WHAT IS ν ? Workshop, 11/06 – 14/07, 2012

The Galileo Galilei Institute for Theoretical Physics, Arcetri, Florence

Theoretical uncertainties in Dark Matter indirect detection with γ -rays

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ArXiv:1206.XXXX

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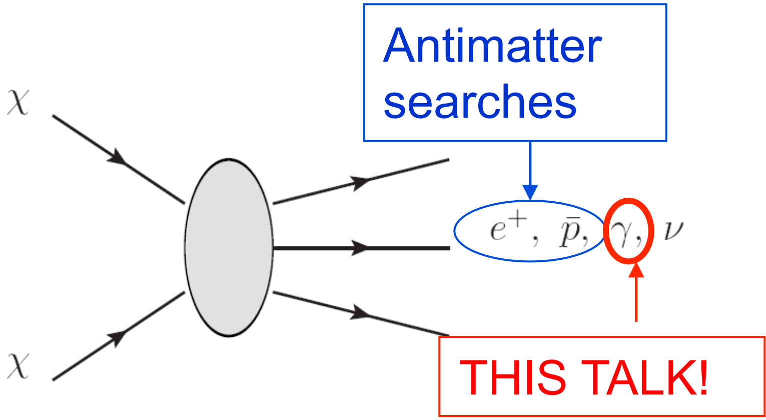
Motivation I

★ Dark matter is a cornerstone of modern cosmology... But we don't know what it's made of!

★ If DM is a WIMP, indirect detection is a promising possibility to learn about its nature and properties:

In regions of high DM density in the Universe, DM can annihilate emitting photons, positrons, antiprotons or neutrinos.



Antimatter searches

THIS TALK!

★ If DM is a WIMP (cold relic), standard structure formation tells you that you should expect DM to clump on all scales down to the free-streaming scale.

★ Clumping means enhanced annihilation rates for indirect detection!

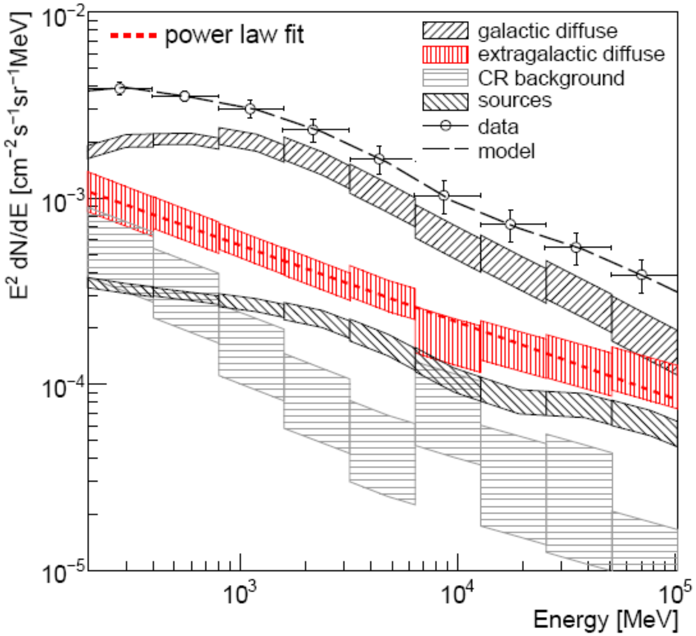
➡ What are the implications on the limits? Theoretical uncertainty?

Motivation II

- ★ Here we analyze in detail the galactic signal, which is subject to less uncertainty than the extragalactic one.

- ★ To derive limits, we use the isotropic diffuse component in the sky measured by Fermi-LAT:

The isotropic diffuse component represents roughly 25% of the total flux (for $|b| > 10°$).



[Abdo, et al., 1002.3603]

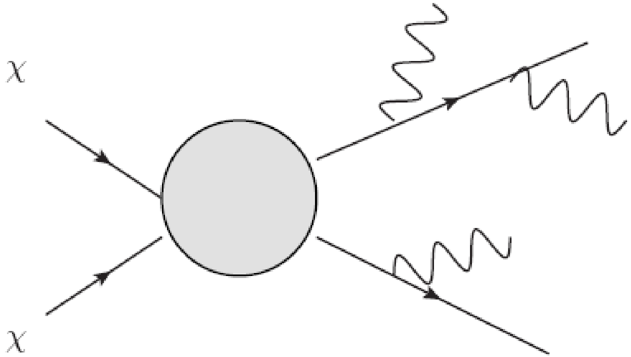
Outline

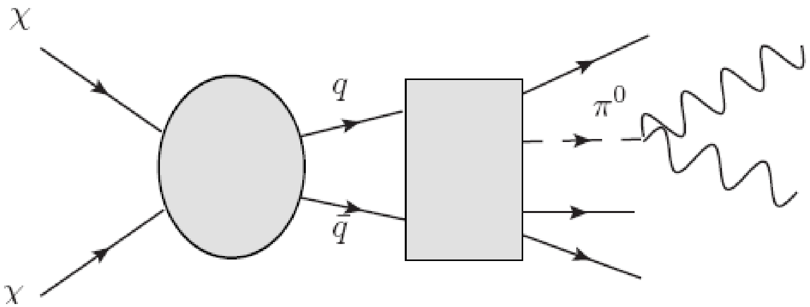
- Gamma-ray emission from DM annihilations
  - Which direction in the sky?
- Transport of final state electrons and positrons
  - Effect of diffusion on the gamma-ray emission
- Galactic substructure: Minimal halo mass and mass function index
- Results: fluxes towards the galactic anticenter, and the galactic poles
  - Flux enhancement due to substructure (Boost factor)
- Constraints on DM annihilation cross-sections
- Conclusions

