李政道研究所
TSUNG-DAO LEE INSTITUTE

Solar neutrinos in DD

NEXUS 2026

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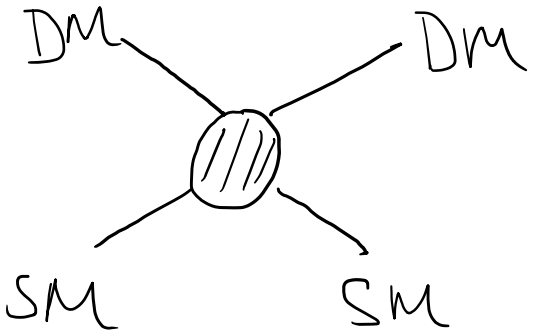
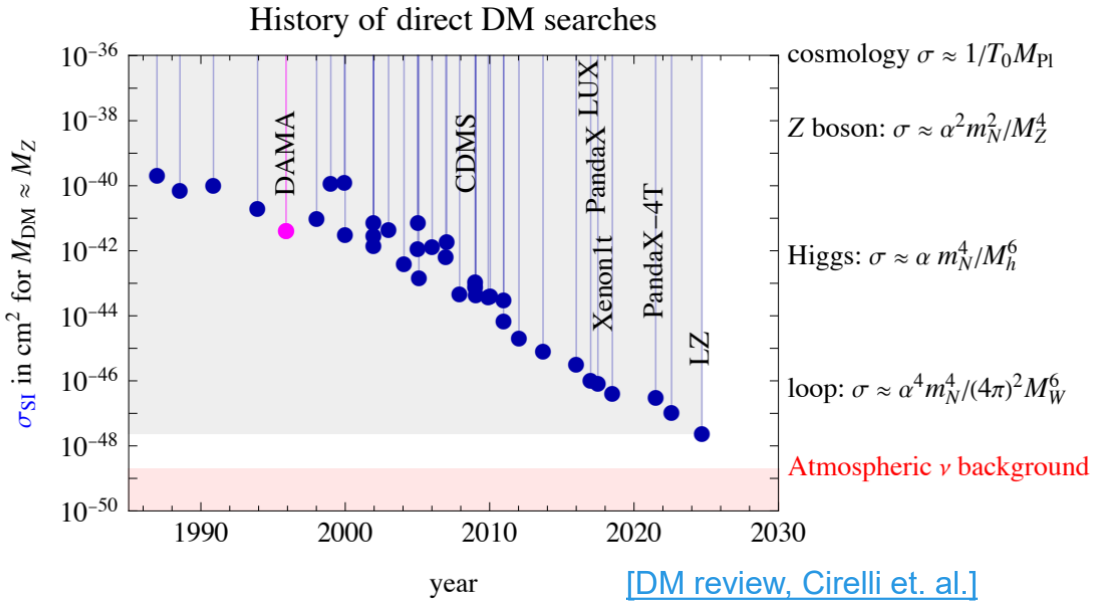
Based on *Eur.Phys.J.C* 81 (2021) 10, 861, *JHEP* 07 (2023) 071, *JHEP* 07 (2026) 243, and arXiv:2607.22817

With D. Amaral, D. Cerdeno, P. Foldenauer, and V. Costa

The search for dark matter

- Looking for a dark matter recoil



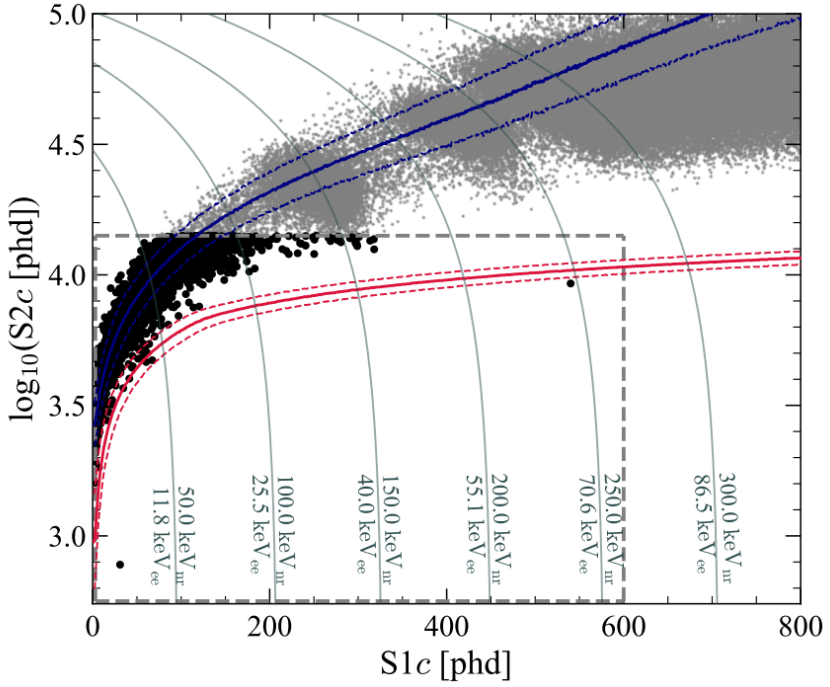


[DM review, Cirelli et. al.]

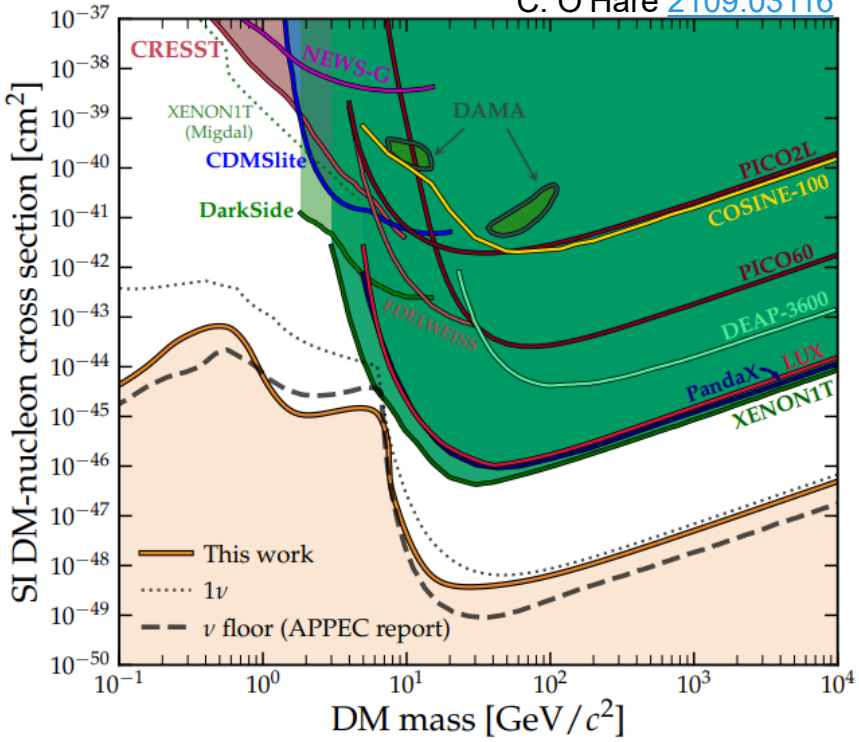
An end in sight?

- Direct detection will detect something, DM or the ‘neutrino fog’

LZ recent result 2609.02823



C. O’Hare 2109.03116

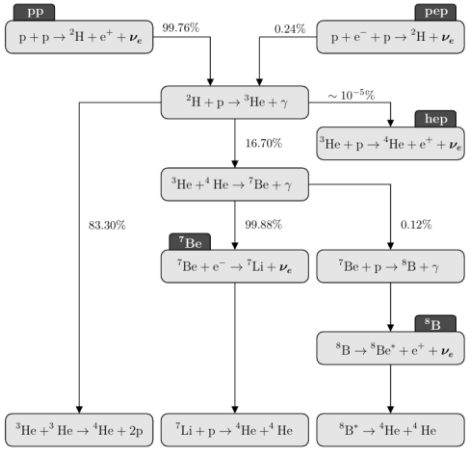


Anatomy of the neutrino “fog”

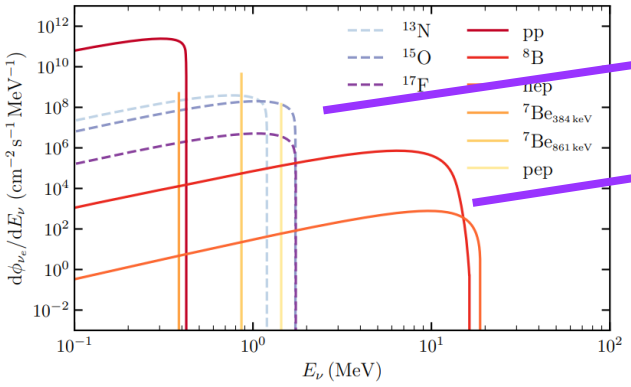
- This background can be broken up into **two*** categories: **solar** and **atmospheric** neutrinos

Solar neutrinos:

Nuclear processes in the Sun

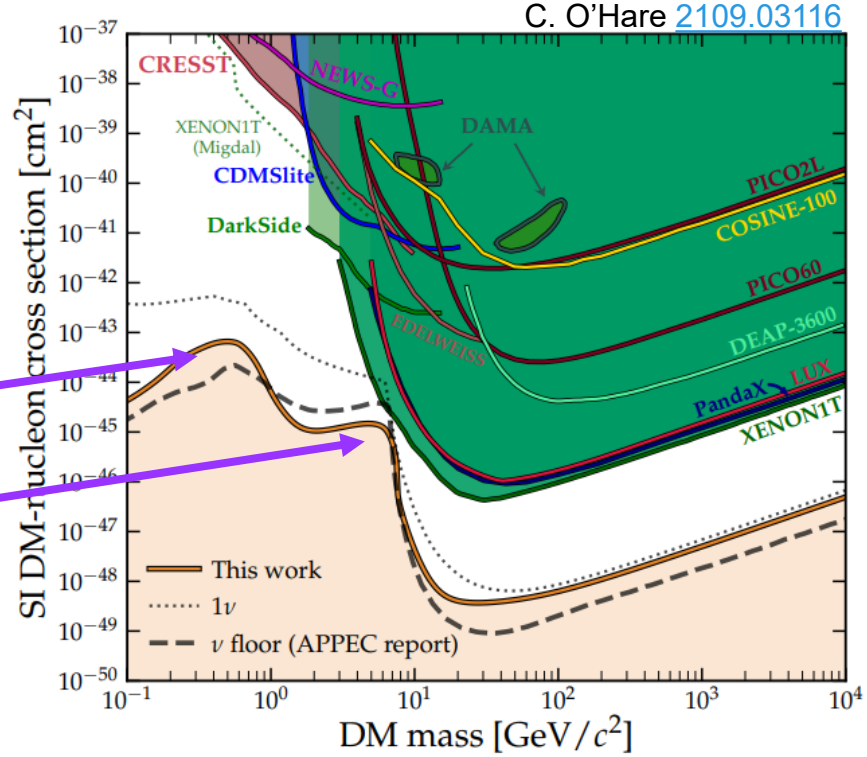


These processes have an associated flux



D. Amaral’s thesis

C. O’Hare 2109.03116



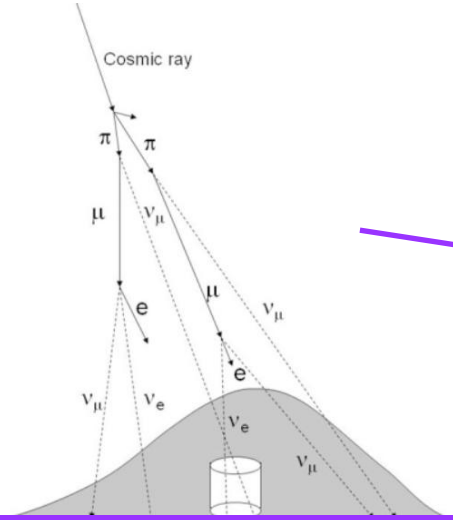
*I’m ignoring diffuse supernova neutrinos

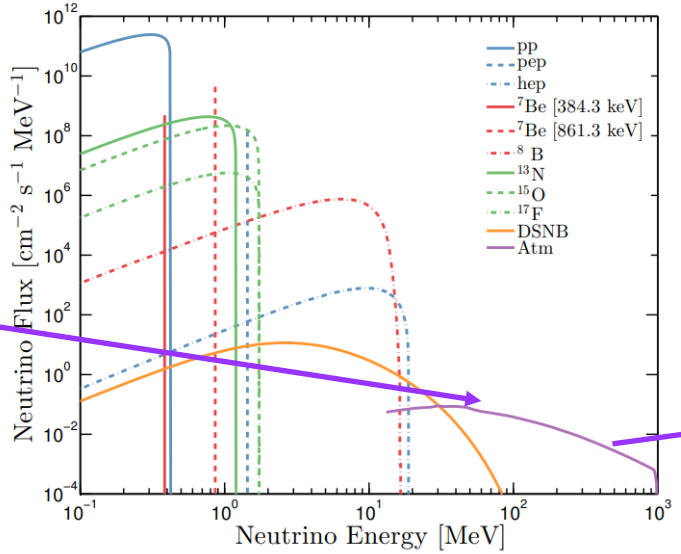
Anatomy of the neutrino “fog”

- This background can be broken up into **two*** categories: **solar** and **atmospheric** neutrinos

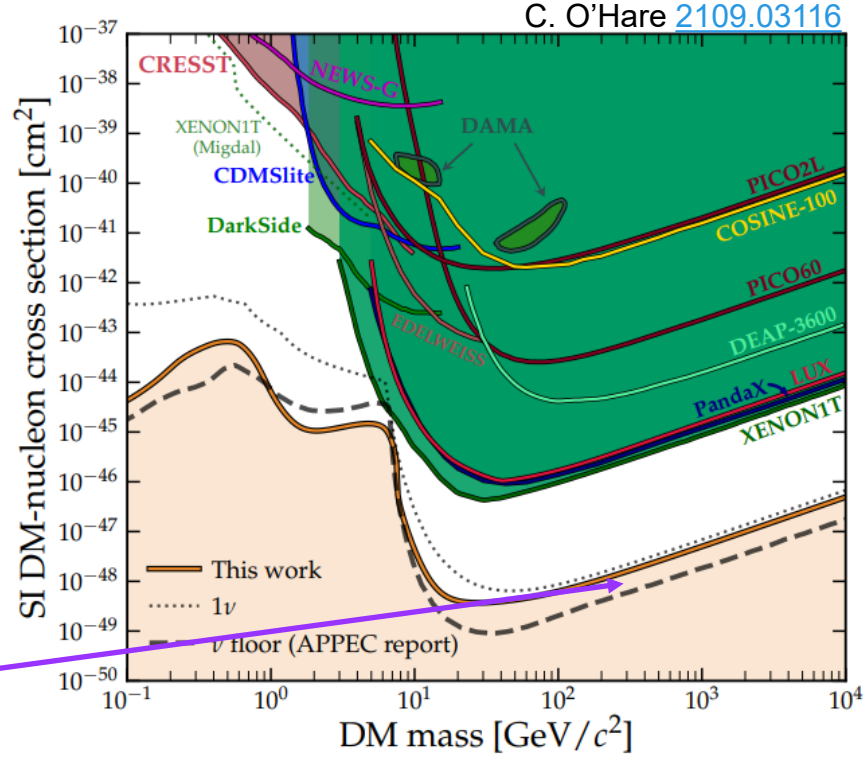
Atmospheric neutrinos:

Cosmic-ray interactions with Earth’s atmosphere





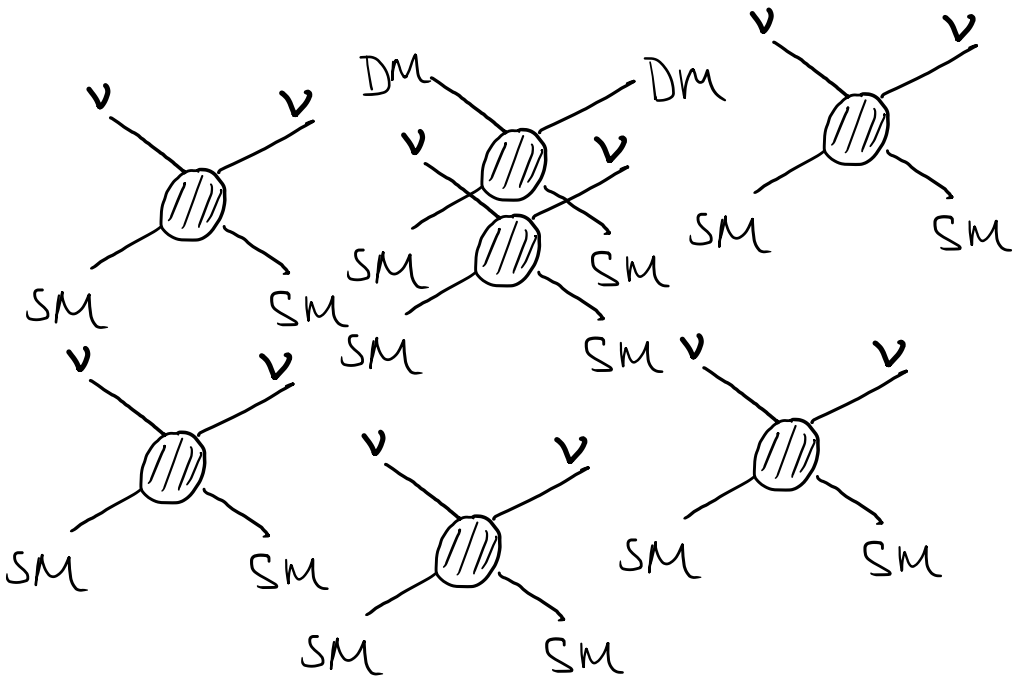
C. O’Hare 2109.03116



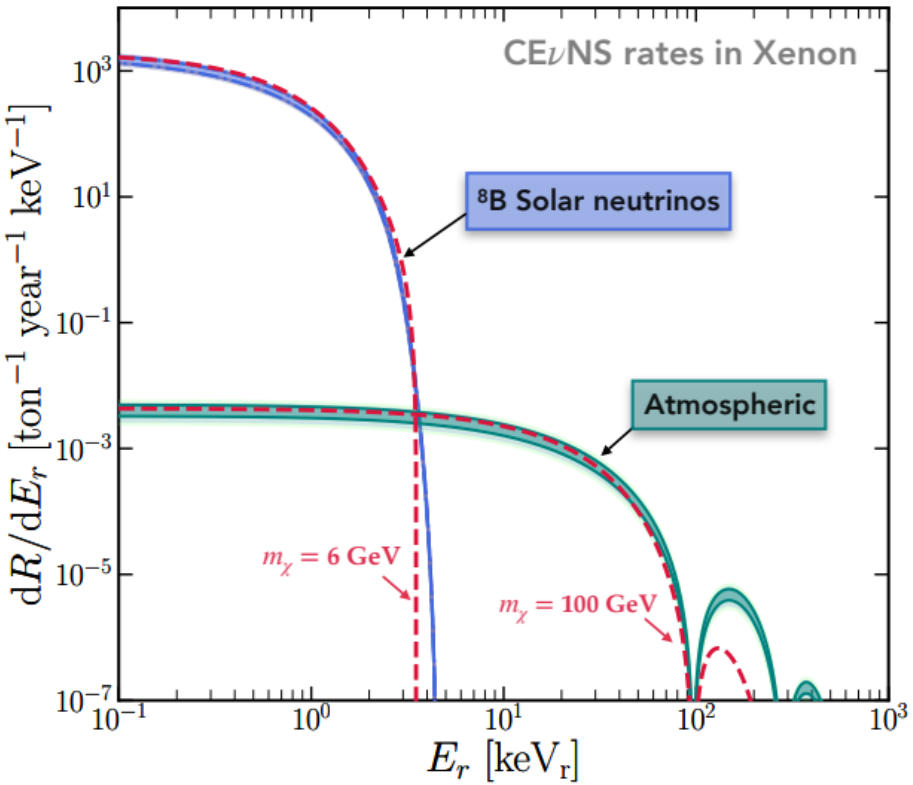
*I’m ignoring diffuse supernova neutrinos

Why the fog is a problem (for DM)

