Direct detection calculations

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Outline

- Basics of dark matter direct detection (DD)
- DD Astrophysics
- DD Particle Physics
- DD Nuclear Physics
- Summary
Direct detection

- Motivation and strategy:

- Kinematics:
  a) For $m_\chi \sim 100$ GeV, incoming flux $\sim 7 \times 10^4$ particles cm$^{-2}$ s$^{-1}$
  b) $E_R = (2\mu_T^2 v^2/m_T) \cos^2 \theta \sim \mathcal{O}(10)$ keV
**Physical observables**

- **Differential rate** of dark matter-nucleus scattering events in terrestrial detectors

\[
\frac{d\mathcal{R}}{dE_R} = \frac{\rho_\chi}{m_\chi m_T} \int_{|\mathbf{v}| > v_{\text{min}}} d^3\mathbf{v} |\mathbf{v}| f_\chi(\mathbf{v} + \mathbf{v}_\oplus) \frac{d\sigma_T}{dE_R}
\]

- **Modulation**: The Earth’s orbit inclination induces an annual modulation in the rate of recoil events

\[
\mathcal{A}(E_-, E_+) = \frac{1}{E_+ - E_-} \left[ \mathcal{R}(E_-, E_+) \bigg|_{\text{June 1st}} - \mathcal{R}(E_-, E_+) \bigg|_{\text{Dec 1st}} \right]
\]
Astrophysics
Highlights

- Local dark matter density from astronomical data:
  - Local methods
  - Global methods

- Local dark matter velocity distribution from astronomical data

- Local dark matter velocity distribution from simulations

- Halo-independent methods
Local methods for $\rho_\chi$

Silverwood et al., 1507.08581

- $\rho_\chi$ from the Jeans-Poisson system:

$$
\Sigma(R, Z) = -\frac{1}{2\pi G} \left[ \int_0^Z dz \frac{1}{R} \frac{\partial (RF_R)}{\partial R} + F_z(R, Z) \right]
$$

$$
F_z(R, Z) = \frac{1}{\nu} \frac{(\nu \sigma_z^2)}{\partial z} + \frac{1}{R\nu} \frac{\partial (R\nu \sigma_{Rz})}{\partial R}
$$

- $F_R(R, Z) = -\partial \Phi/\partial R$, $F_z(R, Z) = -\partial \Phi/\partial z$ and

$$
\Sigma(R, Z) = \int_{-Z}^Z dz \sum_j \rho_j(R, z)
$$
Global methods for $\rho_\chi$ / basic idea

- Assume a mass model for the Milky Way:
  - $\mathbf{x} \rightarrow \rho_j(\mathbf{x}, \mathbf{p})$ \hspace{1cm} $j$ mass densities at $\mathbf{x}$
  - $\mathbf{p} = (p_1, p_2, \ldots)$ \hspace{1cm} model parameters

- Compute physical observables, e.g.:
  - Terminal velocities
  - Radial velocities
  - Velocity dispersion of stellar populations
  - Oort’s constants
  - . . .

- Compare theory and observations

- Infer $\rho_\chi(\mathbf{x}_\odot, \mathbf{p})$ from $\mathbf{p}$
Global methods for $\rho_\chi$ / two implementations

Catena and Ullio, 0907.0018

- **Emphasis on correlations**
  - Large number of model parameters, e.g. $\sim \mathcal{O}(10)$
  - One mass model
  - It allows to assess / identify correlations between parameters / observables

Iocco, Pato and Bertone, 1502.03821, 1504.06324

- **Emphasis on systematics**
  - Few model parameters, e.g. $\sim 2/3$
  - Many mass models can be tested
  - It allows to estimate the systematic error / theoretical bias that might affect the first approach
Determination of $f_\chi / \text{self-consistent methods}$

Catena et. al, 1111.3556; Bozorgnia et al., 1310.0468

- **Solve for** $F_\chi$ **the system:**

  \[
  \rho_\chi(x, p) = \int dv \, F_\chi(x, v; p)
  \]

  \[
  \mathbf{v} \cdot \nabla_x F_\chi - \nabla_x \Phi \cdot \nabla_v F_\chi = 0 \quad \text{(Vlasov)}
  \]

  \[
  \nabla^2 \Phi = 4\pi G \sum_j \rho_j \quad \text{(Poisson)}
  \]

