What (to do with) the fog?

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Energies, not forms, not figures (chant)

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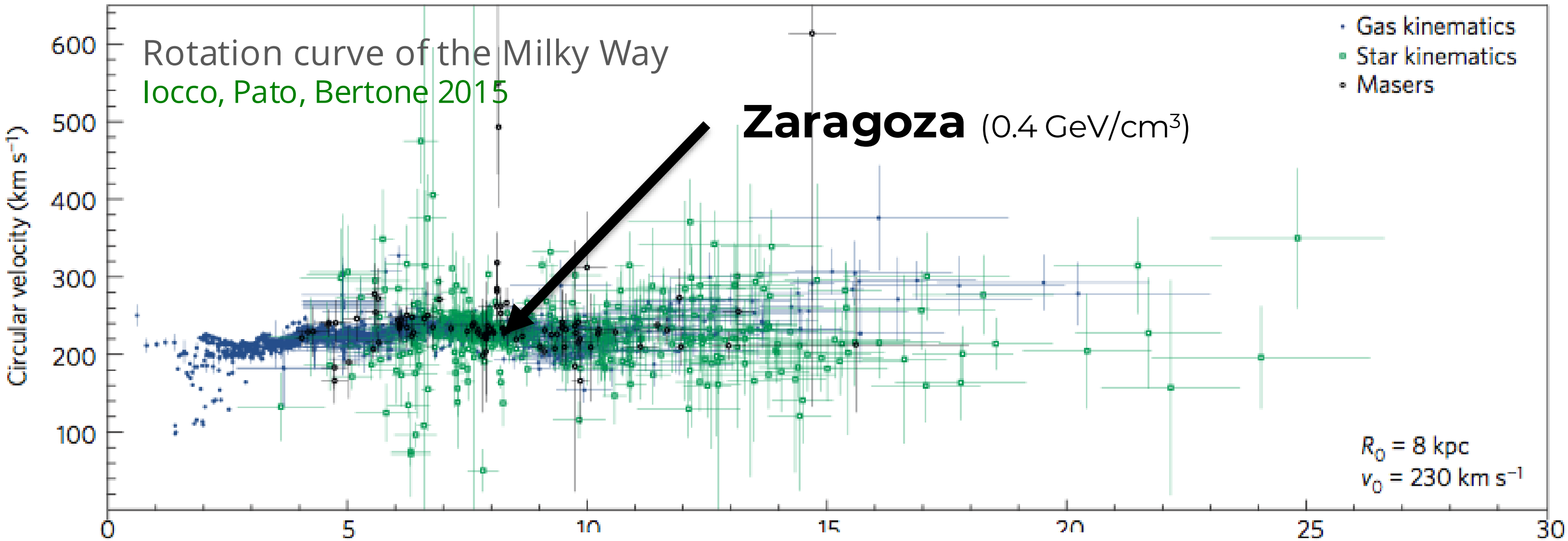
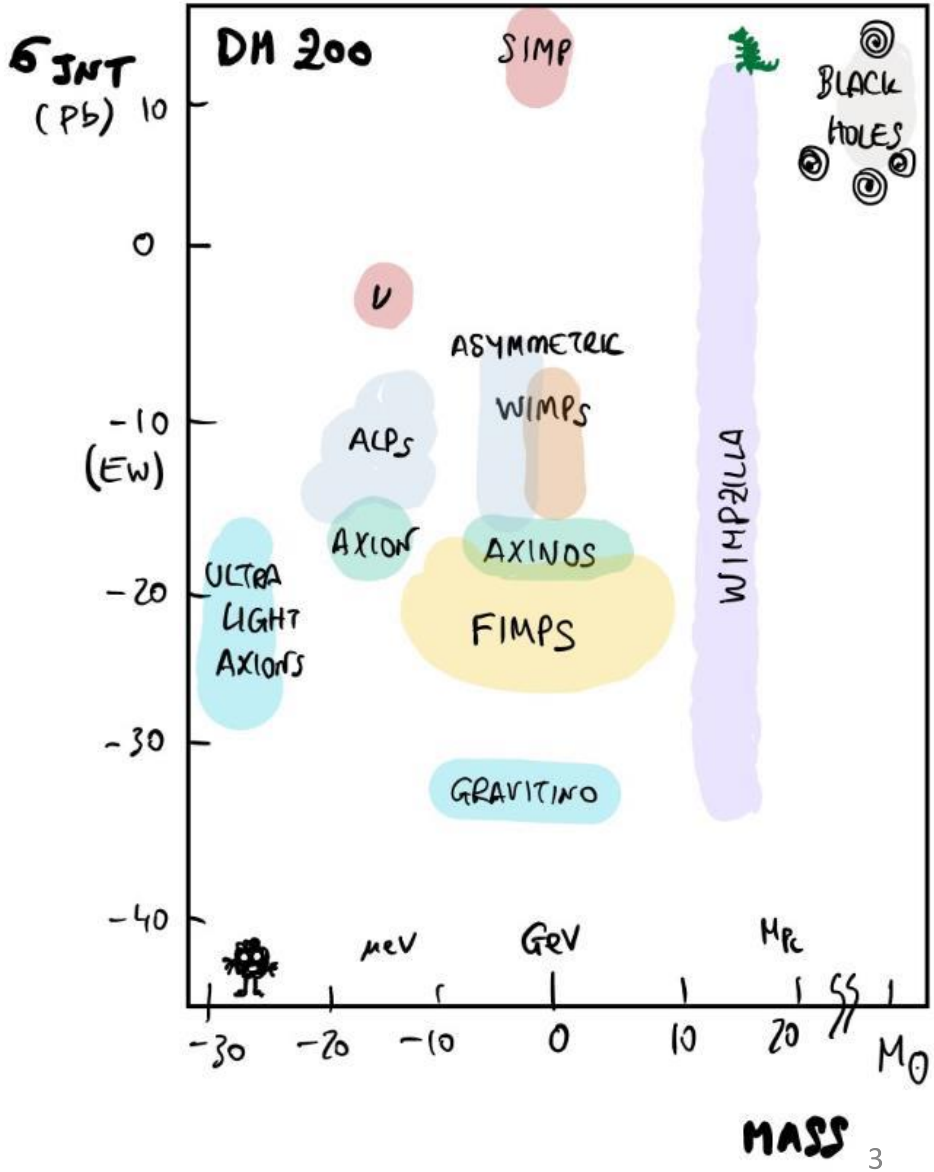
GOBIERNO DE ESPAÑA
AGENCIA ESTATAL DE INVESTIGACIÓN
TheDeAs 2025

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



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

waves particles objects

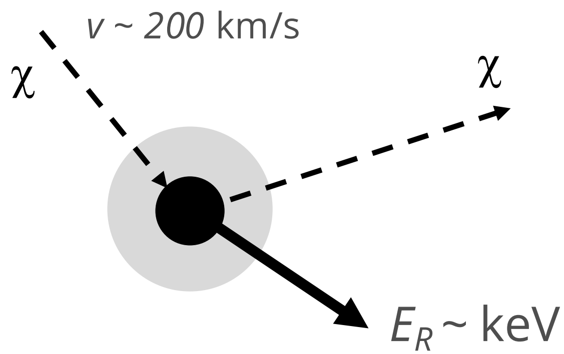


There are plenty of viable candidates, which imply very different **cosmological histories**

- **“Thermal” candidates**: **WIMPs** (weakly-interacting massive particles)
- **Out of equilibrium production**
- **Axions**
- **Asymmetric Dark Matter**
- **Ultra-light Dark Matter**
- **Primordial Black holes**

Finding the dark matter might give us information about **how the Universe came to be**

Dark Matter interactions inside a direct detection experiment

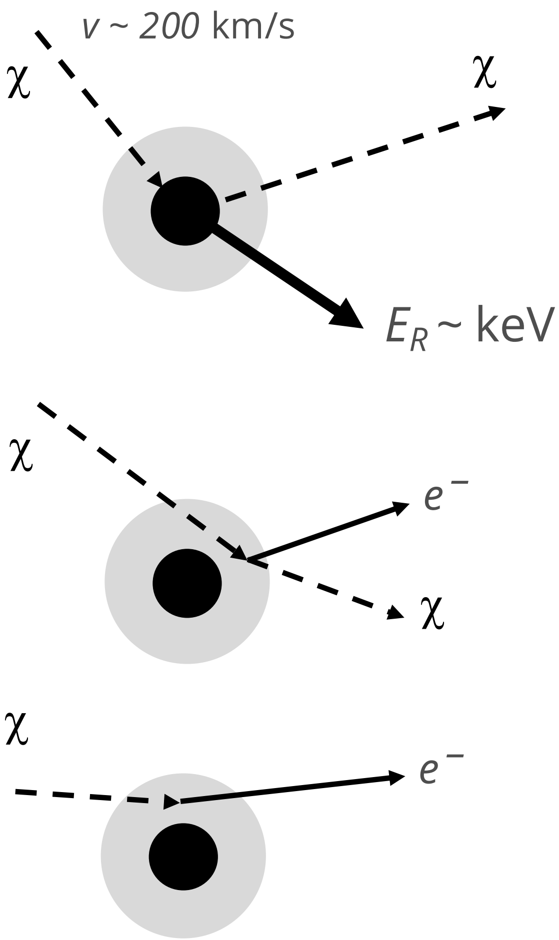


NUCLEAR SCATTERING

- ”Canonical” signature
- Elastic or inelastic scattering
- Sensitive to m>1 GeV

If the DM particle has a mass ~ GeV, its equivalent wavelength is of the order of the nuclear radius. The DM particle sees the nucleus as a whole: **COHERENT SCATTERING**

Dark Matter interactions inside a direct detection experiment (*)



NUCLEAR SCATTERING

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ELECTRON SCATTERING

- Inelastic scattering
- Sensitive to MeV scale DM

ABSORPTION BY ELECTRON

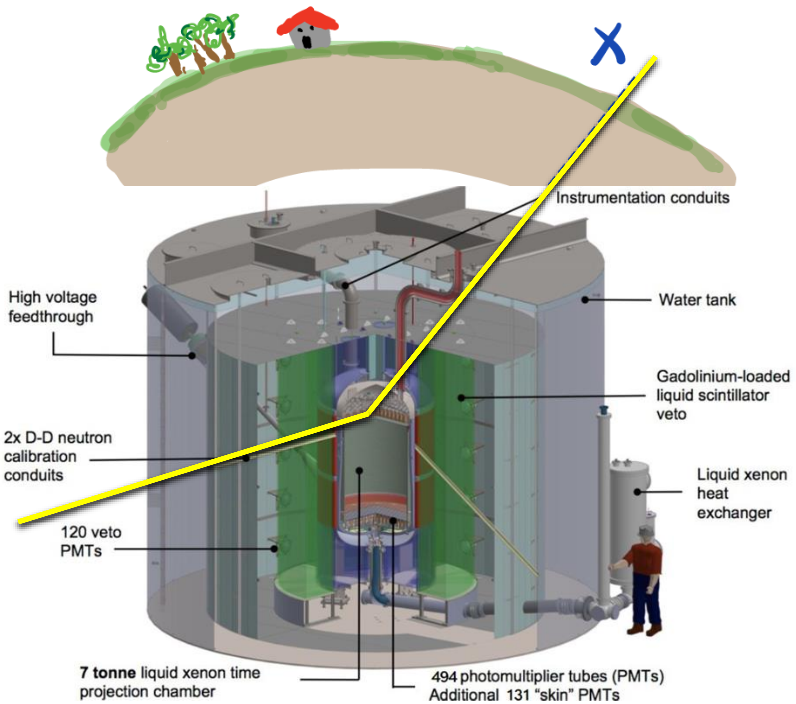
- Sensitive to eV scale DM

(*) Also inelastic processes, conversion to photons, etc…

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)

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Particle (+ nuclear) Physics

