Cosmic antimatter from dark matter annihilation: effects of cosmological subhalos and uncertainties

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Refs (arXiv) : 0603796, 0712.0468, 0709.3634, 0704.2543, 0808.0332, 0809.5268, 0902.3665

Collab: Delahaye, Salati, Taillet (LAPTH) – Maurin (LPNHE) – Nezri (LAM)
Ling (Brussels) – Donato, Fornengo, Lineros (Turin) – Bi, Yuan (Beijing) – Bringmann (Stockholm)

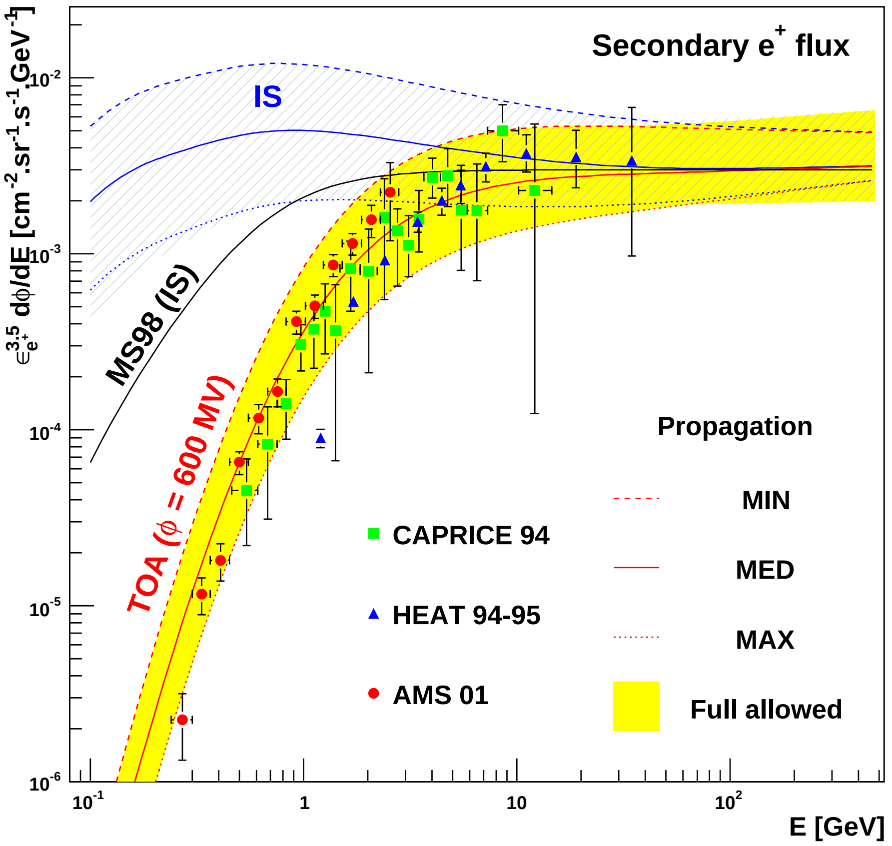
1^{st} Tango in Paris — IAP

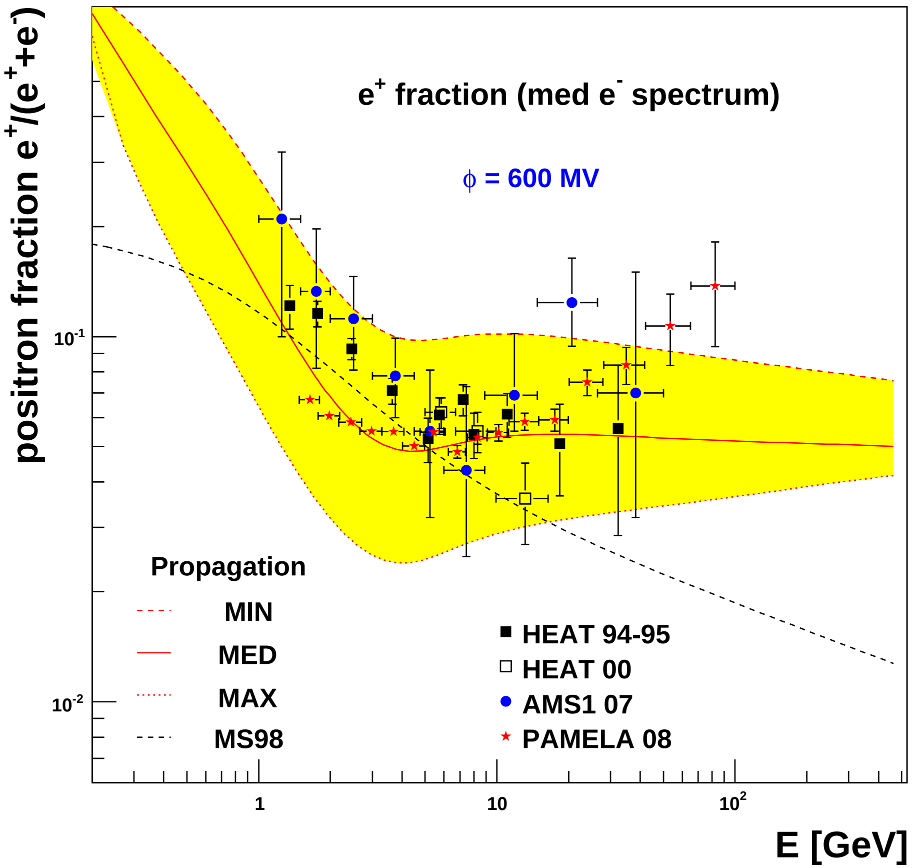
Tuesday, May 5^{th} 2009

Requirements from PAMELA

e^+ background

(Delahaye et al, arXiv:0809.5268)





Requirements from PAMELA

Orders of magnitude for $\chi\chi \to e^+e^-$ (for $E \to m_\chi = 100$ GeV).

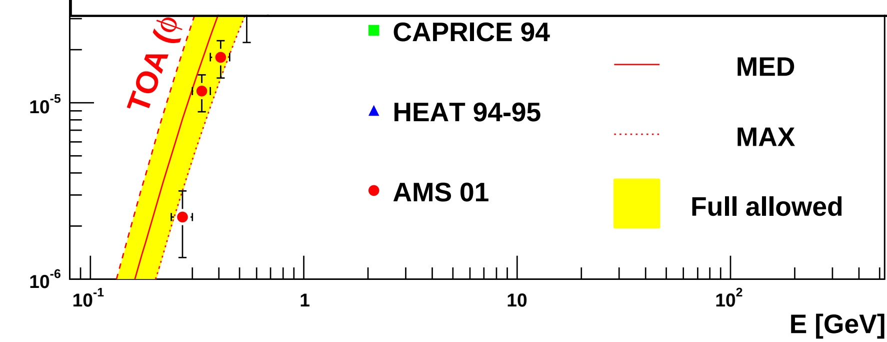
From PAMELA, the excess is $\lesssim 5 \times \phi_{\rm bg}(100\ {\rm GeV}) \sim 1.5 \cdot 10^{-9} {\rm cm}^{-2}.{\rm s}^{-1}.{\rm GeV}^{-1}.{\rm sr}^{-1}$.

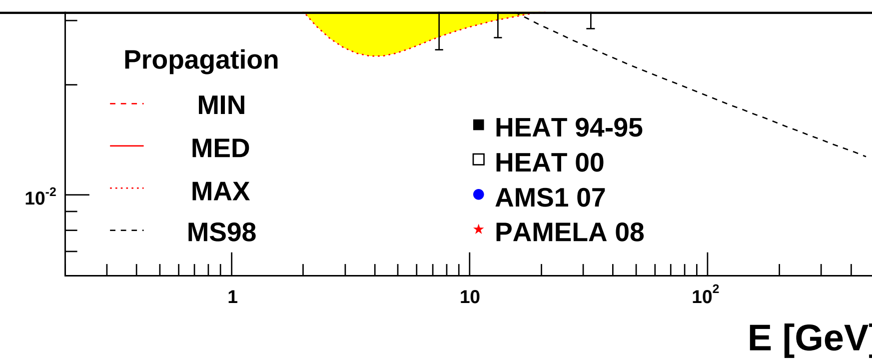
$$\phi_{\rm bg}(100\ {\rm GeV}) \simeq 3 \cdot 10^{-10} \left(\frac{E}{100\ {\rm GeV}}\right)^{-3.5} {\rm cm}^{-2}.{\rm s}^{-1}.{\rm GeV}^{-1}.{\rm sr}^{-1}$$

$$\phi_{\chi\chi}(E \to m_\chi) \simeq \frac{\delta\beta c}{4\pi} \frac{\tau E_0}{E^2} \frac{\langle\sigma v\rangle}{2} \left(\frac{\rho_\odot}{m_\chi}\right)^2$$

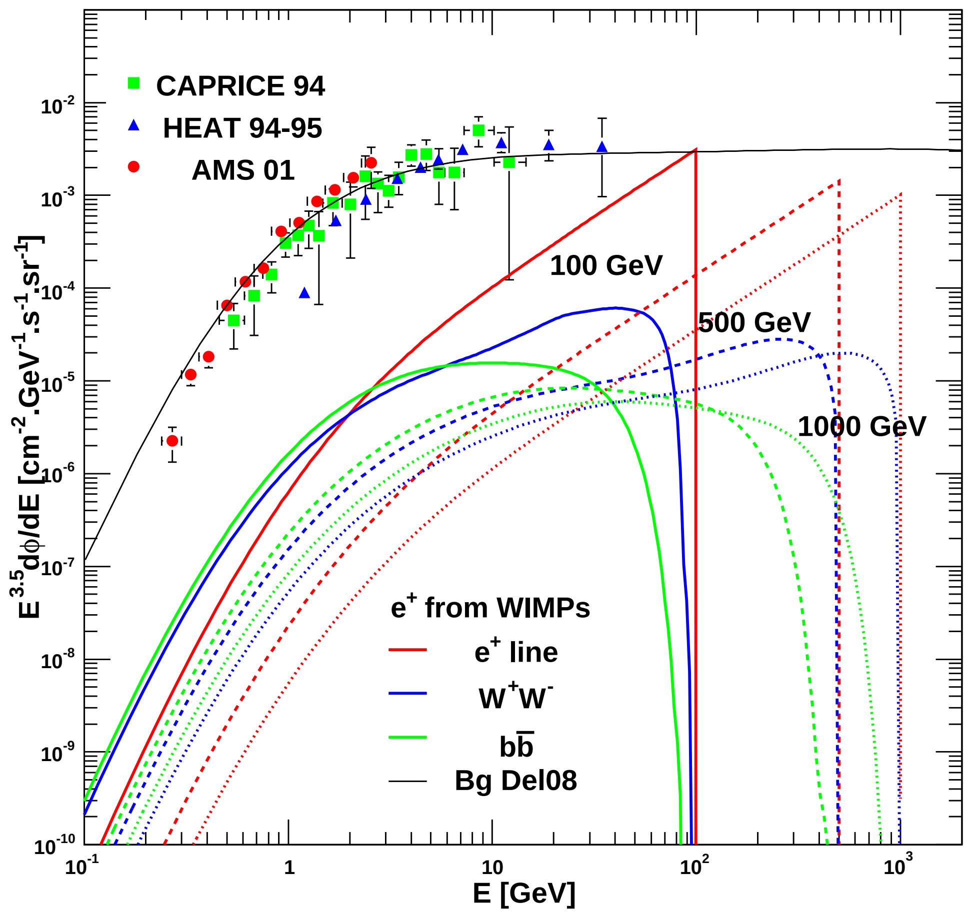
$$\simeq 3 \cdot 10^{-10} \left(\frac{\tau}{10^{16}{\rm s}}\right) \left(\frac{\rho_\odot}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{100\ {\rm GeV}}{m_\chi}\right)^4 \left(\frac{\langle\sigma v\rangle}{3 \cdot 10^{-26}{\rm cm^3/s}}\right)$$

For $m_\chi \simeq 100$ GeV, need for an amplification of: $\mathcal{B} \simeq 5$.





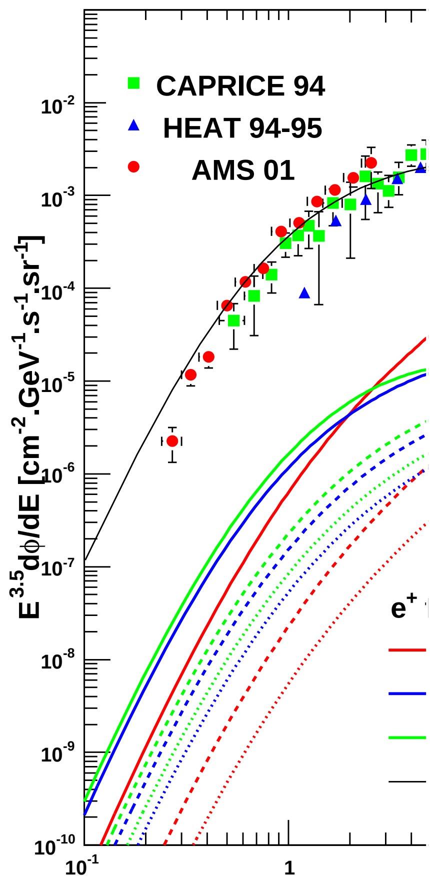
Smooth NFW halo and generic predictions



Boost to get $\sim 5 \times \phi_{\rm bg}$ **at** $\sim$**100 GeV**:

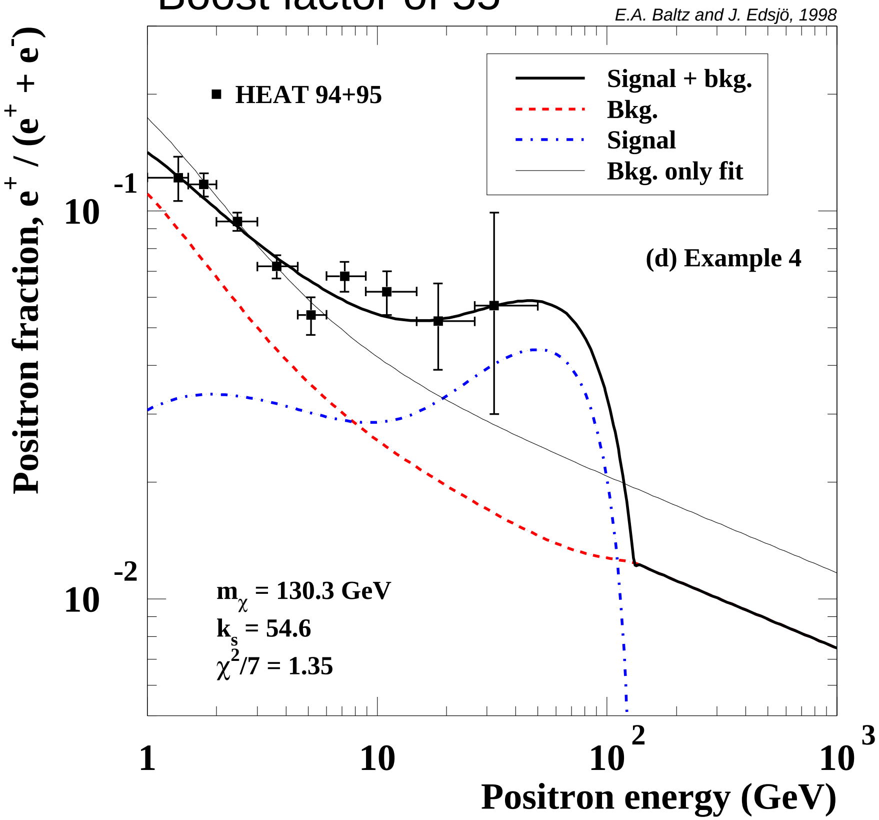
WIMP mass final state	100 GeV	500 GeV	1 TeV
e^+e^-	5	100	350
W^+W^-	80	500	1000
$b\bar{b}$	250	500	1000

