(Aspects of) WIMP phenomenology

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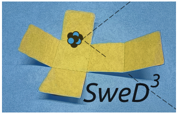


Outline

- Basic properties of WIMPs
- Selected WIMP detection strategies
- A theoretical framework for WIMP dark matter
- Testing the WIMP hypothesis
  - Canonical WIMPs
  - Inelastic WIMPs
  - Self-interacting WIMPs
- Summary

Basic properties of WIMPs

- WIMPs achieve the correct cosmological density today through chemical decoupling;
- They are non-relativistic during cosmological structure formation (e.g. at matter-radiation equivalence);
- Colour and electrically neutral;
- Stable on cosmological time scales.

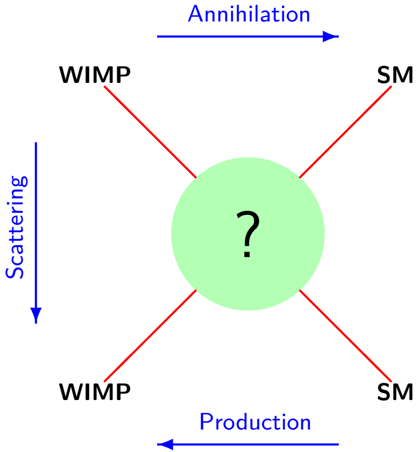
- WIMPs can scatters off nuclei inelastically, e.g.

  J. Bramante, P. J. Fox, G. D. Kribs and A. Martin, Phys. Rev. D **94** (2016) no.11, 115026
- And can have sizeable self-interactions, e.g.

  T. Bringmann, F. Kahlhoefer, K. Schmidt-Hoberg and P. Walia, Phys. Rev. Lett. **118** (2017) no.14, 141802

  F. Kahlhoefer, K. Schmidt-Hoberg and S. Wild, JCAP **1708** (2017) no.08, 003

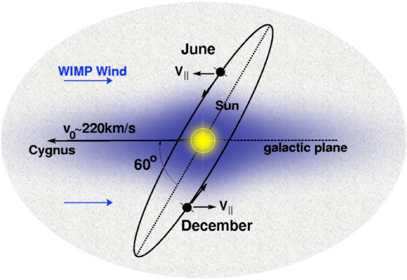
Basic properties of WIMPs



- Direct detection experiments search for DM-nucleus scattering events
- Indirect detection experiments search for DM pair annihilation products
- The LHC searches for missing transverse momentum in proton collisions

WIMP direct detection

- **Motivation and strategy**:

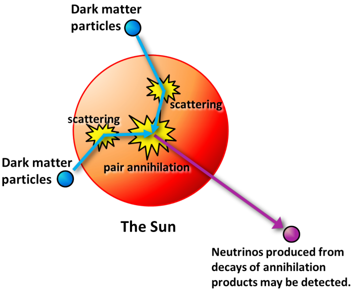


- **Differential rate** of DM-nucleus scattering events in terrestrial detectors

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

WIMP indirect detection / neutrino telescopes

- **Motivation and strategy**:

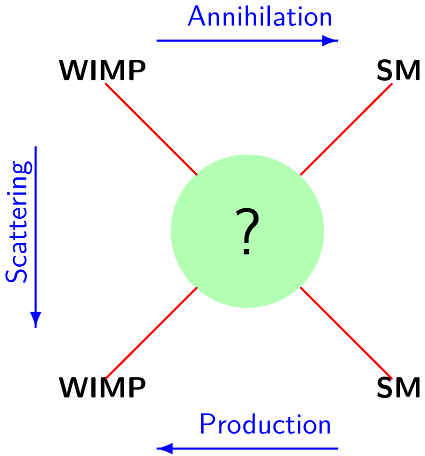


- **Rate of DM scattering** from an initial velocity w to a velocity below $v_{\rm esc}(r)$:

$$\Omega_v^-(w) = \sum_i n_i w\,\Theta(u - u_{m,i})\Theta(E_H^i - E_C)\int_{E_L^i}^{E_H^i} dE_R\,\frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R}$$

Other strategies of interest for this talk

- WIMP indirect searches in γ-rays from dwarf spheroidal galaxies (dSphs)
- WIMP searches at the LHC in final states involving a monojet and missing energy



