Indirect detection of Dark Matter with Antimatter cosmic rays: effect of cosmological sub-halos and uncertainties

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Refs arXiv: astro-ph/0603796 – 0712.0468 – 0709.3634 – 0808.0332

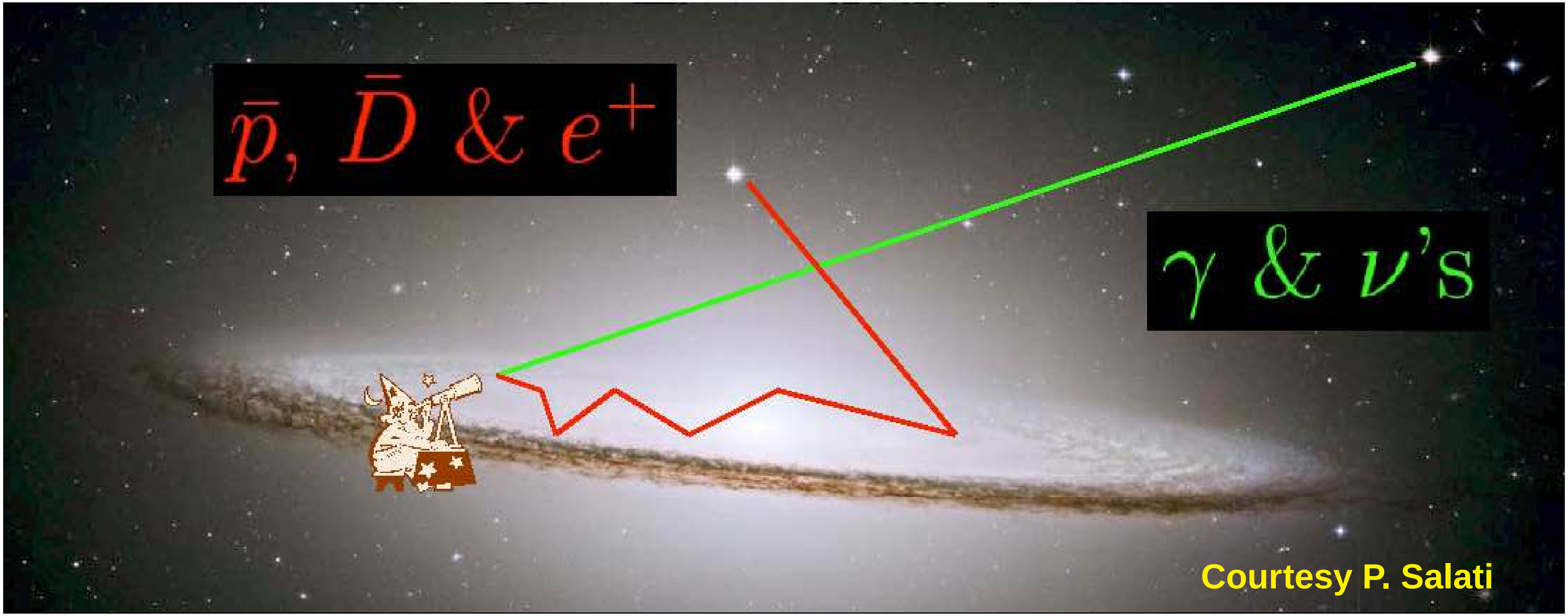
Collab: Delahaye, Salati, Taillet (LAPTH) – Maurin (LPNHE)
Ling, Nezri (ULB) – Donato, Fornengo (Turin) – Bi, Yuan (Beijing)

TeV Particle Astrophysics 2008

IHEP-Beijing, Sept. 24th-28th 2008

Indirect detection of Dark Matter

Non-baryonic DM may explain 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

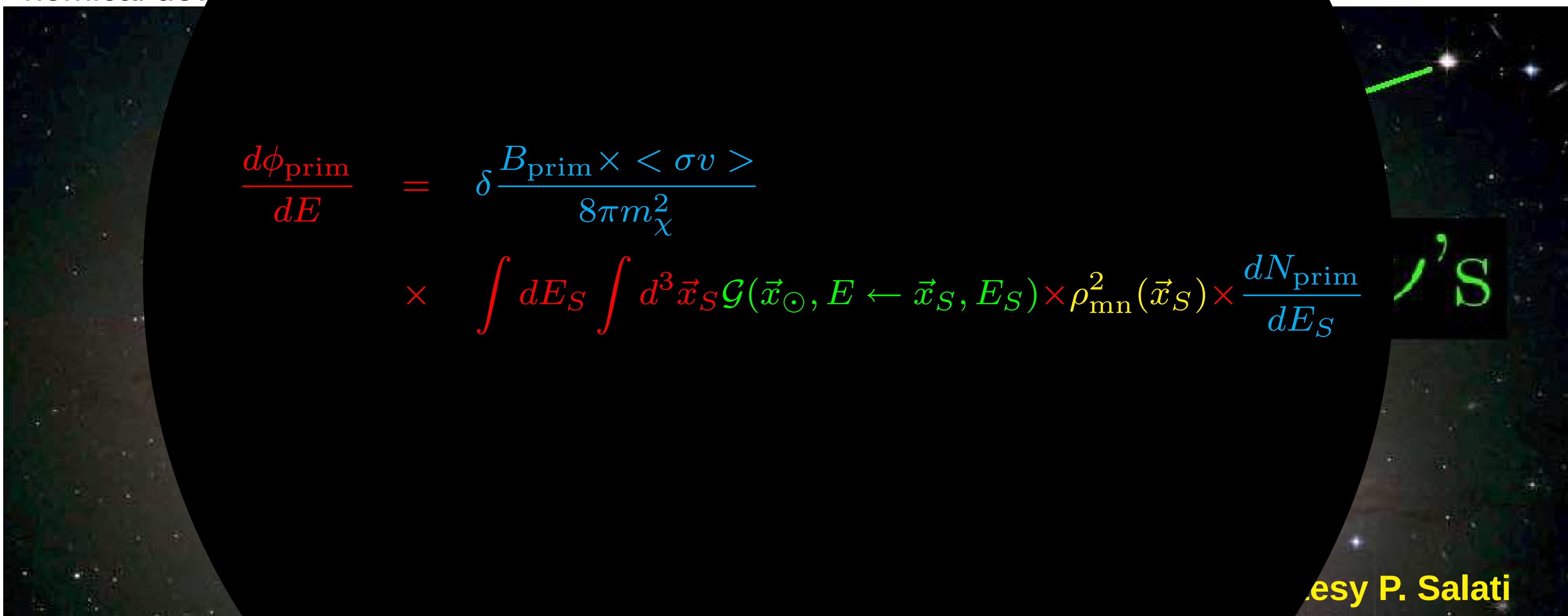


- **γ and ν: travel directly from the source to the observer**
- **Antimatter cosmic rays: diffuse on the magnetic turbulences**

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

# of Dark Matter

Non-baryonic D **and clusters**: If made of **exoti** means of astro-nomical devi



$$\frac{d\phi_{\rm prim}}{dE} = \delta \frac{B_{\rm prim} \times < \sigma v >}{8\pi m_{\chi}^2}$$

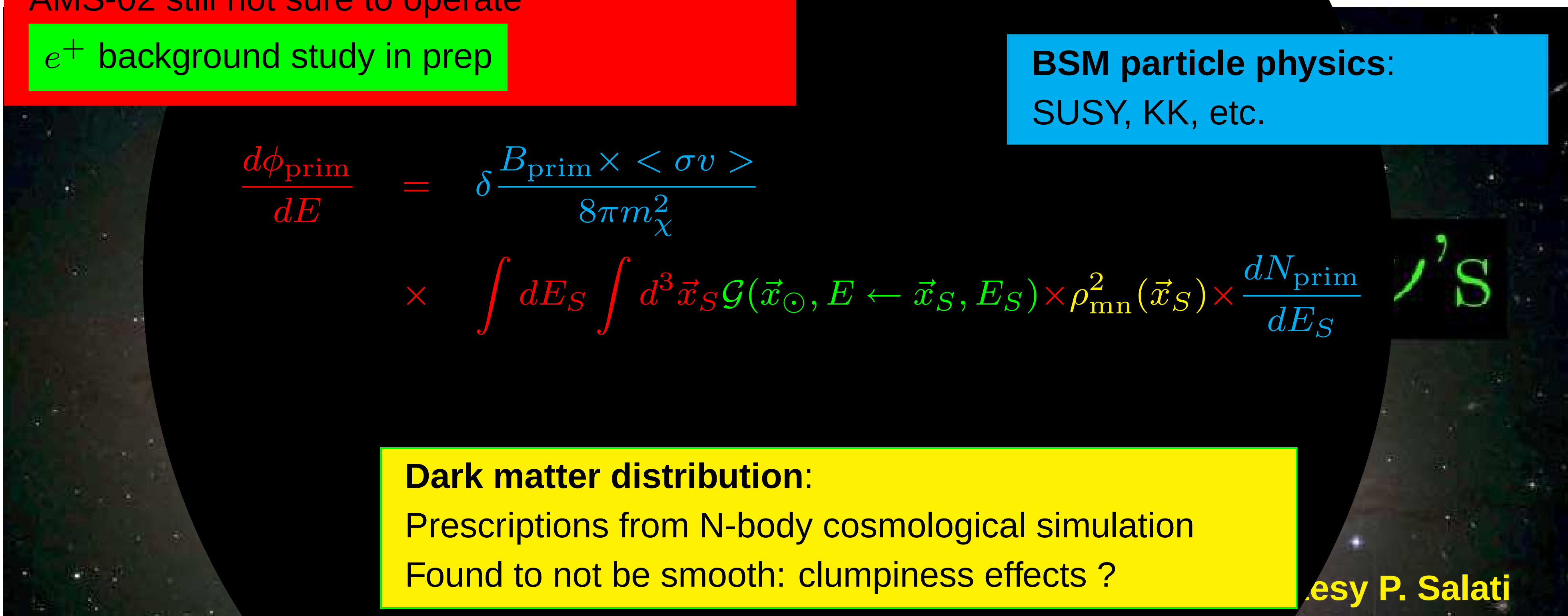
$$\times \int dE_S \int d^3\vec{x}_S \mathcal{G}(\vec{x}_{\odot}, E \leftarrow \vec{x}_S, E_S) \times \rho^2_{\rm mn}(\vec{x}_S) \times \frac{dN_{\rm prim}}{dE_S}$$

- γ **and** ν**: tr**
  to the observ **density regions**
  es)
- **Antimatter cosmic**
  magnetic turbulences

of Dark Matter

and clusters: If

neans of astro-



Flux measurements:
PAMELA satellite data is coming
GLAST (gamma) soon
AMS-02 still not sure to operate

e^+ background study in prep

BSM particle physics:
SUSY, KK, etc.

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Dark matter distribution:
Prescriptions from N-body cosmological simulation
Found to not be smooth: clumpiness effects ?

Propagation Green function

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$\ldots\vec{x}_S) \times \frac{dN_{\rm prim}}{dE_S}$

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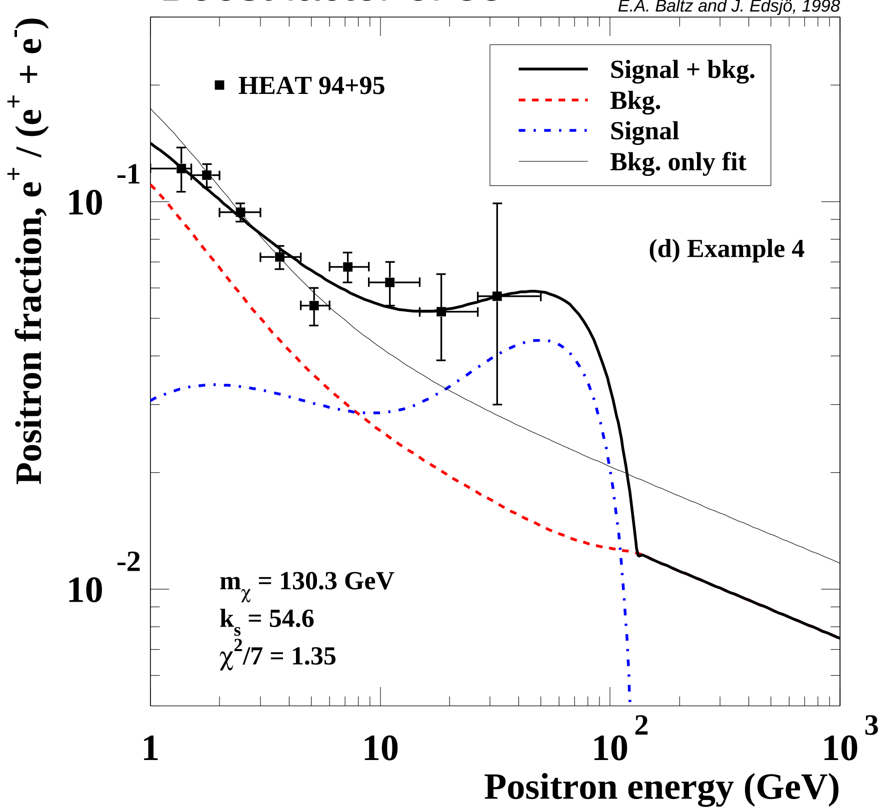
…on

