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

Julien Lavalle

(Dept of Theoretical Physics, University of Turin)

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)

LLR - École Polytechnique — Palaiseau

Thursday, May 18^{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**

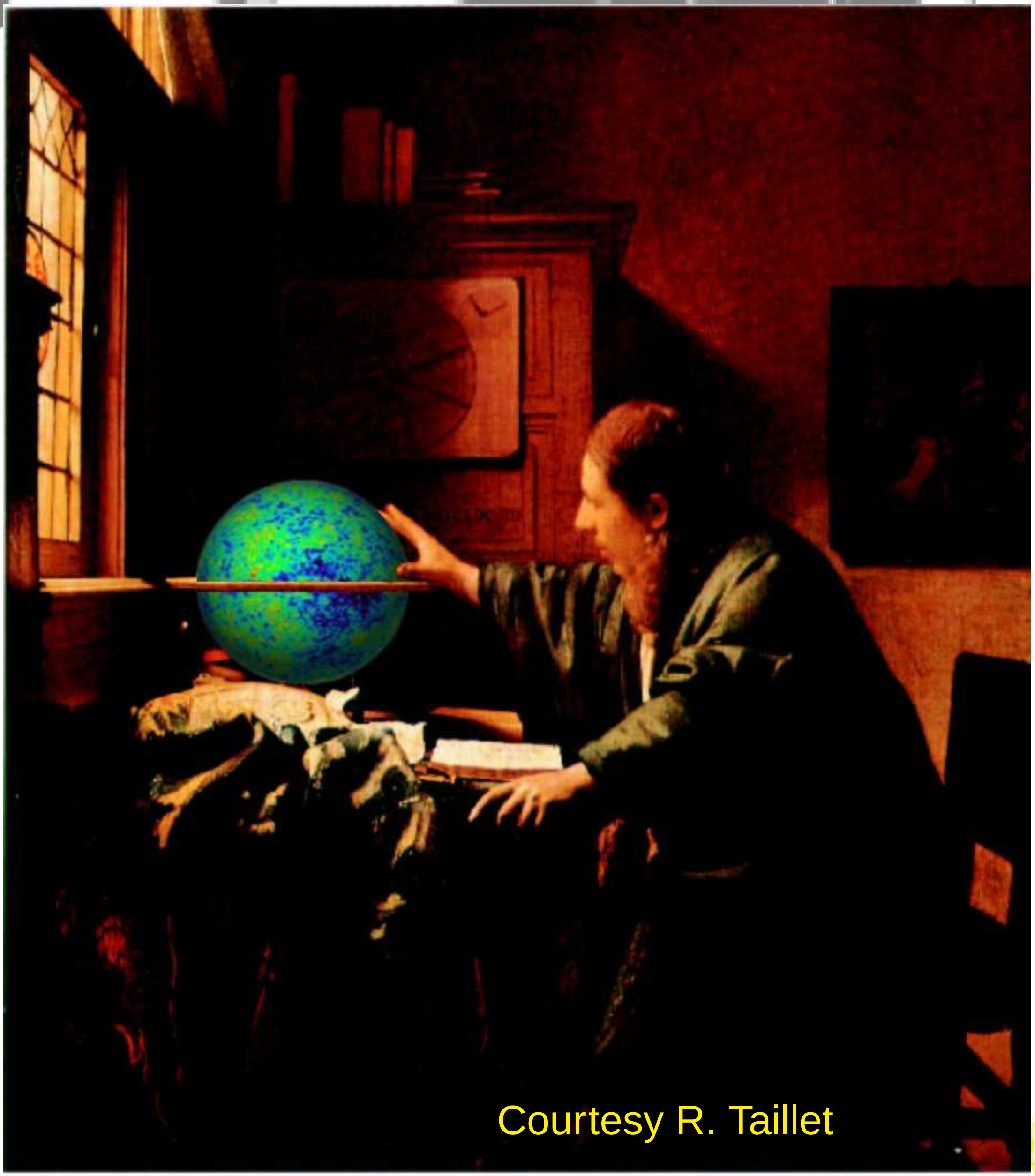
The Dark Matter problem : connecting cosmological to microscopic scales

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)$\rightarrow$ New particles or modified gravity. WIMPs naturally arise from beyond standard model theories (SUSY, ED), without asymmetry matter/antimatter

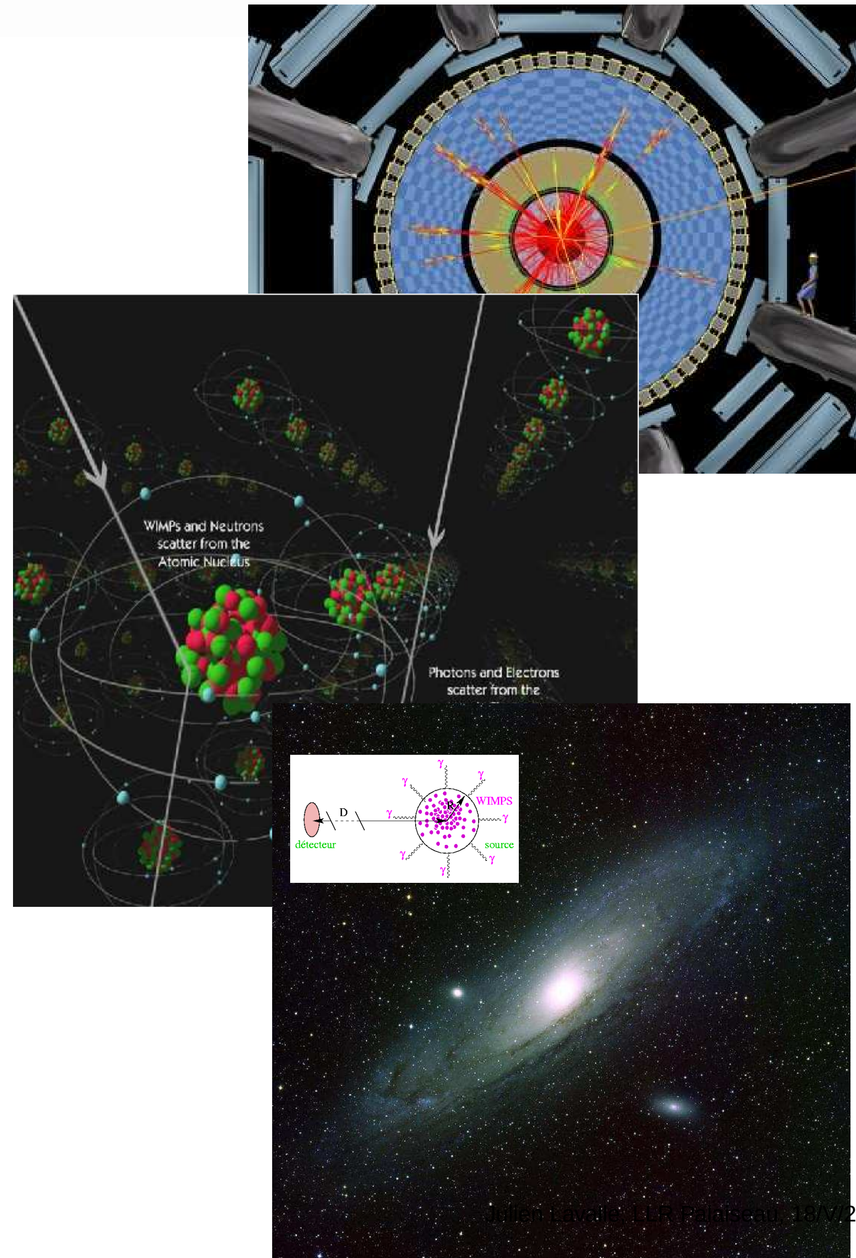
- Relic density (thermal hypothesis): $\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \propto \frac{m_{\rm EW}^2}{g_{\rm EW}^4}$
- DM couples to standard matter (direct detection)
- Annihilation in high density regions (indirect detection)



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)
- **Indirect detection:** **(HESS, PAMELA, GLAST)** (γ**-rays, antimatter cosmic rays, neutrinos**)



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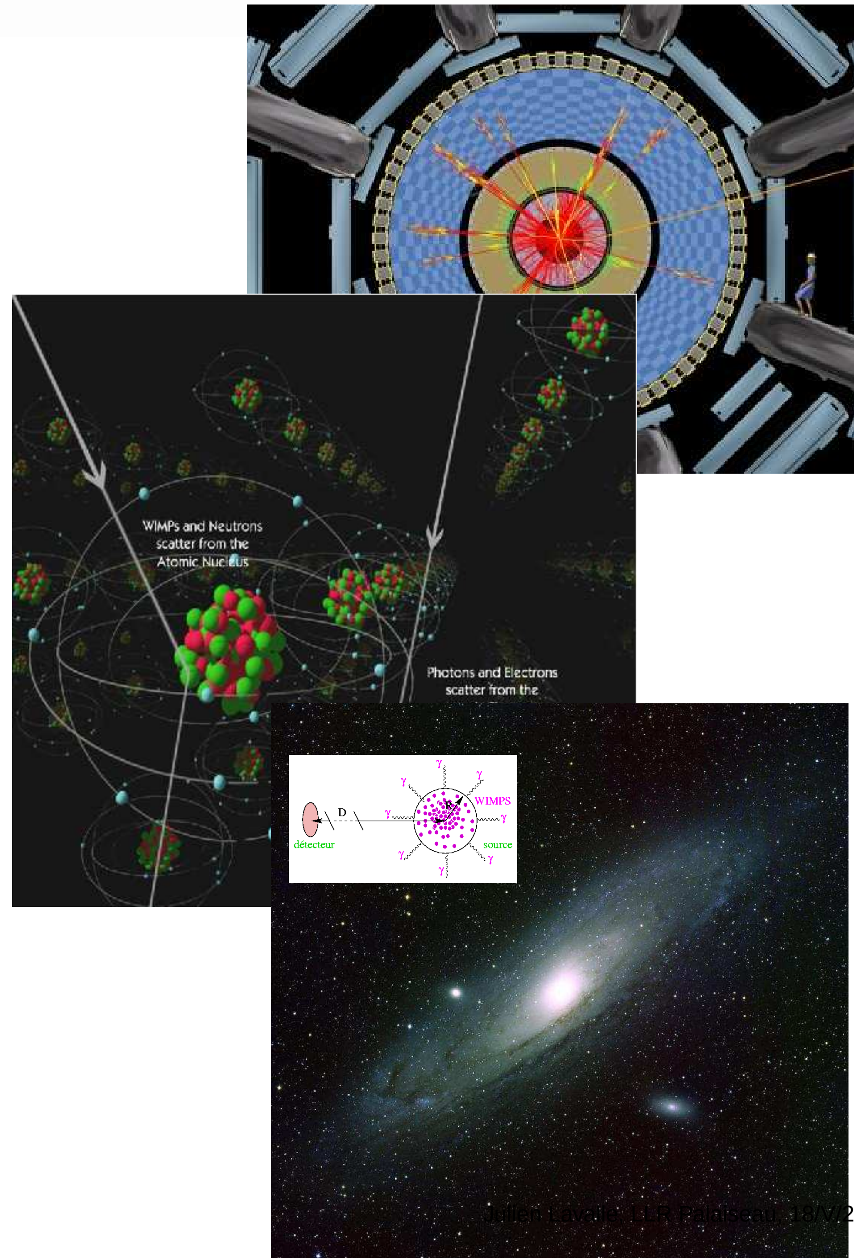
Complementary searches are mandatory for consistent answers

