Signatures of Earth-scattering in the direct detection of sub-GeV Dark Matter

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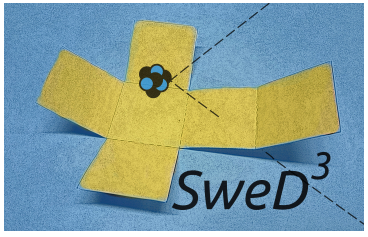
March 12, 2018

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

CHALMERS

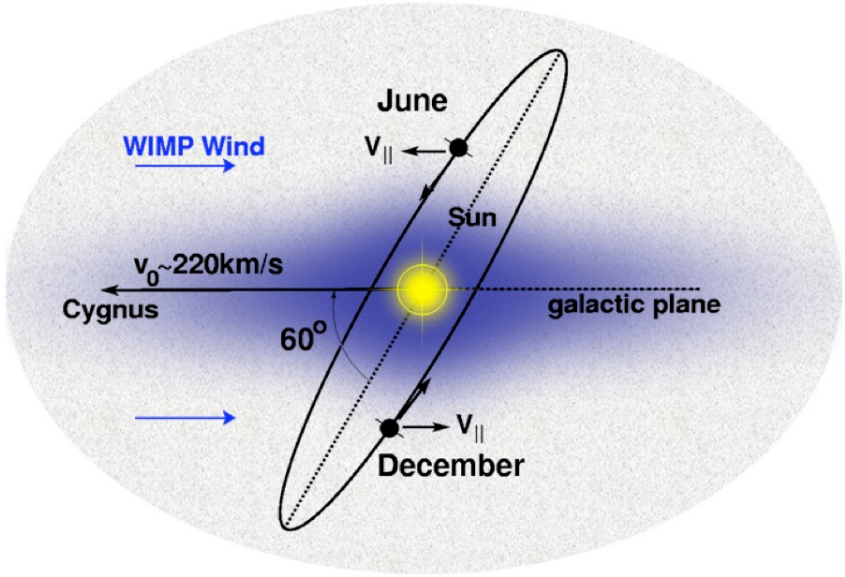


Outiline

- Dark matter direct detection
- Earth-shadowing effect
- Impact on dark matter direct detection
- Summary
- Discussion

Dark matter direct detection

- **Basic idea**:



- **Physical observable**: rate of dark matter-nucleus scattering events in terrestrial detectors

$$\text{Rate} = \text{Flux} \otimes \text{Cross section}$$

Physical observable

- Differential rate of dark matter-nucleus scattering events in a detector of mass $m_T \mathcal{N}_T$:

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_{\mathrm{nr}}} = \mathcal{N}_T n_\chi \int_{|\mathbf{v}|>v_{\mathrm{m}}(E_{\mathrm{nr}})} \mathrm{d}^3\mathbf{v}\,|\mathbf{v}| f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}}$$

Velocity distribution at detector

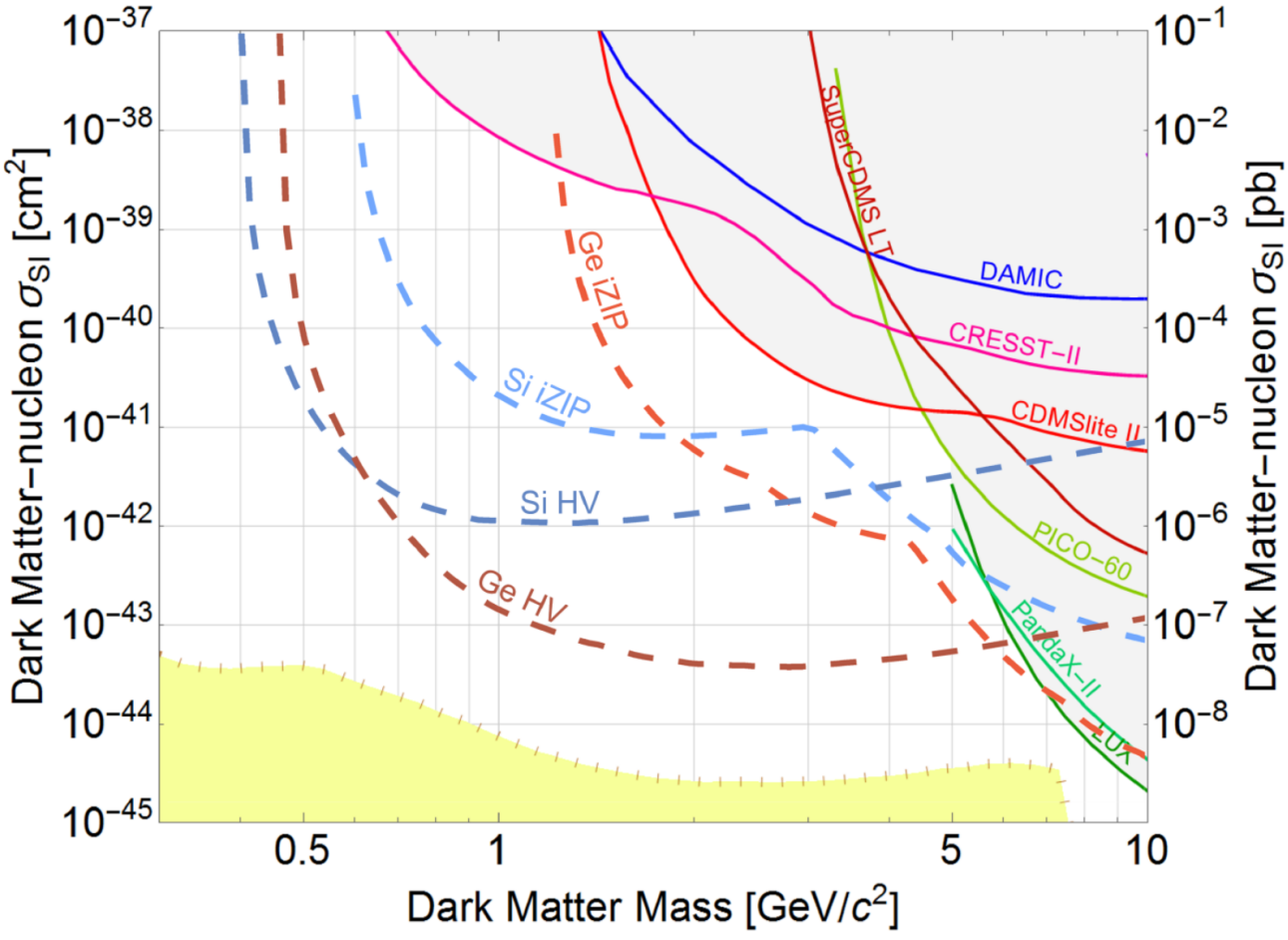
Scattering cross-section

- Number of dark matter-nucleus scattering events in a recoil energy interval ΔE:

$$N_{f,\sigma} = \Delta\mathcal{T} \int_{\Delta E} \mathrm{d}E_{\mathrm{nr}} \frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_{\mathrm{nr}}}$$

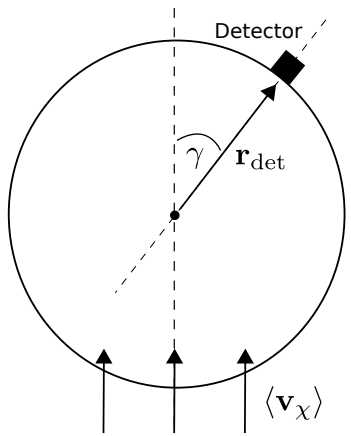
Null results imply limits on σ

SuperCDMS projected sensitivity (UCLA DM 2018)



Earth-shadowing effect

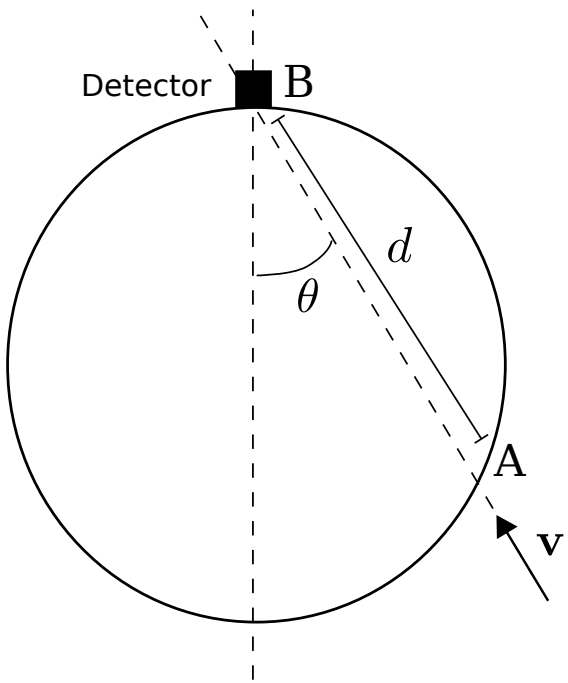
- In the standard paradigm $f = f_{\rm halo}$, where $f_{\rm halo}$ is the velocity distribution in the halo.
- However, before reaching the detector, dark matter particles have to cross the Earth.



