The gamma-ray background from dark matter annihilation

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Preliminary Results

Mark Vogelsberger (CfA, Cambridge)
Tracy Slatyer (IAS, Princeton)
Abraham Loeb (CfA, Cambridge)
Volker Springel (HITS, Heidelberg)
PRD, 83, 12, 2011 (arXiv: 1103.0776)

Volker Springel (HITS, Heidelberg)
Michael Boylan-Kolchin (UC, Irvine)
MNRAS, 405, 593, 2010 (arXiv:0908.2428)

Dark Matter Signatures in the Gamma-ray Sky, May 2012

Outline

- DM annihilation within the Galactic halo
- Extragalactic background from DM annihilation
- Simulated sky maps of the annihilation GB
- Energy spectrum of the GB
- Angular power spectrum of the GB
- Summary and Conclusions

Annihilation within the Galactic halo

- Specific Intensity (energy of photons per unit area, time, solid angle and energy range received by the observer):

$$I(\psi) = f_{\mathrm{PP}} \int_{\mathrm{los}} \rho^2(r, \psi) \mathrm{d}r$$

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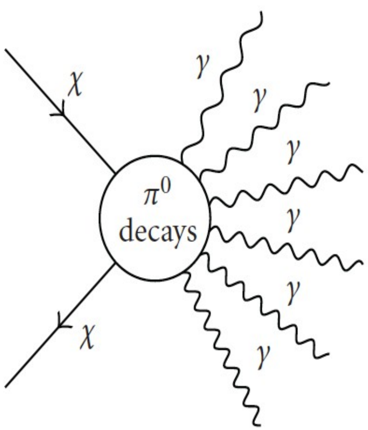
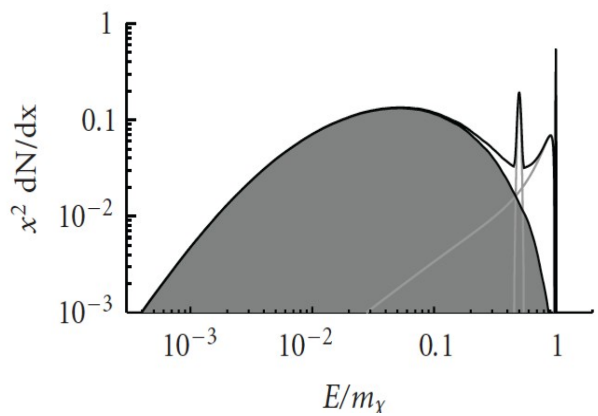
DM as an annihilating particle

$$f_{\mathrm{PP}} = \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{8\pi m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE}$$

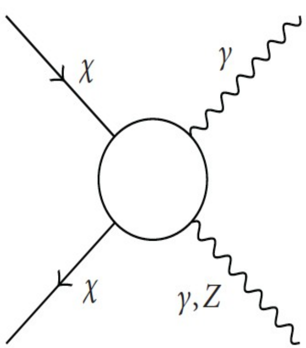
Prompt emission

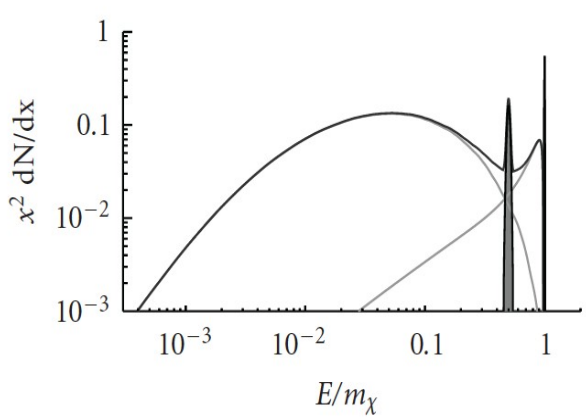
Secondary photons (tree level)





Line signal (loop level $\mathcal{O}(\alpha^2)$)





Additional contribution to the gamma-ray photon yield:

IC scattering with background photons (CMB, stellar and infrared light)

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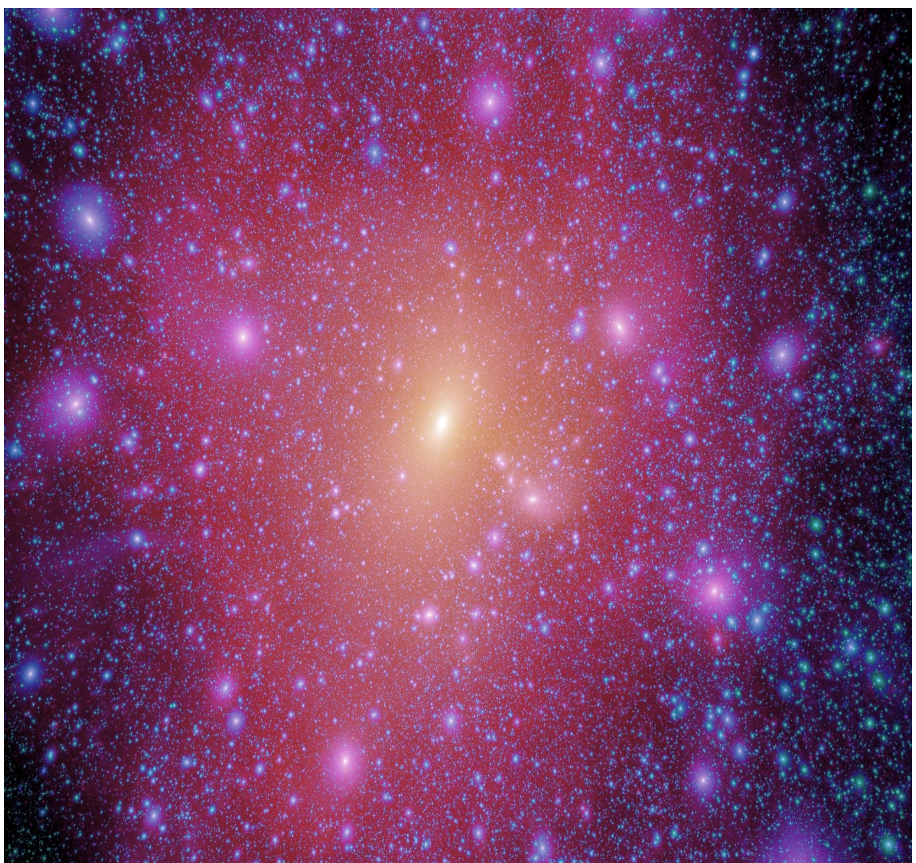
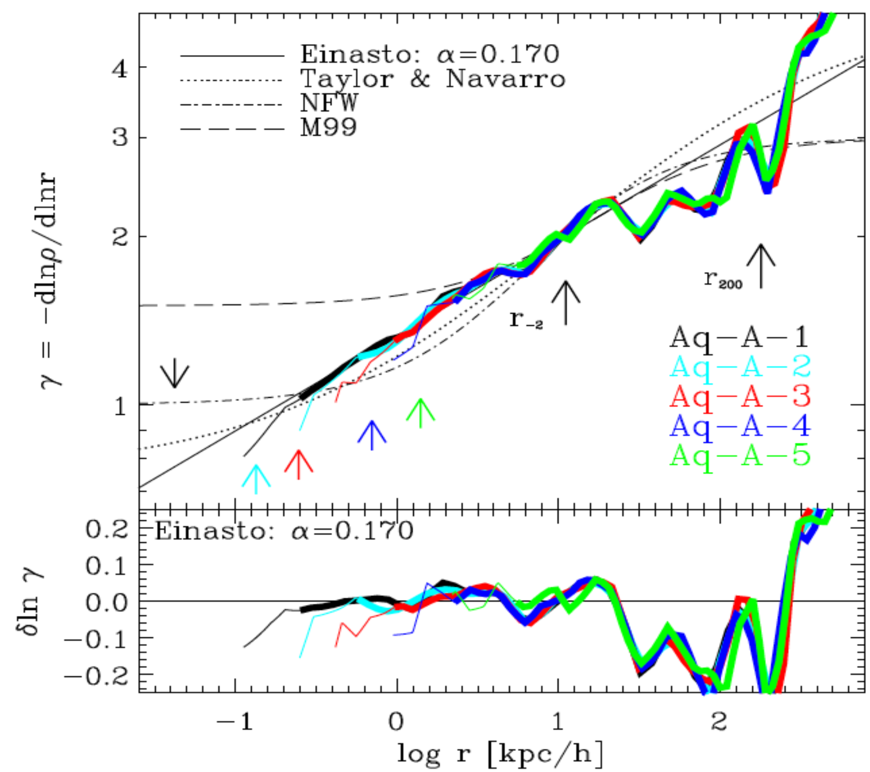
DM clustering (N-body simulations)

