Direct Dark matter detection: leaving no stone unturned

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

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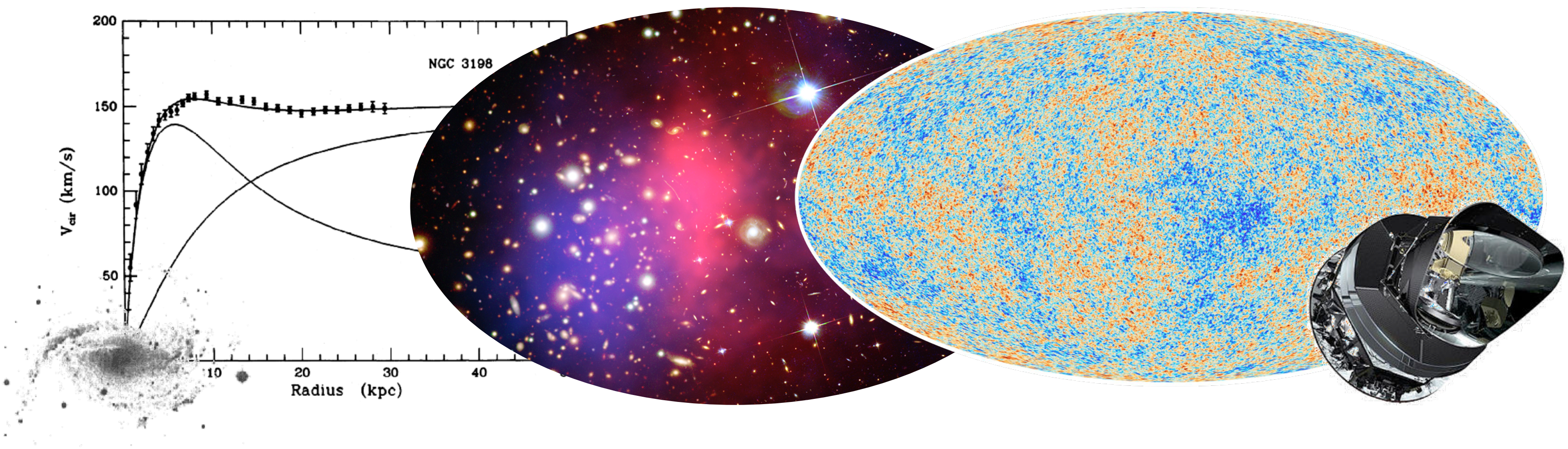
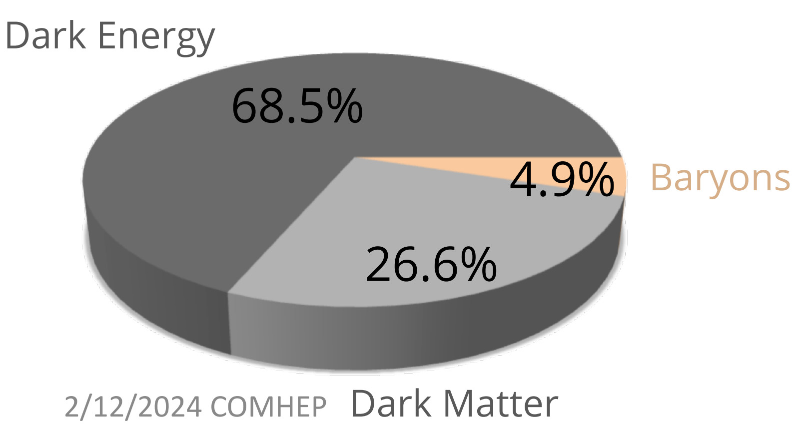
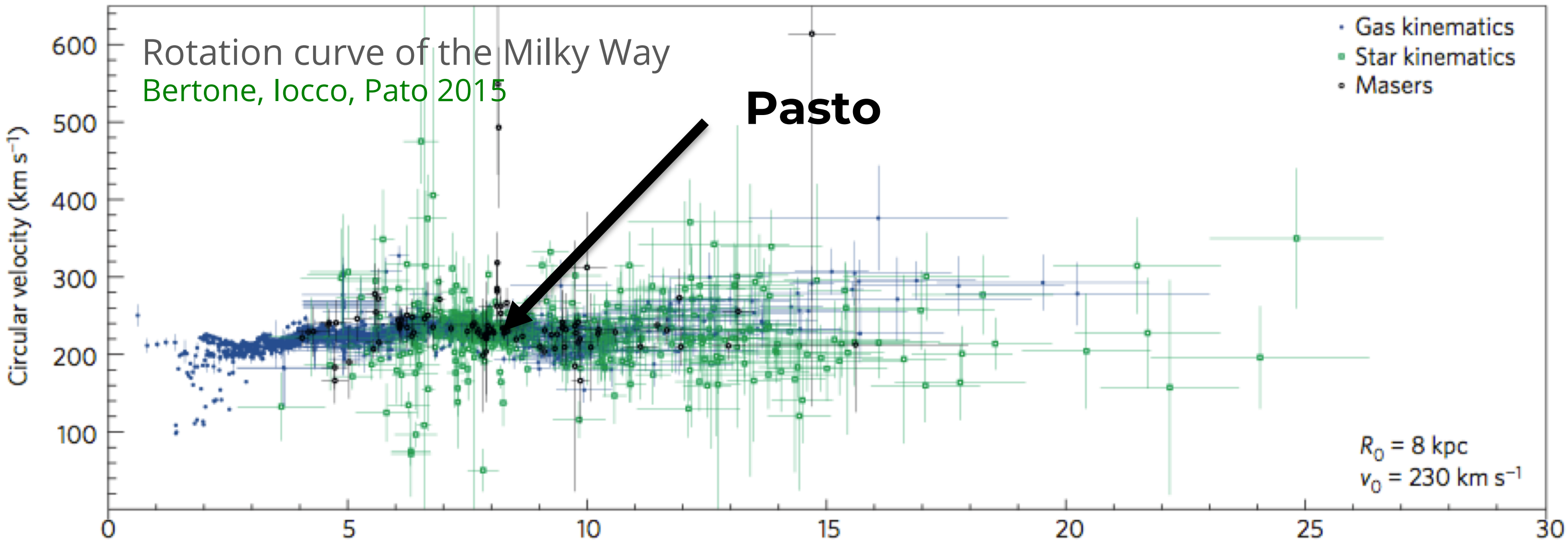
Dark Matter is a necessary and very abundant component in our Universe

We have observed its gravitational effects at different scales





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

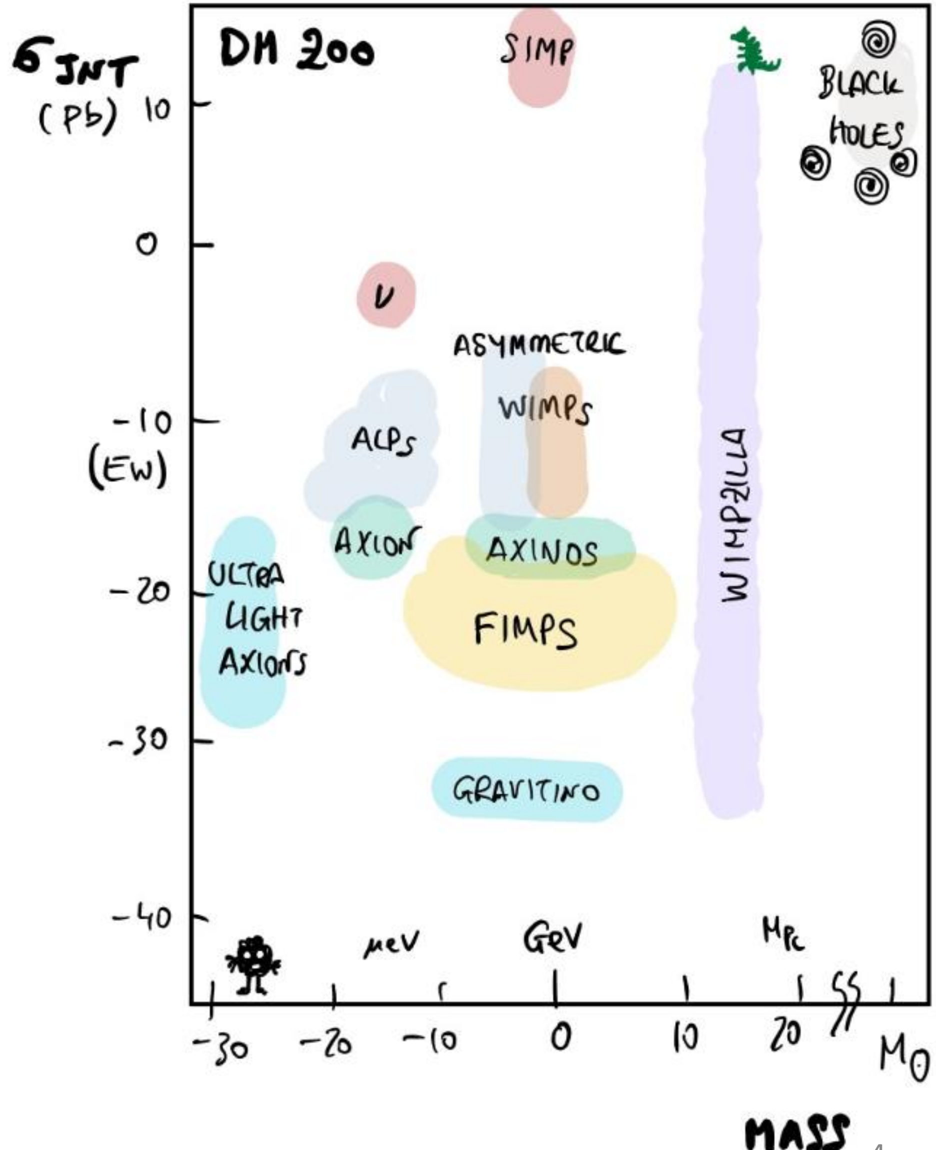


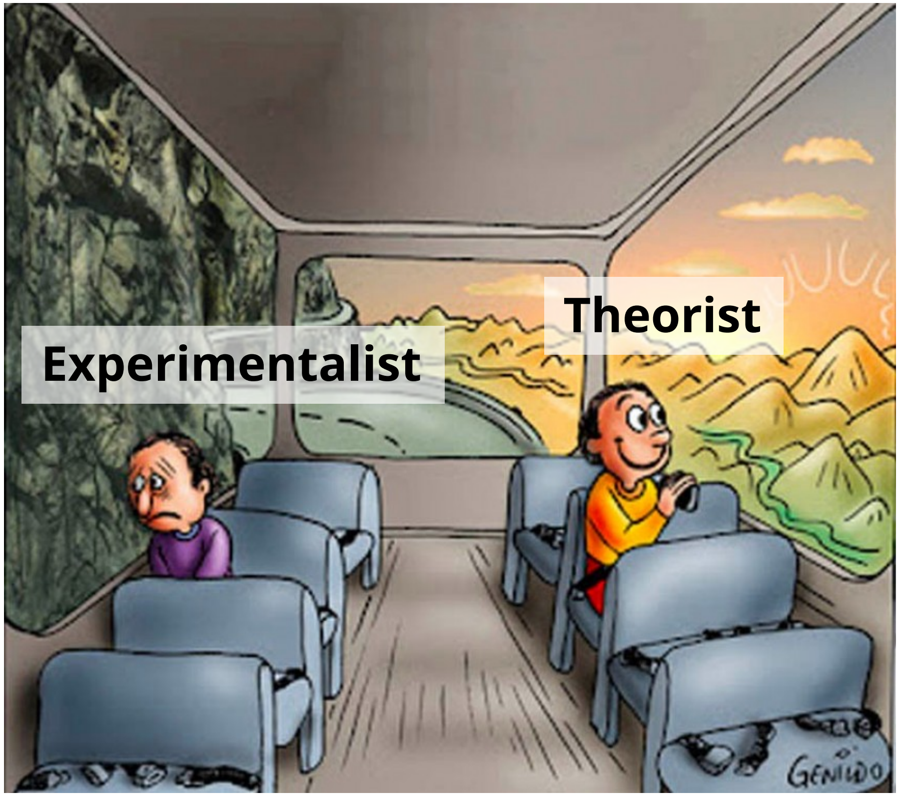
Very few people know this, but the tiny pocket in our jeans is for carrying 10 GeV of dark matter

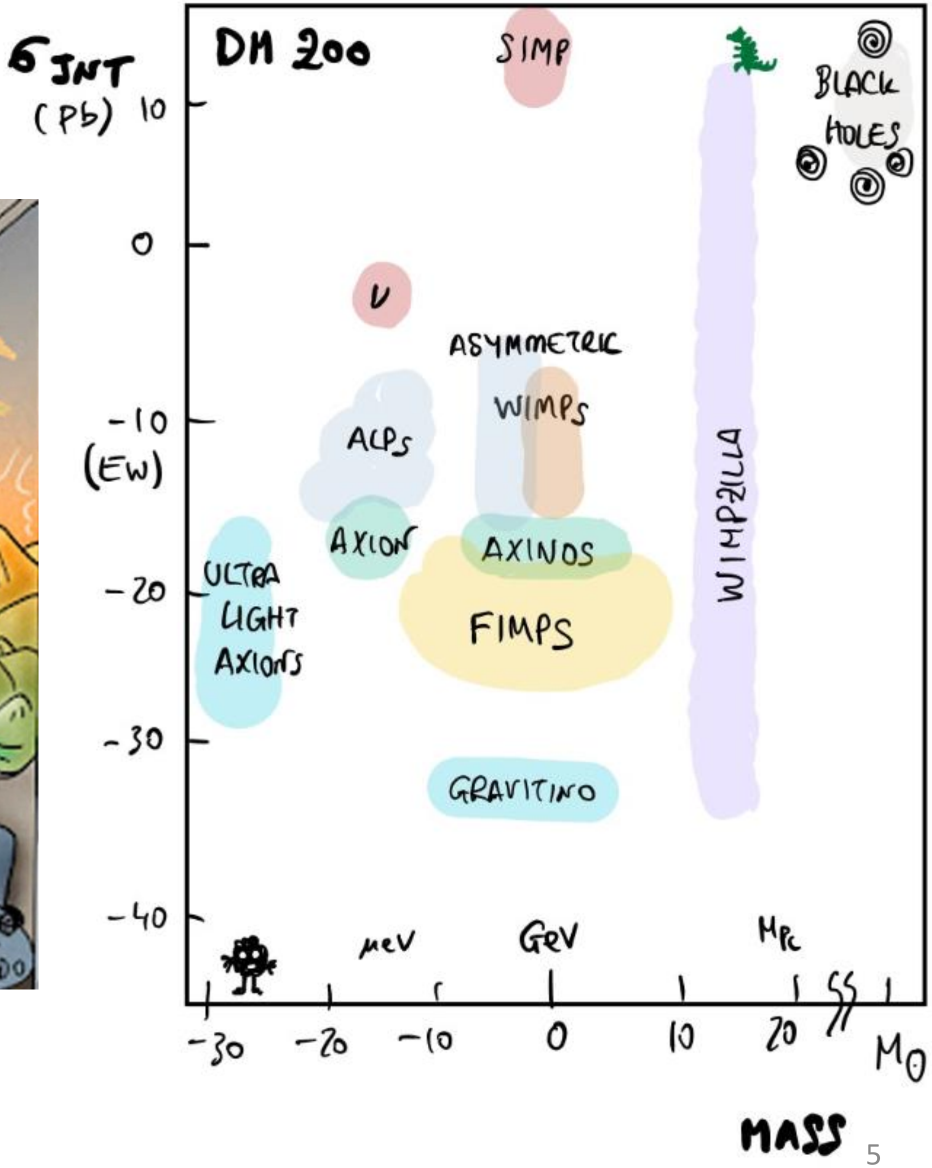
There are plenty of viable **particle physics** candidates, which imply very different **cosmological histories**

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

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




Theorist
Experimentalist


DM ZOO
SIMP
BLACK HOLES
ν
ASYMMETRIC WIMPS
ALPS
AXION
AXINOS
ULTRA LIGHT AXIONS
FIMPS
WIMPZILLA
GRAVITINO
meV
GeV
MPl
-30
-20
-10
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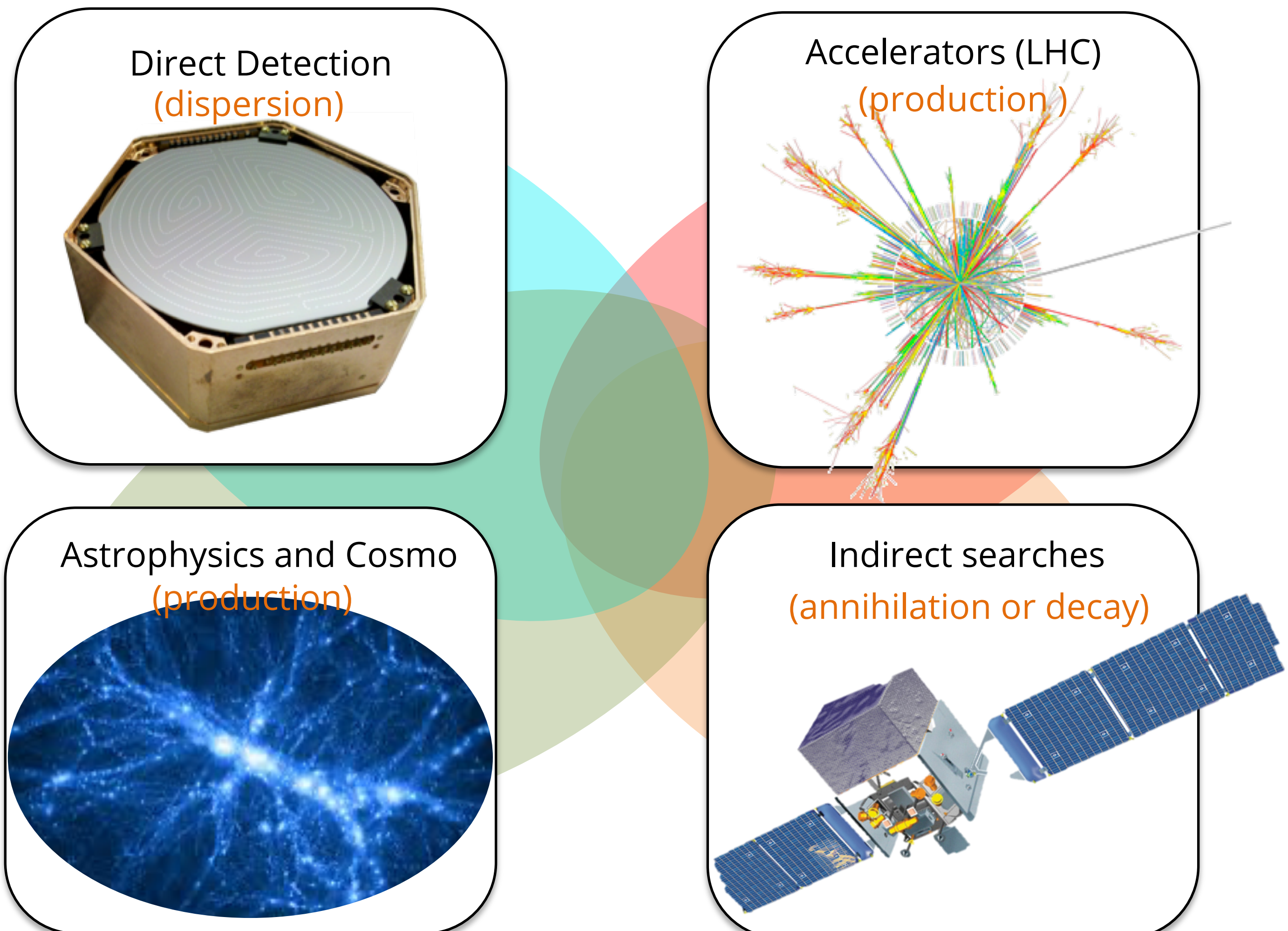
10
20
M⊙
MASS

Dark matter can be searched for in different ways

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



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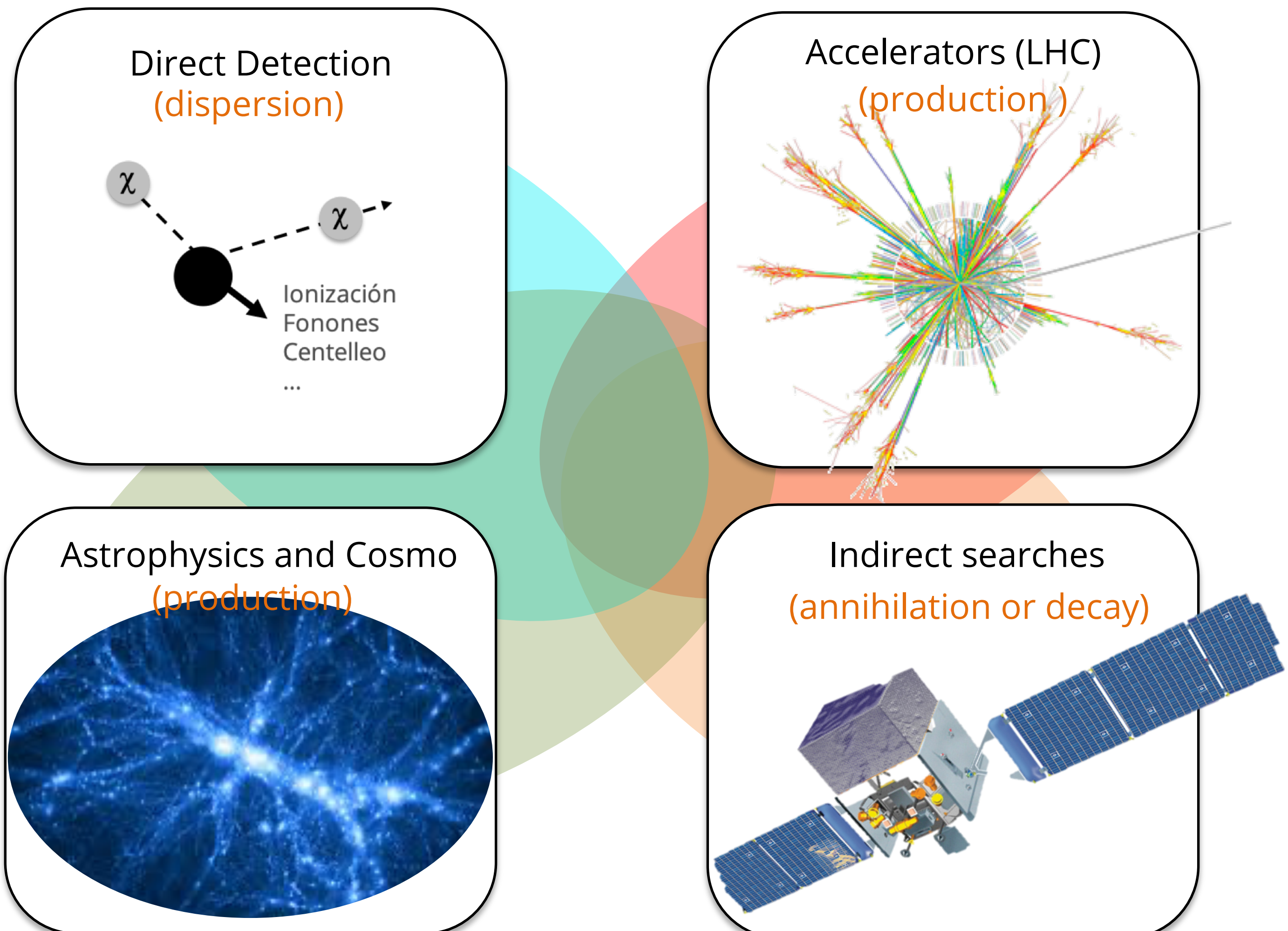