Smooth NFW halo and generic predictions



Baltz & Edsjö, 98

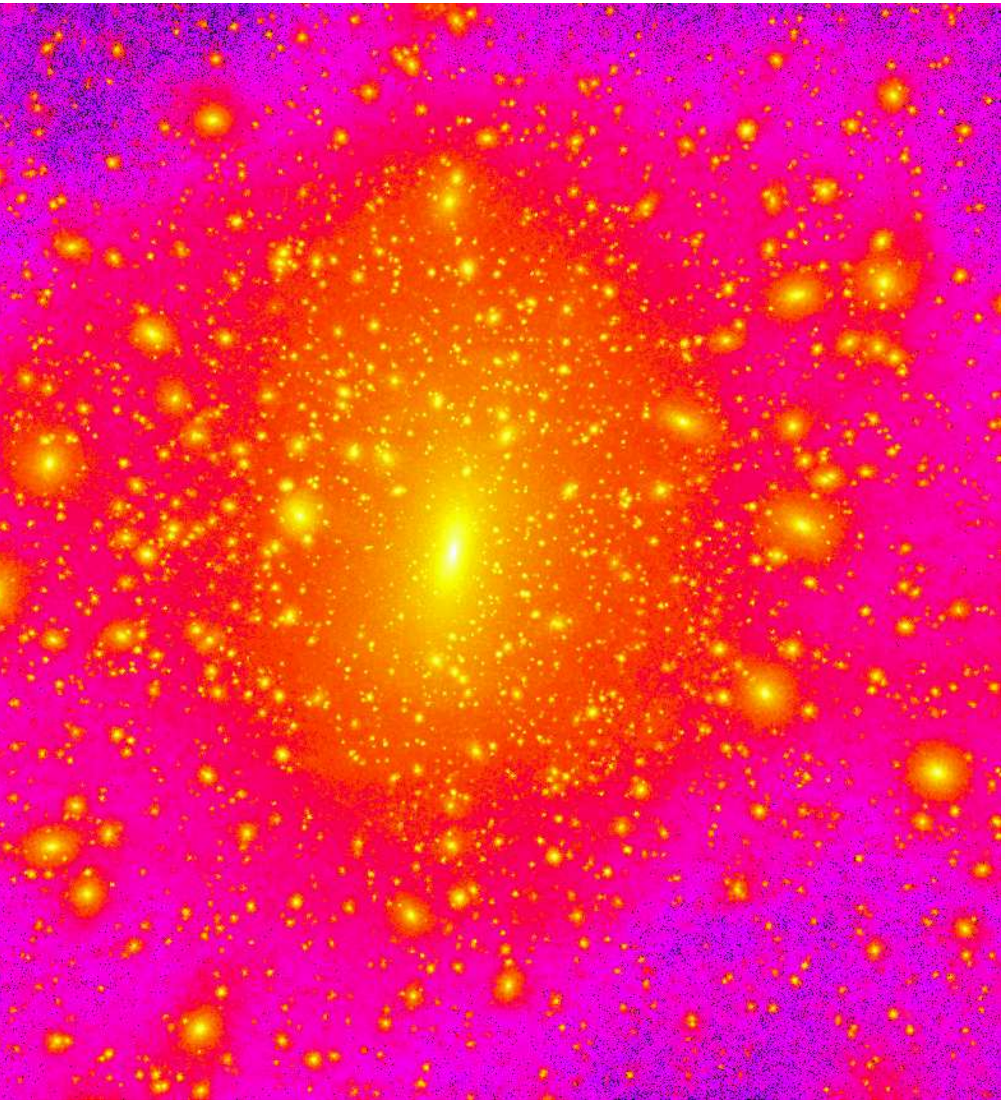
Boost factor of 55



$\phi_{\rm bg}$ **at ~100 GeV**:

) GeV	500 GeV	1 TeV
5	100	350
80	500	1000
!50	500	1000

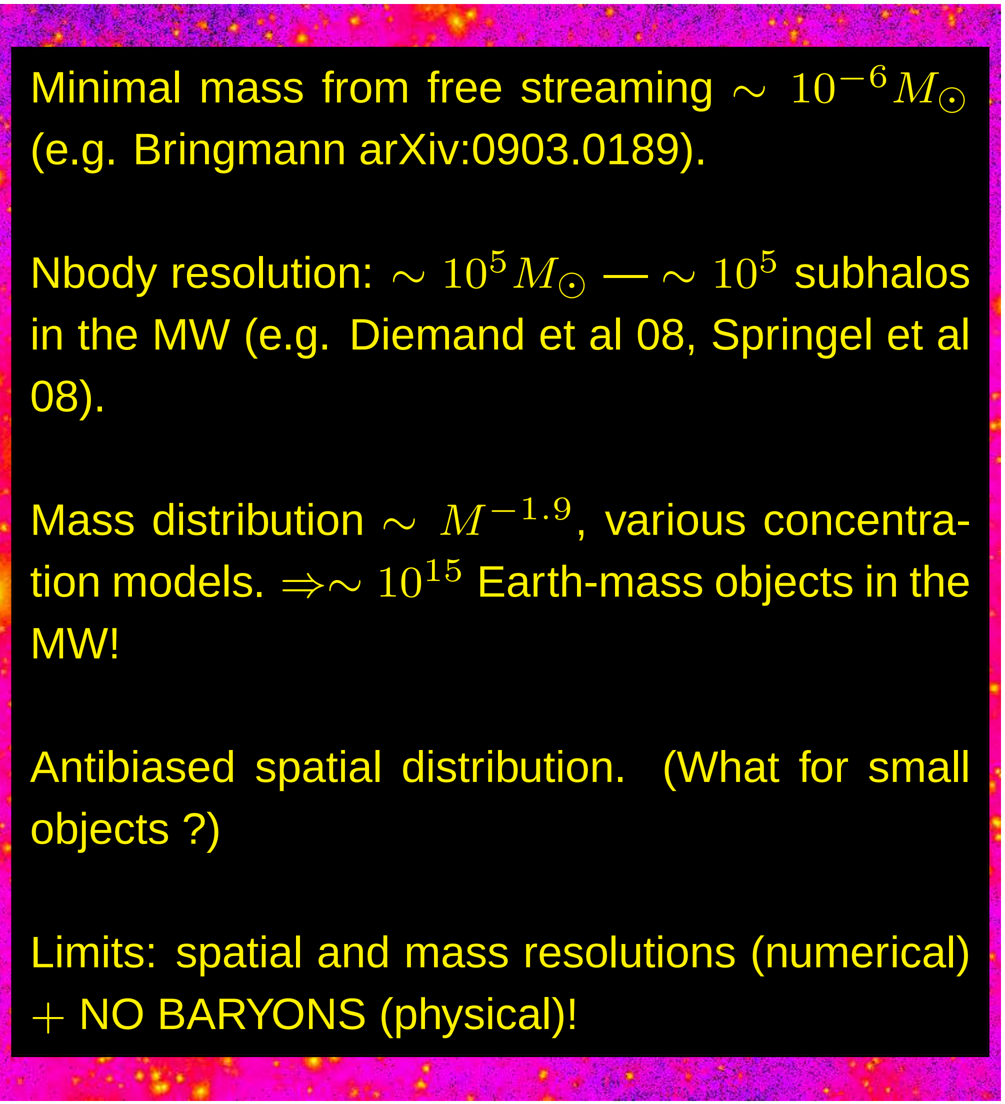
Inhomogeneous halo and boosted annihilation rate



(Fig. from Diemand et al, MNRAS'04)

- Though the topic is still controversial, **clumps are predicted by theory and simulations of hierarchical formation of structures** (in the frame of ΛCDM)
- Annihilation rate is increased in a characteristic volume, because $< n_{\rm dm}^2 > \geq < n_{\rm dm} >^2$ (Silk & Stebbins ApJ'93)
- The boost factor to the annihilation rate is related to the statistical variance via $B_{\rm ann} \sim \frac{< n_{\rm dm}^2 >}{< n_{\rm dm} >^2}$
- **There is some scatter in N-body experiments: how to translate theoretical uncertainties to flux uncertainties ? what and where are the less ambiguous signatures, if so ?**

Inhomogeneous halo and boosted annihilation rate



Minimal mass from free streaming $\sim 10^{-6} M_\odot$ (e.g. Bringmann arXiv:0903.0189).

Nbody resolution: $\sim 10^5 M_\odot$ — $\sim 10^5$ subhalos in the MW (e.g. Diemand et al 08, Springel et al 08).

Mass distribution $\sim M^{-1.9}$, various concentration models. $\Rightarrow \sim 10^{15}$ Earth-mass objects in the MW!

Antibiased spatial distribution. (What for small objects ?)

Limits: spatial and mass resolutions (numerical) $+$ NO BARYONS (physical)!

(Fig. from Diemand et al, MNRAS'04)

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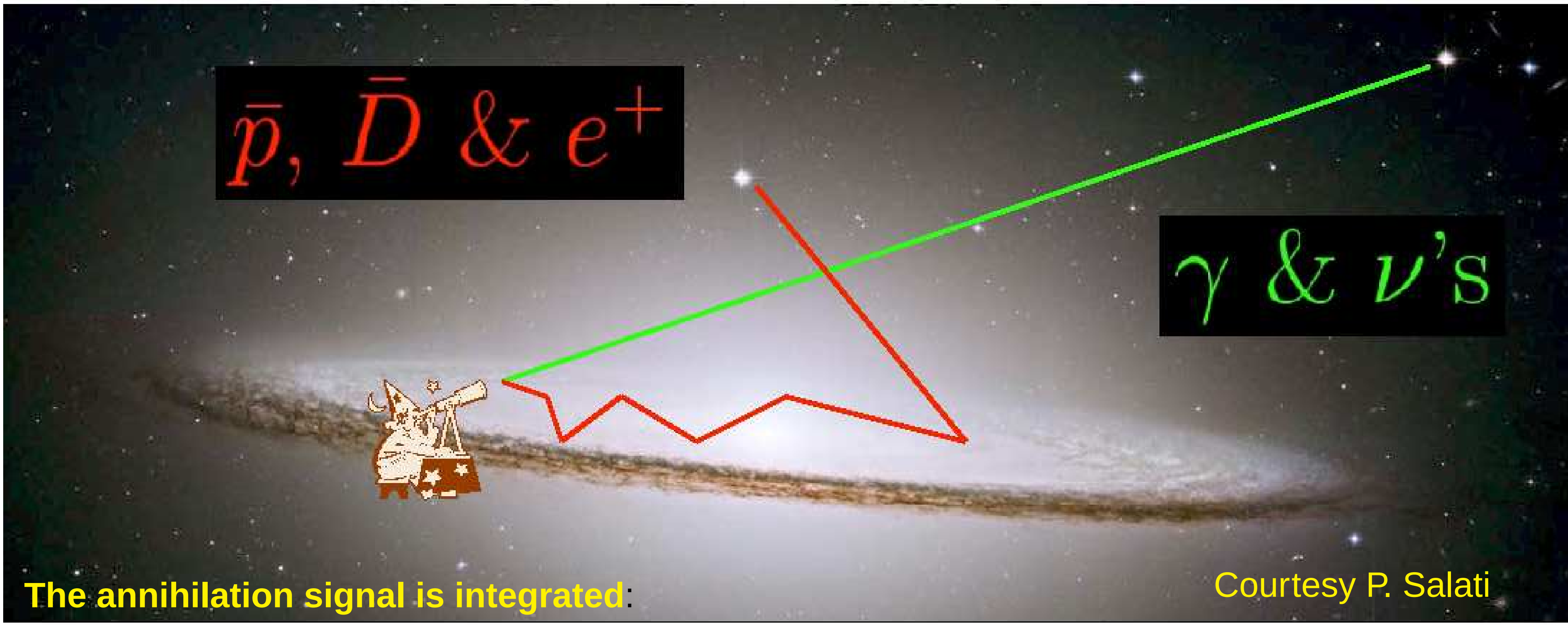
Gamma-rays versus antimatter cosmic rays

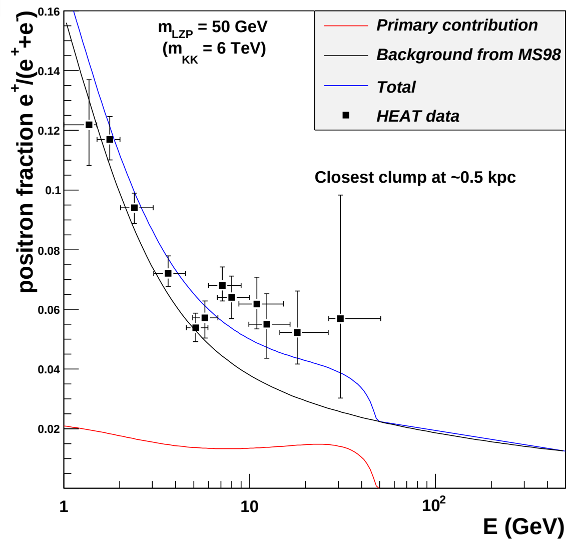


- over a small solid angle around the line of sight for $\gamma-$rays and neutrinos
- over a rather small volume around the Earth for antimatter CRs, due to diffusion processes

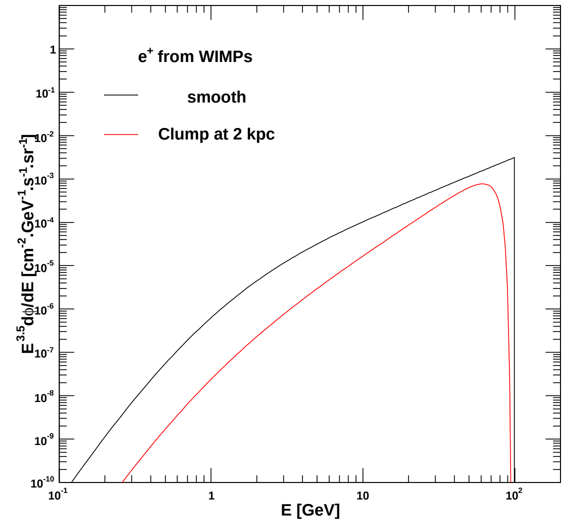
$\Longrightarrow$ **<u>Boost factors are not the same</u> !**

Boost from few objects

- Few massive subhalos are expected in the MW:
  $\sim 100 \times \left(\frac{M}{10^8 M_\odot}\right)^{-1}$
- **By chance**, one or few could wander close to the Earth ...
- Predictions: move a single (or few) object(s) around
- **Very small probability: fine tuned models** !!! ($\sim \mathcal{O}(10^{3-4})\mathrm{objects/MW\ volume}$)
- **Multimessenger analysis**: check radio, γ-ray and antiproton constraints
- **Not a clean prediction of clumpiness $\Rightarrow$ What about global effects?**.



