Cosmic positron and electron excesses: is the dark matter solution a good bet? (principles, backgrounds, effect of cosmological subhalos and uncertainties)

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Refs (arXiv) : 0603796, 0712.0677, 0712.0468, 0709.3634, 0704.2543, 0808.0332, 0809.5268

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

LPSC Grenoble

Thursday, February 05$^{\rm th}$ 2009

Outline

- **General introduction**
- **Why antimatter ?**
- **The positron excess: standards and non standards**
- **Computing the odds of the Galactic Lottery: clumpiness boost factors**
  - Cosmological sub-halos: Analytical vs N-body approach
- **Conclusion**

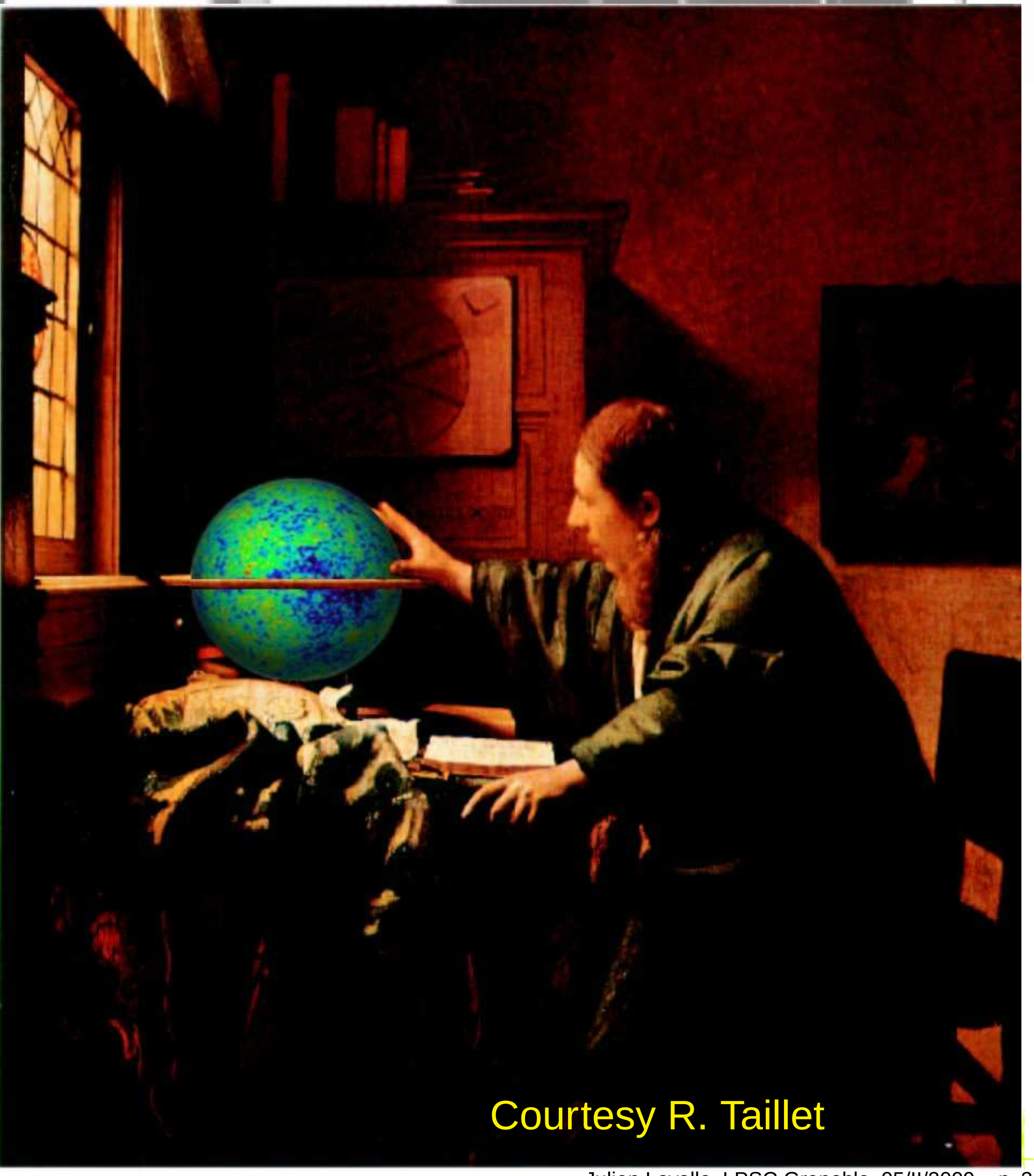
The Dark Matter problem : connecting cosmological to microscopic scales

Cosmological data (WMAP, etc) :

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

85% of the matter is of unknown origin (non-baryonic)→ New particles or modified gravity. WIMPs naturally arise from beyond standard model theories (SUSY, ED), without asymmetry matter/antimatter

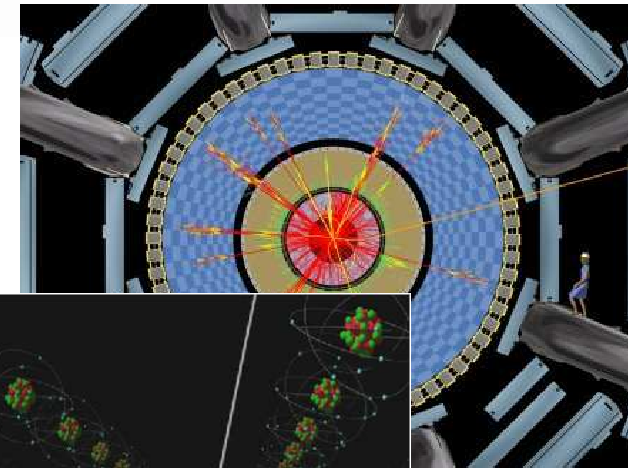
- Relic density (thermal hypothesis): $\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \propto \frac{m^2_{\rm EW}}{g^4_{\rm EW}}$
- DM couples to standard matter (direct detection)
- Annihilation in high density regions (indirect detection)

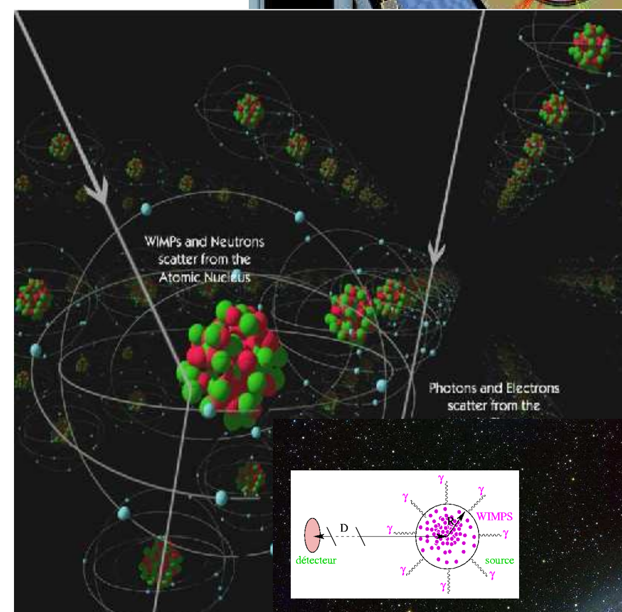


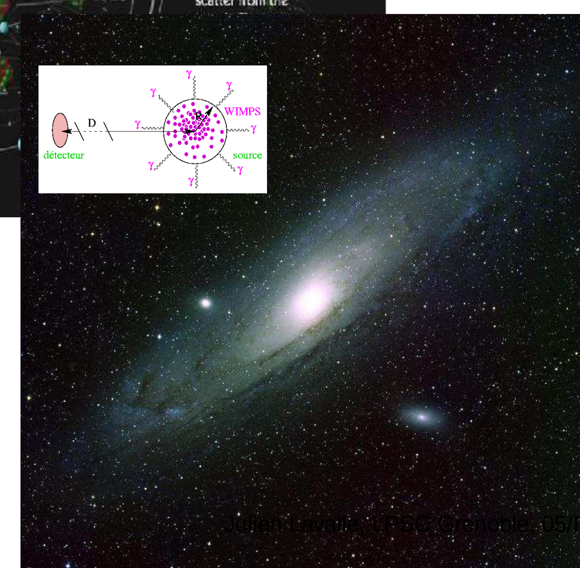
Detection methods

If dark matter couples to ordinary matter, it could be detected thanks to:

- **Particle colliders: (LHC!)** (no difference between any meta-stable particle and a wimp)
- **Direct detection: (many!)** (mainly sensitive to scalar interactions and low wimp masses)
- <u>**Indirect detection:**</u> **(HESS, PAMELA, GLAST)** (γ**-rays, antimatter cosmic rays, neutrinos**)







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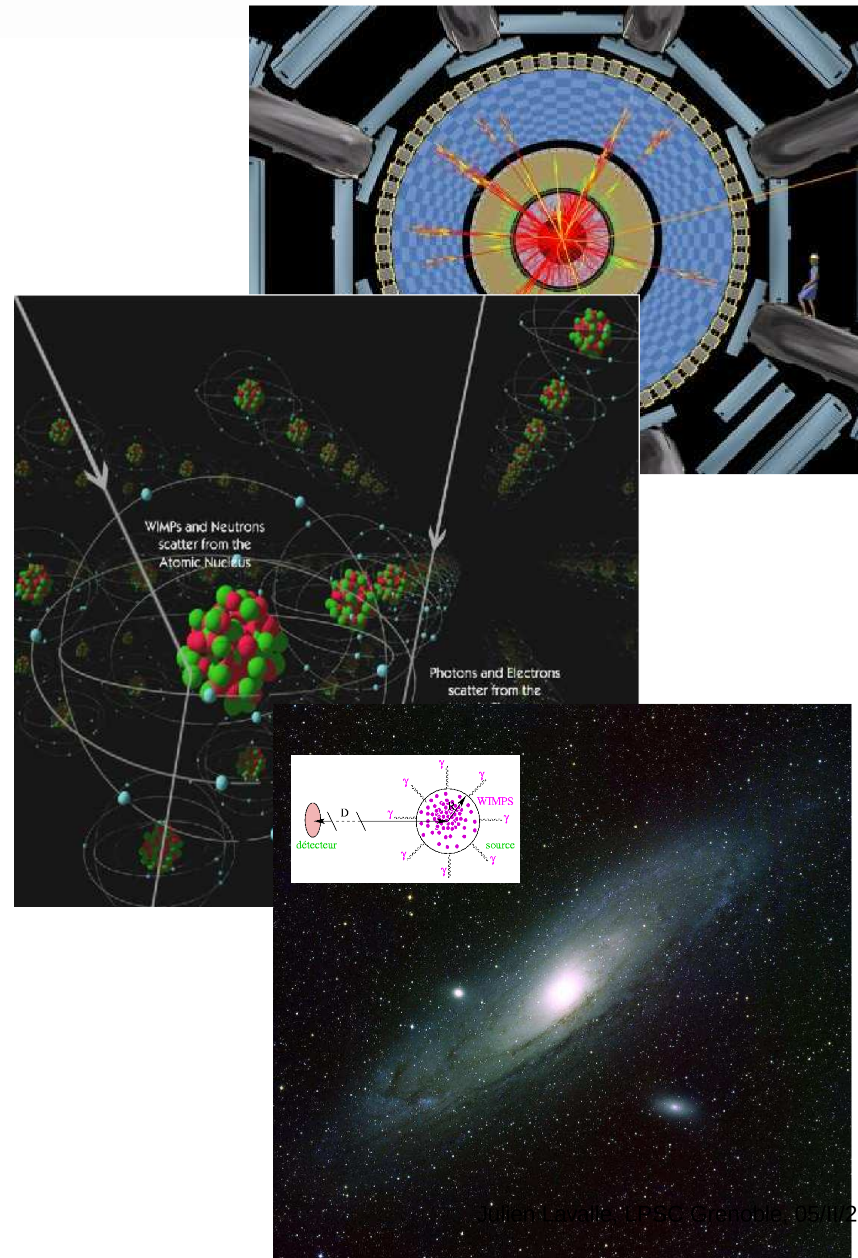
Complementary searches are mandatory for consistent answers

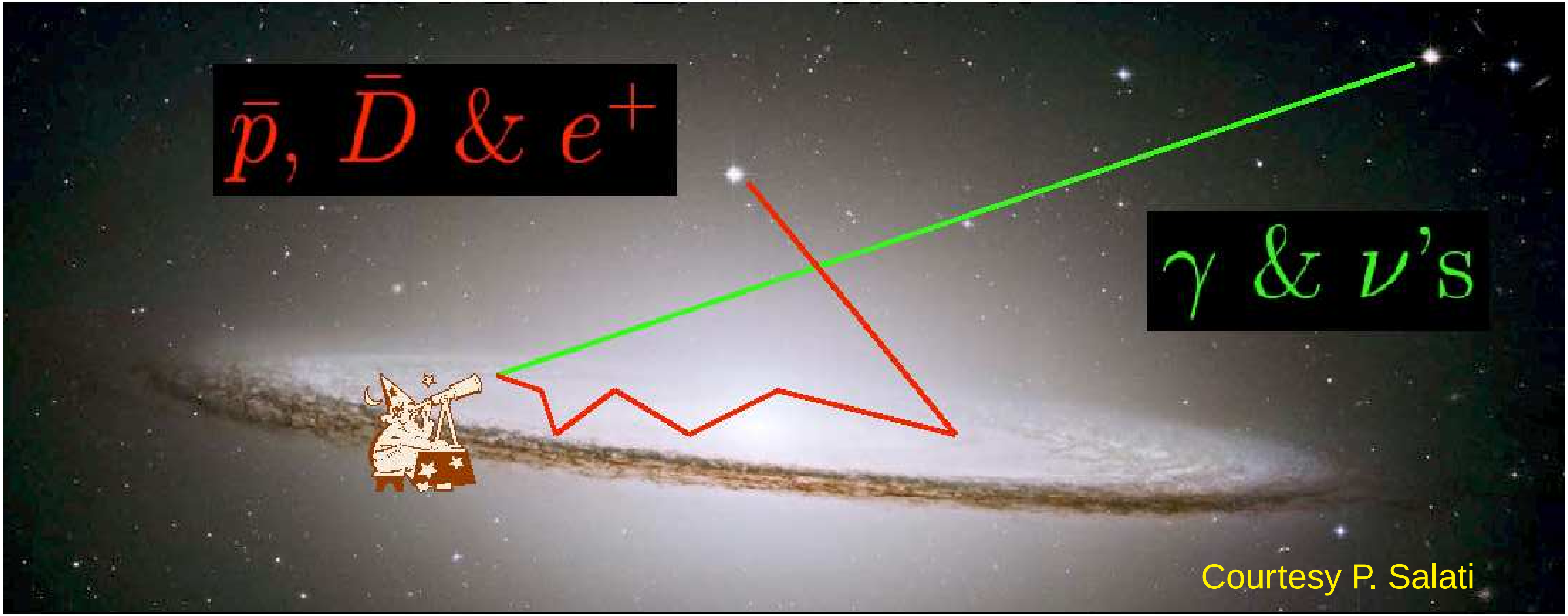


Some candidates

- **Supersymmetry**
  - neutralino (MSSM & mCHOUGRA) – DM:
    $\longrightarrow b\bar{b}$ ($t\bar{t}$), W^+W^-, ZZ, marginally l^+l^- (small slepton masses)
  - gravitino (GMSB & mCHOUGRA) – DM & SUSY breaking & nucleosynthesis:
    $\longrightarrow$ phenomenology of nLSP
  - sneutrino (MSSM) – DM & neutrino masses & leptogenesis:
    $\longrightarrow \nu\bar{\nu}$, W^+W^-
- **Extra-dimensions**
  - LKP (UED) – DM:
    $\longrightarrow l^+l^-$ (60%), up $q\bar{q}$ (35%)
  - LZP (warped GUT) – DM:
    $\longrightarrow$ (depends on LZP mass and KK scale)
- **Other (minimal) models**
  - Inert doublet model, little Higgs, light DM, etc.

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

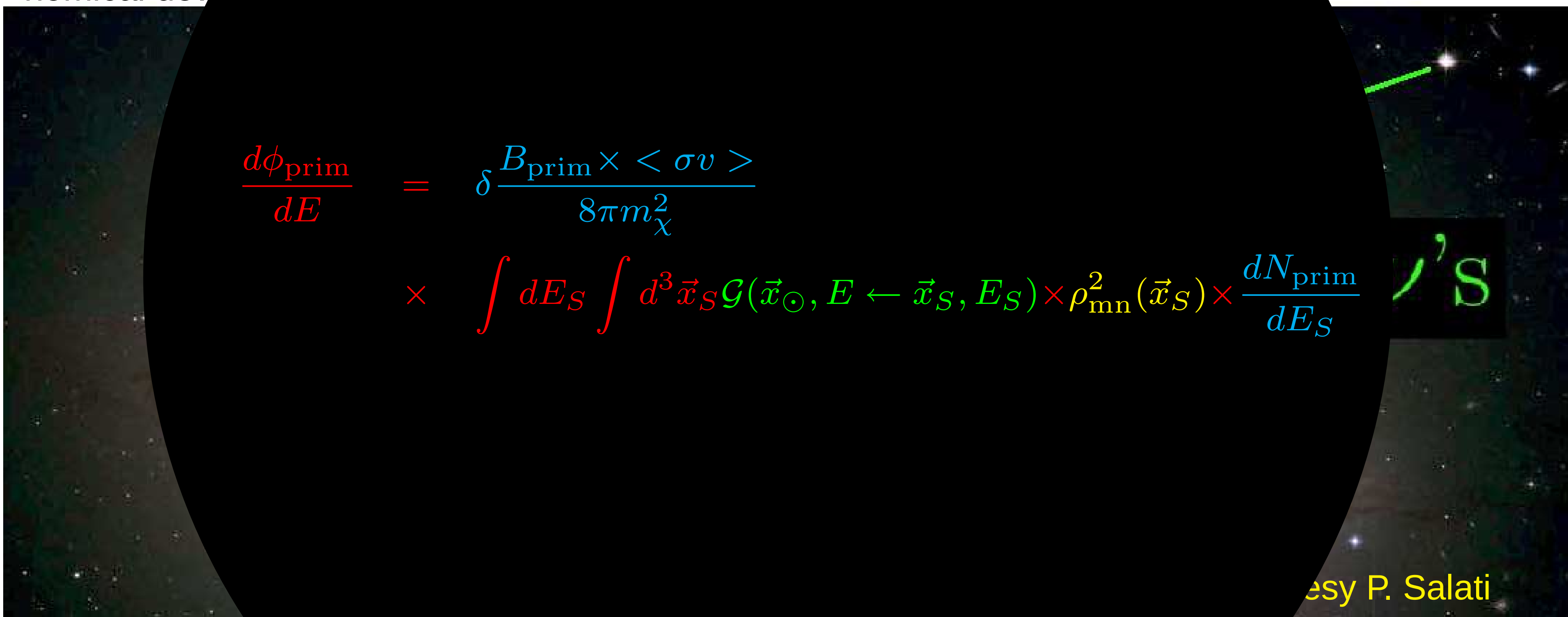


- γ **and** ν**: travel directly from the source to the observer**
- **Antimatter cosmic rays: diffuse on the magnetic turbulences**

$\Longrightarrow$ **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

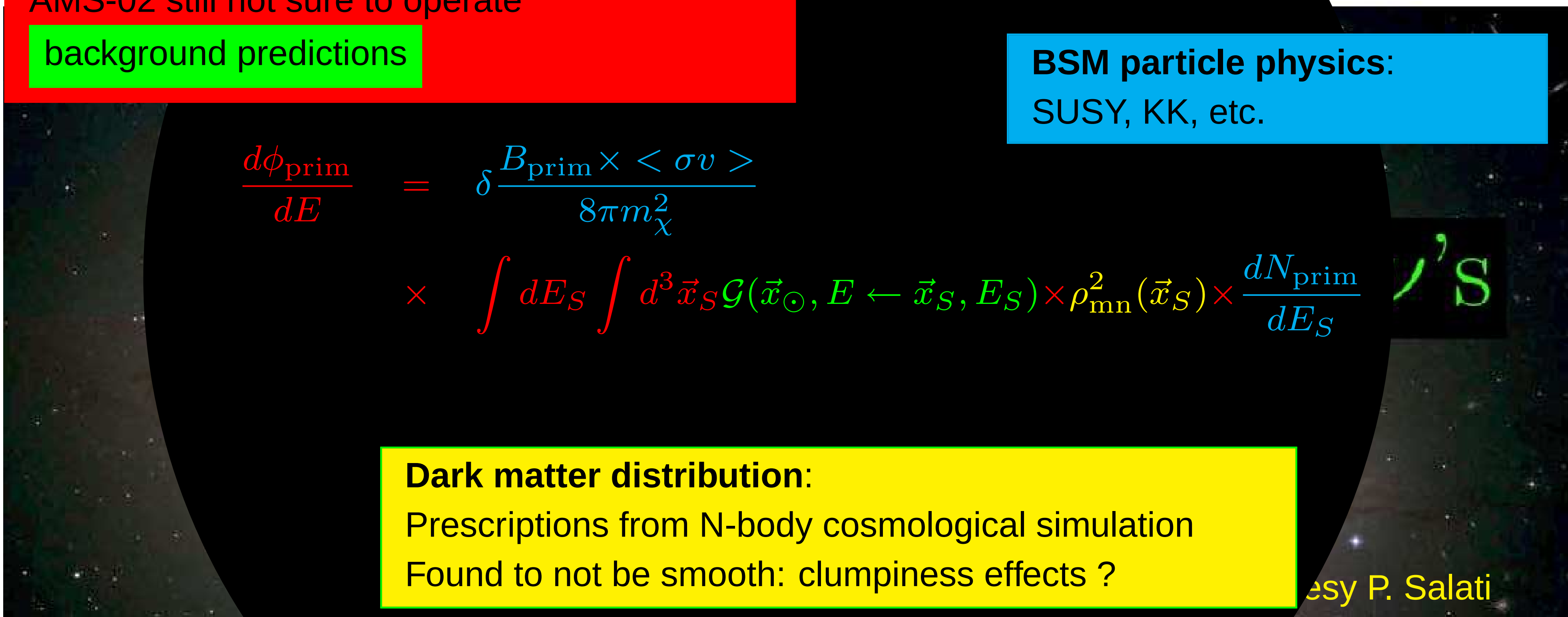
and clusters: If
neans of astro-

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

BSM particle physics:
SUSY, KK, etc.

