Measuring the local Dark Matter density at direct detection experiments

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Overview

- Local Dark Matter (DM) density, $\rho_{\rm loc}$, and DM-nucleon scattering cross section, σ, are degenerate if the DM scattering rate only depends on their product

$$\frac{{\rm d}\mathscr{R}}{{\rm d}E_R} = \frac{\rho_{\rm loc}}{m_\chi m_T} \int_{|\mathbf{v}|>v_{\rm min}} {\rm d}^3\mathbf{v}\, |\mathbf{v}| f(\mathbf{v}, t) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

- However, when DM is lighter than ~ 0.5 GeV, spin-independent DM-nucleon scattering cross sections of the order of 10^{-36} cm^2 are still experimentally allowed

- For these cross section values, the DM velocity distribution becomes a function of the DM-nucleon scattering cross section (the so-called **Earth-crossing effect**)

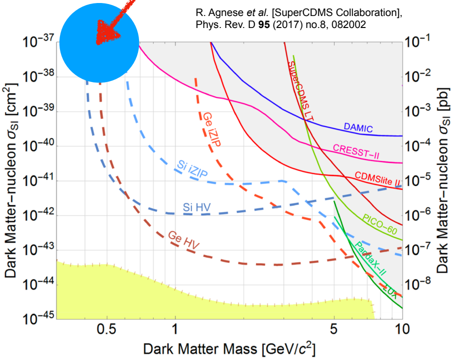
  B. J. Kavanagh, R. Catena and C. Kouvaris, JCAP **1701** (2017) no.01, 012

- This breaks the degeneracy between $\rho_{\rm loc}$ and σ

Overview

If DM lies in this region of parameter space, can we simultaneously measure DM-nucleon scattering cross section and local DM density?

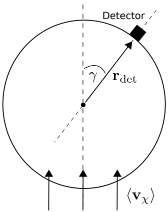
R. Agnese *et al.* [SuperCDMS Collaboration], Phys. Rev. D **95** (2017) no.8, 082002



Outline

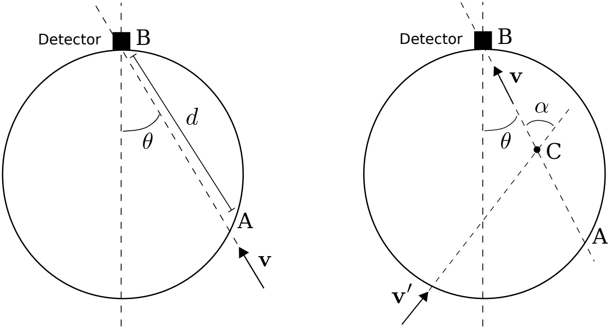
- Earth-crossing effect
- Quantitative impact on the local DM velocity distribution
- Application: Extracting the local DM density from a future signal at direct detection experiments
- Summary

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



- The Earth-crossing of DM unavoidably distorts $f_{\rm halo}$ if DM interacts with nuclei, which implies $f \neq f_{\rm halo}$. I will refer to this distortion as Earth-crossing effect

- Two processes contribute to the Earth-crossing effect; attenuation and deflection:



(a) Attenuation (b) Deflection

Earth-crossing effect

- As a result, the DM 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_{halo}, m_χ, σ, the Earth composition and $\gamma = \cos^{-1}(\langle \hat{\mathbf{v}}_\chi \rangle \cdot \hat{\mathbf{r}}_{\mathrm{det}})$

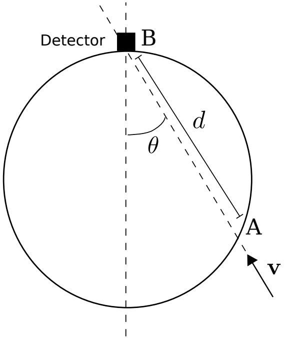
- **Key observation**: since γ depends on the detector position and on time, the same is true for $f(\mathbf{v},\gamma)$