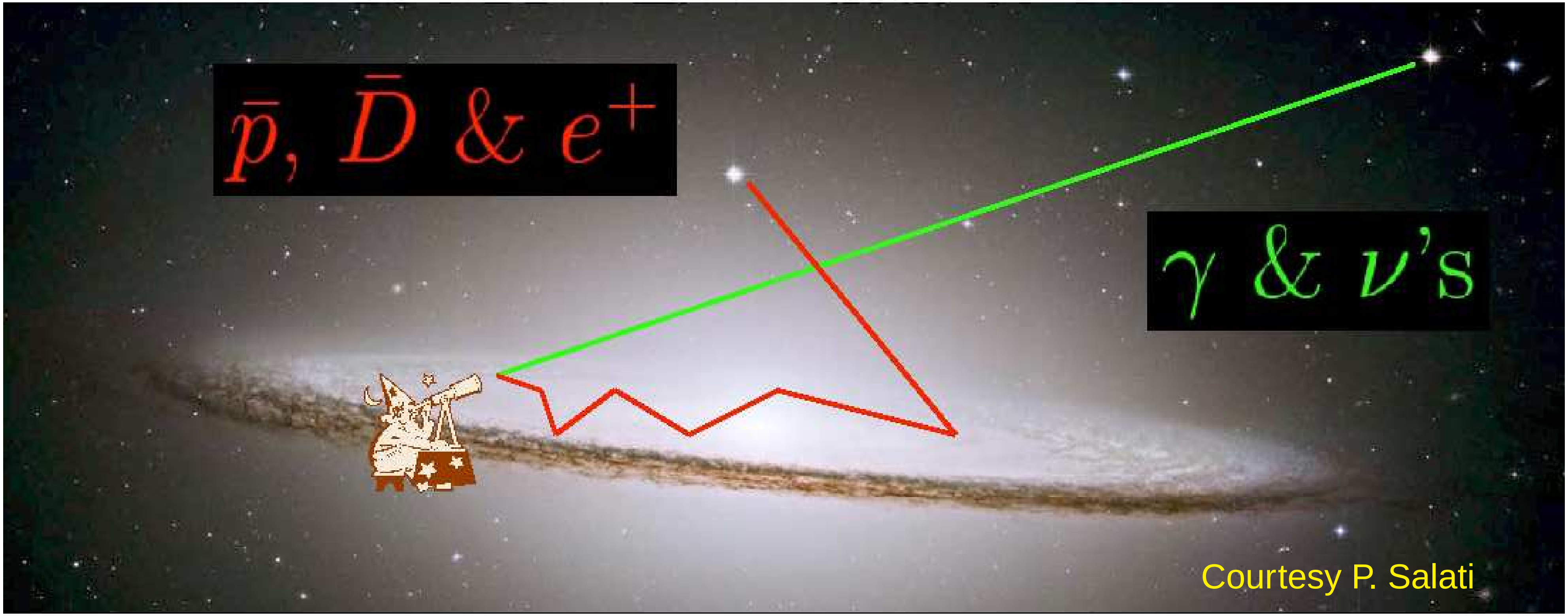


Some candidates

- **Supersymmetry**
  - neutralino (MSSM & mCHOUGRA) – DM:
    $\rightarrow b\bar{b}$ ($t\bar{t}$), W^+W^-, ZZ, marginally l^+l^- (small slepton masses)
  - gravitino (GMSB & mCHOUGRA) – DM & SUSY breaking & nucleosynthesis:
    $\rightarrow$ phenomenology of nLSP
  - sneutrino (MSSM) – DM & neutrino masses & leptogenesis:
    $\rightarrow \nu\bar{\nu}$, W^+W^-
- **Extra-dimensions**
  - LKP (UED) – DM:
    $\rightarrow l^+l^-$ (60%), up $q\bar{q}$ (35%)
  - LZP (warped GUT) – DM:
    $\rightarrow$ (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

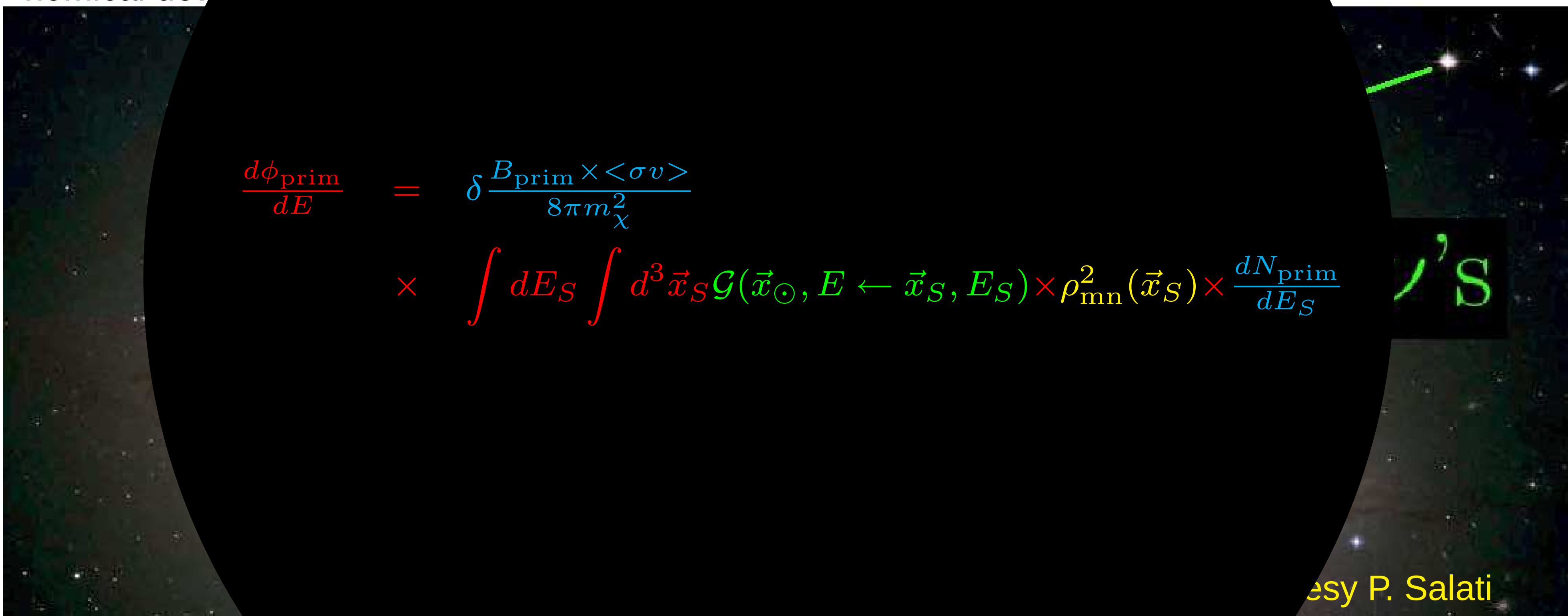


- γ **and** ν**: travel directly from the source to the observer**
- **Antimatter cosmic rays: diffuse on the magnetic turbulences**

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

[redacted] of Dark Matter

Non-baryonic D[redacted] **and clusters**: If made of **exoti**[redacted]neans of astro-nomical devi[redacted]



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

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

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

# of Dark Matter

Flux measurements:
PAMELA satellite — antimatter (ongoing)
Fermi satellite — γ-rays (ongoing)
AMS-02 (2010 ?)

background predictions

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
(merely $\frac{1}{4\pi r^2}$ for γ-rays)

and clusters: If
neans of astro-

ν's

esy P. Salati

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  to the observ
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of Dark Matter