- **Then:** $f_\chi(\mathbf{v}) = F_\chi(x_\odot, \mathbf{v}; p)/\rho_\chi(x_\odot, p)$
If $\rho_\chi(r)$ and $\Phi(r)$ are spherically symmetric, and $F_\chi(x, v) = F_\chi(x, |v|)$ is isotropic, then:

- $F_\chi(x, v) = F_\chi(\mathcal{E})$, where $\mathcal{E} = -1/2|v|^2 + \psi$ and $\psi = -\Phi + \Phi_{vir}$

- There is a unique self-consistent solution for $F_\chi$

It is given by

$$F_\chi(\mathcal{E}) = \frac{1}{\sqrt{8\pi}^2} \left[ \int_{0}^{\mathcal{E}} \frac{d^2 \rho_\chi}{d\psi^2} \frac{d\psi}{\sqrt{\mathcal{E} - \psi}} + \frac{1}{\sqrt{\mathcal{E}}} \left( \frac{d\rho_\chi}{d\psi} \right)_{\psi=0} \right]$$
Determination of $f_{\chi}$ / numerical simulations

Bozorgnia et al., 1601.04707
Halo-independent methods

- For a given $m_\chi$, different experiments can be compared in the $(v_{\text{min}}, \eta)$ plane, where
  \[
  \eta(v_{\text{min}}) = \int_{|\vec{v}| > v_{\text{min}}} d^3\vec{v} \ |\vec{v}| f_\chi(\vec{v} + \vec{v}_\oplus)
  \]
  Fox et al., 1011.1915

- The initial idea has been extended to realistic detectors and general interactions
  Gondolo and Gelmini, 1202.6359; Wild and Kahlhoefer, 1607.04418

- Finding maximal/minimal number of signal events in a direct detection experiment given a set of constraints from other direct detection experiments
  Ibarra and Rappelt, 1703.09168

- Halo-independent determination of the unmodulated WIMP signal in DAMA
  Gondolo and Scopel, 1703.08942
Particle Physics
Highlights

- Non Relativistic Effective Field Theory (NREFT)
  - Introduction
  - Phenomenology

- Earth-scattering of dark matter
It is based upon two assumptions:

- there is a separation of scales: $|q|/m_N \ll 1$, where $m_N$ is the nucleon mass
- dark matter is non-relativistic: $v/c \ll 1$

It follows that the Hamiltonian for dark matter-nucleon interactions is

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

$\hat{O}_k(r)$ are Galilean invariant operators

$t^0 = 1_{\text{isospin}}, t^1 = \tau_3$
Inspection of the operators $\hat{O}_k(\mathbf{r})$ shows that at linear order in the transverse relative velocity $\hat{v}^\perp$, they only depend on 5 nucleon charges and currents:

$$1_N \quad \hat{S}_N \quad \hat{v}^\perp \quad \hat{v}^\perp \cdot \hat{S}_N \quad \hat{v}^\perp \times \hat{S}_N$$

Fan et al., 1008.1591; Fitzpatrick et al., 1203.3542

This leads to 8 independent nuclear response functions (if nuclear ground states are CP eigenstates)
Nuclear cross-sections factorize:

\[ \frac{d\sigma_T}{dE_R} \sim \text{DM response}(c_i^\tau, q^2 \text{ and } v^2) \times \text{nuclear response}(\langle \mathcal{A}''_{LM;\tau} \rangle) \]

Nuclear matrix elements \( \langle \mathcal{A}''_{LM;\tau} \rangle \) factorize:

\[
\langle J, T, M_T | | \mathcal{A}''_{LM;\tau} (q) | | J, T, M_T \rangle = (-1)^{T-M_T} \begin{pmatrix} T & \tau & T \\ -M_T & 0 & M_T \end{pmatrix} \\
\times \sum_{|\alpha||\beta|} \psi^{L;\tau}_{|\alpha||\beta|} \langle |\alpha| : : \mathcal{A}''_{LM;\tau} (q) : : |\beta| \rangle 
\]

where \( \psi^{L;\tau}_{|\alpha||\beta|} \propto \langle J, T : : [a_\dagger_{|\alpha|} \otimes \bar{a}_{|\beta|}]_{L;\tau} : : J, T \rangle \)
NREFT Phenomenology (direct detection)

- Likelihood analysis of NREFT
  Catena and Gondolo, JCAP 1409, 09, 045 (2014)
  Cirelli, Del Nobile and Panci, JCAP 1310 (2013) 019