MW-size halo Aquarius project
Springel et al. 2008



Smooth component (Einasto profile)

$$\ln\left(\frac{\rho(r)}{\rho_{-2}}\right) = \left(\frac{-2}{\alpha}\right)\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]$$



Navarro et al. 2008

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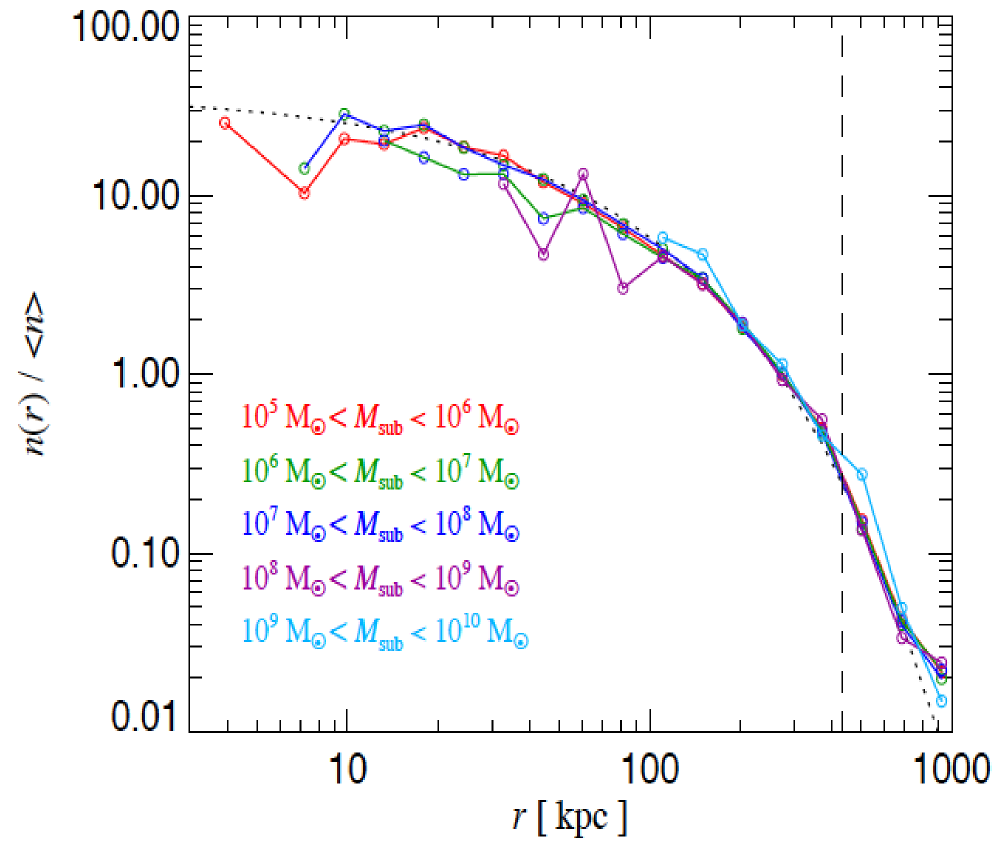
Subhalo number density
("cored" Einasto)



Inner subhalo profile is cuspy

Annihilation within the Galactic halo

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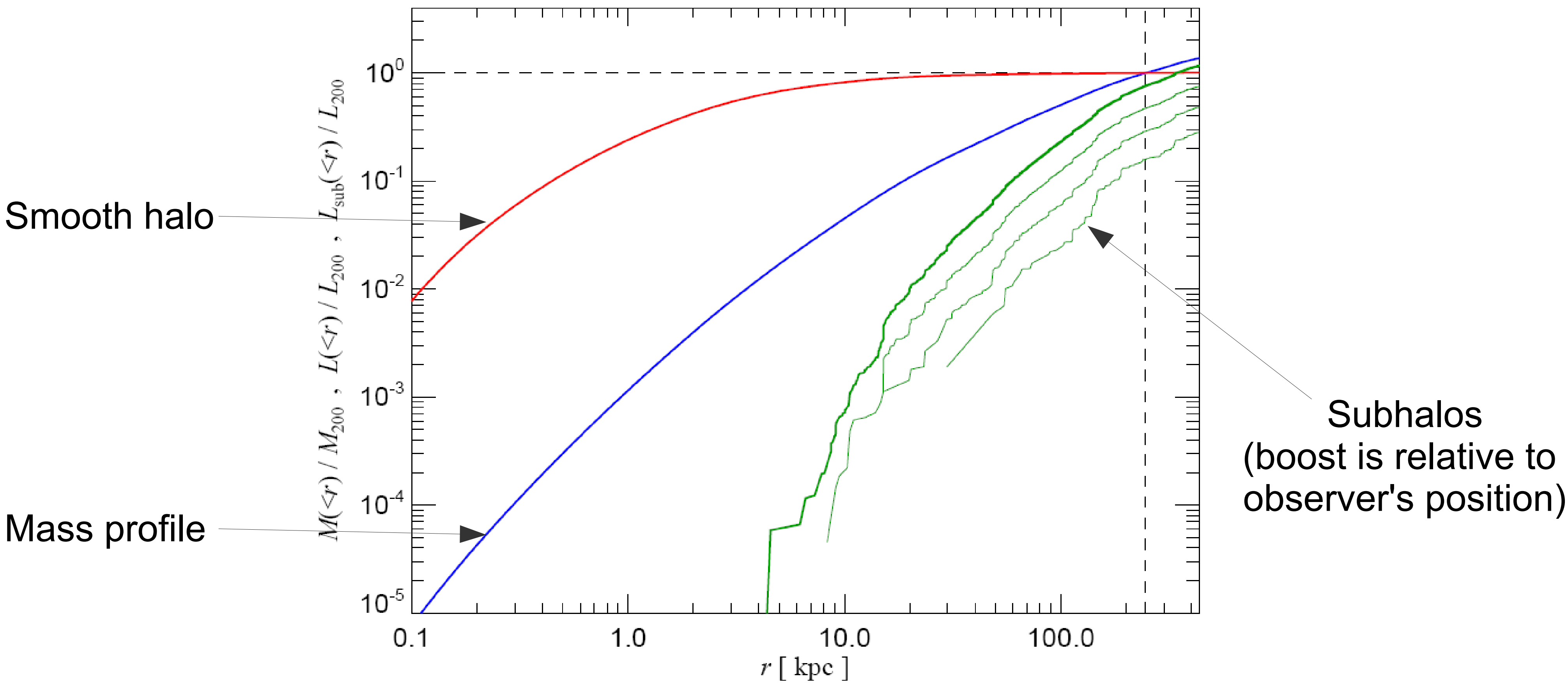
DM clustering (N-body simulations)

Luminosity profile (from halo center)



