The University of Manchester

Maximising sensitivity to low mass DM with the Migdal effect and exploring non-standard models in liquid noble direct detection experiments

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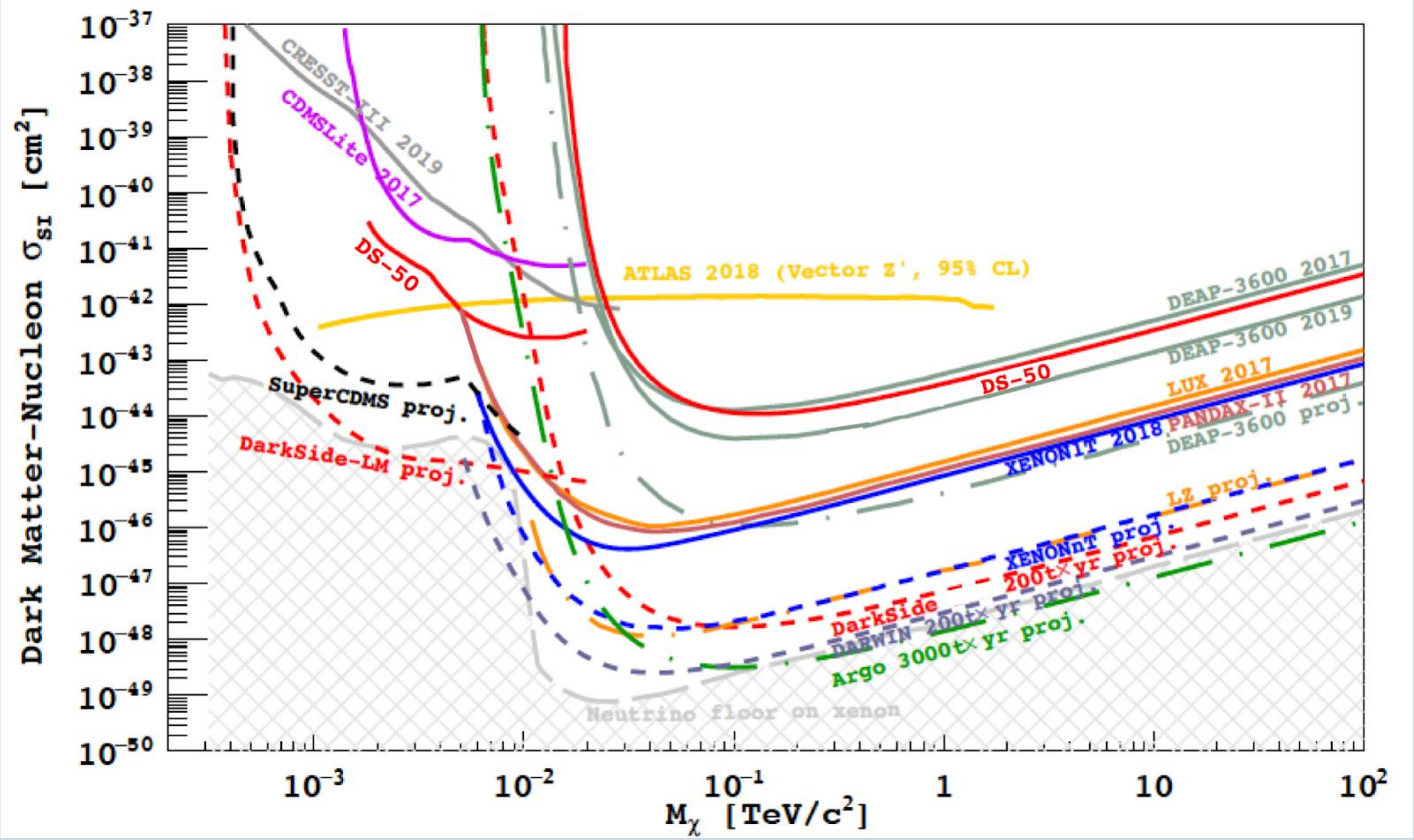
Current landscape

- These exclusion limits and projections make certain **assumptions** about the nature of DM
  - Interaction is spin-independent
  - Velocity- and momentum-independent
  - DM coupling to protons and neutrons are equal
- As positive signals of DM in the lab are elusive it is important to investigate a wide range of DM models



Non-relativistic EFT

- Investigate a **range of possible interactions** with more complex dependencies on momentum and velocity using a non-relativistic EFT framework
- Differential cross-section:

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

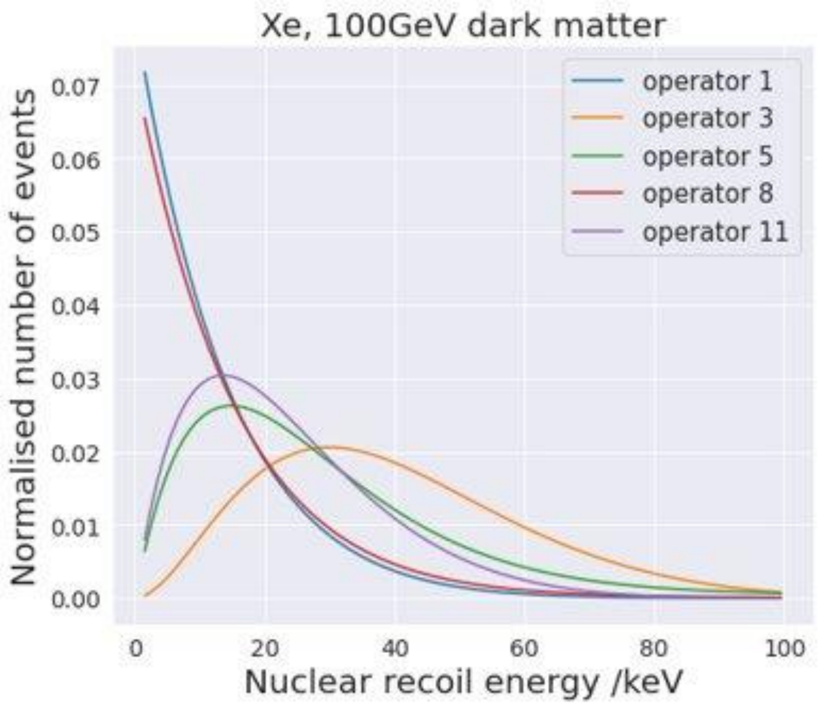
Sum over pairs of operators can lead to interference

