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

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Based (partly) on arXiv:1611.05453
with Riccardo Catena and Chris Kouvaris

AmsterDark@GRAPPA - 24th May 2017

ERC NewDark
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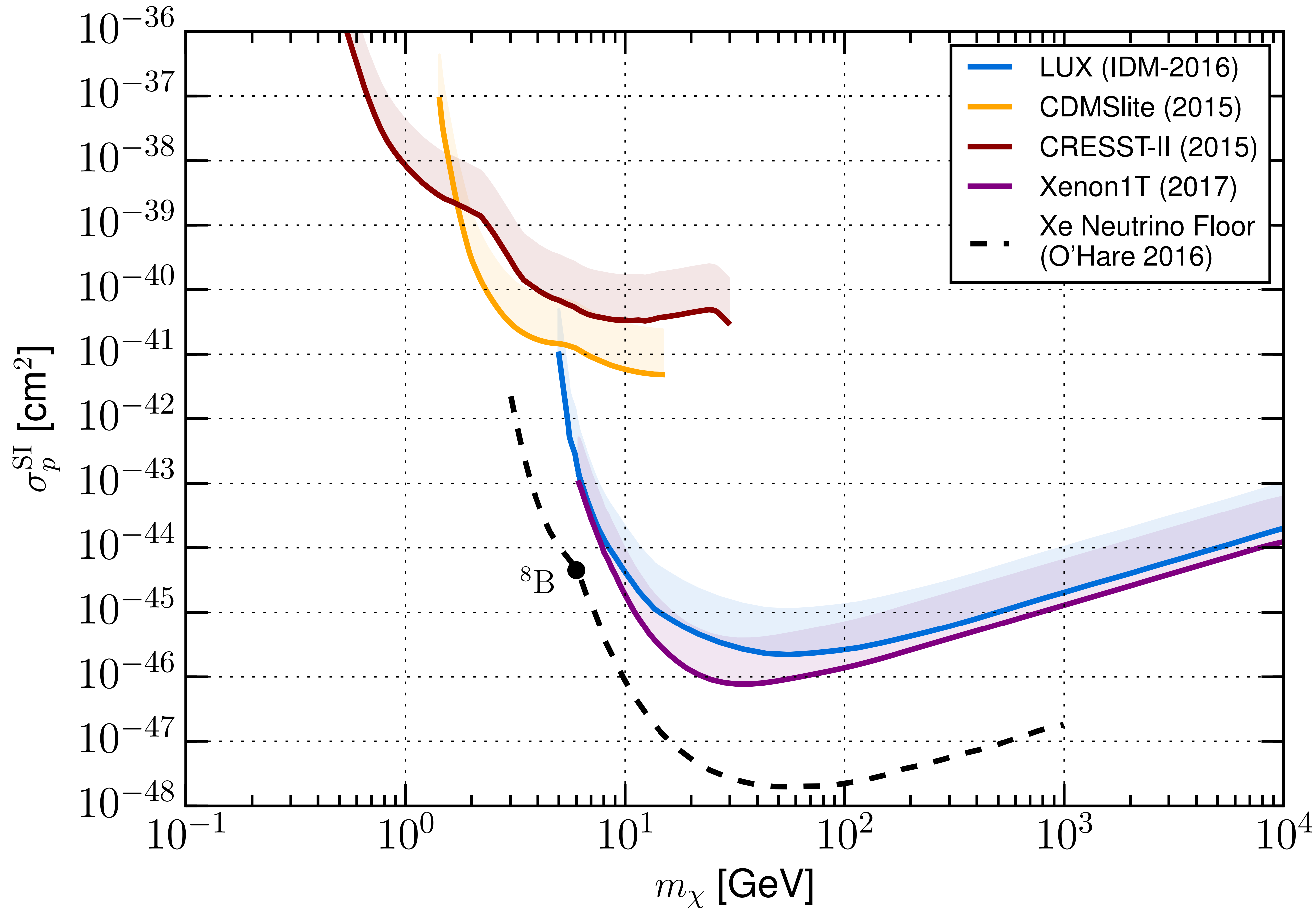
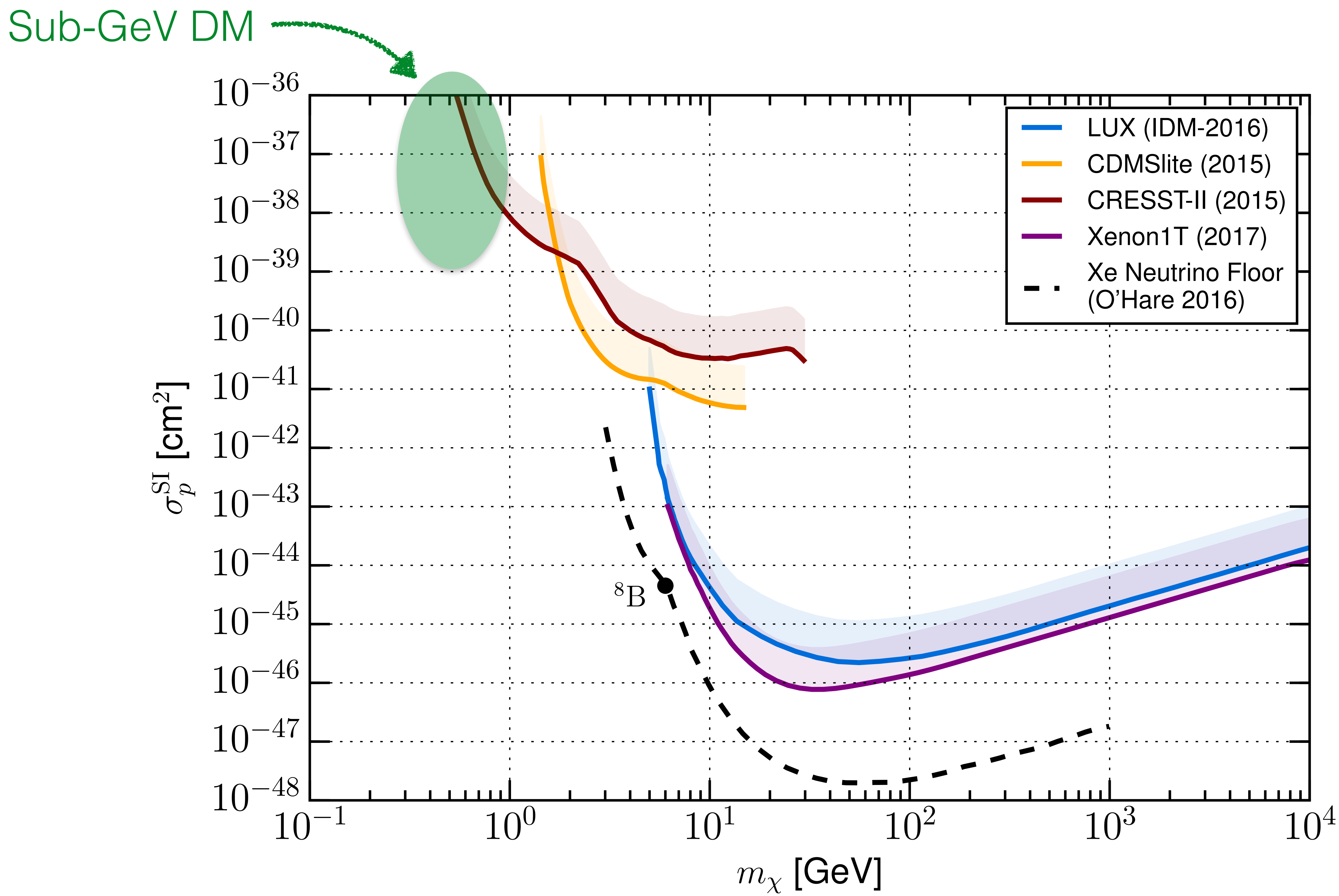
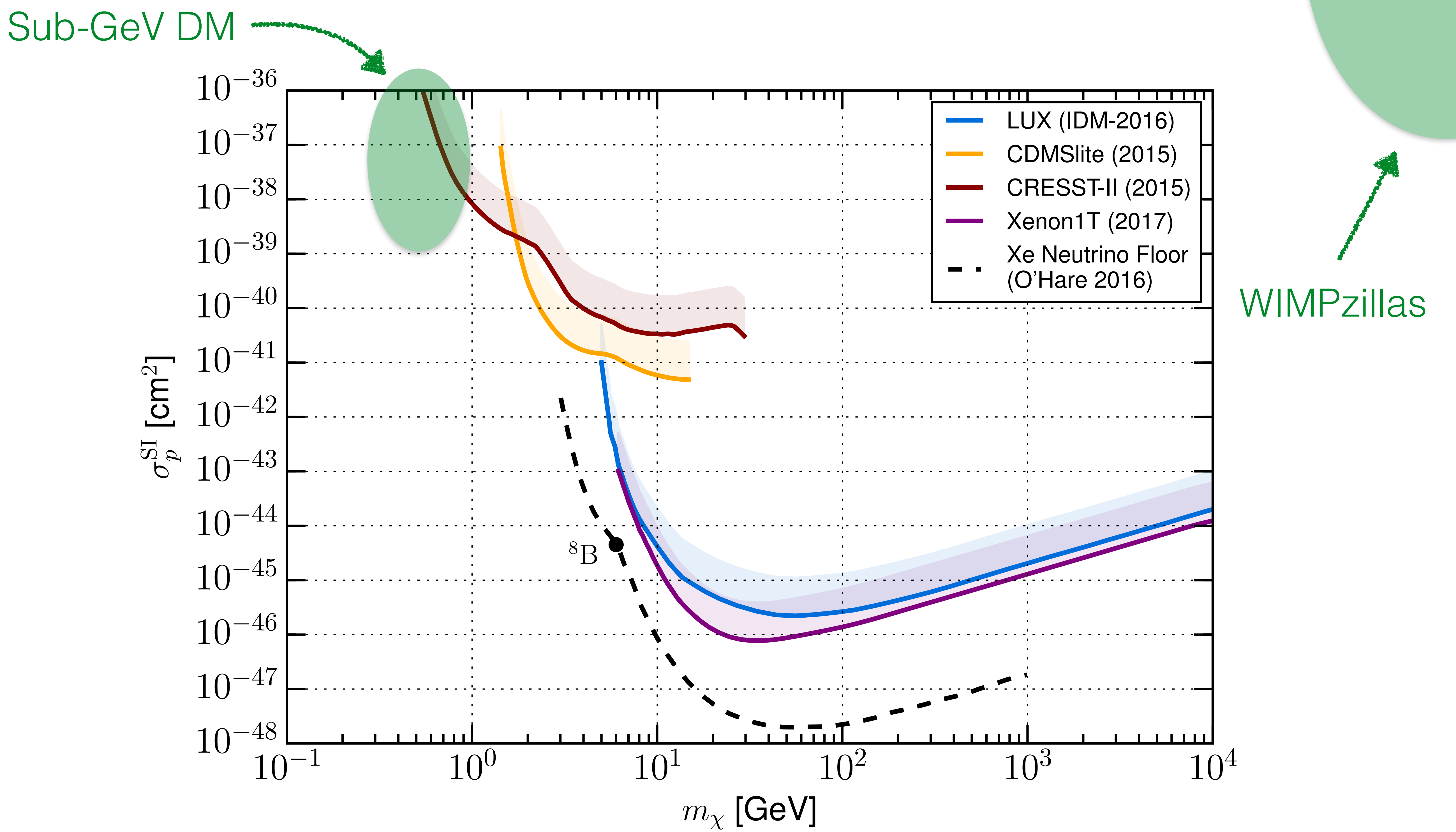
Direct Detection Landscape



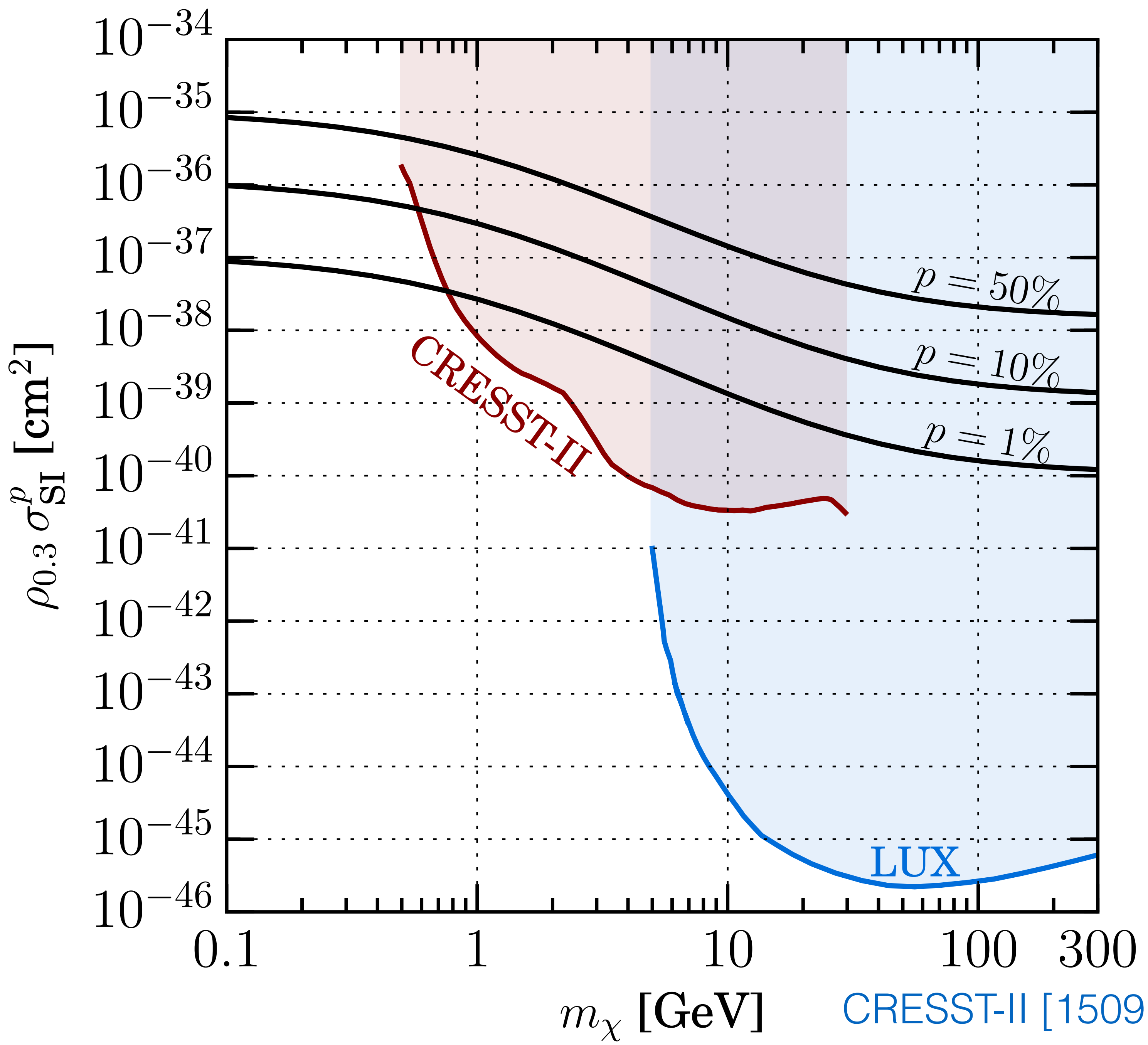
Direct Detection Landscape



Direct Detection Landscape



DD Landscape - Sub-GeV DM



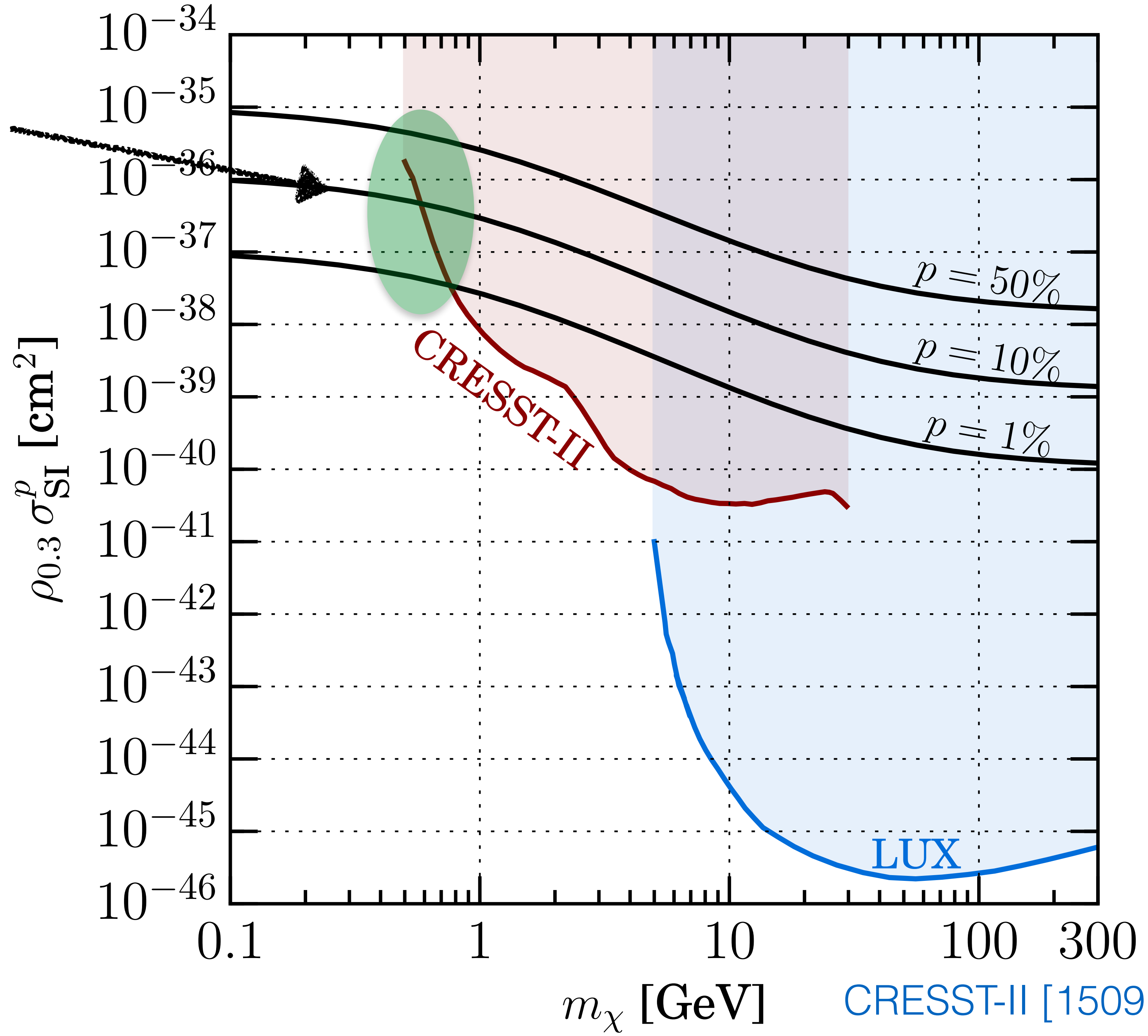
CRESST-II [1509.01515]

LUX [1608.07648]

+ many others…

DD Landscape - Sub-GeV DM

Focus on this region

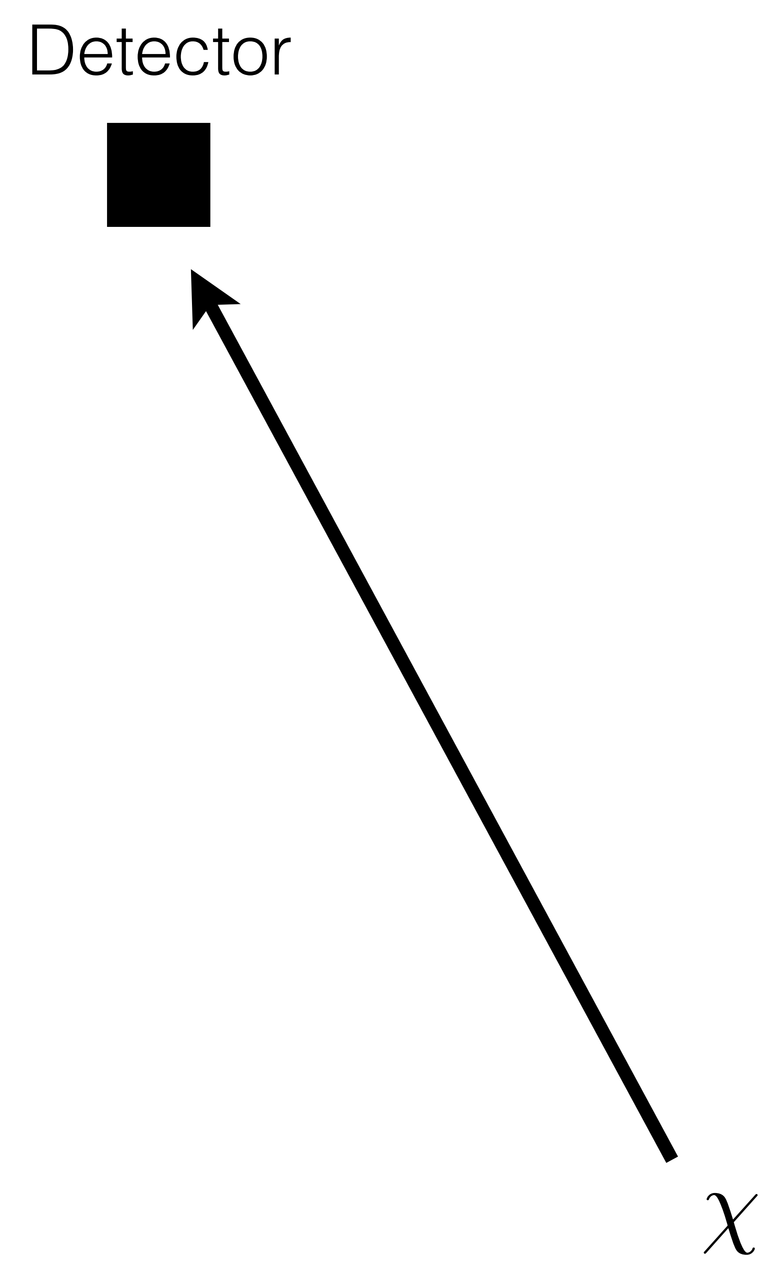


CRESST-II [1509.01515]

LUX [1608.07648]

+ many others…

Direct Detection of DM (in space?)



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

Astrophysics of DM (the simple picture)

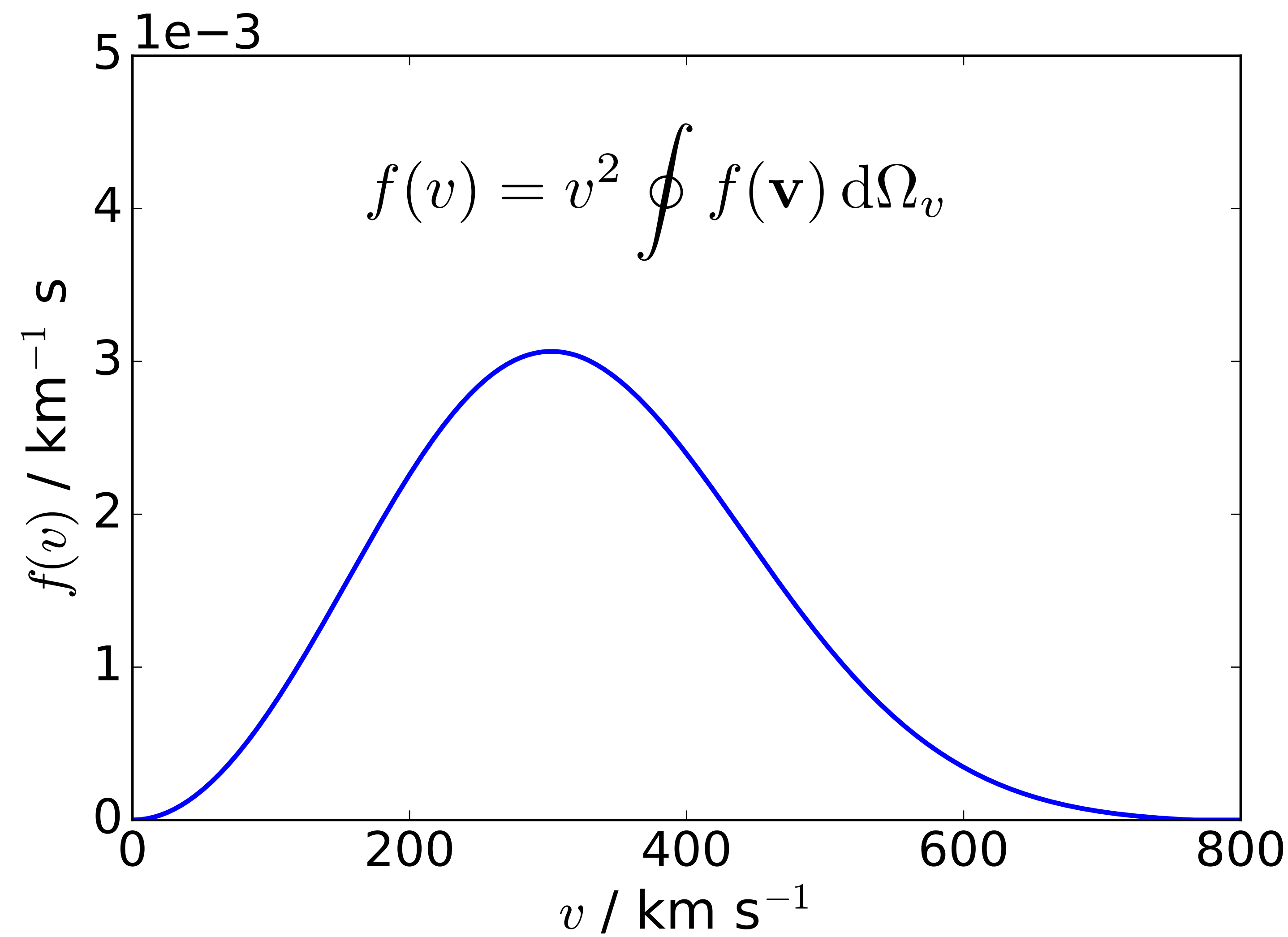
Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

