A direct detection view of new neutrino physics

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SI2/PBG/2020-00005
PID2021-125331NB-I00
CNS2022-135702

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

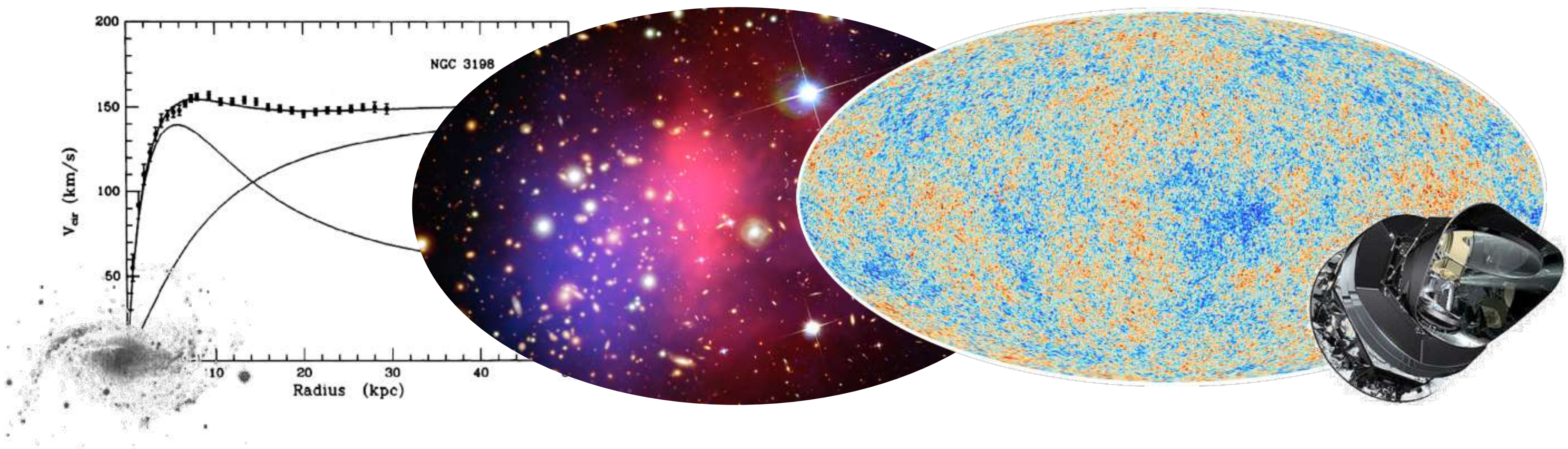
What we do not see in this image:

66 billion (solar) neutrinos/cm^2 s

20 fg of dark matter/cm^2 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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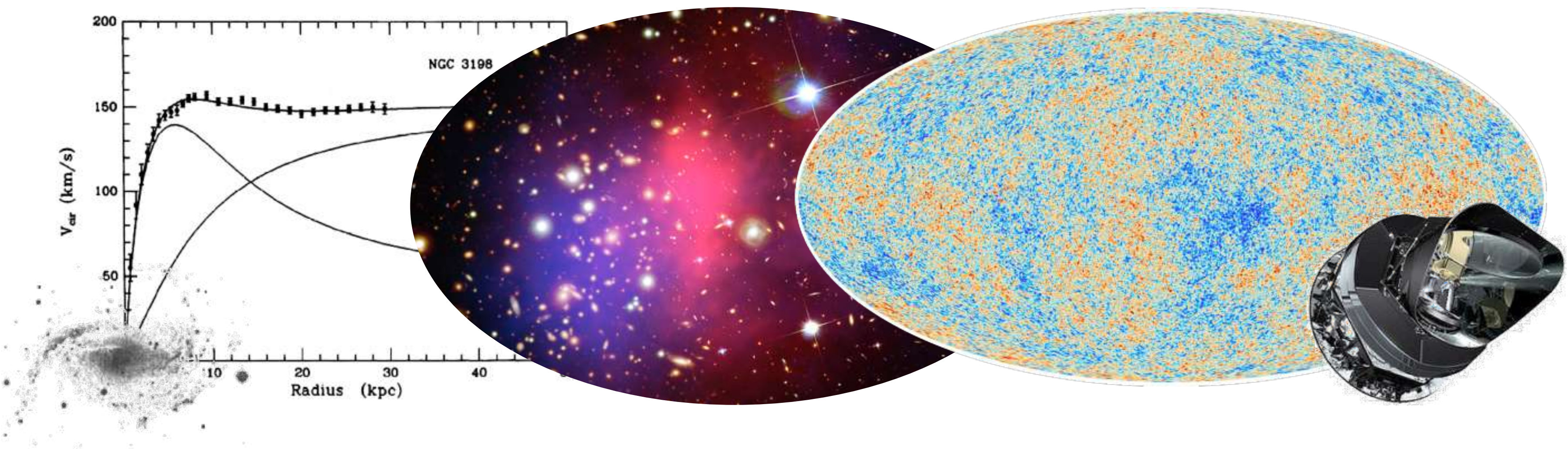
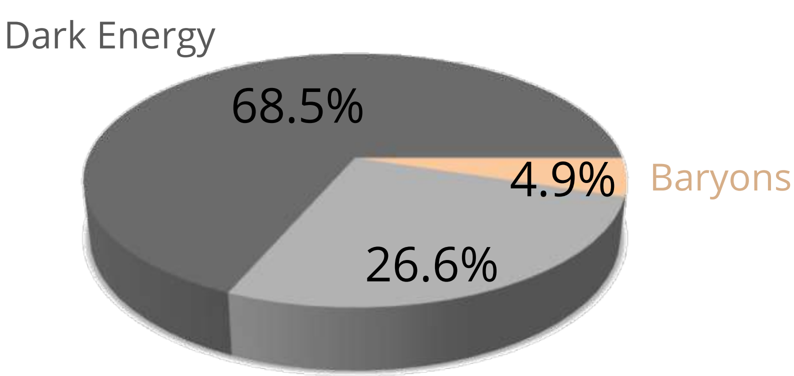
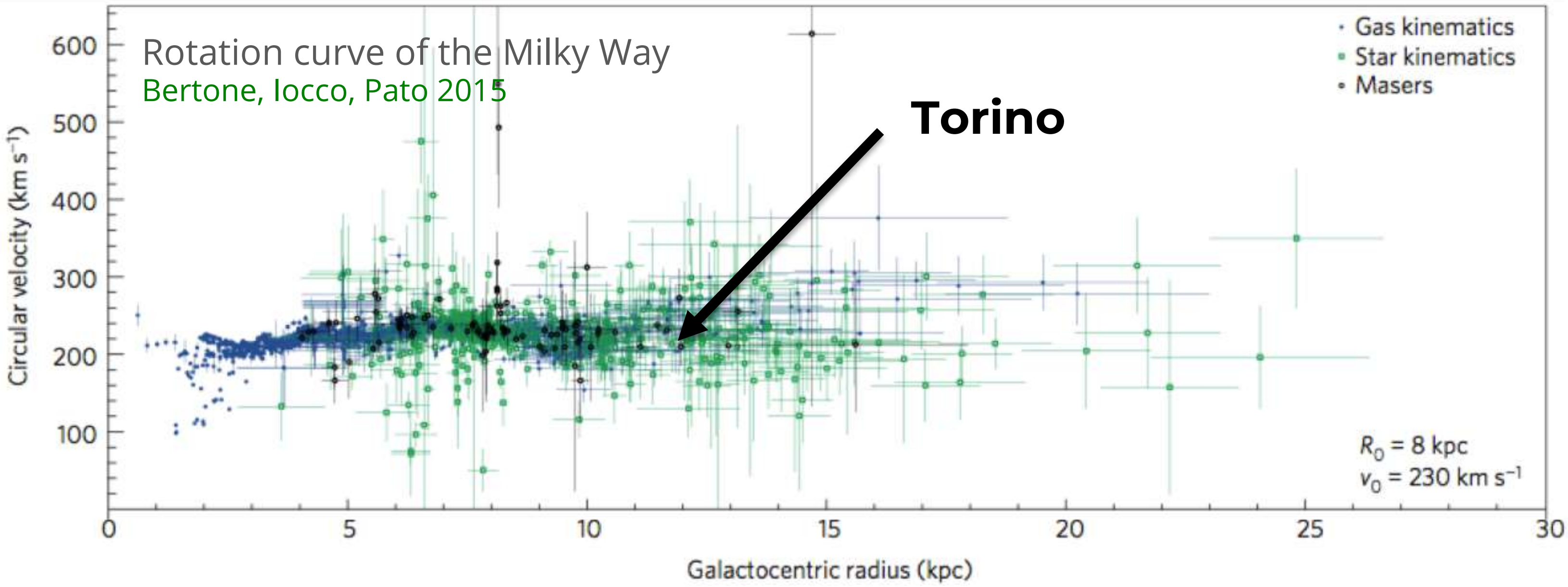
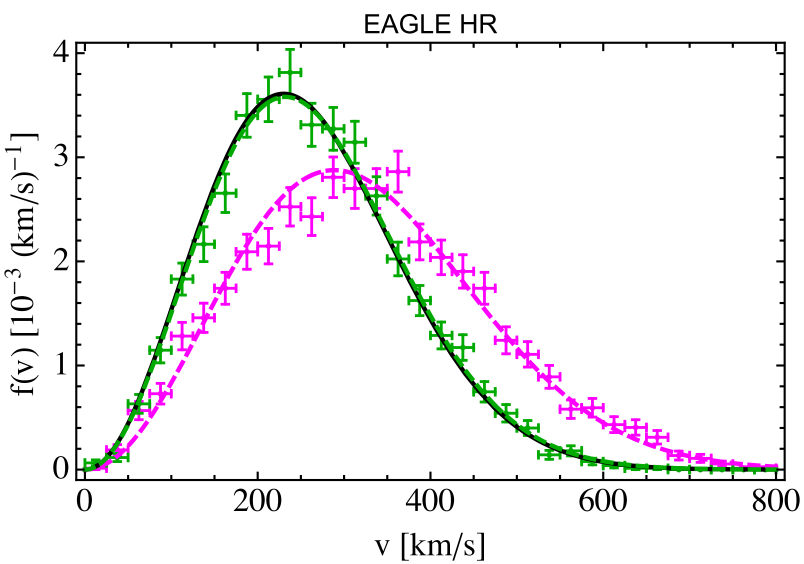




A plausible hypothesis is that dark matter is a new type of (stable, neutral, weakly-interacting) particle





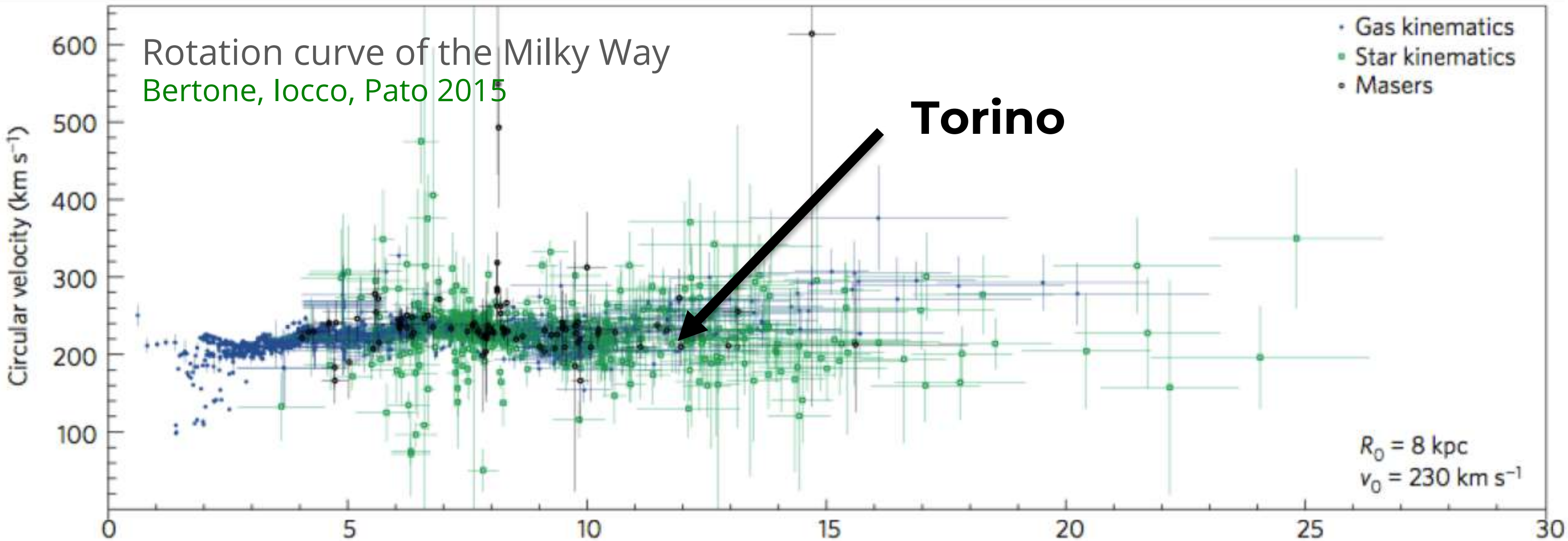
- **local DM density**

$$\rho_{DM}(R_0) \approx 0.4\ \mathrm{GeV/cm^3}$$

- **Velocity distribution of DM particles**

Maxwellian distribution is a good fit in the Milky Way
Uncertainty in astrophysical parameters

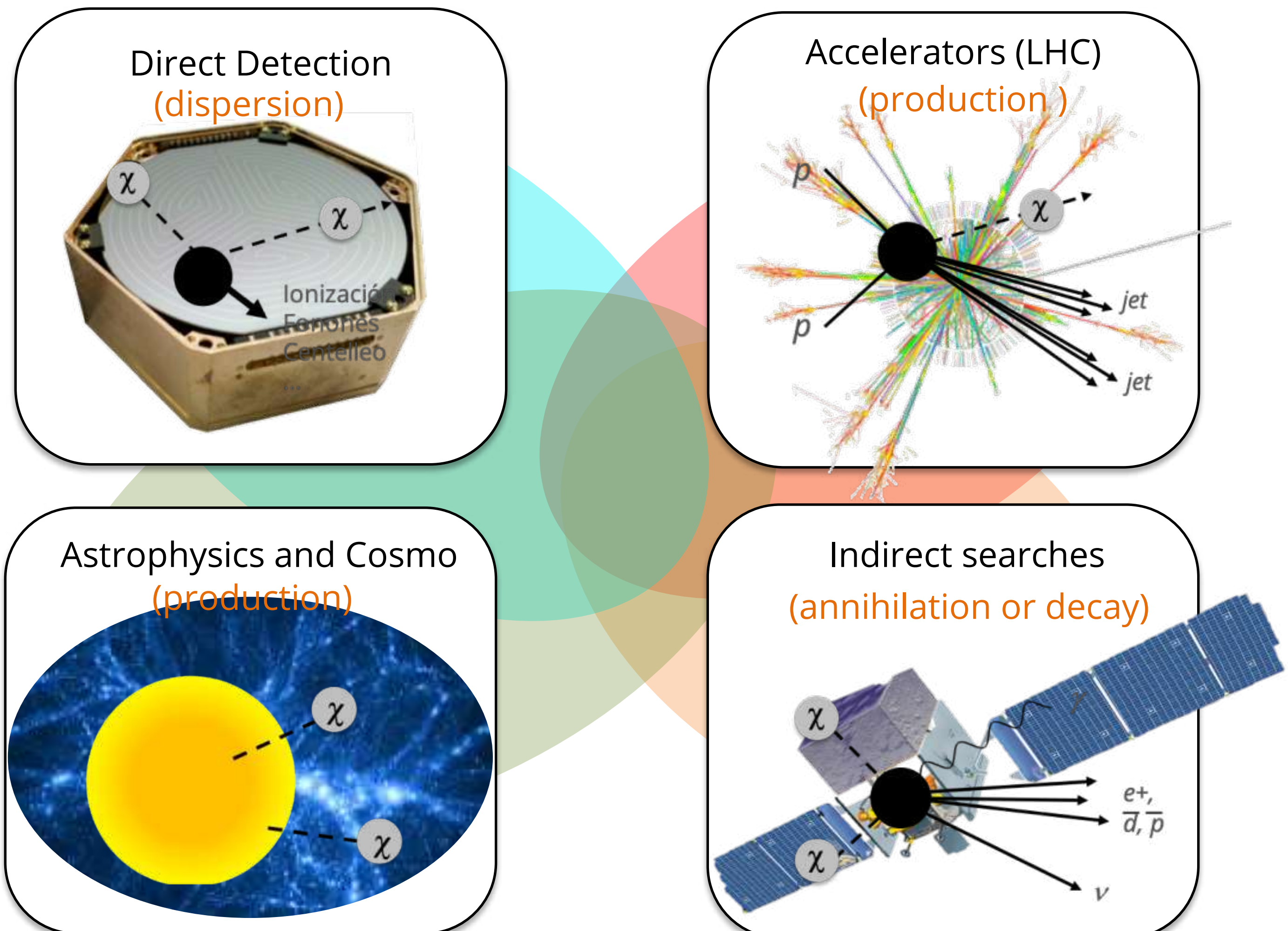
Bozorgnia et al. 1601.04707



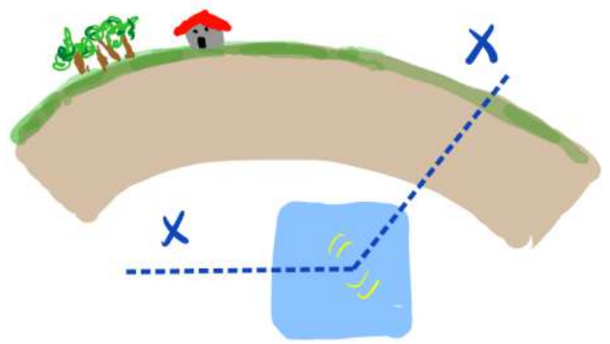
Very few people know this, but the tiny pocket in our jeans is for carrying 10 GeV of dark matter

Dark matter can be searched for in different ways

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



Direct Detection experiments



Ionisation
Scintillation
Phonons (heat)
Bubble nucleation

Underground detectors to look for "invisibles"

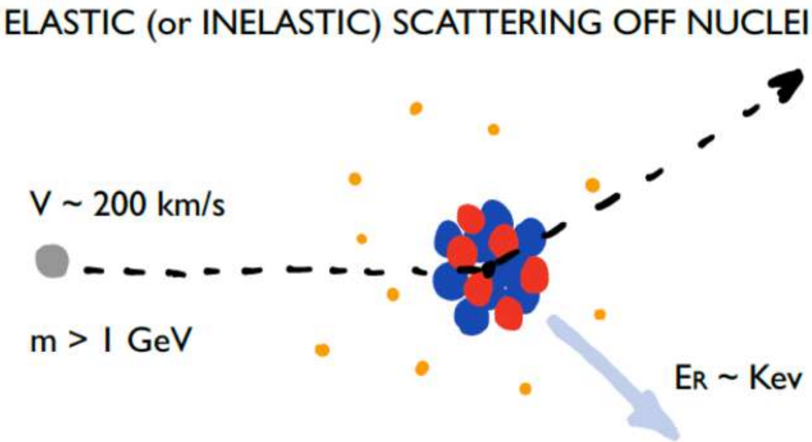
- weakly-interacting (that traverse the Earth)
- Neutral (or millicharged)
- Cosmological or astrophysical origin
- Stable enough