Sum over pairs of protons and neutrons

Operator coefficients

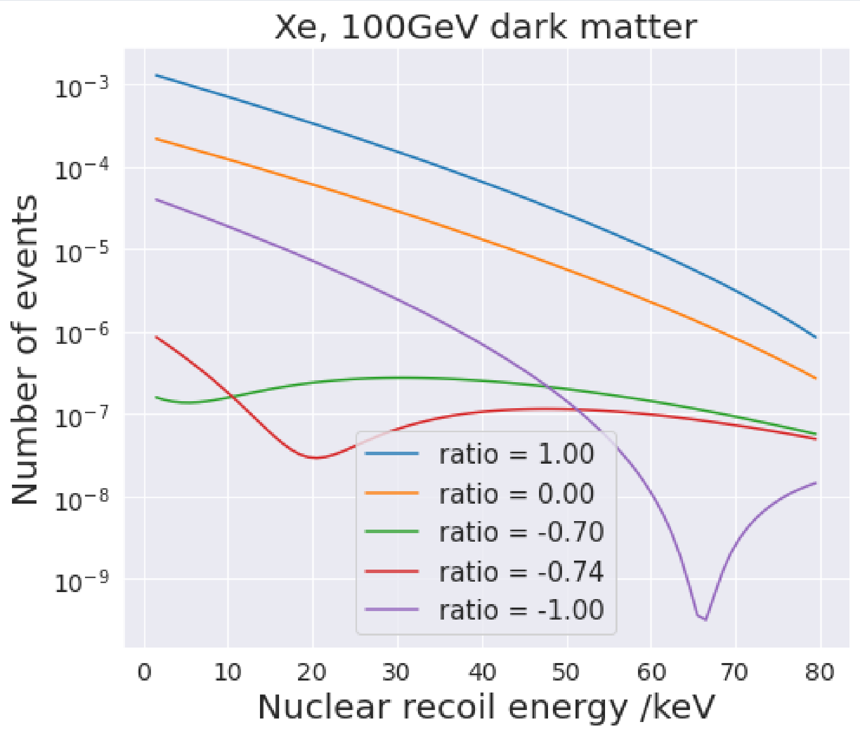
Form factor

These interactions can be dependent on momentum and velocity



Isospin-violating DM

- Allow the DM **coupling to the proton and neutron to be different,** which we call isospin-violating DM
- This can suppress the signal seen in a detector by orders of magnitude
- Additionally, the coupling ratio can affect the shape of the recoil spectrum
- Especially for momentum-dependent operators it is important to investigate this effect with full calculation, rather than in the zero momentum limit (existing work)

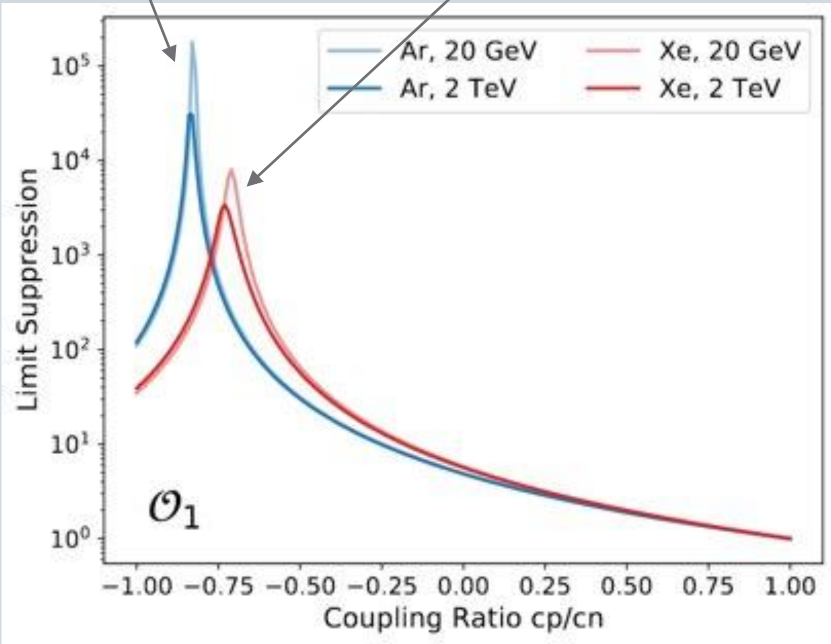


Suppression of exclusion limits

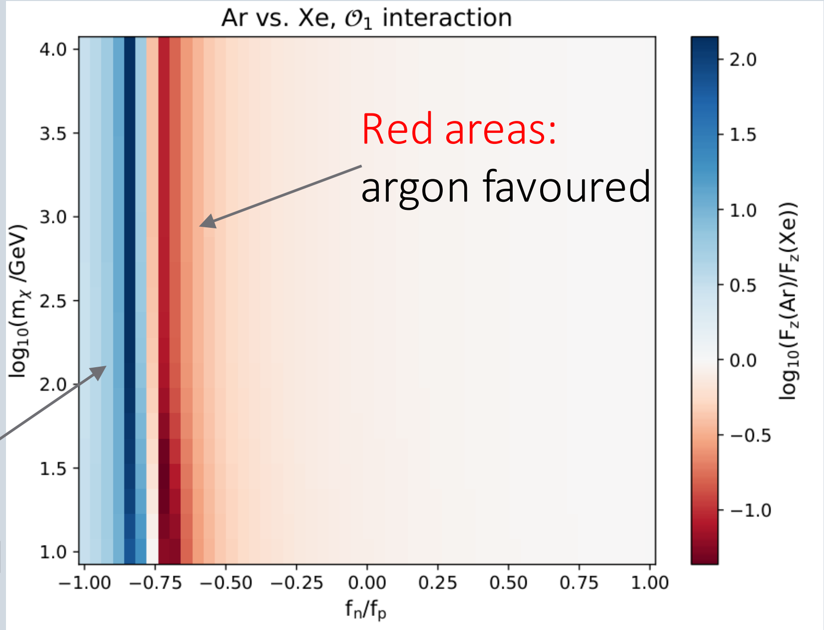
- Calculate the exclusion limits for DS20k and LZ using public information on eg. detector efficiency
- The suppression is defined as the experimental limit at a specific coupling ratio, compared to the nominal limit with equal couplings
- We see that there is a different coupling ratio for Ar and Xe at which the signal is maximally suppressed