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

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



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

Propagation Green function

- **γ and ν: tr**
  to the observ
  l density regions
  es)
- **Antimatter cosmic**
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... of Dark Matter

Flux measurements:
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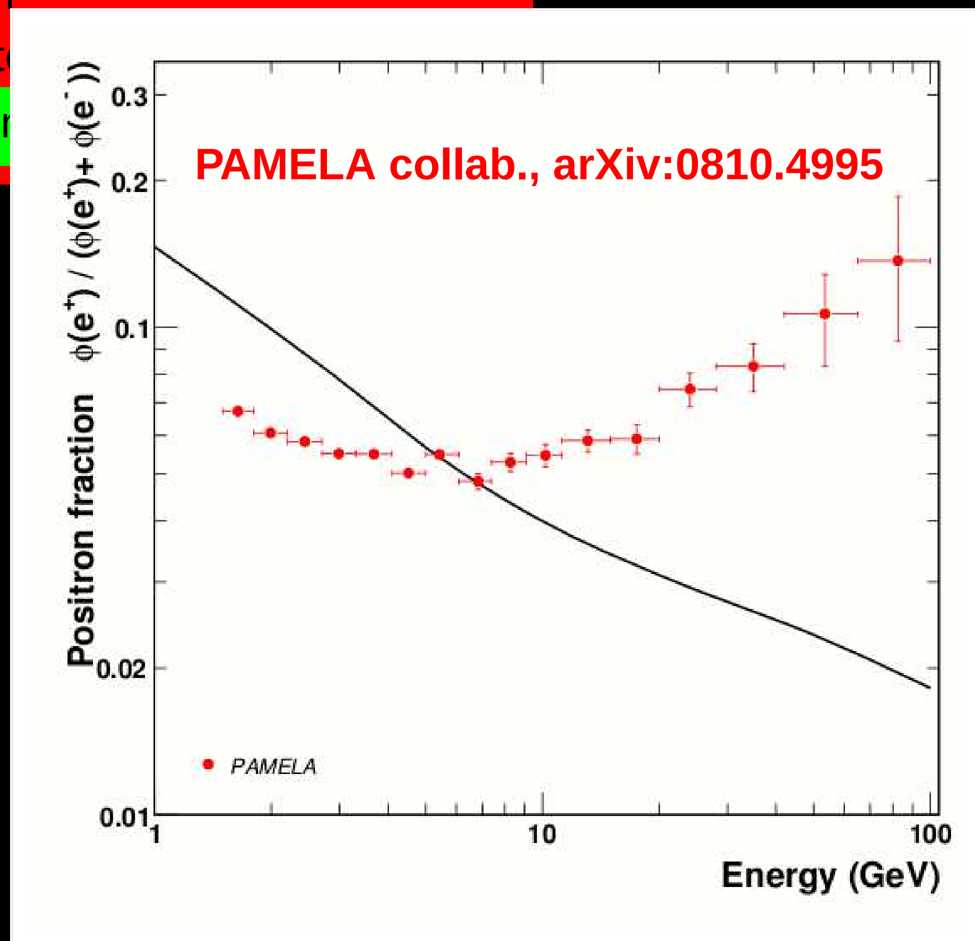

- γ **and** ν**: tr...**
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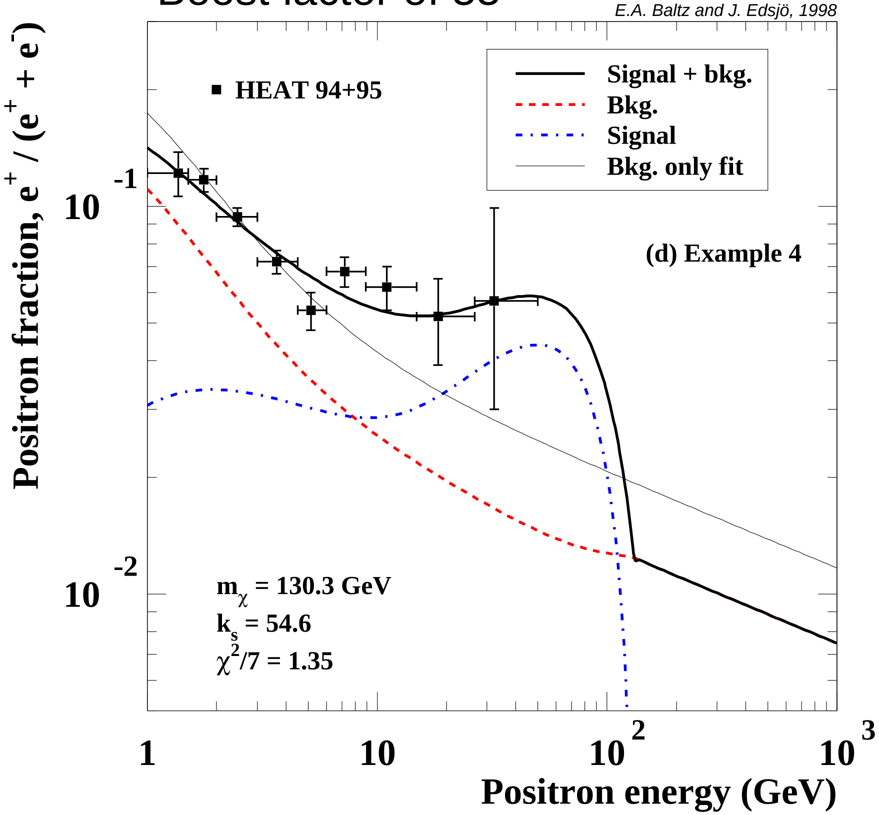
Boost factor of 55



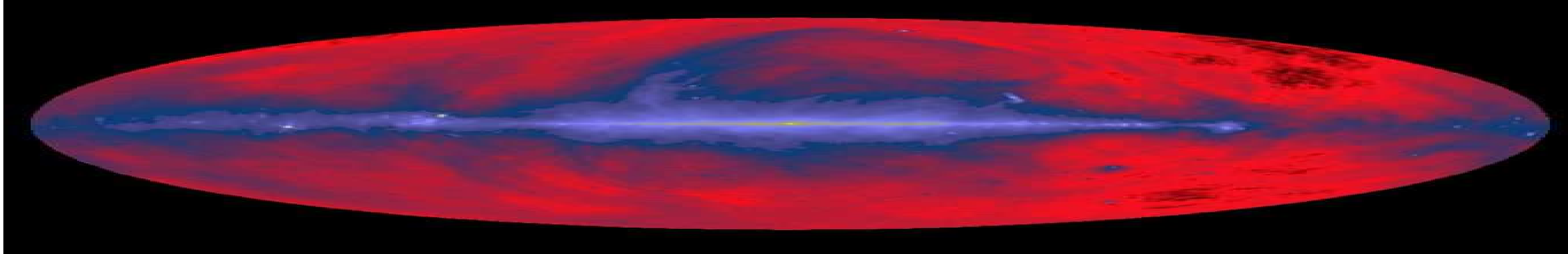
- **γ and ν: tr...** ... **density regions**
  to the observ... ... **...es)**
- **Antimatter cosmic ...**
  magnetic turbulences

On the positron fraction

Before inferring an excess from the data, one needs to:

- properly estimate the secondary positron background;
- properly measure the electron flux;
- ++++ theoretical uncertainties !!!

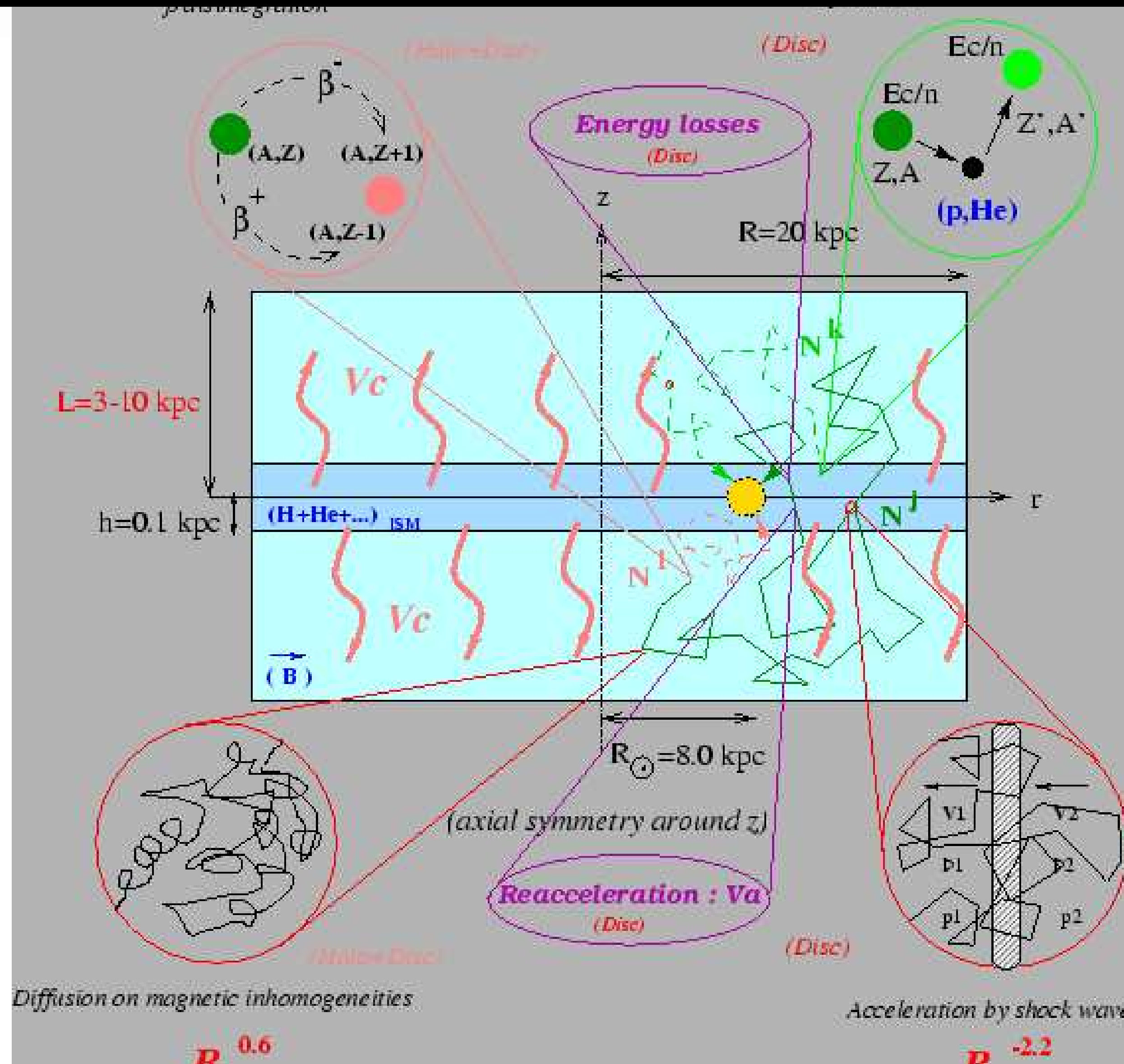
Sub-TeV Cosmic ray propagation in the Galaxy

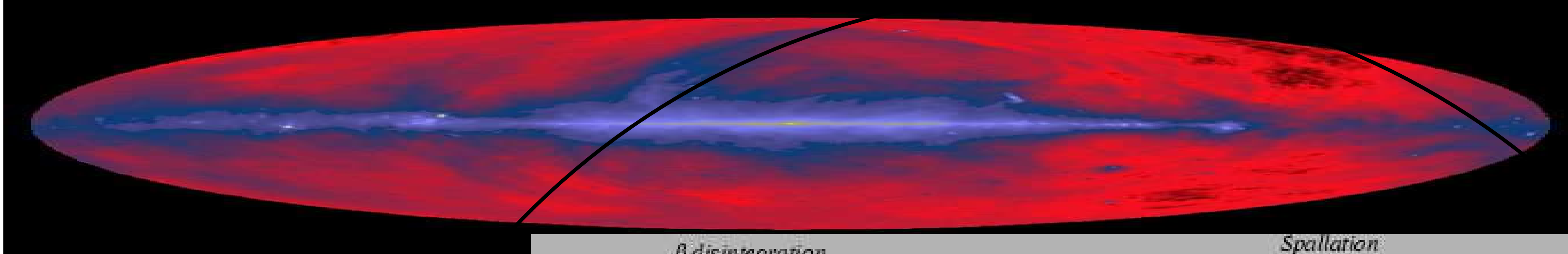


cf. e.g. Berezinsky (1990)

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

.... (Figure by D. Maurin)





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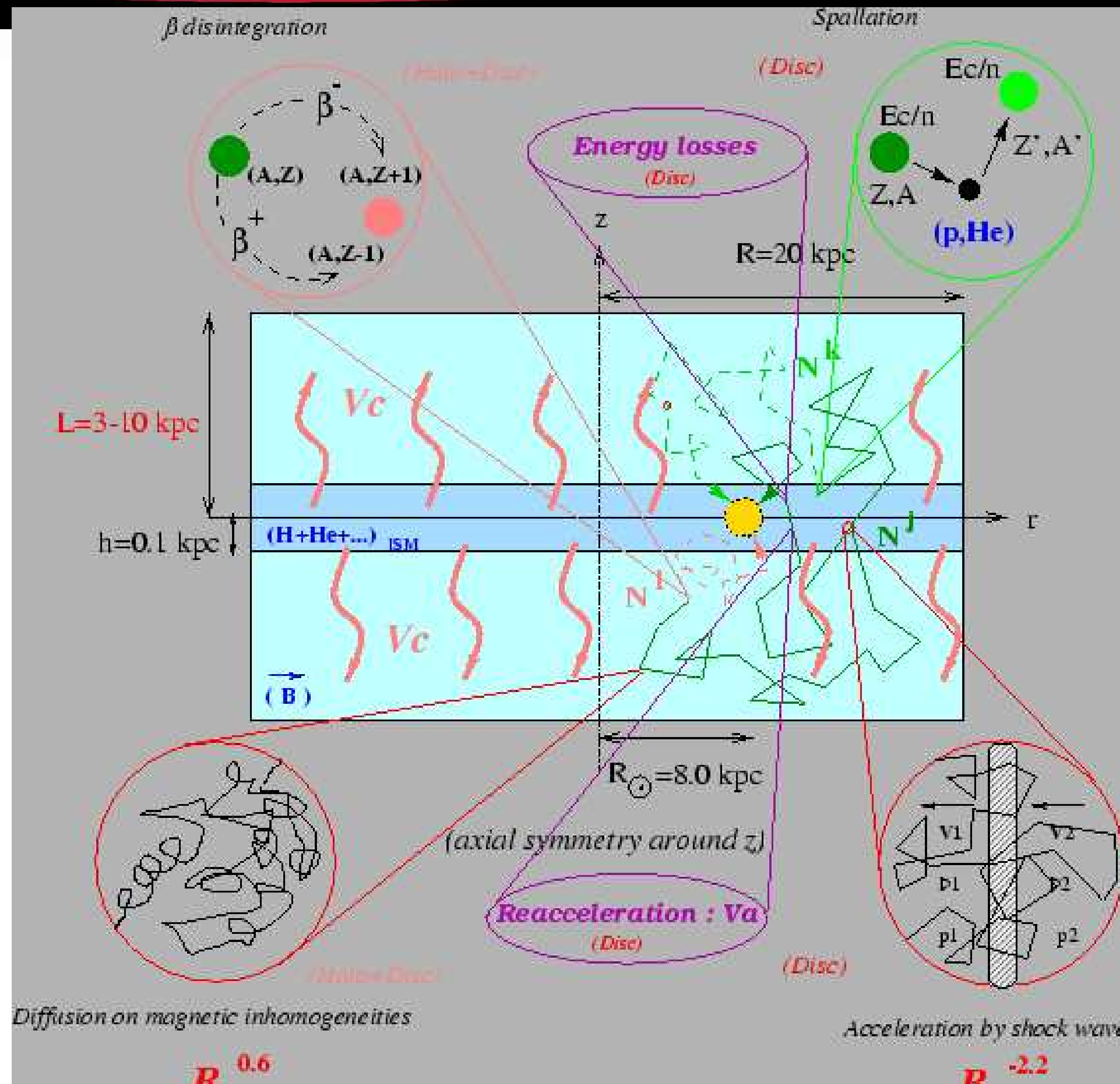


Diffusion equation for $e^{+/-}$ or $p\bar{p}$

$e^{+/-}$, *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)

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

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)

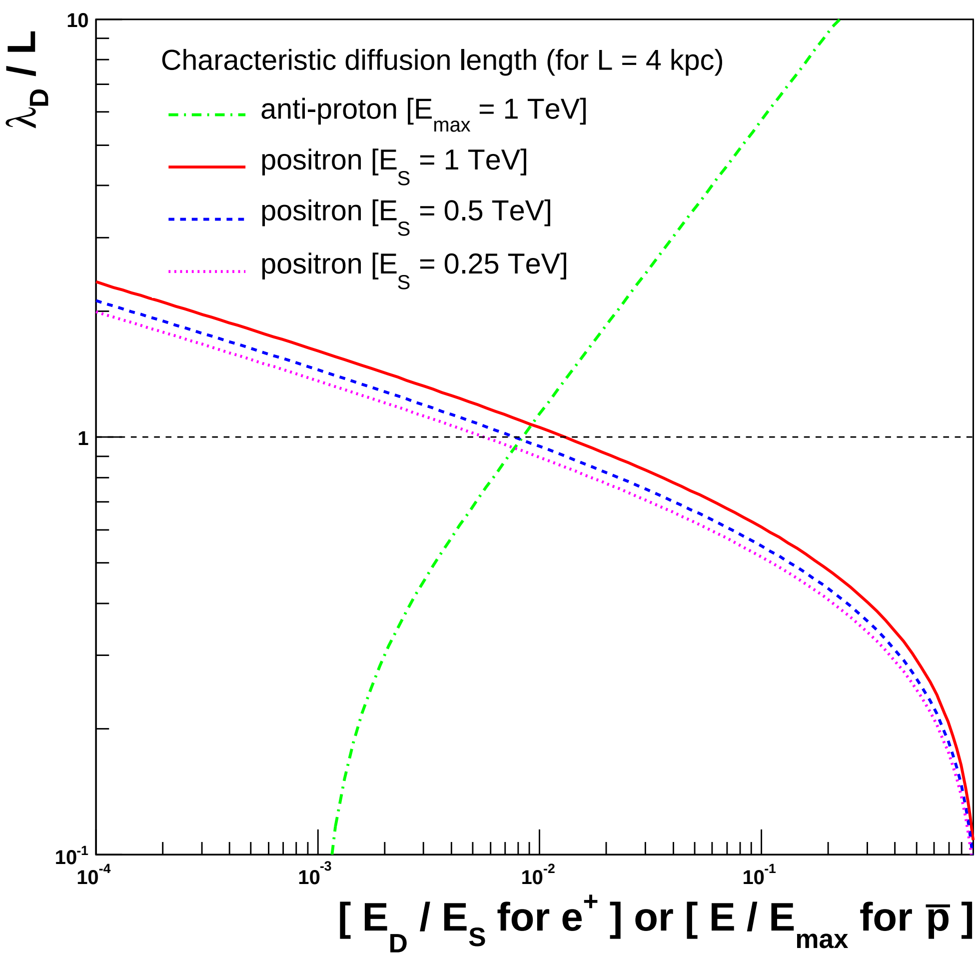
Uncertainties and degeneracies in parameters (Maurin et al 01)