Interactions are (to say the least) rare

- Background attenuation (cleanliness + shielding)
- Increasing target size
- Increasing search window (lower energy thresholds)

Background/signal discrimination

- Discriminate nuclear recoils (NR) and electron recoils (ER)
- Morphology of the signal (energy spectrum)
- Time-dependence (modulations)
- Directionality

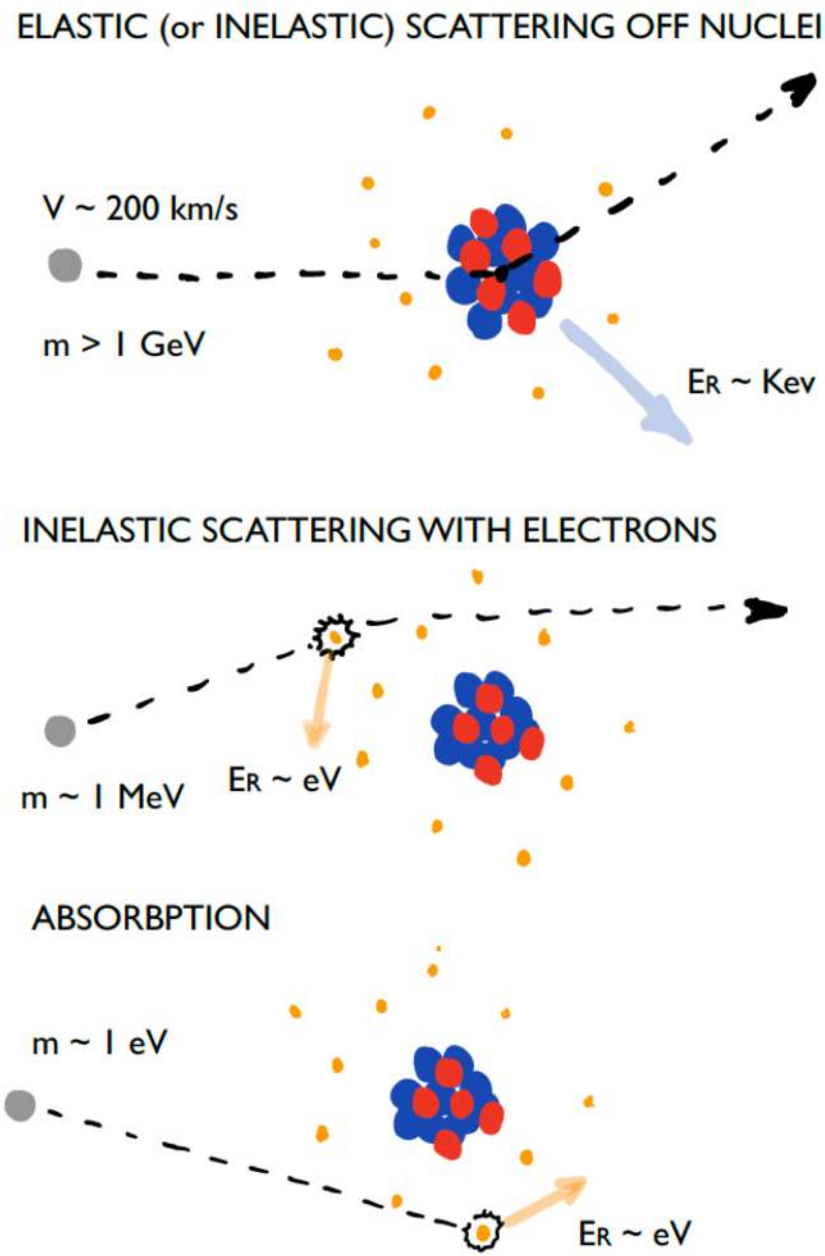


$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

DIRECT DARK MATTER SEARCHES: What can we measure?

NUCLEAR SCATTERING

- "Canonical" signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV



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ELECTRON SCATTERING

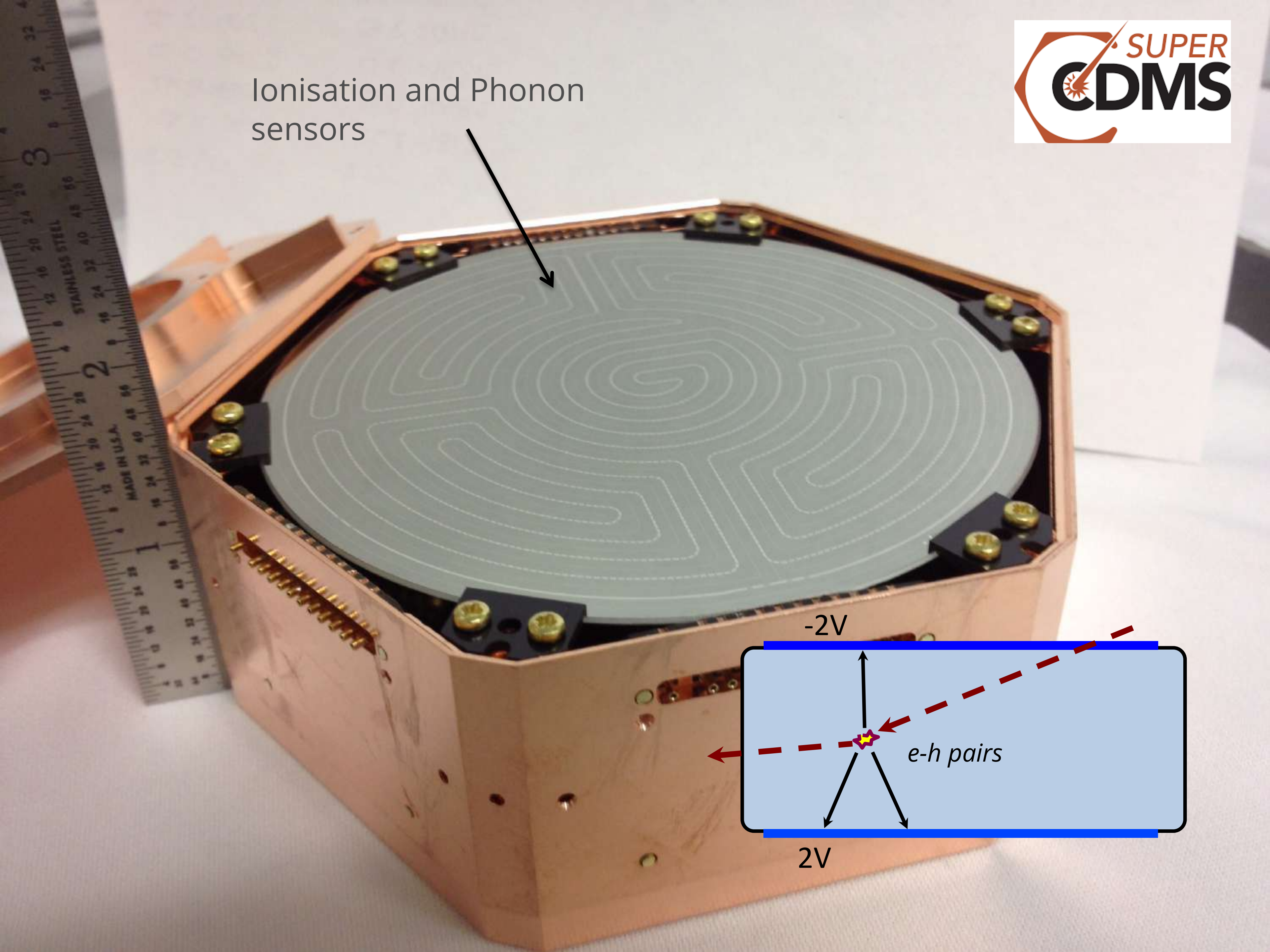
- Sensitive to light WIMPs

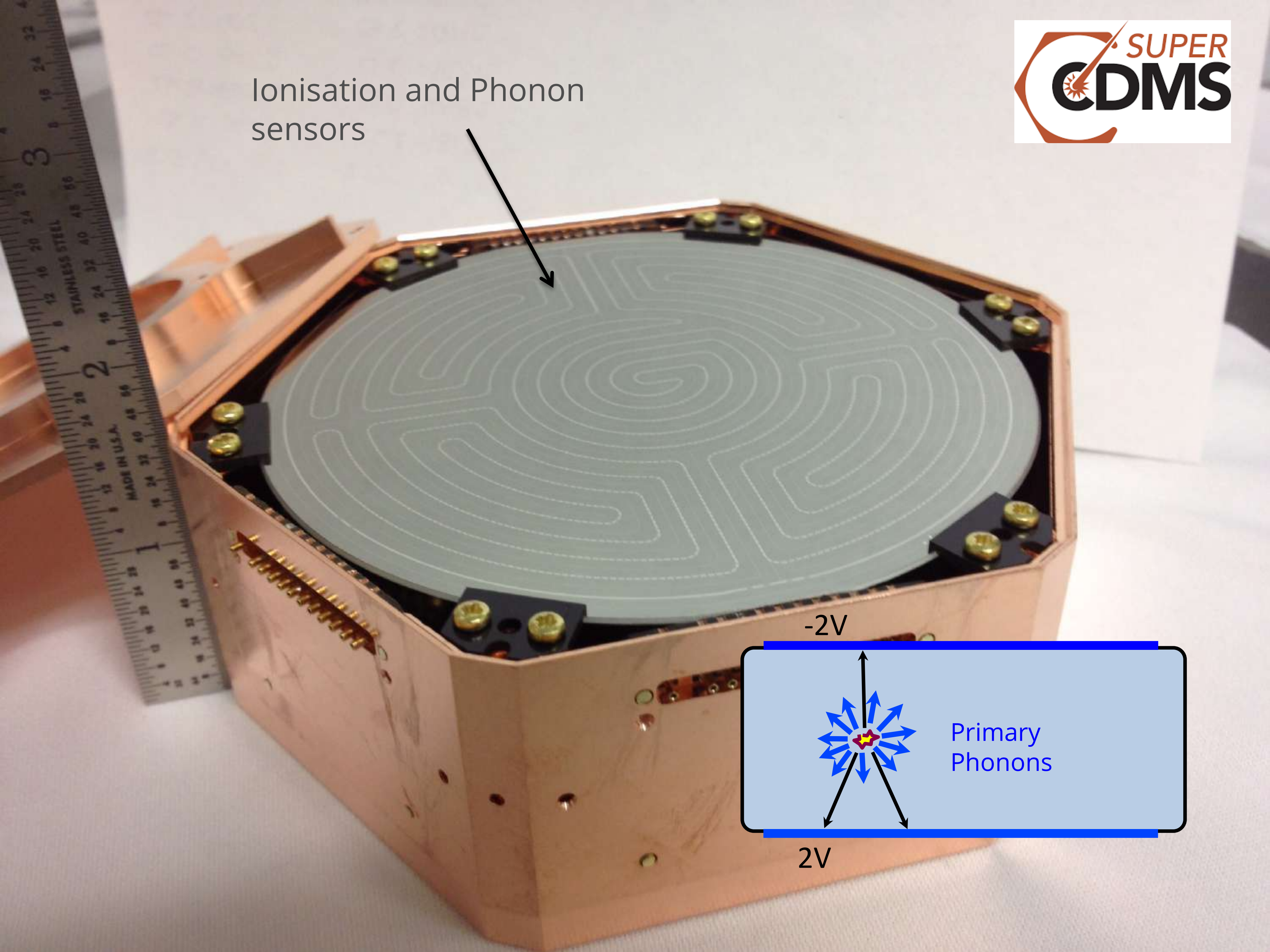
ELECTRON ABSORBPTION

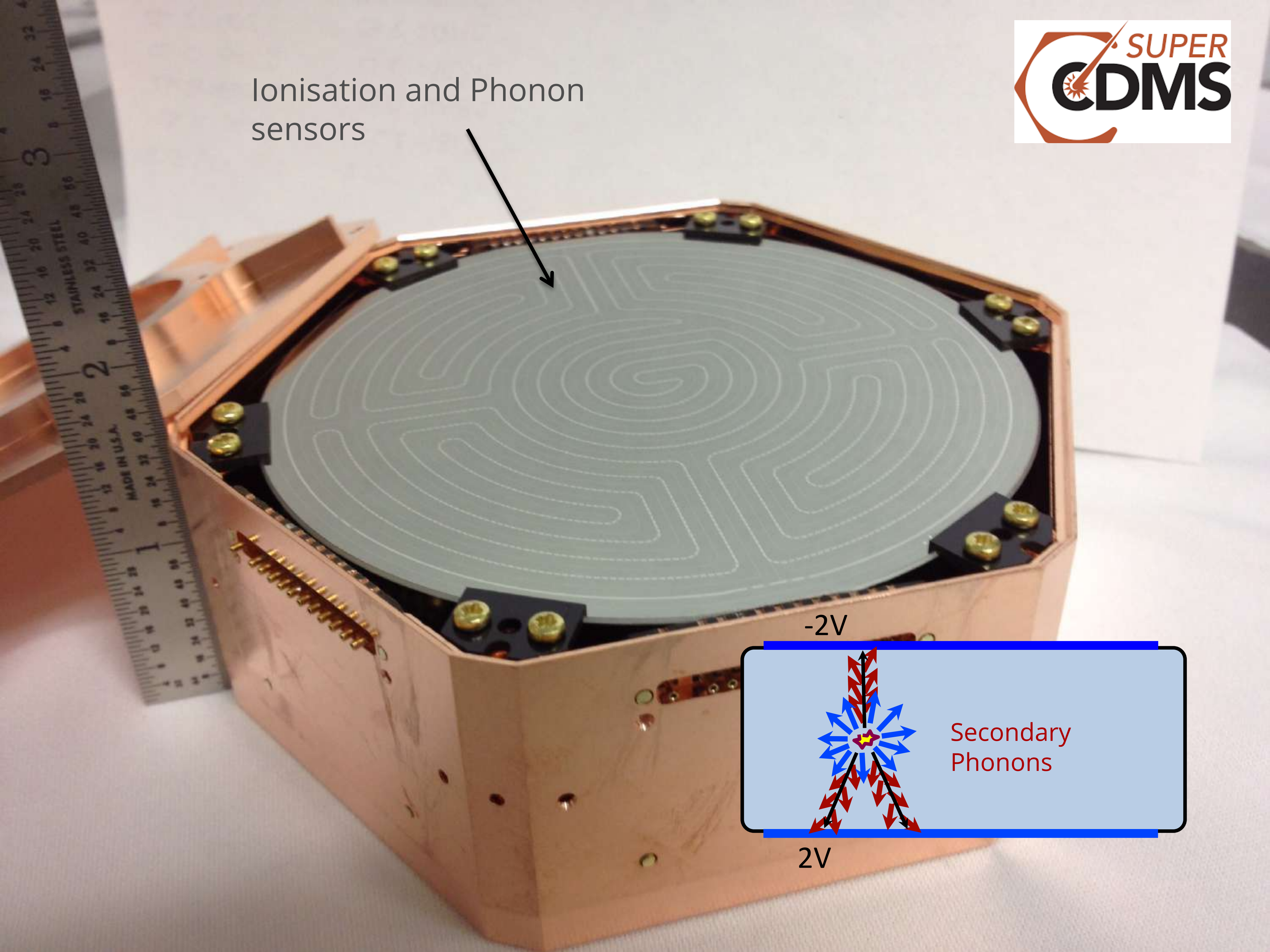
- Very light (non-WIMP)

EXOTIC SEARCHES

- Axion-photon conversion in the atomic EM field
- Light Ionising Particles


SUPER CDMS
Ionisation and Phonon sensors
-2V
e-h pairs
2V

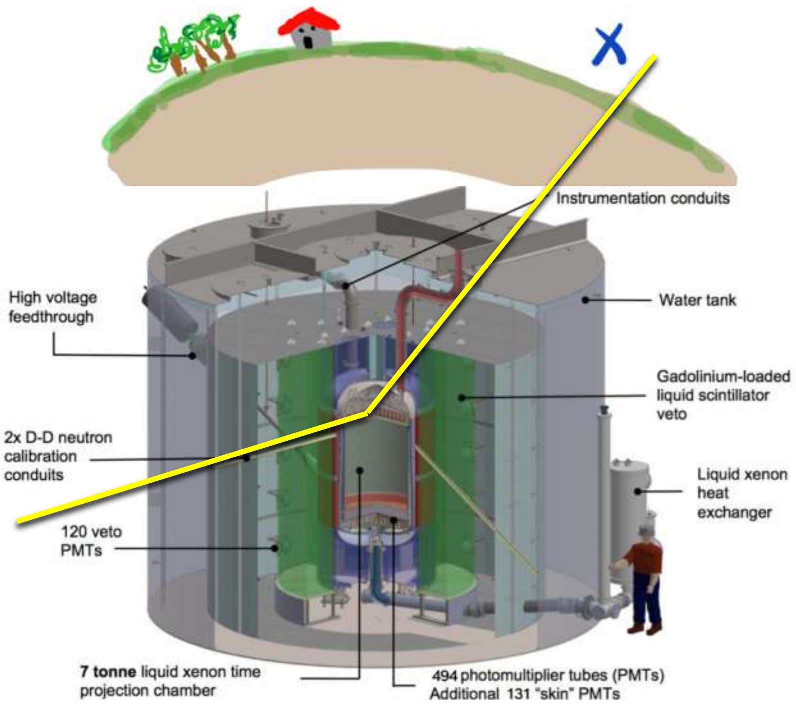

Ionisation and Phonon sensors
SUPER CDMS
-2V
Primary Phonons
2V


Ionisation and Phonon sensors
SUPER CDMS
-2V
Secondary Phonons
2V

Direct dark matter detection often requires large underground experiments

Expected number of events

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



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)

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Dark matter halo parameters

Local density and DM velocity distribution function

Uncertainties in the halo parameters

Directionality and time-dependence

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

Experimental parameters

Size, energy resolution, energy threshold

Backgrounds and signal 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

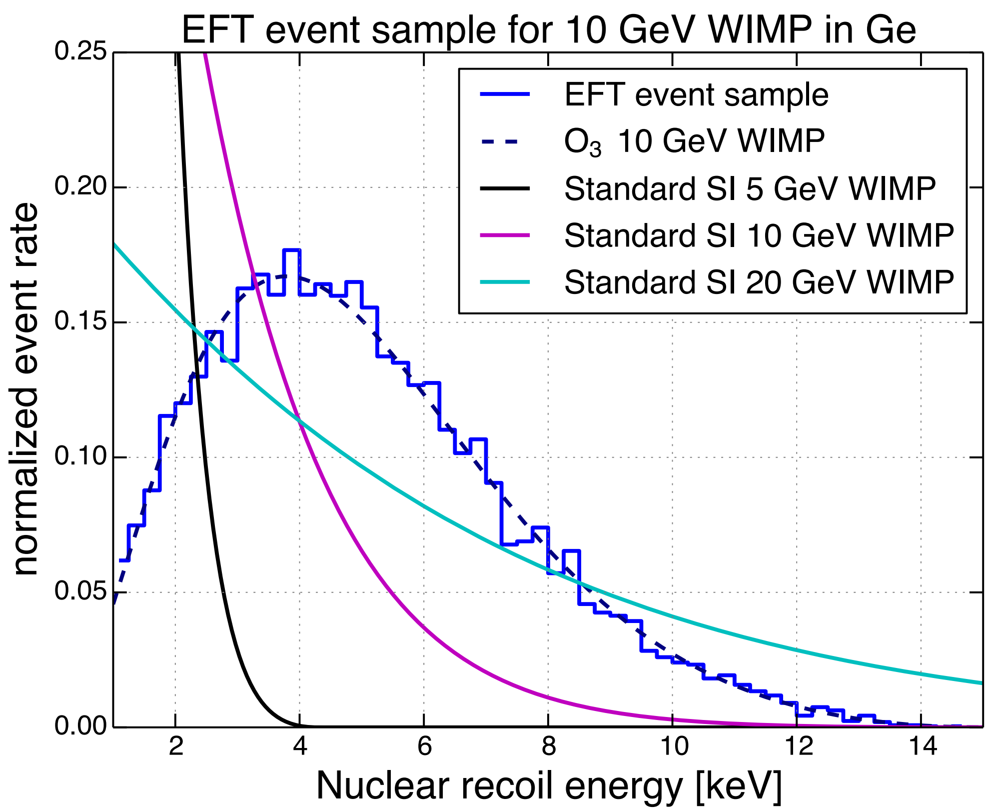
The resulting dark matter signature depends on the microphysics

Different effective operators lead to characteristic spectra (especially if there is a momentum dependence)

Low-mass WIMPs are expected to leave more energy at small energies.

