

Shifting the neutrino fog in Isospin Violating Dark Matter model

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Cinvestav

In collaboration with:

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Hep-ph [2512.19784]

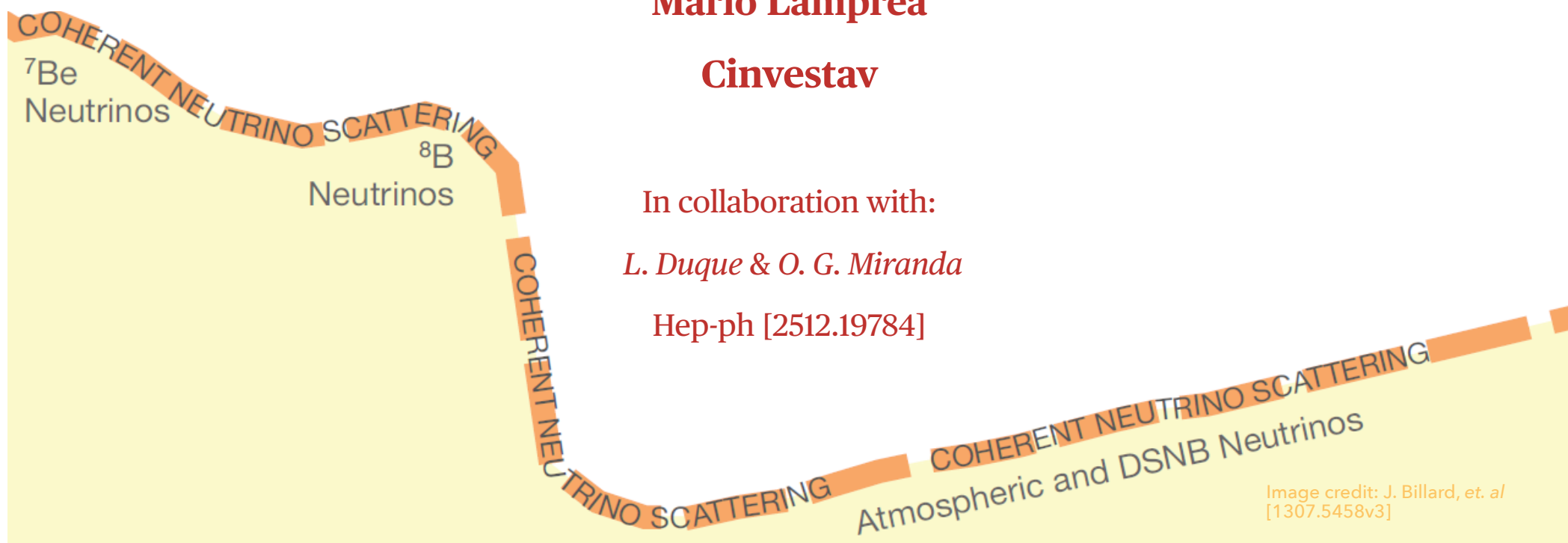
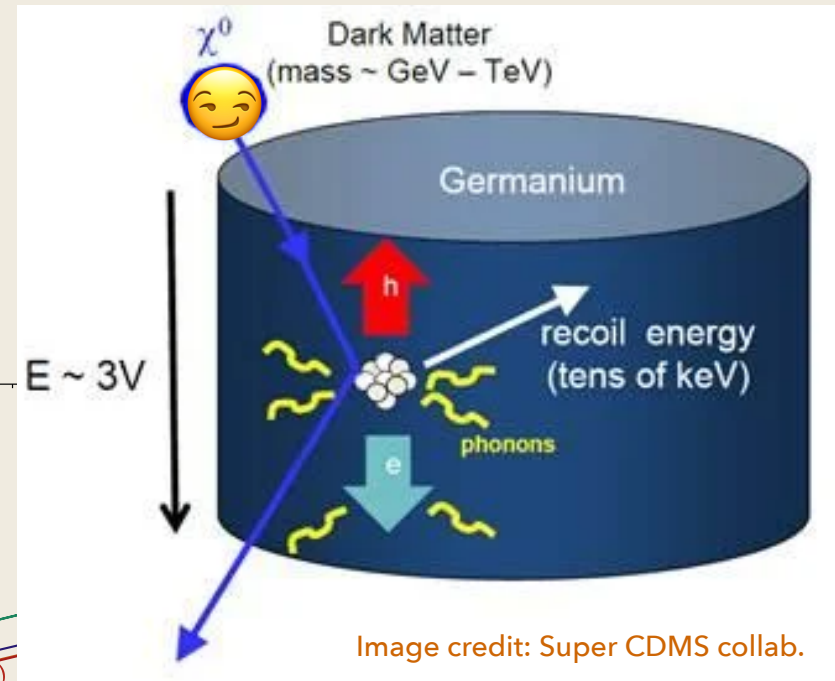
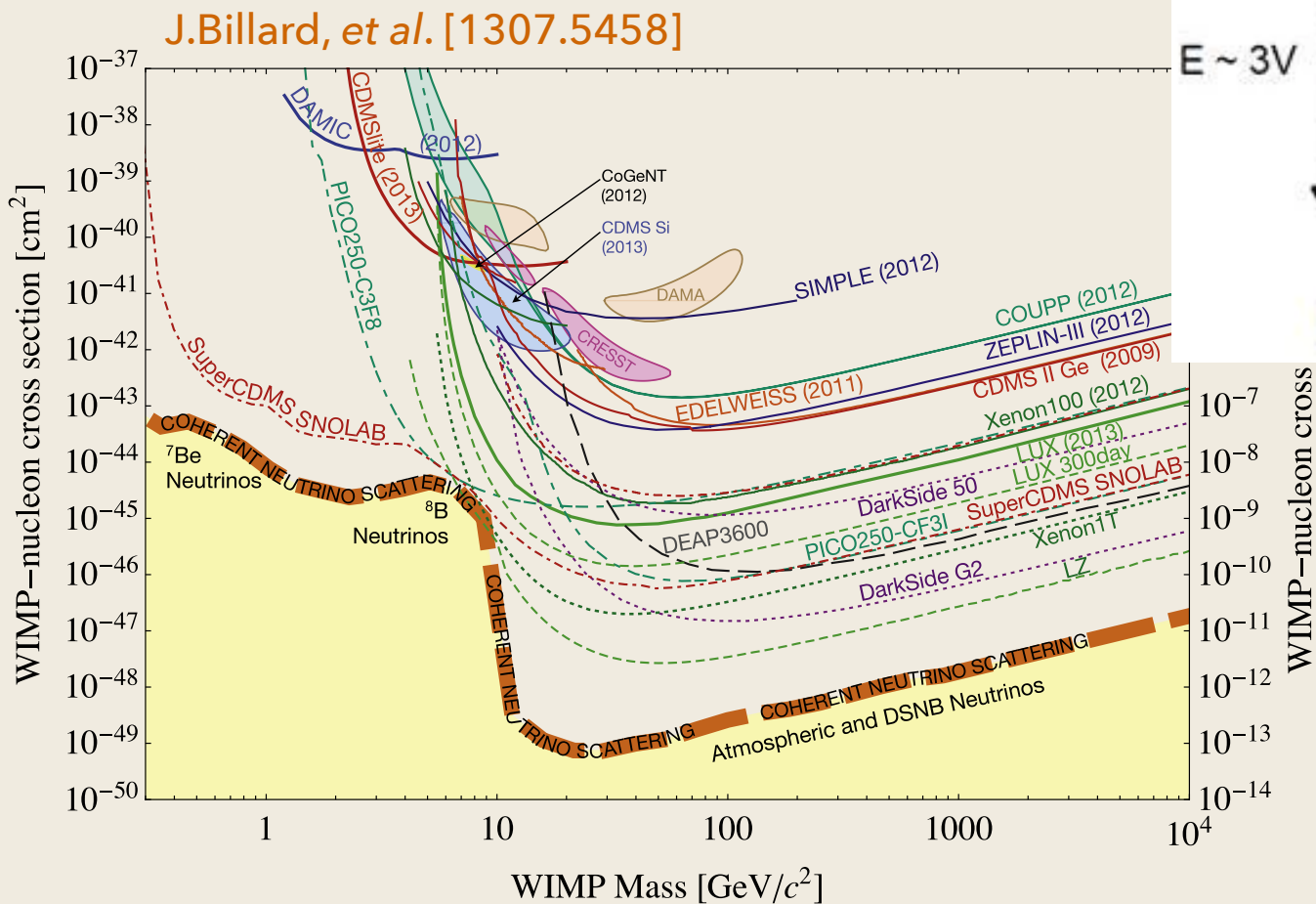