…esy P. Salati

Baltz & Edsjö, 98

Boost factor of 55



- γ **and** ν: tr…
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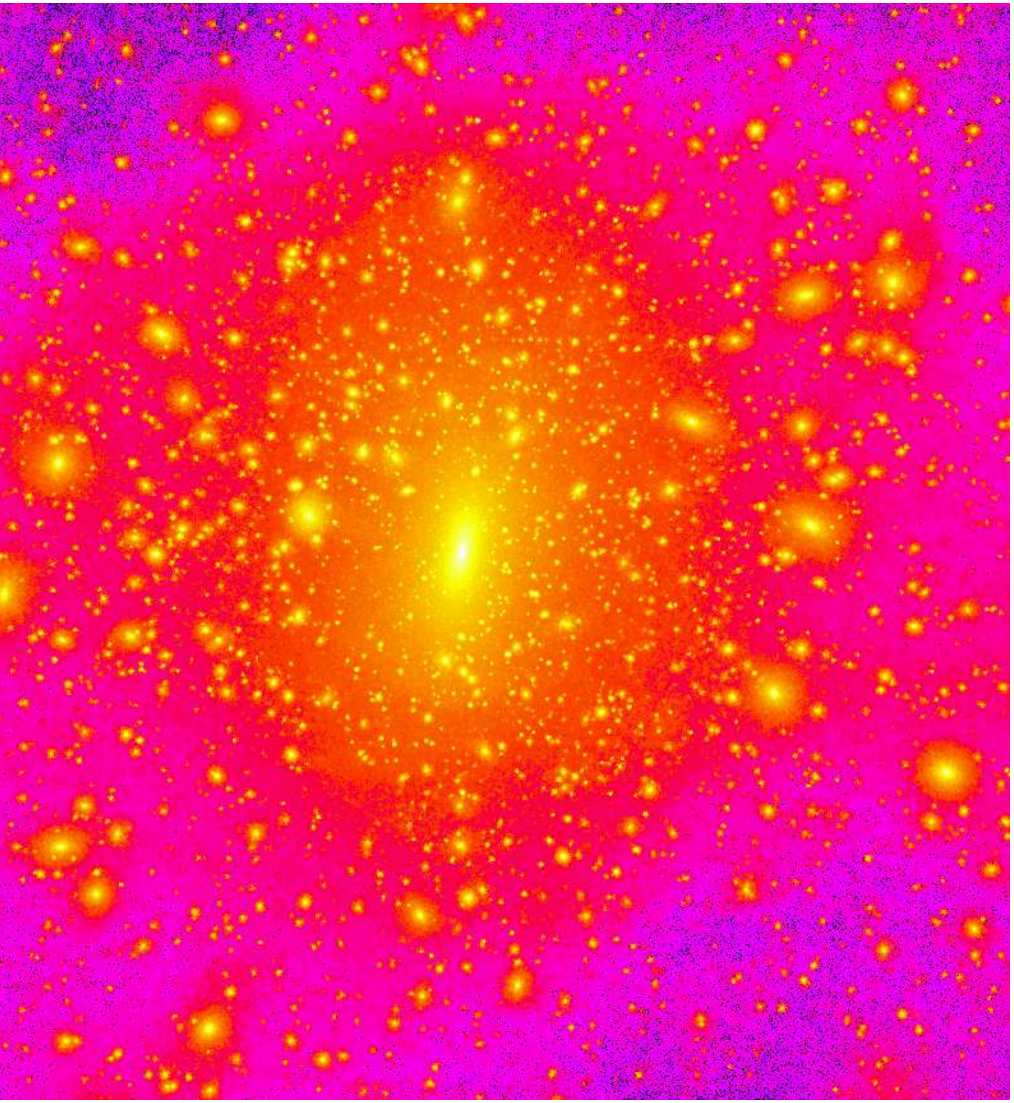
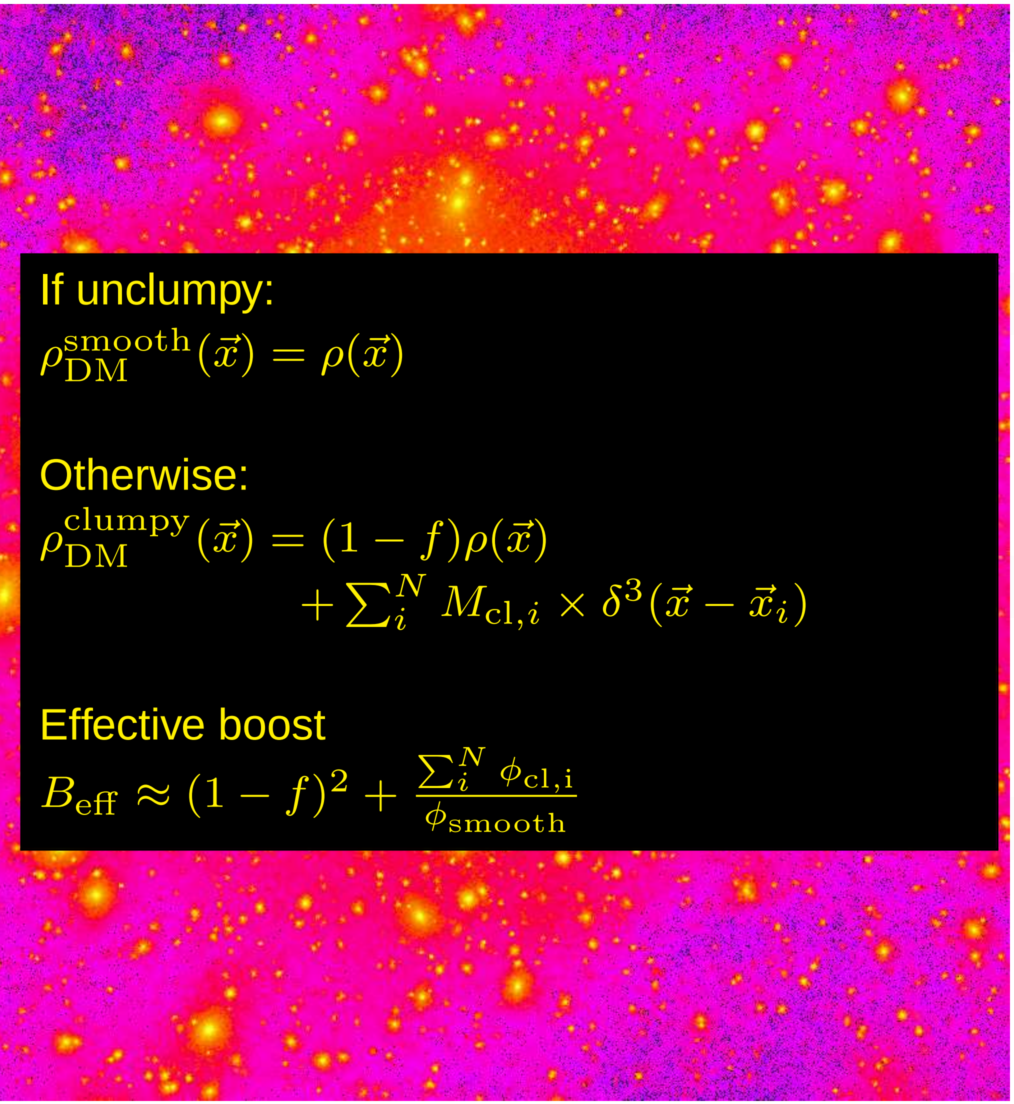
Inhomogeneous halo and boosted annihilation rate



(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 ?**

Inhomogeneous halo and boosted annihilation rate



If unclumpy:

$\rho_{\rm DM}^{\rm smooth}(\vec{x}) = \rho(\vec{x})$

Otherwise:

$$\rho_{\rm DM}^{\rm clumpy}(\vec{x}) = (1-f)\rho(\vec{x}) + \sum_i^N M_{{\rm cl},i} \times \delta^3(\vec{x}-\vec{x}_i)$$

Effective boost

$$B_{\rm eff} \approx (1-f)^2 + \frac{\sum_i^N \phi_{\rm cl,i}}{\phi_{\rm smooth}}$$

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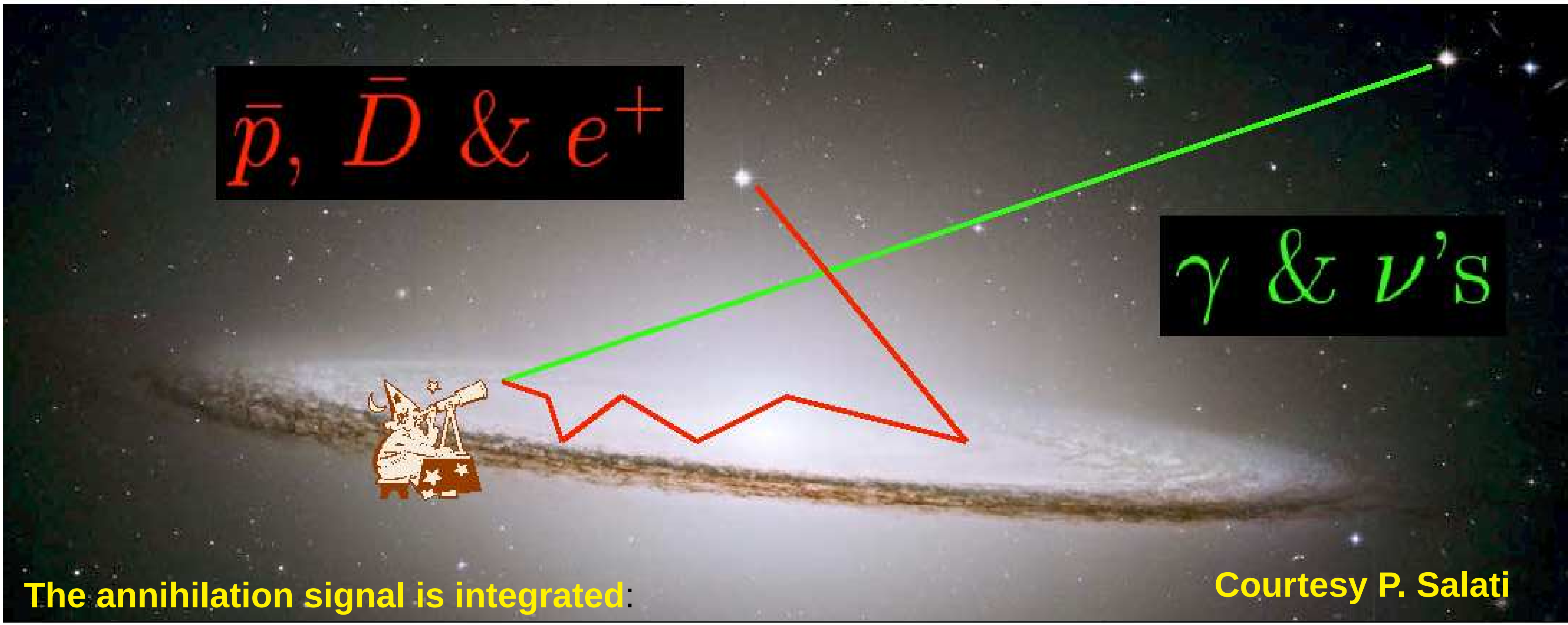
Short remark: γ-rays vs antimatter cosmic rays



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

$\Longrightarrow$ **Boost factors are not the same!**
(see L.Pieri's talk)

Sub-TeV Cosmic ray propagation in the Galaxy

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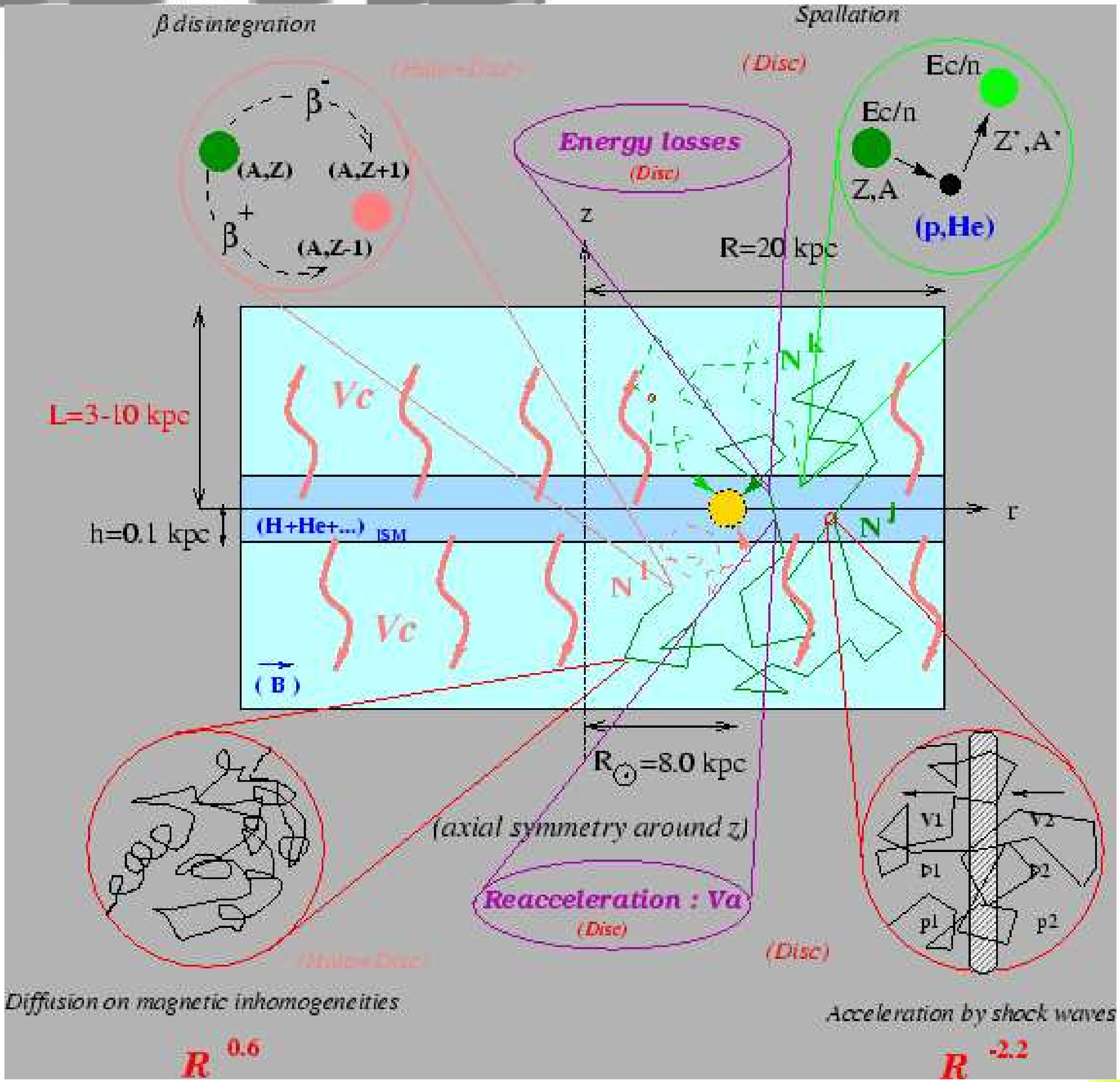
cf. e.g. Berezinsky (1990)