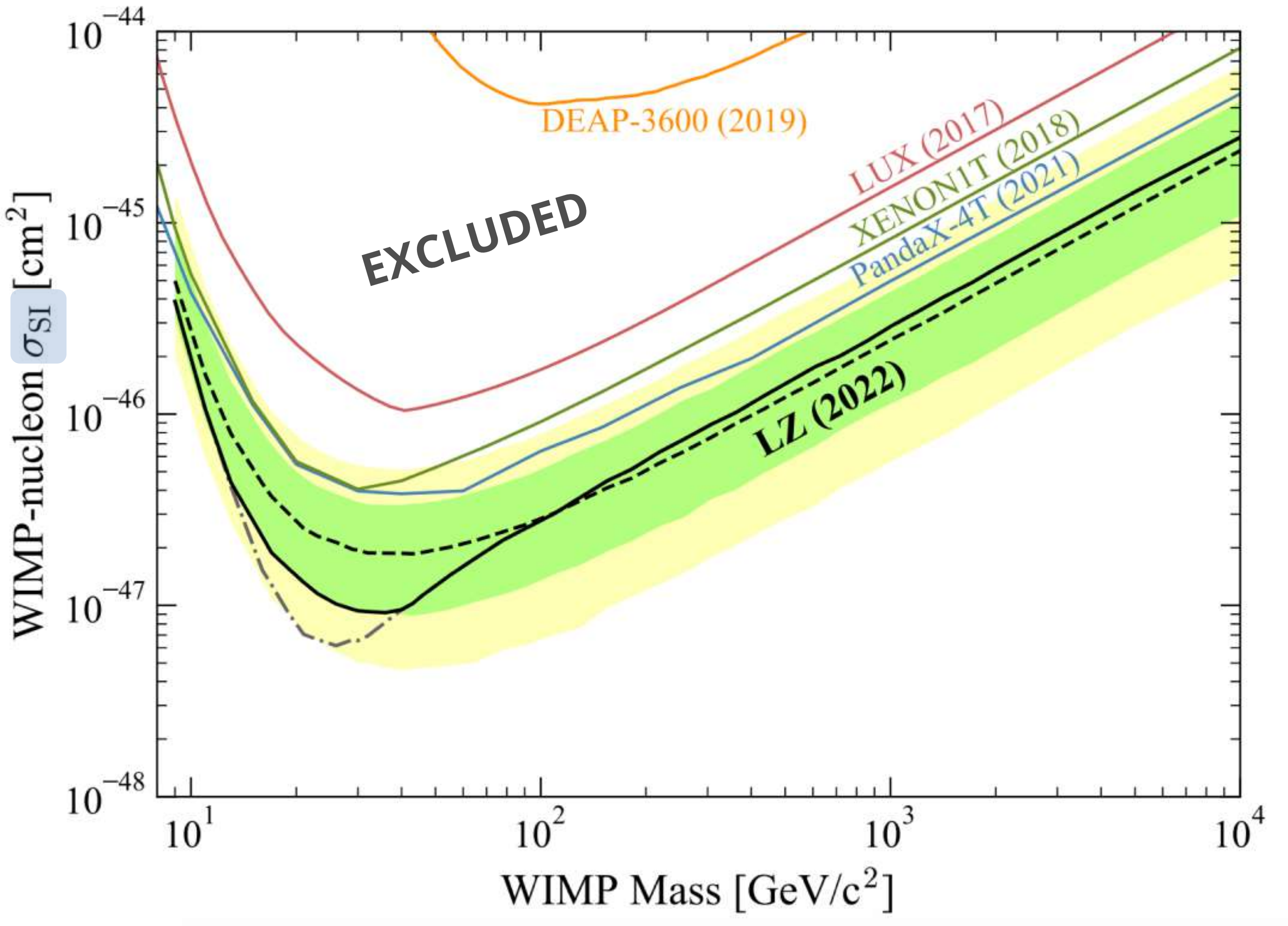
Momentum dependent interactions show a characteristic “bump”

A **low-energy threshold** is crucial to discriminate these features

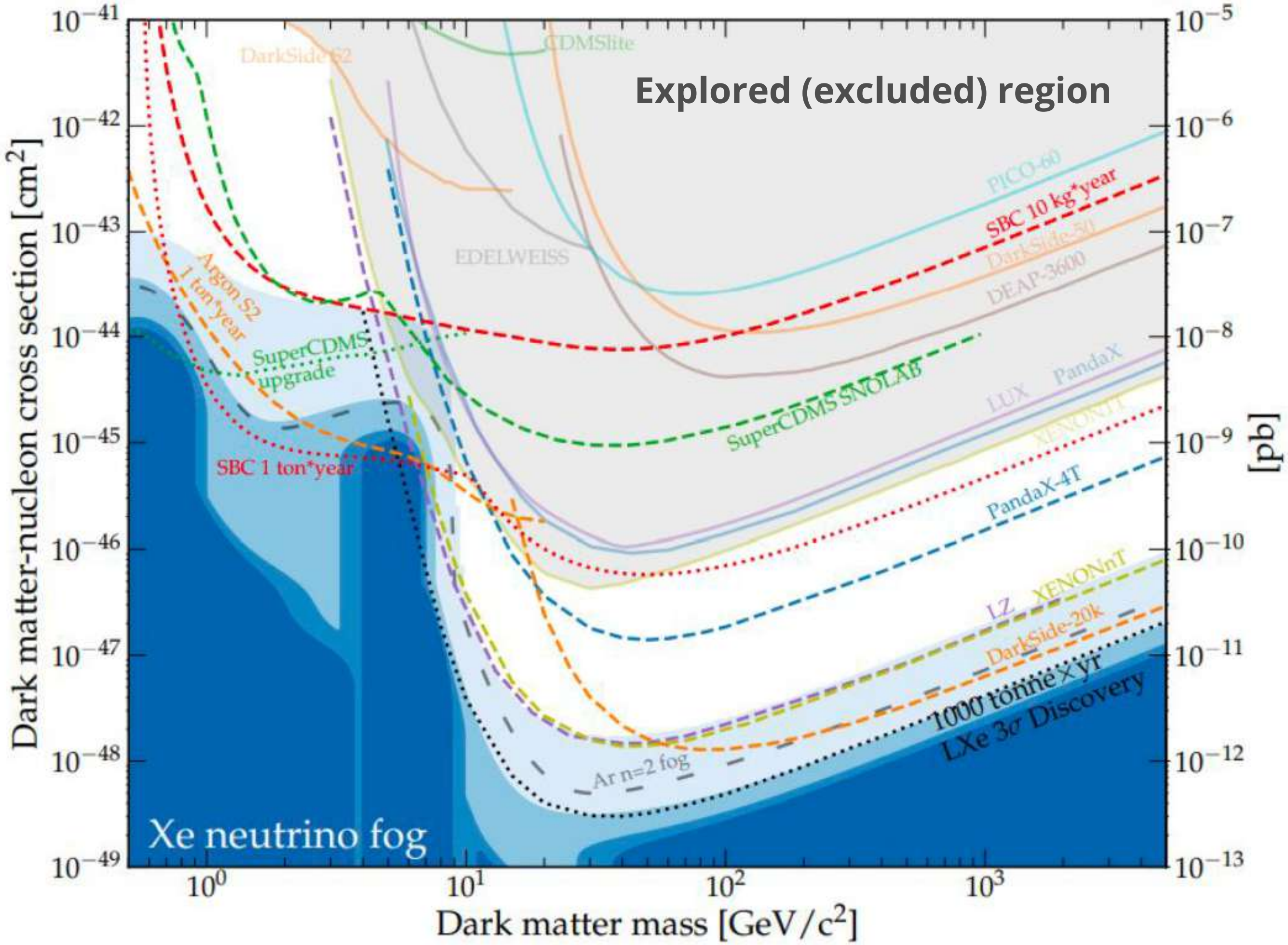


Another characteristic of a hypothetical DM signature would be its **time dependence** (annual modulation) and eventually **directionality**.

Unsuccessful searches have led to upper bounds on the scattering cross-section



Future experiments will further explore the DM parameter space



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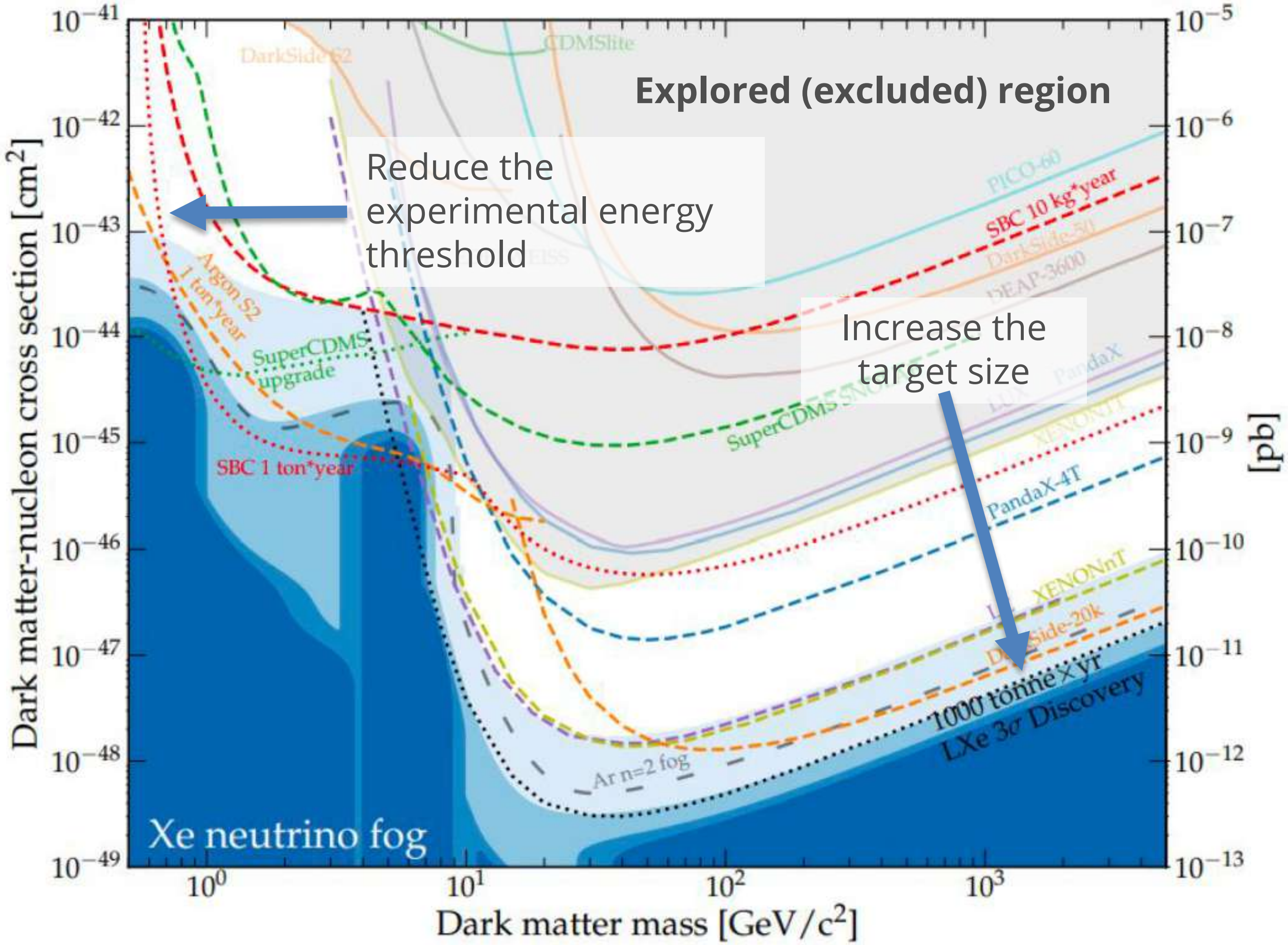

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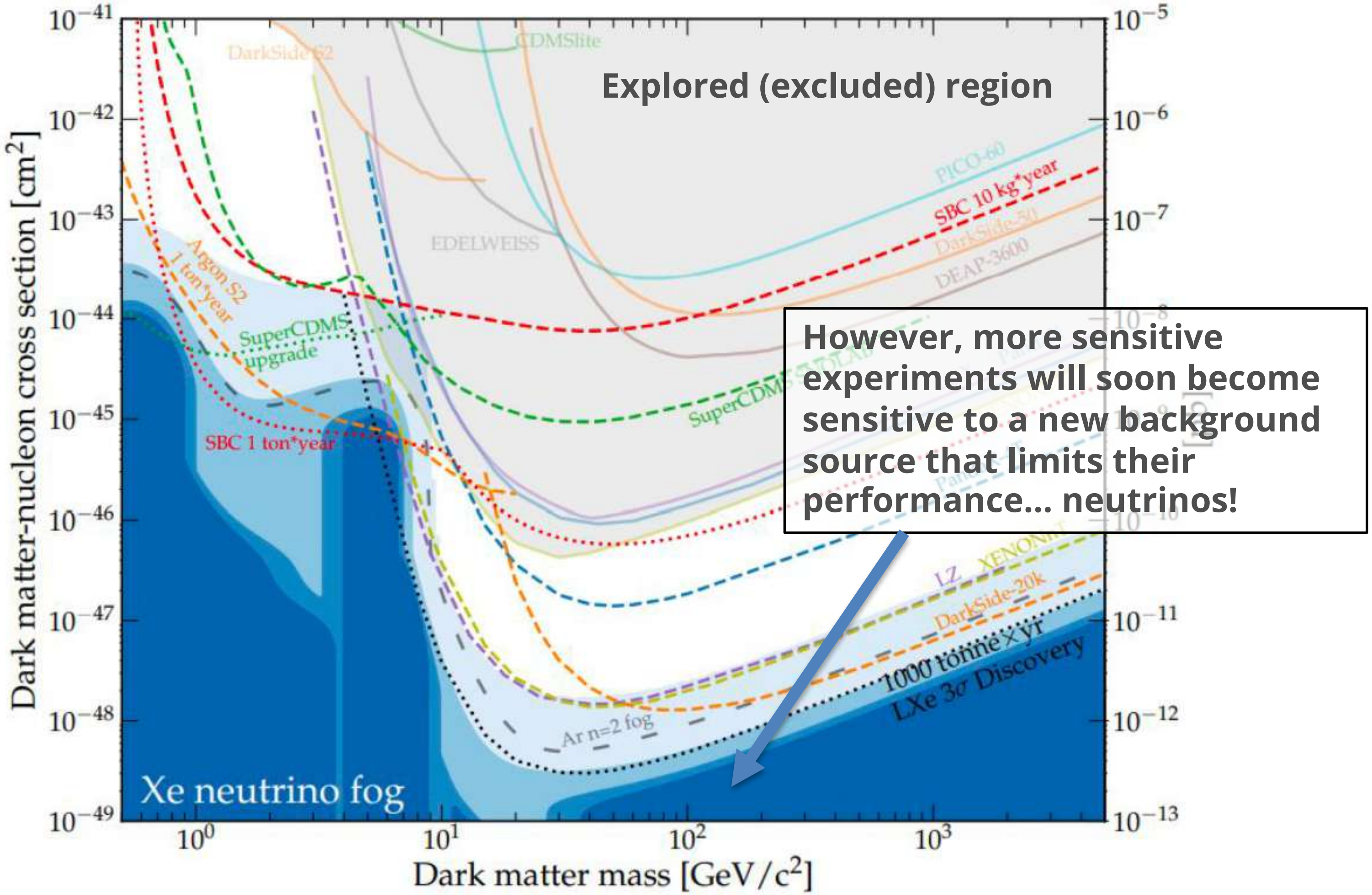


Coherent elastic neutrino-nucleus scattering (CEvNS)

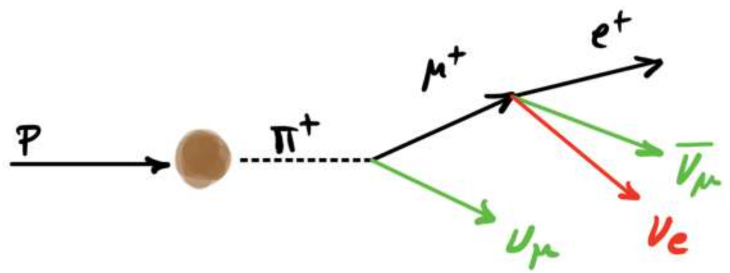
MeV neutrinos have the equivalent length of ~fm and can scatter **coherently** with nuclei

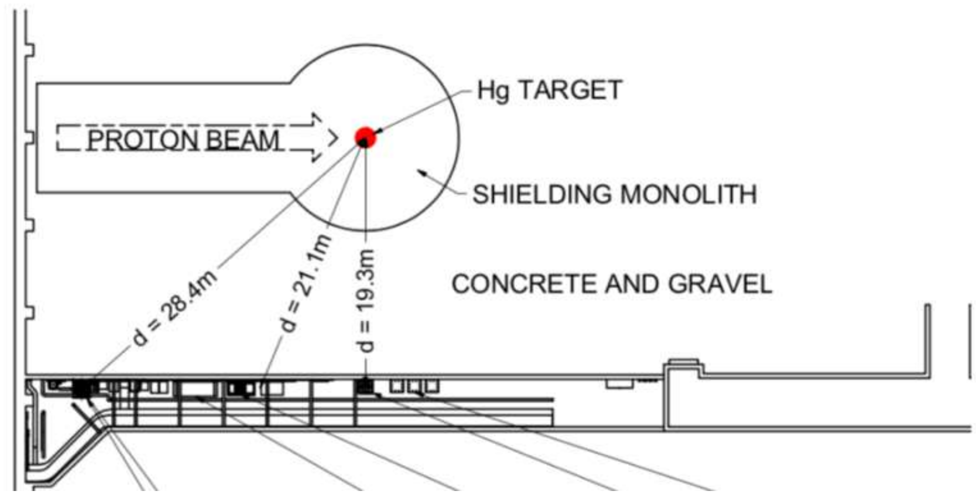
First experimental detection of CEvNS at the COHERENT experiment, on two complementary targets (CsI and Lar).

