Signatures of Dark Matter Earth-Scattering:
from sub-GeV particles to WIMPzillas

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Direct Detection

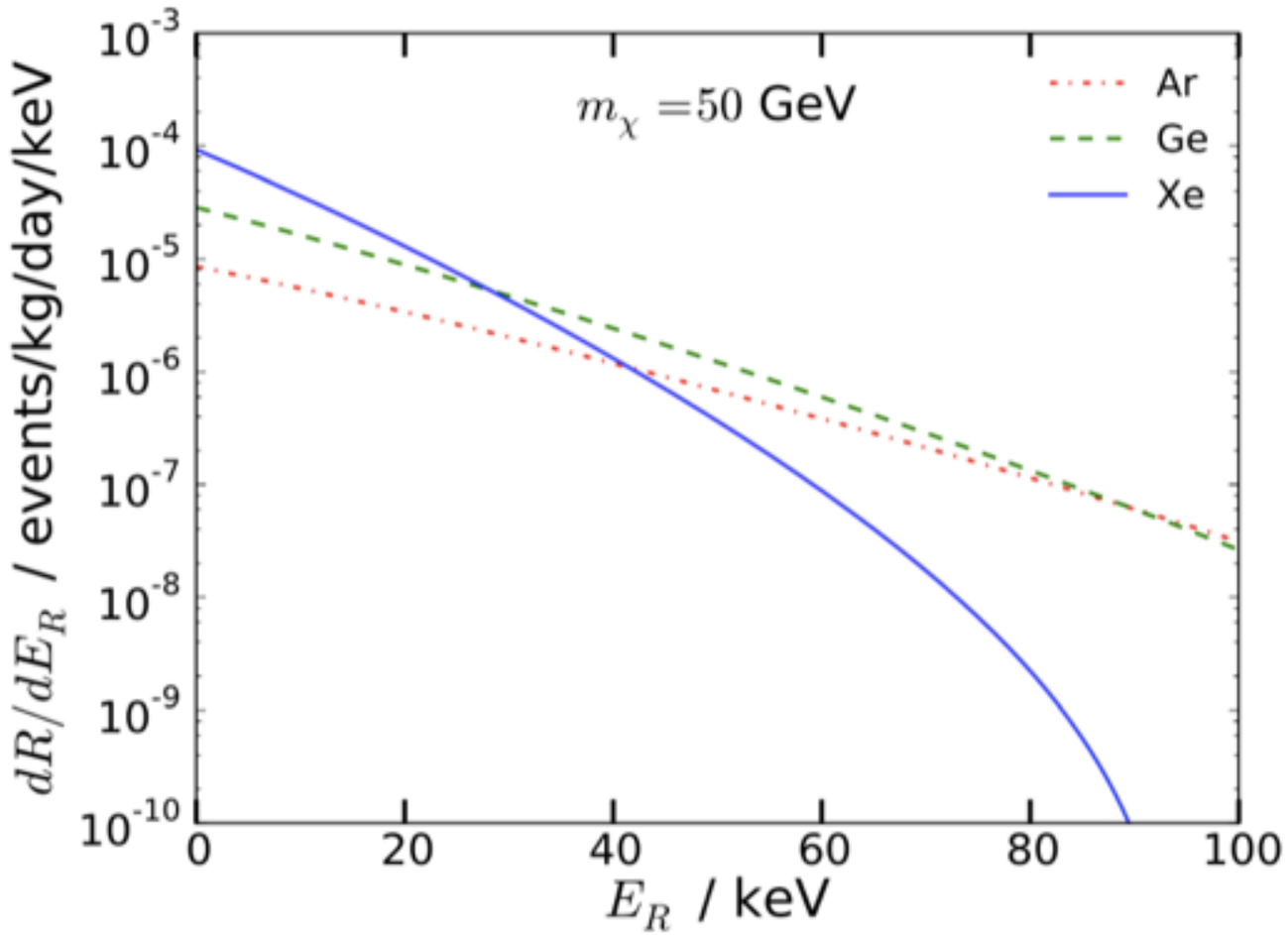
Focus on DM-nucleus scattering for now

DM flux:

$$\Phi_\chi = \frac{\rho_\chi}{m_\chi} v f(\mathbf{v})$$

Convolve with DM-nucleus cross section to obtain nuclear recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \frac{\rho_\chi}{m_\chi} \int_{v_{\mathrm{min}}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \mathrm{d}v$$



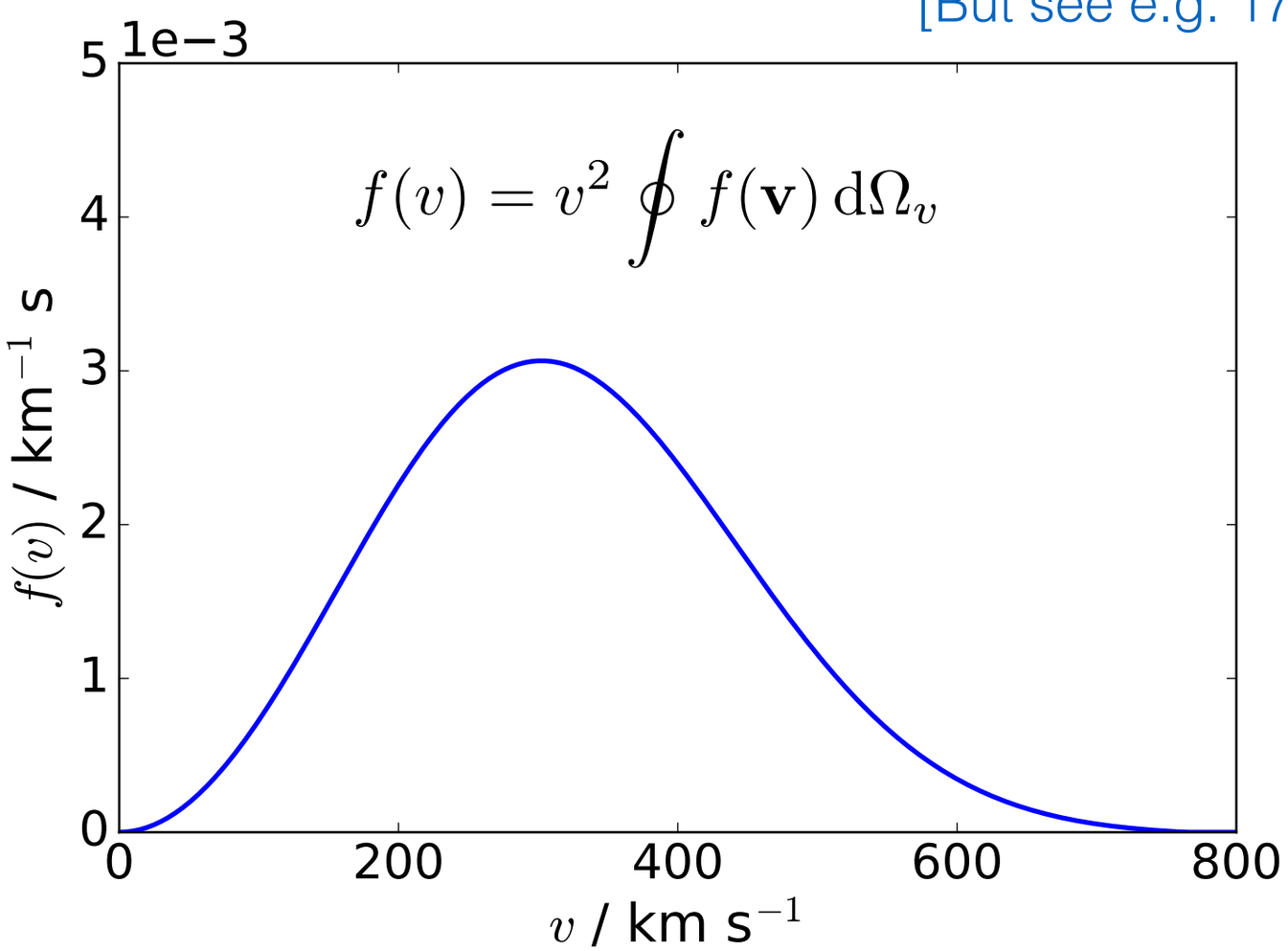
Standard Halo Model

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

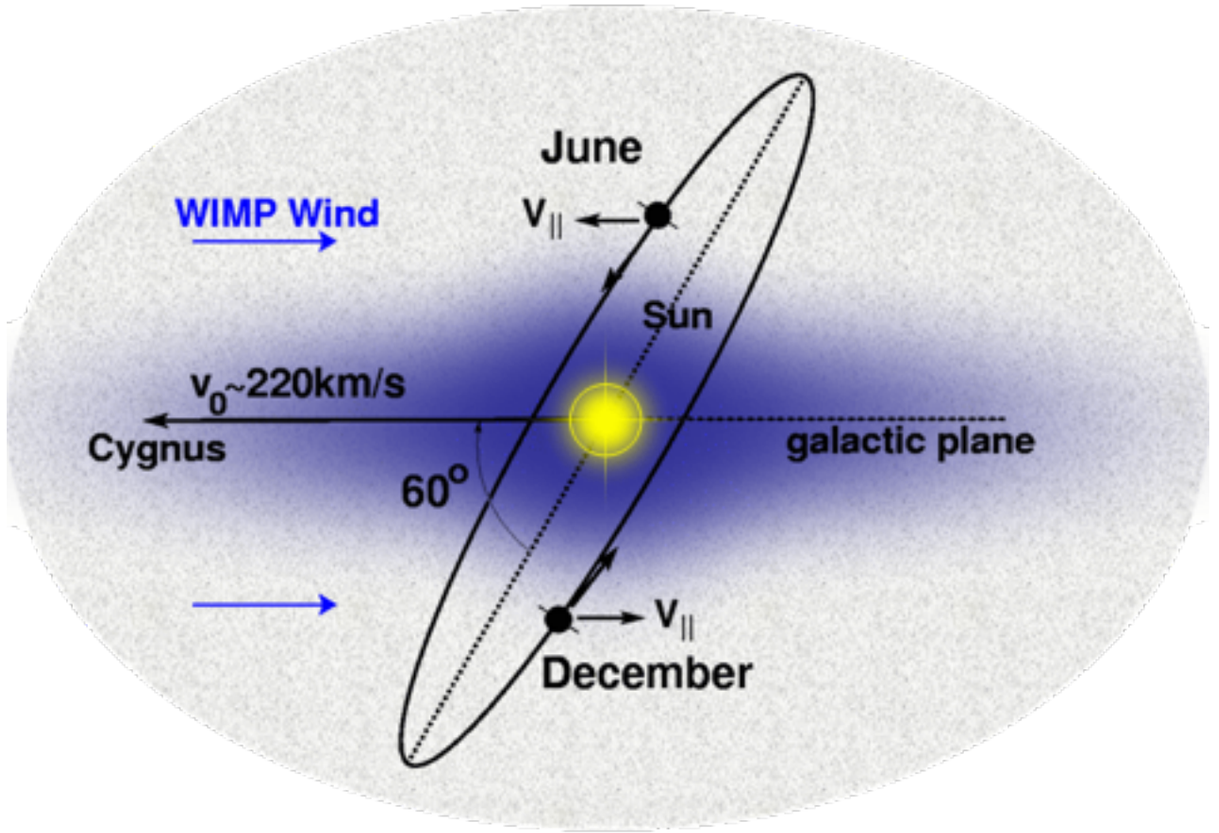
Leads to a Maxwell-Boltzmann (MB) distribution (*in the lab frame*):

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

[But see e.g. 1705.05853]



Annual Modulation (Earth's Orbit)



$$v_{\rm Sun} \approx 230 \text{ km s}^{-1}$$

$$v_{\rm E} \approx 30 \text{ km s}^{-1}$$

$$\mathbf{v}_{\rm Earth}(t) = \mathbf{v}_{\rm Sun} + \mathbf{v}_{\rm E}(t)$$

O(1-10%) annual modulation of DM flux

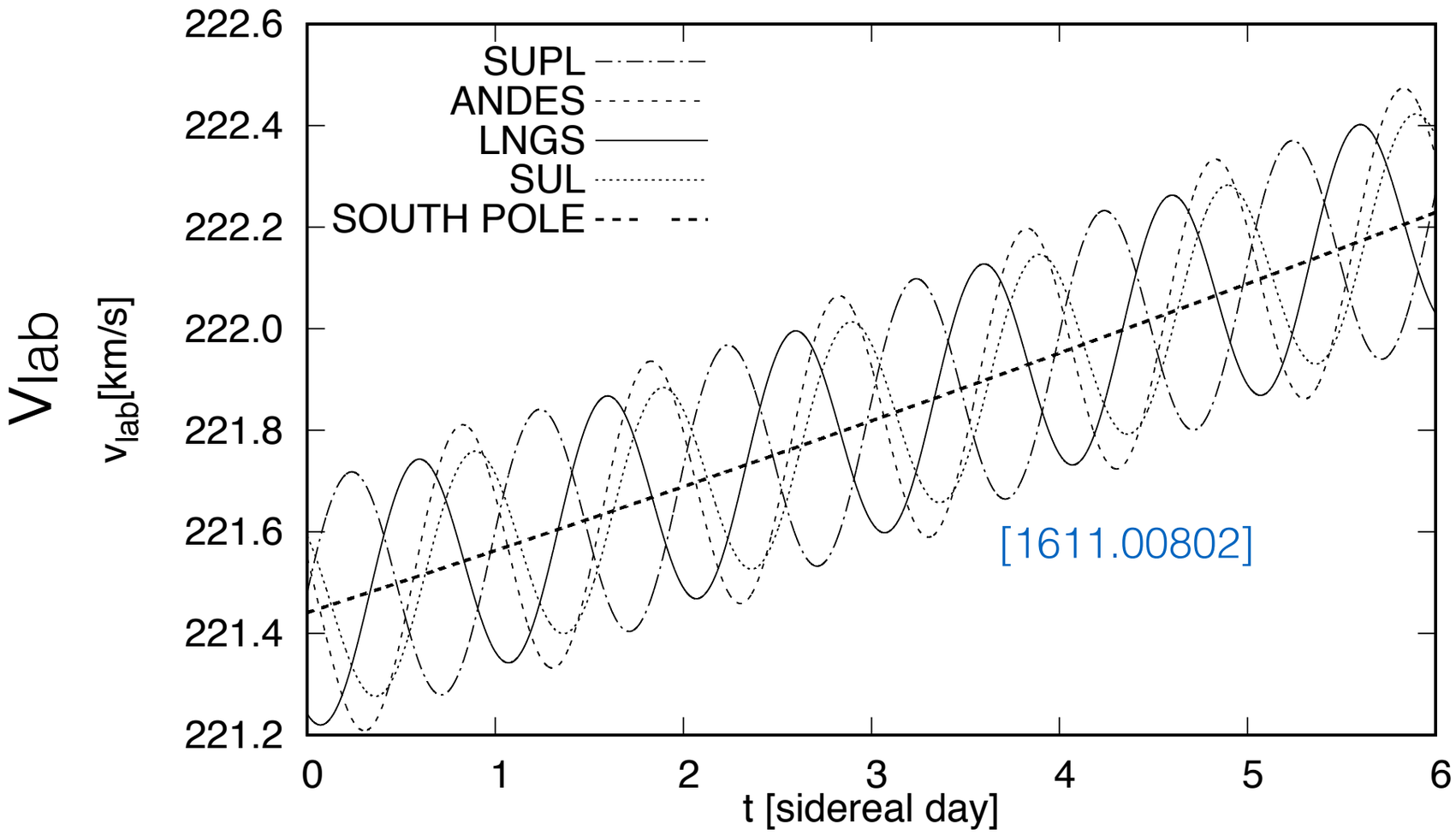
Maximum in June, Minimum in December

[1312.1355]

Daily Modulation (Earth's Rotation)

$$\mathbf{v}_{\rm Earth}(t) = \mathbf{v}_{\rm Sun} + \mathbf{v}_{\rm E}(t) + \mathbf{v}_{\rm rot}(t)$$

$$v_{\rm rot} \approx 0.5 \text{ km s}^{-1}$$

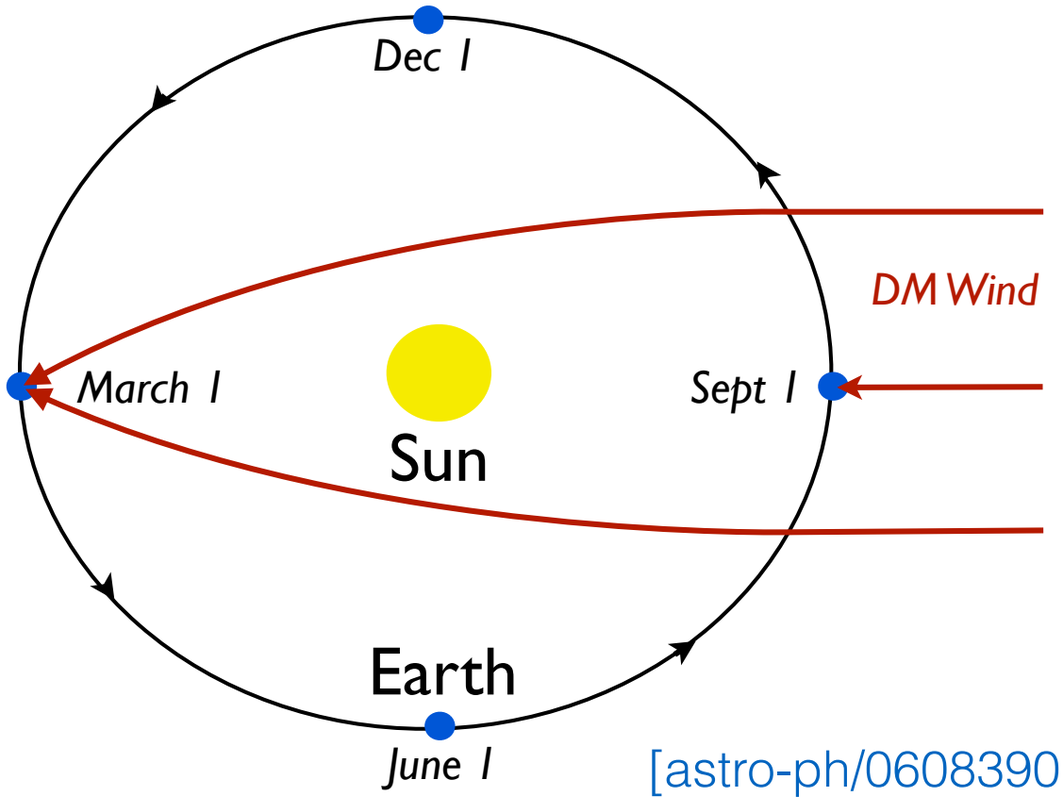


Produces a very small diurnal modulation (amplitude less than 0.1%)

[1505.02615]

Gravitational Focusing (GF)

Also modify DM velocities due to gravitational focusing from Sun and Earth



GF due to Sun produces a %-level annual modulation, *with different phase* compared to Earth's orbital speed

[astro-ph/0608390, 1308.1953, 1405.2340]

Similar effect due to focusing from Earth, comparable to effects of Earth's rotation. [1505.02615]

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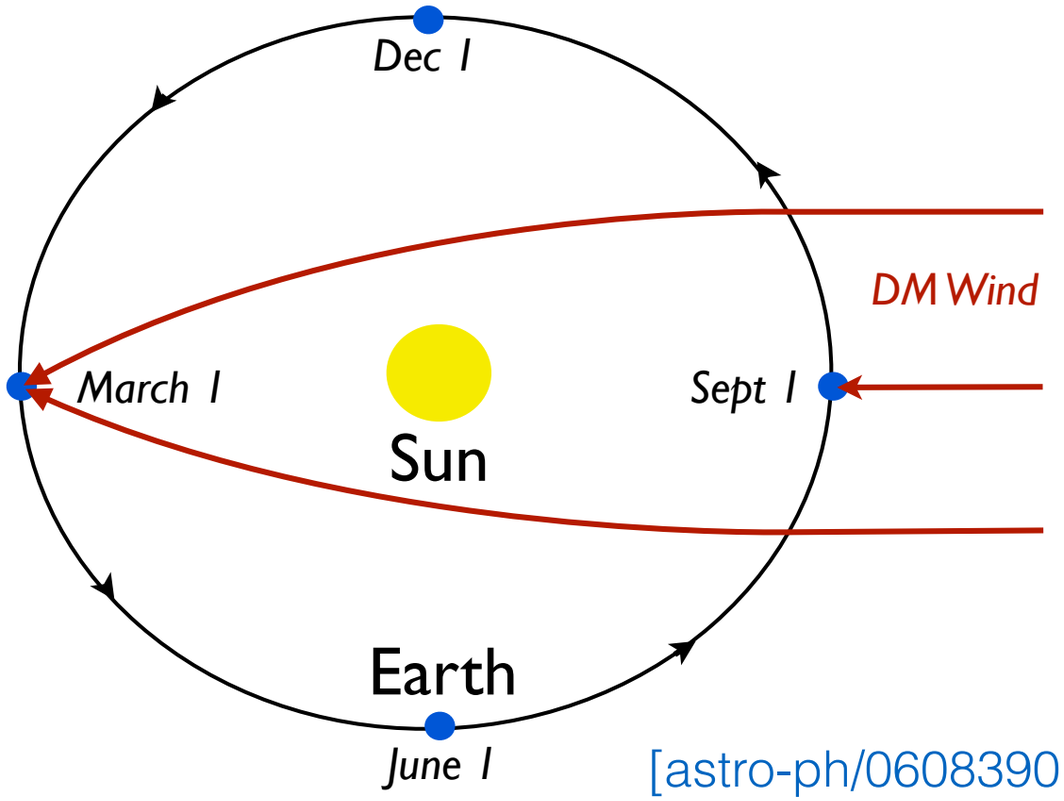

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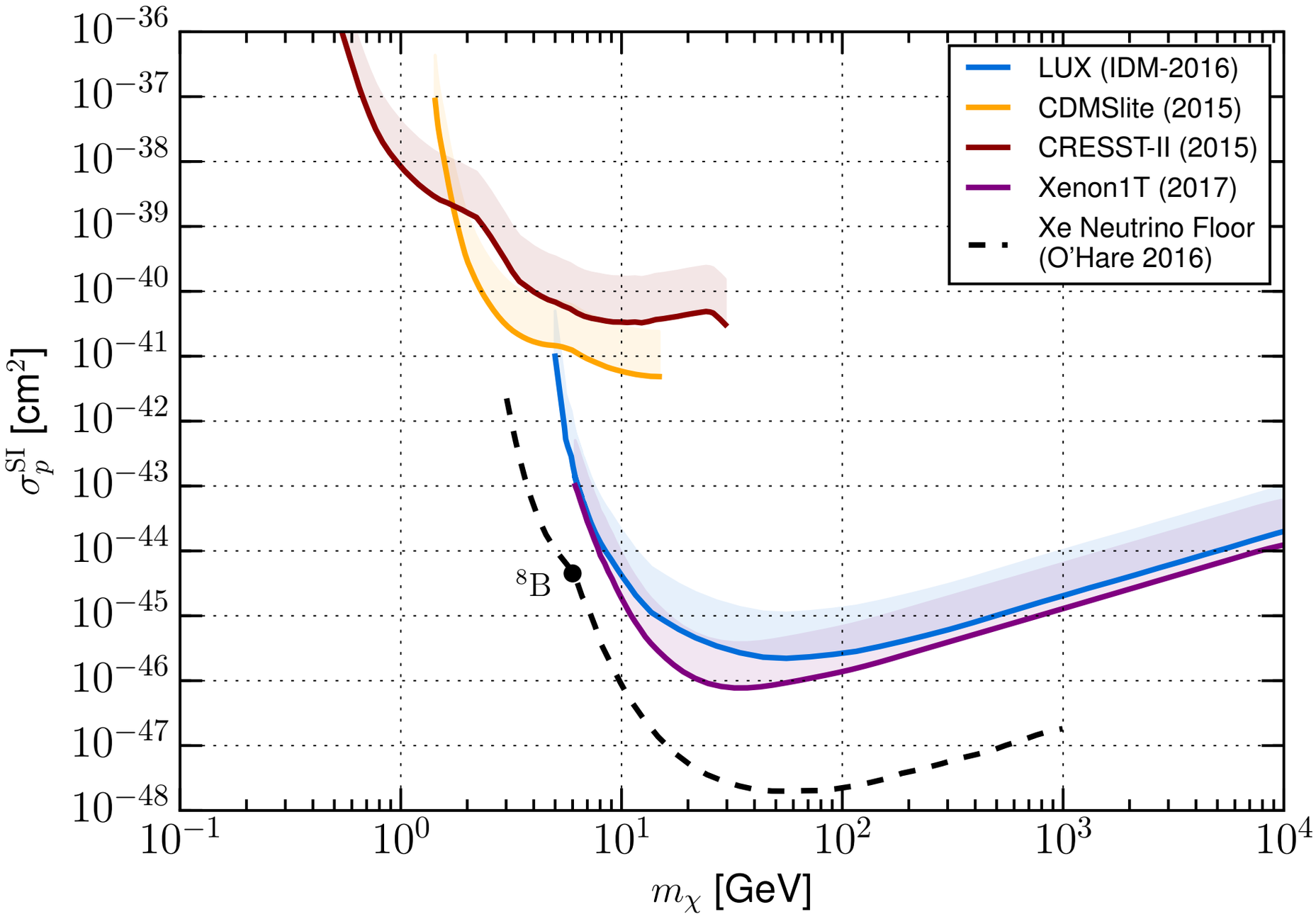
[astro-ph/0608390, 1308.1953, 1405.2340]

Similar effect due to focusing from Earth, comparable to effects of Earth's rotation. [1505.02615]

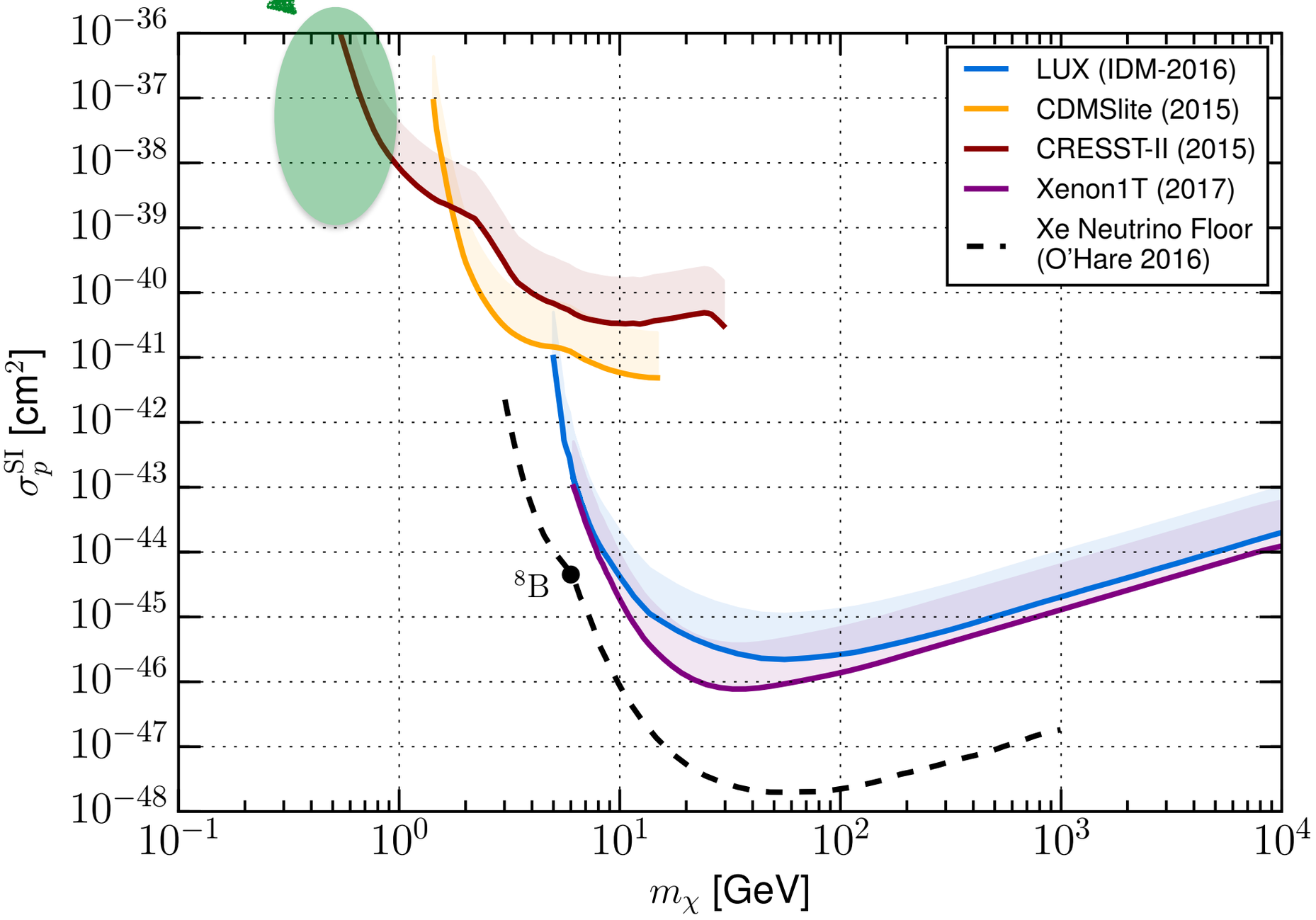
Perturb the velocity distribution, perturb the rate!