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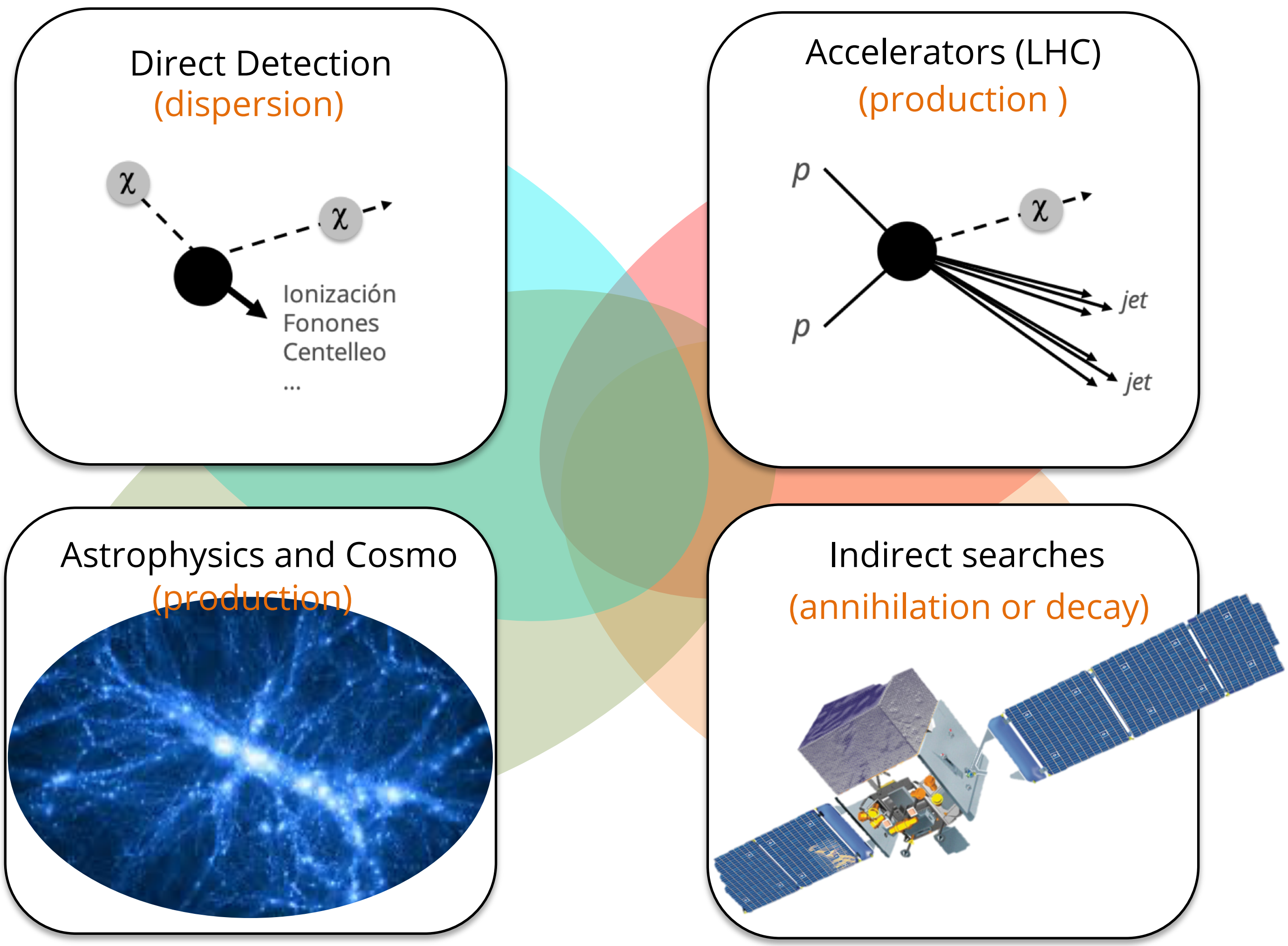

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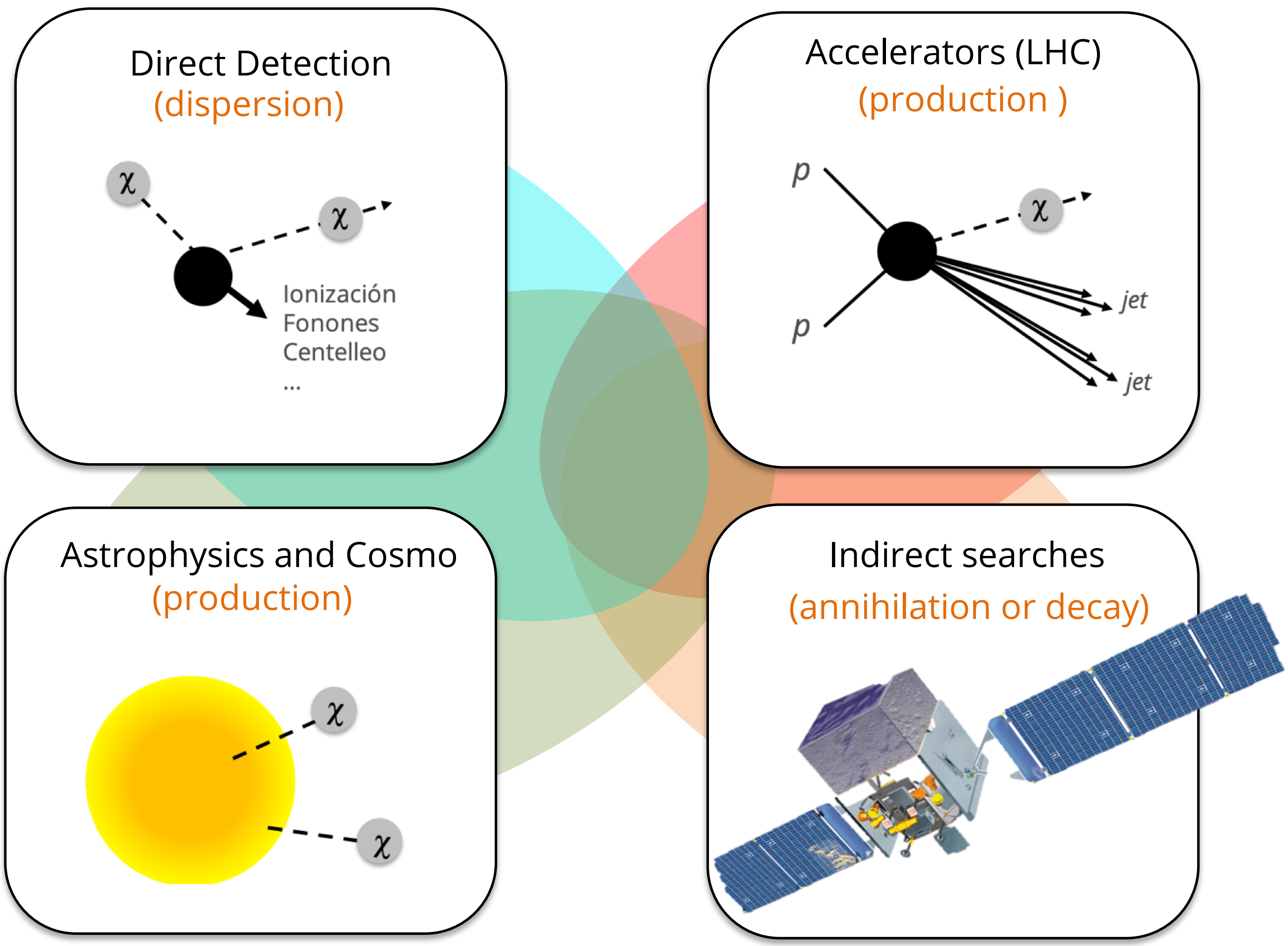

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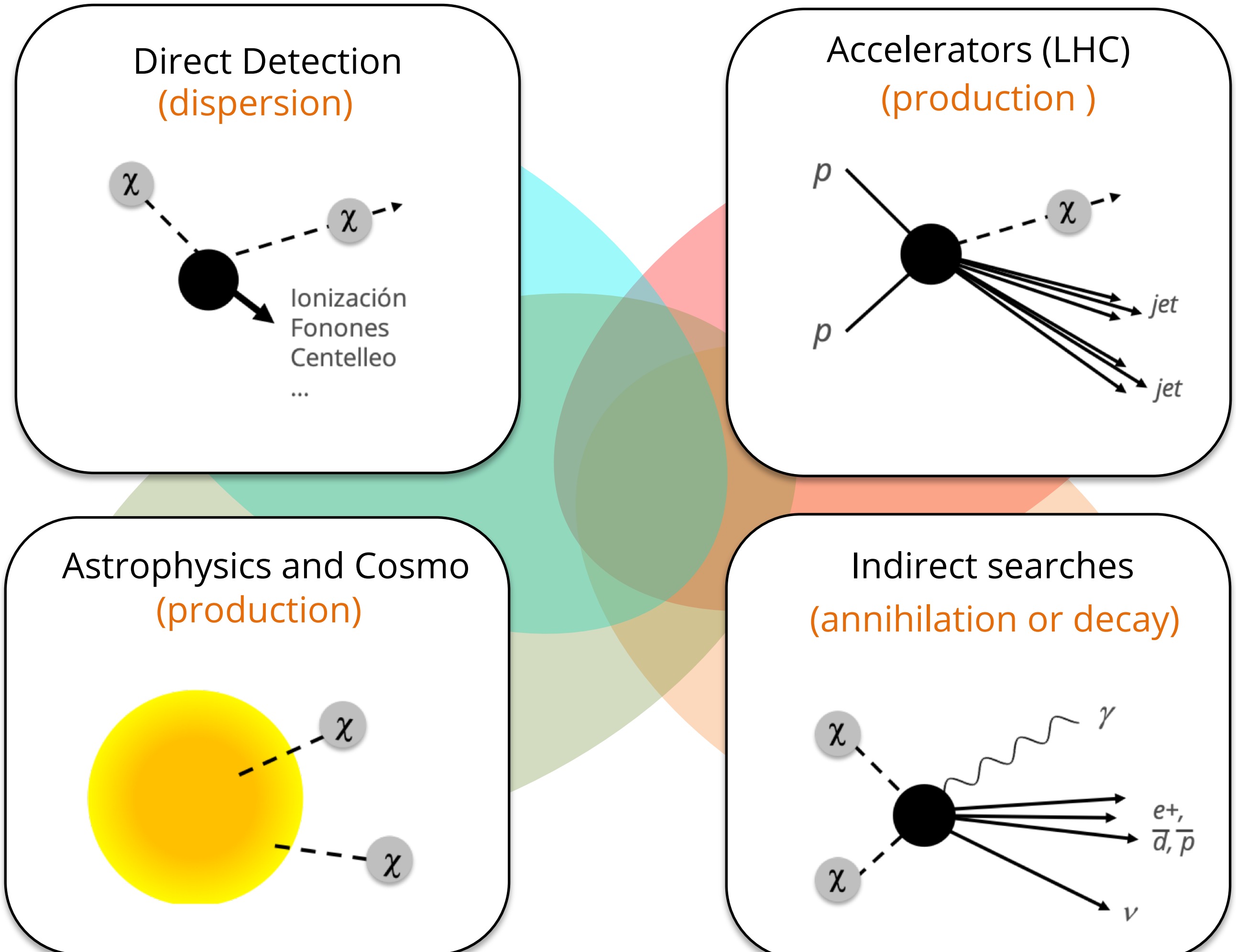

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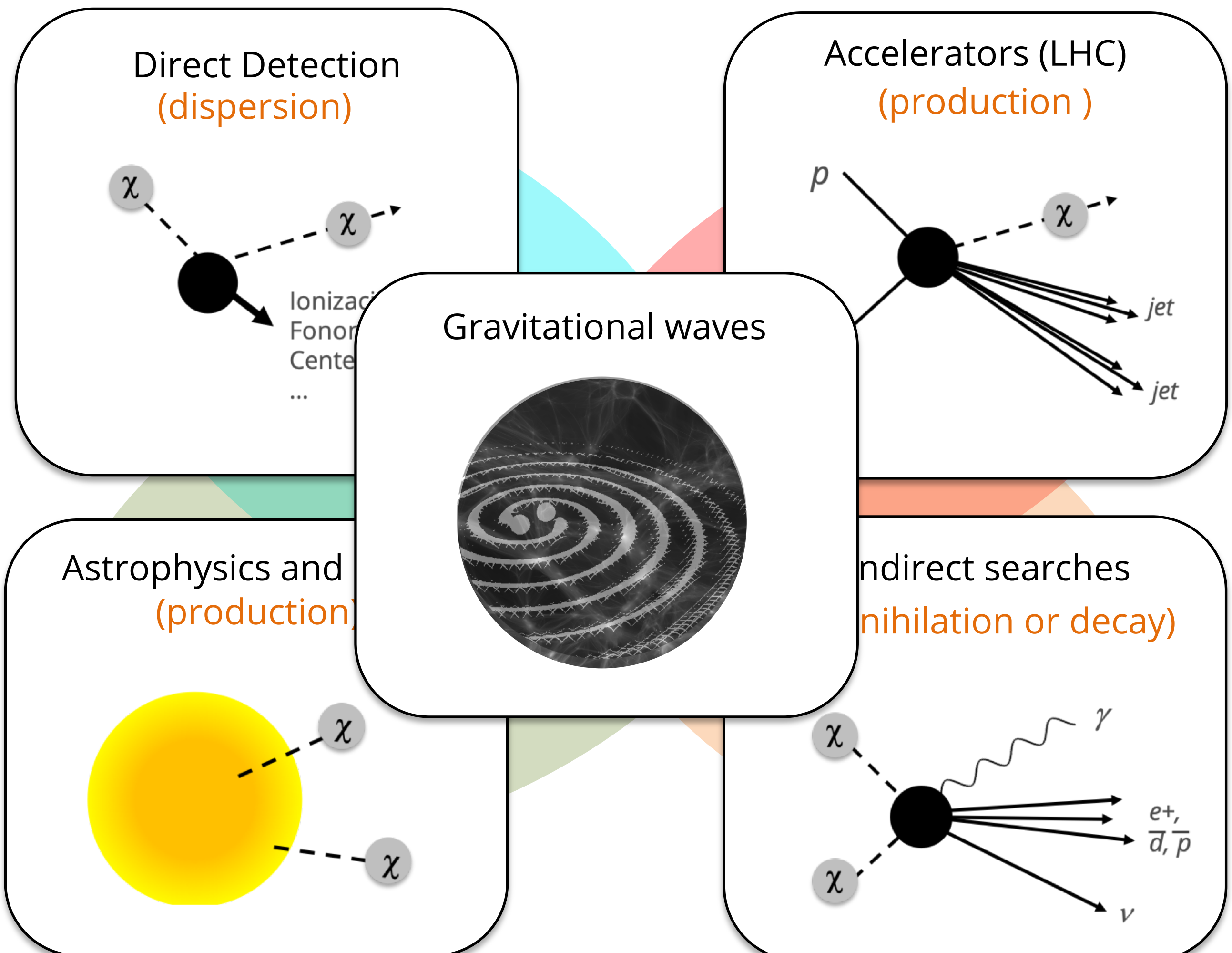
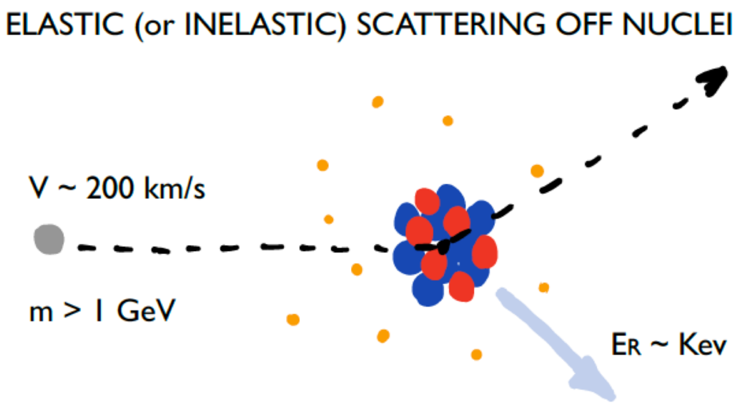
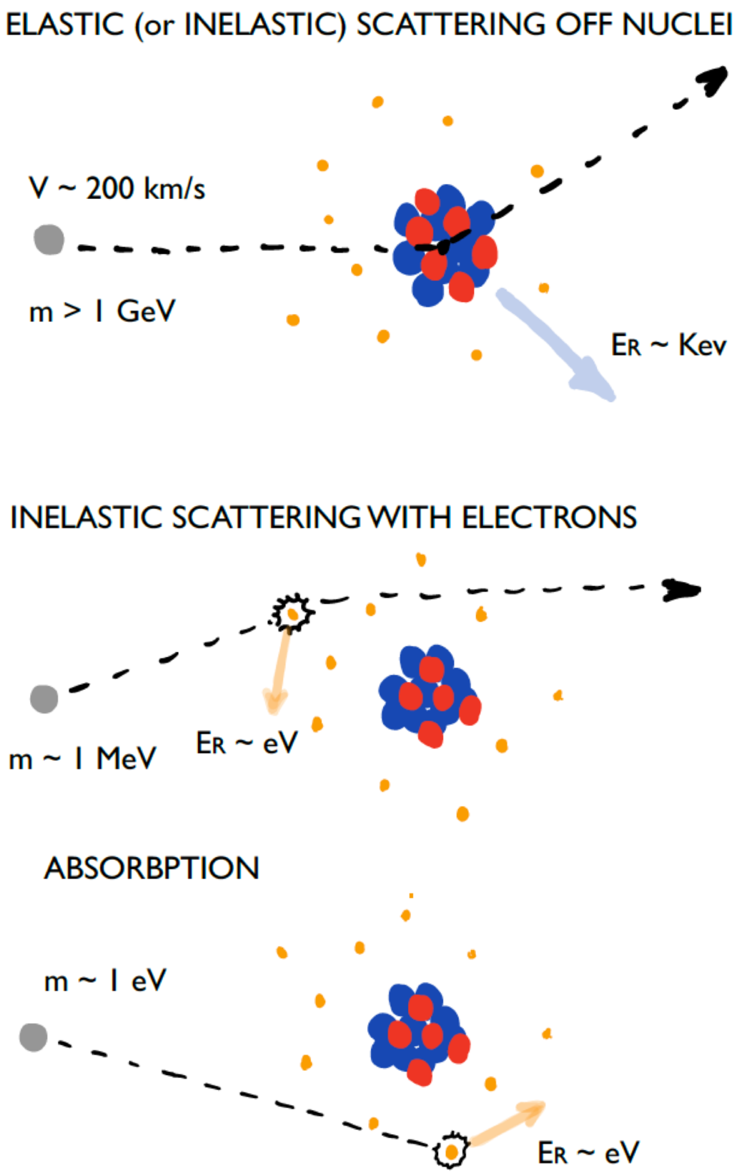




DIRECT DARK MATTER SEARCHES:
What can we measure?

NUCLEAR SCATTERING

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



DIRECT DARK MATTER SEARCHES: What can we measure?