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

Traditionally, split into spin-dependent and -independent

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

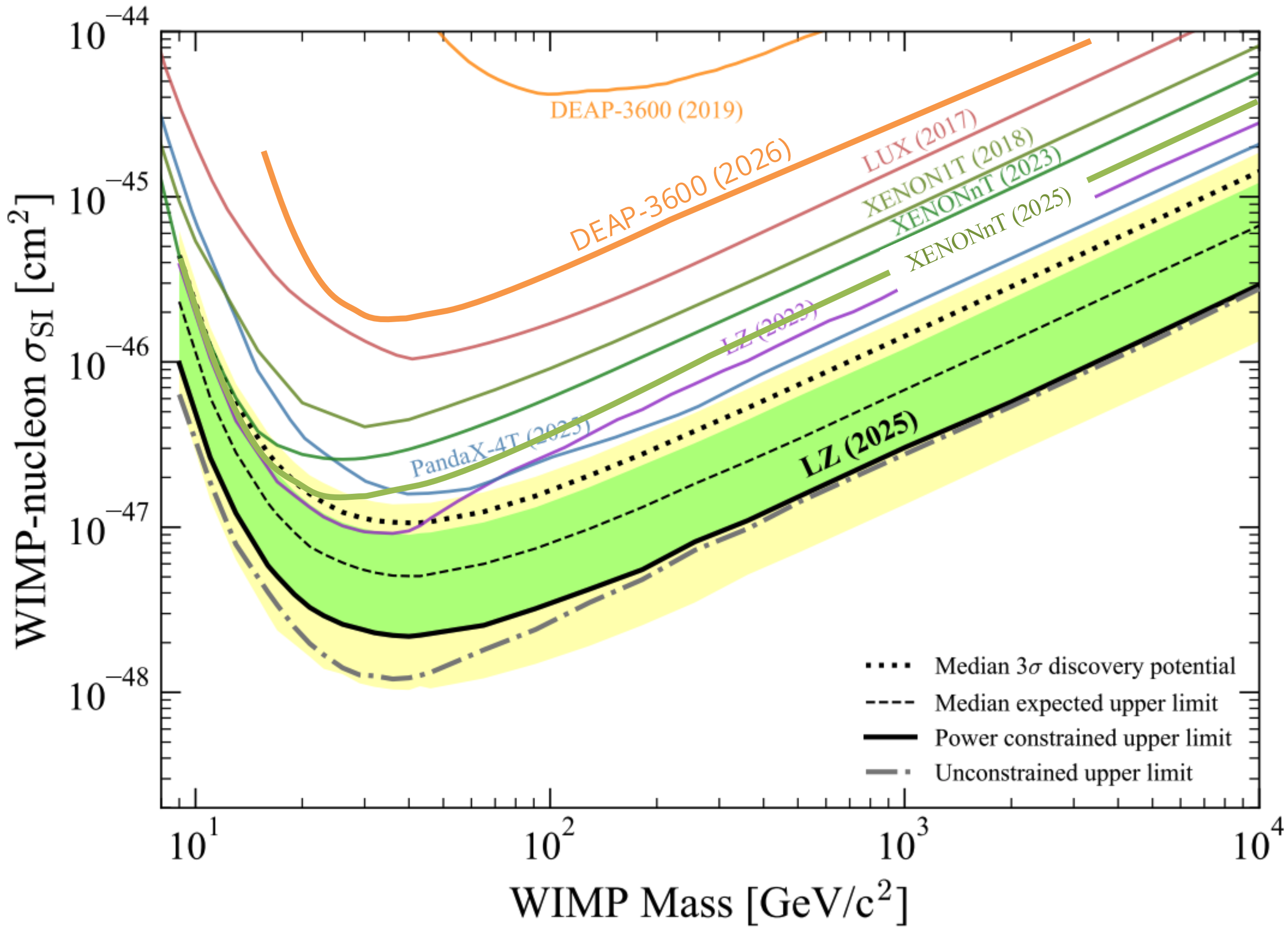
The most general case can be described by means of an Effective Field Theory

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

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

Liquid noble gas detectors are leading the search at masses above 10 GeV

Currently xenon experiments (**LZ**, **XENONnT** and **PandaX-4T**) have provided the best upper bounds on the spin-independent cross section.



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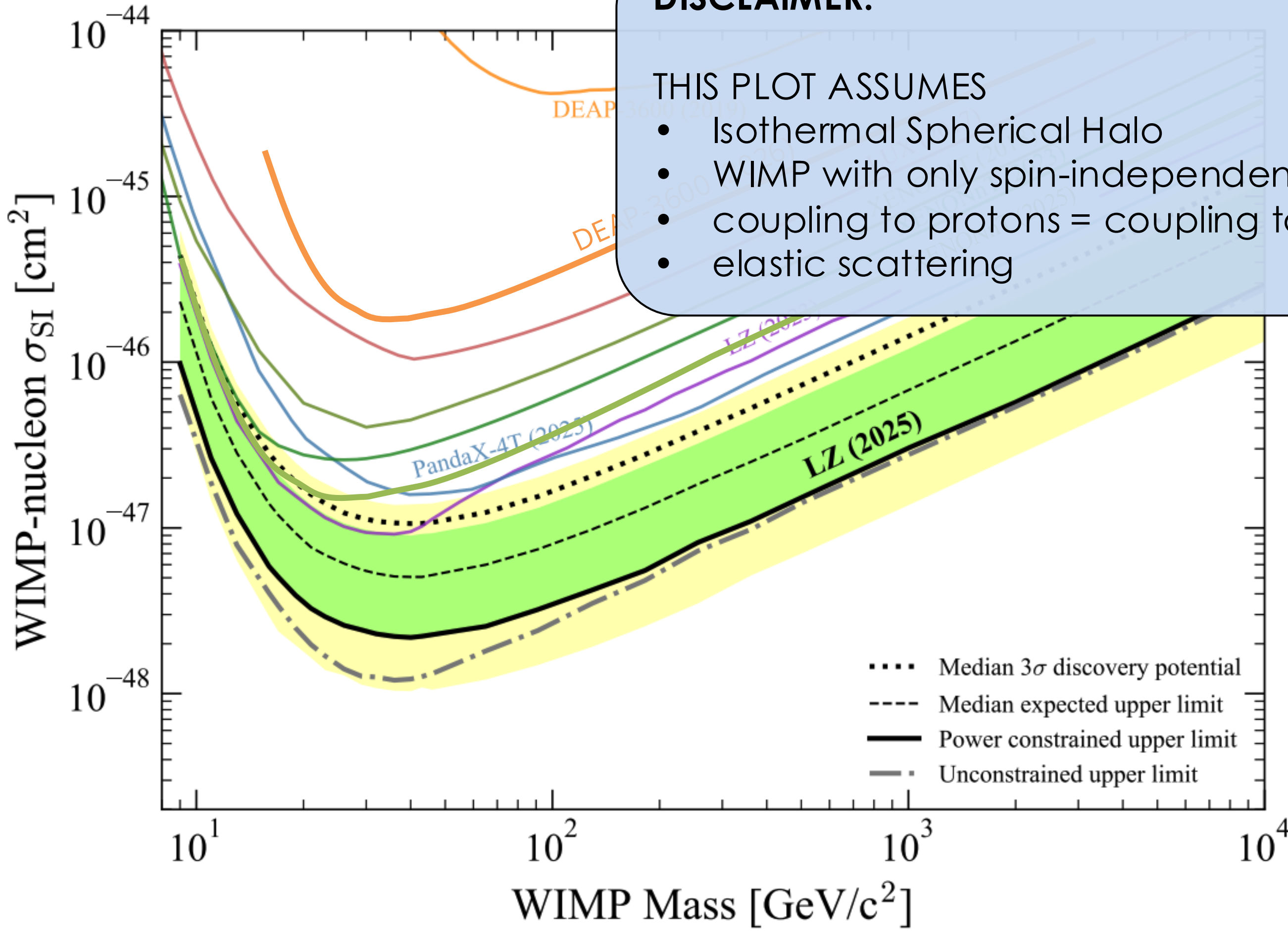


DISCLAIMER:

THIS PLOT ASSUMES

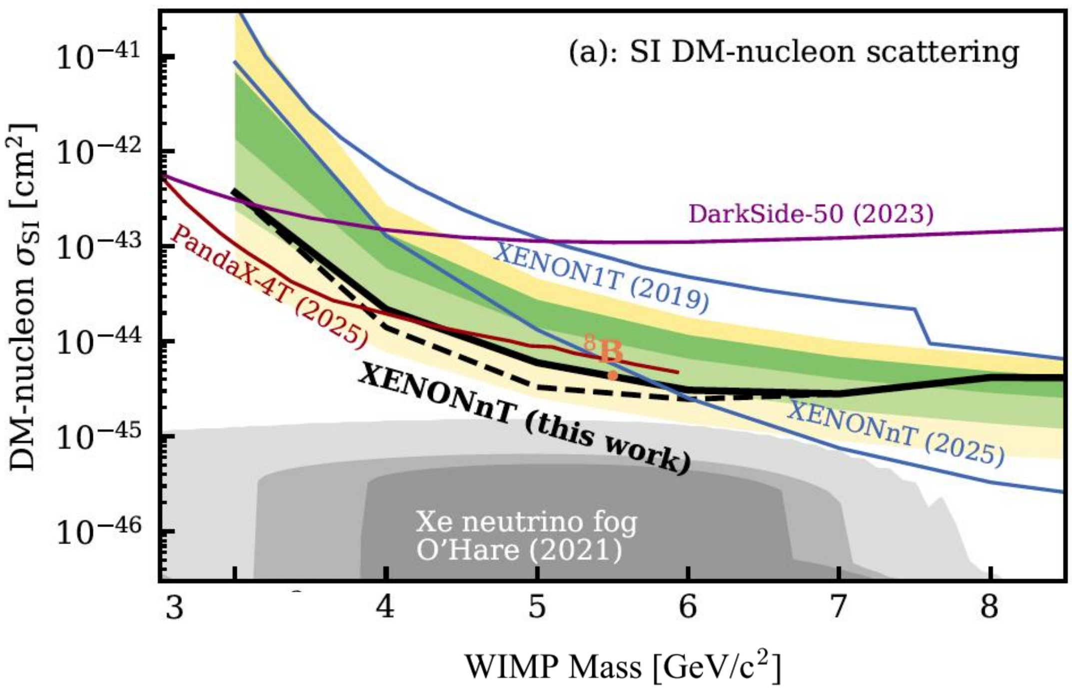
- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering

Liquid noble gas detectors are leading the search at masses above 10 GeV

Currently xenon experiments (**LZ**, **XENONnT** and **PandaX-4T**) have provided the best upper bounds on the spin-independent cross section.