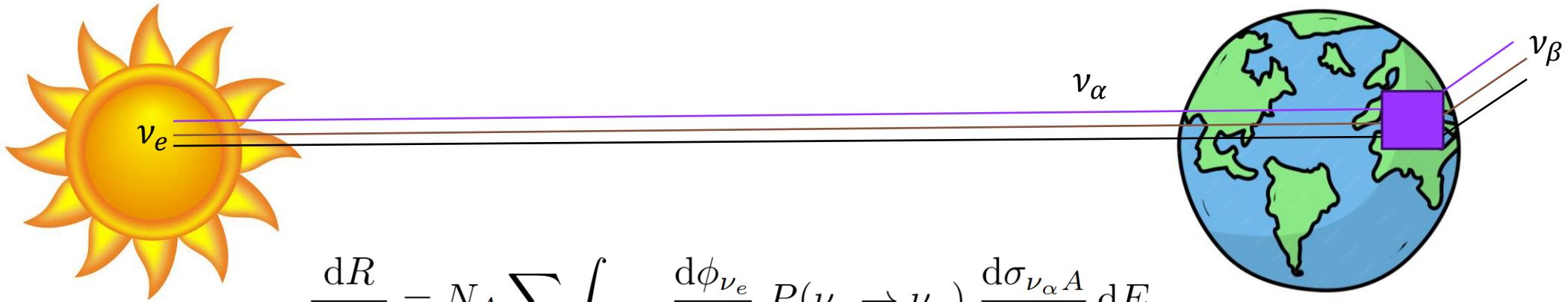
- This is an irreducible background



C. O'Hare



DD Signal Basics (solar ν's)



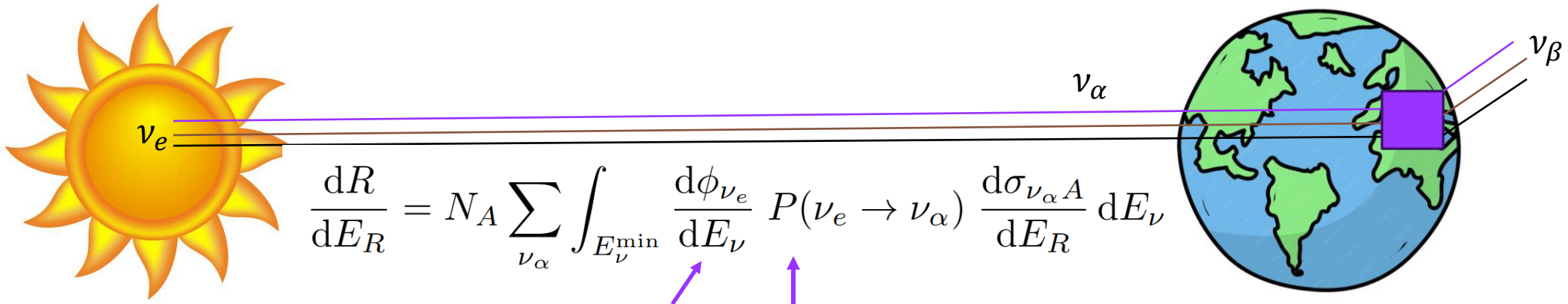
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_A \sum_{\nu_\alpha} \int_{E_\nu^{\min}} \frac{\mathrm{d}\phi_{\nu_e}}{\mathrm{d}E_\nu} \, P(\nu_e \to \nu_\alpha) \, \frac{\mathrm{d}\sigma_{\nu_\alpha A}}{\mathrm{d}E_R} \, \mathrm{d}E_\nu$$

ν-flux

Oscillation probability

Differential cross-section

DD Signal Basics (solar ν's)



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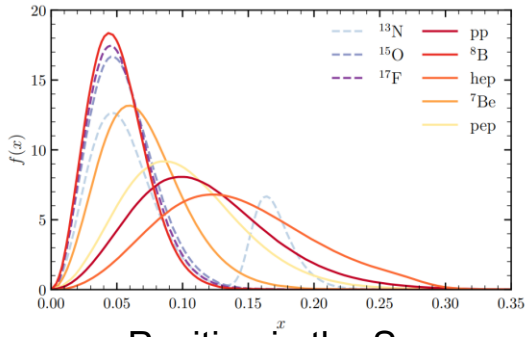
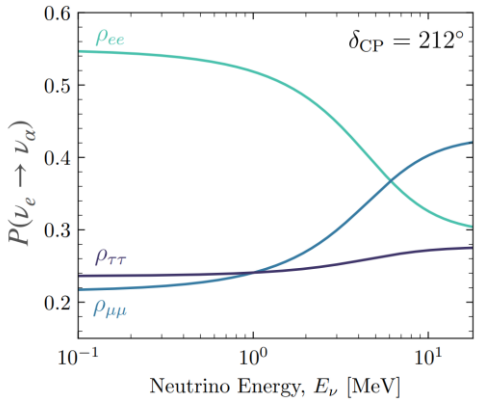
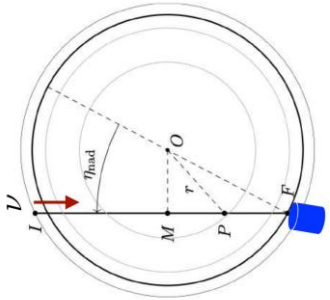
ν-flux

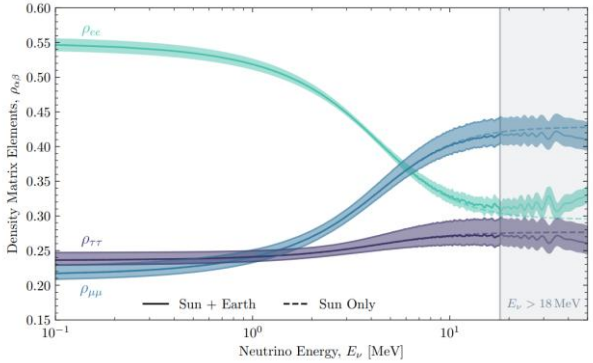
Oscillation probability



Position in the Sun







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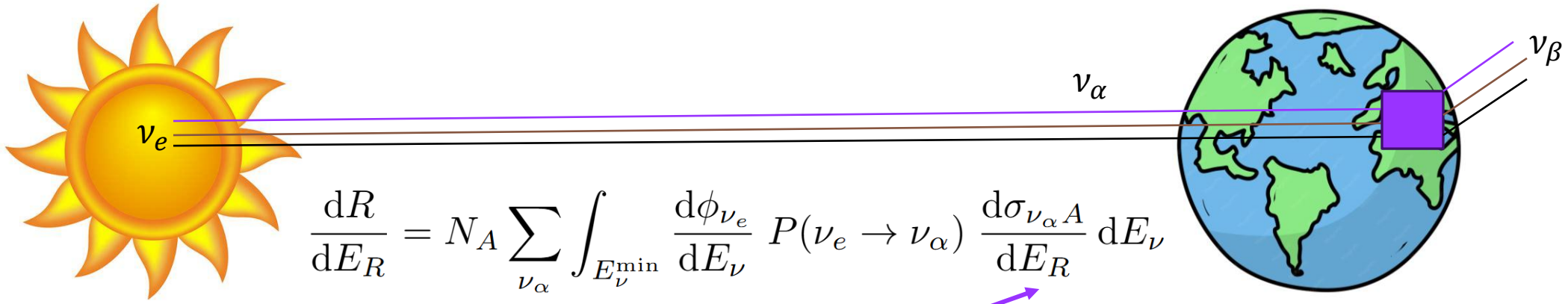

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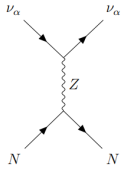
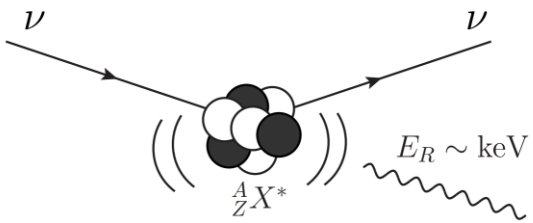
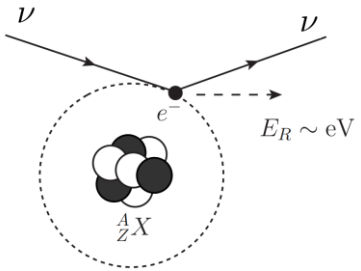
Differential cross-section