Lavalle, Pochon, Salati & Taillet astro-ph/0603796



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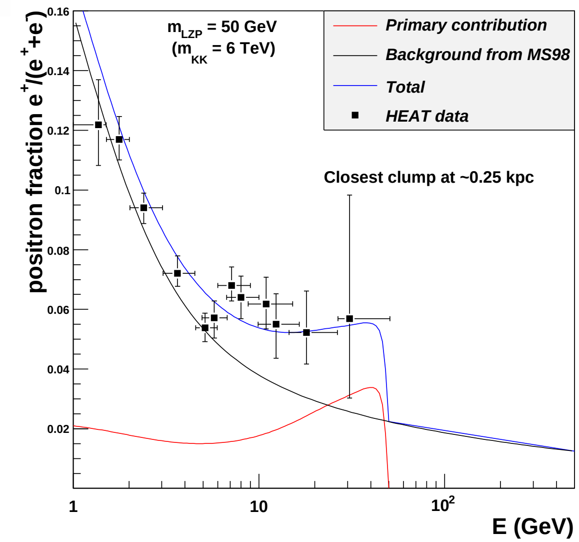

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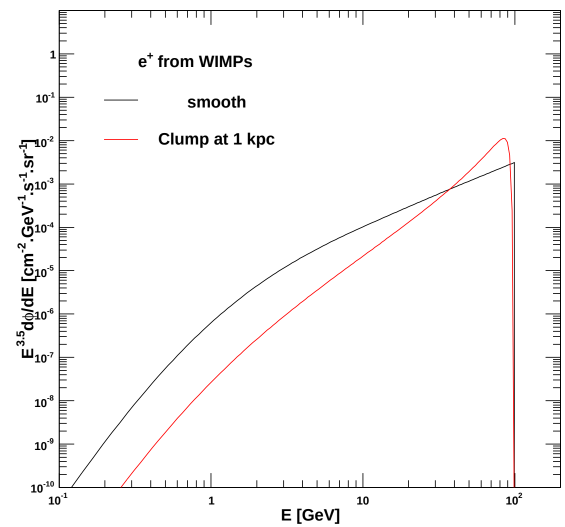

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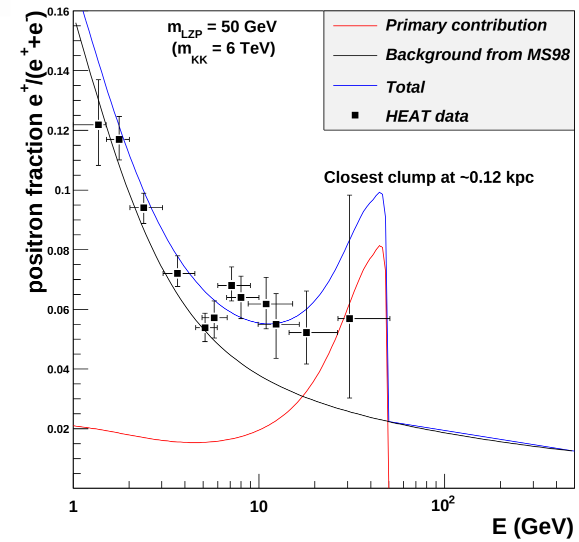

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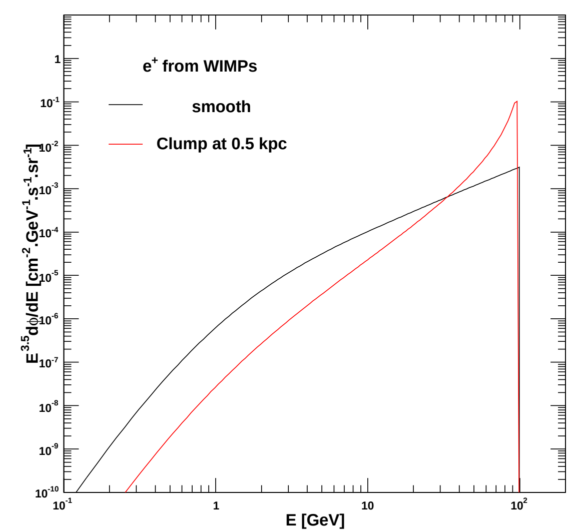

Boost from few objects

Bringmann, Lavalle & Salati
arXiv:0902.3665

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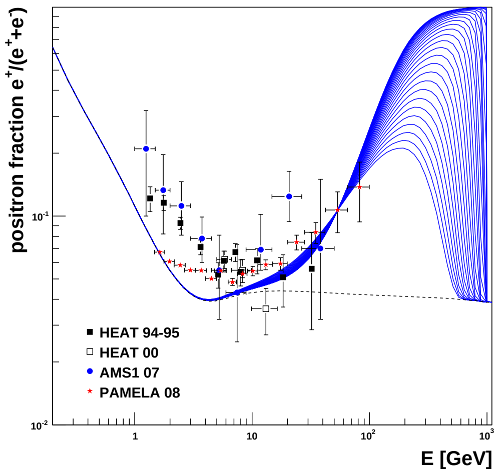

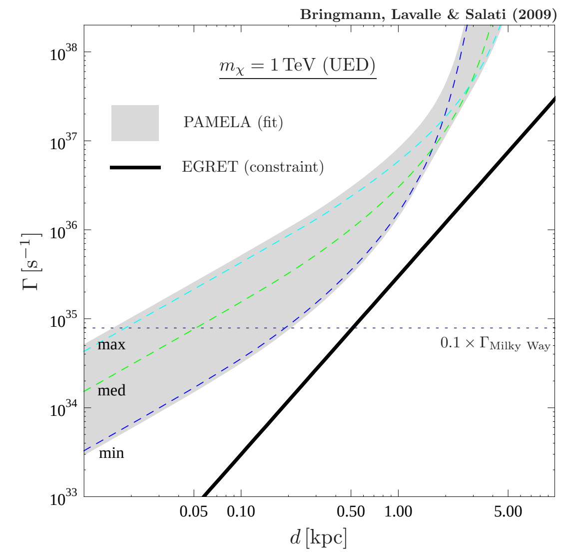

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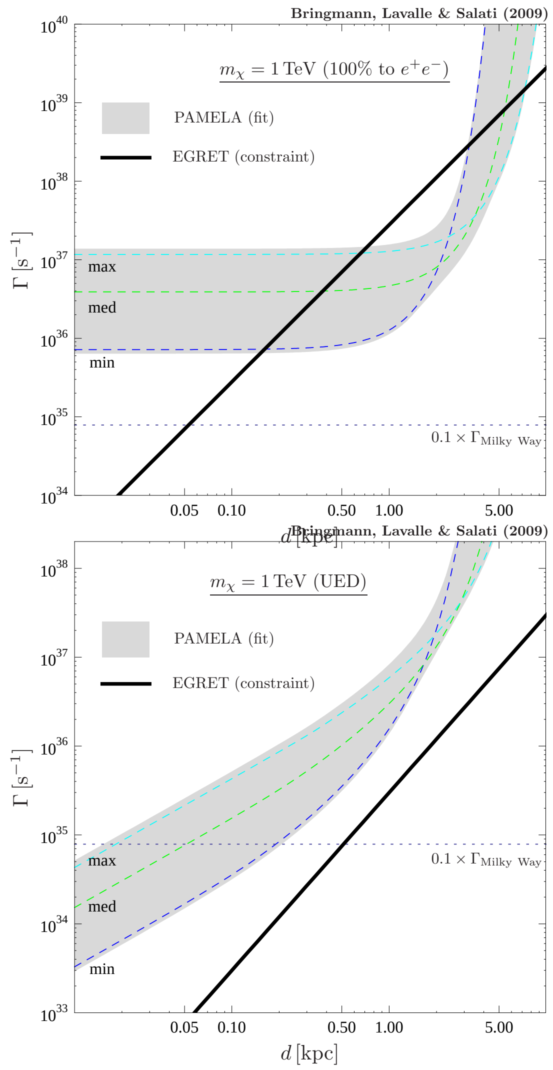
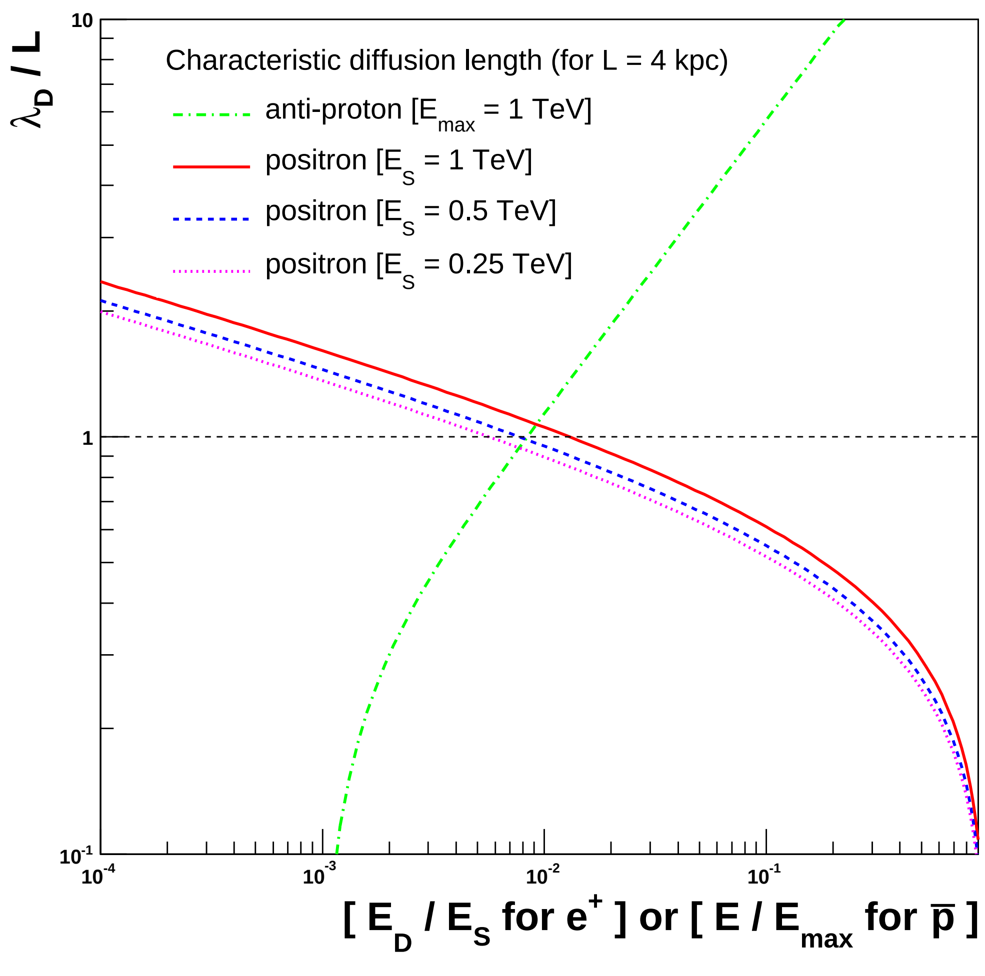


Energy-dependent diffusion scales for e^+ and $\overline{p}$

- e^+**'s lose energy**:
  survey larger and larger volumes when detected at lower and lower energies
  $\longrightarrow$ **importance of energy loss parameters: magnetic field, interstellar radiation field**.
- $\overline{p}$'s do not lose energy, **but convective wind and spallation processes very efficient at low energy**:
  survey larger volume at high ener-gies

Lavalle, Nezri, Ling et al – PRD 78 (2008)



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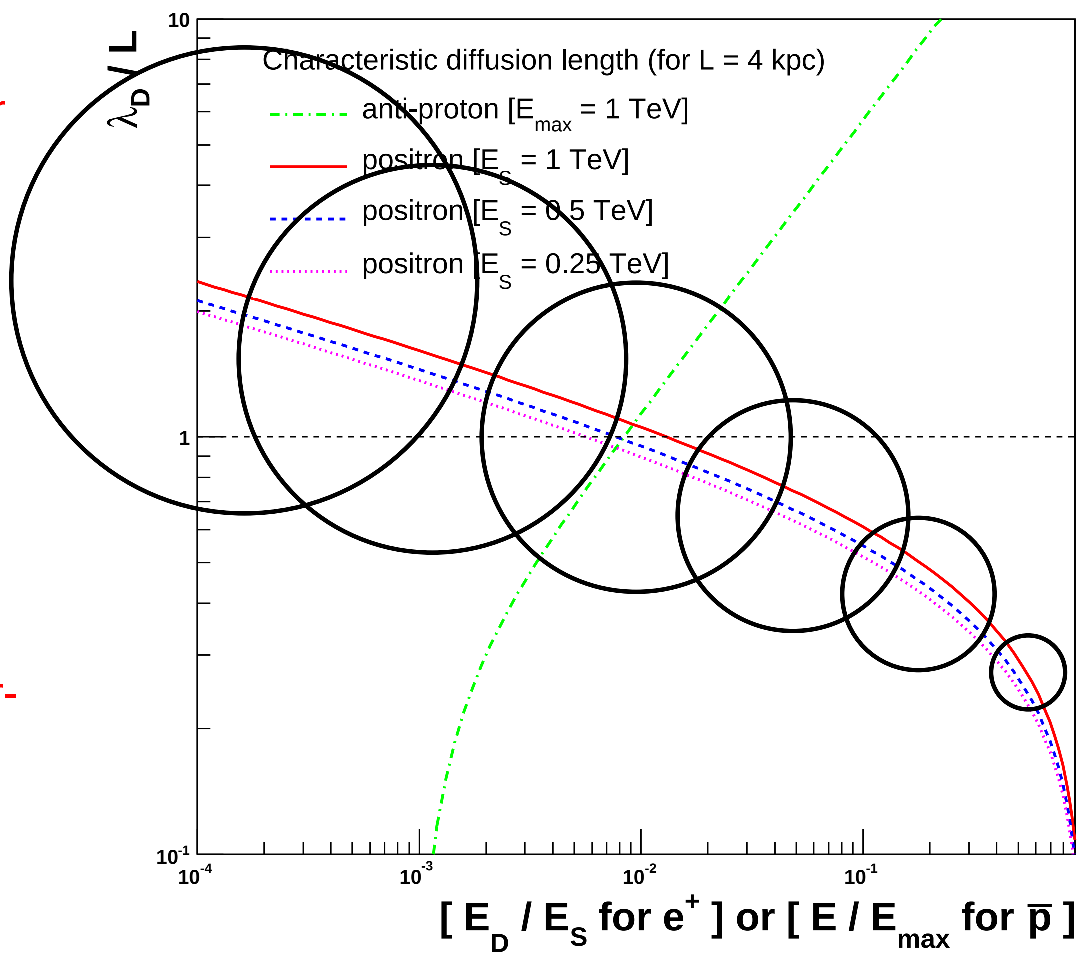


