Clearing the Fog: Constraining Light Mediators with CEvNS Signals

Based on: PBM, P. Coloma, G. Herrera, P. Huber, J. Kopp, I. M. Shoemaker, and Z. Tabrizi JHEP 08 (2025) 043, arXiv:2411.14206

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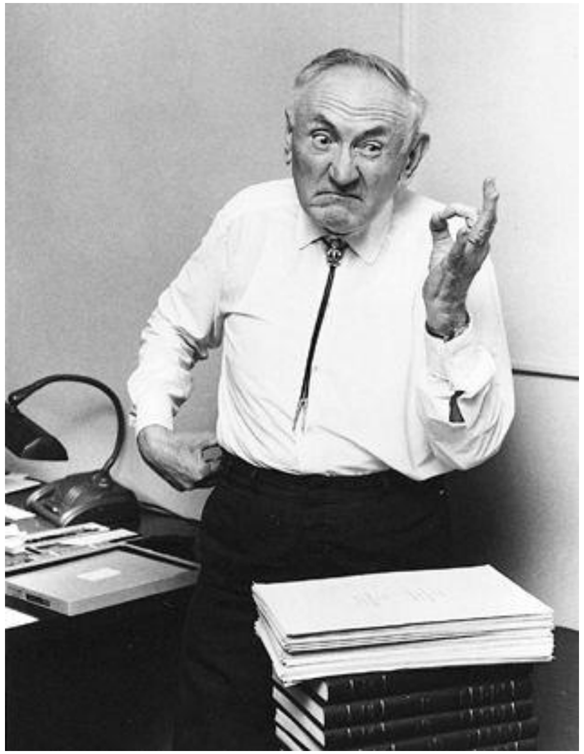
TeVPA 2025 - Valencia

Dark Matter – what is it?

- In 1933, F. Zwicky postulates the existence of "dunkel materie"



"IAA: Información y Actualidad Astronómica", M. A. Pérez-Torres

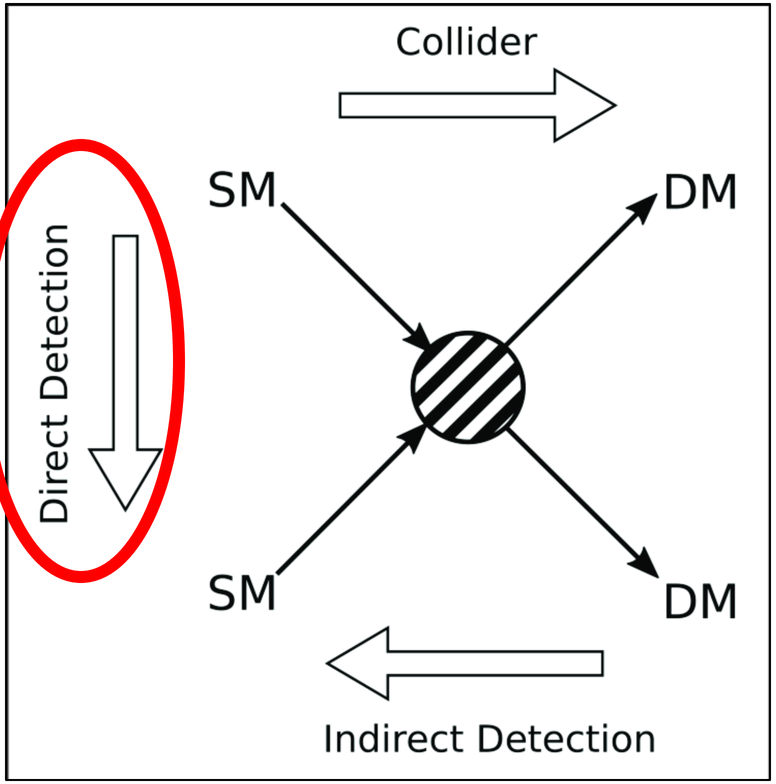
- Today, many hints pointing to ~25% of the energy content of the Universe being cold Dark Matter

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

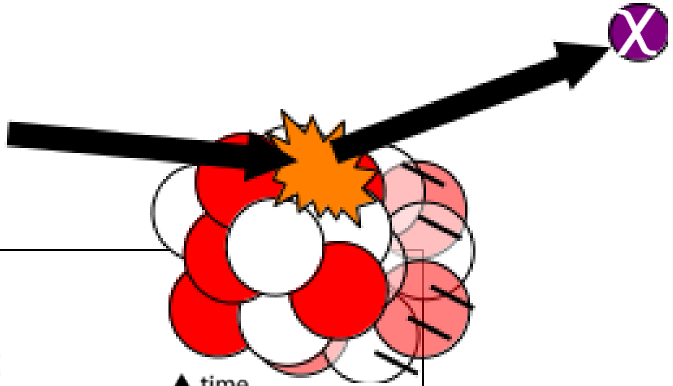
Open problem of the Standard Model!

