Earth-Shadowing effects in Dark Matter direct detection

Bradley J. Kavanagh
LPTHE (Paris)

with Riccardo Catena (Chalmers)
and Chris Kouvaris (CP^3-Origins)

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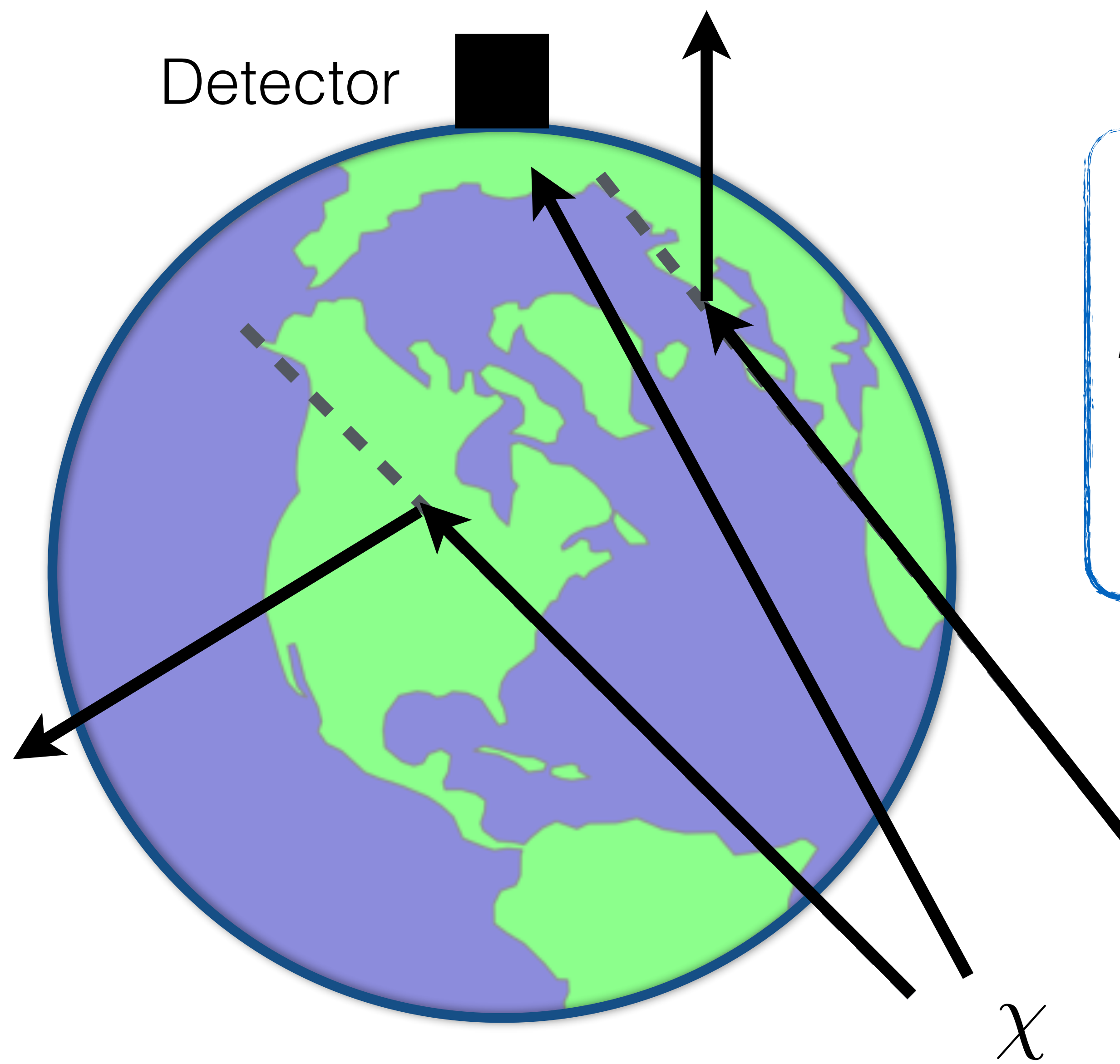
31st August 2016

bradley.kavanagh@lpthe.jussieu.fr

@BradleyKavanagh

Earth Shadowing

DM velocity distribution $f(\mathbf{v})$ is affected by DM interactions in the Earth



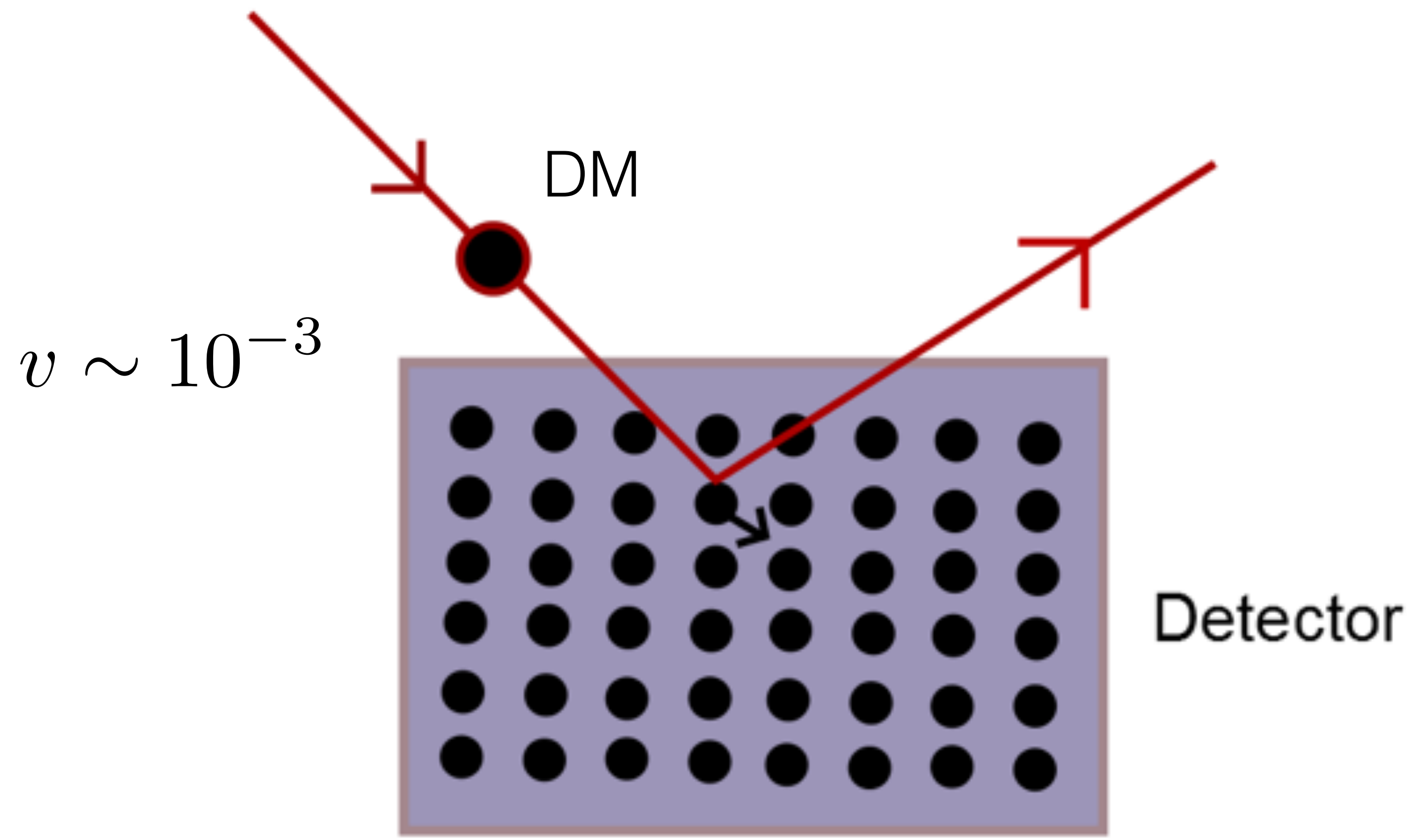
Size of effect depends on *Mean Free Path*:

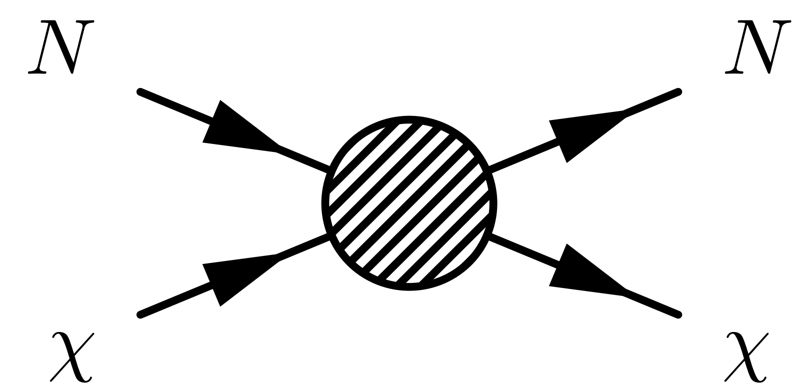
$$\lambda = (\sigma n)^{-1}$$

Variation with detector position and time gives characteristic signatures

→ altered flux, daily modulation, directionality…

Direct detection





Differential recoil rate: $$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_\mathcal{N}} \int_{v_\mathrm{min}}^\infty v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \,\mathrm{d}^3\mathbf{v}$$

Include all DM particles with enough speed to induce a recoil of energy E_R :

$$v_\mathrm{min} = \sqrt{\frac{m_\mathcal{N} E_R}{2\mu_{\chi\mathcal{N}}^2}}$$

Speed distribution

Speed distribution:

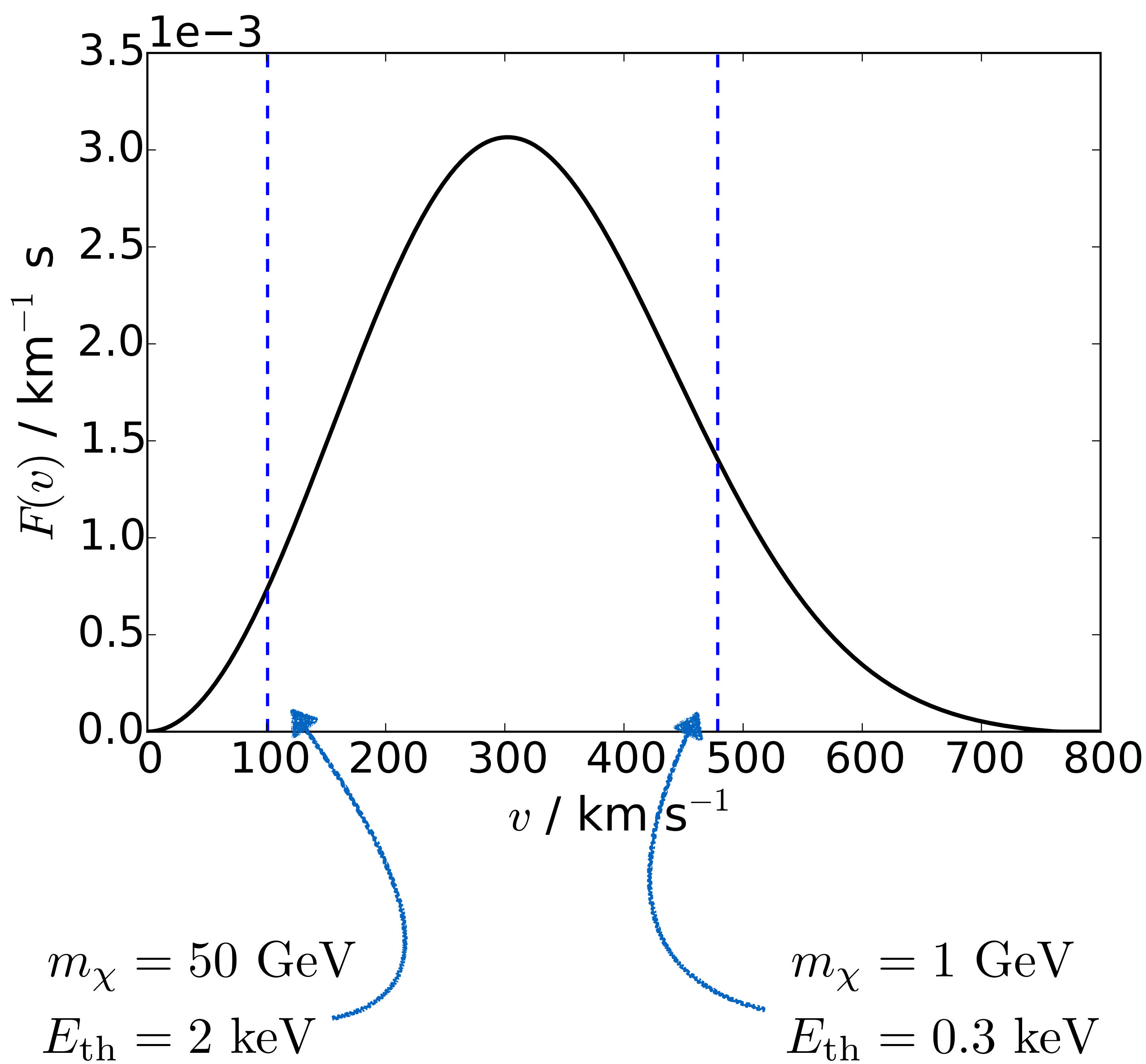
$$F(v) = v^2 \oint f(\mathbf{v})\, \mathrm{d}\Omega_v$$

Minimum speed req. to excite recoil of energy E_R:

$$v_{\min} = \sqrt{\frac{m_\mathcal{N} E_R}{2\mu_{\chi\mathcal{N}}^2}}$$

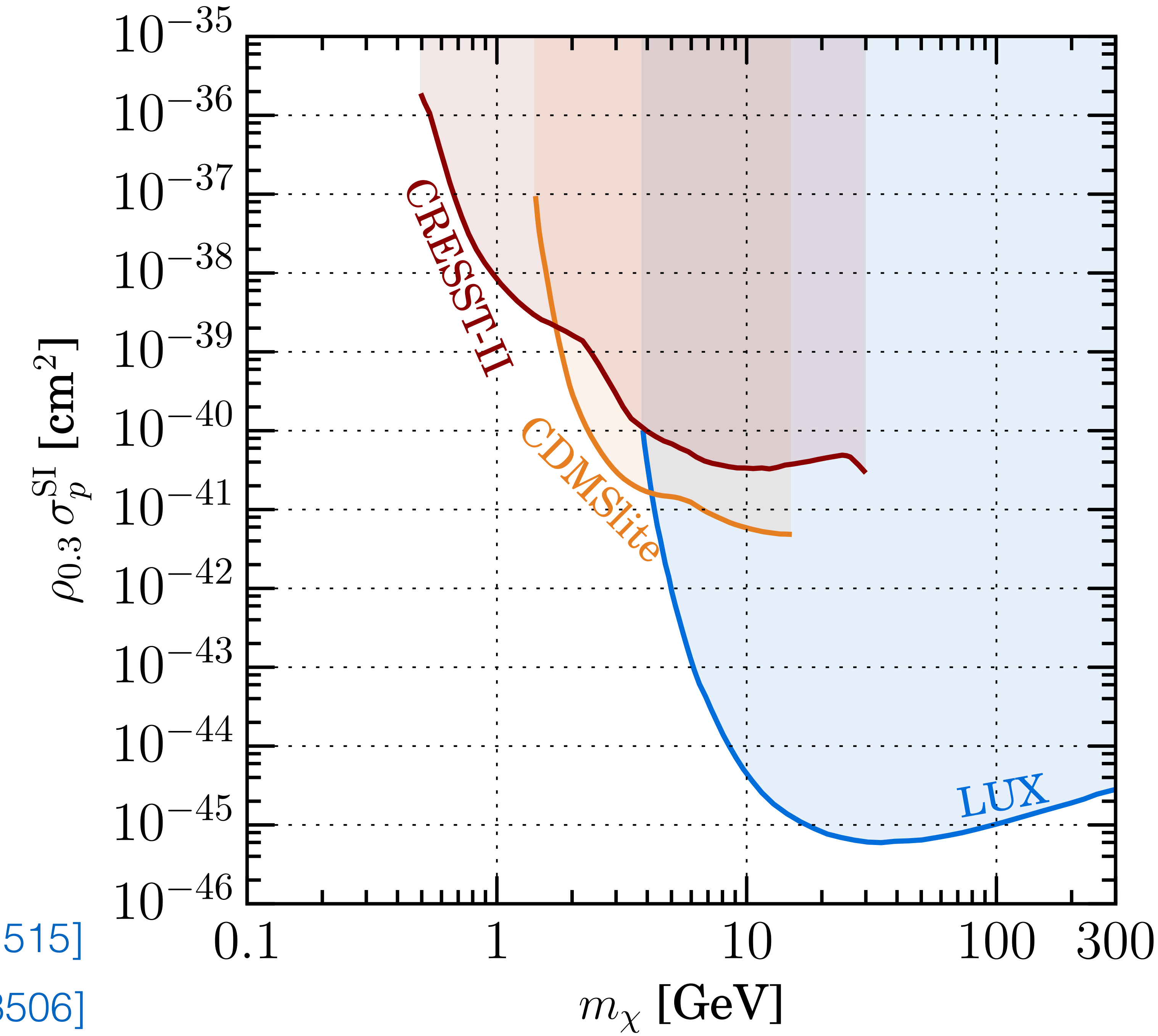
Values of $v_{\min}$ for scattering on Oxygen nuclei for…

Standard Halo Model (SHM)



Current cross section limits

Stringent limits on DM-nucleon SI scattering cross section



CRESST-II [1509.01515]

LUX [1512.03506]

CDMSlite [1509.02448]