Springel et al. 2008

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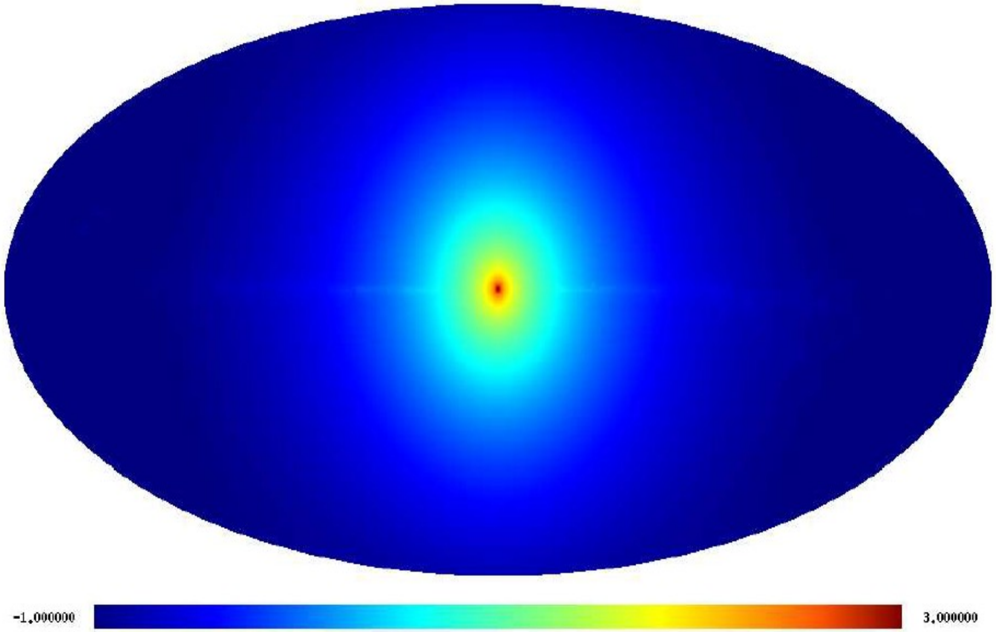
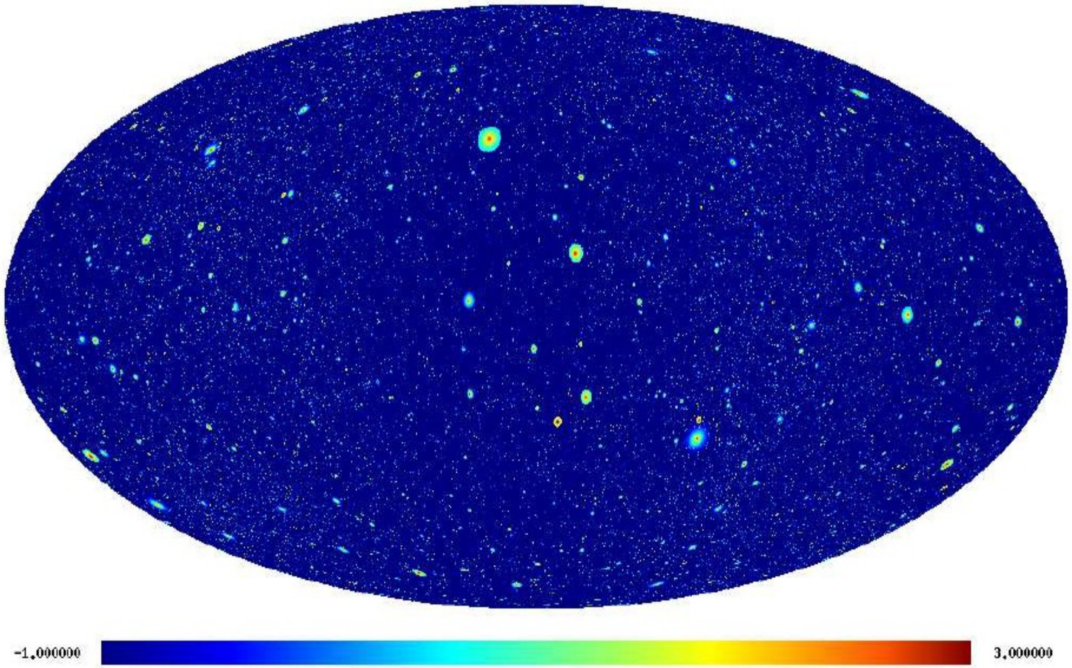
Observer at the solar circle



Smooth component (Einasto)
Prompt emission +
IC emission (ISRF)

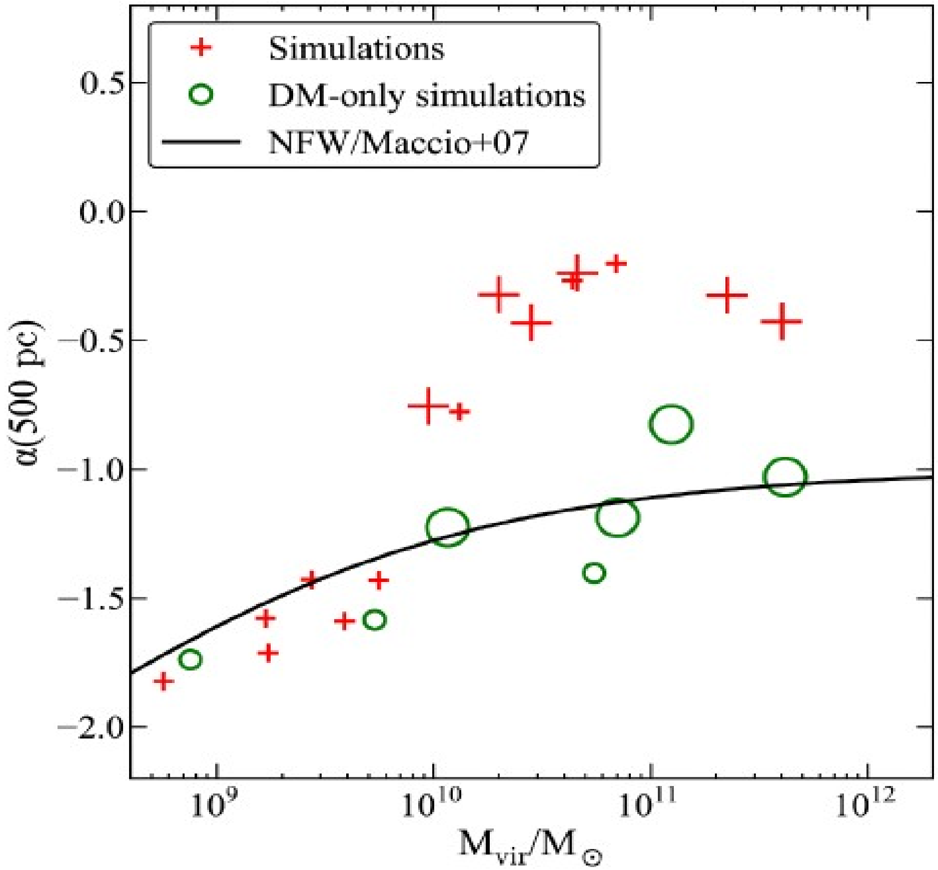
Aquarius subhalos
$M_{sub} > 10^5\ M_{sun}$



Fornasa, JZ, et al. 2012, in prep.

Annihilation within the Galactic halo (uncertainties)

- Inner density profile (50% of total luminosity comes from within 3 kpc): effect of the central galaxy, adiabatic contraction (e.g. Mo et al. 2008) or development of a core by strong SN feedback (e.g. Governato et al. 2012). Factor of <10 difference between a Moore profile and a Burkert profile. Less relevant if center is masked!

