Exploring the current and future physics potential of liquid noble direct dark matter detection experiments

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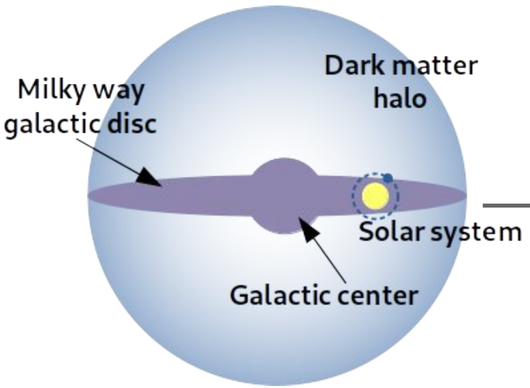
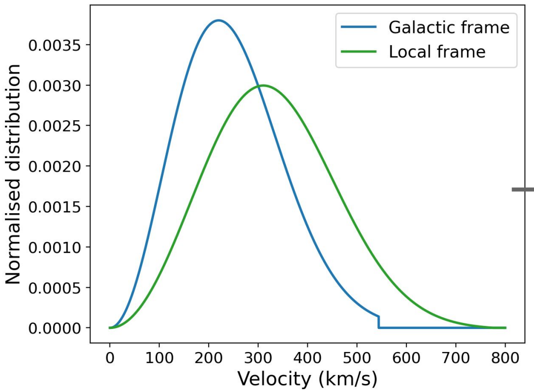
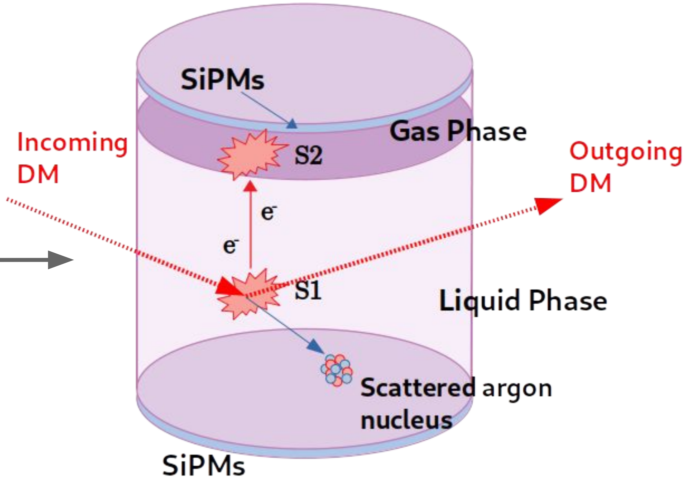
Direct detection experiments







Dark matter halo around the Milky Way

Dark matter (DM) has a certain **velocity distribution** relative to Earth

Earth based detectors may be able to observe DM entering and **interacting** with standard model particles

What are we looking for?

