Antimatter fluxes from DM annihilation in Galactic sub-halos, in the lights of Λ-CDM N-body simulations

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(J. Lavalle, Y. Qiang, D. Maurin & X.-J. Bi)

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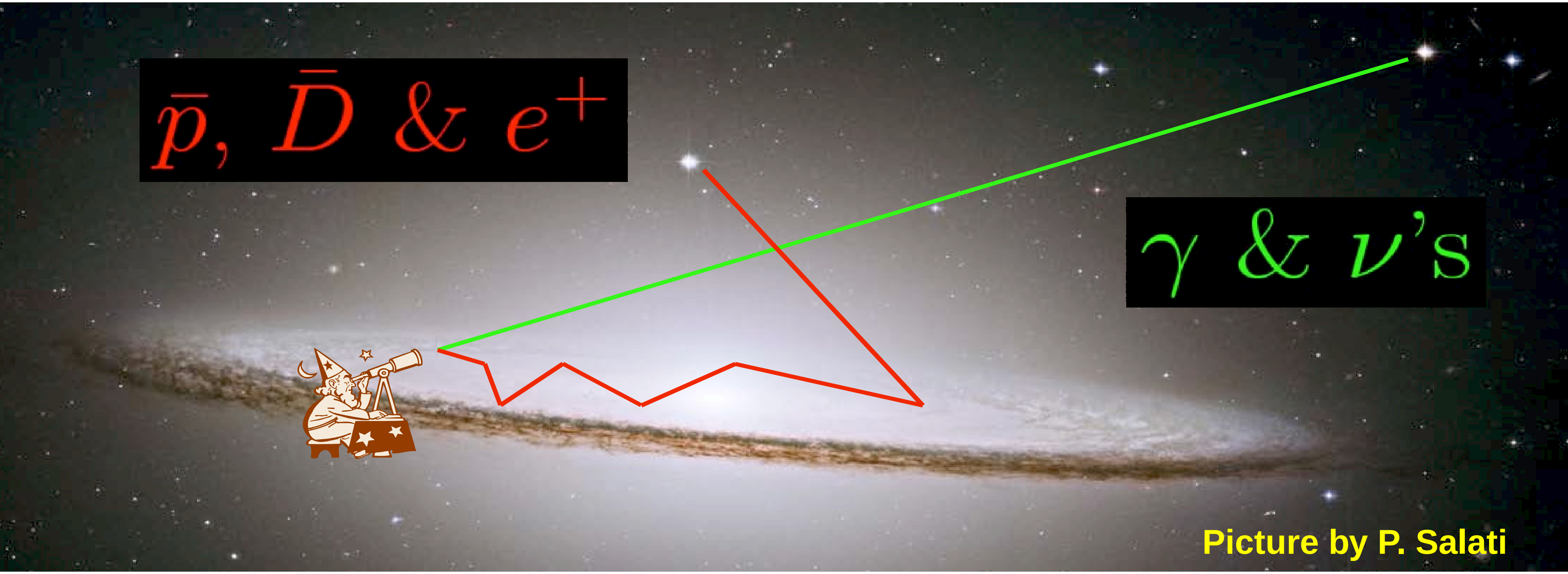
Indirect detection of Dark Matter

Non-baryonic DM may carry a **large fraction of the masses of galaxies and clusters**: If made of **exotic annihilating particles**, we might detect indirect signatures by means of astronomical device



- **γ and ν: travel directly from the source to the observer**
- **Antimatter cosmic rays: diffuse on the magnetic turbulences**

$\Longrightarrow$ **Needs of large DM density regions (Centres of galaxies)**

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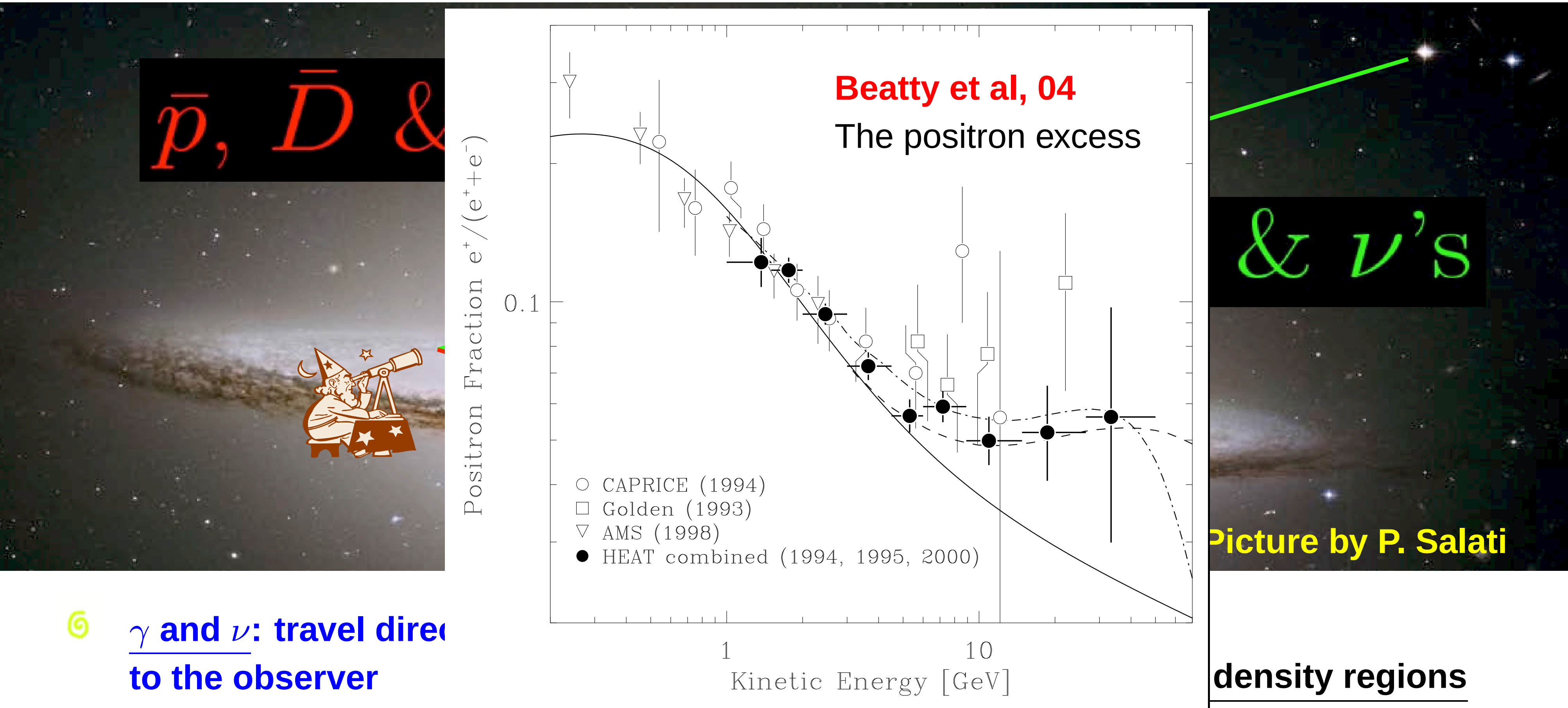

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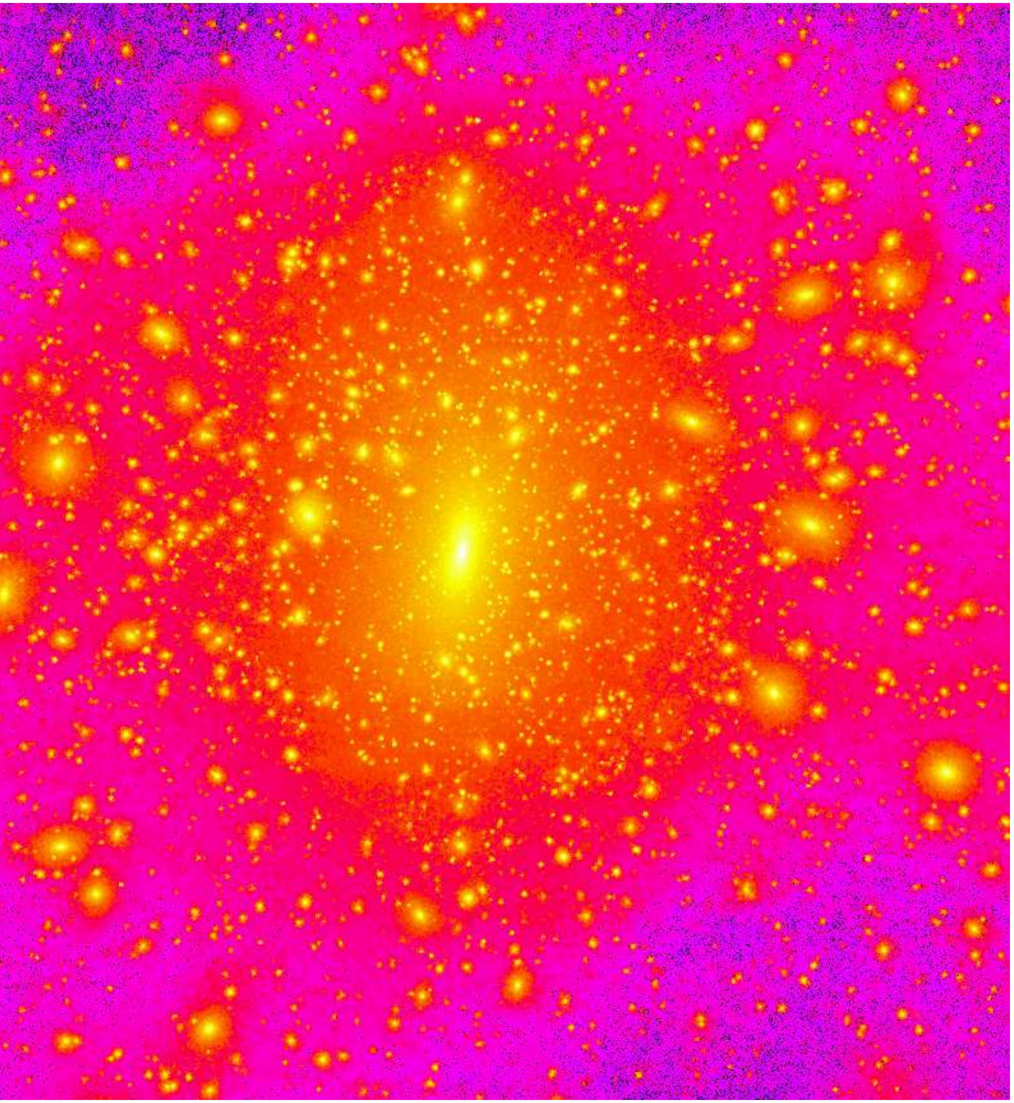
  to the observer

density regions
(Centres of galaxies)

- **Antimatter cosmic rays: diffuse on the magnetic turbulences**

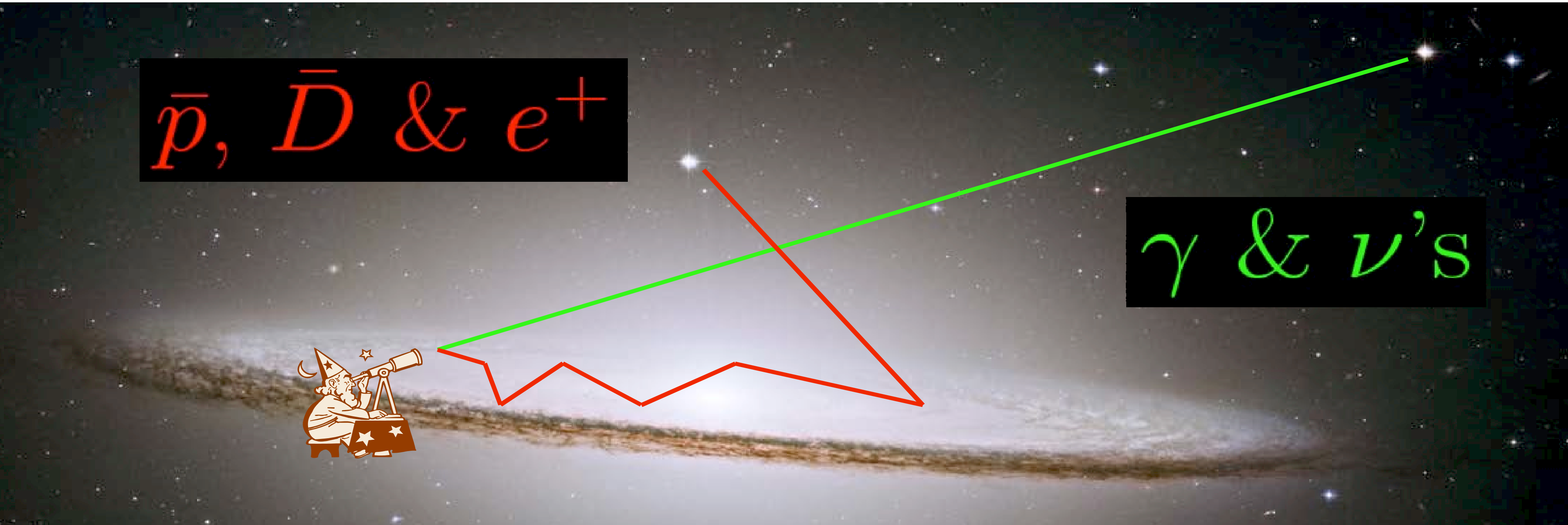
Inhomogeneous halo and boosted annihilation rate



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

- Though the topic is 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 ?**

Gamma-rays versus antimatter cosmic rays



The annihilation signal is integrated:

- **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**

$\Longrightarrow$ **Boost factors are not the same !**

Gamma-rays versus antimatter cosmic rays

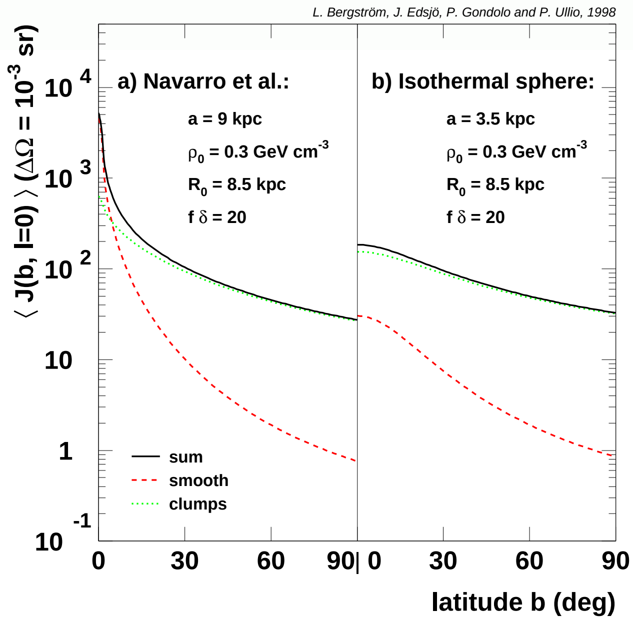
Boost for γ-rays (studied for many years):
– **See Fu-Sin Ling's talk** –

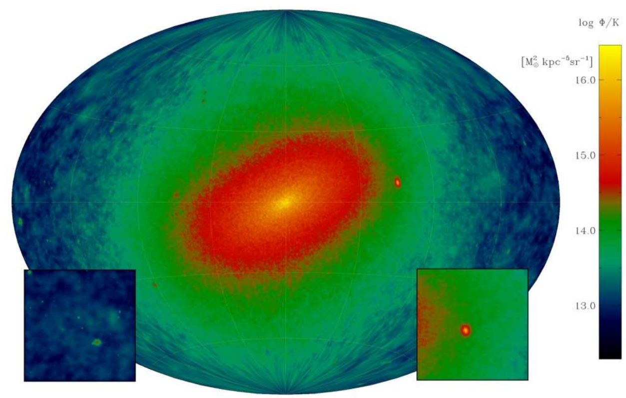
- **Factor to the smooth flux** which depends on the angle between GC direction and line of sight (*cf.* Bergström et al, 1998) ; main effects at high latitude regions (see figure)

- Very small additional contribution to the smooth flux in the GC direction (*cf.* Stoerh et al (2004), Berezinsky et al (2003-2007))

- Statistical M-C analysis by Bi (2006), Pieri et al (2007)

- **A very few objects** could perhaps be resolved **with GLAST** towards the anti-centre (Diemand et al, 2006 | see figure)





