Valentina De Romeri[1]

Gamma-ray tests of dark matter: EGB and anisotropies

Invisibles13 Workshop
18 July 2013, Durham (UK)

Based on:

VDR with Francesca Calore and Fiorenza Donato, "**Conservative upper limits on WIMP annihilation cross section from Fermi-LAT gamma rays**", Phys.Rev. D85 (2012) 023004

and

VDR, with Francesca Calore, Mattia Di Mauro, Fiorenza Donato, Jakob Herpich, Andrea Macciò, Luca Maccione and Greg Stinson, "**Uncertainties on gamma-ray anisotropies from DM annihilation in the Milky Way**", work in progress..

[1]Astroparticle and High Energy Physics Group, IFIC, Valencia, Spain

INTRODUCTION

Preliminary assumptions

✔ DM is in the form of WIMPs

✔ WIMPs cluster in galaxies as dark halos (a main smooth halo and many subhalos), as predicted by N-body simulations

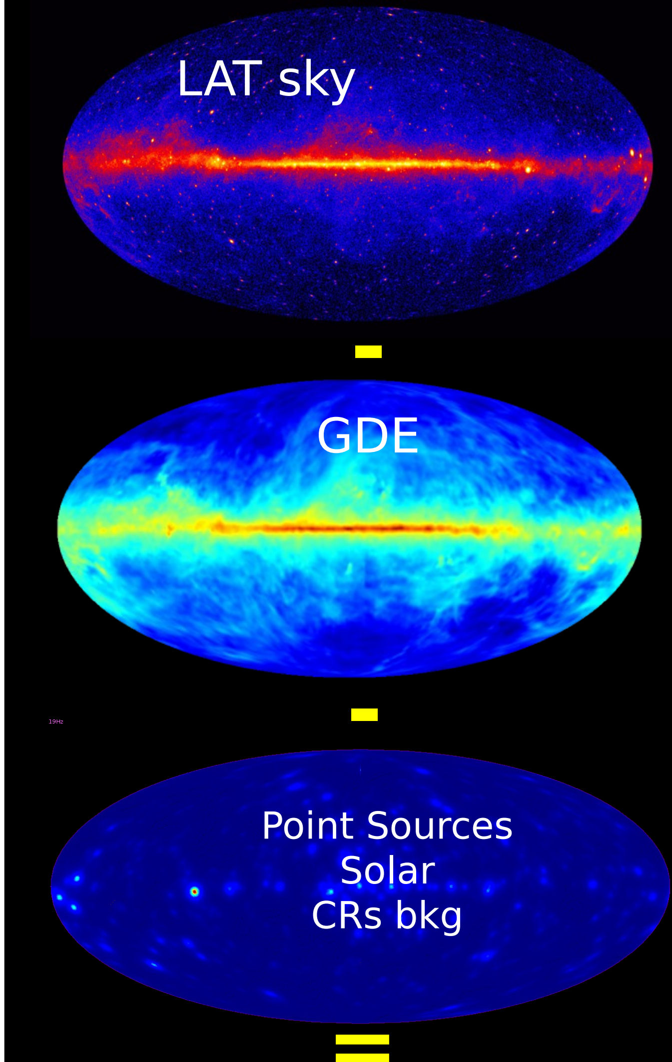
✔ A density profile (cusped or cored) describes the DM distribution inside the halos

✔ WIMPs inside halos annihilate in pairs and produce γ-rays

✔ The search for a DM component in the γ-ray sky is made by the Fermi-LAT telescope with a good angular resolution

Testing DM with the Fermi-LAT EGB

The Isotropic Diffuse Gamma-Ray Emission



Isotropic Diffuse Gamma-Ray or "Extragalactic" Background (EGB)

The Spectrum of the Isotropic Diffuse Gamma-Ray Emission Derived From First-Year Fermi Large Area Telescope Data, The Fermi-LAT Collab. Phys. Rev. Lett. 104 (2010):

- Energy range: 200 MeV – 100 GeV.
- Observational region: $|b| > 10°$ (high-latitude).
- Energy spectrum:

[1] Credit: NASA/DOE/Fermi/LAT collaboration

$$\frac{dN}{dE} = 1.45 \, x \, 10^{-7} \left(\frac{E}{100\, MeV} \right)^{-2.41} MeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

Constraining DM with the EGB

1. Understanding of the astrophysical background:
   Contributions (controversial but guaranteed):
   1. Unresolved pointlike sources extragalactic (*e.g.* AGN, normal and starbursts galaxies, GRBs, Clusters of Galaxies) and galactic (Pulsars and Millisecond Pulsars);
   2. Truly diffuse processes (*e.g.* LSS formation signature, UHECRs vs CMB, cascades of VHE gamma-rays from point sources).

2. Selection of the main contributions:
   Estimation of a residual extragalactic bkg.

3. Conservative upper limits on WIMP annihilation cross section.

Gamma rays from dark matter

The **γ-ray flux** from DM annihilation is defined as the number of photons collected by a detector per unit of time, area, energy and solid angle:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega) = \boxed{\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma)} \times \boxed{J(\psi,\theta,\Delta\Omega)}$$

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$$\boxed{\frac{d\Phi_\gamma^{PP}}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{ann} v\rangle}{2m_\chi^2}\sum_i \frac{dN_\gamma^i}{dE_\gamma} B_i}$$

PARTICLE PHYSICS factor:

- $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$ final states
- $B_i = 1$
- spectra from Cembranos et al. PhysRevD.83.083507

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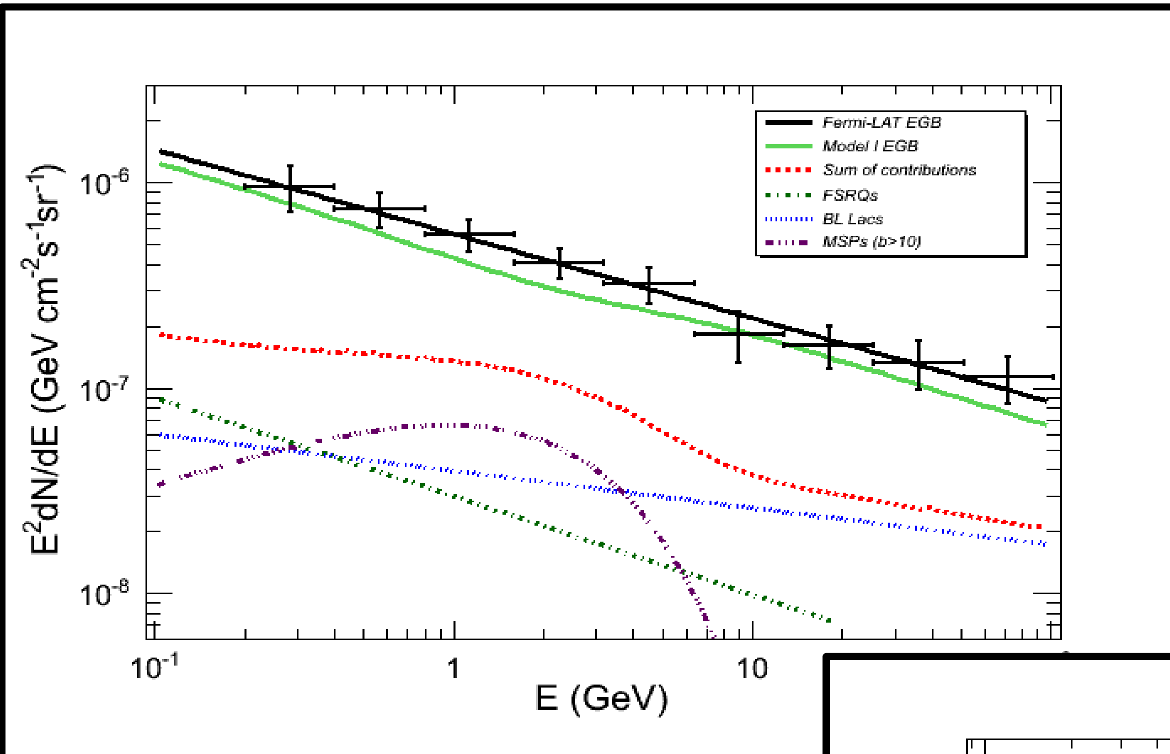
- Sensitivity to different DM halo profiles
- No galactic substructures

ASTROPHYSICAL FACTOR

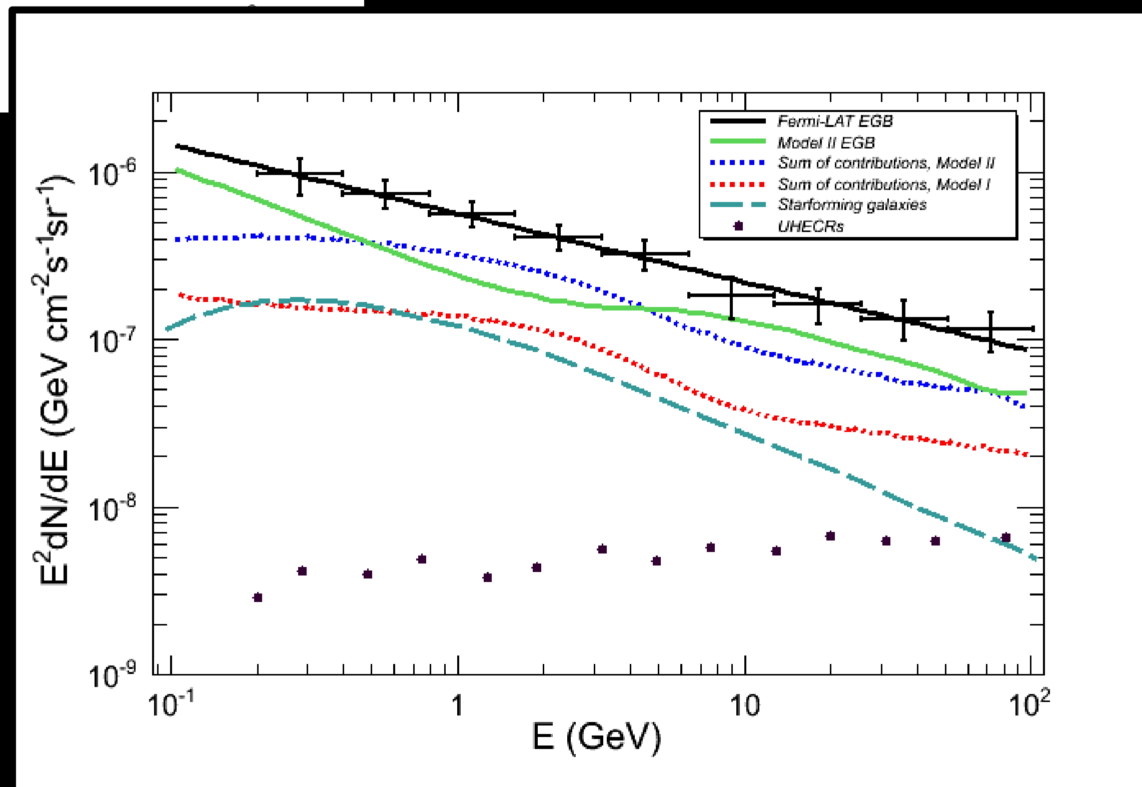
$$\boxed{J(\Psi,\theta,\Delta\Omega) = \int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r(s,\Psi,\theta))\,ds}$$

Integration of the squared DM density at a distance s from the Earth in the direction along the l.o.s and in the observational cone of solid angle ΔΩ