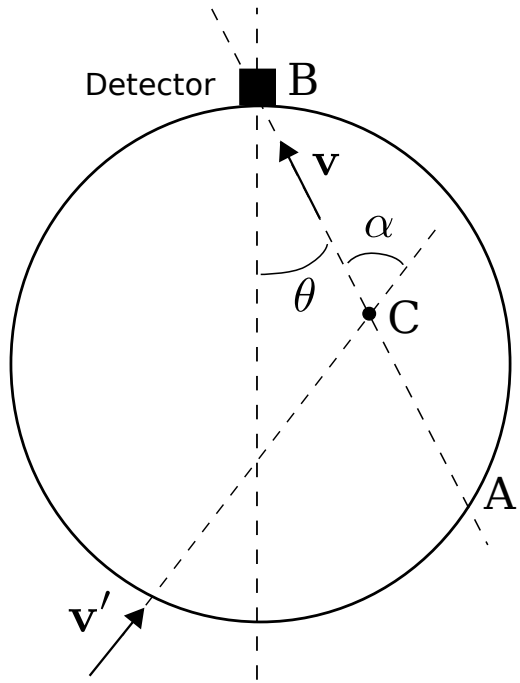
- Earth-crossing unavoidably distorts $f_{\rm halo}$ if dark matter interacts with nuclei, which implies $f \neq f_{\rm halo}$. This distortion is called Earth-shadowing effect.

Earth-shadowing effect

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



(a) Attenuation



(b) Deflection

Earth-shadowing effect

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

Computing the attenuation term, f_A

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

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

- The velocity distribution of the *attenuated* particles (i.e. those which survive the Earth-crossing) is therefore related to the free 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 $\mathrm{d}p_{\mathrm{scat}} = \mathrm{d}\ell / [\lambda(\mathrm{r}, v') \cos\alpha]$.

- The rate of deflected particles leaving the interaction region with velocity $\mathbf{v}$ is defined to be

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

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 $\mathrm{d}\Omega_{\mathbf{v}}$, 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 $P(\mathbf{v}' \to \mathbf{v})$.

Theoretical framework for computing σ

- We use A. L. Fitzpatrick et al., JCAP **1302** (2013) 004
- 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 density for dark matter-nucleon interactions is

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

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

Theoretical framework for computing σ

$$\hat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_N$$
$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$
$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_N$$
$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$
$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_N$$
$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$
$$\hat{\mathcal{O}}_{17} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$
$$\hat{\mathcal{O}}_{18} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{S}}_N$$

Theoretical framework for computing σ

- 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:

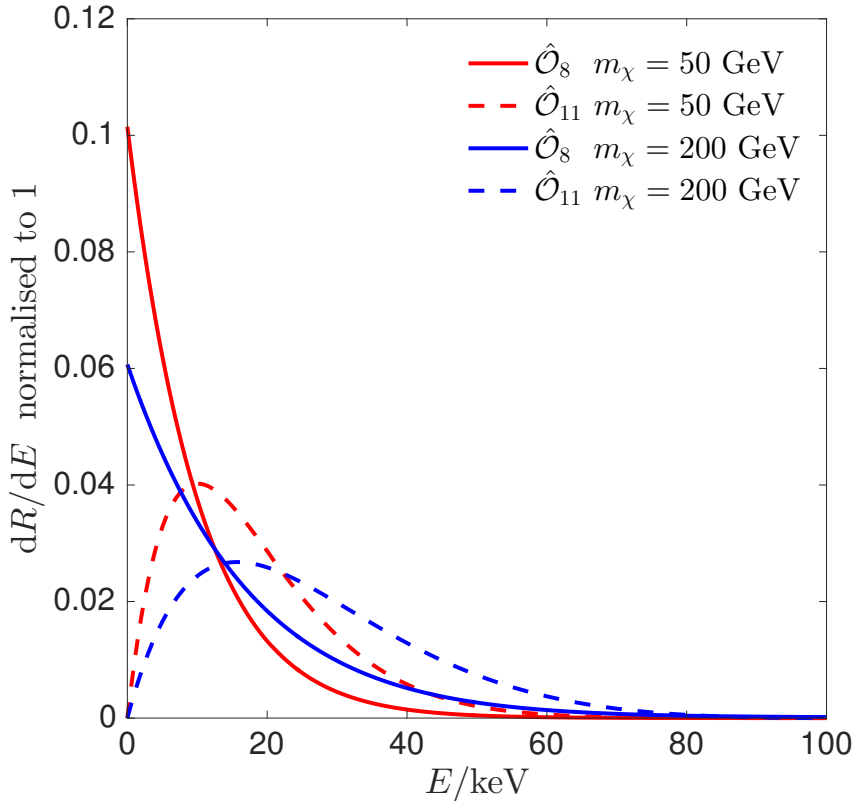
$$\mathbb{1}_N \qquad \hat{\mathbf{S}}_N \qquad \hat{\mathbf{v}}^\perp \qquad \hat{\mathbf{v}}^\perp \cdot \hat{\mathbf{S}}_N \qquad \hat{\mathbf{v}}^\perp \times \hat{\mathbf{S}}_N$$

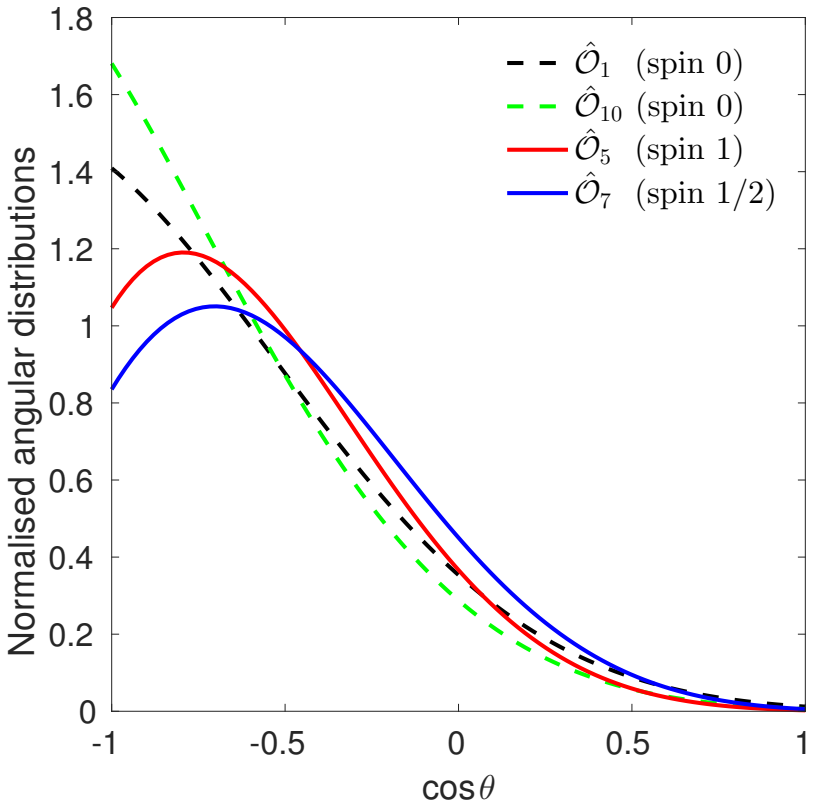
A. L. Fitzpatrick et al., JCAP **1302** (2013) 004

- This leads to 8 independent nuclear response functions (if nuclear ground states are CP eigenstates).
- In the case of dark matter scattering off nuclei in the Sun and Earth, these were computed in