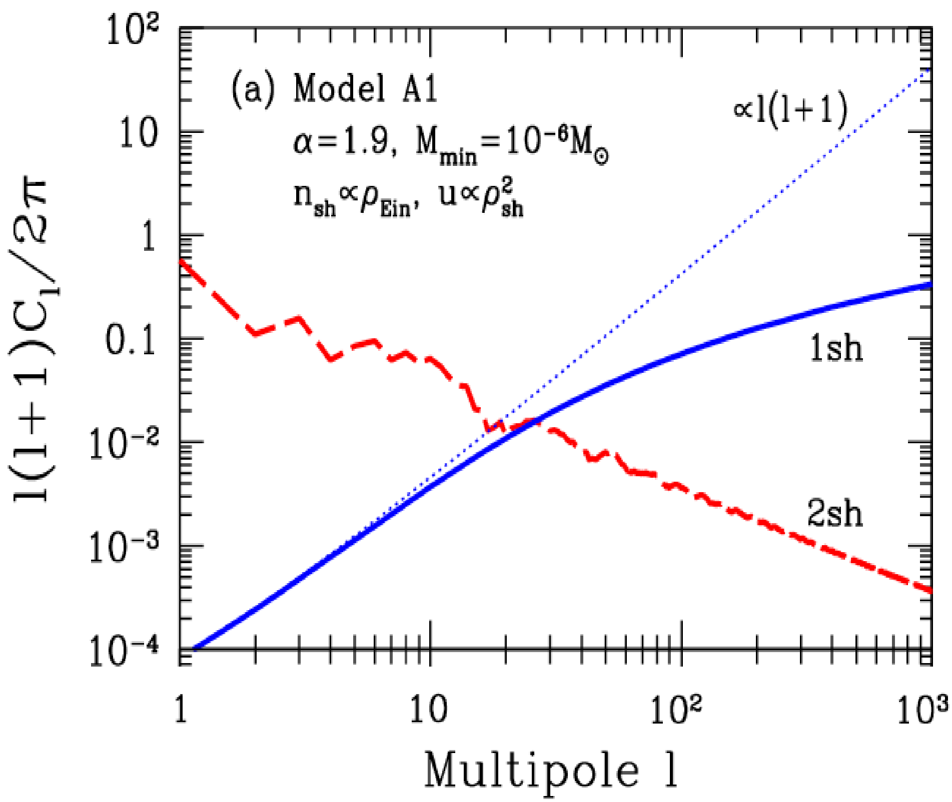


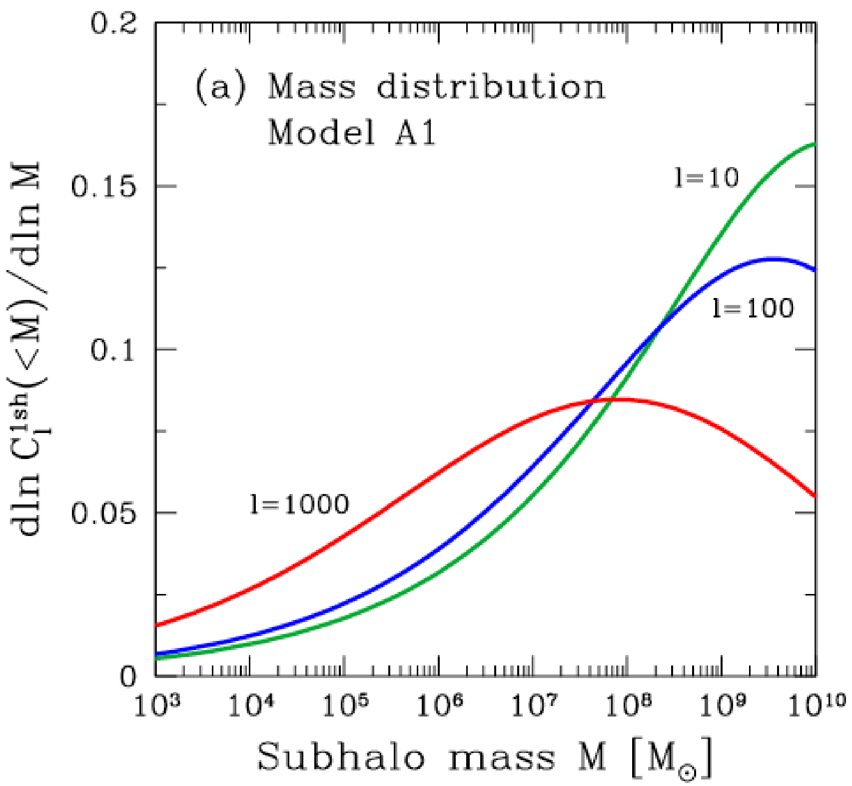
Governato et al. 2012 (hydro sims)

Annihilation within the Galactic halo (uncertainties)

- Missing flux from substructures below 10^5 M_{sun} down to M_{min}: assume subhalo mass function, radial distribution, universal density profile, concentration-mass relation. Extrapolate from sims (Springel et al. 2008), mock realizations (Siegal-Gaskins 2008), analytical models calibrated with sims (Ando 2009, Kamionkowski et al. 2010).

- Total subhalo boost at the solar circle is < 0.01 (10^5 M_{sun}) >1 (10^{-6} M_{sun}). More relevant if center is masked! Maybe not important for anisotropies:





Ando 2009

Cosmic background radiation from DM annihilation

- Specific Intensity (cosmological dimming and photon absorption)

$$I(\psi) = \int_{\mathrm{los}} f_{\mathrm{PP}}(E_\gamma, z)\rho^2(\lambda(z), \psi)e^{-\tau_{\mathrm{EBL}}(z, E_\gamma)}\mathrm{d}\lambda$$

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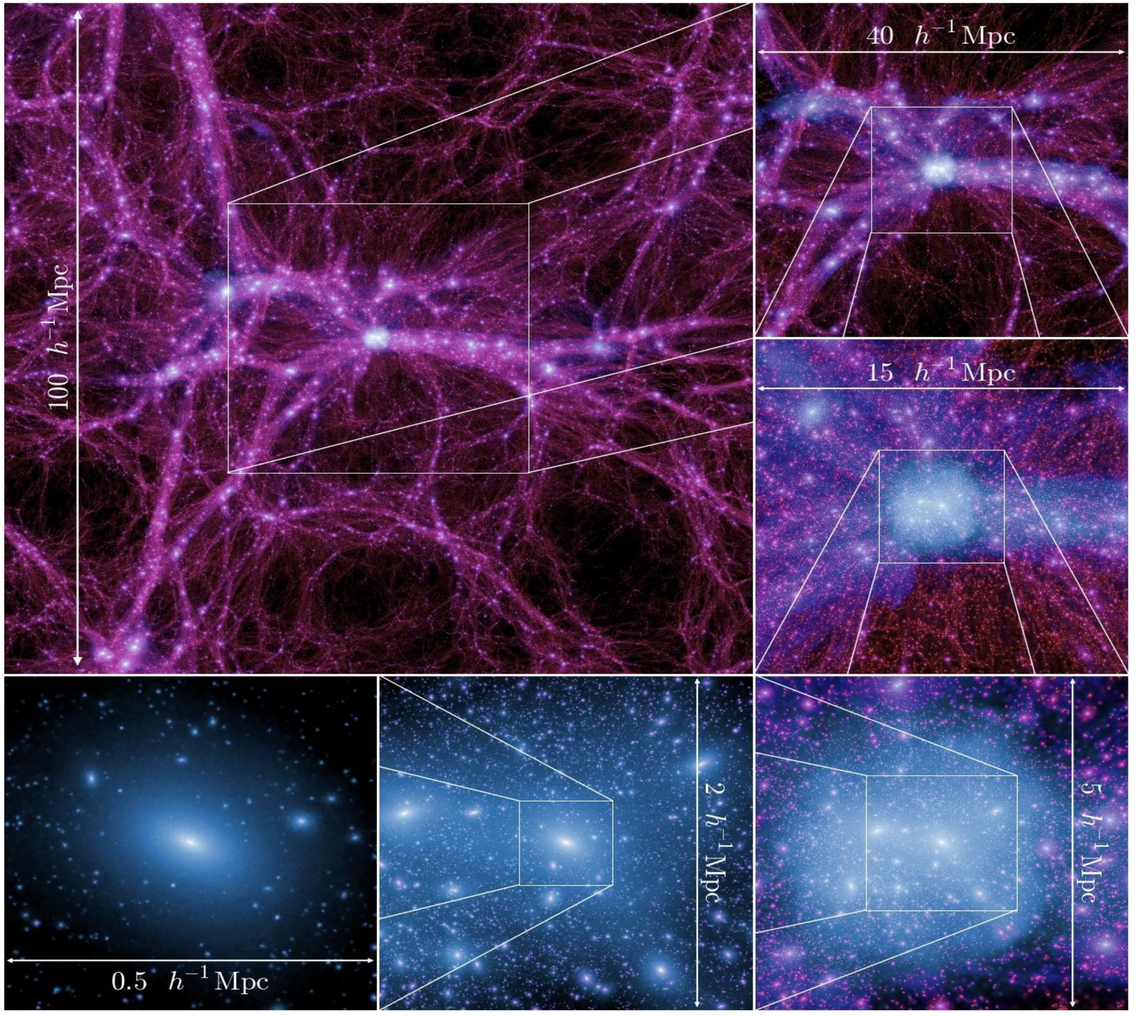
- Contribution from all dark matter structures along the line of sight of the observer (no contribution from unclustered DM).