Ratio of -0.82 gives maximal Ar suppression

Ratio of -0.74 gives maximal Xe suppression

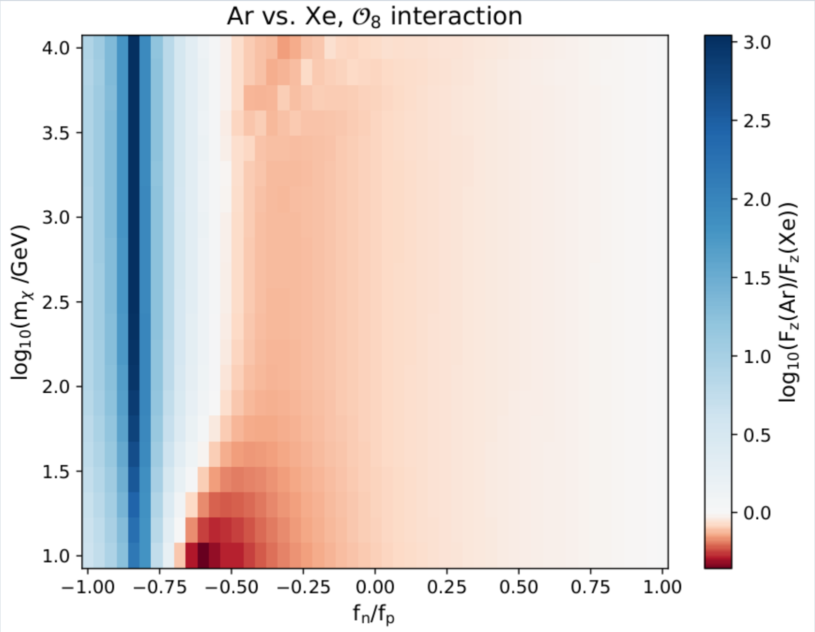


Suppression in Ar vs Xe



Blue areas:
xenon favoured

Mass dependence



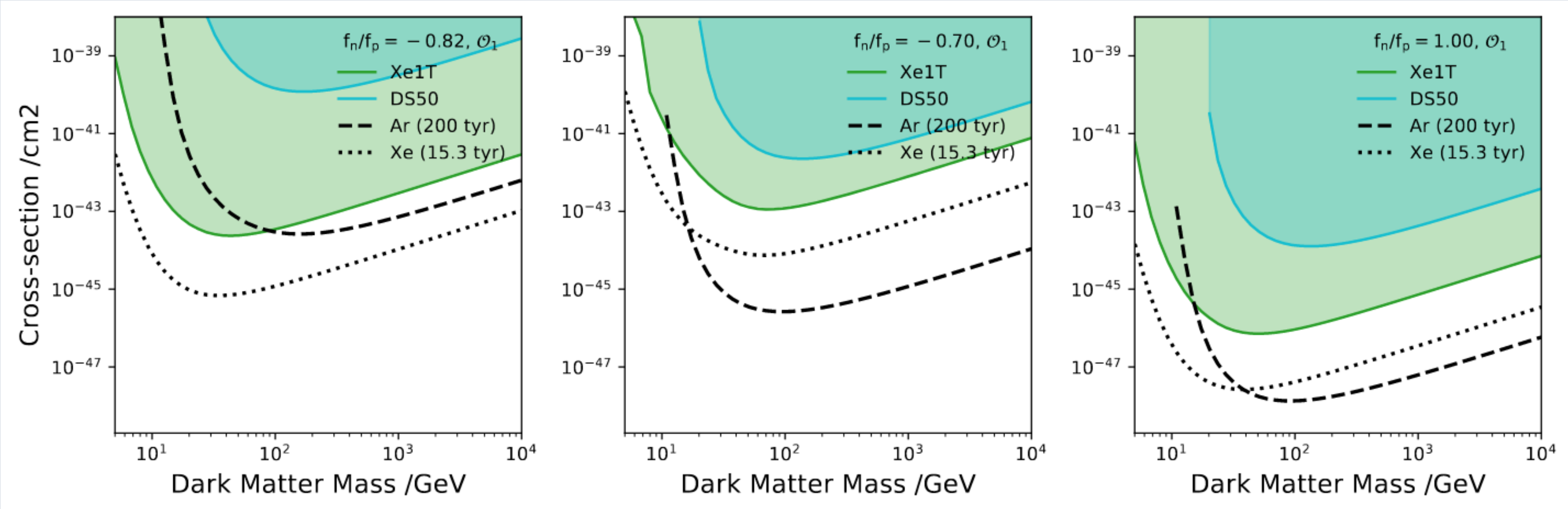
Coupling ratio

These plots show the relative suppression of the Ar experimental limit to the Xe limit for different DM masses and neutron to proton couplings, for the standard O1 interaction and an example of a velocity dependent EFT interaction

Andrew Cheek, Ellen Sandford, Darren Price; paper to appear (2022)