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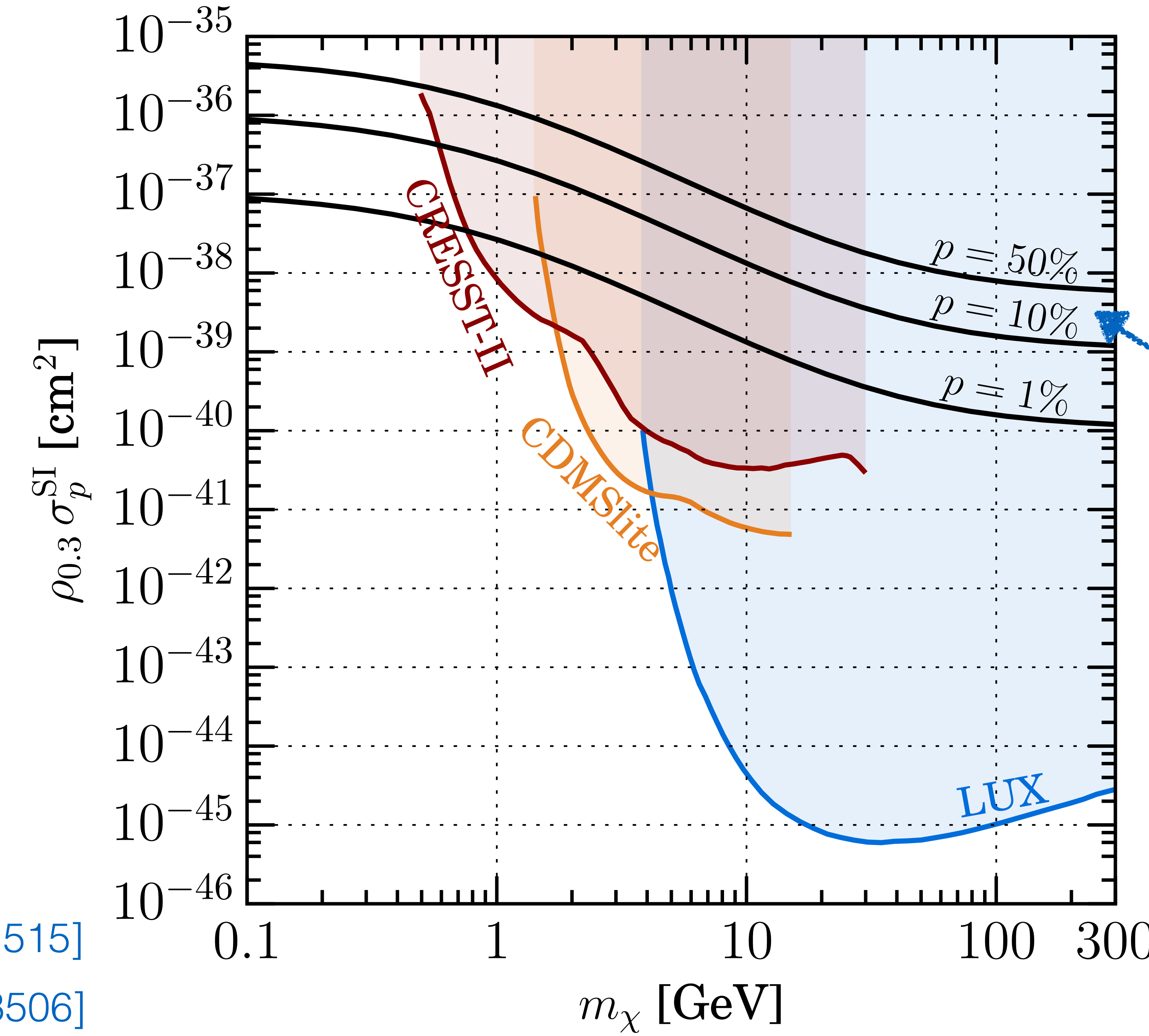


Probability of DM scattering in the Earth

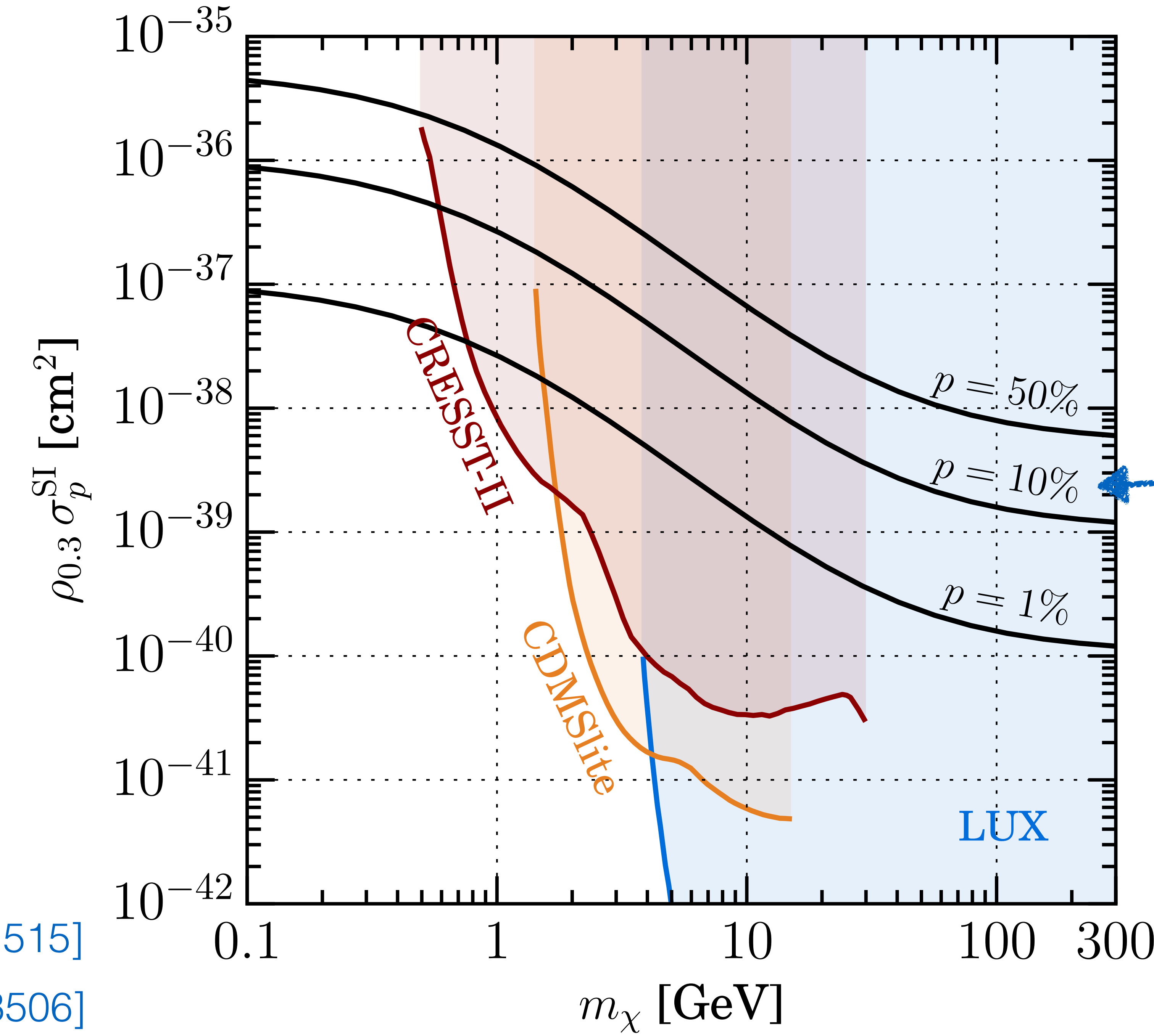
CRESST-II [1509.01515]

LUX [1512.03506]

CDMSlite [1509.02448]

Current cross section limits

Low mass DM may still have large Earth scattering probability



Probability of DM scattering in the Earth

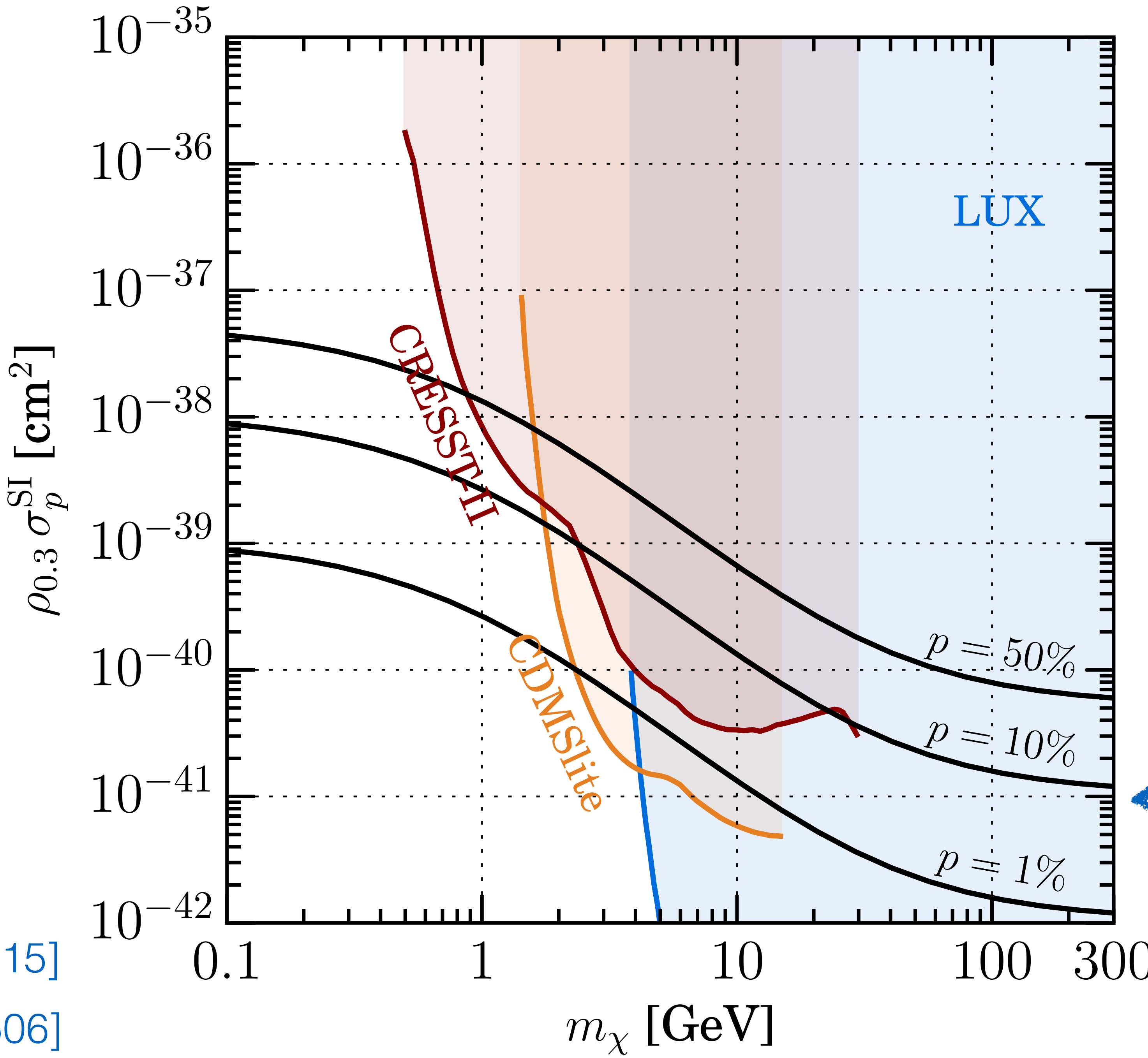
CRESST-II [1509.01515]

LUX [1512.03506]

CDMSlite [1509.02448]

Current cross section limits

Subdominant DM component may still have large cross section



Probability of DM scattering in the Earth

$\rho_\chi \to 1\%\,\rho_\chi$

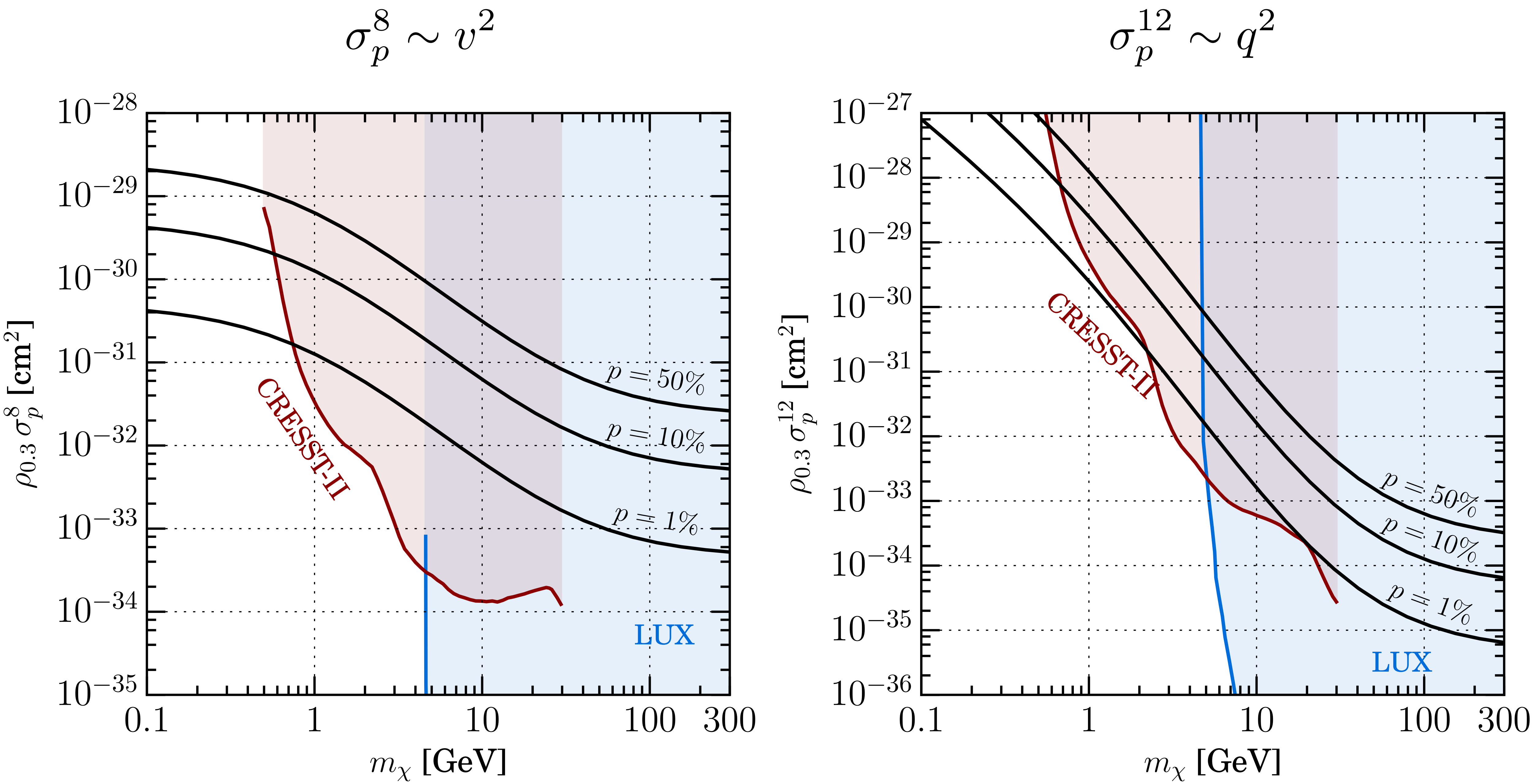
CRESST-II [1509.01515]

LUX [1512.03506]

CDMSlite [1509.02448]

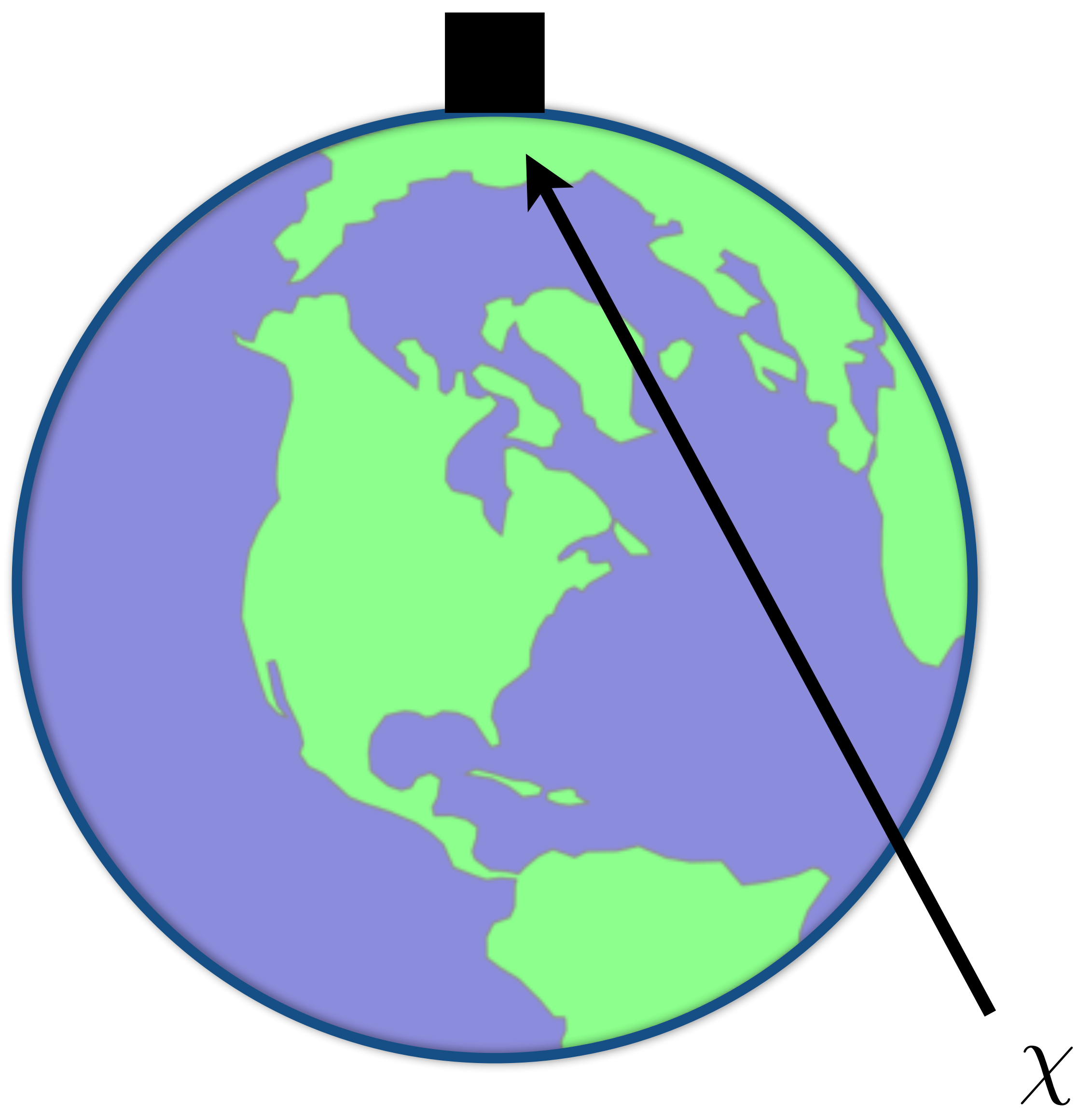
Current cross section limits

Non-standard DM-nucleon interactions:



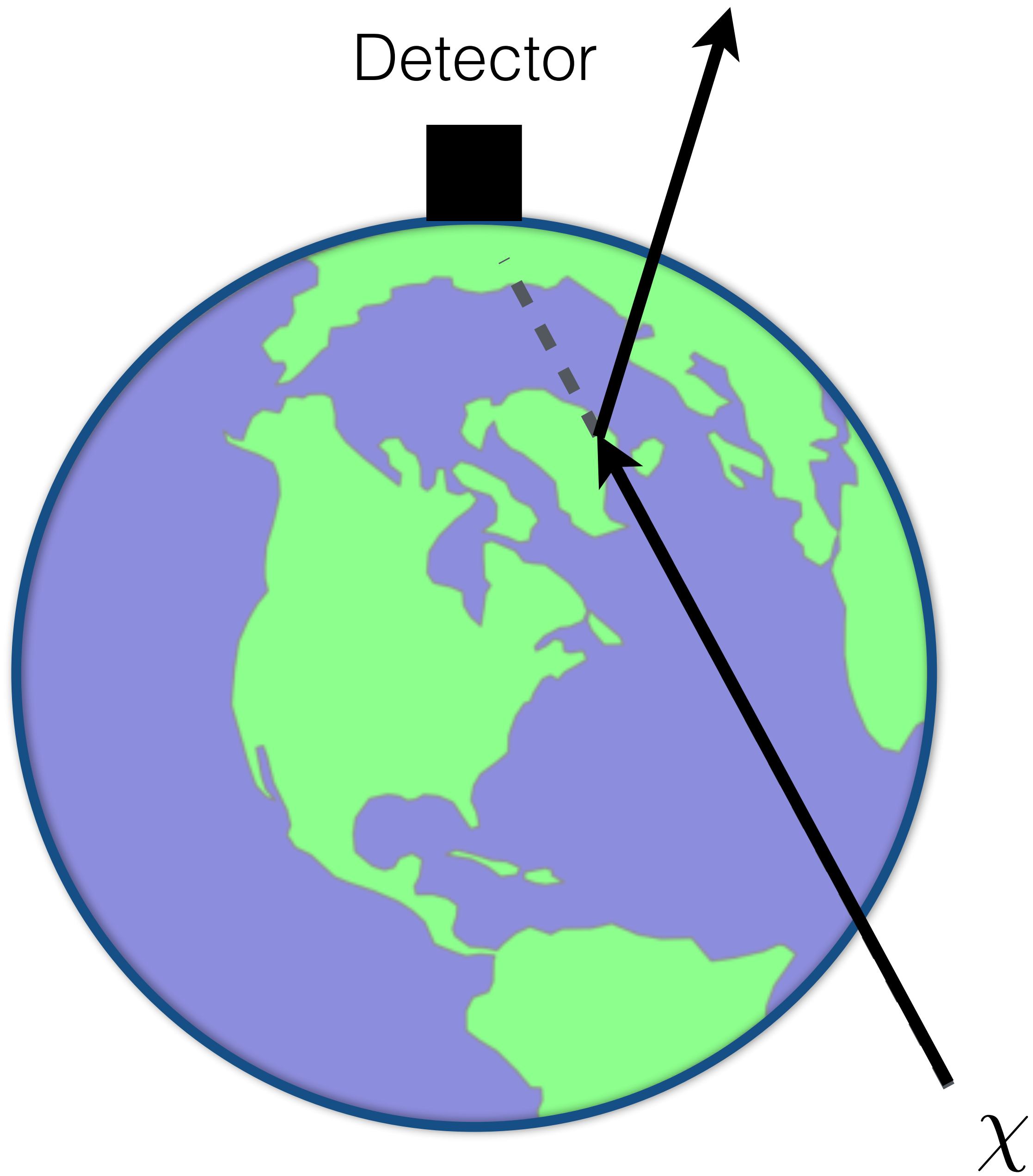
SuperCDMS [1503.03379]
LUX [1504.06554]
CRESST-II [1601.04447]

Earth Shadowing



Unscattered (free) DM: $f_0(\mathbf{v})$

Earth Shadowing



Assuming DM mean free path

$$\lambda \gtrsim R_E$$

Previous calculations usually only consider DM attenuation

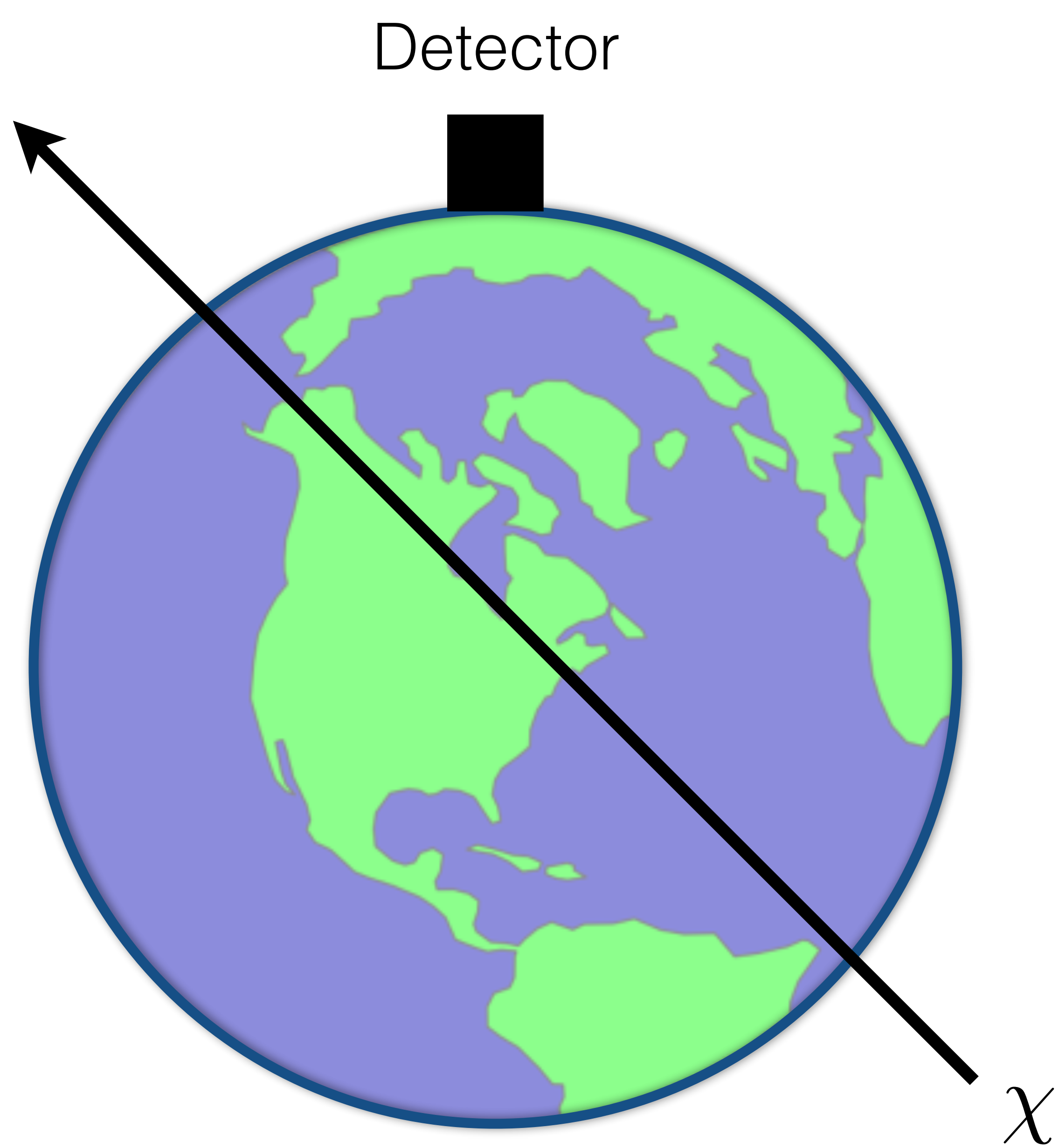
Zaharijas & Farrar [astro-ph/0406531]

Kouvaris & Shoemaker [1405.1729,1509.08720]

DAMA [1505.05336]

Attenuation of DM flux: $f(\mathbf{v}) \rightarrow f_0(\mathbf{v}) - f_A(\mathbf{v})$

Earth Shadowing



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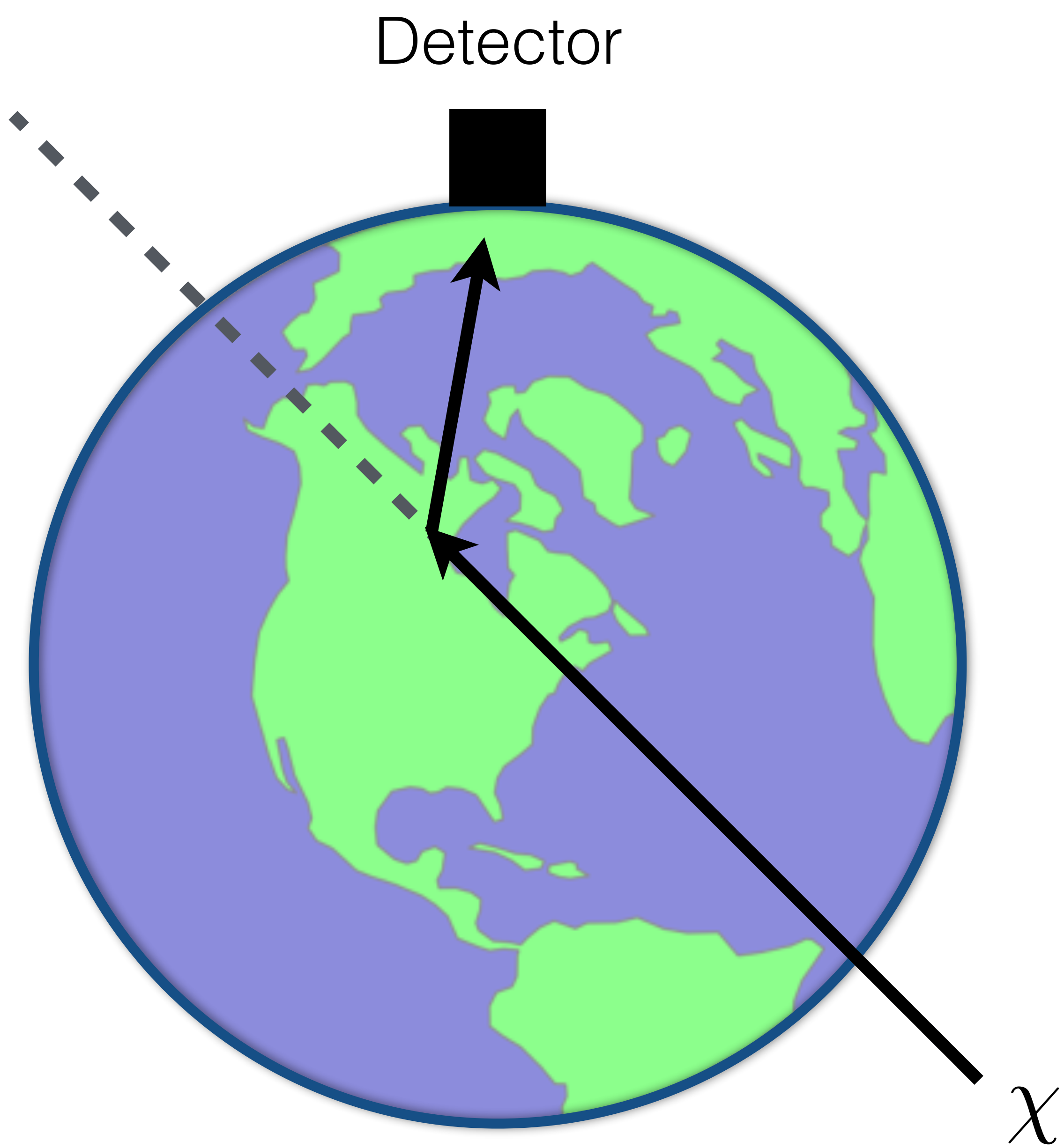
Earth Shadowing



Assuming DM mean free path

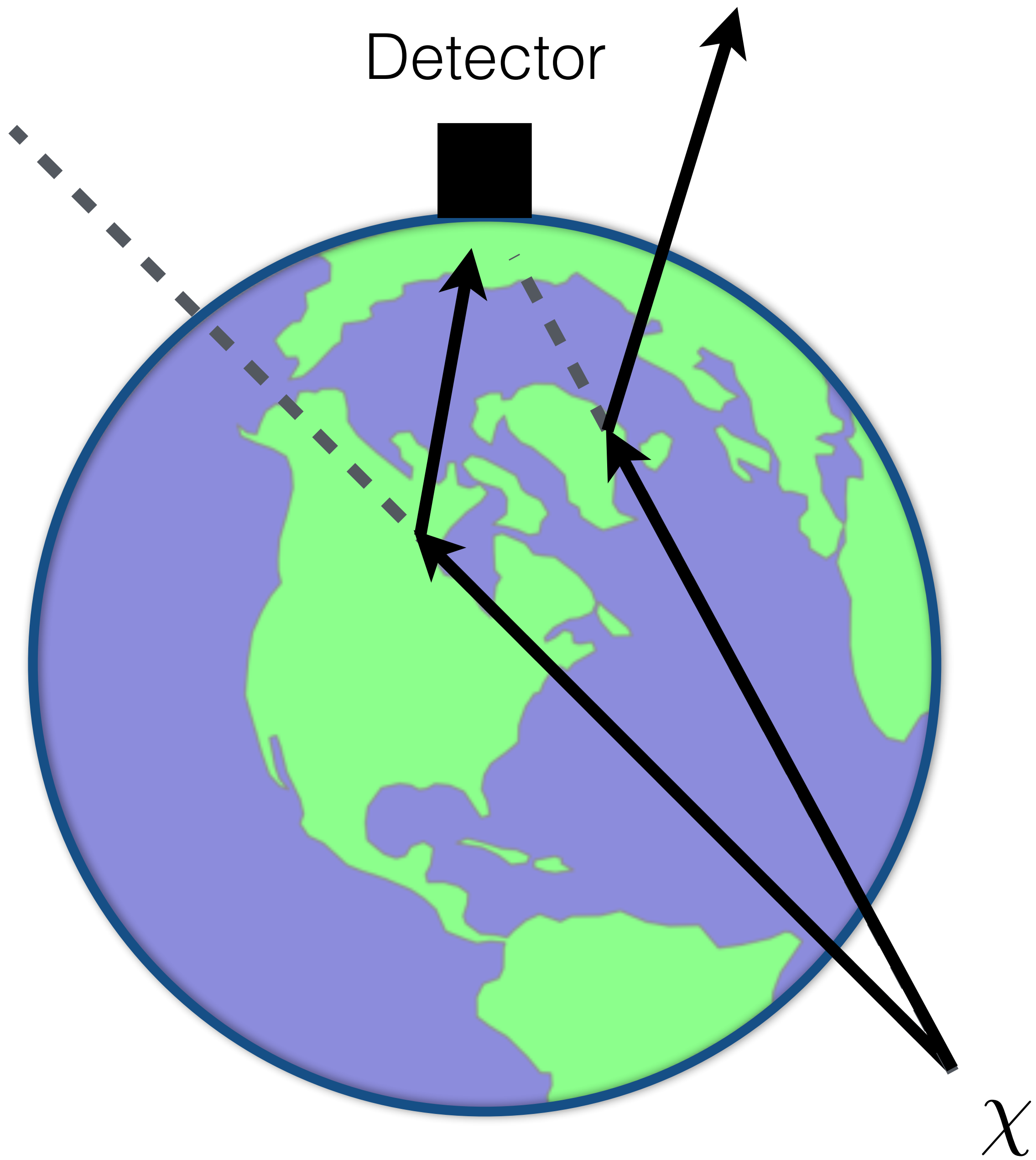
$$\lambda \gtrsim R_E$$

Considered in early Monte Carlo simulations

Collar & Avignone [PLB 275, 1992 and others]

Enhancement of DM flux: $f(\mathbf{v}) \rightarrow f_0(\mathbf{v}) + f_D(\mathbf{v})$

Earth Shadowing



Assuming DM mean free path

$$\lambda \gtrsim R_E$$

Total DM velocity distribution: $f(\mathbf{v}) = f_0(\mathbf{v}) - f_A(\mathbf{v}) + f_D(\mathbf{v})$

→ altered flux, daily modulation, directionality…

Earth scattering calculation

Total DM velocity distribution: $f(\mathbf{v}) = f_0(\mathbf{v}) - f_A(\mathbf{v}) + f_D(\mathbf{v})$

- Calculate perturbed DM velocity distribution analytically to first order in R_E/λ ('Single scatter' approximation)
- Include both contributions to DM flux (both attenuation and deflection)
- Include 9 most abundance elements in the Earth (O, Si, Mg, Fe, Ca, Na, S, Ni, Al)
- Include radial density profile $n_i(r)$ of nuclei in the Earth
- Calculate for 14 non-relativistic DM-nucleon interactions (not just standard SI/SD)
- Valid for all DM masses (but focus for now on light DM)
- Public code to be released

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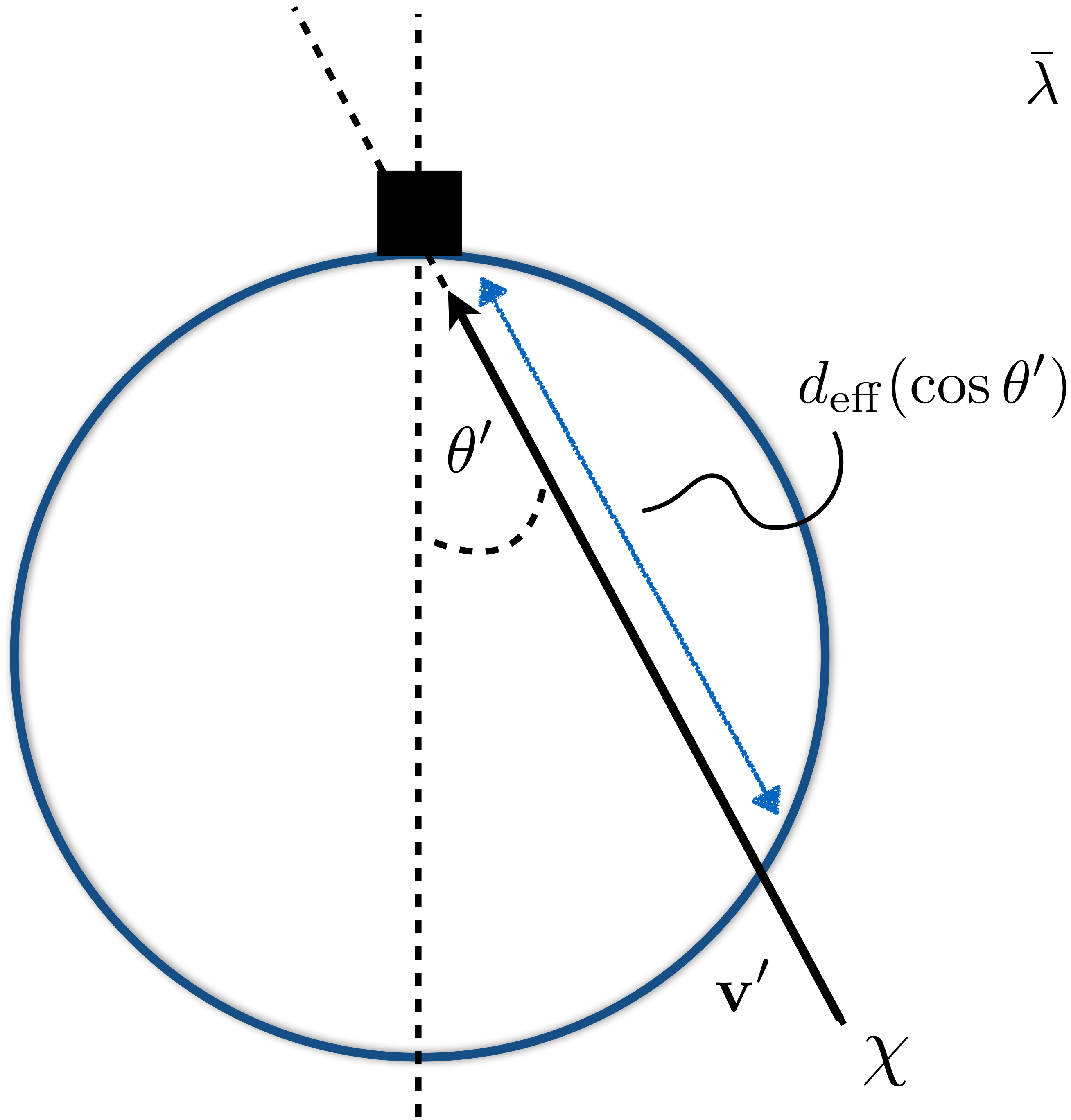
A sketch of the calculation…

