Looking for Dark Matter in the Earth's Shadow

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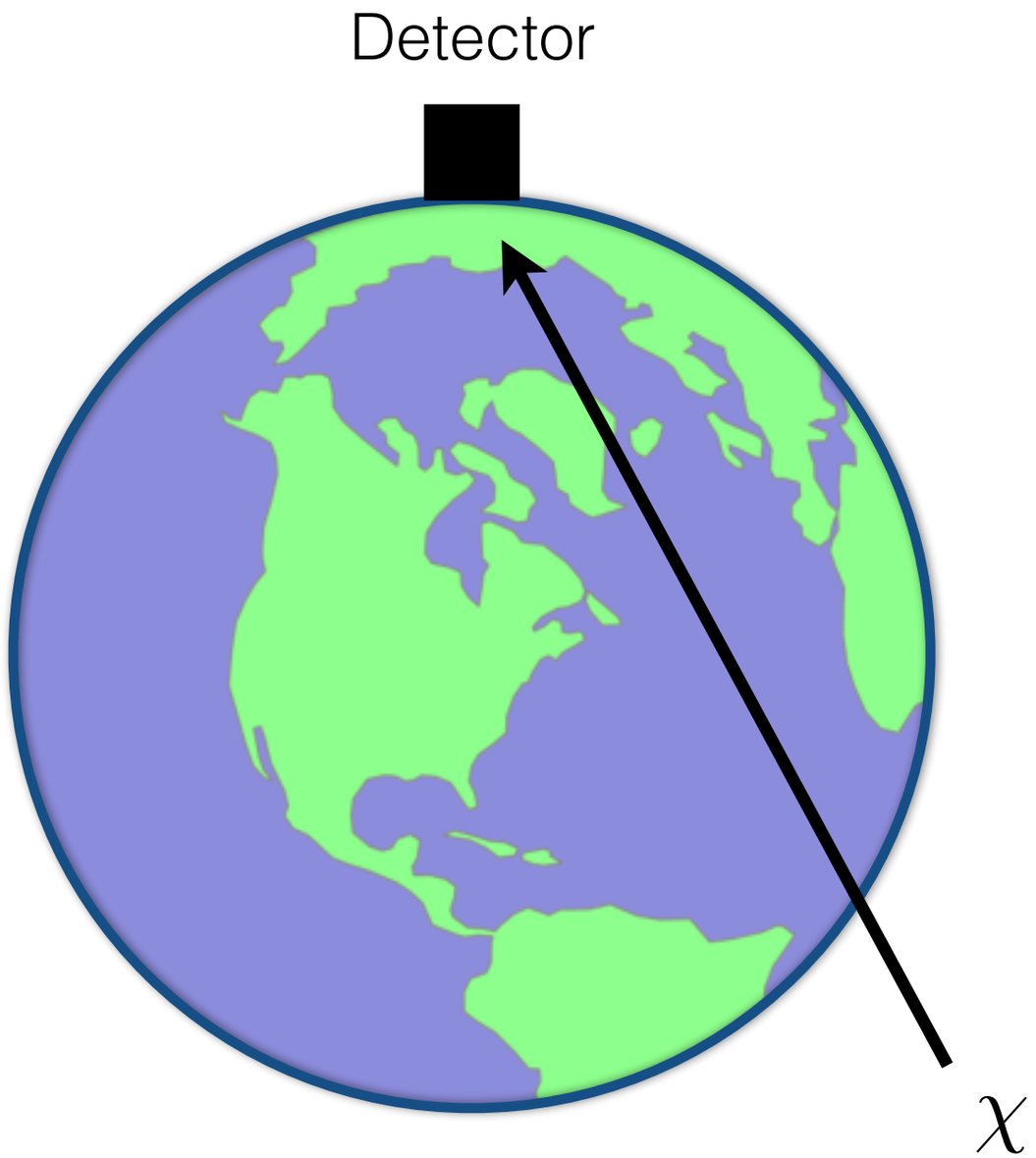
Earth Shadowing



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

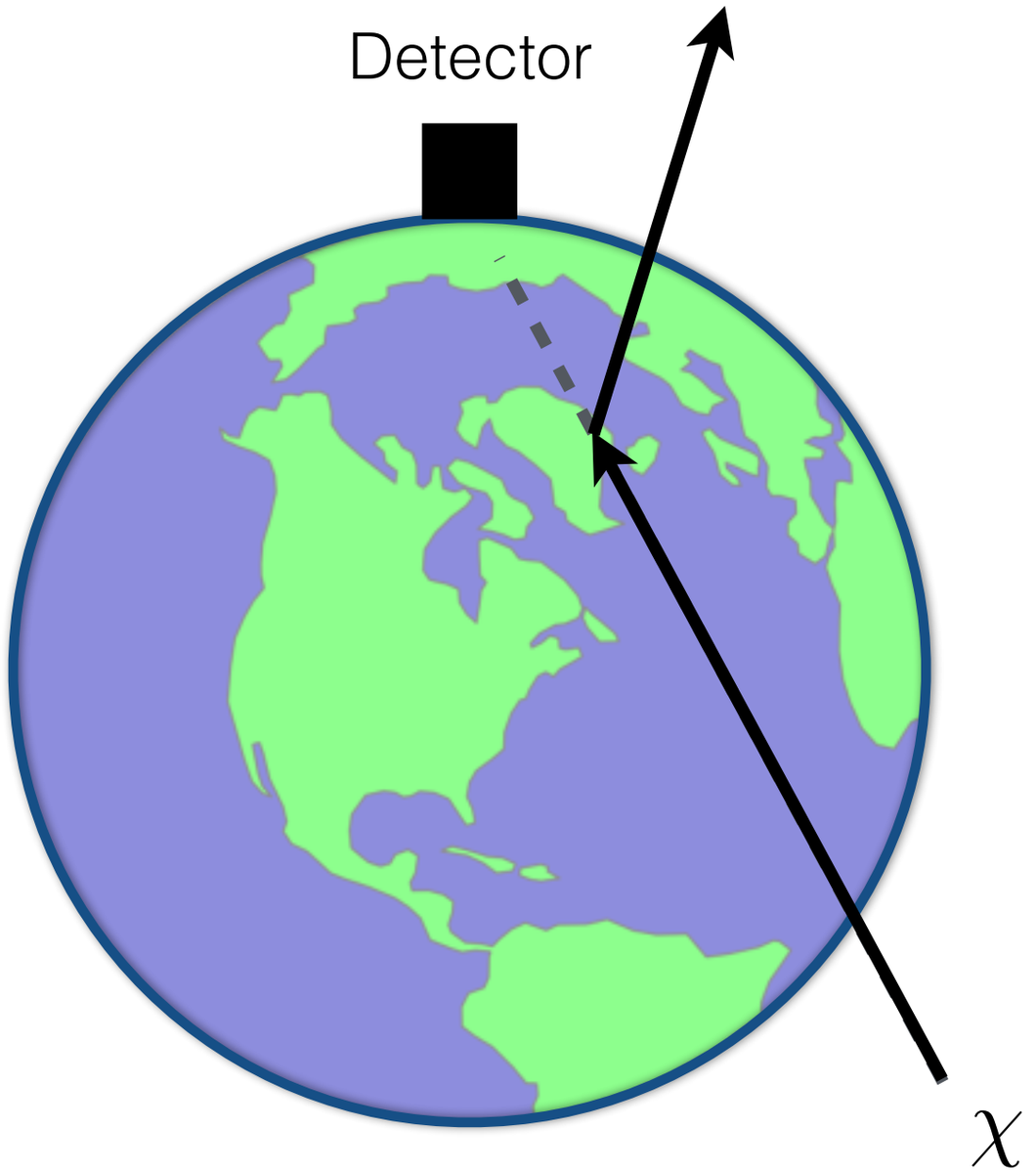
Earth Shadowing

Previous calculations usually only consider DM attenuation

Zaharijas & Farrar
[astro-ph/0406531]

Kouvaris & Shoemaker
[1405.1729,1509.08720]

DAMA
[1505.05336]

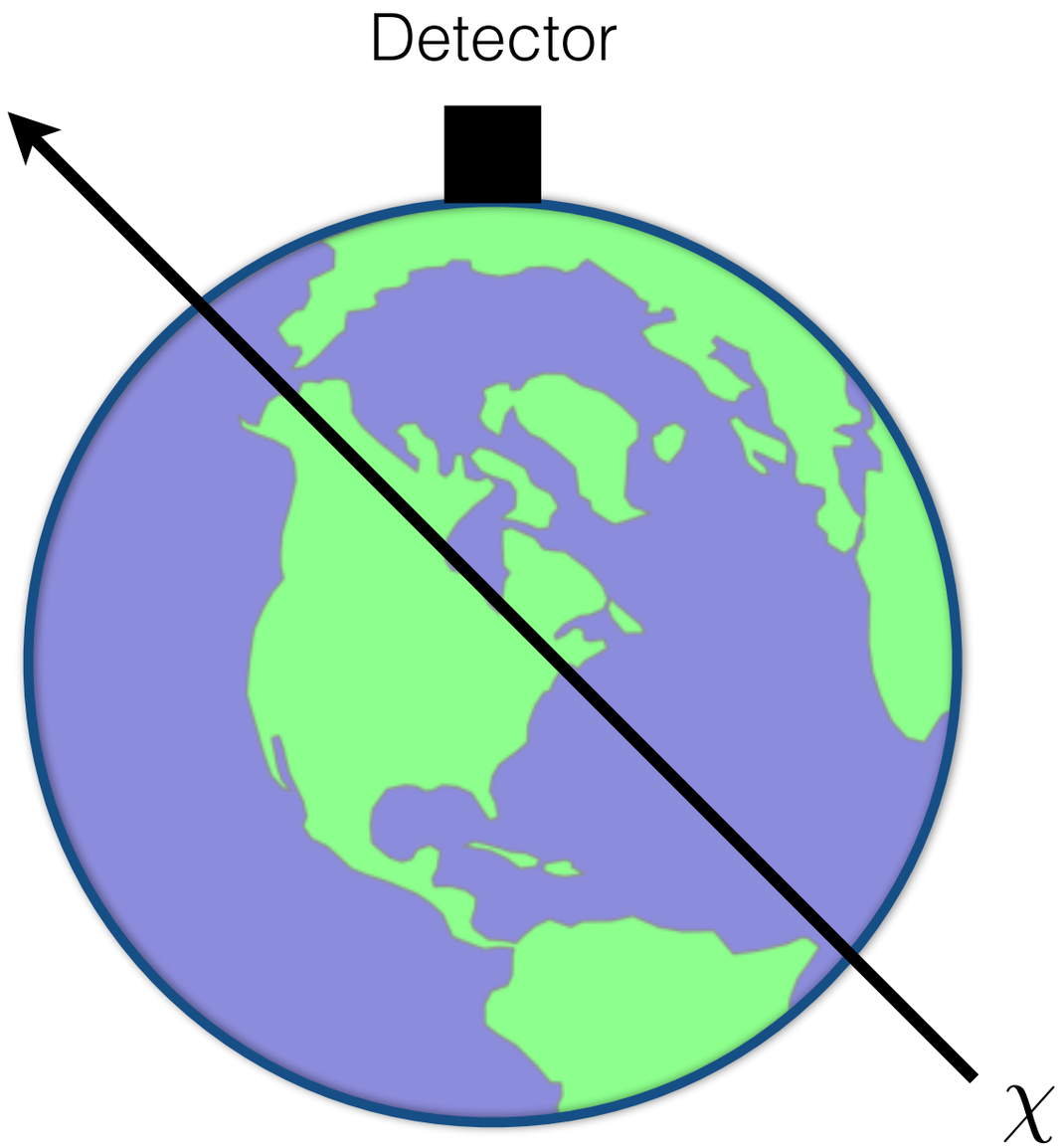


Assuming DM mean free path

$$\lambda \gtrsim R_E$$

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

Earth Shadowing



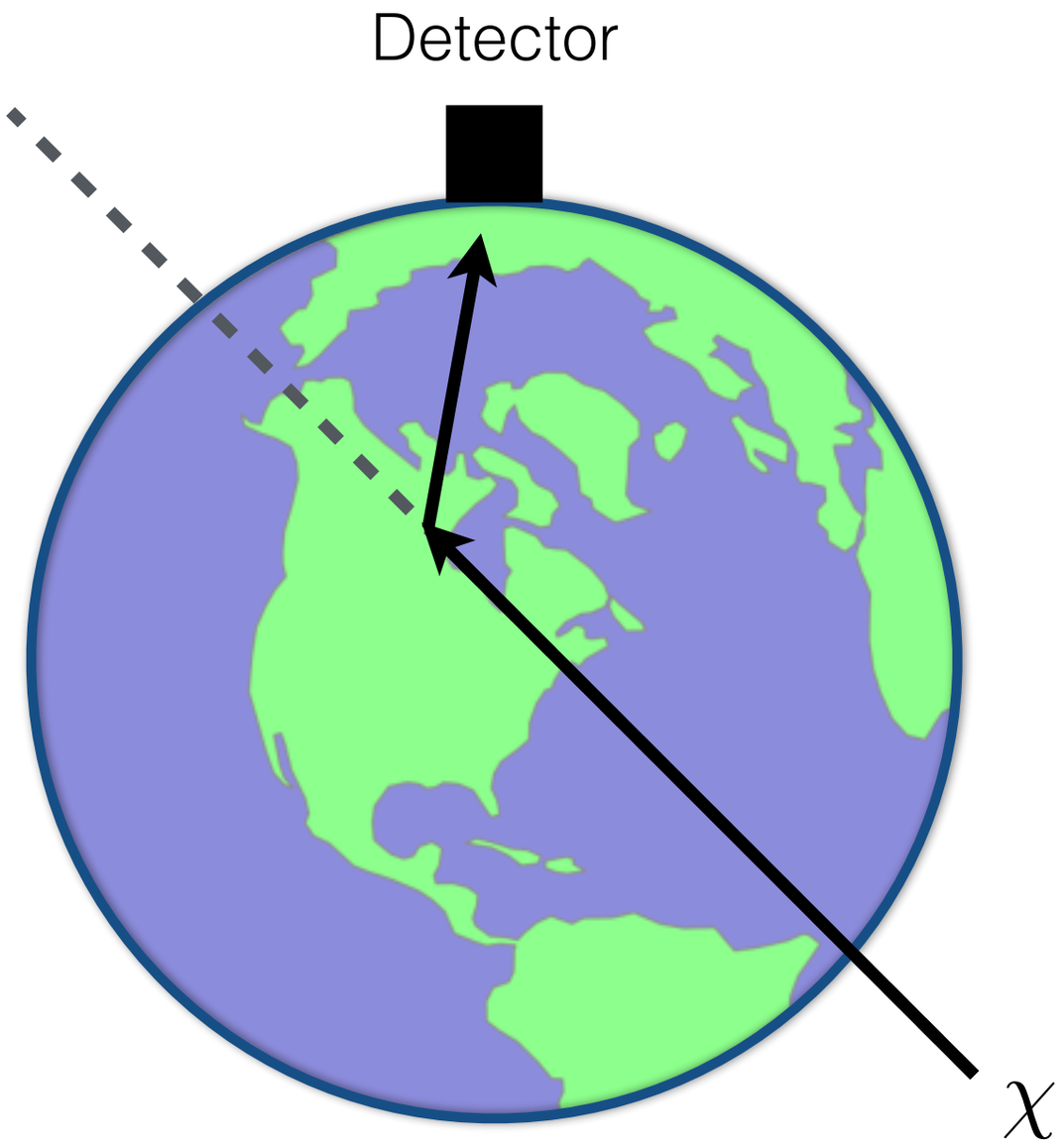
Assuming DM mean free path

$$\lambda \gtrsim R_E$$

Earth Shadowing

Considered in early Monte Carlo simulations

Collar & Avignone [PLB 275, 1992 and others]