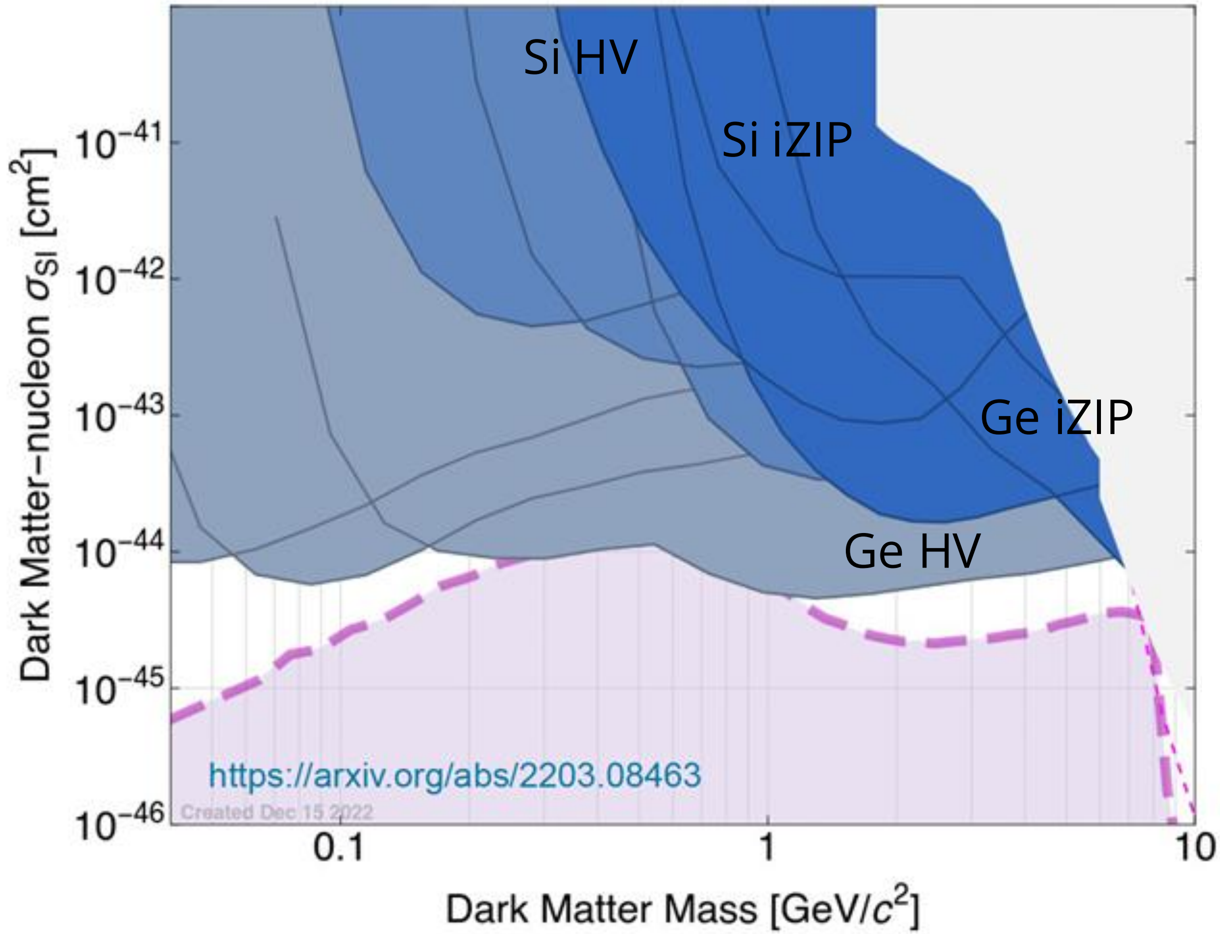
Ionisation only in liquid noble gas detectors (xenon and argon) also probing ~ 1 GeV WIMPs

XENONnT 2601.11296

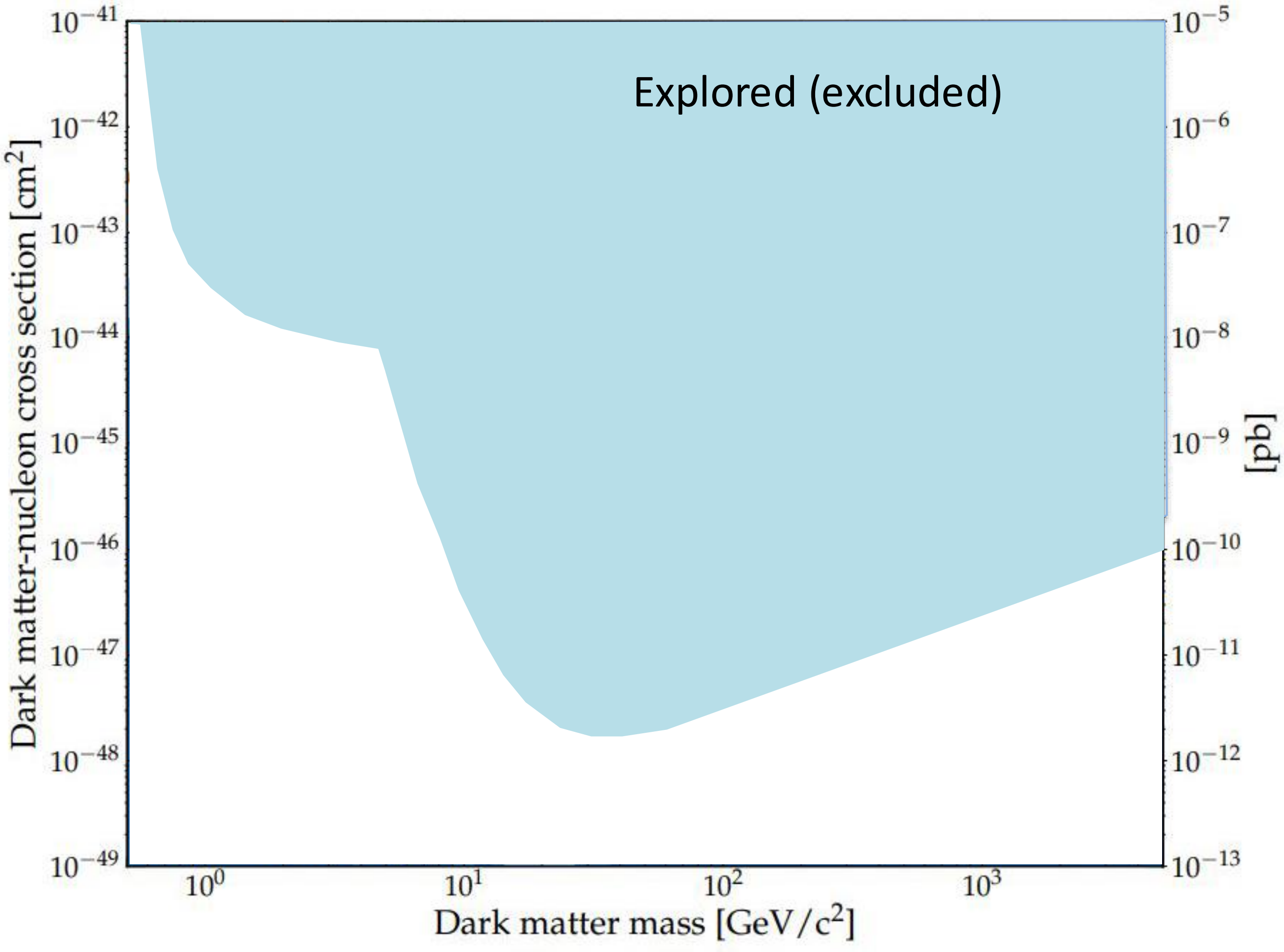


Low-threshold experiments can look for ~ GeV scale DM

Solid state detectors (**SuperCMDS**, **Edelweiss**, **CREESST**) can have a very low threshold. Likewise, gas detectors (**NEWS-G**) can employ very light targets. This gives them sensitivity to sub-GeV DM through nuclear recoils.



Future experiments will further explore the DM parameter space



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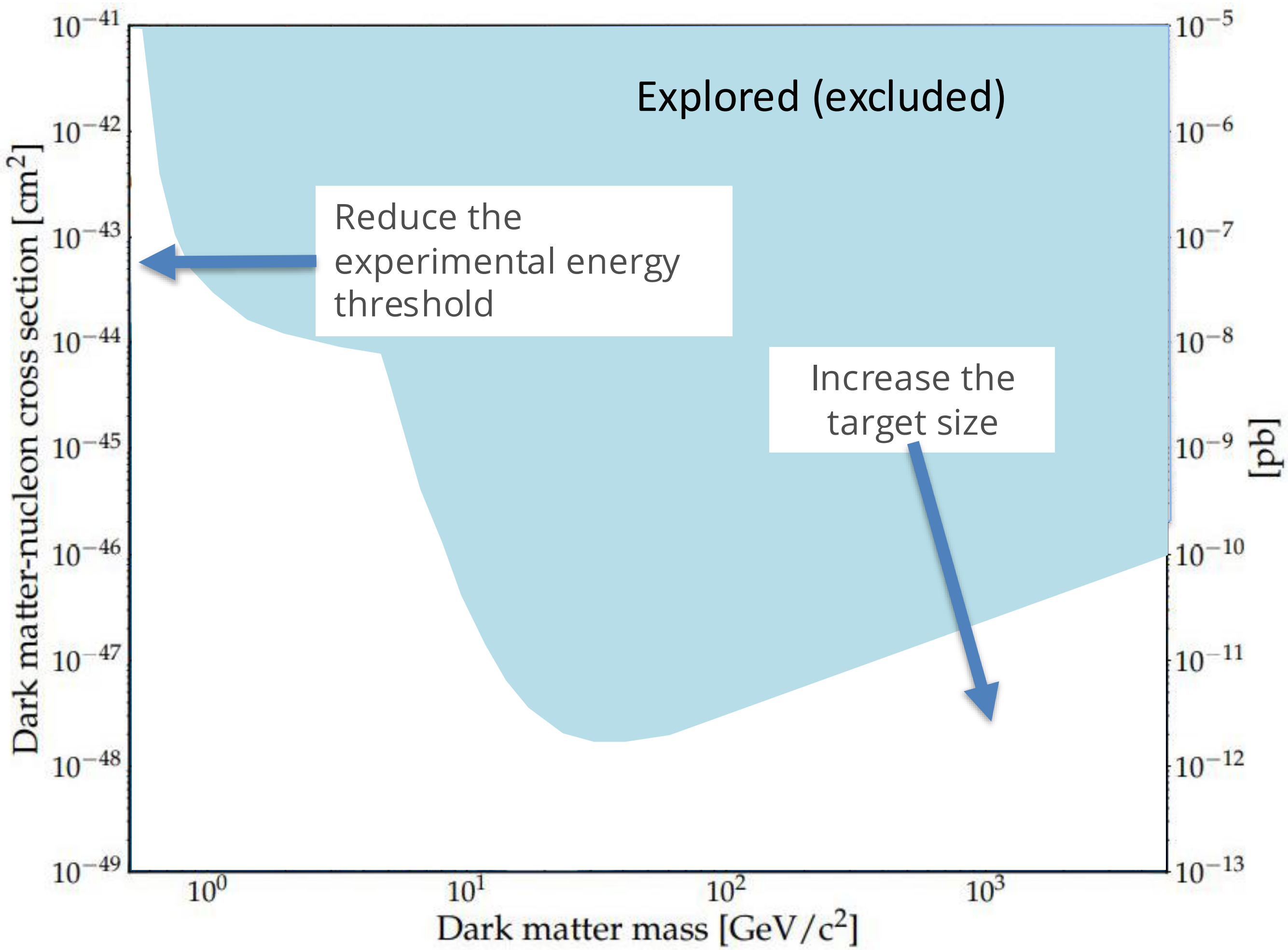

