PLANCK 2012

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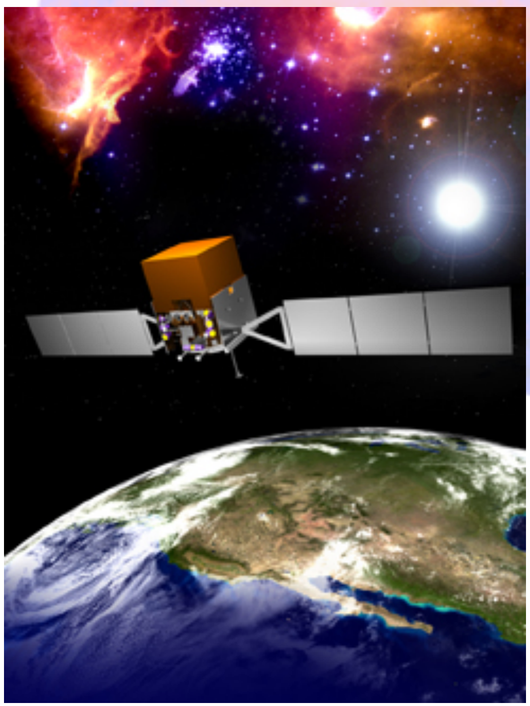
Substructure enhancement in Dark Matter indirect detection with γ -rays



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ArXiv:1205.XXXX

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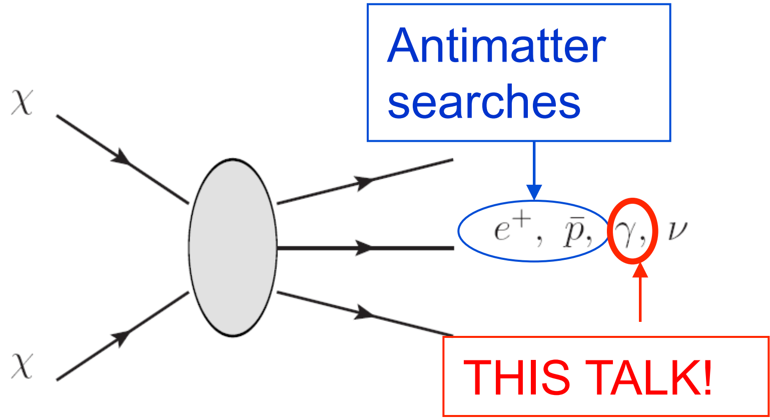
Motivation I

- ★ 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.



- ★ 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!

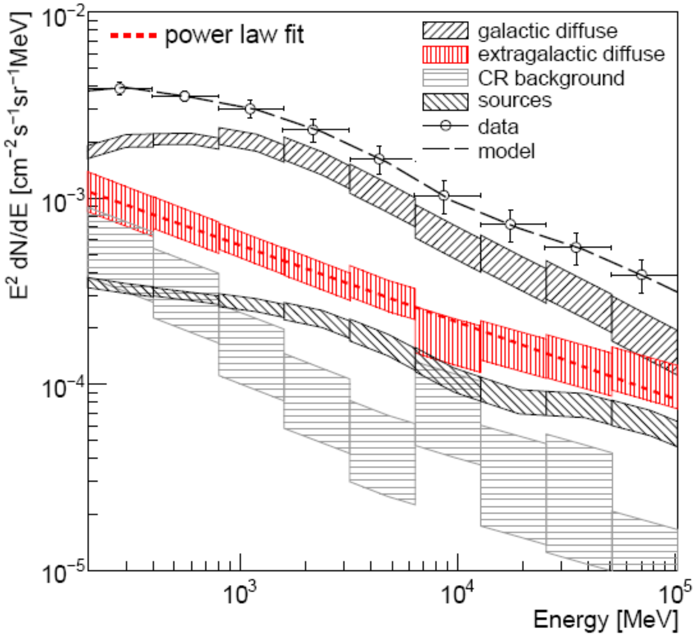
➡ What are the implications on the limits? Theoretical uncertainty?