Image credit: J. Billard, et. al
[1307.5458v3]

Direct Detection of WIMPs



WIMP-nucleon cross

WIMP Signal

$$N_{\chi}^i(m_{\chi}, \sigma_{\chi-n}) = \epsilon \int_{E_i}^{E_{i+1}} \frac{dR_{\text{DM}}}{dE_r} dE_r$$

Number of DM events N_{χ} is calculated through the WIMP differential event rate per recoil energy:

$$\frac{dR_{\text{DM}}}{dE_r} = \epsilon \frac{\sigma_0 \rho_0}{2m_{\chi} \mu_N^2} \int_{v > v_{\text{min}}} \frac{f(\mathbf{v})}{v} d^3v$$

DM velocity
distribution (SHM)

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\text{esc}}} \left(\frac{3}{2\pi\sigma_v^2} \right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{\text{esc}} \\ 0, & \text{otherwise.} \end{cases}$$

Local mass density

$$\rho_0 = 0.3 \text{ GeVc}^{-2}\text{cm}^{-3}$$

velocities

$$v_0 = 220 \text{ km/s,}$$

$$v_{\text{esc}} = 544 \text{ km/s,}$$

Spin-Independent
WIMP-nucleon
cross-section

$$\sigma_0^{\text{SI}} = \frac{4\mu_n^2}{\pi} [Zf_p + (A - Z)f_n]^2 F^2(q)$$

WIMP Signal

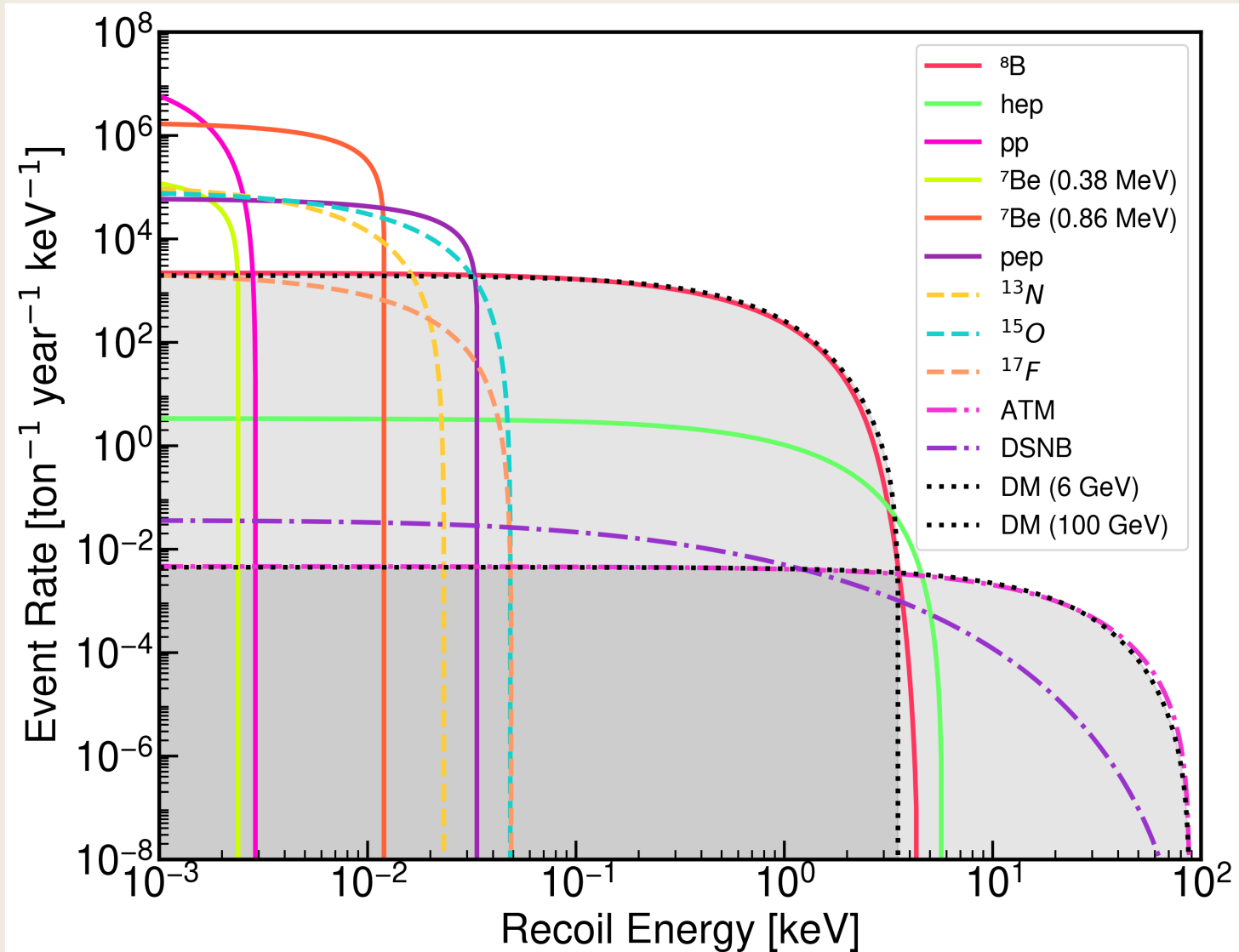
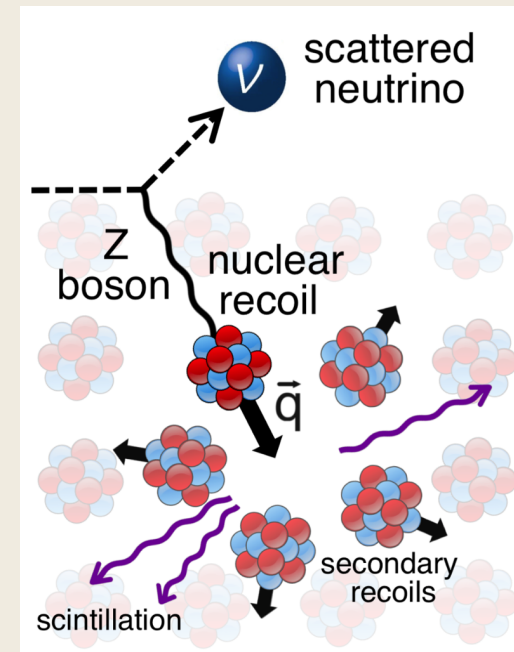
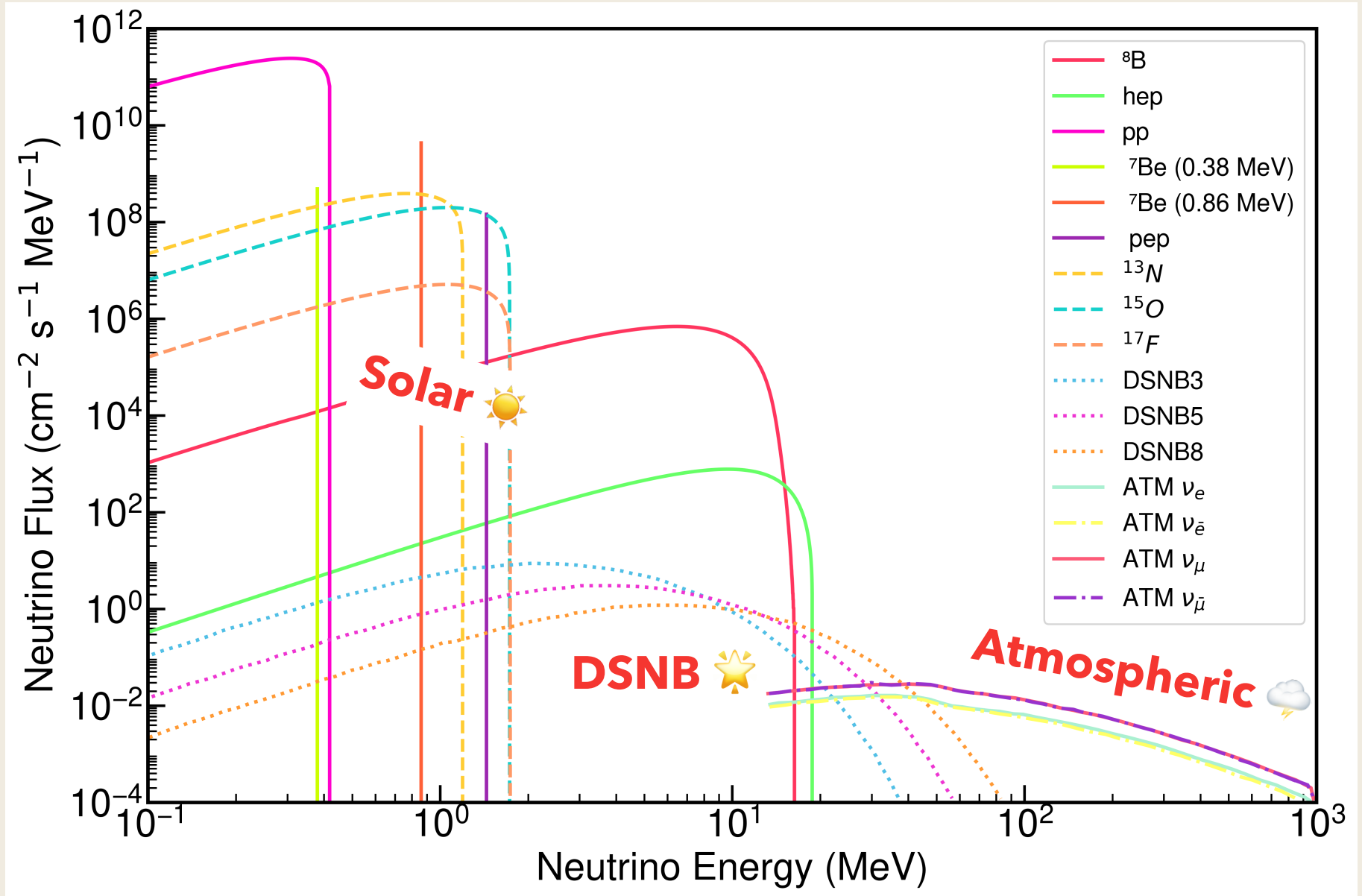


