The cosmic X-ray and gamma-ray background from dark matter annihilation

Jesús Zavala Franco
(CITA National Fellow, University of Waterloo, Canada)

In collaboration with:

Mark Vogelsberger (CfA, Cambridge)
Tracy Slatyer (IAS, Princeton)
Abraham Loeb (CfA, Cambridge)
Volker Springel (HITS, Heidelberg)

arXiv: 1103.0776

TeVPA, Stockholm, August 2011

Why DM annihilation?

"WIMP miracle"

$$m^2 \sim \langle \sigma_A v \rangle^{-1} \sim M_{\rm weak}^2$$

$$\Rightarrow \quad \Omega h^2 \sim 0.1$$

$$\langle \sigma v \rangle_0 \sim 3\times10^{-26}\,{\rm cm}^3{\rm s}^{-1}$$

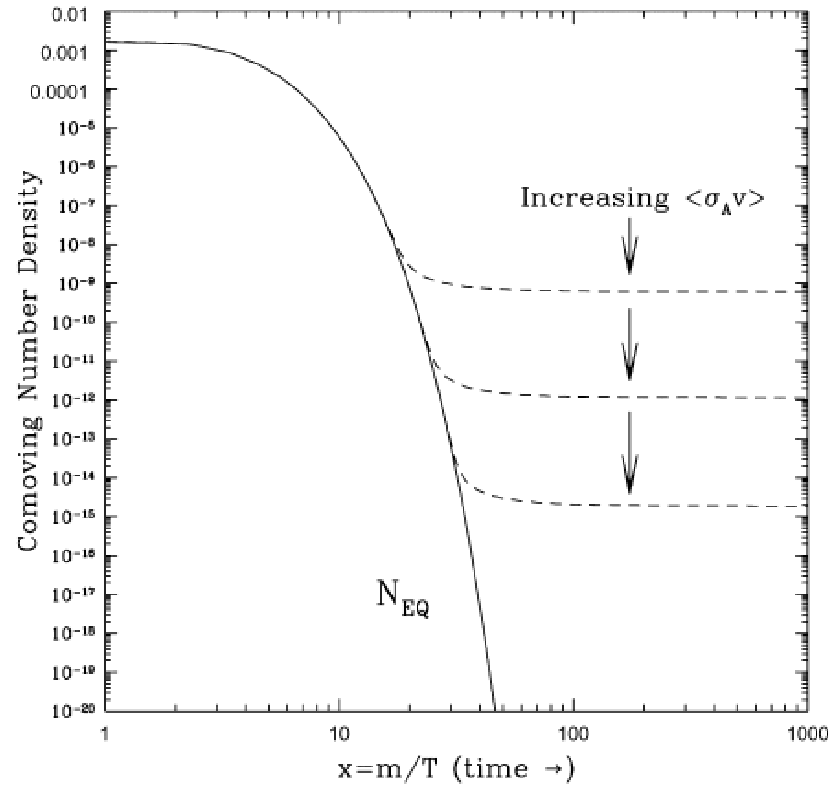
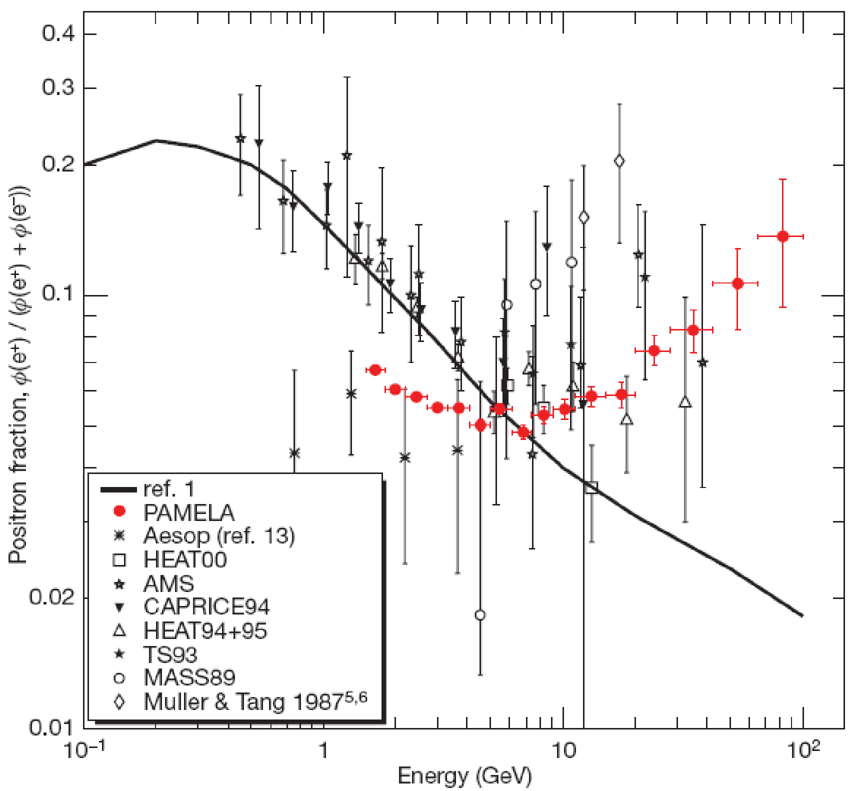


Fig. from Feng, J. L., 2005



PAMELA, Adriani et al. 2009
excess of e+ for E>10GeV

Cosmic ray anomalies

- Large cross section BF > O(100) over thermal relic value (e.g. Bergström et al. 2009)
- Annihilation mainly to leptons, proton/antiproton channel suppressed

⇒ Sommerfeld enhancement
(Hisano et al. 2004,
Arkani-Hamed et al. 2009, ...)

Cosmic background radiation from dark matter annihilation

- Energy of photons per unit area, time, solid angle and energy range received by an observer located at z=0.

$$I = \frac{1}{4\pi}\int \mathcal{E}(E_0(1+z),z)\frac{\mathrm{d}r}{(1+z)^4}e^{-\tau(E_0,z)}$$

- Contribution from all dark matter structures along the line of sight of the observer (assumption: no contribution from unclustered DM).
- The volume emissivity of photons (energy of photons produced per unit volume, time and energy range) can be written as:

$$\mathcal{E} = \frac{f_{\mathrm{WIMP}}}{2}E\rho_\chi(\vec{x})^2$$

- Properties of dark matter as a particle (WIMP factor):

$$f_{\mathrm{WIMP}} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{\langle\sigma v\rangle}{m_\chi^2}$$

- The density squared dependence is connected to the gravitational interactions of dark matter (astrophysical factor).

Photon yield

- In situ photons: Directly created in the annihilation process (annihilation channels).