COHERENT Collab. 2017, 2021

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

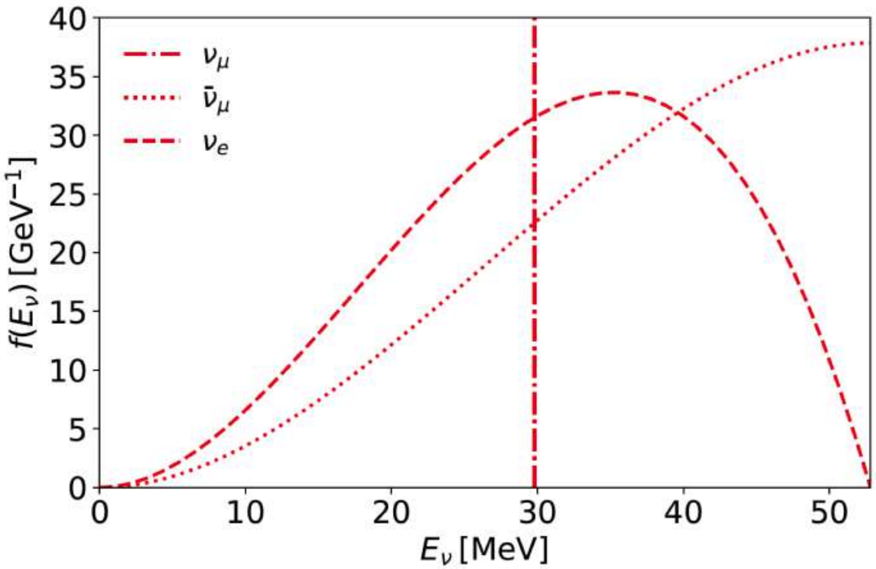
Coloma et al. (2017); Denton et al. (2018); Abdullah et al. (2018); de Romeri et al. (2020)
Amaral et al. (2020); Flores et al. (2020); Miranda et al. (2020); Shoemaker et al. (2021)...





Signal at Spallation Source experiments

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



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

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

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

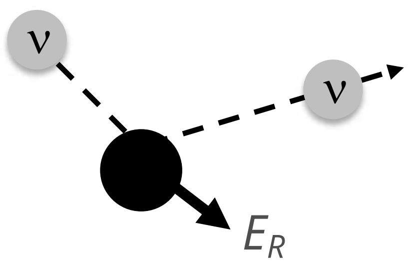
$$\xi \equiv r R_{\mathrm{POT}} / (4\pi L^2)$$

$$\frac{\mathrm{d}R_{\alpha'}}{\mathrm{d}E_R} = \frac{1}{m_A} \int_{E_\nu^{\mathrm{min,CE\nu NS}}}^{E_\nu^{\mathrm{max}}} \frac{\mathrm{d}\phi_{\nu_{\alpha'}}}{\mathrm{d}E_\nu} \frac{\mathrm{d}\sigma_{\mathrm{CE\nu NS}}}{\mathrm{d}E_R}$$

Neutrinos can be observed in direct detection experiments:

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

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



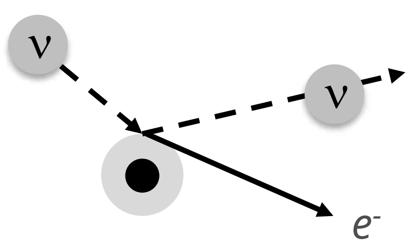
Rare Standard Model process recently measured in spallation source experiments

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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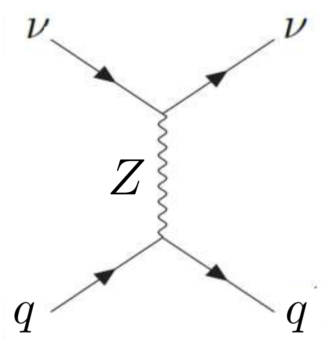

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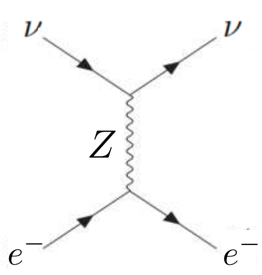
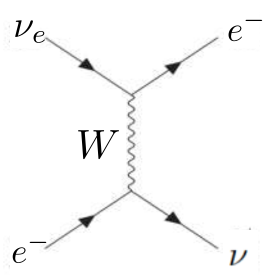


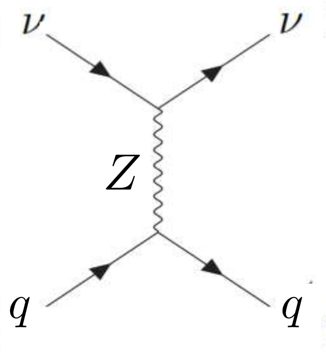


Usual electroweak process mediated by the *Z* and *W* bosons

Expected signal in a direct detection experiment

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

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



The Standard Model rate has no free parameters

(other than the Weak angle at very low energies)

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

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

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

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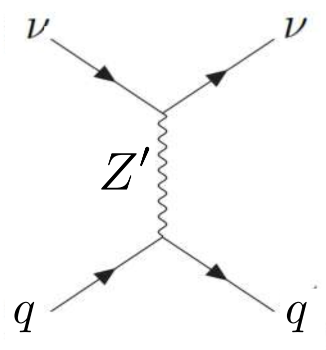


New physics can lead to extra contributions to CEvNS

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

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

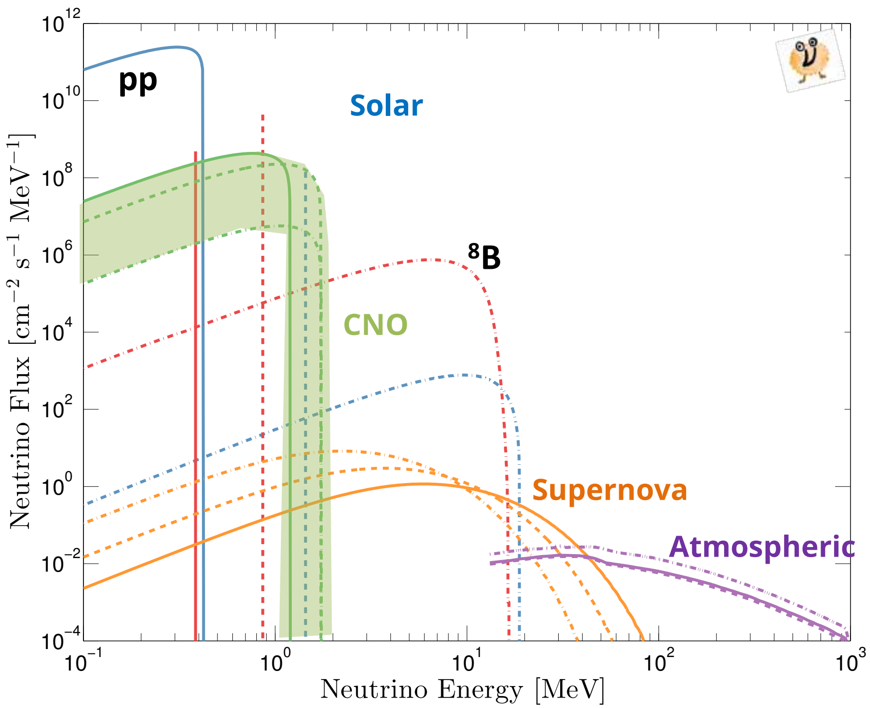
Neutrino flux

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

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

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

Solar neutrinos
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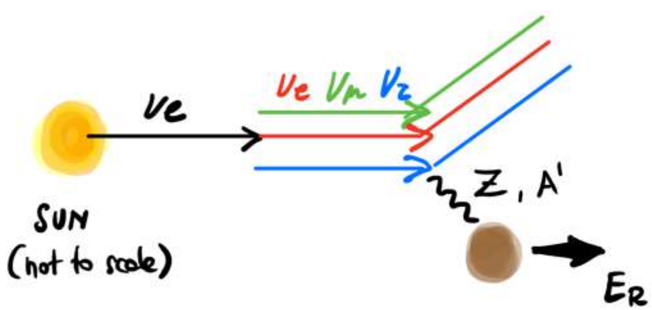
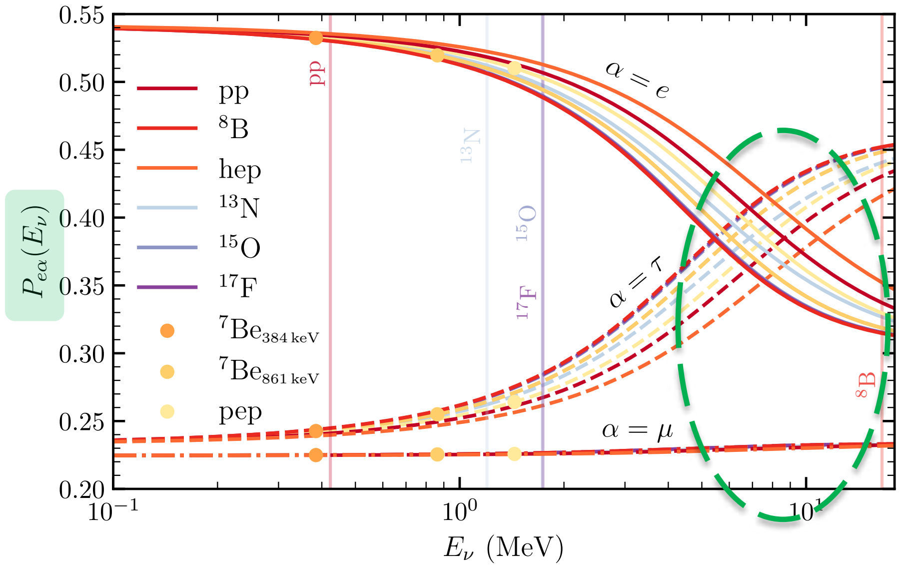
Produced as electron neutrinos, they oscillate into other flavours



Amaral, DGC, Foldenauer, Reid 2020



Matter oscillation in solar medium dominates flavour composition reaching earth: at 10 MeV (^{8}B) there is **significant oscillation** into $\nu_\mu,\ \nu_\tau$

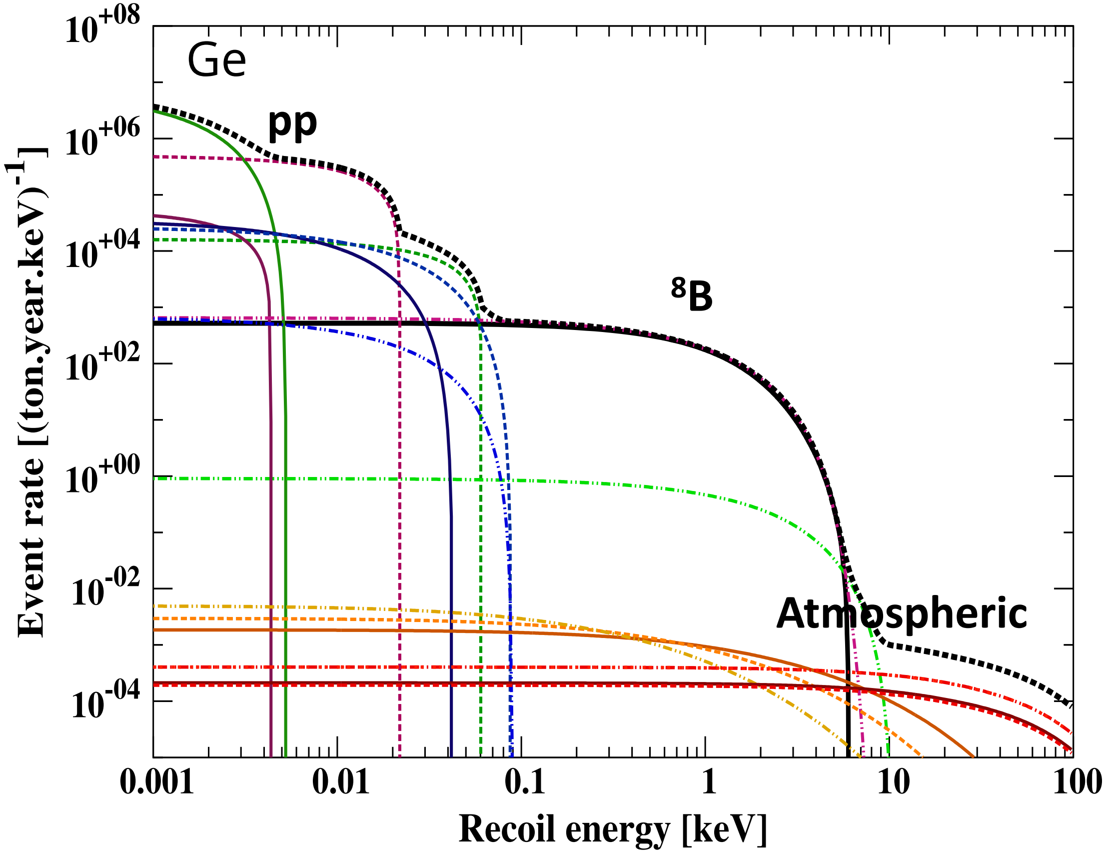
Experimental response to CEvNS

- **Solar neutrinos**
  dominate at low energy – the leading contribution is the pp chain below 1 MeV

- **Atmospheric neutrinos**
  contribute at higher energies but at a much smaller rate

- **Diffuse Supernovae Background**
  relevant around ~20-50 MeV

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014



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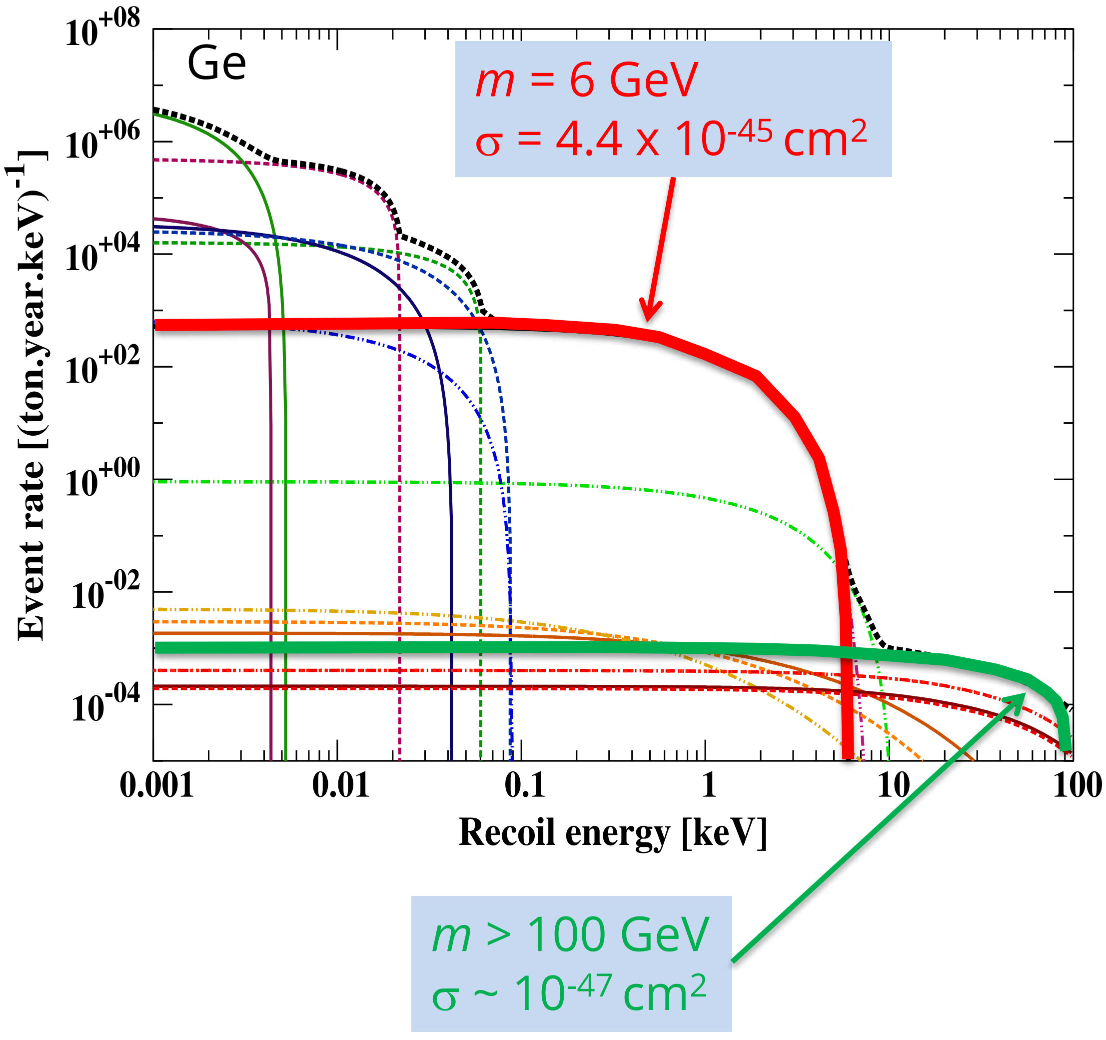
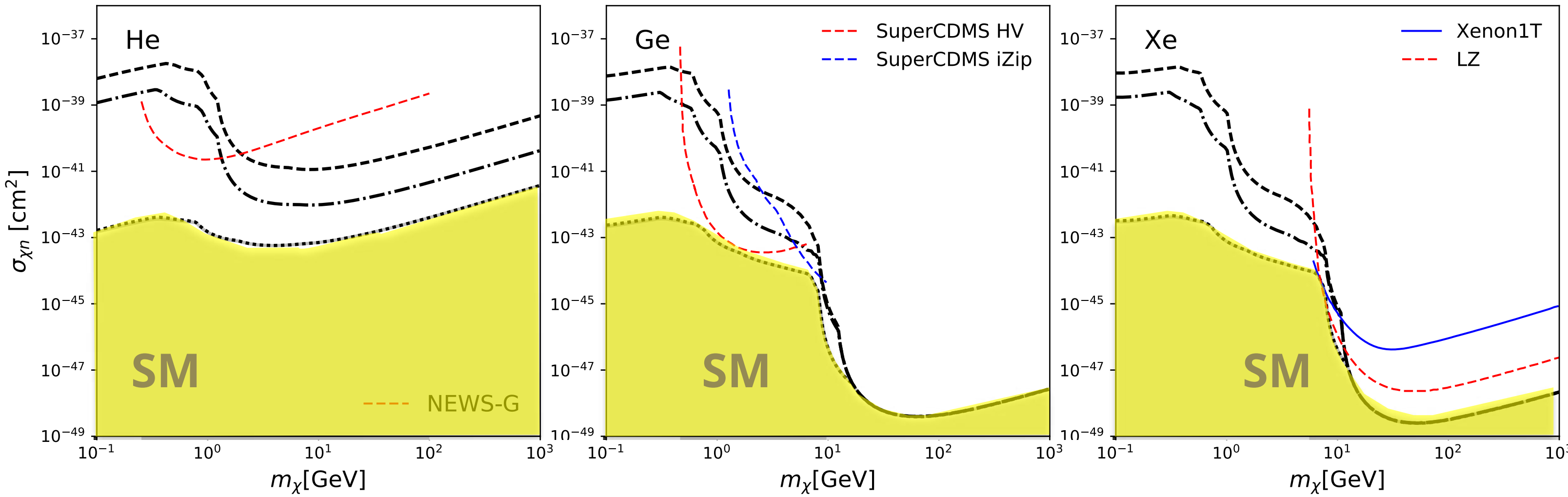