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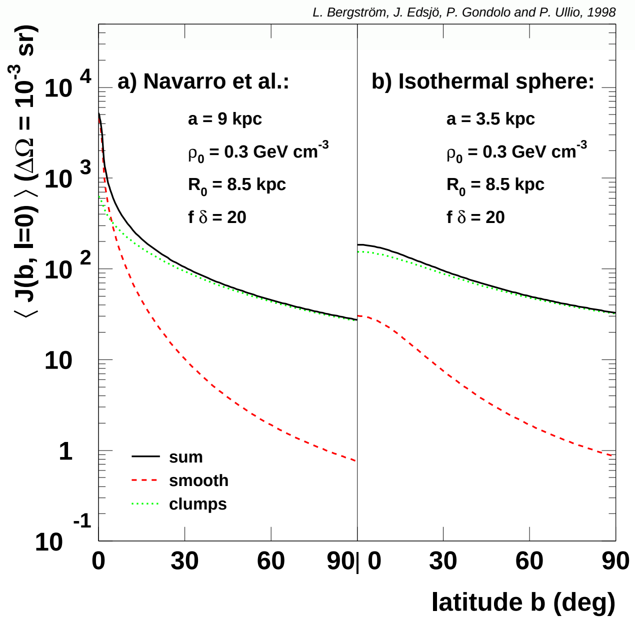
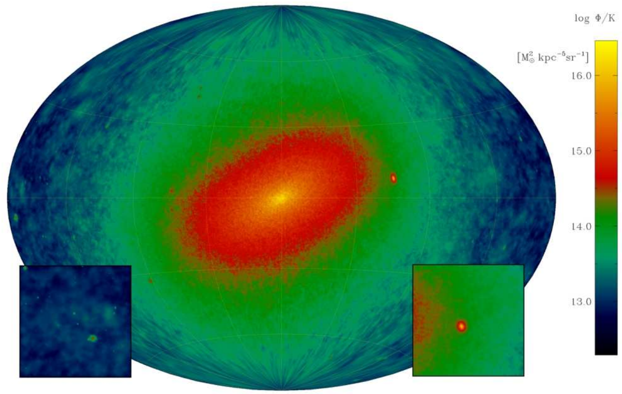


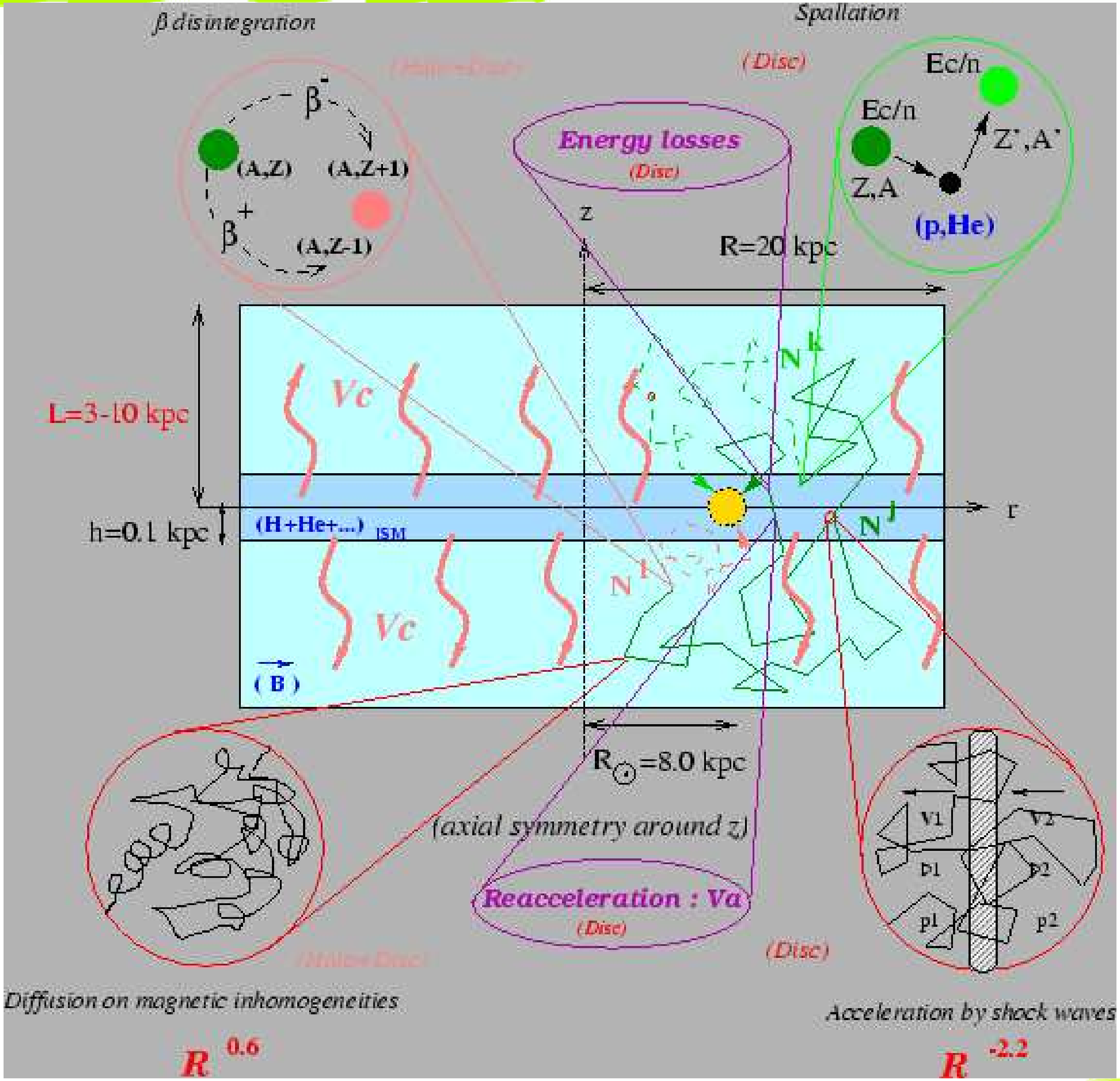


Charged cosmic rays: **Propagation !!!**

Cosmic ray propagation modelling

- Diffusive cylindrical halo : $R \sim 20\mathrm{kpc}, \mathrm{L} \sim 3\mathrm{kpc}$ spallation on ISM and diffusion on magnetic inhomogeneities
- Disc ($h \sim 0.1\mathrm{kpc}$) : convection and reacceleration in addition
- Propagation model free parameters: $K(E), L, R, V_C, V_A$

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



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

The diffusion equation for a positron density dn/dE:

$$\boxed{\partial_t \frac{dn}{dE} = \vec{\nabla}(K(E,\vec{x})\vec{\nabla}\frac{dn}{dE}) + \partial_E(b(E)\frac{dn}{dE}) + Q(E,\vec{x},t) = 0}$$

Green equation for antiprotons:

$$\boxed{\left\{-K\triangle + V_c\frac{\partial}{\partial z} + 2h\Gamma_{\rm tot}\delta(z)\right\}\mathcal{G}^{\,\bar{p}} = \delta(\vec{r} - \vec{r'})}$$

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

spallation

Energy losses :
IC on star light and CMB
+ synchrotron
$b(E) = \frac{E^2}{E_0\tau_E}$
with $\tau_E \sim 10^{16}$s

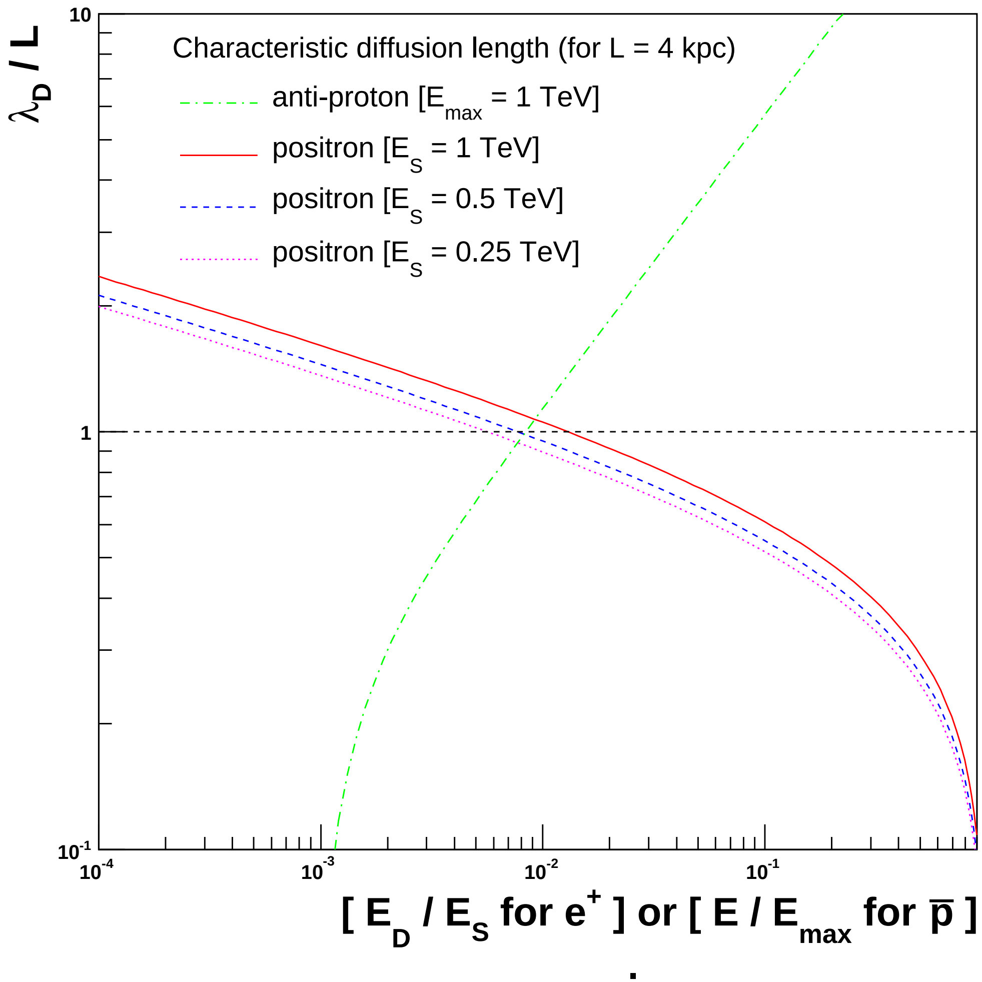
convection

source :
injected spectrum

Uncertainties and degeneracies in parameters

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

- e^+**'s loose energy**: survey larger and larger volumes when detected at lower and lower energies
- $\overline{p}$'s do not loose energy, **but convective wind and spallation processes very efficient at low energy**: survey larger volume at high energies



Effective volume picture:

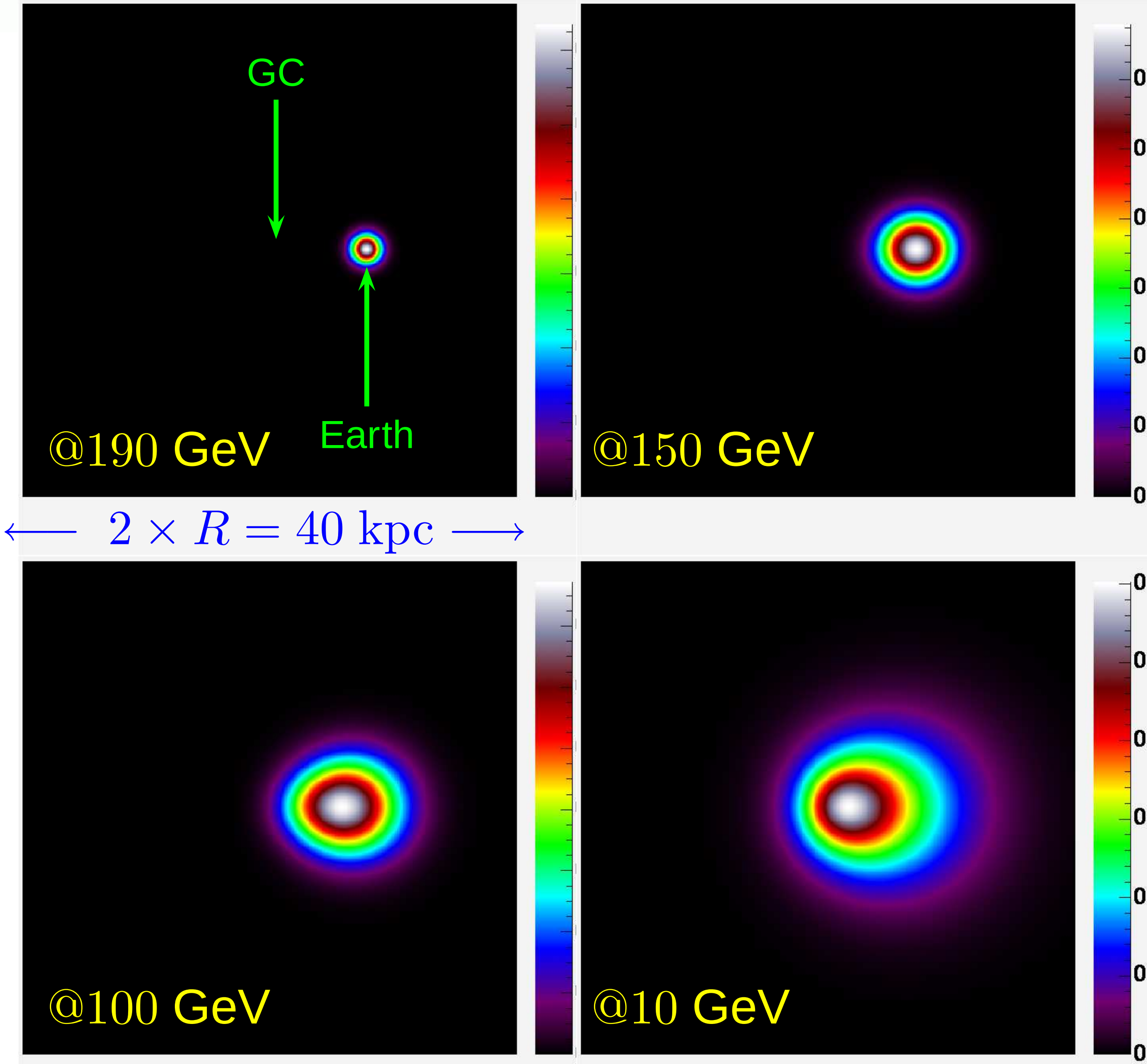
Inject a 200 GeV e^+ with $Q(r) = \rho^2(r) \propto r^{-2}$ ...

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

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

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

Many-object method:
Connecting primary fluxes to the main quantities

A general expression for the **primary flux from a single clump** reads:

$$\boxed{\phi_i(E,\vec{x}_\odot) = S \times \xi_i \times \tilde{\mathcal{G}}_i(E,\vec{x}_\odot \leftarrow \vec{x}_i, E_S)}$$

- Particle physics factor:

  $S \equiv \frac{\delta}{4\pi}\frac{<\sigma v>}{2}\left(\frac{\rho_\odot}{m}\right)^2$

- Effective annihilation volume

  (internal clump properties)

  $$\boxed{\xi_i \equiv \int_{V_i} d^3\vec{x}\left(\frac{\rho_i(\vec{x})}{\rho_\odot}\right)^2}$$

- Propagation (GCRs) or dilution (γ-rays):

$$\tilde{\mathcal{G}}_{i,\gamma}(E_\gamma,\psi) \propto \int d\Omega_{\rm res}(\psi)\,\frac{f(E_\gamma)}{|\vec{x}_i - \vec{x}_\odot|^2}$$

$$\tilde{\mathcal{G}}_{i,{\rm CR}}(E) \propto \int dE_S\; G(E,\vec{x}_\odot \leftarrow E_S,\vec{x}_i) \times f(E_S)$$

In a many clump scenario, ϕ_i **is a stochastic variable** !