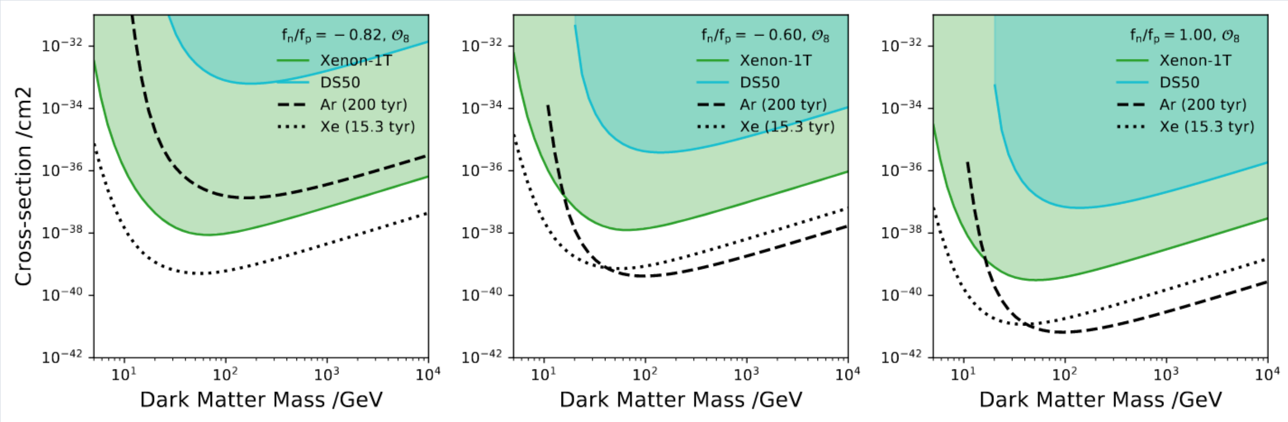
Effect on experimental limits

Xenon favoured couplings **Argon favoured couplings** **Equal couplings**

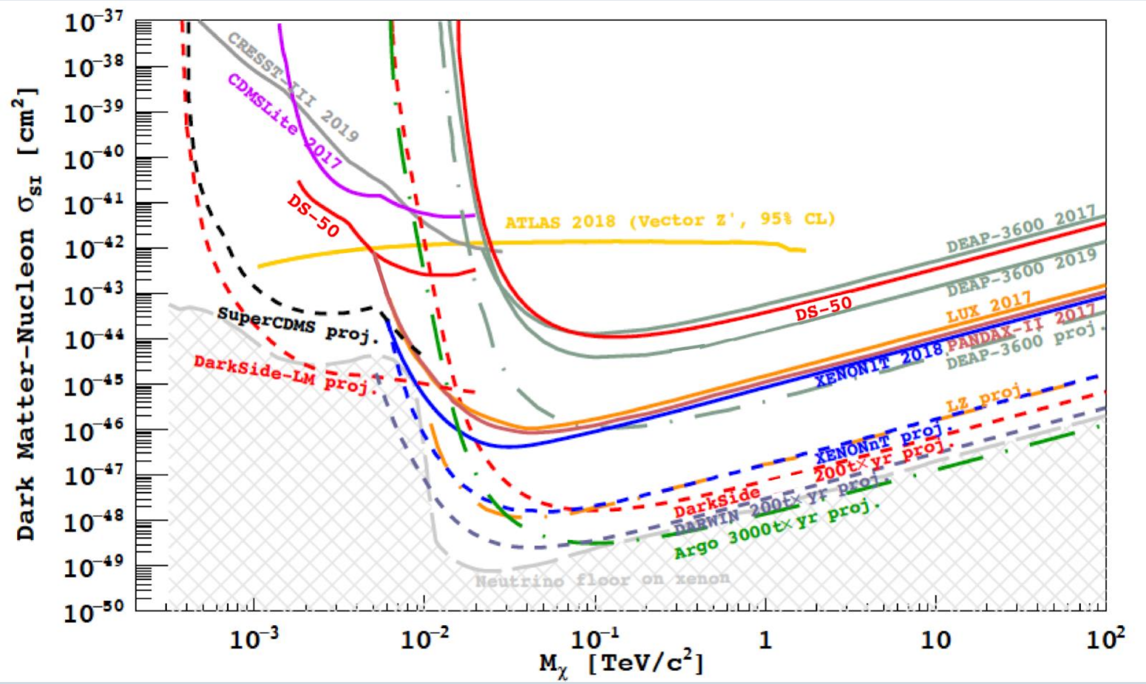


Experimental limits can be suppressed by orders of magnitude, and the ordering of limits from different targets can be changed - these effects are dependent on dark matter mass and interaction type.

Non-standard operators

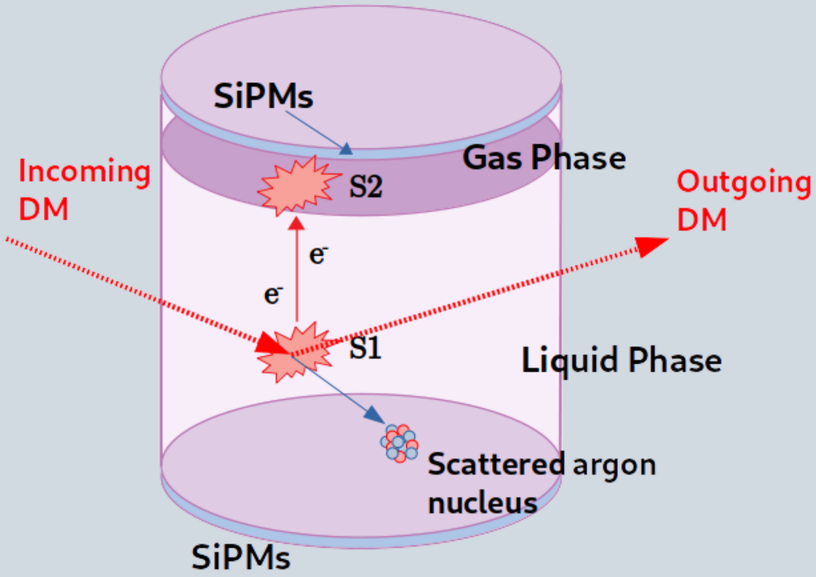


- We can investigate this effect for each operator individually – shown here for the O8 operator (velocity dependent)
- Additionally, we can map specific models onto a combination of these EFT operators, and find areas within theoretically well motivated parameter spaces where isospin violation can affect results
  - This work is in progress



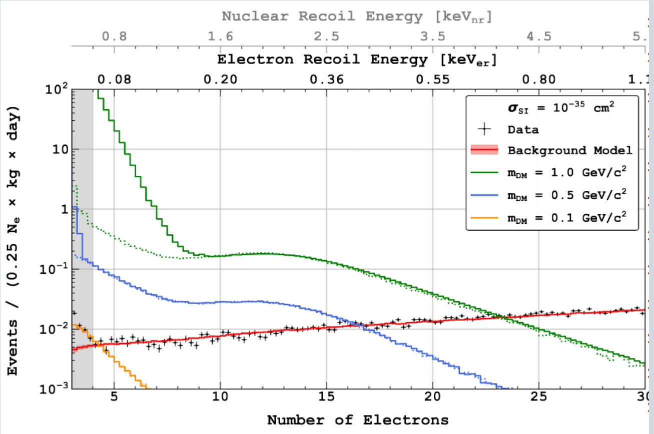
Low mass WIMP dark matter

S2 only searches



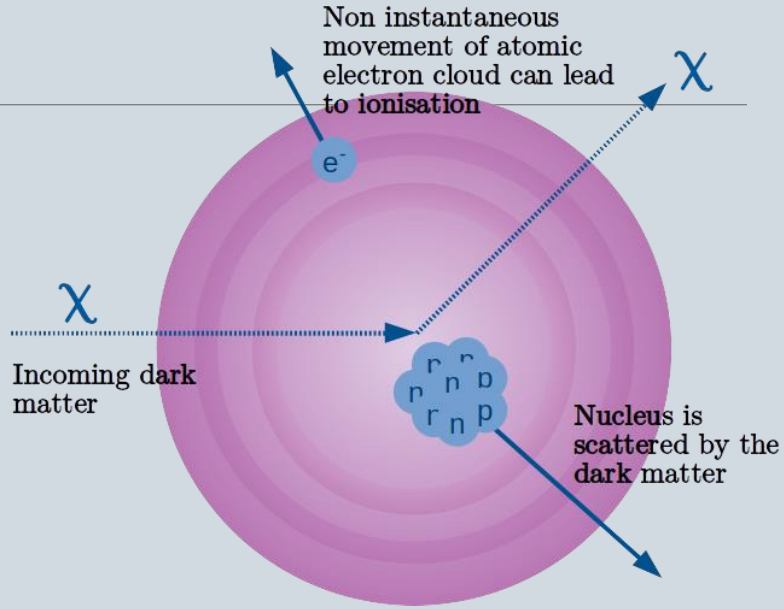
- In order to reach lower energy events, and therefore lower mass DM, we can carry out S2-only searches where the S1 signal is too small to be seen - ‘cost’ of this is that there are ER backgrounds which can no longer be rejected.
- Within S2 only searches, is it possible to reach even lower DM masses using the Migdal effect

DarkSide-50 S2 only backgrounds
(arxiv 2207.11966)