- For DM particles crossing the Earth with velocity $\mathbf{v}$, the survival probability is given by

$$p_{\rm surv}(v) = \exp\left[-\int_{\rm AB} \frac{\mathrm{d}\ell}{\lambda(\mathbf{r}, v)}\right]$$

- The velocity distribution of particles entering the Earth with velocity $\mathbf{v}$ is related to the free halo distribution $f_0(\mathbf{v}) = f_{\rm halo}(\mathbf{v})$ by

$$f_A(\mathbf{v}, \gamma) = f_0(\mathbf{v})\, p_{\rm surv}(v)$$



Computing the deflection term, f_D

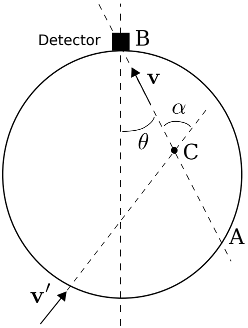
- Rate of particles entering an infinitesimal interaction region at C and scattering into the direction $\mathbf{v}$:

$$\left[n_\chi f_0(\mathbf{v}')\, \mathbf{v}' \cdot \mathrm{d}\mathbf{S}\, \mathrm{d}^3\mathbf{v}' \right] \left[\mathrm{d}p_{\mathrm{scat}}\, P(\mathbf{v}' \to \mathbf{v})\, \mathrm{d}^3\mathbf{v} \right]$$

where $\mathrm{d}p_{\mathrm{scat}} = \mathrm{d}\ell / [\lambda(\mathbf{r}, v')\cos\alpha]$.

- The rate of deflected particles leaving the interaction region with velocity $\mathbf{v}$ can also be written in terms of f_D

$$n_\chi f_D(\mathbf{v}, \gamma)\, \mathbf{v} \cdot \mathrm{d}\mathbf{S}\, \mathrm{d}^3\mathbf{v}$$



Computing the deflection term, f_D

- The contribution to $f_D(\mathbf{v},\gamma)$ from the interaction point C, and velocities around $\mathbf{v}'$ is

$$f_D(\mathbf{v},\gamma) = \frac{\mathrm{d}\ell}{\lambda(\mathbf{r},v')}\frac{v'}{v}f_0(\mathbf{v}')P(\mathbf{v}'\to\mathbf{v})\,\mathrm{d}^3\mathbf{v}'$$

- The final expression for f_D is obtained by integrating over $\mathrm{d}\ell$ and $\mathrm{d}^3\mathbf{v}'$.

- Multiplying $f(\mathbf{v},\gamma) = f_A(\mathbf{v},\gamma) + f_D(\mathbf{v},\gamma)$ by $v^2 = |\mathbf{v}|^2$, and integrating over $\mathrm{d}\mathbf{\Omega}_{\mathbf{v}}$, one obtains the dark matter speed distribution at detector after Earth-crossing.

- Comments: v'/v determined by kinematics; f_D depends upon σ through λ and $P(\mathbf{v}'\to\mathbf{v})$.

Dark matter speed distribution at detector

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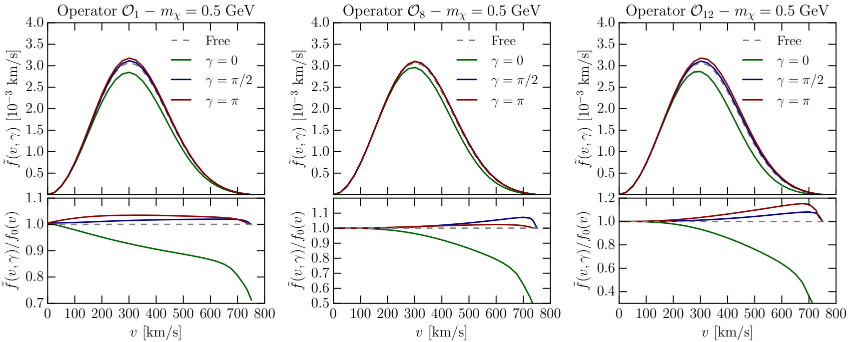
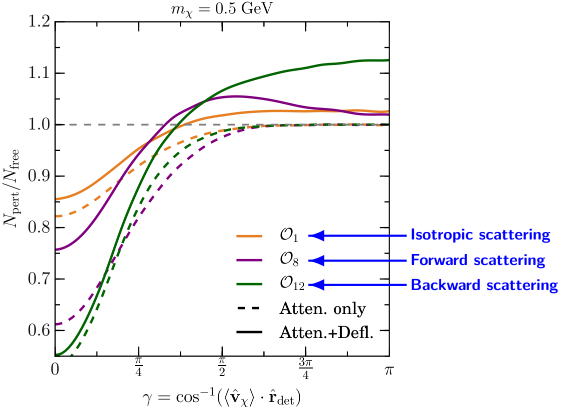