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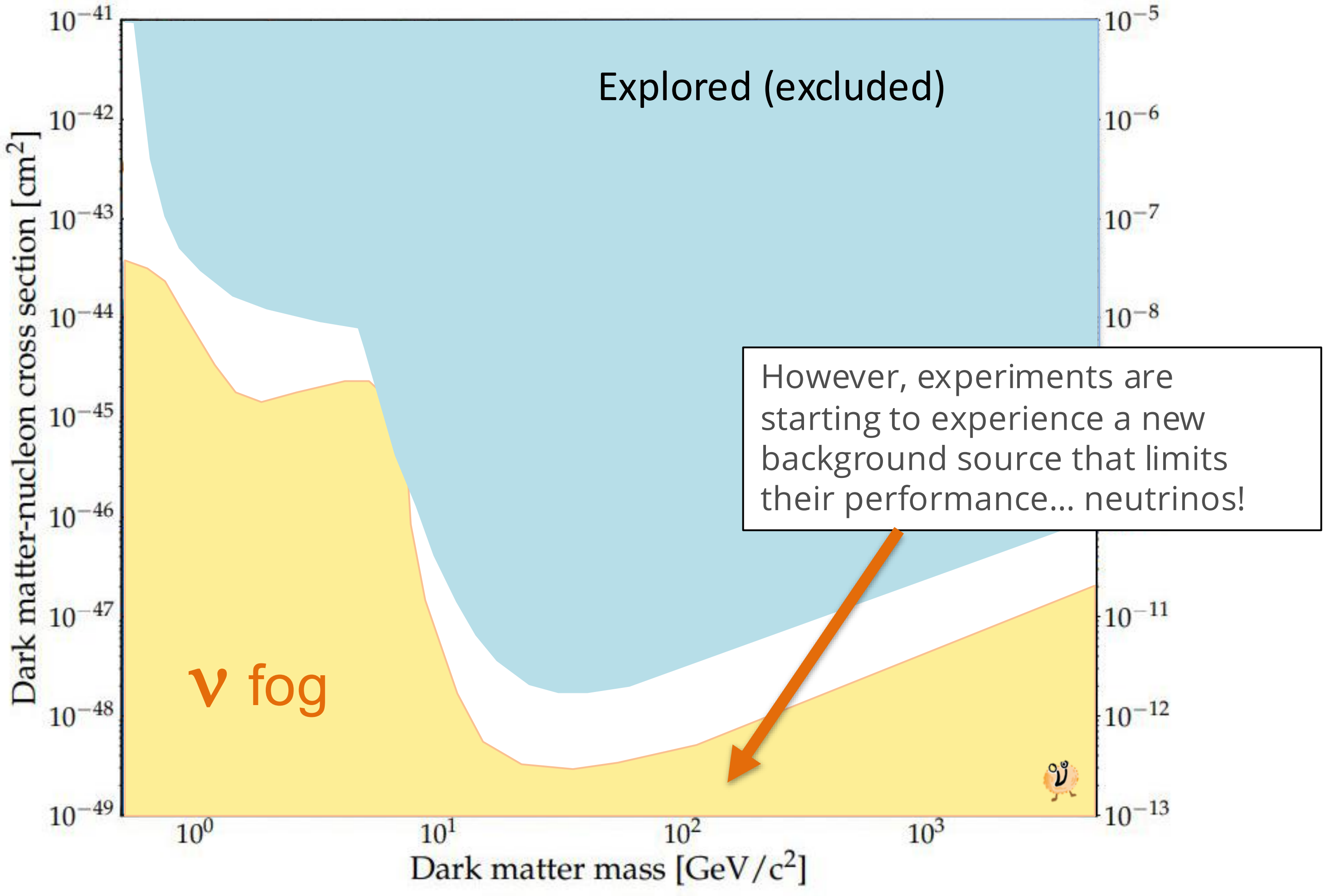

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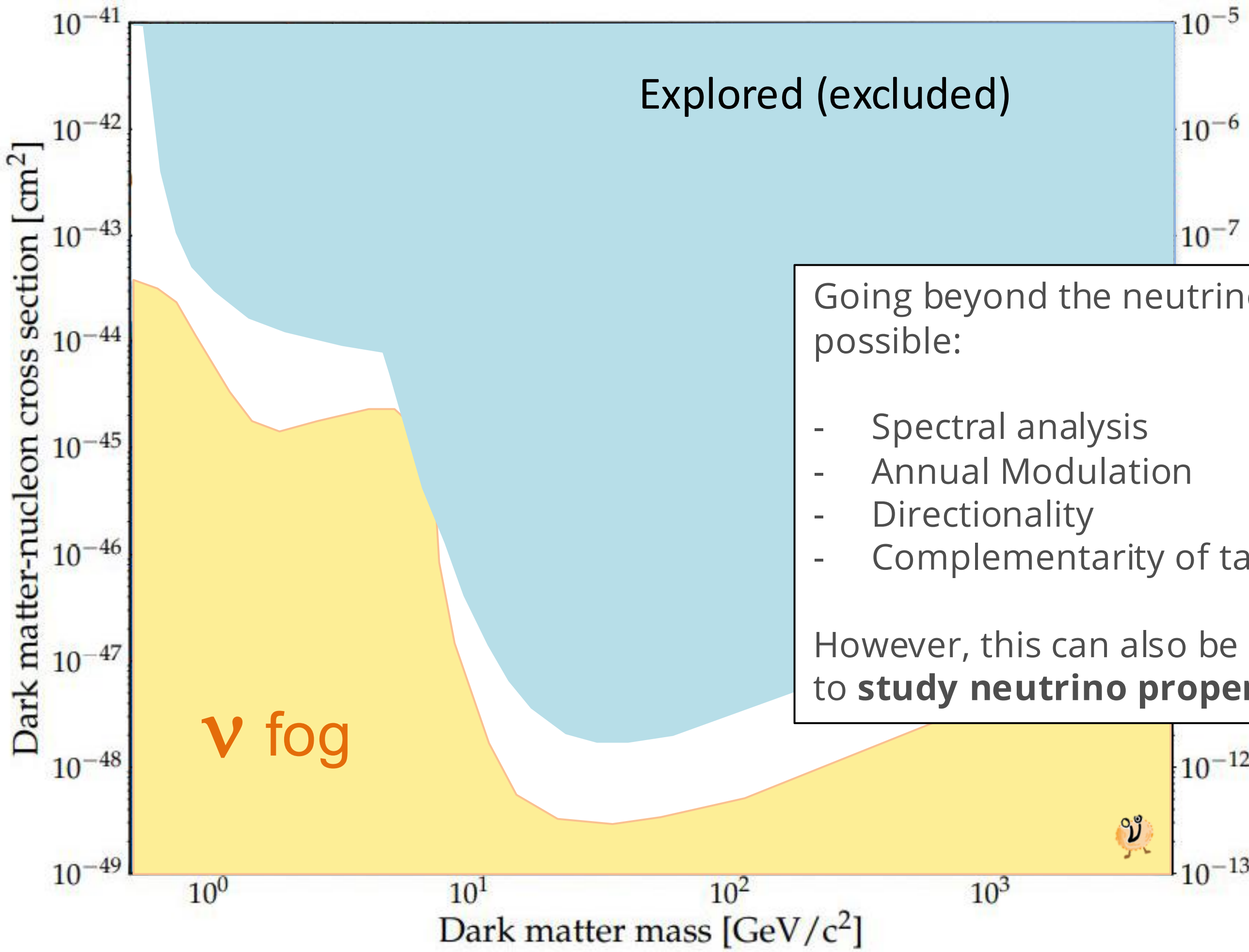


Going beyond the neutrino fog is possible:

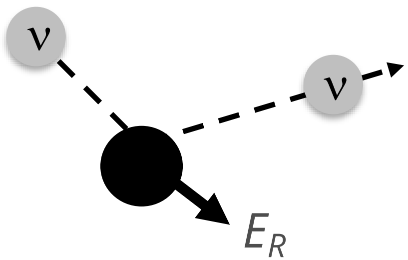
- Spectral analysis
- Annual Modulation
- Directionality
- Complementarity of targets

However, this can also be an opportunity to **study neutrino properties**.

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)



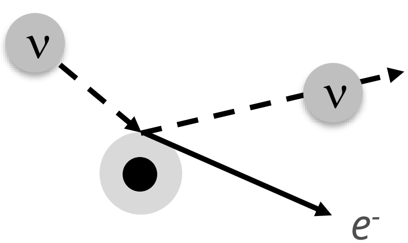
Rare Standard Model process recently measured in spallation source experiments

COHERENT Collab. 2017, 2021

Irreducible background – neutrino fog/floor

O'Hare et al 2017

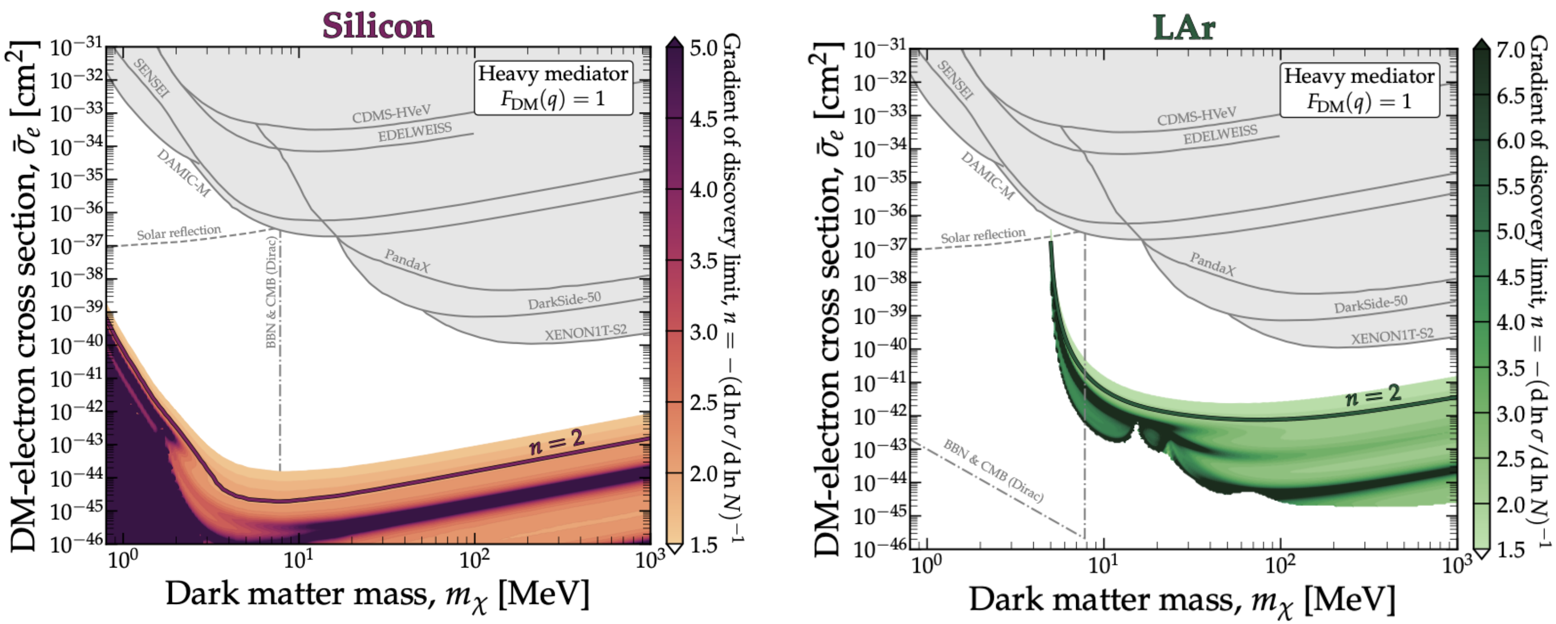
(Inelastic) electron scattering



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

The neutrino fog for electron recoils

Carew et al. 2023



Defined in an analogous way: when do neutrino-electron recoils become an obstacle to detect Dark Matter.

