The Neutrino ~~Floor~~ Fog

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Mini-RPM
October 22, 2020

Outline

I. What is the “neutrino floor”?

II. Why is *not* a floor?

III. Can we overcome it?

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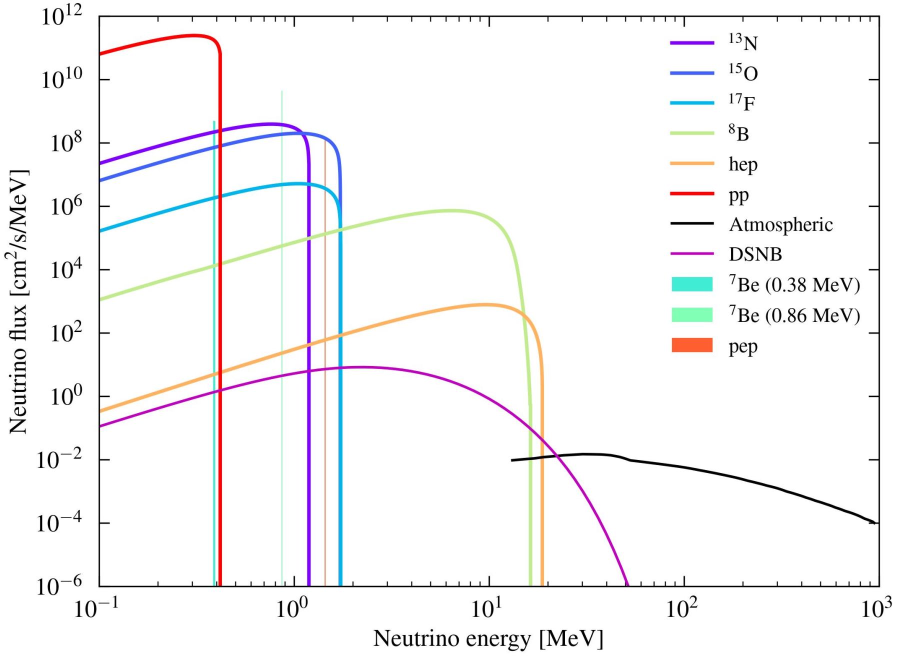
Neutrino fluxes

- Direct detection experiments will be sensitive to the flux of:
  - Solar neutrinos
    - proton-proton chain
    - CNO cycle
  - Atmospheric neutrinos
    - Only sensitive to the sub-GeV part of the total spectrum
  - Diffuse supernova neutrinos (DSNB)
    - Accumulated flux from all the past supernova explosions



Neutrino fluxes

- In general, the value of the integrated fluxes are not precisely known:
  - Solar neutrinos
    - Uncertainties ranging from 1 to 30%
  - Atmospheric neutrinos
    - 20-25% due to uncertainty on the cross section between cosmic rays and nuclei, and the Earth's cutoff rigidity
  - Diffuse supernova neutrinos (DSNB)
    - 50% due to assumptions in the flux calculation

ν **type**		$E_\nu^{\max}$ [MeV]	$E_{\mathrm{Xe}}^{\max}$ [keV]	$E_{\mathrm{Ar}}^{\max}$ [keV]	$\Phi(1 \pm \delta\Phi/\Phi)$ [cm^{-2} s^{-1}]	$\times 10^n$	Ref.
Solar	pp	0.423	0.003	0.010	$5.98\,(1 \pm 0.006)$	10^{10}	[58]
	pep	1.440	0.035	0.114	$1.44\,(1 \pm 0.01)$	10^{8}	[58]
	hep	18.77	5.859	19.37	$7.98\,(1 \pm 0.30)$	10^{3}	[58]
	^{7}Be	0.384	0.003	0.008	$4.93\,(1 \pm 0.06)$	10^{8}	[58]
	^{7}Be	0.861	0.012	0.041	$4.50\,(1 \pm 0.06)$	10^{9}	[58]
	^{8}B	16.36	4.443	14.70	$5.16\,(1 \pm 0.02)$	10^{6}	[59]
	^{13}N	1.199	0.024	0.078	$2.78\,(1 \pm 0.15)$	10^{8}	[58]
	^{15}O	1.732	0.050	0.165	$2.05\,(1 \pm 0.17)$	10^{8}	[58]
	^{17}F	1.740	0.050	0.166	$5.29\,(1 \pm 0.20)$	10^{6}	[58]
DSNB		91.20	138.2	455.7	$8.57(1 \pm 0.50)$	10^{1}	[62]
Atmospheric		10^{4}	1000	1000	$1.07(1 \pm 0.25)$	10^{1}	[63]

