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# The Expanding Frontier of Direct Detection Experiments

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DAVID CERDEÑO

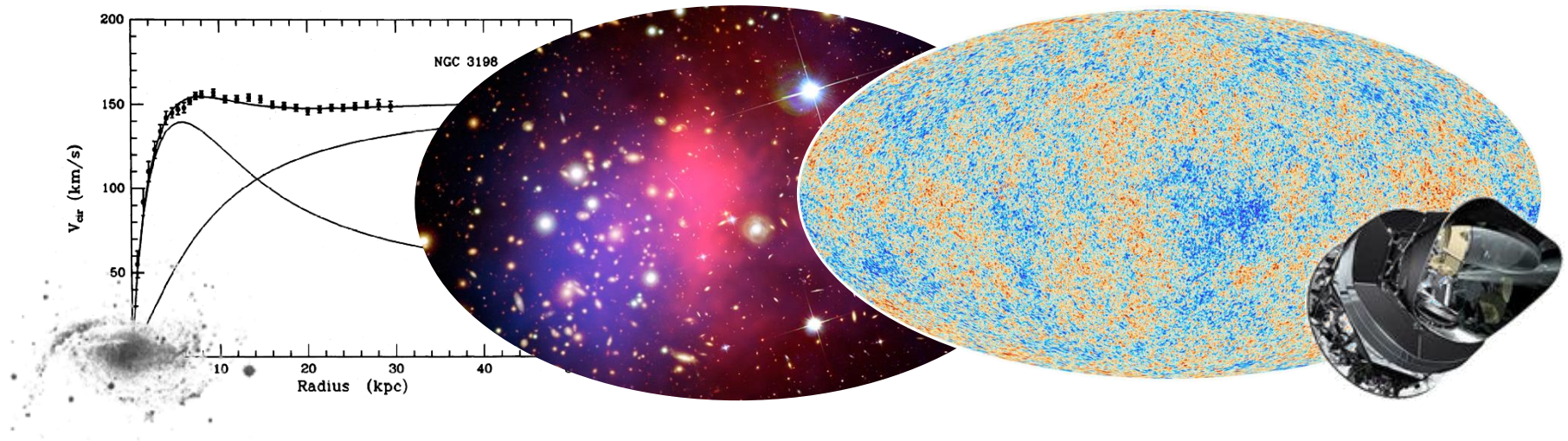
<https://projects.ift.uam-csic.es/thedeas/>



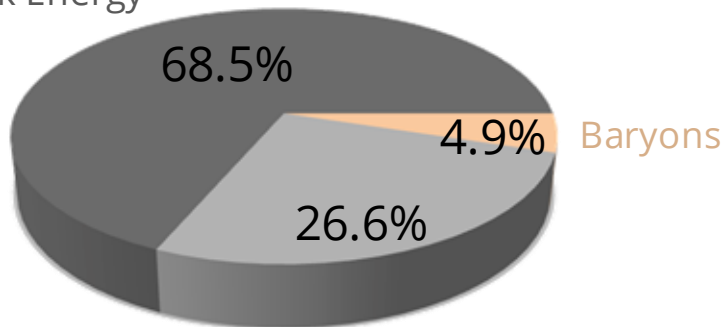
Energies, not forms, not figures  
(chant)

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

We have observed its gravitational effects at different scales

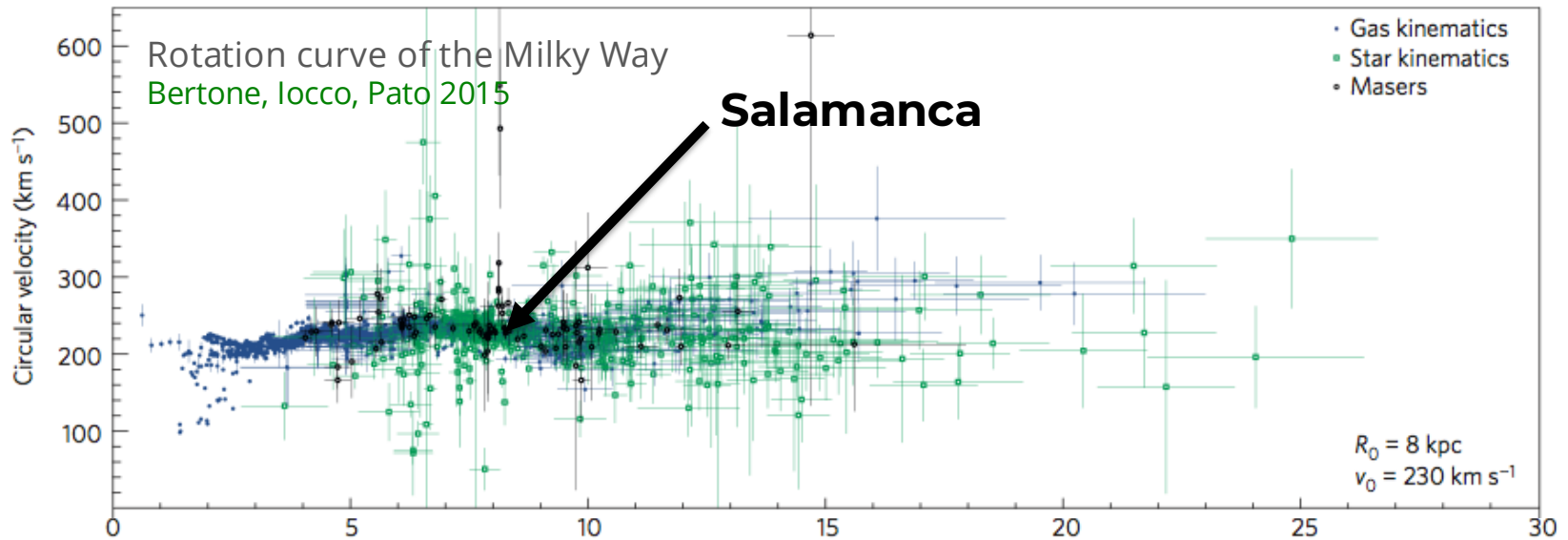


Dark Energy



Dark Matter

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



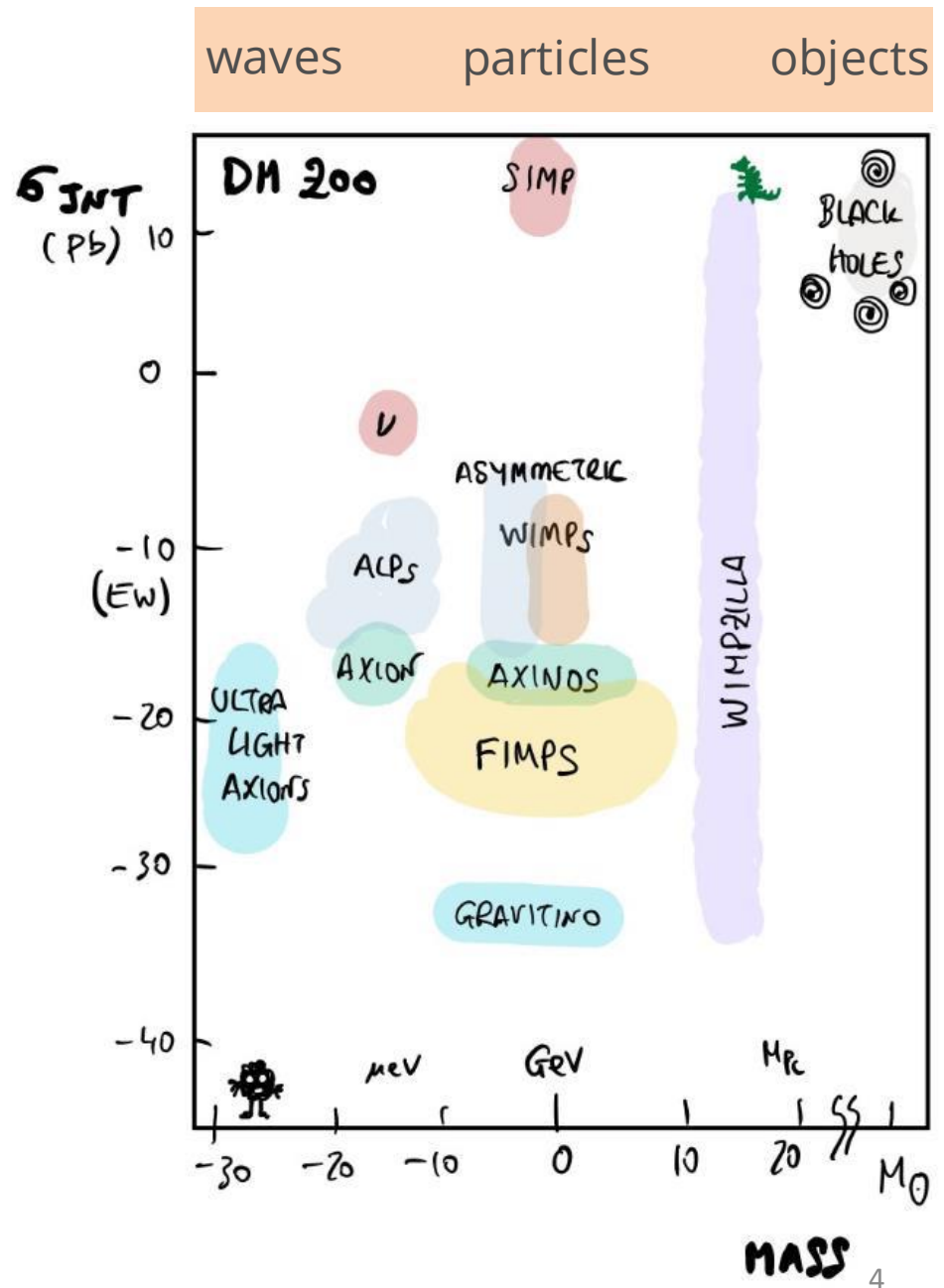
Very few people know this, but the tiny pocket in our jeans is for carrying 10 GeV of dark matter



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**

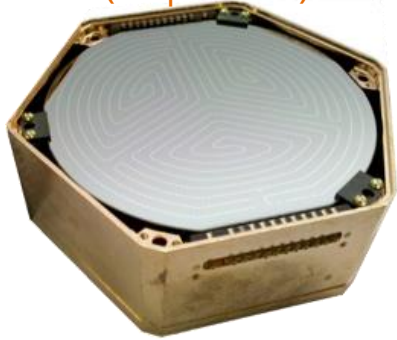
Finding the dark matter might give us information about **how the Universe came to be**



## Dark matter can be searched for in different ways

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

Direct Detection  
(dispersion)



Accelerators (LHC)  
(production)



Astrophysics and Cosmo  
(production)

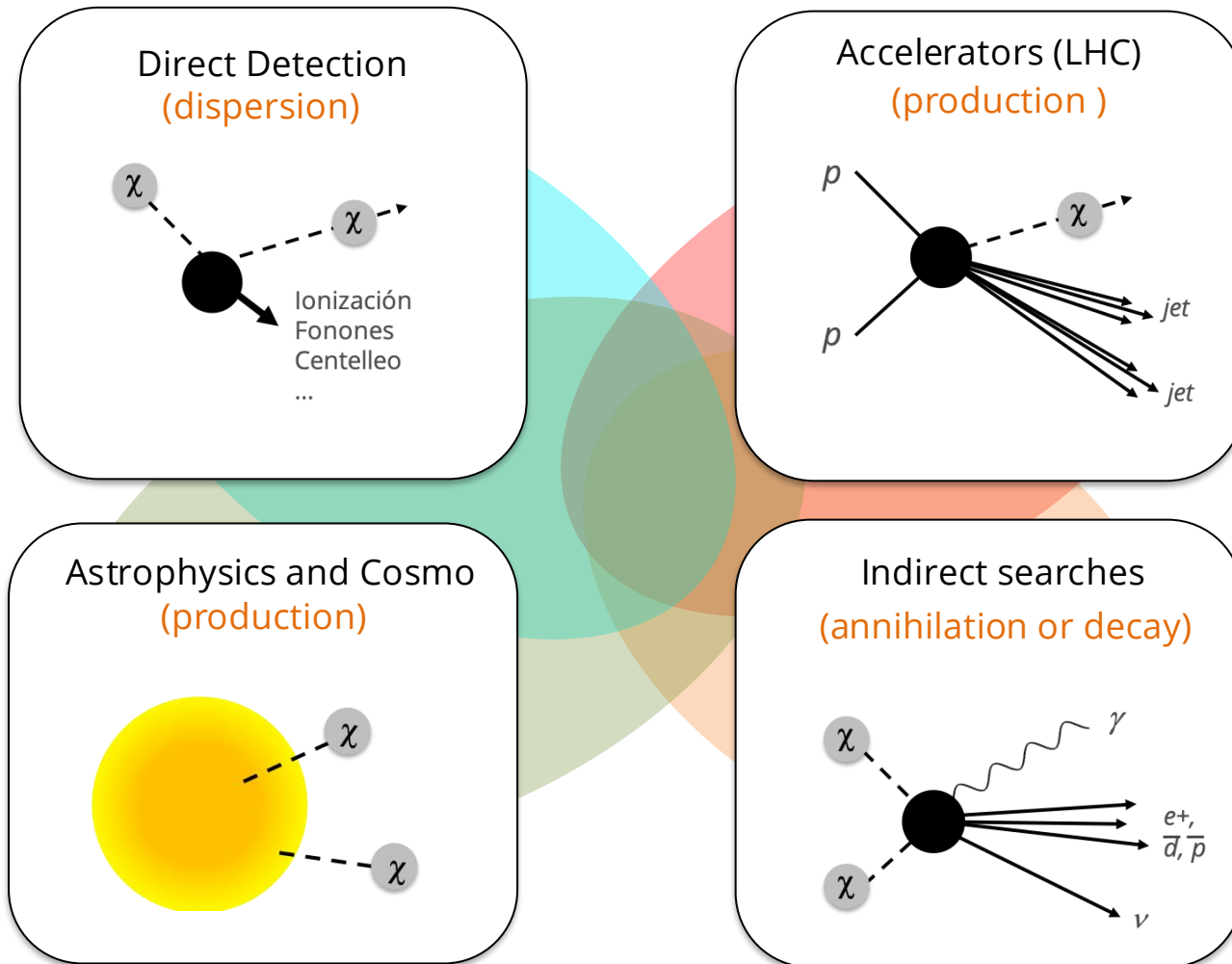


Indirect searches  
(annihilation or decay)



## Dark matter can be searched for in different ways

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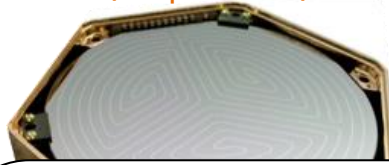


The search for DM is inextricably linked to the efforts in other areas (and benefits from advances in them)

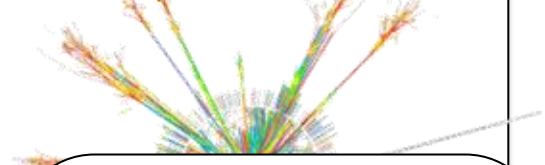
Axion Searches  
(decay or conversion)



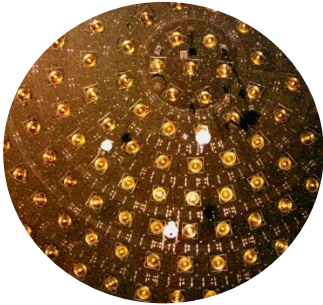
Direct Detection  
(dispersion)



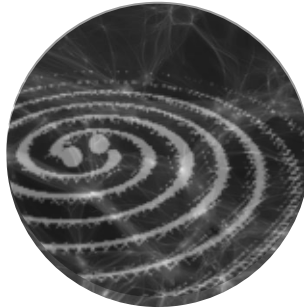
Accelerators (LHC)  
(production)



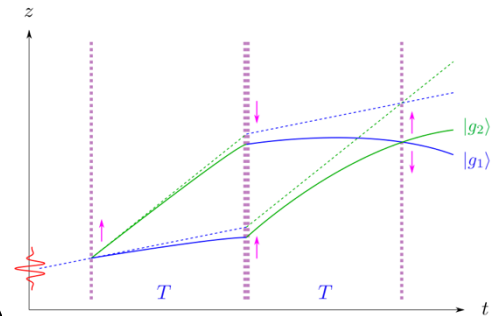
Neutrino detectors



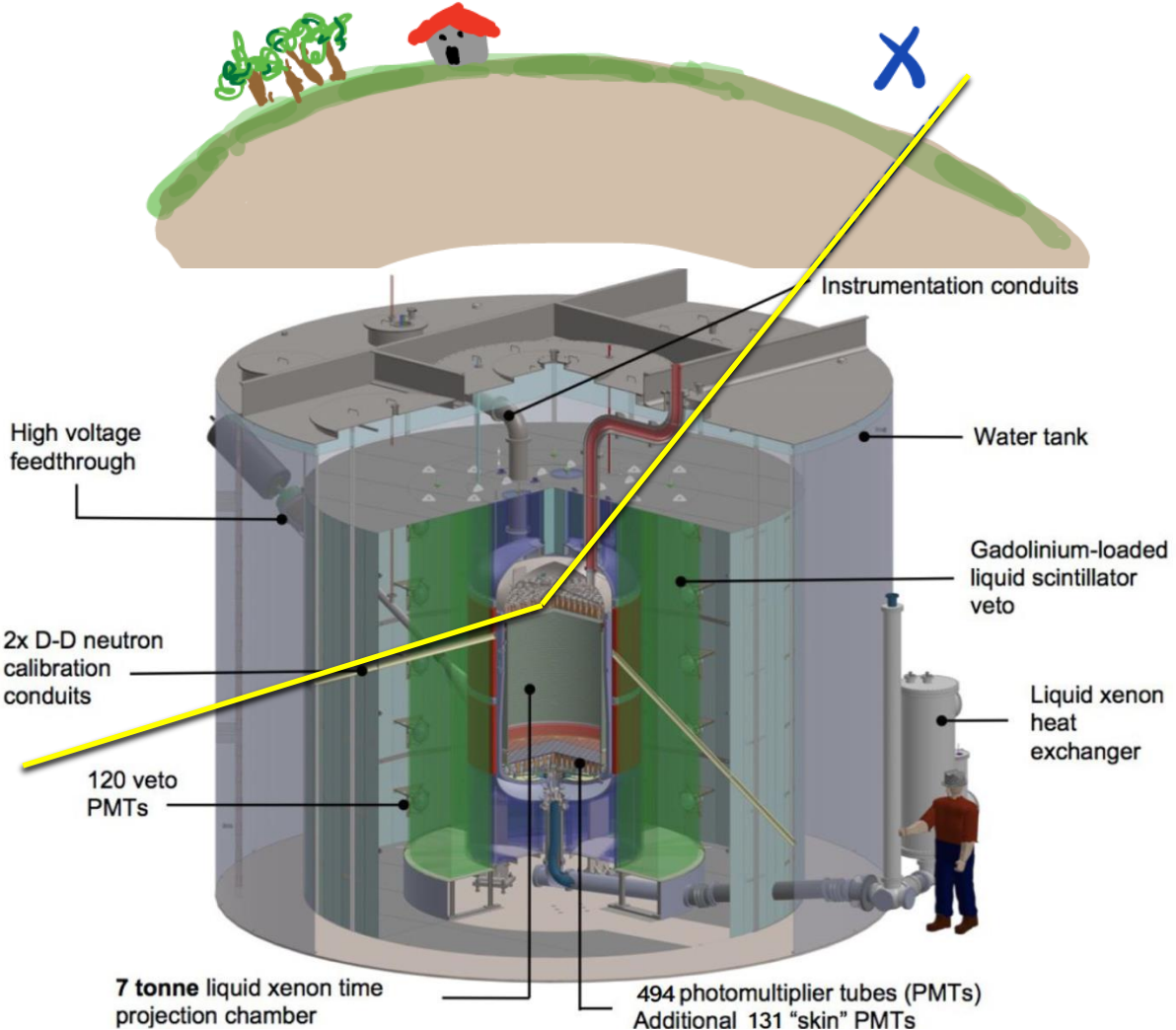
Gravitational waves



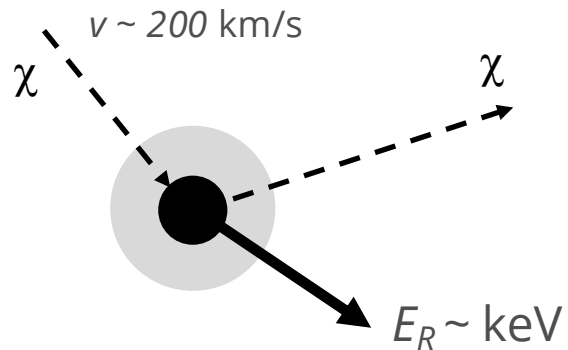
Quantum Technologies



# Dark Matter interactions inside a detector



## Dark Matter interactions inside a detector

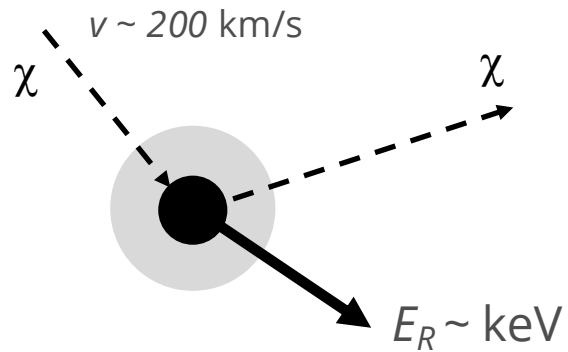


### NUCLEAR SCATTERING

- "Canonical" signature
- Elastic or inelastic scattering
- Sensitive to  $m > 1 \text{ GeV}$

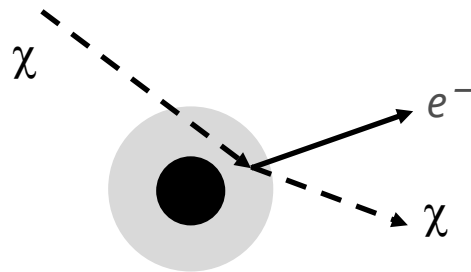
If the DM particle has a mass  $\sim \text{GeV}$ , its equivalent wavelength is of the order of the nuclear radius. The DM particle sees the nucleus as a whole: **COHERENT SCATTERING**

## Dark Matter interactions inside a detector



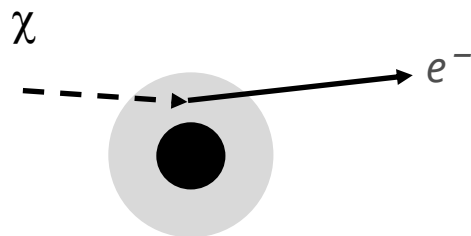
### NUCLEAR SCATTERING

- "Canonical" signature
- Elastic or inelastic scattering
- Sensitive to  $m > 1 \text{ GeV}$



### ELECTRON SCATTERING

- Inelastic scattering
- Sensitive to MeV scale DM

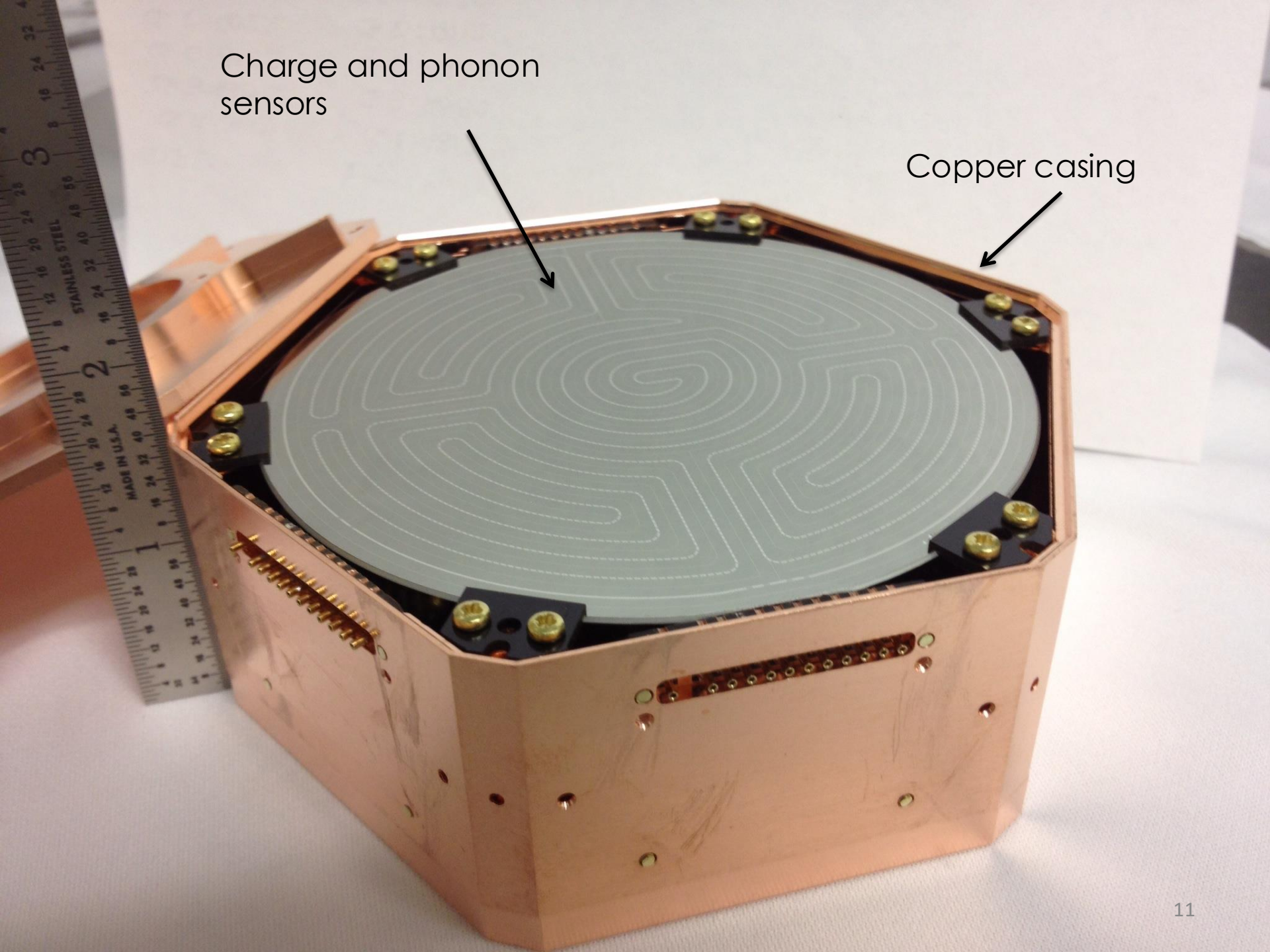


### ABSORPTION BY ELECTRON

- Sensitive to eV scale DM

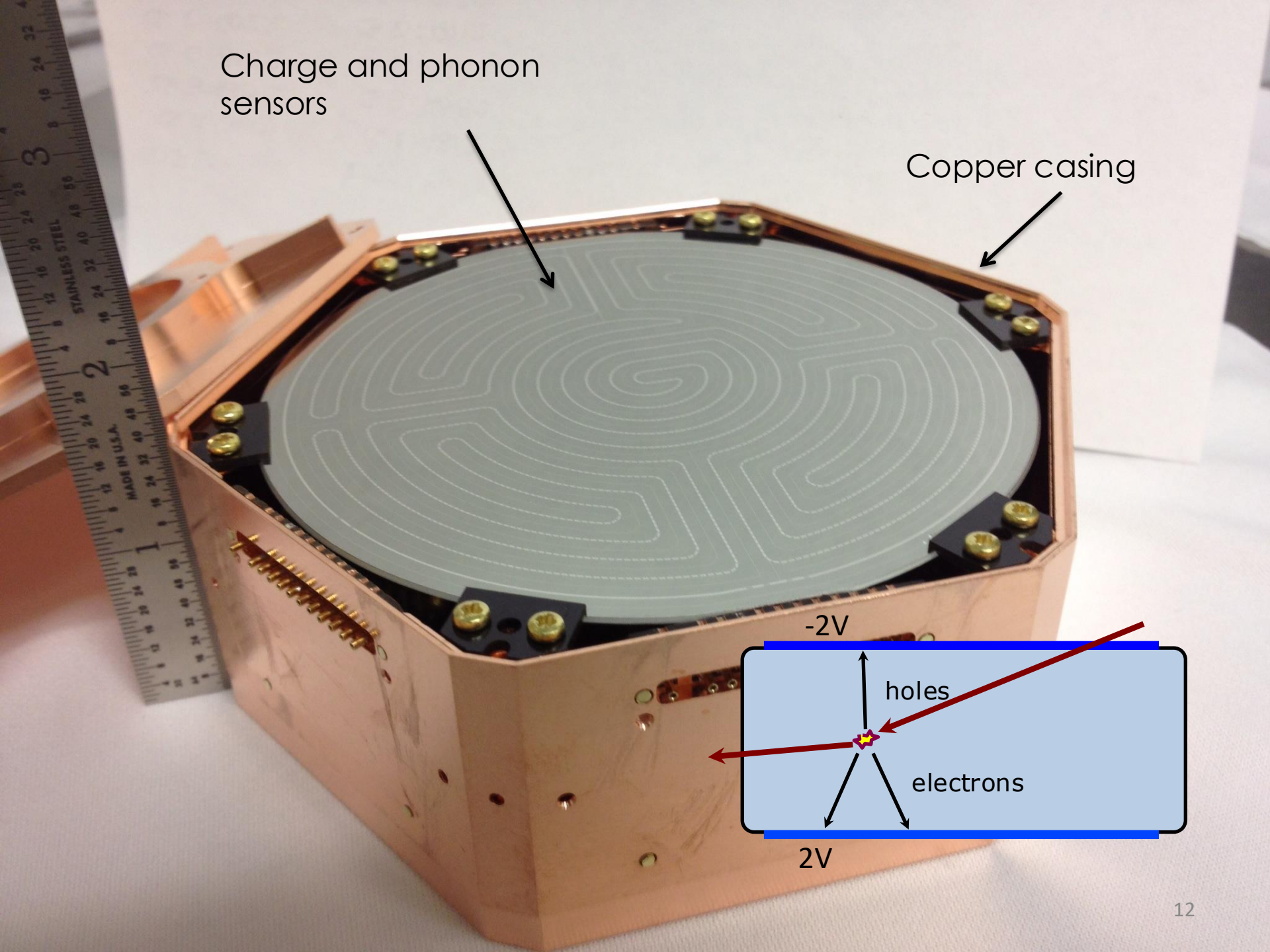
Charge and phonon sensors

Copper casing



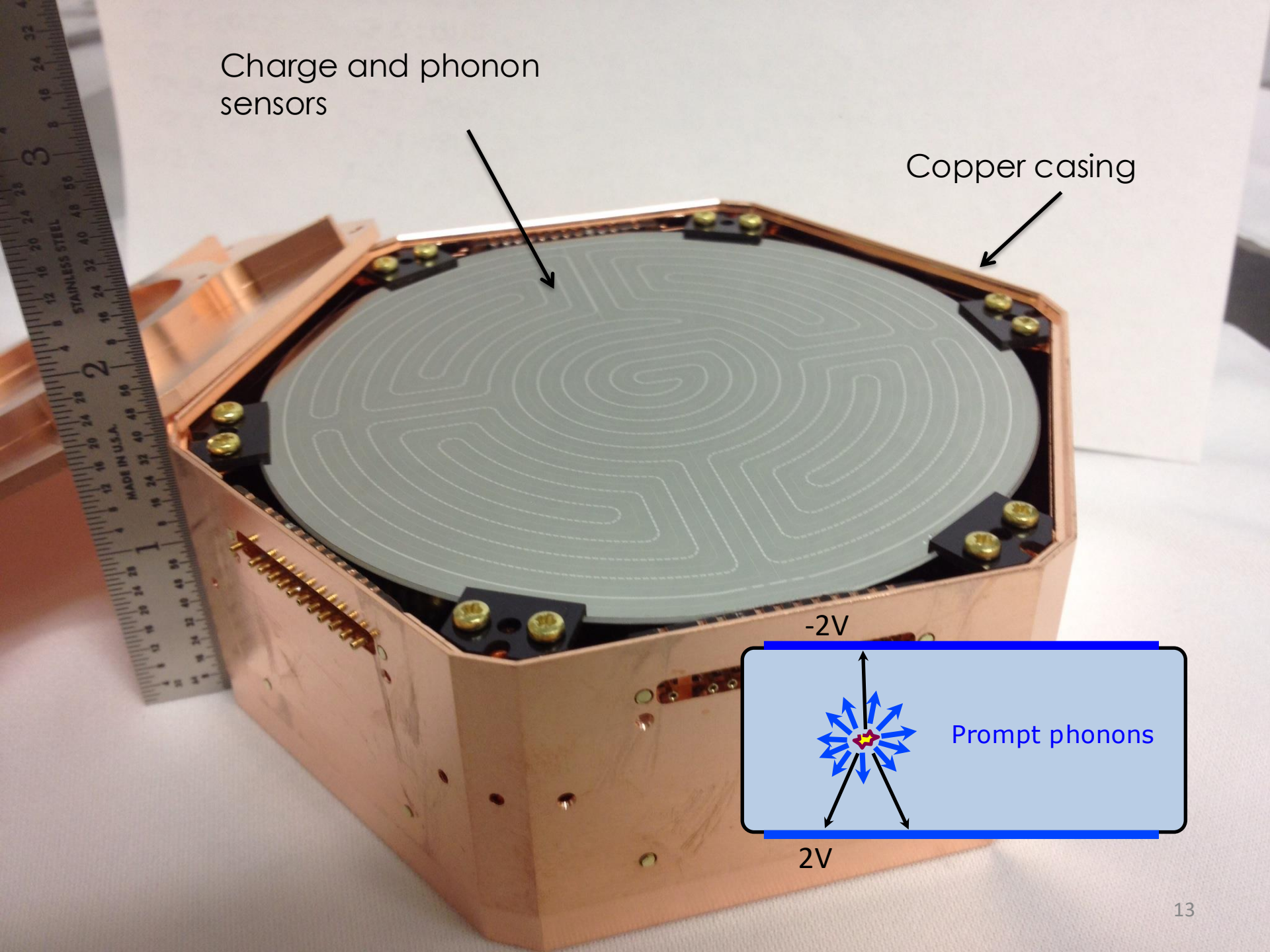
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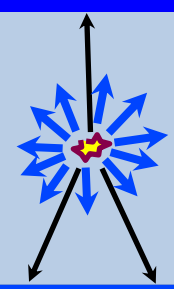