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 $|b| > 10°$).



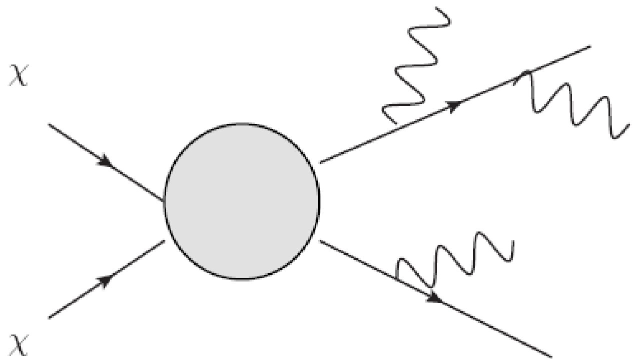
[Abdo, et al., 1002.3603]

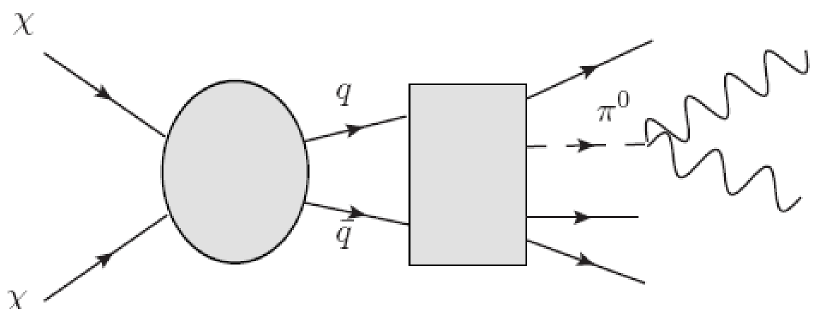
Outline

- ★ 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 high latitudes
  - □ Flux enhancement due to substructure (Boost factor)
- ★ Constraints on DM annihilation cross-sections
- ★ Conclusions

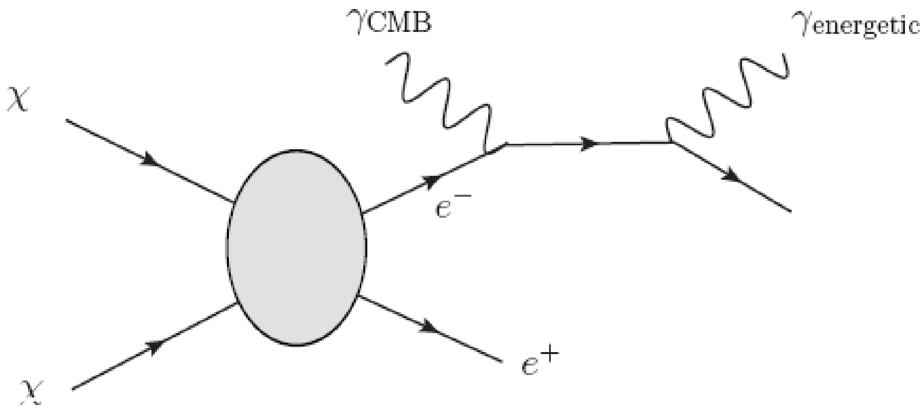
★ Dark matter annihilation can emit photons in many ways:

1. PROMPT EMISSION





2. INVERSE-COMPTON COMPONENT



The interstellar radiation field (IRF) is composed of:

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

Components of the IRF

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

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

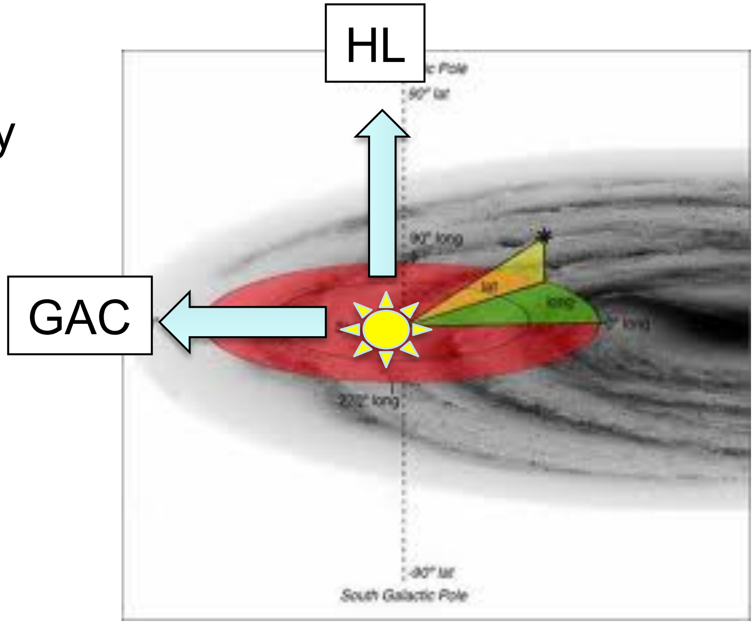
★ When constraining DM annihilation cross-sections with the IGRB, it is customary to calculate the gamma-ray flux in the direction where it is minimal.

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

★ Here we argue that the direction of the highest latitudes (galactic poles, b=90°, l=0°) can also be used for the following reason:

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

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

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

Diffusion coefficient	Energy losses	Source term
$K(E) = K_0 E^\delta$	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

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

in which case the gamma-ray spectrum from IC scattering is given by

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

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.

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

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

Bias radius

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

Anti-biased distribution of subhalos (see Via Lactea II simulation)

★ 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:

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

$$\begin{cases} \int_0^{R_{\rm vir}} \frac{\mathrm{d}\mathcal{P}_V(r)}{\mathrm{d}V}\mathrm{d}V = 1 \\ \int_{M_{\rm min}}^{M_{\rm max}} \frac{\mathrm{d}\mathcal{P}_M(M_{\rm cl})}{\mathrm{d}M_{\rm cl}}dM_{\rm cl} = 1 \end{cases}$$

Minimal subhalo mass

Mass function index!

Mass distribution function:

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

Spatial distribution function:

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

Anti-biased!

Galactic substructure II

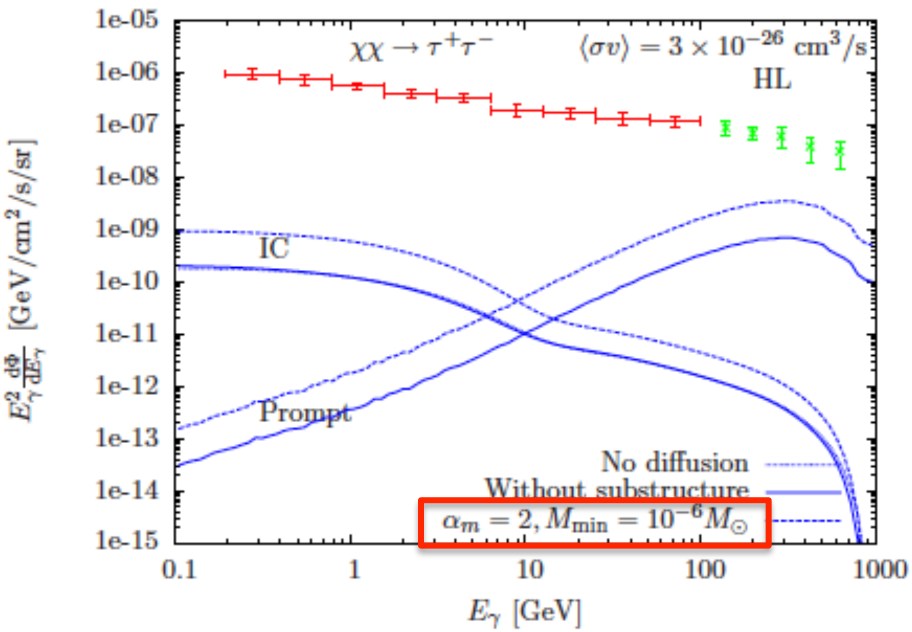
- The mass function index and the minimal halo mass are the two most crucial parameters.
- The minimal halo mass depends on the precise interactions of the DM particle with the SM, as it derives from the kinetic decoupling temperature. Here we consider $M_{\rm min} \in (10^{-11} M_\odot, 10^{-4} M_\odot)$
- 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 $\alpha_m = 1.9$ whereas the Press-Schechter theory (and extended versions) on the smallest scales predict $\alpha_m = 2$.