arxiv:2002.07499

Recoil rate

WIMP-nucleus elastic scattering

- Isotropic and isothermal spherical model (SHM)
- Important uncertainties exist for the astrophysical parameters ρ_0, v_{esc} and $\mathbf{v}_{lab}$

$$\frac{\mathrm{d}R_\chi}{\mathrm{d}E_r} = \frac{\rho_0 \sigma_{\chi-n}}{2 m_\chi \mu_{\chi n}^2} A^2 F^2(E_r) g(v_{\min}, t)$$

$$g(v_{\min}, t) = \int_{v_{\min}}^{\infty} \frac{f(\mathbf{v} + \mathbf{v}_{\mathrm{lab}}(t))}{v} \, \mathrm{d}^3 v$$

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(Relevant) Neutrino elastic scattering

1. Coherent neutrino-nucleus scattering
2. Neutrino-electron scattering
   a. Electroweak interaction
   b. Neutrino magnetic moment

$$\frac{dR}{dE_r} = \mathcal{N} \times \int_{E_\nu^{\min}} \frac{dN}{dE_\nu} \times \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu$$

Neutrino flux

Differential cross section (different for each type of interaction)

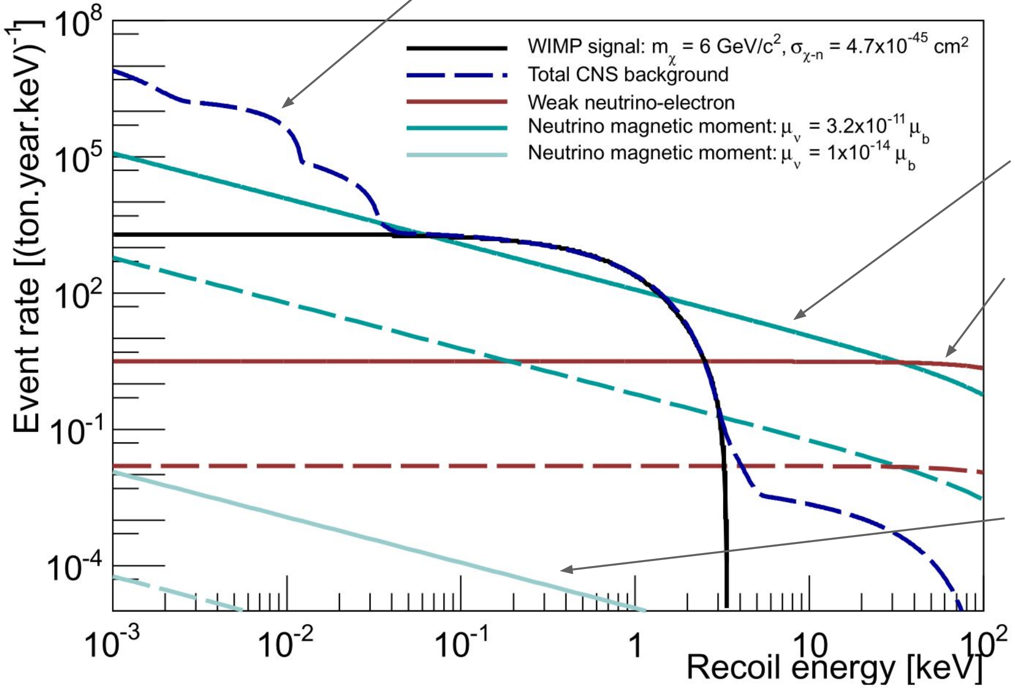
Recoil rate

Coherent neutrino-nucleus scattering (combined)

Neutrino magnetic moment (at current experimental sensitivity)

Electroweak neutrino-electron scattering

Neutrino magnetic moment (at upper bound for most extensions to the SM)



