Signatures of Earth-Scattering in the Direct Detection of Dark Matter

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Based on arXiv:1611.05453
with Riccardo Catena and Chris Kouvaris

MPIK, Heidelberg - 9th January 2017

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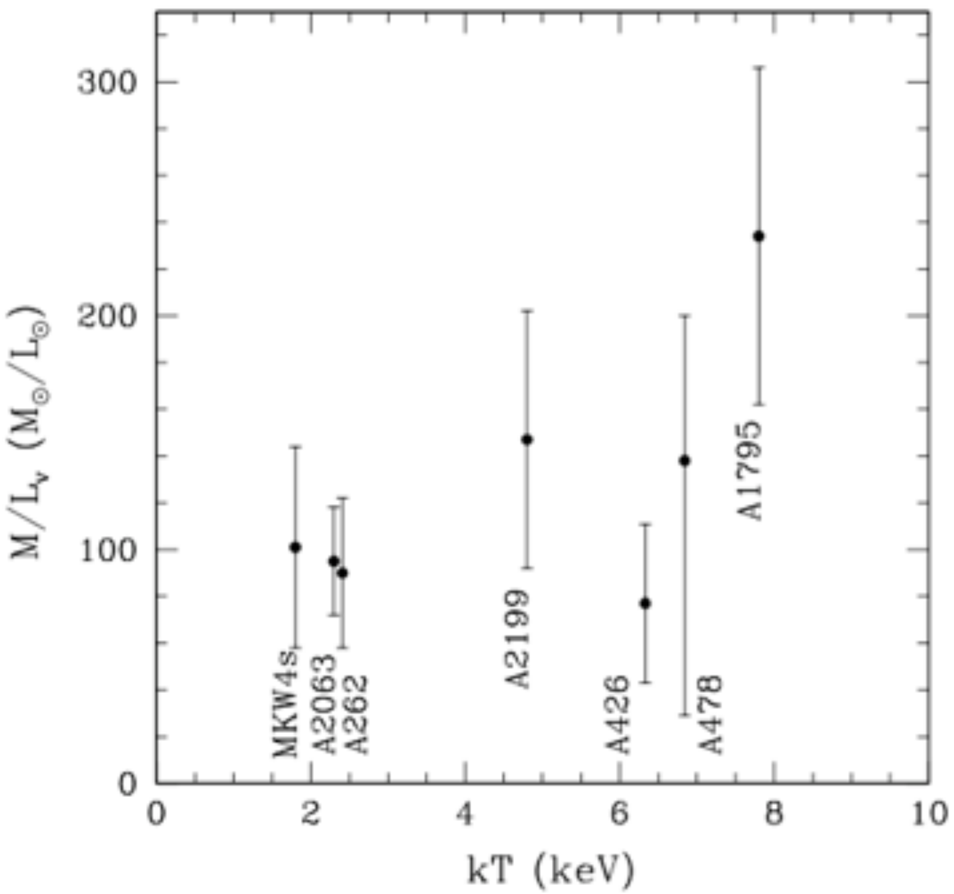
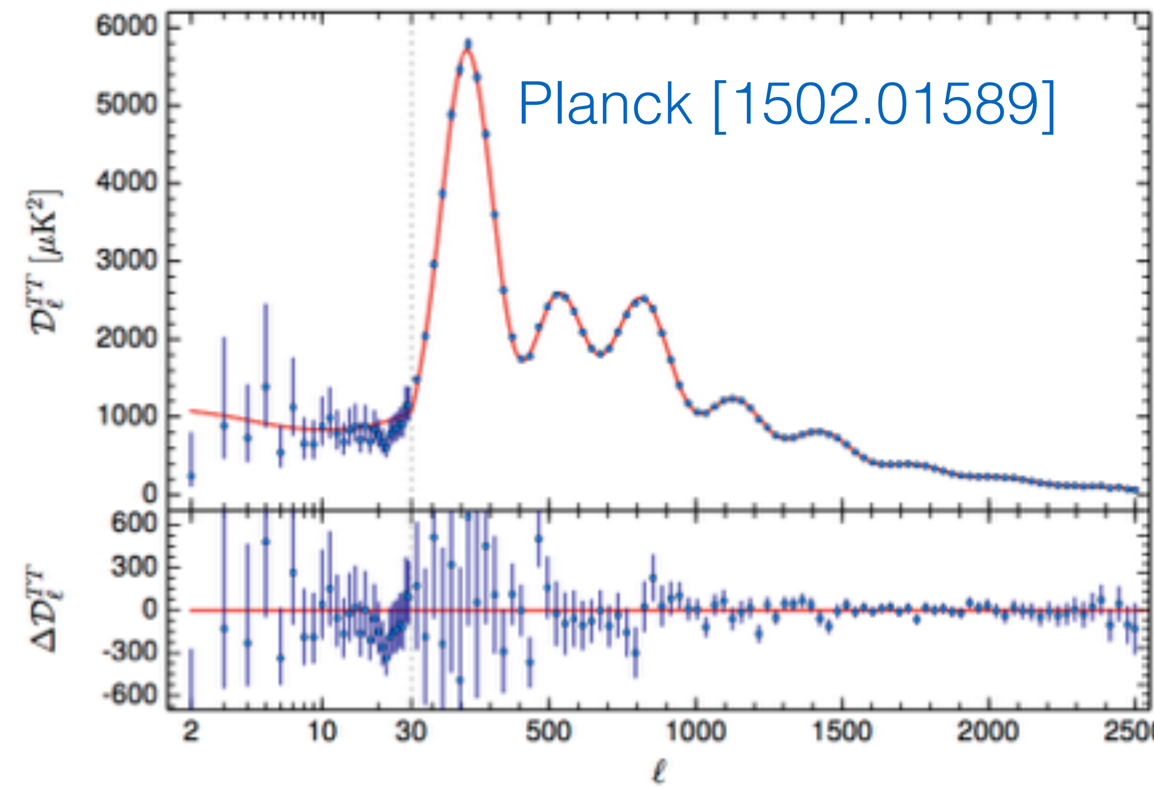
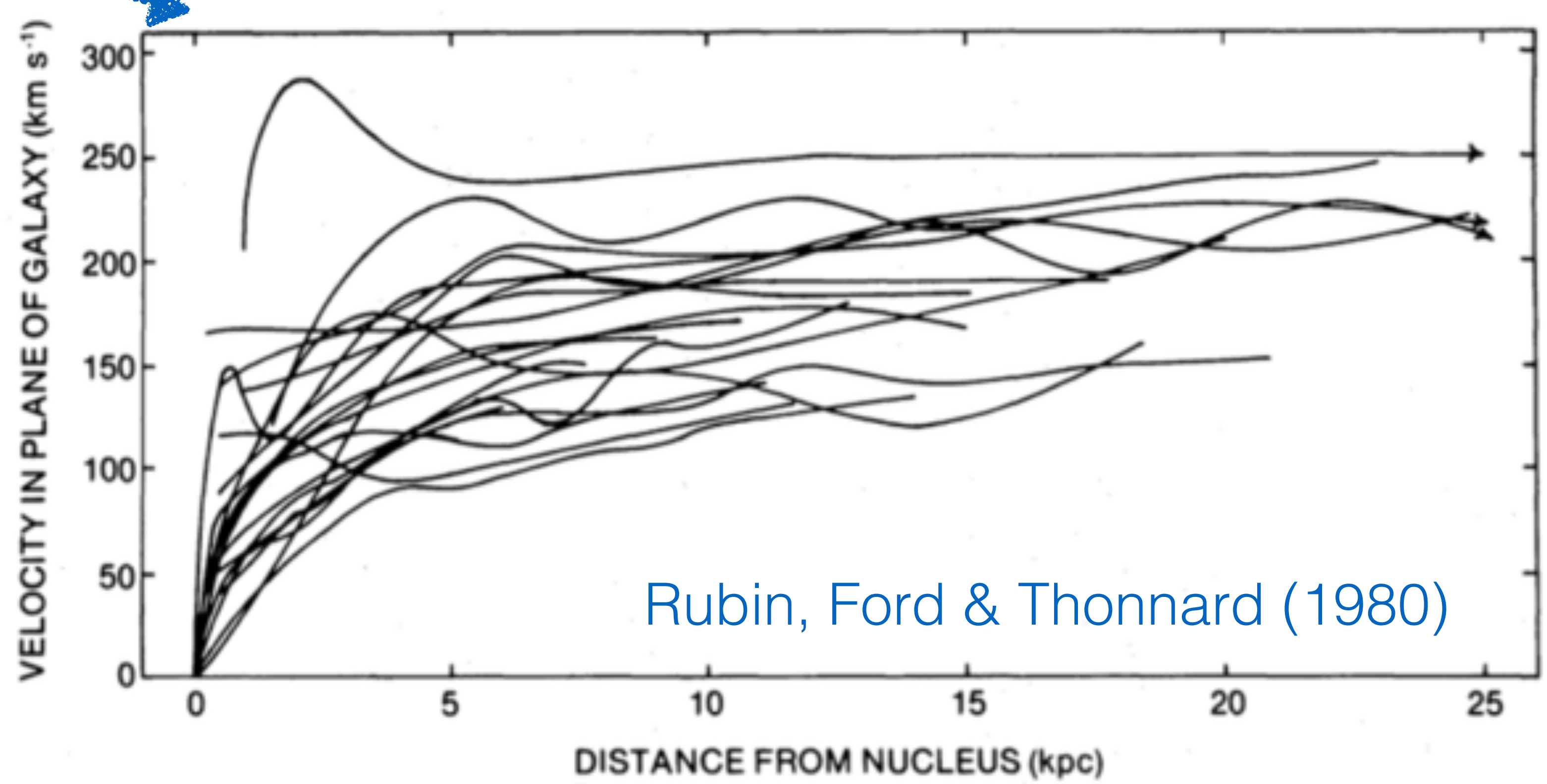
Dark Matter



Hradecky et al. [astro-ph/0006397]





Dark Matter at the Sun's Radius

Global

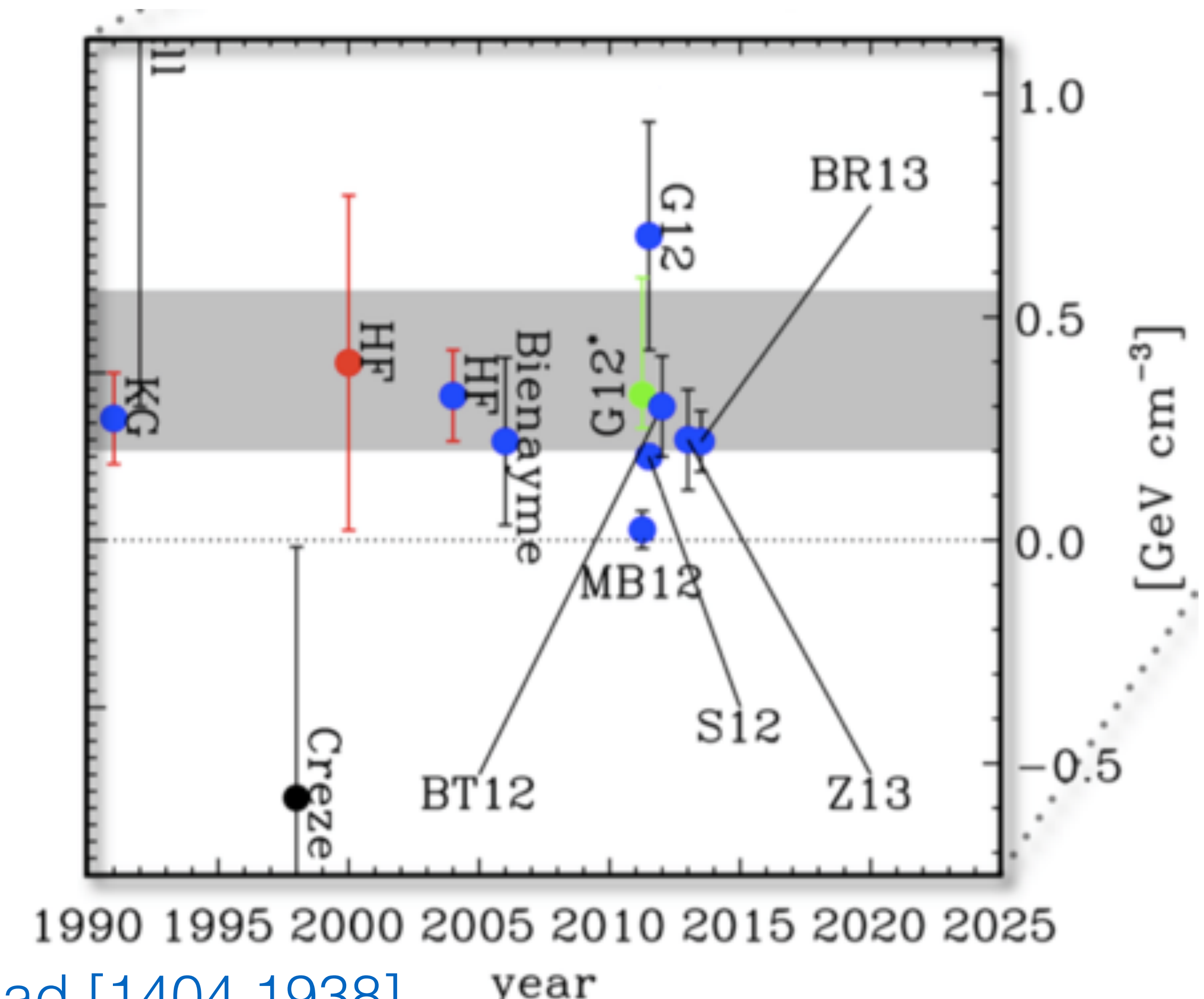
Model total mass distribution in Milky Way and extract DM density at Solar Radius (~8 kpc)

E.g. Iocco et al. [1502.03821]

Local

Estimate local DM density from kinematics of local stars (assuming local disk equilibrium)

E.g. Garbari et al. [1206.0015]



Read [1404.1938]

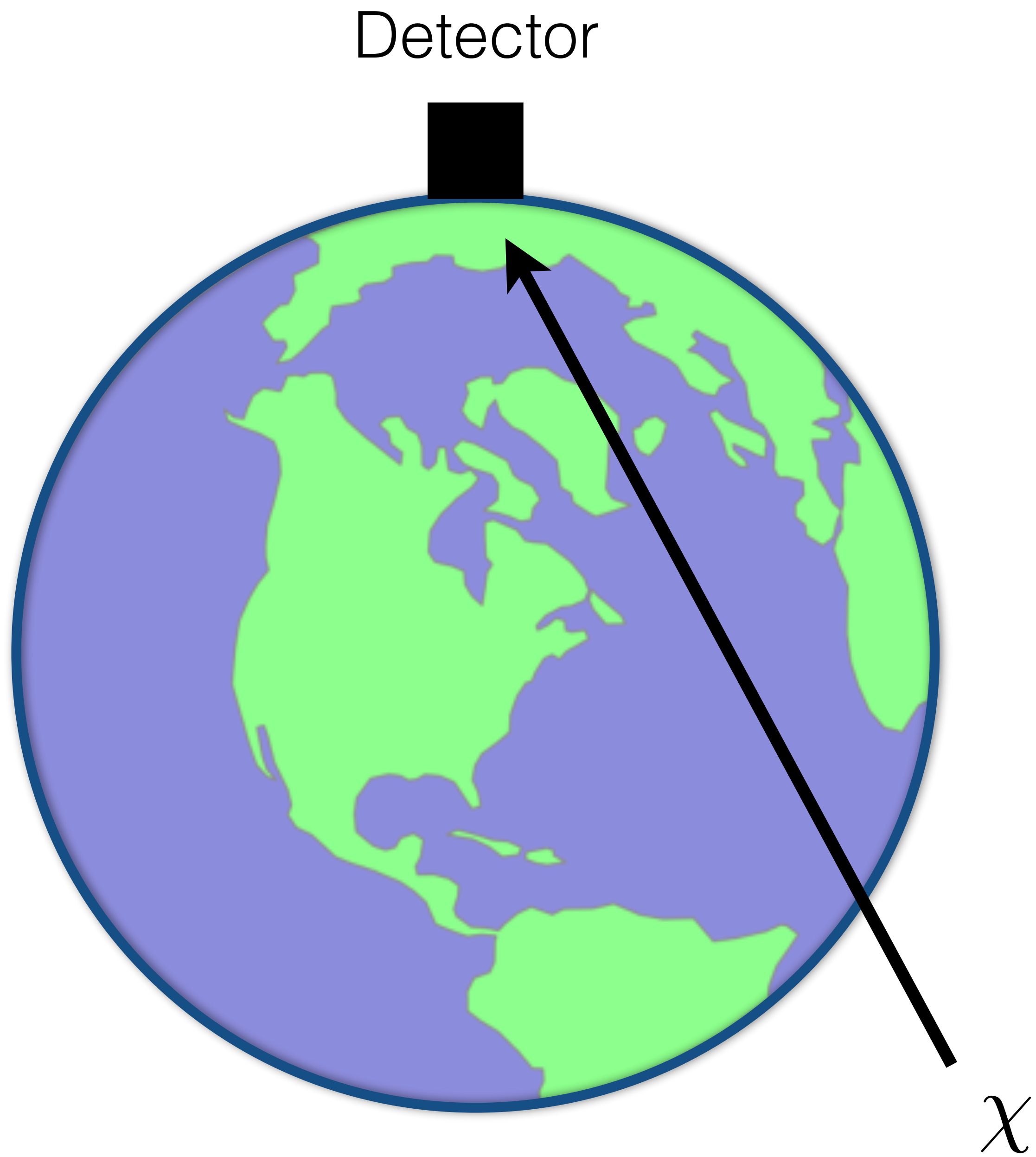
Values in the range:

$$\rho_\chi \sim 0.2\text{–}0.8 \text{ GeV cm}^{-3}$$

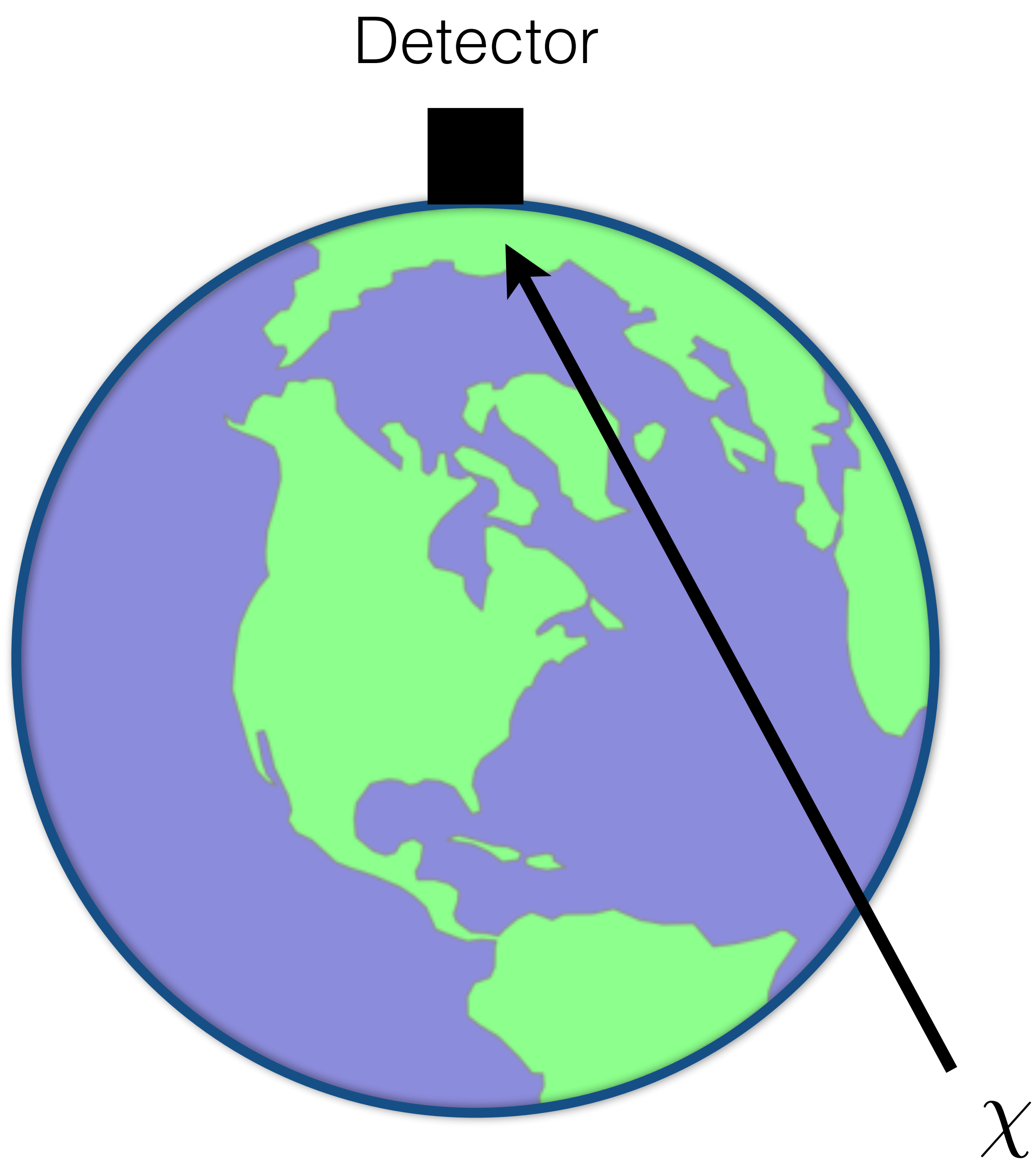
But **not** zero!

c.f. Garbari et al. [1204.3924]

Direct Detection of DM on Earth

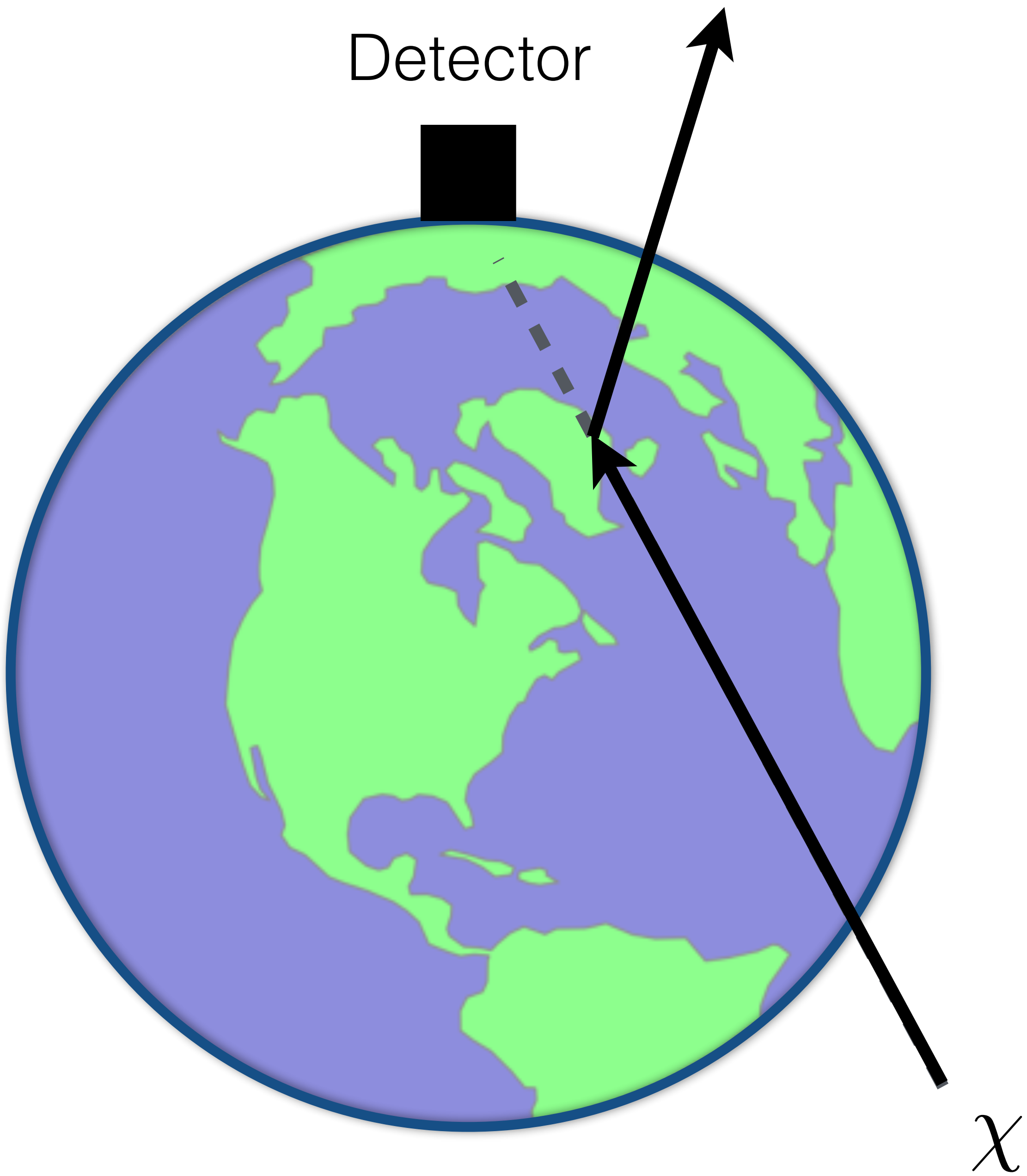


Direct Detection of DM on Earth



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

Earth-Scattering - Attenuation



Previous calculations usually only consider DM attenuation

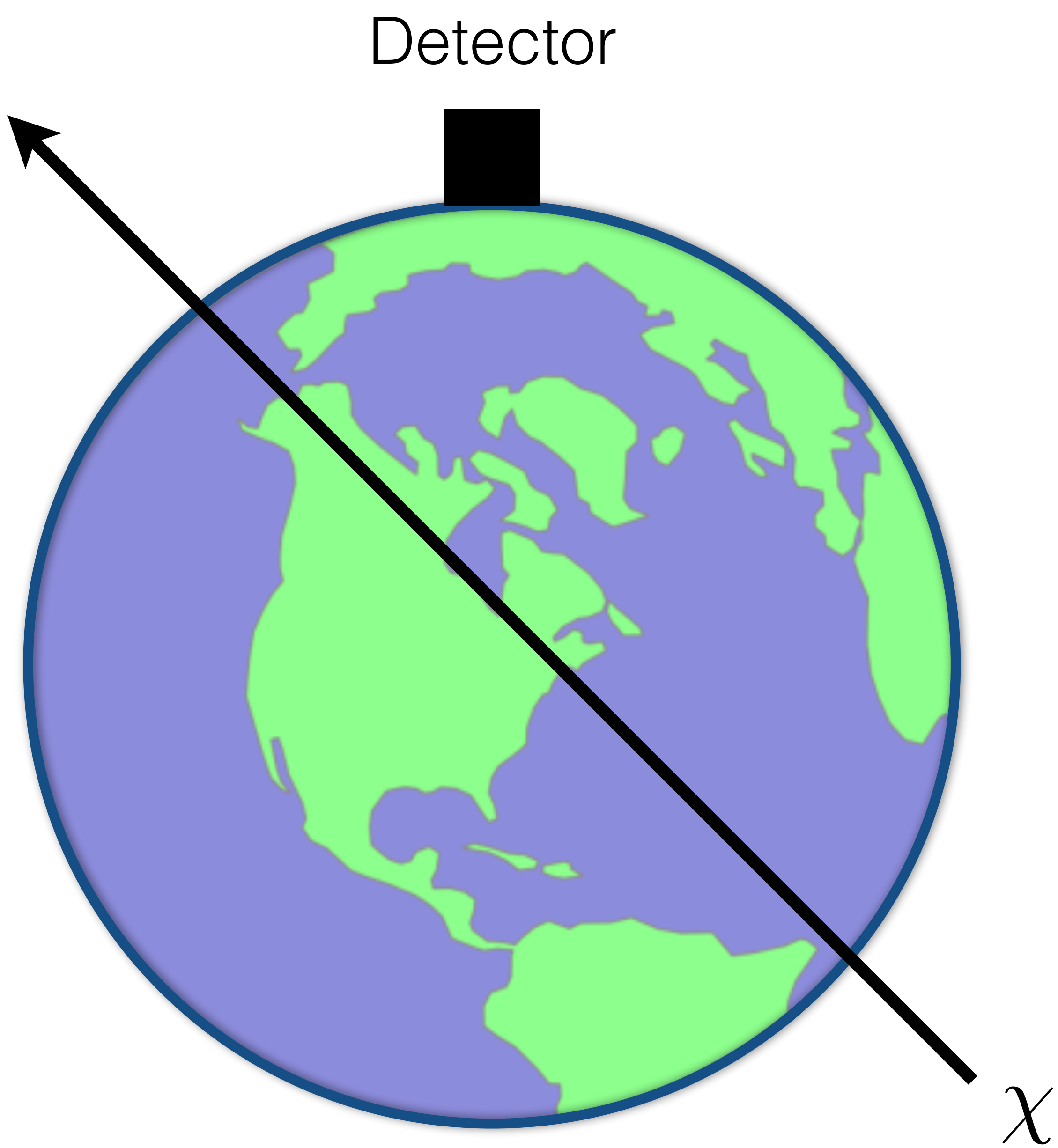
Zaharijas & Farrar [astro-ph/0406531]

Kouvaris & Shoemaker [1405.1729,1509.08720]

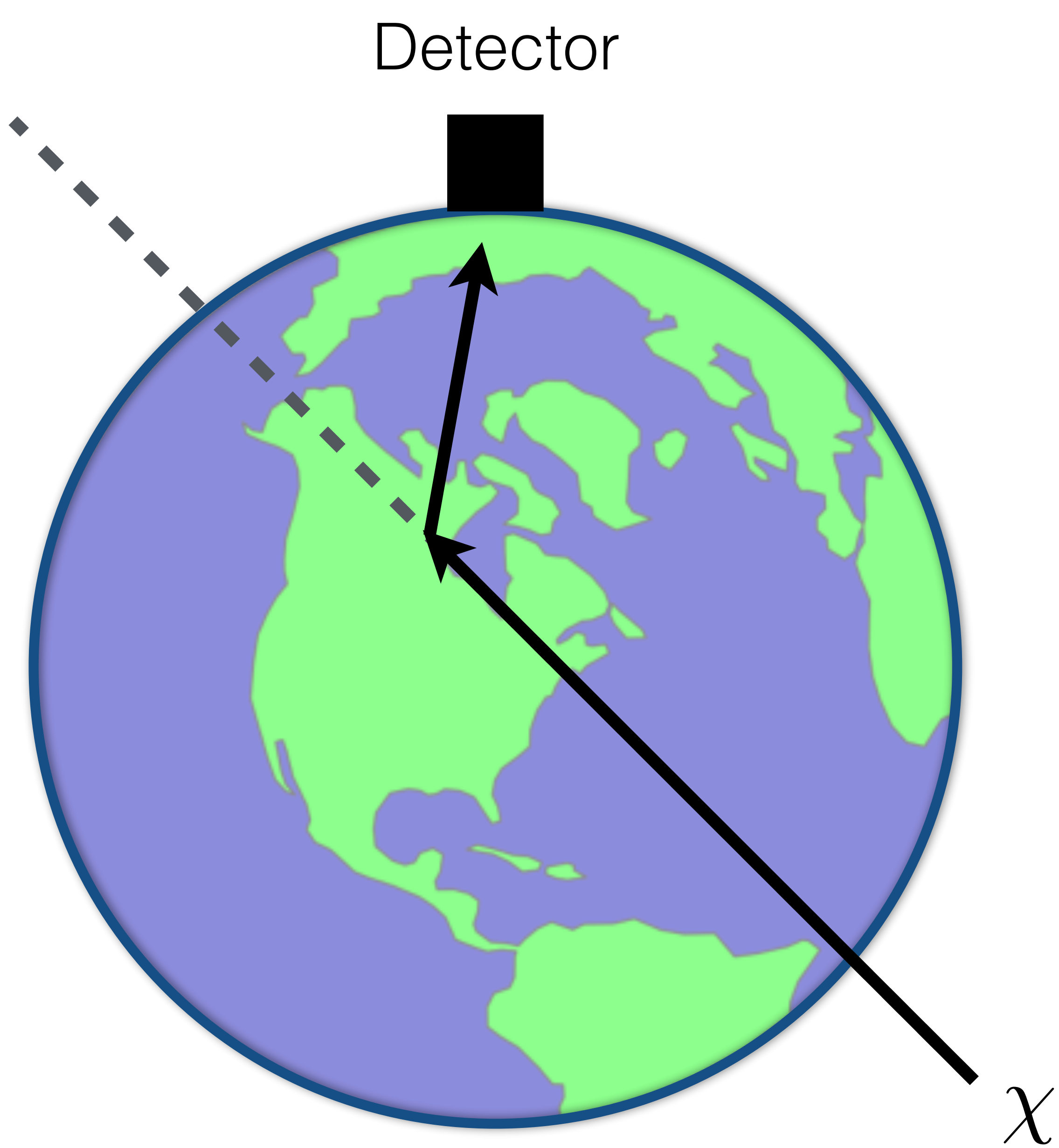
DAMA [1505.05336]