Image credit: COHERENT Collaboration.



Neutrino Background



Neutrino Background

$$N_{\nu}^i(\Phi) = \int_{E_i}^{E_{i+1}} \frac{dR_{\nu}}{dE_r} dE_r$$

Number of neutrino events \mathbf{N}_{ν} is calculated through the differential event rate per recoil energy:

$$\frac{dR_{\nu}}{dE_r} = \epsilon \frac{N_A}{m_N} \int_{E_{\nu, \min}}^{E_{\nu, \max}} \frac{d\Phi}{dE_{\nu}} \frac{d\sigma}{dE_r} dE_{\nu}$$

Neutrino fluxes

CEvNS differential cross-section:

$$\frac{d\sigma}{dE_r}(E_r, E_{\nu}) = \frac{G_F^2 m_N}{2\pi} Q_W^2 F^2(q) \left(2 - \frac{m_N E_r}{E_{\nu}^2} \right)$$

Vector weak charge:

$$Q_W^2 = (Zg_p^V + Ng_n^V)^2 \quad g_p^V = 1/2 - 2\sin^2\theta_W \quad g_n^V = -1/2$$

Form factor (KN):

$$F_{KN}(q) = 3 \frac{j_1(qR_A)}{qR_A} [1 + (qa_k)^2]^{-1}$$

Profile Likelihood Ratio Test

Billard, et. al. (2012, 2014)

- Binned Likelihood function ($N_{\text{bin}} = 150$):

$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \Theta) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(N_{\text{obs}}^i | N_{\text{exp}}^i) \prod_{j=1}^{n_\nu} \mathcal{G}(\phi^j) \quad \mathcal{P}(N_{\text{obs}} | N_{\text{exp}}) = \frac{(N_{\text{exp}})^{N_{\text{obs}}} e^{-N_{\text{exp}}}}{N_{\text{obs}}!}$$

- Compare two hypothesis:

Background

$$H_0 : \quad N_{\text{obs}}^i = N_\nu^i + N_\chi^i, \quad N_{\text{exp}} = N_\nu^i,$$

