

A direct detection view of new neutrino physics



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<https://projects.ift.uam-csic.es/thedeas/>



IMAGE CREDIT: Mehmet Ergün (top) Matt Kapust/Sanford Lab (bottom)¹

Outline:

Direct (dark matter) detection experiments will soon observe solar neutrinos. This offers a unique possibility to use them to test **new physics in the neutrino sector**.

I will illustrate this with two examples:

- Exploring the parameter space of neutrino Non-Standard Interactions (NSI) in a complementary way to dedicated neutrino experiments

Amaral, Cerdeño, Cheek, Foldenauer, JHEP 07 (2023) 071 ([2302.12846](#))

- Searching for sterile neutrinos in the MeV mass range and determining their mass

Alonso-González, Amaral, Bariego-Quintana, Cerdeño, de los Ríos ([2307.05176](#))

What we do not see in this image:

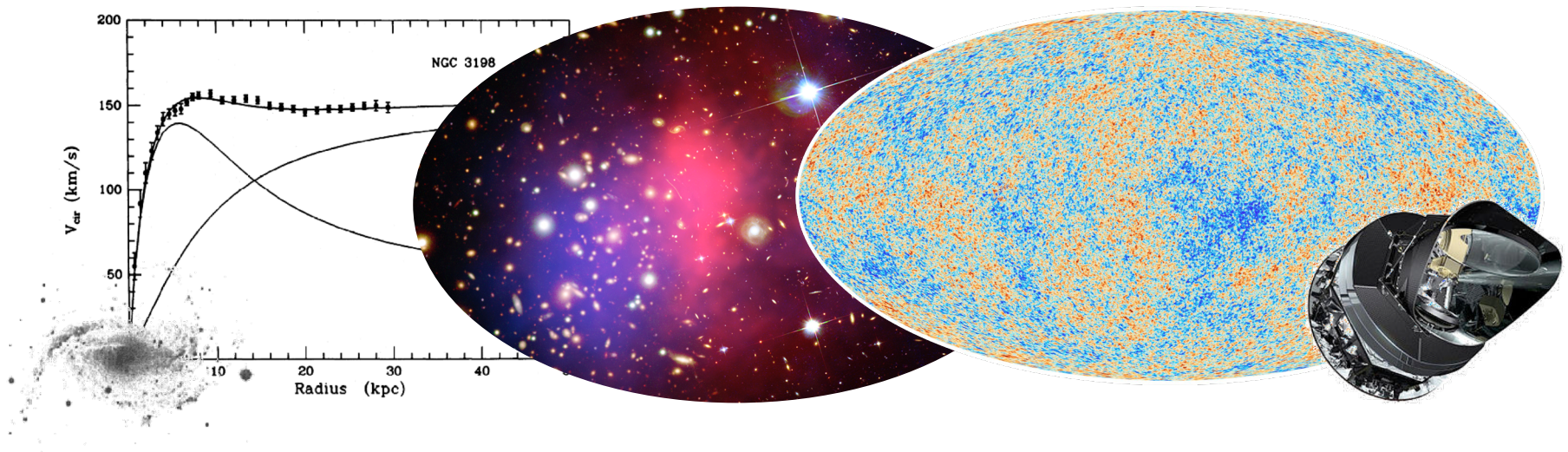
66 billion (solar) neutrinos/cm² s

20 fg of dark matter/cm² s



Dark Matter is a necessary and very abundant component in our Universe

We have observed its gravitational effects at different scales



Galaxies:

The rotation velocity is incompatible with the visible mass (stars and gas) and **non-luminous** matter is needed.

Galaxy clusters

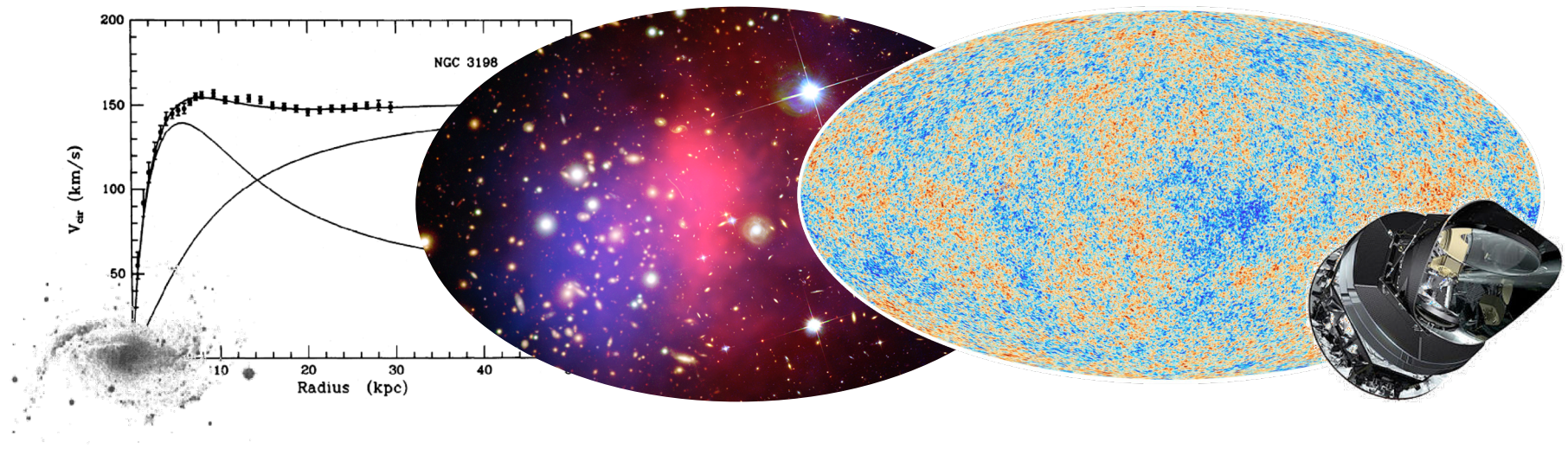
Their typical velocities and dynamics suggest that dark matter has **weak interactions** with ordinary matter and is **not self-interacting**.

Cosmological scales

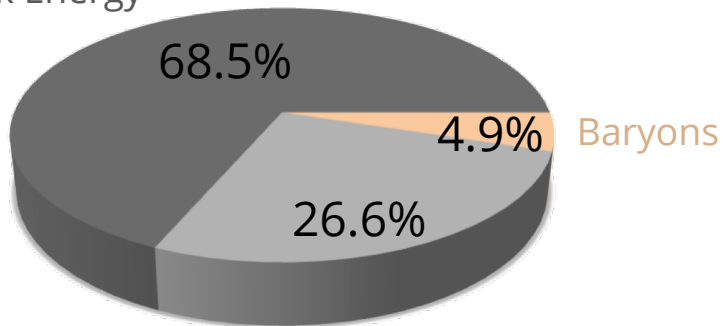
CMB anisotropies together with BBN compatible with a **new type of matter**.

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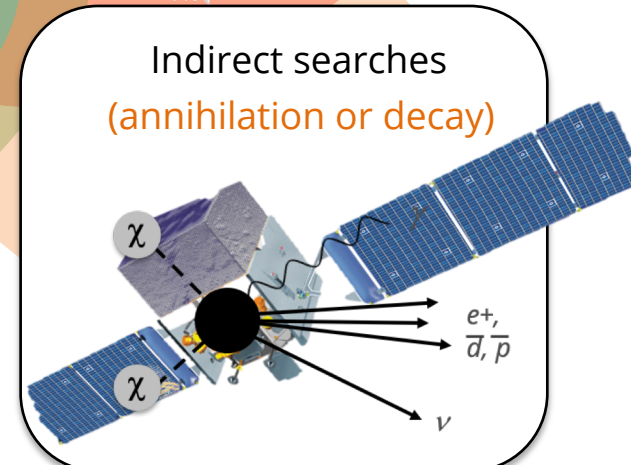
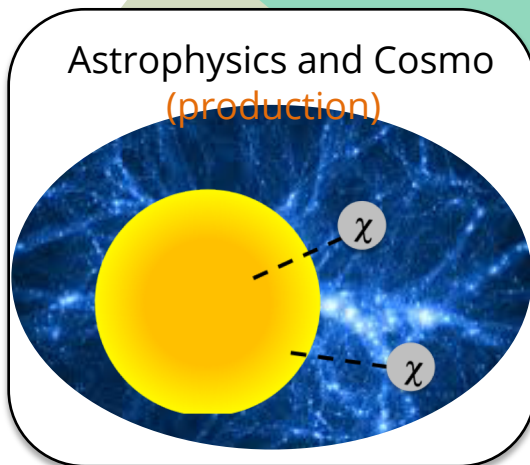
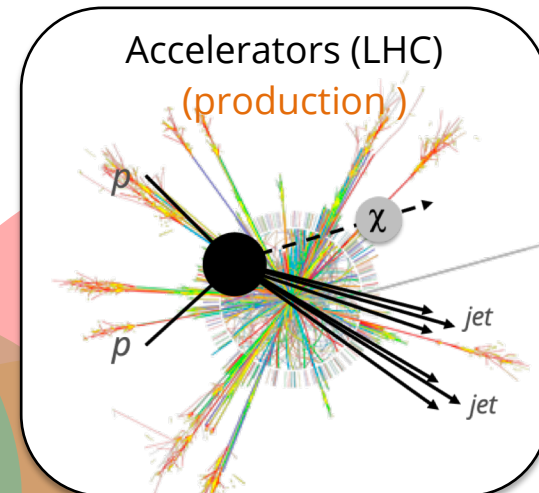
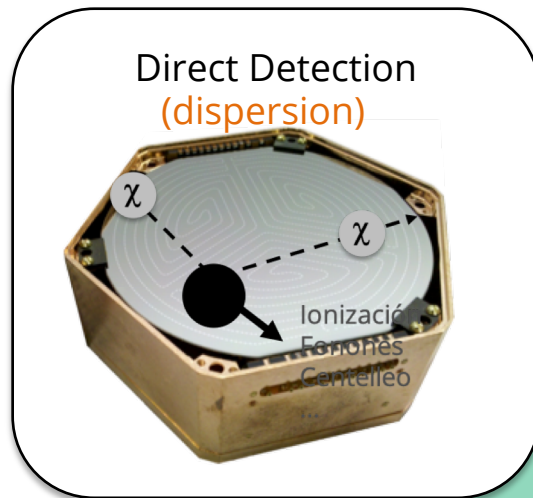
Dark Energy



A plausible hypothesis is that dark matter is a new type of (stable, neutral, weakly-interacting) particle

Dark matter can be searched for in different ways

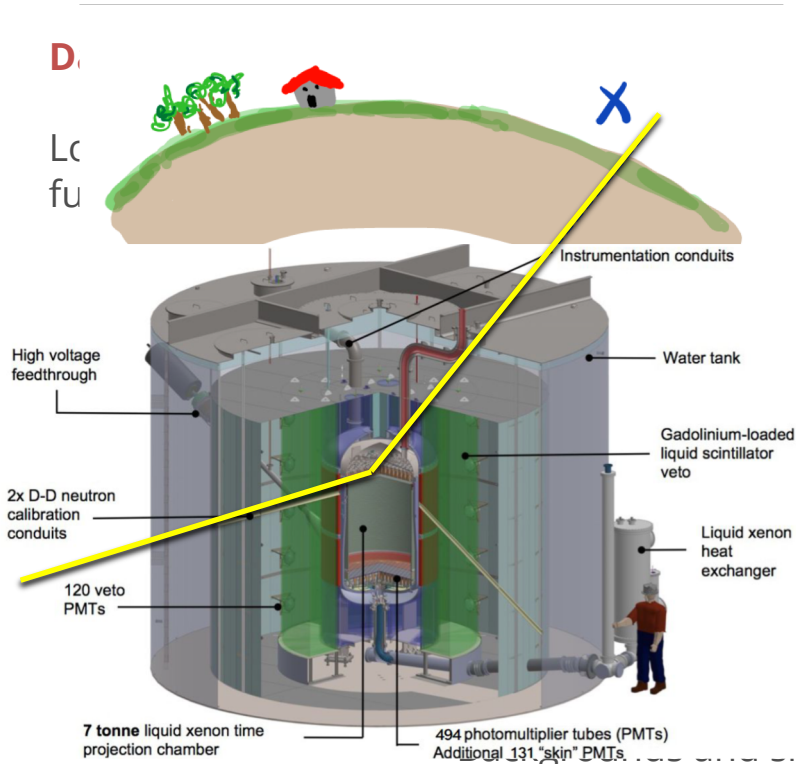
These explore **complementary** properties of dark matter particle models



Direct dark matter detection often requires large underground experiments

Expected number of events

$$N = \int_{E_T} \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\min}} v f(\vec{v}) \frac{d\sigma_{WN}}{dE_R} d\vec{v} dE_R$$



Scattering cross section

Particle physics (dark matter model)

Nuclear Physics (form factors)

Materials Science, solid-state physics etc
(describe the structure of the target in the detector)

reters

n, energy threshold

nal identification

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The scattering cross section contains the details about the microphysics of the DM model

The most general case can be described by means of an Effective Field Theory

$$\mathcal{L}_{\text{int}} = \sum_{i=1,15} c_i \chi^* \mathcal{O}_\chi \chi \Psi_N^* \mathcal{O}_i \Psi_N$$