Gamma-rays from Dark Matter I

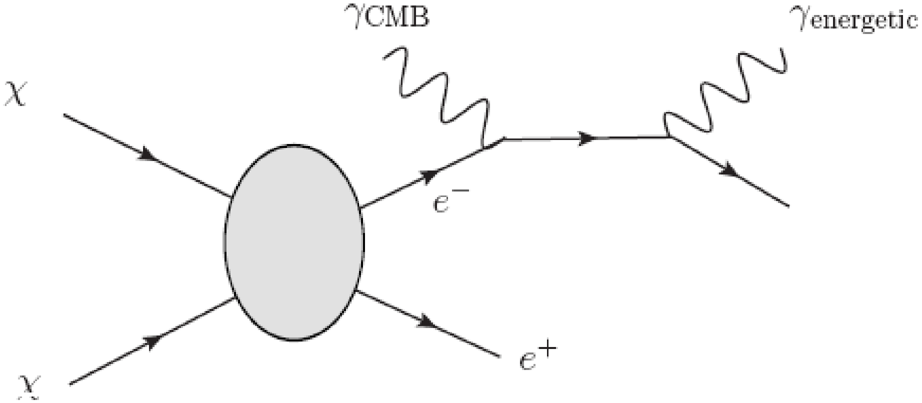
- ★ Dark matter annihilation can emit photons in many ways:

1. PROMPT EMISSION





2. INVERSE-COMPTON COMPONENT



The interstellar radiation field (IRF) is composed of:

- ✓ Starlight
- ✓ Infrared radiation
- ✓ CMB

Gamma-rays from Dark Matter II

- Dark matter annihilation can take place in our galaxy or outside. Here we concentrate on the galactic contribution only.

- The differential gamma-ray flux from DM annihilation within our galaxy is given by

Direct output from Pythia

PROMPT

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2} r_\odot \frac{\rho_\odot^2}{M_\chi^2}\boxed{\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}}\int \mathrm{d}\Omega \int_{\mathrm{los}} \frac{\mathrm{d}s}{r_\odot}\left(\frac{\rho(r)}{\rho_\odot}\right)^2$$

Components of the IRF

IC

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{4\pi} r_\odot \int \mathrm{d}\Omega \int_{\mathrm{los}} \frac{\mathrm{d}s}{r_\odot} \int_{m_e}^{M_\chi} \mathrm{d}E\, \boxed{\mathcal{N}_e(r,E)} \sum_i \boxed{\mathcal{P}_i(E_\gamma,E,r)}$$

Electron density, calculated from the transport equation

Differential photon power emitted from IC scattering

Where we use an NFW density profile for our MW:

$$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

$$r_s = 20.2\ \mathrm{kpc}, \quad \rho_\odot = 0.395\ \mathrm{GeV/cm^3}, \quad r_\odot = 8.29\ \mathrm{kpc}$$

Direction in the sky

- ★ When constraining DM annihilation cross-sections with the IGRB, it is customary to calculate the gamma-ray flux in the direction where it is minimal.

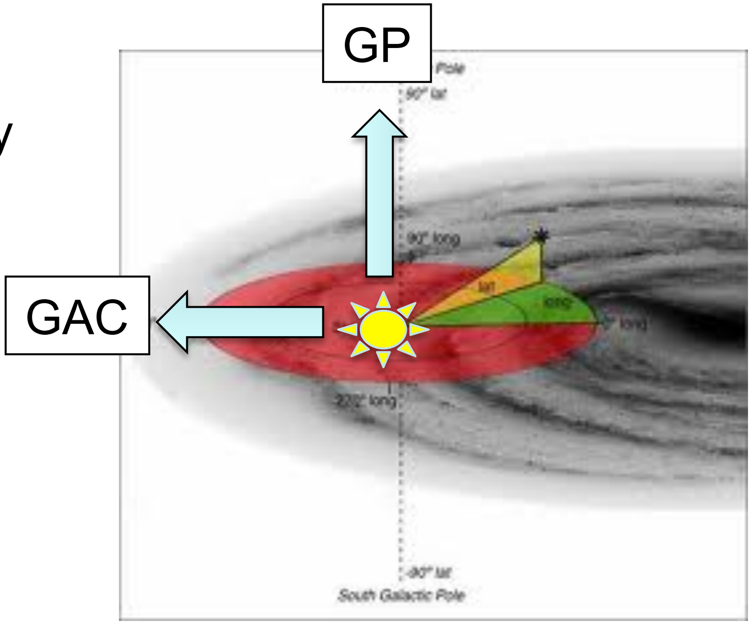
  → galactic anticenter (b=0°, l=180°) when the DM halo is smooth.

- ★ Here we argue that the direction of the galactic pole (b=90°, l=0°) can also be used :

The galactic diffuse component is dominated in this direction by proton-gas emission and γ-ray sources, which are subject to little uncertainty!

→ Residual flux at the level of the IGRB!

(also: the presence of substructure makes the signal more isotropic…)



Transport of galactic electrons I

- ★ The diffusion-loss equation for electrons in steady state is given by

$$K(E)\triangle\mathcal{N}(\vec{x},E)-\frac{\partial}{\partial E}\left\{b(\vec{x},E)\mathcal{N}(\vec{x},E)\right\}+Q(\vec{x},E)=0$$

Diffusion coefficient	Energy losses	Source term
$K(E)=K_0E^\delta$	IC, synchrotron	$Q(\vec{x}_s,E_s)=\langle\sigma v\rangle\frac{\rho(\vec{x}_s)^2}{2M_\chi^2}\frac{\mathrm{d}N_e}{\mathrm{d}E_s}$

- ★ The diffusion-loss equation can be solved analytically in the absence of boundary conditions, and if energy losses are independent of position (true for the CMB!).

$$\mathcal{N}_e(\vec{x},E)=\frac{1}{b(E)}\int_{E_s=E}^{E_s=\infty}\mathrm{d}E_s\int\mathrm{d}^3\vec{x}_s\,G_e(\vec{x}_s,E_s\to\vec{x},E)\,Q(\vec{x}_s,E_s)$$

with the Green's function given by

$$G_e(\vec{x}_s,E_s\to\vec{x},E)=\frac{1}{(4\pi K_0\tilde{\tau})^{3/2}}\exp\left(-\frac{|\vec{x}-\vec{x}_s|^2}{4K_0\tilde{\tau}}\right)$$