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$\frac{d\phi_{prim}}{dE}$

$S) \times \frac{dN_{prim}}{dE_S}$

ν's

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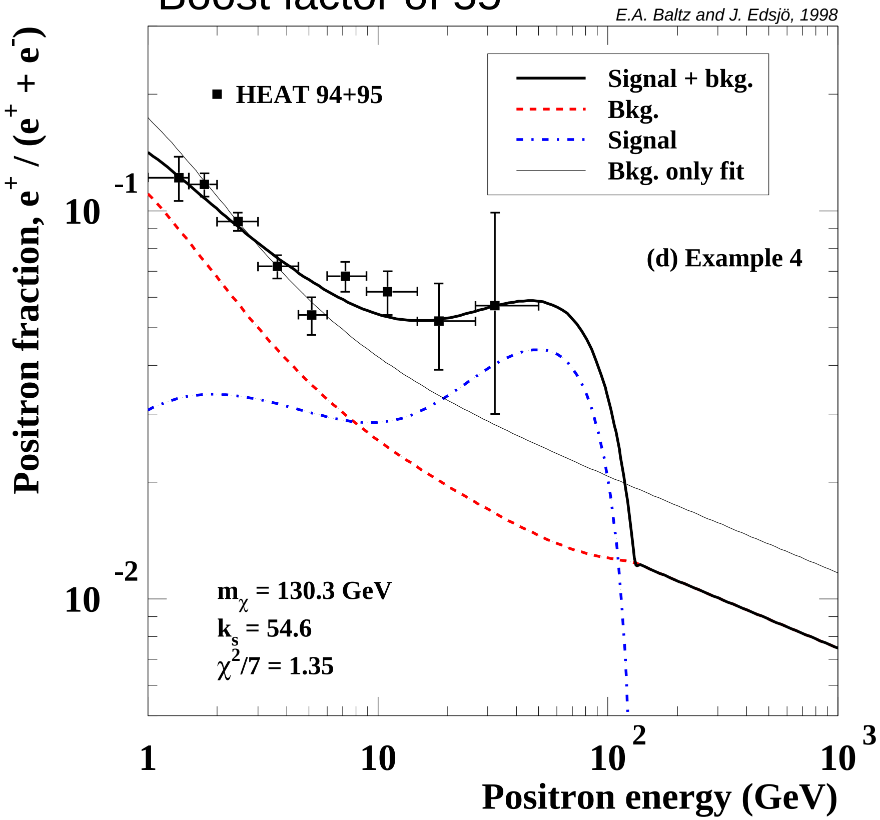
Baltz & Edsjö, 98

Boost factor of 55



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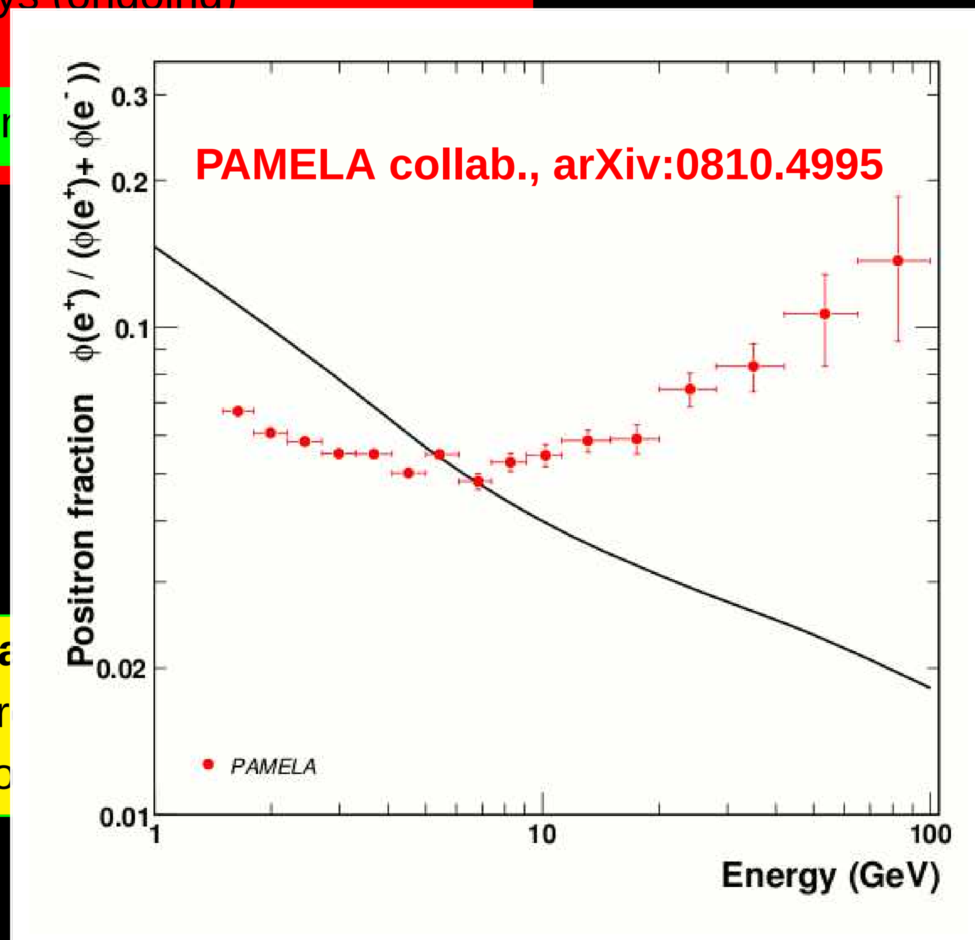

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  to the observ
- **Antimatter cosmic**
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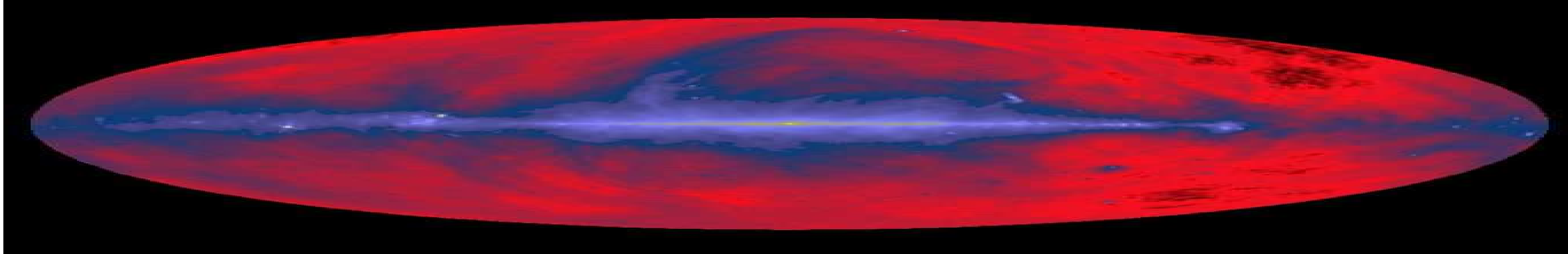
On the positron fraction

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

- properly estimate the secondary positron background;
- properly measure the electron flux (prediction not necessary if measurements!!!);
- ++++ theoretical uncertainties !!!

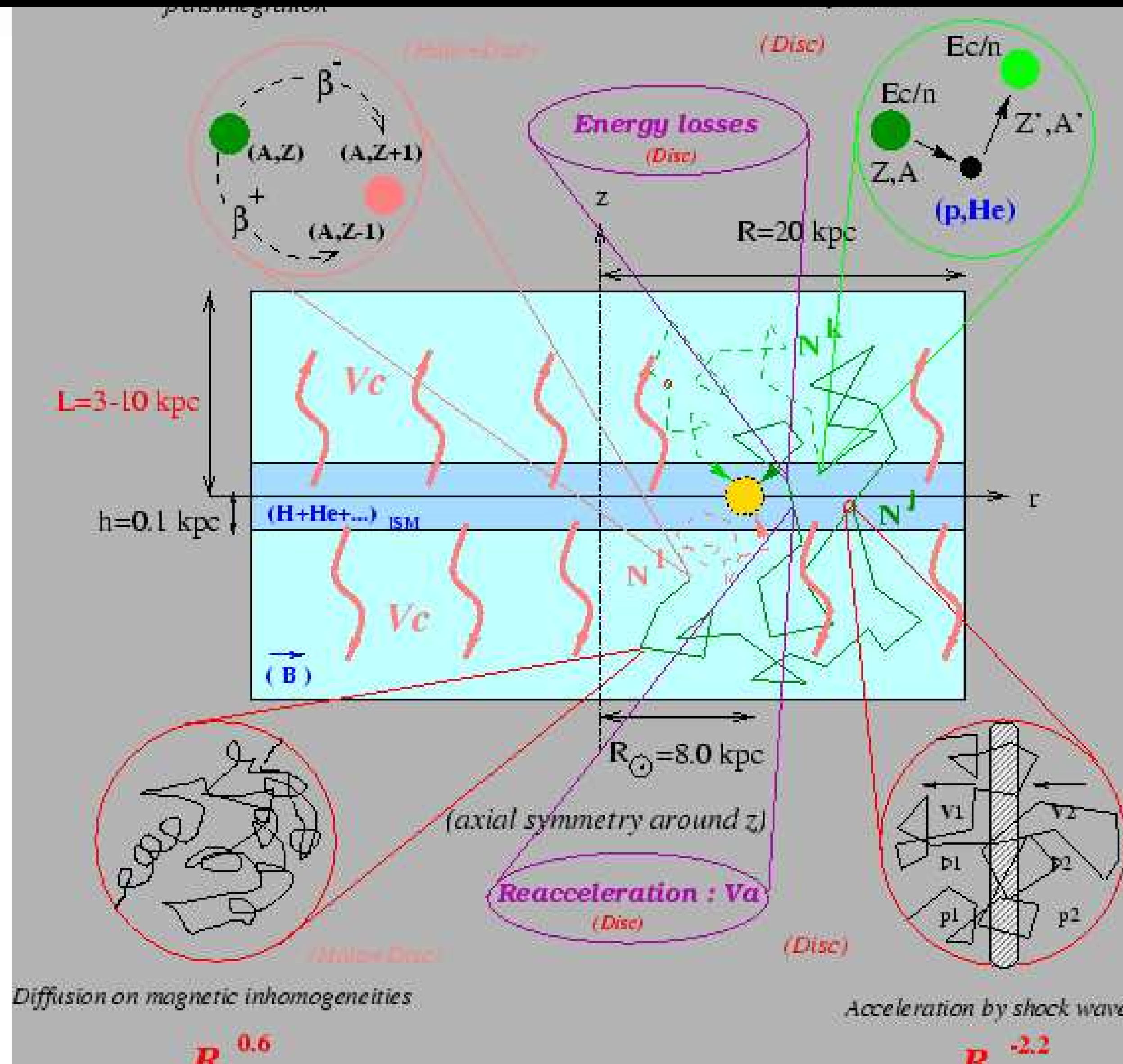
Sub-TeV Cosmic ray propagation in the Galaxy