The neutrino floor can be substantially higher than in the SM

There are areas of the parameter space where direct detection experiments might mistake dark matter and neutrinos (with new interactions)

Boehm, DGC, Machado, Olivares, Reid 2018



Ultimately, some discrimination is possible through

- Spectral shape
- Timing (annual modulation)
- Directionality (if available)

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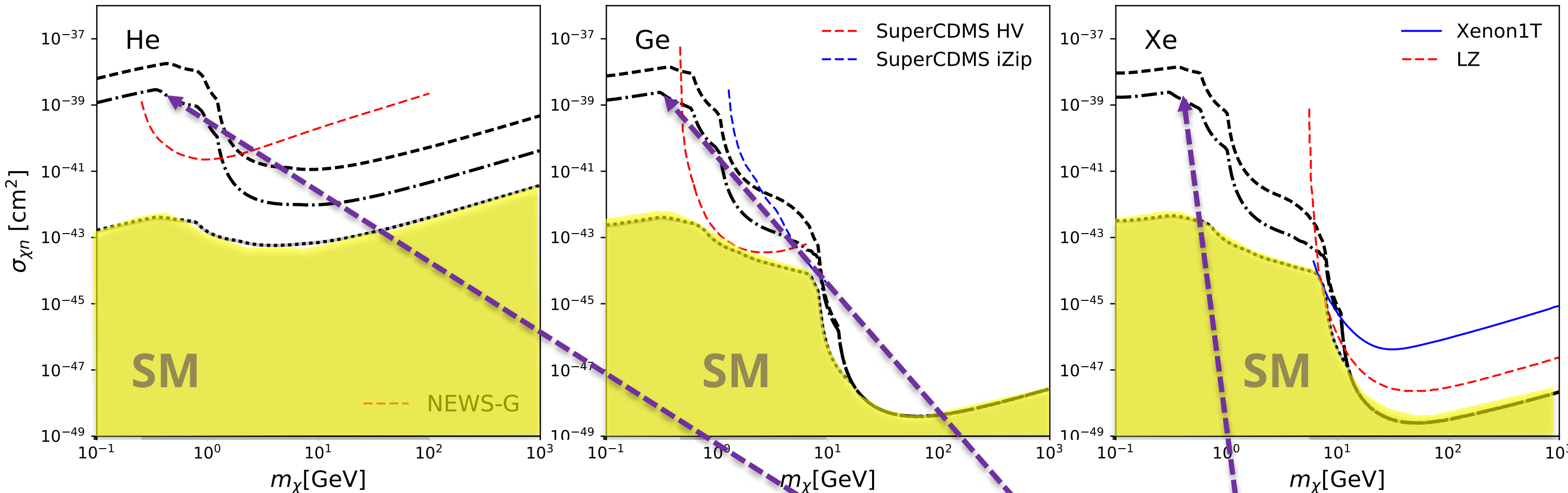

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- Directionality (if available)

This big increase is due to the reevaluation of Supernovae constraints

DGC, Cermeño, Pérez, Reid 2021

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, DGC, Cheek, Foldenauer 2023

- It can also help to reconstruct the **sterile neutrino** mass when combined with data from spallation source experiments.

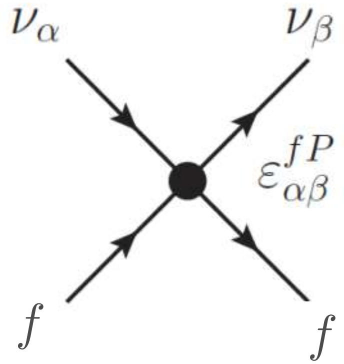
Alonso, Amaral, Bariego, DGC, de los Ríos 2023

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)

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

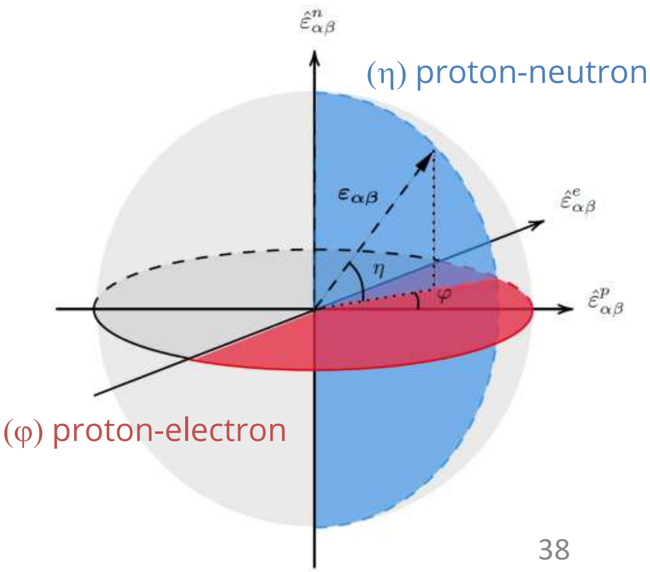
$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$$



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

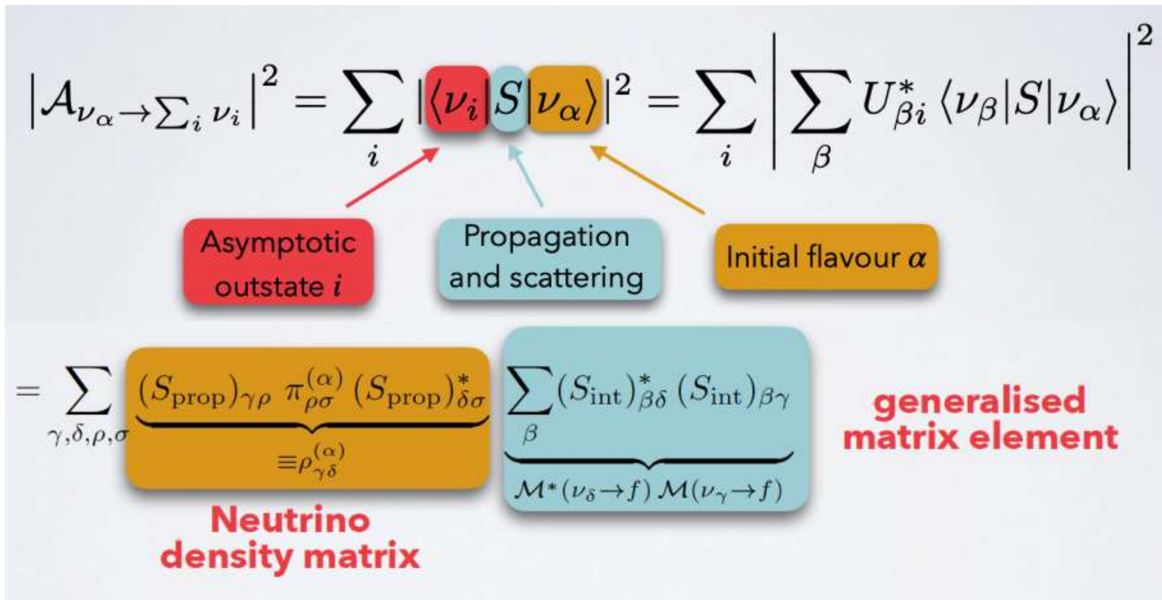
New parametrisation including electron recoils

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



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**



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

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

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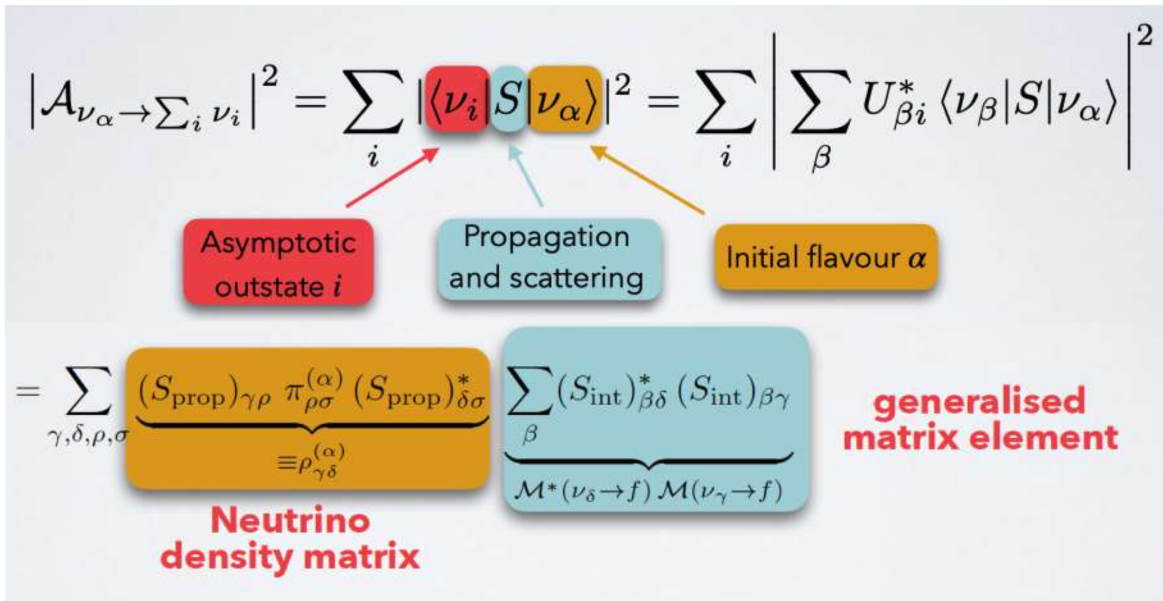

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Amaral, DGC, Cheek, Foldenauer 2023
Coloma, Maltoni, González García 2023

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

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

$$E^m_{1,2} = c_{13}^2 A_{\rm cc} \mp \frac{\Delta m_{21}^2}{4E_\nu} \sqrt{p^2 + q^2}\,,$$

$$p \equiv \sin 2\theta_{12} + 2\,\varepsilon_N^{\eta,\varphi}\left[\xi^e + \xi^p + Y_n(x)\,\xi^n\right] \frac{A_{\rm cc}}{\Delta m_{21}^2}\,,$$

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

SNuDD: *Solar Neutrinos for Direct Detection*

https://github.com/SNuDD/SNuDD

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

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

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

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

ELECTRON RECOILS

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

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

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

NUCLEAR SCATTERING

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

Coloma, Esteban, González-García, Maltoni 2020

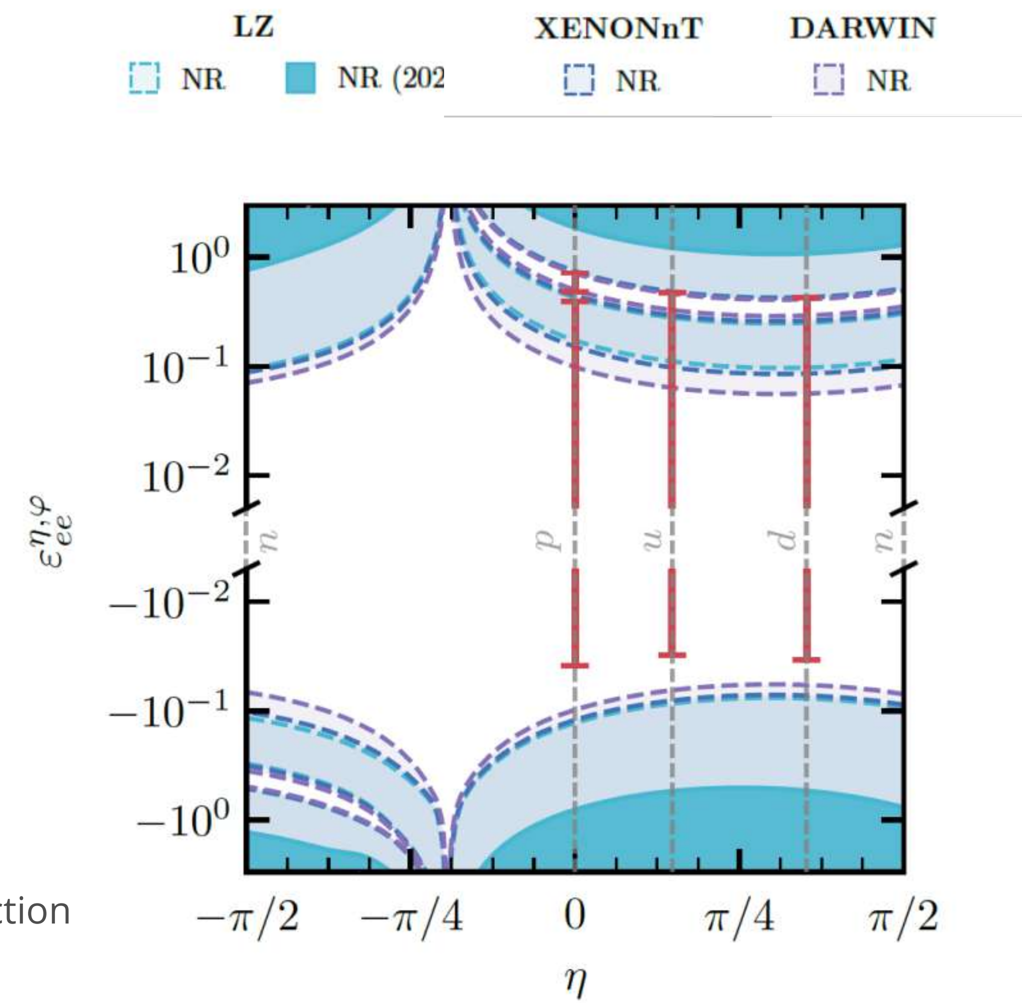
Future DD experiments will be able to improve existing constraints

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

$$\epsilon^{\eta,\varphi}_{\alpha\alpha} = \frac{Q_{\nu N}}{\xi^p + Z^x i^n N}$$



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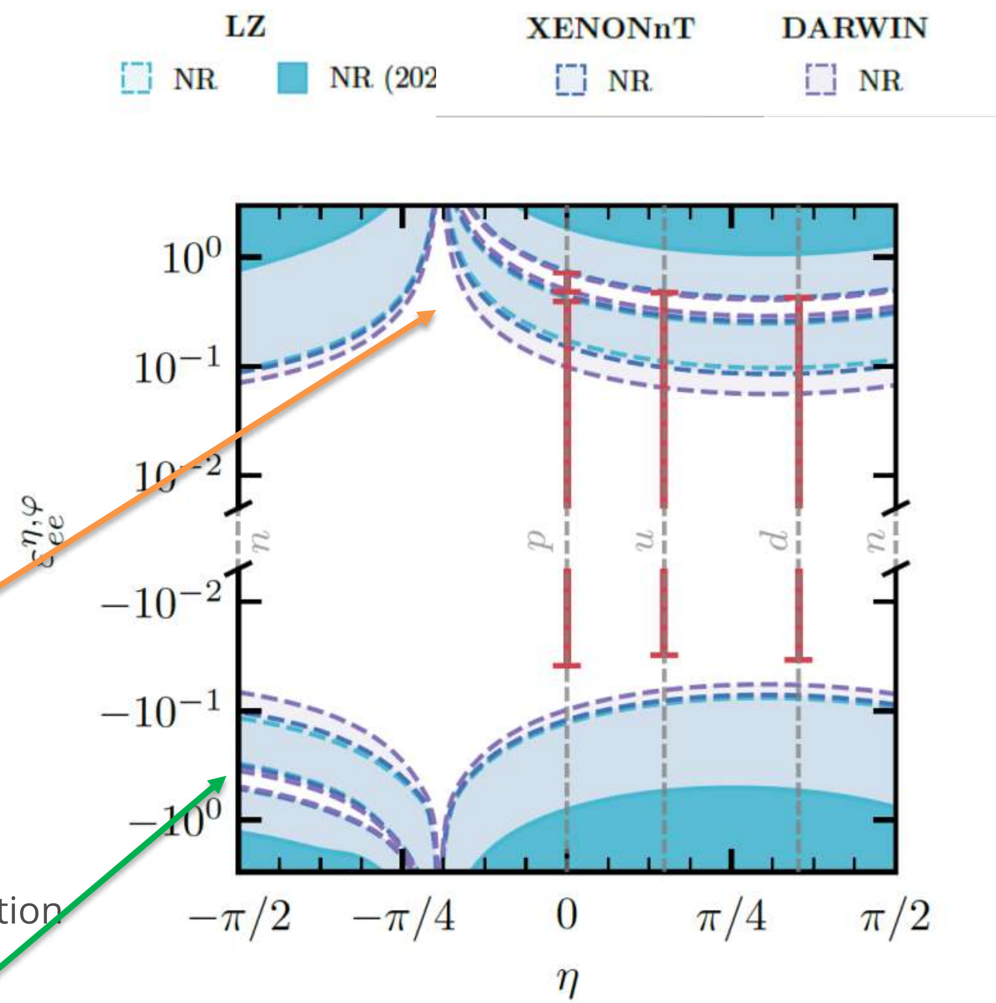

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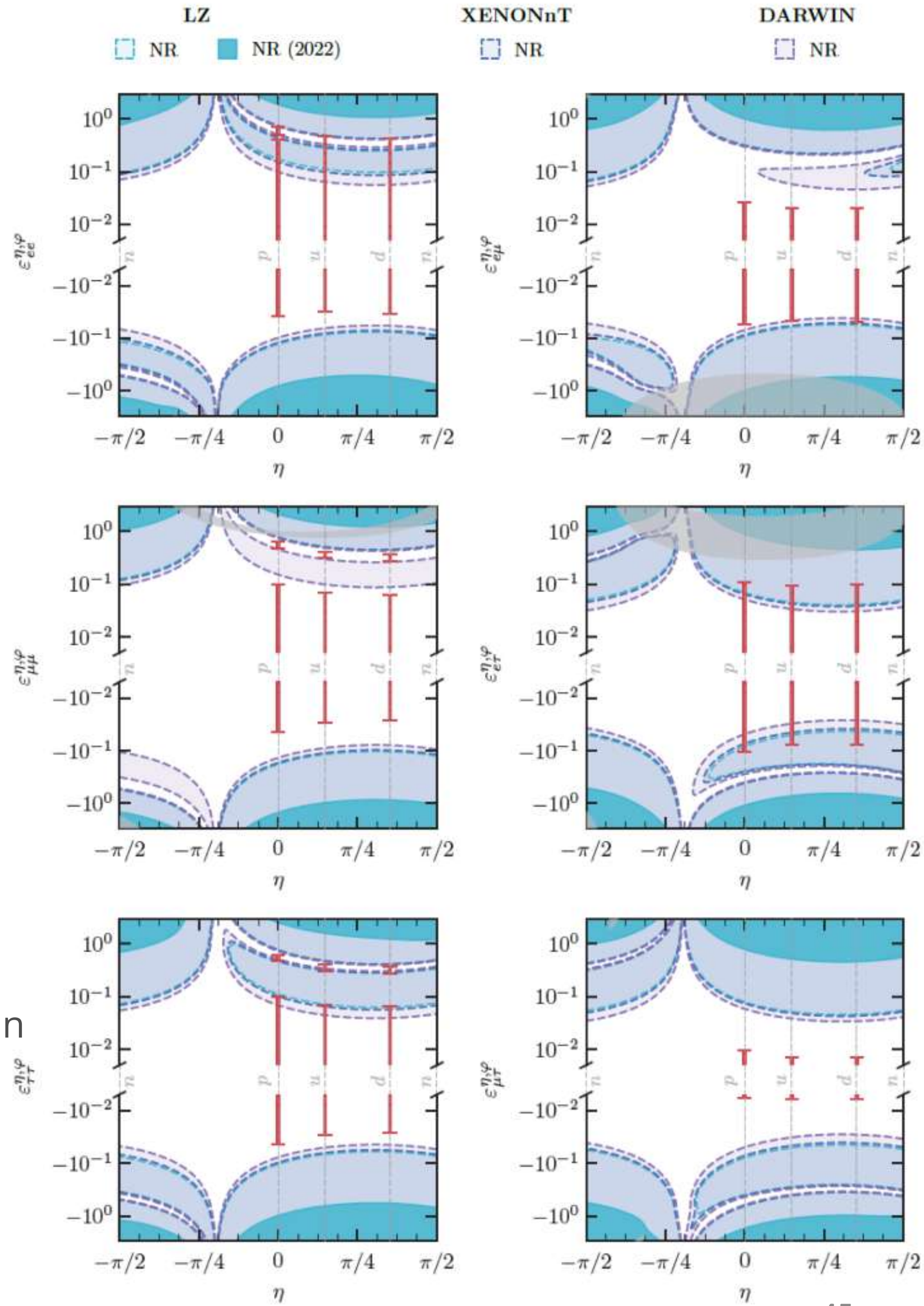


