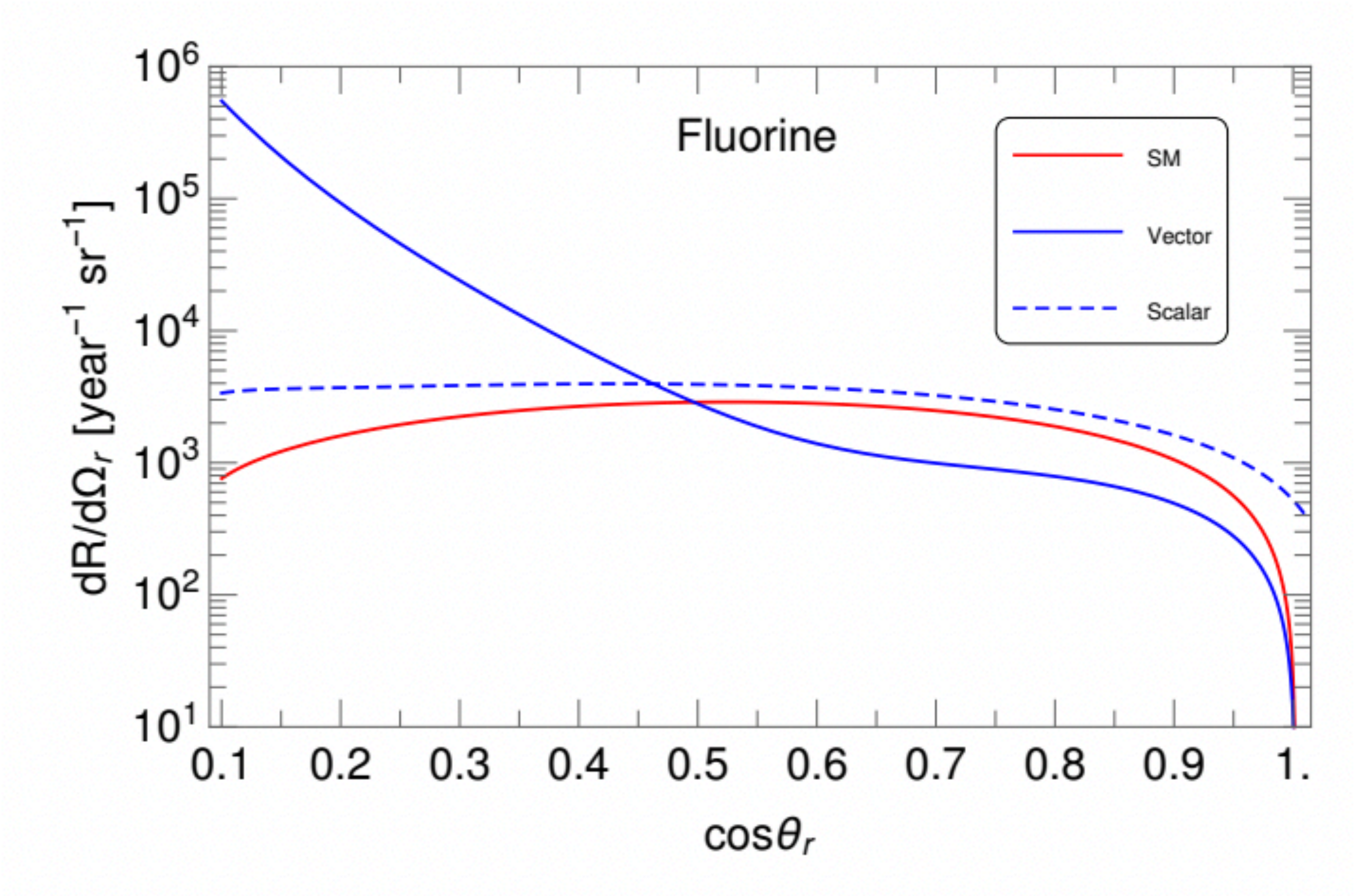
3d tracks of low-energy neutron-inured Helium recoils

Jaegle+ [1901.06657]