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i \vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i \vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp \right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right] \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i \vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N} \right]$$

$$\mathcal{O}_{10} = i \vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

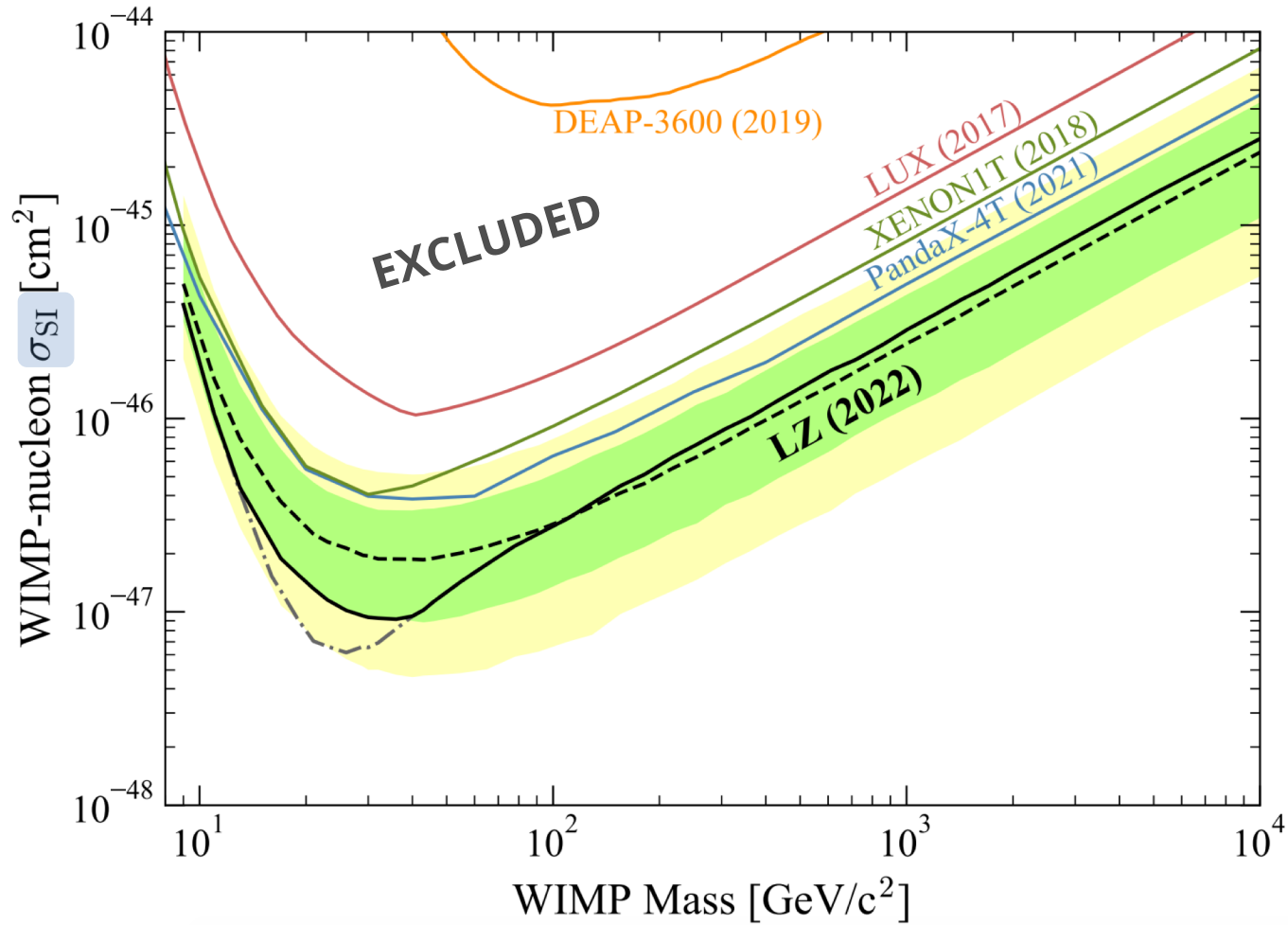
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp \right]$$

$$\mathcal{O}_{13} = i \left[\vec{S}_\chi \cdot \vec{v}^\perp \right] \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right]$$

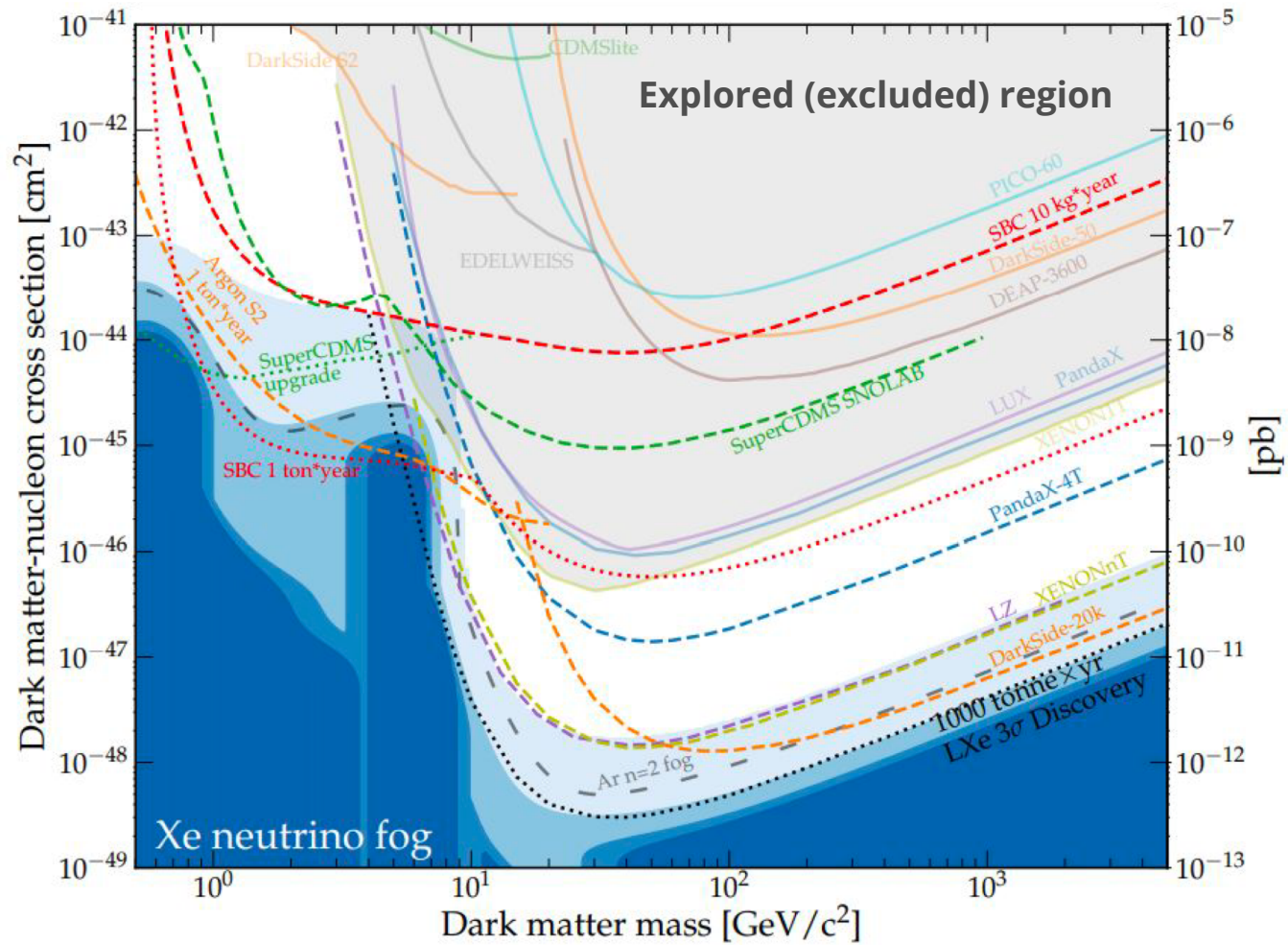
$$\mathcal{O}_{14} = i \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right] \left[\vec{S}_N \cdot \vec{v}^\perp \right]$$

$$\mathcal{O}_{15} = - \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right] \left[\left(\vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_N} \right]$$

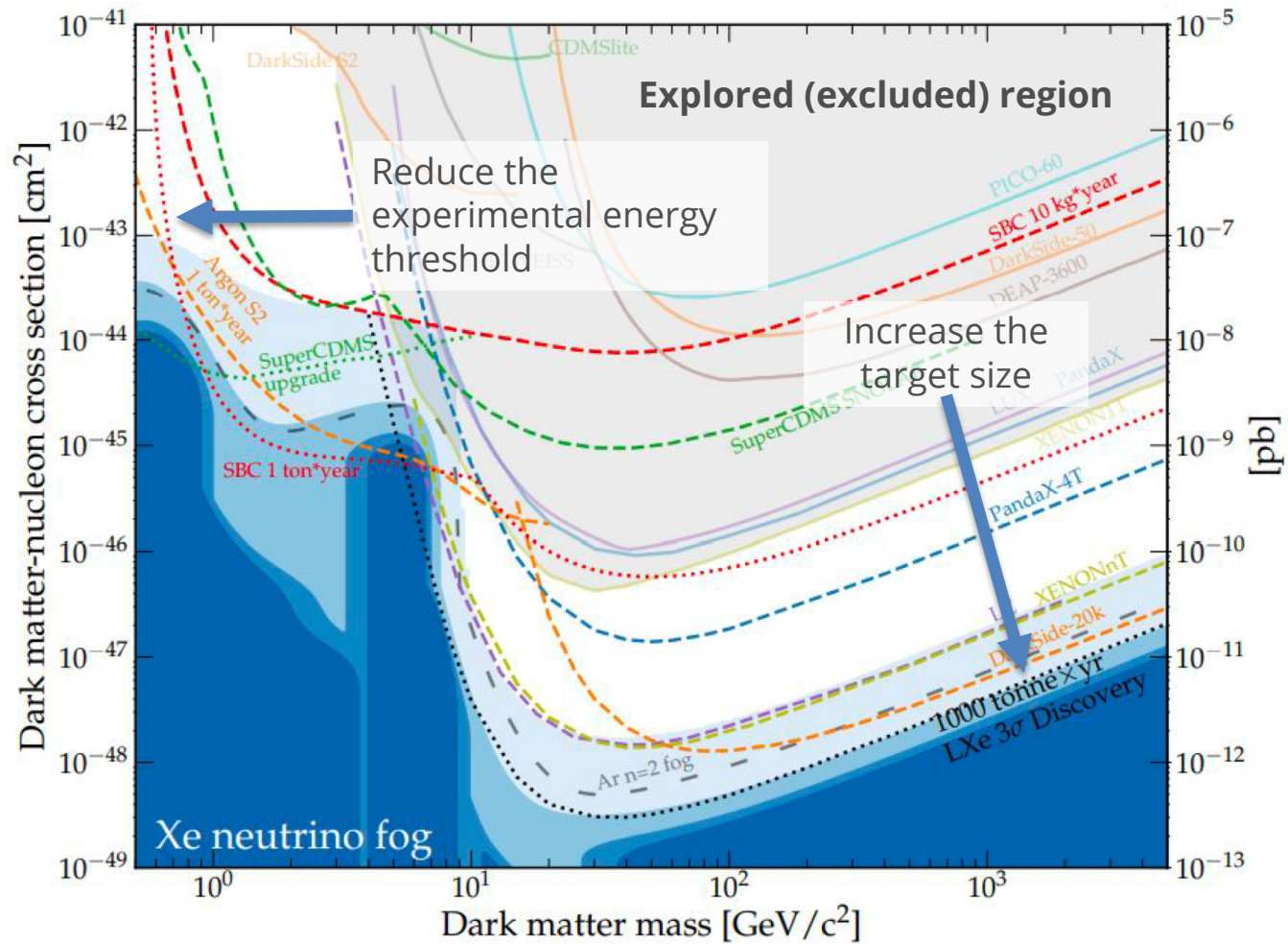
Unsuccessful searches lead to upper constraints on the scattering cross-section



Future experiments will further explore the DM parameter space



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Coherent elastic neutrino-nucleus scattering (CEvNS)

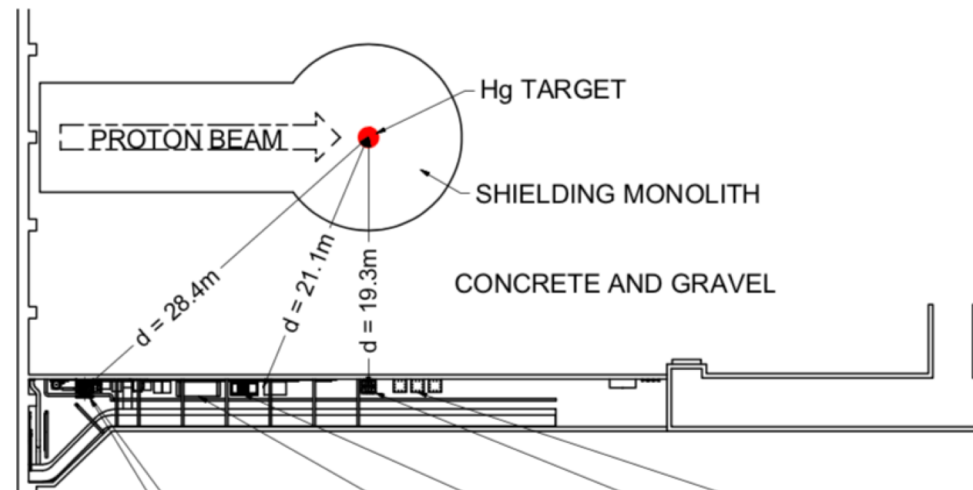
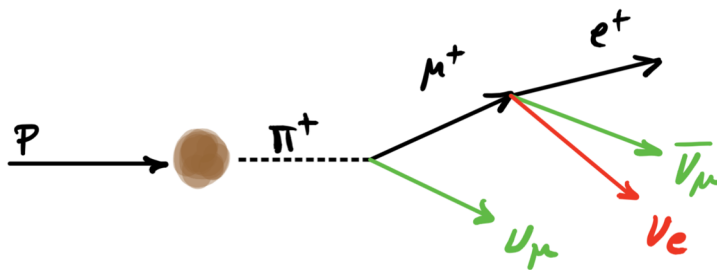
MeV neutrinos have the equivalent length of \sim fm and can scatter **coherently** with nuclei

First experimental detection of CEvNS at the COHERENT experiment, on two complementary targets (Csl and Lar).