Direct Detection Landscape



Direct Detection Landscape

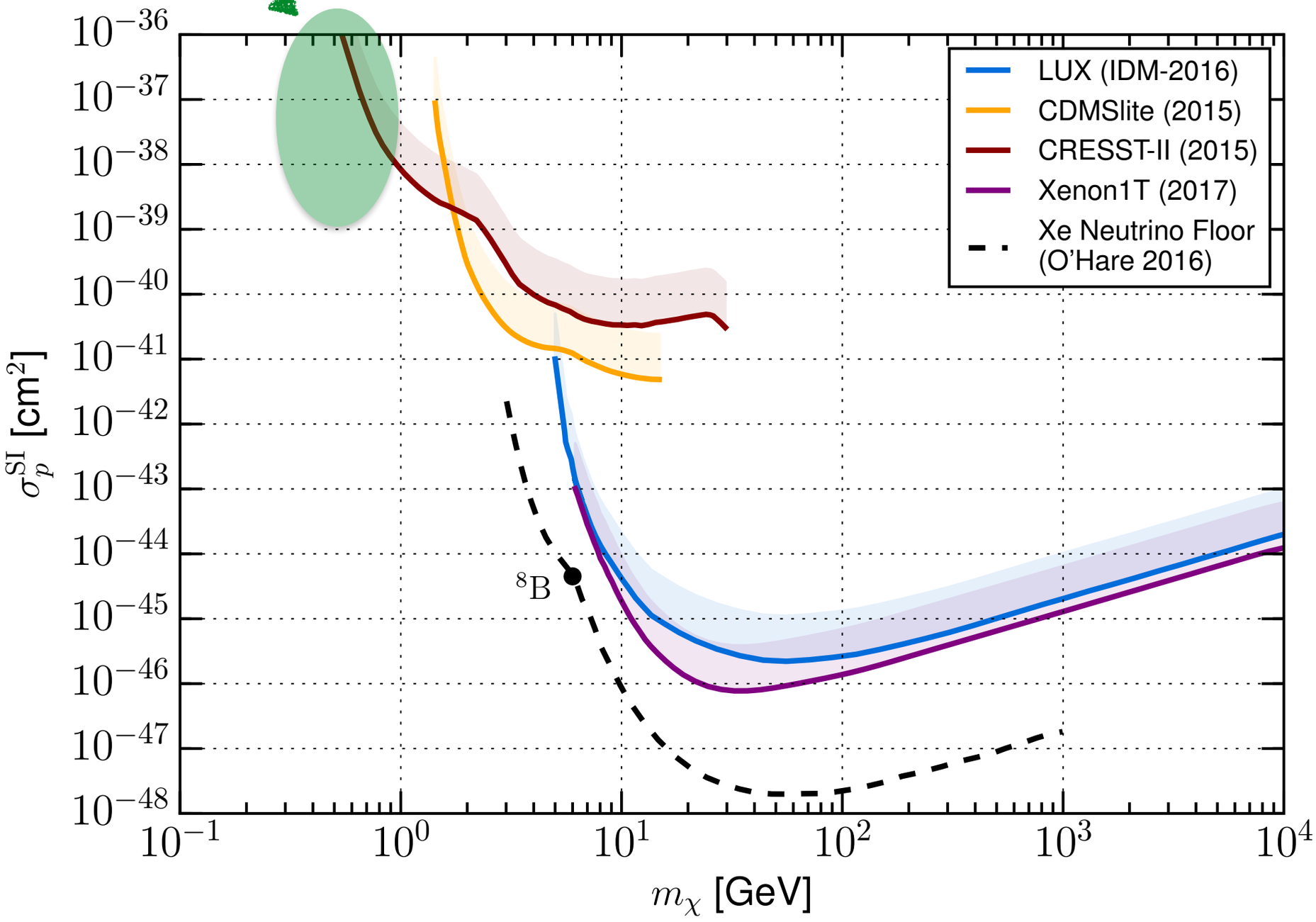
Sub-GeV DM



Direct Detection Landscape

Sub-GeV DM

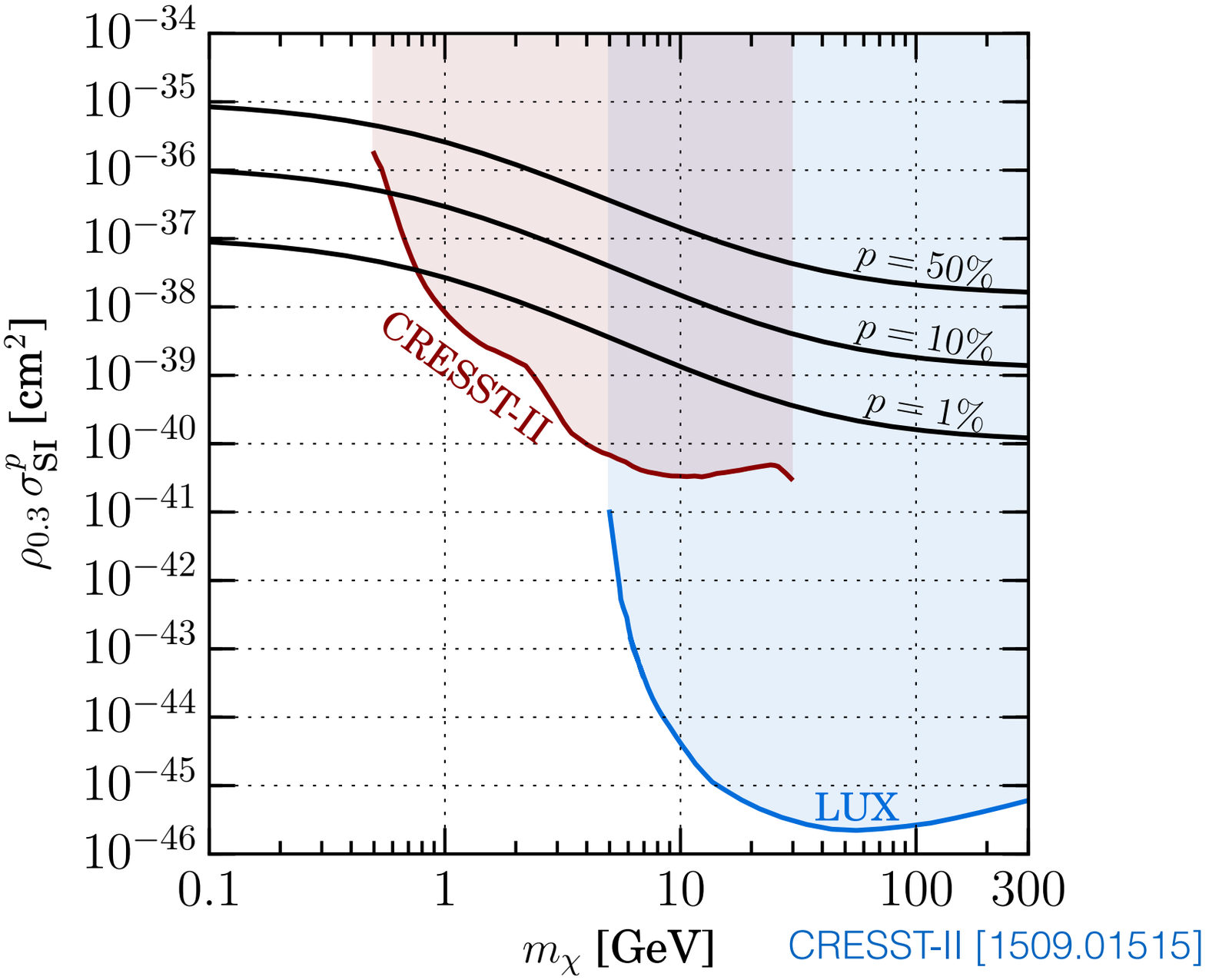
WIMPzillas



Earth-Scattering of sub-GeV DM

BJK, Catena, Kouvaris [1611.05453]
Emken, Kouvaris, Shoemaker [1702.07750]
Emken & Kouvaris [1706.02249]

DD Landscape - Sub-GeV DM



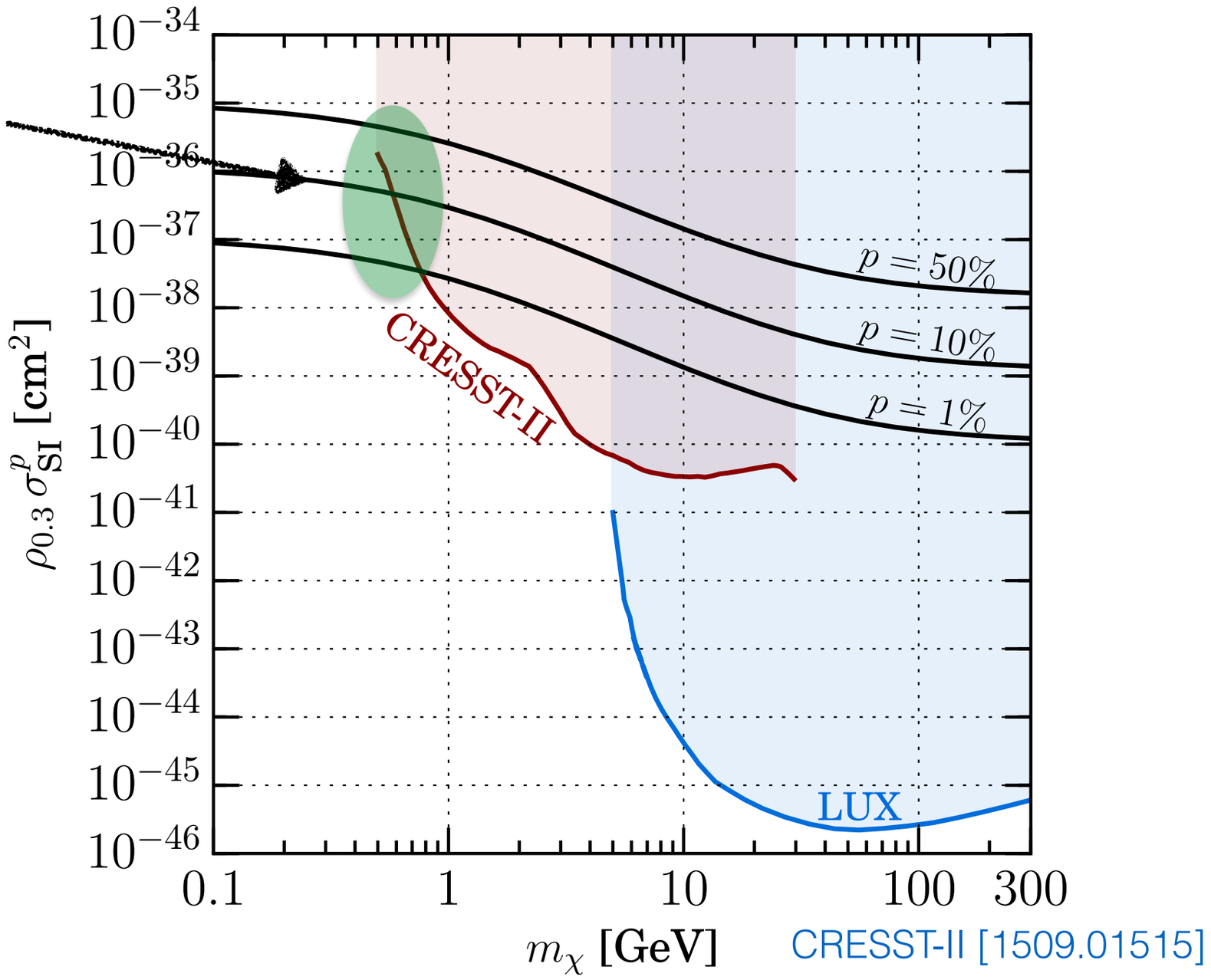
CRESST-II [1509.01515]

LUX [1608.07648]

+ many others…

DD Landscape - Sub-GeV DM

Focus on this region



CRESST-II [1509.01515]

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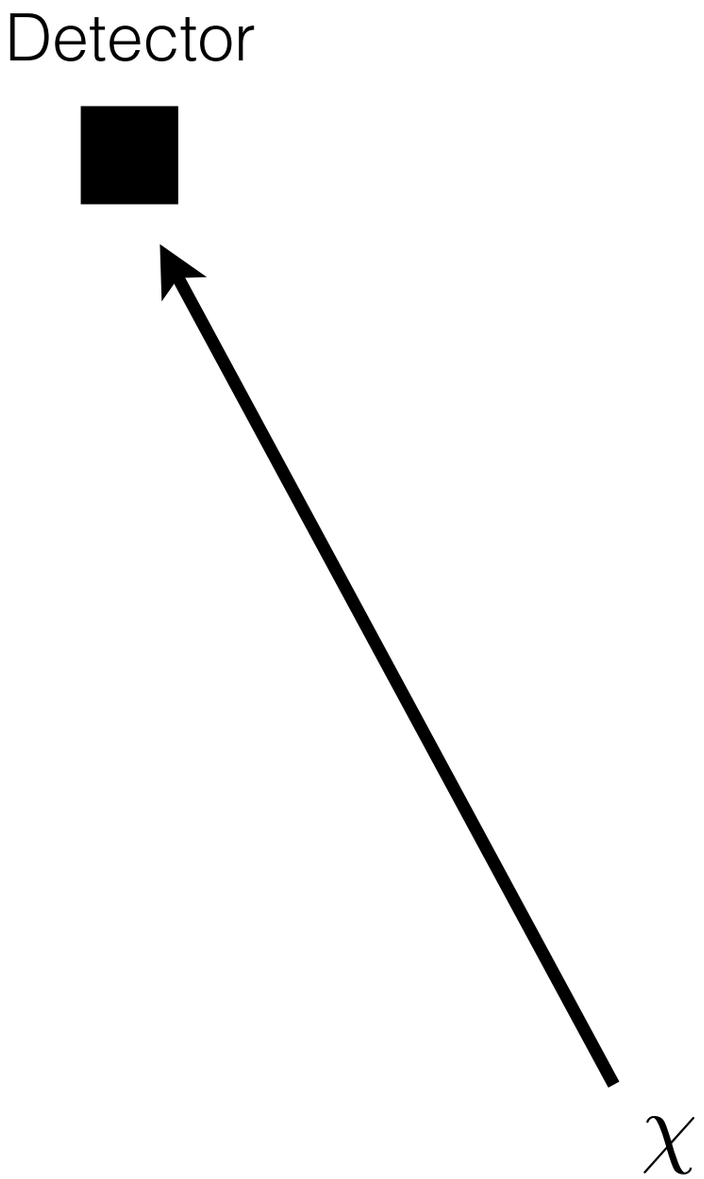
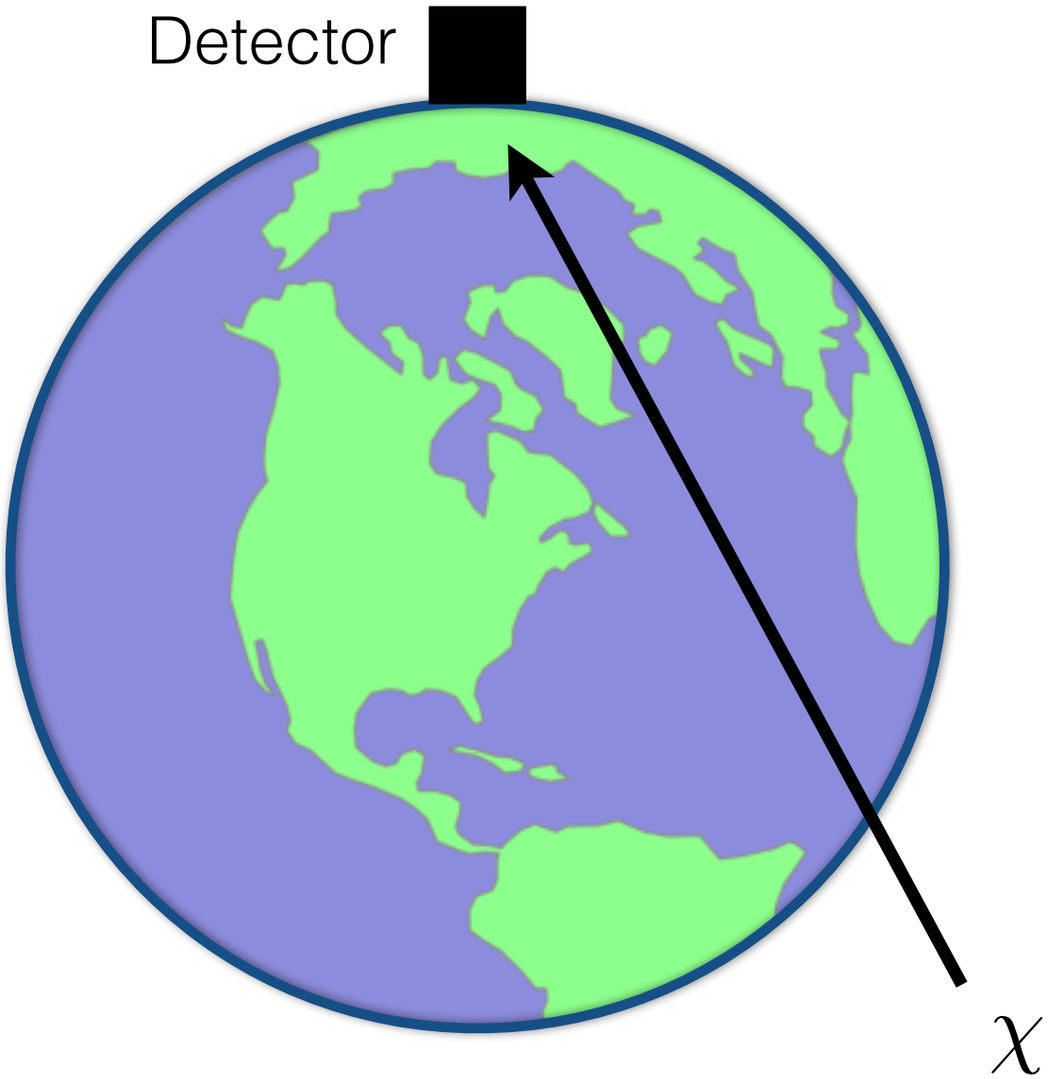
+ many others…

Direct Detection of DM (in space?)



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

Direct Detection of DM on Earth



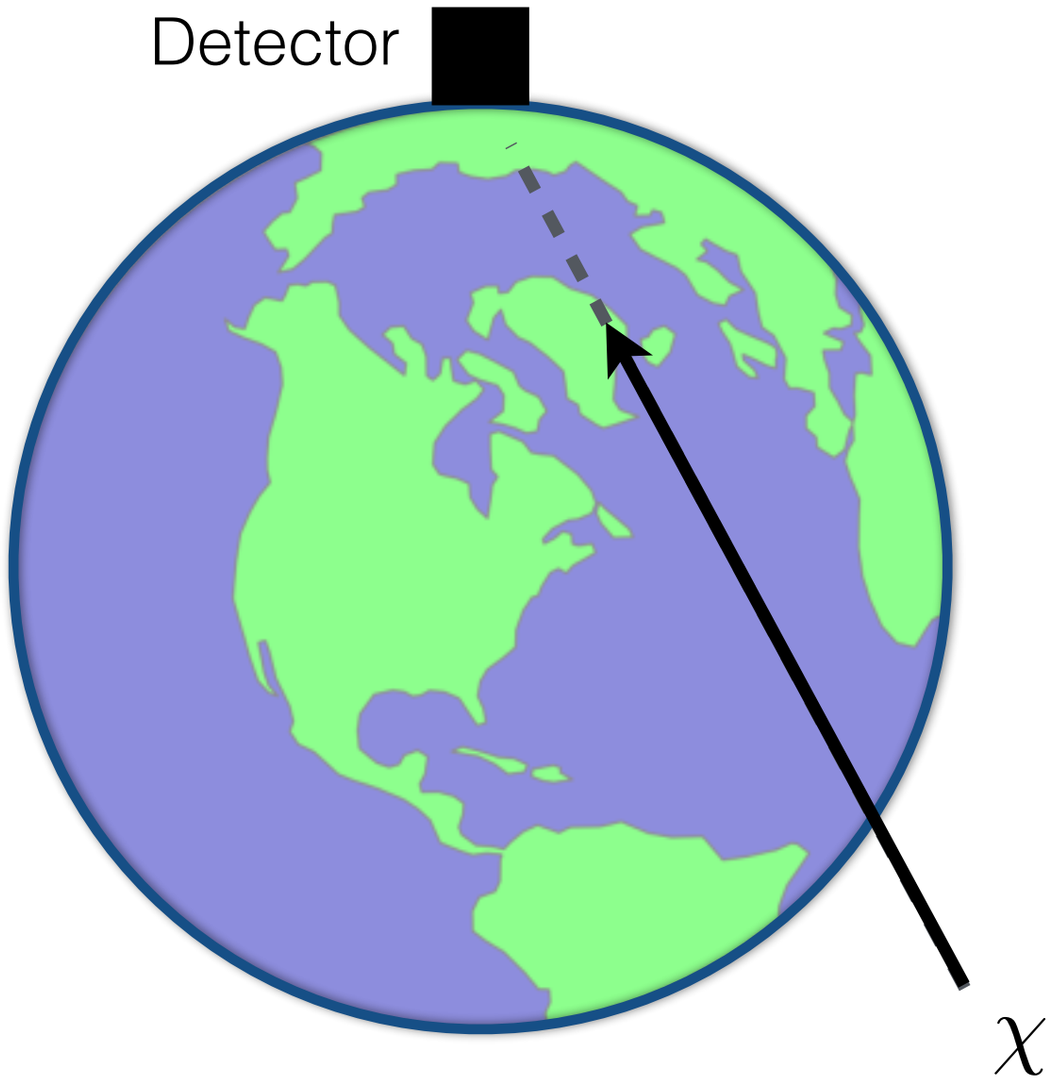
Earth-Scattering - Stopping

Previous calculations usually only consider DM *stopping:*

Zaharijas & Farrar
[astro-ph/0406531]

Kouvaris & Shoemaker
[1405.1729,1509.08720]

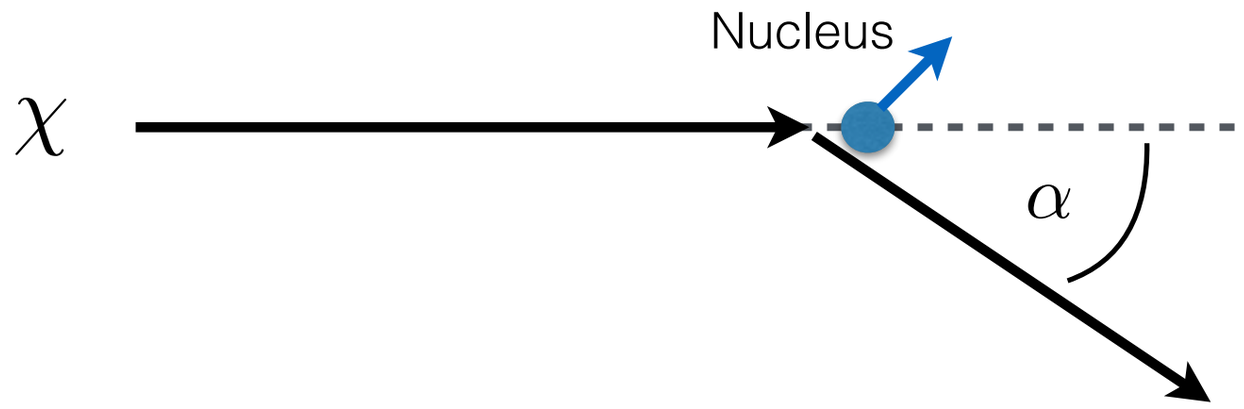
DAMA
[1505.05336]



Slowing/stopping of DM, $v_i \to v_f < v_i$ *without changing direction*

Deflection of Dark Matter

How good is the ‘stopping’ approximation?



Need to calculate the distribution of the deflection angle α :

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

For standard SI, we have $\dfrac{\mathrm{d}\sigma}{\mathrm{d}E_R} \propto \mathrm{const.}$ at low mass

But let’s be more general…

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]

SI → $\mathcal{O}_1 = 1$

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

[1008.1591, 1203.3542, 1308.6288, 1505.03117]
See also Riccardo Catena's talk for more details…

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SI

$$\mathcal{O}_1 = 1$$

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

SD

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

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

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

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

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

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

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

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

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

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

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

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

$$\vdots$$

Recoil momentum $\vec{q}$

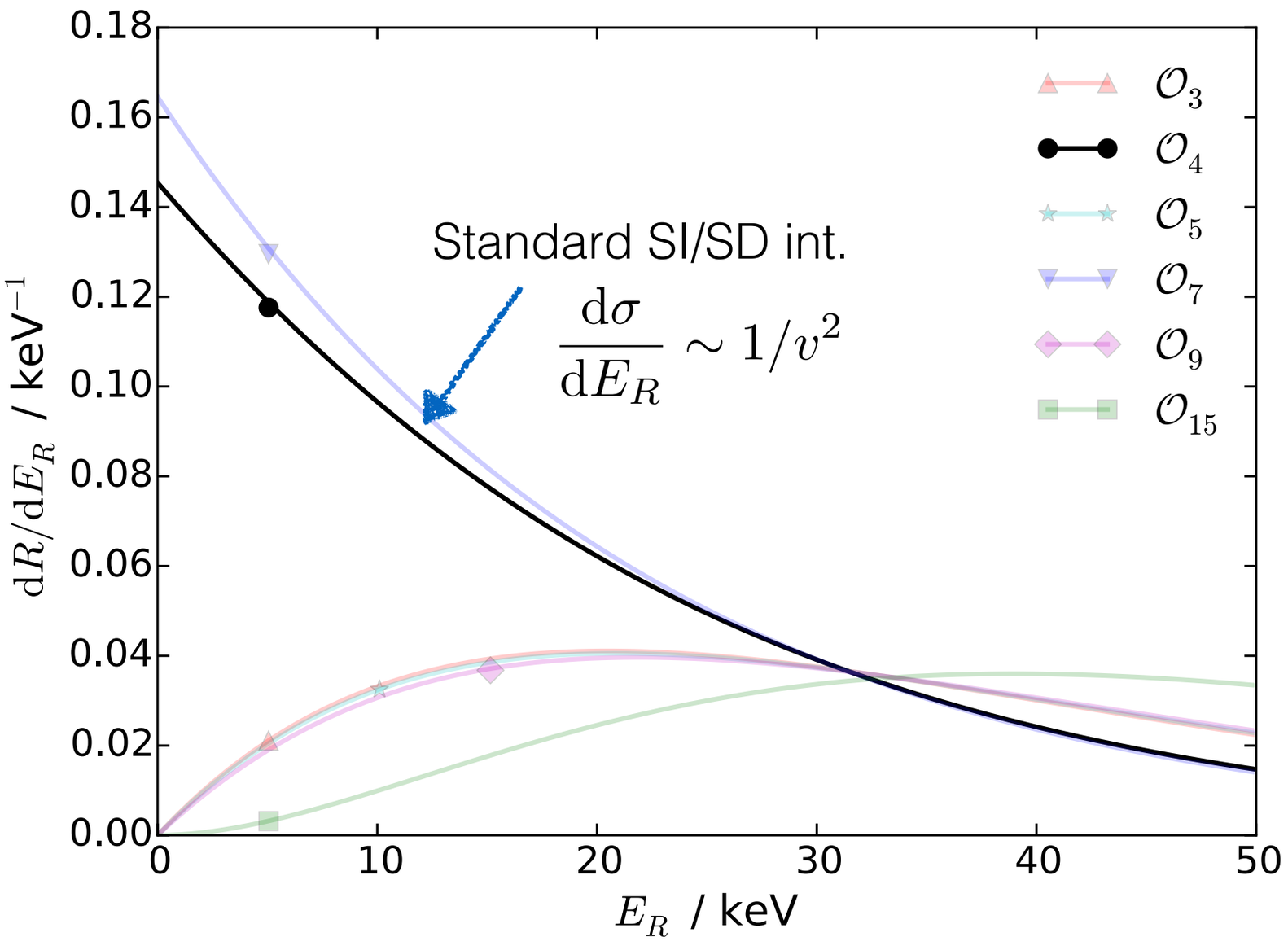
$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}}$$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

See also Riccardo Catena's talk for more details…

Energy spectra

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



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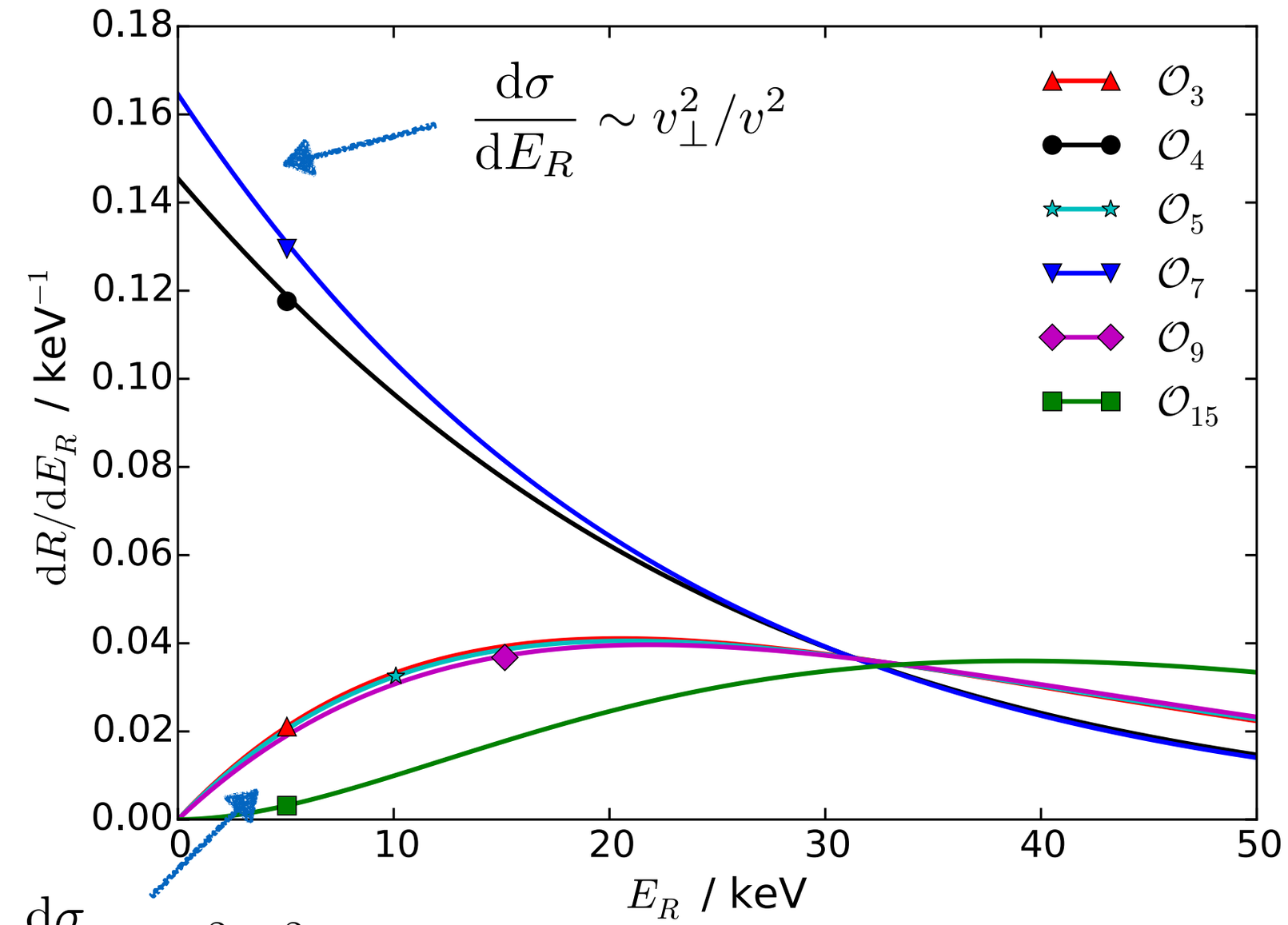
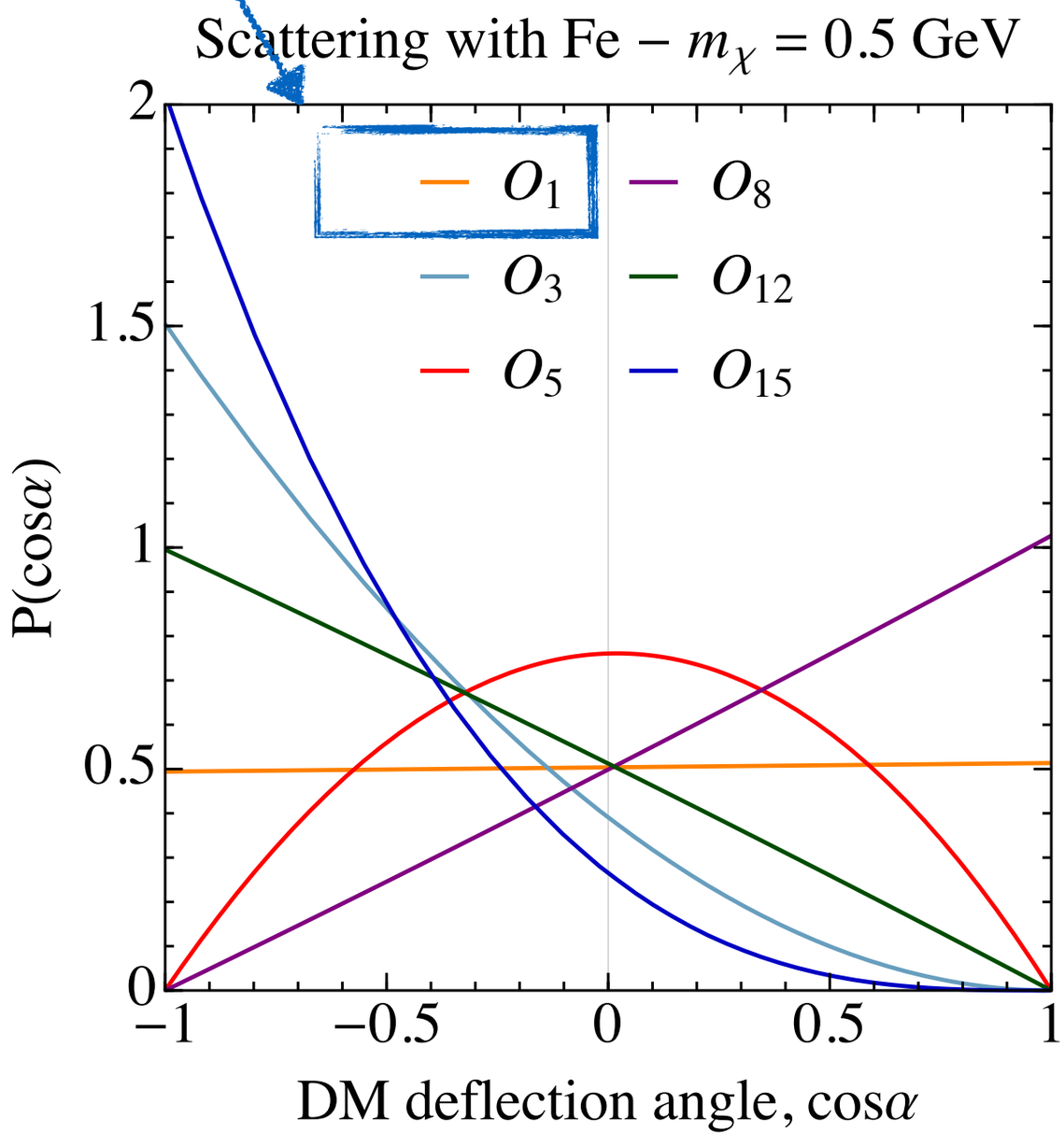
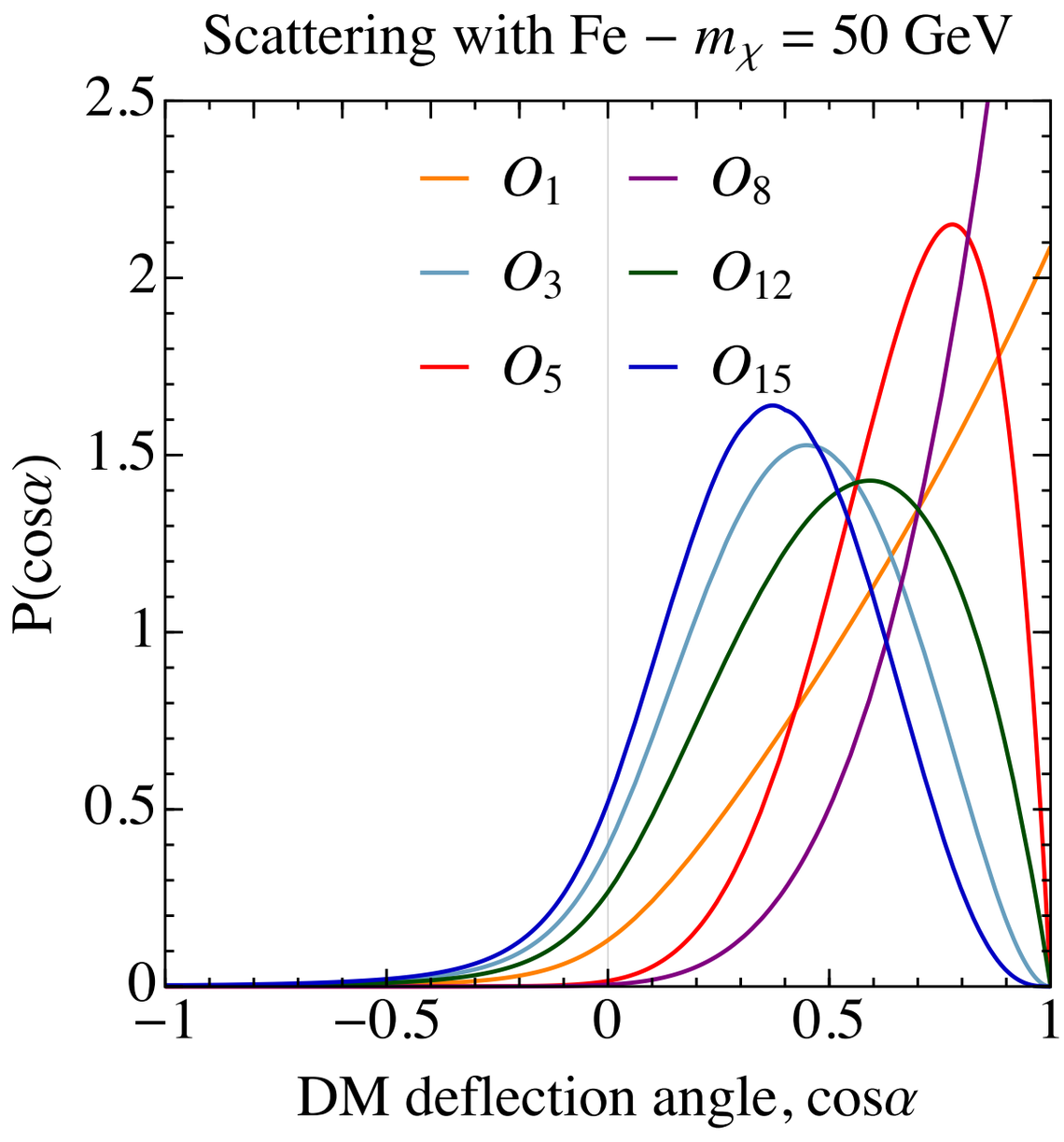