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

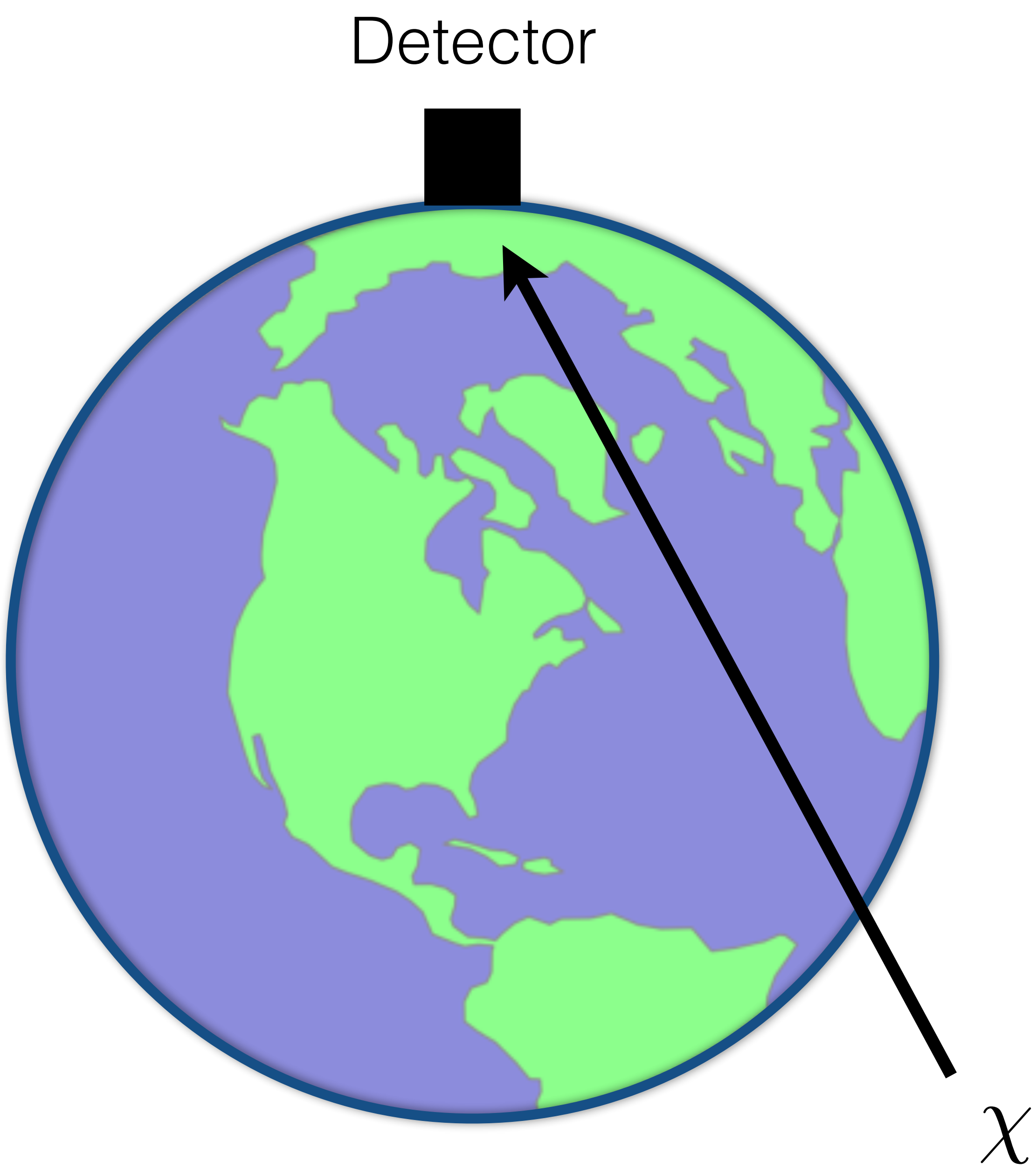
$$f_{\mathrm{Lab}}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_\mathrm{e})^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v}-\mathbf{v}_\mathrm{e}| - v_\mathrm{esc})$$

[But see e.g. 1705.05853]

This is our 'free' distribution: $f_0(v)$



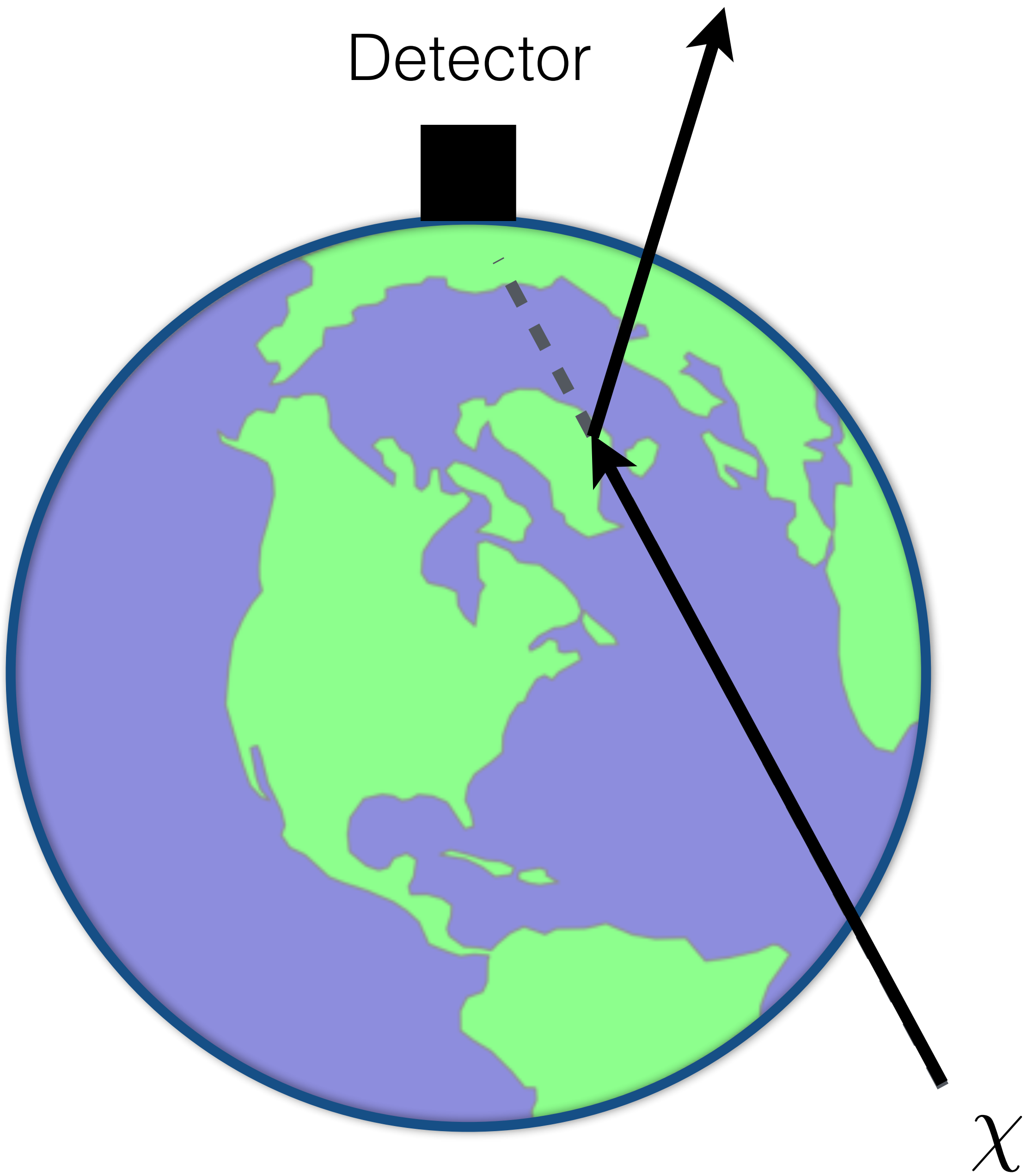
Direct Detection of DM on Earth



But DM scattering in the Earth can distort the velocity distribution

→ Perturbed/scattered DM: $\tilde{f}(\mathbf{v})$

Earth-Scattering - Attenuation



Previous calculations usually only consider DM attenuation

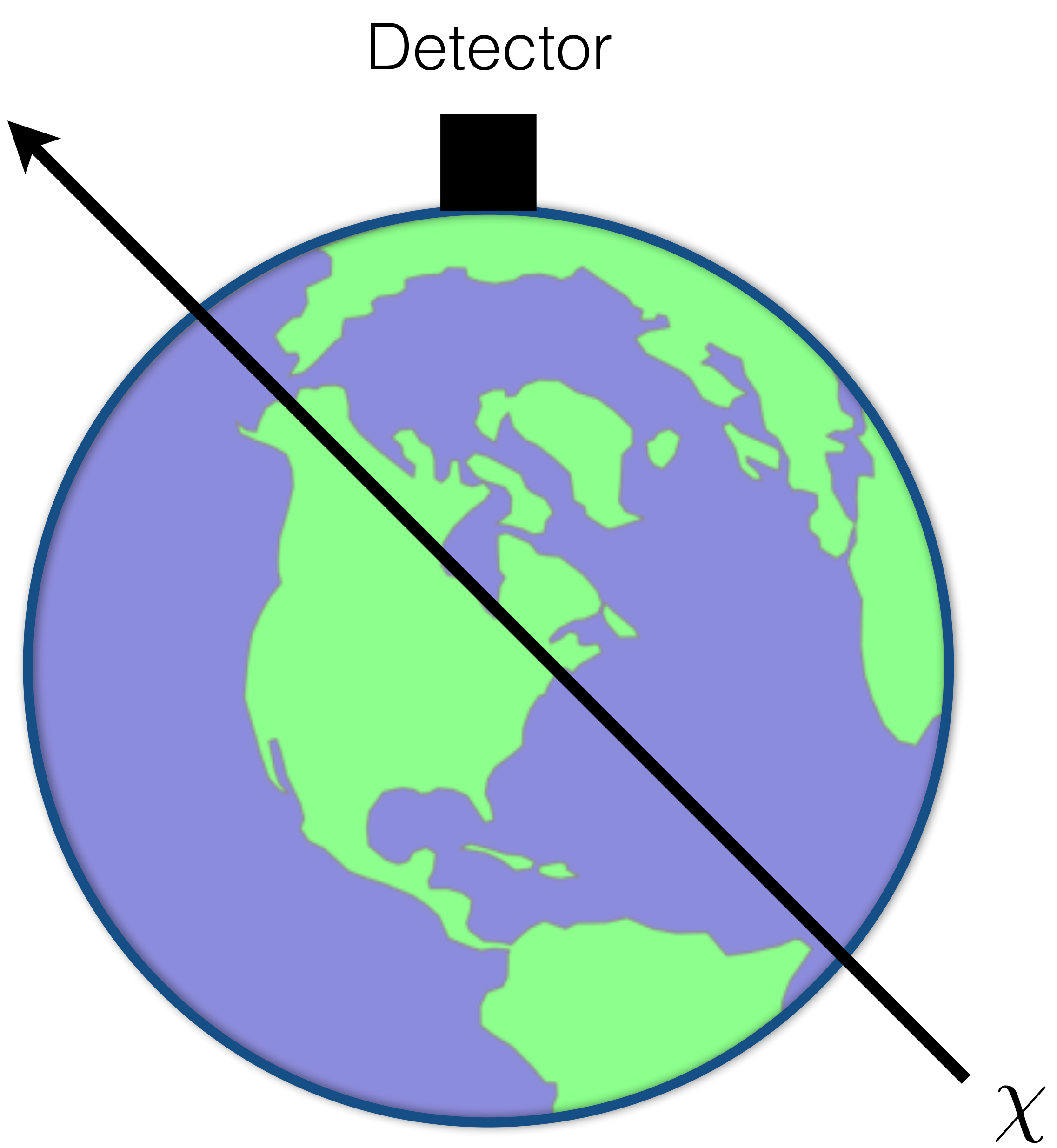
Zaharijas & Farrar [astro-ph/0406531]

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



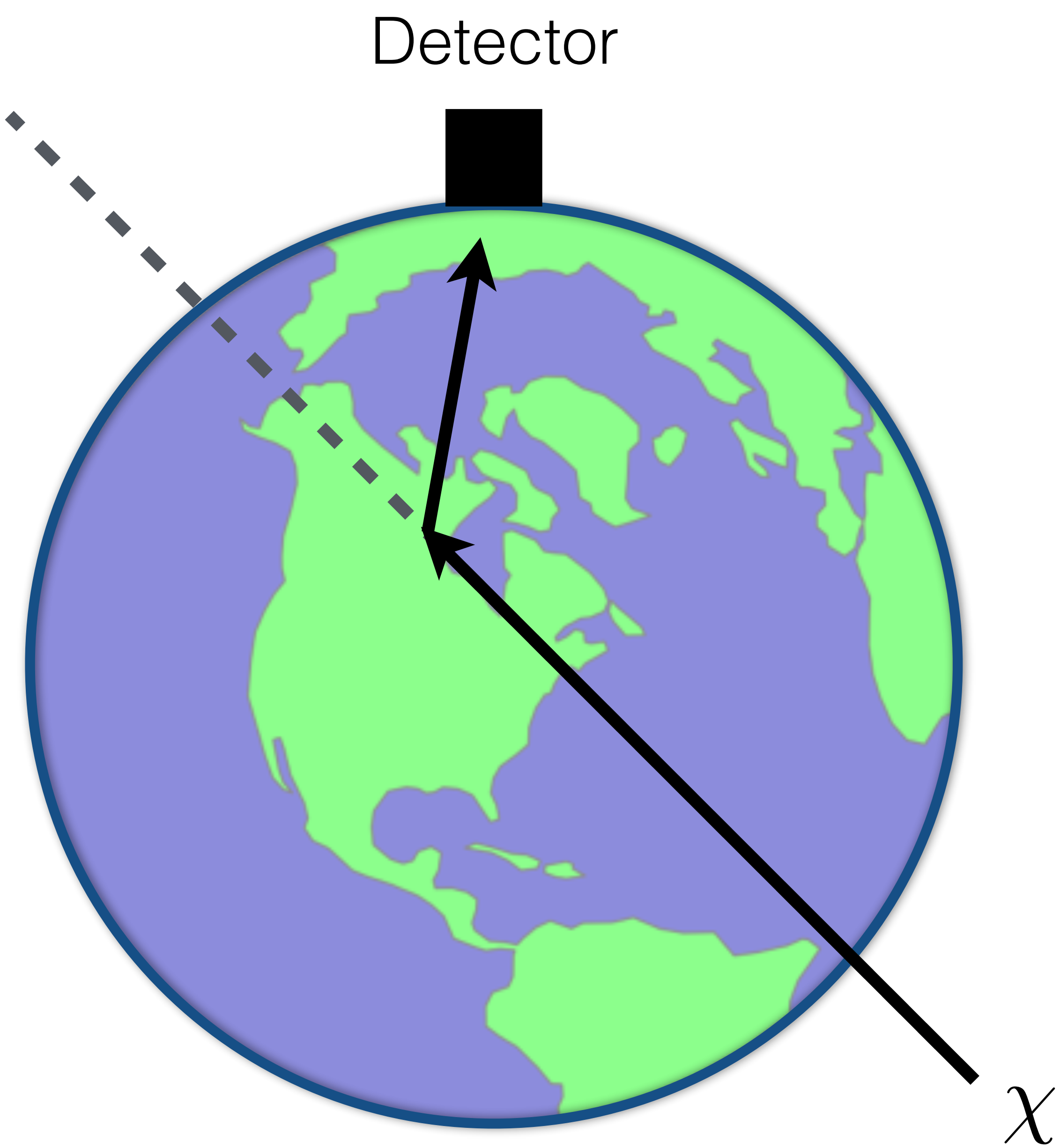
Earth-Scattering - Deflection

Considered in early Monte Carlo simulations…

Collar & Avignone [PLB 275, 1992 and others]

As well as more recent ones…

Emken, Kouvaris & Shoemaker [1702.07750] (see later)



Assuming DM mean free path

$$\lambda \gtrsim R_E$$

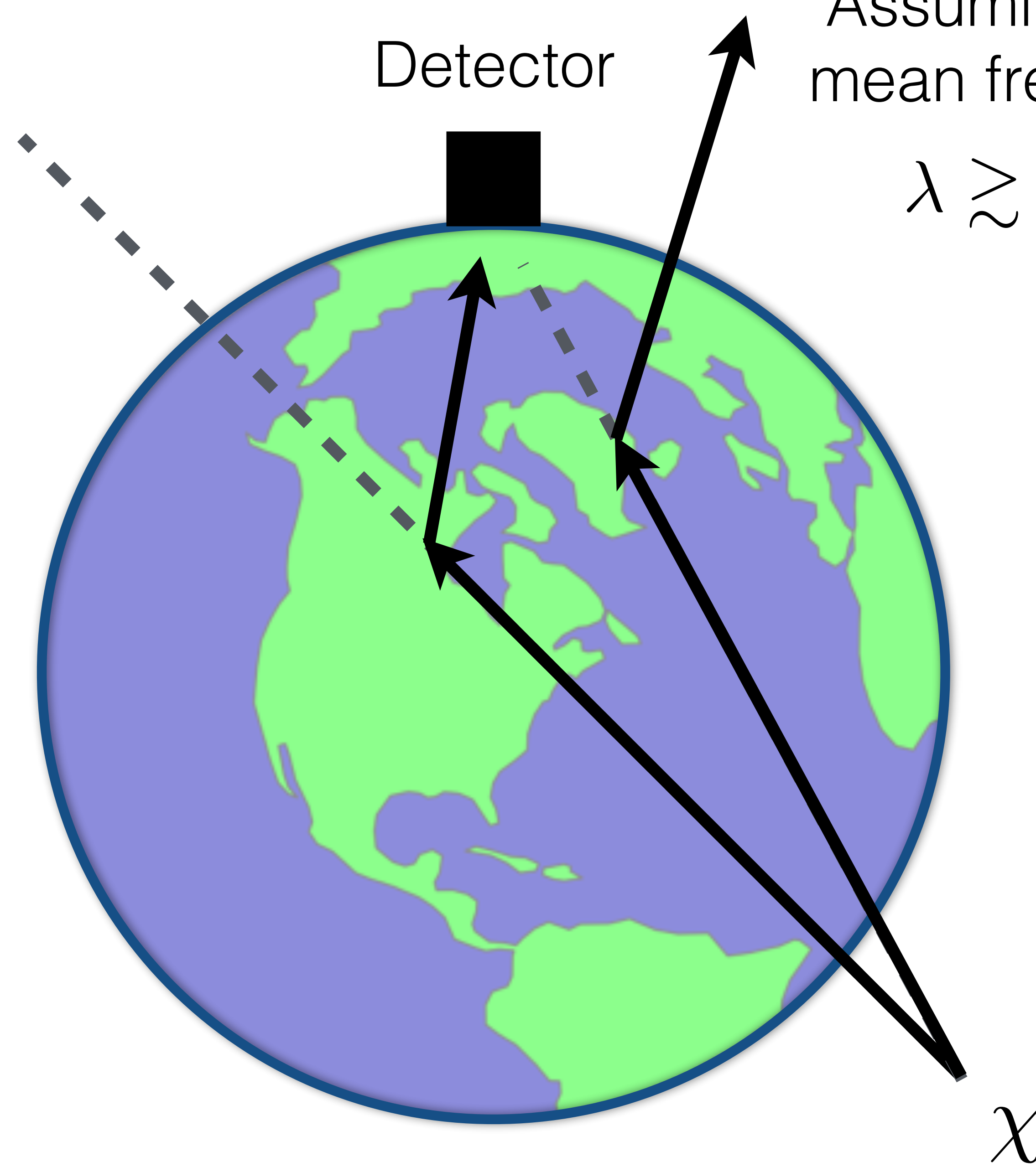
Can be very important for light DM.

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)



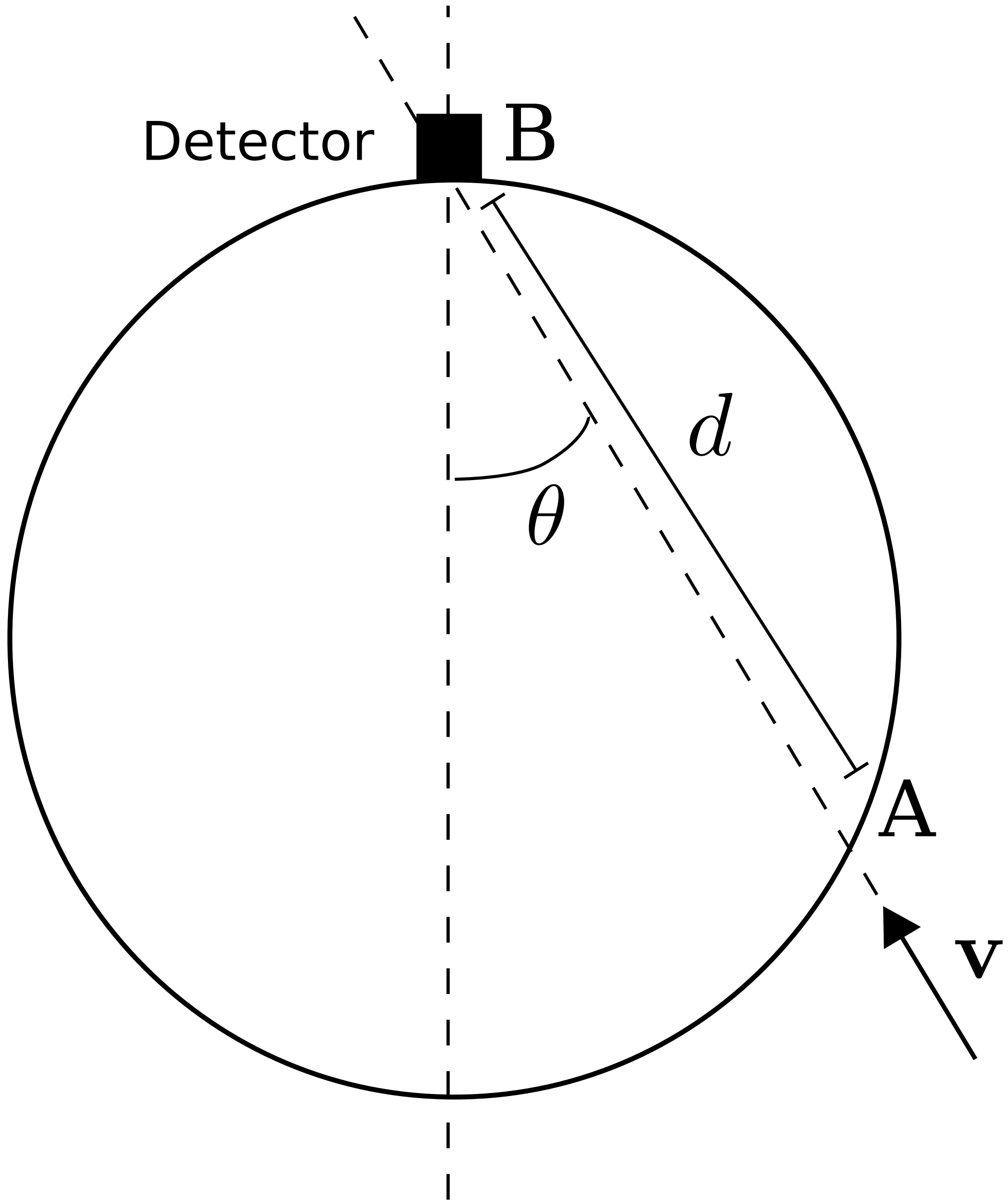
Total DM velocity distribution: $\tilde{f}(\mathbf{v}) = f_0(\mathbf{v}) - f_A(\mathbf{v}) + f_D(\mathbf{v})$

→ altered flux, daily modulation, directionality…

Attenuation

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

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



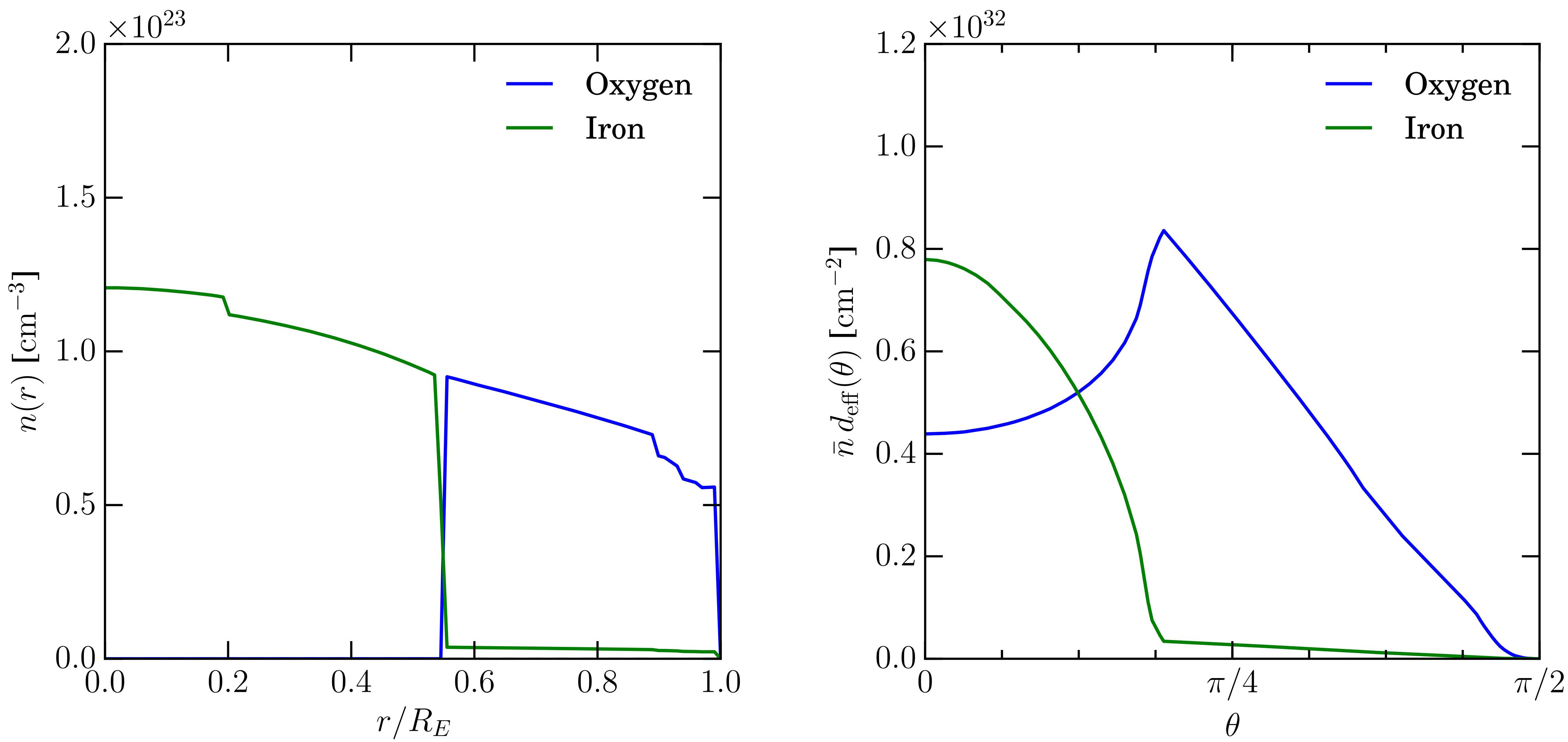
$$d_{\mathrm{eff},i} = \frac{1}{\bar{n}_i}\int_{\mathrm{AB}} n_i(\mathbf{r})\mathrm{d}l$$

