The Neutrino Floor for the Next Generation of Liquid Noble Dark Matter Detectors:

The Impact of Detector Properties and of Model Uncertainties

Andréa Gaspert[1,2], Pietro Giampa[1] and David Morrissey[1]

[1] TRIUMF, [2] Université de Montréal

The neutrino floor typically shown in papers is computed for a liquid xenon time projection chamber, using a Maxwellian speed distribution for the Dark Matter in the Milky Way [1]. Although it represents a good estimation, it is of insufficient precision when good predictions for specific experiments are needed. In this work, the objective is twofold:

I. To compute an accurate neutrino floor for realistic next-generation DM detectors
II. To show how uncertainties on neutrino fluxes and on the distribution of dark matter in our vicinity impact predictions

I. Neutrino Floor Definition

As DM detectors become more sensitive, neutrinos become an important (and irreducible) source of background. **The neutrino floor is computed by using a Monte Carlo simulation of the profile likelihood ratio, and defines the limit below which the neutrino events would dominate in the detector:**

- The likelihood ratio $\lambda(0)$, with its corresponding test statistics q_0, are defined as [2]:

$$\lambda(0) = \frac{\mathcal{L}(\sigma = 0, \hat{\hat{\vec{\phi}}})}{\mathcal{L}(\hat{\sigma}, \hat{\hat{\vec{\phi}}})} \qquad q_0 = \begin{cases} -2\ln(\lambda(0)) & \sigma > 0 \\ 0 & \sigma < 0 \end{cases}$$

- Where the binned likelihood is defined as:

$$\mathcal{L}(\sigma, \vec{\phi}) = \prod_{h=1}^{N_{bins}} P(N^h | \mu_\chi^h(\sigma, \vec{\phi}) + \sum_j \mu_\nu^{j,h}(\vec{\phi})) \times \prod_k \mathcal{L}_k(\phi_k)$$

  - σ: DM-nucleon interaction cross-section
  - N^h : Observed events in a given energy bin
  - $\mu_\chi^h/\mu_\nu^{j,h}$: Expected number of DM/neutrino events from source j
  - ϕ_k: Nuisance parameters
  - L_k: PDFs for the nuisance parameters (normal distributions)

- We profile over the neutrinos fluxes (see fig. 1), the DM density ρ_{DM} and the parameters of the DM velocity distribution (escape velocity v_{esc} and the circular rotation speed v_0).
- If more than 10% of the pseudo-experiments don't allow DM detection with a significance of at least **3σ**, a point is below the neutrino floor.

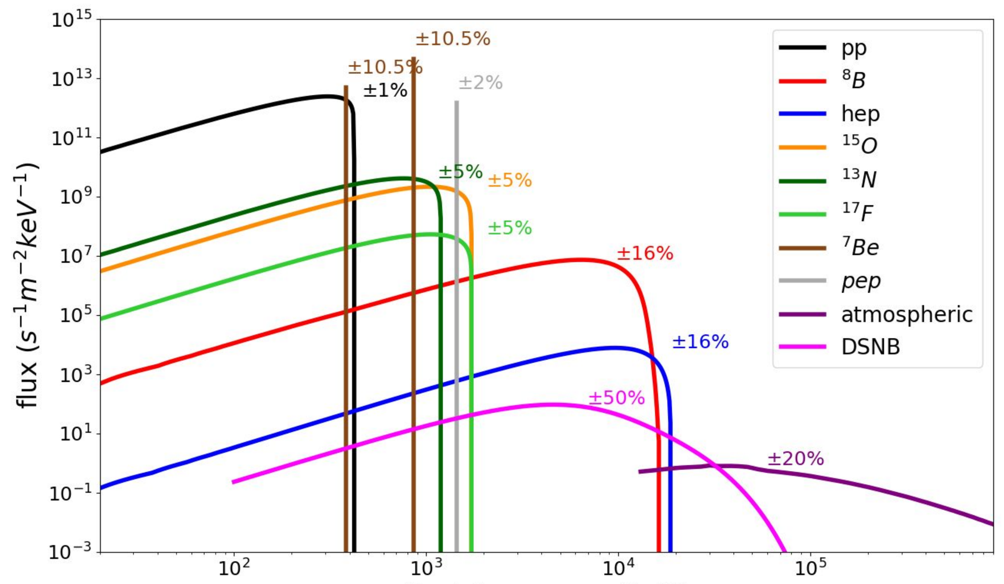

Fig. 1. Sources of neutrino fluxes on Earth, with theoretical uncertainties [3,4,5,6]

Param.	Canonical Value	Value Used (updated)
V_{esc} (km/s)	544 ± 70	528 ± 25 [7]
V_0 (km/s)	220 ± 30	233 ± 5 [8]
ρ_{DM} (GeV/cm^3)	0.3 ± 0.1	0.5 ± 0.2 [8]