DM deflection distribution

Standard SI interaction

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



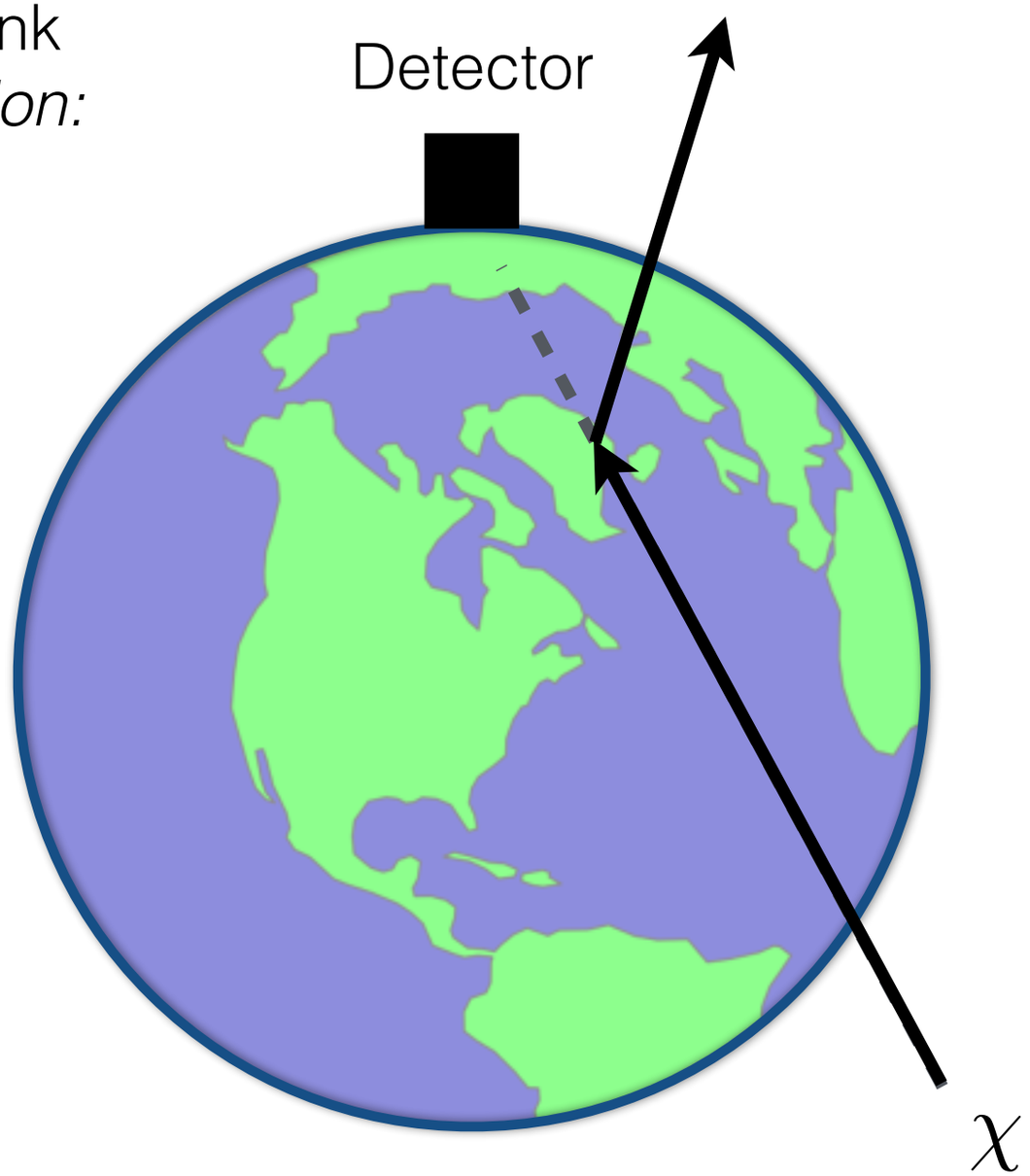


Backward

Forward

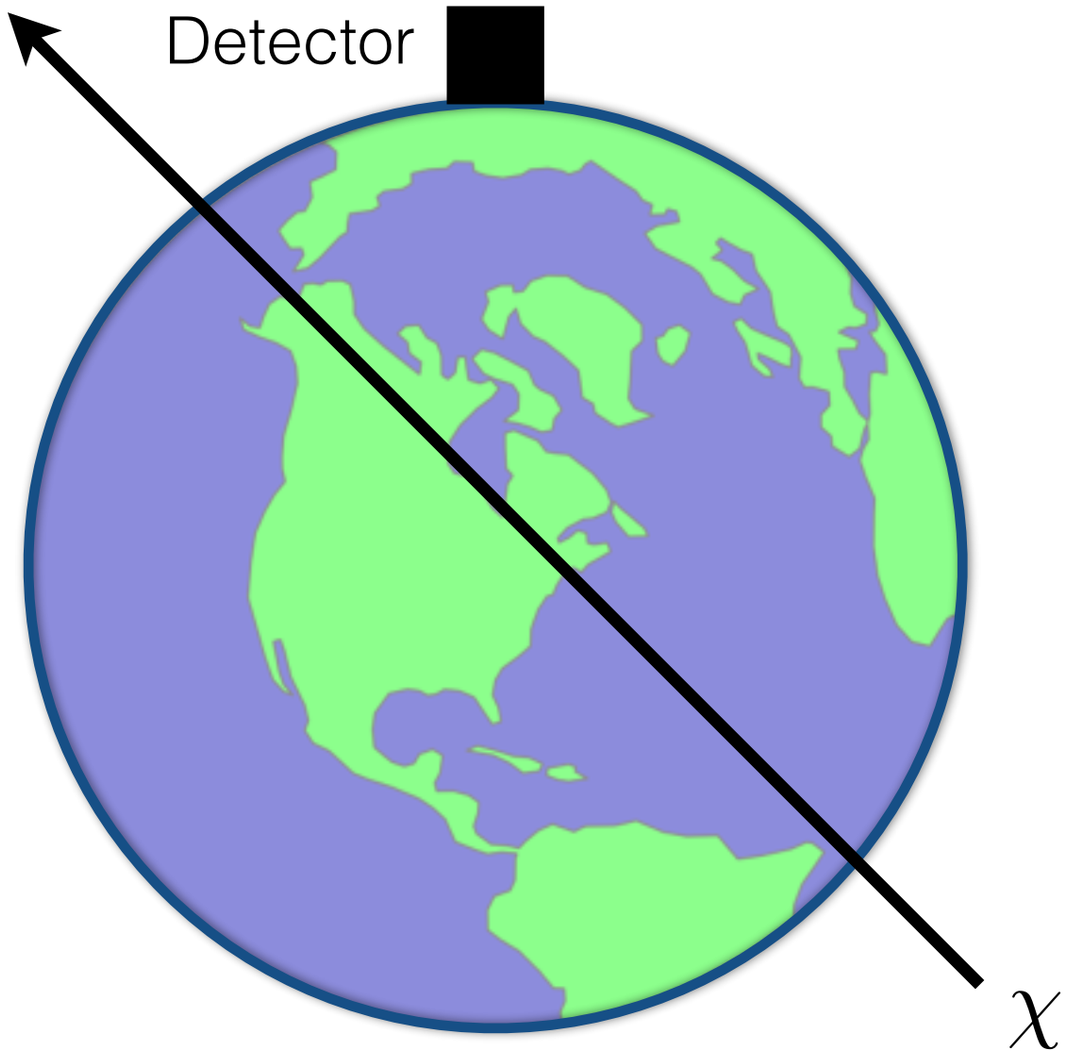
Earth-Scattering - Attenuation

Forget *slowing* and think instead about *attenuation:*



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

Earth-Scattering - Deflection



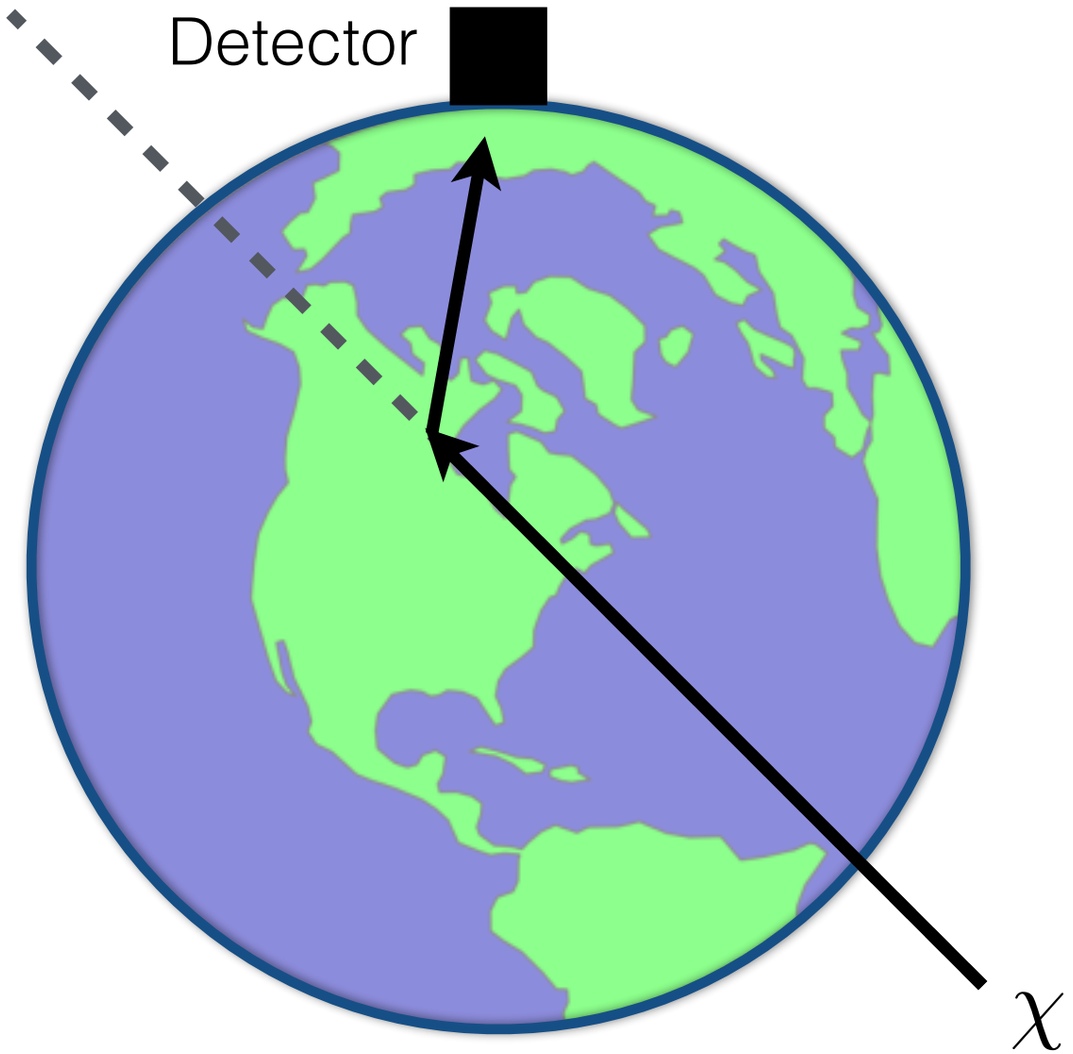
Earth-Scattering - Deflection

Considered in early Monte Carlo simulations…

Collar & Avignone [PLB 275, 1992 and others]

As well as more recent ones…

[1702.07750, 1706.02249] (see later)



Assuming DM mean free path

$$\lambda \gtrsim R_E$$

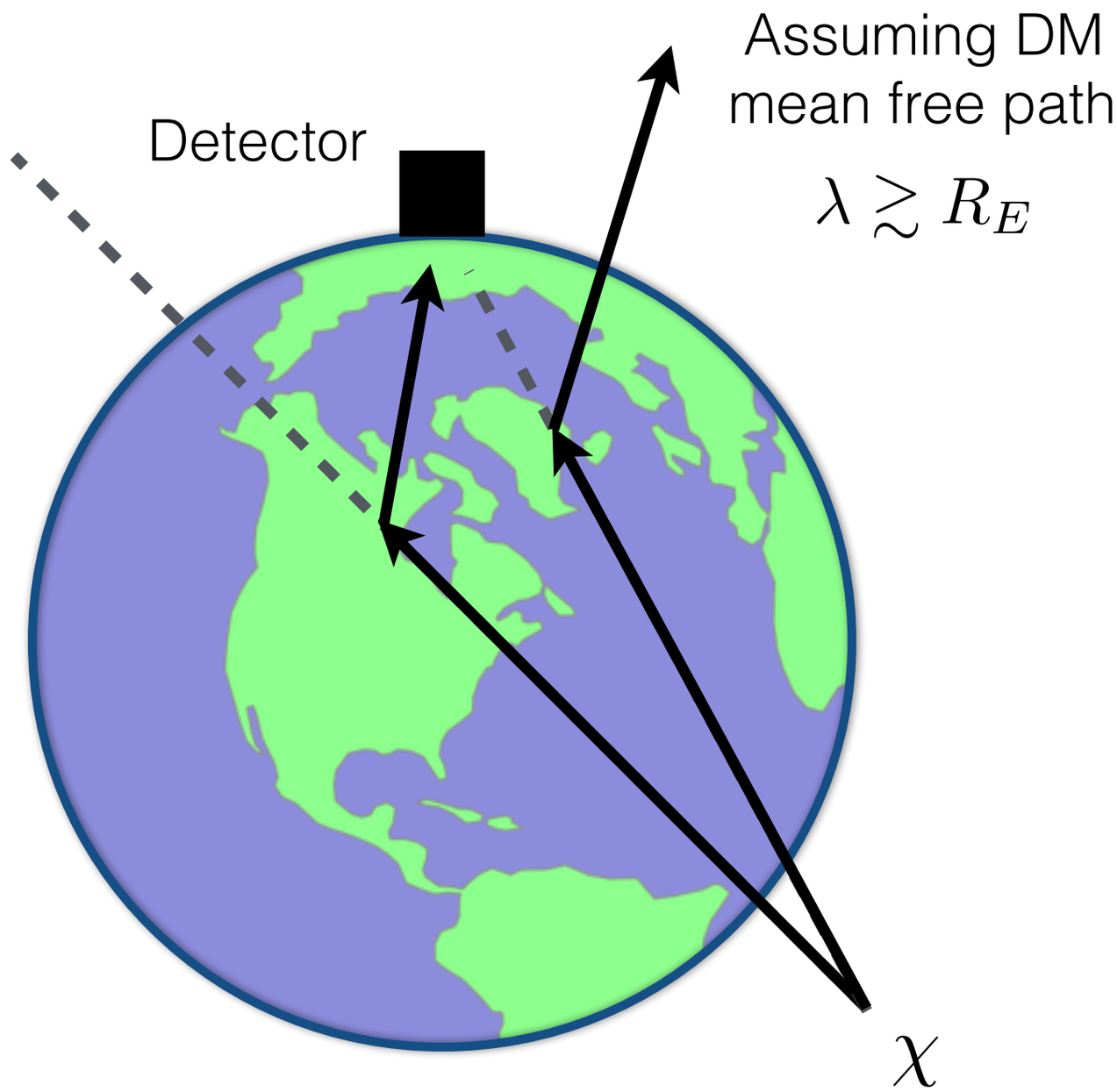
Can be very important for light DM.

Can treat (without MC) in the ‘single scatter’ approximation…

Earth-Scattering

Consider both
attenuation and deflection
in an analytic framework
('Single scatter')

Consider **non-standard**
DM-nucleon interactions
(e.g. NREFT)

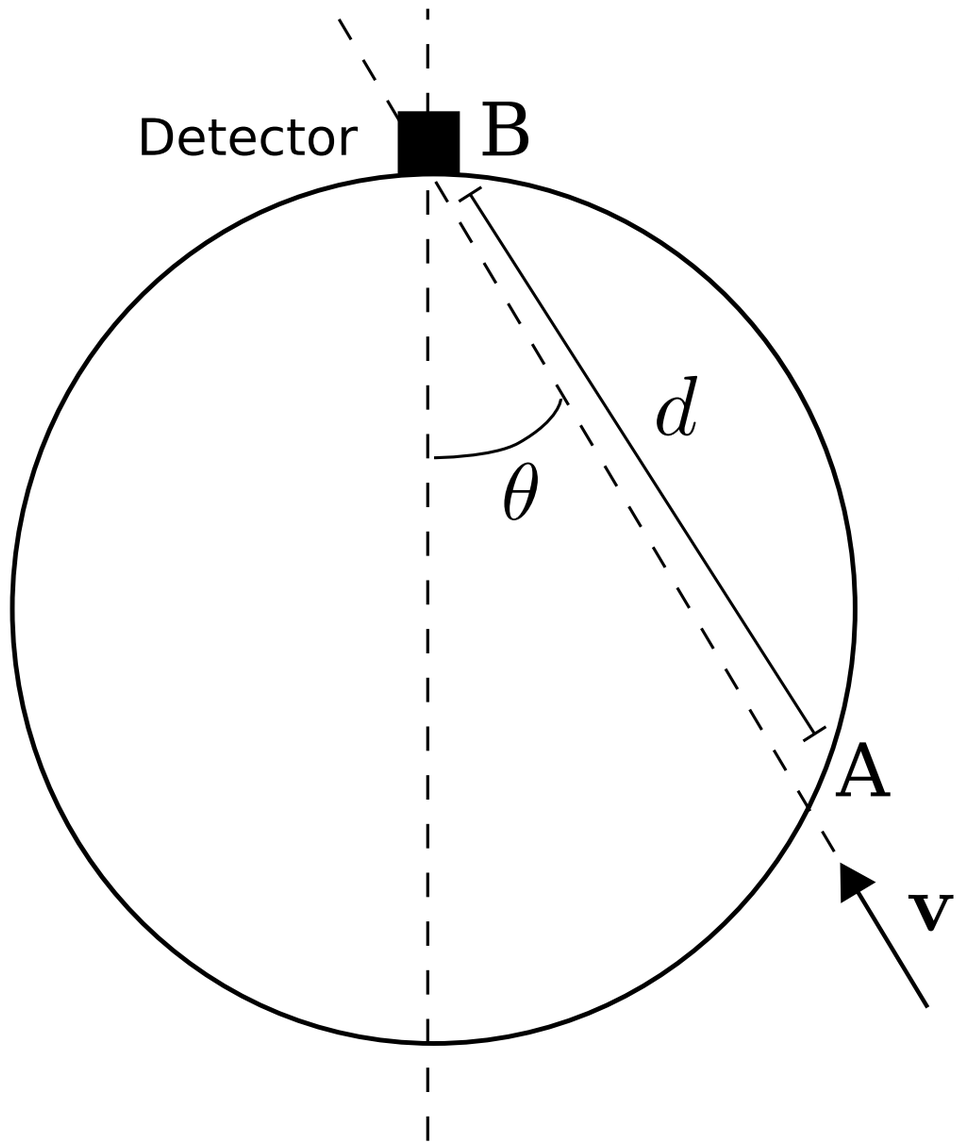


Total DM velocity distribution: $\tilde{f}(\mathbf{v}) = f_0(\mathbf{v}) - f_A(\mathbf{v}) + f_D(\mathbf{v})$

↳ altered flux, daily modulation, directionality…

Attenuation

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



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

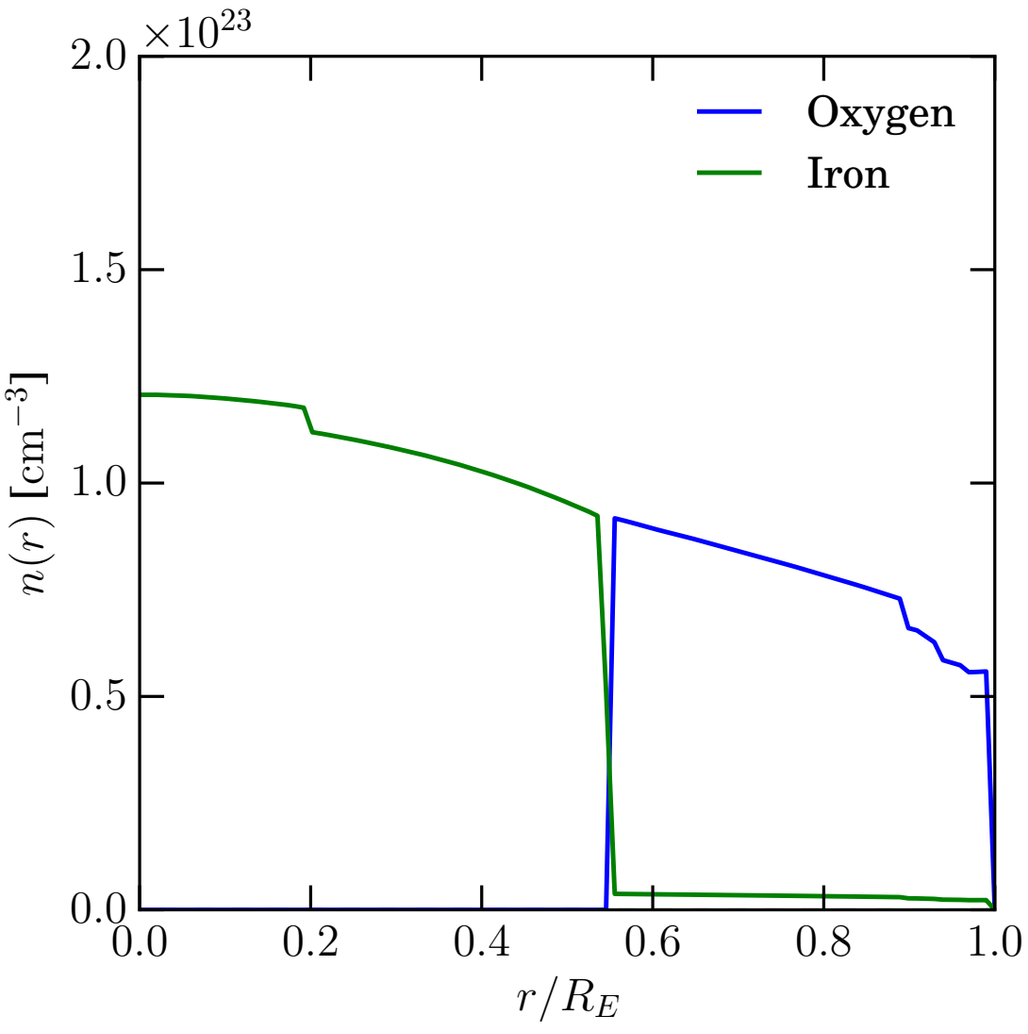
$$d_{\mathrm{eff},i} = \frac{1}{\bar{n}_i}\int_{\mathrm{AB}} n_i(\mathbf{r})\mathrm{d}l$$

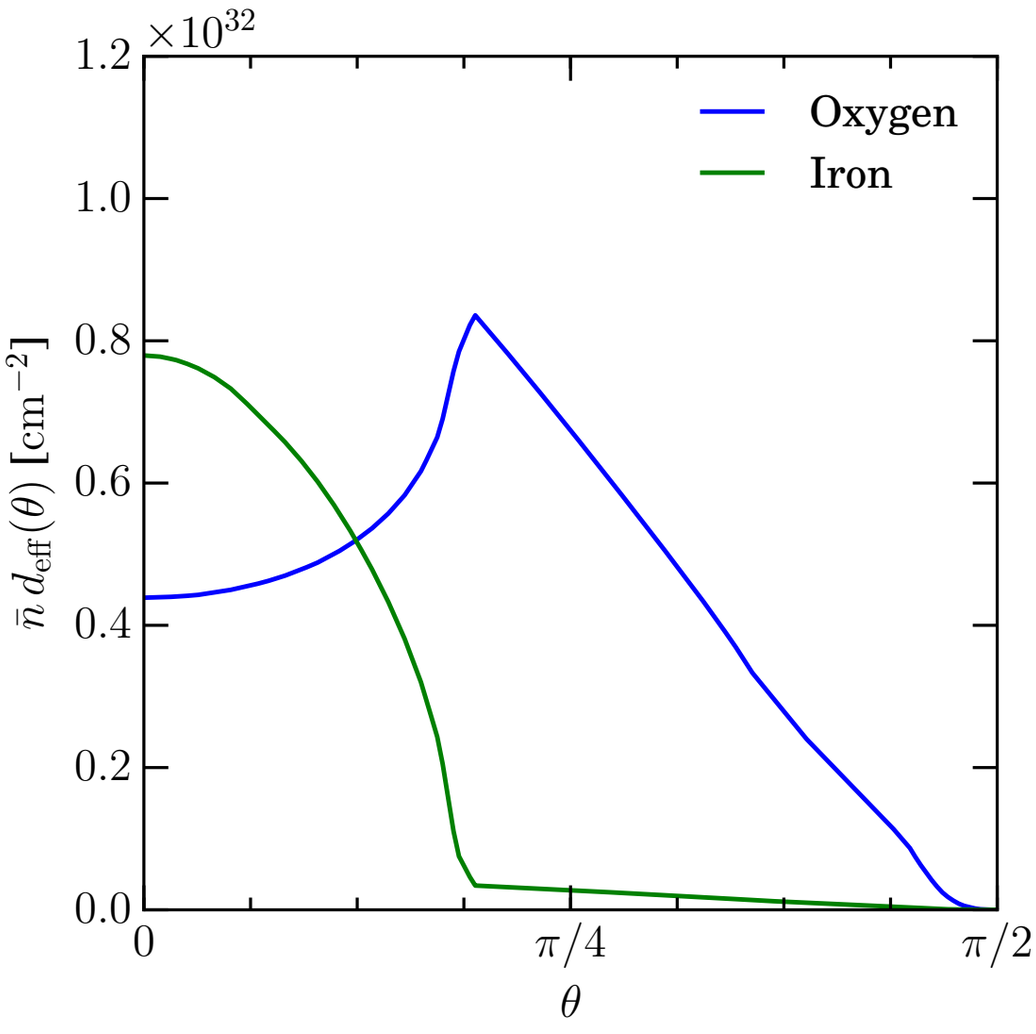
$$f_0(\mathbf{v}) - f_A(\mathbf{v}) = f_0(\mathbf{v})\exp\left[-\sum_i^{\text{species}}\frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(v)}\right]$$

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)