NUCLEAR SCATTERING

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ELECTRON SCATTERING

- Sensitive to light WIMPs

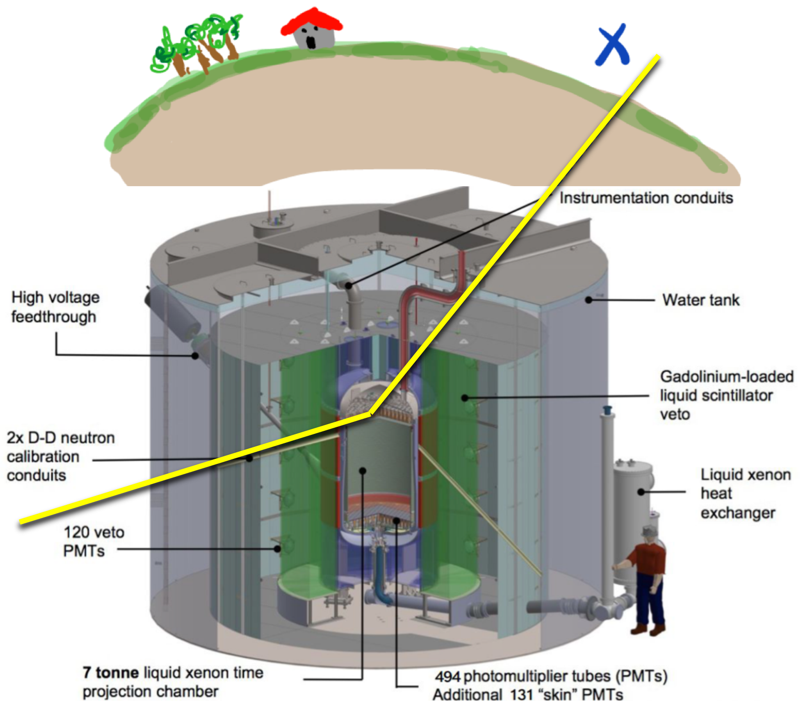
ELECTRON ABSORBPTION

- Very light (non-WIMP)

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)

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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

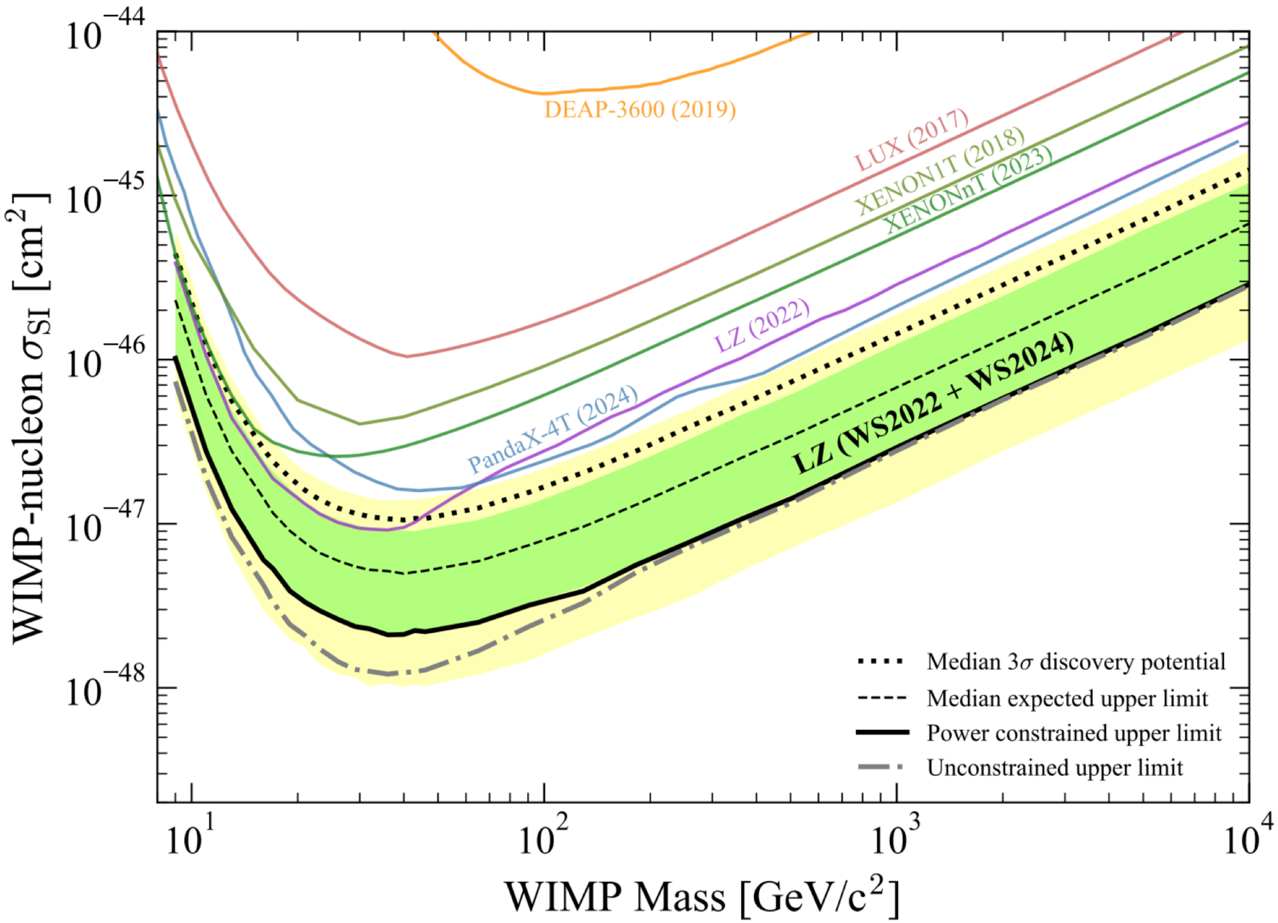
$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

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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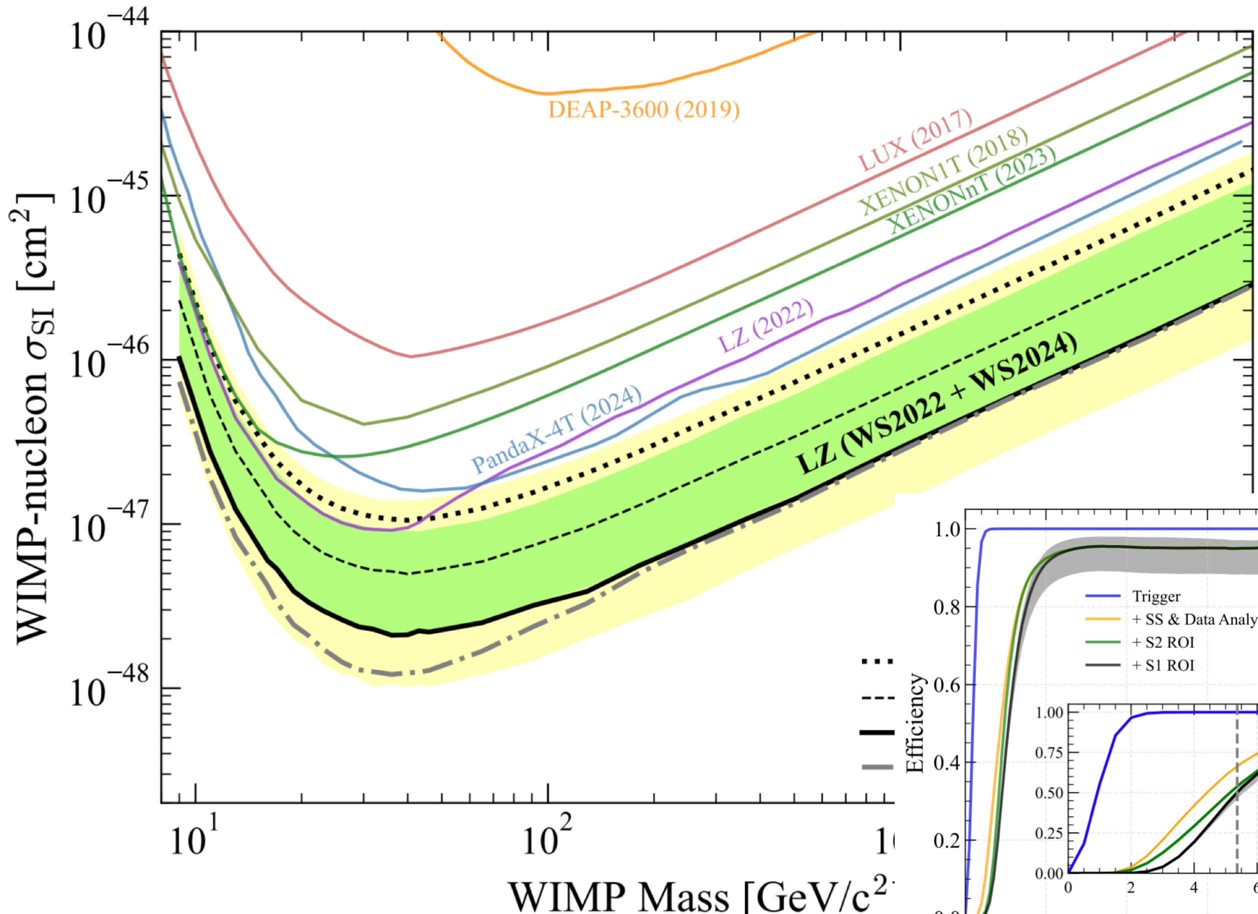
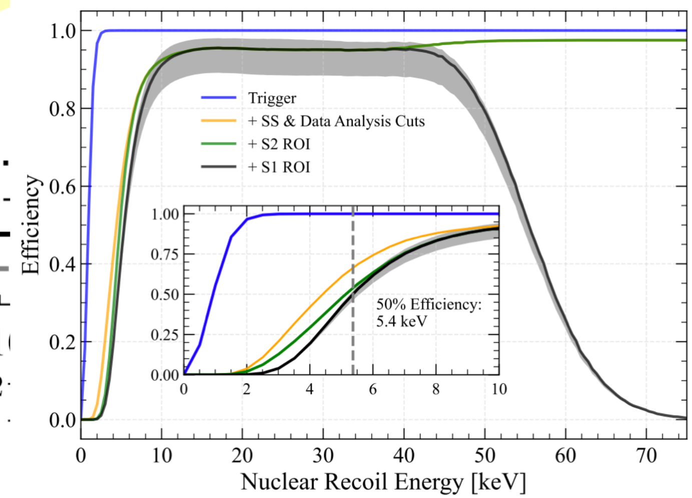
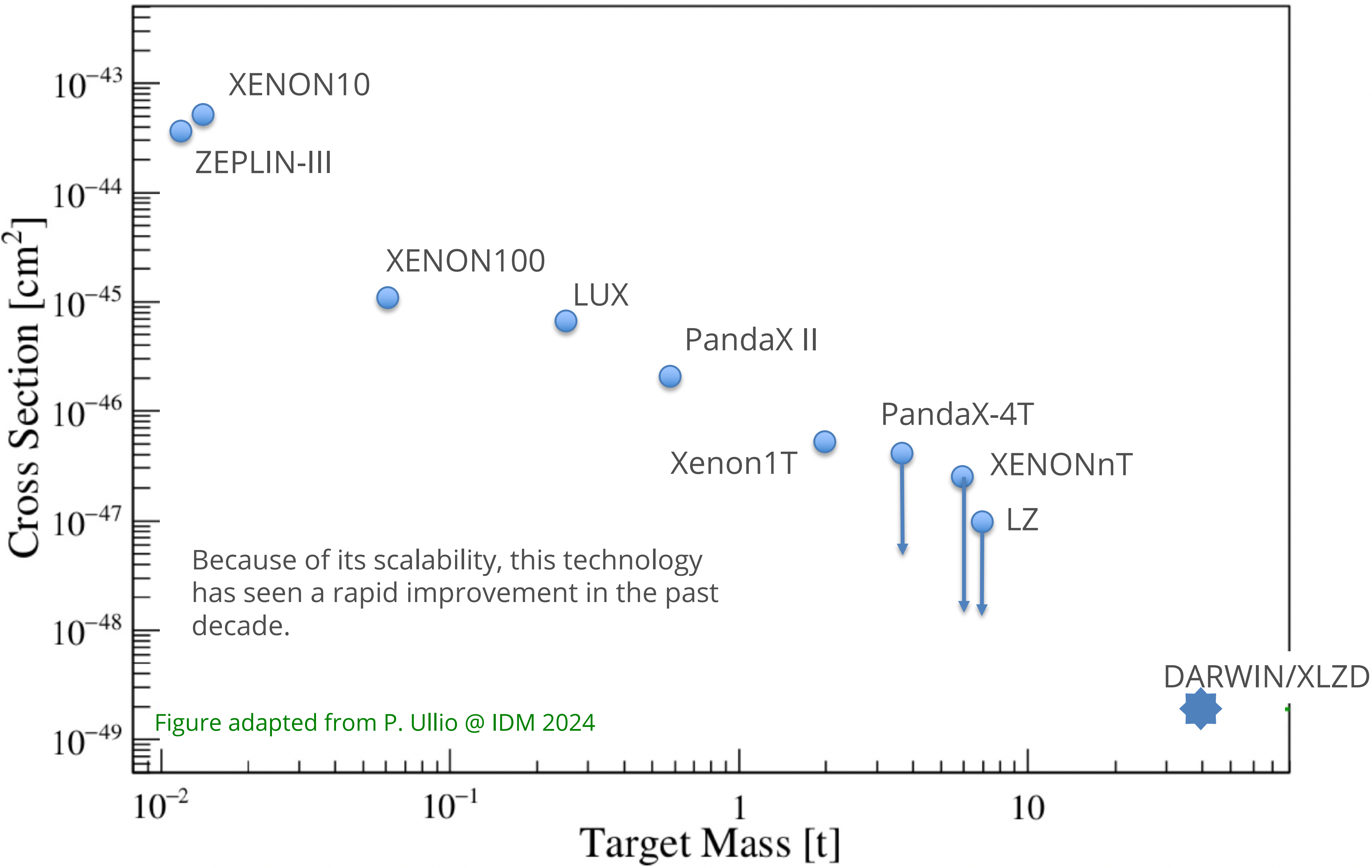


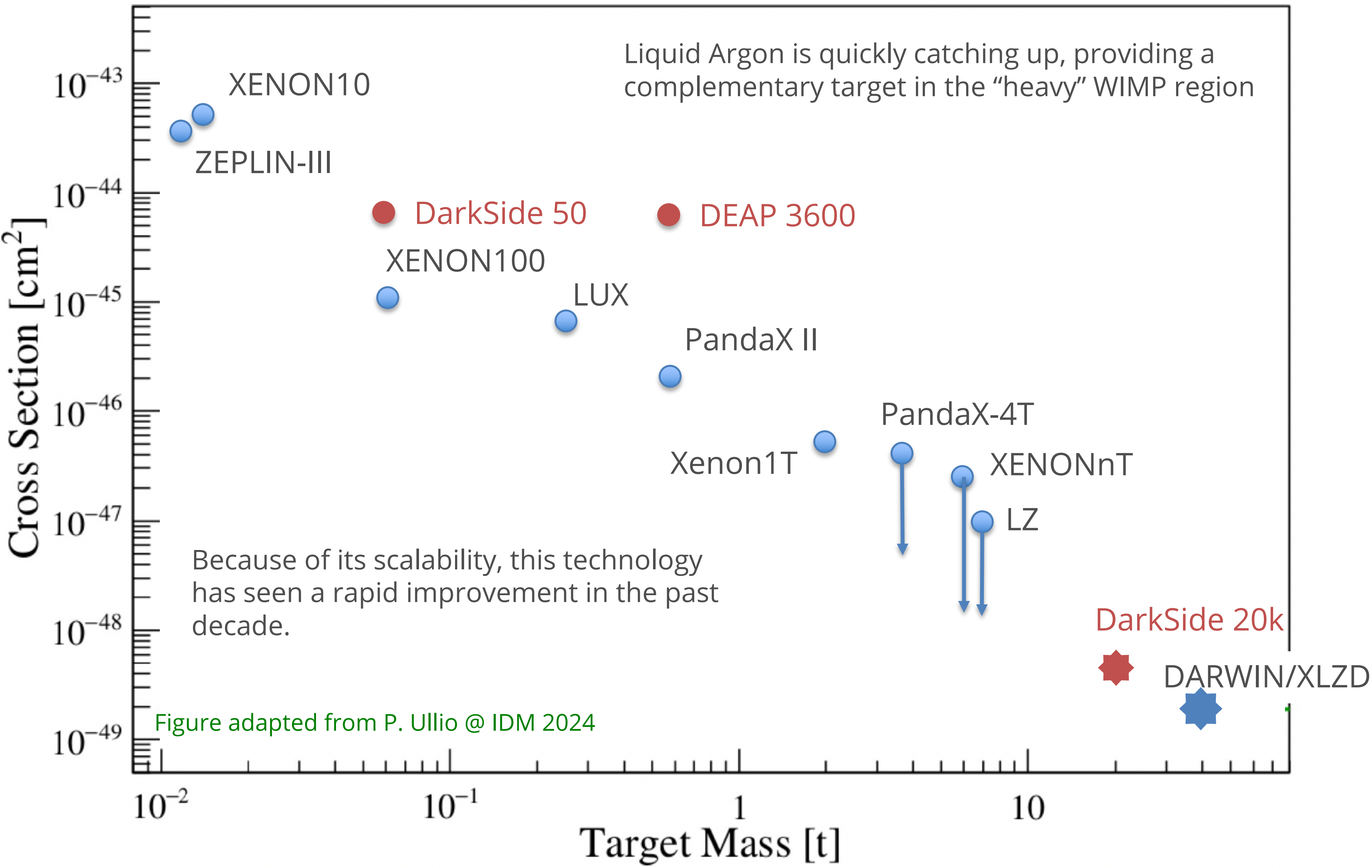
4.2 ton y

Eth = 5.4 keV
Emax ~60 keV





Cross Section [cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
XENON10
ZEPLIN-III
XENON100
LUX
PandaX II
PandaX-4T
Xenon1T
XENONnT
LZ
DARWIN/XLZD
Because of its scalability, this technology has seen a rapid improvement in the past decade.
Figure adapted from P. Ullio @ IDM 2024
10^{-2}
10^{-1}
1
10
Target Mass [t]


Liquid Argon is quickly catching up, providing a complementary target in the “heavy” WIMP region
XENON10
ZEPLIN-III
DarkSide 50
DEAP 3600
XENON100
LUX
PandaX II
PandaX-4T
Xenon1T
XENONnT
LZ
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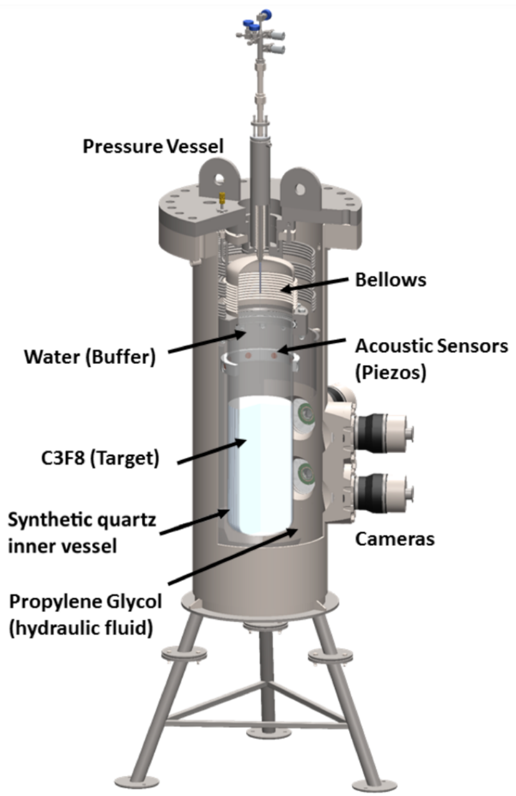
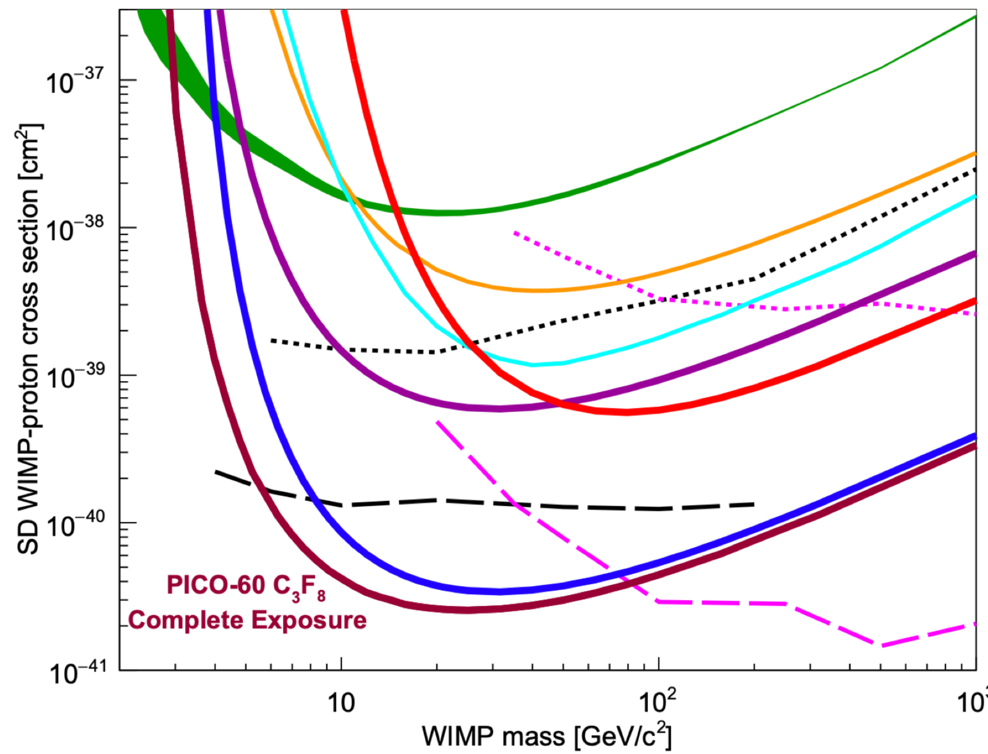
Limits on Spin-dependent cross section

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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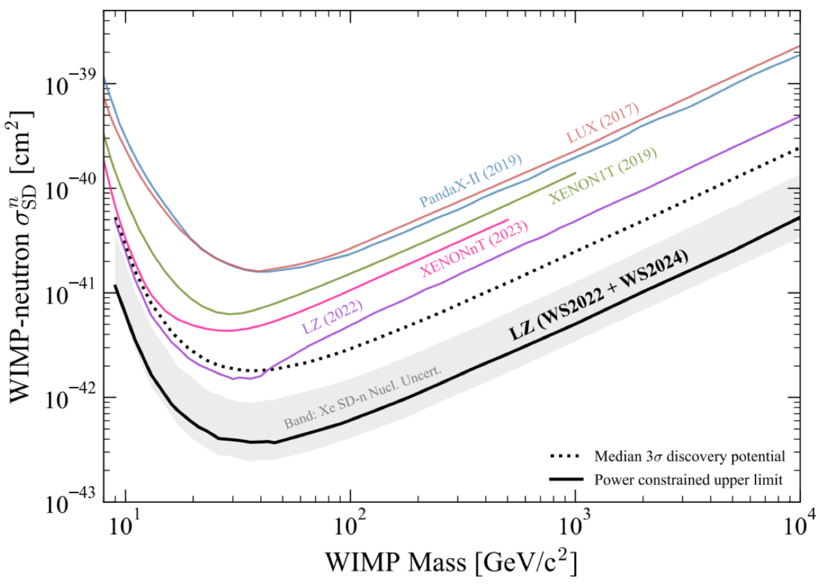

Two isotopes have non-zero nuclear spin: ^{129}Xe (4% isotopic abundance) and ^{131}Xe (21.2%).

