Dark Matter, Clumpiness

and

Positron propagation in the Galaxy

Julien Lavalle

CPPM IN2P3/CNRS - Université Aix-Marseille II

(Collaboration with J. Pochon, P. Salati and R. Taillet – LAPTH Annecy)

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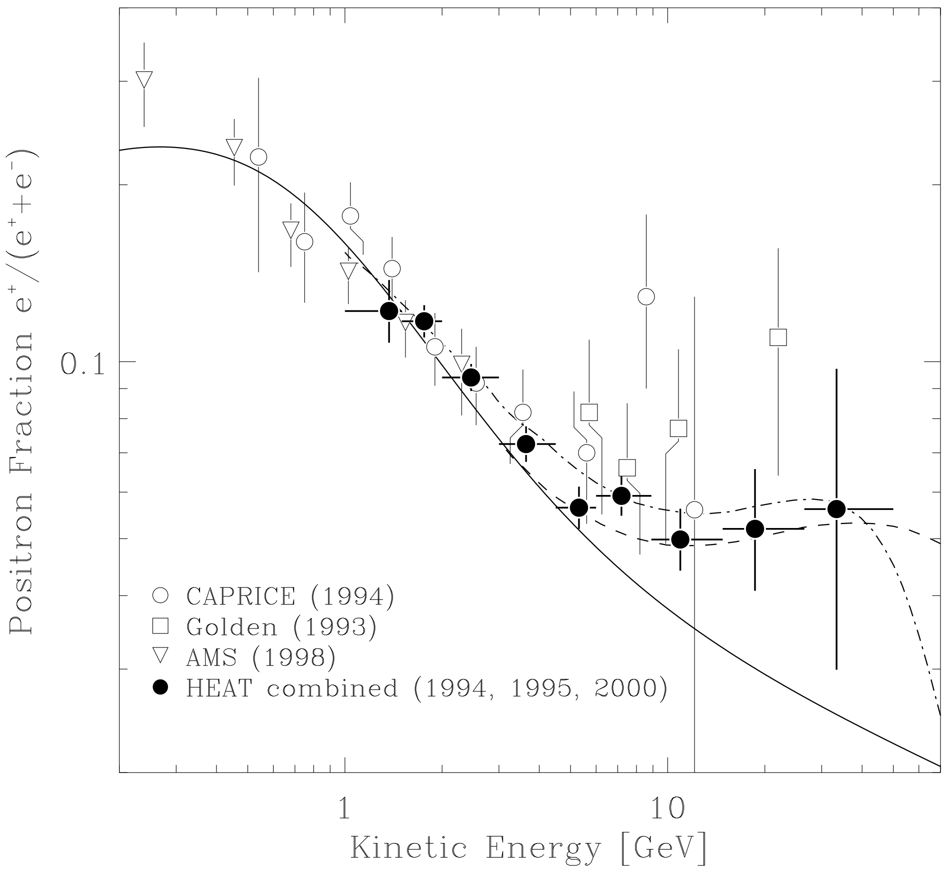
Outline

- Motivations
- Dark matter distribution in the Galaxy
- Cosmic ray propagation in the Galaxy
- The specific case of positrons
  - What does *boost* mean ?
  - Signal distorsion
  - Statistical properties
- Conclusions

Motivation 1 : The specific case of positrons

- Motivations come from HEAT results (1997 & 2000).
- Predictions for secondary positrons do not fit the $(e^+)/(e^- + e^+)$ spectrum (Strong & Moskalenko, 1998).
- Since then, many attempts to fit with annihilating dark matter :
  - SUSY : Baltz & Edsjo (1999), de Boer et al (2003)
  - KK : Hooper et al. (2004) – positron line !
  - **They all require boost factors.**

Beatty et al, 2004



Motivation 2 : The hot debate about clumpiness

Earth-mass dark-matter haloes as the first structures in the early Universe

J. Diemand[1*], B. Moore[1] & J. Stadel[1],

[1] Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

Before a redshift z=100, about 20 million years after the big bang, the universe was nearly smooth and homogenous.[1] After this epoch tiny fluctuations imprinted in the matter distribution during the initial expansion began to collapse via gravitational instability. The properties of these fluctuations depend on the unknown nature of dark matter,[2–4] which is one of the biggest challenges in present day science.[5–7] Here we present supercomputer simulations of the concordance cosmological model assuming neutralino dark matter and find the first objects to form are numerous earth mass dark matter halos about as large as the solar system. They are stable against gravitational disruption, even within the central regions of the Milky Way, and we expect over 10^{15} to survive within the Galactic halo with one passing through the solar system every few thousand years. The nearest structures will be amongst the brightest sources for gamma-rays from particle-particle annihilation.

DARK MATTER DISTRIBUTION

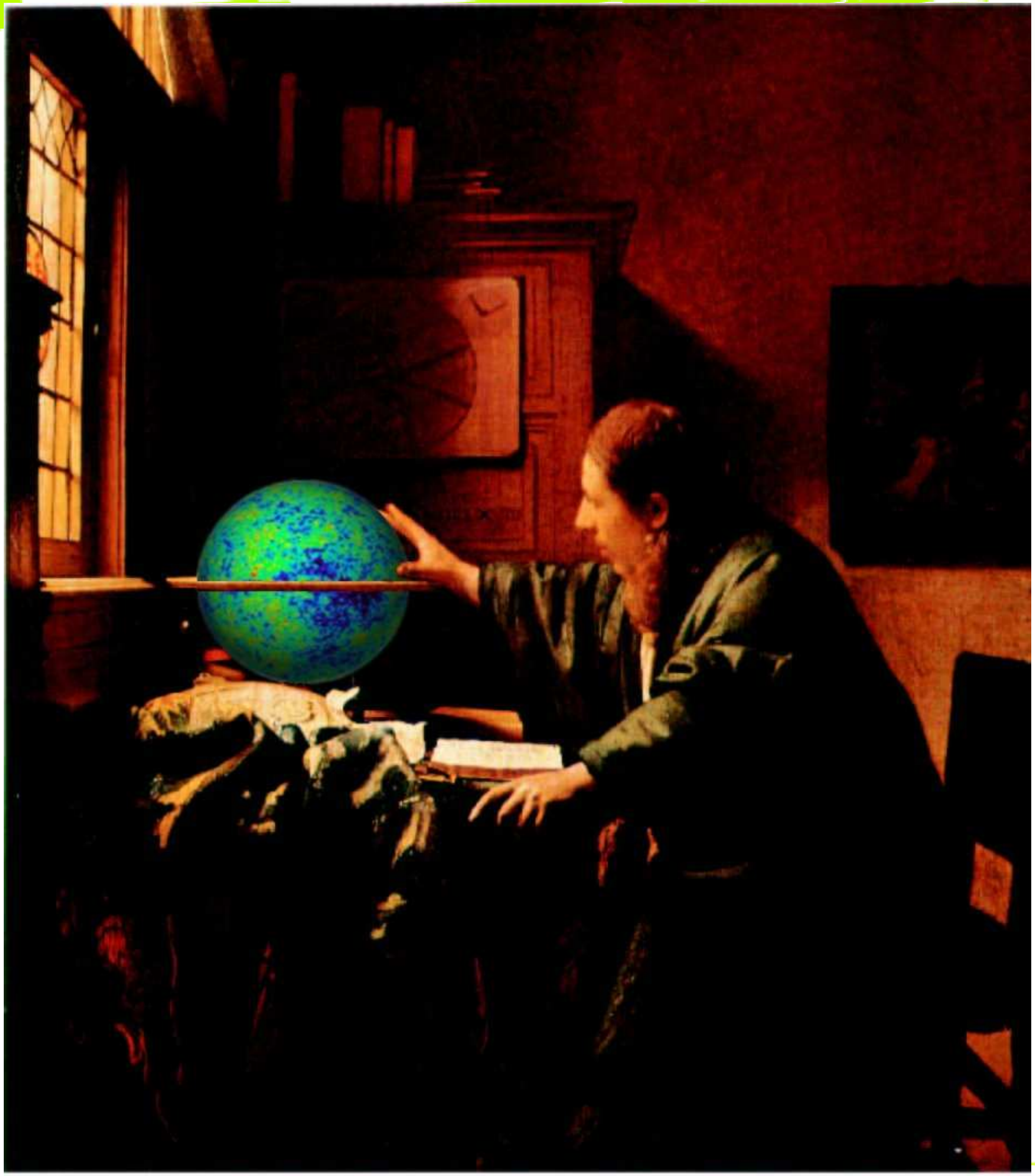
The cosmological budget : how much dark matter ?

WMAP gives :

$$\Omega_{\rm matter} \sim 0.3$$
$$\Omega_{\Lambda} \sim 0.7$$

and provides initial conditions for structure formation.

The quantum nature of Dark Matter can be constrained by relic density calculations, which depend on particle interactions and on the early universe content $\longrightarrow$ many good candidates (SUSY, KK, etc) !