Target dependent (and different lines for heavy/light mediators)

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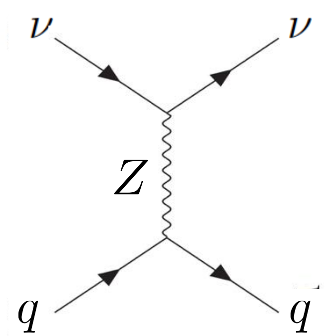

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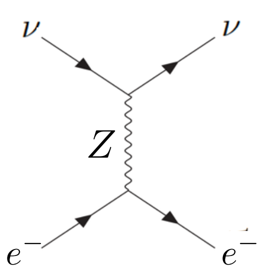

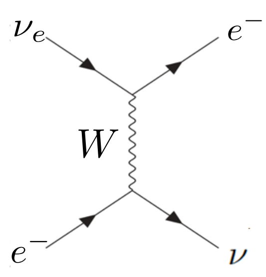

Usual electroweak process mediated by the *Z* and *W* bosons

Expected signal in a direct detection experiment

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

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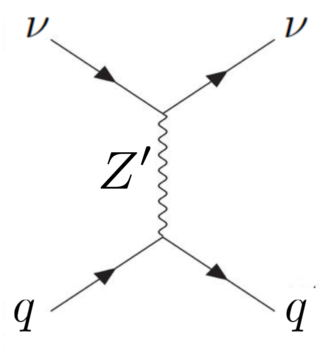


New physics can lead to extra contributions to CEvNS

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

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

SM

New Physics

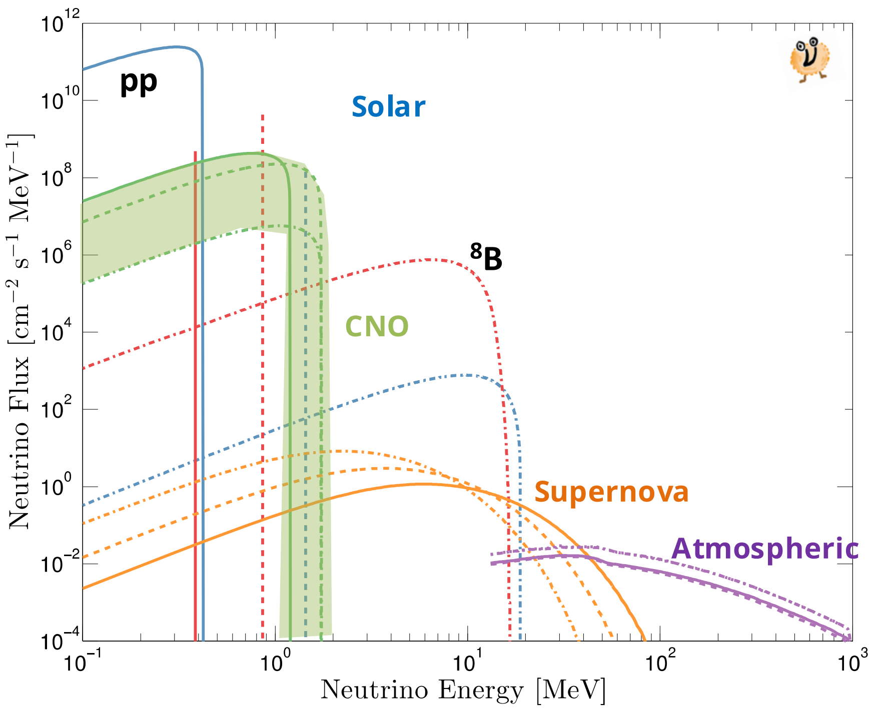
Neutrino flux

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

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



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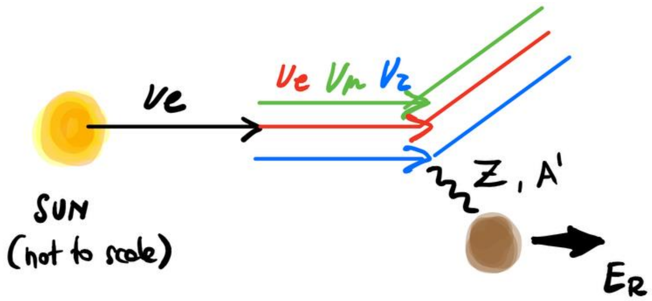
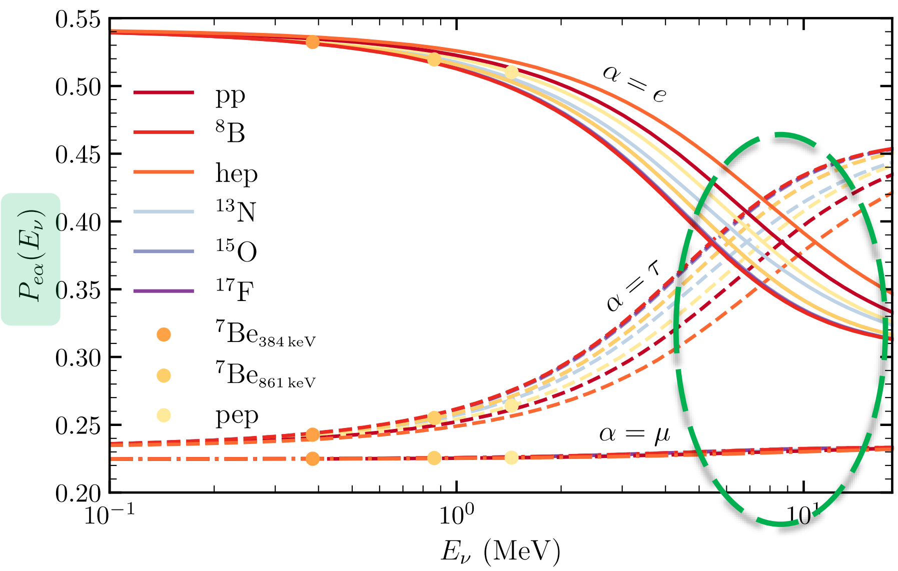
Produced as electron neutrinos, they oscillate into other flavours



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 $\nu_\mu,\ \nu_\tau$

Direct (DM) detectors can be excellent **complementary test of new neutrino physics**

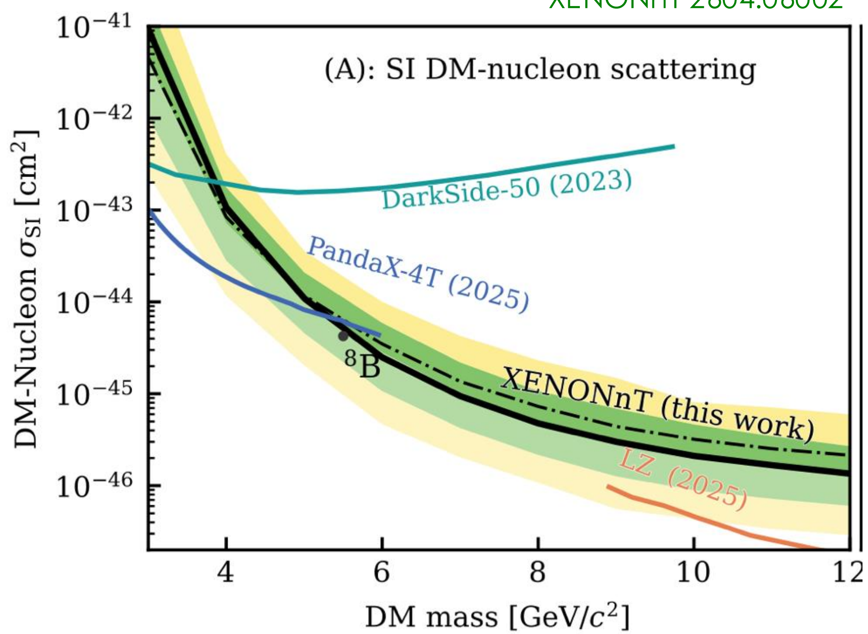
- Low energy threshold and excellent energy resolution
- Sensitive to both nuclear and electron recoils
- Sensitive to the three neutrino flavours $\nu_e,\, \nu_\mu,\, \nu_\tau$

There have been recent claims by **XENONnT**, **LZ** and **PANDAX-4T** that they have data consistent with the observation of ^{8}B neutrinos.

Set constraints on **non-standard interactions (NSI)**.

Future direct detectors will complement information from dedicated neutrino experiments

XENONnT 2604.06002

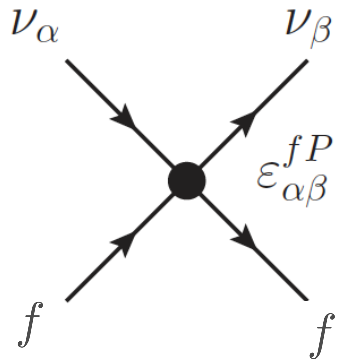


Effective theories: Non-standard Interactions

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)

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

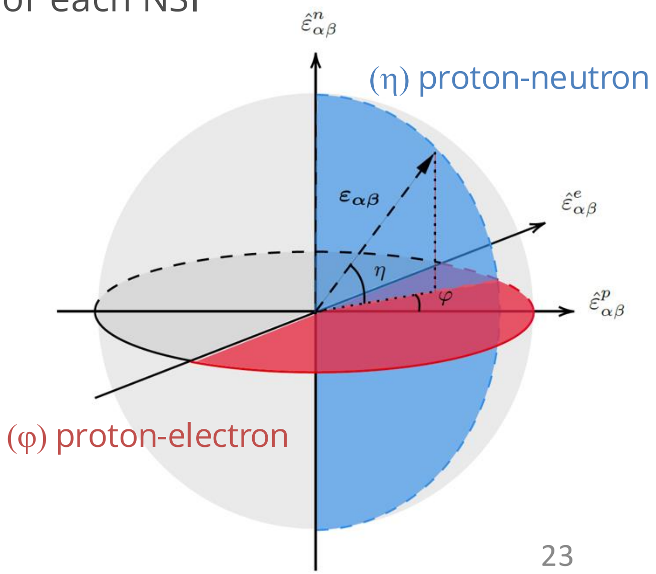
$$\varepsilon_{\alpha\beta}^{f} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$$



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

New parametrisation including electron recoils

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



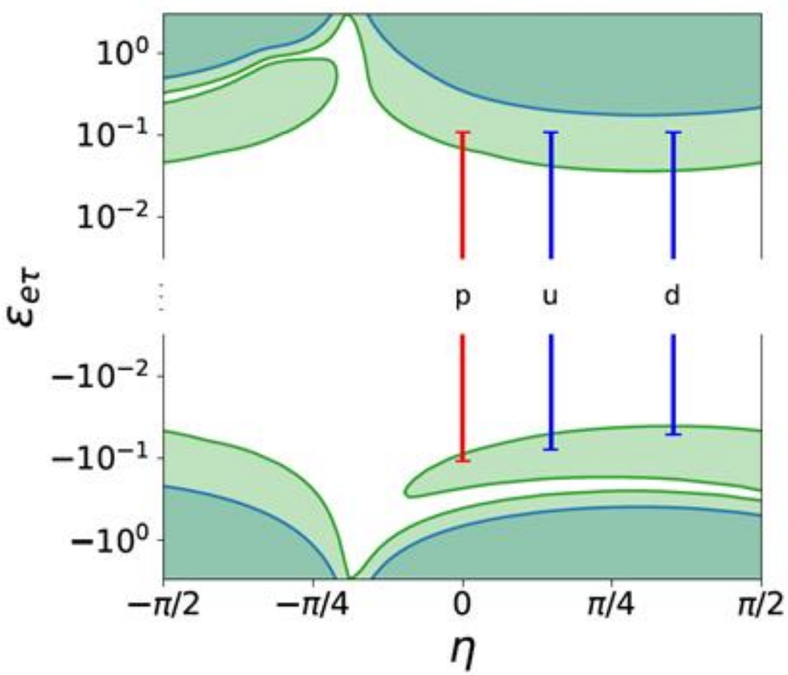
A prospective study on archaeological lead with **RES-NOVA**

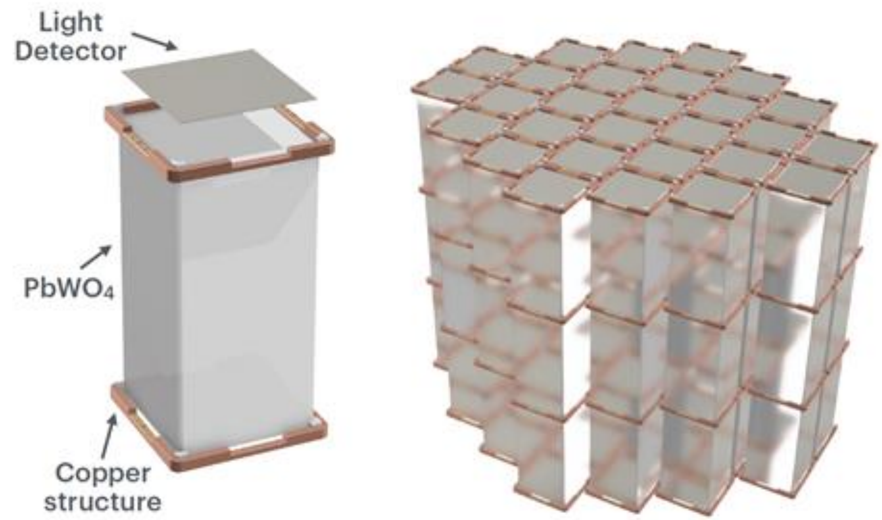
SNuDD

Based on $PbWO_4$ crystals, we computed predictions for a nominal configuration of 1 tonne-year.