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

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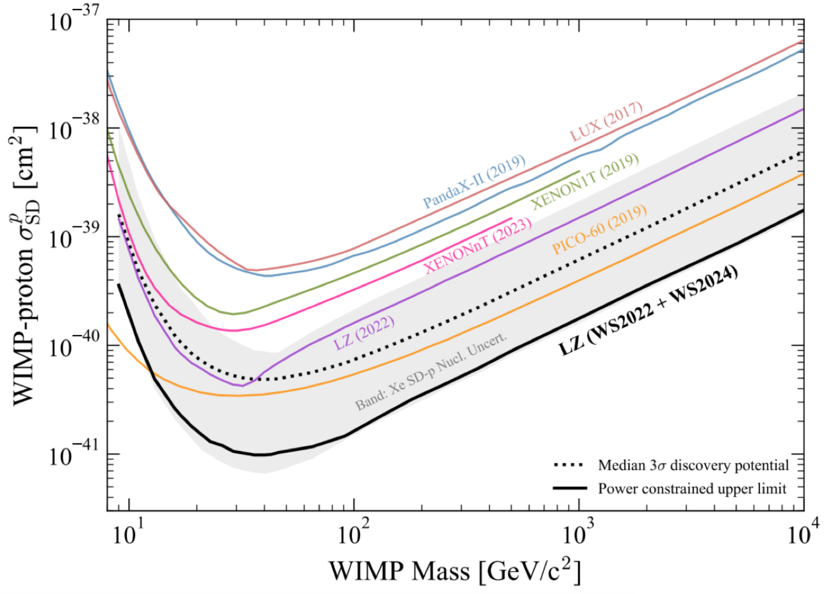
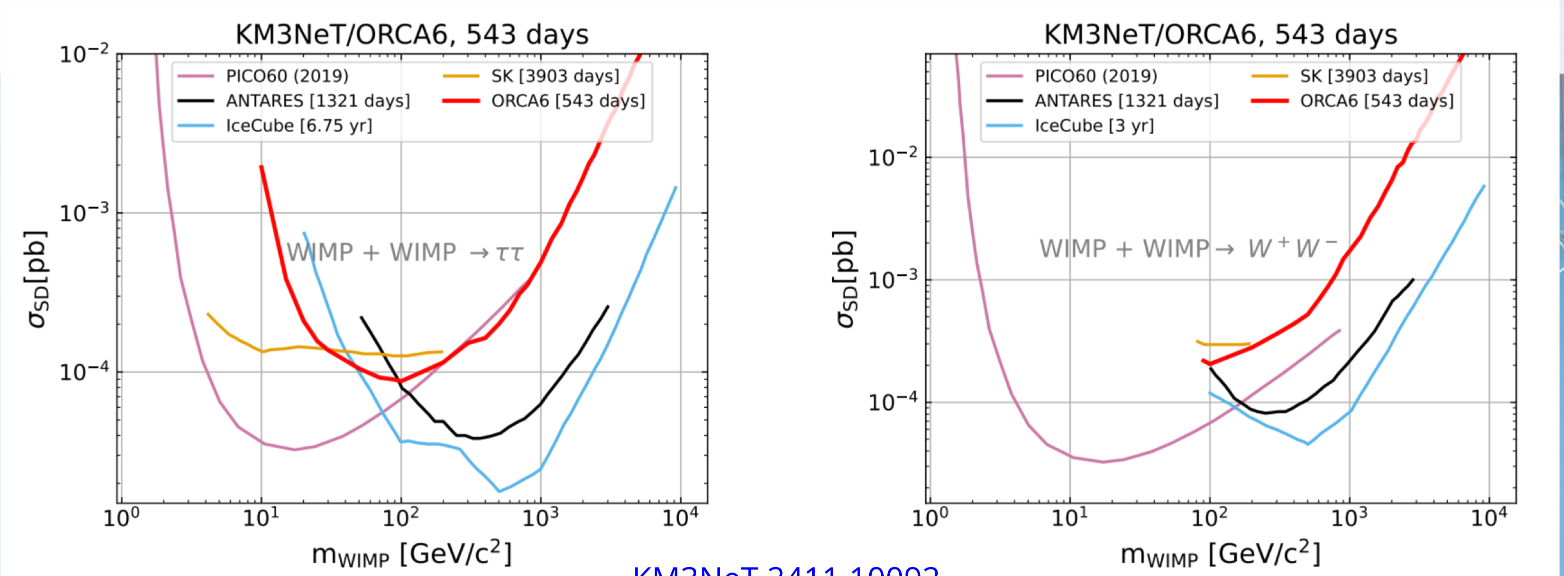
Sensitivity to **SD proton** interaction is possible through mixing between proton and neutron spin states (but with large uncertainty)

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



Limits on Spin-dependent cross section

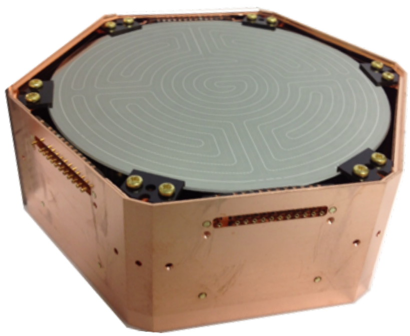
Indirect detection limits from dark matter annihilation in the Sun by **IceCube**, **Antares**, and more recently **KM3NeT/ORCA6** lead the SDp bounds at larger masses.



KM3NeT 2411.10092

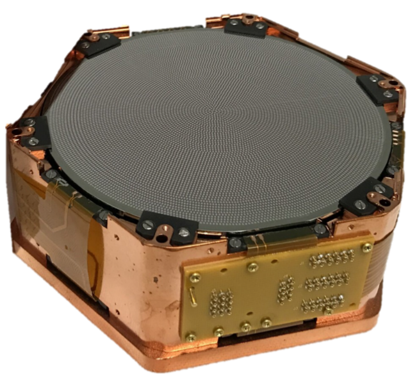
Low-threshold experiments can look for ~ GeV scale DM

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

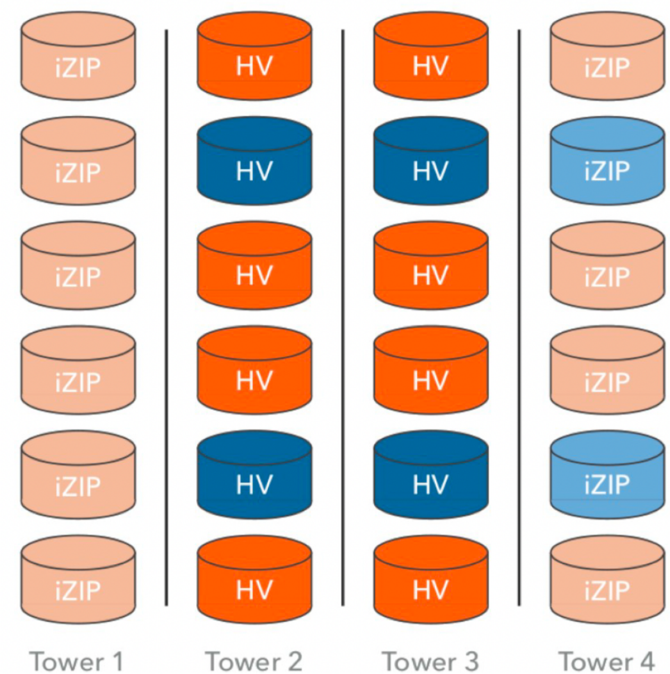
Excellent discrimination between nuclear recoils (NR) and electronic ones (ER) of $1/10^5$



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)



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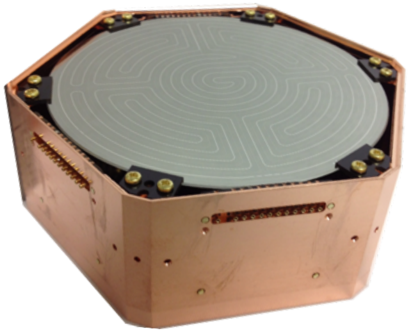
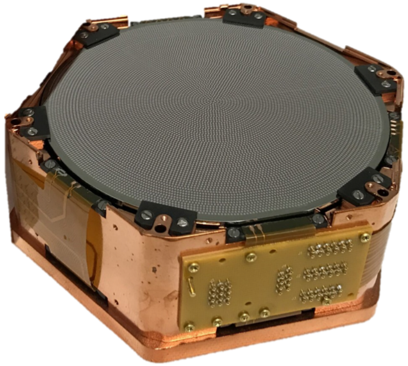
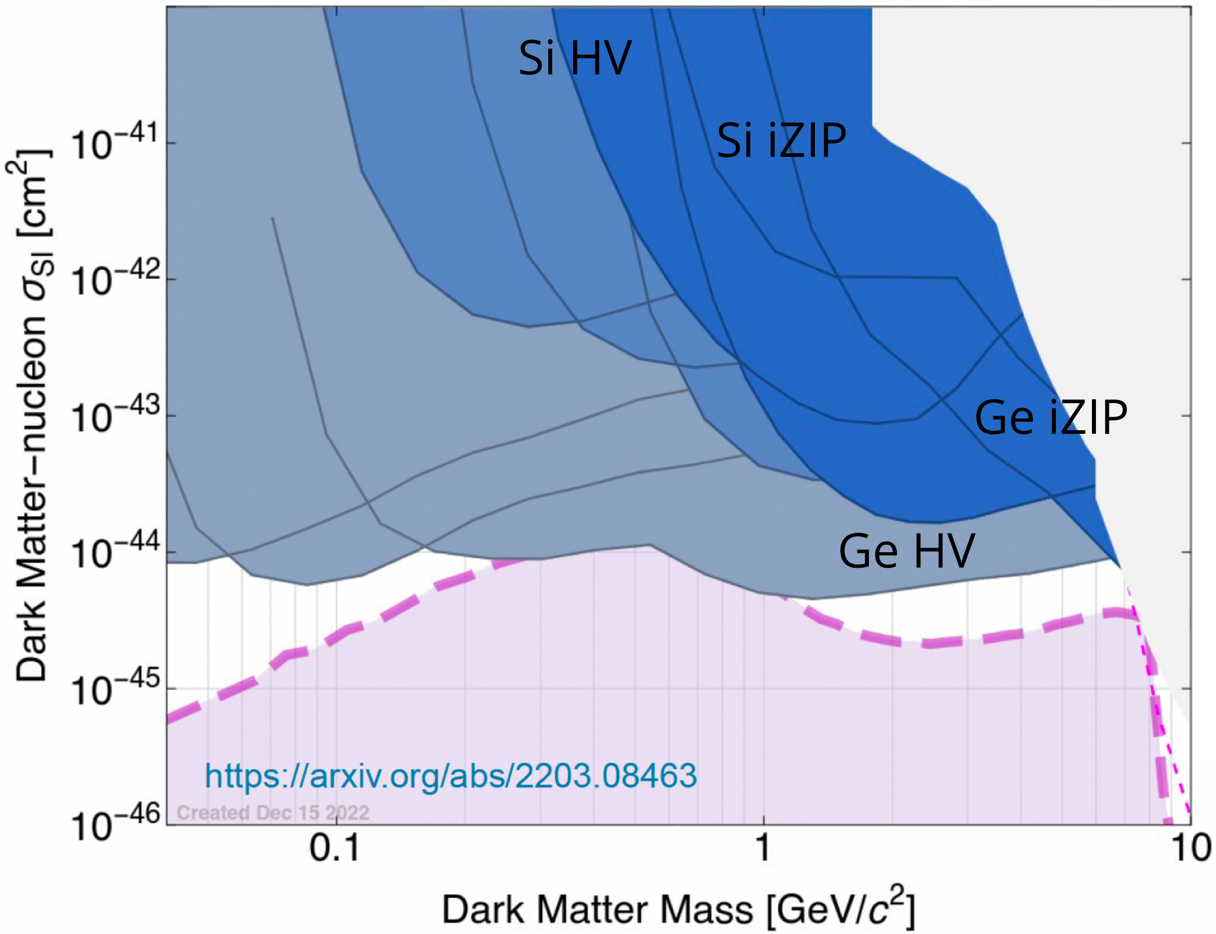


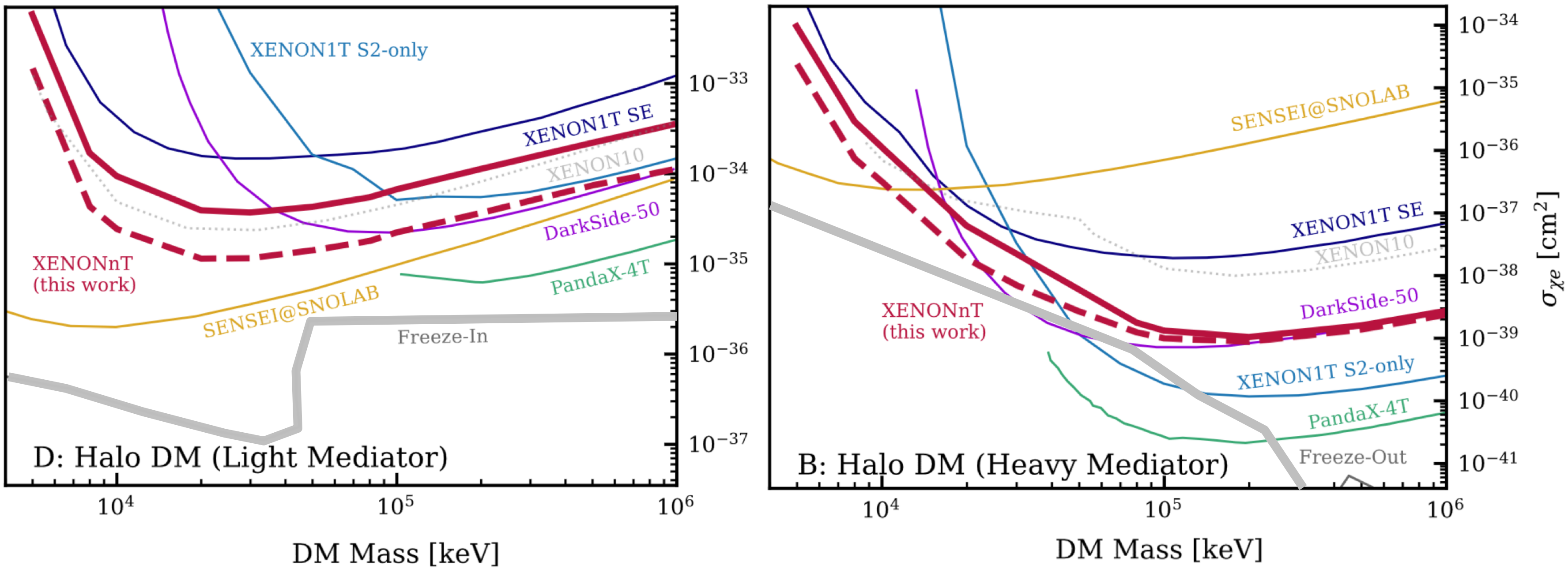




DM-Electron interactions allow to probe keV scale DM

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**

XENONnT 2411.15289



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

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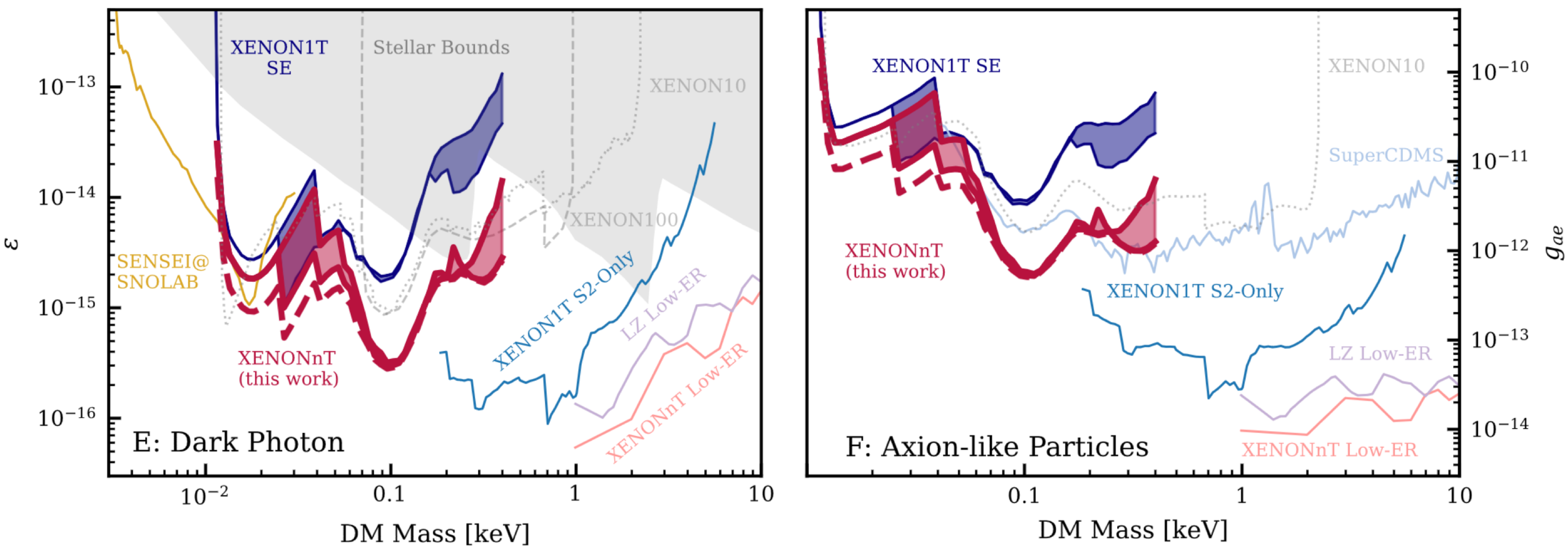
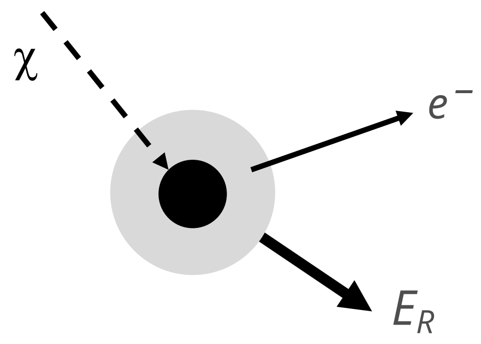


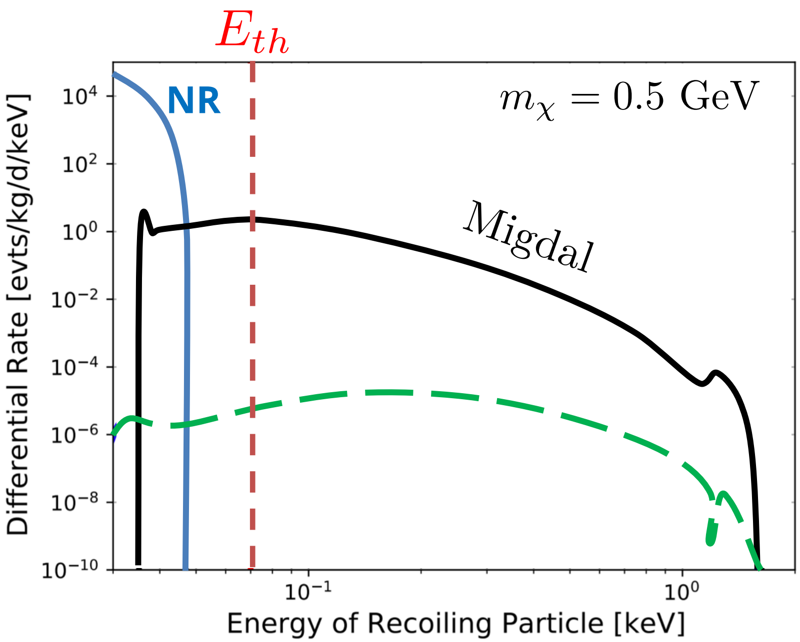
Also **dark photons** or **axion-like particles**!

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



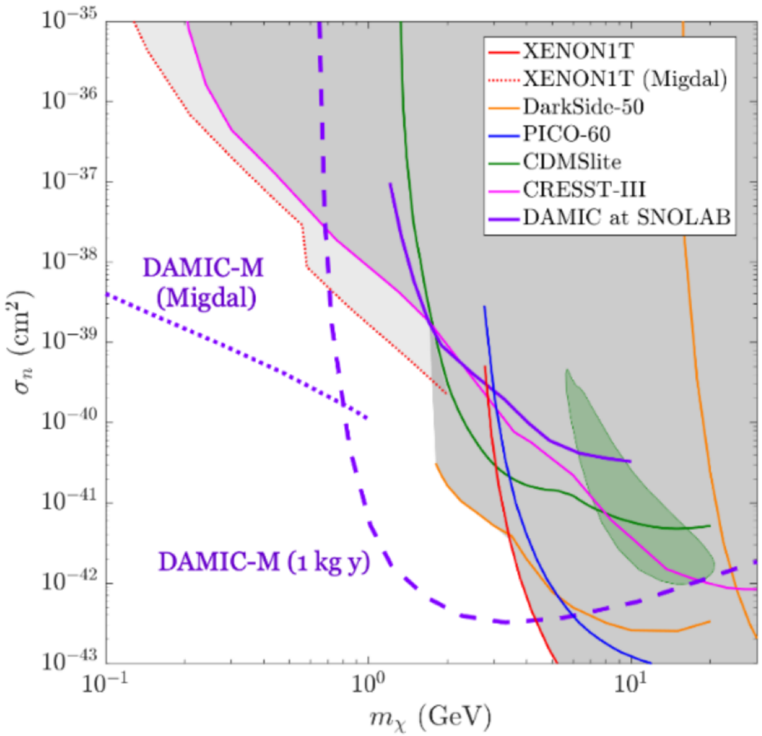


The emitted electron is easier to observe than the nuclear recoil (**NR**), as it is more energetic (and more easily exceeds the threshold energy)

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

It is **NOT new physics**, but it has not been observed yet.

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

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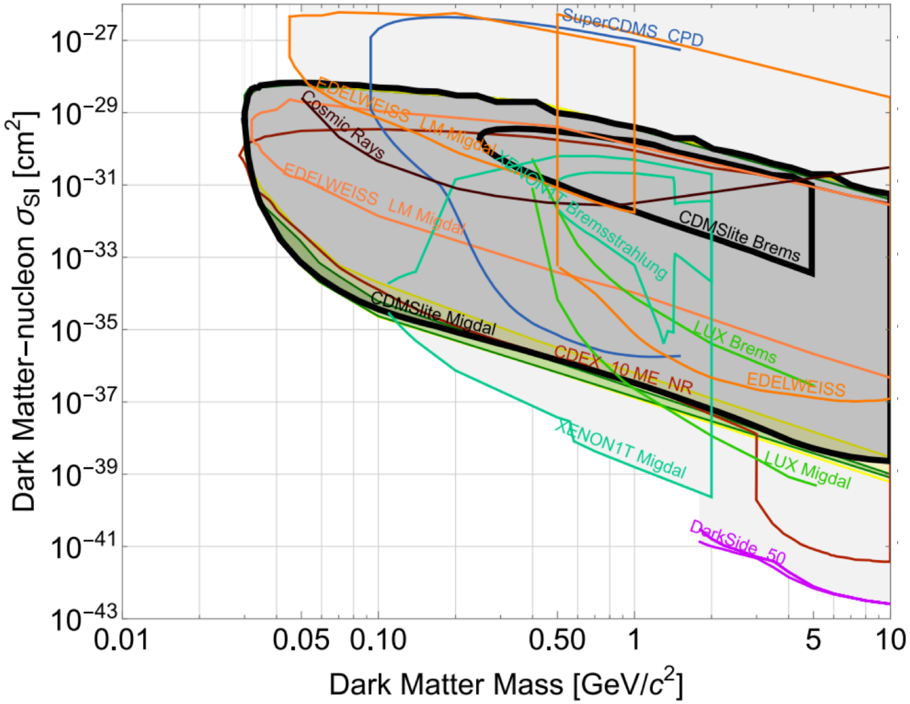

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This greatly improves the sensitivity to **low-mass WIMPs**, allowing to explore new regions!

If the Migdal effect is real, 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.

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.

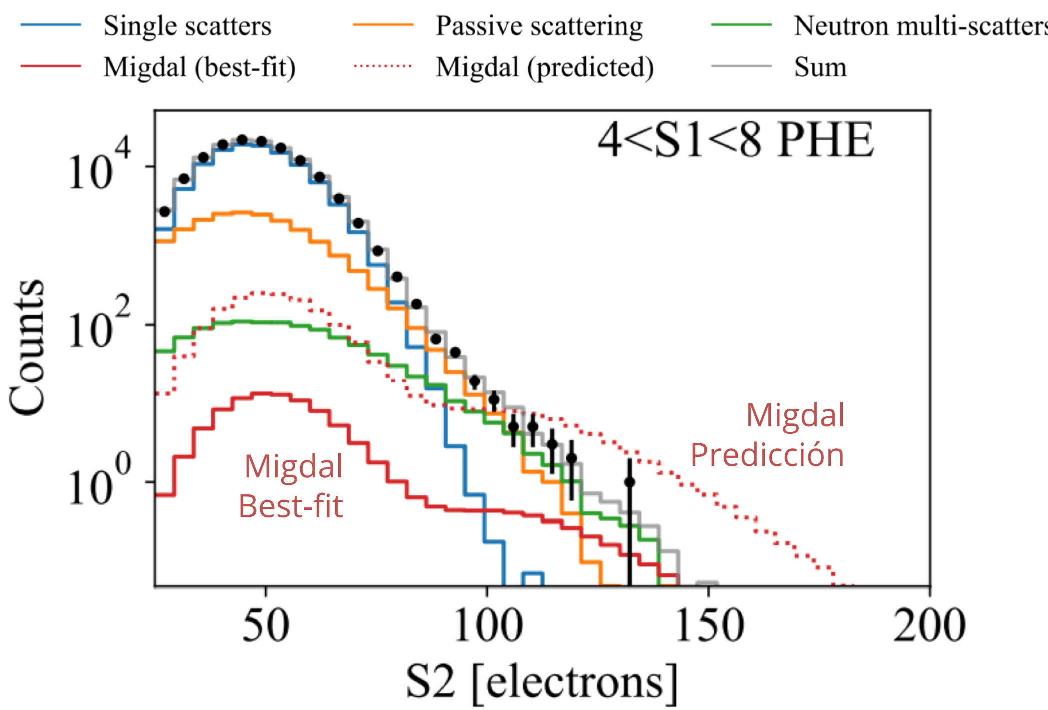
Bell et al. 2022

A recent search at the Livermore National Laboratory using XeNu TPC has not found it!