R. Catena and B. Schwabe JCAP **1504** 04, 042 (2015)

Theoretical framework for computing σ





Theoretical framework for computing σ

- Likelihood analysis of current data

  R. Catena and P. Gondolo, JCAP **1409**, 09, 045 (2014) R. Catena and P. Gondolo, JCAP **1508**, 08, 022 (2015)

- Prospects for dark matter detection

  Catena, JCAP **1409**, 09, 049 (2014); Catena, JCAP **1407**, 07, 055 (2014)

- Directional detection

  Catena JCAP **1507** 07, 026 (2015); R. Catena, J. Conrad, C. Döring, A. D. Ferella and M. B. Krauss, Phys. Rev. D **97**, no. 2, 023007 (2018)

- Compatibility of different experimental results

  Catena, Ibarra and Wild, JCAP **1605**, 05, 039 (2016)' R. Catena, A. Ibarra, A. Rappelt and S. Wild, arXiv:1801.08466 [hep-ph]

- Operator mixing

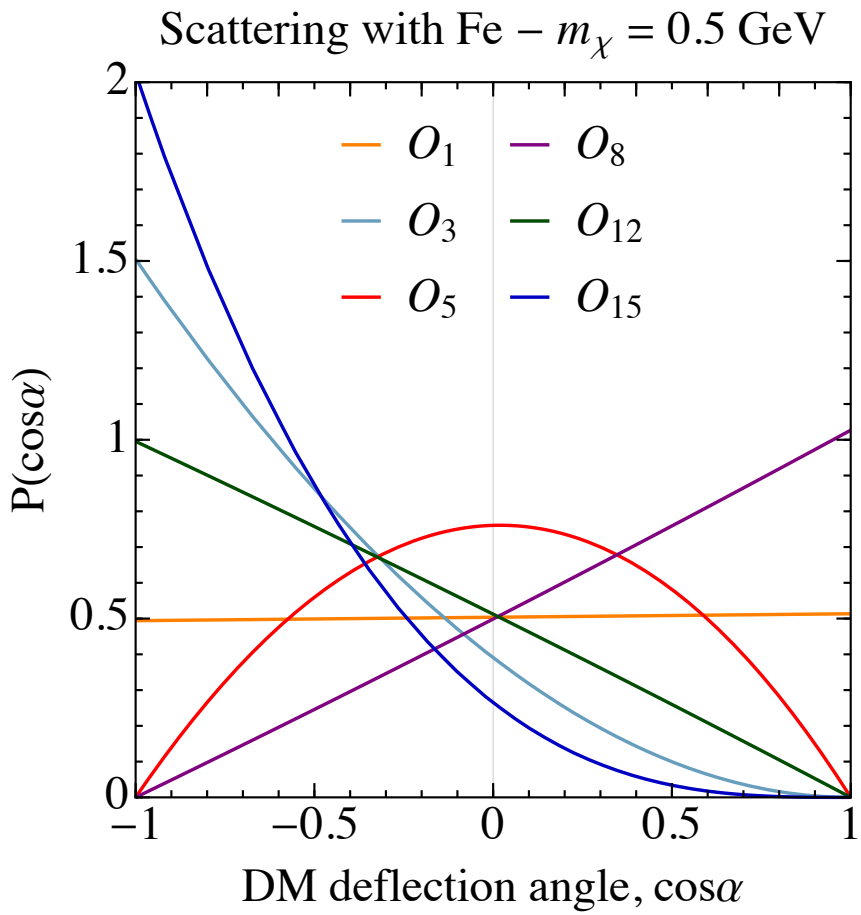
  Crivellin, D'Eramo and Procura, Phys. Rev. Lett. **112**, 191304 (2014)

- Chiral EFT corrections to operator coefficients

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

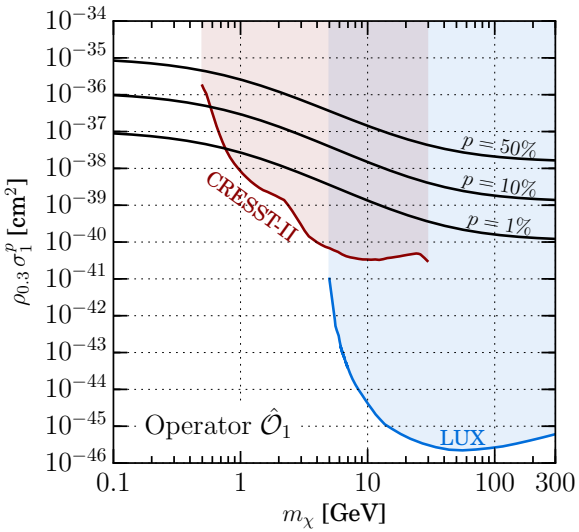
Scattering probability $P(\mathbf{v}' \to \mathbf{v})$

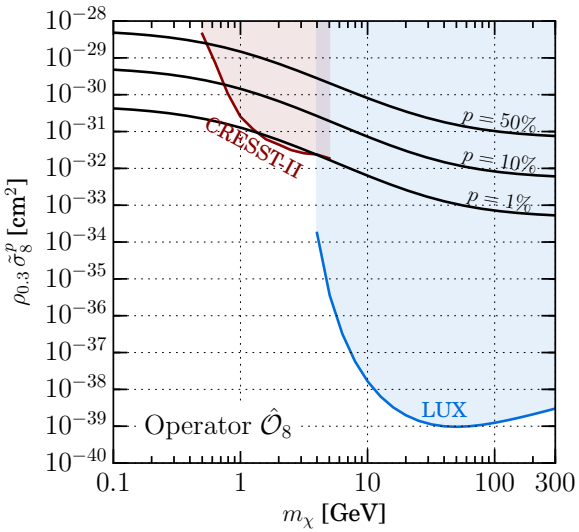
Below, $P(\cos\alpha) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\alpha}$