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

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)

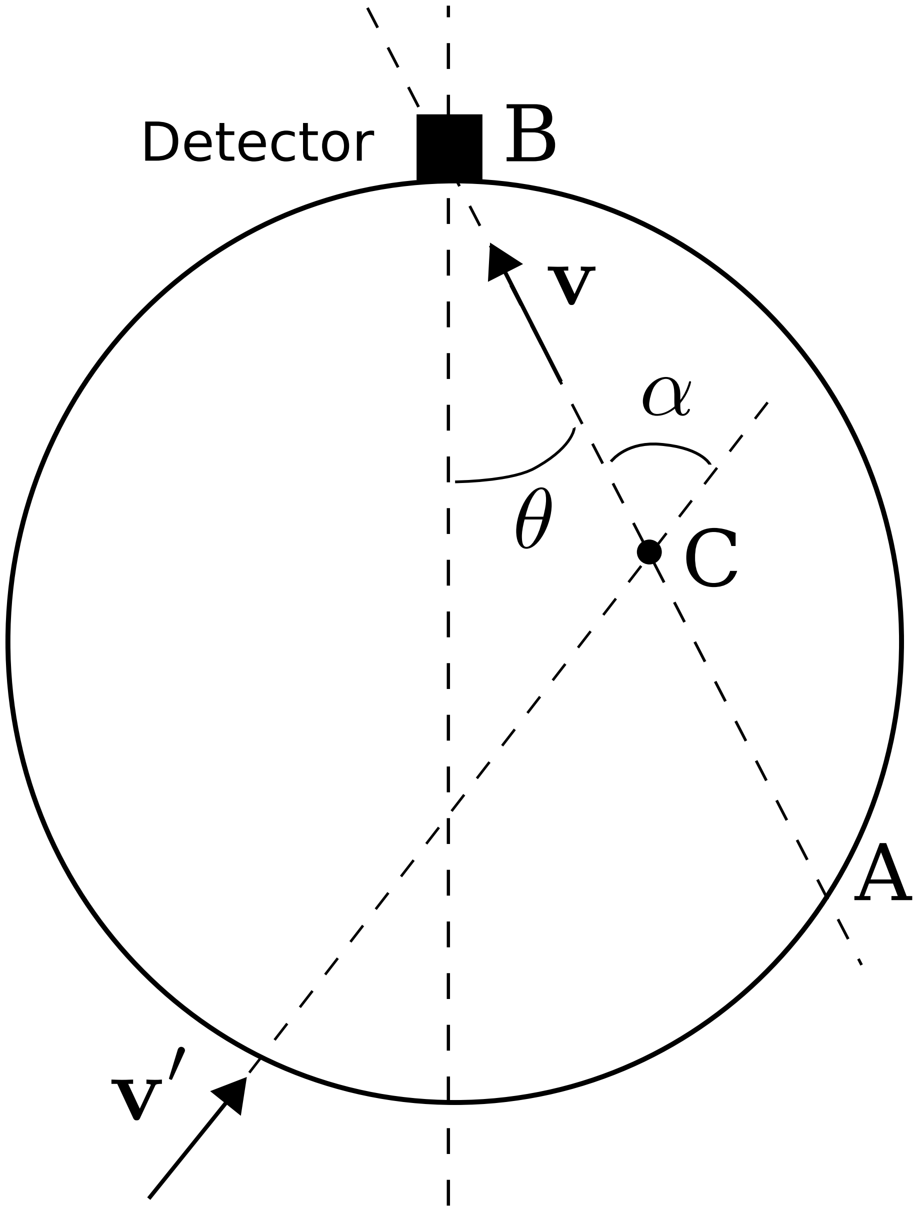


NB: little Earth-scattering for spin-dependent interactions

Deflection

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

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



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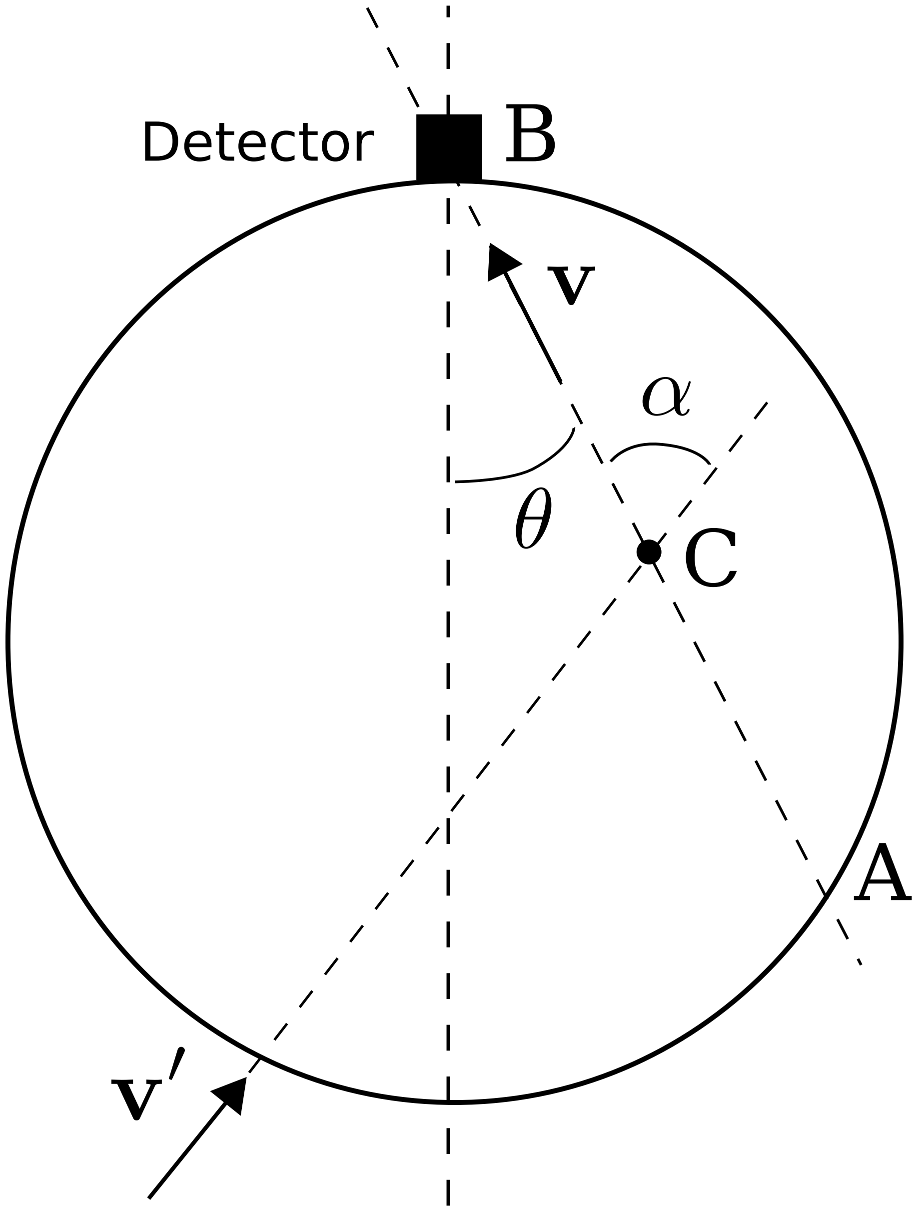


$$f_D(\mathbf{v}) = \sum_i^{\mathrm{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \; \frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)} \frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

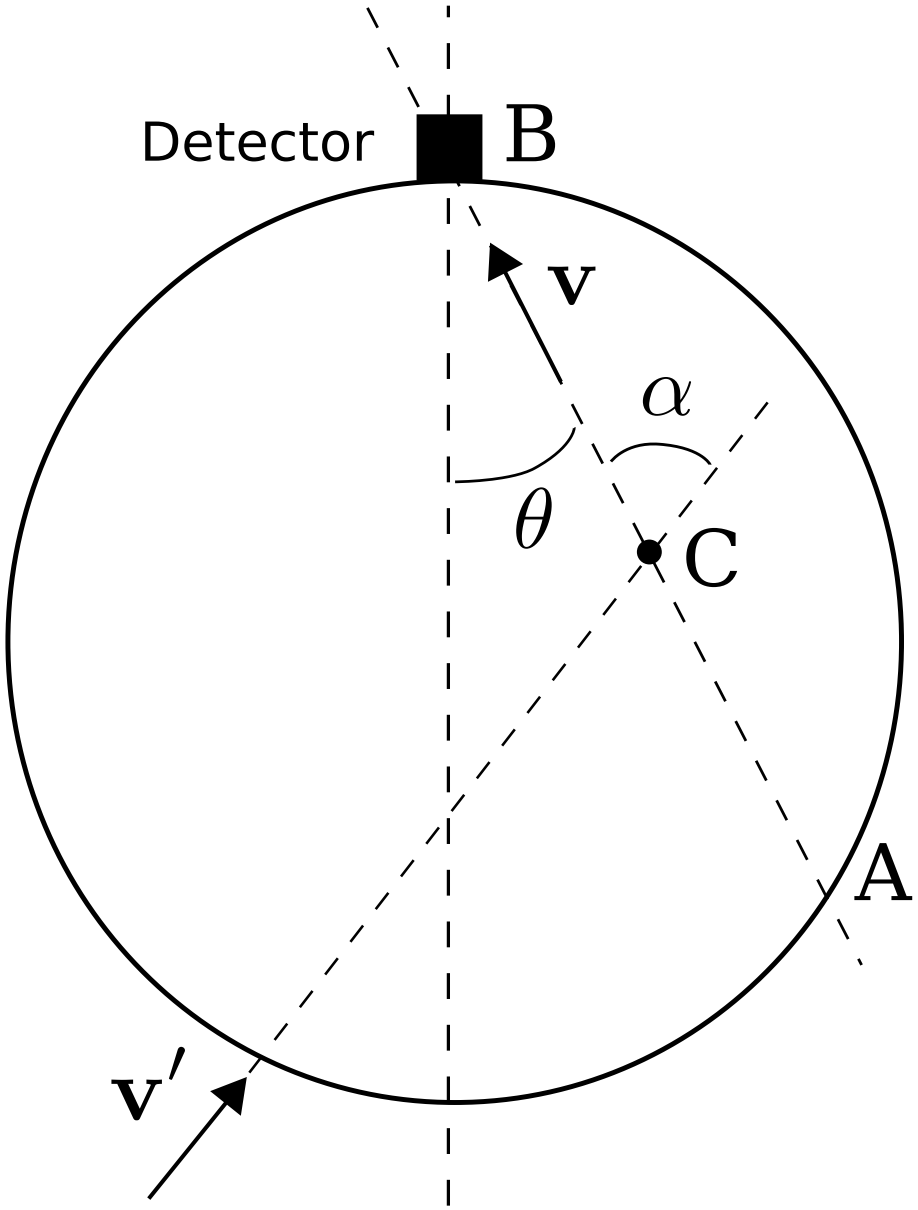
[Detailed calculation in the paper]

$$\kappa_i = v'/v$$

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

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

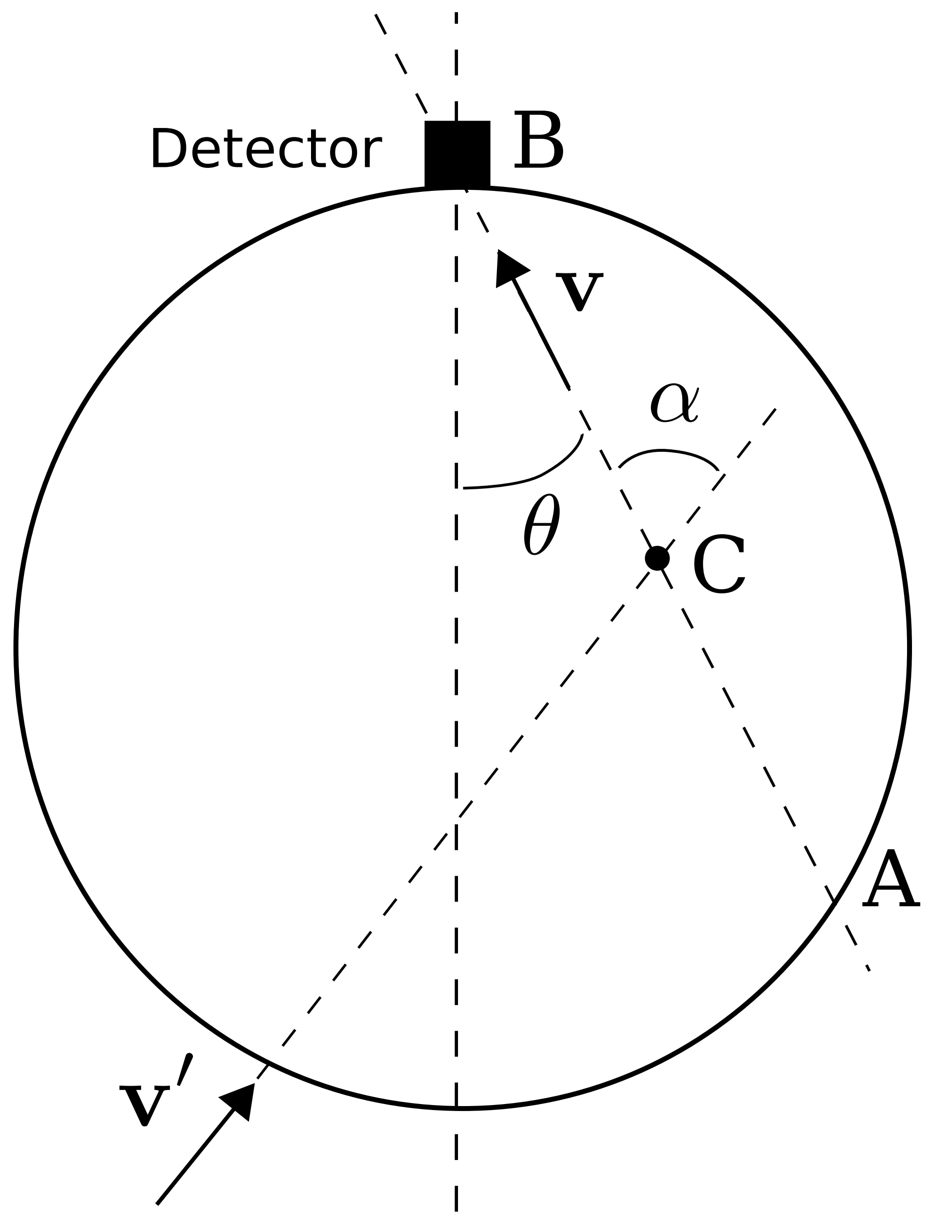
Depends on total cross section

$$\kappa_i = v'/v$$

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

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

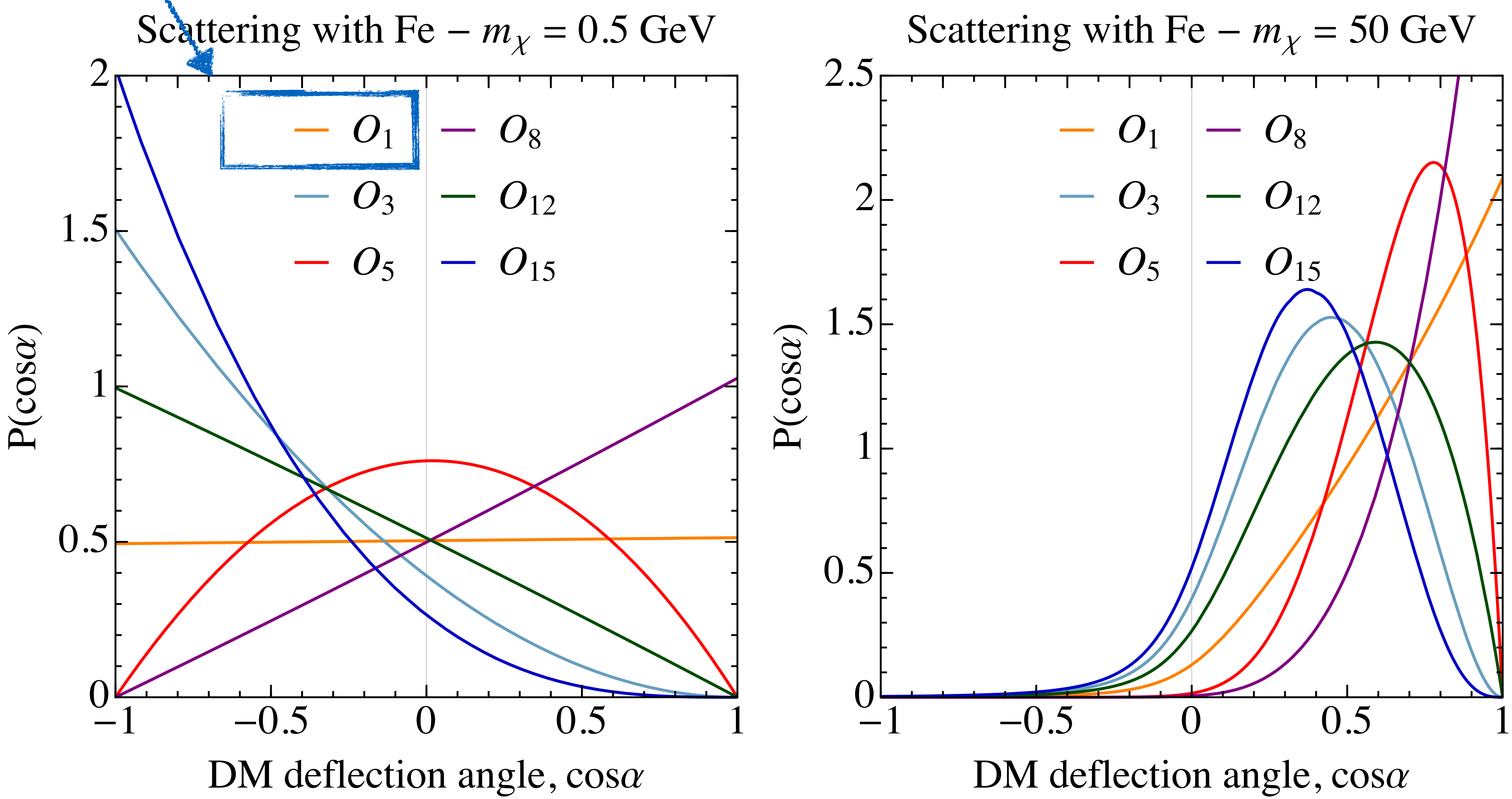
Depends on total cross section

$$\kappa_i = v'/v$$

DM deflection distribution

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

Standard SI interaction



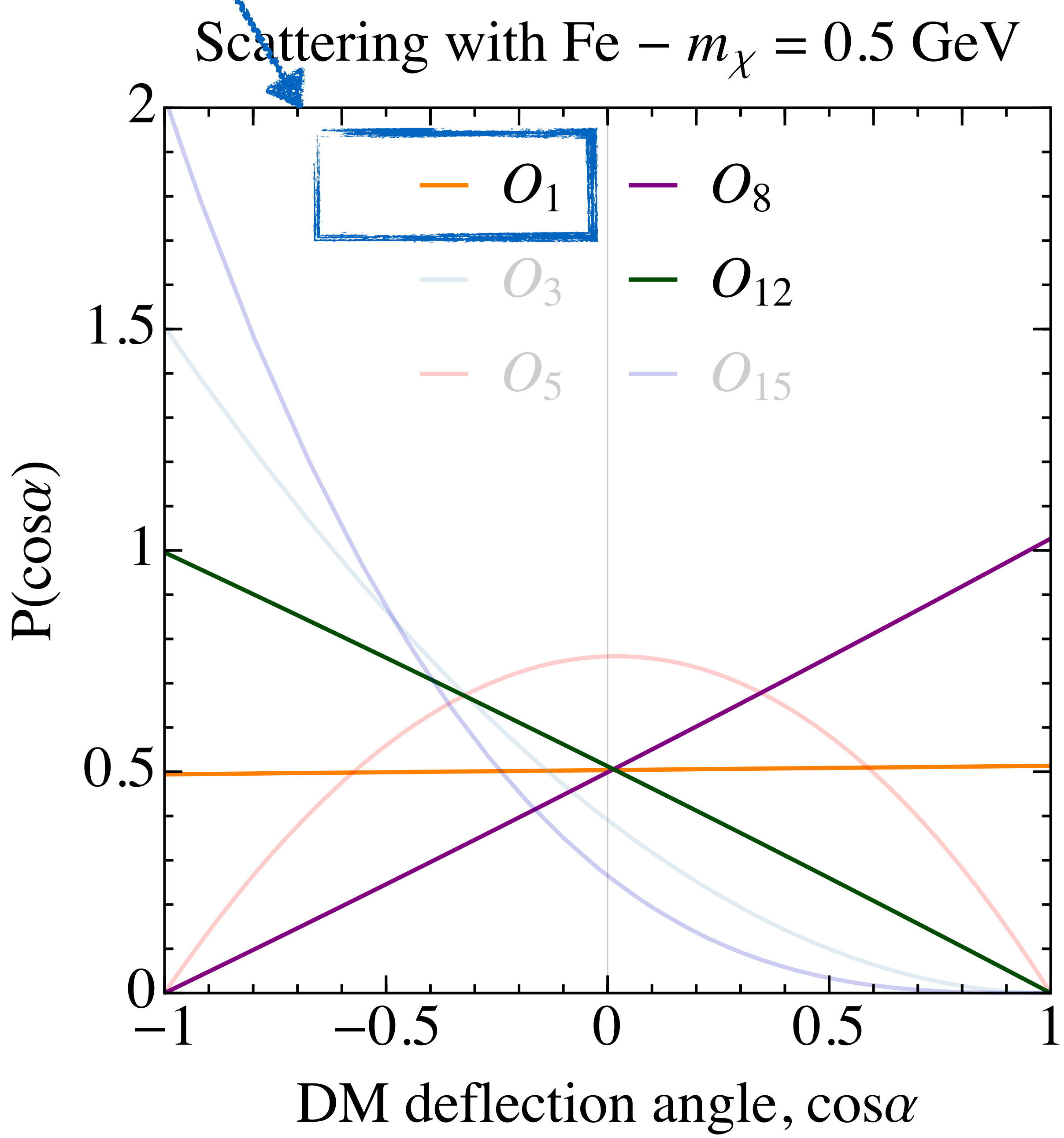
Backward

Forward

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

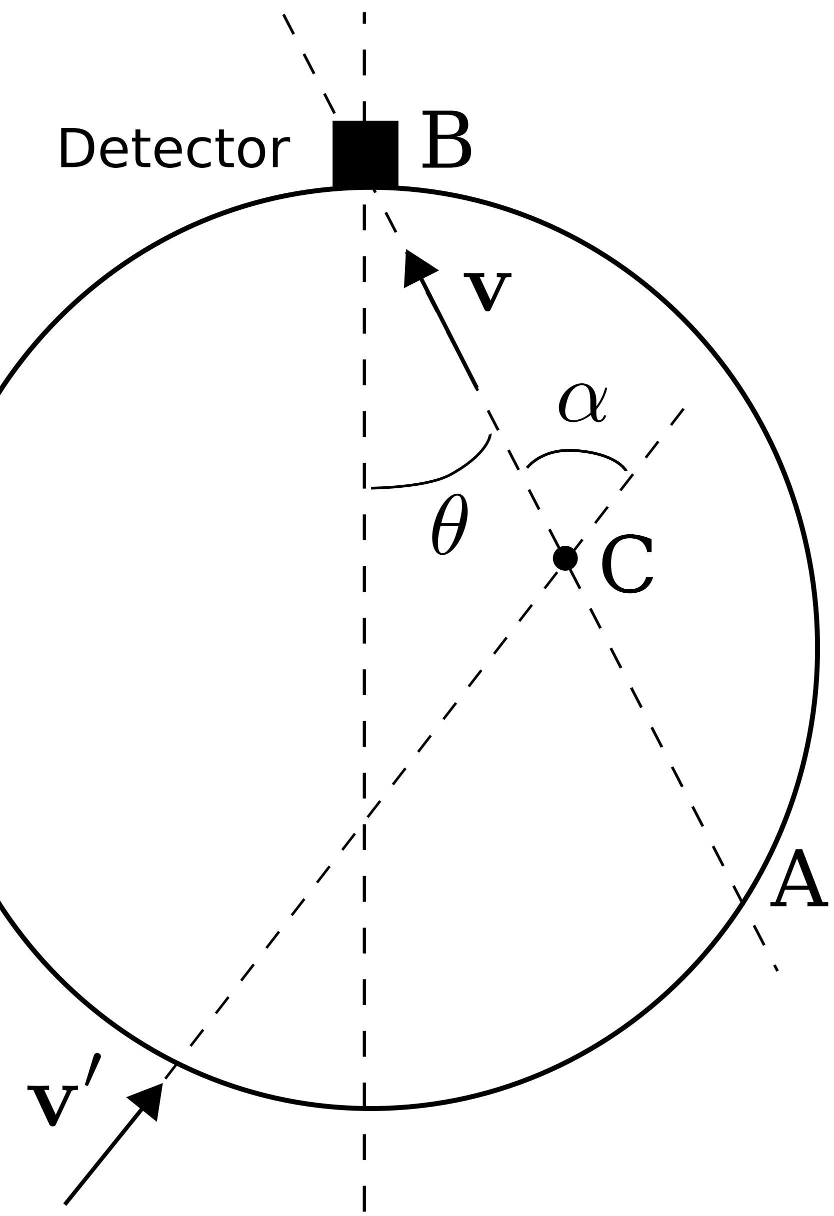
$$\mathcal{O}_1 = \mathbb{1} \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim \frac{1}{v^2}$$

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

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

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!