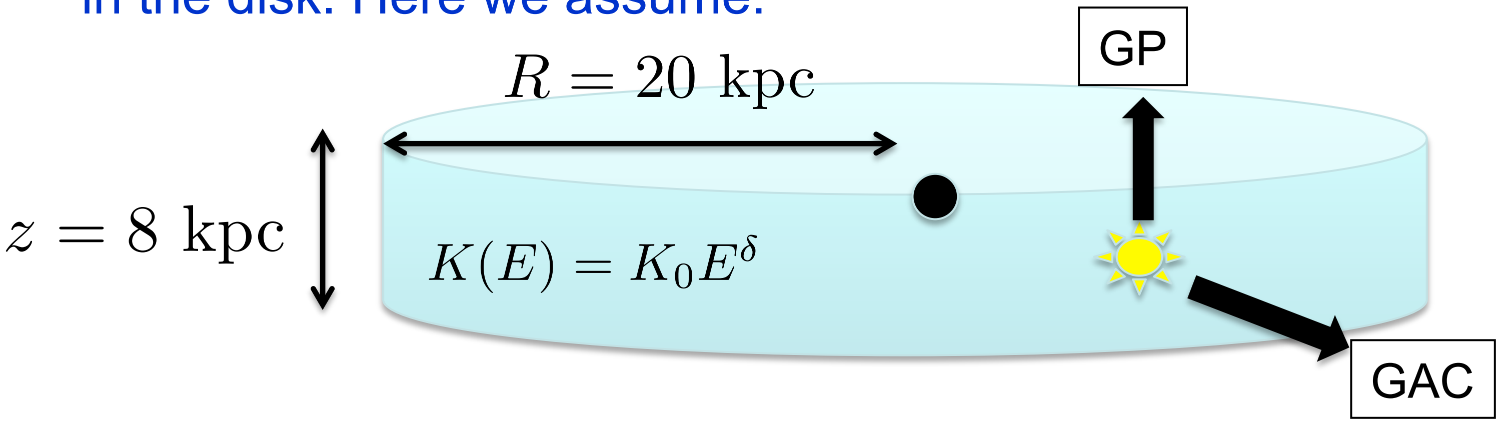
- ★ The assumption of no-diffusion corresponds to the limit

$$G_e(\vec{x}_s,E_s\to\vec{x},E)\to\delta^3(\vec{x}_s-\vec{x})$$

Transport of galactic electrons II

- ★ When computing the IC emission, it is not correct to assume a vanishing electron density at the boundary of the diffusion cylinder. (it is ok for the local electron flux from astrophysical sources)

- ★ It is also not accurate to use a diffusion coefficient that is constant throughout the DM halo. Magnetic inhomogeneities are mainly present in the disk. Here we assume:

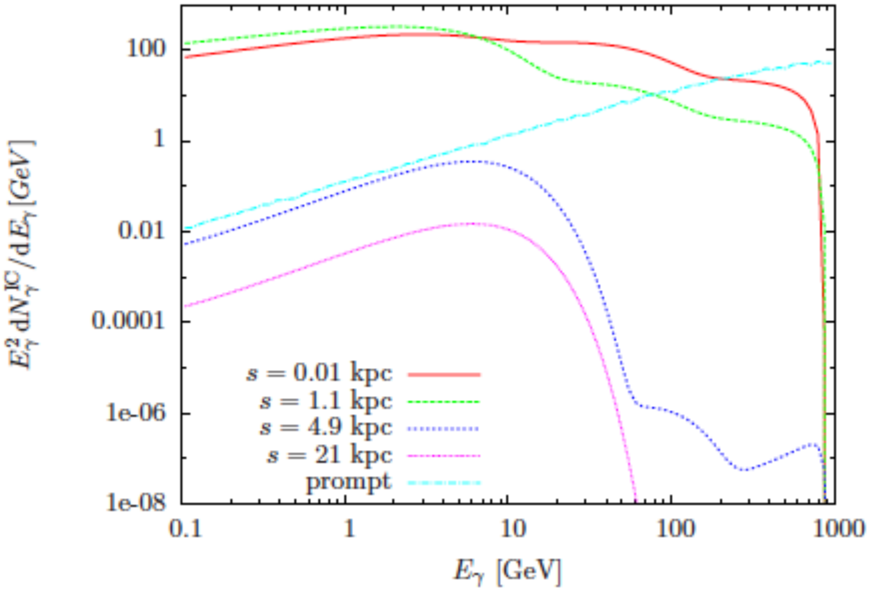


$K(E) \to \infty$ ➡ Only electrons with undegraded energy $E = E_s$ contribute!

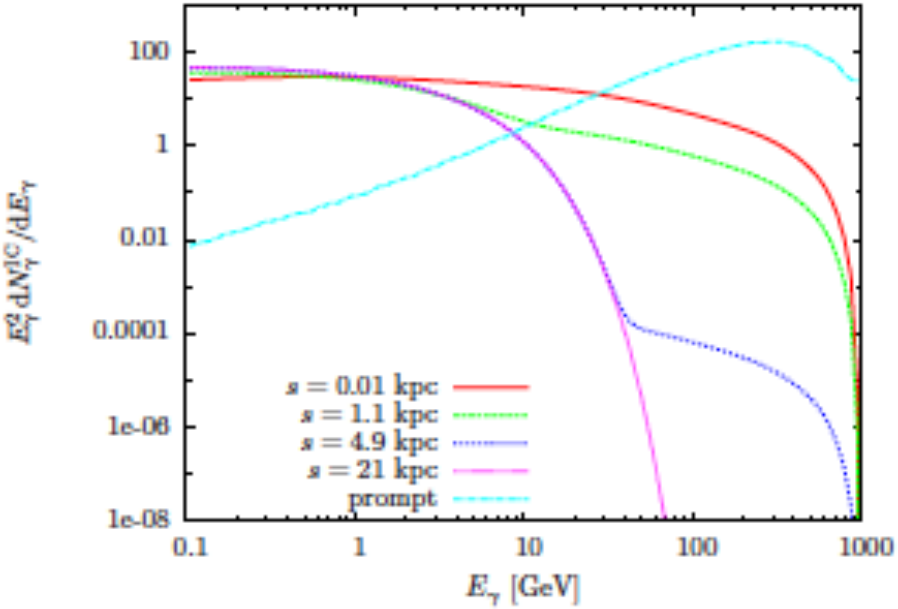
Emission spectrum

Direction of Galactic Poles

$$\chi\chi \to e^+e^-$$



$$\chi\chi \to \tau^+\tau^-$$



Galactic substructure I

- ★ It is expected on theoretical grounds and confirmed in N-body simulations that DM forms clumps on a wide range of scales.

