Title: Astrophysical Constraints on Dark Matter Annihilation with Sommerfeld Enhancement

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Abstract: Dark matter models with an annihilation cross section enhanced by a Sommerfeld mechanism have been proposed in the past years to explain a number of observed anomalies, such as the excess of high energy positrons in cosmic rays reported by PAMELA. However, this enhancement can not be arbitrarily large without violating a number of astrophysical measurements. In this talk, I will discuss the degree to which these measurements can constrain Sommerfeld-enhanced models. In particular, I will talk about constraints coming from the observed abundance of dark matter and the extragalactic background light measured at multiple wavelengths.

Astrophysical constraints on dark matter annihilation with Sommerfeld enhancement

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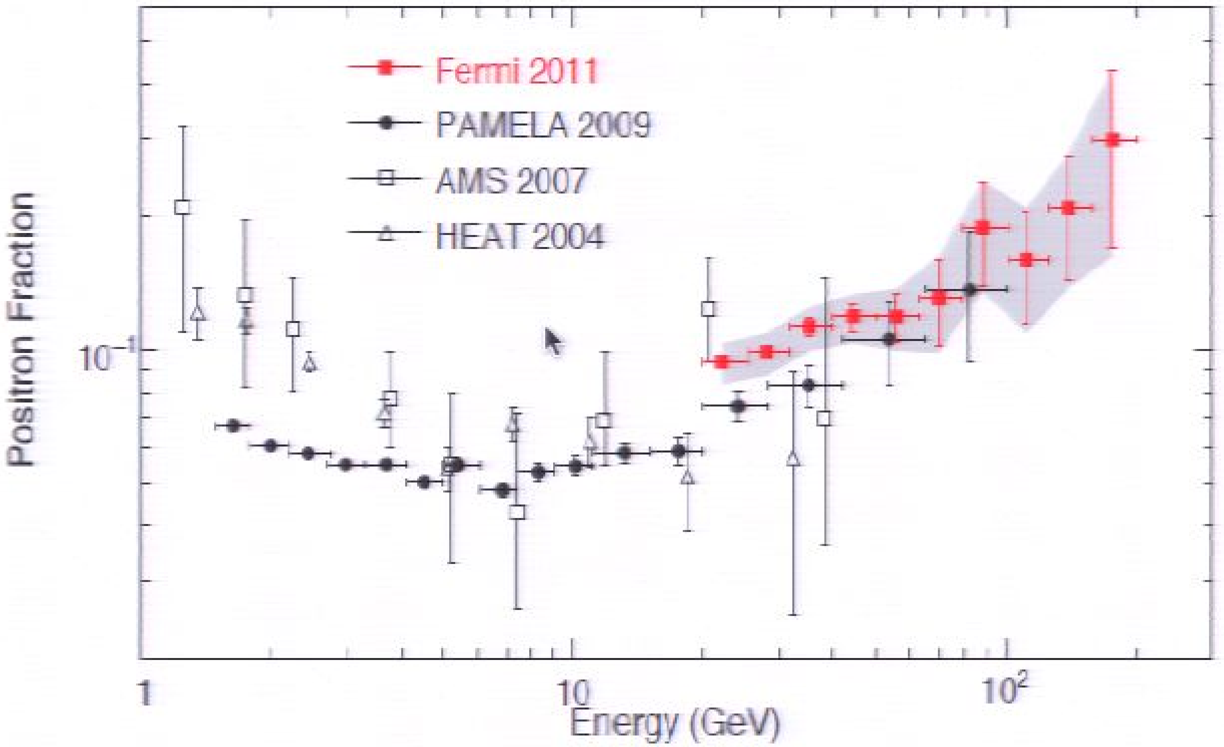
Papers: PRD, 81, 083502 (0910.5221), PRD, 83, 123513 (1103.0776)

Unravelling Dark Matter, September 2011

Outline

- Sommerfeld enhancement (brief motivation and description)
- Relic density constraints
- CMB constraints
- DM annihilation in halos and the Extragalactic Background Light (X- and Gamma-rays)
- EBL constraints

Why boosting DM annihilation?



PAMELA and Fermi e+ excess (E>10GeV)
Ackermann et al. 2011

The case for DM annihilation

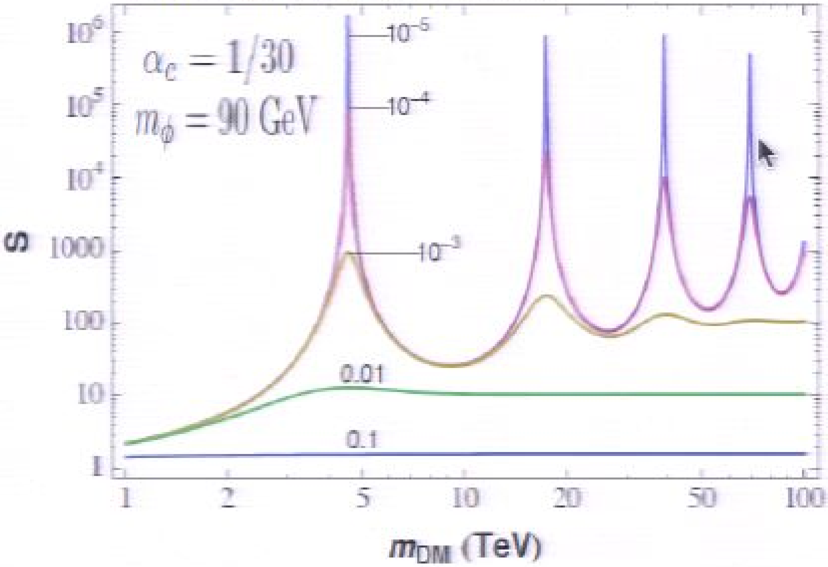
- WIMP annihilation can explain cosmic ray anomalies but: large cross section BF > O(100) over thermal relic value: $3\mathrm{x}10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$(e.g. Bergström et al. 2009) and annihilation mainly to leptons, proton/antiproton channel suppressed (PAMELA data).
- A new force carrier (m_ϕ~GeV) acting between the annihilating WIMPs enhances the cross section via a Sommerfeld mechanism (Hisano et al. 2004, Arkani-Hamed et al. 2009, ..). If $m_\phi<2m_p$, then decay into antiprotons is kinematically forbidden.

Sommerfeld enhancement

Simplified case, a scalar boson as a force carrier, Yukawa potential

$$\frac{1}{m_\chi}\frac{d^2\Psi(r)}{dr^2} + V(r)\Psi(r) = -m_\chi \beta^2 \Psi(r) \qquad V(r) = -\frac{\alpha_c}{r}e^{-m_\phi r}$$

Lattanzi and Silk 2009



$$\sigma = \sigma_0 S_k \qquad S_k = \frac{|\psi_k(0)|^2}{|\psi_k^{(0)}(0)|^2}$$

Coulomb approximation (m_φ -> 0):

$$S = \frac{\pi\alpha_c}{\beta}\left(1 - e^{-\pi\alpha_c/\beta}\right)^{-1}$$

$$\boxed{S(\beta) \propto 1/\beta \quad \text{if} \quad \beta \ll \pi\alpha_c}$$

General behaviour:

1) if $\beta^2 \gg m_\phi \alpha_c / m_\chi$ -> Coulomb case

2) if $\beta^2 \ll m_\phi \alpha_c / m_\chi$ -> bound states if $m_\chi = 4 m_\varphi n^2/\alpha$

3) Close to "resonances" -> $S(\beta) \propto 1/\beta^2$

4) Saturation at very low velocities, finite life time of the bound states

Relic density constraints

Boltzmann equation: $\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - \left(n_\chi^{EQ}\right)^2\right)$

Thermal average: $x_\chi = m_\chi / T_\chi$

$$\langle\sigma v\rangle = \langle\sigma v\rangle_S \left(\frac{x^{3/2}}{2\pi^{1/2}}\int_0^1 S(\beta)\ \beta^2 e^{-x\beta^2/4} d\beta\right) = \langle\sigma v\rangle_S\,\mathcal{S}(x_\chi)$$

Note that:

$$S(\beta) \propto 1/\beta \quad \rightarrow \quad \mathcal{S}(x_\chi) \propto x_\chi^{1/2} \propto 1/\sigma_{vel}$$

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Dark matter abundance: $\Omega_\chi h^2 = \Omega_{DM} h^2 \sim 0.1143$

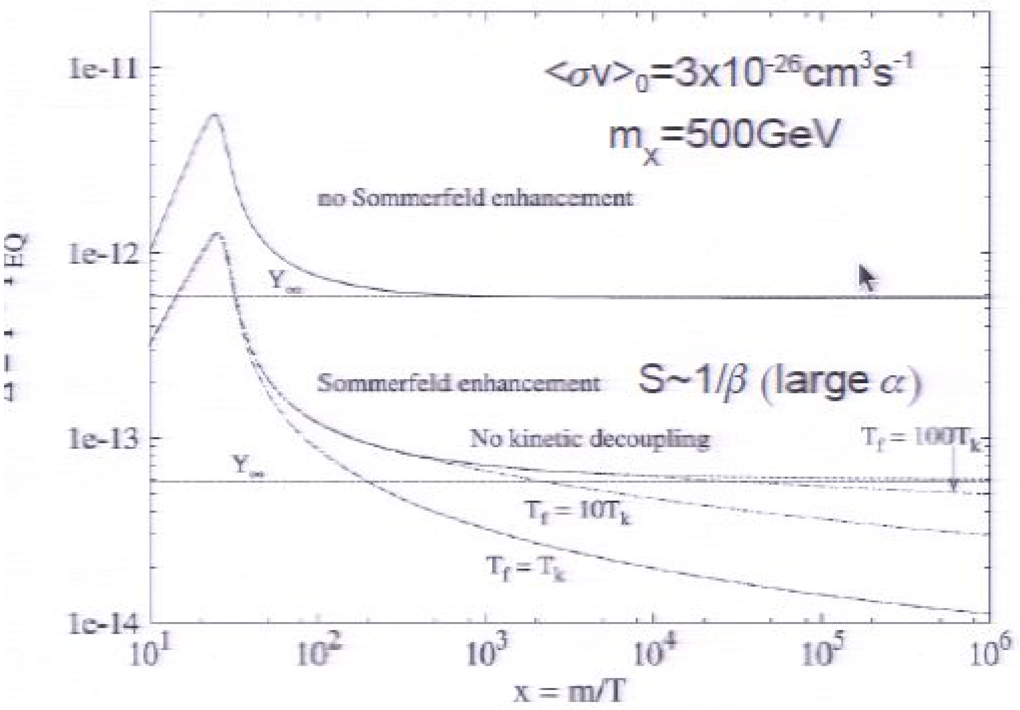
Kinetic decoupling: after freeze-out, scattering with SM particles keep T_χ=T, after kinetic decoupling T_χ drops as $1/a^2$ (“colder” than radiation):