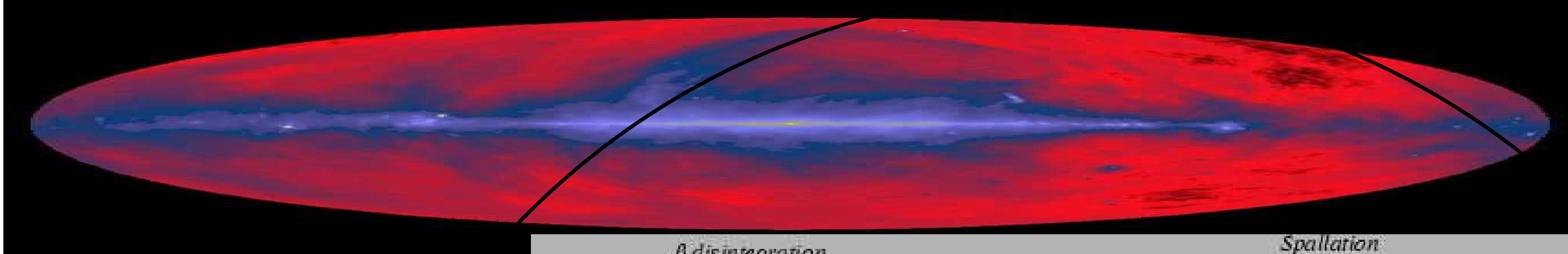


cf. e.g. Berezinsky (1990)

- **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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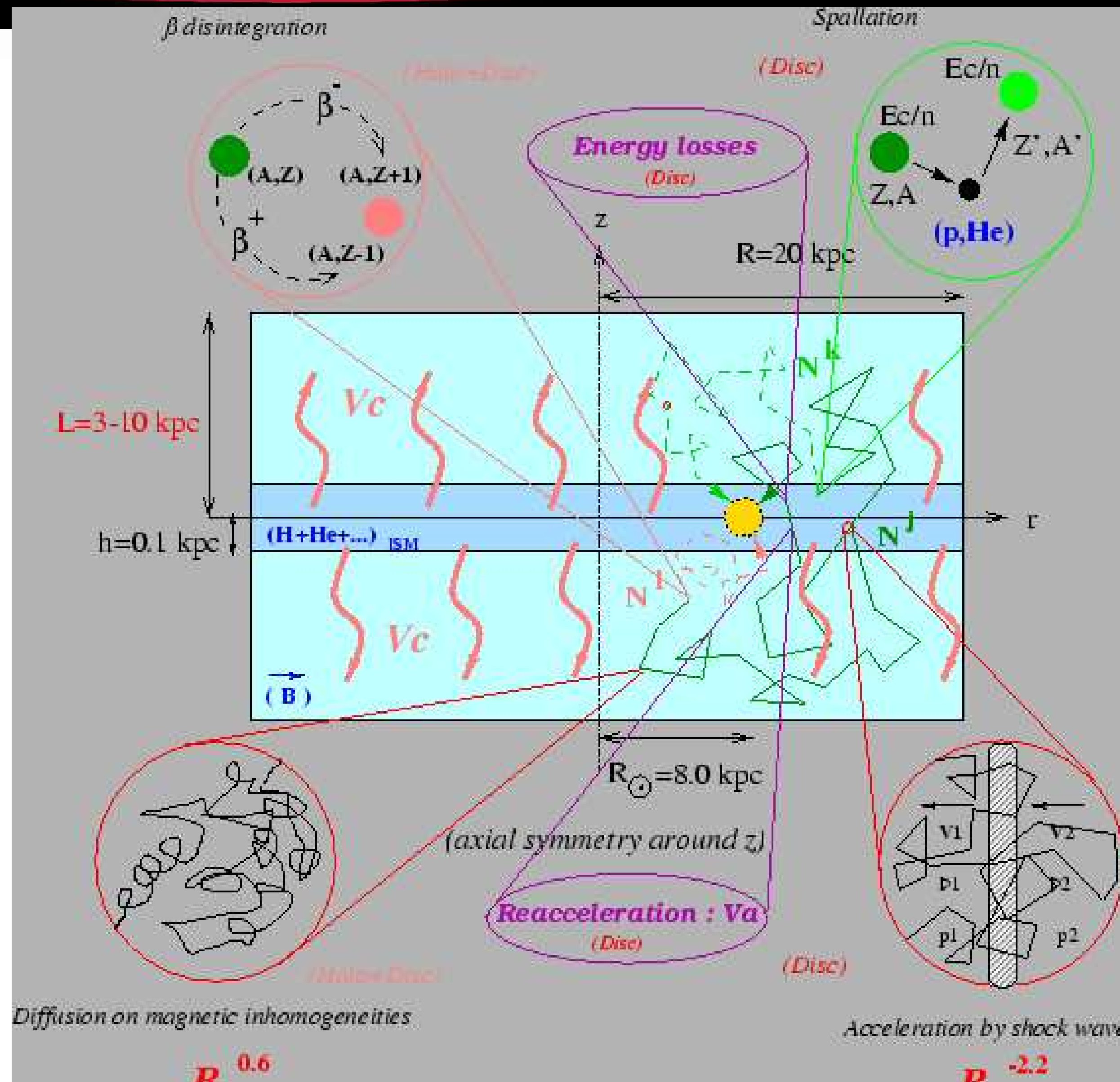


Diffusion equation for $e^{+/-}$ or $p\bar{p}$

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

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

source: injected spectrum

spatial current: diffusion and convection

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

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

Energy losses and reacceleration

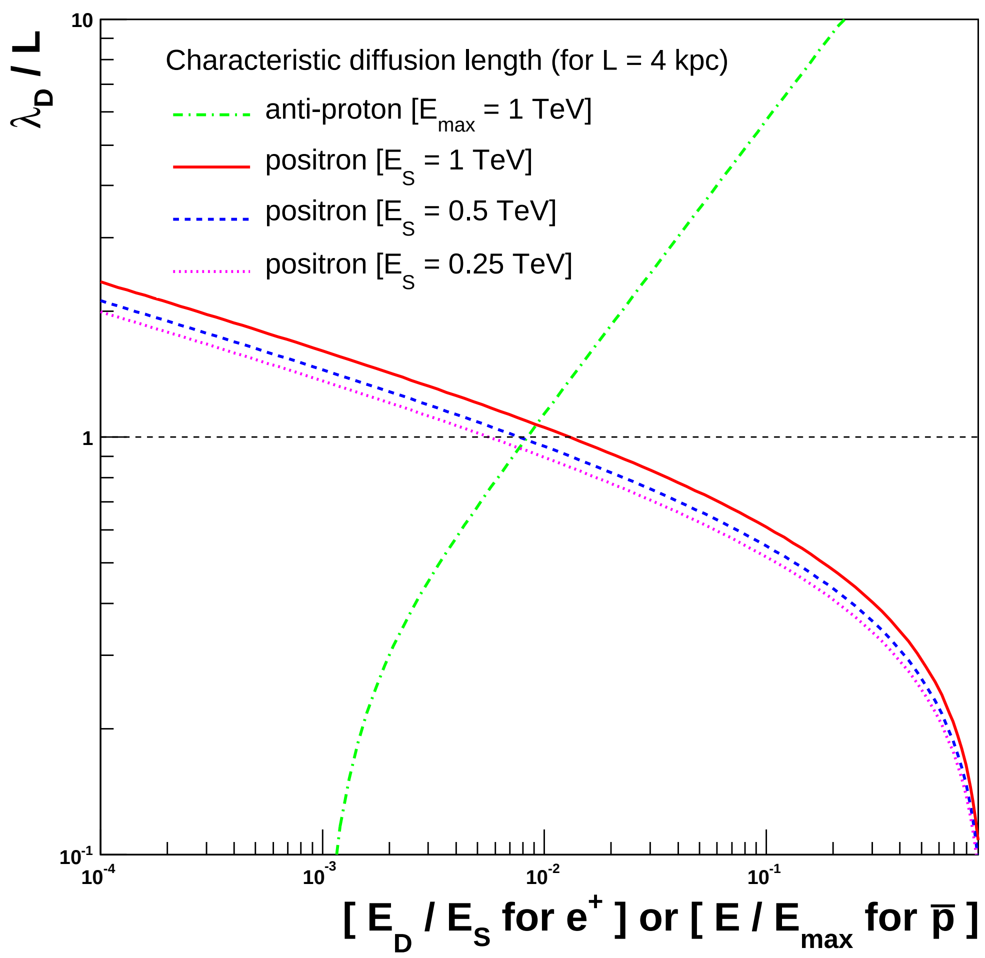
spallation (nuclei)