DM attenuation

$\mathbf{v}' = (v', \cos\theta', \phi')$

$\bar{\lambda} = (\sigma \bar{n})^{-1}$



Sum over
Earth nuclei

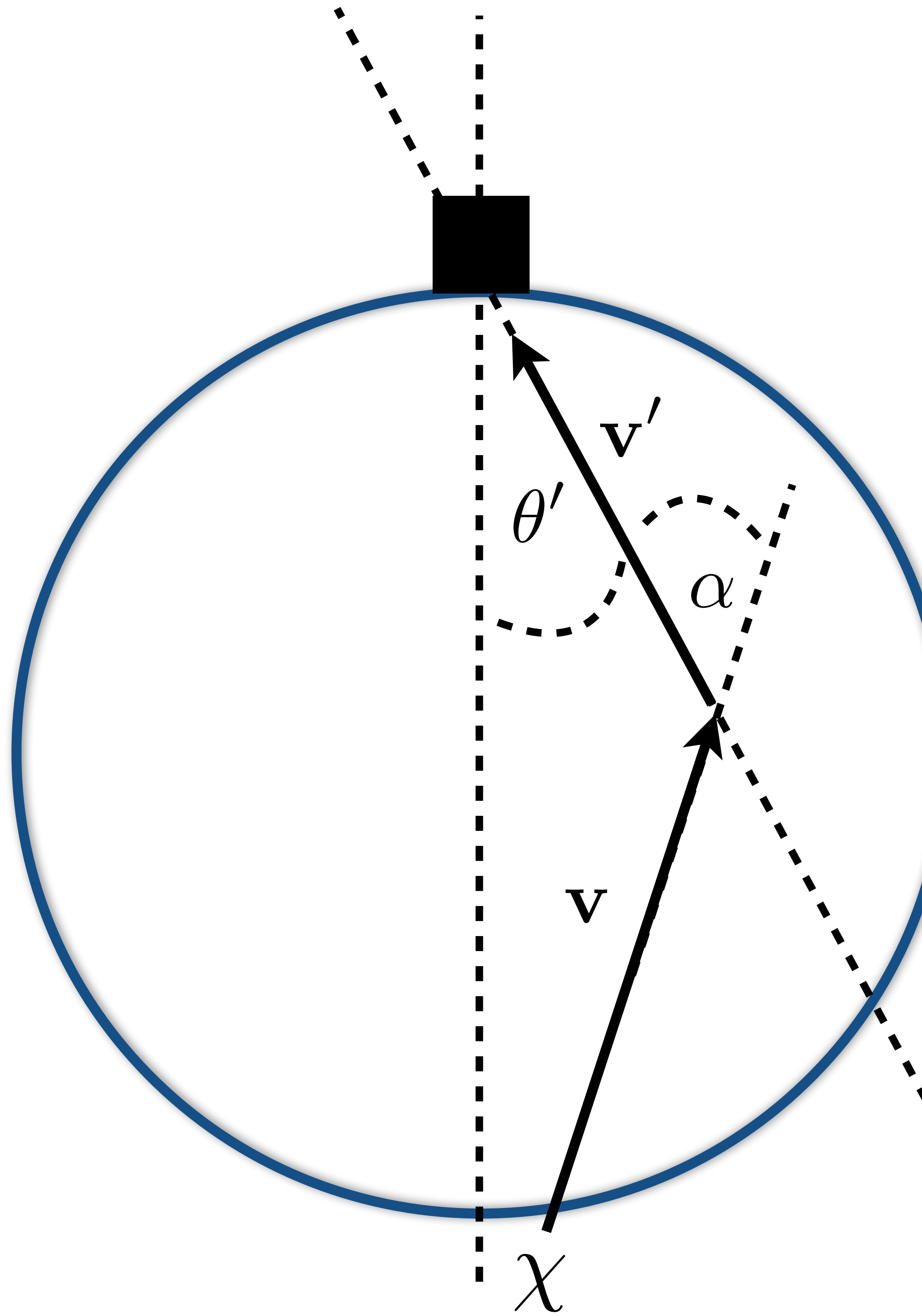
$$f_0(\mathbf{v}') - f_A(\mathbf{v}') = f_0(\mathbf{v}')\, \exp\left[-\frac{d_{\rm eff}(\cos\theta')}{\bar{\lambda}(v')}\right]$$

DM deflection

$\mathbf{v}' = (v', \cos\theta', \phi')$

$\mathbf{v} = (v, \cos\theta, \phi)$

$\bar{\lambda} = (\sigma \bar{n})^{-1}$



$\kappa = v/v'$
fixed by kinematics

$$f_D(\mathbf{v}') = \int_{-1}^{1} \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \, \frac{d_{\mathrm{eff}}(\cos\theta')}{\bar{\lambda}(\kappa v')} \frac{(\kappa)^4}{2\pi} P(\cos\alpha) \, f(\kappa v', \cos\theta, \phi)$$

DM deflection

$$\mathbf{v}' = (v', \cos\theta', \phi')$$

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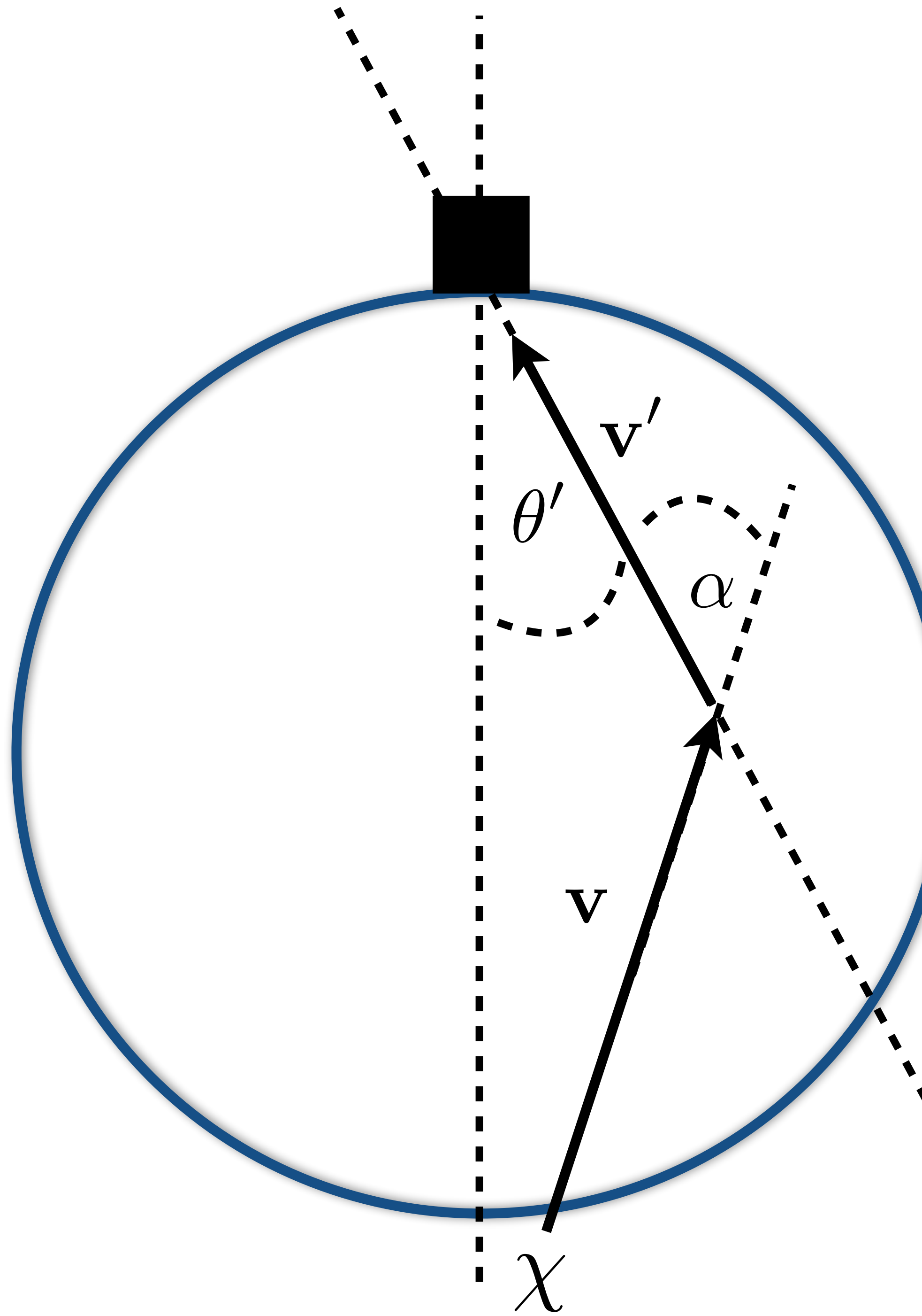

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DM-nucleon operators

In order to obtain $P(\cos\alpha)$, we need to know $\mathrm{d}\sigma/\mathrm{d}E_R$.

Consider different possible operators in a non-relativistic EFT (NREFT) framework :

Fitzpatrick et al. [1203.3542]

Construct interactions from relevant NR degrees of freedom:

$$\vec{S}_\chi\,, \quad \vec{S}_N, \quad \frac{\vec{q}}{m_N}\,, \quad \vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}}$$

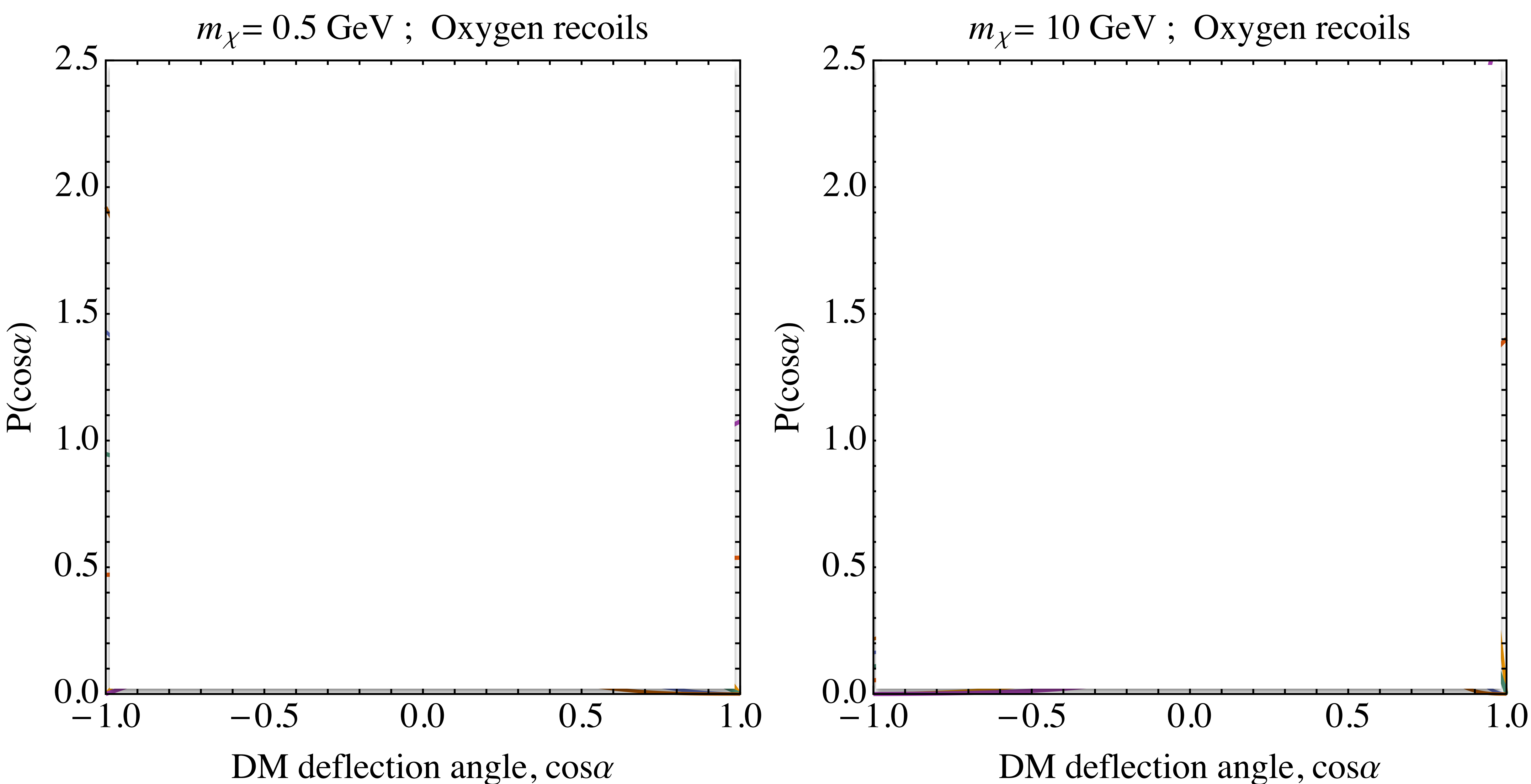
Standard spin-independent operator: $\mathcal{O}_1 = 1$

Standard spin-dependent operator: $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

But we can construct operators higher-order in $\vec{v}$ and $\vec{q}$ …

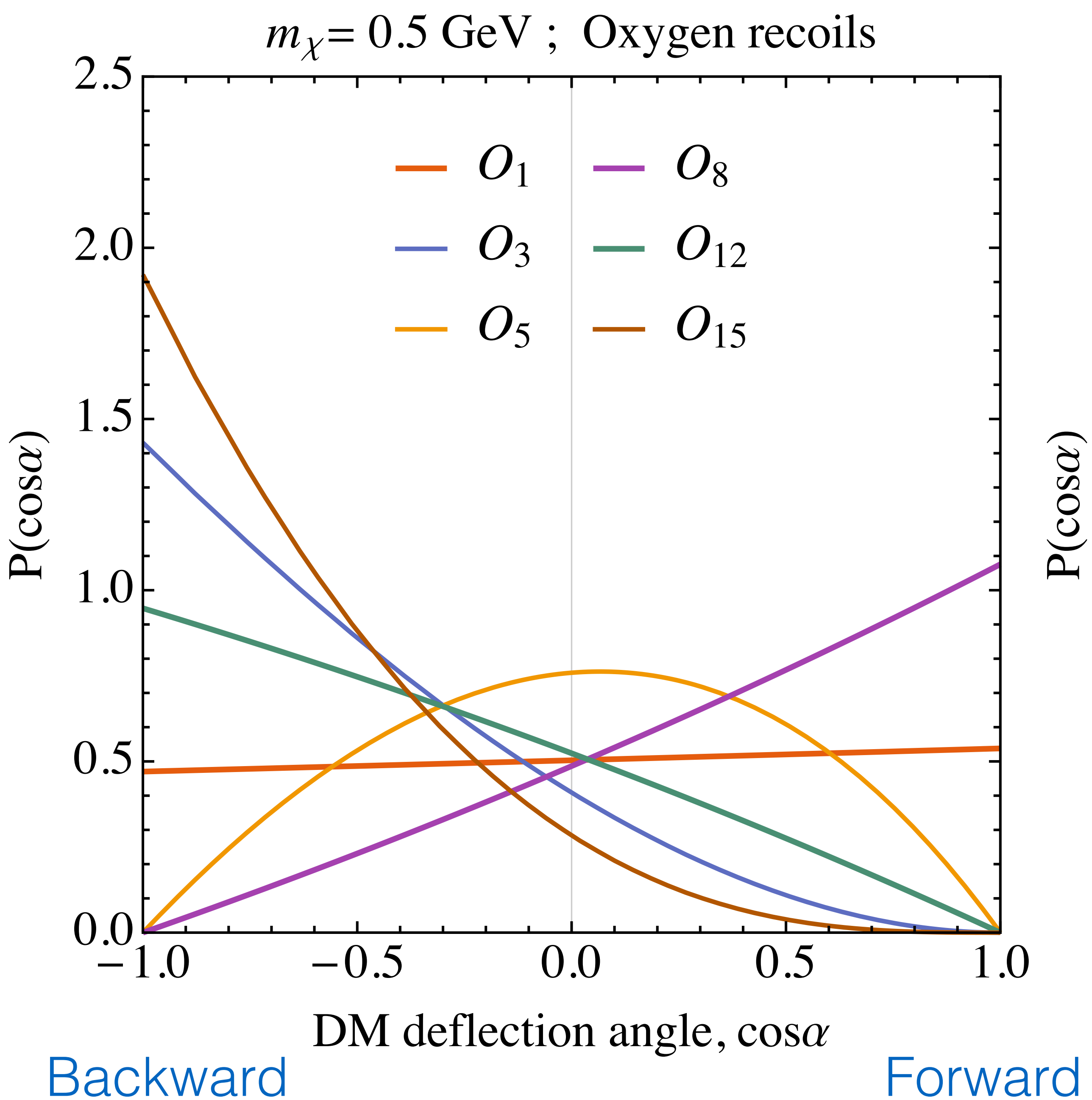
[1008.1591, 1203.3542, 1308.6288, 1505.03117]