Table 1. Values and uncertainties for DM distribution parameters

II. Impact of Detector Properties

- We focused on the comparison between Argon single phase and Xenon dual phase detectors.
- We considered neutrino-induced electron recoils and coherent neutrino-nuclei scattering in the computation of the neutrino floor.
- We find that **the necessary exposure to reach the neutrino floor is higher for Argon detectors** (by roughly 2 orders of magnitude)
- We find that **the neutrino floor for Argon is lower** for higher dark matter masses, because of the **higher ER rejection efficiency** (fig. 2)

	Xenon [9]	Argon [10]
A / Z	131.293 u / 54	39.948 u / 18
Electron recoil rejection efficiency	~10^3	>10^8
Threshold (keV)	1	15
Exposure to reach floor (Ton-years)	**>1E2**	**>1E4**

Table 2. Detector properties for future Xenon and Argon-based DM detectors

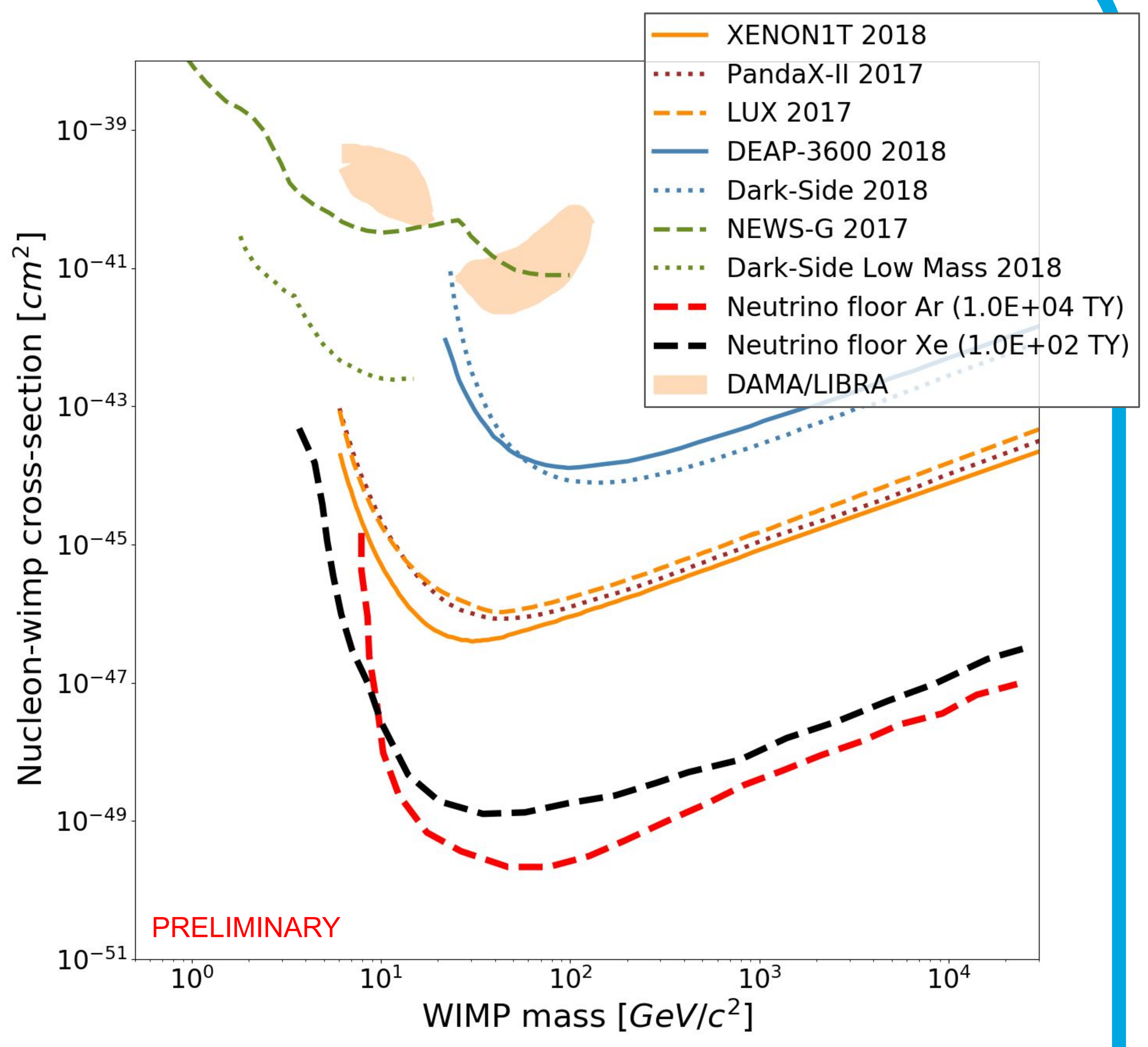

Fig 2. Comparison of neutrino floors for ideal future Darwin-like Xenon dual-phase detector and DEAP-3600-like Argon single-phase detector experiments

III. Dark Matter in Disequilibrium

- Astrophysical observations suggest that a recent merger with our galaxy might have left the DM around us in disequilibrium.
- A fraction η of the DM around the sun would originate from this merger and have an **anisotropic velocity distribution** parameterized by a "sausage anisotropy factor" β [8,11].