Background + Signal

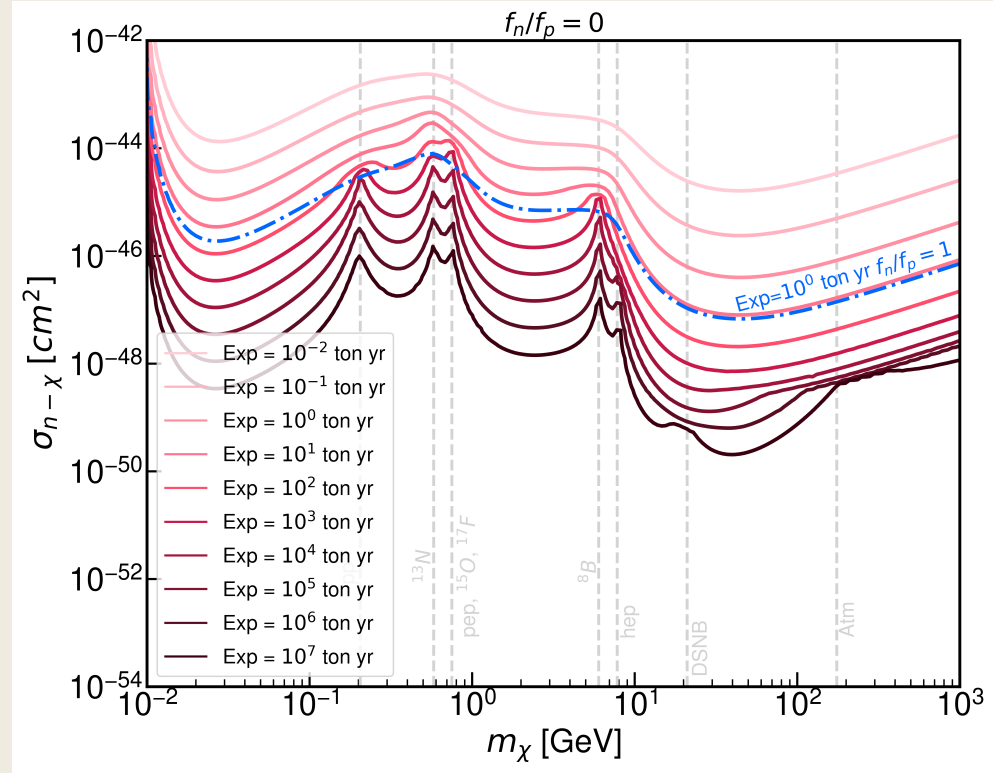
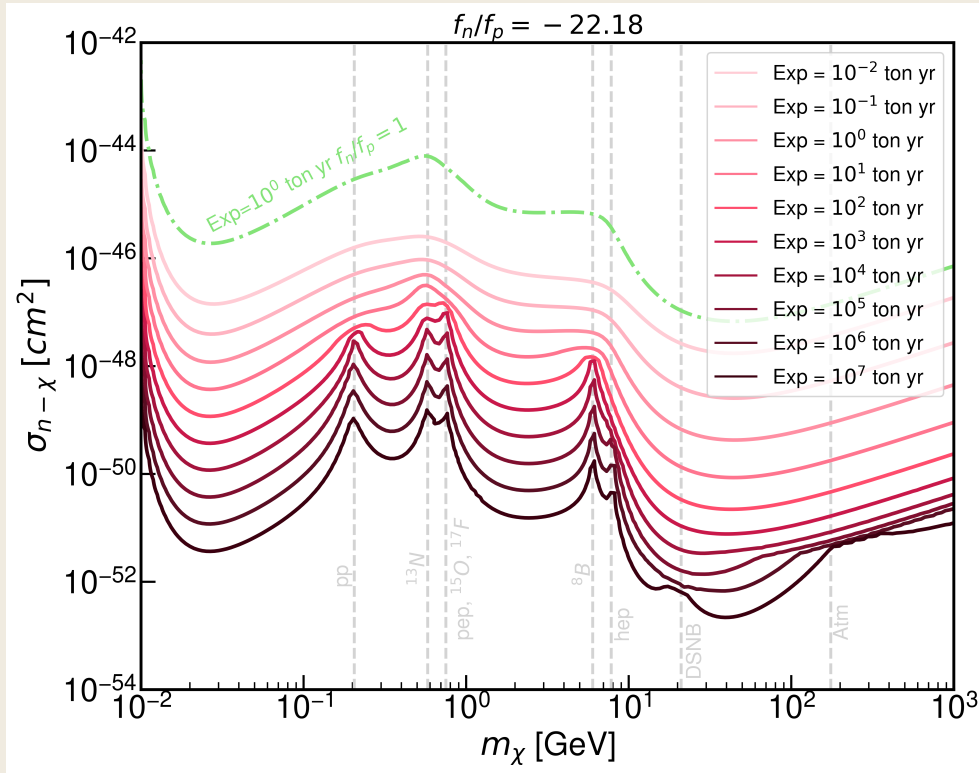
$$H_1 : \quad N_{\text{obs}}^i = N_\nu^i + N_\chi^i, \quad N_{\text{exp}} = N_\nu^i + N_\chi^i.$$

- Ratio Test q_0 :

$$q_0 = \begin{cases} -2 \log \lambda(0), & \hat{\sigma}_{\chi-n} > 0 \\ 0, & \hat{\sigma}_{\chi-n} \leq 0 \end{cases} \quad \lambda(0) = \frac{L_0(m_\chi, \sigma_{\chi-n} = 0, \hat{\Phi})}{L_1(m_\chi, \hat{\sigma}_{\chi-n}, \hat{\Phi})}$$

- From Wilk's theorem, q_0^{obs} asymptotically follows an 1D χ^2 dist. Then, $Z = \sqrt{q_0^{\text{obs}}}$.

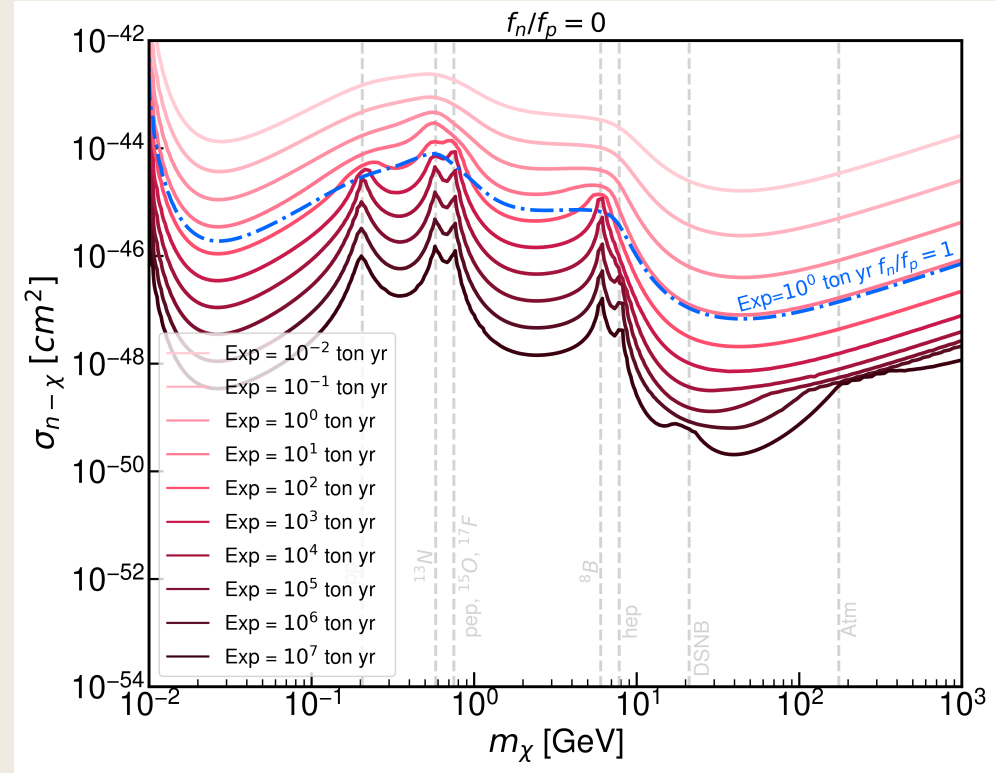
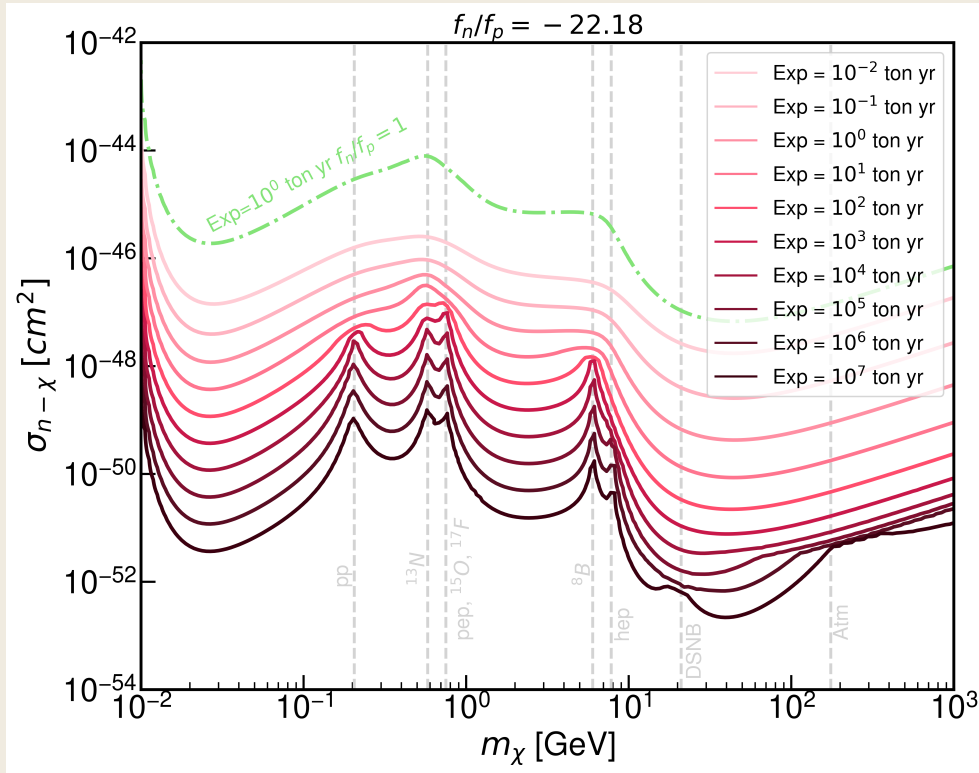
The Neutrino Fog



