Determining dark matter particle properties with direct detection experiments

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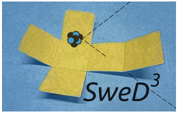
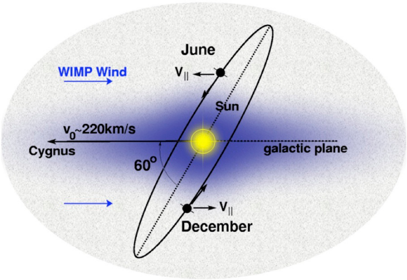


Outline

- Dark matter (DM) direct detection
- Current status and prospects
- New! Determining the DM particle spin with next generation direct detection experiments
- Summary

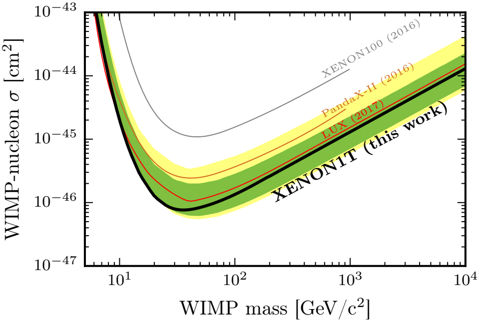
- **Motivation and strategy**:



- **Differential rate** of DM-nucleus scattering events in terrestrial detectors

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_T} \int_{|\mathbf{v}|>v_{\min}} \mathrm{d}^3\mathbf{v}\, |\mathbf{v}| f_\chi(\mathbf{v}+\mathbf{v}_\oplus) \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}$$

- So far, DM particles escaped detection
- Upper limits on $\mathrm{d}\mathcal{R}/\mathrm{d}E_R$ translated into upper limits on $\mathrm{d}\sigma_T/\mathrm{d}E_R$
- **Standard strategy**: set exclusion limits on SI and SD DM-nucleon interactions
- **Extended strategy**: set exclusion limits on the complete set of Galilean invariant DM-nucleon interactions



E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **119**, no. 18, 181301 (2017)

The next decade

- Direct detection experiments will probe a significant fraction of the WIMP parameter space
- Priorities will be:
  - to identify optimal strategies to extract DM properties from data, assuming a WIMP signal
  - to search for an alternative to WIMPs, assuming there will be no detection
- In this talk, I'll focus on our recent contributions to the first line of research

- **DM spin** from directional detection

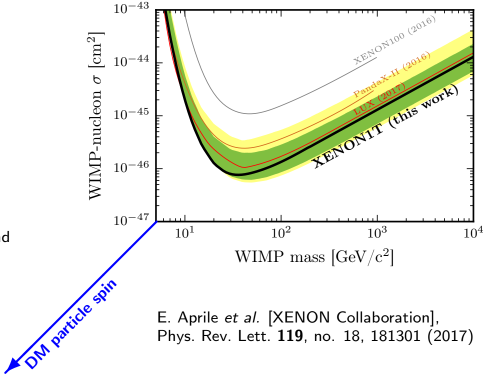
  R. Catena *et al.*,

  Phys. Rev. D **97** (2018) no.2, 023007

- **DM spin** combining direct detection and LHC

  S. Baum, R. Catena, J. Conrad, K. Freese and

  M. B. Krauss, arXiv:1709.06051



E. Aprile *et al.* [XENON Collaboration],
Phys. Rev. Lett. **119**, no. 18, 181301 (2017)

- We focus on the most general set of renormalisable models preserving Lorentz and gauge symmetry, and extending the Standard Model by one DM candidate of spin ≤ 1 and one particle mediating DM-quark interactions.

  J. B. Dent, L. M. Krauss, J. L. Newstead and S. Sabharwal, Phys. Rev. D **92**, no. 6, 063515 (2015)

- Models classified in terms of WIMP and mediator spin, e.g.:

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator
$1/2$	0	h_1, λ_1	$\mathcal{O}_1$
$1/2$	0	h_2, λ_1	$\mathcal{O}_{10}$
$1/2$	0	h_1, λ_2	$\mathcal{O}_{11}$
$1/2$	0	h_2, λ_2	$\mathcal{O}_6$
$1/2$	1	h_3, λ_3	$\mathcal{O}_1$
$1/2$	1	h_4, λ_3	$\mathcal{O}_9$
$1/2$	1	h_3, λ_4	$\mathcal{O}_8$
$1/2$	1	h_4, λ_4	$\mathcal{O}_4$

Non-relativistic effective theory of DM-nucleon interactions (NRET)

J. Fan, M. Reece and L. T. Wang, JCAP **1011**, 042 (2010);
A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, JCAP **1302**, 004 (2013)

- NRET is based upon two assumptions:
  - there is a separation of scales: $|\mathbf{q}|/m_N \ll 1$, where m_N is the nucleon mass
  - DM is non-relativistic: $v/c \ll 1$

- It follows that the Hamiltonian for DM-nucleon interactions is

$$\hat{\mathcal{H}}(\mathbf{r}) = \sum_{\tau=0,1} \sum_k c_k^\tau \hat{\mathcal{O}}_k(\mathbf{r})\, t^\tau$$