Xu et al. 2023

This could be due the electron-ion recombination in Xe (if the nuclear and electron tracks are near)…

… or to issues with the theoretical prediction.



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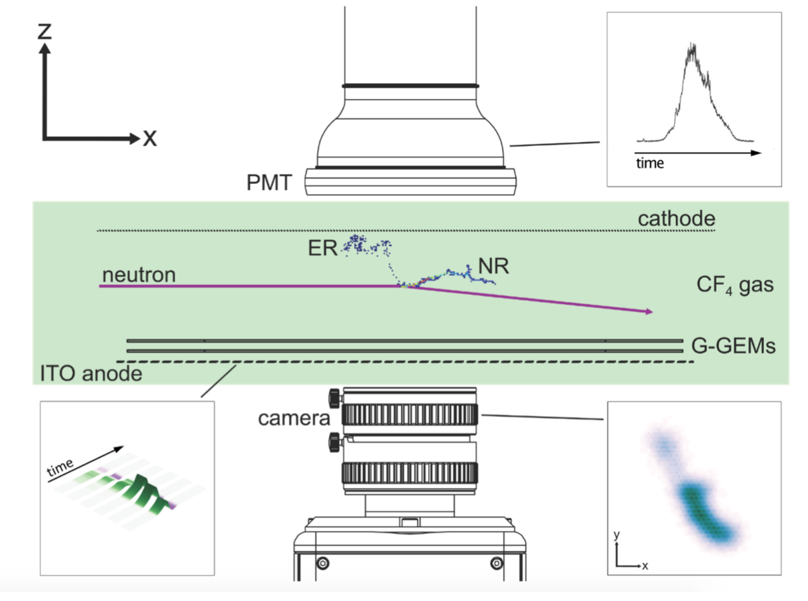
The **MIGDAL** collaboration is trying to measure this effect at the Rutherford Appleton Laboratory.

The 1st phase of the experiment is already running with a C_4F_{10} target.

A 2nd phase is planned to start in 2025 with updated primary scintillation detectors.



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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

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

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

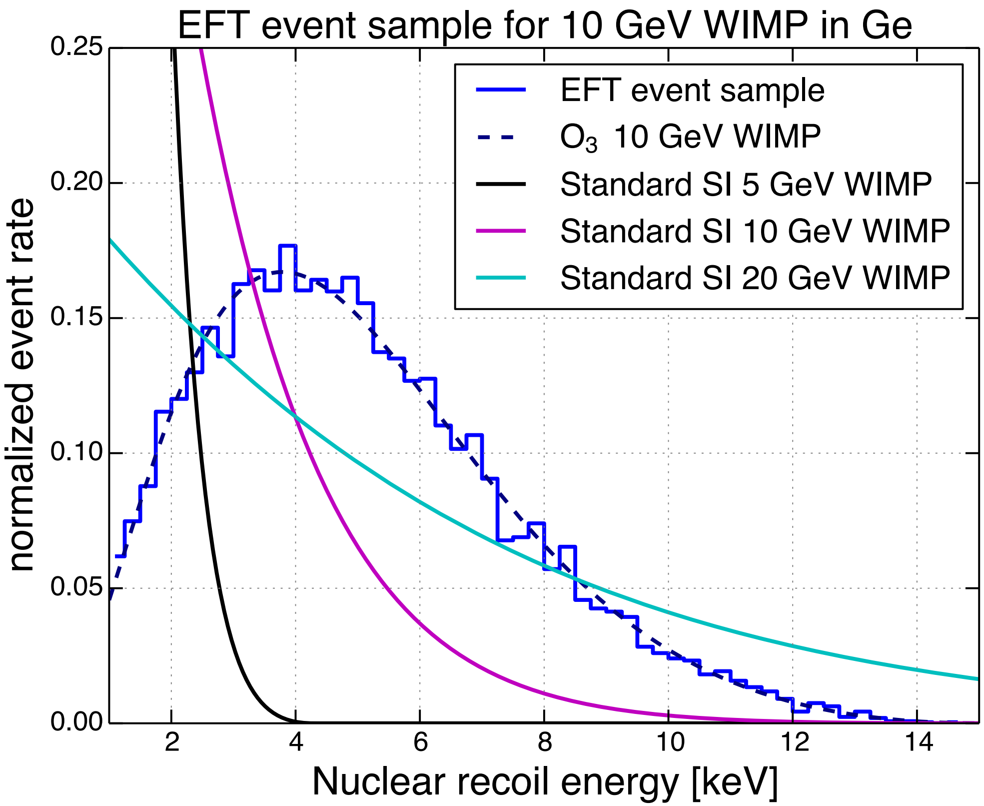
Haxton, Fitzpatrick 2012

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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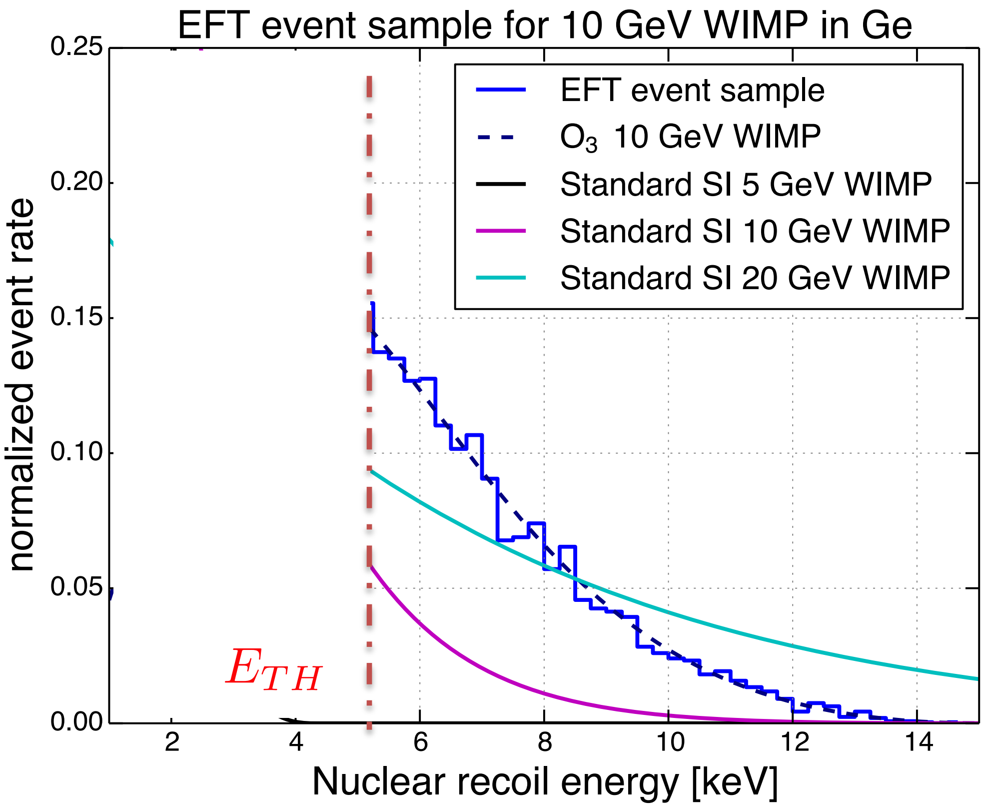

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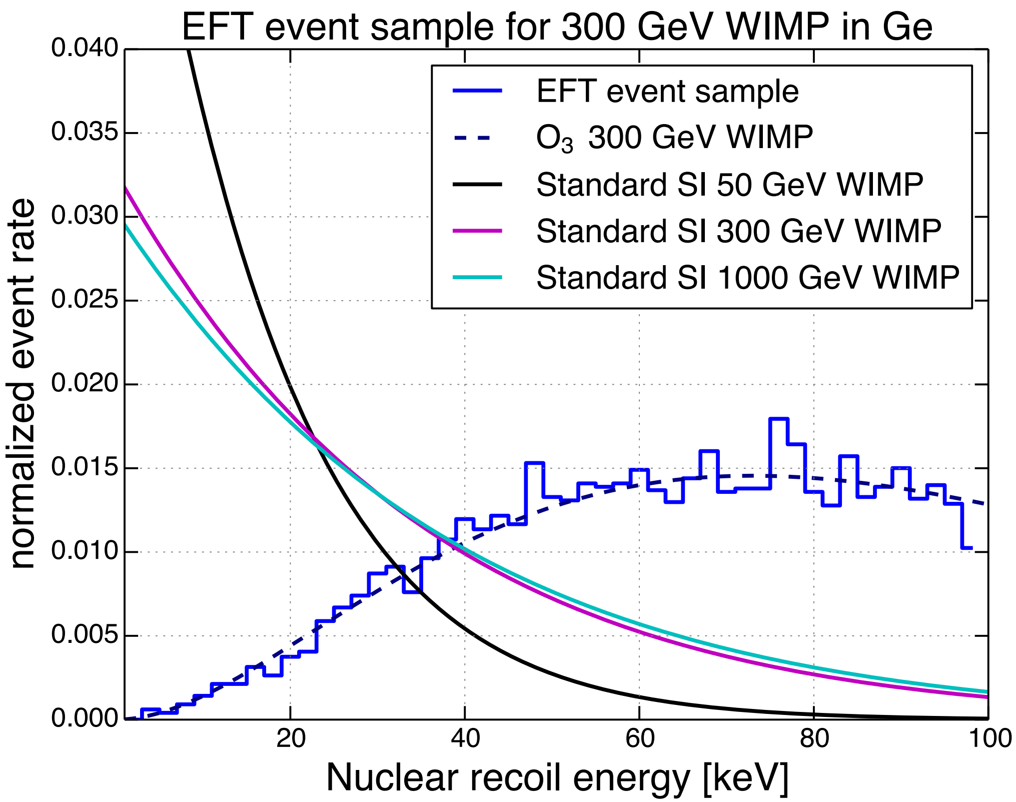
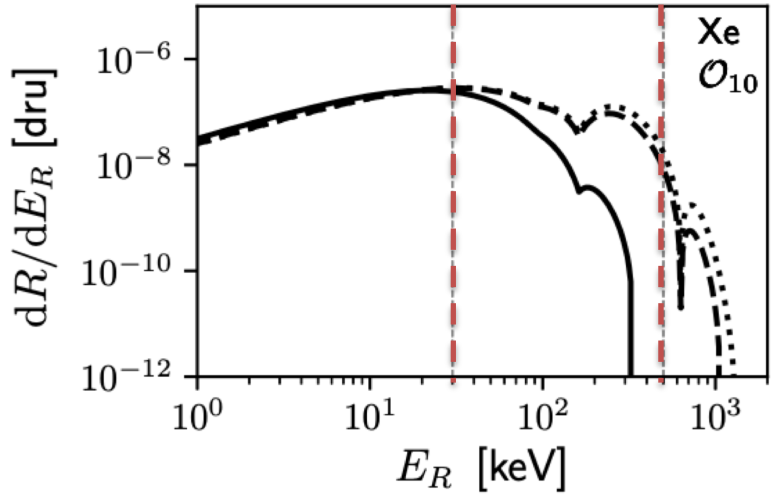
Some signatures could be confused with new sources of background.



Schneck et al [SuperCDMS] 2015

The resulting dark matter signature depends on the microphysics

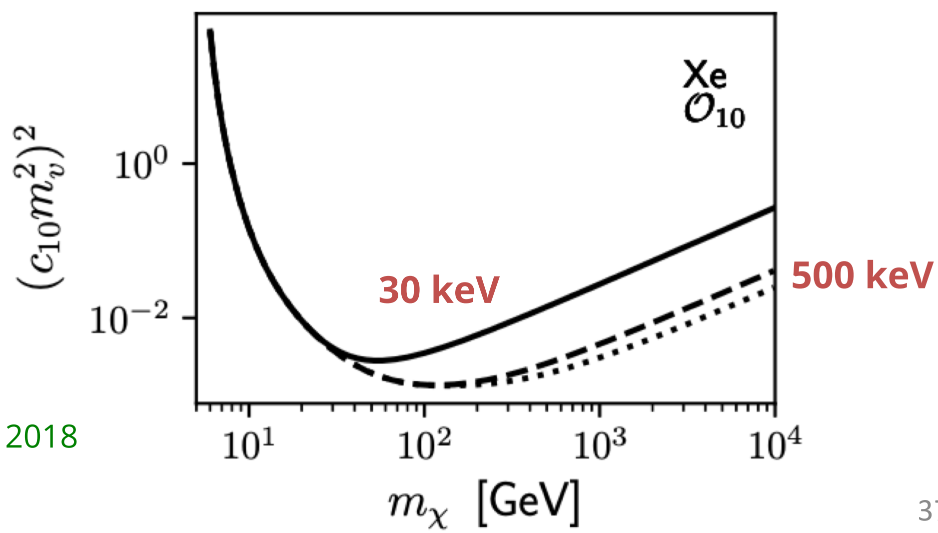
Different effective operators lead to characteristic spectra (especially if there is a momentum dependence)



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

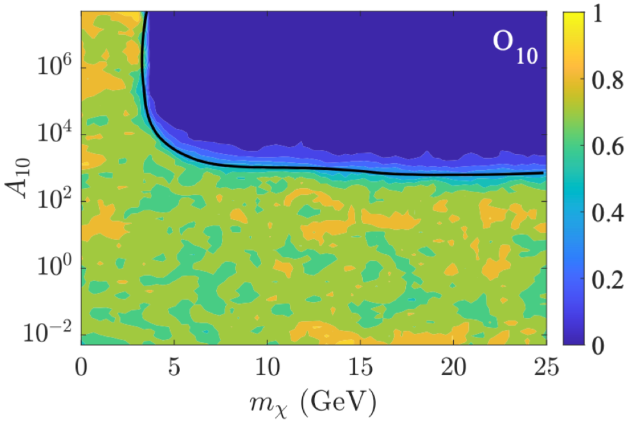


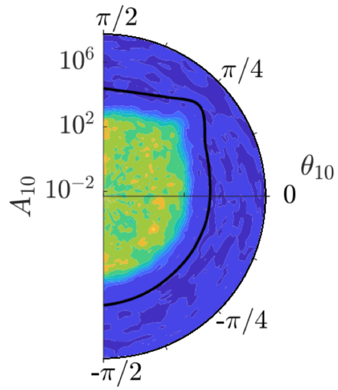
Enlarging the **maximum energy** in the signal region allows to set better constraints (or mass reconstruction)

Bozorgnia, DC, Cheek, Penning 2018

Experimental results on EFTs

SuperCDMS carried out an analysis with HV detectors (low threshold) and allowing for isospin violation



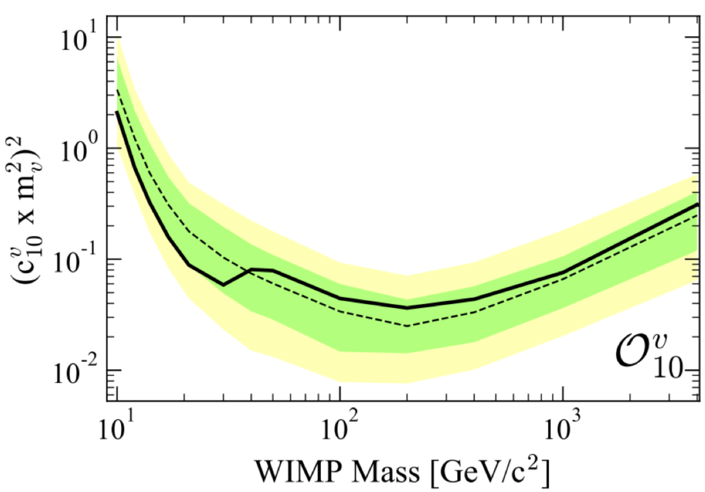


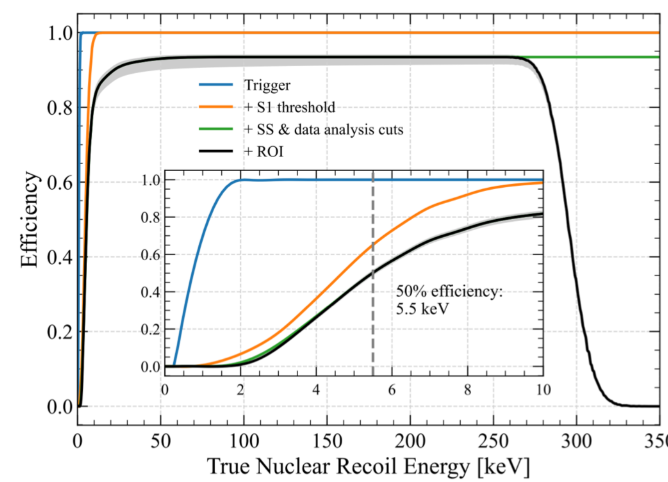
$$\sigma_1^0 = \frac{A^2 m_N^2}{4\pi \langle V \rangle^4 (1+A)^2} A_1$$

$$c_i^0 = A_i \sin(\theta_i)$$
$$c_i^1 = A_i \cos(\theta_i)$$

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

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

Dark matter halo parameters

Local density and DM velocity distribution function

Uncertainties in the halo parameters

Directionality and time-dependence (annual modulation)

Scattering cross section

Particle physics (dark matter model)

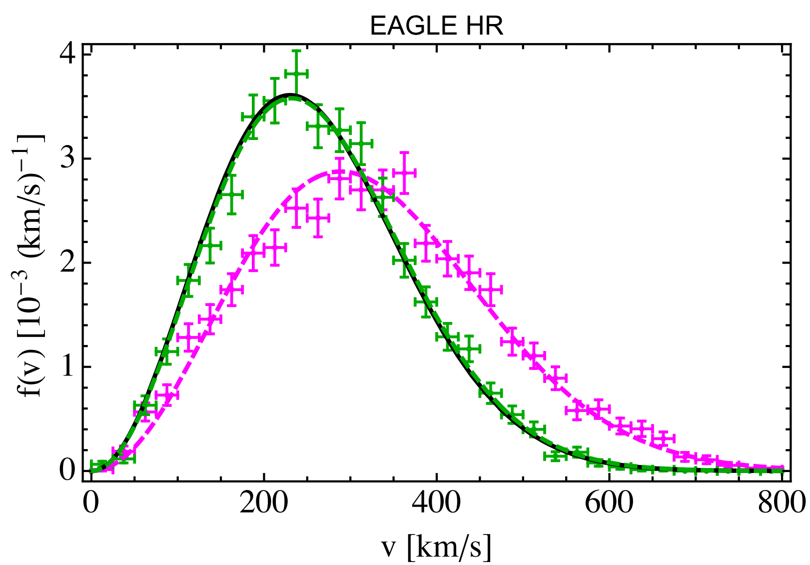
Nuclear Physics (form factors)

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

How well do we know our dark matter halo?

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

Astrophysics



- local DM density

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

- Velocity distribution of DM particles

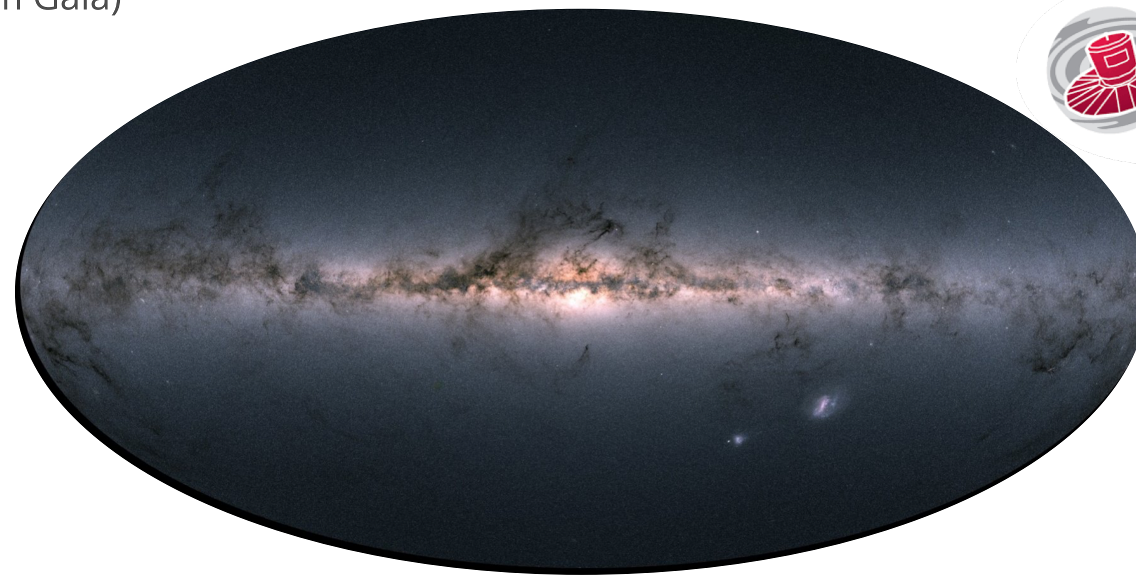
Maxwellian distribution is a good fit in the Milky Way

Bozorgnia et al. 1601.04707

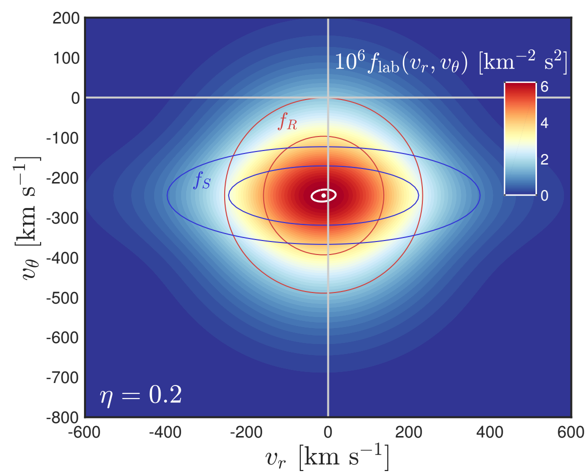
How well do we know our dark matter halo?