$$x_\chi = x \quad \text{for} \quad t < t_{\mathrm{KD}}$$

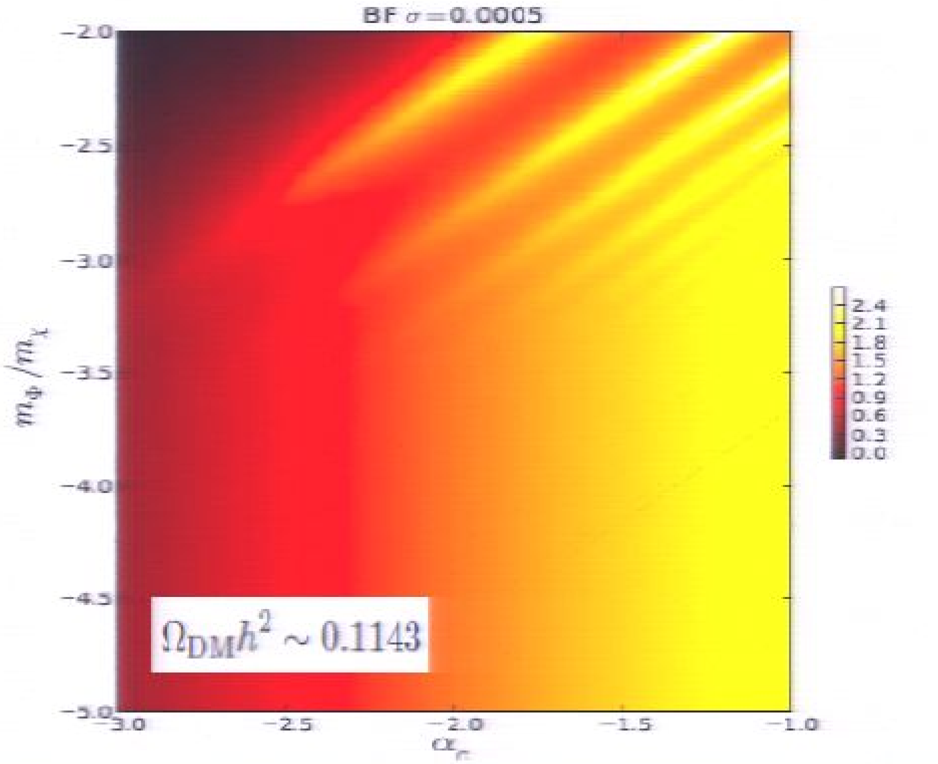
$$x_\chi = x^2/x_{\mathrm{KD}} \quad \text{for} \quad t > t_{\mathrm{KD}}$$

Relic density constraints

Dent et al. 2010



Zavala et al. 2010



- If $S\sim1/\sigma$ then $Y\sim1/\ln x$ for $x>x_{kd}$
- If $S\sim1/\sigma^2$ then $Y\sim1/x$ for $x>x_{kd}$
- $<\sigma v>_0$ needs to be lower than the case without enhancement (a factor of a few) to give the correct relic density
- Kinetic decoupling temperature is a relevant parameter, the larger it is, the stronger the suppression on the relic density

BF(relative to $<\sigma v>_0=3x10^{-26}cm^3s^{-1}$) <100
for $\alpha<10^{-2}$, $m_\phi/m_\chi<10^{-3}$, m_χ~100GeV, T_{kd}=8MeV

$$\mathrm{BF} = \frac{\langle\sigma v\rangle_0^{\Omega_{DM}} S(\sigma_{\mathrm{vel,h}})}{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}$$

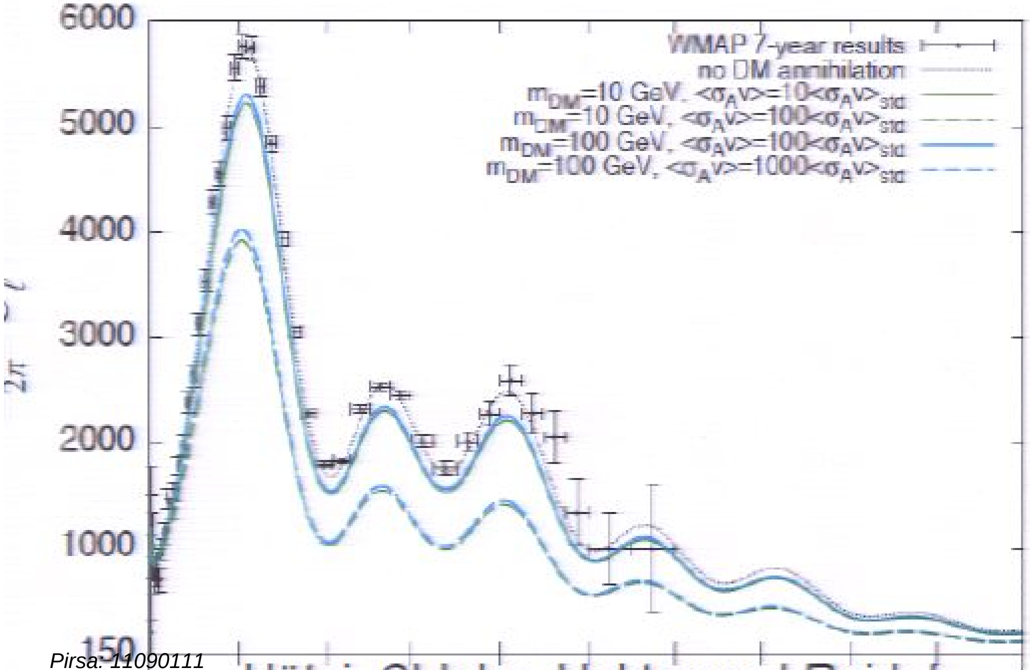
Feng et al.2010, “maximal” BF up to m_χ ~3TeV is < 300

CMB constraints

MB energy spectrum: energy injection at $10^4<z<10^6$ ffectively produces a Bose-Einstein energy spectrum vith chemical potential μ instead of a pure black body pectrum (Illarionov and Sunyaev 1975). Limit by OBE/FIRAS $|\mu|<9\times10^{-5}$. "f" is the fraction that ionizes and eats the IGM.

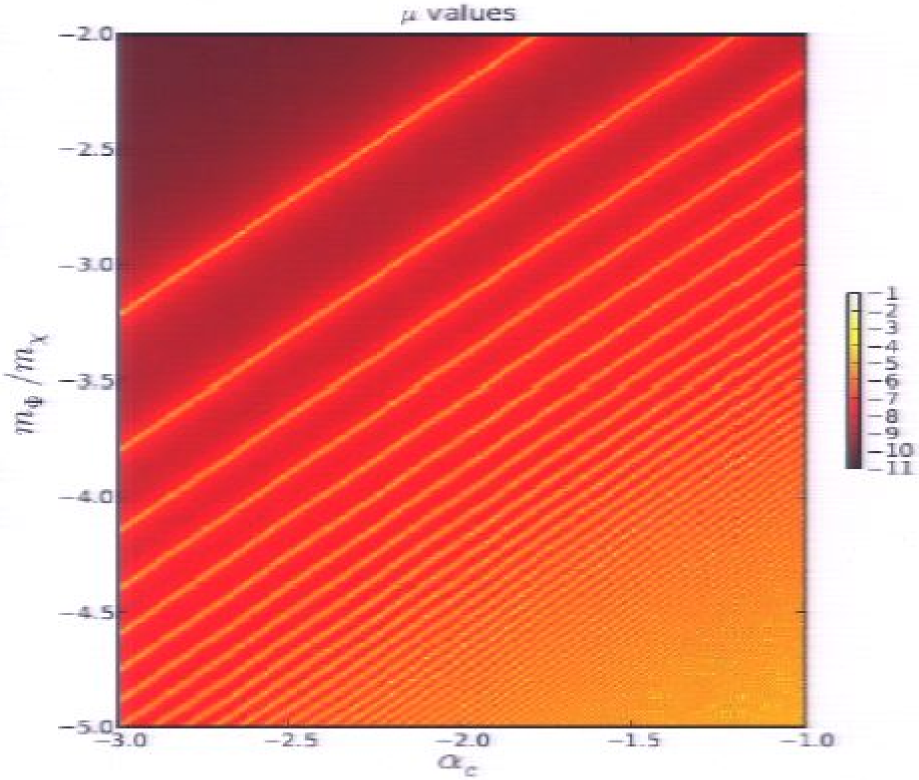
$$\mu = 1.4\frac{\delta\rho_\gamma}{\rho_\gamma} = 1.4\int_{t_1}^{t_2}\frac{\dot{\rho}_\gamma}{\rho_\gamma}dt = 1.4\int_{t_1}^{t_2}\frac{f m_\chi\langle\sigma v\rangle n_\chi^2}{\rho_{\gamma,0}a^{-4}}dt,$$

njection at $10^3<z<10^4$ produces a y-type distortion to the MB (Hannestad and Tram 2011). Both are weak onstraints.