Charge and phonon sensors

Copper casing



-2V

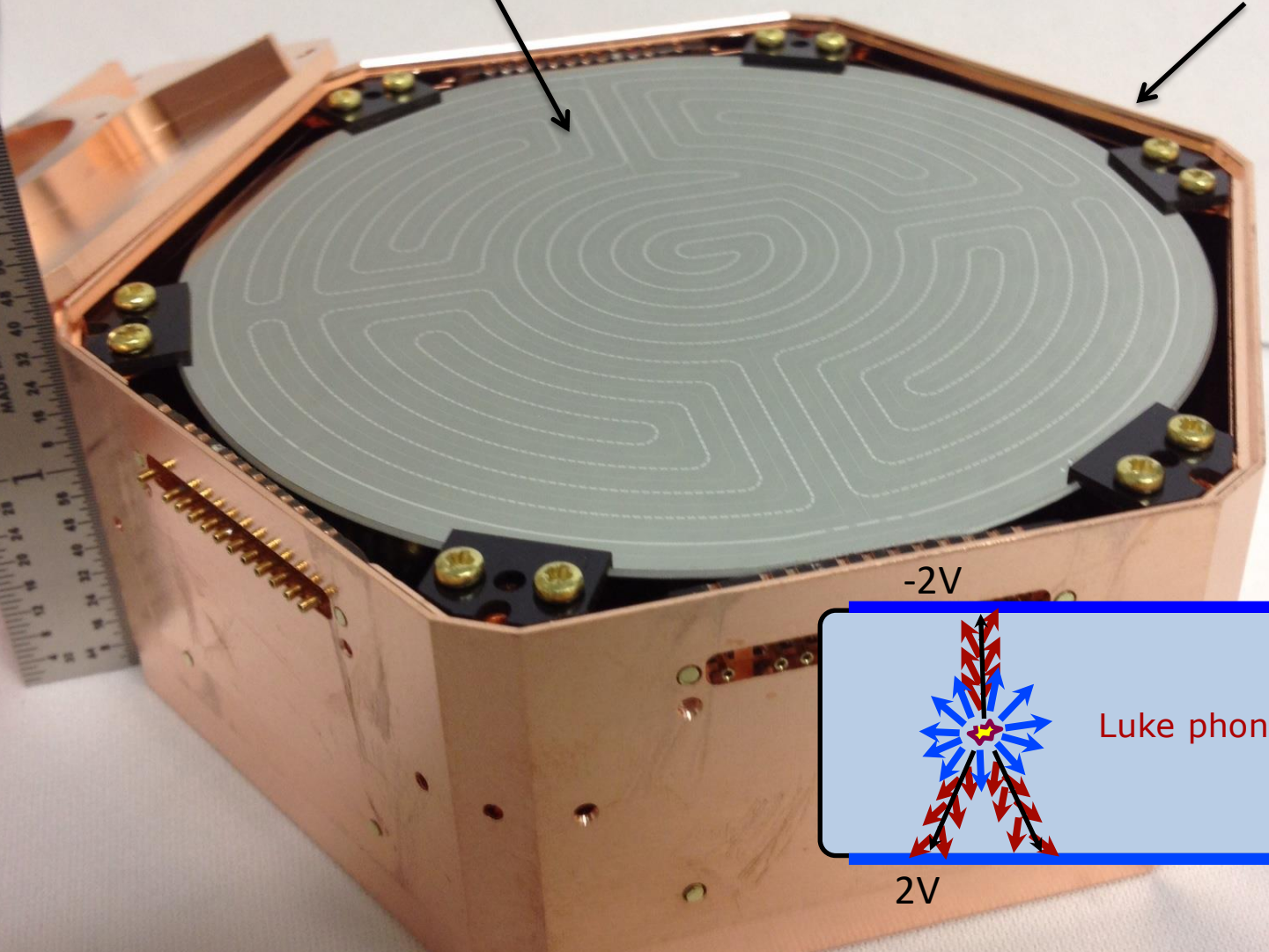
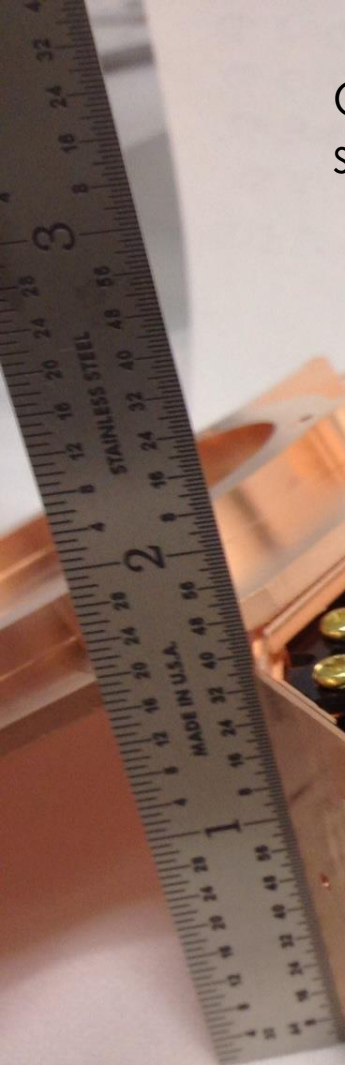


Prompt phonons

2V

Charge and phonon sensors

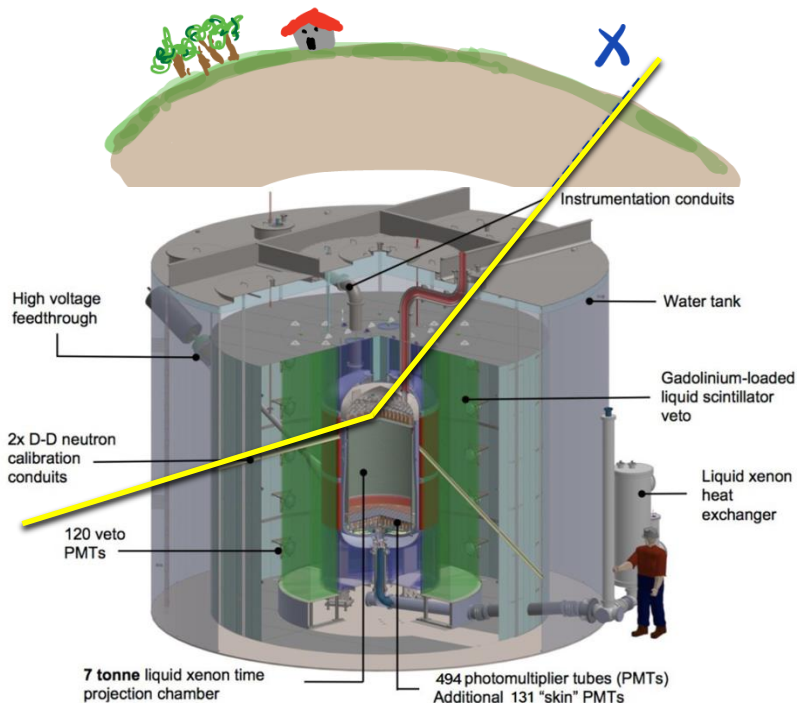
Copper casing



# 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)

## Conventional direct detection approach (nuclear scattering)

Expected number of events

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

### Particle (+ nuclear) Physics

The scattering cross section contains the details about the microphysics of the DM model  
Traditionally, it has been split into two components: spin-dependent and -independent

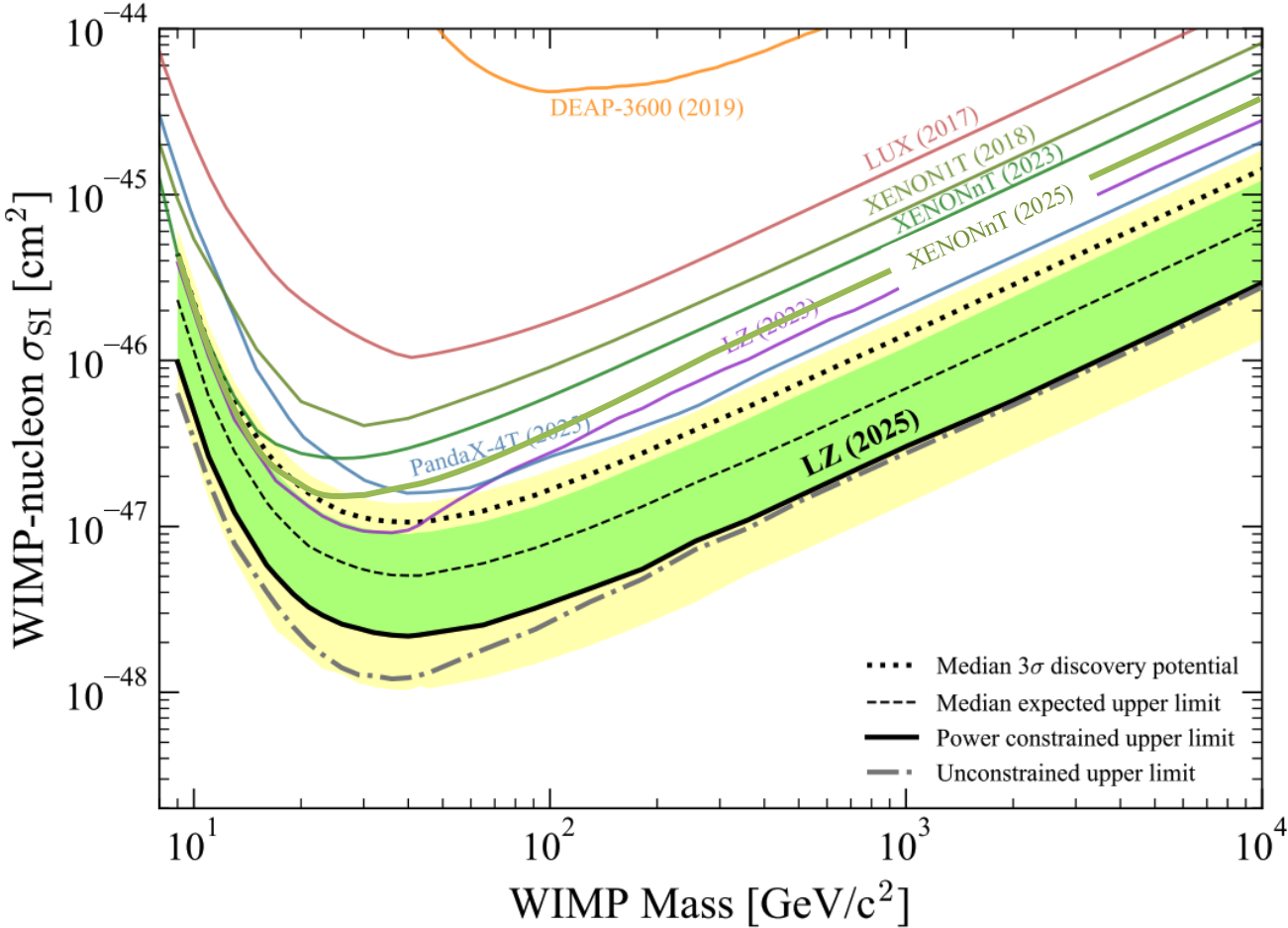
$$\frac{d\sigma_{WN}}{dE_R} = \left( \frac{d\sigma_{WN}}{dE_R} \right)_{SI} + \left( \frac{d\sigma_{WN}}{dE_R} \right)_{SD}$$

These include nuclear form factors that encode the coherent scattering with the nucleus.

**If nothing is found, we derive upper limits on the scattering cross section.**

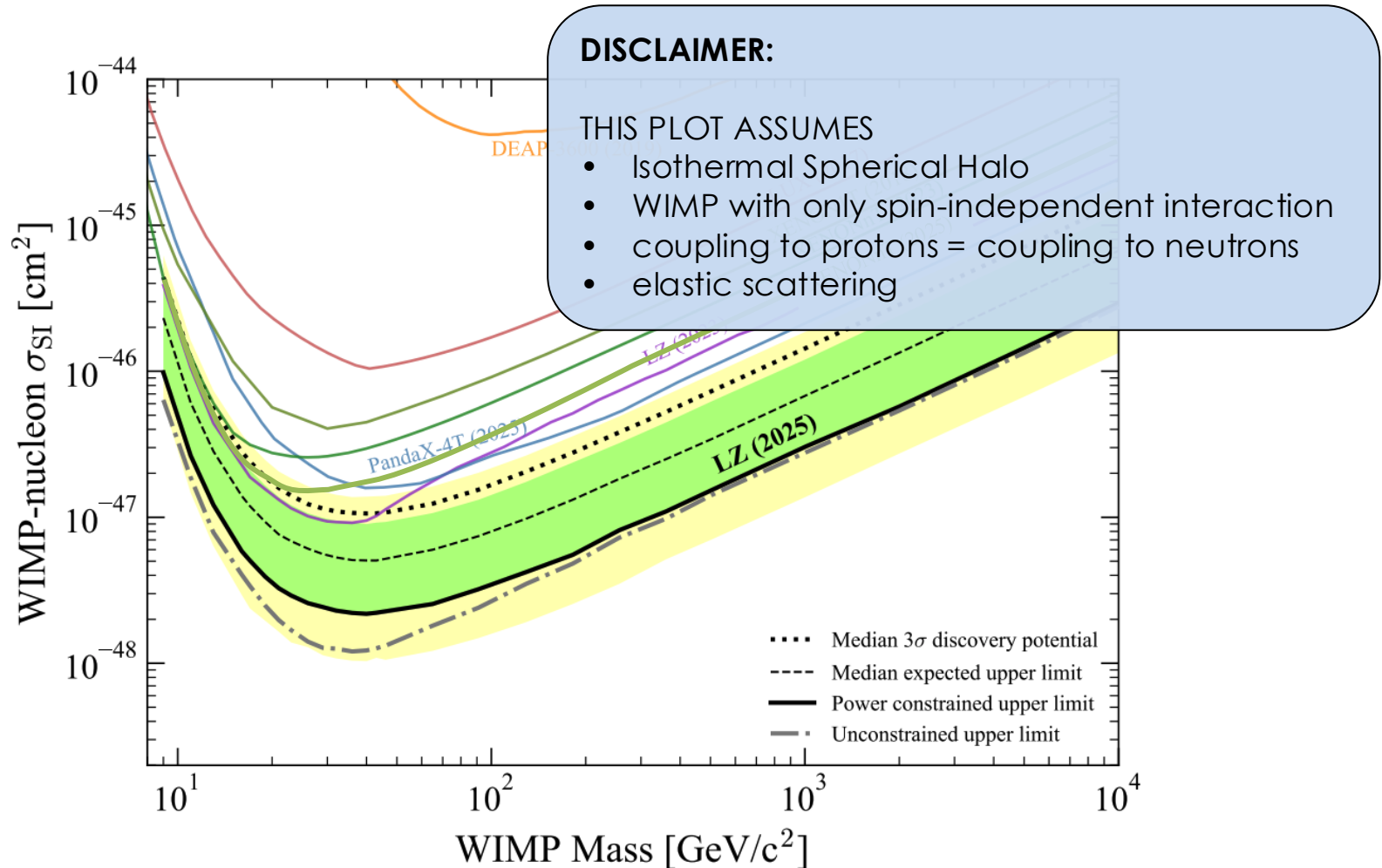
# Liquid noble gas detectors are leading the search at masses above 10 GeV

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



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



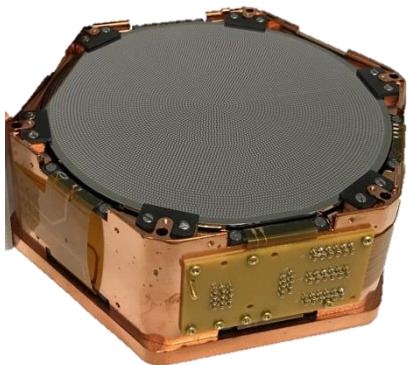
## Low-threshold experiments can look for ~ GeV scale DM

Solid state detectors (**SuperCMDS**, **Edelweiss**, **CREESST**) can have a very low threshold.



**iZIP**: Ionisation + Phonons

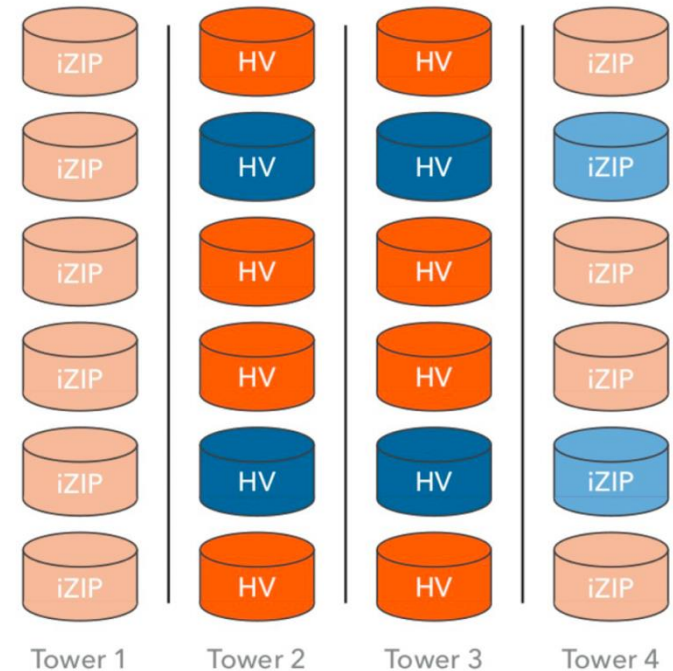
Excellent discrimination between nuclear recoils (NR) and electronic ones (ER) of  $1/10^5$



**HV**: Phonons (High Voltage)

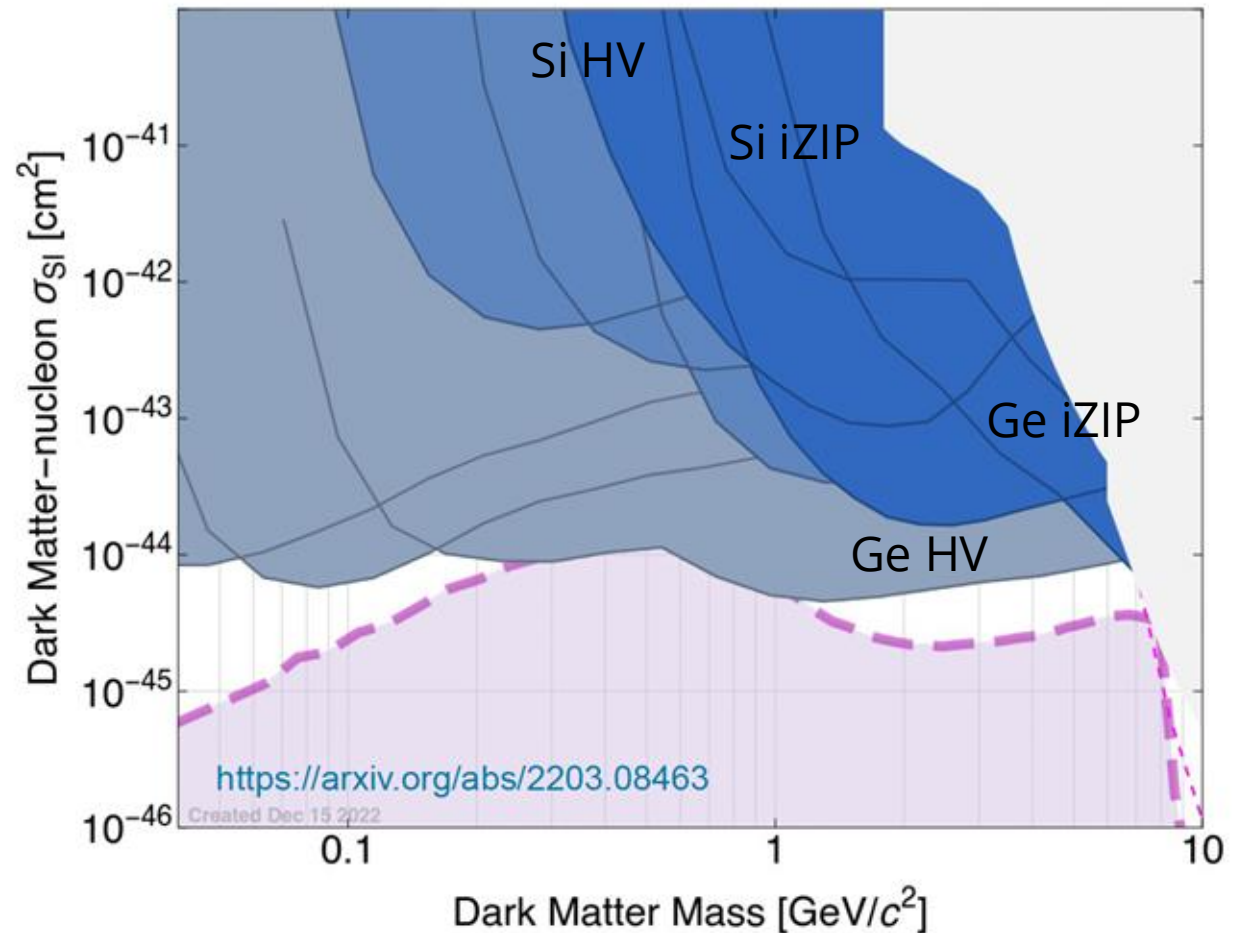
Amplify the signal through the Luke-Neganov-Trofimov effect. Greater sensitivity to low mass DM (no discrimination)

4 towers of crystals  
Ge (1.4 kg) and Si (0.6 kg)



## Low-threshold experiments can look for $\sim$ 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.



## Direct dark matter detection often requires large underground experiments

Expected number of events

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

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

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

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

## The resulting dark matter signature depends on the microphysics

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

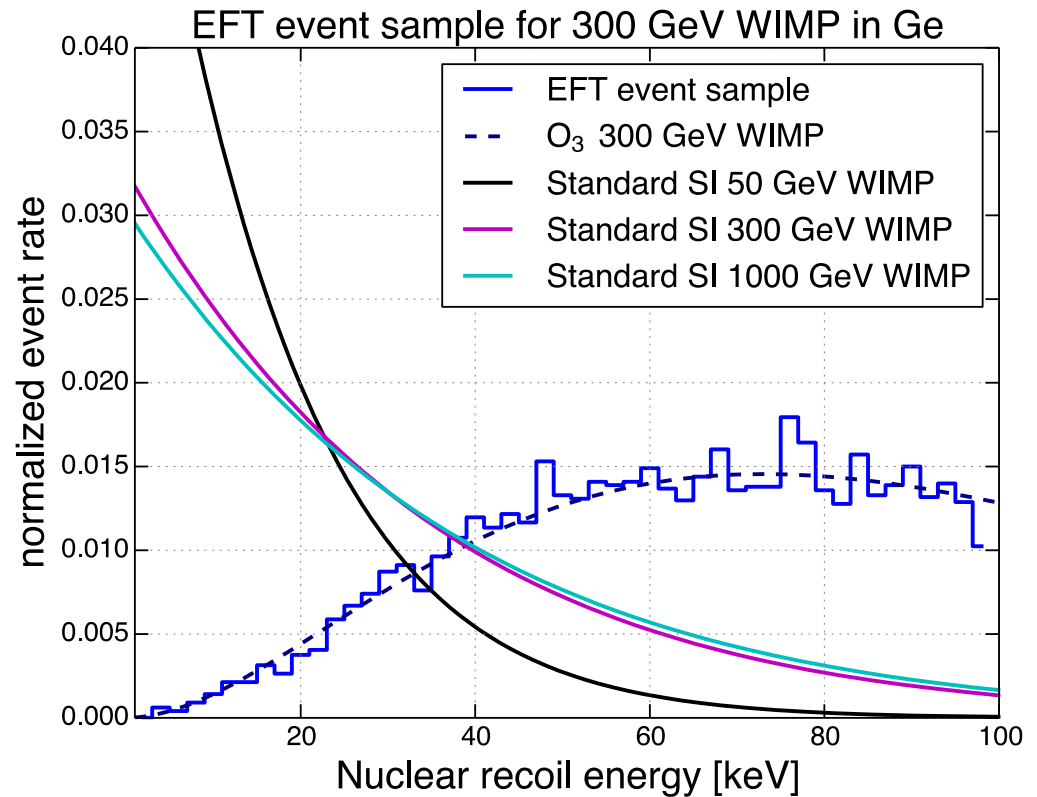
**Momentum dependent interactions** show a characteristic “bump”

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

Some signatures could be confused with new sources of background.

Enlarging the **maximum energy** in the signal region allows to set better constraints (or mass reconstruction)

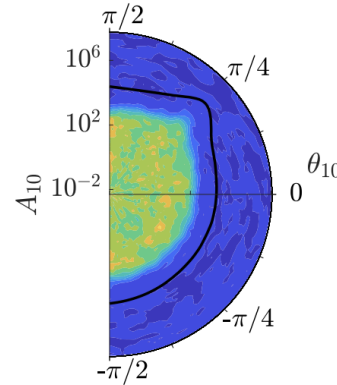
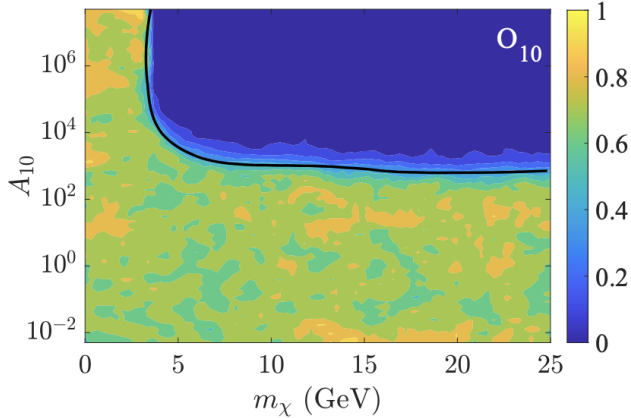
Bozorgnia, DC, Cheek, Penning 2018



Schneck et al [SuperCDMS] 2015

## Experimental results on EFTs

SuperCDMS 2022



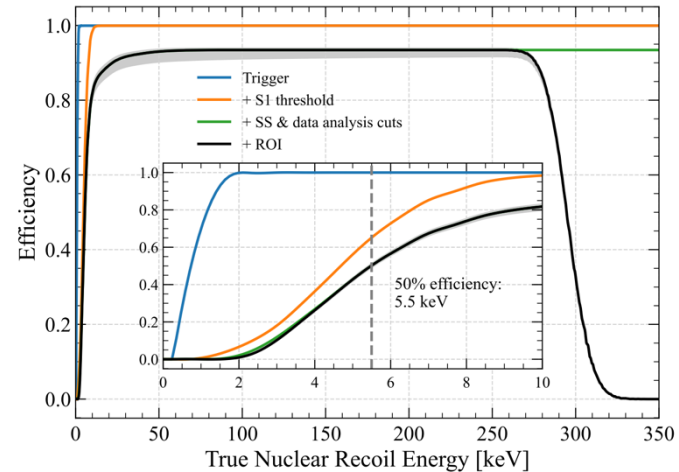
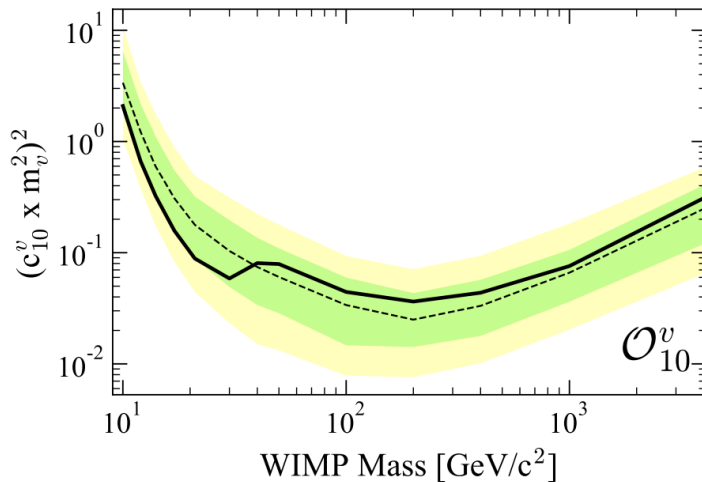
$$\sigma_1^0 = \frac{A^2 m_N^2}{4\pi \langle V \rangle^4 (1+A)^2} A_1$$

$$c_i^0 = A_i \sin(\theta_i)$$

$$c_i^1 = A_i \cos(\theta_i)$$

Xenon experiments (PandaX, Xenon1T) improve at large masses. **LZ** implemented the extended analysis range in energies

[LZ 2024](#)



## Direct dark matter detection often requires large underground experiments

Expected number of events

Astrophysics

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### Dark matter halo parameters

Local density and DM velocity distribution function

Uncertainties in the halo parameters

Directionality and time-dependence (annual modulation)

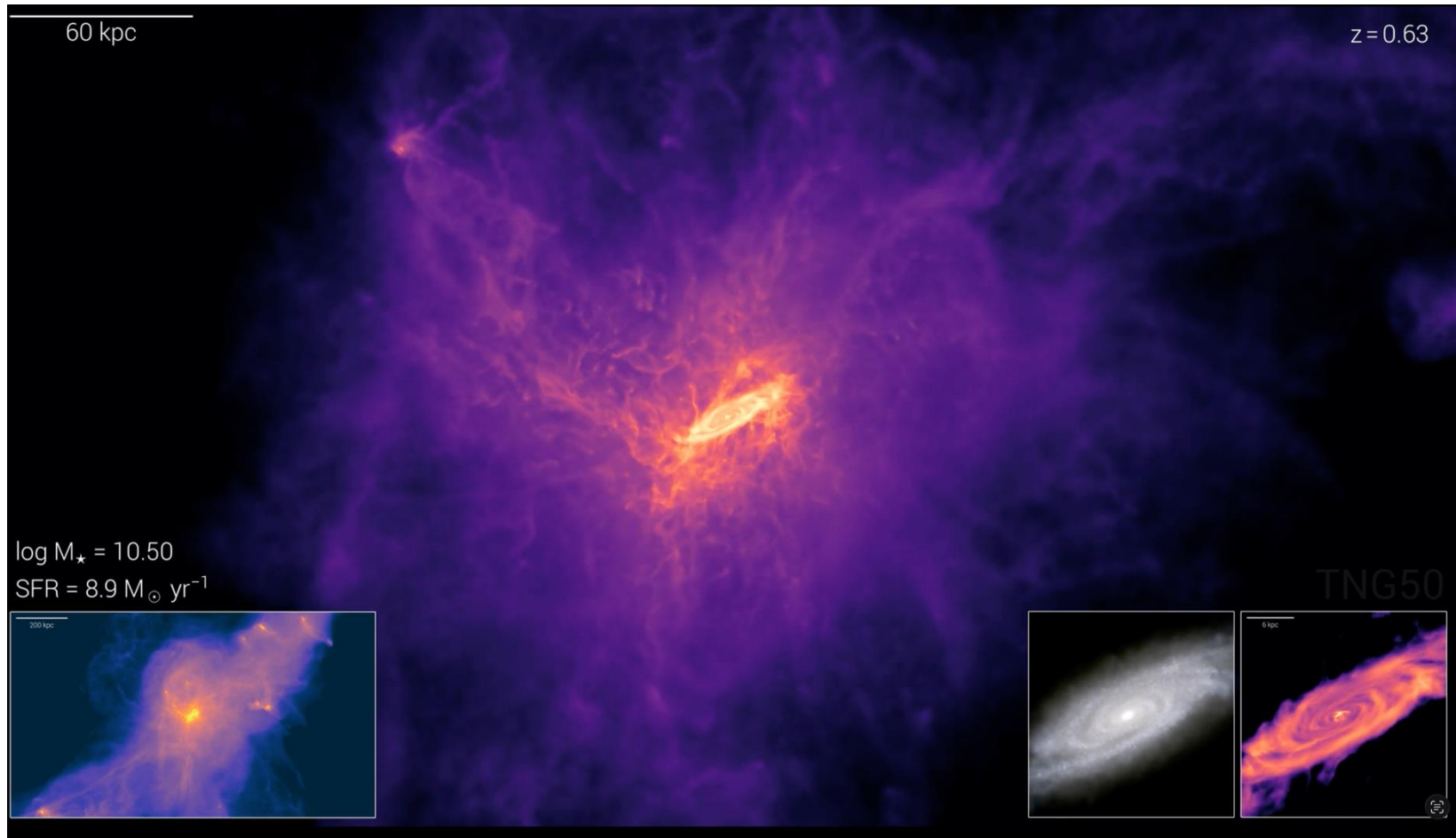
### Scattering cross section

Particle physics (dark matter model)

Nuclear Physics (form factors)

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

# Numerical simulations of the Dark Matter halo

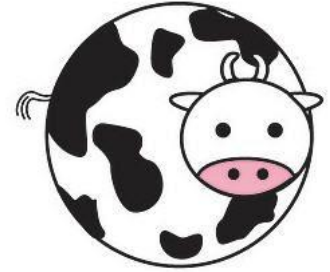


**TNG50**

# How well do we know our dark matter halo?

## Astrophysics

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

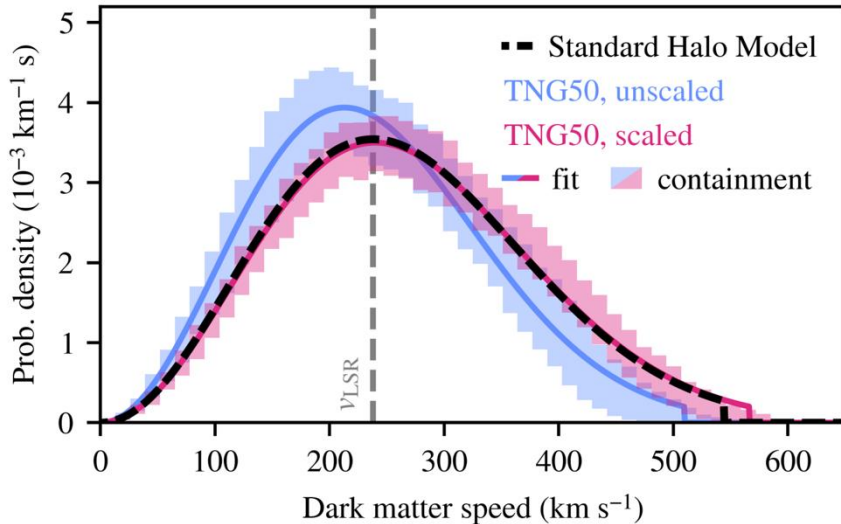


### Standard Halo Model

$$f(\vec{v}) = \frac{1}{(2\pi\sigma)^{3/2}} e^{-|\vec{v}-v_E(t)|^2/2\sigma^2} \Theta(v_{esc} - |v|)$$

Smooth, spherical, isotropic, truncated Gaussian (two parameters,  $v_{esc}$  and  $\sigma$ )

Folsom et al. 2015.07924



local DM density

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

Velocity distribution of DM particles

Maxwellian distribution is (globally) a good fit

Bozorgnia et al. 2016.04707

How well can  $f(v)$  be inferred from visible stars?