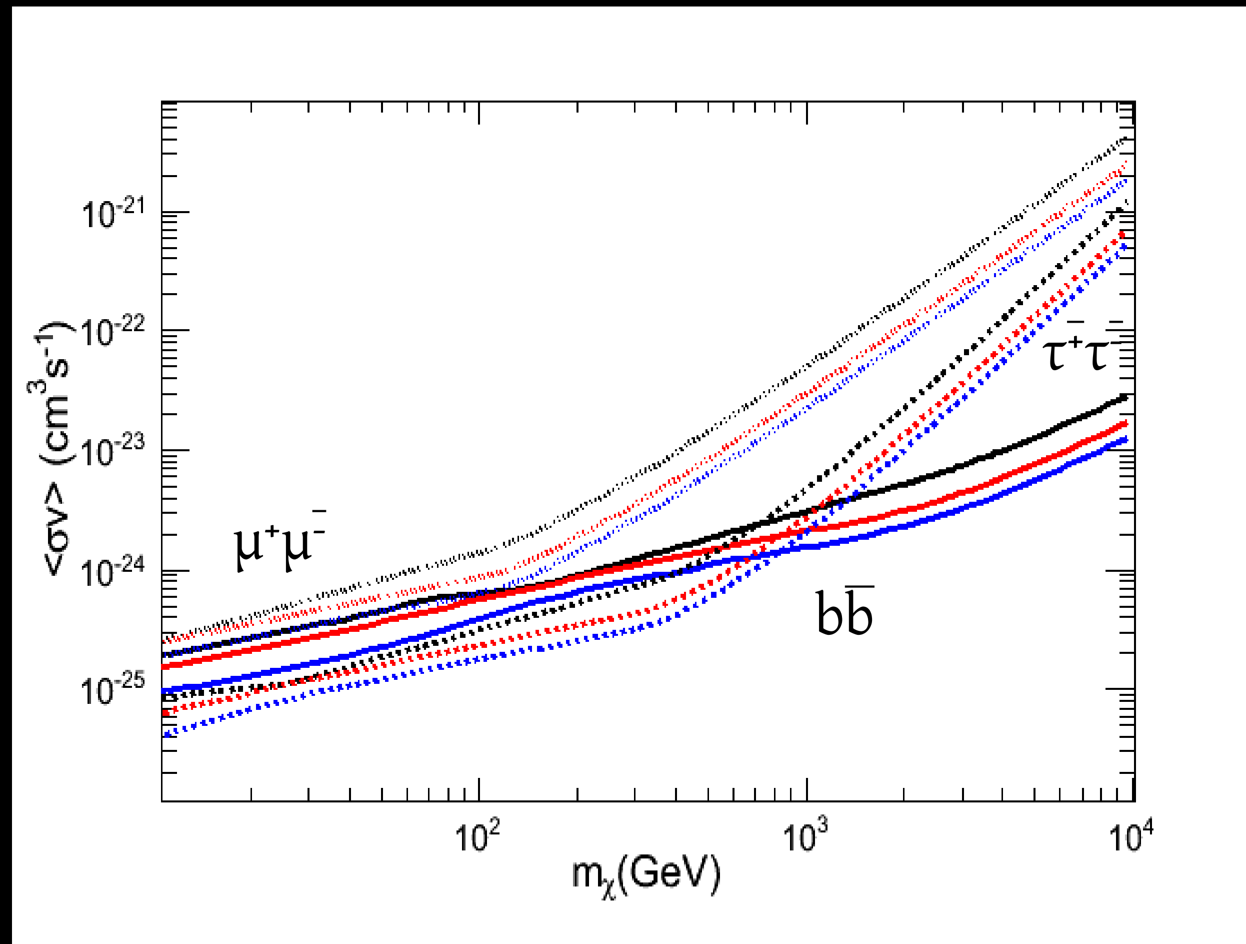
Two scenarios:

- Conservative (subtracting the emission from unresolved blazars and MSPs)
- Relaxed (further subtracting starforming galaxies and gamma rays from UHECRs).



Conservative upper limits on <σv>

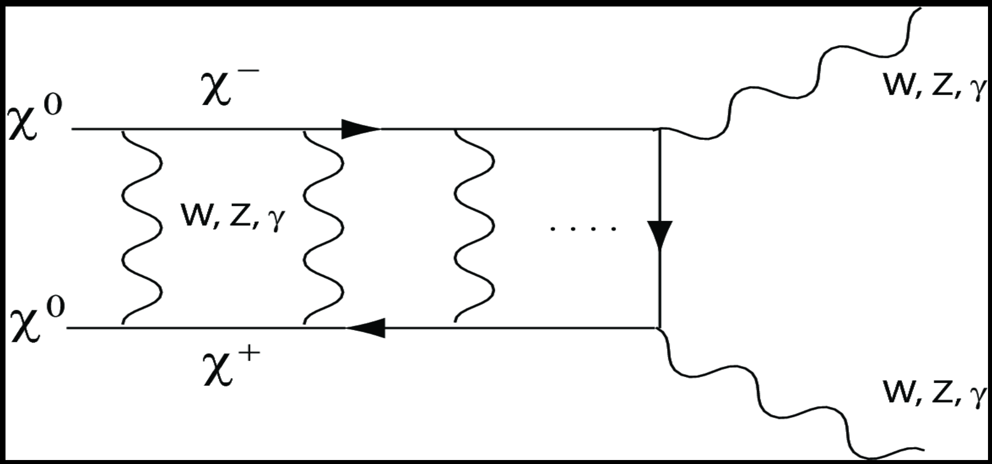
- Cored isothermal density profile for the Galactic halo;
- Smooth halo (no clumpiness);
- DM final states: $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$



  - Conservative limits;
  - Mild differences due to final states;
  - Advantages of indirect detection through gamma rays (propagation not affected by magnetic fields)

Updated limits, with the inclusion of MAGN and ICS: Calore et al., arXiv:1303.3284

Bounds on the Sommerfeld enhanced $\langle\sigma v\rangle$

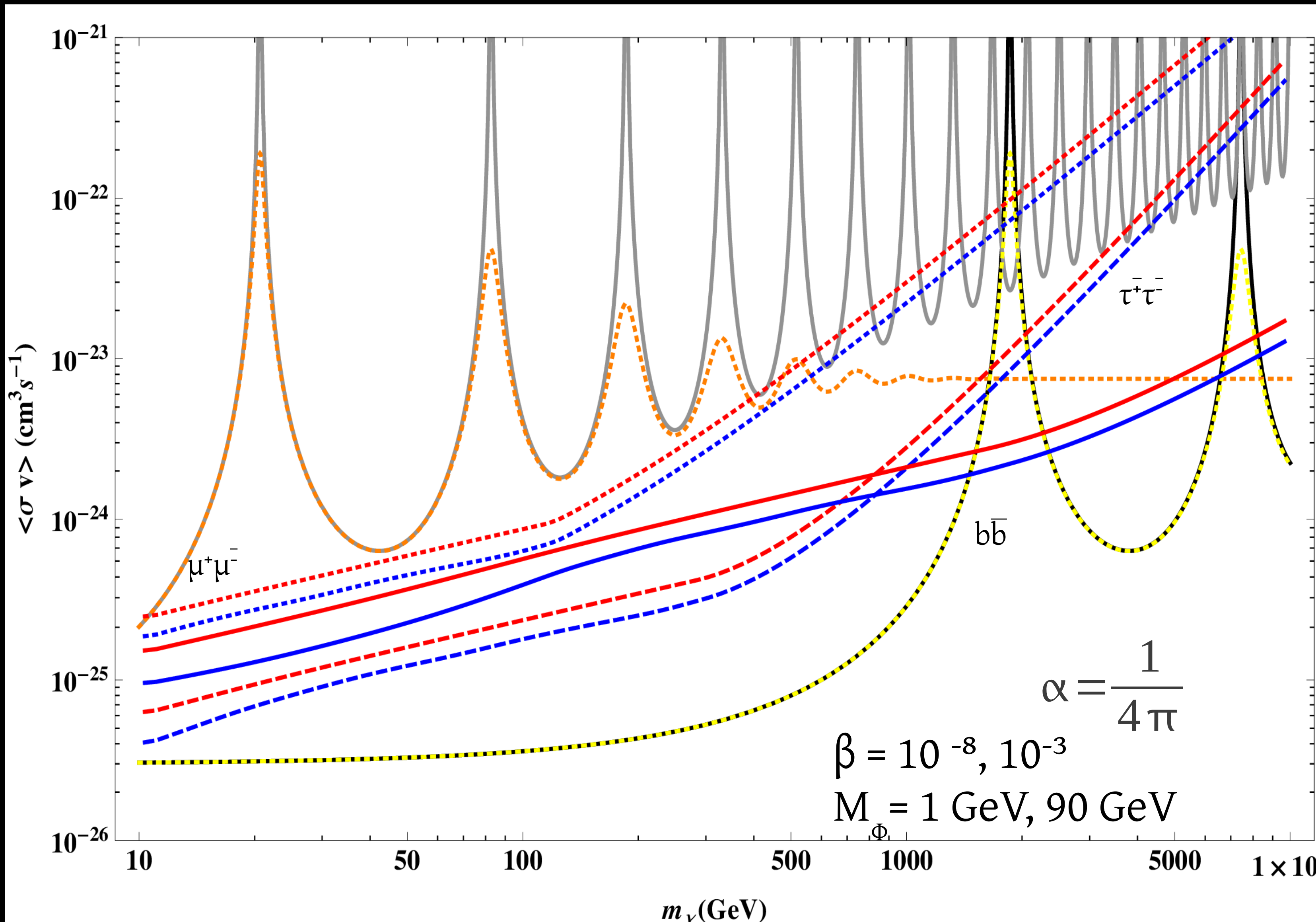


$$\sigma v = S\left(\sigma v\right)_0$$

- At large velocities ($\beta \gg \alpha$) there is no enhancement, $\mathbf{S \simeq 1}$
- In the intermediate range, the enhancement goes like $1/v$: $\mathbf{S \simeq \pi\alpha/\beta}$
- At small velocities ($\beta^2 \ll (\alpha\, M_\Phi)/m$), a series of resonances appear, due to the presence of bound states: $\mathbf{S \simeq \pi\alpha/\beta^2}$

Arnold J. W. Sommefeld. **Uber die Beugung und Bremsung der Elektronen**. Annalen der Physik, 403, 1931.
Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, and Neal Weiner. **A Theory of Dark Matter**., 2009.
Nojiri, Hisano, Matsumoto. **Explosive dark matter annihilation**. Physical Review Letter, 2004.

Bounds on the Sommerfeld enhanced ⟨σv⟩



Uncertainties on gamma-ray anisotropies from DM in the Milky Way

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PARTICLE PHYSICS factor:

- $b\bar{b}$ channel
- $B_i = 1$
- $m_\chi = 200$ GeV
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Integration of the squared DM density at a distance s from the Earth in the direction along the l.o.s and in the observational cone of solid angle ΔΩ

DM halos' profiles: cusped or cored?

Einasto [1]

$$\rho(R)=\rho_0 \exp\left(\frac{-2}{\alpha}\left[\left(\frac{R}{R_s}\right)^{\alpha}-1\right]\right)$$

Moore and Stadel [2]

$$\rho(R)=\rho_0 \exp\left(-\lambda\left[\ln\left(1+\frac{R}{R_\lambda}\right)\right]^2\right)$$

NFW [3]

$$\rho(R)=\rho_s\left(\frac{R}{R_s}\left(1+\frac{R}{R_s}\right)^2\right)^{-1}$$

[1] Einasto (1965), Trudy Inst. Astrofiz. Alma-Ata 51, 87
[2] Stadel et al., MNRAS (2009) 398 (1): L21-L25.
[3] Navarro,Frenk and White, Astrophys.J. 462 (1996) 563-575

Angular power spectrum

The angular power spectrum (APS) C_l of an intensity map I (Ψ) where Ψ is the direction in the sky, is given by the coefficients:

$$C_l = \frac{1}{2l+1}\left(\sum_{m>l} \langle |a_{l\,m}{}^2| \rangle\right)$$

$$I(\Psi) = \frac{\mathrm{d}\Phi}{\mathrm{d}E}(\Psi) - \langle \frac{\mathrm{d}\Phi}{\mathrm{d}E}(\Psi) \rangle = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y^*_{\ell m}(\Psi).$$

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- Intensity APS : **dimensionful** size of intensity fluctuations and can be compared with predictions for astrophysical sources whose collective intensity is known or assumed; it is an **additive** quantity.

- Fluctuation APS, by dividing the intensity APS C_l of a map by the mean sky intensity squared; it is **dimensionless**.

Why anisotropies?

The Fermi-LAT collab. has reported the detection of angular power above the photon noise level in the multipole range from ℓ=155 to 504 (Phys.Rev. D85 (2012) 083007).

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The study of the angular power spectrum (APS) is interesting because:

- Complementary with the analysis of the intensity energy spectrum;
- Depends on the spatial distribution of sources, alternative to the study of point sources.

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- Complementary with the analysis of the intensity energy spectrum;
- Depends on the spatial distribution of sources, alternative to the study of point sources.

