Spin-dependent dark matter sensitivity of DarkSide-20k

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MANCHESTER 1824
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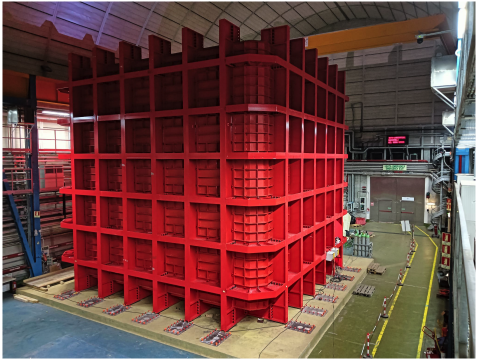
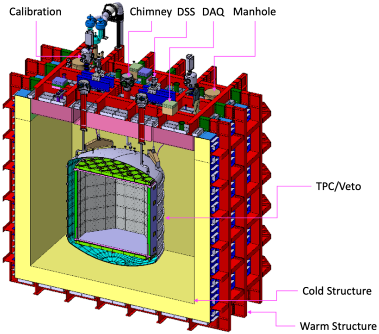
DarkSide-20k - A world leading dark matter experiment



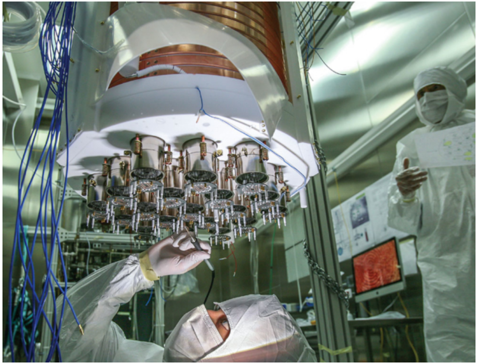
The DarkSide-20k cryostat at LNGS



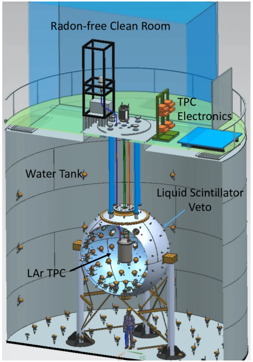
DarkSide-20k CAD cutaway

A direct dark matter detection experiment centring a 50 tonne dual-phase argon TPC.
Currently under construction at LNGS, in L'Aquila, Italy.

DarkSide-50 - 2013-2019



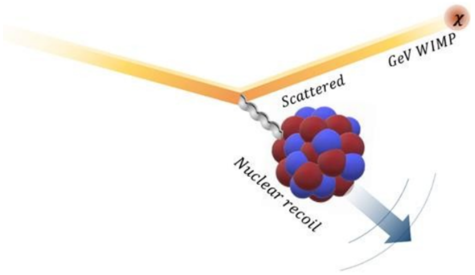
The DarkSide-50 TPC

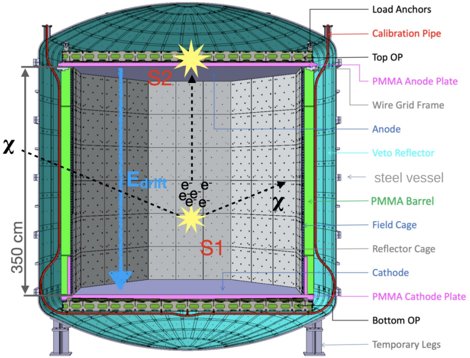


DarkSide-50 CAD cutaway

A direct dark matter detection experiment centring a 50 kg dual-phase argon TPC. (total exposure 12 000 kg days)
Currently world leading sensitivity in 40 MeV - 3 GeV range.

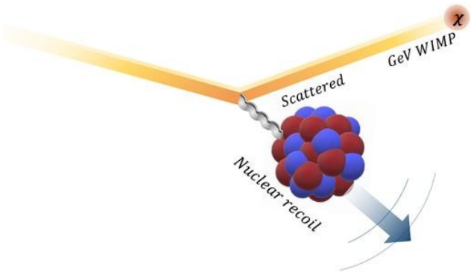
Direct dark matter detection

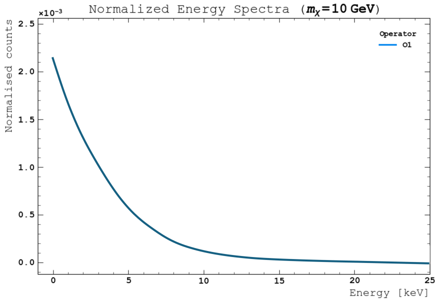




Galactic dark matter scatters on detector material.
The resulting nuclear recoil ionizes Ar atoms in the TPC, creating a detectable signal.

