Neutrino Fog and DM Direct Detection: Generalized Mediator Approach with recent XENONnT data

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[Work in Progress]
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Overview of DM

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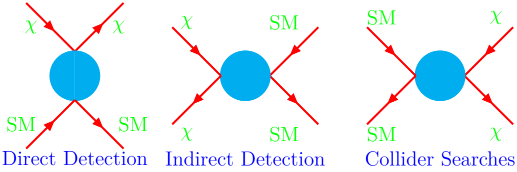
Motivation for searching the Dark Matter (DM)

- Cold DM: It is a non-luminous matter which occupies 27% of the mass and energy in the observable Universe. It does not interact with photons and might interact with ordinary matter "weakly".
- Astronomical and cosmological observations at various scales:
  (i) Rotation curves of spiral galaxies and galaxy clusters
  (ii) Gravitational lensing
  (iii) Cosmic Microwave background (CMB) fluctuations



- **Direct Detection Experiments:** *XENONnT, LUX-ZEPLIN, Super-CDMS, Dark-Side, PandaX-4T, etc.*
- **Indirect Detection Experiment:** *IceCube, HESS, MAGIC, Fermi-LAT, KM3NeT etc.*
- **Accelerator searches:** *ATLAS, CMS at CERN*

DM direct detection

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$$\left[\frac{\mathrm{d}R}{\mathrm{d}T_{\mathcal{N}}}\right]_{\chi\mathcal{N}} = \underbrace{t_{\mathrm{run}} N_{\mathrm{target}}}_{\text{Experimental input}} \int_{v_{\min}}^{v_{\max}} \mathrm{d}^3 v \underbrace{n_\chi f(\mathbf{v})}_{\text{DM halo model}} \; v \underbrace{\frac{\mathrm{d}\sigma_{\chi\mathcal{N}}}{\mathrm{d}T_{\mathcal{N}}}}_{\text{DM particle model}}$$

$$\frac{\mathrm{d}}{\mathrm{d}T_{\mathcal{N}}}\langle \sigma_{\chi\mathcal{N}} v \rangle$$

ν background in direct detection

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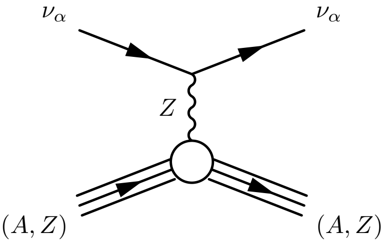
Recently, the XENONnT and PandaX-4T dark matter experiments have reported indications of a solar ^{8}B neutrino–induced CEνNS signal detection, which constitutes an important irreducible background in dark matter searches.

Freedman, 1974; Drukier and Stodolsky, 1984

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathcal{N}}}\right]_{\mathrm{SM}} = \frac{G_F^2 m_{\mathcal{N}}}{\pi}\left[\mathcal{F}_W^2(\mathfrak{q}^2)\,(Q_W^V)^2\left(1 - \frac{m_{\mathcal{N}} T_{\mathcal{N}}}{2E_\nu^2} - \frac{T_{\mathcal{N}}}{E_\nu}\right)\right]$$



Astrophysical neutrinos

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Component	Normalization [cm^{-2} s^{-1}]	Unc.	Component	Normalization [cm^{-2} s^{-1}]	Unc.
^{7}Be (0.38 MeV)	4.84×10^{8}	3%	^{7}Be (0.86 MeV)	4.35×10^{9}	3%
pep	1.44×10^{8}	1%	pp	5.98×10^{10}	0.6%
^{8}B	5.25×10^{6}	4%	hep	7.98×10^{3}	30%
^{13}N	2.78×10^{8}	15%	^{15}O	2.05×10^{8}	17%
^{17}F	5.29×10^{6}	20%	DSNB	86	50%
Atm	10.5	20%			

[Eur.Phys.J.C 81 (2021) 907]

Flux	XENONnT		PandaX-4T	
	Normalization [cm^{-2} s^{-1}]	Unc.	Normalization [cm^{-2} s^{-1}]	Unc.
^{8}B	4.7×10^{6}	37%	8.4×10^{6}	63%

[XENONnT: Phys.Rev.Lett. 133 (2024) 19, 191002; PandaX-4T: Phys.Rev.Lett. 133 (2024) 19, 191001]