- **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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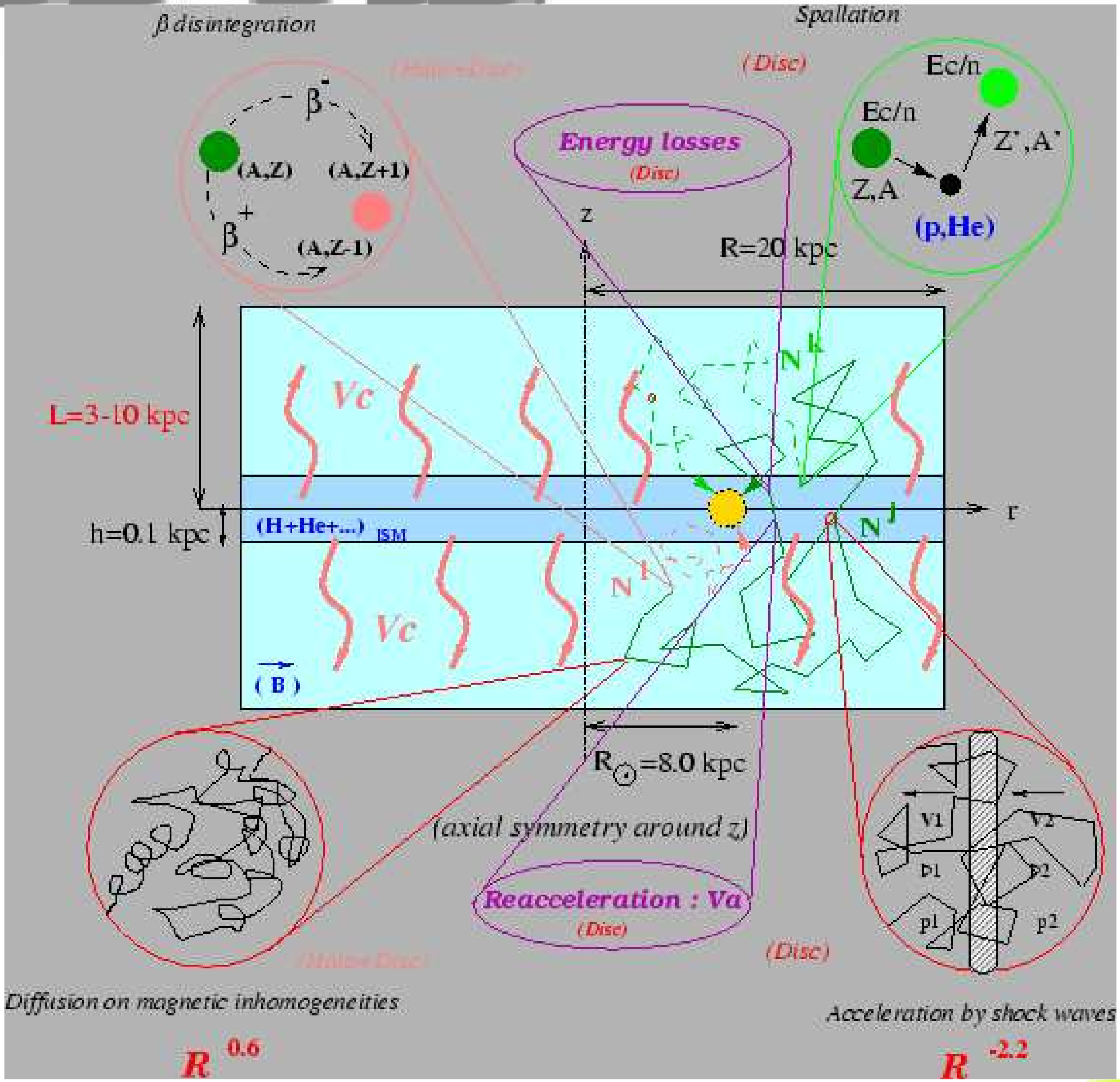


Diffusion equation for $e^+/\bar{p}$

Diffusion equation for e^+

(*cf.* Bulanov & Dogel 73, Baltz & Edsjö 98, Lavalle et al 07, etc):

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

Green equation for antiprotons (*cf.* e.g. Maurin et al 01):

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

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 :

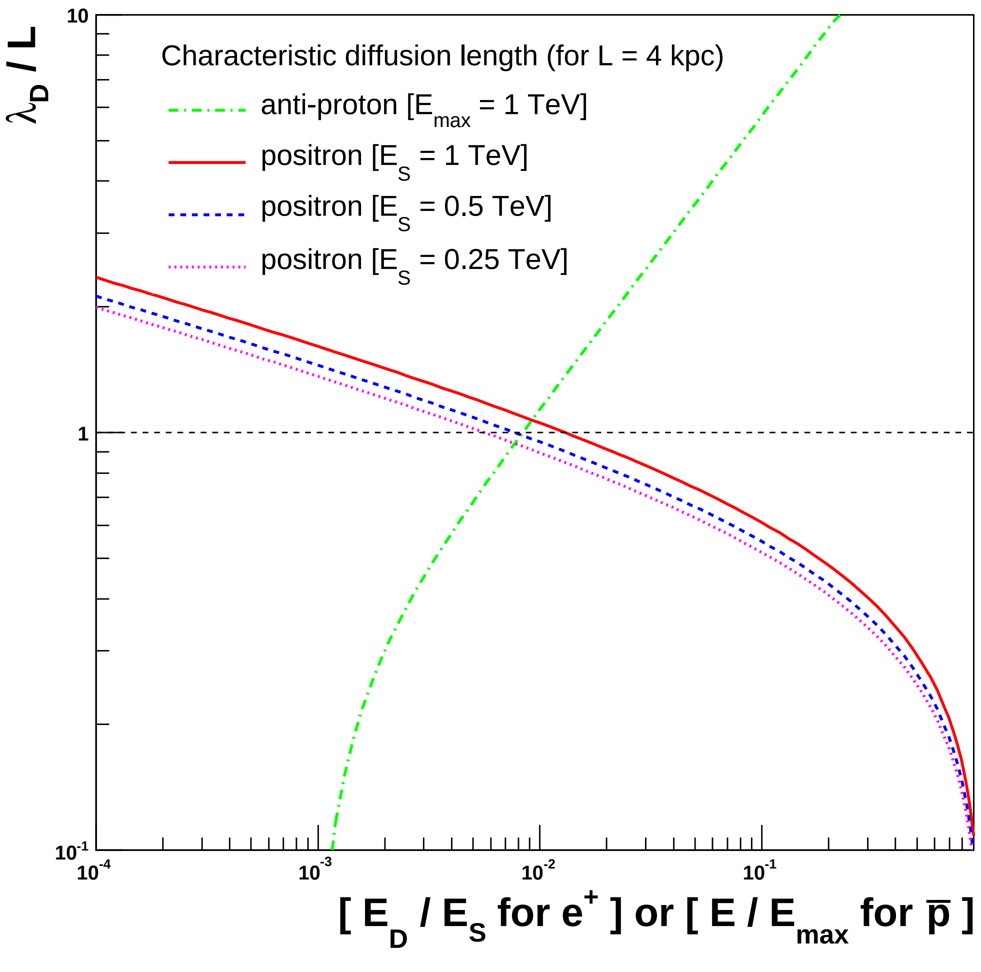
injected spectrum

Uncertainties and degeneracies on parameters in Maurin et al 01

(Complementary & full numerical: **Galprop**, Strong & Moskalenko 98-08)

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
- $\overline{p}$'s do not lose energy, **but convective wind and spallation processes very efficient at low energy**: survey larger volume at high energies



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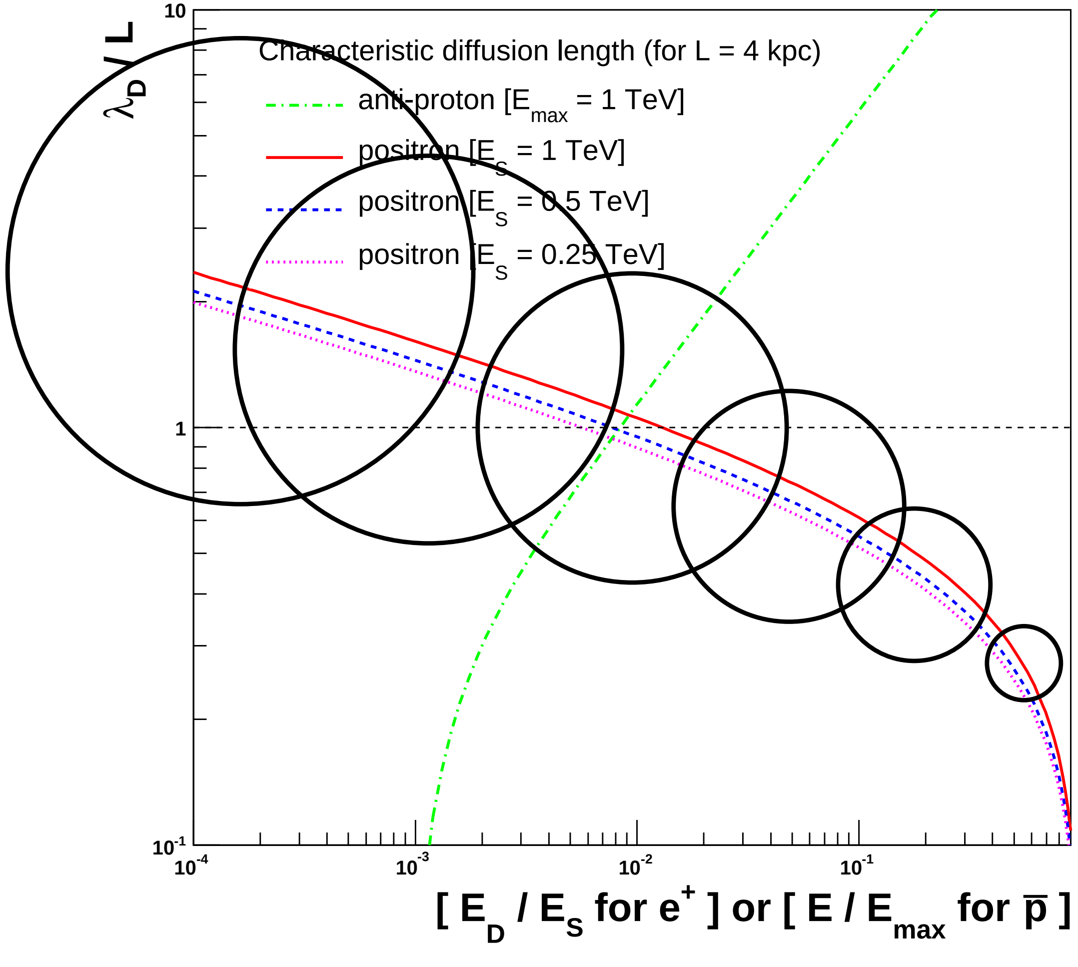

Effective volume picture for the smooth contribution

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

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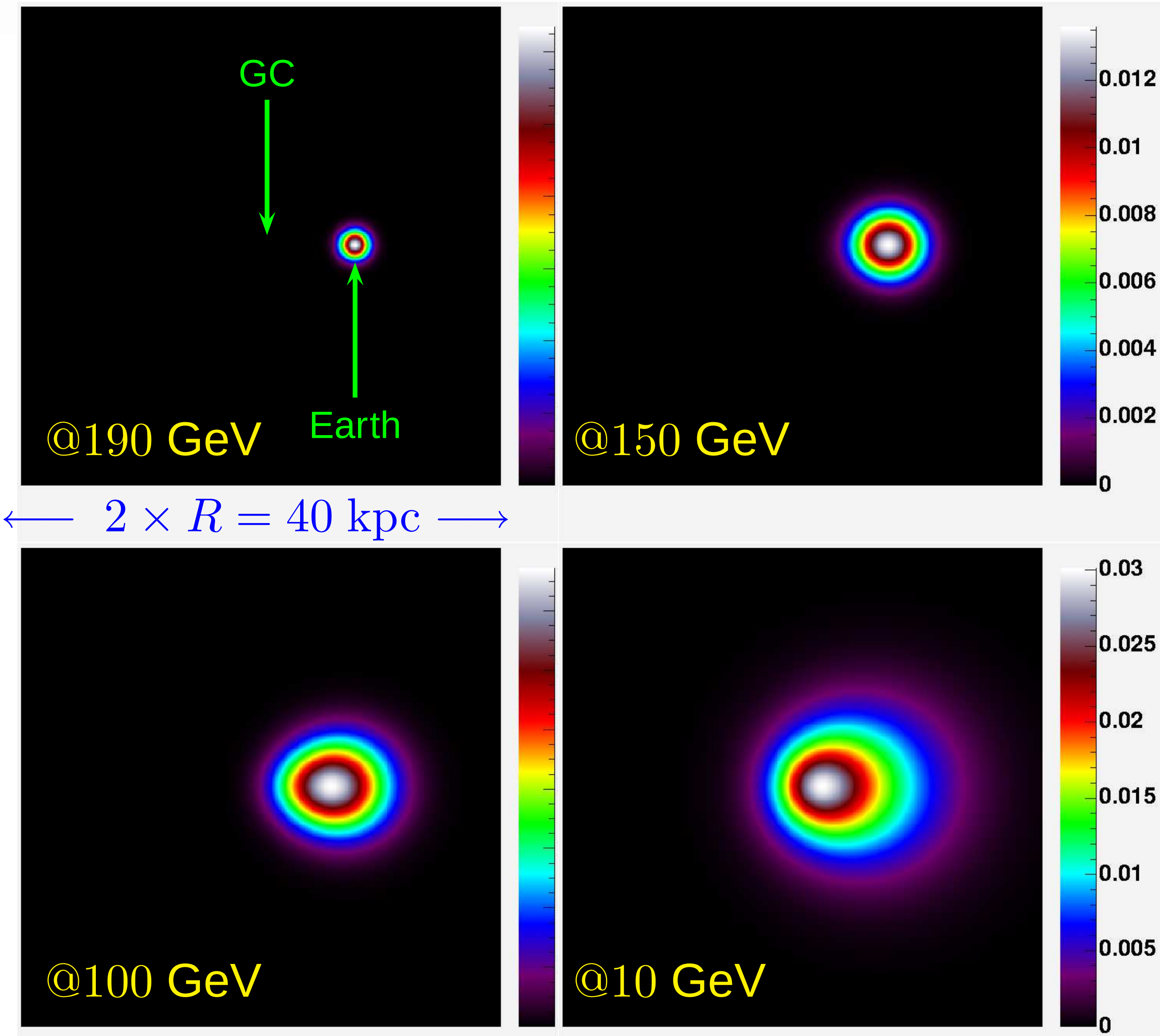
Simplest view of propagation