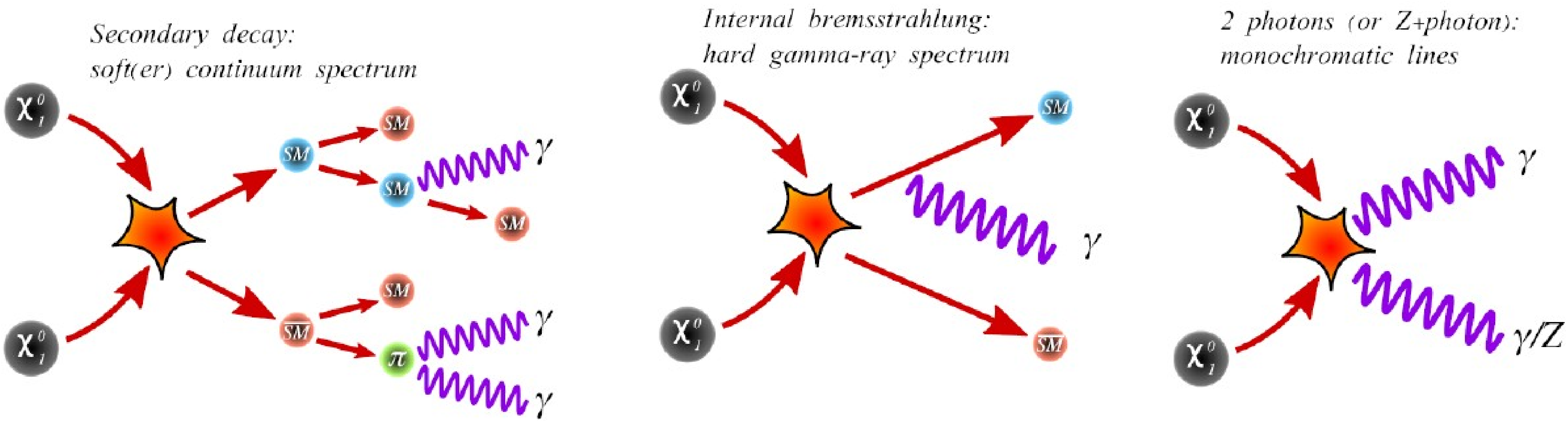
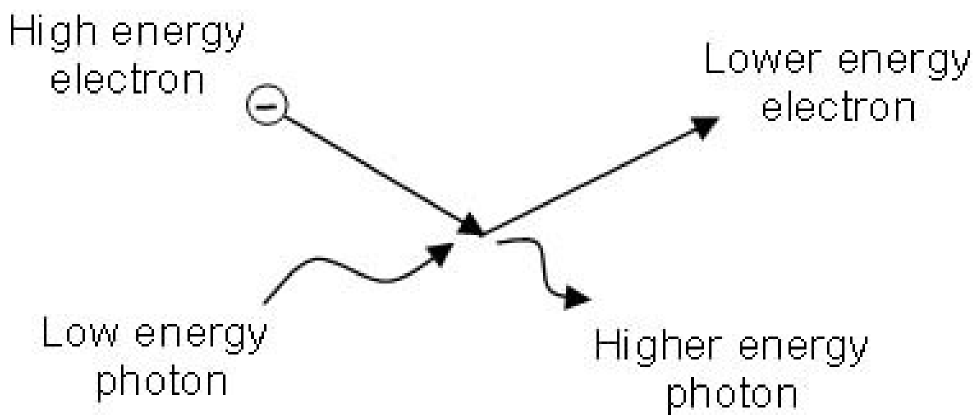
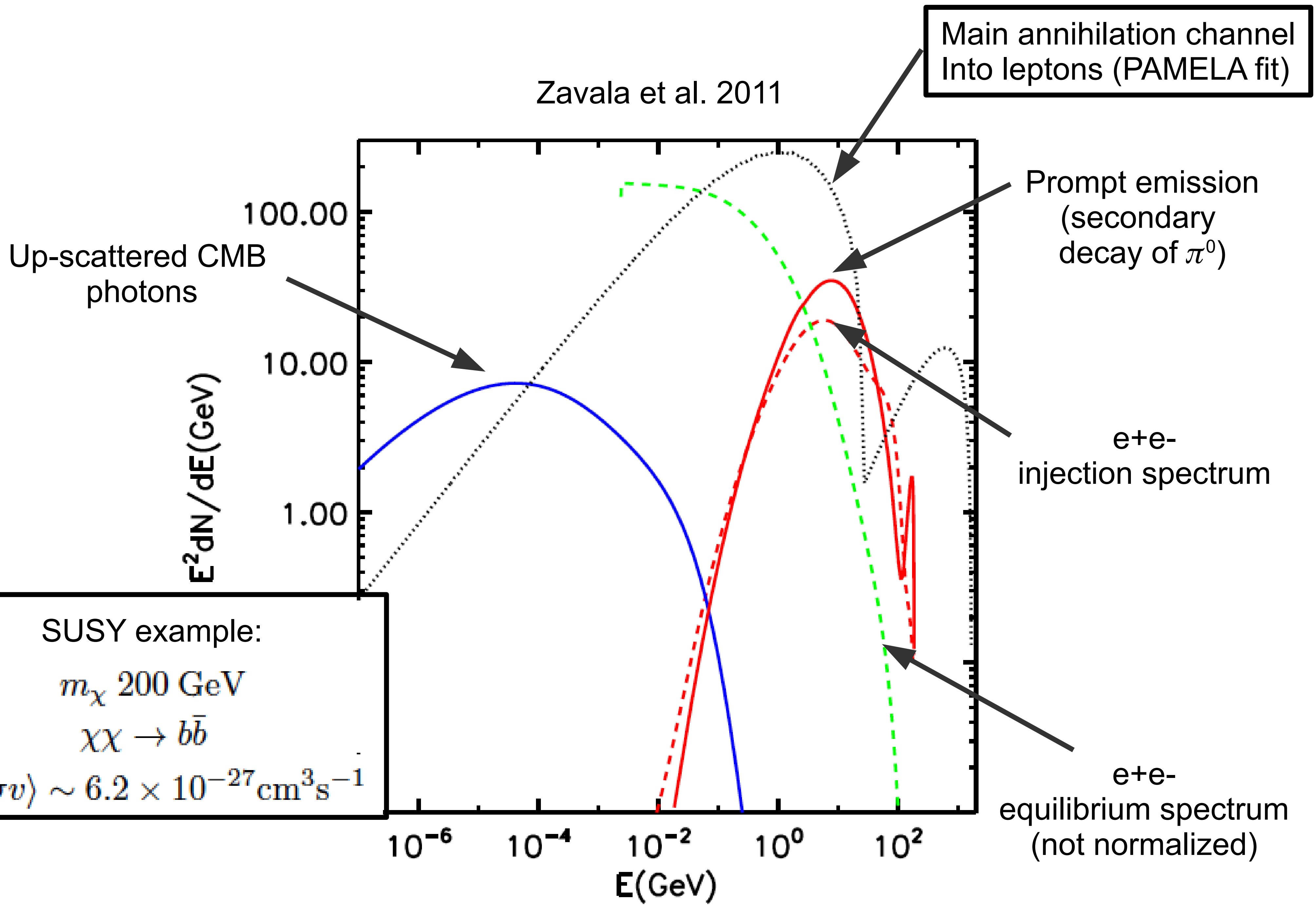


Fig. from P. Scott, Fermi Symposium 2009

- Up-scattered photons: Background photons gain energy through Inverse Compton scattering with electrons and positrons produced in the annihilation: e+e- injection spectra → e+e- equilibrium solution → photon background → final IC photon spectrum.