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

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 energies



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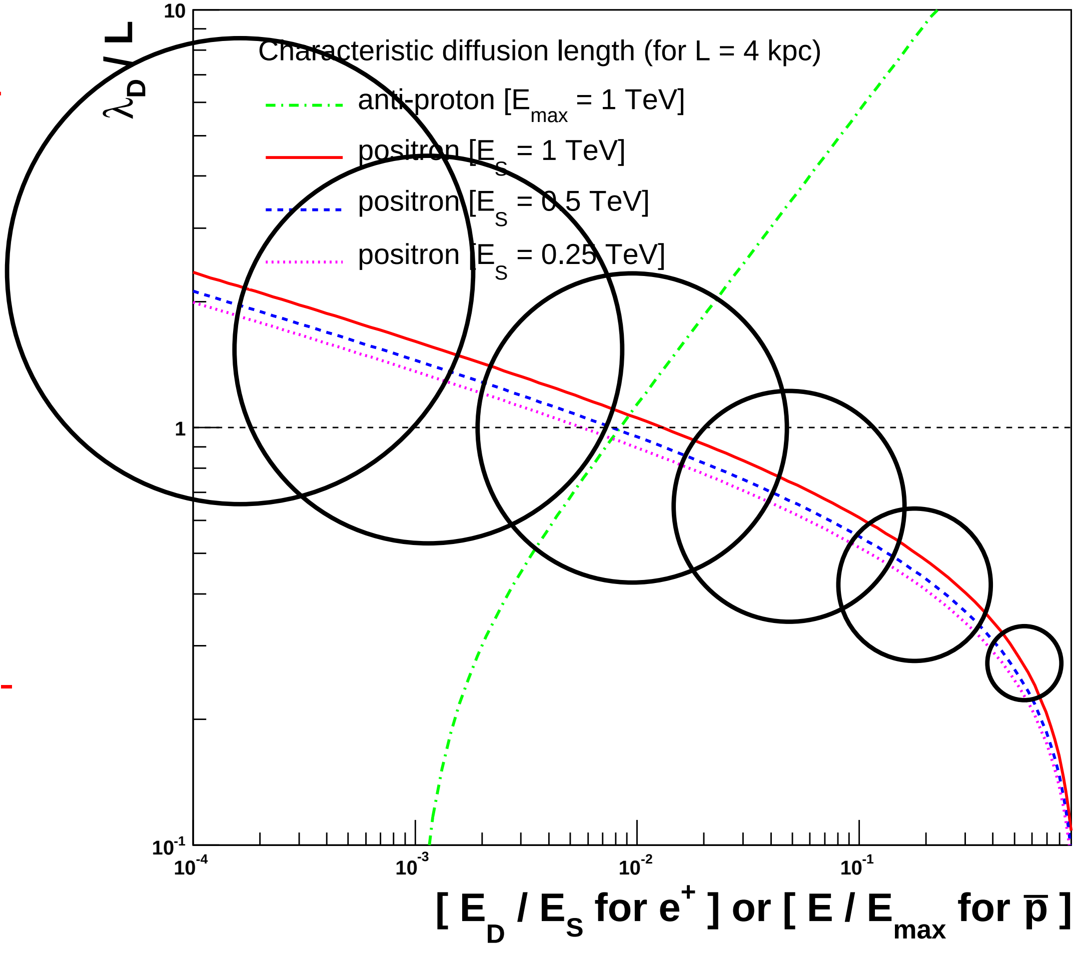
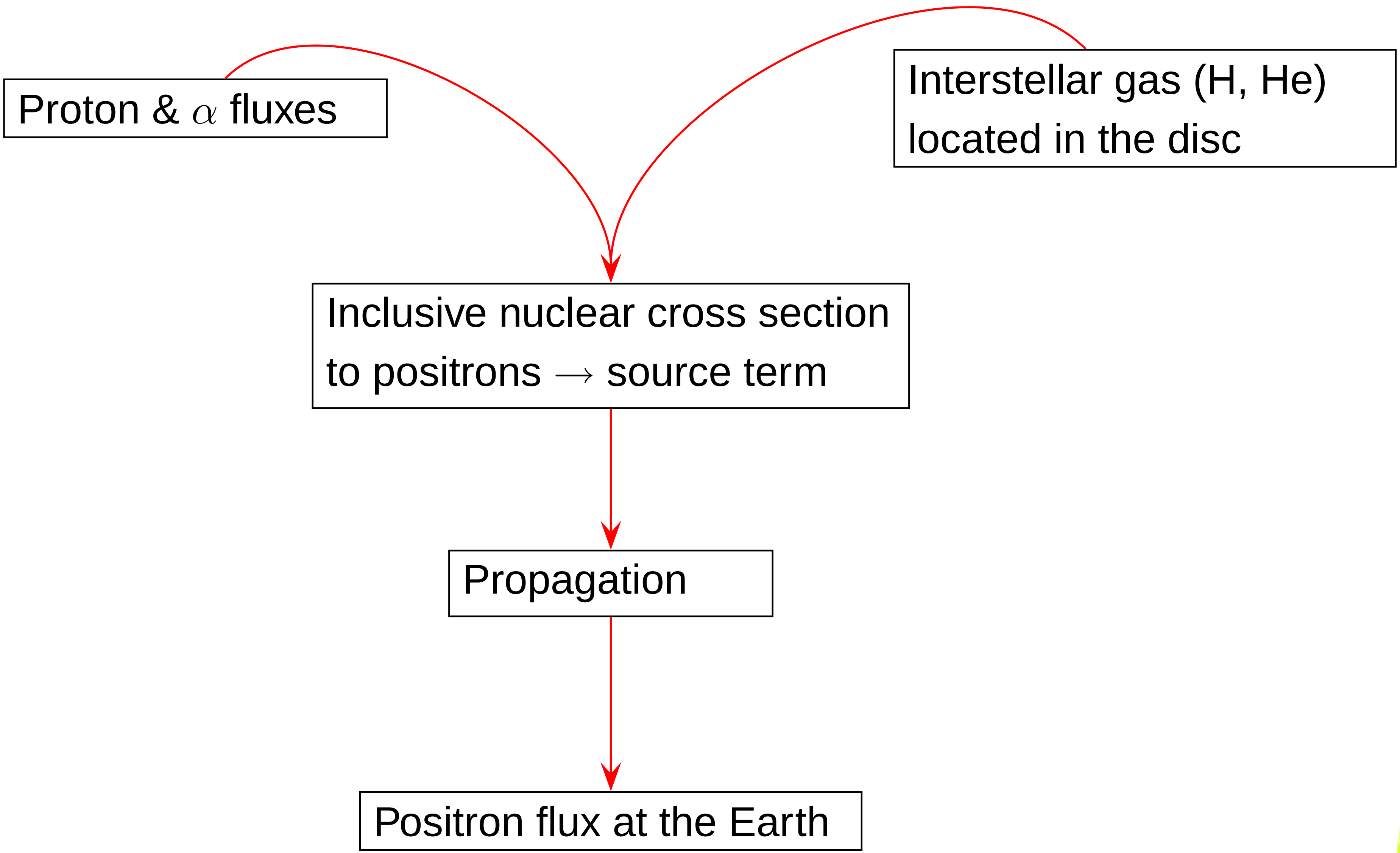


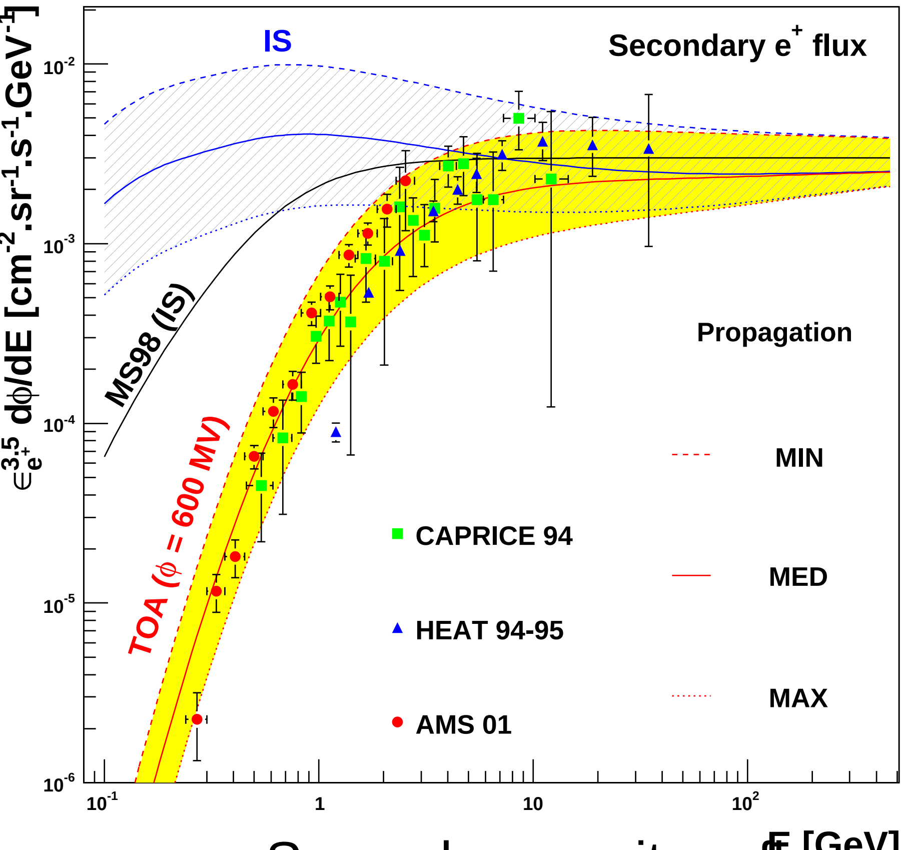
Short recipe for secondary positrons



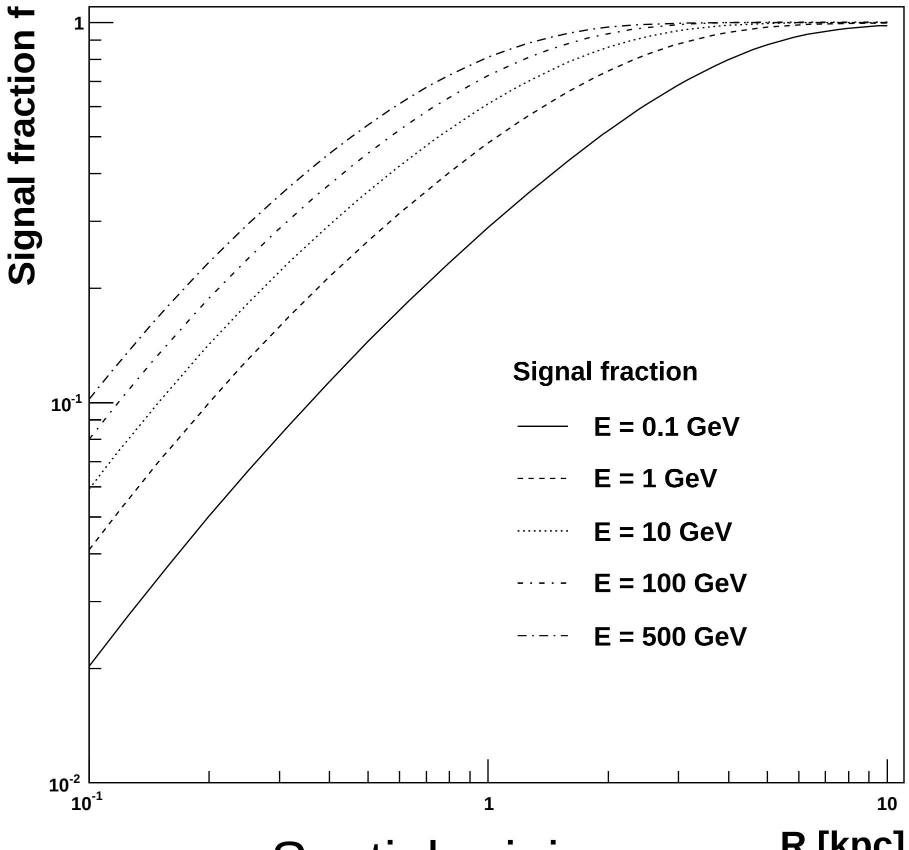
Prediction of the secondary e^+ flux and uncertanties

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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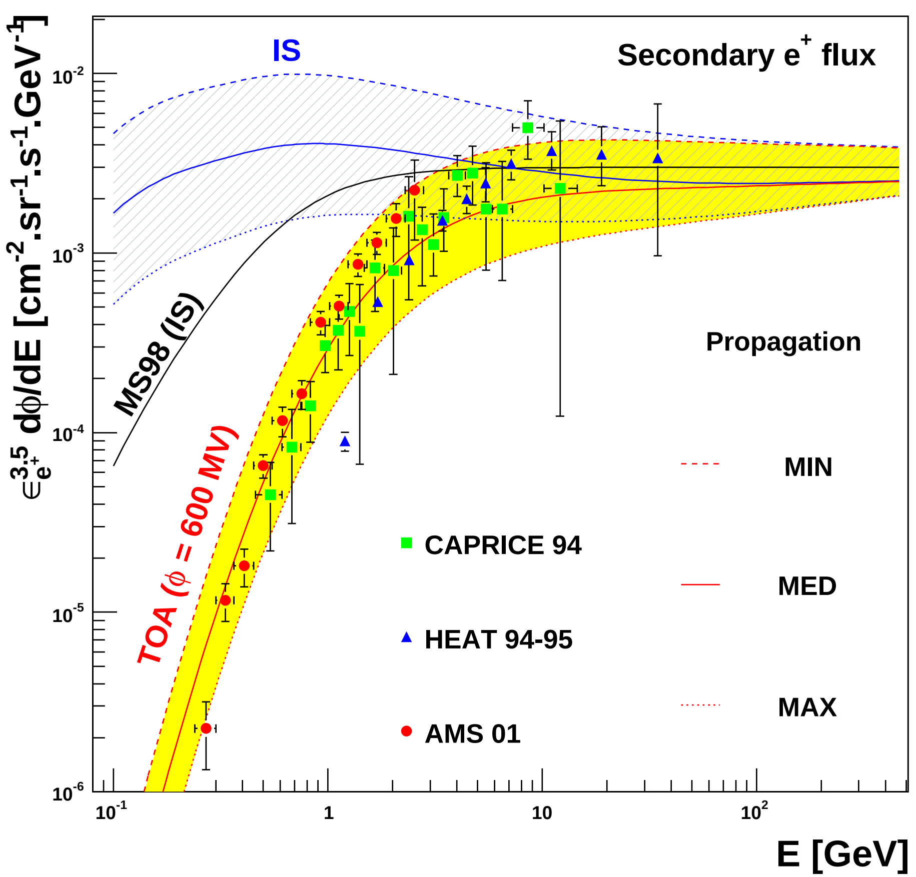

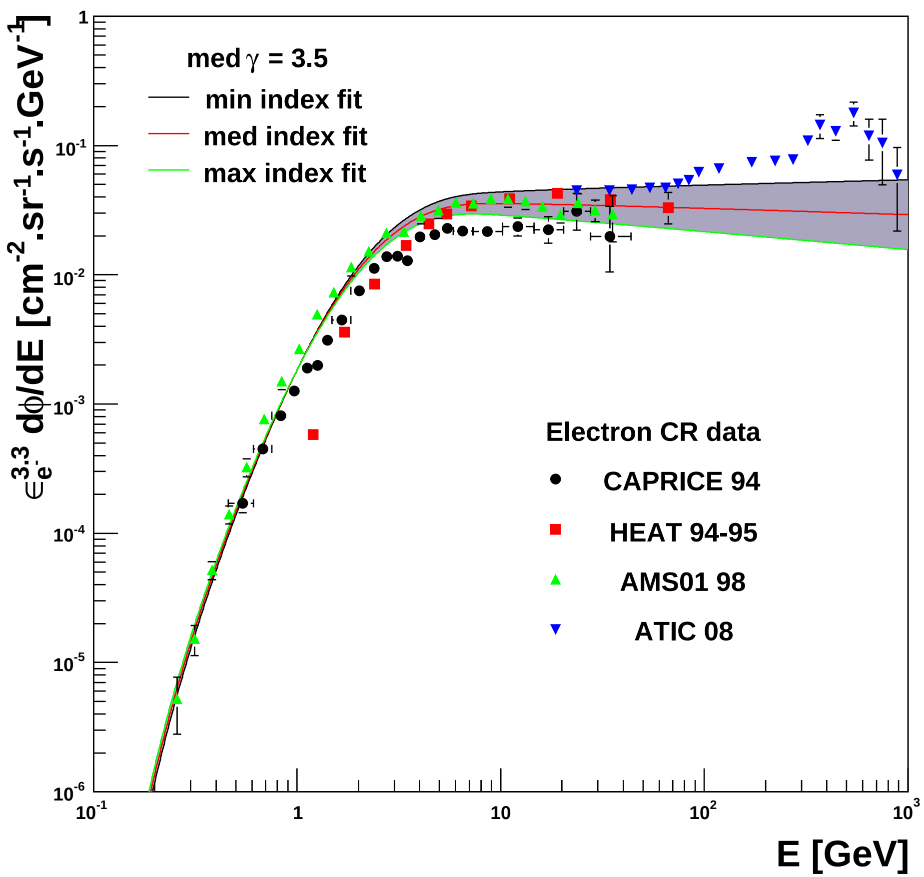

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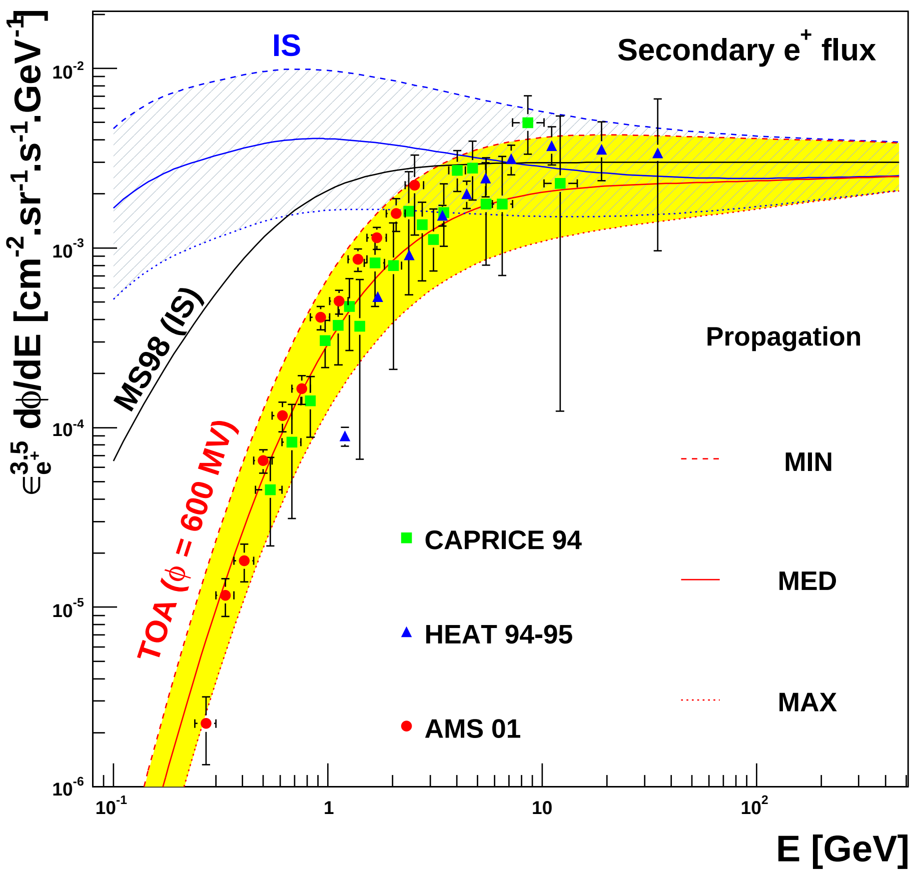