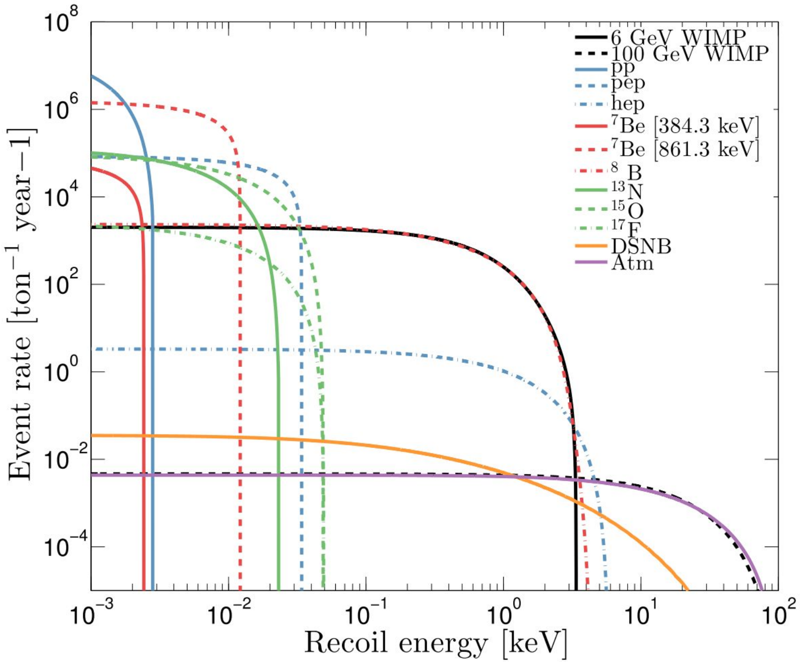
arxiv:1307.5458

Dashed lines: after electron rejection factor of 99.5%

Mimicking WIMP signals

Neutrino signals can mimic the expected WIMP recoil rate:

- < 10 GeV: pp and 8B neutrinos
- 10-100 GeV: DSNB
- > 100 GeV: atmospheric neutrinos

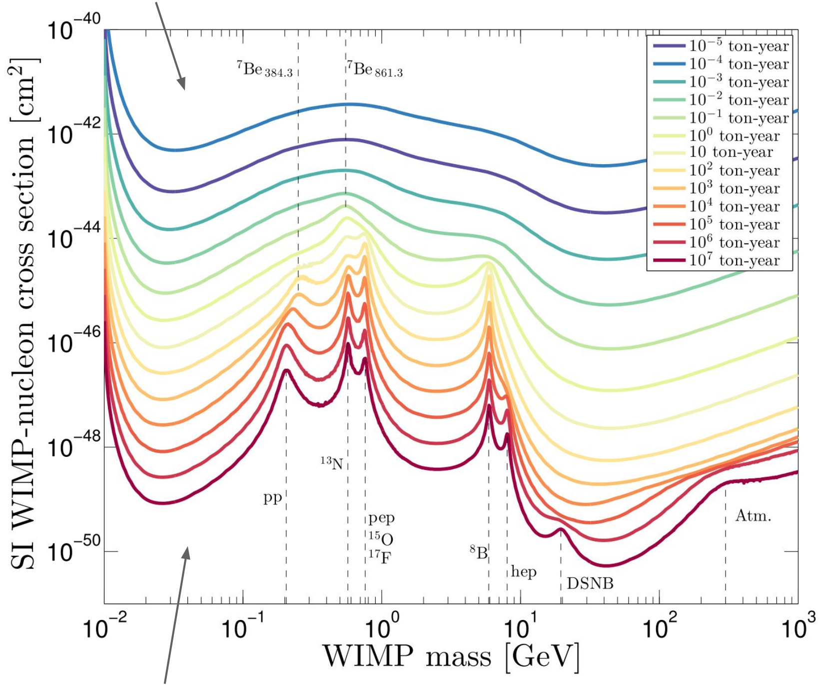


arxiv:1604.03858

Neutrino floor

- For low enough WIMP cross sections, an experiment which observes an excess of events over the expected background won’t be able to determine if the excess is due to WIMPs or an overfluctuation of the neutrino background.
- *Here it comes the (in)famous “Neutrino floor”:* when the WIMP discovery is limited by the systematic uncertainty on the neutrino background.

S/√B is large enough to distinguish a WIMP signal



S/√B is not large enough to distinguish a WIMP signal

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Neutrino floor: calculation

Likelihood

Poisson function in each bin

Model that is assumed

$$\mathscr{L}(m_\chi, \sigma, \mathbf{\Phi} | \mathcal{M}) = \prod_{i=1}^{N_{\rm bins}} \mathscr{P}\left(N^i_{\rm obs} \middle| N^i_\chi + \sum_{j=1}^{n_\nu} N^i_\nu(\phi^j) \right) \times \prod_{j=1}^{n_\nu} \mathscr{G}(\Phi^j) \, .$$

WIMP parameters of interest

Neutrino flux normalisations

Gaussian likelihood for each neutrino flux

Neutrino floor: calculation

Methodology

- Compute <u>discovery limits</u> based on the profile likelihood ratio (PLR) test

Conditional likelihood fit

B-only model

$$\Lambda = \frac{\mathscr{L}(0, \hat{\hat{\boldsymbol{\Phi}}} | \mathcal{M}_{\sigma=0})}{\mathscr{L}(\hat{\sigma}, \hat{\boldsymbol{\Phi}} | \mathcal{M})}$$