Effective volume picture for the smooth contribution

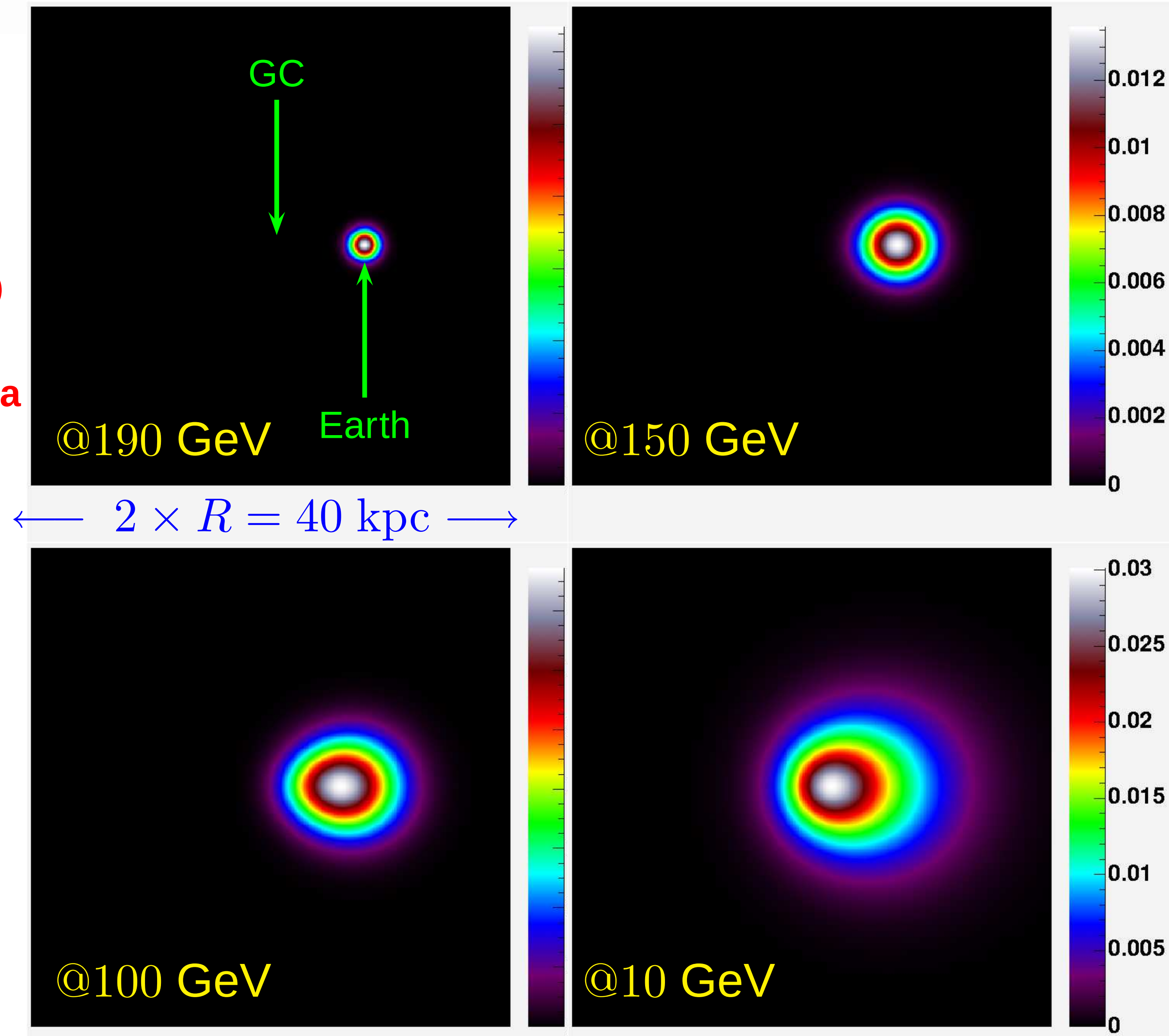
Inject a 200 GeV e^+ with $Q(r) = \rho^2(r) \propto r^{-2}$ ...

Simplest view of propagation

$$G \propto \exp\left(-\frac{|\vec{x}_S - \vec{x}_\odot|^2}{\lambda_D^2}\right)$$

with $\lambda_D = \sqrt{4K_0\Delta\tilde{t}} = f(E_S, E_D)$

$\rightarrow$ **Detection volume scaling a sphere of radius λ_D**



Figures:

galactic plane at z=0 kpc

x and y from -20 to 20 kpc

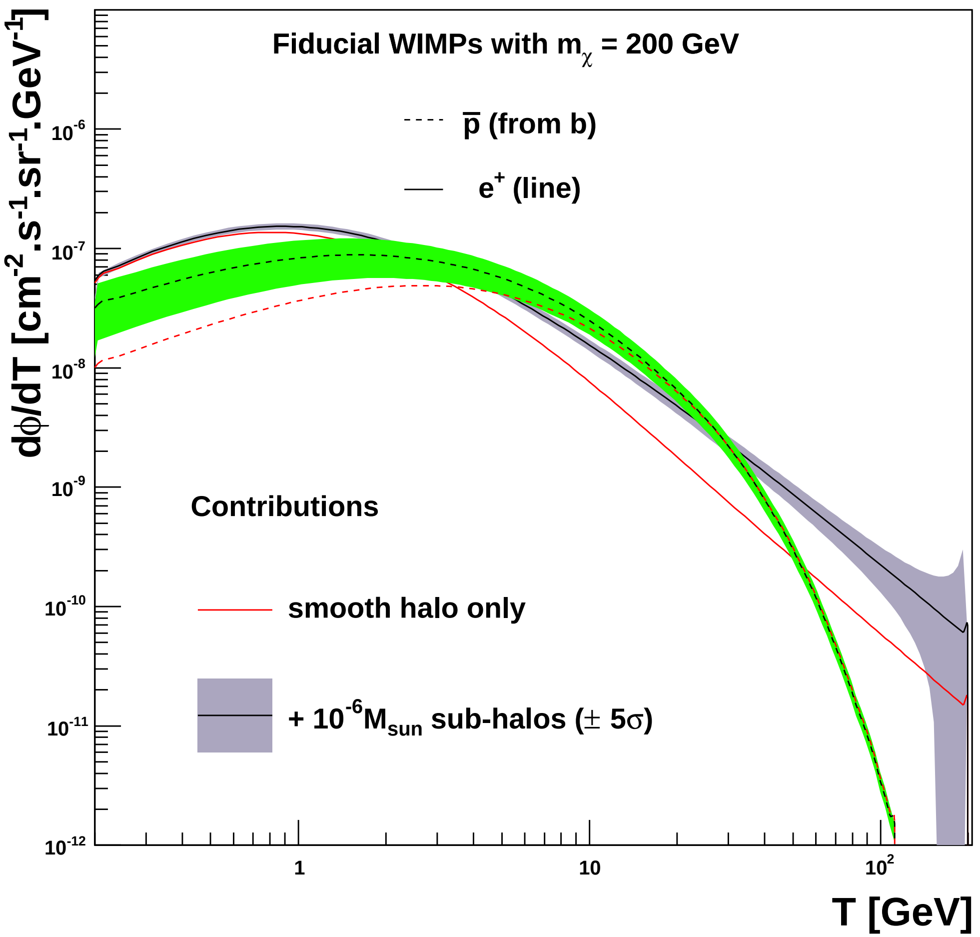
Earth located at ($x = 8, y = 0$) kpc

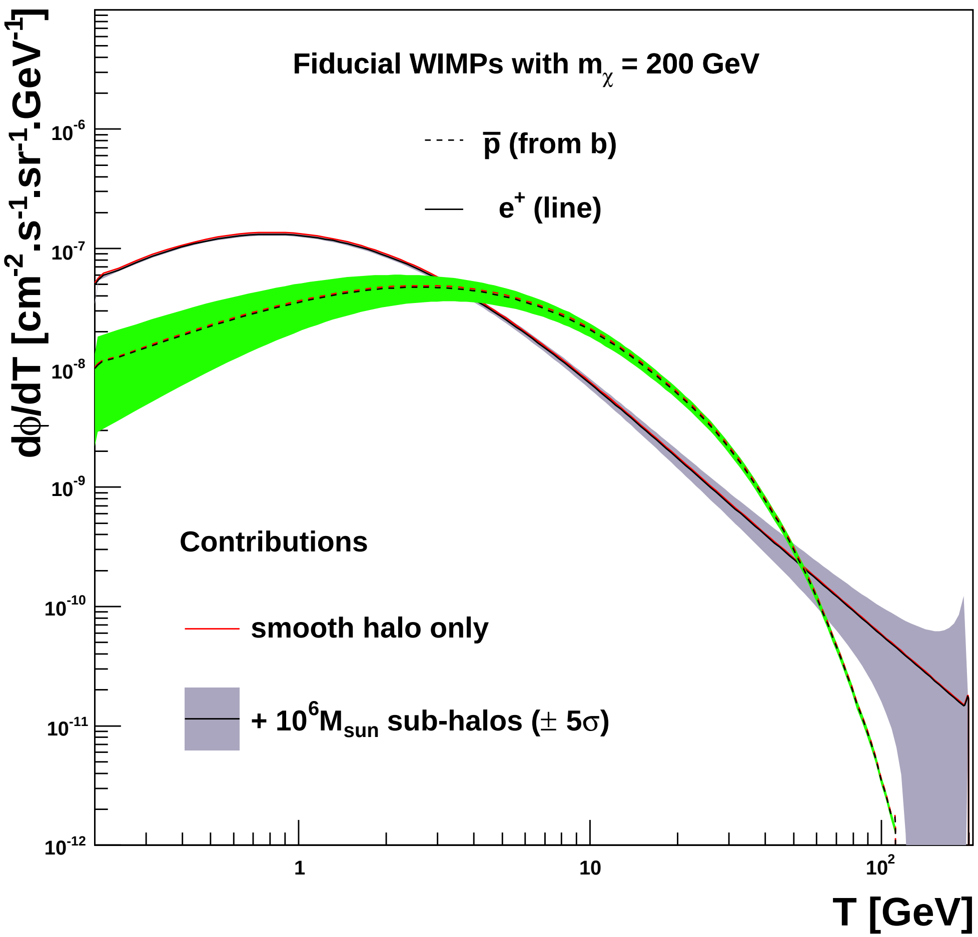
2D plots of

$G(\vec{x}, 200\mathrm{GeV} \rightarrow \tilde{\mathrm{x}}_\odot, \mathrm{E}) \times \rho^2$

Primary fluxes for a 200 GeV e^+ line / antiprotons

Configurations: $M_{\rm min} = 10^{-6}|10^{6} M_{\odot}$, $\alpha_{\rm m} = 2.0$, inner-NFW, B01, smooth-like space distribution (smooth = NFW)



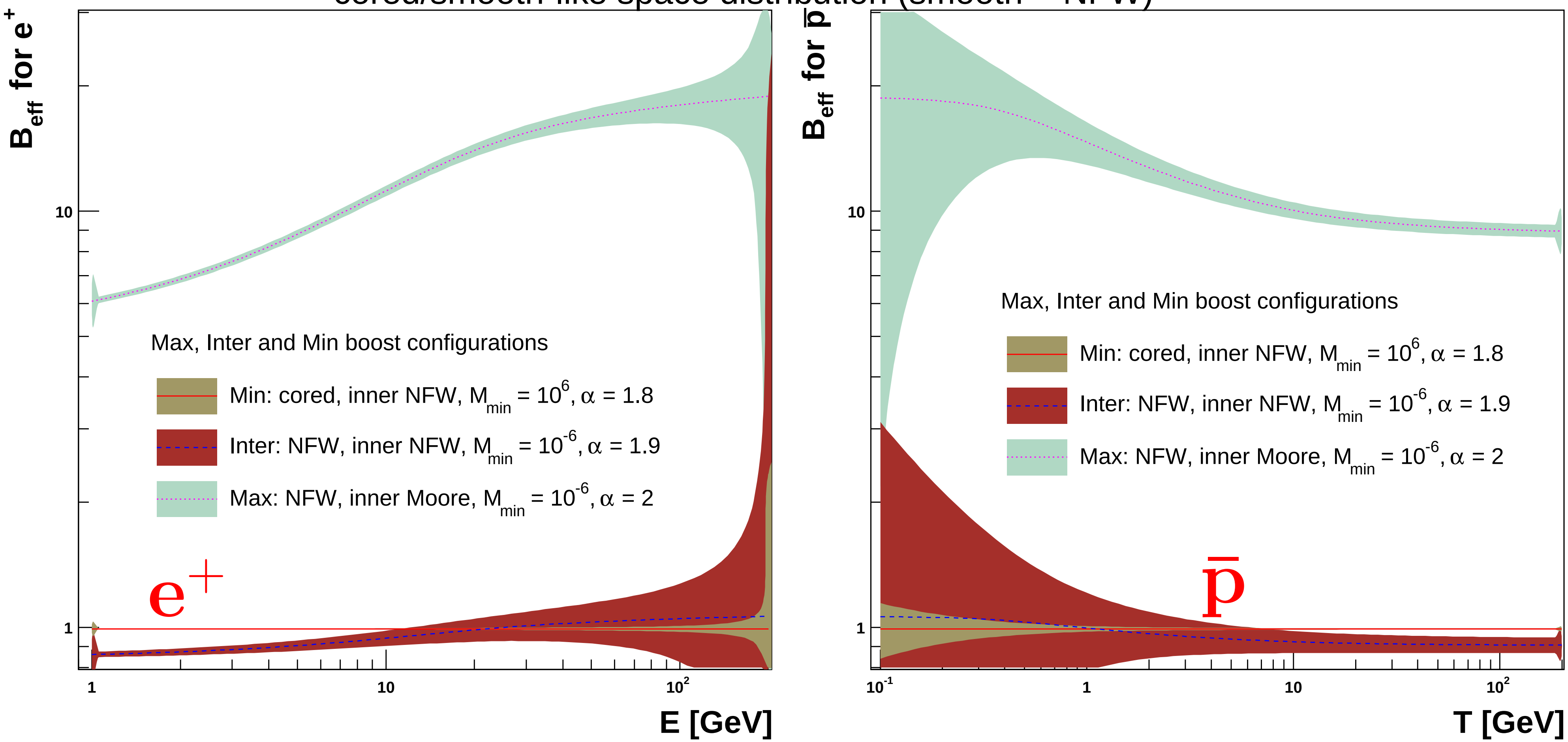


Lavalle, Maurin et al – A&A 429, 427 (2008)