Hütsi, Chluba, Hektor and Raidal et al. 2009

Zavala et al. 2010



CMB power spectrum: e.g. Slatyer et al. 2009, limits based on WMAP5:

$$\frac{\lim_{v\to0}\langle\sigma v\rangle}{3\times10^{-26}\mathrm{cm}^3/\mathrm{s}} \lesssim \frac{120}{f}\left(\frac{m_\chi}{1\mathrm{TeV}}\right)$$

f~0.25 for annihilation into SM particles, except electrons (f~0.7) and neutrinos (f~0)

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:

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

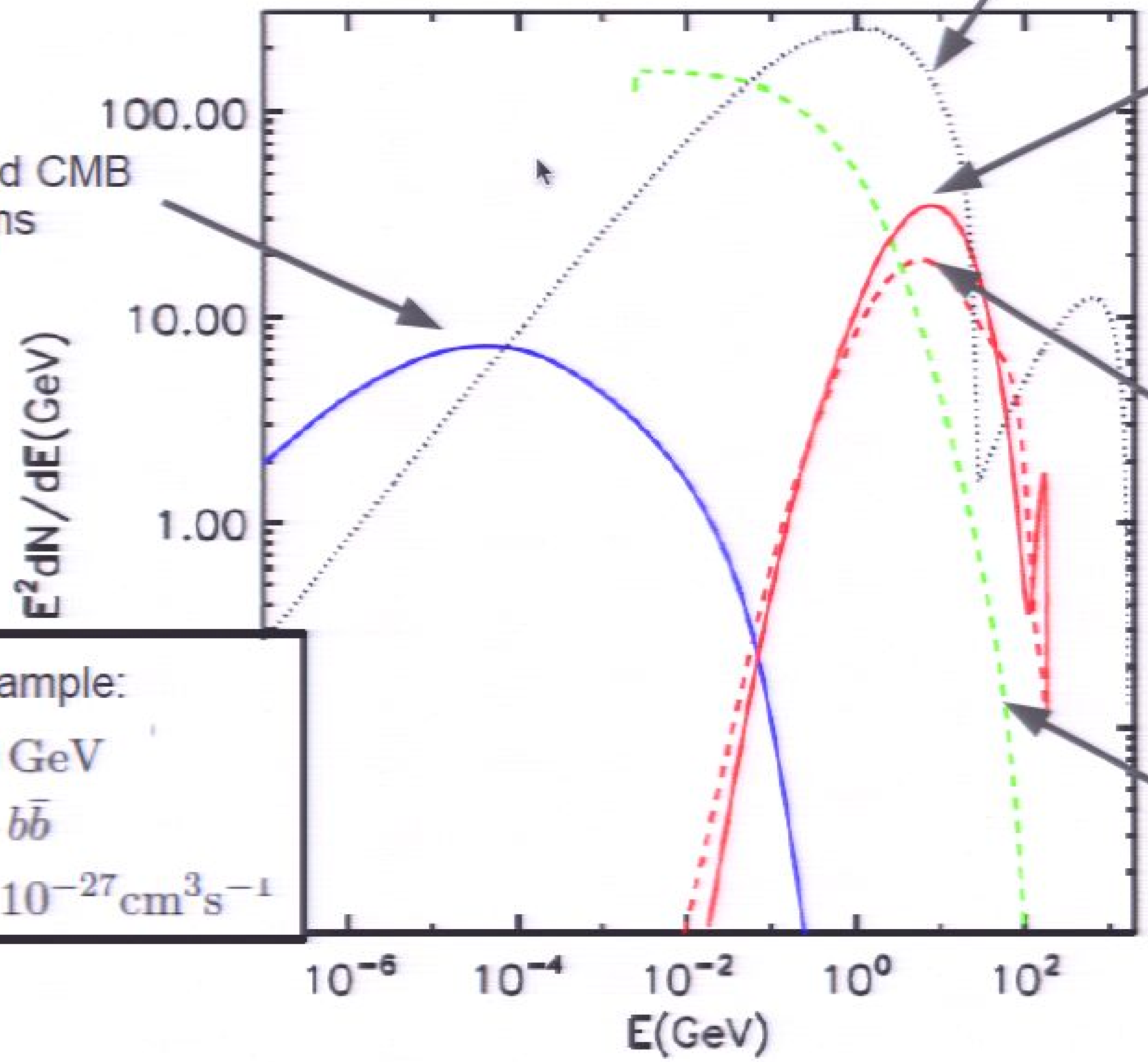
- Properties of dark matter as a particle:

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

- The density squared dependence is connected to the gravitational interactions of dark matter.

Photon yield

Zavala et al. 2011



Main annihilation channel Into leptons (PAMELA fit)

Up-scattered CMB photons

Prompt emission (secondary decay of π^0)

e+e- injection spectrum

e+e- equilibrium spectrum (not normalized)

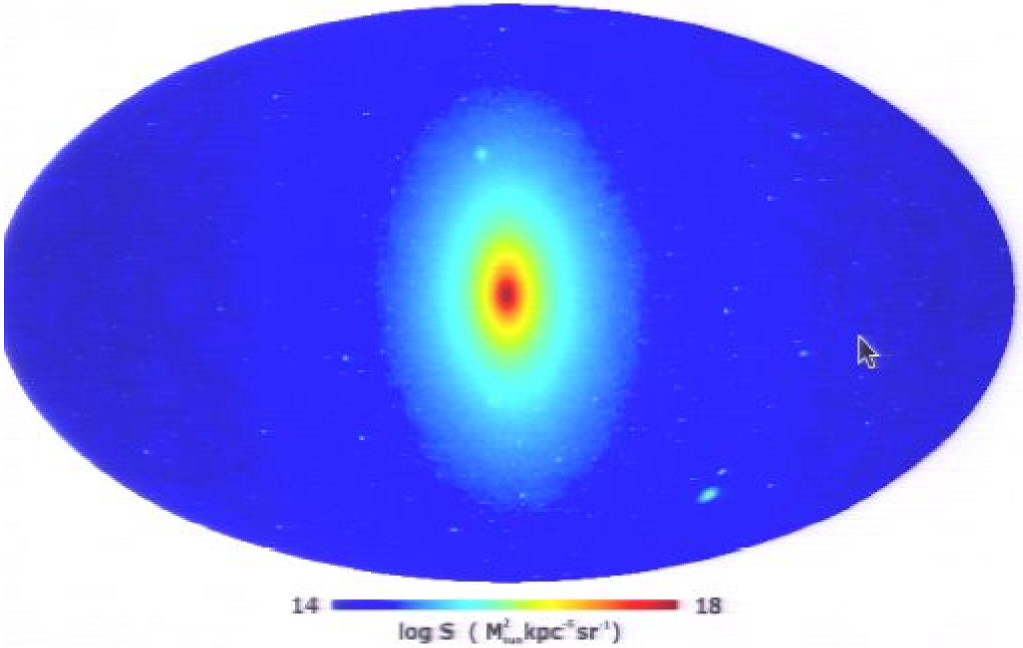
SUSY example:

m_χ 200 GeV

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

$\sigma v\rangle \sim 6.2 \times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$

Annihilation in DM halos



Via-Lactea II simulation

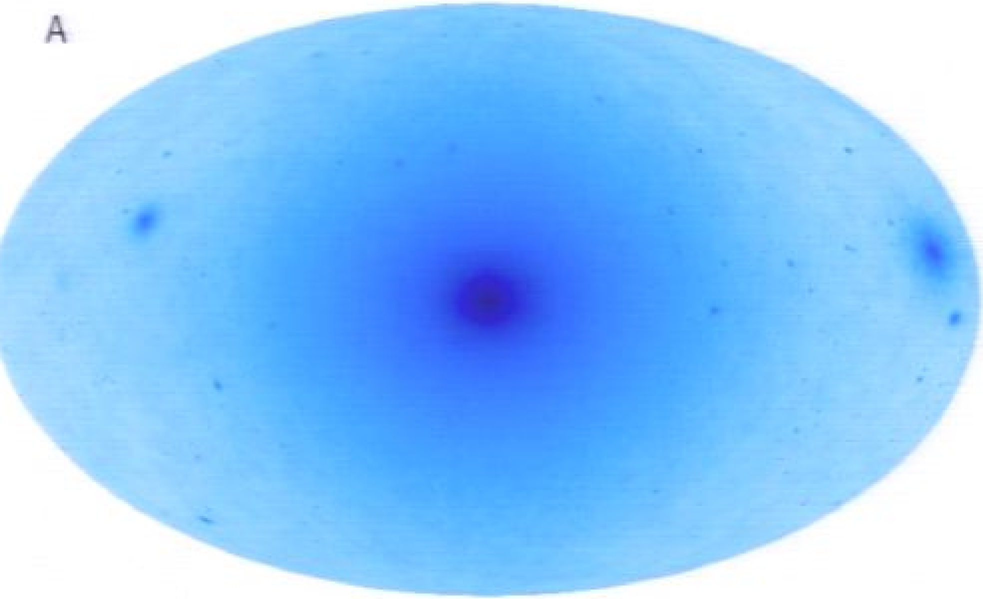
MW-like halo

m_{DM}~4100 Msun (Kuhlen et al. 2009)

Virgo Consortium's Aquarius Project

MW-like halo

m_{DM}~1500 Msun (Springel et al. 2008)

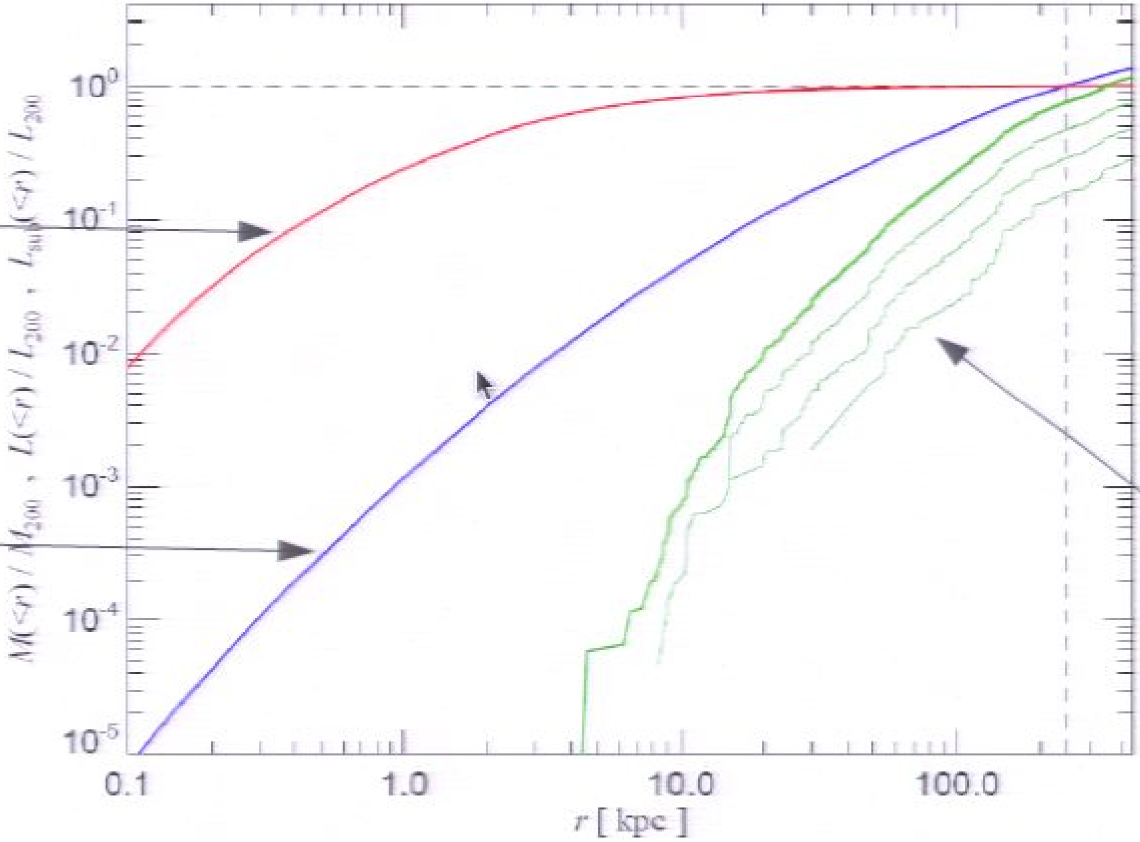


- Total luminosity of a smooth DM halo (formula roughly agrees with summation over particle densities):

$$\boxed{L'_{\rm h} = \int \rho^2_{\rm NFW}(r)\, {\rm d}V = \frac{1.23\, V^4_{\rm max}}{G^2 r_{\rm max}}}$$