PDFs of ξ and G translate to the PDF of ϕ.

$$\frac{d\mathcal{P}}{d\phi} = \frac{d^2\mathcal{P}}{dV\;d\xi}(\vec{x},\xi) \approx \frac{d\mathcal{P}_V}{dV}(\vec{x}) \times \frac{d\mathcal{P}_\xi}{d\xi}(\xi)$$

$$\boxed{\phi_{\rm cl}^{\rm tot} = \sum_i \phi_i = N_{\rm cl}\times <\phi> = N_{\rm cl}\times S <\xi \times \tilde{\mathcal{G}}> \approx N_{\rm cl}\times S <\xi> \times <\tilde{\mathcal{G}}>}$$

The Effective Boost factor

Pure smooth flux:

$$\phi_{\rm sm}(E,\vec{x}_\odot) \propto S \times \int_{\rm halo} d^3\vec{x}\,\tilde{\mathcal{G}}(\vec{x}_\odot \leftarrow \vec{x}) \times \left(\frac{\rho(\vec{x})}{\rho_\odot}\right)^2$$

$$B_{\rm eff}(E) = (1-f_\odot)^2 + \frac{\phi_{\rm cl}^{\rm tot}}{\phi_{\rm sm}} \;\approx\; 1 + N_{\rm cl} \times <\xi> \frac{d\mathcal{P}}{dV}(\vec{x}_\odot)$$

Total sub-halo flux:

$$\phi_{\rm cl}^{\rm tot}(E,\vec{x}_\odot) \propto N_{\rm cl} \times S \times <\xi> \times <\tilde{\mathcal{G}}(\vec{x}_\odot \leftarrow \vec{x})>$$

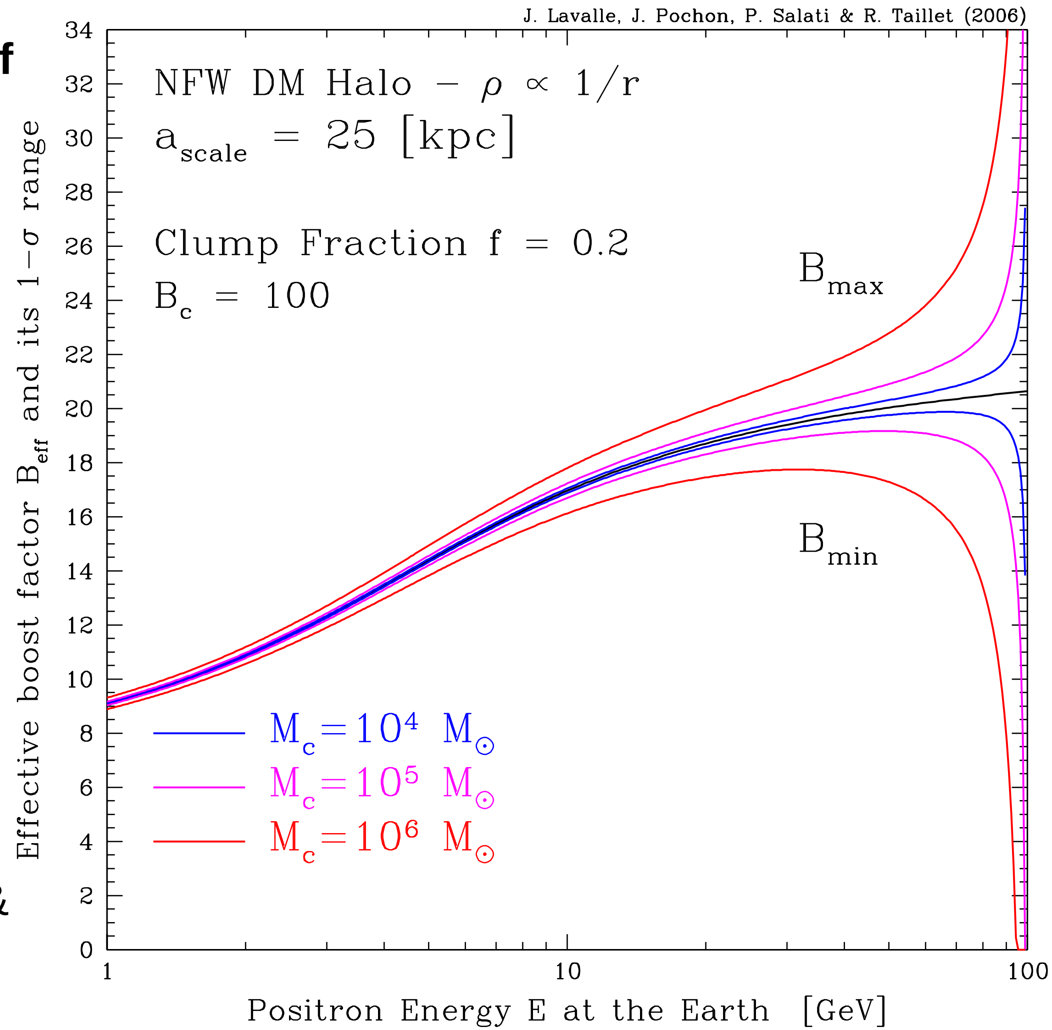
Statistical variance !:

$$\left(\frac{\sigma_{\rm cl}^{\rm tot}}{\phi_{\rm cl}^{\rm tot}(E,\vec{x}_\odot)}\right)^2 = \frac{1}{N_{\rm cl}} \times \left(\frac{\sigma_G^2}{<\tilde{\mathcal{G}}>^2} + \frac{\sigma_\xi^2}{<\xi>^2} + \frac{\sigma_G^2}{<\tilde{\mathcal{G}}>^2} \times \frac{\sigma_\xi^2}{<\xi>^2}\right)$$

Toy model:
Identical clumps tracking the smooth halo

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 ($\sim 1/\sqrt{N_{\rm eff}}$).
- Recipe applied to IMBHs (Bertone et al (2003-2007)) for $\bar{p}$ and e^+ (Bringmann & Salati (2006), Brun et al (2007))
- **Predictions for N-body-like models ???**



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

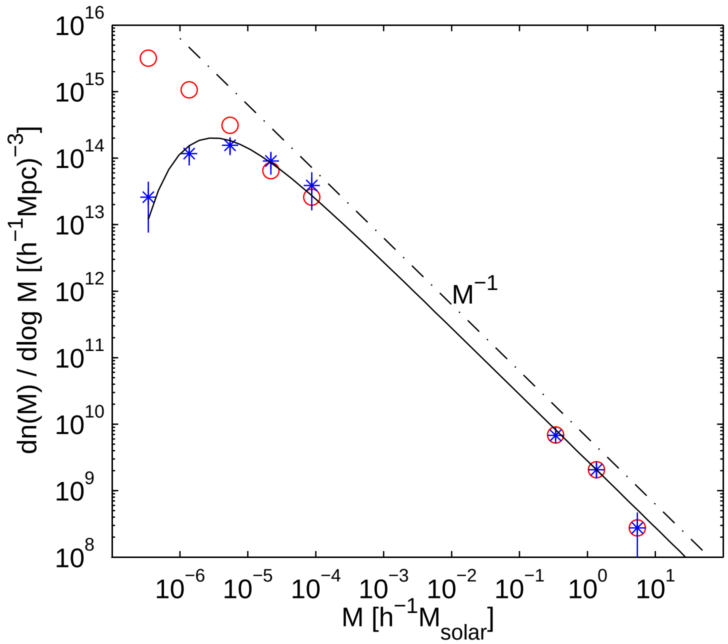
N-body results are used as input ingredients and [ranges]:

- **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
  [NFW-Moore]
  and **concentration** [Eke et al 01 – Bullock et al 01]

Diemand et al (2005)



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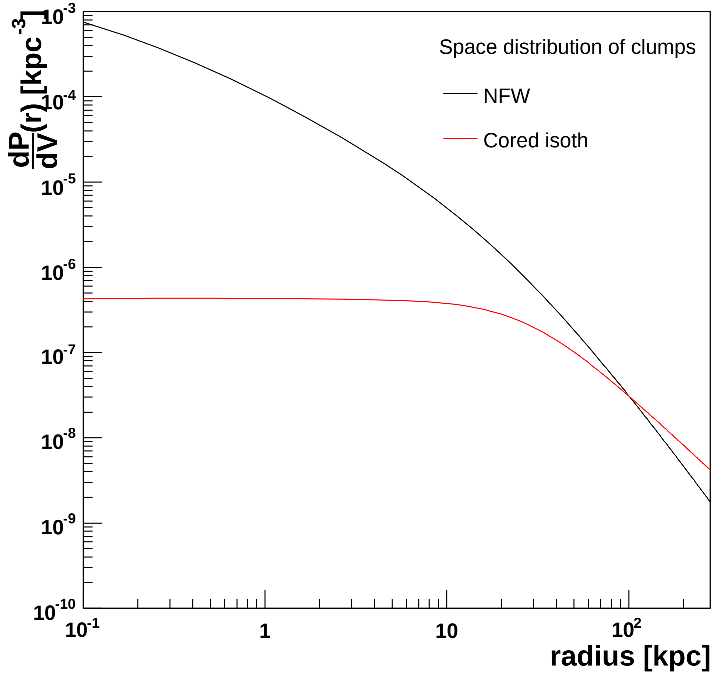
NFW vs cored isothermal



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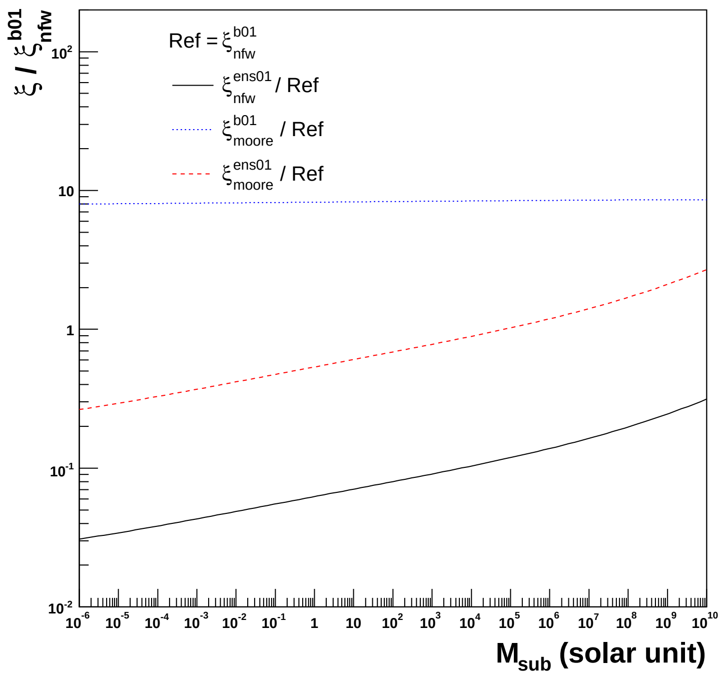
$$\xi^{\rm B01}_{\rm NFW} \simeq 0.1 \times \xi^{\rm B01}_{\rm Moore} \simeq 10 \times \xi^{\rm ENS01}_{\rm NFW}$$

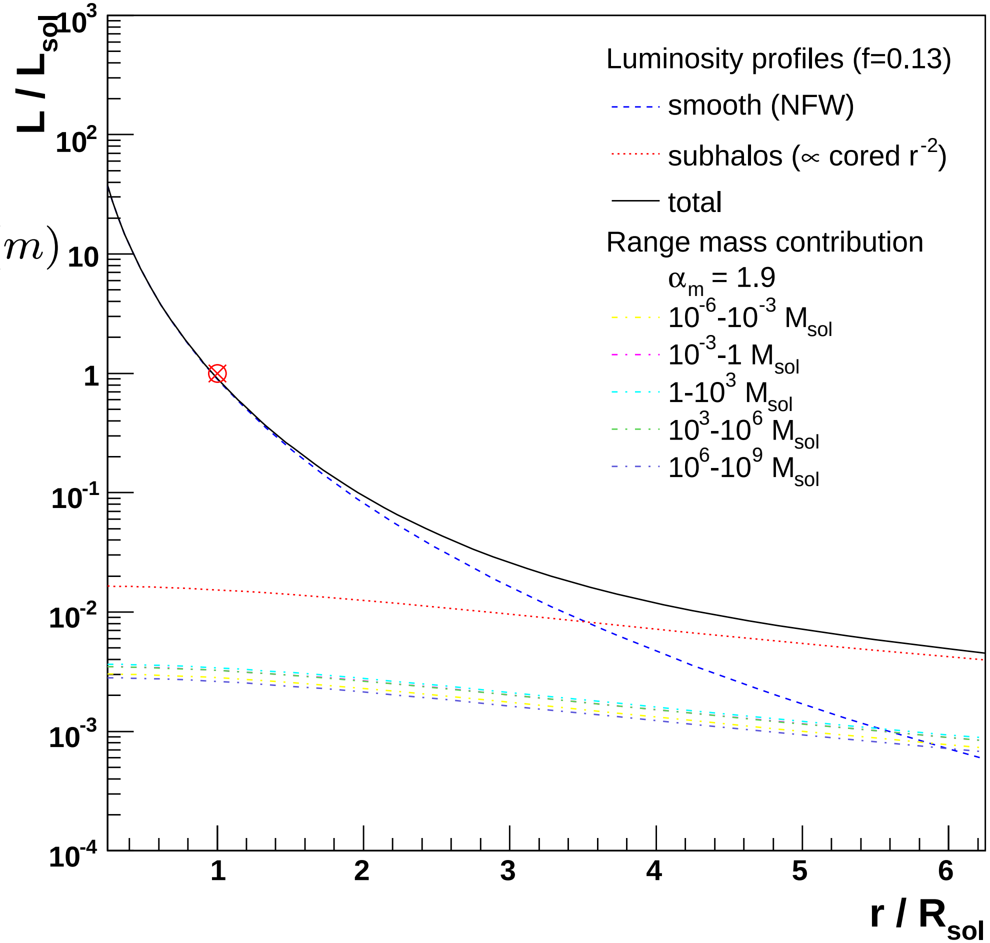


Luminosity profiles: effects of α_m

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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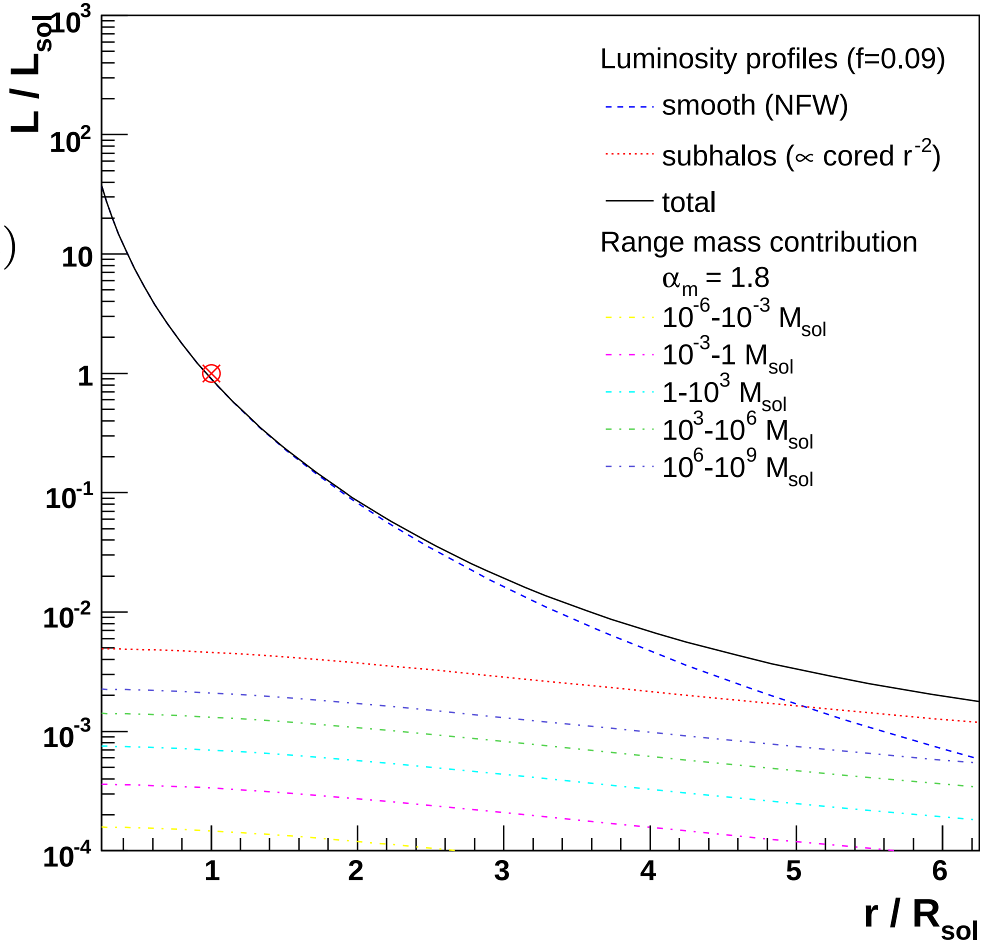