Attempts to use old (halo) stars

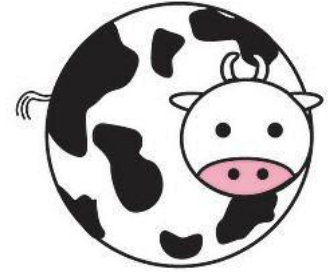
Necib, Lisanti et al. 2017.02591

Bozorgnia et al, 2018-05576 26

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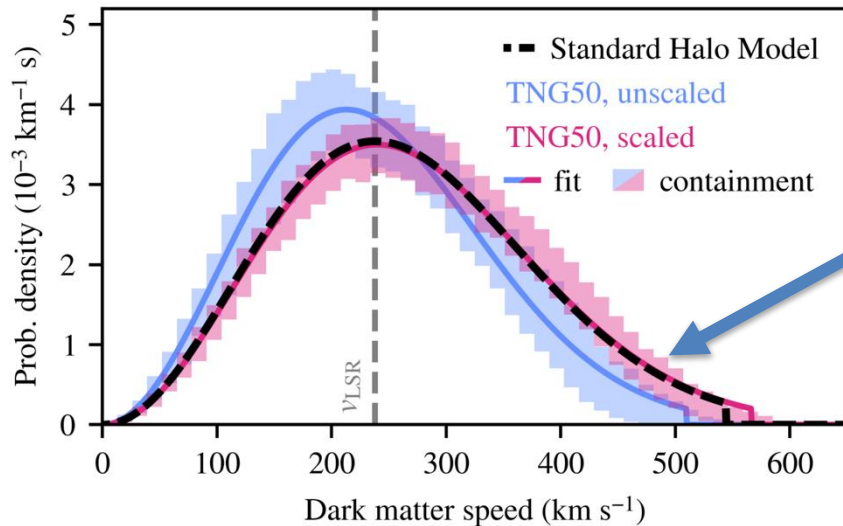


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Smooth, spherical, isotropic, truncated Gaussian (two parameters,  $v_{esc}$  and  $\sigma$ )

Folsom et al. 2505.07924



Direct detection is extremely sensitive to the **high-velocity tail** of the distribution

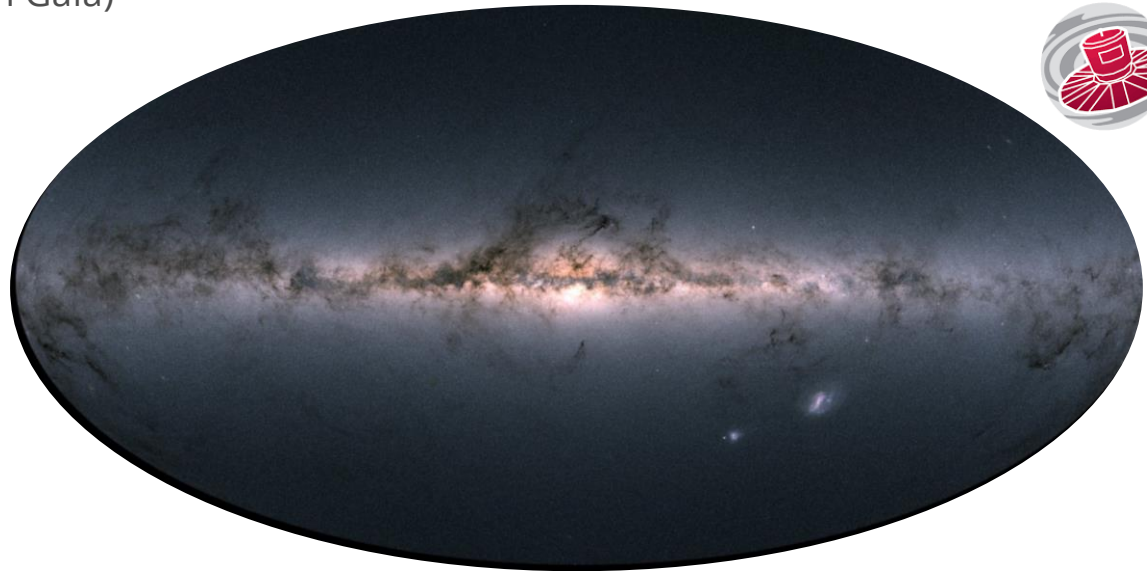
Particularly important for low-mass DM

## How well do we know our dark matter halo?

Most of what we know comes from comparing results from n-body simulations and observations (recently from Gaia)

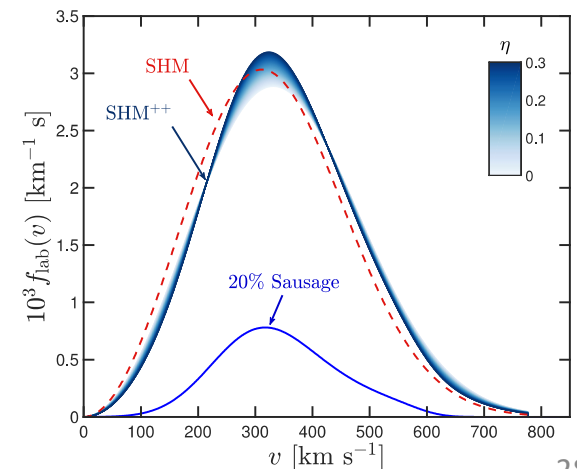
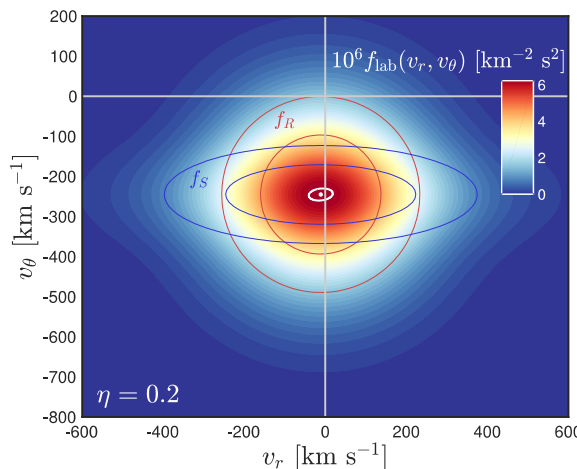


The **positions and velocities of 2000 million stars** in our Galaxy inform us about the dark matter distribution in the halo.



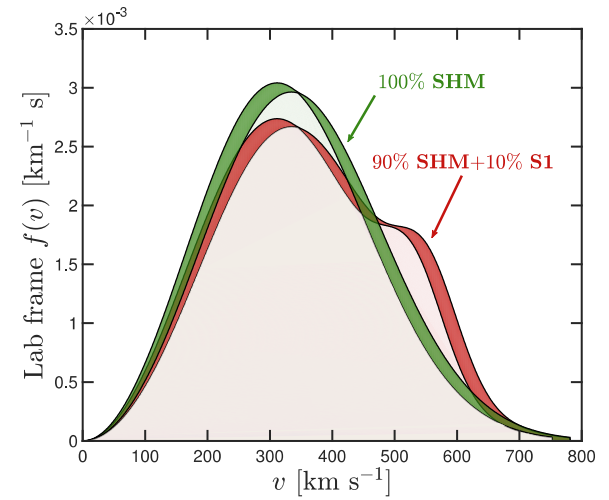
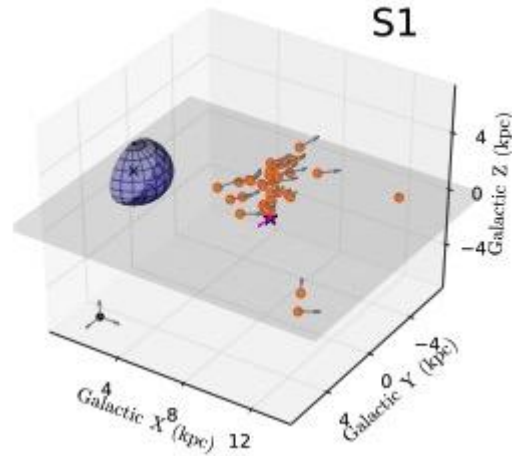
Several **non virialised components** have been identified that alter the DM velocity distribution function.

A Radially Anisotropic Component (sausage?)



# How well do we know our dark matter halo?

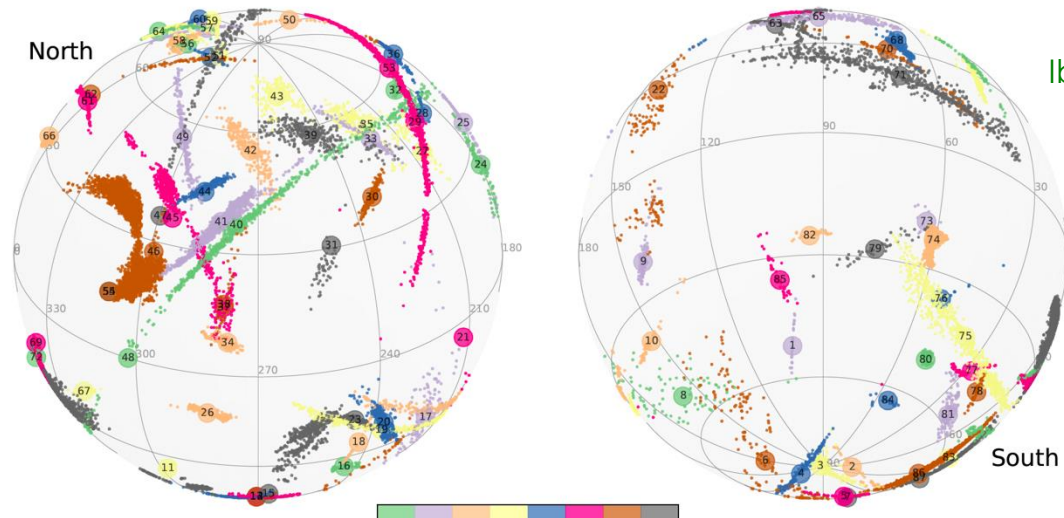
Similarly, **stellar streams** also hint at the existence of similar **dark matter** structures.



O'Hare, McCabe, Evans, Myeong, Berlokurov 2018

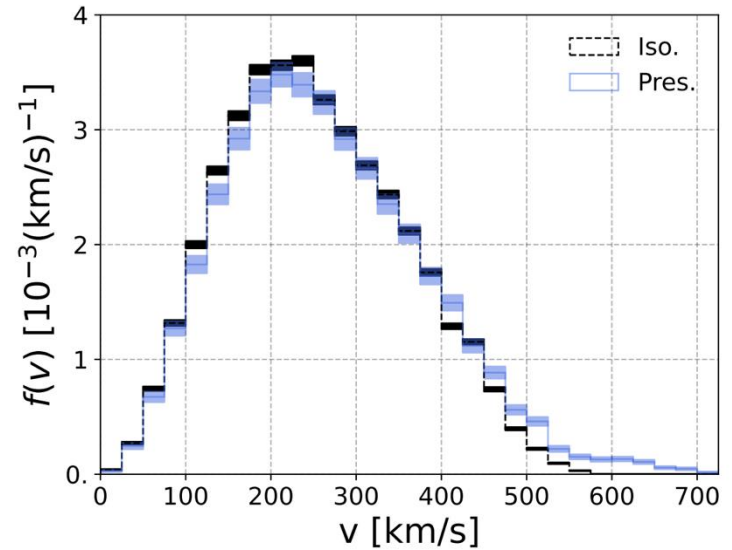
Plenty of streams identified that have an impact on the **DM** velocity distribution function

Especially important for direct detection of light particles.



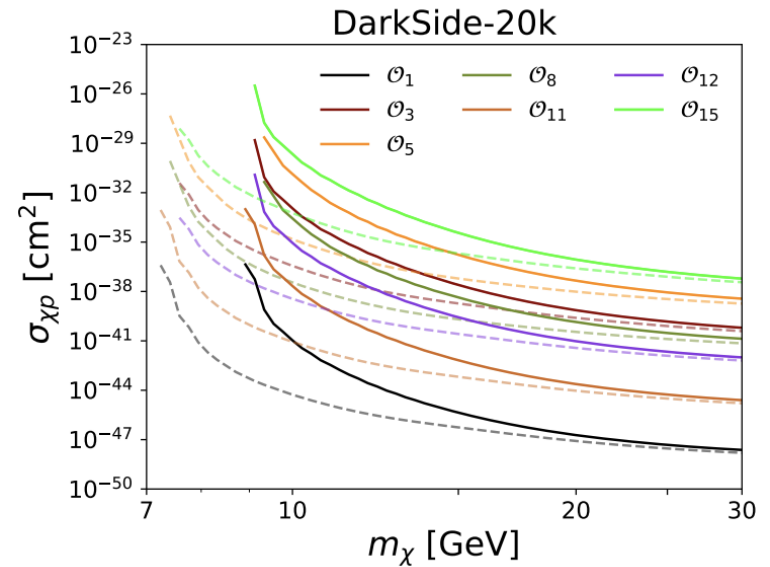
Ibata et al. 2023

The presence of the **LMC** can also alter the DM velocity distribution function, introducing larger velocity particles and improving the detection rate of low-mass WIMPs.

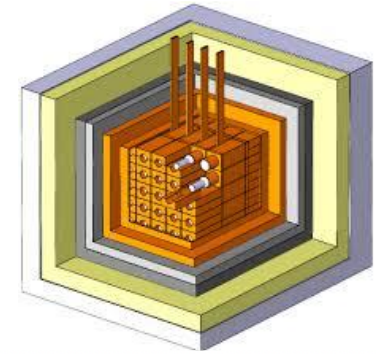


Limits are affected, and **can extend well below 10 GeV**.

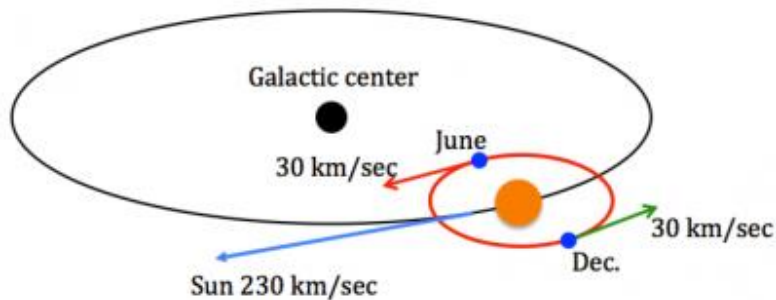
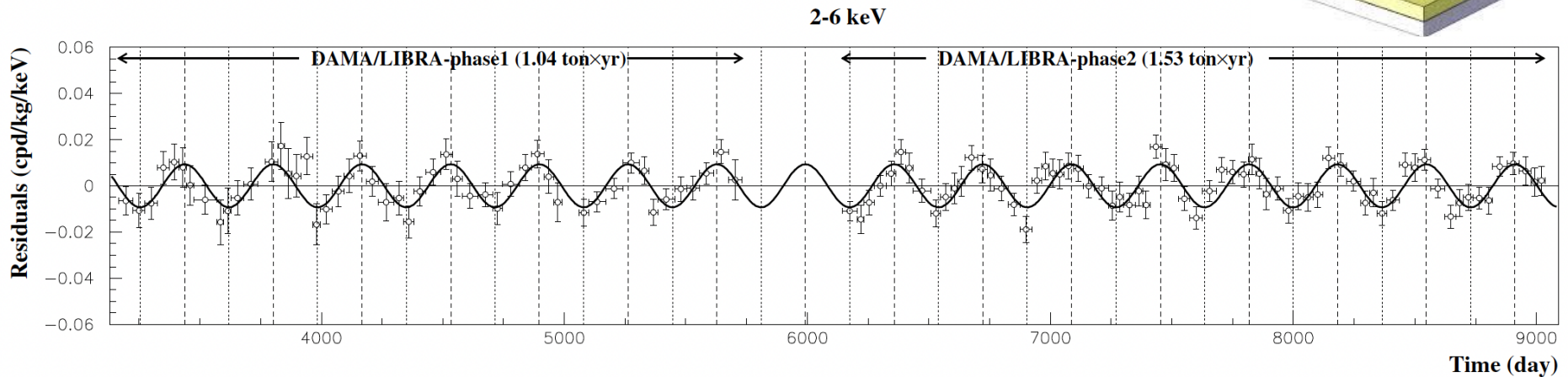
**EFT operators** are affected in different ways (depending on their velocity and momentum dependence).



## Annual Modulation of dark matter direct detection



The DAMA/LIBRA (NaI) collaboration has reached 2.86 ton yr over 22 annual cycles. It observes a clear modulation in the [1-6] and [2-6] keV regions with very high CL (13.7  $\sigma$ )



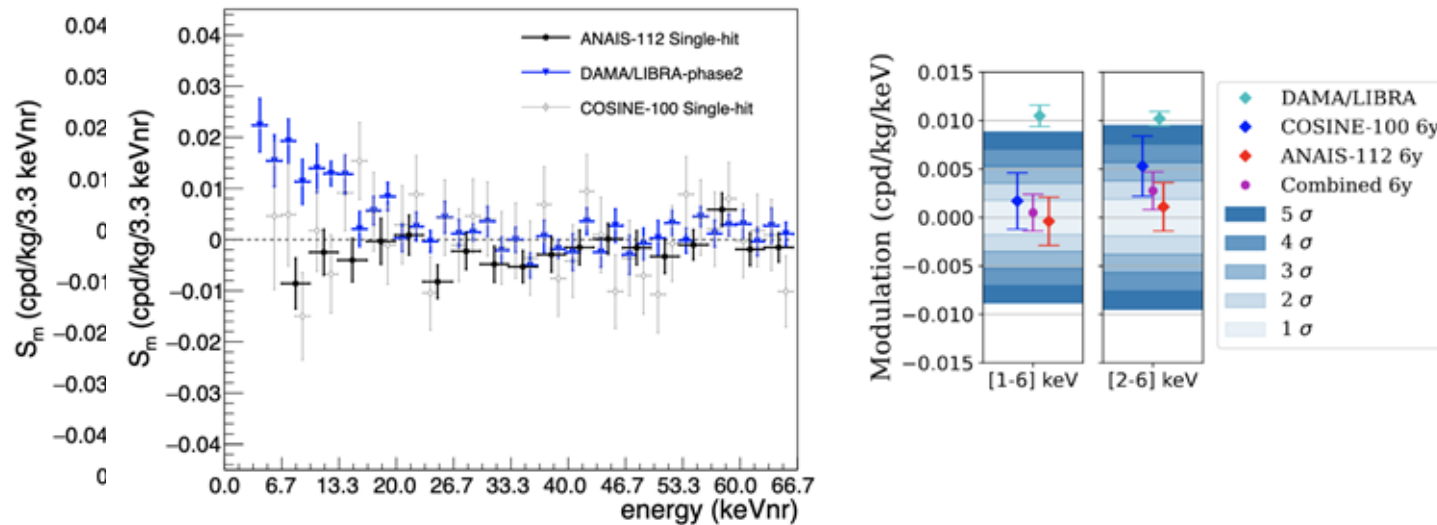
The interpretation in terms of dark matter is not compatible with the non-observation by any other experiment. However, comparison is sensitive to the target, DM model, halo parameters...

A number of experiments are testing DAMA/LIBRA **with the same target**: ANAIS, COSINE, SABRE, COSINUS, DM-ICE...

## The DAMA/LIBRA annual modulation signature has not been confirmed

Because of the seasonal dependence of the Earth's velocity through the DM halo, one can expect an annual modulation in the number of DM events detected in direct detection experiments (with an amplitude of  $\sim 7\%$ ).

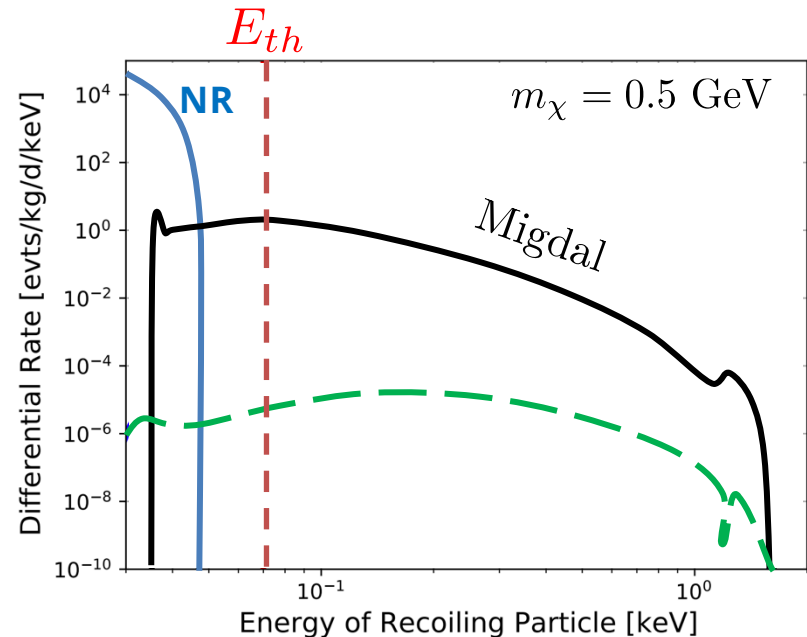
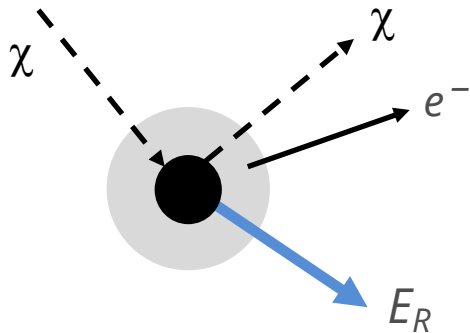
The ANAIS collaboration (NaI target) has done an excellent job in putting the DAMA/LIBRA signal to the test and virtually excluded the DM interpretation of its annual modulation.



## Migdal effect and implications for low mass DM searches

Emission of an electron (ionisation) when a neutral particle impacts a nucleus. Simultaneous signal of **electron and nuclear recoil**.

Migdal 1939; Feinberg 1941



The emitted electron is easier to observe than the nuclear recoil (**NR**), as it is more energetic (and more easily exceeds the threshold energy)

Bernabei et al. 2007; Ibe et al. 2017; Dolan et al. 2017

It is **NOT** new physics

## The Migdal effect is being searched for with various targets

Xenon and liquid argon can be ideal targets to observe the Migdal effect, thanks to their scintillation efficiency.

Bell et al. 2022

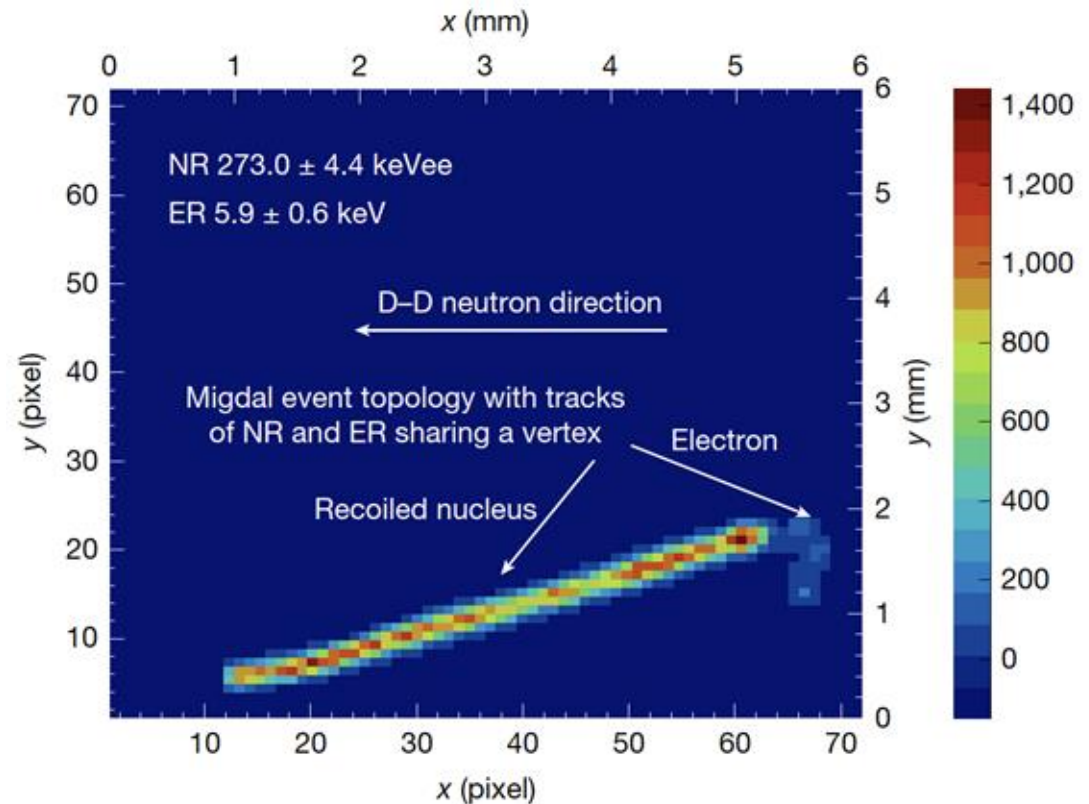
A first search at the Livermore National Laboratory using XeNu TPC did not find it.

Xu et al. 2023

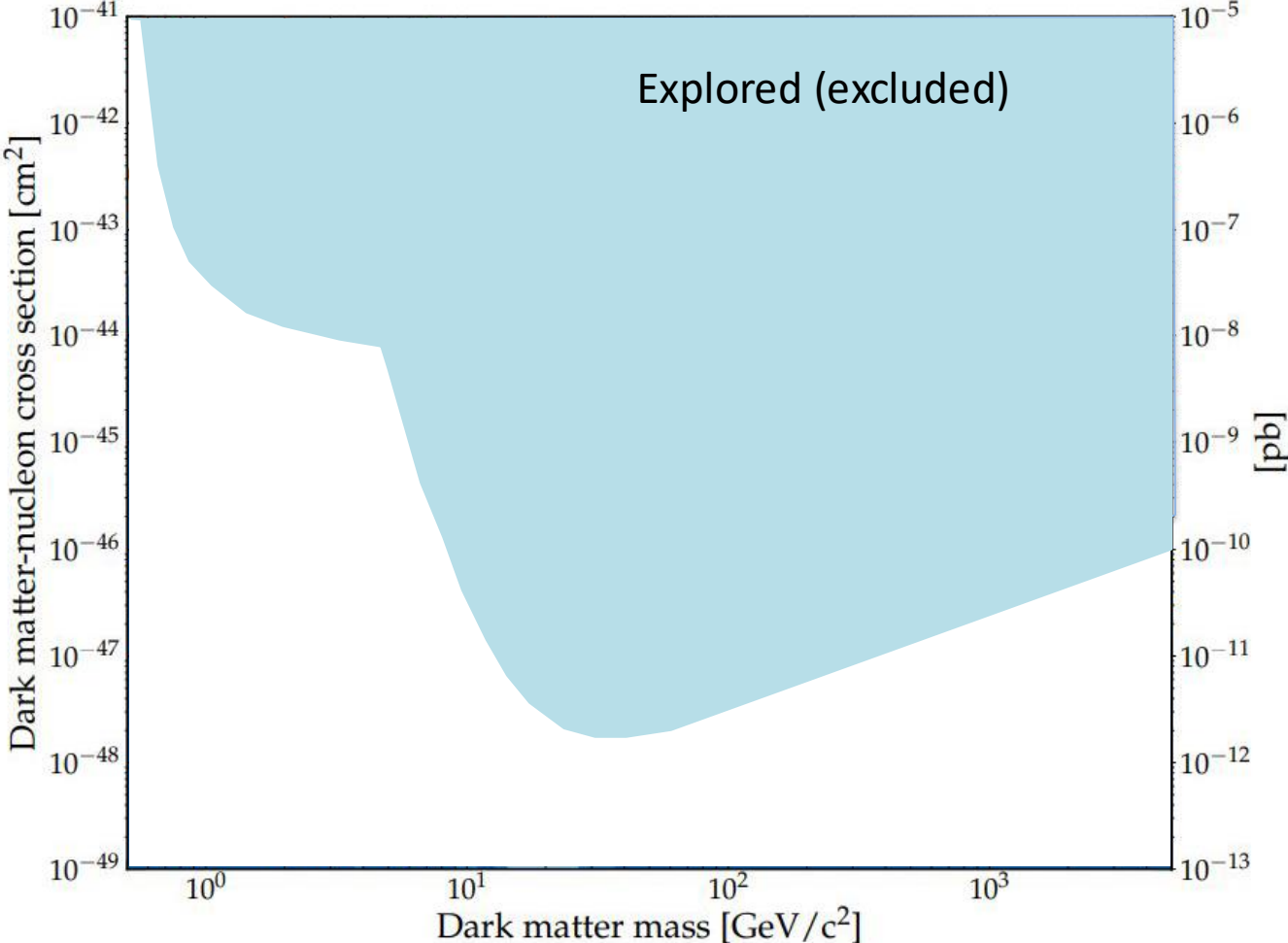
A recent search on dimethyl ether  $\text{CH}_3\text{OCH}_3$  claims first observation!

Yi et al. 2026

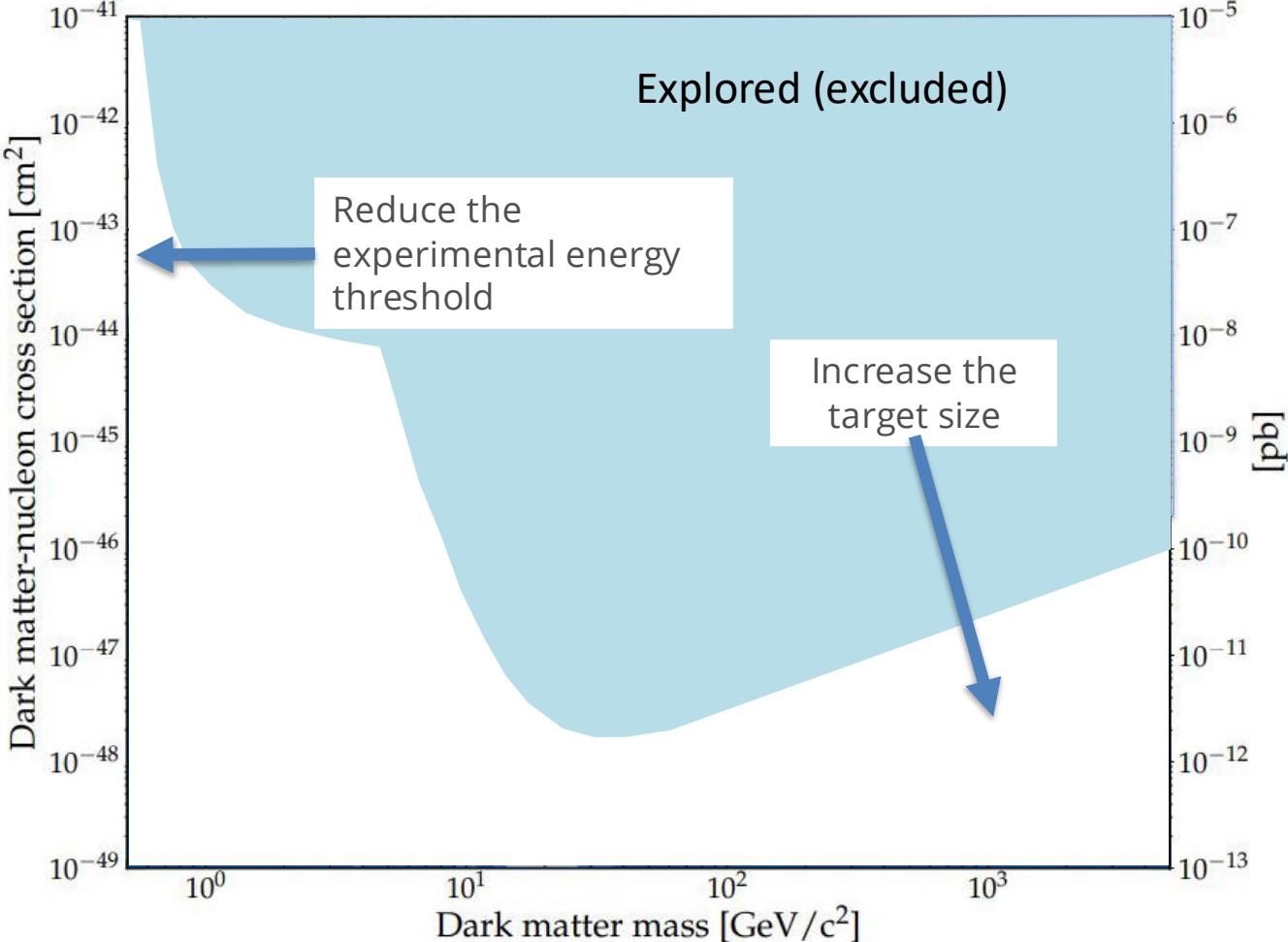
The **MIGDAL** collaboration is trying to measure this effect at the Rutherford Appleton Laboratory.