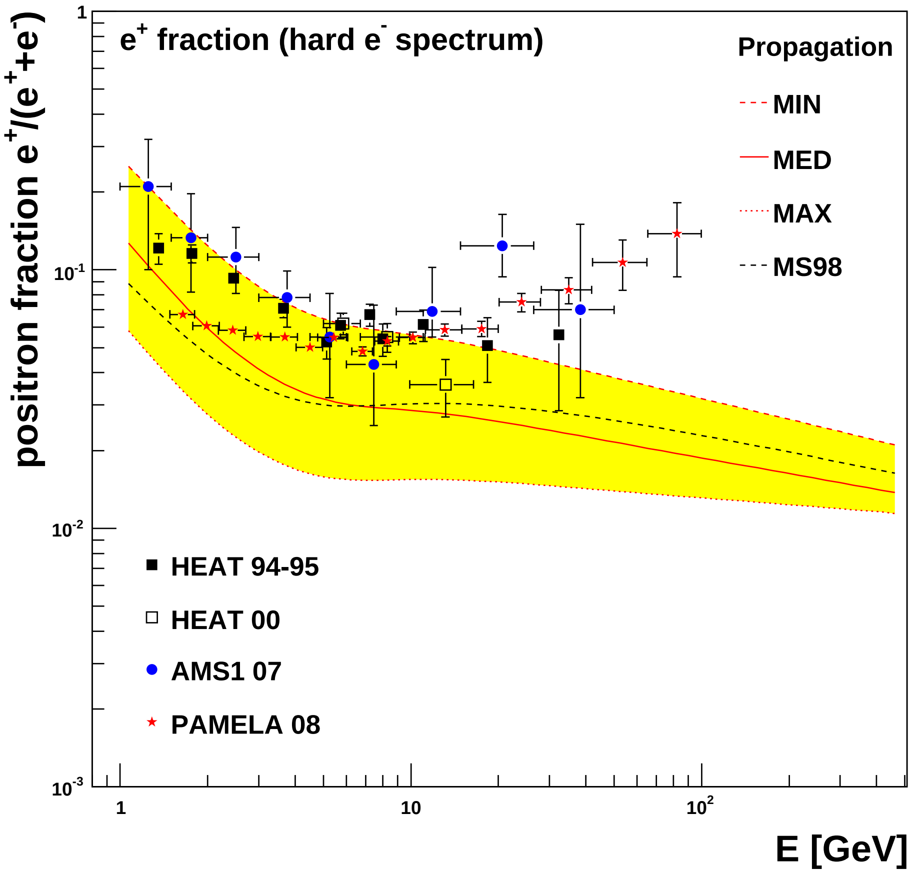

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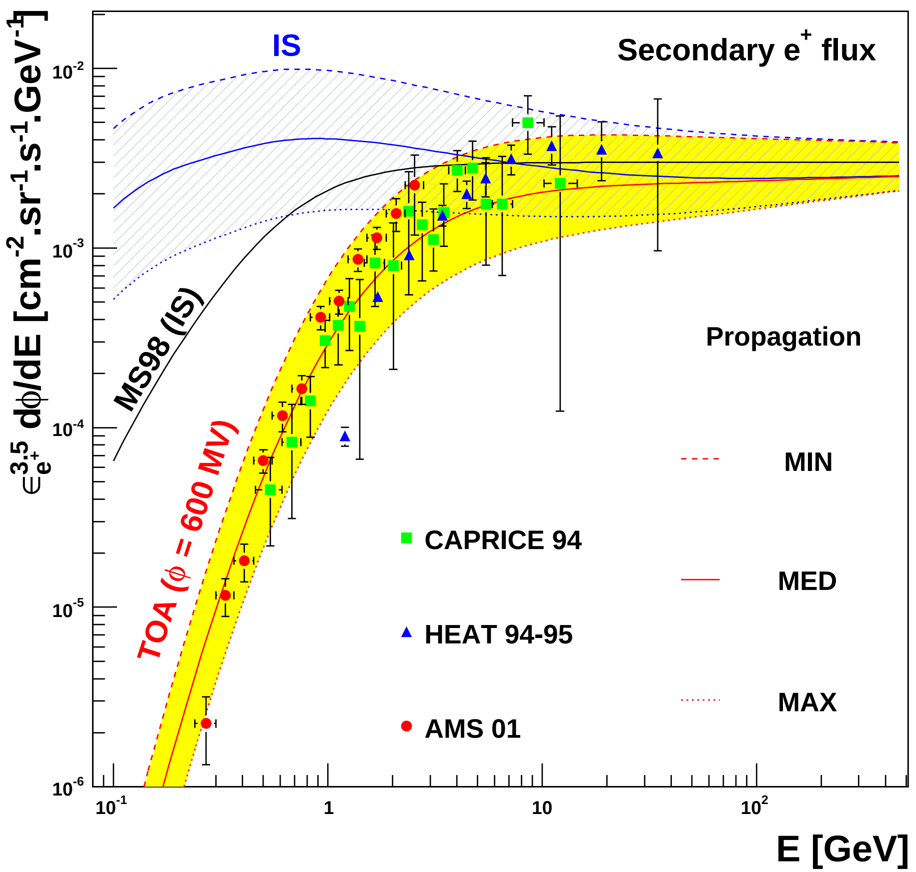
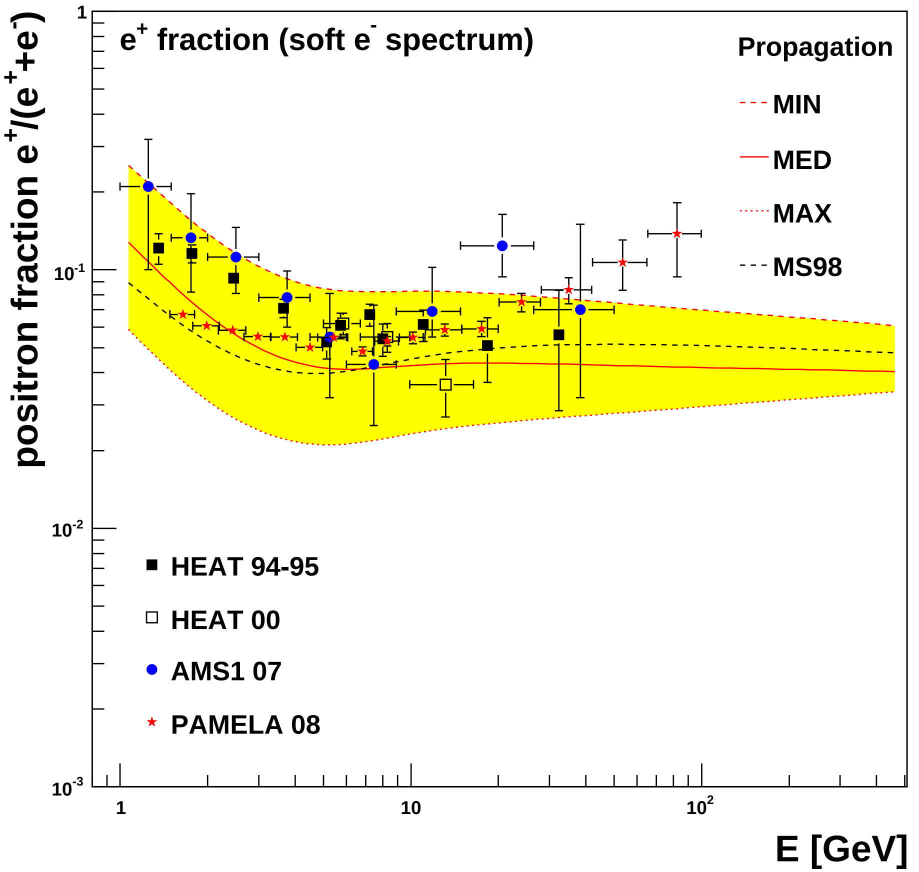




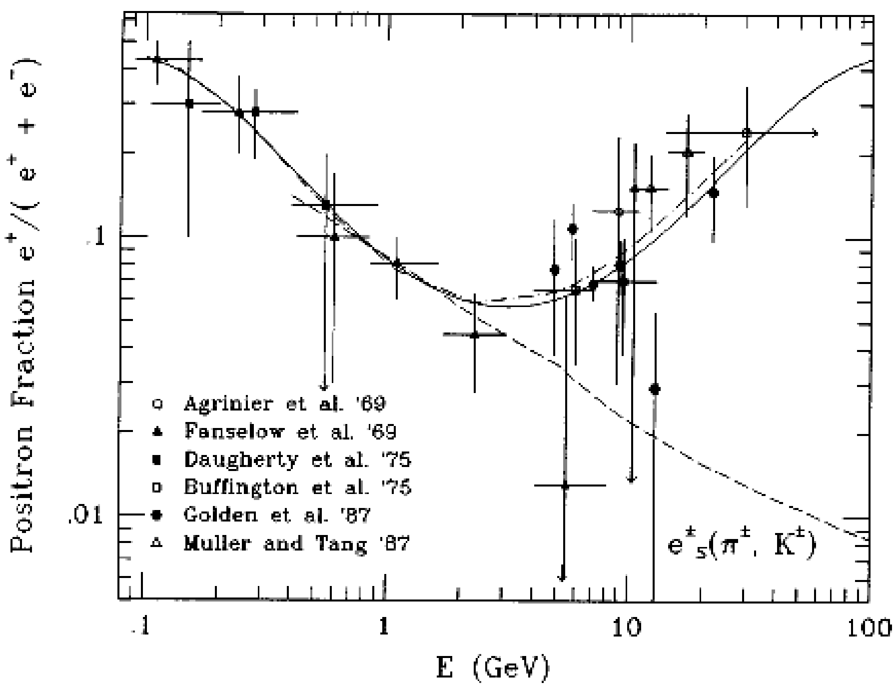
PAMELA excess: standard candidates?

THE ASTROPHYSICAL JOURNAL, 342:807–813, 1989 July 15

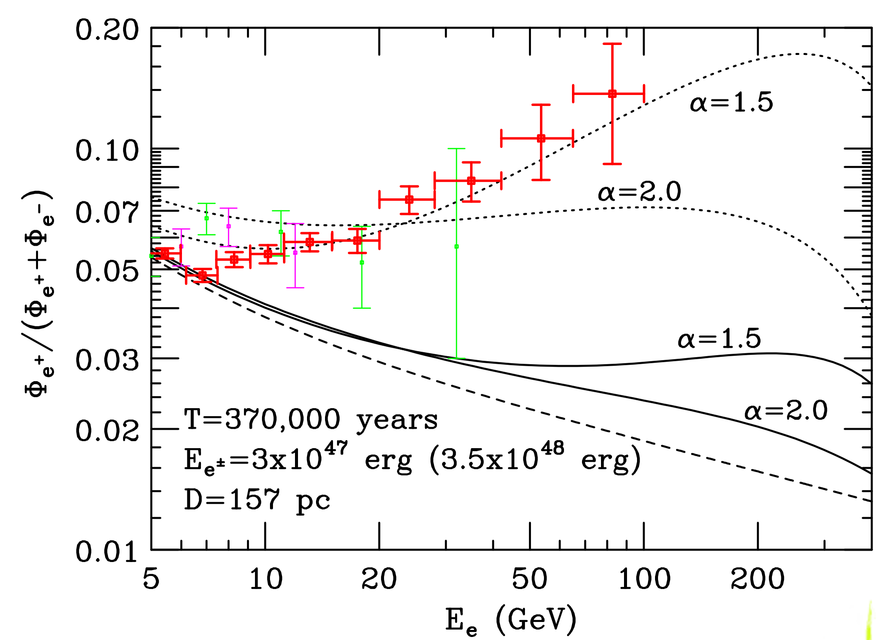
THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

AHMED BOULARES
Physics Department, Space Physics Laboratory, University of Wisconsin–Madison
Received 1988 October 24; accepted 1988 December 29

BOULARES



Hooper et al arXiv:0810.1527



PAMELA excess: dark matter?

Possible, but **needs huge annihilation rate**. Several limits exists.

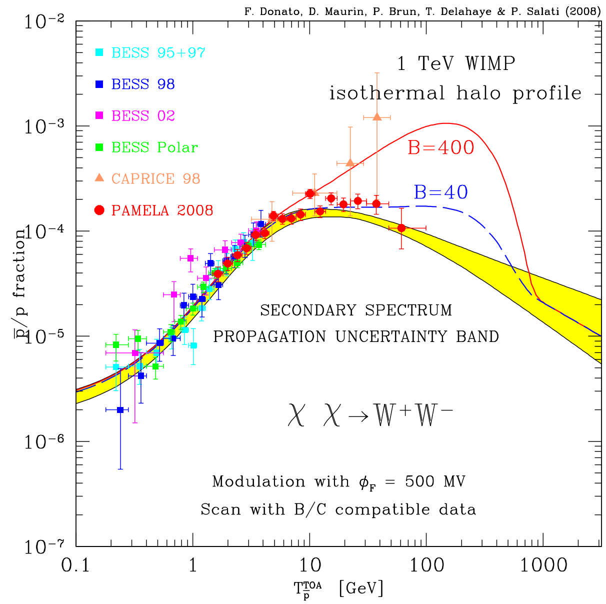
If dark matter annihilates into quarks or heavy bosons

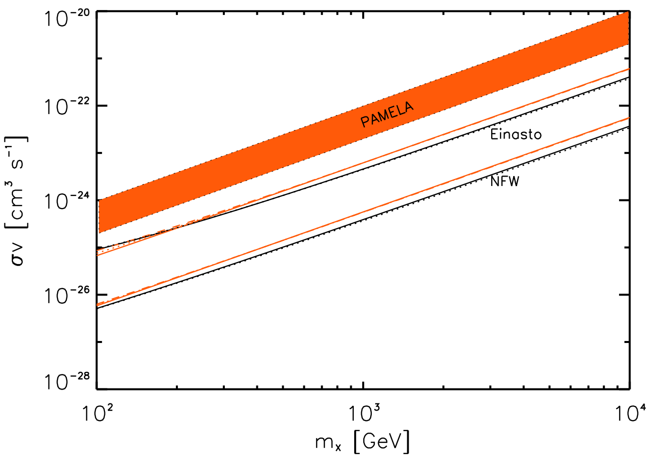
- gamma-rays (next slide)
- antiprotons
  (cf Donato et al arXiv:0810.5292)

If dark matter annihilates into leptons:

- gamma-rays (cf next slide)
- radio emission from GC
  (cf Bergström et al arXiv:0812.3895)

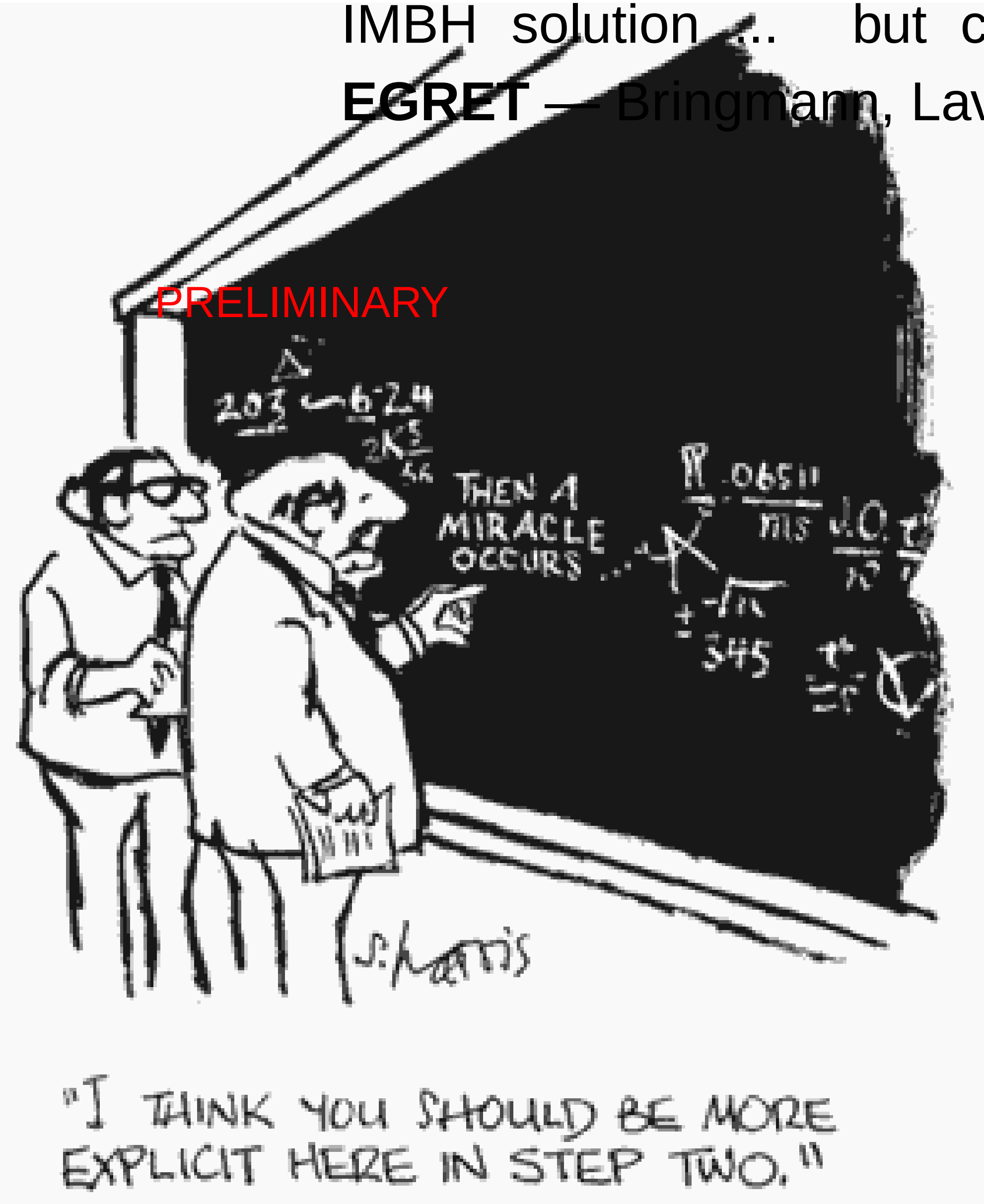
In any case, boosting the annihilation rate is a serious issue.

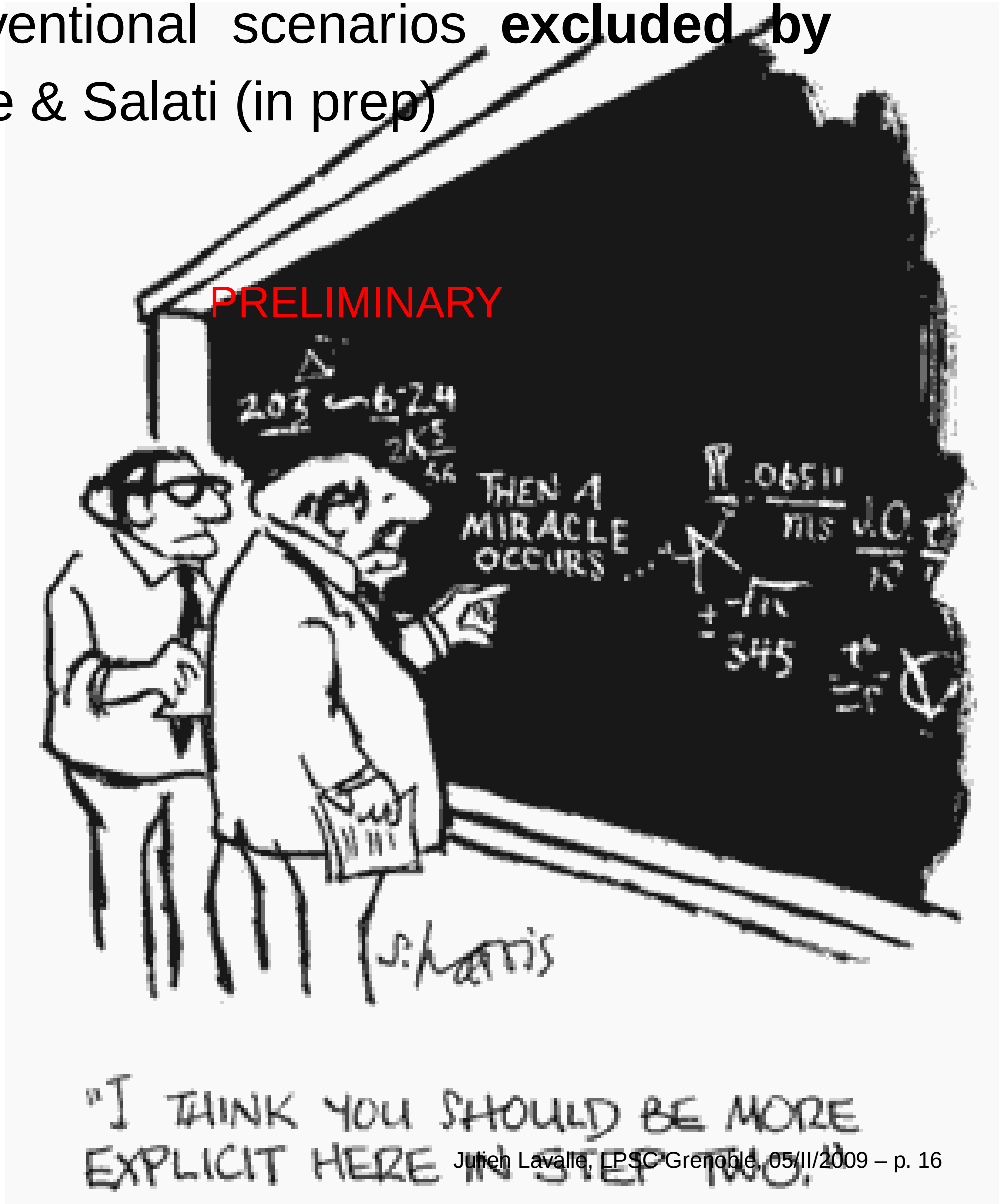




PAMELA excess: nearby dark sources?

IMBH solution ... but conventional scenarios **excluded by EGRET** — Bringmann, Lavalle & Salati (in prep)





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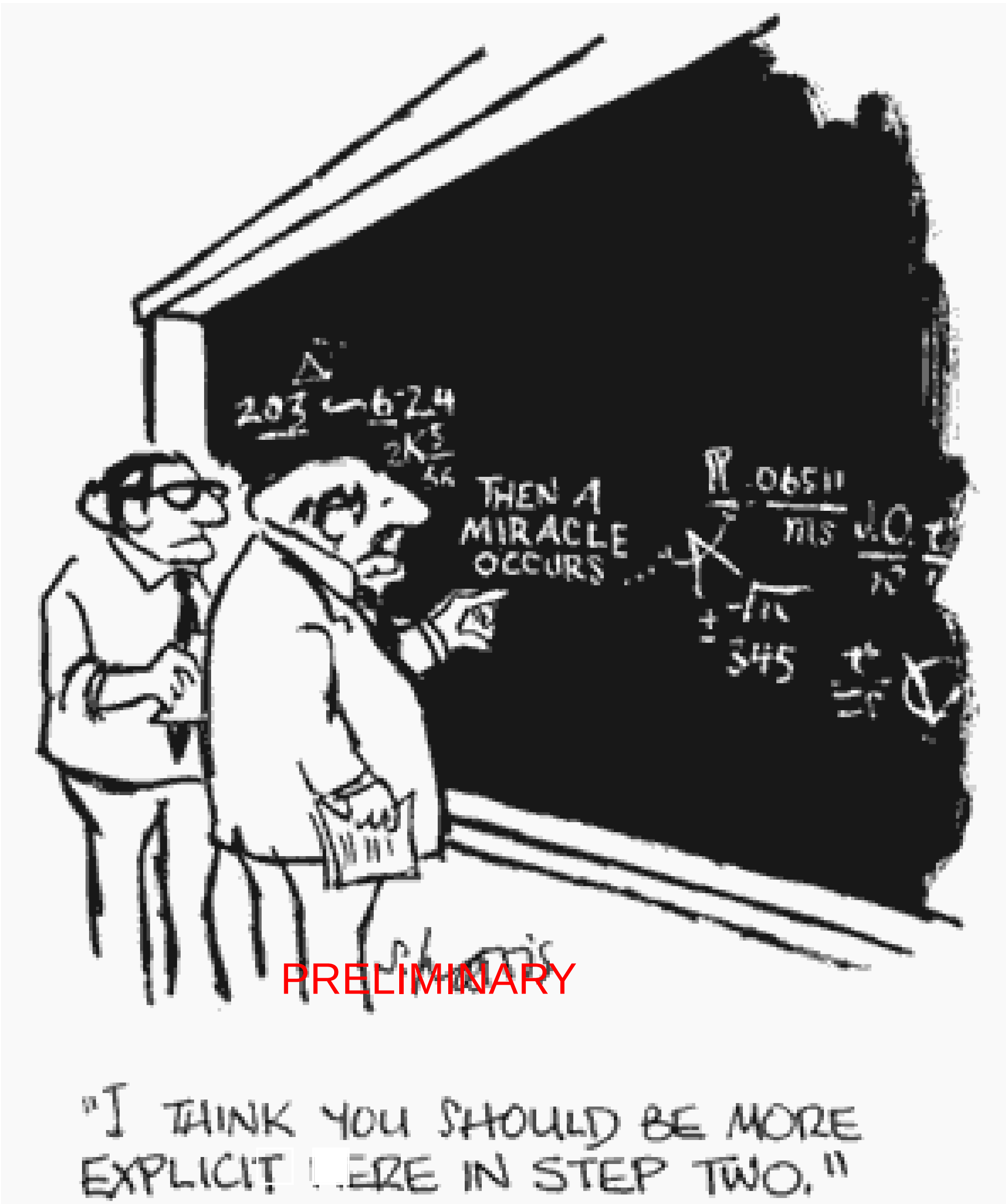
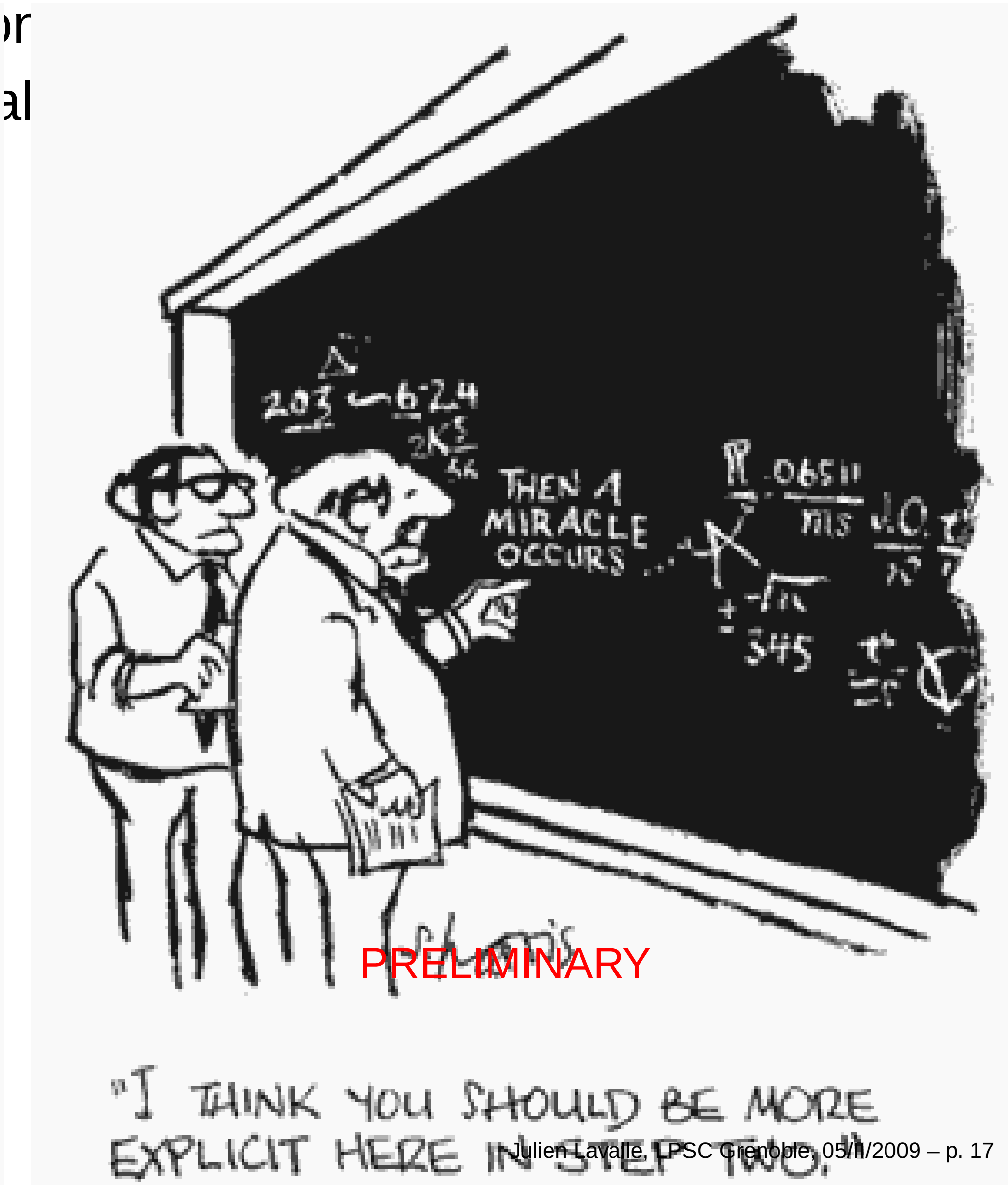