Keep in mind: uncertainty on the DM density profile (+effects of baryons)

Annihilation in DM halos (substructure)



Smooth halo

Mass profile

Subhalos

Springel et al. 2008

- Substructures within halos have a dominant 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

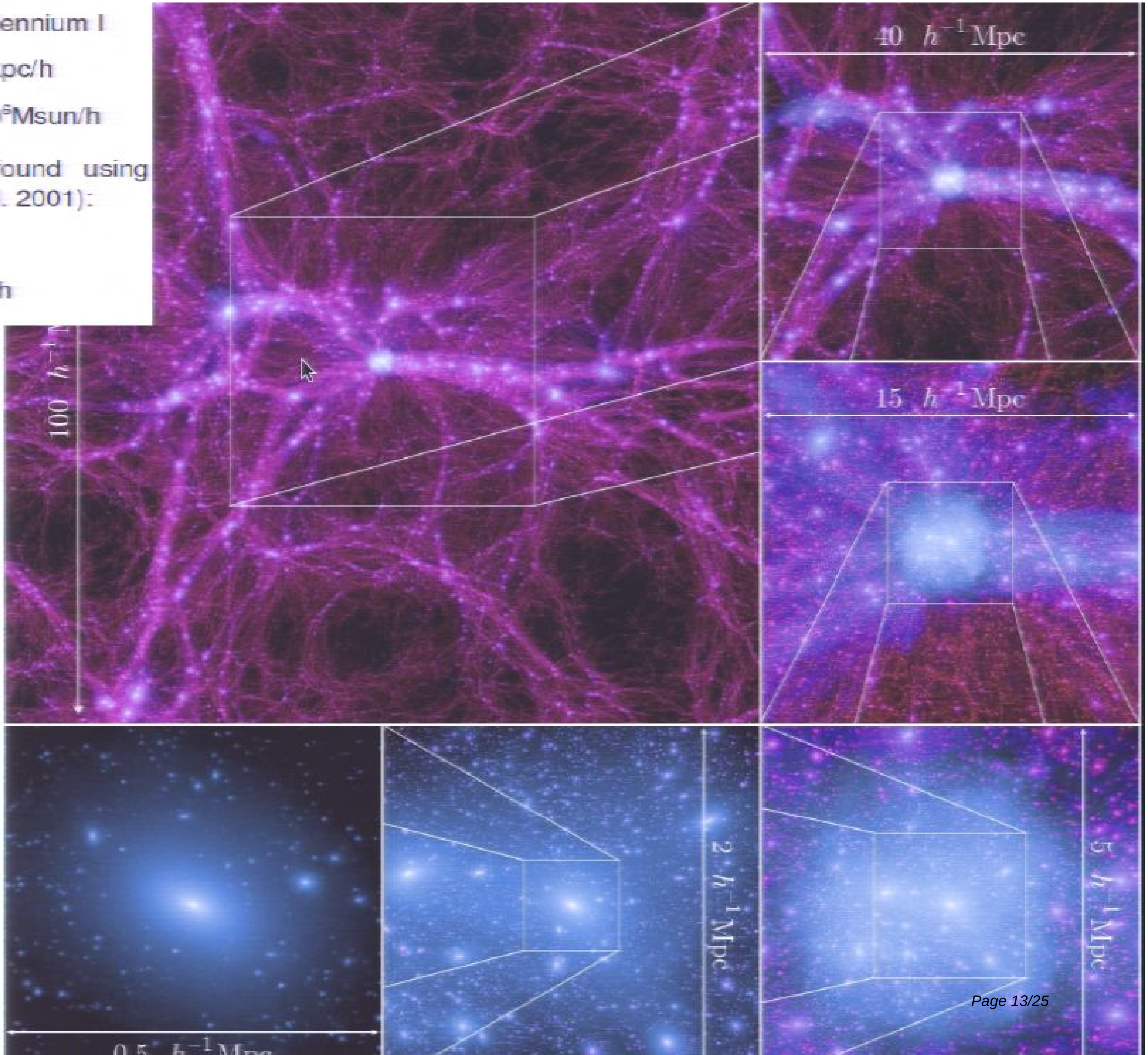
100 Mpc/h box and ε=1kpc/h

$N_p=2160^3$, $m_{DM}=6.89\times10^6$Msun/h

Bound substructures found using SUBFIND (Springel et al. 2001):

11×10^6 subs at z=0

M_{sb} (min)~1.4×10^8Msun/h



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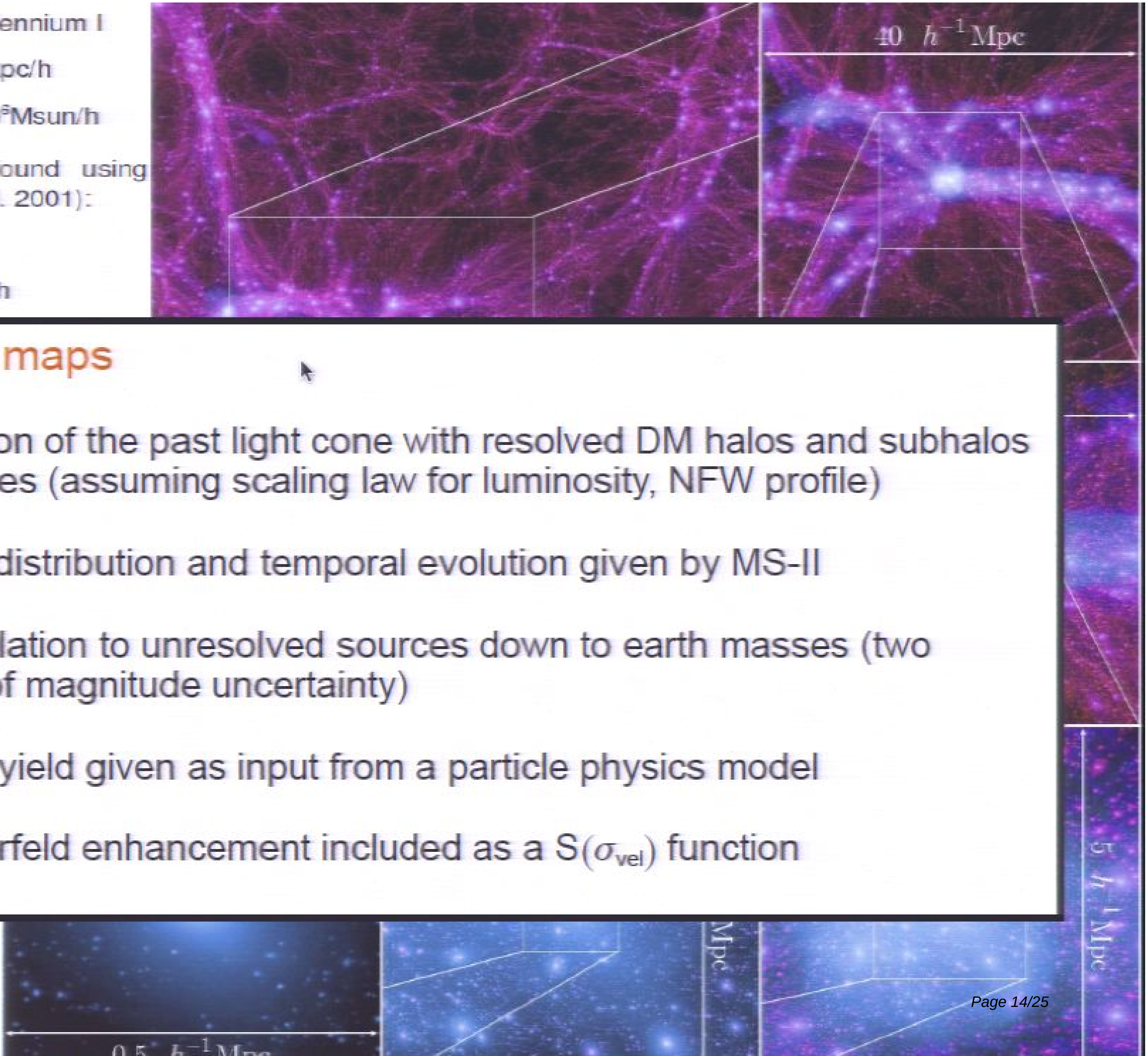
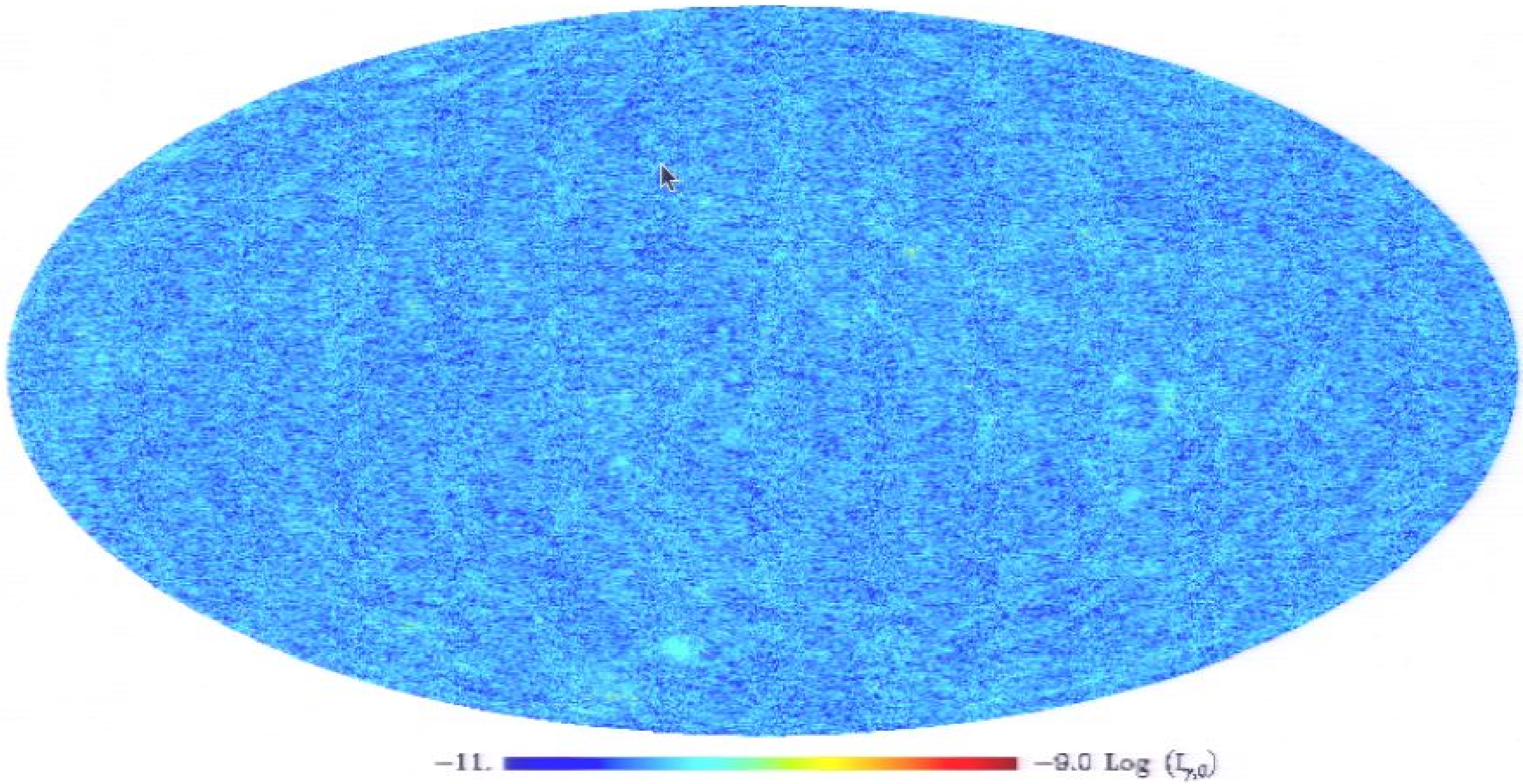