Vermeer-WMAP by R. Taillet
http://lappweb.in2p3.fr/∼taillet/

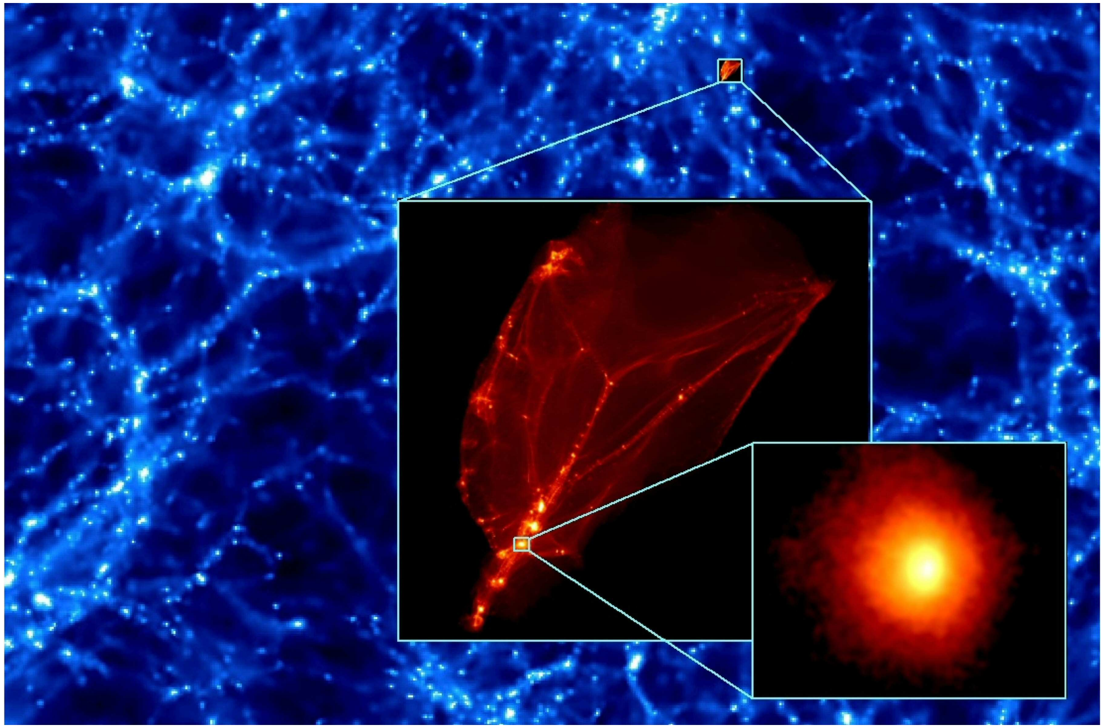
Dark matter and structure formation

- All observed structures result from gravitational collapse of density inhomogeneities (Peebles, ApJ 1967)
- The growth of structures is affected by free streaming, violent relaxation (Lyndell-Bell, MNRAS 1967) and tidal effects
- In the CDM paradigm, small structures form first (because large scale inhomogeneities are causally disconnected)
- **Many uncertainties, e.g : central cores/cusps ? clumpiness ? tidal effects ?**
- Two complementary schools : analytical (e.g. Gurevich, Berezinsky, Joyce, etc), numerical (Navarro-Frenk-White, Moore, etc)

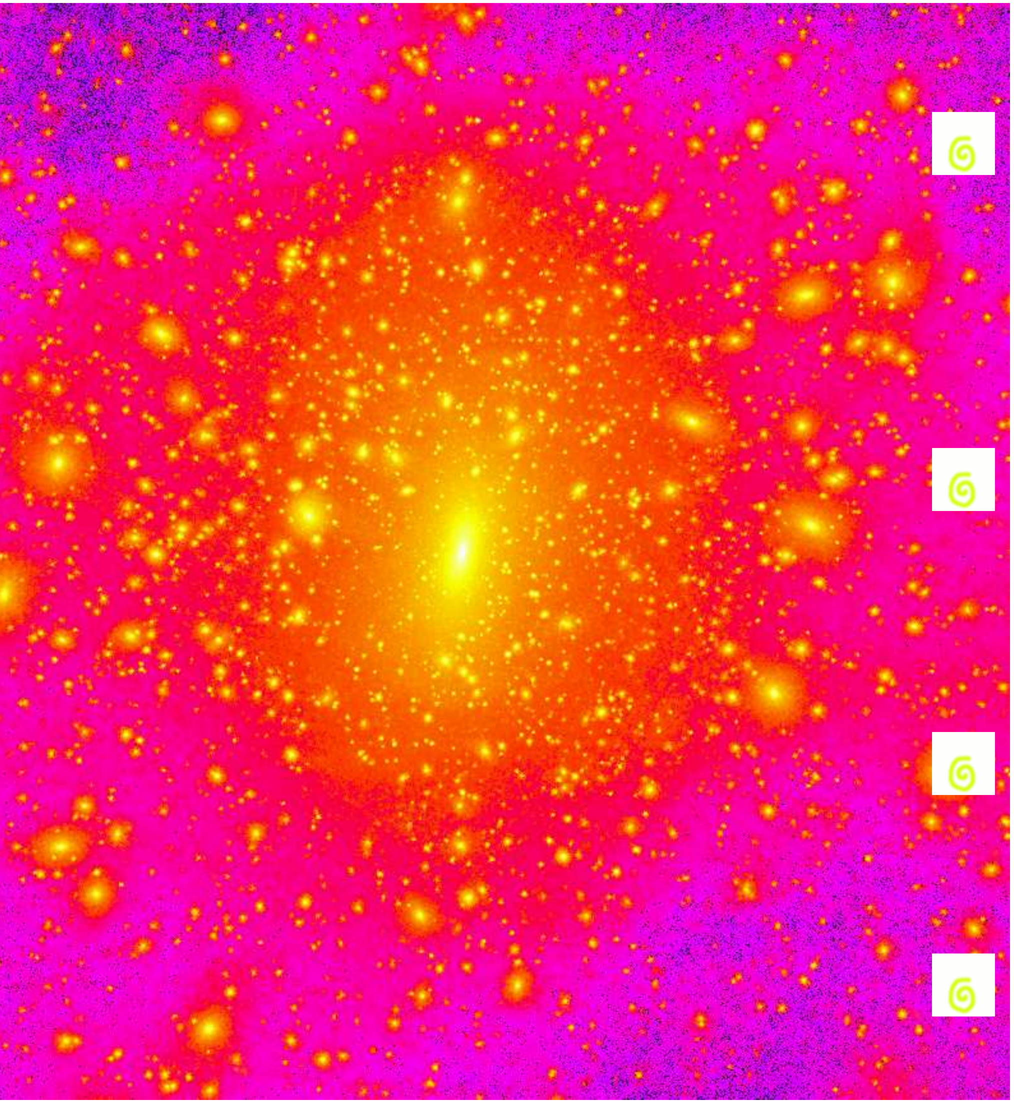
Dark matter distribution

What is the dark matter density profile in galaxies ?

- Lyndell-Bell (1967): isothermal $\rho \propto r^{-2}$
- Navarro-Frenk-White (1998) : $\rho \propto r^{-1}$
- Moore (1999) : $\rho \propto r^{-1.5}$
- Effects of adiabatic compression, angular momentum exchange, etc.



Substructures: How clumpy is the world we live in ?



(picture by B. Moore)

- Free streaming defines the minimal mass of substructures (Berezinsky et al, 2003) $\sim 10^{-8} M_{\odot}$ for a 100 GeV neutralino
- Substructures are predicted, and seen in numerical simulations, but the smallest ones are believed to be disrupted by tidal effects. Beresinsky says their surviving probability is $\sim$ 0.1-0.5%.
- Recently, Diemand et al (Nature, 2005) claim from their simulation results that a **huge amount of small clumps may survive and populate the Galaxy** : $\sim 1000 \mathrm{pc}^{-3}$, with $10^{-6} M_{\odot}$!
- Zhao et al (2005) attack : these clumps should have been disrupted by tidal effects due to stars in the galactic disc !
- Moore responds : they survive because the timescale is too short ! (... we'd like such interesting debates in politics !)

Issues connected to indirect detection

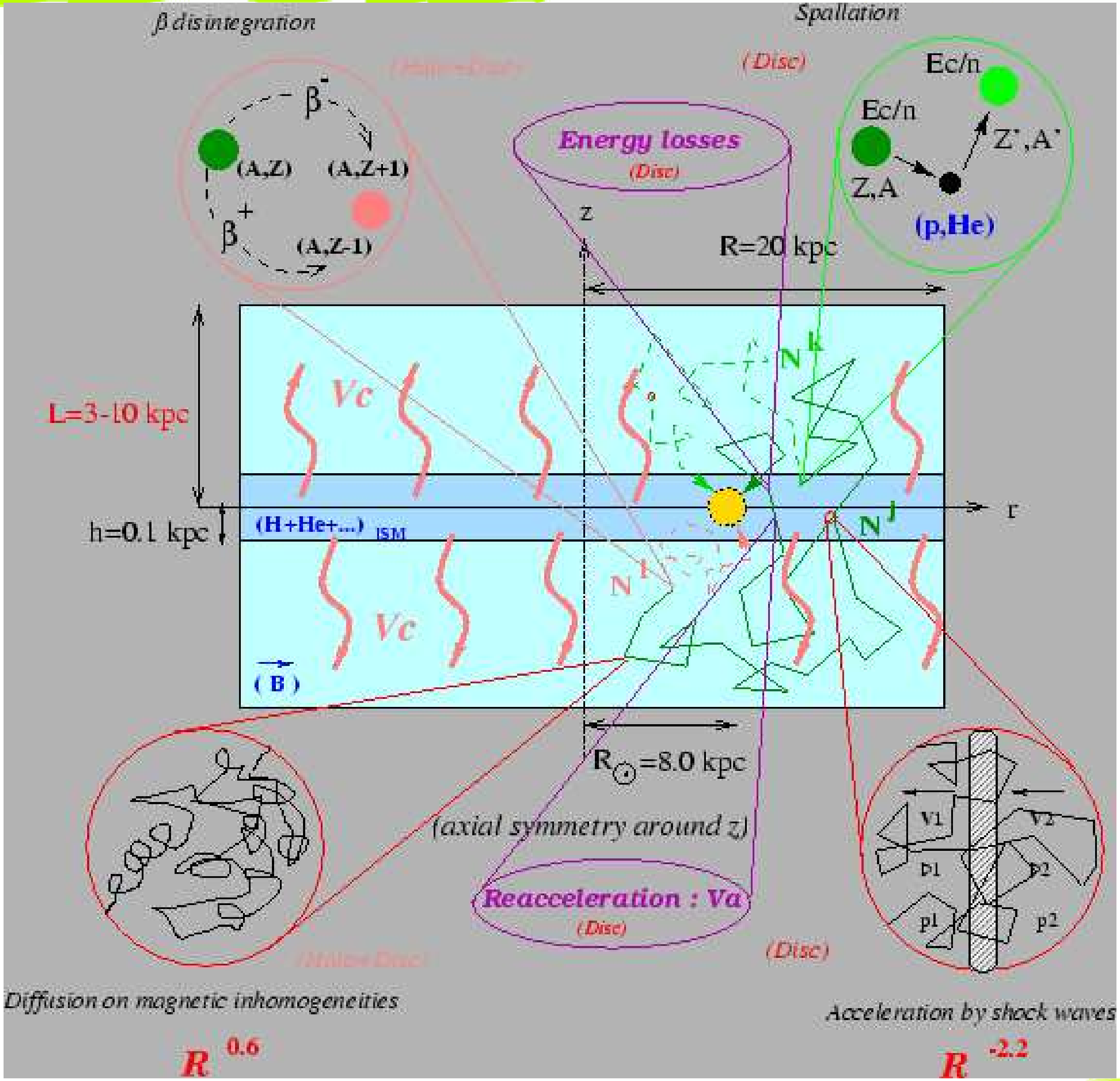
- **What is the density profile shape in the centres of galaxies ?**
  - (this drives the annihilation rate $\propto (\rho/m_\chi)^2$)
- **How numerous, massive and concentrated are clumps, if so ?**
  - (this could enhance a lot expected signals – *boost factor*)