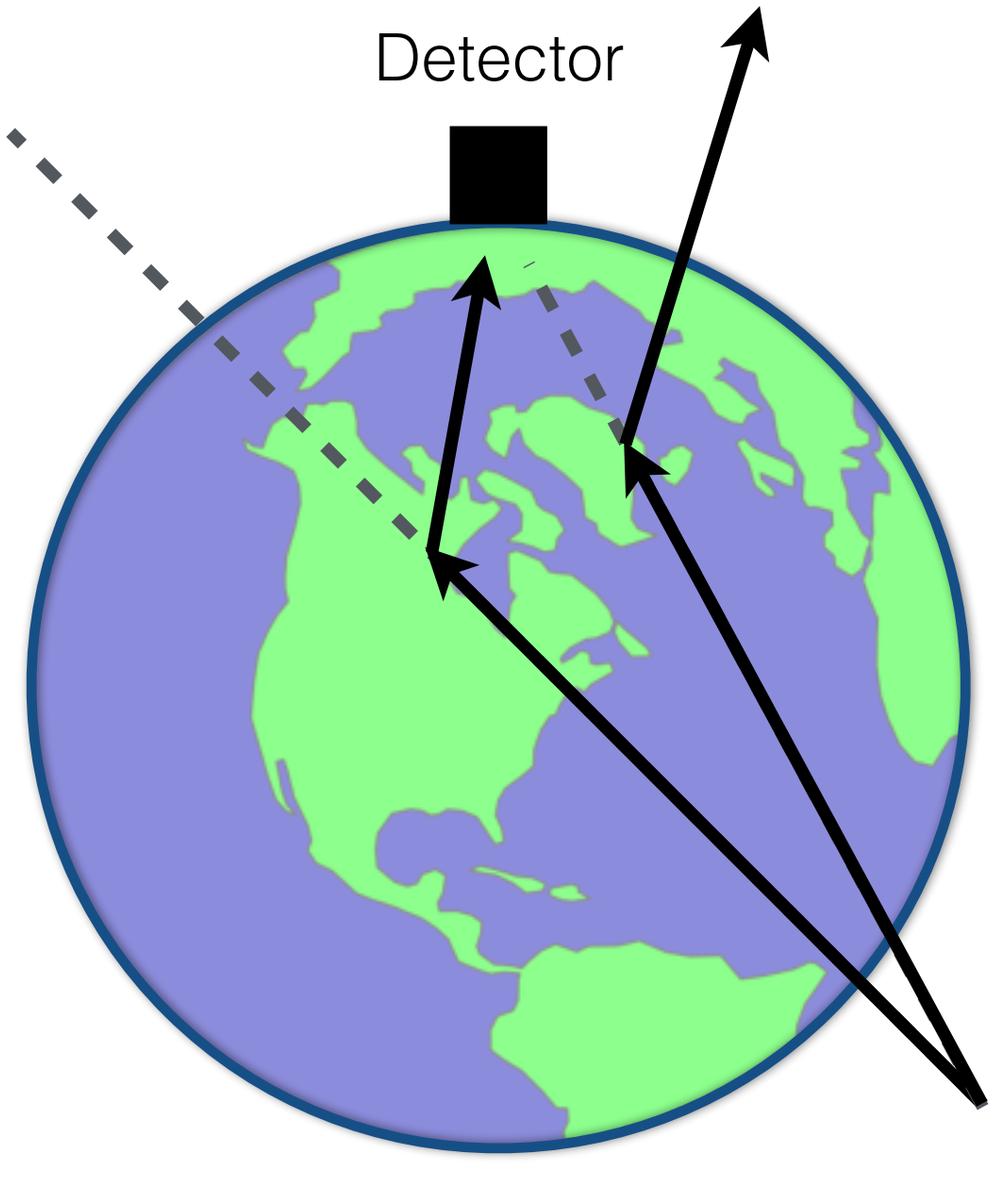


Assuming DM mean free path

$$\lambda \gtrsim R_E$$

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

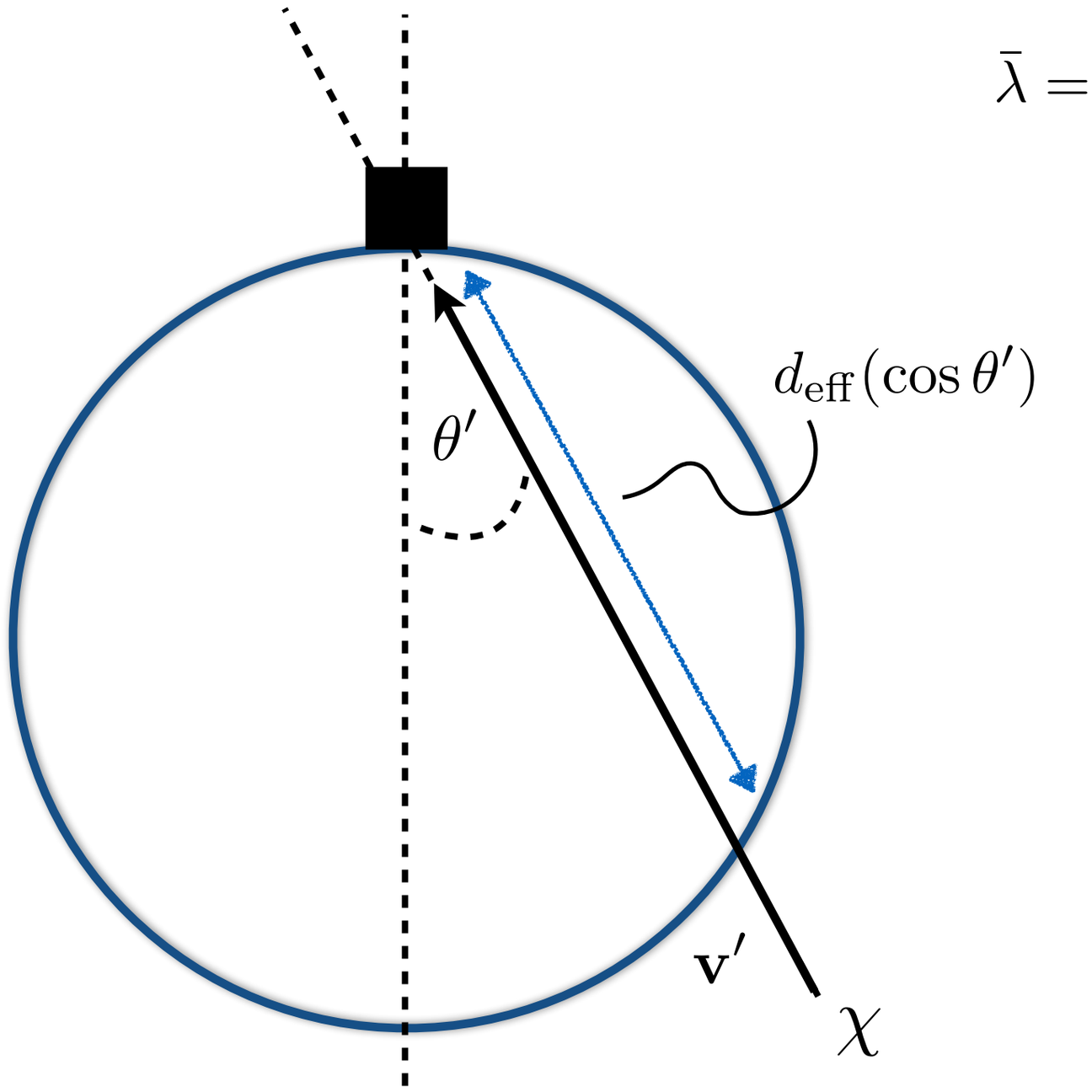
Total DM velocity distribution: $f(\mathbf{v}) = f_0(\mathbf{v}) - f_A(\mathbf{v}) + f_D(\mathbf{v})$

- 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)

DM attenuation

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

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



Sum over
Earth nuclei

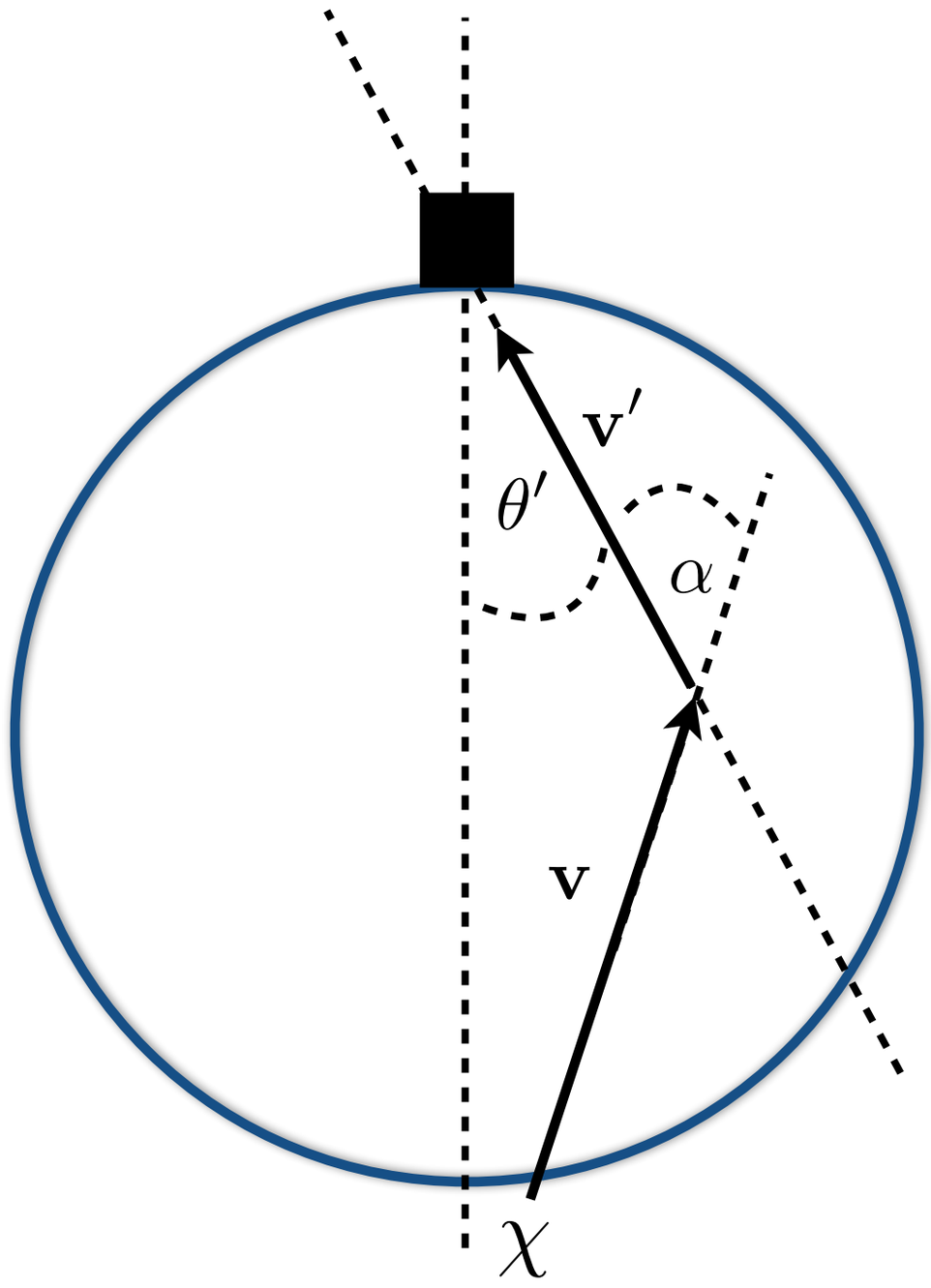
$$f_0(\mathbf{v}') - f_A(\mathbf{v}') = f_0(\mathbf{v}') \exp\left[-\frac{d_{\rm eff}(\cos\theta')}{\bar{\lambda}(v')}\right] \approx f_0(\mathbf{v}')(1 - \frac{d_{\rm eff}(\cos\theta')}{\bar{\lambda}(v')})$$