Amaral, DGC, Cheek, Foldenauer
+ RES-NOVA 2026

0.1 keV threshold





Pb benefits from the large atomic number, but **argon experiments** might be useful if the **energy threshold is small**.

NUCLEAR + ELECTRON SCATTERING

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

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

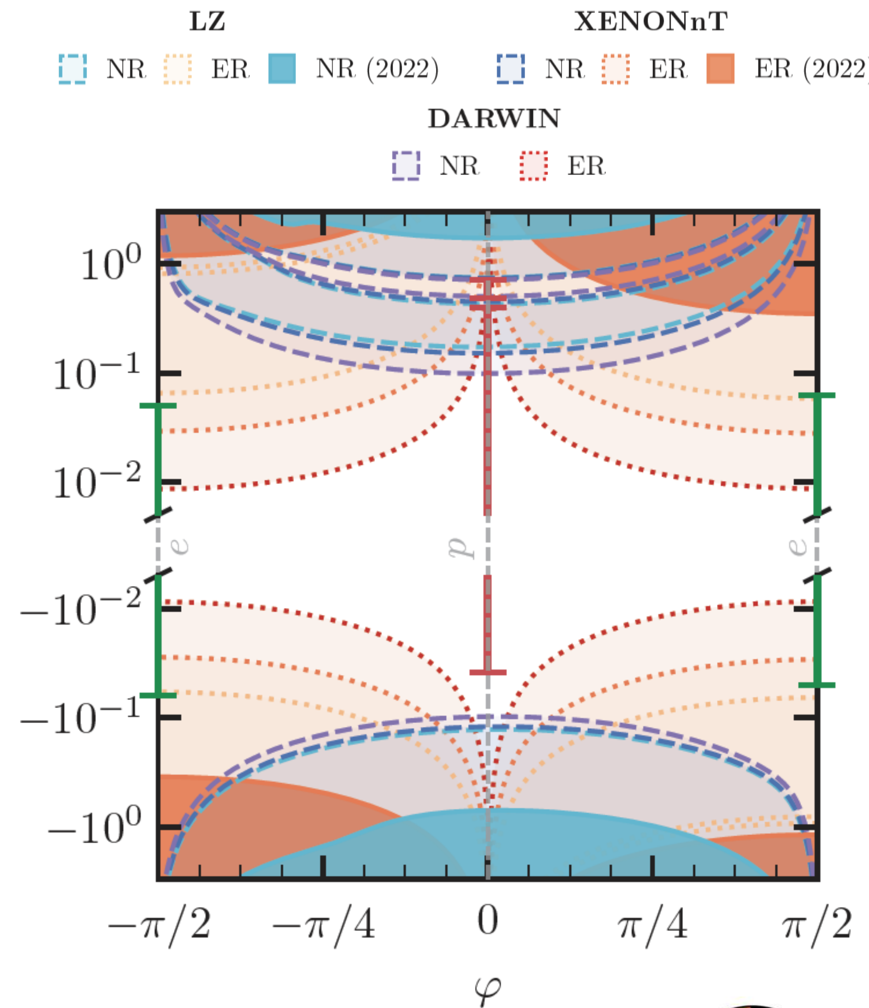
Future **XLZD** can potentially improve by an order of magnitude over current electron NSI bounds

Direct detection will become crucial to constrain neutrino parameters.

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

Coloma, Esteban, González-García, Maltoni 2020

Amaral, DC, Cheek, Foldenauer 2023



Amaral, Cerdeño, Cheek, Costa, Foldenauer
https://github.com/SNuDD/SNuDD

SNuDD

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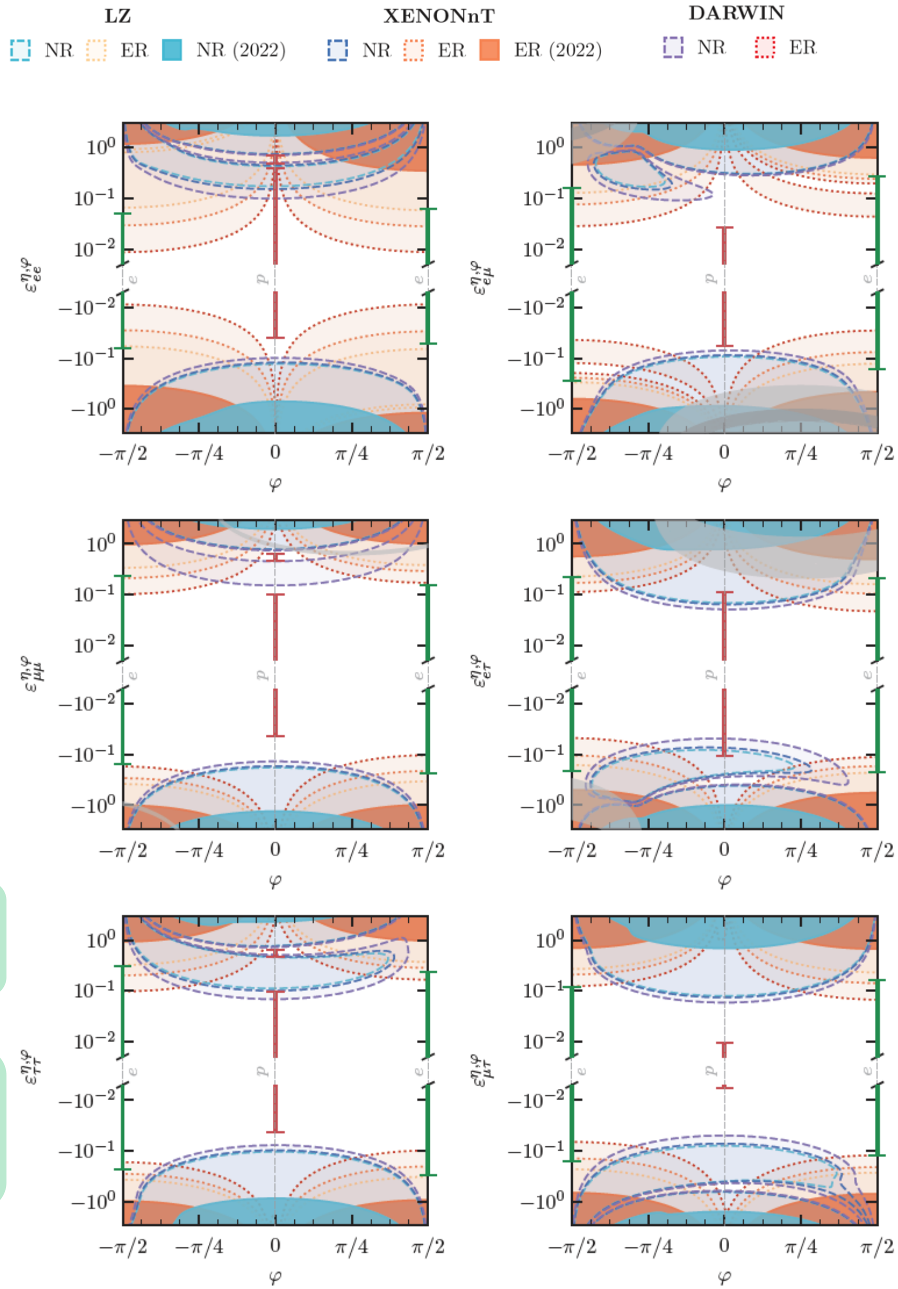
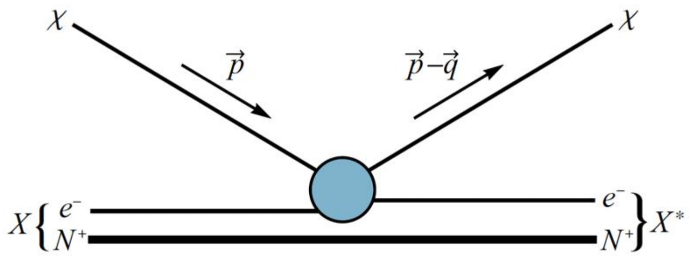


DM-Electron interactions allow to probe keV scale DM

When the target is an isolated (noble gas) atom, the ionisation form factor is easier to compute. In solid state crystals, this is more complicated.

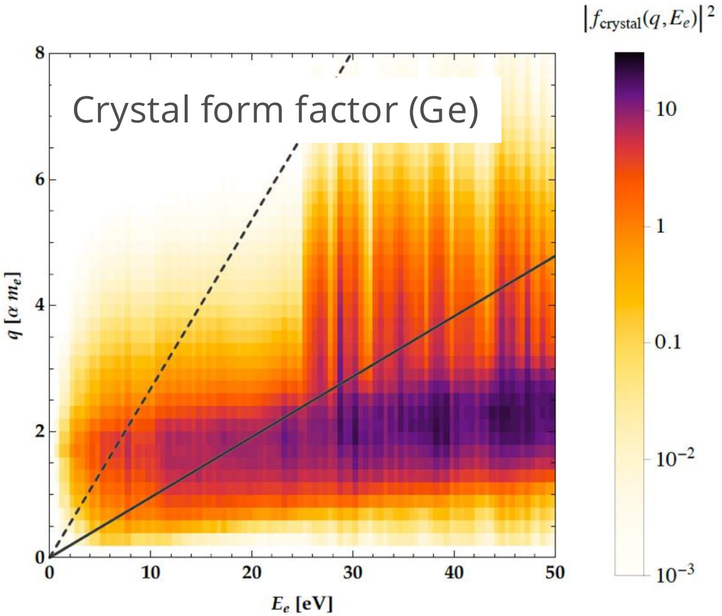


$$\frac{dR^{ER}}{dE_e} = \bar{\sigma}_e \frac{\rho_\chi}{m_\chi} \frac{1}{8\mu_{e\chi}} \int q dq \, |F_\chi(q)|^2 \, |f^{ion}(e, E_e)|^2 \, \eta(v_{min})$$

The Dark Matter "form factor" encapsulates the momentum dependence of the interaction

~1/q for low-mass mediators

~1 for heavy mediators



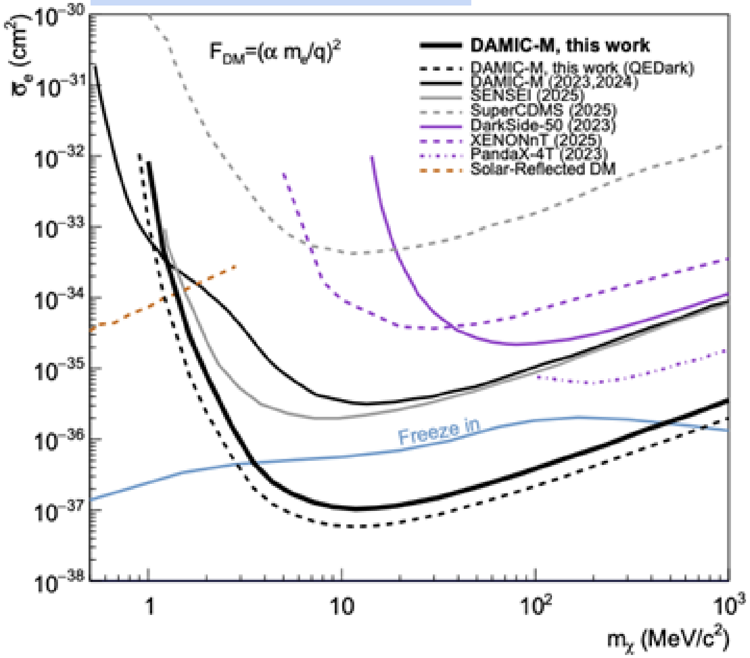
Essig et al. 1509.01598

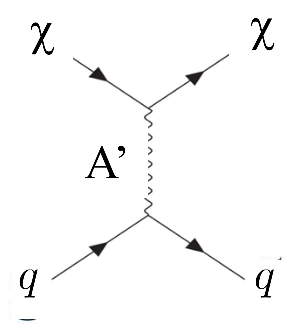
DM-Electron interactions allow to probe keV scale DM

Liquid noble gas experiments (xenon and argon) can look for only scintillation S2 signal, interpreting the results as DM-electron interactions. CCD detectors (**SENSEI**, **DAMIC**, **OSCURA**). Single electron detection in **SuperCDMS** or **EDELWEISS**

Dark Photon Model

DAMIC-M 2503.14617





The dark photon mediates DM interactions with the SM

These searches are starting to probe other ways of producing DM in the early Universe, namely **freeze-in** models.