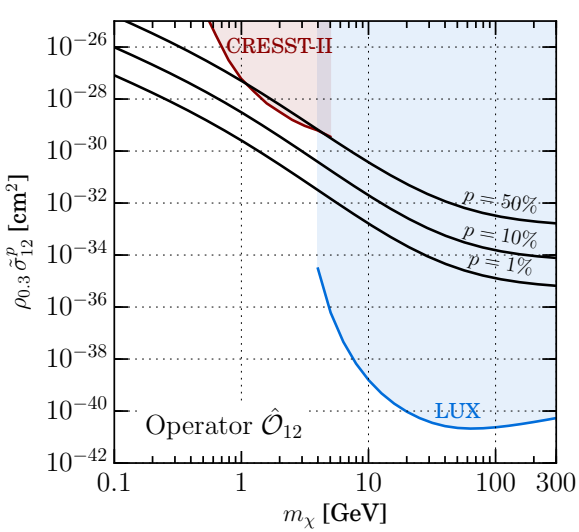


When Earth-shadowing is expected to be important

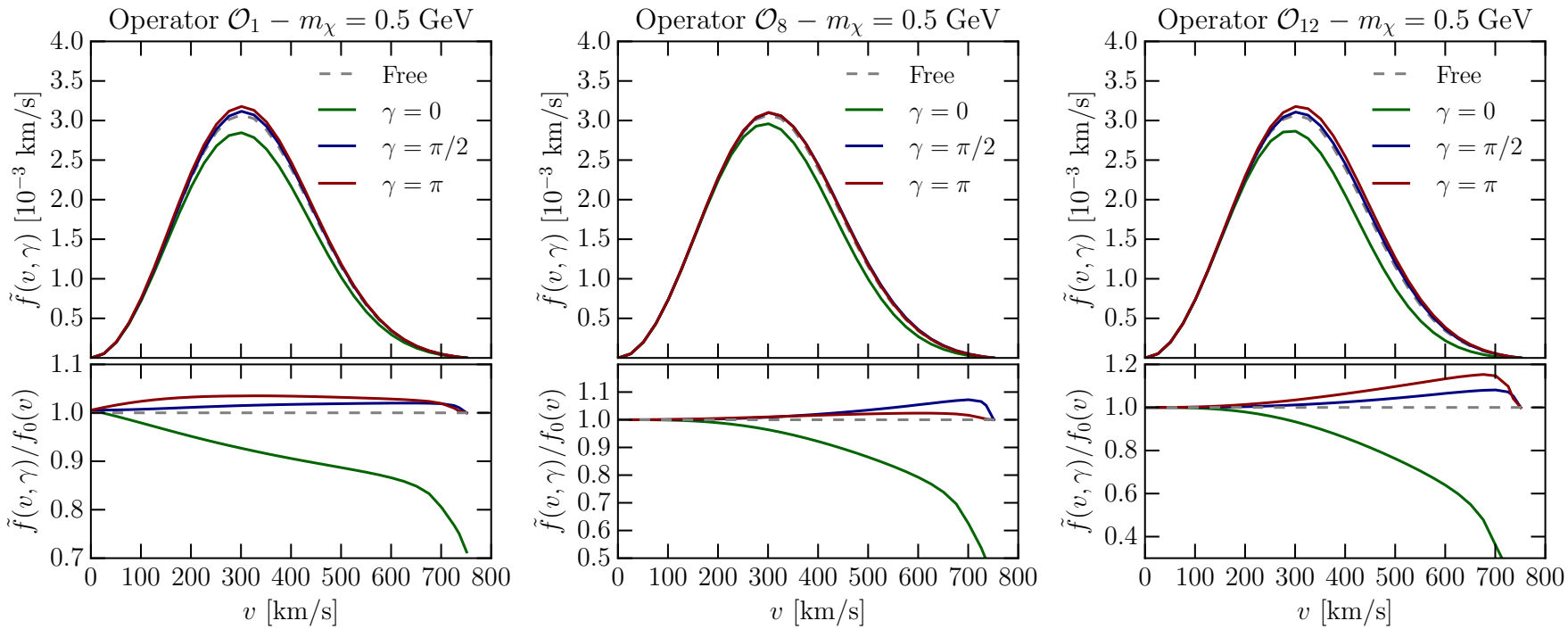
Below, p is the average probability that dark matter scatters at least once while crossing the Earth