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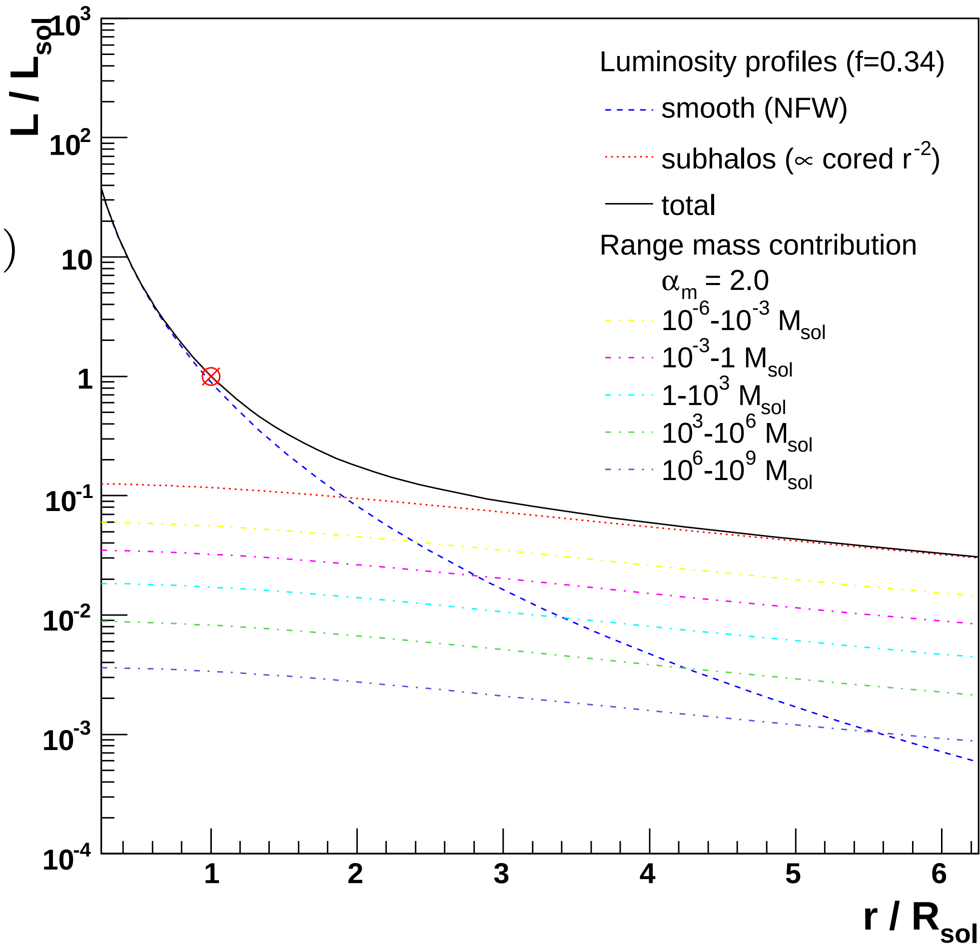
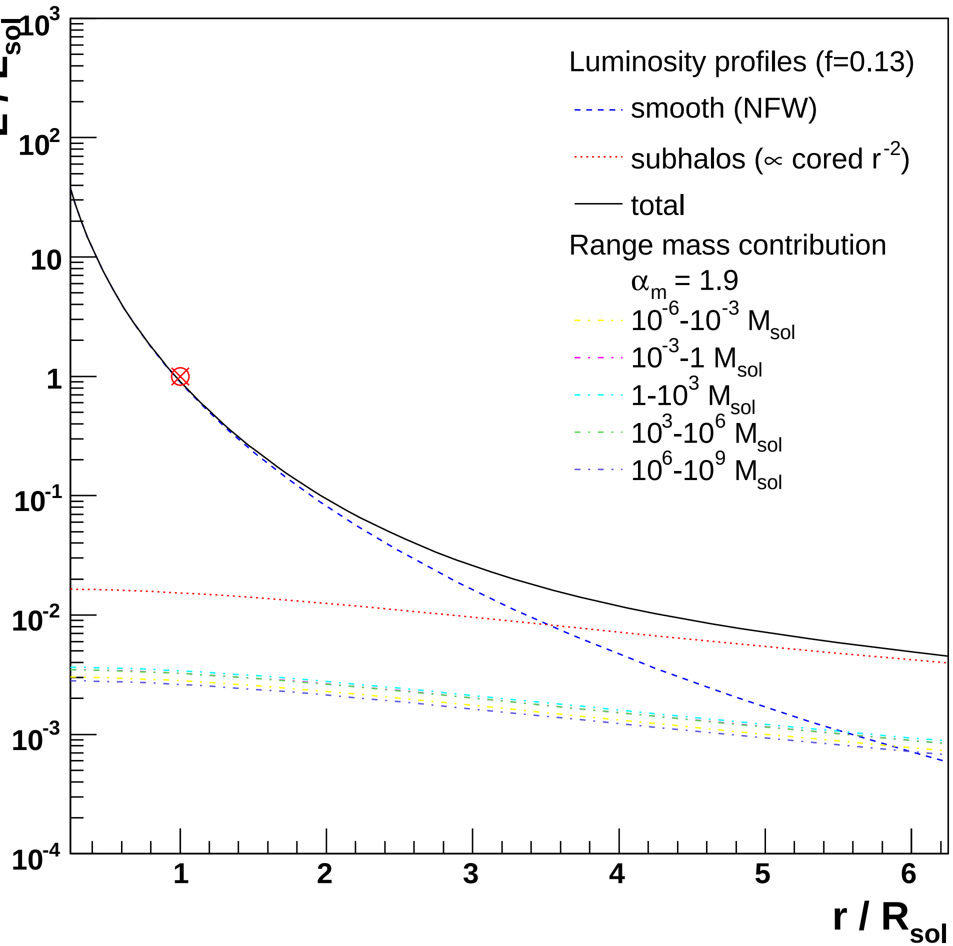
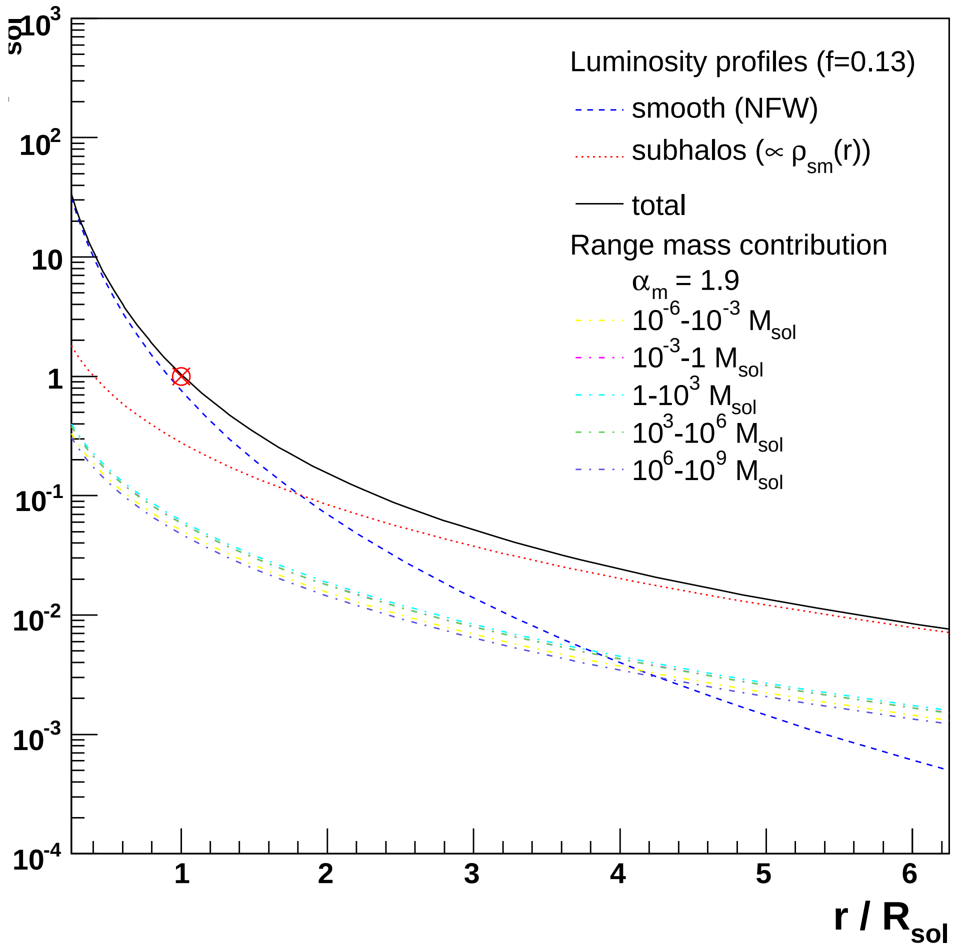


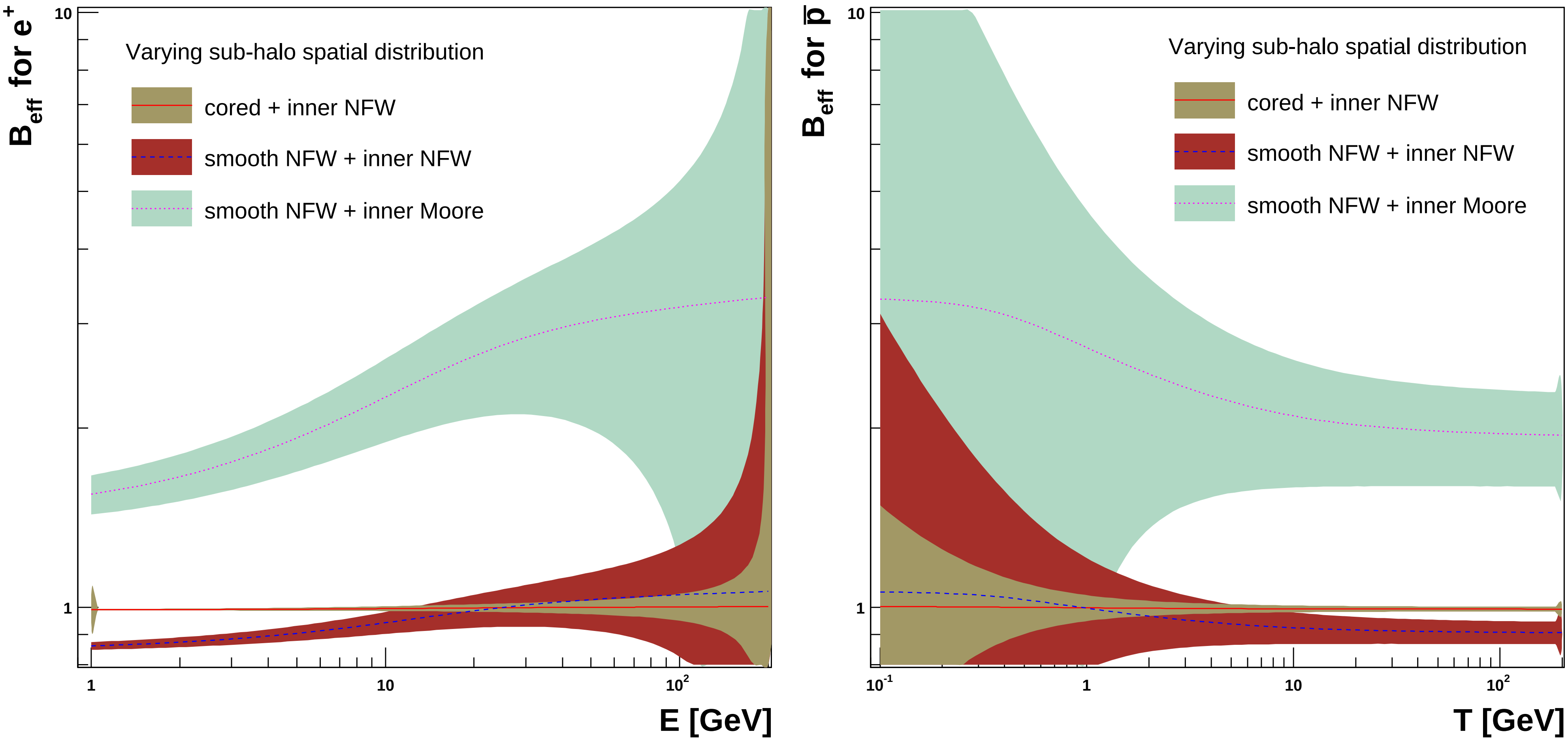
Luminosity profiles: effects of dP/dV





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)



