Science & Technology Facilities Council

Durham University

Using Surrogate Models for Direct Detection

Andrew Cheek

In collaboration with N. Borzorgnia, D. Cerdeño and B. Penning

in progress

Invisibles18 Workshop,
Karlsruhe Institute of Technology, Germany

Durham University

We want to explore the ultimate reach of DD

In order to interpret any DD data in a model independent way, we go to the Non-Relativistic Effective Field Theory (NREFT) basis.

A. L. Fitzpatrick *et al.* , JCAP **1302** (2013) 004

$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^- .$$

Fields, DM and nucleon.

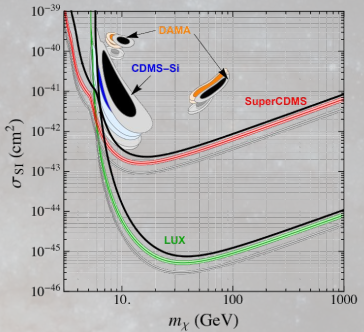
Coefficients to each operator. Can be matched to UV-model

Operators built out of relevant degrees of freedom at the DD scale, velocity, spin, momentum.

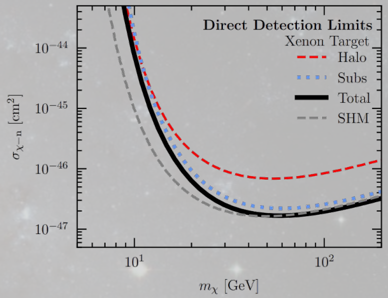
$$\begin{aligned}
O_1 &= 1_\chi 1_N & O_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
O_3 &= i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) & O_8 &= \vec{S}_\chi \cdot \vec{v}^\perp \\
O_4 &= \vec{S}_\chi \cdot \vec{S}_N & O_9 &= i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right) \\
O_5 &= i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) & O_{10} &= i\vec{S}_N \cdot \frac{\vec{q}}{m_N} \\
O_6 &= \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) & O_{11} &= i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}
\end{aligned}$$

Astrophysical uncertainties are also a major factor in DD experiments.

N. Bozorgnia *et al.* , JCAP **1605**, no. 05, 024 (2016)



L. Necib *et al.* , arXiv:1807.02519



Overall, this can result in a high number of parameters that you'd want to fit.

Surrogate Model

A surrogate model is an emulator of the true calculation.

We developed Reconstruction Analysis using Polynomials in Direct Detection (RAPIDD).

This software accurately reproduces our full physics calculations with much increased speed (up to 200 times faster).

$$N_k^a(\boldsymbol{\Theta}) \approx \mathcal{P}_k^a(\boldsymbol{\Theta}) = \sum_{l=1}^{N_{\mathrm{coeffs}}} d_{k,l}^a\, \tilde{\Theta}_l \equiv \mathbf{d_k^a} \cdot \tilde{\boldsymbol{\Theta}}$$

In JCAP **1808** no. 011 (2018), we used this technique to assess whether we could determine the correct simplified model from a series of benchmarks.

Name	Model	DM Parameters	N_{Xe}	N_{Ge}	N_{Ar}	
BP1	SS	$m_\chi = 10$ GeV $c_1 = 1\times10^{-4}$ $c_{10} = 5$	93	10	50	Fully Degenerate
BP2	SS	$m_\chi = 100$ GeV $c_1 = 3\times10^{-5}$ $c_{10} = 5\times10^{-1}$	206	2	30	
BP3	FS	$m_\chi = 30$ GeV $c_1 = 0.0$ $c_6 = 60$ $c_{10} = 0.0$ $c_{11} = 0.0$	256	1	0	Partially Degenerate

Opening the Energy Window for DD

We decided to make use of the surrogate model to estimate what the values of maximum nuclear recoil energy would optimise the potential for direct detection.

This has garnered some attention from people interested in inelastic DM [1], but we're focussing on elastic scattering.

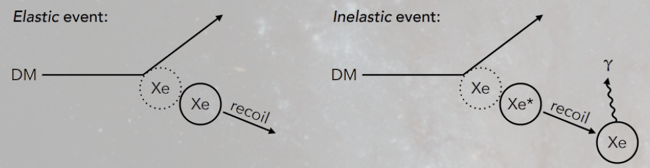
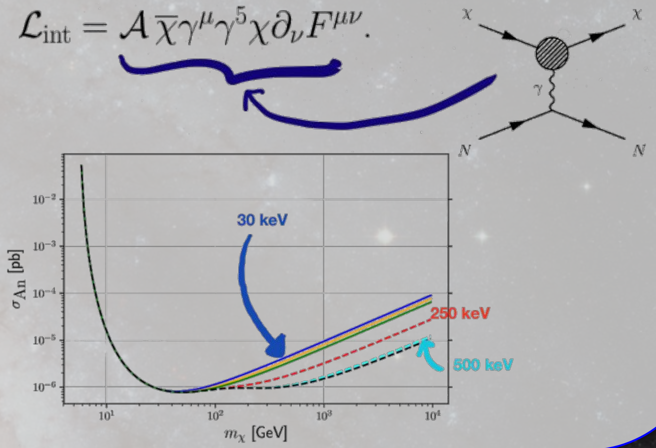