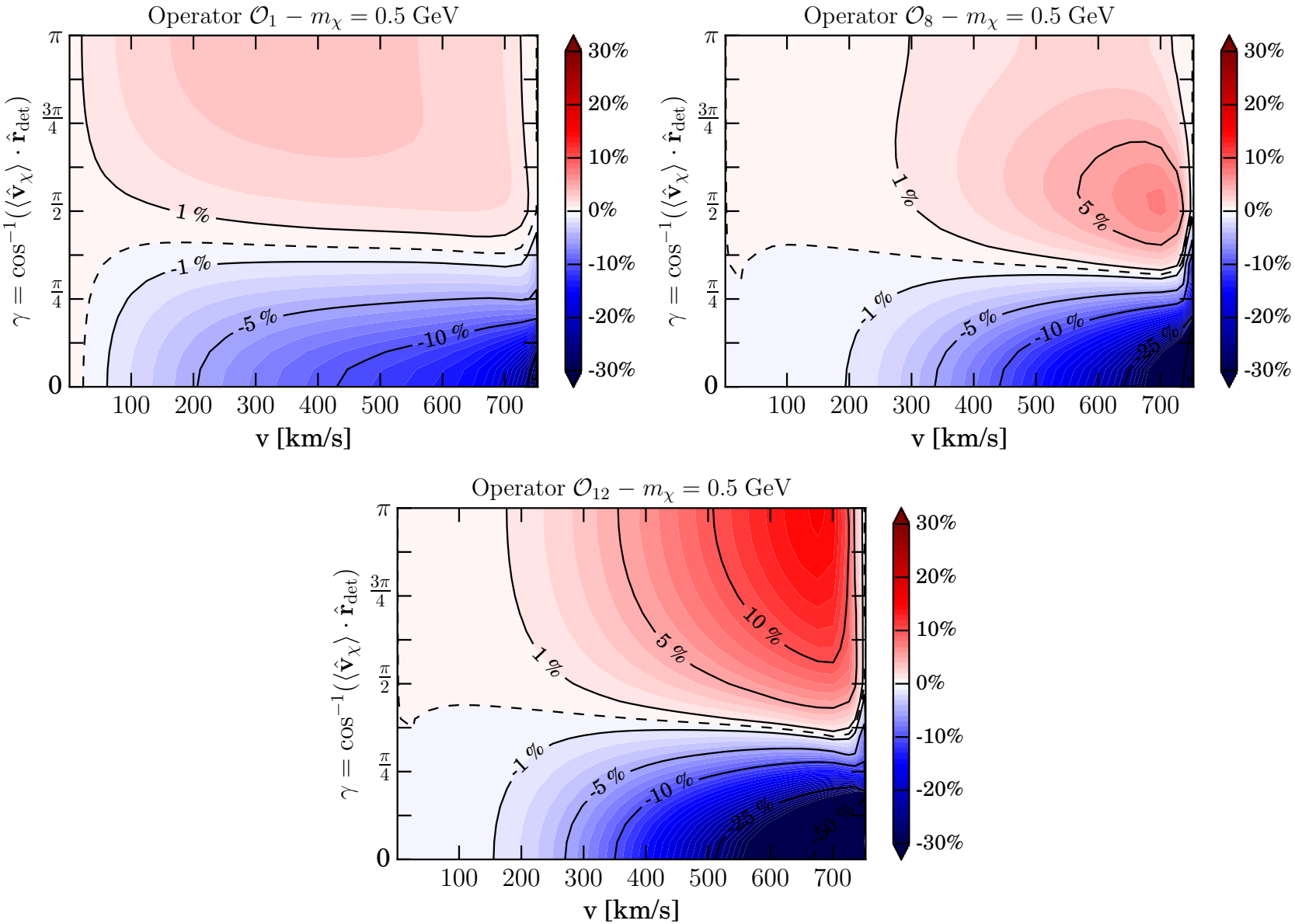




Dark matter speed distribution at detector

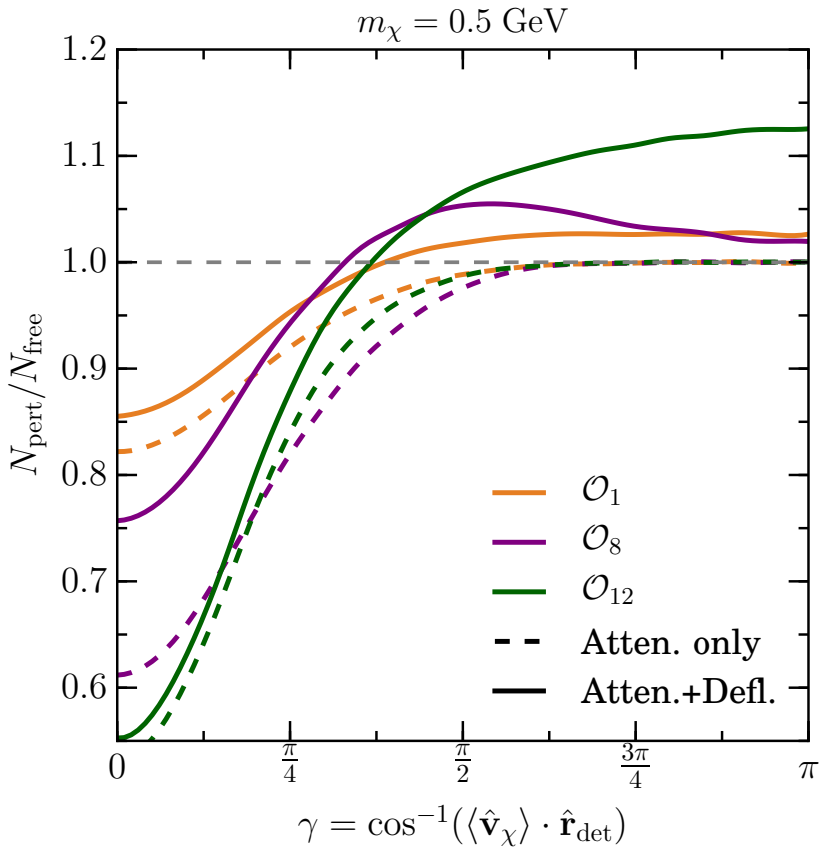


Dark matter speed distribution at detector



Earth-shadowing effect / position dependence

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



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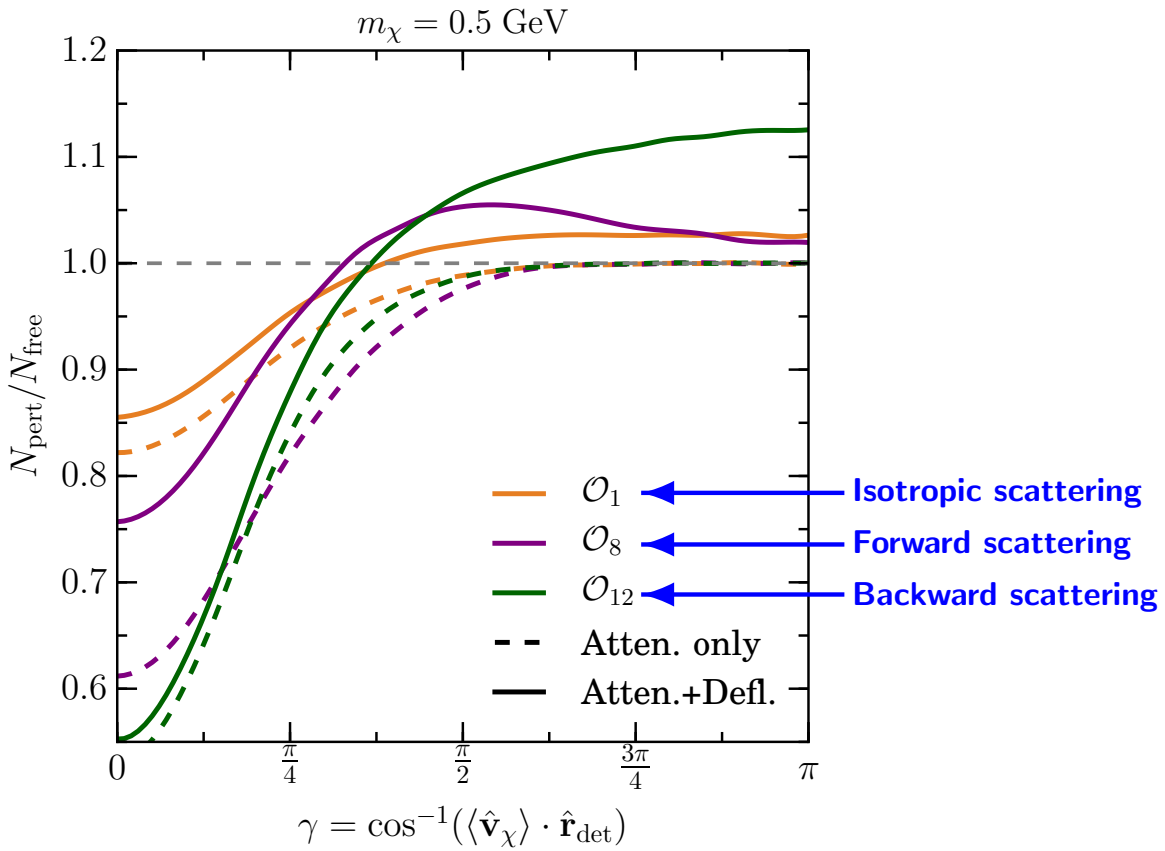
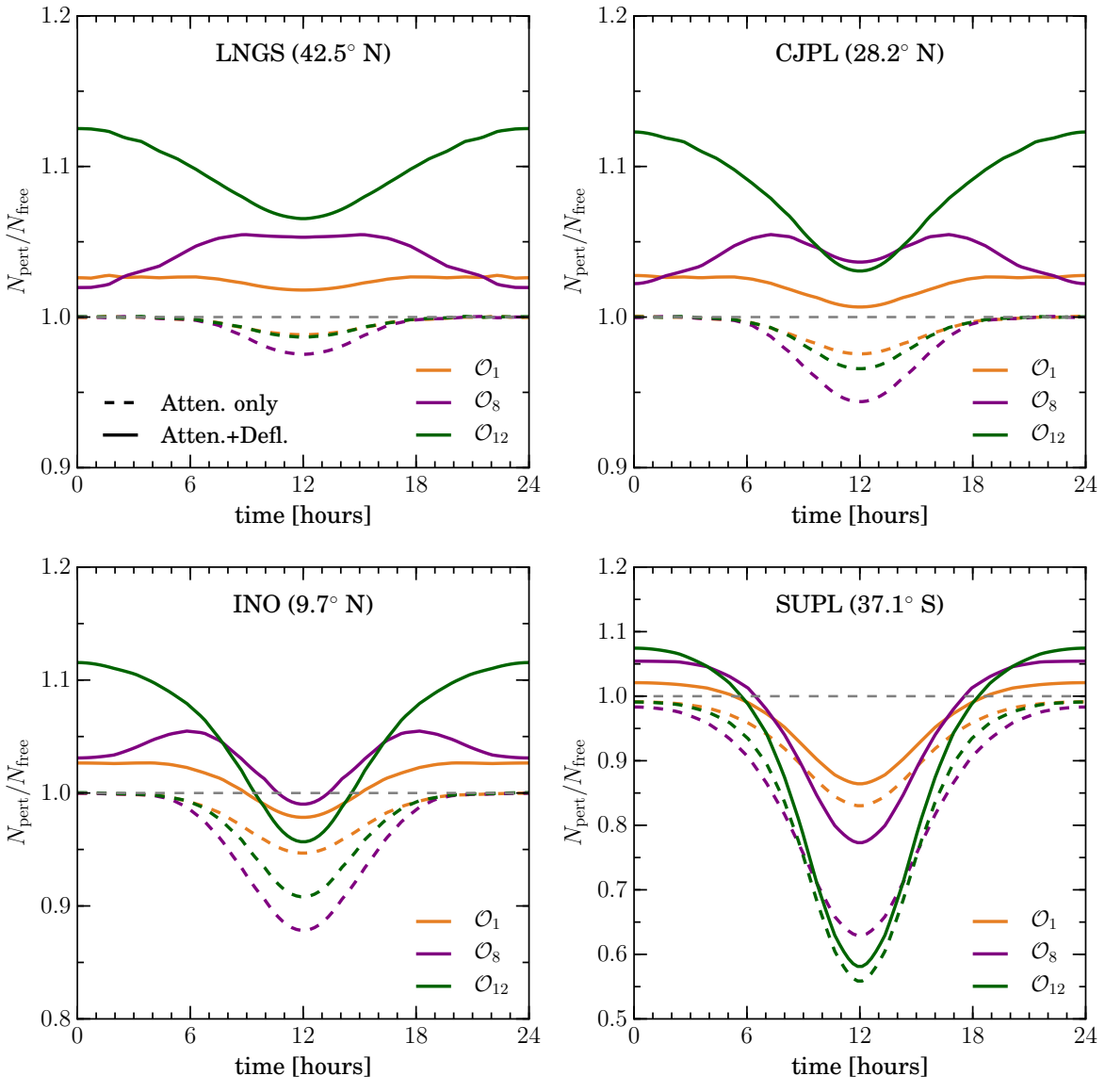
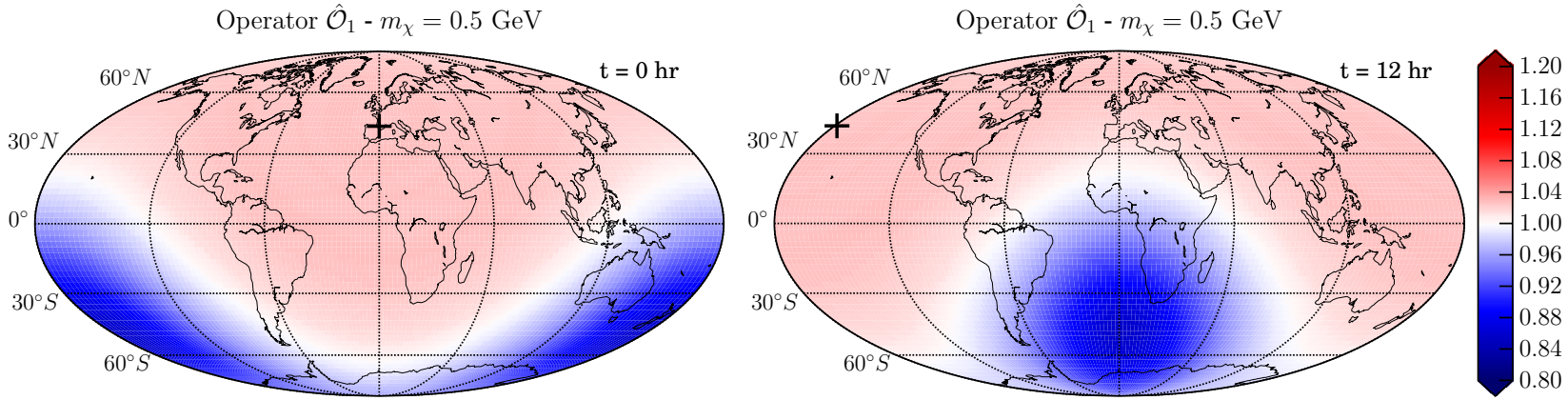


