Direct detection calculations

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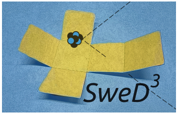
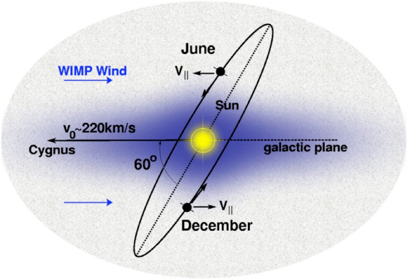


Outline

- 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

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

Astrophysics (ρ_χ, $f_\chi(\mathbf{v} + \mathbf{v}_\oplus)$)

Particle and Nuclear Physics ($\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}$)

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

$$\mathcal{A}(E_-, E_+) = \frac{1}{E_+ - E_-} \frac{1}{2} \left[\mathcal{R}(E_-, E_+)\Big|_{\text{June 1st}} - \mathcal{R}(E_-, E_+)\Big|_{\text{Dec 1st}} \right]$$

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 ρ_χ

Silverwood et al., 1507.08581

- ρ_χ from the Jeans-Poisson system:

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

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

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

$$\Sigma(R,Z) = \int_{-Z}^{Z} \mathrm{d}z \sum_j \rho_j(R,z)$$

Global methods for ρ_χ / basic idea

- Assume a mass model for the Milky Way:
  - $\mathbf{x} \to \rho_j(\mathbf{x}, \mathbf{p})$ — j mass densities at $\mathbf{x}$
  - $\mathbf{p} = (p_1, p_2, \dots)$ — 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 ρ_χ / 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_χ / self-consistent methods

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

- Solve for F_χ the system:

$$\rho_\chi(\mathbf{x},\mathbf{p}) = \int \mathrm{d}\mathbf{v}\, F_\chi(\mathbf{x},\mathbf{v};\mathbf{p})$$

$$\mathbf{v}\cdot\nabla_{\mathbf{x}}F_\chi - \nabla_{\mathbf{x}}\Phi\cdot\nabla_{\mathbf{v}}F_\chi = 0 \qquad \text{(Vlasov)}$$

$$\nabla^2\Phi = 4\pi G\sum_j \rho_j \qquad \text{(Poisson)}$$

- Then: $f_\chi(\mathbf{v}) = F_\chi(\mathbf{x}_\odot,\mathbf{v};\mathbf{p})/\rho_\chi(\mathbf{x}_\odot,\mathbf{p})$

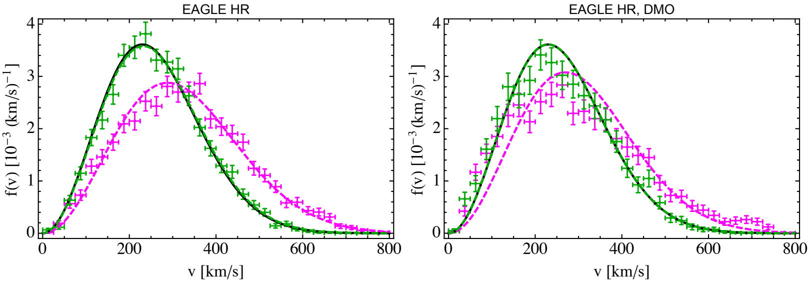
Determination of f_χ / self-consistent methods

- If $\rho_\chi(r)$ and $\Phi(r)$ are **spherically symmetric**, and $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathbf{x},|\mathbf{v}|)$ is **isotropic**, then:
  - $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathcal{E})$, where $\mathcal{E} = -1/2|\mathbf{v}|^2 + \psi$ and $\psi = -\Phi + \Phi_{vir}$
  - There is a unique self-consistent solution for F_χ
- 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_χ / numerical simulations

Bozorgnia et al., 1601.04707



Halo-independent methods

- For a given m_χ, different experiments can be compared in the $(v_{\min}, \eta)$ plane, where

$$\eta(v_{\min}) = \int_{|\mathbf{v}|>v_{\min}} \mathrm{d}^3\mathbf{v}\ |\mathbf{v}| f_\chi(\mathbf{v} + \mathbf{v}_\oplus)$$

  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

NREFT I

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

- It is based upon two assumptions:
  - there is a separation of scales: $|\mathbf{q}|/m_N \ll 1$, 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

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

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

NREFT II

- Inspection of the operators $\hat{\mathcal{O}}_k(\mathbf{r})$ shows that at linear order in the transverse relative velocity $\hat{\mathbf{v}}^{\perp}$, they only depend on 5 nucleon charges and currents:

$$\mathbb{1}_N \qquad \hat{\mathbf{S}}_N \qquad \hat{\mathbf{v}}^{\perp} \qquad \hat{\mathbf{v}}^{\perp} \cdot \hat{\mathbf{S}}_N \qquad \hat{\mathbf{v}}^{\perp} \times \hat{\mathbf{S}}_N$$

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:

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

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

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

where $\psi^{L;\tau}_{|\alpha||\beta|} \propto \langle J, T \vdots\vdots\ [a^\dagger_{|\alpha|} \otimes \tilde{a}_{|\beta|}]_{L;\tau}\ \vdots\vdots J, T \rangle$

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 compatibilty with null results revisited

  Catena, Ibarra and Wild, JCAP **1605**, 05, 039 (2016)

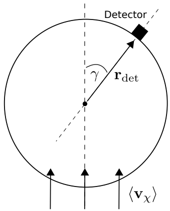
- RG effects and operator mixing

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

Earth-scattering of dark matter

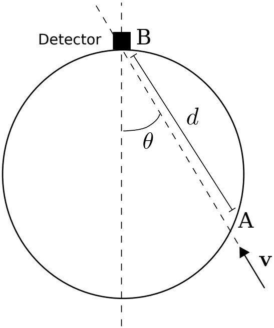
Kavanagh, Catena and Kouvaris, JCAP **1701** (2017) no.01, 012

- In the standard paradigm $f = f_{\rm halo}$, where $f_{\rm halo}$ is the velocity distribution in the halo
- However, before reaching the detector, dark matter particles have to cross the Earth.