COHERENT Collab. 2017, 2021

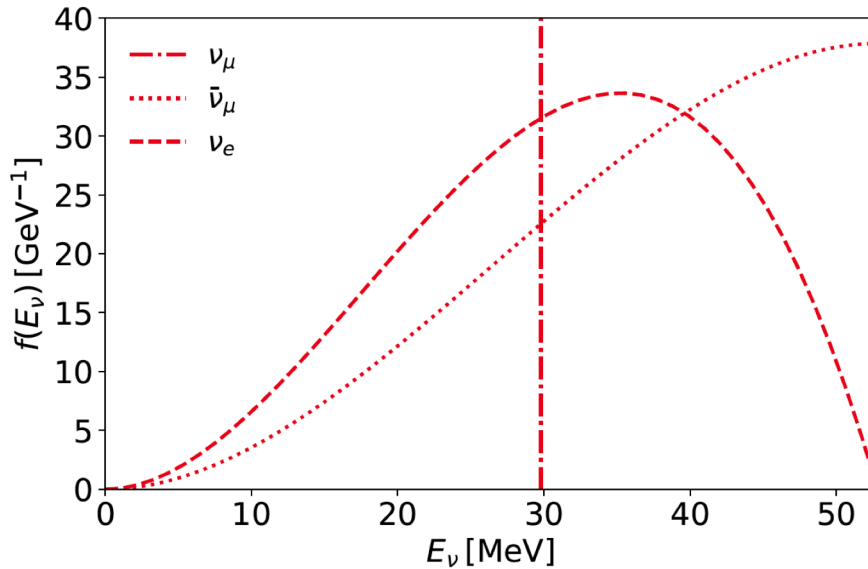
The results are compatible with the SM prediction, leading to constraints on potential new physics.

Coloma et al. (2017); Denton et al. (2018); Abdullah et al. (2018); Amaral et al. (2020)
Flores et al. (2020); Miranda et al. (2020); Shoemaker et al. (2021)



Signal at Spallation Source experiments

The neutrino flux contains three components: the continuous ν_e and ν_μ and the monochromatic $\bar{\nu}_\mu$



$$\frac{d\phi_{\nu_\mu}}{dE_\nu} = \xi \delta \left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \right),$$

$$\frac{d\phi_{\bar{\nu}_\mu}}{dE_\nu} = \xi \frac{64}{m_\mu} \left[\left(\frac{E_\nu}{m_\mu} \right)^2 \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right) \right]$$

$$\frac{d\phi_{\nu_e}}{dE_\nu} = \xi \frac{192}{m_\mu} \left[\left(\frac{E_\nu}{m_\mu} \right)^2 \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right) \right]$$

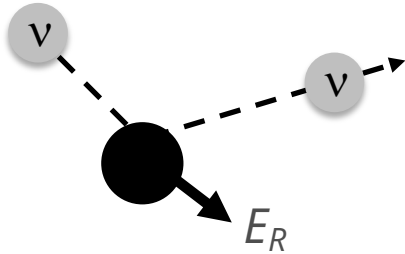
$$\xi \equiv r R_{\text{POT}} / (4\pi L^2)$$

$$\frac{dR_{\alpha'}}{dE_R} = \frac{1}{m_A} \int_{E_\nu^{\text{min, CE}\nu\text{NS}}}^{E_\nu^{\text{max}}} \frac{d\phi_{\nu_{\alpha'}}}{dE_\nu} \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}$$

Neutrinos can be observed in direct detection experiments:

Direct detection experiments are becoming so sensitive that they will soon be able to detect solar and atmospheric neutrinos.

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



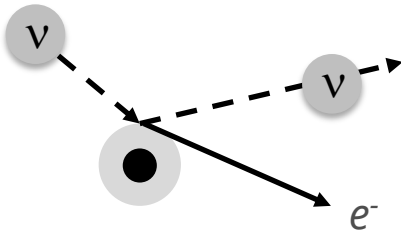
Rare Standard Model process recently measured in spallation source experiments

COHERENT Collab. 2017, 2021

Irreducible background – neutrino fog/floor

O'Hare et al 2017

(Inelastic) electron scattering

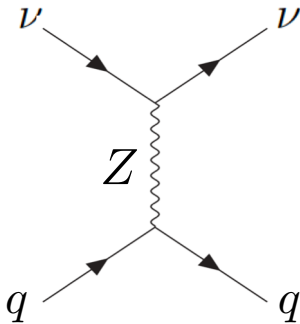


Usual electroweak process mediated by the Z and W bosons

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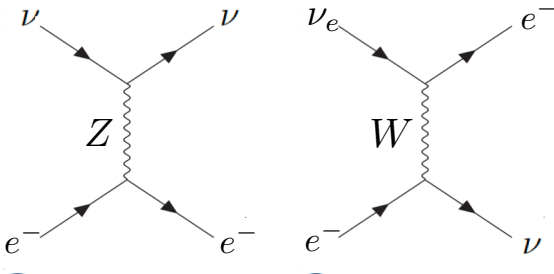
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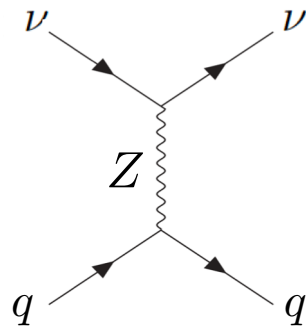


Usual electroweak process mediated by the Z and W bosons

Expected signal in a direct detection experiment

$$N = \varepsilon n_T \int_{E_{\text{th}}}^{E_{\text{max}}} \sum_{\nu_\alpha} \int_{E_\nu^{\text{min}}} \frac{d\phi_{\nu_\alpha}}{dE_\nu} \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



The Standard Model rate has no free parameters

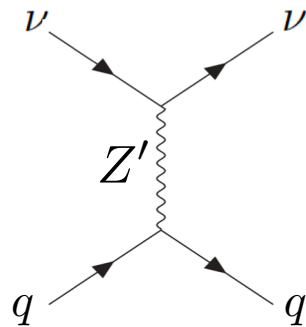
$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_\nu^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_\nu = N - (1 - 4 \sin^2 \theta_W) Z$$

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Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



New physics can lead to extra contributions to CEvNS

- The neutrino floor rises
- It makes it possible to observe the new low-mass mediators

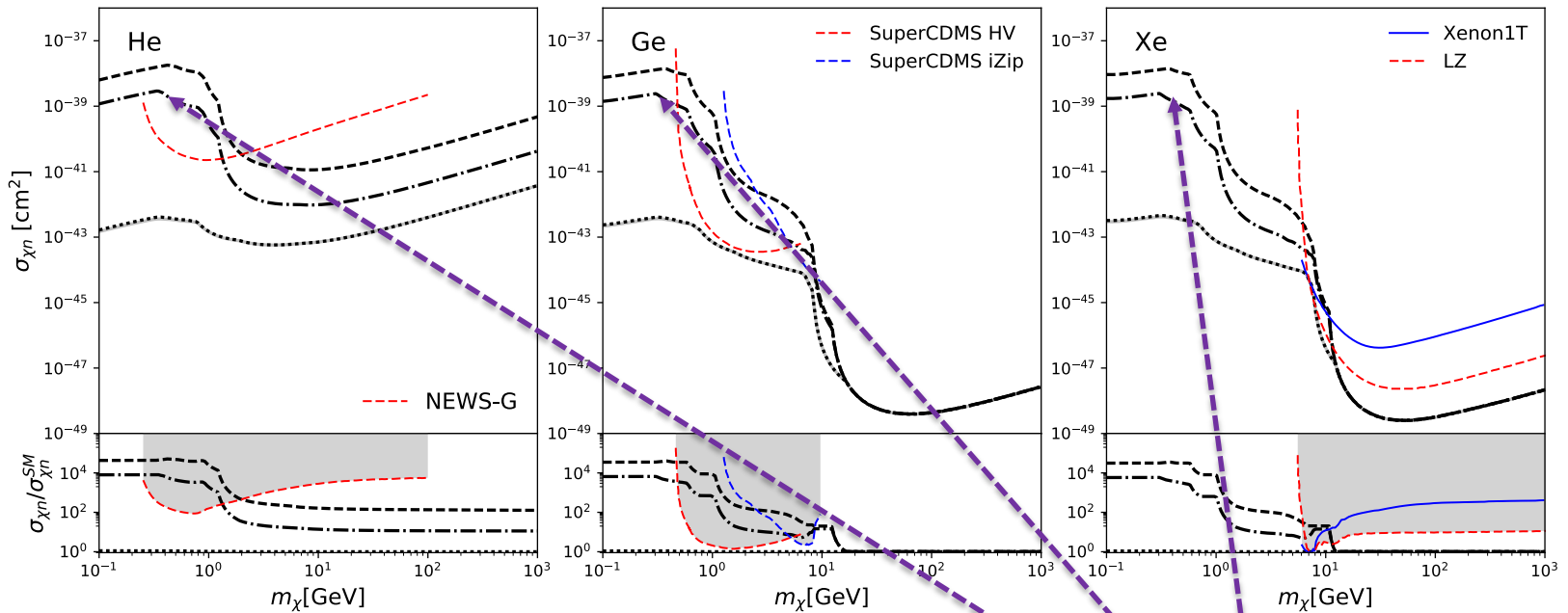
$$\frac{d\sigma_{\nu_\alpha N}}{dE_R} = \frac{G_F^2 M_N}{\pi} \left(1 - \frac{M_N E_R}{2E_\nu^2} \right) \times \left\{ \frac{Q_{\nu N}^2}{4} + \frac{g_x \epsilon_x e Z Q_{\nu_\alpha}^x Q_{\nu N}}{\sqrt{2} G_F (2M_N E_R + M_{A'}^2)} + \frac{g_x^2 \epsilon_x^2 e^2 Z^2 Q_{\nu_\alpha}^{x^2}}{2 G_F^2 (2M_N E_R + M_{A'}^2)^2} \right\} F^2(E_R)$$

SM
New Physics

How high is the neutrino floor?

Scalar-mediated models

Boehm, Cerdeño, Machado, Olivares, Reid 2018



The neutrino floor can be orders of magnitude higher than in the SM

This big increase is due to the reevaluation of Supernovae constraints

Cerdeño, Cermeño, Pérez, Reid 2021

Neutrino flux

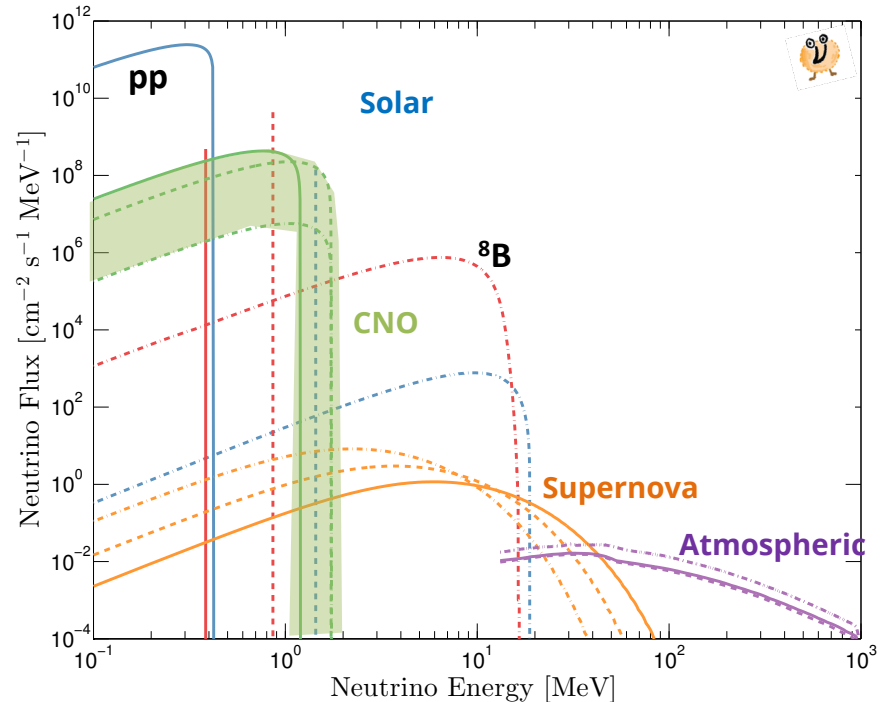
$$N = \varepsilon n_T \int_{E_{\text{th}}}^{E_{\text{max}}} \sum_{\nu_\alpha} \int_{E_\nu^{\text{min}}} \left[\frac{d\phi_{\nu_\alpha}}{dE_\nu} \right] \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

Solar neutrinos

dominate at low energy – the leading contribution is the pp chain below 1 MeV

Diffuse supernova neutrino background
relevant around ~20-50 MeV. Yet undetected

Atmospheric
very energetic but with a much smaller rate



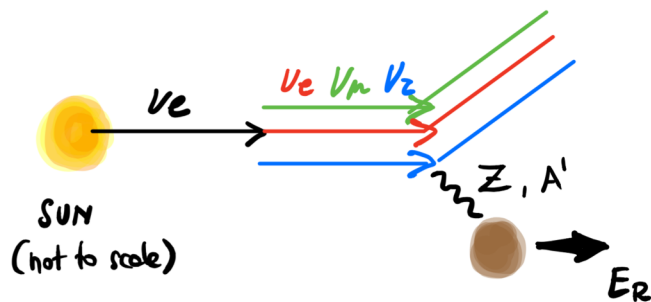
Neutrino flux

$$N = \varepsilon n_T \int_{E_{th}}^{E_{max}} \sum_{\nu_\alpha} \int_{E_\nu^{min}} \frac{d\phi_{\nu_e}}{dE_\nu} P(\nu_e \rightarrow \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

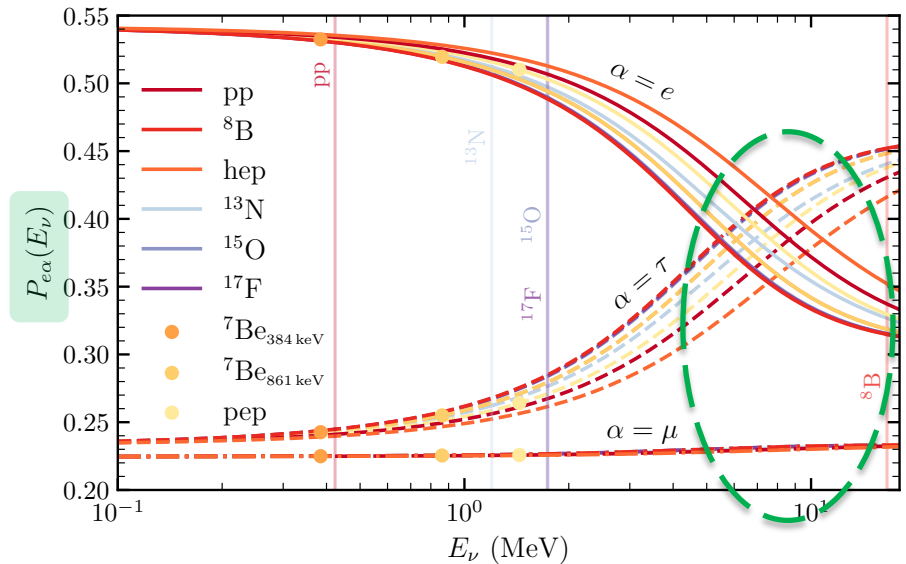
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Produced as electron neutrinos, they oscillate into other flavours