Earth-shadowing effect / time dependence

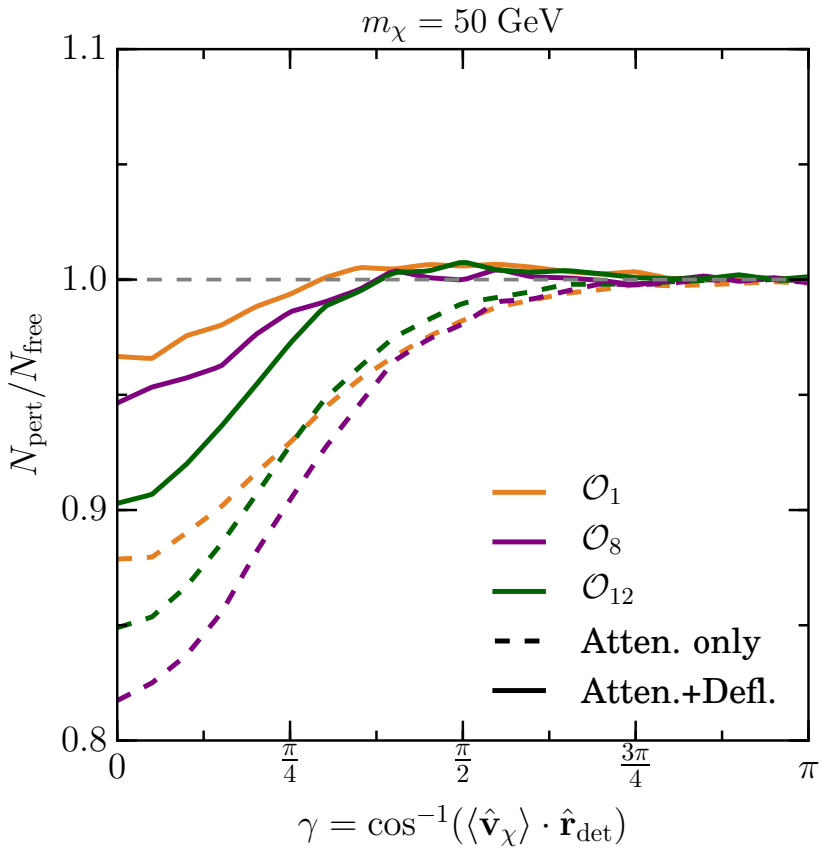


Earth-shadowing effect / position & time dependence

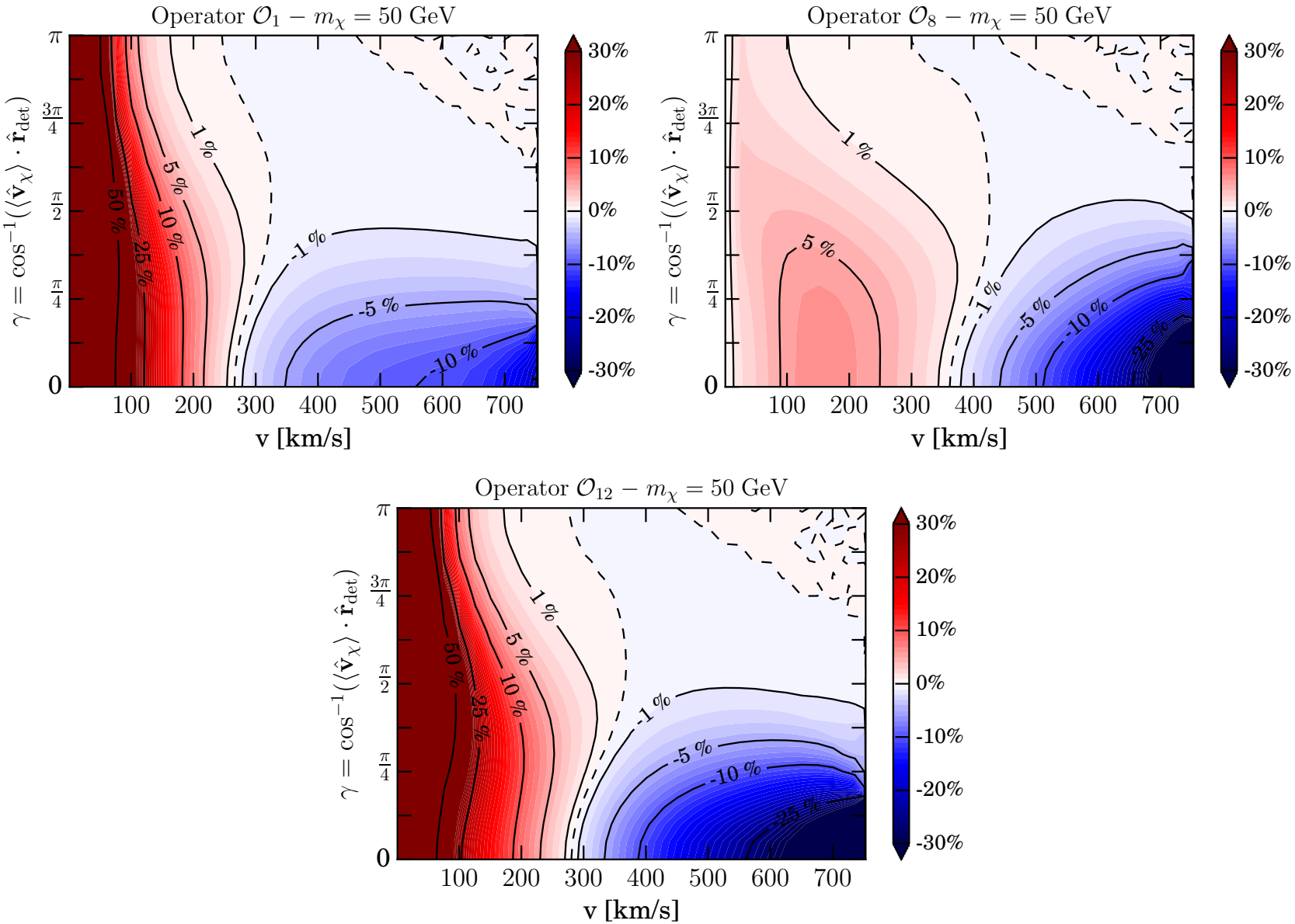
- $N_{\rm pert}/N_{\rm free}$ over the surface of the Earth for $\mathcal{O}_1$. There is a 12 hour time difference between panels