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

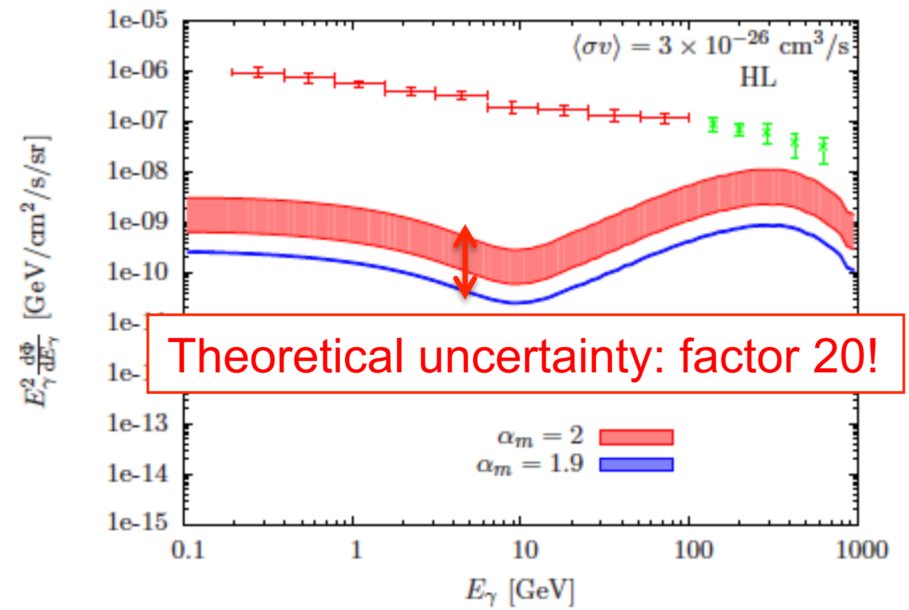
α_m	$M_{\rm min} = 10^{-11} M_\odot$	$M_{\rm min} = 10^{-4} M_\odot$
2	$f_{\rm sub}^{\rm tot} = 0.699$ $N_{\rm sub}^{\rm tot} = 2.66 \times 10^{21}$ $r_b = 35.08$ kpc	$f_{\rm sub}^{\rm tot} = 0.467$ $N_{\rm sub}^{\rm tot} = 2.66 \times 10^{14}$ $r_b = 117.63$ kpc
1.9	$f_{\rm sub}^{\rm tot} = 0.187$ $N_{\rm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