A theoretical framework for WIMPs

- I will focus on a general class of simplified models for spin ≤ 1 DM interacting with quarks

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

- Within this framework, models can be classified in terms of WIMP and mediator spin

- Each model is characterised by 4 parameters: two masses and two coupling constants

- Each model can be mapped onto a (linear combination) of DM-nucleon interaction operators

- These operators define the non relativistic effective theory of DM-nucleon interactions (NRET)

NRET

- 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

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

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

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

$$\hat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_N$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_\chi$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_N$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_\chi$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_N$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

$$\hat{\mathcal{O}}_{17} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$

$$\hat{\mathcal{O}}_{18} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \cdot \hat{\mathbf{S}}_N$$

NRET limitations

- NRET does not account for renormalisation group effects, e.g. operator mixing

  A. Crivellin, F. D'Eramo and M. Procura, Phys. Rev. Lett. **112** (2014) 191304

- NRET with constant coupling constants cannot describe scenarios where DM interacts with pions exchanged between nucleons bound in nuclei (i.e. pion pole)

  F. Bishara, J. Brod, B. Grinstein and J. Zupan, JCAP **1702** (2017) no.02, 009

  F. Bishara, J. Brod, B. Grinstein and J. Zupan, arXiv:1708.02678 [hep-ph] (DirectDM)

Canonical WIMPs

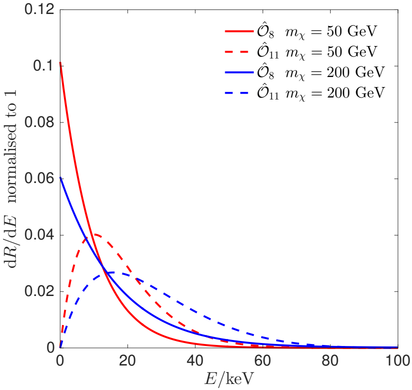
Research questions

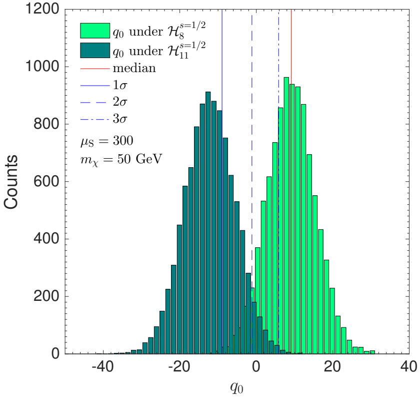
XENONnT has detected a WIMP signal

- WIMP spin?
- Compatibility with the WIMP thermal production mechanism?

The XENONnT input

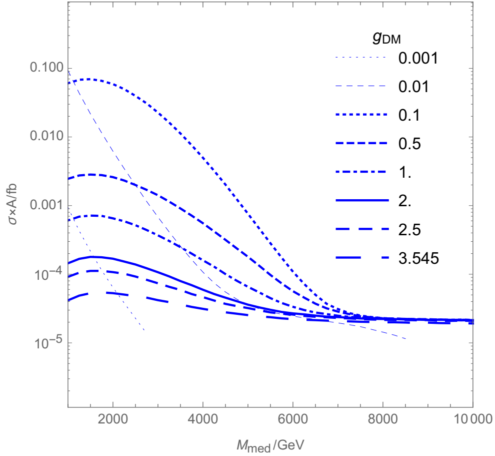
S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, Phys. Rev. D **97** (2018) no.8, 083002





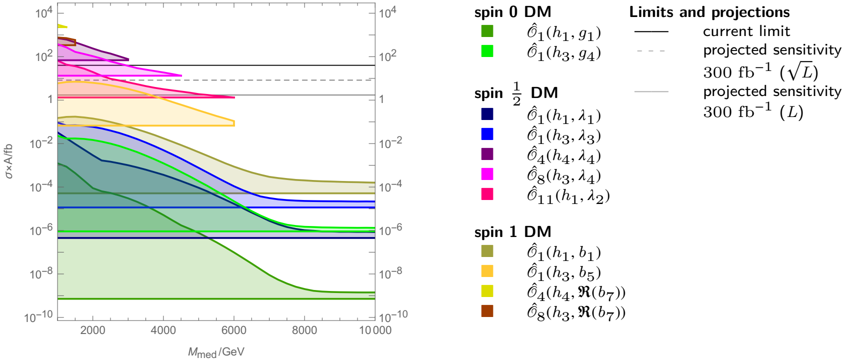
Compatibility regions in the $M_{\text{med}} - \sigma$ plane

