Isospin Violating Dark Matter and the Neutrino Fog

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Cinvestav

work in progress

In collaboration with:

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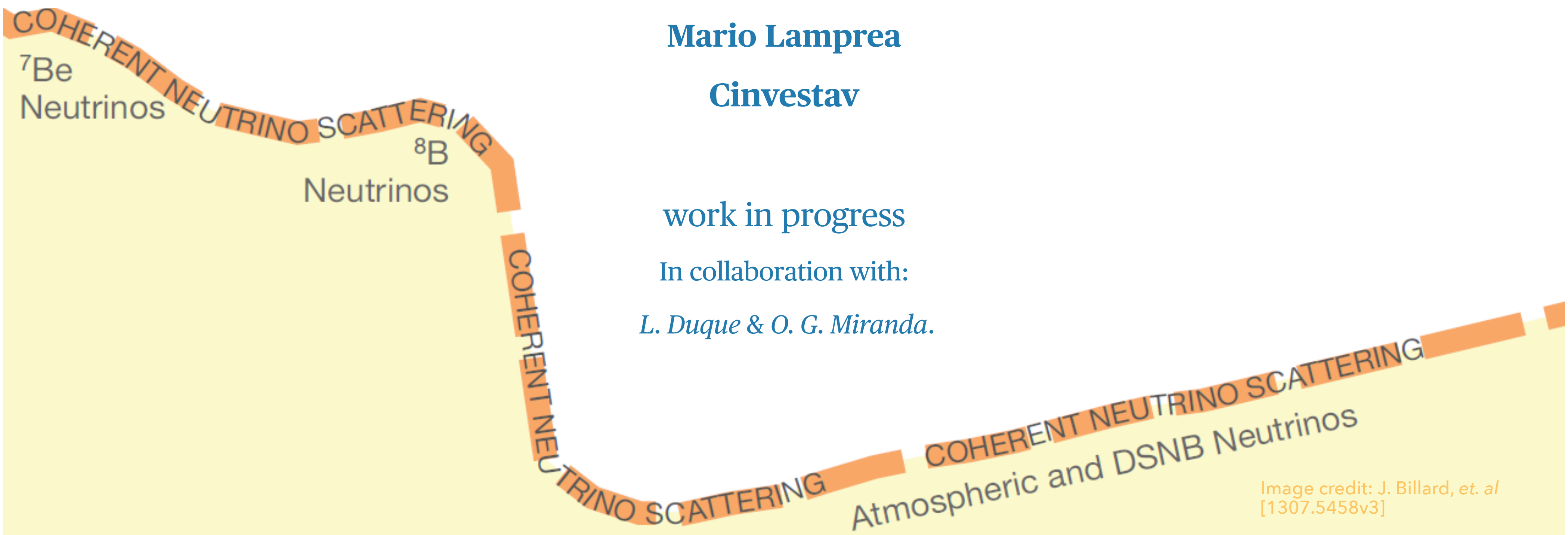


SM and Beyond

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w} M \phi^0 \phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

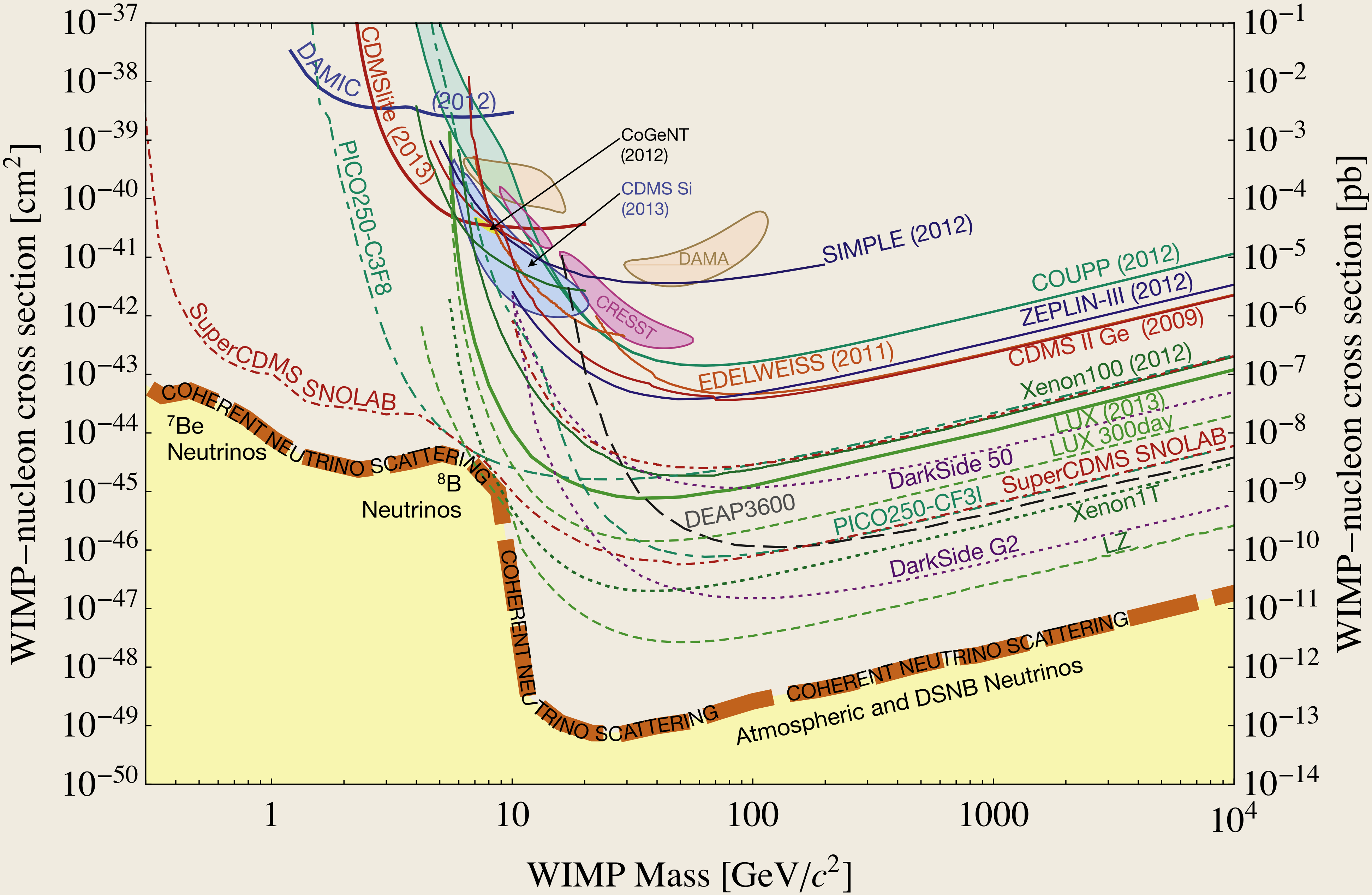
$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