Global fit

S+B model

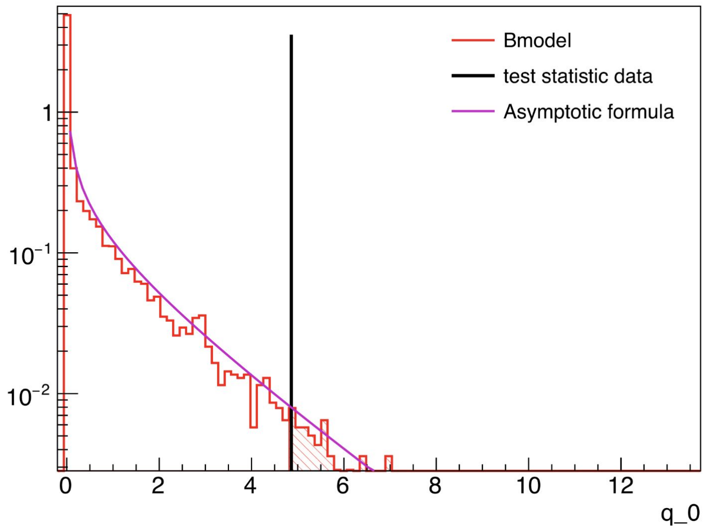
Discovery test statistic:

$$q_0 = \begin{cases} -2 \ln \Lambda & \hat{\sigma} > 0\,, \\ 0 & \hat{\sigma} \leq 0, \end{cases}$$

Neutrino floor: calculation

Methodology

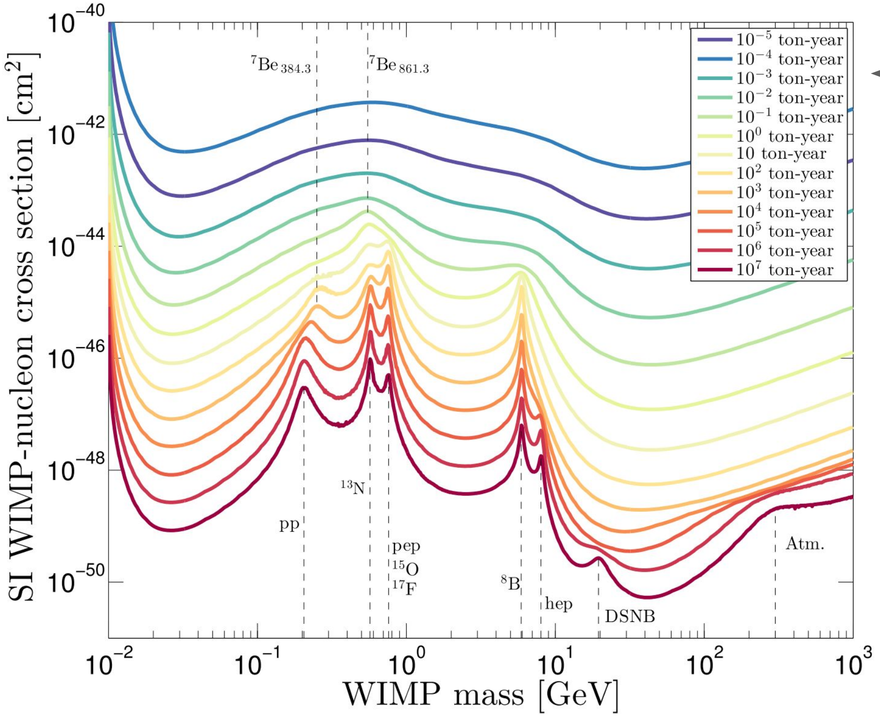
- Compute discovery limits based on the profile likelihood ratio (PLR) test
- Avoid costly MC calculation by relying on the asymptotic formula
- Under this assumption, Z=√(q_o_obs)
    - Make a scan over σ and simulate distributions of Z for each σ value
    - Find the minimum σ for which 50% of the distribution of Z is greater than 3
    - In other words, if the true WIMP cross section lies above this limit, then a given experiment has a *50% probability to get at least a 3σ discovery