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

Earth-Scattering - Deflection



Earth-Scattering - Deflection



Assuming DM mean free path

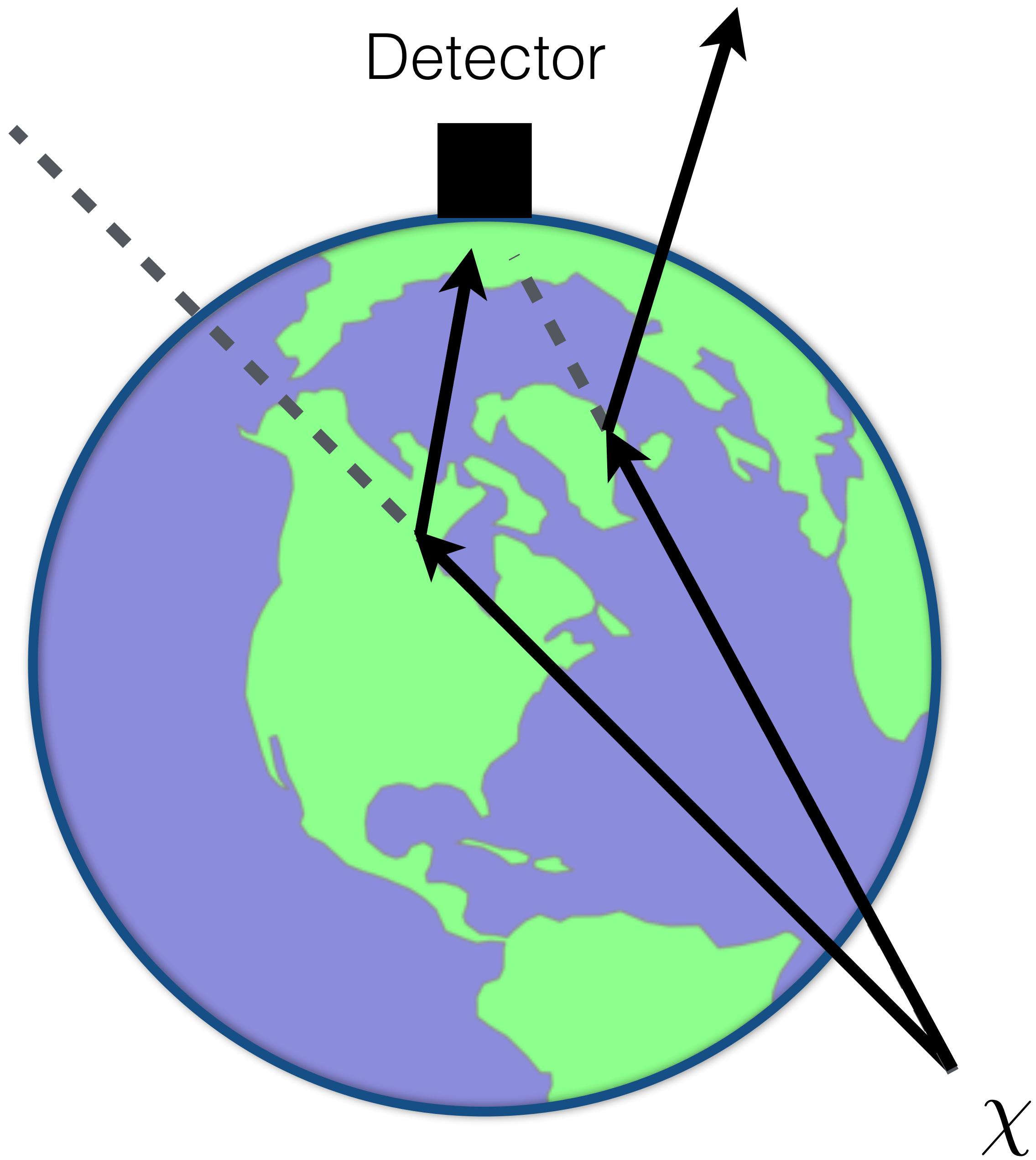
$$\lambda \gtrsim R_E$$

Considered in early Monte Carlo simulations

Collar & Avignone [PLB 275, 1992 and others]

We'll use the 'single scatter' approximation…

Earth-Scattering



Assuming DM mean free path

$$\lambda \gtrsim R_E$$

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

→ altered flux, daily modulation, directionality…

Outline

Direct Detection (a more detailed look)

Calculating the Earth-Scattering effect

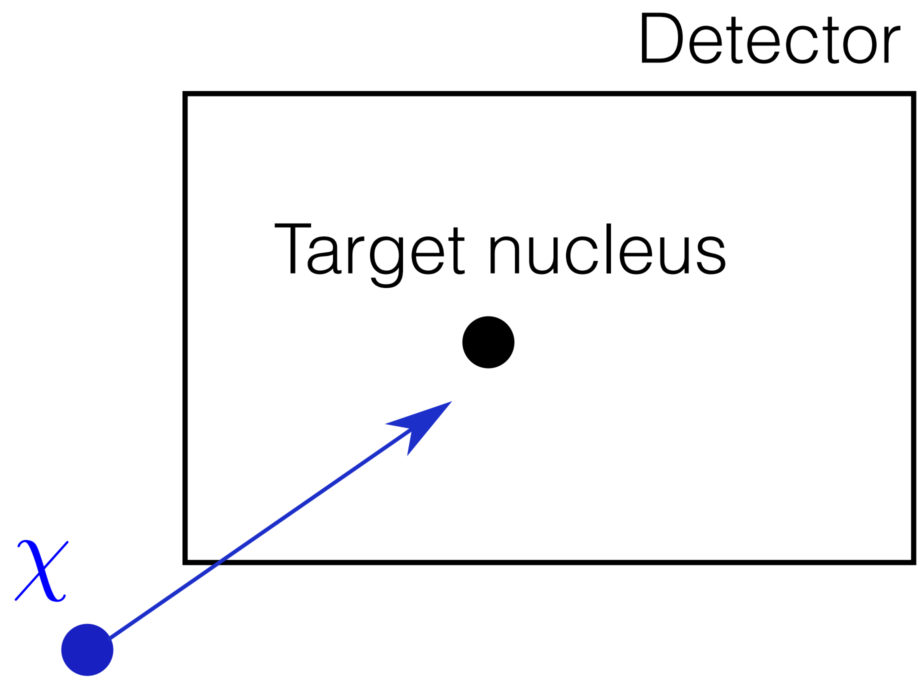
Non-relativistic Effective Field Theory of DM

Impact on the DM velocity distribution and modulation signatures

Future work

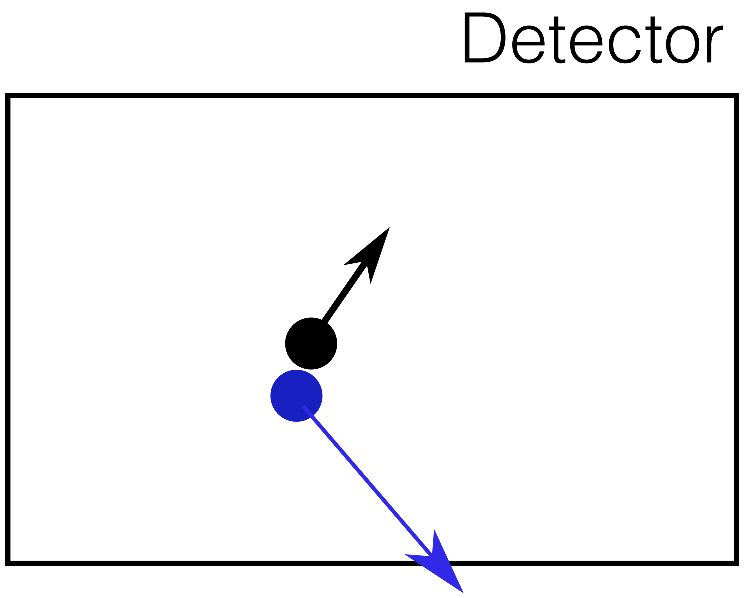
Direct detection

$$m_\chi \gtrsim 1\ \mathrm{GeV}$$
$$v \sim 10^{-3}$$



Direct detection

$$m_\chi \gtrsim 1 \text{ GeV}$$
$$v \sim 10^{-3}$$



Direct detection

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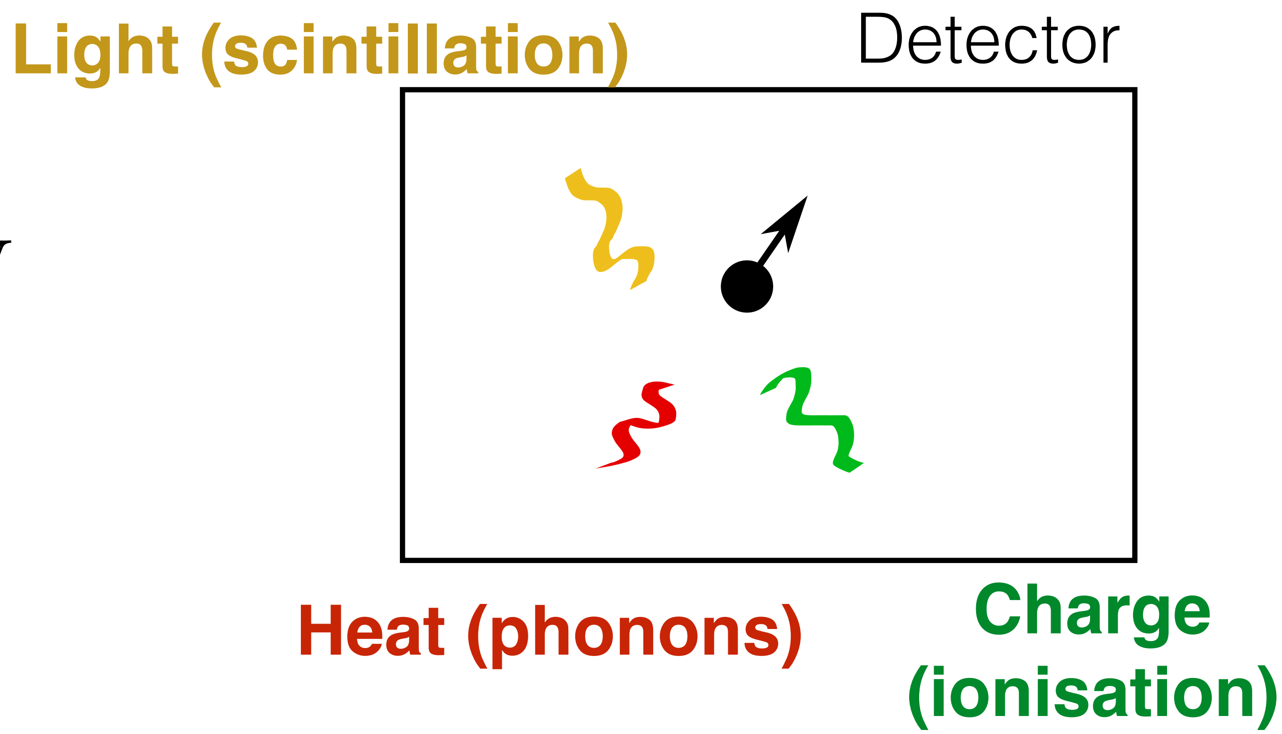
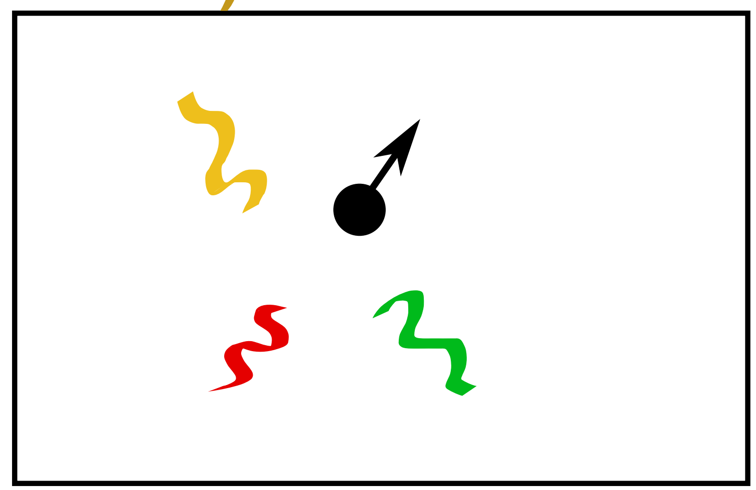


Direct detection



$$m_\chi \gtrsim 1 \text{ GeV}$$
$$v \sim 10^{-3}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{\mathrm{min}}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \, \mathrm{d}^3\mathbf{v}$$

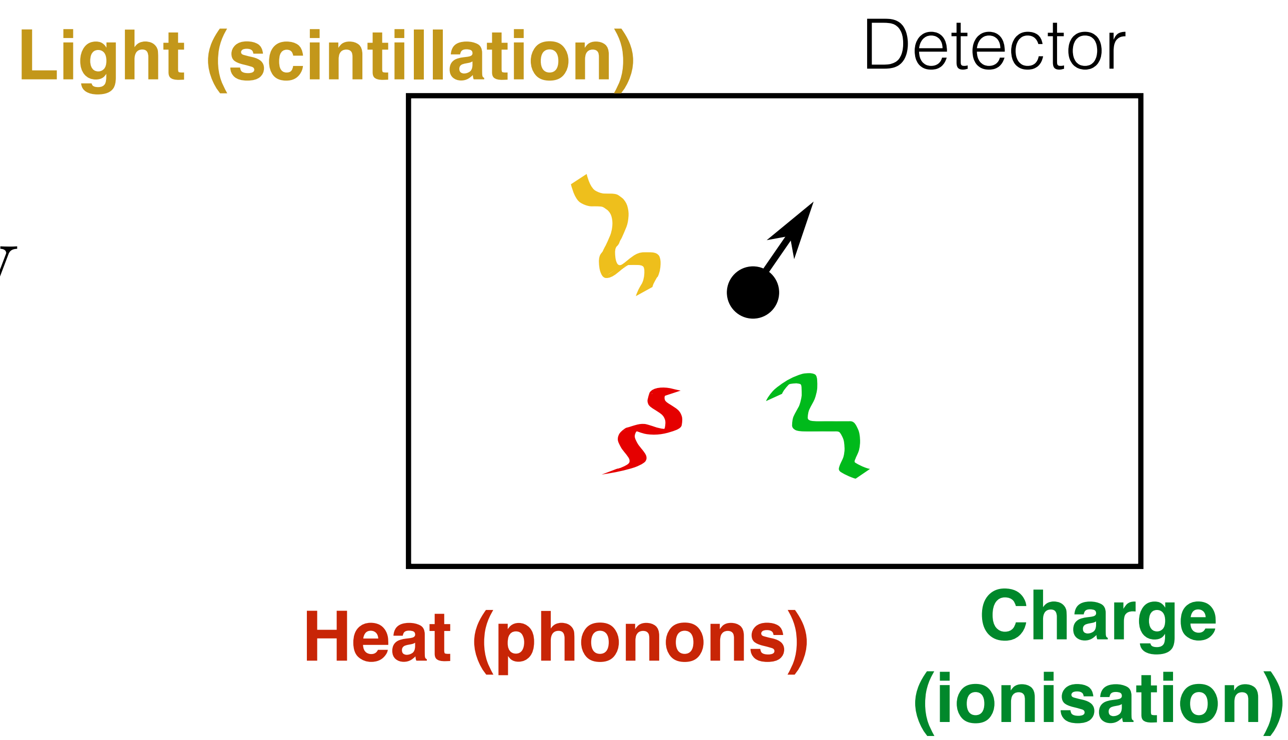
Include all particles with enough speed to excite recoil of energy E_R:

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

Direct detection

$m_\chi \gtrsim 1$ GeV

$v \sim 10^{-3}$



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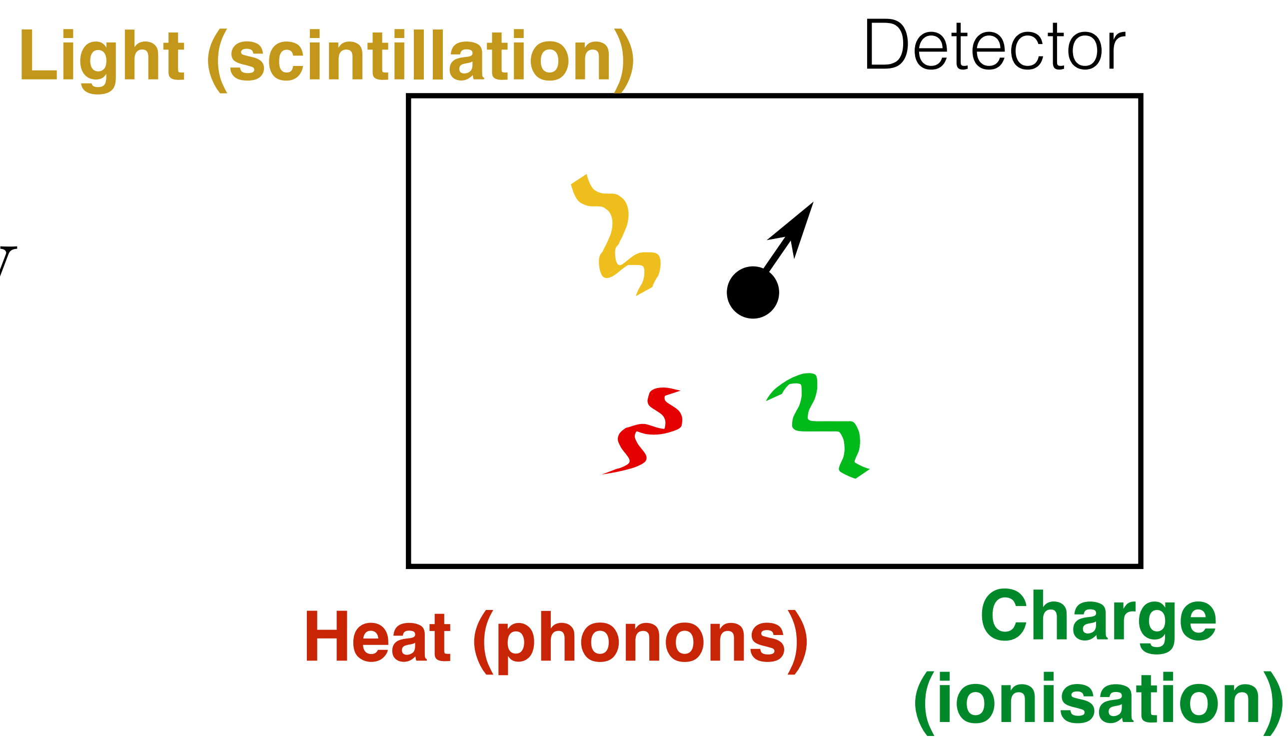
Astrophysics

Particle and nuclear physics

Include all particles with enough speed to excite recoil of energy E_R:

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

Direct detection



$$m_\chi \gtrsim 1\ \mathrm{GeV}$$
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Astrophysics

Particle and nuclear physics

Include all particles with enough speed to excite recoil of energy E_R:

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

But plenty of alternative ideas:
DM-electron recoils [1108.5383]
Superconducting detectors [1504.07237]
Axion DM searches [1404.1455]

Particle Physics of DM (the simple picture)

Typically assume contact interactions (heavy mediators).
In the non-relativistic limit, obtain two main contributions.
Write in terms of DM-proton cross section σ^p:

$$\frac{\mathrm{d}\sigma^A}{\mathrm{d}E_R} \propto \frac{\sigma^p}{\mu_{\chi p}^2 v^2} \mathcal{C}_A F^2(E_R)$$

Form factor accounts for loss of coherence at high energy

Enhancement factor different for:

spin-independent (SI) interactions - $\mathcal{C}_A^{\mathrm{SI}} \sim A^2$

spin-dependent (SD) interactions - $\mathcal{C}_A^{\mathrm{SD}} \sim (J+1)/J$

Interactions which are higher order in v are possible - see later…

Astrophysics of DM (the simple picture)

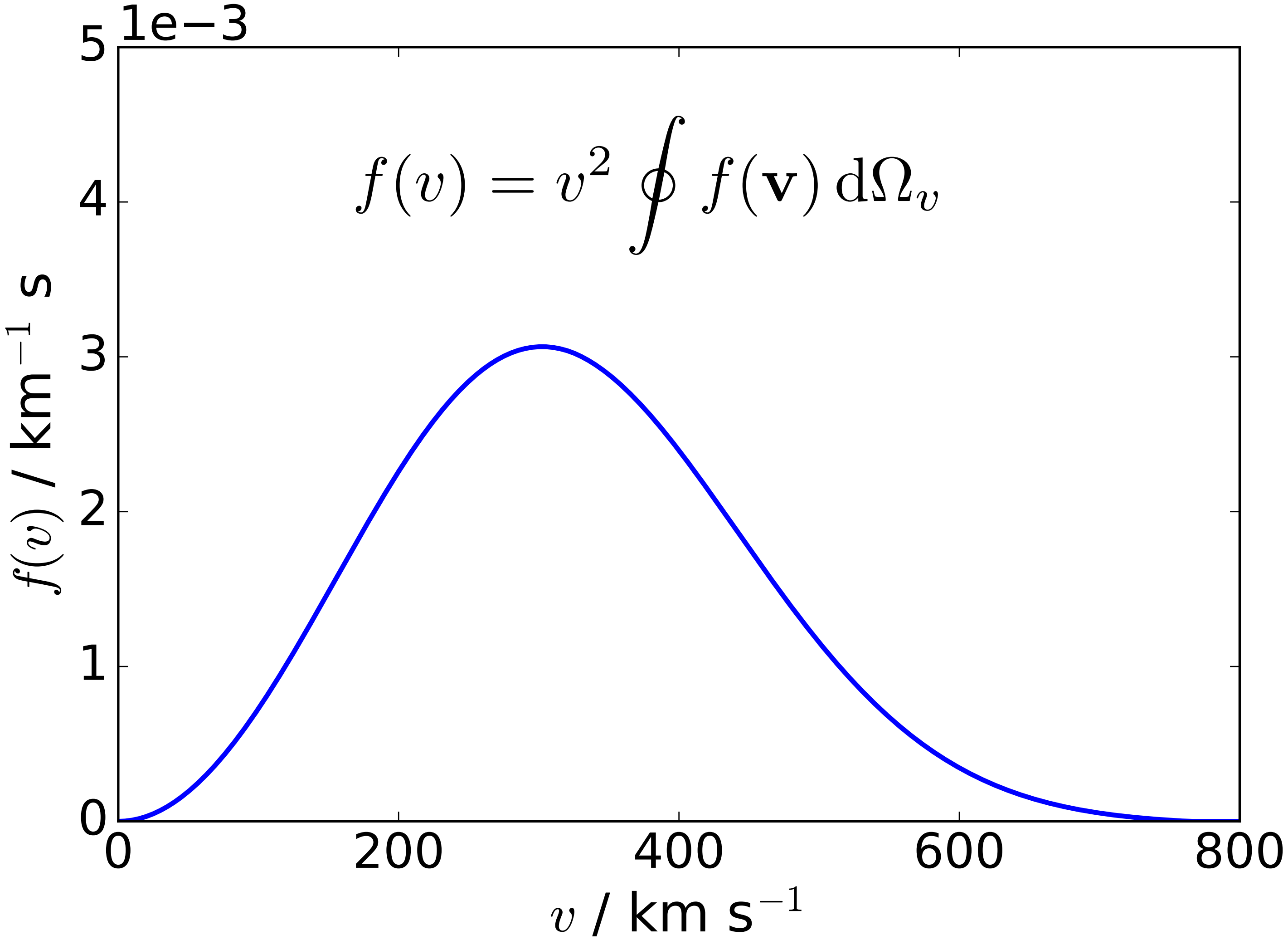
Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution (in the lab frame):

$$f_{\mathrm{Lab}}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v} - \mathbf{v}_\mathrm{e})^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v} - \mathbf{v}_\mathrm{e}| - v_\mathrm{esc})$$

which is well matched in some hydro simulations.

[1601.04707, 1601.04725, 1601.05402]



$\mathbf{v}_e$ - Earth's Velocity

$$v_e \sim 220 - 250\,\mathrm{km\,s^{-1}}$$

$$\sigma_v \sim 155 - 175\,\mathrm{km\,s^{-1}}$$

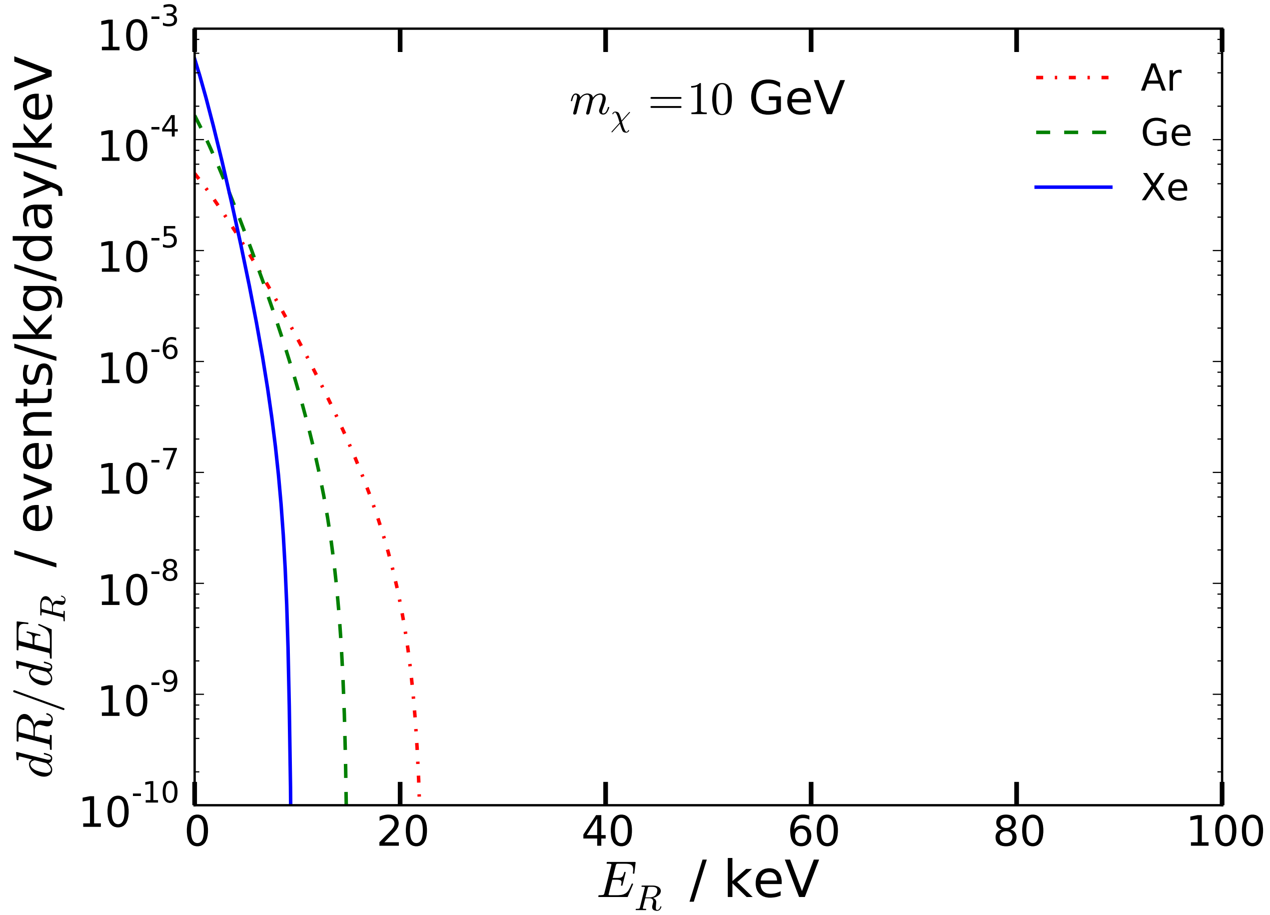
Feast et al. [astro-ph/9706293], Bovy et al. [1209.0759]

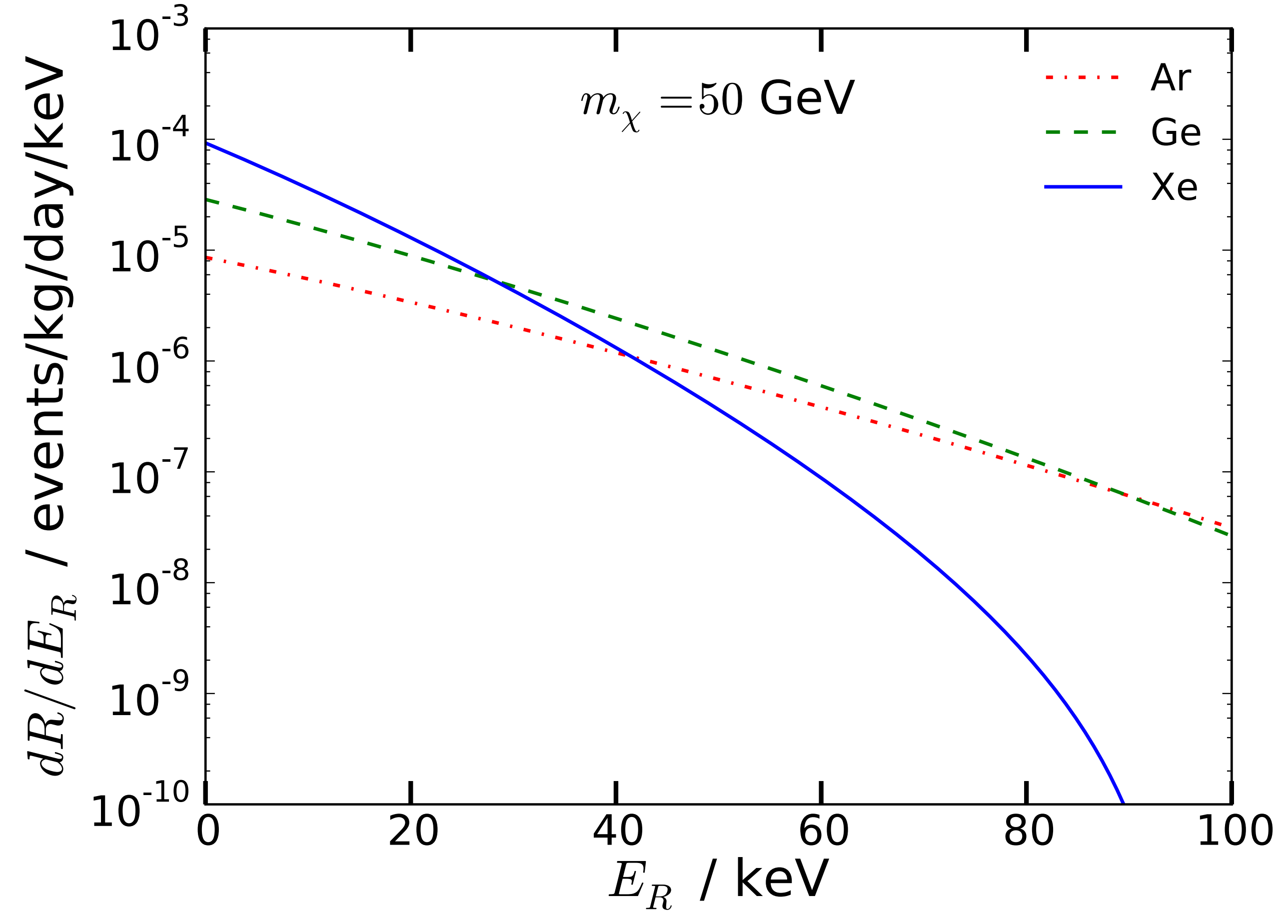
$$v_\mathrm{esc} = 533^{+54}_{-41}\,\mathrm{km\,s^{-1}}$$

Piffl et al. (RAVE) [1309.4293]