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

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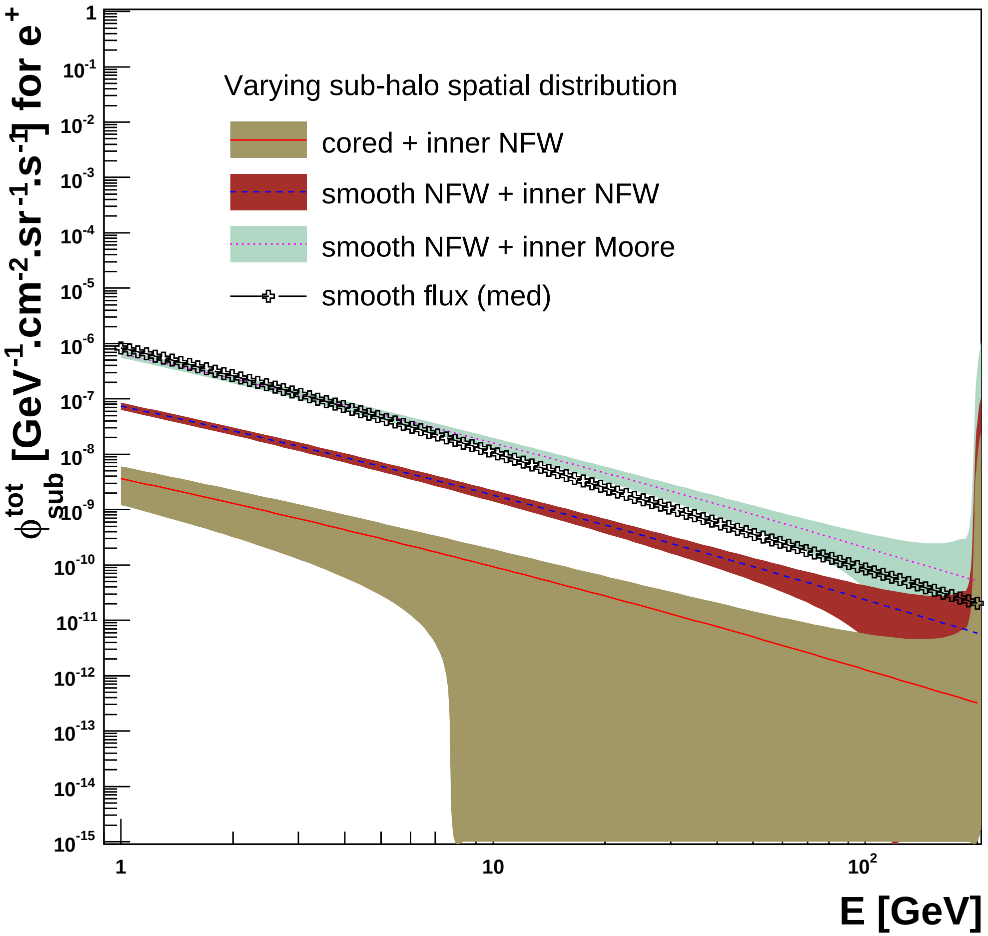
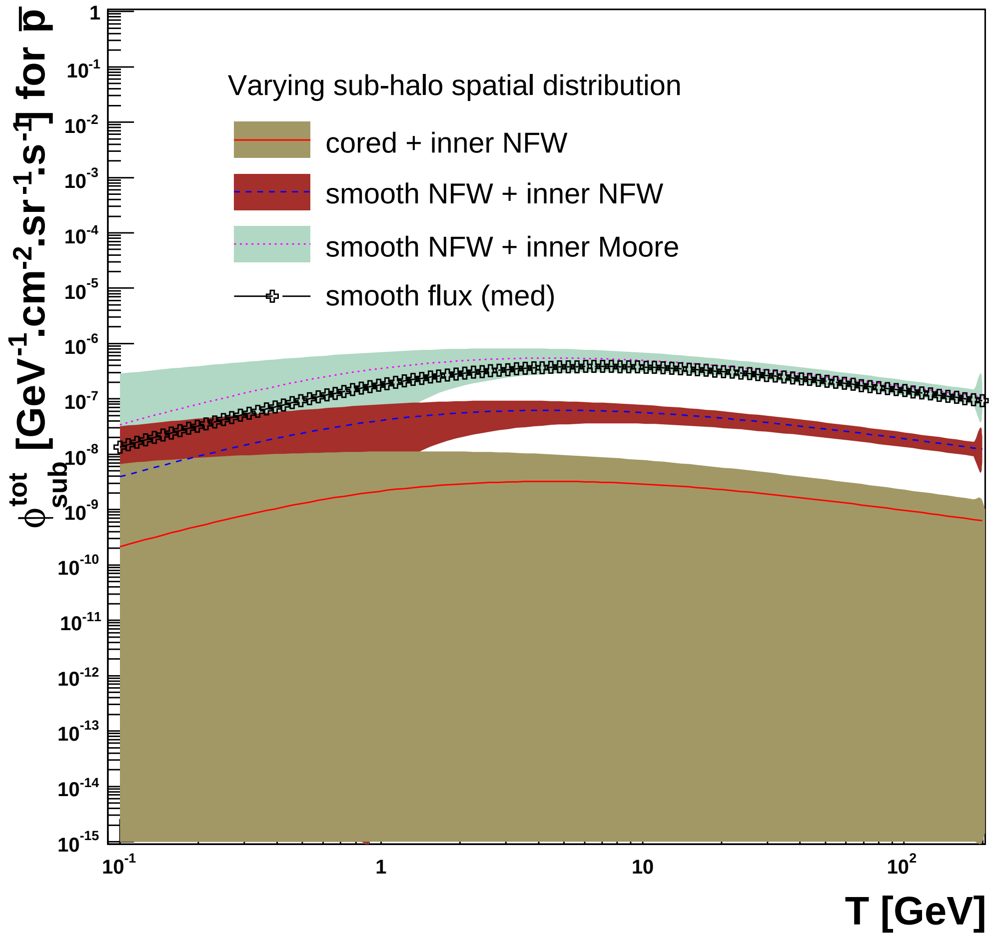
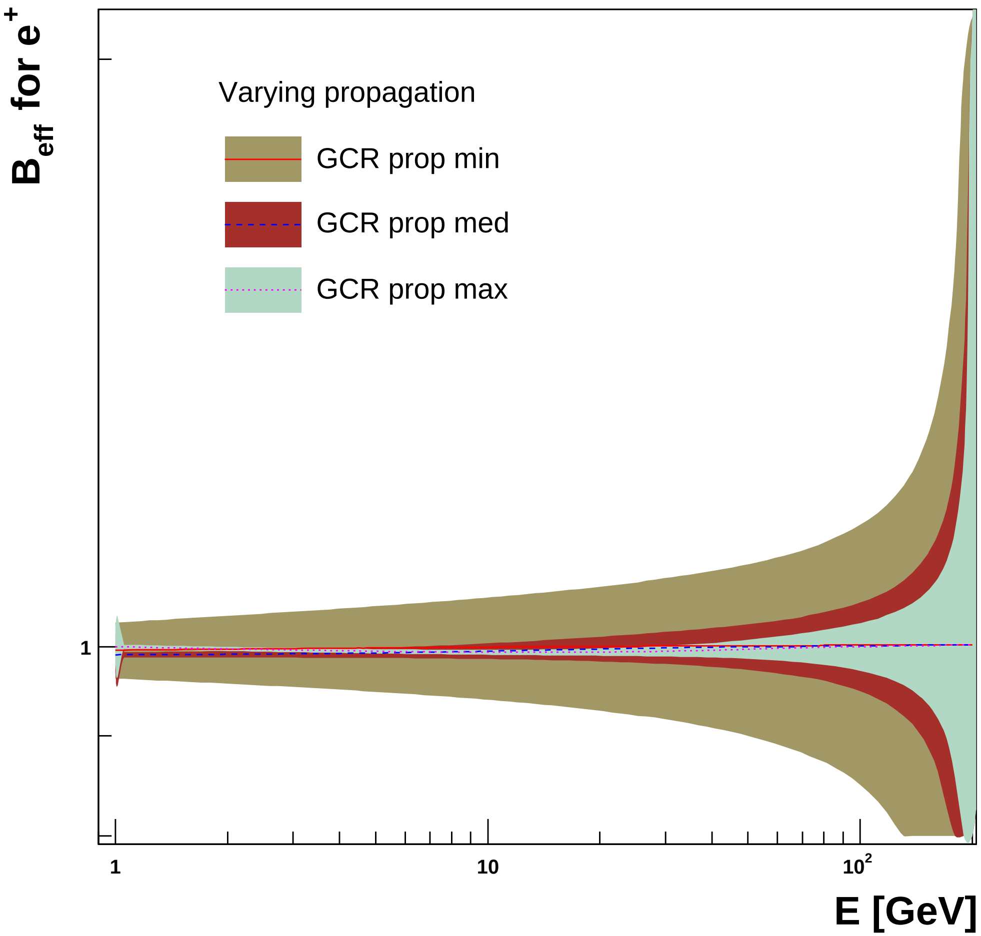
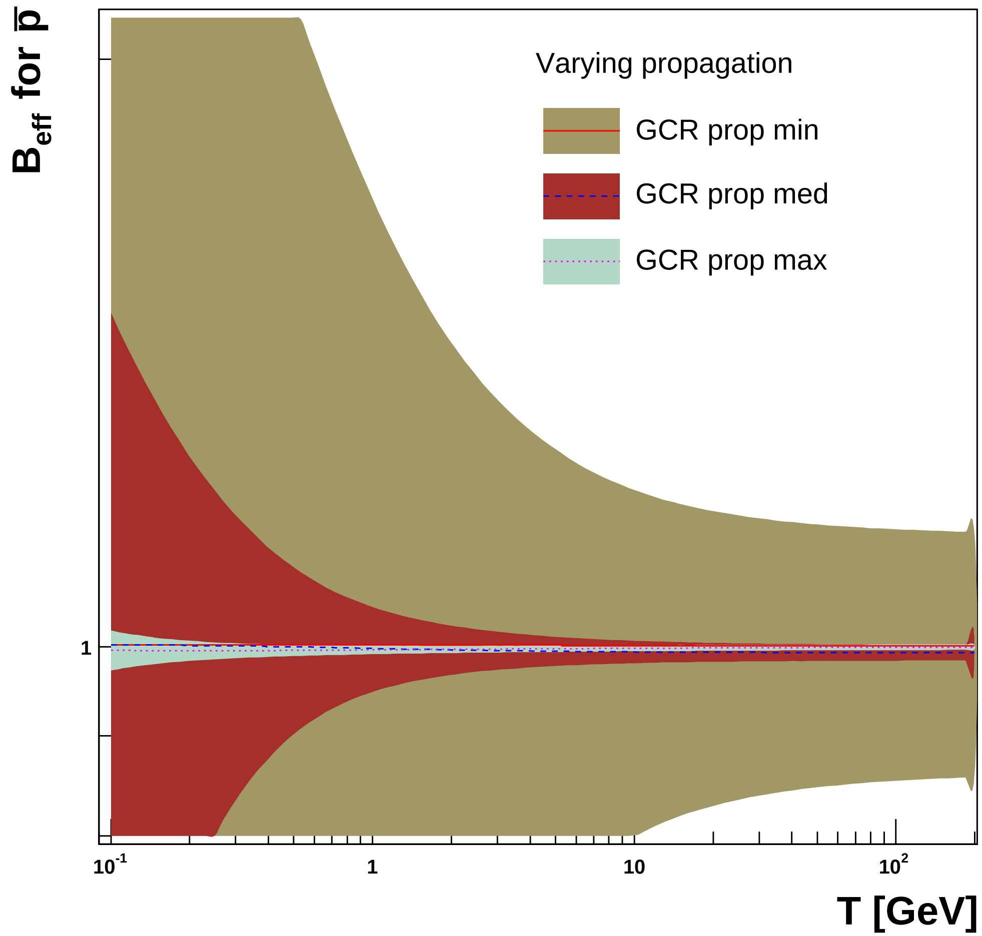




Propagation effects on boost factors

$M_{\rm min} = 10^{-6} M_{\odot}$, $\alpha_{\rm m} = 1.9$, inner-NFW, B01, cored space distribution, *min*, *med* and *max* propagation sets of Maurin et al 01





Propagation effects on primary fluxes

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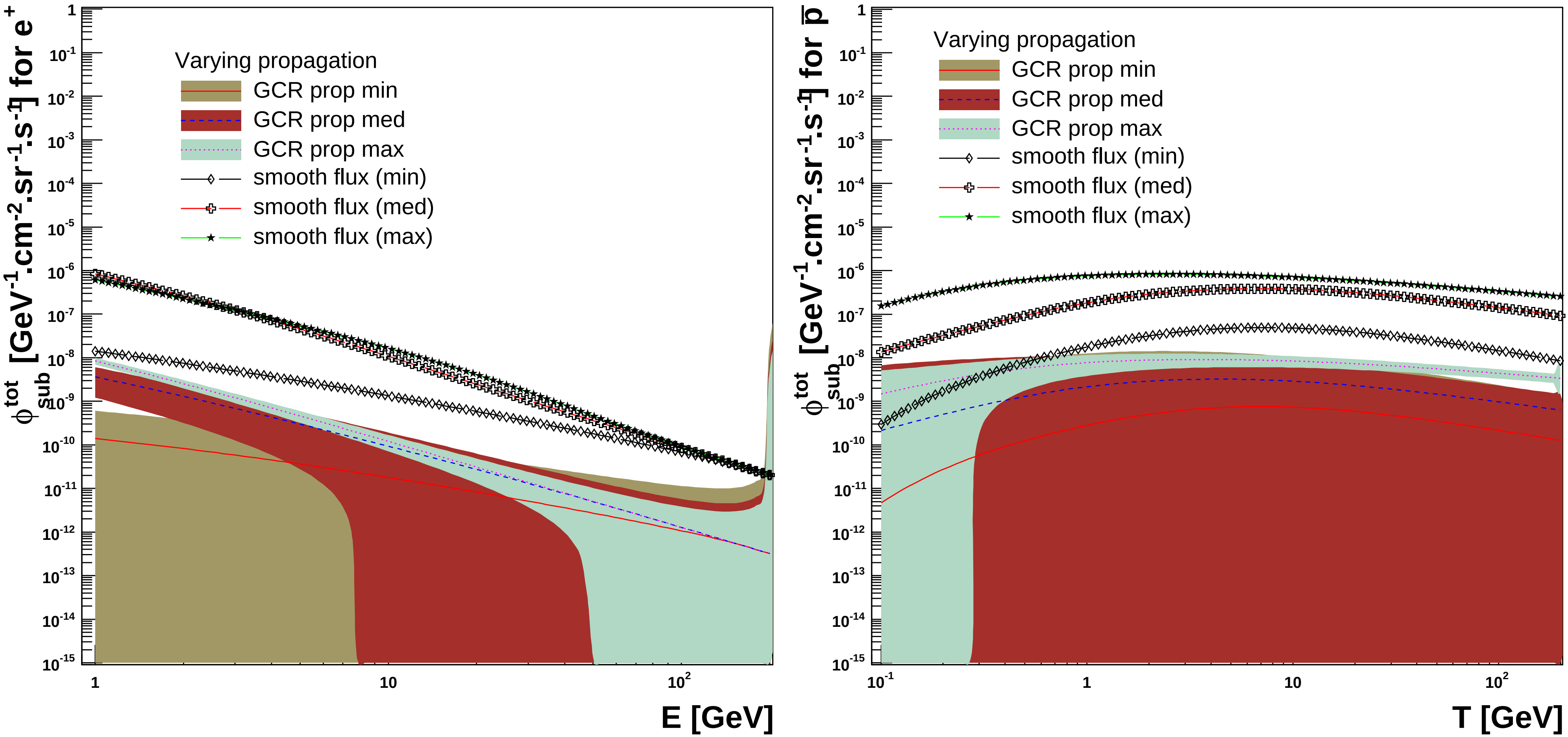
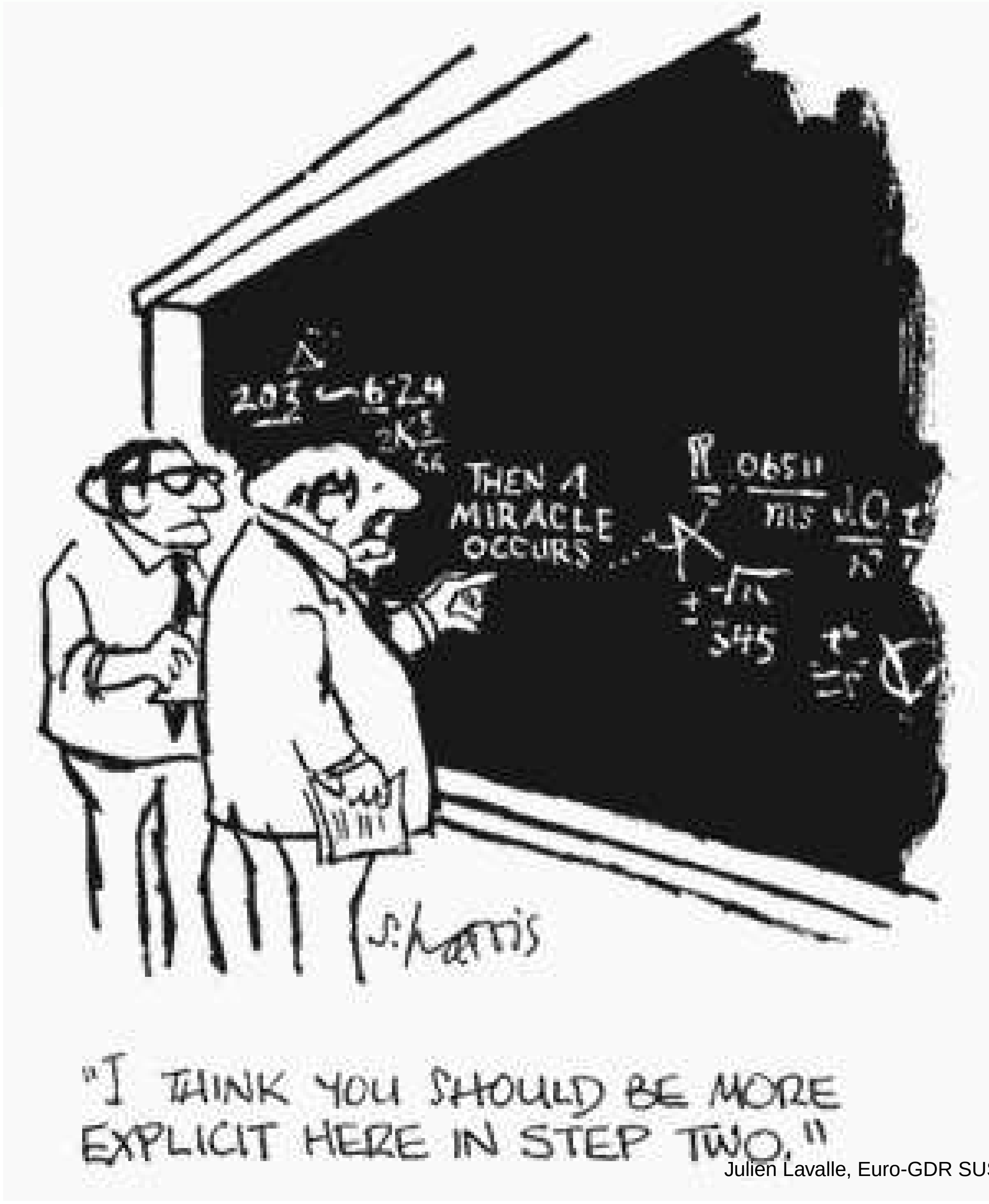


Summary

We explicitly determined how to correctly semi-analytically predict cosmic ray fluxes and errors given inhomogeneity properties:

- **Clump properties are still under debate, though their presence is now well accepted**
- **Within the standard view of clumpiness, and constraints coming from N-body simulations, boost factors are too low to significantly enhance the primary flux**
- **This study somewhat demystifies the substructure effect for antimatter signatures**
- **Need for a renewed estimate of the positron background: LAPTH-Annecy and Univ. of Torino on the road !**
- **Need for better constraints on propagation parameters (PAMELA, AMS-02)**
- **New data is coming: PAMELA**
- **Complementarity with other messengers (γ, ν) and detection methods!**

Backup


THEN A MIRACLE OCCURS
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Two main approaches for clumpiness

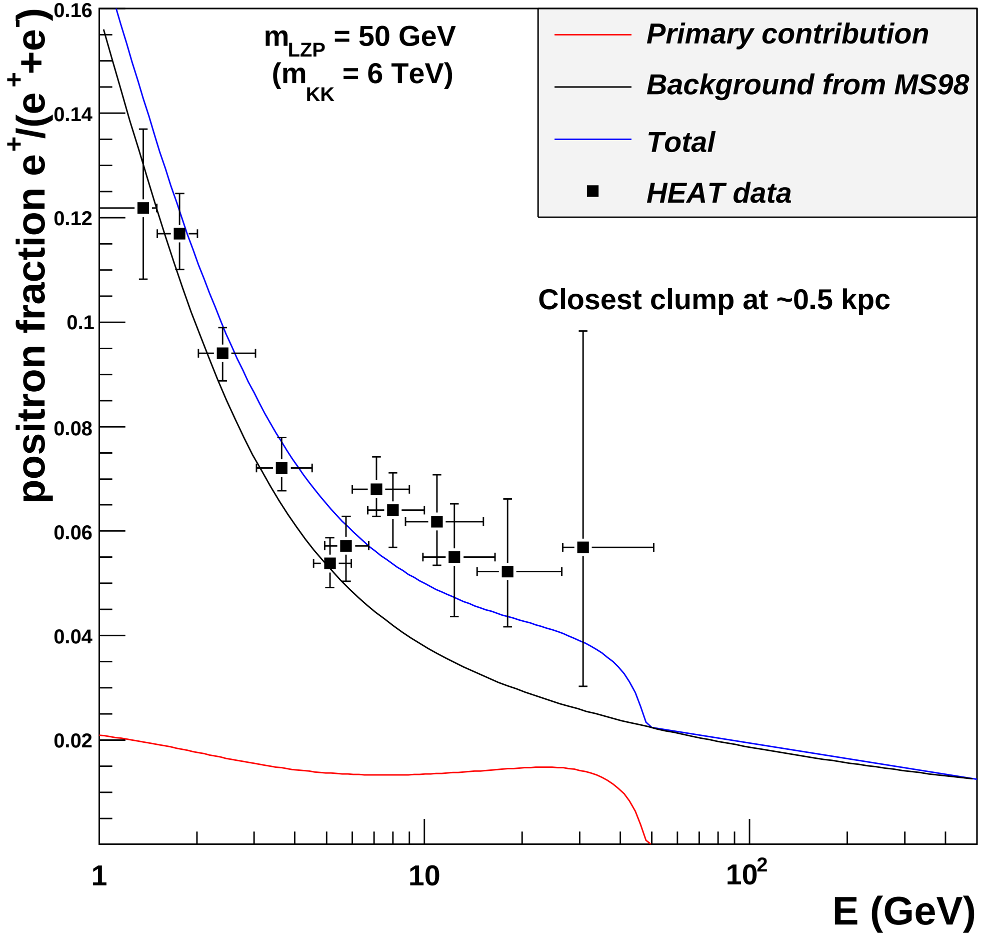
Small number of objects:

- Make sure that your scenario does not involve many other objects likely to contribute to the signal
- Search for isolated objects: OK if locations are known (DSPh), otherwise **quantify probability wrt theoretical spatial distribution** – needs of large *fov* experiments
- **If unknown, make a bet on the location, compute the fluxes, and send your predictions to the International Galactic Lottery**

Large number of objects:

- Perform a statistical analysis, **taking into account the whole phase space properties** (PDFs)
- Give **predictions associated with systematic/statistical uncertainties**: this **provides indications on the best places to search for signatures**

A single nearby source: Play the Galactic Lottery



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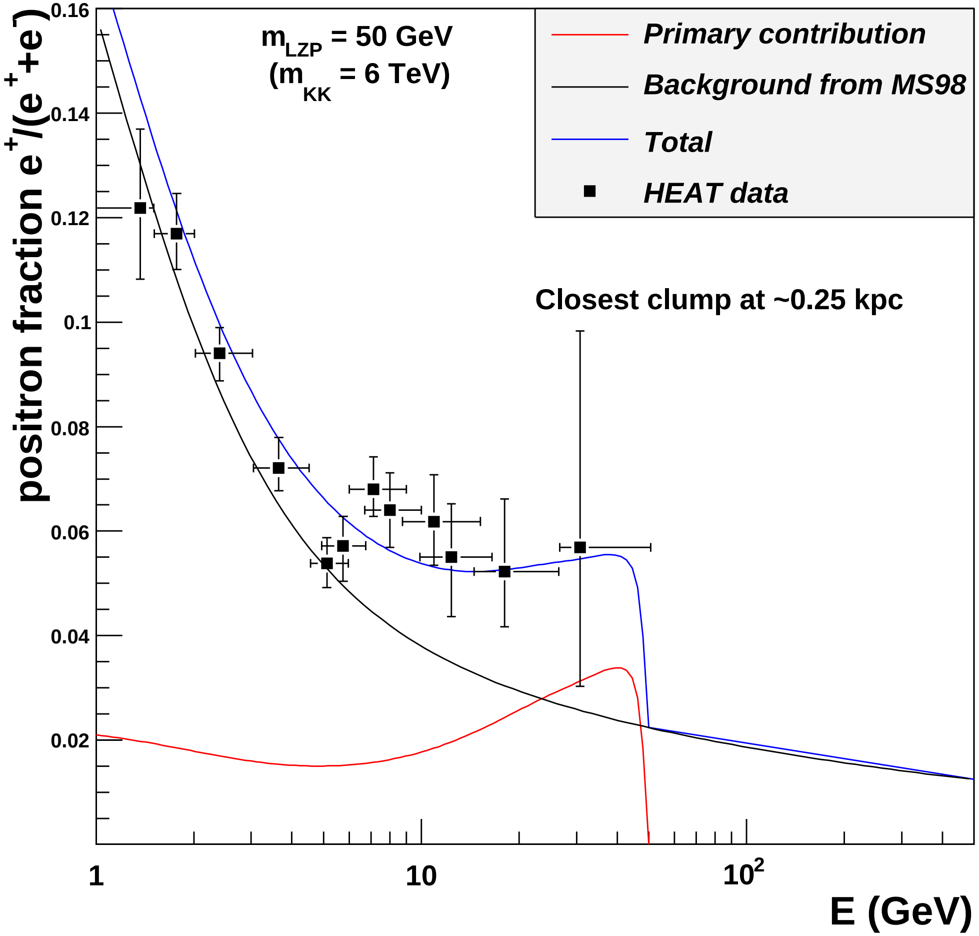

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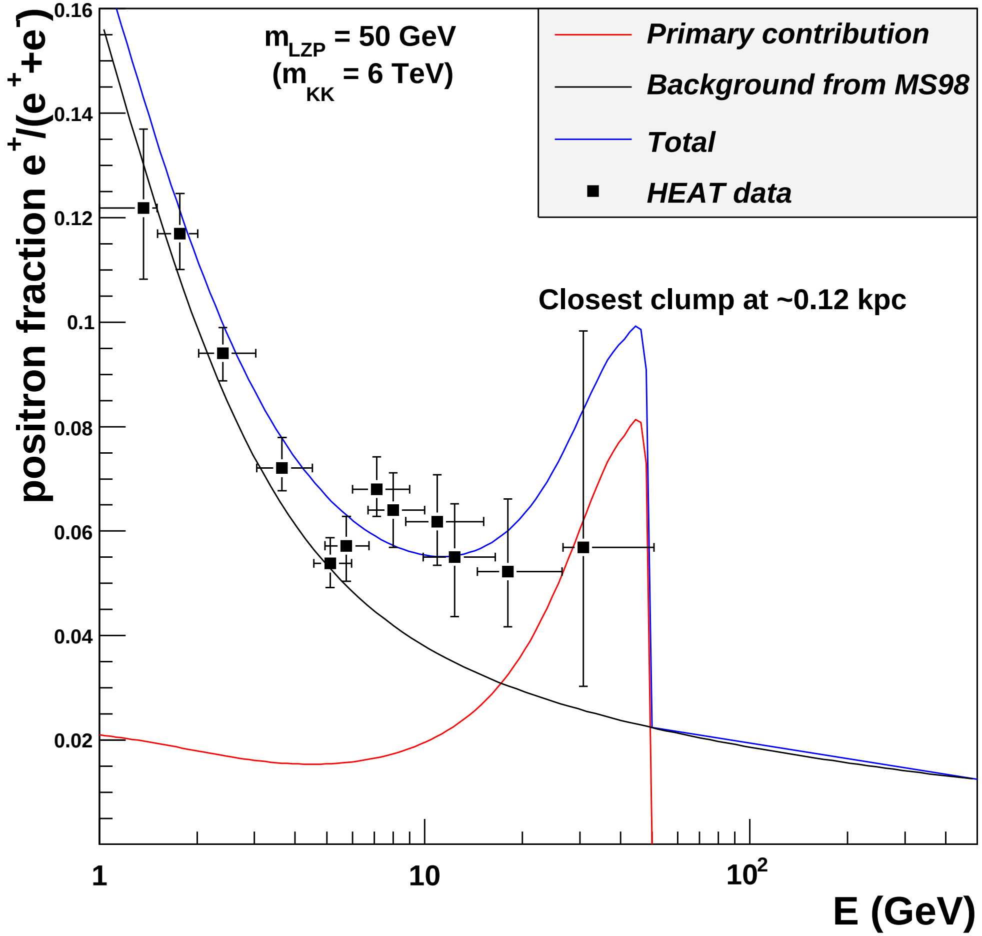

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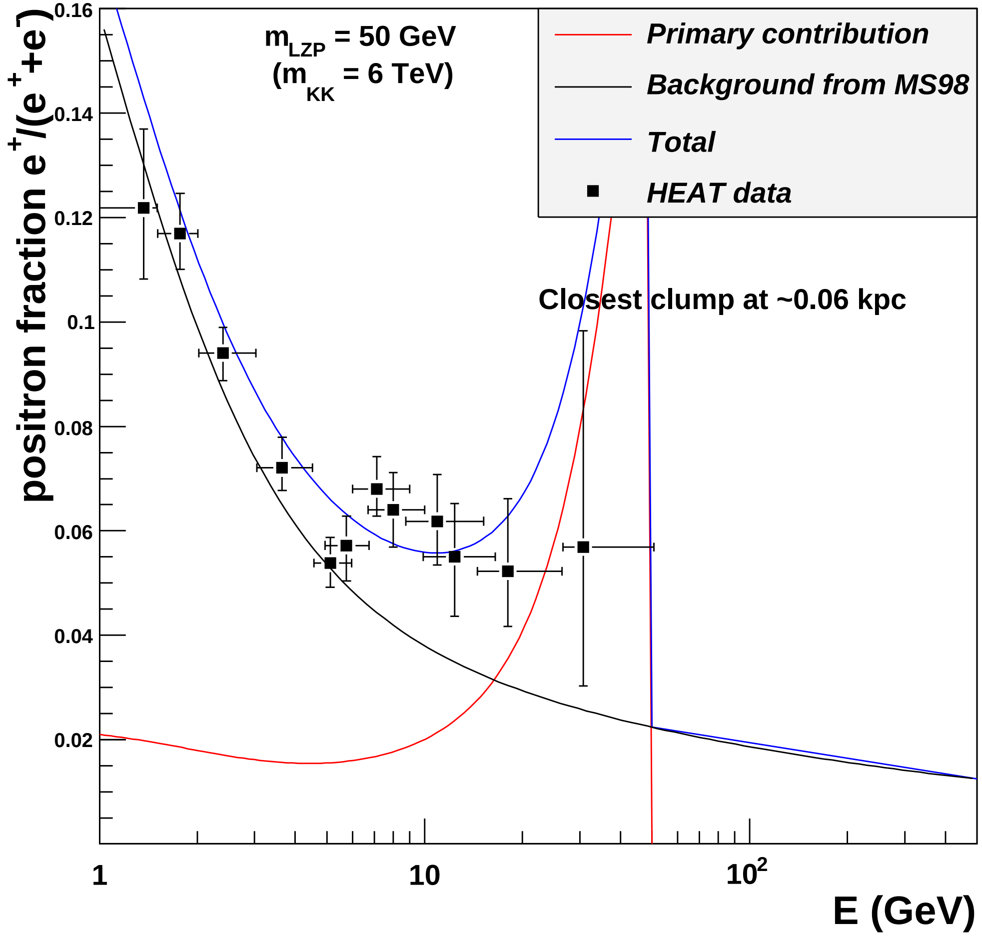

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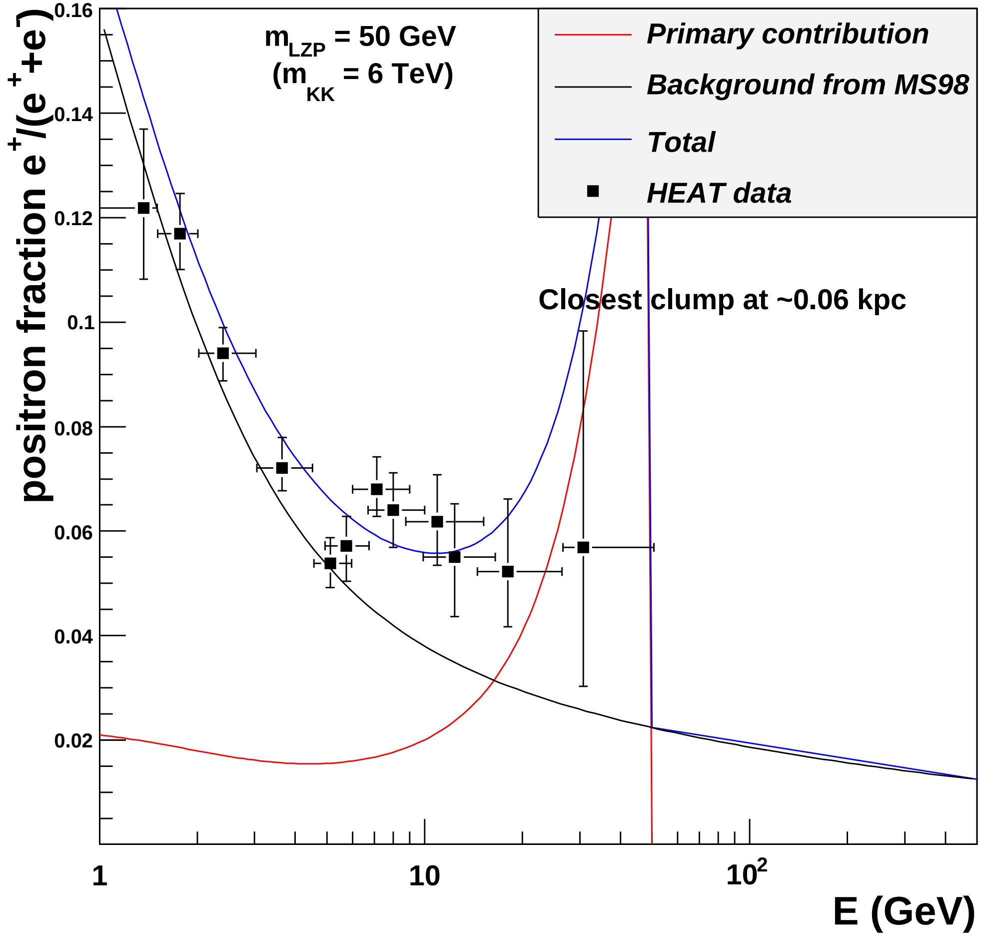


HOW PROBABLE IS THAT ????