S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, Phys. Rev. D **97** (2018) no.8, 083002



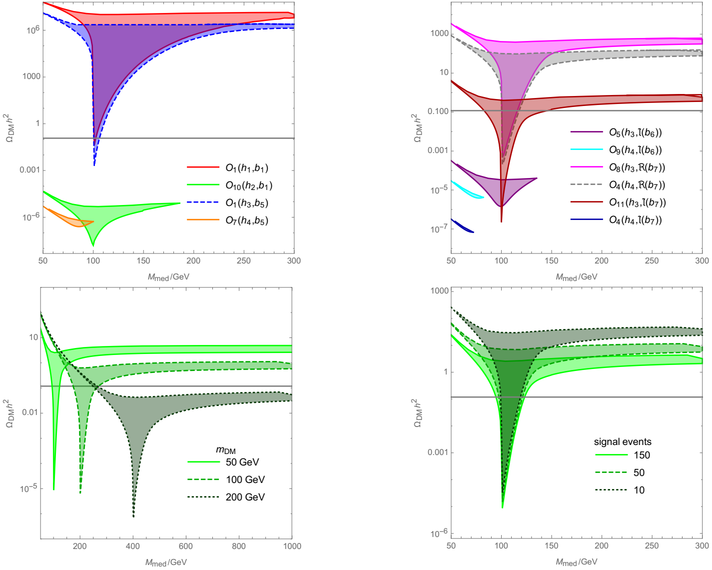
WIMP spin combining direct detection and LHC

S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, Phys. Rev. D **97** (2018) no.8, 083002



Compatibility with the WIMP thermal production mechanism

R. Catena, J. Conrad and M. B. Krauss, Phys. Rev. D **97** (2018) no.10, 103002



Inelastic WIMPs

Kinematics of inelastic DM-nucleus scattering

- When there is a mass splitting δ between incoming and outgoing DM particle, one has

$$E_R^{\mathrm{max}} = \frac{\mu^2}{m_T} w_i^2 \left(1 + \sqrt{1 - \frac{2\delta}{\mu w_i^2}} \right) - \frac{\mu}{m_T}\delta$$

$$E_R^{\mathrm{min}} = \frac{\mu^2}{m_T} w_i^2 \left(1 - \sqrt{1 - \frac{2\delta}{\mu w_i^2}} \right) - \frac{\mu}{m_T}\delta$$

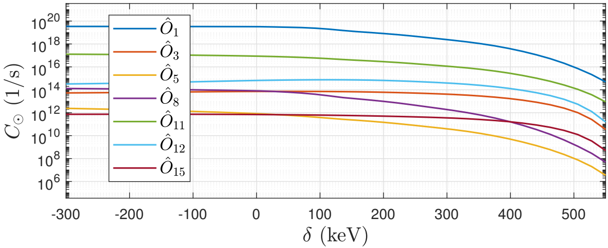
$$w_i \geq w_{\mathrm{min}} \equiv \mathfrak{R}\sqrt{2\delta/\mu}$$

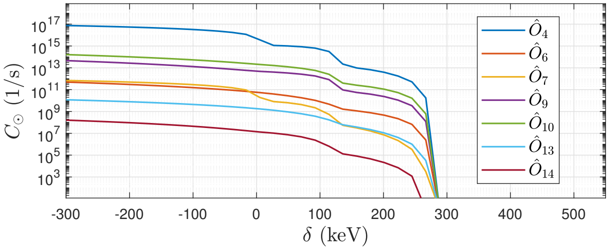
- Furthermore, when the DM particle is heavier than the target nucleus, one finds

$$E_R^{\mathrm{min}} \simeq \delta \, ; \qquad w_{\mathrm{min}} \simeq \mathfrak{R}\sqrt{2\delta/m_T}$$