$$\rho_{\rm tot}(r) = \rho_{\rm sm}(r) + \rho_{\rm sub}(r)$$

$$\rho_{\rm sm}(r) = \frac{\rho_{\rm tot}(r)}{1+r/\boxed{r_b}} \qquad \rho_{\rm sub}(r) = \frac{\rho_{\rm tot}(r)}{1+r/r_b}\frac{r}{r_b}$$

Bias radius

Anti-biased distribution of subhalos

- ★ Knowing the distribution of clumps in our MW is of crucial importance to estimate the flux from DM annihilations. We use the formalism of probability functions:

$$\frac{dN_{\rm cl}(r,M_{\rm cl})}{dV\,dM_{\rm cl}} = N_{\rm cl}\frac{d\mathcal{P}_M(M_{\rm cl})}{dM_{\rm cl}}\frac{d\mathcal{P}_V(r)}{dV}$$

$$\left\{\begin{array}{l} \int_0^{R_{\rm vir}} \frac{{\rm d}\mathcal{P}_V(r)}{{\rm d}V}{\rm d}V = 1 \\ \int_{\boxed{M_{\rm min}}}^{M_{\rm max}} \frac{{\rm d}\mathcal{P}_M(M_{\rm cl})}{{\rm d}M_{\rm cl}}dM_{\rm cl} = 1 \end{array}\right.$$

Minimal subhalo mass

Mass function index!

Mass distribution function:

$$\frac{{\rm d}\mathcal{P}_M(M_{\rm cl})}{{\rm d}M_{\rm cl}}(M_{\rm cl}) = K_m\left(\frac{M_{\rm cl}}{M_\odot}\right)^{\boxed{-\alpha_m}}$$

Spatial distribution function:

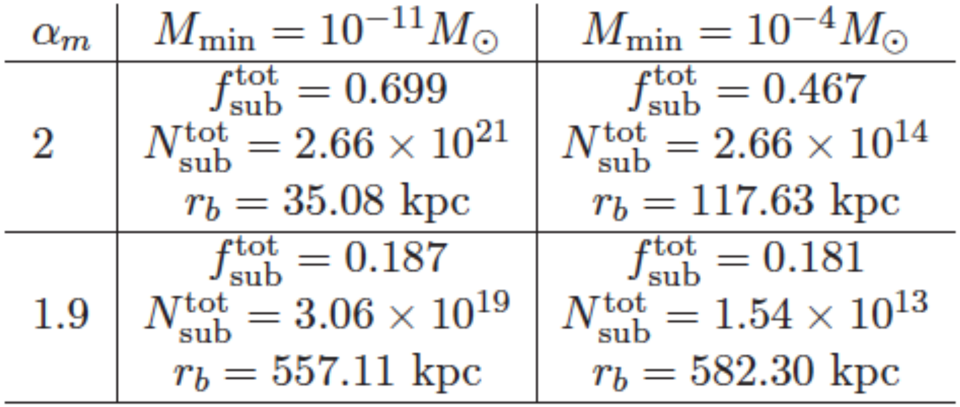
$$\frac{{\rm d}\mathcal{P}_V(r)}{{\rm d}V} = \frac{\rho_{\rm sub}(r)}{M_{\rm sub}^{\rm tot}}$$

Anti-biased!

Galactic substructure II

- ★ The mass function index and the minimal halo mass are the two most crucial parameters.
- ★ The minimal halo mass depends on the precise interactions of the DM particle with the SM, as it follows from the kinetic decoupling temperature. Here we consider $M_{\rm min} \in (10^{-11} M_\odot, 10^{-4} M_\odot)$
- ★ The mass function index can be accessed in N-body simulations (VLII, Aquarius), but their resolution is still very far from $M_{\rm min}$. The latest simulations find α_m = 1.9 whereas the Press-Schechter theory (and extended versions) on the smallest scales predict α_m = 2.