Fluctuations on small angular scales are different for unresolved source populations (whose APS is constant with multipoles) and a truly isotropic emission

APS from DM annihilation

If the APS is DM-induced, it consists of :

Extragalactic contribution, expected to be almost isotropic
Smooth galactic contribution, characterized by an intrinsic anisotropy
Galactic subhalos contribution

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Extragalactic contribution, expected to be almost isotropic
Smooth galactic contribution, characterized by an intrinsic anisotropy
Galactic subhalos contribution

Here we want to study:

(1) **The intrinsic uncertainty due to the extrapolation to short distances of the DM distribution determined from numerical simulations**

(2) **The statistical fluctuations implied by the mass and space distribution of sub-halos**

of the **GALACTIC** contribution

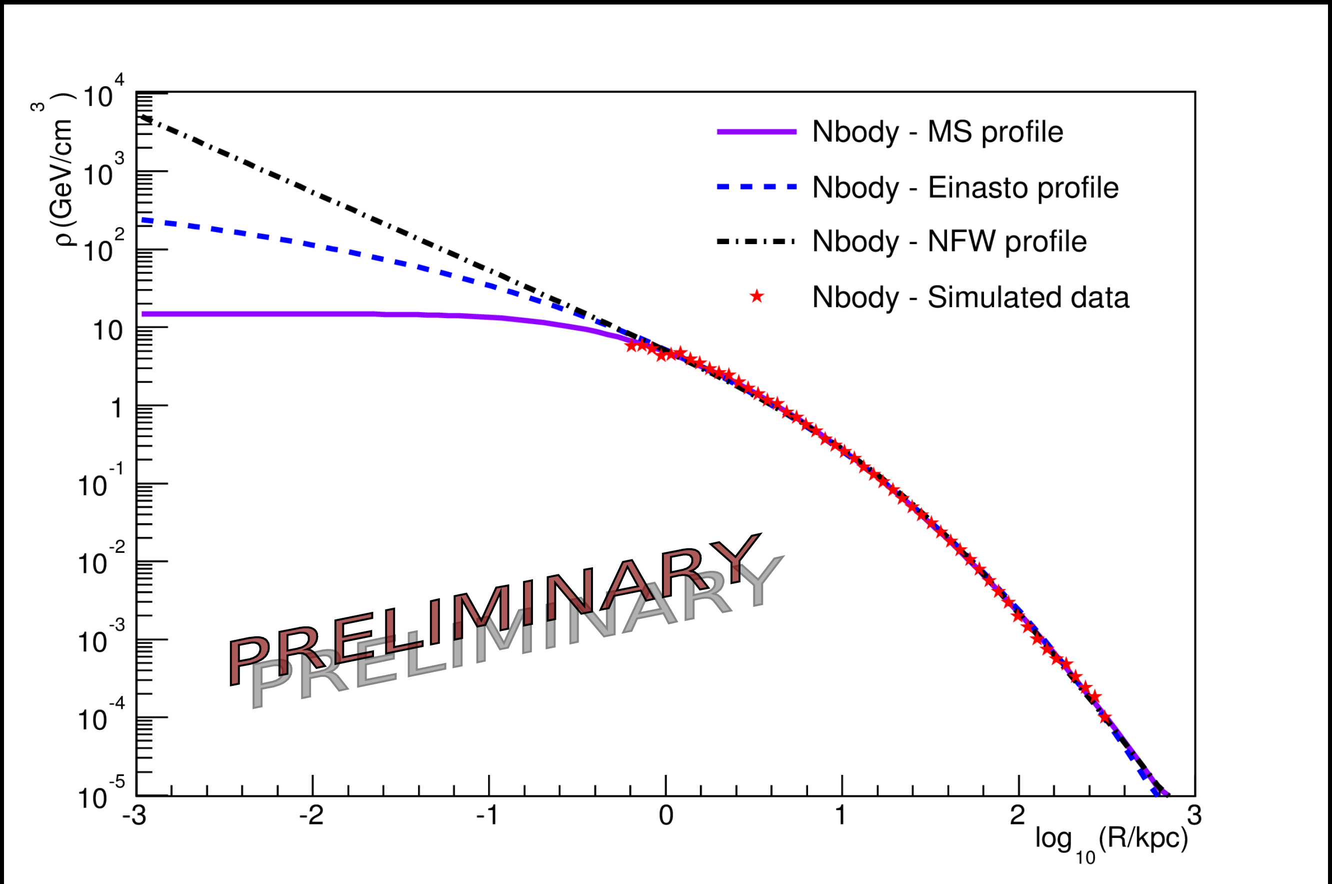
Extrapolation to short distances of DM distribution

The relation between distance and multipole is: $$R \sim \frac{\pi}{l}$$

The power spectrum at **l > 100** requires to extrapolate the DM profile at R ~ **200 pc**,
much below the resolution of current numerical simulations.

Image: http://www.mpa-garching.mpg.de/aquarius/

DM spatial profiles for smooth halo in a typical N-body simulation



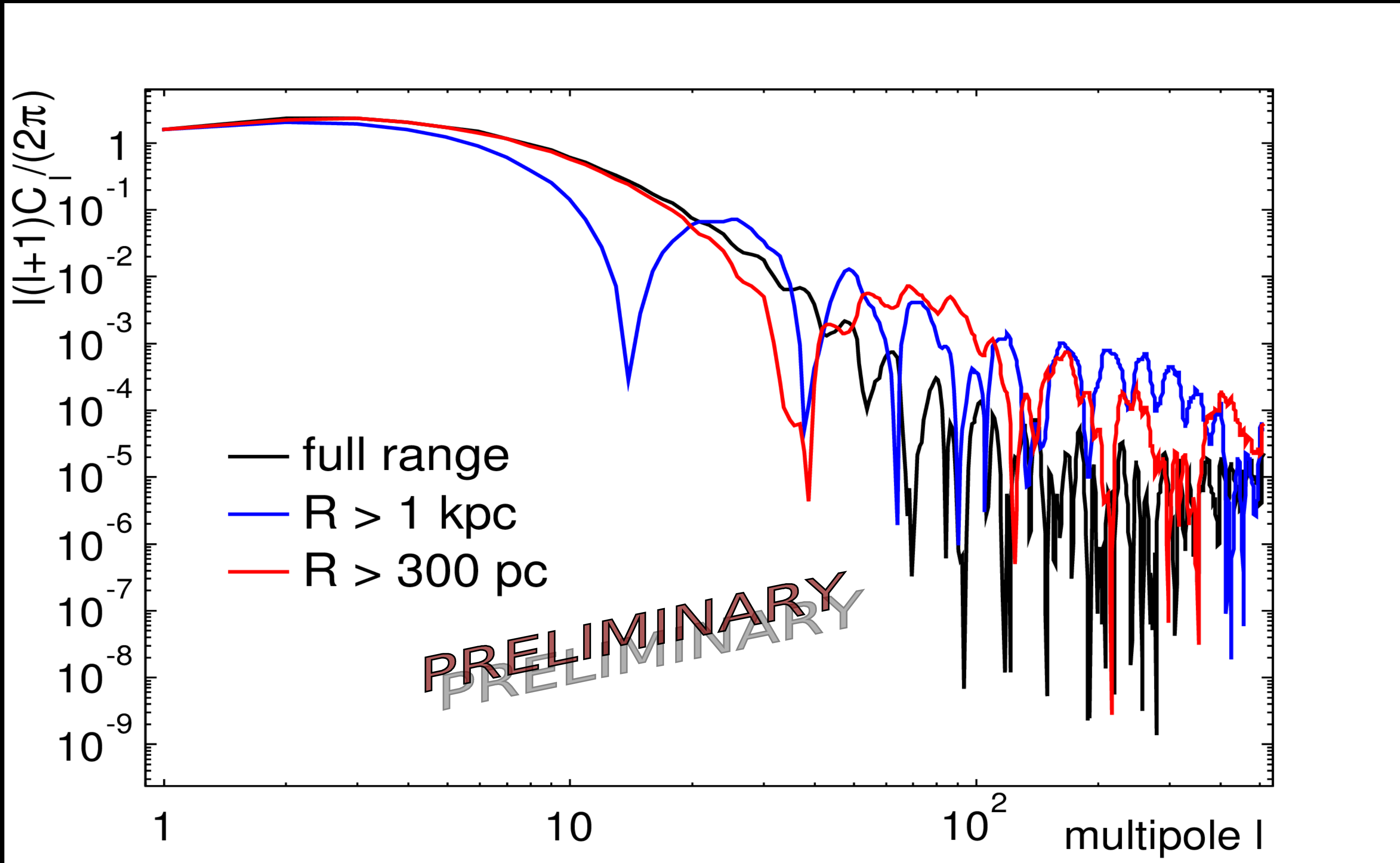
Galaxy of mass $1.48 \times 10^{12}\ M_{sun}$

$R_{min} \sim 0.75$ kpc

This simulation is part of the MaGICC project of MPIA-Heidelberg.

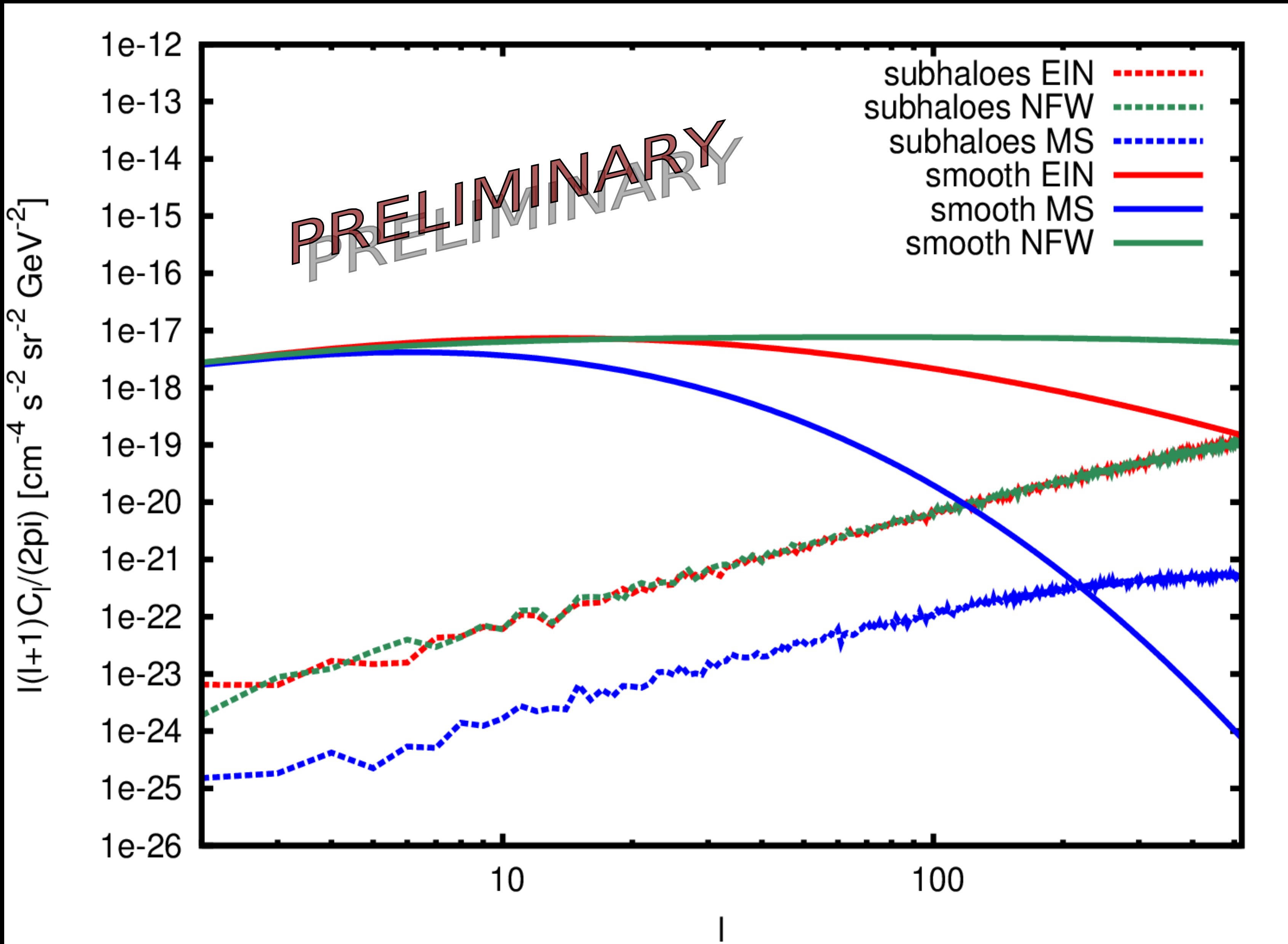
Macció et al., ApJL, Volume 744, Issue 1, article id. L9, 5 pp. (2012)
Stinson et al., MNRAS Volume 428, Issue 1, p.129-140 (2013)
Stinson et al., MNRAS Volume 408, Issue 2, pp. 812-826 (2010)