DM deflection

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

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

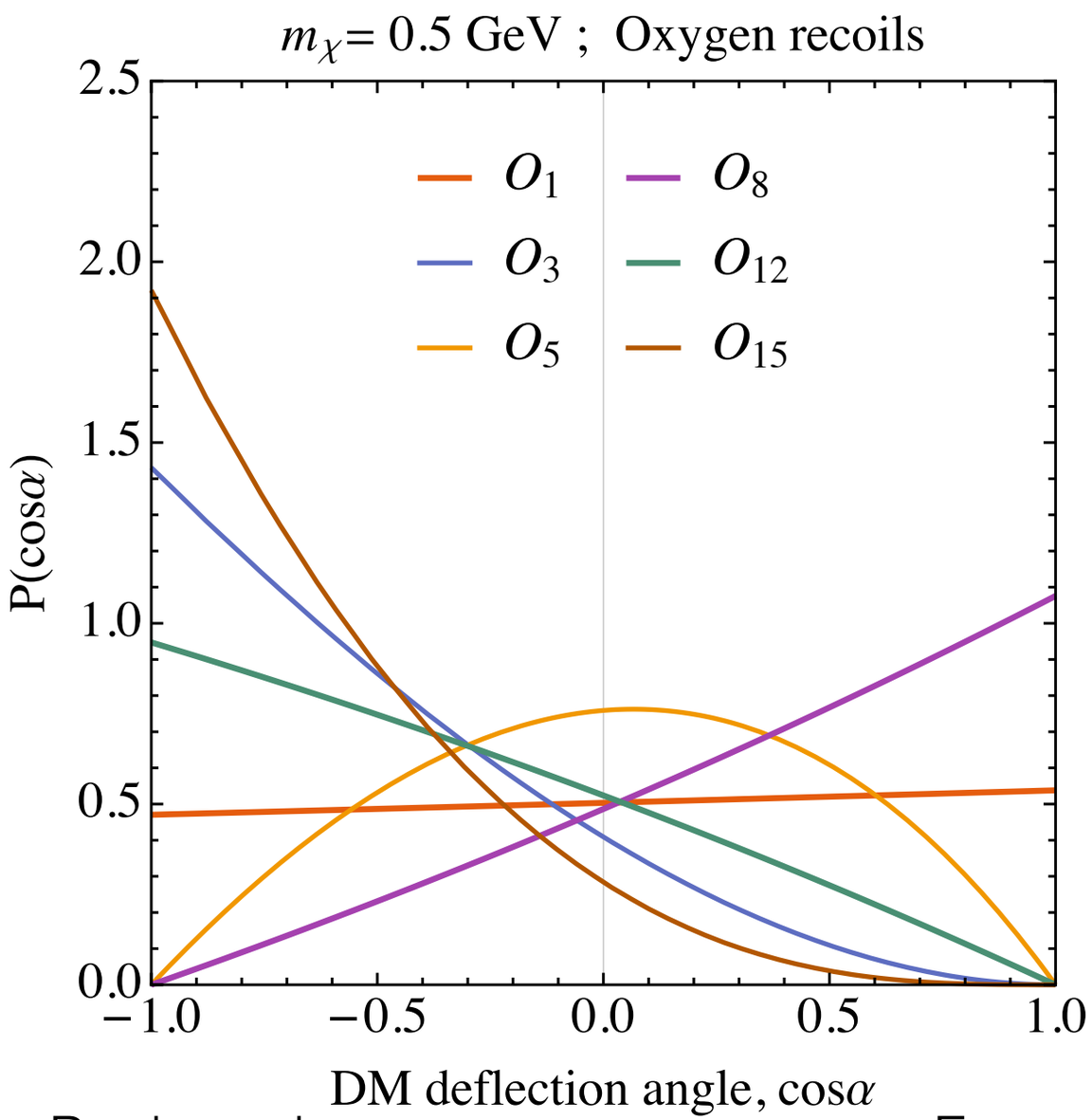
$$\bar{\lambda} = (\sigma \bar{n})^{-1}$$