Millennium-II simulation
Boylan-Kolchin et al. 2009

140 Mpc box
10 billion particles ($m_p \sim 10^7 M_{sun}$)
$M_{res} \sim 10^9 M_{sun}$ (100 particles)



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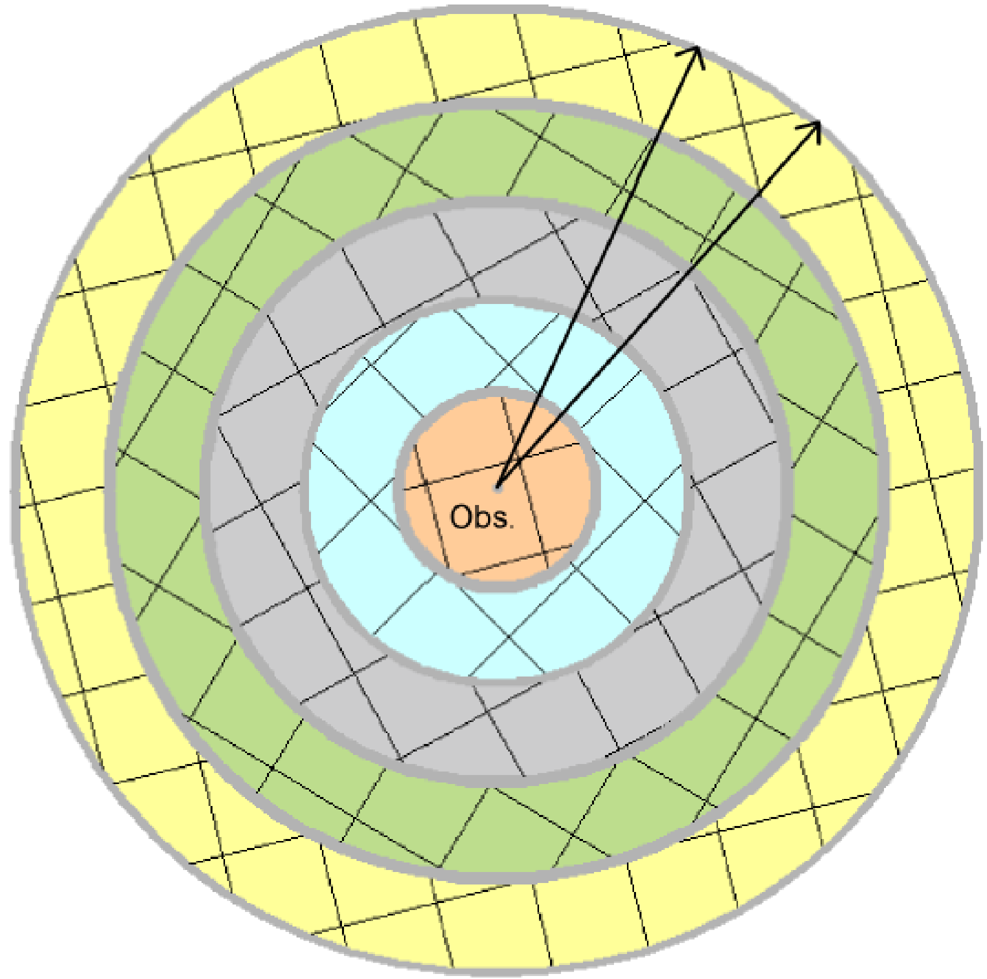
Past light cone simulation
(Zavala et al. 2010, Fornasa, JZ, et al. 2012)

Spatial and temporal evolution given by MS-II



Total luminosity of DM (sub)halos
(NFW profile):

$$L' \equiv L_{\text{ann}} = 1.23\frac{V_{\text{max}}^4}{G^2 r_{\text{max}}}\left[1 - \frac{1}{(1+c_{200})^3}\right]$$

Luminosity doubles for Einasto profile

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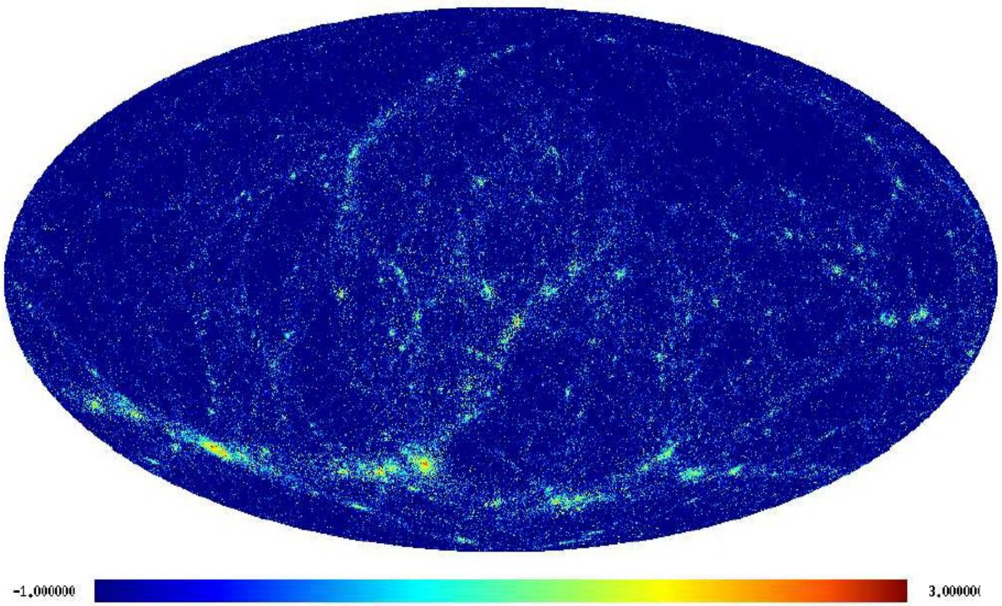
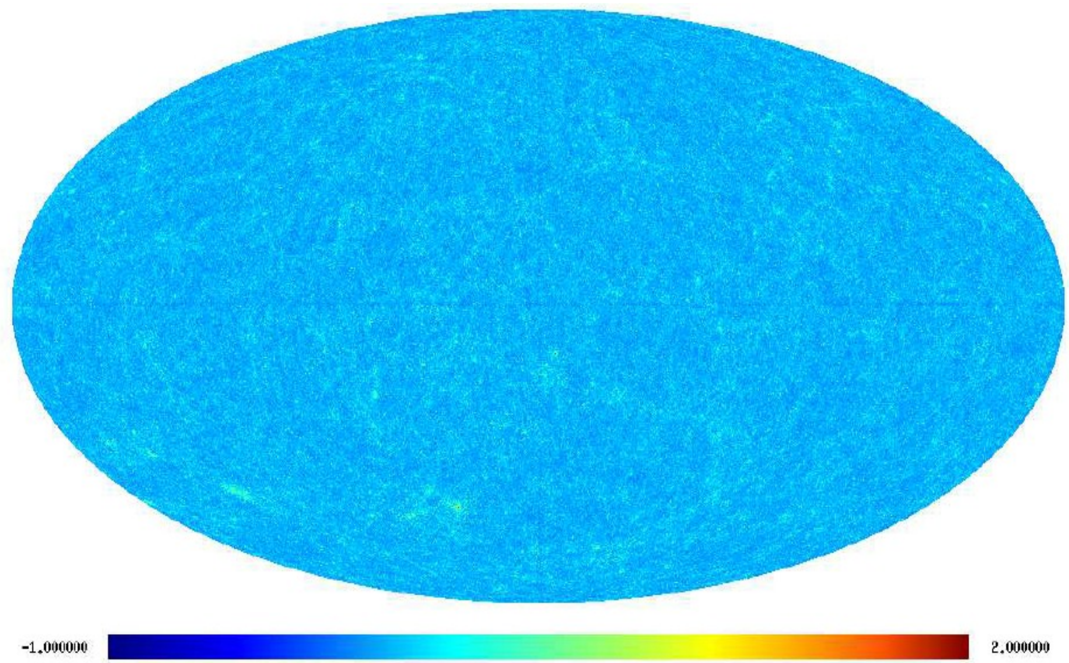


Nearby structures E=4GeV
(first shell 30 Mpc)

Integration up to z=2, E=4GeV
(90% of prompt gamma-ray emission at z<1)