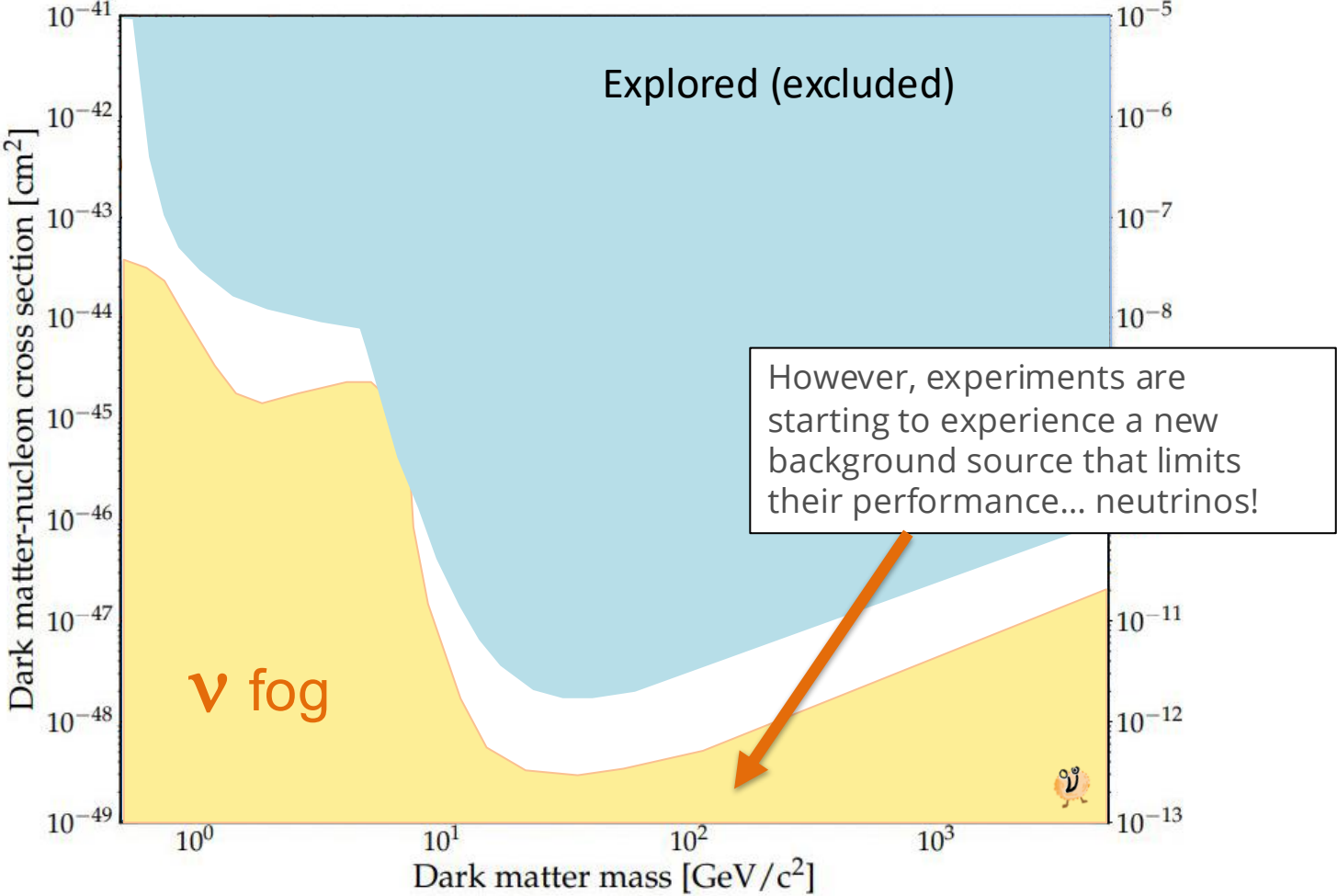
# Future experiments will further explore the DM parameter space



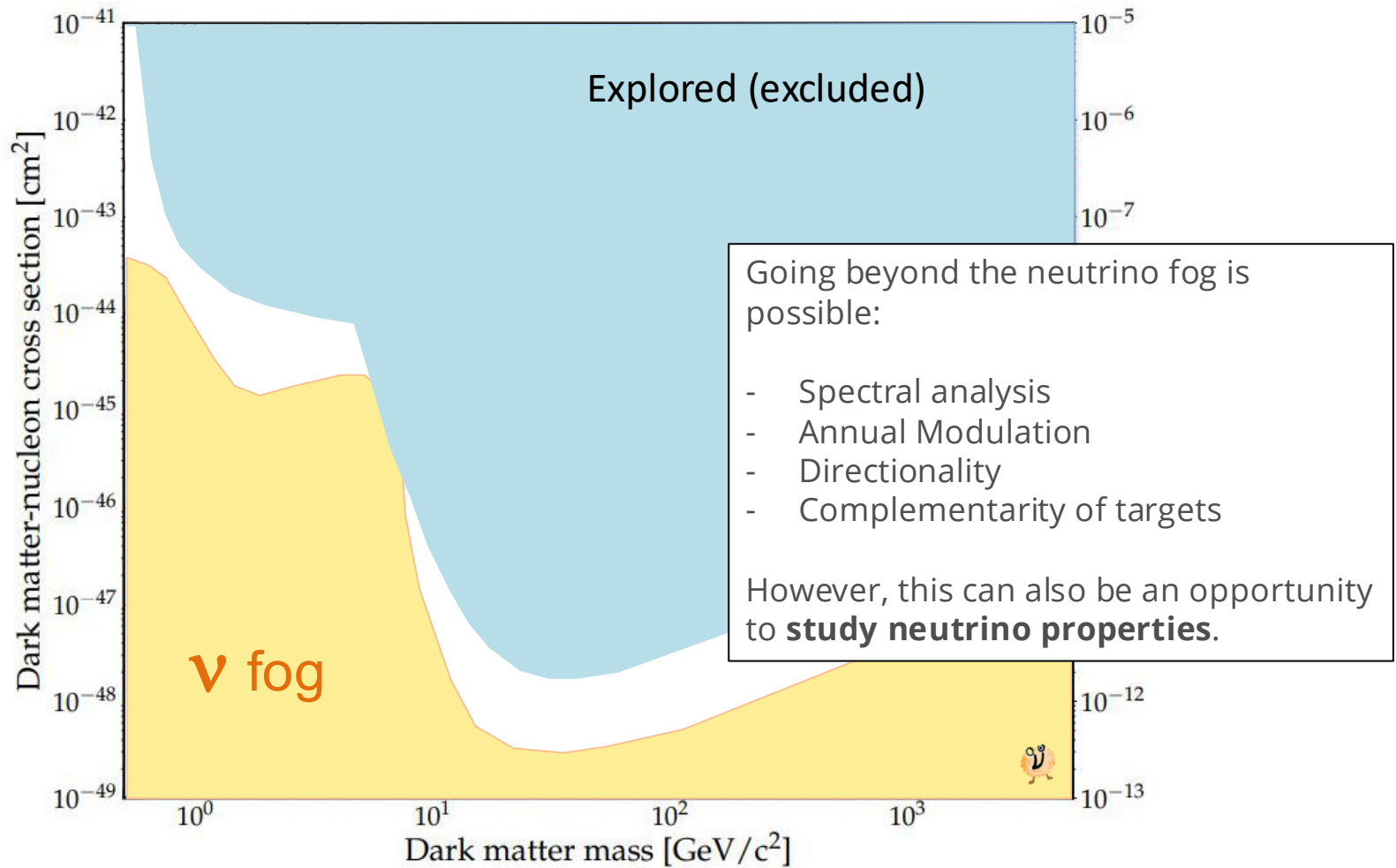
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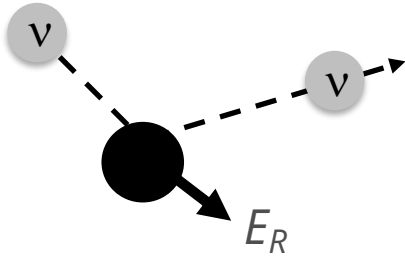
# Future experiments will further explore the DM parameter space



## 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)



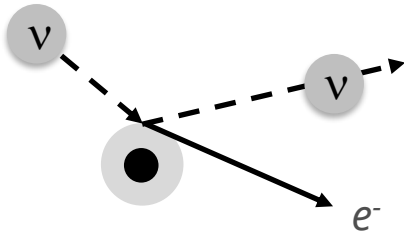
Rare Standard Model process recently measured in spallation source experiments

COHERENT Collab. 2017, 2021

Irreducible background – neutrino fog/floor

O'Hare et al 2017

### (Inelastic) electron scattering

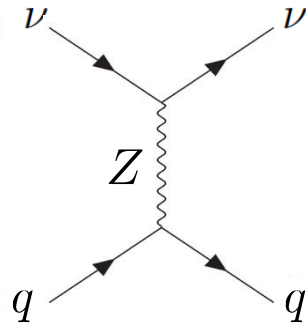


Usual electroweak process mediated by the Z and W bosons

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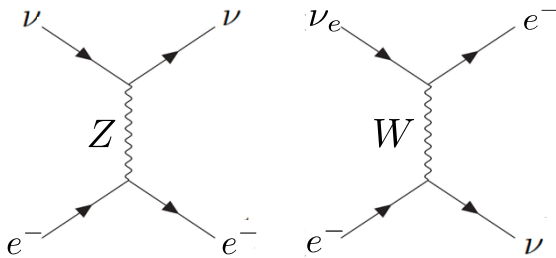
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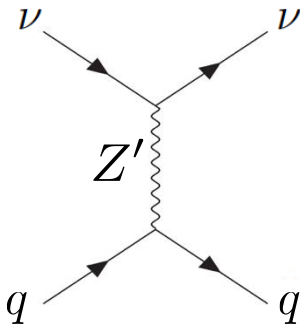


Usual electroweak process mediated by the Z and W bosons

# Expected signal in a direct detection experiment

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

## 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

# Neutrino flux

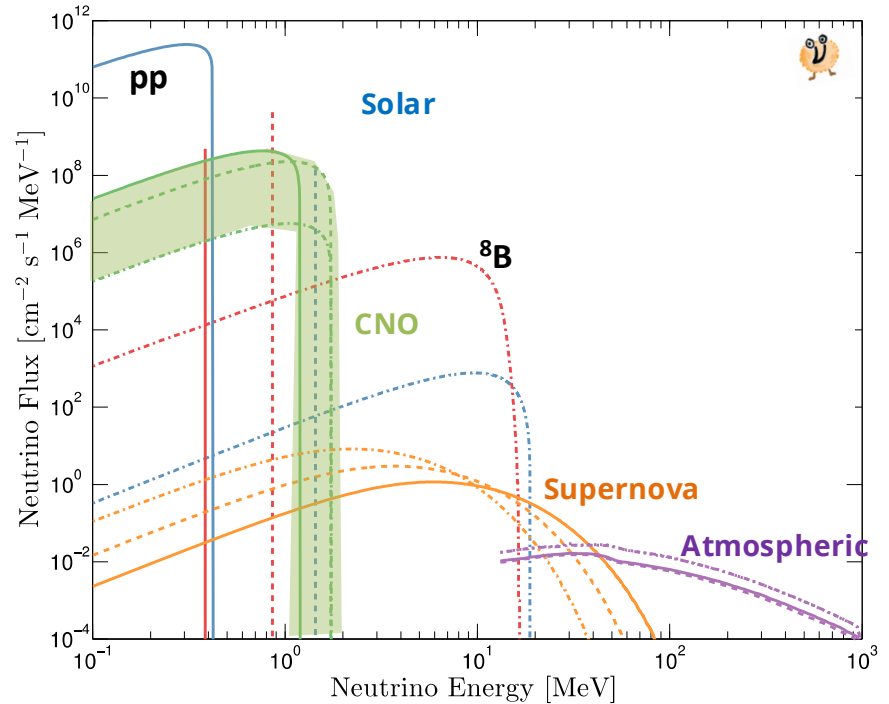
$$N = \varepsilon n_T \int_{E_{\text{th}}}^{E_{\text{max}}} \sum_{\nu_\alpha} \int_{E_\nu^{\text{min}}} \frac{d\phi_{\nu_e}}{dE_\nu} P(\nu_e \rightarrow \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

## 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



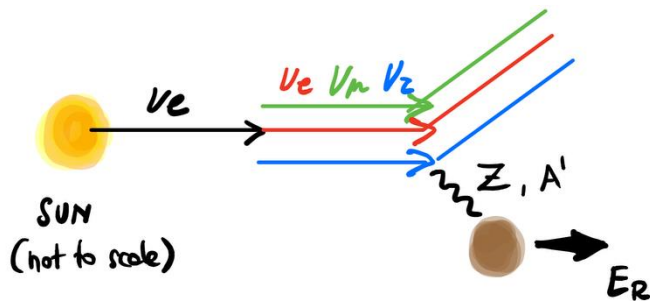
# Neutrino flux

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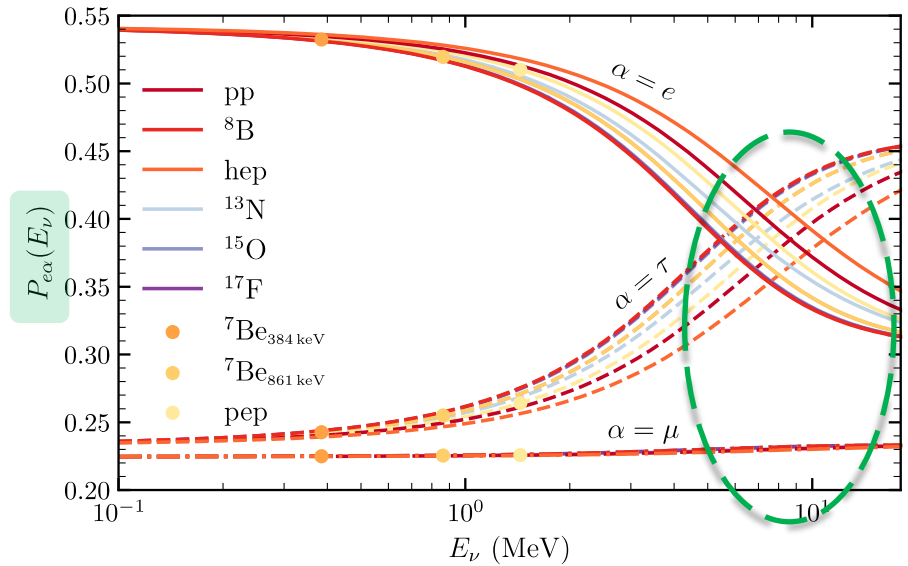
## Solar neutrinos

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

Produced as electron neutrinos, they oscillate into other flavours



Amarel, DGC, Foldenauer, Reid 2020



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

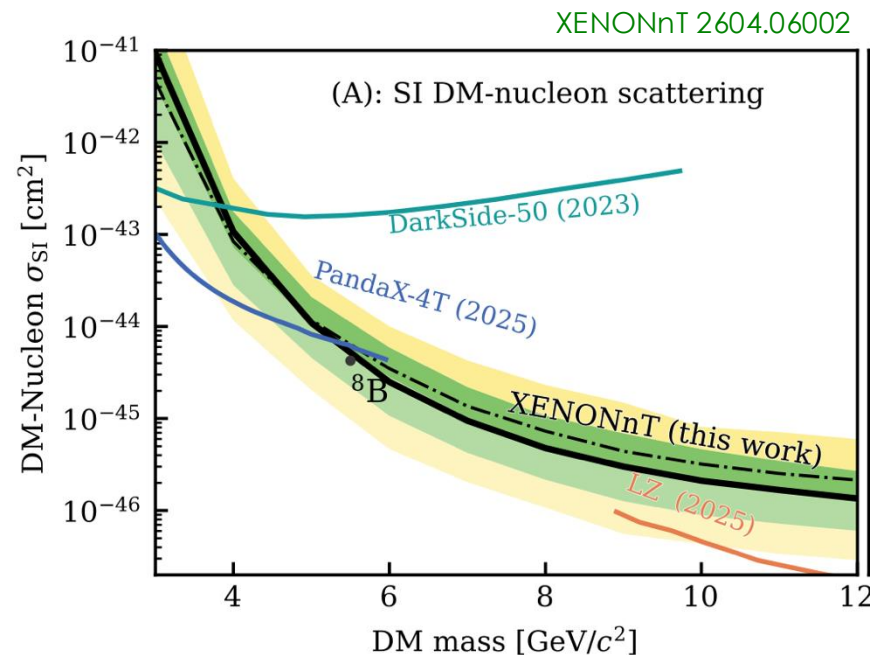
## Direct (DM) detectors can be excellent **complementary test of new neutrino physics**

- 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  $^8\text{B}$  neutrinos.

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

Future direct detectors will complement information from dedicated neutrino experiments

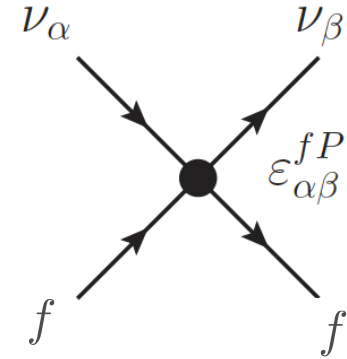


## Effective theories: Non-standard Interactions

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 also sensitive to **electron recoils**.

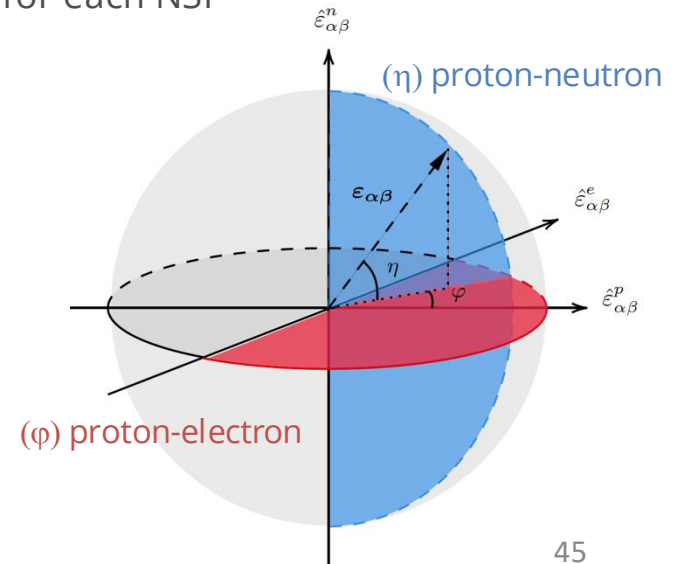
Therefore we must use a three-dimensional parameter space for each NSI

New parametrisation including electron recoils

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

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

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

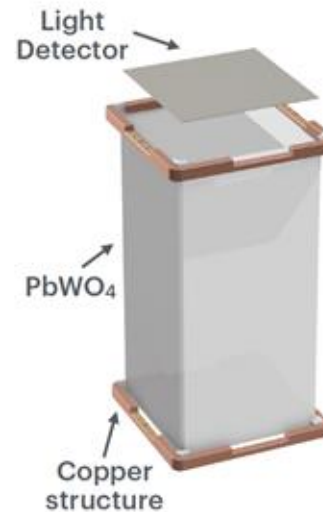
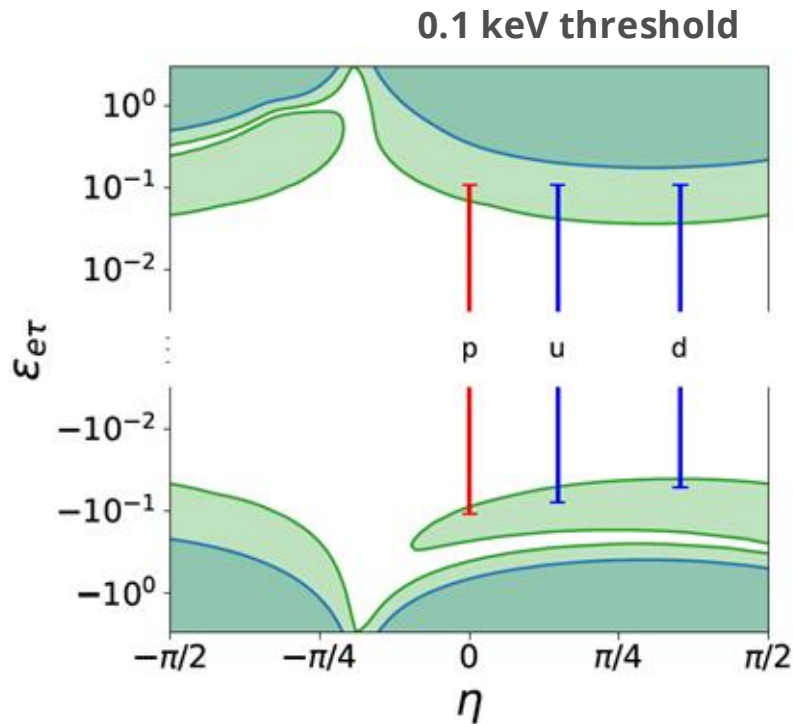




## A prospective study on archaeological lead with **RES-NOVA**

Based on  $\text{PbWO}_4$  crystals, we computed predictions for a nominal configuration of 1 tonne-year.

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



**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**.

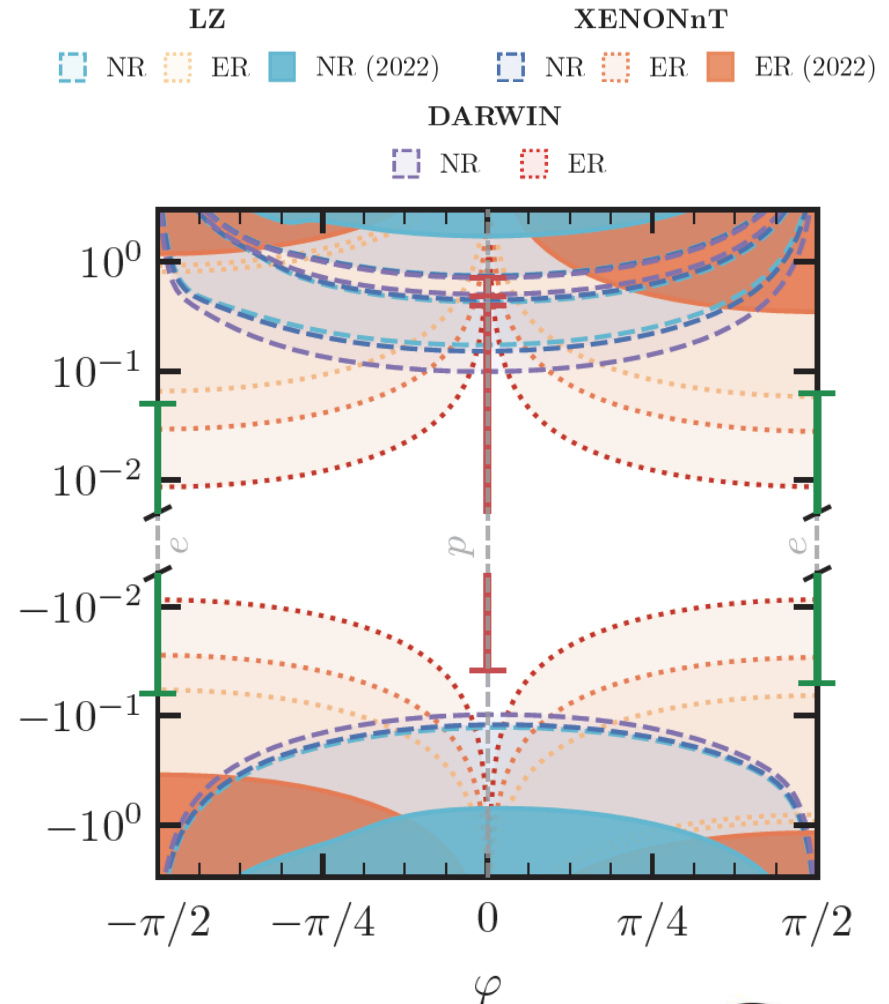
Future **DARWIN-like** experiments can potentially improve by an order of magnitude over current electron NSI bounds

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

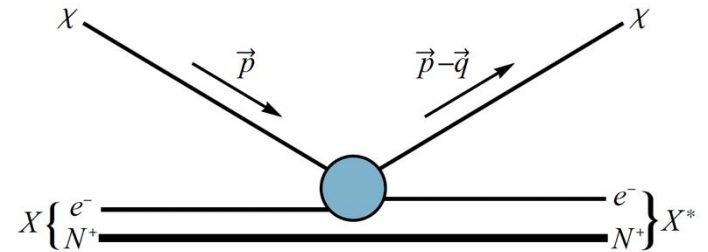


Amaral, Cerdeño, Cheek, Costa, Foldenauer  
<https://github.com/SNuDD/SNuDD>



## 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.

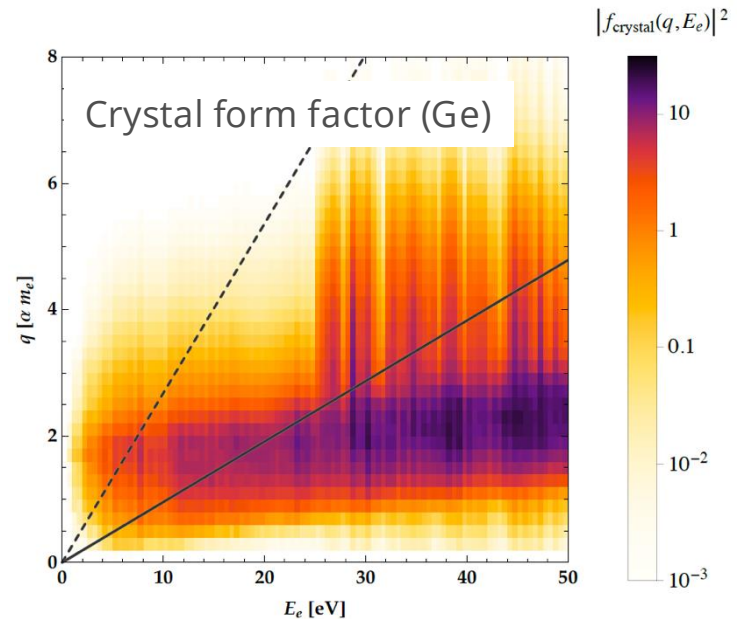


$$\frac{dR^{ER}}{dE_e} = \bar{\sigma}_e \frac{\rho_\chi}{m_\chi} \frac{1}{8\mu_{e\chi}} \int q dq |F_\chi(q)|^2 |f^{ion}(e, E_e)|^2 \eta(v_{min})$$

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

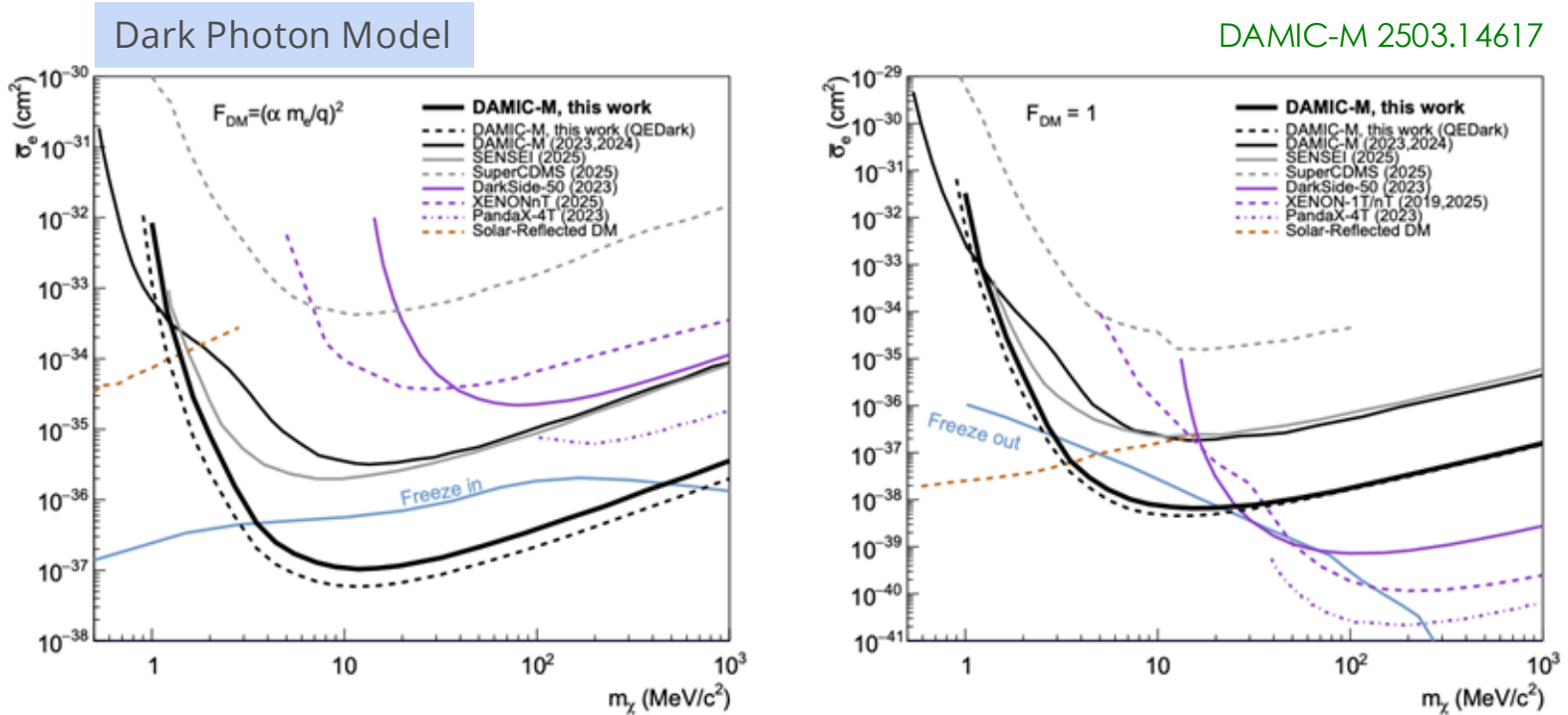
$\sim 1/q$  for low-mass mediators

$\sim 1$  for heavy mediators



## 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**



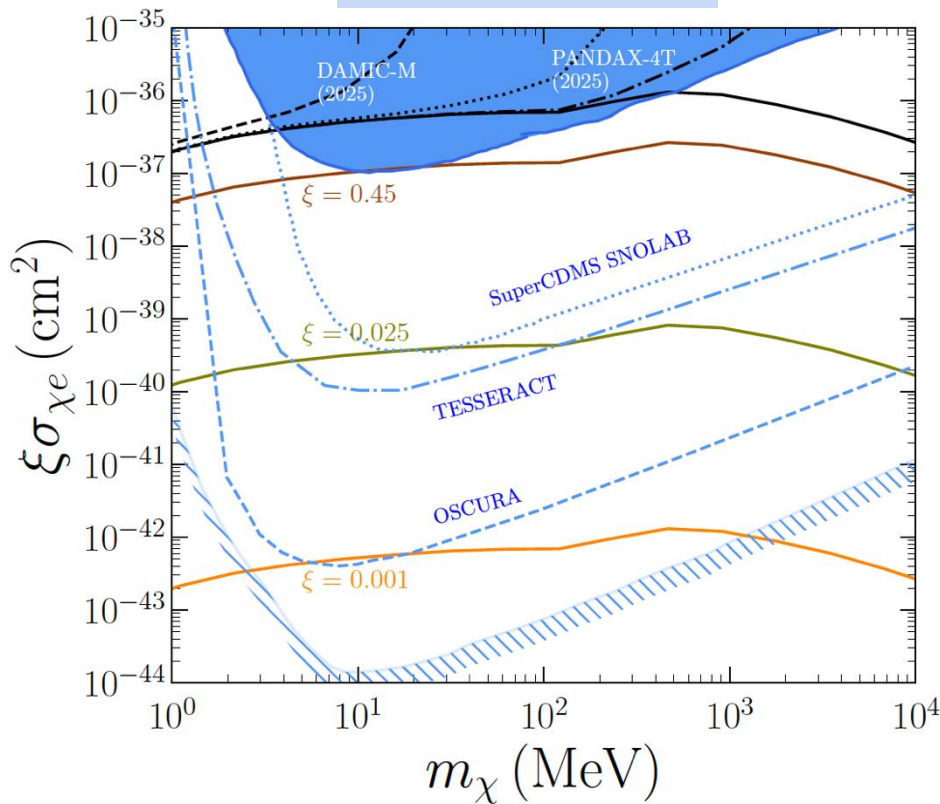
These searches are starting to probe other ways of producing DM in the early Universe, namely **freeze-in** models.