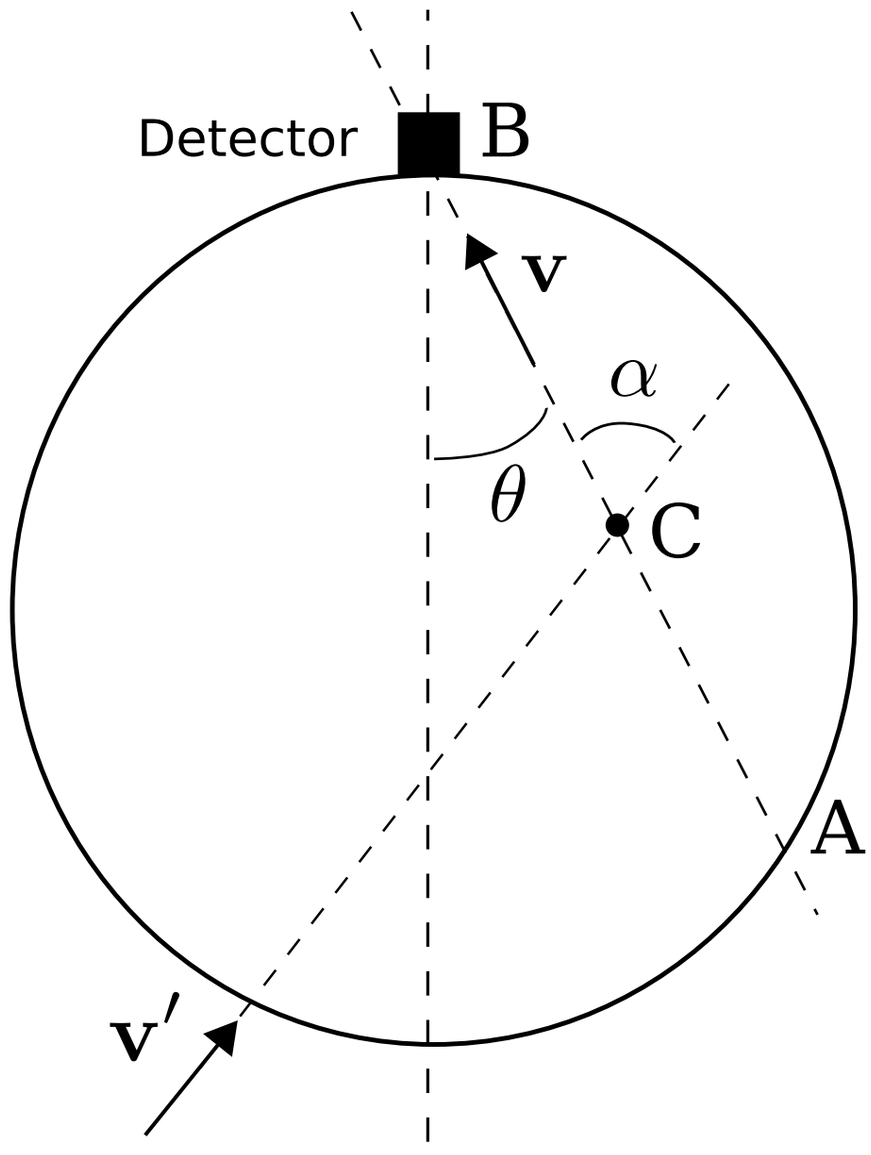




NB: little Earth-scattering for spin-dependent interactions

Deflection

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



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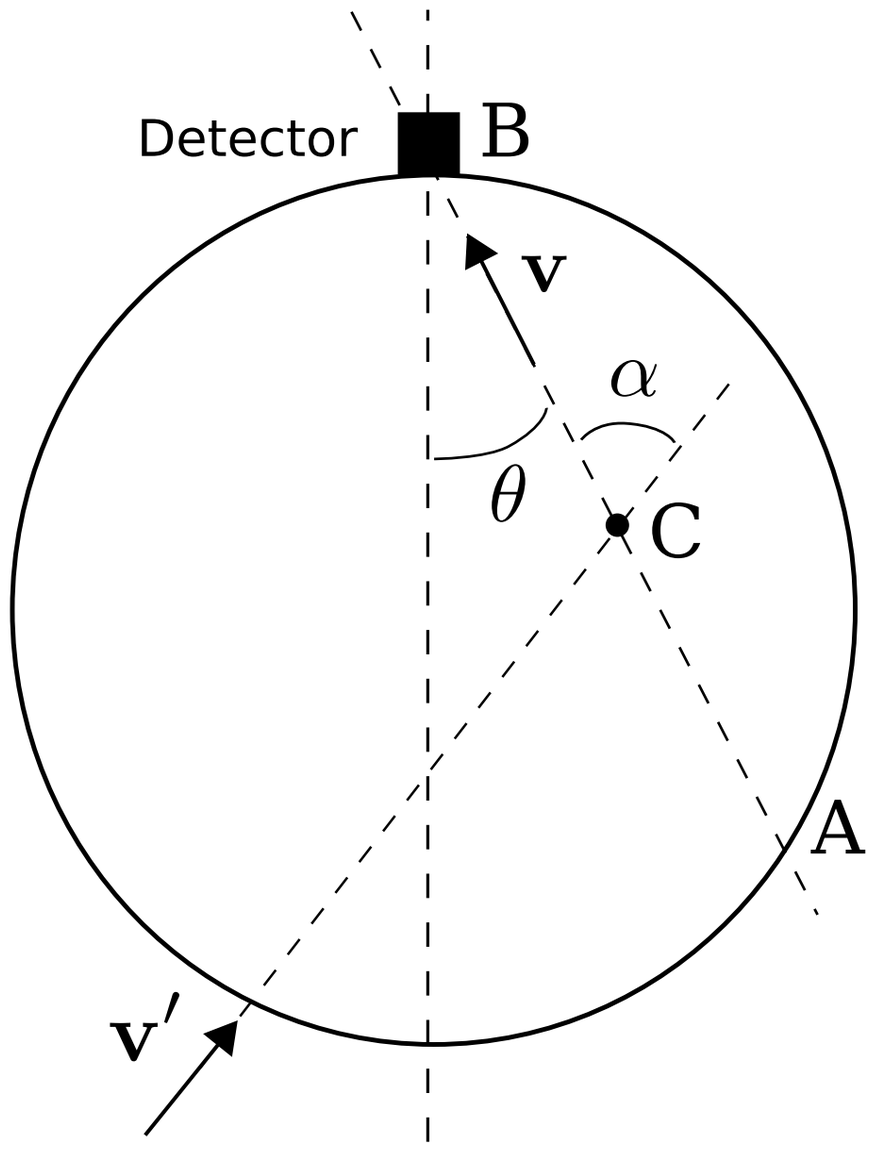


$$\bar{\lambda}_i(v)^{-1} = \bar{n}_i\,\sigma(v)$$

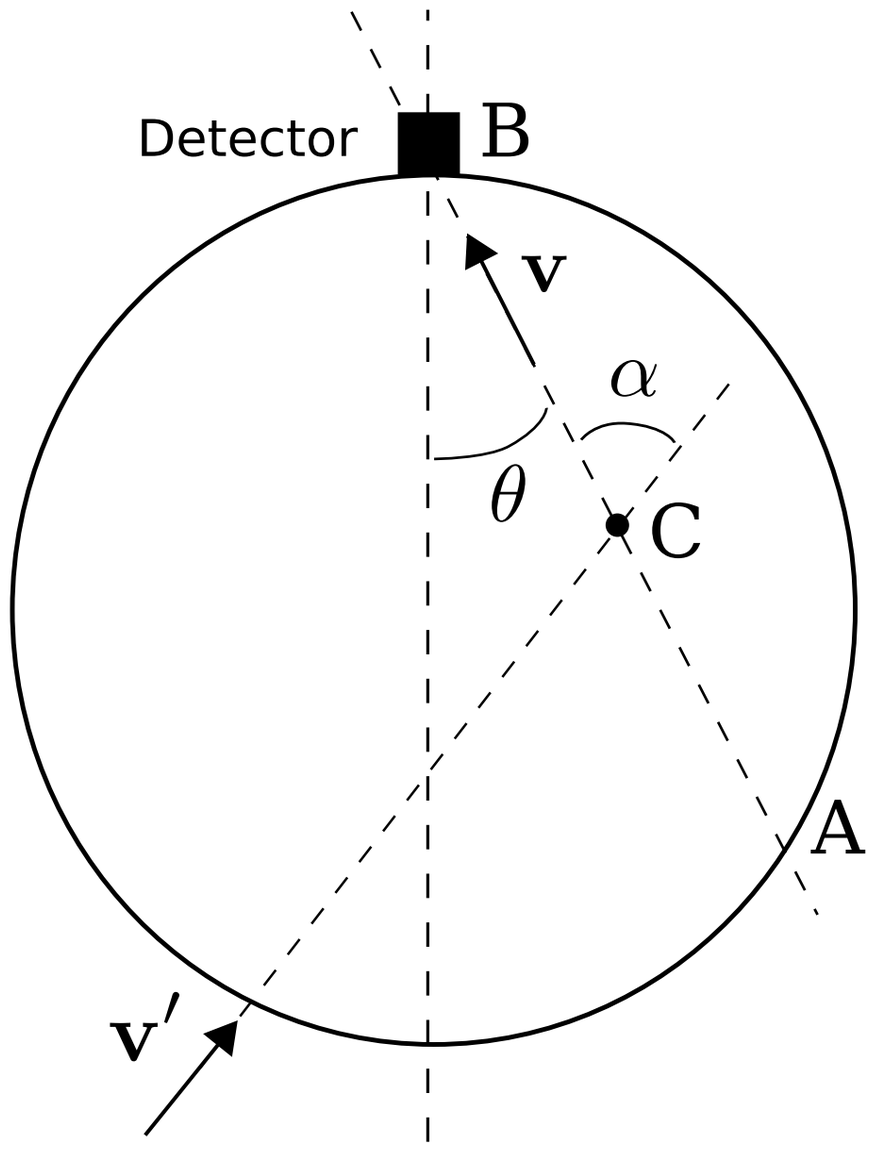
$$f_D(\mathbf{v}) = \sum_i^{\text{species}} \int \mathrm{d}^2\hat{\mathbf{v}}'\ \frac{d_{\text{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)} \frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

[Detailed calculation in 1611.05453]

$$\kappa_i = v'/v$$

Deflection

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



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Depends on differential cross section

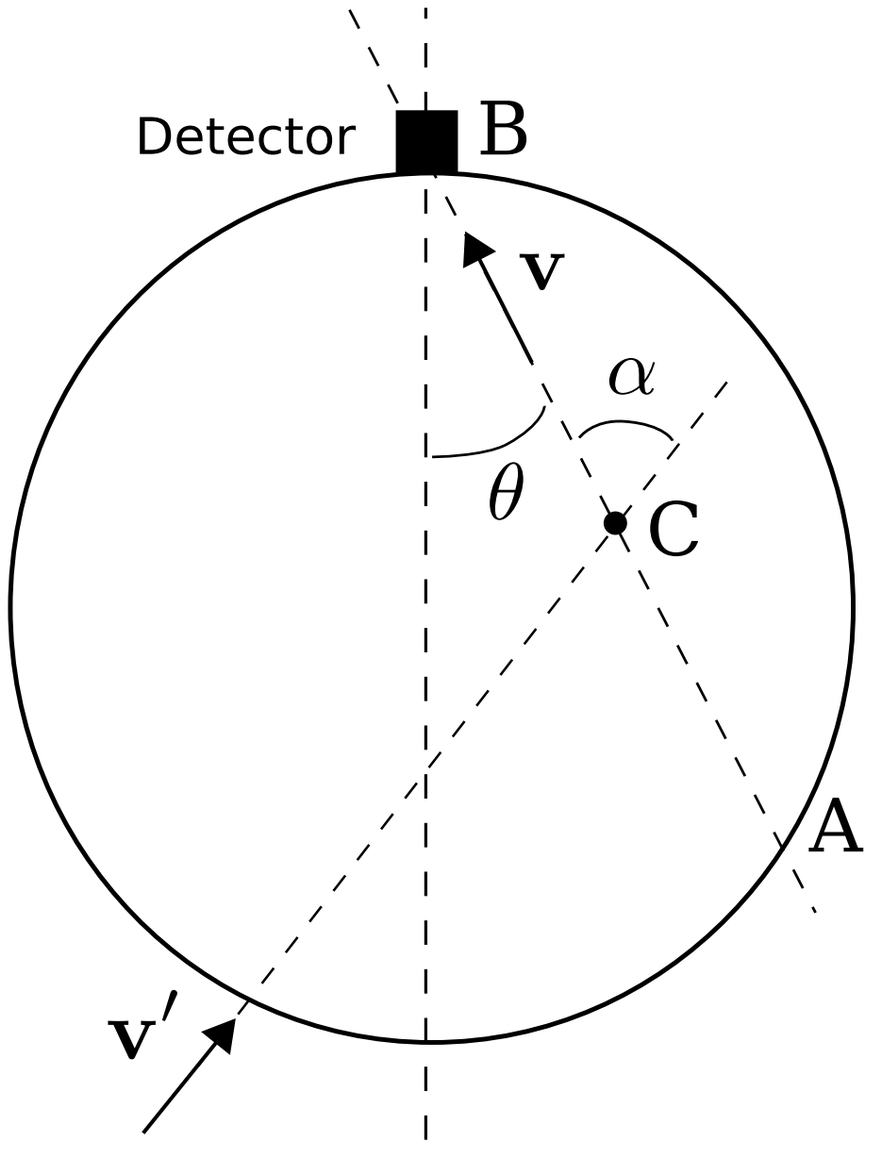
Depends on total cross section

$$\kappa_i = v'/v$$

Deflection

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

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



Focus on low mass DM:

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

Fix couplings to give 10% probability of scattering in the Earth

Depends on differential cross section

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

Depends on total cross section

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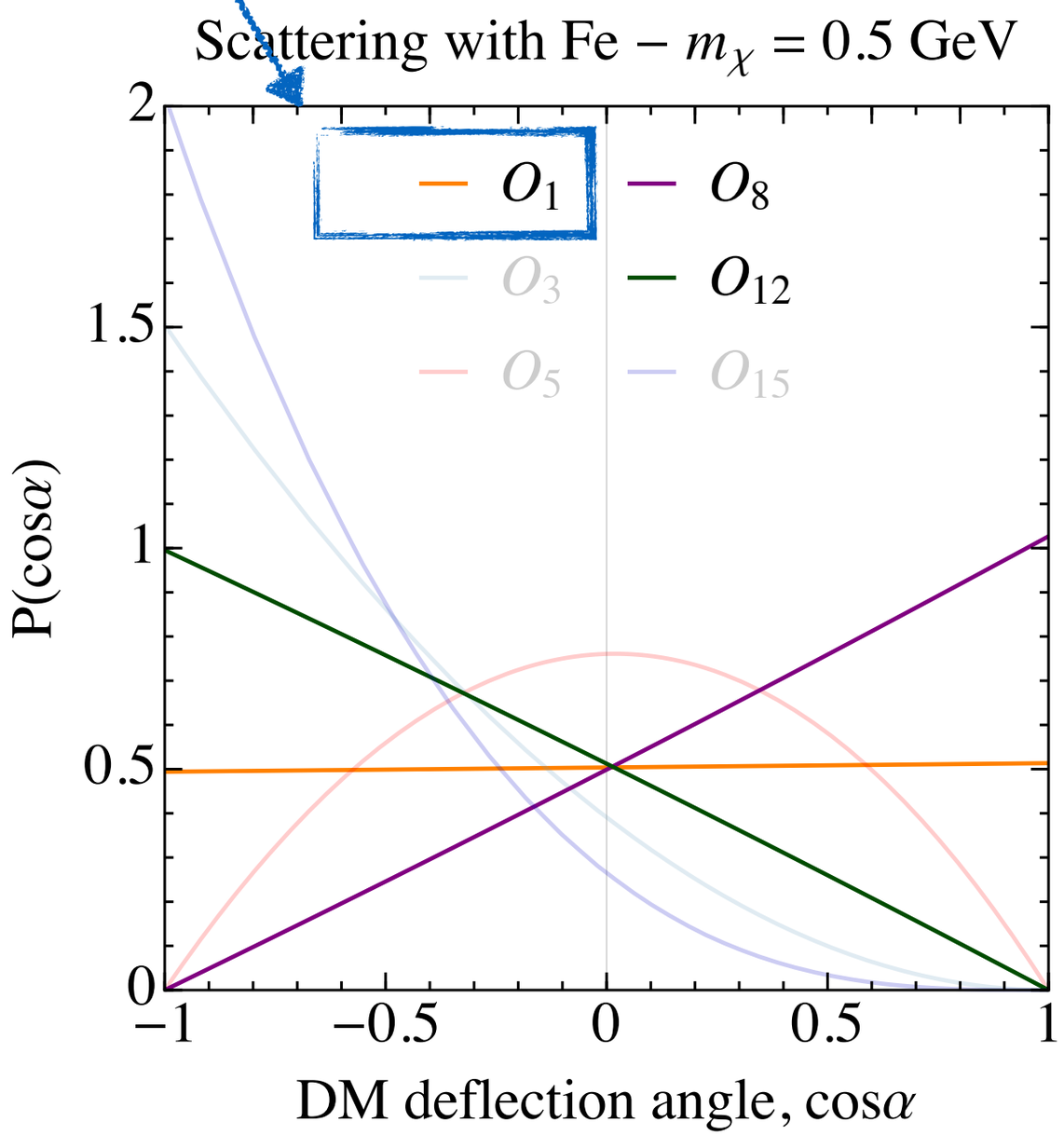
DM deflection distribution

Standard SI interaction

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



Backward

Forward

Standard SI interaction

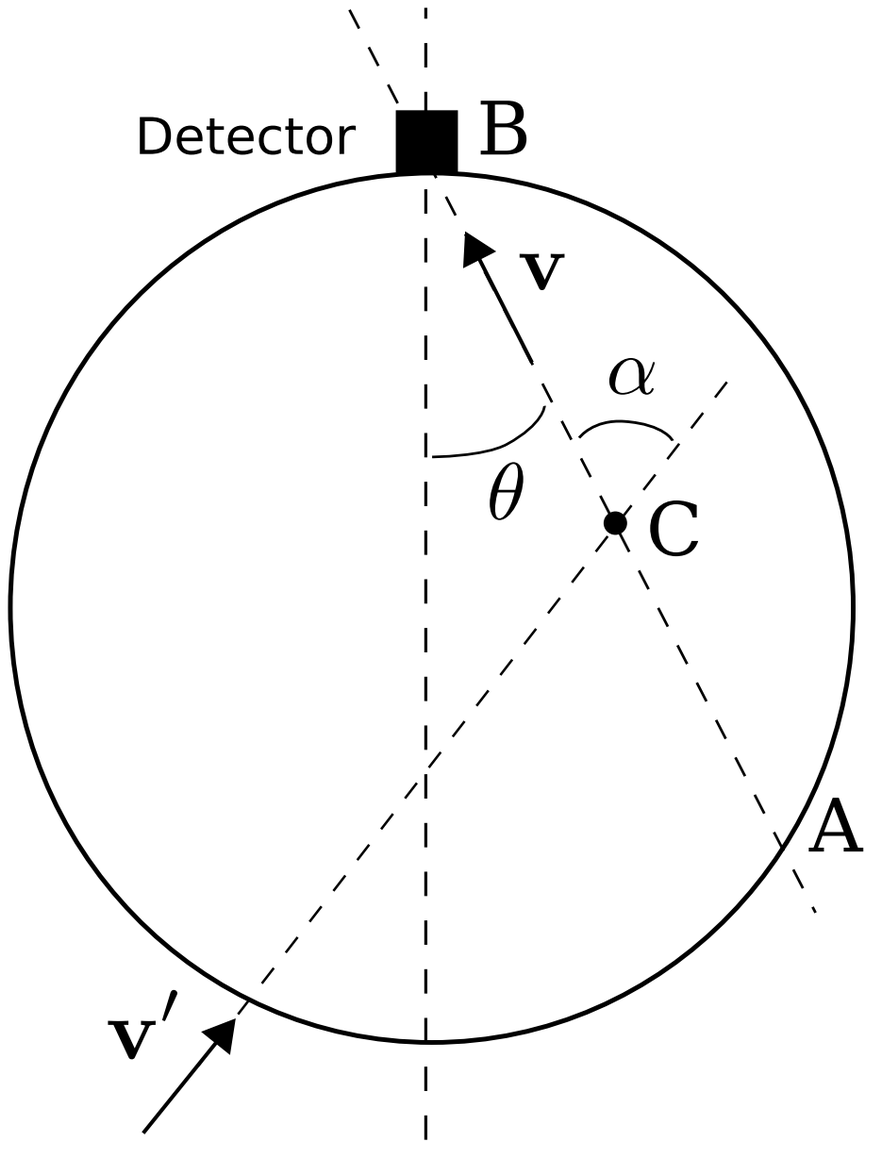
$$\mathcal{O}_1 = \mathbb{1} \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim \frac{1}{v^2}$$

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

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

Deflection

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



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

Now we have everything we need!

Focus on low mass DM:

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

Fix couplings to give 10% probability of scattering in the Earth

Depends on differential cross section

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

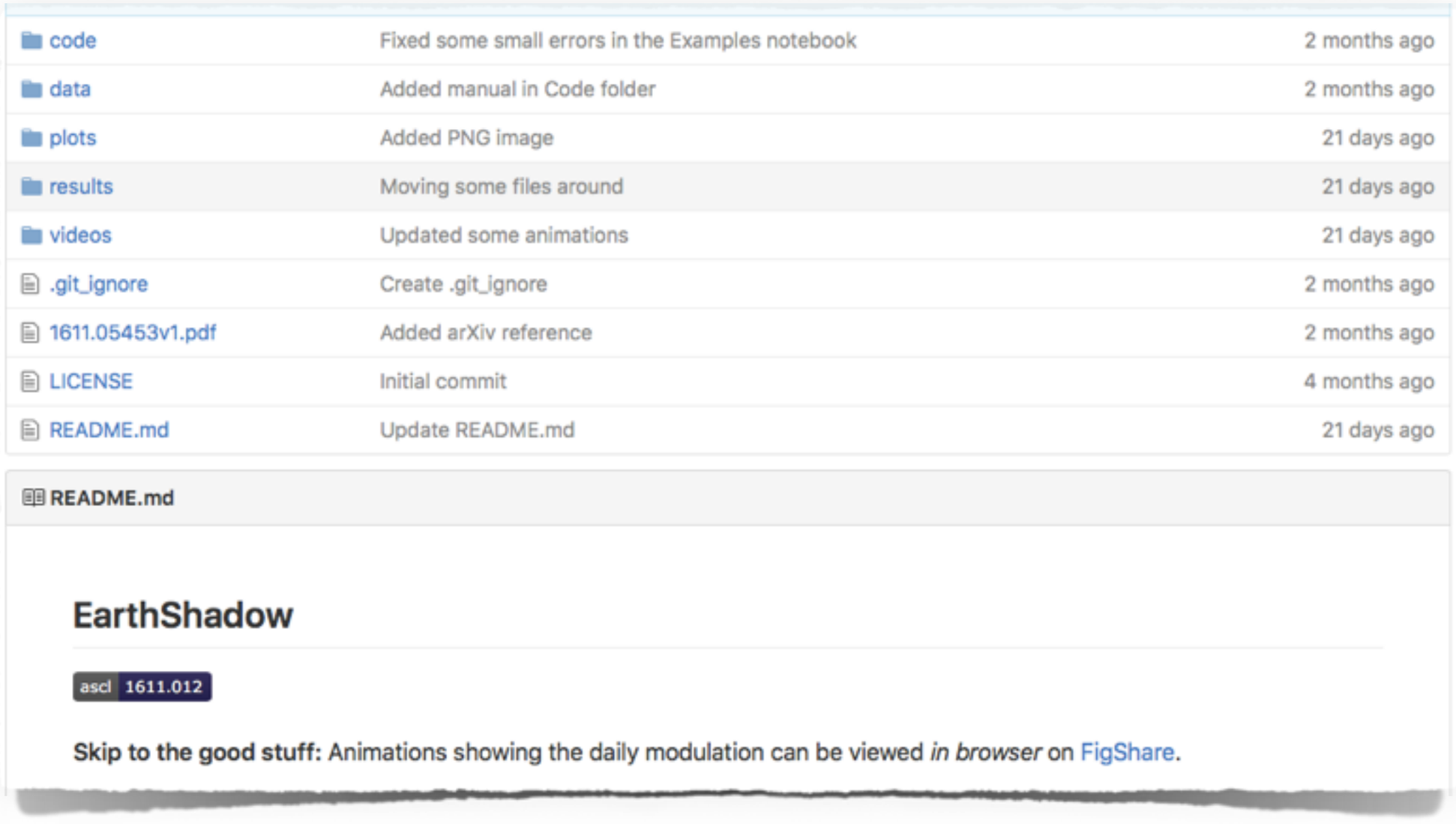
Depends on total cross section

$$\kappa_i = v'/v$$

EARTHSHADOW Code

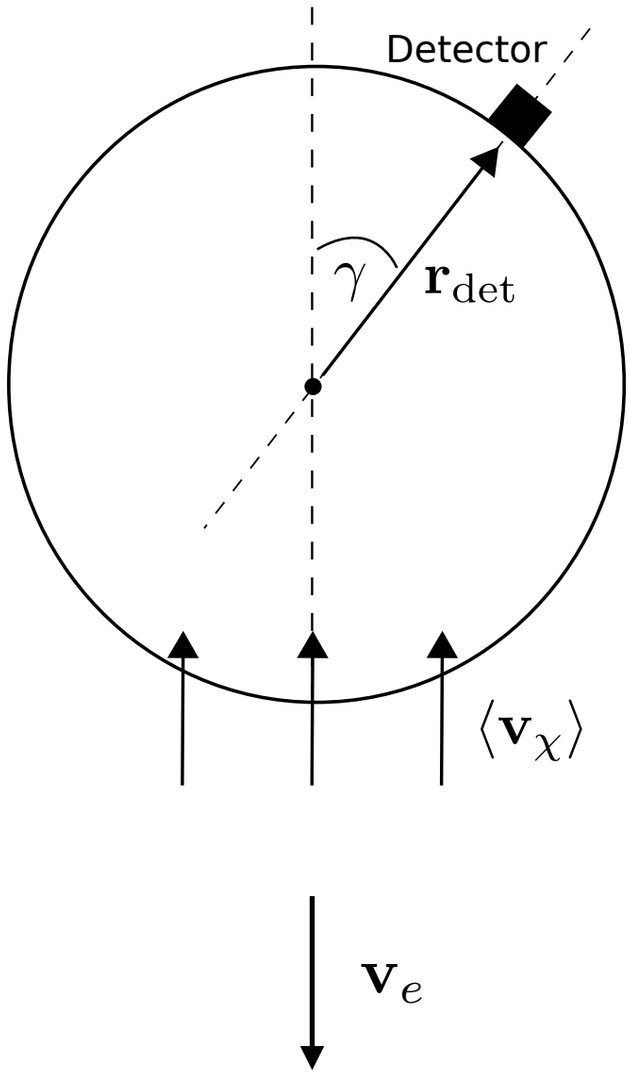
EARTHSHADOW code is available online at:
github.com/bradkav/EarthShadow

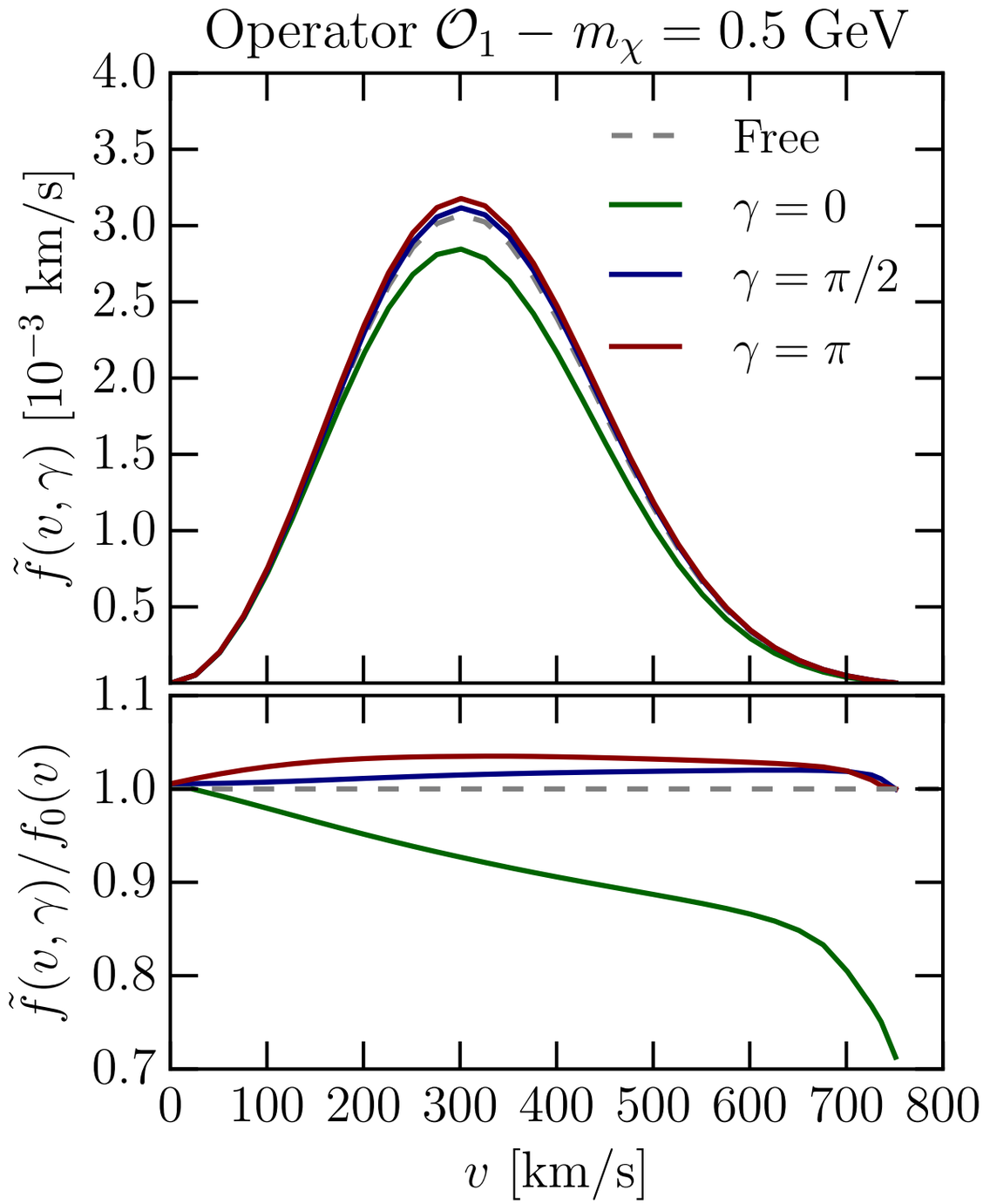
Including routines, numerical results, plots and animations…