The Migdal effect

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



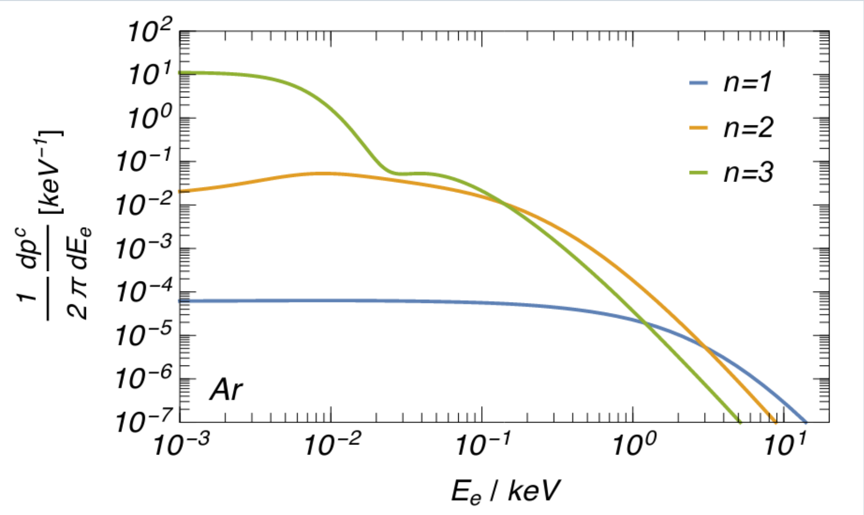
$$\frac{dR}{dE_R\, dE_{EM}\, dv_{DM}} \simeq \frac{dR_0}{dE_R\, dv_{DM}} \times \frac{1}{2\pi} \sum_{n,\ell} \frac{d}{dE_e} p^c_{q_e}(n\ell \rightarrow (E_{EM} - E_{n\ell}))$$

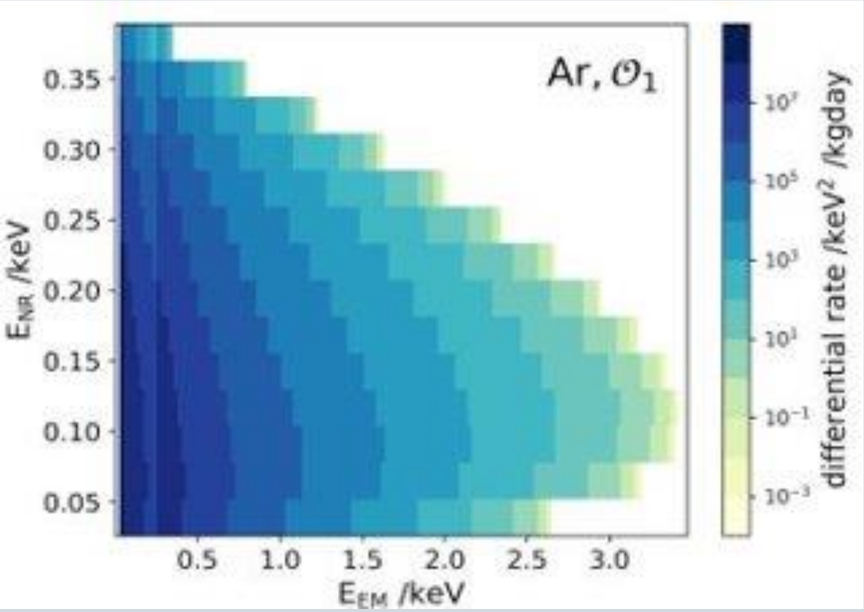
Sum over different energy levels

Ionisation probability

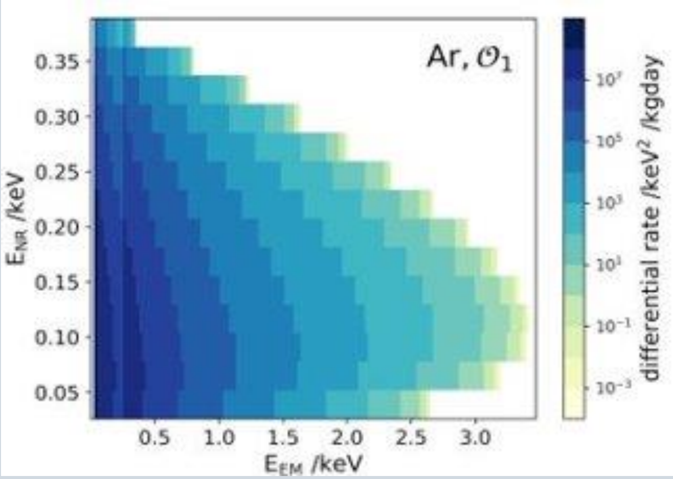
Migdal effect calculation

- Differential rate is calculated, summing over energy levels and utilising ionisation probabilities from Ibe et al (arxiv 1707.07258)
- Total EM energy is taken as the Migdal electron recoil energy summed with the binding energy of the atom - taken as a single deposit
- Differential rate is calculated depending on both the NR and EM energy, giving us the correlation between these energies for a specific DM mass and EFT operator

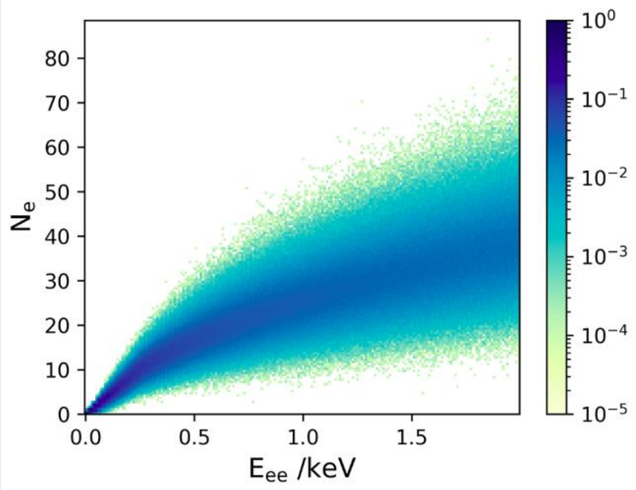




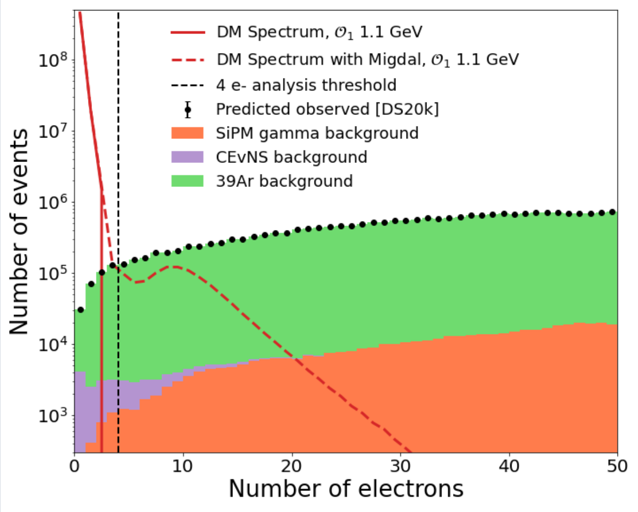
Producing signal spectra



Produce a 2d map of the differential rate depending on both the EM energy and NR energy