softwaredocs:LZStats

*Caveat: some authors use 90%

Neutrino floor: calculation



S/√B is large enough to distinguish a WIMP signal

S/√B is not large enough to distinguish a WIMP signal

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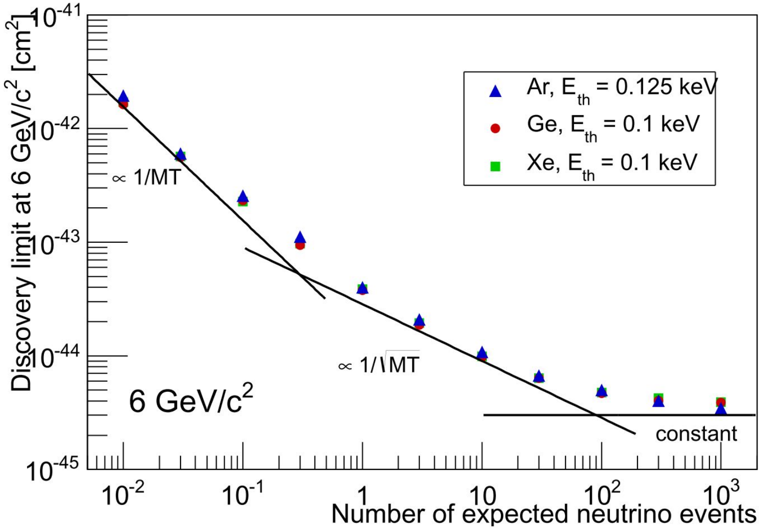
Neutrino floor: evolution with exposure

As the exposure of an experiment grows, the experiments' sensitivity goes over different regimes:

1. Linear
   a. Neutrino background is negligible
   b. Sensitivity scales as 1/ε
      (i.e. background-free)
2. Poisson regime
   a. Neutrinos become relevant
   b. Sensitivity scales as 1/$\sqrt{\varepsilon}$
3. Saturation
   a. The WIMP signal only provides excess events at a lower level than the expected systematic fluctuation: $\sqrt{\varepsilon}/\varepsilon$ < □$\boldsymbol{\Phi}$



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Outline

I. What is the “neutrino floor”?

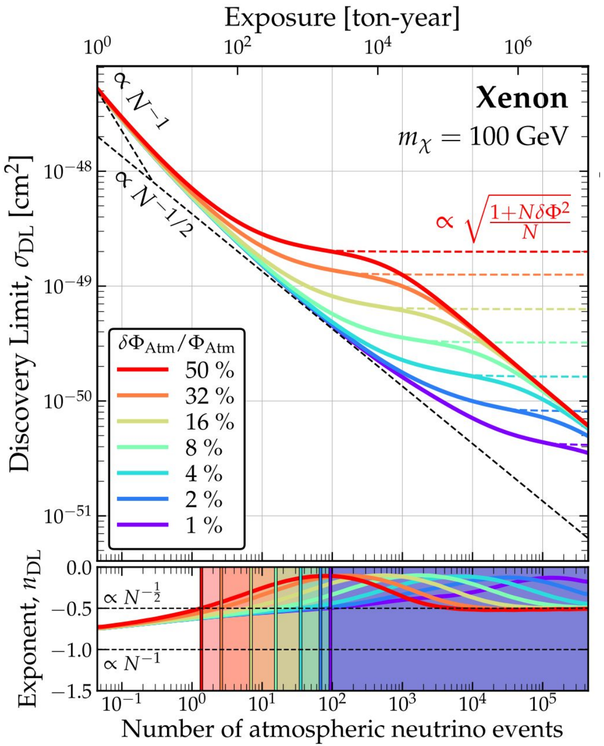
II. Why is *not* a floor?

III. Can we overcome it?

I. It's not a hard floor, but rather a soft barrier

- The saturation regime is only realised if there is a *perfect match* between the WIMP and neutrino signals
- If not, enough statisticals are eventually collected that allow discrimination between the energy spectra
- So in reality, for most WIMP masses:
  - Linear → Poisson → Saturation → Poisson

However, note that O(10^4) events are needed to "cross the floor"



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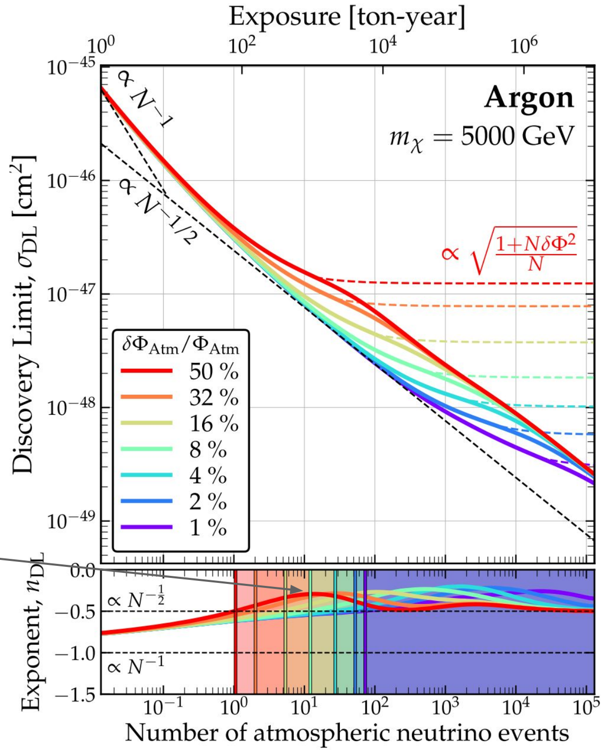
I. It’s not a hard floor, but rather a soft barrier