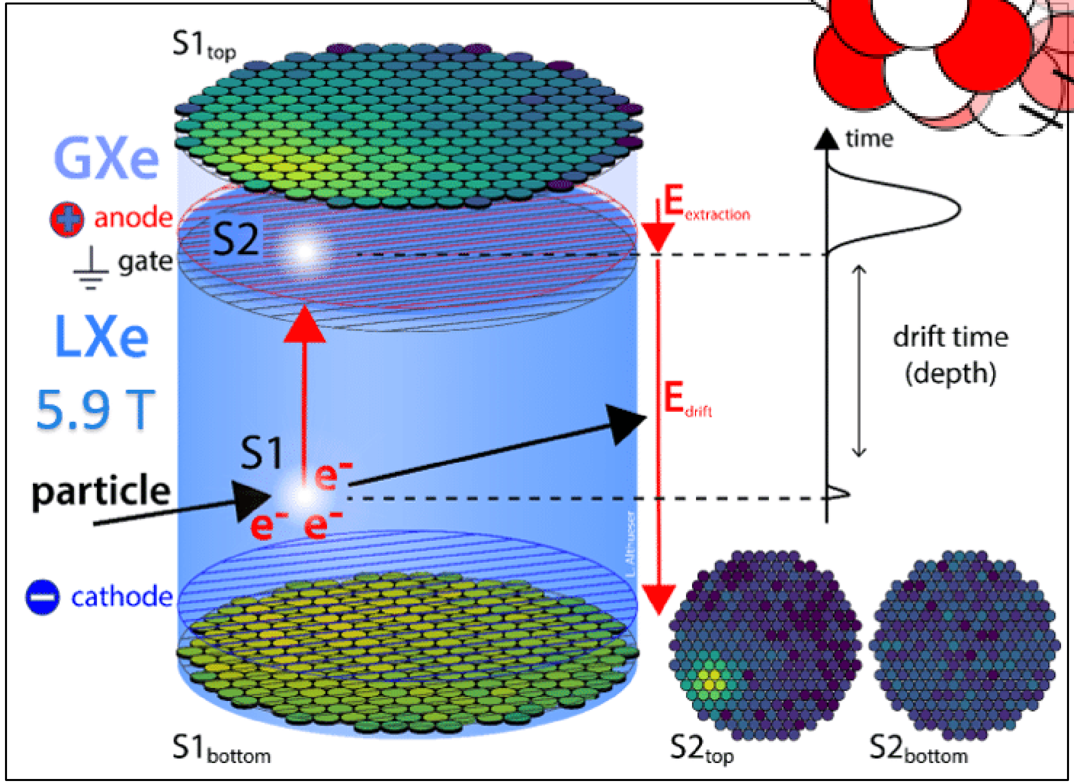
DM Direct Detection experiments

- DM detection has harnessed a huge experimental effort



S. Giagu, *Front. Phys.* 7 (2019), 75. doi:10.3389/fphy.2019.00075



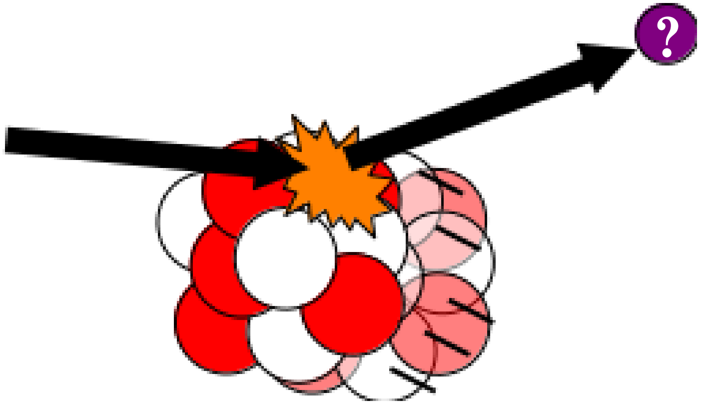


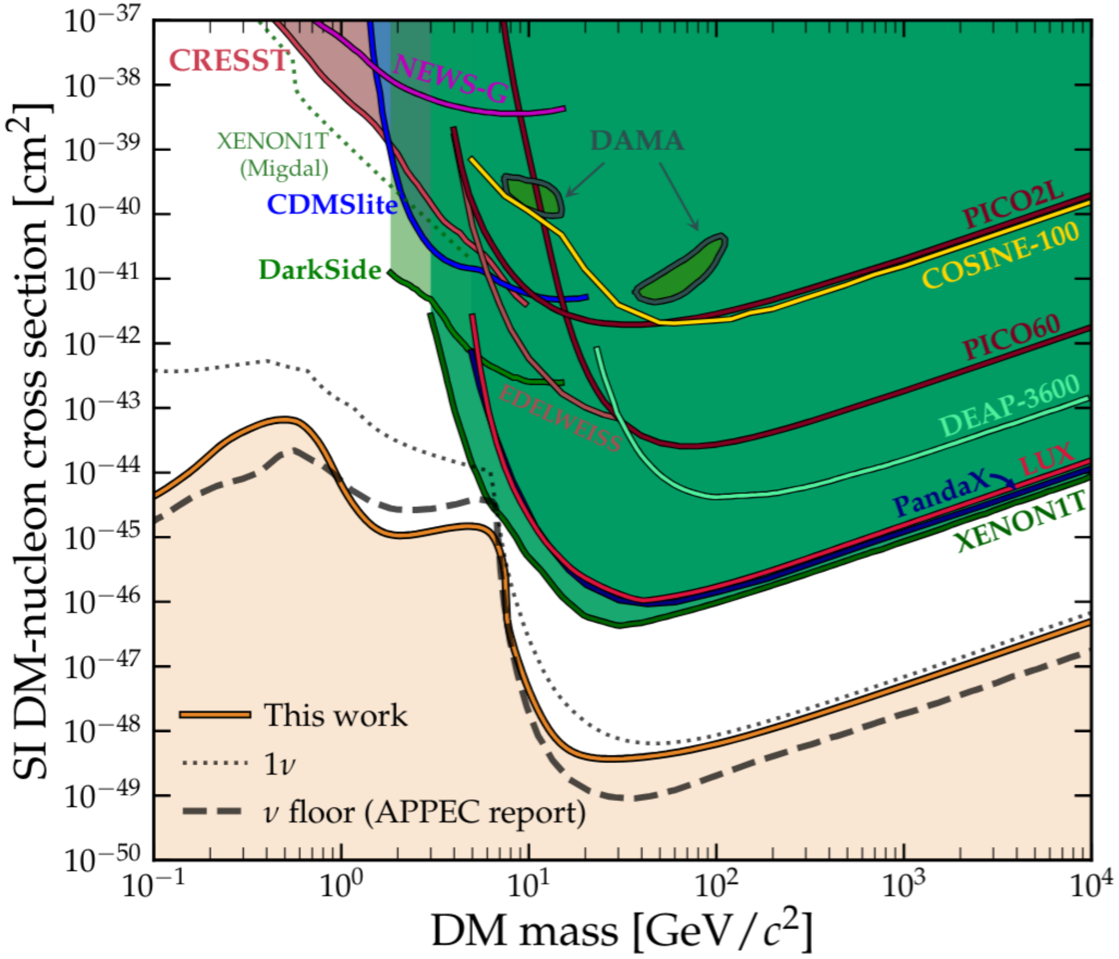
M. Guida, *Zenodo* (2021). doi:10.5281/zenodo.6347581

The neutrino ~~floor~~ fog

- Neutrinos are an irreducible background once DM experiments get enough sensitivity

- Floor or fog?

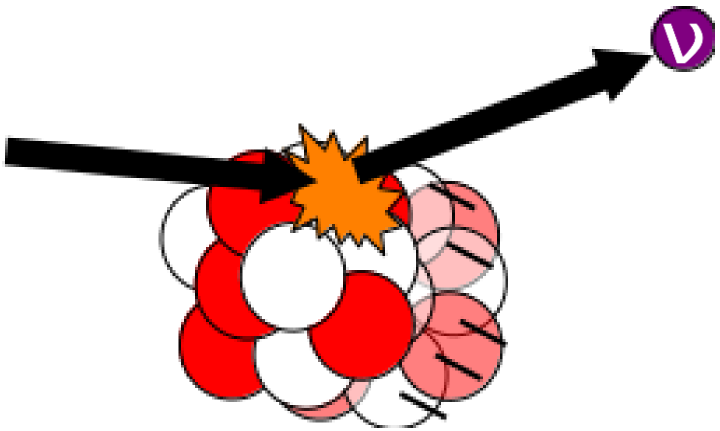


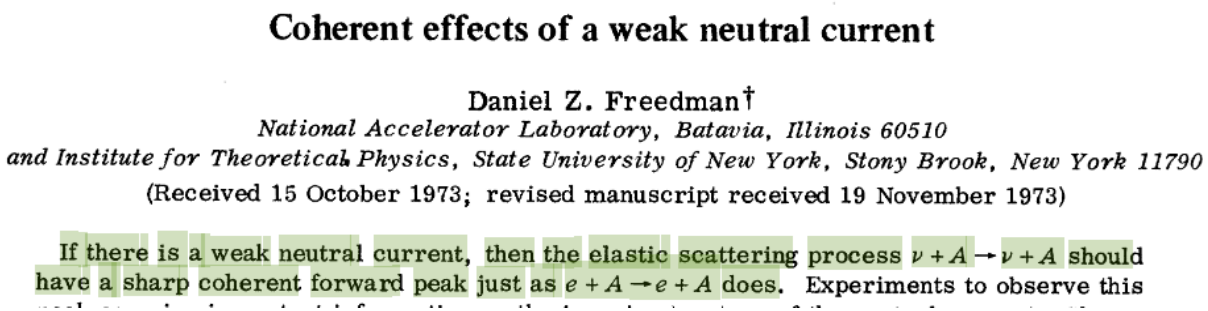


O'Hare, Ciaran A. J., PRL, DOI: 10.1103/PhysRevLett.127.251802.

CEvNS – What is it?

- Coherent Elastic neutrino-Nucleus scattering
- Purely a Standard Model process: ν + A → ν + A
- First proposed in 1974, discovered 43 years later!