High mass region I

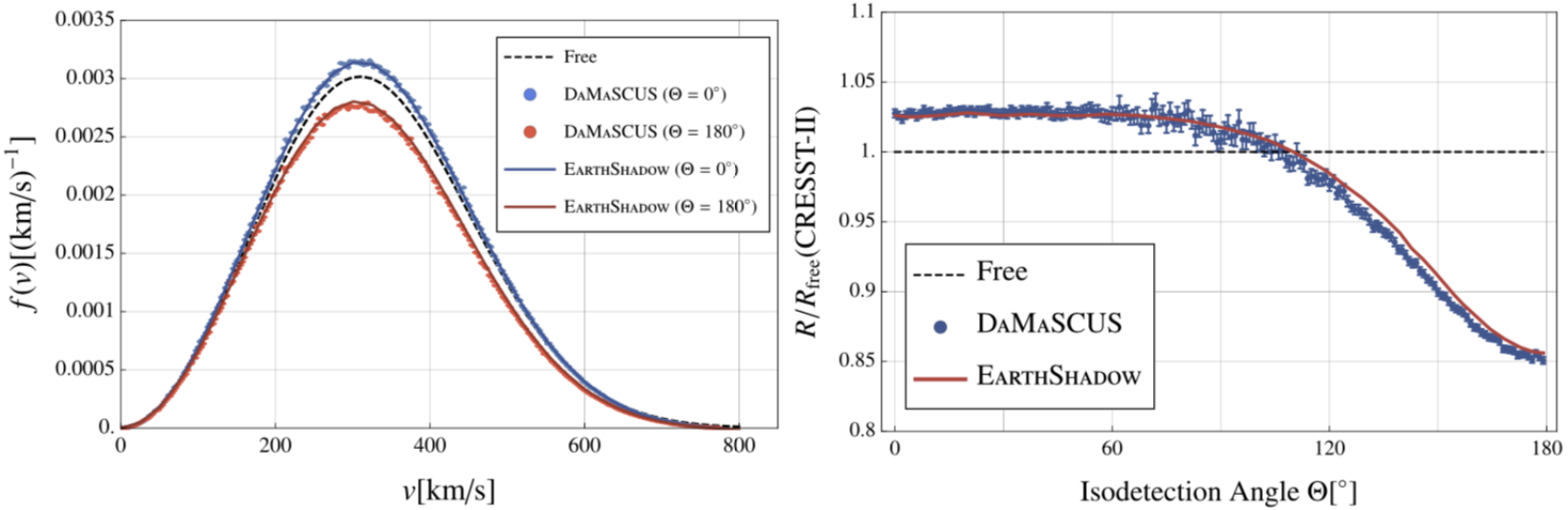


High mass region II



Comparison with the MC code DAMASCUS

T. Emken and C. Kouvaris, JCAP **1710** (2017) no.10, 031



Summary

- If dark matter interacts with nuclei, $f \neq f_{\mathrm{halo}}$ (Earth-shadowing effect).
- This occurs since halo dark matter particles cross the Earth before reaching a detector.

- The amplitude of this effect depends on the detector position and varies over the day.

- If dark matter is light, $m_\chi \sim 0.5$ GeV, these distinctive signatures are within reach of present (CRESST-II) and future (SuperCDMS) experiments.

Discussion

- What are the strongest theoretical motivations for sub-GeV dark matter? Is there a leading paradigm?
- Among the many new strategies for sub-GeV dark matter detection proposed recently, which one is indeed feasible?
- New experimental techniques entail new types of uncertainties, e.g. atomic structure calculations for dark matter-electron scattering. Are these under control?

- If XENON1T detects dark matter, shall we keep searching for sub-GeV dark matter?
- And the other way round?

- In general, what can we learn from dark matter direct detection? Mass and couplings only? Spin?? CP??

Dark matter bound to the Earth

- Dark matter particles crossing the Earth scatter to gravitationally bound orbits in $\mathrm{d}e\,\mathrm{d}r_m$ at a rate

$$\mathrm{d}\dot{N}(r_m, e) = 8\pi^2 G M_\oplus m_\chi \sum_A K_A(r_m, e) \times \int_{r_m}^{R_\oplus} \mathrm{d}r\, n_A(r) \left(1 - \frac{r_m^2}{r^2}\right)^{-1/2} \mathrm{d}e\,\mathrm{d}r_m$$

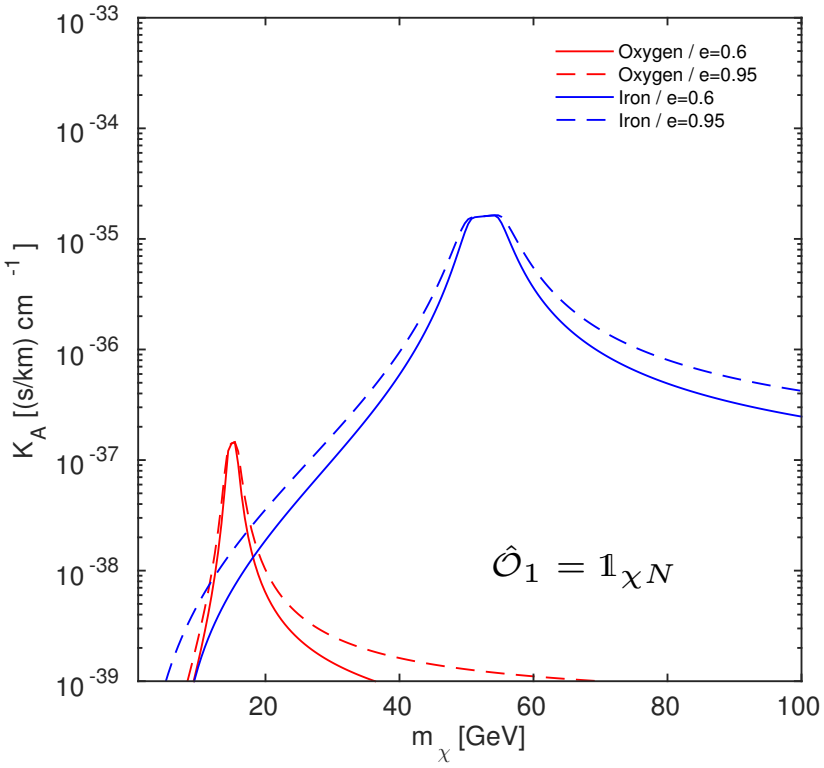
- Flux of bound dark matter particles crossing a detector at ℓ_c

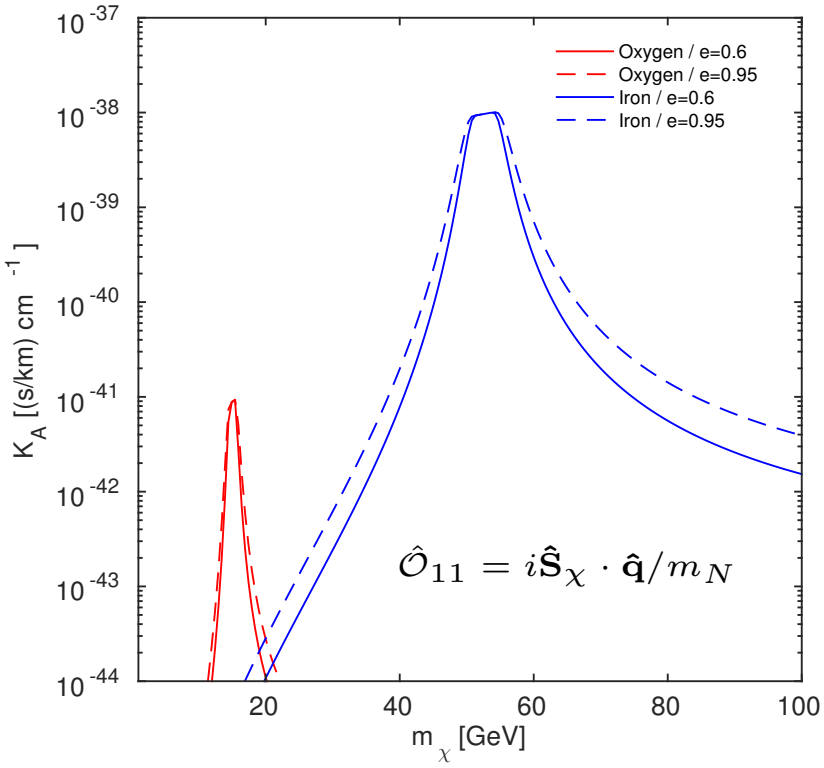
$$\mathrm{d}\mathcal{F}(r_m, e) = \frac{d\dot{N}(r_m, e)}{4\pi\ell_c^2} \frac{2T(r_m, e)}{\tau(r_m, e)}$$