Earth-crossing effect / position dependence

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



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Earth-crossing effect / time dependence

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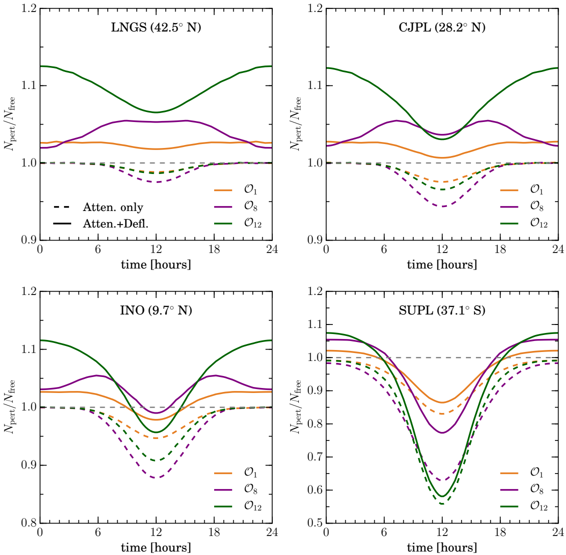

Comparison with the MC code DAMASCUS

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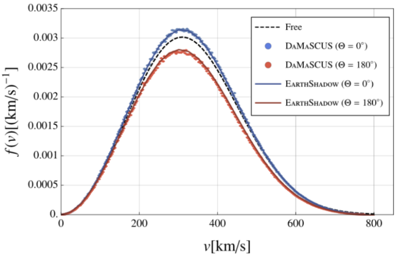

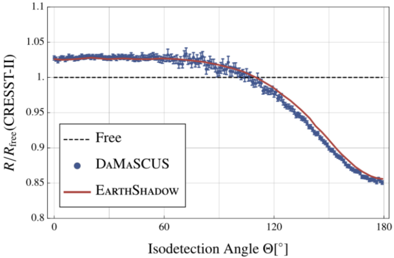

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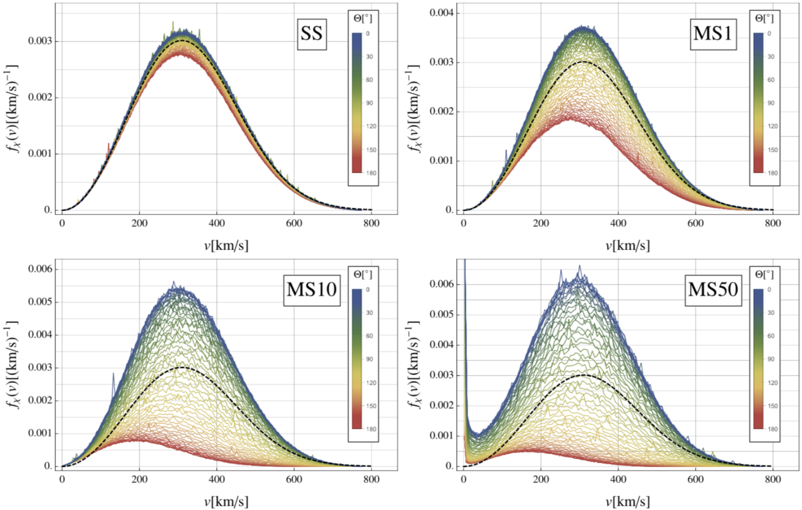