Direct dark matter detection

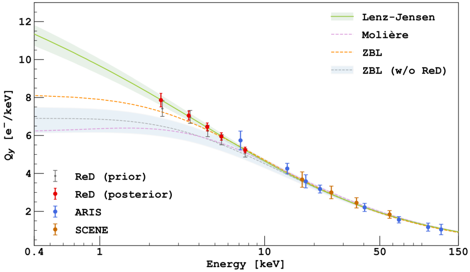




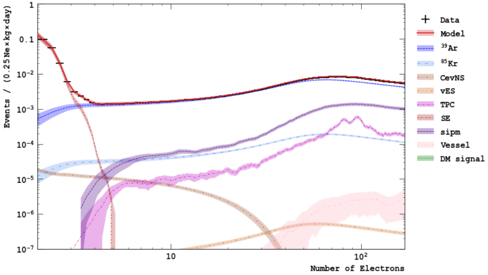
Galactic dark matter scatters on detector material.
The resulting nuclear recoils are considered according to our signal model.

Direct dark matter detection

Ionisation yield from nuclear recoils



DS-20k background model (S2 only)

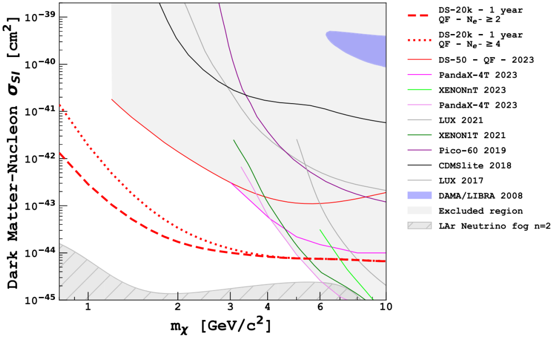


Expected signal considers energies deposited, ionisation yield, detector efficiency and exposure time.
Sensitivity curves are calculated by comparing our expected signal and background.

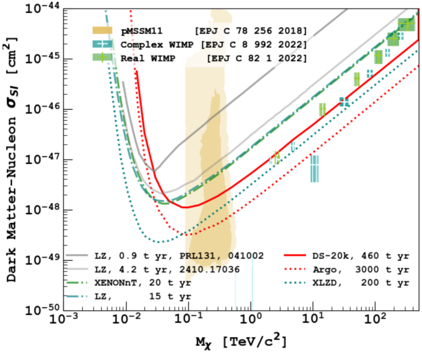
https://arxiv.org/abs/2511.13629
https://doi.org/10.1038/s42005-024-01896-z

DarkSide-20k - A world leading dark matter experiment

Low mass 90 % C.L. exclusion limits for spin-independent WIMP–nucleon cross-section



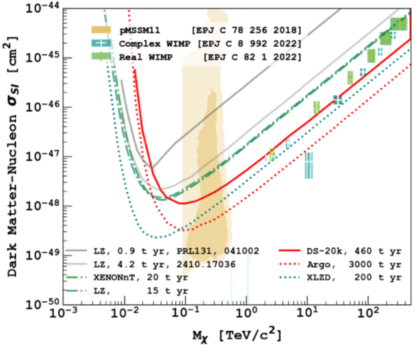
High mass 90 % C.L. exclusion limits for spin-independent WIMP–nucleon cross-section



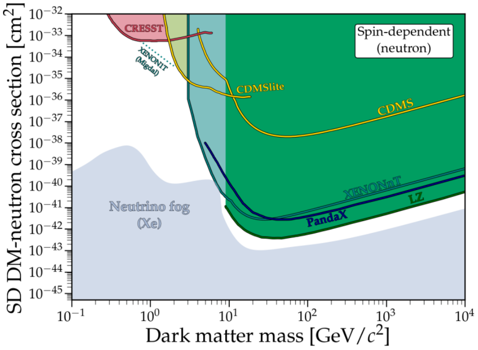
DarkSide-20k is projected to have world leading sensitivity to dark matter candidates in the GeV-TeV range.
DS-50 sensitivity currently leads in the lower mass (1 GeV) region

https://doi.org/10.1038/s42005-024-01896-z
https://indico.cern.ch/event/1439855/contributions/6461670/