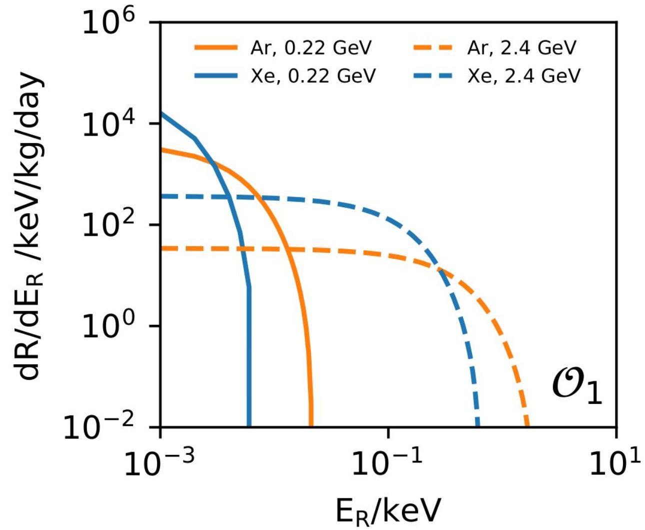
Local DM density

Differential cross-section

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\ \mathrm{d}^3 v$$

DM mass

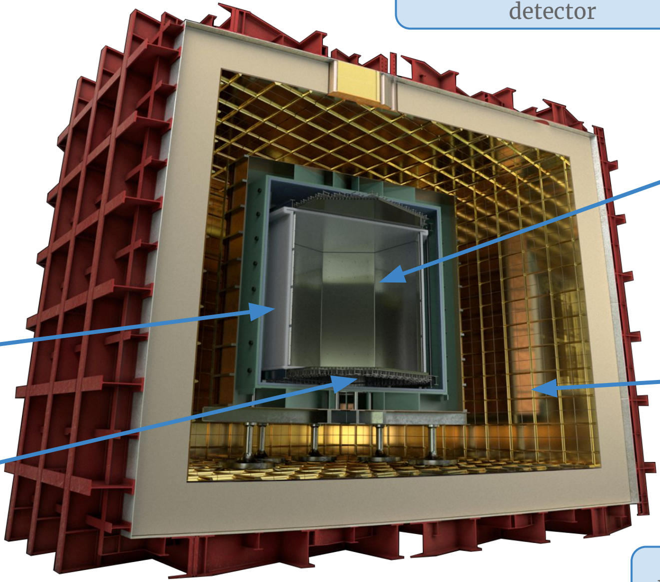
DM velocity distribution



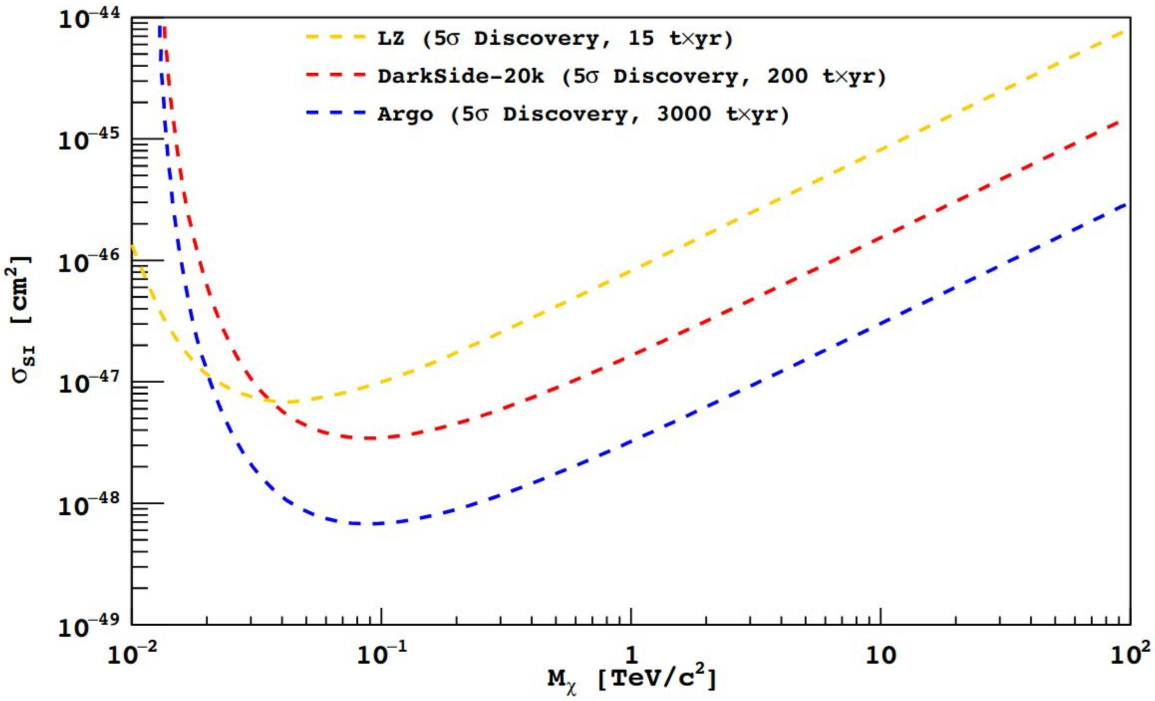
Assumptions usually made: interaction is momentum-independent and velocity-independent, and the DM coupling to proton and neutron is equal. This results is an exponential like recoil energy spectrum.

How will DarkSide-20k achieve world-leading sensitivity?

- DarkSide-20k is a DM detector currently being constructed with 50 tonnes of liquid argon in the inner TPC
- DS20k will be the most sensitive direct detection experiment while running

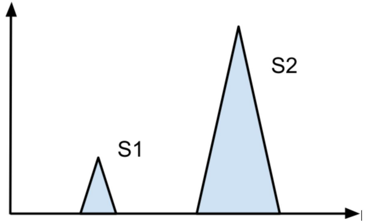


Next generation experimental limits



How can we extend sensitivity to lower dark matter masses?