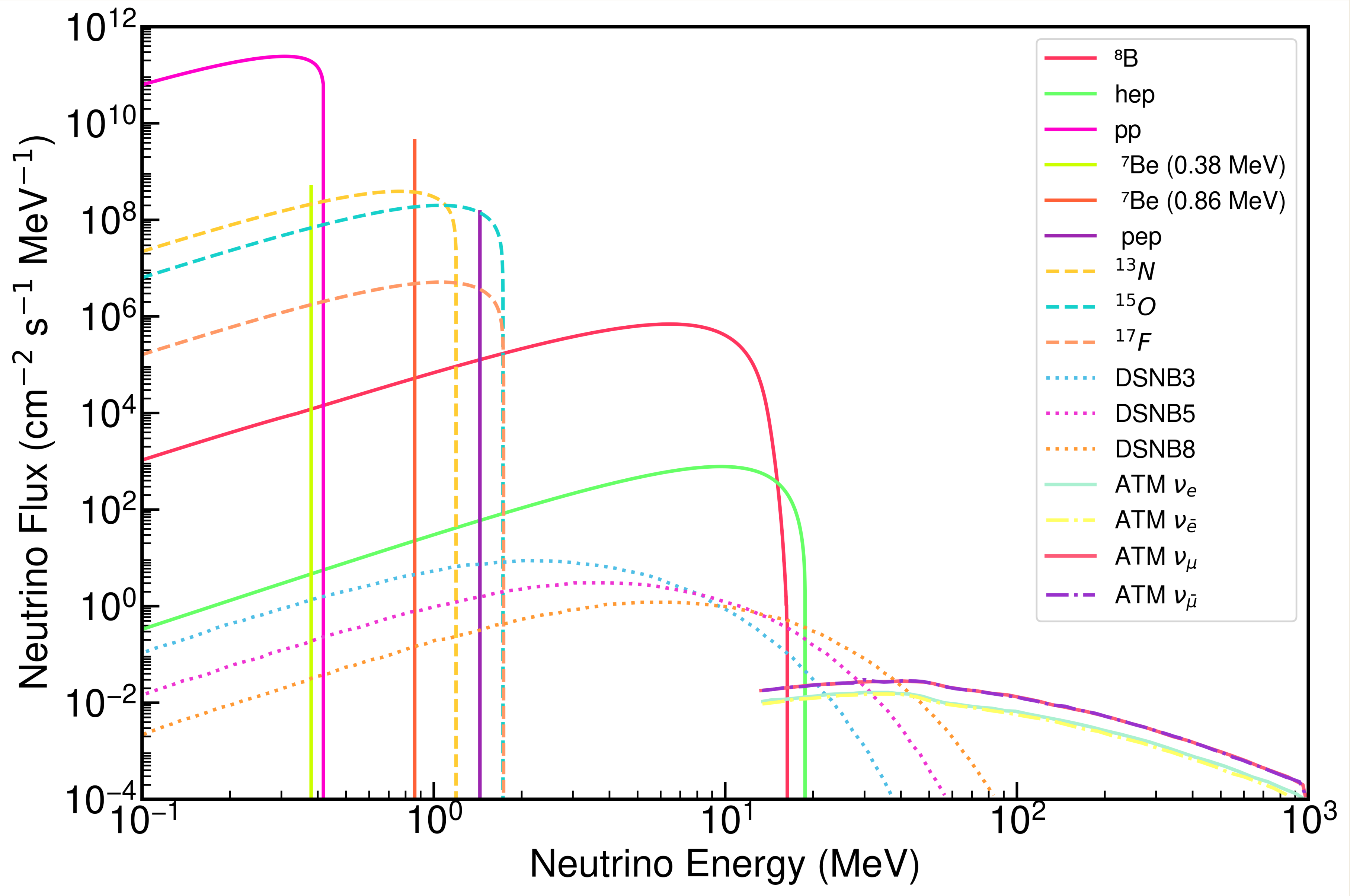
$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Image credit: Yvonne Tang, SLAC National Accelerator Laboratory

J.Billard,L.Strigari,E.Figueroa-Feliciano [1307.5458]