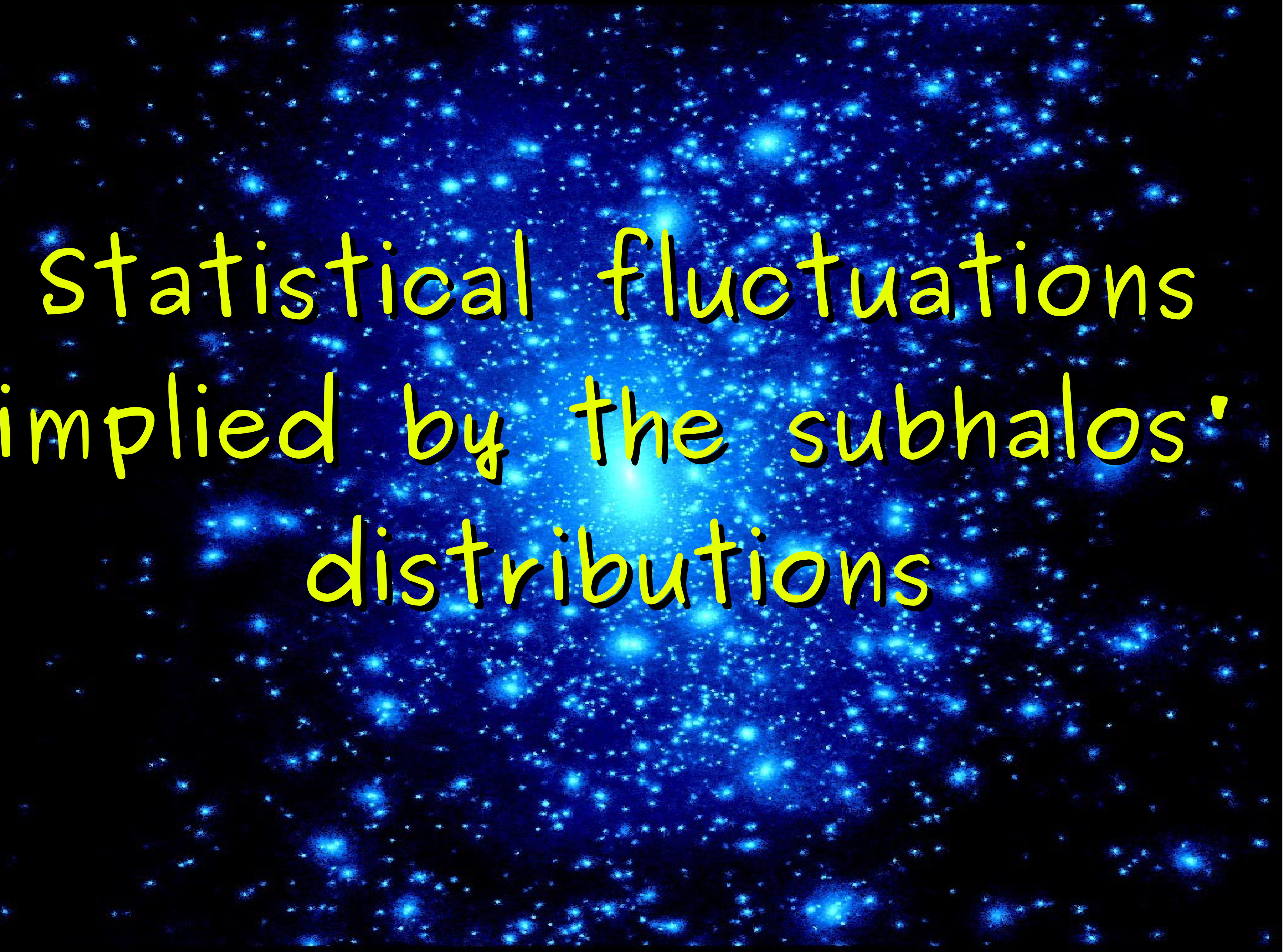
APS for smooth halo



HEALPix software (Górski, Eric Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke, M. Bartelmann, 2005, ApJ 622, 759)

APS for smooth halo and subhalos




Statistical fluctuations
implied by the subhalos'
distributions

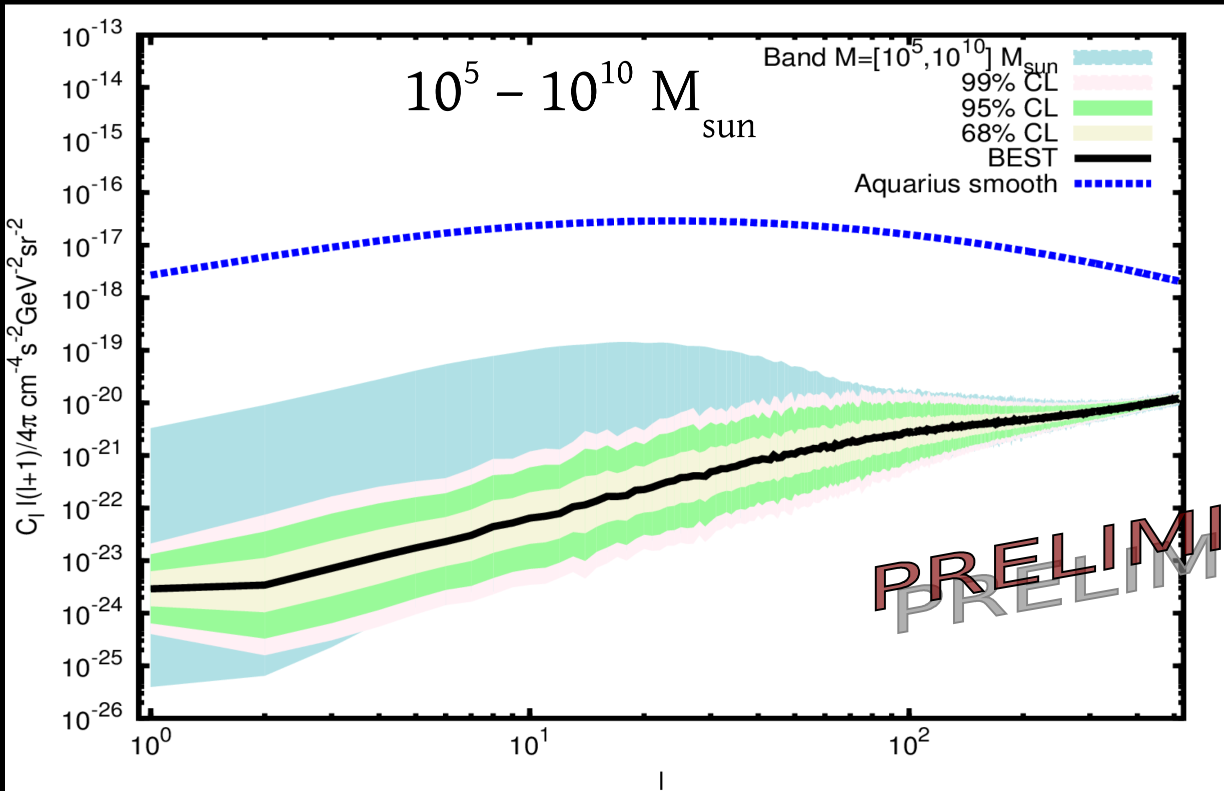
Procedure

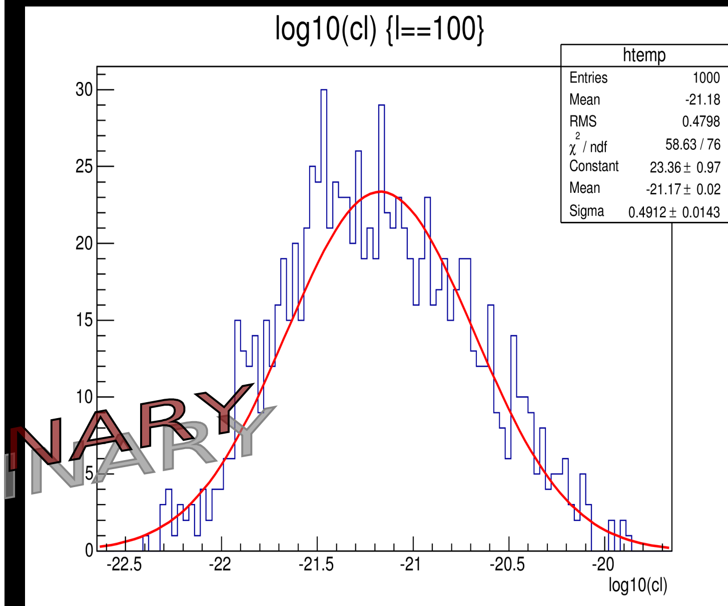
✔ We performed **several realizations** (MonteCarlo) of the galactic distribution of substructures according to the analytical fits in Pieri et al. Phys.Rev. D83 (2011) 023518, inspired by high resolution PDM simulation of MW-sized galactic halos (Aquarius - Springel et al. MNRAS 391:1685-1711,2008)

✔ We built the intensity **maps** by using the **HEALPix software** (Górski, Eric Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke, M. Bartelmann, 2005, ApJ 622, 759)

✔ We calculated the **APS for the γ-ray flux** from DM annihilation, for both smooth halo and subhalos in the mass range $10^5 - 10^{10}\ M_{sun}$

Statistical fluctuations





Log-normal distribution: realizations are independent and convergent.

500 realizations of the subhalos distribution

Clumps with mass > $10^8 M_{sun}$ are expected to be only a few, hence the statistical fluctuations associated to their distribution can be large.

CONCLUSIONS

Testing DM with the Fermi-LAT EGB

- ✔ New estimation for a residual EGB, subtracting the emission from some guaranteed (though controversial) astrophysical sources.

- ✔ A conservative (i.e. it is unlikely that a higher cross section is compatible with the "true" extragalactic bkg) upper bound on $<\sigma v>$ is derived by assuming that the Model I and II EGB are entirely due to WIMPs pair-annihilating in the halo of our Galaxy.

- ✔ The bounds on $<\sigma v>$ have been interpreted in terms of Sommerfeld enhancement of the annihilation cross section. A Sommerfeld enhancement due to a force carrier of $m_\varphi < 1$ GeV ($\alpha = 1/4\pi$) is strongly excluded.

Anisotropies

✔We have calculated the APS of the γ-ray flux from DM annihilation in the halo of our Galaxy

• We have studied the intrinsic uncertainty due to the extrapolation to short distances of the DM distribution determined from numerical N-body simulations:

- at high ℓ the difference between APS from different DM profiles becomes important, up to 6 orders of magnitude (at ℓ~500)

✔ We have then studied the statistical fluctuations implied by the subhalos' distributions:

- for ℓ<100 the uncertainty on the total APS can exceed one order of magnitude
- however at high multipoles, in principle testable with Fermi-LAT or other future experiments, the uncertainty band does shrink to ~ few %


Thanks for the attention

BACKUP SLIDES

Galactic DM subhalos distribution

We refer to the analytical fits given in Pieri et al. Phys.Rev. D83 (2011) 023518, inspired by high resolution PDM simulation of MW-sized galactic halos.

R: galactocentric radial coordinate
R: clump-centric radial coordinate

$$\rho_{sm}(R) = \rho_{tot}(R) - \rho_{sh}(R)$$

Subhalo mass density profile: $$\frac{d\rho_{sh}(M_{sh}, R)}{dM_{sh}} = \rho_{sh}(R)\mathcal{F}(\mu, M_{sh})$$

$$\mathcal{F}(\mu, M_{sh}) = \mathcal{F}_0(M_{sh}/M_{\odot})^{-\mu}$$

Normalized mass function, μ=1.9 (Aquarius)

$$\frac{dP_M}{dM} = \mathcal{F}(\mu, M_{sh})$$
$$\frac{dP_R}{dV} = \frac{\rho_{sh}(R)}{f_{\rm tot}\, M_{\rm MW}}$$

Mass and spatial probability distribution functions

$$c_{200}(M_{sub}, R) = \left(\frac{R}{R_{vir}}\right)^{-\alpha_R} \times \left[C_1 \left(\frac{M_{sub}}{M_\odot}\right)^{-\alpha_1} + C_2 \left(\frac{M_{sub}}{M_\odot}\right)^{-\alpha_2}\right]$$

$$\rho_{tot}(R) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{R}{r_s}\right)^{\alpha} - 1\right]\right\}$$

$$\rho_{\mathrm{sh}}(R) = \rho_a \exp\left\{-\frac{2}{\alpha_a}\left[\left(\frac{R}{r_a}\right)^{\alpha_a} - 1\right]\right\}$$

$$\rho_{cl}(r) = \rho_{s,cl} \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{s,cl}}\right)^{\alpha} - 1\right]\right\}$$

The MonteCarlo algorithm, within the MW virial radius and until the total substructure mass is not reached, dials the position and the mass of the clump.

Then, if it survives tidal disruption (Roche critetion), its concentration is computed and the scale radius is inferred. All the relevant parameters are stored in a ROOT TTree file.

	Aquarius
Ω_m	0.25
Ω_Λ	0.75
σ_8	0.9
n_s	1
H_0 (km/s/Mpc)	73
Minimum resolved mass ($M_\odot$)	$10^{4.5}$
ρ_s ($10^6 M_\odot$ kpc^{-3})	2.8
$R_{\rm vir}$ (kpc)	433
$M_{\rm MW}$ ($M_\odot$)	2.5×10^{12}
r_s (kpc)	20
α	0.17
$\mathcal{F}_0$ ($M_\odot^{-1}$)	3.6×10^{-6}
$N_{\rm sub}$	1.1×10^{15}
$M_{\rm sub}^{\rm tot}(< R_{\rm vir})$ ($M_\odot$)	4.2×10^{11}
$f_{\rm tot}(< R_{\rm vir})$	0.17
f	0.132
M_1 ($M_{\rm MW}$)	1.8×10^{-8}
M_2 ($M_{\rm MW}$)	10^{-2}
ρ_a ($M_\odot$ kpc^{-3})	2840.3
α_a	0.678
$R_a \equiv r_b$ (kpc)	199
μ	1.9
α_R	0.237
C_1	232.15
C_2	-181.74
α_1	0.0146
α_2	0.008

Sky maps generation

$$J = \int_{\mathrm{l.o.s.}} \left(\rho_{\mathrm{sm}}(s) + \sum_i \rho_{\mathrm{cl},i}(s) \right)^2 ds$$

$$= \int_{\mathrm{l.o.s.}} \left(\rho_{\mathrm{sm}}(s)^2 + \sum_i \rho_{\mathrm{cl},i}(s)^2 + 2\,\rho_{\mathrm{sm}}(s) \cdot \sum_i \rho_{\mathrm{cl},i}(s) + \sum_i \sum_{j \neq i} \rho_{\mathrm{cl},i}(s) \cdot \rho_{\mathrm{cl},j}(s) \right) ds$$

$$= J_{\mathrm{sm}} + J_{\mathrm{cl}} + J_{\mathrm{cl,sm}} + J_{\mathrm{cl,cl}}$$

$$J_{\mathrm{sm}} = \int_{\mathrm{l.o.s.}} \rho_{\mathrm{sm}}(s)^2\, ds$$

$$J_{\mathrm{cl}} = \int_{\mathrm{l.o.s.}} \sum_i \rho_{\mathrm{cl},i}(s)^2\, ds$$

$$J_{\mathrm{cl,sm}} = 2 \int_{\mathrm{l.o.s.}} \sum_i \rho_{\mathrm{sm}}(s) \cdot \rho_{\mathrm{cl},i}(s)\, ds$$

$$J_{\mathrm{cl,cl}} = \int_{\mathrm{l.o.s.}} \sum_i \sum_{j \neq i} \rho_{\mathrm{cl},i}(s) \cdot \rho_{\mathrm{cl},j}(s)\, ds$$

The interference terms are subdominant and very CPUtime-consuming.