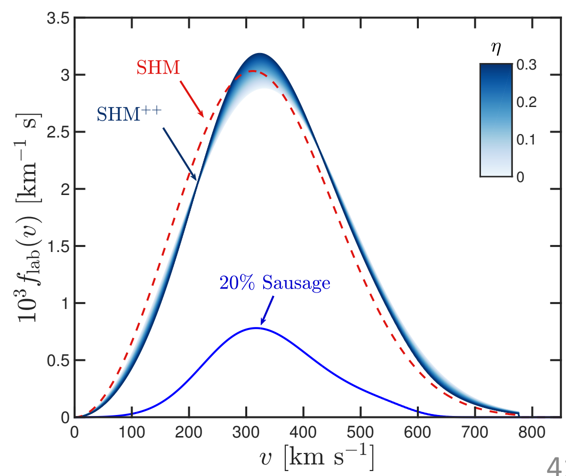
Most of what we know comes from comparing results from n-body simulations and observations (recently from Gaia)

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.





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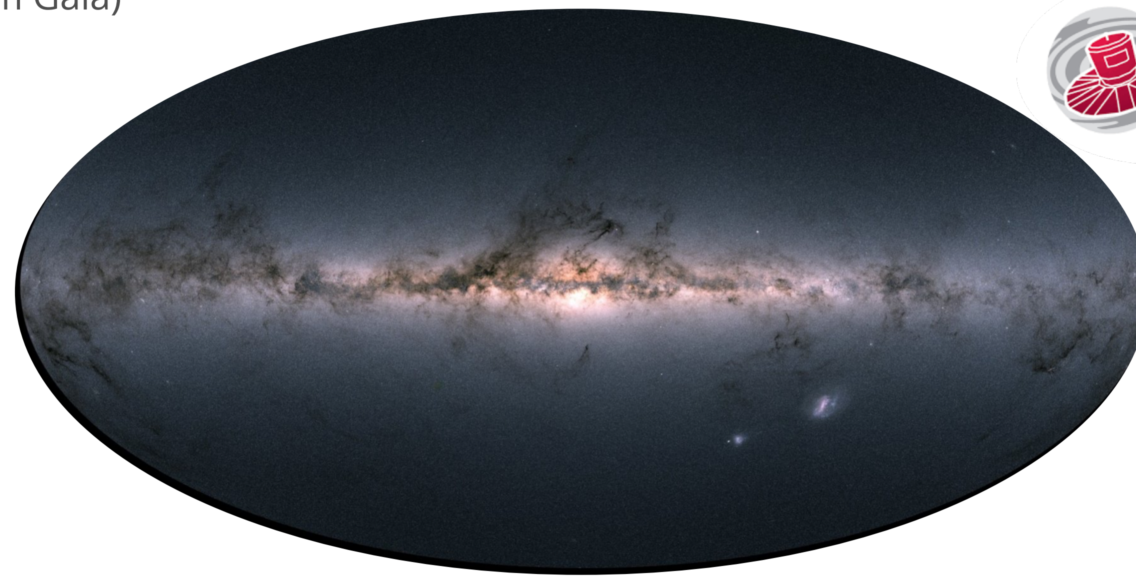

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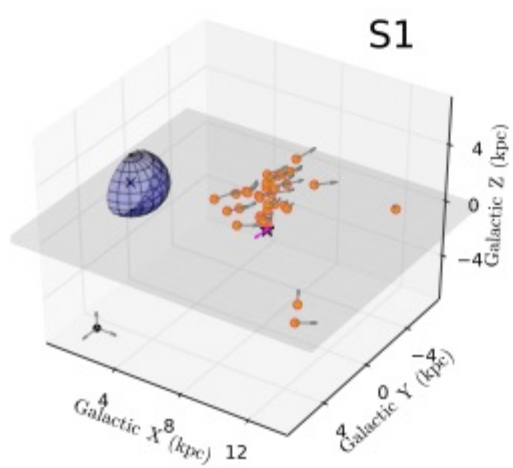

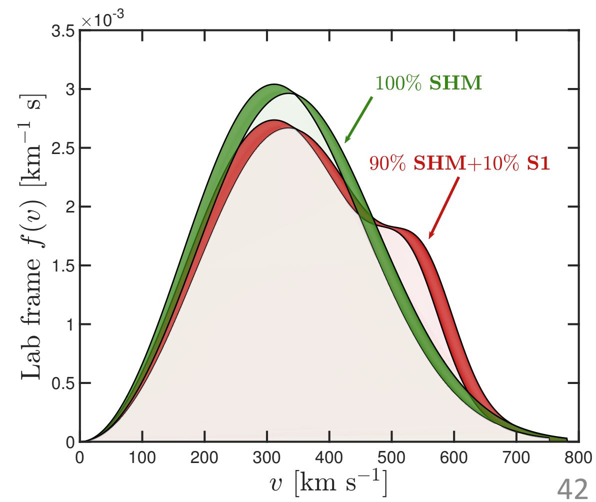

O'Hare, McCabe, Evans, Myeong, Berlokurov 2018

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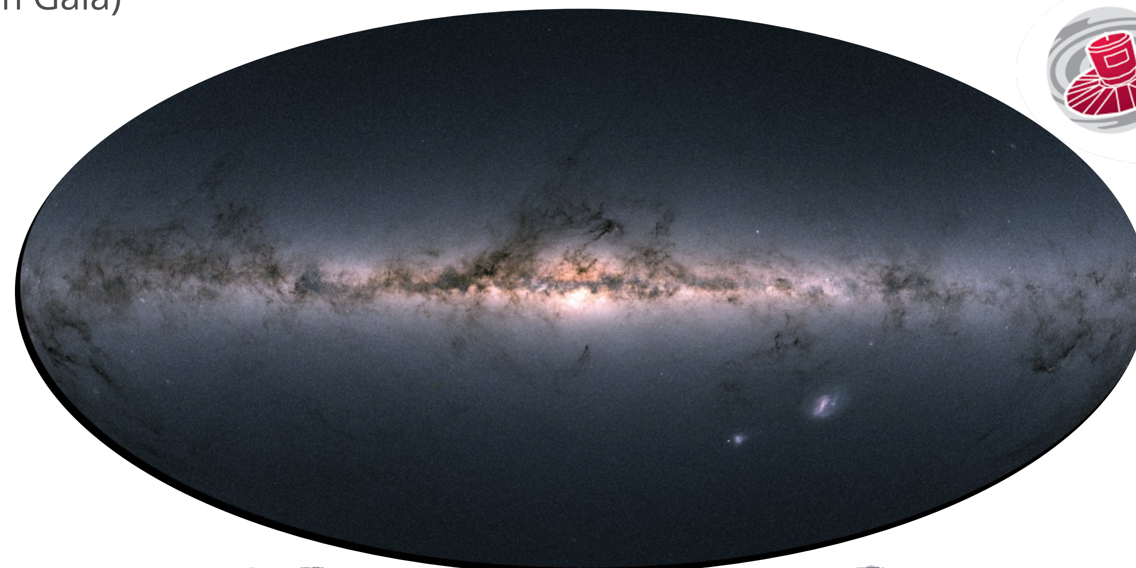
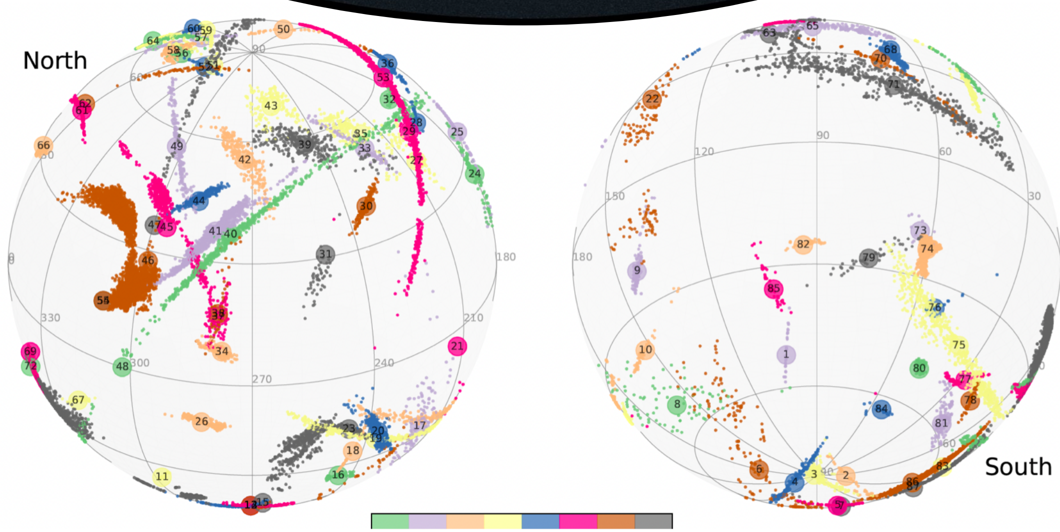


The **positions and velocities of 2000 million stars** in our Galaxy inform us about the dark matter distribution in the halo.

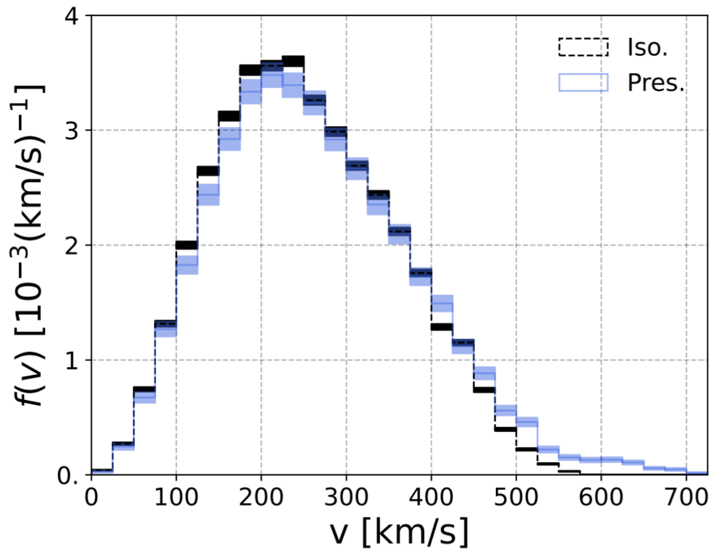
Several **non virialised components** have been identified that alter the DM velocity distribution function.

These impact direct detection limits.



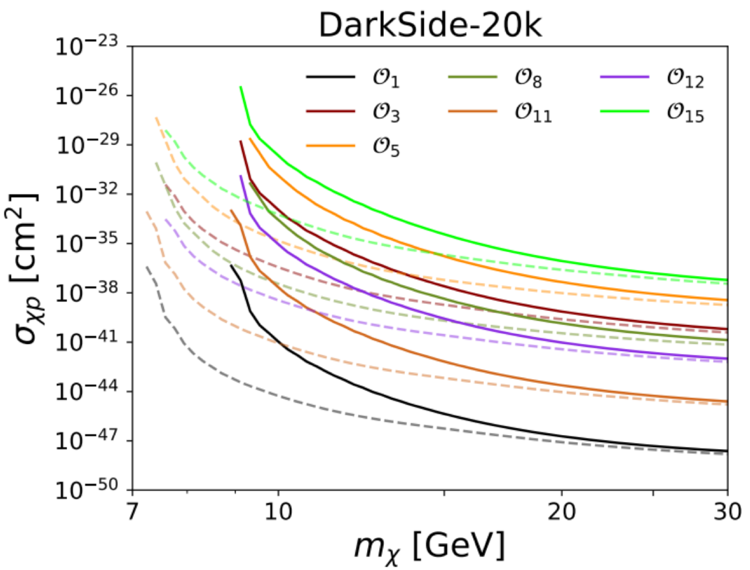
Ibata et al. 2023

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.



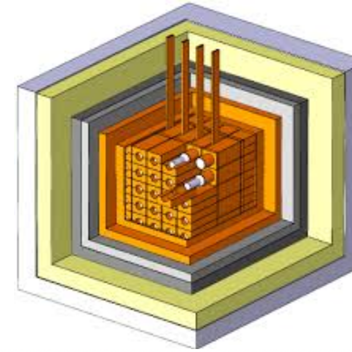
Limits are affected, and can extend well below 10 GeV.

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

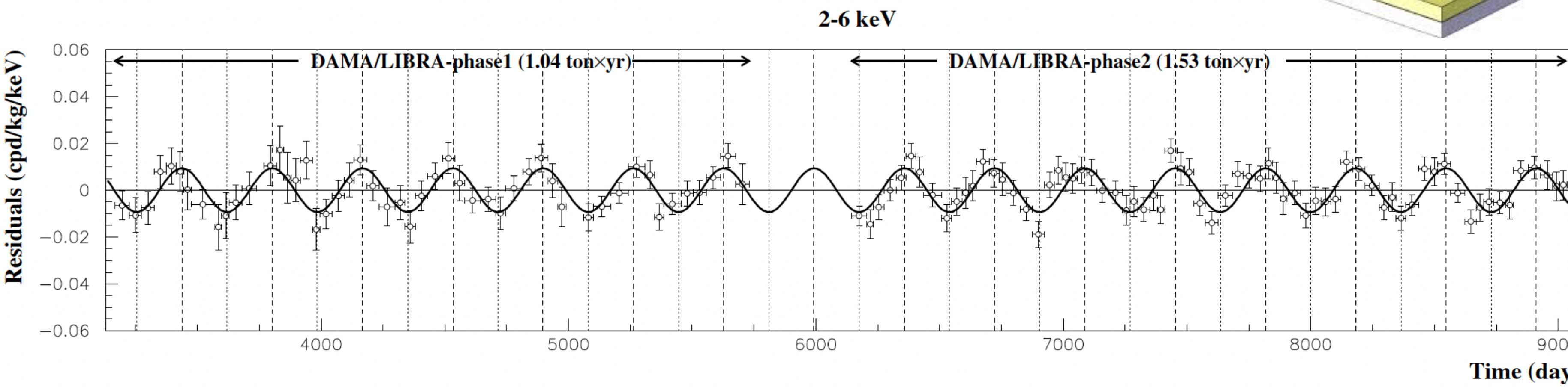


Reynoso-Cordova, Bozorgnia, Piro 2024

Annual Modulation of dark matter direct detection



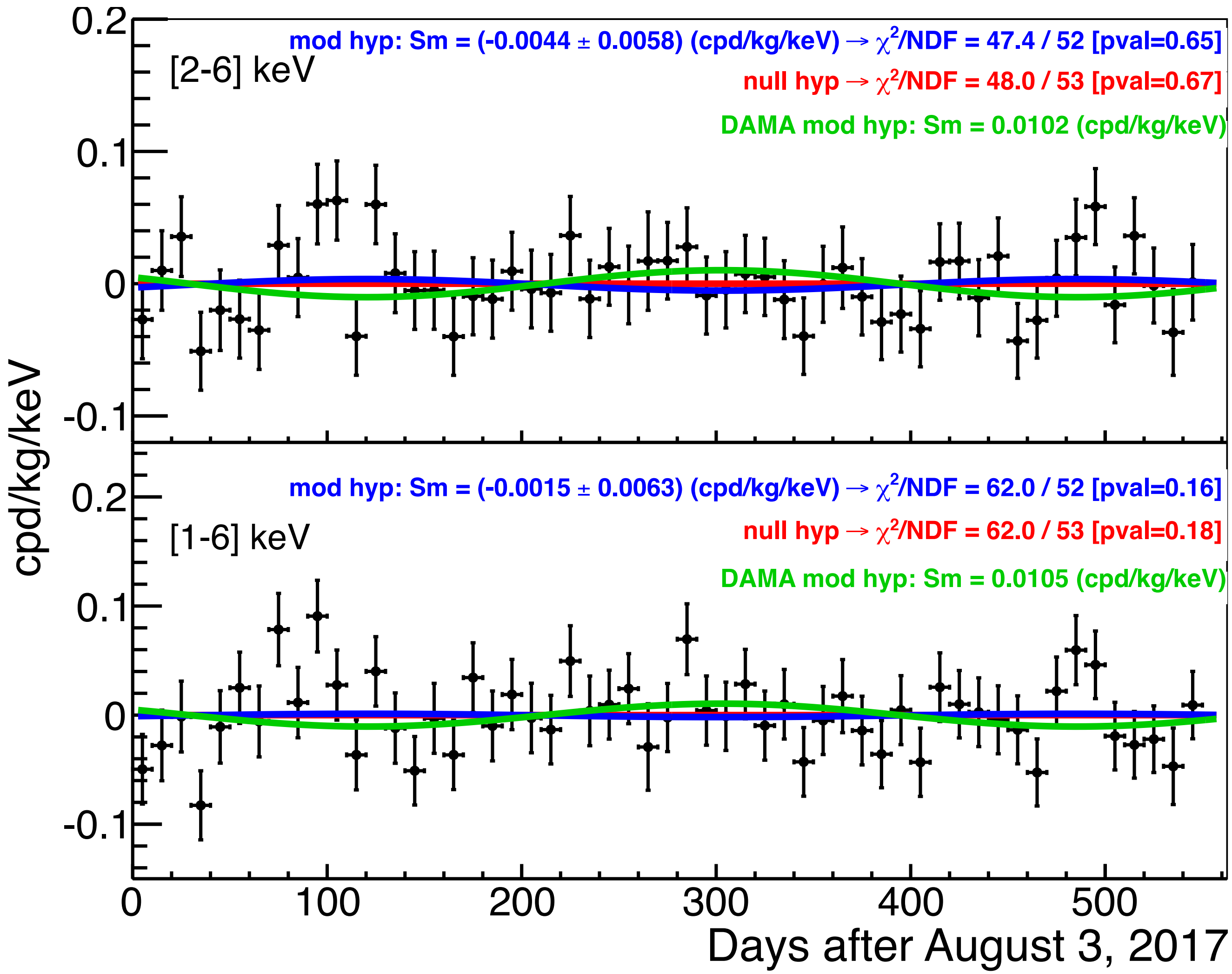
The DAMA/LIBRA (NaI) collaboration has reached 2.86 ton yr over 22 annual cycles. It observes a clear modulation in the [1-6] and [2-6] keV regions with very high CL (13.7 σ)



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)

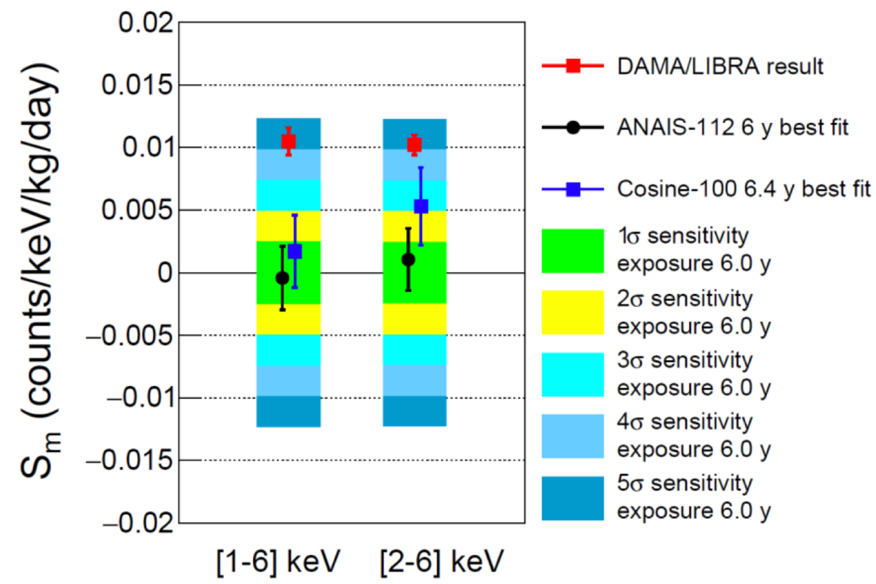


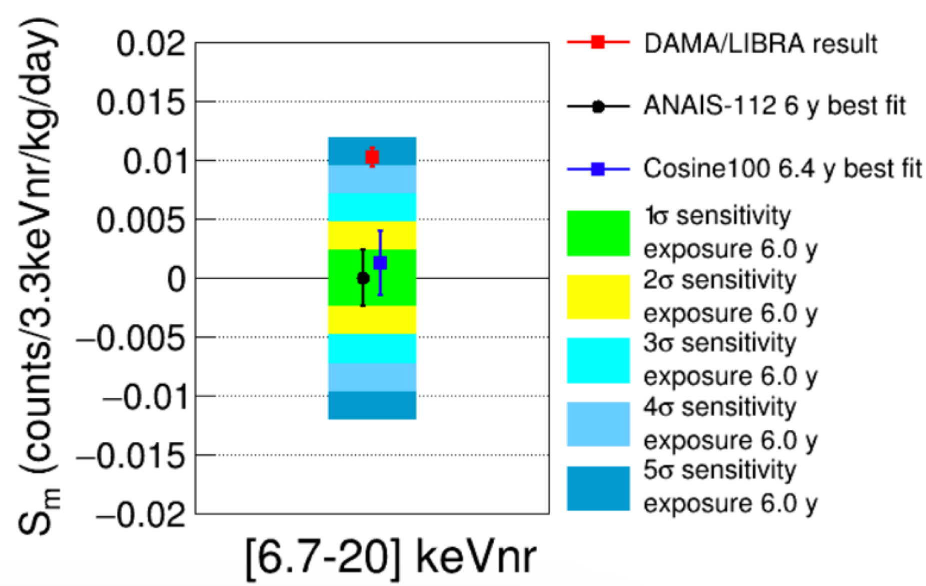
ANAIS 6y and COSINE 6.4y

Results from ANAIS and COSINE show no modulation.