NUCLEAR + ELECTRON SCATTERING

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

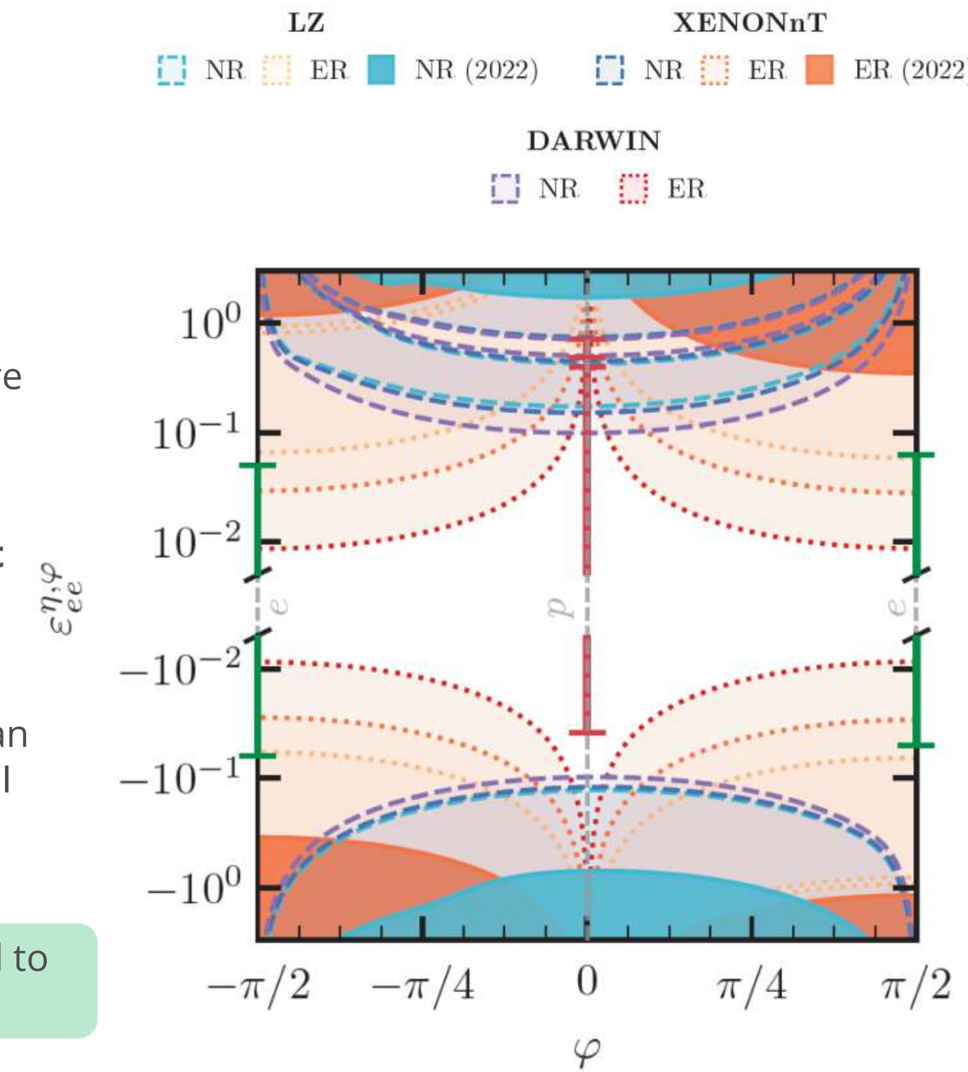
ER sensitivities drop off towards $\varphi = 0$ (pure proton), whereas NR sensitivities become maximal.

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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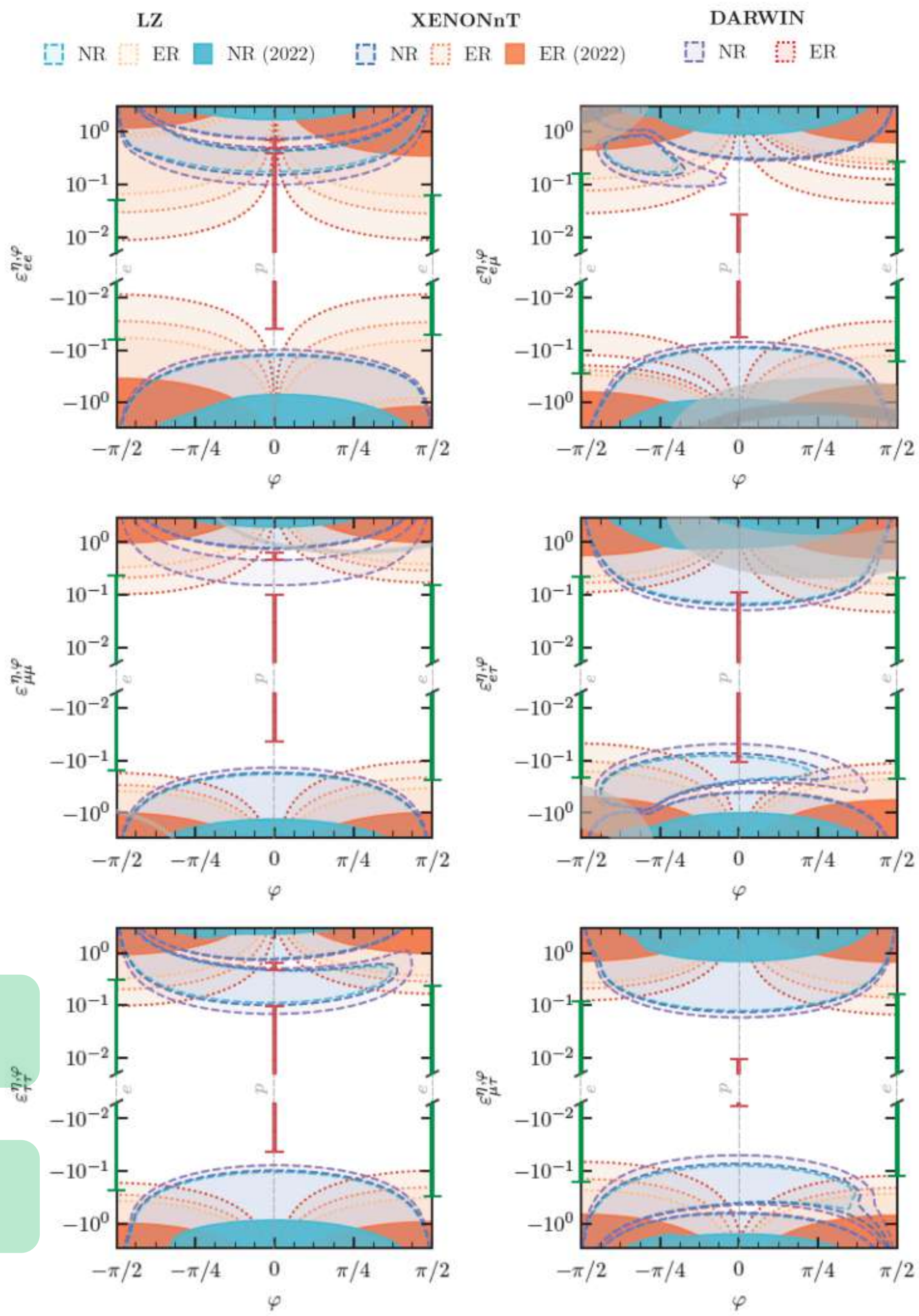

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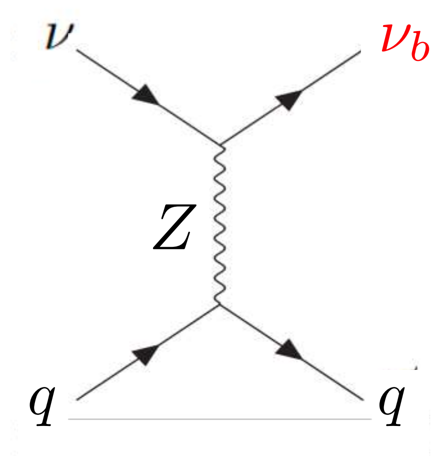
INELASTIC SCATTERING INTO A STERILE NEUTRINO

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**?

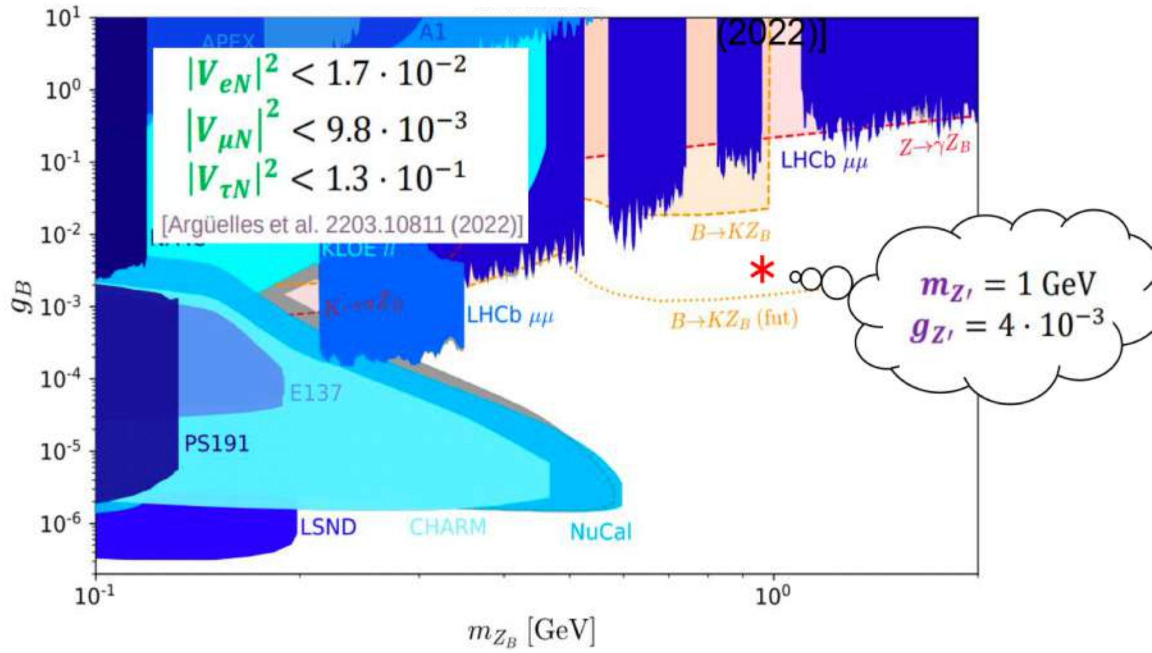
Example: sterile baryonic neutrino

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

Pospelov 2011

Foguel et al. 2201.01788

Parameter space



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

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

	m_4 [GeV]	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
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

$$\frac{\mathrm{d}R_{\alpha'}}{\mathrm{d}E_R} = \frac{1}{m_A}\left(\int_{E_\nu^{\mathrm{min,CE}\nu\mathrm{NS}}}^{E_\nu^{\mathrm{max}}} \frac{\mathrm{d}\phi_{\nu_{\alpha'}}}{\mathrm{d}E_\nu}\frac{\mathrm{d}\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{\mathrm{d}E_R}\,\mathrm{d}E_\nu + \int_{E_\nu^{\mathrm{min},\alpha'4}}^{E_\nu^{\mathrm{max}}} \frac{\mathrm{d}\phi_{\nu_{\alpha'}}}{\mathrm{d}E_\nu}\frac{\mathrm{d}\sigma_{\alpha'4}}{\mathrm{d}E_R}\,\mathrm{d}E_\nu\right)$$

Neutrino-Nucleus Scattering

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

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

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

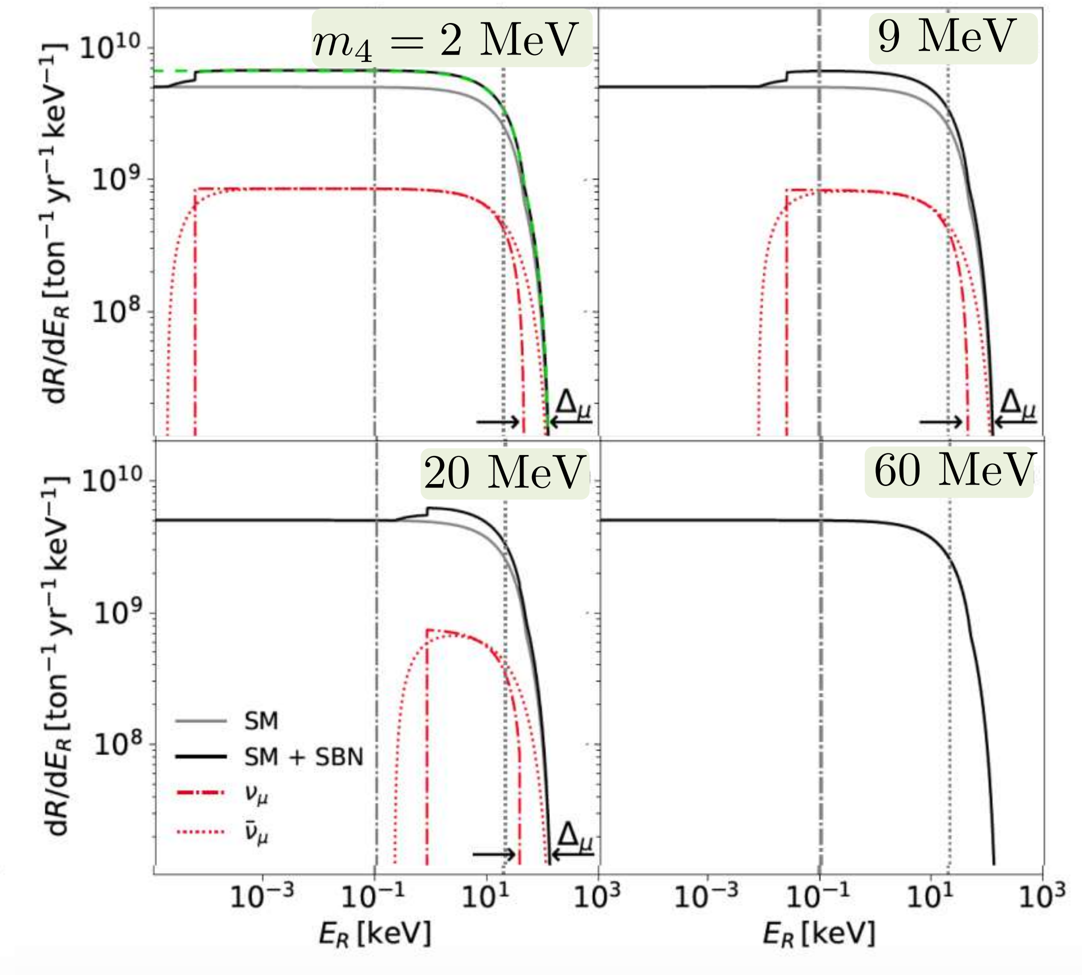
$$E_\nu^{\mathrm{min},\,\alpha'4} = \left(1+\frac{m_4^2}{2m_A E_R}\right)E_\nu^{\mathrm{min,\,CE}\nu\mathrm{NS}}$$

