# Astro-, Particle and Nuclear Physics of Dark Matter Direct Detection


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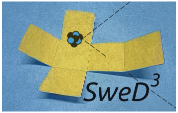
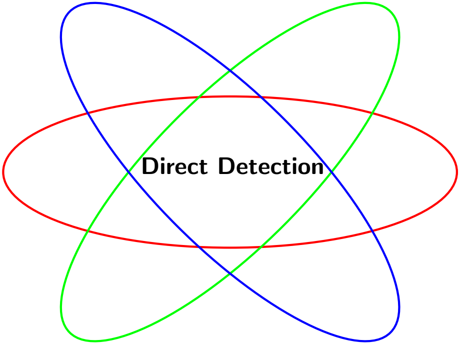



# Astro-, Particle and Nuclear Physics of Dark Matter Direct Detection

Astrophysics
Nuclear Physics
Particle Physics

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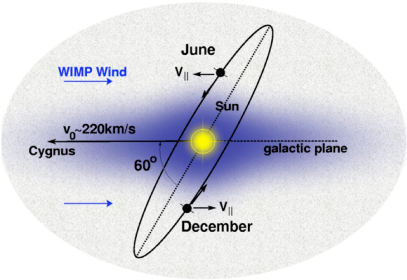
# Outline

- 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) $E_{\rm nr} = (2\mu_T^2 v^2/m_T)\cos^2\theta \sim \mathcal{O}(10)$ keV

# Physical observables

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

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_{\mathrm{dm}}}{m_\chi m_T} \int_{|\mathbf{v}|>v_{\min}} \mathrm{d}^3\mathbf{v}\, |\mathbf{v}| f(\mathbf{v}) \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{nr}}}$$

Astrophysics

Particle and Nuclear Physics

- **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 $\rho_\chi$

Silverwood et al., 1507.08581

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

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

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

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

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

# Global methods for $\rho_\chi$ / 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
  - $\dots$
- 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 $f_\chi$ / self-consistent methods

Catena et. al, 1111.3556; Bhattacharjee et al., 1210.2328; Bozorgnia et al., 1310.0468

- Solve for $F_\chi$ 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 $f_\chi$ / self-consistent methods

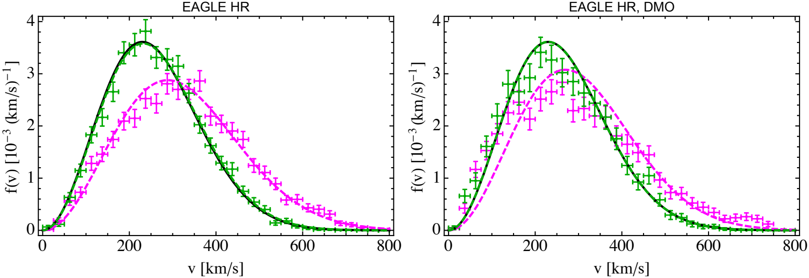
- If $\rho_\chi(r)$ and $\Phi(r)$ are **spherically symmetric**, and $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathbf{x},|\mathbf{v}|)$ is **isotropic**, then:
  - $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathcal{E})$, where $\mathcal{E} = -1/2|\mathbf{v}|^2 + \psi$ and $\psi = -\Phi + \Phi_{vir}$
  -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

- 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 $(v_{\min}, \eta)$ 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

See Gondolo's and Wild's talks, respectively

- A halo-independent method to, e.g., optimize compatibility between different experiments has been presented at MIAPP

See Rappelt's talk

# Particle Physics

# Highlights

- Non Relativistic Effective Field Theory (NREFT)
- New signatures:
  - Earth-scattering of dark matter
  - Dark matter-induced bremsstrahlung
  - Dark matter-induced inelastic nuclear transitions

# NREFT I

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

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

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

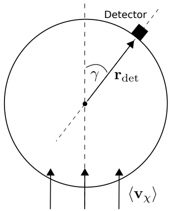
see also Gondolo's talk

- This leads to 8 independent nuclear response functions (if nuclear ground states are CP eigenstates)

# Earth-scattering of dark matter

Kavanagh, Catena and Kouvaris, 1611.05453

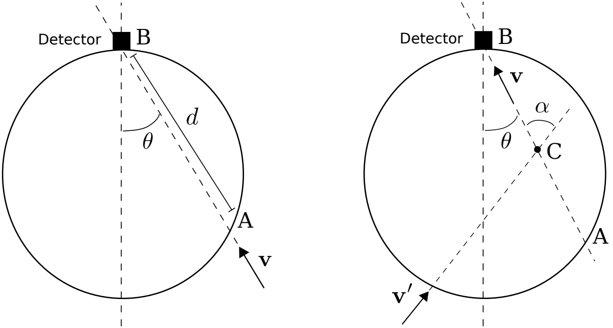
- In the standard paradigm $f = f_{\mathrm{halo}}$, where $f_{\mathrm{halo}}$ is the velocity distribution in the halo
- However, before reaching the detector, dark matter particles have to cross the Earth.