The most important contribution is $J_{\mathrm{cl,sm}}$ that we computed taking into account the emission from the clump up to a radial distance~4 r_{vir} .

$$s_{\max} = \sqrt{R_{\mathrm{vir}}^2 + R_\odot^2 - 2\, R_\odot\, R_{\mathrm{vir}}\, \cos(\mathrm{b})\, \cos(\mathrm{l})}$$

Unresolved subhalos contribution

Average contribution from the unresolved clump distribution:

$$\langle J_{\rm cl}^{\rm unres} \rangle = N_{\rm tot} \int_{\rm l.o.s.} \frac{dP_{\rm R}}{dV}\, dl \int_{M_{\rm min}}^{M_{\rm max}} \mathcal{L}(M)\, \frac{dP_{\rm M}}{dM}\, dM$$

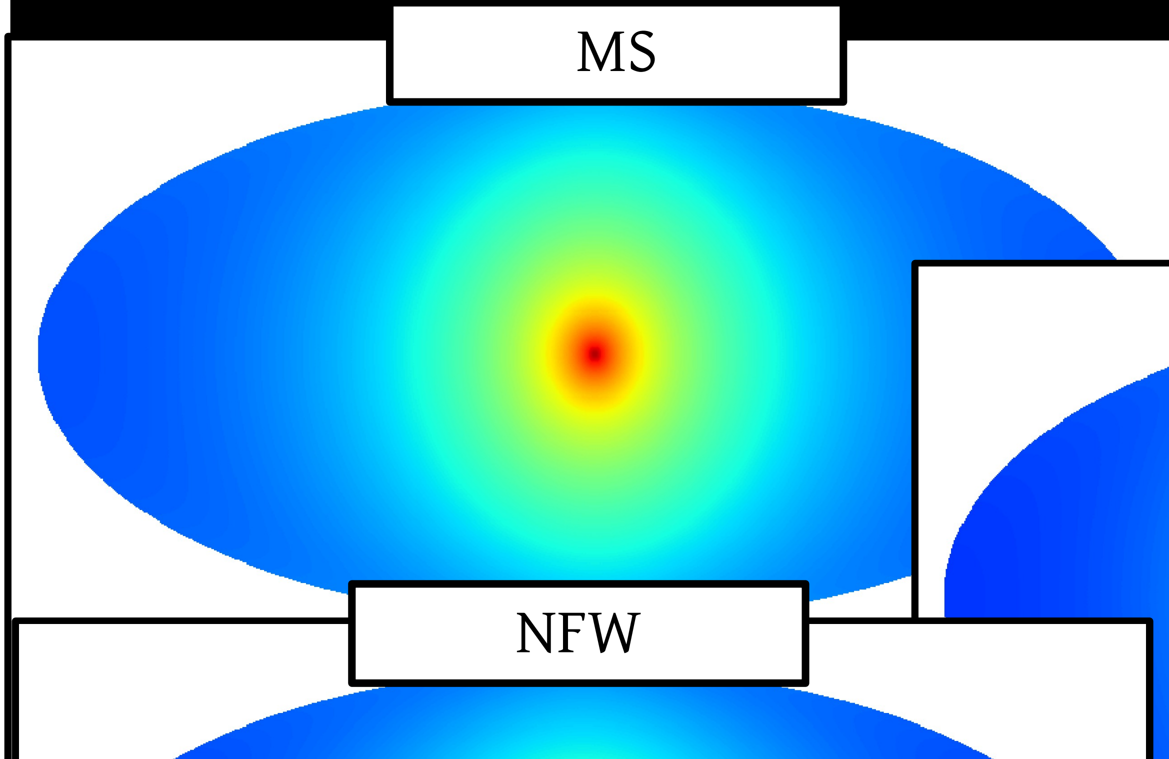
CLUMPY: a code for gamma-ray signals from dark matter structures
A. Charbonnier, C. Combet, D. Maurin : Comput.Phys.Commun. 183 (2012) 656-668

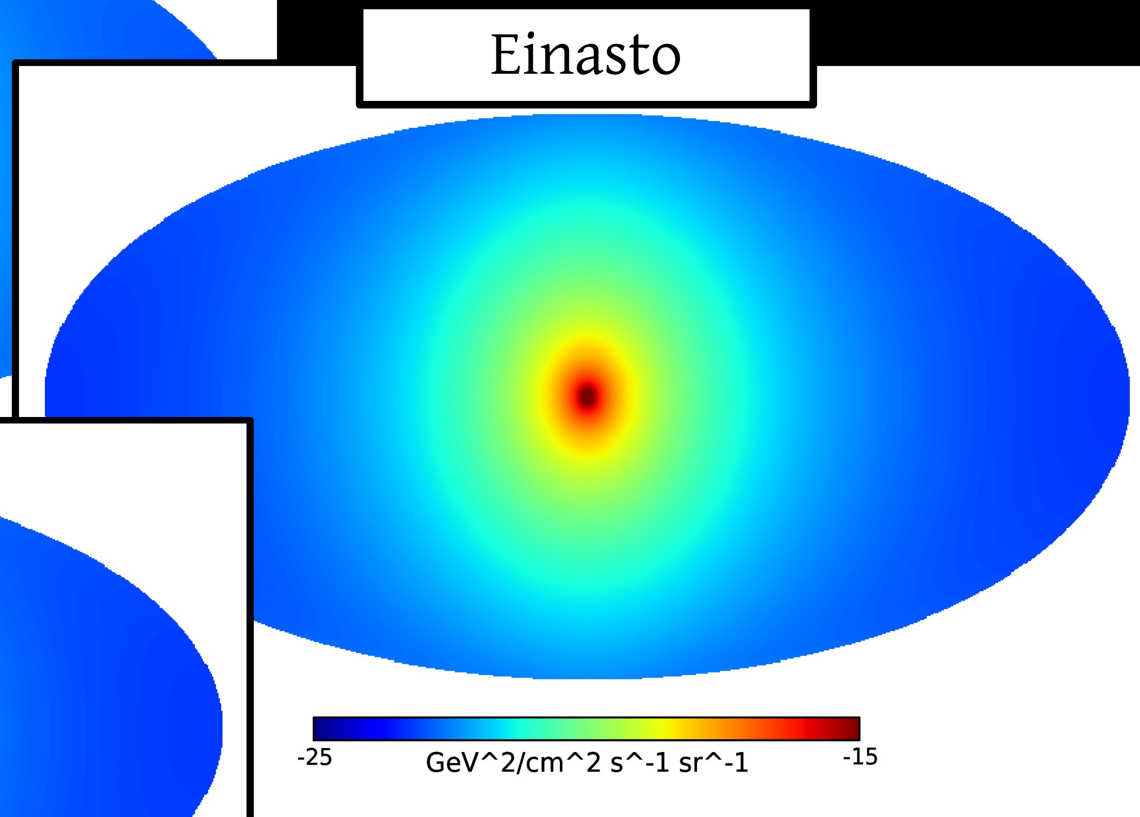
Where the luminosity of a single clump is:

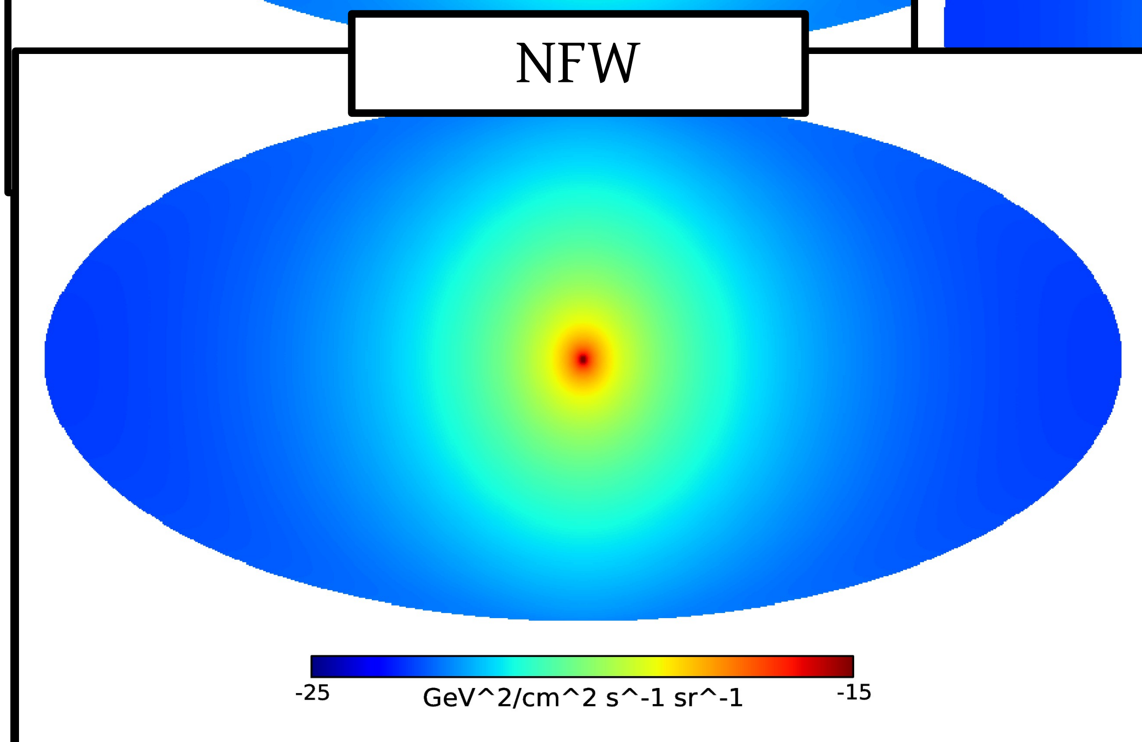
$$\mathcal{L}(M) = \int_{V_{\rm cl}} \rho_{\rm cl}(r)^2 dV = 4\,\pi \int_0^{R_{\rm vir,cl}} \rho_{\rm cl}(r)^2\, r^2\, dr$$