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** $\bar{\nu}_\mu$



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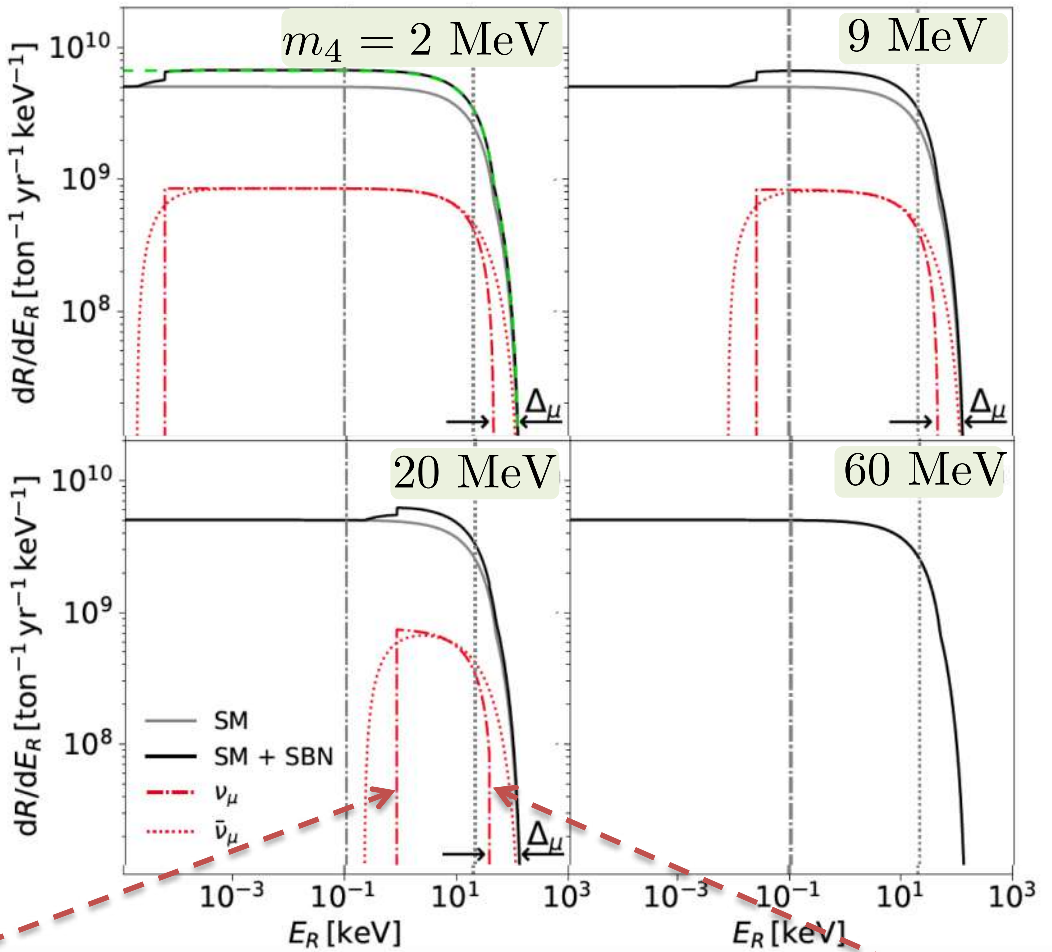
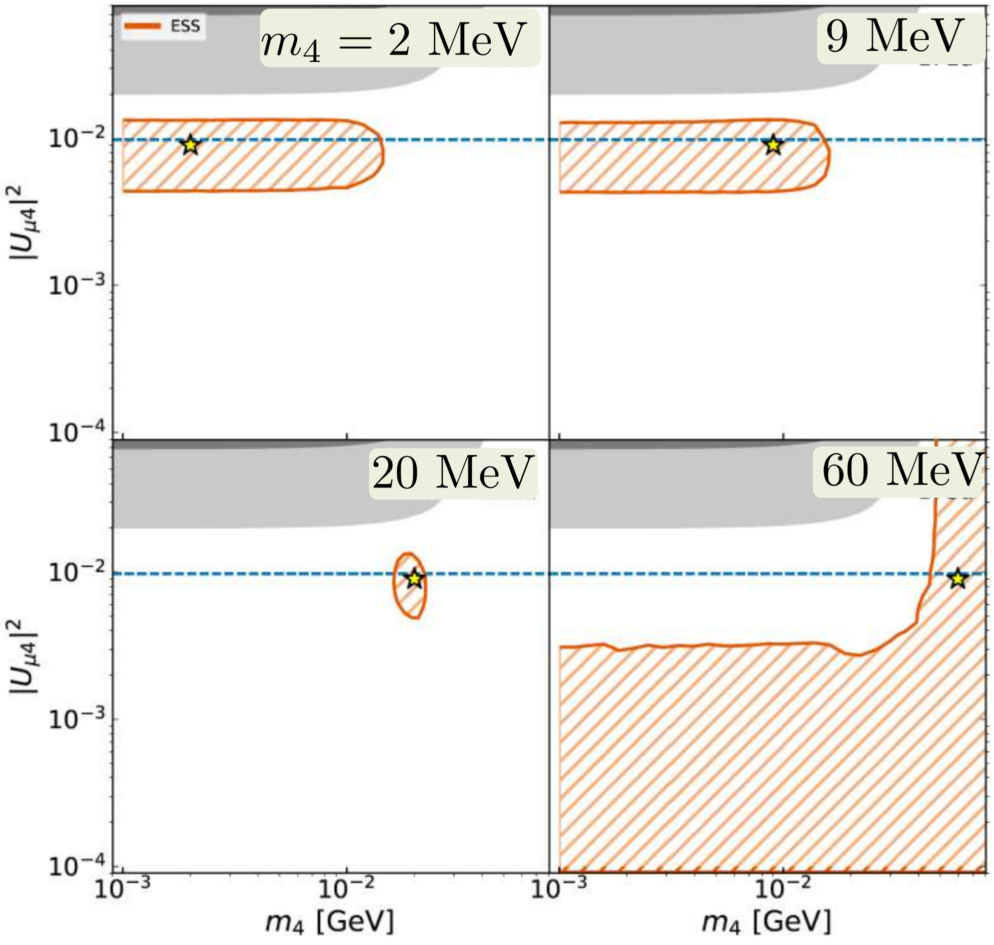


$$\frac{1}{2m_A}\left(2(E_\nu^{\max})^2 - m_4^2 - 2E_\nu^{\max}\sqrt{(E_\nu^{\max})^2 - m_4^2}\right)$$

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

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.

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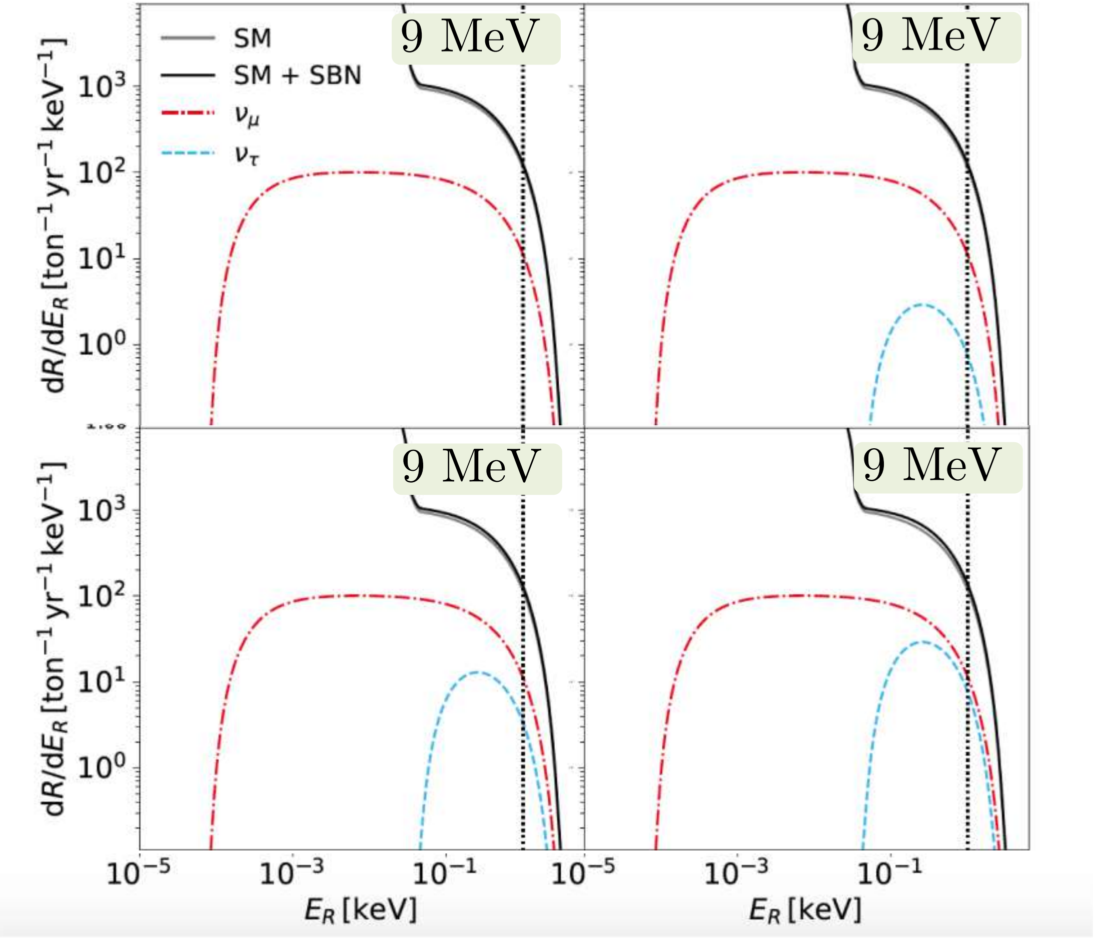
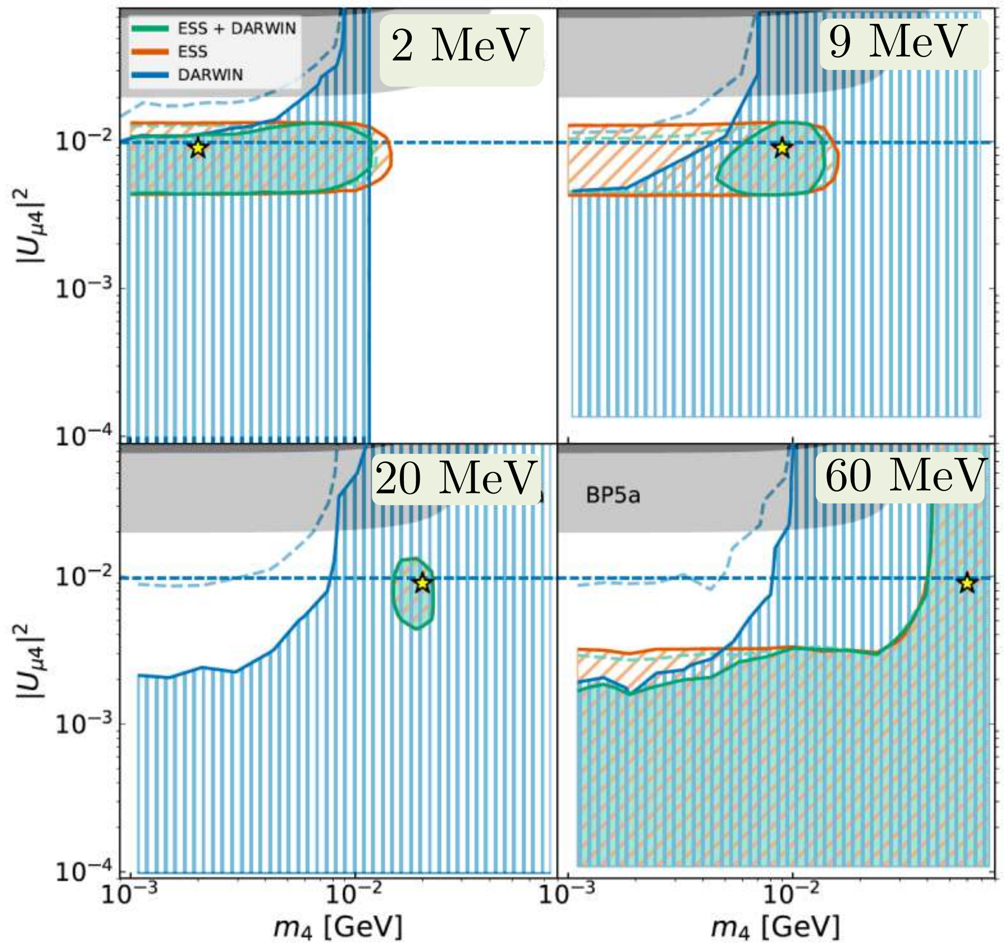


Parameter reconstruction: combination DD+SS

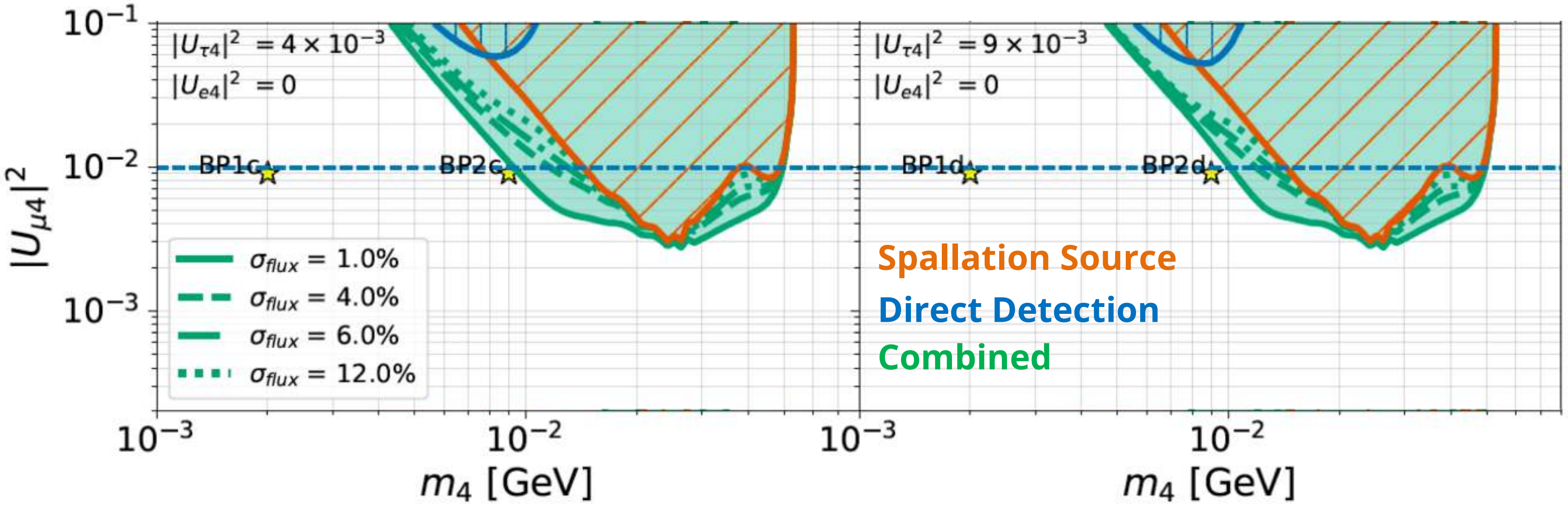
The combination allows to reconstruct smaller sterile neutrino masses.

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.

Funding: This work was supported by a Grant for I+D Projects by the Madrid Government (Comunidad de Madrid-Spain) under the Multiannual Agreement with Universidad Autonoma de Madrid in the line of action encouraging young research doctors in the context of the V PRICIT (Regional Program of Research and Technological Information) (project SI2/PBG/2020-00005)

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AGENCIA ESTATAL DE INVESTIGACIÓN

SI2/PBG/2020-00005
PID2021-125331NB-I00
CNS2022-135702

Universidad Autónoma de Madrid

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**

$$
\begin{aligned}
\left|\mathcal{A}_{\nu_\alpha\to\sum_i\nu_i}\right|^2 &= \sum_i \left|\sum_\beta U^*_{\beta i}\,\langle\nu_\beta|S_{\rm int}\left(\sum_\gamma|\nu_\gamma\rangle\langle\nu_\gamma|\right)S_{\rm prop}|\nu_\alpha\rangle\right|^2 \\
&= \sum_{\beta,\gamma,\delta,\lambda}\overbrace{\sum_i U^*_{\beta i}U_{\lambda i}}^{\delta_{\beta\lambda}}\,\langle\nu_\beta|S_{\rm int}|\nu_\gamma\rangle\langle\nu_\gamma|S_{\rm prop}\left(\sum_\rho|\nu_\rho\rangle\langle\nu_\rho|\right)|\nu_\alpha\rangle\langle\nu_\alpha|\left(\sum_\sigma|\nu_\sigma\rangle\langle\nu_\sigma|\right)S^\dagger_{\rm prop}|\nu_\delta\rangle \\
&\quad\times\langle\nu_\delta|S^\dagger_{\rm int}|\nu_\lambda\rangle \\
&= \sum_{\gamma,\delta,\rho,\sigma}\underbrace{(S_{\rm prop})_{\gamma\rho}\,\pi^{(\alpha)}_{\rho\sigma}\,(S_{\rm prop})^*_{\delta\sigma}}_{\equiv\rho^{(\alpha)}_{\gamma\delta}}\;\underbrace{\sum_\beta(S_{\rm int})^*_{\beta\delta}\,(S_{\rm int})_{\beta\gamma}}_{\mathcal{M}^*(\nu_\delta\to f)\,\mathcal{M}(\nu_\gamma\to f)}
\end{aligned}
$$

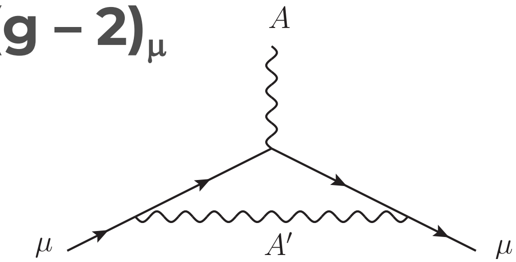
Neutrino density matrix

generalised matrix element

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

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

Light vector mediator as a solution to $(g-2)_\mu$



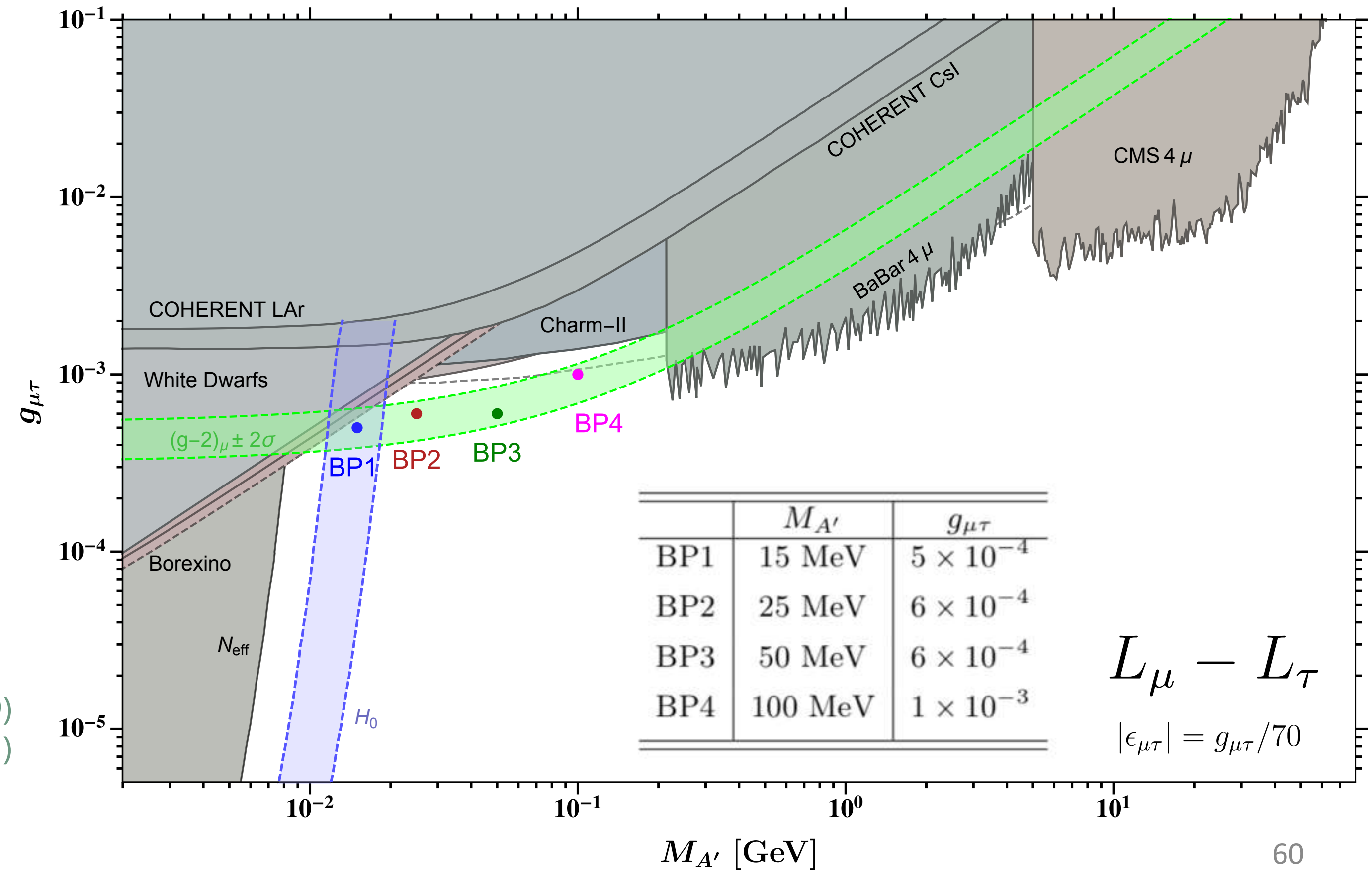
$$\Delta a_\mu = Q_\mu^{x\,2}\ \frac{\alpha_x}{\pi}\int_0^1 \mathrm{d}u\ \frac{u^2(1-u)}{u^2+\frac{(1-u)}{x_\mu^2}}$$

$\alpha_x = g_x^2/4\pi$

$x_\mu = m_\mu/M_{A'}$

Lynch (2001)
Pospelov (2008)