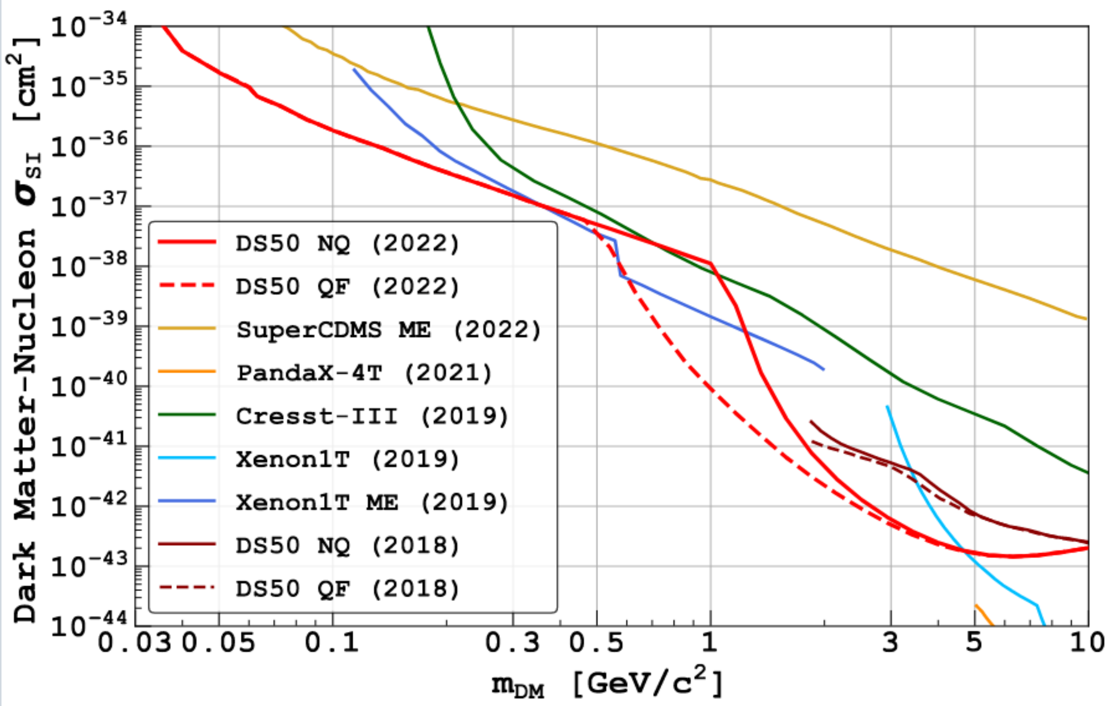
Sample from 2d map and apply detector response separately for two components, combining only once in terms of the observable

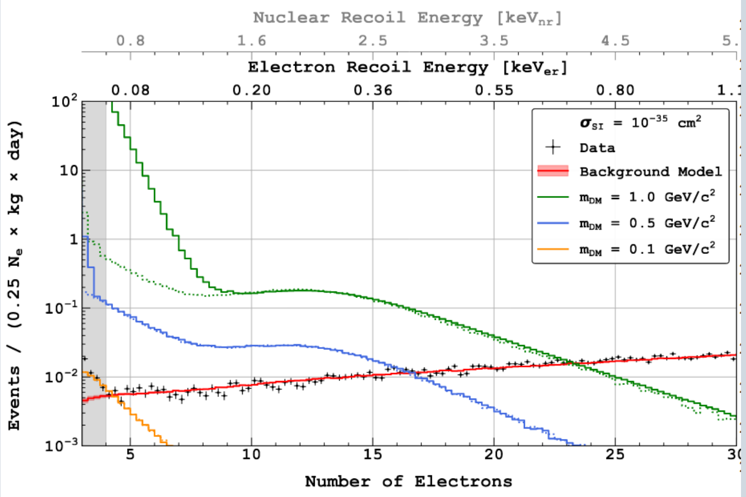


Combine Migdal + non Migdal events and produce total spectra in terms of observable

DarkSide-50 Migdal limit

Updated results with larger dataset (650 days), and improved calibration and background model + included the Migdal effect



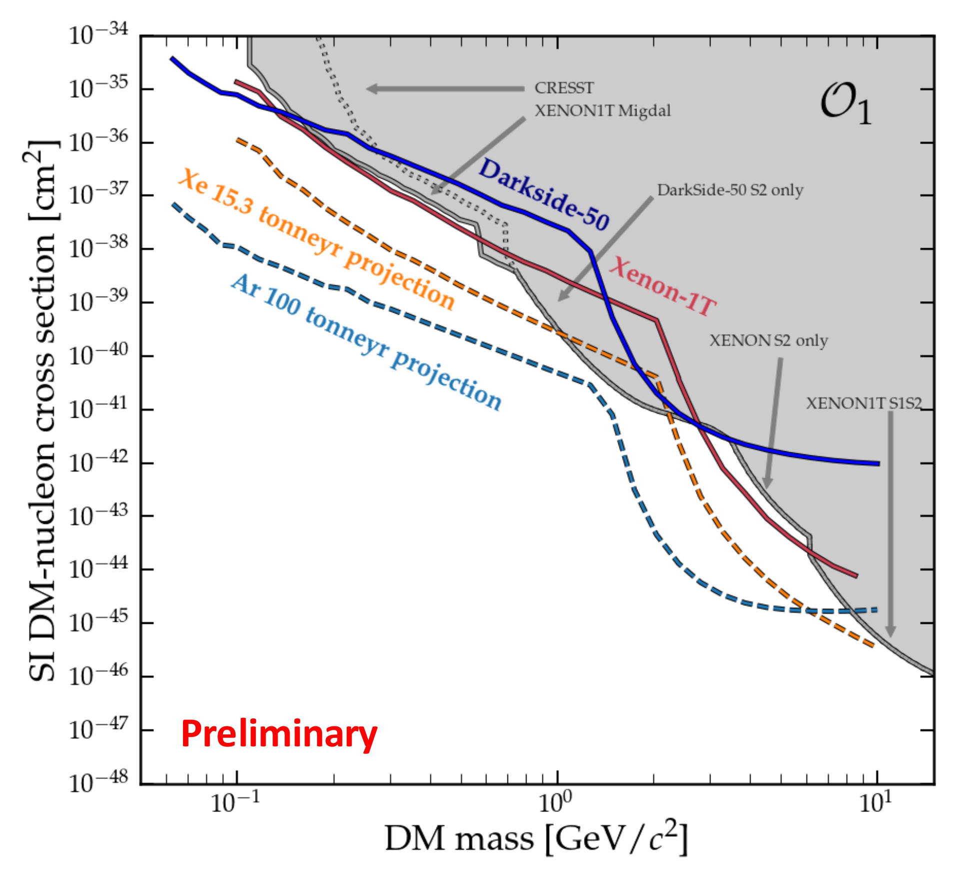


The Migdal effect allows a DarkSide-50 limit to be set down to ~40MeV dark matter mass, compared to around ~1GeV without Migdal.