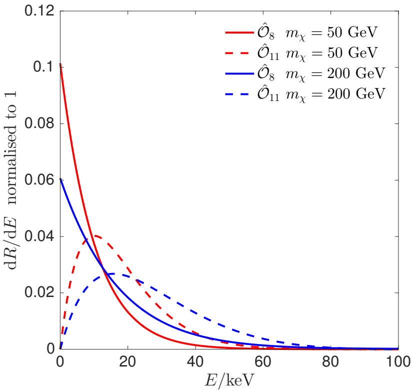
- $\hat{\mathcal{O}}_k(\mathbf{r})$ are Galilean invariant operators
- $t^0 = \mathbb{1}_{\text{isospin}}$, $t^1 = \tau_3$

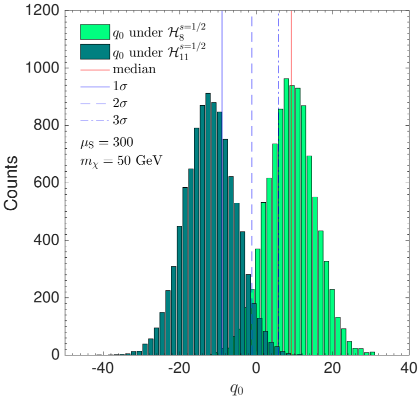
NRET

$\hat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_N$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_\chi$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_\chi$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_N$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_N$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$	$\hat{\mathcal{O}}_{17} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$
$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{18} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{S}}_N$

DM particle spin combining direct detection and LHC (I)

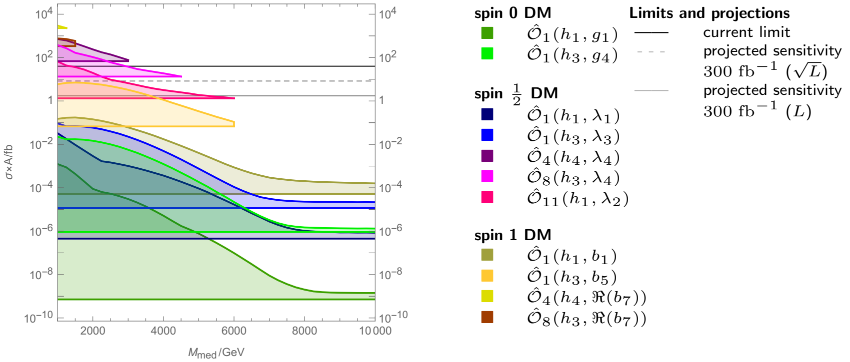
S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, arXiv:1709.06051





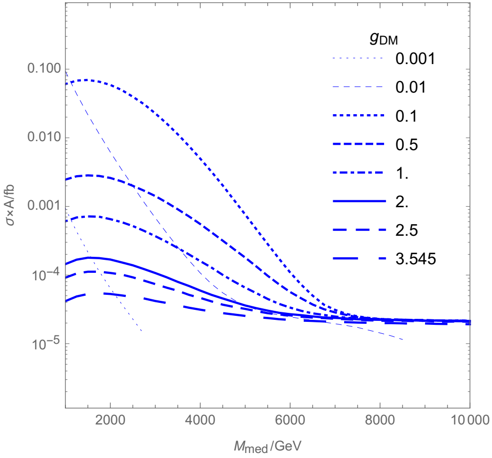
DM particle spin combining direct detection and LHC (II)

S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, arXiv:1709.06051



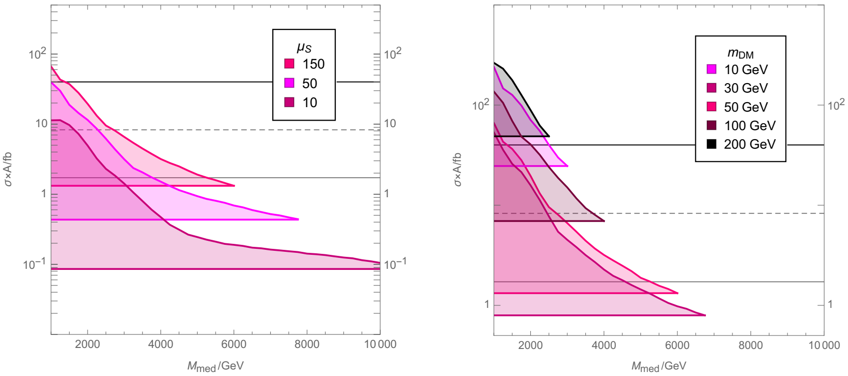
Compatibility regions in the $M_{\text{med}} - \sigma$ plane

S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, arXiv:1709.06051



Changing assumptions

S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, arXiv:1709.06051



Summary

- We are currently developing analysis strategies to extract the DM particle spin based upon the detection of a DM signal at direct detection experiments

- I briefly mentioned two examples
  - DM spin from directional detection
  - DM spin combining direct detection and the LHC (*)

- **Scenario 1**: Featureless spectrum. If a LHC mono-jet signal is detected, DM has spin $1/2$ and interacts via a unique velocity-dependent operator. If not, DM interacts through canonical spin-independent interactions.

- **Scenario 2**: Bumpy spectrum. DM has spin $1/2$ and interacts via a unique momentum-dependent operator.