See also Hambye et al. 2011, 2018

## 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

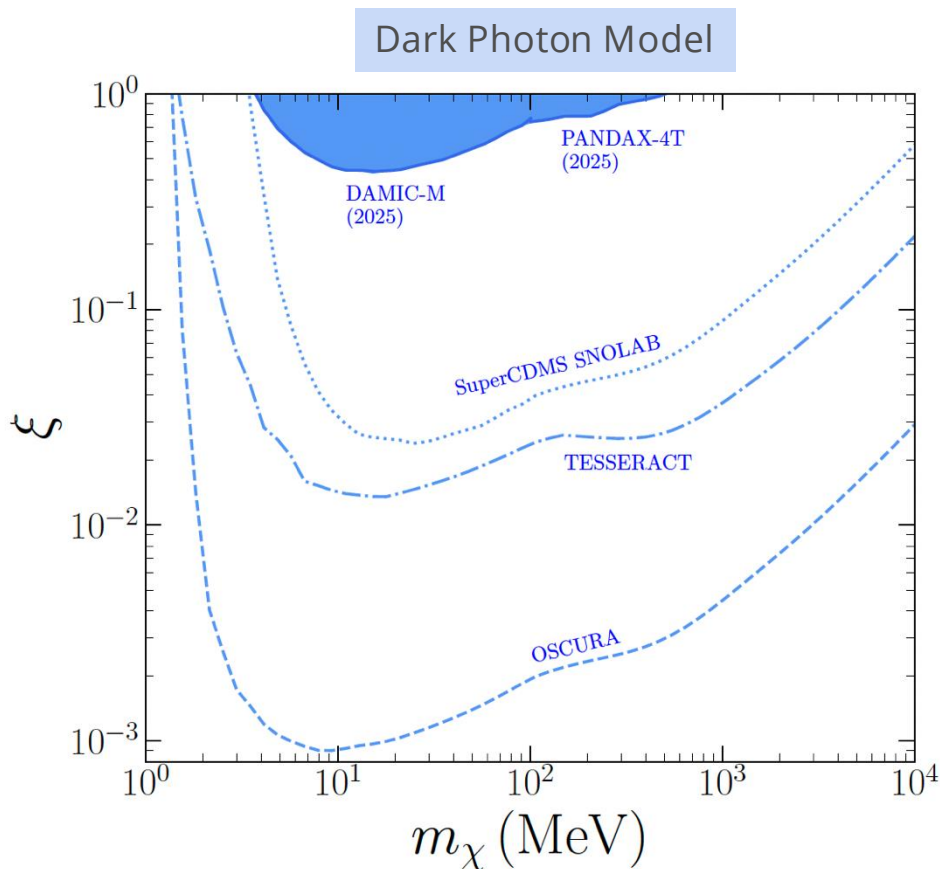
$$\xi = \Omega h_\chi^2 / \Omega h_{\text{DM}}^2$$

- 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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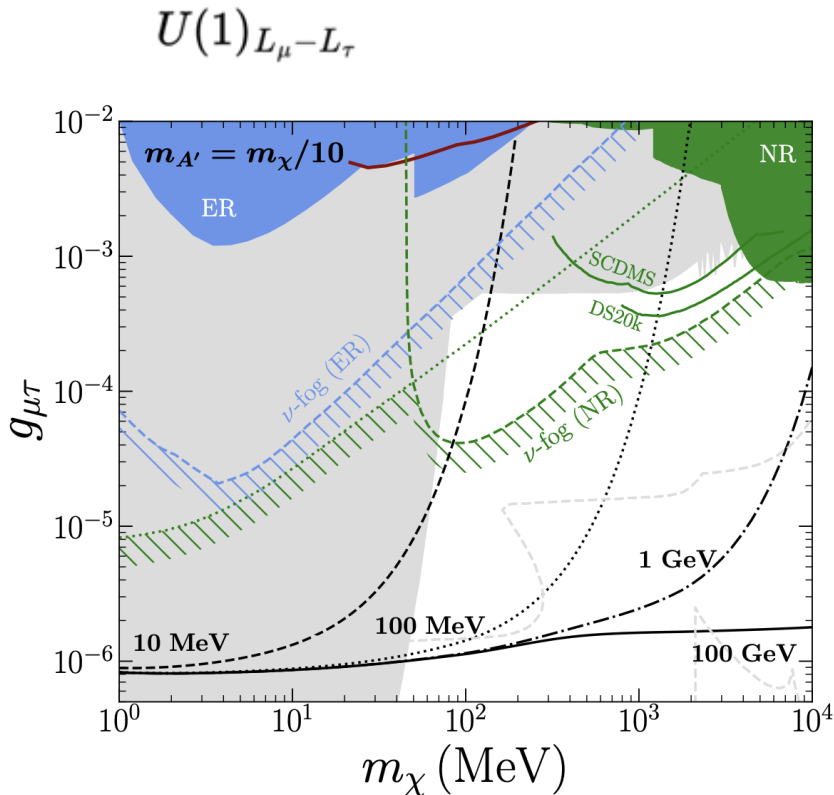


Direct detection experiments can probe MeV freeze-in dark matter **even if its abundance is 1000 times smaller** than the total DM relic density.

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 both ER and NR signals are possible at low energies.



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

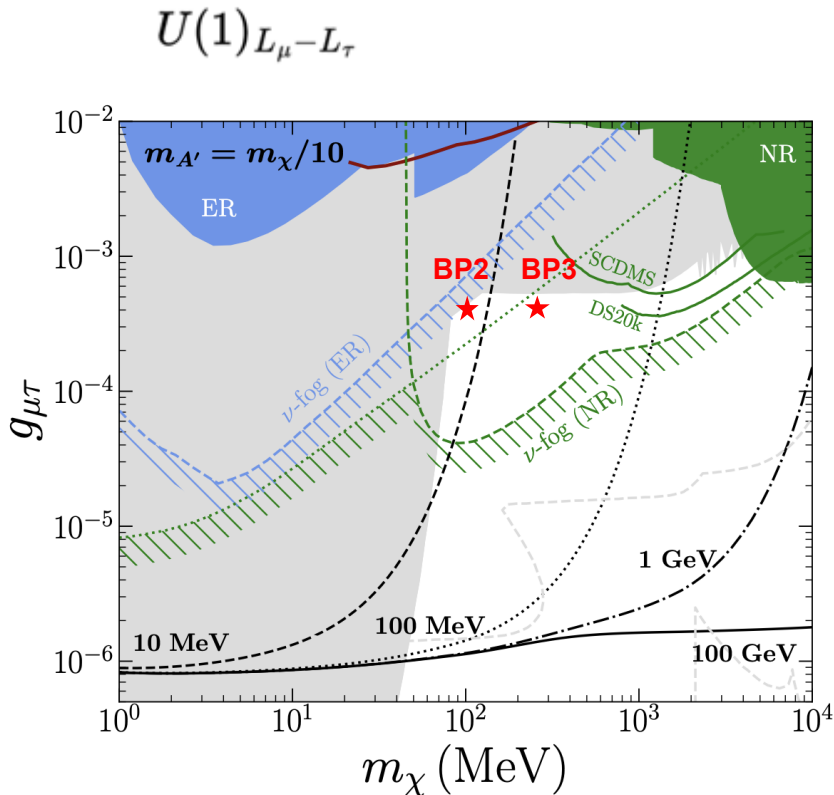
Signal mainly on NR in an interesting region for **DarkSide 20k, XENONnT S2 or solid-state detectors.**

Potential to observe **new neutrino physics!!**  
 DC, Foldenauer, López Noé, Zapata 2026

New opportunities for **directional detection** to help separate both signals

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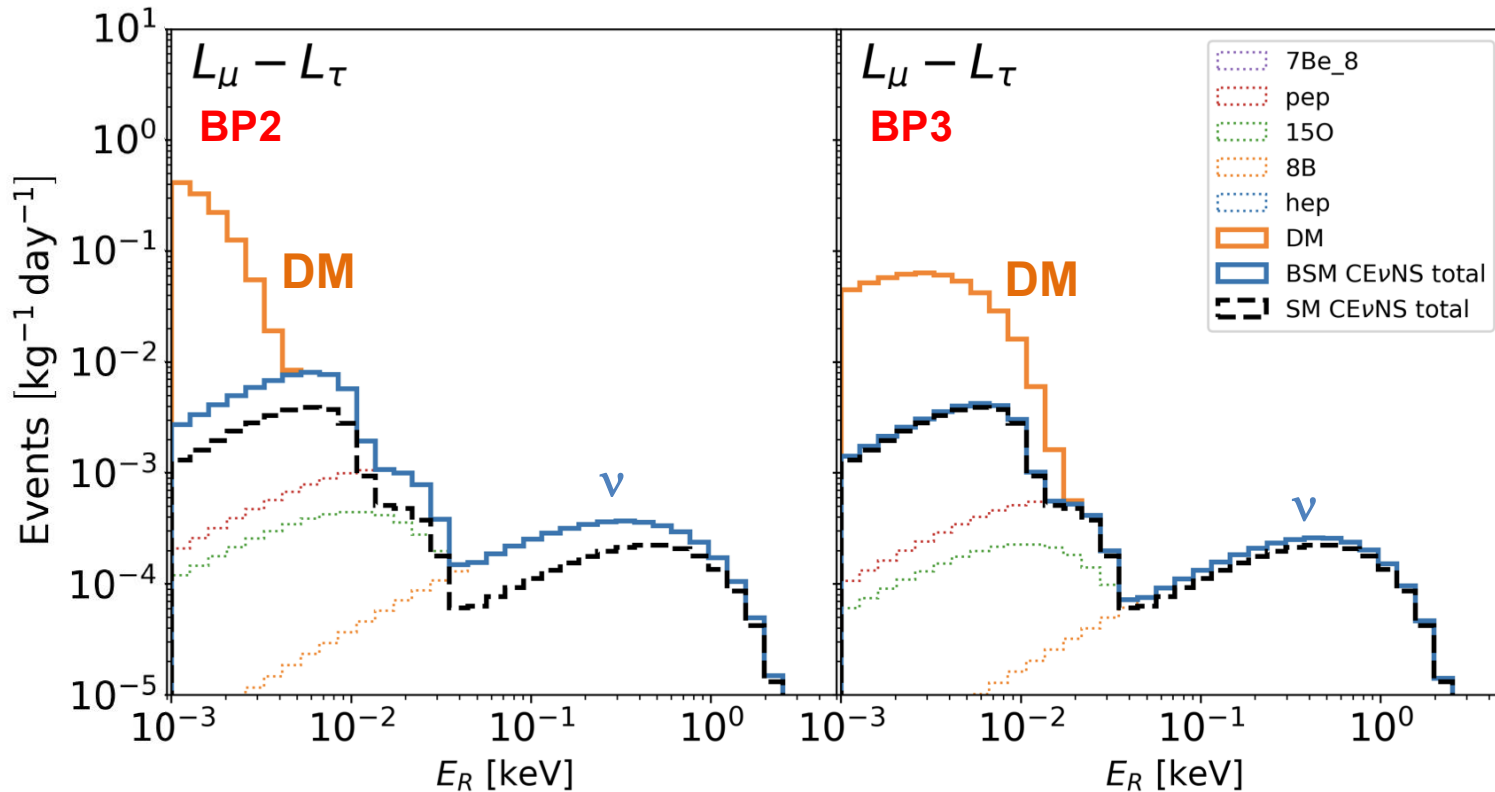
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DC, Foldenauer, López Noé, Zapata 2026

New opportunities for **directional detection** to help separate both signals

## 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  $\sim 1$  GeV
- DM electron interactions accessible with several technologies, probe less standard cosmologies and candidates (freeze-in, axions, dark photons)

Open questions about the DM distribution and Migdal effect are relevant to properly reconstruct the DM mass.

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

## Direct dark matter detection often requires large underground experiments

Expected number of events

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

### Dark matter halo parameters

Local density and DM velocity distribution function

Uncertainties in the halo parameters

Directionality and time-dependence

### 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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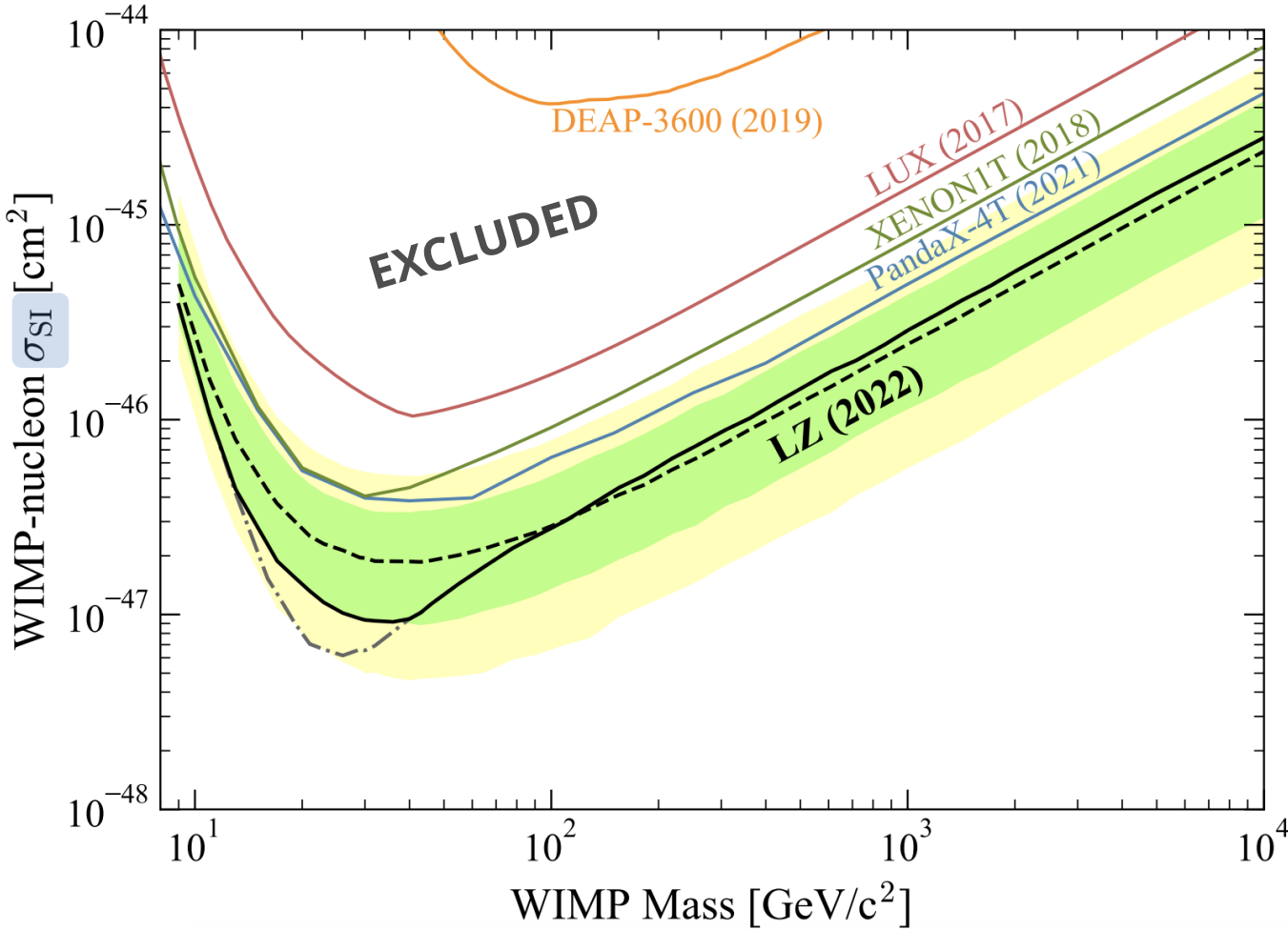
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### Experimental parameters

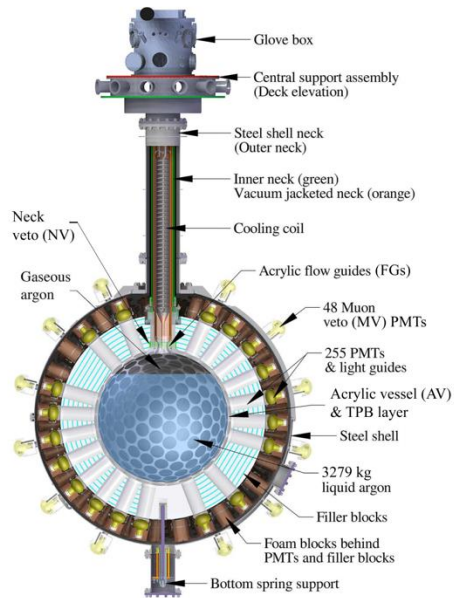
Size, energy resolution, energy threshold

Backgrounds and signal identification

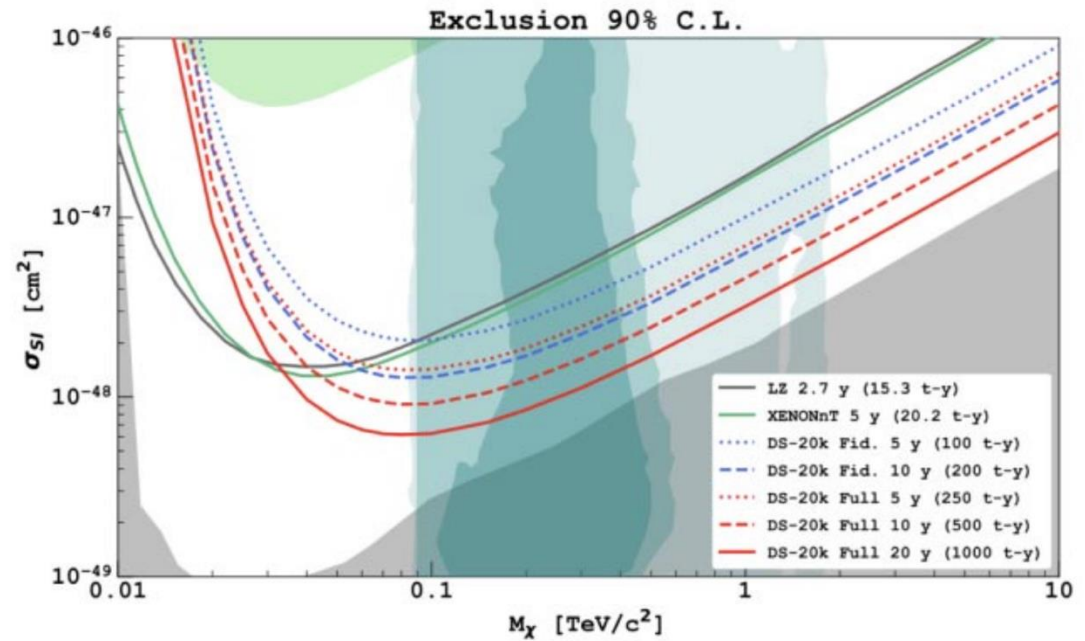
Unsuccessful searches have led to upper bounds on the scattering cross-section



# DEAP 3600



## DarkSide 20k prospects



## Proyección de sensibilidad de SuperCDMS (Retrocesos Nucleares)

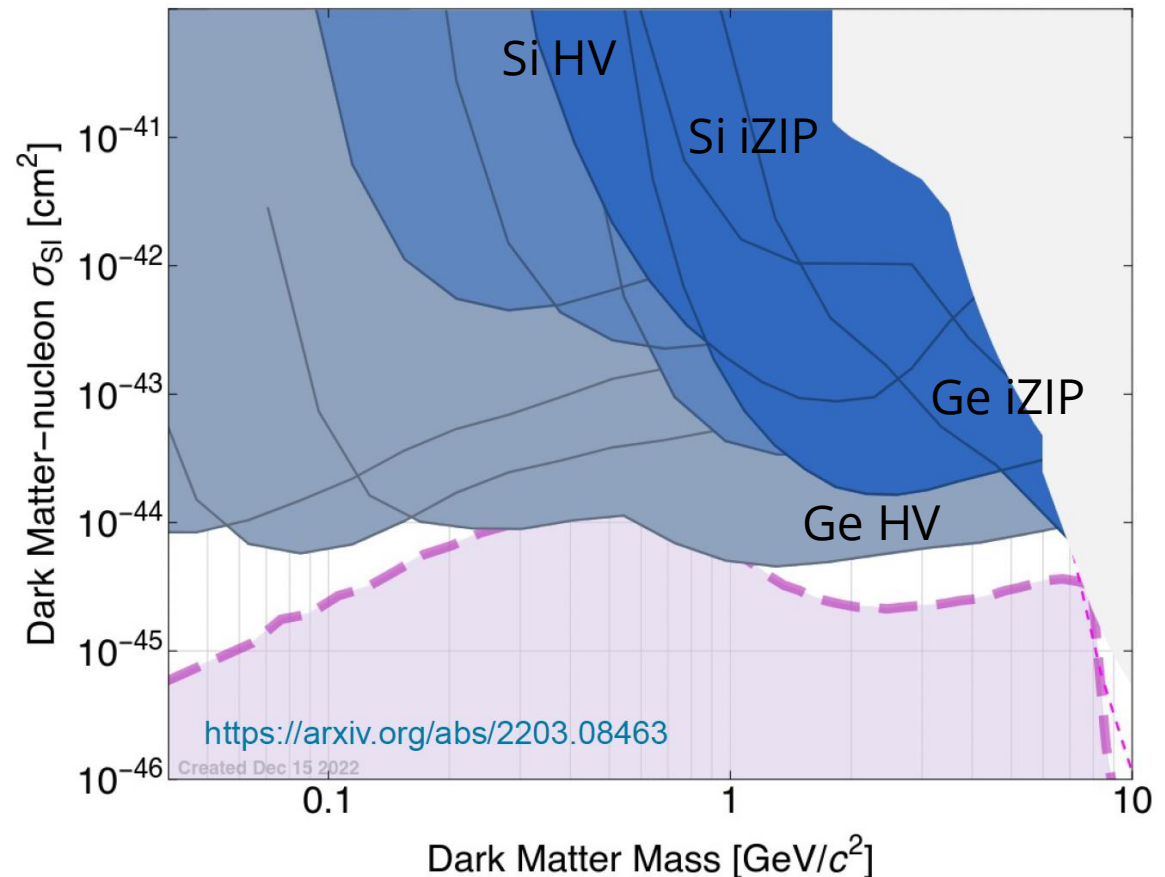
SuperCDMS va a explorar nuevas regiones de MO ligera, siendo uno de los detectores con mejor sensibilidad por debajo de 1 GeV.

Los blancos Ge y Si exploran áreas complementarias (entre sí y con otros detectores)

Mejora de sensibilidad en Teorías Efectivas

El criostato está preparado para incluir más torres de detectores en una fase posterior, y se esperan mejoras en el ruido de fondo.

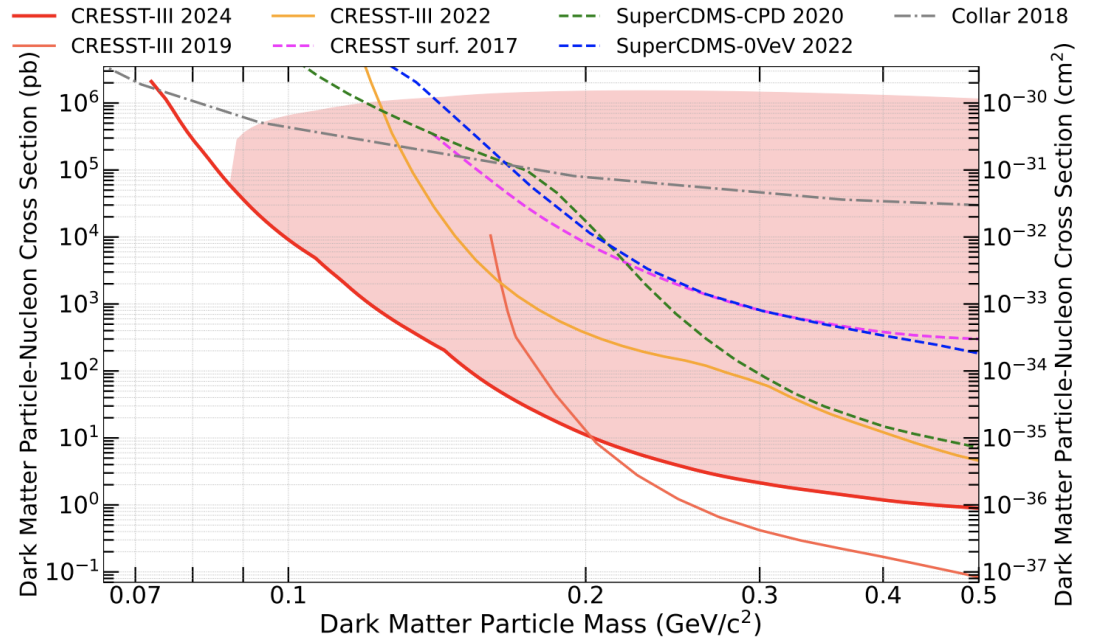
Se acerca al "suelo de neutrinos" y permitirá explorar nueva física en este sector



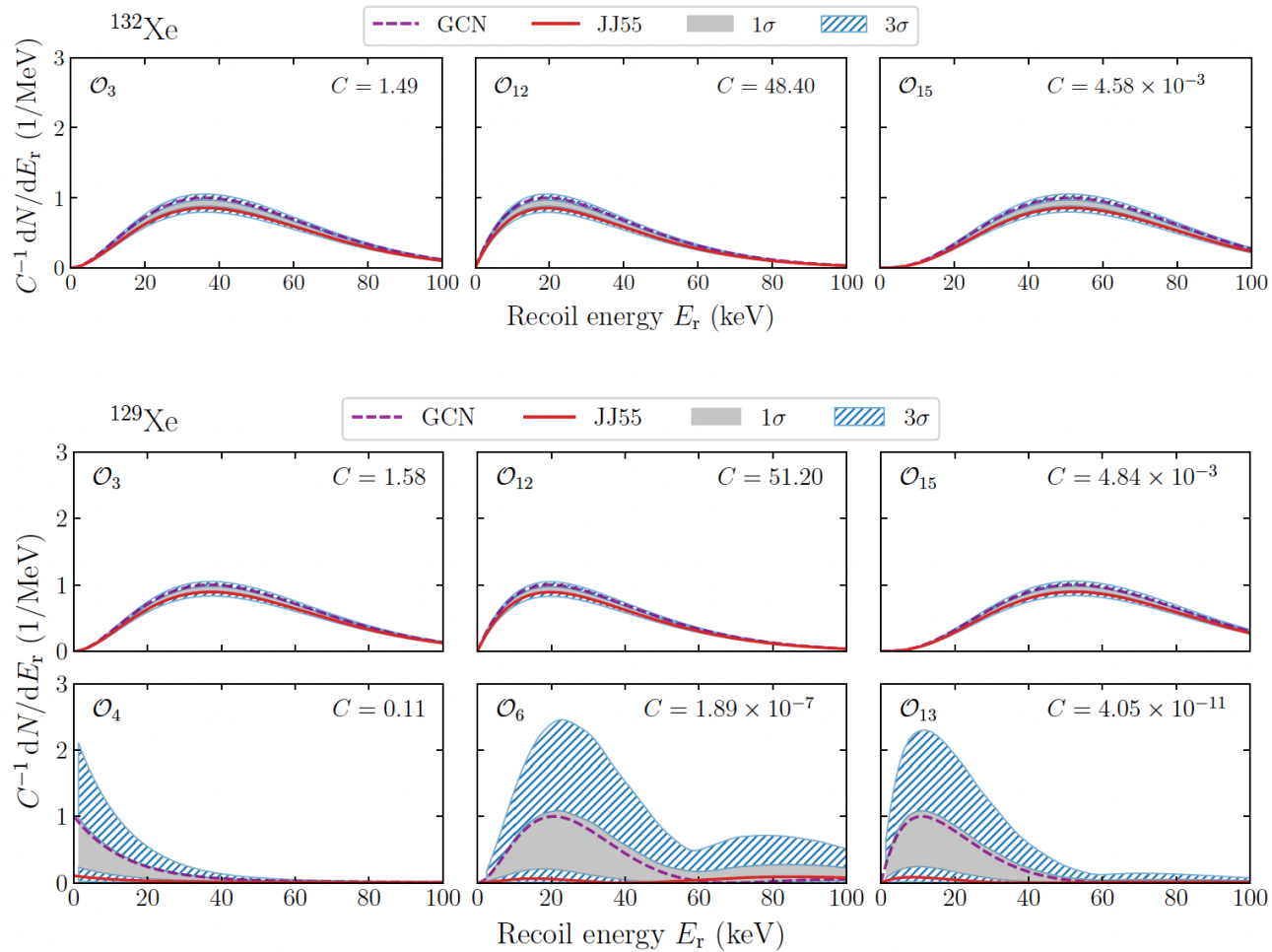
# CRESST

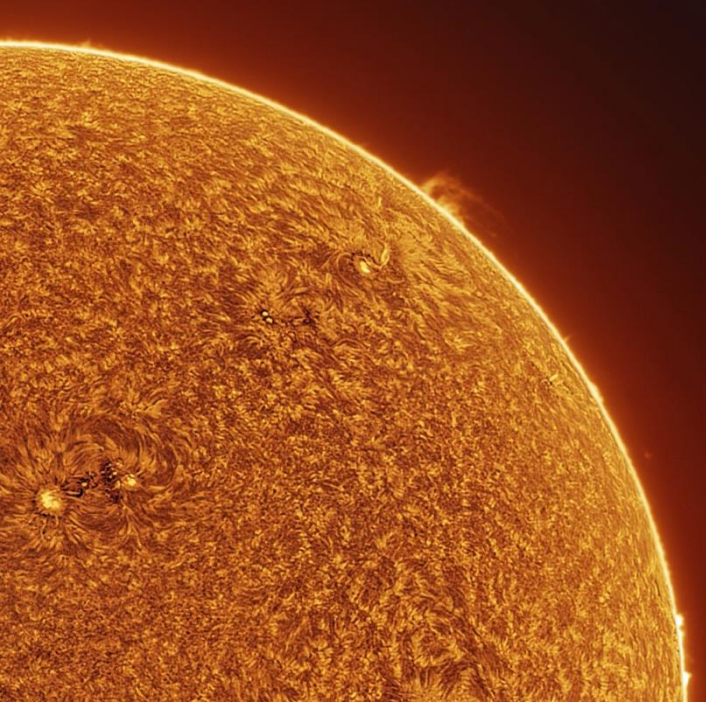
These techniques allow us to probe MeV scale DM.

Upper bound on the excluded region due to DM particles scattering on the rock overburden (not making it to the detector)



## Uncertainties on nuclear form factors





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# Direct Dark matter detection: leaving no stone unturned

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DAVID CERDEÑO

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

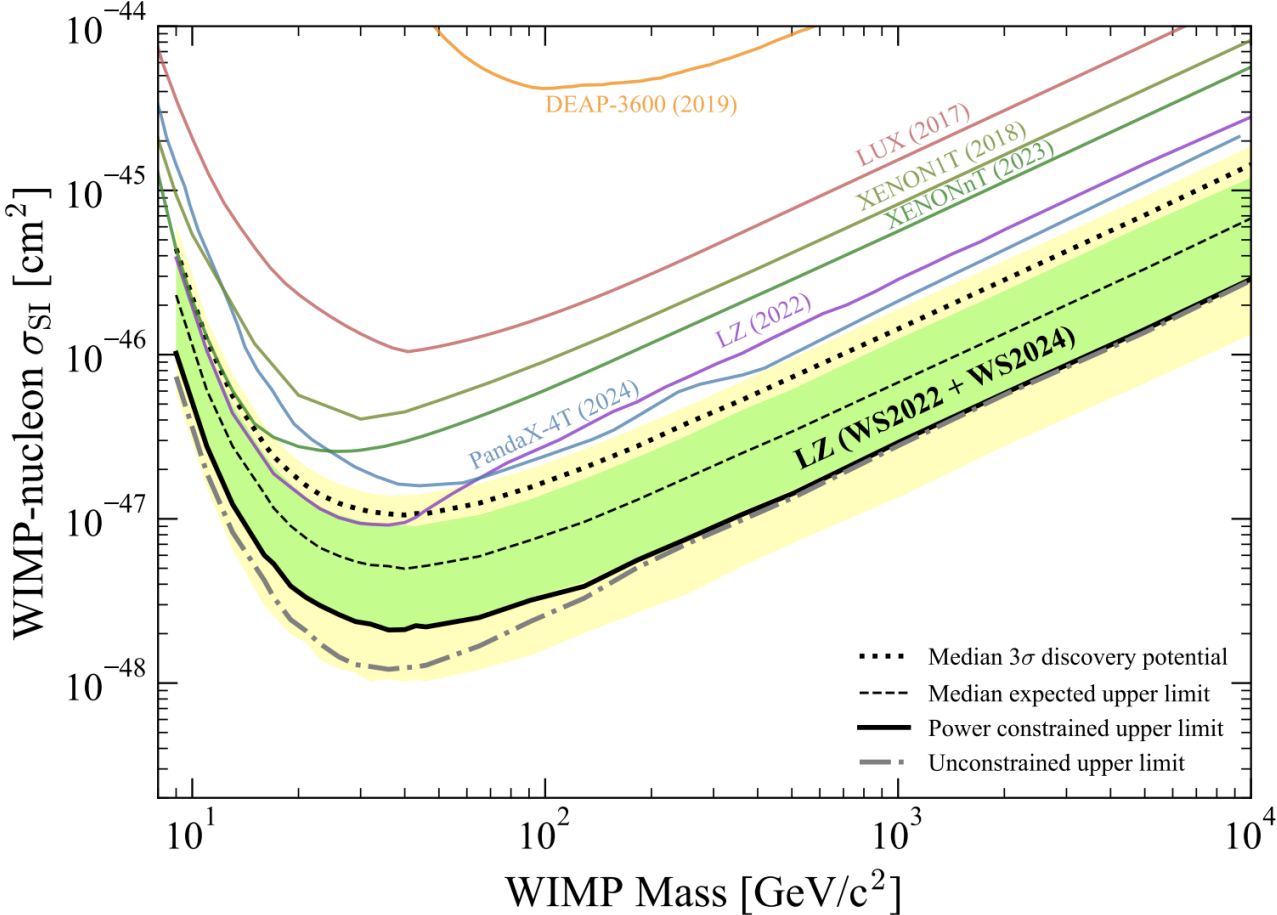


Instituto de  
Física  
Teórica  
UAM-CSIC



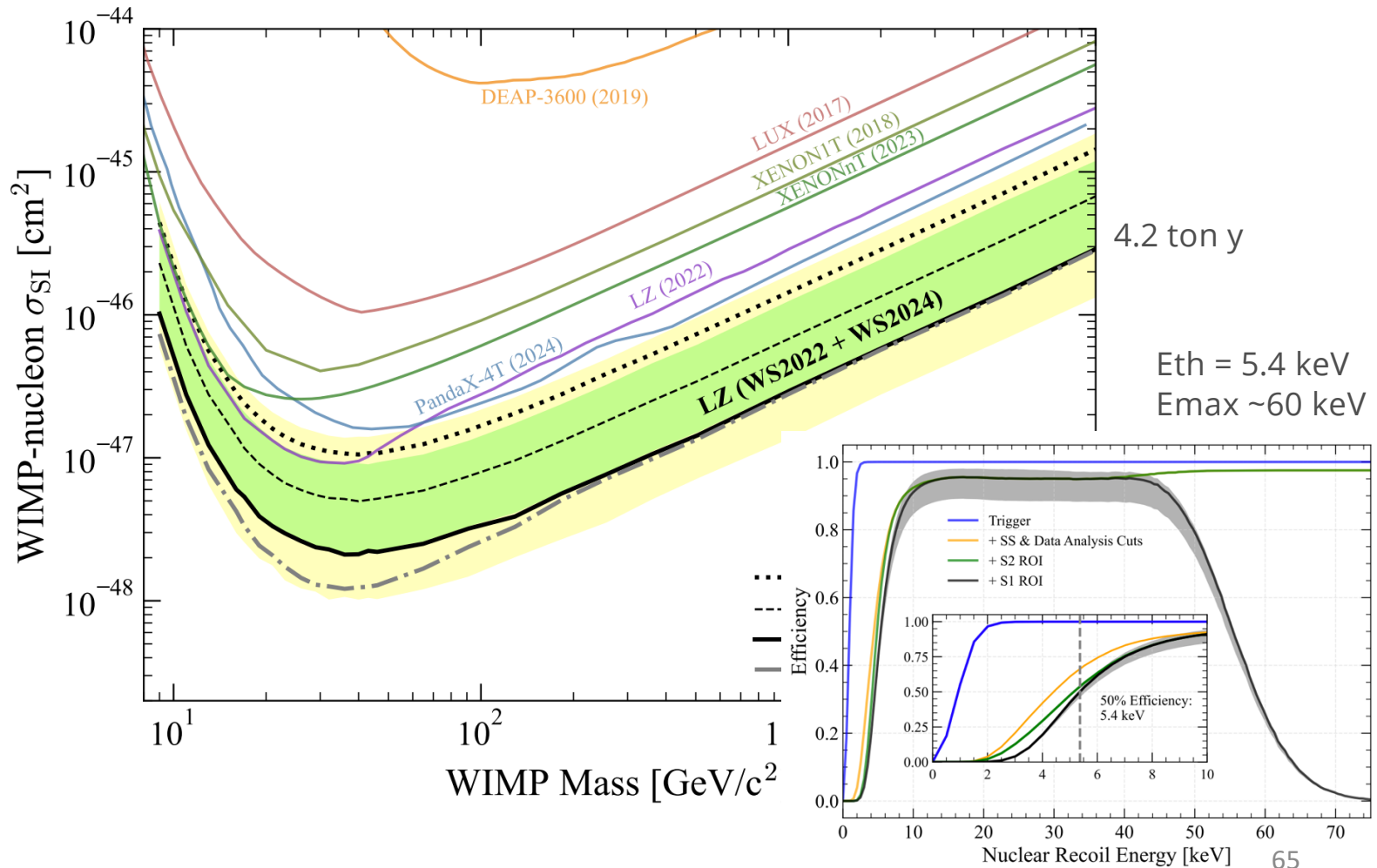
# Liquid noble gas detectors are leading the search at masses above 10 GeV