Mass distribution

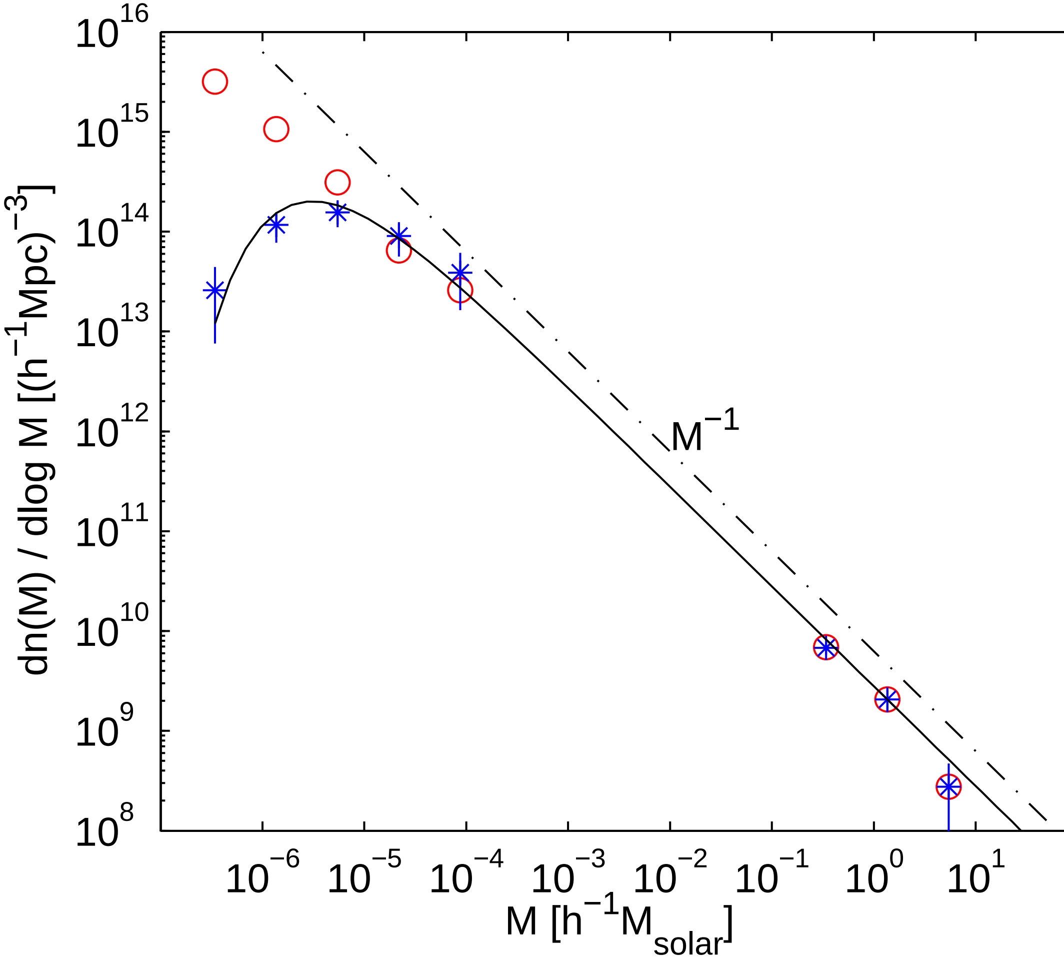
- $\frac{dP_M}{dM} = K_M \left(\frac{M}{M_\odot}\right)^{-\alpha_\mathrm{m}}$
  with $\alpha_\mathrm{m} \sim 1.7 - 2.1$ (Shaw et al, 2007), and $K_M = f(M_\mathrm{min}, M_\mathrm{max}, \alpha_\mathrm{m})$ allows normalisation to 1 in the mass range

- The mass range ??? $M_\mathrm{max} \sim 10^{10} M_\odot$ $M_\mathrm{min} \gtrsim M_\mathrm{fs} \sim 10^{-12} - 10^{-4}$ depending on the particle physics model (Profumo et al, 2006). Diemand et al (2005) resolve masses down to $10^{-6} M_\odot$ at $z = 26$. Survival to tidal stripping from GC ? Encounters with stars ? $\rightarrow M_\mathrm{min}$ is a free parameter, lying between $\sim 10^{-6} - 10^4$

- N_0 fixed by number of well resolved objects in various N-body experiments: $N_\mathrm{ref}(> M_\mathrm{ref} = 10^8 M_\odot) \simeq 100$ => $N_0 = f(N_\mathrm{ref} M_\mathrm{ref}, M_\mathrm{min}, M_\mathrm{max})$

- The mass fraction depends on M_min and α_m

Diemand et al (2005)

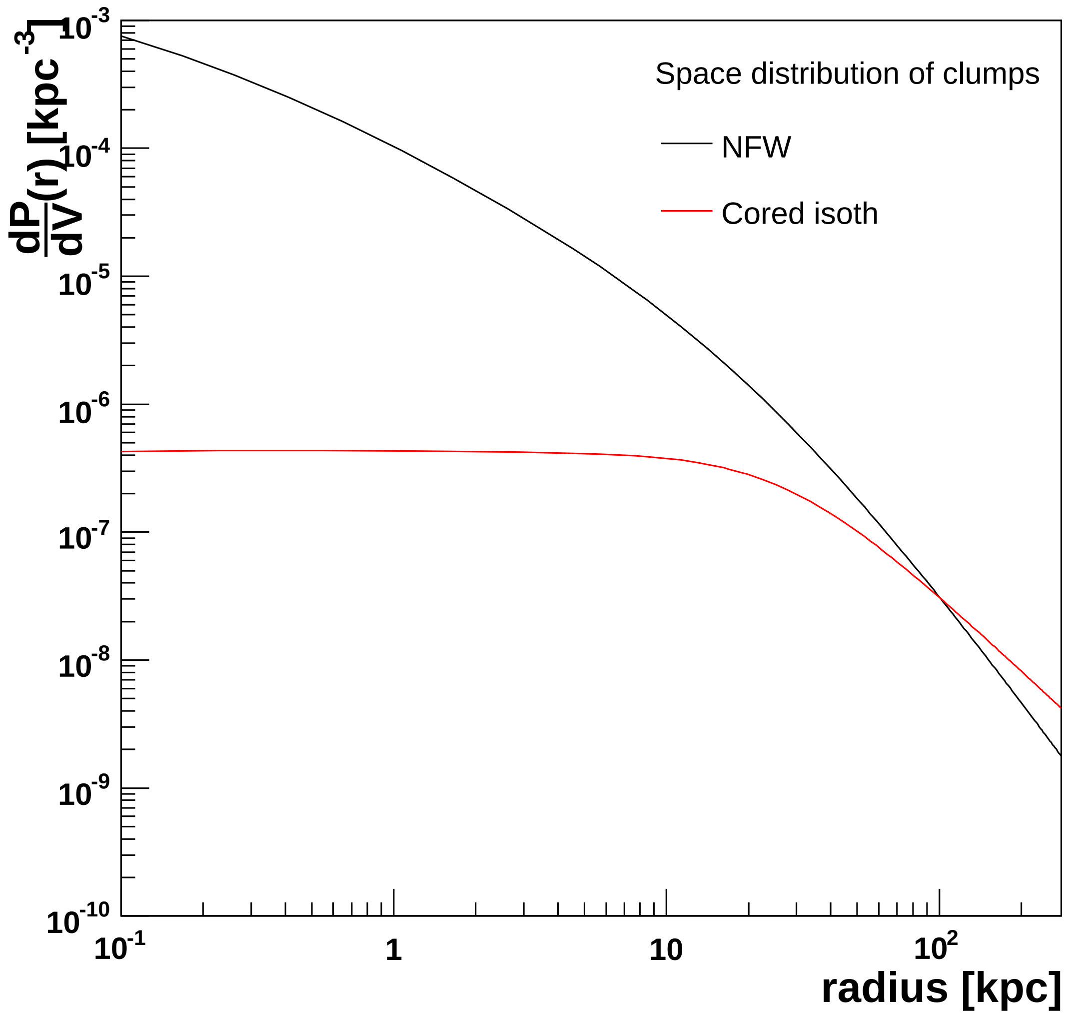


Space distribution of clumps

The space distribution of clumps is found to be well approximated with a **spherical cored isothermal distribution** with $r_h \simeq 0.1 \times R^{\rm h}_{\rm vir} \sim r_s$:

- $$\frac{dP_V(r)}{4\pi r^2 dr} = K_V \left(1 + \left(\frac{r}{r_h}\right)^2\right)^{-1}$$
  where K_V normalises the distribution to 1 within the halo extension $R^{\rm h}_{\rm vir}$.

- Caution: many authors use the same space distribution for the smooth halo and clumps. There are arguments for very light clumps (Berezinsky et al, 2004), but it is not seen is simulations



Clump internal properties: profiles and concentration models

Clump profile $\sim$ NFW $\propto r^{-1}(r+r_s)^{-2}$

- Virial radius given by mass:
  $R_{\rm vir} \propto M_{\rm vir}{}^{1/3}$

- Scale radius r_s fixed by the concentration parameter:
  $c_{\rm vir} \equiv \frac{R_{\rm vir}}{r_{-2}} = \frac{R_{\rm vir}}{r_s^{nfw}}$

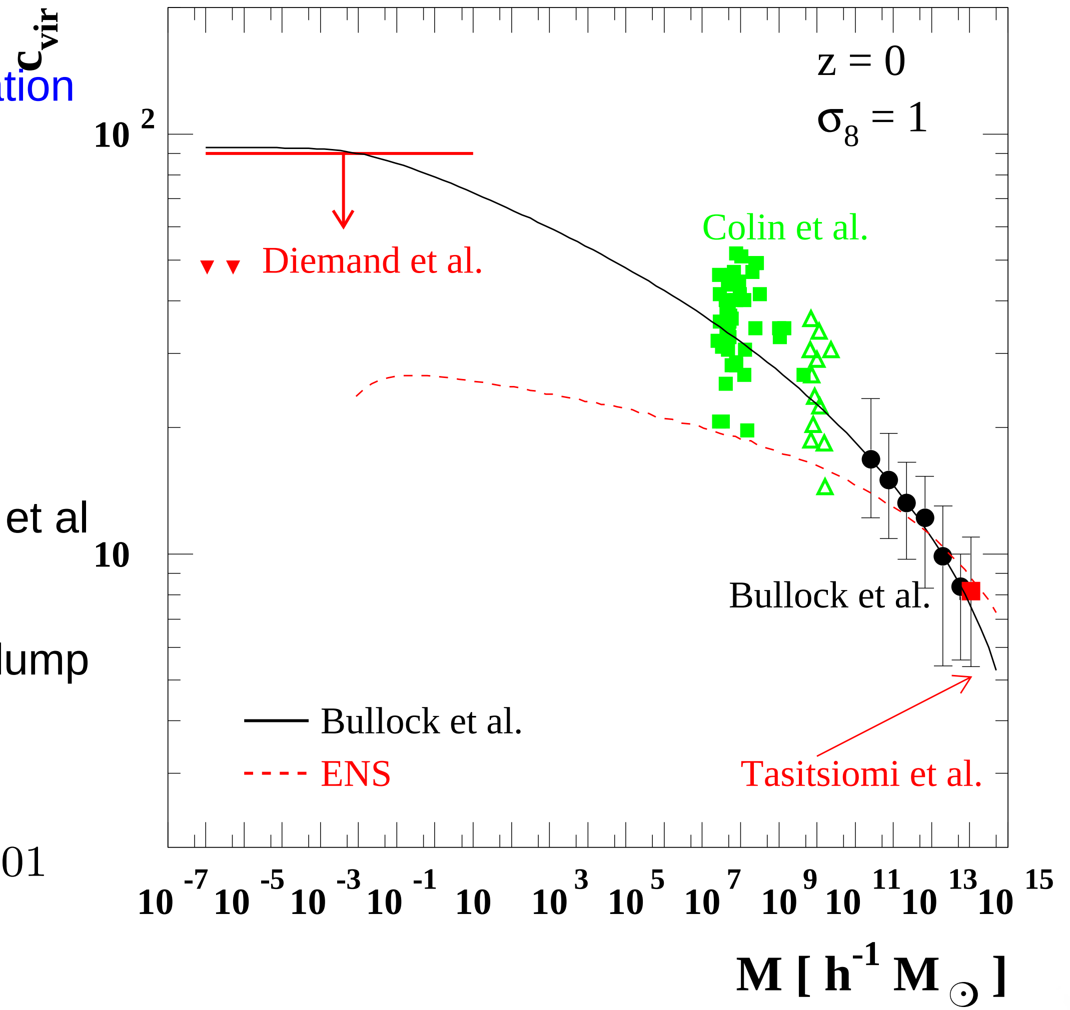
- Concentration parameter given by simulations:
  $c_{\rm vir} = f(M_{\rm vir})$
  2 extreme parameterizations: Bullock et al (2001), Eke et al (2001)

Once the relation $c_{\rm vir} - M_{\rm vir}$ is known, clump internal properties are fixed by its mass.

$$\xi = \frac{B(M)\times M}{\rho_\odot} \rightarrow \propto M^{0.9} \text{ for B01}$$

$$\frac{dP_\xi}{d\xi} = \frac{dP_M}{dM}$$

Colafrancesco et al (2005)



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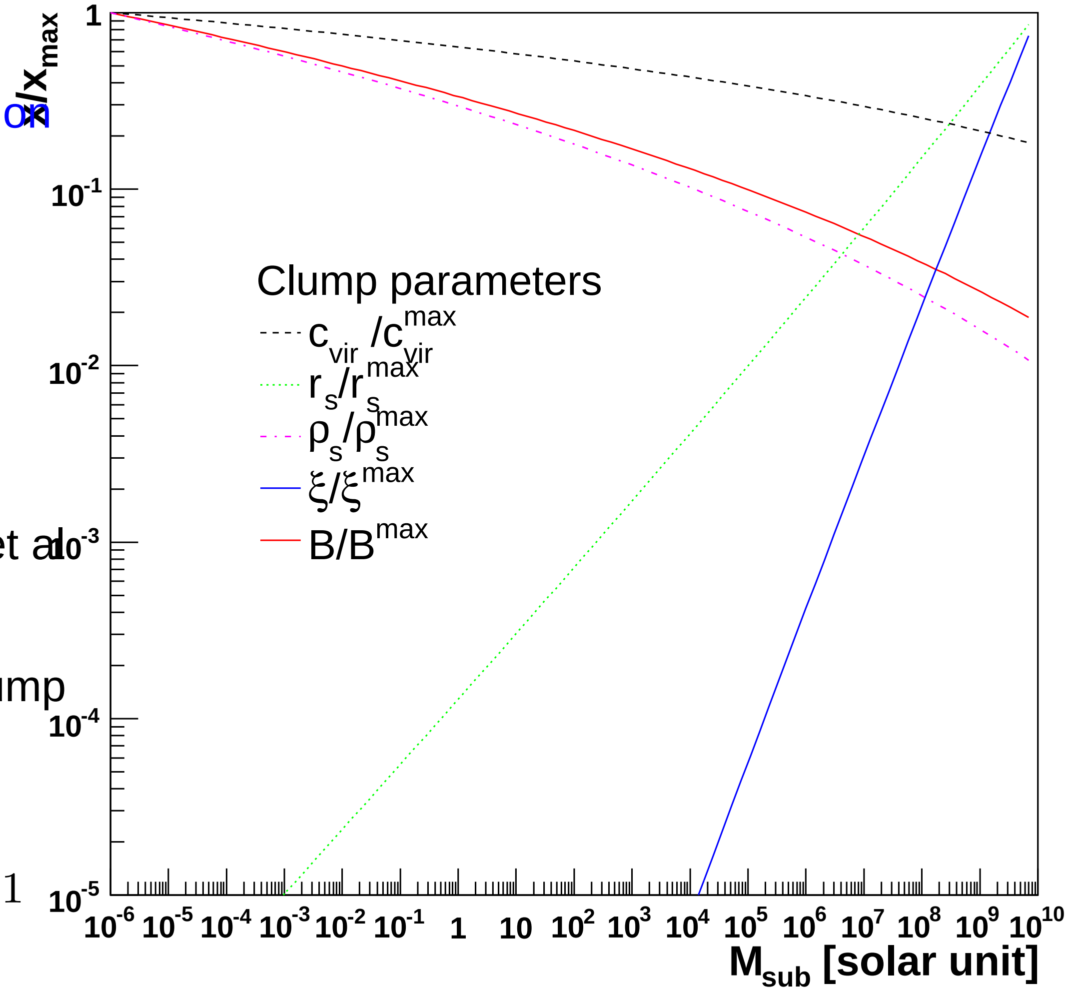