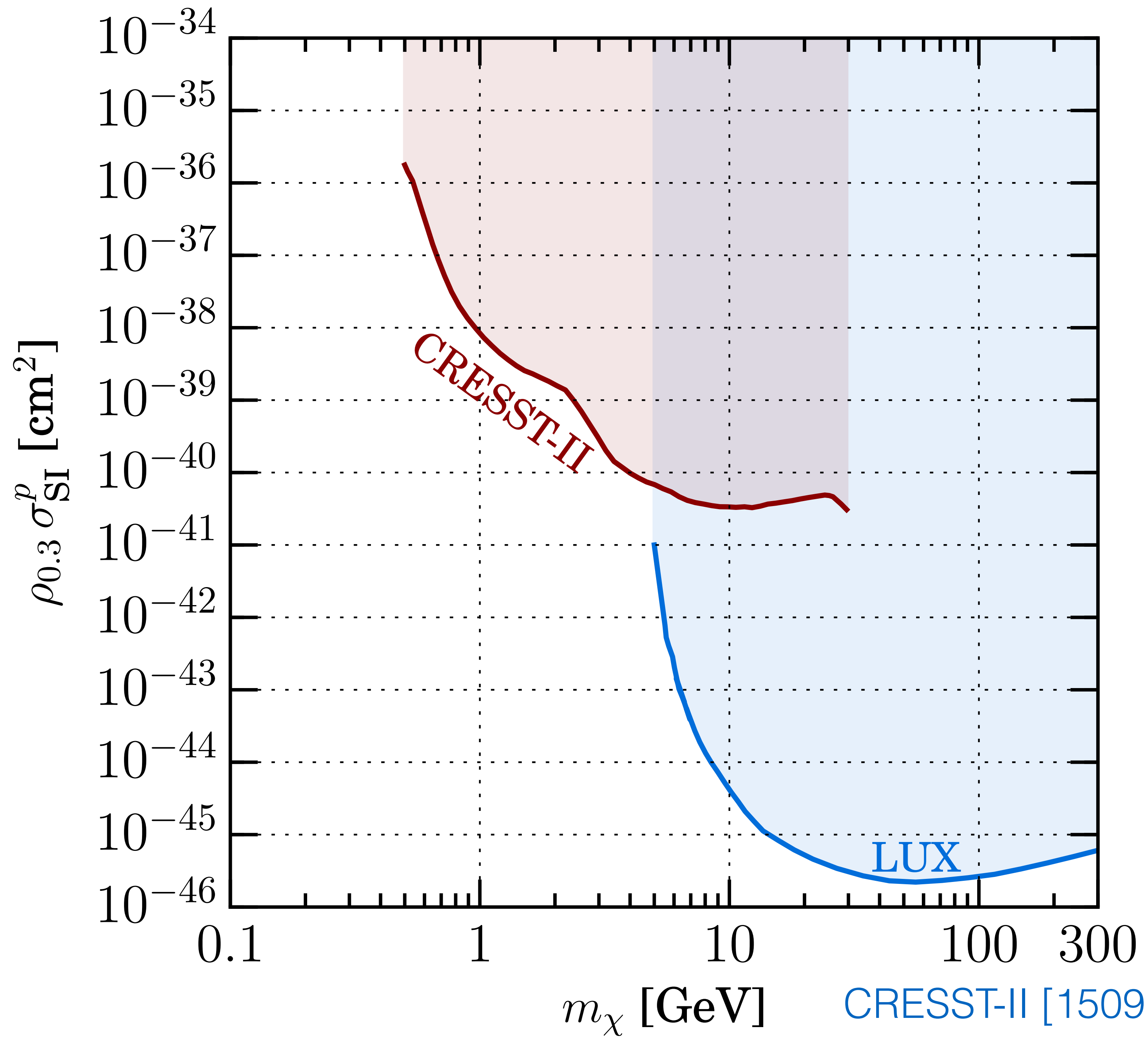
The final event rate

SI interactions, SHM distribution





The current landscape



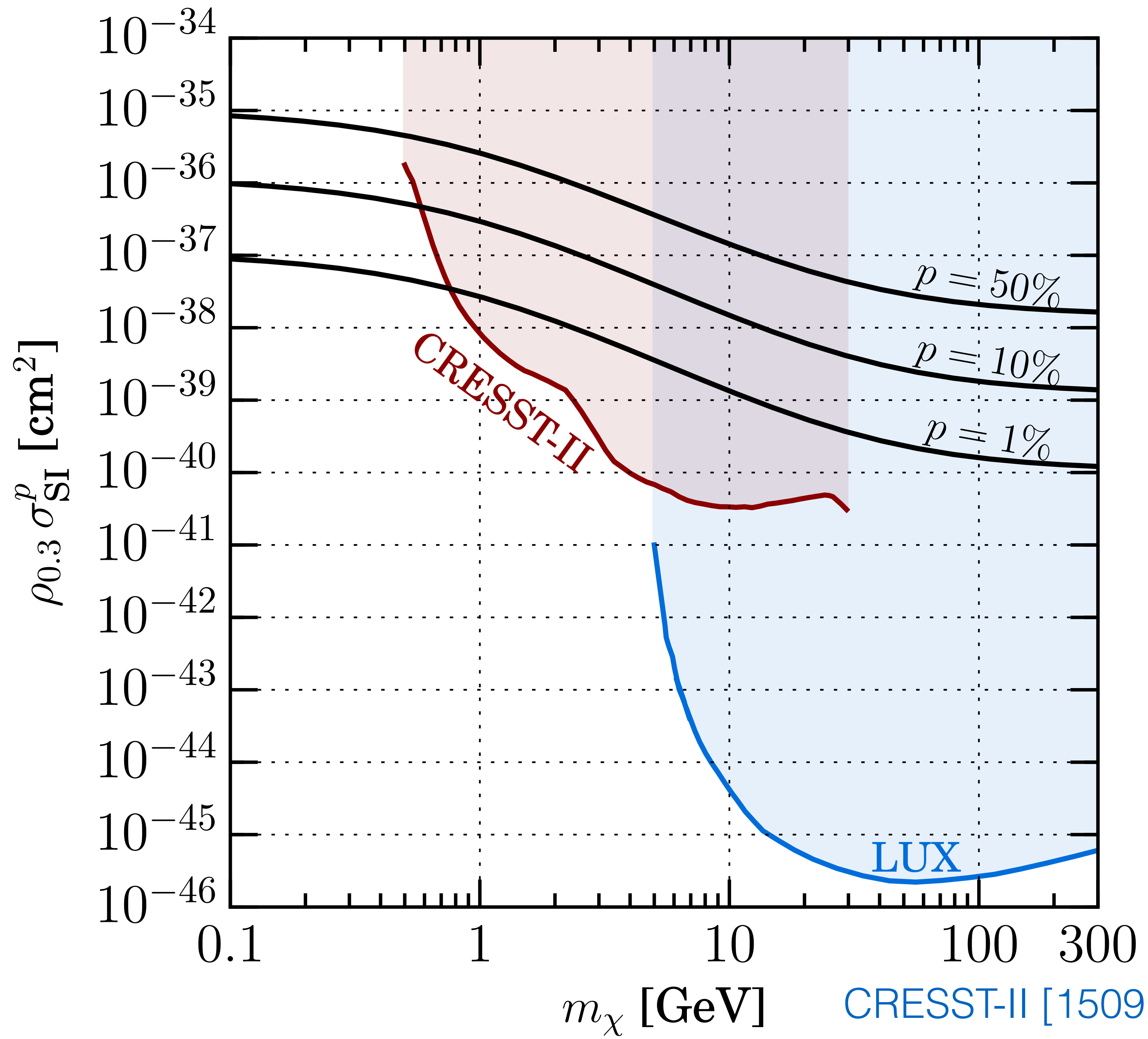
CRESST-II [1509.01515]

LUX [1608.07648]

+ many others…

How big is the probability of scattering in the Earth?

The current landscape



CRESST-II [1509.01515]

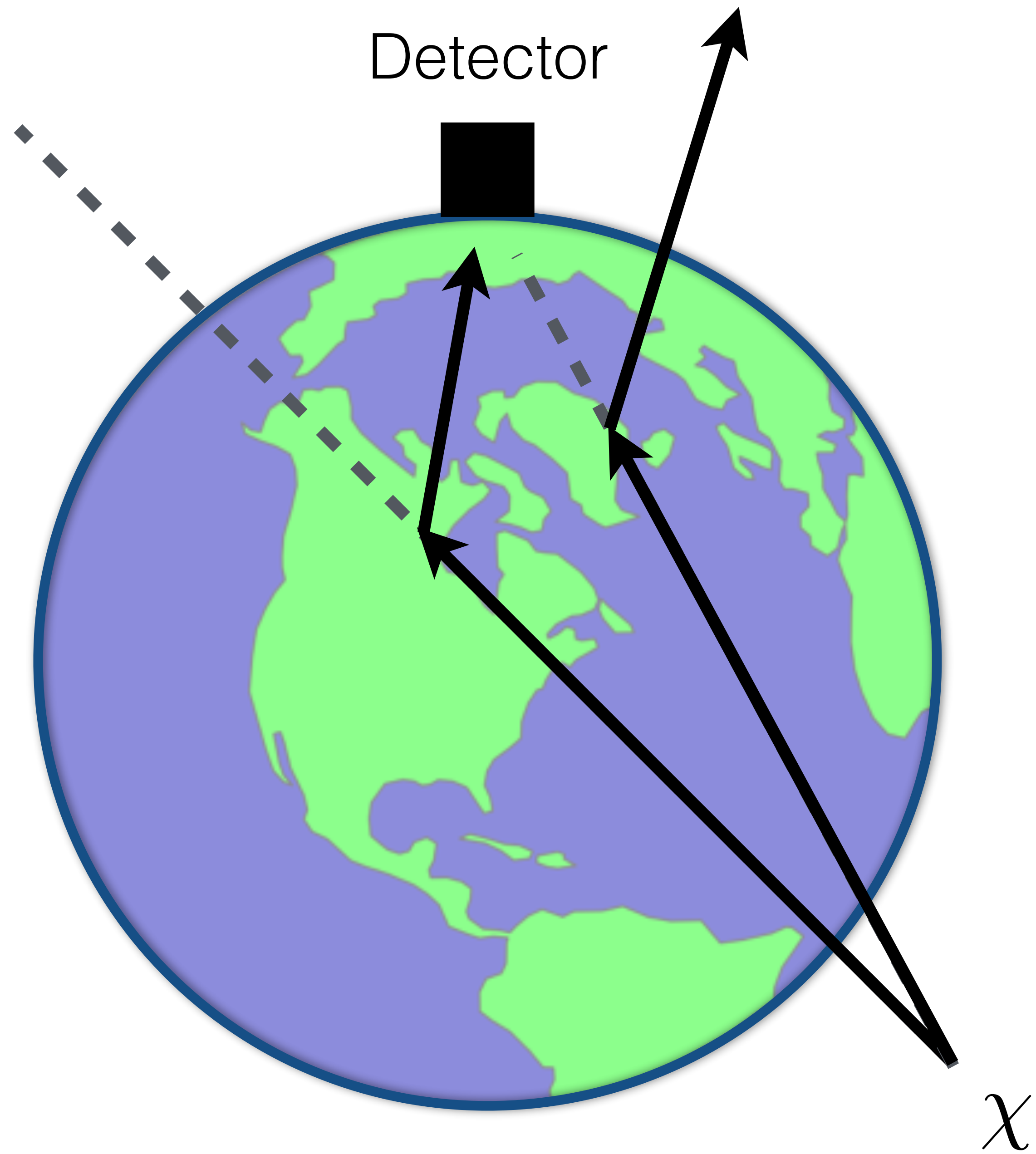
LUX [1608.07648]

+ many others…

What effect can DM scattering in the Earth have?

Earth-Scattering

Earth-Scattering Calculation



Assuming DM mean free path

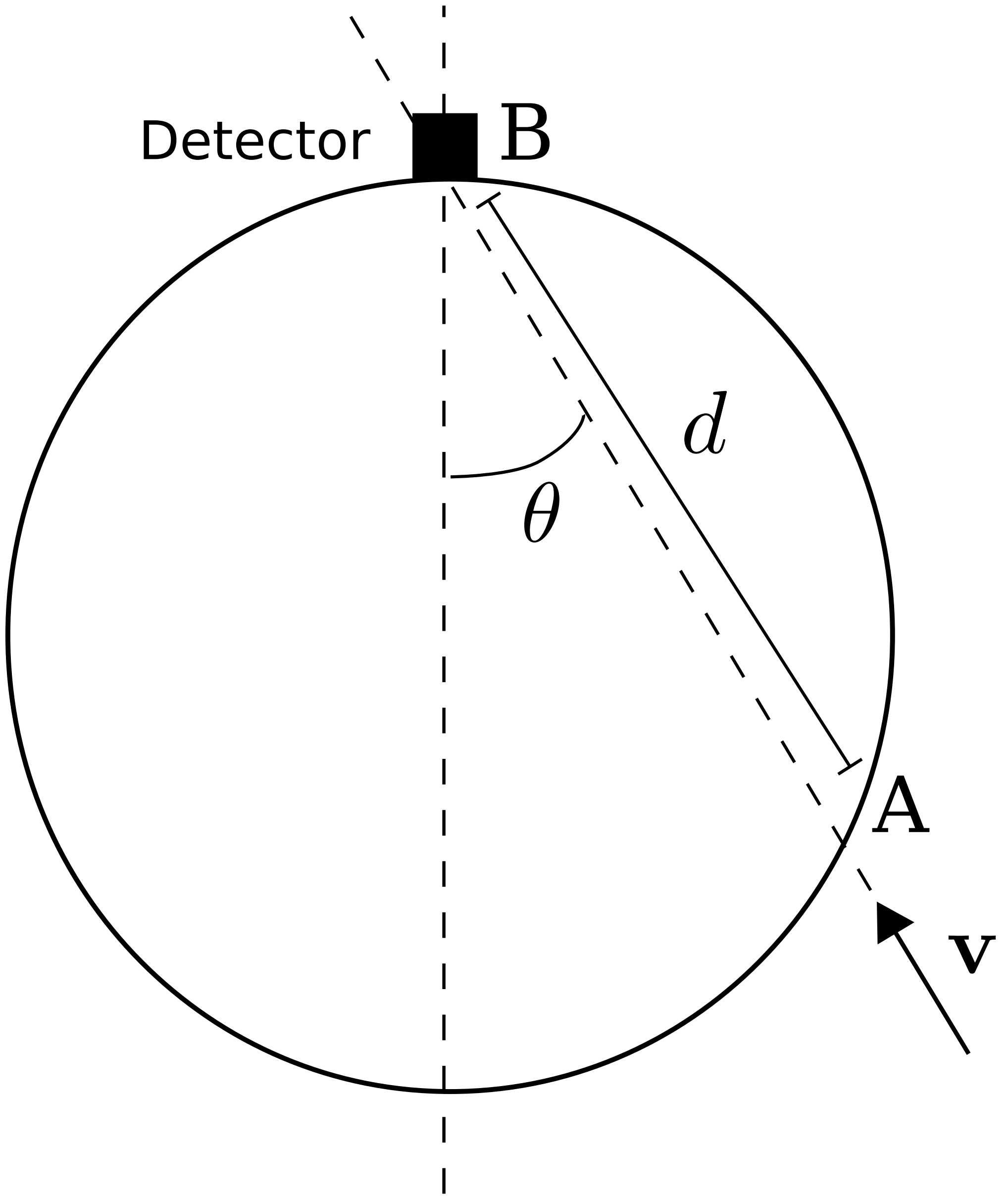
$$\lambda \gtrsim R_E$$

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

Attenuation

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

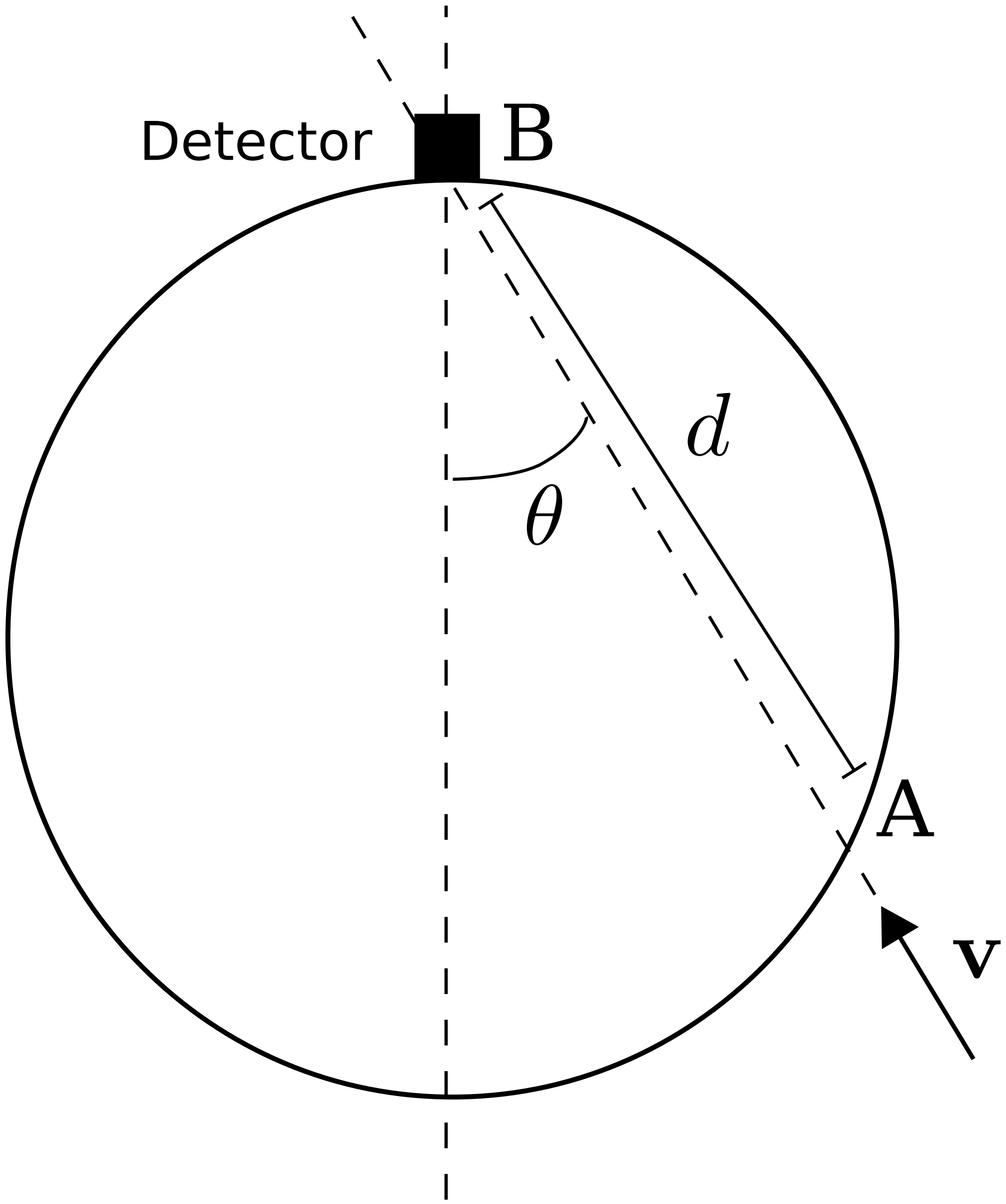
$\lambda(v)^{-1} = n\,\sigma(v)$



$$f_0(\mathbf{v}) - f_A(\mathbf{v}) = f_0(\mathbf{v}) \exp\left[-\frac{d(\cos\theta)}{\lambda(v)}\right]$$

Attenuation

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



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

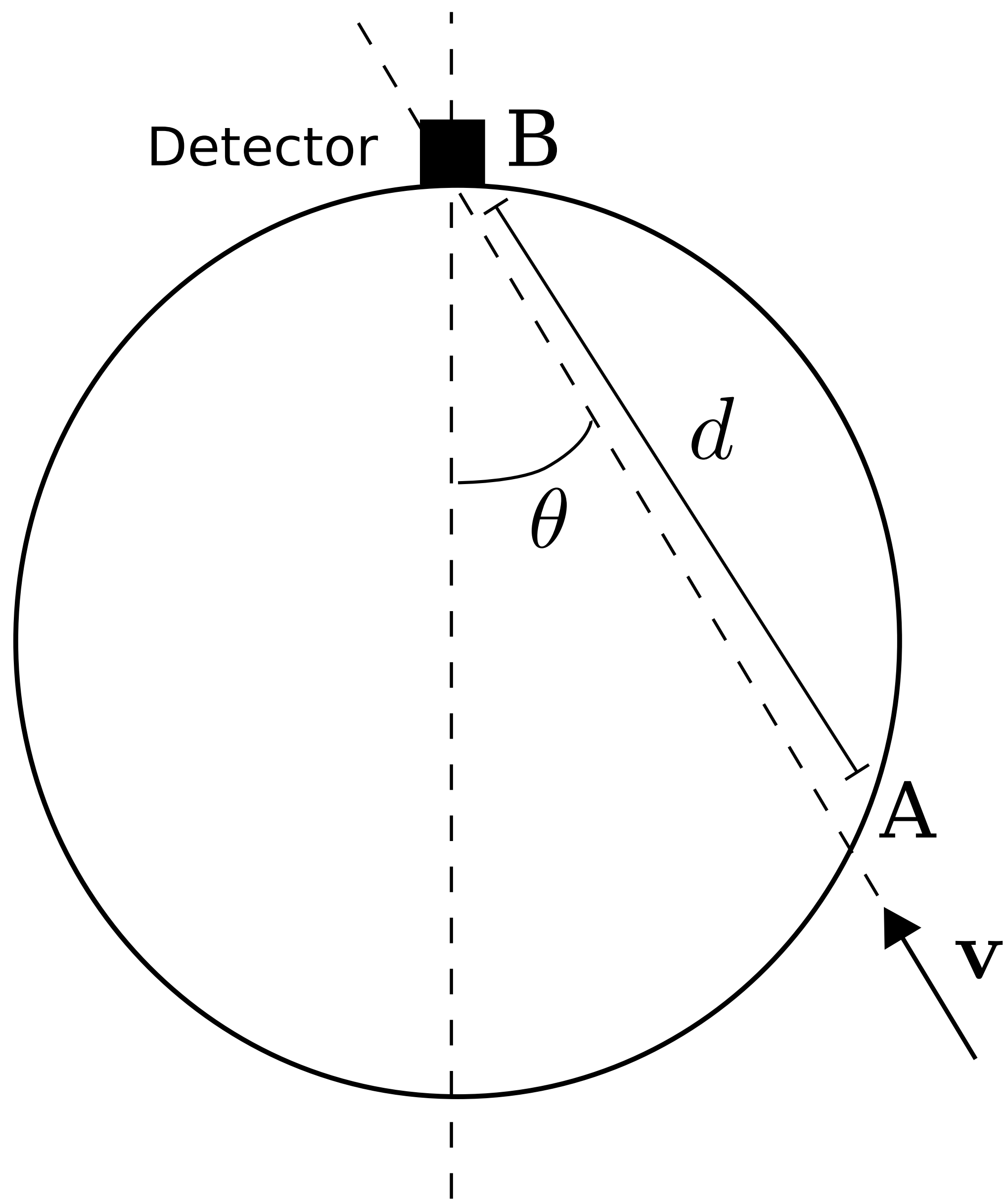
$$d_{\mathrm{eff}} = \frac{1}{\bar{n}} \int_{\mathrm{AB}} n(\mathbf{r})\mathrm{d}l$$

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

Attenuation

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

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



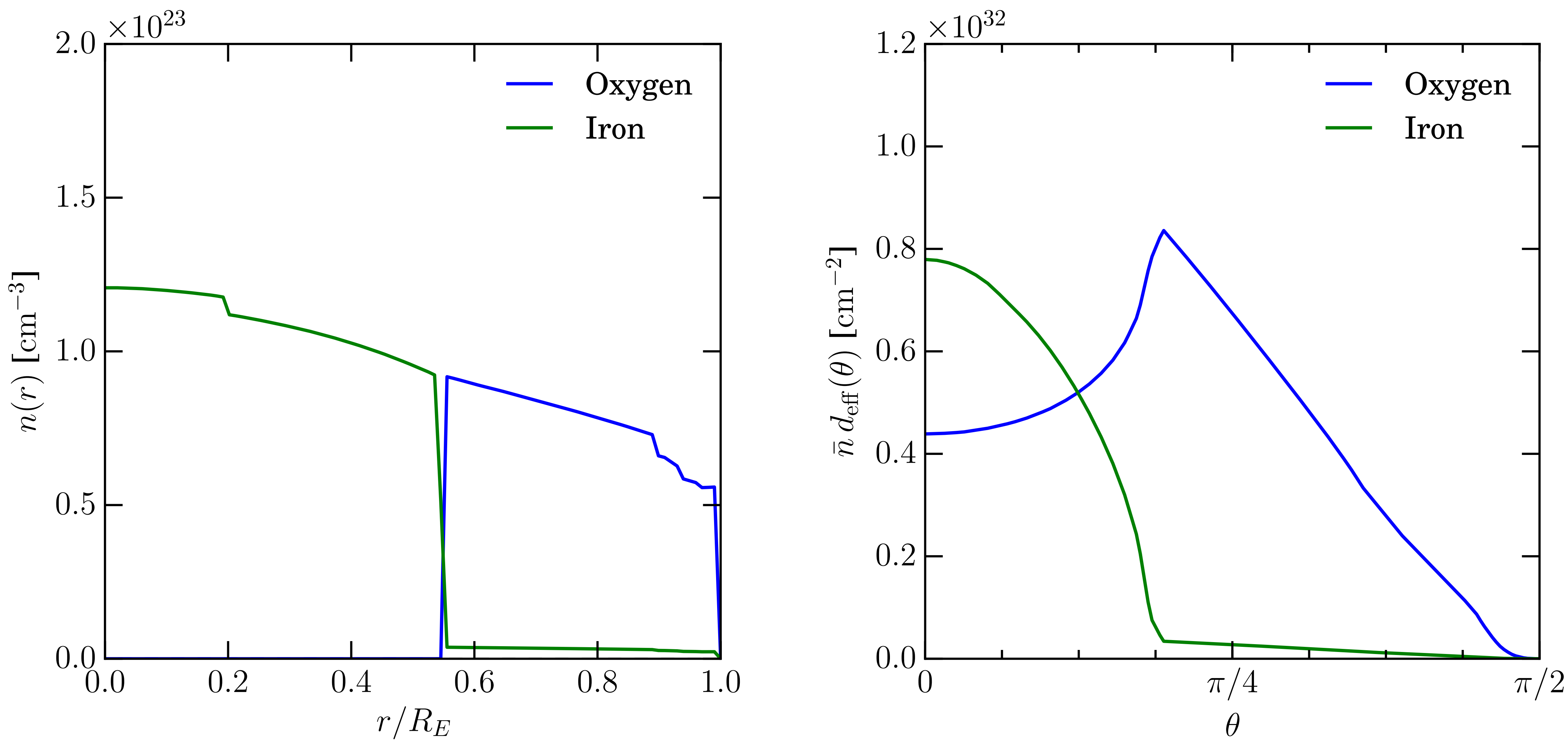
$$d_{\mathrm{eff},i} = \frac{1}{\bar{n}_i}\int_{\mathrm{AB}} n_i(\mathbf{r})\mathrm{d}l$$

$$f_0(\mathbf{v}) - f_A(\mathbf{v}) = f_0(\mathbf{v})\exp\left[-\sum_i^{\mathrm{species}} \frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(v)}\right]$$

Sum over 8 most abundant elements in the Earth: O, Si, Mg, Fe, Ca, Na, S, Al

Effective Earth-crossing distance

Most scattering comes from Oxygen (in the mantle) and Iron (in the core)

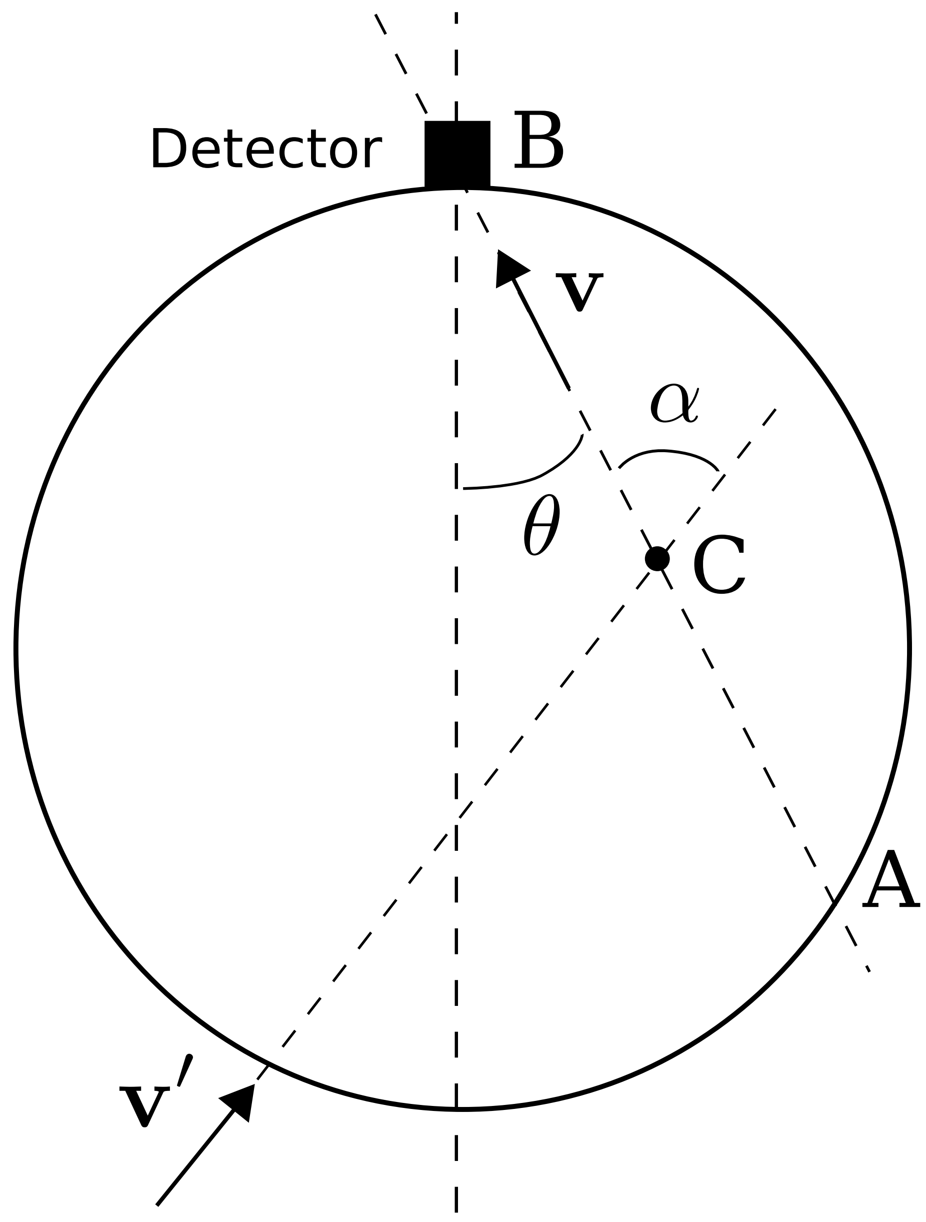


NB: little Earth-scattering for spin-dependent interactions

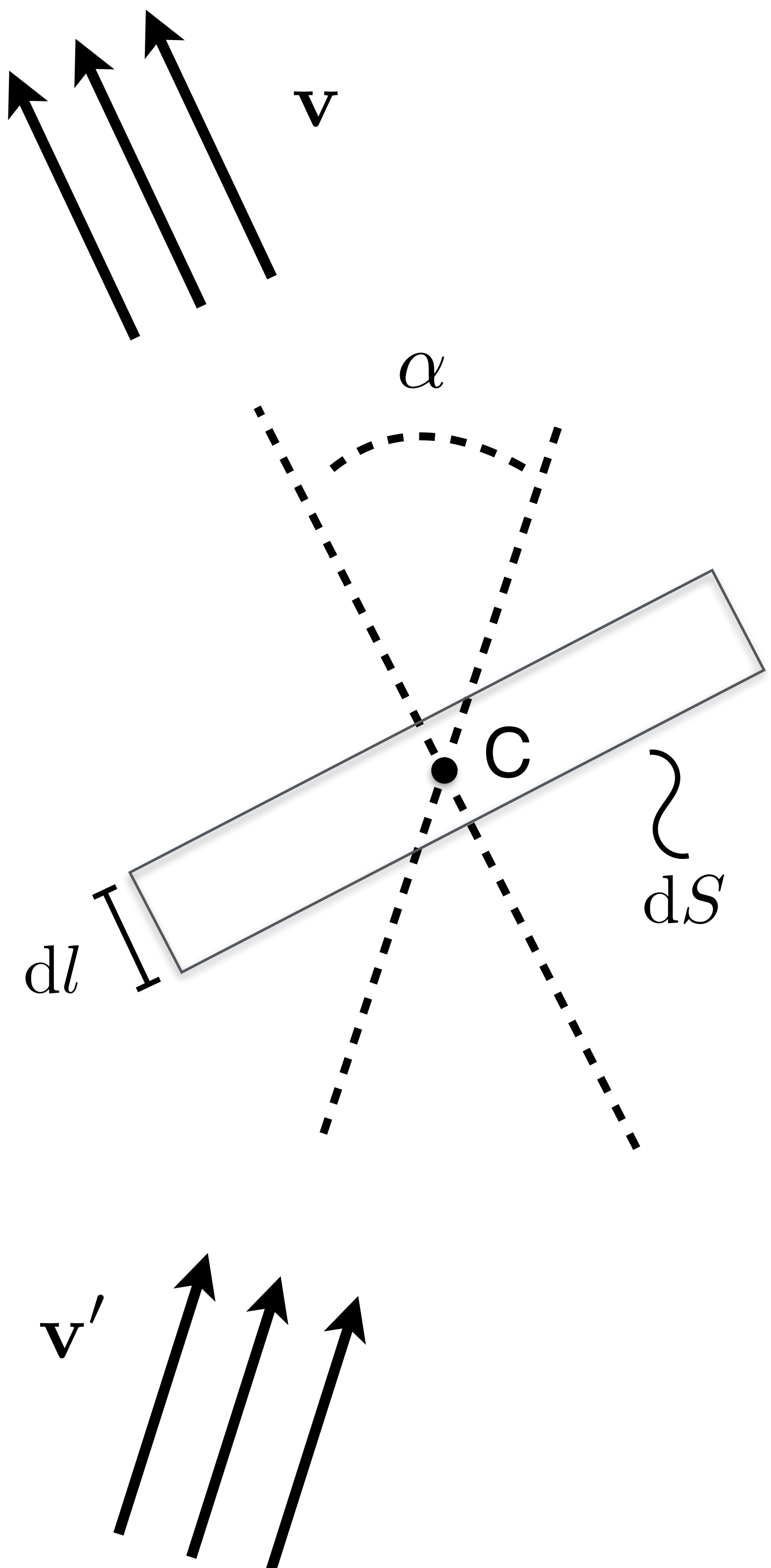
Deflection

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

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



Deflection



Equate rate of particles entering and leaving region, having scattered…

Then integrate over all incoming velocities and over all points C:

$$f_D(\mathbf{v}) = \frac{1}{2\pi}\int_{AB}\frac{\mathrm{d}l}{\lambda_i(\mathbf{r},v')}\int \mathrm{d}^3\mathbf{v}'\ \frac{v'^2}{v^4} f_0(v',\hat{\mathbf{v}}')P_i(\cos\alpha)$$

$$v'/v \equiv \kappa_i$$

fixed by kinematics (for a given α)