The Clumpiness issue

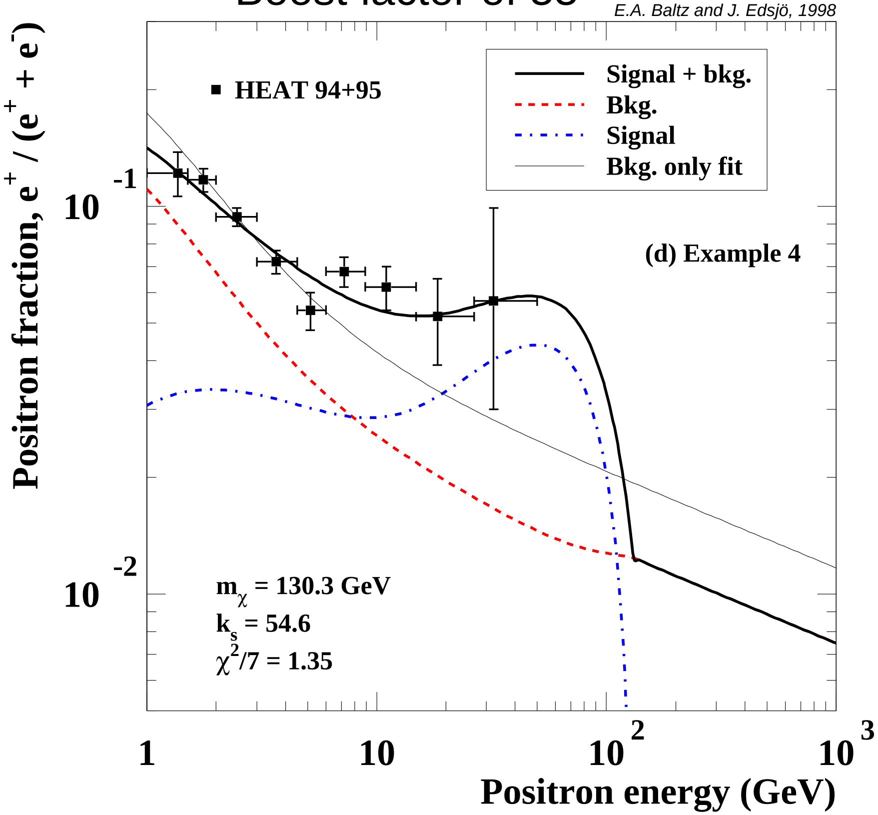
Clumpiness has long been invoked to boost the antimatter yield from dark matter annihilation.

- clumps are not expected in the GC: no synchrotron constraints
- they are expected to be numerous from cosmological simulations

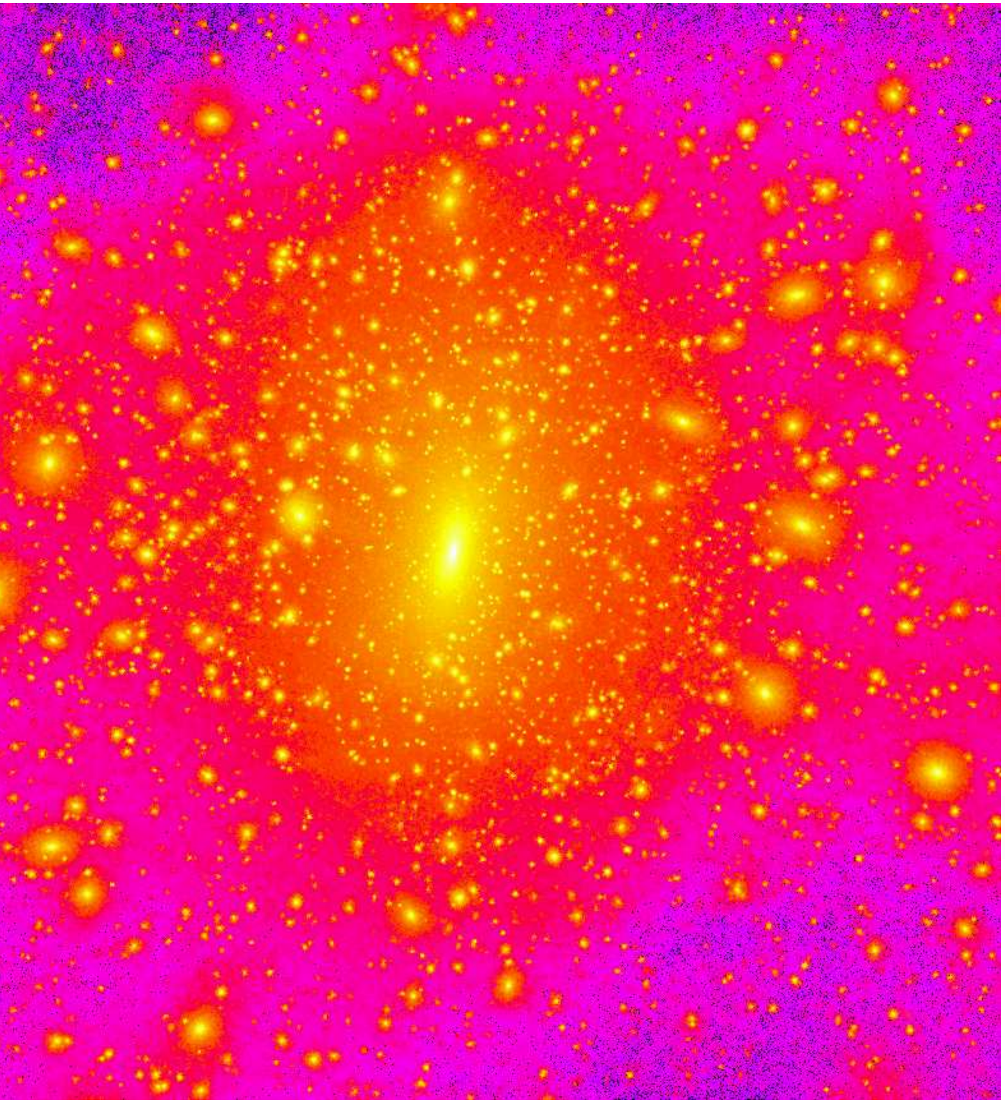
Are they able to boost enough the positron signal?

Baltz & Edsjö, 98

Boost factor of 55



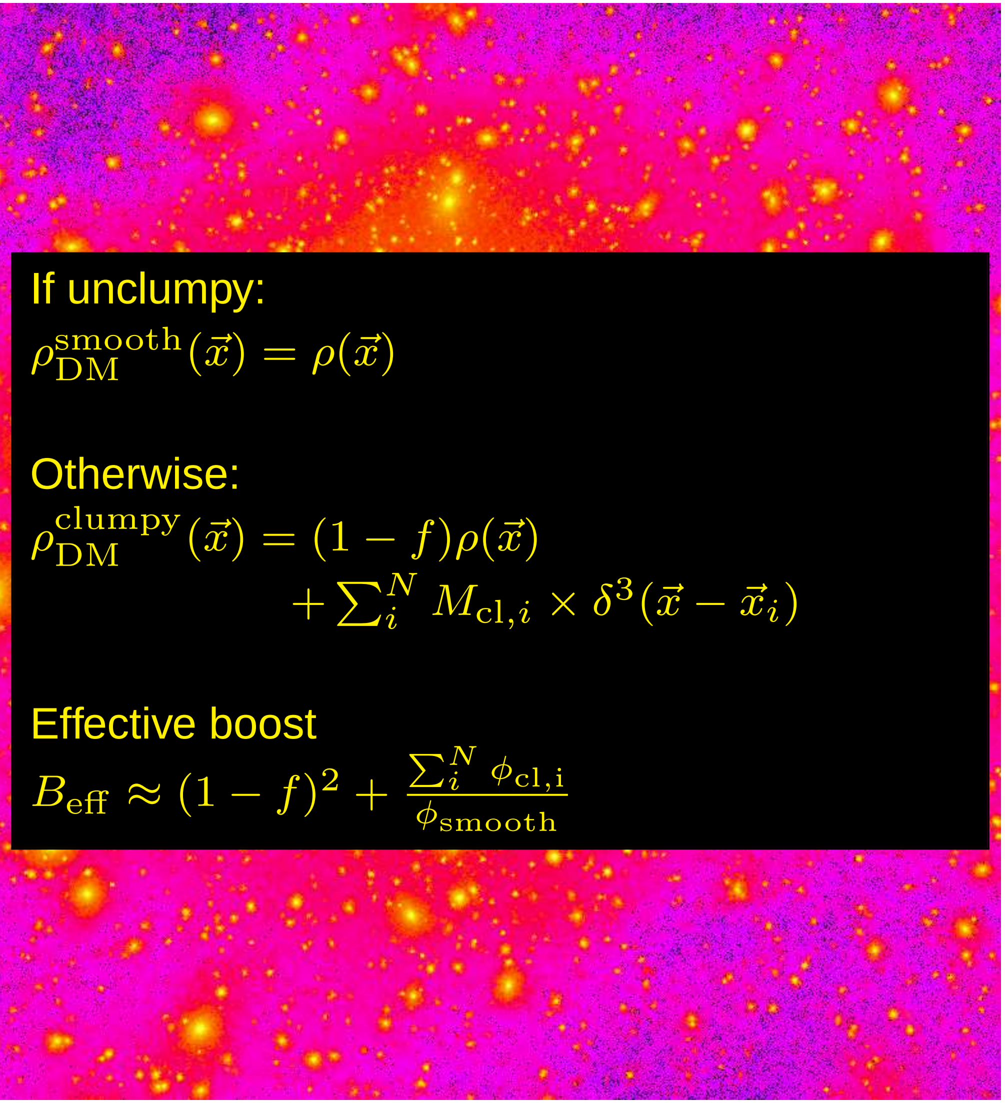
Inhomogeneous halo and boosted annihilation rate



(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

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

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

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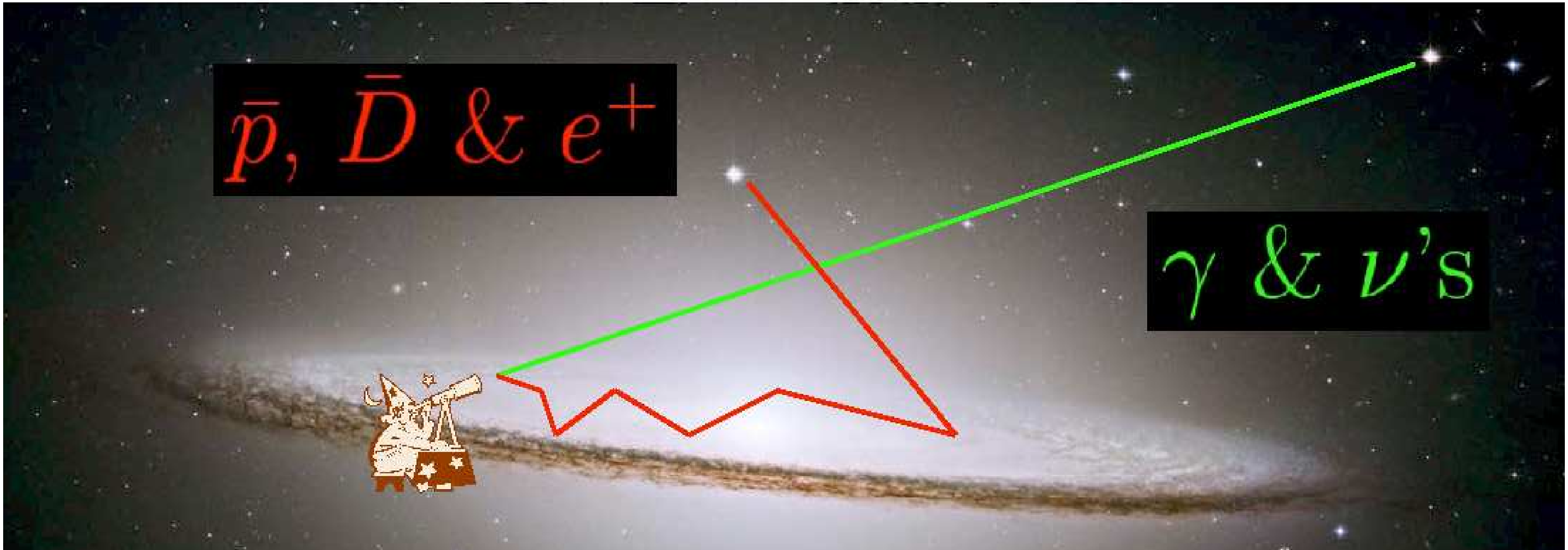
Gamma-rays versus antimatter cosmic rays



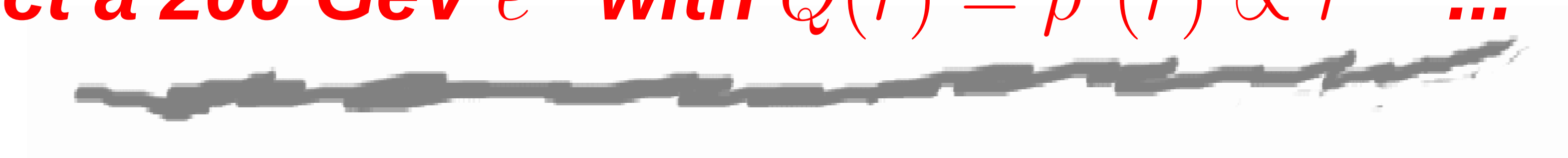
The annihilation signal is integrated:

- **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 !**

Effective volume picture for the smooth contribution

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



Effective volume picture for the smooth contribution

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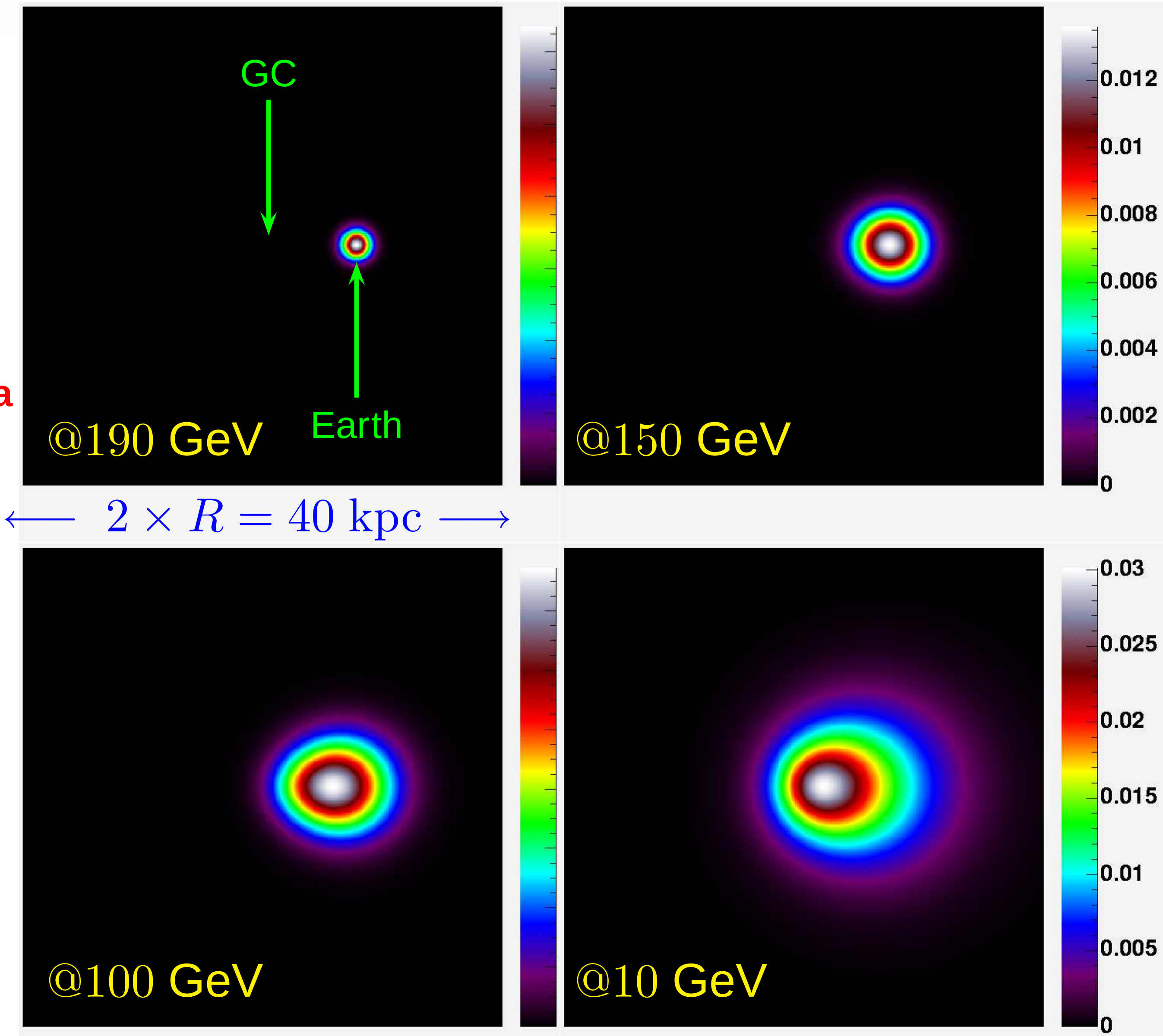
Simplest view of propagation