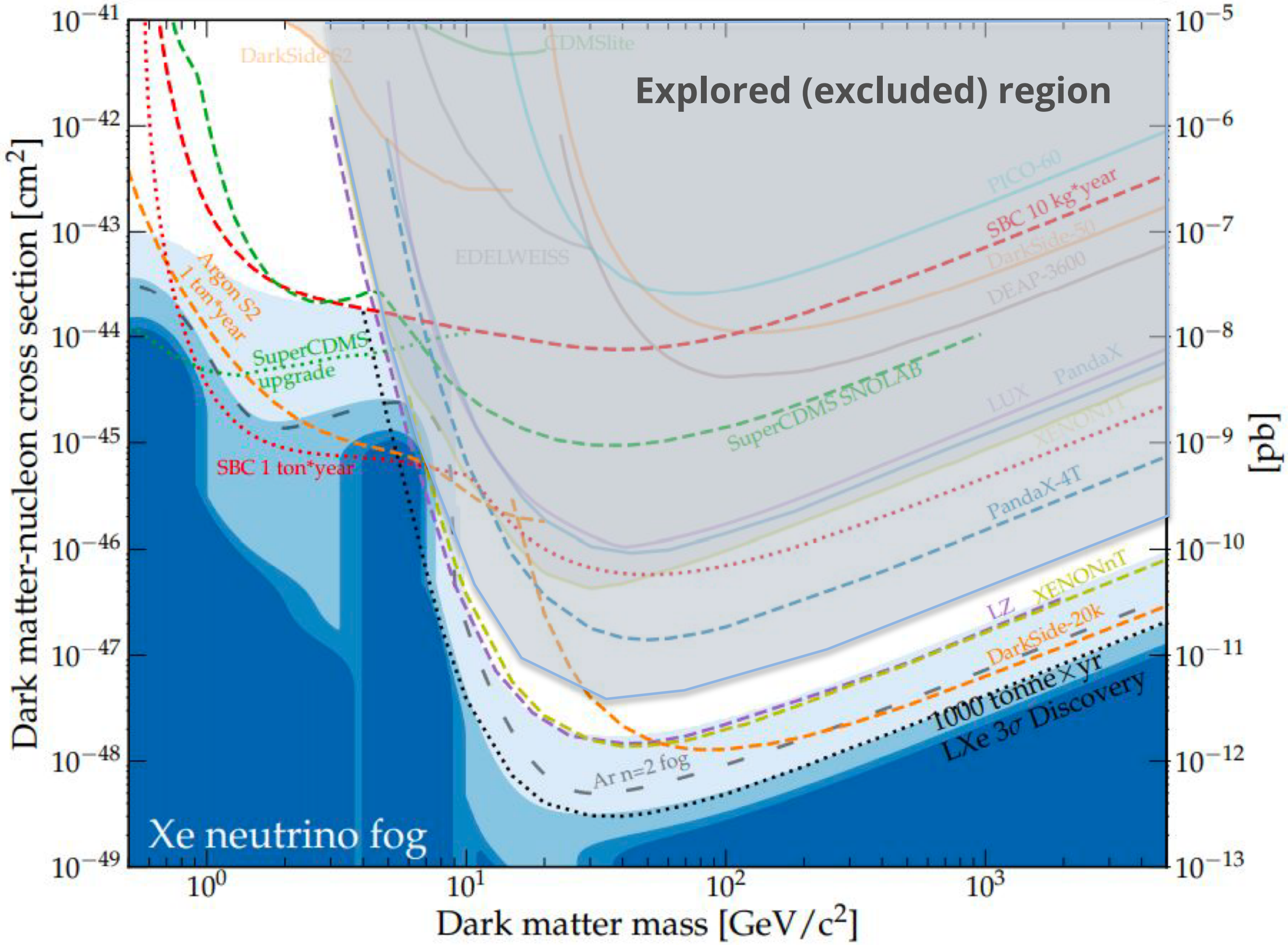
Incompatibility with DAMA/LIBRA at ~4.3 σ (ANAIS) and ~3.6 σ (COSINE)

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





Future experiments will further explore the DM parameter space



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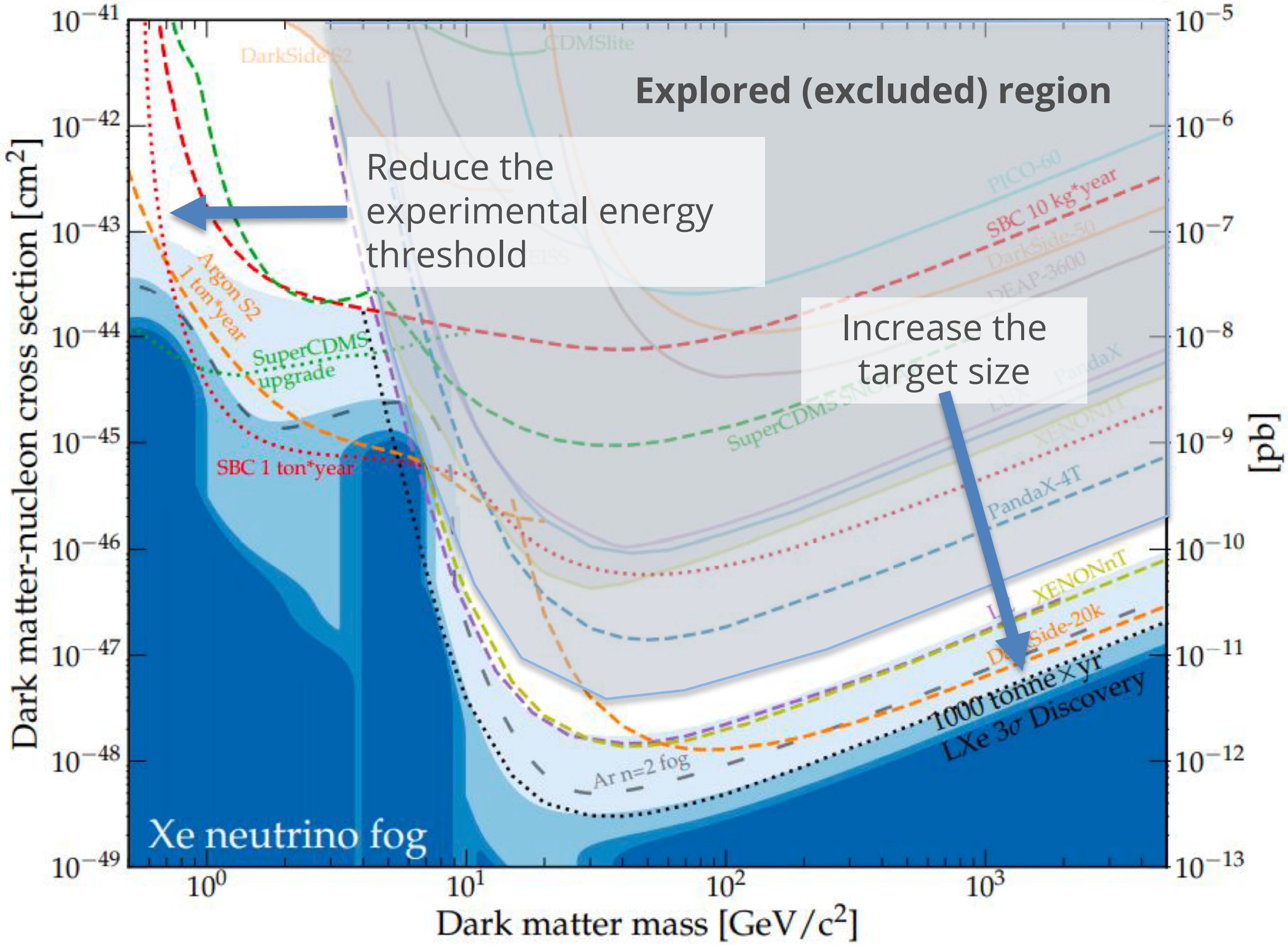

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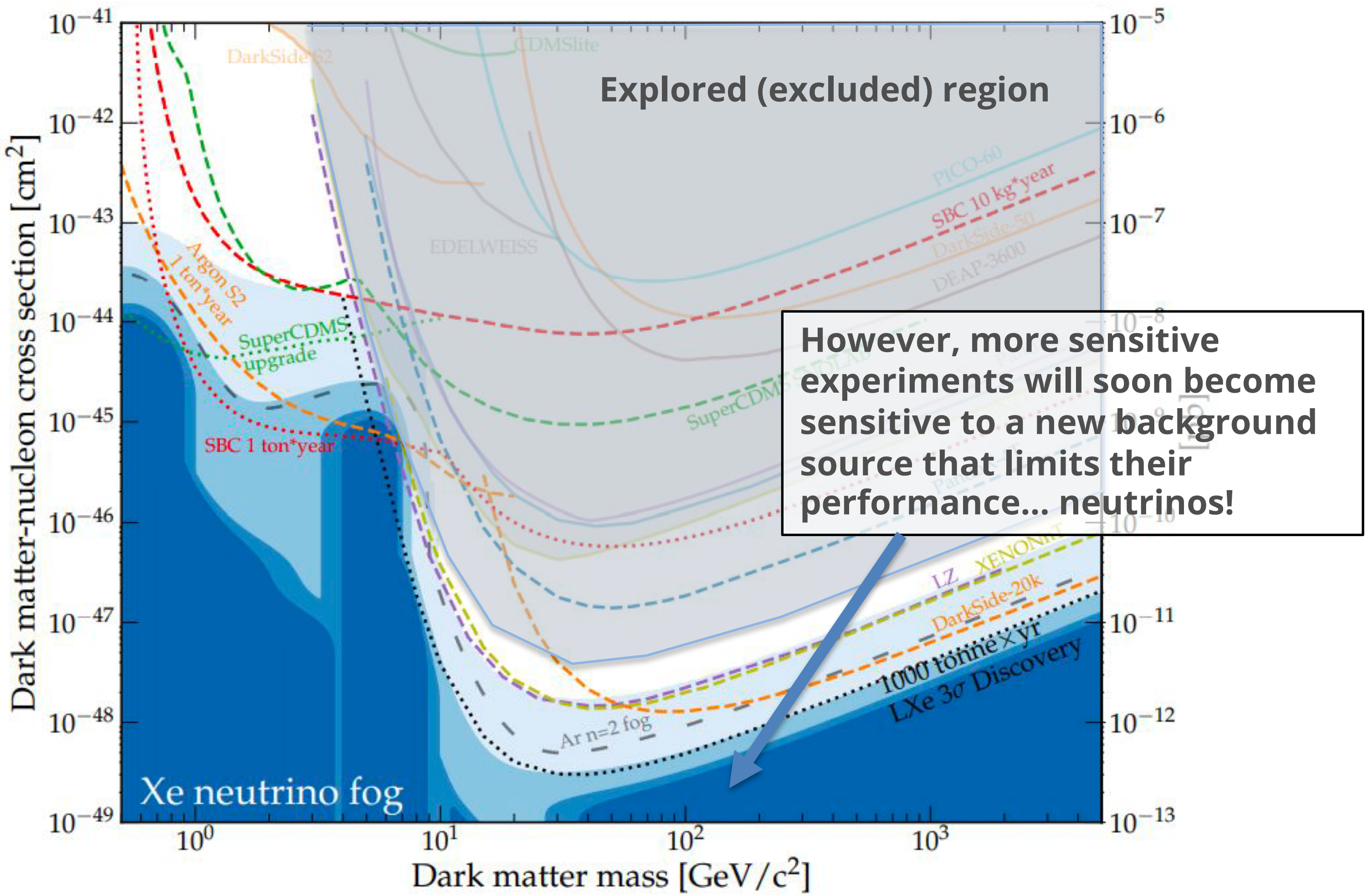
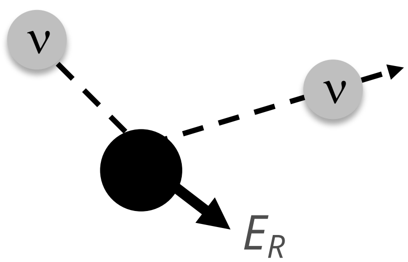


Neutrinos can be observed in direct detection experiments:

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)



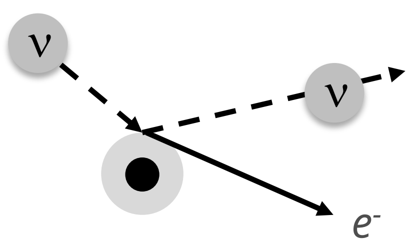
Rare Standard Model process recently measured in spallation source experiments

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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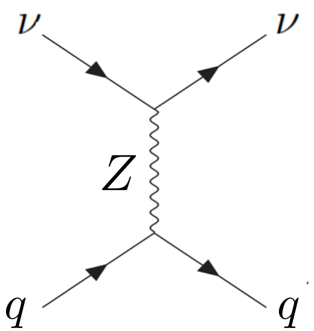

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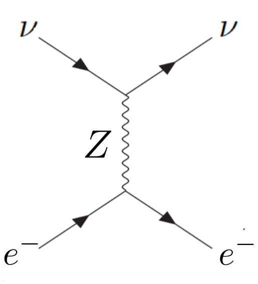

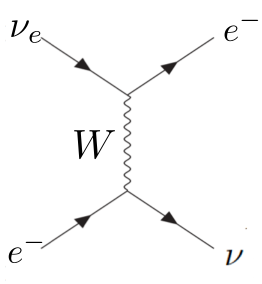

Usual electroweak process mediated by the *Z* and *W* bosons

Expected signal in a direct detection experiment

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

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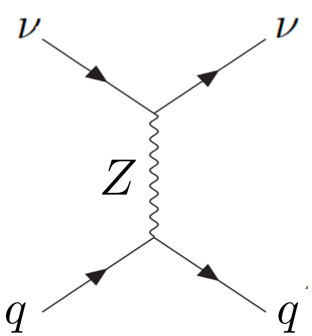

The Standard Model rate has no free parameters

(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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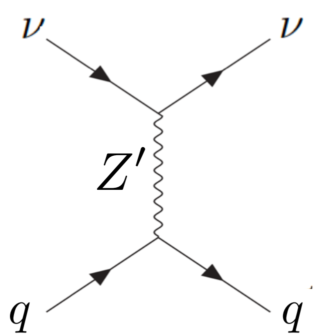


New physics can lead to extra contributions to CEvNS

- 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

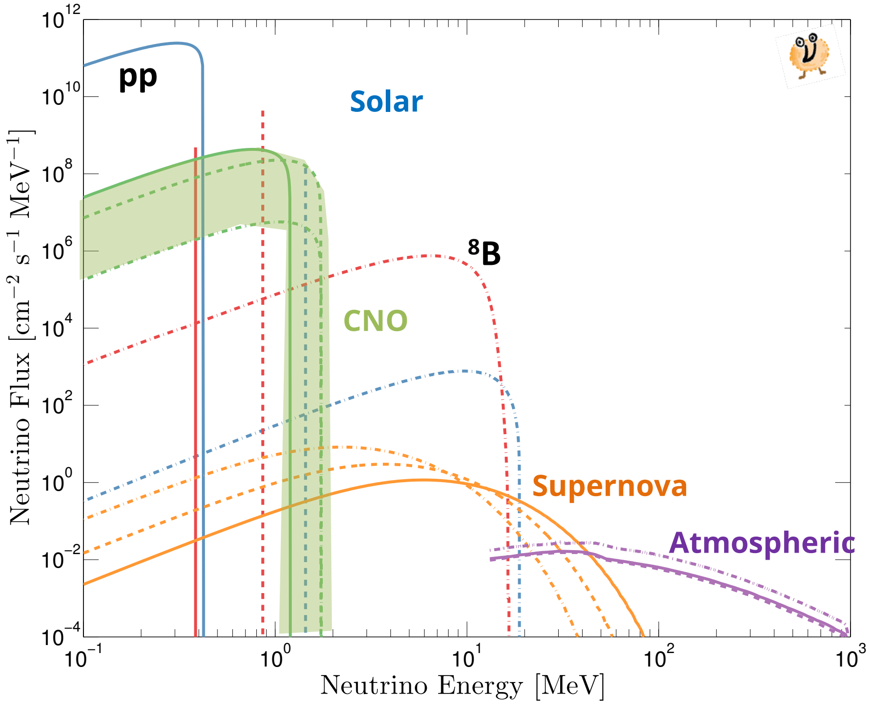
Neutrino flux

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

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

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

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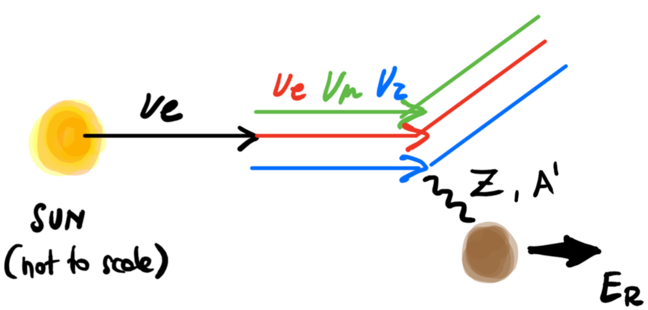
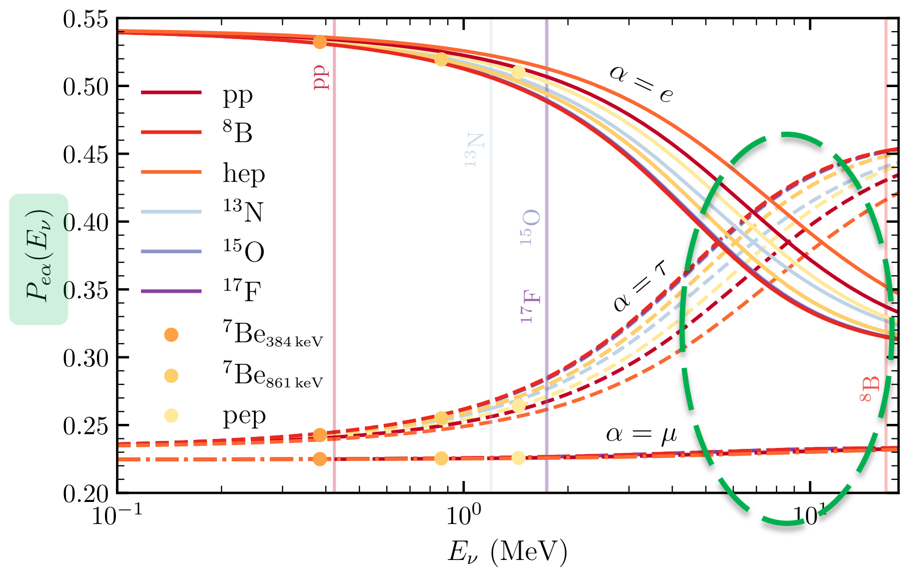
Produced as electron neutrinos, they oscillate into other flavours



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

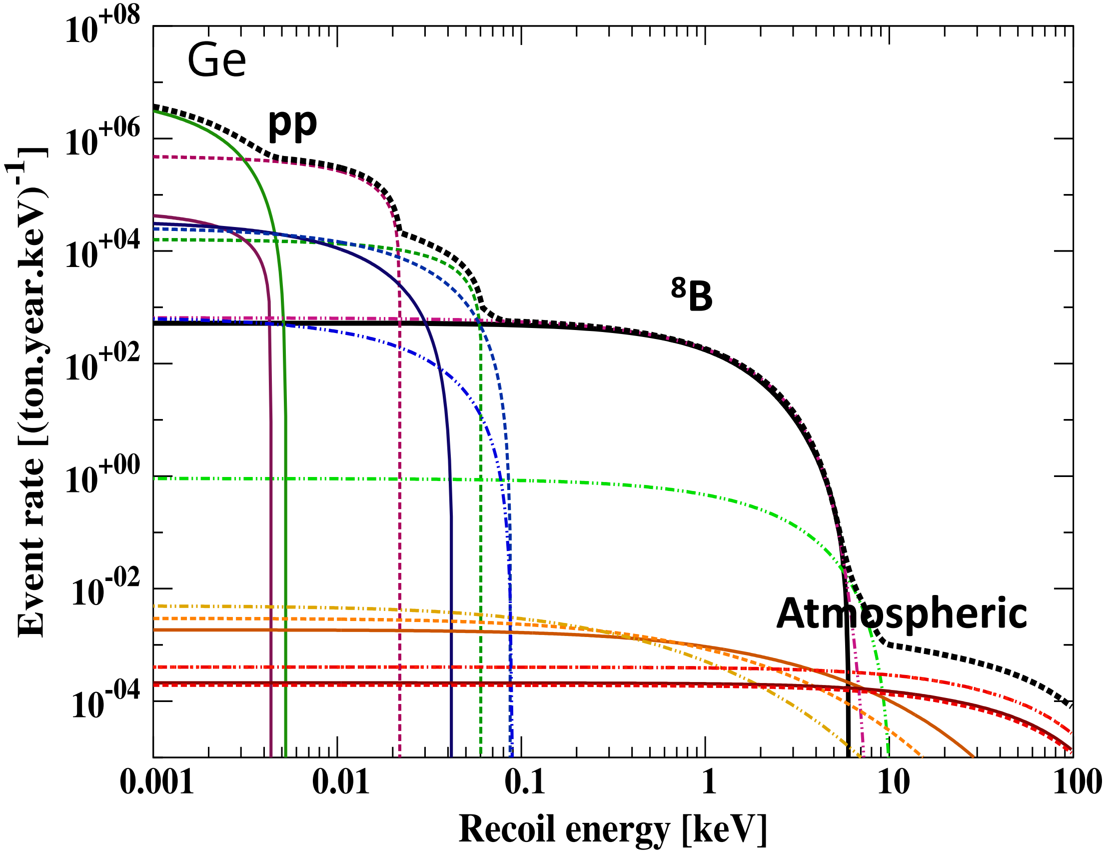
Experimental response to CEvNS

- **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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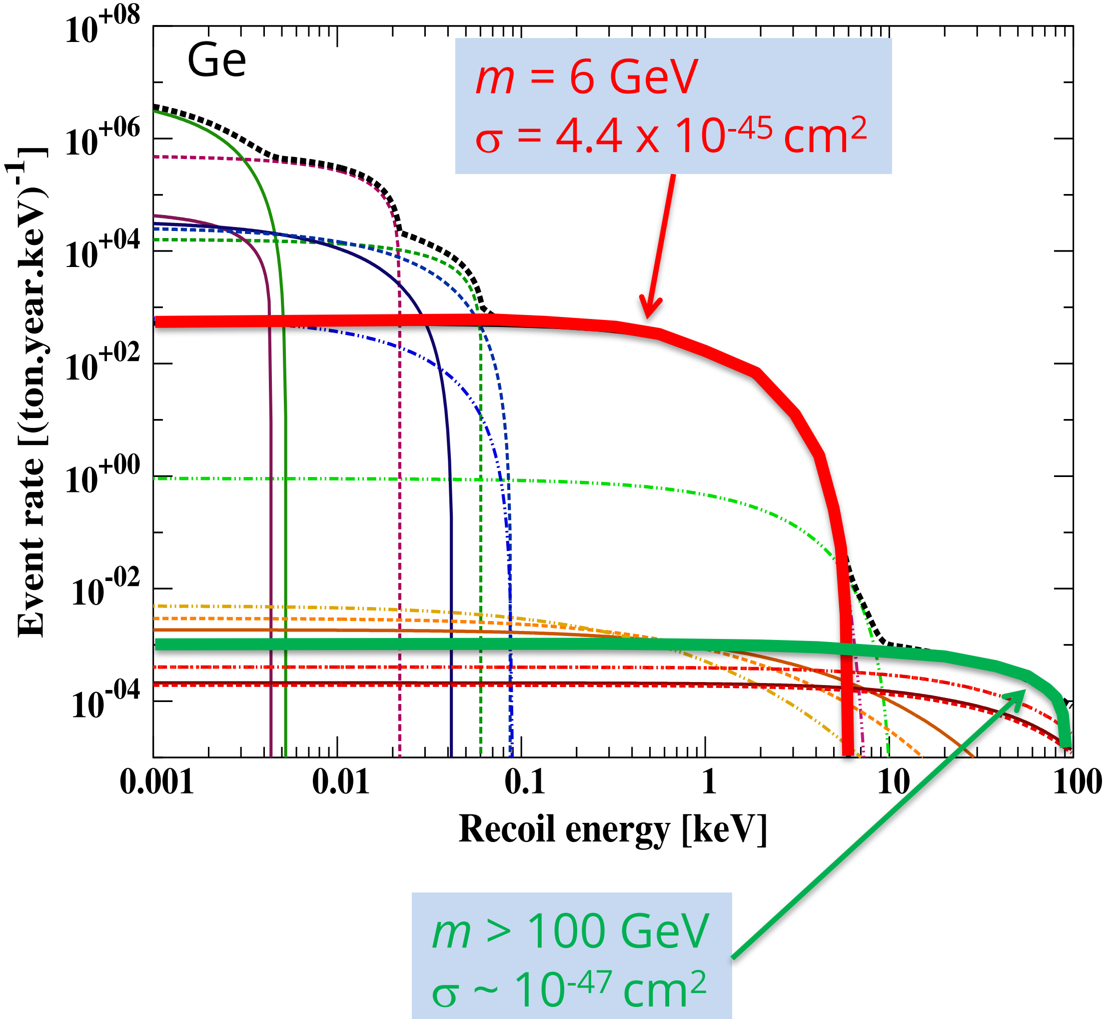