The neutrino fog is defined as a Discovery Limit

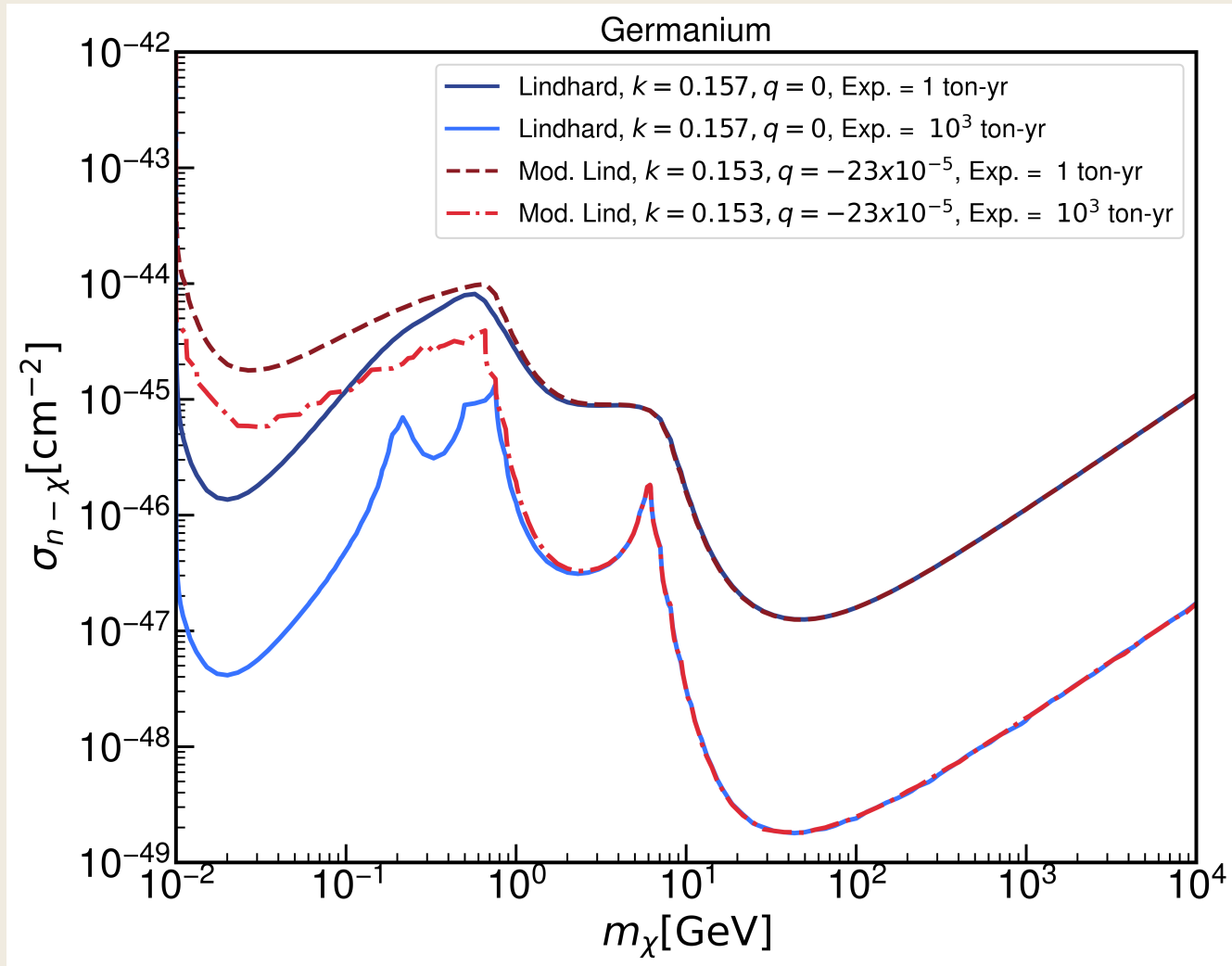
Minimum cross-section $\sigma_{n-\chi}$ for which a 3σ discovery of a WIMP is possible in 90% of hypothetical experiments.