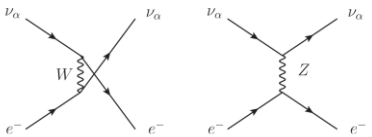
Nuclear recoil





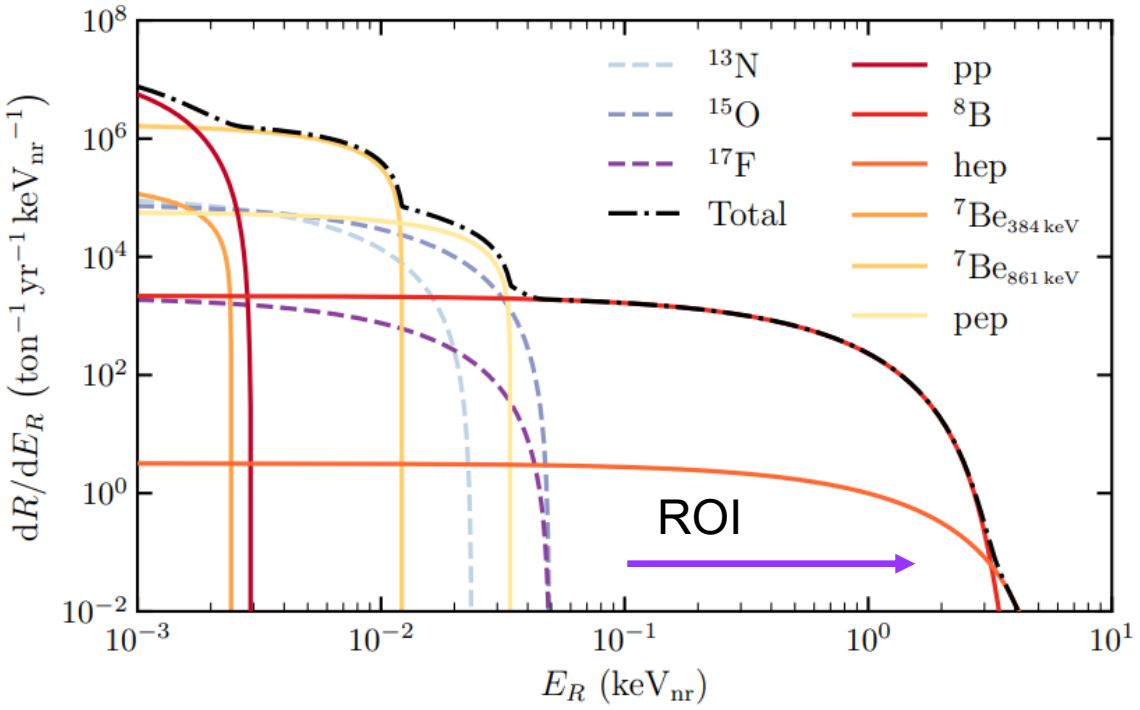
Electron recoil



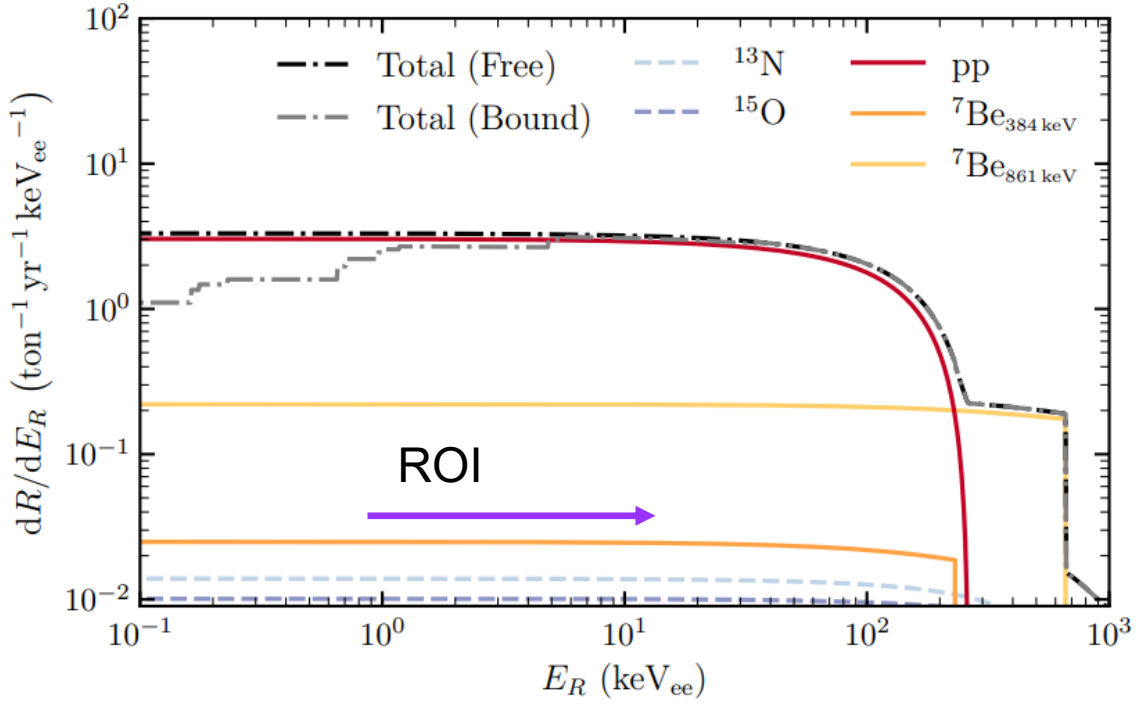


DD signal region of interest (ROI)

Nuclear recoil

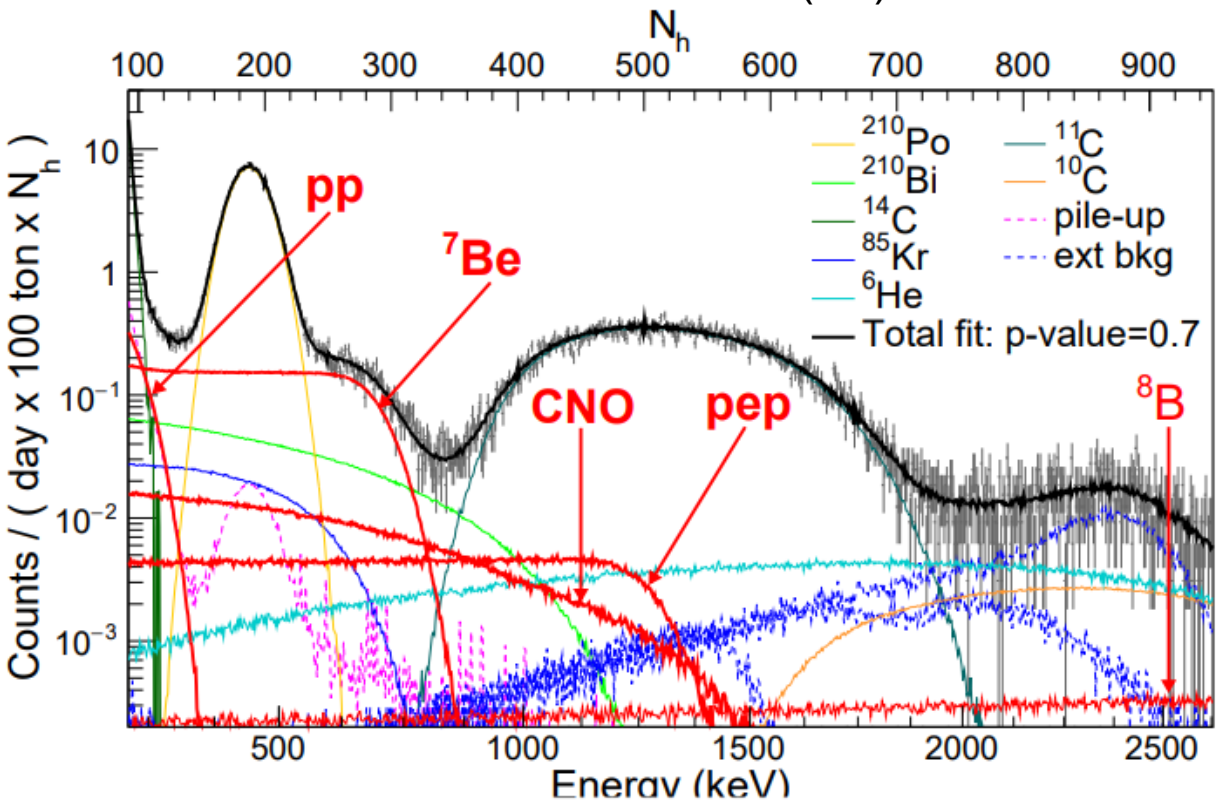


Electron recoil



Other solar ν probes

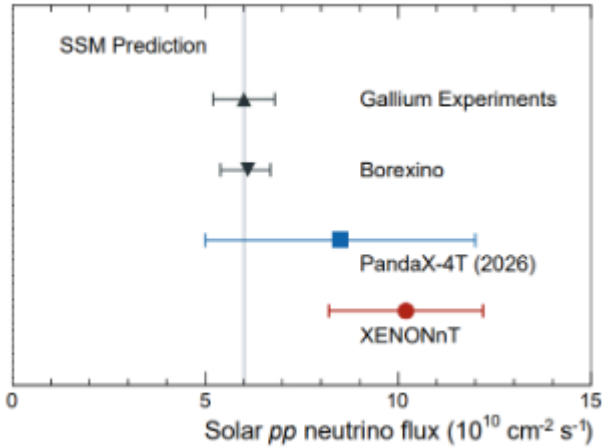
Dedicated solar neutrino detectors have been detecting EνES for a while. DD will have a much cleaner measurement of Boron-8 (8B) neutrinos in the nuclear recoil band (CEνNS).



Borexino

M. Agostini et al. 1707.09279

Recent DD measurements of pp

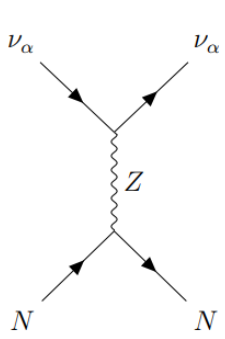


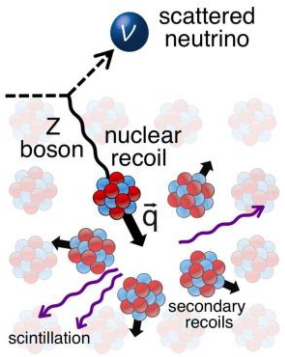
Han, Ji and Liu 2609.02950

New physics in neutrinos?

- Neutrinos are one of the least well understood particles in the Standard Model.
- If we (dark matter searchers) want to overcome this background, we should make sure we characterize the background well.
- Coherent neutrino-nucleus interactions were first observed only a decade ago.

COHERENT collab., arXiv:1708.01294





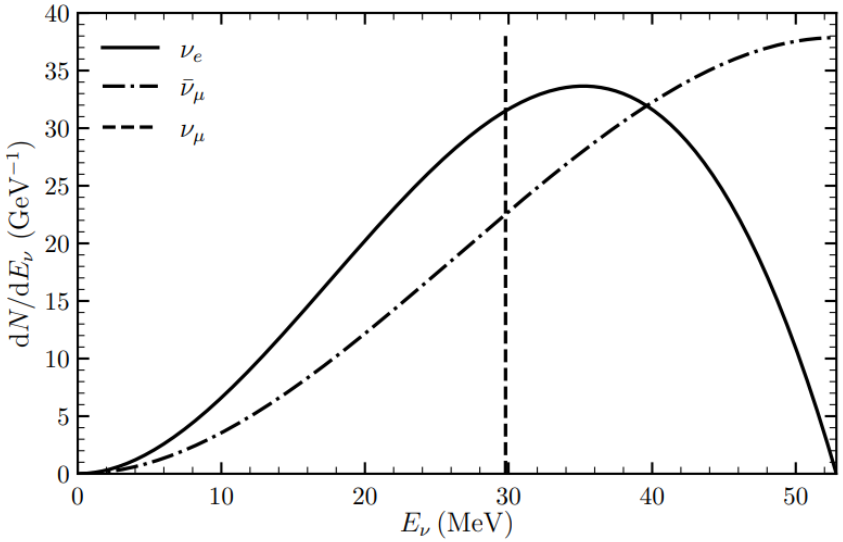
Spallation source experiments

- Beam of neutrinos hits a “fixed target”.