Neutrino Backgrouds



DM Signal

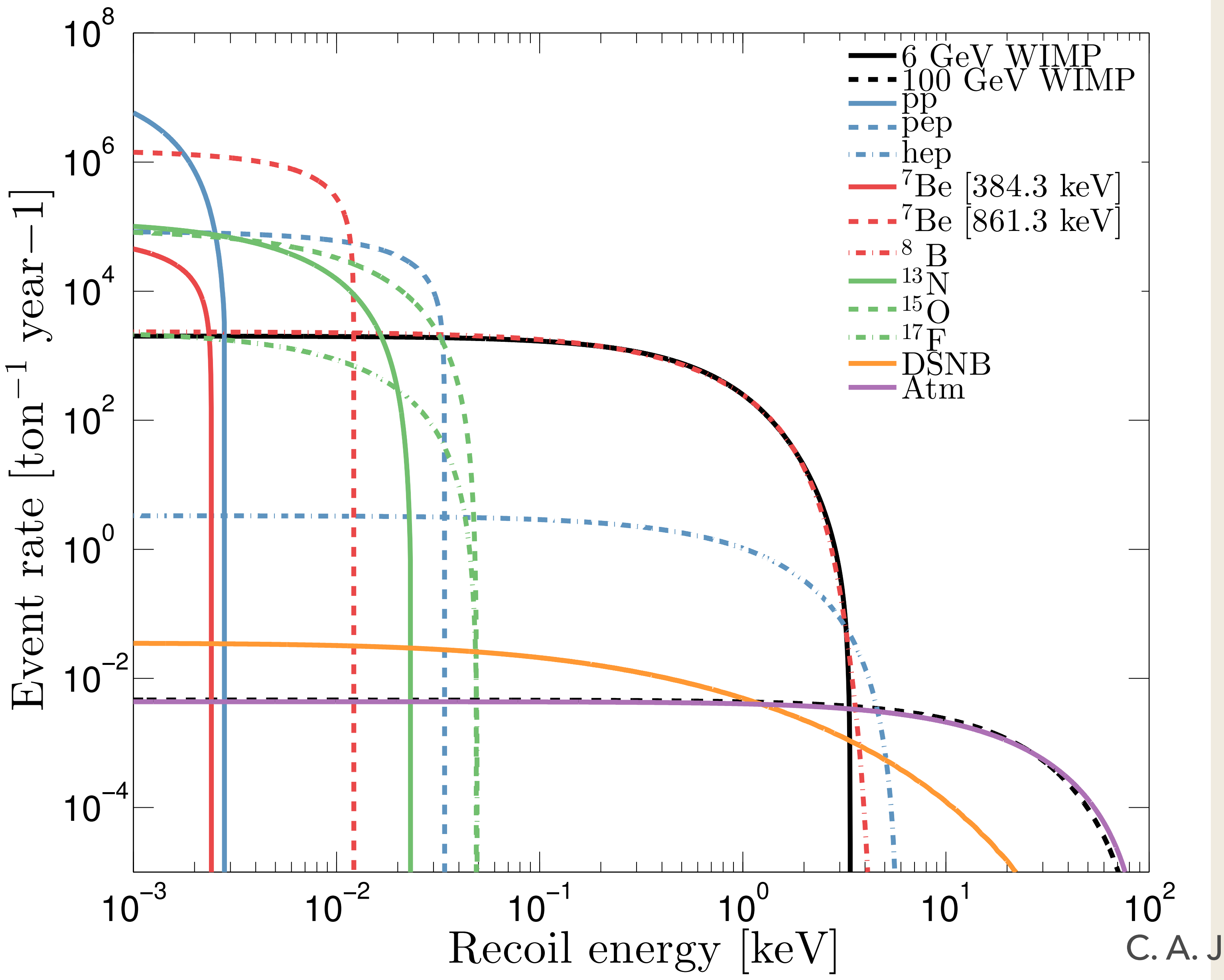
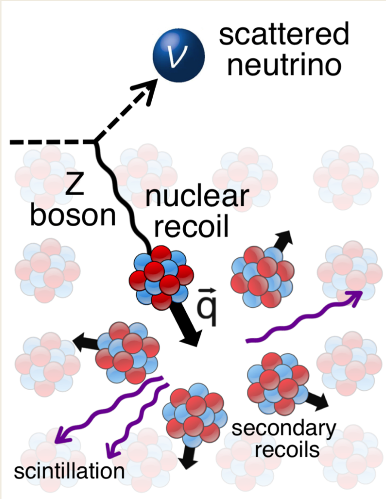


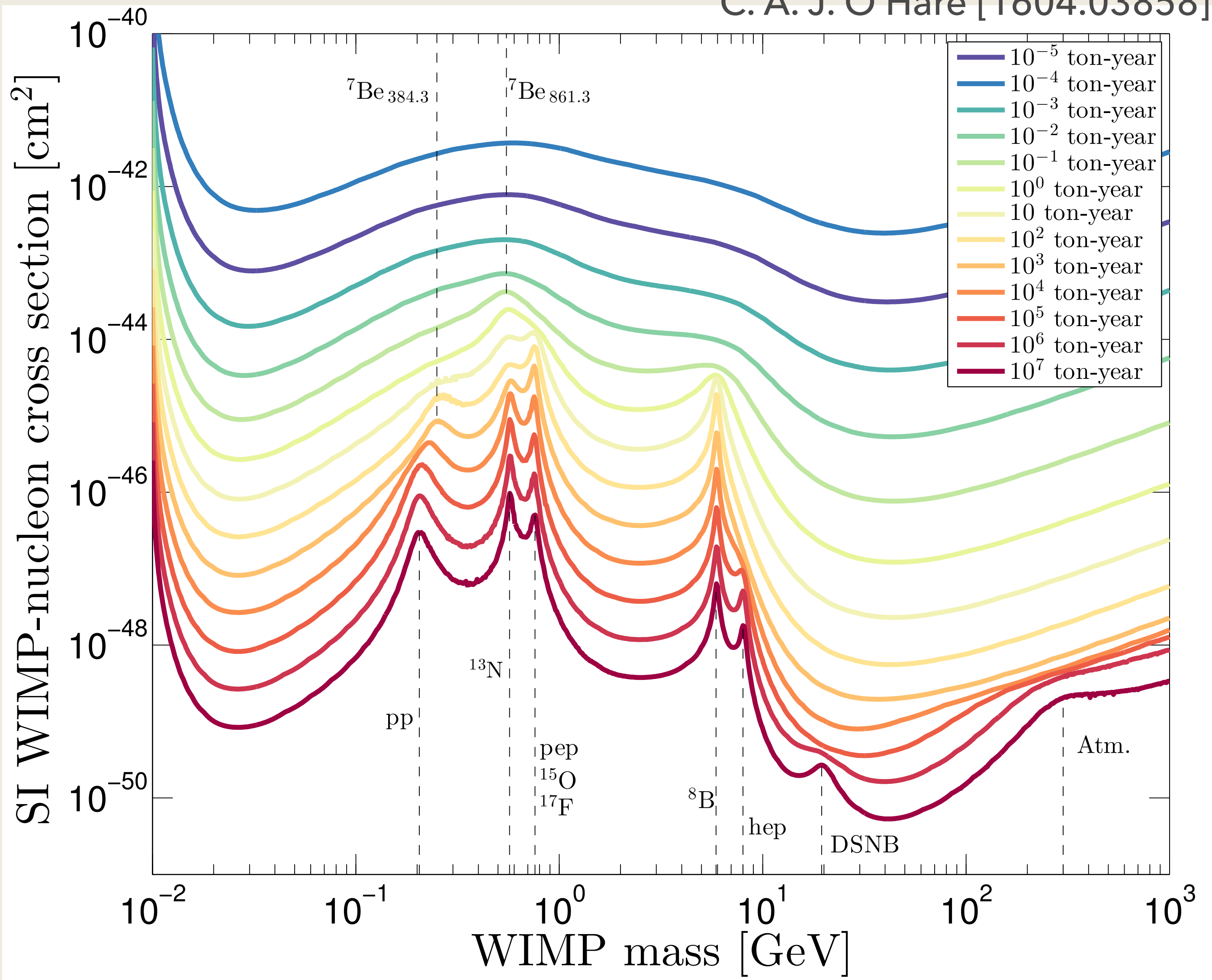
Image credit: COHERENT Collaboration.