⇒ Here we choose to vary $\alpha_m \in (1.9, 2)$

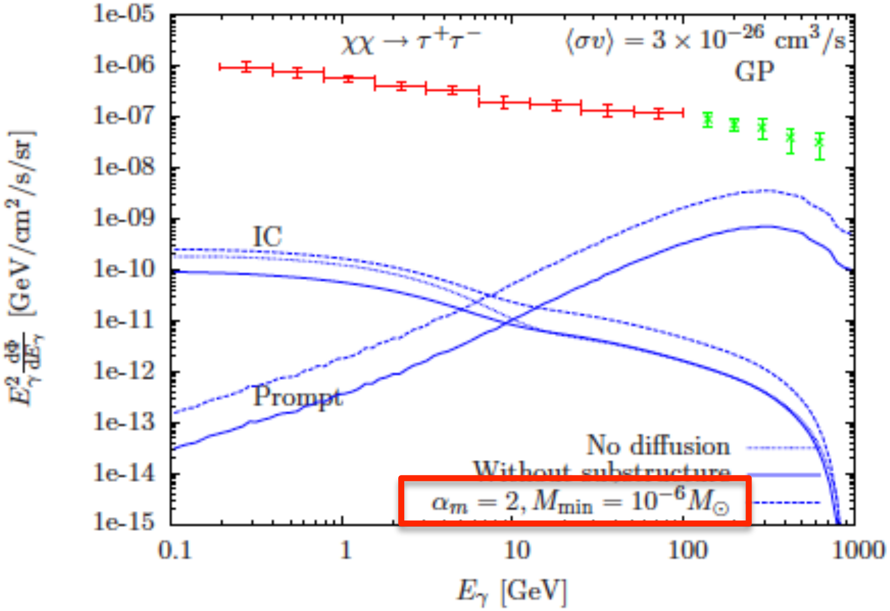


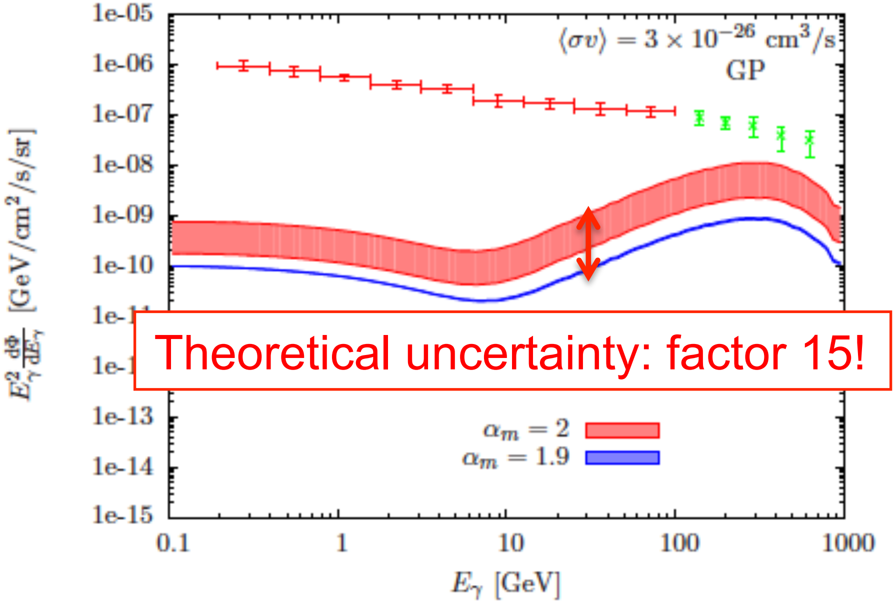
α_m	$M_{\rm min} = 10^{-11} M_\odot$	$M_{\rm min} = 10^{-4} M_\odot$
2	$f_{\rm sub}^{\rm tot} = 0.699$ $N_{\rm sub}^{\rm tot} = 2.66 \times 10^{21}$ $r_b = 35.08$ kpc	$f_{\rm sub}^{\rm tot} = 0.467$ $N_{\rm sub}^{\rm tot} = 2.66 \times 10^{14}$ $r_b = 117.63$ kpc
1.9	$f_{\rm sub}^{\rm tot} = 0.187$ $N_{\rm sub}^{\rm tot} = 3.06 \times 10^{19}$ $r_b = 557.11$ kpc	$f_{\rm sub}^{\rm tot} = 0.181$ $N_{\rm sub}^{\rm tot} = 1.54 \times 10^{13}$ $r_b = 582.30$ kpc

Gamma-ray fluxes on Earth

- ★ The gamma-ray flux on Earth from DM annihilations in our Galaxy can be calculated to be:

$$M_{\rm min} \in (10^{-11} M_\odot, 10^{-4} M_\odot)$$





Theoretical uncertainty: factor 15!

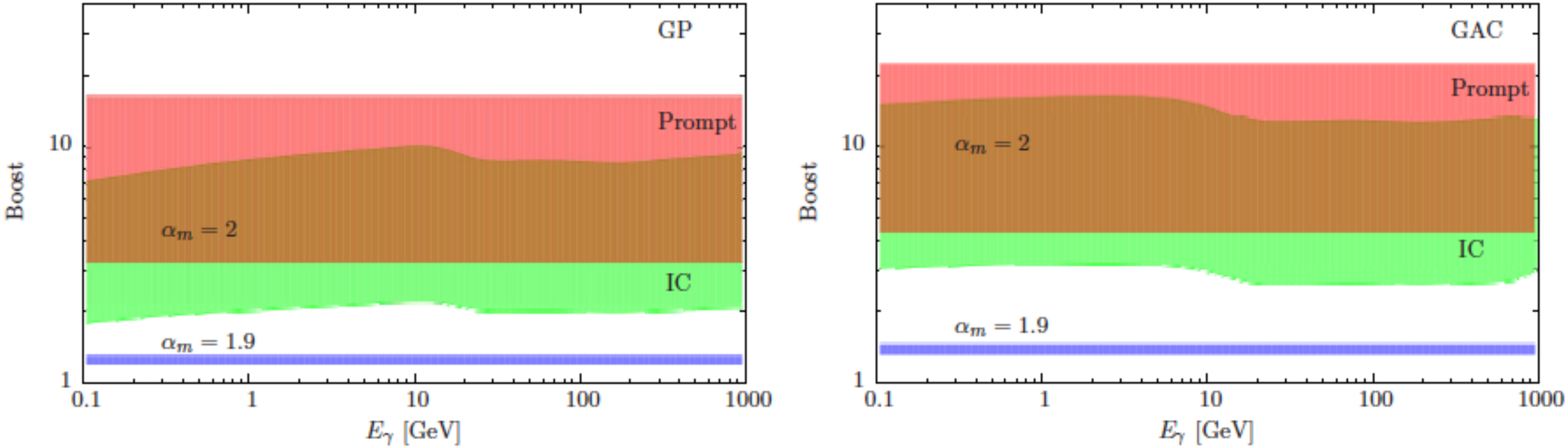
1. Effects of diffusion moderate
2. Substructure important, especially for prompt rad.!

With α_m = 1.9, almost no dependence on M_{min} !

Boost factor

- ★ The boost factor gives the flux enhancement due to the presence of substructure in our Galaxy.