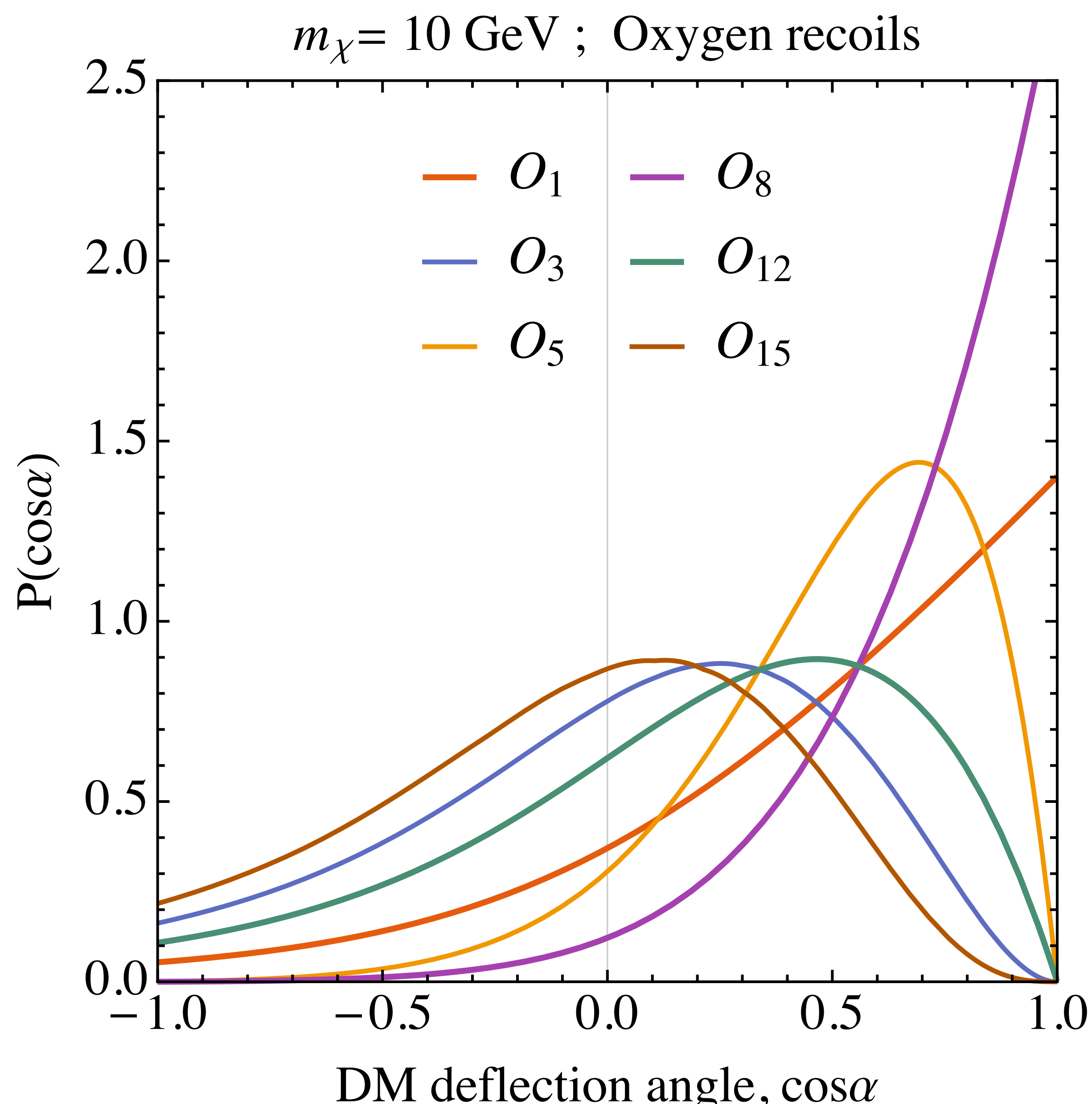
DM deflection



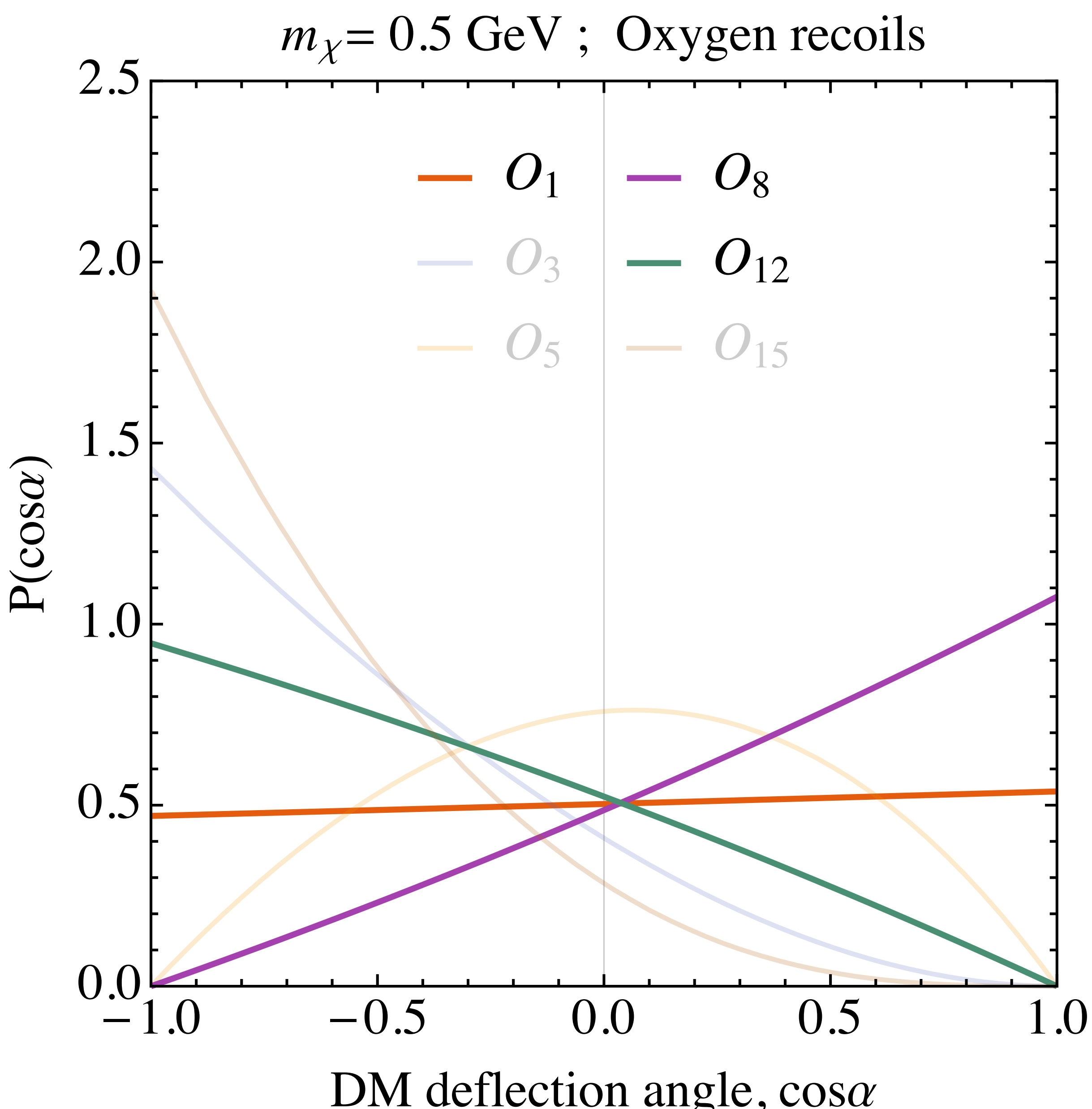
Backward Forward

DM deflection





DM deflection



Backward

Forward

Standard SI

$$\mathcal{O}_1 = \mathbb{1} \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim \frac{1}{v^2}$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim (1 - \frac{m_\mathcal{N} E_R}{2\mu_{\chi\mathcal{N}}^2 v^2})$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp) \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim \frac{E_R}{v^2}$$

Preliminary Results

- Focus on low mass DM (for now): $m_\chi = 0.5\ \mathrm{GeV}$
- Fix cross section such that average probability of DM scatter in the Earth is 10% (well below current limits for all operators considered)
- Look at DM speed distribution…

$$F(v) = v^2 \oint f(\mathbf{v})\,\mathrm{d}\Omega_v$$

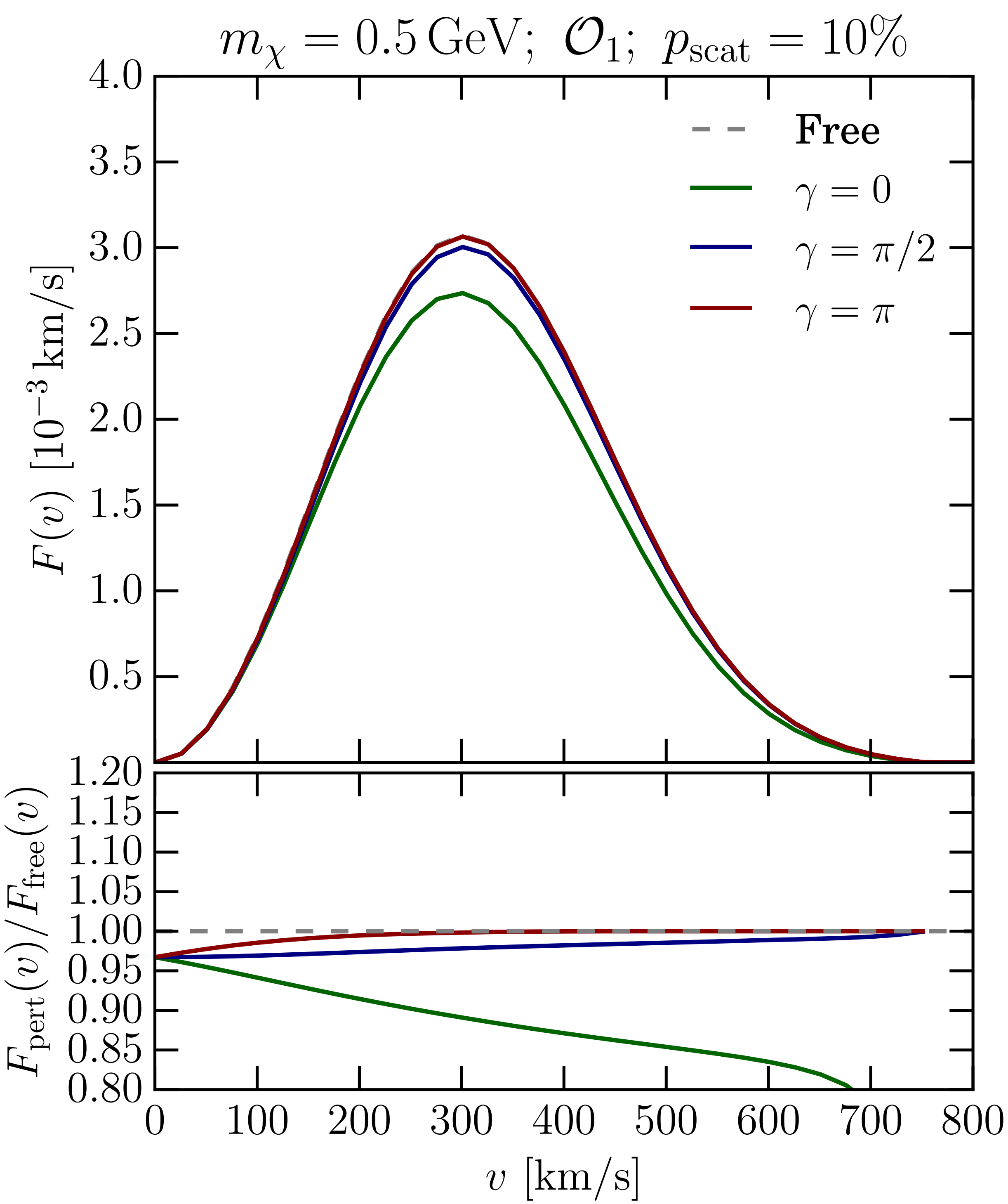
- … and differential event rate (in CRESST-II) [1601.04447]

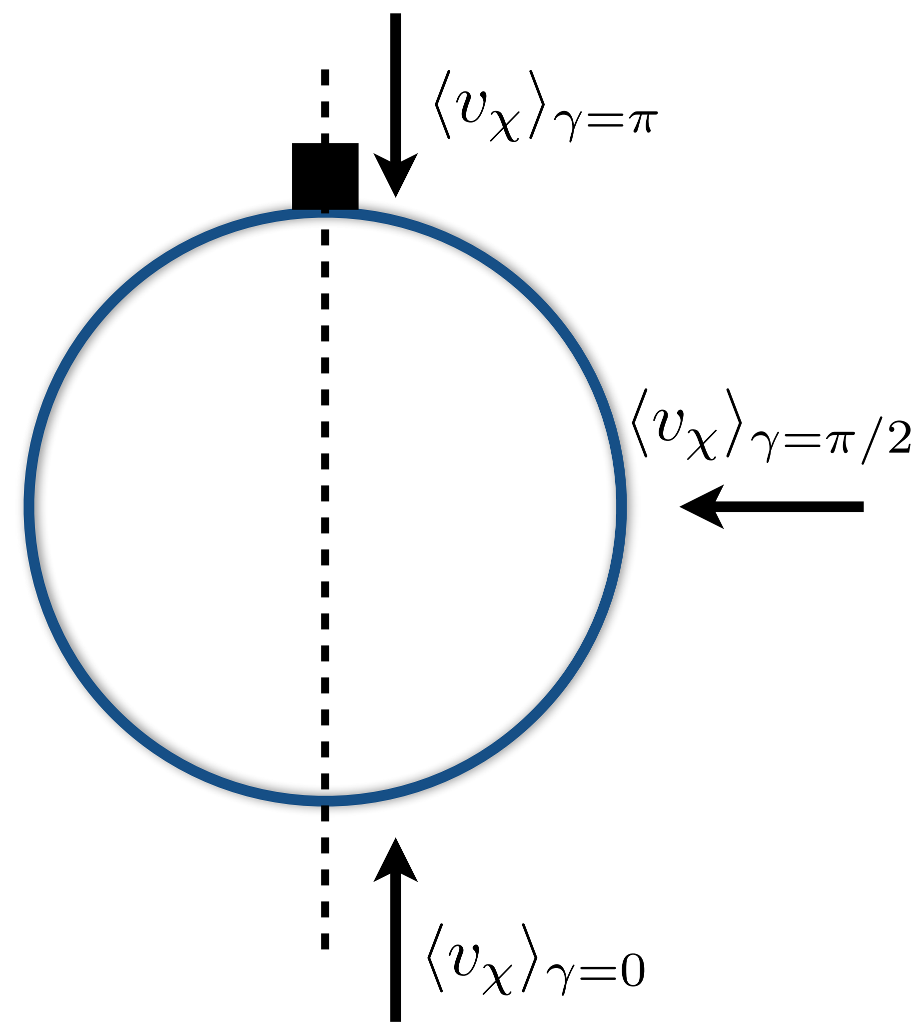
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \int_{v_{\mathrm{min}}}^{\infty} vF(v)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\,\mathrm{d}v$$

- For different DM-nucleon operators and different average incoming DM directions (denoted by the angle γ) corresponding to different detector positions and times

Operator 1 - attenuation only

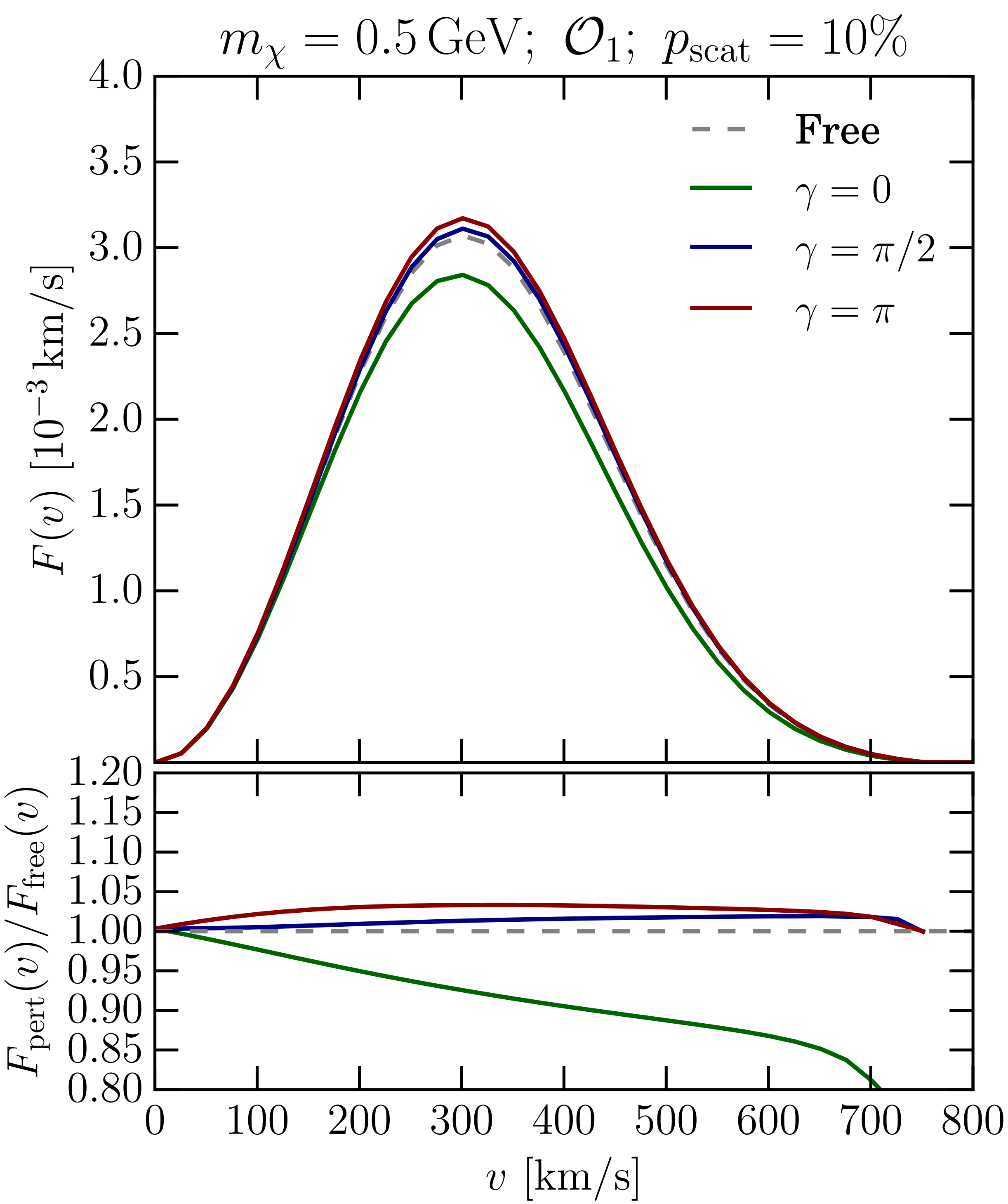
$\mathcal{O}_1 = \mathbb{1}$ → Isotropic deflection