Gamma-ray photon spectrum



SUSY example:

m_χ 200 GeV

$\chi\chi \to b\bar{b}$

$\langle\sigma v\rangle \sim 6.2\times10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$

Annihilation in DM haloes (smooth component)

- For a region of volume V, the annihilation luminosity is proportional to:

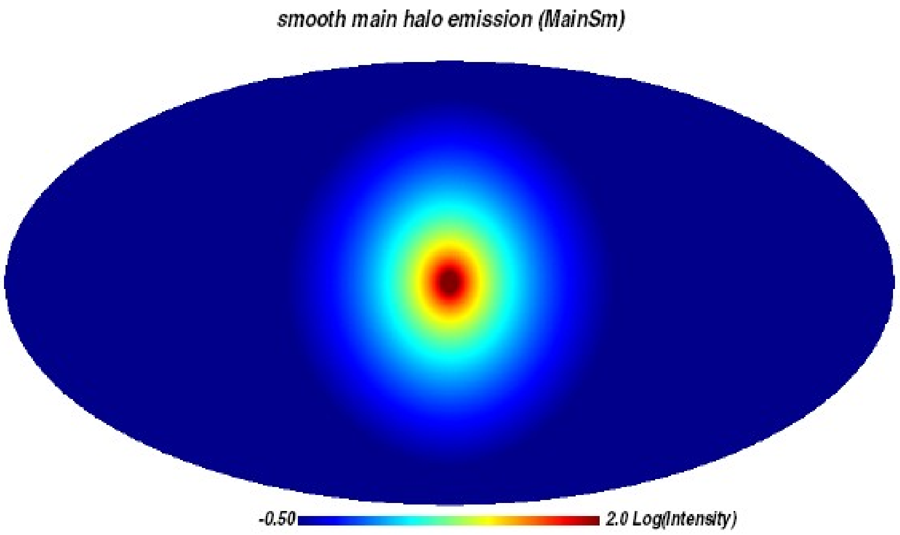
$$L_\gamma \propto \int_V \rho_\chi^2(\vec{x})\, d^3x$$

- Nearby regions of high DM density are promising in the search for an annihilation signal: GC (Abramowski et al. 2011, 1103.3226), MW satellites (Abdo et al. 2010, ApJ 712,147)...

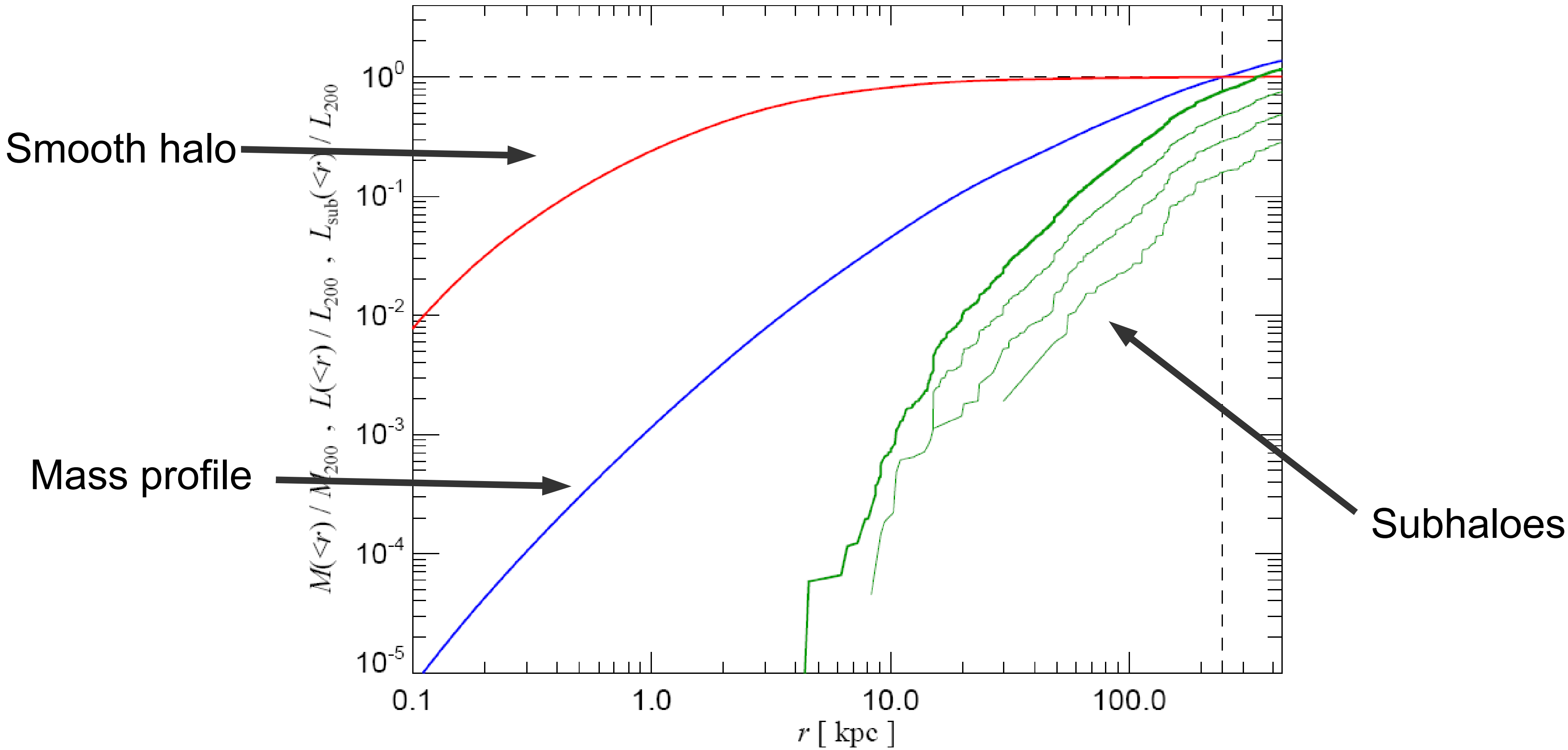
- For a smooth DM halo (Springel et al. 2008): $L'_{\mathrm{h}} = \int \rho^2_{\mathrm{NFW}}(r)\,\mathrm{d}V = \frac{1.23\,V^4_{\mathrm{max}}}{G^2 r_{\mathrm{max}}}$

  - Virgo Consortium's Aquarius Project (Simulation of MW-like haloes).

  - For the highest resolution:
    - M_h=1.84x10^{12} Msun
    - m_{DM}=1712 Msun
    - ε= 20pc