C. A. J. O'Hare [1604.03858]

Neutrino 'Fog'

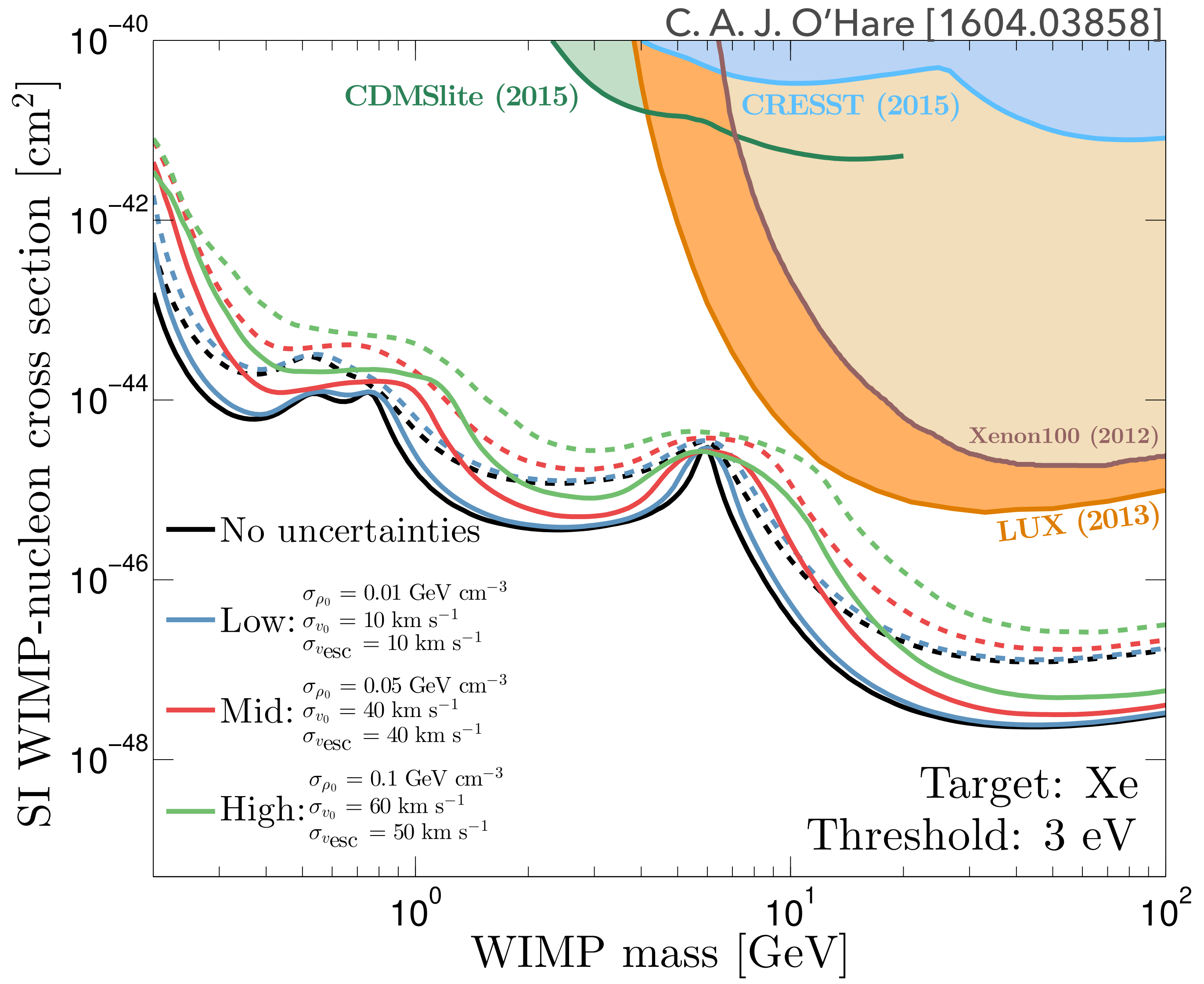
C. A. J. O'Hare [1604.03858]