COSMIC RAY PROPAGATION

Cosmic ray diffusion : the standard picture

- Diffusive cylindrical halo :
  $R \sim 20\text{kpc}, \text{L} \sim 3\text{kpc}$
  spallation on ISM and diffusion on magnetic inhomogeneities
- Disc ($h \sim 0.1\text{kpc}$) :
  convection and reacceleration in addition

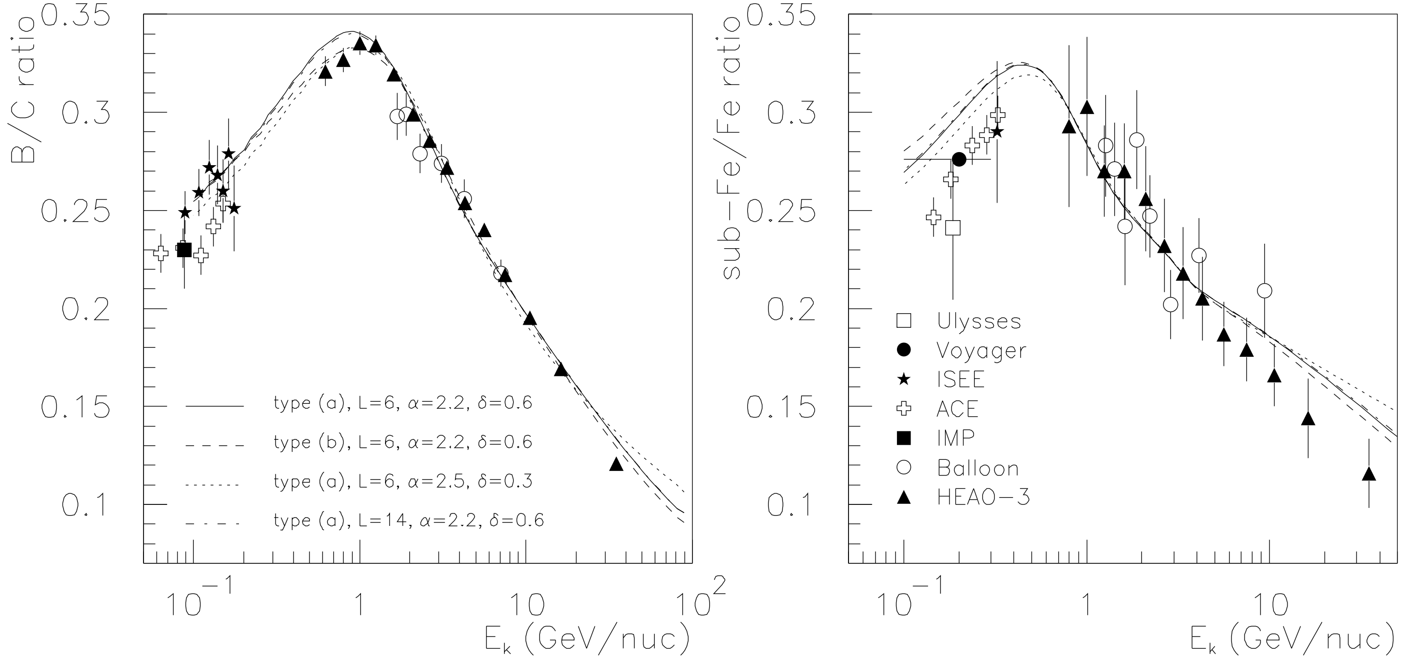
..... (Figure by D. Maurin)



Cosmic ray diffusion : constraints

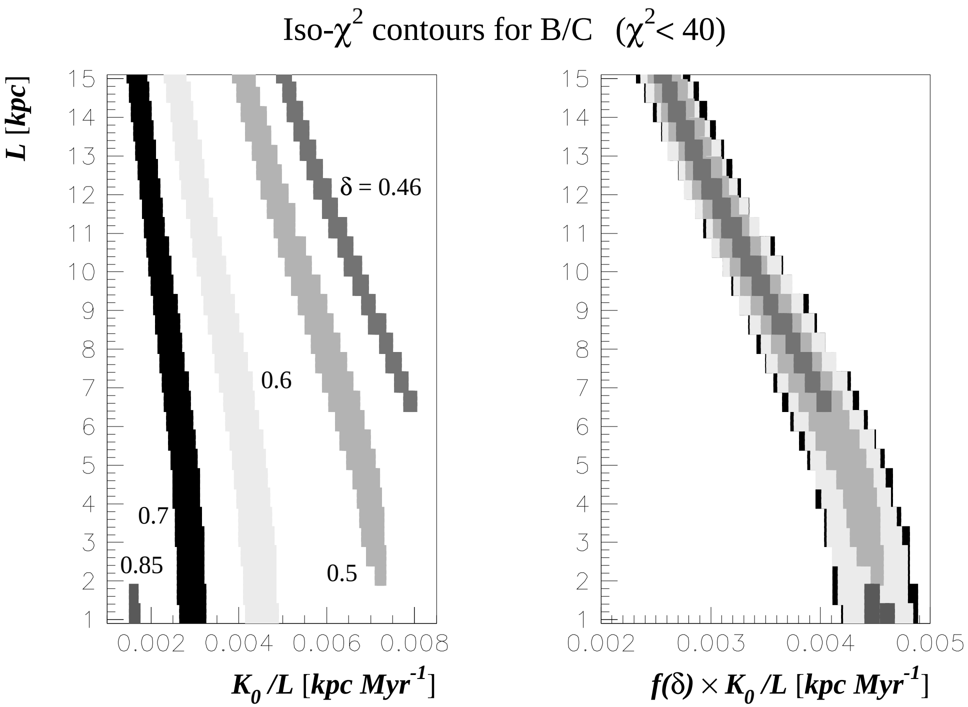
Secondary/Primary : $I^{\text{ary}} + (p, \text{He}, ...) \rightarrow ... + \text{II}^{\text{ary}}$ (spallation). Better kowledge of nuclear cross sections for B/C : usually used to fit the propagation parameters