Depends on differential cross section

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

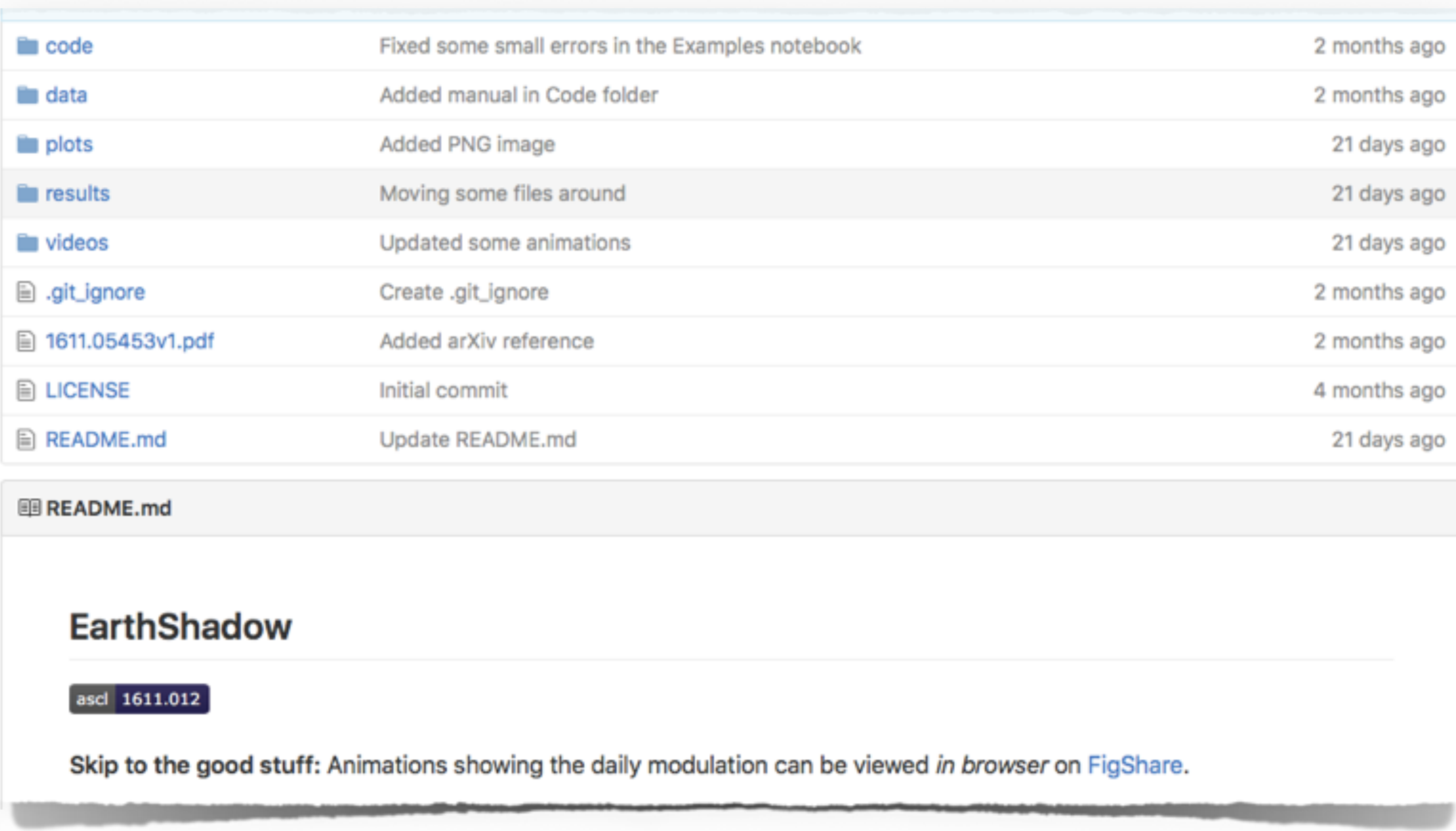
Depends on total cross section

$$\kappa_i = v'/v$$

EARTHSHADOW Code

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

Including routines, numerical results, plots and animations…



code	Fixed some small errors in the Examples notebook	2 months ago
data	Added manual in Code folder	2 months ago
plots	Added PNG image	21 days ago
results	Moving some files around	21 days ago
videos	Updated some animations	21 days ago
.git_ignore	Create .git_ignore	2 months ago
1611.05453v1.pdf	Added arXiv reference	2 months ago
LICENSE	Initial commit	4 months ago
README.md	Update README.md	21 days ago

README.md

EarthShadow

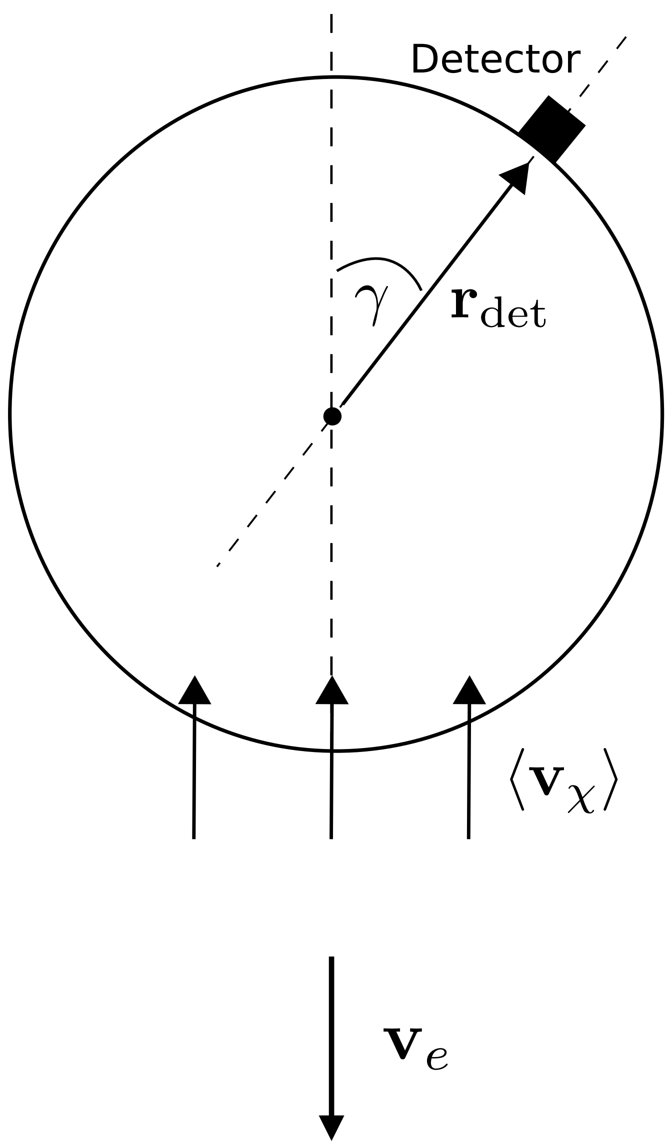
ascl 1611.012

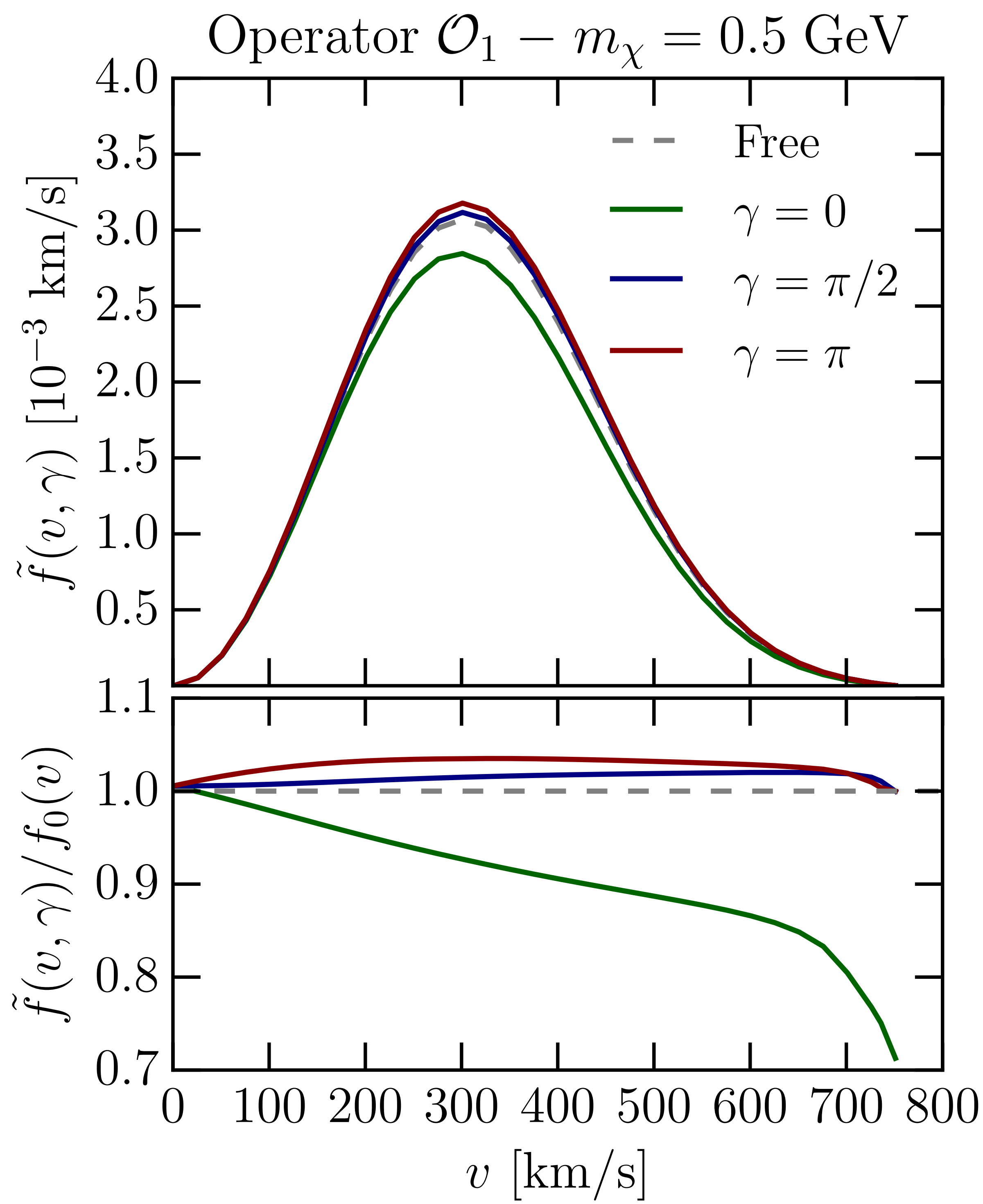
Skip to the good stuff: Animations showing the daily modulation can be viewed *in browser* on FigShare.

Results

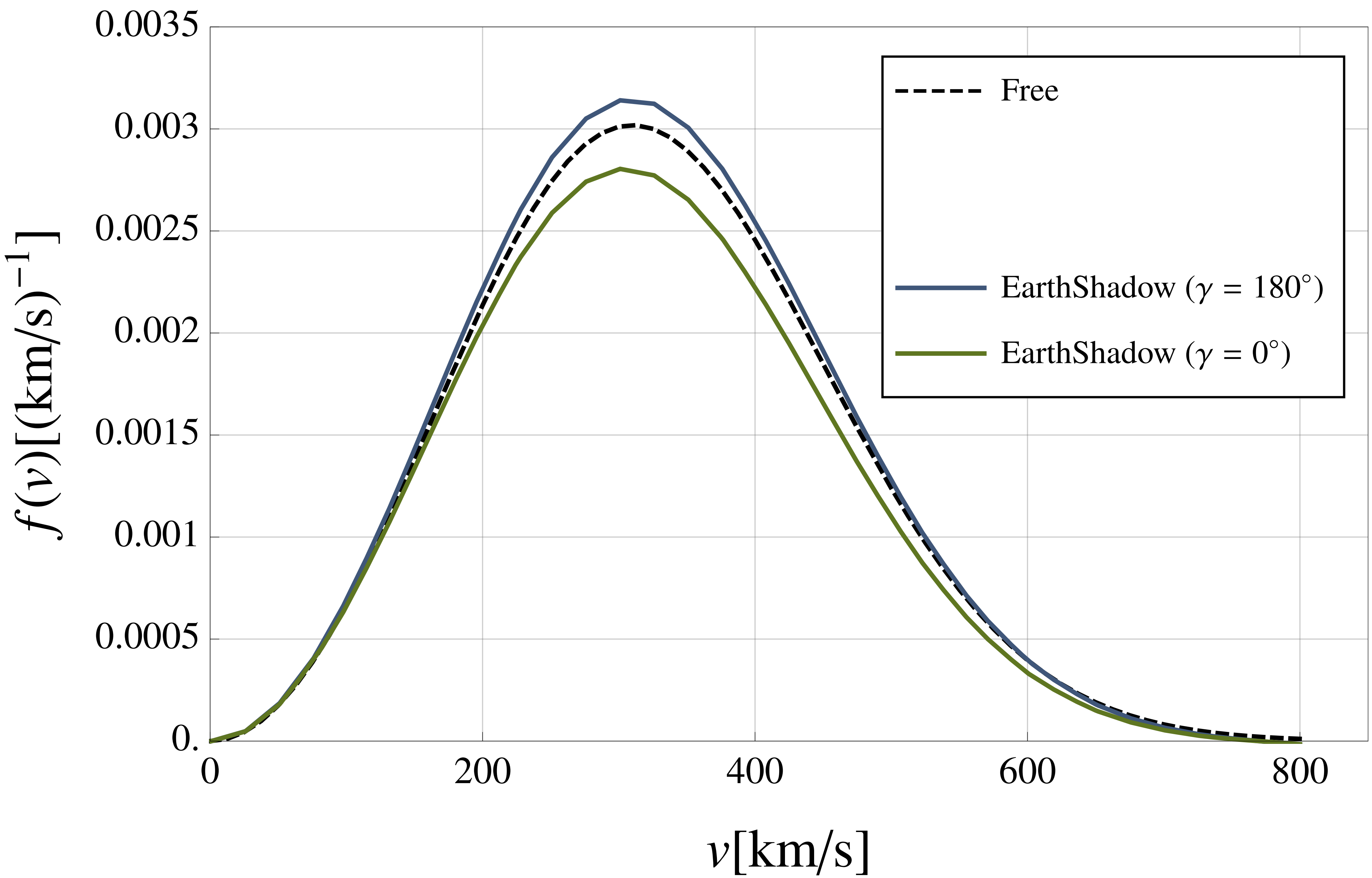
Speed Distribution - Operator 1

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





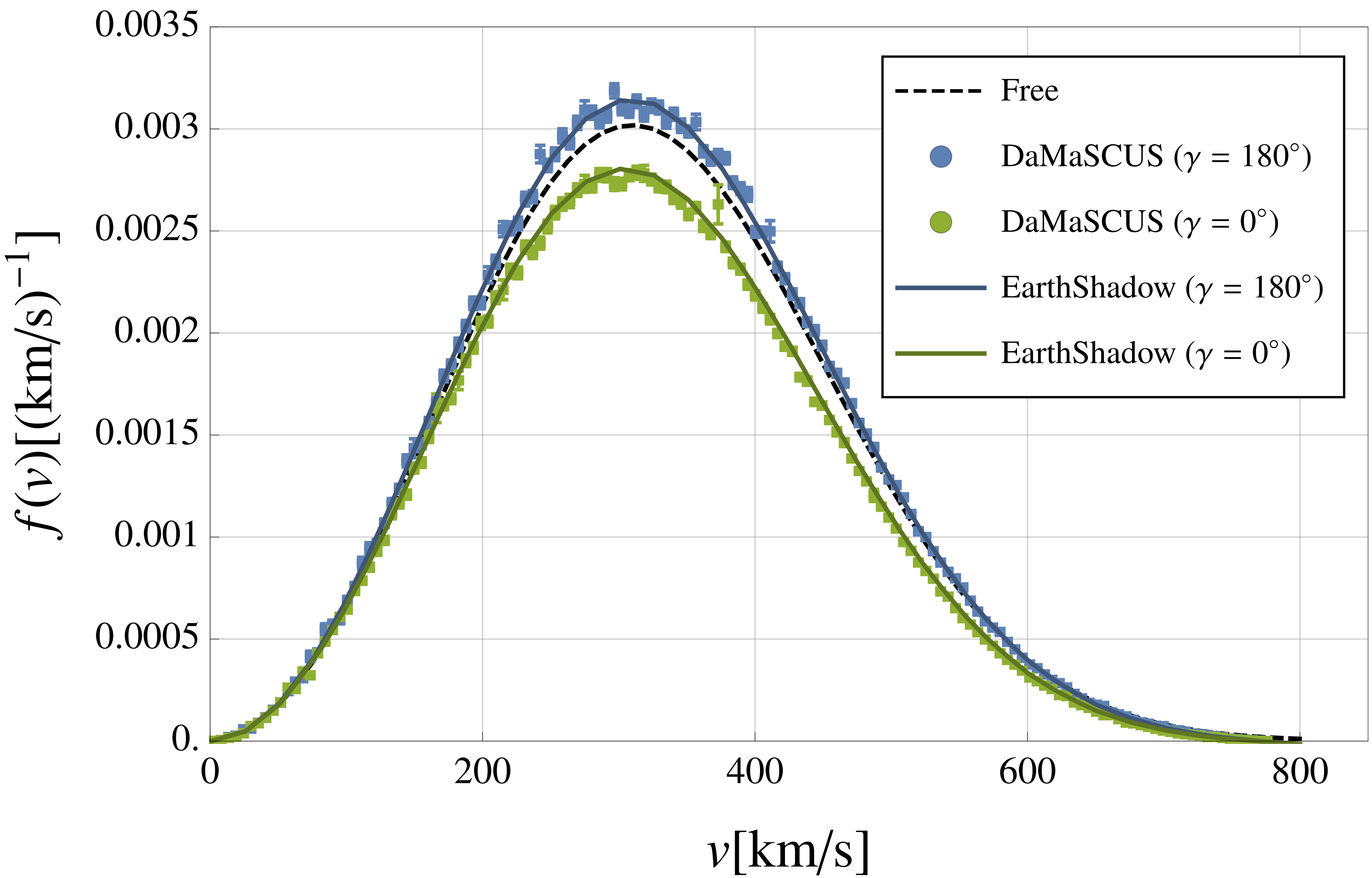
Comparison with Monte-Carlo



Monte-Carlo results from the DaMaSCUS code

[Emken & Kouvaris - paper appearing soon]
http://cp3-origins.dk/site/damascus

Comparison with Monte-Carlo



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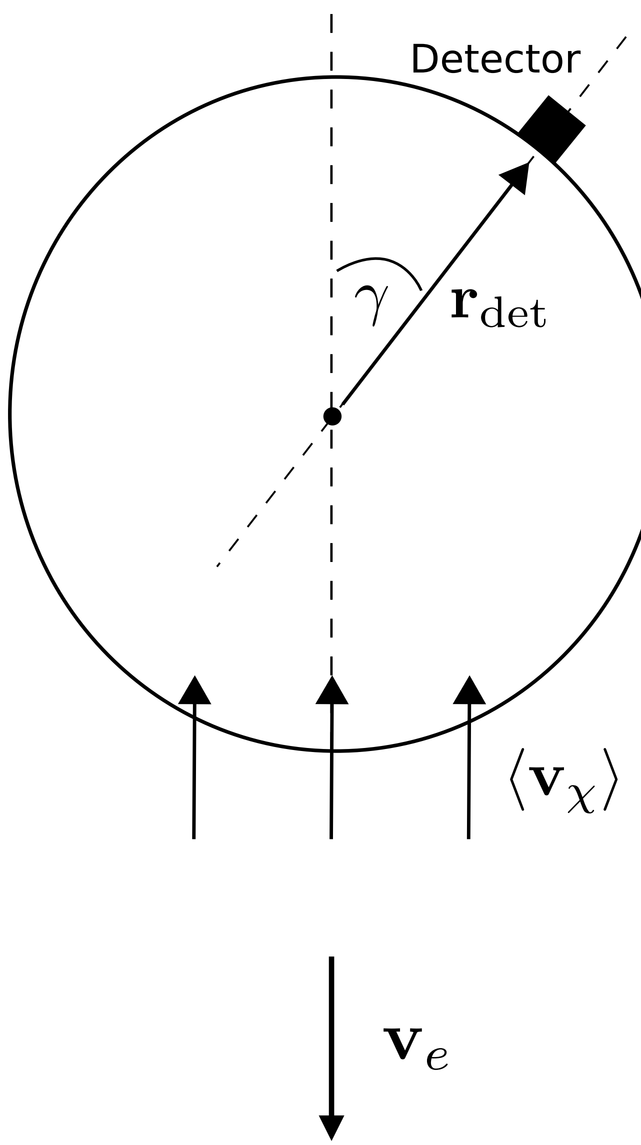
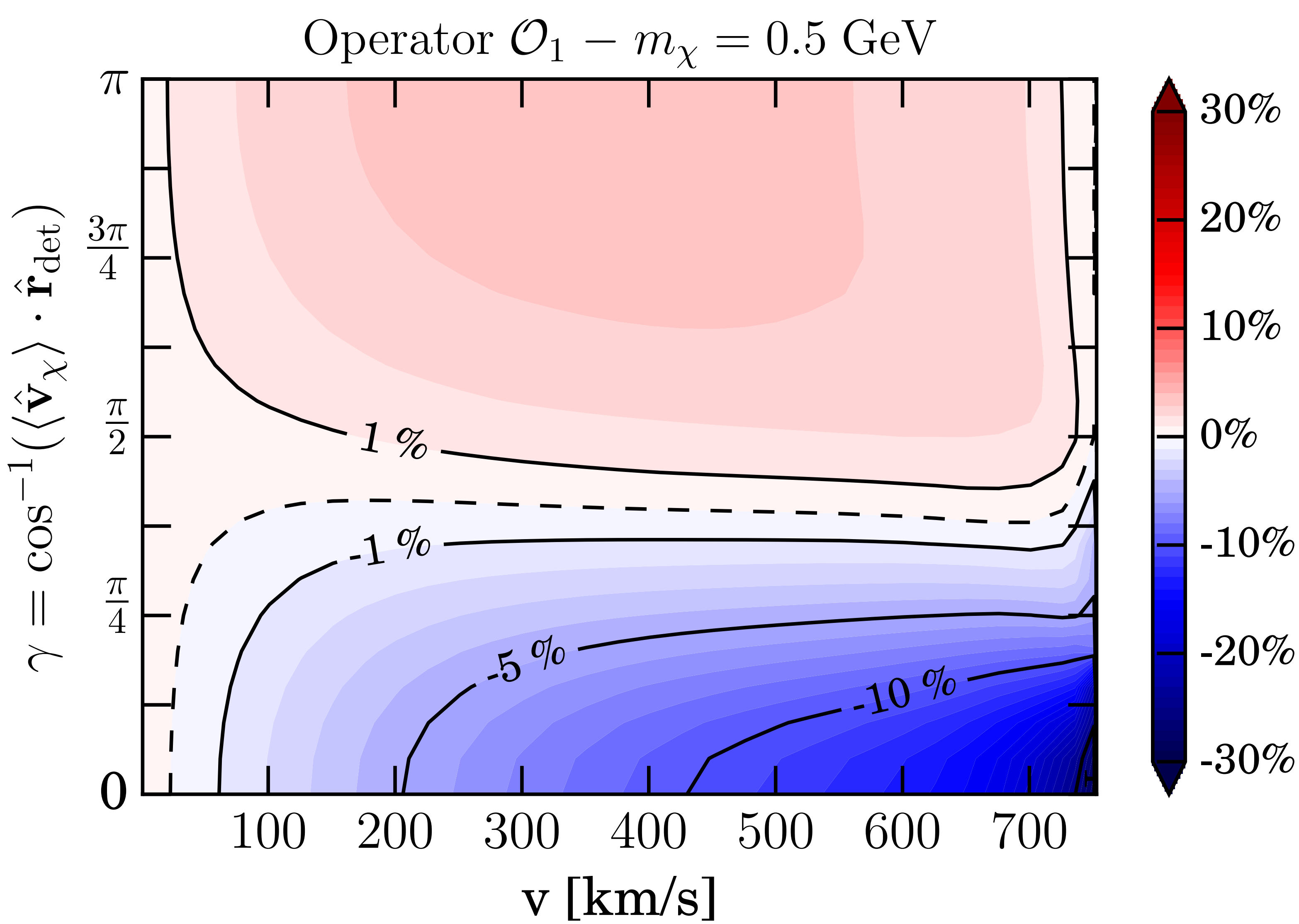
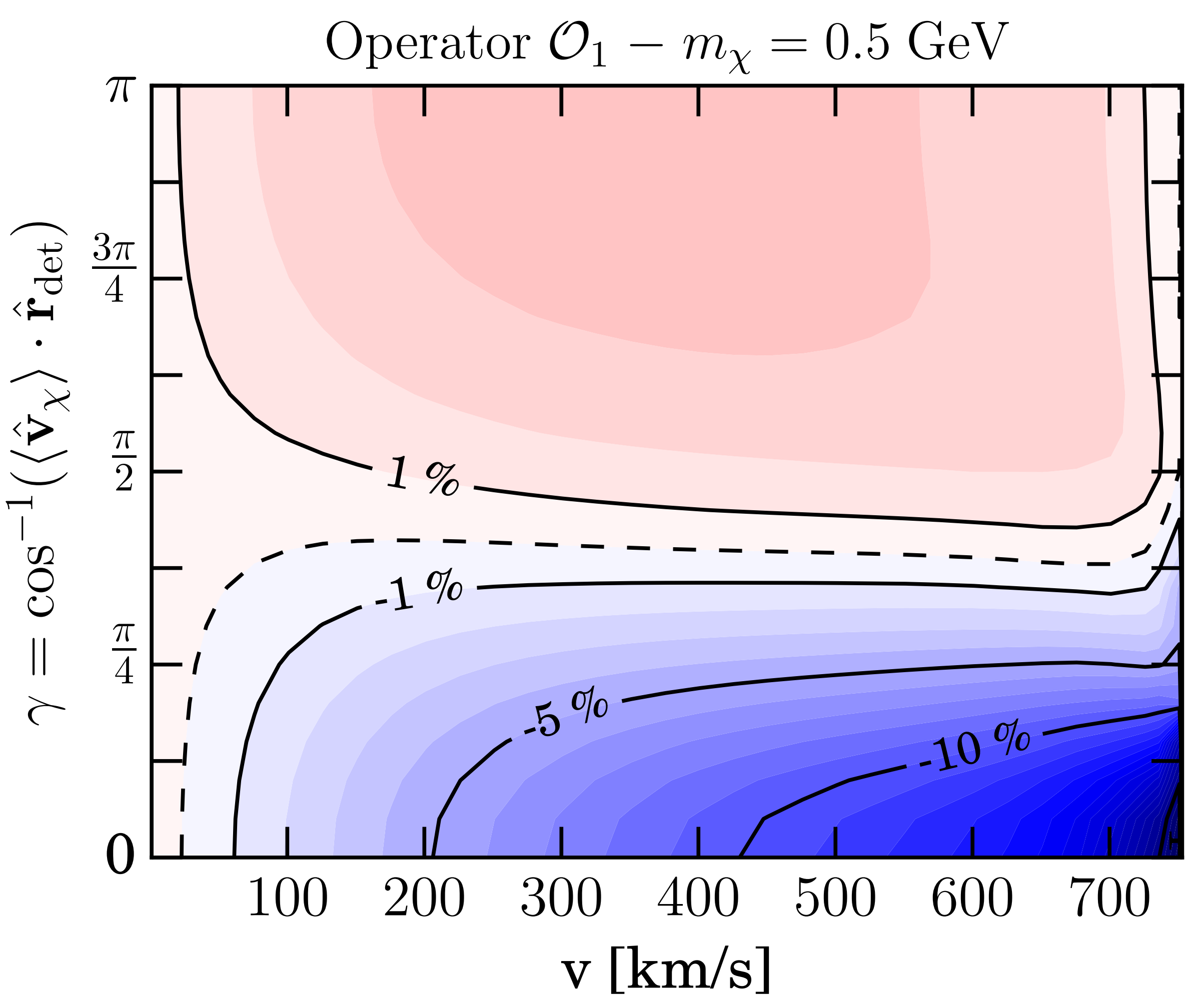


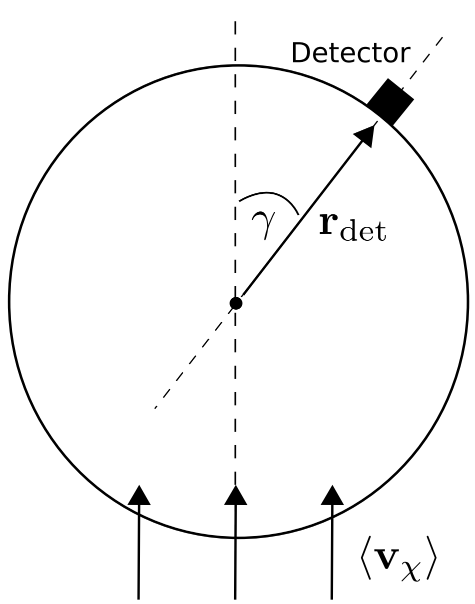
Percentage change in speed dist.