Role of substructures

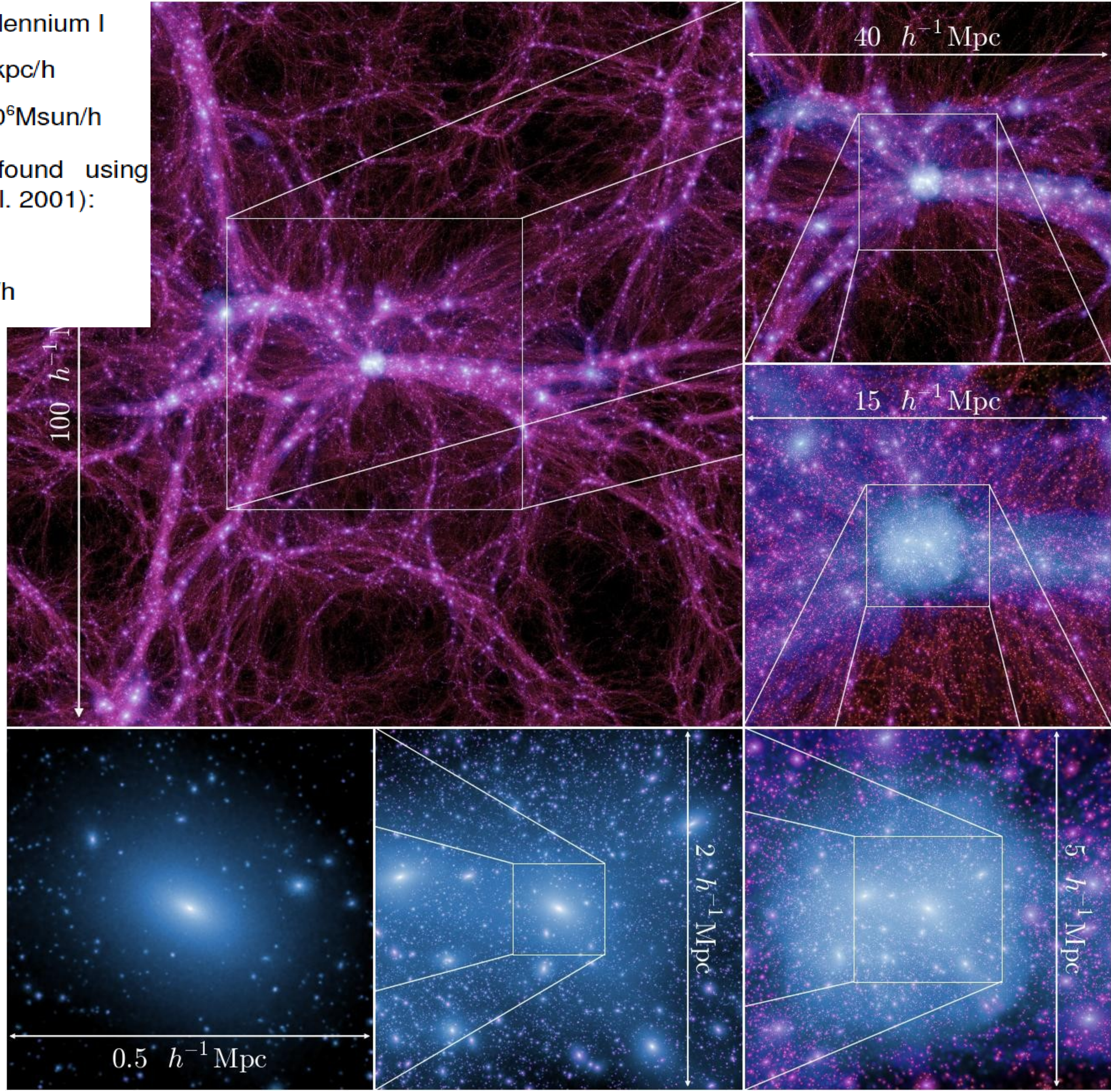


Springel et al. 2008

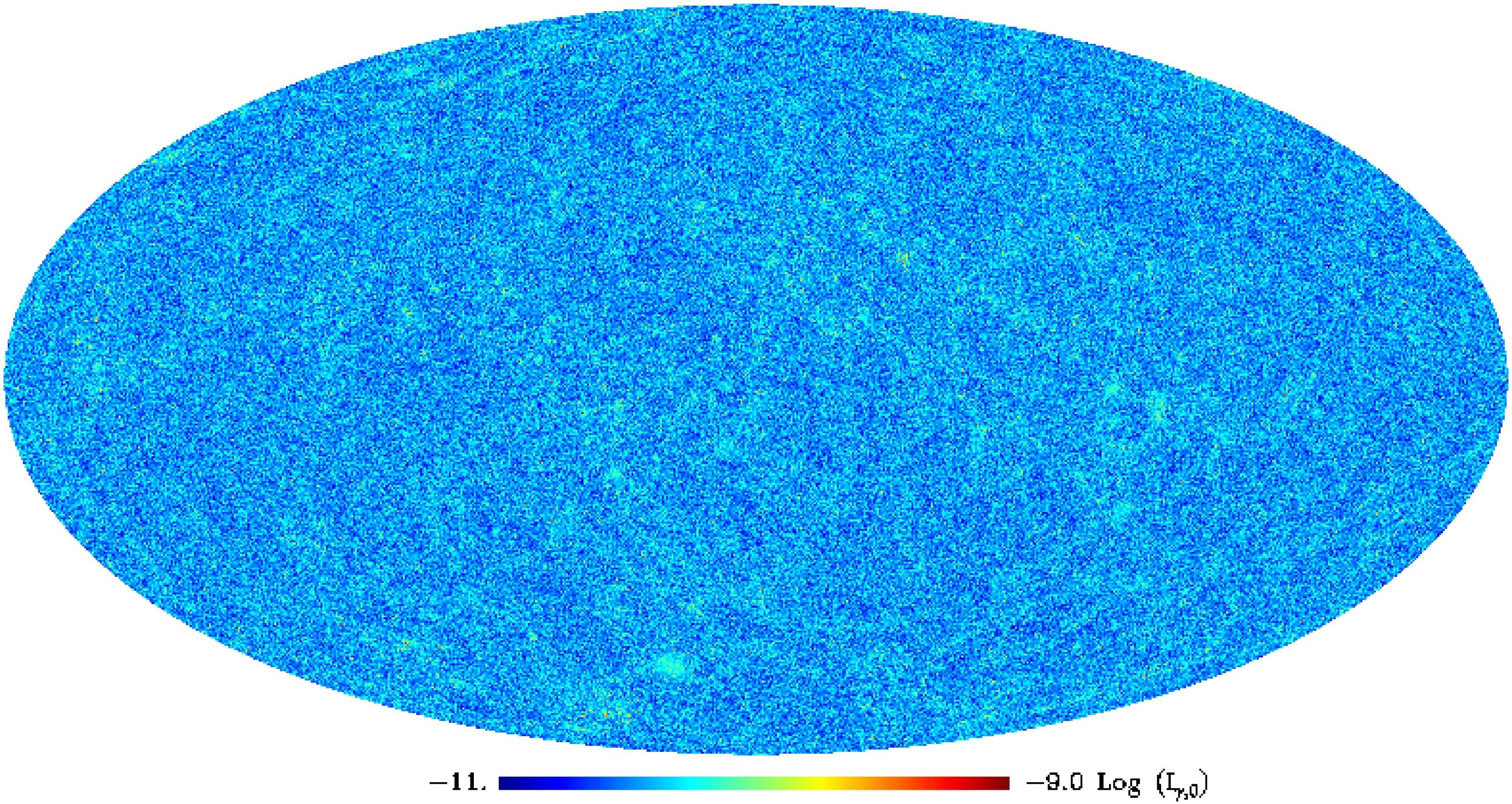
- Substructures within haloes have a significant role for external observers. Their contribution to the total luminosity is uncertain ~ 2 - 2000 times the contribution of the smooth component for a MW-like halo (once their minimum mass is extrapolated to ~Earth mass).