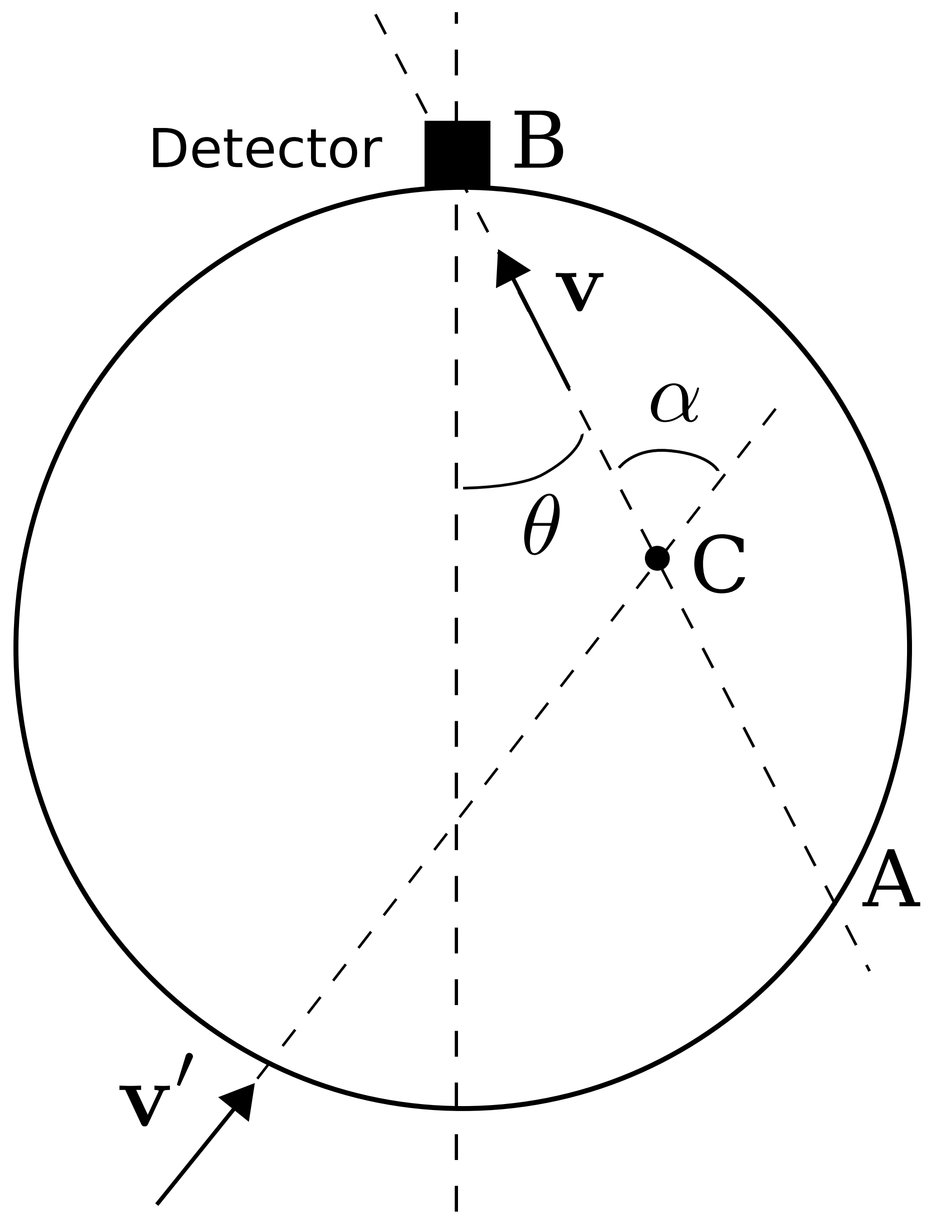
Collect everything together, and sum over Earth species…

[Detailed calculation in the paper]

Deflection

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

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



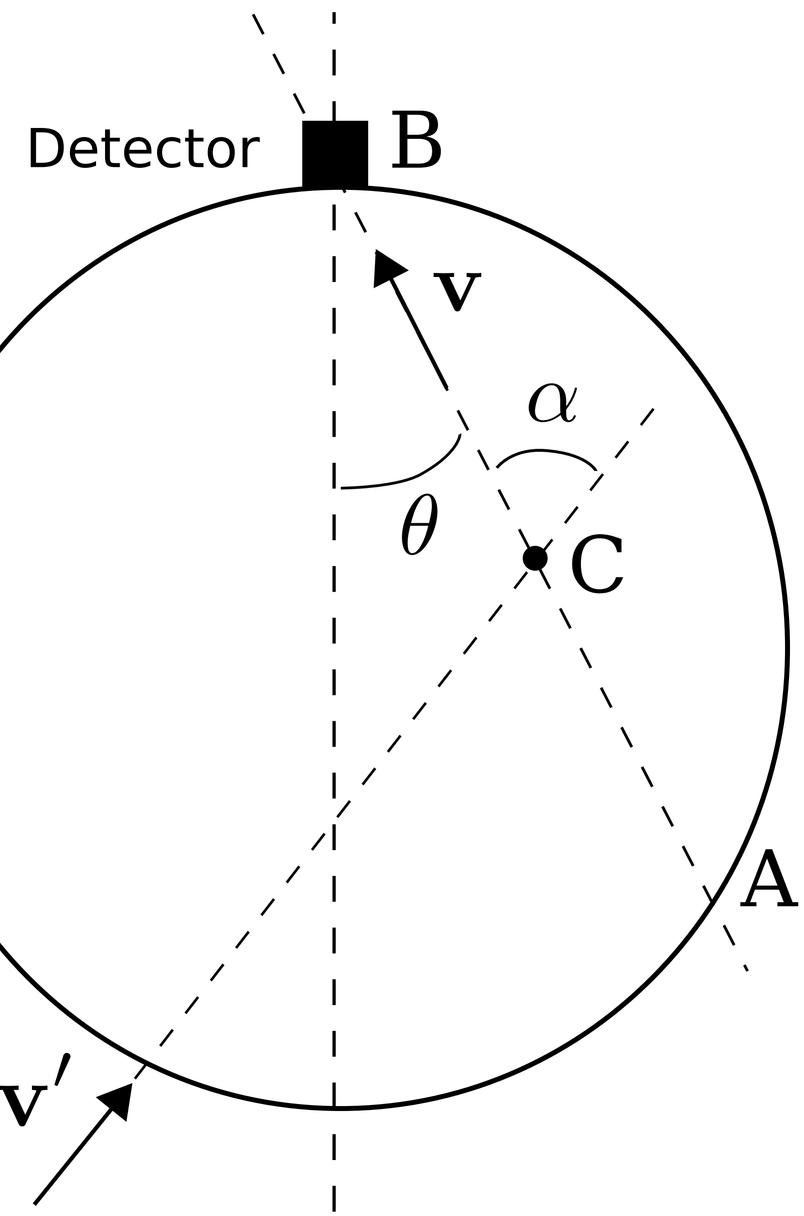
$$f_D(\mathbf{v}) = \sum_i^{\text{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \, \frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)} \frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

$$\kappa_i = v'/v$$

Deflection

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

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



Depends on differential cross section

$$f_D(\mathbf{v}) = \sum_i^{\mathrm{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \, \frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)} \frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

Depends on total cross section

$$\kappa_i = v'/v$$

Non-standard DM operators

Non-relativistic Effective Field Theory (NREFT)

Write down all possible non-relativistic (NR) WIMP-*nucleon* operators which can mediate the *elastic* scattering.

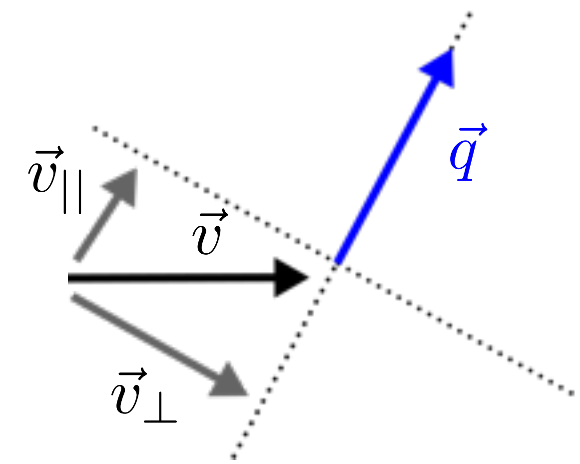
[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

The building blocks of these operators are:

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

The WIMP velocity operator is not Hermitian, so it can appear only through the Hermitian *transverse velocity*:

$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}} \qquad \Rightarrow \vec{v}_\perp \cdot \vec{q} = 0$$



NREFT operator basis

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI → $\mathcal{O}_1 = 1$

SD → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

NREFT operator basis

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI → $\mathcal{O}_1 = 1$

$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)/m_N$

SD → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)/m_N$

$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})/m_N^2$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

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

$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})/m_N$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}/m_N$

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

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

$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})/m_N$

$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)/m_N$

$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q}/m_N^2$

$\vdots$

NB: two sets of operators, one for protons and one for neutrons…

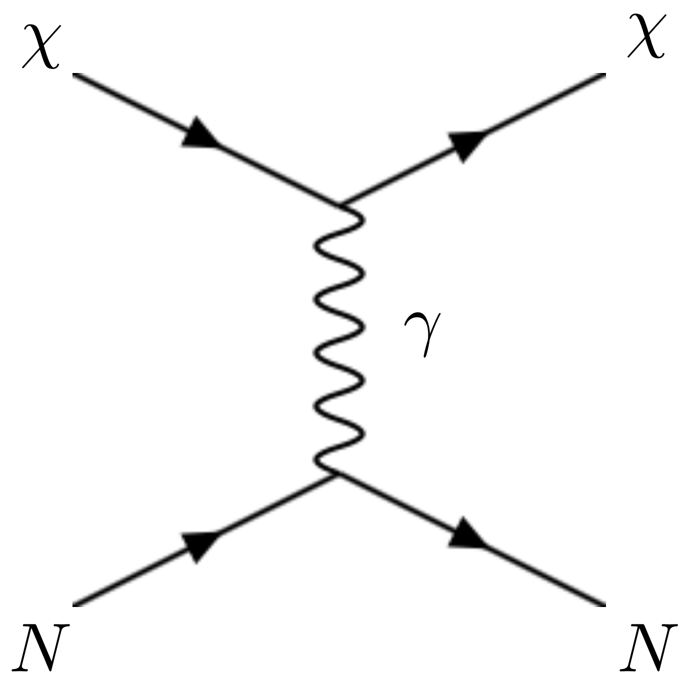
[1008.1591, 1203.3542, 1308.6288, 1505.03117]

Example: Anapole DM

[1211.0503, 1401.4508, 1506.04454]

Lowest order interaction of Majorana DM with EM fields:

$$\mathcal{O}_A = \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$



Induces an interaction with nucleons:

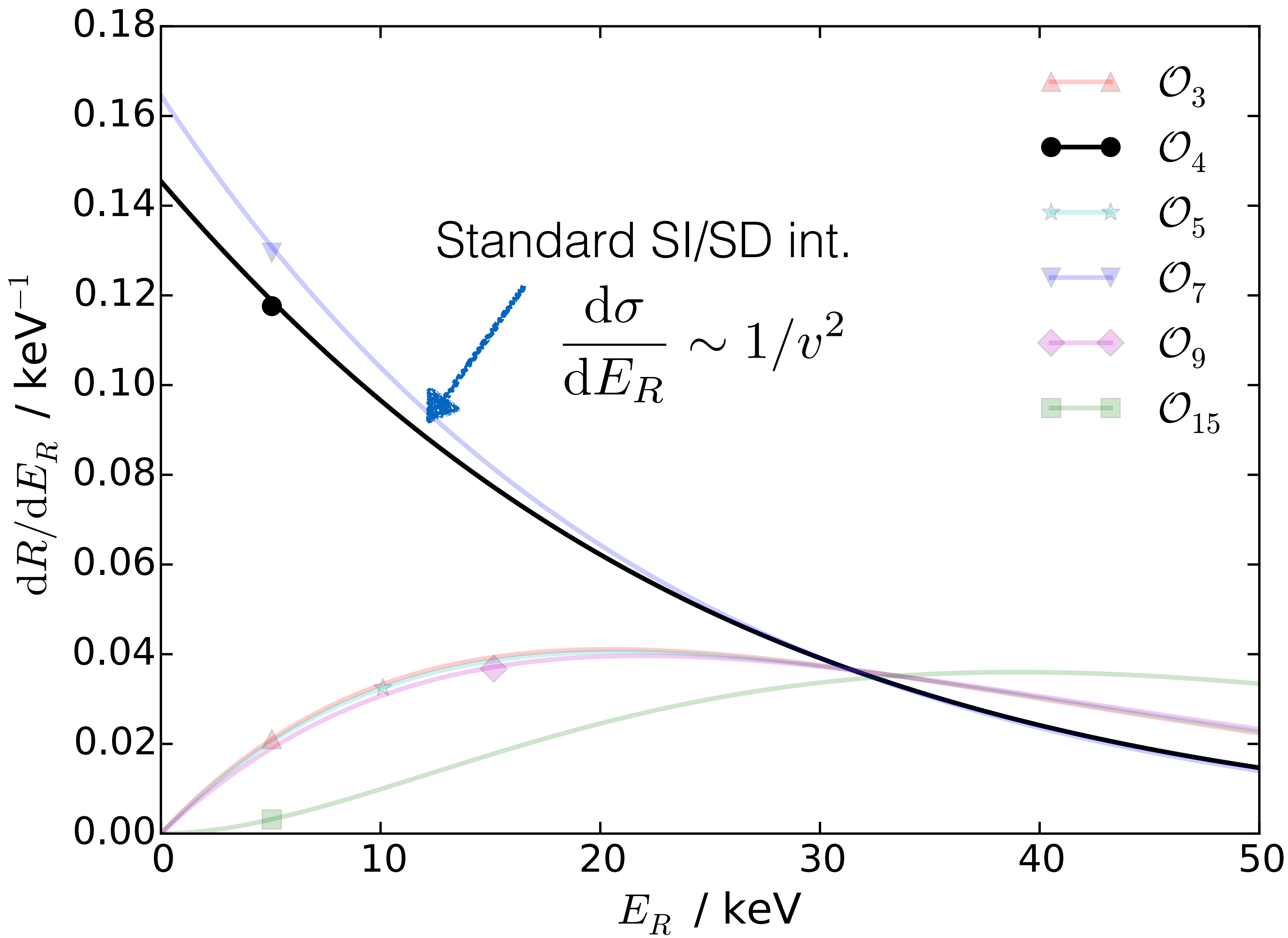
$$\mathcal{O}_A^{(N)} = eQ_N\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu N$$

Leading to a NR matrix element:

$$\begin{aligned}\mathcal{M}_A^{(N)} &= -eQ_N m_\chi m_N \vec{S}_\chi \cdot (\vec{v}^\perp + i\vec{S}_N \times \vec{q}) \\ &= -eQ_N m_\chi m_N (\mathcal{O}_8 + \mathcal{O}_9)\end{aligned}$$

Energy spectra

$m_\chi = 100\ \mathrm{GeV}$



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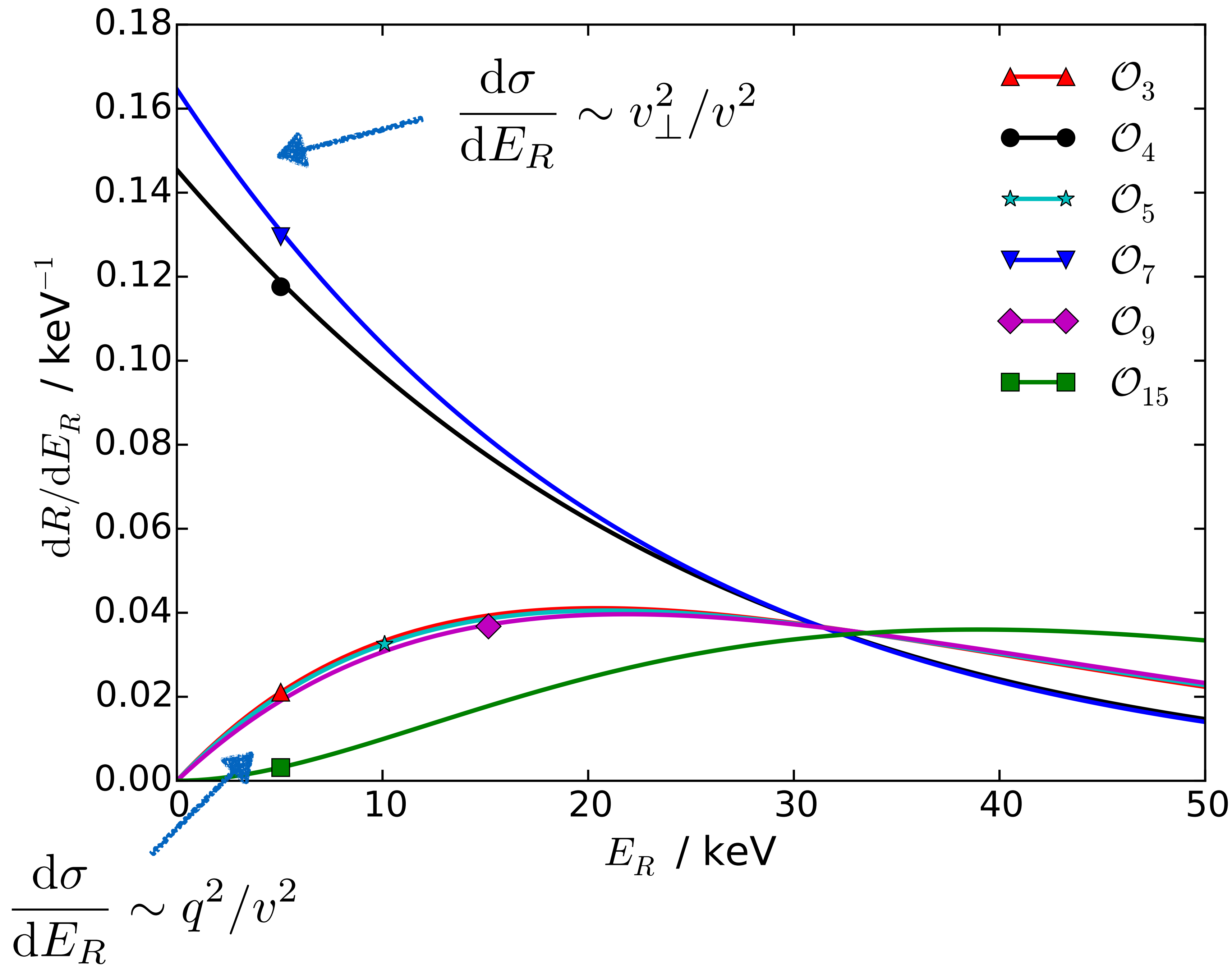
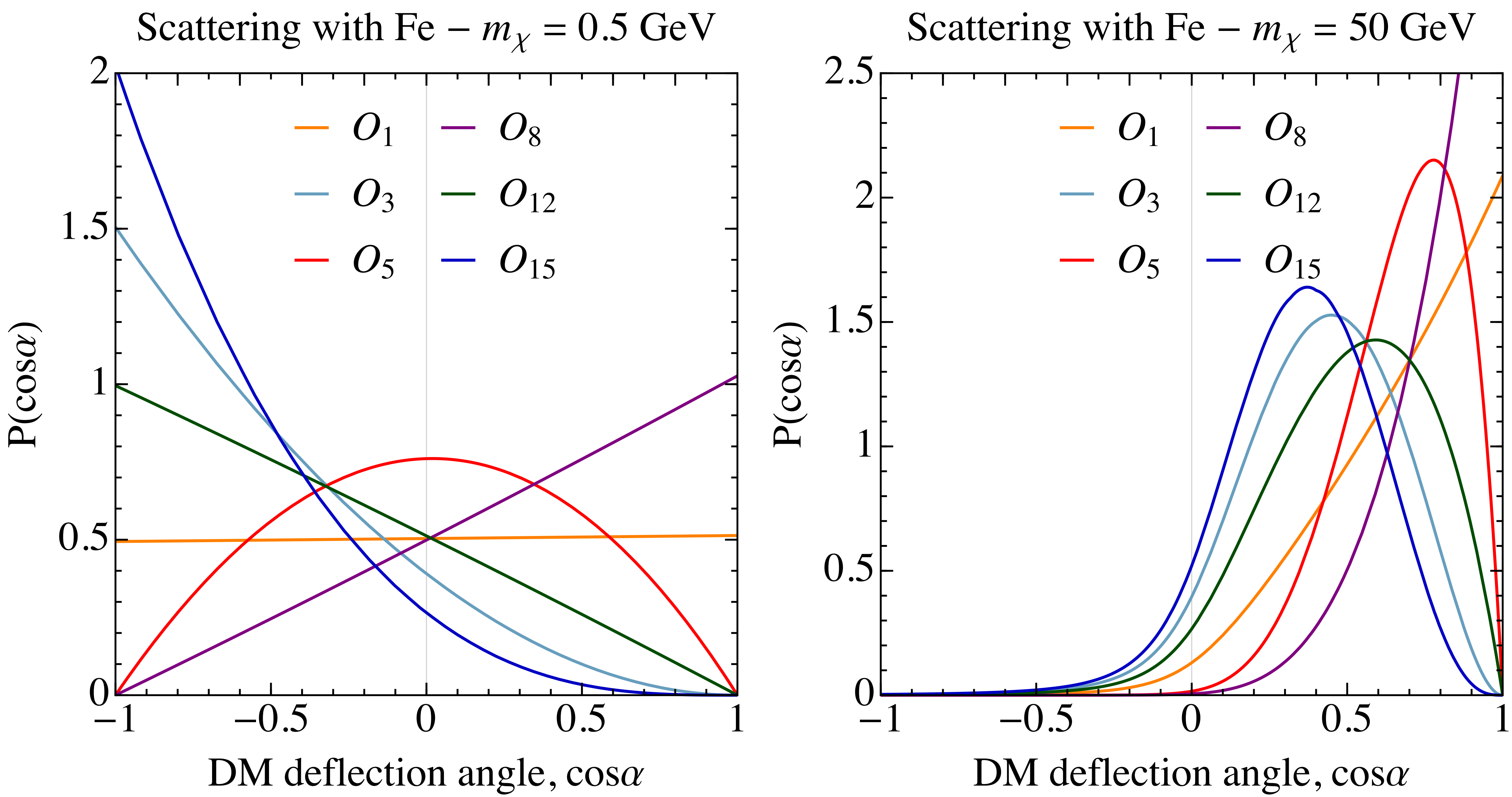


DM deflection distribution

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

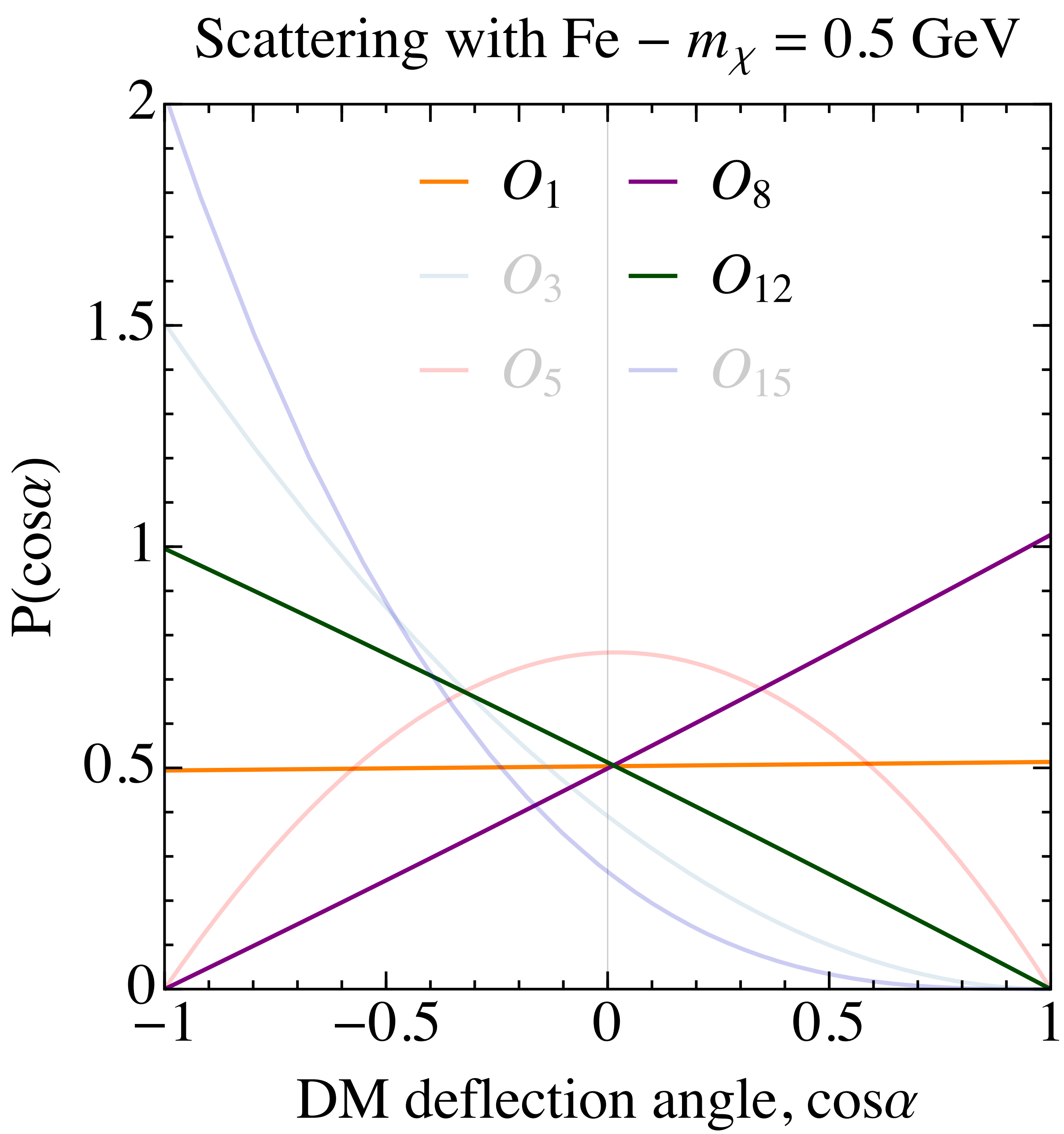


Backward

Forward

DM deflection distribution

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



Backward

Forward

Standard SI

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

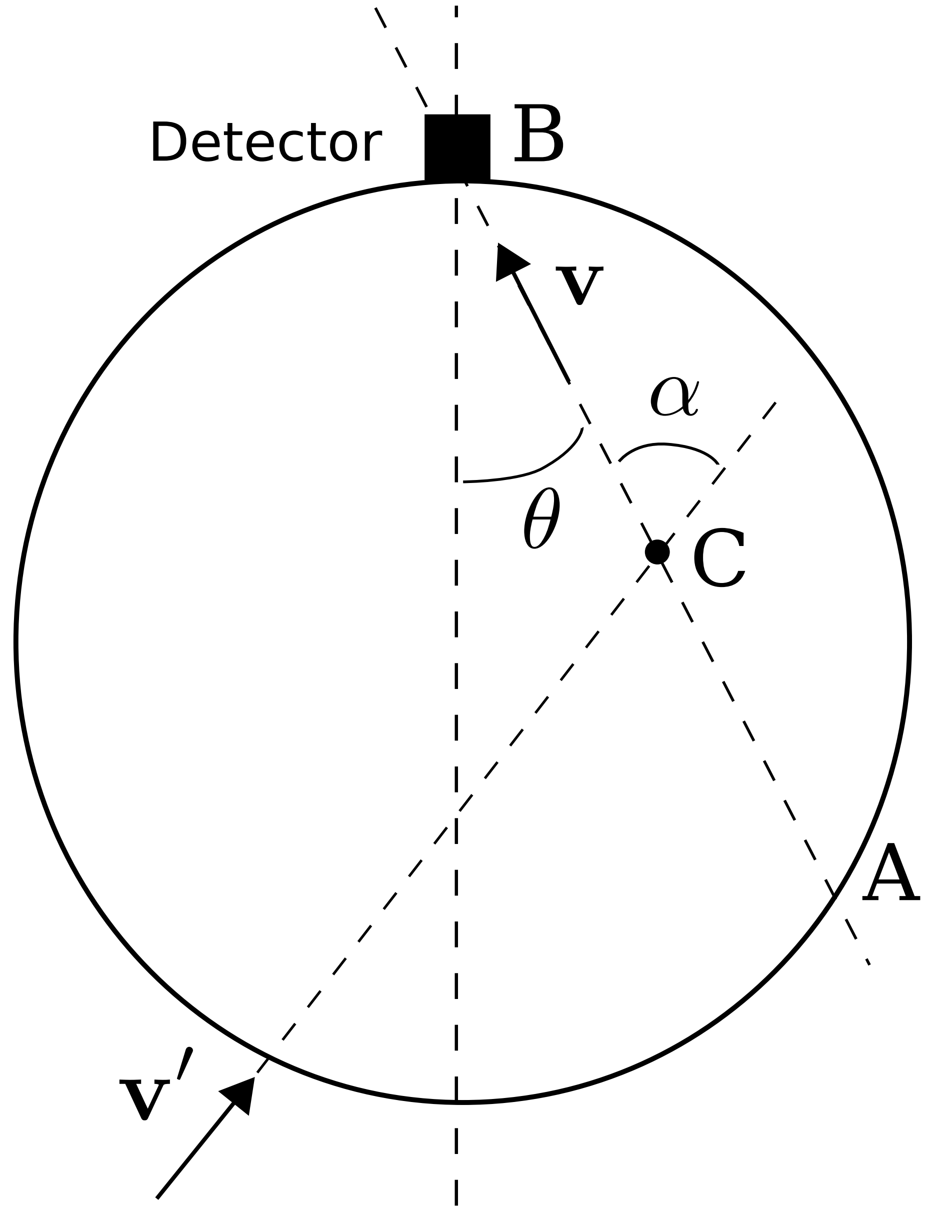
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim (1 - \frac{m_\mathcal{N} E_R}{2\mu_{\chi\mathcal{N}}^2 v^2})$$