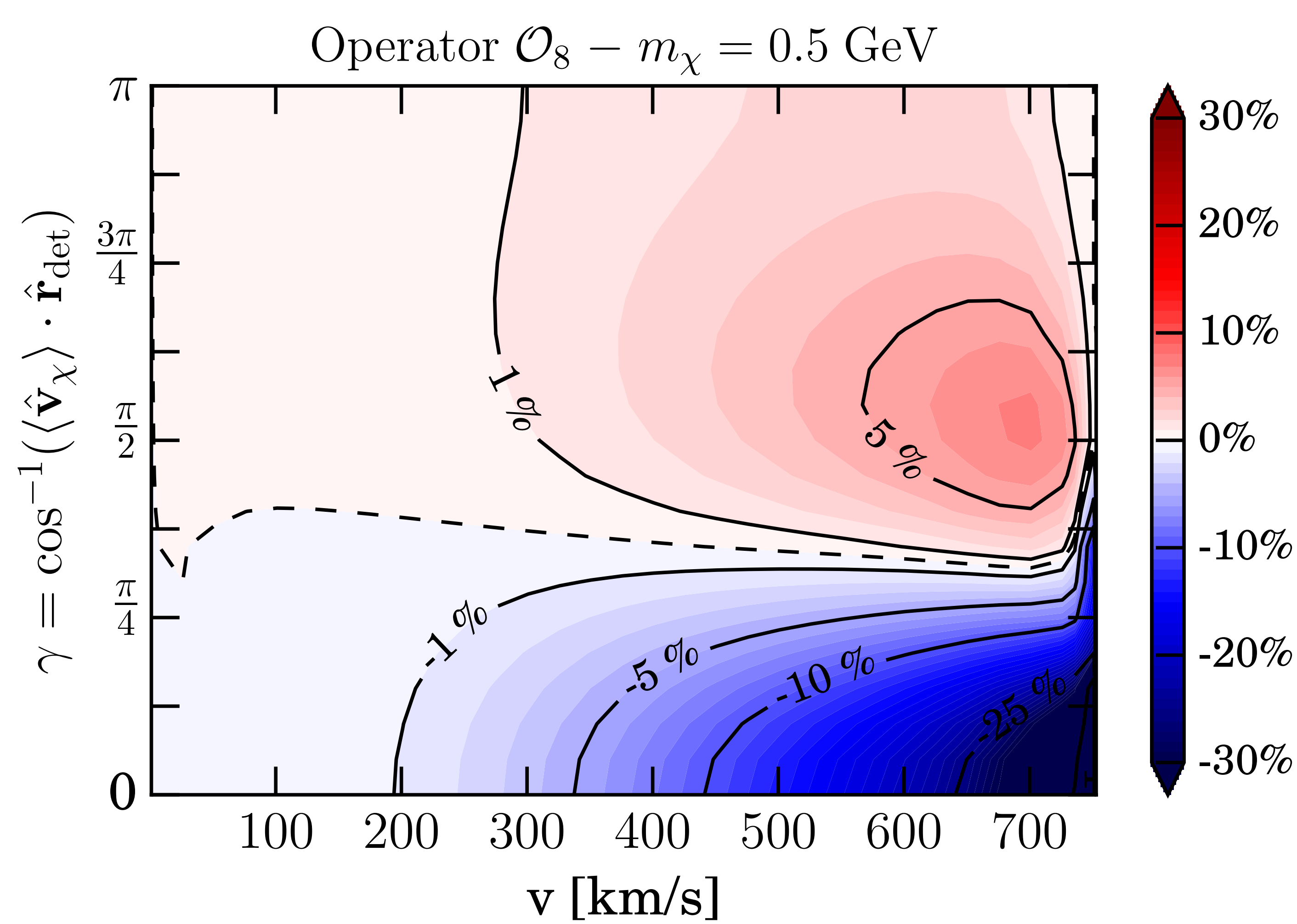


Speed Distribution - O_1 vs O_8

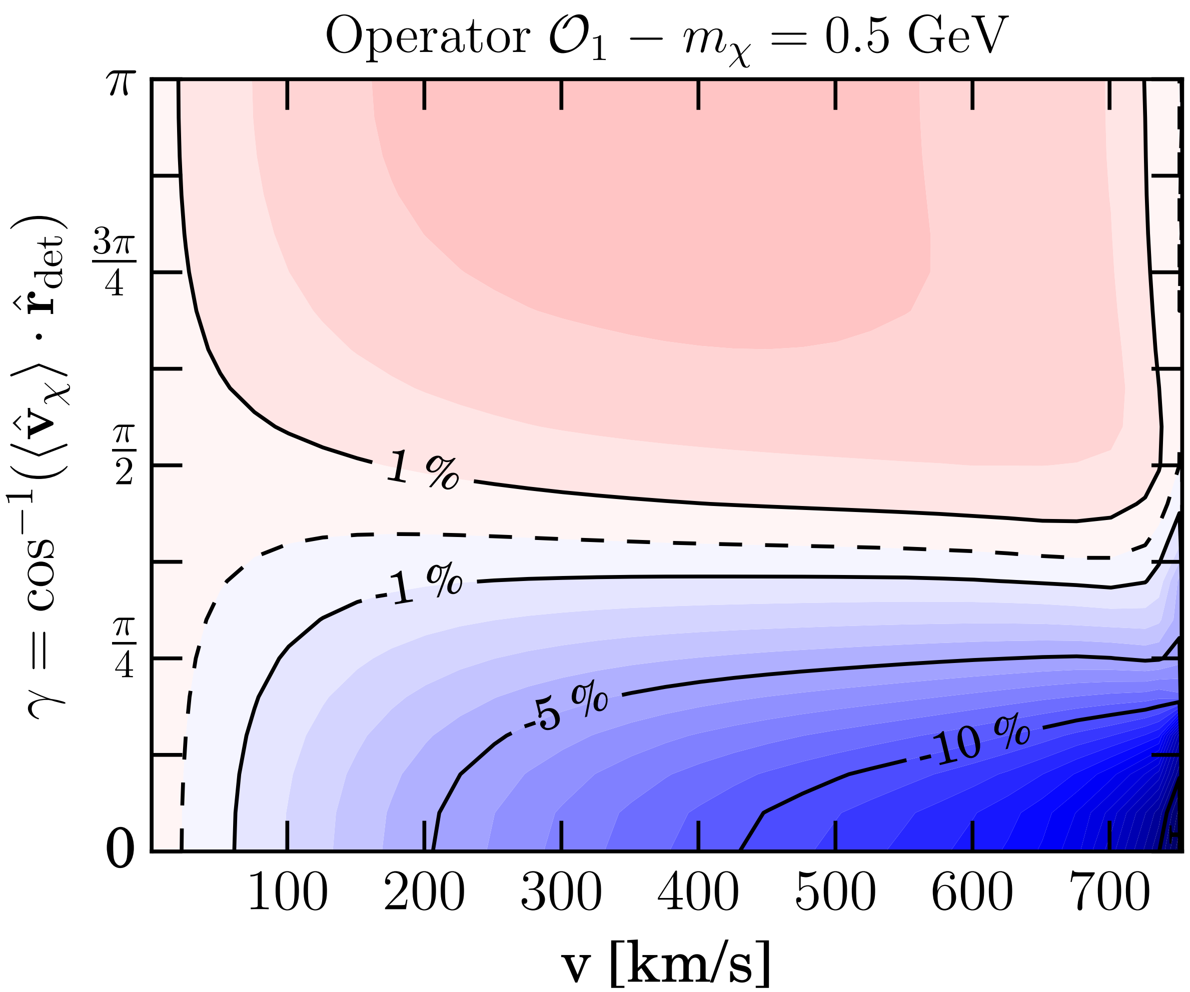


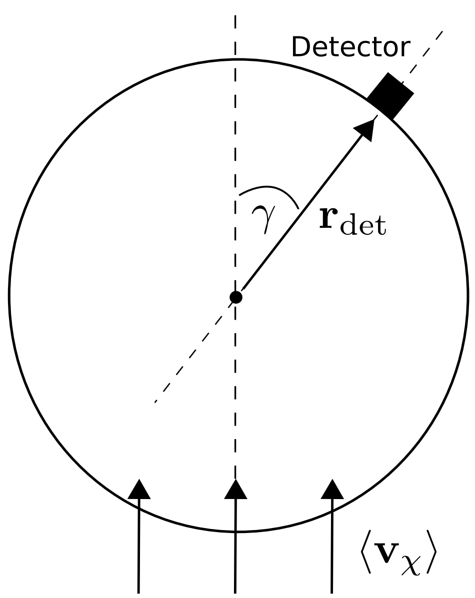
Operator 8 -
preferentially *forward* deflection



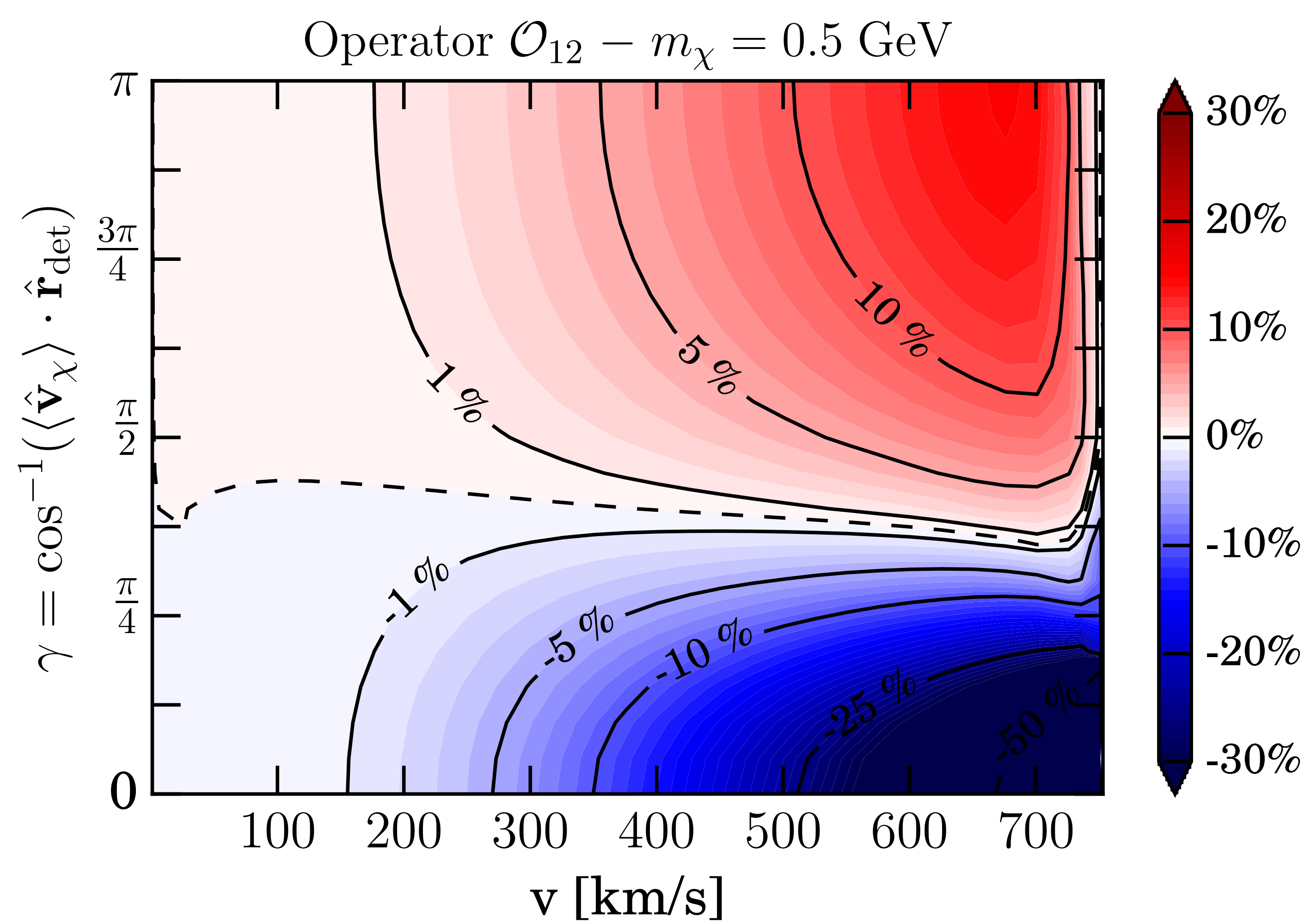


Speed Distribution - O1 vs O12





Operator 12 -
preferentially *backward* deflection



Sanity check

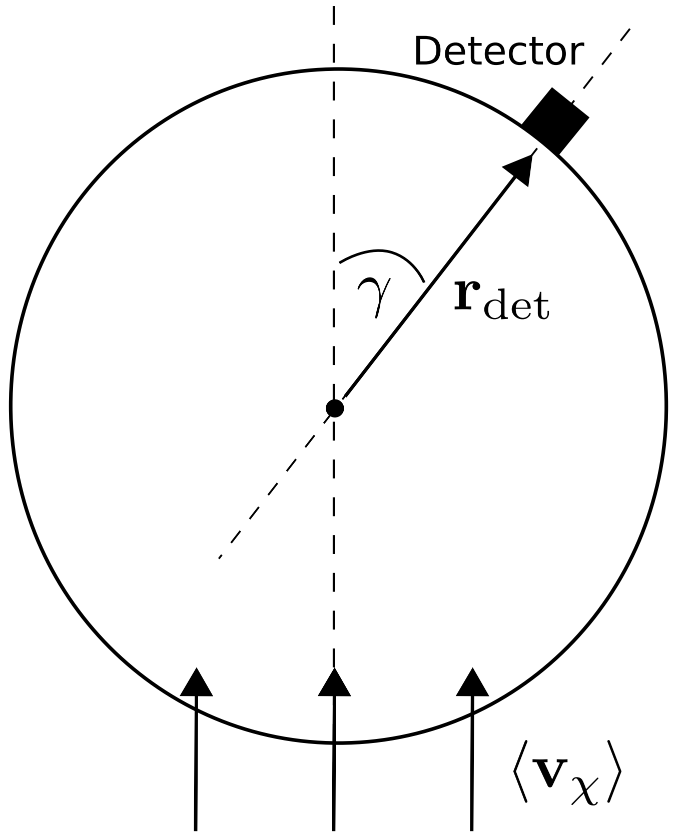
Compare rate of DM particles entering the Earth…

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

…and rate of DM particle leaving the Earth…

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

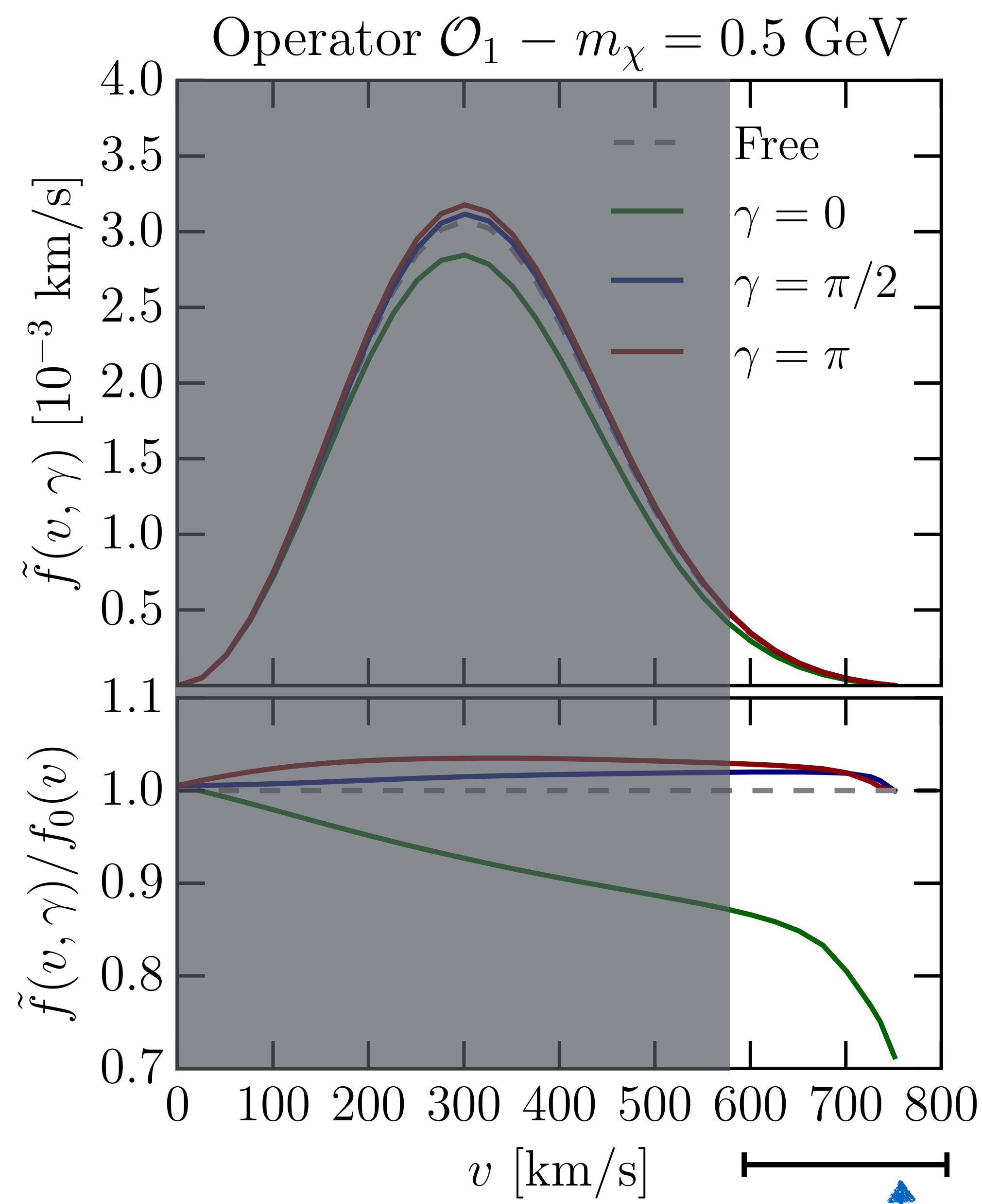
DM mass [GeV]	Operator	$\Delta\Gamma_{\mathrm{out}}^{\mathrm{Atten.}}/\Gamma_{\mathrm{in}}$	$\Delta\Gamma_{\mathrm{out}}^{\mathrm{Defl.}}/\Gamma_{\mathrm{in}}$	$\Gamma_{\mathrm{out}}/\Gamma_{\mathrm{in}}$
0.5	$\hat{\mathcal{O}}_1$	−7.8%	+7.0%	99.2%
0.5	$\hat{\mathcal{O}}_8$	−8.0%	+7.3%	99.2%
0.5	$\hat{\mathcal{O}}_{12}$	−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}.

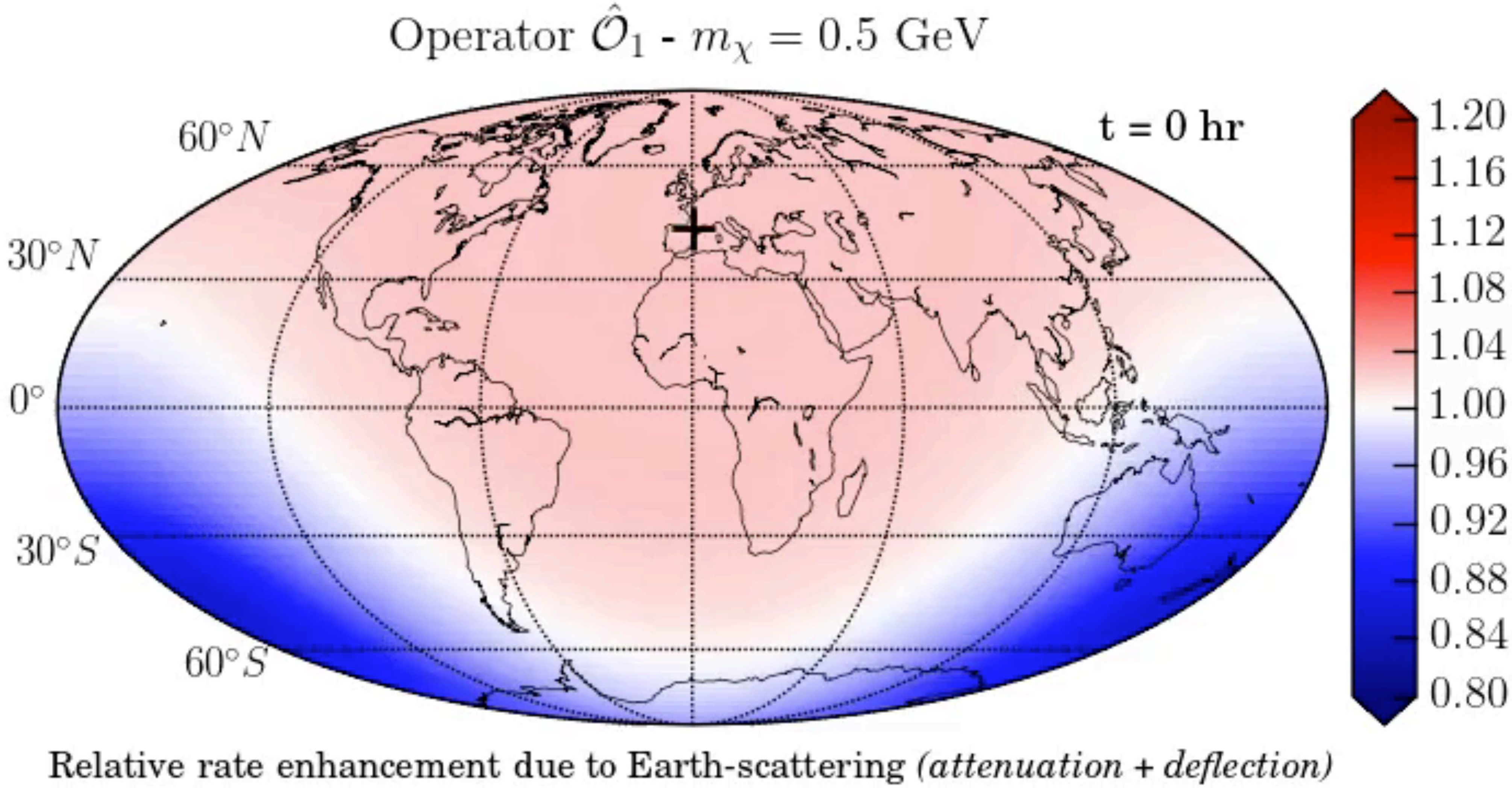
Scattering predominantly with Oxygen and Calcium.