Astrophysical neutrinos

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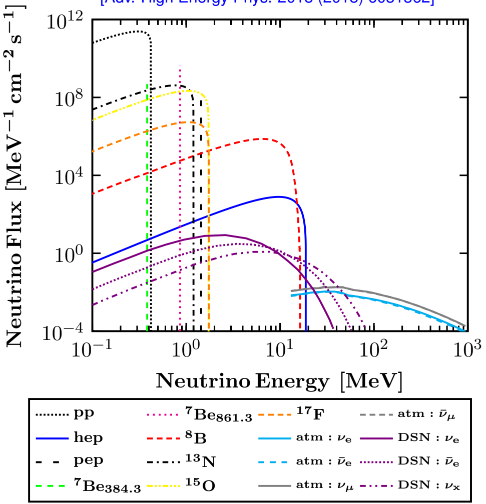
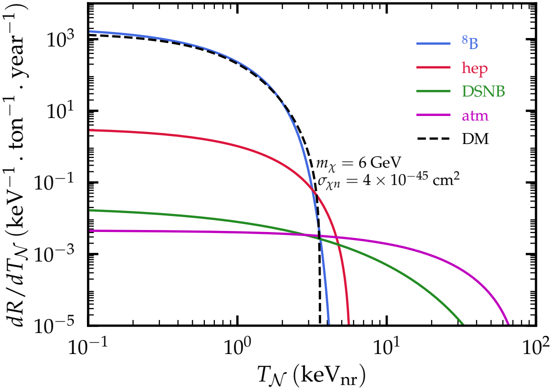
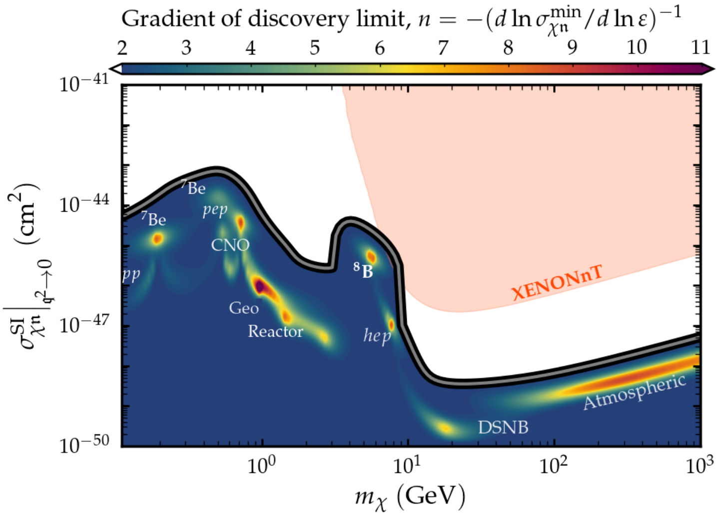
[Adv. High Energy Phys. 2018 (2018) 6031362]





Neutrino Fog



[C. O'Hare, Phys.Rev.Lett. 127 (2021) 25, 251802]

Physics Beyond the Standard Model

Physics Beyond the Standard Model

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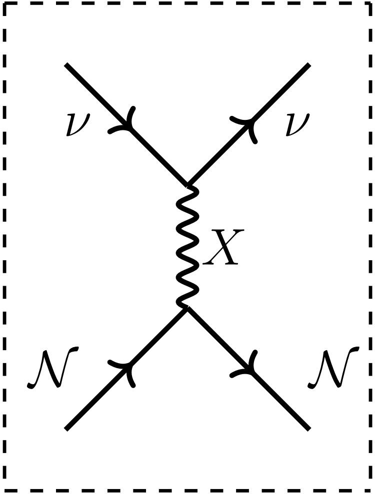
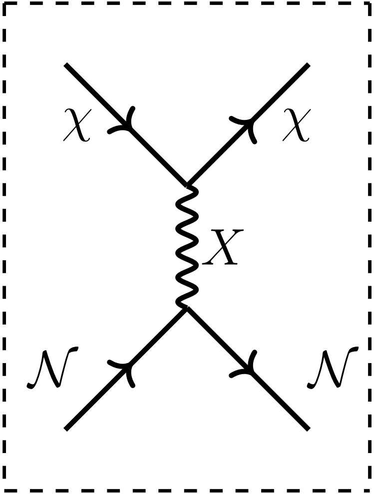


CEνNS



$\chi - \mathcal{N}$

Light new physics in the neutrino sector

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Neutrino Interactions: The framework of generalized neutrino interactions extends the Standard Model by introducing all Lorentz-invariant effective operators up to dimension 6 that couple neutrinos to nucleons. Such operators can be classified as scalar, pseudoscalar, vector, axial-vector, and tensor types.