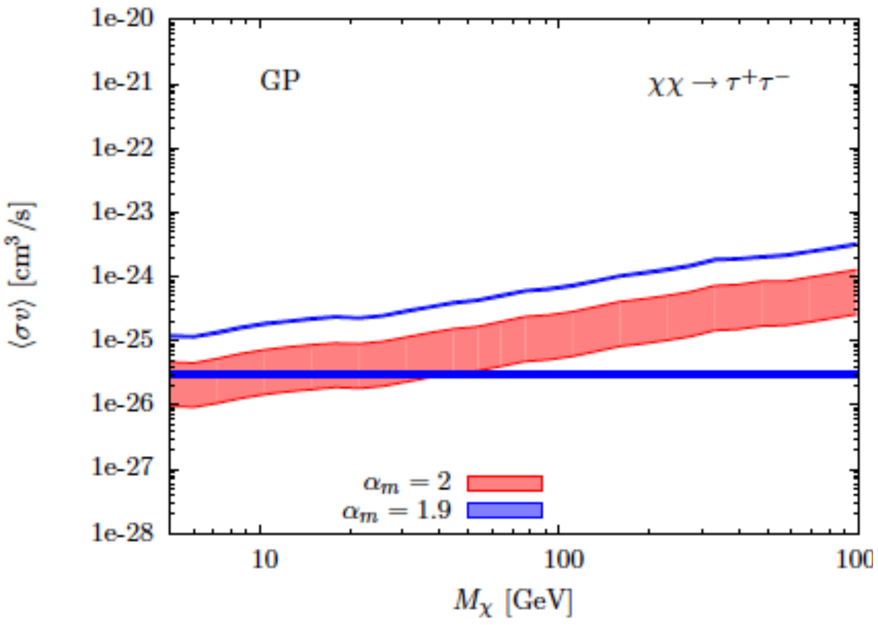
$$\mathrm{Boost} \equiv \frac{\mathrm{d}\Phi^{\mathrm{sub}}/\mathrm{d}E_\gamma + \mathrm{d}\Phi^{\mathrm{smooth}}/\mathrm{d}E_\gamma}{\mathrm{d}\Phi^{\mathrm{nosub}}/\mathrm{d}E_\gamma}$$

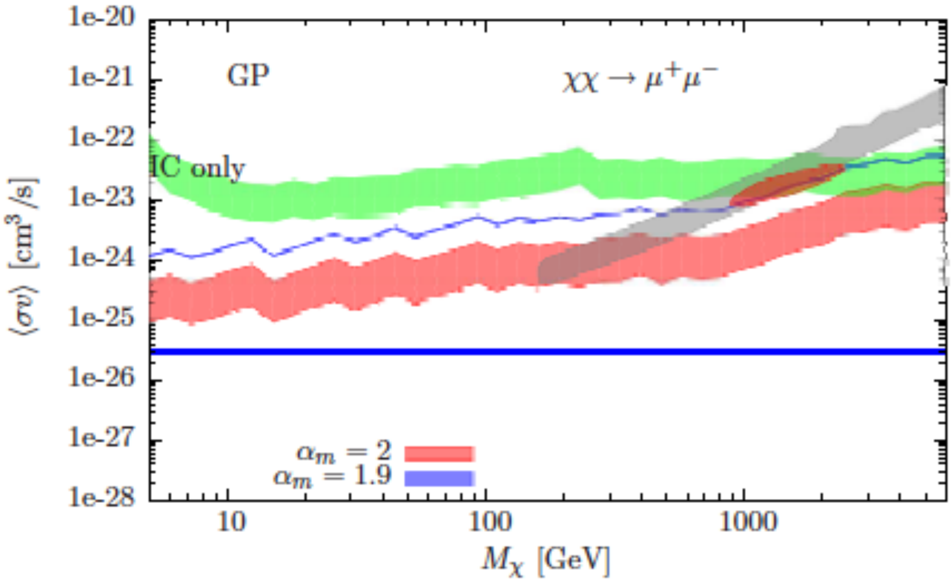


$$M_{\min} \in (10^{-11} M_\odot, 10^{-4} M_\odot)$$

Exclusion limits

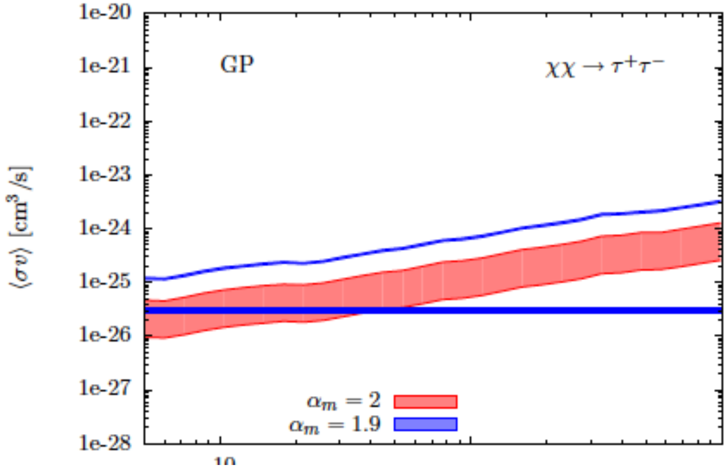
- One can then extract exclusion limits by requiring that the flux does not exceed the IGRB.