See also Hambye et al. 2011, 2018

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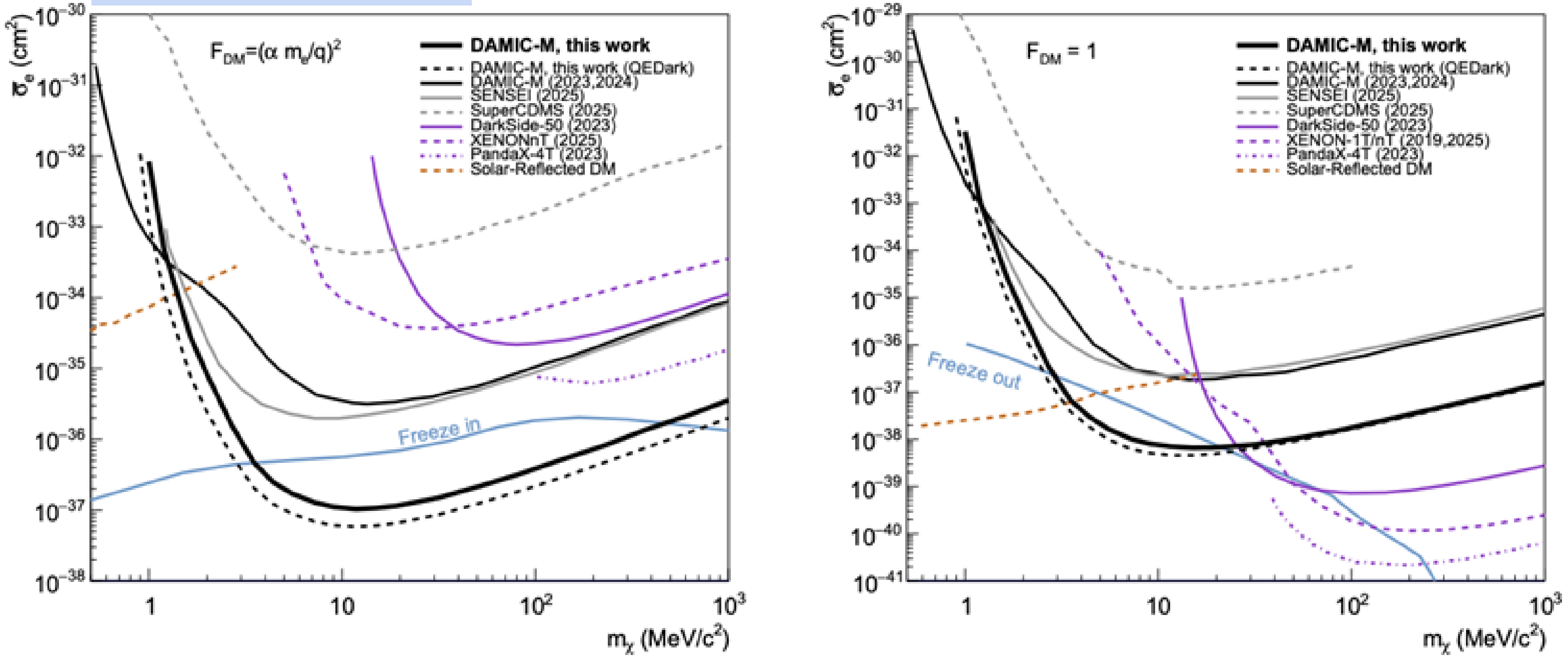

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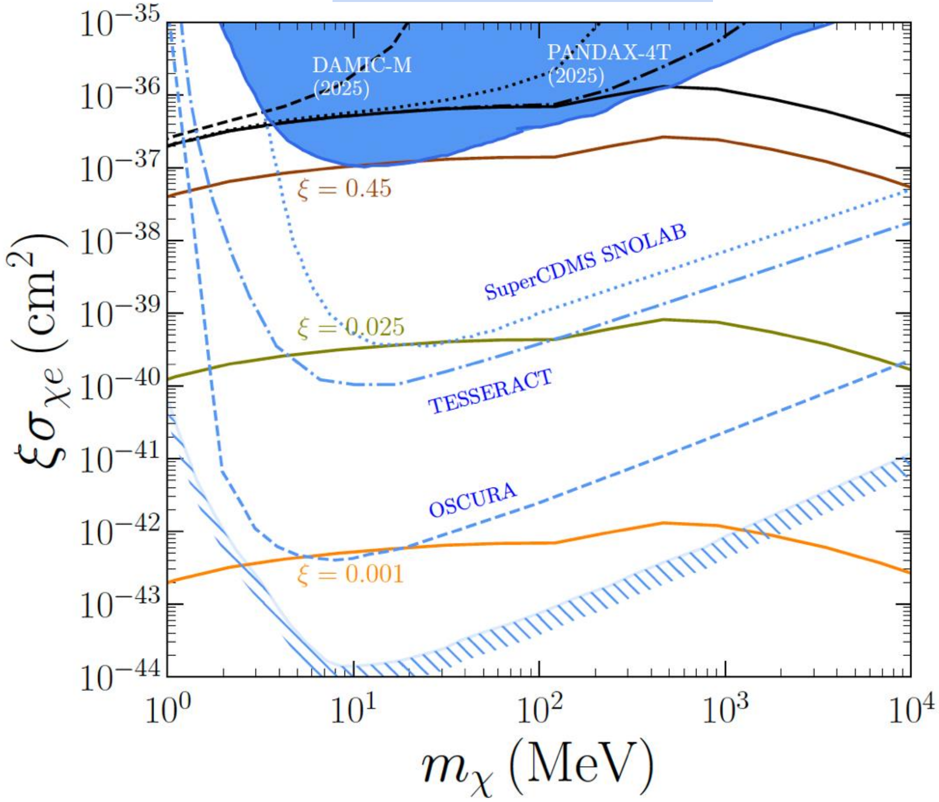
Is freeze-in Dark Matter dead?

Because of the scaling of the relic density and the scattering cross-section in freeze-in models, a slight under-abundance of DM leads to a reduction in the number of detected events.

Dark Photon Model



Direct detection experiments can only probe the local DM density times the cross section

$$\xi = \Omega h_\chi^2 / \Omega h_{\mathrm{DM}}^2$$

- Freeze-in: $\xi \sim \Omega_\chi h^2 \propto k^2$
  $\xi \sigma_{\chi e} \propto k^4$
- Freeze-out: $\xi \sim \Omega_\chi h^2 \propto k^{-2}$
  $\xi \sigma_{\chi e} \propto 1$

DC, Foldenauer, López Noé, Zapata 2026

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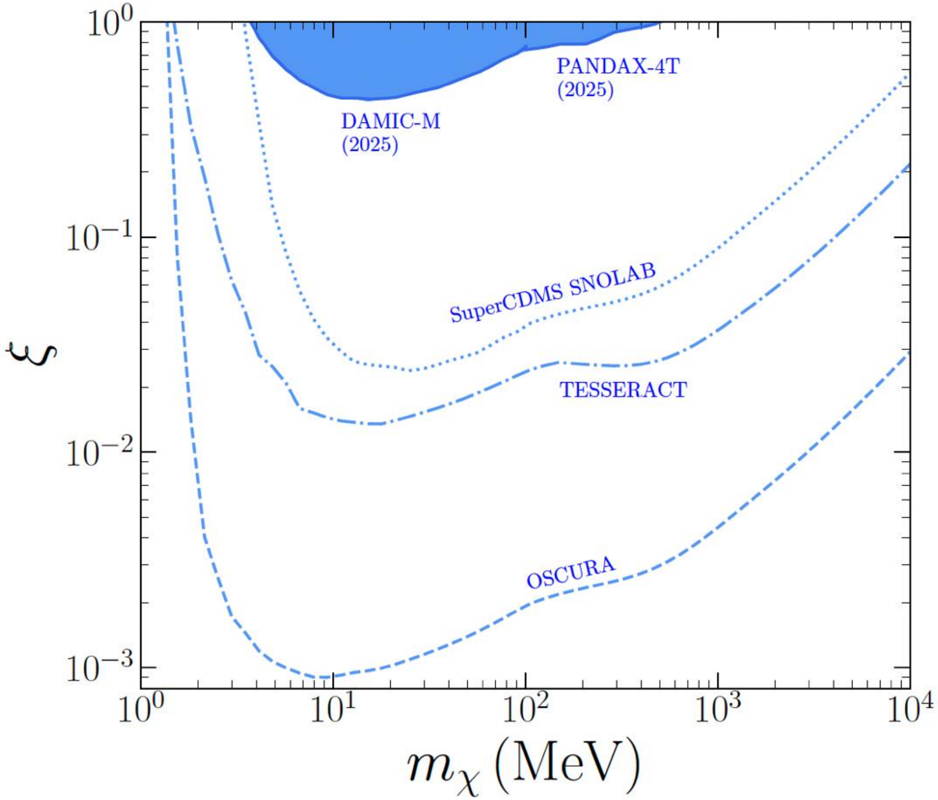
Because of the scaling of the relic density and the scattering cross-section in freeze-in models, a slight under-abundance of DM leads to a reduction in the number of detected events.

Dark Photon Model

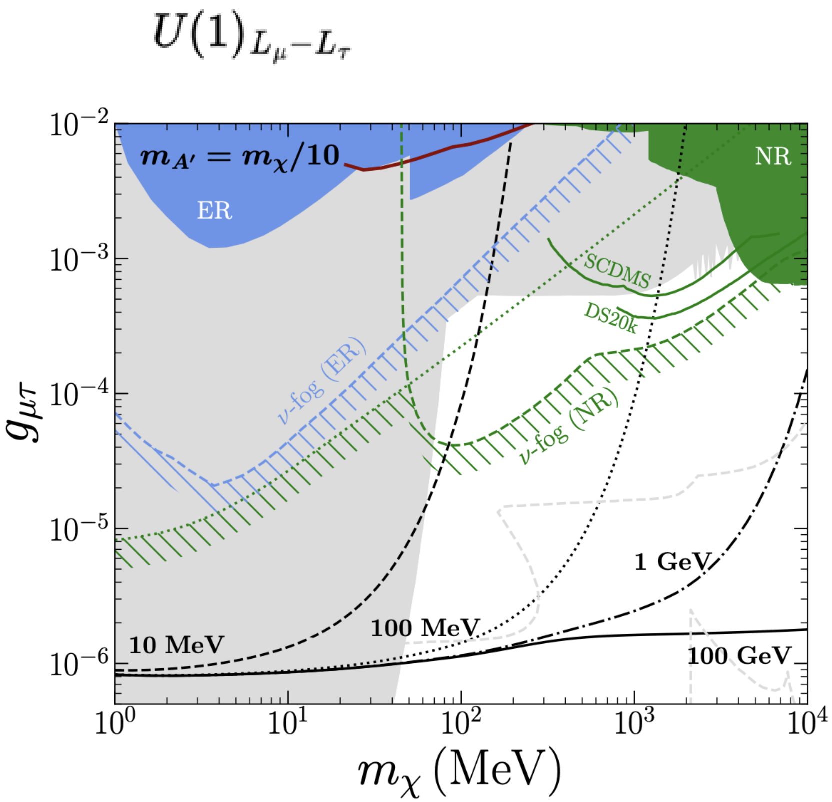


Direct detection experiments can probe MeV freeze-in dark matter **even if its abundance is 1000 times smaller** than the total DM relic density.