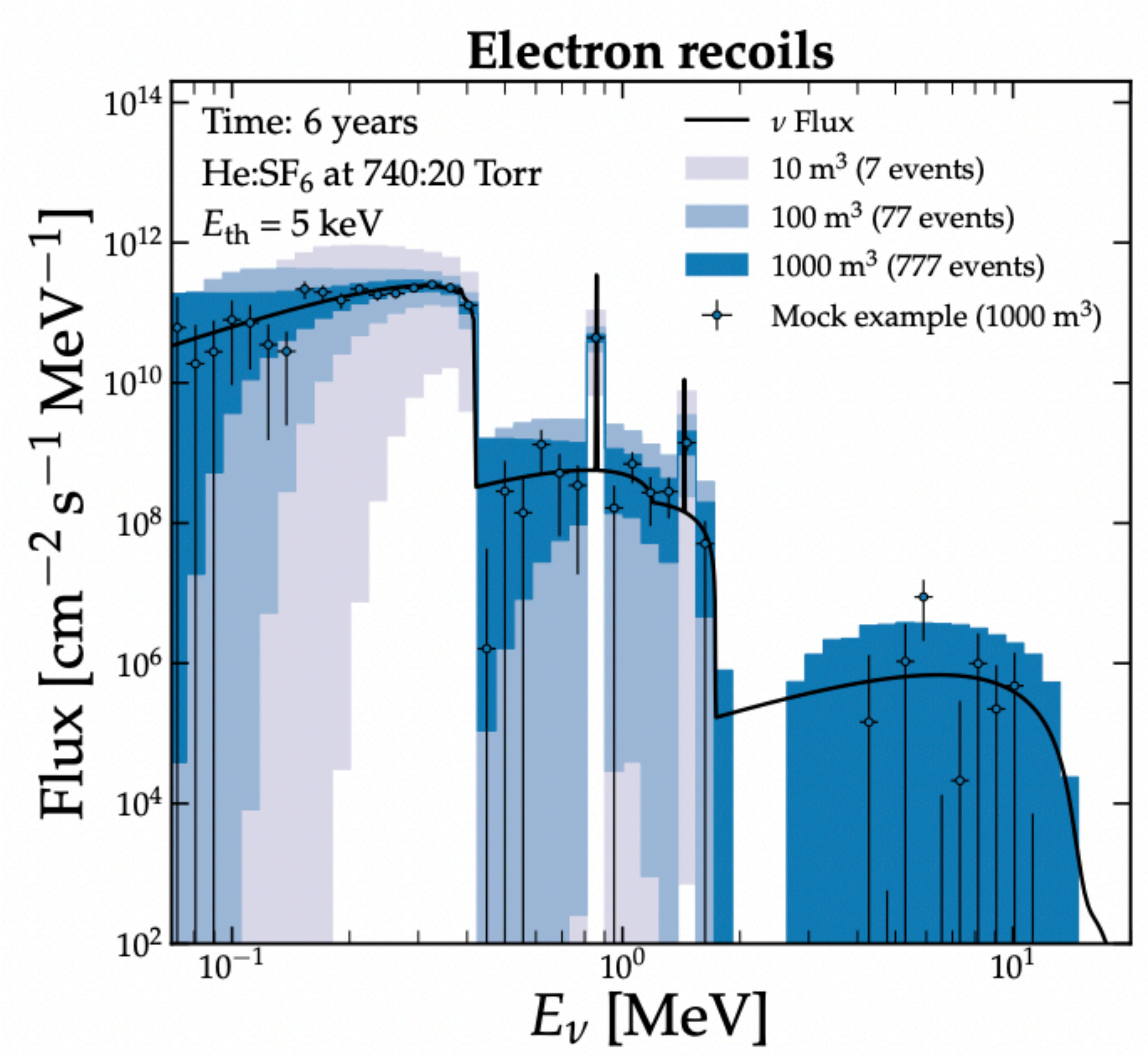
Directional gas TPCs as neutrino detectors?

Turn background into signal. Can do interesting measurements using detectors with smaller footprints than the ~1000 m³ scale needed to clear the neutrino fog.

Measure directionality of CEvNS
e.g. Abdullah+ [2003.11510], Aristizabal-Sierra+ [2103.10857]



ERs+NRs for solar neutrino spectroscopy
e.g. Lisotti, O'Hare+ [2404.03690]



Takeaways

- There is no neutrino "floor". We can rebrand it as a neutrino "fog", quantified by how badly the CEvNS background slows progress through DM parameter space.
- Neutrino fog still represents ultimate boundary to direct DM detection—diminishing returns for what are already very expensive and challenging experiments. Critical decision must be made by community to decide if we want to continue.
- Improvement in knowledge of CEvNS cross-section and neutrino fluxes can suppress the neutrino fog.
- 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 consortium is working towards this