- Hence, the “neutrino fog” would be a more fitting name to highlight that it is not an ultimate limit
- Even more, the neutrino fog has an intrinsic “thickness” depending on the target element
    - Xenon: sensitivity almost saturates for a large enough exposure (i.e. exponent≃0)
        - “You can barely see anything”
    - Argon: the saturation regime is never realised (e.g. max exponent≃-0.25)
        - “It’s foggy, but you can see”



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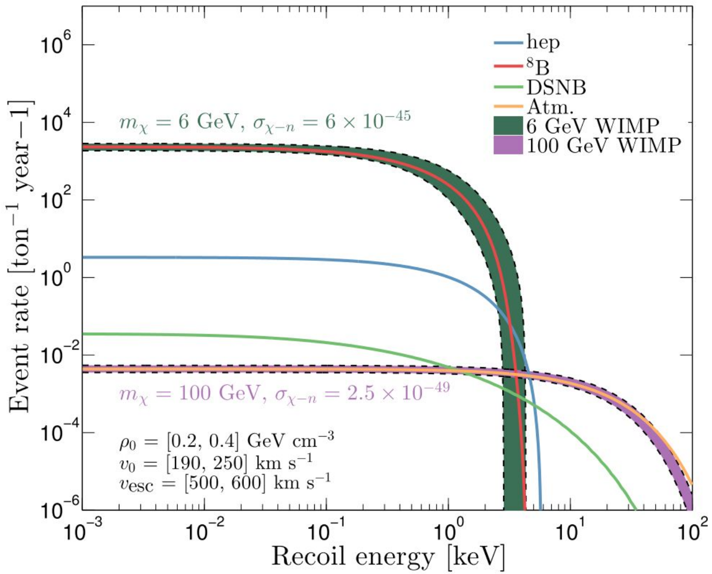
II. Its position is not fixed

- Different assumptions on some key astrophysical parameters will impact the shape and expected event recoil rate
- This will naturally affect which and when neutrinos become a dominant background
- Obviously, the same could be argued about uncertainties on the neutrino fluxes



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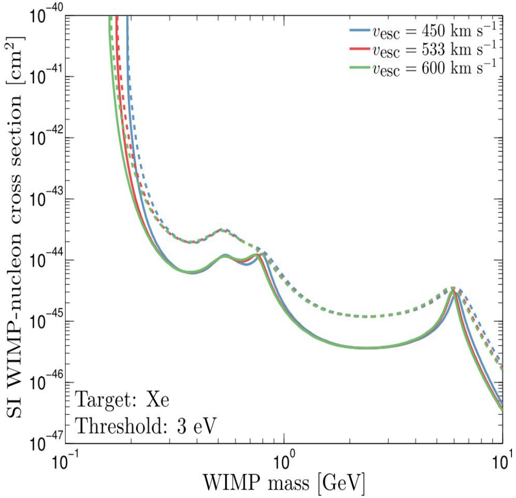
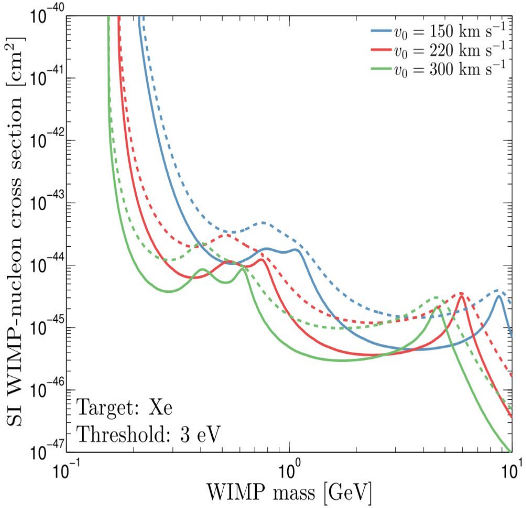
II. Its position is not fixed