The Neutrino Fog



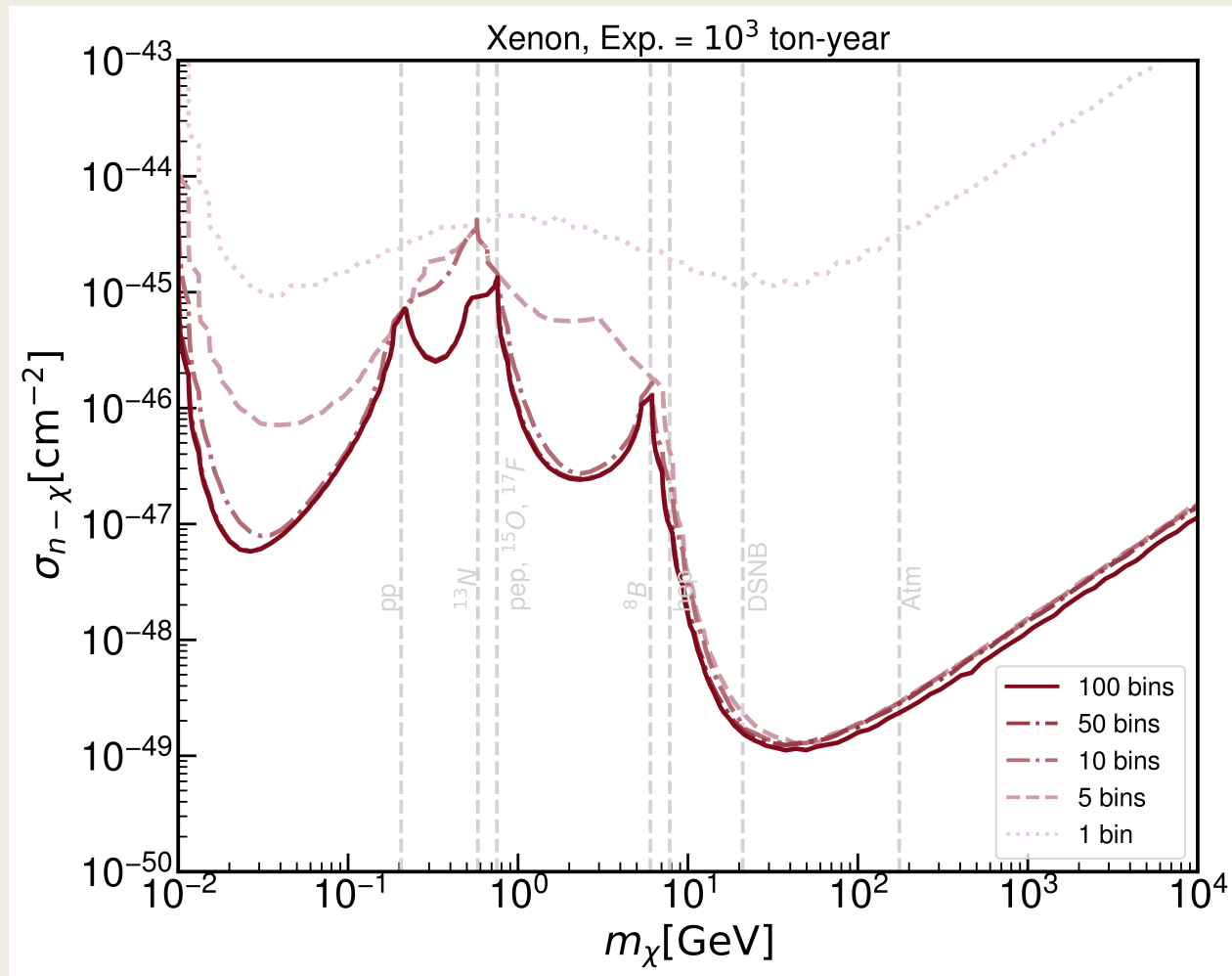
The neutrino fog is not a hard limit, it rather depends on the uncertainties of the parameters (neutrino, DM), E_{th} , exposure ϵ , among others.

The Neutrino Fog



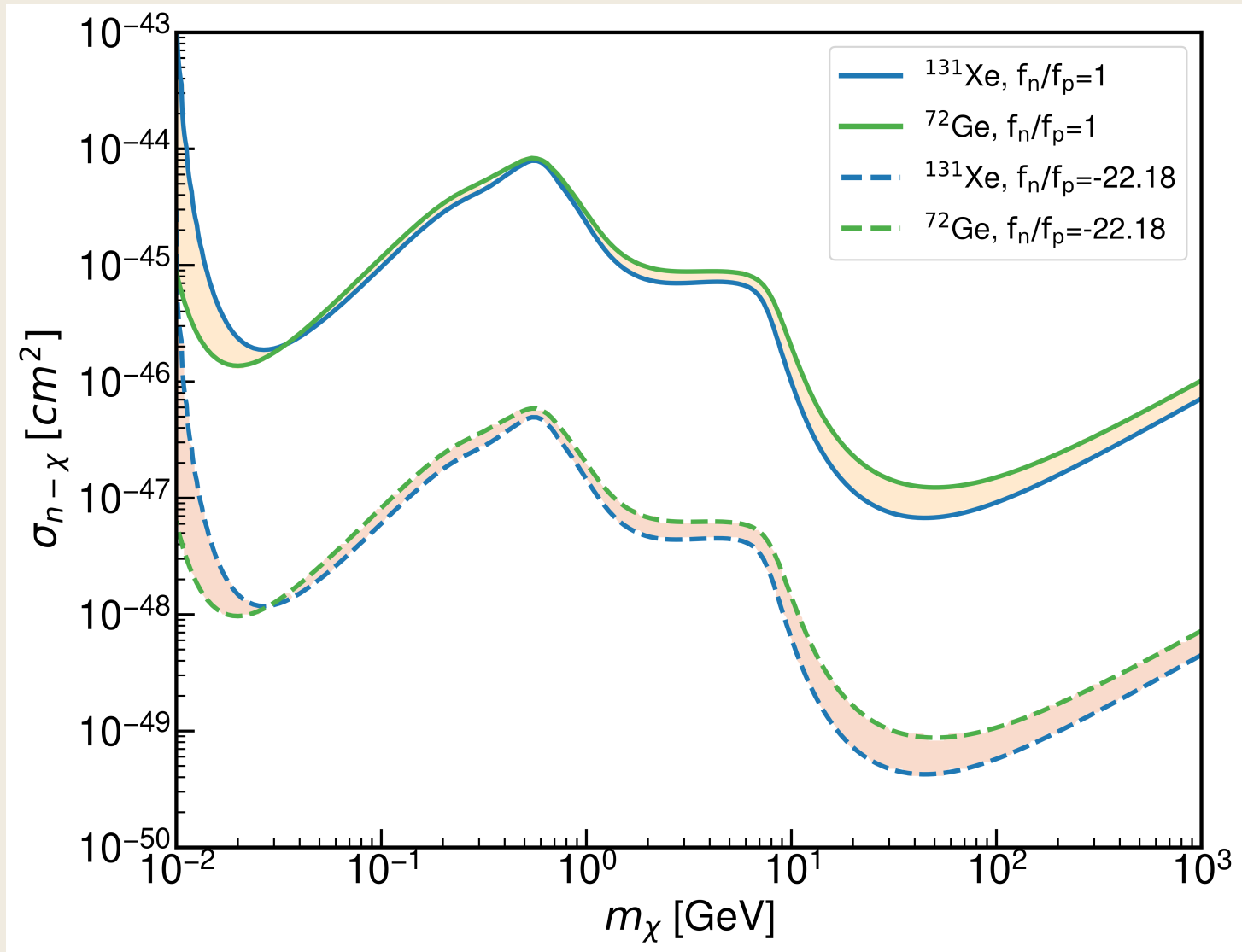
The neutrino fog and systematics: Impact of the Migdal effect at low DM masses