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



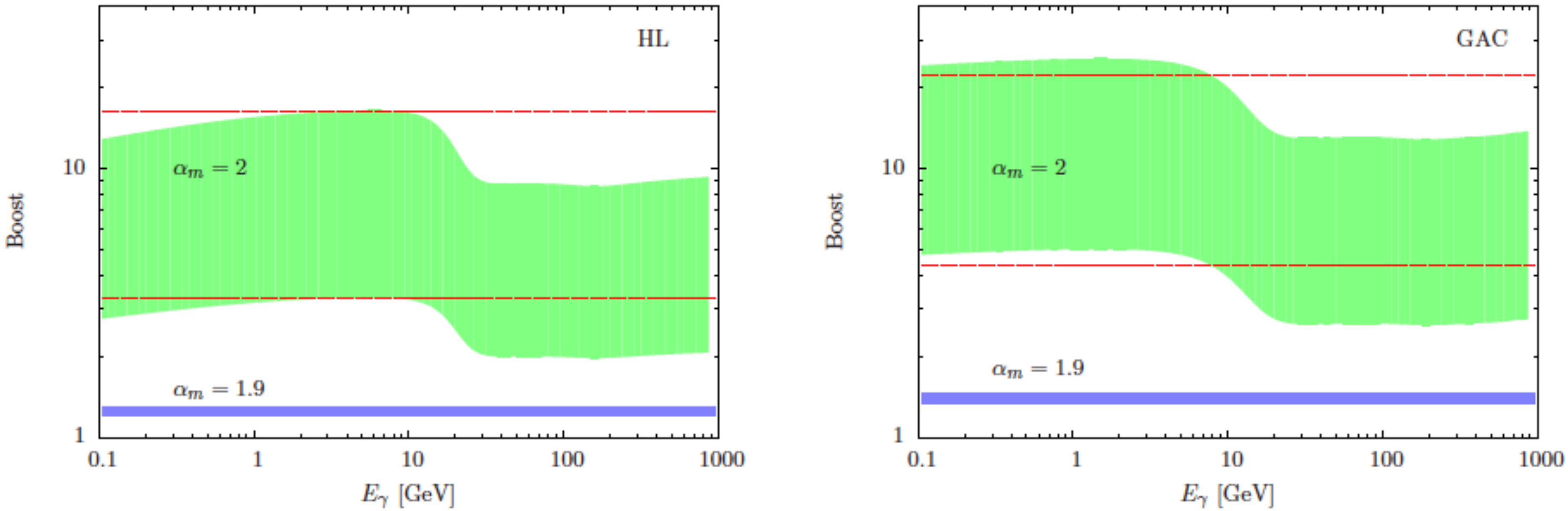
1. Effects of diffusion tiny!!
2. Substructure important

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.

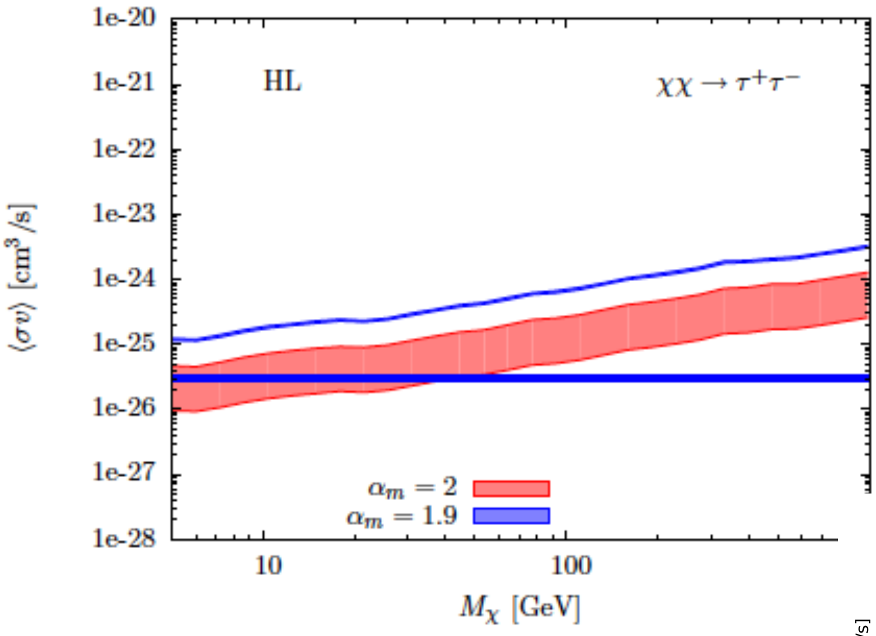
$$\text{Boost} \equiv \frac{d\Phi^{\text{sub}}/dE_\gamma + d\Phi^{\text{smooth}}/dE_\gamma}{d\Phi^{\text{nosub}}/dE_\gamma}$$