Mass range of unresolved subhalos $10^{-6} - 10^{5}\ M_{\rm sun}$

Smooth halo maps

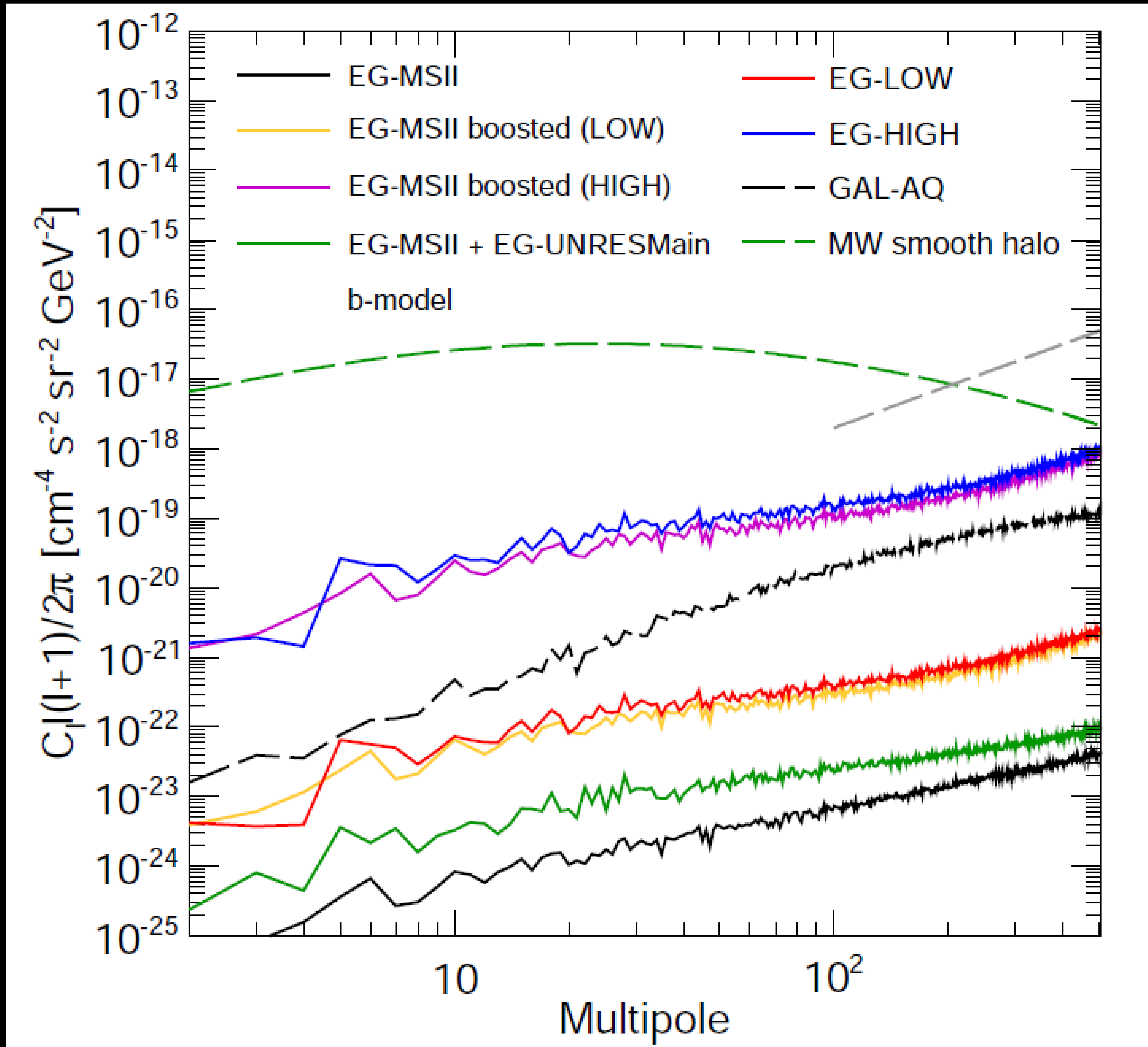






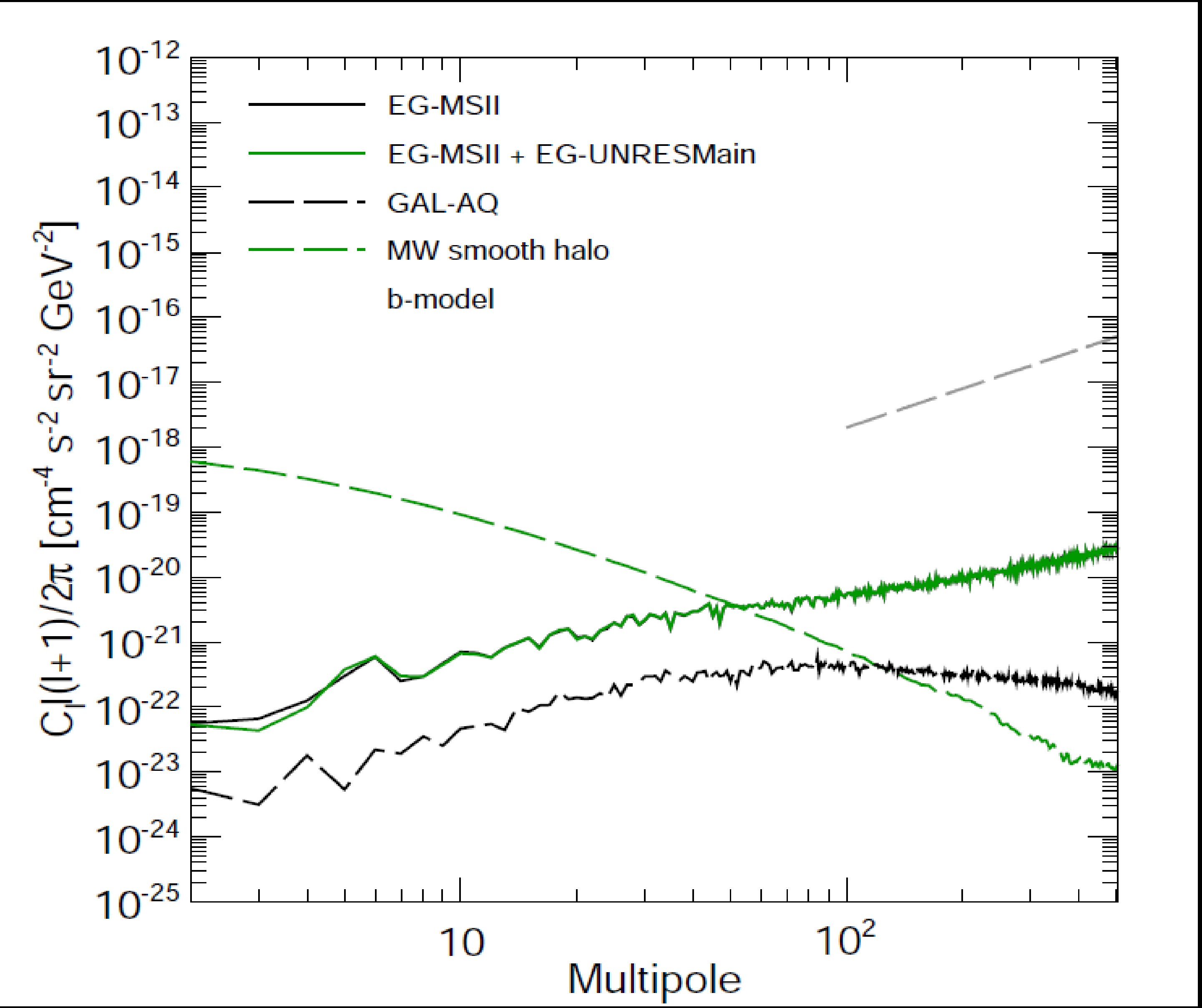
Built with **HEALPix software**

(Górski, Eric Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke, M. Bartelmann, 2005, ApJ 622, 759)

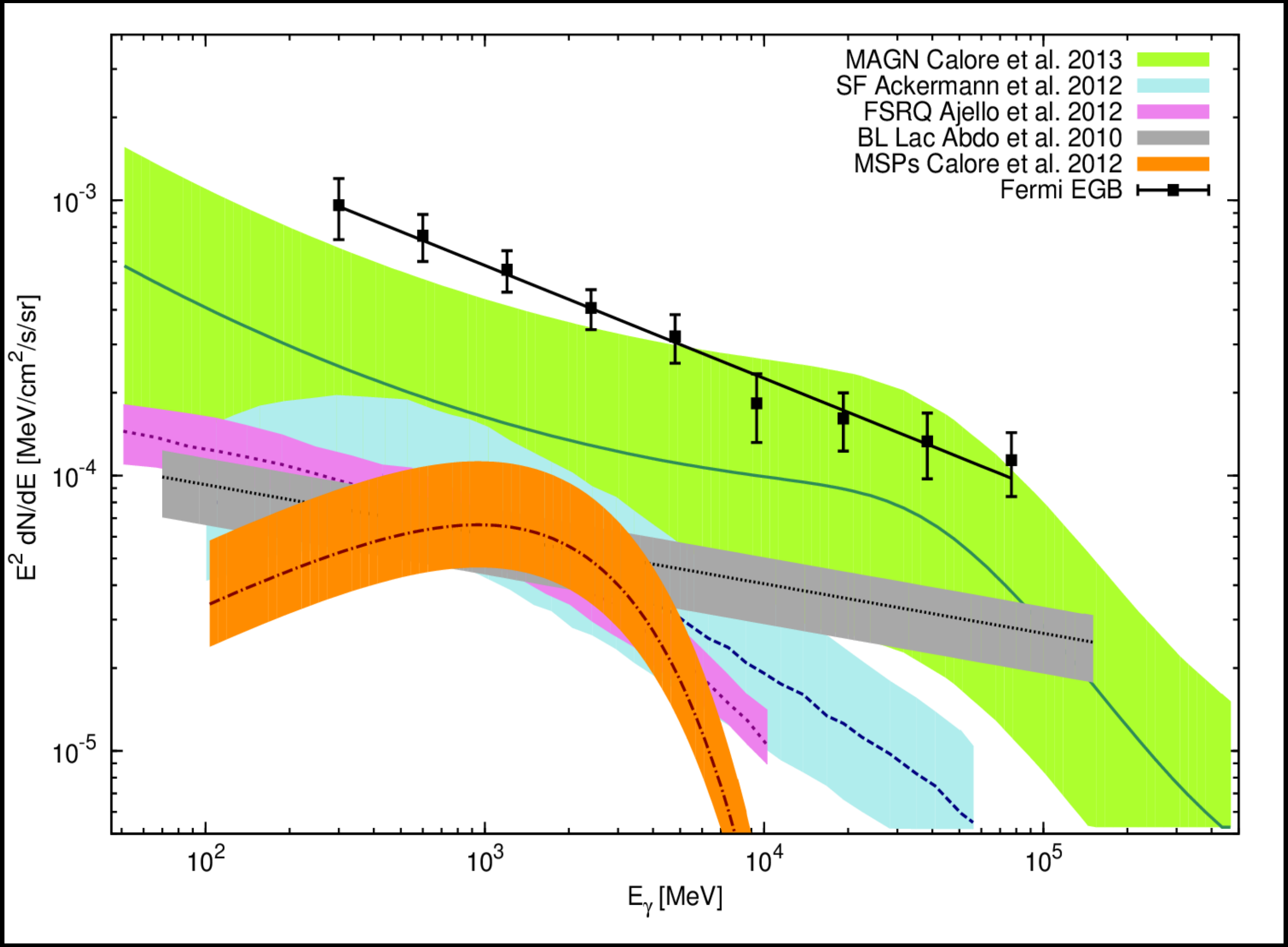


Characterization of Dark-Matter-induced anisotropies in the diffuse gamma-ray background, Mattia Fornasa et al. arXiv:1207.0502

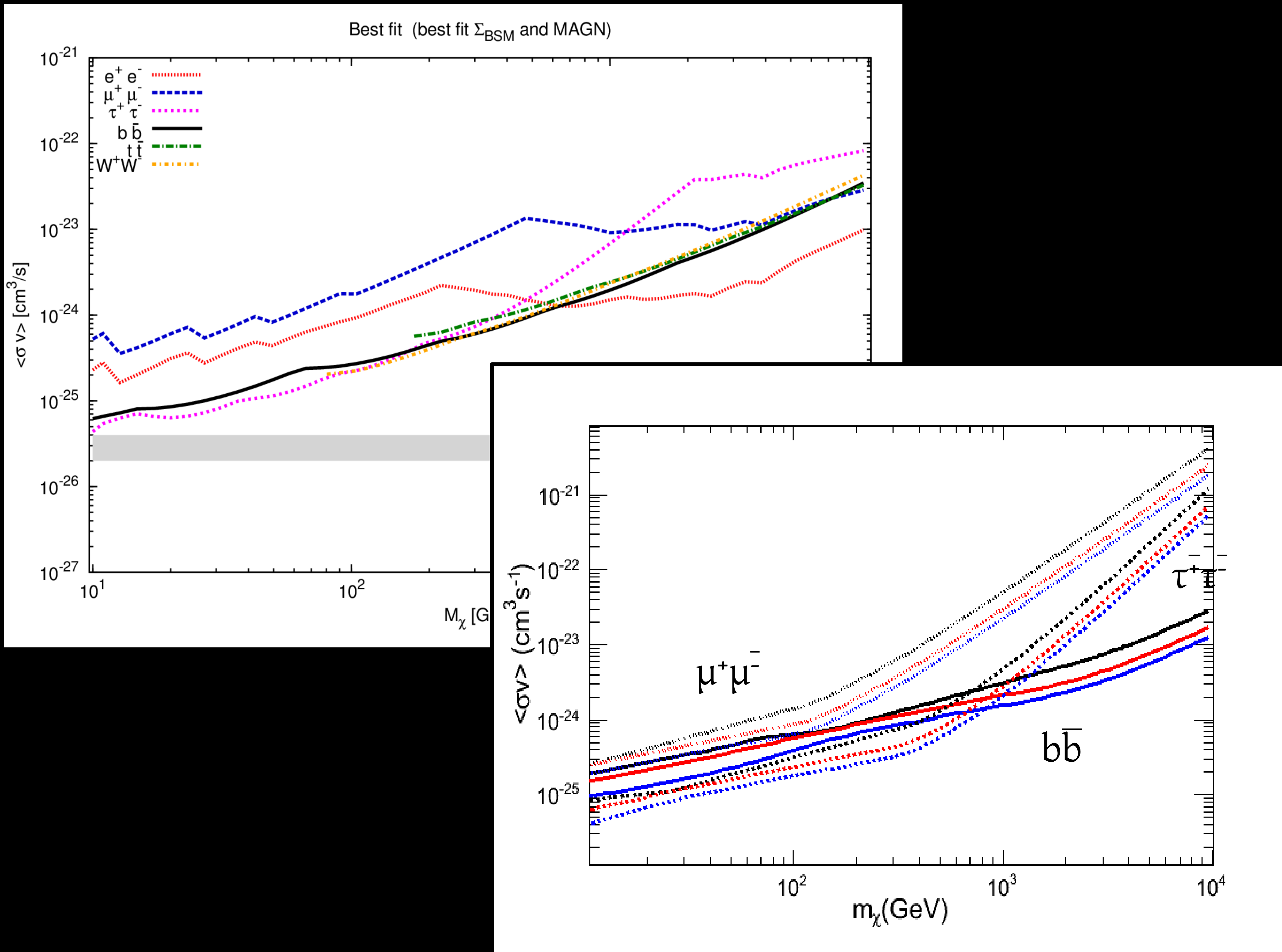
Decaying dark matter



Characterization of Dark-Matter-induced anisotropies in the diffuse gamma-ray background, Mattia Fornasa et al. arXiv:1207.0502