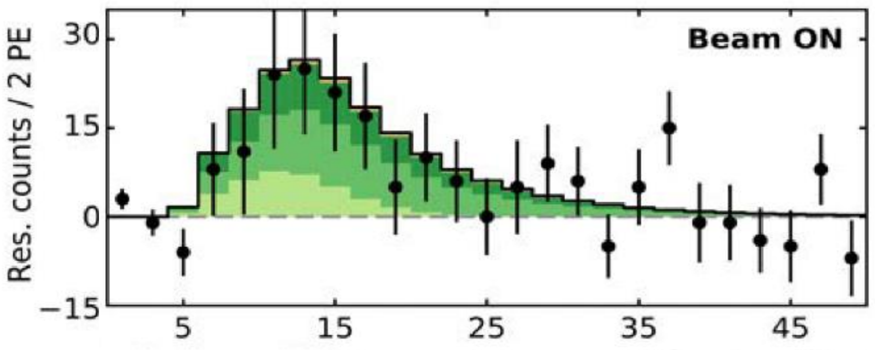



Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this

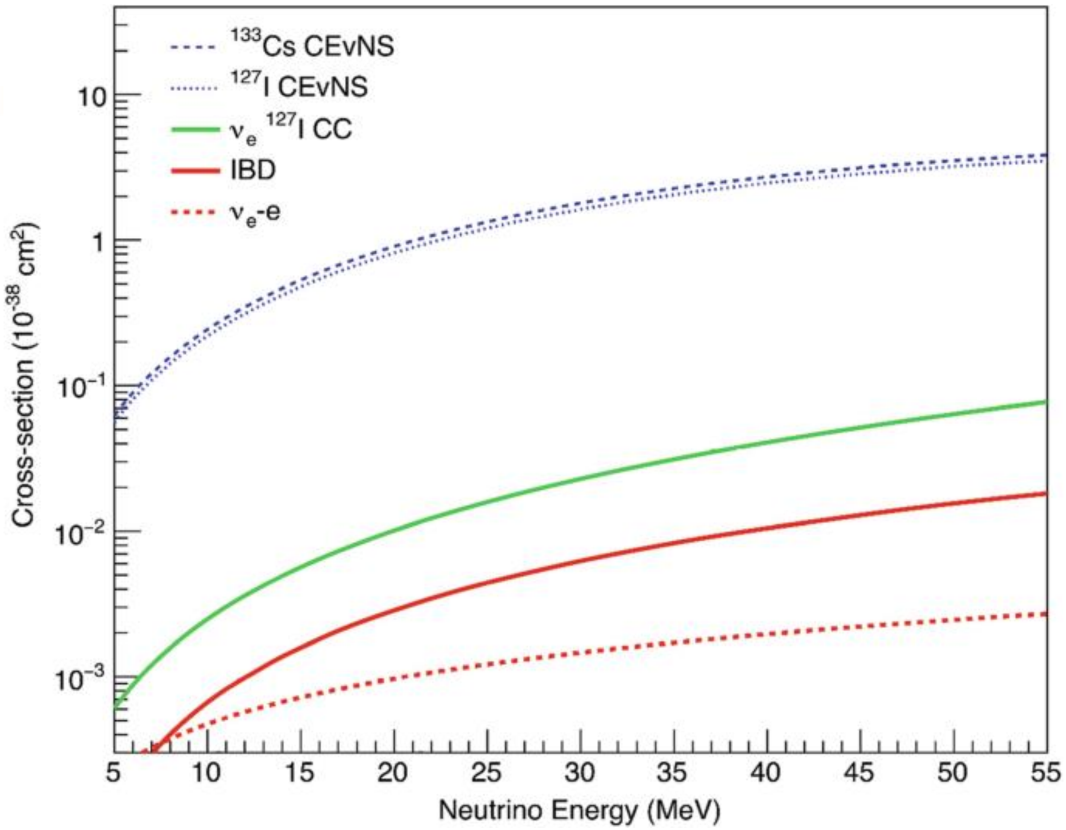
D.Z. Freedman, PRD (1974)



Akimov et al., *Science* (2017), doi: 10.1126/science.aao0990

CEvNS – What is it?

- Coherence condition implies $E_\nu \lesssim 50\text{MeV}$
- Maximum recoil energy $\sim E_\nu^2/M$
- Tiny (O(keV)) recoil energies!
- Coherent effect $\sigma \sim N^2$
- Cross-section is "large" for neutrinos



Scholz, B. (2018). Springer Theses. Springer

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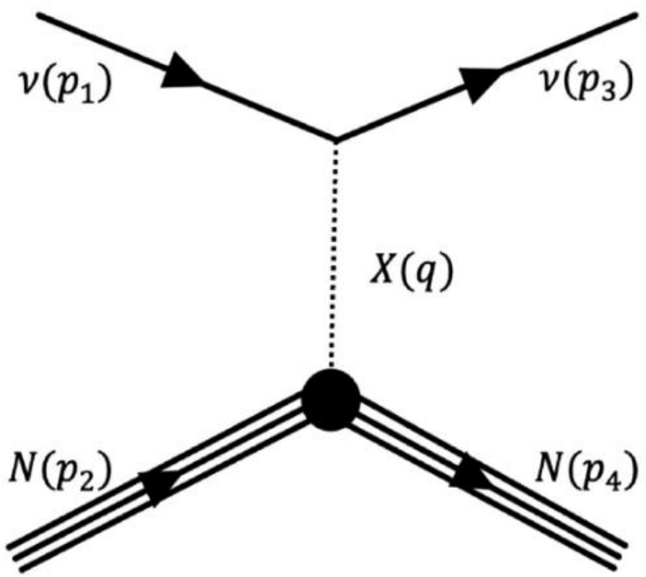
New mediators in CEvNS

- No signals in collider experiments: window for light BSM
- Models for different new light mediators studied

(simplified models):



S. Karadağ et al. (TEXONO Collaboration), *Phys. Rev. D* 112 (2025), doi: 10.1103/PhysRevD.112.035038

Scalar: $$\mathcal{L} \supset \phi\left(g_\nu \bar{\nu}_R \nu_L + g_q \bar{q} q + \text{h.c.}\right) - \frac{1}{2} m_\phi^2 \phi^2$$

"Leptophilic" $$\mathcal{L}_{\phi,e} \supset \phi\left(g_\nu \bar{\nu}_R \nu_L + g_e \bar{e} e + \text{h.c.}\right) - \frac{1}{2} m_\phi^2 \phi^2$$

Vector $$\mathcal{L} \supset g_q \bar{q} \gamma^\alpha Z'_\alpha q + g_\nu \bar{\nu} \gamma^\alpha Z'_\alpha \nu$$

Full models see eg.:

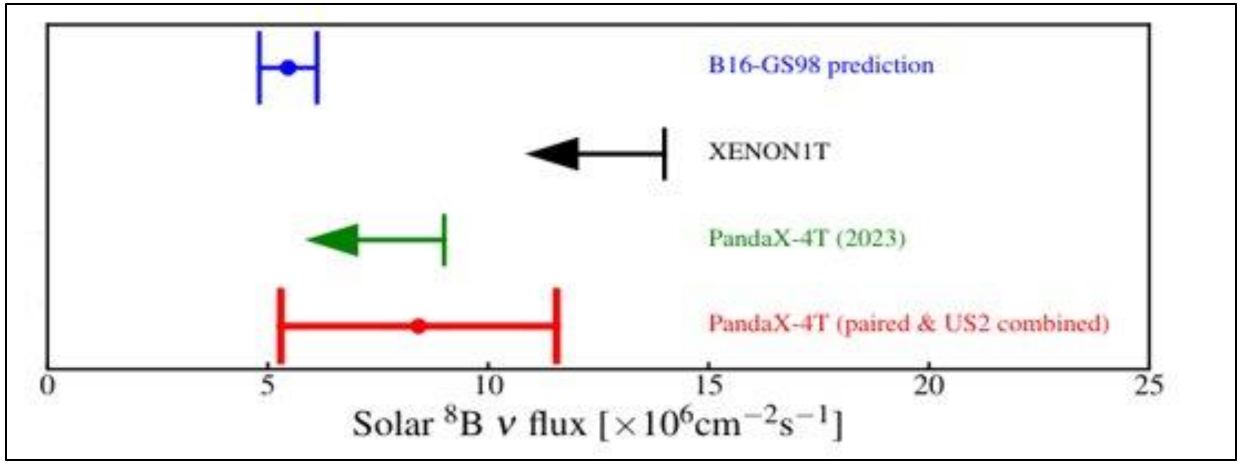
Y. Farzan, M. Lindner, W. Rodejohann, X.-J. Xu, *JHEP* doi: 10.1007/JHEP05(2018)06606

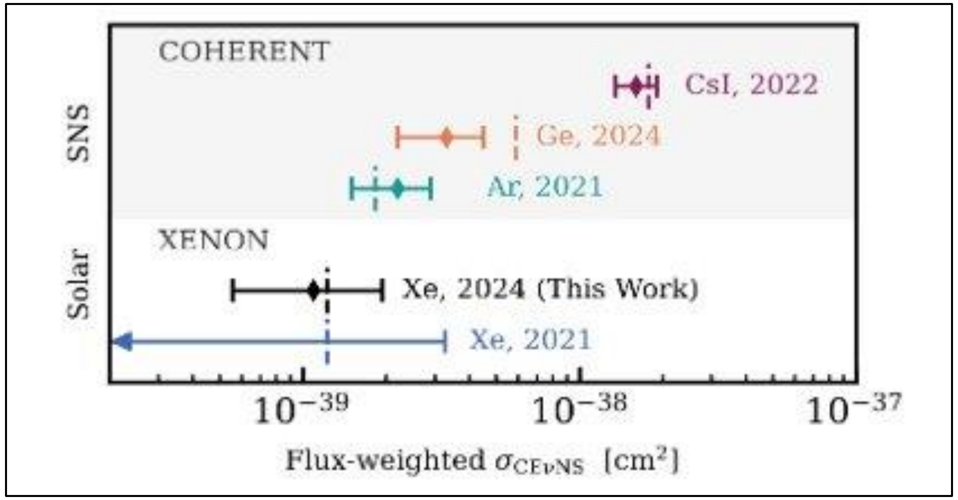
S. Abbaslu, Y. Farzan, NewPhysB, doi: 10.1016/j.nuclphysb.2025.117070.

G.-J. Ding, F. Feruglio, *JHEP*, doi: 10.1007/JHEP06(2020)134134)

Seeing the neutrino fog

- Recently (July-August 2024), two DM experiments have given hints of the solar neutrino floor, XENONnT and PandaX-4T





- Detection of CEvNS from Boron-8 solar neutrinos at 2.73 σ (PandaX-4T) and 2.64 σ (XENONnT)

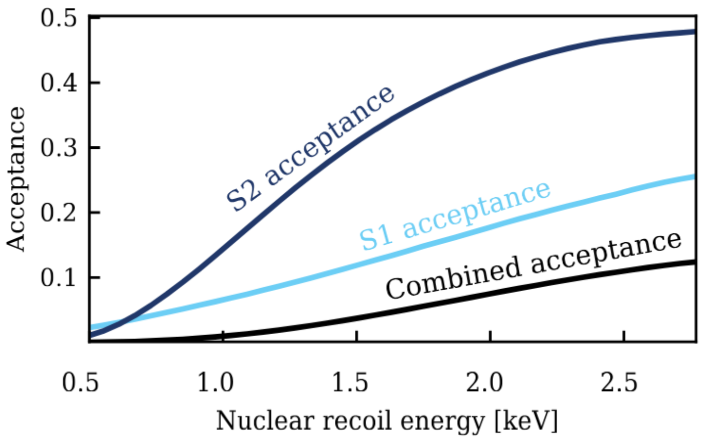
PandaX Collaboration, PRL, DOI: 10.1103/PhysRevLett.133.191001

XENON Collaboration, PRL. DOI: 10.1103/PhysRevLett.133.191002.

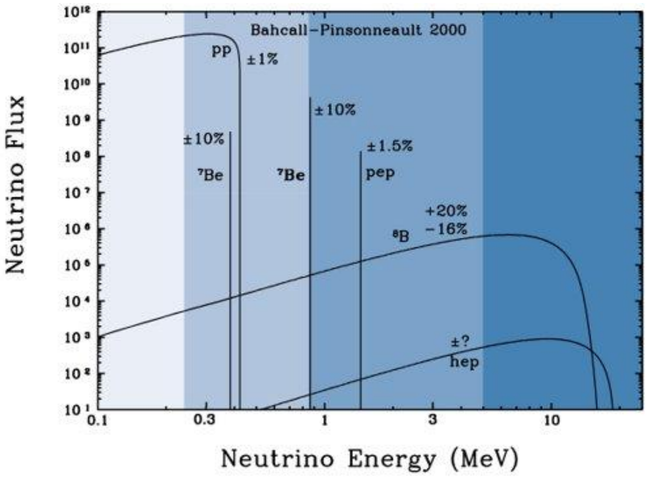
Seeing the neutrino fog

- We compute the expected SM CEvNS event rate in DM DD experiments

$$\frac{dR}{dE_{\rm er}} = \epsilon N_T \sum_\alpha \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} dE_\nu \frac{d\phi^\alpha}{dE_\nu}\frac{d\sigma_\alpha}{dE_{\rm er}}$$



XENON Collaboration, PRL. DOI: 10.1103/PhysRevLett.133.191002.



Bellerive, A., JMPA. 10.1142/S0217751X04019093

$$\frac{d\sigma_{\rm SM}(T,E_\nu)}{dT} = \frac{G_F^2}{2\pi} Q^2(Z,N) F^2(Q^2) M \left(2 - \frac{MT}{E_\nu^2}\right)$$