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

DM deflection

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

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



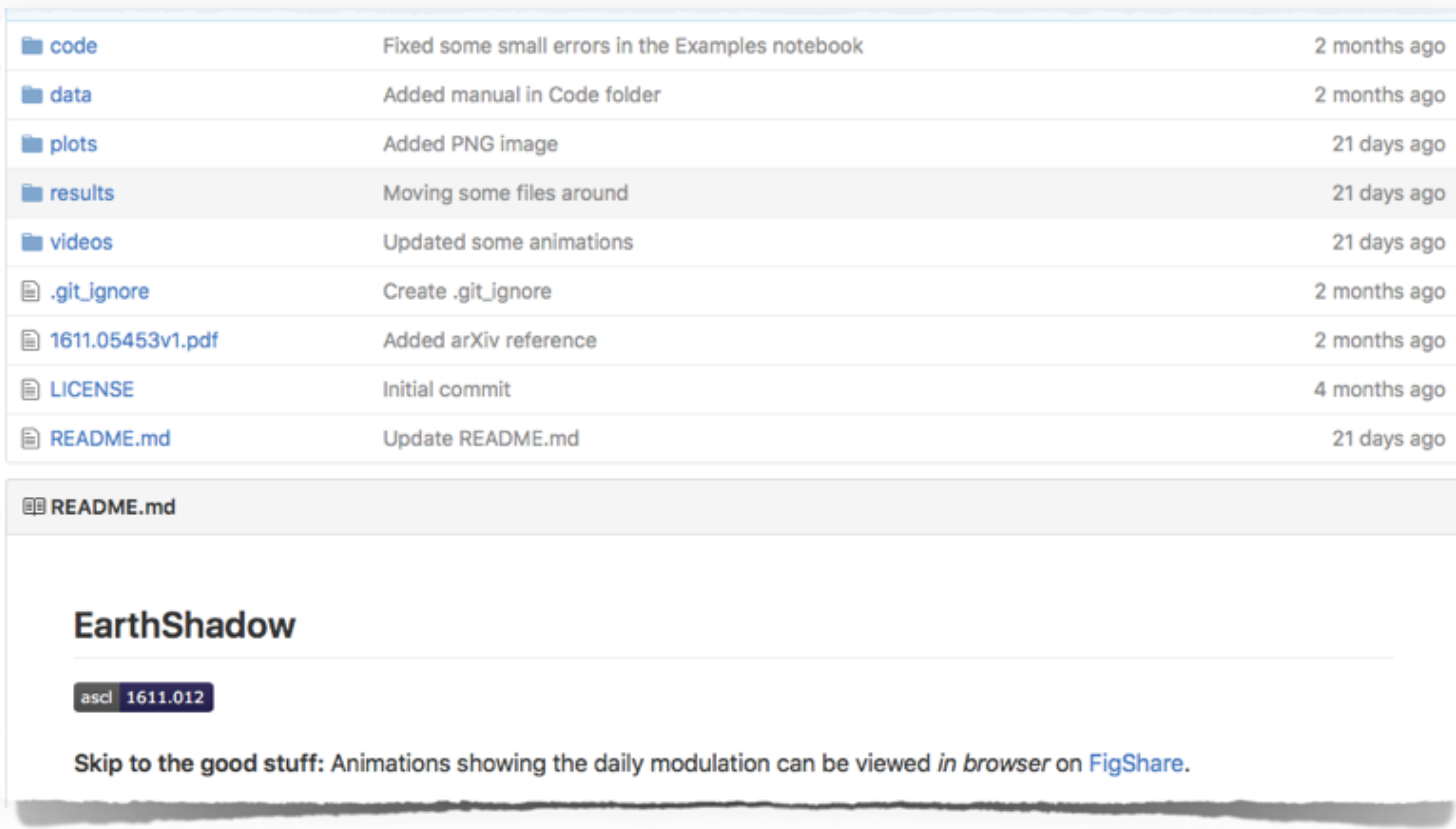
$$f_D(\mathbf{v}) = \sum_i^{\text{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \,\frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)}\frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

$$\kappa_i = v'/v$$

EARTHSHADOW Code

EARTHSHADOW code is available online at:
github.com/bradkav/EarthShadow

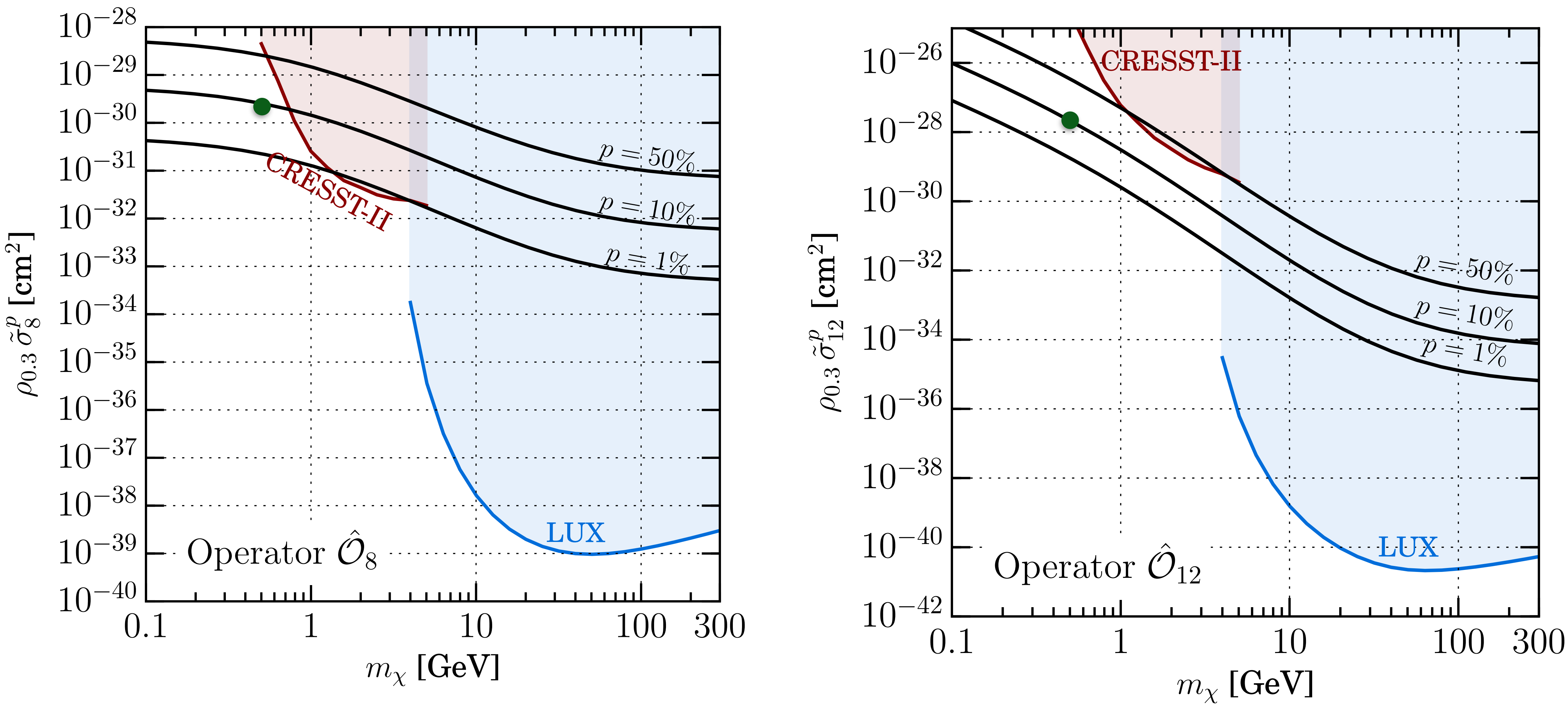
Including routines, numerical results, plots and animations…



Results

Constraints on NREFT operators

Focus on SI operator (O_1), as well as O_8 and O_{12}:

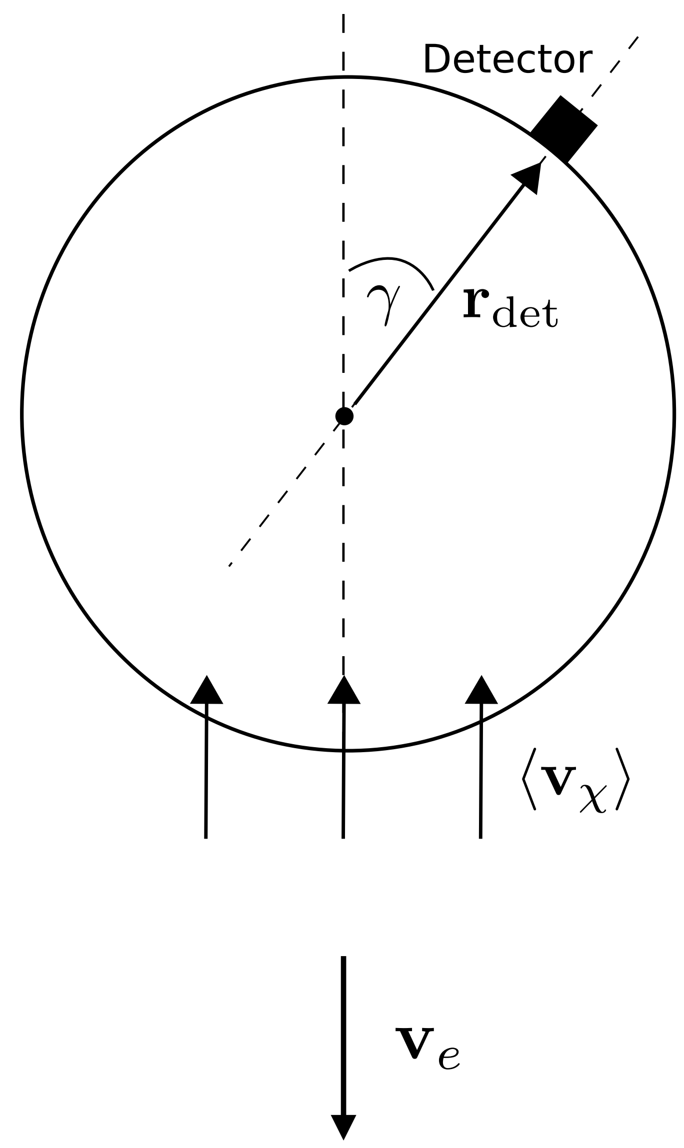


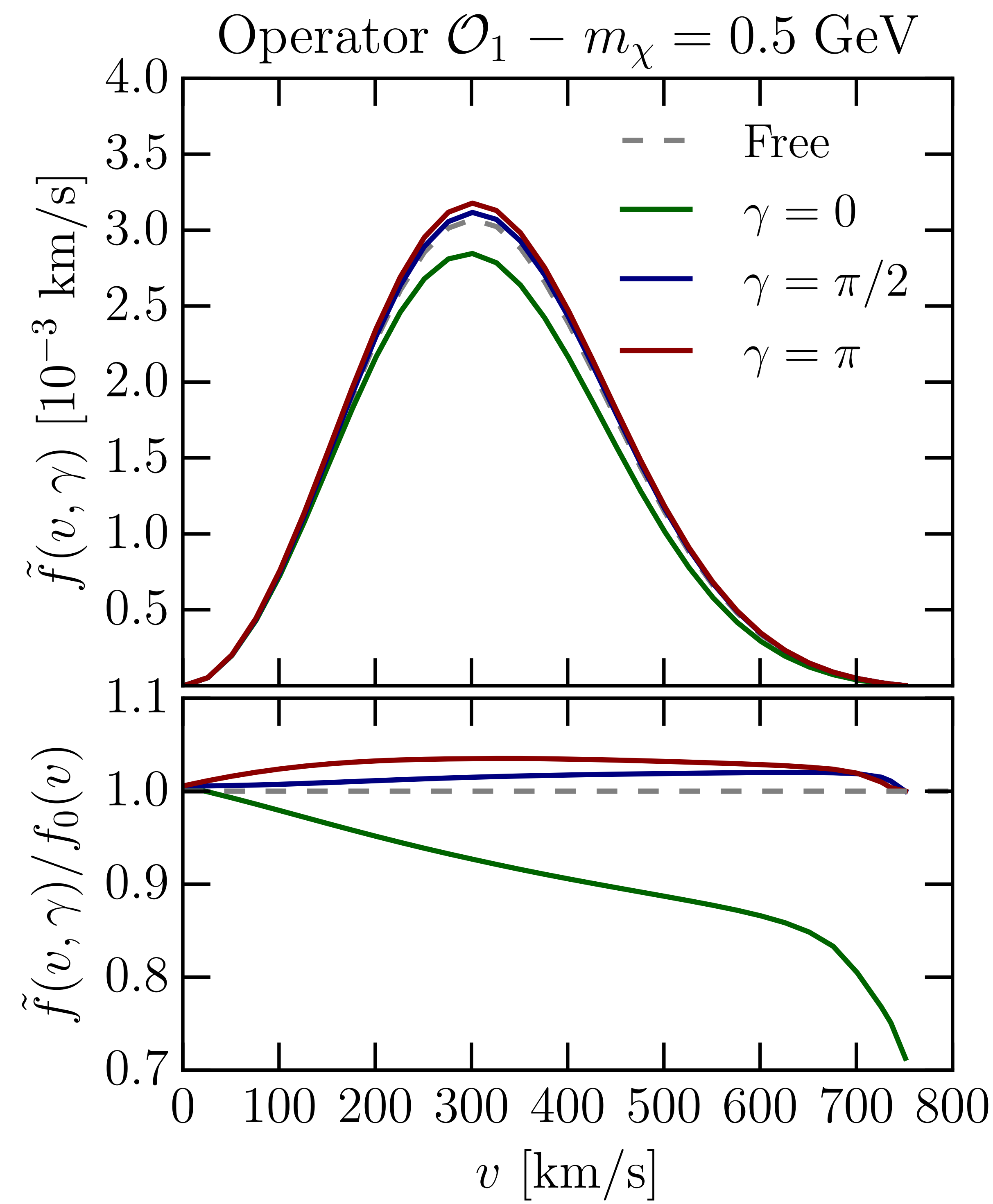
Focus on low mass DM: $m_\chi = 0.5$ GeV

Fix couplings to give 10% probability of scattering

Speed Distribution - Operator 1

Calculate DM speed distribution after Earth scattering: $\tilde{f}(v, \gamma)$





Speed Distribution - Operator 1

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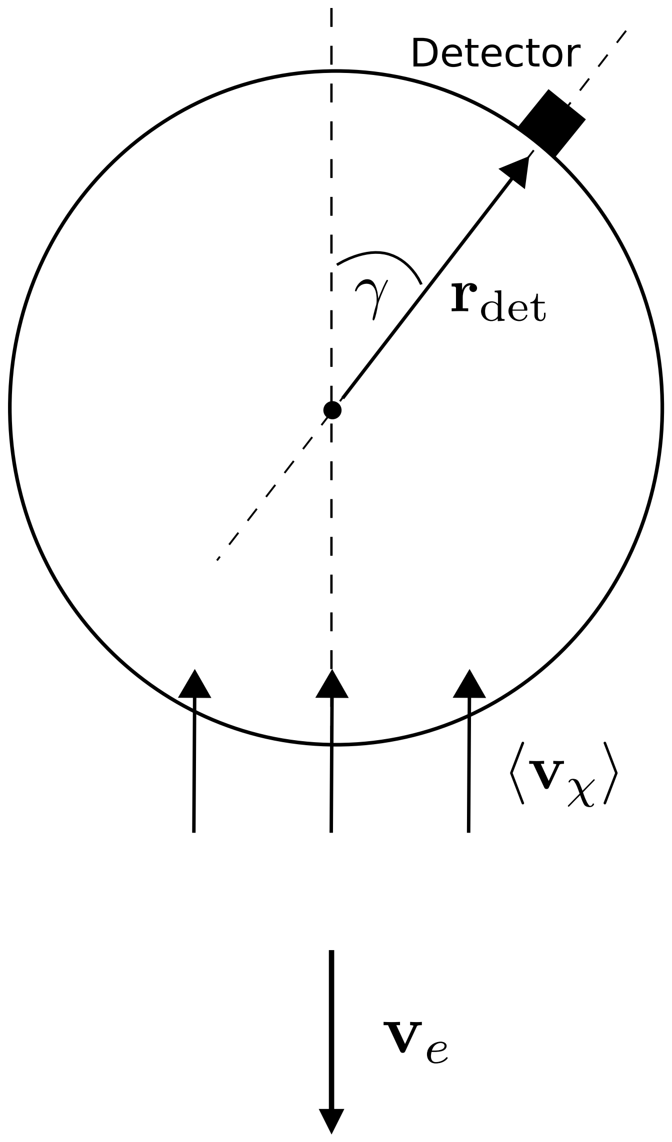
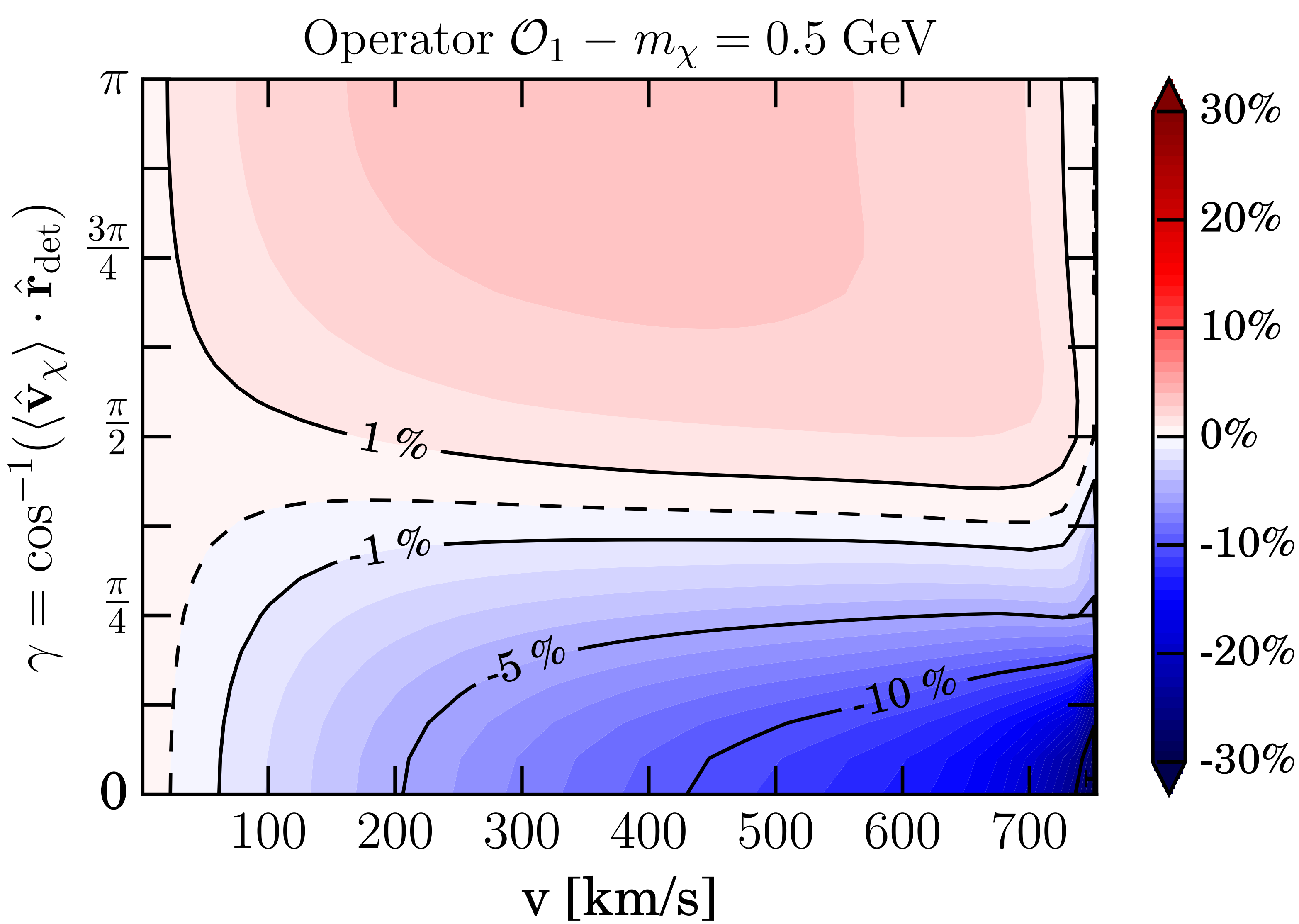
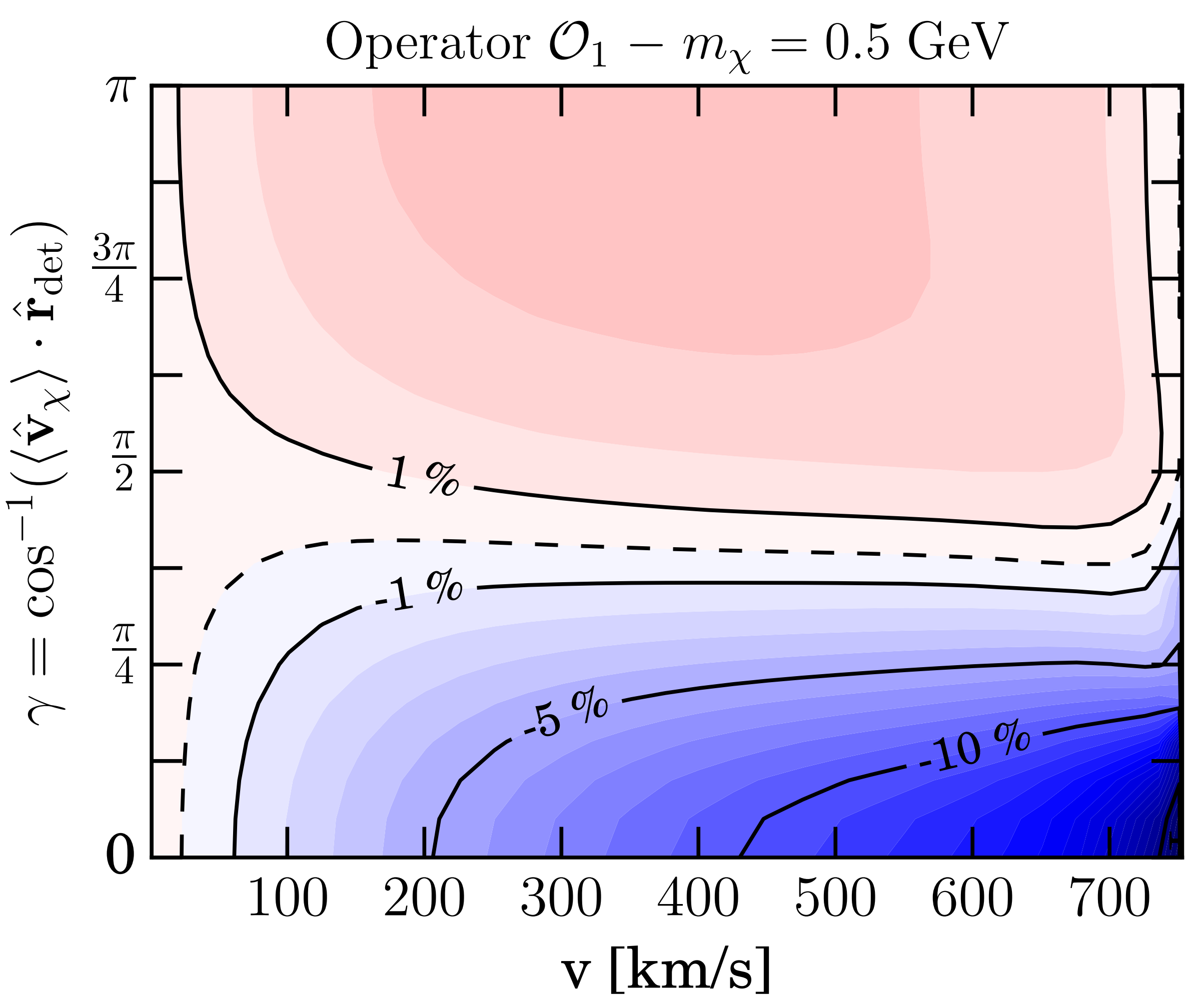
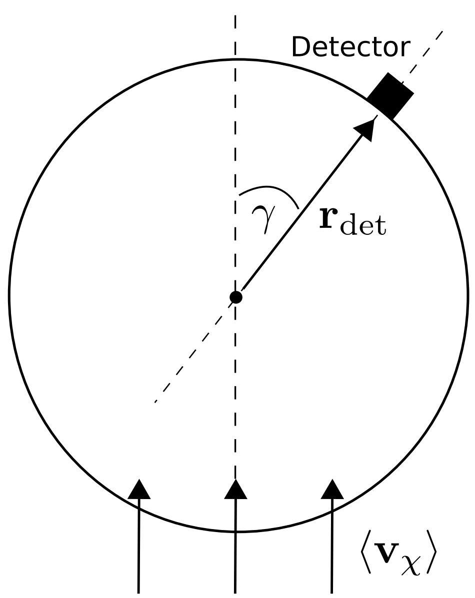


Percentage change in speed dist.

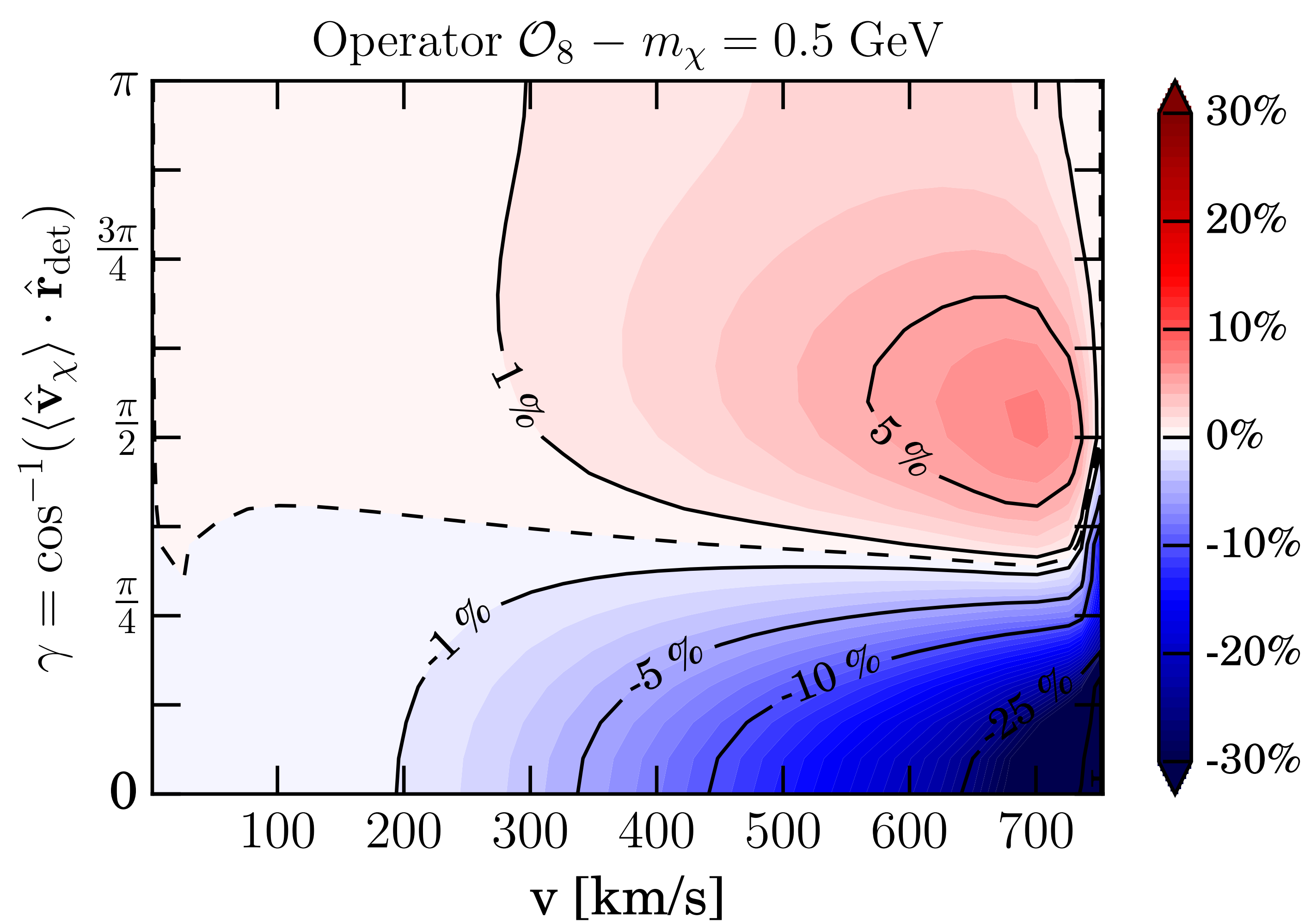


Speed Distribution - O_1 vs O_8

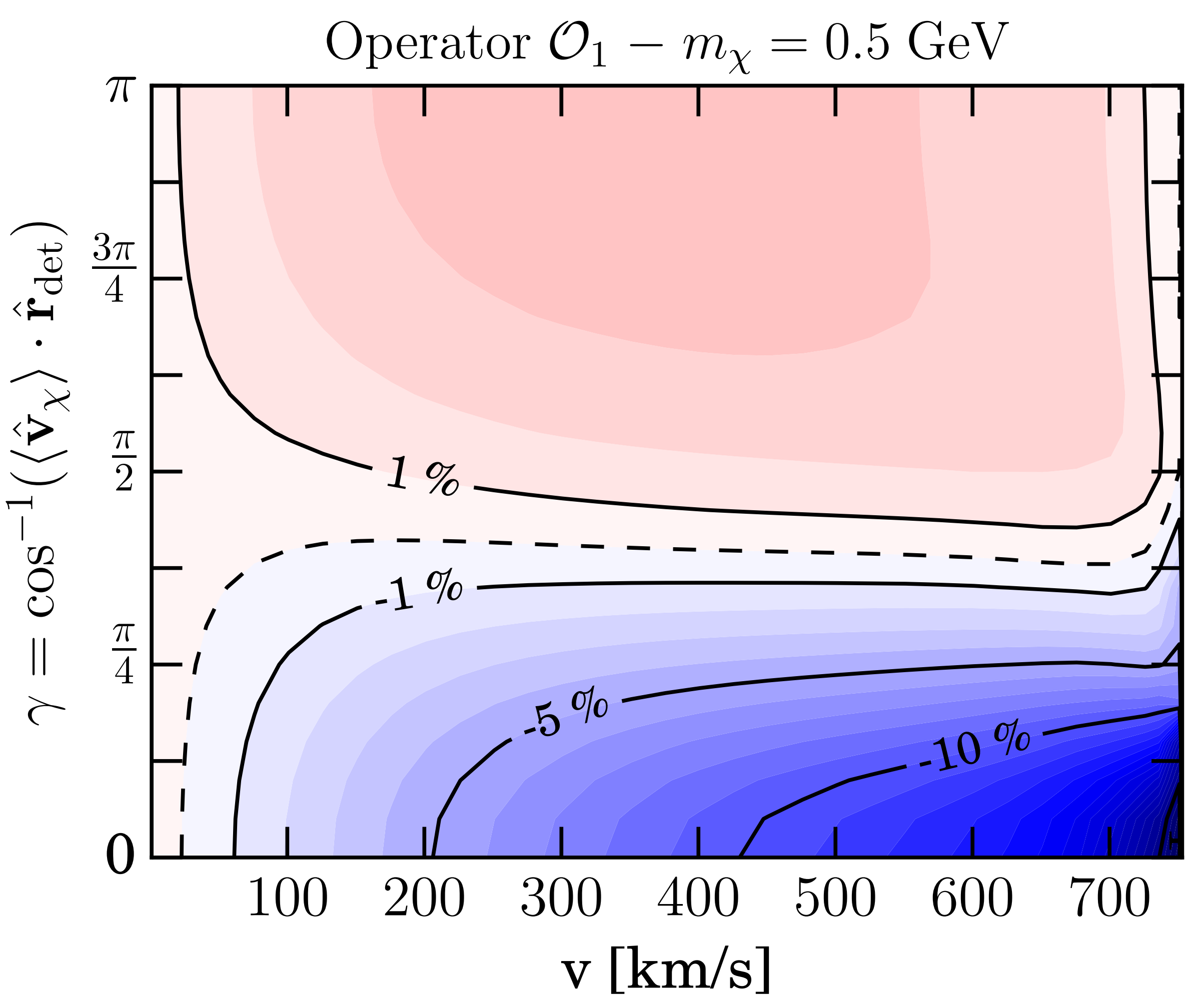




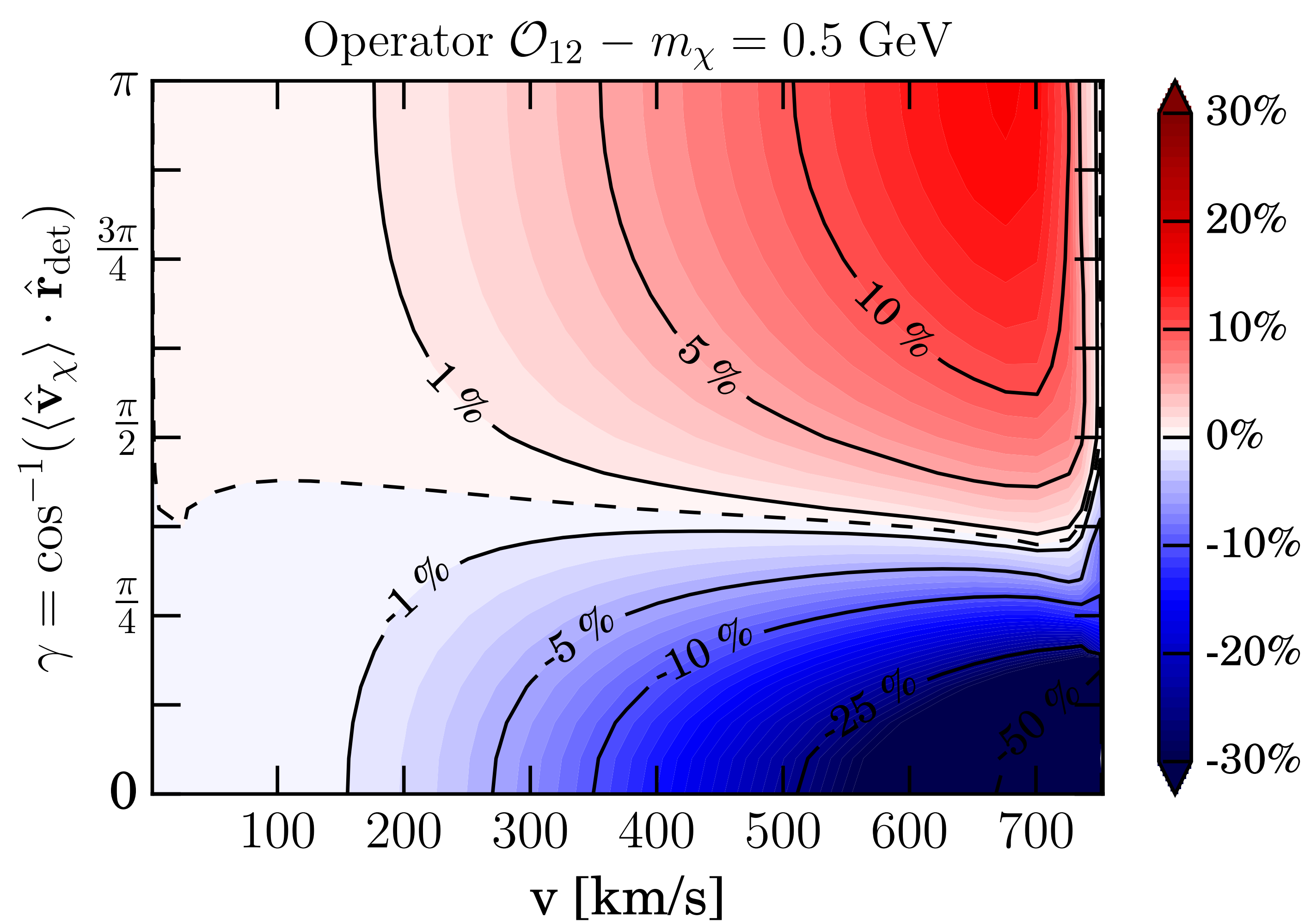
Operator 8 -
preferentially *forward* deflection