Amaral, Cerdeño, Foldenauer, Reid 2020

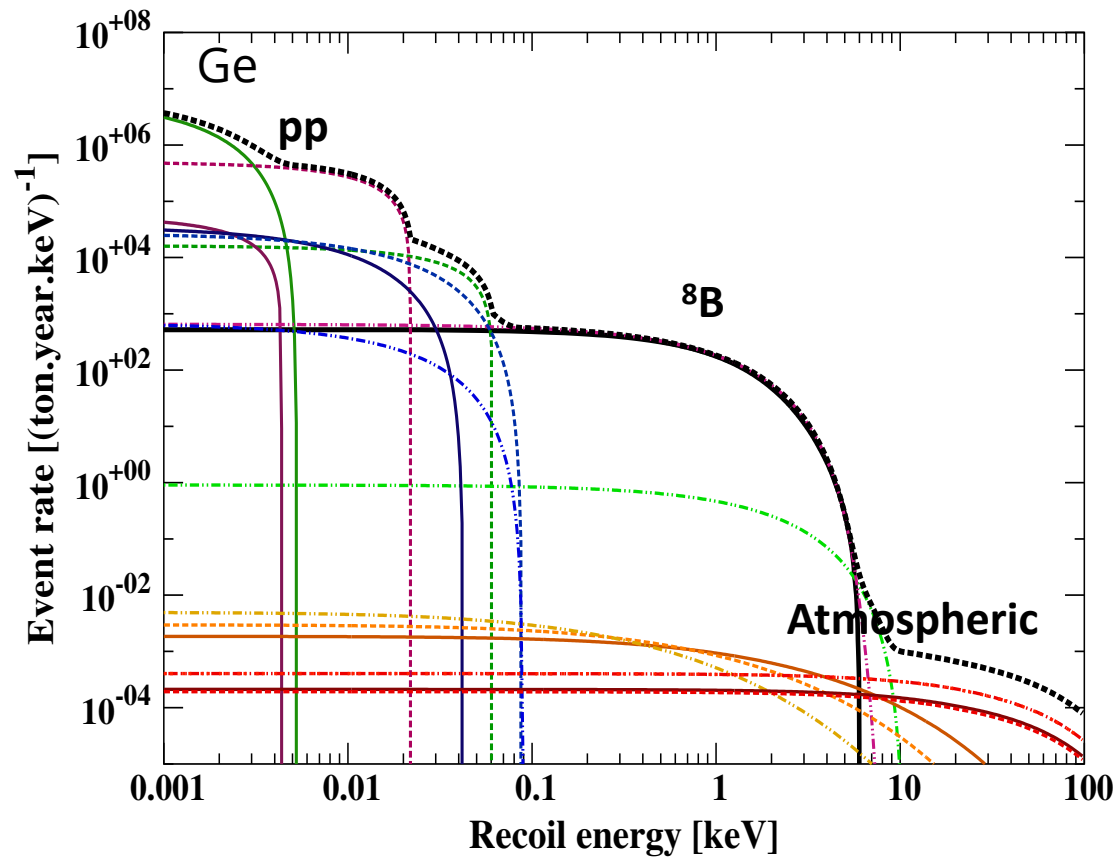


Matter oscillation in solar medium dominates flavour composition reaching earth: at 10 MeV (⁸B) there is **significant oscillation** into ν_μ , ν_τ

Experimental response to CEvNS

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014

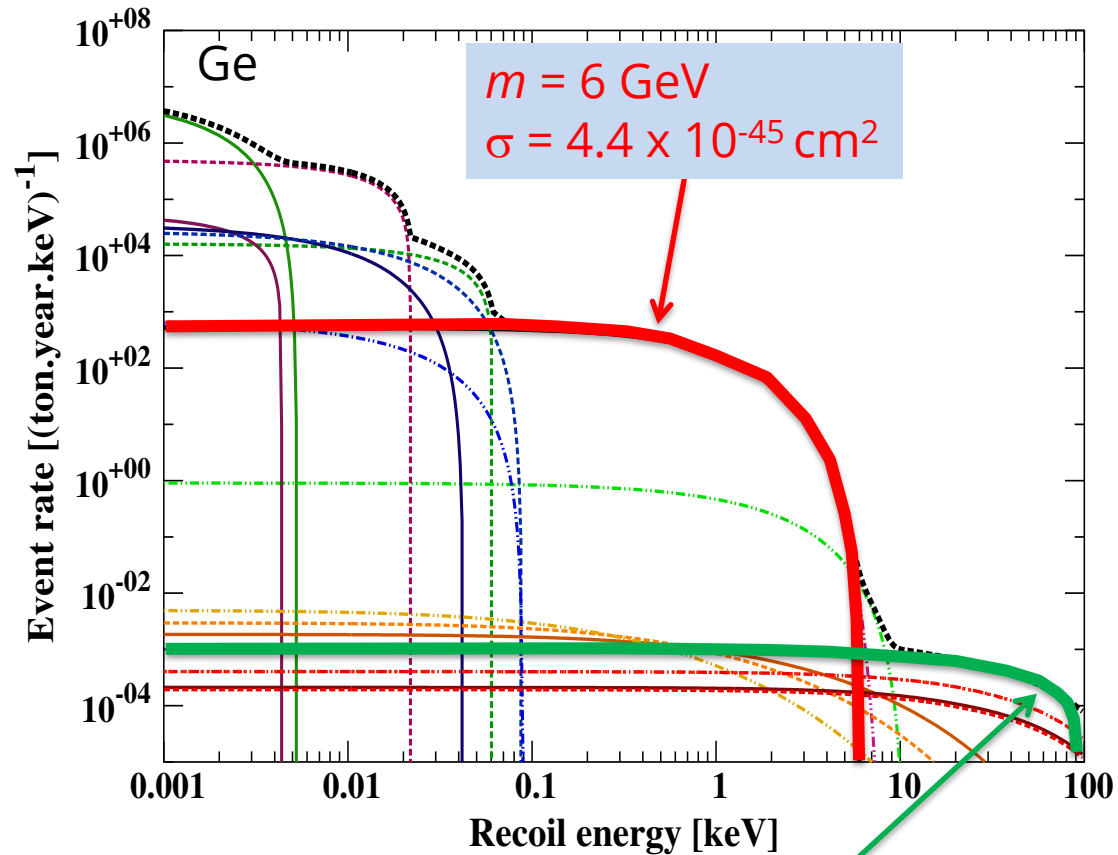
- **Solar neutrinos**
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contribute at higher energies but at a much smaller rate
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Direct (DM) detectors can be excellent **complementary test of new neutrino physics**

- Low energy threshold and excellent energy resolution
- Sensitive to both nuclear and electron recoils
- Sensitive to the three neutrino flavours ν_e, ν_μ, ν_τ

Two examples:

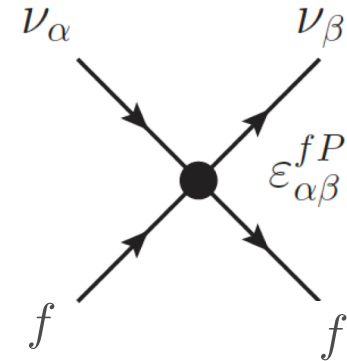
- Direct detection can already set constraints on the general neutrino **non-standard interaction (NSI)** parameter space. Future direct detectors will complement information from dedicated neutrino experiments
[Amaral, Cerdeño, Cheek, Foldenauer 2023](#)
- It can also help to reconstruct the **sterile neutrino** mass when combined with data from spallation source experiments.
[Alonso, Amaral, Bariego, Cerdeño, de los Ríos 2023](#)

Effective theories: Non-standard Interactions

The new physics can be expressed in terms of an effective theory, which parametrises corrections wrt the SM in terms of neutrino **Non-Standard Interactions** (NSI)

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

$$\varepsilon_{\alpha\beta}^f = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$$



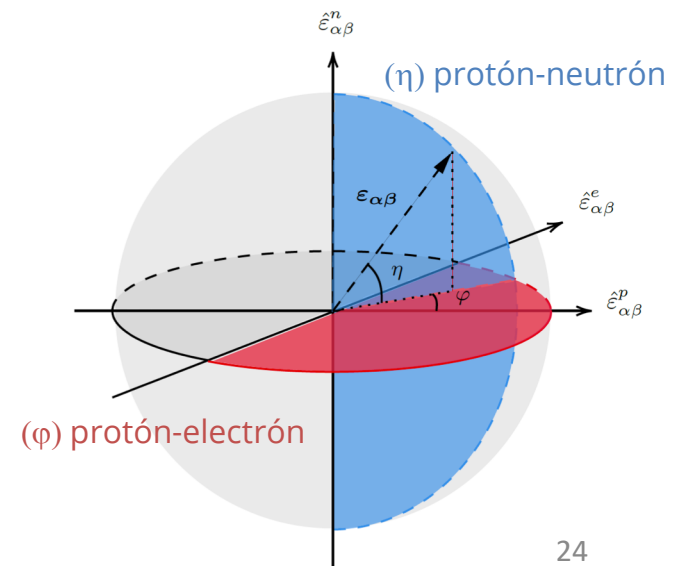
Direct detection experiments are sensitive to **electron recoils**. Therefore we must use a three-dimensional parameter space for each NSI

New parametrisation including electron recoils

$$\xi^e = \sqrt{5} \cos \eta \sin \varphi ,$$

$$\xi^p = \sqrt{5} \cos \eta \cos \varphi ,$$

$$\xi^n = \sqrt{5} \sin \eta .$$



Effective theories: Non-standard Interactions

Neutrinos scatter in the detector in any of the neutrino final states. We **need to sum over all asymptotic final states**

$$\begin{aligned}
 |\mathcal{A}_{\nu_\alpha \rightarrow \sum_i \nu_i}|^2 &= \sum_i |\langle \nu_i | S | \nu_\alpha \rangle|^2 = \sum_i \left| \sum_\beta U_{\beta i}^* \langle \nu_\beta | S | \nu_\alpha \rangle \right|^2 \\
 &= \sum_{\gamma, \delta, \rho, \sigma} \underbrace{(S_{\text{prop}})_{\gamma\rho} \pi_{\rho\sigma}^{(\alpha)} (S_{\text{prop}})_{\delta\sigma}^*}_{\equiv \rho_{\gamma\delta}^{(\alpha)}} \underbrace{\sum_\beta (S_{\text{int}})_{\beta\delta}^* (S_{\text{int}})_{\beta\gamma}}_{\mathcal{M}^*(\nu_\delta \rightarrow f) \mathcal{M}(\nu_\gamma \rightarrow f)} \quad \text{generalised matrix element} \\
 &\quad \text{Neutrino density matrix}
 \end{aligned}$$

$$\frac{dR}{E_R} = N_T \int_{E_\nu^{\min}} \frac{d\phi_\nu}{E_\nu} \text{Tr} \left[\rho \frac{d\zeta}{E_R} \right] dE_\nu,$$

Amaral, Cerdeño, Cheek, Foldenauer 2023
 Coloma, Maltoni, González García 2023

Neutrino propagation inside the Sun assumes adiabaticity $|\Delta E_{12}^m| \gg 2|\dot{\theta}_{12}^m|$

$$S \approx \underbrace{OU_{12}}_{U_{\text{PMNS}}} \left(\exp \left[-i \int_0^L \begin{pmatrix} E_1^m & 0 \\ 0 & E_2^m \end{pmatrix} dx \right] \begin{matrix} 0 \\ \exp[-i \frac{\Delta m_{31}^2}{2E_\nu} L] \end{matrix} \right) \underbrace{U_{12}^m(x_0)^\dagger O^\dagger}_{U_{\text{PMNS}}^m(x_0)^\dagger}$$

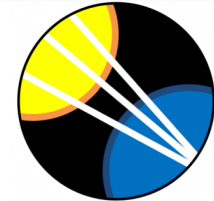
$$E_{1,2}^m = c_{13}^2 A_{\text{cc}} \mp \frac{\Delta m_{21}^2}{4E_\nu} \sqrt{p^2 + q^2}, \quad p \equiv \sin 2\theta_{12} + 2\varepsilon_N^{\eta,\varphi} [\xi^e + \xi^p + Y_n(x) \xi^n] \frac{A_{\text{cc}}}{\Delta m_{21}^2},$$

$$q \equiv \cos 2\theta_{12} + (2\varepsilon_D^{\eta,\varphi} [\xi^e + \xi^p + Y_n(x) \xi^n] - c_{13}^2) \frac{A_{\text{cc}}}{\Delta m_{21}^2}$$

SNuDD: Solar Neutrinos for Direct Detection

<https://github.com/SNuDD/SNuDD>

D. Amaral, A. Cheek, D. Cerdeño, P. Foldenauer



SNuDD

Implemented the full chain of propagation, scattering plus detector effects for NSI in solar neutrinos. Open-source Python package

We determine the new expressions for the generalized “scattering cross section” in terms of the NSI parameters