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

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

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



$\longleftarrow\ 2 \times R = 40$ kpc $\longrightarrow$

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

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

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

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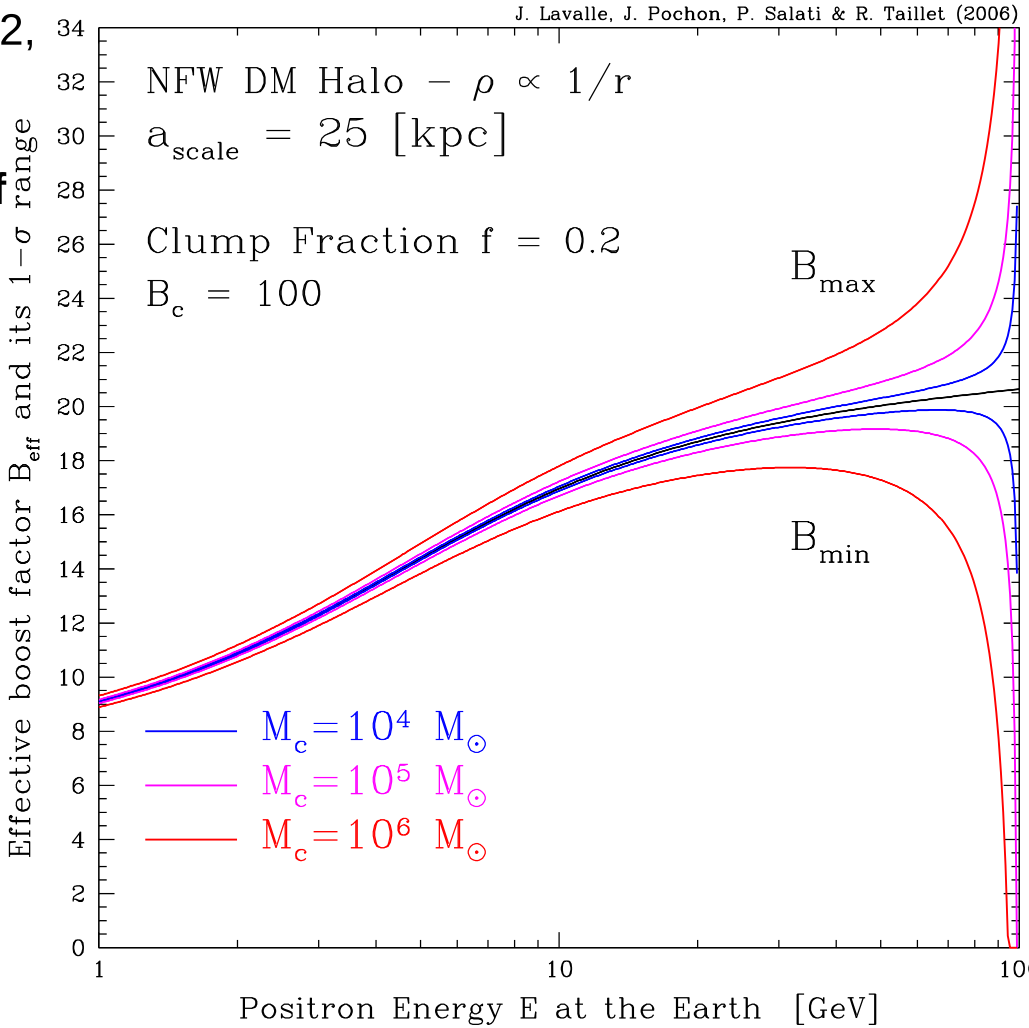
Boost for antimatter CRs:
(J.L, J.Pochon, P.Salati & R.Taillet – A&A 462, 2007)

- Long believed to be **simple rescaling of fluxes** ...
- **This picture is wrong**. Due to propagation effects, ***boost* is a non-trivial function of energy**
- 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 ???**



Cosmological sub-halos:

Results of the state-of-the-art N-body experiments

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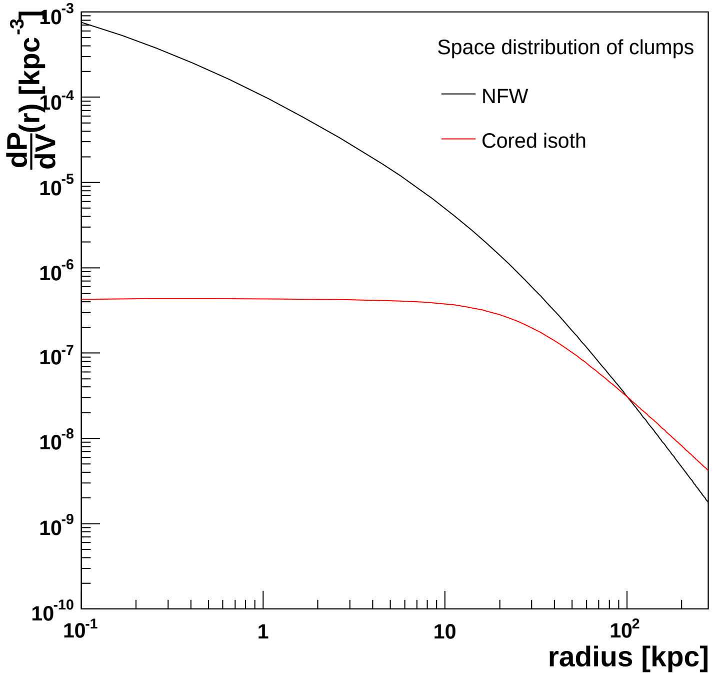
Results of the state-of-the-art N-body experiments

What is important is to know the luminosity PDF and spatial PDF.
N-body results as input ingredients, and allowed [ranges]:

- **Spatial distribution**:
  . [cored isothermal – smooth-like]
- **Mass distribution**:
  minimal clump mass $M_{\rm min}$
  $[10^6 - 10^{-6} M_\odot]$,
  logarithmic slope $\alpha_{\rm m}$ [1.8-2.0]
- **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]

$[\text{ Clump luminosity } \equiv \xi = f(M)]$

NFW vs cored isothermal



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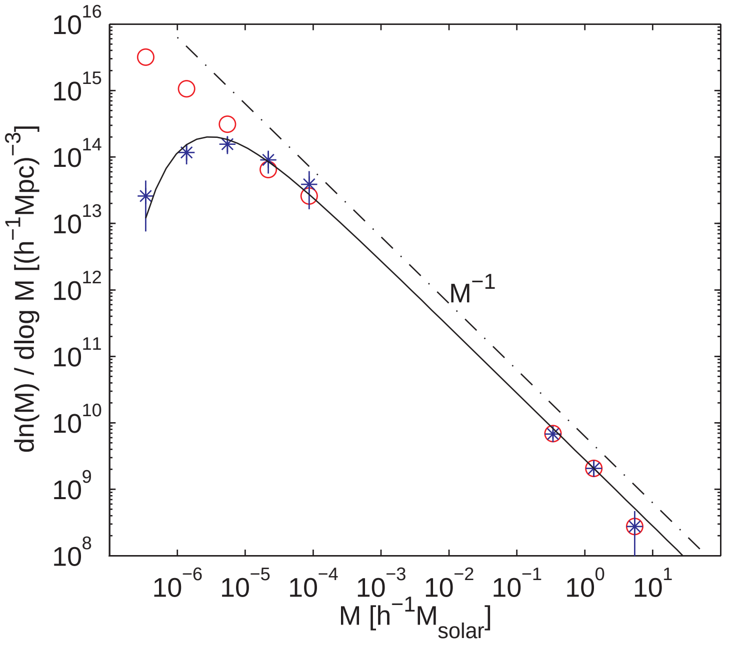
Diemand et al (2005)



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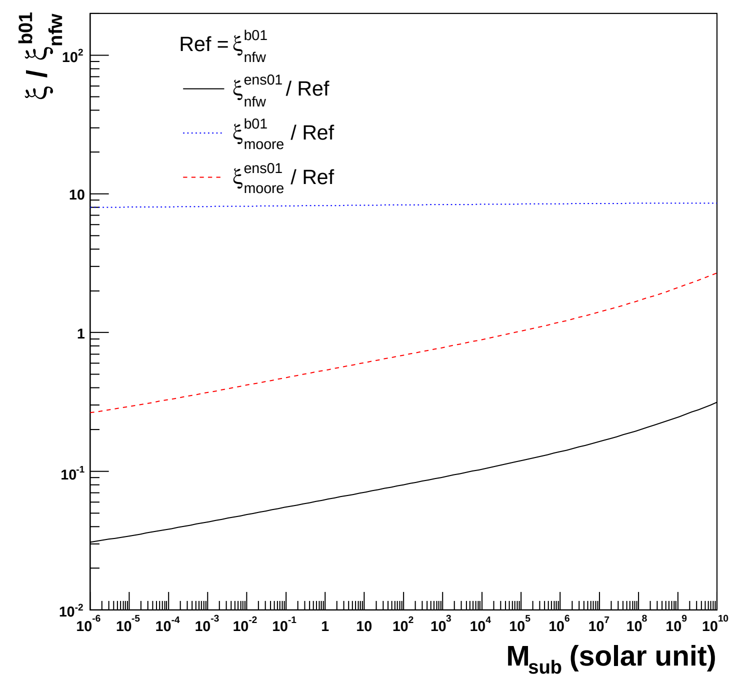
$$\xi^{\rm B01}_{\rm NFW} \simeq 0.1 \times \xi^{\rm B01}_{\rm Moore} \simeq 10 \times \xi^{\rm ENS01}_{\rm NFW}$$



Results for e^+ and $\bar{p}$ using different models of N-body-like clumps

Next slides: (i) Fluxes – smooth & clumps (ii) Boosts

$$\phi_{\rm cl}^{\rm tot}(\oplus) = S \times \left\{ \int dM \xi_{\rm cl}(M) \times \frac{dP_M^{\rm cl}}{dM} \right\} \times \left\{ \int d^3\vec{x} \frac{dP_V^{\rm cl}}{dV} \times \int dE' \, \mathcal{G}(\oplus, E \leftarrow \vec{x}, E') \times \frac{dN}{dE'} \right\}$$

$$\boxed{B_{\rm eff} \simeq 1 + \frac{\phi_{\rm cl}^{\rm tot}(\oplus)}{\phi_{\rm smooth}(\oplus)}}$$

Positrons:

- Source: injection of a 200 GeV line

Antiprotons:

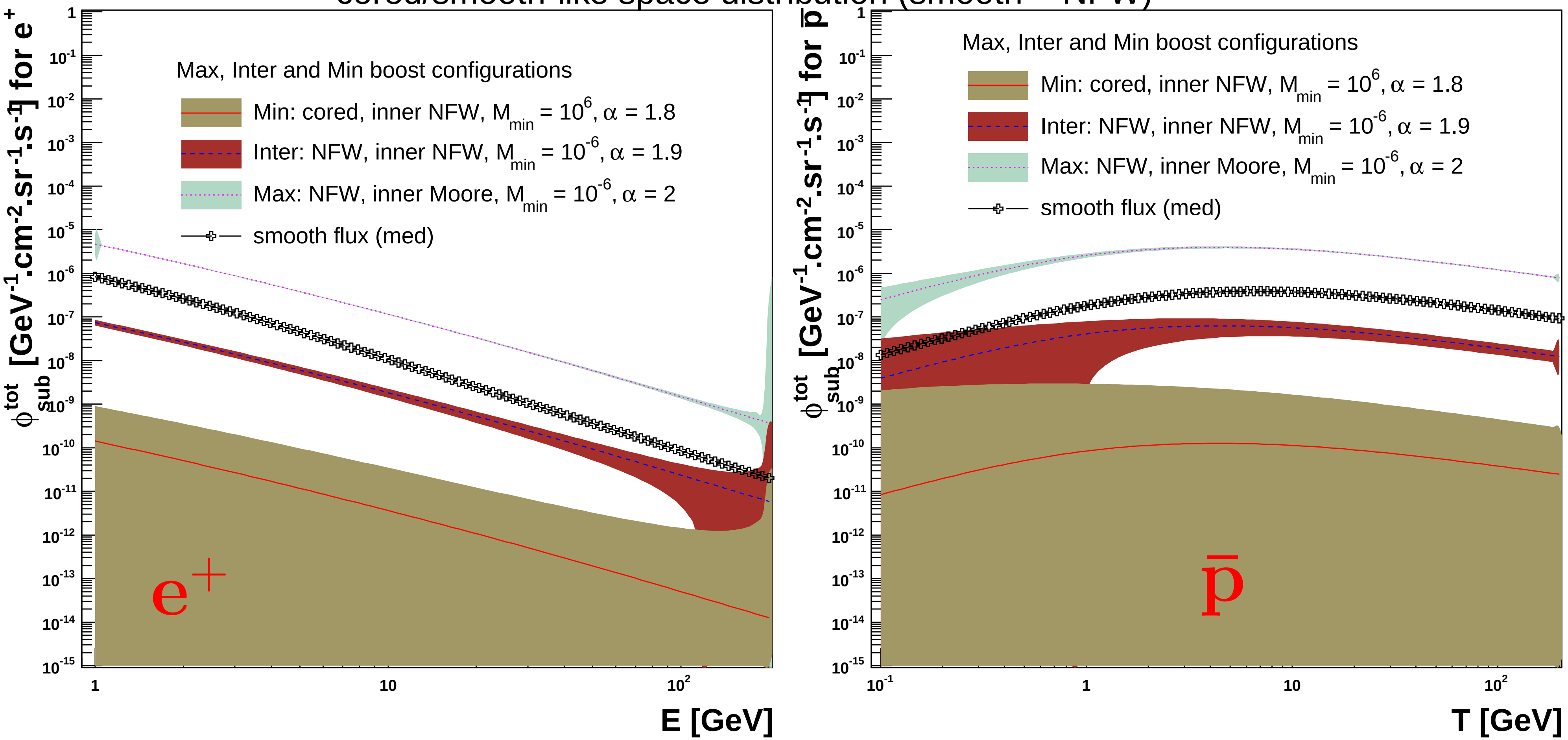
- Source: flat spectrum (1/GeV)

Both:

- Assume annihilation rate of $m_\chi = 200 GeV$ and $\langle \sigma v \rangle = 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
- Spectra between 0.1-200 GeV