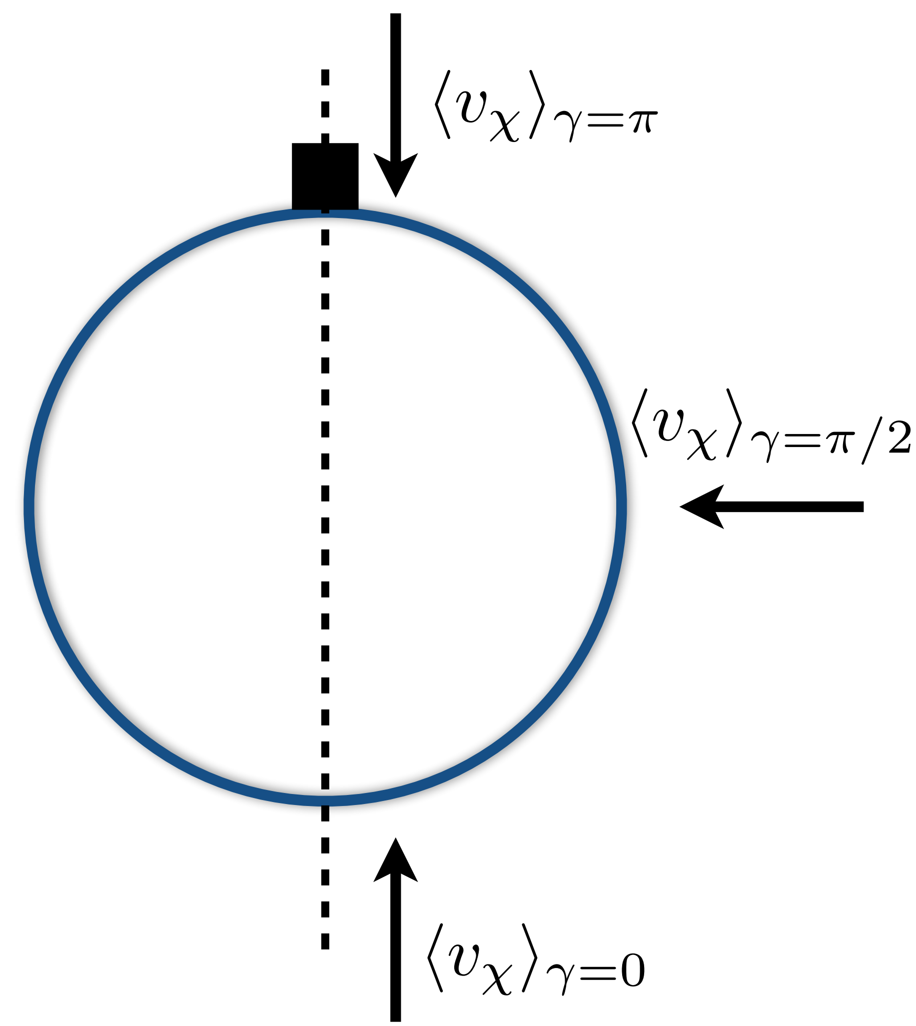




Operator 1 - attenuation + deflection

$\mathcal{O}_1 = \mathbb{1}$ → Isotropic deflection





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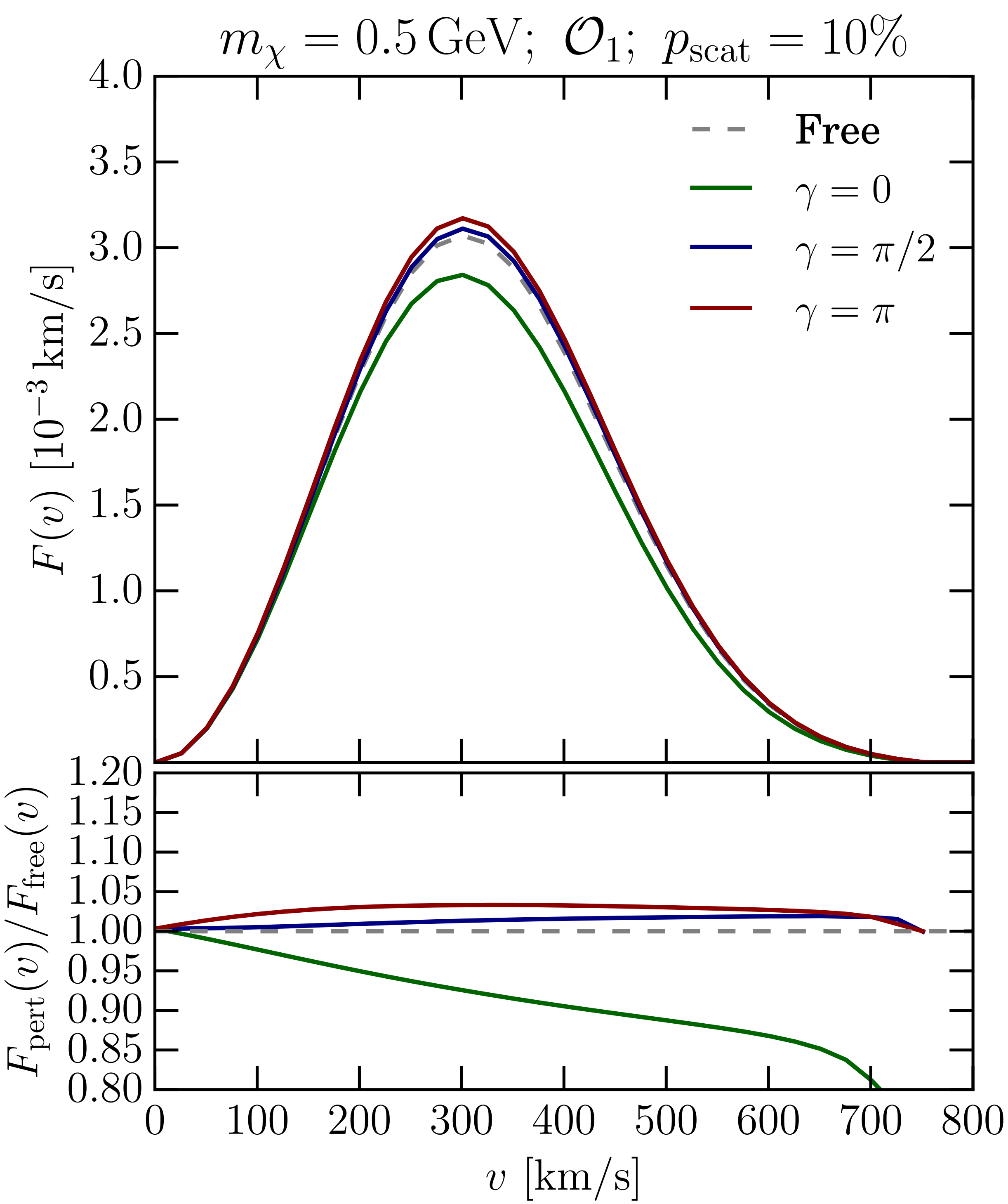
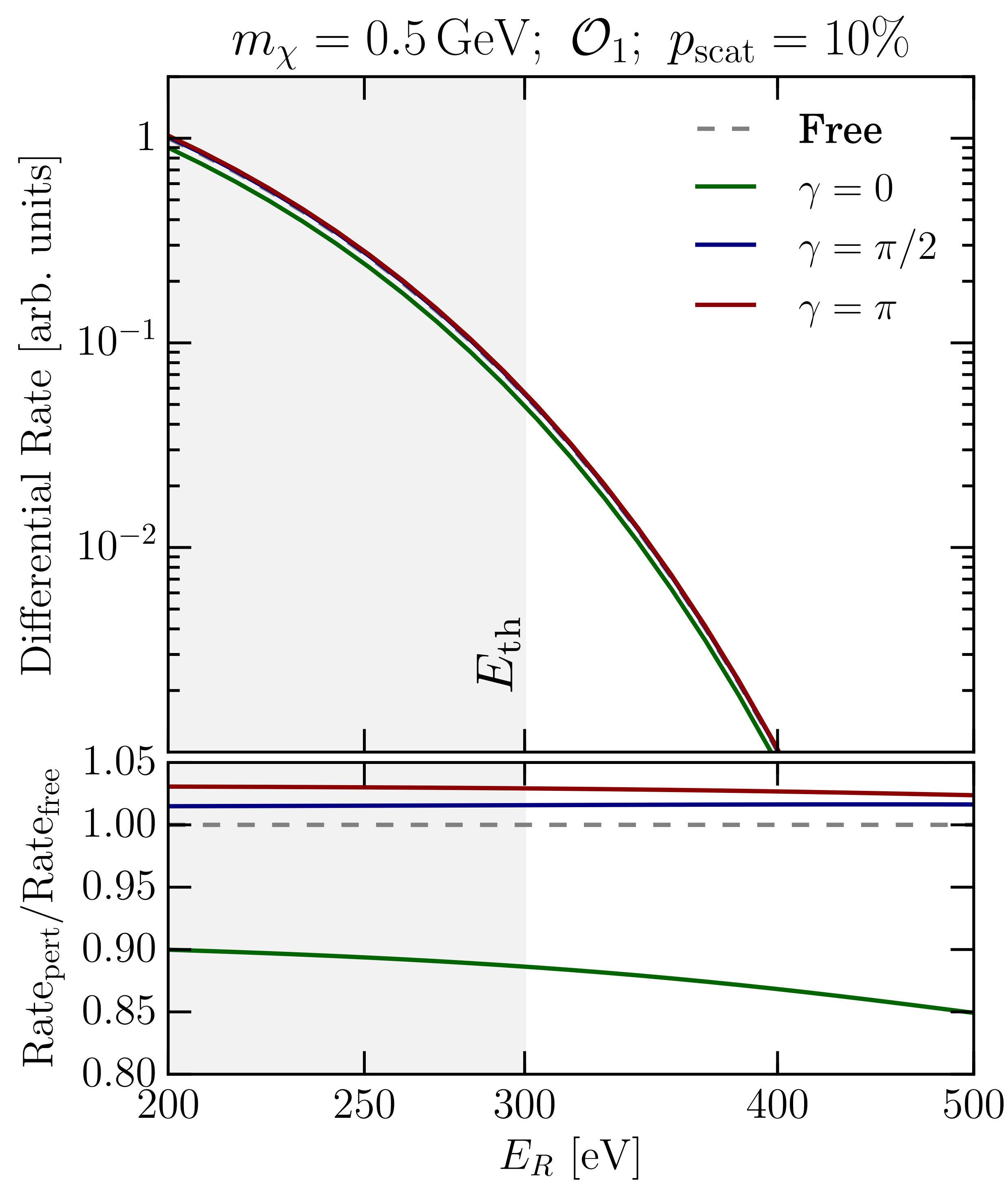
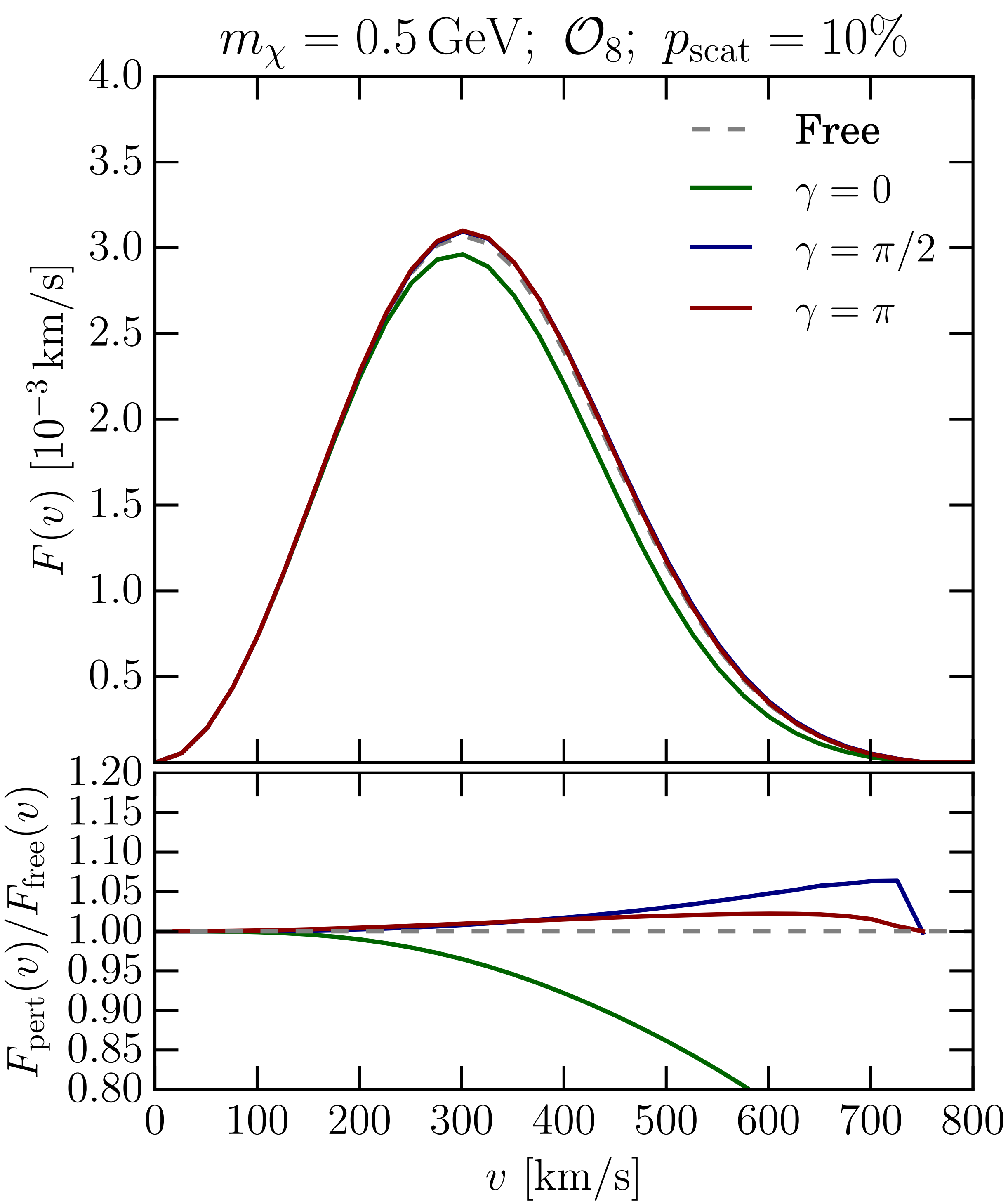
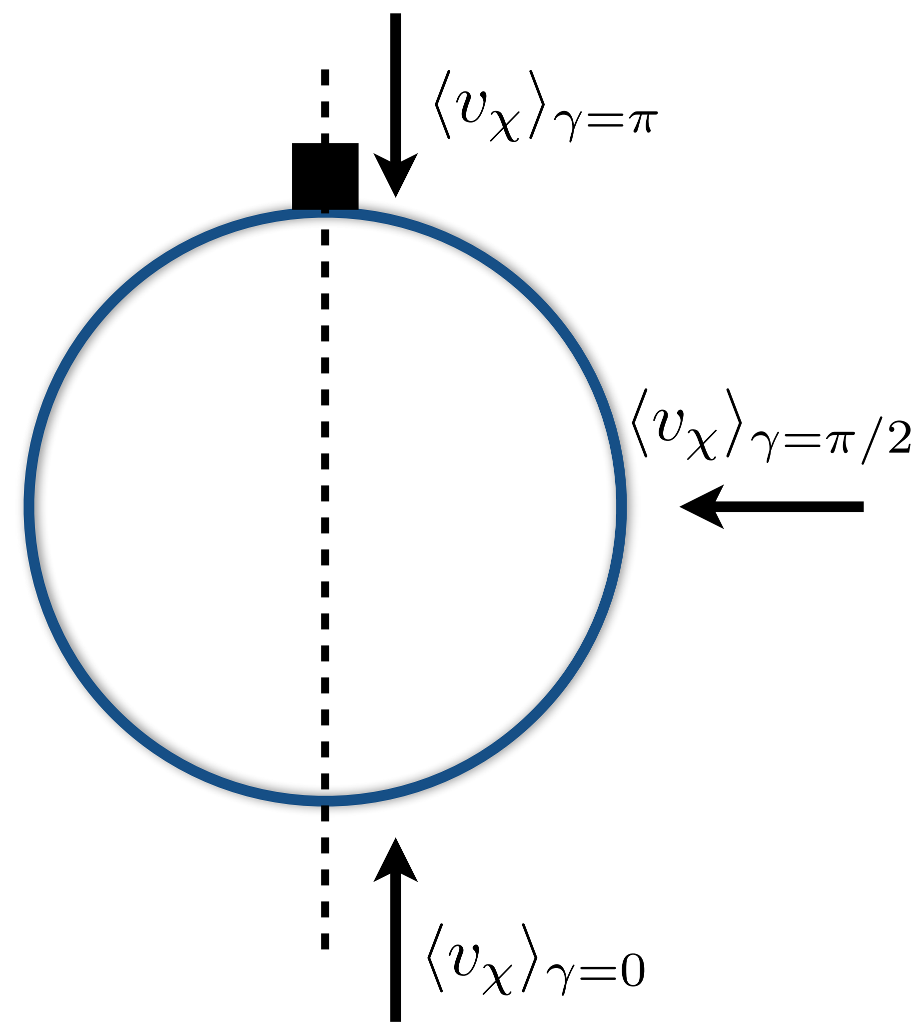




Operator 8 - attenuation + deflection

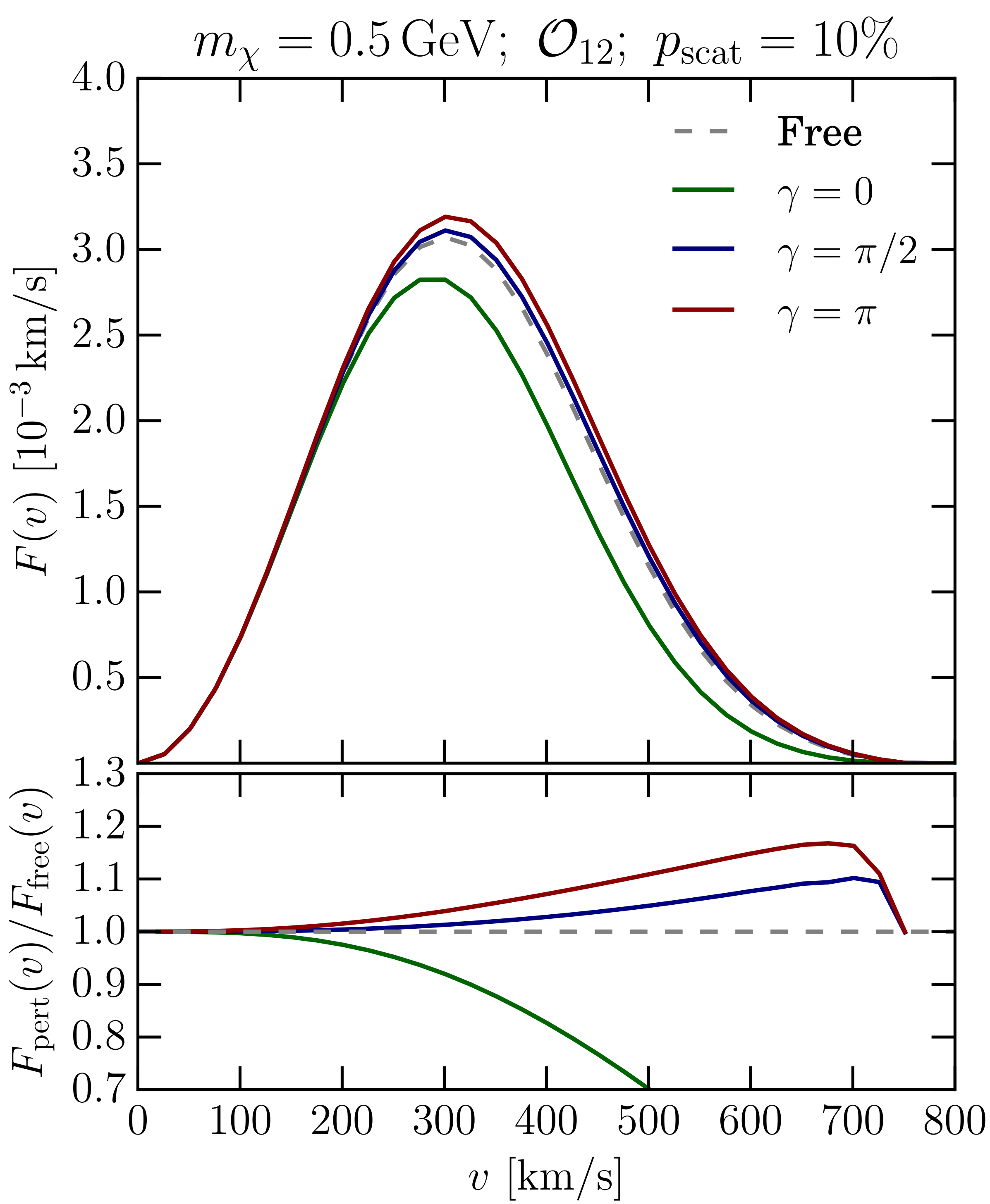
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$ → Mostly forward deflection