Solar capture rate

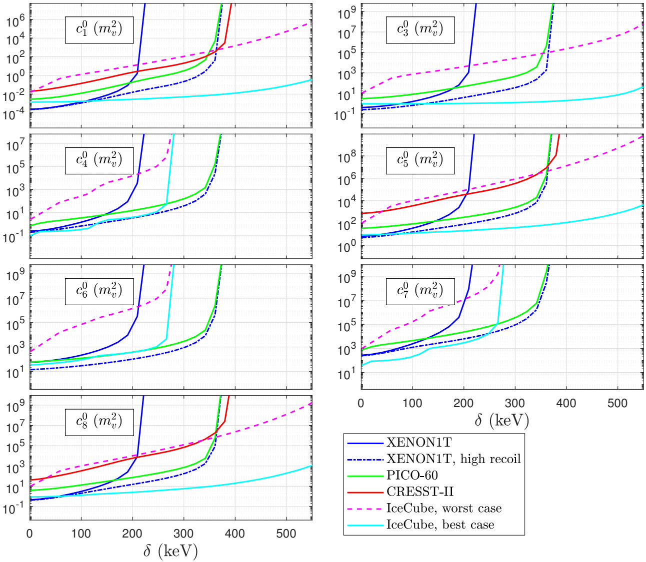
R. Catena and F. Hellström, arXiv:1808.08082





Exclusion limits from IceCube and direct detection

R. Catena and F. Hellström, arXiv:1808.08082
M. Blennow, S. Clementz and J. Herrero-Garcia, Eur. Phys. J. C **78** (2018) no.5, 386



Self-interacting WIMPs

Velocity dependent $\sigma_{\rm ann} v_{\rm rel}$

- I am interested in models for self-interacting WIMPs where $\sigma_{\rm ann} v_{\rm rel}$ is velocity dependent

- In this case, the γ-ray flux from DM annihilation in dSphs can be written as follows

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma} = \frac{1}{8\pi}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\int_{\Delta\Omega}\mathrm{d}\Omega\int_{\rm l.o.s.}\mathrm{d}s\int \mathrm{d}^3\boldsymbol{v}_{\rm rel}\,\mathscr{J}(s,\theta,\boldsymbol{v}_{\rm rel})$$

where

$$\mathscr{J}(s,\theta,\boldsymbol{v}_{\rm rel}) = n_\chi^2(s,\theta)\,P_{r(s,\theta),{\rm rel}}(\boldsymbol{v}_{\rm rel})\,\sigma_{\rm ann} v_{\rm rel}$$

Velocity dependent $\sigma_{\rm ann} v_{\rm rel}$

- If $(\sigma_{\rm ann})_0$ is the DM annihilation cross-section in the limit of negligible self-interactions, then

$$\sigma_{\rm ann} = S(v_{\rm rel})(\sigma_{\rm ann})_0$$

- With this notation, the γ-ray flux from DM annihilation in dSphs is proportional to

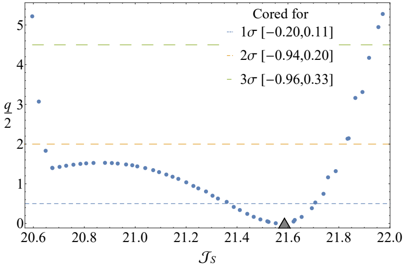
$$J_S = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\rm l.o.s.} \mathrm{d}s \int \mathrm{d}^3\boldsymbol{v}_{\rm rel}\, \widetilde{\mathscr{J}}(s,\theta,\boldsymbol{v}_{\rm rel})$$

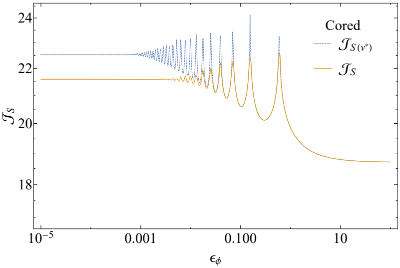
where

$$\widetilde{\mathscr{J}}(s,\theta,\boldsymbol{v}_{\rm rel}) = n_\chi^2(s,\theta)\, P_{r(s,\theta),{\rm rel}}(\boldsymbol{v}_{\rm rel})\, S(v_{\rm rel})$$