Primary fluxes 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

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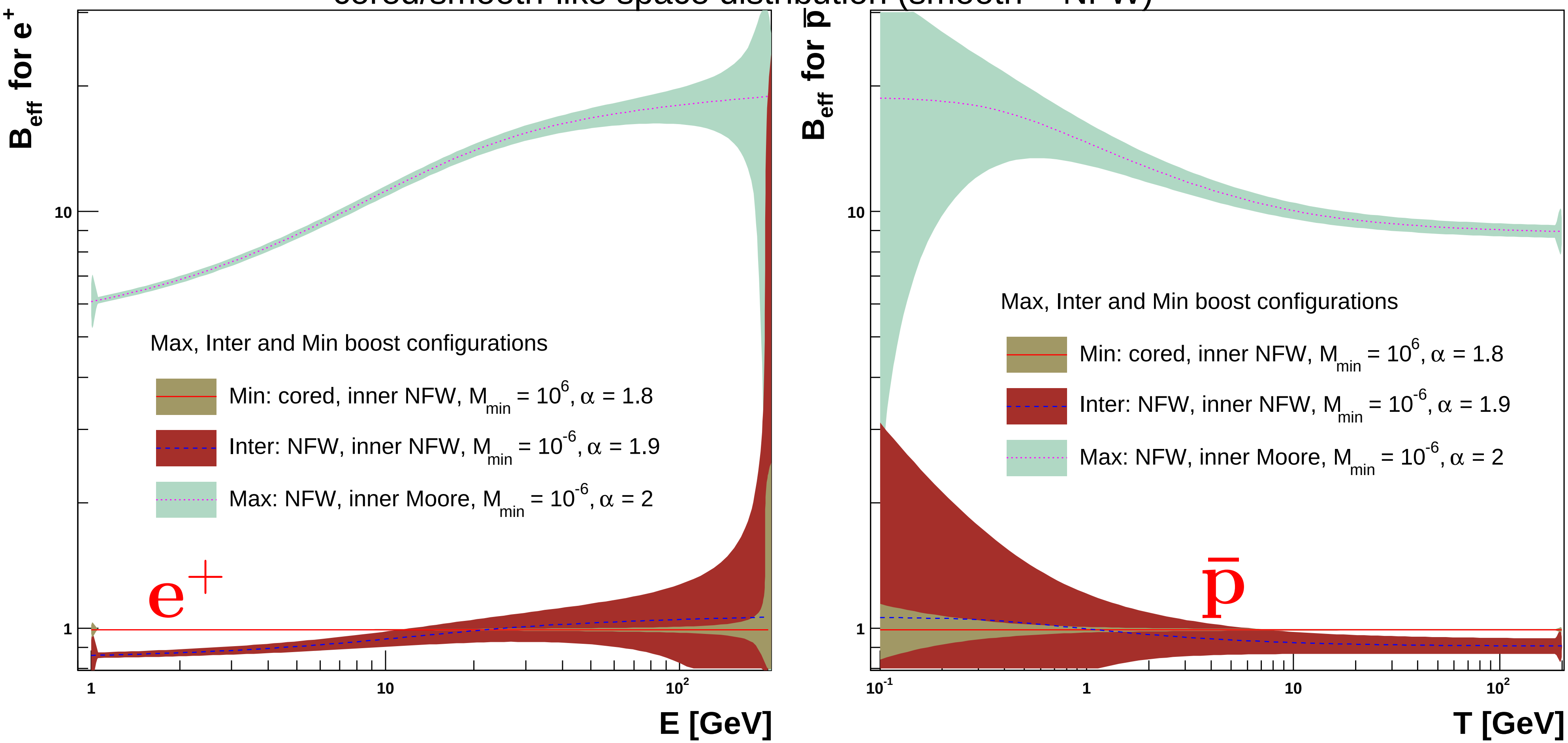

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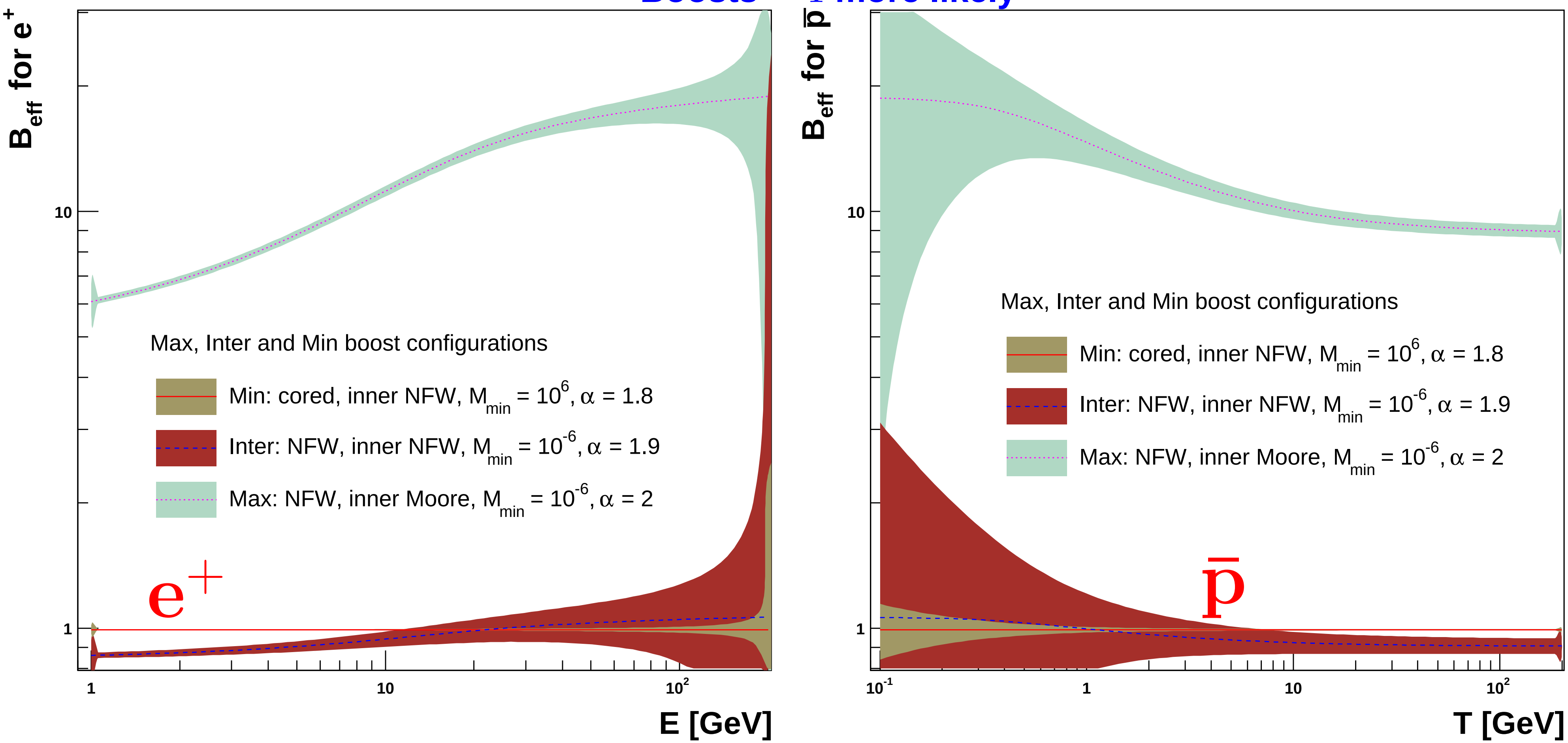
Small concentration models favored !!!

(e.g. Neto et al (2007), Springel et al (2008) – Aquarius)

Boosts ~ 1 more likely



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3D map of DM density from N-body simulations

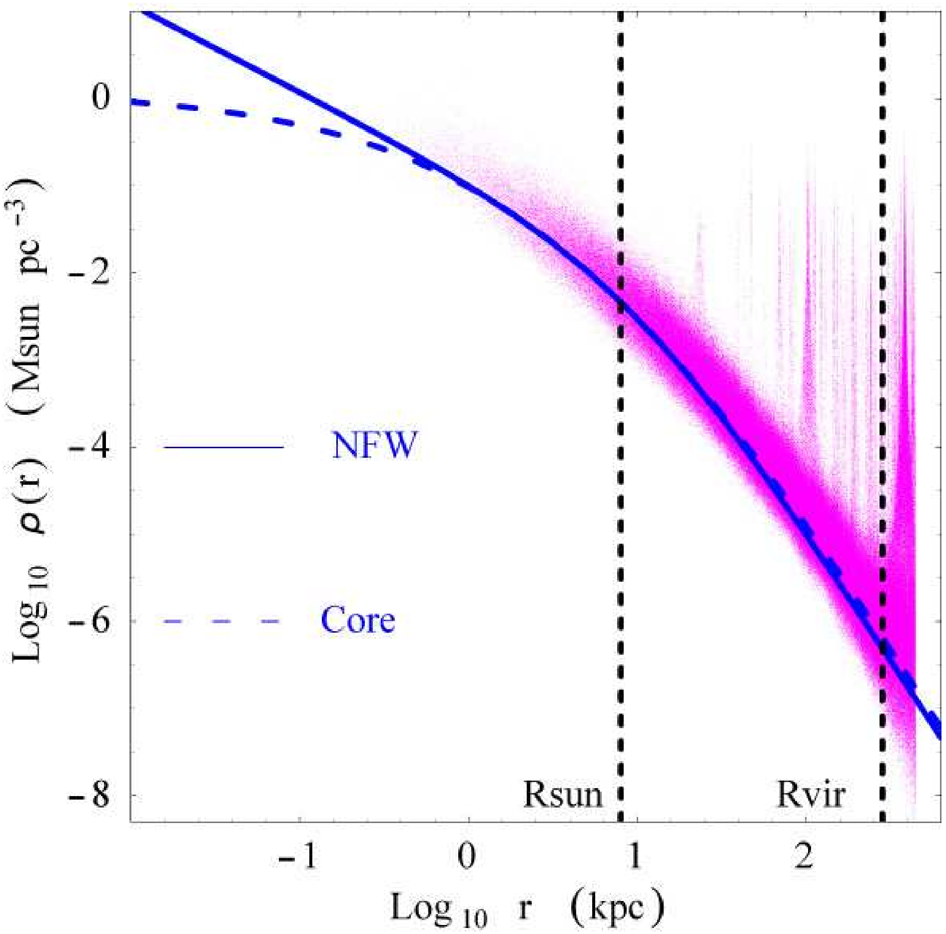
Going farther :
3D map of DM density from N-body simulations

(**arXiv:0808.0332**
Lavalle, Nezri, Ling, Athanassoula & Teyssier)

- N-body data from the HORIZON Project (Teyssier, 2002) – $M_{\rm res} = 10^6 M_\odot \; ; \; L_{\rm res} = 200$ pc
- Analysis already made for γ-rays (arXiv:0801.4673) – but not as good as Diemand et al(2008) or Springel et al (2008)
- $1^{\rm st}$ trial for GCRs: study of the effects due to actual density fluctuations and departure from spherical symmetry

Results: $\sim$ 1-2 order of magnitude uncertainty on antimatter flux (local density fluctuations or asphericity), but still below the data: no excess expected below 100 GeV.

Athanassoula, Ling, Nezri & Teyssier (arXiv:0801.4673)



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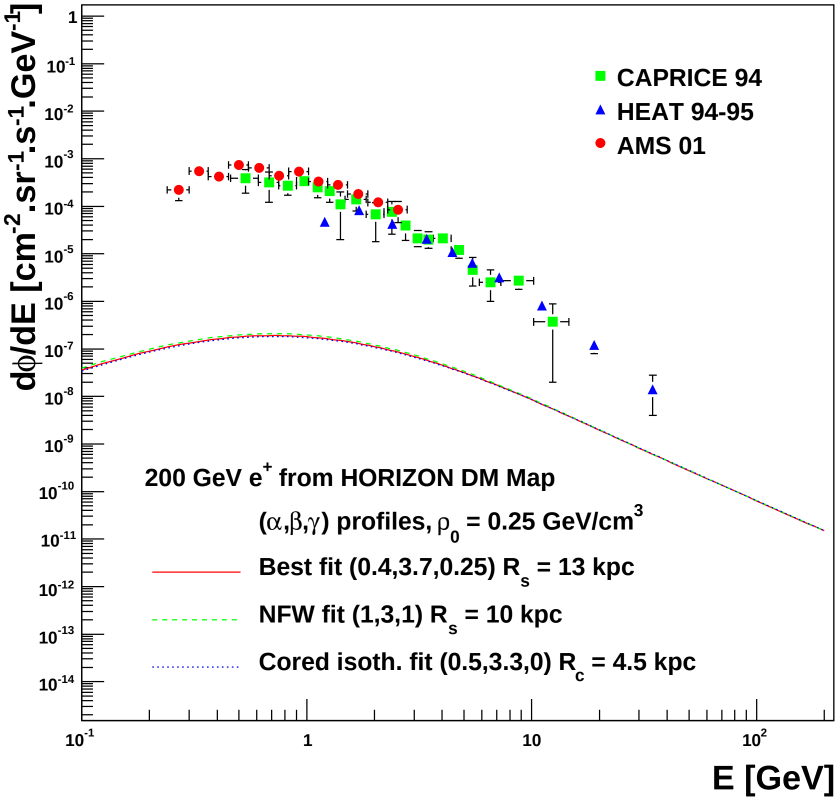
Different spherical fits give $\sim$ the same fluxes



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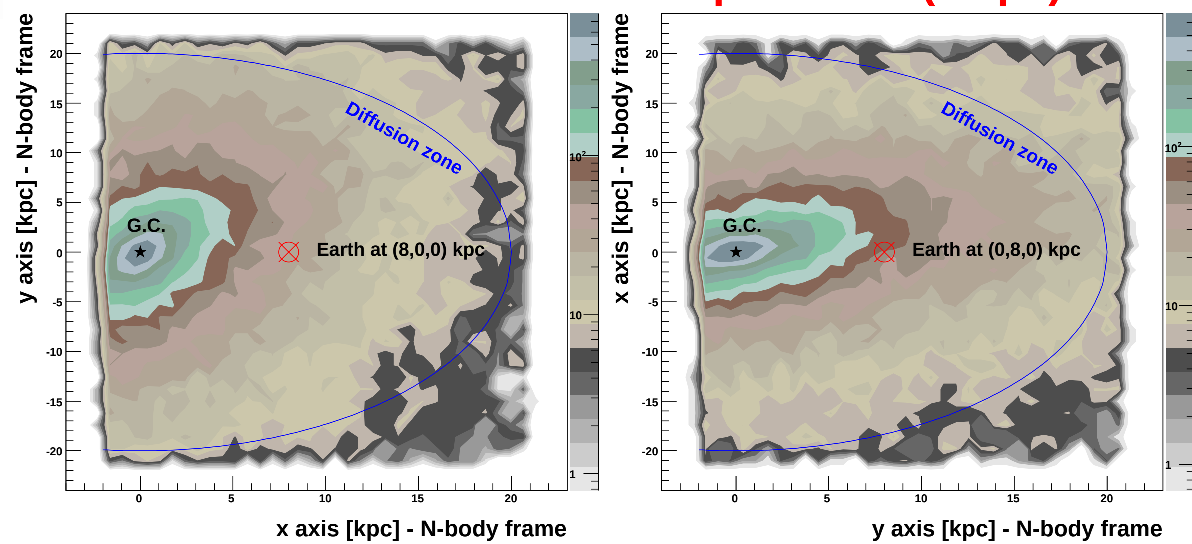
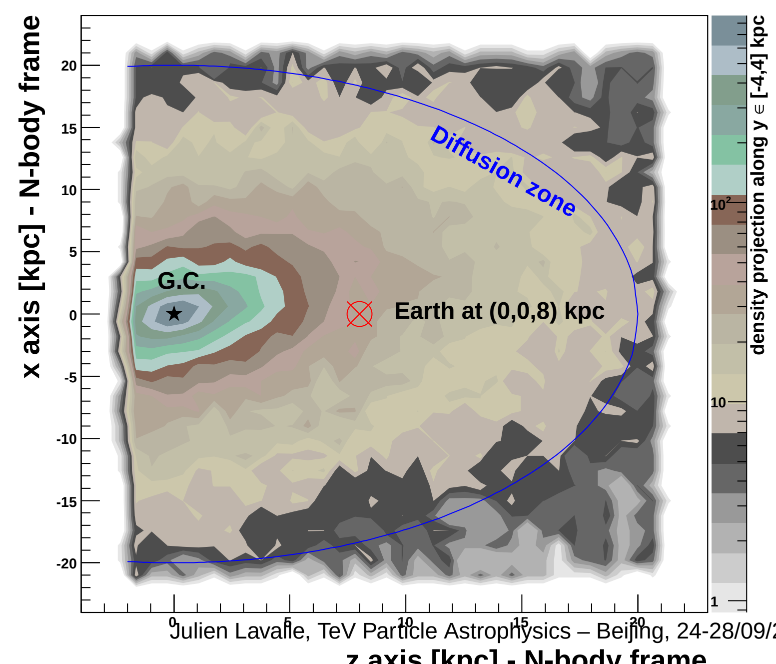
Earth at different 3 positions (8 kpc)