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

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

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



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

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

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

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

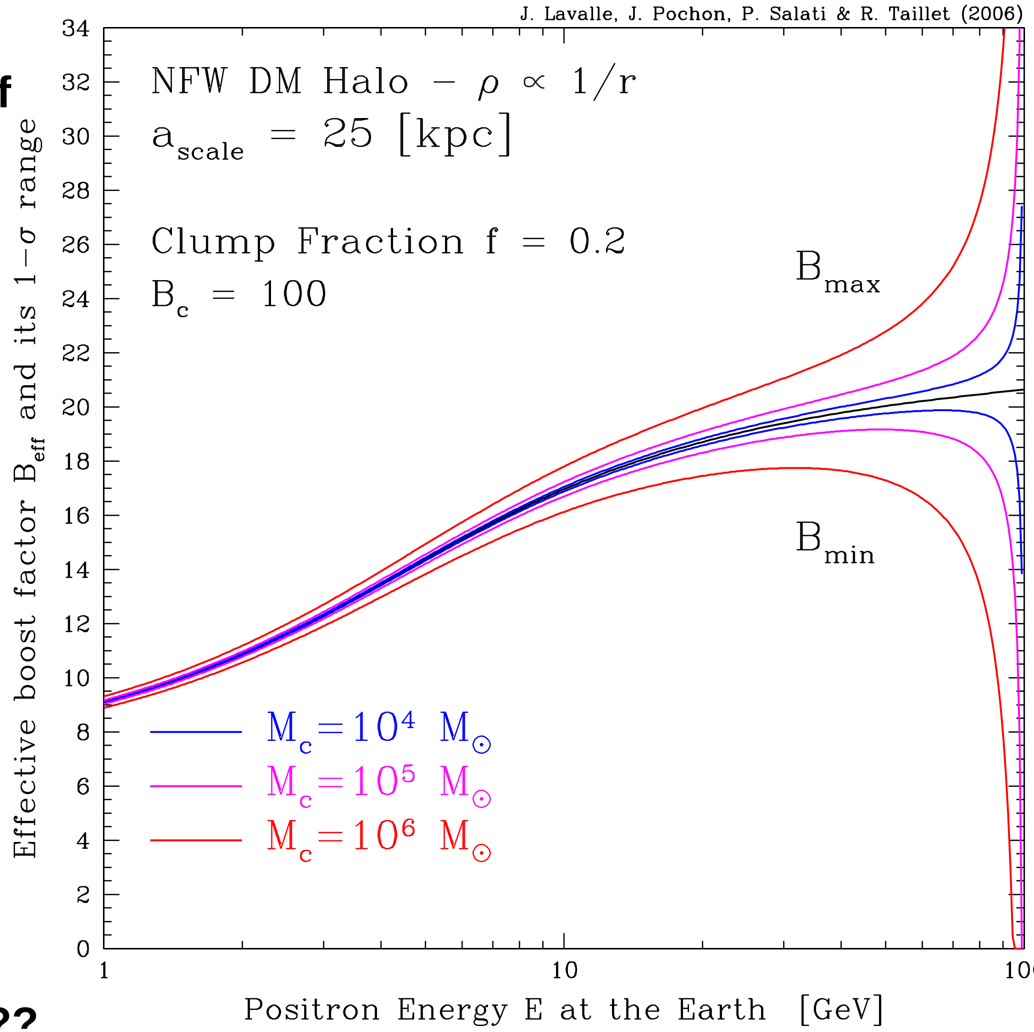
PDFs allow to compute mean values and associated statistical variances for some physical quantities

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

Computing the odds of the Galactic Lottery: 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 ($\sim 1/\sqrt{N_{\rm eff}}$).
- **The recipe applies to any kind of sources**
- **Predictions for N-body-like models ???**



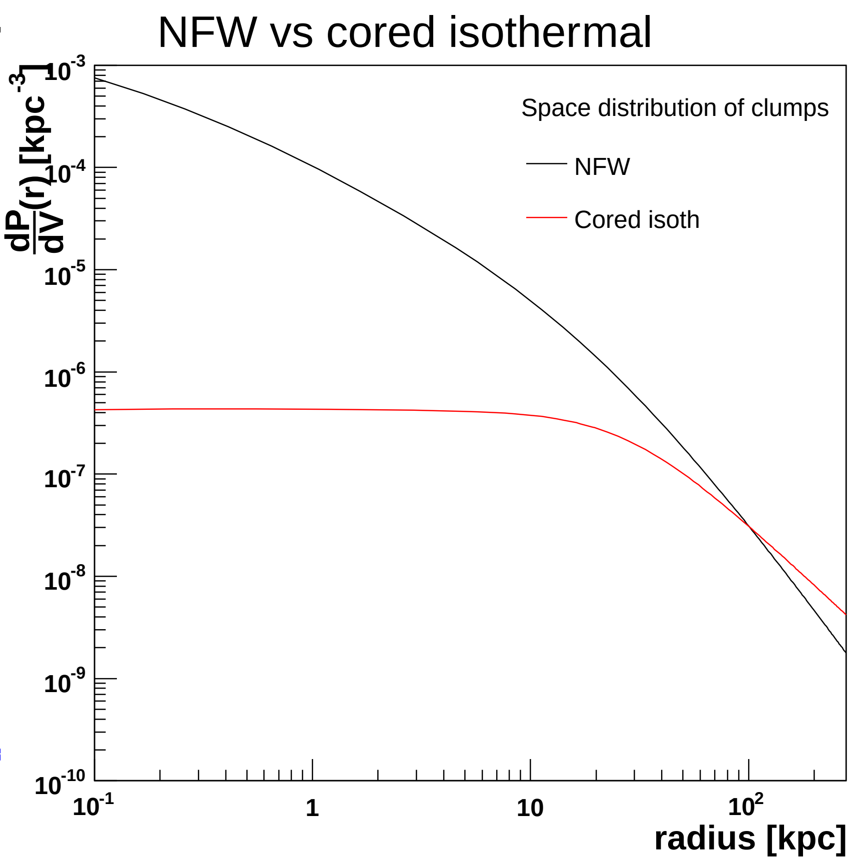
Lavalle et al, A&A 462 (2007)

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

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

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]



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

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

Positrons:

- Source: injection of a 200 GeV line

Antiprotons:

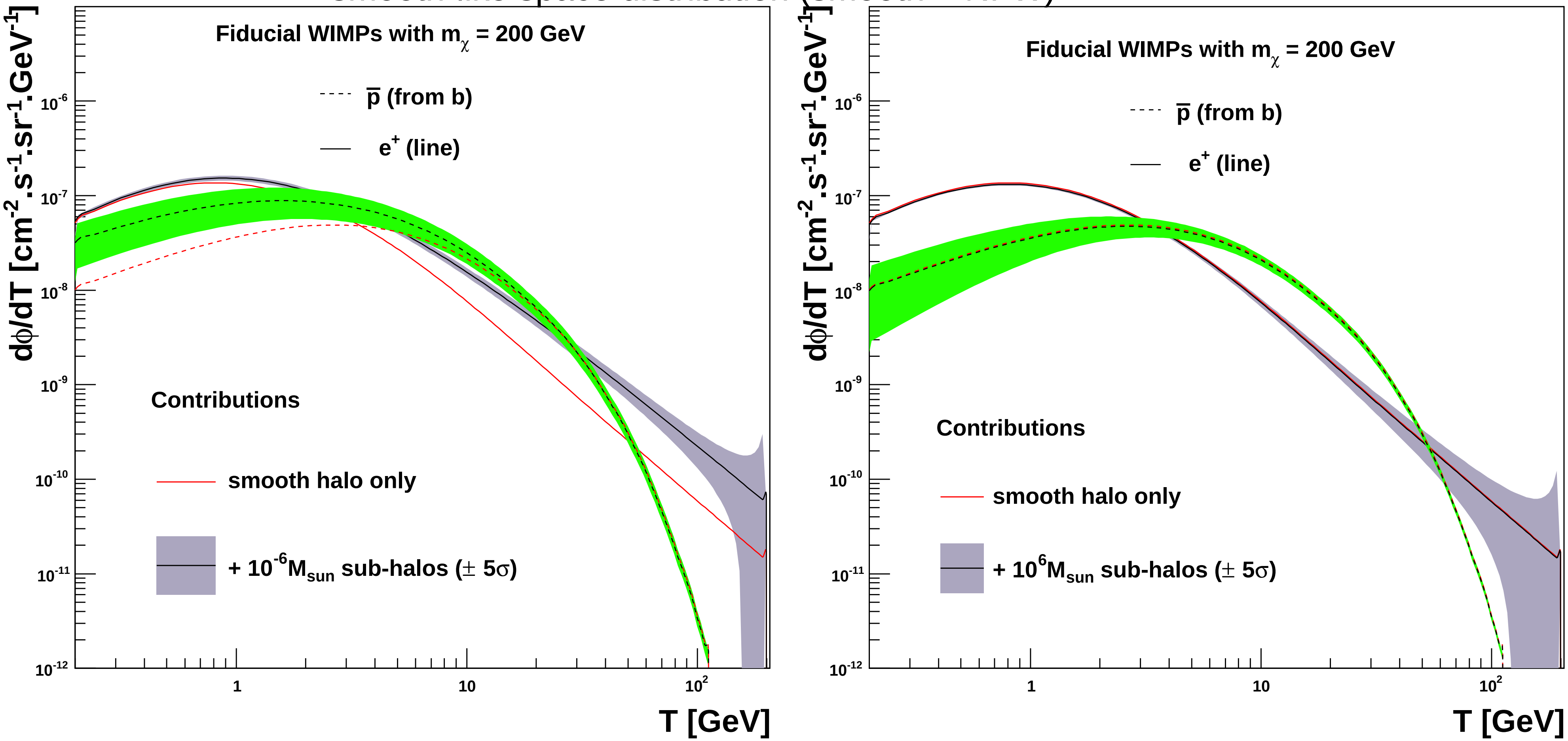
- Source: flat spectrum (1/GeV)

Both:

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

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

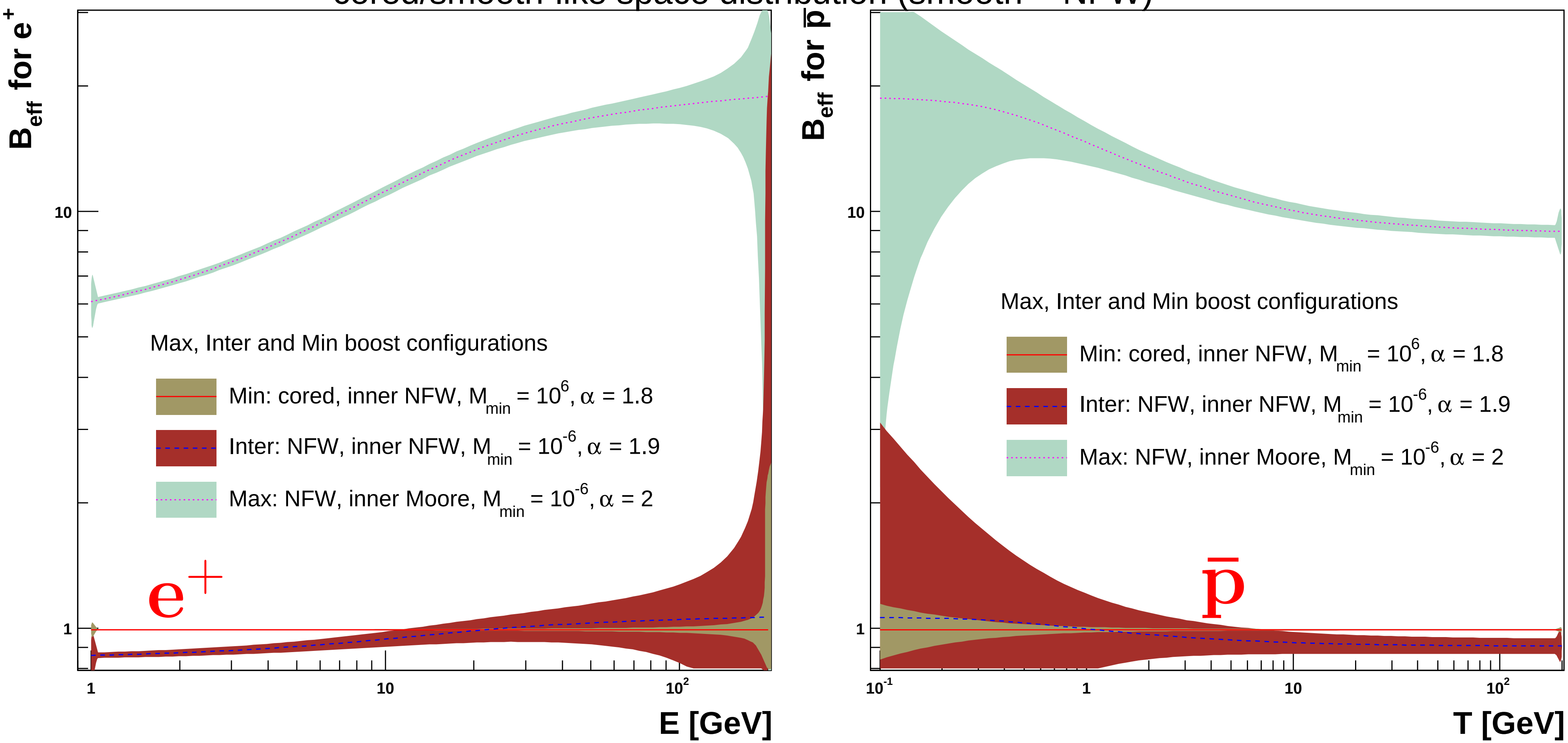
Configurations: $M_{\rm min} = 10^{-6}|10^{6} M_{\odot}$, $\alpha_{\rm m} = 2.0$, inner-NFW, B01,
smooth-like space distribution (smooth = NFW)



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



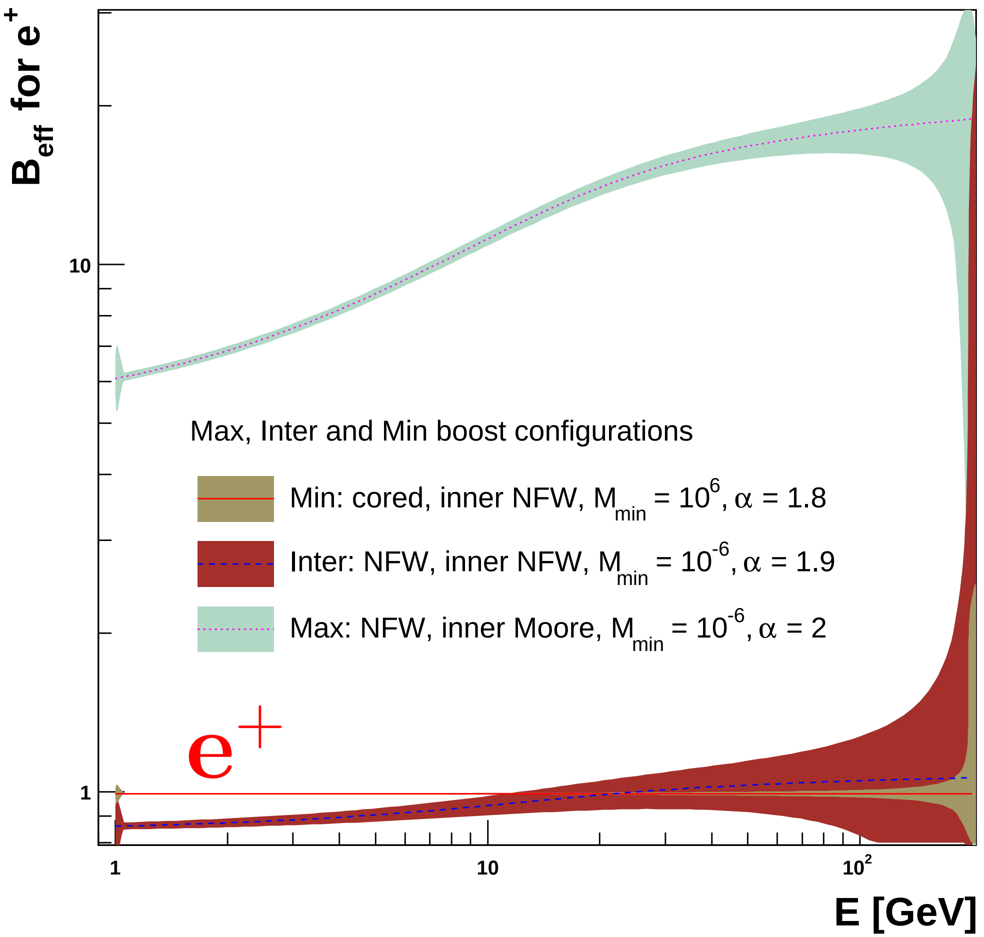
Lavalle, Yuan, Maurin & Bi – A&A 429, 427 (2008)

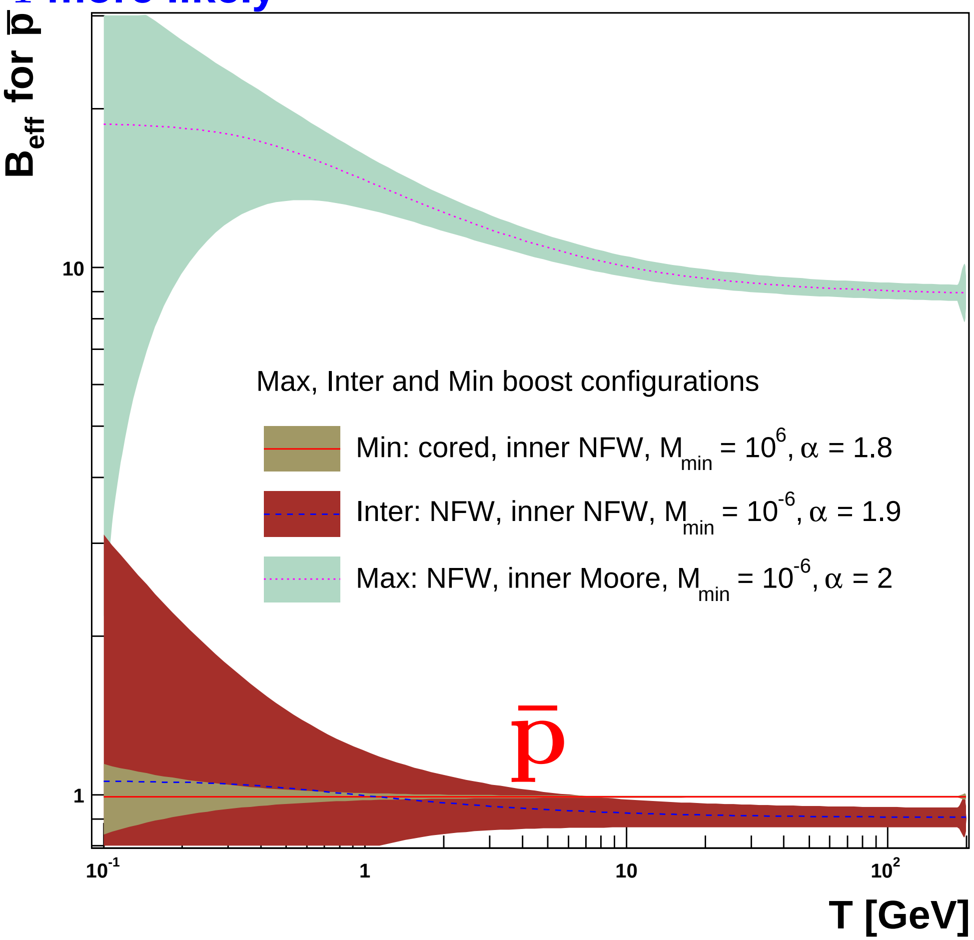
Boost factors for a 200 GeV e^+ line / antiprotons

Small concentration models favored !!!

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

Boosts ~ 1 more likely





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

Going farther :

3D map of DM density from N-body simulations

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Lavalle, Nezri, Ling, Athanassoula & Teyssier)

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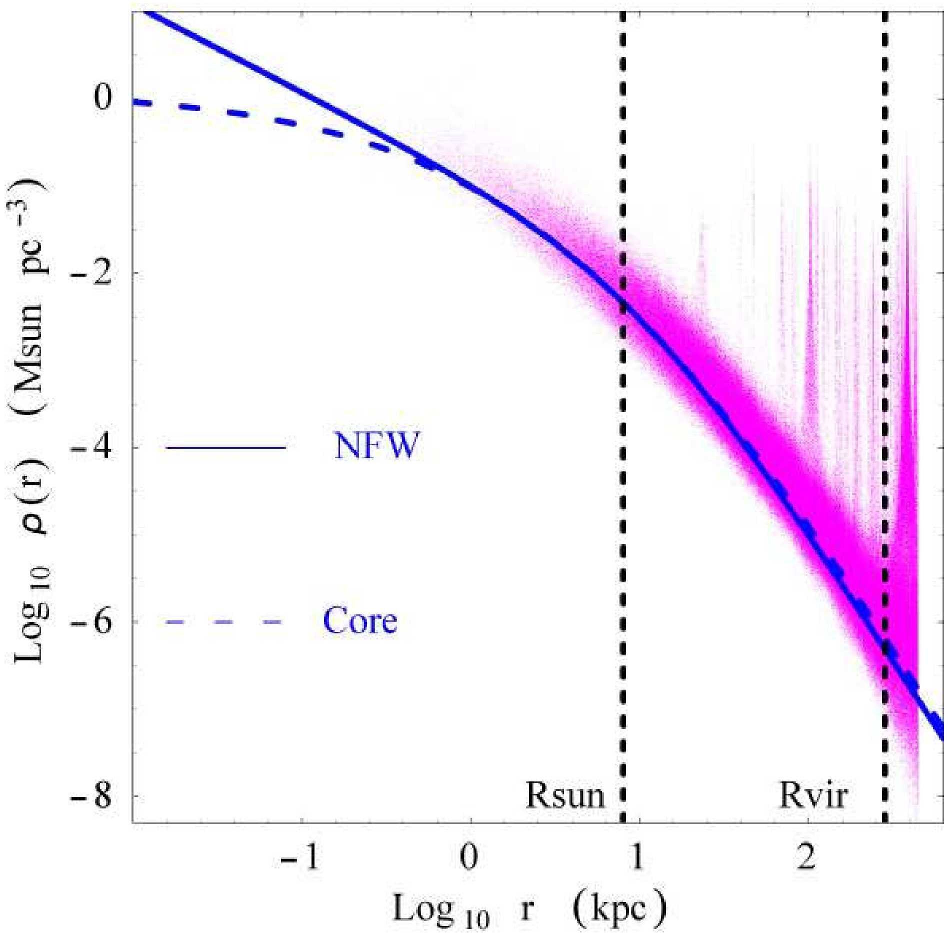
Results: $\sim$ 1-2 order of magnitude uncertainty on antimatter flux (local density fluctuations or asphericity), but still below the data: no excess expected below 100 GeV.