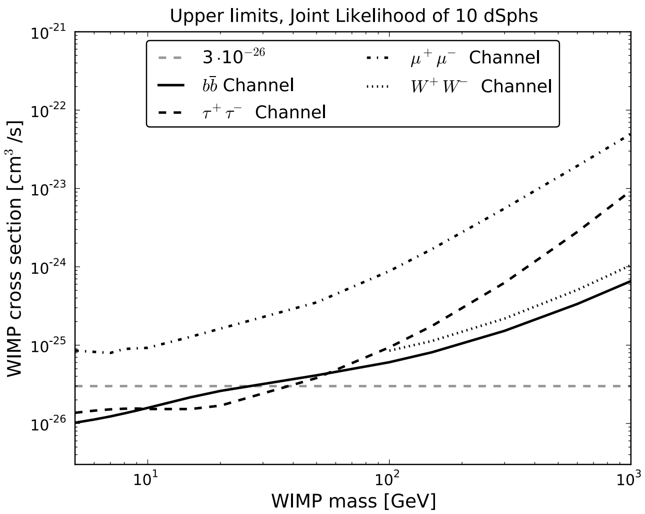




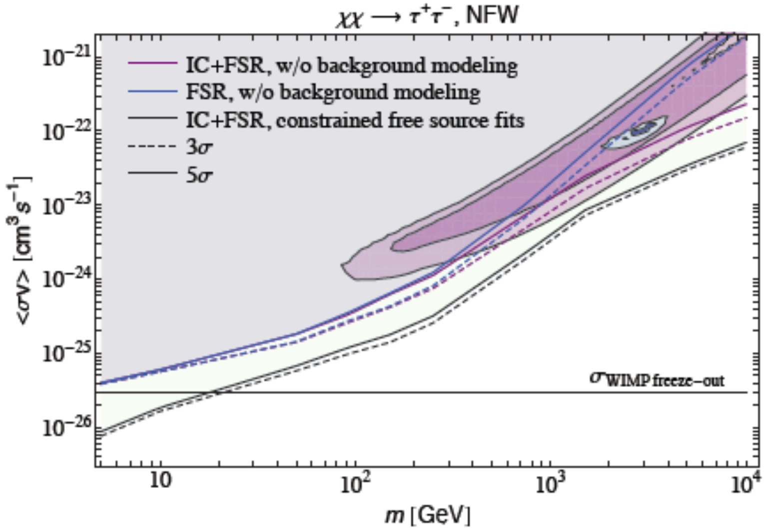
Exclusion limits

- We can compare our bounds to the most recent ones by the Fermi collaboration:





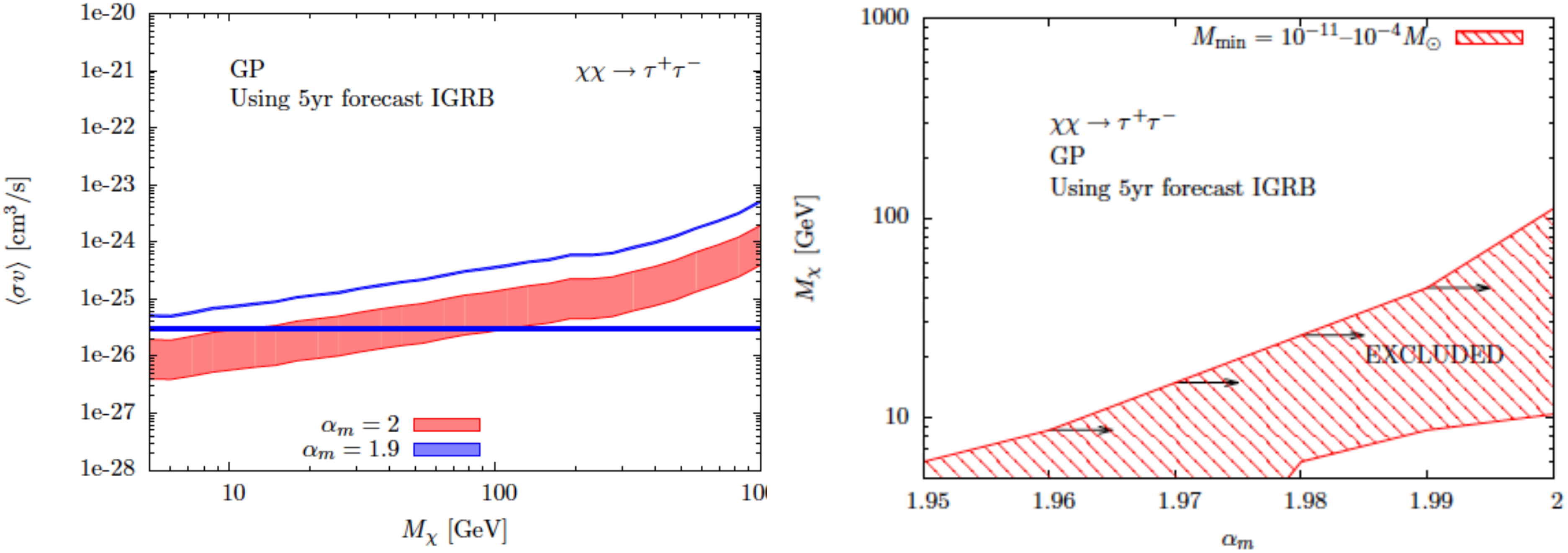
[1108.3546]



[1205.6474]

Exclusion limits

- The most likely origin for the IGRB is from blazars. Assuming that they make most of it, we obtain more stringent constraints:



Conclusions

- ★ Fermi-LAT gamma-ray measurements offers great probes of the WIMP DM paradigm.

- ★ Transport of final state electrons/positrons can play a role, especially at low energies and for the GP direction. It also affects substructure enhancement.

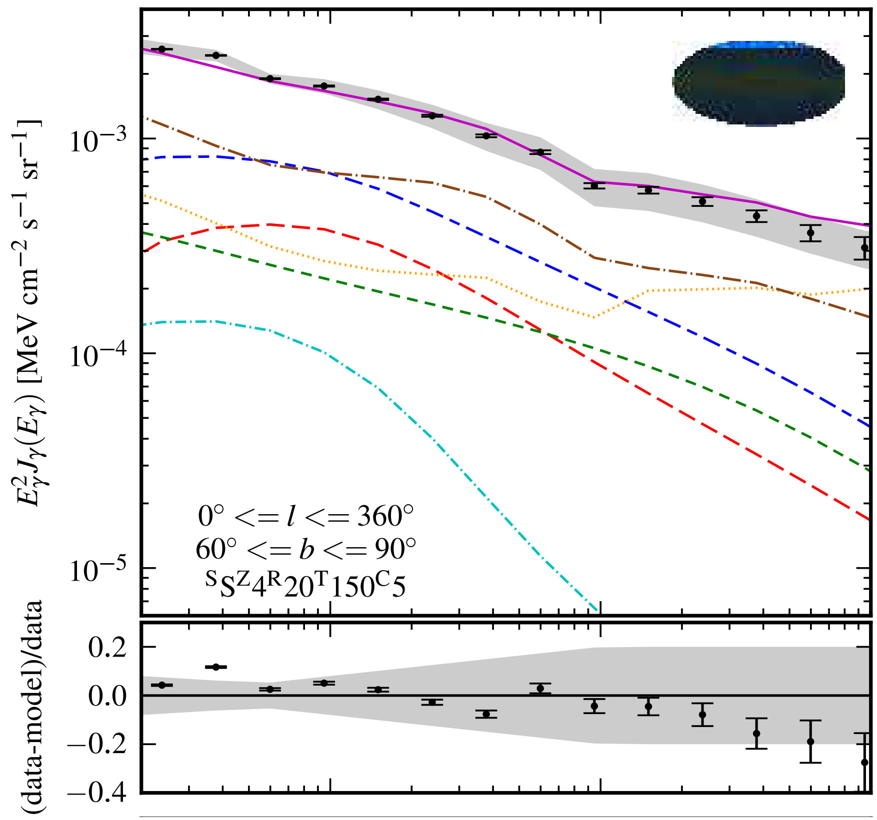
- ★ We have taken into account DM galactic substructure, in agreement with recent N-body simulations. The two most relevant parameters are the mass function index, and the minimal subhalo mass.