Discovery Limits

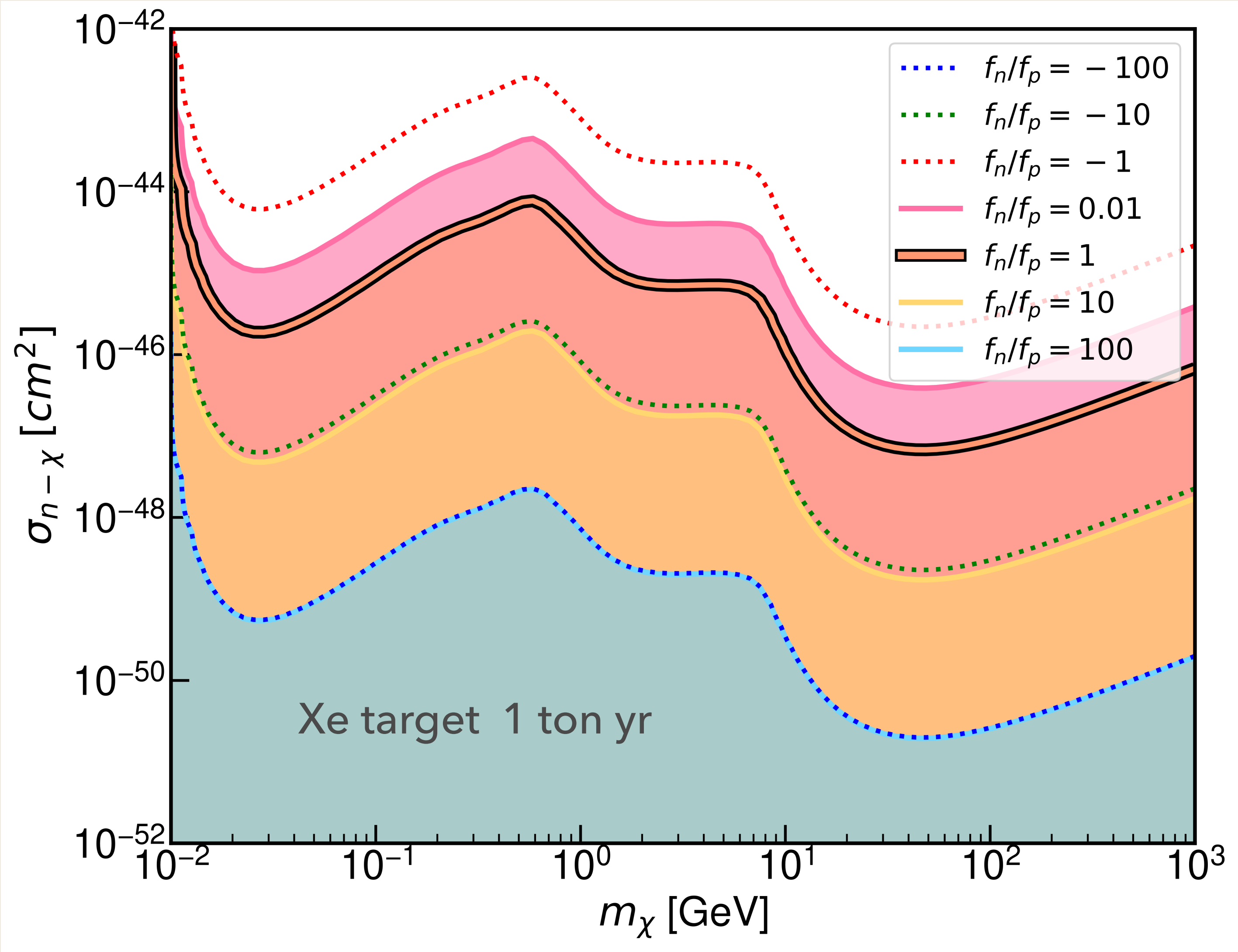
The minimum cross section for which a *3σ* discovery of a WIMP is possible in *90%* of hypothetical experiments.

Neutrino 'Fog'



This is not a solid limit, It rather depends on the uncertainties of the parameters (mainly neutrino fluxes), E_{th} and exposure ϵ.

Isospin Violating DM



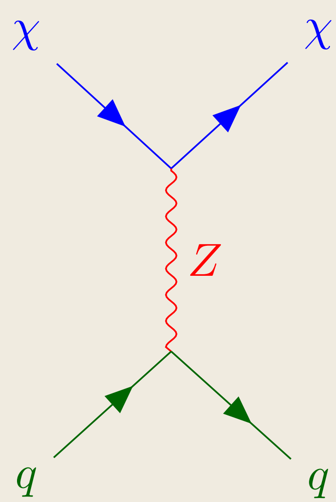
$$\sigma_0 = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

- DM has not the same SI coupling to *protons* f_p and *neutrons* f_n, the neutrino fog is depends on the ratio

f_n/f_p.

Z portal DM

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



- Simple SM extension where the Z boson couples to a DM fermion χ (dark sector).

- The lagrangian

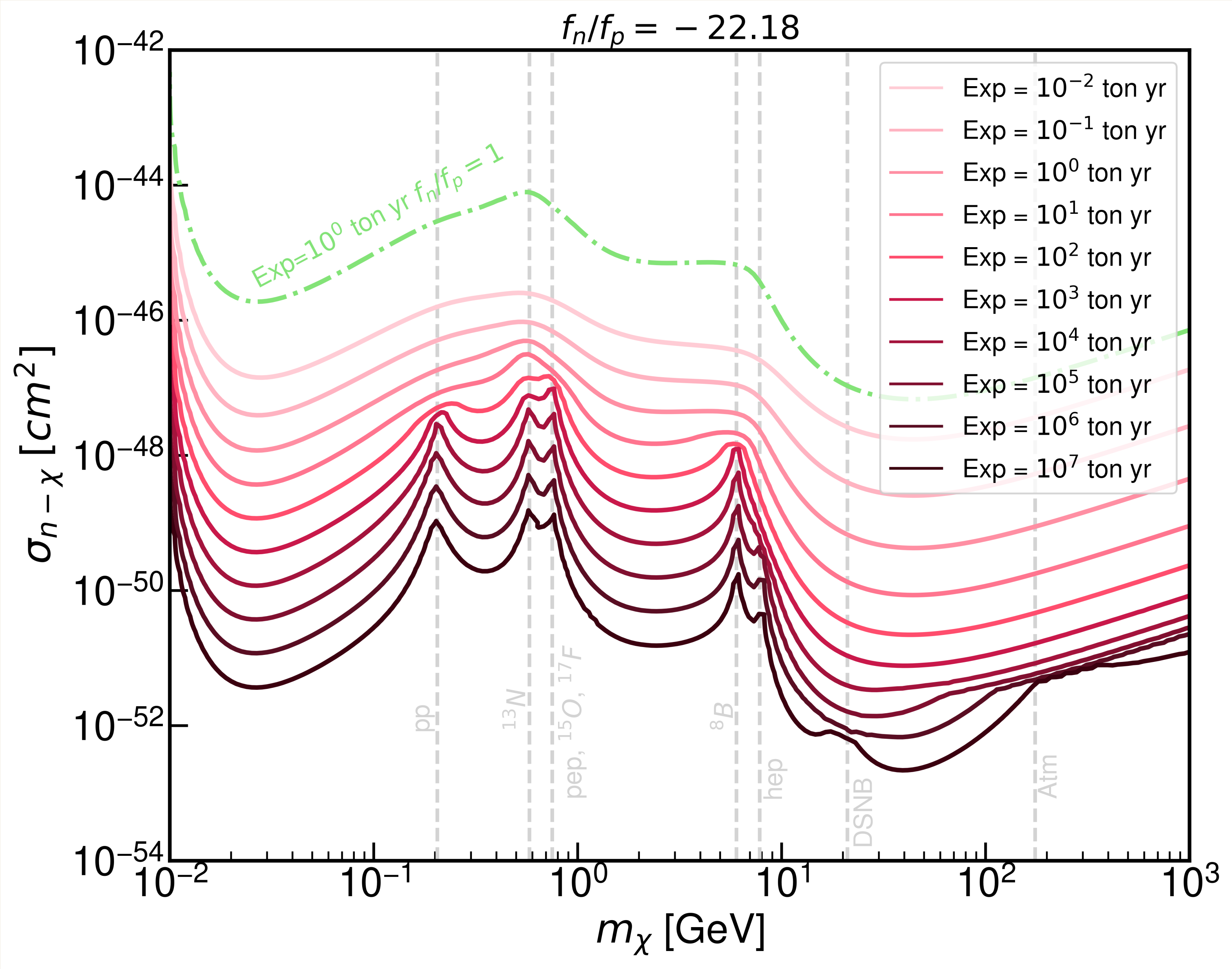
$$\mathscr{L} = \frac{g}{4\cos\theta_W}\left(\bar{\chi}\,\gamma^\mu\left(V_\chi - A_\chi\gamma^5\right)\chi\, Z_\mu + \bar{f}\,\gamma^\mu\left(V_f - A_f\gamma^5\right) f\, Z_\mu\right)$$