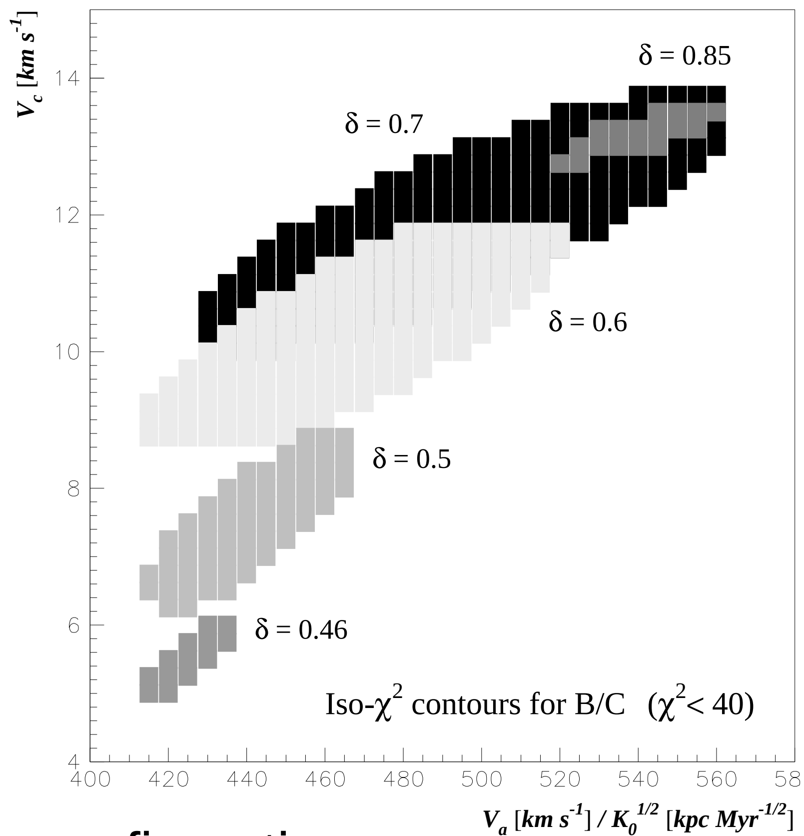
Maurin, Taillet et al., 2002



Cosmic ray diffusion : parameter degeneracy

Maurin, Salati, Taillet et al., 2001





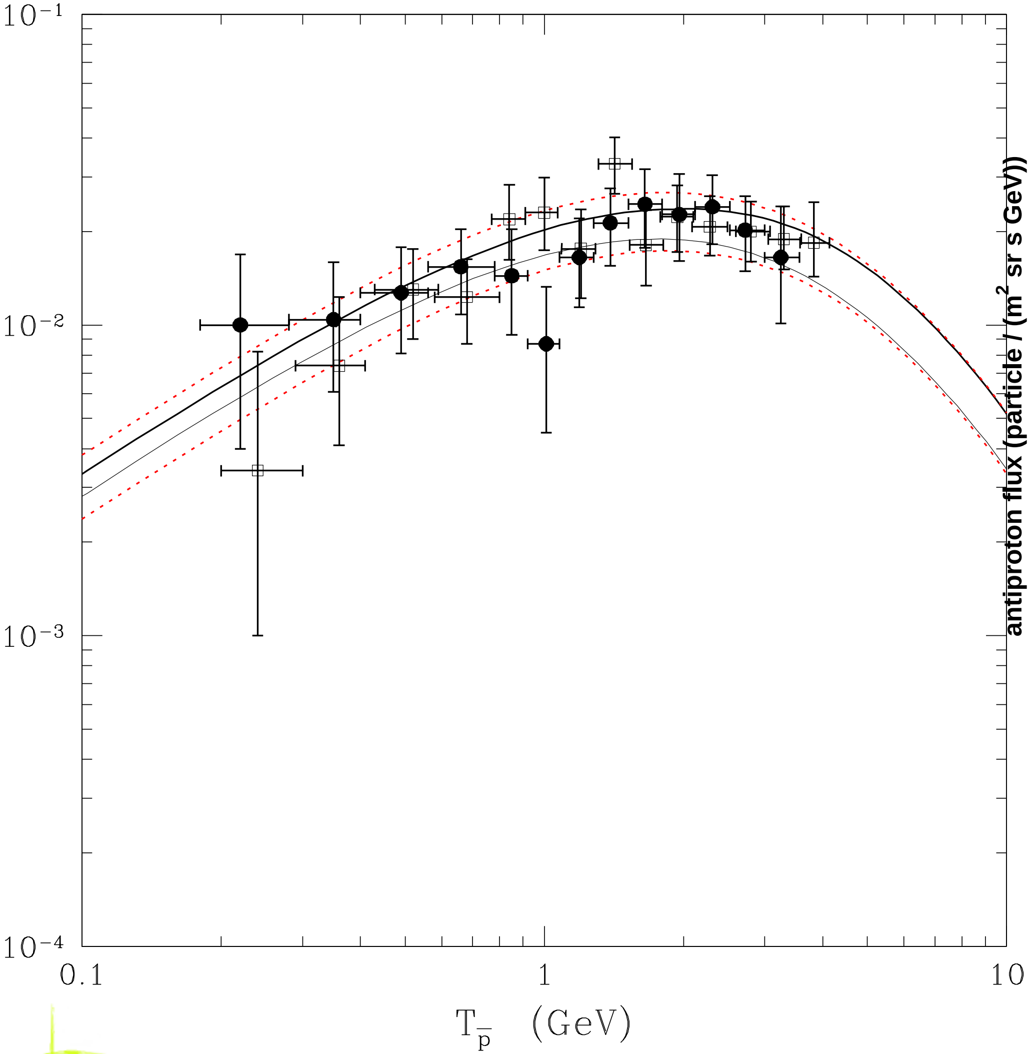
Good B/C fit allows various parameter configurations :

degeneracy difficult to escape at the moment (Donato et al., 2003)

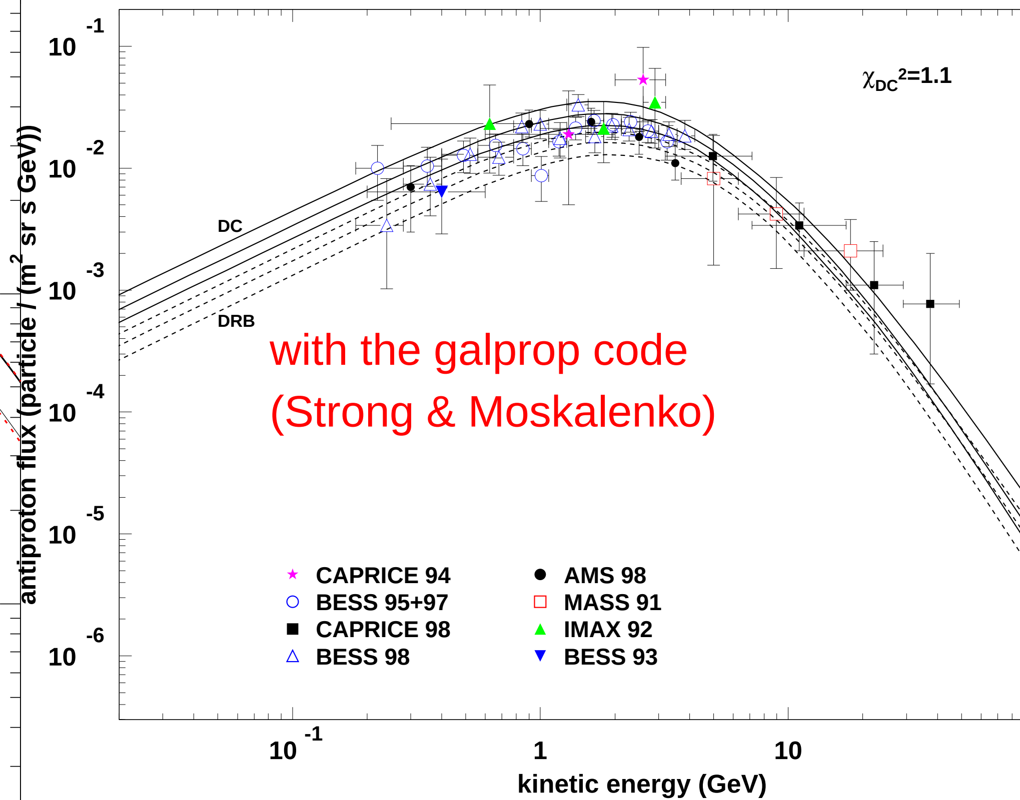
$\longrightarrow$ systematic uncertainties !!!

Example : Systematics for secondary antiprotons

Maurin, Taillet et al., 2002



Lionetto et al., 2005



... NOW POSITRONS !

Diffusion equation for positrons

The diffusion equation for a positron density dn/dE:

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

diffusion

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

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

source :

injected spectrum

Stationary equation

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

Analogy with the classical *heat* equation (Baltz & Edsjö, 1998):

$$\boxed{K_0 \Delta F + \partial_{\tilde{t}} F = \tilde{Q}}$$

$F \equiv E^2 \frac{dn}{dE}$

pseudo-time:

$\tilde{t} \equiv \frac{\tau_E}{1-\alpha}\left(\frac{E}{E_0}\right)^{\alpha-1}$

pseudo-source:

$\tilde{Q} \equiv E_0^{\alpha} E^{2-\alpha} Q(E,\vec{x})$

The full solution

The solution is given by:

$$
\begin{aligned}
F(\vec{x},\tilde{t}) &= \int_{t_s}^{\tilde{t}} d\tilde{t}' \int_{\text{slab}} d^3\vec{x}' G(\vec{x}',\tilde{t}' \to \vec{x},\tilde{t})\tilde{Q}(\vec{x}',\tilde{t}') \\
\frac{dn}{dE}(\vec{x},E) &= \frac{\tau_E E_0}{E^2} \int_{\text{slab}} d^3\vec{x}' \int_E^{\infty} dE' G(\vec{x}',E' \to \vec{x},E) Q(\vec{x}',E')
\end{aligned}
$$

where G is the Green function describing the **probability for a positron of energy E' and position $\vec{x}'$ to be detected with energy E at position $\vec{x}$**.

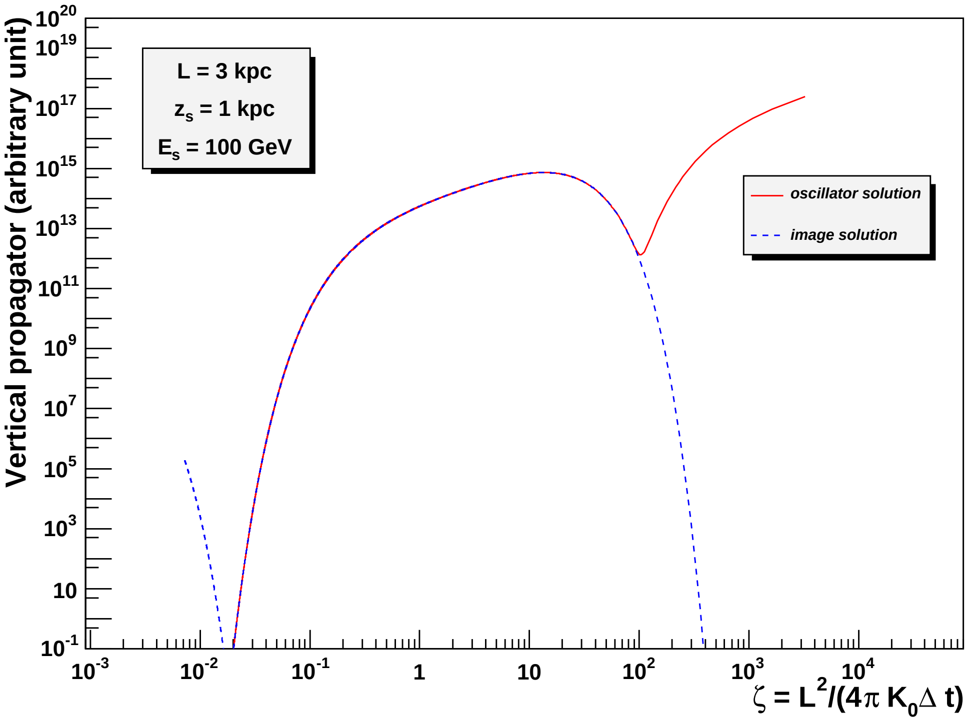
Boundary conditions : vertical propagation

We use a slab geometry characterised by $R = 20\mathrm{kpc}$ and $L = 3\mathrm{kpc}$. The Green function factorizes :