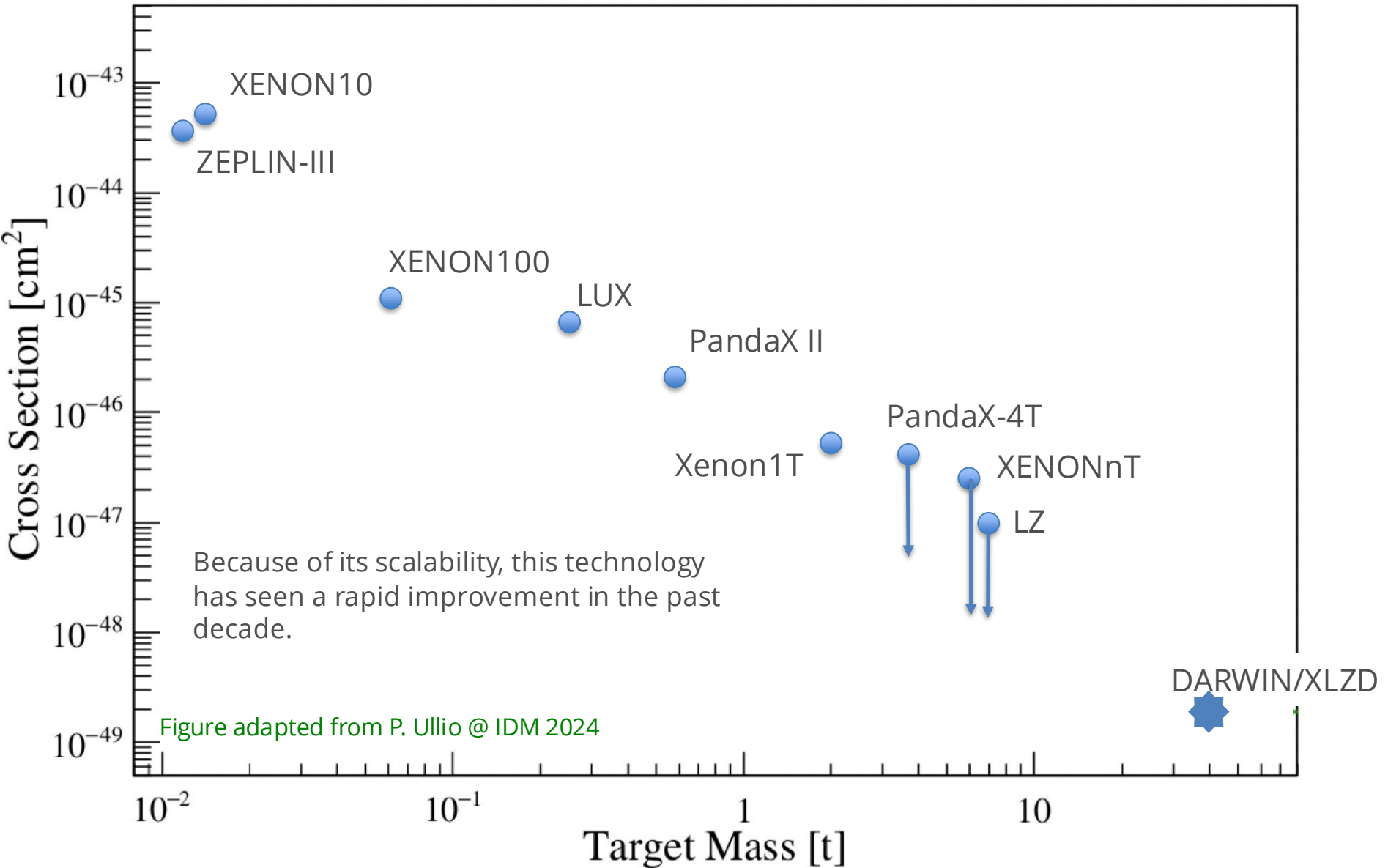
Currently xenon experiments (**LZ**, **XENONnT** and **PandaX-4T**) have provided the best upper bounds on the spin-independent cross section.

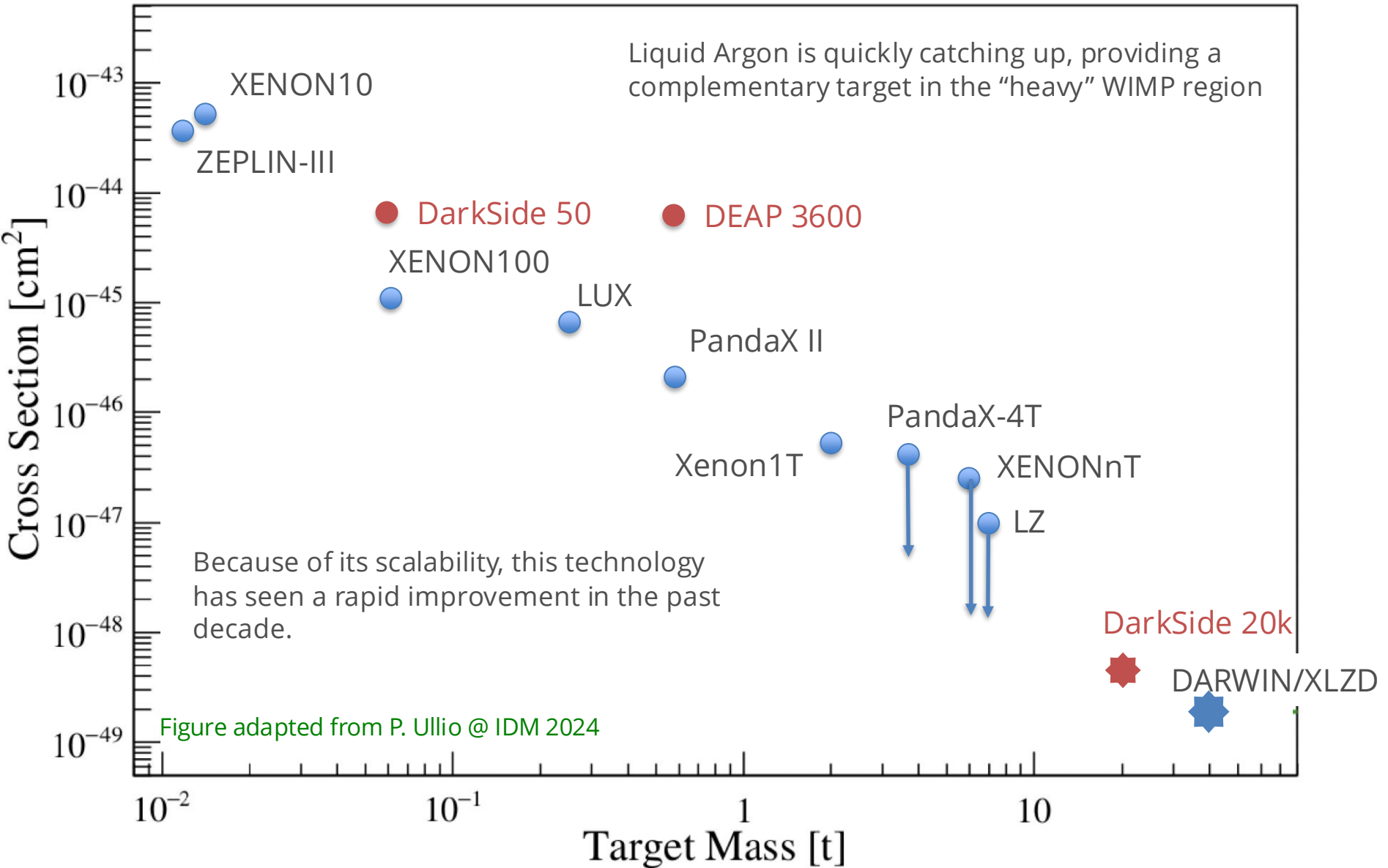


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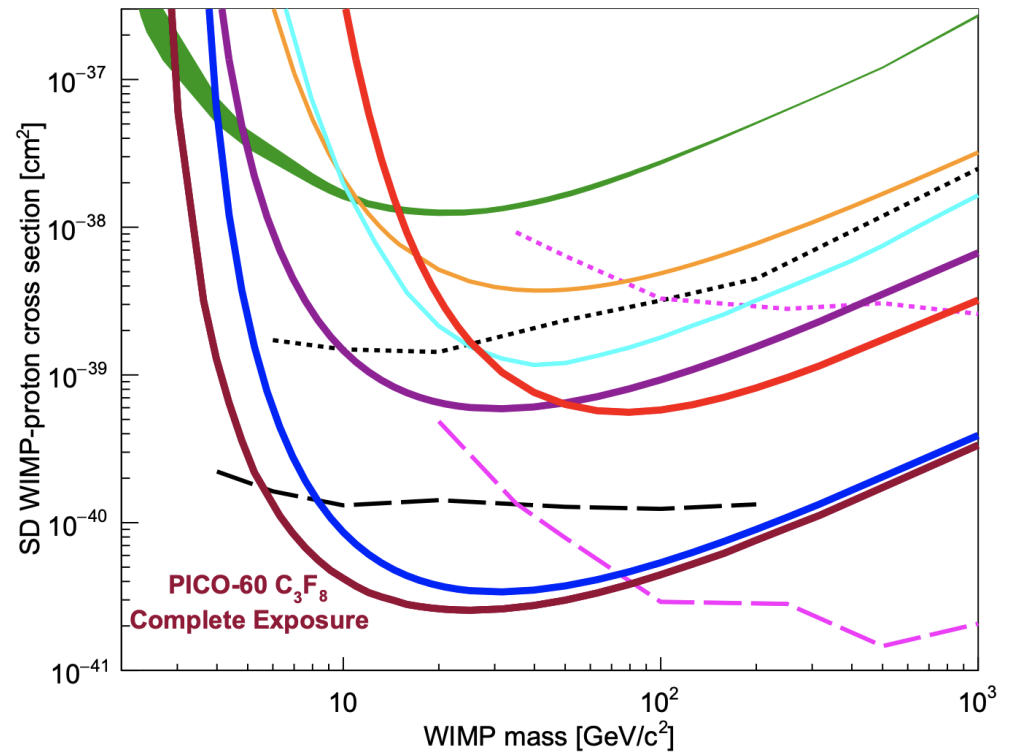
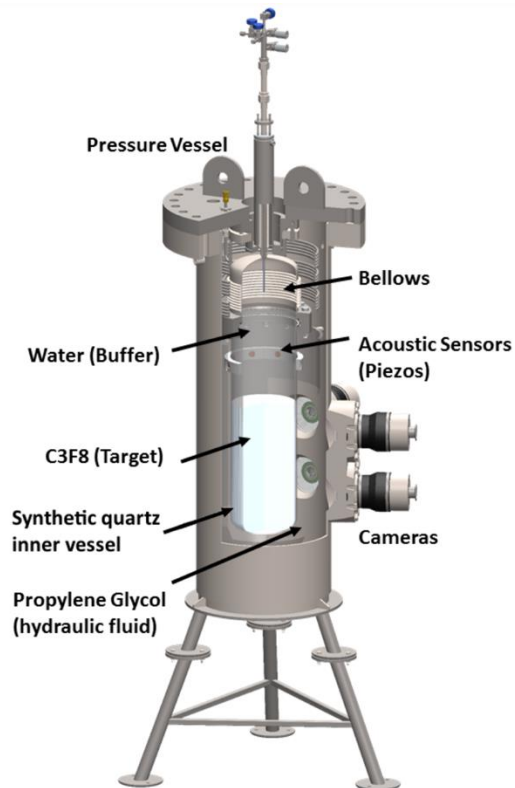






## Limits on Spin-dependent cross section

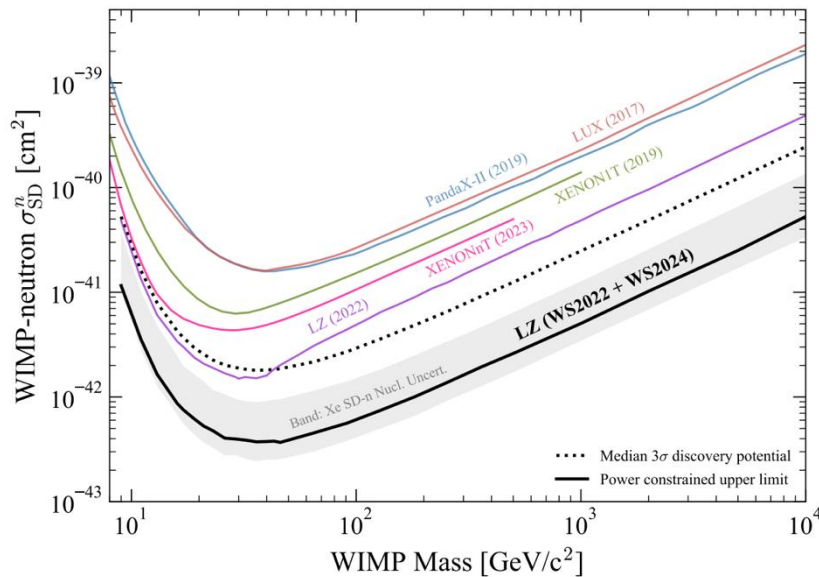
The best limits for the SD coupling to protons direct detection came from the **PICO-60** experiment, employing 52 kg of  $C_3F_8$  (1404 kg day exposure).



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However, these may be superseded by **LZ**!



Two isotopes have non-zero nuclear spin:  $^{129}\text{Xe}$  (4% isotopic abundance) and  $^{131}\text{Xe}$  (21.2%).

These have an unpaired **neutron**, leading to strong SDn limits.

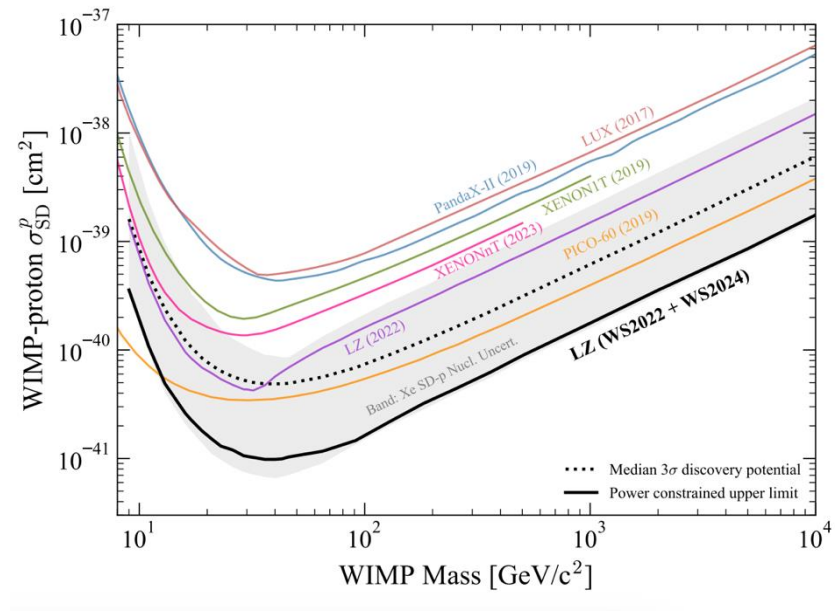
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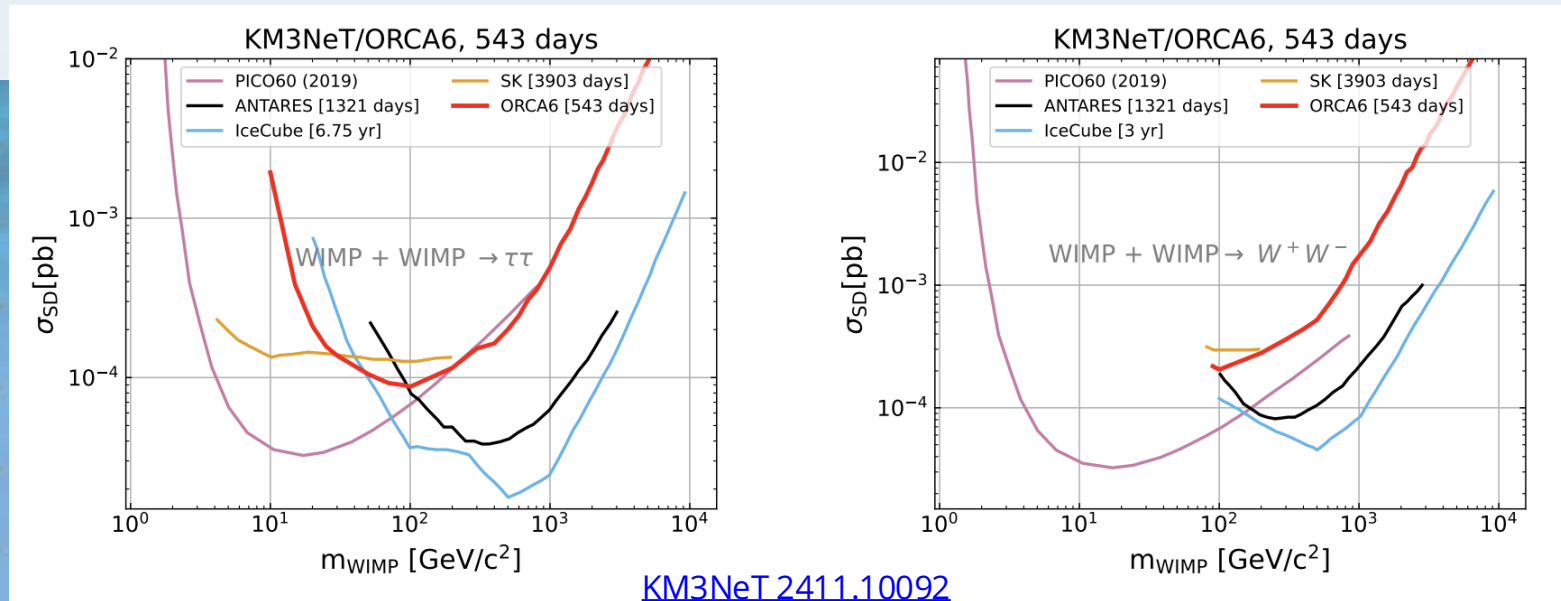
Sensitivity to **SD proton** interaction is possible through mixing between proton and neutron spin states (but with large uncertainty)

Hoferichter, Menéndez, Schwenk 2020  
Pirinen, Kotila, Suhonen 2019



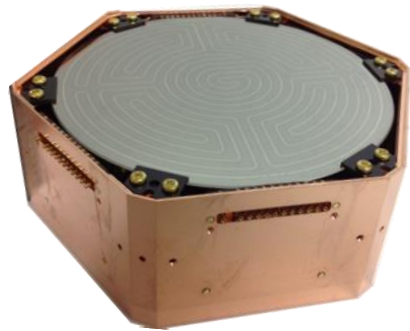
## Limits on Spin-dependent cross section

Indirect detection limits from dark matter annihilation in the Sun by **IceCube**, **Antares**, and more recently **KM3NeT/ORCA6** lead the SDp bounds at larger masses.



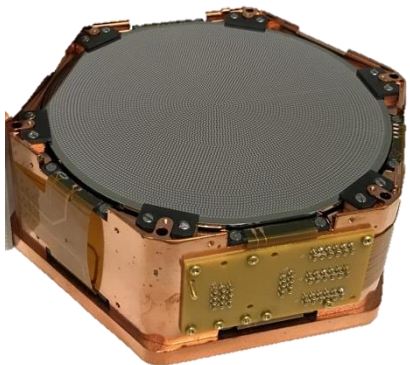
## Low-threshold experiments can look for ~ GeV scale DM

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.



**iZIP**: Ionisation + Phonons

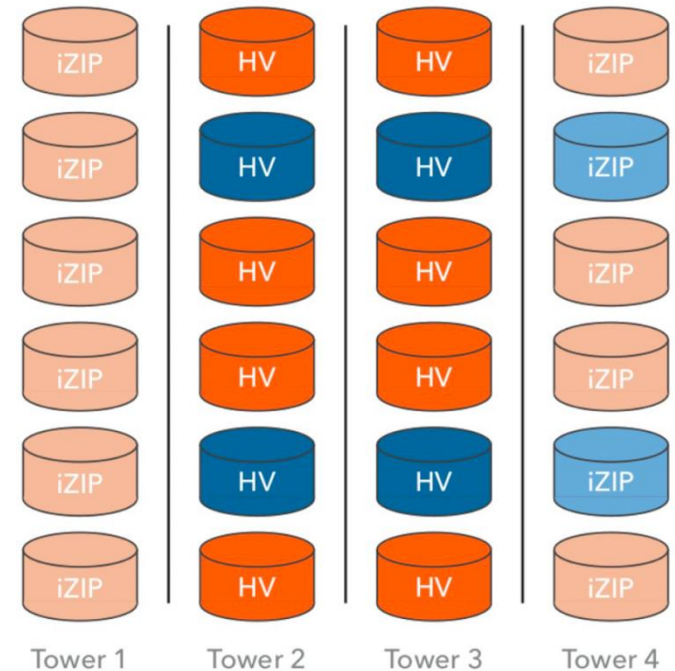
Excellent discrimination between nuclear recoils (NR) and electronic ones (ER) of  $1/10^5$



**HV**: Phonons (High Voltage)

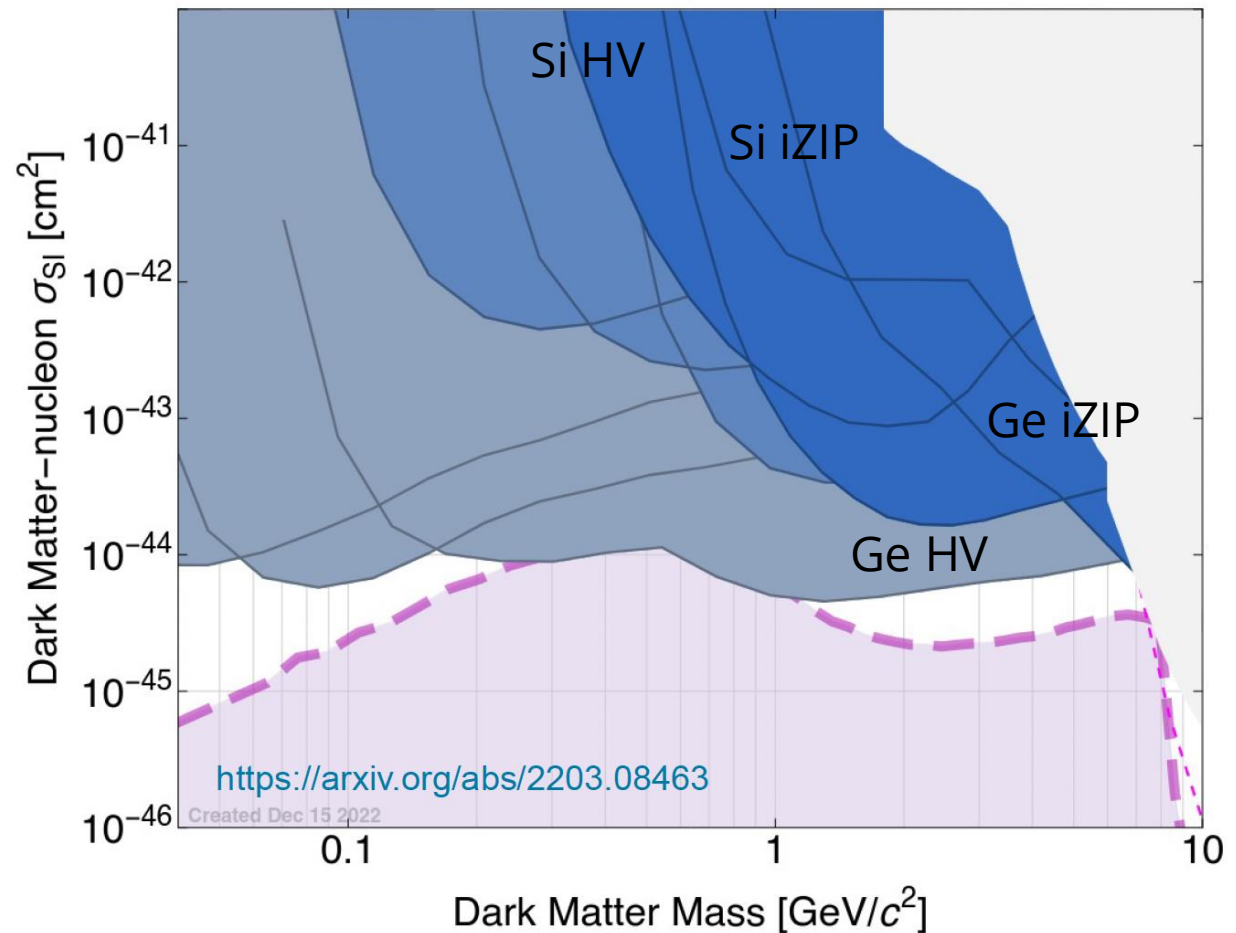
Amplify the signal through the Luke-Neganov-Trofimov effect. Greater sensitivity to low mass DM (no discrimination)

4 towers of crystals  
Ge (1.4 kg) and Si (0.6 kg)



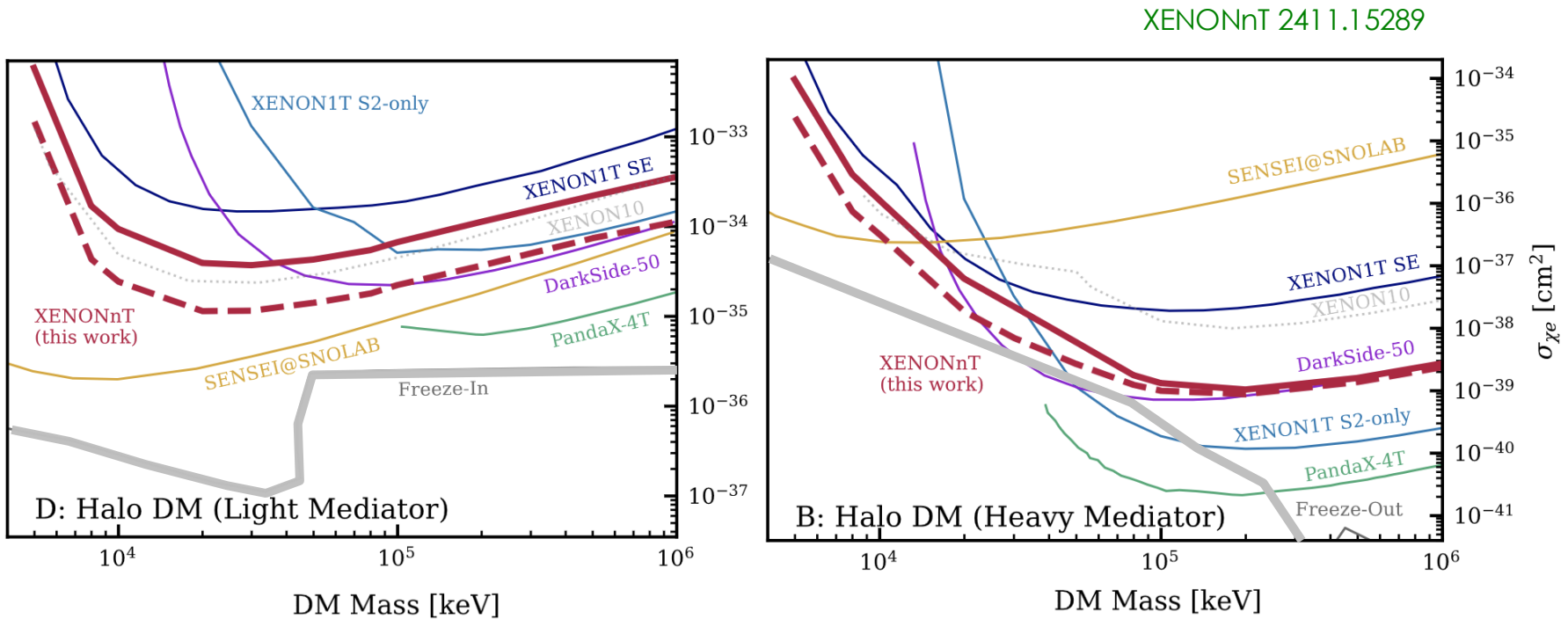
## Low-threshold experiments can look for $\sim$ GeV scale DM

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.



## 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**

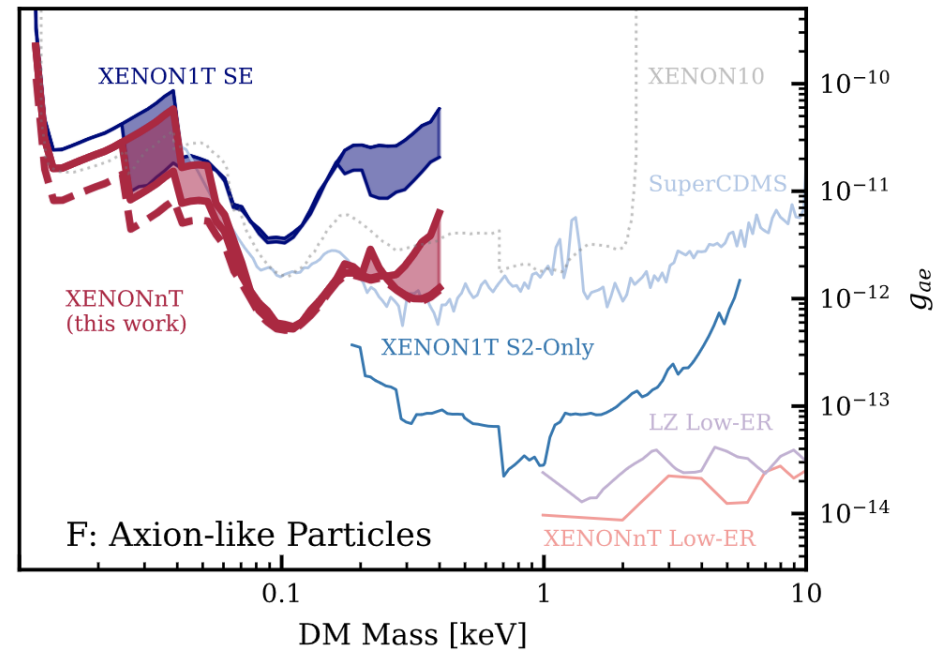
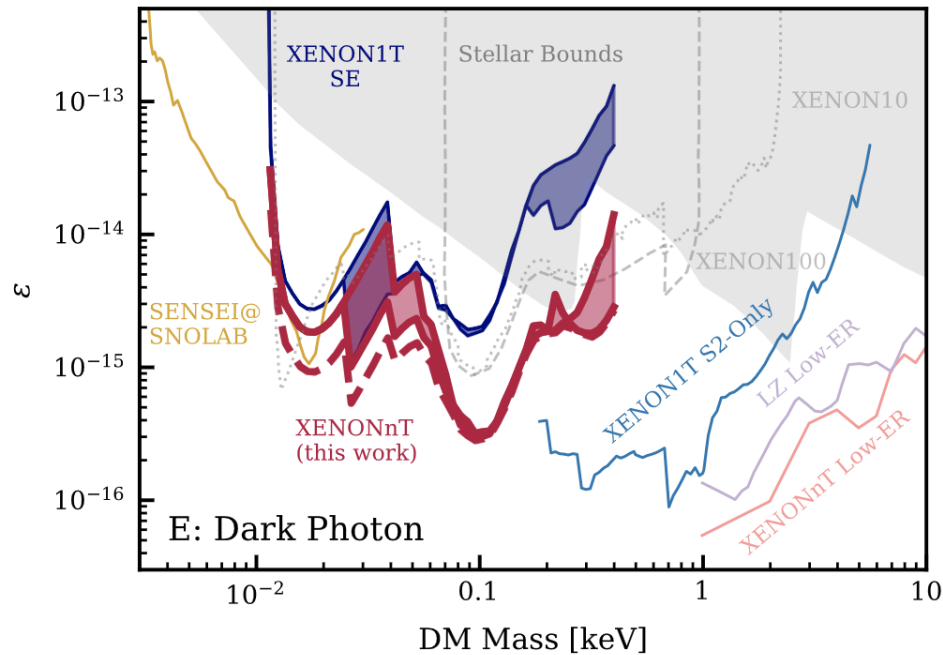


These searches are starting to probe other ways of producing DM in the early Universe, namely **freeze-in** models.