- At tree level, the ratio

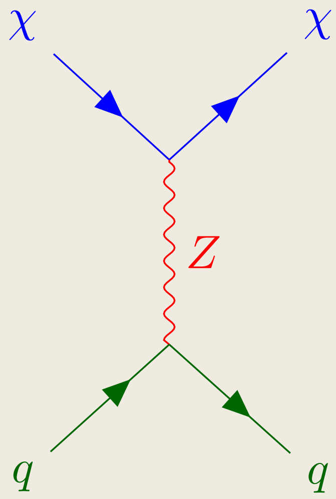
$$\frac{f_n}{f_p} = \frac{2g_d + g_u}{g_d + 2g_u} = -\frac{1}{1 - 4\sin\theta_W^2} \approx -22.18,$$

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

Z portal DM

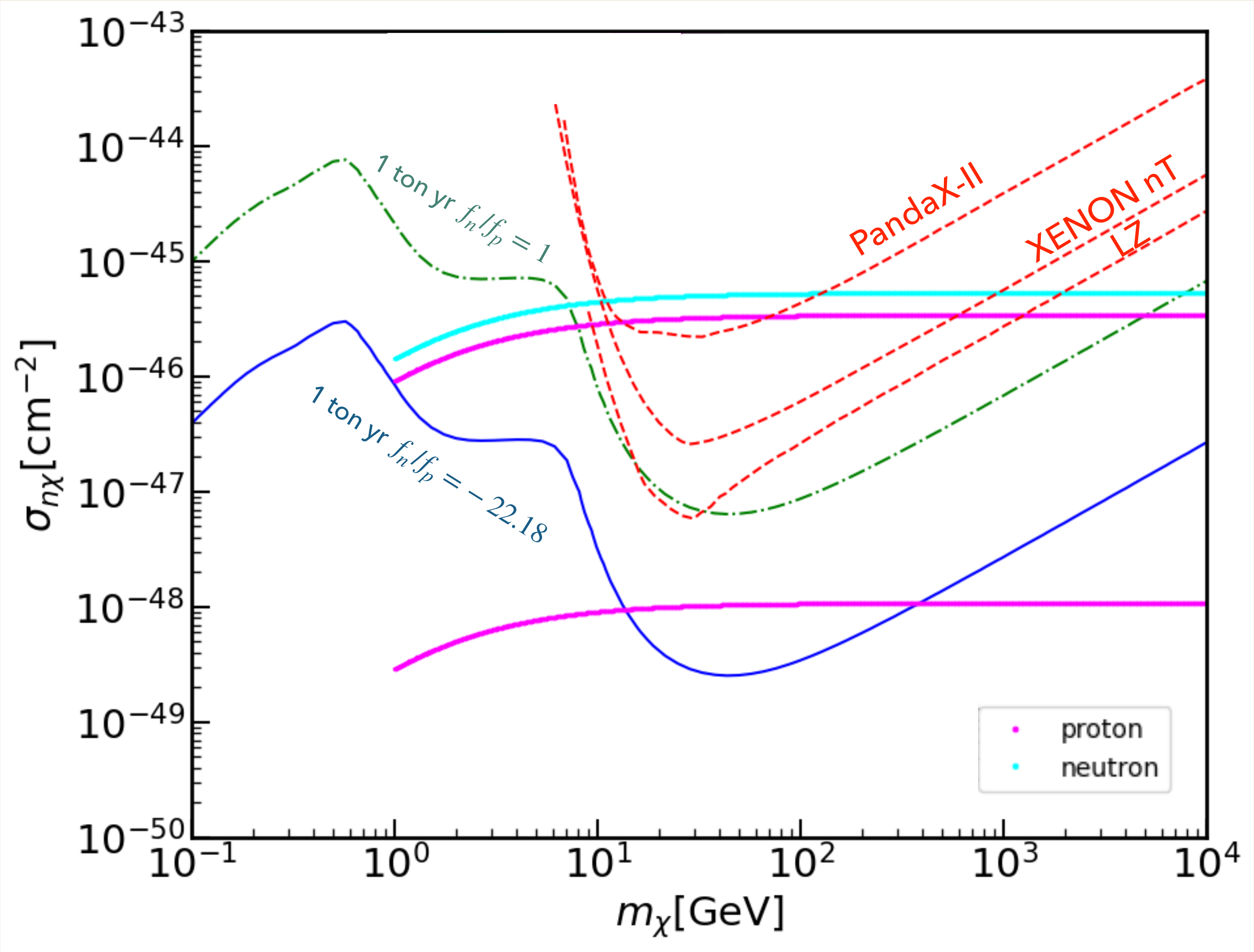


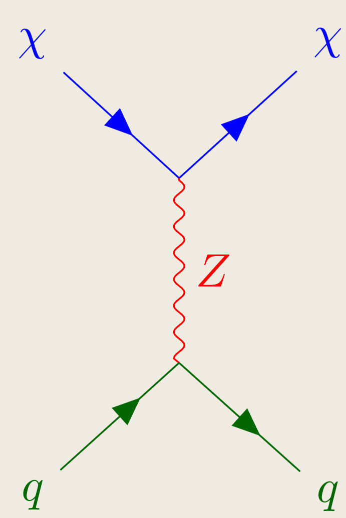
$f_n/f_p = -22.18$
Exp = 10^{-2} ton yr
Exp = 10^{-1} ton yr
Exp = 10^{0} ton yr
Exp = 10^{1} ton yr
Exp = 10^{2} ton yr
Exp = 10^{3} ton yr
Exp = 10^{4} ton yr
Exp = 10^{5} ton yr
Exp = 10^{6} ton yr
Exp = 10^{7} ton yr
Exp=10^0 ton yr $f_n/f_p = 1$
pp
^{13}N
pep, ^{15}O, ^{17}F
^{8}B
hep
DSNB
Atm
$\sigma_{n-\chi}\ [cm^2]$
m_χ [GeV]



χ
χ