Lavalle, Nezri, Ling et al – PRD 78 (2008)

Boost factors for a 200 GeV e^+ line / antiprotons

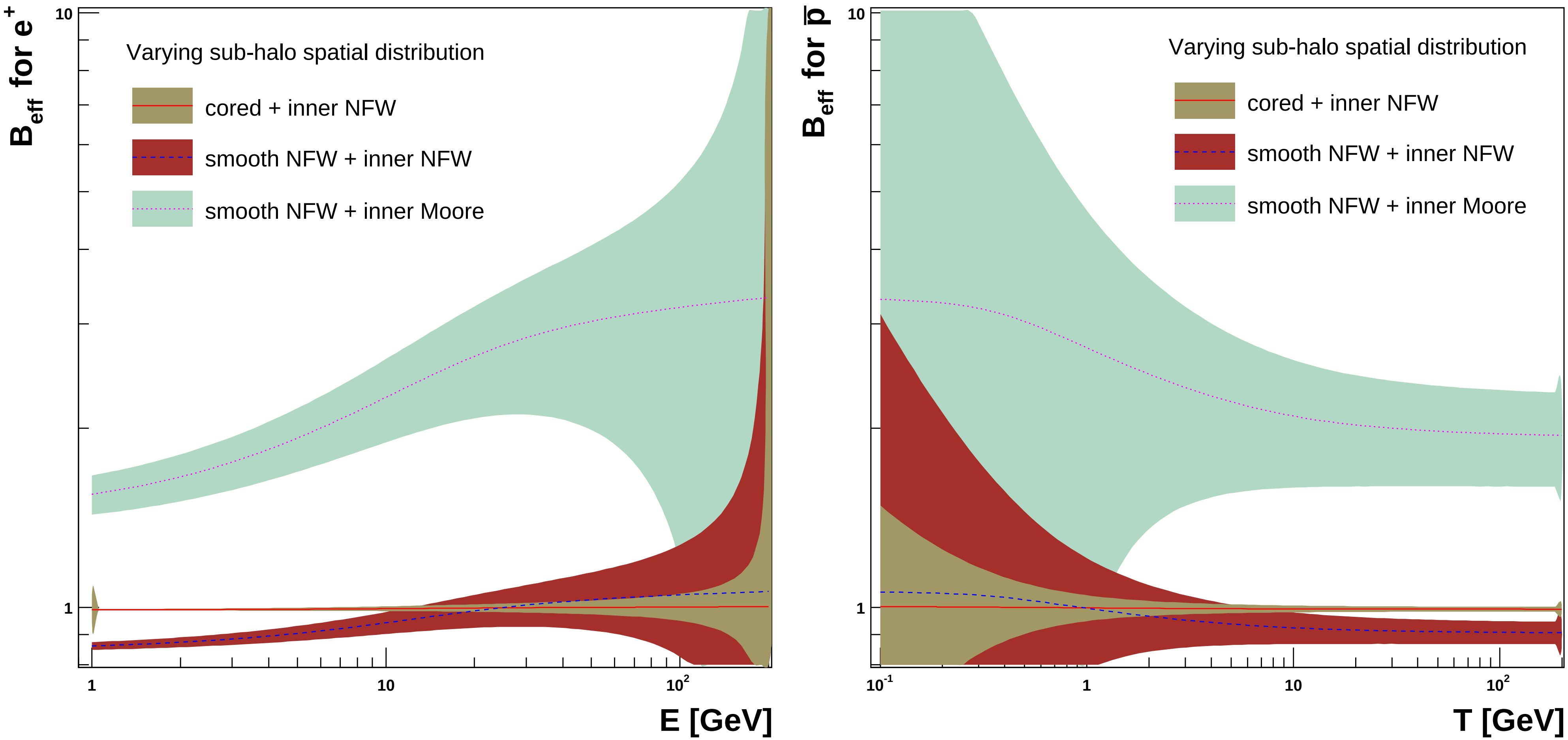
Extreme configurations $M_{\rm min} = 10^{-6}|10^6 M_\odot$, $\alpha_{\rm m} = 1.8|2.0$,
inner-NFW/Moore, B01/ENS01,
cored/smooth-like space distribution (smooth = NFW)



Lavalle, Yuan, Maurin & Bi — A&A 429, 427 (2008)

Boost factors for a 200 GeV e^+ line / antiprotons

$M_{\rm min} = 10^{-6} M_\odot$, $\alpha_{\rm m} = 1.9$, inner-NFW vs Moore, B01, cored vs smooth-like space distribution (smooth = NFW)

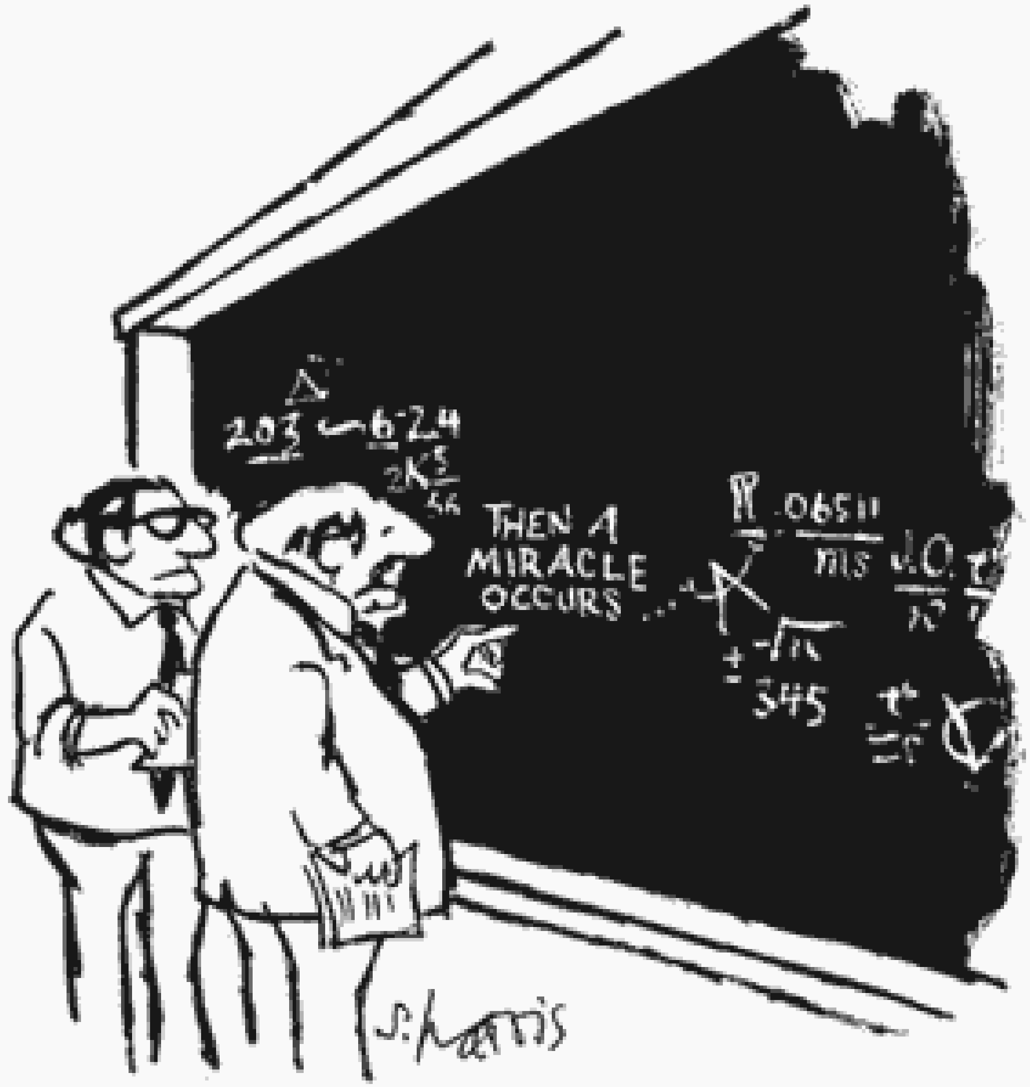


Lavalle, Yuan, Maurin & Bi — A&A 429, 427 (2008)

Summary

- Clumps are predicted and observed in pure DM Nbody simulations: what will happen with baryons? (more efficient tidal disruption expected, but small scales should survive)
- Invoking a nearby clump $=$ playing the Galactic Lottery
- Global clumpiness effects cannot amplify the signal, $\mathrm{BOOST} \lesssim 20$ for usual WIMP models (VLII analysis — Bertone et al, in progress)
- Complementarity with other messengers (multiwavelength photons and $\bar{p}$) is very important
- Clumpiness can boost the Sommerfeld boost (Lattanzi & Silk, 2008 — Lattanzi, Lavalle, Salati & Silk, in progress)
- If DM is made of WIMPs, clumps should be there ... seen or unseen ...
- Uncomfortable to look for exotic explanations when standard astrophysics (e.g. pulsars) provides significant contributions: local e^+s <u>at the GeV scale</u> may not be interesting anymore to look for DM

Backup

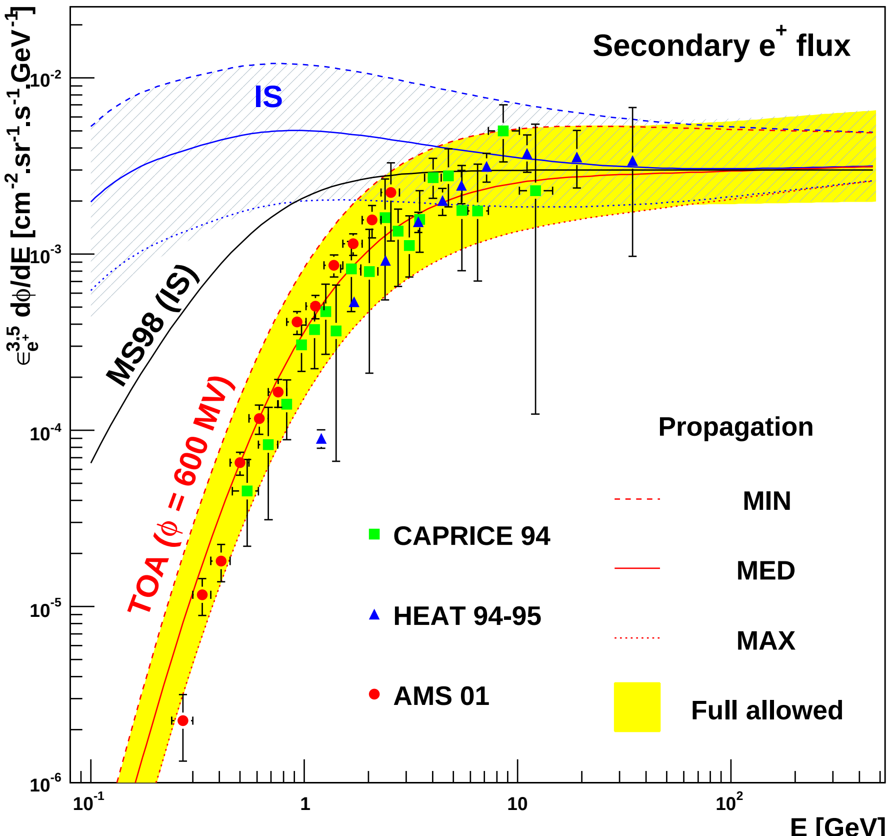


"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

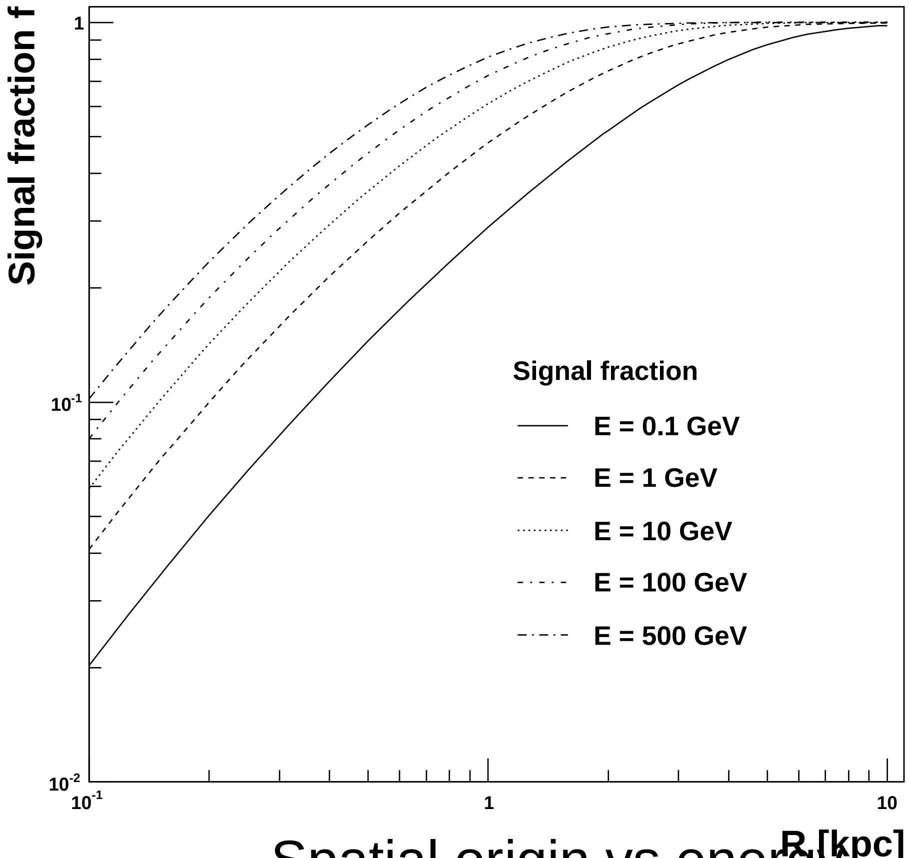
Prediction of the secondary e^+ flux and uncertanties

The Alpine connection e^+ background (Annecy & Torino)

Delahaye et al, arXiv:0809.5268



Secondary positron flux



Spatial origin vs energy

PAMELA: to predict the e^+ fraction, we need e^-s!