- ★ We found that substructure can boost the signal by up to a factor of 20. With the most pessimistic assumptions, the boost is as low as 20%.

- ★ We extracted exclusion limits for DM annihilation cross-sections, and found our limits for optimistic choices of the mass function index to be competitive with the most stringent to date.

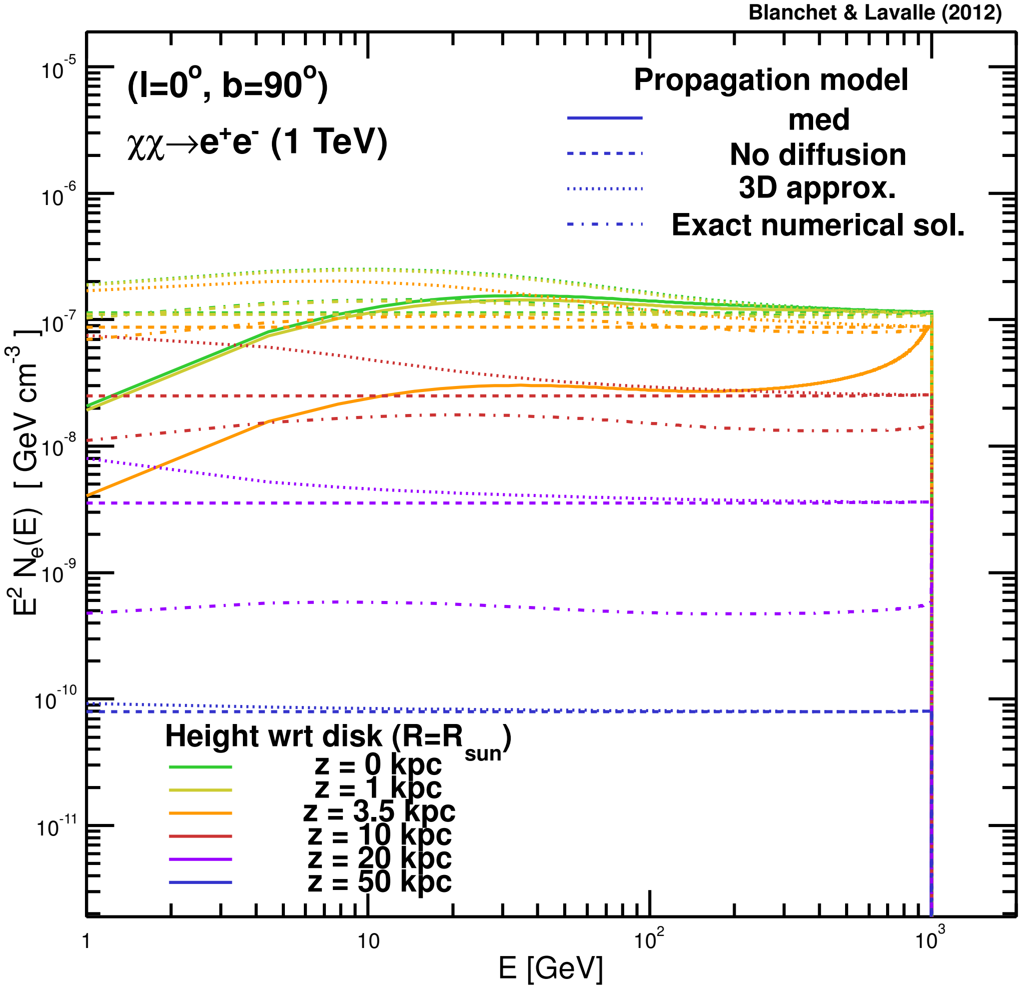
Back-up

Galactic diffuse emission



[1202.4039]

Transport of galactic electrons



Galactic substructure

- The gamma-ray flux from annihilations in galactic substructure can then be calculated with

mass distribution

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2} r_\odot \frac{\rho_\odot^2}{M_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\int \mathrm{d}\Omega \int_{\mathrm{los}}\frac{\mathrm{d}s}{r_\odot}\frac{\mathrm{d}\mathcal{P}_V}{\mathrm{d}V}(r)\int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M_{\mathrm{cl}}\,\xi(M_{\mathrm{cl}},r)\,\frac{\mathrm{d}\mathcal{P}_M(M_{\mathrm{cl}})}{\mathrm{d}M_{\mathrm{cl}}}$$

Spatial distribution

$$\xi(M_{\mathrm{cl}},\vec{x}_s) \equiv \int_{V_{\mathrm{cl}}} \mathrm{d}V \left(\frac{\rho_{\mathrm{cl}}(M_{\mathrm{cl}},\vec{x}_s)}{\rho_\odot}\right)^2$$

annihilation volume

$$\frac{\mathrm{d}N_\gamma^{\mathrm{IC}}}{\mathrm{d}E_\gamma}(r) = \int_{m_e}^{M_\chi} \mathrm{d}E \,\frac{\sum_i \mathcal{P}_i(E_\gamma,E,r)}{\sum_i b_i(E,r)} \int_E^{M_\chi} \mathrm{d}E_s \frac{\mathrm{d}N_e}{\mathrm{d}E_s}$$