Spallation vs. DD

Spallation source experiments

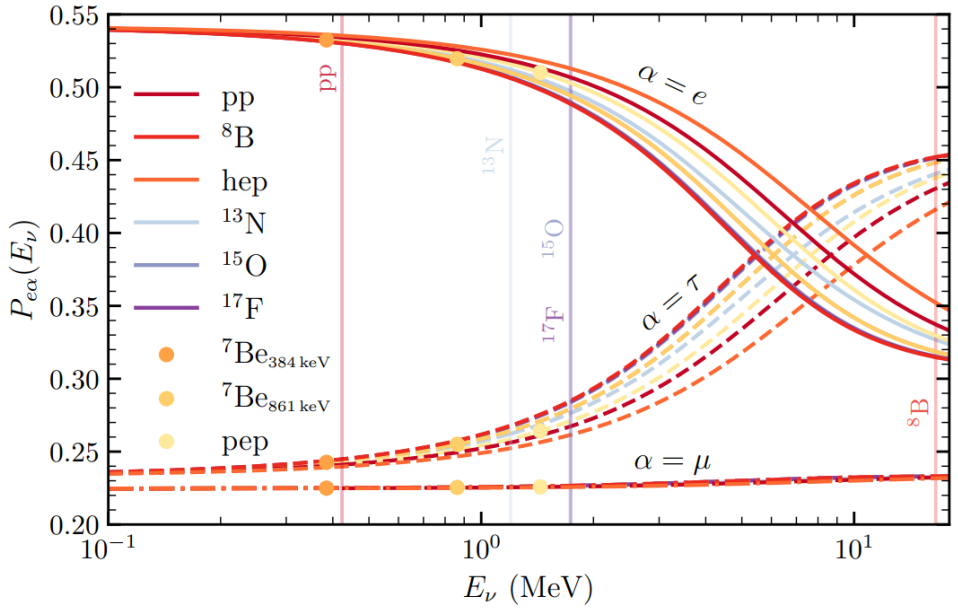
In dedicated CEνNS experiments, neutrinos come from spallation source.



Neutrino flavors are just 1st and 2nd generation.

Direct detection experiments

Solar neutrinos produced in the sun are all 1st generation (ν_e) but oscillate to other flavors.



Pivotal for testing $U(1)_{L_\mu - L_\tau}$!

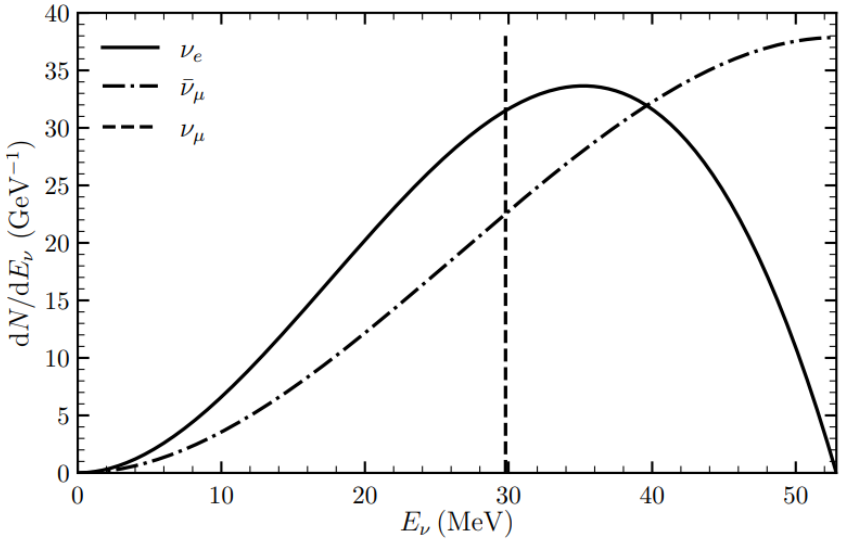
D. Amaral, D. Cerdeno, **AC**, P. Foldenauer, arXiv:2104.03297

Spallation vs. DD

Spallation source experiments

Energy spectra is perfect for nuclear recoils.

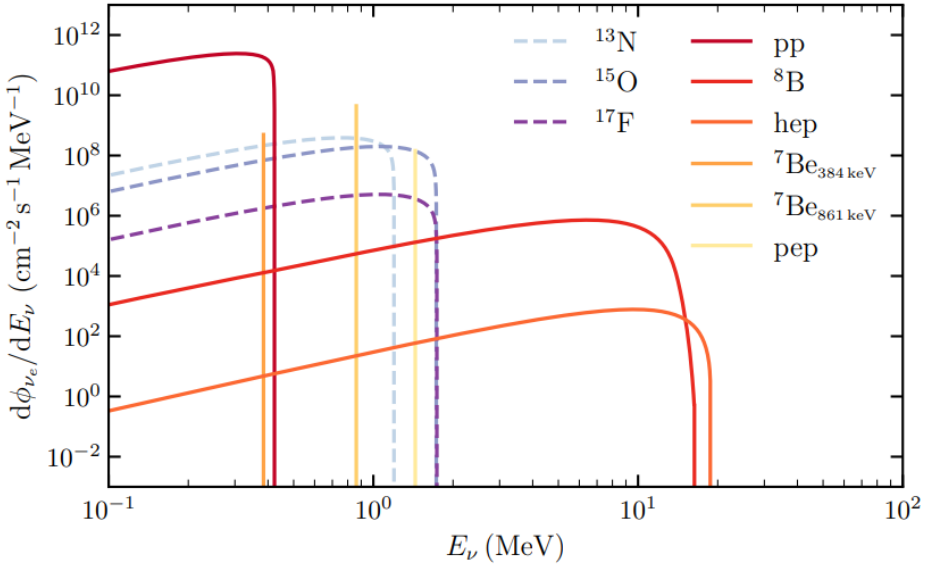
Recoil energy, $E_R \sim 1$ keV requires minimum neutrino energy $E_\nu^{\min} \sim 10$ MeV



Direct detection experiments

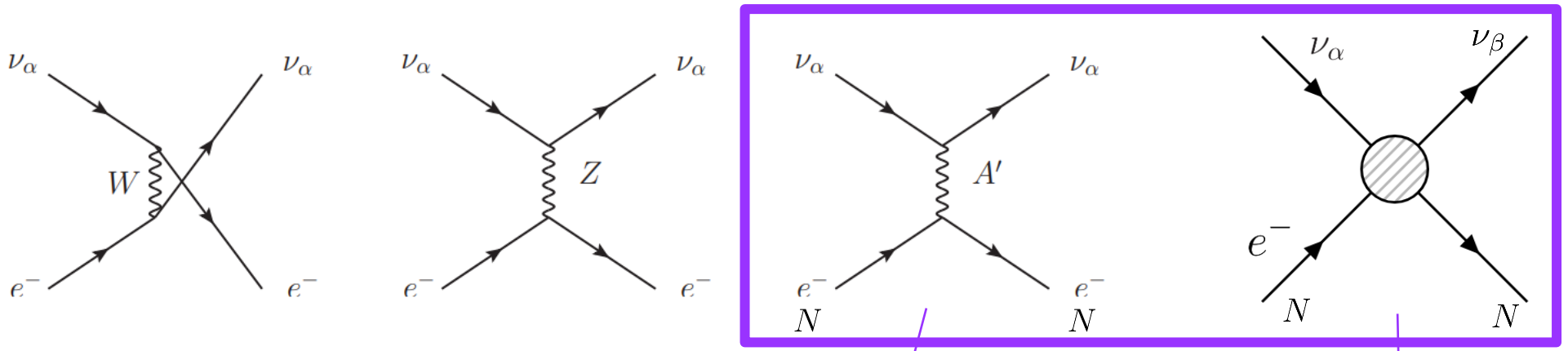
Neutrino flux higher for lower energies.

Electron recoils **and** nuclear recoils in DD.
$E_R \sim 1$ keV requires $E_\nu^{\min} \sim 10$ keV



A simple test of the SM

- With all new measurements, a standard test is to compare the SM hypothesis with something else.



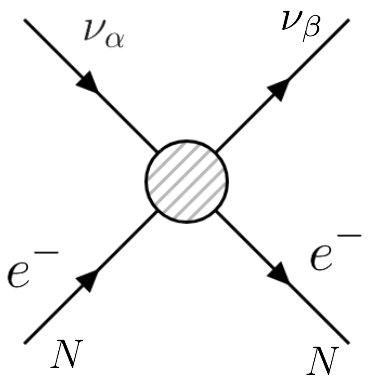
"Full renormalizable model"

$M_A \lesssim q^2$

"Effective interactions"

$M_A \gg q^2$

Effective neutrino interactions (NSI)



$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{\substack{f=e,u,d \\ \alpha,\beta=e,\mu,\tau}} \varepsilon^{fP}_{\alpha\beta}\,[\bar{\nu}_\alpha \gamma_\rho P_L \nu_\beta]\,[\bar{f}\gamma^\rho P f]$$

Neutrino

Charged SM fermion

The conventional effective framework for studying non-standard neutrino interactions assumes you can factorize the new interaction.

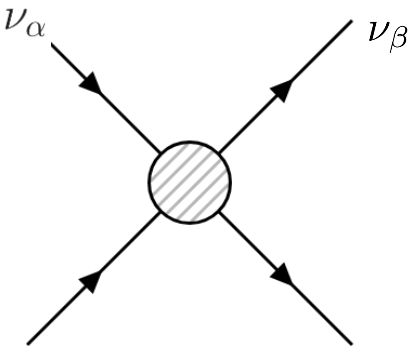
Notice interactions do not have to be flavour diagonal $\alpha \neq \beta$

Non-flavor diagonal interactions

The $|\nu_e\rangle$ is created in Sun

This propagates and states oscillate. $|\nu_e\rangle \rightarrow \hat{S}_{\text{prop}}|\nu_e\rangle$

Then an interaction happens, $\hat{S}_{\text{int}}$ and the final state, in general is undetermined $|f\rangle = \sum_\beta |\nu_\beta\rangle$



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto |\mathcal{A}_{e\to f}|^2 = \left|\sum_\beta \langle\nu_\beta|\hat{S}_{\text{int}}\hat{S}_{\text{prop}}|\nu_e\rangle\right|^2 \Rightarrow \left|\mathcal{A}_{\nu_\alpha\to\sum_i \nu_i}\right|^2 \propto \mathrm{Tr}\left[\boldsymbol{\rho}^{(\alpha)}\,\frac{\mathrm{d}\boldsymbol{\zeta}}{\mathrm{d}E_R}\right]$$

Density matrix

Generalized cross-section

$$\left(\frac{\mathrm{d}\zeta}{\mathrm{d}E_R}\right)_{\alpha\beta} = \left(\frac{\mathrm{d}\zeta}{\mathrm{d}t}\right)_{\alpha\beta}\frac{\mathrm{d}t}{\mathrm{d}E_R} = \frac{\mathcal{M}^*(\nu_\alpha\to f)\,\mathcal{M}(\nu_\beta\to f)}{32\pi\, m_T\, E_\nu^2},$$