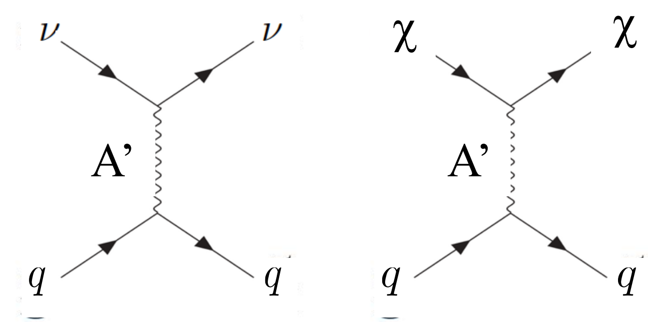
DC, Foldenauer, López Noé, Zapata 2026

Direct detection can test particle models of freeze-in.

Moreover, in slightly more complicated models (but still anomaly free) there are coupling to leptons (and quarks) and bot ER and NR signals are possible at low energies.



In extended U(1) models, the vector boson mediates both DM and new neutrino interactions



There are, simultaneously, new signals in DM and neutrinos, and both with nuclei and electrons!

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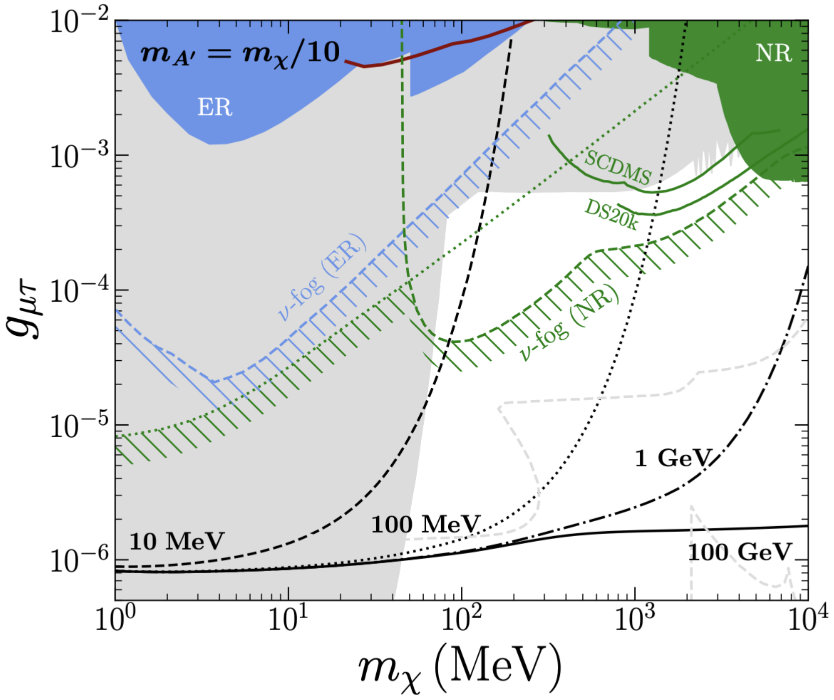
$U(1)_{L_\mu - L_\tau}$



Viable regions of the parameter space exist but **require freeze-in with a low reheating temperature.**

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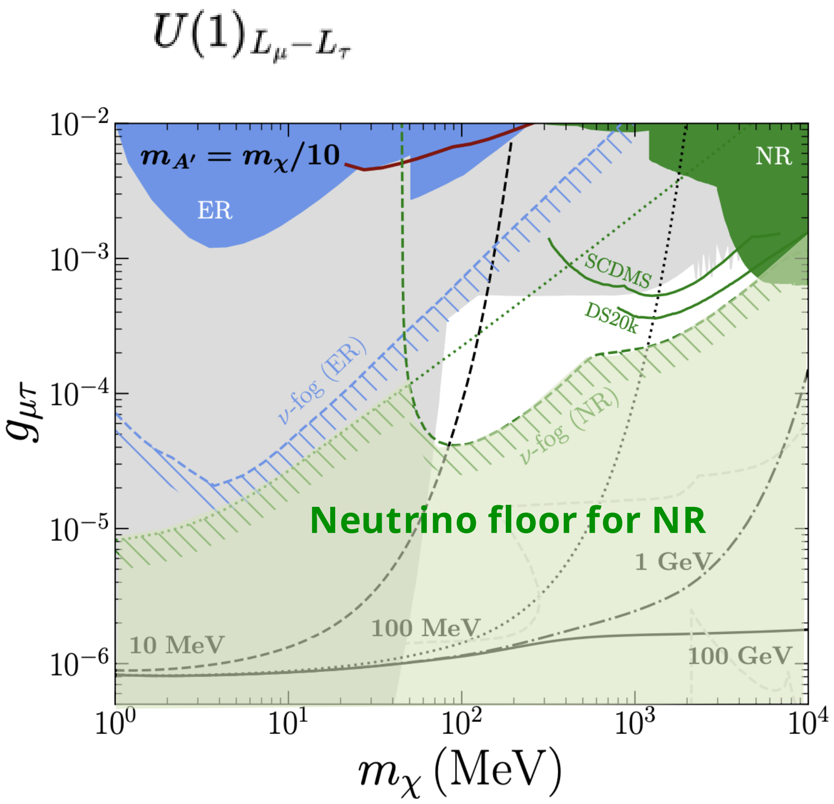

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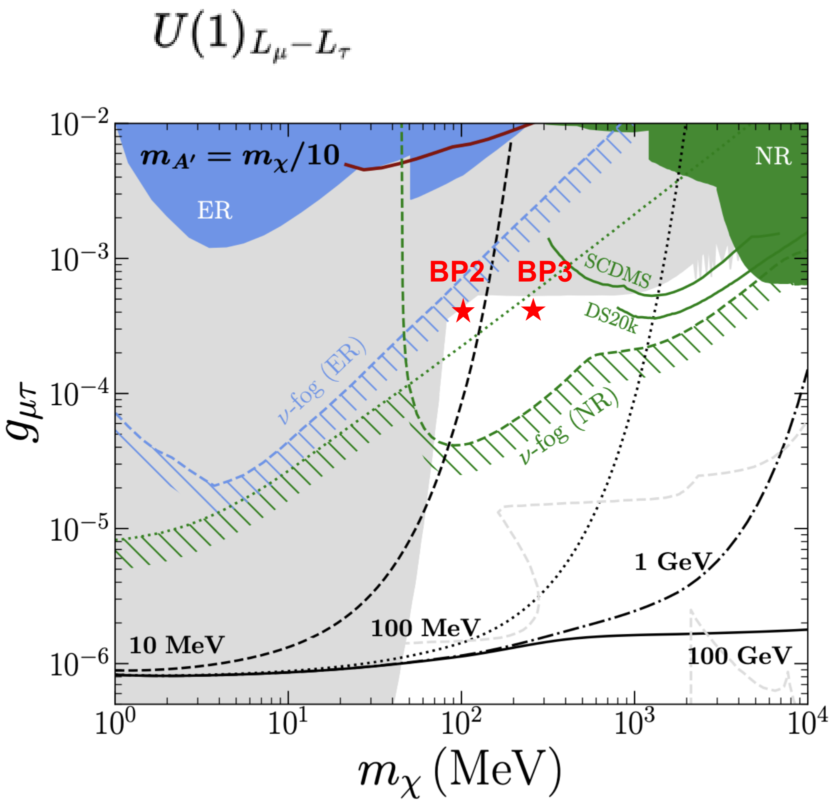

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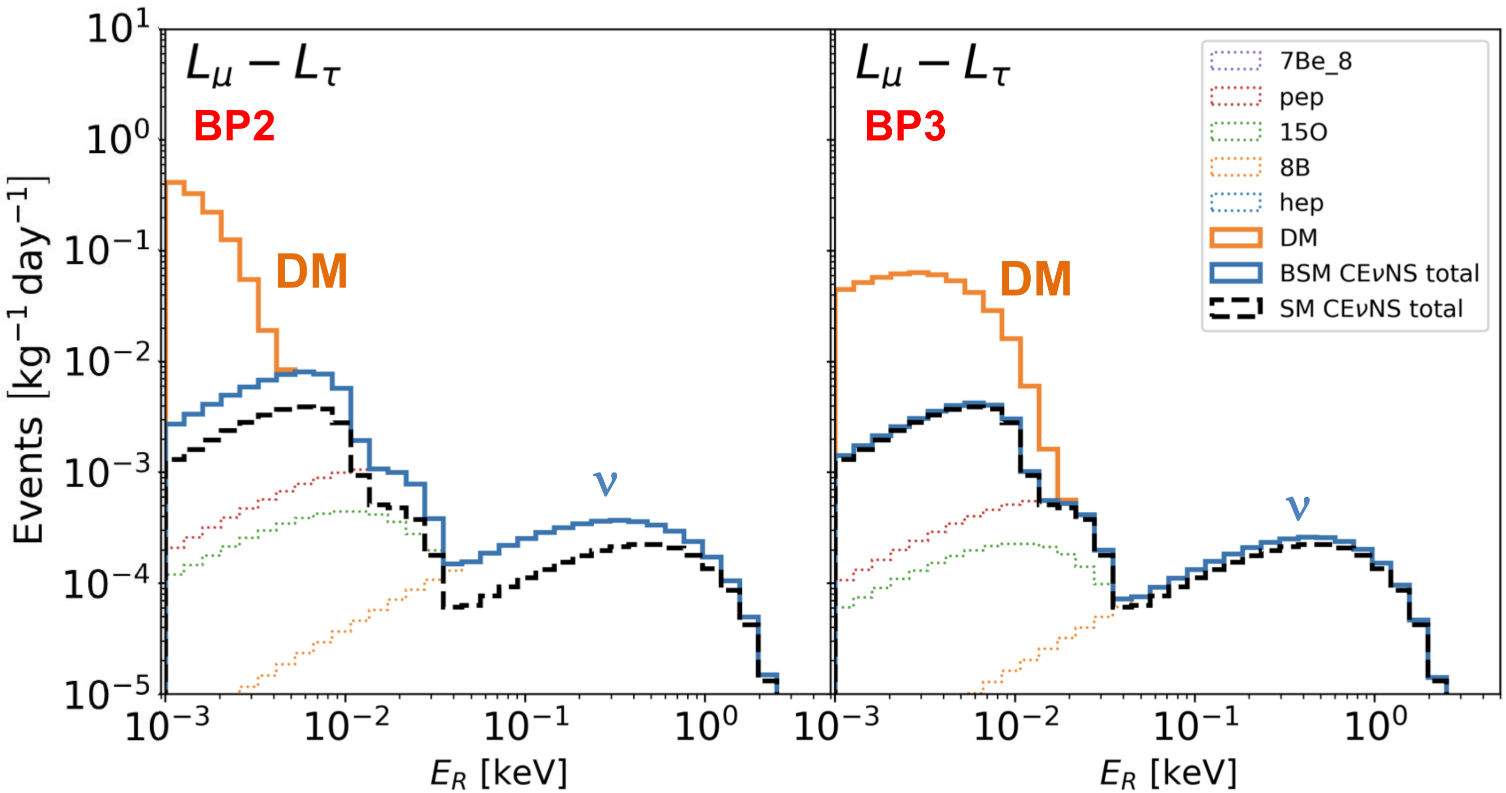
Signal mainly on NR in an interesting region for **DarkSide 20k**, **XENONnT S2** or solid-state detectors like **SuperCDMS**

Seeing DM and neutrinos simultaneously?

These models can display a **simultaneous Dark Matter and neutrino signal** in direct detection experiments!



DC, Foldenauer, López Noé, Zapata 2026

Conclusions

Direct (DM) detectors have become very versatile probes of DM across a wide mass range.

- Liquid noble gas detectors (Xe, Ar) will continue probing the WIMP paradigm above 10 GeV
- Solid state detectors and gas TPC ideal for masses ~ 1GeV
- DM electron interactions accessible with several technologies, probe less standard cosmologies and candidates (freeze-in, axions, dark photons)

Direct DM detectors are starting to see solar neutrinos. This is a great opportunity to test new physics in this sector.

- Testing new interactions in the neutrino sector with different targets (Pb, Xe, Ar)
- Searching for low-mass DM with light mediators in complementary way to collider probes
- Probing different cosmological histories (freeze-in with low reheating temperatures)