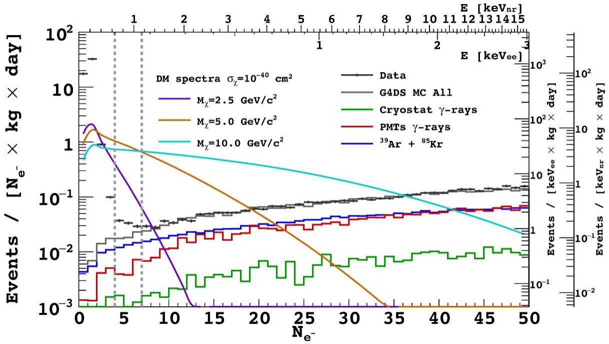
Observing events from low mass DM



We see two signals in the detector: the S2 ionisation signal is much larger

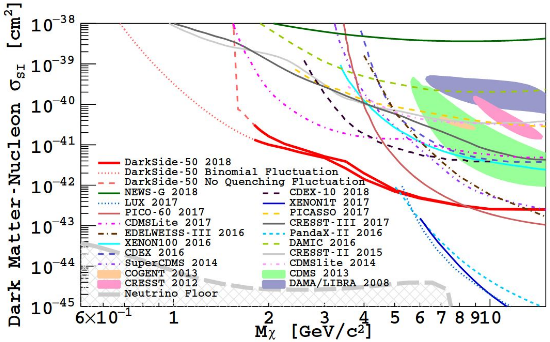
- In order to be sensitive to lower dark matter masses, we can carry out searches using **only the S2** ionisation pulse of light.
- This allows us to reach dark matter masses for which the S1 pulse would be too small to see, at the cost that there are now large number of background events

arxiv 1802.06994

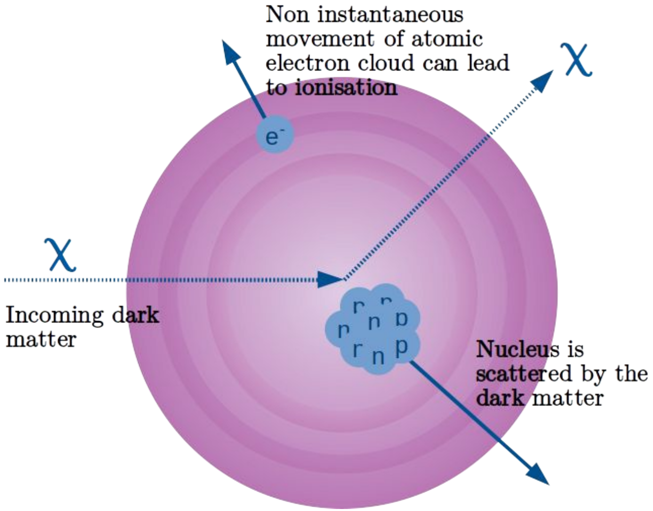


This allows DS50 to reach DM masses of **1.8 GeV**

But there are models which predict DM at even lower masses which we also want to be sensitive to



The Migdal effect



- The **Migdal effect** can occur during a nuclear recoil event due to the lack of instantaneous movement of the electron cloud.
- This additional energy in the form of an **electromagnetic signature** can boost the observable signal.
- Low energy events can be **pushed above the detector threshold** by this ER signal - increase sensitivity to low mass dark matter.

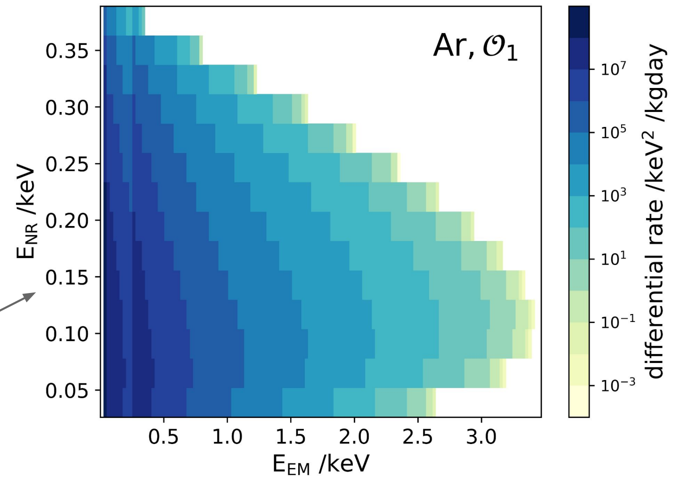
Calculating the Migdal event rate

Differential rate:

$$\frac{\mathrm{d}^3 R_{\mathrm{ion}}}{\mathrm{d}E_{\mathrm{R}}\,\mathrm{d}E_e\,\mathrm{d}v} = \frac{\mathrm{d}^2 R_{\mathrm{nr}}}{\mathrm{d}E_{\mathrm{R}}\,\mathrm{d}v} \times \left|Z_{\mathrm{ion}}(E_{\mathrm{R}}, E_e)\right|^2$$

Where

$$\left|Z_{\mathrm{ion}}(E_R, E_e)\right|^2 = \sum_{nl} \frac{1}{2\pi} \frac{\mathrm{d}p^c_{q_e}(nl \to E_e)}{\mathrm{d}E_e}$$



For the sub-set of events with a Migdal component, we have a differential rate in terms of a correlated NR and EM signal energy

What if dark matter – nucleus interaction is not velocity and momentum independent?

How could dark matter interact?