Millennium-II
(Boylan-Kolchin et al. 2009)

- Same cosmology as Millennium I
- 100 Mpc/h box and ε=1kpc/h
- N_p=2160^3, m_{DM} =6.89x10^{6}Msun/h
- Bound substructures found using SUBFIND (Springel et al. 2001):
- 11x10^6 subs at z=0
- M_{sub} (min)~1.4x10^{8}Msun/h



All-sky maps (resolved structures up to z~10, E=10GeV)

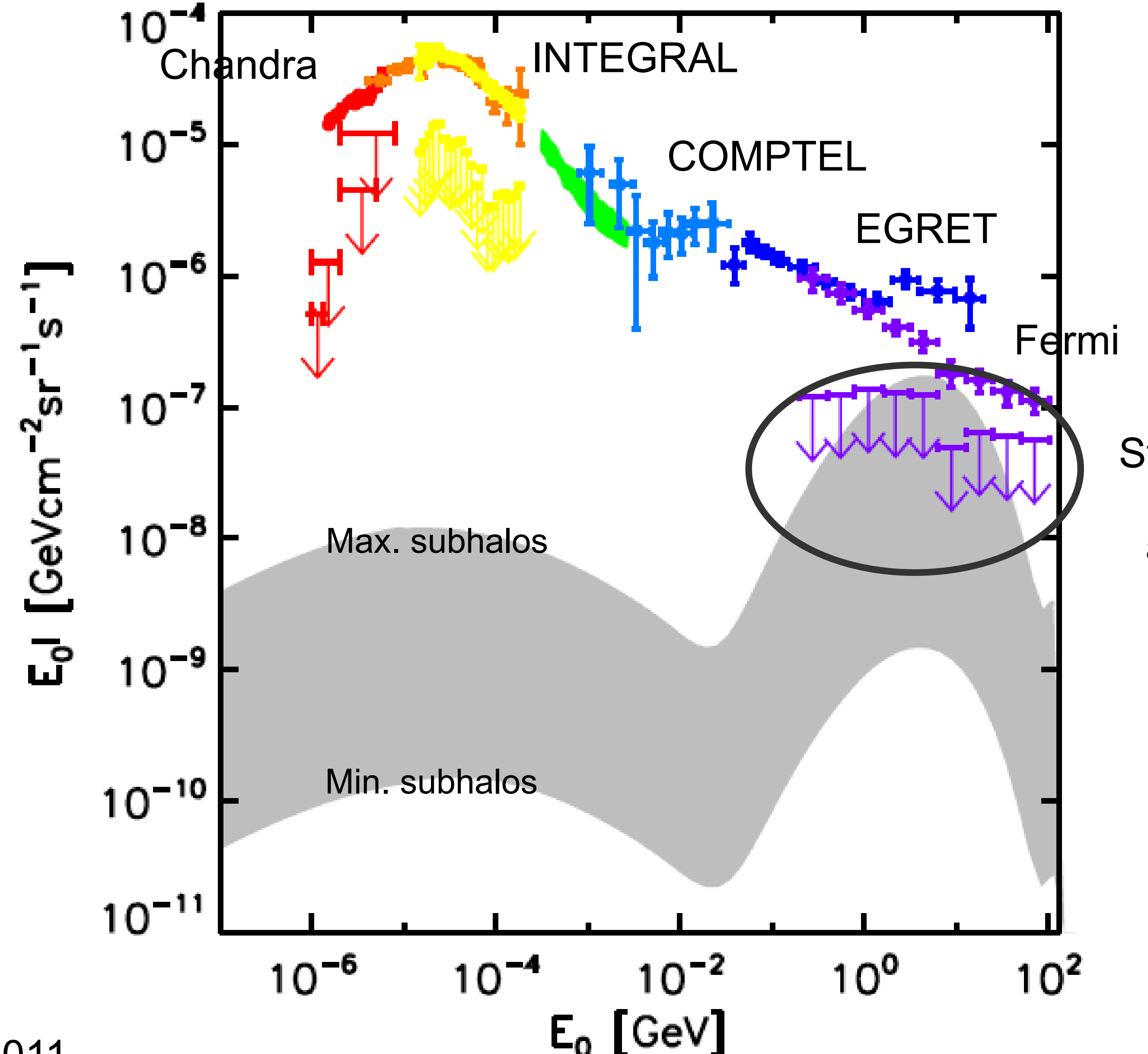


$N_{pix}=12(512)^2 \sim 3\times10^6$ ang. res. ~ 0.115°

Extrapolation for unresolved halos down to earth masses (~2 orders of magnitude uncertainty)

Isotropic component

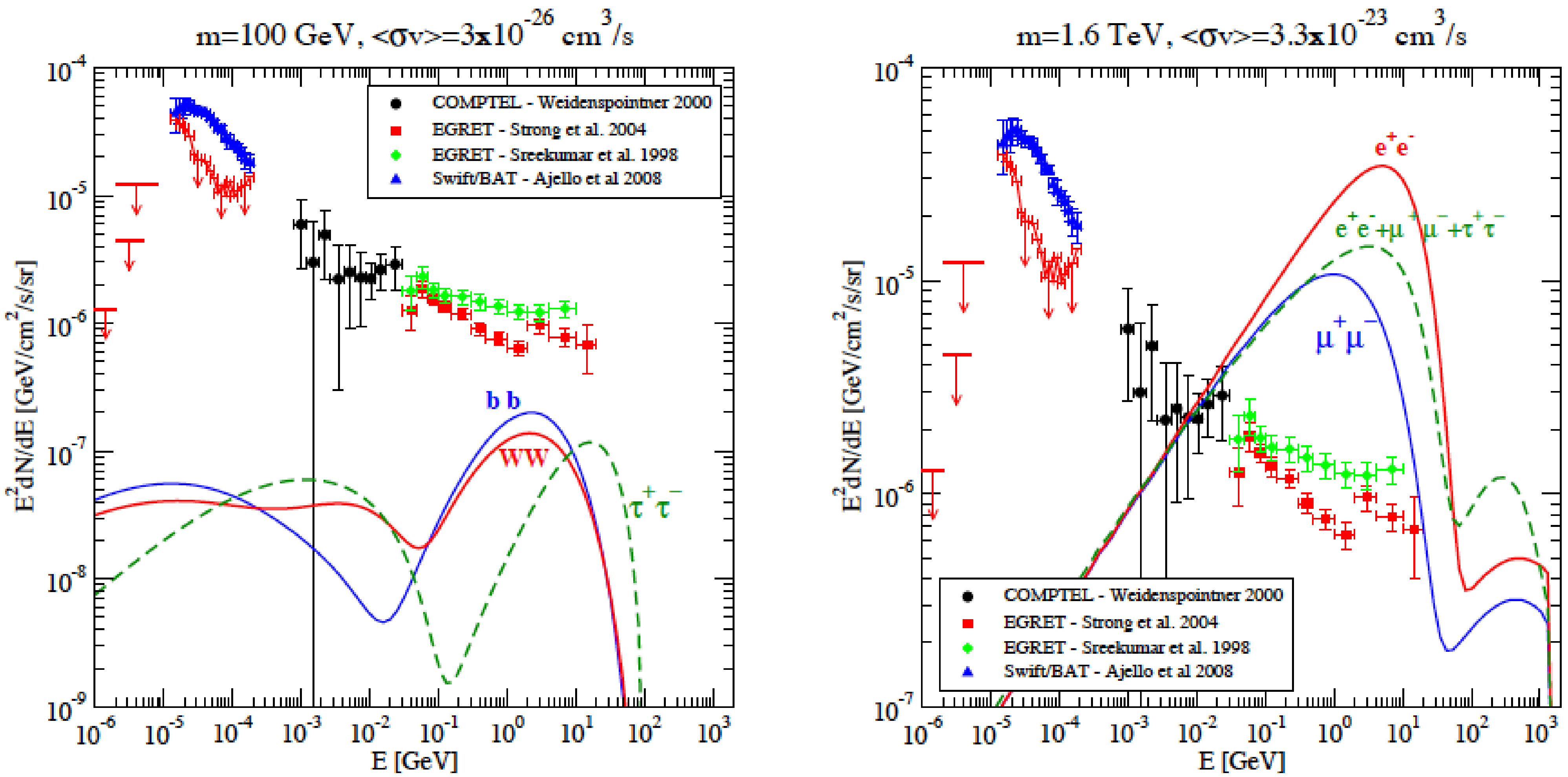
$$m_\chi \sim 200\,GeV, \chi\chi \rightarrow b\bar{b} \text{ and } \langle\sigma v\rangle \sim 6.2 \times 10^{-27}\text{cm}^3\text{s}^{-1}$$