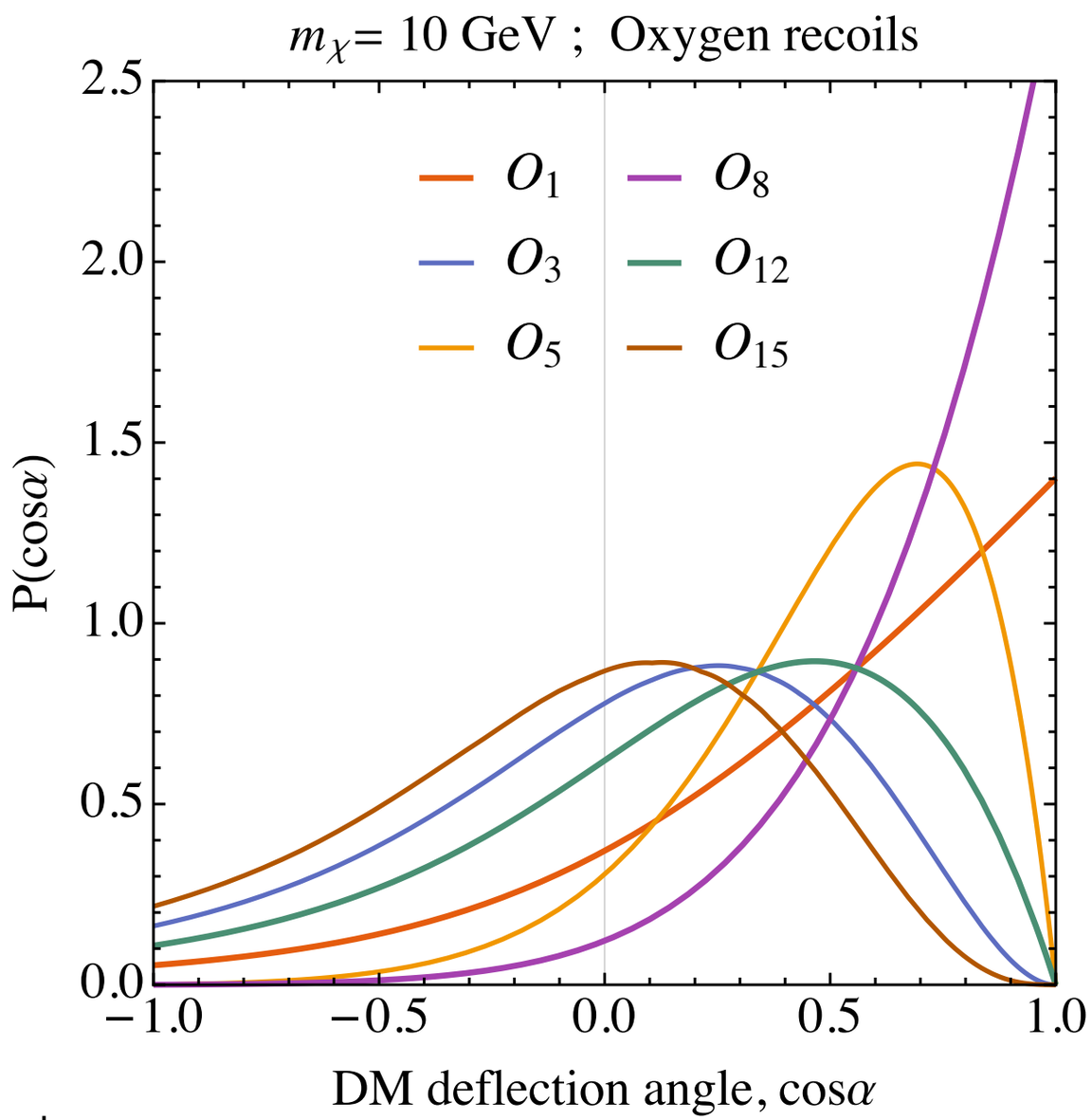
$\kappa = v/v'$
fixed by
kinematics

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

DM deflection

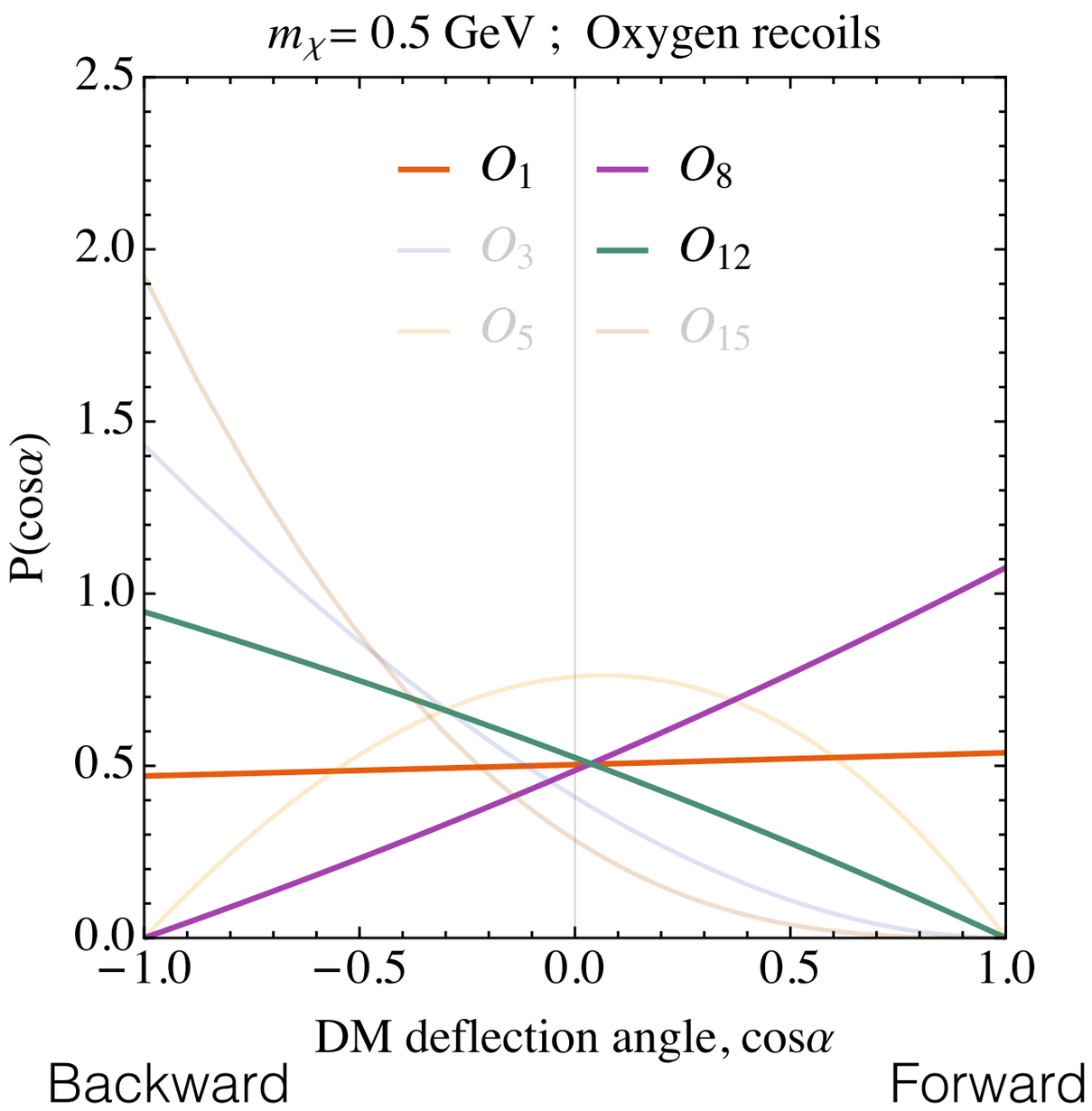


Backward



Forward

DM deflection



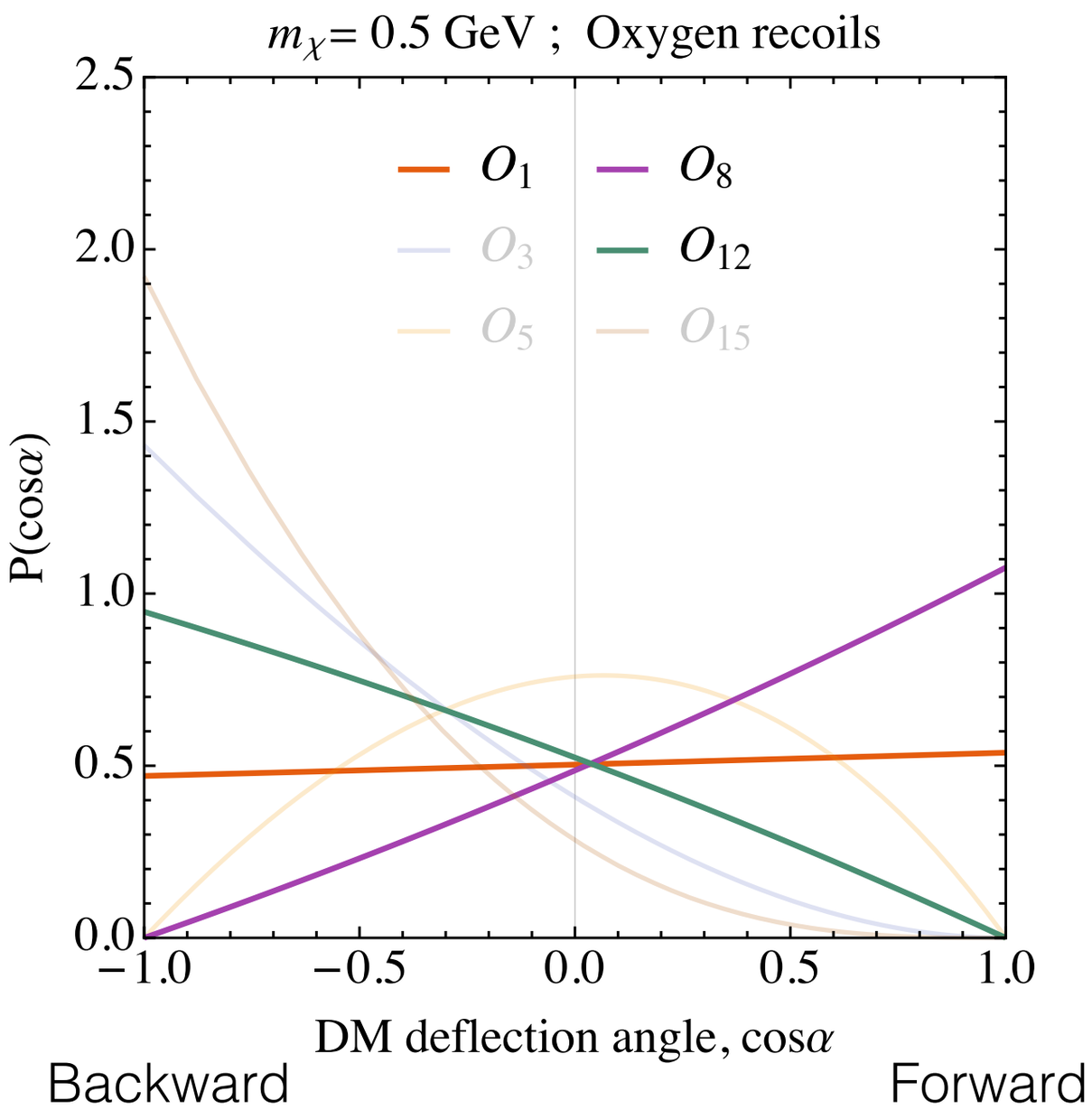
Standard SI

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

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

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

DM deflection



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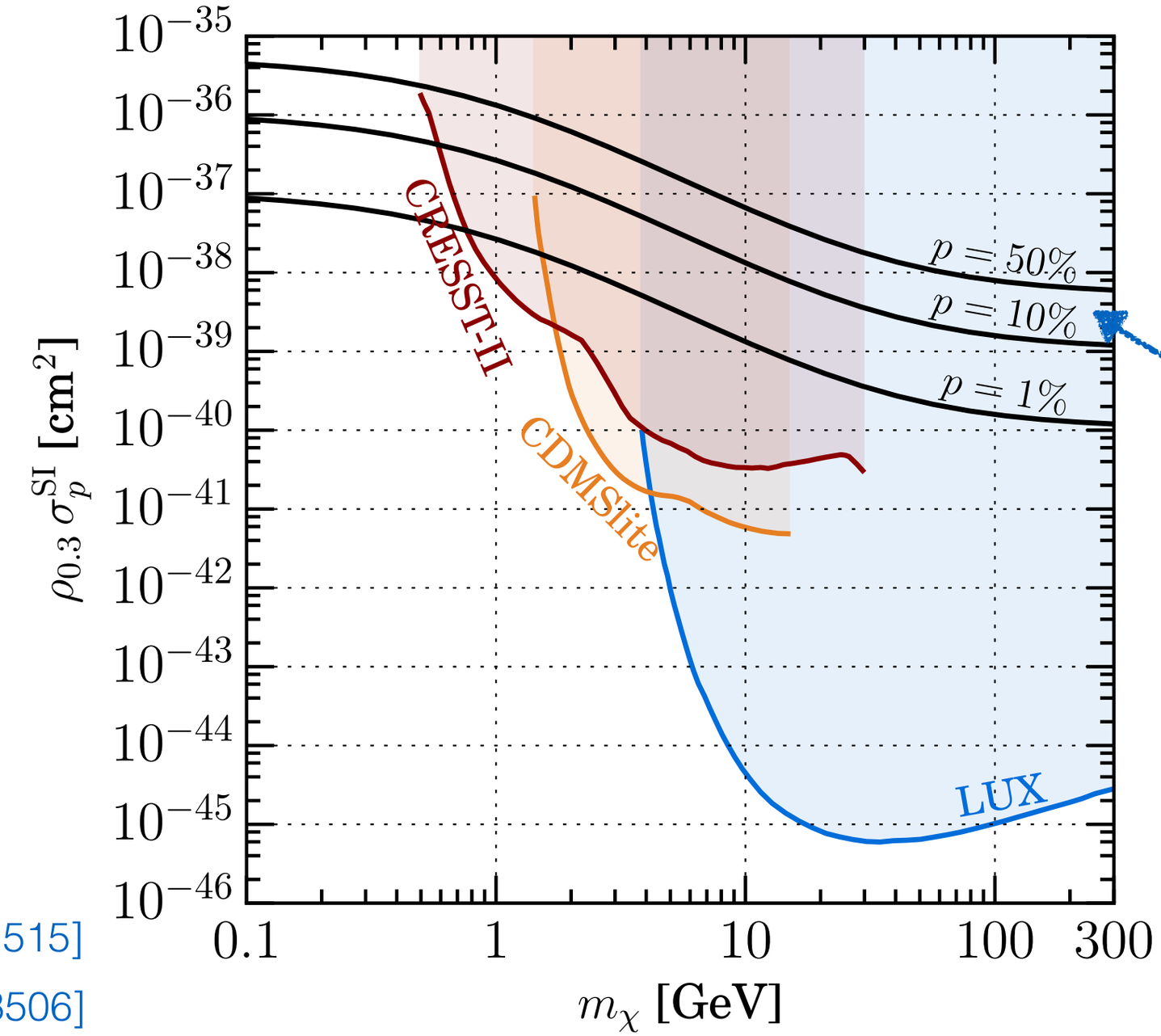
Size of effect depends on m*ean free path*:

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

Current cross section limits

Stringent limits on DM-nucleon SI scattering cross section



Probability of DM scattering in the Earth

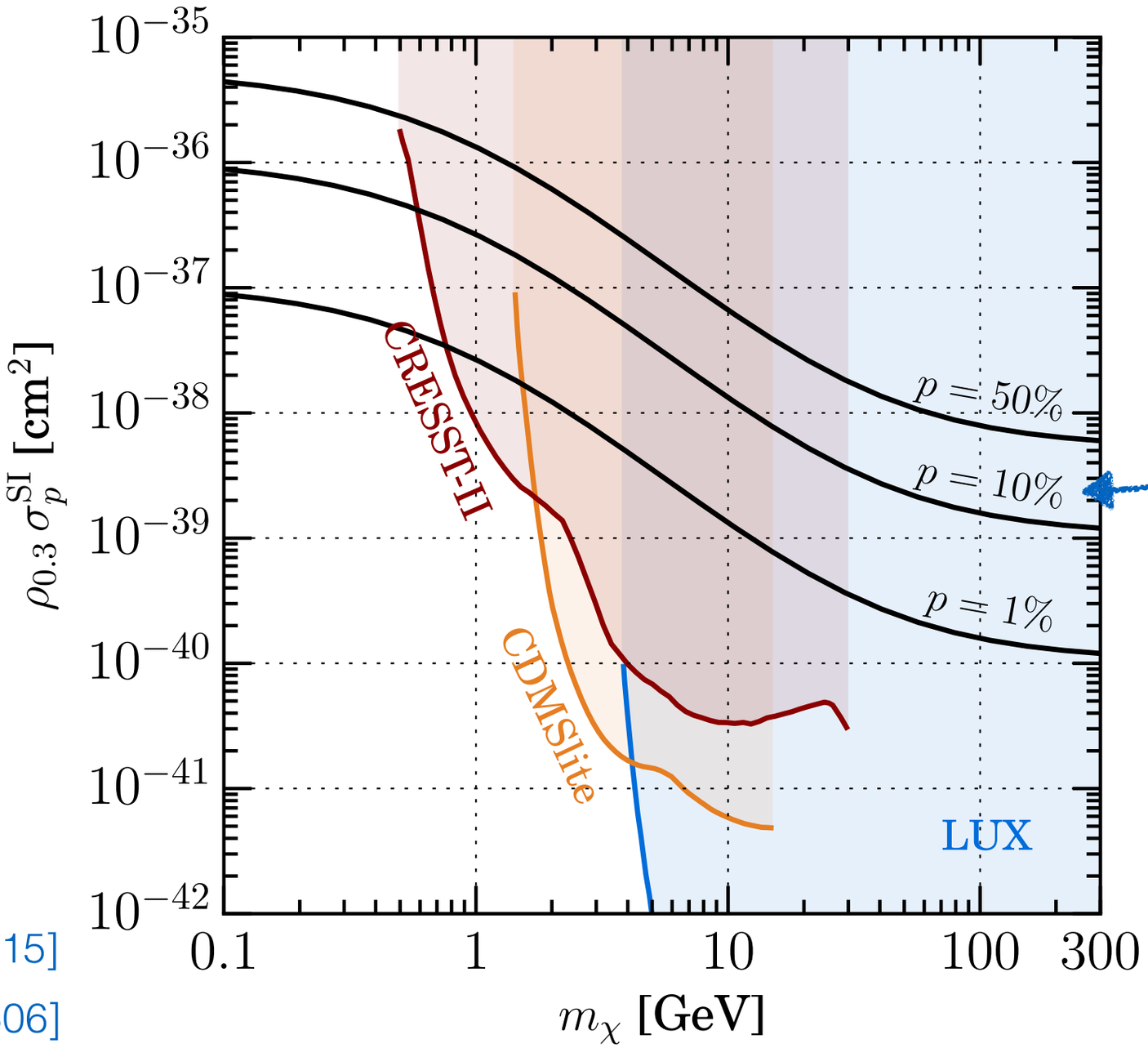
CRESST-II [1509.01515]

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

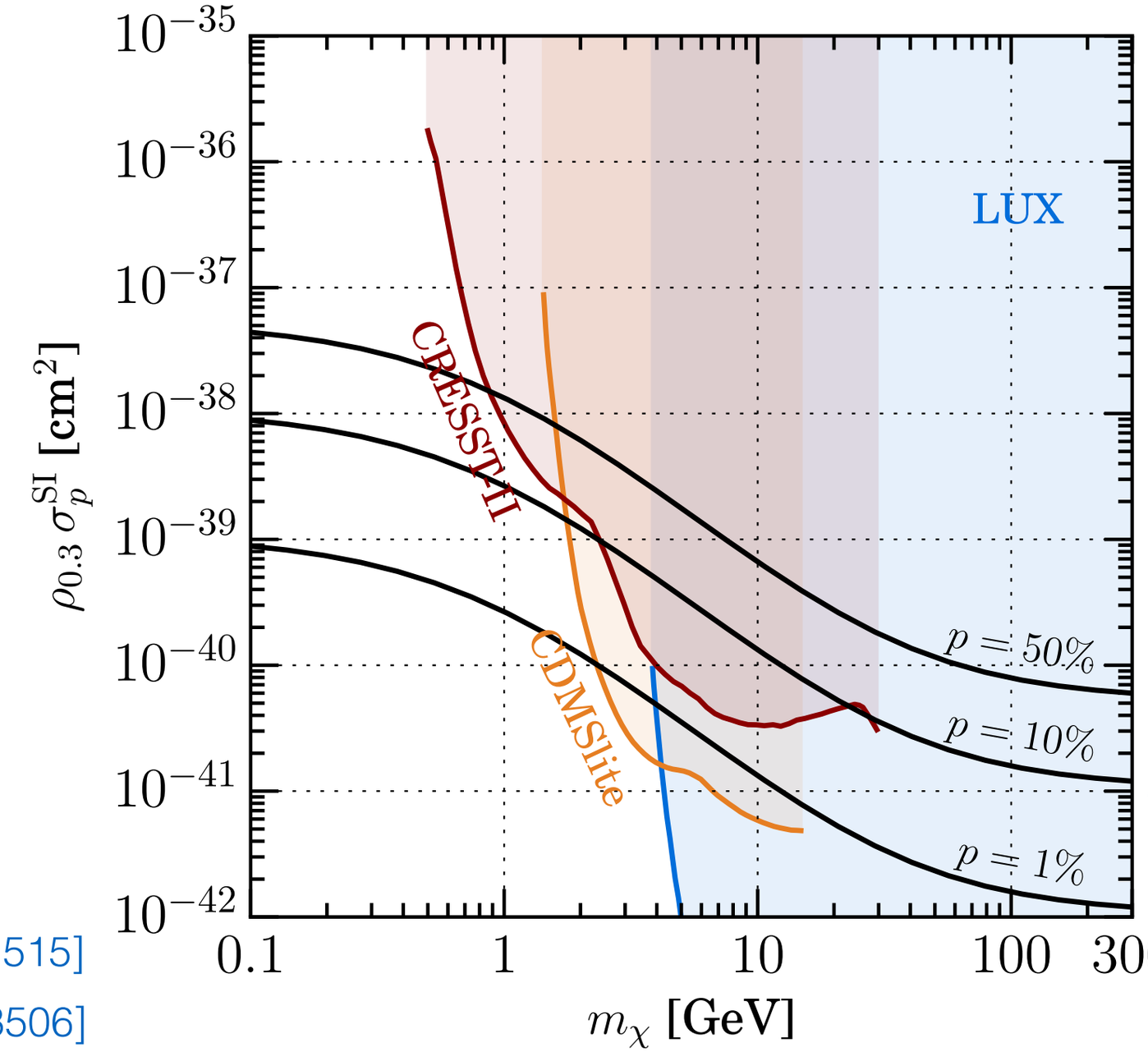
CRESST-II [1509.01515]

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]