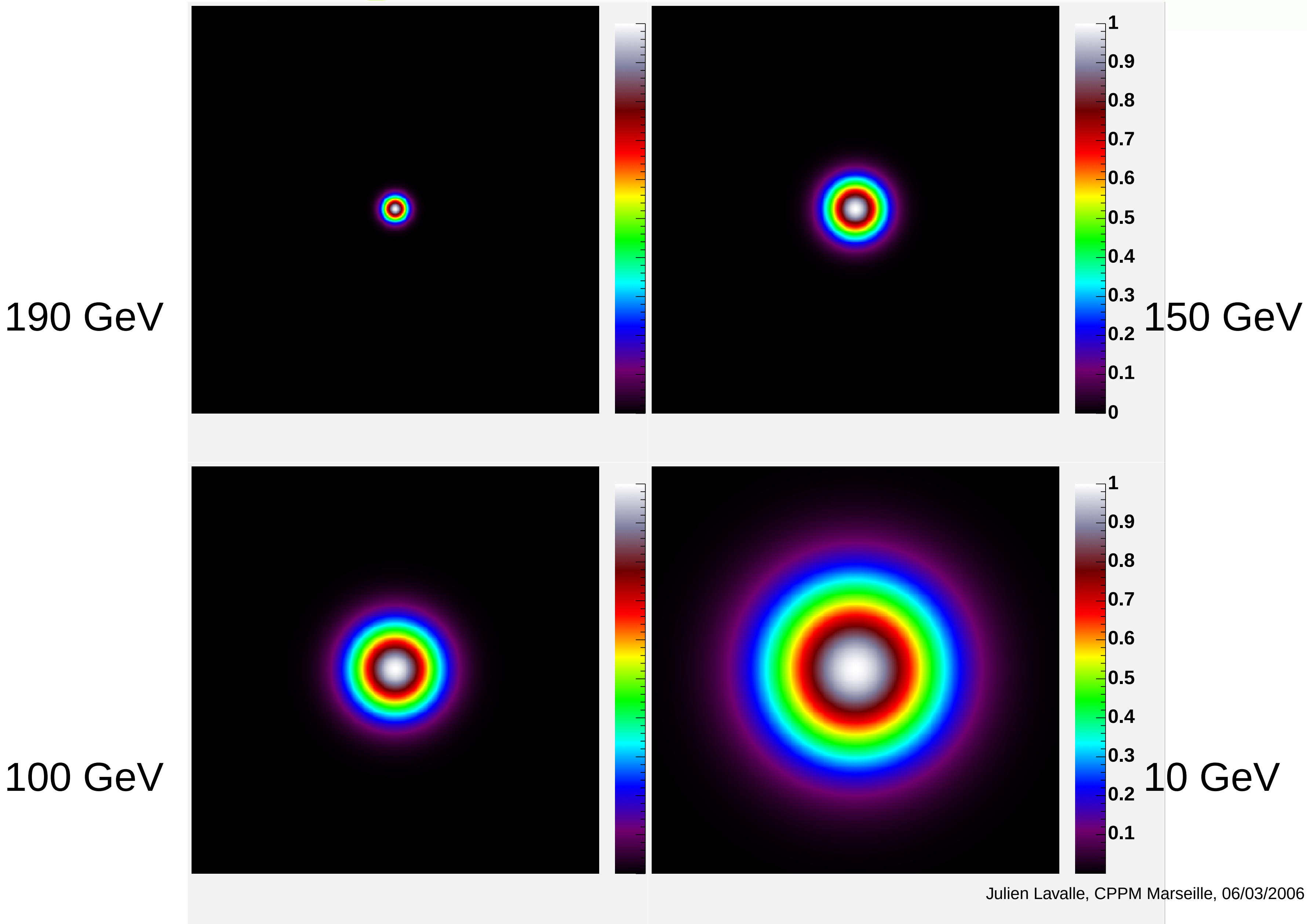
$$G = G_z \otimes G_R$$

Radial solution is simple 2D propagator, while there are 2 possibilities for the vertical one :

- analogy with electric images
- analogy with Shrödinger equation with an infinite potential : oscillator expansion



Simple 2D diffusion : $E_S = 200$ GeV



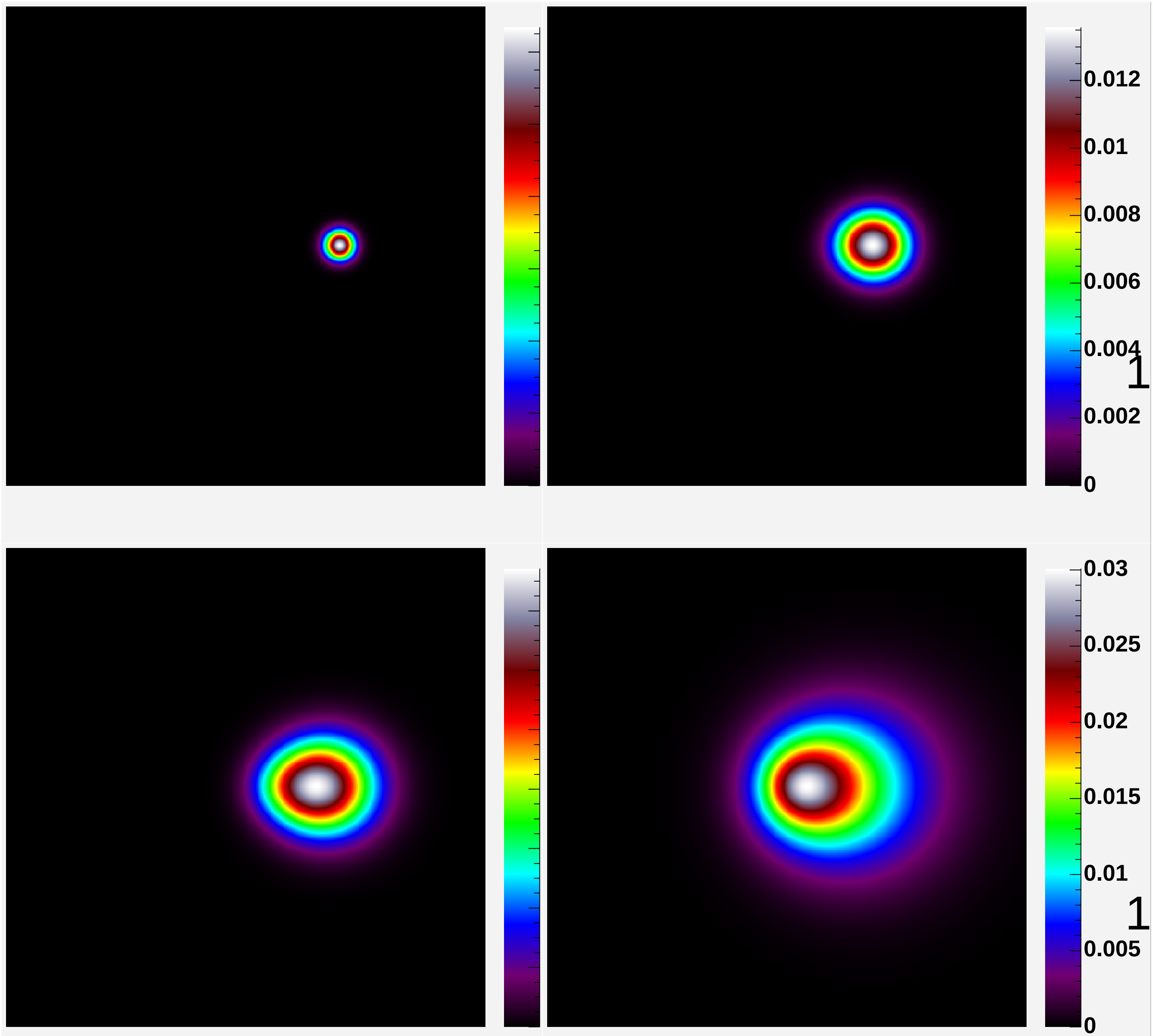
From the Earth : $E_S = 200$ **GeV** + $\rho \propto r^{-1}$

190 GeV

150 GeV

100 GeV

10 GeV



Add clumps, and make assumptions

Assumptions :

- clumps have the same mass M_{cl}
- they follow the smooth distribution, i.e. $\rho(\vec{x})/M_{halo}$
- they carry a fraction f of the halo mass, so their number is fixed by $N_{cl} = f M_{halo}/M_{cl}$

...

We define an **absolute dimensionless boost factor** B_{cl} with respect to the local density :

$$B_{cl} \equiv \frac{\int_{V_{cl}} \rho_{cl}^2 d\vec{x}}{\rho_{\odot} M_{cl}} \{= \frac{\rho_{cl}}{\rho_{\odot}} \text{ if } \rho_{\rm cl} = \text{cst}\}$$

Define the **actual** ***boost factor***

We then define the **effective boost factor** as :

$$B_{eff} \equiv \frac{d\phi/dE(f\times\mathrm{smooth}+\mathrm{clumps})}{d\phi/dE(\mathrm{smooth\ halo})}$$

which measures the **actual flux enhancement** due to a clumpy distribution

A focus on the effective boost factor

After a bit of algebra, and considering the limit of a continue distribution of clumps, we obtain :

$$\boxed{B_{eff}(E) = (1-f)^2 + f B_\star \frac{I_1}{I_2}}$$

which is independant of M_{cl}, with :

$$I_n \equiv \int_E^\infty dE_S \int_{slab} d^3\vec{x}' \left(\frac{\rho(\vec{x}')}{\rho_\odot}\right)^n \times G(\vec{x}', E_S \rightarrow \vec{x}_\odot, E) Q(\vec{x}', E_S)$$

and ($B\star \sim B_{cl}$)

...