All-sky maps

- Simulation of the past light cone with resolved DM halos and subhalos as sources (assuming scaling law for luminosity, NFW profile)
- Spatial distribution and temporal evolution given by MS-II
- Extrapolation to unresolved sources down to earth masses (two orders of magnitude uncertainty)
- Photon yield given as input from a particle physics model
- Sommerfeld enhancement included as a $S(\sigma_{\mathrm{vel}})$ function

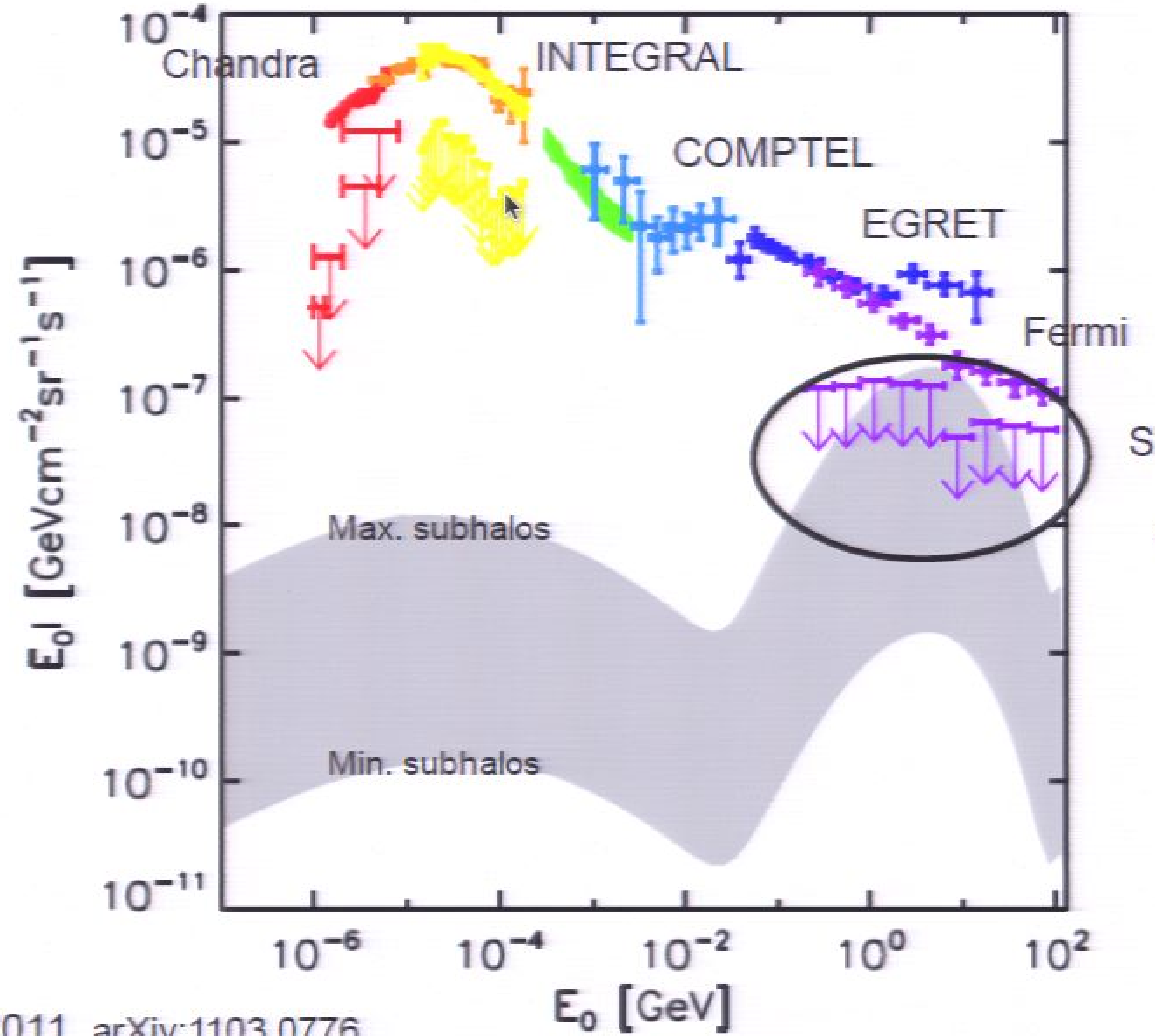
All-sky maps
(resolved structures up to z~10, E=10GeV)



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

Isotropic component (example)

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



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

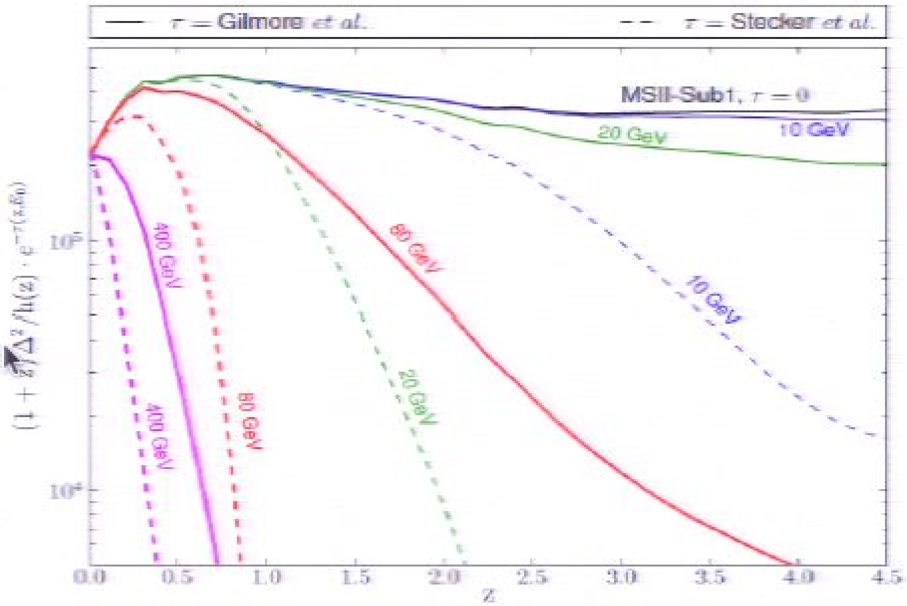
avala et al. 2011, arXiv:1103.0776

Constraints on particle physics models

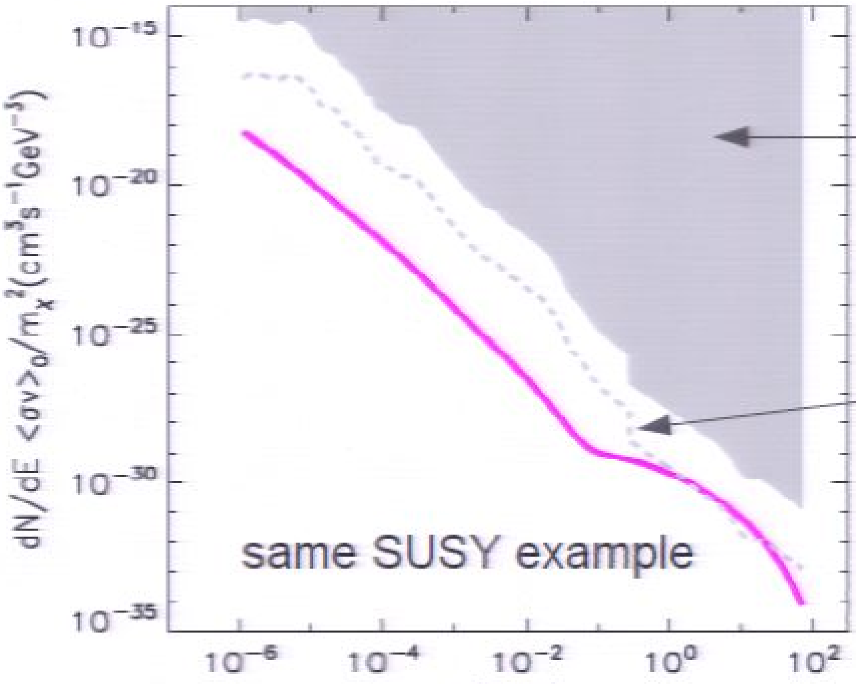
"factoring out" the
astrophysical part of
the signal