- Use a **non-relativistic effective field theory** to investigate different possible interactions
- This is important so that we do not make assumptions about the nature of DM, for example that it interacts in a momentum-dependent way
- Combinations of EFT operators can map onto specific DM models

Operator coefficients

$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_T}{2\pi}\frac{1}{v^2}\sum_{ij}\sum_{N,N'=p,n} c_i^N c_j^{N'} \mathcal{F}_{i,j}^{N,N'}(v^2, q^2)$$

Form factor

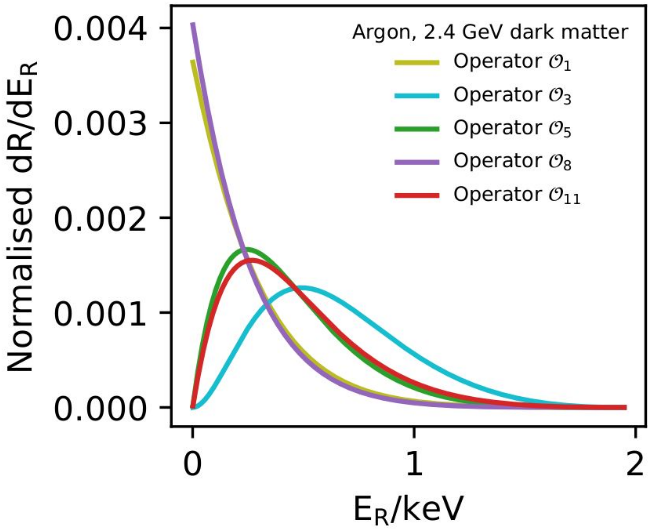
Sum over pairs of operators can lead to interference

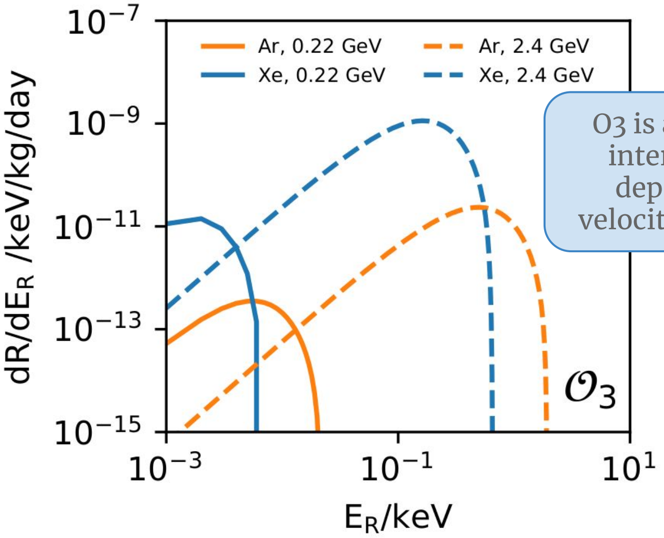
Sum over pairs of protons and neutrons

These interactions can be dependent on momentum and velocity

Non-standard recoil spectra

Focus on five operators which are visible in both argon and xenon. We can show that these can have a very different shape compared to the standard exponential:



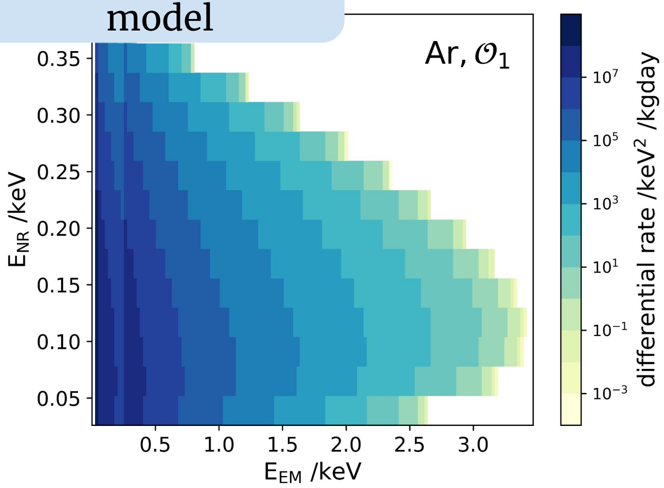


O3 is an example of an interaction which is dependent on both velocity and momentum

How do we calculate exclusion limits?