Updated limits, with the inclusion of MAGN and ICS: Calore et al., arXiv:1303.3284



Best fit (best fit Σ_BSM and MAGN)
e⁺ e⁻
μ⁺ μ⁻
τ⁺ τ⁻
b b̄
t t̄
W⁺W⁻
<σ v> [cm³/s]
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
10¹
10²
<σv> (cm³s⁻¹)
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10²
10³
10⁴
m_χ(GeV)
μ⁺μ⁻
τ⁺τ⁻
bb̄

(1) The non-DM astrophysical bkg: guaranteed contributions

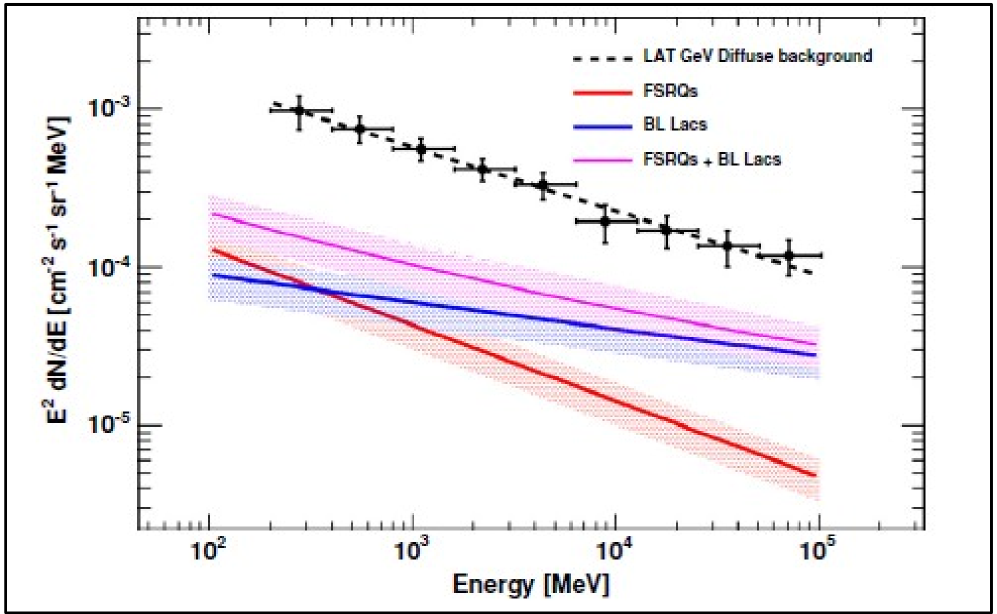


Fig:Fields, Pavlidou, Prodanovic, ApJ 722 (2010)

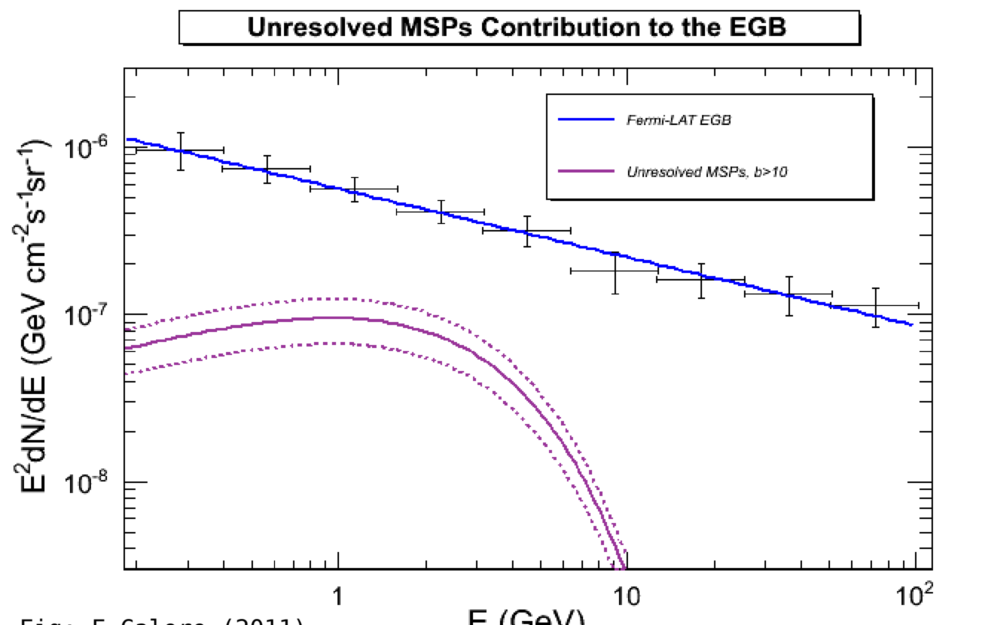


Fig: F.Calore (2011)

1. Unresolved blazars: FSRQs and BL Lacertae objects;
2. Millisecond Pulsars;
3. Normal StarForming Galaxies.

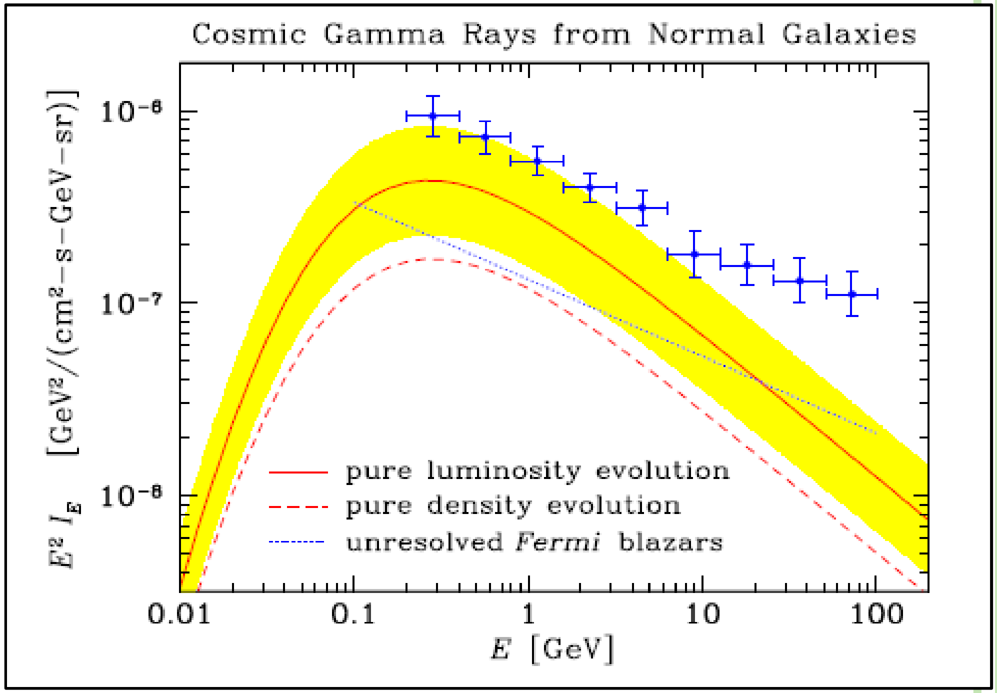


Fig:Fermi-LAT Collab. ApJ, 720 (2010)

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs e BL Lacertae objects.
2. Millisecond pulsars.
3. Normal Starforming Galaxies.
4. Gamma-rays from UHECRs:
   - *Truly diffuse emission*:

     $p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$

     $\gamma\gamma_b \rightarrow e^{+}e^{-}$ (PP); $e^{\pm}\gamma_b \rightarrow e^{\pm}\gamma$ (ICS)
   - *Theoretical uncertainties*: injection spectrum of primary protons and source evolution.

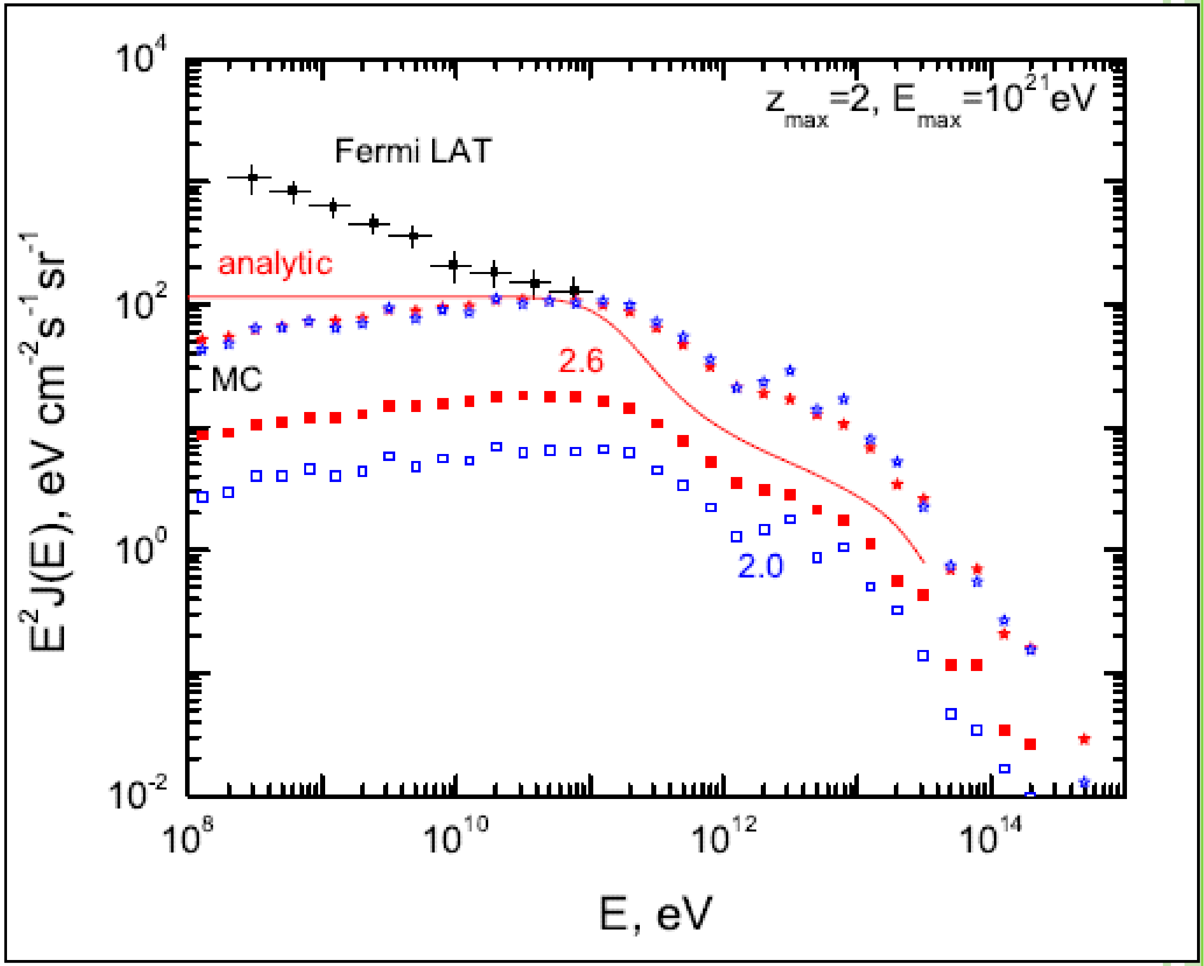
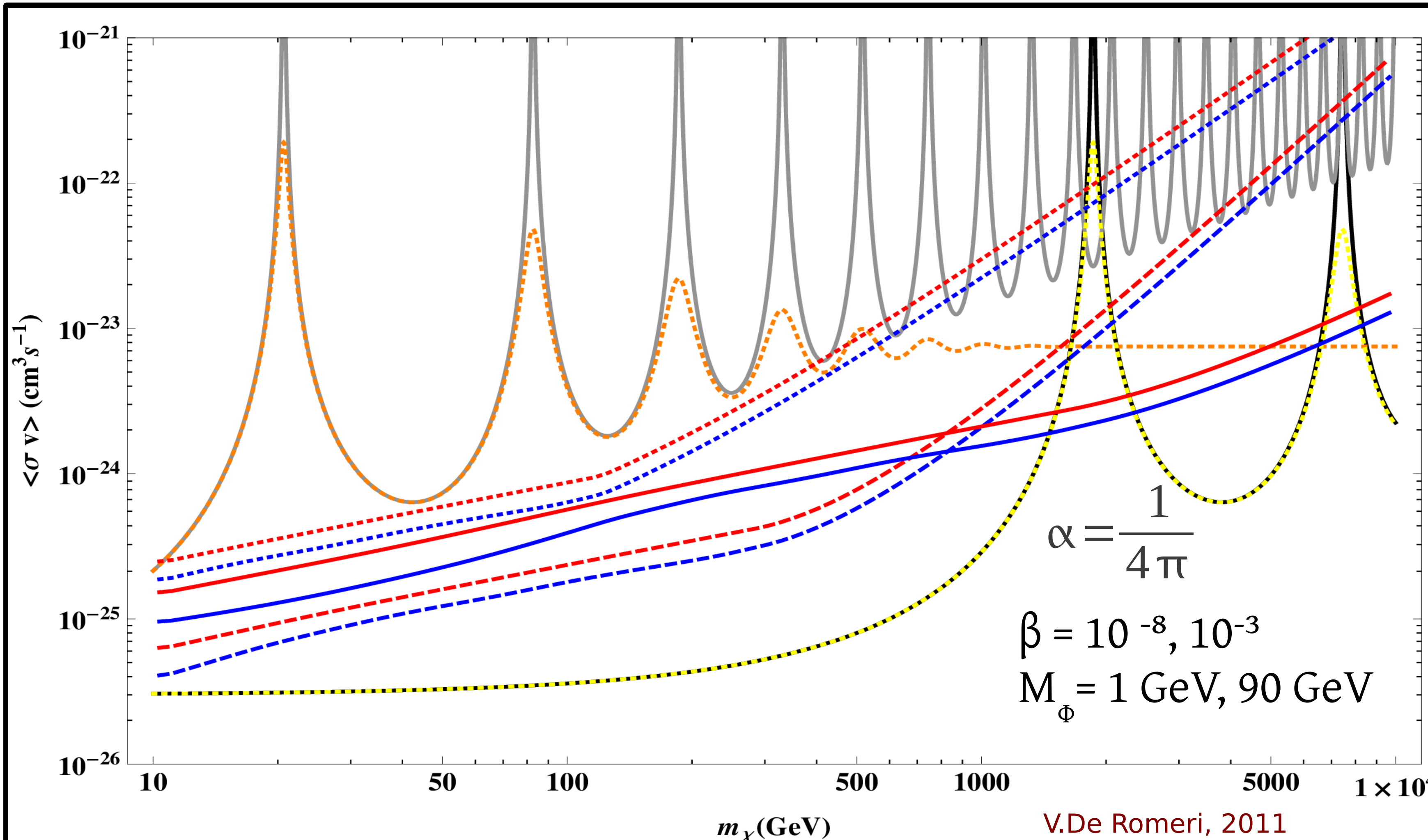