Z
q
q

Z portal DM

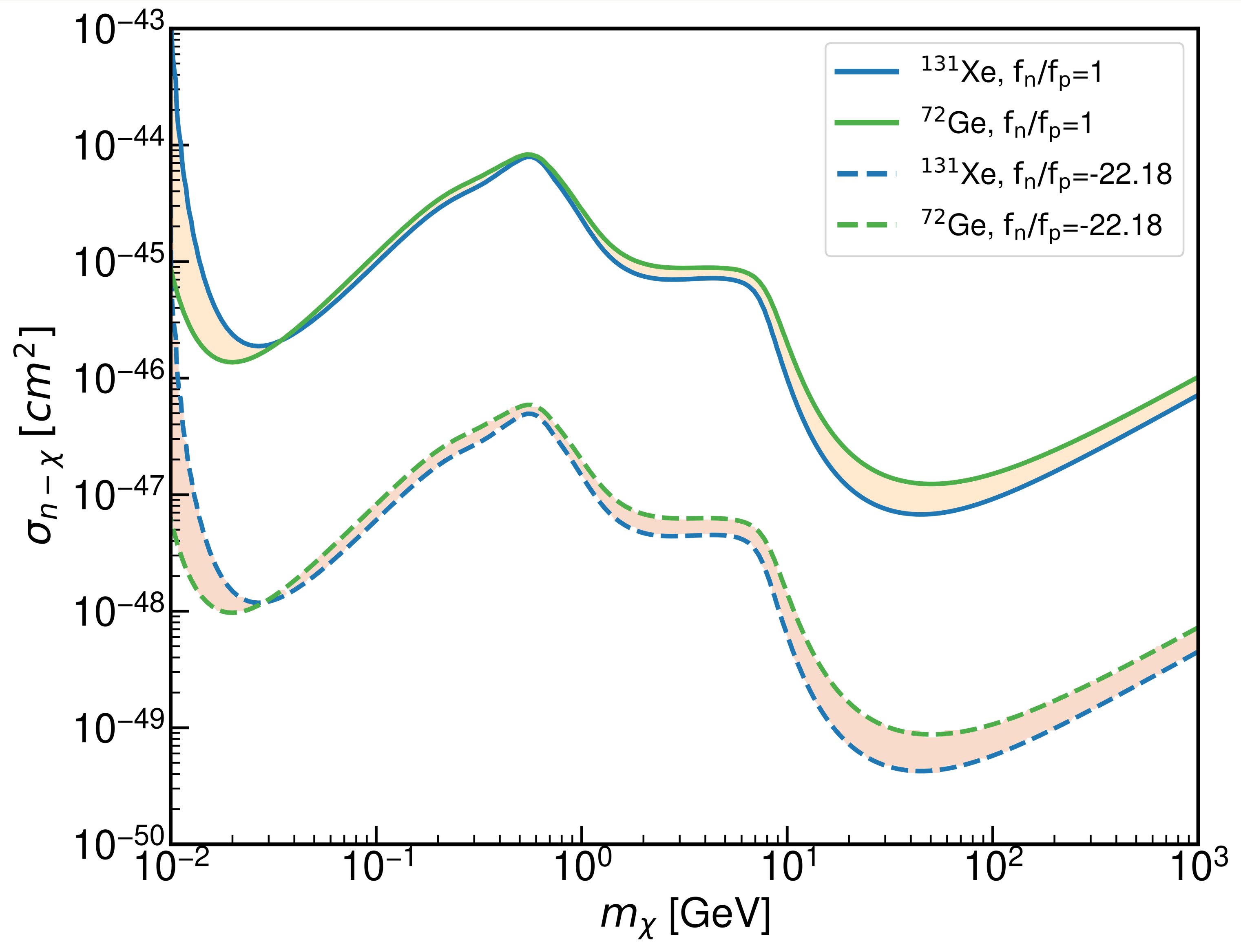




$V_\chi = 10^{-4}$,

$A_\chi = 0.$

Isotopic DM Detectors(?)



Concluding Remarks

- Dark matter direct detection experiments increase their sensitivity reaching the unavoidable neutrino- nucleus coherent background.

- This limit depends on the uncertainties of the neutrino and DM parameters (manly neutrino fluxes), threshold energy & exposure.

- The neutrino floor can be overcome with more statistic -> neutrino ‘fog’.

- Case of IVDM (Z - portal) the neutrino fog can be lowered by one order of magnitude, enhancing the possibility of a signal in this models.

Thank you for your attention.