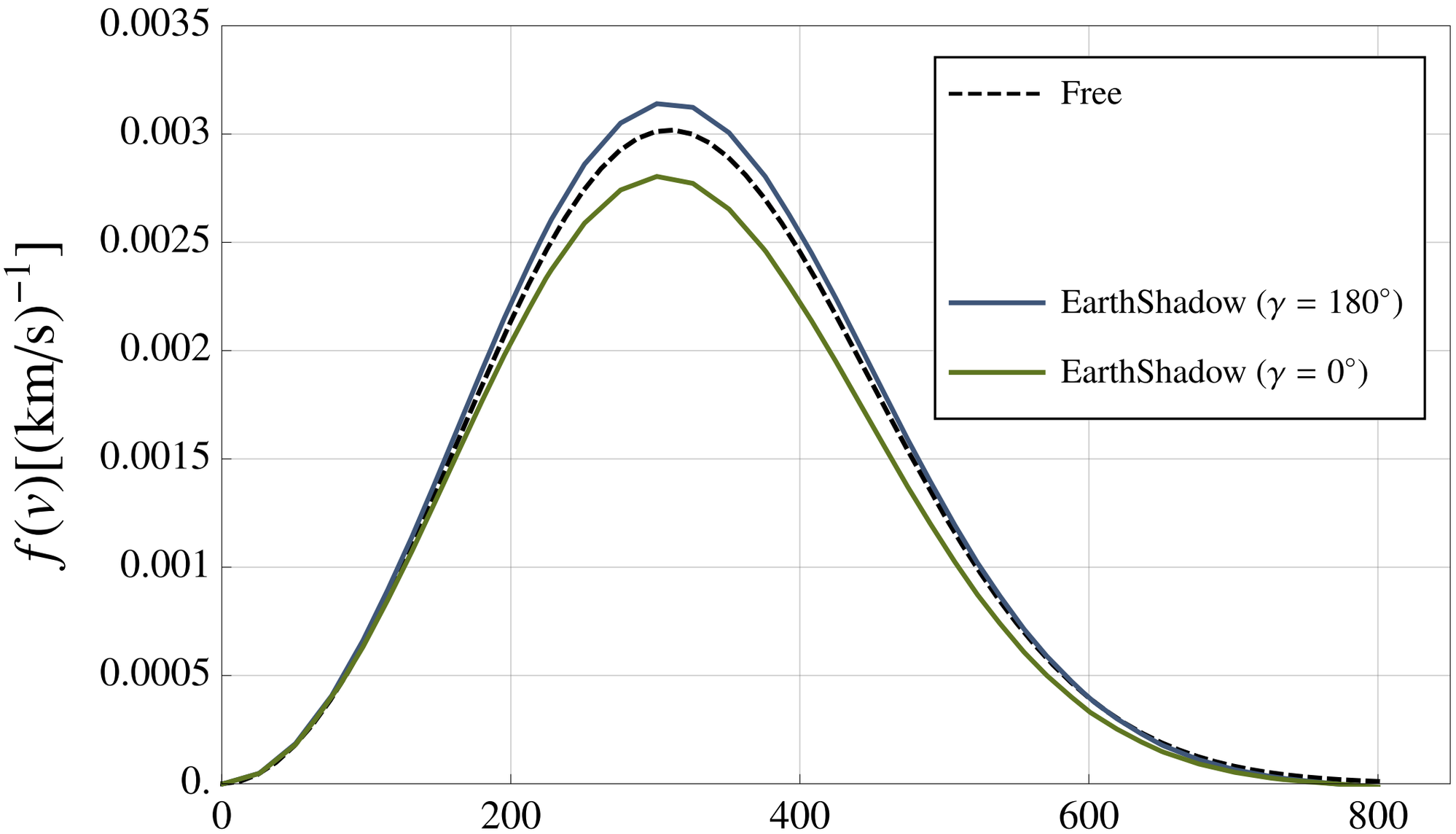
Speed Distribution - Operator 1

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





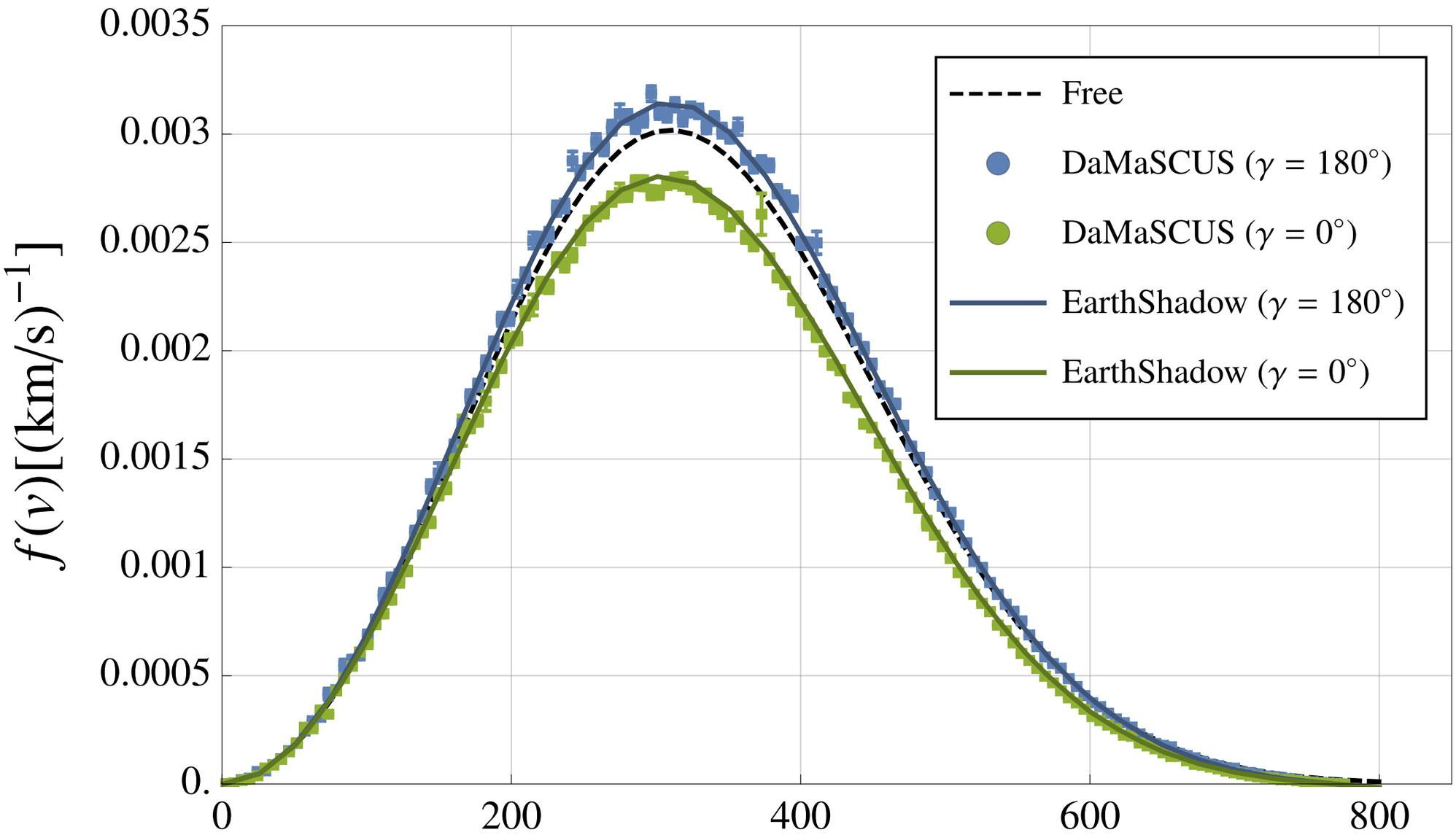
Comparison with Monte-Carlo



Monte-Carlo results from the DaMaSCUS code

[Emken & Kouvaris - 1706.02249]
http://cp3-origins.dk/site/damascus

Comparison with Monte-Carlo



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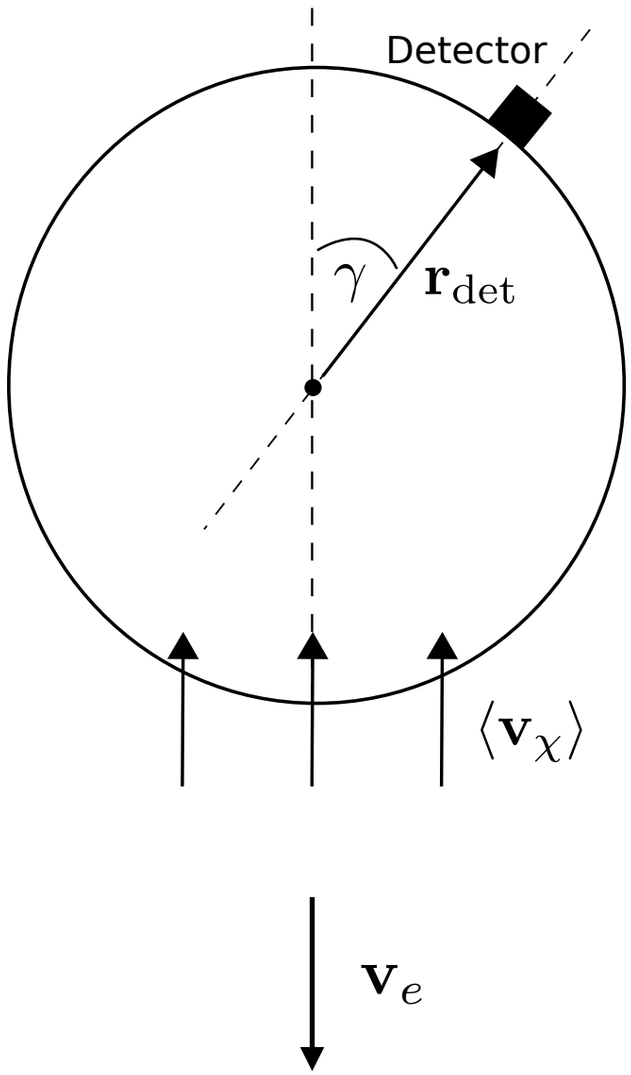
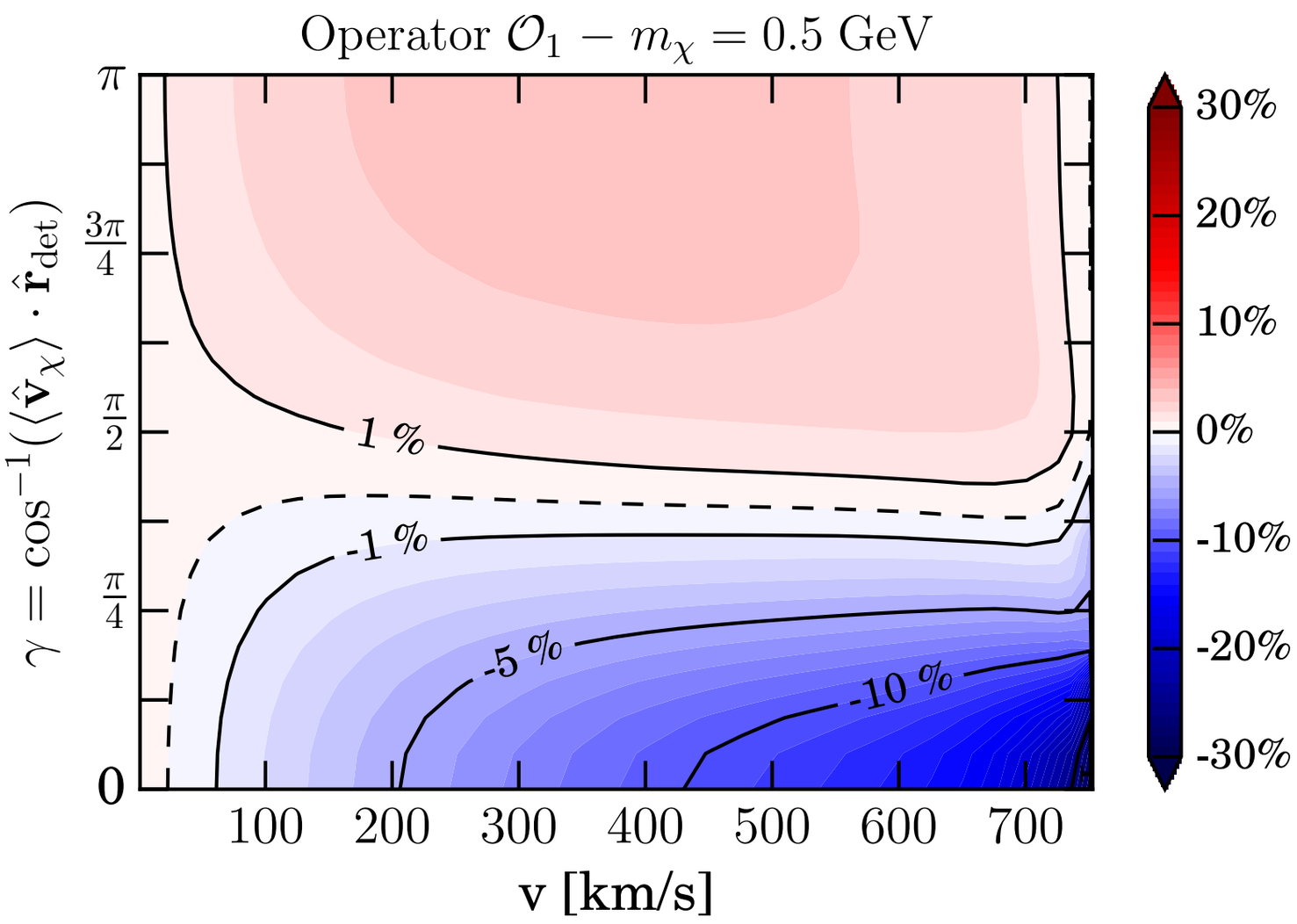
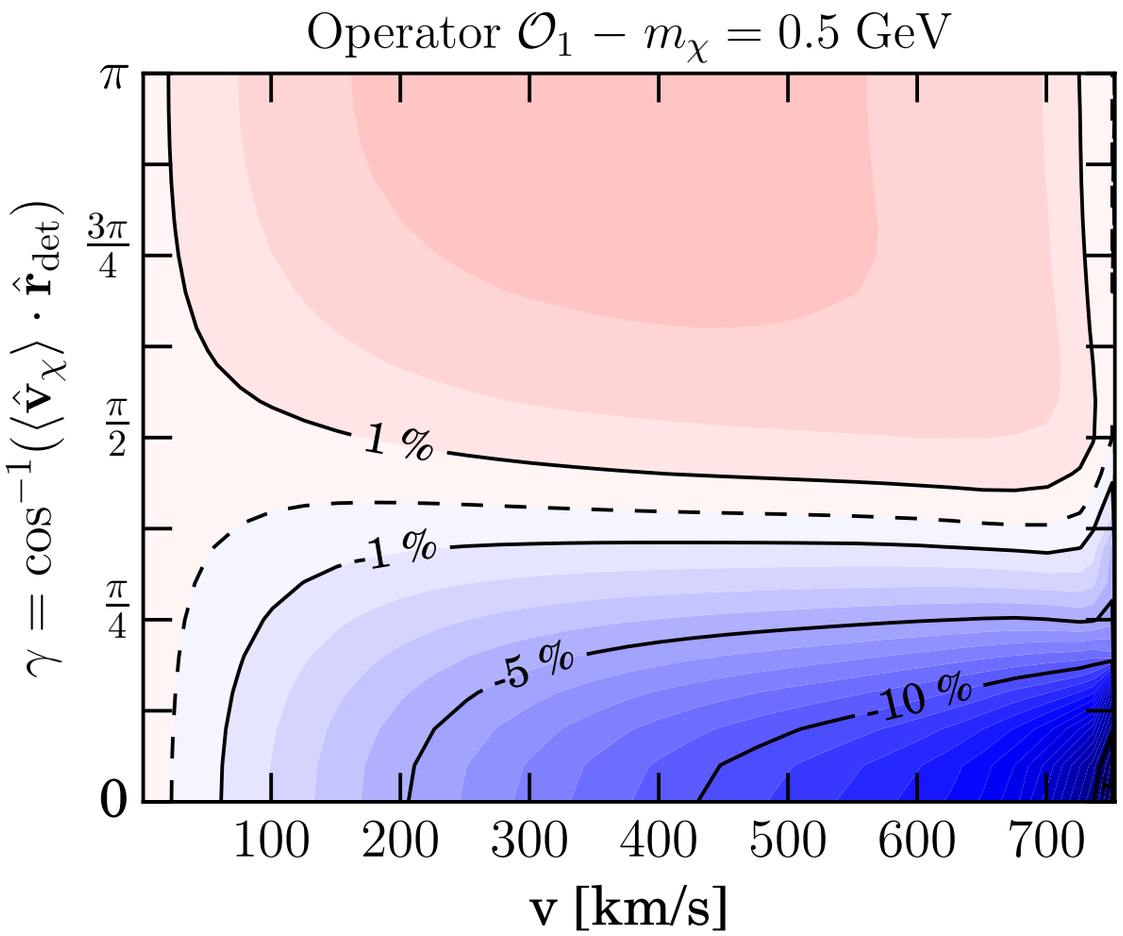
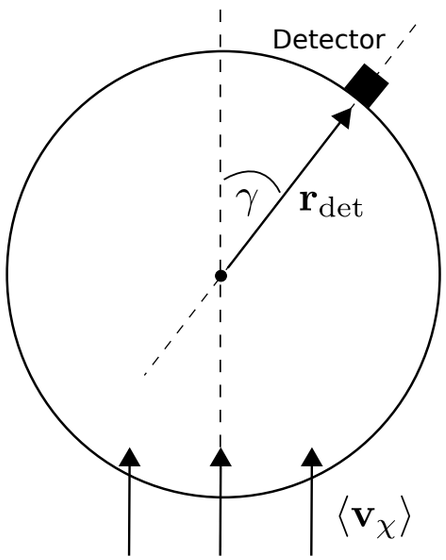


Percentage change in speed dist.

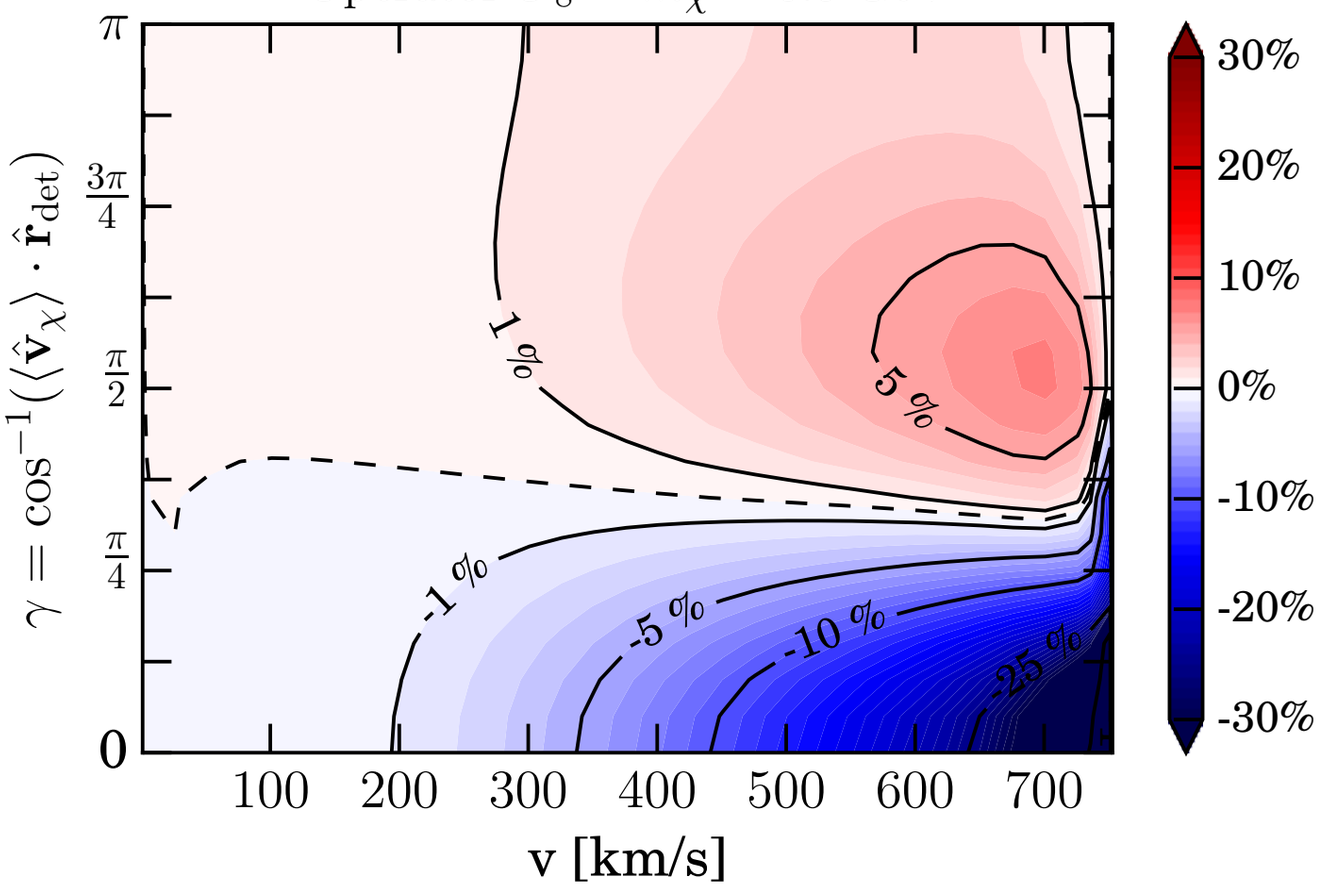


Speed Distribution - O_1 vs O_8

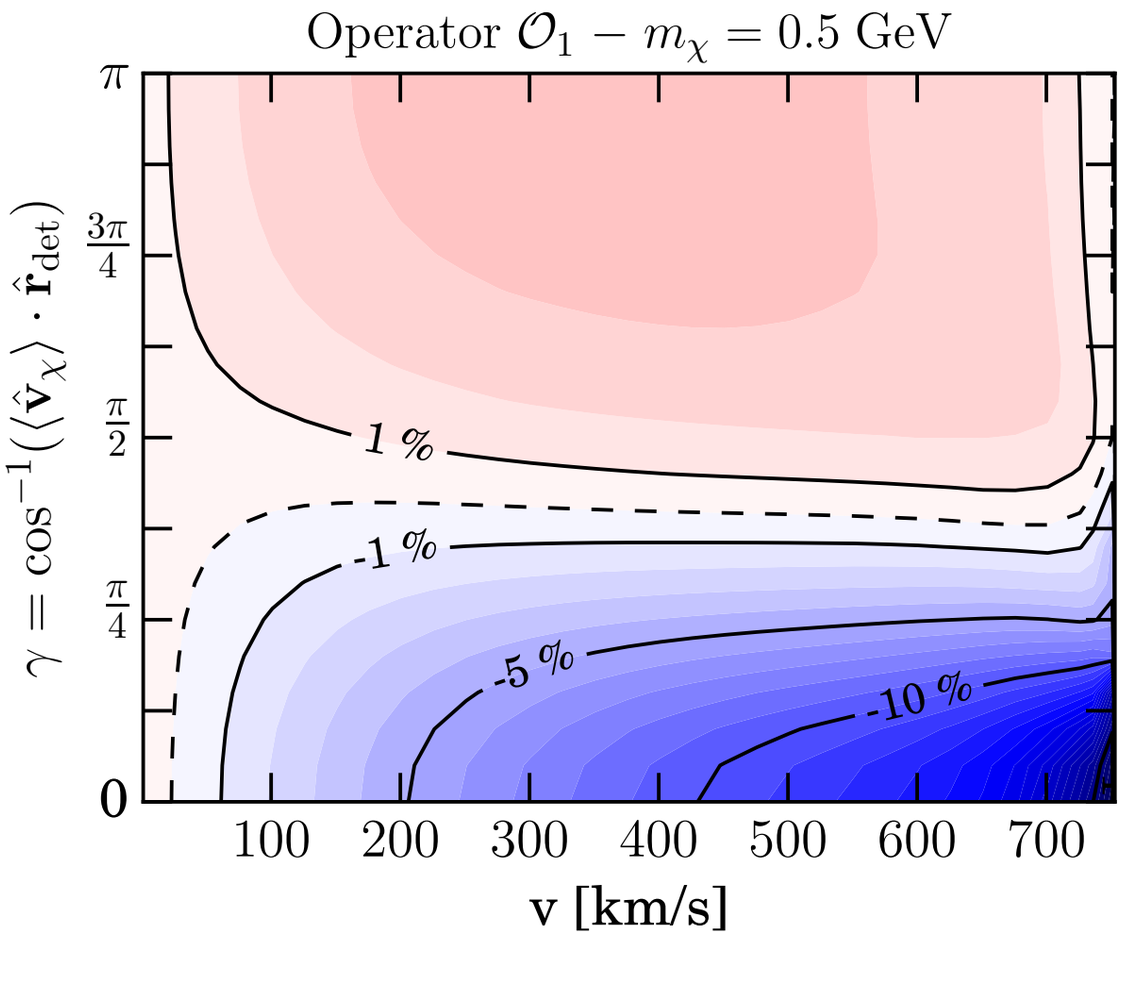


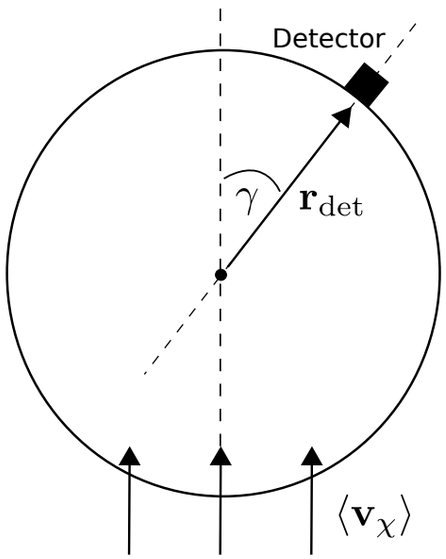


Operator 8 -
preferentially *forward* deflection

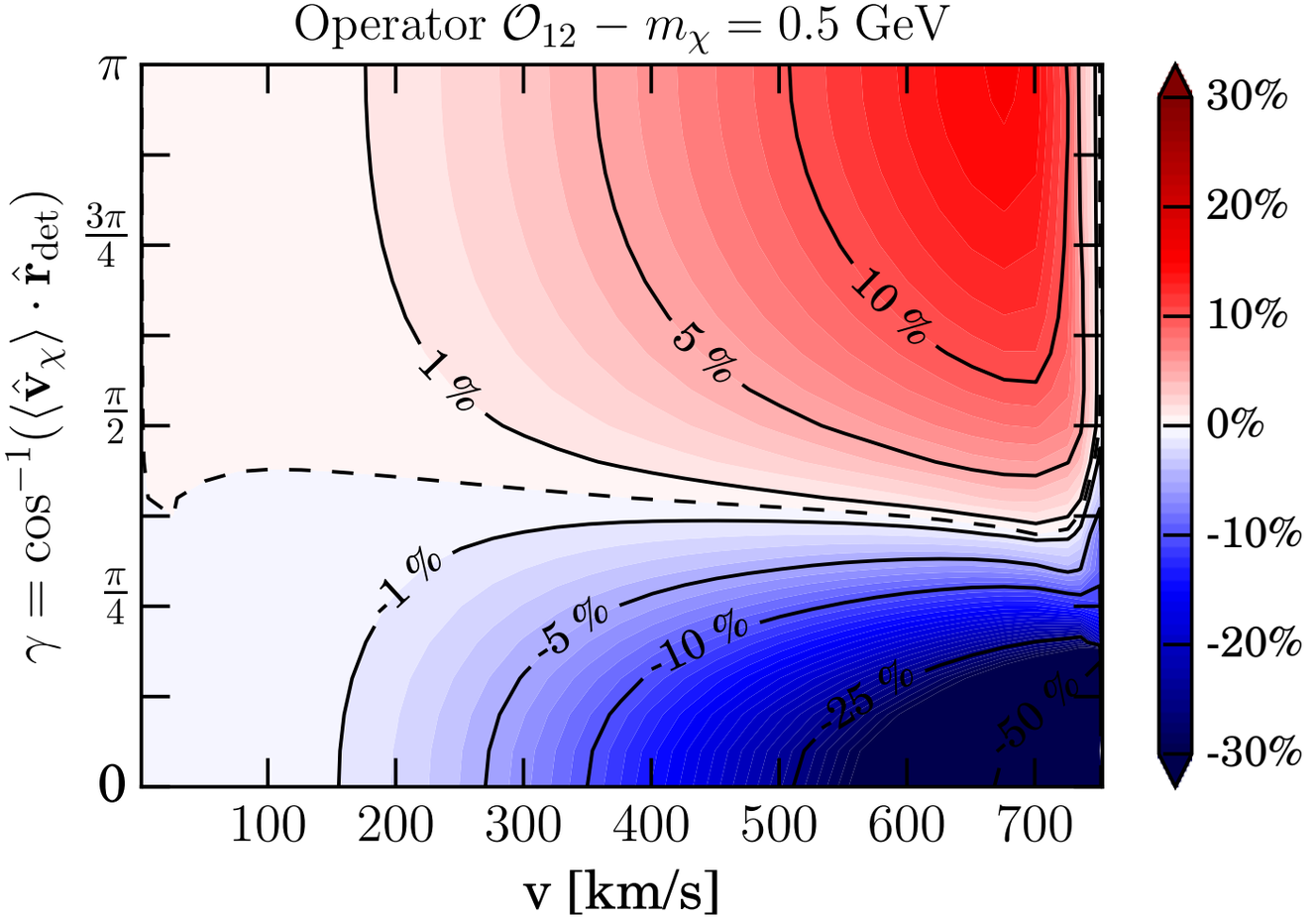


Speed Distribution - O_1 vs O_{12}





Operator 12 -
preferentially *backward* deflection

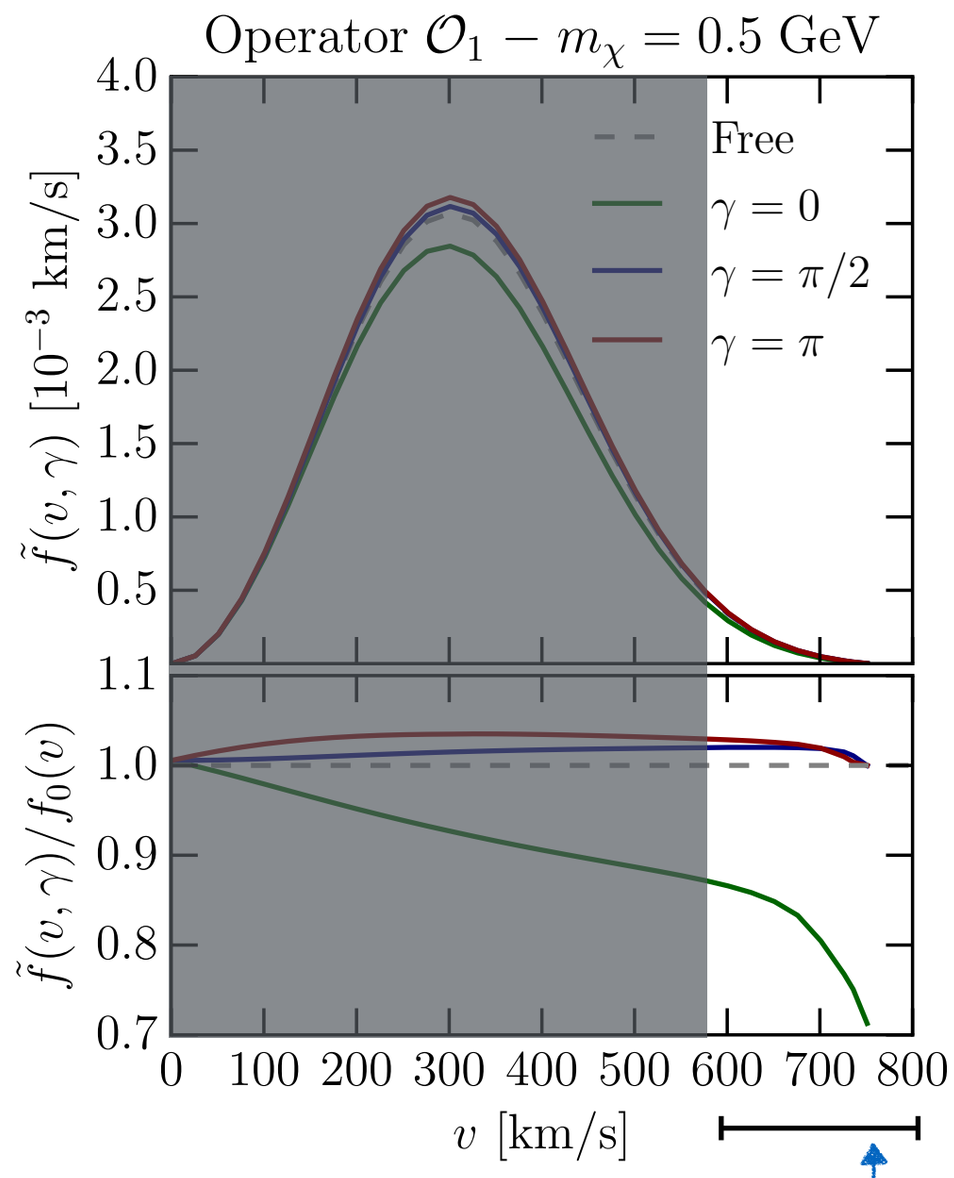


Event Rate

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

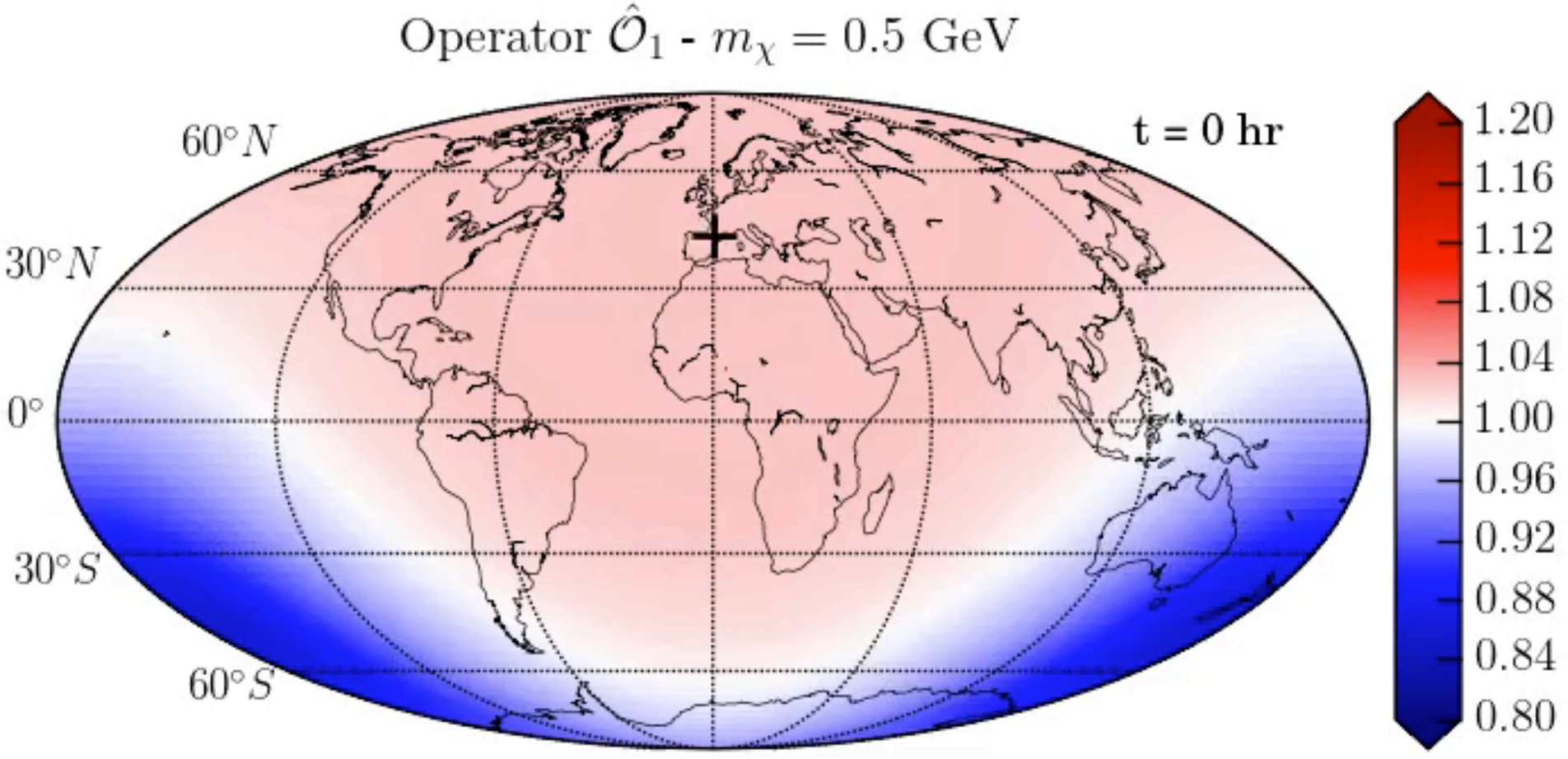
Scattering predominantly with Oxygen and Calcium.