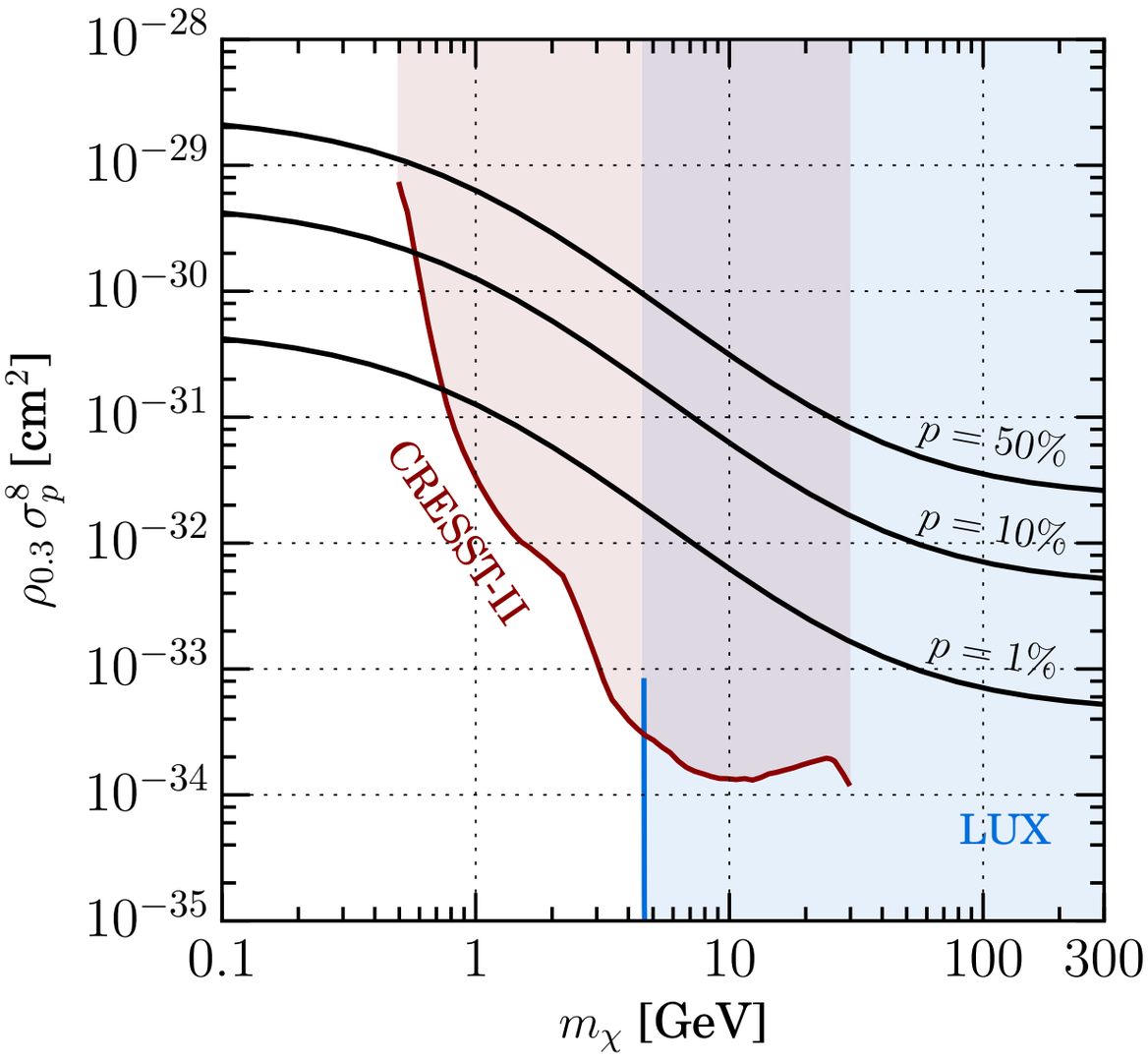
CDMSlite [1509.02448]

Current cross section limits

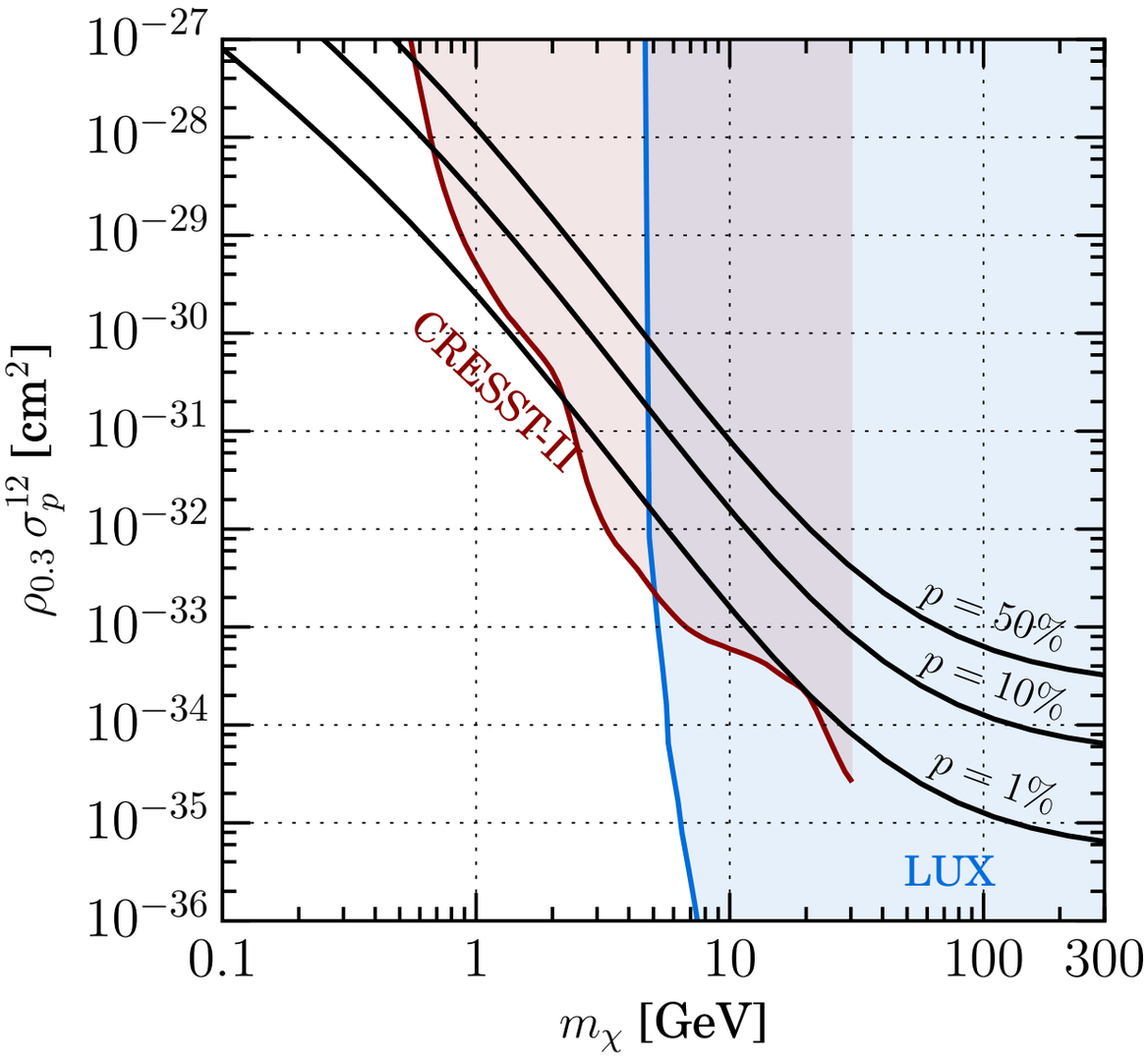
Non-standard DM-nucleon interactions:

See talk by Riccardo Catena

$\sigma_p^8 \sim v^2$



$\sigma_p^{12} \sim q^2$



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

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…

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

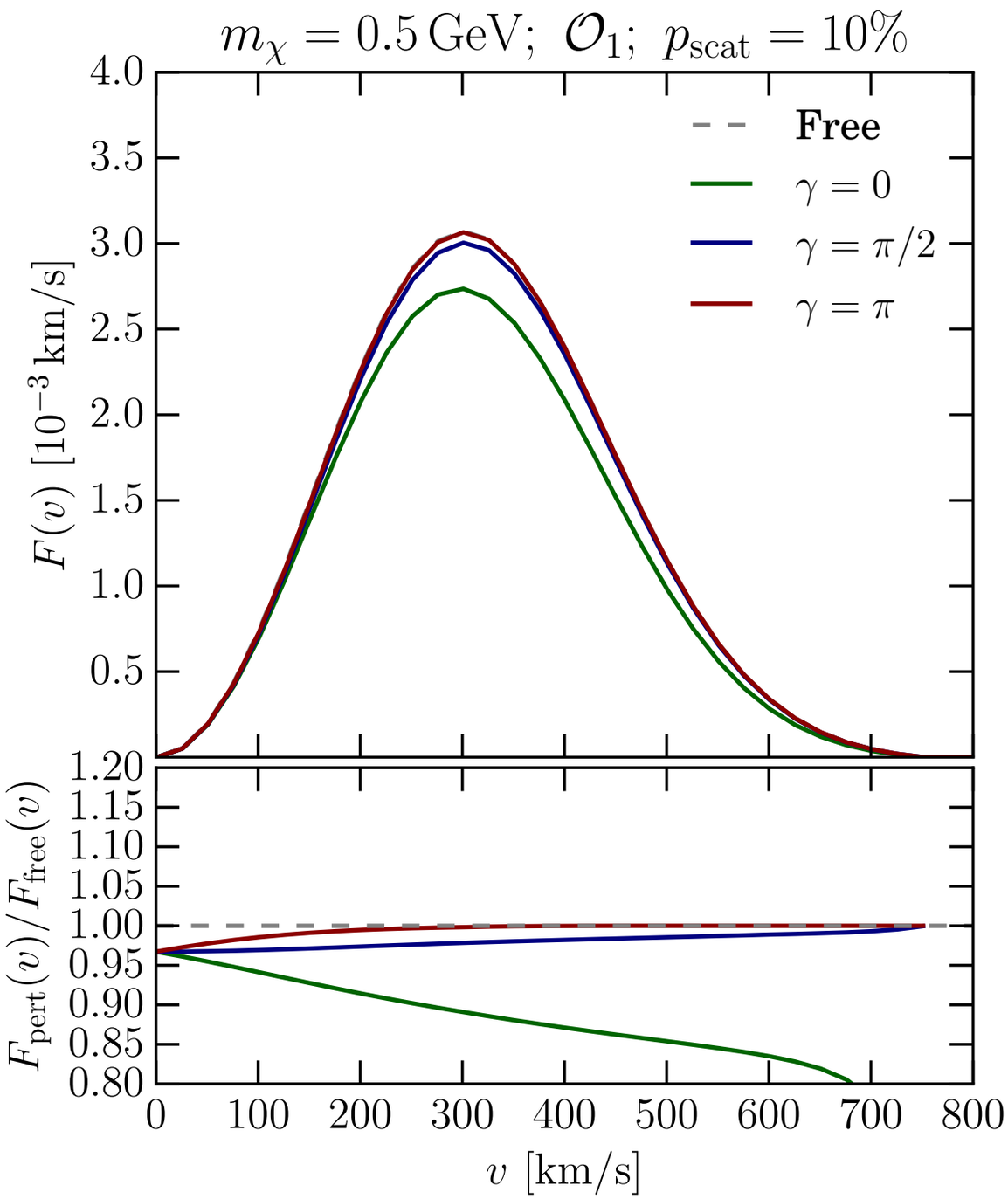
- … and differential event rate (in CRESST-II)

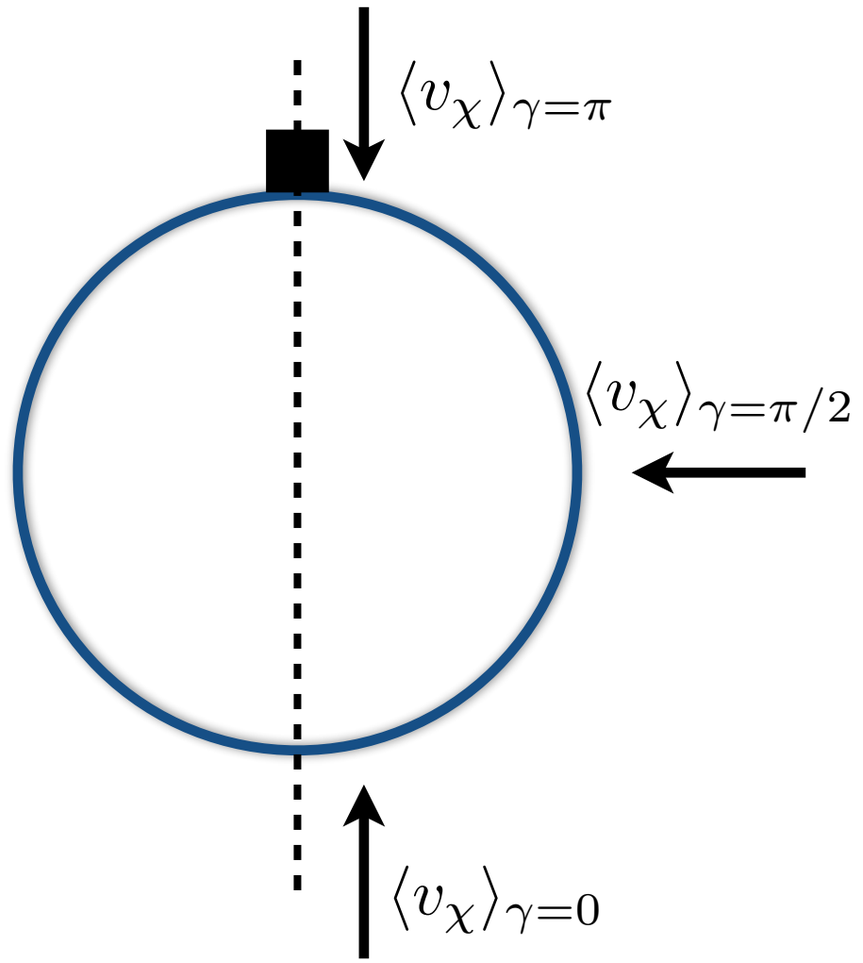
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \int \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} v F(v)\, \mathrm{d}v$$

- For different DM-nucleon operators and different incoming DM velocities (equivalent to different detector positions…)