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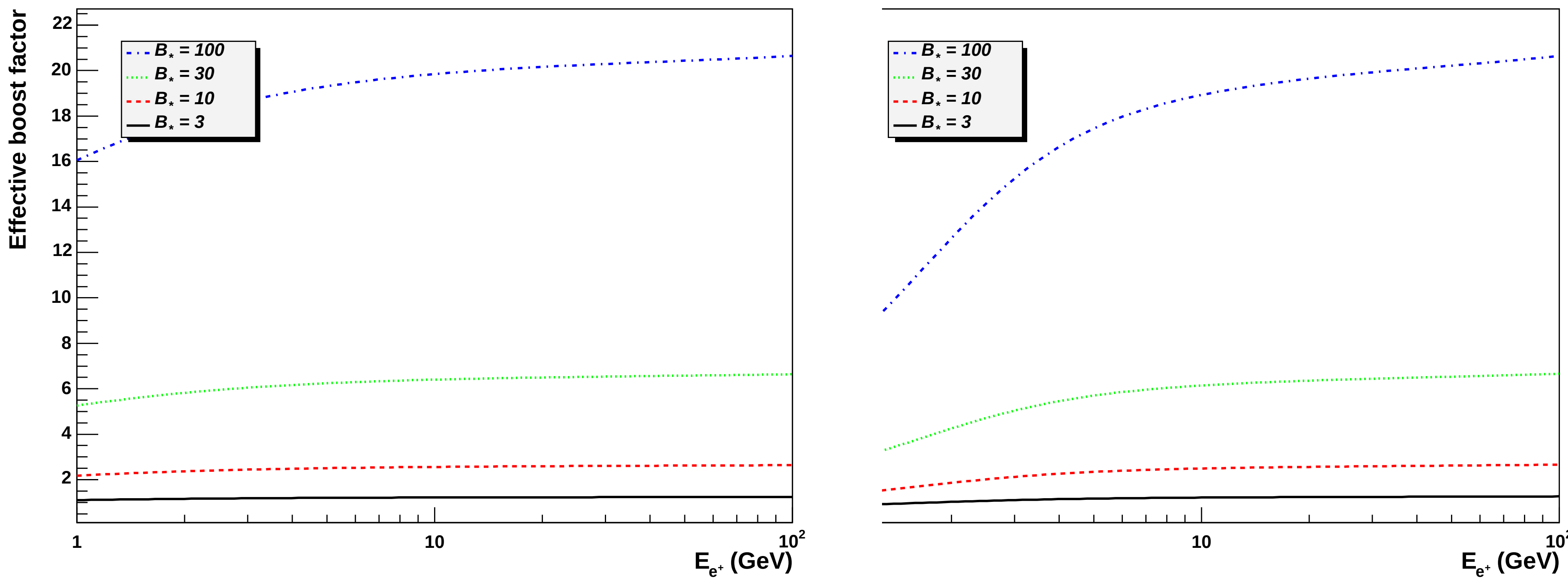
and ($B\star \sim B_{cl}$)

NOT EQUAL TO THE GAMMA-RAY BOOST FACTOR

Boost factor for a $b\bar{b}$ spectrum, $m_\chi = 100$ GeV

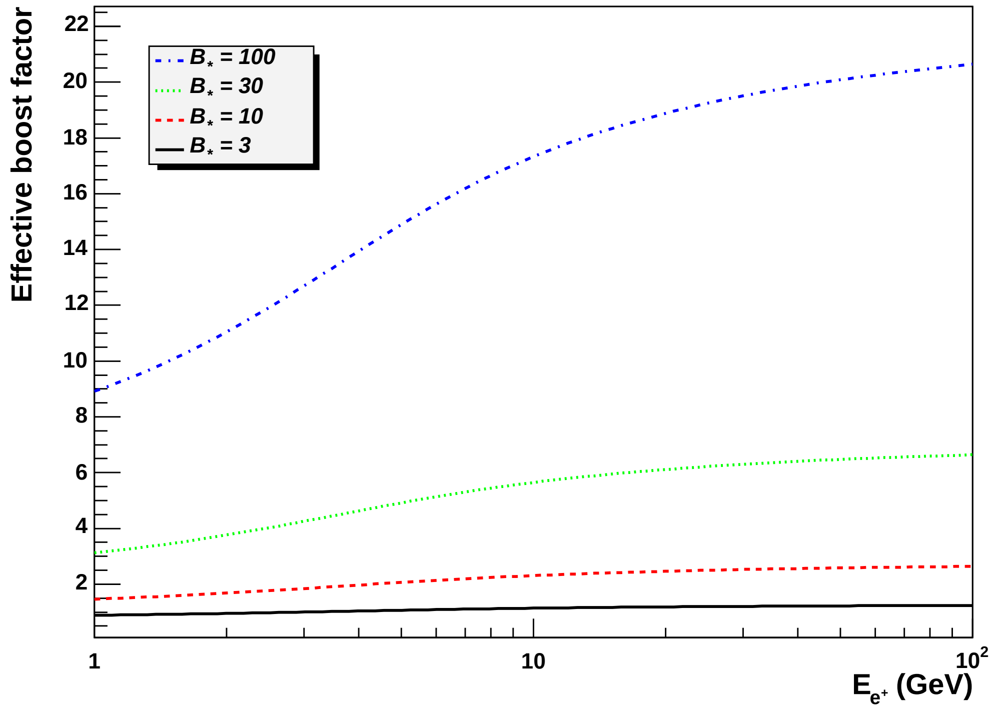
NFW $(\propto r^{-1})$ $[a_{\rm scale} = 25$ kpc$]$ Isothermal $(\propto r^{-2})$ $[a_{\rm core} = 0.5$ kpc$]$

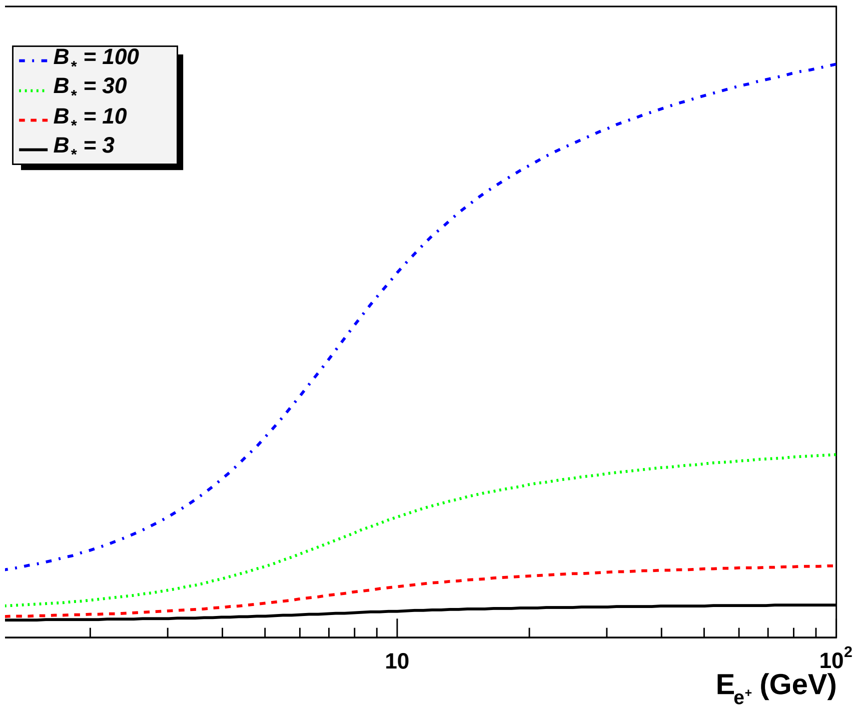


Boost factor for a positron line $E_S = 100$ ***GeV***

NFW $(\propto r^{-1})$ $[a_{\rm scale} = 25 \text{ kpc}]$

Isothermal $(\propto r^{-2})$ $[a_{\rm core} = 0.5 \text{ kpc}]$





Next step : statistical properties

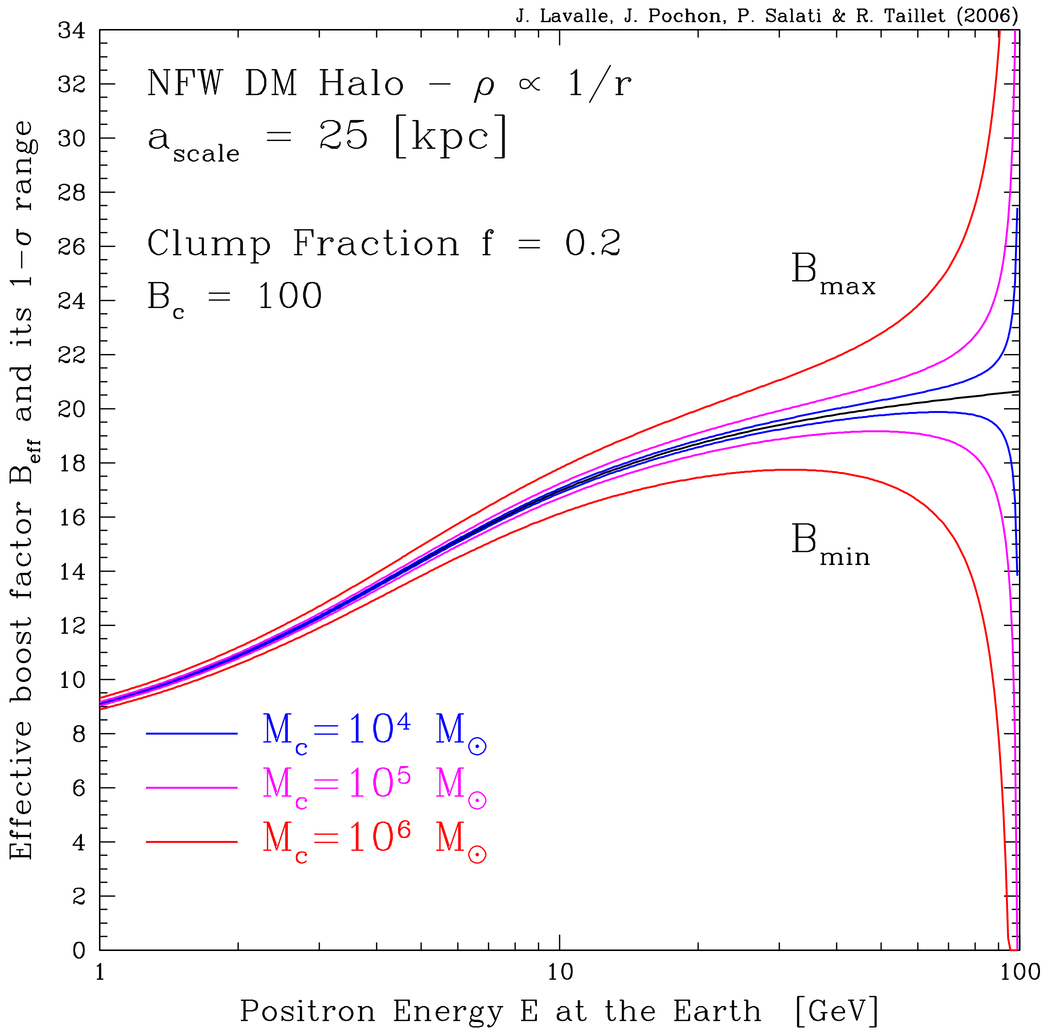
- Although there is **one unique realization of the halo**, we do not know about it !
- How **granularity properties** translate in **signal variance** ?