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



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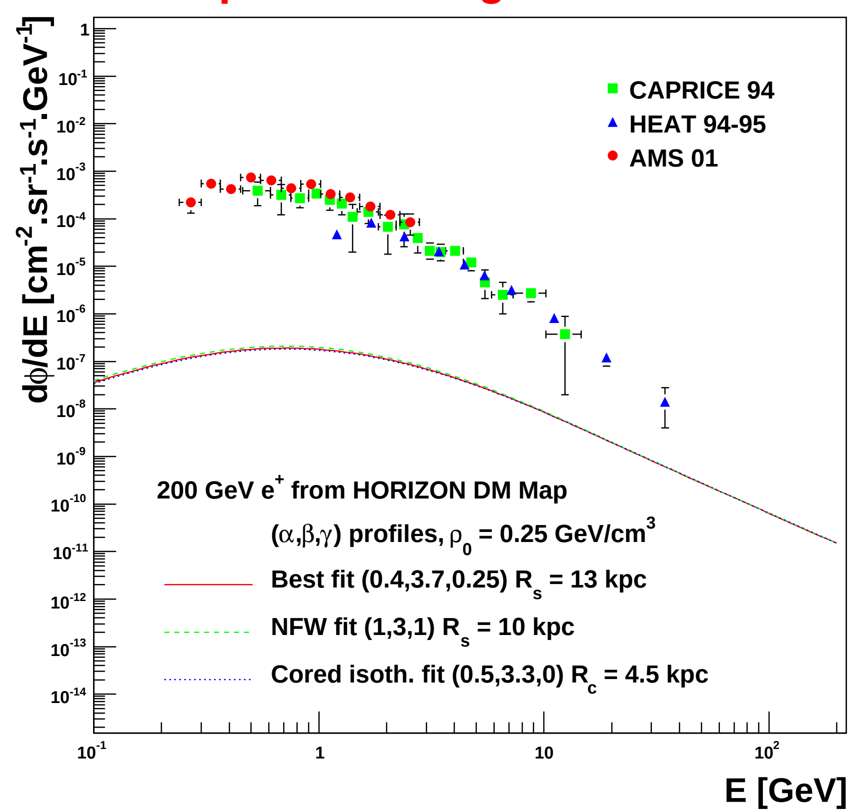
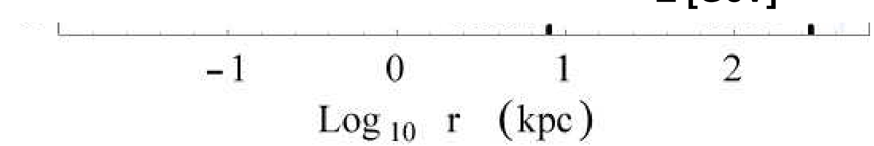
Different spherical fits give $\sim$ the same fluxes





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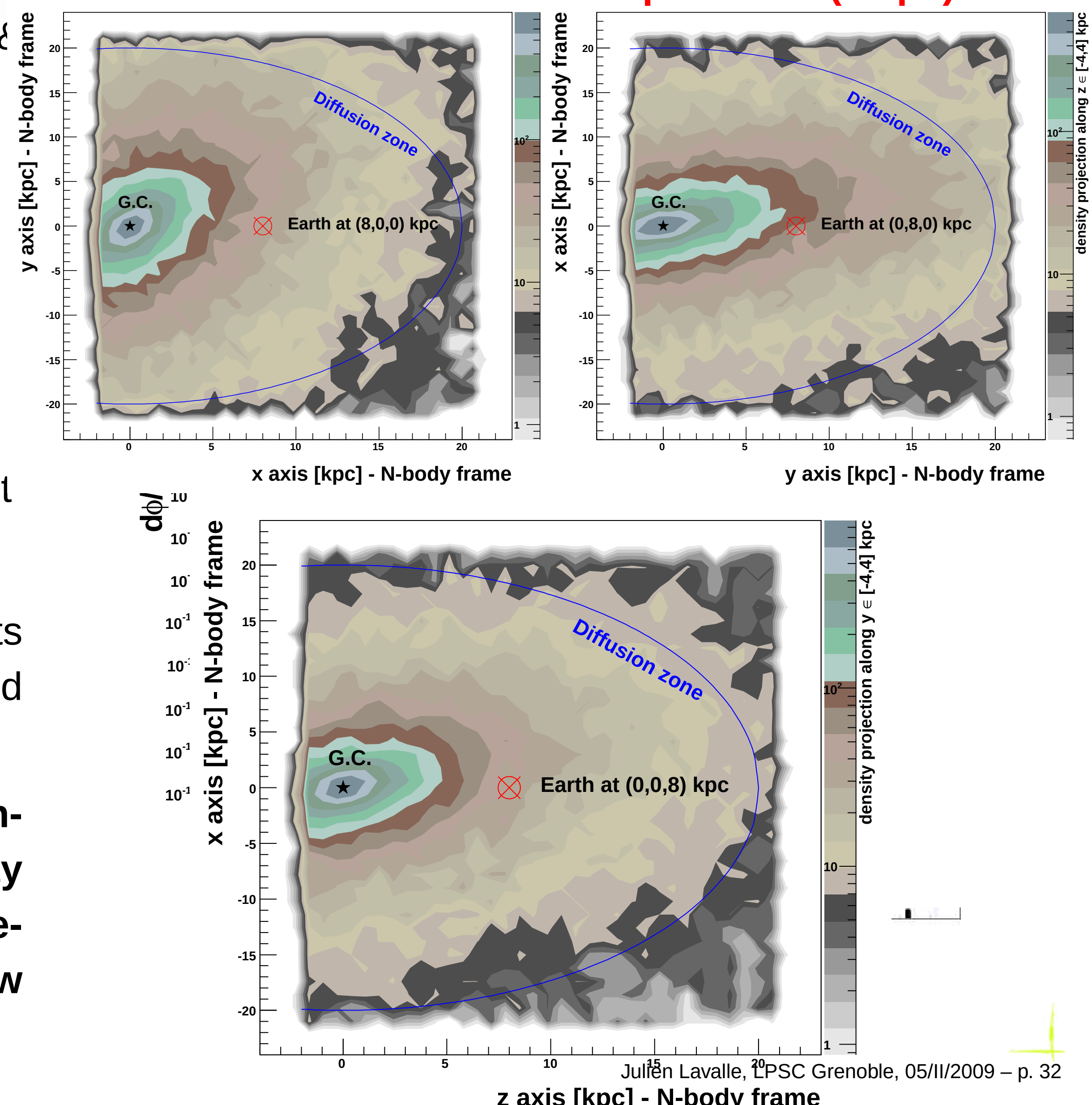
Earth at different 3 positions (8 kpc)



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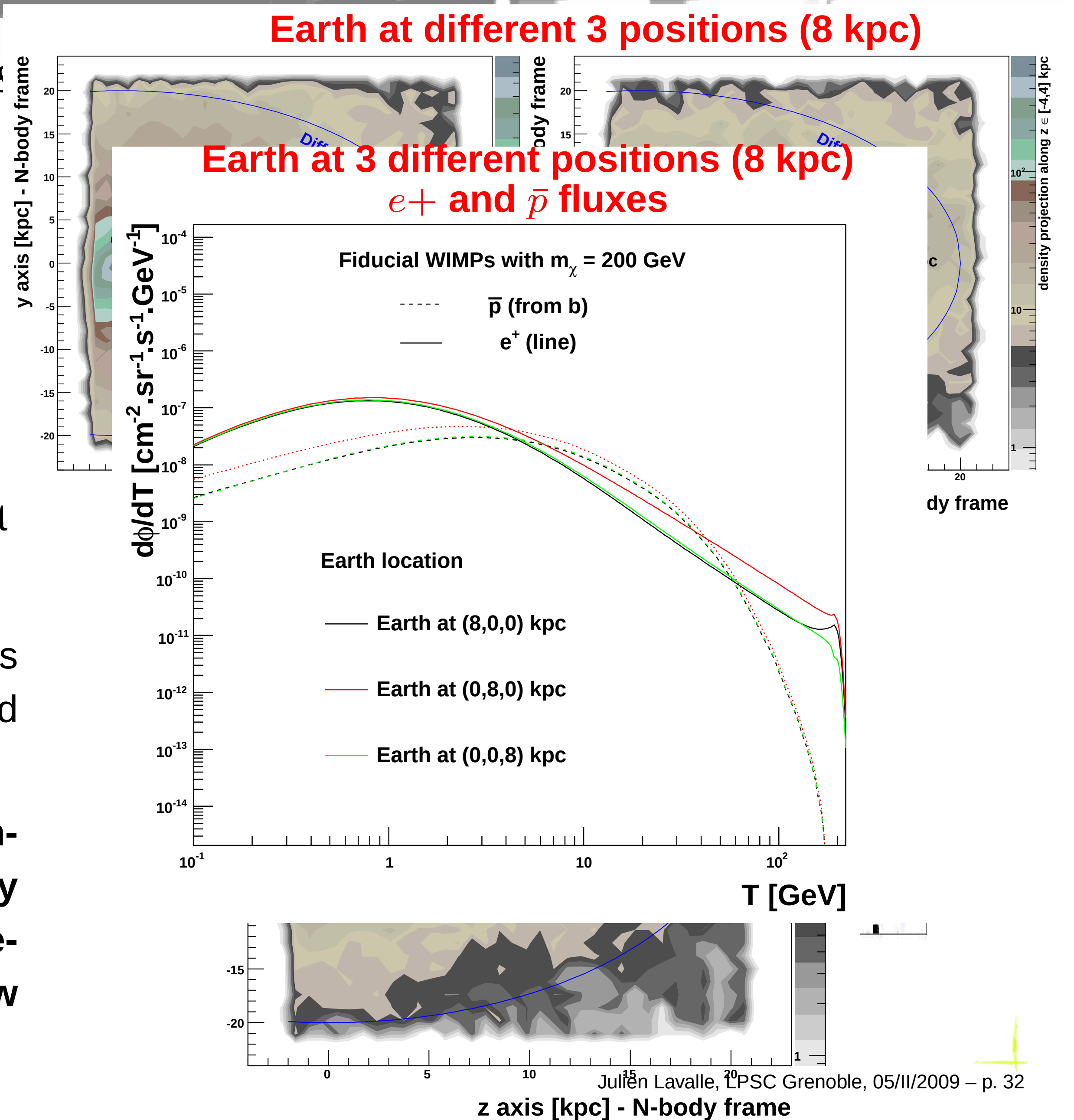

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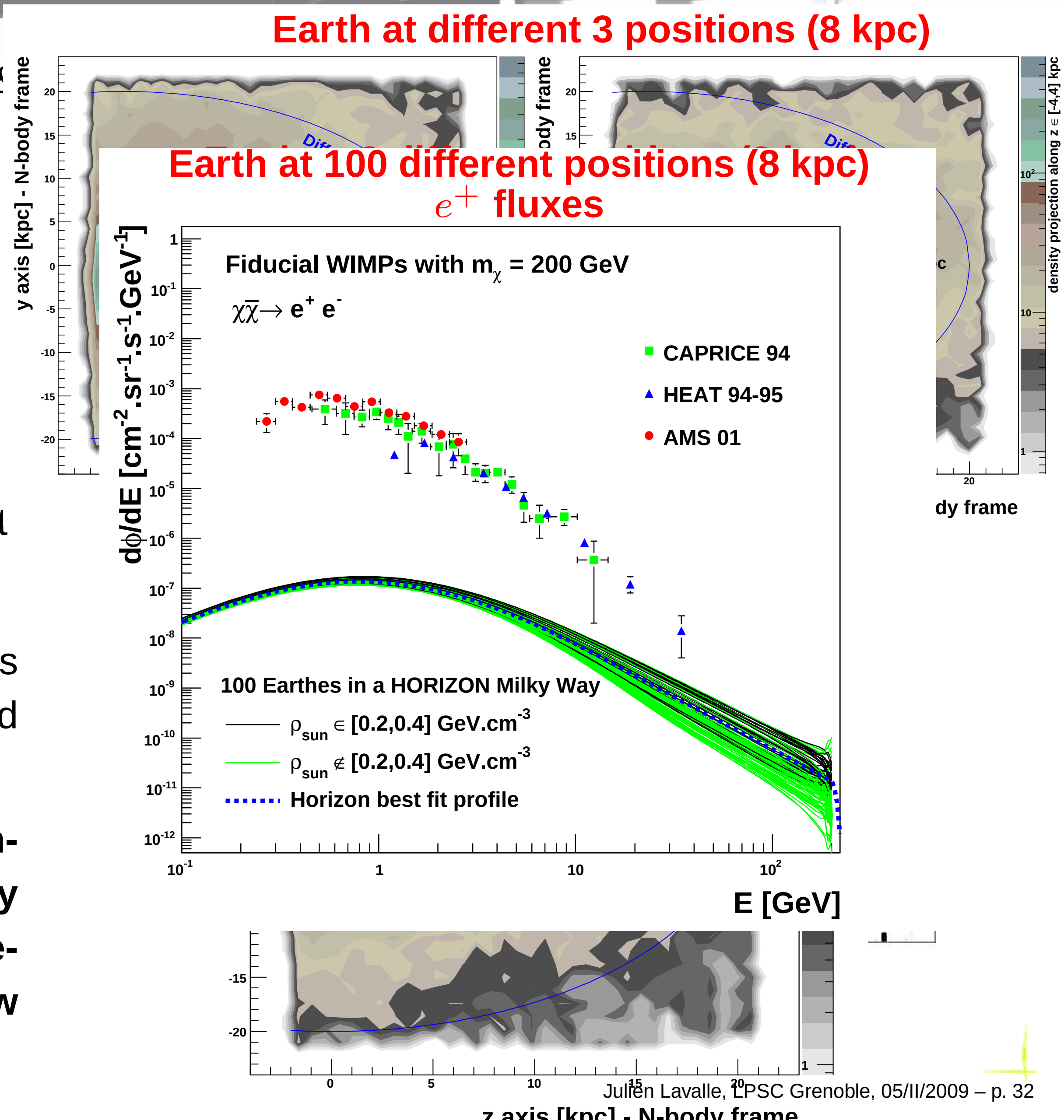

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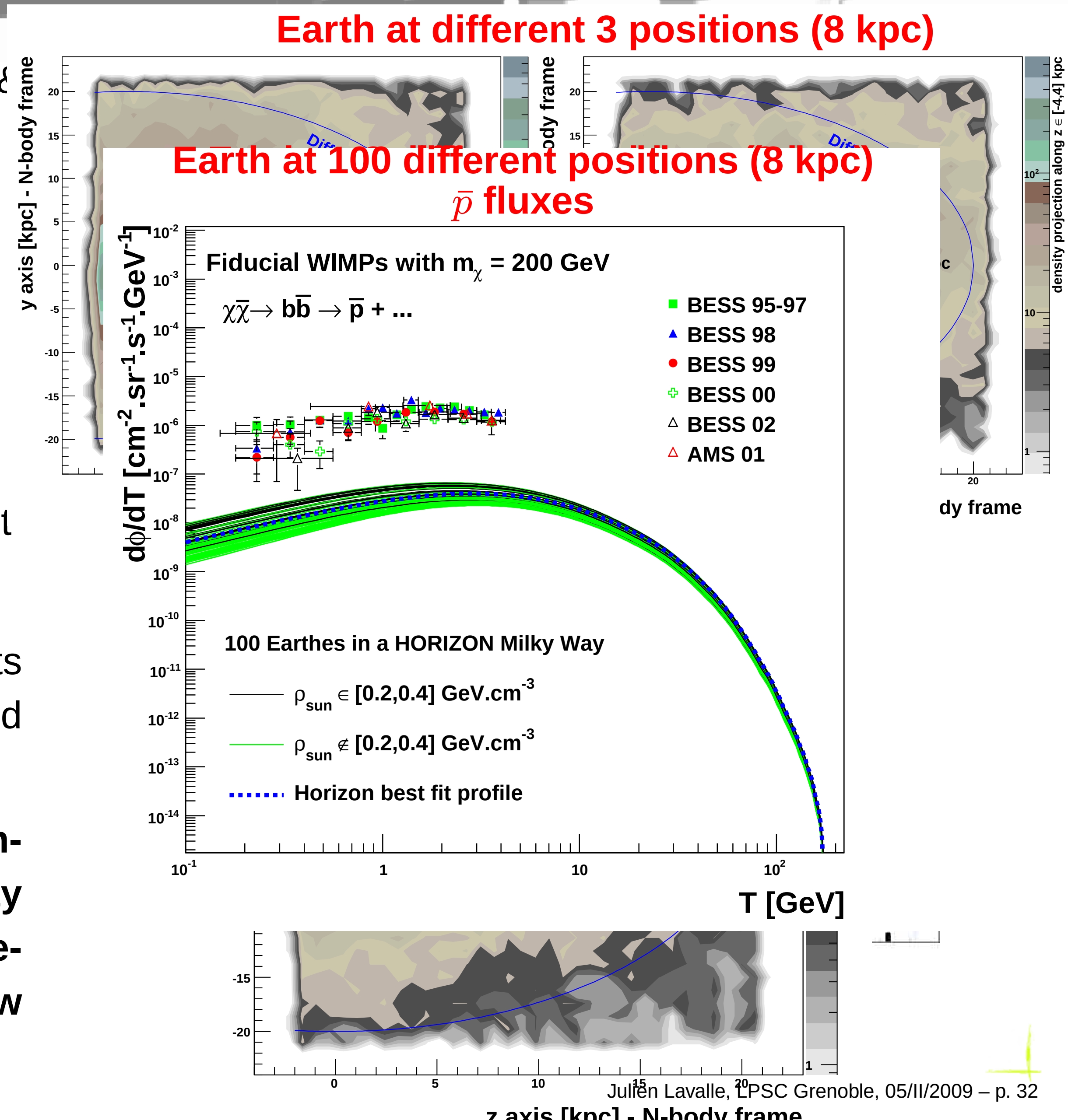

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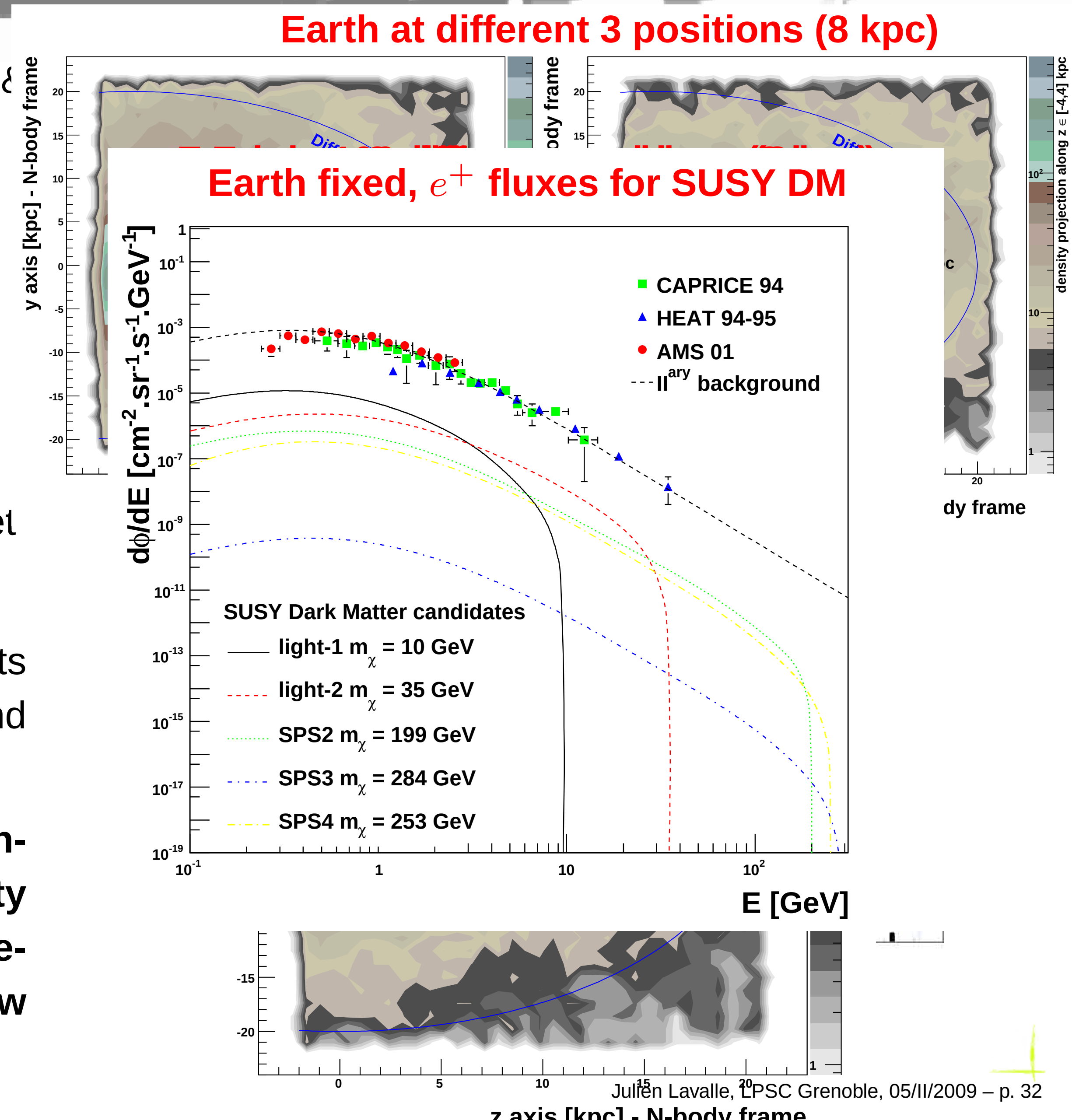