Star forming galaxies (53%) and blazars (16%)

Zavala et al. 2011

Isotropic component (annihilation channel)



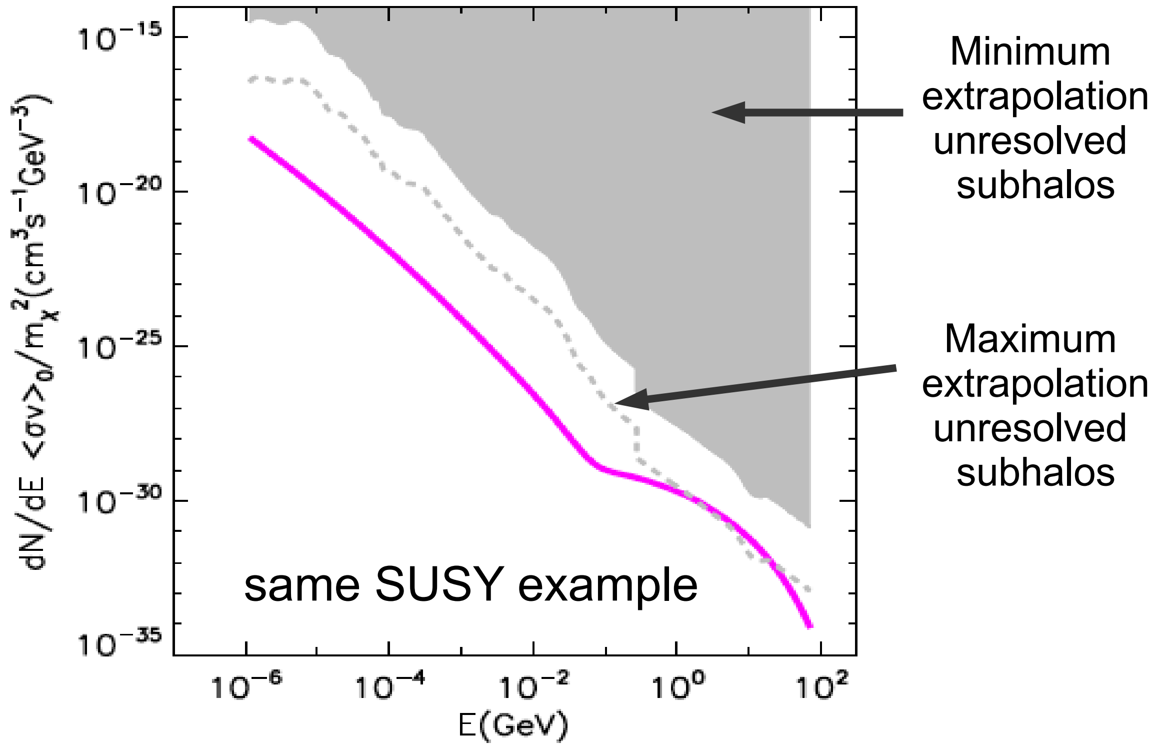
Profumo and Jeltema 2010

Constraints on particle physics models

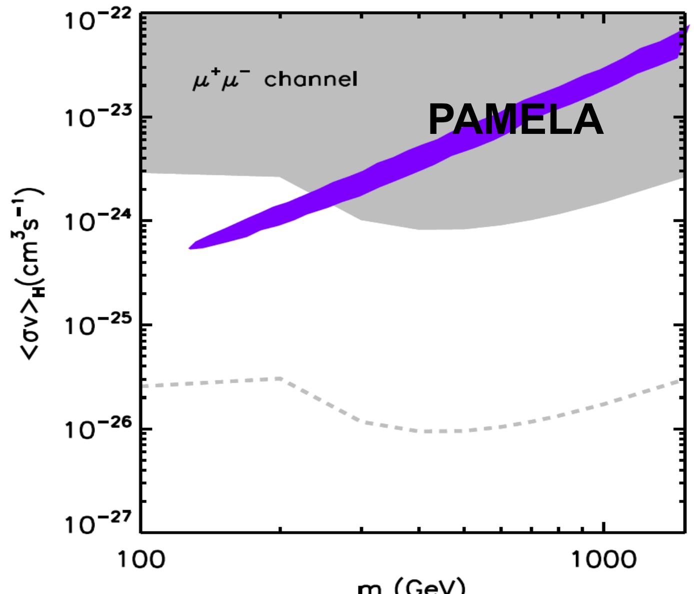
"factoring out" the astrophysical part of the signal

$$I(E_0) = \frac{c}{8\pi} E_0 f_{\mathrm{WIMP}}(E_0(1+z^*)) \int \frac{\rho_\chi^2(\vec{x}, z)}{(1+z)^3} \frac{e^{-\tau(E_0,z)}}{H(z)} \mathrm{d}z$$