J-factors for self-interacting DM

S. Bergström, R. Catena *et al.*, Phys. Rev. D **98** (2018) no.4, 043017





J-factors for self-interacting DM

Galaxy	$N_\star$	$\mathcal{J}$ (cored)	$\mathcal{J}_{S(v^*)}$ (cored)	$\mathcal{J}_S$ (cored)	$\mathcal{J}$ (NFW)	$\mathcal{J}_{S(v^*)}$ (NFW)	$\mathcal{J}_S$ (NFW)
Bootes I	14	$19.34^{+0.38}_{-2.07}$	$23.17^{+0.38}_{-2.07}$	$21.65^{+0.34}_{-0.92}$	$17.95^{+0.54}_{-0.74}$	$21.79^{+0.54}_{-0.74}$	$21.13^{+0.40}_{-0.48}$
Leo IV	17	$16.46^{+1.75}_{-0.61}$	$20.29^{+1.75}_{-0.61}$	$19.89^{+0.94}_{-0.45}$	$16.89^{+0.83}_{-0.92}$	$20.73^{+0.83}_{-0.92}$	$20.46^{+0.65}_{-0.78}$
Leo T	19	$17.45^{+0.49}_{-0.95}$	$21.29^{+0.49}_{-0.95}$	$20.53^{+0.34}_{-0.84}$	$17.44^{+0.43}_{-0.87}$	$21.28^{+0.43}_{-0.87}$	$20.60^{+0.37}_{-0.81}$
Bootes II	20	$18.78^{+1.46}_{-1.01}$	$22.61^{+1.46}_{-1.01}$	$22.10^{+1.00}_{-0.83}$	$18.89^{+1.20}_{-1.11}$	$22.72^{+1.20}_{-1.11}$	$22.21^{+1.16}_{-0.89}$
Ursa Major II	20	$20.29^{+0.43}_{-0.72}$	$24.12^{+0.43}_{-0.72}$	$22.77^{+0.29}_{-0.28}$	$19.87^{+0.27}_{-0.18}$	$23.71^{+0.27}_{-0.18}$	$22.76^{+0.25}_{-0.14}$
Canes Venatici II	25	$18.53^{+0.35}_{-0.74}$	$22.36^{+0.35}_{-0.74}$	$21.23^{+0.34}_{-0.50}$	$18.49^{+0.31}_{-0.70}$	$22.32^{+0.31}_{-0.70}$	$21.27^{+0.23}_{-0.46}$
Hercules	30	$18.00^{+0.35}_{-0.29}$	$21.83^{+0.35}_{-0.29}$	$21.14^{+0.28}_{-0.21}$	$18.12^{+0.27}_{-0.35}$	$21.95^{+0.27}_{-0.35}$	$21.35^{+0.22}_{-0.31}$
Ursa Major I	39	$17.77^{+0.80}_{-0.28}$	$21.60^{+0.80}_{-0.28}$	$21.00^{+0.59}_{-0.28}$	$18.22^{+0.95}_{-0.58}$	$22.06^{+0.95}_{-0.58}$	$21.52^{+0.66}_{-0.70}$
Willman 1	45	$19.40^{+1.20}_{-0.45}$	$23.24^{+1.20}_{-0.45}$	$22.43^{+0.62}_{-0.24}$	$19.69^{+0.31}_{-0.52}$	$23.52^{+0.31}_{-0.52}$	$22.54^{+0.29}_{-0.23}$
Coma Berenices	59	$19.93^{+0.77}_{-0.87}$	$23.77^{+0.77}_{-0.87}$	$22.56^{+0.36}_{-0.47}$	$19.42^{+0.28}_{-0.45}$	$23.26^{+0.28}_{-0.45}$	$22.35^{+0.21}_{-0.31}$
Segue 1	66	$19.10^{+0.47}_{-0.30}$	$22.93^{+0.47}_{-0.30}$	$22.39^{+0.28}_{-0.23}$	$19.26^{+0.48}_{-0.46}$	$23.09^{+0.48}_{-0.46}$	$22.72^{+0.42}_{-0.44}$
Ursa Minor	196	$19.47^{+0.22}_{-1.04}$	$23.31^{+0.22}_{-1.04}$	$22.46^{+0.18}_{-1.29}$	$19.57^{+0.08}_{-0.25}$	$23.41^{+0.08}_{-0.25}$	$22.62^{+0.06}_{-0.27}$