90 % C.L. exclusion limits for spin-independent WIMP–nucleon cross-section



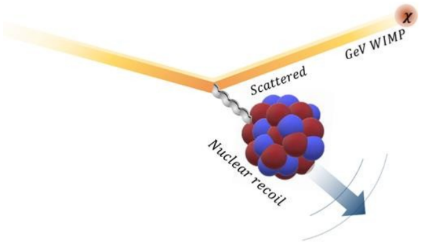
90 % C.L. exclusion limits for spin-dependent WIMP–nucleon cross-section



Dark matter detection sensitivities are typically also presented for spin-dependent dark matter interactions. Experiments using argon as an interaction medium are not considered to be sensitive to such interactions.

https://indico.cern.ch/event/1439855/contributions/6461670/
https://arxiv.org/abs/2109.03116

Direct dark matter detection in a non-relativistic effective field theory framework



$$\mathcal{L}_{\text{int}} = \sum_N \sum_i c_i^N \mathcal{O}_i \chi^+ \chi^- N^+ N^-,$$

where
χ = dark matter field,
N = nucleon field,
$\mathcal{O}$ = operator built from momentum, q, transverse velocity, $\vec{v}^{\perp}$ and spin of the dark matter and nucleon, S_χ and S_N
c = corresponding coupling strength.

Consider non-relativistic operators coupling dark matter to nuclei.

Re-characterising DM-matter interactions via NREFT

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\,\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\,\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\,\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_{10} = i\,\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\,\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

q = momentum,
$\vec{v}^\perp$ = transverse velocity,
S_χ, S_N = spins of the dark matter and nucleon.

A minimal list of operators in the non-relativistic effective field theory (NREFT) framework.
Suppressed interactions are not traditionally considered, what if we consider them?

Consider a realisation of this model as described in Eur. Phys. J. C 83, 914 (2023) arXiv:2302.05458

Previous sensitivity projections only consider two types of interaction

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\,\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\,\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$
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$$\mathcal{O}_{11} = i\,\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

q = momentum,
$\vec{v}^\perp$ = transverse velocity,
S_χ, S_N = spins of the dark matter and nucleon.

Previous sensitivities consider only $\mathcal{O}_1$, the simple velocity and momentum independent interaction,
and $\mathcal{O}_4$, the simplest spin-dependent interaction.

Several types of spin-dependent DM-argon interaction are non-zero

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\,\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$
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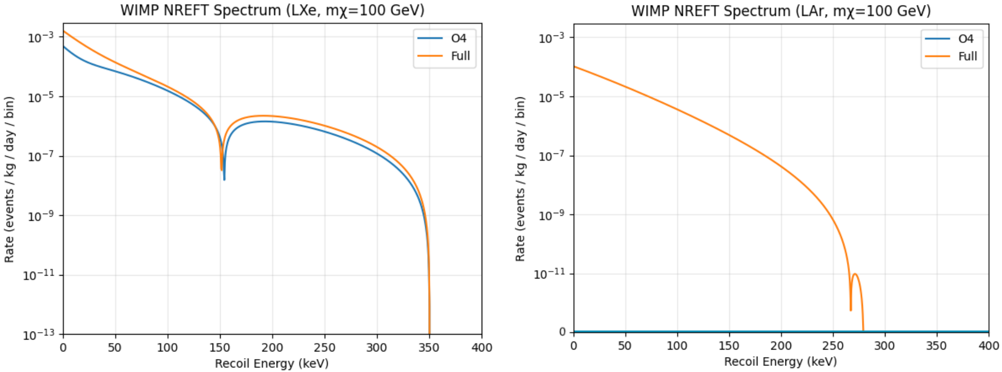
$$\mathcal{O}_{11} = i\,\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

q = momentum,
$\vec{v}^\perp$ = transverse velocity,
S_χ, S_N = spins of the dark matter and nucleon.