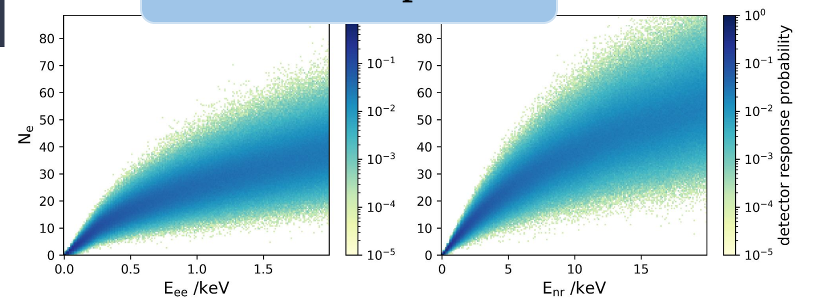
Producing signal spectra

Theory: dark matter Migdal model

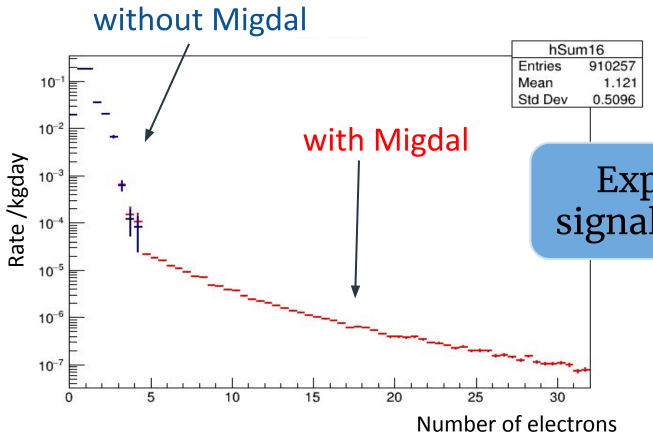


Sample from the 2d differential rate to get an event with a NR and EM energy

Detector response

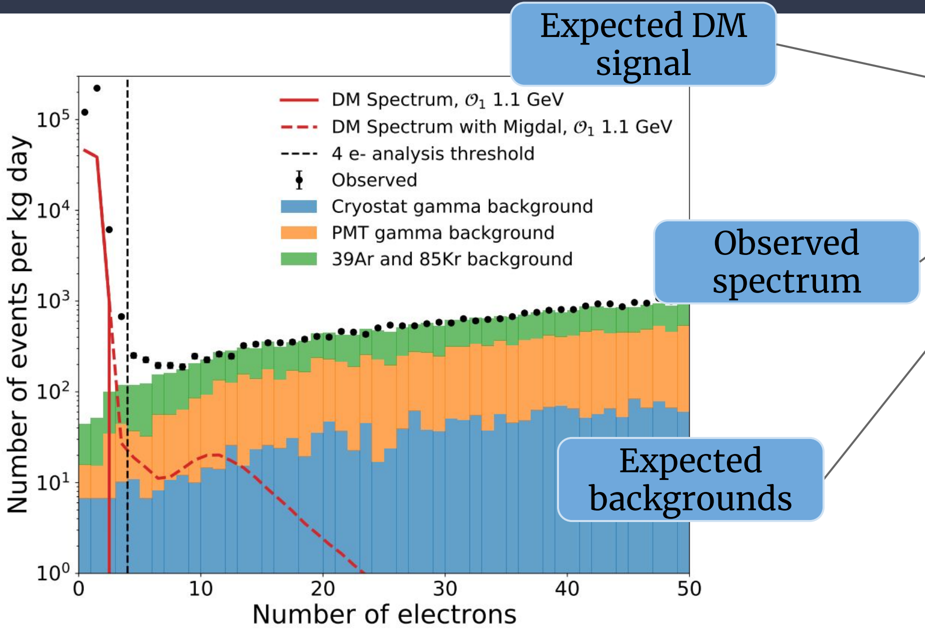


Convert the two parts of the interaction into a number of detected electrons



Expected signal spectra

Producing exclusion limits



These background and observed spectra come from DS50 low mass search (arxiv 1802.06994), and the corresponding Xe1T spectra come from data release relating to arxiv 1907.11485