D. Amaral, D. Cerdeno, **AC**, P. Foldenauer, *JHEP* **07** (2023) 071

Typical NSI parameterization

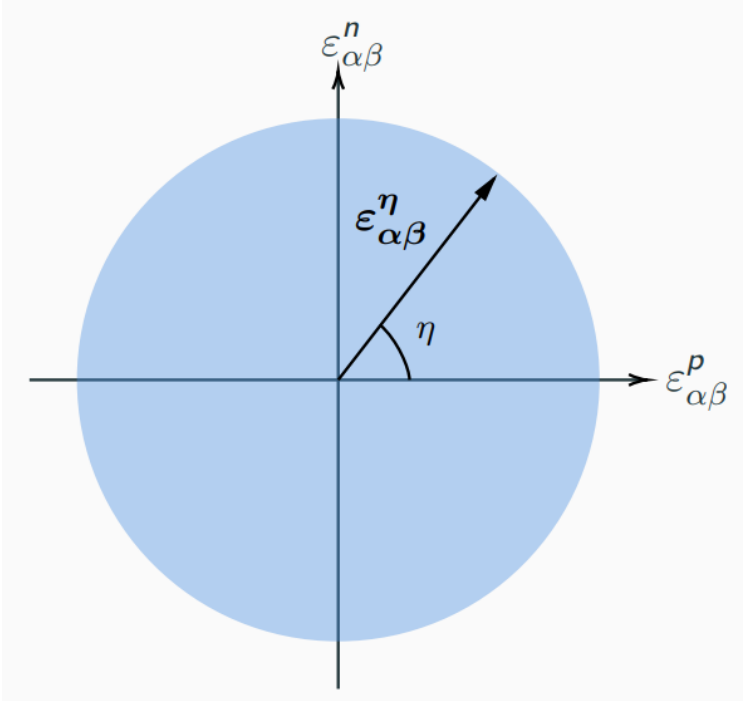
Define the space with proton and neutron directions, i.e. 2D spherical coordinates! Why?

Neutrino-matter oscillations can be separated out like this

$$\mathcal{H}_{\text{matter}} \propto [\overbrace{(\varepsilon^{p}_{\alpha\beta} + \varepsilon^{e}_{\alpha\beta})}^{\text{Total Charged Contrib.}} + Y_n(x)\varepsilon^{n}_{\alpha\beta}]$$

For oscillation effects, one is free to choose any direction in the proton-electron plane.

Pure proton or electron direction makes less sense with DD because they will see electron and nuclear recoils!



Ivan Esteban et al. 1805.04530

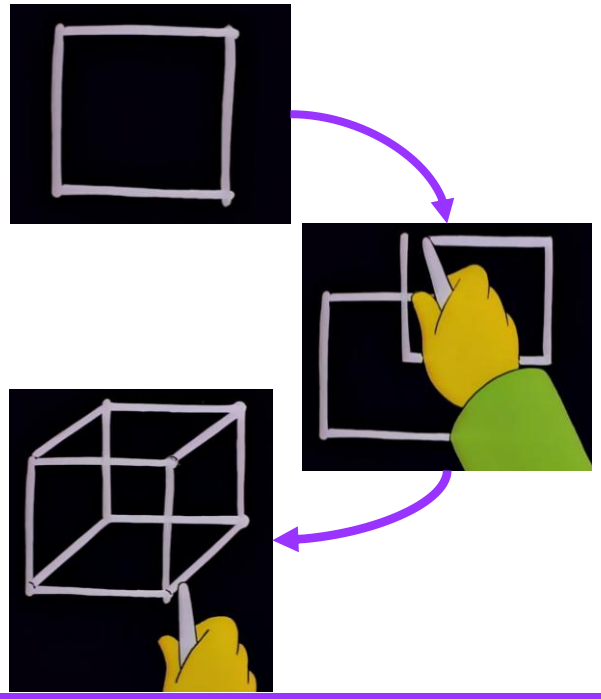
Our extended parameterization

Direct detection requires an NSI parametrization with electron and proton NSIs simultaneously.

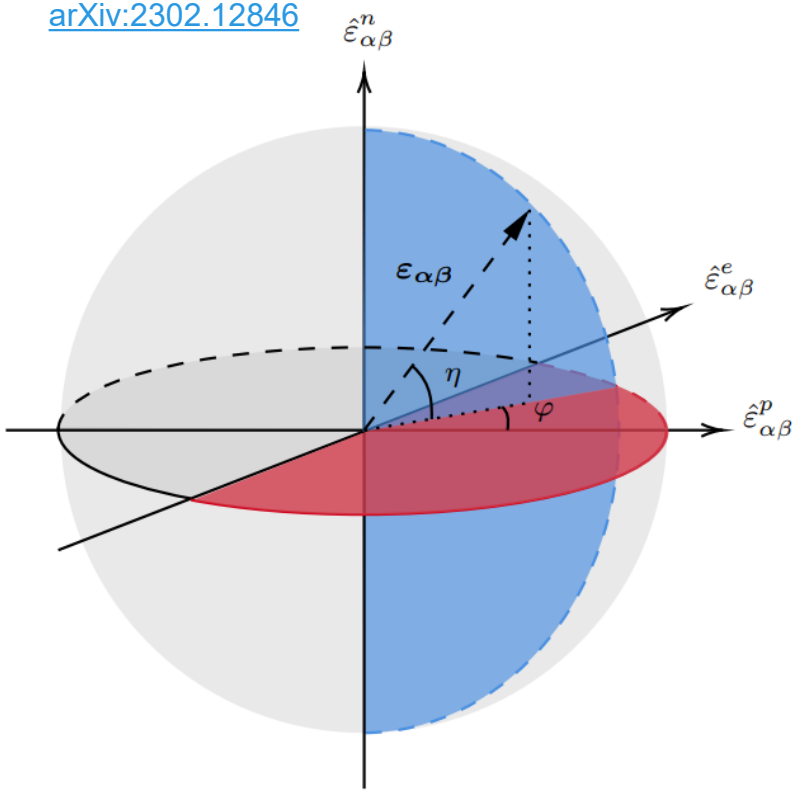
We extend the standard parameterization

$$\varepsilon^{p}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \cos\phi$$
$$\varepsilon^{e}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \sin\phi$$
$$\varepsilon^{n}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \sin\eta$$

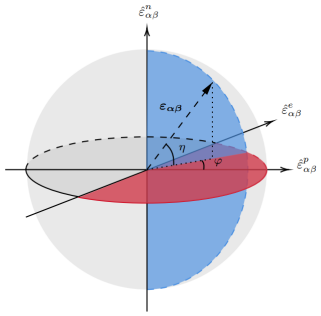
Where usually $\phi = 0$ or $\phi = \pm\frac{\pi}{2}$



D. Amaral, D. Cerdeno, **AC**, P. Foldenauer, arXiv:2302.12846

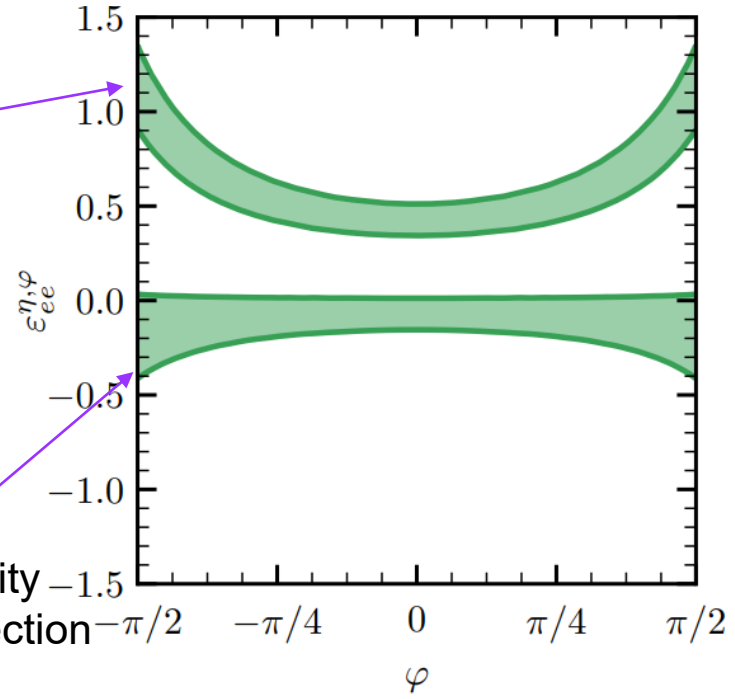


More general framework



CENNS-10

$\eta = \arctan(1/2)$ electron-up plane



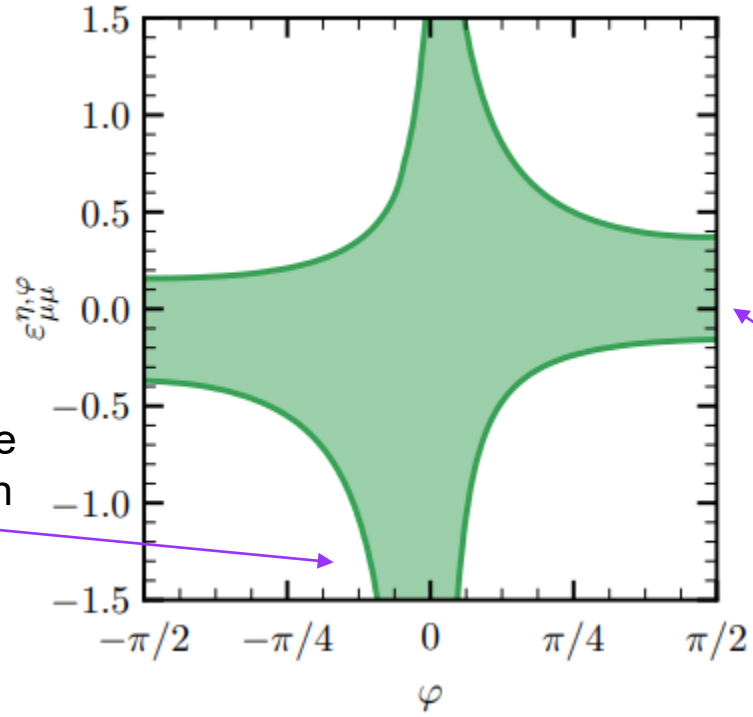
NSI-SM interference

Less sensitivity in proton direction

$$\varepsilon^{p}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \cos\phi$$
$$\varepsilon^{e}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \sin\phi$$
$$\varepsilon^{n}_{\alpha\beta} \sim \varepsilon^{\eta,\phi}_{\alpha\beta} \sin\eta$$

Borexino

$\eta = 0$ electron-proton plane



New physics effects purely the matter oscillation

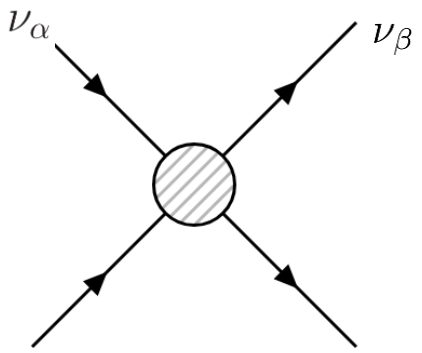
Matter osc. effects and electron interaction.