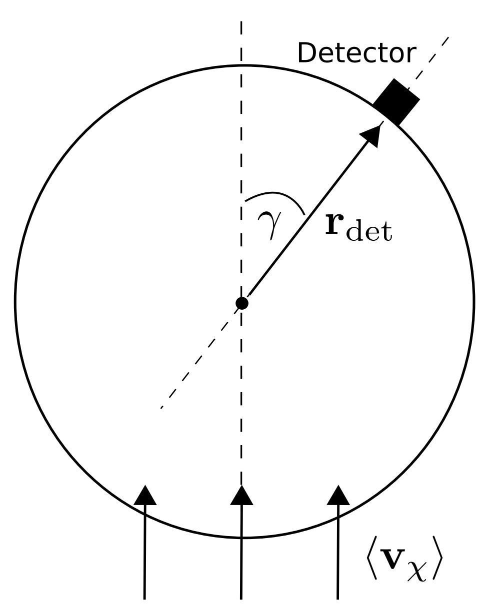


Speed Distribution - O1 vs O12

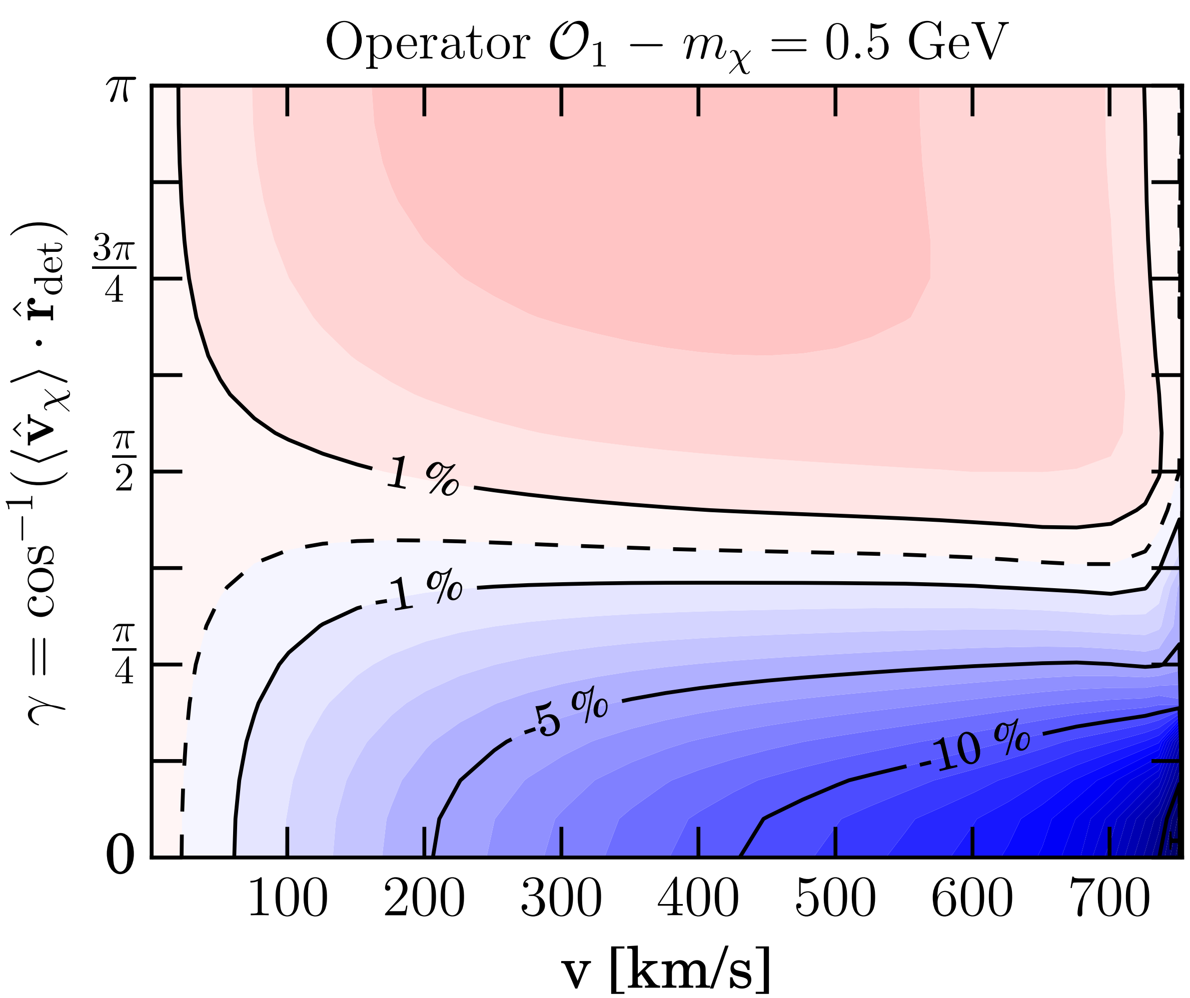


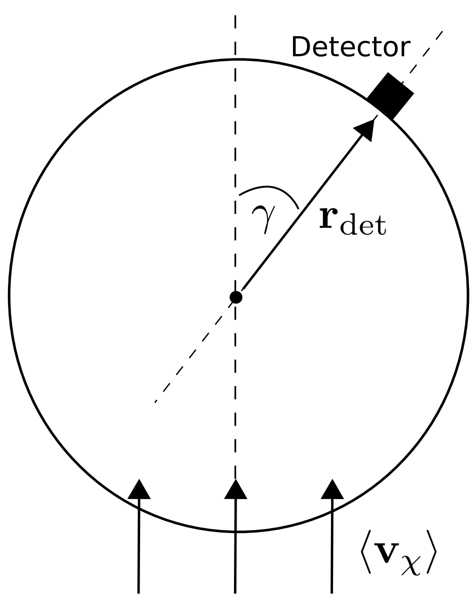
Operator 12 -
preferentially *backward* deflection



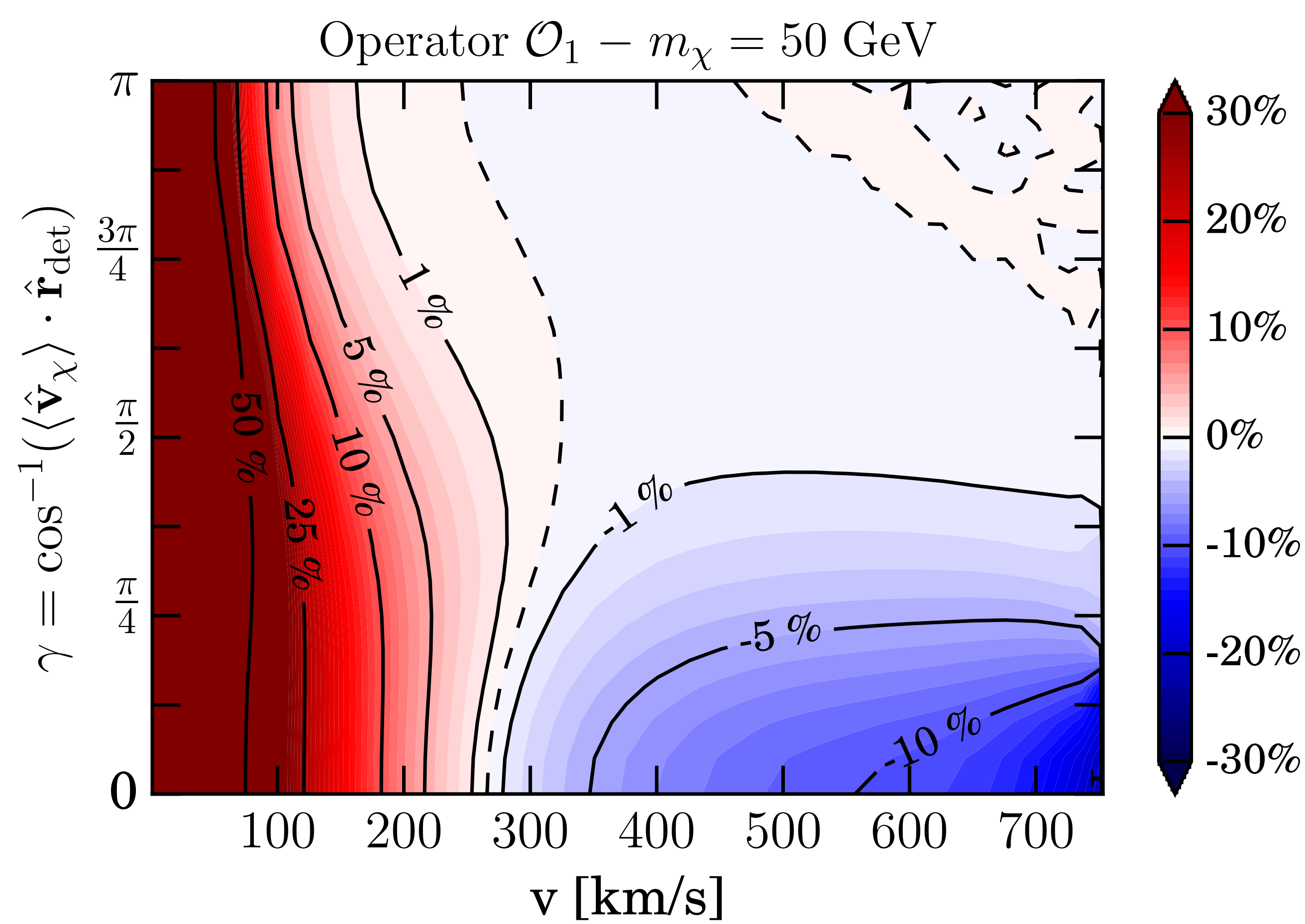


Low mass vs High mass





Higher mass DM



Sanity check

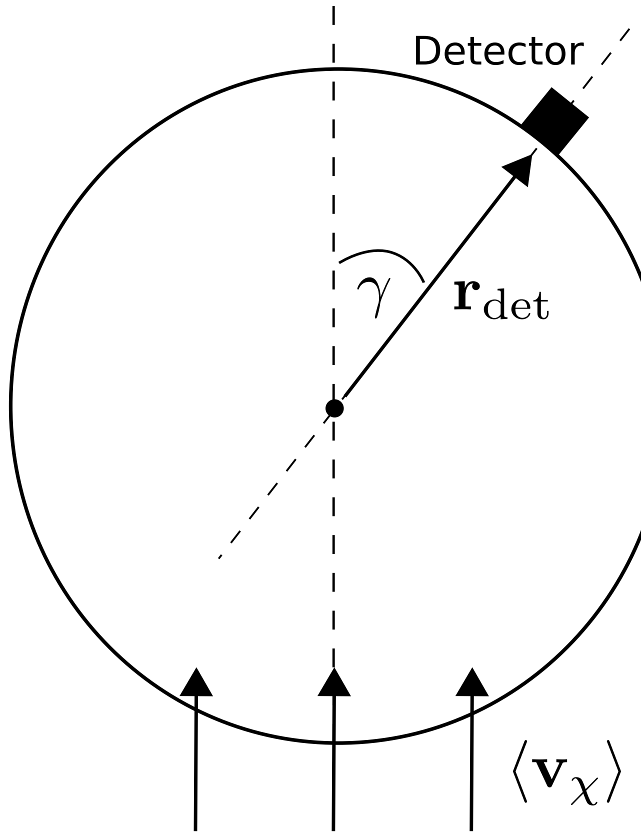
Compare rate of DM particles entering the Earth…

$$\Gamma_\mathrm{in} = \pi R_\oplus \langle v \rangle$$

…and rate of DM particle leaving the Earth…

$$\Gamma_\mathrm{out} = \int_{\mathbf{v}\cdot\mathbf{r}>0} \mathrm{d}^2\mathbf{r} \int \mathrm{d}^3\mathbf{v}\, \tilde{f}(\mathbf{v},\mathbf{r})\,(\mathbf{v}\cdot\mathbf{r})$$

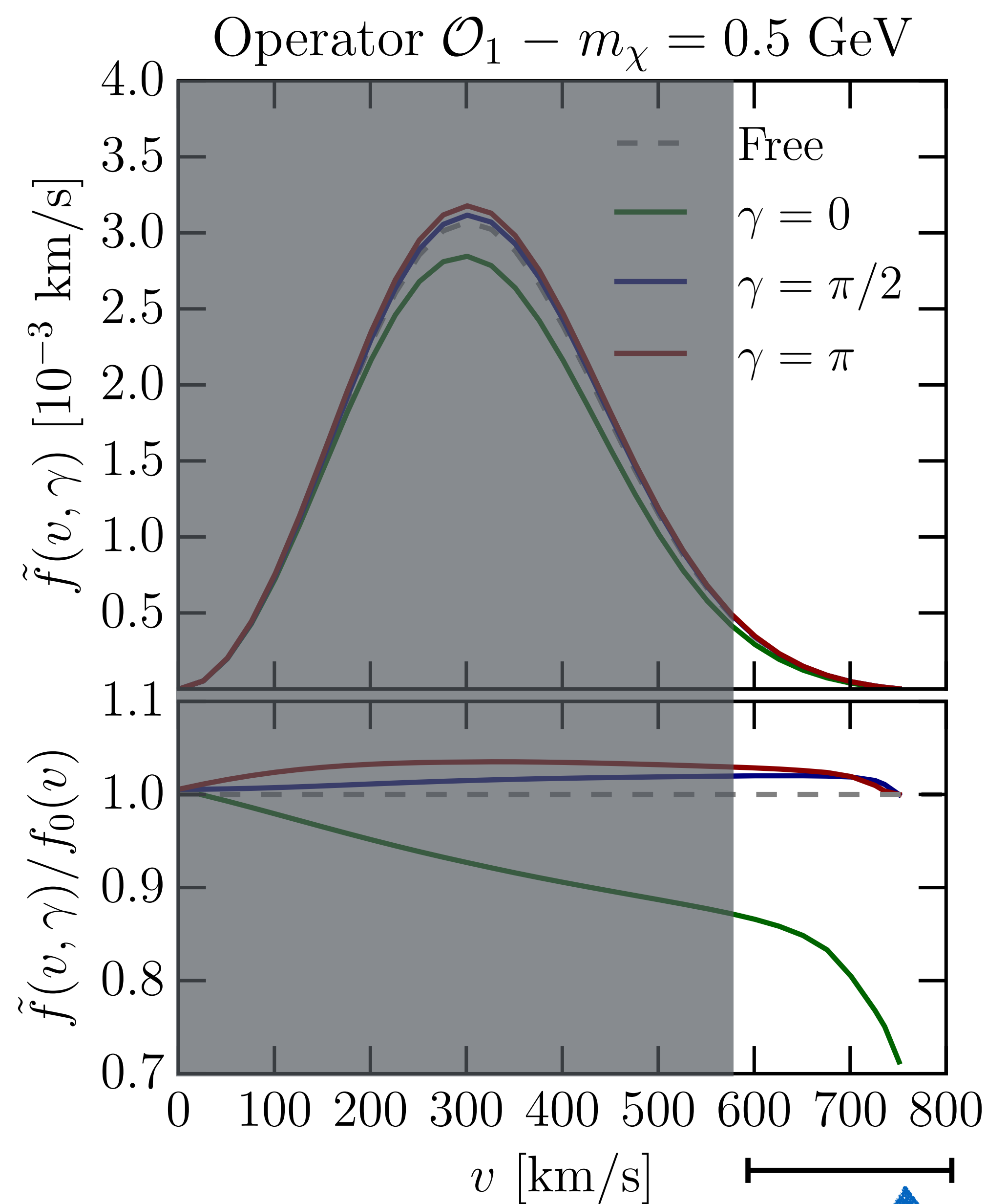
DM mass [GeV]	Operator	$\Delta\Gamma_\mathrm{out}^\mathrm{Atten.}/\Gamma_\mathrm{in}$	$\Delta\Gamma_\mathrm{out}^\mathrm{Defl.}/\Gamma_\mathrm{in}$	$\Gamma_\mathrm{out}/\Gamma_\mathrm{in}$
0.5	$\hat{\mathcal{O}}_1$	-7.8%	$+7.0\%$	99.2%
0.5	$\hat{\mathcal{O}}_8$	-8.0%	$+7.3\%$	99.2%
0.5	$\hat{\mathcal{O}}_{12}$	-7.8%	$+7.2\%$	99.4%
50	$\hat{\mathcal{O}}_1$	-7.5%	$+7.3\%$	99.9%
50	$\hat{\mathcal{O}}_8$	-8.0%	$+8.4\%$	100.4%
50	$\hat{\mathcal{O}}_{12}$	-7.3%	$+6.6\%$	99.3%



Event Rate

Calculate number of signal events in a CRESST-II like experiment, with and without the effects of Earth-Scattering, N_{pert} and N_{free}.

Scattering predominantly with Oxygen and Calcium.



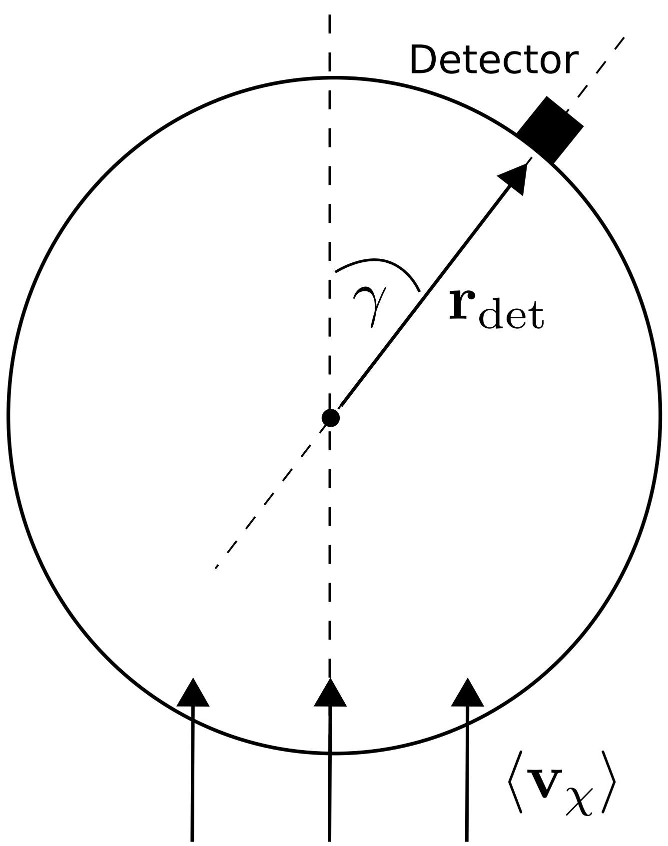
DM particles within $3\,\sigma_E$ of the energy threshold
$E_{\mathrm{th}} \sim 300$ eV

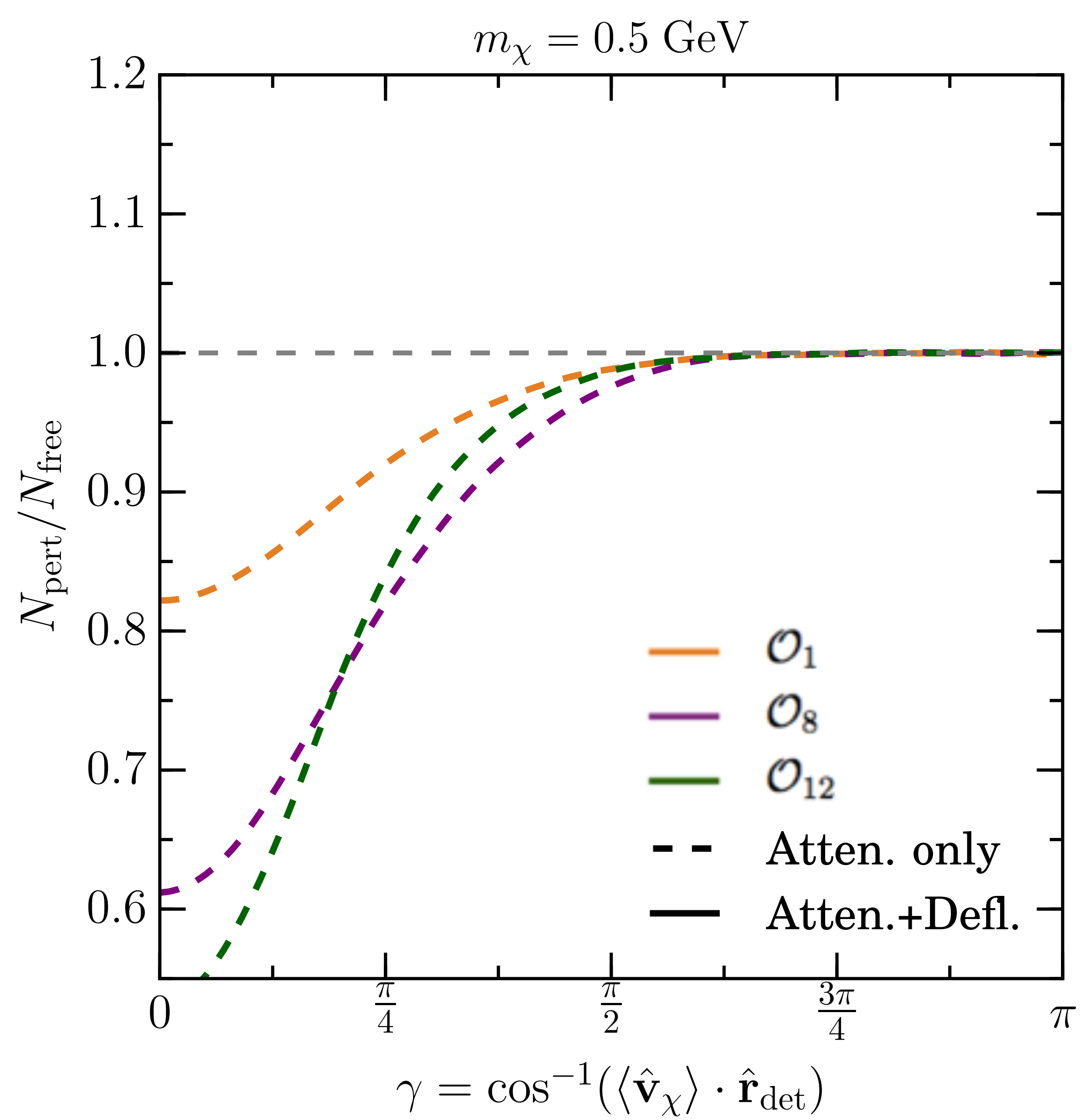
CRESST-II Rate (attenuation-only)

Operator 1 - isotropic deflection

Operator 8 - forward deflection

Operator 12 - backward deflection



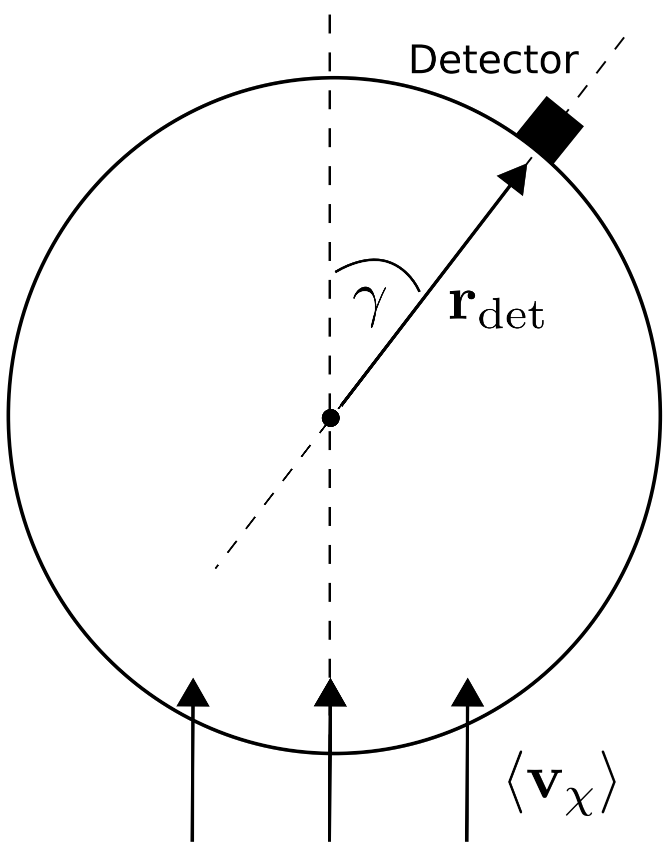


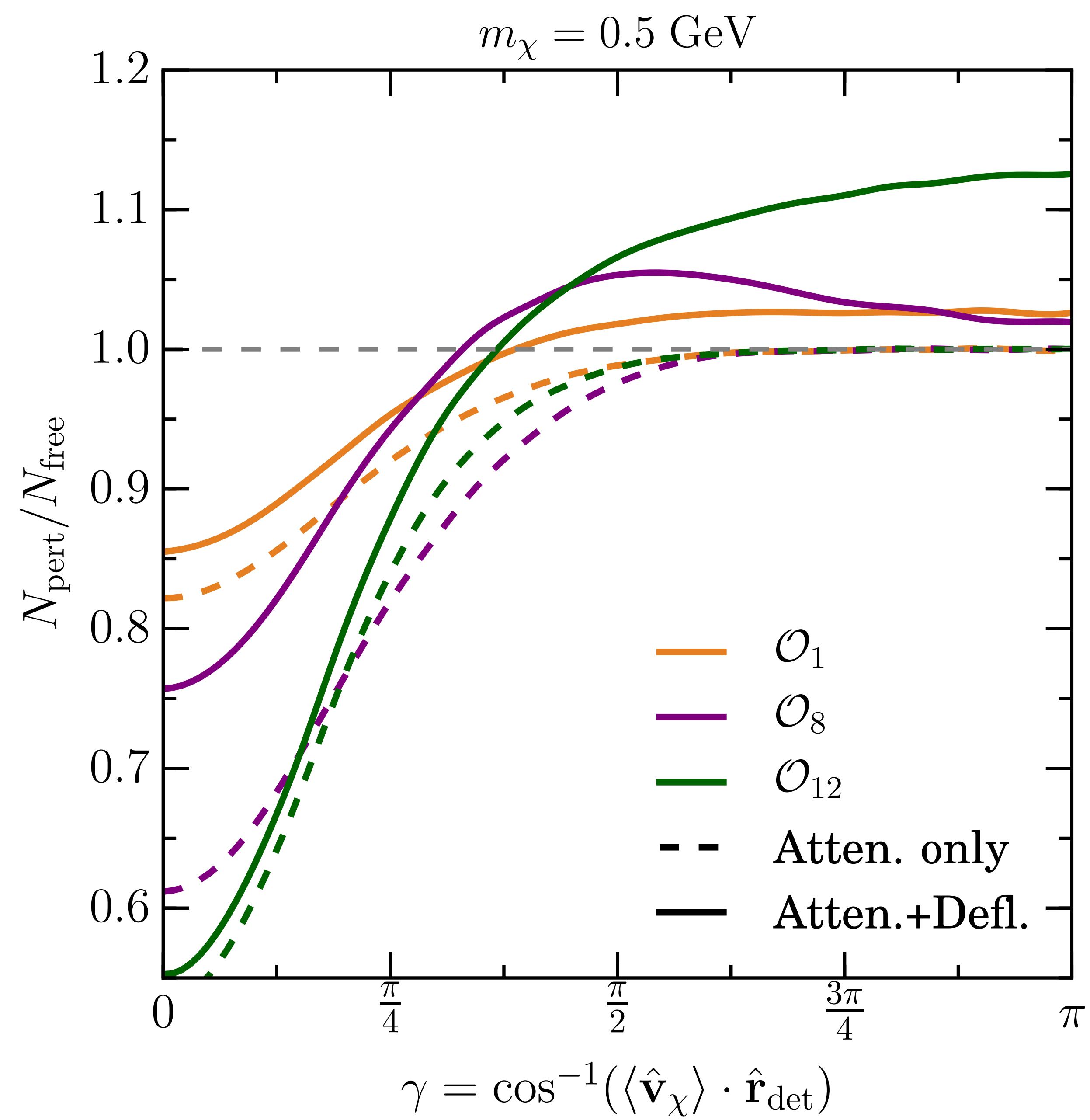
CRESST-II Rate (attenuation + deflection)