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

# Earth-scattering of dark matter

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

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

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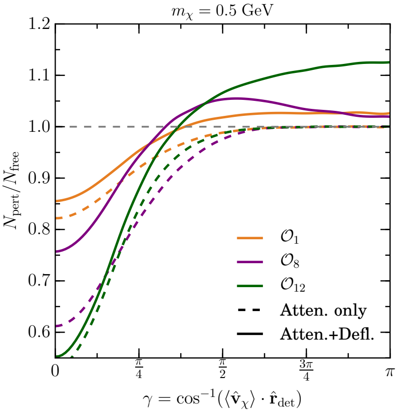
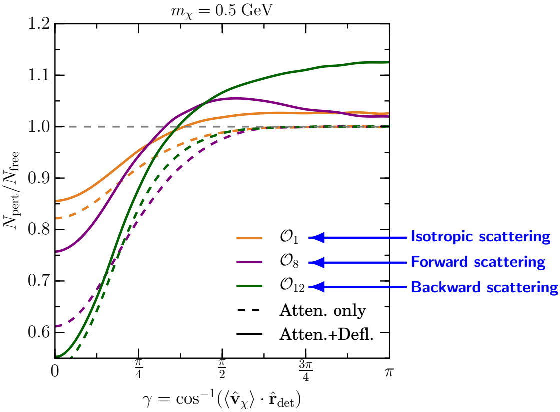
- In the following, $N_{\rm pert} = N_{f_A+f_D,\sigma}$ and $N_{\rm free} = N_{f_{\rm halo},\sigma}$

Kavanagh, Catena and Kouvaris, 1611.05453



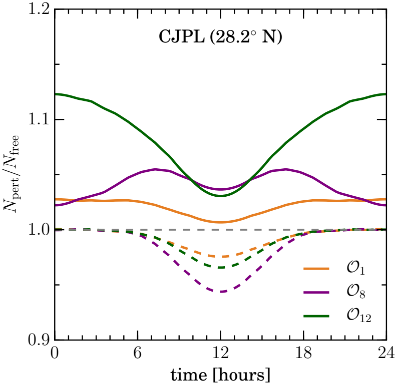
# Earth-scattering of dark matter / position dependence

Kavanagh, Catena and Kouvaris, 1611.05453



# Earth-scattering of dark matter / time dependence

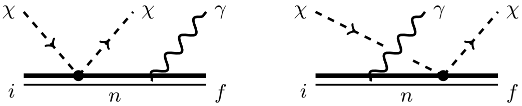
Kavanagh, Catena and Kouvaris, 1611.05453



## Dark matter-induced bremsstrahlung

Kouvaris and Pradler, 1607.01789

- Photon emission resulting from DM-nucleus scattering:

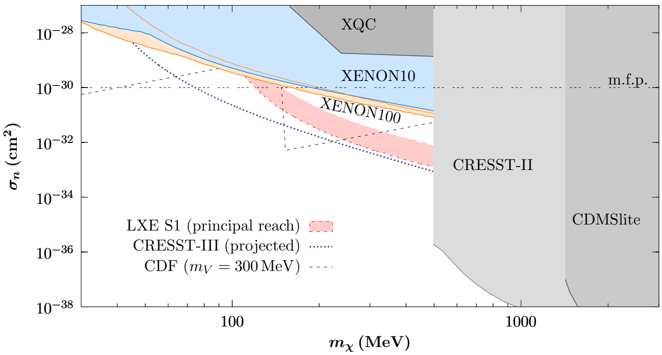



- The available photon energy obeys $\omega \leq \mu_T v^2/2$, and therefore

$$E_{\mathrm{nr;max}} = 4(m_\chi/m_T)\omega_{\mathrm{max}} \ll \omega_{\mathrm{max}}$$