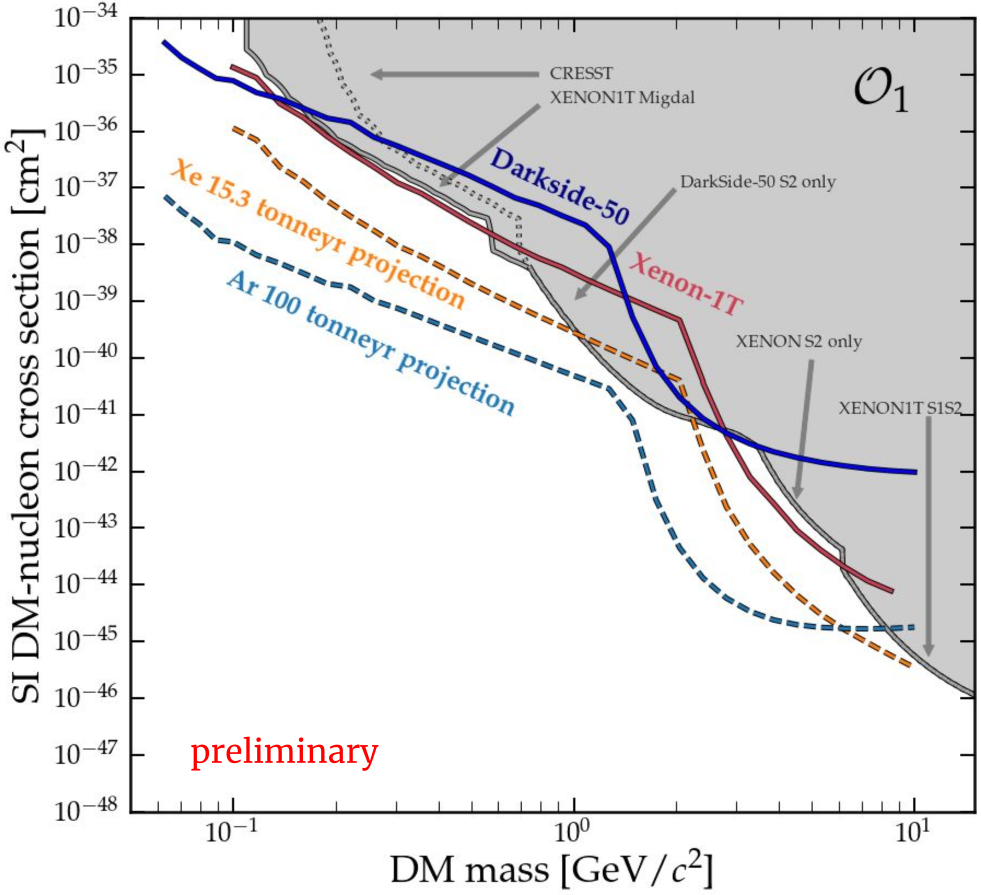
Likelihood model

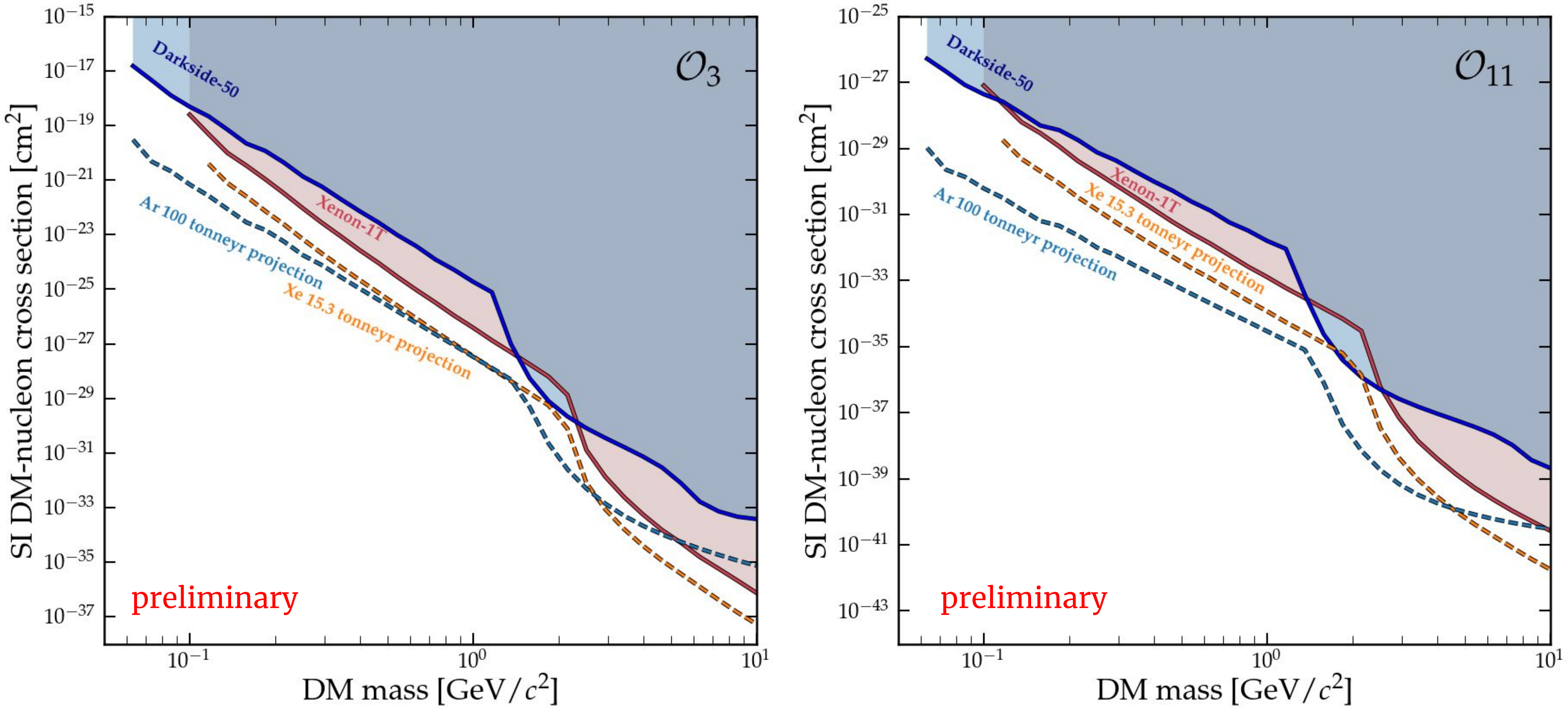
- Use DS50 and Xe1T public data for backgrounds and observed spectra, plus our calculated signal spectrum
- These are inputs into a binned maximum likelihood statistical test
- Take into account normalisation, statistical and energy scale uncertainties
- Can calculate 90% exclusion limits