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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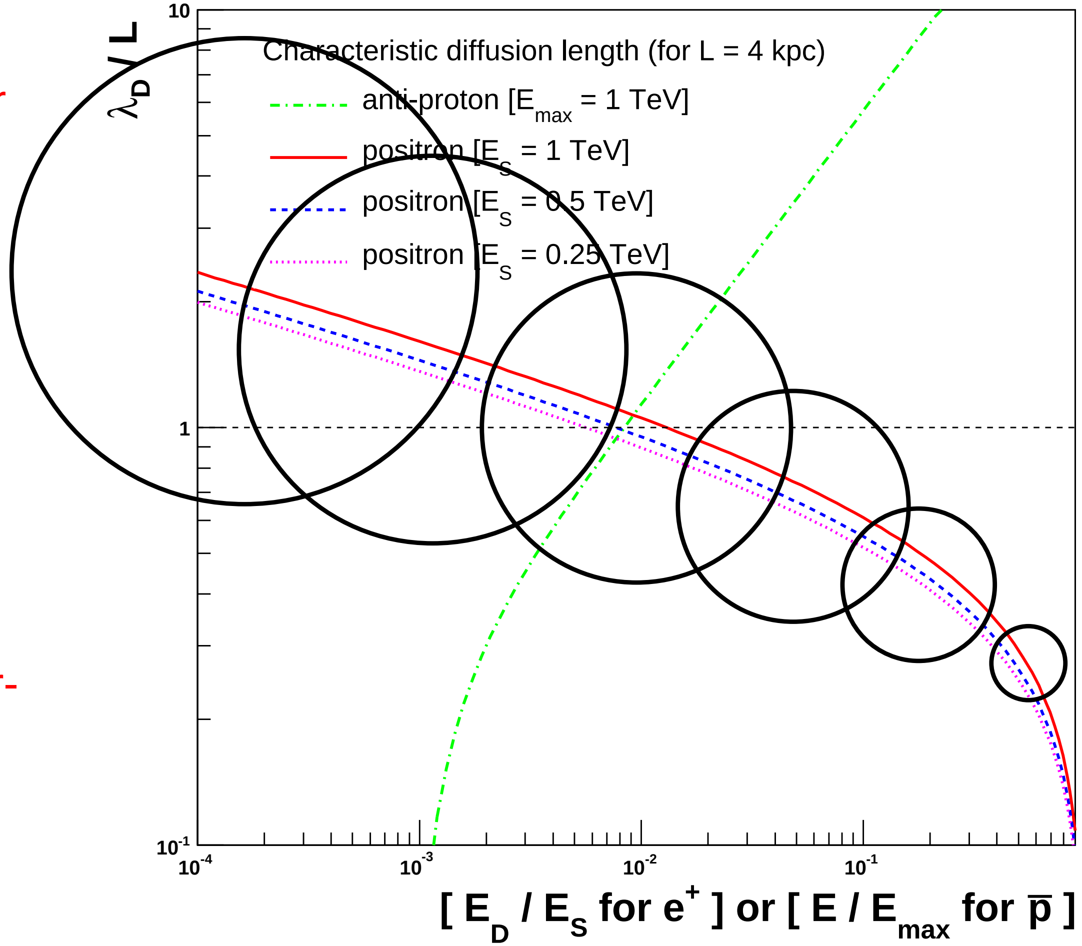
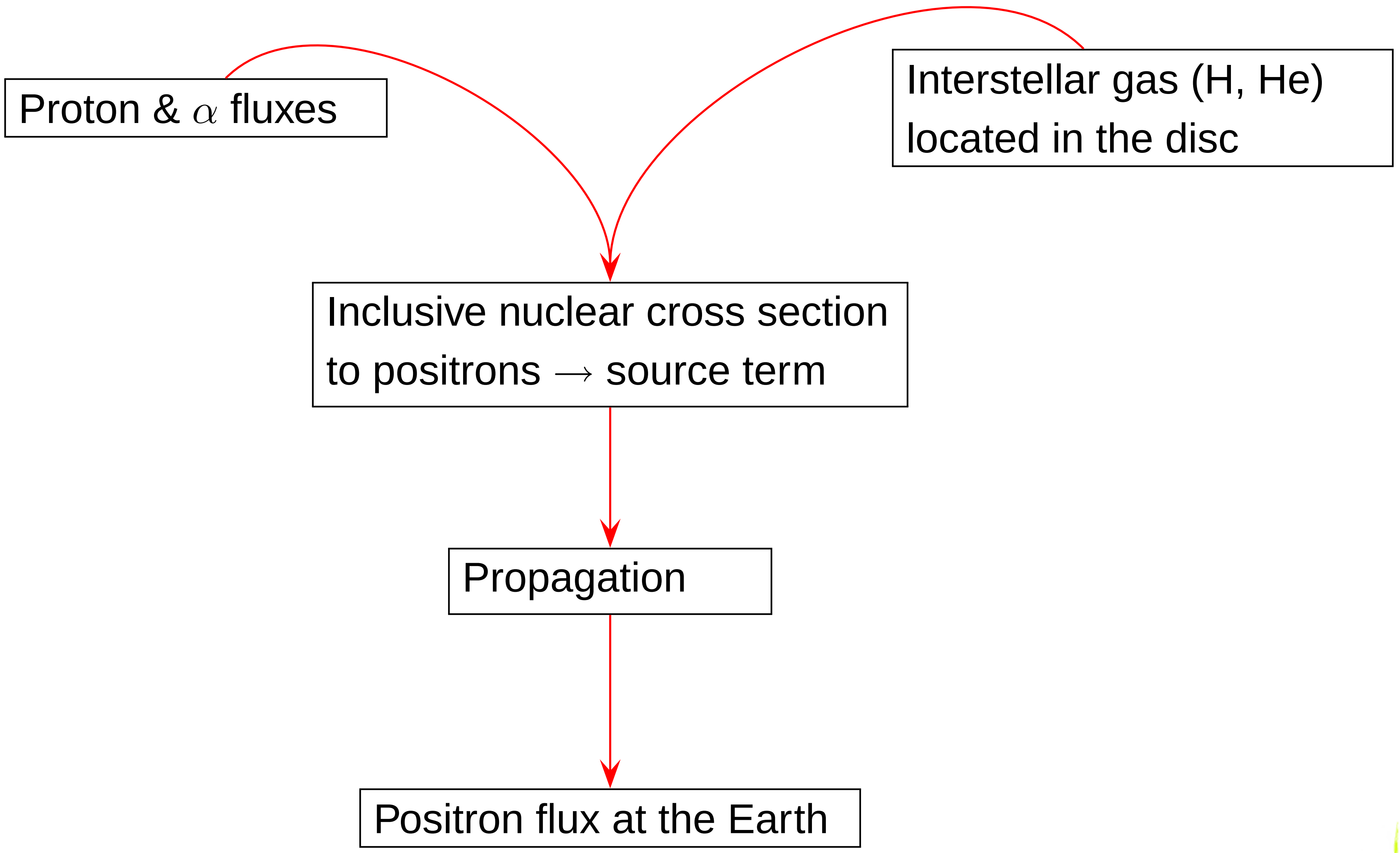