Operator 1 - isotropic deflection

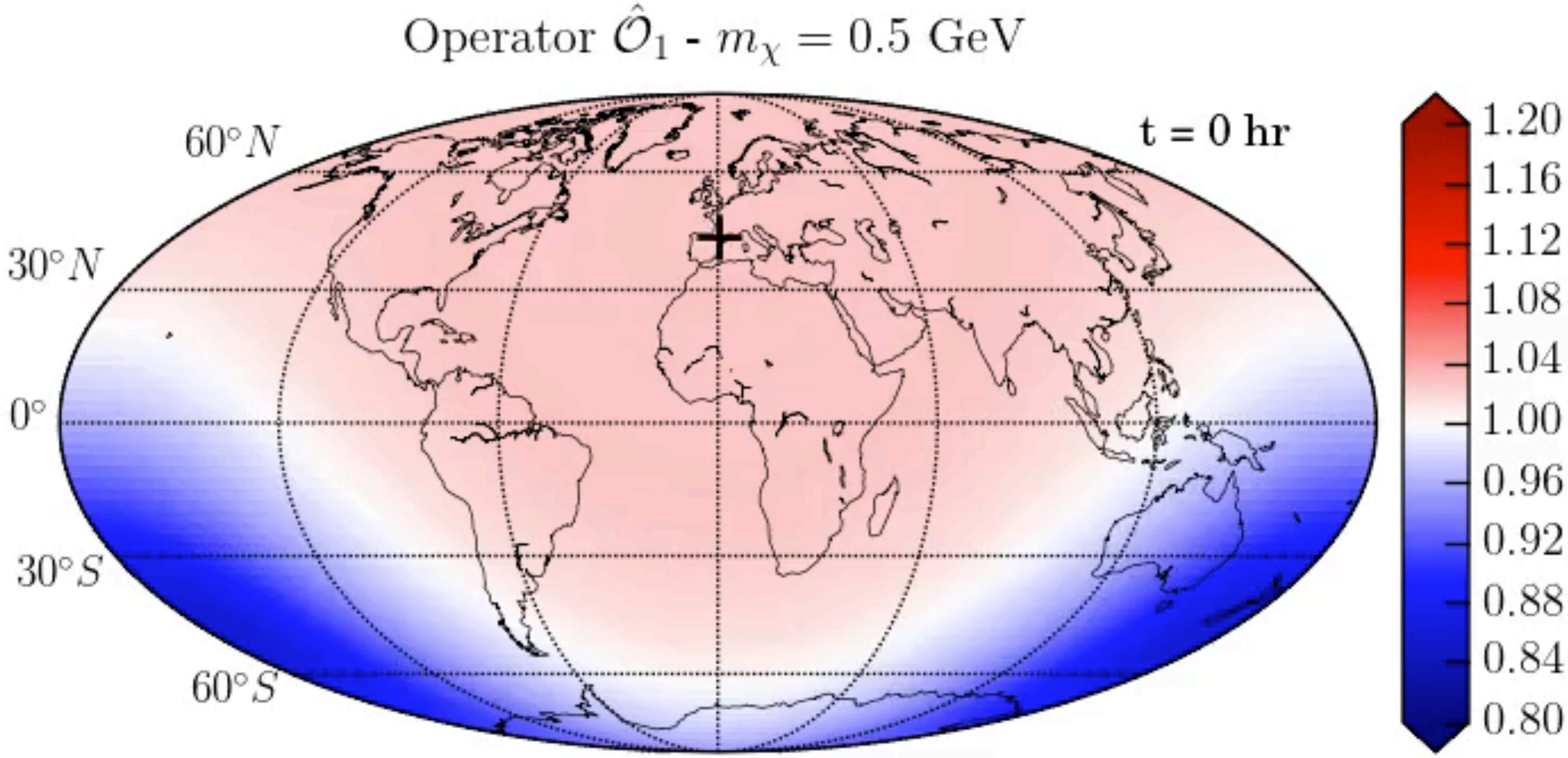
Operator 8 - forward deflection

Operator 12 - backward deflection





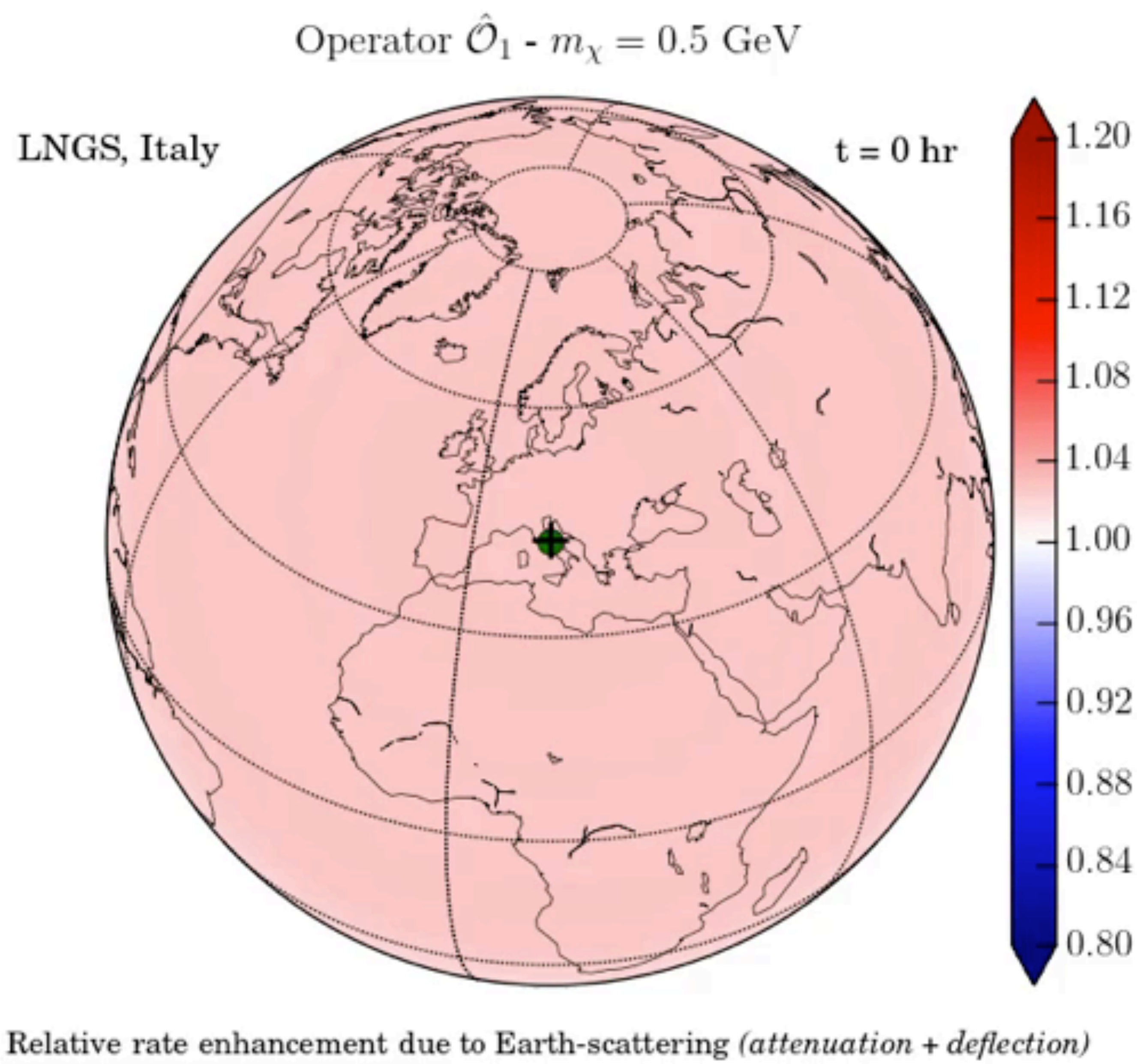
Mapping the CRESST-II Rate

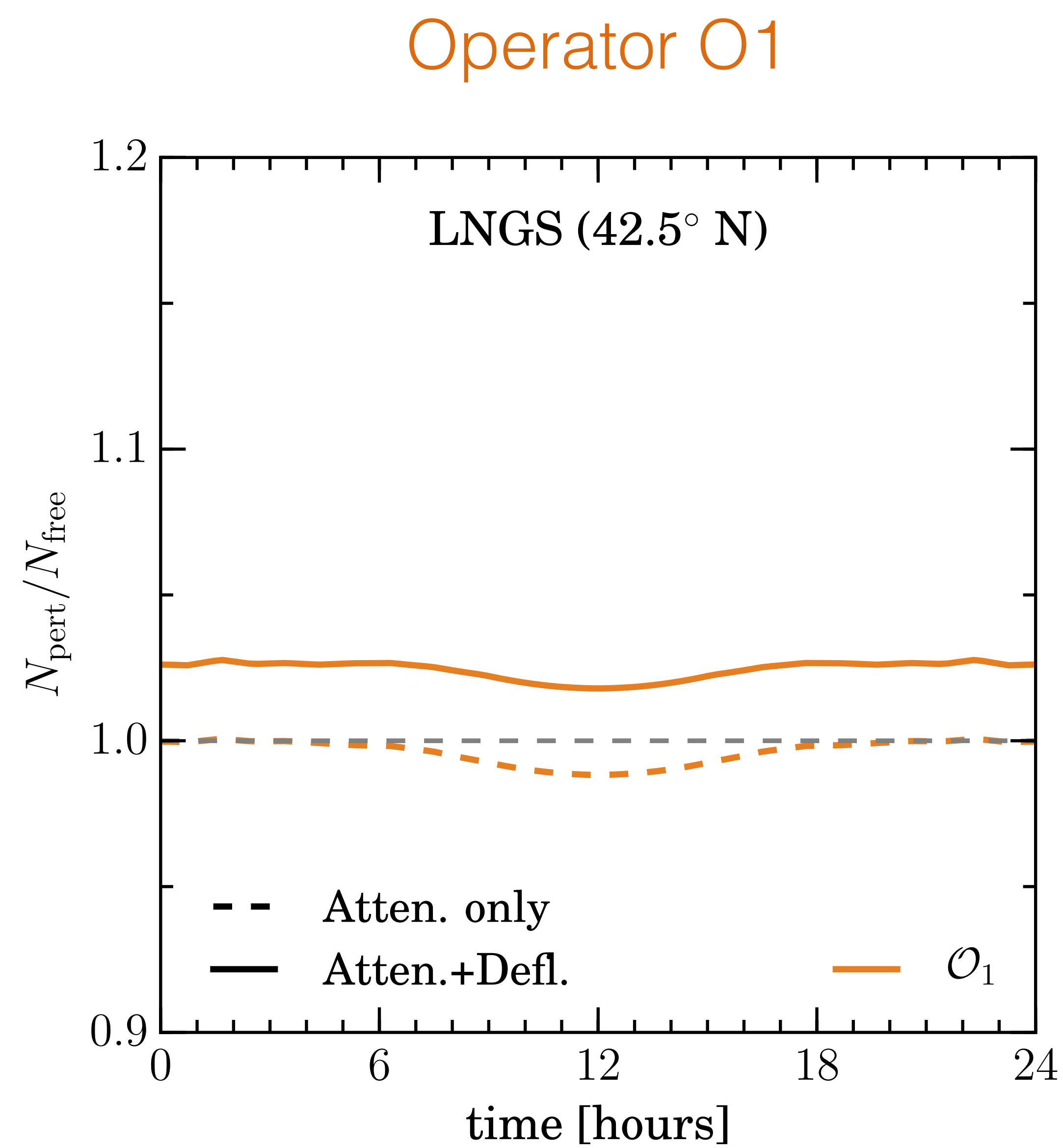


Relative rate enhancement due to Earth-scattering ***(attenuation + deflection)***

LNGS - Operator 1

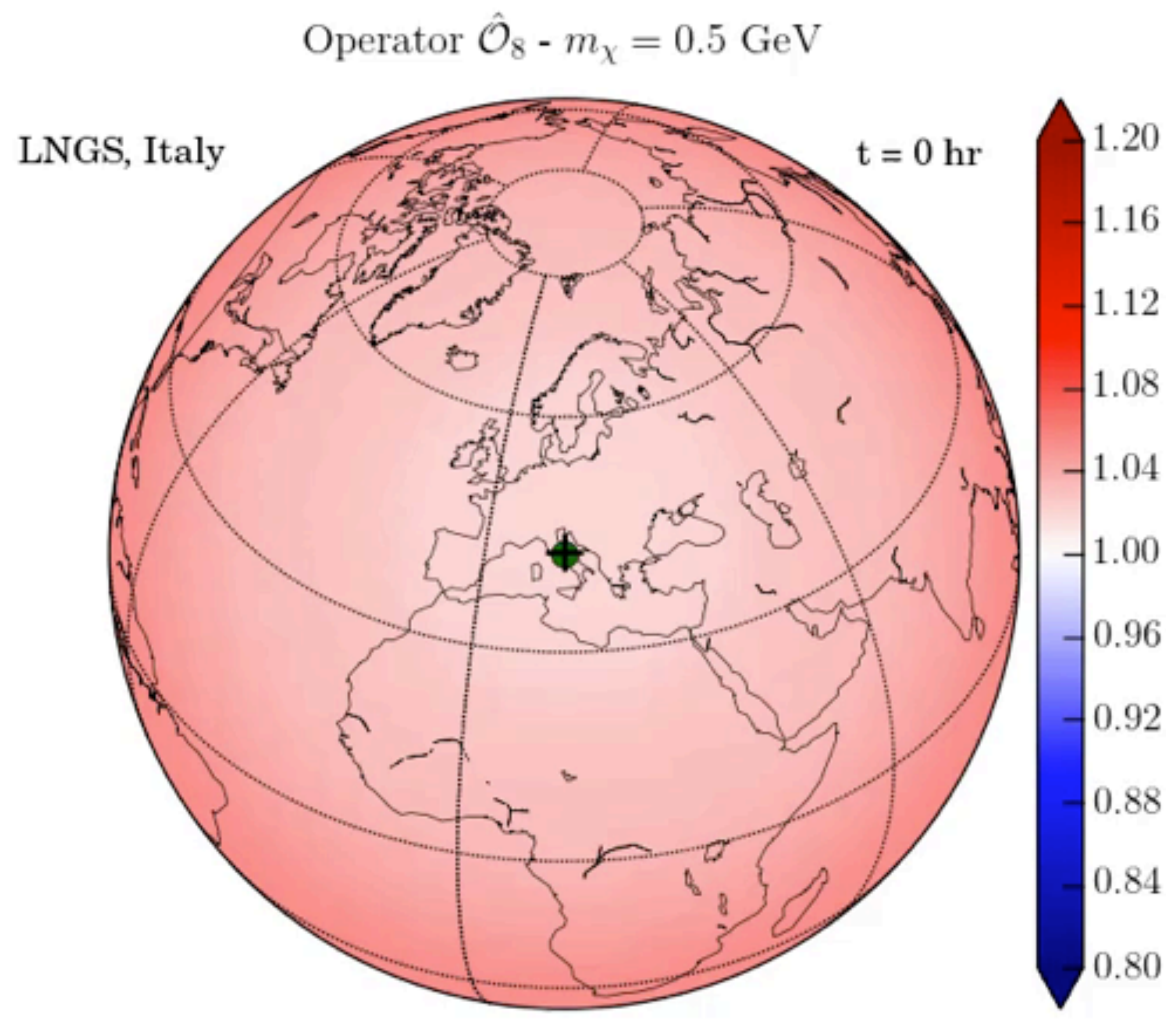
LNGS - Gran Sasso Lab, Italy





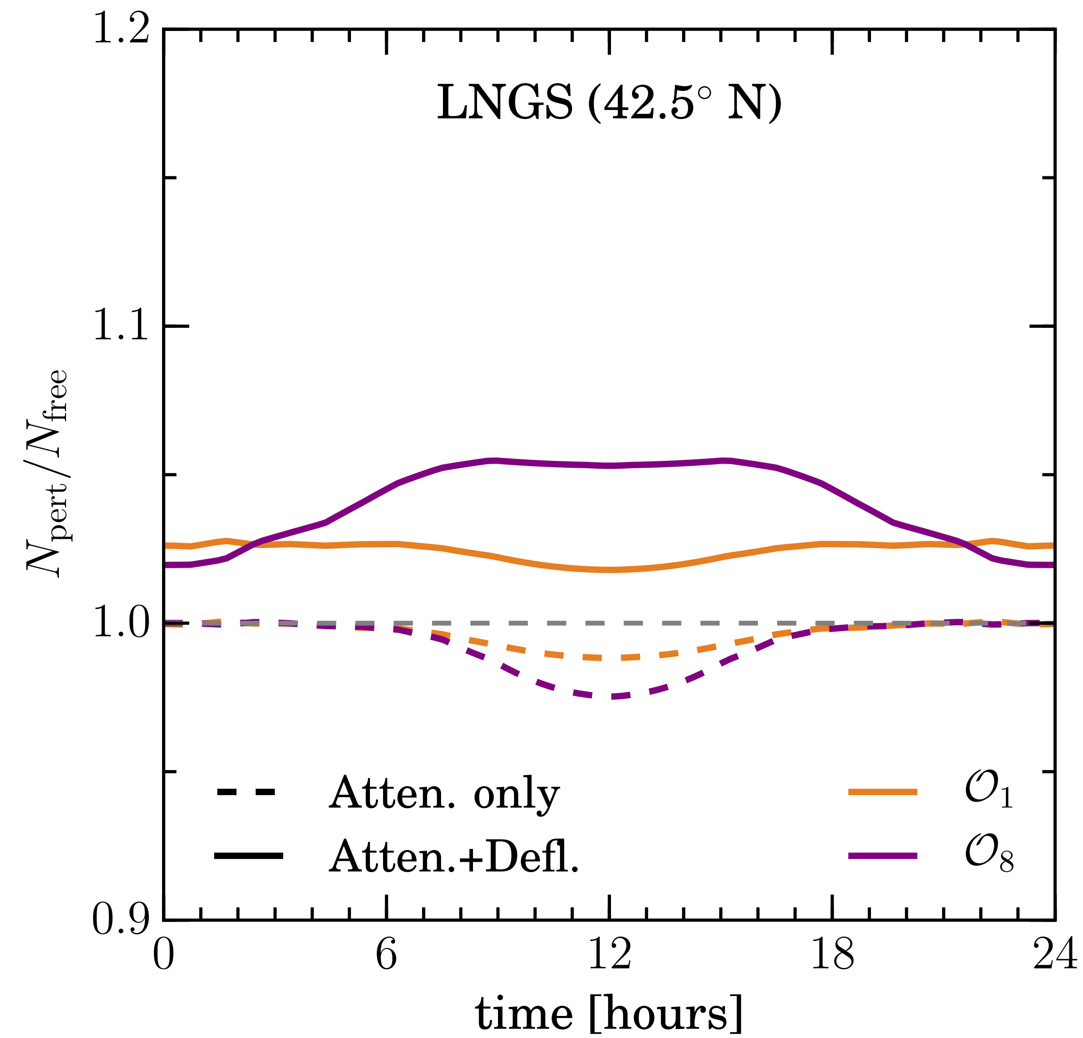
LNGS - Operator 8

LNGS - Gran Sasso Lab, Italy



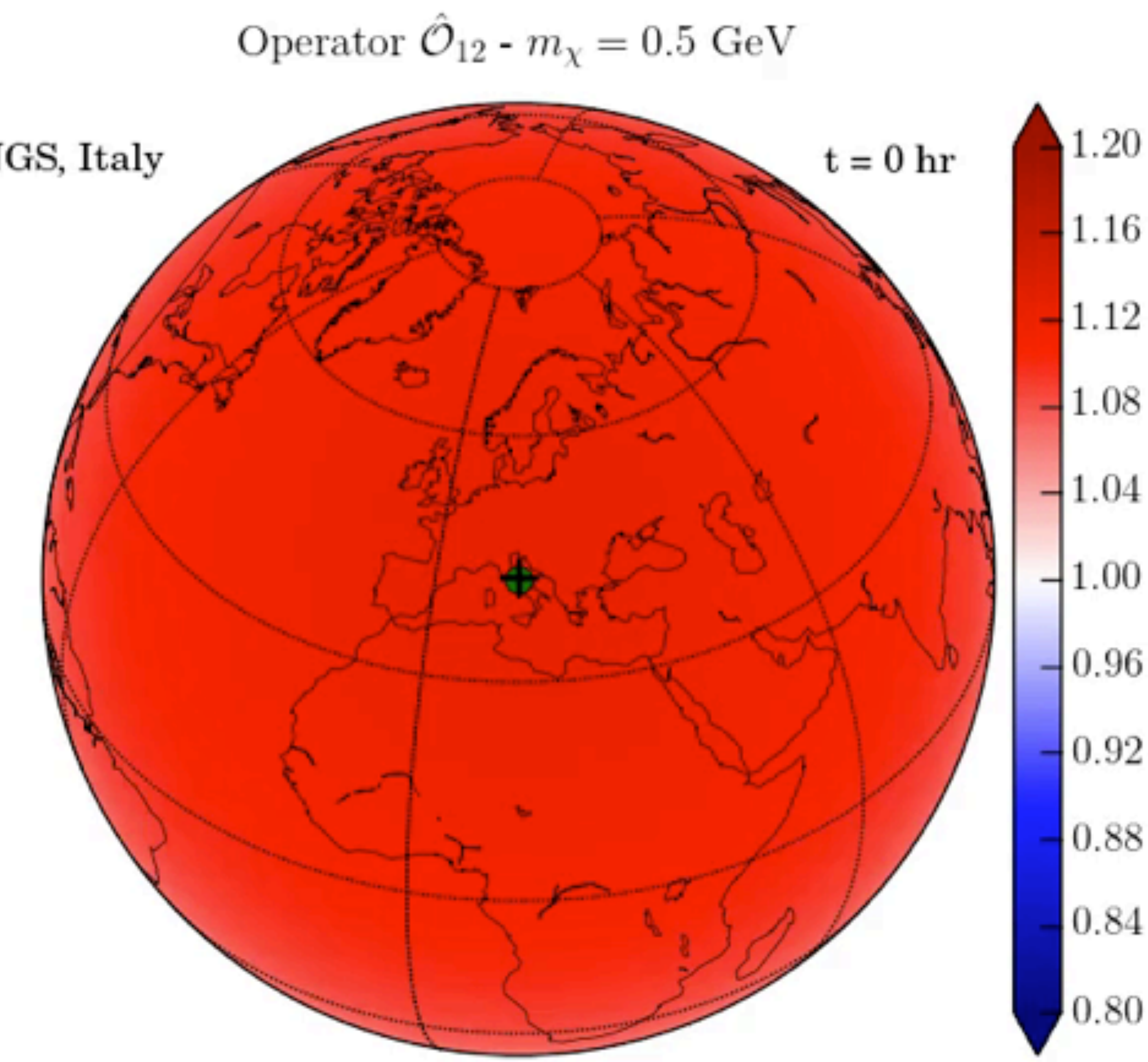
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator O8



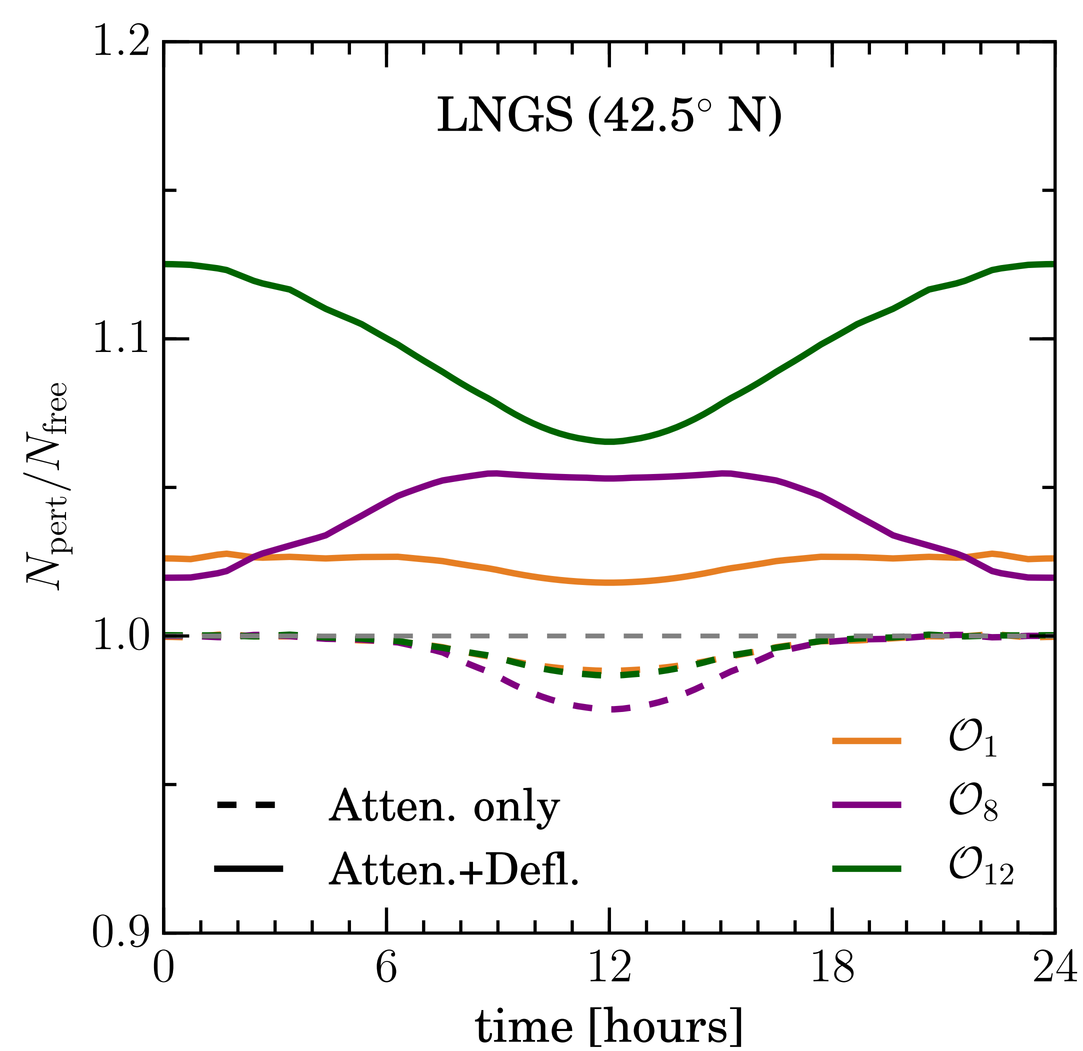
LNGS - Operator 12

LNGS - Gran Sasso Lab, Italy



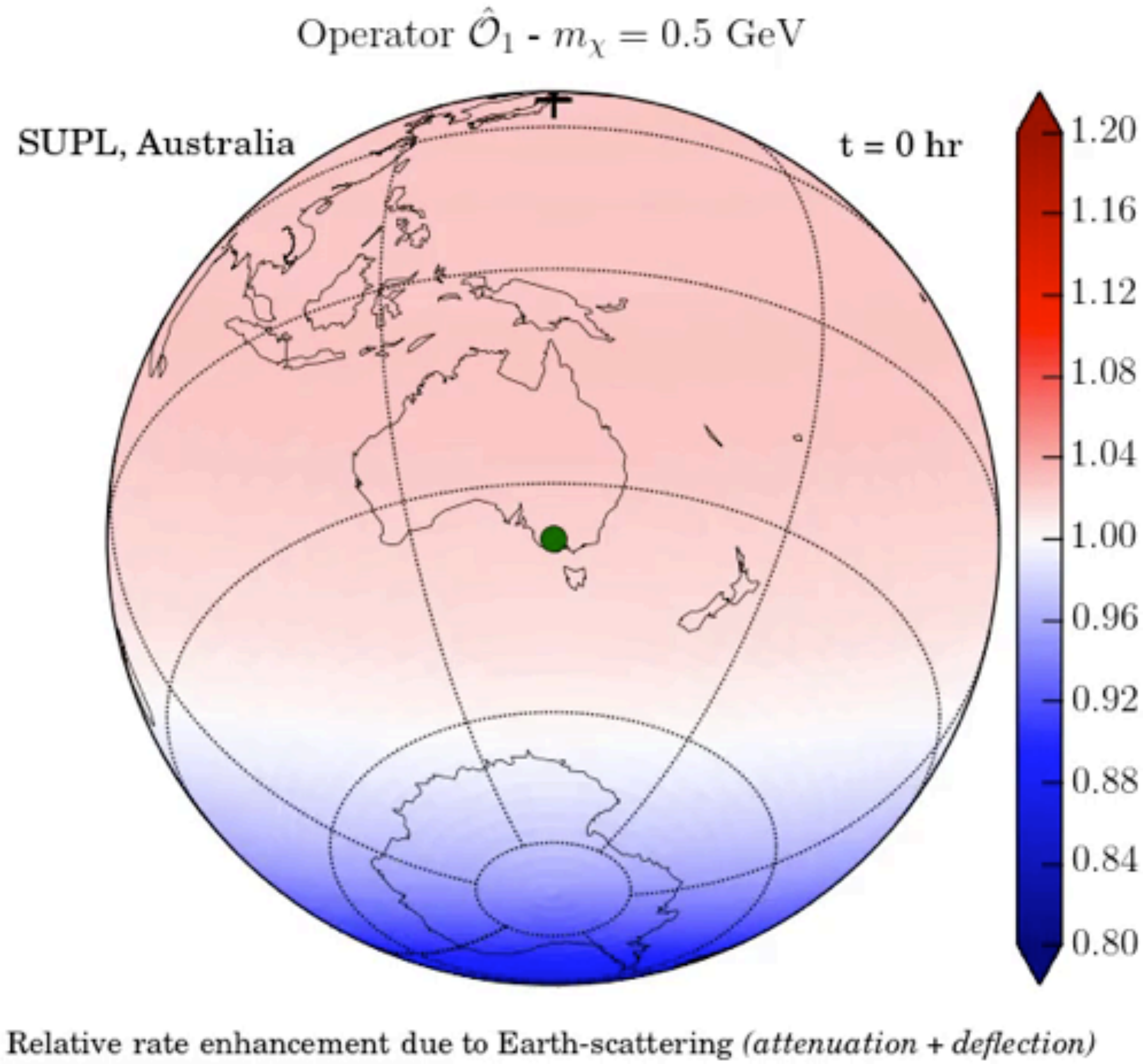
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator O12

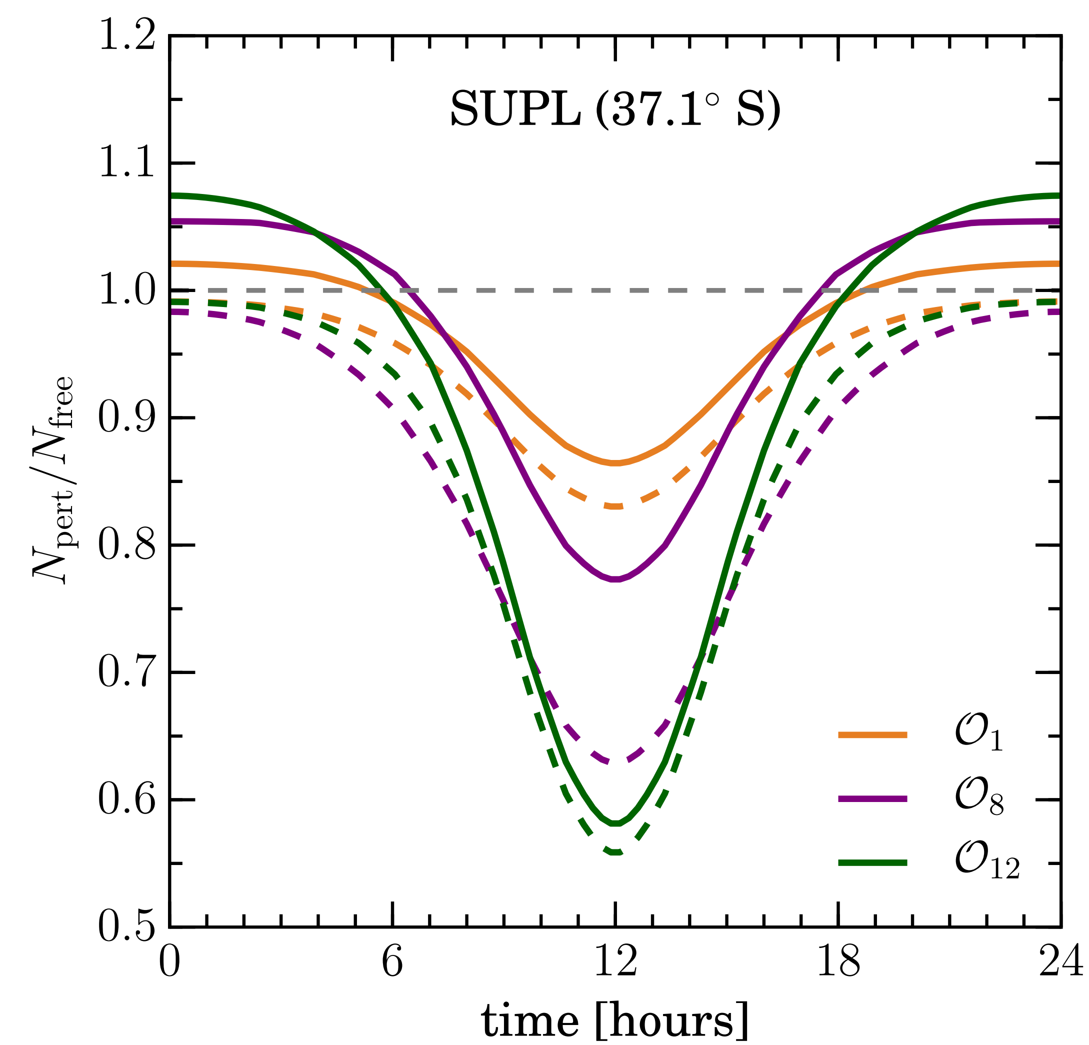


SUPL - Operator 1

SUPL - Stawell Underground Physics Lab, Australia

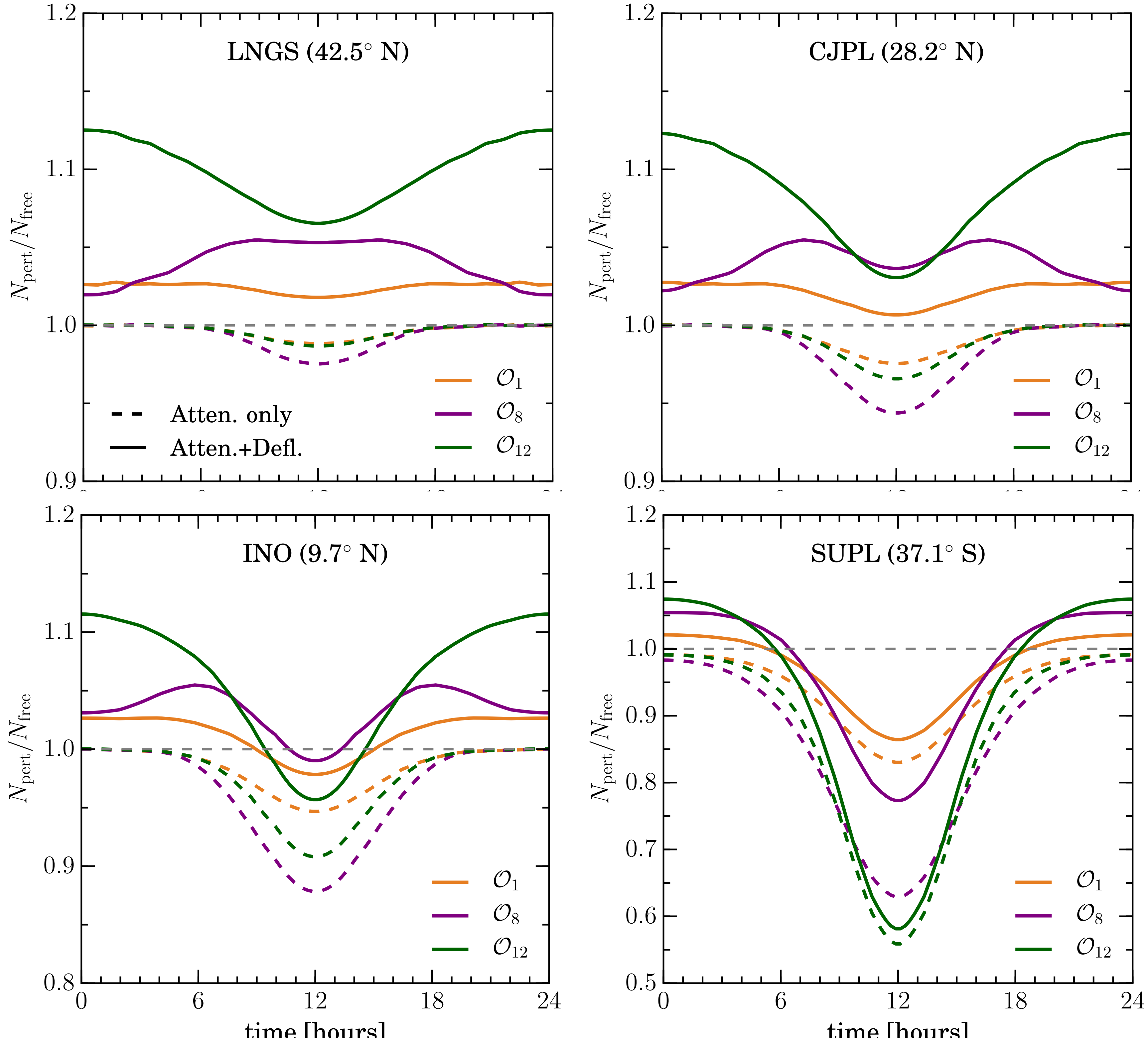


Operator O1



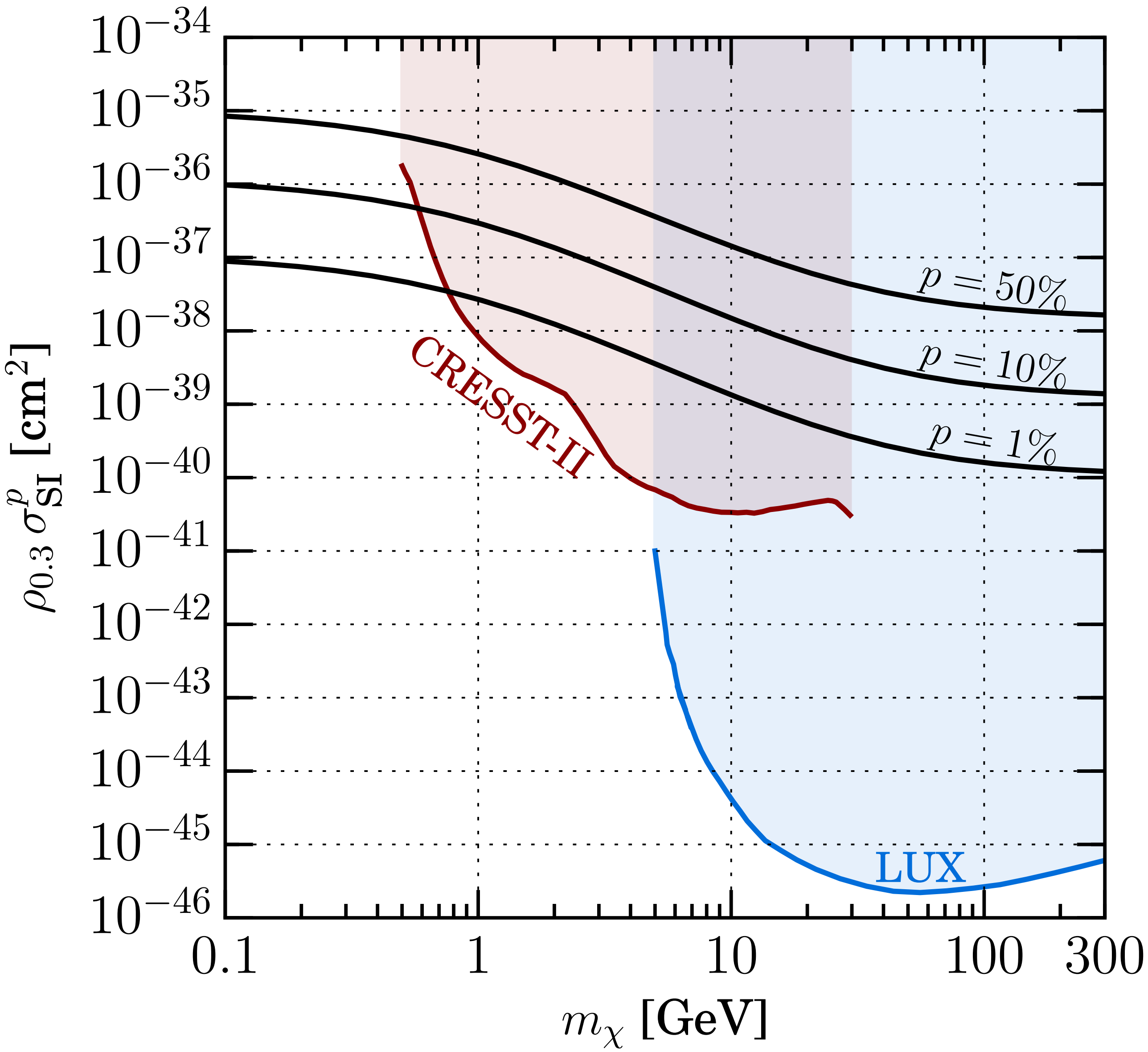
Around the world

China Jinping Lab



India-based Neutrino Observatory

Implications of Earth-Scattering



Smoking gun signature:
daily modulation +
location dependence

Possibility to distinguish different interactions with distinctive modulation signals

Possibility to measure the local DM density (by breaking degeneracy with cross section)

Future work

Here, we have considered only the DM *speed* distribution. Need to look at the full 3-D *velocity* distribution to explore directional signatures of Earth-Scattering.