Canes Venatici I	214	$17.88^{+0.19}_{-0.99}$	$21.72^{+0.19}_{-0.99}$	$20.91^{+0.19}_{-0.99}$	$18.01^{+0.28}_{-0.29}$	$21.84^{+0.28}_{-0.29}$	$21.11^{+0.29}_{-0.25}$
Leo I	328	$17.53^{+0.22}_{-0.10}$	$21.36^{+0.22}_{-0.10}$	$20.43^{+0.25}_{-0.04}$	$17.68^{+0.23}_{-0.17}$	$21.52^{+0.23}_{-0.17}$	$20.56^{+0.29}_{-0.13}$
Draco	353	$18.59^{+0.20}_{-0.13}$	$22.42^{+0.20}_{-0.13}$	$21.36^{+0.30}_{-0.03}$	$18.78^{+0.21}_{-0.26}$	$22.61^{+0.21}_{-0.26}$	$21.65^{+0.23}_{-0.16}$
Sextans	424	$18.52^{+0.19}_{-0.29}$	$22.35^{+0.19}_{-0.29}$	$21.58^{+0.18}_{-0.29}$	$18.73^{+0.22}_{-0.19}$	$22.57^{+0.22}_{-0.19}$	$21.86^{+0.16}_{-0.18}$
Carina	758	$17.68^{+0.44}_{-0.07}$	$21.51^{+0.44}_{-0.07}$	$20.74^{+0.48}_{-0.03}$	$17.71^{+0.79}_{-0.02}$	$21.54^{+0.79}_{-0.02}$	$20.84^{+0.86}_{-0.02}$
Sculptor	1352	$18.68^{+0.14}_{-0.22}$	$22.52^{+0.14}_{-0.22}$	$21.63^{+0.15}_{-0.23}$	$18.92^{+0.10}_{-0.14}$	$22.76^{+0.10}_{-0.14}$	$21.94^{+0.12}_{-0.15}$
Sagittarius	1373	$19.77^{+0.16}_{-0.17}$	$23.61^{+0.16}_{-0.17}$	$22.51^{+0.16}_{-0.16}$	$20.25^{+0.09}_{-0.12}$	$24.09^{+0.09}_{-0.12}$	$23.16^{+0.09}_{-0.11}$
Fornax	2409	$18.70^{+0.13}_{-0.23}$	$22.54^{+0.13}_{-0.23}$	$21.59^{+0.11}_{-0.20}$	$18.94^{+0.08}_{-0.07}$	$22.77^{+0.08}_{-0.07}$	$21.88^{+0.12}_{-0.11}$

Summary

- I have discussed selected aspects of WIMP phenomenology, focusing on: 1) Canonical WIMPs; 2) Inelastic WIMPs; and 3) Self-interacting WIMPs

- For canonical WIMPs, it is possible to map a XENONnT signal onto specific predictions for the LHC run 3, and extract information on the WIMP spin

  S. Baum, R. Catena, J. Conrad, K. Freese and M. B. Krauss, Phys. Rev. D **97** (2018) no.8, 083002

  R. Catena, J. Conrad and M. B. Krauss, Phys. Rev. D **97** (2018) no.10, 103002

- For inelastic WIMPs, neutrino telescopes are superior to direct detection experiments above $\delta \sim 200$ keV

  R. Catena and F. Hellström, arXiv:1808.08082

- For self-interacting WIMPs, I presented an updated calculation of J-factors for dSphs

  S. Bergström, R. Catena *et al.*, Phys. Rev. D **98** (2018) no.4, 043017

  K. K. Boddy, J. Kumar, L. E. Strigari and M. Y. Wang, Phys. Rev. D **95**, no. 12, 123008 (2017) M. Petac, P. Ullio and M. Valli, arXiv:1804.05052