The Neutrino Fog



The neutrino fog and systematics: Impact of the binning

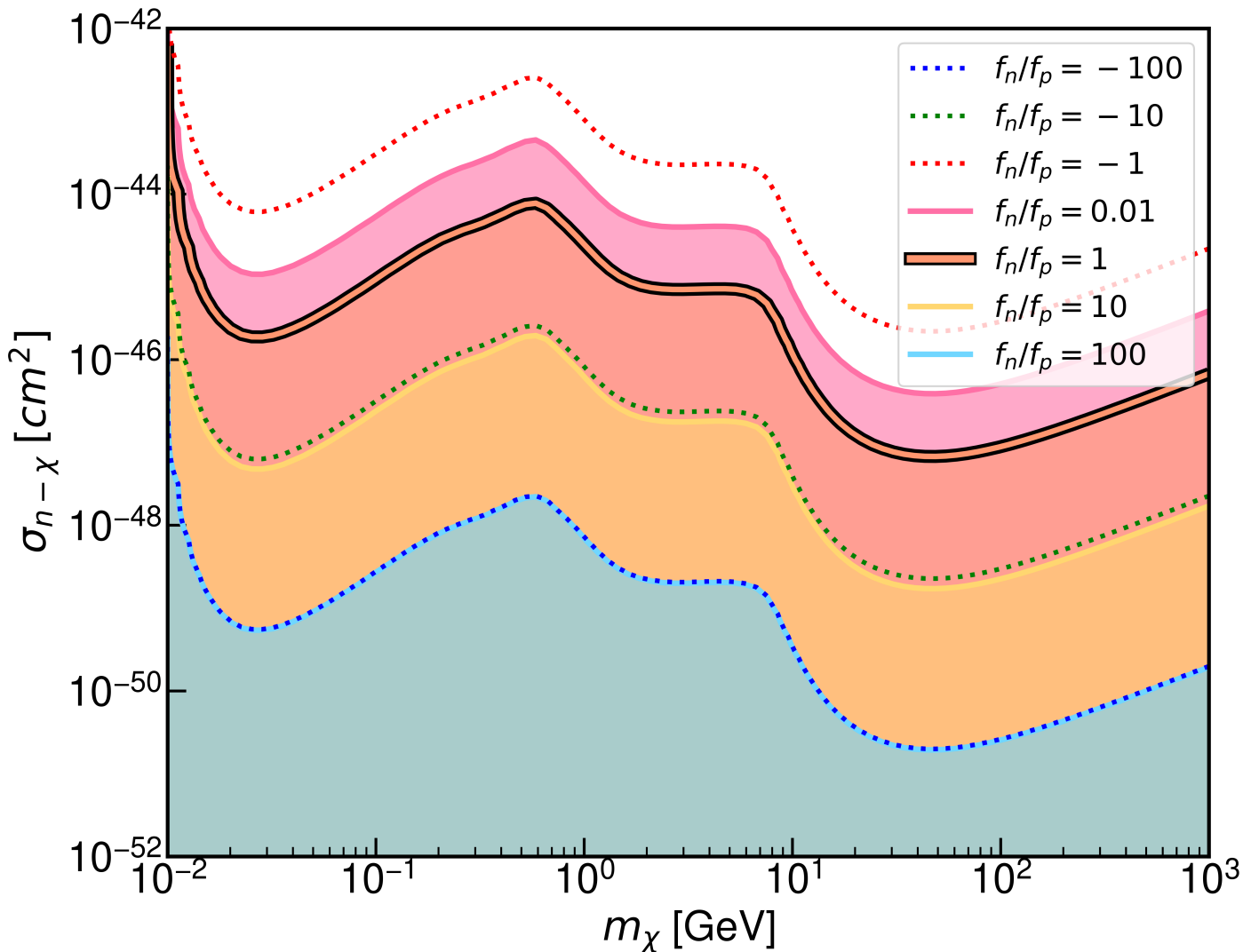
The Neutrino Fog



The neutrino fog: Impact of the detector material

IVDM & the Neutrino Fog

Xenon type experiment, Exposure: 1 ton-year



When the DM has not the same coupling to *protons* f_p and *neutrons* f_n (Isospin-violating), the SI cross section is:

$$\sigma_0 = \frac{4\mu^2}{\pi} \left[Zf_p + (A - Z)f_n \right]^2$$

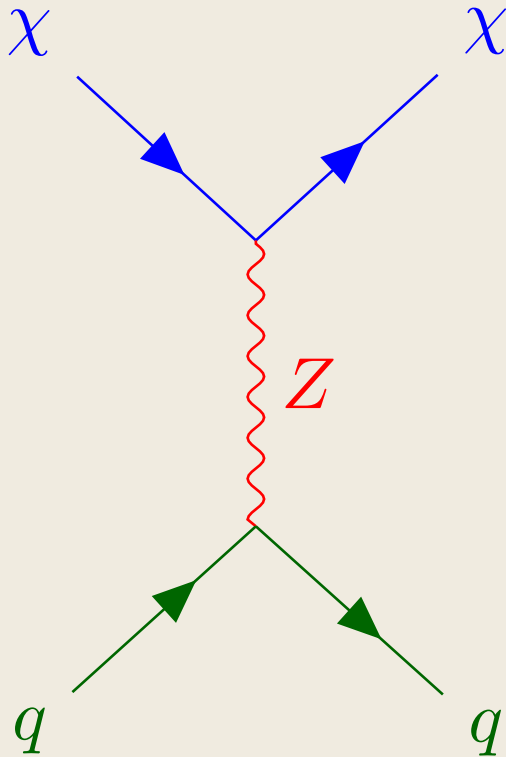
And the neutrino fog suppression (or enhancement) depends on the ratio:

$$f_n/f_p.$$

IVDM: Z portal DM

see e.g. G. Arcadi, et. al. *JCAP03(2015)018*

- A minimal SM extension where the Z boson couples to a DM fermion χ (Z_2 odd).



- The effective lagrangian

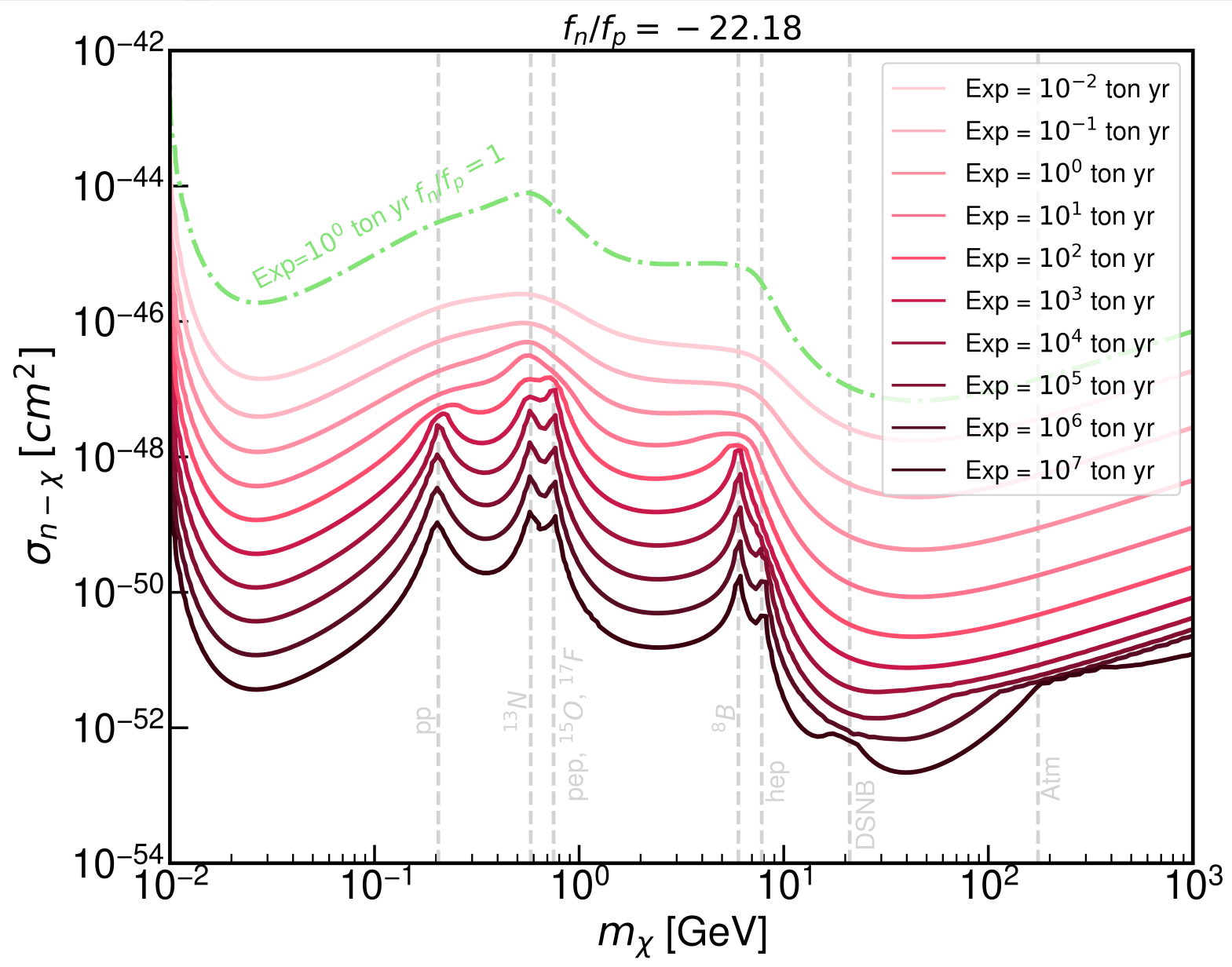
$$\mathcal{L} = \frac{g}{4 \cos \theta_W} \left(\bar{\chi} \gamma^\mu \left(V_\chi - A_\chi \gamma^5 \right) \chi Z_\mu + \bar{f} \gamma^\mu \left(V_f - A_f \gamma^5 \right) f Z_\mu \right)$$