z* < 4 for X-rays
z* < 1 for E>10GeV

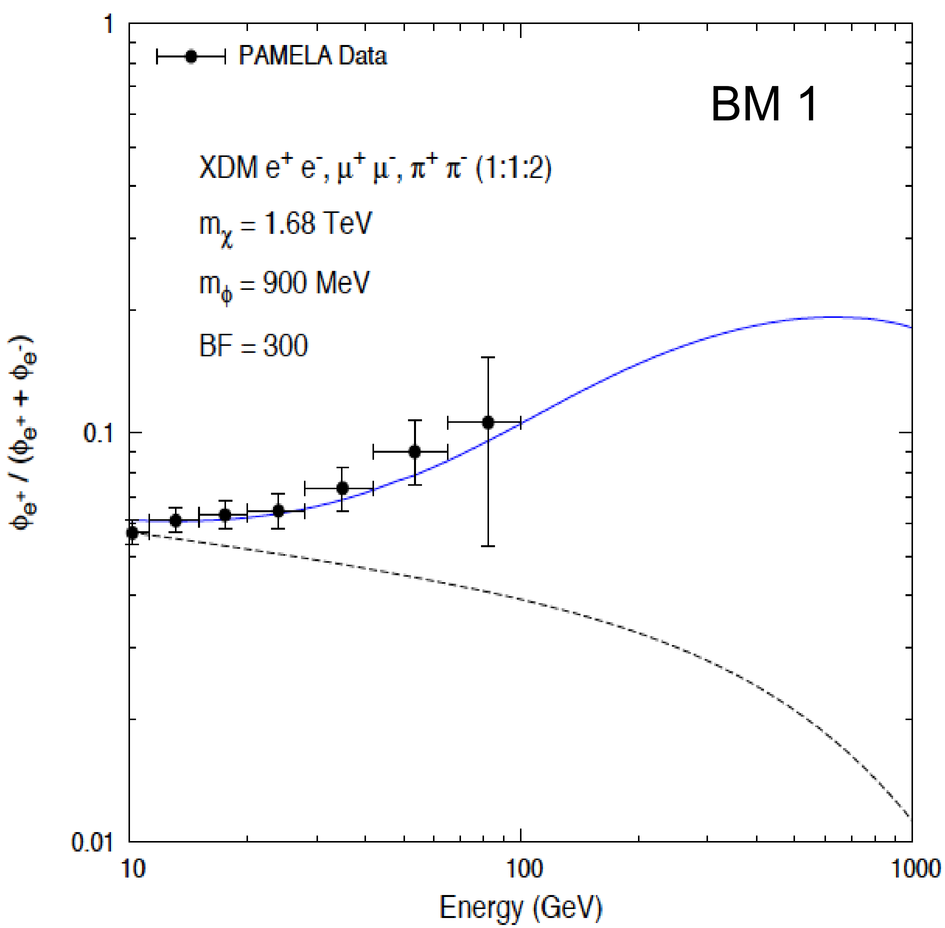


Photon yield spectrum from particle physics model



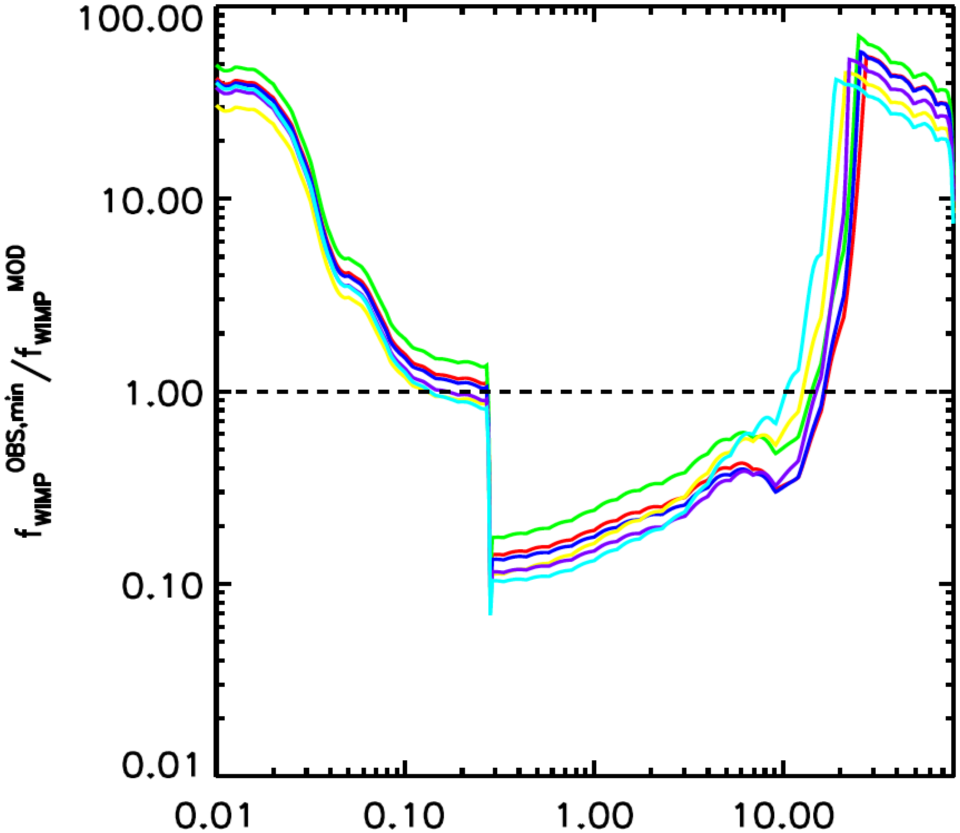
Sommerfeld-enhanced models fitting the cosmic ray excesses (Finkbeiner et al. 2011)

Benchmark no.	Annihilation Channel	m_ϕ (MeV)	m_χ (TeV)	α_c	δ (MeV)	$\frac{S_{max}\langle\sigma v\rangle_0}{3\times10^{-26}\text{cm}^3\ \text{s}^{-1}}$
1	1:1:2 $e^\pm : \mu^\pm : \pi^\pm$	900	1.68	0.04067	0.15	530
2	1:1:2 $e^\pm : \mu^\pm : \pi^\pm$	900	1.52	0.03725	1.34	360
3	1:1:1 $e^\pm : \mu^\pm : \pi^\pm$	580	1.55	0.03523	1.49	437
4	1:1:1 $e^\pm : \mu^\pm : \pi^\pm$	580	1.20	0.03054	1.00	374
5	1:1 $e^\pm : \mu^\pm$	350	1.33	0.02643	1.10	339
6	$e^\pm$ only	200	1.00	0.01622	0.70	171

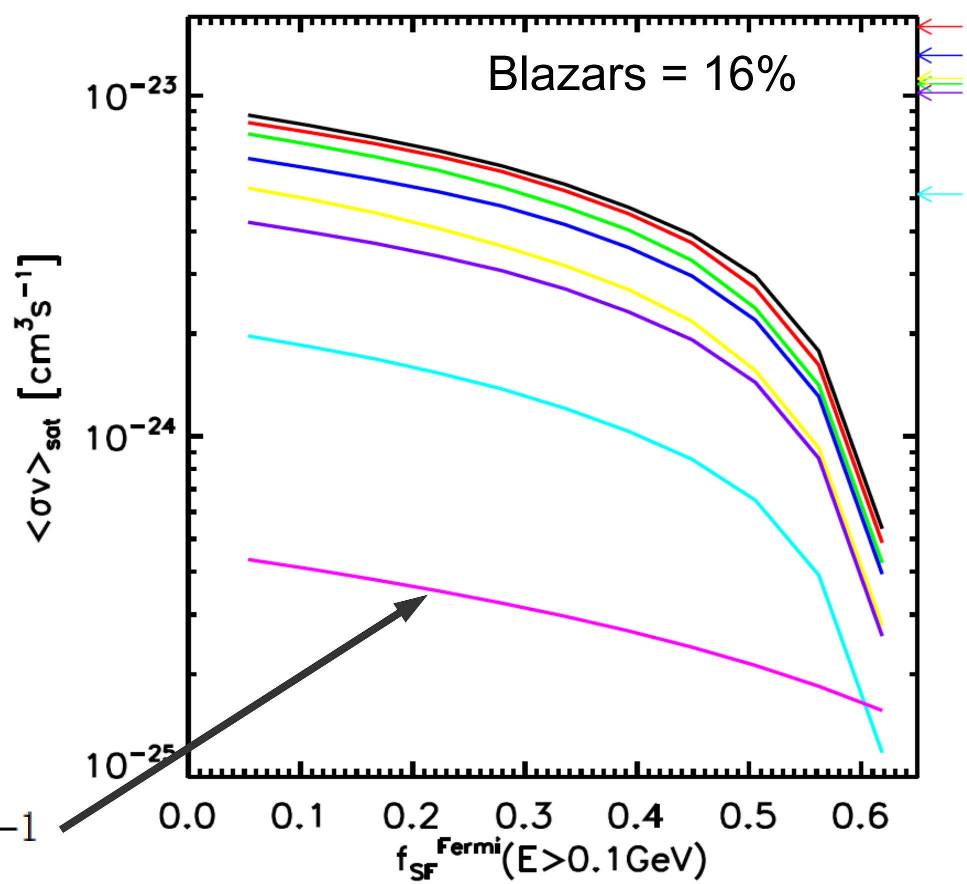


- New force carrier in the "dark sector"
- Annihilation cross section enhanced by a Sommerfeld mechanism
- Correct relic density
- Fit to the cosmic ray excesses measured by PAMELA and Fermi
- Allowed by bounds on Smax from the CMB
- IC contribution dominates the photon yield