Projected Migdal limits

Calculate projected exclusion limits of next generation experiments such as LZ and DS20k using public information on expected performances and scaling backgrounds

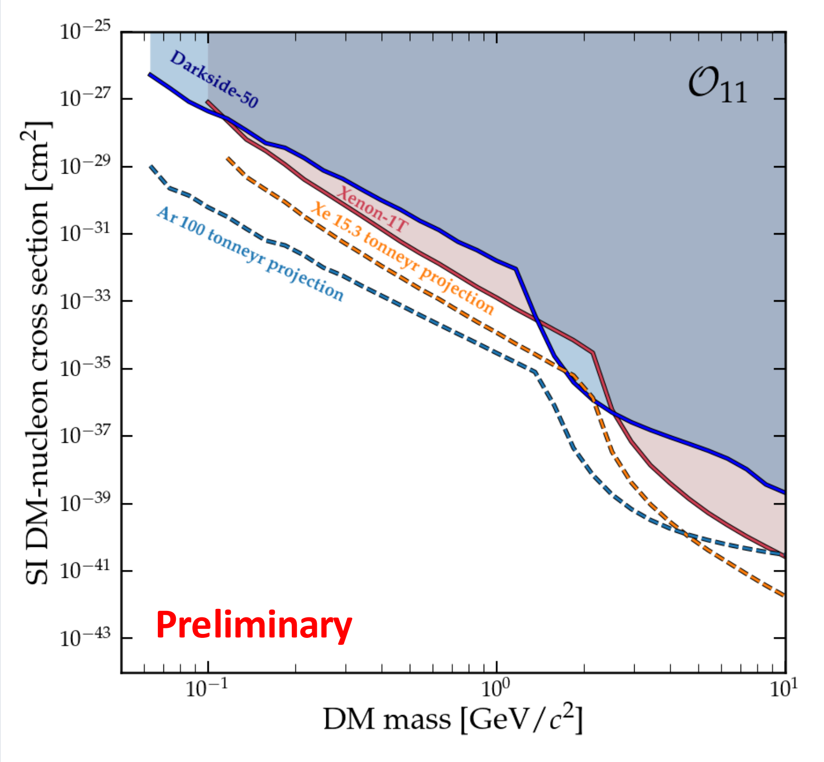
These are compared to current limits – reinterpretation of DarkSide-50 and Xenon1T data from public information

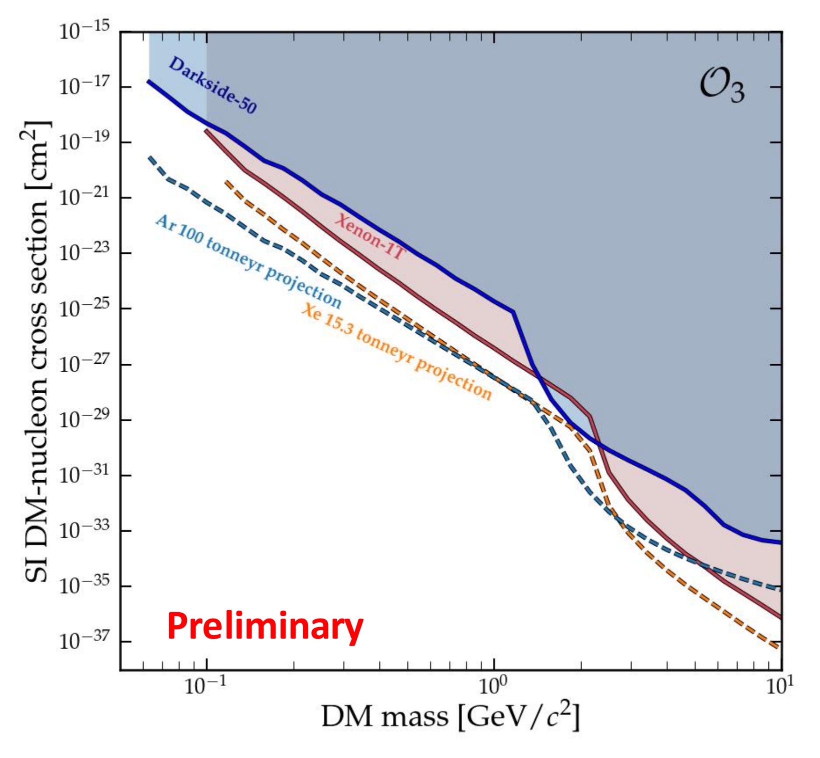


Paolo Agnes, Miguel Campos, Malcolm Fairbairn, Jocelyn Monroe, Darren Price, Ellen Sandford; to appear (2022)

Non-standard operators with Migdal

We can include the Migdal effect within the calculation of any of the non-standard operators in the EFT framework





Conclusions

- We can generalise the dark matter interaction type using a non-relativistic EFT framework, and investigate momentum and velocity dependent operators
- Isospin violation can affect experimental limits of different target materials, and is dependent on both mass and interaction type (rate and recoil spectra shape)
- Can maximise sensitivity to low mass dark matter in S2 only searches by including the EM energy contribution from the Migdal effect
  - Migdal effect allows DarkSide-50 to have sensitivity down to ~40 MeV
- We calculate this Migdal effect within different non-standard EFT operators, reinterpreting public limits and scaling up backgrounds to calculate projected sensitivities of Ar and Xe next generation experiments within this mass range

Back up

EFT operators

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

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.