NUCLEAR RECOILS

$$\left(\frac{d\zeta_{\nu N}}{dE_R} \right)_{\alpha\beta} = \frac{G_F^2 M_N}{\pi} \left(1 - \frac{M_N E_R}{2E_\nu^2} \right) \left[\frac{1}{4} Q_{\nu N}^2 \delta_{\alpha\beta} - Q_{\nu N} G_{\alpha\beta}^{\text{NSI}} + \sum_{\tilde{\gamma}} G_{\alpha\tilde{\gamma}}^{\text{NSI}} G_{\tilde{\gamma}\beta}^{\text{NSI}} \right] F^2(E_R)$$

$$G_{\alpha\beta}^{\text{NSI}} = (\xi^p Z + \xi^n N) \varepsilon_{\alpha\beta}^{\eta,\varphi}$$

ELECTRON RECOILS

$$\left(\frac{d\zeta_{\nu e}}{dE_R} \right)_{\alpha\beta} = \frac{2 G_F^2 m_e}{\pi} \sum_{\gamma} \left\{ G_{\alpha\gamma}^L G_{\gamma\beta}^L + G_{\alpha\gamma}^R G_{\gamma\beta}^R \left(1 - \frac{E_R}{E_\nu} \right)^2 - (G_{\alpha\gamma}^L G_{\gamma\beta}^R + G_{\alpha\gamma}^R G_{\gamma\beta}^L) \frac{m_e E_R}{2E_\nu^2} \right\}$$

$$G_{\alpha\beta}^L = (\delta_{e\alpha} + g_L^e) \delta_{\alpha\beta} + \frac{1}{2} \left(\varepsilon_{\alpha\beta}^{\eta,\varphi} \xi^e + \tilde{\varepsilon}_{\alpha\beta}^{\eta,\varphi} \tilde{\xi}^e \right),$$

$$G_{\alpha\beta}^R = g_R^e \delta_{\alpha\beta} + \frac{1}{2} \left(\varepsilon_{\alpha\beta}^{\eta,\varphi} \xi^e - \tilde{\varepsilon}_{\alpha\beta}^{\eta,\varphi} \tilde{\xi}^e \right),$$

NUCLEAR SCATTERING

Consider one NSI coupling at a time and compare sensitivity to global fit limits from

Coloma, Esteban, González-García, Maltoni 2020

Future DD experiments will be able to improve existing constraints

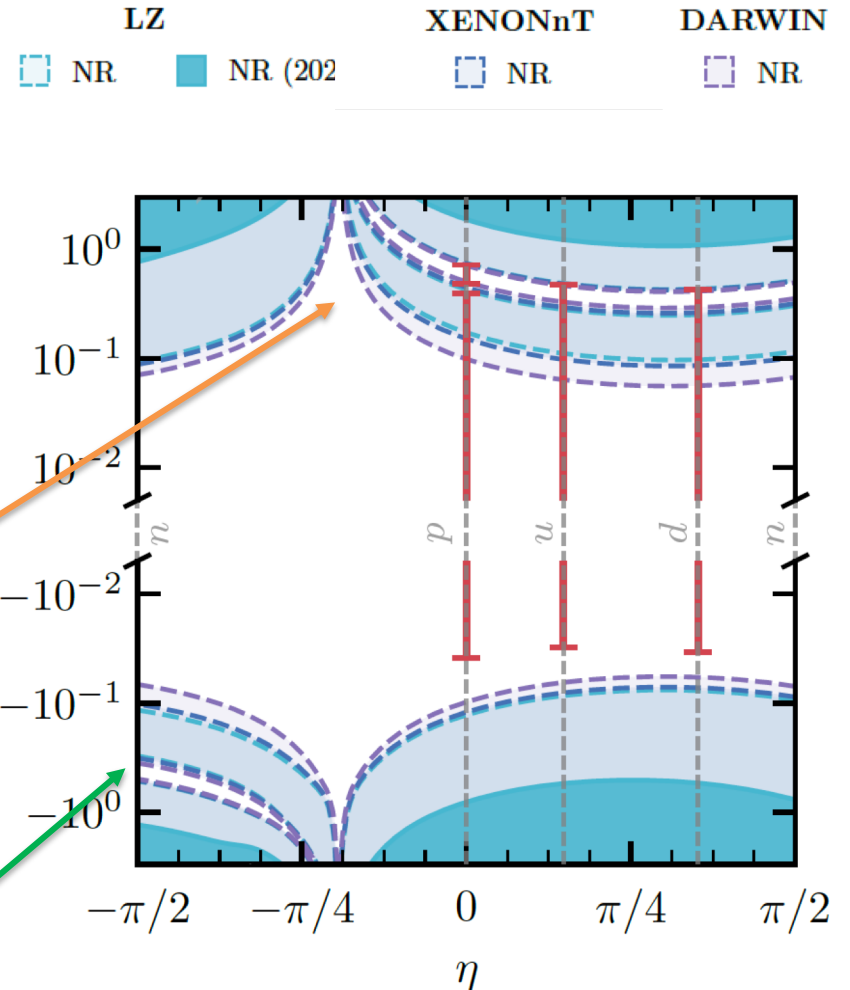
Blind spots:

accidental cancellation between proton and neutron contributions.

$$\eta = \tan^{-1} \left(-\frac{Z}{N} \cos \varphi \right)$$

SM-NSI interference terms in CEvNS cross section

$$\epsilon_{\alpha\alpha}^{\eta,\varphi} = \frac{Q_{\nu N}}{\xi^p + Z x_i^n N}$$



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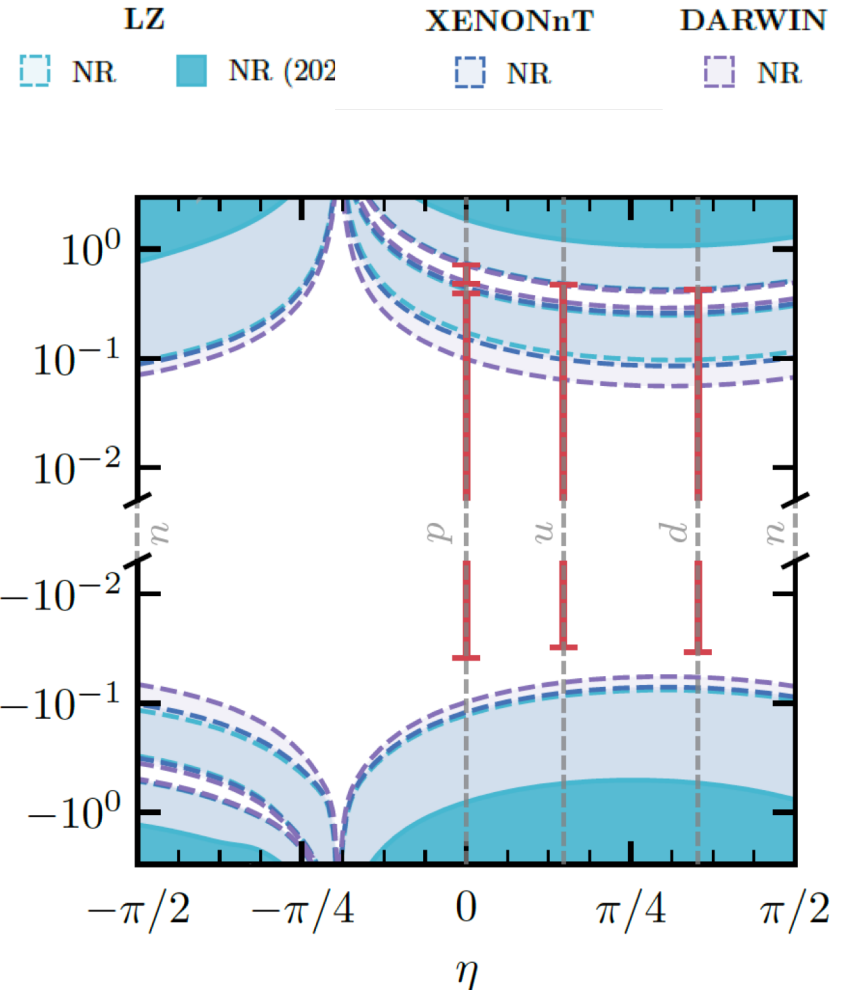
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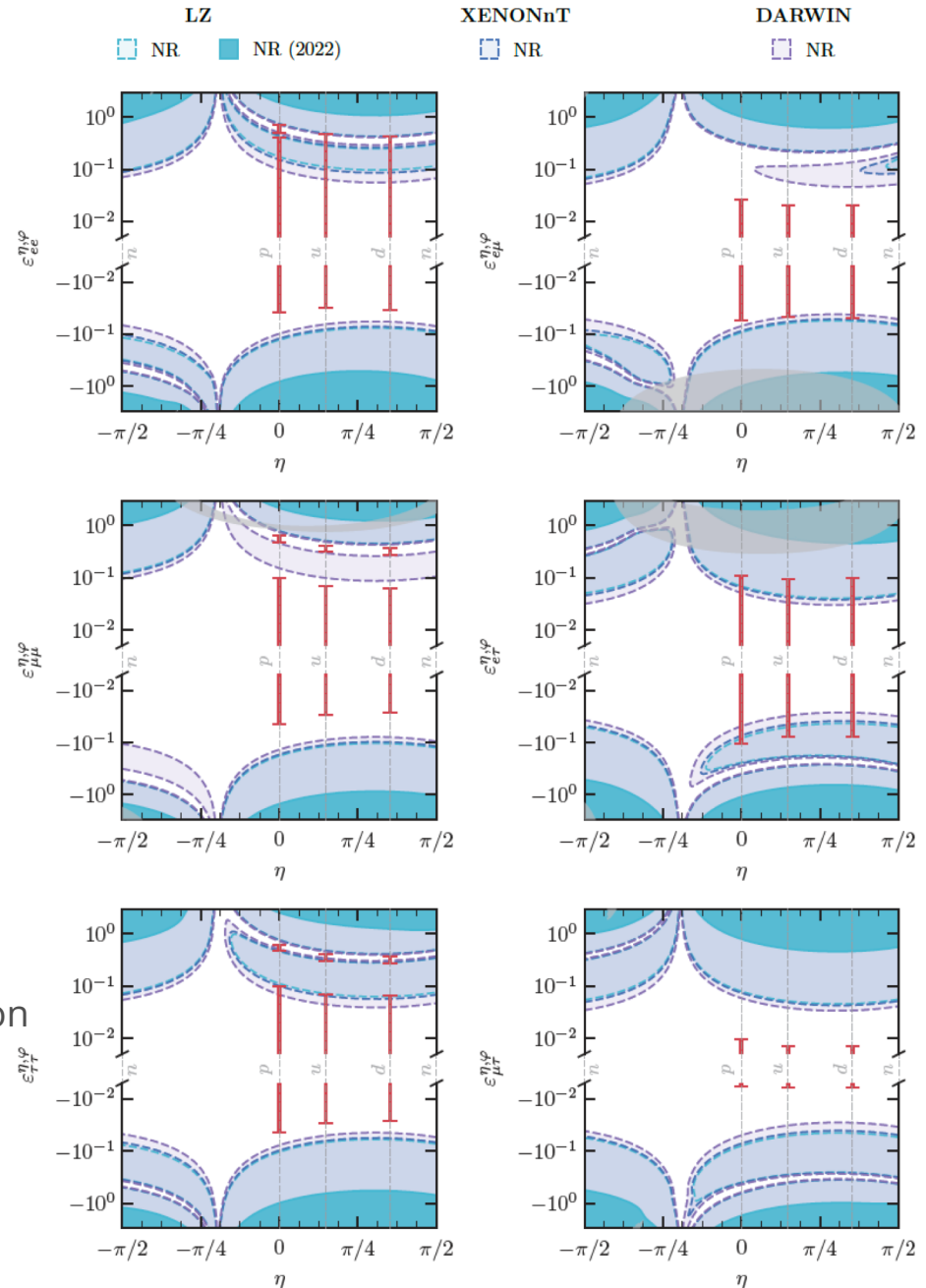
Blind spots:

accidental cancellation between proton and neutron contributions.

$$\eta = \tan^{-1} \left(-\frac{Z}{N} \cos \varphi \right)$$

SM-NSI interference terms in CEvNS cross section

$$\epsilon_{\alpha\alpha}^{\eta,\varphi} = \frac{Q_{\nu N}}{\xi^p + Zx_i^n N}$$



NUCLEAR + ELECTRON SCATTERING

We show the results on the $\{\xi^p, \xi^e\}$ plane.

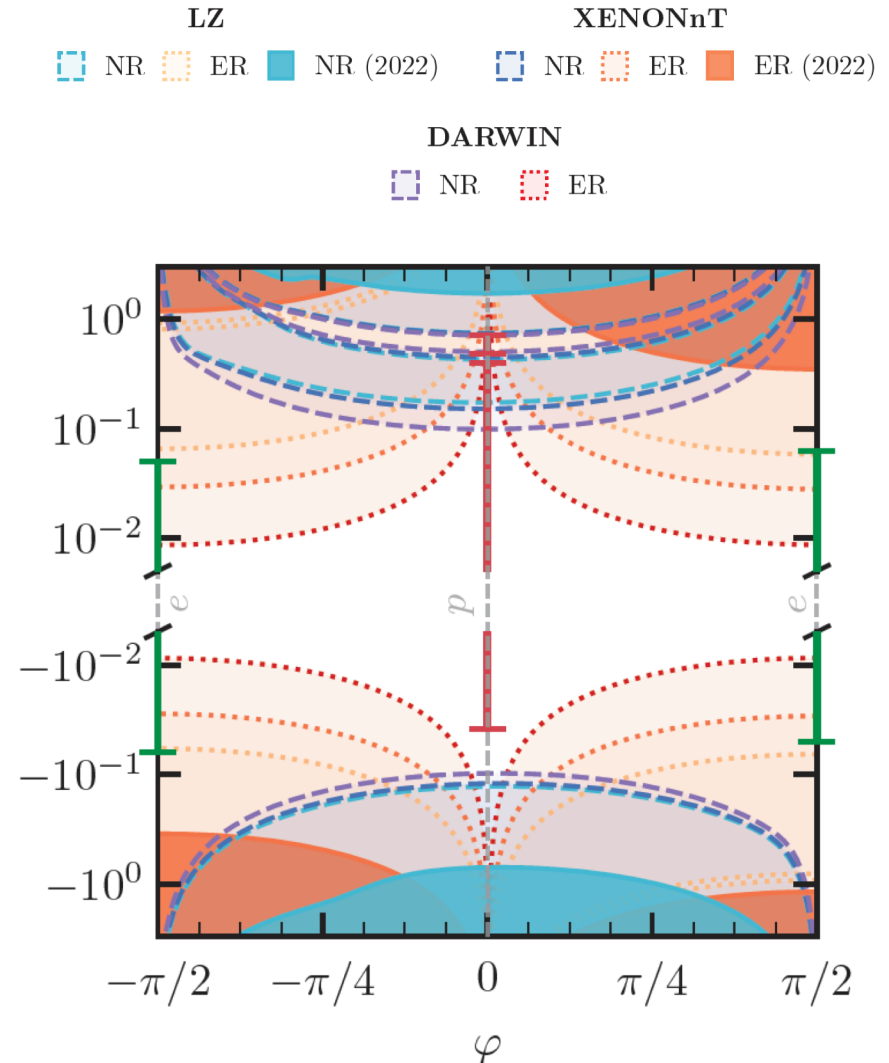
ER sensitivities drop off towards $\varphi = 0$ (pure proton), whereas NR sensitivities become maximal.