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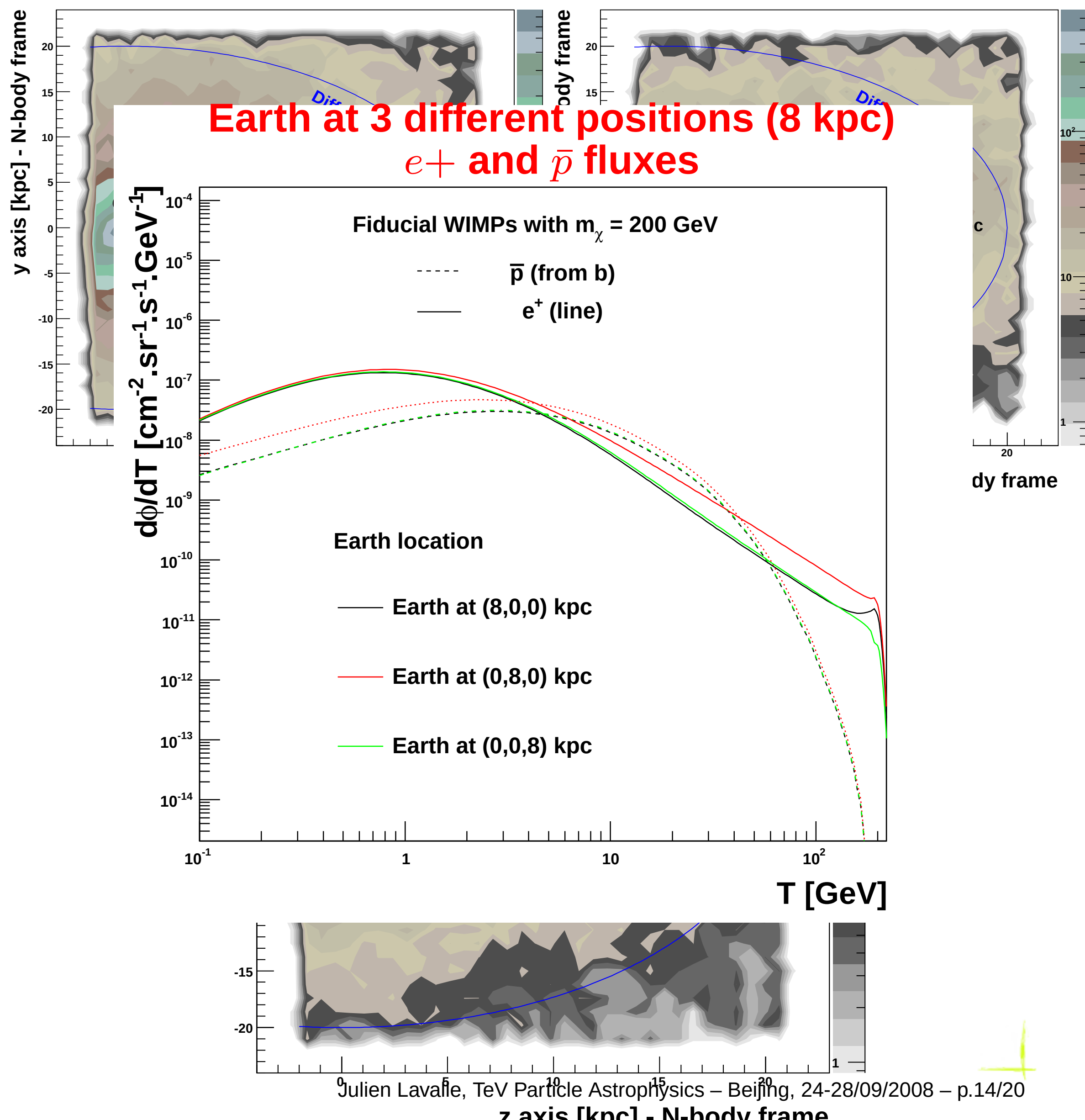

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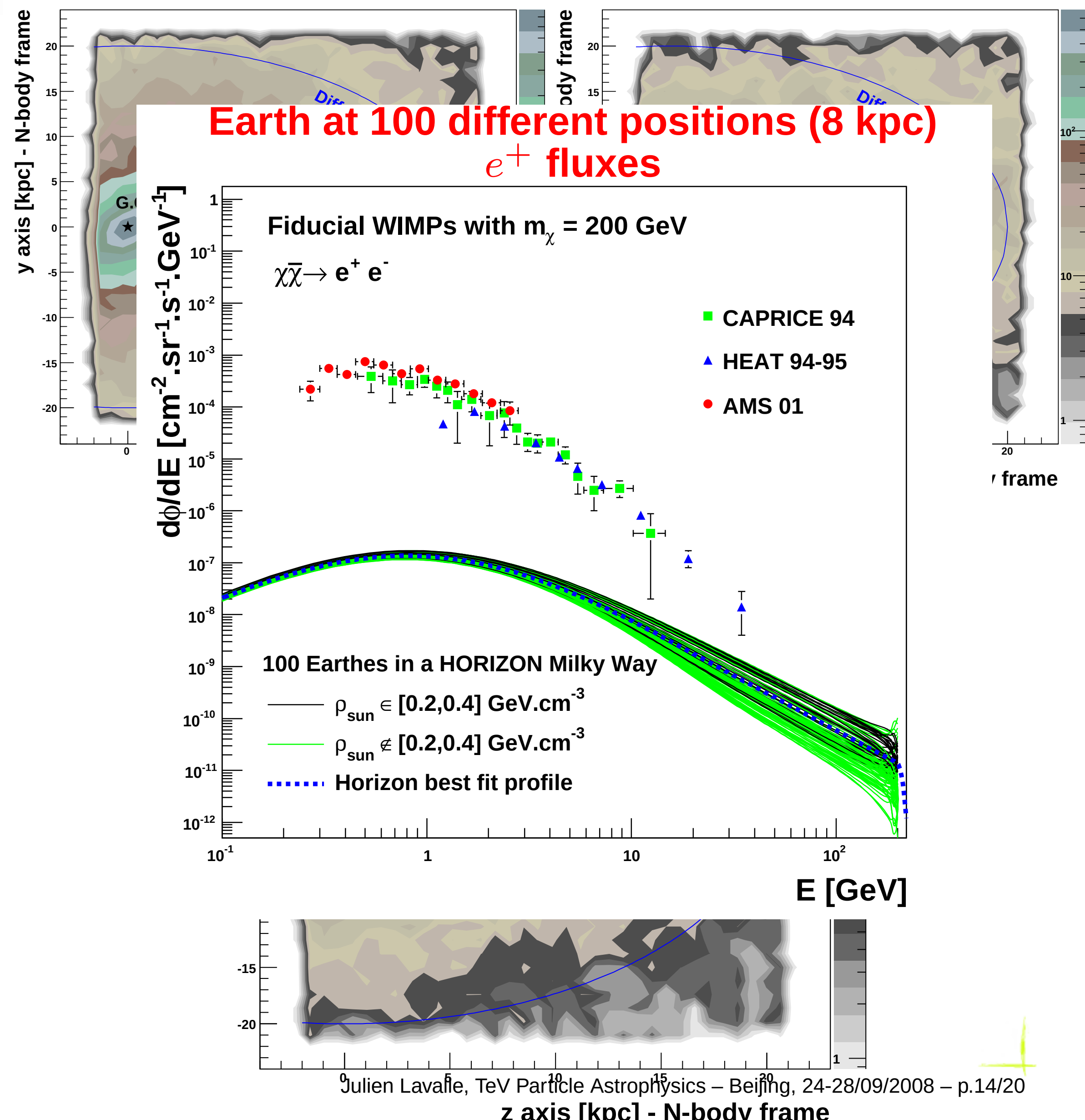

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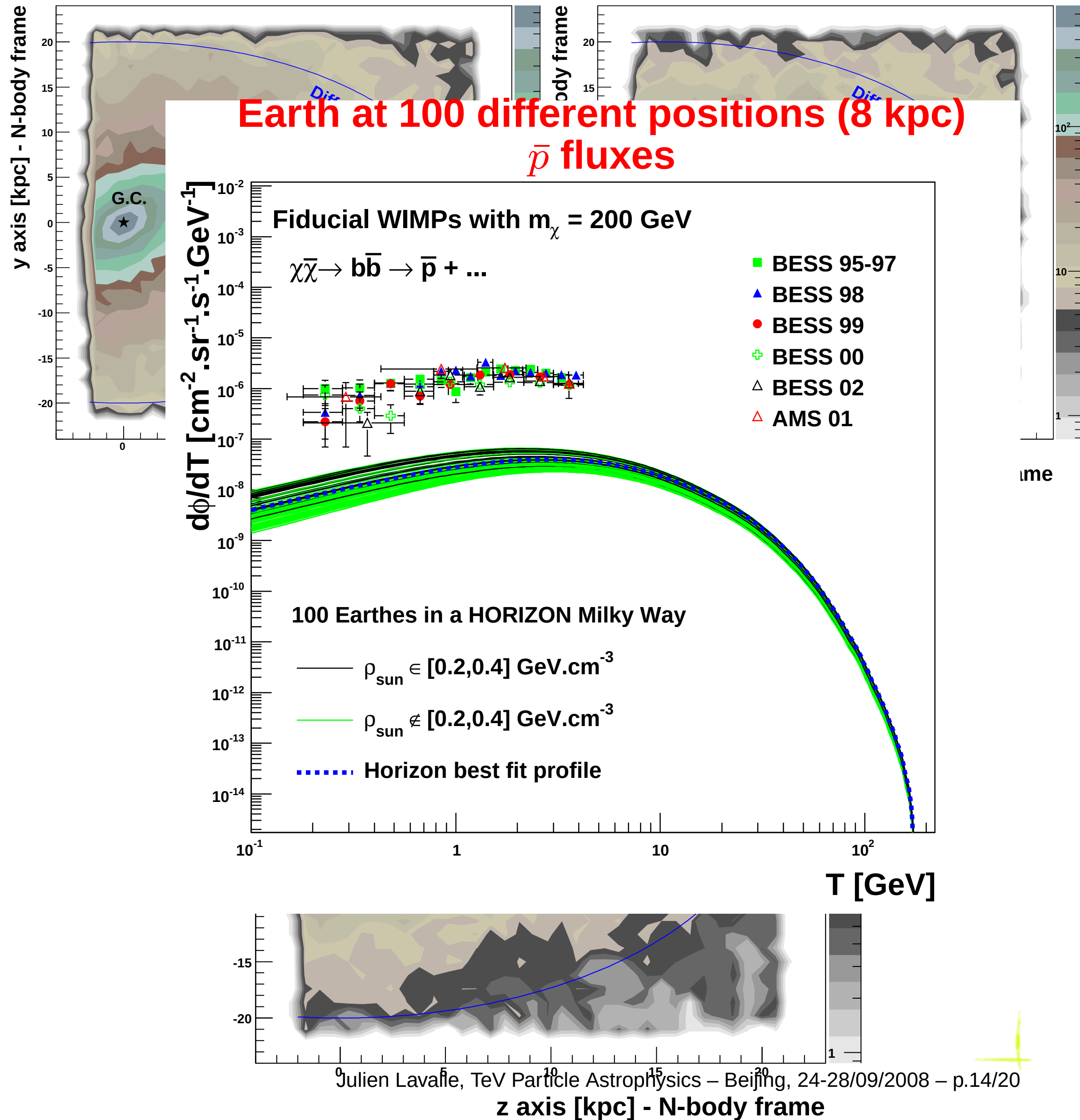

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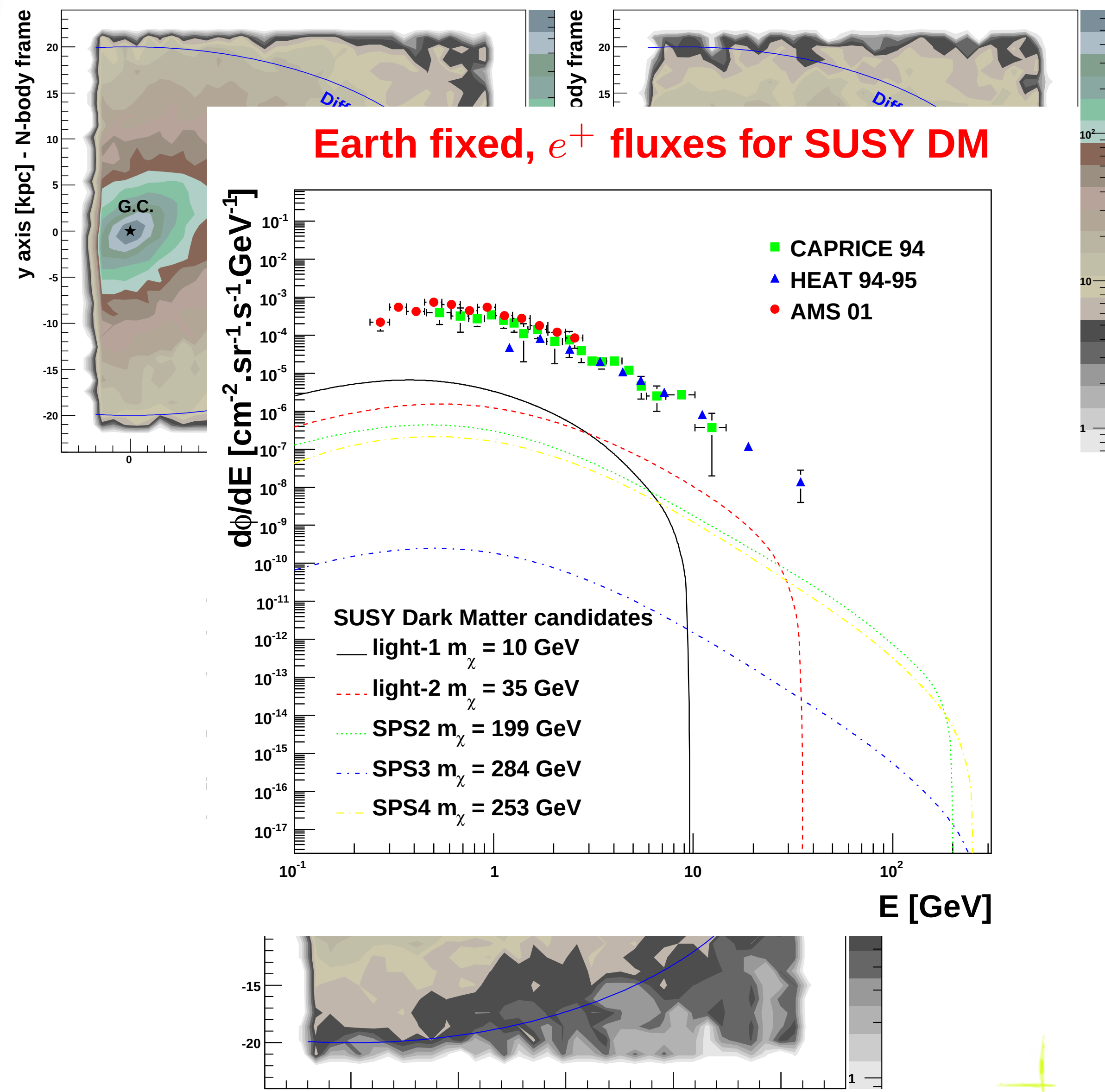
Lavalle, Nezri, Ling, Athanassoula & Teyssier)