- At tree level, the ratio

$$\frac{f_n}{f_p} = \frac{2g_d + g_u}{g_d + 2g_u} = -\frac{1}{1 - 4 \sin^2 \theta_W} \approx -22.18,$$

taking the low energy weak mixing angle $\sin^2 \theta_W \sim 0.23873$ [*PDG-2024*].

IVDM: Z portal DM



Concluding remarks

- Currently some Dark Matter direct detection experiments have increased their sensitivity (Xenon & PandaX) reaching the astrophysical neutrino background (^8B and **hep** neutrinos) neutrino fog.
- The neutrino fog is not a hard limit, it can be overcome with more statistics.
- The neutrino fog also depends on the systematic uncertainties of the neutrinos and DM, e.g. **neutrino flux normalisation**, energy resolution **energy calibration**, among others.
- Certain IVDM models can modify the neutrino fog, e.g. in the case of a model where $|\mathbf{f}_n/\mathbf{f}_p| > 1$, this limit **decreases, enhancing** the **parameter space** where the models have a clear detection signal.

Thank you for your attention

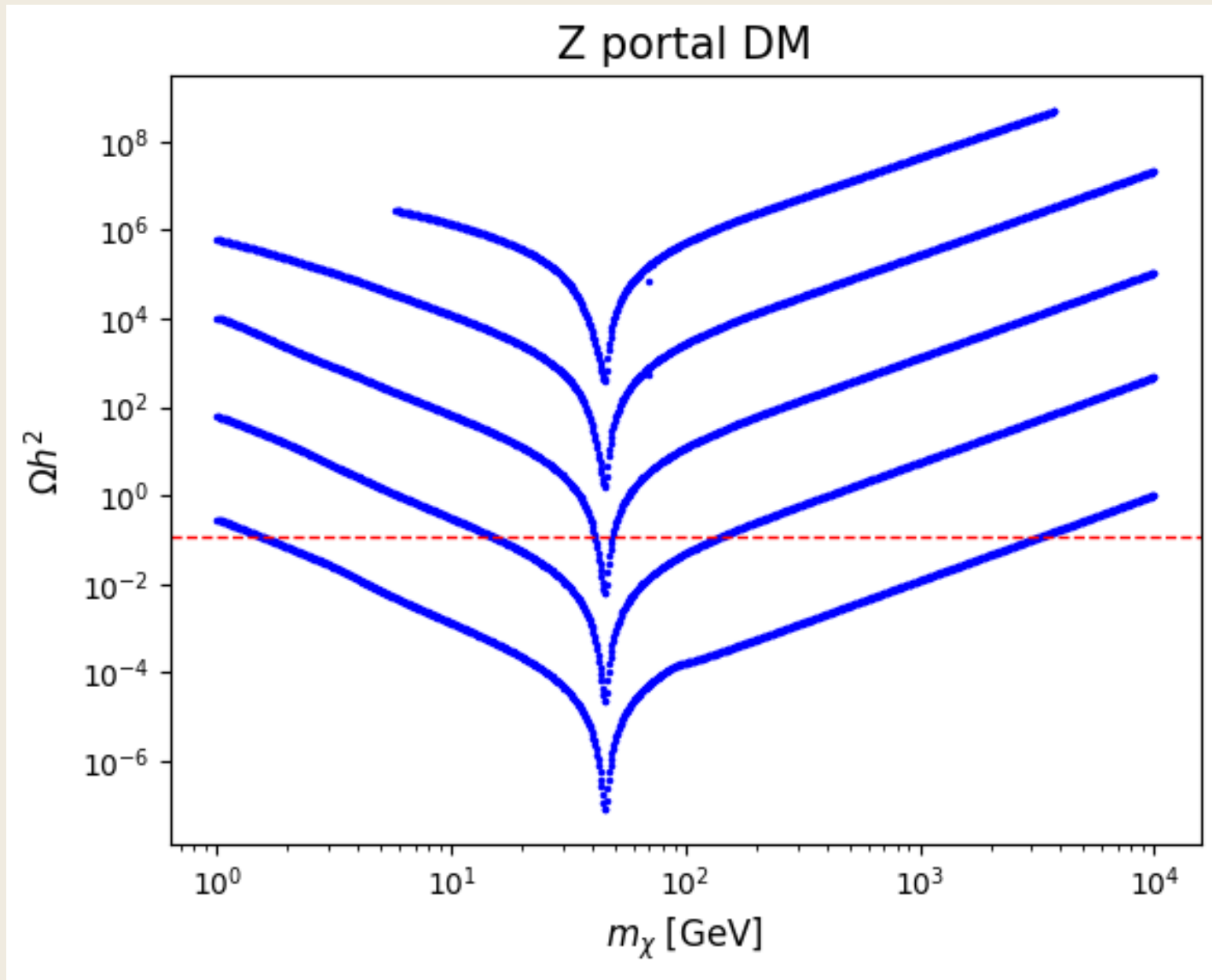


Backup Slides

Neutrino Fluxes

	Normalization Factor	Unc.		Normalization Factor	Unc.
pp	5.98×10^{10}	0.6%	^{13}N	2.78×10^8	15%
pep	1.44×10^8	1%	^{15}O	2.05×10^8	17%
^7Be (0.861 MeV)	4.35×10^9	3%	^{17}F	5.29×10^6	20%
^7Be (0.383 MeV)	4.84×10^8	3%	DSNB	86	50%
^8B	5.25×10^6	4%	Atm	10.5	20%
hep	7.98×10^3	30%			

DM abundance



Branching ratio $Z \rightarrow \text{DM DM}$