Direct detection experiments have **excellent sensitivity to ER**.

Future **DARWIN** can potentially improve by an order of magnitude over current electron NSI bounds

Direct detection experiments become crucial to constrain neutrino parameters.

They will need to be included in global neutrino parameter fits.



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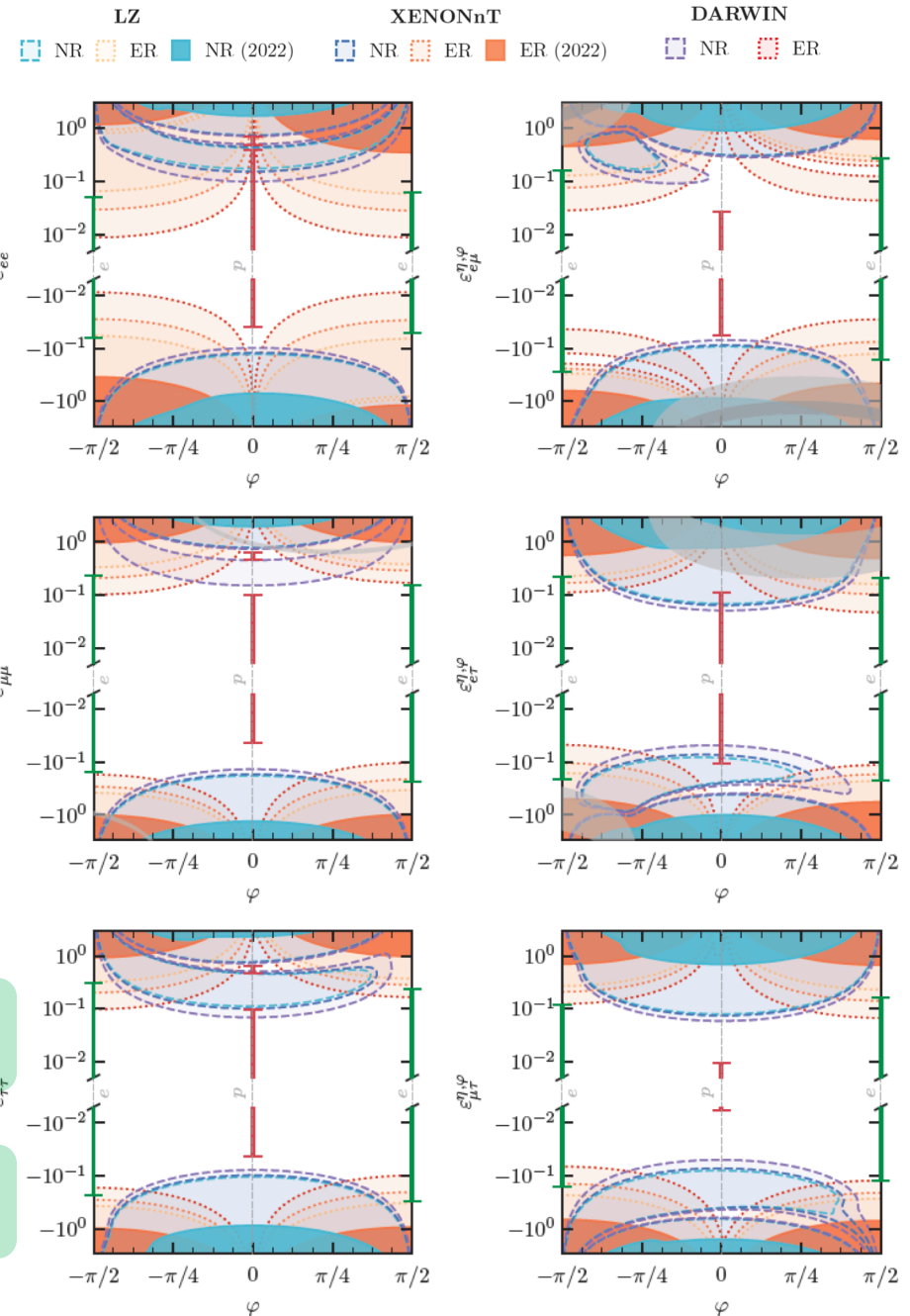
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INELASTIC SCATTERING INTO A STERILE NEUTRINO

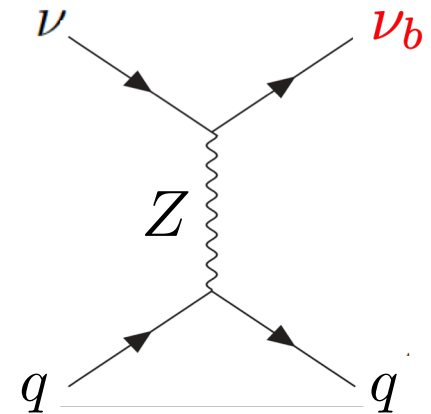
Neutrinos can also undergo an “**upscattering**” into sterile states if the mass of the sterile neutrino is smaller than the incident neutrino energy (~10 MeV for Solar neutrinos; ~45 MeV for Spallation Source experiments)

Direct detection experiments can probe this process. Current detectors not enough to probe new parameter space but good potential for future ones.

Shoemaker, Tsai, Wyenberg 2007

Shoemaker, Wyenberg 2018

If there is a detection, how can we tell if the observed interaction is a sterile neutrino or some sort of NSI? Can we **measure the sterile neutrino mass**?



Example: sterile baryonic neutrino

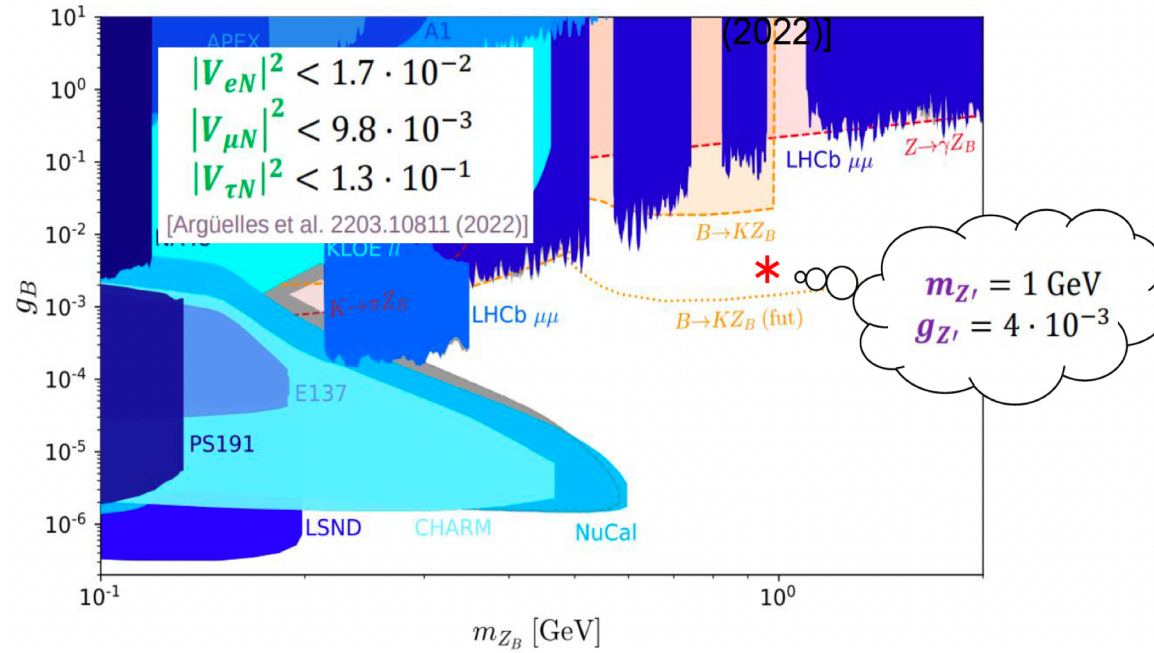
$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + g_b Z'^{\mu} \bar{\nu}_b \gamma_{\mu} \nu_b + \frac{1}{3} g_q Z'^{\mu} \sum_q \bar{q} \gamma_{\mu} q$$

Pospelov 2011

Parameter space

$g_{Z'}$, $m_{Z'}$

m_N , $|V_{eN}|$, $|V_{\mu N}|$, $|V_{\tau N}|$



	m_4 [GeV]	$ U_{e4} ^2$	$ U_{\mu 4} ^2$	$ U_{\tau 4} ^2$
BP1a	2×10^{-3}	0	9×10^{-3}	0
BP1d	2×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP2a	9×10^{-3}	0	9×10^{-3}	0
BP2b	9×10^{-3}	0	9×10^{-3}	9×10^{-4}
BP2c	9×10^{-3}	0	9×10^{-3}	4×10^{-3}
BP2d	9×10^{-3}	0	9×10^{-3}	9×10^{-3}
BP3a	20×10^{-3}	0	9×10^{-3}	0
BP4a	40×10^{-3}	0	9×10^{-3}	0
BP5a	60×10^{-3}	0	9×10^{-3}	0

Inelastic contribution to neutrino-nucleus scattering

$$\frac{dR_{\alpha'}}{dE_R} = \frac{1}{m_A} \left(\int_{E_\nu^{\min, \text{CE}\nu\text{NS}}}^{E_\nu^{\max}} \frac{d\phi_{\nu\alpha'}}{dE_\nu} \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R} dE_\nu + \int_{E_\nu^{\min, \alpha'4}}^{E_\nu^{\max}} \frac{d\phi_{\nu\alpha'}}{dE_\nu} \frac{d\sigma_{\alpha'4}}{dE_R} dE_\nu \right)$$

Neutrino-Nucleus Scattering

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_\nu^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2} \right) F^2(E_R)$$

$$E_\nu^{\min, \text{CE}\nu\text{NS}} = \frac{1}{2} \left(E_R + \sqrt{E_R^2 + 2m_A E_R} \right) \simeq \sqrt{\frac{m_A E_R}{2}}$$

$$\frac{d\sigma_{\alpha 4}}{dE_R} = \frac{g_{Z'}^4 A^2 |U_{\alpha 4}|^2 m_A}{2\pi E_\nu^2 (2m_A E_R + m_{Z'}^2)^2} \left[4E_\nu^2 - 2E_R (m_A - E_R + 2E_\nu) - \frac{m_4^2}{m_A} (m_A - E_R - E_\nu) \right] F^2(E_R)$$

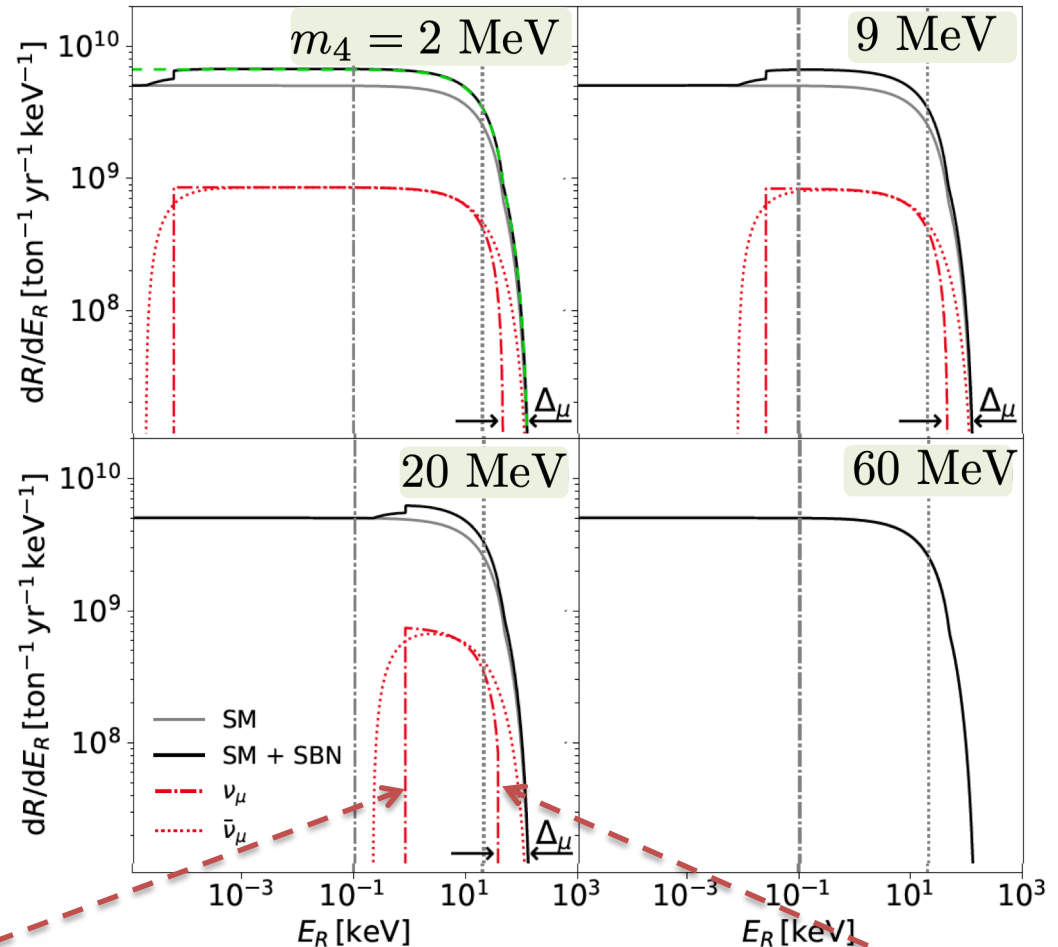
$$E_\nu^{\min, \alpha'4} = \left(1 + \frac{m_4^2}{2m_A E_R} \right) E_\nu^{\min, \text{CE}\nu\text{NS}}$$

Features in the recoil spectrum in spallation source experiments

The inelastic contribution leads to a **distortion of the recoil spectrum**.