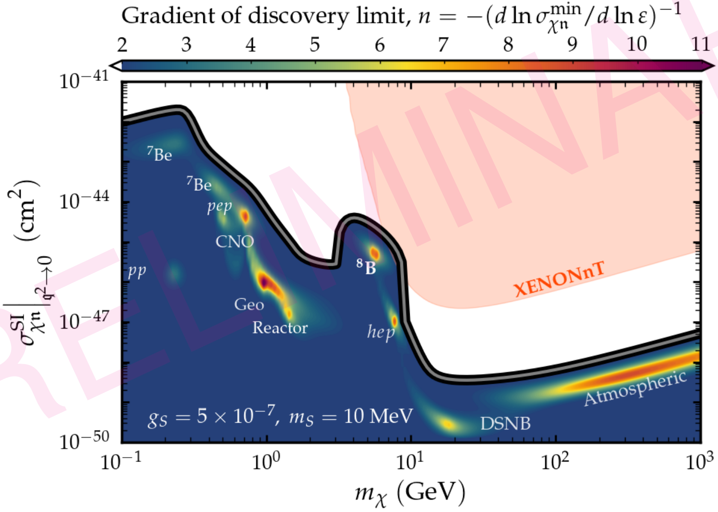
$$\mathscr{L}_{\text{eff}}^{\nu\mathcal{N}} \supset - \sum_{X=S,P,V,A,T} \frac{C_X}{q^2 + M_X^2} \left[\bar{\nu}\, \Gamma^X \nu\right] \left[\bar{\mathcal{N}}\, \Gamma_X \mathcal{N}\right], \qquad \Gamma_X = \left\{\mathbb{I},\, \gamma_5,\, \gamma_\mu,\, \gamma_\mu\gamma_5,\, \sigma_{\mu\nu}\right\}.$$

C_X denote the effective coupling strengths and M_X the corresponding mediator masses.

Dark Matter Interactions: Dark matter couples to nucleons through an effective, contact-type spin-independent interaction. This corresponds to the regime of a heavy mediator that has been integrated out, resulting in a constant cross section in the zero momentum-transfer limit.

Light new physics in the neutrino sector

Scalar Mediator



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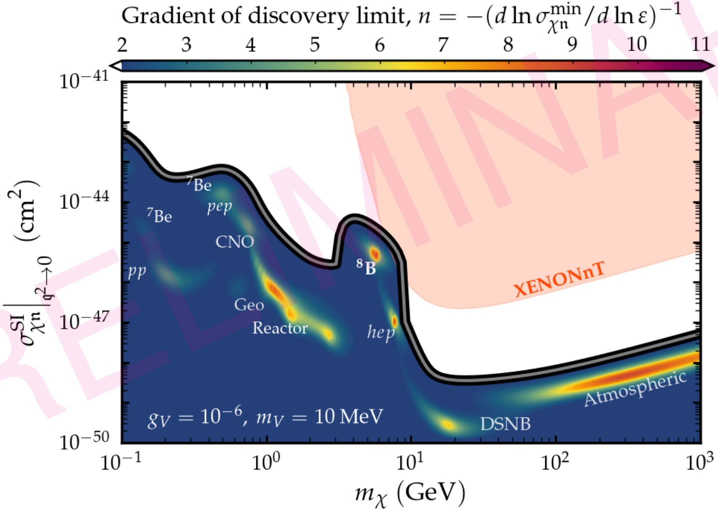
Vector Mediator



Light new physics in the DM sector

Neutrino Interactions: In this case, neutrino interactions are considered within the SM only, i.e. SM CEνNS cross section is considered.

Dark Matter Interactions: Dark matter can couple to nucleus through BSM mediators, giving rise to generalized Lorentz-invariant effective operators up to dimension 6. The scalar and vector interactions constitute spin-independent (SI) couplings, while the axial-vector term lead to spin-dependent (SD) interactions.

$$\mathscr{L}_{\text{eff}}^{\chi\mathcal{N}} \supset -\sum_{X=S,V,A} \frac{C_X}{q^2 + M_X^2} \left[\bar{\chi}\,\Gamma^X\,\chi\right]\left[\bar{\mathcal{N}}\,\Gamma_X\,\mathcal{N}\right], \qquad \Gamma_X = \{\mathbb{I},\, \gamma_\mu,\, \gamma_\mu\gamma_5\}\,.$$