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

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



Fermi collaboration
Abdo et al. 2010



Minimum
extrapolation
unresolved
subhalos

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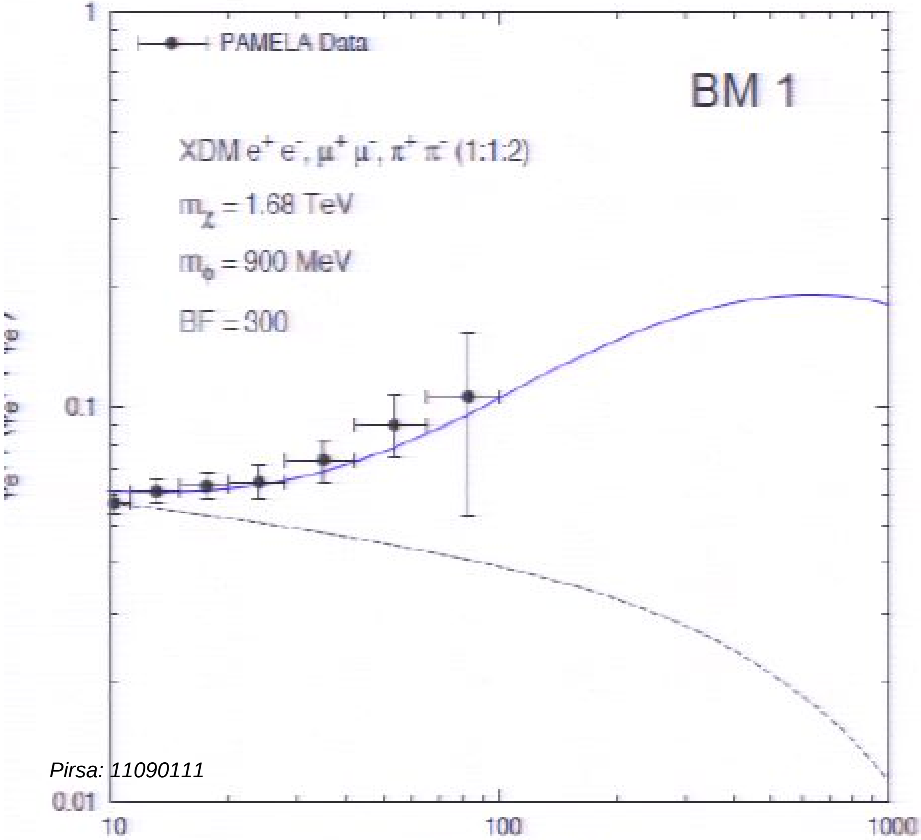
Sommerfeld-enhanced models fitting the cosmic ray excesses (Finkbeiner et al. 2011)

Benchmark no.	Annihilation Channel	m_ϕ (MeV)	m_χ (TeV)	α_c	δ (MeV)	$\frac{S_{\max}\langle\sigma v\rangle_0}{3\times10^{-26}\mathrm{cm}^3\ \mathrm{s}^{-1}}$
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:

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 S(\sigma_{\mathrm{vel}})$$

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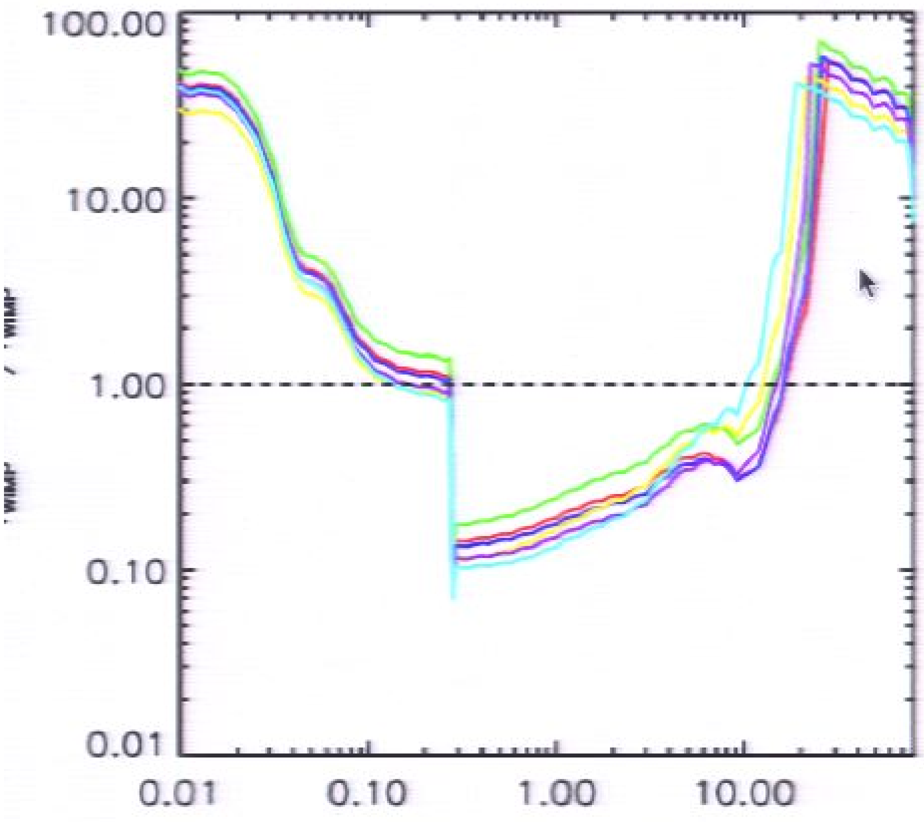

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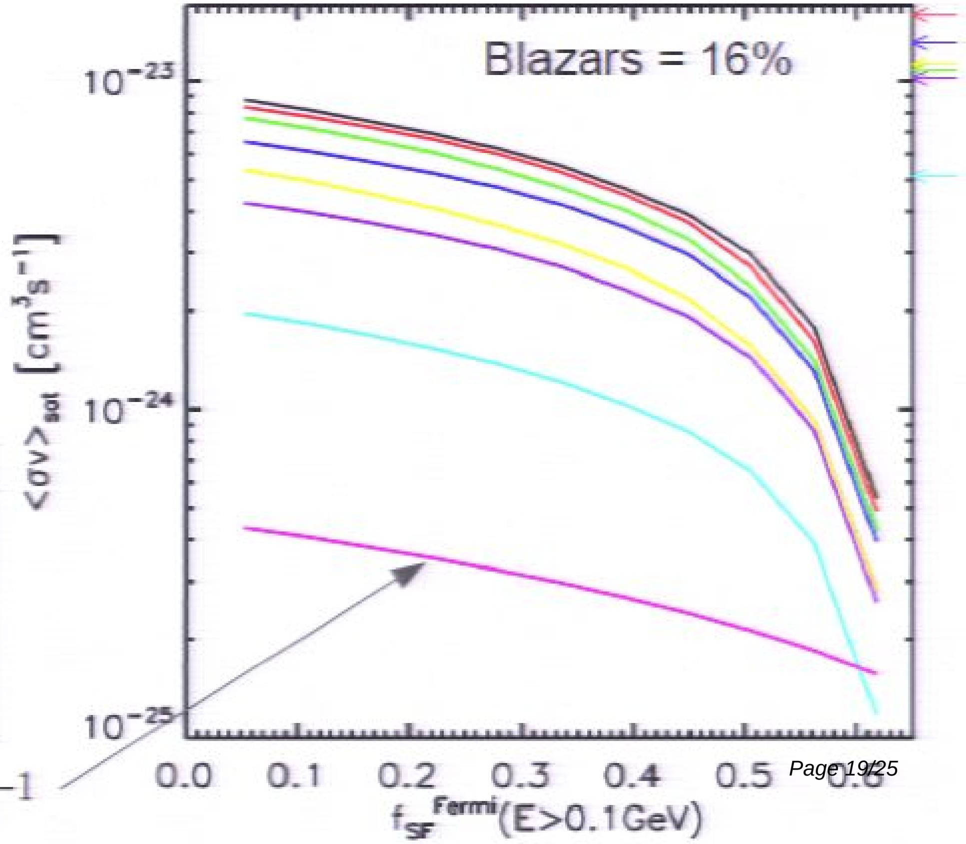
- SFG = 53%of EGB(E>1GeV)
- Blazars = 16% of EGB (E>1GeV)