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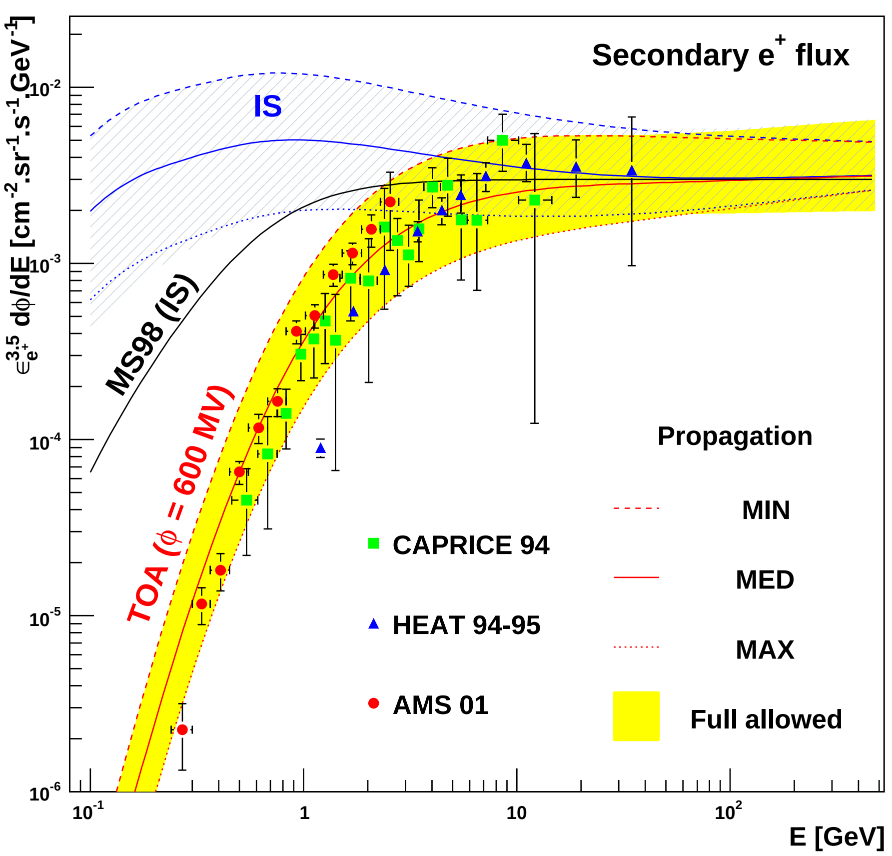

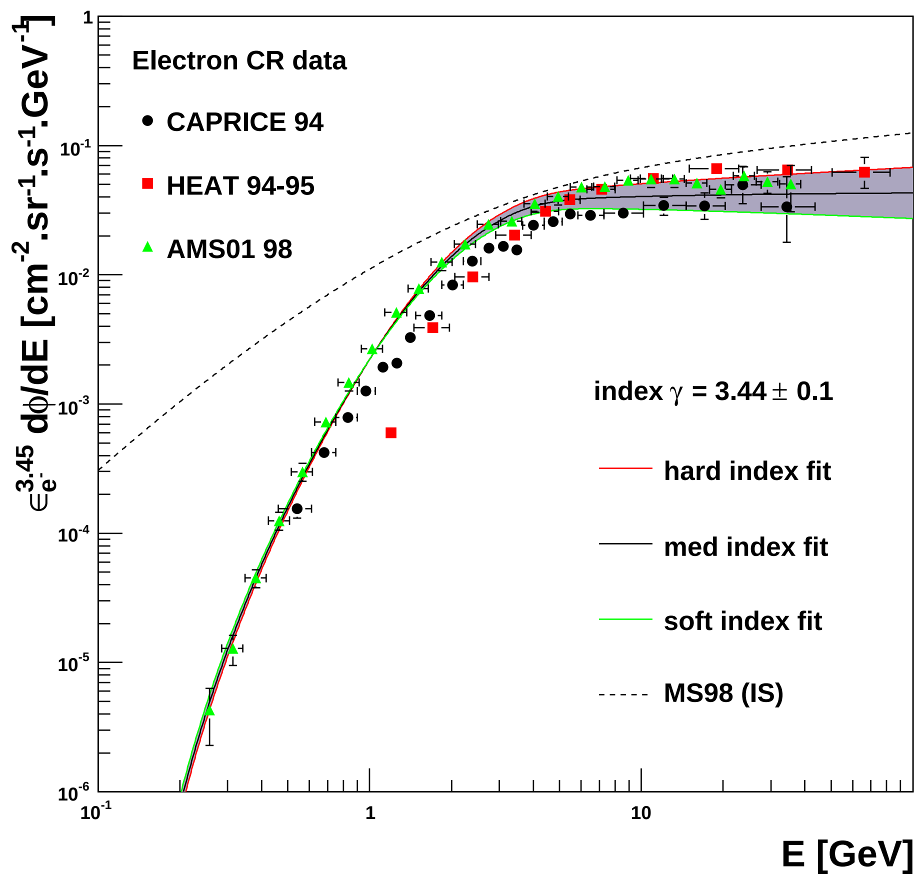

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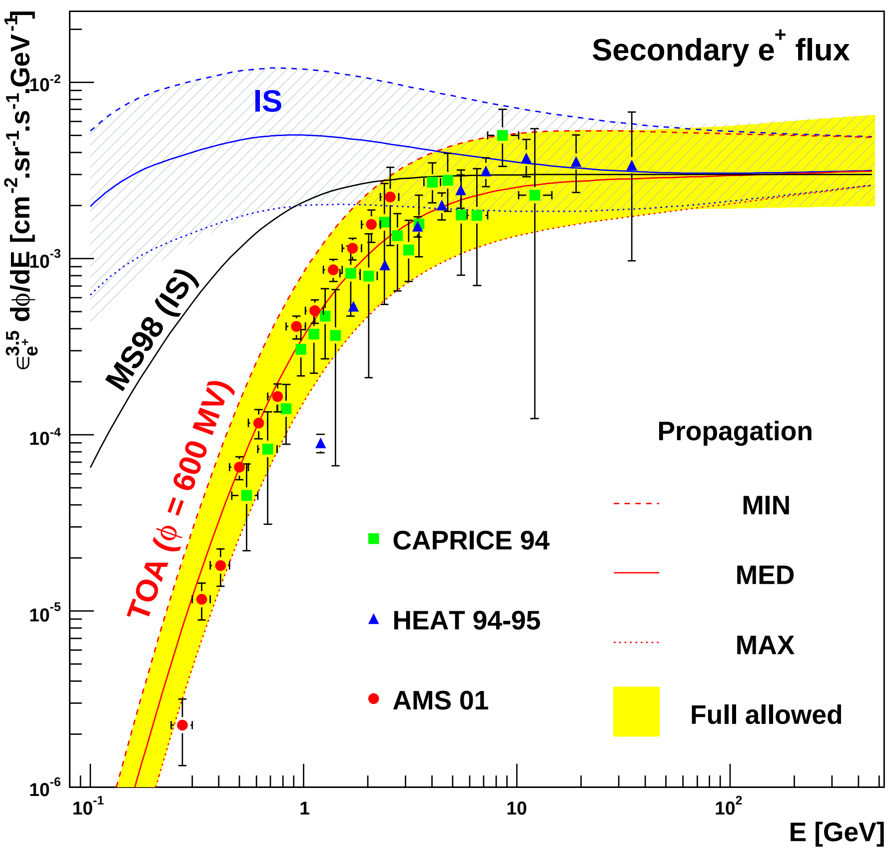

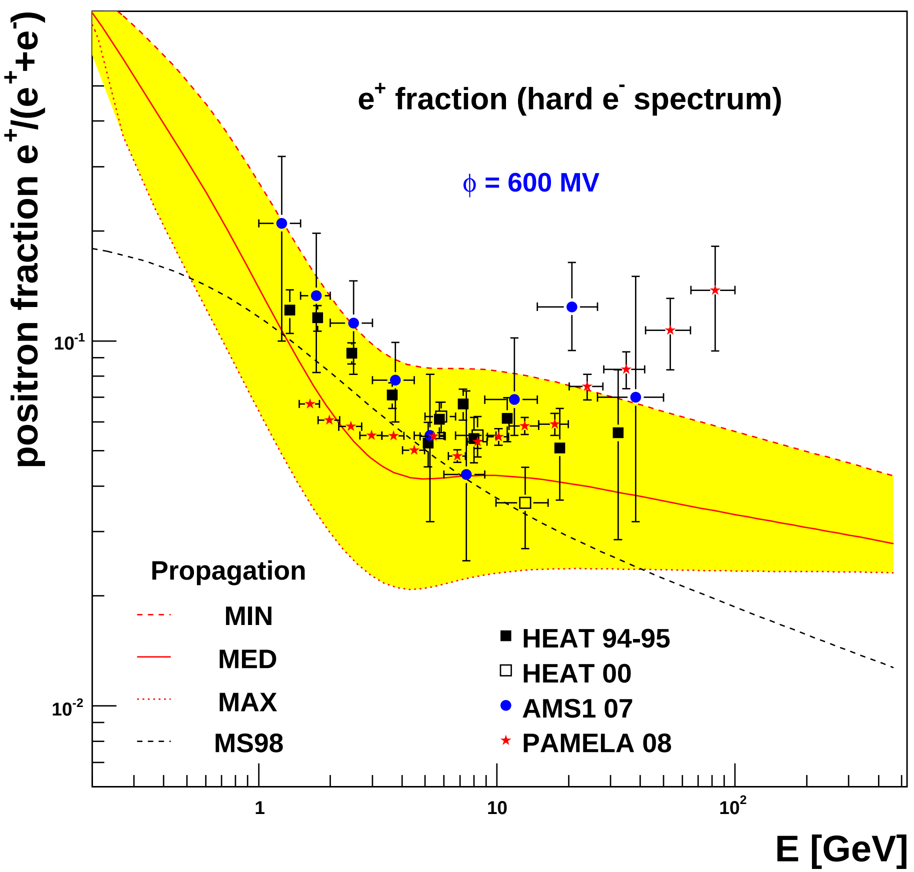

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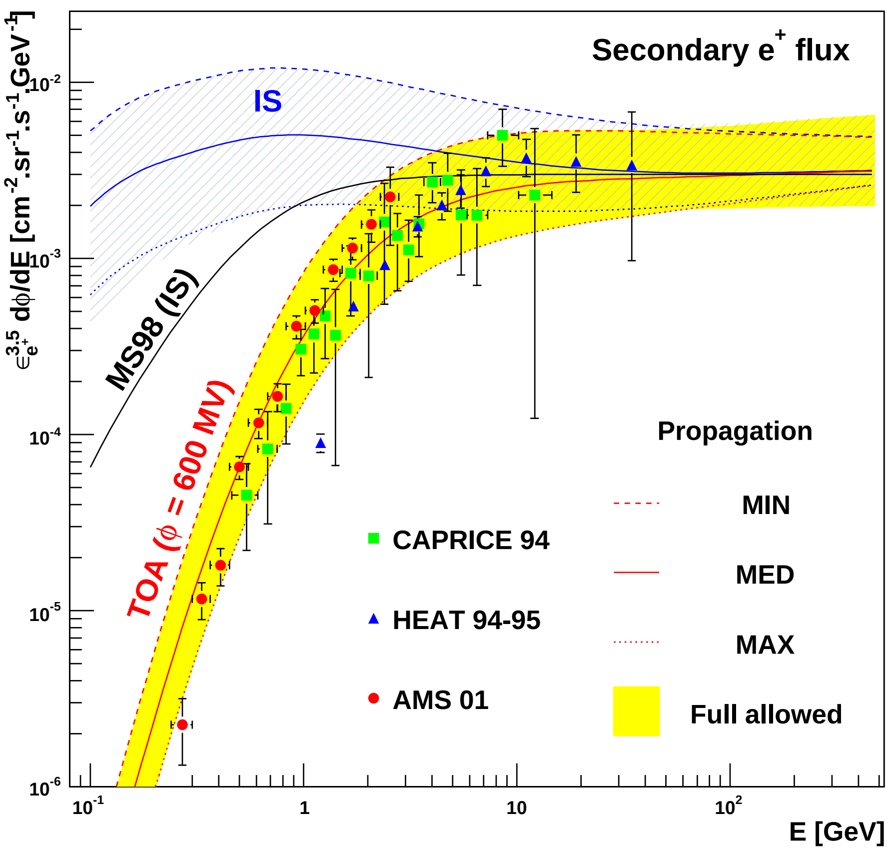
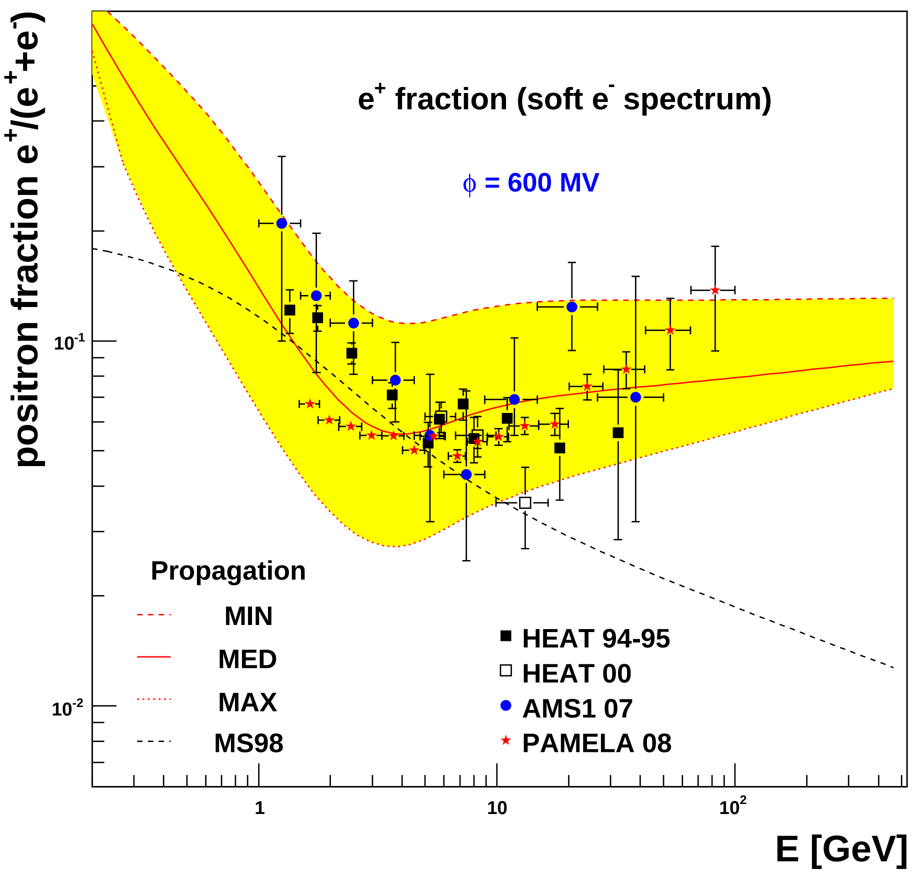
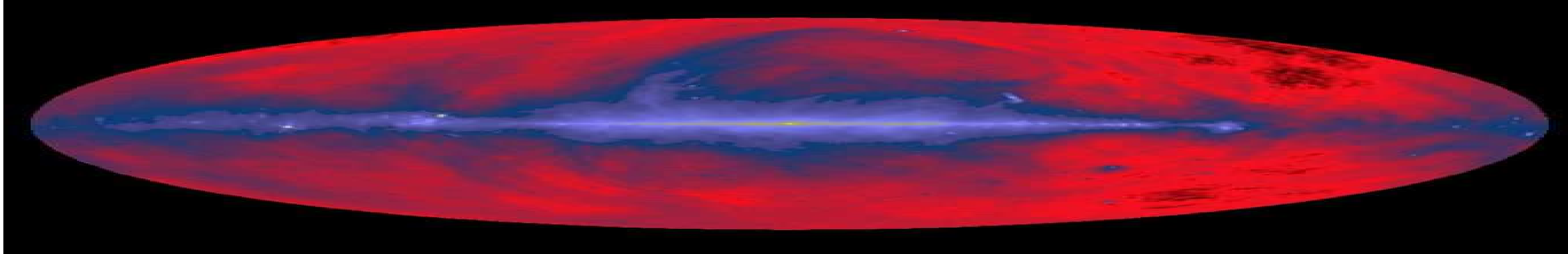