# Dark matter-induced bremsstrahlung

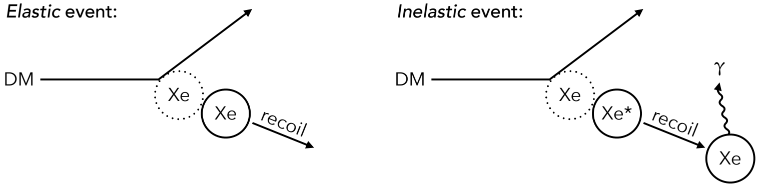
Kouvaris and Pradler, 1607.01789



## Dark matter-induced inelastic nuclear transitions

McCabe, 1512.00460

- Elastic scattering vs. inelastic scattering where an excited xenon isotope decays emitting a photon:

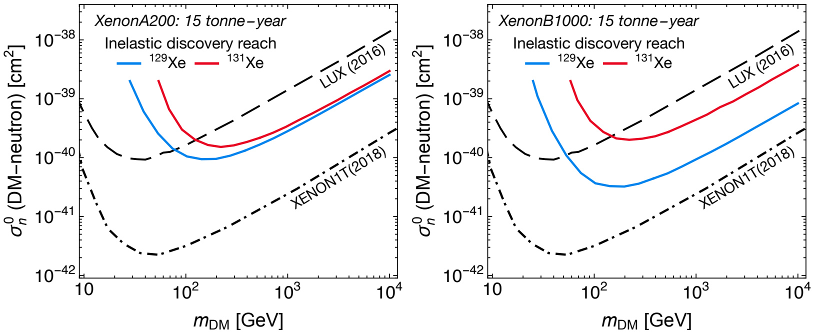



- The minimum speed to recoil with an energy $E_{\rm nr}$ additionally depends on the excitation energy $E^*$:

$$v_{\rm min} = \sqrt{\frac{m_T E_{\rm nr}}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_A E_{\rm nr}}}$$

# Dark matter-induced inelastic nuclear transitions

McCabe, 1512.00460



# Nuclear Physics

# Highlights

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

    see Hoferichter's and Gazit's talks

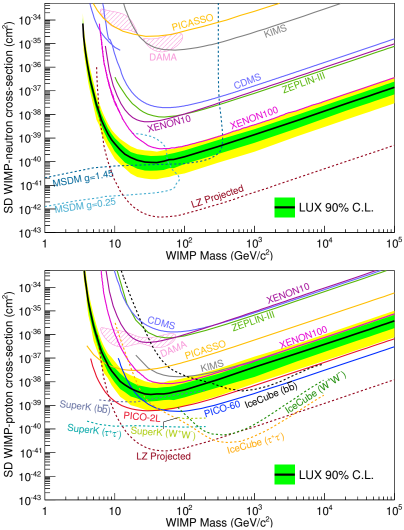
- Ab initio methods
  - Uncertainties quantification

    see Gazda's talk

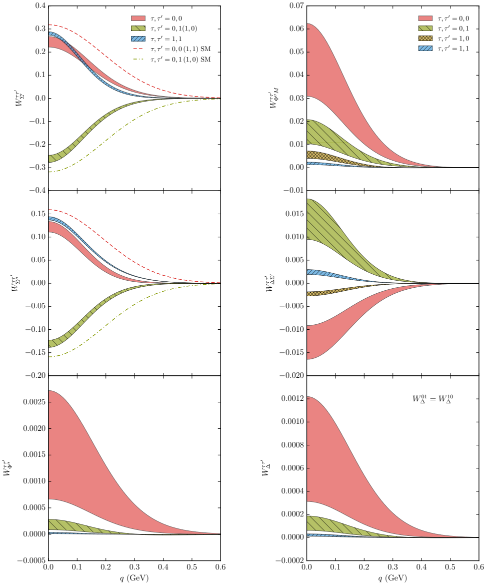
# Two-body currents

Klos, Menendéz, Gazit and Schwenk, 1304.7684;

Akerib et al., 1602.03489



Gazda, Catena and Forssén, 1612.09165



# Summary

- Dark matter direct detection is evolving into 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
- Dedicated large-scale nuclear structure calculations have been performed. Ab initio methods have recently been explored, and will be further developed
- Experimental methods have improved dramatically in the past few years. Hopefully, what we have learned in our MIAPP programme will soon be applied to interpret real data.