Translate the angle γ into time and detector position



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

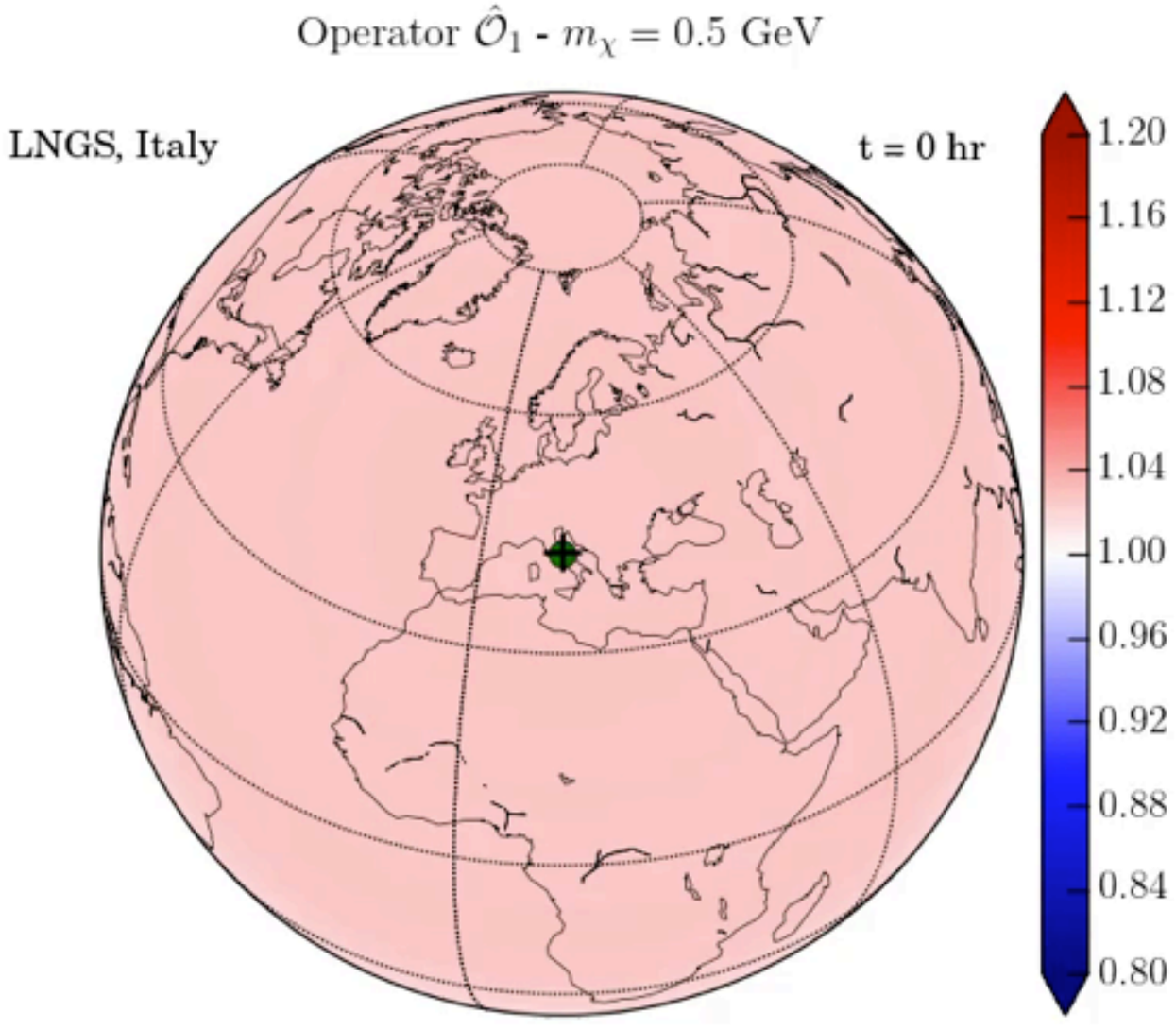
Mapping the CRESST-II Rate



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

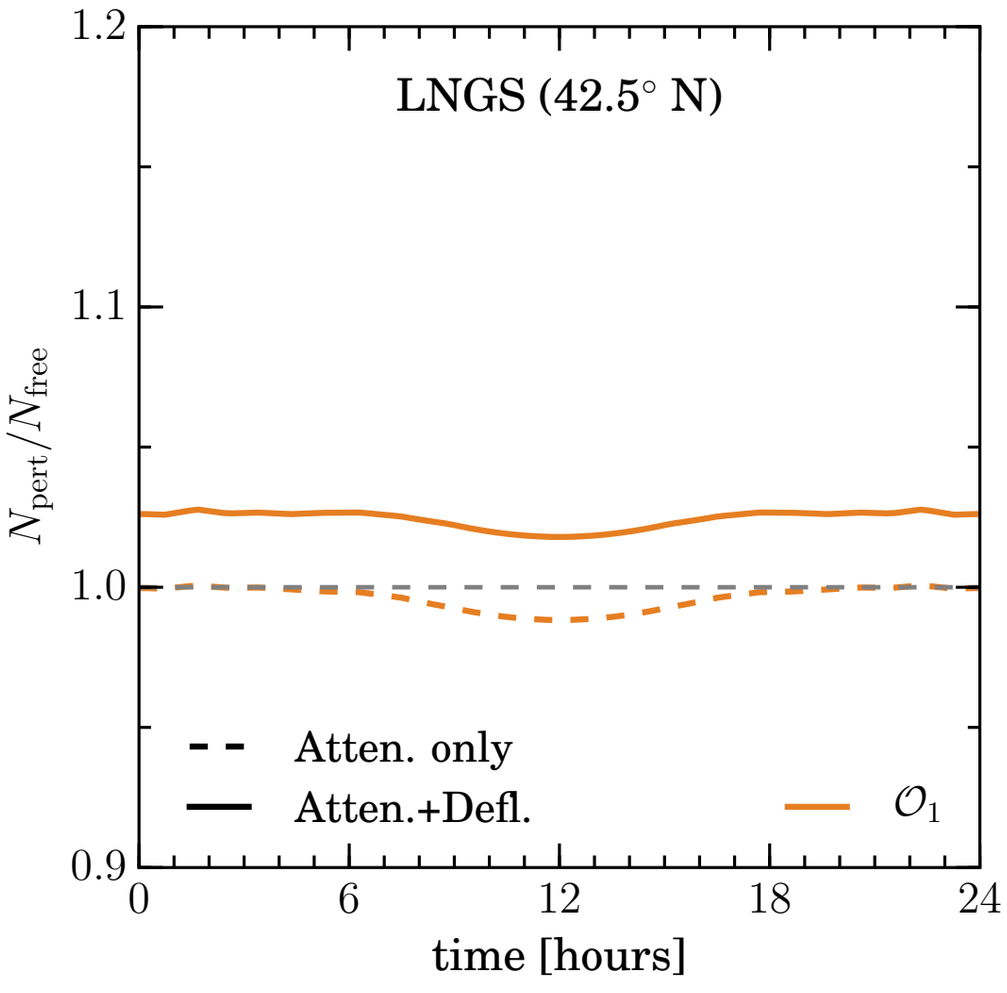
LNGS - Operator 1

LNGS - Gran Sasso Lab, Italy



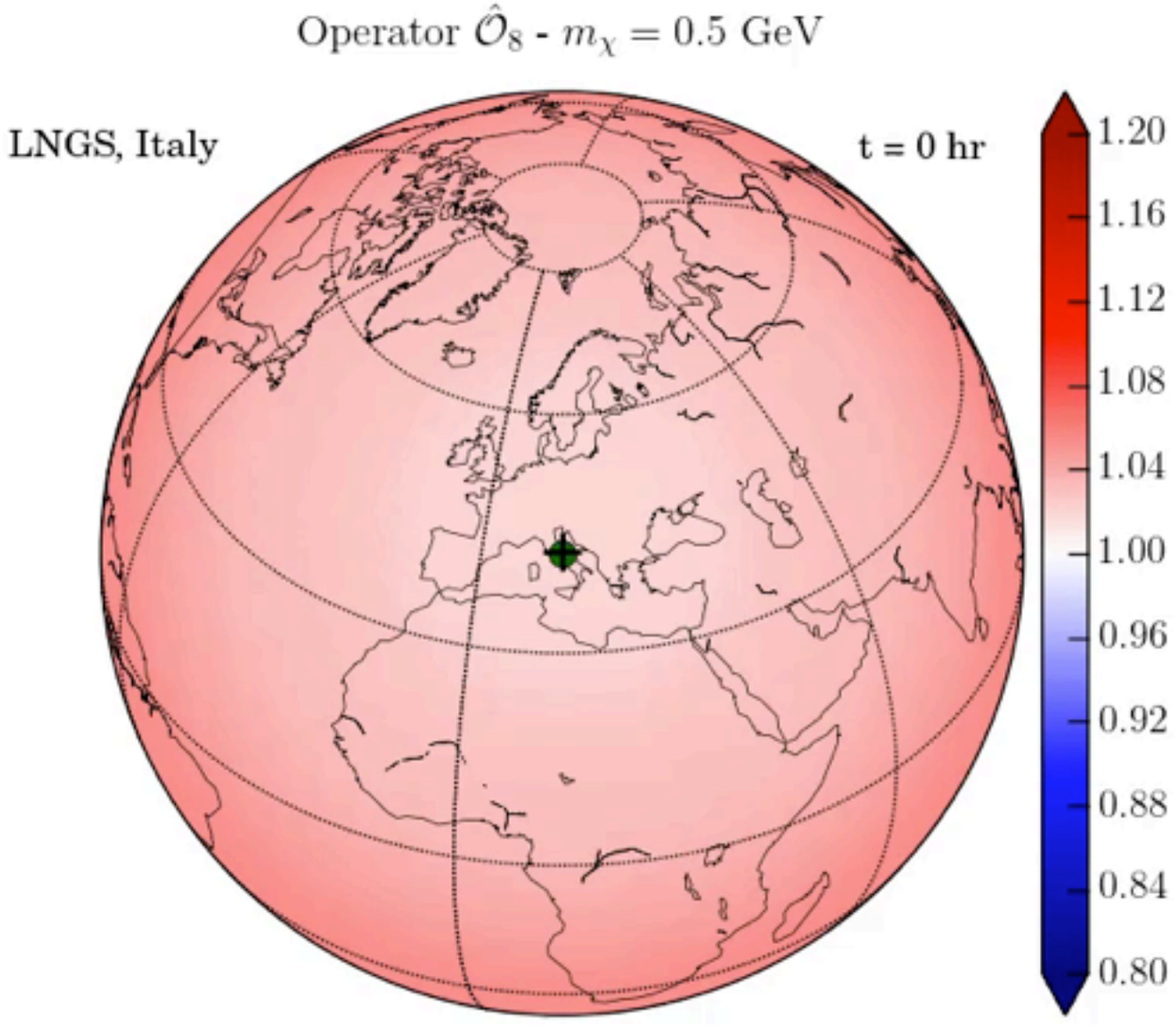
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 1 - isotropic deflection



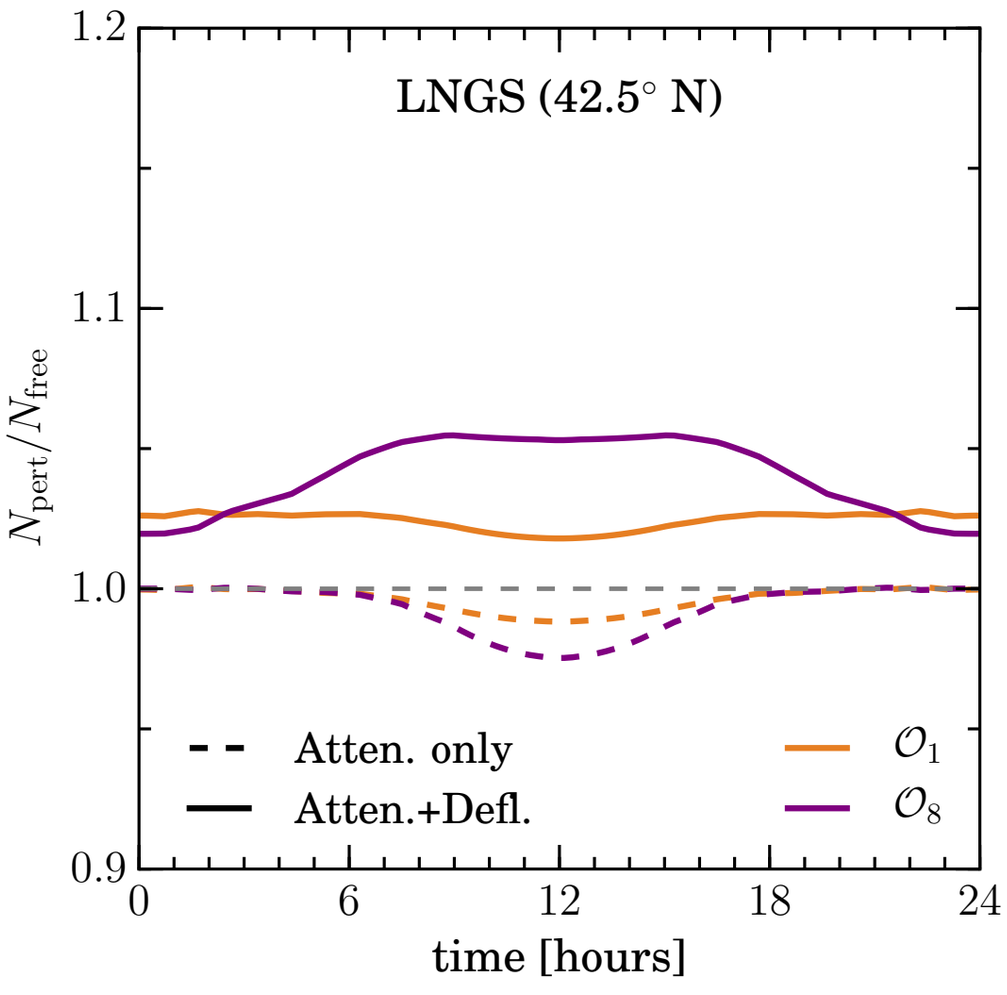
LNGS - Operator 8

LNGS - Gran Sasso Lab, Italy



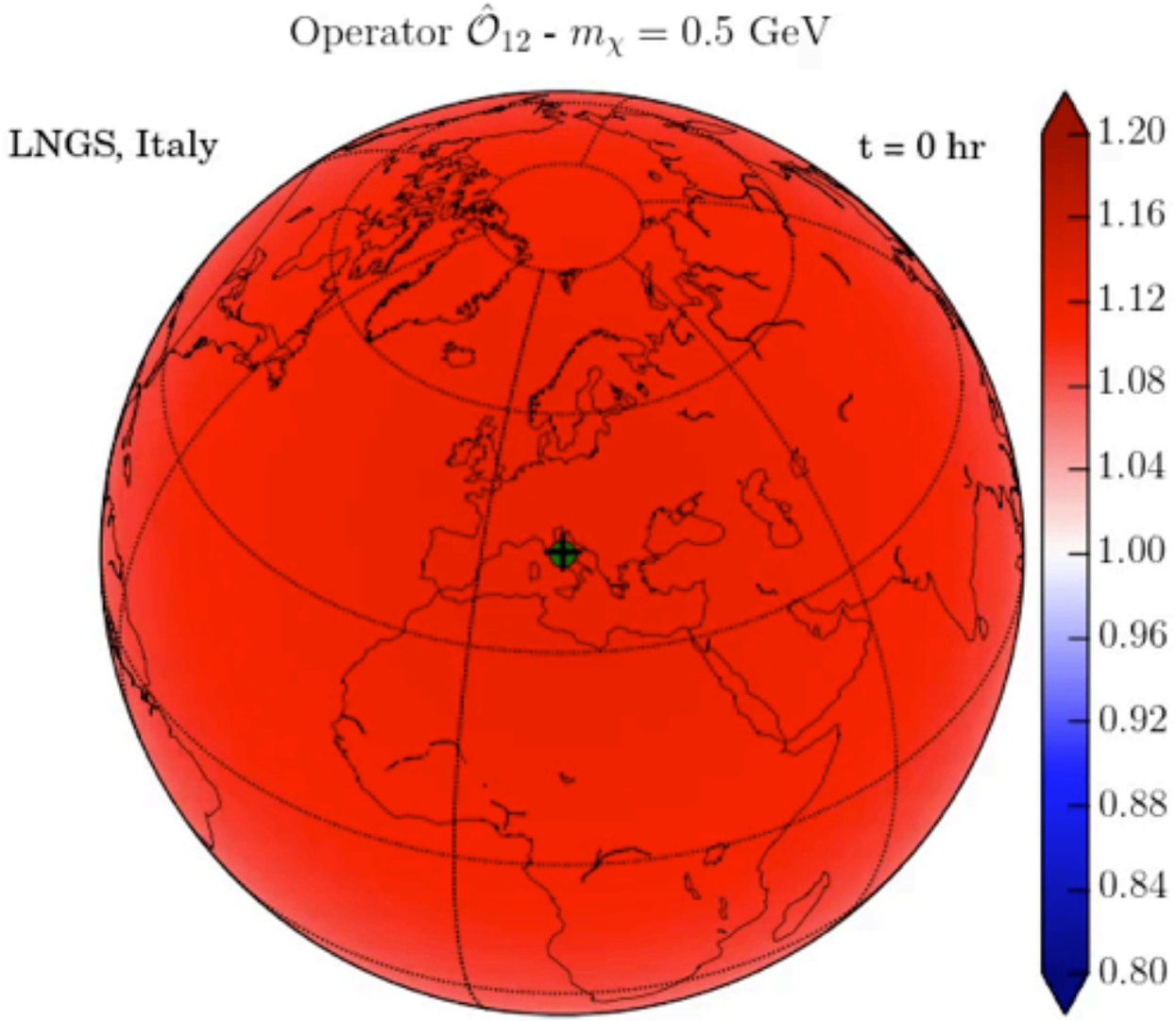
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 8 - forward deflection



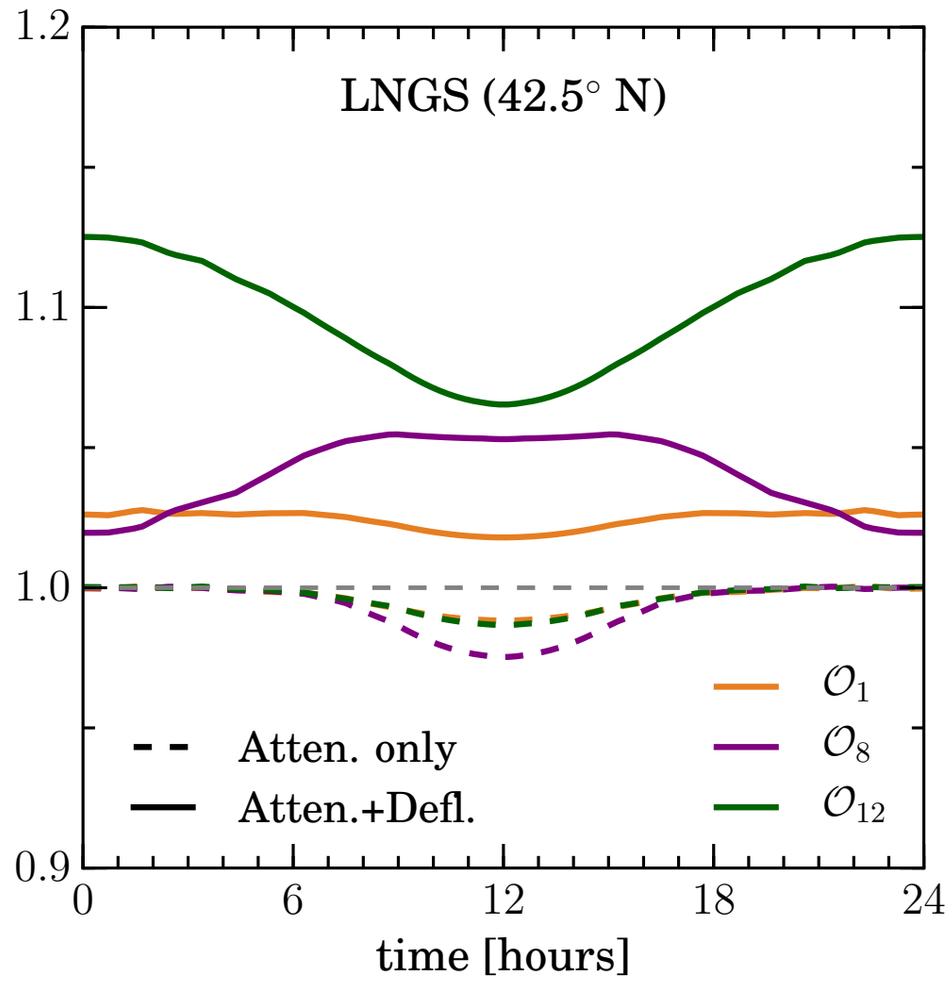
LNGS - Operator 12

LNGS - Gran Sasso Lab, Italy



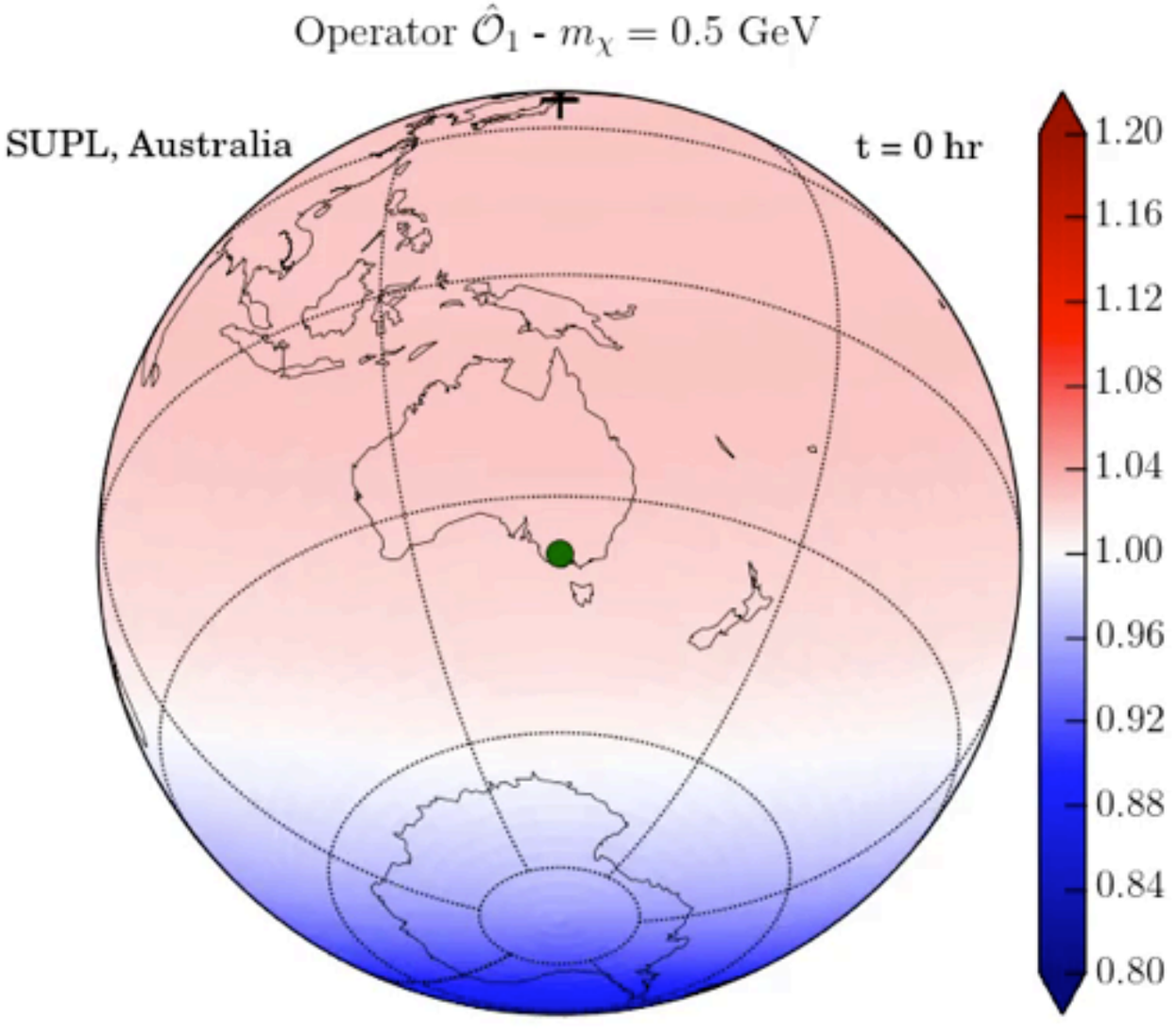
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 12 - backward deflection



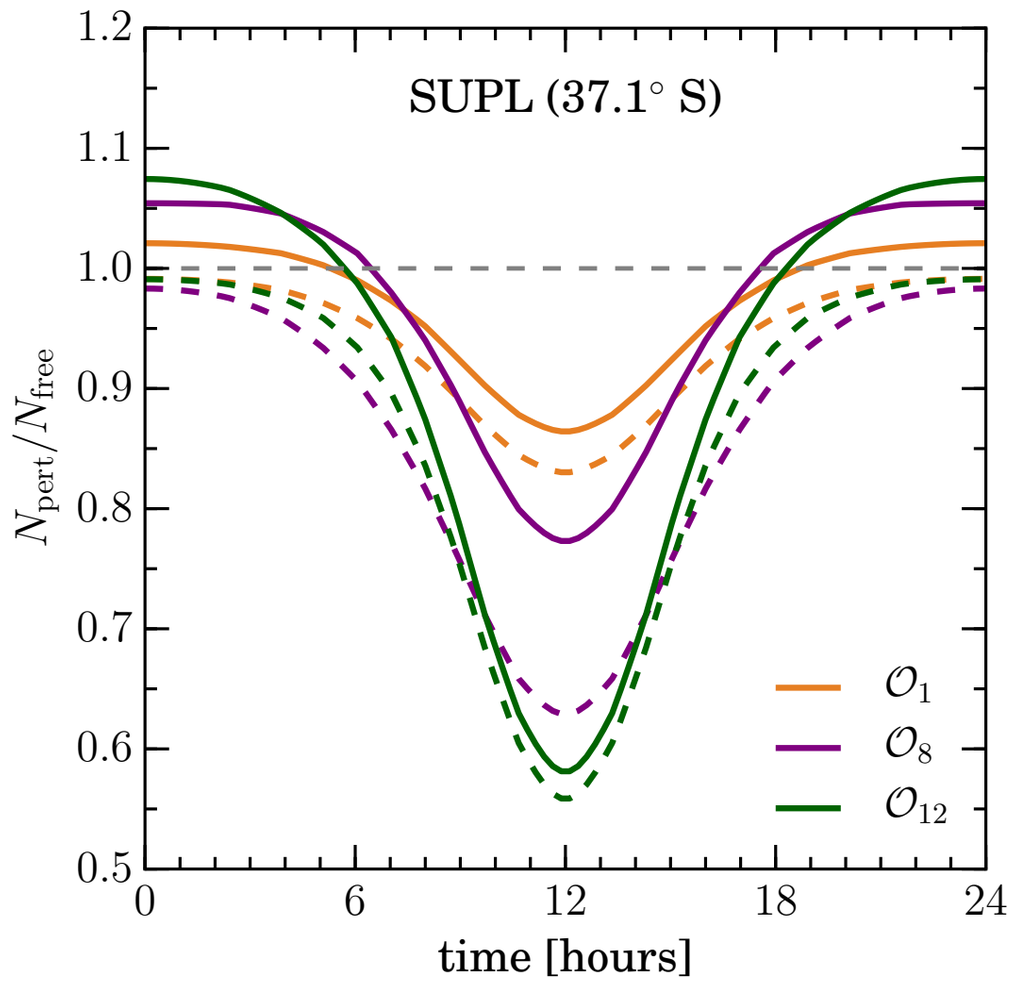
SUPL - Operator 1

SUPL - Stawell Underground Physics Lab, Australia

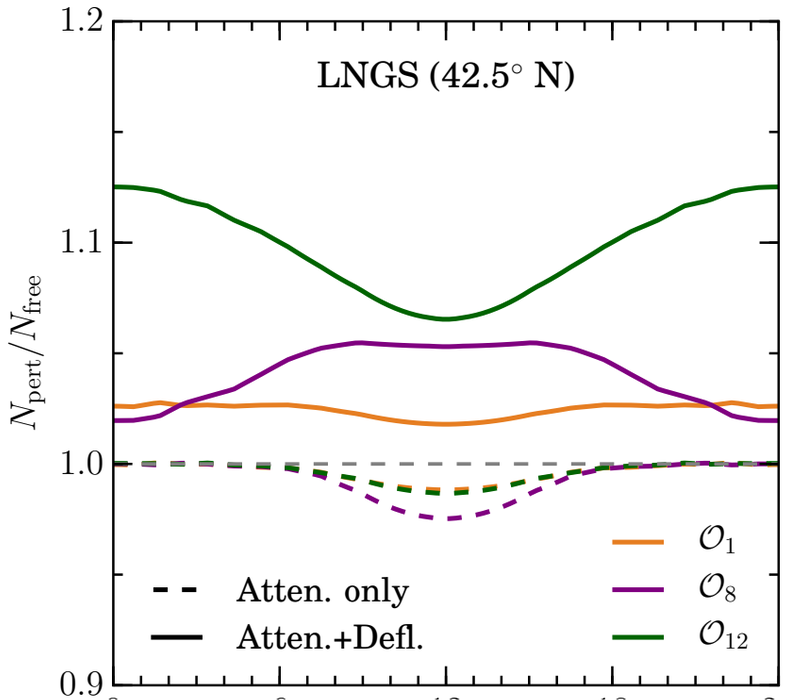


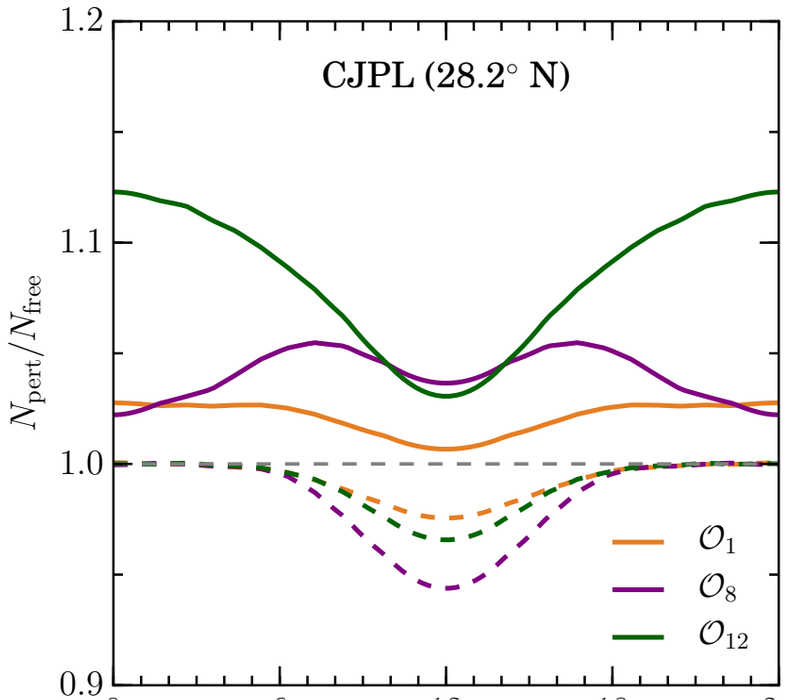
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 1 - isotropic deflection