DM particles within $3\,\sigma_E$ of the energy threshold

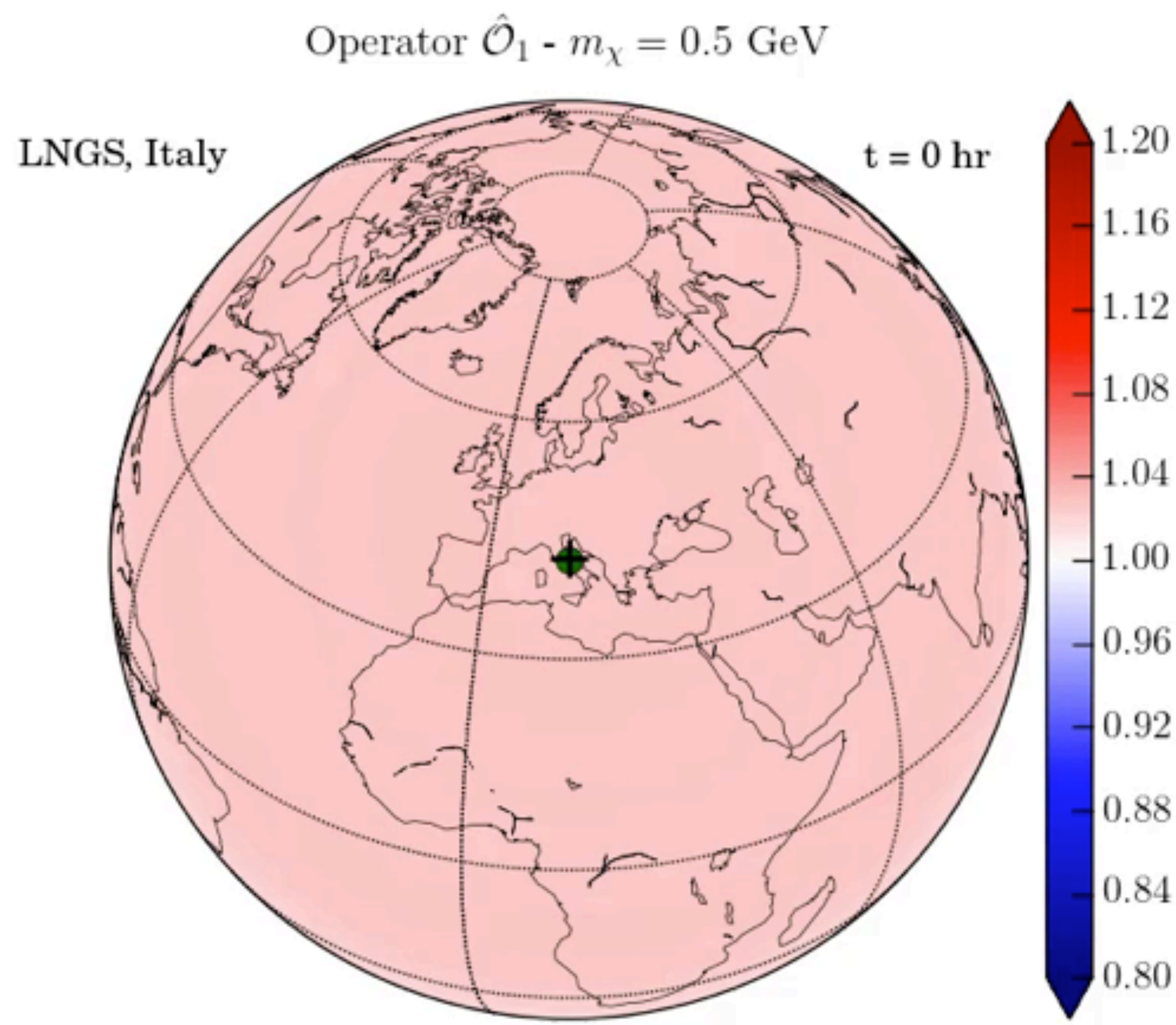
$E_{\mathrm{th}} \sim 300$ eV

Mapping the CRESST-II Rate



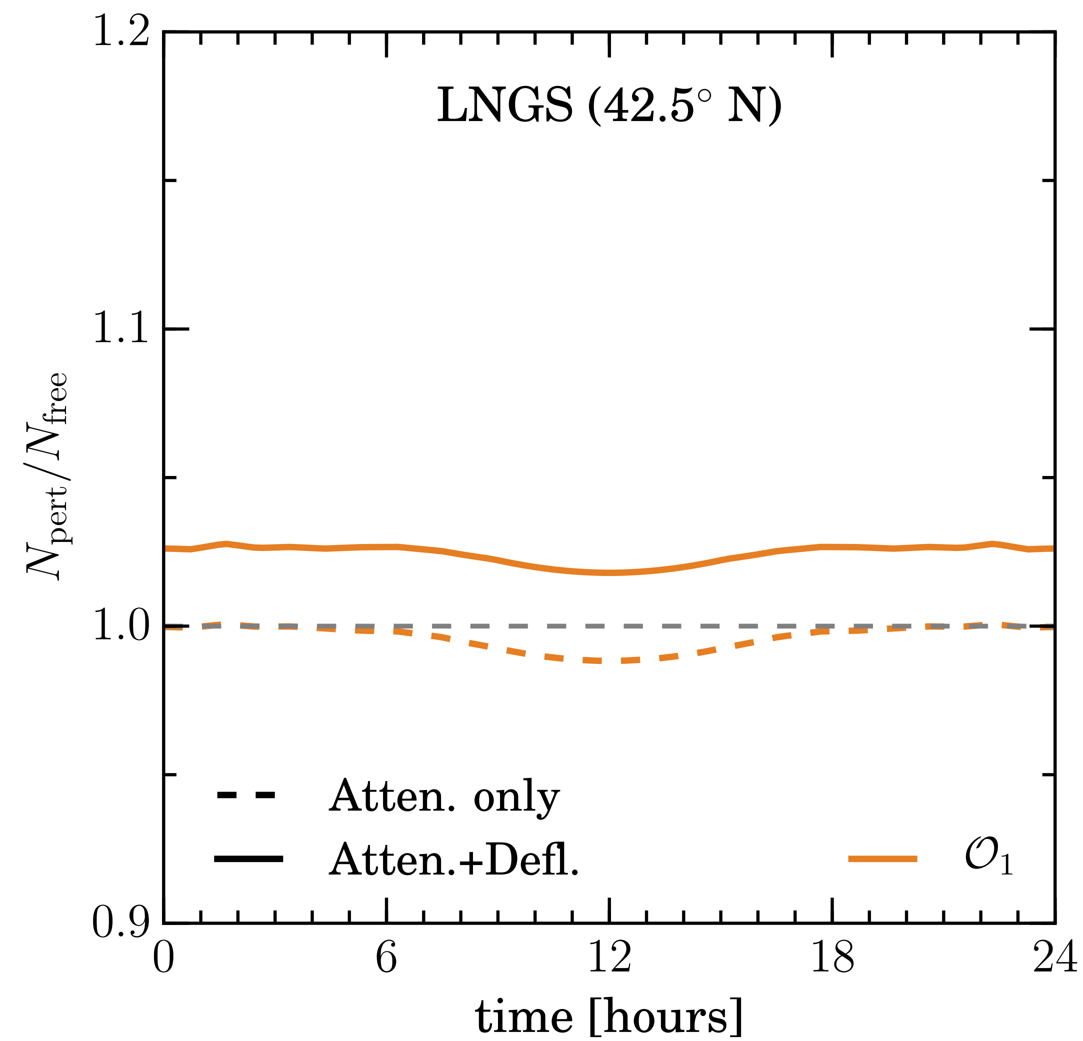
LNGS - Operator 1

LNGS - Gran Sasso Lab, Italy



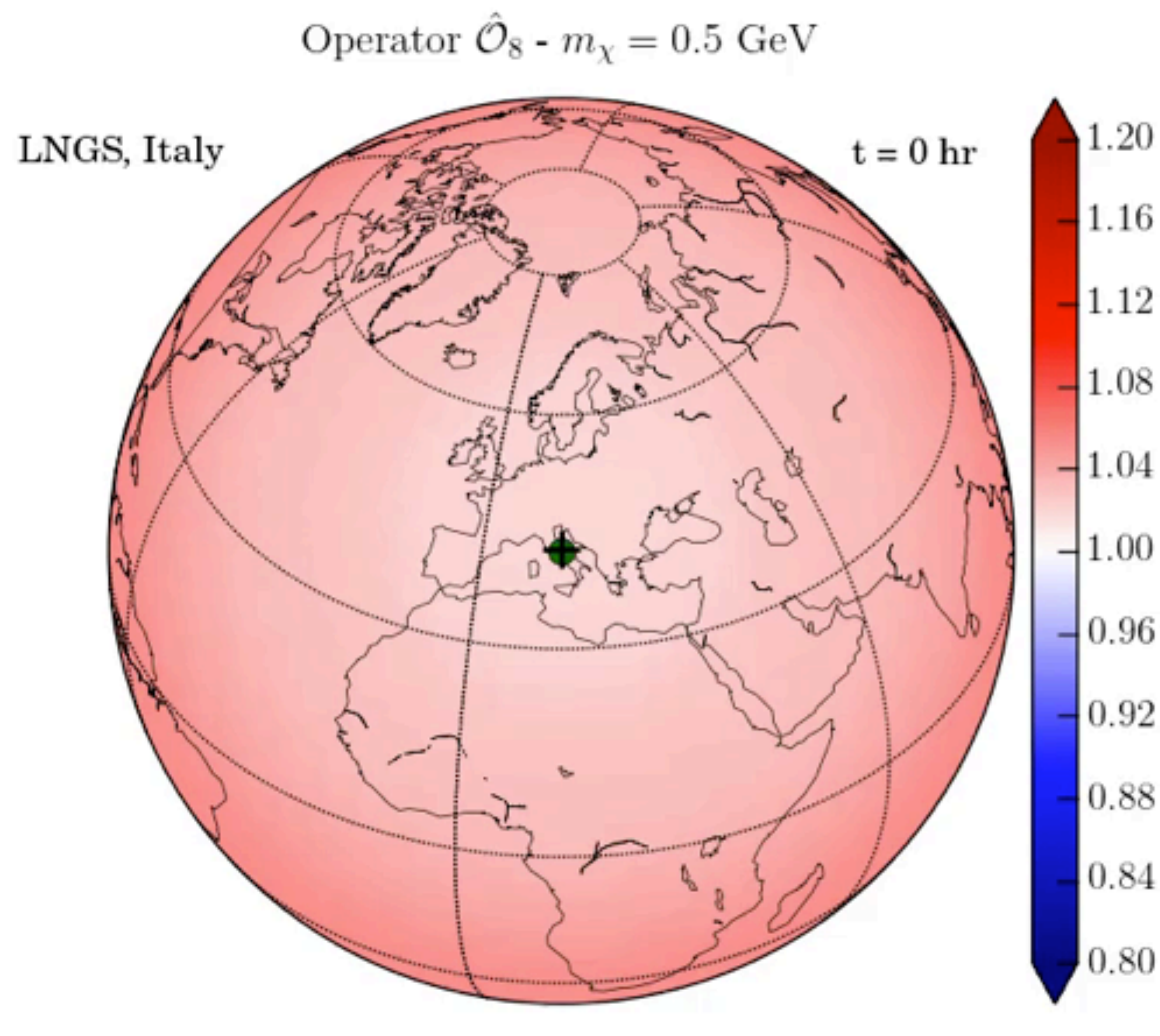
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 1 - isotropic deflection

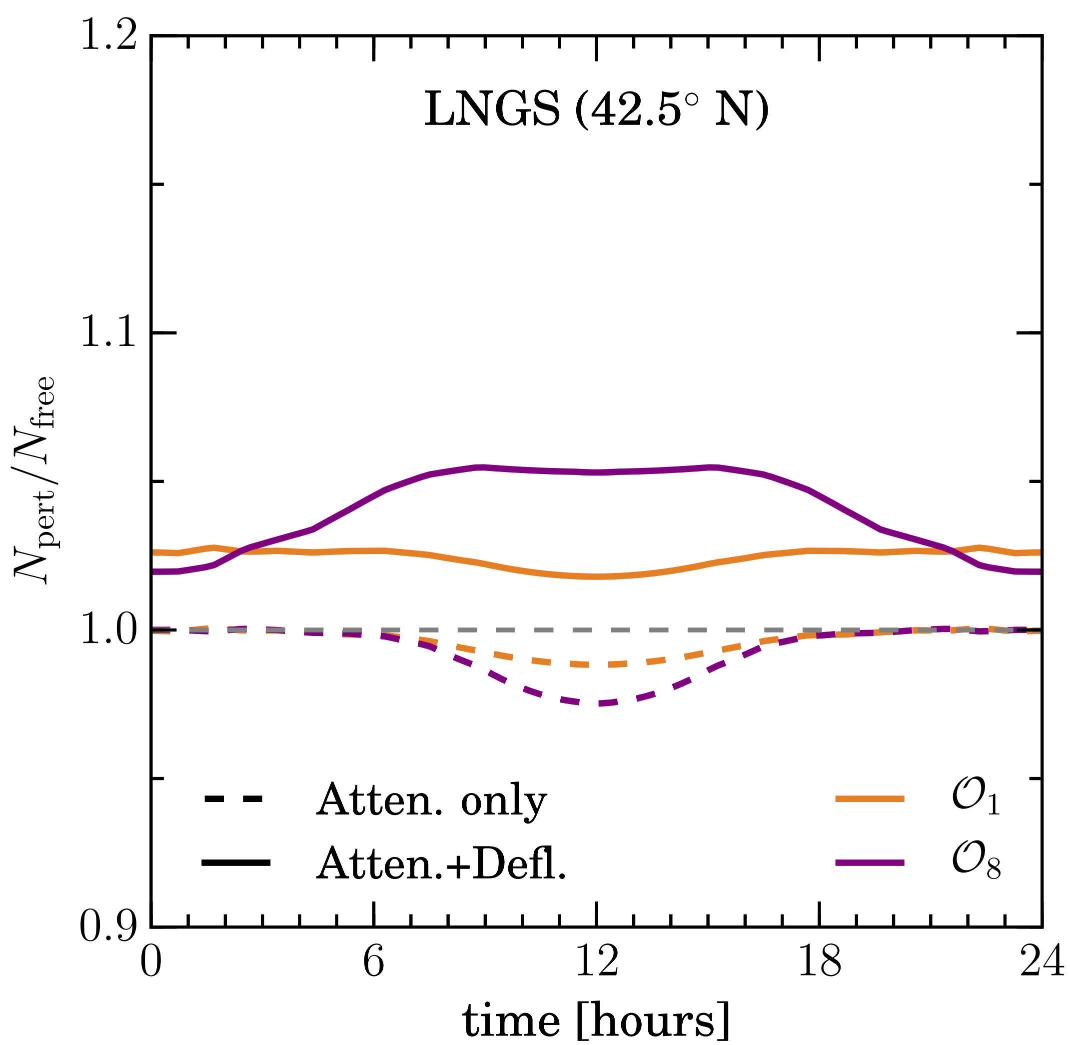


LNGS - Operator 8

LNGS - Gran Sasso Lab, Italy

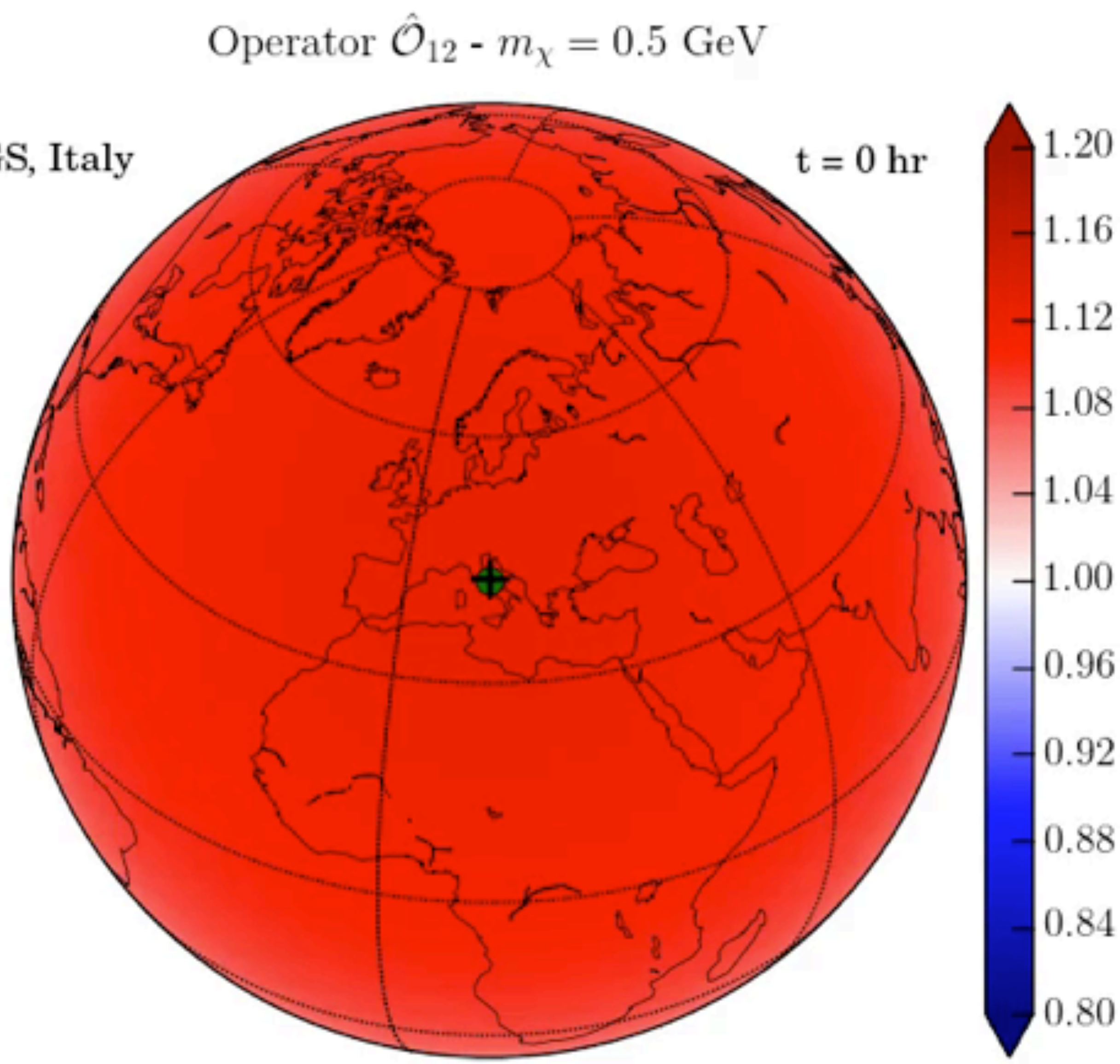


Operator 8 - forward deflection



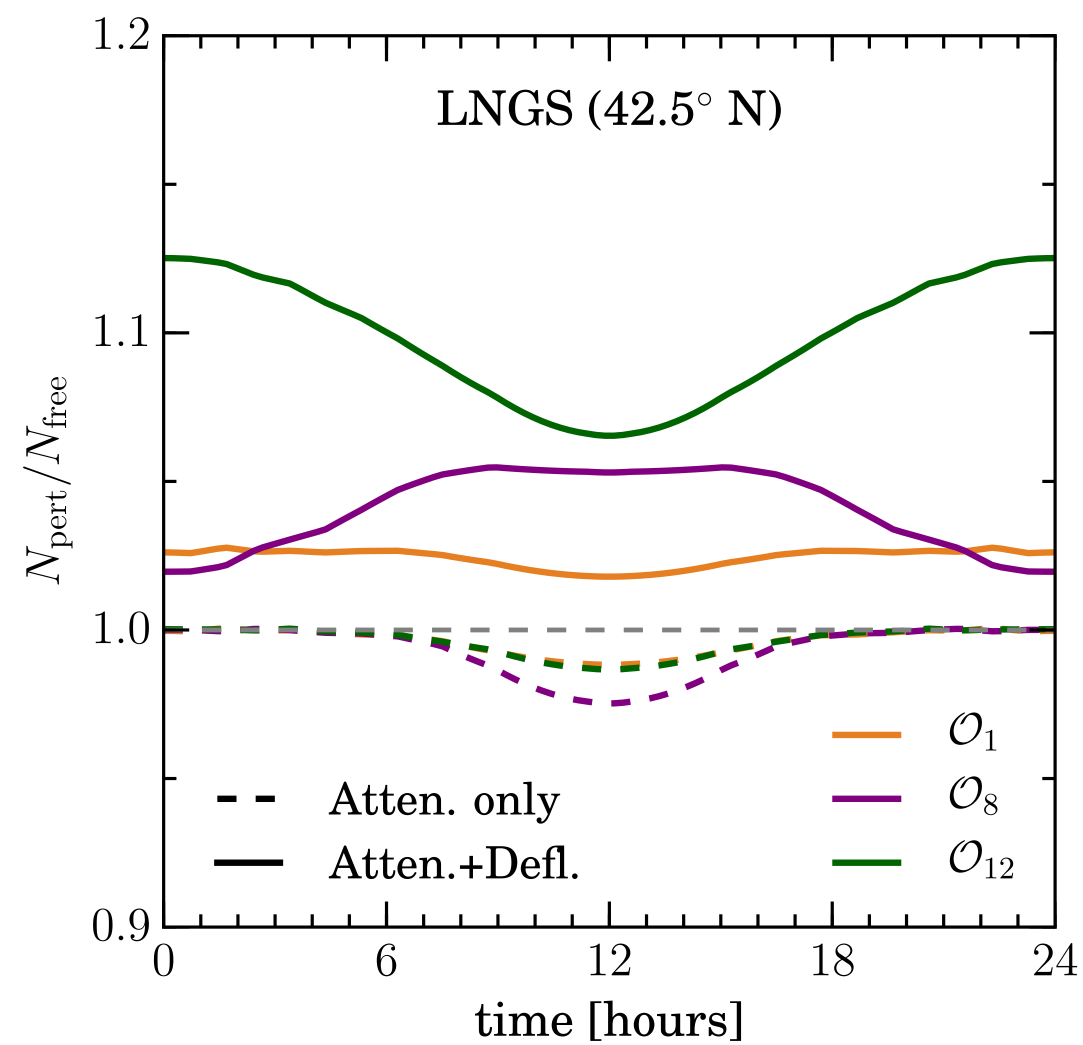
LNGS - Operator 12

LNGS - Gran Sasso Lab, Italy



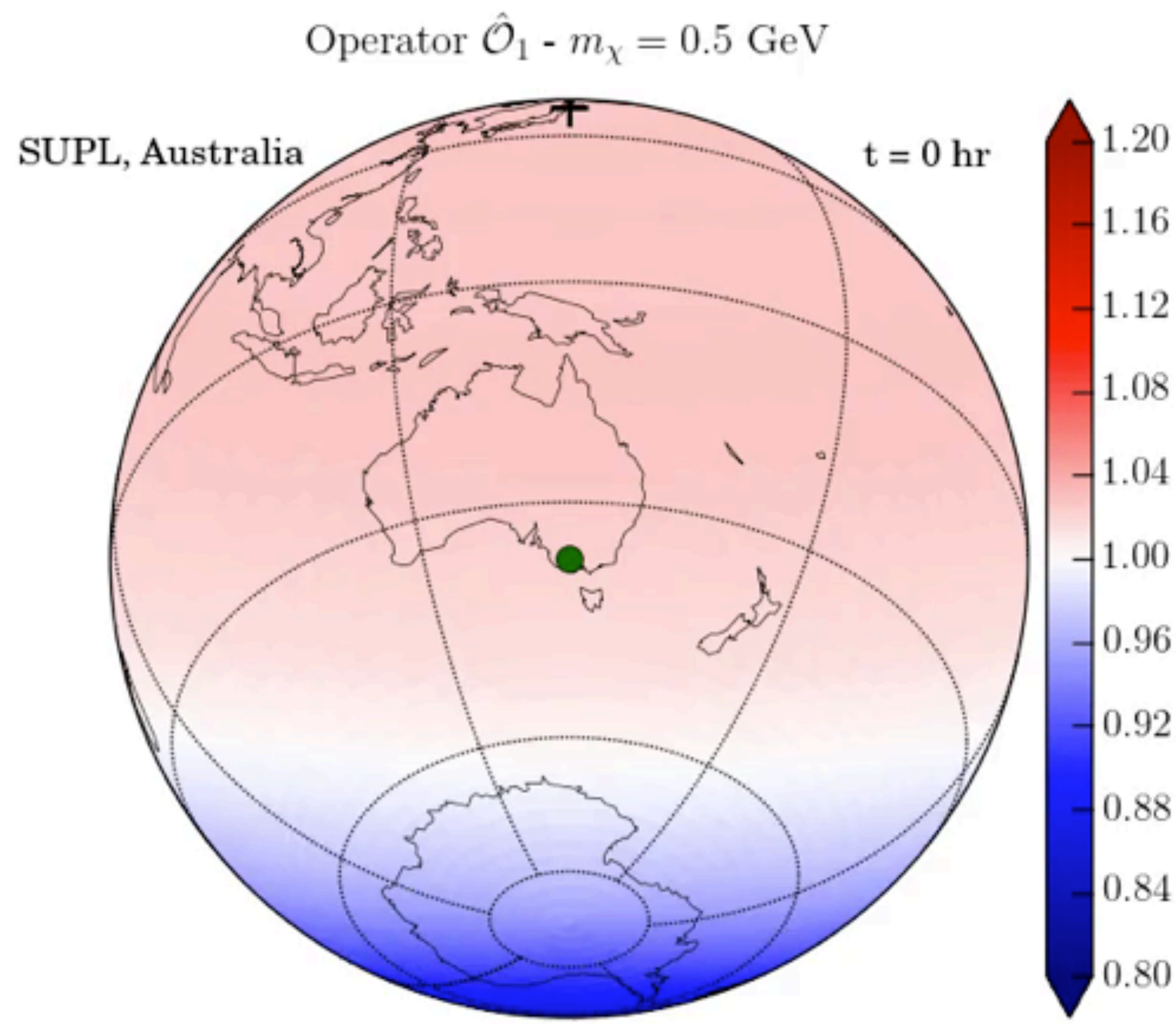
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Operator 12 - backward deflection