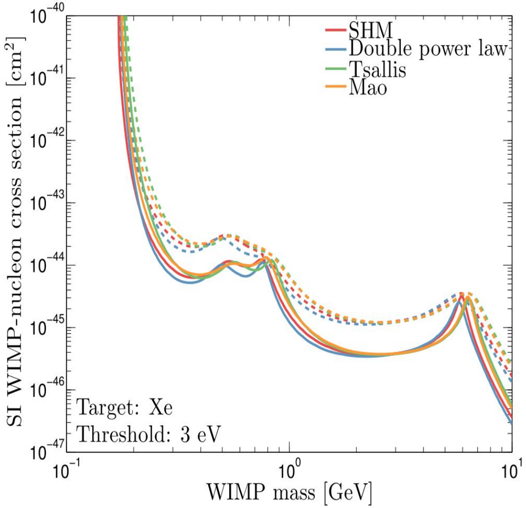
Escape velocity



Local circular velocity



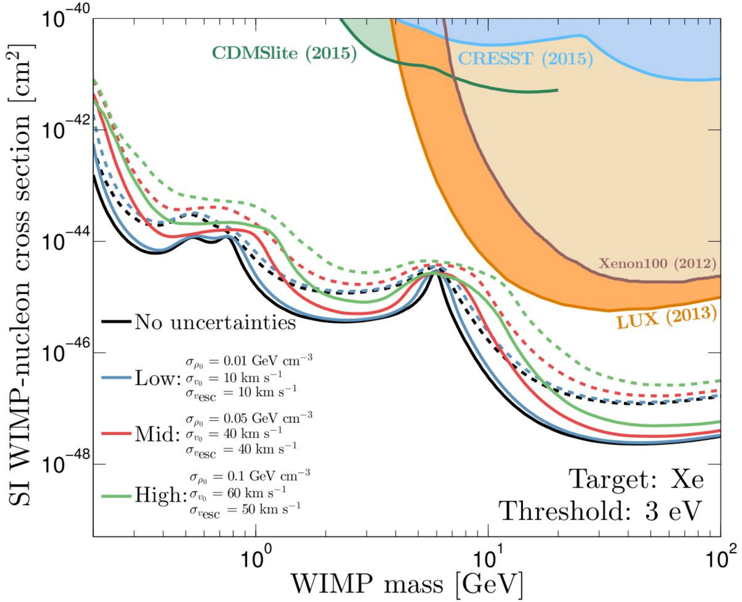
Velocity distribution function



Dashed: 1 ton-year
Solid: 10 ton-year

arxiv:1604.03858

II. Its position is not fixed



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The discovery limit changes once you account for the uncertainties on some of the astrophysical parameters.

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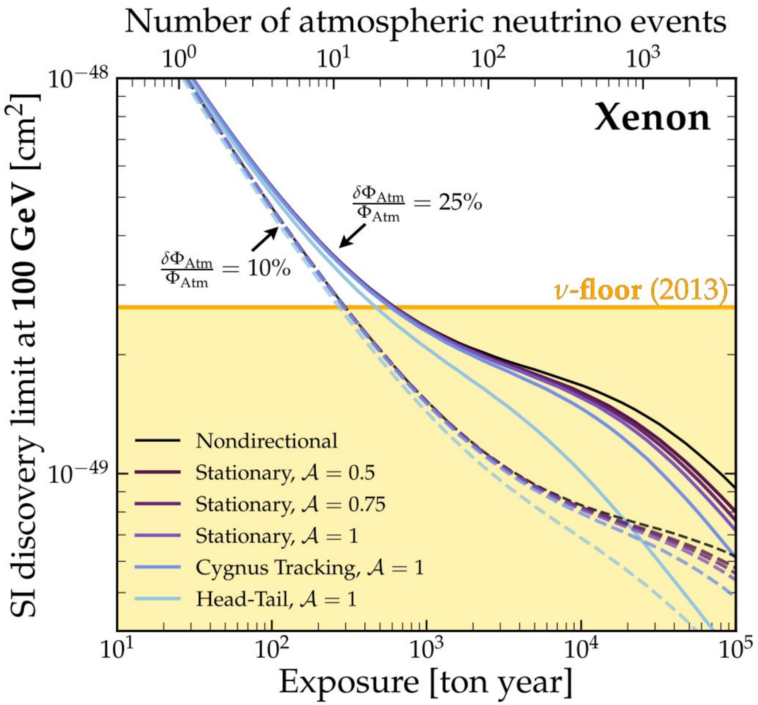
Strategies