Direct (DM) detectors can be excellent **complementary test of new neutrino physics**

- 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

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

NUCLEAR + ELECTRON SCATTERING

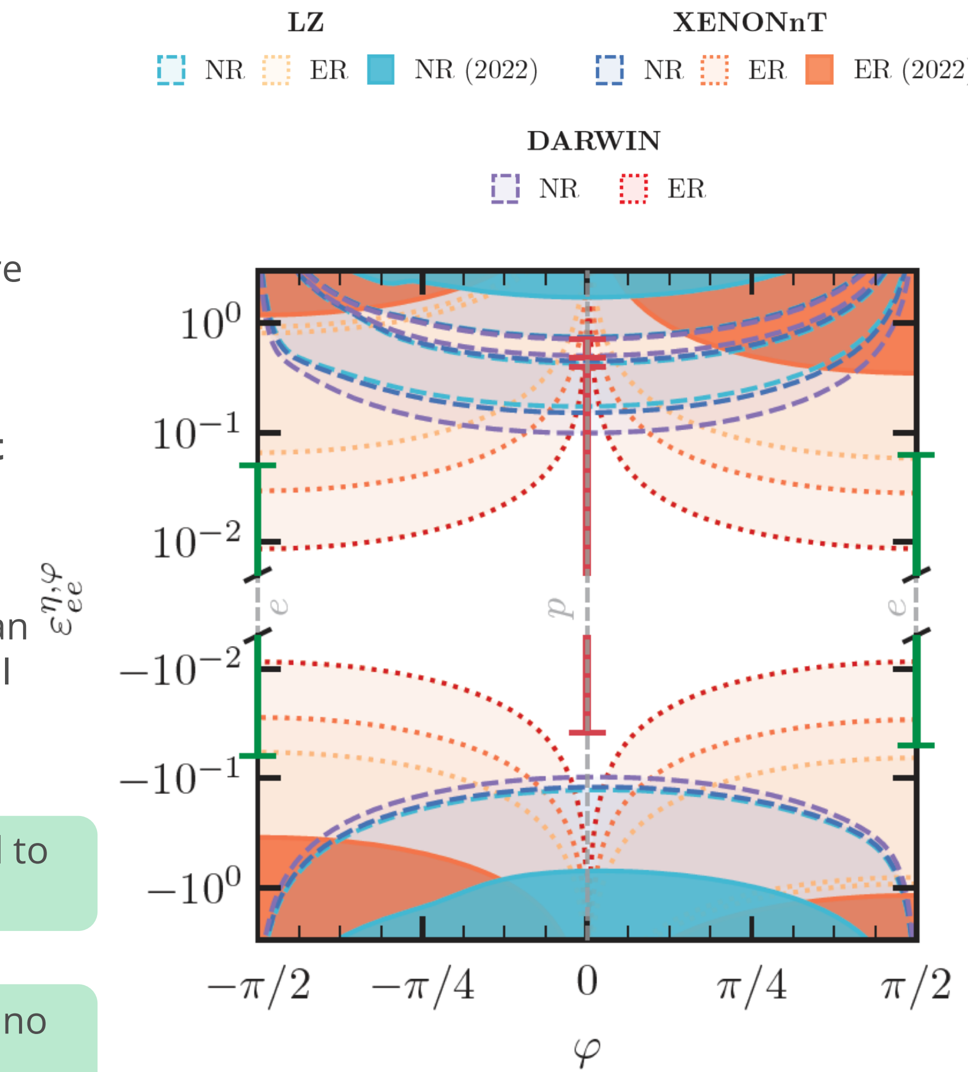
ER sensitivities drop off towards $\varphi = 0$ (pure proton), whereas NR sensitivities become maximal.

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

Future **DARWIN** 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.



Amaral, DGC, Cheek, Foldenauer 2023

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)

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

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

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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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Particle physics (dark matter model)

Nuclear Physics (form factors)

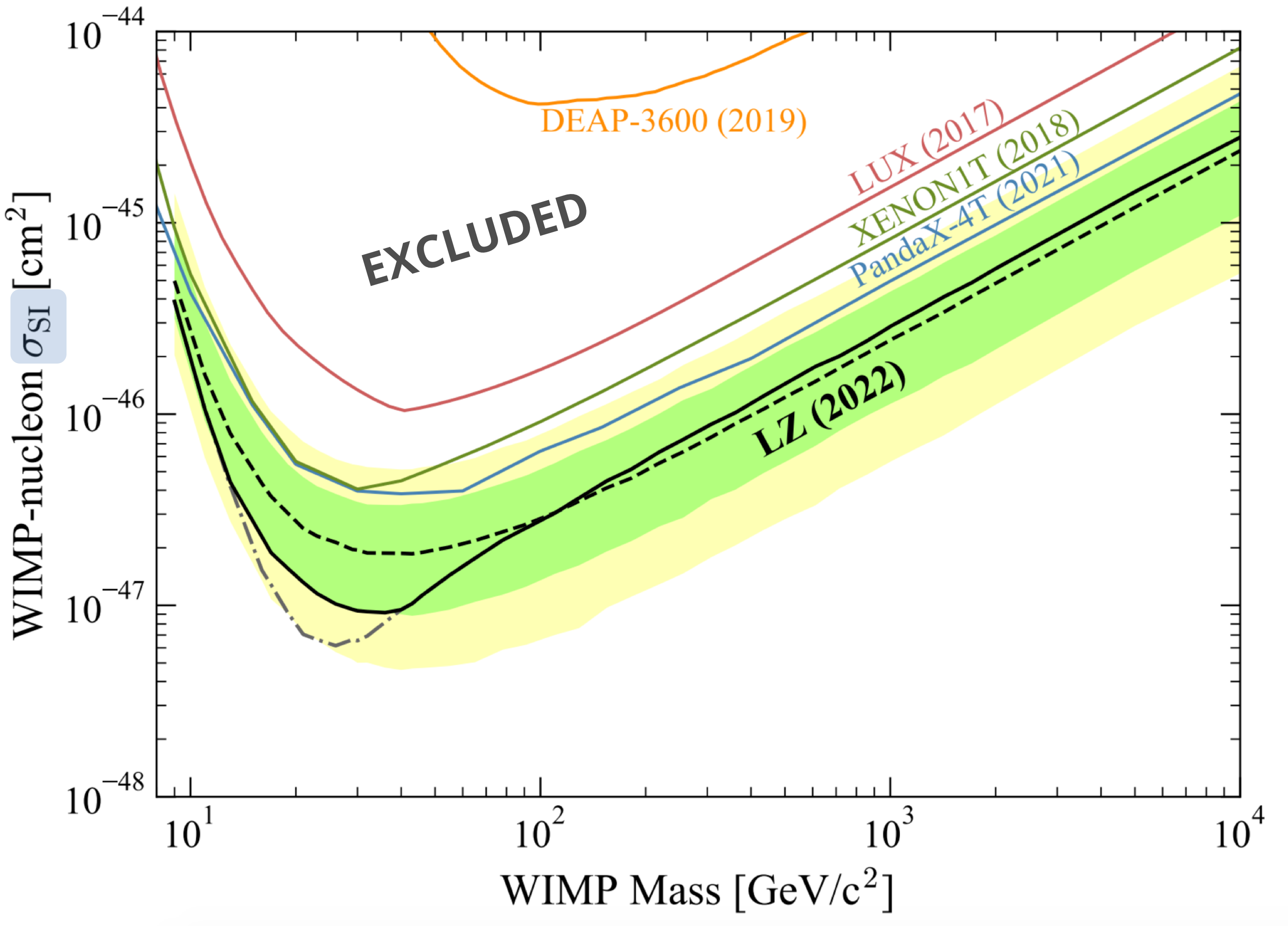
Materials Science, solid-state physics etc (describe the structure of the target in the detector)

Experimental parameters

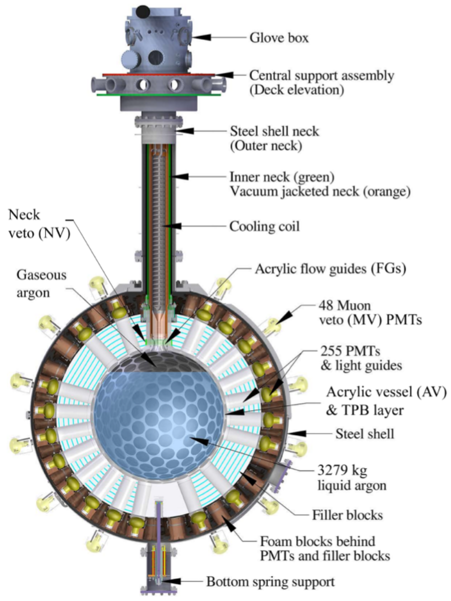
Size, energy resolution, energy threshold

Backgrounds and signal identification

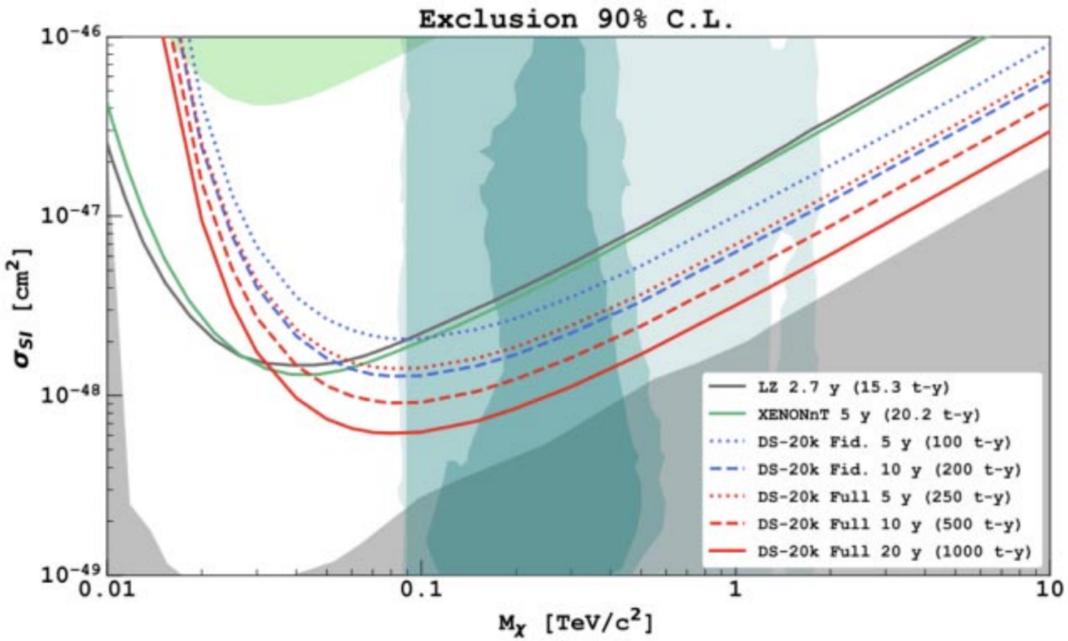
Unsuccessful searches have led to upper bounds on the scattering cross-section



DEAP 3600



DarkSide 20k prospects



Proyección de sensibilidad de SuperCDMS (Retrocesos Nucleares)

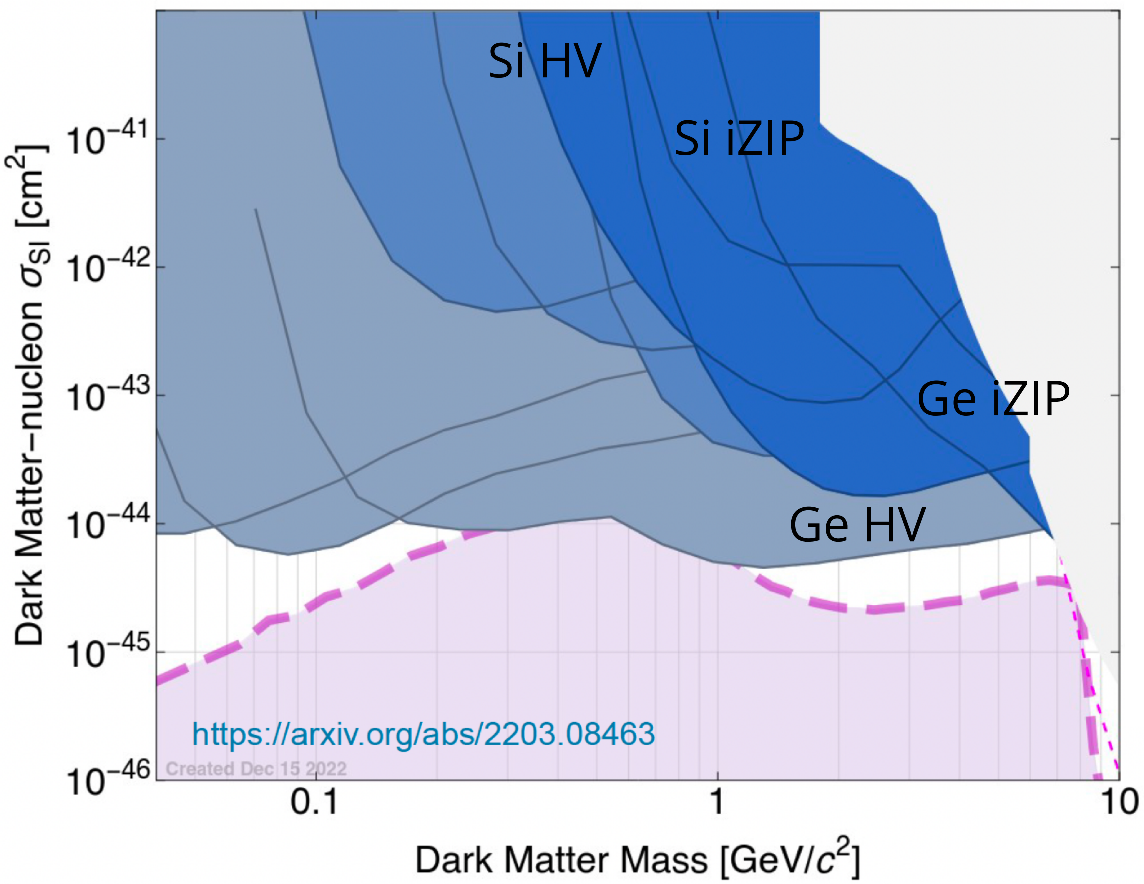
SuperCDMS va a explorar nuevas regiones de MO ligera, siendo uno de los detectores con mejor sensibilidad por debajo de 1 GeV.

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.

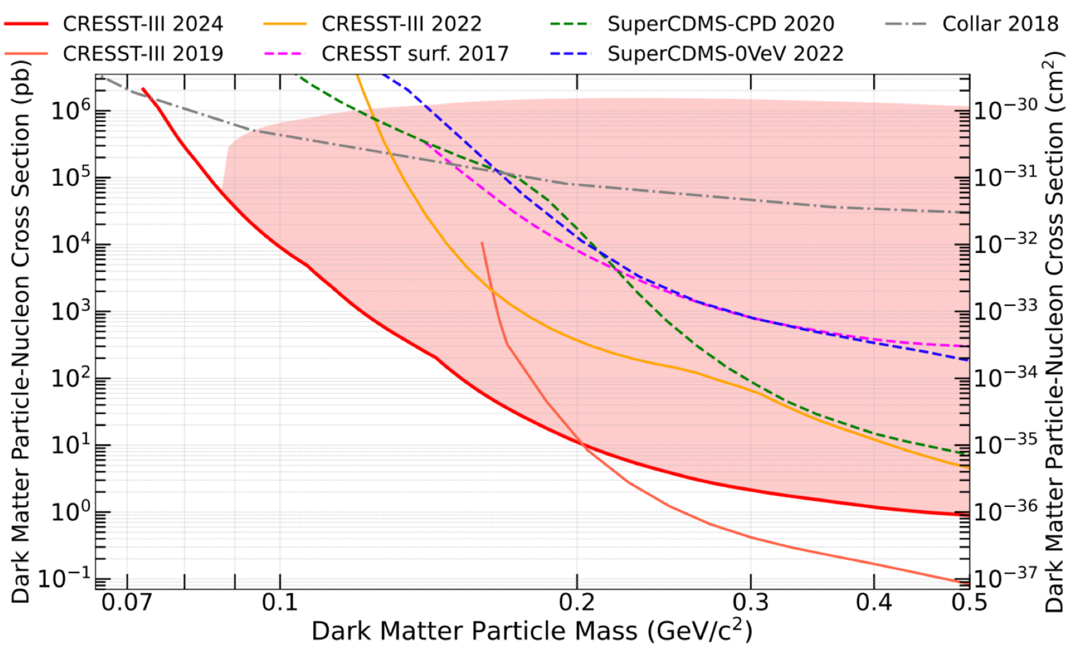
Se acerca al "*suelo de neutrinos*" y permitirá explorar nueva física en este sector



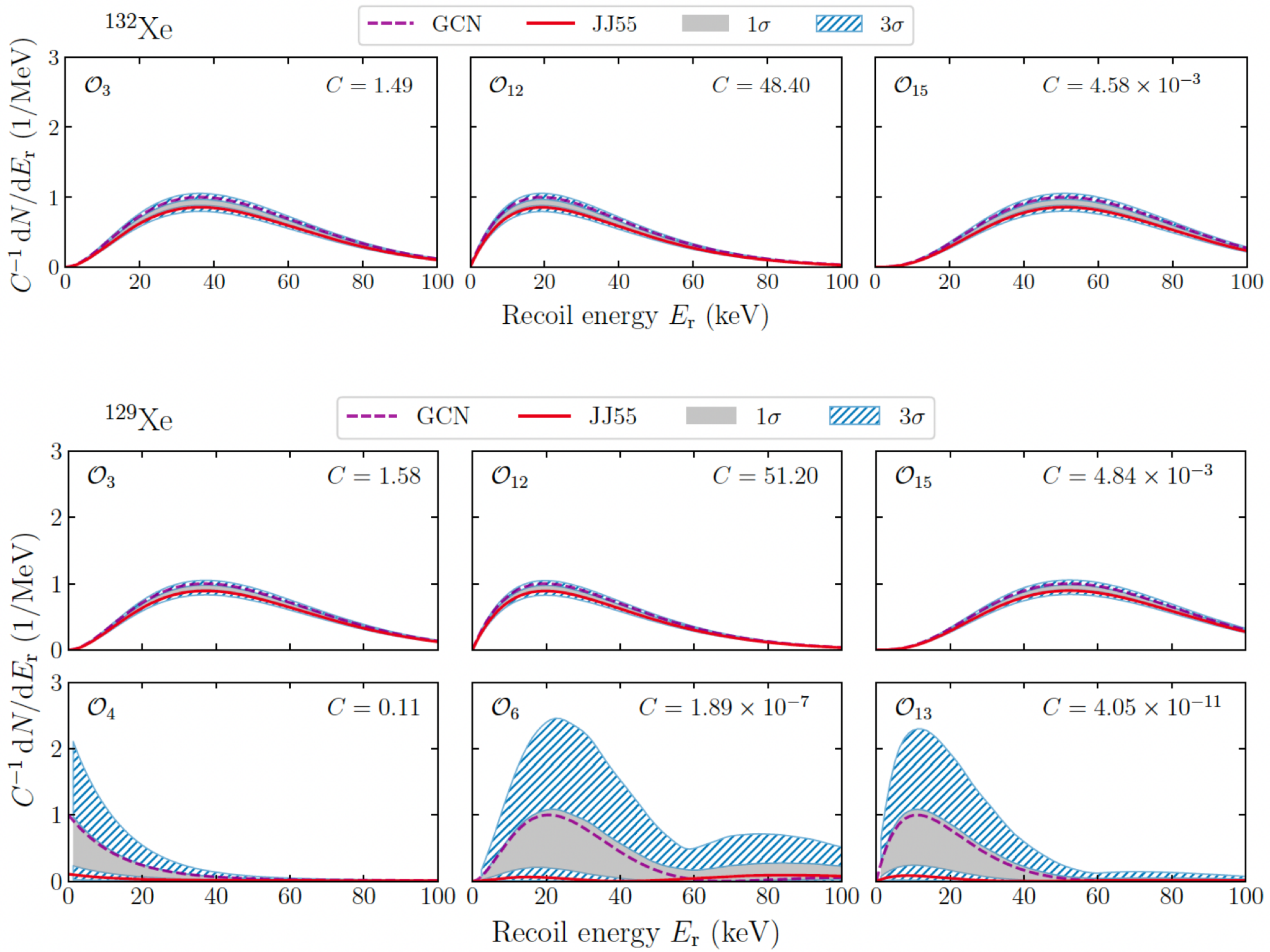
CRESST

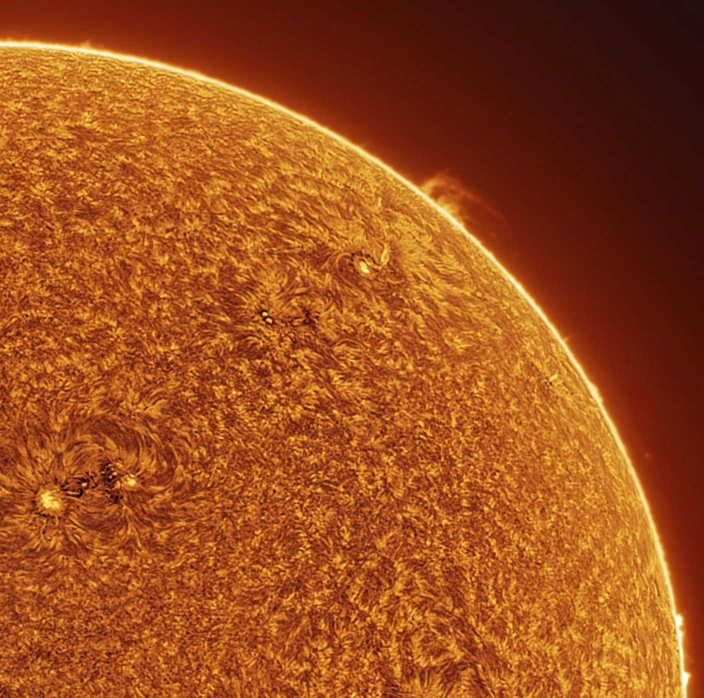
These techniques allow us to probe MeV scale DM.

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





Direct Dark matter detection: leaving no stone unturned

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

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