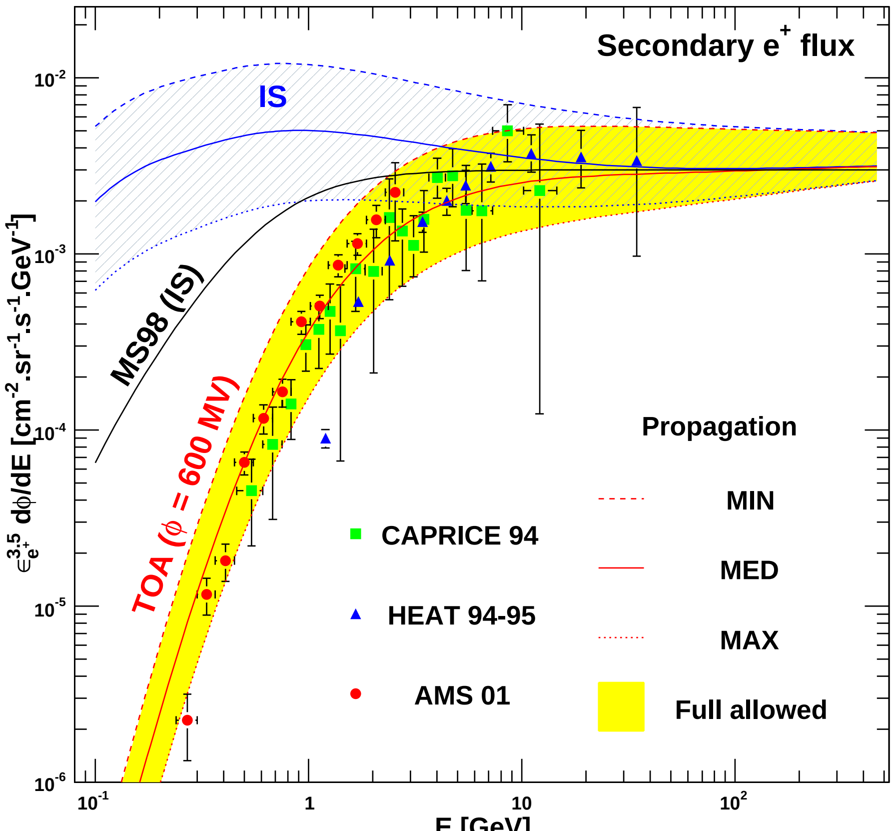
Short recipe for secondary positrons



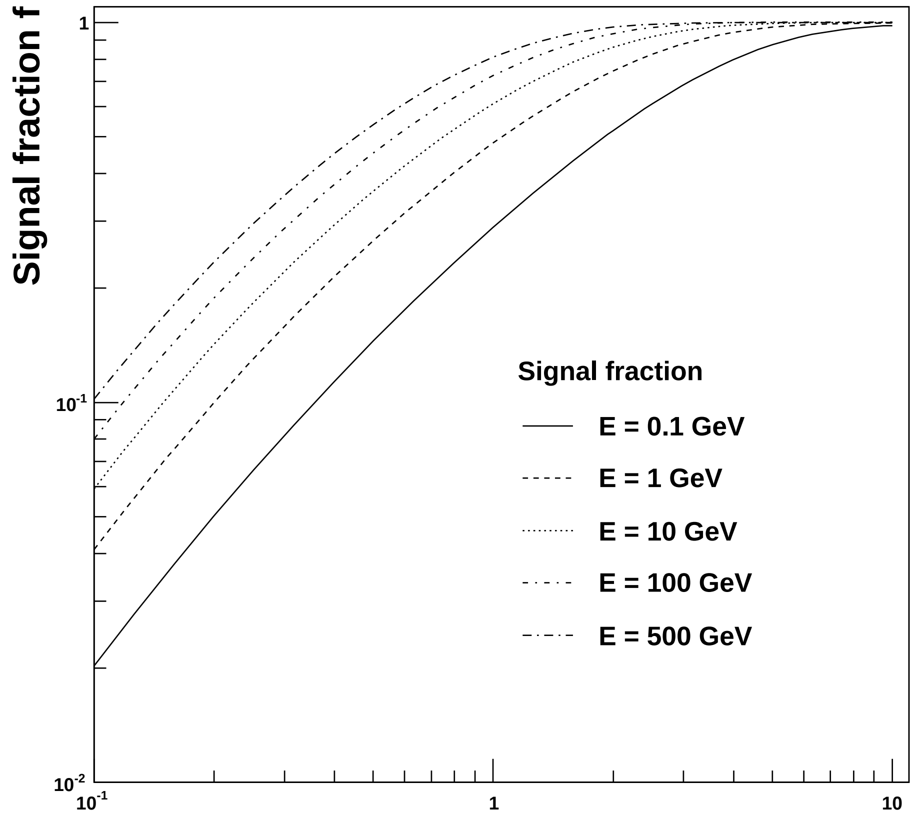
Prediction of the secondary e^+ flux and uncertanties

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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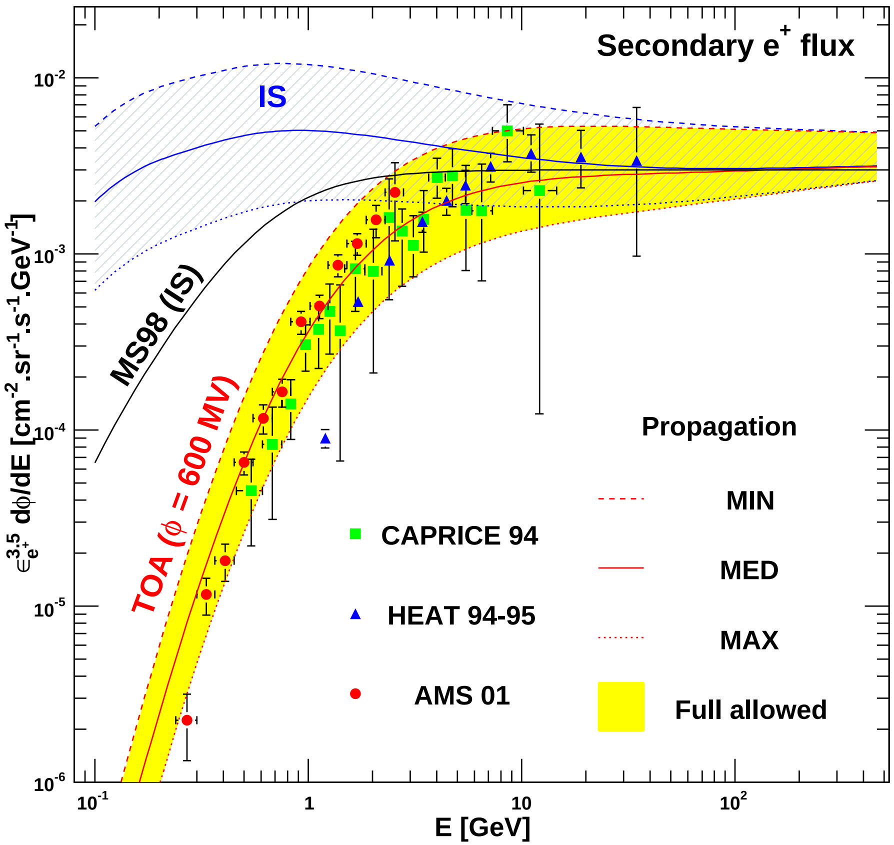

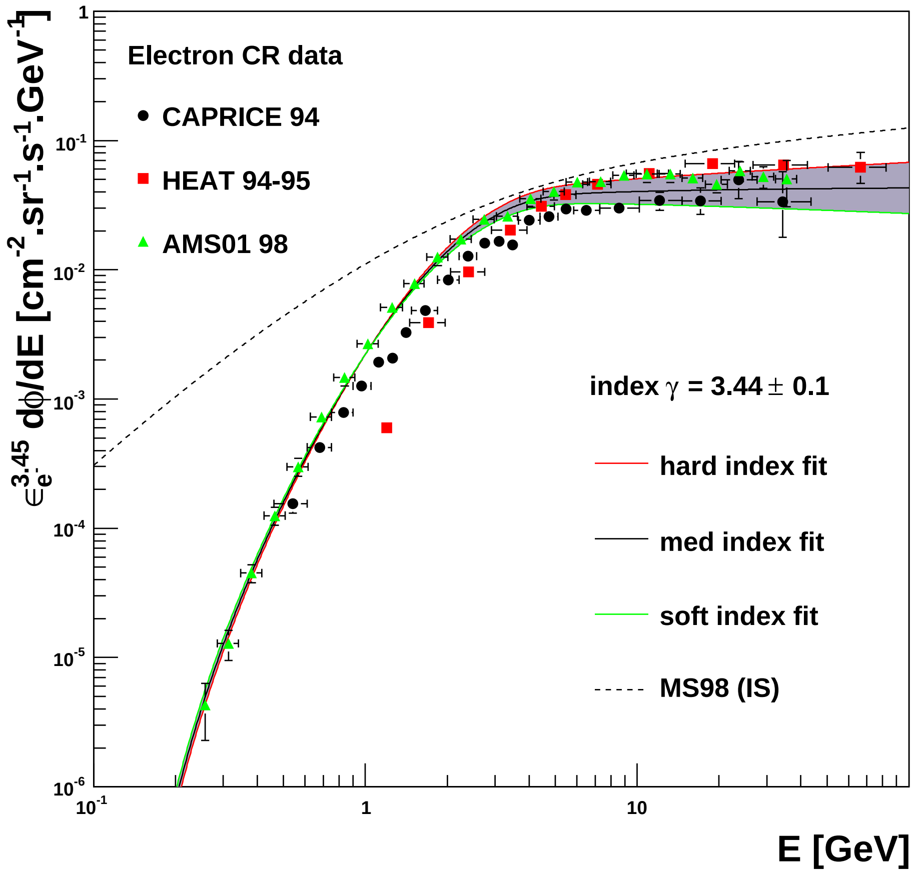

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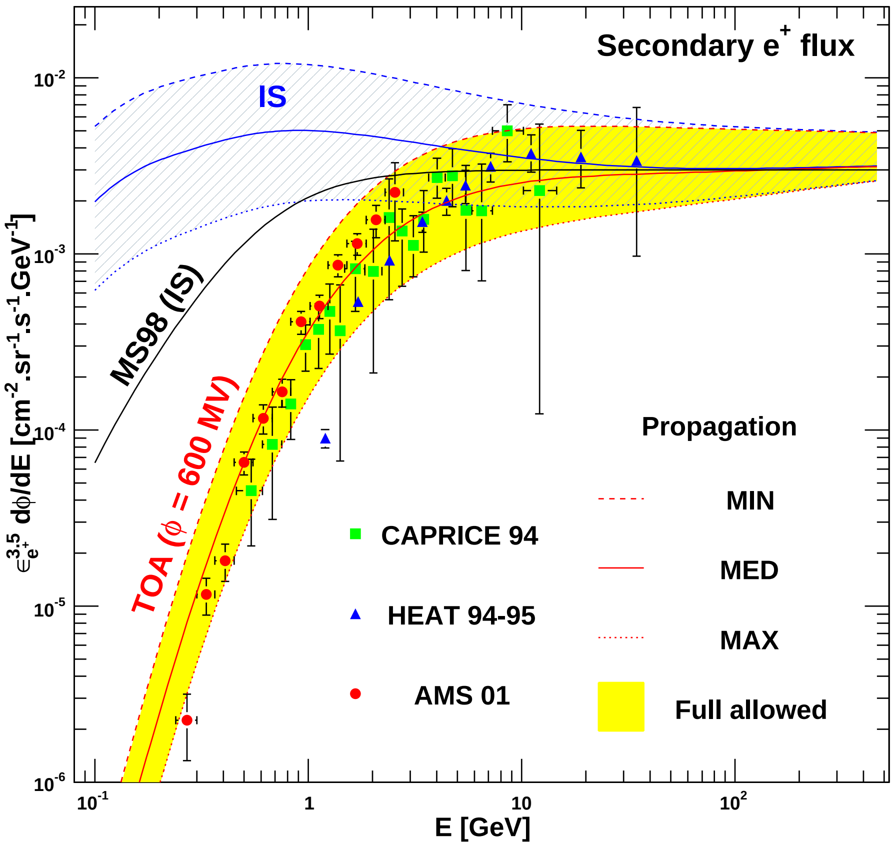