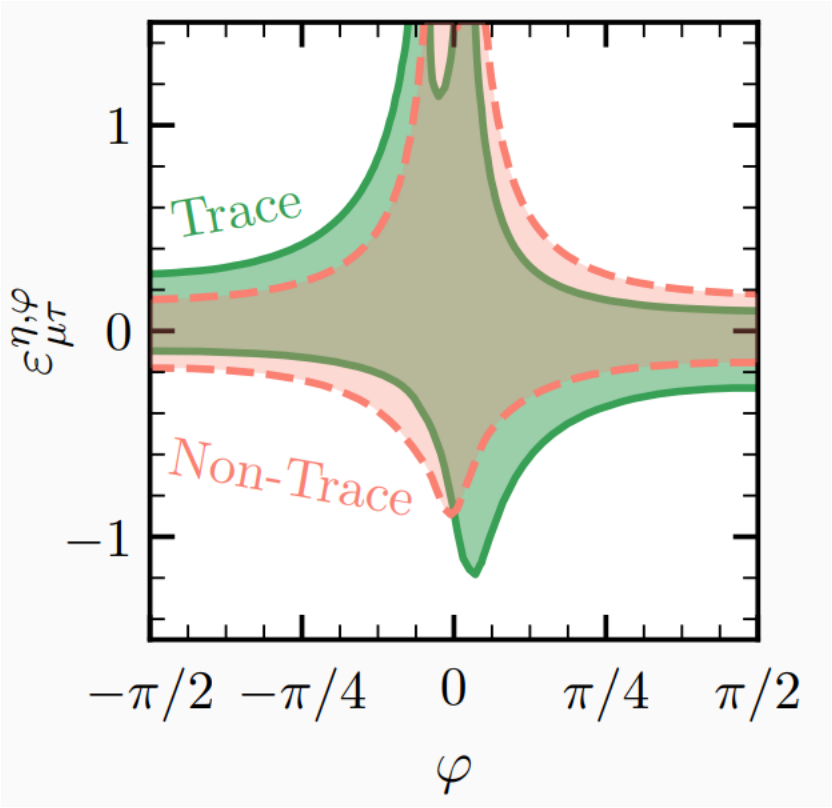
D. Amaral, D. Cerdeno, **AC**, P. Foldenauer, *JHEP* **07** (2023) 071

Off-diagonal effects

- Here I show the effects of using the density matrix formulism

$$\left|\mathcal{A}_{\nu_\alpha \to \sum_i \nu_i}\right|^2 \propto \mathrm{Tr}\left[\boldsymbol{\rho}^{(\alpha)} \frac{\mathrm{d}\boldsymbol{\zeta}}{\mathrm{d}E_R}\right]$$





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arXiv:2607.22817

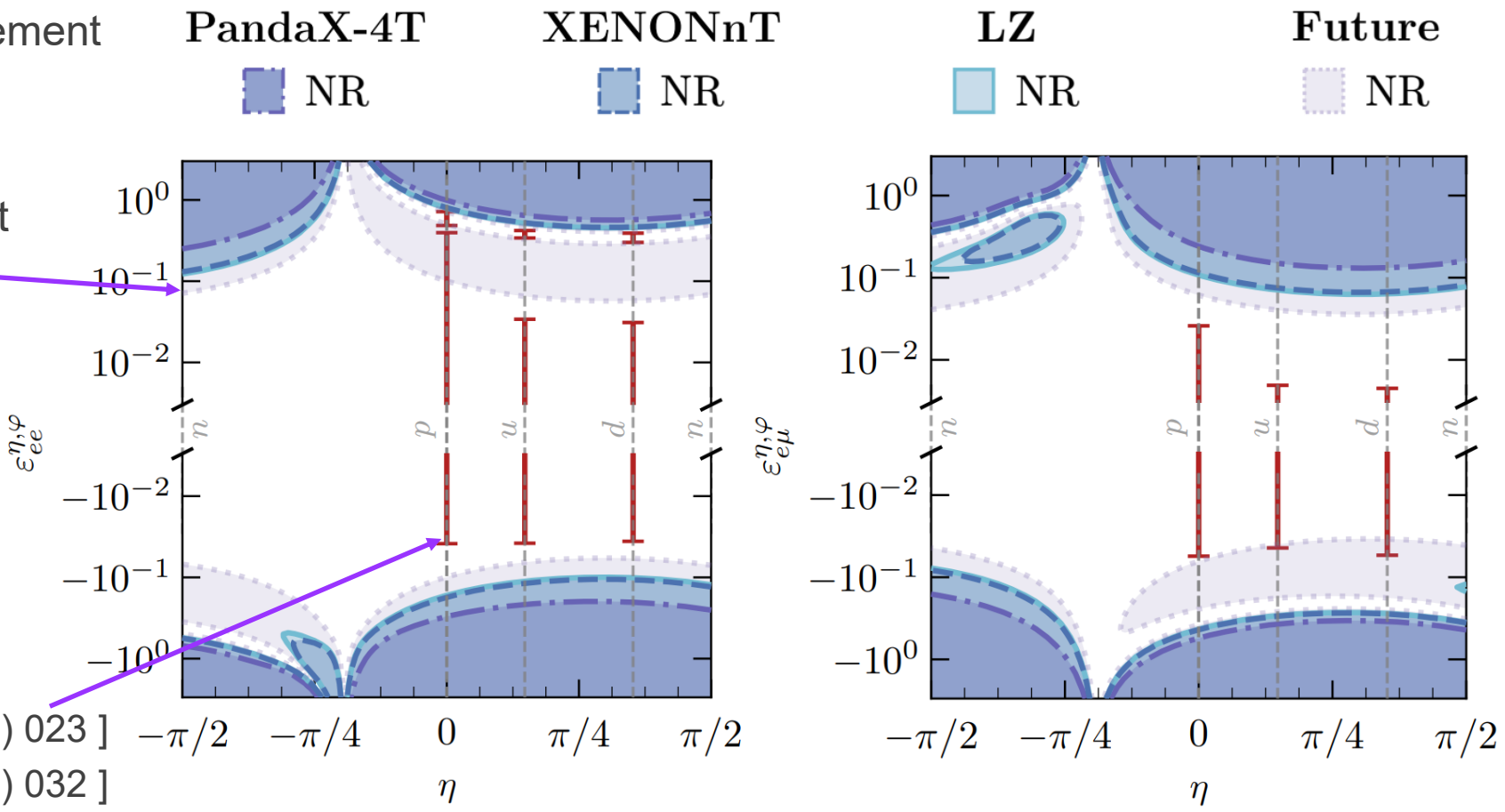
Results from Boron-8 (NR)

Direct detection will complement global NSI studies.

Future Xe exposure doesn't improve the limit much.

Limit is dominated by 8B systematic uncertainty.

Results from global fits
[Coloma et al., *JHEP* **02** (2020) 023]
[Coloma et al., *JHEP* **08** (2023) 032]



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arXiv:2607.22817

Results from pp and Boron-8

In the electron-proton plane **both** CEνNS and EνES signals can deviate.

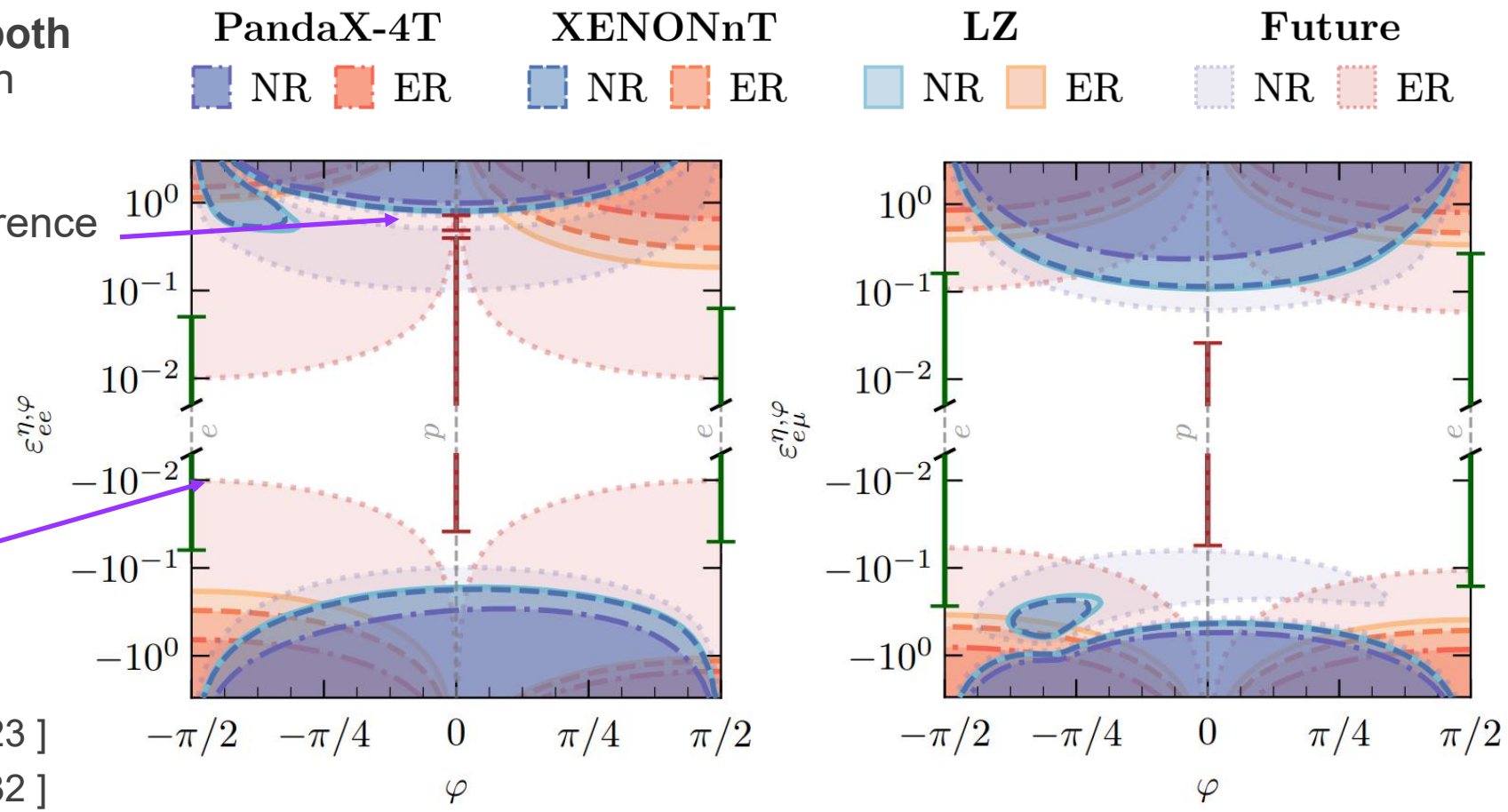
Can probe BSM + SM interference regions.