- N-body data from the HORIZON Project (Teyssier, 2002) – $M_{\rm res} = 10^6 M_\odot$; $L_{\rm res} = 200$ pc
- Analysis already made for γ-rays (arXiv:0801.4673) – but not as good as Diemand et al(2008) or Springel et al (2008)
- $1^{\rm st}$ trial for GCRs: study of the effects due to actual density fluctuations and departure from spherical symmetry

Results: $\sim$ **1-2 order of magnitude uncertainty on antimatter flux (local density fluctuations or asphericity), but still below the data: no excess expected below 100 GeV.**



Going farther :

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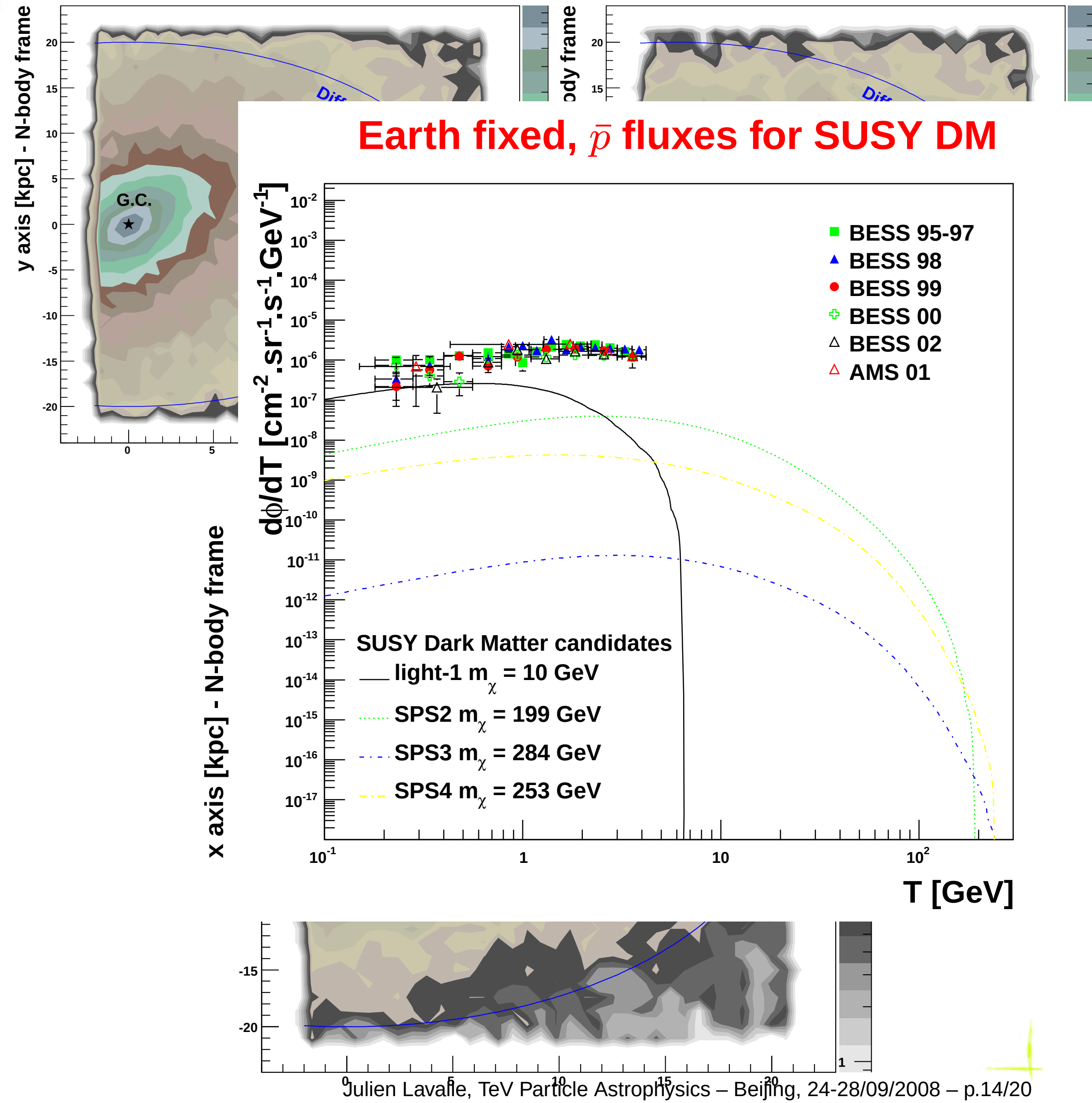

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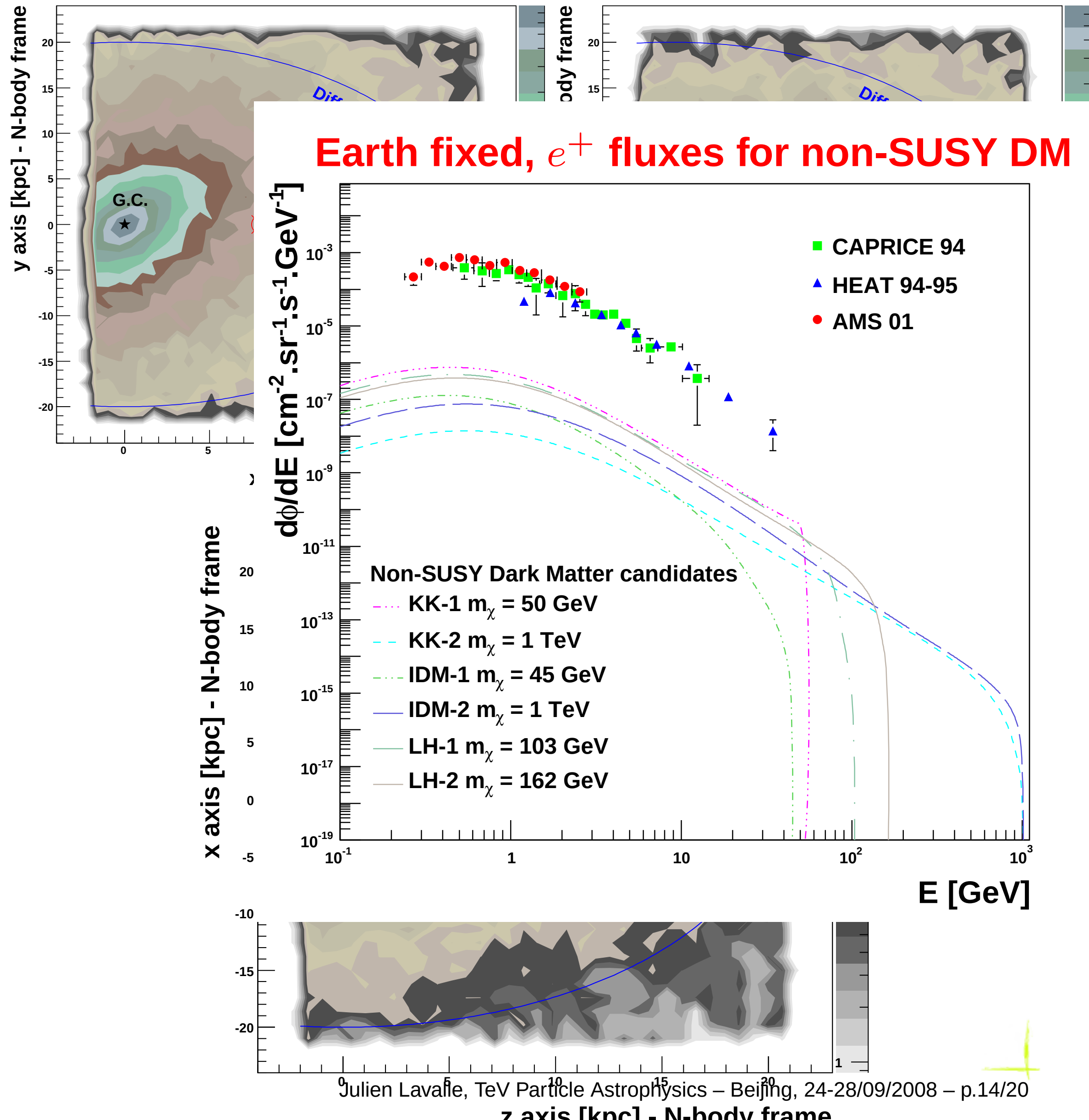

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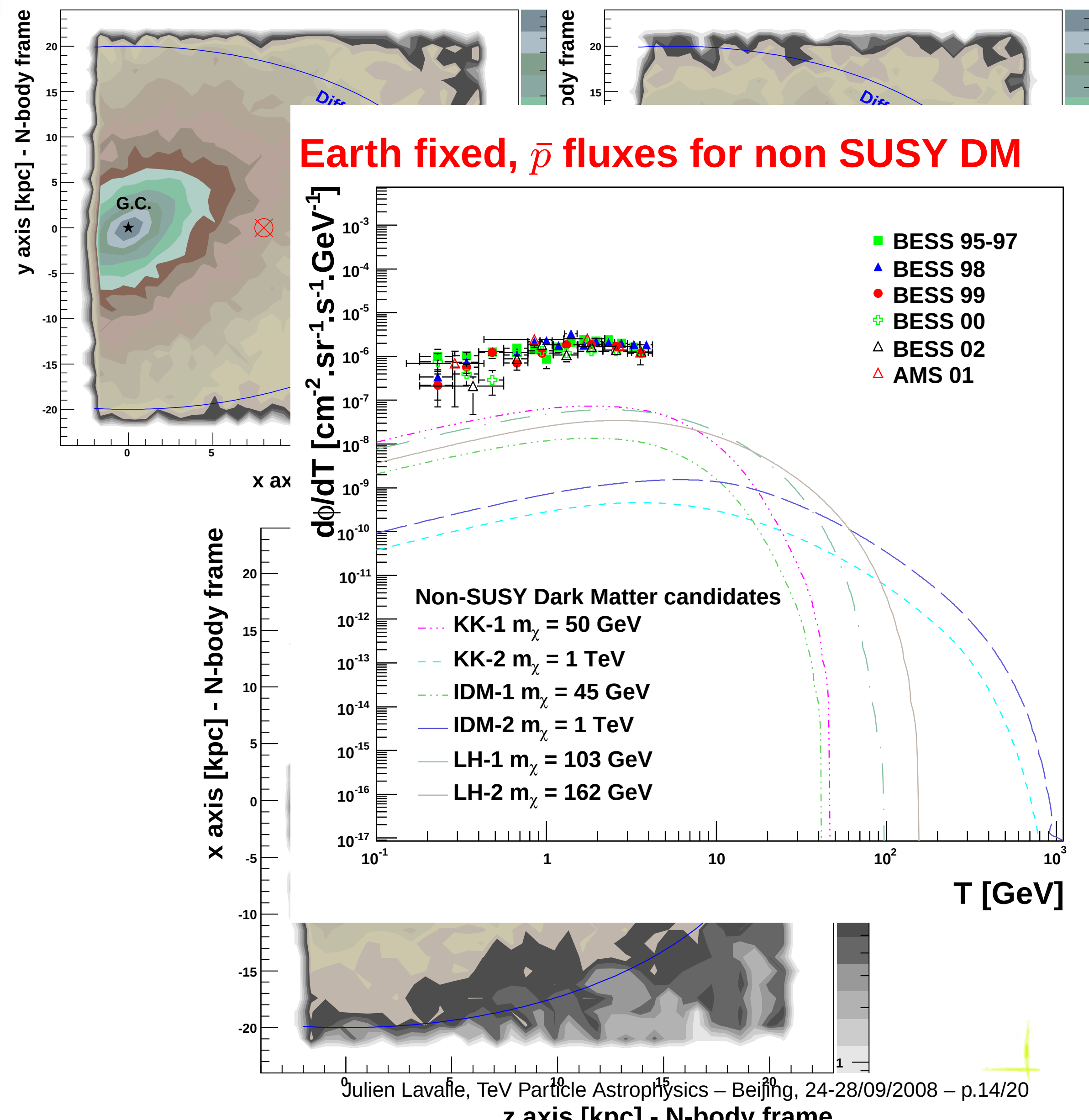
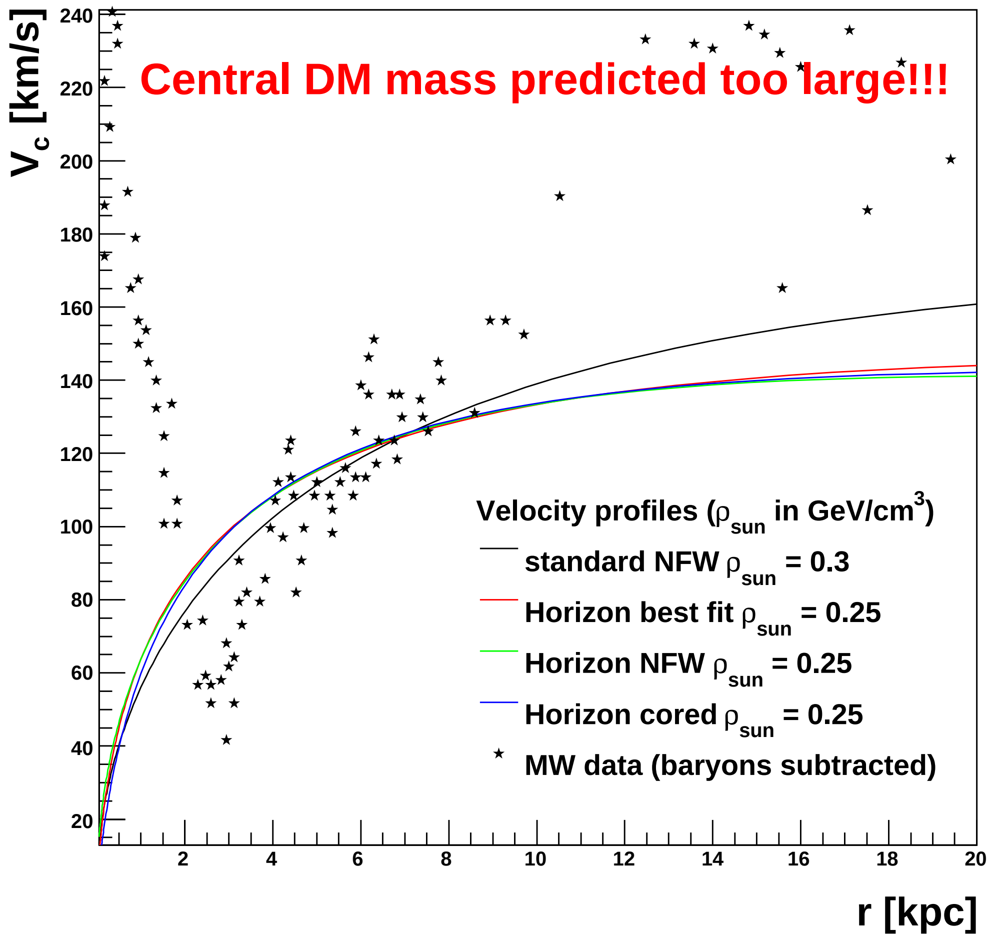