Dark matter bound to the Earth

Catena and Kouvaris Phys. Rev. D **94** (2016) no.2, 023527

Catena and Kouvaris Phys. Rev. D **96** (2017) no.6, 063012





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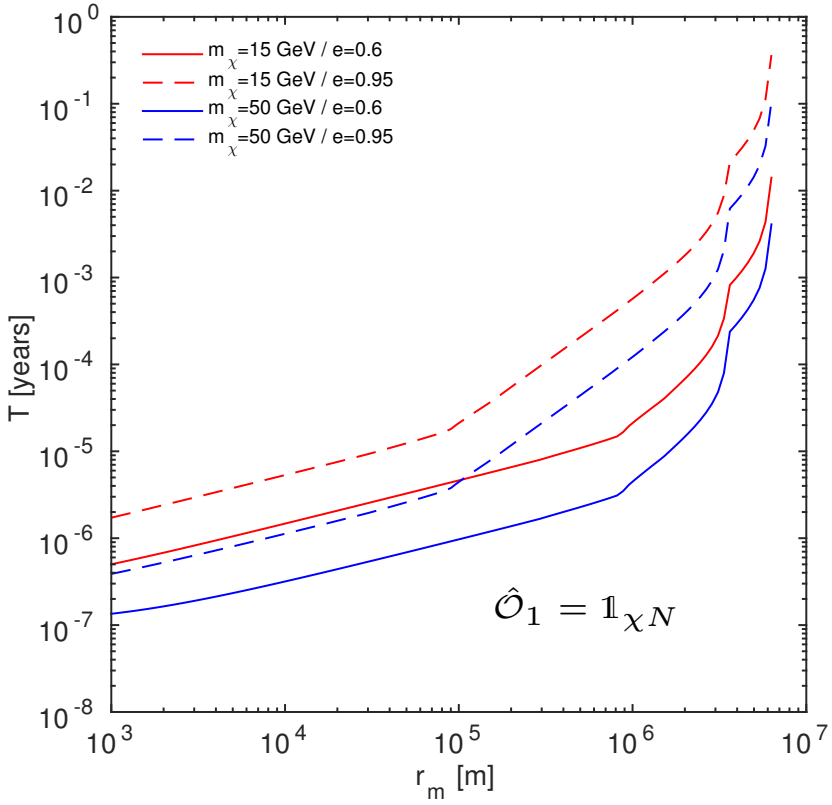

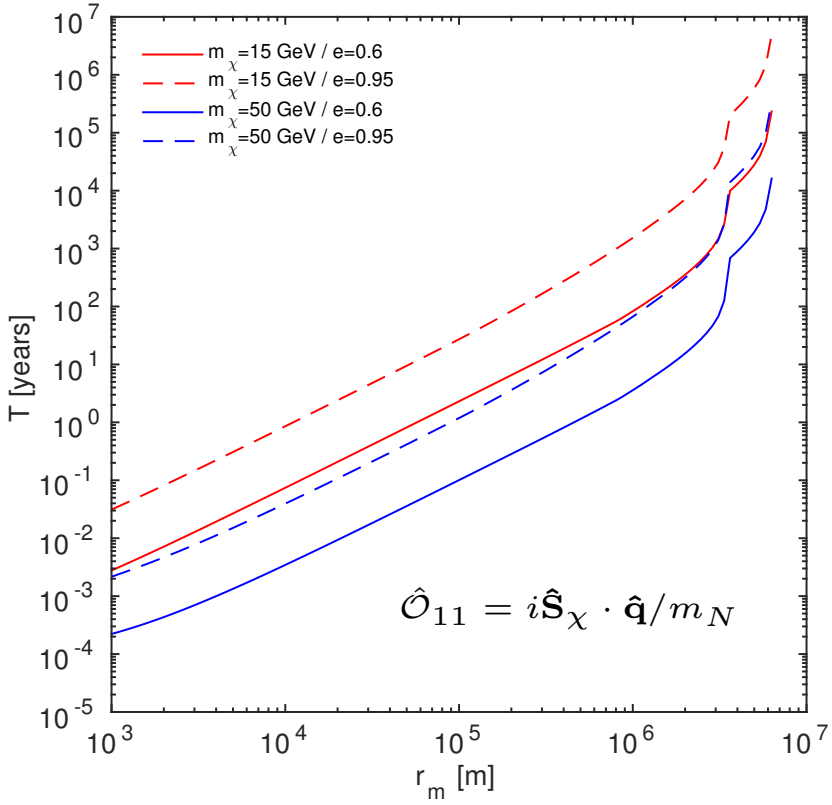

Dark matter bound to the Earth

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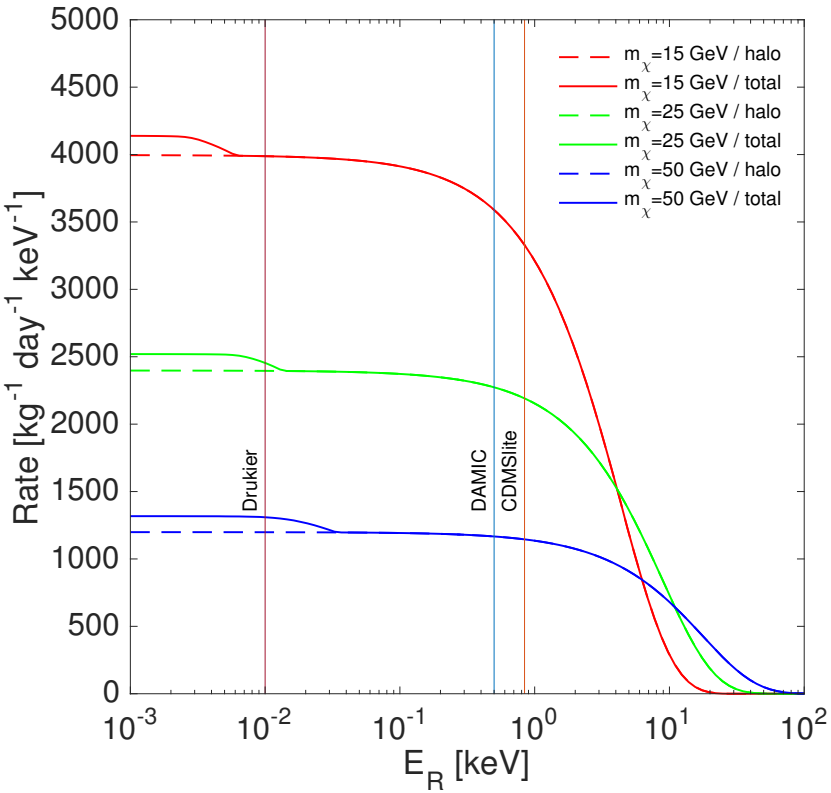

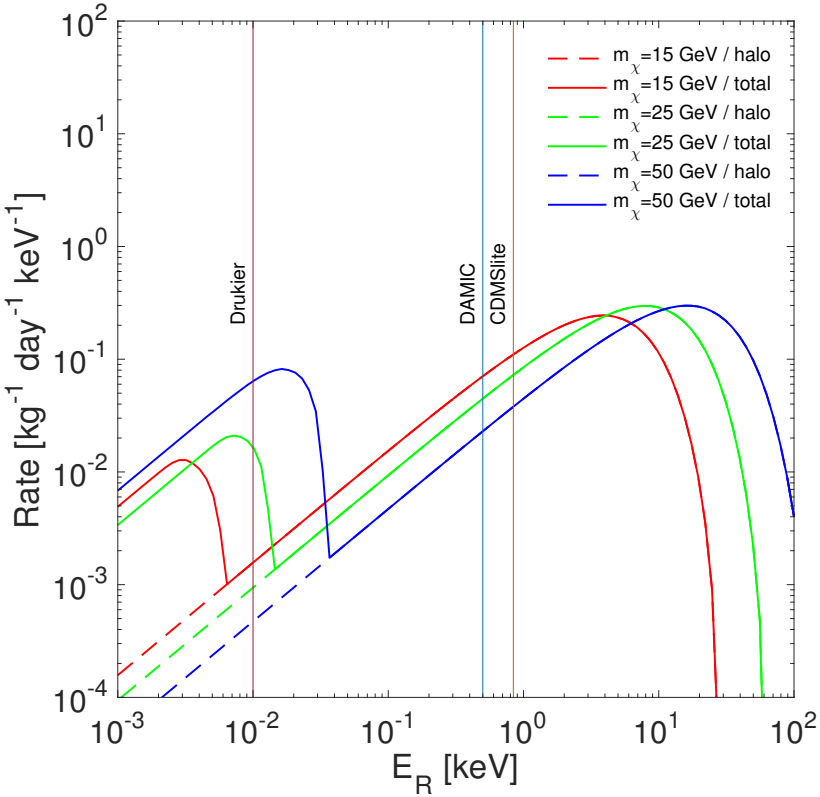

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$

$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$