Fig:Berezinsky et al. Phys.Lett. B695 (2011)

Bounds on the Sommerfeld enhanced <σv>

Recent claims on the excess of CR positrons have stimulated the interpretation of data in terms of annihilating DM with fairly large <σv>:

One way of boosting is through the Sommerfeld enhancement.

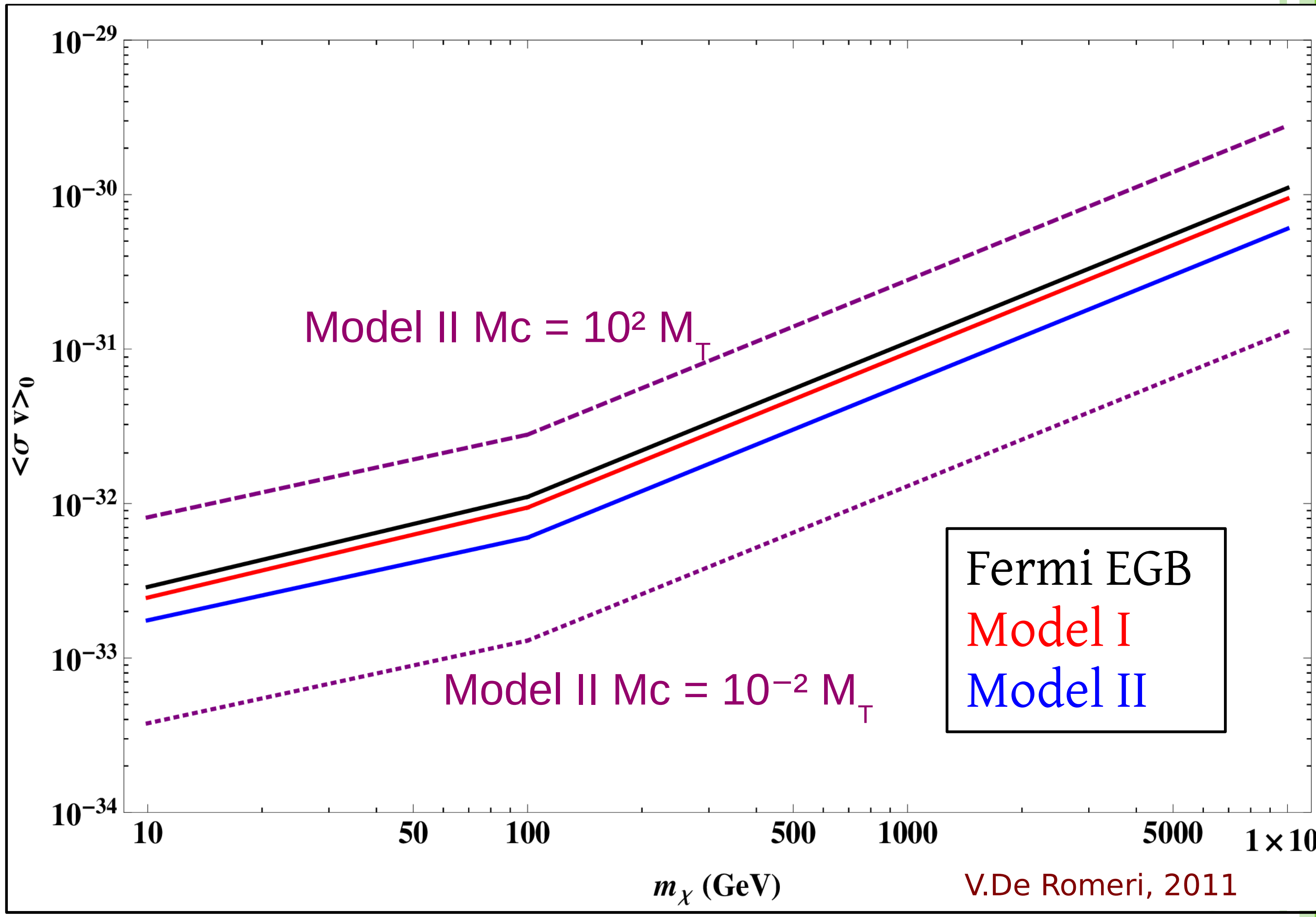


Conservative upper limits from early proto halos

A boosted production of gamma rays in models with <σv> depending on 1/v has been predicted for the first DM bound objects

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 \frac{c}{v} cm^3/sec$$

Energy density in photons today from WIMP annihilation in protohalos:



$$\rho_\gamma = 5.28\times10^6 \left(\frac{M_c}{M_T}\right)^{-1/3} \left(\frac{1}{\beta}\right) <\sigma v>_0 B_{2.6} \left(\frac{m_\chi}{TeV}\right)^{-1} GeV\, cm^{-3}$$

Unresolved Point Sources

SOURCES	References	DOMINANT PHYSICAL PROCESSES	%	Notes
Blazars: BL Lacs & FSRQs	*A.A.Abdo&others, Submitted to ApJ. , 2010*	*IC emission and synchrotron radiation*	*16% - 23% (population analysis)*	*Fermi-LAT data and sources count distribution analysis*
Starforming Galaxies (normal & starburst)	*B.D.Fields, V.Pavlidou, T.Prodanovic, arXiv:1003.3647, 2010*	*Diffuse emission due to collisions of CR with IS gas → gamma-rays mainly from pion decay in flight or leptonic interactions (electrons)*	*63% - 19% at peak (0.3 GeV)*	*Fermi-LAT data*
Starburst Galaxies	*T.A.Thompson, E.Quataert, E.Waxman, Astrophys.J., 654, 2006*	*CR protons vs ISM nuclei, lose energy rapidly via inelastic scattering → resulting pions decaying in secondary particles and gamma-rays (gamma ray emission associated with pion production)*	*< 20%*	*Prediction based on EGRET data (some predictions fulfilled by Fermi-LAT observations)*
Clusters of Galaxies	*P.Blasi, S.Gabici, G.Brunetti, Int.J.Mod.Phys., A22, 2007*	*GeV-TeV gamma-ray fluxes from π^0 decays, ICS and UHE protons in the ICM*	*1% - 10%*	*Prediction based on EGRET data*
Pulsars	*C.A.Faucher-Giguère & A.Loeb, Phys.Rev.Lett., 1001, 2010*	*IC, curvature radiation and synchrotron radiation from electrons-positrons cascades*	*5% - 15% (MSPs)*	*Prediction based on EGRET data*

Truly Diffuse Emission Processes

SOURCES	References	DOMINANT PHYSICAL PROCESSES	%	Notes
Signature of LSS formation	*·S.Gabici & P.Blasi, Astroparticle Phys., 19, 2003* *·U.Keshet, E.Waxman, A.Loeb, Astrophys.J., 585, 2003*	*Shock waves produced in clusters mergers and LSS formation give rise to highly relativistic electrons → IC of the CMB photons to GeV energies*	*10%*	*Prediction based on EGRET data*
UHECRs	*O.Kalashev, D.Semikoz, G.Sigl, Phys. Rev. D, 79, 2009*	*Interactions of UHECRs with CMB photons → secondary electromagnetic cascades*	*1% - 50%*	*Prediction based on EGRET data and dependent from the primary cosmic rays flux*
VHE Gamma-Rays from Blazars	*T.M.Venter, arXiv:1001.1363, 2010*	*VHE gamma-rays from blazars vs soft photons of EBL → EM cascades*	*+50% of intrinc blazar spectra contribution*	*Dependence on blazar gamma-ray luminosity function and spectral properties*

(1) The non-DM astrophysical bkg: other sources explored, but neglected

- RADIO QUIET AGN: contribution still uncertain (ApJ 672, L5, ApJ.702, 523);
- BL LAC OBJECTS and FSRQs whose jets are not aligned along the line of sight (Fanaroff and Riley radio galaxies I and II): high uncertanty in the model, few objects of the sample already subtracted in the Fermi-LAT EGB (arXiv: 1103.3946);
- GAMMA RAY BURSTS: less than the 1% contributes to the EGB (ApJ. 700, 10261033);
- STARBUST and Luminous Infrared galaxies (LIG): they may cover a significant fraction of the EGB (up to the 20%), but the model-dependance is still too high (ApJ. 654, 219);
- Gamma ray emission from nearby clusters of galaxies: in the first 18 months, no gamma rays have been detected yet;
- Gravitational induced shocked waves produced during cluster mergers and large-scale structure formation may contribute for some percent, via Inverse Compton scattering of highly relativistic electrons.

Sommerfeld enhancement

Through this mechanism it is possible to obtain the behaviour 1/v in the WIMPs annihilation cross section.
It's a non elementary effect in non relativistic quantum mechanics, which arises when the particles interact through a force in the presence of a potential and subsequentely their wave function comes out to be distorted.

$$\sigma v = S(\sigma v)_0$$

It may be depicted through two particles spreading in the space-time which interact by exchanging vector bosons before annihilating. This gives origin to non perturbative corrections in the cross section of the process considered.

In case of WIMPs annihilation the Sommerfeld enhancement is a consequence of the presence of a Yukawa potential and light force carriers.

Reff. Arnold J. W. Sommefeld. **Uber die Beugung und Bremsung der Elektronen**. Annalen der Physik, 403, 1931.
Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, and Neal Weiner. **A Theory of Dark Matter**., 2009.
Nojiri, Hisano, Matsumoto. **Explosive dark matter annihilation**. Physical Review Letter, 2004. ArXiv hepph/ 037216v1.

3)Analitical solution through the approximation with the Hulthèn potential

The third method for solving for the Schrodinger equation makes use the analytical approximation of the Yukawa potential with the Hulthèn potential :

$$V_Y \approx V_H = \frac{C\delta\, e^{-\delta r}}{1-e^{-\delta r}} \qquad \delta = \frac{\pi^2 m_\phi}{6}$$

$$S = \frac{\pi}{\varepsilon_v} \frac{\sinh\left(\dfrac{2\pi\varepsilon_v}{\pi^2\varepsilon_\phi/6}\right)}{\cosh\left(\dfrac{2\pi\varepsilon_v}{\pi^2\varepsilon_\phi/6}\right) - \cos\left(2\pi\sqrt{\dfrac{1}{\pi^2\varepsilon_\phi/6} - \dfrac{\varepsilon_v{}^2}{(\pi^2\varepsilon_\phi/6)^2}}\right)}$$

$$\varepsilon_v \equiv v/\alpha \quad \text{e} \qquad \varepsilon_\phi \equiv m_\phi/(\alpha m_\chi)$$

Sebastian Cassel. **Sommerfeld factor for arbitrary partial wave processes**. ArXiv hep-ph/0903.5307v1.
Tracy R. Slatyer. **The Sommerfeld enhancement for dark matter with an excited state**. JCAP, 2010. ArXiv hepph/0910.5713.