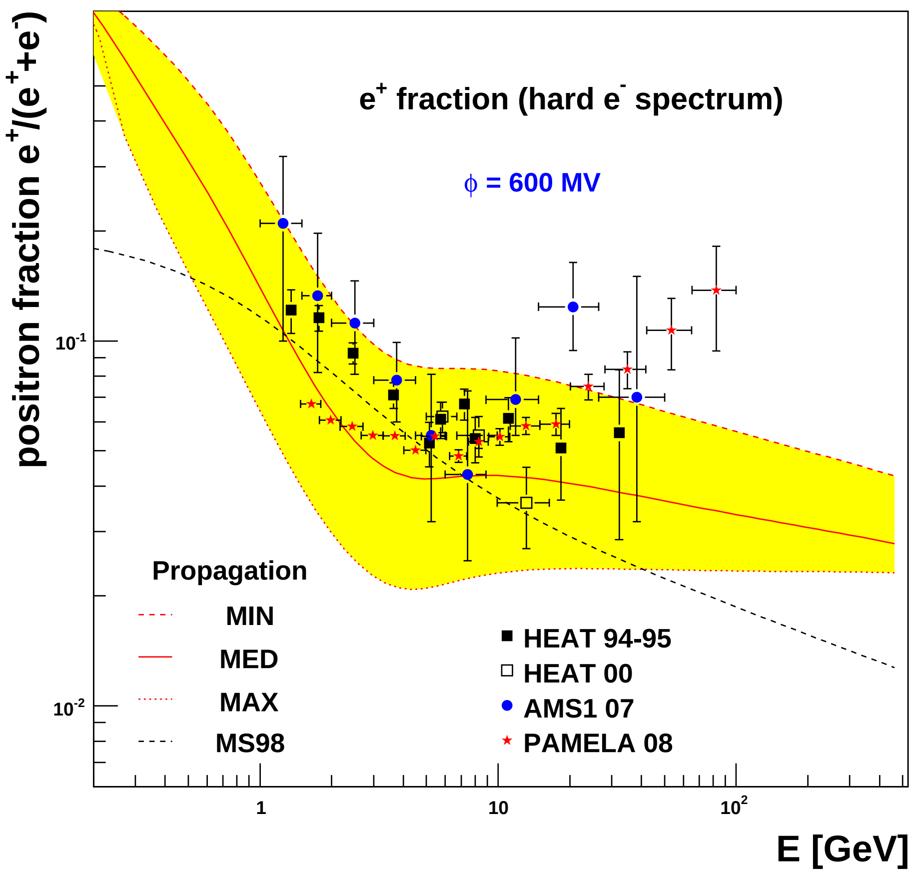

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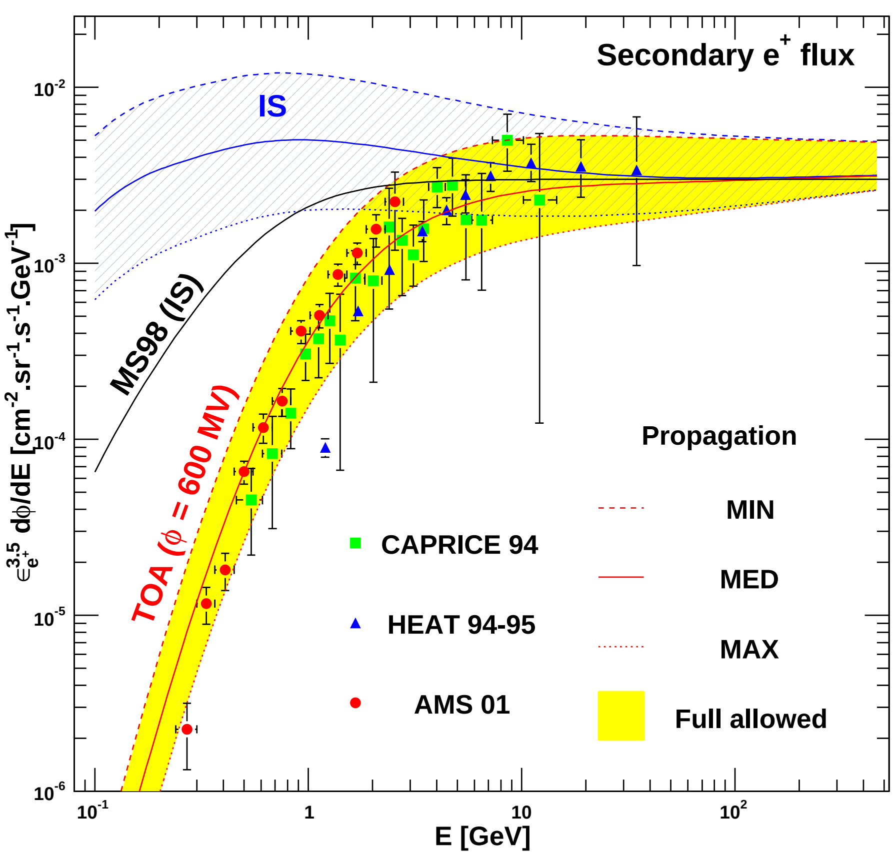

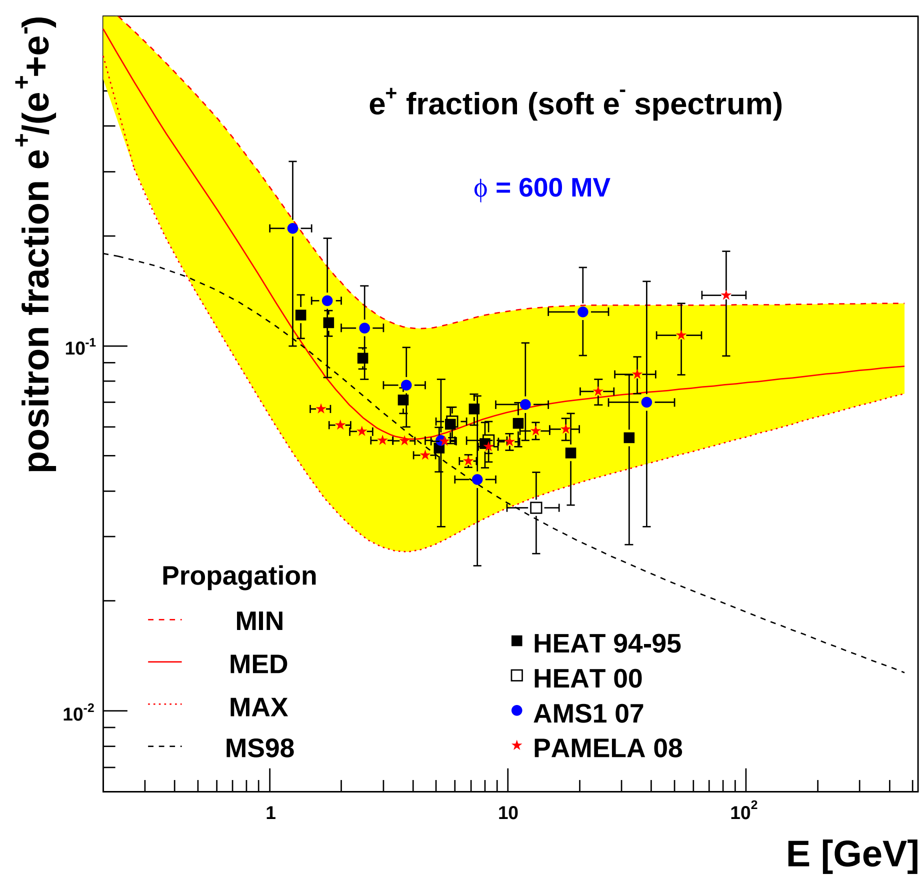

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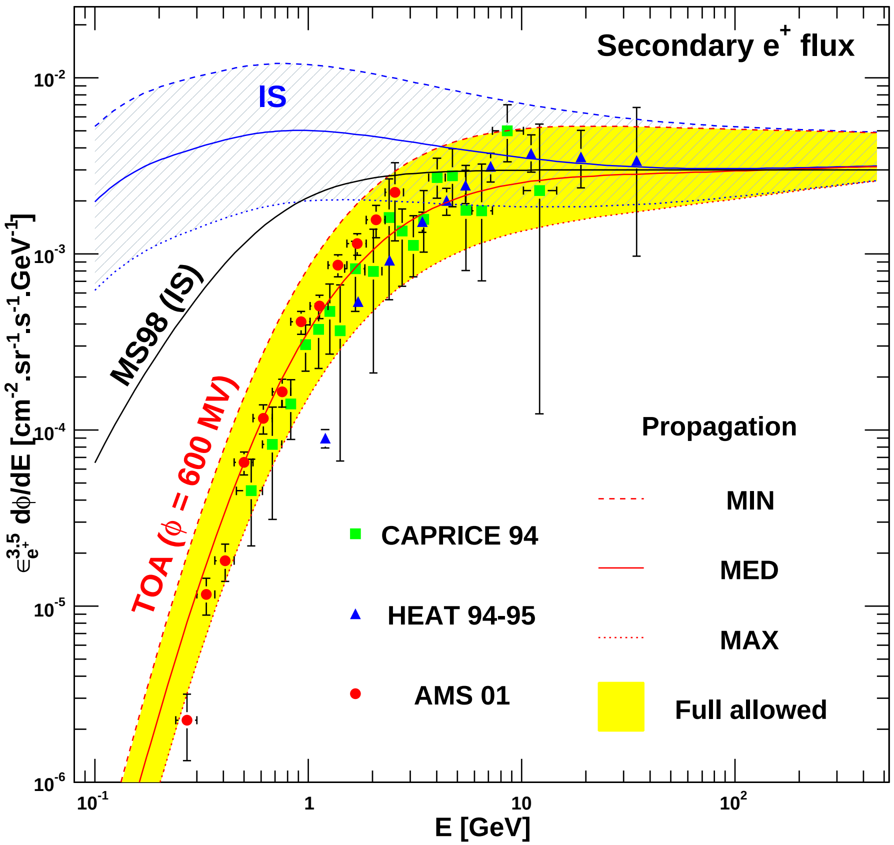