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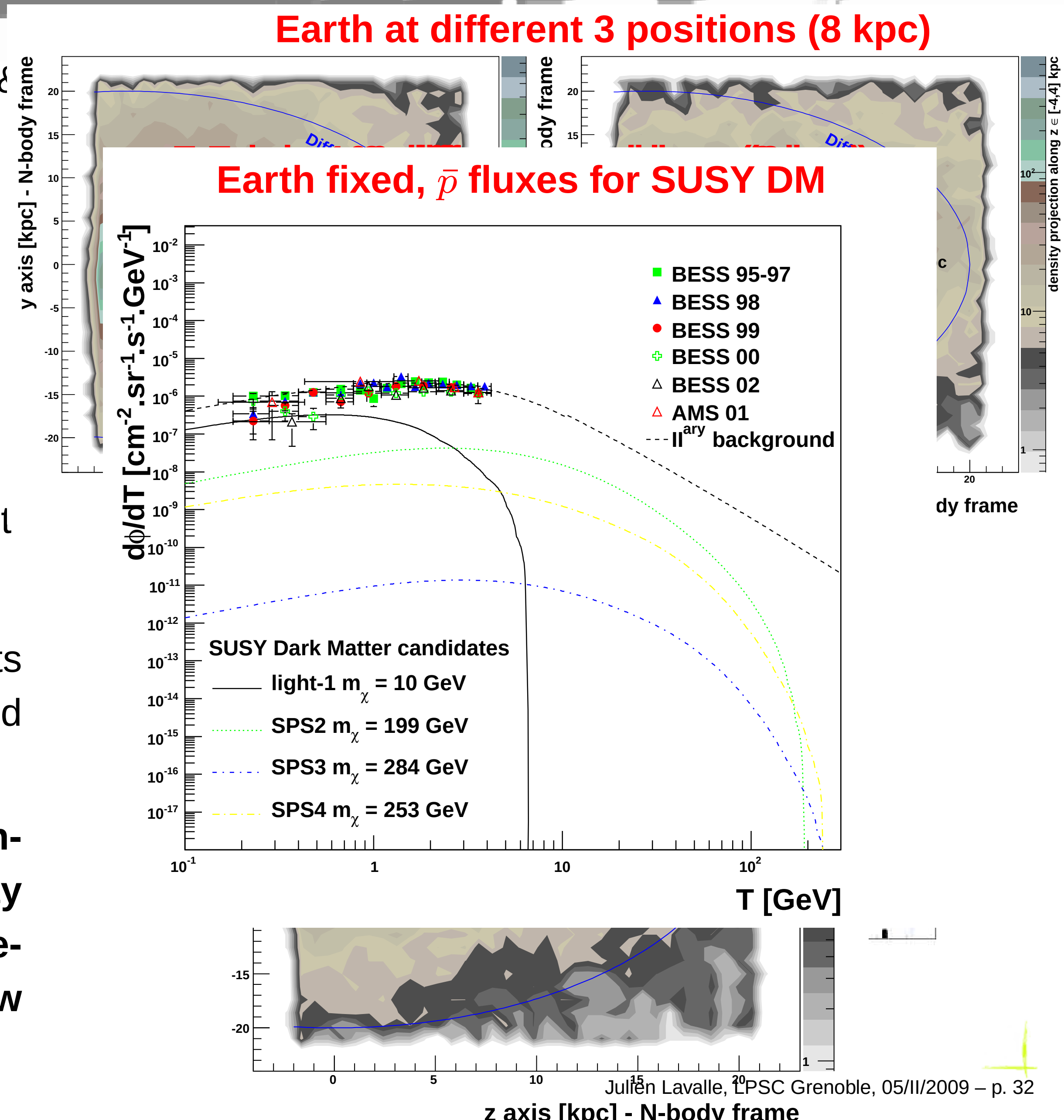

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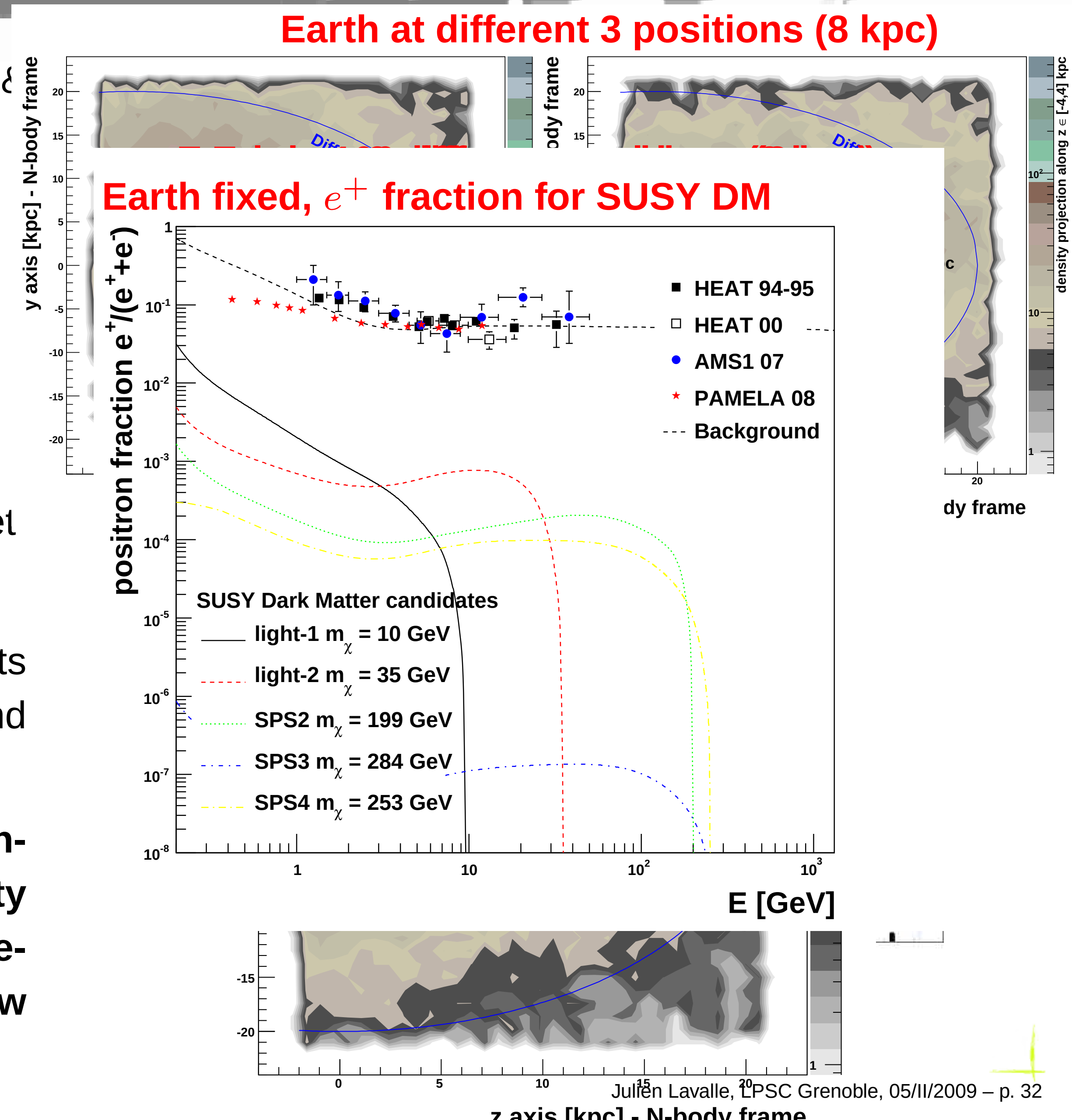

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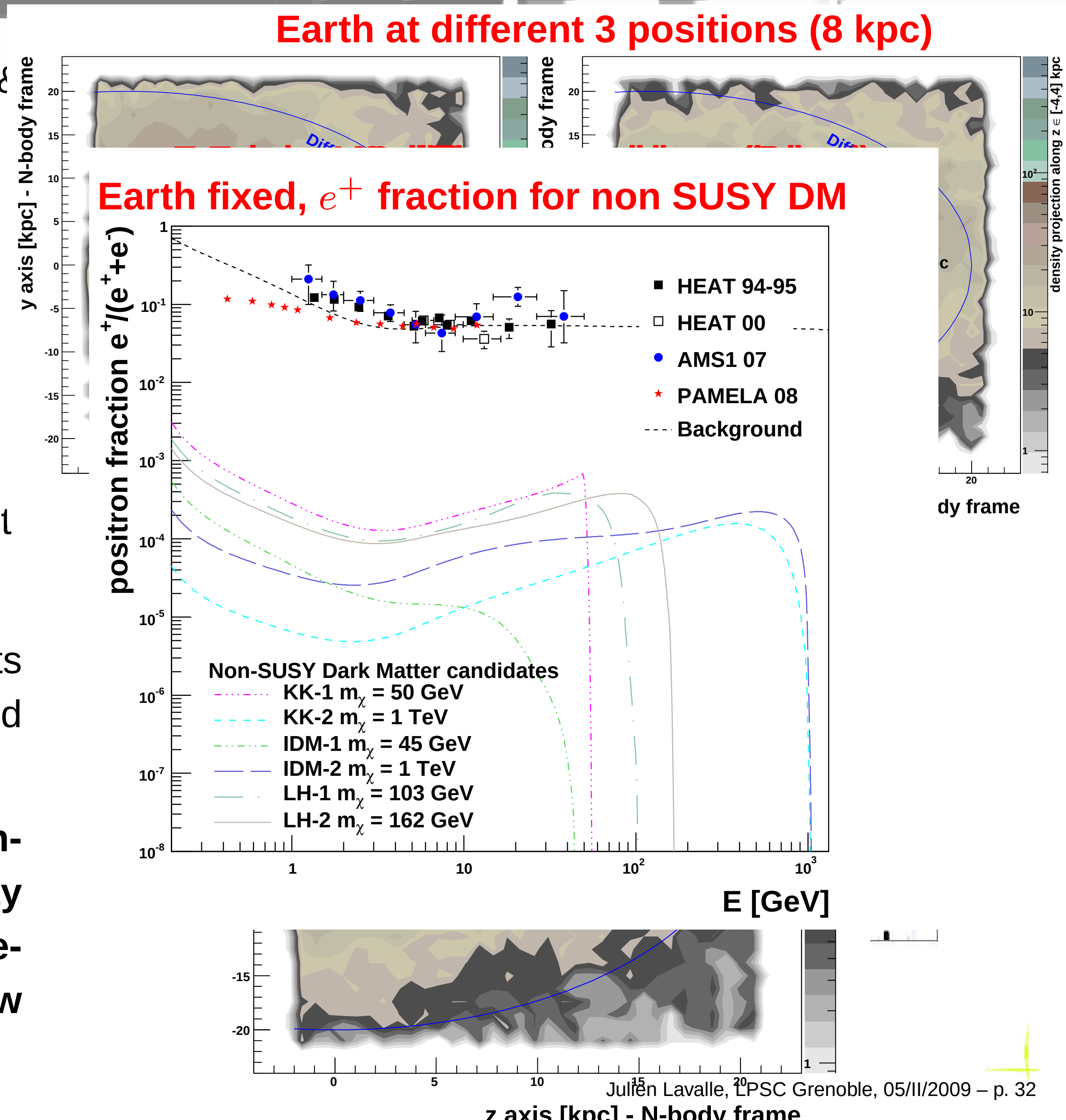
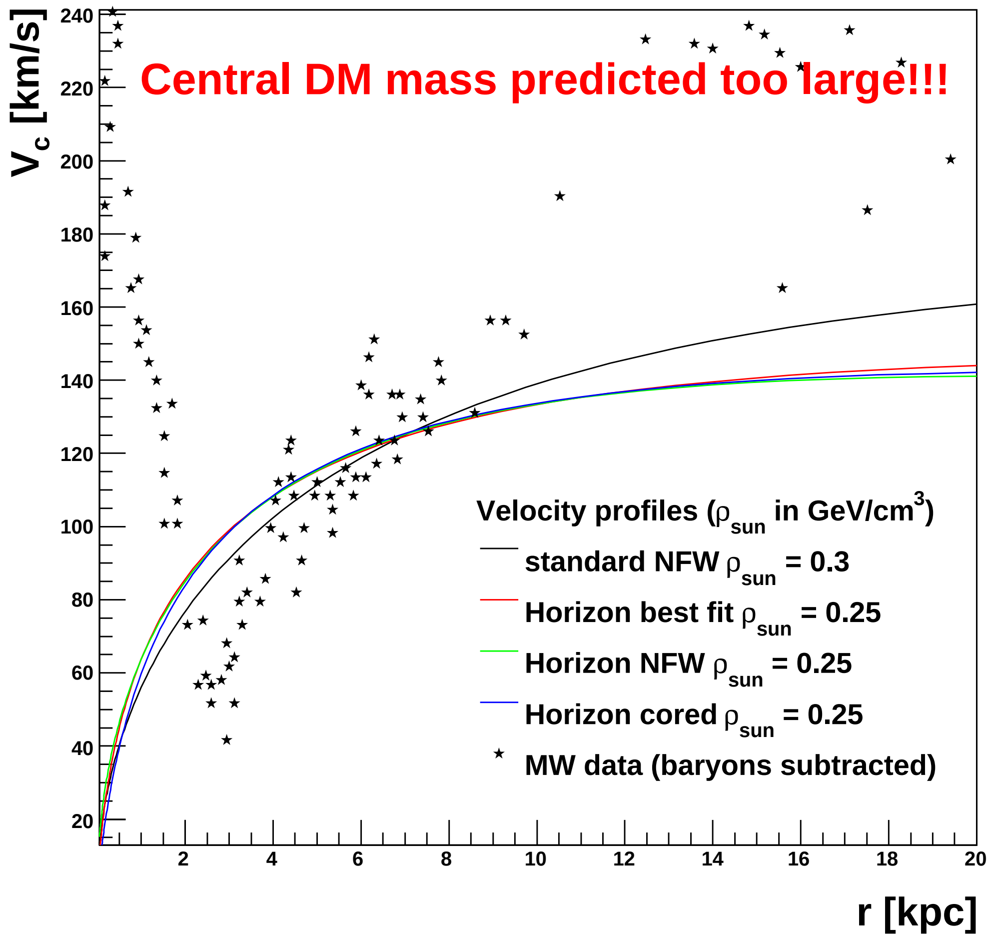


CAVEATS: too simplistic galaxy model

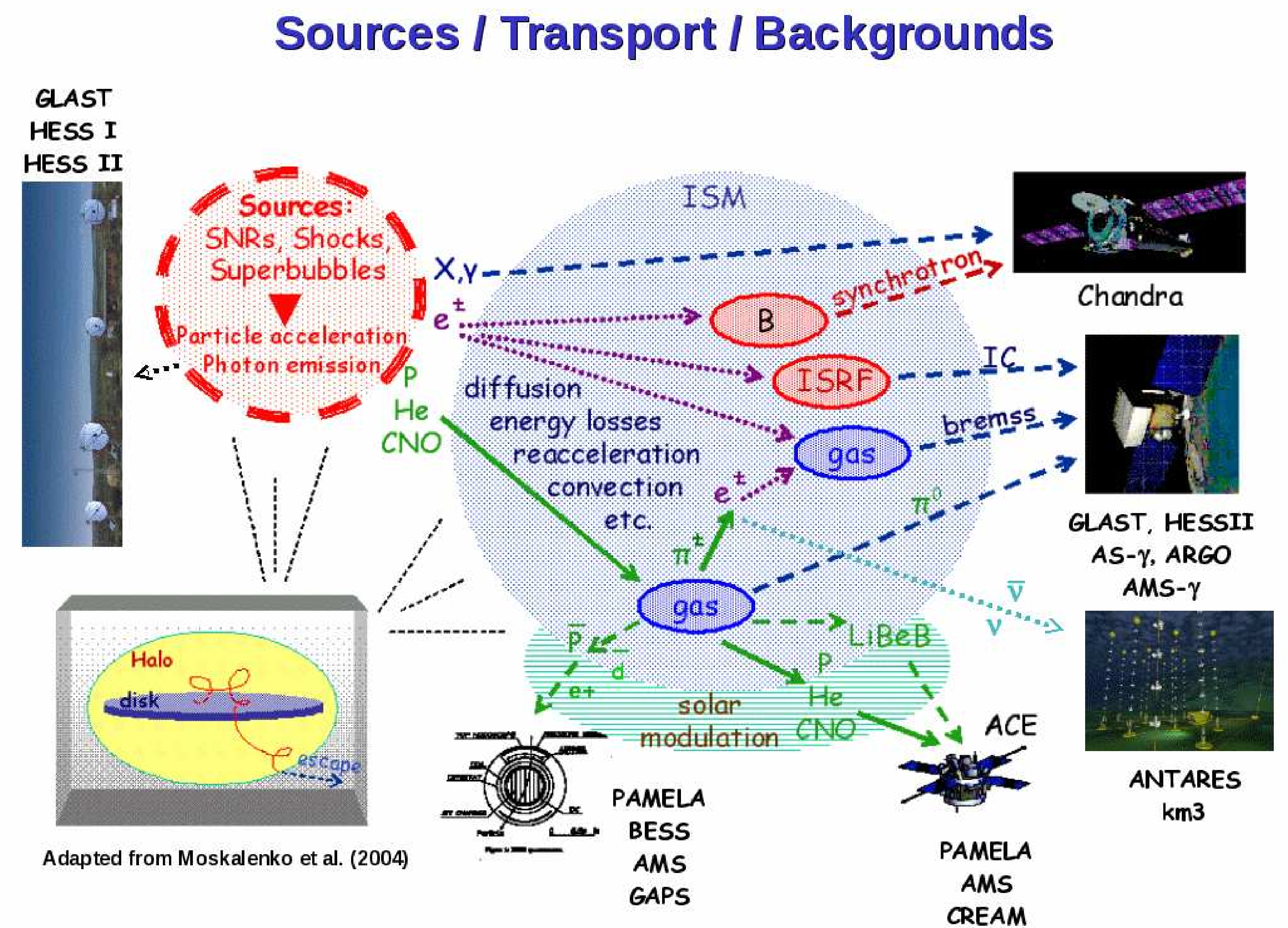
Rotation curves with baryon contribution subtracted
(Englmaier & Gerhard 2006, Bissantz & Gerhard 2002)



Lavalle, Nezri et al – PRD 78 (2008)

Cosmic Rays:

the necessity/tools to understand the backgrounds



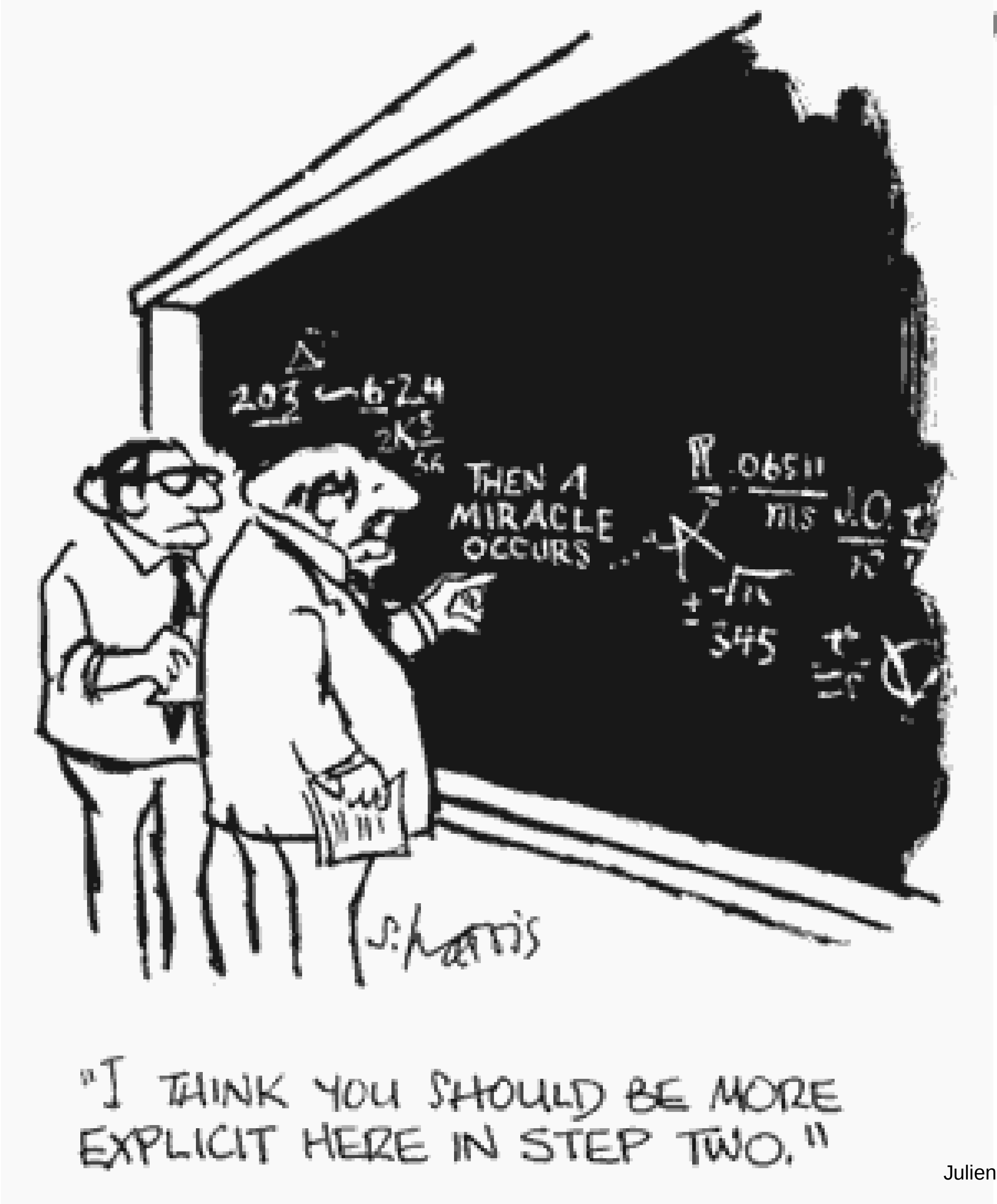
Summary

- **Dark Matter: a link between LHC physics, astrophysics and cosmology**
- **Antimatter cosmic rays are interesting messengers to study new physics**

On the positron fraction:

- **Standard sources are enough**
- **Dark matter may contribute, but needs very specific properties (strong couplings to leptons, Sommerfeld enhancement)**
- **Nearby dark sources or clumpiness enhancement are disfavored**
- **Need much better precision in the predictions of both exotic and standard signals**
- **Propagation a the key ingredient**
- **Need much better constraints on propagation parameters: PAMELA, Fermi results (e.g. CREAM, AMS-02 later)**
- **Complementarity with other messengers ($\gamma, \bar{p}$) and detection methods!**

Backup


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