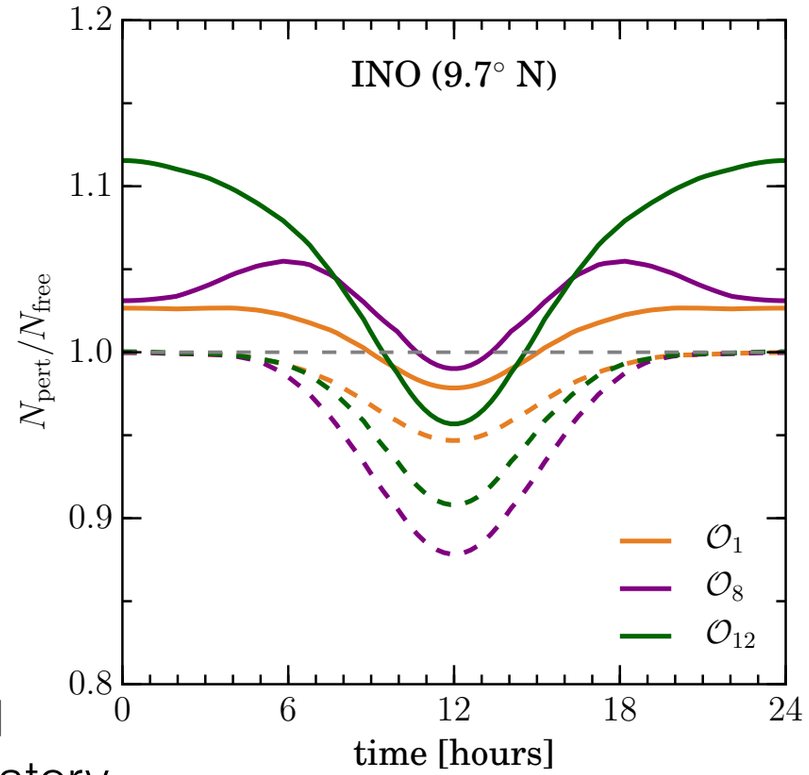


Around the world

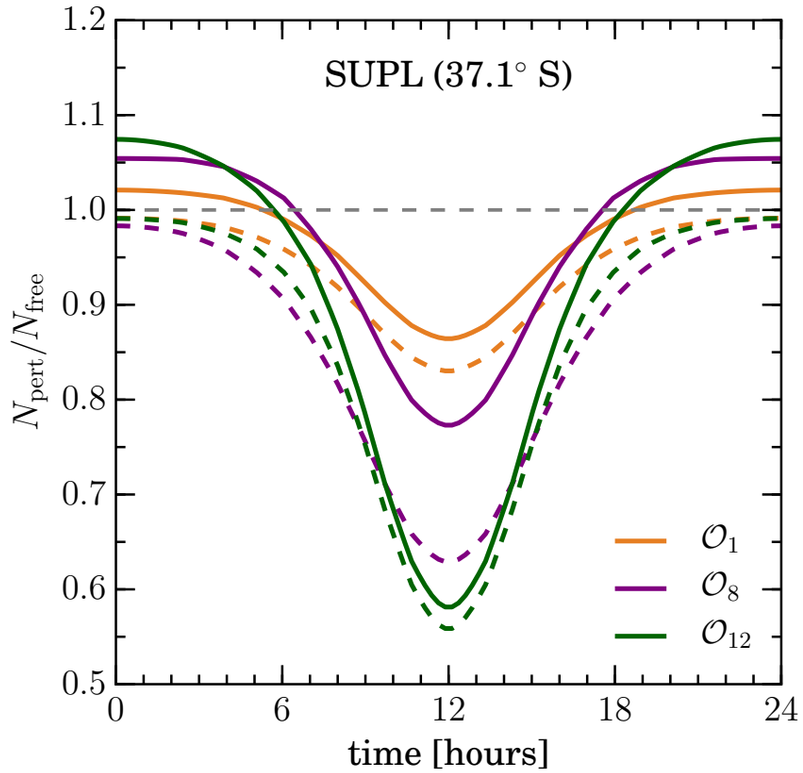




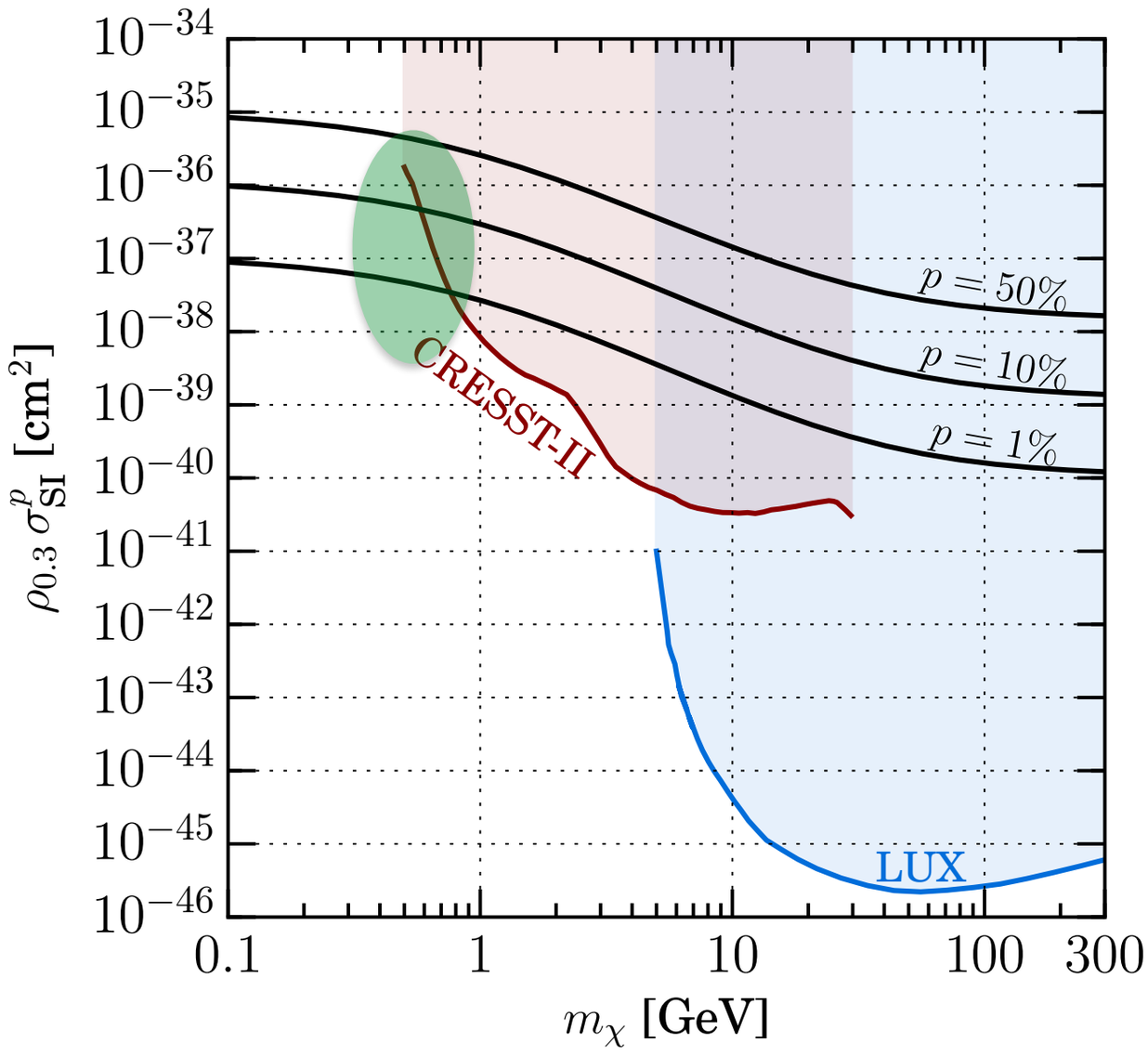
China Jinping Lab



India-based
Neutrino Observatory



Beyond ‘single-scatter’

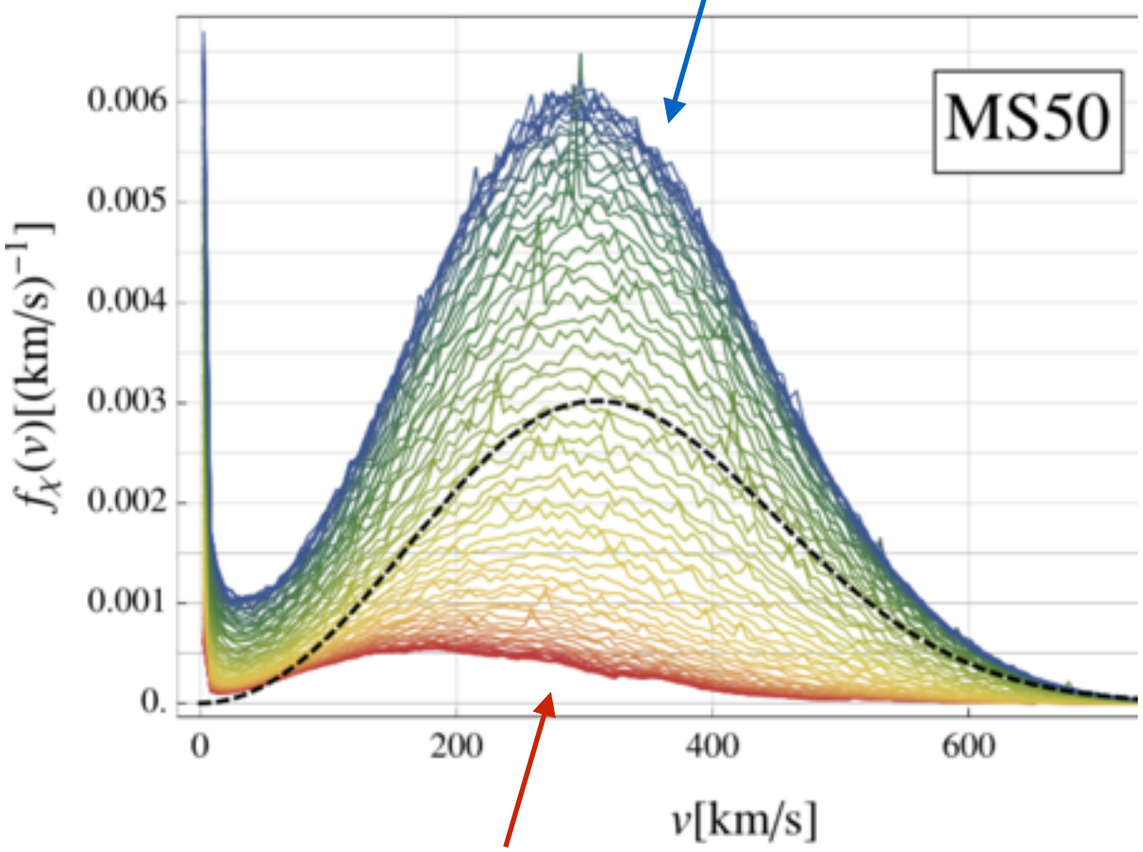


To go beyond the ‘single-scatter’ approximation, we need a Monte Carlo simulation…

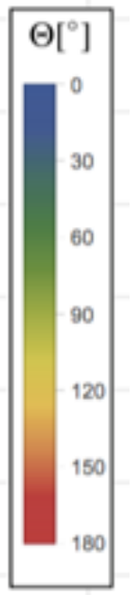
DaMaSCUS: http://cp3-origins.dk/site/damascus Emken & Kouvaris [1706.02249]

DaMaSCUS

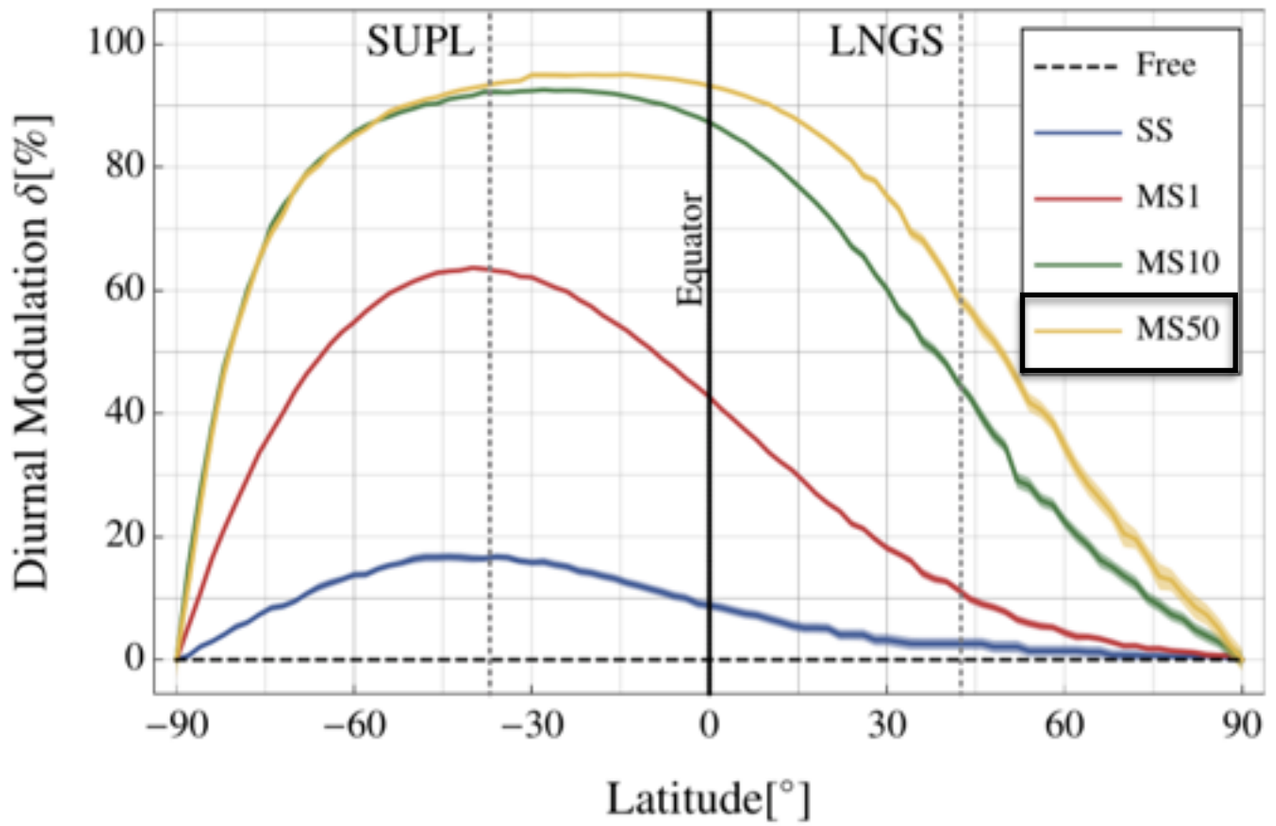
DM comes from above



DM comes from below



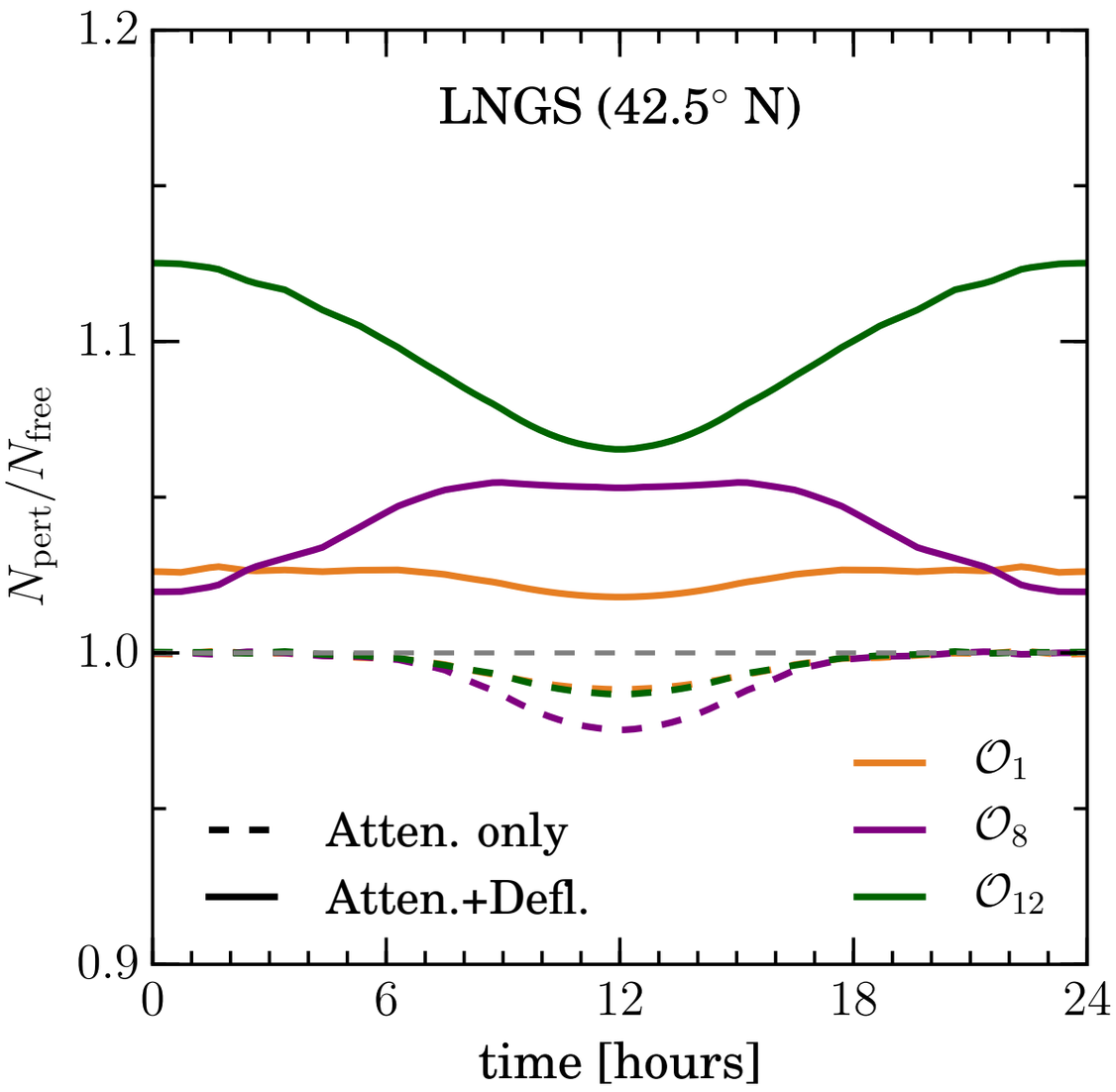
Large O(1) daily modulation if DM scatters ~50 times during Earth-crossing



Emken & Kouvaris [1706.02249]

Implications of Earth-Scattering for light DM

BJK, Catena & Kouvaris
[1611.05453]



Smoking gun signature:
daily modulation
+ location dependence
could confirm DM nature

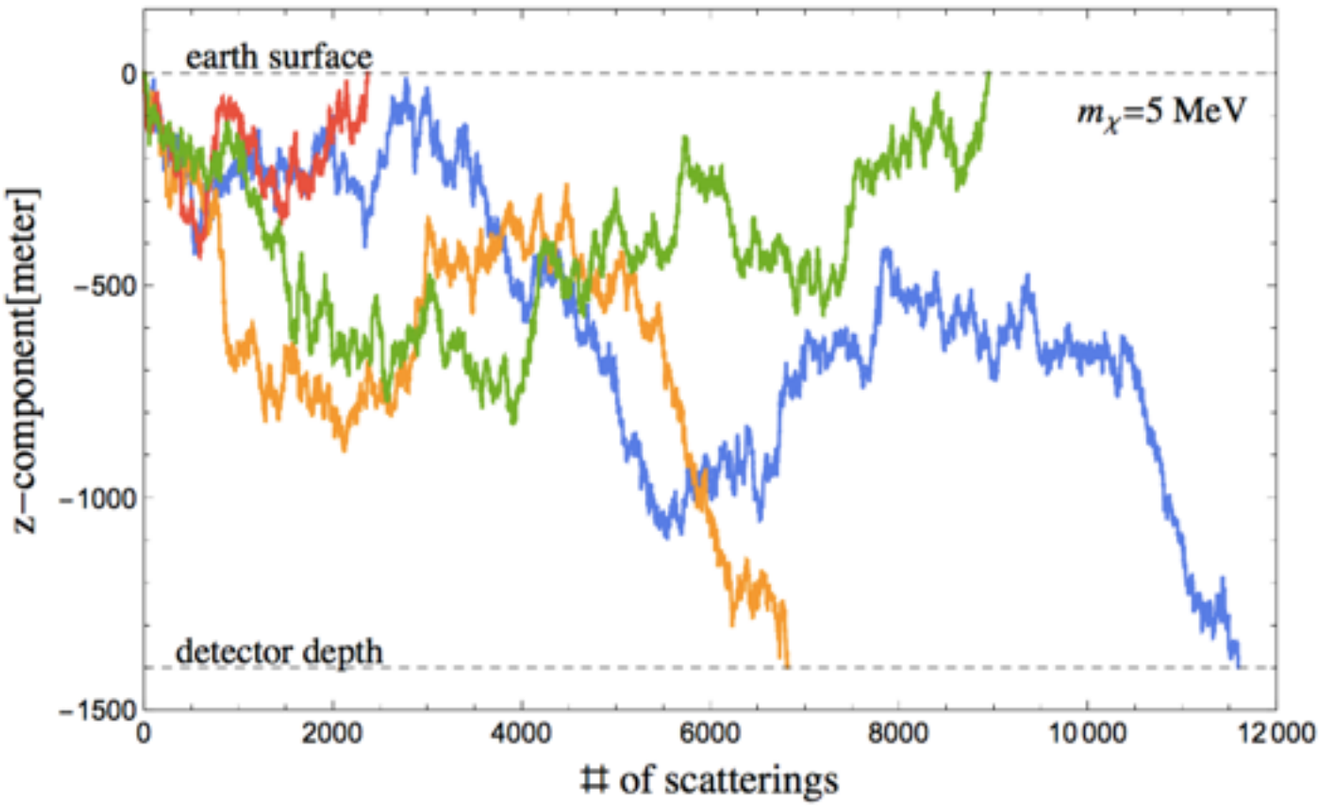
Possibility to distinguish different interactions with different amplitude and phase of modulation

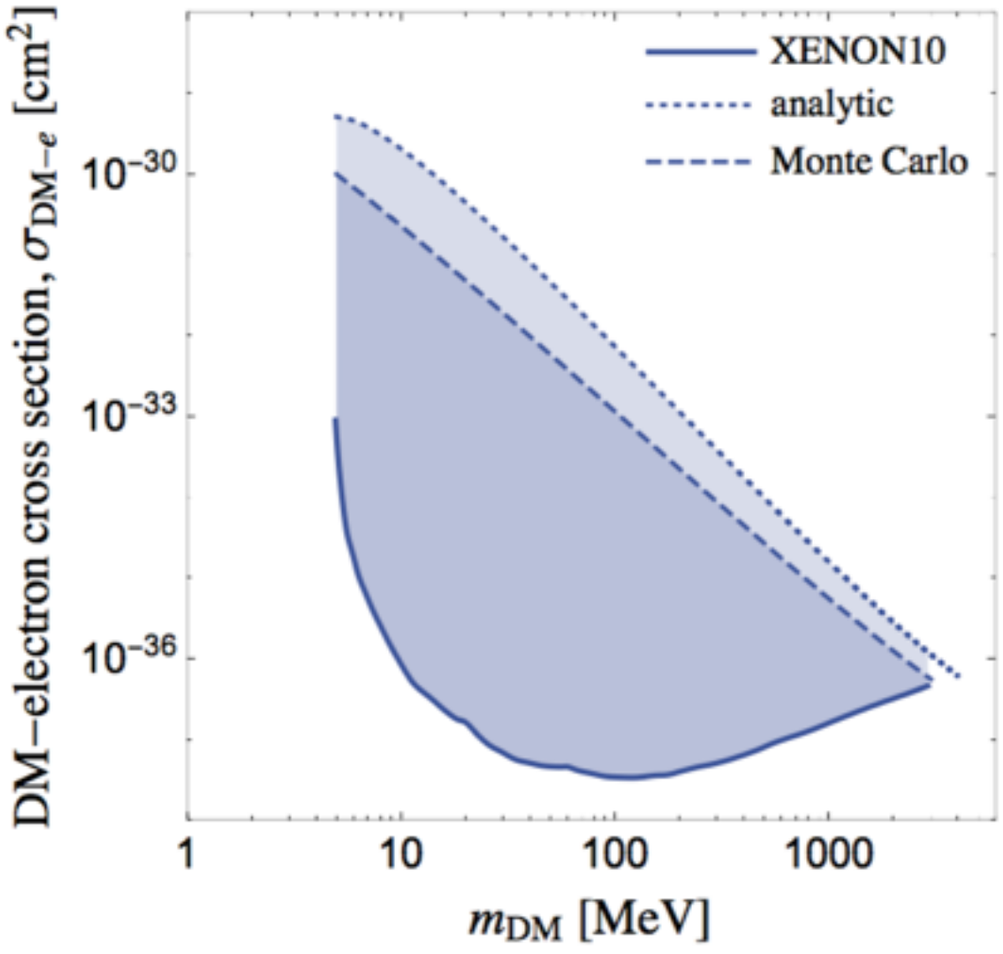
Possibility to measure the local DM density (by breaking degeneracy with cross section)

DM-Electron scattering + Monte Carlo

Consider energy loses for very strongly-interacting light DM

Bounds on MeV Dark Matter are cut off above some critical cross section:
DM lose too much energy and fall below threshold



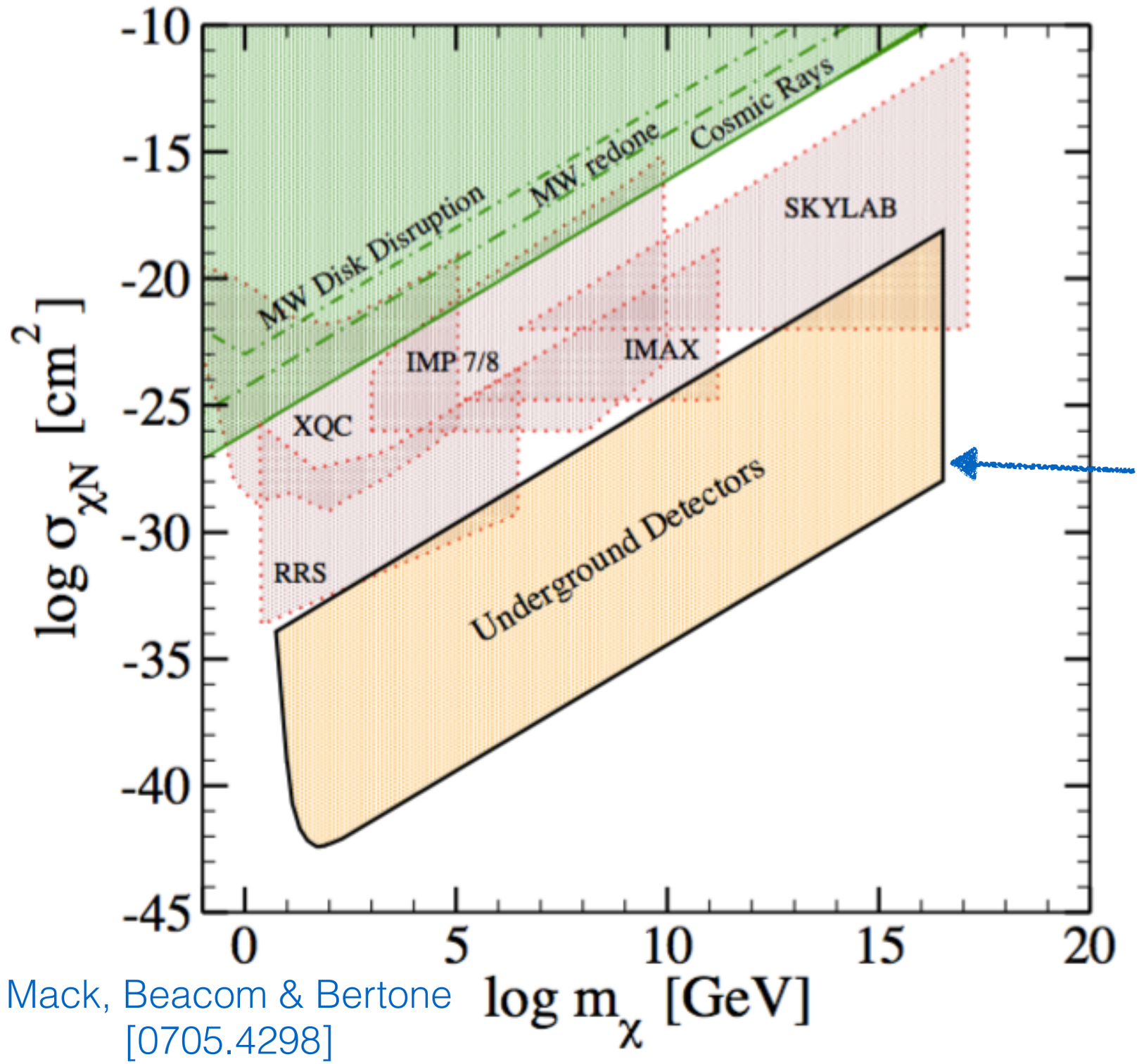


Emken, Kouvaris & Shoemaker [1702.07750]

WIMPzillas!