Momentum transfer: $Q = \sqrt{2MT}$

D. Z. Freedman, Phys. Rev. D 9, 1389 – DOI: 10.1103/PhysRevD.9.1389

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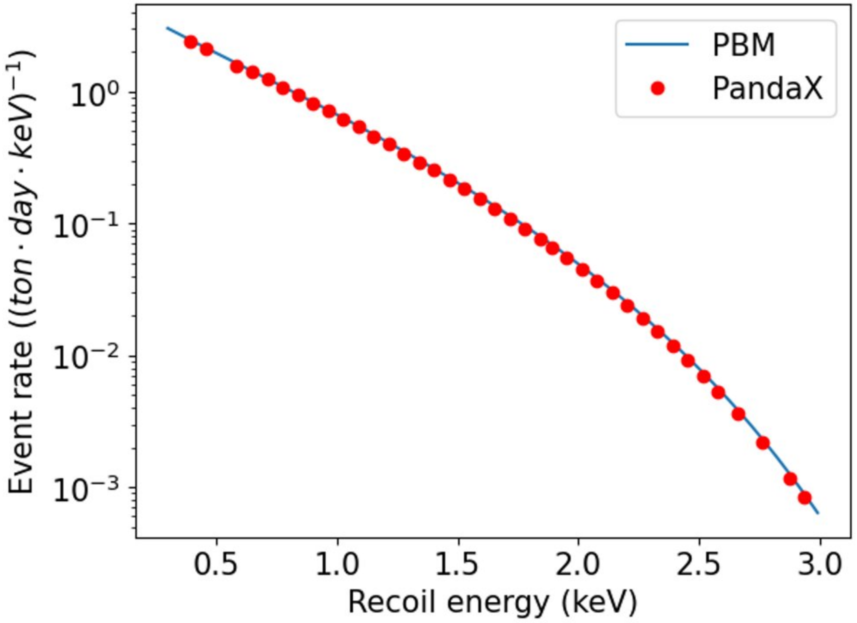
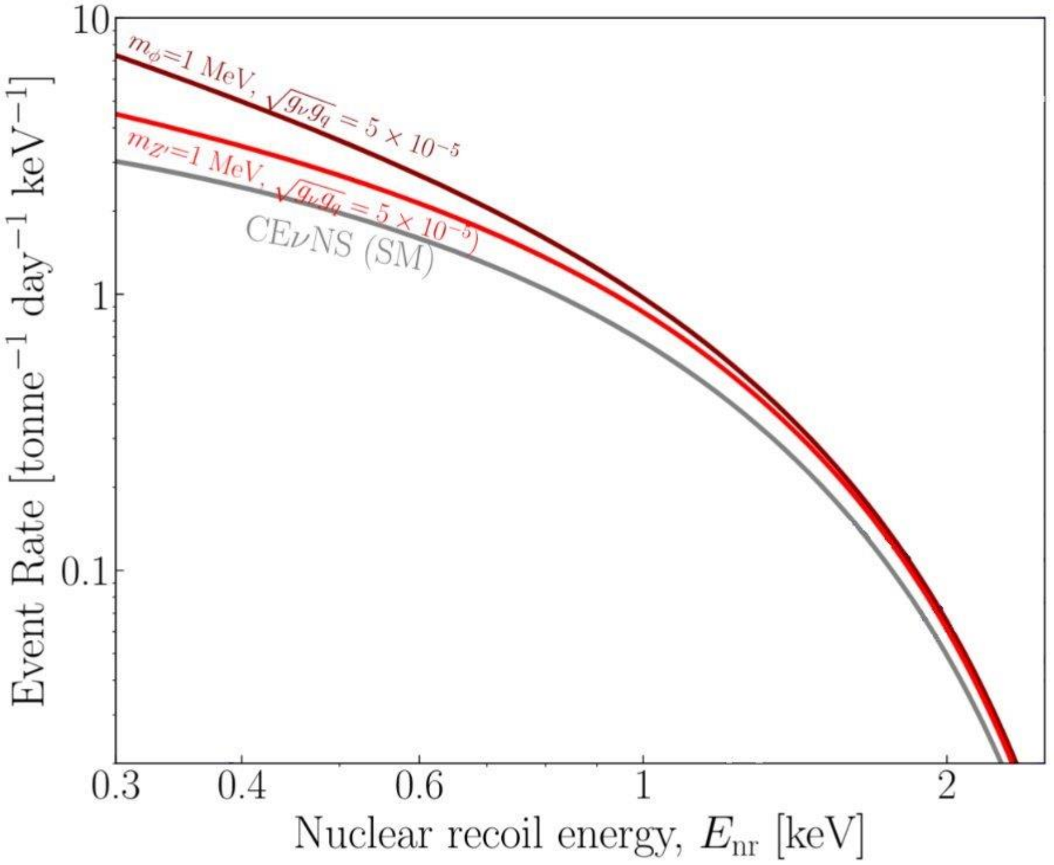


PandaX Collaboration, PRL, DOI: 10.1103/PhysRevLett.133.191001

Seeing the neutrino fog



- What about New Physics?
- NP in the neutrino fog has been proposed:
  - NP "lifting" the fog's limit

    C. Bøhm, D. G. Cerdeño, et al., *JCAP*, doi:10.1088/1475-7516/2019/01/043
- Other people searched for NP using Xenon and PandaX events:
  - Non Standard Interactions (NSIs)

    D. Aristizabal Sierra, N. Mishra, L. Strigari, PRD, doi 10.1103/PhysRevD.111.055007
  - Neutrino Generalized Interactions

    V. De Romeri, D. K. Papoulias, C. A. Ternes, *JCAP*, doi:10.1088/1475-7516/2025/05/012

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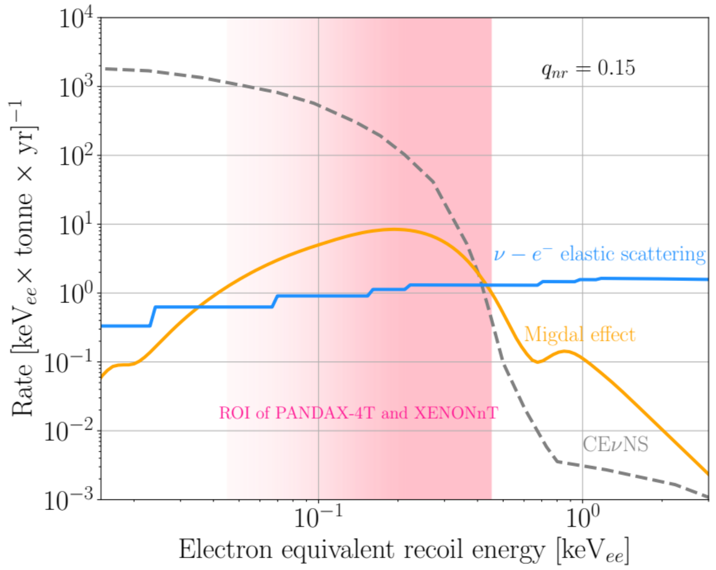
Analysis – search for BSM in the fog

- With data from the collaborations, we compute our 90% CL bounds in excess (or defect) number of events

	PandaX-4T	
	S1+S2	S2 only
exposure [tonne yrs]	1.20	1.04
observed events	1	158
background events	1.16	126
SM events	1	18

- Neutrino recoil rate -> quenching to nuclear recoil rate



- Neutrino-electron scattering is negligible in SM (BSM?)