Since the distortion depends on the sterile neutrino mass, it is useful to **reconstruct** this quantity if there is a detection.

This is more easily observable in the contribution from the **monochromatic** $\bar{\nu}_\mu$



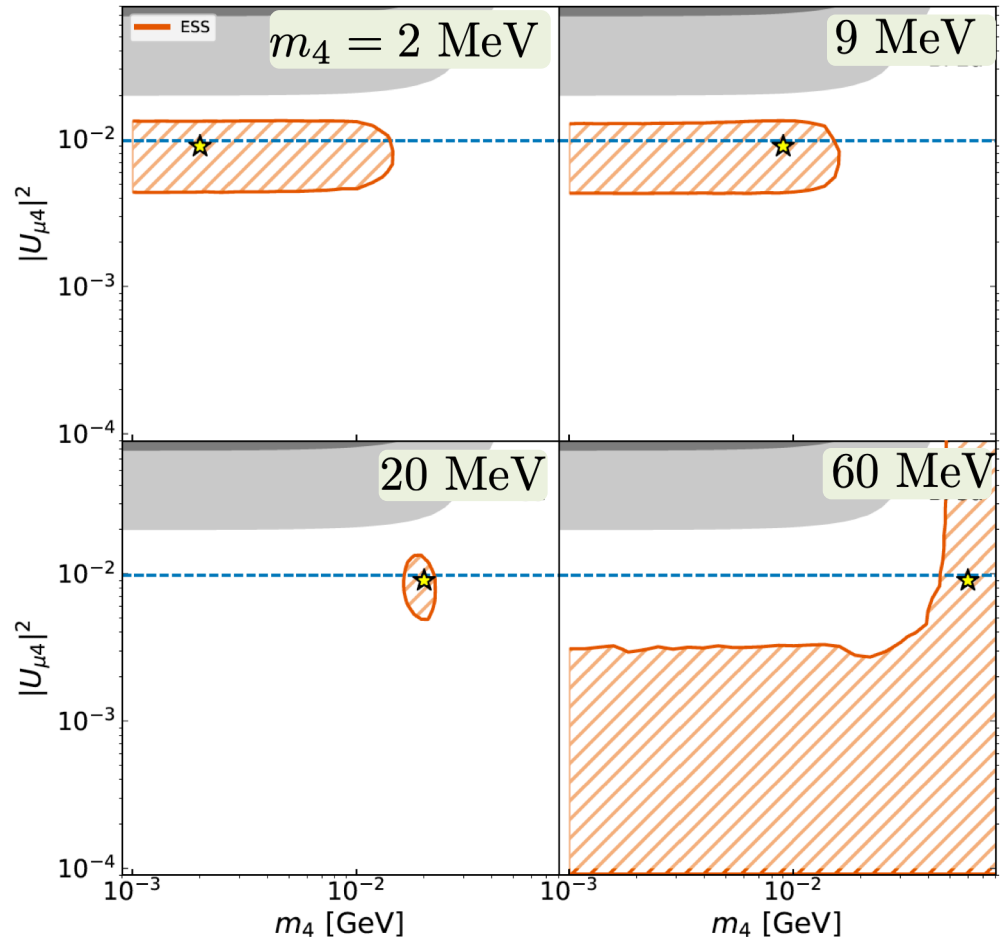
$$\frac{1}{2m_A} \left(2(E_\nu^{\max})^2 - m_4^2 - 2E_\nu^{\max} \sqrt{(E_\nu^{\max})^2 - m_4^2} \right)$$

$$\frac{1}{2m_A} \left(2(E_\nu^{\max})^2 - m_4^2 + 2E_\nu^{\max} \sqrt{(E_\nu^{\max})^2 - m_4^2} \right)$$

Parameter reconstruction in spallation source experiments

We assume a future experiment at the European Spallation Source (ESS) facility.

The mixing (with the muon neutrino) can be determined, but **the sterile neutrino mass is normally unbounded from below.**



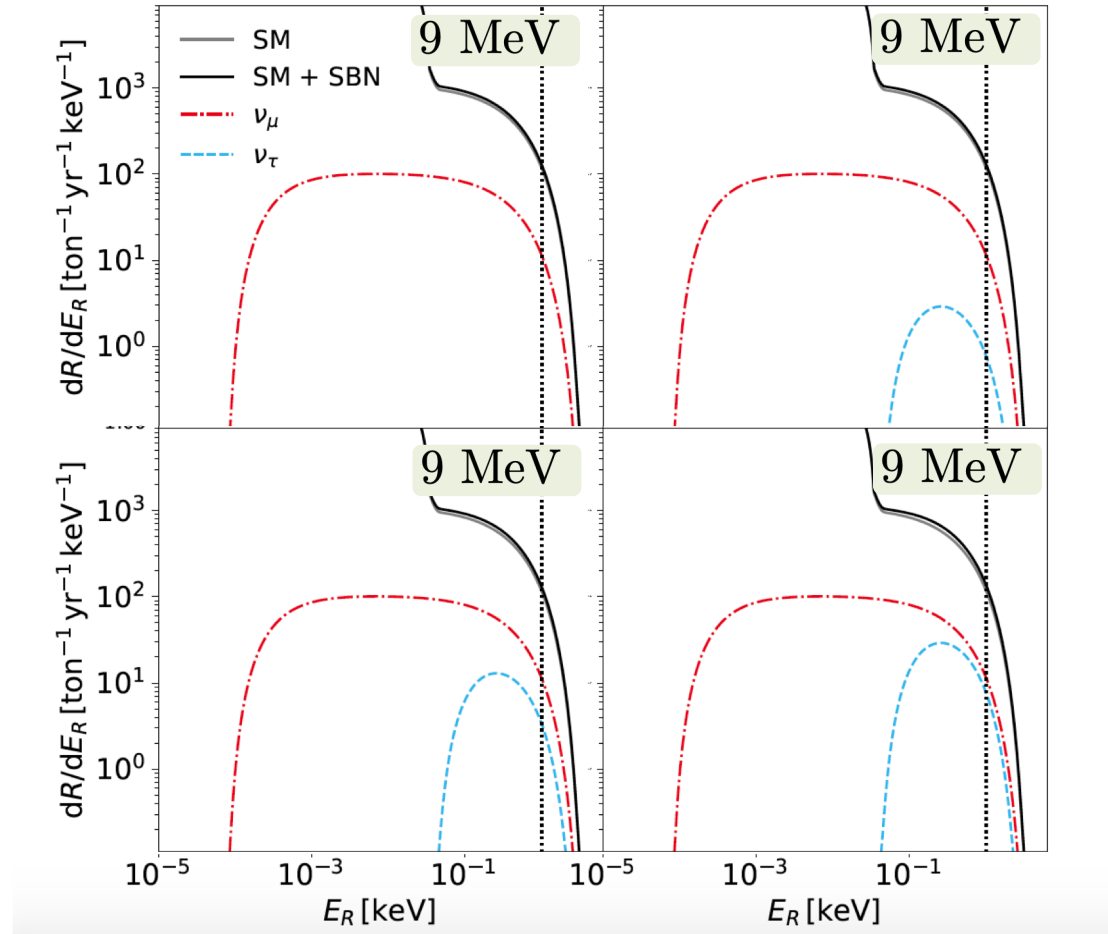
The mass can be reconstructed in a small range around $m_4 \sim 15 - 50$ MeV.

Features in the recoil spectrum in direct detection

The features are not that prominent as in spallation source experiments.

The sterile neutrino mass is more difficult to determine.

The sterile neutrino mass is more difficult to determine.

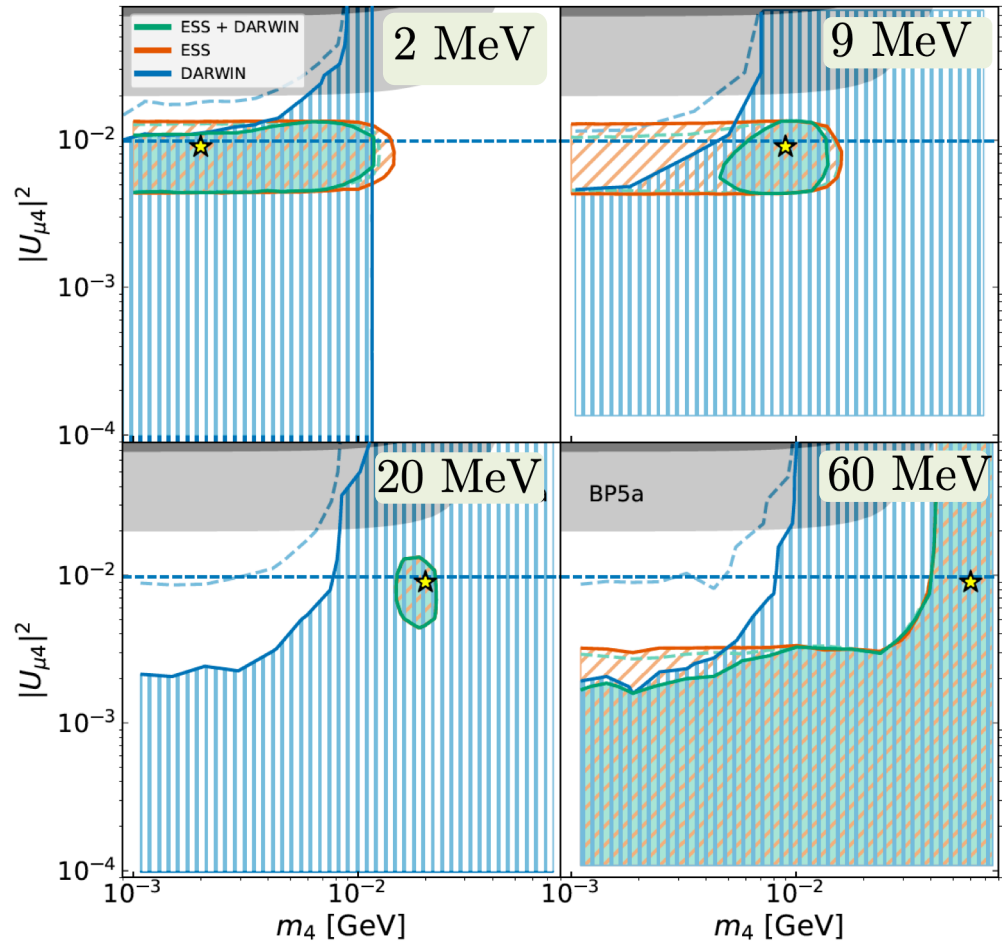


Parameter reconstruction: combination DD+SS

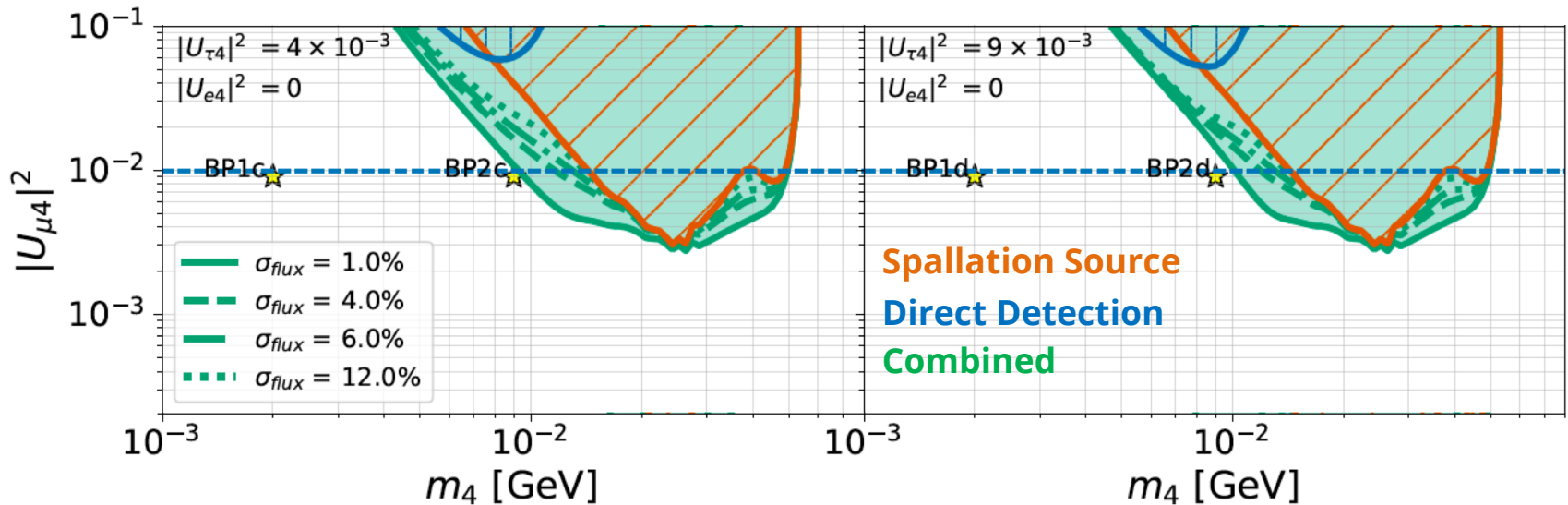
The combination allows to reconstruct smaller sterile neutrino masses.

The sterile neutrino cannot be produced from Solar neutrinos if their mass is larger than ~ 12 MeV.

It also leads to better exclusion limits if nothing is observed.