Operator 1 - attenuation only

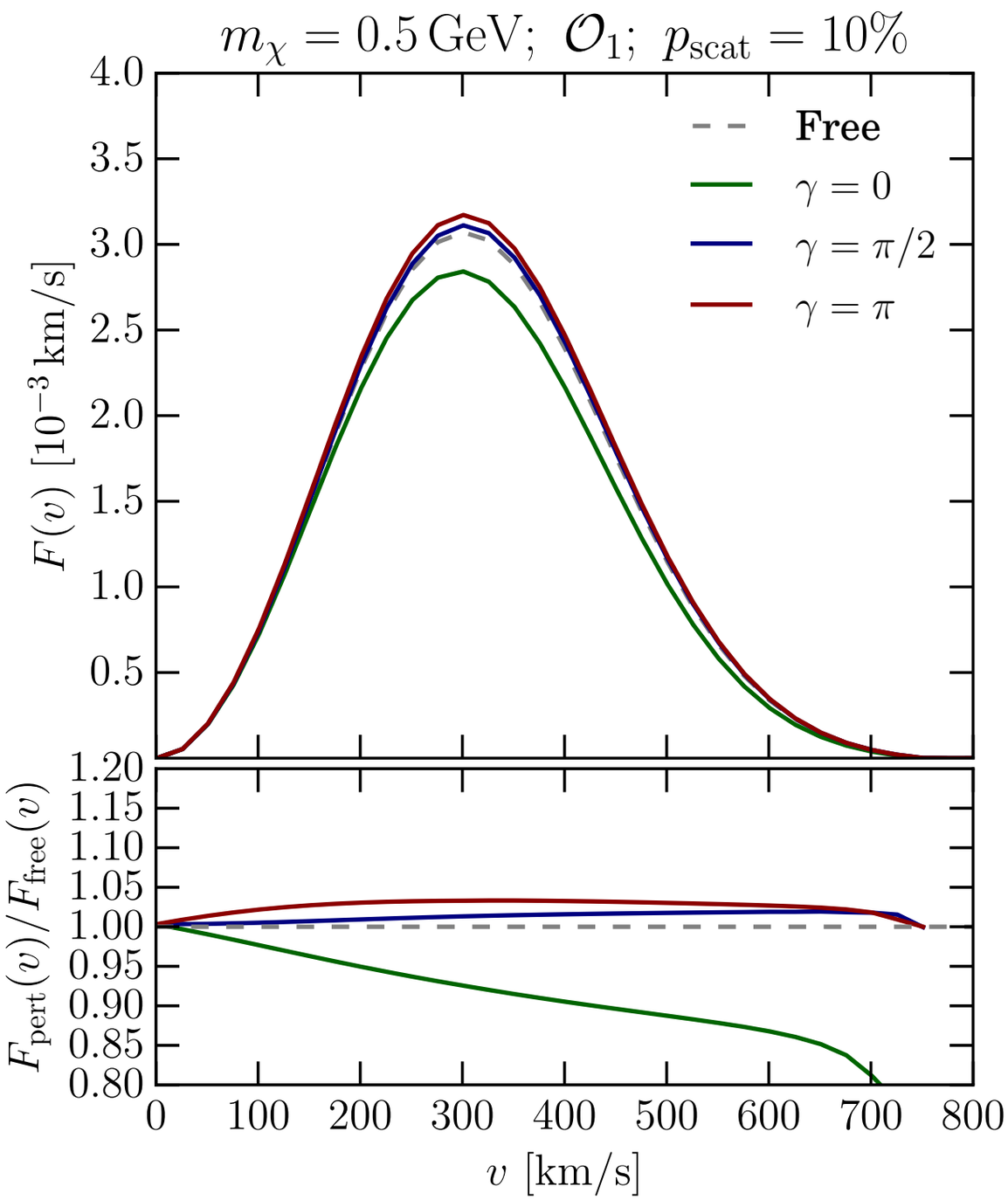
$\mathcal{O}_1 = \mathbb{1}$ → Isotropic deflection

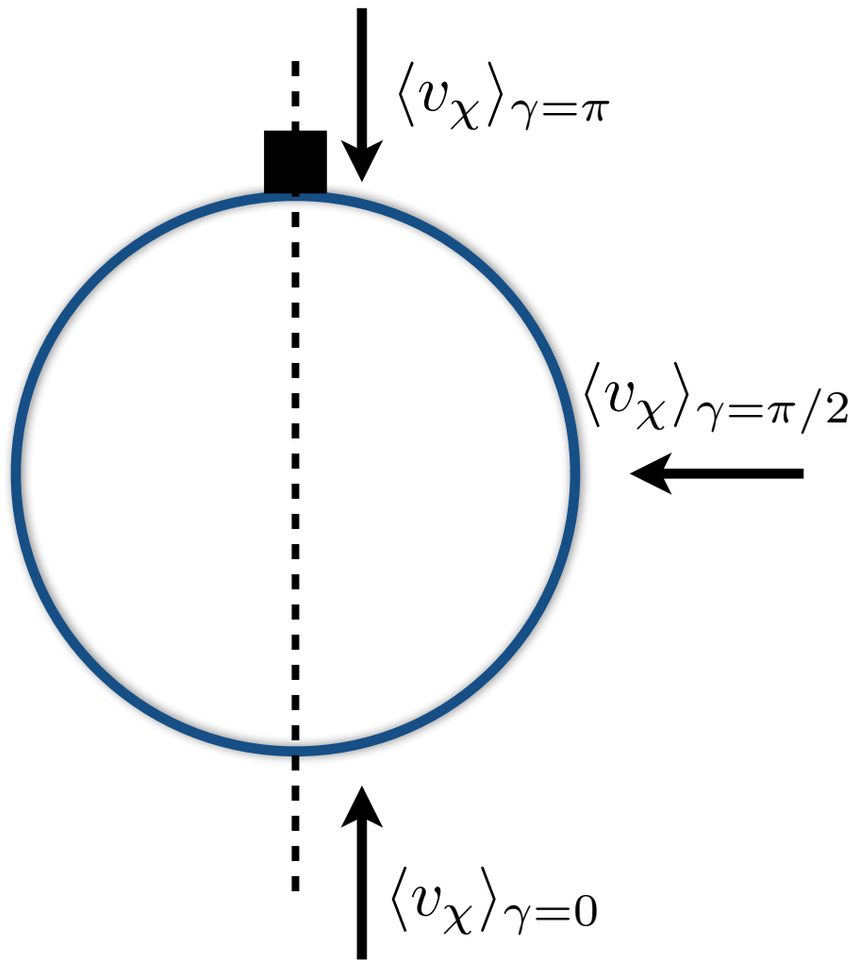




Operator 1 - attenuation + deflection

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





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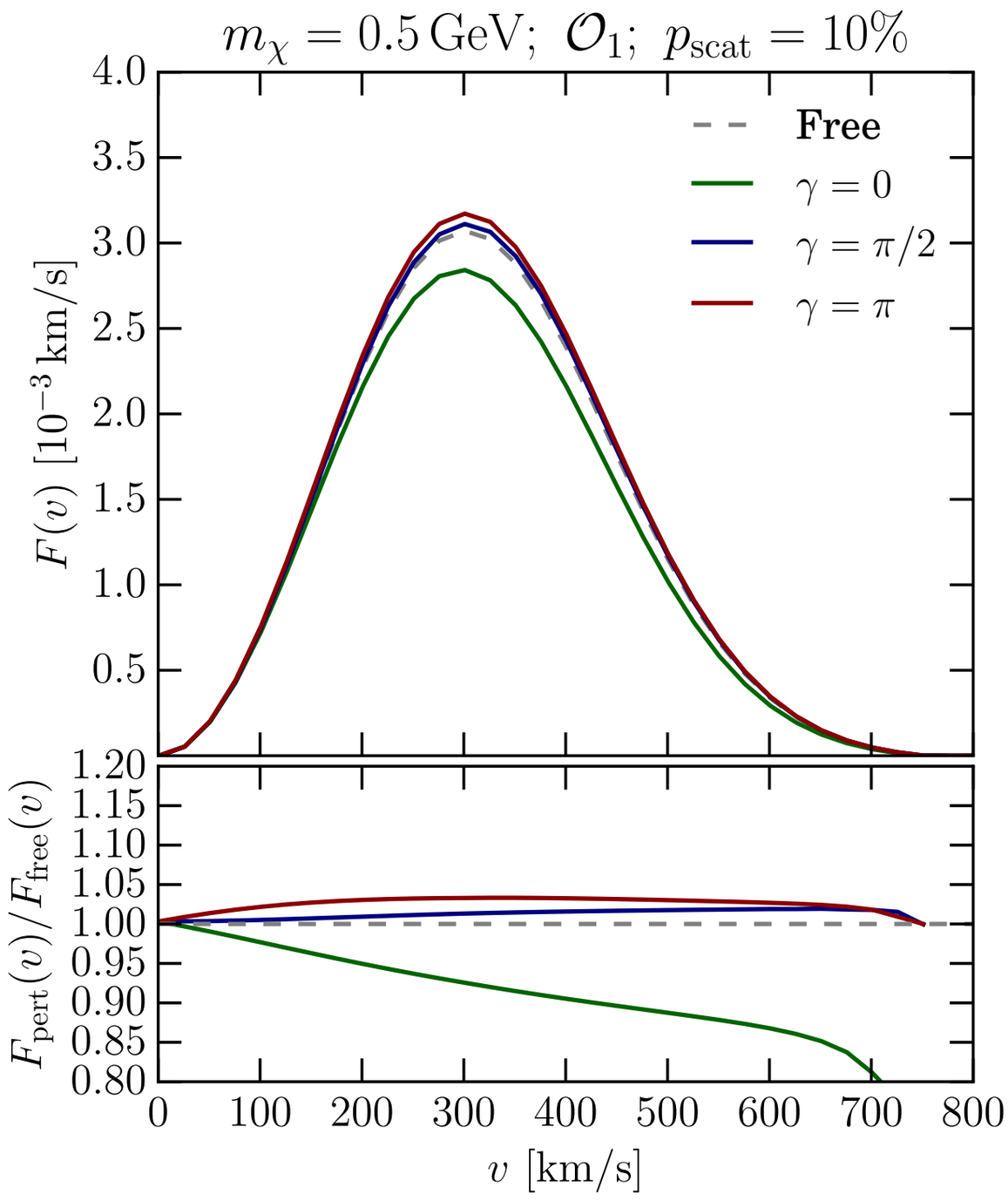
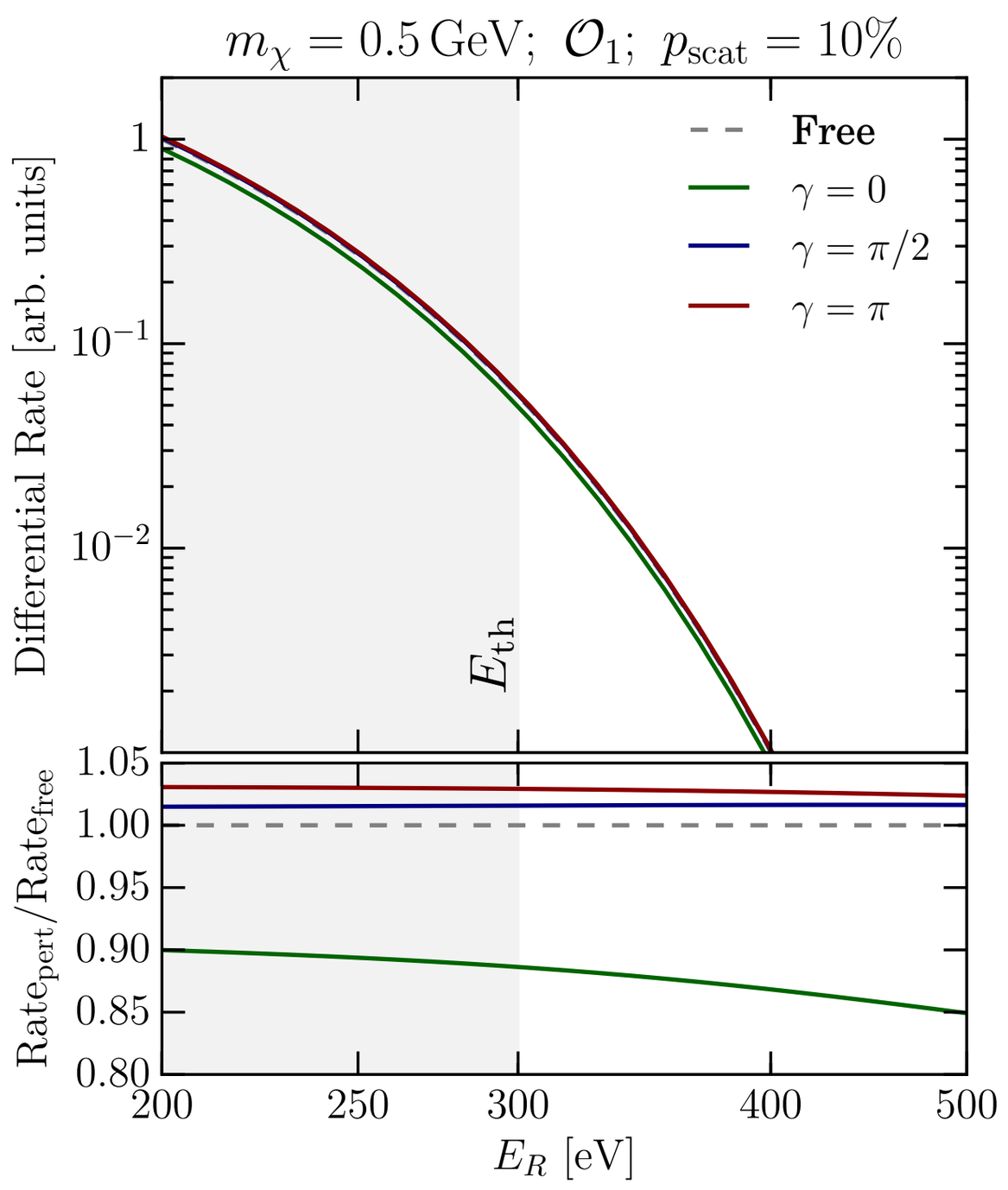
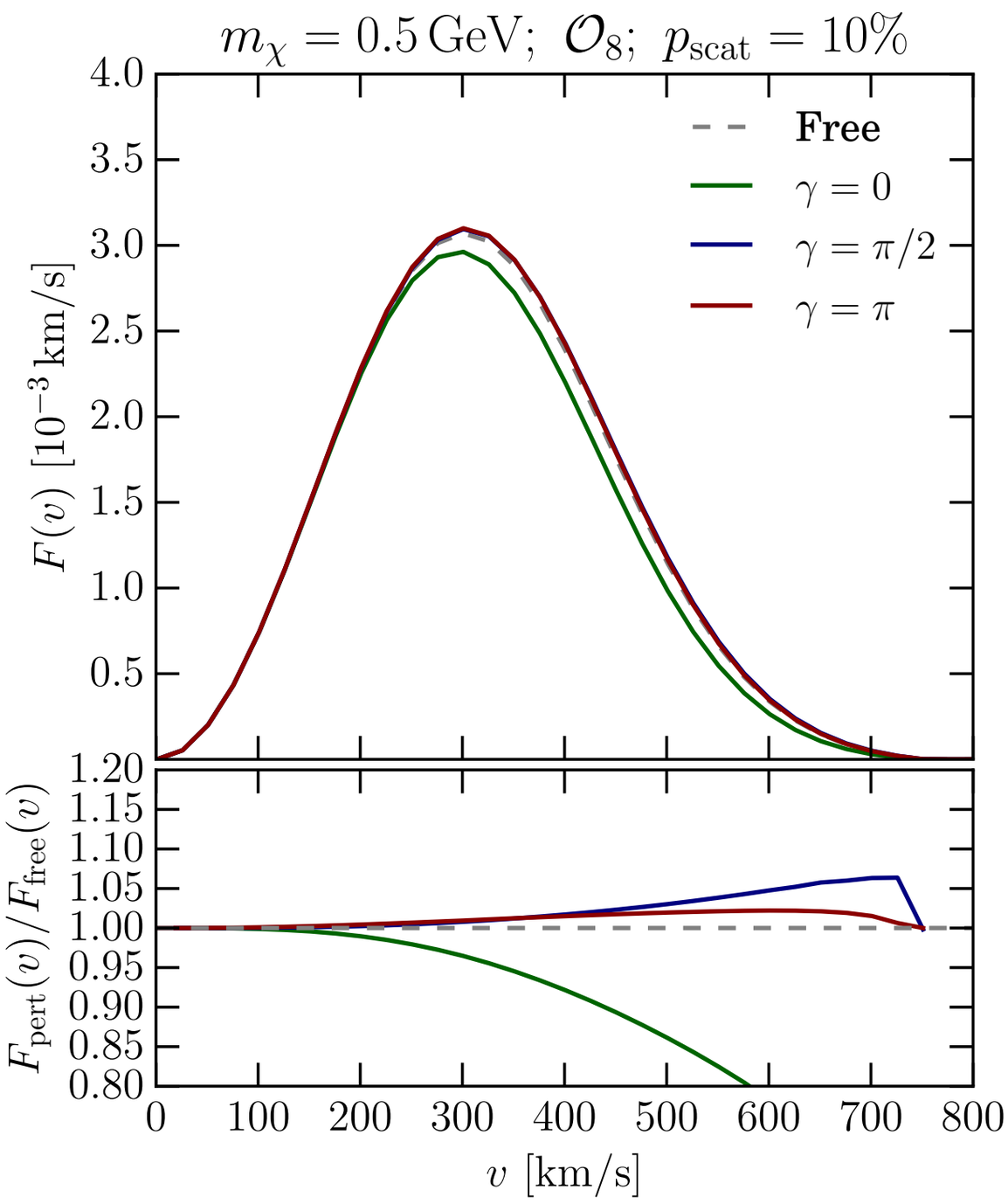
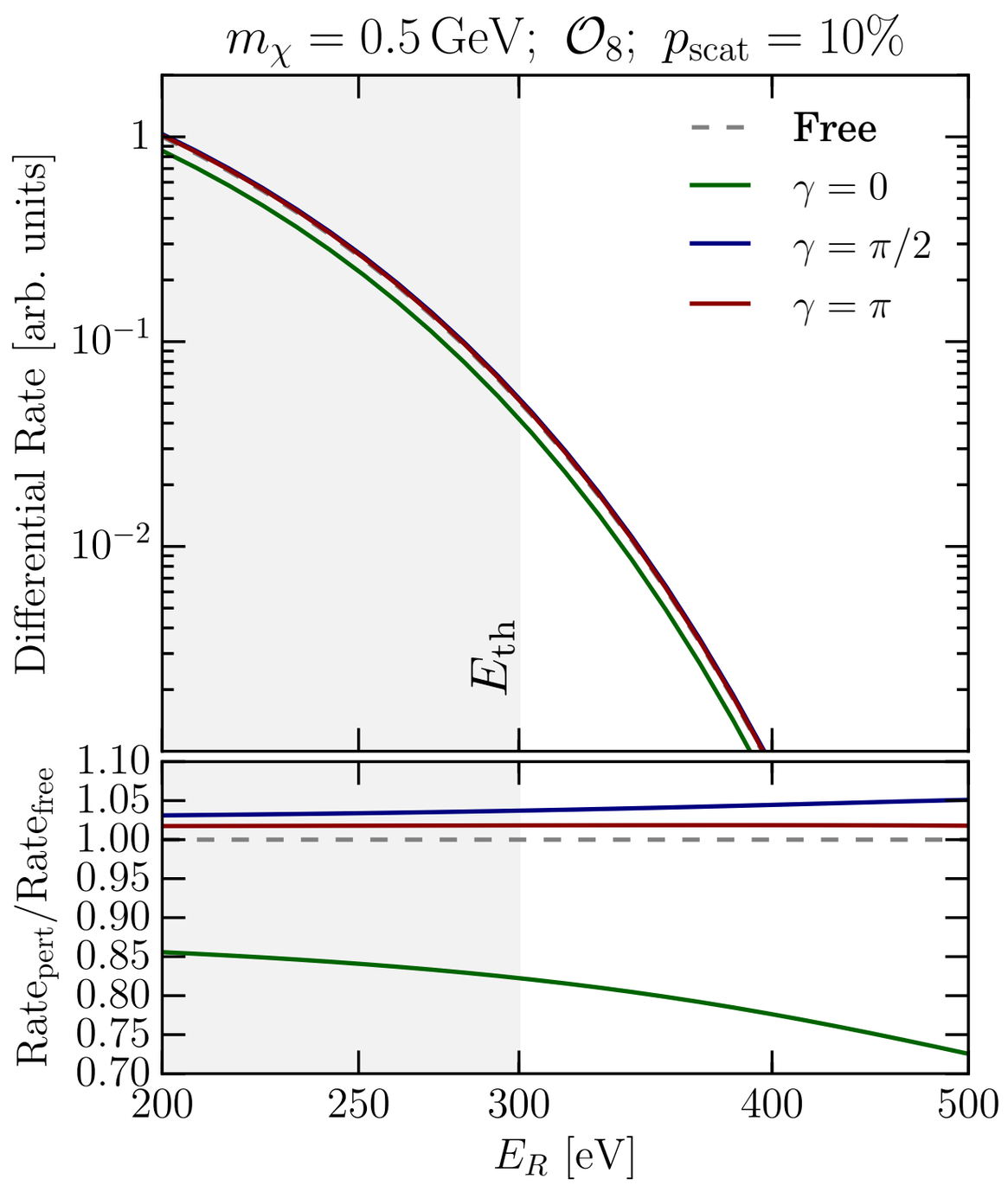