$$\sigma_r^2 = \frac{3v_0^2}{2(3-2\beta)}, \qquad \sigma_\theta^2 = \sigma_\phi^2 = \frac{3v_0^2(1-\beta)}{2(3-2\beta)} \qquad \mathbf{0.8 < \beta < 0.98}$$

- We profiled over possible values of η and β to evaluate how this new uncertainty affects the neutrino floor (see fig. 4).
- The new DM velocity distribution is defined as:

$$f(\mathbf{v}) = (1-\eta) f_{\mathrm{R}}(\mathbf{v}) + \eta f_{\mathrm{S}}(\mathbf{v}) \qquad \mathbf{0.1 < \eta < 0.8}$$

$$\rightarrow f_{\mathrm{R}}(\mathbf{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2} N_{\mathrm{R,esc}}} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma_v^2}\right) \times \Theta(v_{\mathrm{esc}} - |\mathbf{v}|)$$

$$\rightarrow f_{\mathrm{S}}(\mathbf{v}) = \frac{1}{(2\pi)^{3/2}\sigma_r\sigma_\theta^2 N_{\mathrm{S,esc}}} \exp\left(-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{v_\phi^2}{2\sigma_\phi^2}\right) \times \Theta(v_{\mathrm{esc}} - |\mathbf{v}|)$$

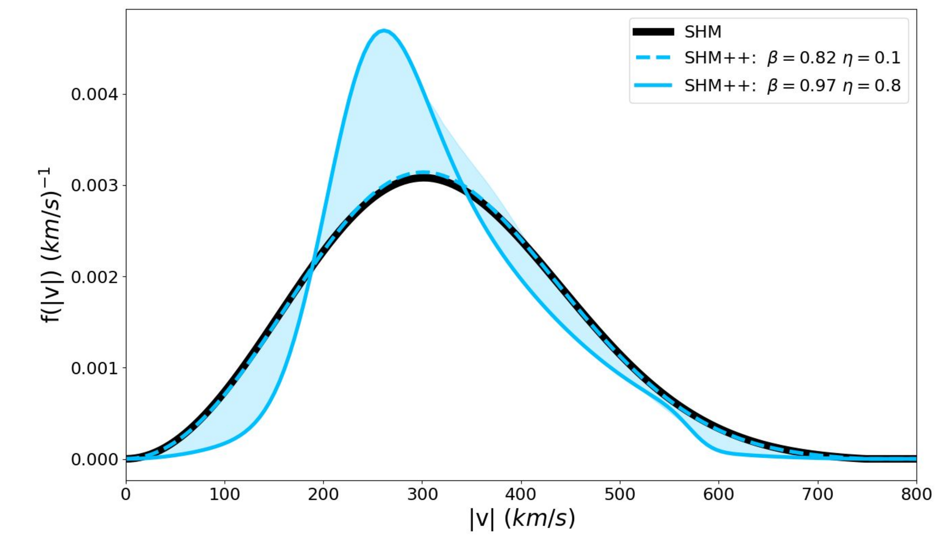

Fig. 3. Local DM speed distribution in the frame of the Earth. Standard Halo Model compared to model with anisotropy

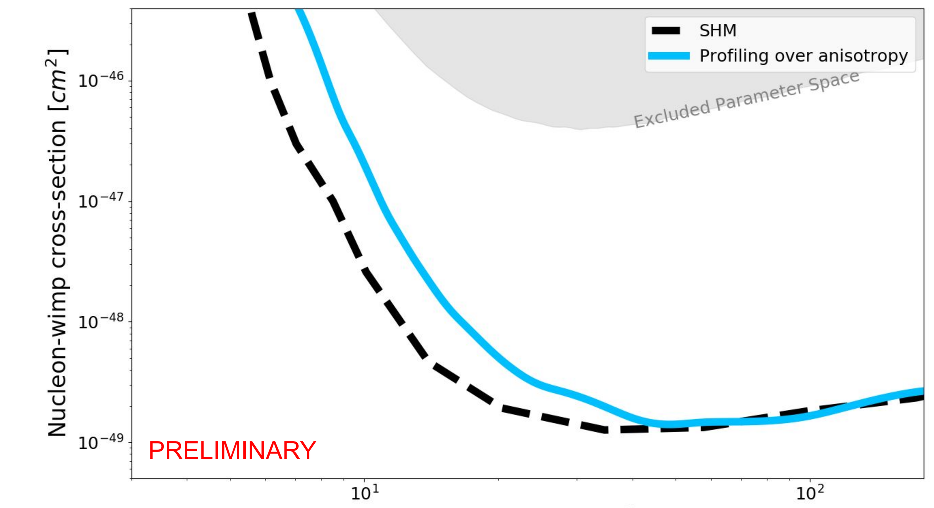

Fig. 4. Impact of a potential anisotropy in the local DM speed distribution on the neutrino floor for a Xenon detector with a 1 keV threshold.

IV. Conclusions

- Detector properties have a major impact on the neutrino floor and argon-based detectors have a lower neutrino floor at higher WIMP masses.
- Although the potential anisotropy of the dark matter velocity distribution has only a small impact of the neutrino floor, this impact is most important for lower dark matter masses.

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