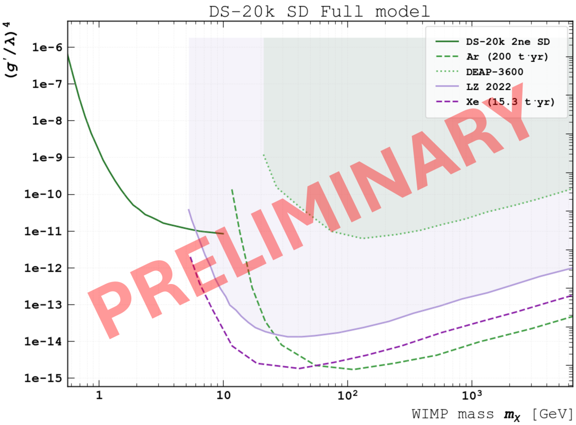
Considering many DM-matter interactions, if $\mathcal{O}_4$ is non-zero, a number of other operators will also be non-zero.
This includes interactions which could be measured with an argon target.

Spin-dependent recoil energy spectra in xenon and argon



Comparing spin-dependent recoil energy spectra in xenon (left) and argon (right).
Curves are shown considering only the O4 operator and considering many operators.

DarkSide-20k sensitivity projections considering full framework



g' = coupling strength,
Λ = energy scale,
$(\frac{g'}{\Lambda})^4$ characterises the interaction rate.

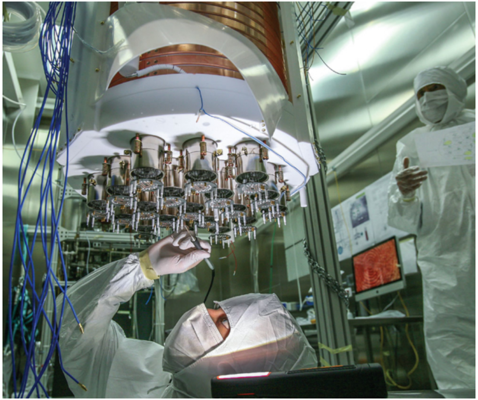
Projected sensitivities of direct detection experiments to spin-dependent dark matter interactions.

Summary

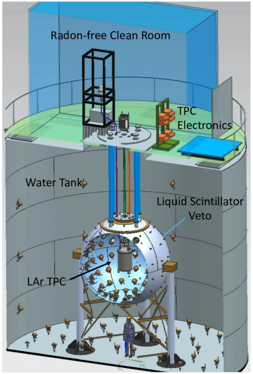
- Direct dark matter detection experiments using argon as an interaction target have previously be considered insensitive to spin-dependent dark matter interactions due to the absence of nuclear spin in the dominant isotope $^{40}\mathrm{Ar}$.
- This statement is, however, specific to the simplest spin–spin interaction.
- By re-characterising dark matter interactions through a non-relativistic effective field theory (NREFT), several types of dark matter-matter interactions can be considered.
- These include interactions which argon targets would be sensitive to.
- By considering these suppressed interactions, we are able to calculate sensitivities for argon-based experiments DS-50 and DS-20k.
- Due to the large target mass of these detectors, their sensitivities are, perhaps surprisingly, competitive with experiments using typical "spin-dependent sensitive" target materials.

Thank you!

DarkSide-50 - 2013



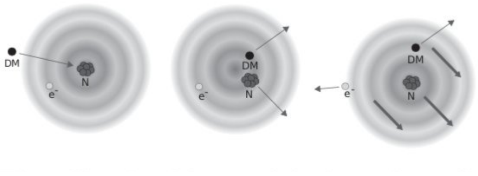
The DarkSide-50 TPC



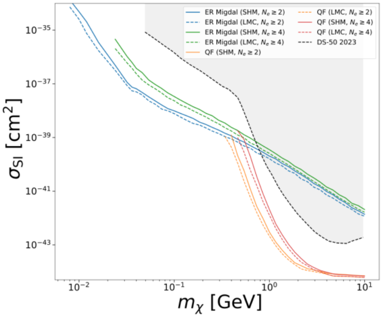
DarkSide-50 CAD cutaway

A direct dark matter experiment at LNGS, in L'Aquila, Italy.

Non-standard DM interactions - How would the Migdal effect affect our sensitivities?



The Migdal effect
A nucleus displaced by a DM particle induces ionization



Projected sensitivity for DS-20k, accounting for the Migdal effect.

Accounting for the Migdal effect, DS-20k projected sensitivities are improved particularly for lower DM masses.