Amaral, DGC, Cheek, Foldenauer 2104.03297



	$M_{A'}$	$g_{\mu\tau}$
BP1	15 MeV	5×10^{-4}
BP2	25 MeV	6×10^{-4}
BP3	50 MeV	6×10^{-4}
BP4	100 MeV	1×10^{-3}

Could also account for an observed tension in the Hubble parameter

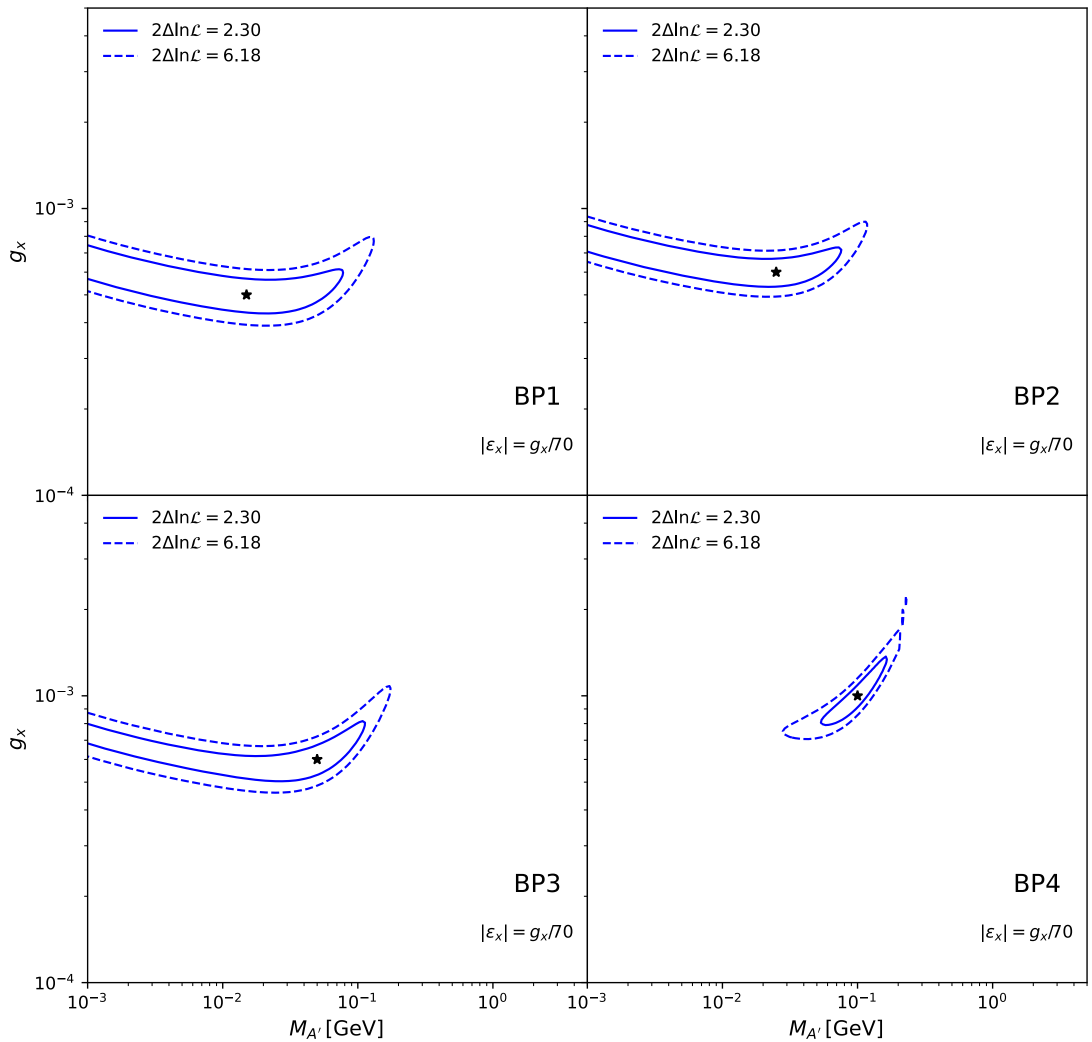
($\Delta N_{\rm eff} = 0.4$)

Escudero et al. (2019)
Araki et al. (2021)

The reconstruction is optimal for masses of the order of 100 MeV. For smaller masses, an upper limit can be found.

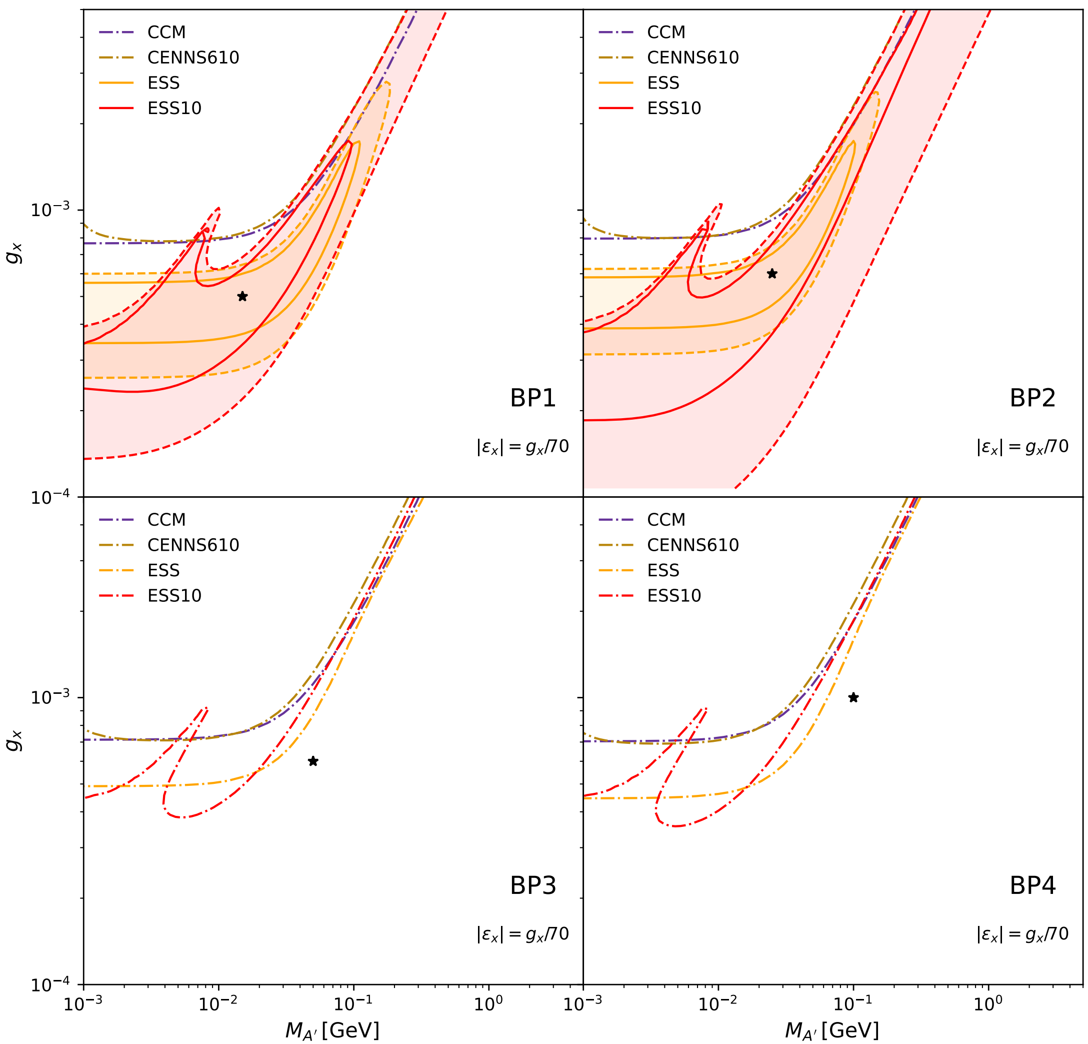
The coupling to muons can be determined in all BPs.

But we do not know which model it is.

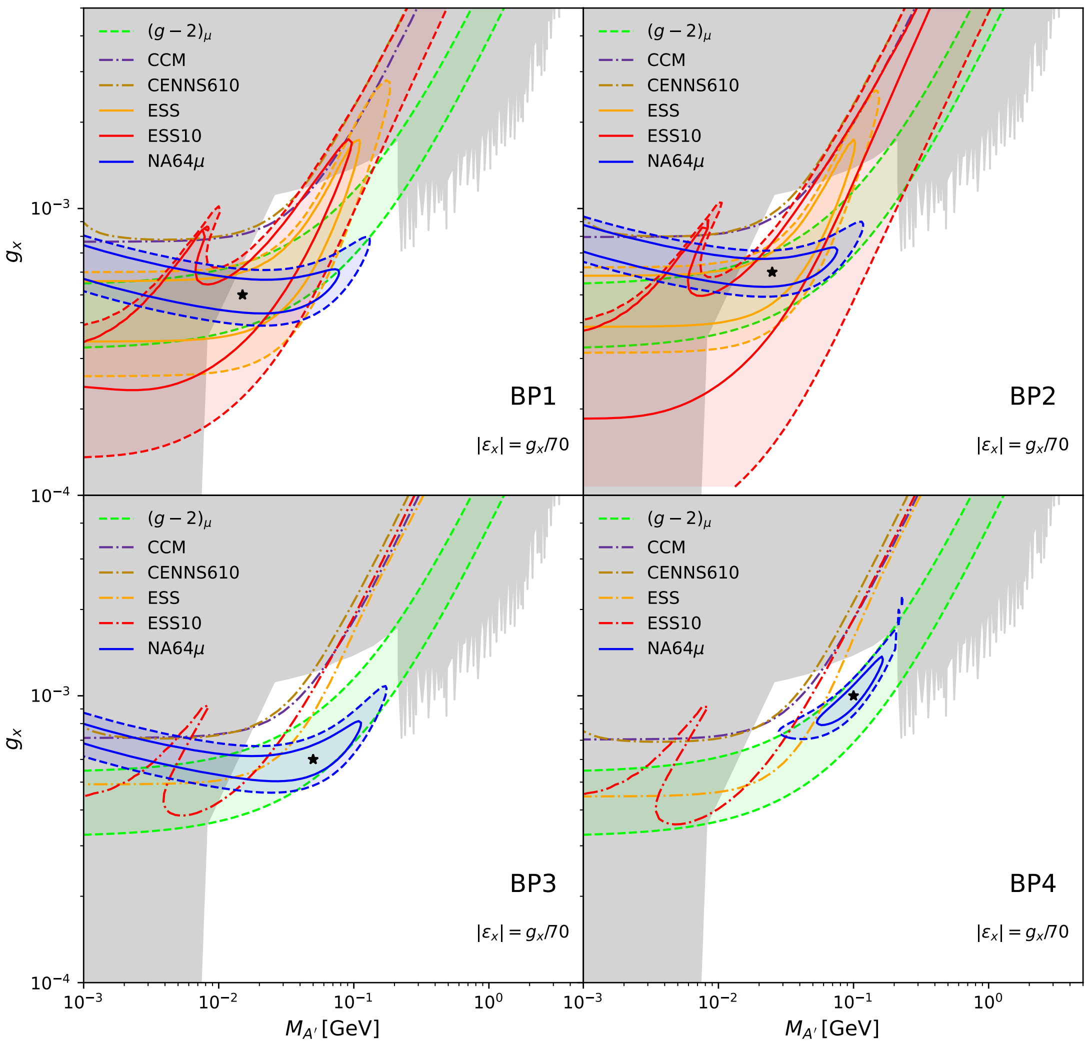


CEvNS alone can only measure $g_x\,\epsilon_x$. Some sensitivity to the mediator mass, especially for detectors with very low threshold (e.g., ESS10)

Loose sensitivity for masses above ~30 MeV

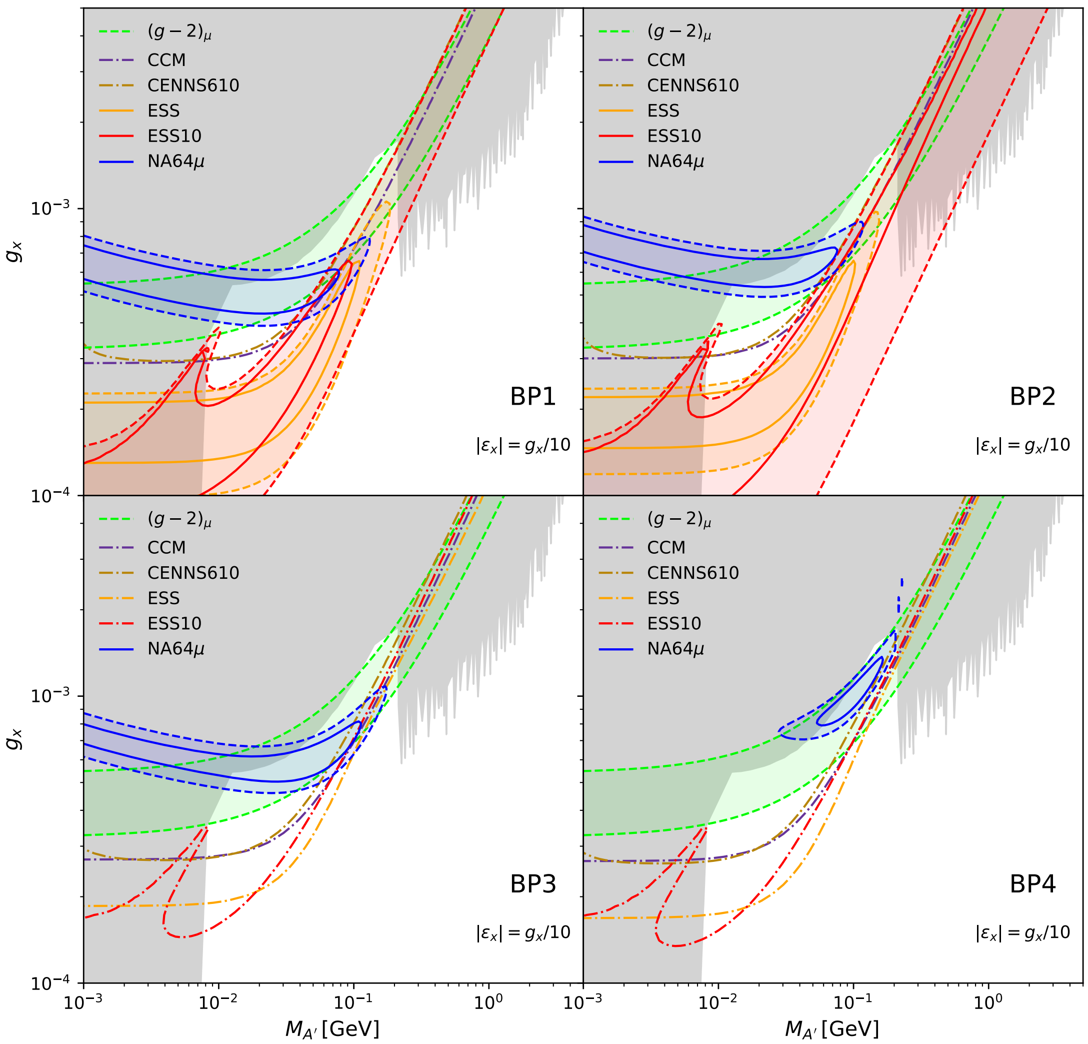


If the correct relation is chosen, combined data shows consistency, as well as a better reconstruction of the mediator mass

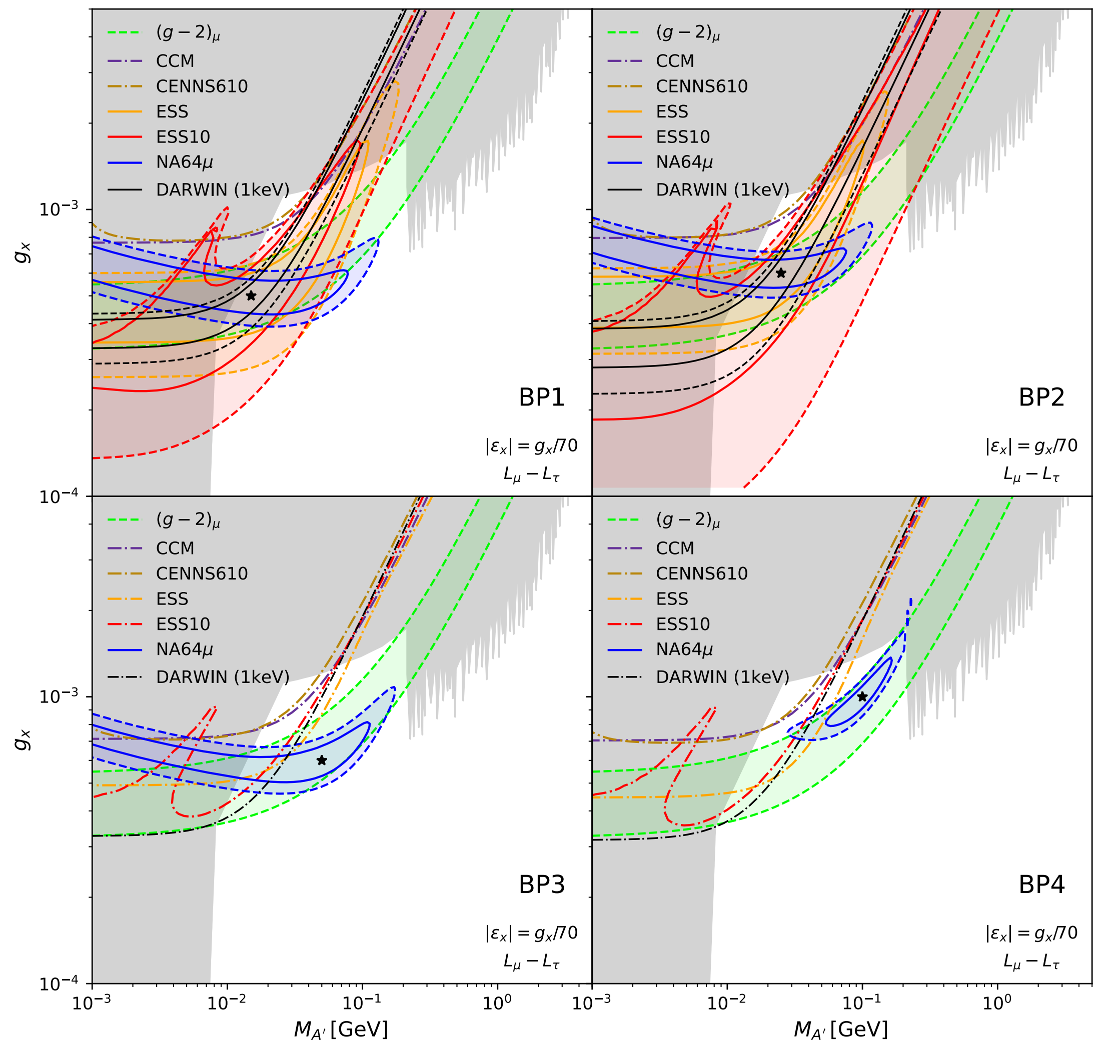


Inconsistencies in the reconstruction exclude some choices of kinetic mixing

(for example, we attempt to reconstruct for $|\epsilon_x| = g_x/10$)



Combining the information from direct detection, assuming the correct model, direct detection leads to a better reconstruction.



The whole area is inconsistent if the wrong model is assumed.