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Under the NR limits the differential cross sections of DM-nuclei scattering for different interactions can be written as,

$$\frac{d\sigma^S_{\chi\mathcal{N}}}{dT_\mathcal{N}} = \frac{m_\mathcal{N}}{2\pi v_\chi^2} \cdot \frac{g_S^4}{(\mathrm{q}^2 + m_S^2)^2} \cdot \left[Z \sum_q \frac{m_p}{m_q} f^p_{Tq} + (A - Z) \sum_q \frac{m_n}{m_q} f^n_{Tq} \right]^2 \cdot F^2_{\mathrm{SI}}(\mathrm{q}^2)$$

$$\frac{d\sigma^V_{\chi\mathcal{N}}}{dT_\mathcal{N}} = \frac{m_\mathcal{N}}{2\pi v_\chi^2} \cdot \frac{g_V^4}{(\mathrm{q}^2 + m_V^2)^2} \cdot (3A)^2 \cdot F^2_{\mathrm{SI}}(\mathrm{q}^2)$$

$$\frac{d\sigma^A_{\chi\mathcal{N}}}{dT_\mathcal{N}} = \frac{2m_\mathcal{N}}{\pi v_\chi^2} \cdot \frac{g_A^4}{(\mathrm{q}^2 + m_A^2)^2} \cdot \frac{\mathcal{J}+1}{\mathcal{J}} \cdot \left[\sum_q \Delta^p_q \mathbb{S}_p + \sum_q \Delta^n_q \mathbb{S}_n \right]^2 \cdot F^2_{\mathrm{SD}}(\mathrm{q}^2)$$

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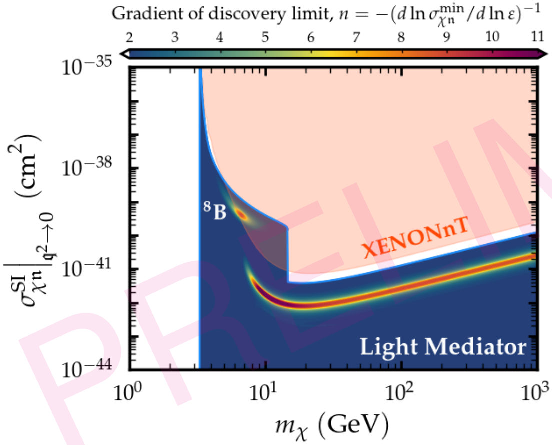
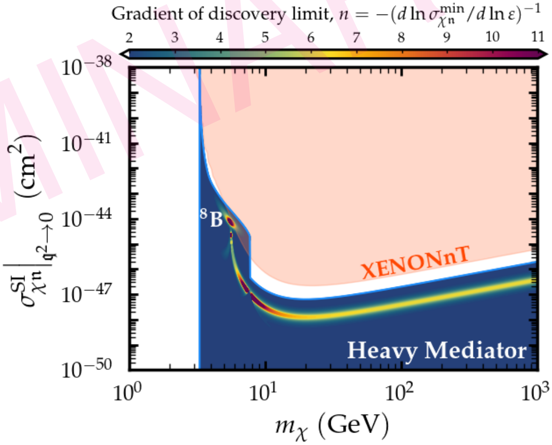
SI Interactions:

$$\sigma_{\chi\mathfrak{n}}\Big|_{q^2\to 0} \propto \frac{g^4}{m^4}$$





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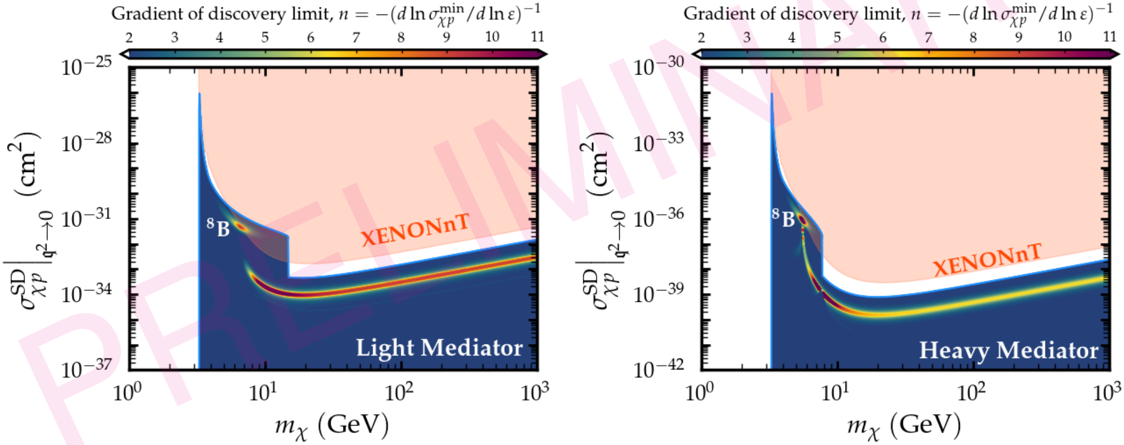
SD p Interactions:

$$\sigma_{\chi\mathfrak{n}}\Big|_{q^2\to 0} \propto \frac{g^4}{m^4}$$



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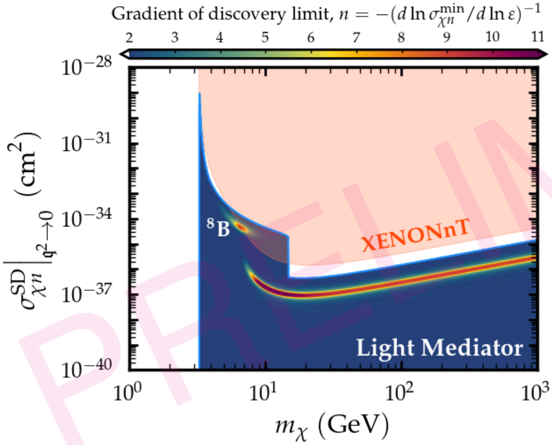
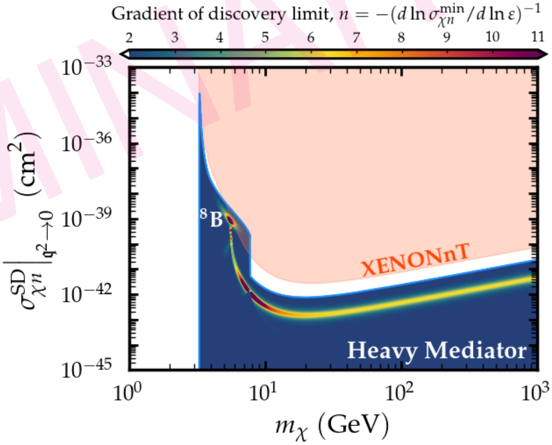
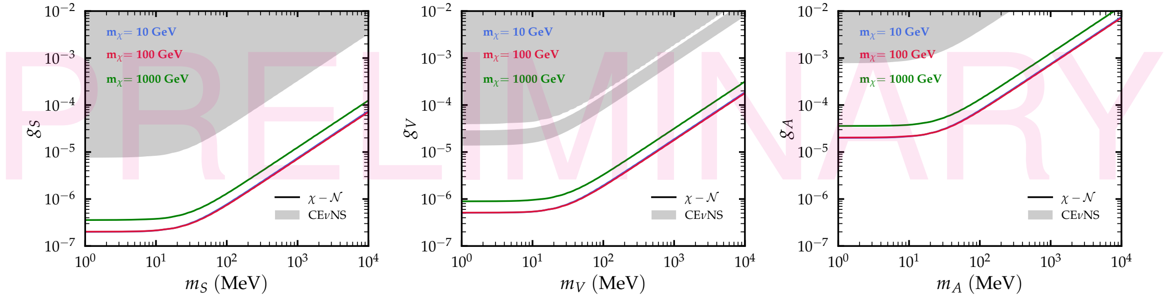
SD n Interactions:

$$\sigma_{\chi n}\Big|_{q^2\to 0} \propto \frac{g^4}{m^4}$$





Limits on new interactions



N.B.: In a third benchmark scenario, if we consider that neutrinos and DM couple with the same strength to the new mediator, the neutrino signal remains essentially SM–like unless the coupling ratio satisfies approximately

$$g_{\nu X} \gtrsim 20\, g_{\chi X},$$

Conclusions

- Generalized neutrino and dark matter interactions provide a unified framework to probe new light mediators and effective interactions beyond the SM.
- Coherent elastic neutrino–nucleus scattering serves as a precision tool to constrain such interactions, while their effects extend to the irreducible neutrino background in the solar neutrino sector—far beyond the current direct detection sensitivity.
- The recent observation of CEνNS from solar ^{8}B neutrinos by XENONnT marks the onset of the neutrino fog in direct dark matter searches. This enables a unified study of CEνNS and WIMP–nucleus scattering within a common mediator framework, offering a coherent interpretation of current and future direct detection data in the presence of neutrino backgrounds.

THANK YOU