PRELIMINARY

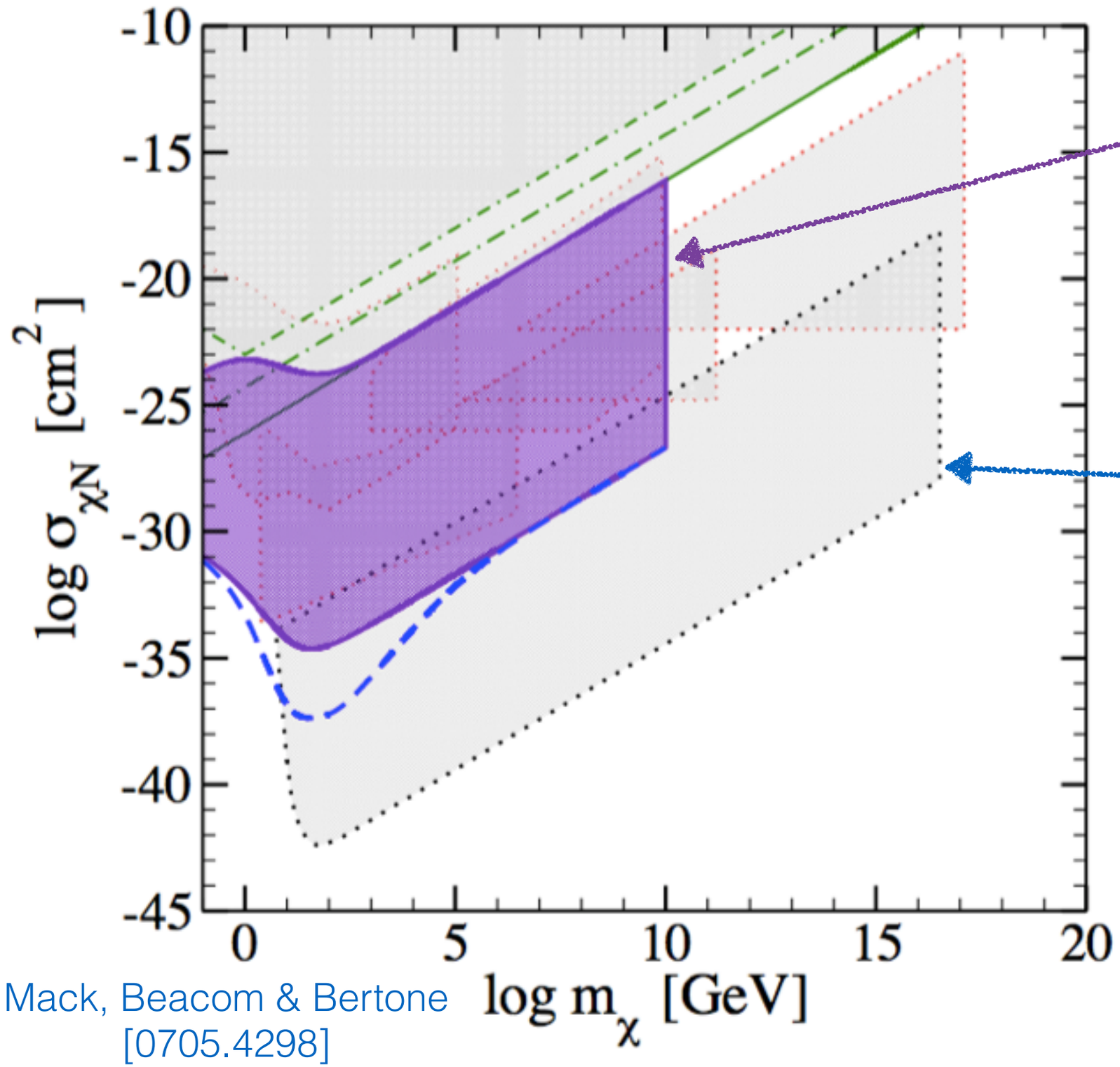
Direct Detection Landscape - zoomed out



Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]

Direct Detection Landscape - zoomed out

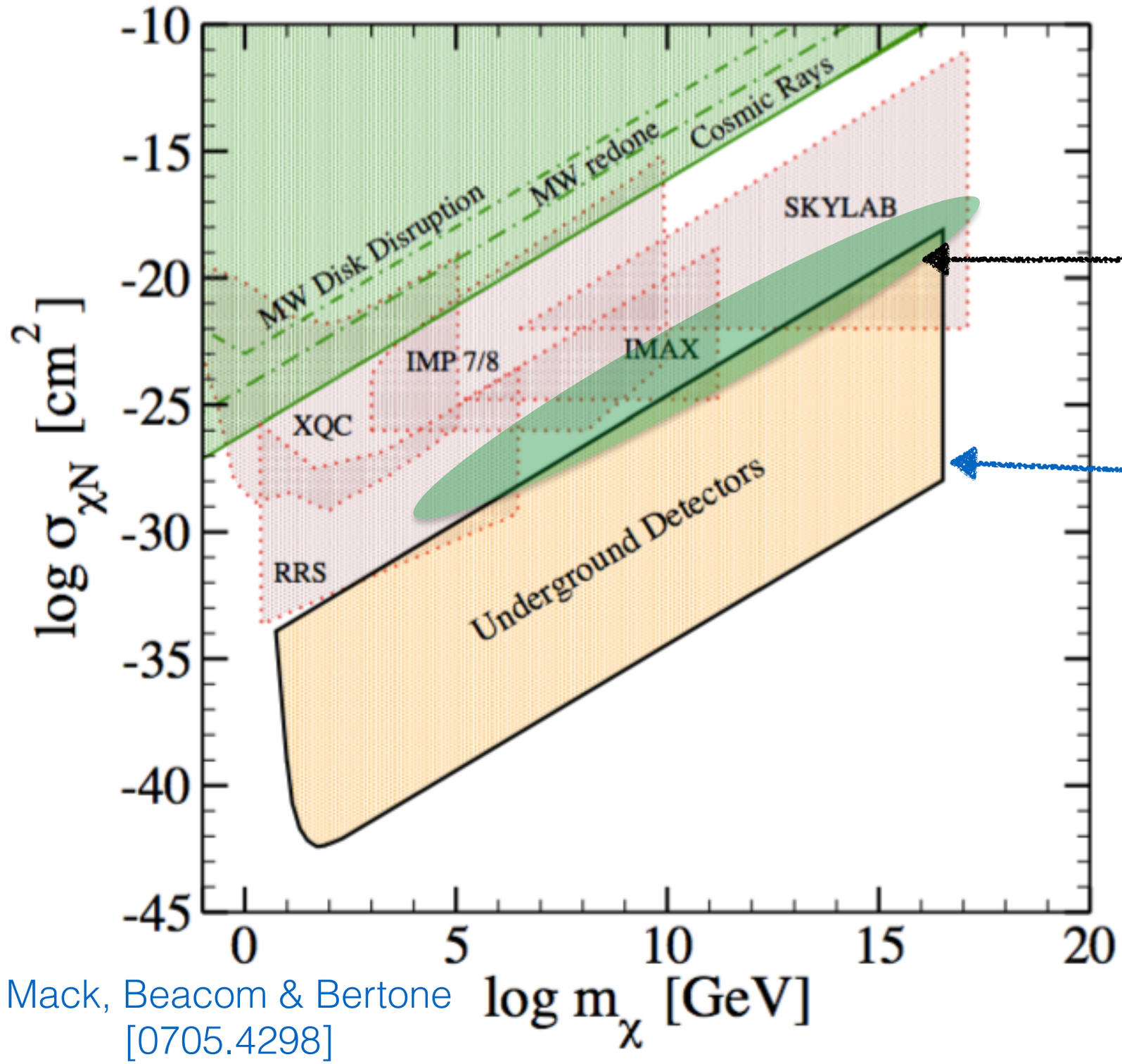


Earth's heat flow from DM capture + annihilation

Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]

Direct Detection Landscape - zoomed out



Assume e.g. asymmetric DM: no heat flux from annihilation

Focus on this region

Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]

Earth-scattering for super-heavy DM

Large cross section means *huge* number of scattering events (>>100)

↳ Monte Carlo may not be the most efficient tool

Luckily, deflection of DM can be neglected:
angle of deflection (per scatter) goes as $m_A/m_\chi \ll 1$.

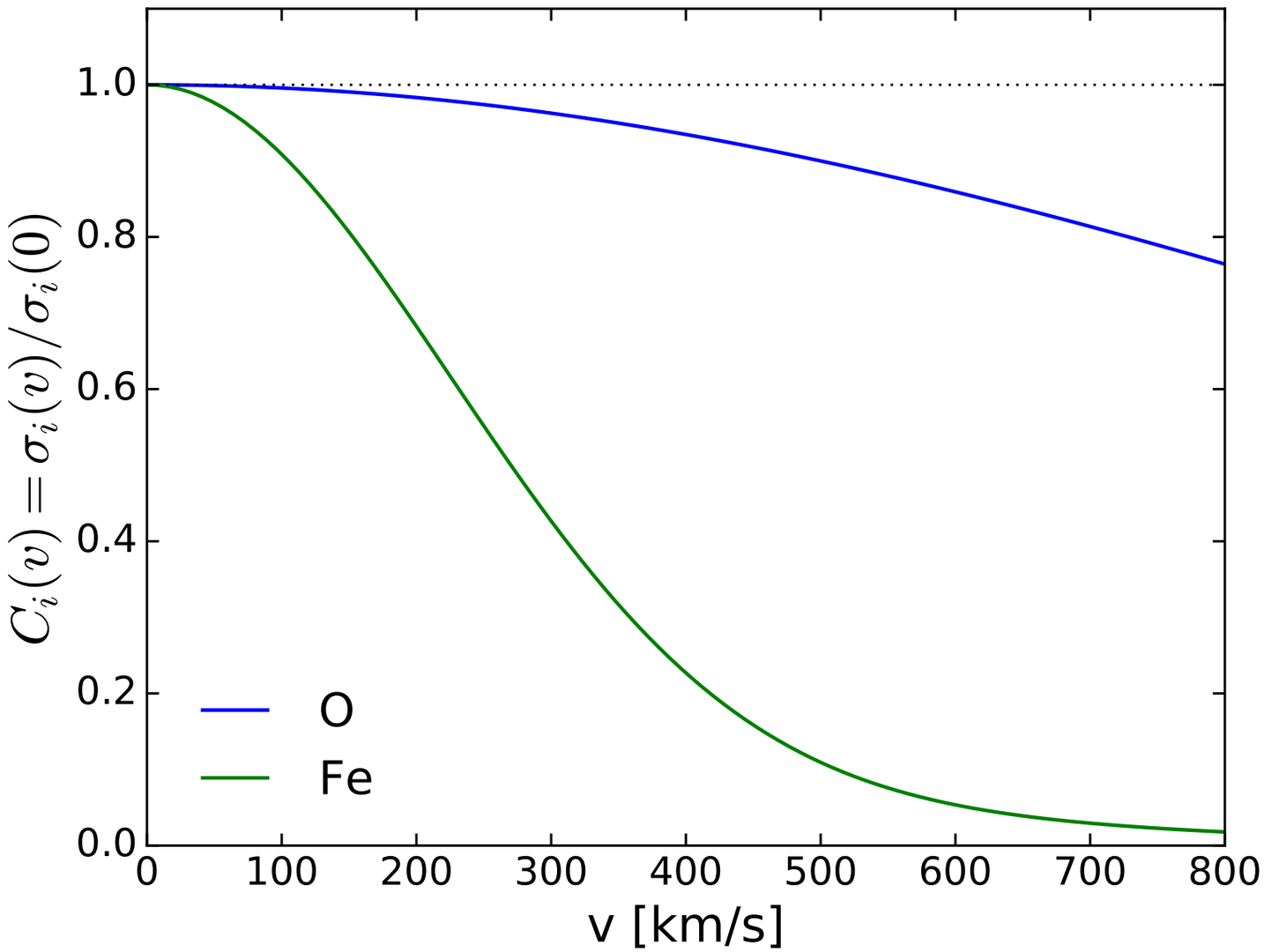
Consider *only* stopping/slowing of the DM particles!

Need to calculate v_f as a function of v_i ….

Nuclear Stopping Equation

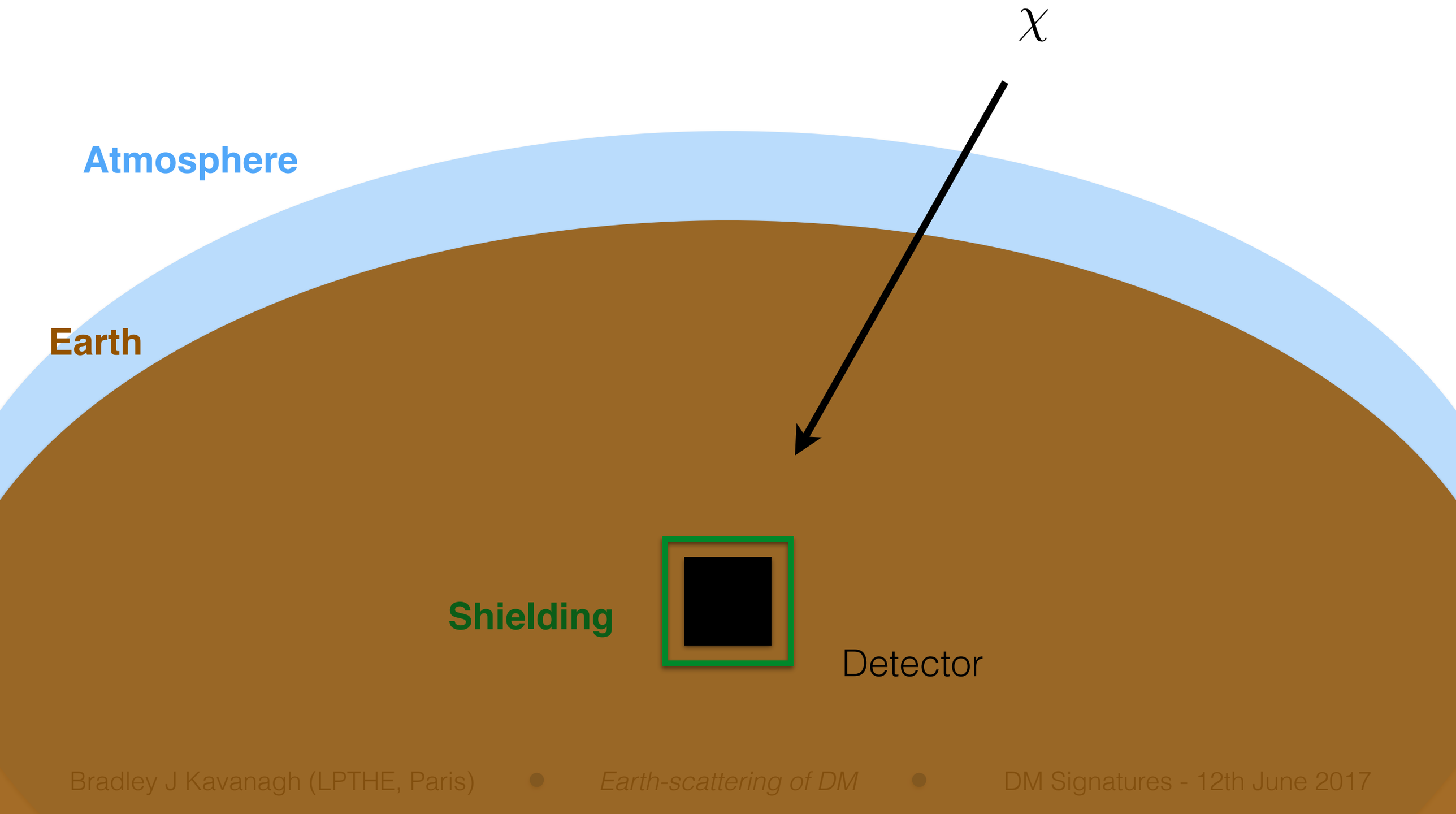
$$\frac{\mathrm{d}v}{\mathrm{d}x} = -\frac{1}{m_\chi v}\sum_i^{\text{species}} n_i(\mathbf{r})\sigma_i(v)\langle E_R\rangle_i = -v\sigma_p^{\text{SI}}\sum_i^{\text{species}} n_i(\mathbf{r})\left(\frac{m_i}{m_\chi}\right)A_i^4 C_i(v)$$

‘Correction factor’ due to nuclear form factors



Solve numerically for a given initial speed and incoming direction (which affects how much of the Earth has to be crossed)

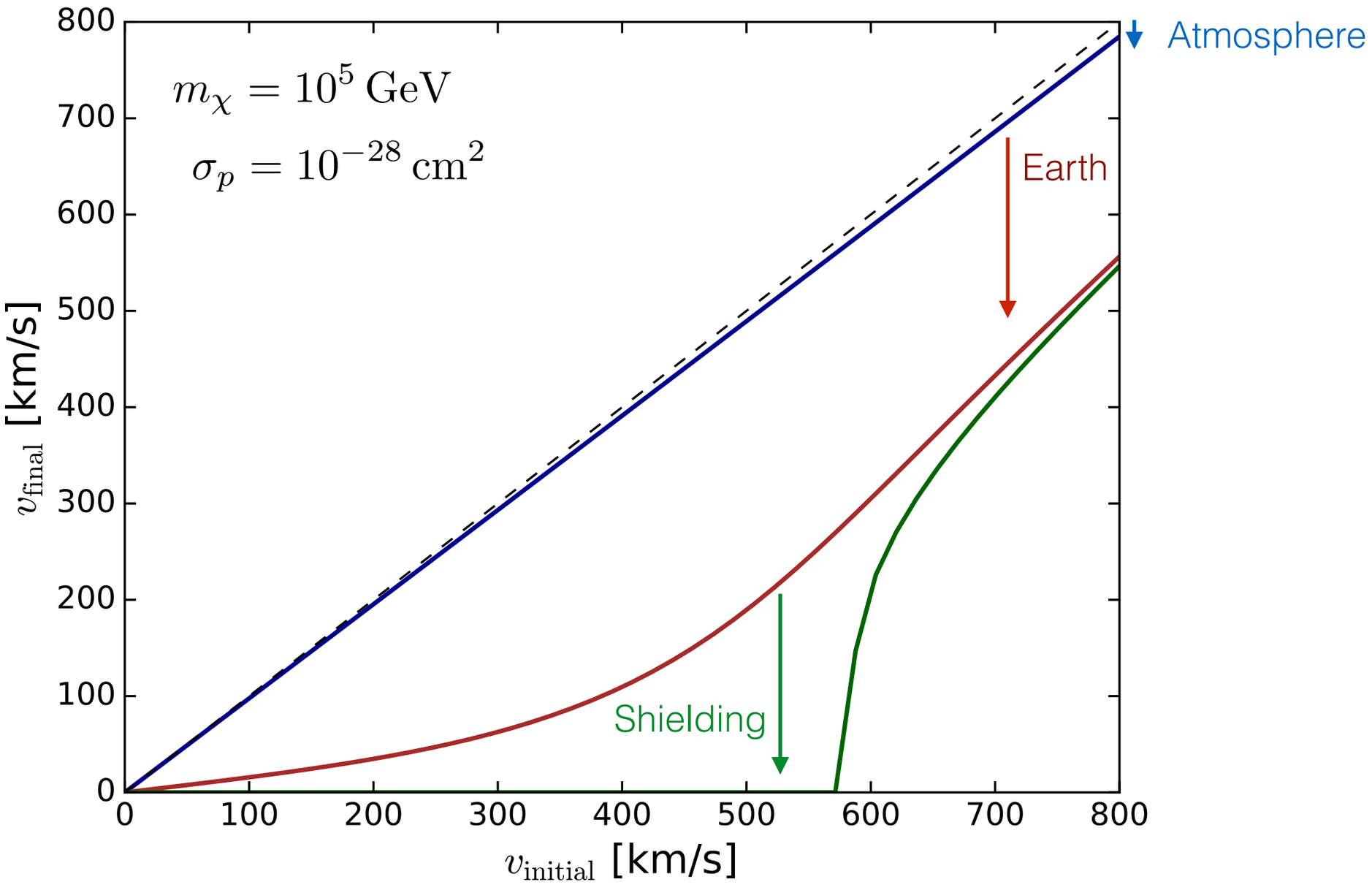
Journey to the centre of the Earth



Stopping power

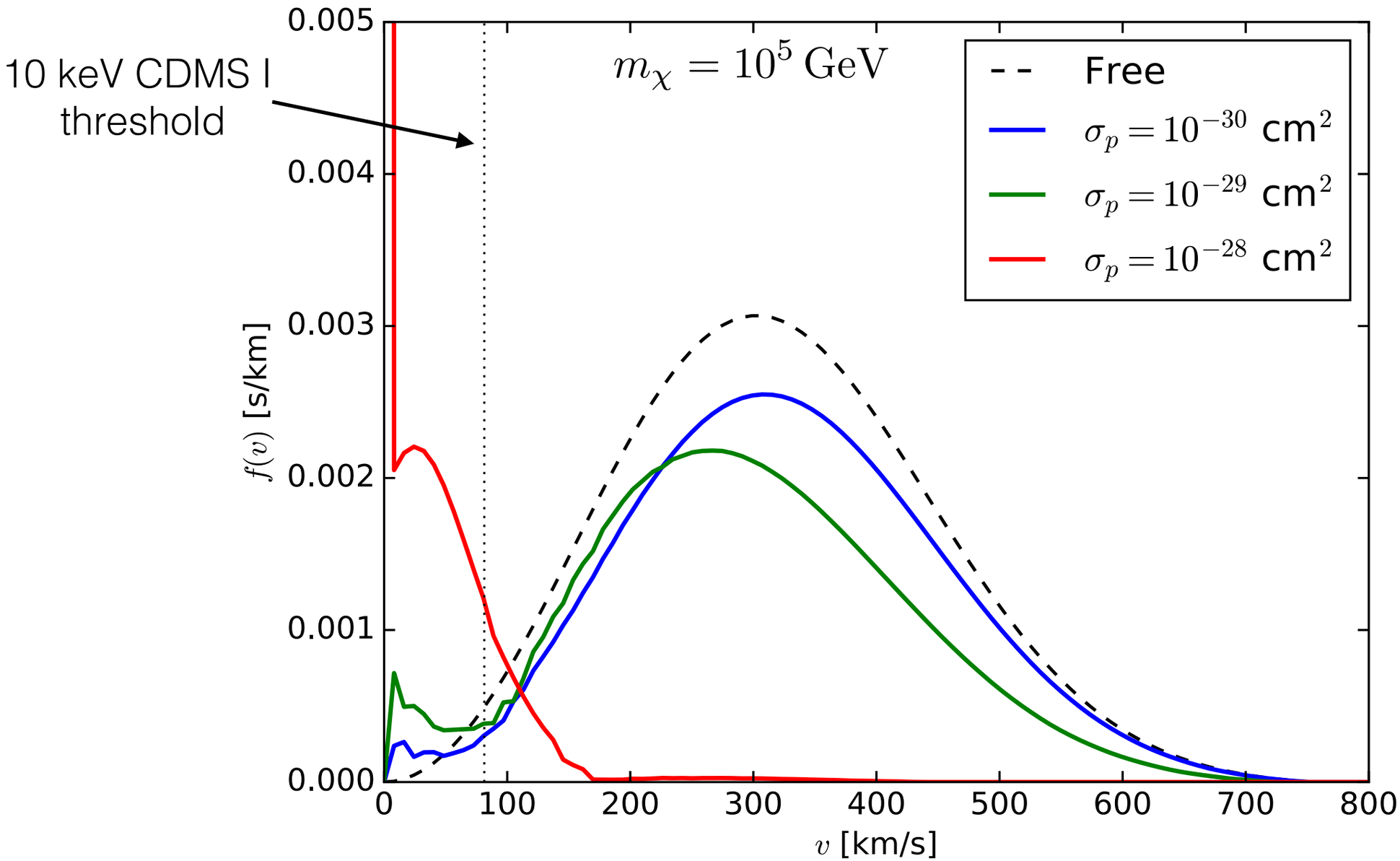
Consider a detector at a depth of 10.6m, with DM particles coming from directly overhead:

CDMS I at the Stanford Underground Facility [astro-ph/0203500]

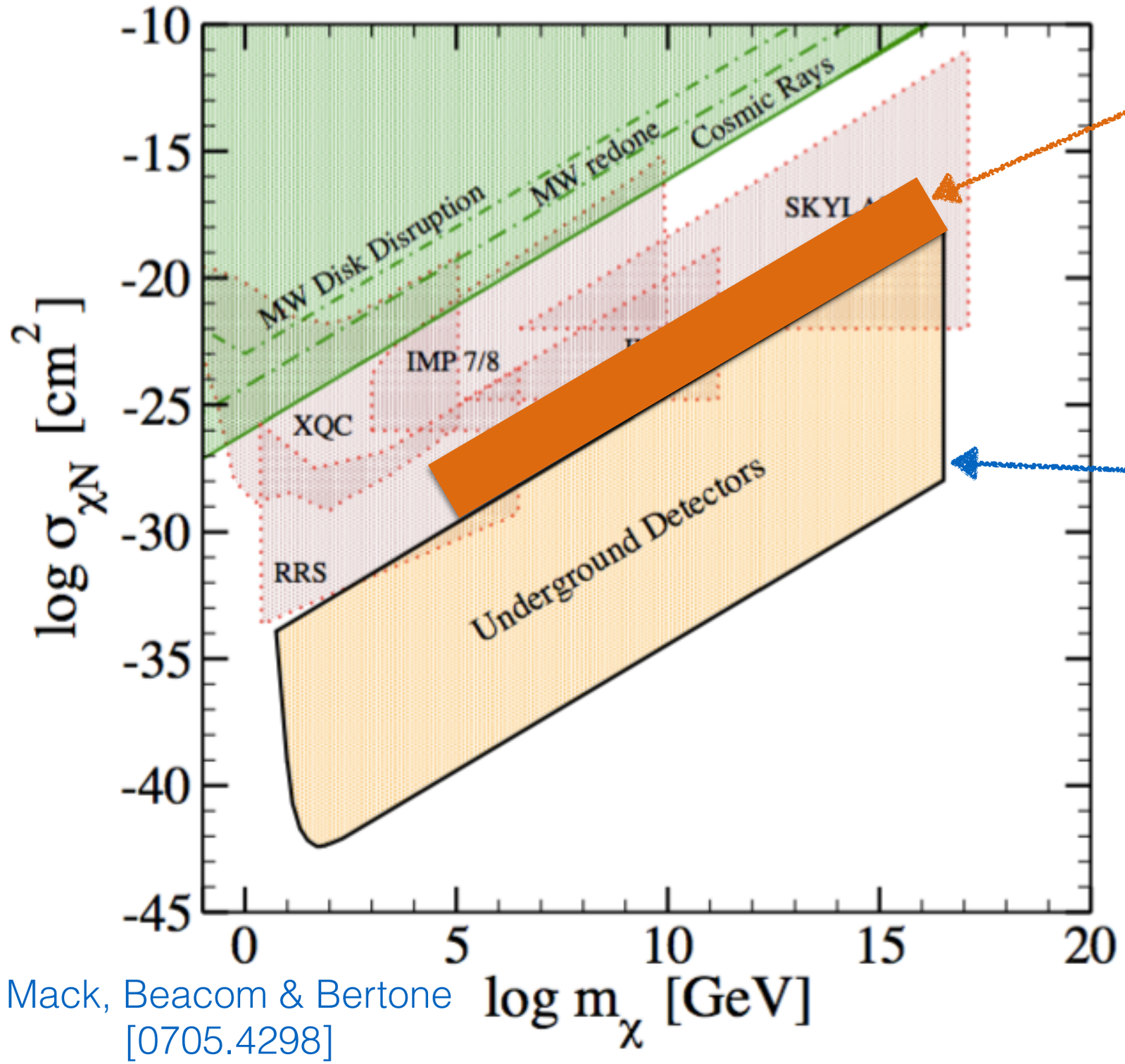


Speed Distribution

$$\tilde{f}(\mathbf{v}_f) = f_0(\mathbf{v}_i) \left(\frac{v_i}{v_f}\right)^2 \frac{\mathrm{d}v_i}{\mathrm{d}v_f}$$



Preliminary Results



Mack, Beacom & Bertone [0705.4298]

Possible gain of about 2 orders of magnitude in cross section

Albuquerque & Baudis [astro-ph/0301188]

Caveat:
Need to perform full rate calculation, taking into account time variation

Summary

Experiments are currently exploring the Earth-Scattering regime!
Need careful calculations + Monte Carlo to explore signatures

Sub-GeV DM:

Smoking gun modulation signature

May help us distinguish DM-nucleon interactions

Could allow us to measure local DM density

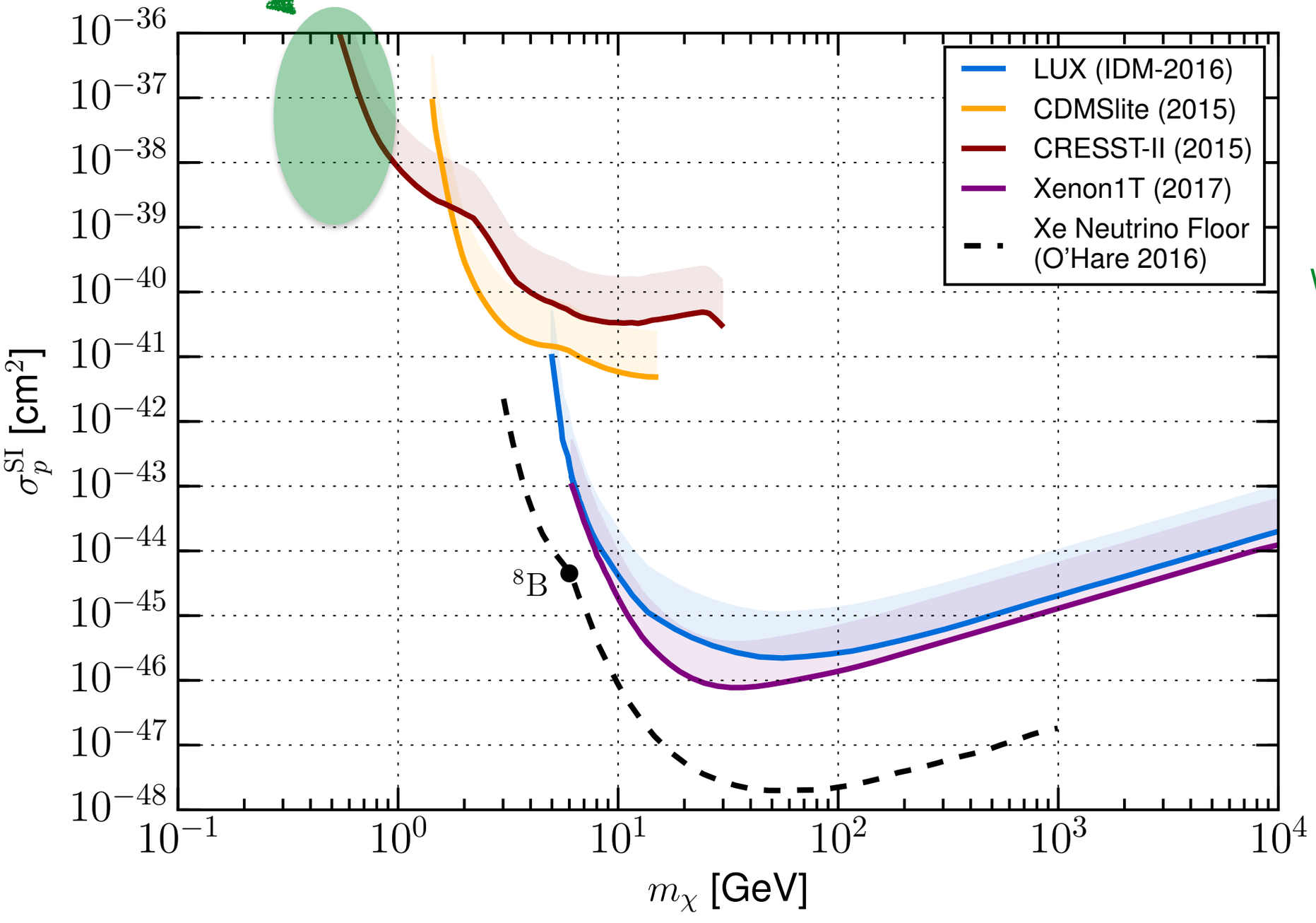
WIMPzillas:

Strongly interacting particles are *stopped*

Old experiments may actually rule out interesting parameter space

Direct Detection Landscape

Sub-GeV DM



WIMPzillas

Interesting parts of the landscape where Earth-scattering soon to be explored…