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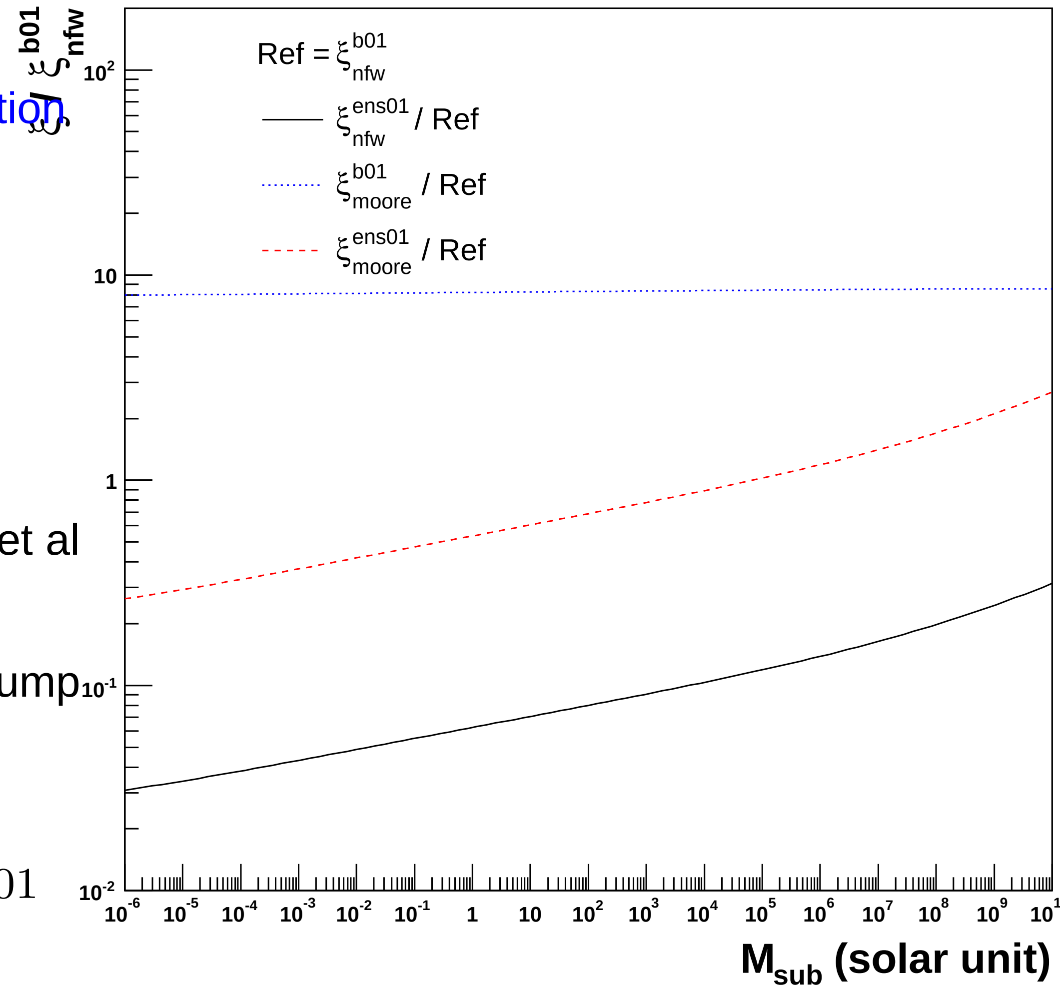

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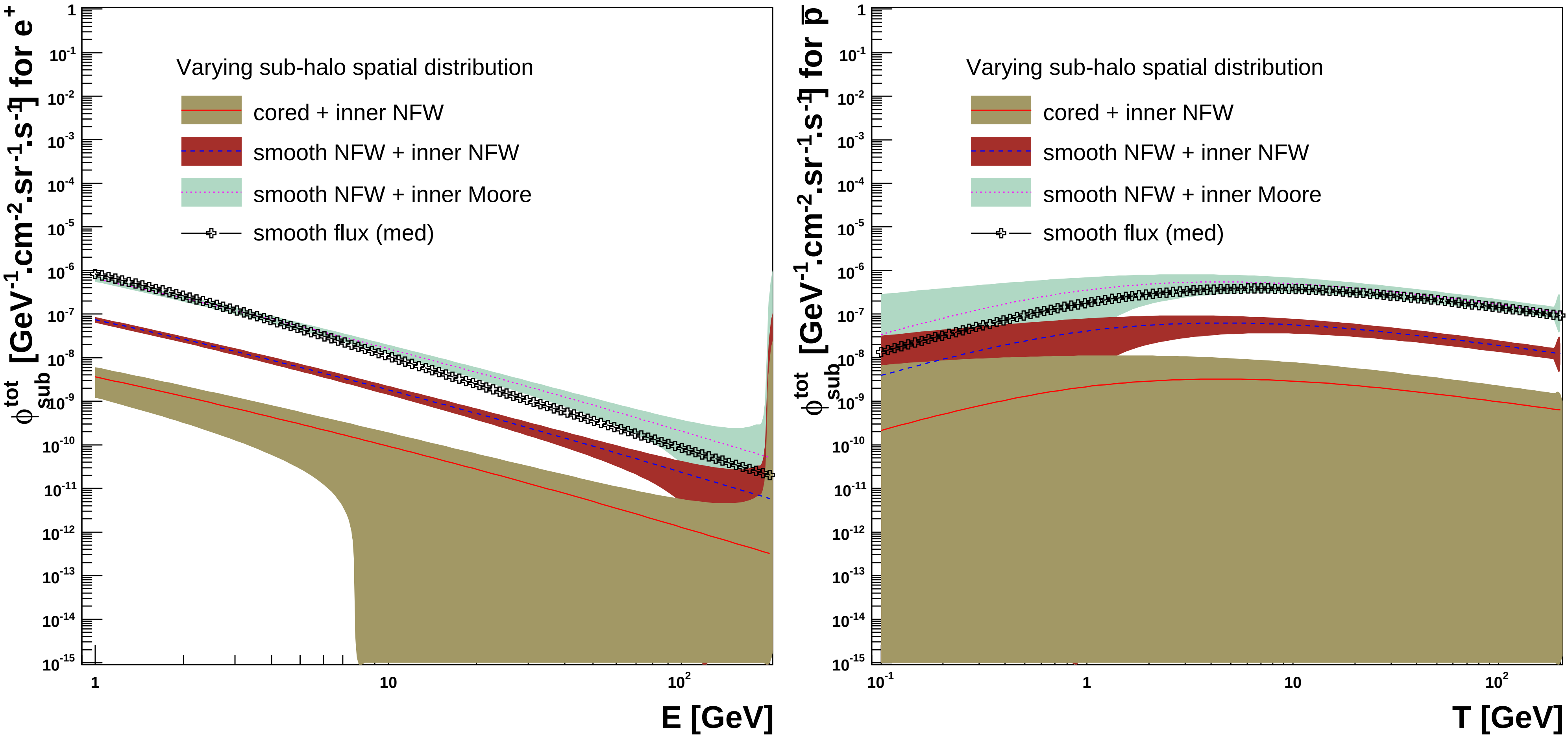
Important features

$M_{\rm sub}$ ($M_\odot$)	r_v (kpc)	r_s (kpc)	ρ_s ($M_\odot$/kpc^3)	c_v	ξ (kpc^3)	B
10^{-6}	2×10^{-4}	1.7×10^{-6}	4.1×10^{9}	120	5.8×10^{-12}	46
10^{-3}	2×10^{-3}	2.1×10^{-5}	2.3×10^{9}	98	3.5×10^{-9}	27
1	2×10^{-2}	2.7×10^{-4}	1.2×10^{9}	77	1.9×10^{-6}	15
10^{3}	0.2	3.6×10^{-3}	5.6×10^{8}	58	9.8×10^{-4}	8
10^{6}	2	5.1×10^{-2}	2.2×10^{8}	41	0.43	3
10^{9}	20	0.8	6.7×10^{7}	26	153	1

Table 0: *Sub-halo parameters for different masses: virial radius r_v, scale radius r_s, scale density ρ_s, concentration parameter c_v, effective volume ξ, intrinsic boost B.*

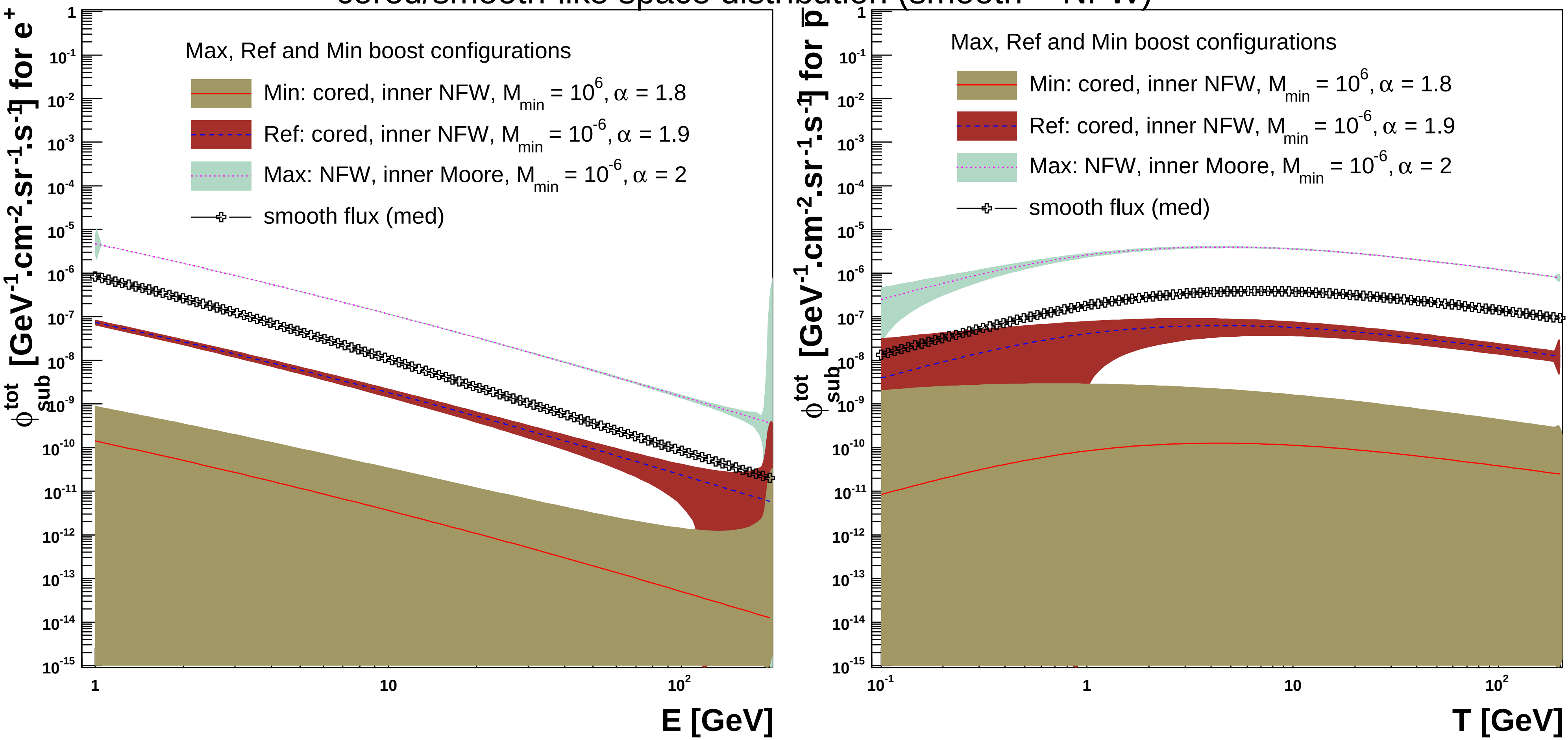
Fluxes for a 200 GeV e^+ line / antiprotons

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



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)



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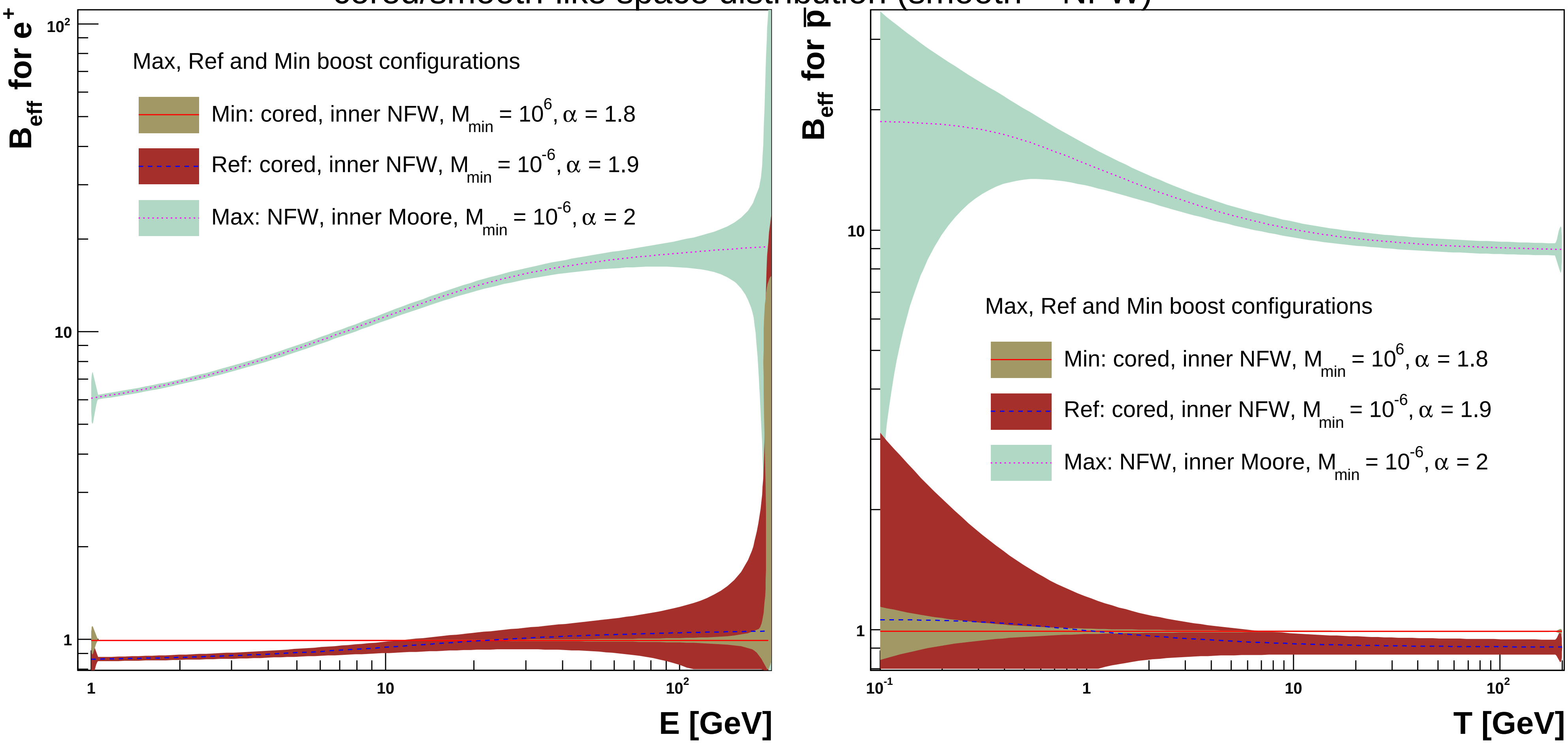

Propagators for $e^+/\bar{p}$

$\bar{p}$ (see e.g. Maurin et al 2001)

$$\mathcal{G}_{\odot}^{\bar{p}}(r,z) = \frac{\exp^{-k_v z}}{2\pi K L} \times \sum_{n=0}^{\infty} c_n^{-1} K_0(r\sqrt{k_n^2 + k_v^2}) \sin[k_n L] \sin[k_n(L-z)] \quad \text{(-14)}$$

e^+ (see e.g. Lavalle et al 2006)

$$\hat{\mathcal{G}}_{\odot}(r,z,\hat{\tau}) = \frac{\theta(\hat{\tau})}{4\pi K_0 \hat{\tau}} \exp\left(-\frac{r^2}{4K_0\hat{\tau}}\right) \times \mathcal{G}^{1D}(z,\hat{\tau})$$

with $\mathcal{G}^{1D}$ image-like or Shrödinger-like depending on the source location.