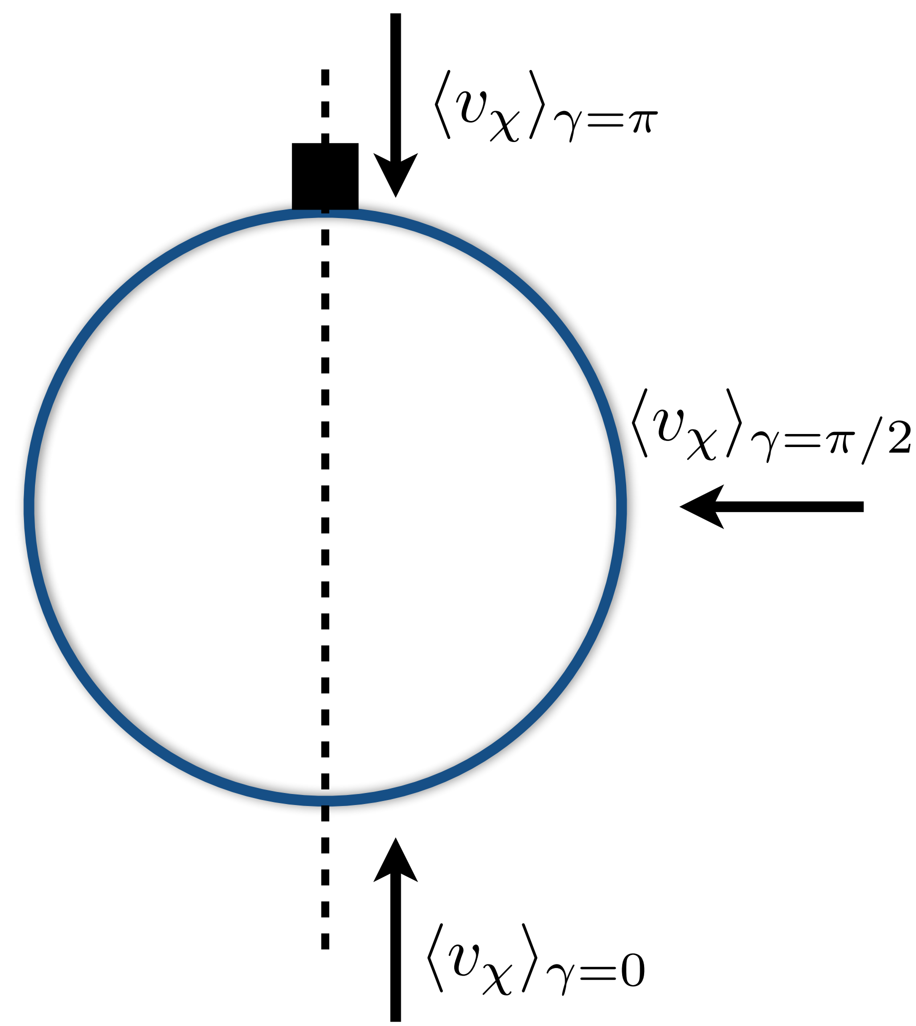




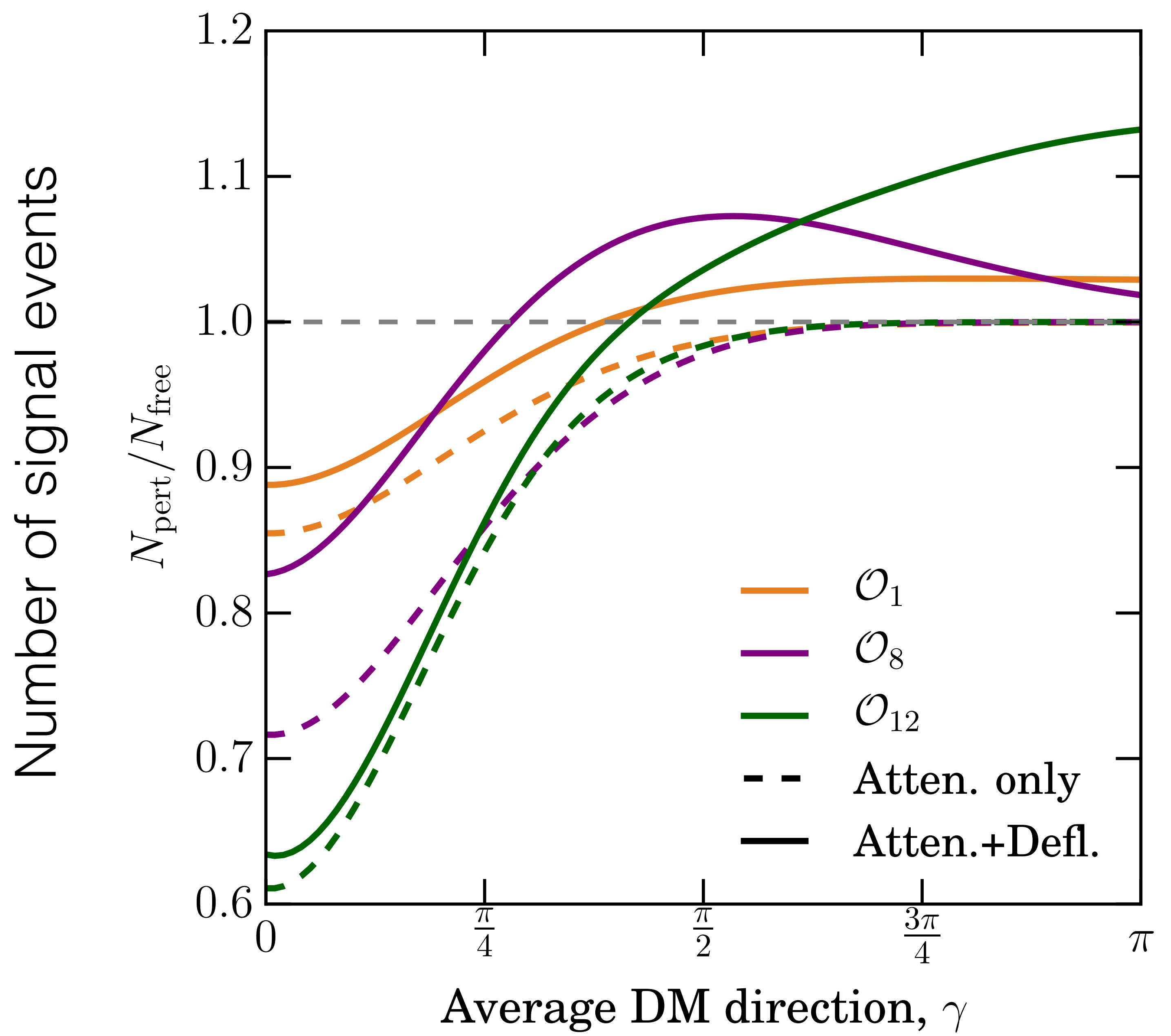
Operator 12 - attenuation + deflection

$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$ → Mostly backward deflection



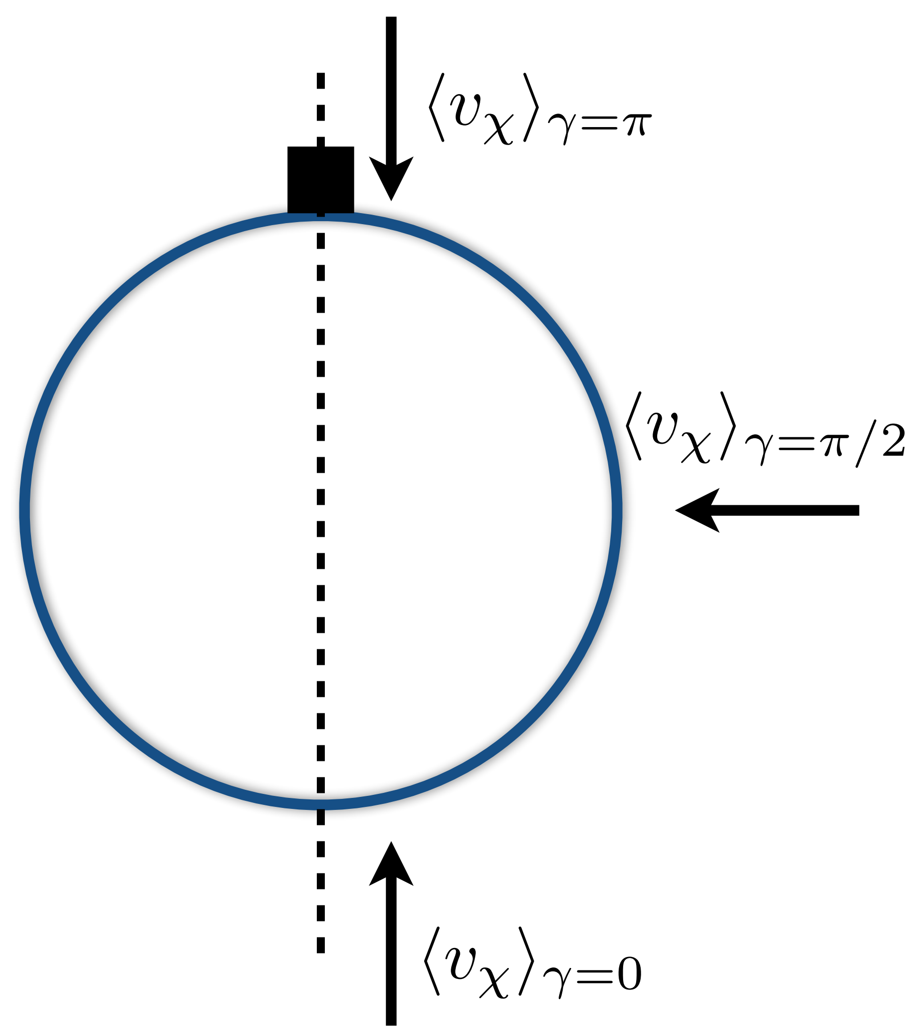


Modulation signal



$m_\chi = 0.5$ GeV

$p_{scat} = 10\%$



Modulation due to time-variation of γ

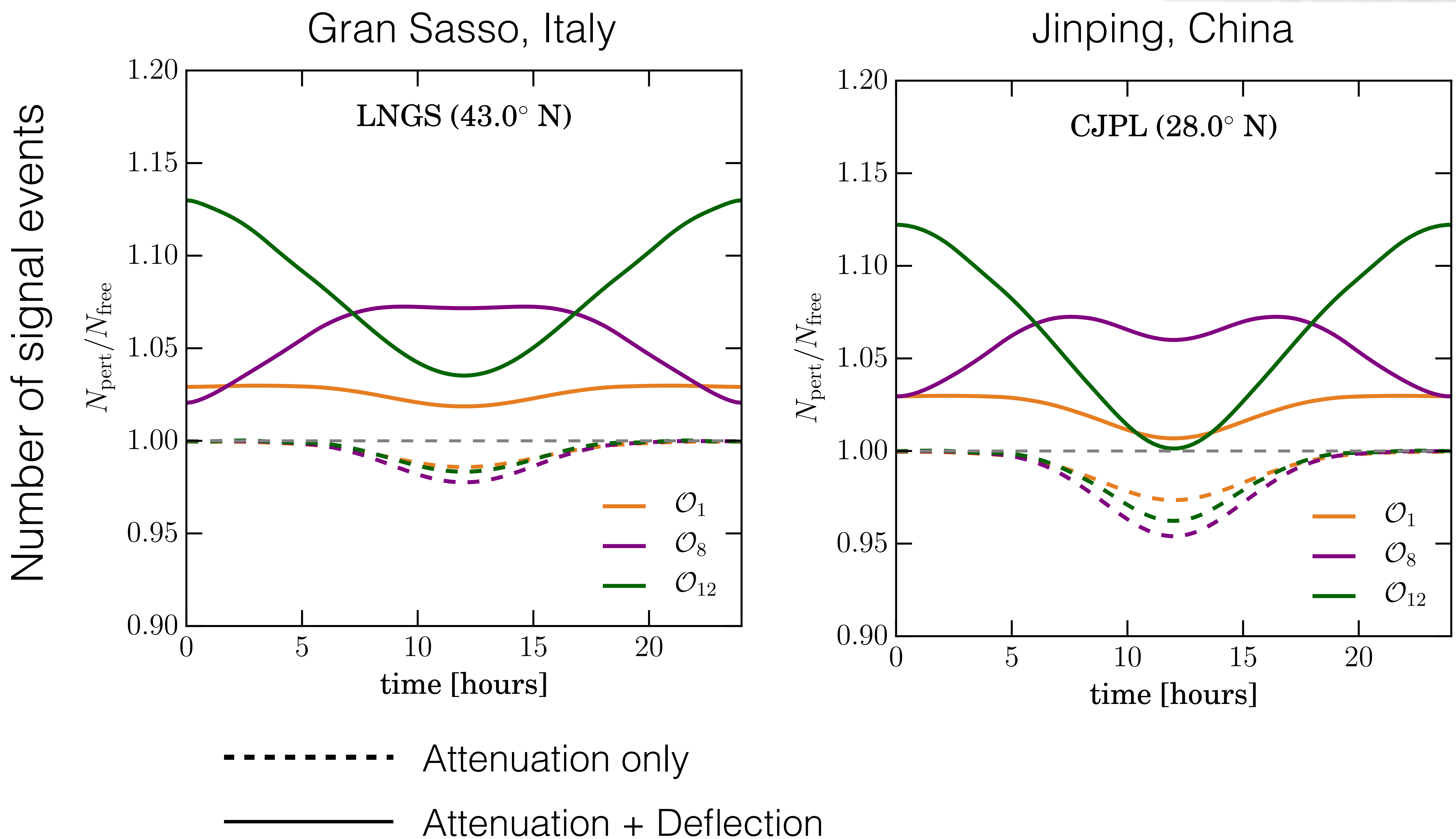
→ Different phase for different interactions!

Modulation signal

Need to calculate γ as
a function of time and location:

$m_\chi = 0.5$ GeV

$p_{\rm scat} = 10\%$



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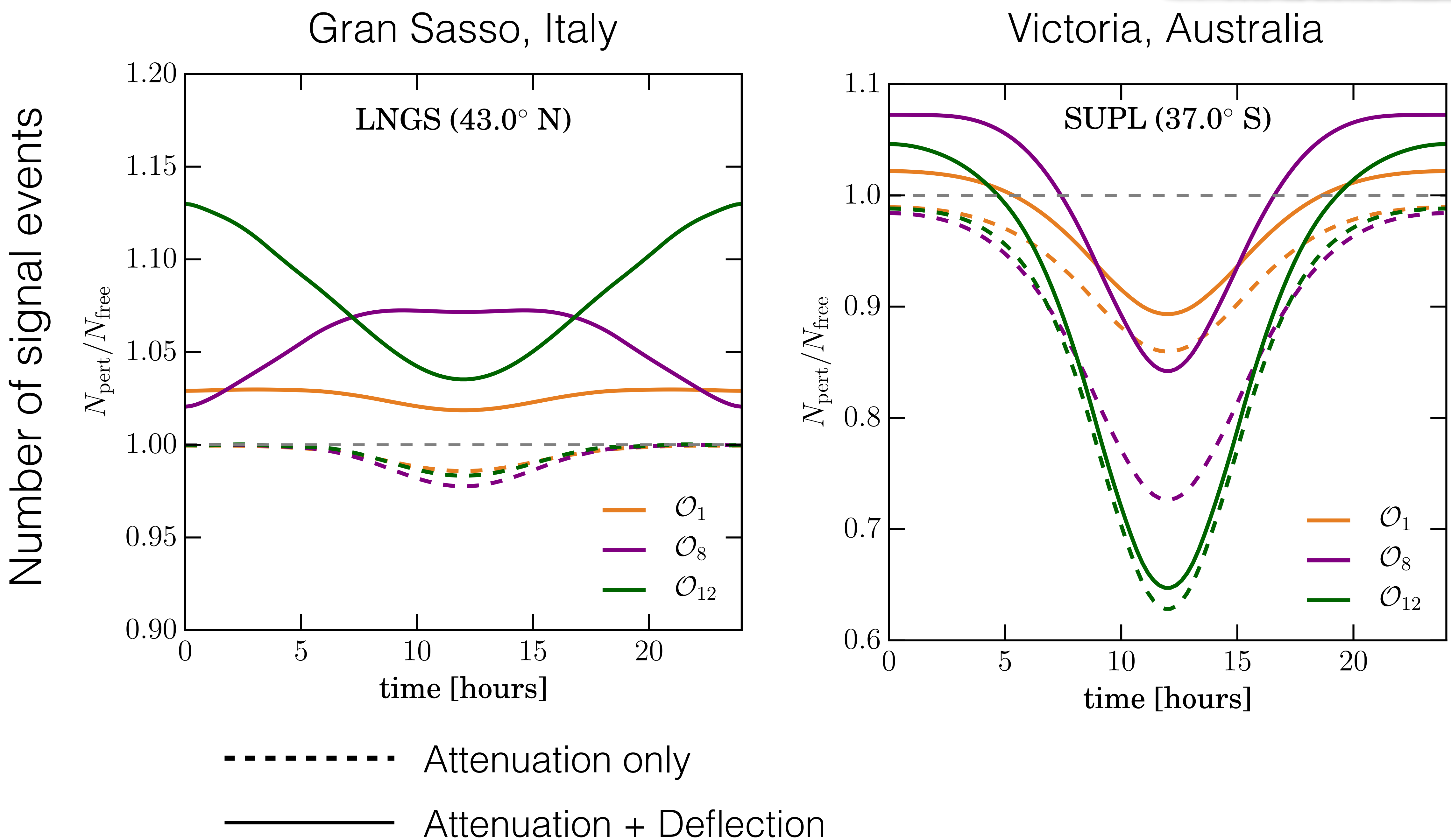


Signatures

- Overall change in the DM flux (depending on detector location)
- Daily modulation signal as DM direction (in the detector frame) varies with Earth's rotation
- Annual modulation signal as DM direction varies with the Earth's orbit [not shown here…]
- Effects are latitude-dependent - could cross check with detectors in different locations
- Look at directional rate - expect up-going flux to be decreased (increased) when the detector is maximally (minimally) shielded

Single-scatter Approximation

[With thanks to Pat Scott]

The Single-scatter approximation is important to capture the effects of deflection.

The limits don't always allow *very strongly* interacting DM, but…

…the single-scatter approximation will obviously break down as the interaction cross section increases. What then?