Projections in ee strongest!

Naive EFT interpretation

$$\Lambda_{\rm NP}/\sqrt{C} \sim 1.8\,{\rm TeV}$$

Results from global fits
[Coloma et al., *JHEP* **02** (2020) 023]
[Coloma et al., *JHEP* **08** (2023) 032]



New Technologies: RES-NOVA

- Upcoming underground cryogenics scintillator neutrino observatory based in Gran Sasso.
- Arry of 8 tons of $\mathrm{PbWO_4}$ crystals.

- Background suppression: simultaneous phonon and light readout, coincidence analysis with modules.
- **Problem**: commercial lead has $10^4 \mathrm{Bq/ton}$ of radioactive $^{210}\mathrm{Pb}$**.**
- **Solution:** Us 2000 yr old lead from sunken Roman ship. (1 $\mathrm{mBq/ton}$ of radioactive $^{210}\mathrm{Pb}$)

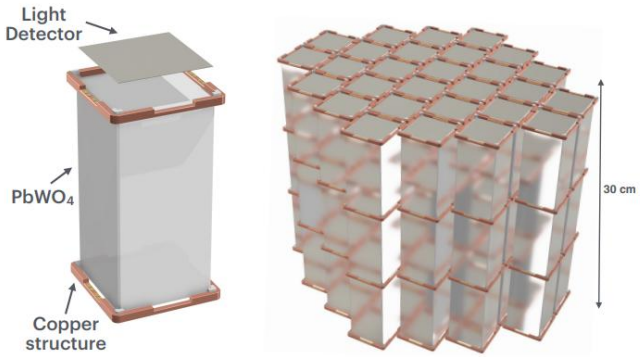
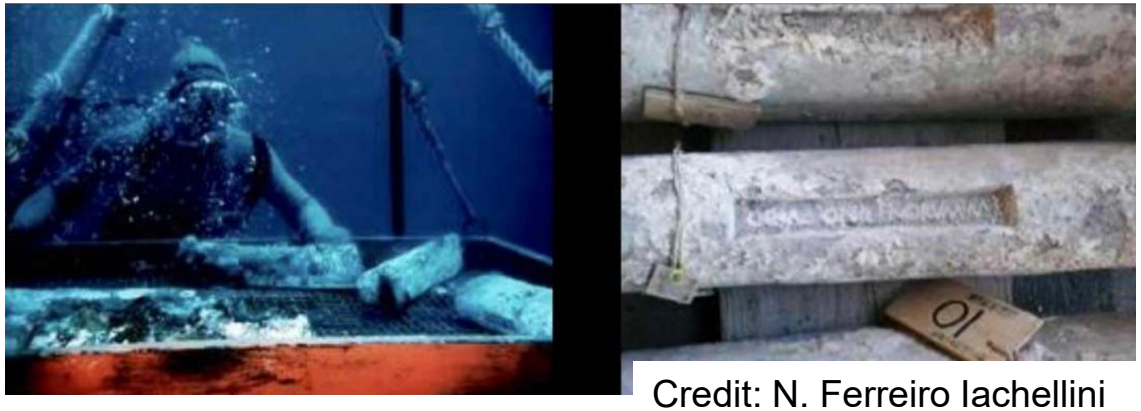


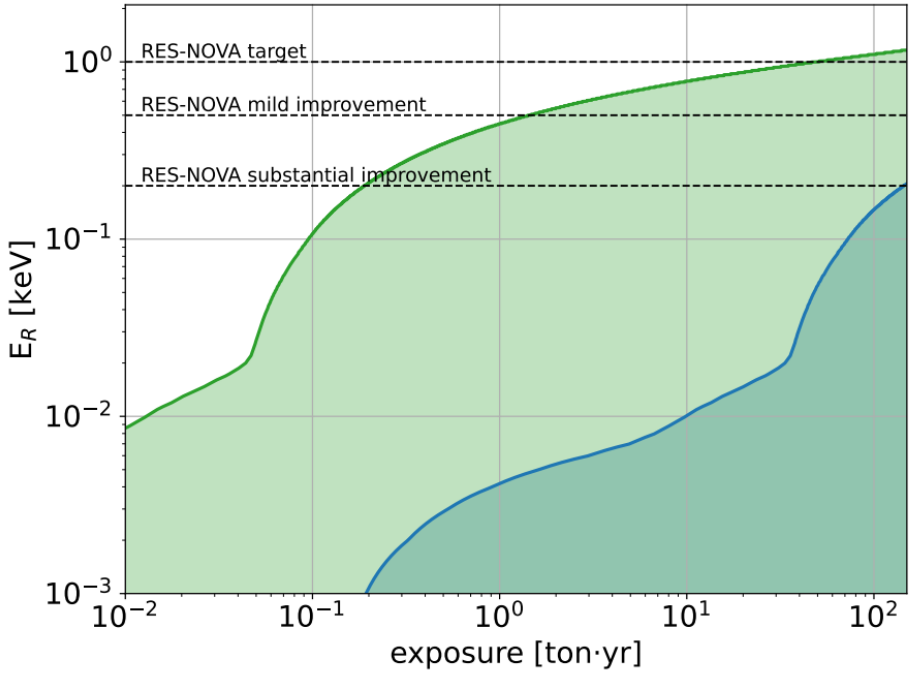
Figure 1. Schematic view of a single detector unit (left) and the full RES-NOVA detector (right). The setup includes a $\mathrm{PbWO_4}$ crystal absorber, a cryogenic light detector and copper mechanical structure.



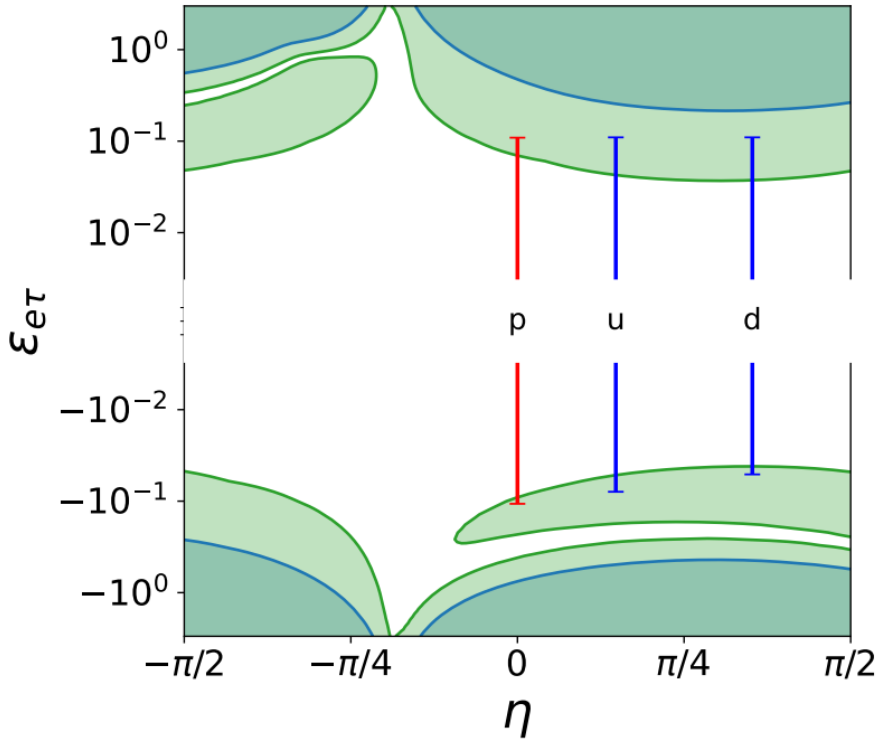
Credit: N. Ferreiro Iachellini

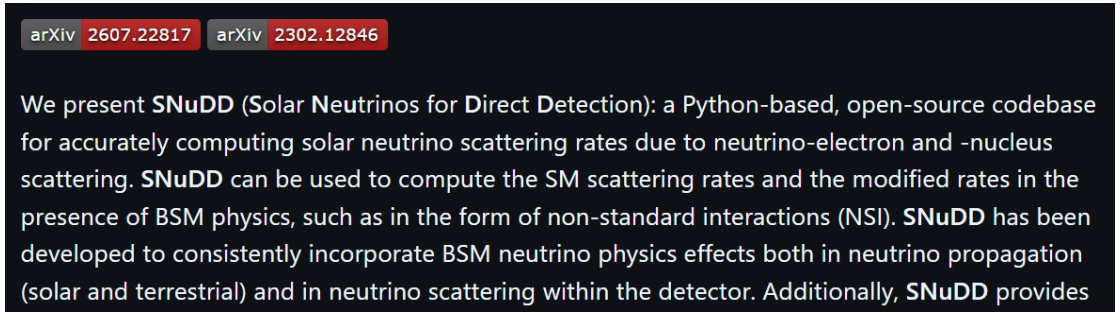
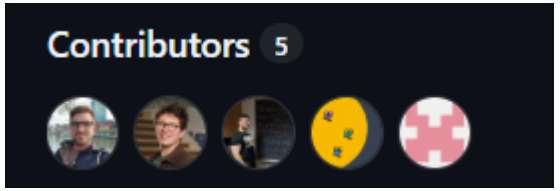
New Technologies: RES-NOVA

Solar ν discovery reach (3σ)



- Projections for RES-NOVA demonstrator for **1-ton** fiducial volume and threshold of **0.5 keV**.



Summary

- Direct dark matter detectors are measuring solar neutrinos, both pp and $^{8}\mathrm{B}$ simultaneously.
- They can be used to probe new physics in the neutrino sector.
- We have developed an open-source code for generating such signals (github.com/SNuDD).