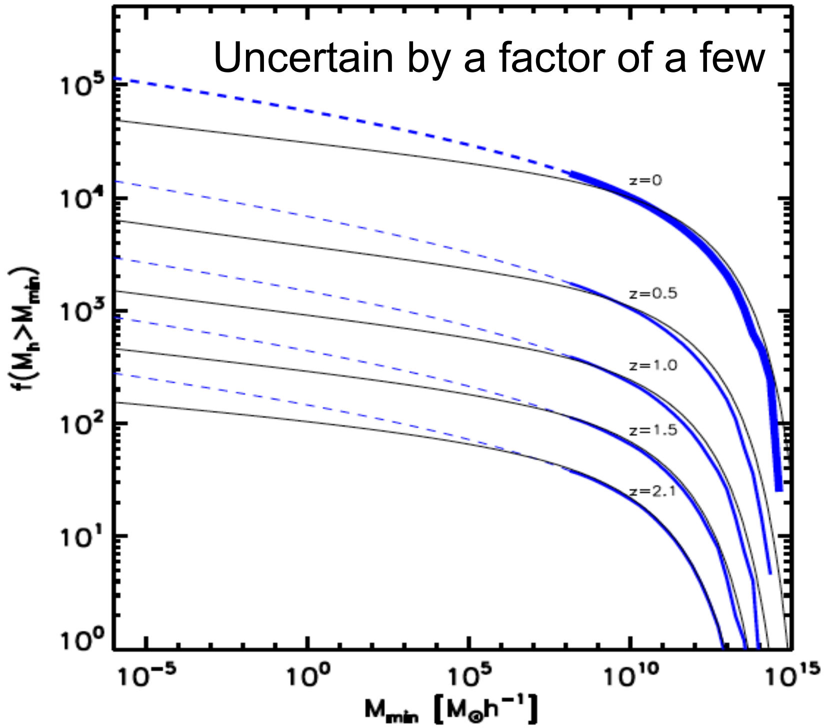
Fornasa, JZ et al. 2012

CBR from DM annihilation (uncertainties)

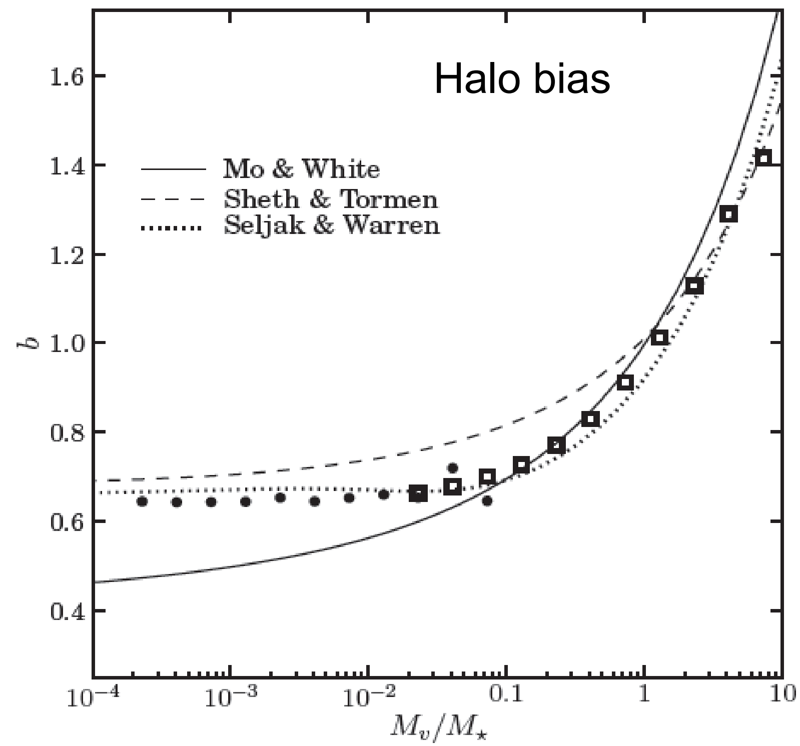
- Inner density profile: effect of the central galaxy for massive halos (cuspy or cored). Less relevant once $M<10^9 M_{sun}$ (sub)halos are considered, they dominate the signal.

- Extrapolation to “main” halos below $M<10^9 M_{sun}$ and down to M_{min}: asssume halo mass function, universal density profile, concentration-mass relation, halo clustering.

Zavala et al. 2010



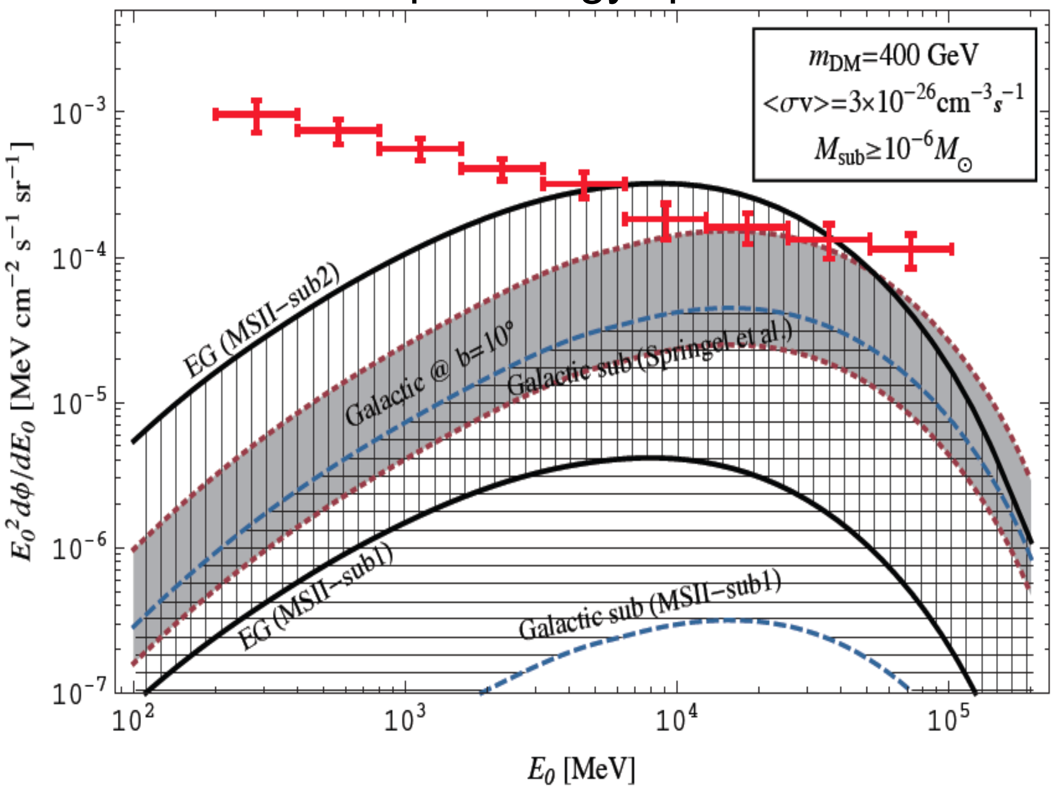
Boylan-Kolchin et al. 2009



- Substructures within halos have a dominant role for external observers. Uncertainty depends on subhalo abundance as a function of halo mass: total boosts to the CBR vary between a factor of 10 - 1000 for $M_{min}=10^{-6}$ M_{sun} (Zavala et al. 2010, Sanchez-Conde et al. 2011, Fornasa, JZ et al. 2012). Largest source of uncertainty!