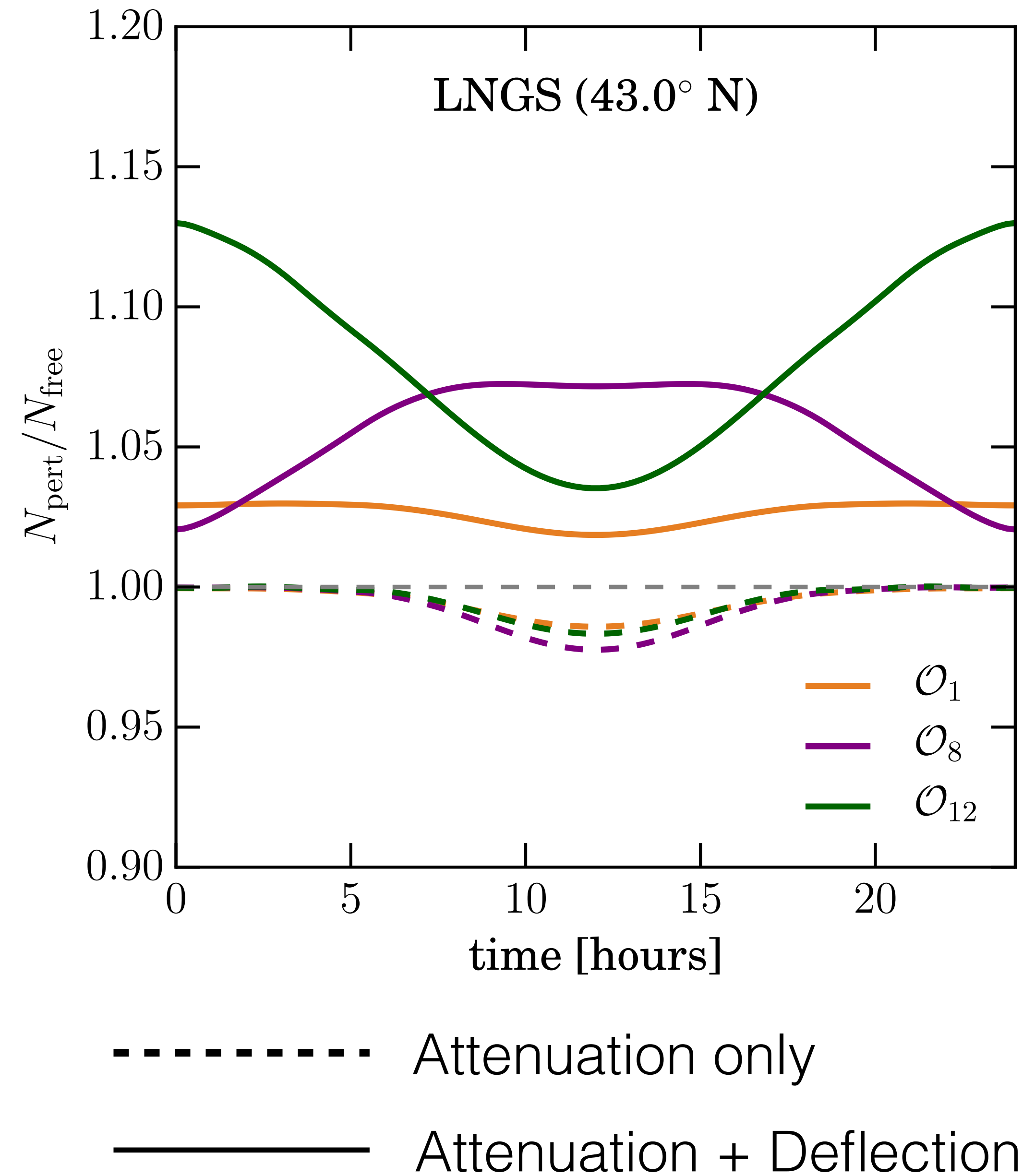
- Calculations in the many-scatter/'diffusion' regime
- Dedicated simulations to test the single-scatter regime and connect to very high cross sections
- For interactions which give DM deflection peaked in a particular direction, additional scatters will effectively broaden this distribution (may be able to account for this?)

Summary

- Significant Earth-scattering is still allowed and detectable by current experiments
- Need to include both attenuation and deflection of DM
- Careful calculation including multiple elements, correct density profiles and different interactions

- The average incoming DM direction varies with time - interesting daily and annual modulation signals
- Different interactions may lead to modulations with different phases - and may therefore be distinguishable
- Need to carefully calculate modulation, location dependence, directionality…and effects on current limits

Gran Sasso, Italy



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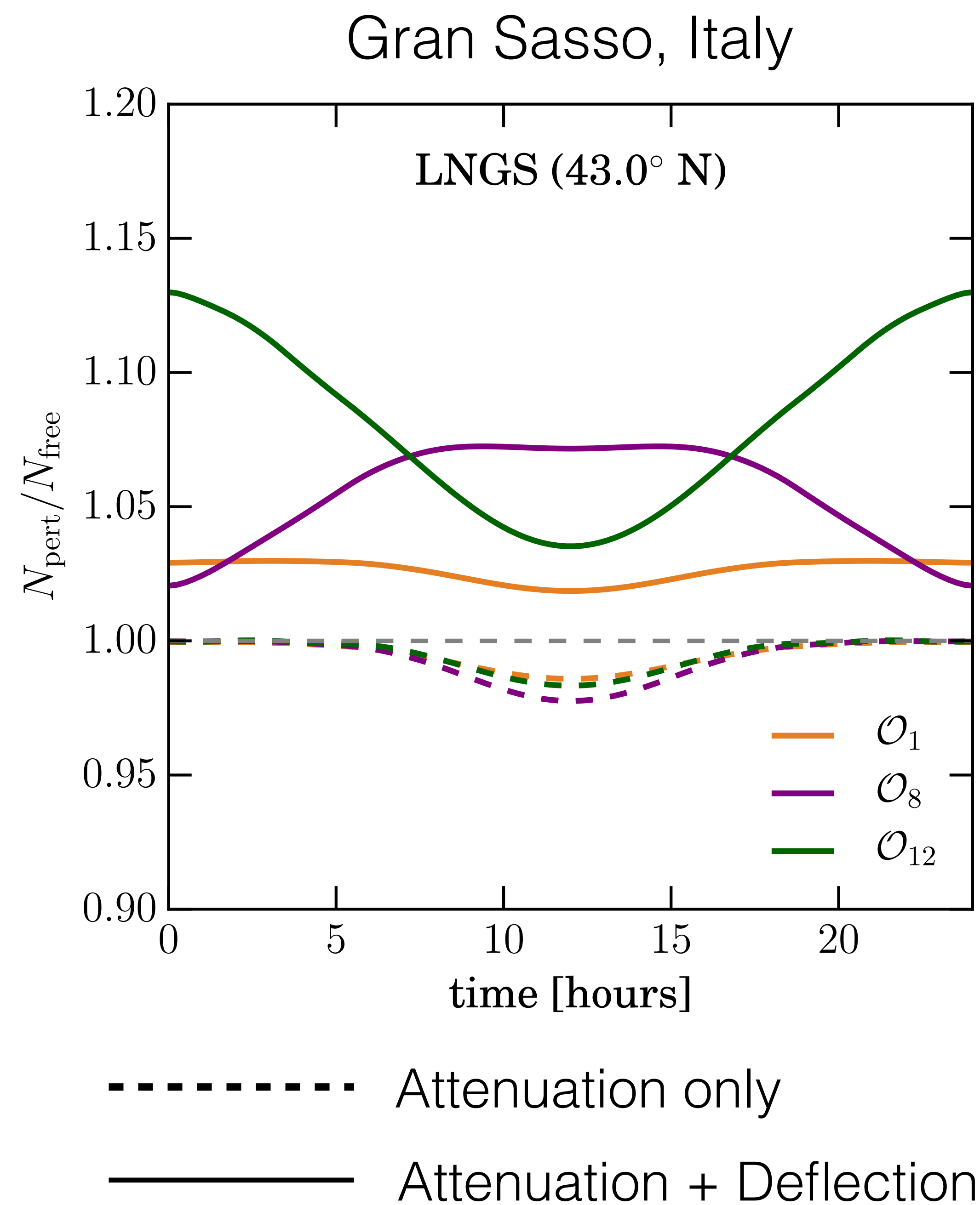
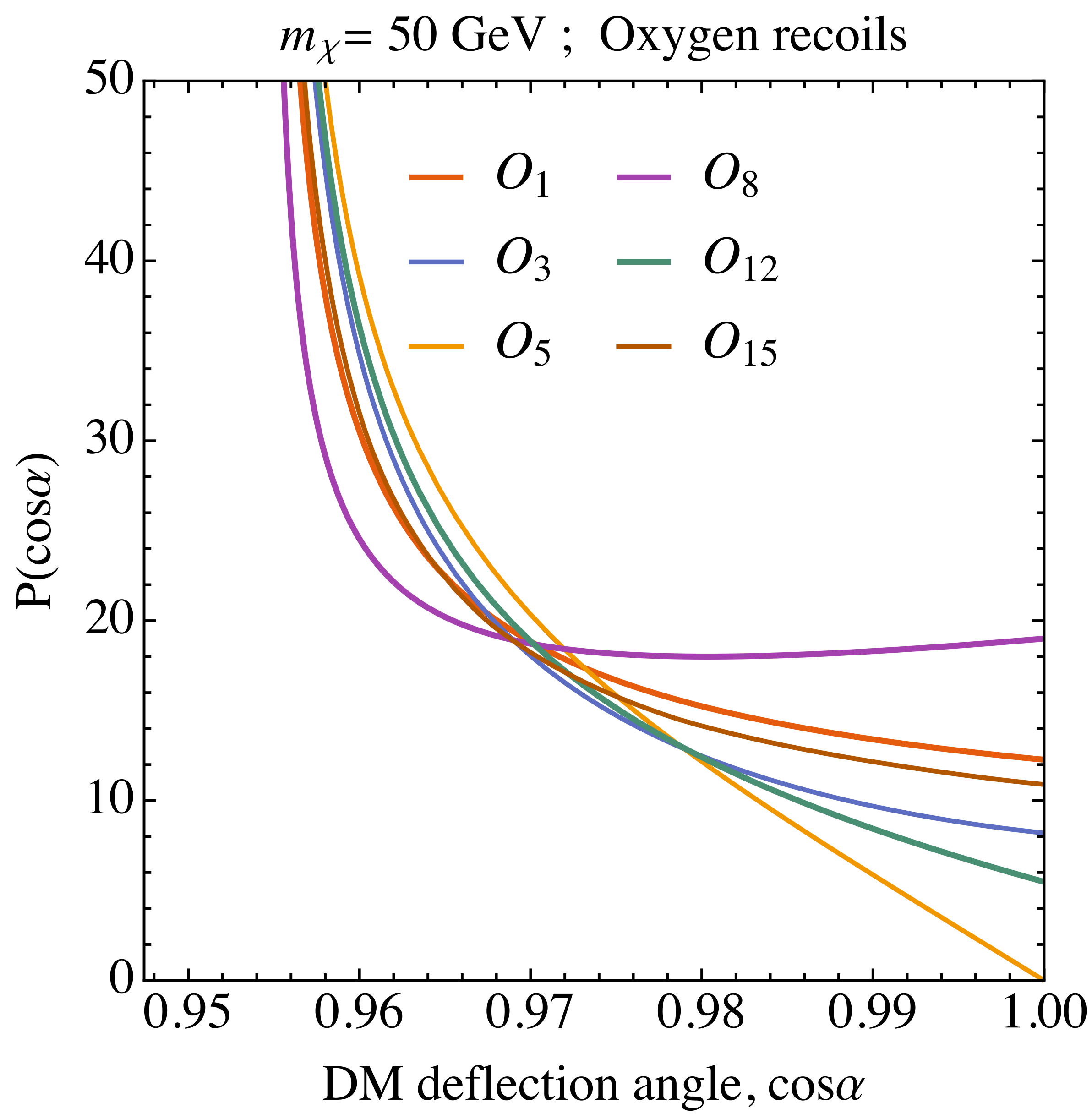


Thank you!

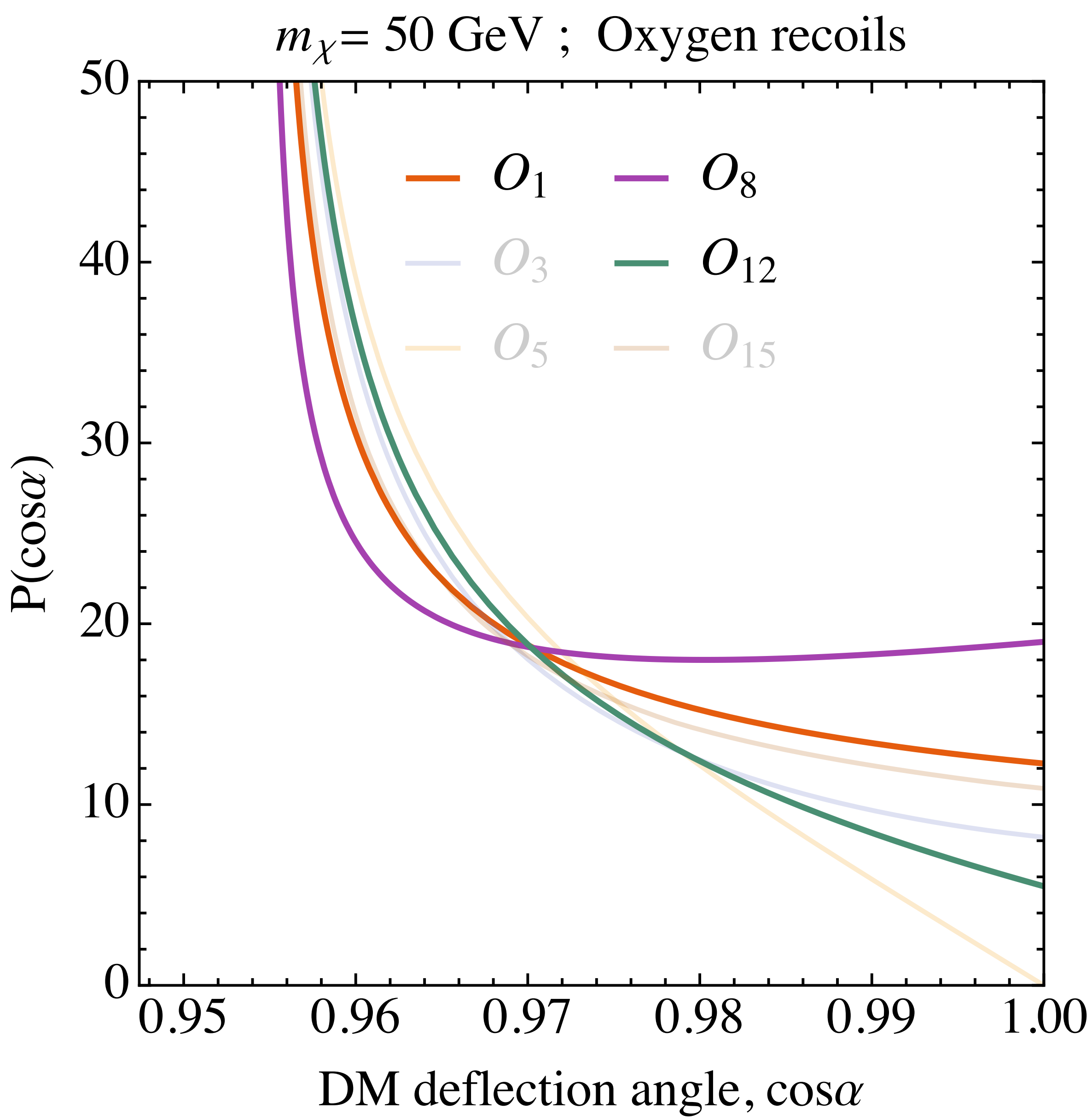
Backup Slides

Heavier DM



m_χ= 50 GeV ; Oxygen recoils
P(cosα)
DM deflection angle, cosα
0
10
20
30
40
50
0.95
0.96
0.97
0.98
0.99
1.00
O_1
O_3
O_5
O_8
O_{12}
O_{15}

Heavier DM



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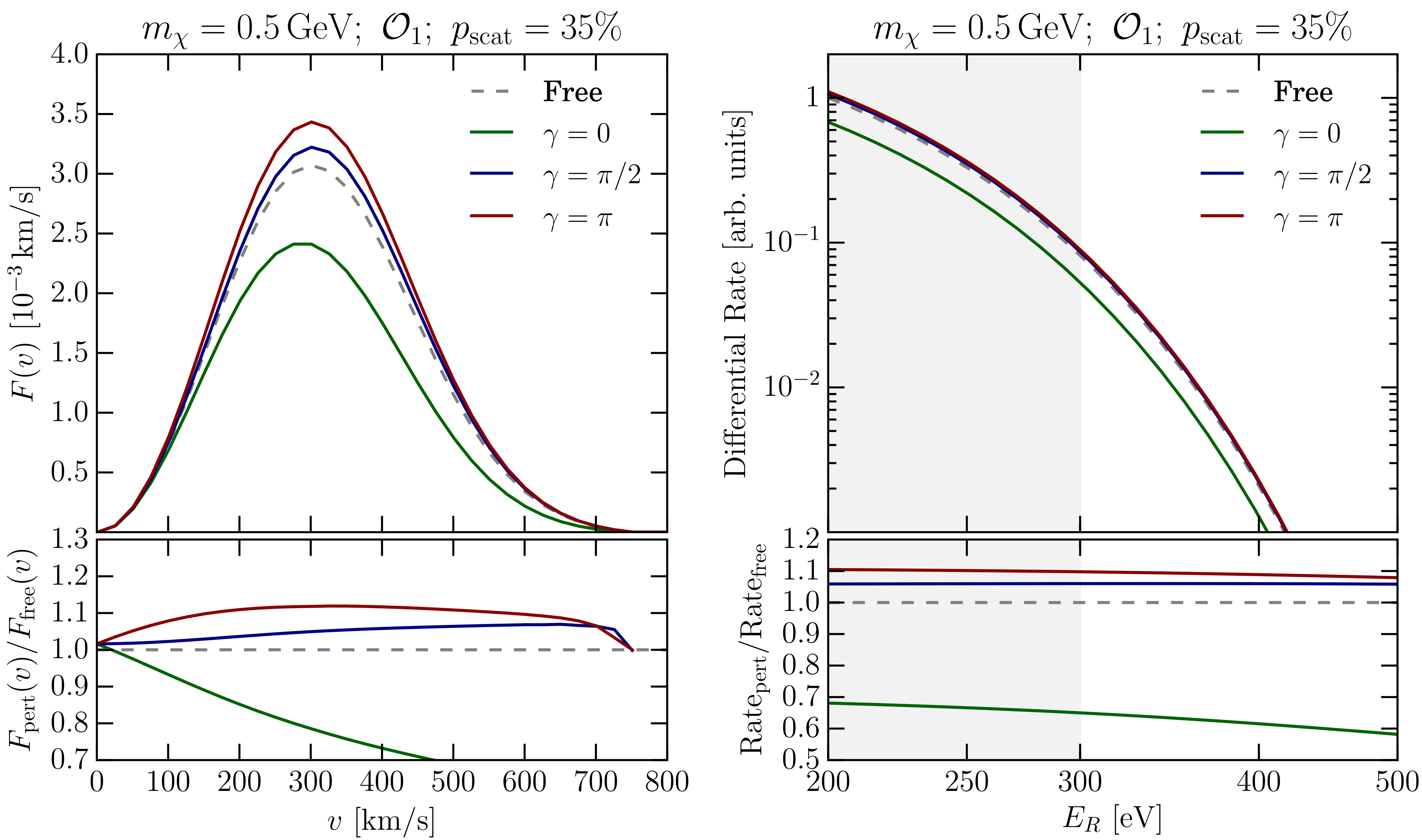
DM deflection angle, cosα
O_1
O_8
O_3
O_{12}
O_5
O_{15}

Maximum cross section



CRESST-II rate at the Equator