PandaX Collaboration, PRL, DOI: 10.1103/PhysRevLett.133.191001

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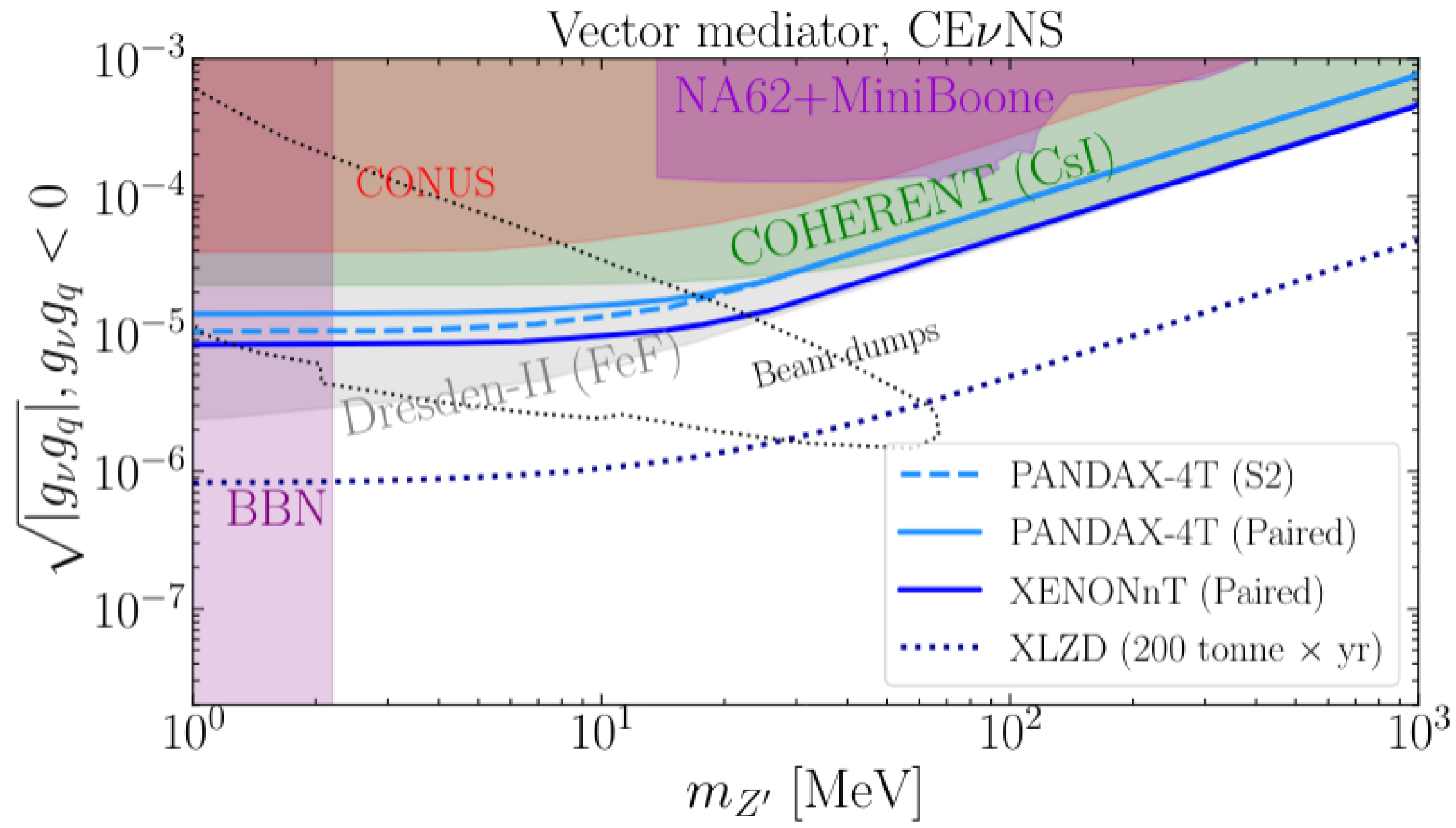
Seeing beyond the fog – vector case

- We have interference!

$$Q_V \to Q_V + \frac{3 g_q g_\nu}{\sqrt{2} G_F} \frac{(Z+N) F_N(E_{\rm nr})}{2 m_A E_{\rm nr} + m_{Z'}^2}$$

- As $d\sigma_{\rm SM}/dT \propto Q_V^2$ now the signs of the couplings matter



PBM et al., JHEP, doi:10.1007/JHEP08(2025)043

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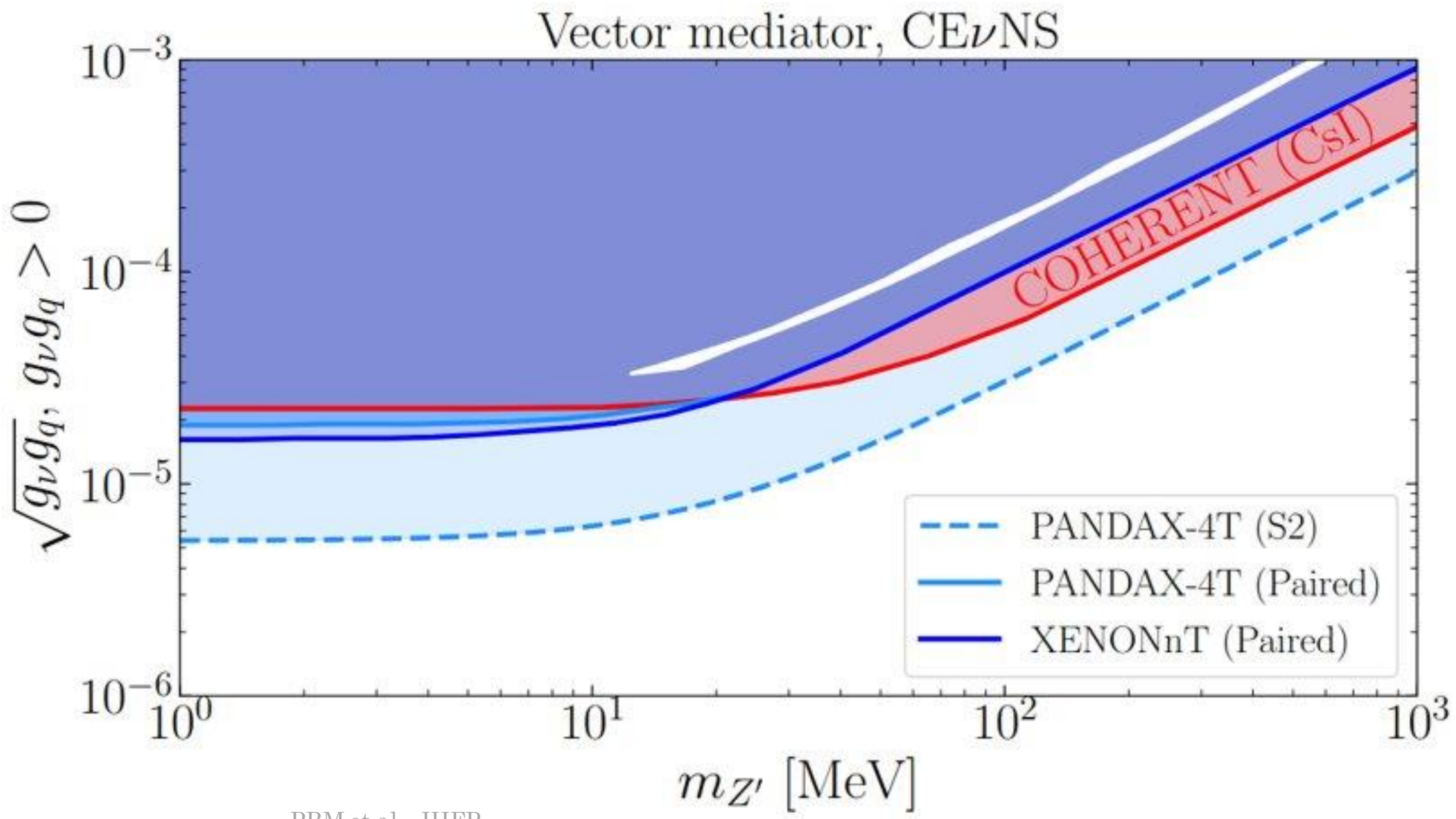