## DM-Electron interactions allow to probe keV scale DM

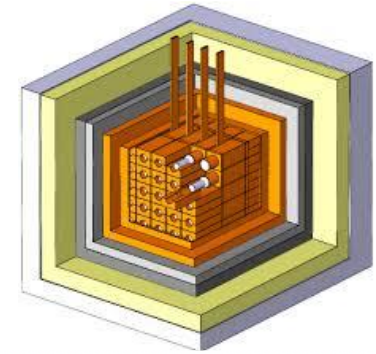
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XENONnT 2411.15289

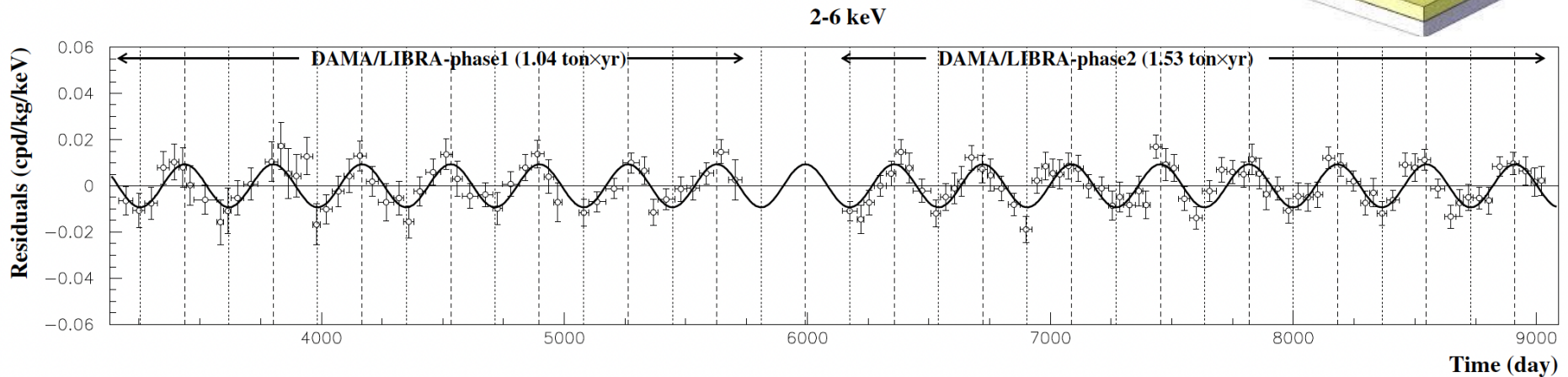


Also **dark photons** or **axion-like particles**!

## Annual Modulation of dark matter direct detection



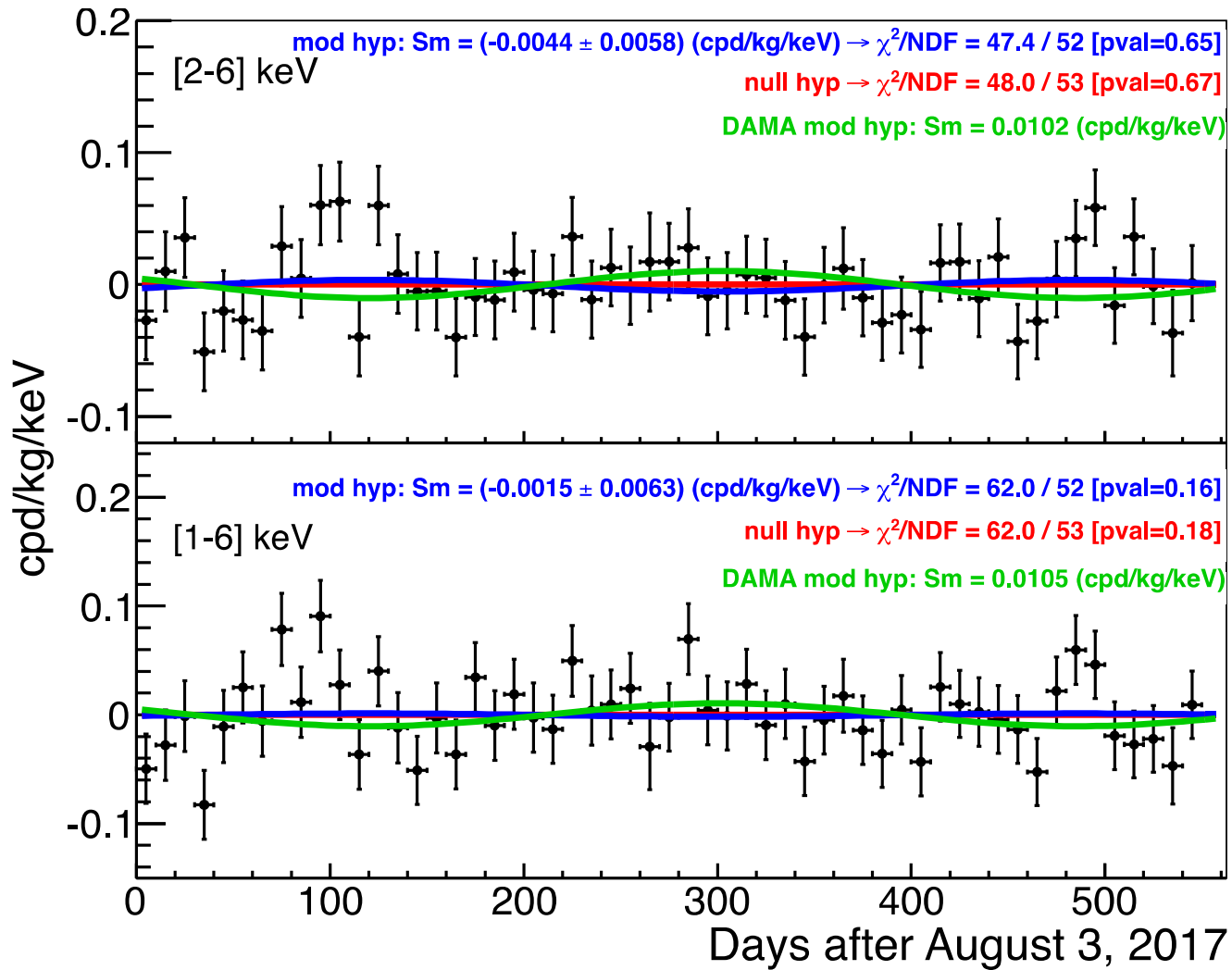
The DAMA/LIBRA (NaI) collaboration has reached 2.86 ton yr over 22 annual cycles. It observes a clear modulation in the [1-6] and [2-6] keV regions with very high CL (13.7  $\sigma$ )



The interpretation in terms of dark matter is not compatible with the non-observation by any other experiment. However, comparison is sensitive to the target, DM model, halo parameters...

A number of experiments are testing DAMA/LIBRA **with the same target**: ANAIS, COSINE, SABRE, COSINUS, DM-ICE...

# ANAIS-112 sees no modulation employing the same target (NaI)

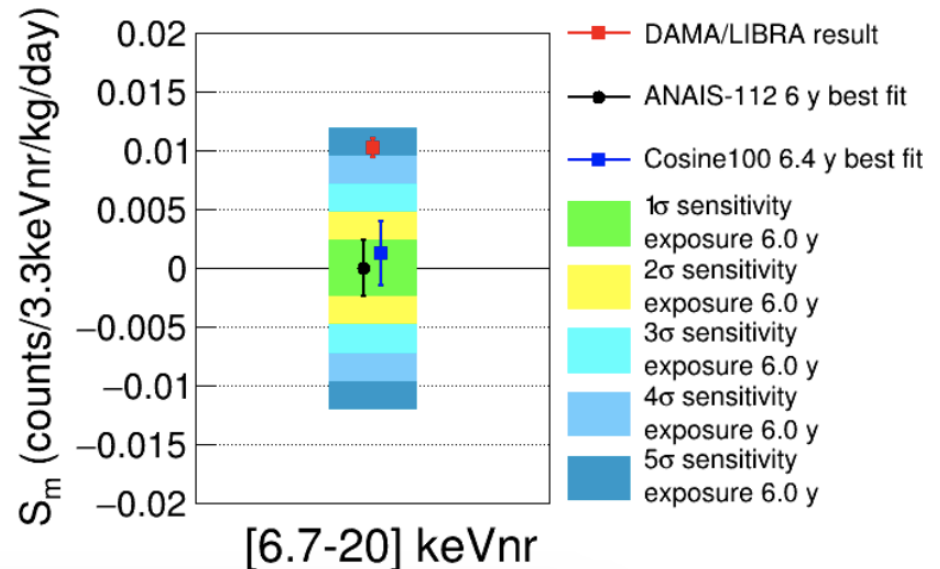
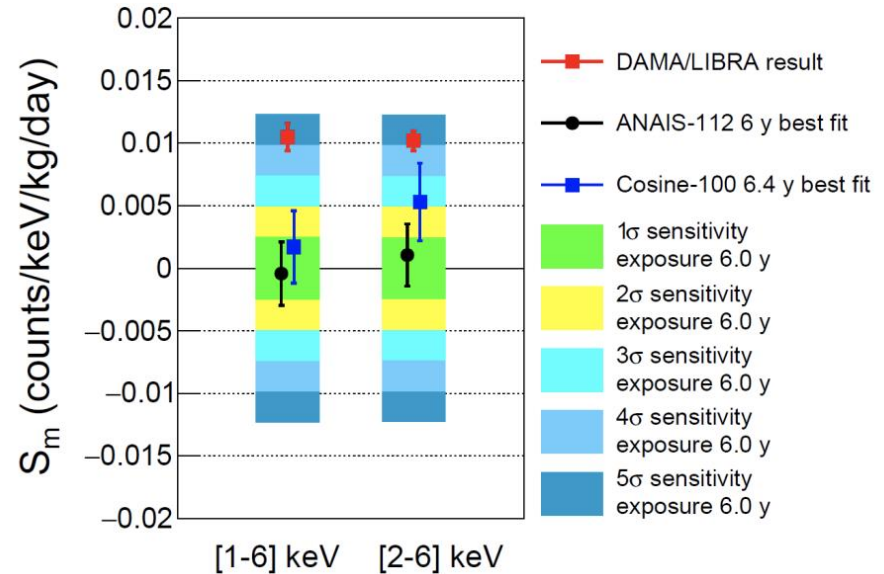


## ANAIS 6y and COSINE 6.4y

Results from ANAIS and COSINE show no modulation.

Incompatibility with DAMA/LIBRA at  $\sim 4.3 \sigma$  (ANAIS) and  $\sim 3.6 \sigma$  (COSINE)

There are still questions about the quenching factor (which ANAIS finds to be lower than DAMA/LIBRA).



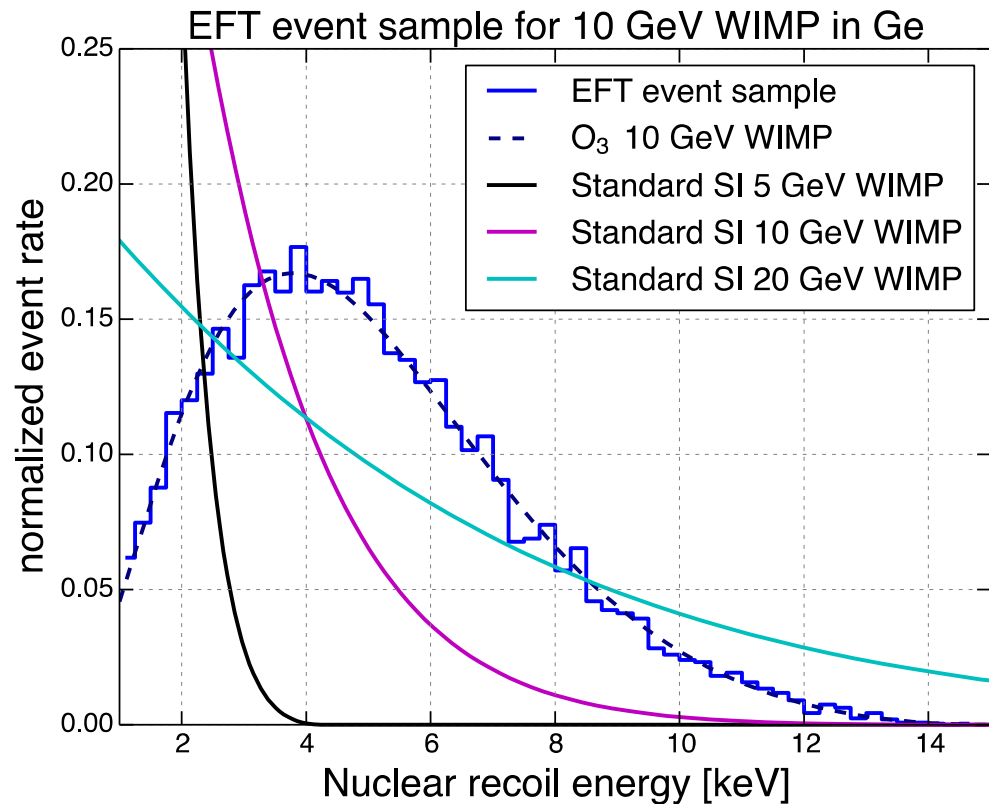
Courtesy of María Martínez (ANAIS)  
Presented at 9th MultiDark IBS workshop  
11/2024

## 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”



Schneck et al [SuperCDMS] 2015

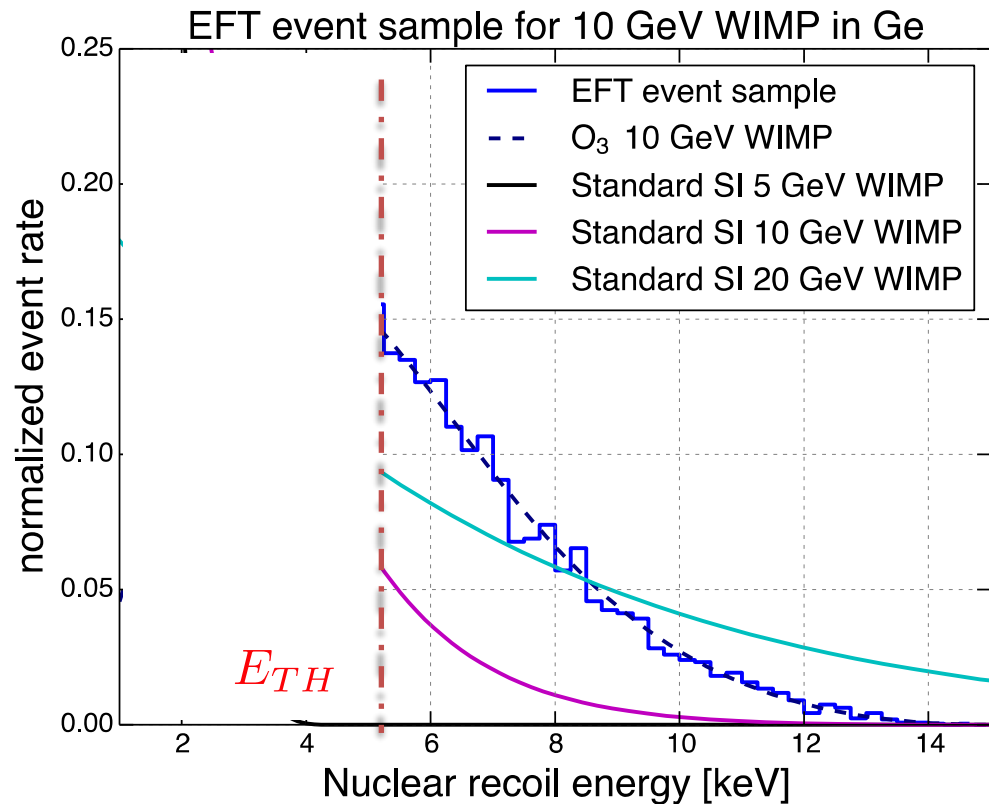
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Schneck et al [SuperCDMS] 2015

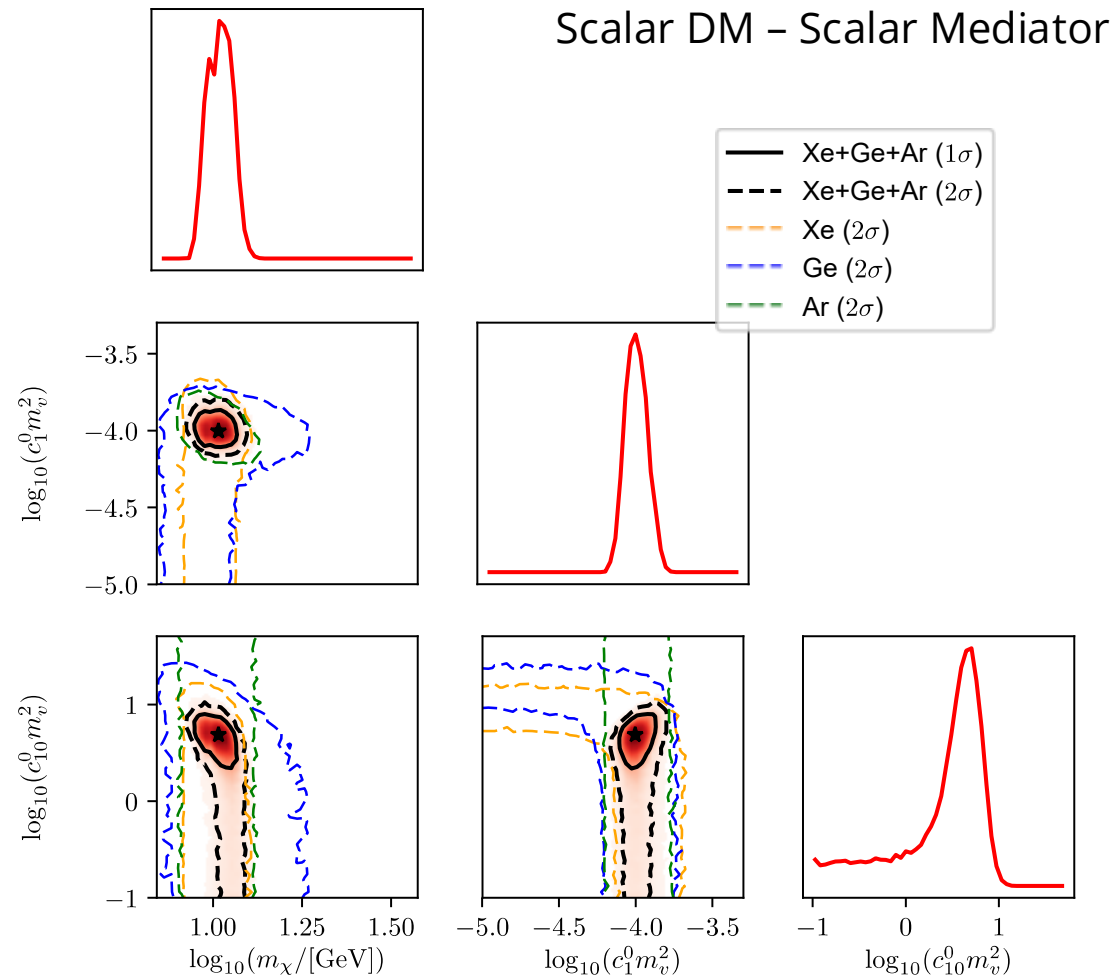
## How can we deal with such a large number of parameters?

For a positive detection:

Parameter reconstruction is possible through the combination of different experimental targets

Challenges:

- Large Dimensionality
- Flat directions in the likelihood
- Combination of data from different experiments





## Possible strategies (2):

### Devise strategies to sample a wide parameter space

- Run 3D Bayesian fits for each EFT operator separately, considering the coupling to proton, neutron and the DM mass
- Use the Bayesian evidence to determine the most likely operators (or set of operators) to reduce the parameter space
- Run 5D Bayesian fits (or higher-D) for the combination of two or more relevant operators from the previous step.

See e.g., Rogers et al. 1612.09038

### Truncated Neural Networks

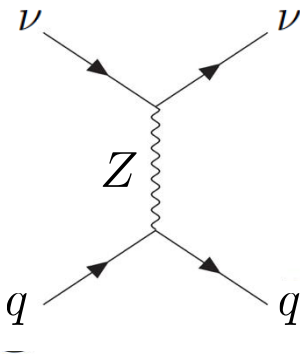
For example, through the use of parametrisations or “surrogate models” (e.g. RAPIDD). The energy spectrum is, in general, a well-behaved function (however potential accidental cancellations can make this more complicated)

See e.g., Rogers et al. 1612.09038

## Expected signal in a direct detection experiment

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

### Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



The Standard Model rate has no free parameters  
(other than the Weak angle at very low energies)

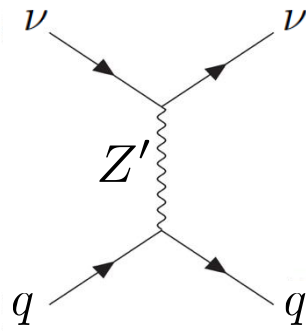
$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left( 1 - \frac{m_N E_R}{2E_\nu^2} \right) F^2(E_R)$$

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

# Expected signal in a direct detection experiment

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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

# Neutrino flux

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

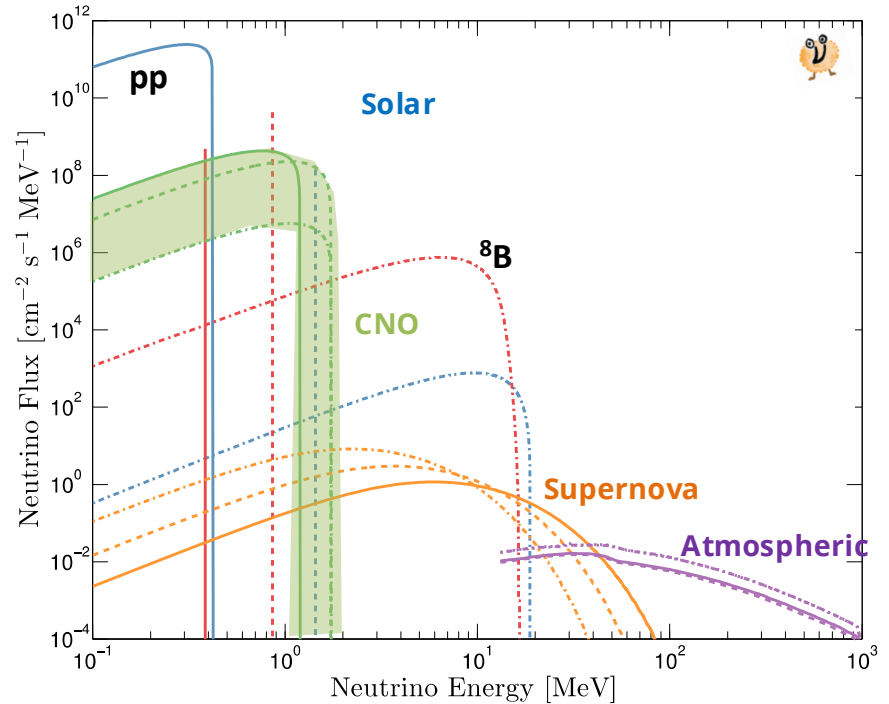
## Solar neutrinos

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



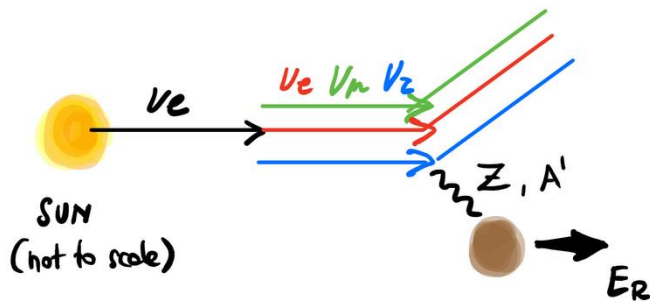
# Neutrino flux

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

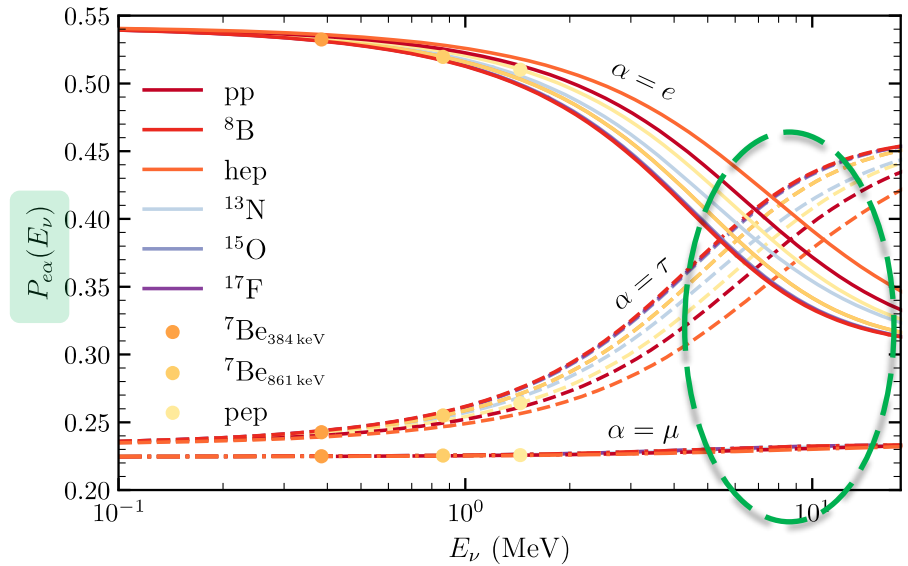
## Solar neutrinos

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

Produced as electron neutrinos, they oscillate into other flavours



Amard, DGC, Foldenauer, Reid 2020

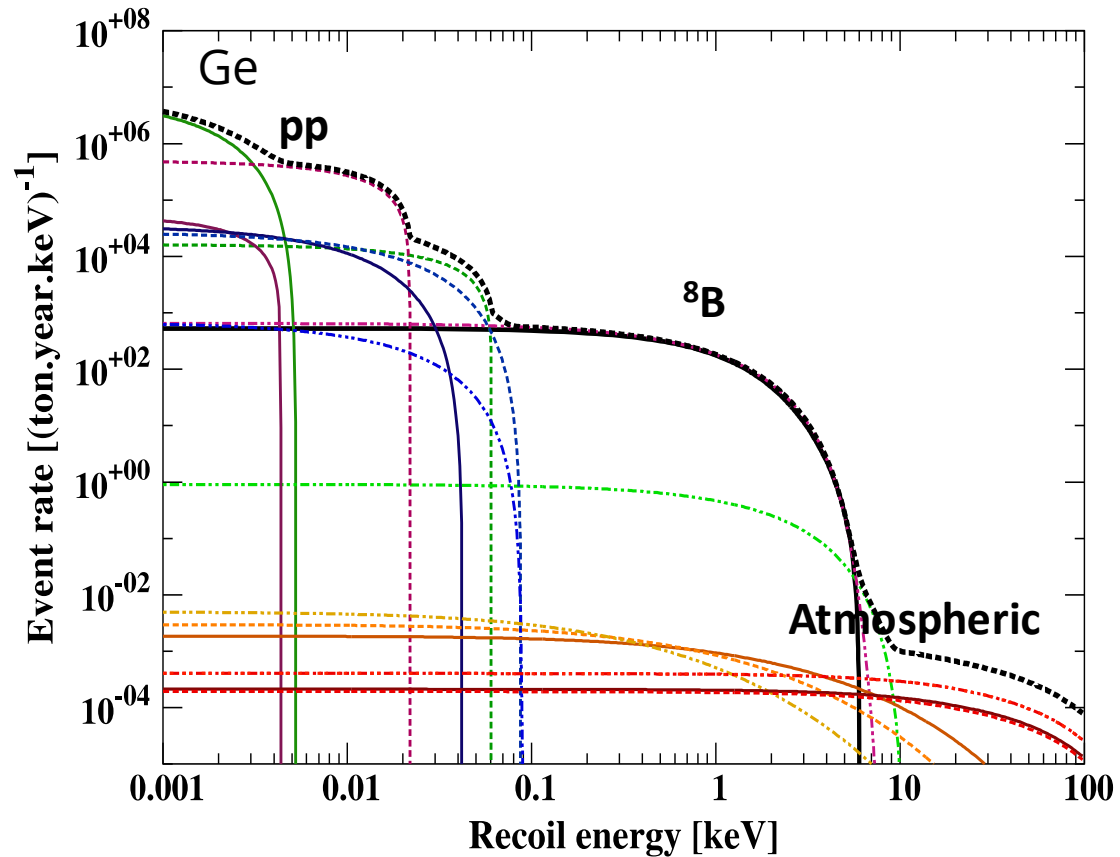


**Matter oscillation** in solar medium dominates flavour composition reaching earth: at 10 MeV (<sup>8</sup>B) there is **significant oscillation** into  $\nu_\mu, \nu_\tau$

# Experimental response to CEvNS

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014

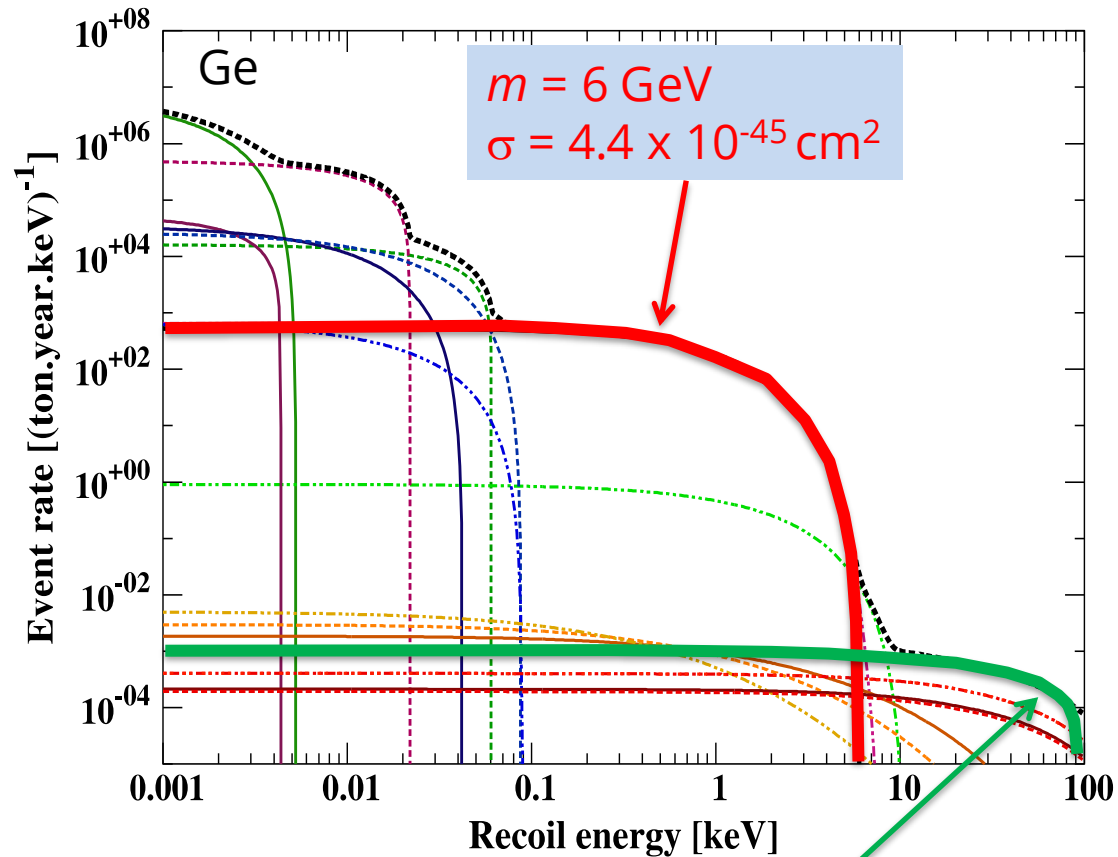
- **Solar neutrinos**  
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- **Atmospheric neutrinos**  
contribute at higher energies but at a much smaller rate
- **Diffuse Supernovae Background**  
relevant around ~20-50 MeV



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

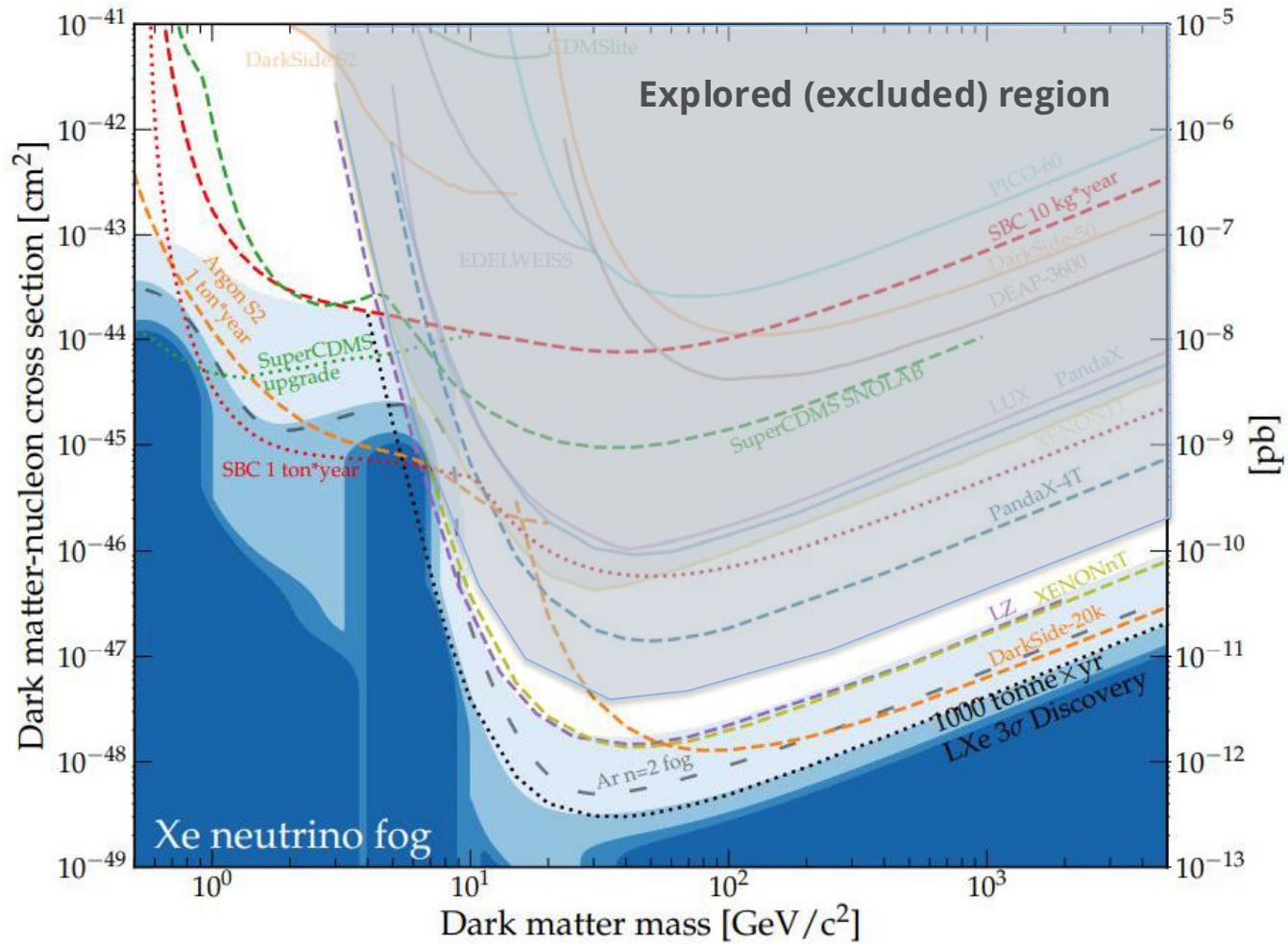
- Low energy threshold and excellent energy resolution
- Sensitive to both nuclear and electron recoils
- Sensitive to the three neutrino flavours  $\nu_e, \nu_\mu, \nu_\tau$