CAVEATS: too simplistic galaxy model

Rotation curves with baryon contribution subtracted
(Englmaier & Gerhard 2006, Bissantz & Gerhard 2002)

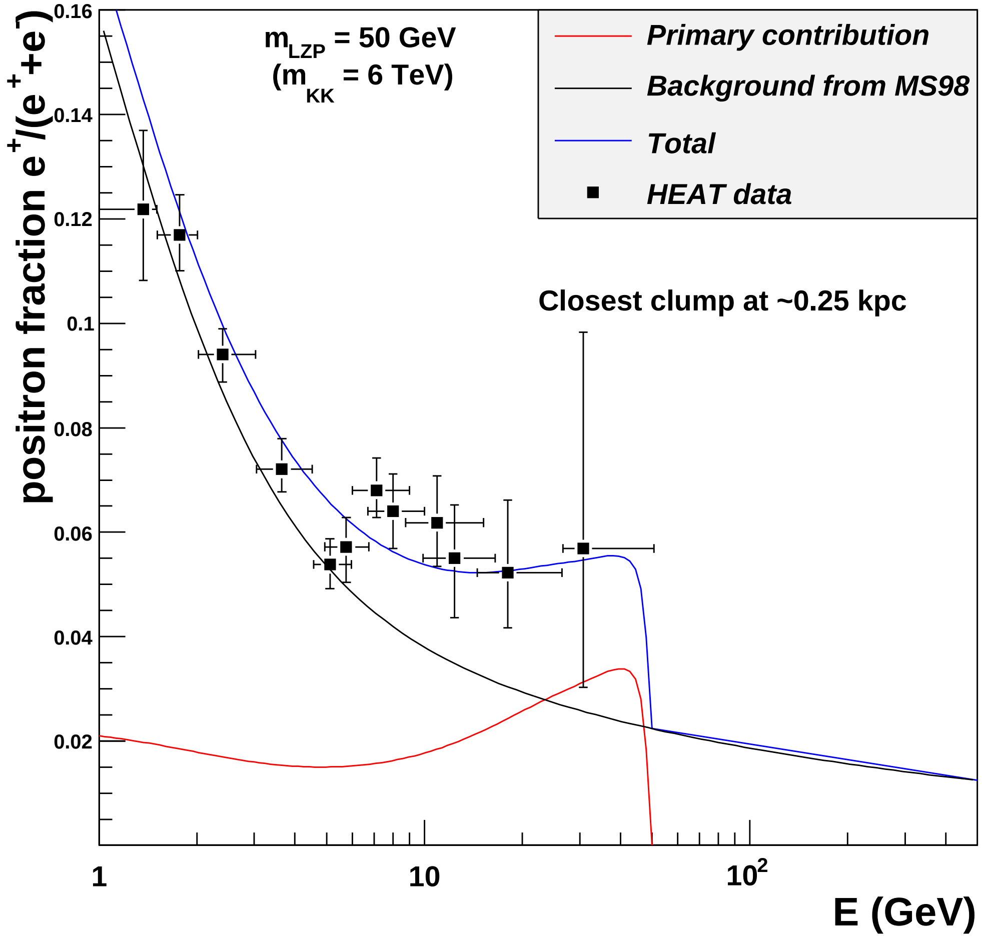


Lavalle, Nezri, Ling, Athanassoula & Teyssier – arXiv:0808.0332

WARNING:
theoretical uncertainties on backgrounds !!!!

Clump model and LKP dark matter:

Positron fraction (energy-dependent) **excess possible, but ...**



Lavalle, Pochon, Salati & Taillet – A&A 462, 827 (2007)

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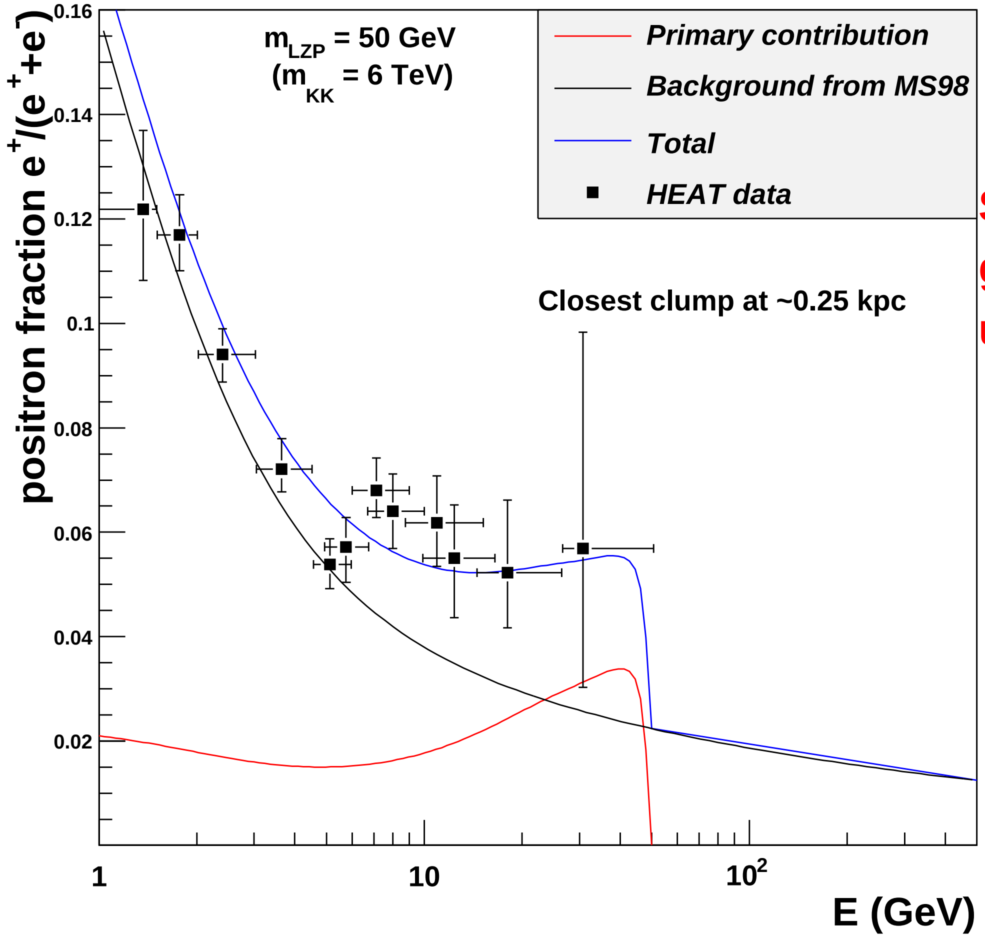

Self consistent back-gound predictions and uncertainties required!!!

Lavalle, Pochon, Salati & Taillet – A&A 462, 827 (2007)

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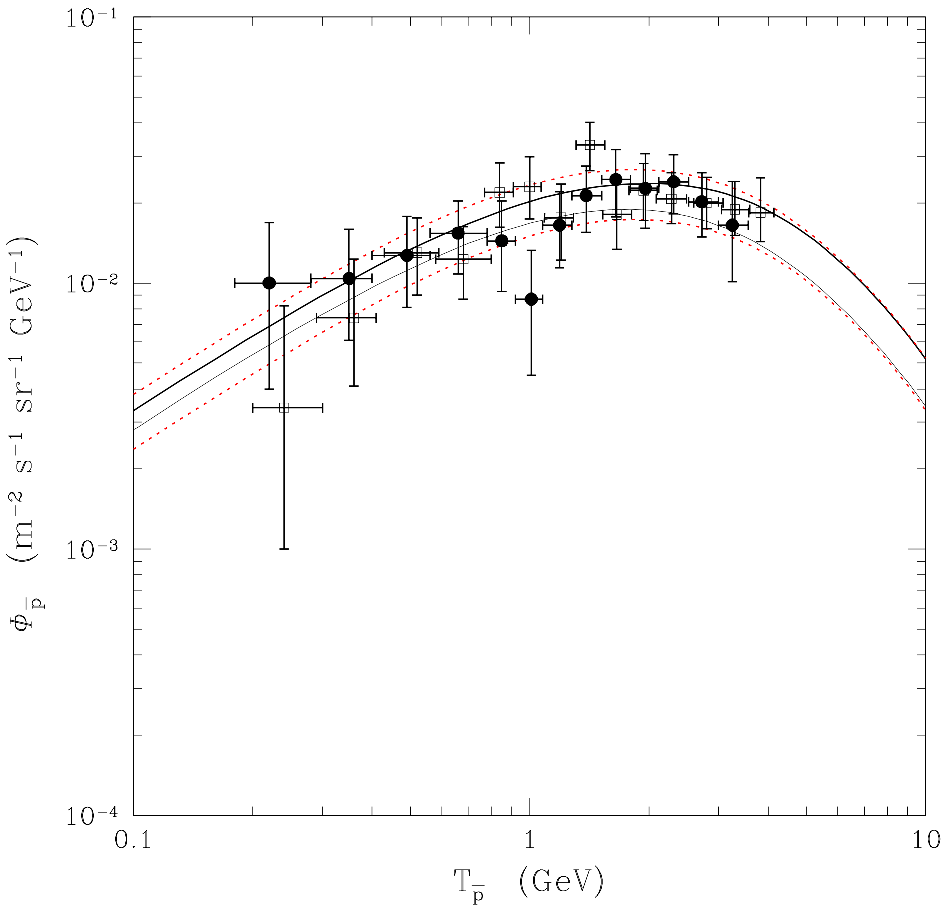
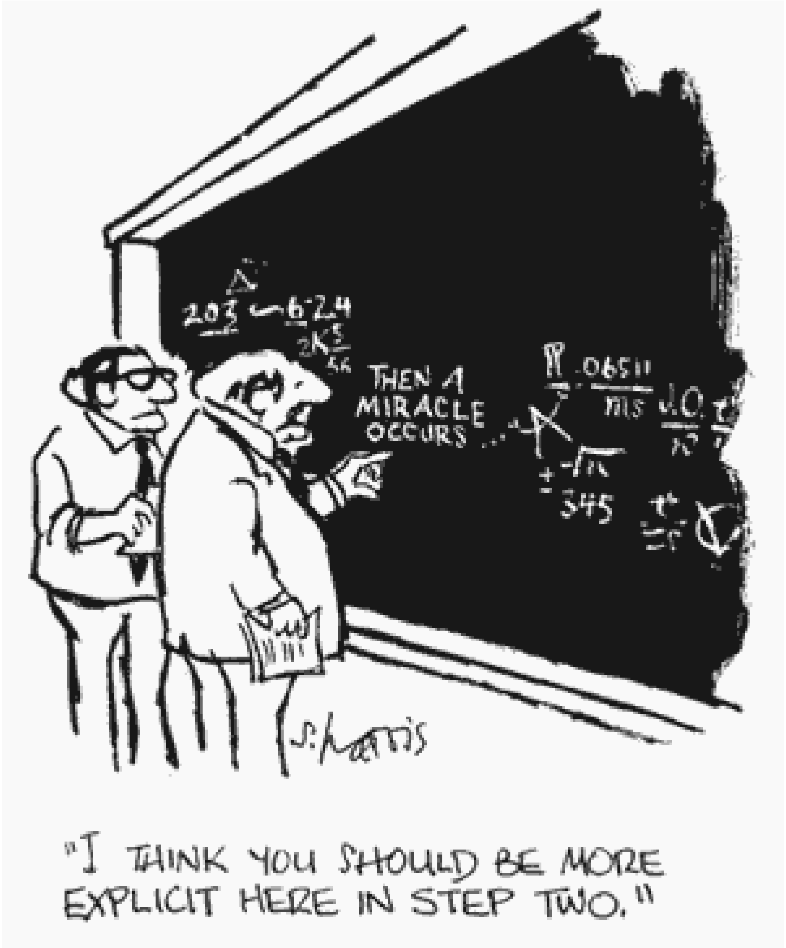
Maurin, Taillet et al (2002)

(antiprotons)



Delahaye et al, in prep (2008)

(positrons – preliminary)



Summary

I

We derived a method to account for DM inhomogeneities when predicting antimatter fluxes

- **Clump properties are still under debate, though their presence is now well accepted**
- **The observational effects of sub-halos are different for annihilation signatures in γ-rays and antimatter cosmic rays**
- **Boost factors for antimatter CRs < 20 !!!**
- **This study provides estimates of the combined theoretical uncertainties due to both (i) DM inhomogeneities (ii) CR propagation**

II **We need high energy data: where the background is falling down**

III

Estimate of theoretical uncertainties on the e^+ bgd is mandatory: Delahaye et al in prep

IV **Need of better constraints on propagation parameters: PAMELA results soon (AMS-02 later)**

V **Complementarity with other messengers (γ, ν) and detection methods! (LHC will help)**