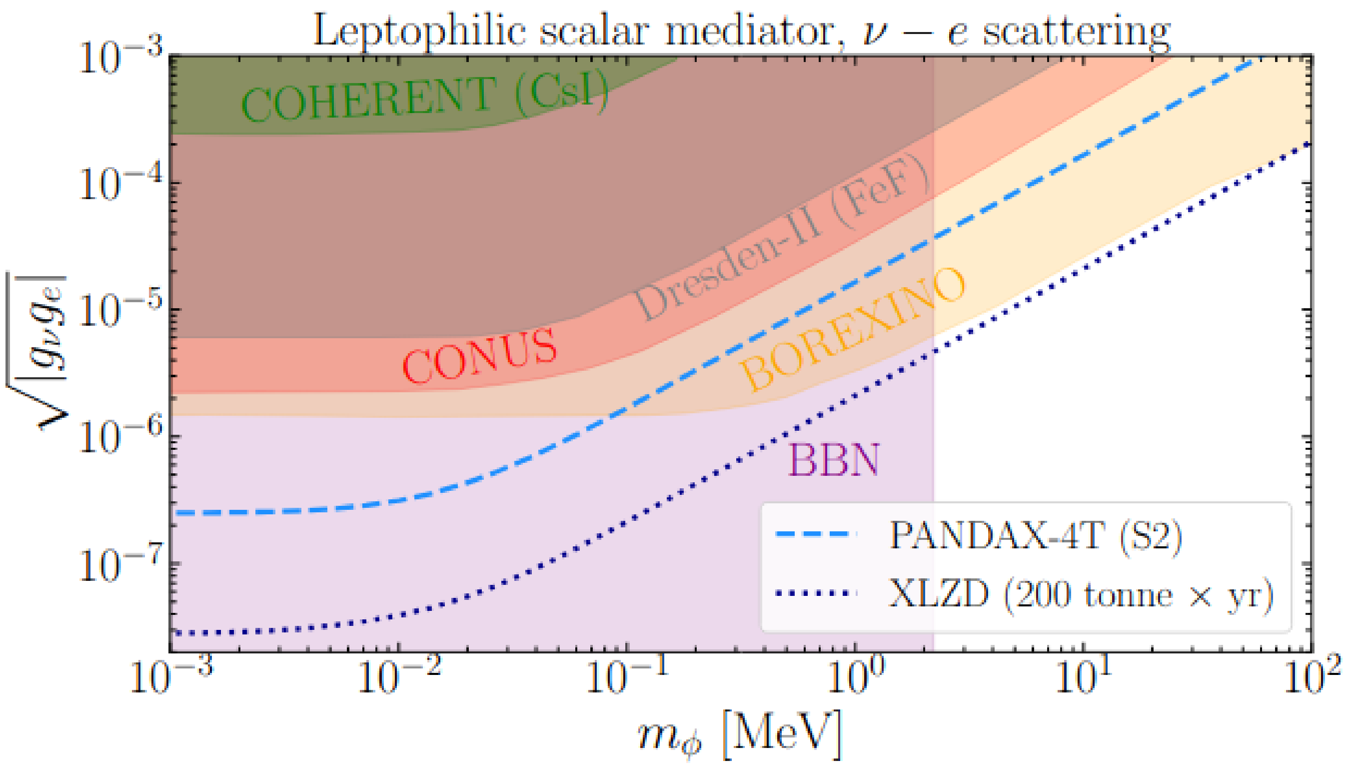
PBM et al., JHEP, doi:10.1007/JHEP08(2025)043

Seeing beyond the fog – leptophilic scalar

- PandaX S2 only (combined analysis extracts EvES)

- We include other neutrino fluxes from the Sun

$$\frac{d\sigma_\alpha^\phi}{dE_{\rm er}} = \frac{g_\nu^2 g_e^2 m_e^2 E_{\rm er}}{4\pi E_\nu^2 \left(2m_e E_{\rm er} + m_\phi^2\right)^2}$$



PBM et al., JHEP,
doi:10.1007/JHEP08(2025)043

Conclusions

- We are starting to reach the neutrino fog (bad for DM experimentalists, good for neutrino physicists)
- Bounds to light mediators can be derived using neutrino fog data
- The bounds are relevant, sometimes better than dedicated experiments
- **TAKE HOME**: Dark Matter direct detection experiments are becoming excellent at catching neutrinos!!

Conclusions

Thank you!

- We are starting to reach the neutrino fog (bad for DM experimentalists, good for neutrino physicists)

- Bounds to light mediators can be derived using neutrino fog data

- The bounds are relevant, sometimes better than dedicated experiments

- **TAKE HOME**: Dark Matter direct detection experiments are becoming excellent at catching neutrinos!!

Backup slides

- Poisson likelihood ratio ~ χ^2 distribution

$$-2\ln\lambda = -2\ln\frac{P_1}{P_0}$$

$$P_1 \sim \frac{(N_{bkg}+N_{sig})^{N_{obs}}}{N_{obs}!}e^{-(N_{bkg}+N_{sig})}$$

$$P_0 \sim \frac{N_{bkg}^{N_{obs}}}{N_{obs}!}e^{-N_{bkg}}$$

$$-2.10 < N_{sig}^{PA,S1+S2} < 2.01 \qquad (\mathrm{PandaX-4T, S1+S2})$$

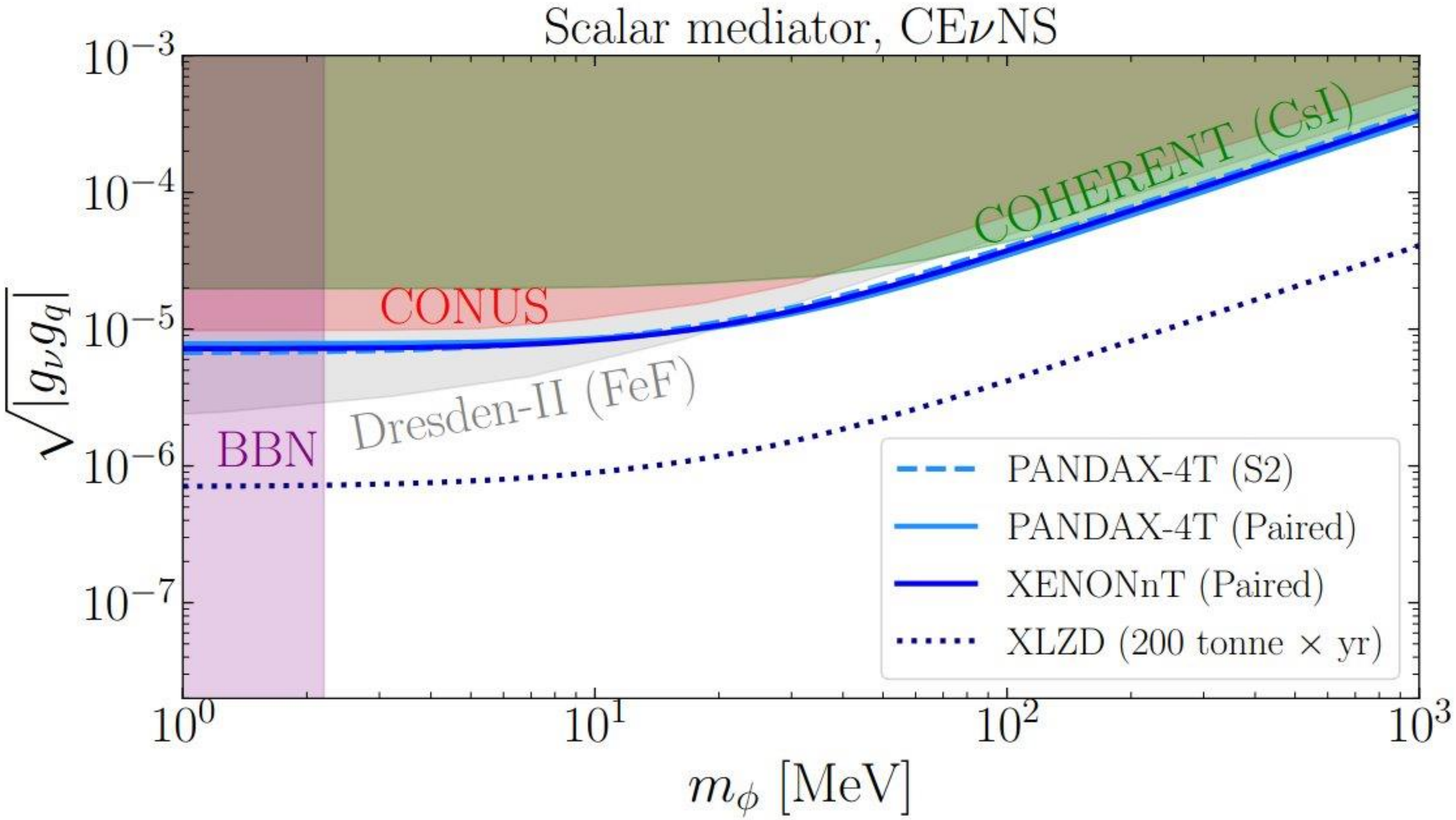
$$-5.79 < N_{sig}^{PA,S2} < 35.59 \qquad (\mathrm{PandaX-4T, S2\ only})$$