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

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

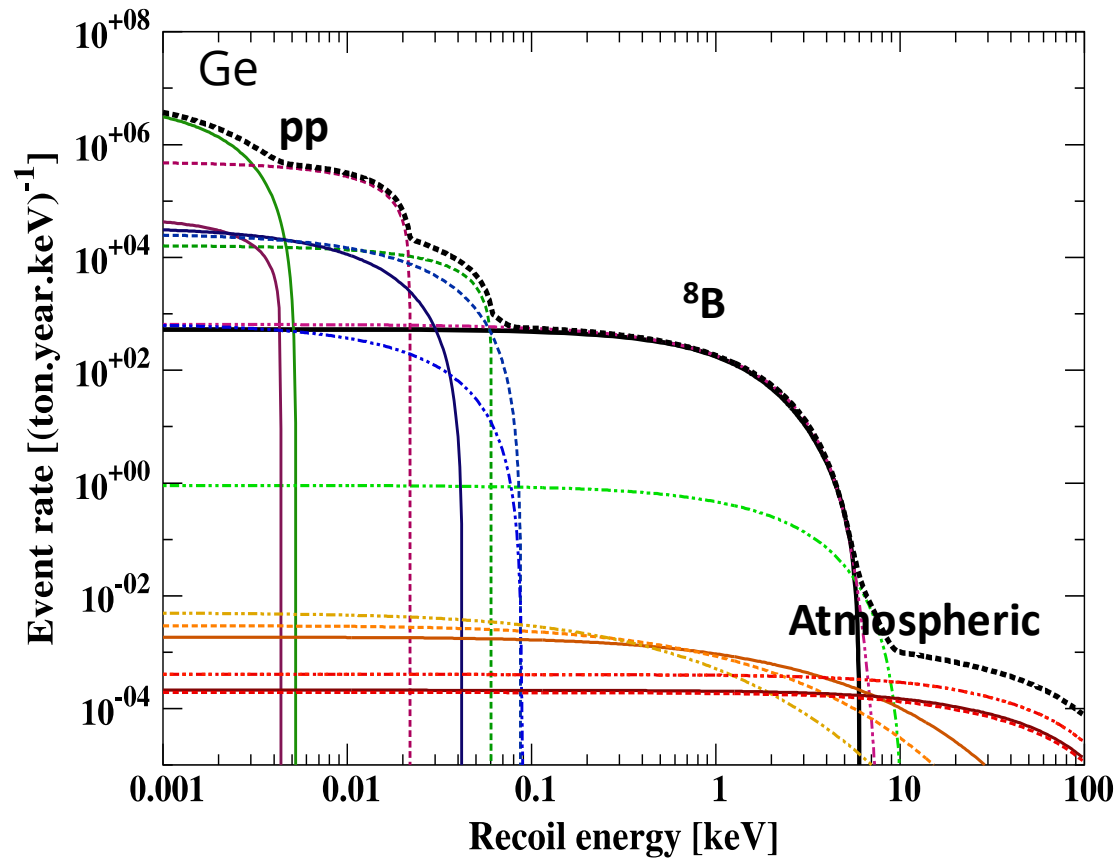
# Future experiments will further explore the DM parameter space



# Experimental response to CEvNS

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014

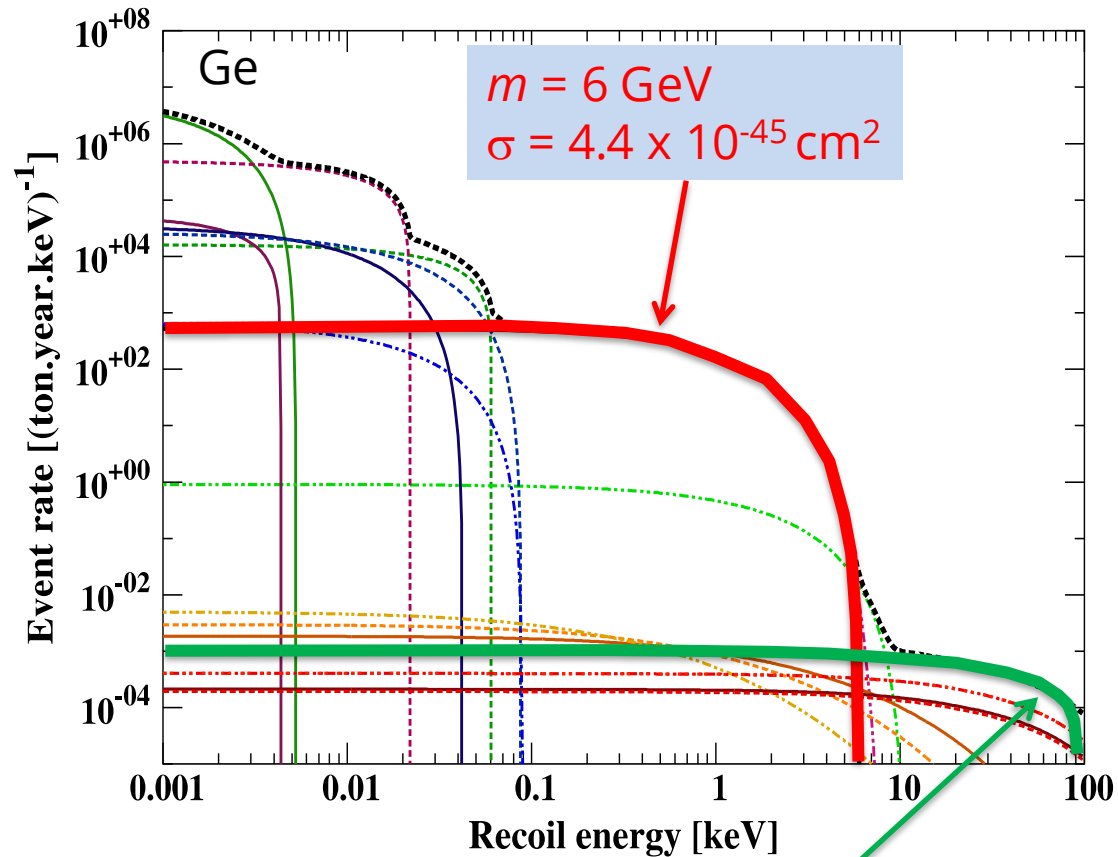
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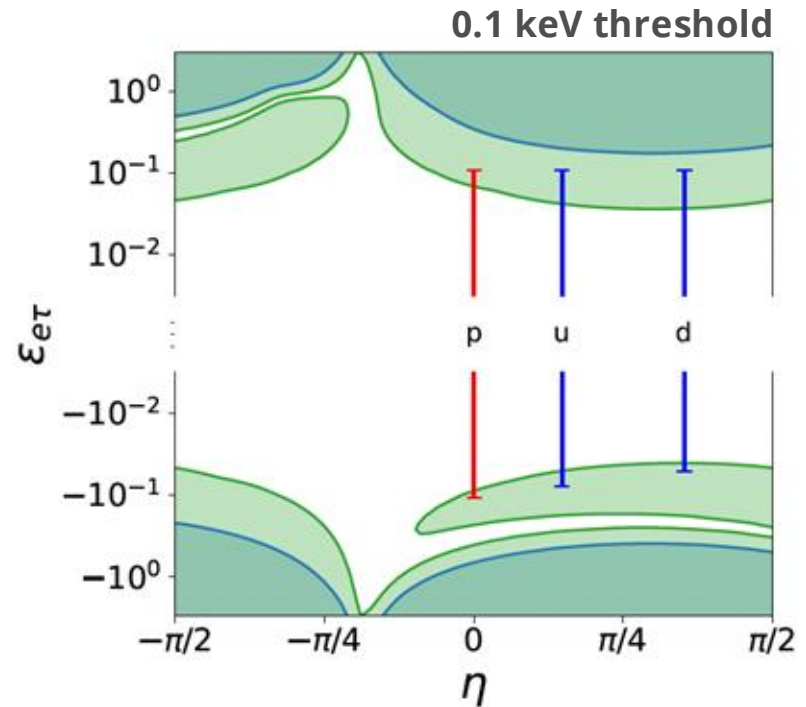
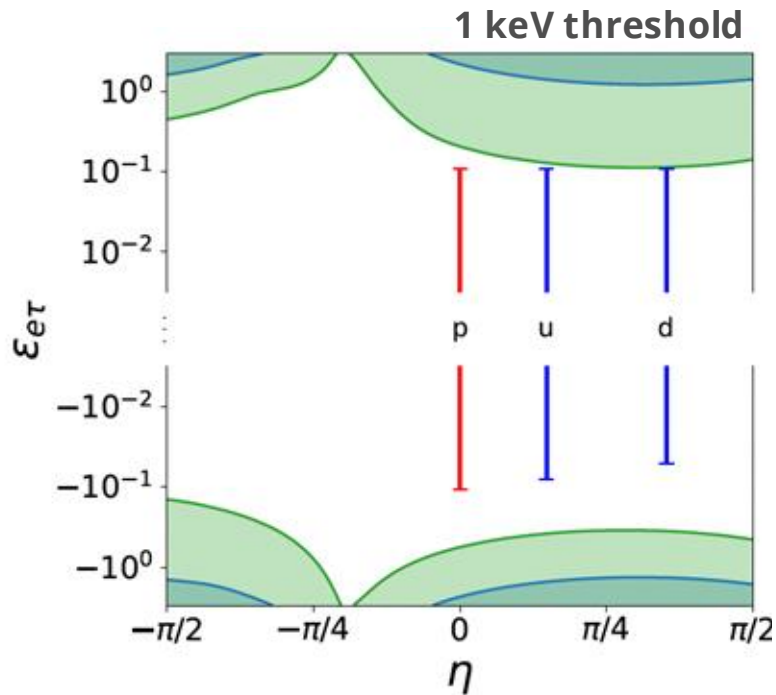


# A prospective study on archaeological lead with RES-NOVA



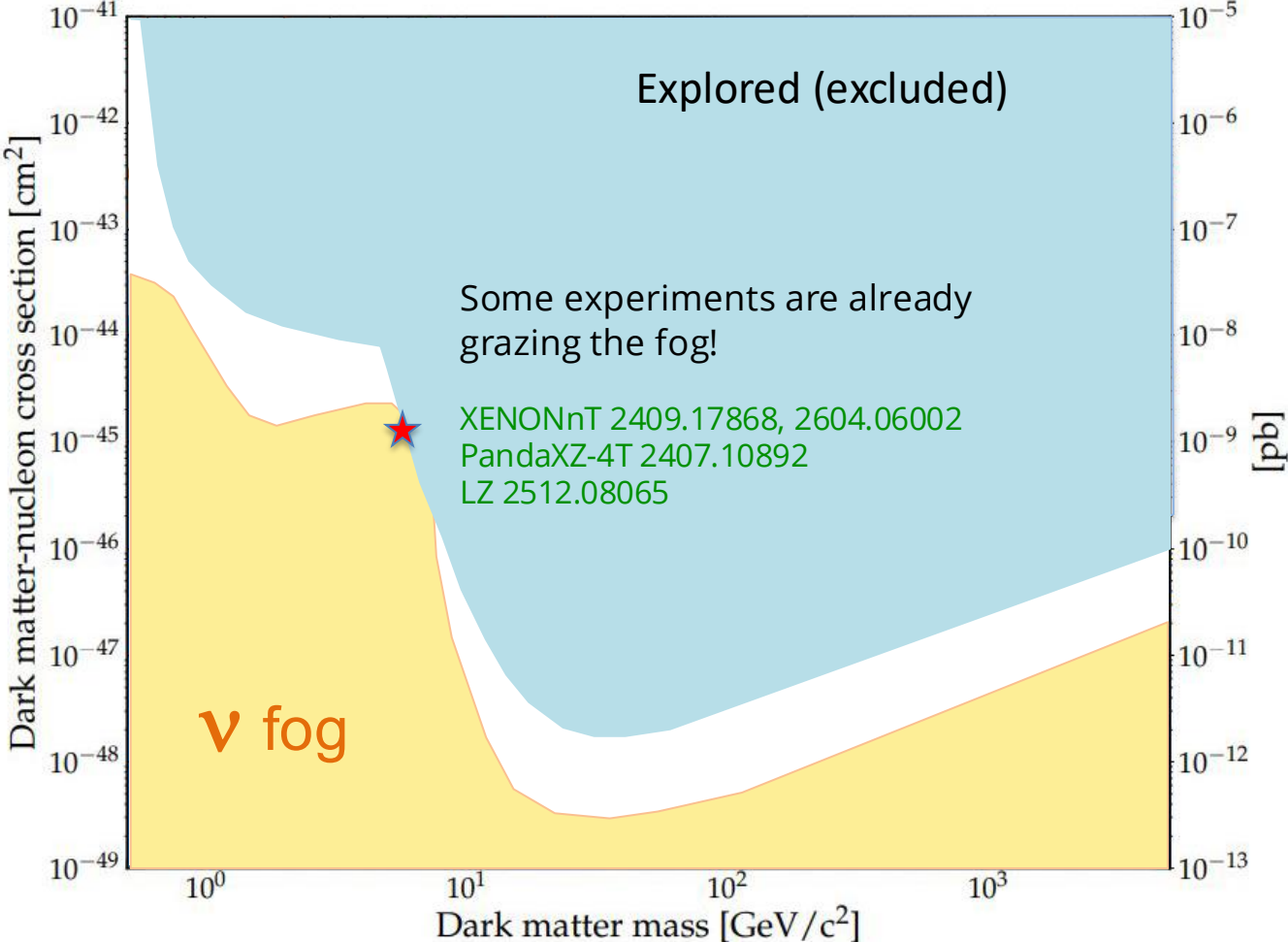
Based on  $\text{PbWO}_4$  crystals, we computed predictions for a nominal configuration of 1 tonne-year.

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



New neutrino physics is not only within the reach of xenon experiments. Other targets also viable. **Pb** benefits from the large atomic number, but **argon experiments** might be useful if the **energy threshold is small**.

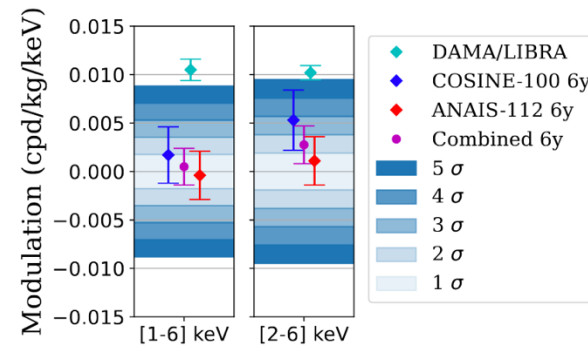
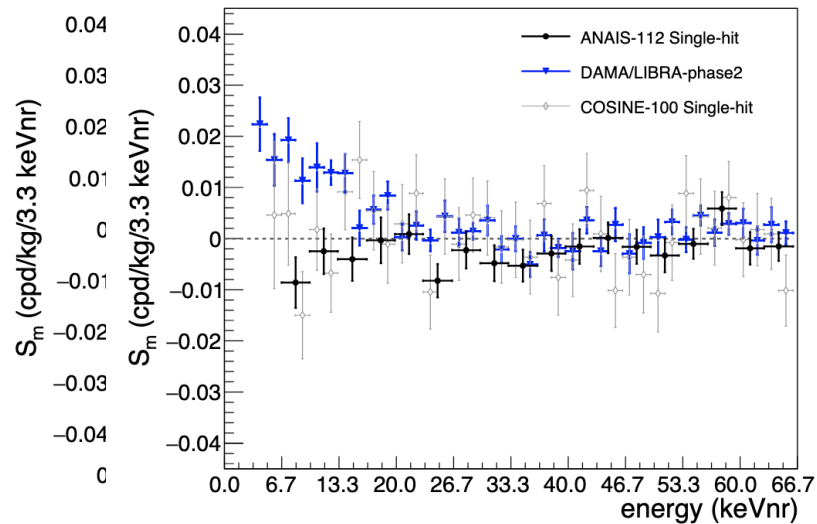
# Future experiments will further explore the DM parameter space



## The DAMA/LIBRA annual modulation signature has not been confirmed

Because of the seasonal dependence of the Earth's velocity through the DM halo, one can expect an annual modulation in the number of DM events detected in direct detection experiments (with an amplitude of  $\sim 7\%$ ).

The ANAIS collaboration (NaI target) has done an excellent job in putting the DAMA/LIBRA signal to the test and virtually excluded the DM interpretation of its annual modulation.

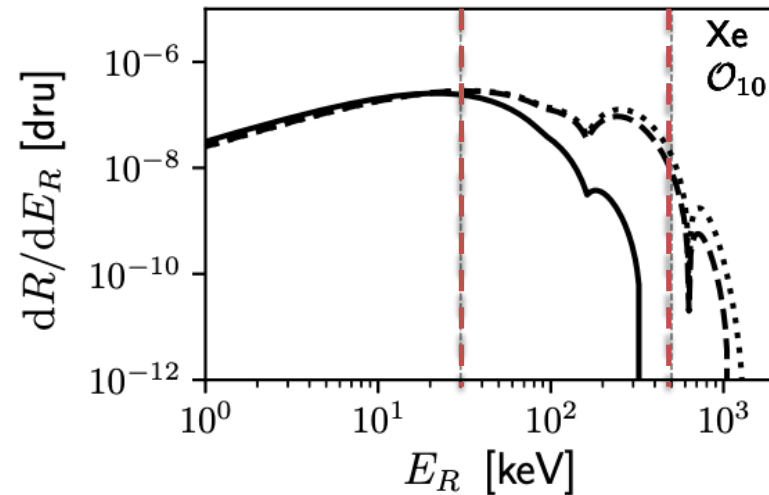


## The resulting dark matter signature depends on the microphysics

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

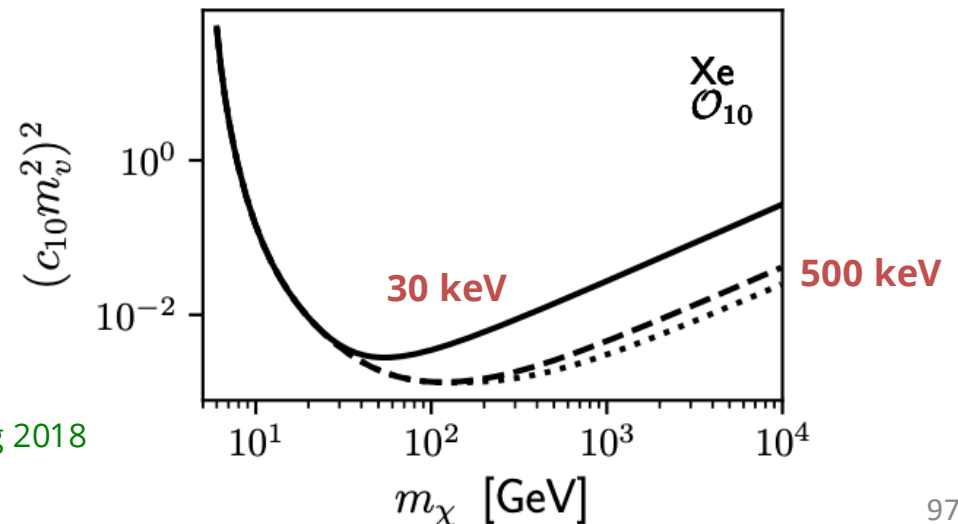
Low-mass WIMPs are expected to leave more energy at small energies.

**Momentum dependent interactions** show a characteristic “bump”



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

Enlarging the **maximum energy** in the signal region allows to set better constraints (or mass reconstruction)



Bozorgnia, DC, Cheek, Penning 2018

# NUCLEAR + ELECTRON SCATTERING

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

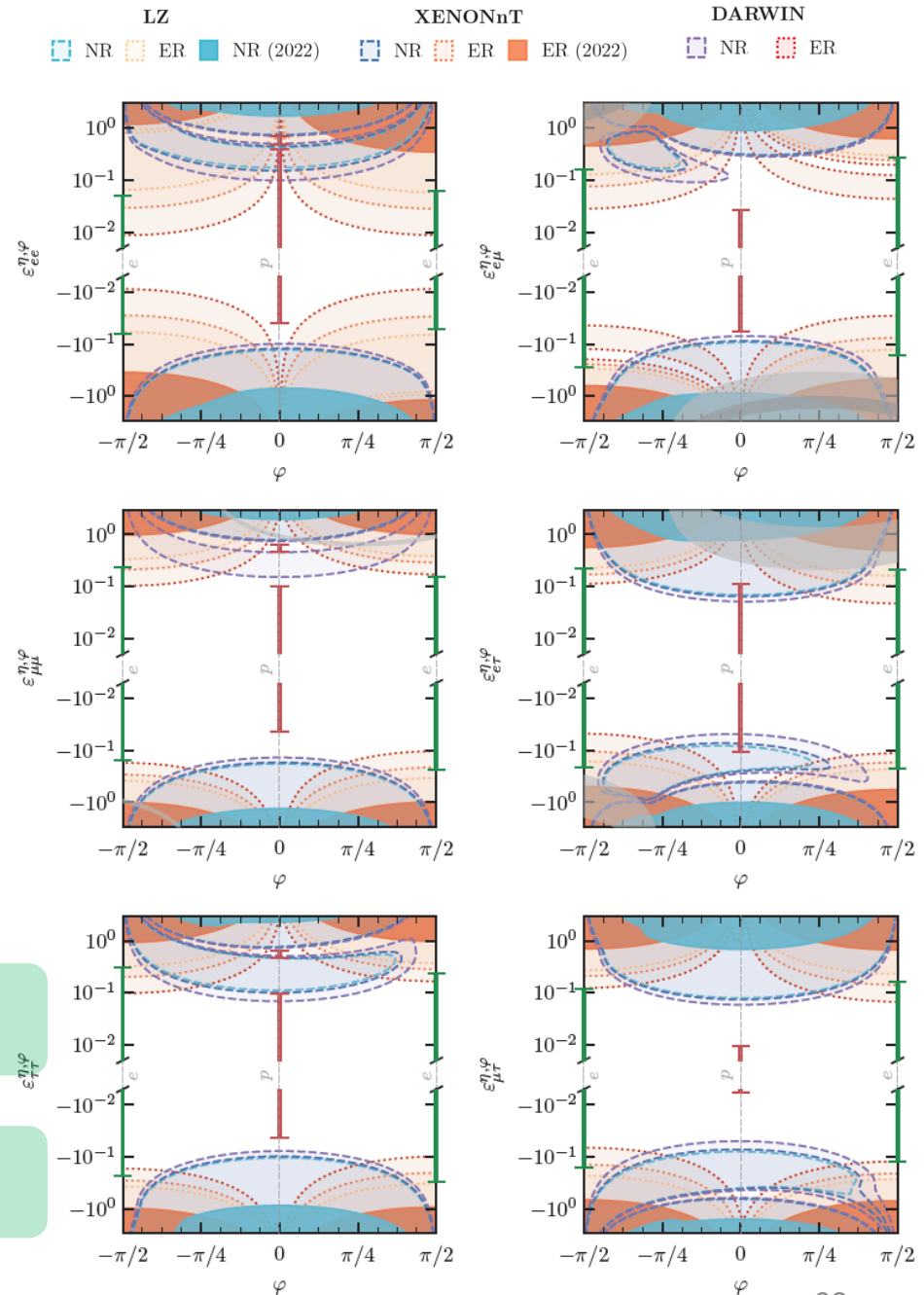
ER sensitivities drop off towards  $\varphi = 0$  (pure proton), whereas NR sensitivities become maximal.

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.



## Low-mass DM can be tested if it is **BOOSTED**!

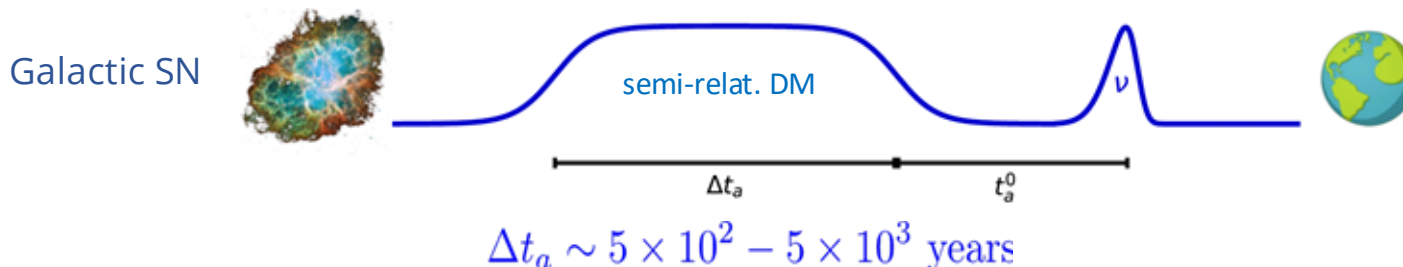
DM in the halo moves at a slow velocity (300-800 km/s) and this limits its kinetic energy (and energy deposition in an experiment).

There are different mechanisms for **boosting** DM, which allows to detect lighter candidates.

- Cosmic Ray upscattering
- Semi-annihilation in the Galactic Centre
- Up-scattering from cosmic neutrinos
- Solar/stellar capture and re-emission
- Decay or annihilation of heavier Dark Matter component
- Non-galactic astrophysical sources

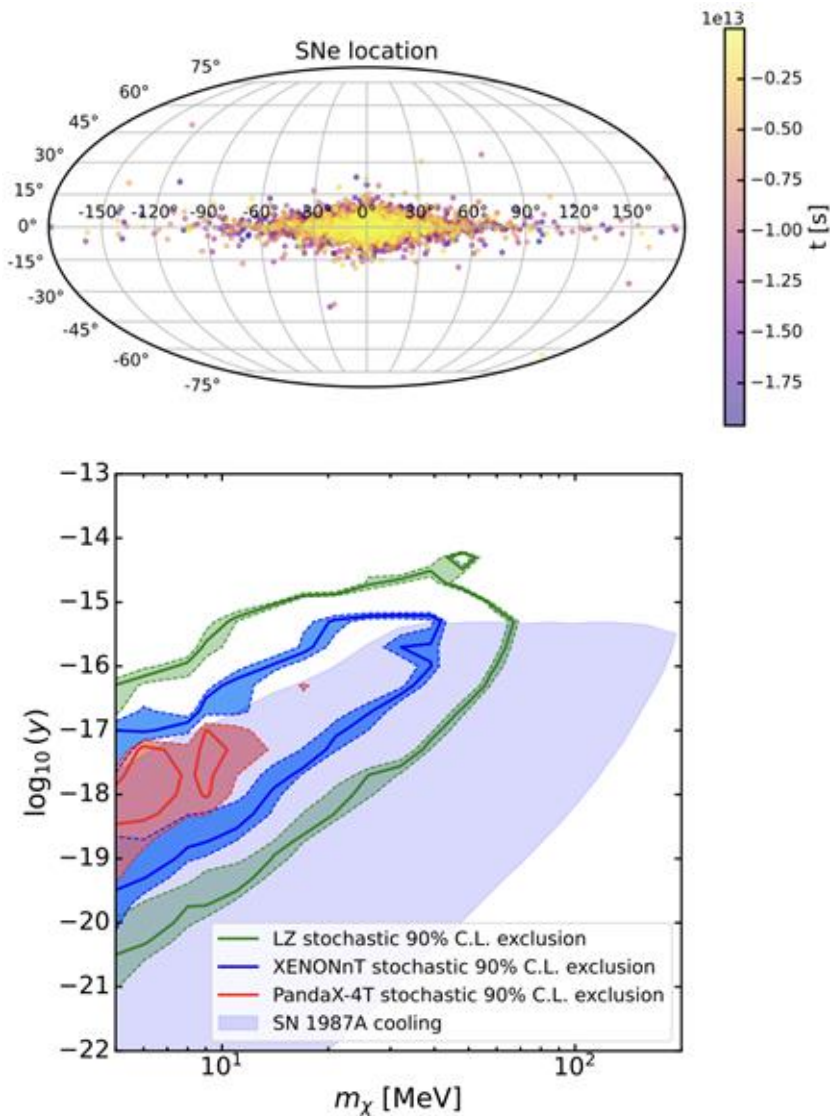
One particularly interesting case is production of **semi-relativistic DM** in supernovae explosions. The superposition from different supernovae gives rise to a **diffuse flux** of particles at Earth

deRocco et al. 2019



Alonso, DGC, Cermeño, Perez, 2025

## Signal in direct detection experiments



To compute the flux at Earth, we have simulated the Galactic Supernova history over the past  $10^6$  years.

We have discovered that **the flux is not smooth** as previously assumed.

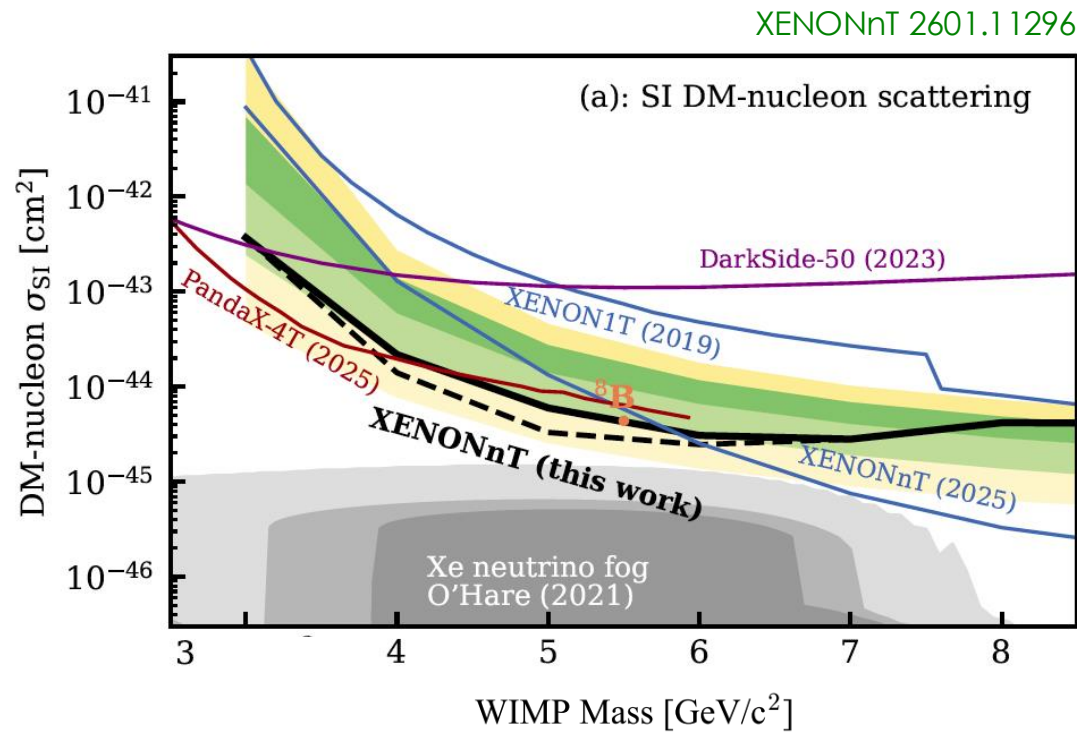
Results from **XenonNT**, **PandaX-4T** and **LZ** set very strong constraints on these models.

deRocco et al. 2019  
Alonso, DGC, Cermeño, Perez 2602.17597

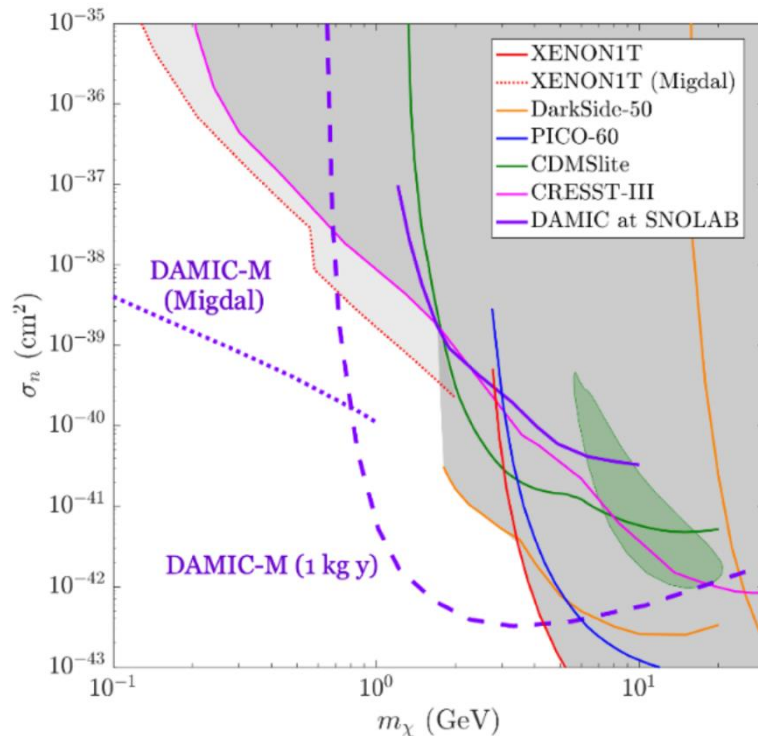
## Liquid noble gas detectors are leading the search at masses above 10 GeV

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  $\sim 1$  GeV WIMPs



## It improves the sensitivity to low mass WIMPs!



Experiments are interpreting their data using the prediction for the Migdal effect.

LUX 2019, XENON 2019, SuperCDMS 2023  
DAMIC 2023

This greatly improves the sensitivity to **low-mass WIMPs**, allowing to explore new regions!

It is crucial to measure it and characterise it in the targets employed by DM experiments.

Otherwise, we might mis-reconstruct the mass of light DM particles.