Operator 8 - attenuation + deflection

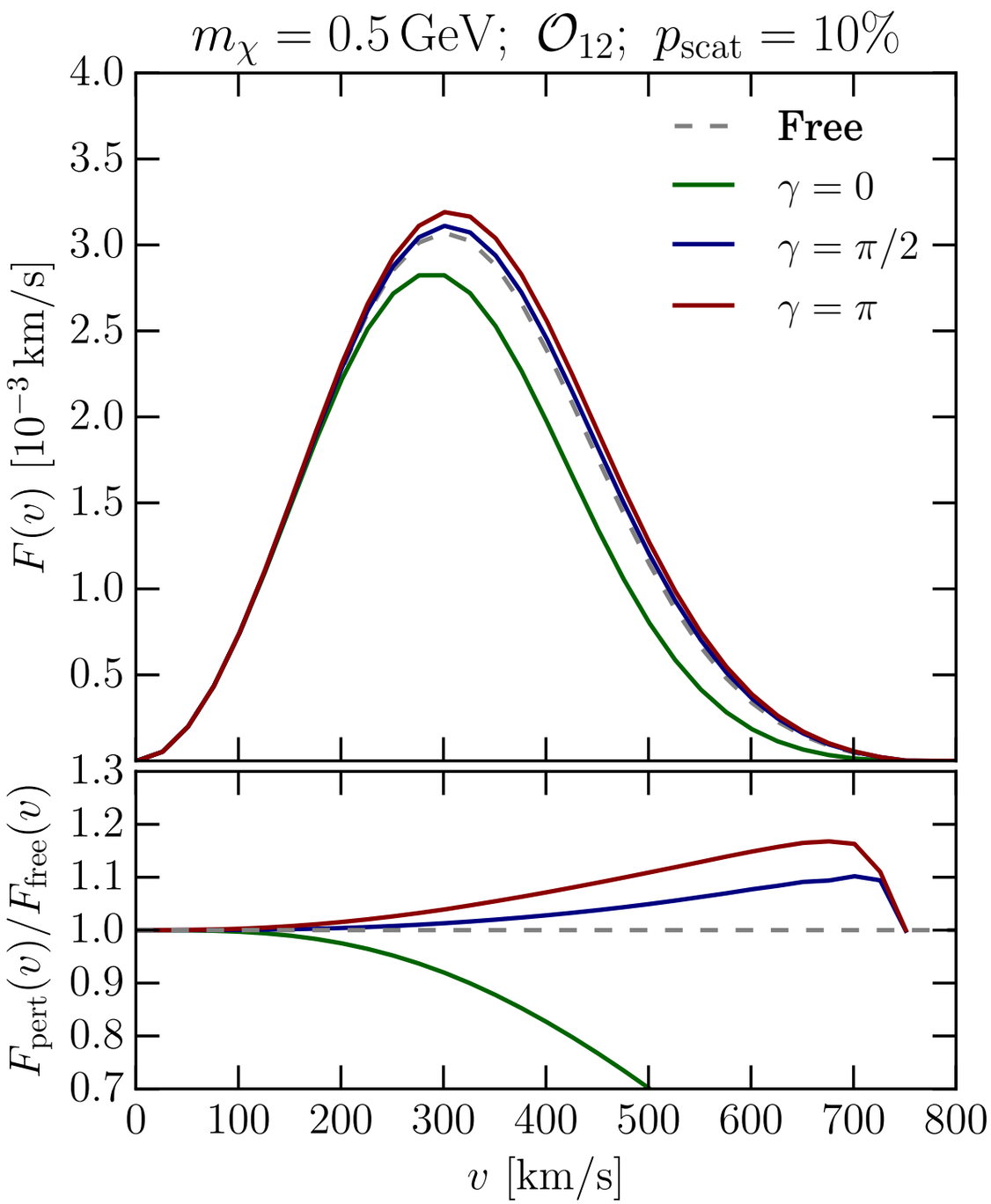
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \longrightarrow$$ Mostly forward deflection