Backup Slides

Neutrino events

- Differential event rate for CEvNS

Neutrino flux

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

CEvNS diffefential Cross section

$$\frac{d\sigma}{dE_r} = \frac{G_F^2 M}{2\pi} \mathcal{Q}_W^2 F^2(Q^2) \left(2 - \frac{MT}{E_\nu^2}\right)$$

$$\mathcal{Q}_W^2 = \left(Z g_p^V + N g_n^V\right)^2 \qquad g_p^V = 1/2 - 2\sin^2\theta_W \qquad g_n^V = -1/2$$

$$F_{KN} = 3\frac{j_1(QR_A)}{QR_A}\left[1 + (Qa_k)^2\right]^{-1}$$

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%
^{7}Be (0.861 MeV)	4.35×10^{9}	3%	^{17}F	$5.29\times^{6}$	20%
^{7}Be (0.383 MeV)	4.84×10^{8}	3%	DSNB	86	50%
^{8}B	5.25×10^{6}	4%	Atm	10.5	20%
hep	7.98×10^{3}	30%			

DM events

- Differential event rate for DM

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

Astrophysical part

DM Velocity distribution in the Halo

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

$$N_{\rm esc} = erf(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}$$

$$z = v_{esc}/v_0$$

$$v_0 = \sqrt{2/3}\sigma_v.$$

Spin Independent DM-Nucleus Cross section

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

Profile likelihood ratio test

- Likelihood funtion

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

$$\mathcal{P}(N_{obs}|N_{exp}) = \frac{(N_{exp})^{N_{obs}} e^{-N_{exp}}}{N_{obs}!}$$

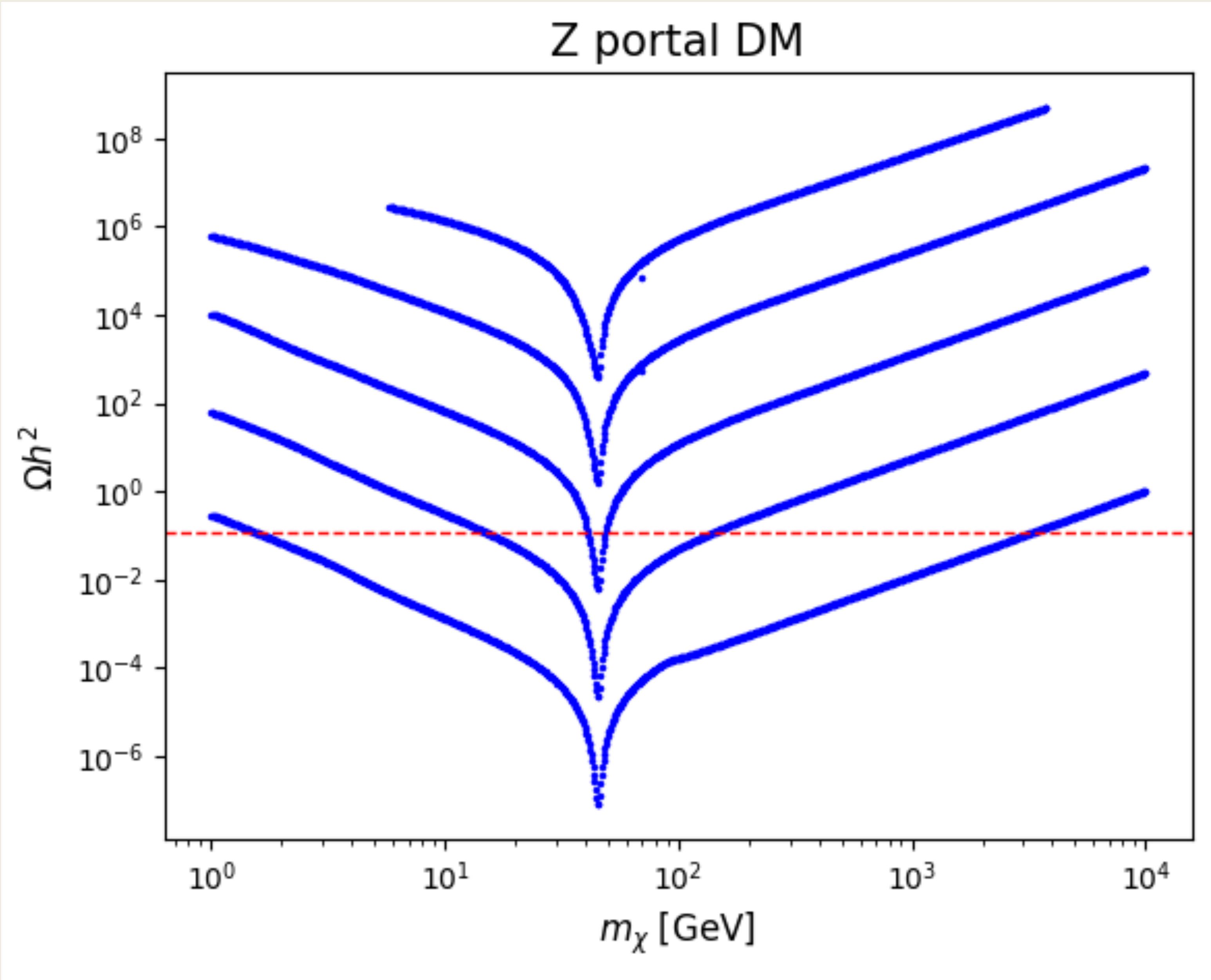
- Ratio test **Background** vs. **Background + WIMP**

$$\lambda(0) = \frac{\mathscr{L}_0}{\mathscr{L}_1} \qquad q_0 = \begin{cases} -2\ln\lambda_0, & \hat{\sigma} > 0 \\ 0, & \hat{\sigma} \leq 0 \end{cases}$$

ν: $\quad \mathscr{L}_0 \quad \rightarrow \quad N_{obs} = N_\nu + N_\chi, \quad N_{exp} = N_\nu$

$\nu + \chi$: $\quad \mathscr{L}_1 \quad \rightarrow \quad N_{obs} = N_\nu + N_\chi, \quad N_{exp} = N_\nu + N_\chi$

DM abundance



Branching ratio
Z -> DM DM