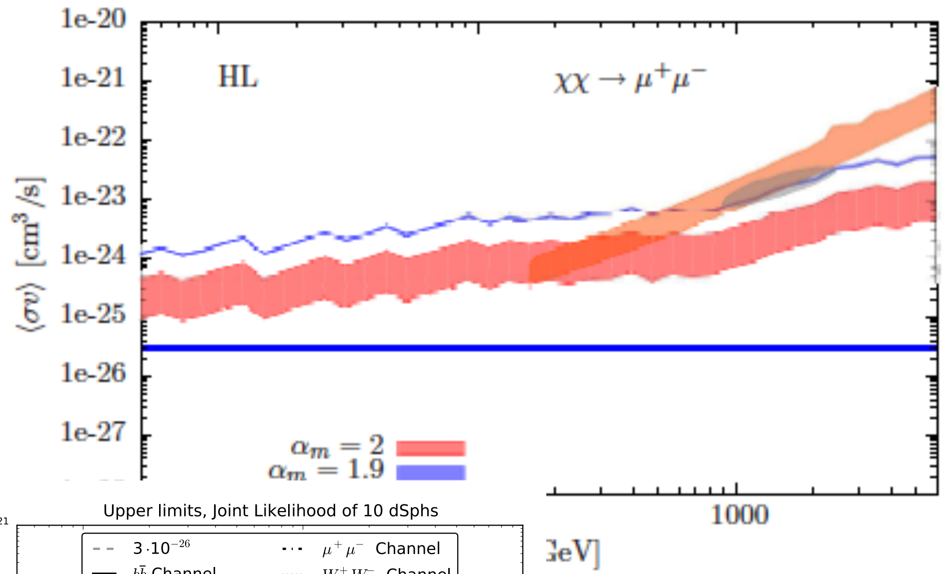


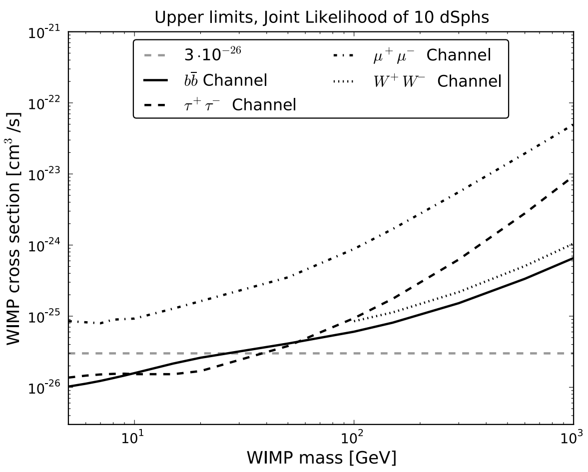
$$M_{\text{min}} \in (10^{-11} M_\odot, 10^{-4} M_\odot)$$

Exclusion limits

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







➡ To be compared with the most stringent constraints to date:

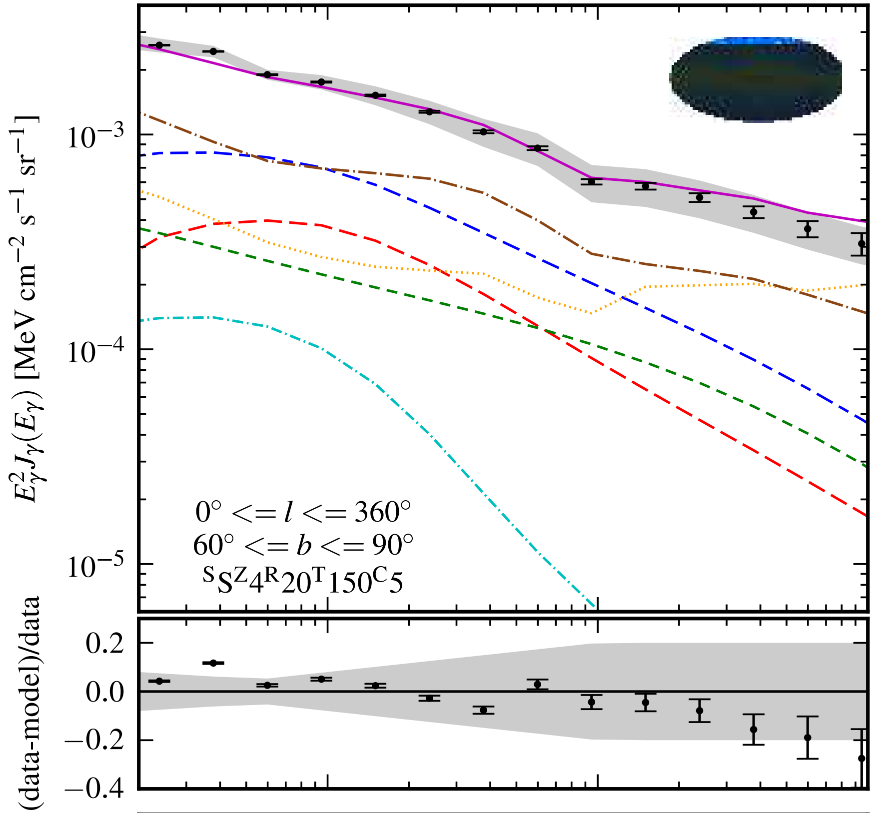
[1108.3546]

Conclusions

- Fermi-LAT gamma-ray measurements offers great probes of the WIMP DM paradigm.
- The signal from the highest latitudes can be constrained by the IGRB measurement.
- Diffusion of final state electrons/positrons plays a marginal role both for the galactic anticenter and the poles.
- 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.