SUPL - Operator 1

SUPL - Stawell Underground Physics Lab, Australia



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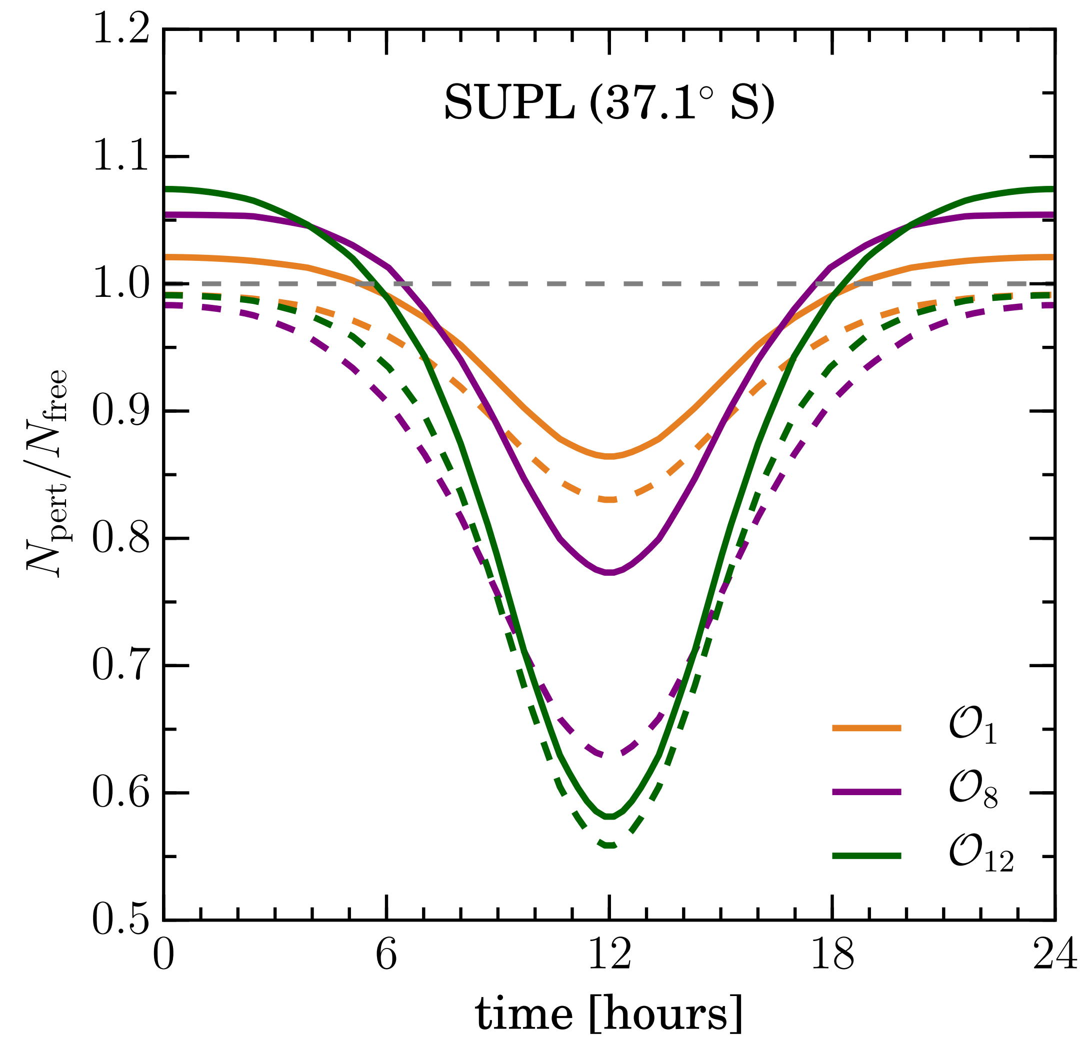
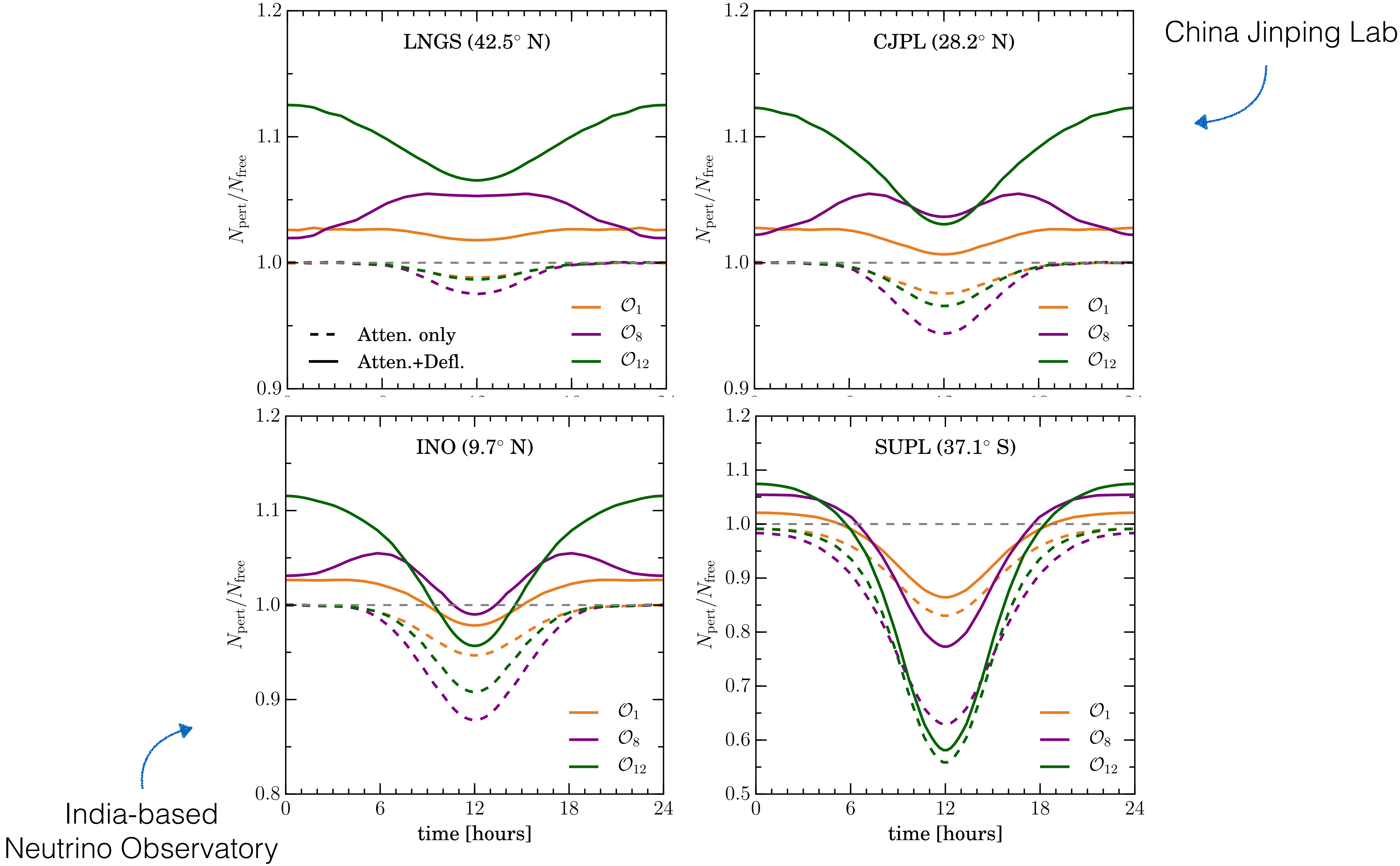
Operator 1 - isotropic deflection



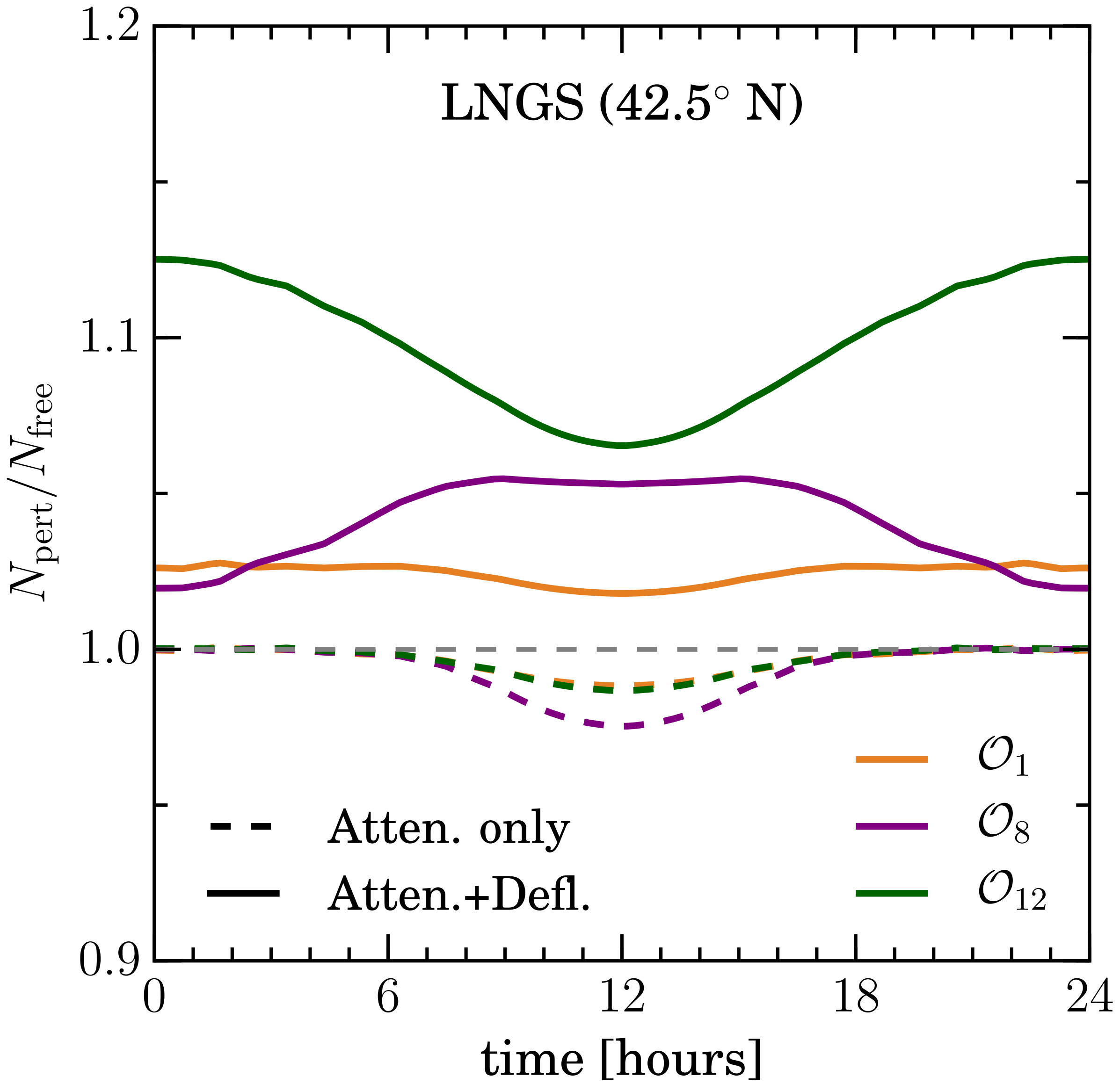
Around the world



Implications of Earth-Scattering

Careful calculation (including deflection and attenuation)
in the 'single-scatter' regime

BJK, Catena & Kouvaris
[1611.05453]



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

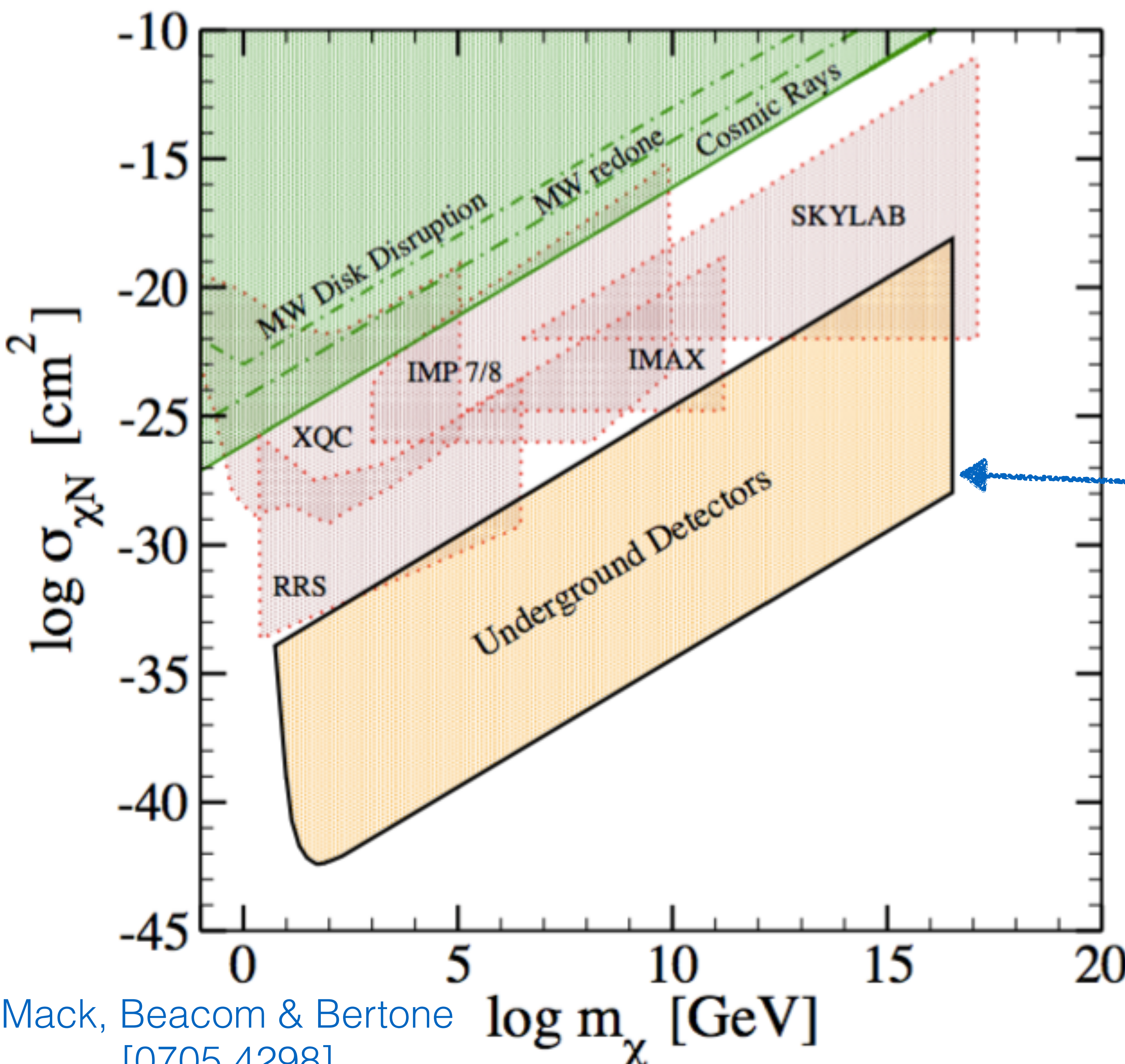
Possibility to distinguish different interactions with different amplitude and phase of modulation

EarthShadow code available online to include these effects:
github.com/bradkav/EarthShadow

WIMPzillas!

PRELIMINARY

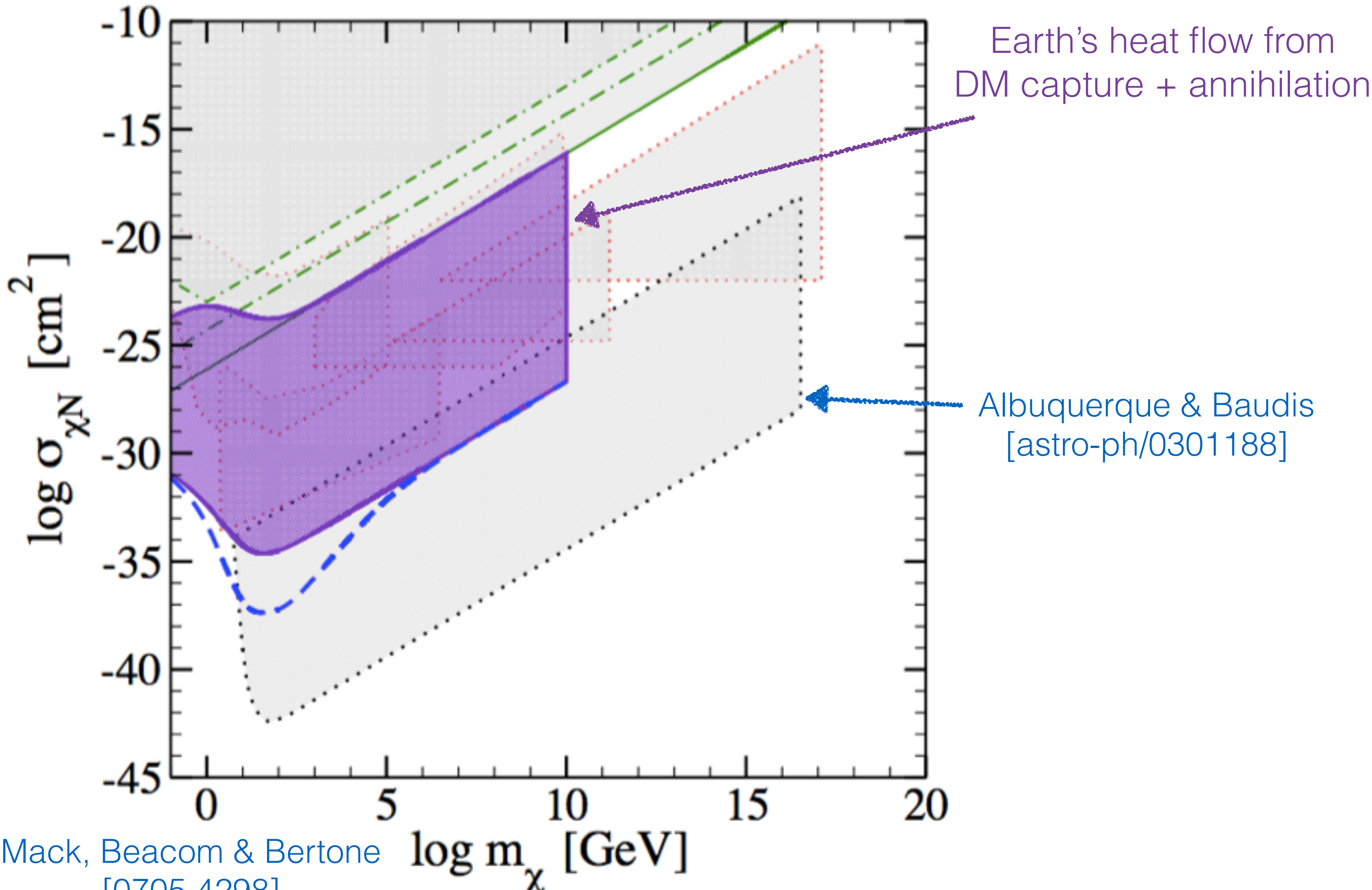
Direct Detection Landscape - zoomed out



Albuquerque & Baudis [astro-ph/0301188]

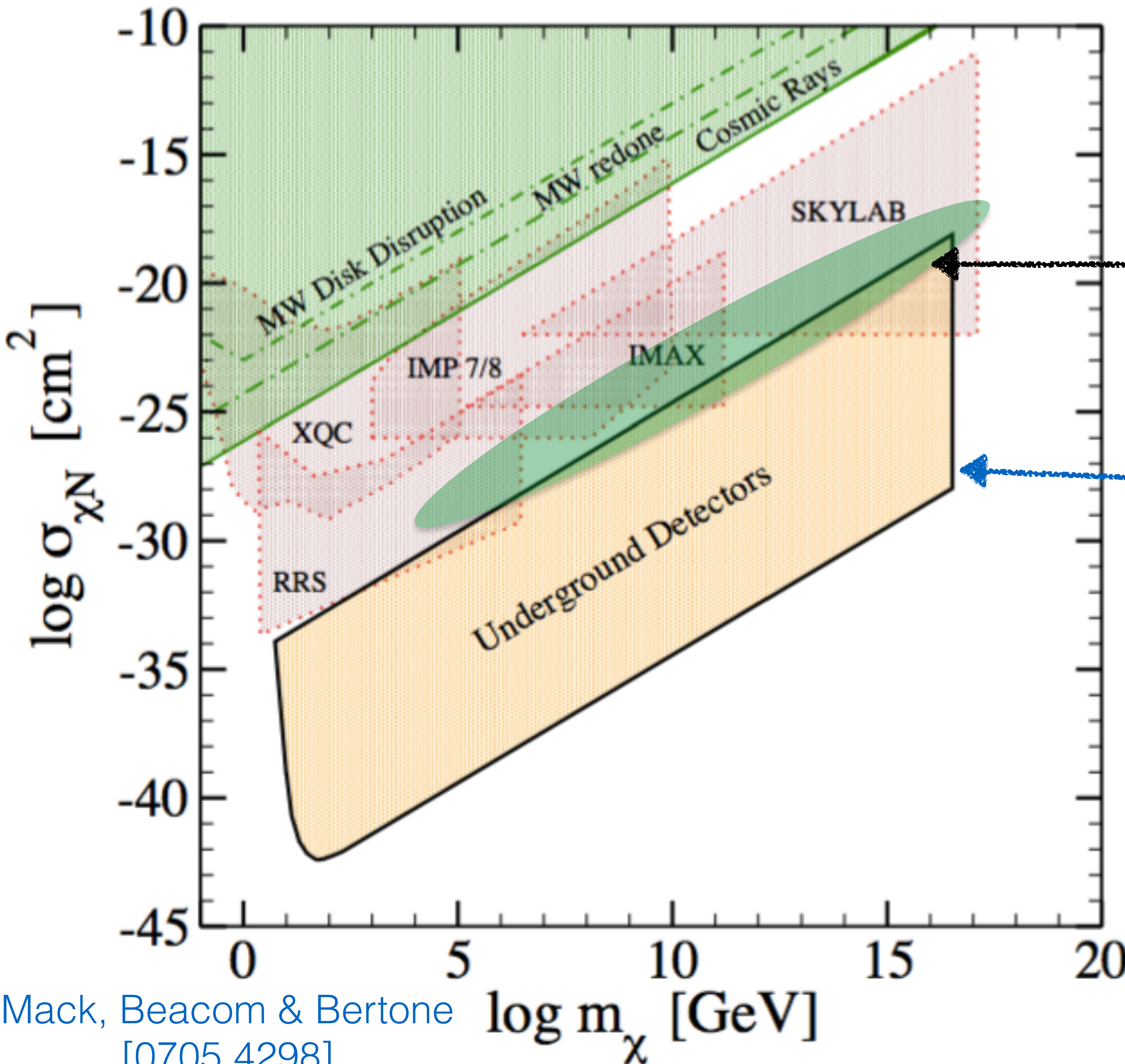
Mack, Beacom & Bertone [0705.4298]

Direct Detection Landscape - zoomed out



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

Deflection of DM (per scatter) goes as $m_A/m_\chi \ll 1$

Can show that $v_\perp(t)^2 \sim \sigma n_A \frac{m_A^2}{m_\chi^2} v_0^4 t \lll v_0^2$

Deflection is almost always negligible

Only need to consider *stopping* of ultra-heavy DM:

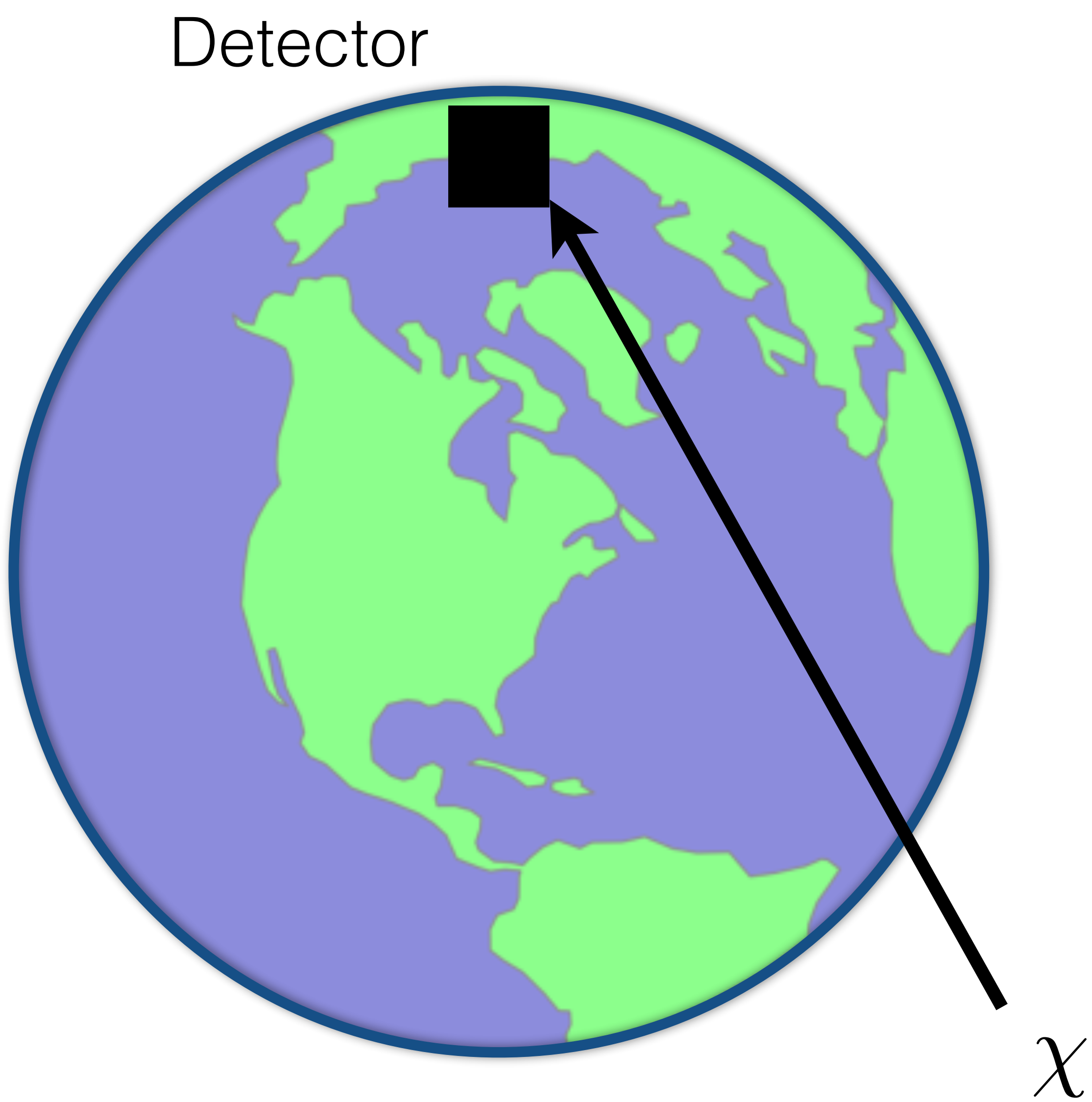
$$\frac{\mathrm{d}v}{\mathrm{d}x} = -v\sigma_p^{\mathrm{SI}} \sum_i^{\mathrm{species}} n_i(\mathbf{r}) \left(\frac{m_i}{m_\chi}\right) A_i^4 C_i(v)$$

'Correction factor' due to nuclear form factors

Solve to find final DM speed v_f given initial DM speed v_i and incoming direction $\hat{\mathbf{v}}$:

$$v_f = \phi(v_i, \hat{\mathbf{v}})$$

Earth-*stopping* for super-heavy DM



Distribution of DM reaching the detector with velocity $\mathbf{v}_f$:

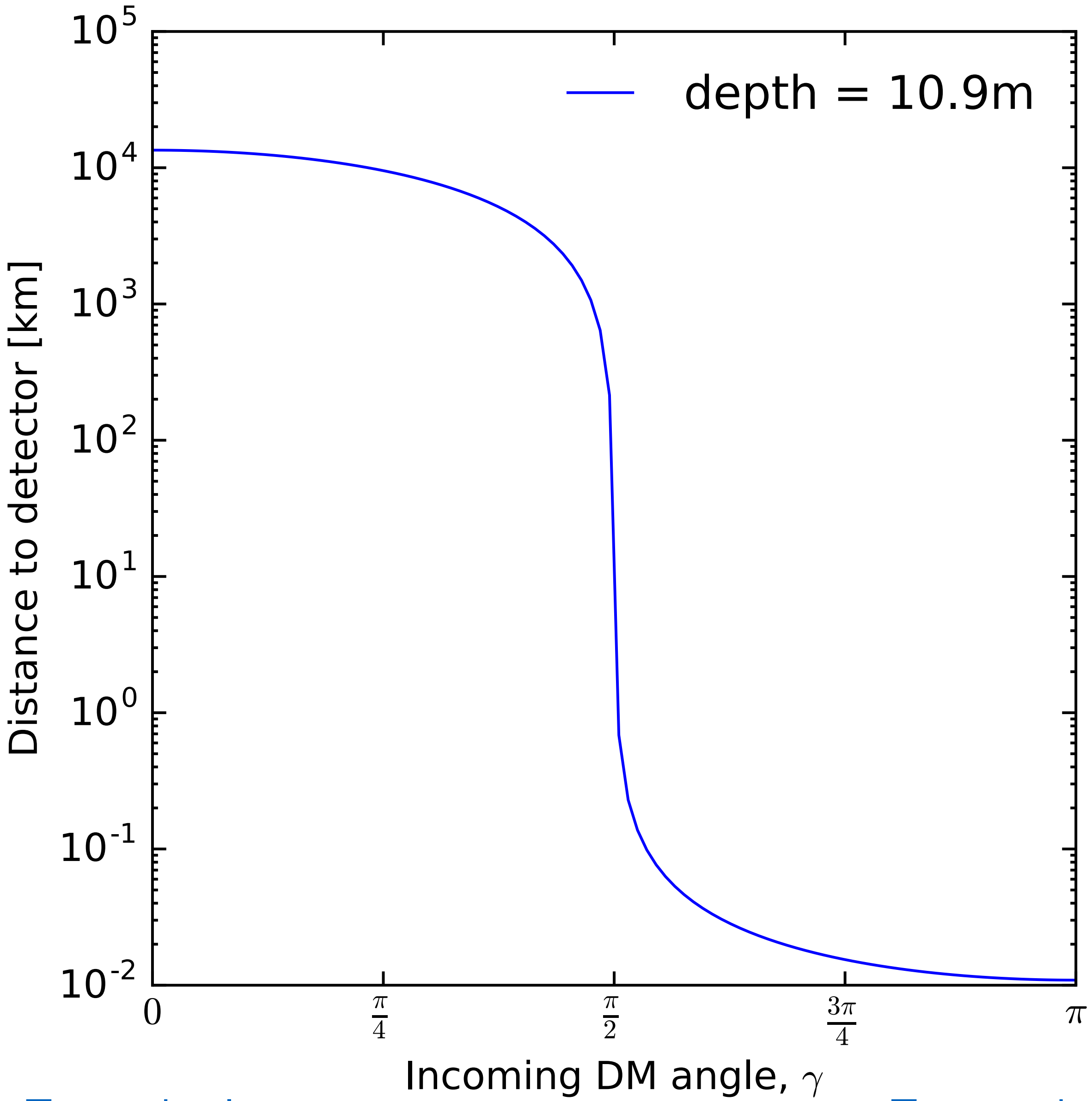
$$\tilde{f}(\mathbf{v}_f) = f_0(\phi^{-1}(v_f, \hat{\mathbf{v}}), \hat{\mathbf{v}})$$

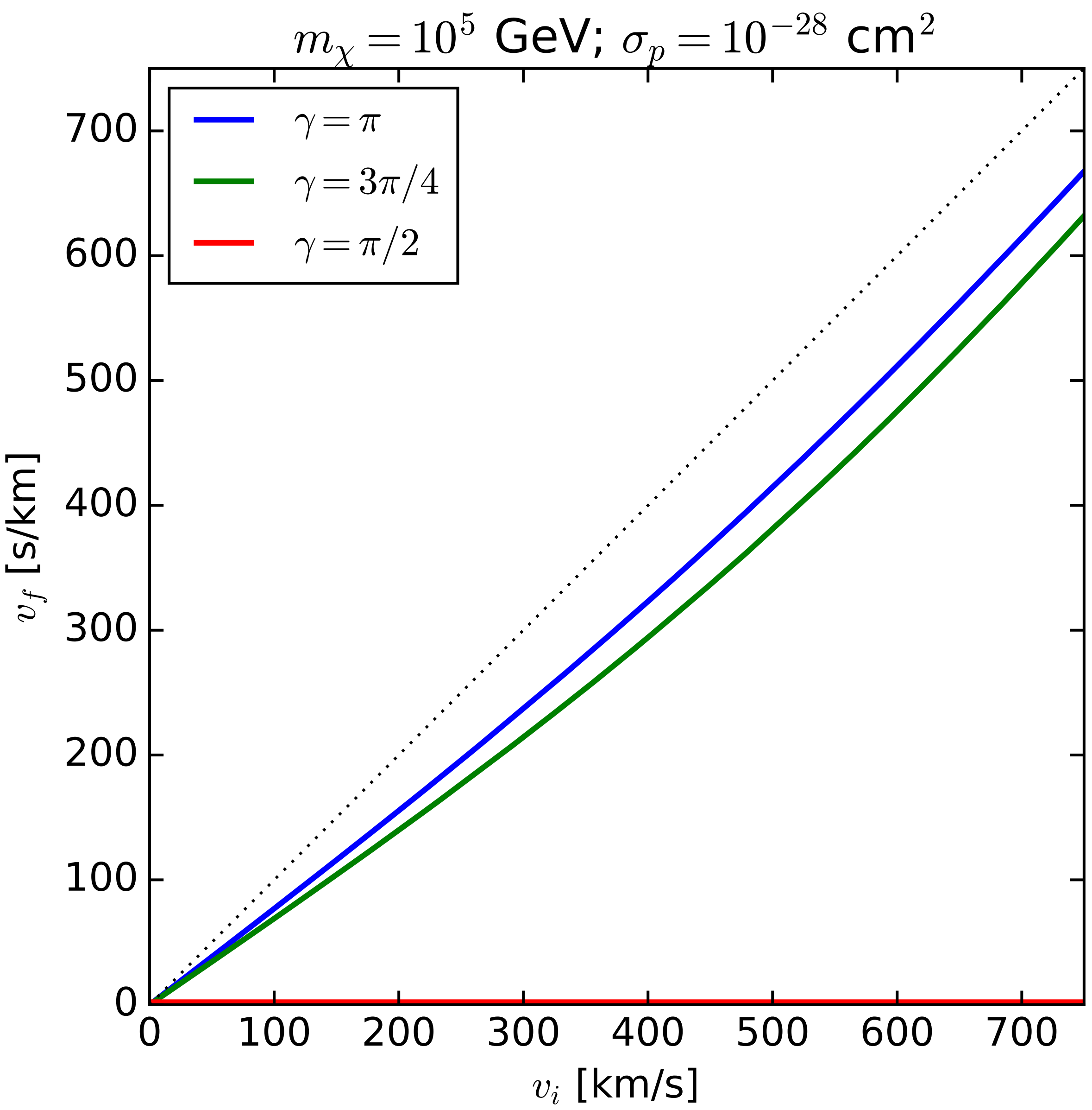
$v_i = \phi^{-1}(v_f, \hat{\mathbf{v}})$ is the initial velocity the particle must have had

Preliminary Results

Consider scattering only from Silicon in the Earth,
and a detector at a depth of ~11m.

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





From below

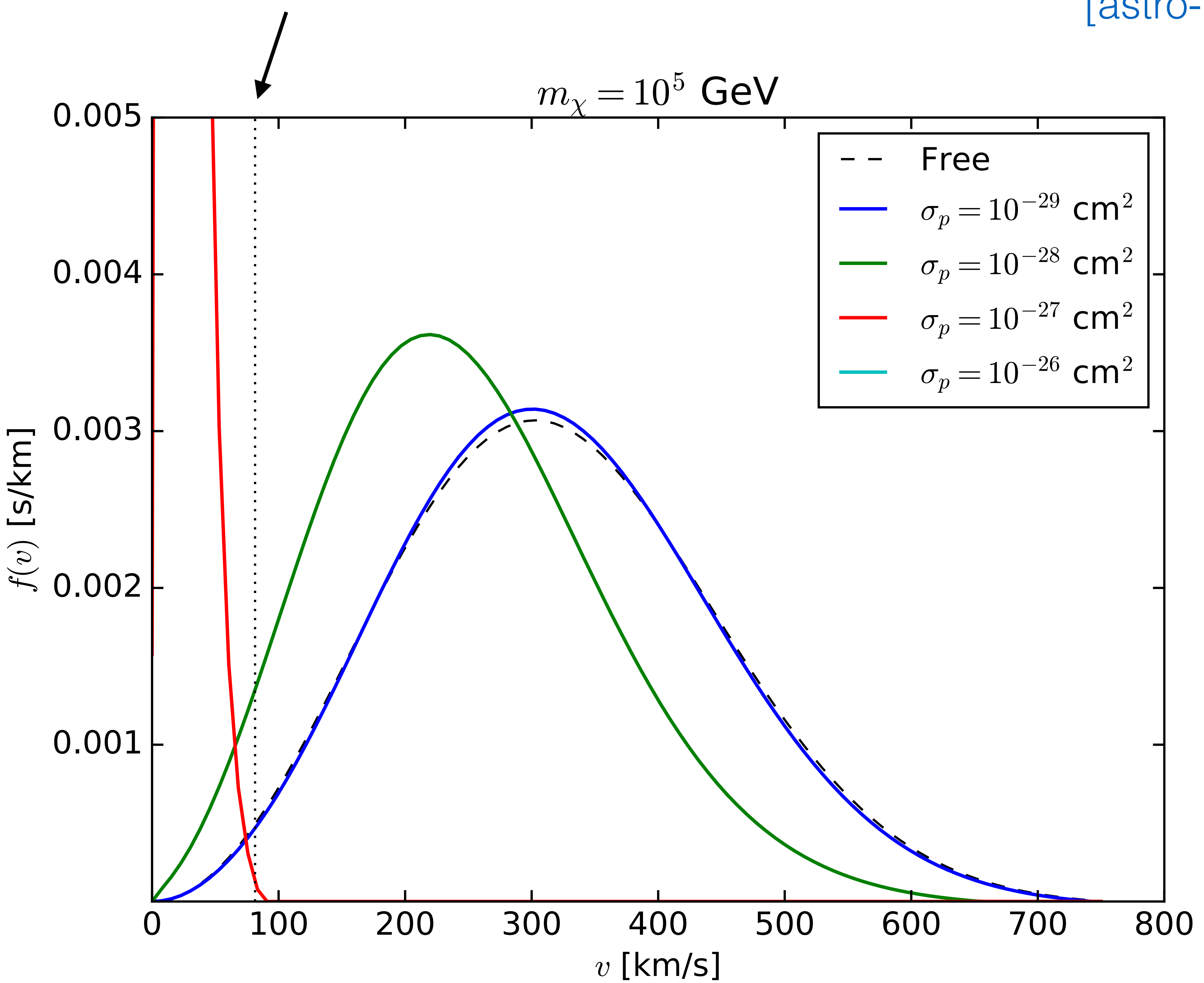
From above

Preliminary Results

Consider scattering only from Silicon in the Earth,
and a detector at a depth of ~11m.

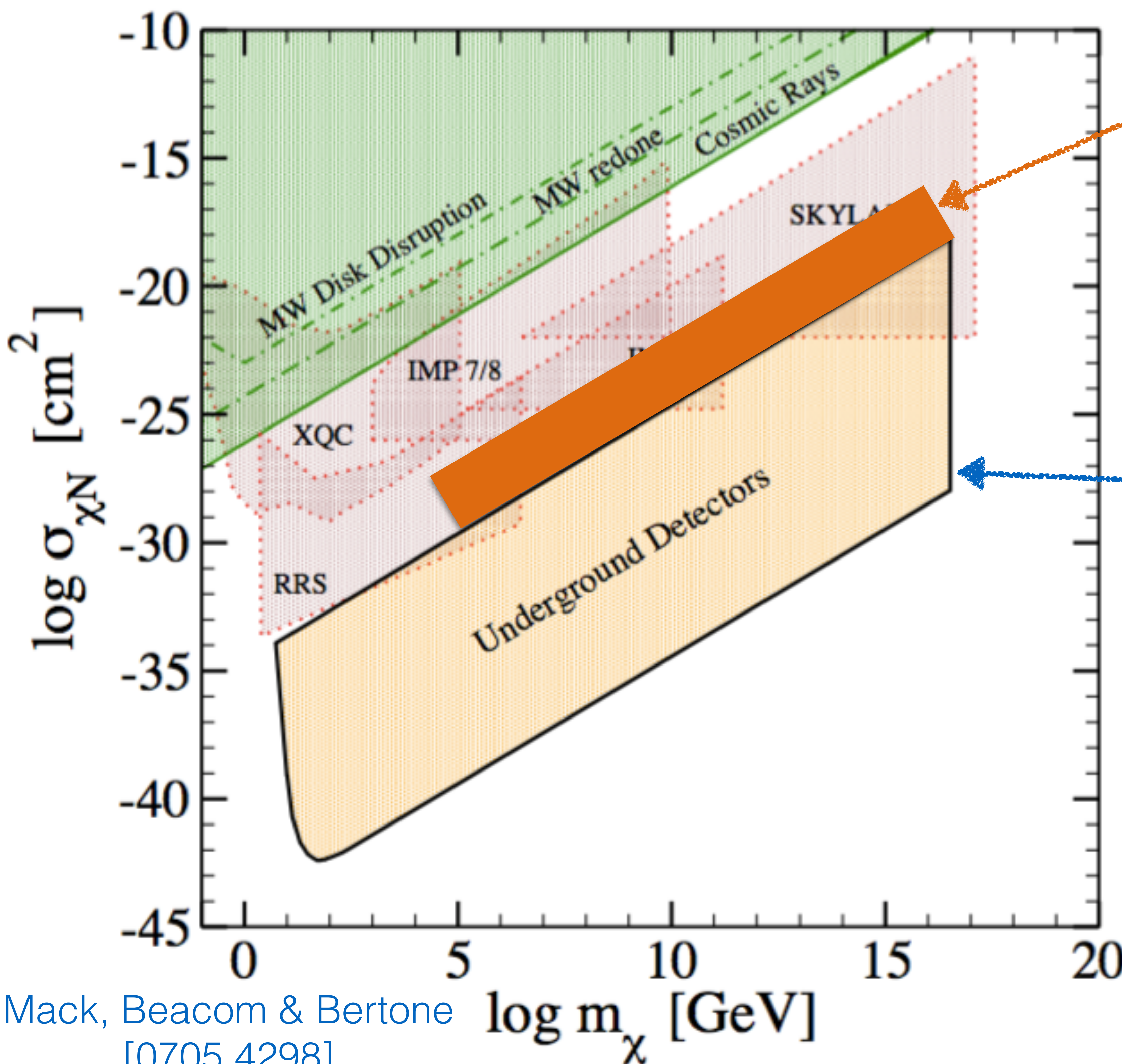
CDMS I at the Stanford Underground Facility
[astro-ph/0203500]

10 keV CDMS I threshold



Assume on average that the DM flux comes from about 40 degrees off vertical

Preliminary Results



Possible gain of about 3 orders of magnitude in cross section

Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]

Caveats

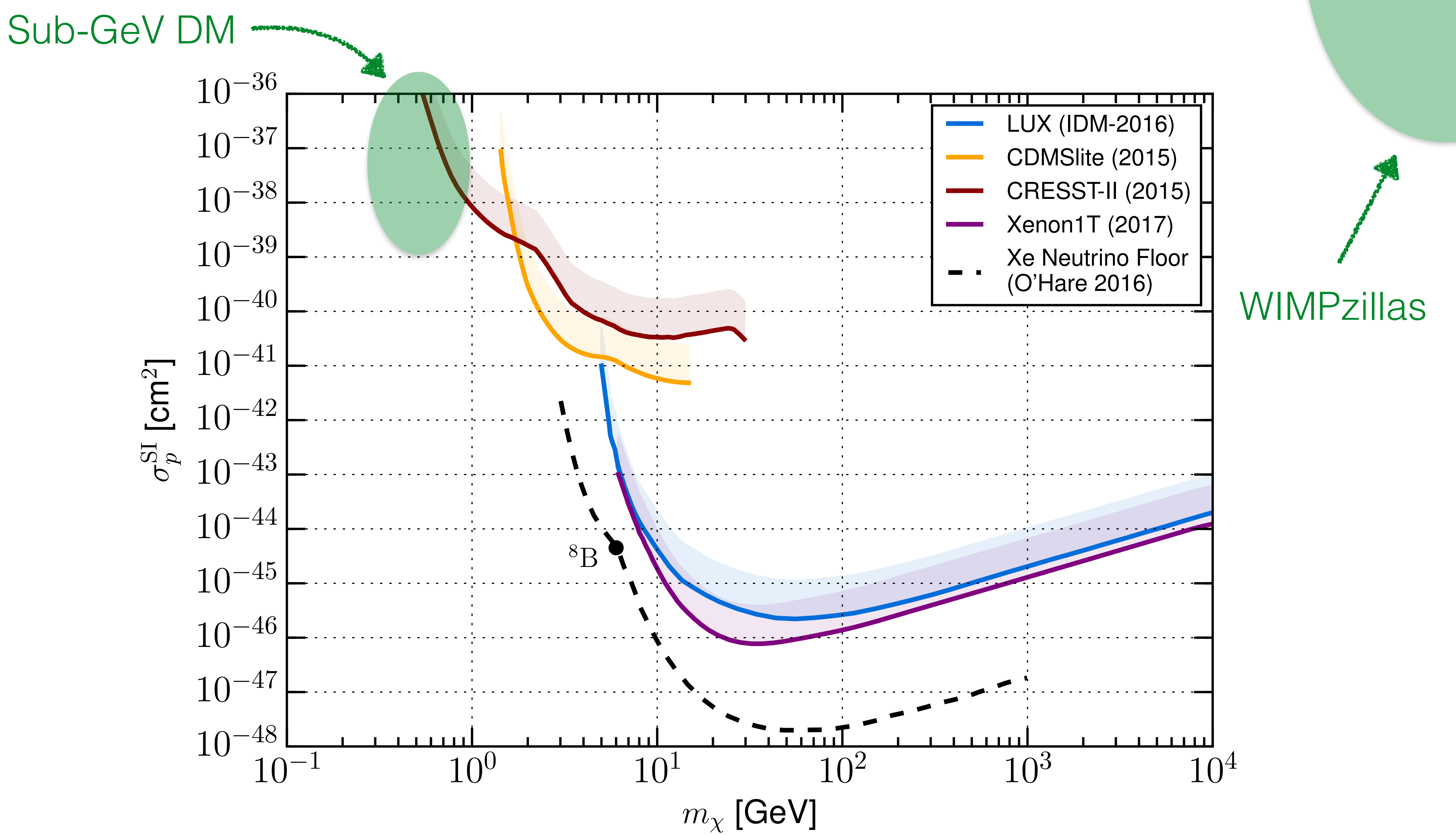
Need to include *all* Earth elements (but expect Silicon to dominate)

Need to take into account energy losses in the detector shielding
(e.g. 1cm thick lead shield)

Need to perform full *careful* rate calculation

Expect ~2 orders of magnitude improvement in limits (rather than 3), once I've calmed down and done everything properly…

Direct Detection Landscape



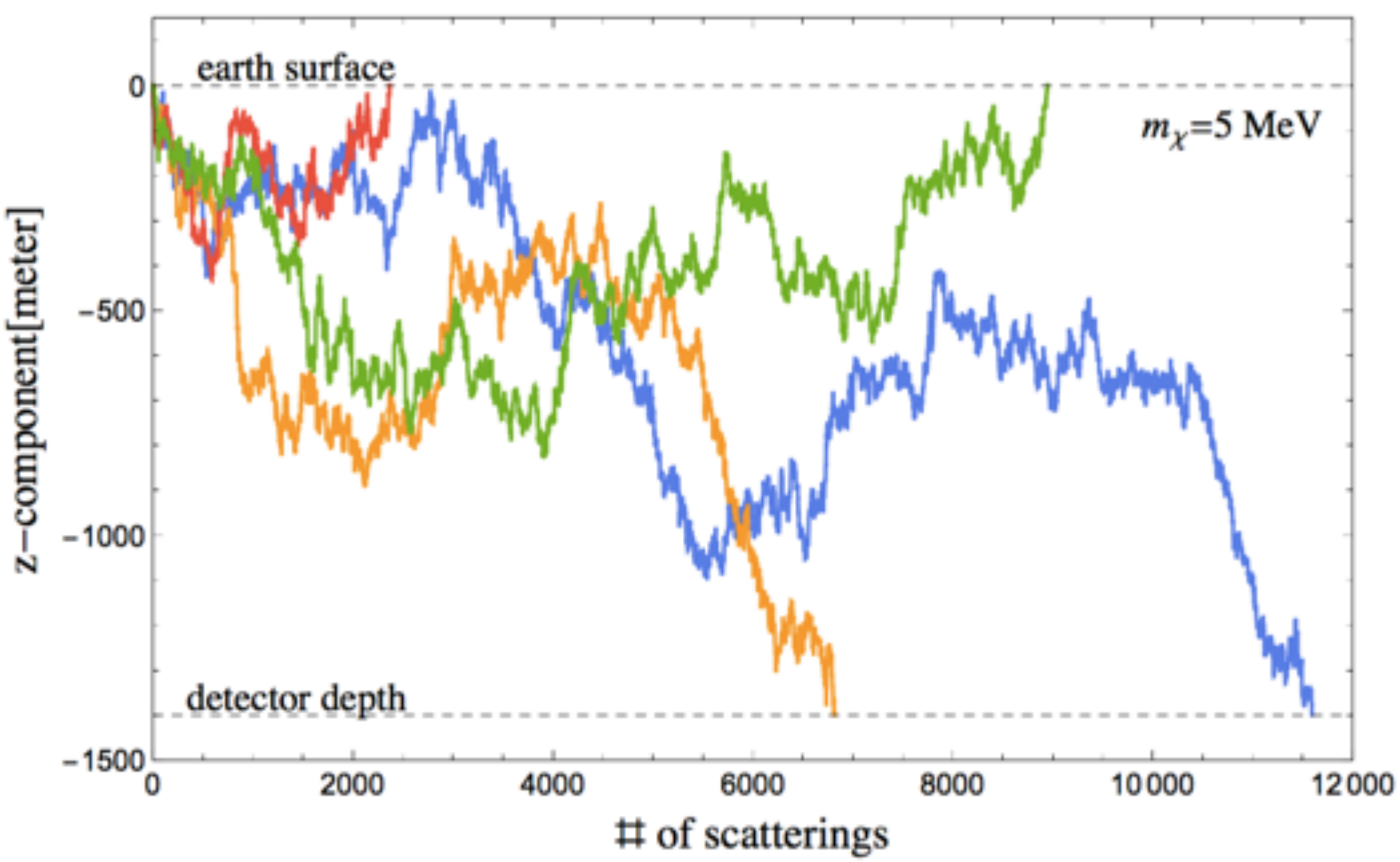
Still interesting parts of the landscape where Earth-scattering can be explored…

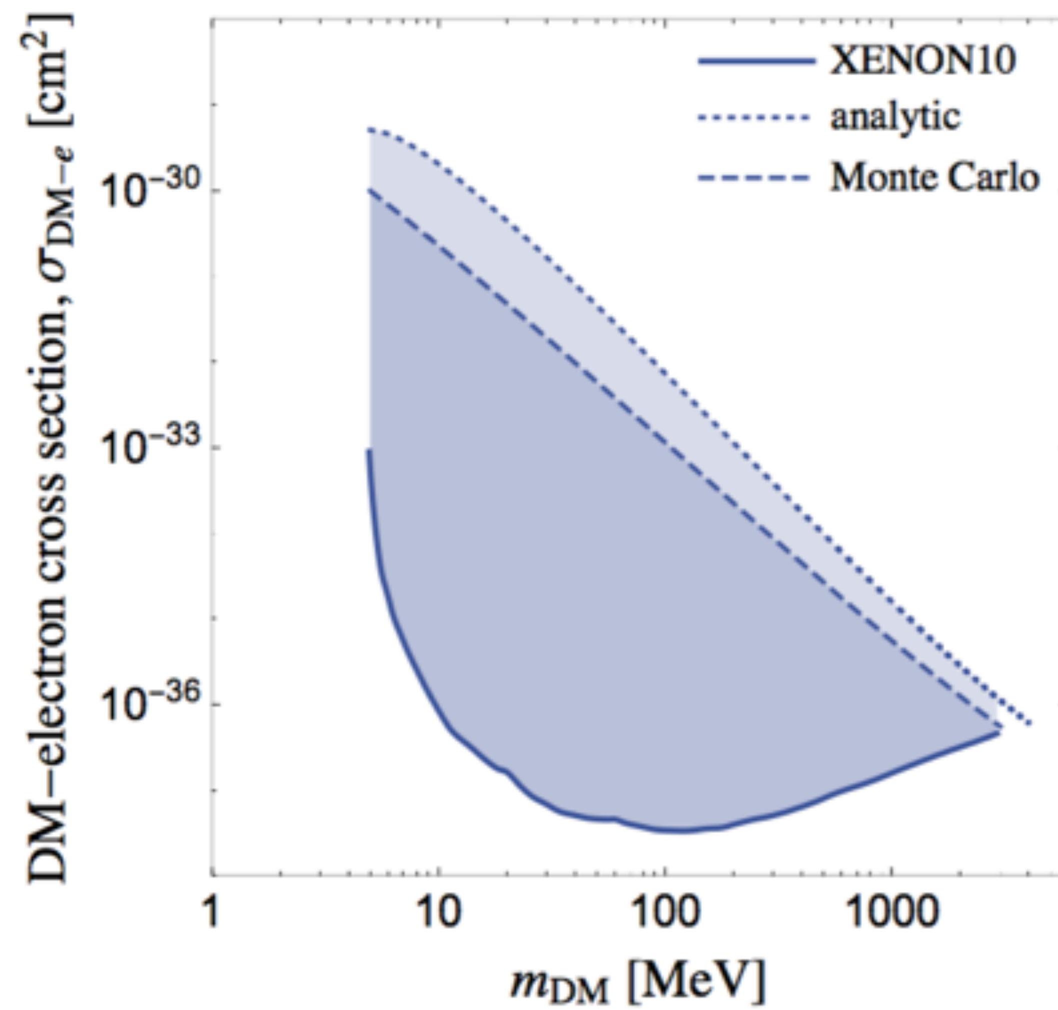
Backup Slides

Monte Carlo Simulations

State-of-the-art MC simulations are currently in development - see Emken, Kouvaris & Shoemaker [1702.07750]

Takes deflection into account in a thin portion of Earth's crust:





But still need analytic calculations to test and calibrate!