$$-10.50 < N_{sig}^{XE,S1+S2} < 9.71 \qquad (\mathrm{XENONnT, S1+S2})$$

Seeing beyond the fog – scalar case

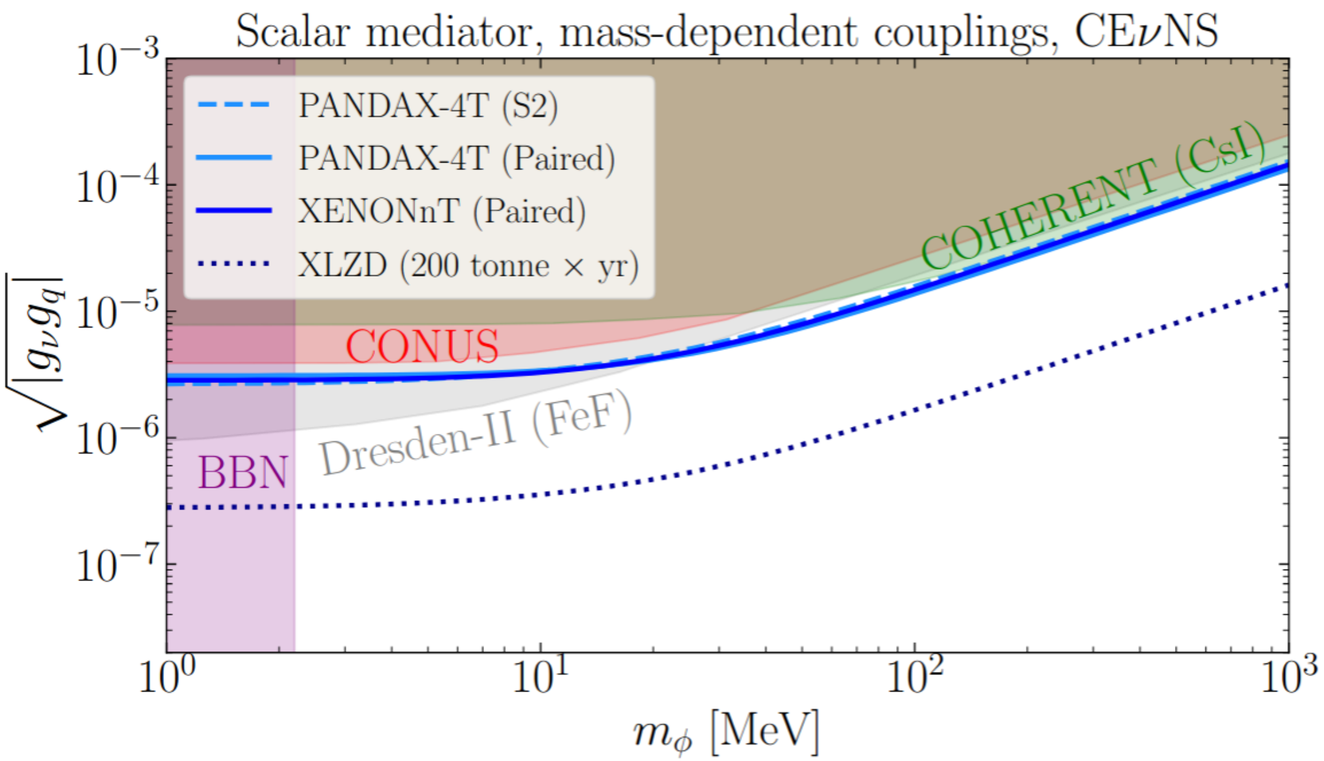
- The scalar coupling adds events to the total rate

$$\left(\frac{d\sigma_{\nu N-\nu N}}{dE_{\mathrm{nr}}}\right)_\phi = \frac{g_\nu^2 \mathcal{Q}_\phi^2 m_A^2}{4\pi} \frac{E_{\mathrm{nr}}}{E_\nu^2 (2m_A E_{\mathrm{nr}} + m_\phi^2)^2}$$



Backup slides - plots

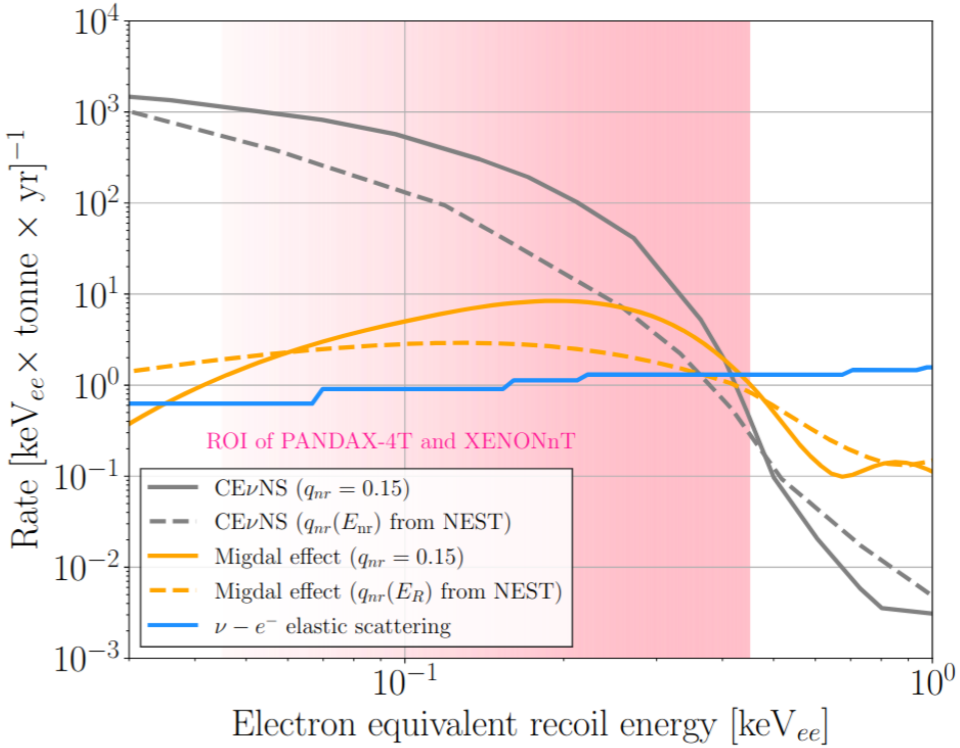
$$g_q \rightarrow \frac{g_q m_q}{v_H}$$



Backup slides – quenching factor

- Quenching factor transforms NR into the detected rate (usually in terms of ER)

- For Xe, uncertain at low E



M Szydagis, N Barry, K Kazkaz, J Mock, D Stolp, M Sweany, M Tripathi, S Uvarov, N Walsh, and M Woods, Journal of Instrumentation 6, P10002–P10002 (2011)