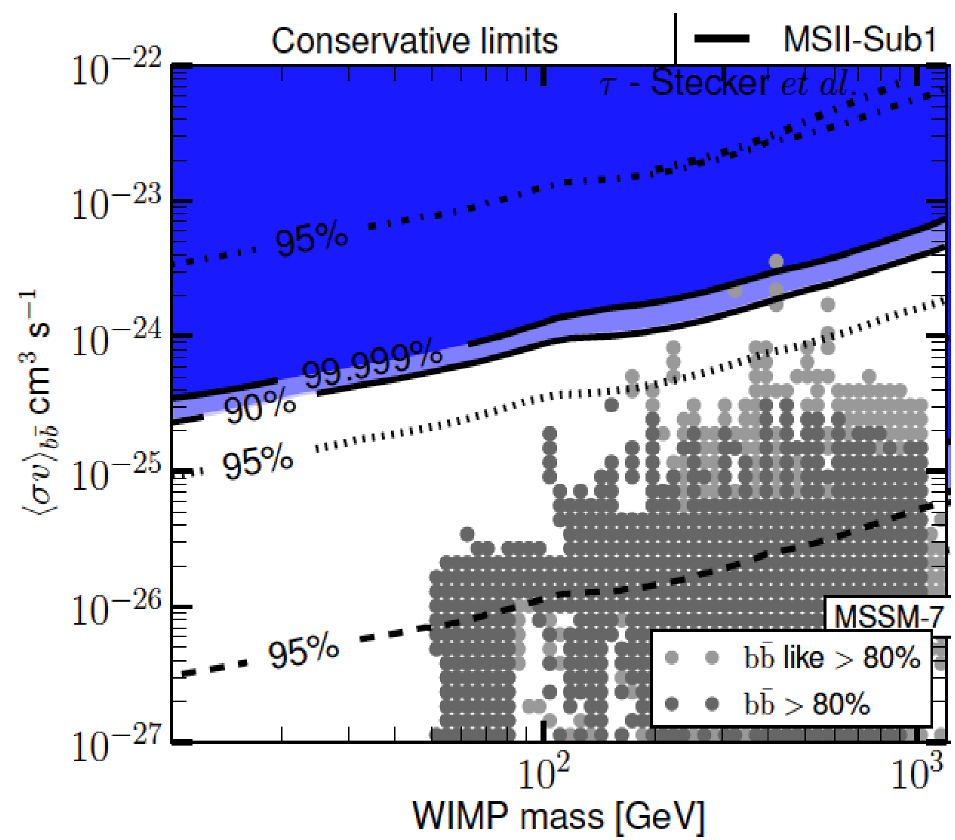
Constraints to the annihilation cross section from the Isotropic Gamma-ray Background

Isotropic energy spectrum



Abdo et al. 2010 based on Zavala et al. 2010
And Springel et al. 2008

Competitive limits



Constraints on Sommerfeld-enhanced annihilation

- Benchmark models from Finkbeiner et al. 2011
- New force carrier in the “dark sector” (Arkani-Hamed et al. 2009)
- Annihilation cross section enhanced by a Sommerfeld mechanism
- Fit to the cosmic ray excesses measured by PAMELA and Fermi
- Correct relic density
- Allowed by bounds from the CMB
- IC contribution dominates the photon yield

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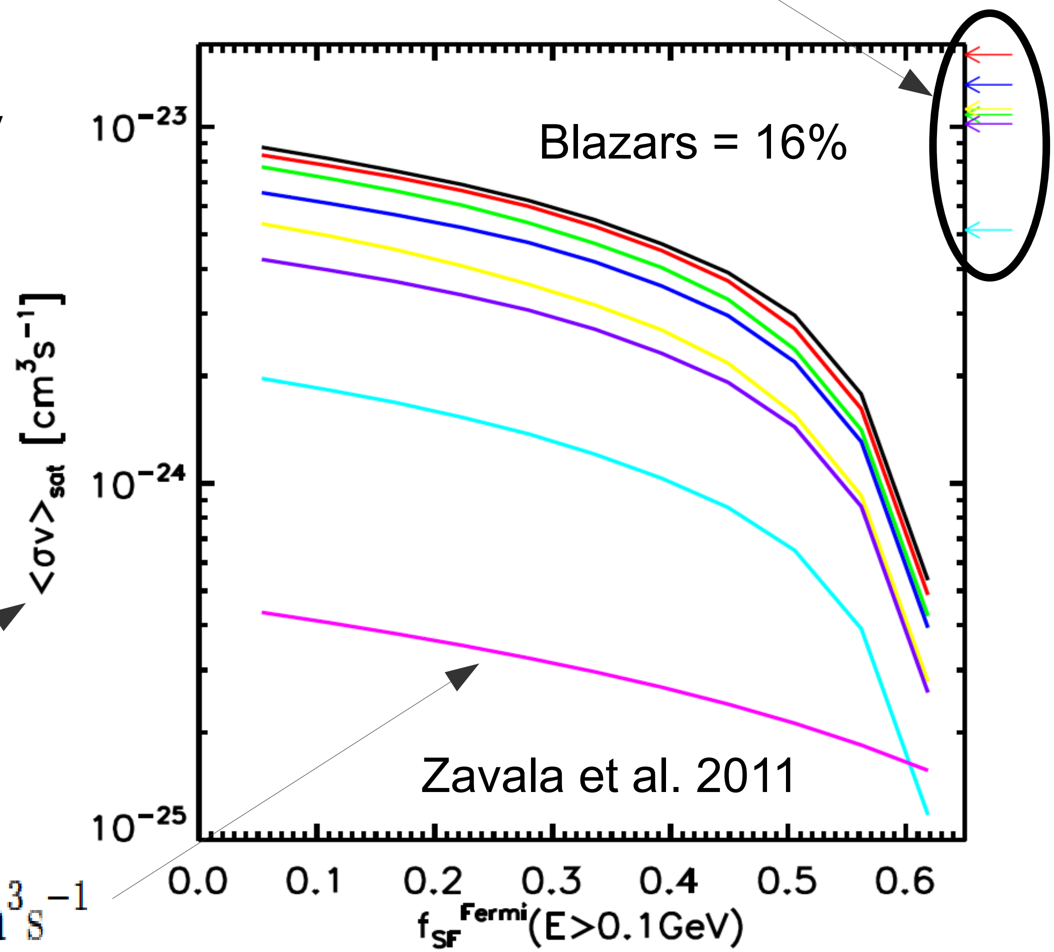
Levels needed to fit PAMELA



Maximum cross section allowed by Fermi data. Extragalactic annihilation only and minimum subhalo boost!

$$m_\chi \sim 200\,GeV, \chi\chi \rightarrow b\bar{b} \text{ and } \langle\sigma v\rangle \sim 6.2\times10^{-27}\text{cm}^3\text{s}^{-1}$$

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• Annihilation cr
Sommerfeld m

• Fit to the cosm
PAMELA and F

• Correct relic d

• Allowed by bo

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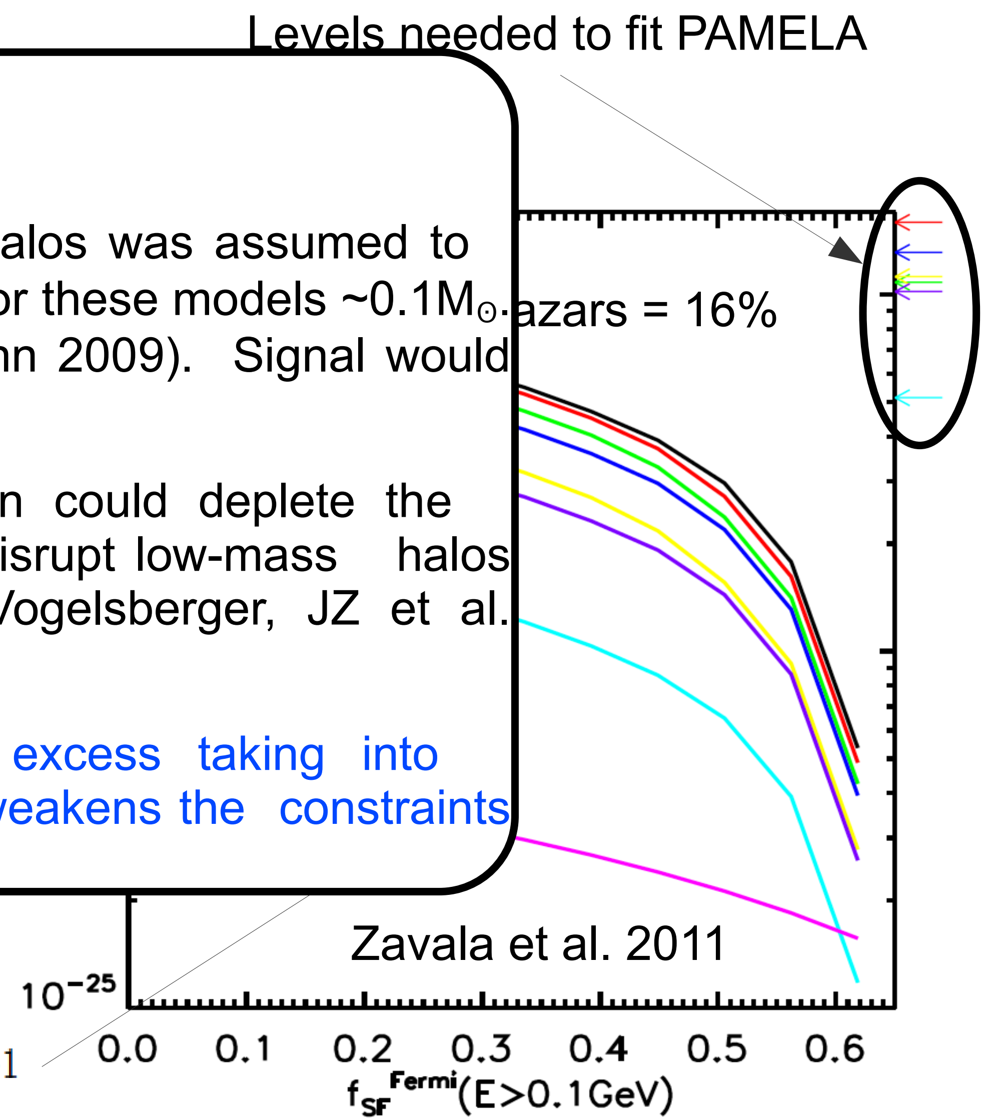
Caveats