Sommerfeld-enhanced models fitting the cosmic ray excesses



- Minimum contribution from subhalos
- SFG = 53%of EGB(E>1GeV)
- Blazars = 16% of EGB (E>1GeV)



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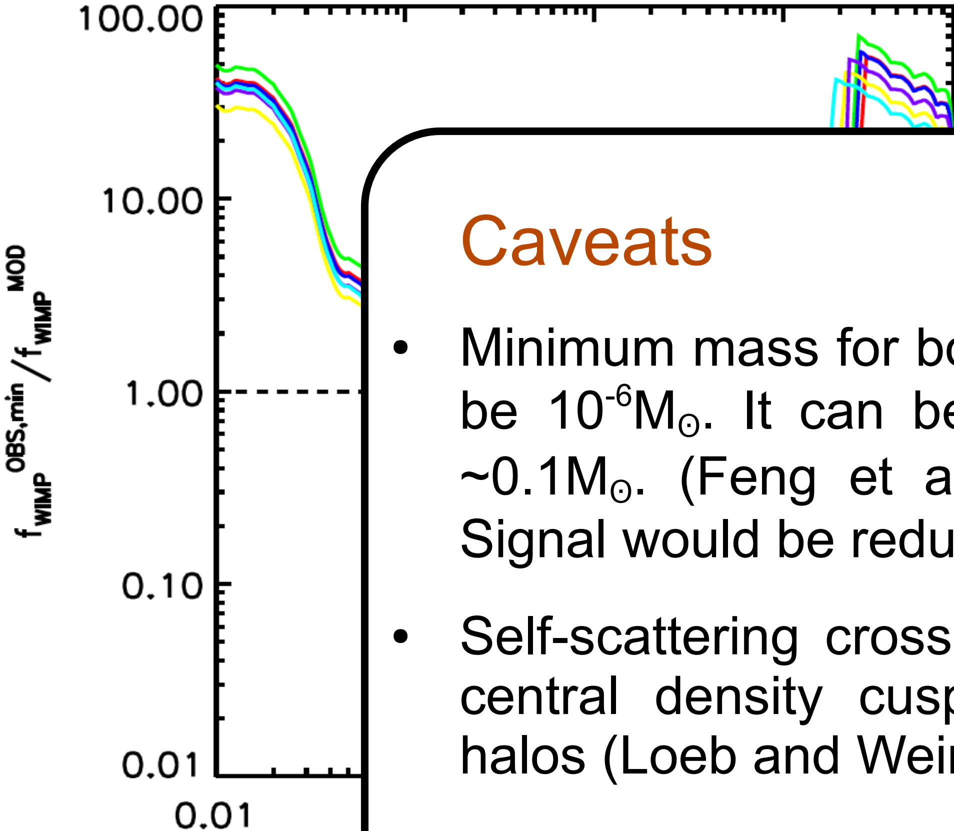
Sommerfeld-enhanced models fitting the cosmic ray excesses



- Minimum contribution from subhalos
- SFG = 53%of EGB(E>1GeV)
- …>1GeV)

…rs = 16%

Benchmark no.		Annihilation Ch…					
1	(red)	1:1:2 $e^{\pm}$: $\mu^{\pm}$: …					
2	(green)	1:1:2 $e^{\pm}$: $\mu^{\pm}$: …					
3	(blue)	1:1:1 $e^{\pm}$: $\mu^{\pm}$: …					
4	(yellow)	1:1:1 $e^{\pm}$: $\mu^{\pm}$: …					
5	(purple)	1:1 $e^{\pm}$: $\mu^{\pm}$					
6	(cyan)	$e^{\pm}$ only	200	1.00	0.01622	0.70	171

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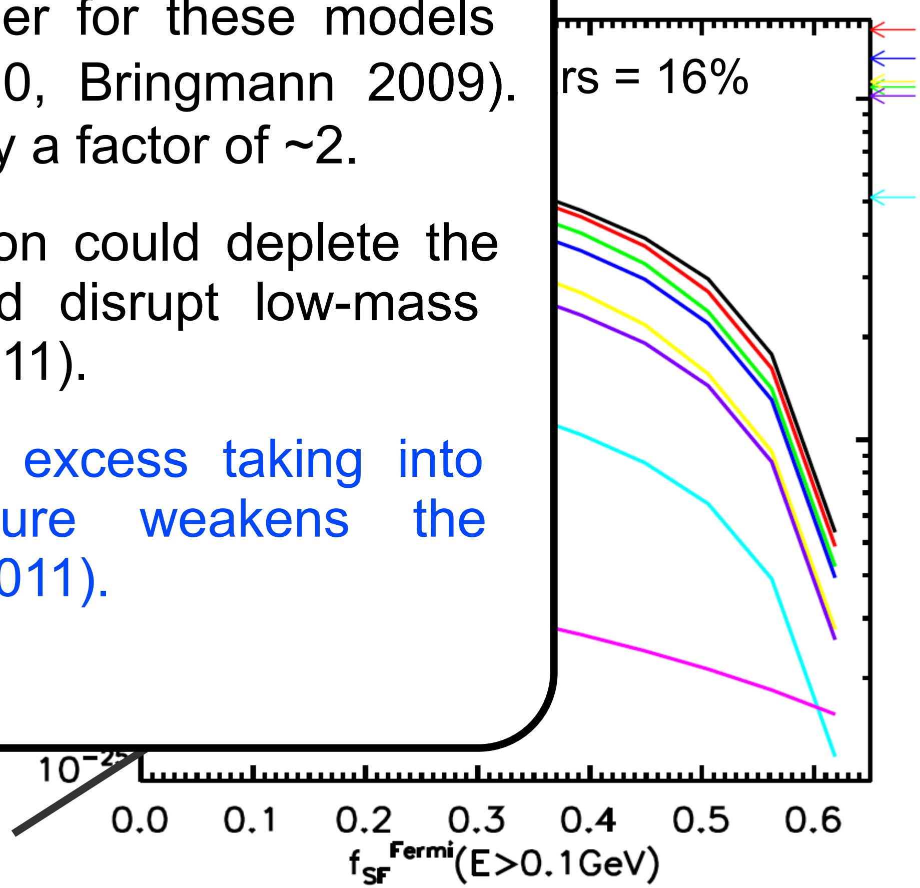

Caveats

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

Summary and Conclusions

- We have constructed simulated all-sky maps of the cosmic X- and gamma-ray background from DM annihilation including:
  - Photon yield given by a WIMP model (in situ photons and up-scattered photons of the CMB). In particular, it can be used for Sommerfeld-enhanced models.
  - Dark matter spatial distribution using Millennium-II simulation, uncertainty of ~2 orders of magnitude in extrapolation to unresolved structures.
- Isotropic component constrained by observations of the cosmic background, and contributions from blazars and star forming galaxies: although is not as clean as the CMB, it is also a powerful tool to constrain the intrinsic properties of dark matter.
- Results seem to disfavour an explanation of the e+ excess measured by PAMELA based on DM annihilation (keeping in mind the caveats)