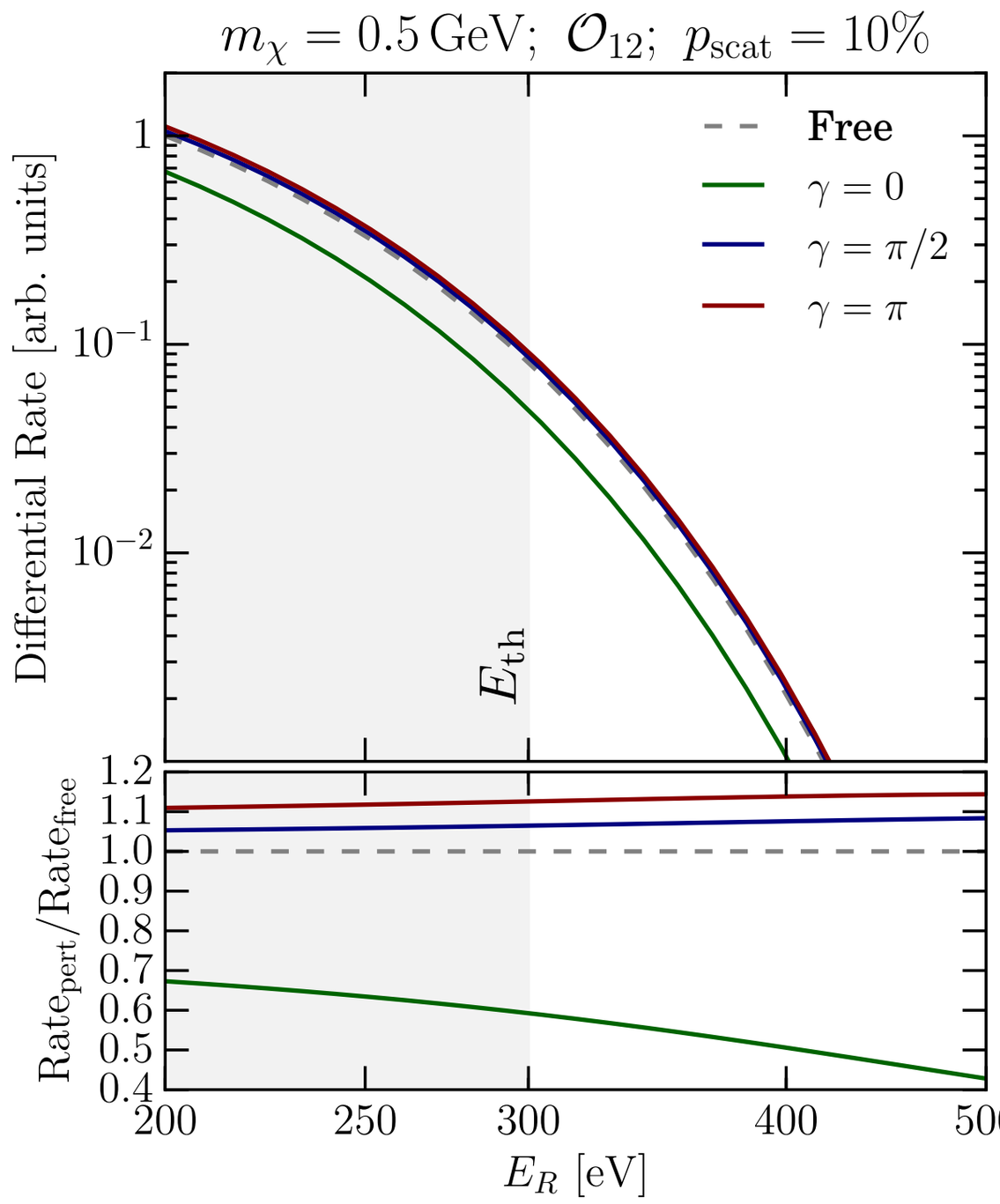




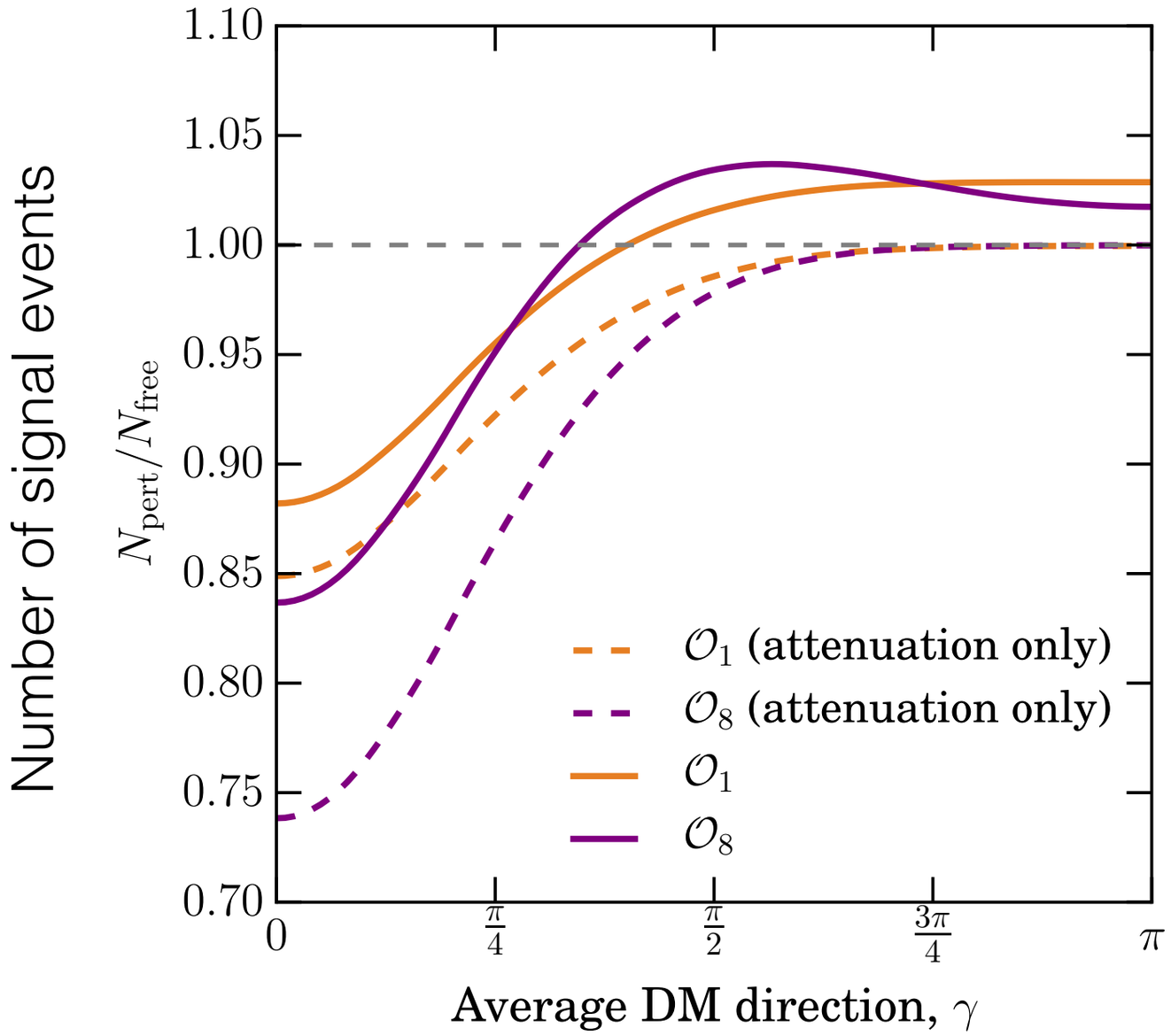
Operator 12 - attenuation + deflection

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



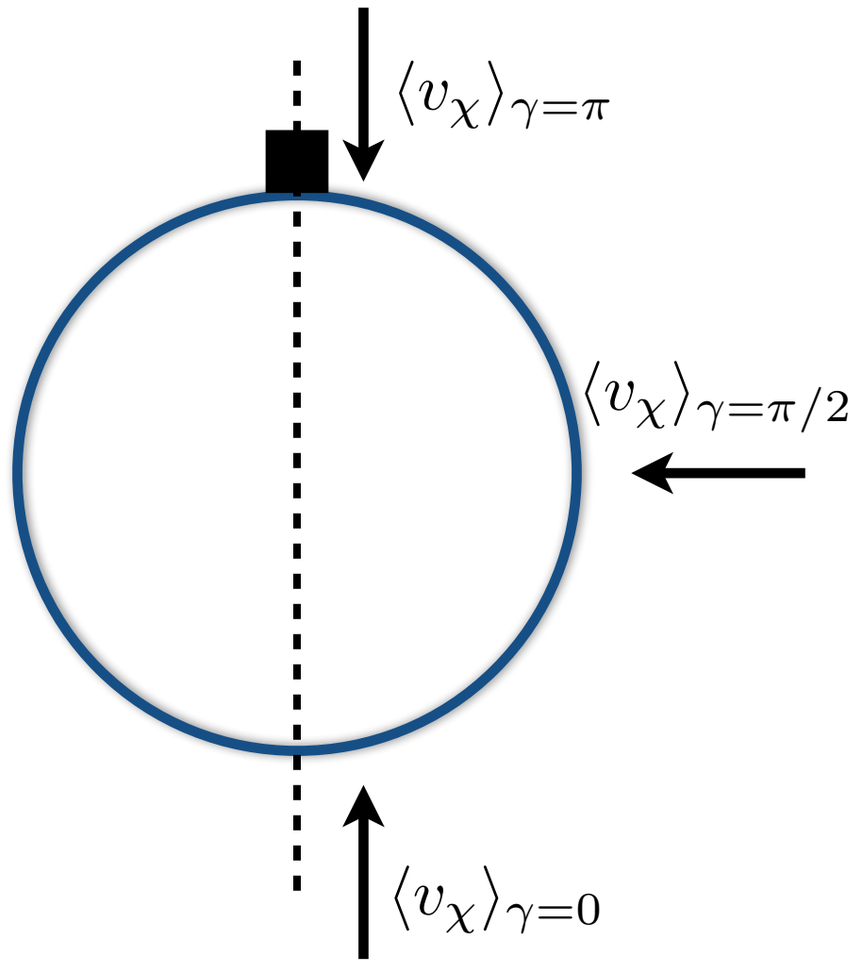


Modulation signal



$$m_\chi = 0.5 \text{ GeV}$$

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



Modulation due to time-variation of γ

↳ Different phase for different interactions!

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
- 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

Conclusions

- Significant Earth-scattering is still allowed and detectable given current constraints
- Need to include both attenuation and deflection of DM - which may enhance the flux
- Careful calculation including multiple elements, correct density profiles and different interactions

- Attenuation only dominates if DM particles must cross the Earth before reaching the detector
- 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

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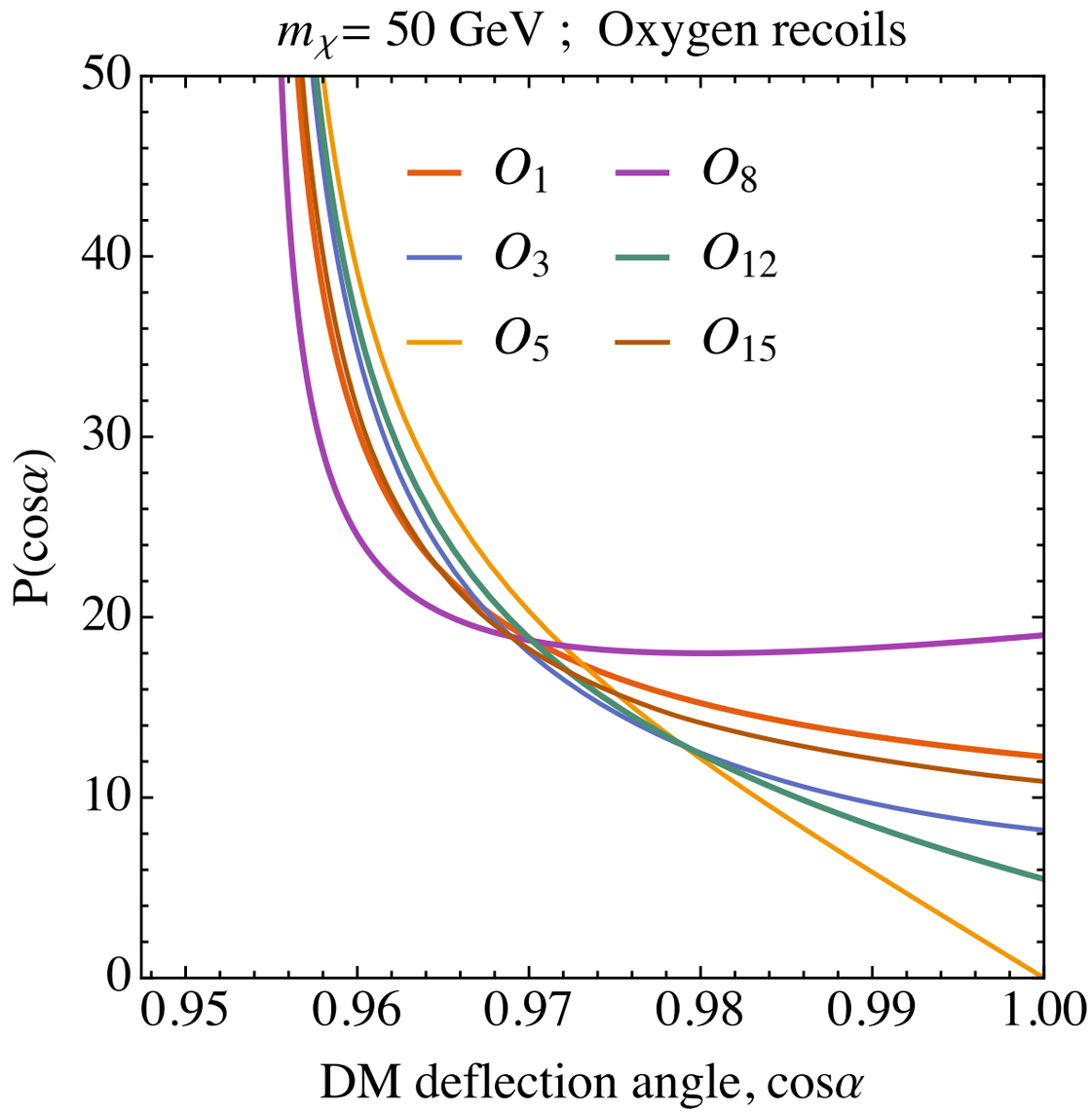
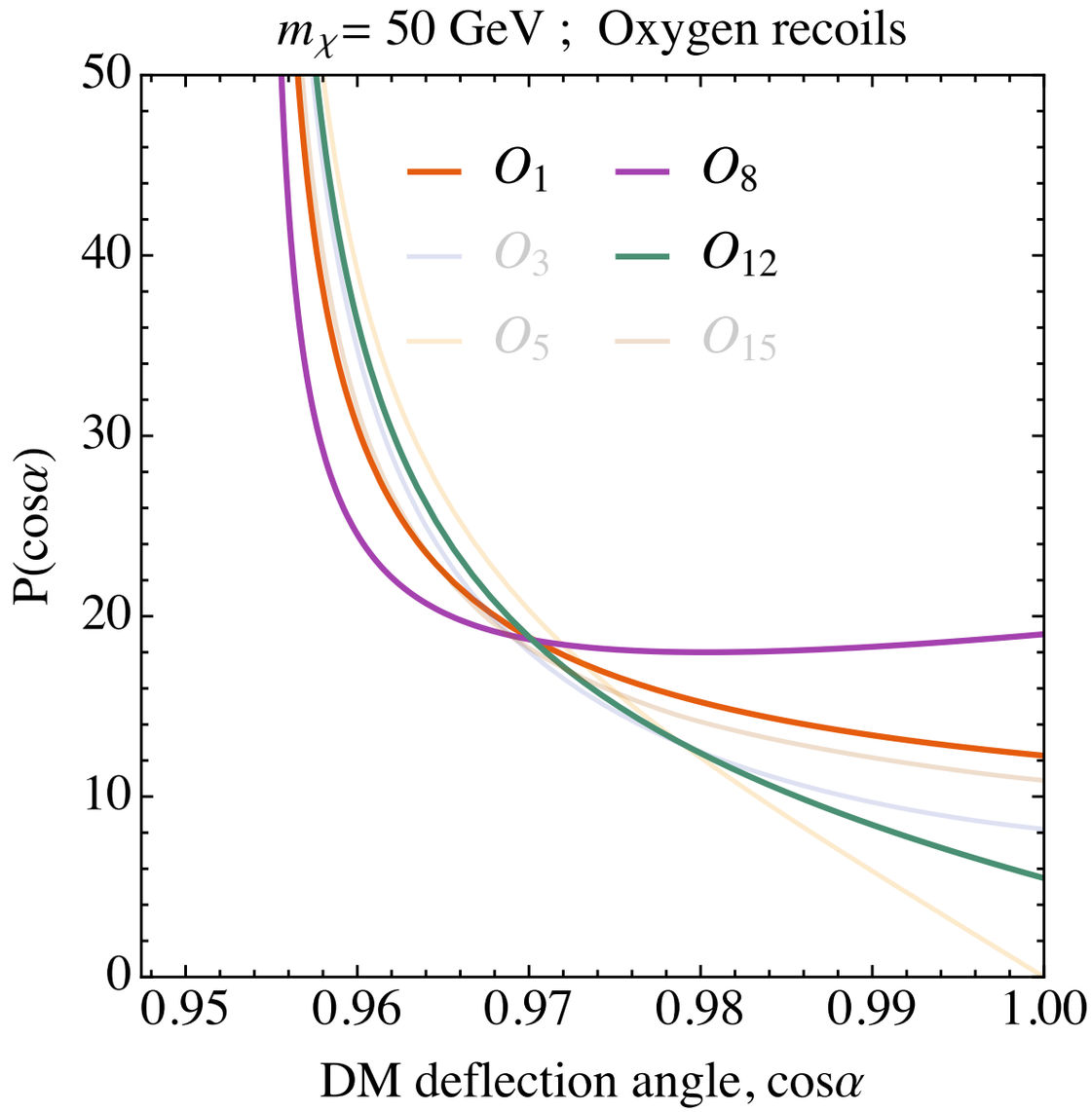
Thank you!

Backup Slides

Heavier DM


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

Heavier DM


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

Maximum cross section