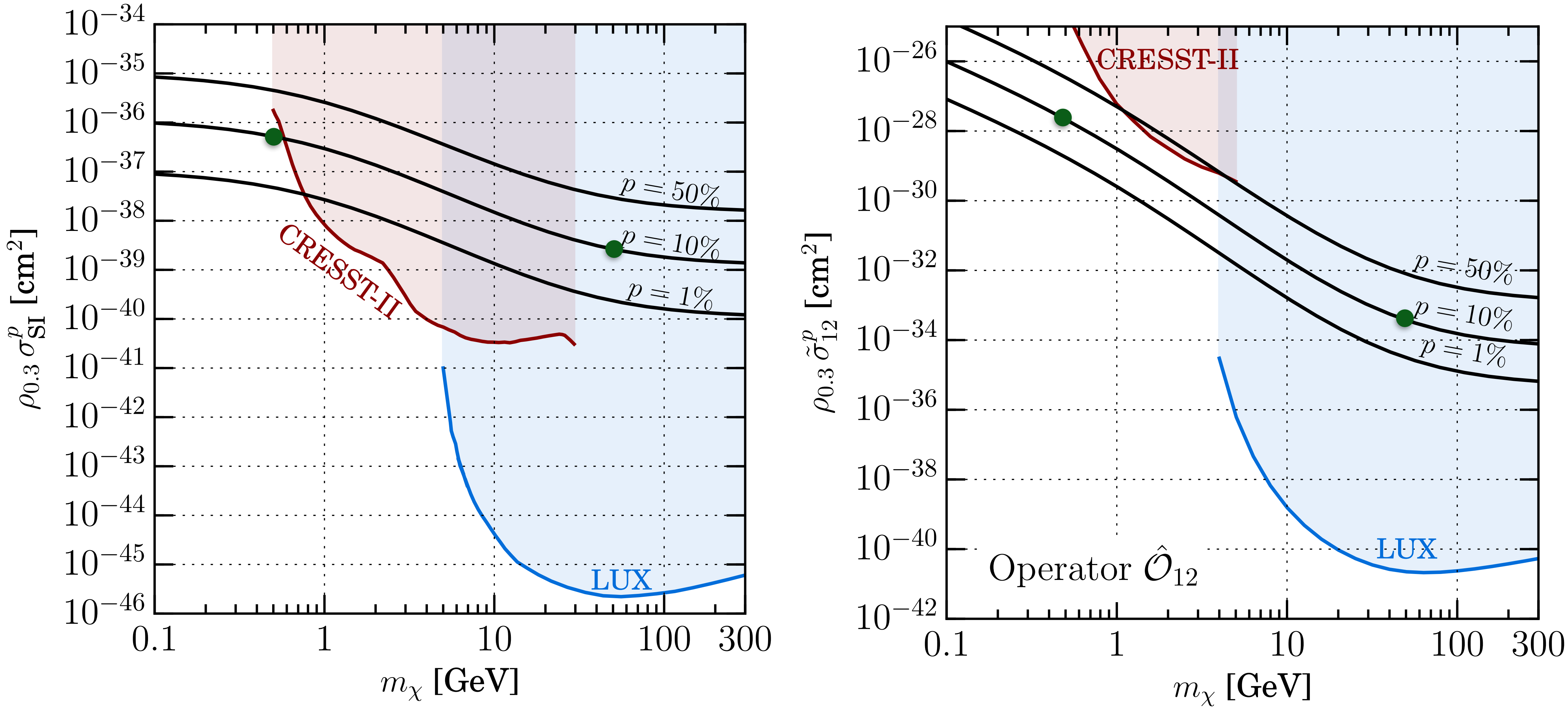
The Single-scatter approximation is important to capture the effects of deflection. But it will break down rapidly as we increase the DM cross section. Next steps:

- Calculations in the many-scatter/‘diffusion’ regime

- Dedicated simulations to test the single-scatter regime and connect to very high cross sections (work in progress by Chris Kouvaris and Timon Emken)

Mapping out the parameter space

Continue mapping out parameter space (m_χ, σ_p) and explore impact on upper limits for a range of interactions…

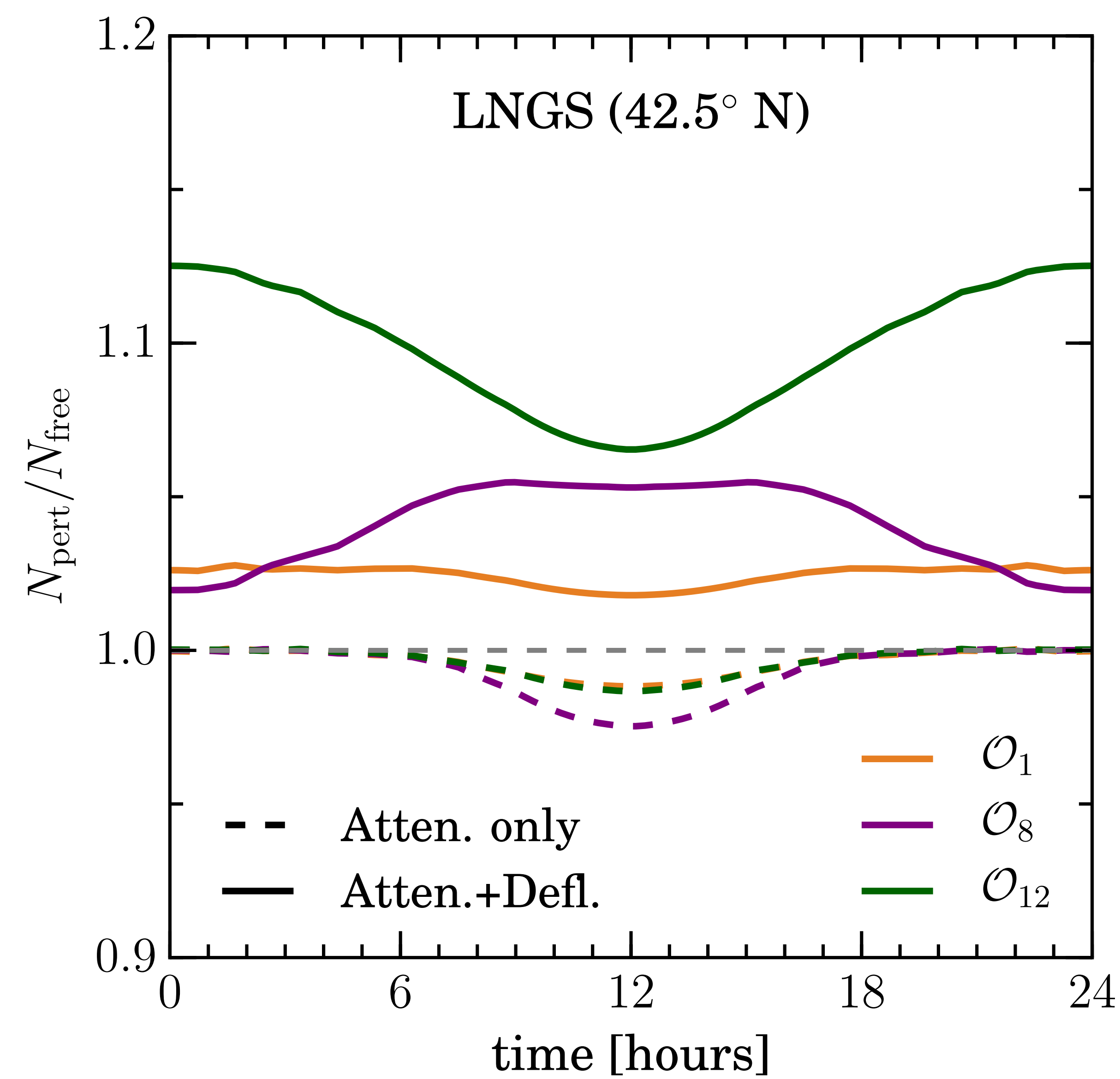


…and encourage experimental collaborations to explore full NREFT parameter space.

Conclusions

arXiv:1611.05453

- 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



Conclusions

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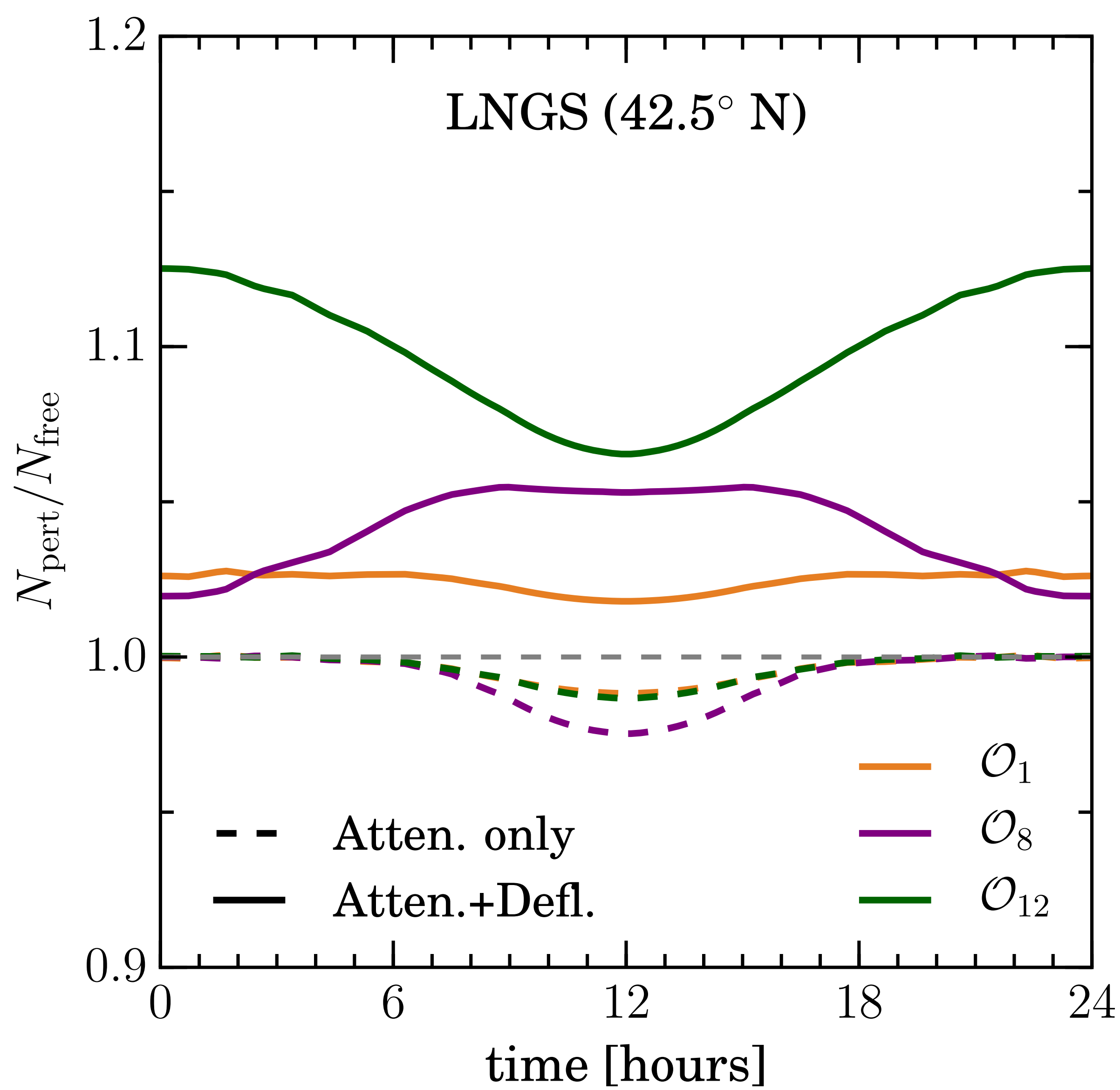
- Significant Earth-Scattering is still allowed and detectable by current experiments
- Need to include both attenuation and deflection of DM
- Careful calculation including multiple elements, correct density profiles and different interactions
- The average incoming DM direction varies with time - distinctive daily modulation signals
- Different interactions may lead to modulations with different size and phases - and may therefore be distinguishable
- EARTHSHADOW code available online to include these effects: github.com/bradkav/EarthShadow



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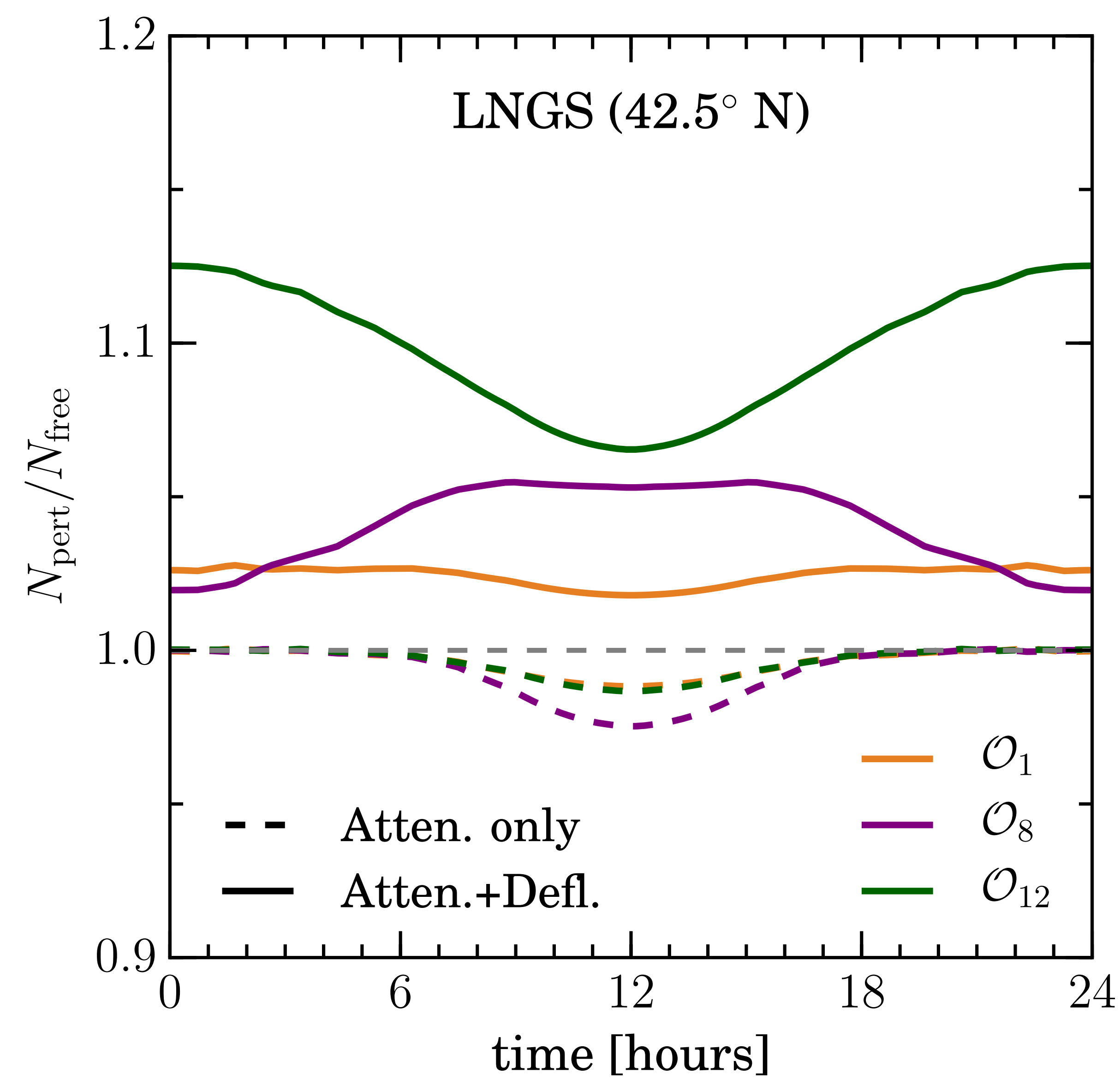
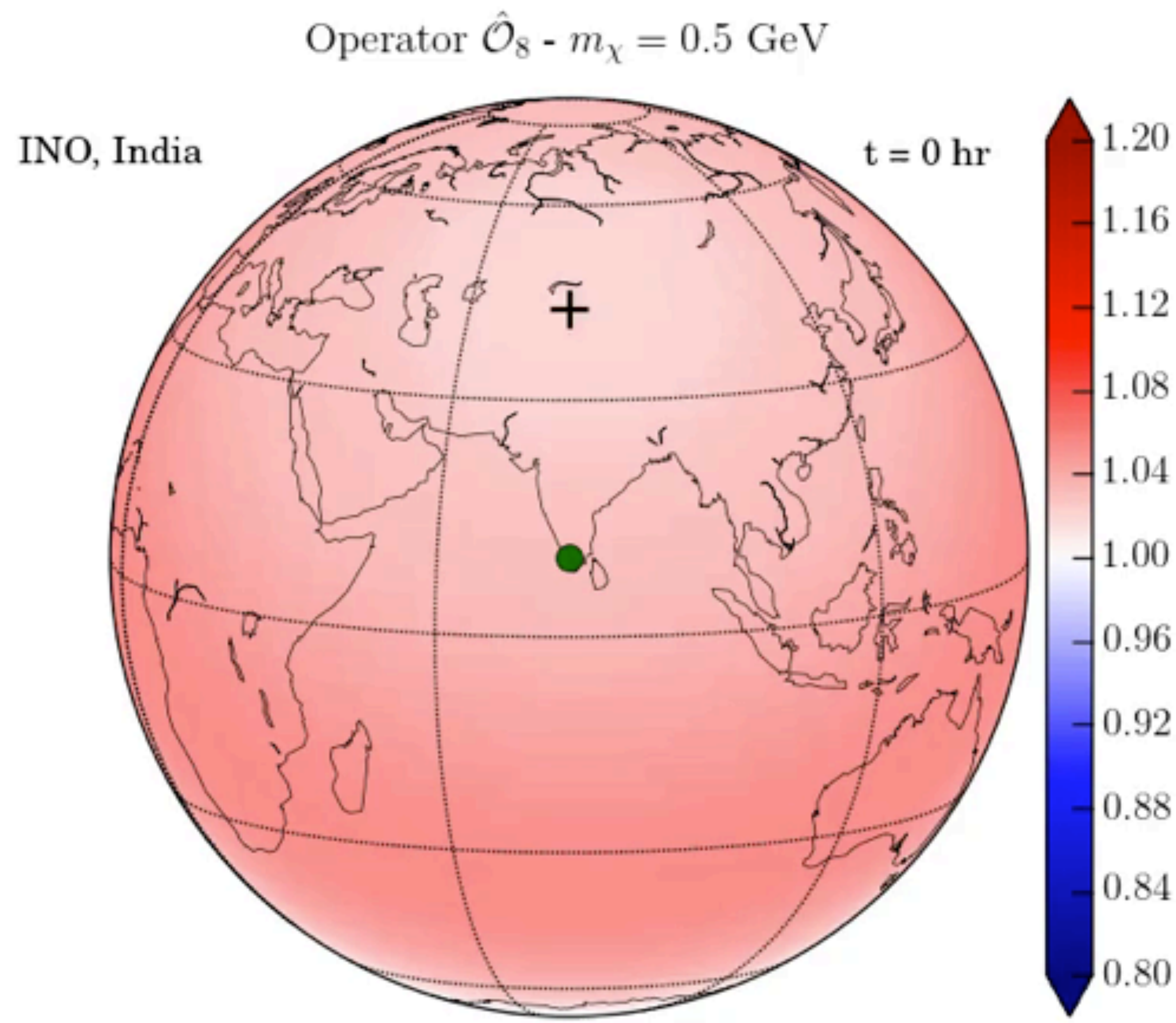


Thank you!

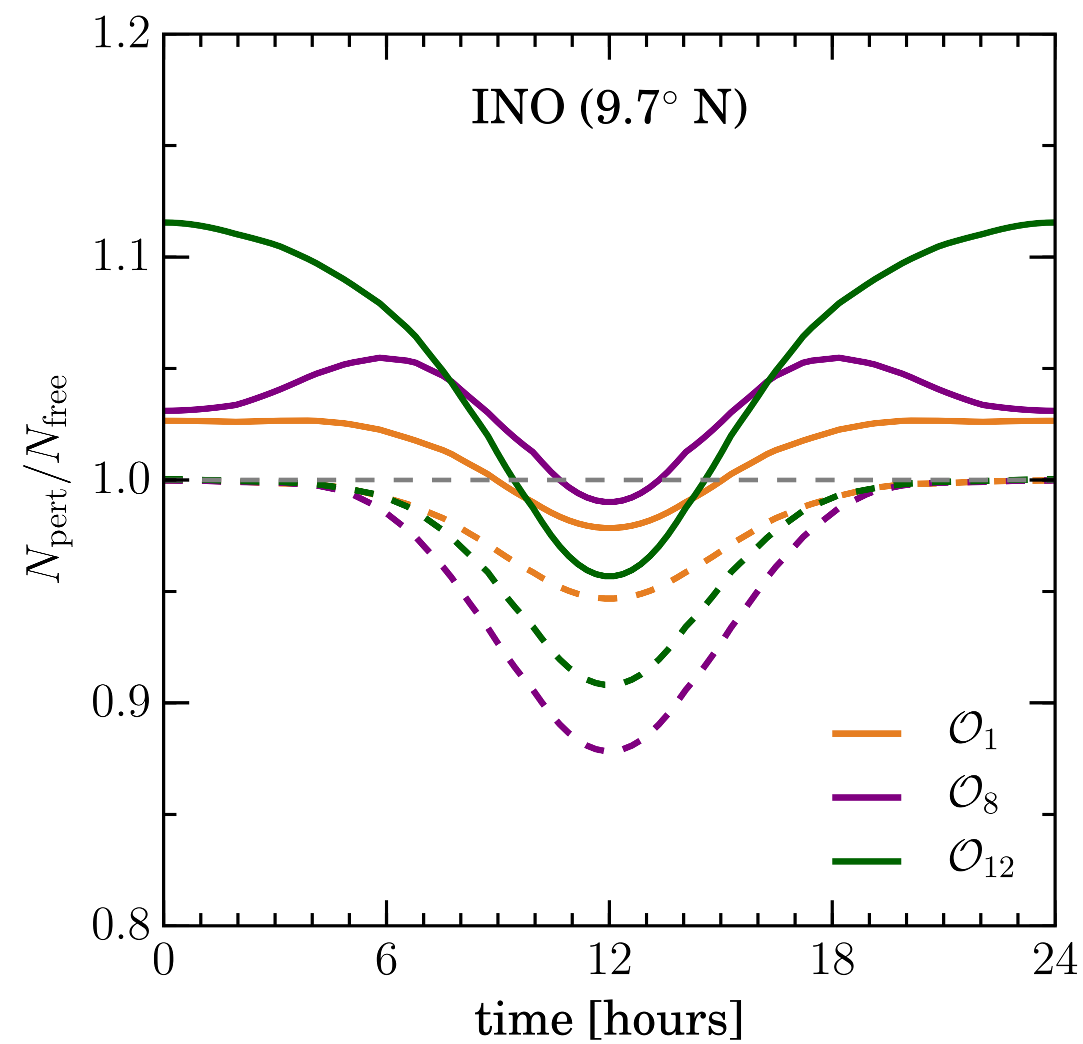
Backup Slides

INO - Operator 8

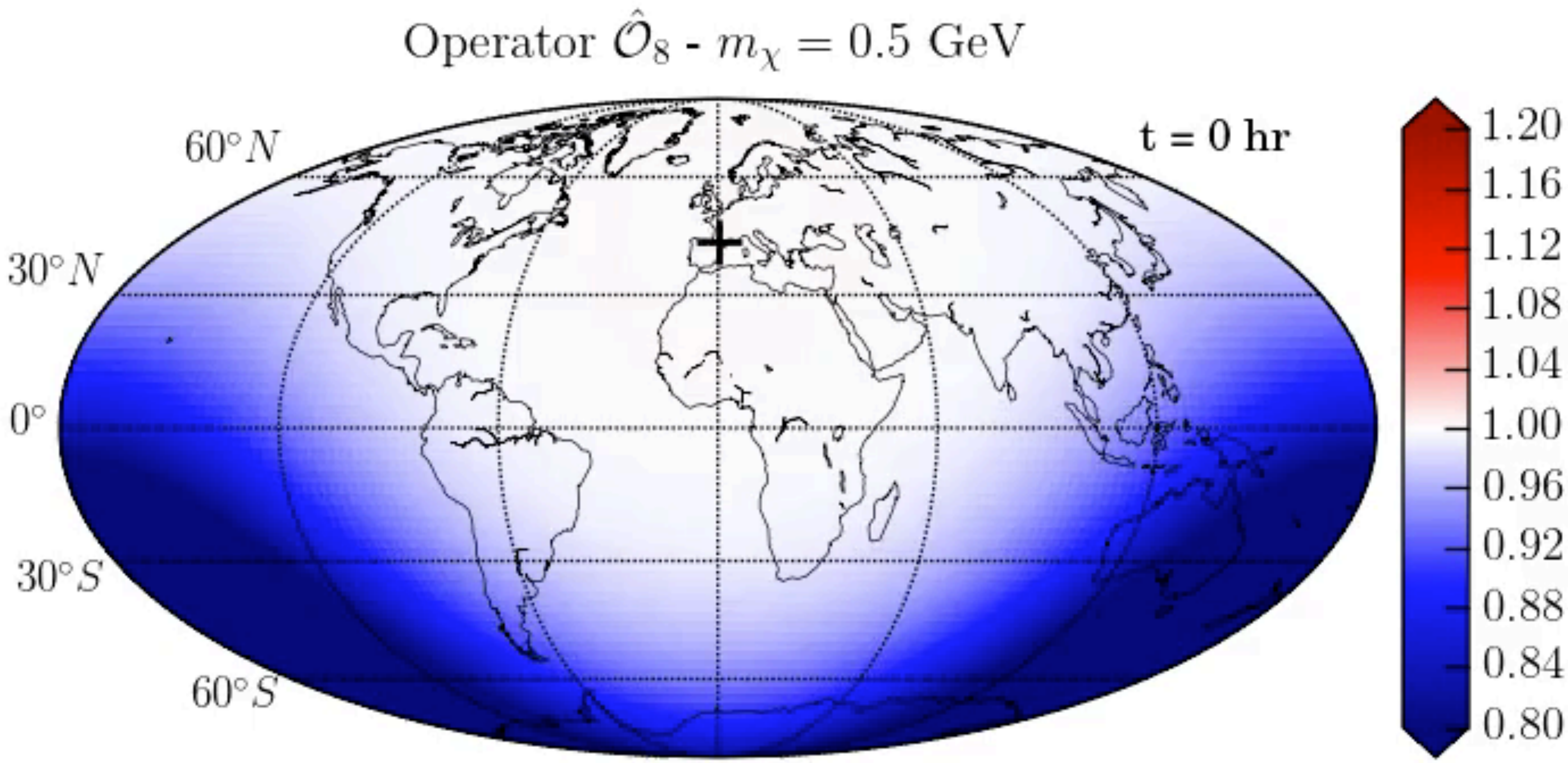


Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator O8

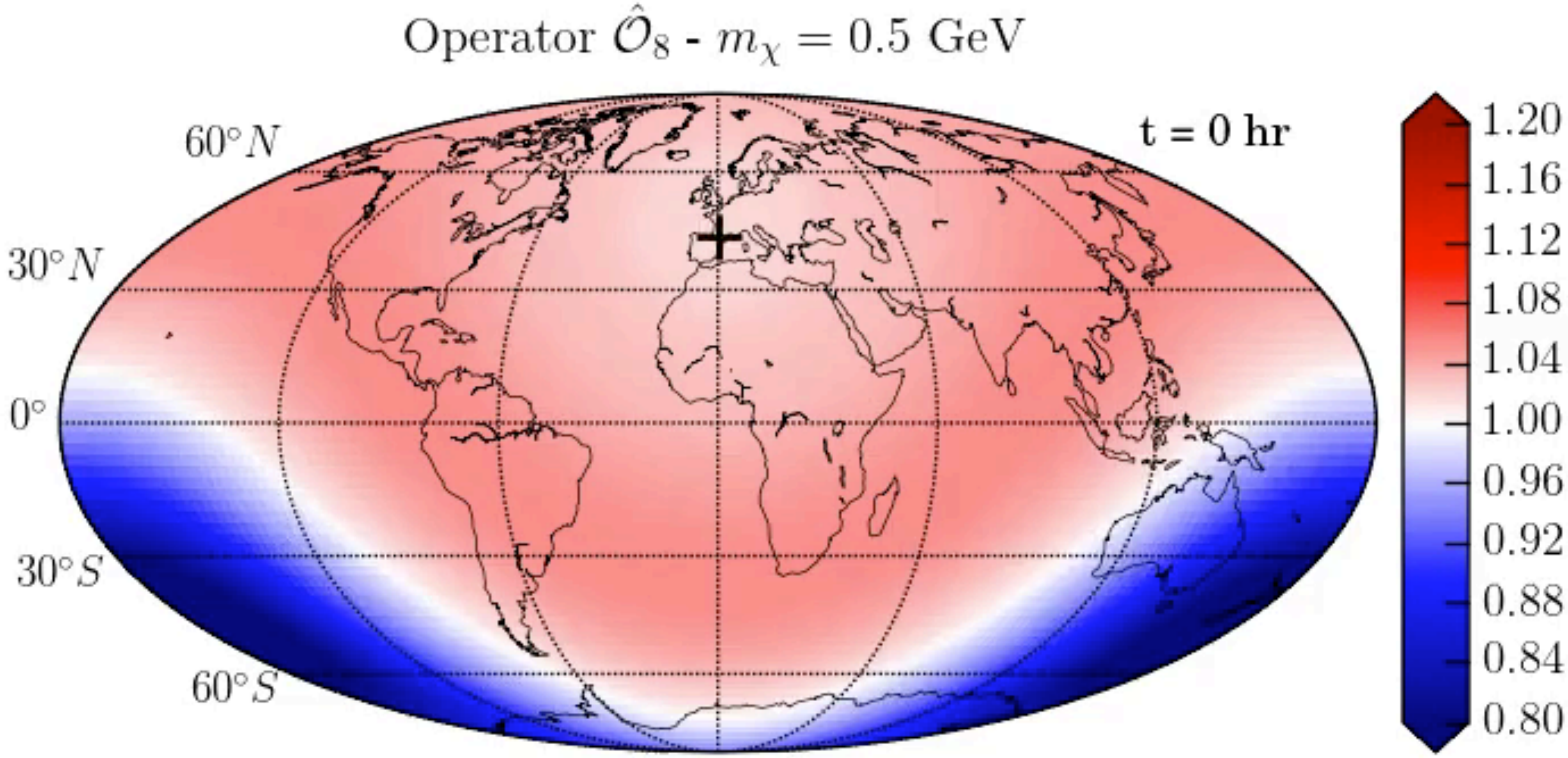


Mapping the CRESST-II Rate



Relative rate enhancement due to Earth-scattering *(attenuation only)*

Mapping the CRESST-II Rate



Relative rate enhancement due to Earth-scattering ***(attenuation + deflection)***

Mapping the CRESST-II Rate