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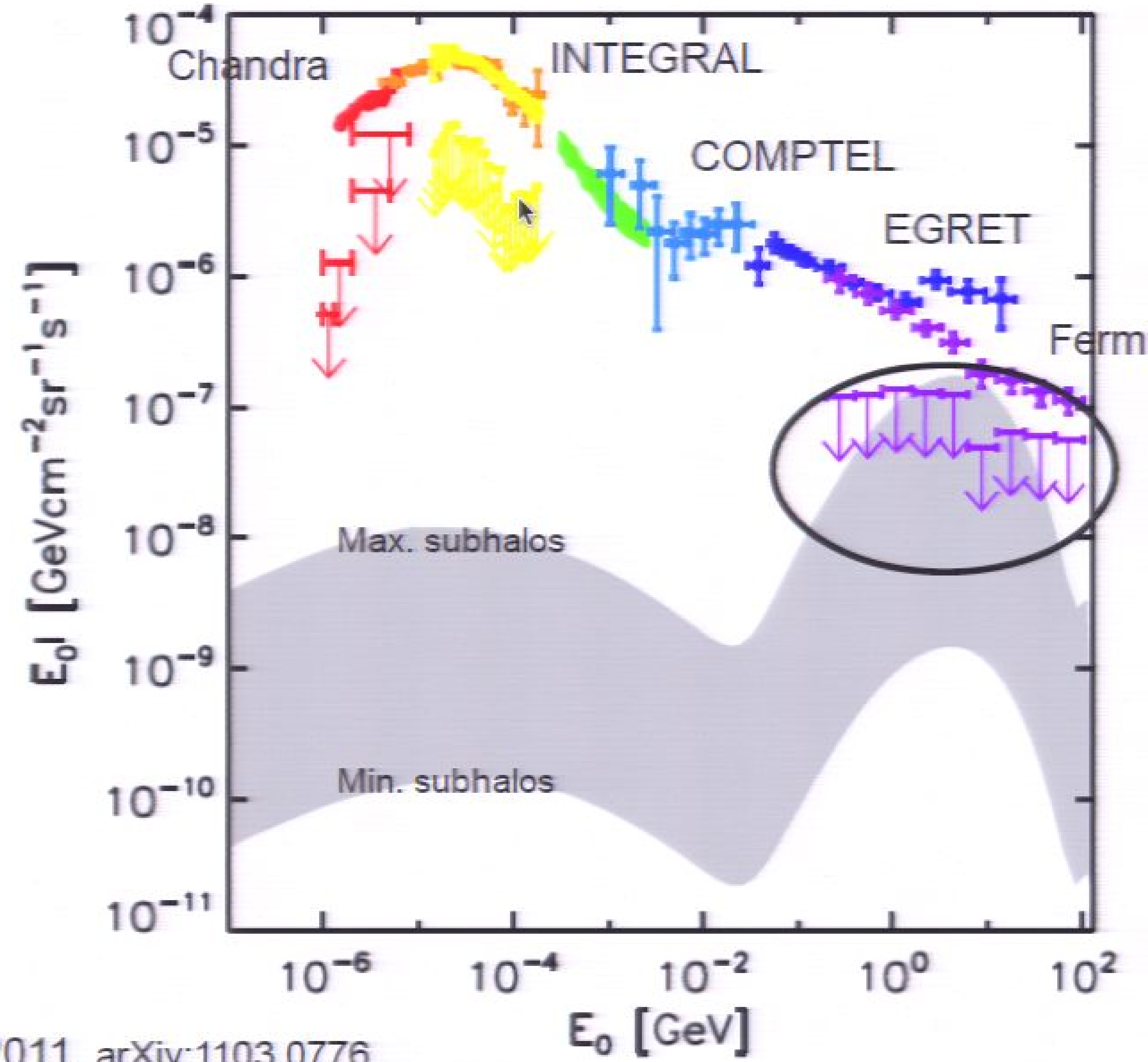

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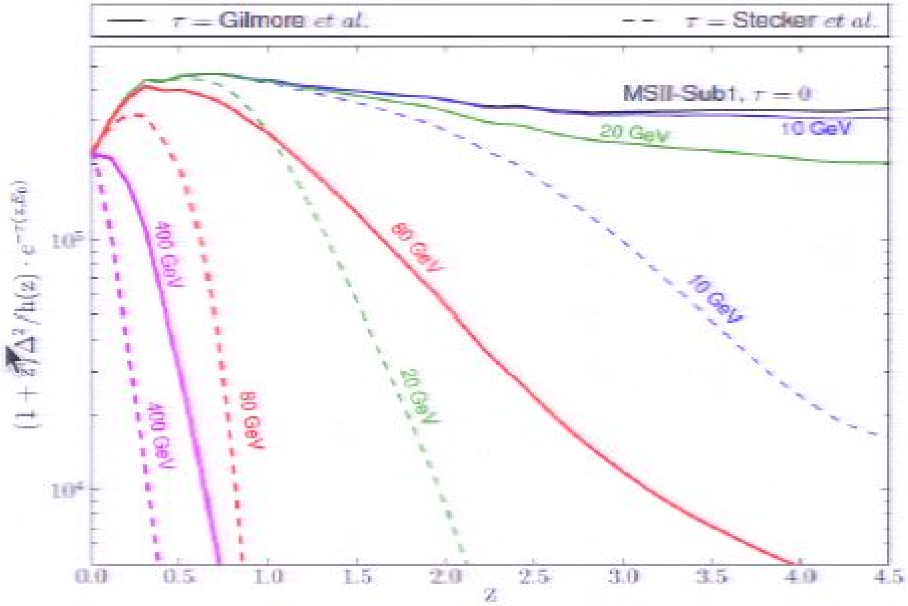

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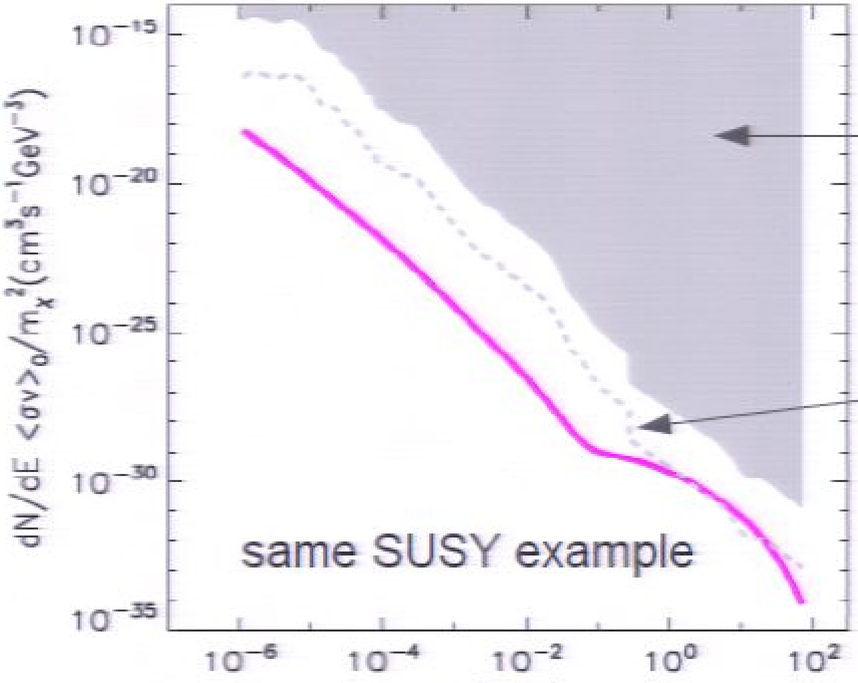

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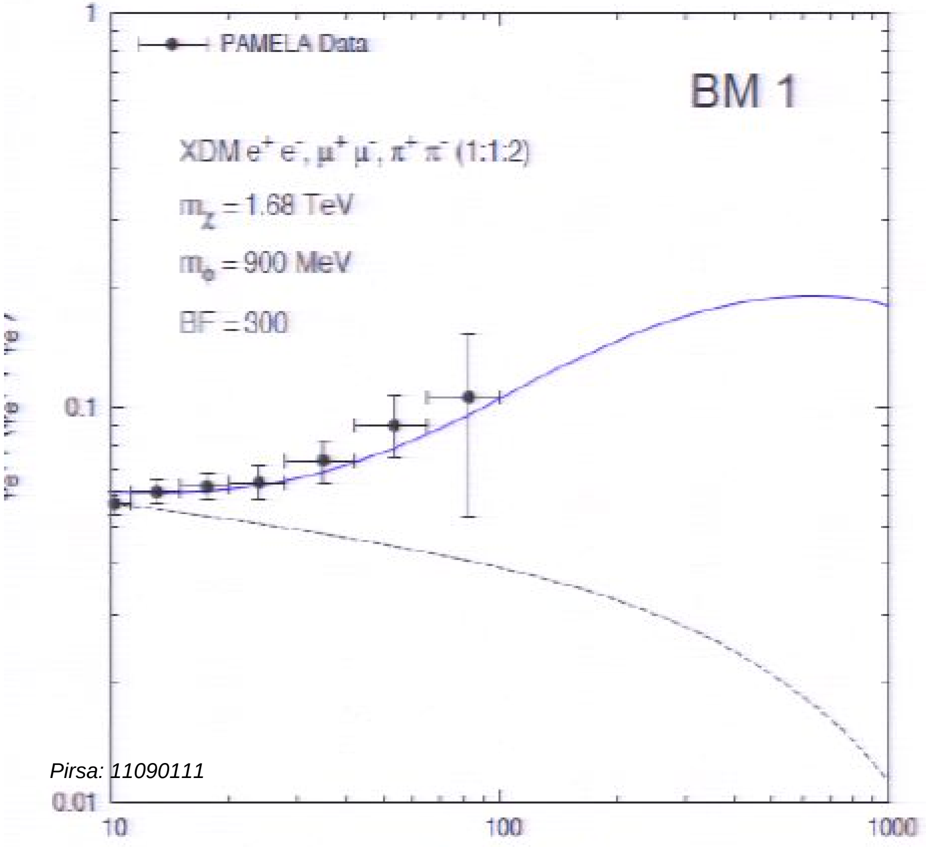

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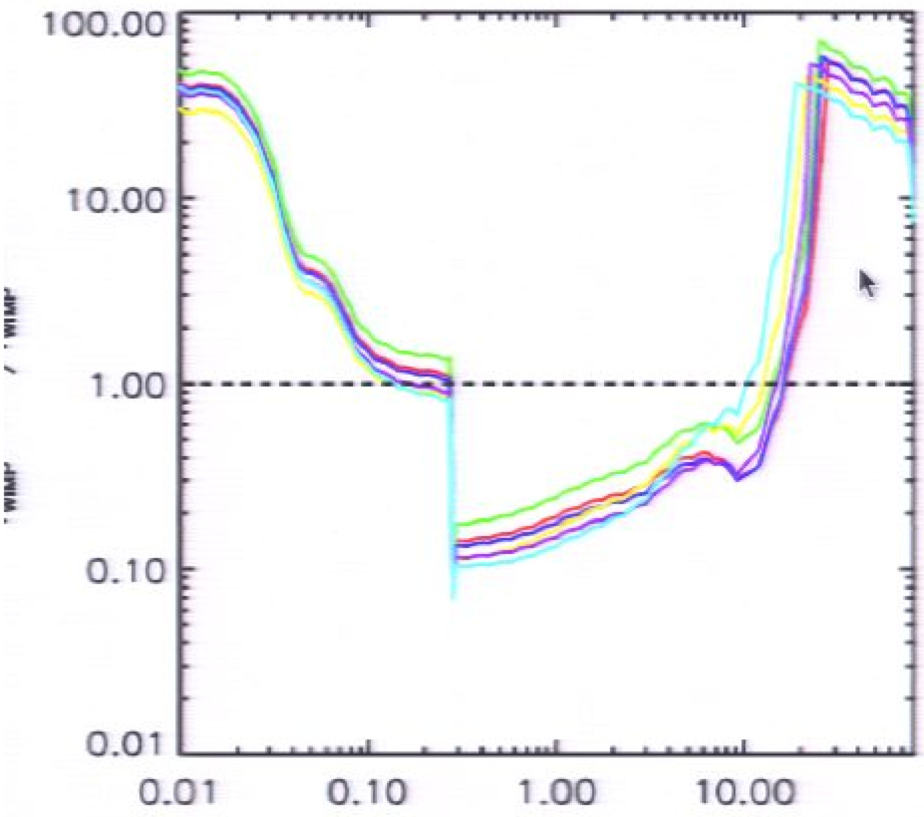