Image: Chris McCabe

It's been stated [2] that for certain models, there would be an improvement in exclusion limits by increasing Emax.

For example, take the anapole moment

$$\mathcal{L}_{\text{int}} = \mathcal{A}\,\underbrace{\overline{\chi}\gamma^{\mu}\gamma^{5}\chi\partial_{\nu}}F^{\mu\nu}.$$



[1] J. Bramante *et al.* ,
Phys. Rev. D **94**, no. 11, 115026

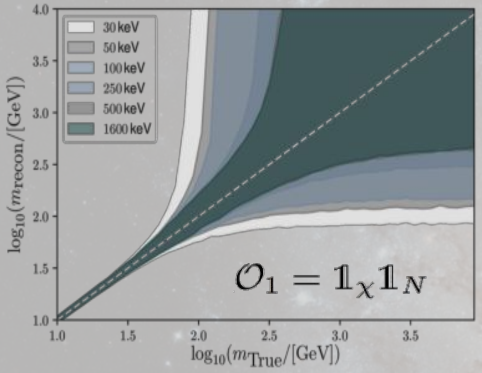
[2] E. Aprile *et al.* [XENON Collaboration],
Phys. Rev. D **96**, no. 4, 042004

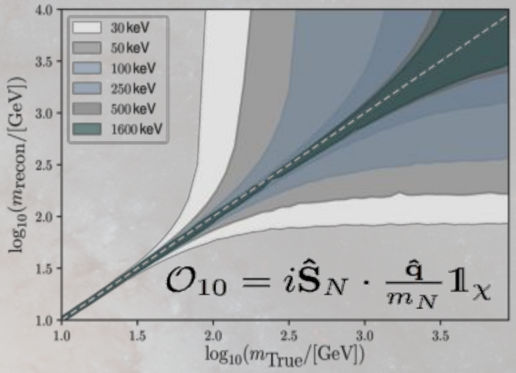
Improving Parameter Reconstruction

Further improvements include being better able to determine the "true" particle model.

This relies on determining the dominant contribution to the nuclear response. Much of which depends on whether you can precisely determine the mass.

We evaluated this by performing parameter reconstructions on a series of data for different "true" mass values, defined by the number of recoils they produce in the [3,30] keV window.