- Minimum mass for bound halos was assumed to be $10^{-6}M_{\odot}$. It can be higher for these models ~$0.1M_{\odot}$. (Feng et al. 2010, Bringmann 2009). Signal would be reduced by a factor of ~2.

- Self-scattering cross section could deplete the central density cusps and disrupt low-mass halos (Loeb and Weiner 2011, Vogelsberger, JZ et al. 2012).

- Fits to PAMELA positron excess taking into account local substructure weakens the constraints (Slatyer et al. 2011).

Maximum cro
Fermi data. Extragalactic annihilation
only and minimum subhalo boost!



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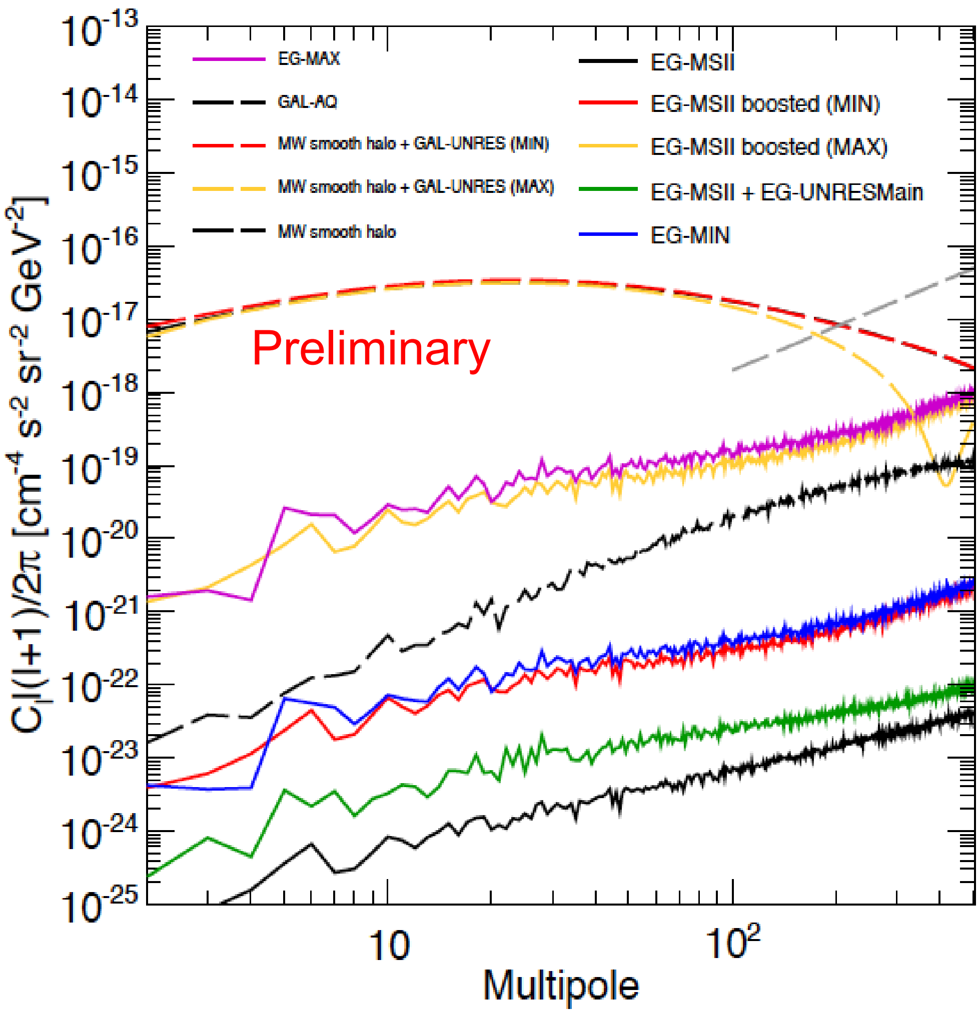
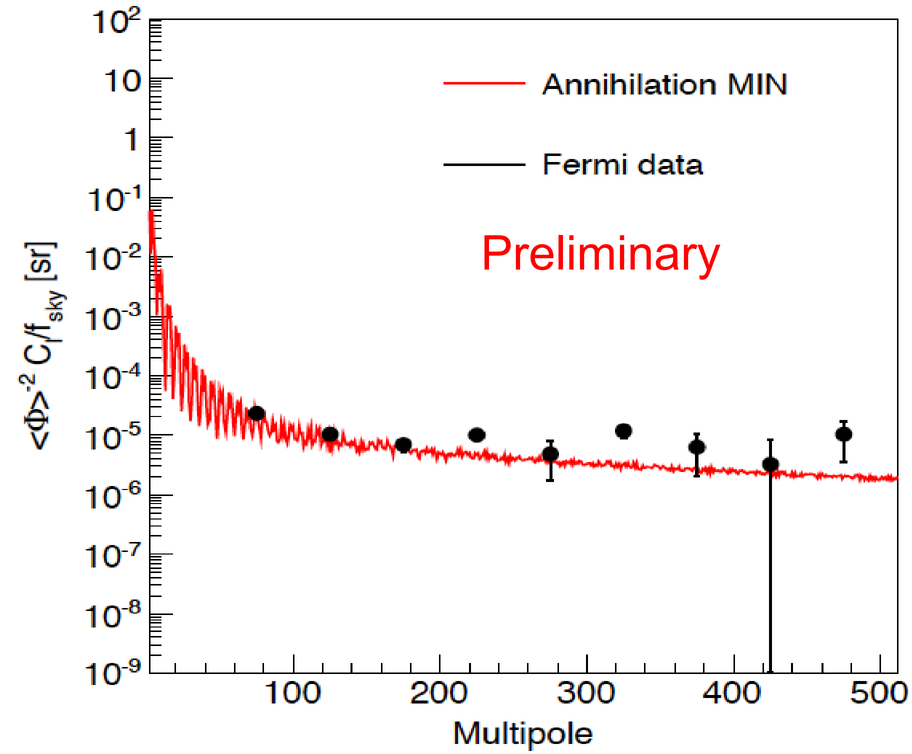
Revised predictions on the anisotropy of the Gamma-ray Background

Intensity APS (no mask)



Masked b<30 deg (2-5 GeV)



FLUCTUATION APS!!

Fornasa, JZ et al. 2012, in preparation

Summary and Conclusions

- The Gamma-ray Background is a powerful observation to constrain dark matter matter annihilation (although not as clean as the CMB). It offers competitive constraints to those from the MW satellites and the GC.
- If the value of the minimum self-bound (sub)halo mass is several orders of magnitude below current simulations then the background is dominated by low-mass sub(halos), where the complications of galaxy formation are irrelevant.
- The largest uncertainty comes from the extrapolation on the abundance and clustering of the lowest masses of the DM hierarchy, particularly from substructures
- The GB energy spectrum already puts strong constraints, specially when other astro sources are considered such as blazars. These constraints are particularly stringent for Sommerfeld-enhanced models.
- The GB angular power spectrum offers a complimentary constraint which is worthy to explore, specially through its energy dependence.