  The signal due to clumpiness and detected at energy E depends on the number of contributing clumps in the relevant volume : **the smaller the number, the larger the variance** (statistical connection to the central-limit theorem)
- The starting point :

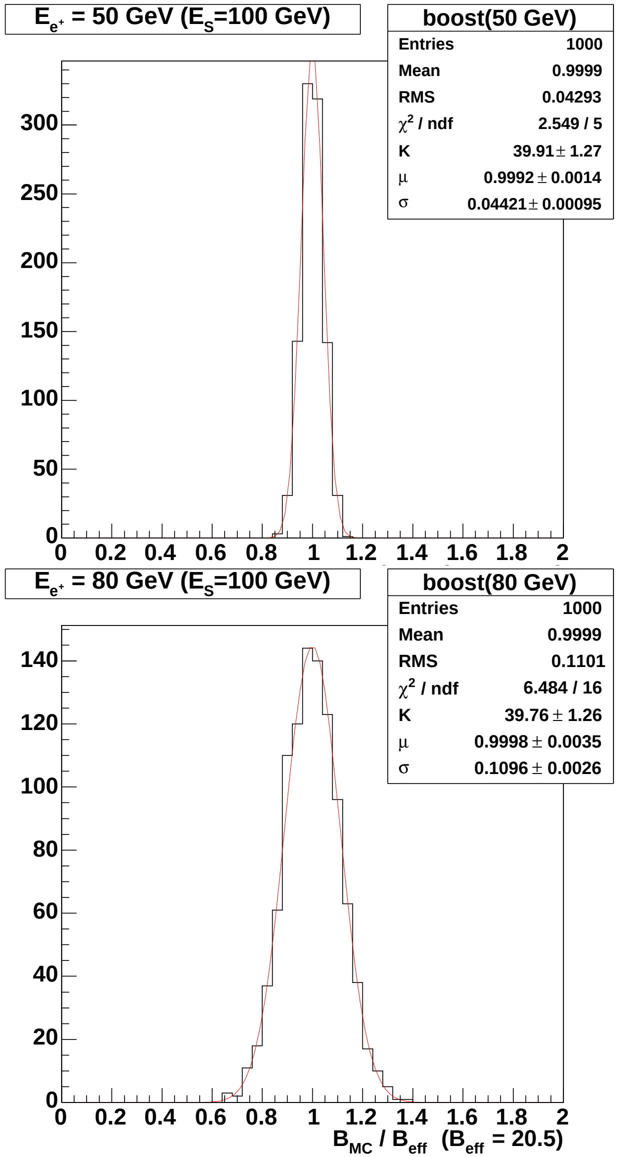
  the flux from clumps is a random variable

$$\phi = (1-f)^2 \phi_{\rm smooth} + \left\{ \sum_i^N \phi_i = \phi_{\rm random} \right\}$$

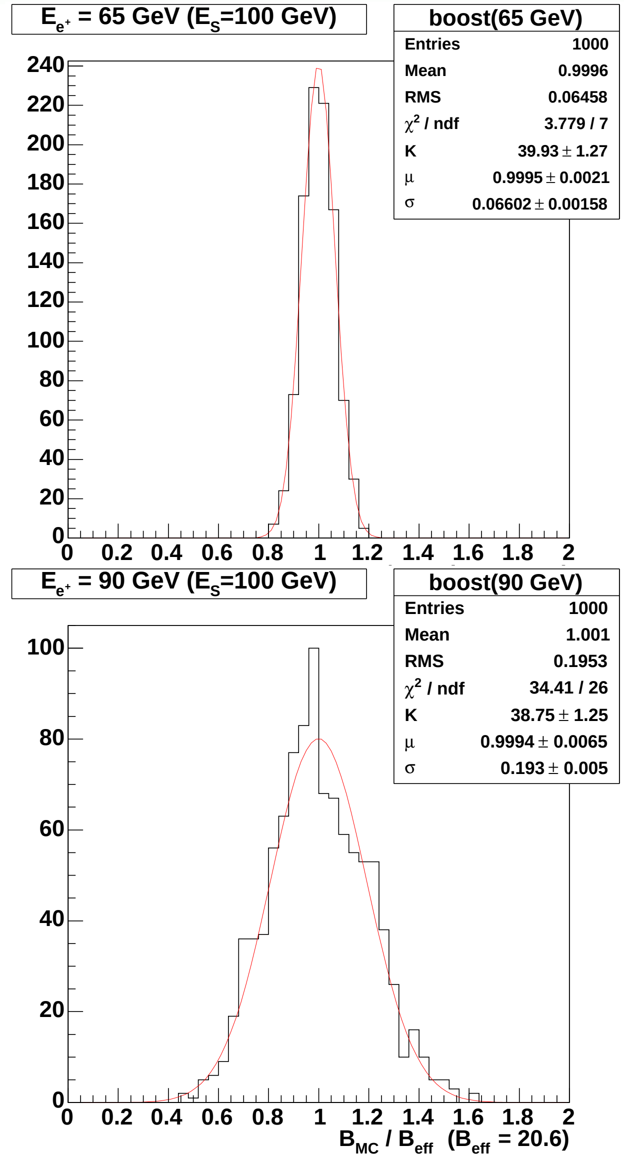
Variance of the effective boost factor B_{eff}



Monte-Carlo simulations reproduce the results



$$M_{\rm clump} = 10^5 M_\odot$$



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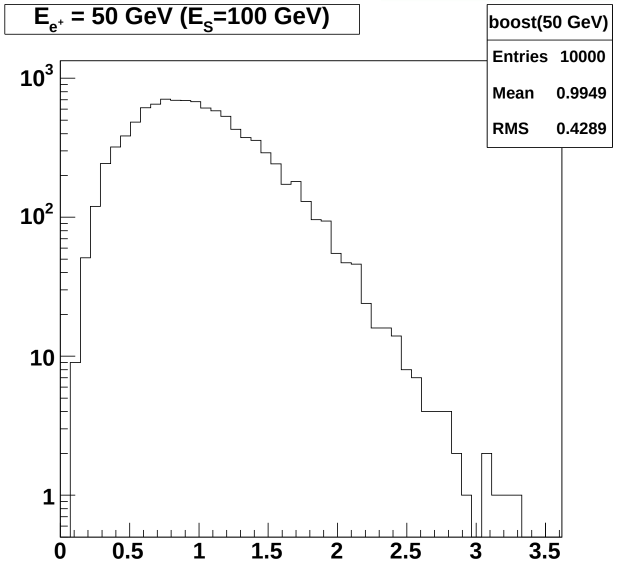
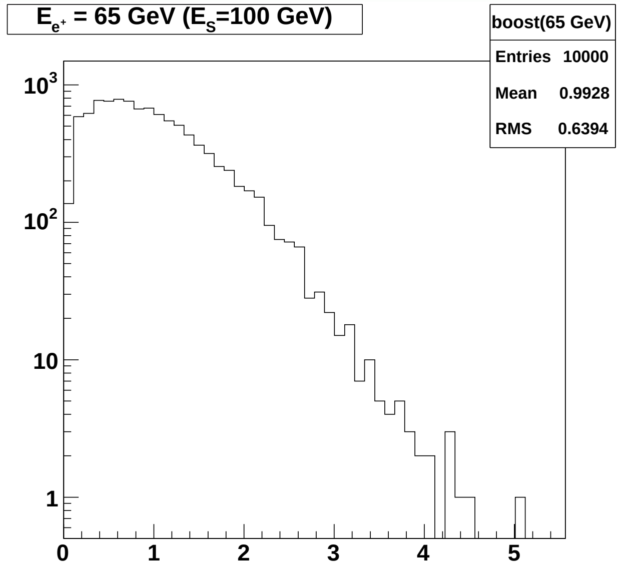
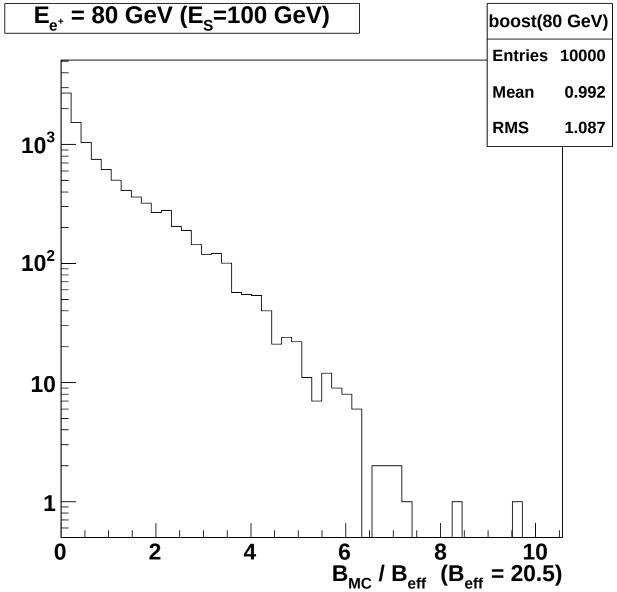
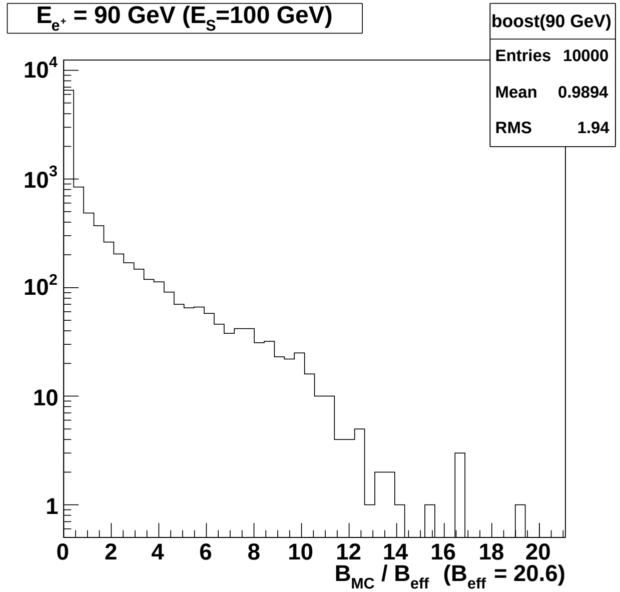