Current and projected Migdal limits

For DarkSide-50, including the Migdal effect extends the mass range down to ~0.06 GeV

Starting from the public data from DS50 and Xe1T we also calculate projected limits for future Ar and Xe experiments, by scaling up and modifying backgrounds



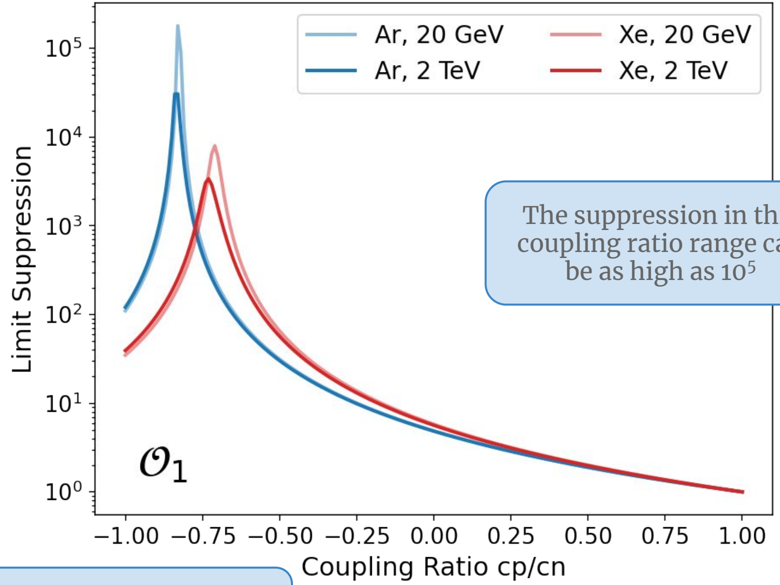


Current and projected limits for two non-standard EFT operators

What if the dark matter couplings to the proton and neutron are not equal?

Isospin-violating dark matter

- Dark matter could interact differently with the proton and neutron
- This can be important because different target materials have different combinations of protons and neutrons in their nucleus
- The exclusion limit with a specific coupling ratio is found and compared to the limit at ratio of 1, this is taken as the **limit suppression**