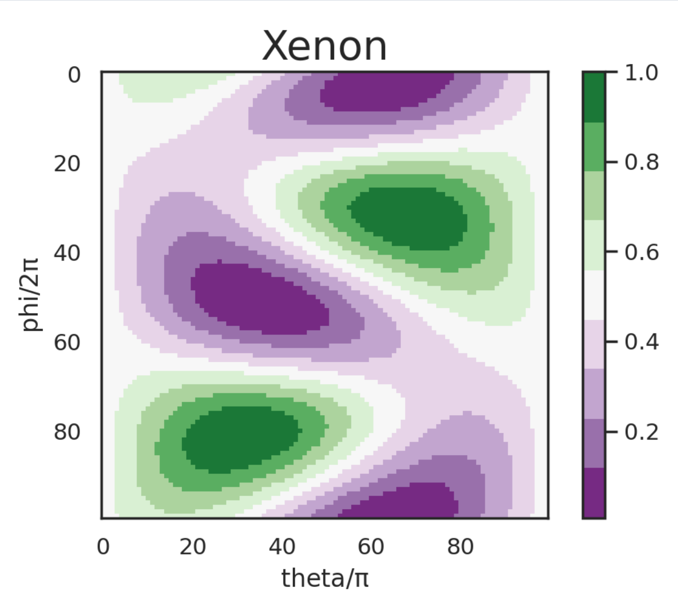
Table from https://arxiv.org/pdf/1810.05576.pdf

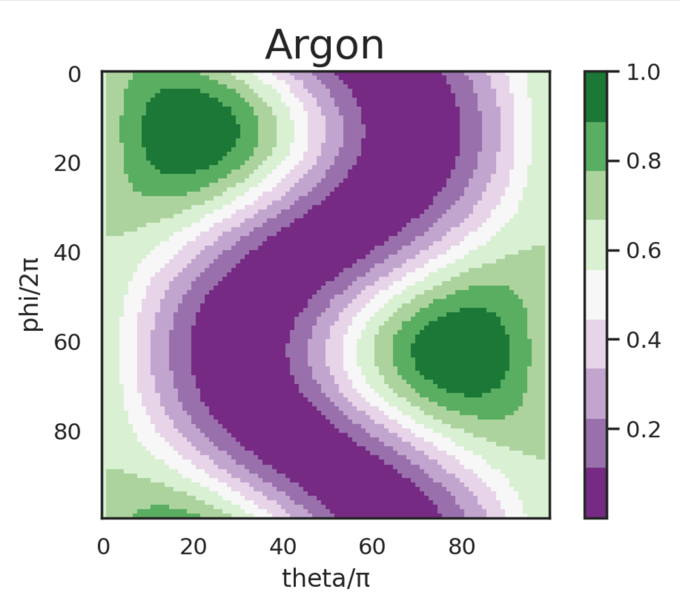
Specific models

The EFT operators in this framework can be mapped onto specific models

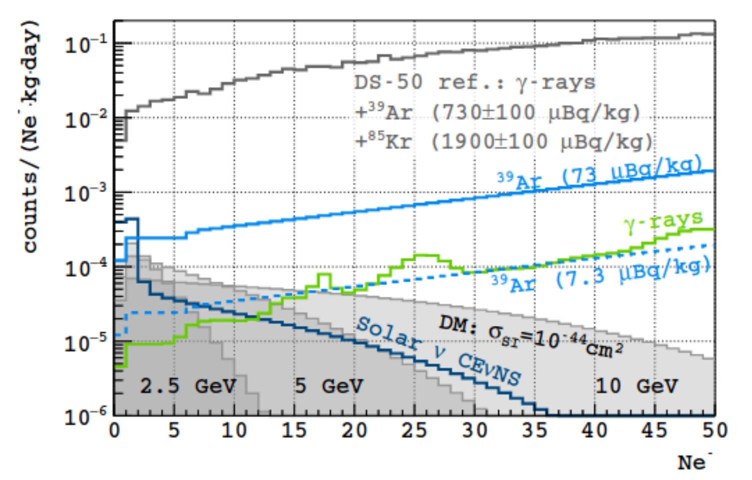
In this case we consider an axial-vector model ("Z′-mediated Majorana dark matter: suppressed direct-detection rate and complementarity of LHC searches" https://arxiv.org/abs/2202.02292) which includes contributions from O8 (spin-independent) as well as O4 and O9

This means there are very different regions of parameter space where signals are suppressed in argon vs xenon





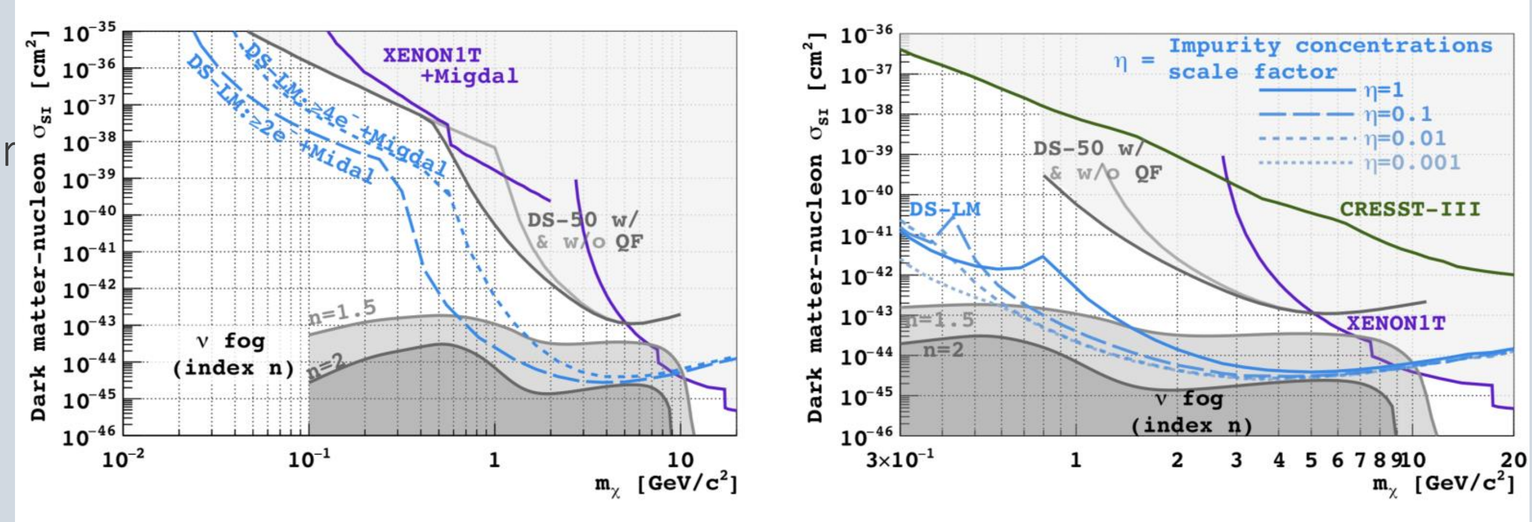
DarkSide-LowMass



Projected backgrounds

https://arxiv.org/abs/2209.01177

- DarkSide-LowMass: proposed detector optimised for S2 only searches
- Sensitivities shown for 1tonneyear exposure
- Probes into to the neutrino fog down to 30 MeV DM mass
- Requires SiPM R&D and ultra-radiopure Ar
- Boulby proposed as a potential site



Projected sensitivity