$$M_{\rm clump} = 10^7 M_\odot$$

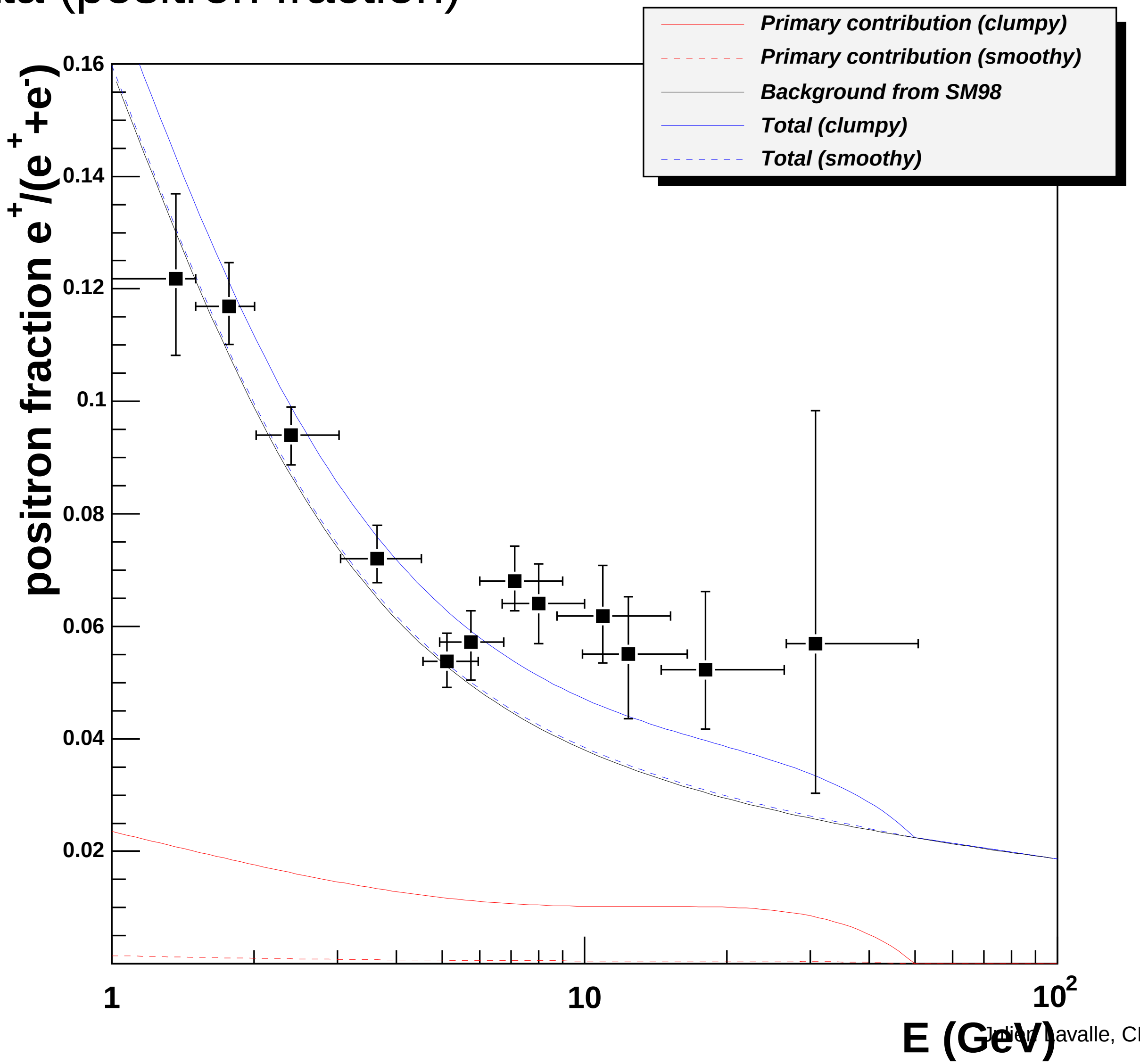




Application : the warped GUT candidate

Neutrino LZP, $m_\nu = 50$ GeV, (properties in Agashe and Servant, 2005)

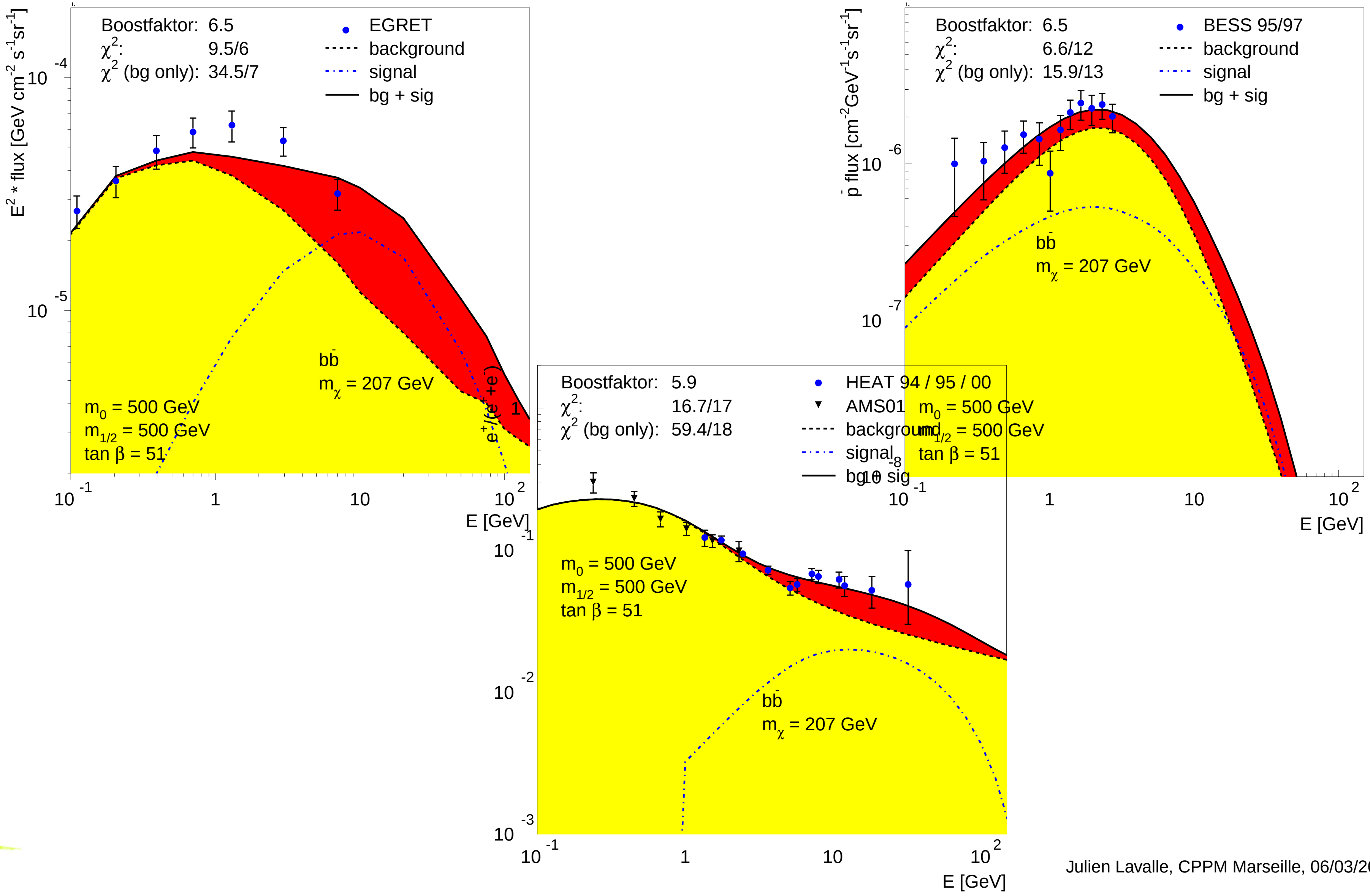
..... HEAT data (positron fraction)



In short ...

Take care when using the word "*boost factor*" ...

Example of cross-analysis : de Boer et al.



Conclusion

- **CCRs propagation studies are essential for indirect detection**, because they provide a coherent picture of the dark matter distribution, in addition to γ and ν
- **Clumpiness is still an open debate**
- **The positron case allows a specific study of granularity effects**
- We have shown that **the current picture of the *boost factor* is misleading** : when diffusion is involved, spectral distorsions occur, depending on the injected spectrum, the density profile, and the clump distribution
- Statistical properties of clump signatures are meaningful for indirect detection