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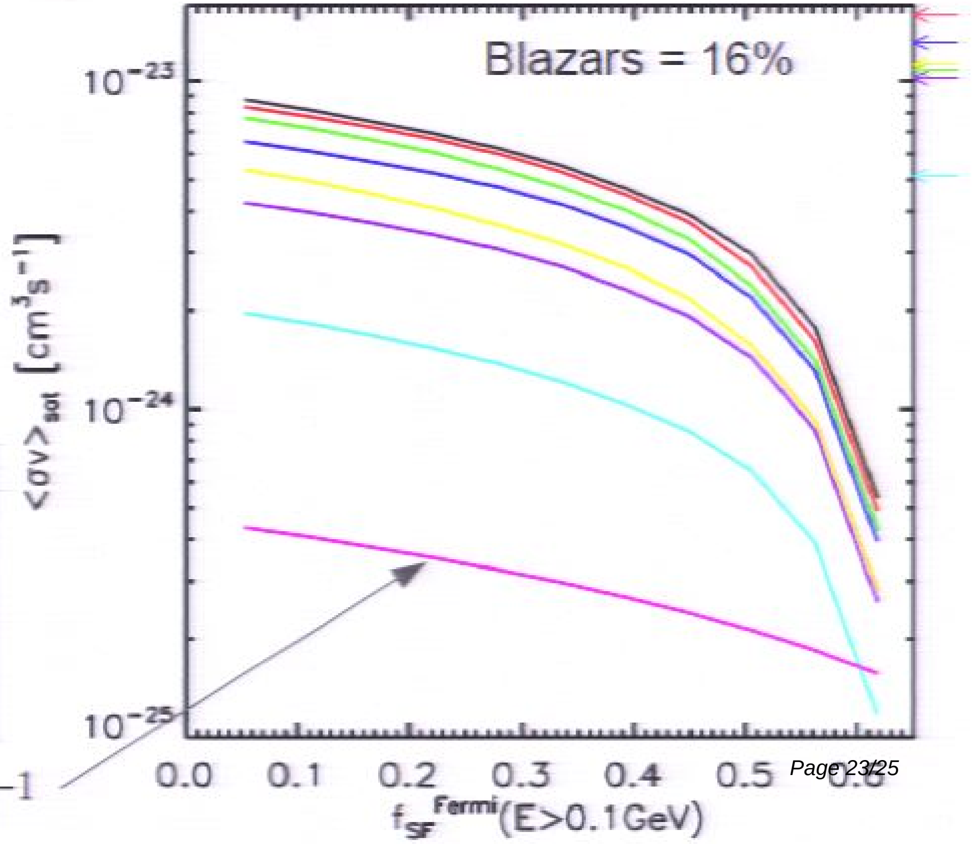

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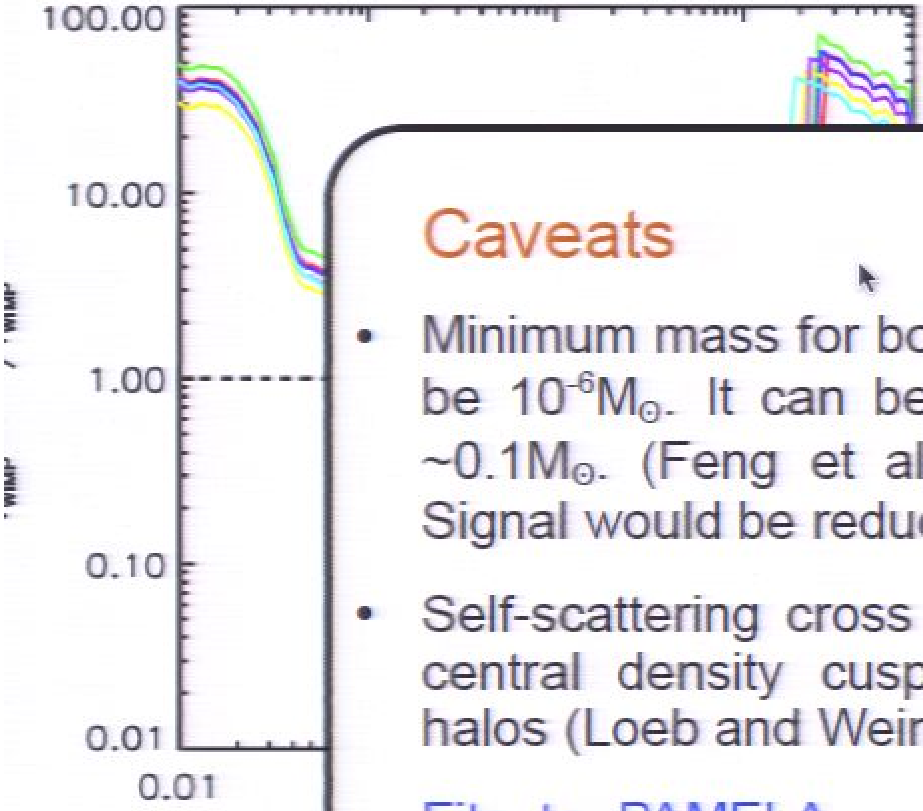

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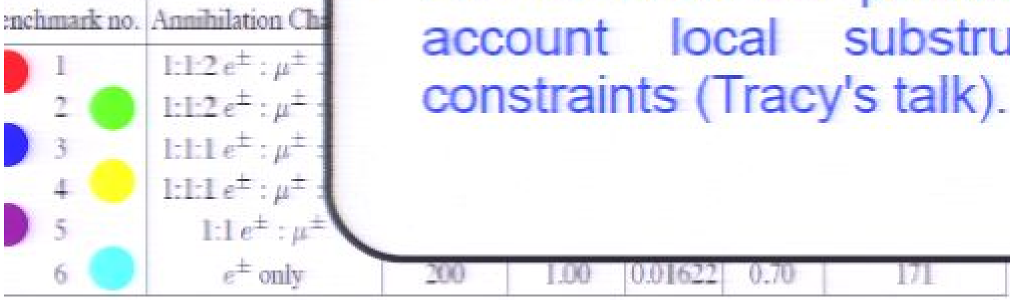
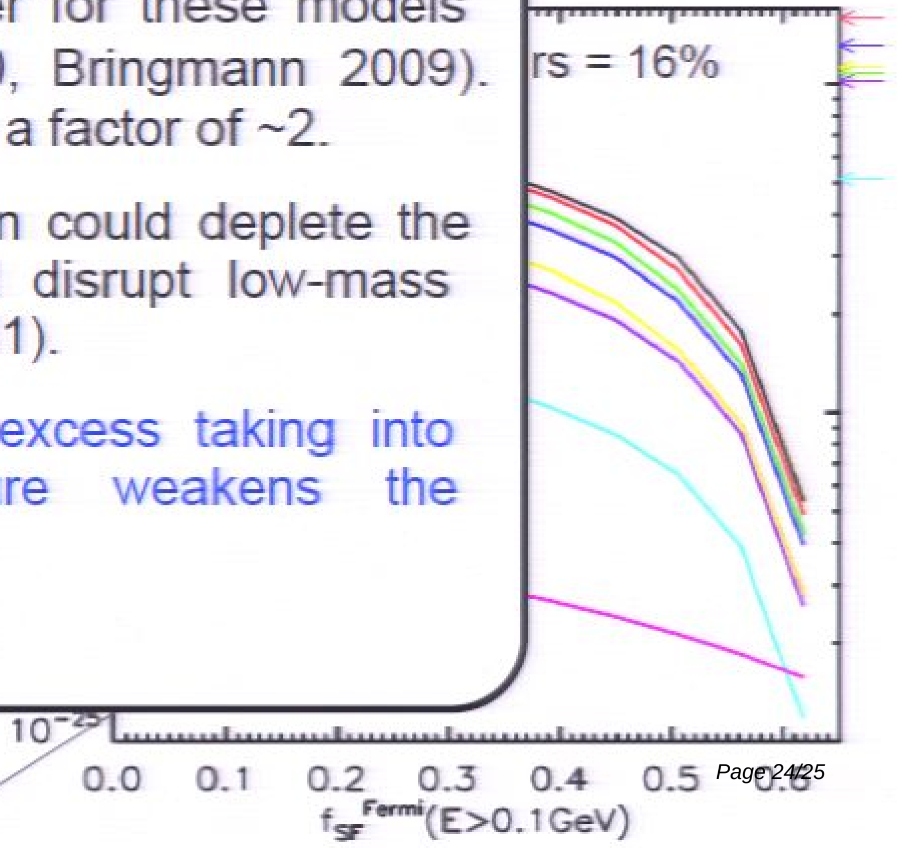
rs = 16%

Caveats

- Minimum mass for bound halos was assumed to be $10^{-6}M_{\odot}$. It can be higher for these models $\sim 0.1M_{\odot}$. (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 (Tracy's talk).



nchmark no.	Annihilation Ch					
🔴 1	1:1:2 $e^{\pm}:\mu^{\pm}$					
🟢 2	1:1:2 $e^{\pm}:\mu^{\pm}$					
🔵 3	1:1:1 $e^{\pm}:\mu^{\pm}$					
🟡 4	1:1:1 $e^{\pm}:\mu^{\pm}$					
🟣 5	1:1 $e^{\pm}:\mu^{\pm}$					
🔵 6	$e^{\pm}$ only	200	1.00	0.01622	0.70	171



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

Summary and Conclusions

- Sommerfeld-enhanced models can explain the cosmic-ray anomalies, but they need to be consistent with independent astrophysical constraints: correct relic abundance and CMB already constrain the boost factor to be less ~ few hundred.
- We have obtained predictions from the 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). Model-independent, 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 a powerful tool to constrain the intrinsic properties of dark matter.