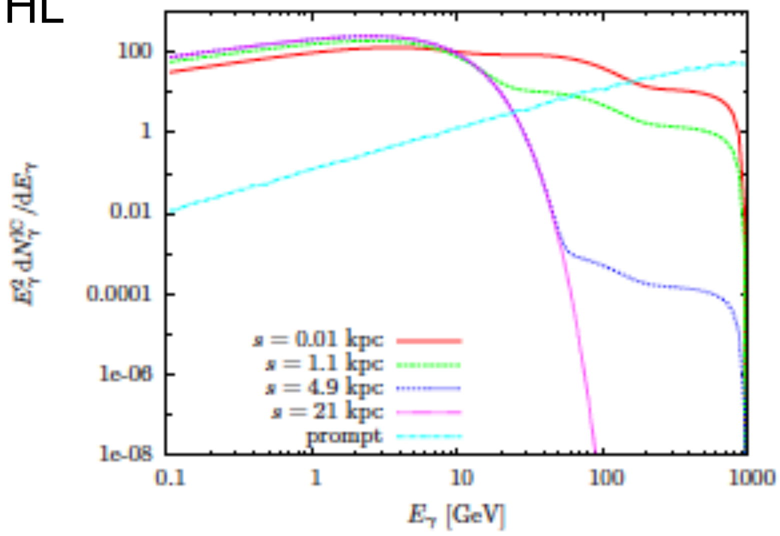
Back-up

Galactic diffuse emission

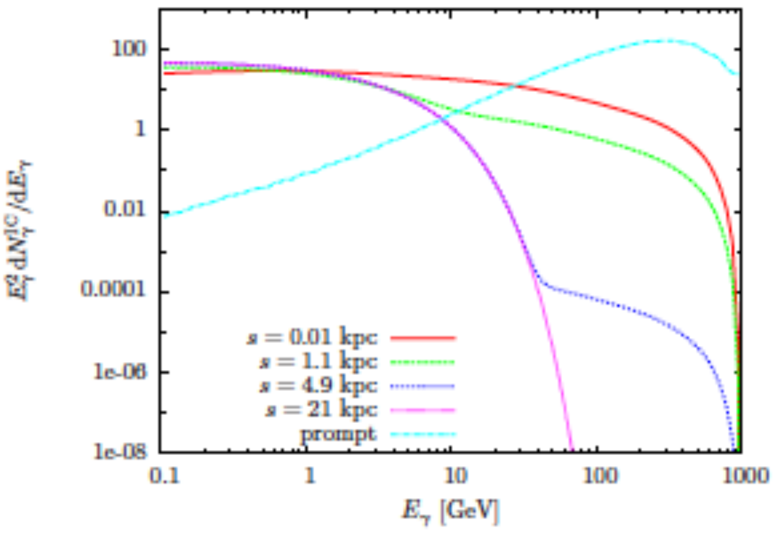


$$\chi\chi \to e^+e^-$$

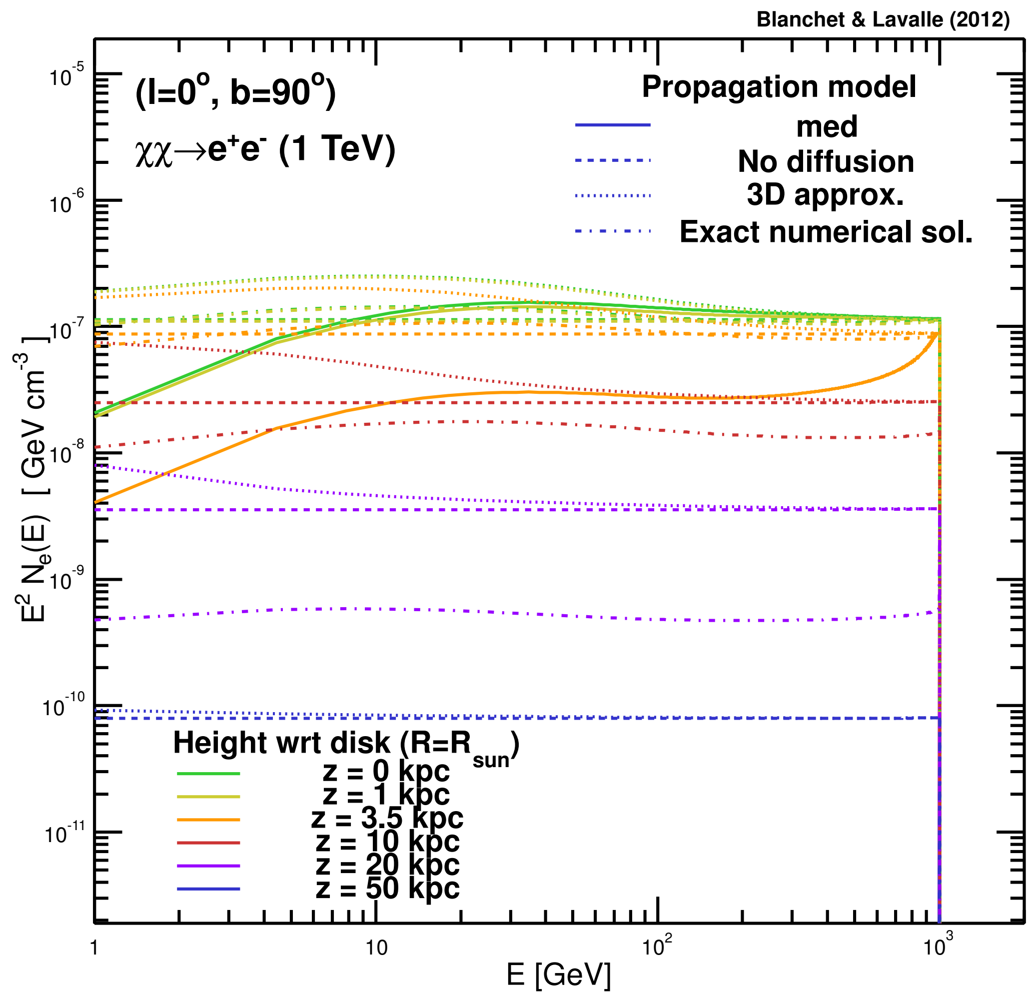
HL



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



Transport of galactic electrons



Galactic substructure

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

mass distribution

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

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

Exclusion limits

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