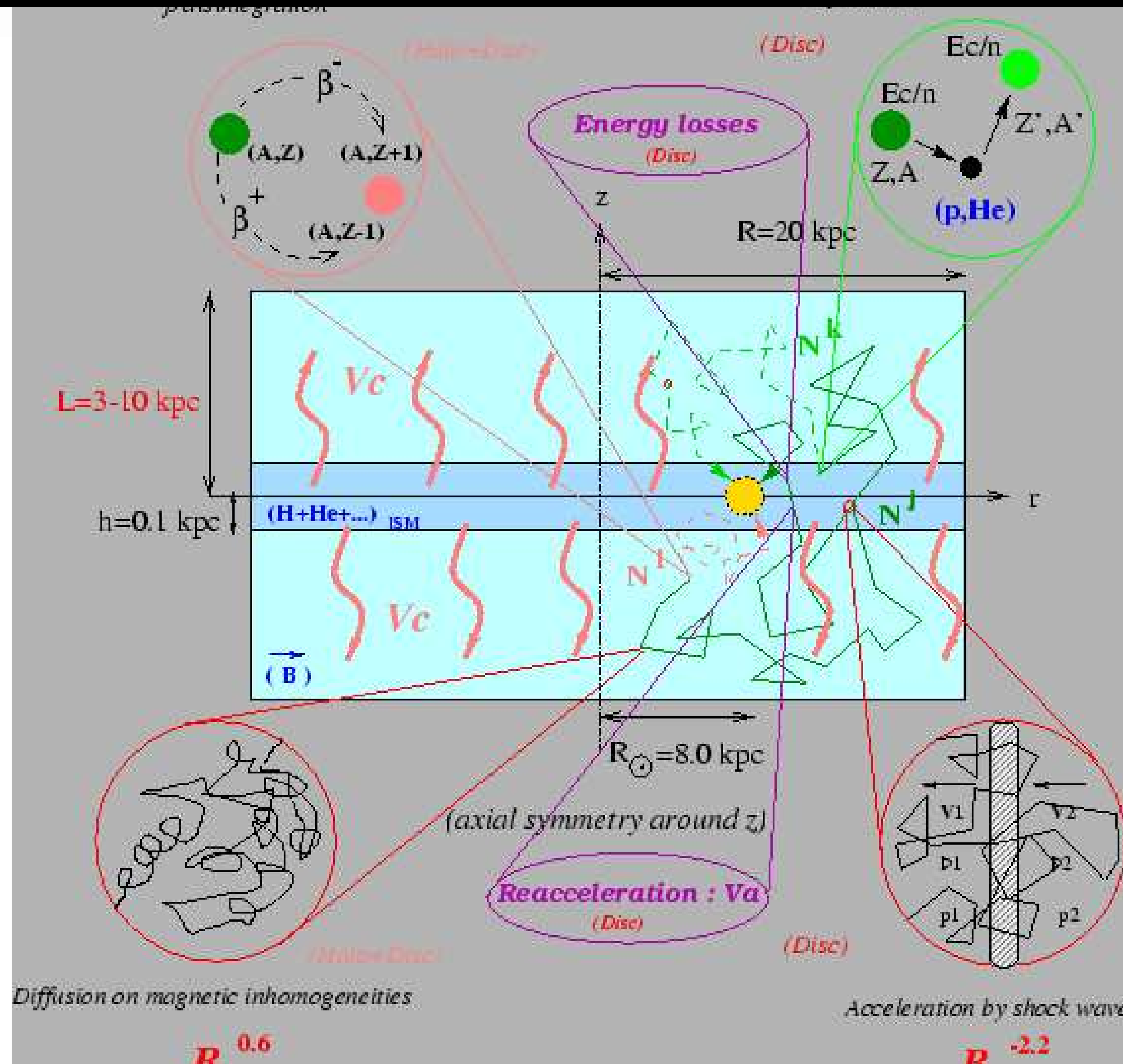
Sub-TeV Cosmic ray propagation in the Galaxy

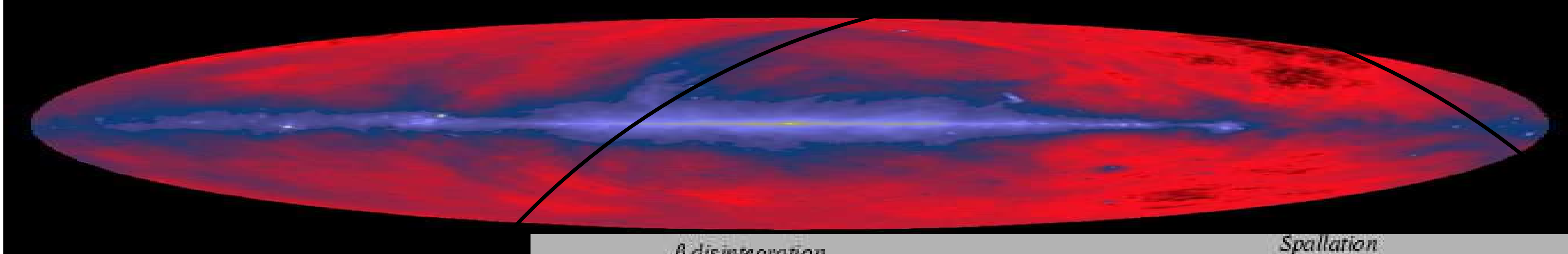


cf. e.g. Berezinsky (1990)

- **Cylindrical diffusive halo** :
  $R \sim 20\mathrm{kpc}, \mathrm{L} \sim 3\mathrm{kpc}$
  diffusion off magnetic inhomogeneities, reacceleration.
- **Gaseous disc** ($h \sim 0.1\mathrm{kpc}$) : spallation + convection upside down.
- **free parameters**: $K(E), L, R, V_C, V_A$

...... (Figure by D. Maurin)





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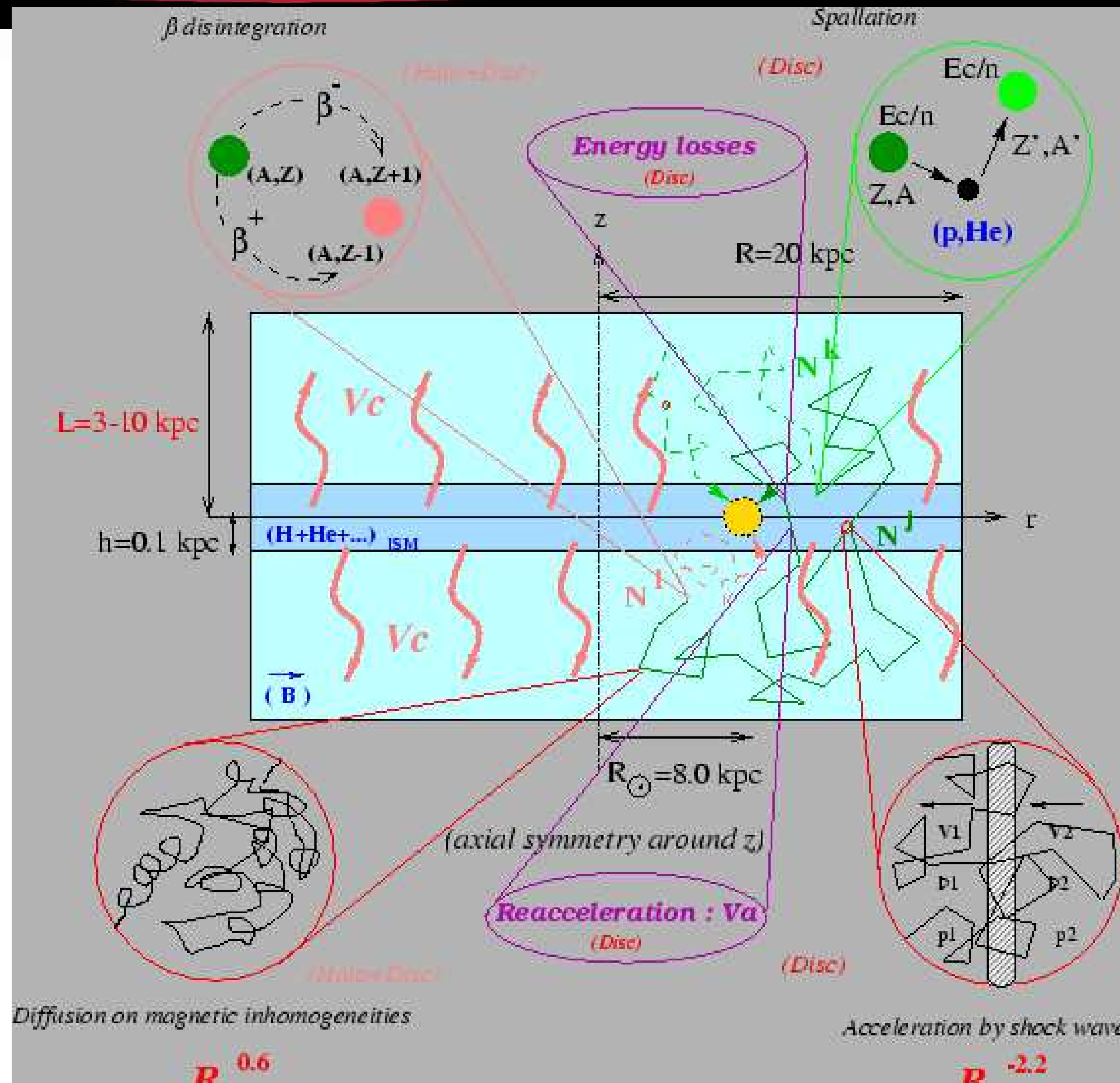

Diffusion equation for $e^{+/-}$ ***or*** $p\bar{p}$

$e^{+/-}$, *cf.* Bulanov & Dogel 73, Baltz & Edsjö 98, Lavalle et al 07, Delahaye et al 08
Nuclei, *cf.* Strong et al (98-08), Maurin et al (01-08)

$$
\begin{aligned}
\partial_t \frac{dn}{dE} &= Q(E,\vec{x},t) \\
&+ \left\{\vec{\nabla}(K(E,\vec{x})\vec{\nabla} - \vec{V}_{\rm c})\right\}\frac{dn}{dE} \\
&- \left\{\partial_E(\frac{dE}{dt} - \partial_E E^2 K_{\rm pp}\partial_p E^{-2})\right\}\frac{dn}{dE} \\
&- \left\{\Gamma_{\rm spal}\right\}\frac{dn}{dE}
\end{aligned}
$$

source: injected spectrum

spatial current: diffusion and convection

$K(E) = K_0 \left(\frac{E}{E_0}\right)^\alpha$

$\vec{V}_{\rm c}(z) = sign(z) \times V_{\rm c}$

Energy losses and reacceleration

spallation (nuclei)

Uncertainties and degeneracies in parameters (Maurin et al 01)

(Complementary & full numerical: **Galprop**, Strong et al)

Many-object method:

Define the phase space of substructures

The phase space distribution depends on two main quantities:

- the **spatial distribution** of objects
- the **luminosity function** of objects

$$\frac{dn_{\rm cl}}{d\mathcal{L}}(\mathcal{L},\vec{x}) = \frac{dN_{\rm cl}}{dV\, d\mathcal{L}}(\mathcal{L},\vec{x}) = N_0 \times \frac{d\mathcal{P}}{dV}(\vec{x}) \times \frac{d\mathcal{P}}{d\mathcal{L}}(\mathcal{L},\vec{x})$$

PDFs allow to compute mean values and associated statistical variances for some physical quantities

Computing the odds of the Galactic Lottery: Identical clumps tracking the smooth halo

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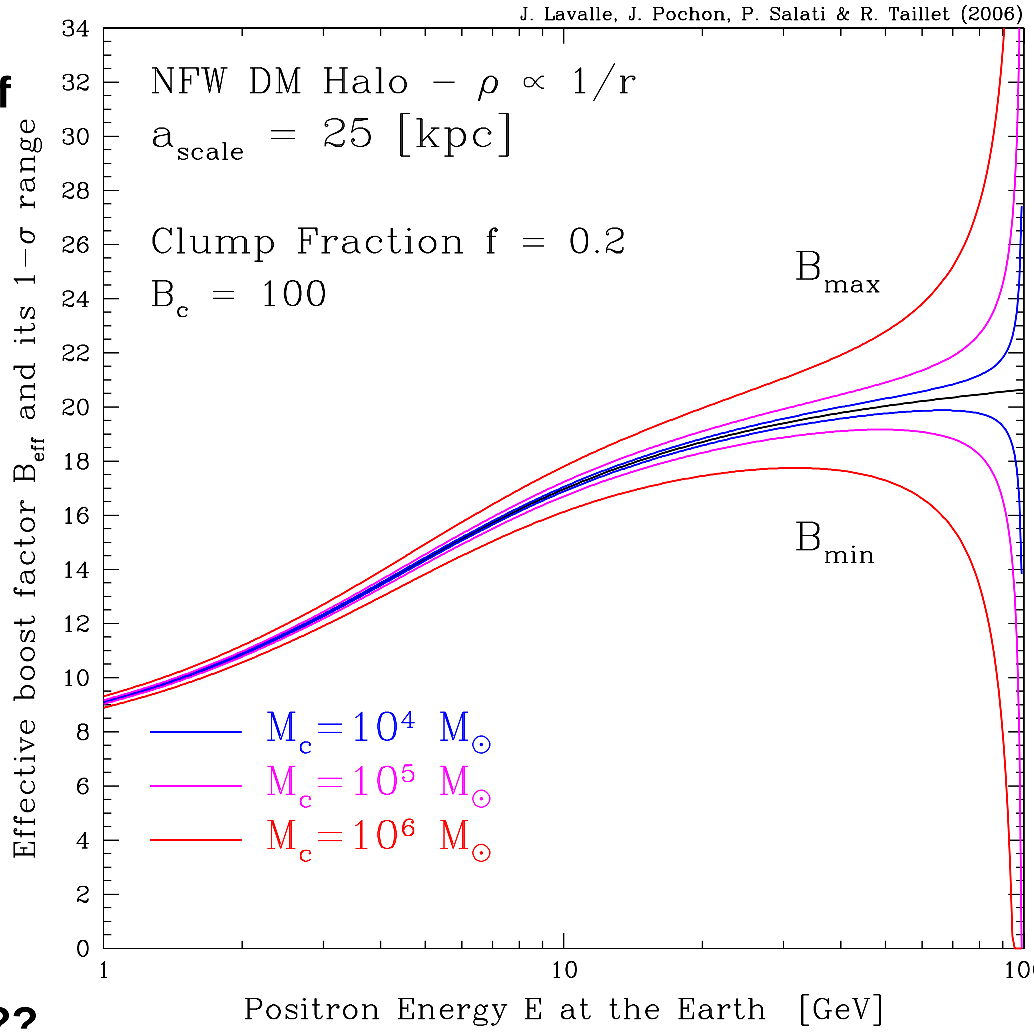
Boost for antimatter CRs:

- Long believed to be **simple rescaling of fluxes** ...
- **This picture is wrong**. Due to propagation effects, ***boost* is a non-trivial function of energy** (J.L, Pochon, Salati & Taillet, 2006).
- Variance depends on the number of clumps within the volume bounded by diffusion length λ_D: increases when the population when λ_D decreases ($\sim 1/\sqrt{N_{\rm eff}}$).
- **The recipe applies to any kind of sources**
- **Predictions for N-body-like models ???**



Lavalle et al, A&A 462 (2007)

Cosmological sub-halos:
Results of the state-of-the-art N-body experiments

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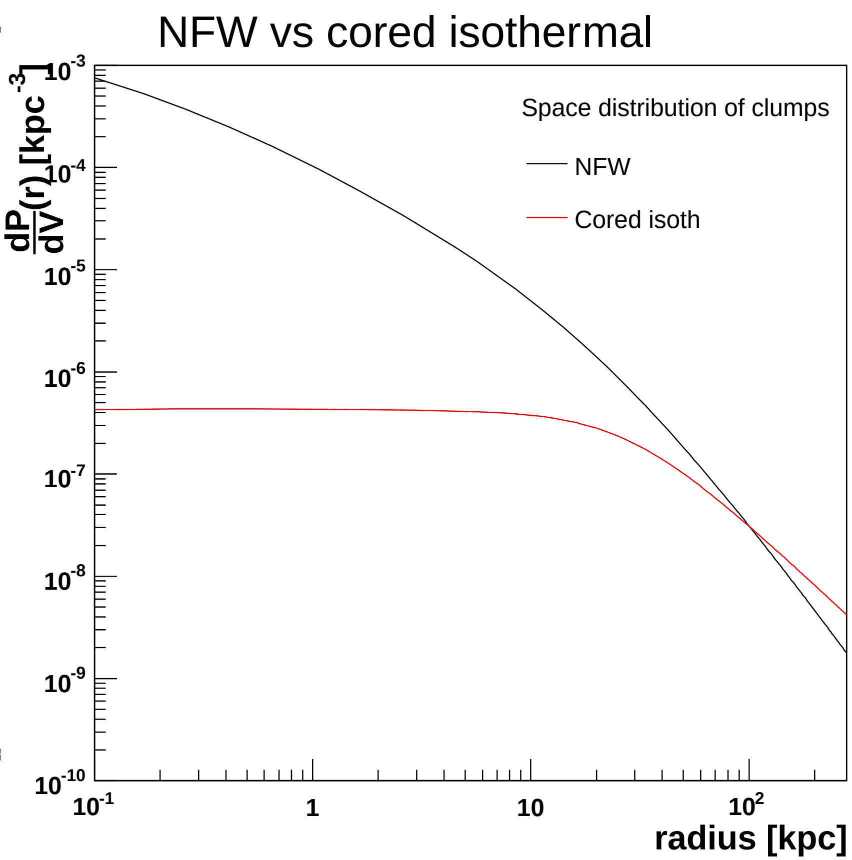
N-body results as input ingredients, and allowed [ranges]:

- **Mass distribution**:
  minimal clump mass $M_{\rm min}$
  $[10^6 - 10^{-6} M_\odot]$,
  logarithmic slope $\alpha_{\rm m}$ [1.8-2.0]
- **Spatial distribution**:
  . [cored isothermal – smooth-like]
- **Spherical inner profile(s)** for clumps
  $\propto r^{-\gamma}$, with $\gamma \in$[NFW-Moore]=[1,1.5]
  and **concentration** [Eke et al 01 – Bullock et al 01]

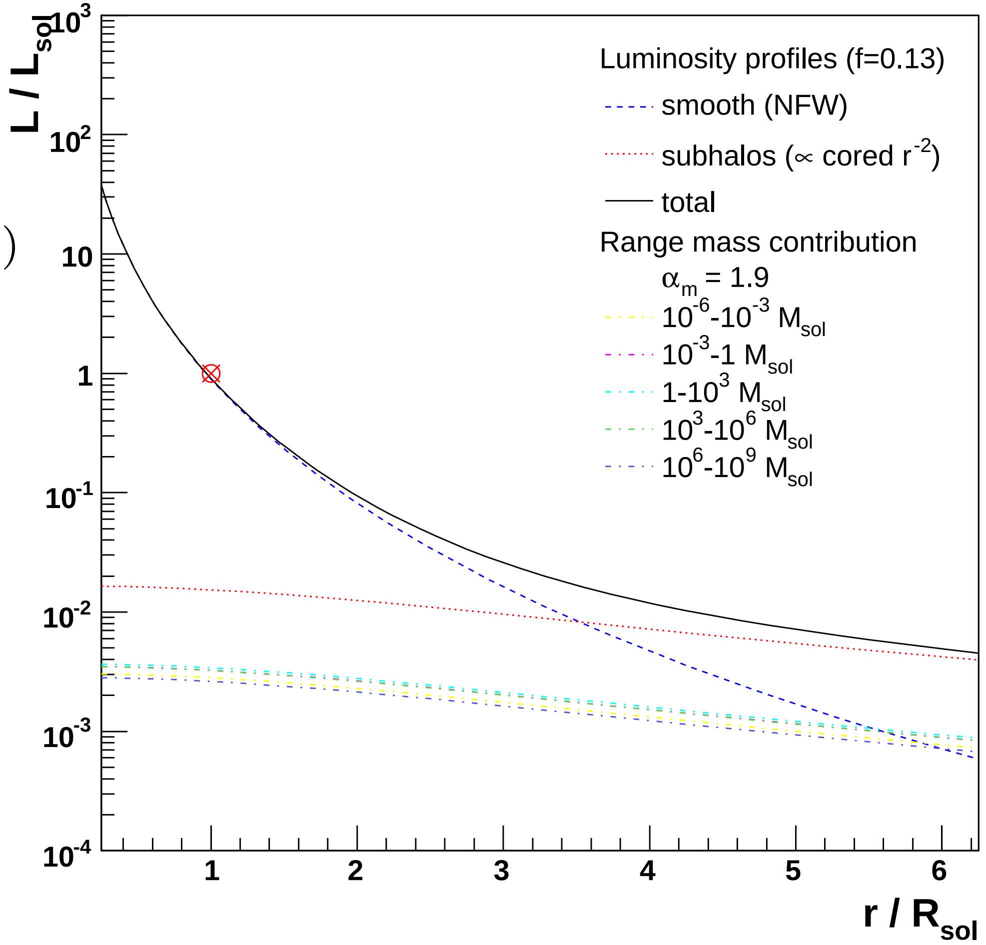


Luminosity profiles: effects of α_m

Luminosity profiles for different mass ranges

$$\mathcal{L}_i = N_0 \times \frac{dP_V(r)}{dV} \int_{\Delta_i=3} d\log(m) \frac{dP_m}{d\log(m)} \xi(m)$$

- luminosity $\propto$ local number of annihilations
- $N(> M_{\rm ref}) \propto M^{1-\alpha_{\rm m}}$: if $\xi \propto M^{\beta}$ and each decade of mass contributes the same to the annihilation rate when $\alpha_{\rm m} - \beta = 1$ (for B01, $\beta \sim 0.9$)



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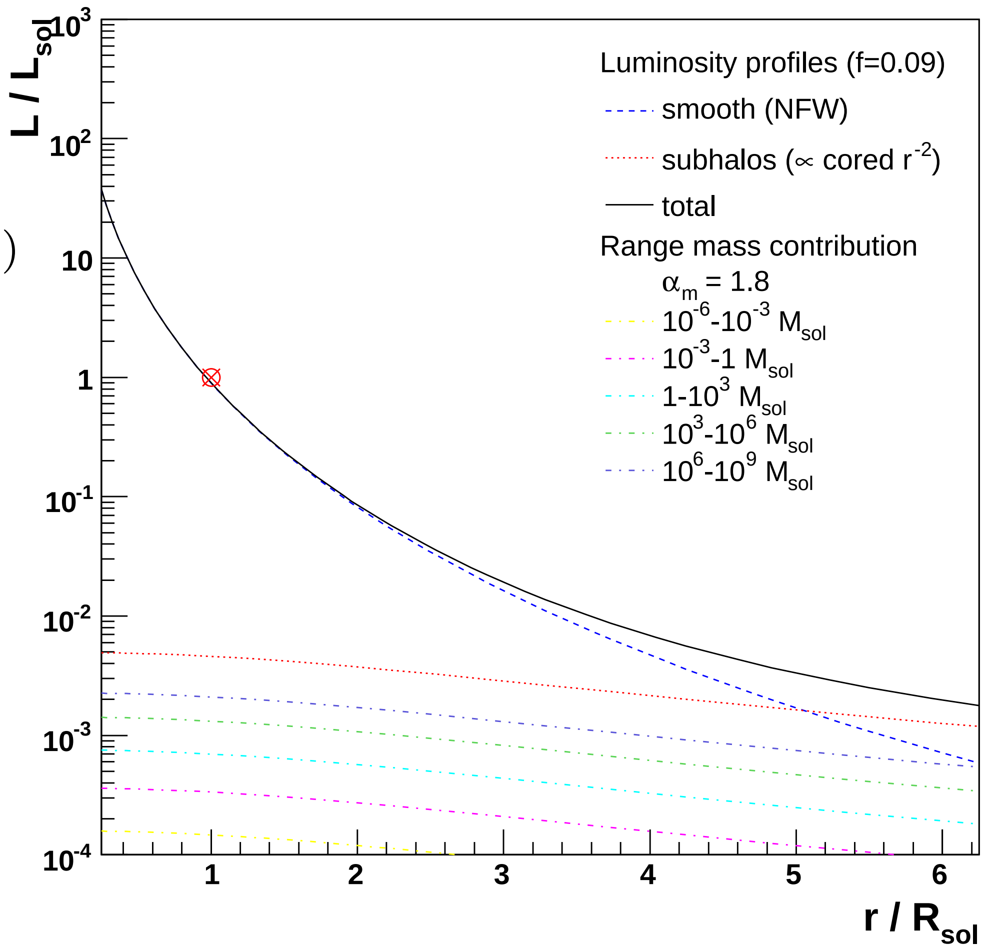

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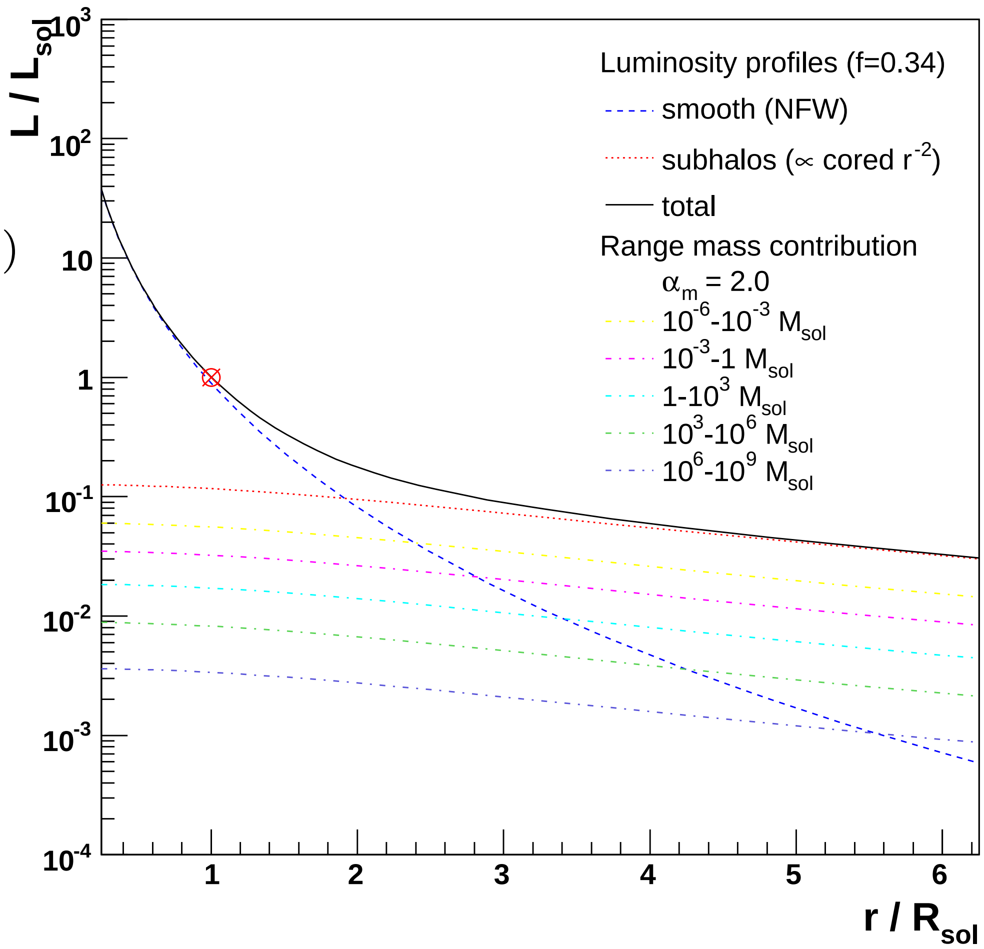

Luminosity profiles: effects of dP/dV