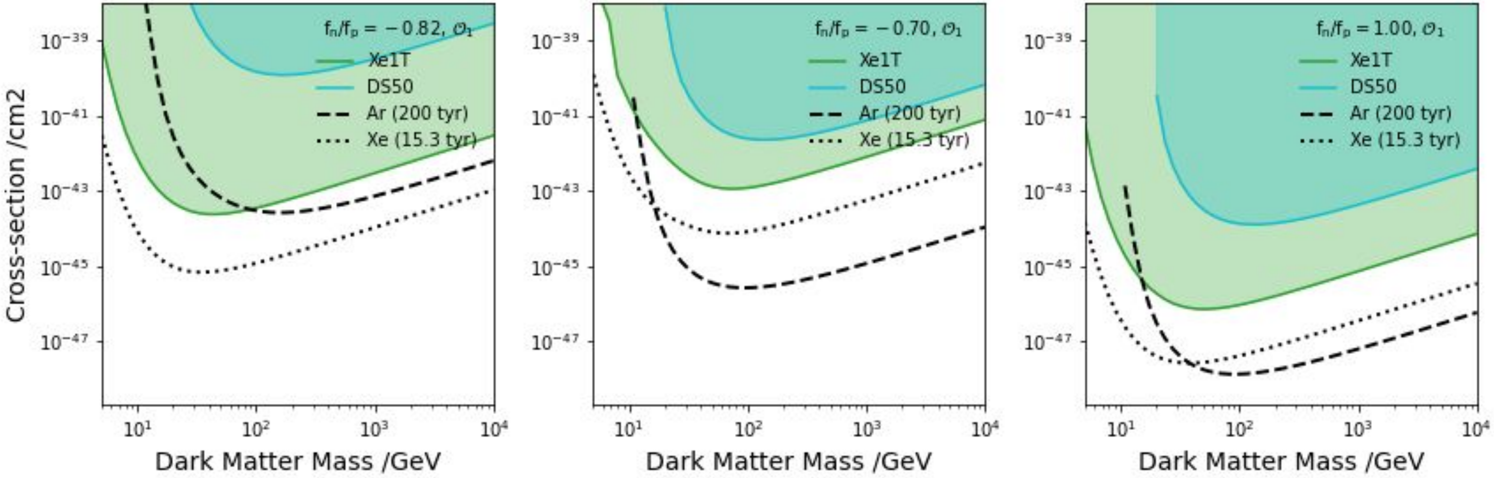


The suppression in this coupling ratio range can be as high as 10^5

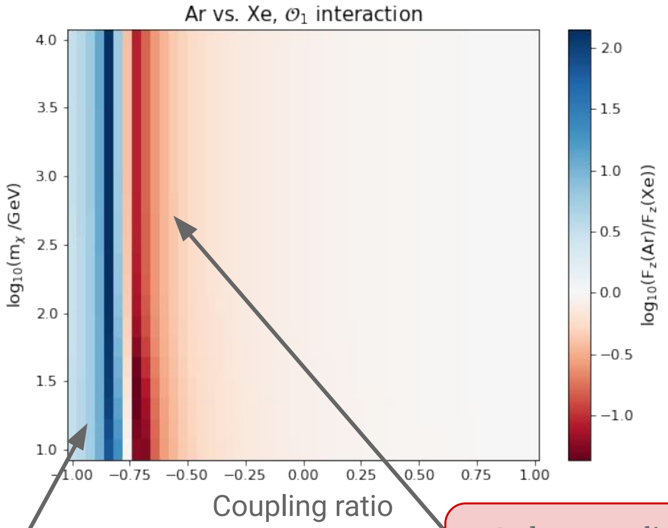
Maximal suppression occurs at different coupling ratio in Ar and Xe

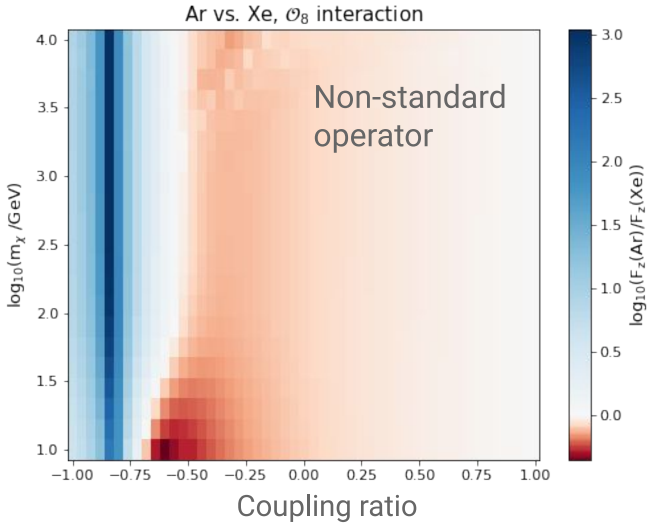
Effect on the projected limits

Coupling ratio -0.82 (max. argon suppression)	Coupling ratio -0.70 (max. xenon suppression)	Coupling ratio 1.0 (usual assumption)



Ar vs Xe suppression ratio





Blue = argon limits are more suppressed than xenon

Red = xenon limits are more suppressed than argon

In some non-standard operators, we see much greater **mass-dependence** in the suppression behaviour

Conclusions

- It is important not to make assumptions about the nature of dark matter - we use an EFT to investigate possible **non-standard interactions** in a model-independent way

- The **Migdal effect** can be used to extend the sensitivity of direct detection experiments down to lower dark matter masses

- We have compared current and projected argon and xenon limits using public data-sets and find that limits can be set down to 0.06 GeV

- We investigate **isospin violating dark matter** and find that different proton to neutron coupling ratios can hugely affect both the size of an experimental limit but also the ordering of limits with different target materials

EFT operators

q-independent	q-dependent	q^2-dependent
$\mathcal{O}_1 = 1_\chi 1_N$ $\mathcal{O}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$ $\mathcal{O}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$ $\mathcal{O}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$ $\mathcal{O}_{12} = \hat{\mathbf{S}}_\chi \cdot \left[\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right]$	$\mathcal{O}_3 = i\hat{\mathbf{S}}_N \cdot \left[\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right]$ $\mathcal{O}_5 = i\hat{\mathbf{S}}_\chi \cdot \left[\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right]$ $\mathcal{O}_9 = i\hat{\mathbf{S}}_\chi \cdot \left[\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right]$ $\mathcal{O}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$ $\mathcal{O}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$ $\mathcal{O}_{13} = i\left[\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right]\left[\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$ $\mathcal{O}_{14} = i\left[\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}\right]\left[\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right]$ $\mathcal{O}_{15} = -\left[\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$	$\mathcal{O}_6 = \left[\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]\left[\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Table 1. List of non-relativistic EFT operators for spin-1/2 and spin-1 DM particles, classified according to their dependence on the momentum exchange.

Table from https://arxiv.org/pdf/1810.05576.pdf