Regions where the sterile neutrino mass can be measured



Spallation source experiments alone can measure the sterile neutrino mass down to ~ 15 MeV

Including future data from direct detection allows to extend the range in which the sterile neutrino mass can be reconstructed.

It is also crucial to break the degeneracy between couplings to the muon and tau neutrinos.

Conclusions

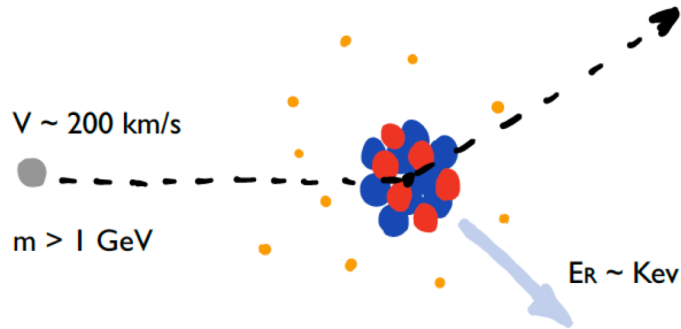
Direct (dark matter) detection experiments will soon detect **solar neutrinos**, thereby contributing to probing new physics in this sector

Their low energy threshold and resolution, and, specially, the fact that they are sensitive to both **electron and nuclear recoils** will allow them to provide complementary information to that of dedicated neutrino detector and spallation source experiments.

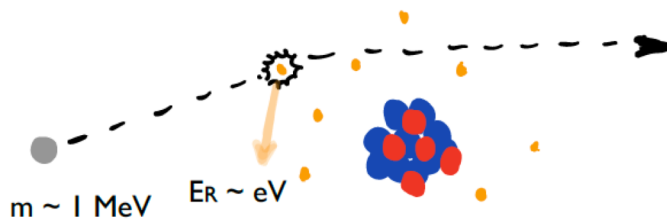
Liquid noble gas detectors (Xe) will probe new areas of the parameter space of **non-standard interactions**, and their results will need to be included in neutrino global fits.

They might also make it possible to better reconstruct the **sterile neutrino mass**, improving the results from spallation source experiments.

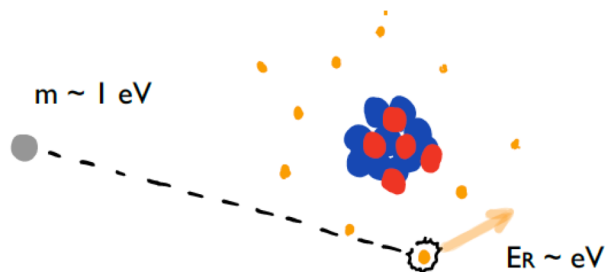
ELASTIC (or INELASTIC) SCATTERING OFF NUCLEI



INELASTIC SCATTERING WITH ELECTRONS



ABSORPTION



DIRECT DARK MATTER SEARCHES: What can we measure?

NUCLEAR SCATTERING

- “Canonical” signature
- Elastic or Inelastic scattering
- Sensitive to $m > 1 \text{ GeV}$

ELECTRON SCATTERING

- Sensitive to light WIMPs

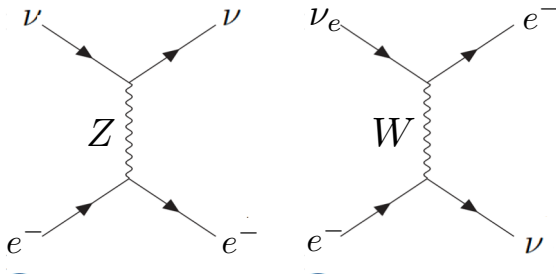
ELECTRON ABSORPTION

- Very light (non-WIMP)

Expected signal in a direct detection experiment

$$N = \varepsilon n_T \int_{E_{\text{th}}}^{E_{\text{max}}} \sum_{\nu_\alpha} \int_{E_\nu^{\text{min}}} \frac{d\phi_{\nu_e}}{dE_\nu} P(\nu_e \rightarrow \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

(Inelastic) electron scattering

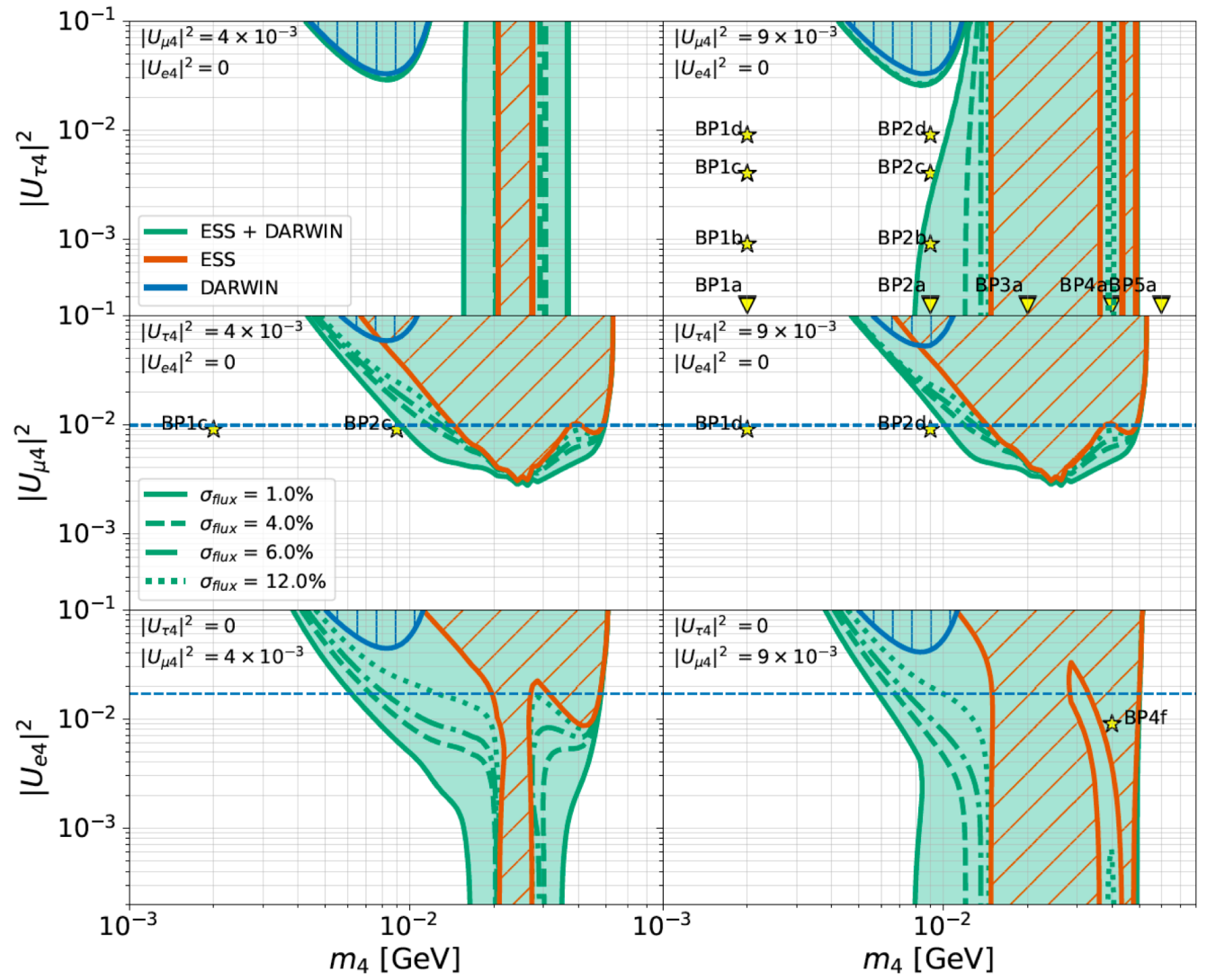


$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi} \left[(g_\nu + g_a)^2 + (g_\nu - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_\nu^2) \frac{m_e E_R}{E_\nu^2} \right]$$

Electron neutrinos
Mu and Tau neutrinos

$$g_{\nu;\mu,\tau} = 2 \sin^2 \theta_W - \frac{1}{2}; \quad g_{a;\mu,\tau} = -\frac{1}{2}$$

$$g_{\nu;e} = 2 \sin^2 \theta_W + \frac{1}{2}; \quad g_{a;e} = +\frac{1}{2}$$



Effective theories: Non-standard Interactions

Neutrinos scatter in the detector in any of the neutrino final states. We **need to sum over all asymptotic final states**

$$\begin{aligned}
 |\mathcal{A}_{\nu_\alpha \rightarrow \sum_i \nu_i}|^2 &= \sum_i \left| \sum_\beta U_{\beta i}^* \langle \nu_\beta | S_{\text{int}} \left(\sum_\gamma |\nu_\gamma\rangle \langle \nu_\gamma| \right) S_{\text{prop}} | \nu_\alpha \rangle \right|^2 \\
 &= \sum_{\beta, \gamma, \delta, \lambda} \overbrace{\sum_i U_{\beta i}^* U_{\lambda i}}^{\delta_{\beta\lambda}} \langle \nu_\beta | S_{\text{int}} | \nu_\gamma \rangle \langle \nu_\gamma | S_{\text{prop}} \left(\sum_\rho |\nu_\rho\rangle \langle \nu_\rho| \right) | \nu_\alpha \rangle \langle \nu_\alpha | \left(\sum_\sigma |\nu_\sigma\rangle \langle \nu_\sigma| \right) S_{\text{prop}}^\dagger | \nu_\delta \rangle \\
 &\quad \times \langle \nu_\delta | S_{\text{int}}^\dagger | \nu_\lambda \rangle \\
 &= \sum_{\gamma, \delta, \rho, \sigma} \underbrace{(S_{\text{prop}})_{\gamma\rho} \pi_{\rho\sigma}^{(\alpha)} (S_{\text{prop}})_{\delta\sigma}^*}_{\equiv \rho_{\gamma\delta}^{(\alpha)}} \underbrace{\sum_\beta (S_{\text{int}})_{\beta\delta}^* (S_{\text{int}})_{\beta\gamma}}_{\mathcal{M}^*(\nu_\delta \rightarrow f) \mathcal{M}(\nu_\gamma \rightarrow f)}
 \end{aligned}$$

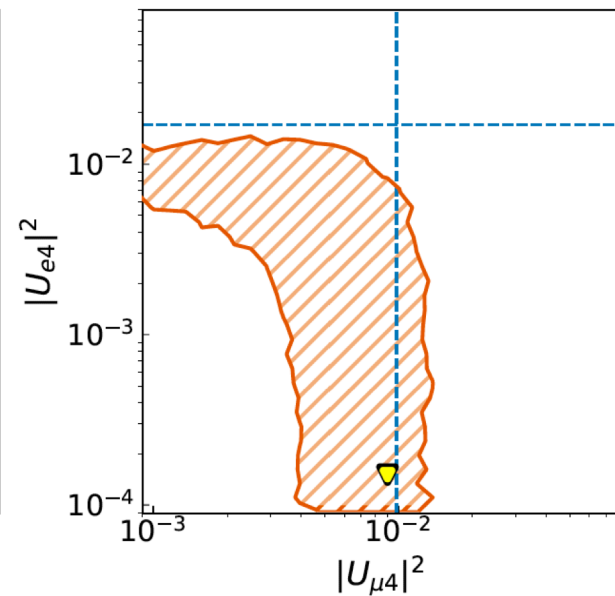
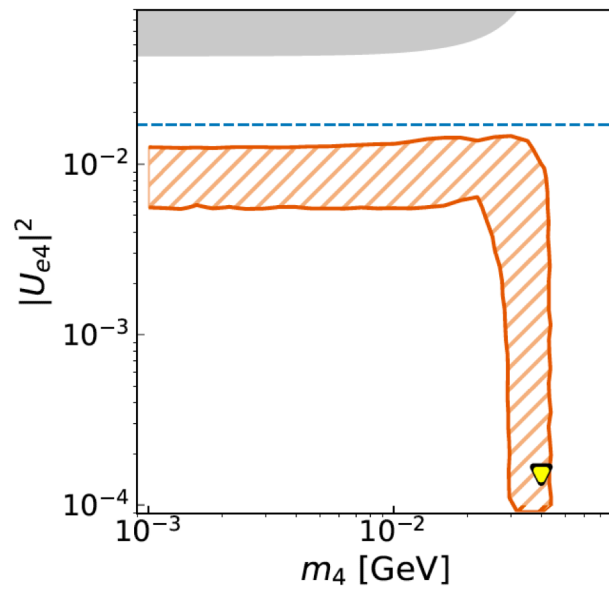
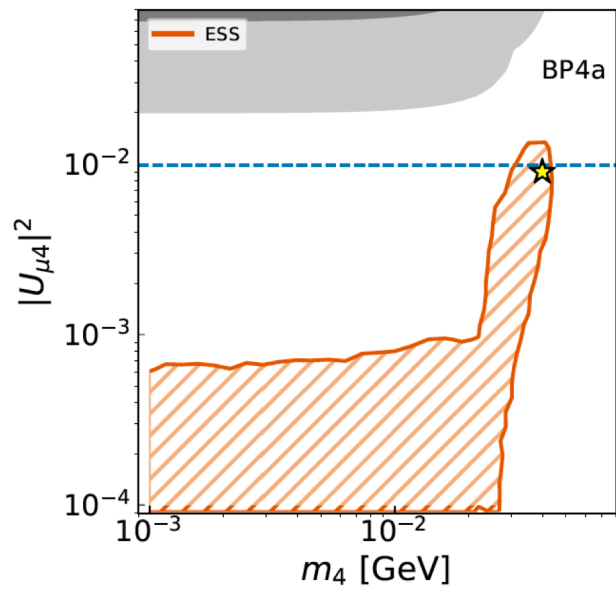
Neutrino density matrix
generalised matrix element

$$\frac{dR}{E_R} = N_T \int_{E_\nu^{\min}} \frac{d\phi_\nu}{E_\nu} \text{Tr} \left[\rho \frac{d\zeta}{E_R} \right] dE_\nu,$$

Amaral, Cerdeño, Cheek, Foldenauer 2023

Coloma, Maltoni, González García 2023

Some interesting cases



Some interesting cases