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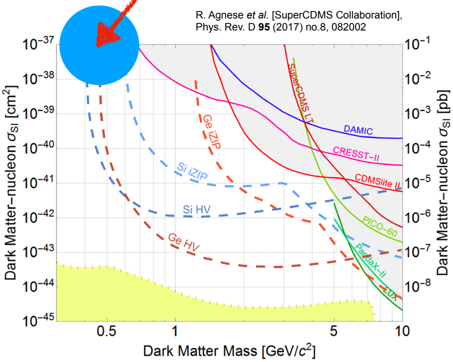
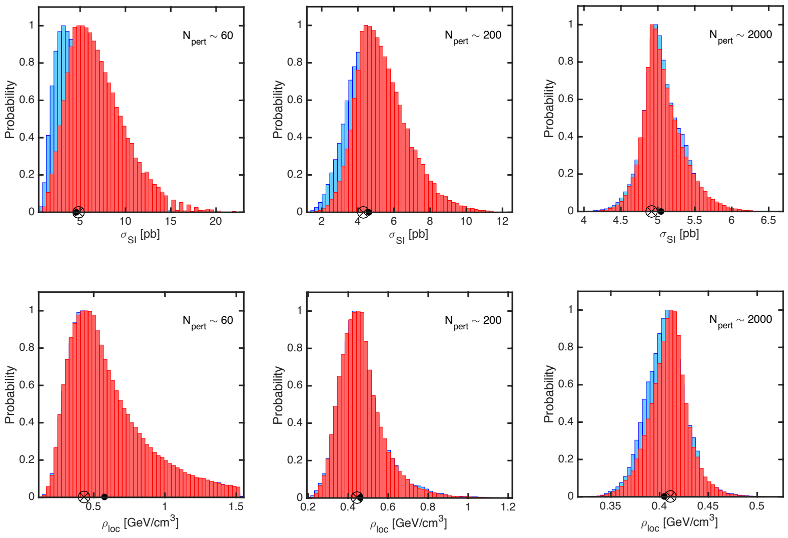


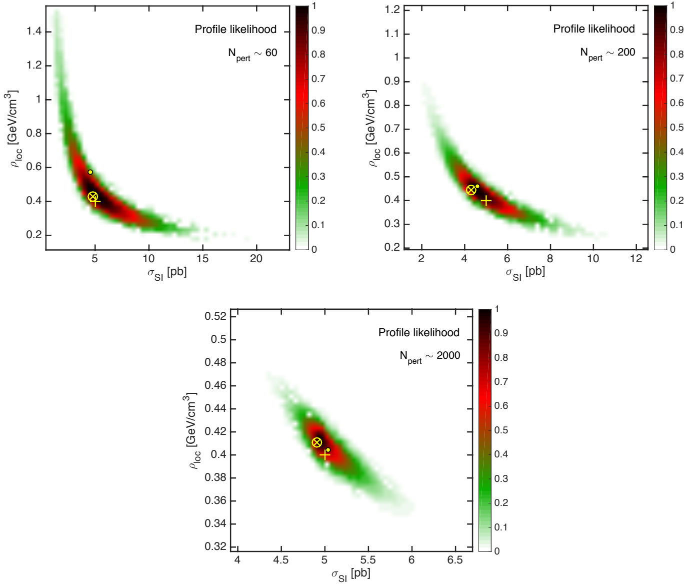
Reconstructing $\rho_{\rm loc}$ and σ: 1D profile likelihood

R. Catena, T. Emken and B. Kavanagh, in preparation



Reconstructing $\rho_{\rm loc}$ and σ: 2D profile likelihood

R. Catena, T. Emken and B. Kavanagh, in preparation



Summary

- Analytic and MC calculations of Earth-scattering effects can be used to simultaneously extract local DM density and DM-nucleon scattering cross section from data

- For $\sim$ 60 signal events, the relative error on $\rho_{\rm loc}$ is of a factor of 2; for $\sim$ 200 signal events is of about 50%; and for $\sim$ 2000 signal events is of about 10%