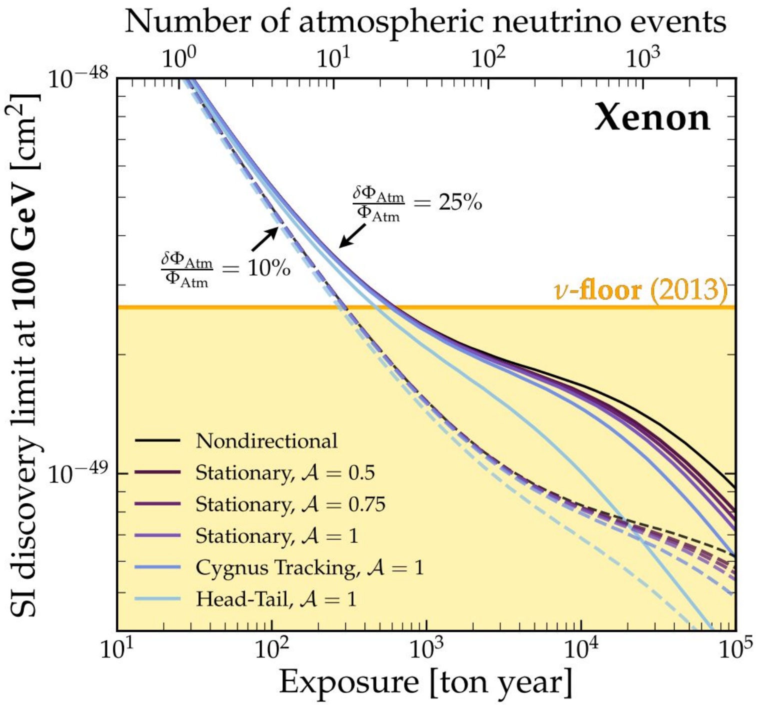
- There is a path forward to overcoming the neutrino fog: expand the range of strategies to discriminate between neutrino and WIMP signals.
- So far we have discussed using recoil energy as a discriminant, but there are other methods, including:
    - *Annual modulation:* exploit WIMP annual modulation and the small seasonal modulation of the angular dependence of the atmospheric neutrino flux.
    - *Target complementarity:* combine the different recoil energy distributions from experiments employing different targets.
    - *Directionality:* use the angular information to discriminate WIMP events against background.
    - *Improved flux measurements:* reducing some of these uncertainties can reduce dramatically the obstacles imposed by the neutrino fog.

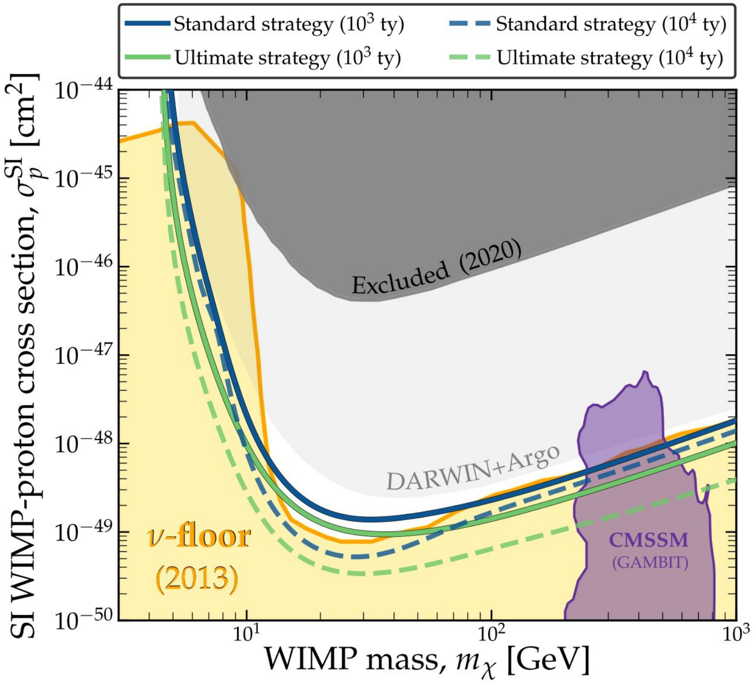
Going beyond the neutrino fog



Dashed: atm flux uncertainty is 10%
Solid: atm flux uncertainty is 25%

Going beyond the neutrino fog





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Solid: atm flux uncertainty is 25%

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Food for thought

- Given the large variability of the neutrino floor, does it make sense to always plot the same one along different dark matter experiments (which have different energy thresholds and may use different targets)?
    - I think that is fine as long as the reader interprets the neutrino floor correctly and only takes it as a rough reference.
- Is it a good strategy to devote so much effort to “cover the last available region of WIMP space”? The end of that region is not even well-defined.
    - I think it does. We can get that far with the current technology and therefore we should keep pushing down in the parameter space. Obviously, the work of O’Hare and others show us that there is a lot to be gained from exploring new technologies and establishing new collaborations between different experiments.