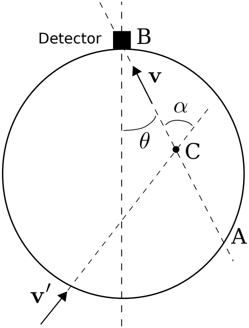


- Earth-crossing unavoidably distorts $f_{\rm halo}$ if dark matter interacts with nuclei, which implies $f \neq f_{\rm halo}$

- Two processes contribute to the Earth-scattering of dark matter; attenuation and deflection:



(a) Attenuation



(b) Deflection

- 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 depends on the input $f_{\rm halo}$, m_χ, σ, the Earth composition and $\gamma = \cos^{-1}(\langle \hat{\mathbf{v}}_\chi \rangle \cdot \hat{\mathbf{r}}_{\rm det})$

- **Key result**: since γ depends on the detector position and on time, the same is true for $f(\mathbf{v},\gamma)$

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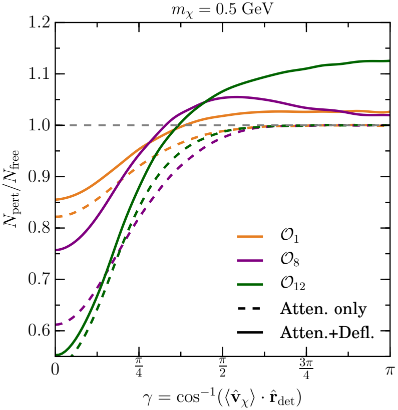
- **Key result**: since γ depends on the detector position and on time, the same is true for $f(\mathbf{v},\gamma)$

- In the following, $N_{\rm pert} = N_{f_A+f_D,\sigma}$ and $N_{\rm free} = N_{f_{\rm halo},\sigma}$

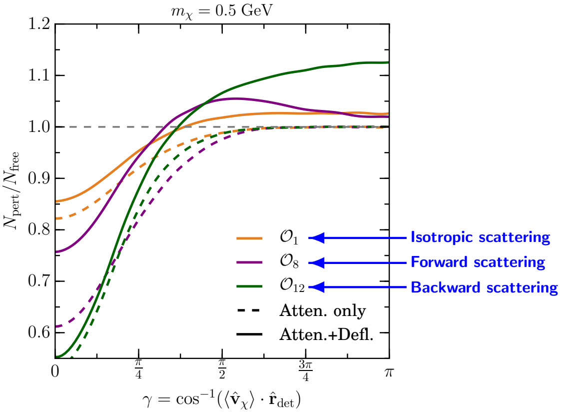
Earth-scattering of dark matter / position dependence

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



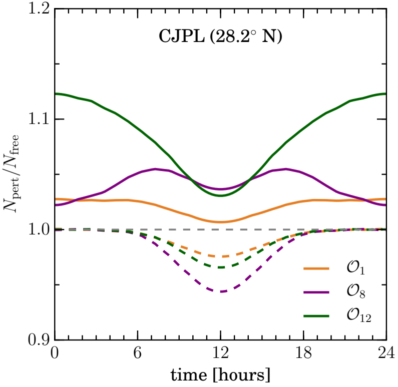
Earth-scattering of dark matter / position dependence

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



Earth-scattering of dark matter / time dependence

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



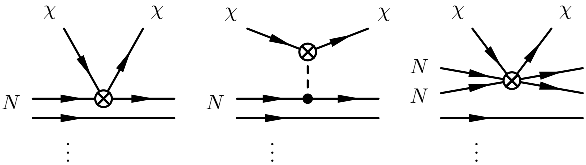
Nuclear Physics

Highlights

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

- Ab initio methods:
  - Uncertainties quantification

- Selected ChEFT diagrams for dark matter-nucleus scattering:



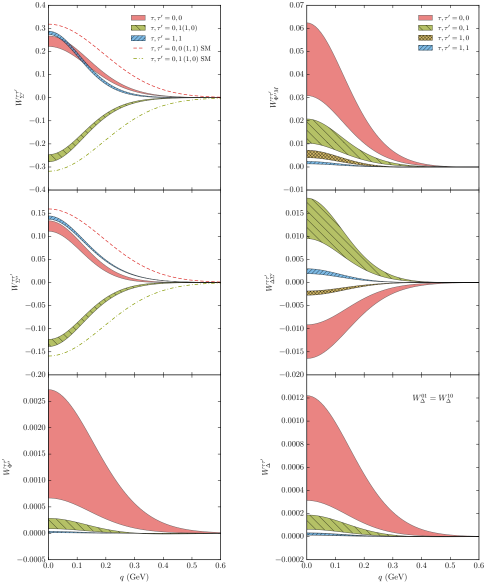
- Chiral EFT prediction for the NREFT coupling constants

$$c_{\mathrm{NREFT}} = \mathcal{C} + \frac{q^2}{q^2 + m_\pi^2}\mathcal{C}' + \mathcal{O}(q^2)$$

M. Hoferichter, P. Klos, and A. Schwenk Phys. Lett. **B746**, 410 (2015)

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

Gazda, Catena and Forssén, Phys. Rev. **D95** (2017) no. 10, 103011



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