- Operator interference
  Catena and Gondolo, JCAP 1508, 08, 022 (2015)

- Standard analyses can be significantly biased if WIMPs do not interact via SI or SD interactions
  Catena, JCAP 1409, 09, 049 (2014)
  Catena, JCAP 1407, 07, 055 (2014)

- New ring-like features are expected in the angular distribution of nuclear recoil events
  Catena JCAP 1507 07, 026 (2015)
  Catena et al., 1706.09471

- DAMA compatibility with null results revisited
  Catena, Ibarra and Wild, JCAP 1605, 05, 039 (2016)

- RG effects and operator mixing
Earth-scattering of dark matter

Kavanagh, Catena and Kouvaris, JCAP 1701 (2017) no.01, 012

- In the standard paradigm $f = f_{\text{halo}}$, where $f_{\text{halo}}$ is the velocity distribution in the halo.

- However, before reaching the detector, dark matter particles have to cross the Earth.

- Earth-crossing unavoidably distorts $f_{\text{halo}}$ if dark matter interacts with nuclei, which implies $f \neq f_{\text{halo}}$. 
Two processes contribute to the Earth-scattering of dark matter; attenuation and deflection:

(a) Attenuation

(b) Deflection
Earth-scattering of dark matter

- As a result, the dark matter velocity distribution at detector can be written as follows:

\[ f(\mathbf{v}, \gamma) = f_A(\mathbf{v}, \gamma) + f_D(\mathbf{v}, \gamma) \]

- \( f_A \) and \( f_D \) depend on the input \( f_{halo}, m_\chi, \sigma \), the Earth composition and
\[ \gamma = \cos^{-1}(\langle \hat{v}_\chi \rangle \cdot \hat{r}_{det}) \]

- **Key result**: since \( \gamma \) depends on the detector position and on time, the same is true for \( f(\mathbf{v}, \gamma) \)
As a result, the dark matter velocity distribution at detector can be written as follows:

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**Key result**: since \( \gamma \) depends on the detector position and on time, the same is true for \( f(v, \gamma) \)

In the following, \( N_{\text{pert}} = N_{f_A+f_D, \sigma} \) and \( N_{\text{free}} = N_{f_{\text{halo}}, \sigma} \)
Earth-scattering of dark matter / position dependence

Kavanagh, Catena and Kouvaris, JCAP 1701 (2017) no.01, 012

\[ \gamma = \cos^{-1}(\langle \hat{v}_\chi \rangle \cdot \hat{r}_{\text{det}}) \]

\[ \frac{N_{\text{part}}}{N_{\text{free}}} \]

\[ m_\chi = 0.5 \text{ GeV} \]

Isotropic scattering
Forward scattering
Backward scattering

\[ \gamma = \cos^{-1}(\langle \hat{v}_\chi \rangle \cdot \hat{r}_{\text{det}}) \]

\[ \frac{N_{\text{part}}}{N_{\text{free}}} \]

\[ m_\chi = 0.5 \text{ GeV} \]

\[ \gamma = \cos^{-1}(\langle \hat{v}_\chi \rangle \cdot \hat{r}_{\text{det}}) \]

\[ \frac{N_{\text{part}}}{N_{\text{free}}} \]

\[ m_\chi = 0.5 \text{ GeV} \]
Nuclear Physics
Highlights

- Chiral Effective Field Theory predictions:
  - Matching
  - Two-body currents

- Ab initio methods:
  - Uncertainties quantification
Chiral EFT predictions

- Selected ChEFT diagrams for dark matter-nucleus scattering:

- Chiral EFT prediction for the NREFT coupling constants

\[ c_{NREFT} = C + \frac{q^2}{q^2 + m_\pi^2} C' + O(q^2) \]

Bishara, Brod, Grinstein and Zupan, JCAP 1702, 009 (2017)
Summary

- Dark matter direct detection is a cross-disciplinary research field at the interface of Astro-, Particle and Nuclear Physics.

- Astrophysical uncertainties remain significant, but are increasingly better understood. Halo-independent methods have progressed rapidly in recent years.

- Novel signatures of particle dark matter have been identified and are currently under investigation via NREFT.

- Dedicated large-scale nuclear structure calculations have been performed. Ab initio methods have recently been explored, and will be further developed.