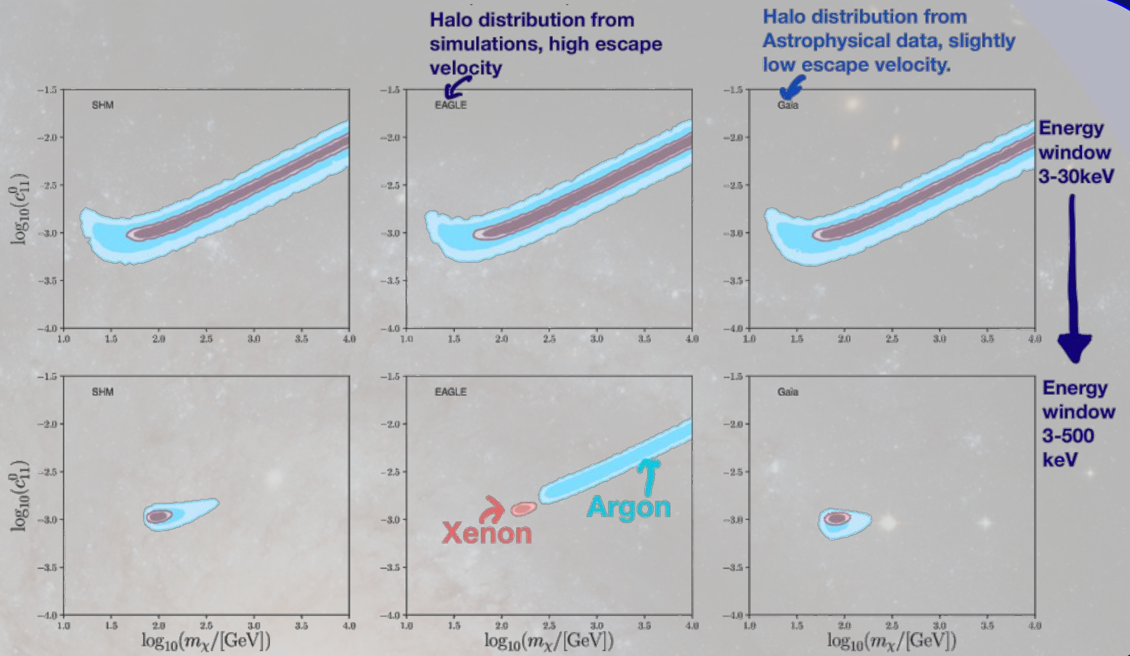


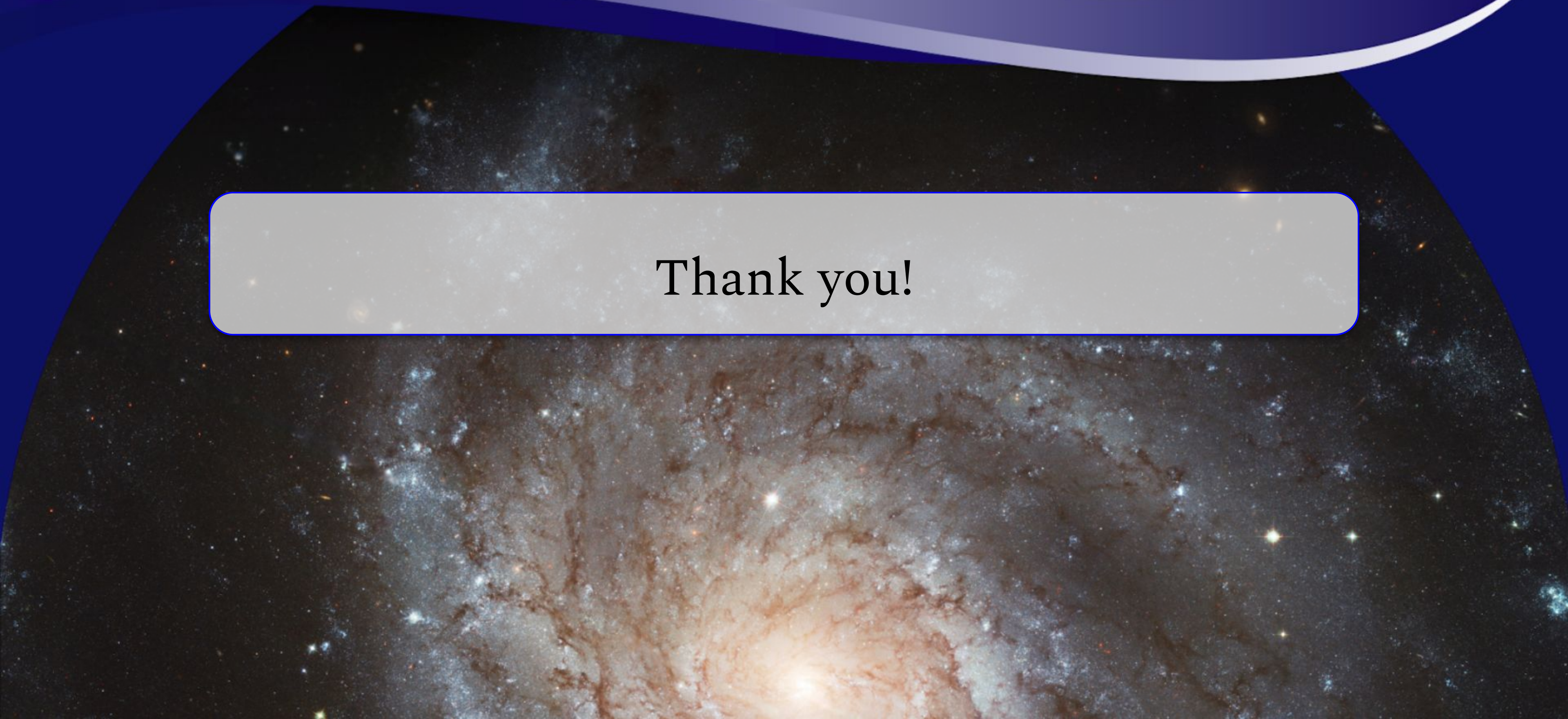
Improving our Understanding of the Astrophysics

It also looks like we will be able to learn more about the DM halo if we extend our ROI to higher energies.

Performing parameter reconstructions on simulated data generated using different astrophysical halos.

We observe tensions between experiments only when we go to higher energies.





Thank you!