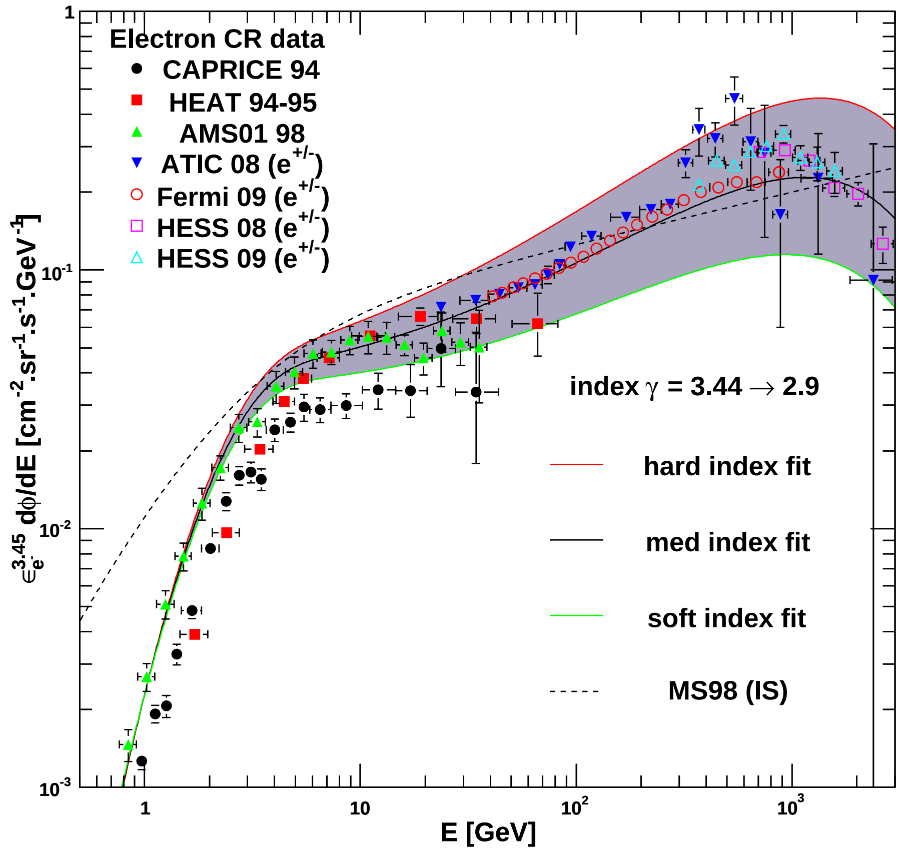

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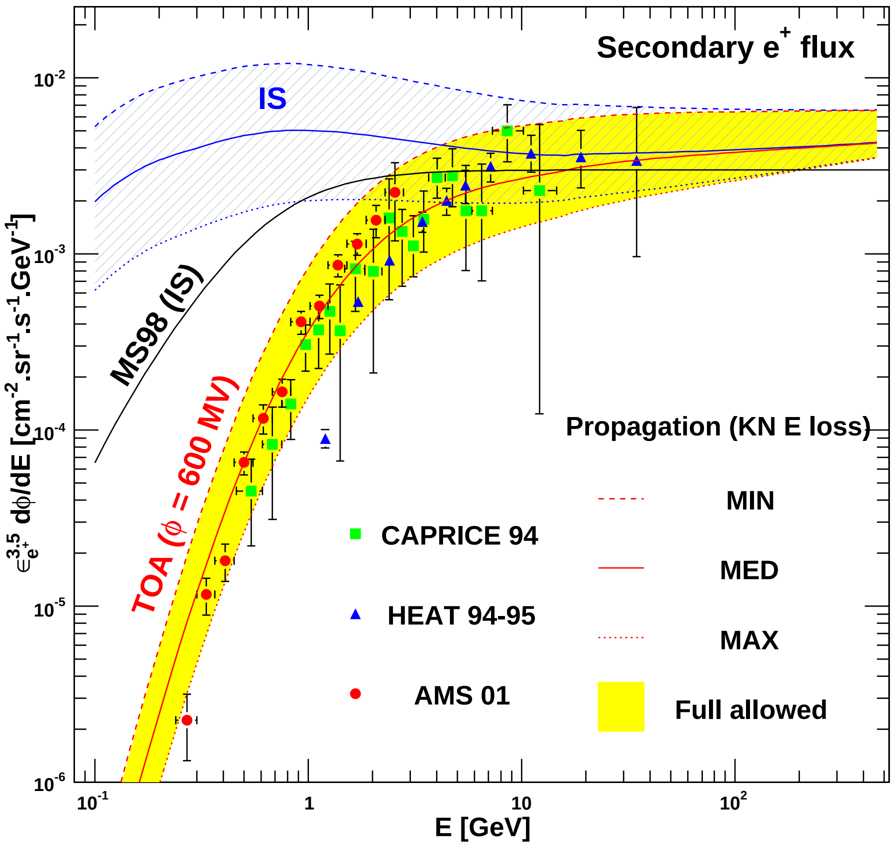

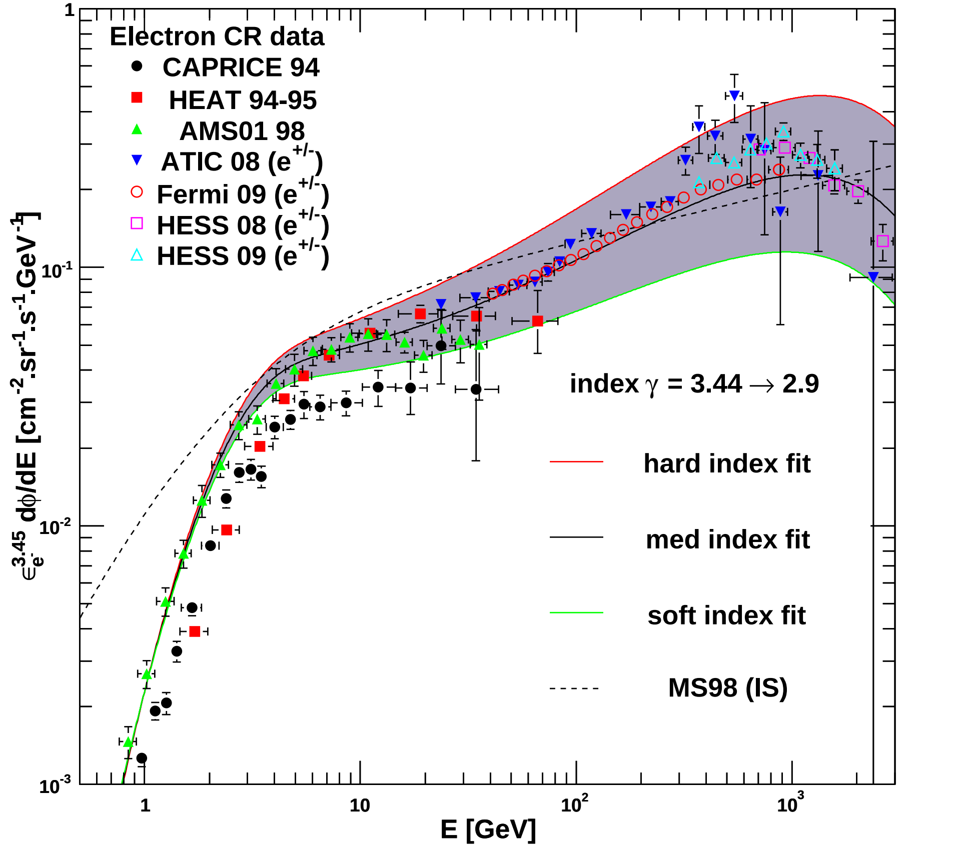

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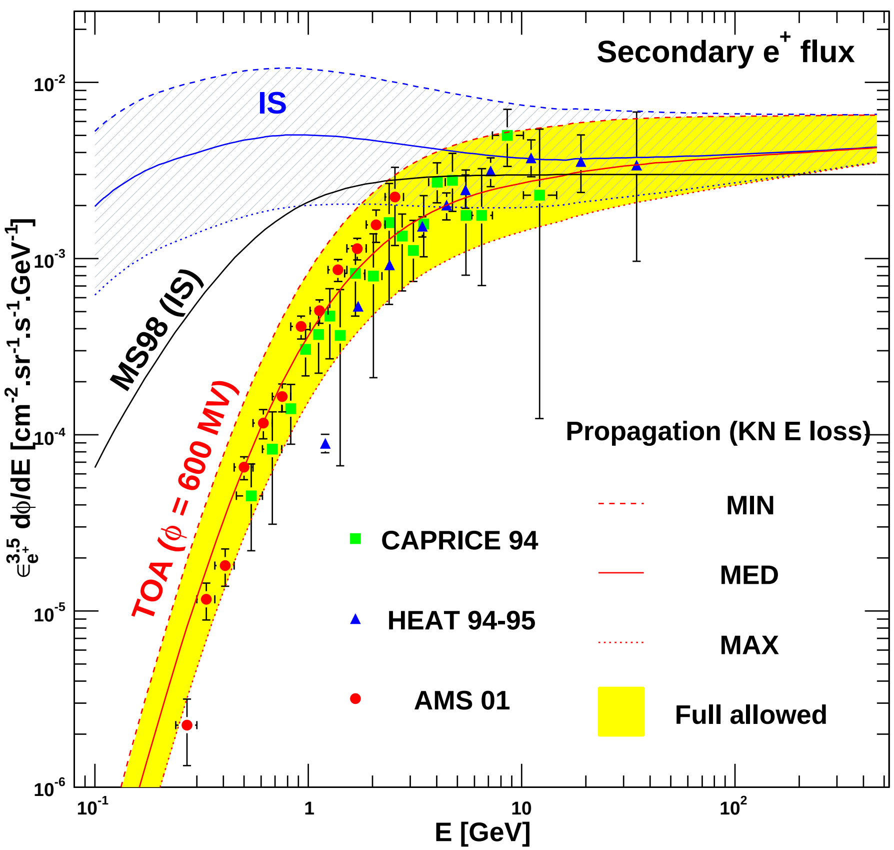
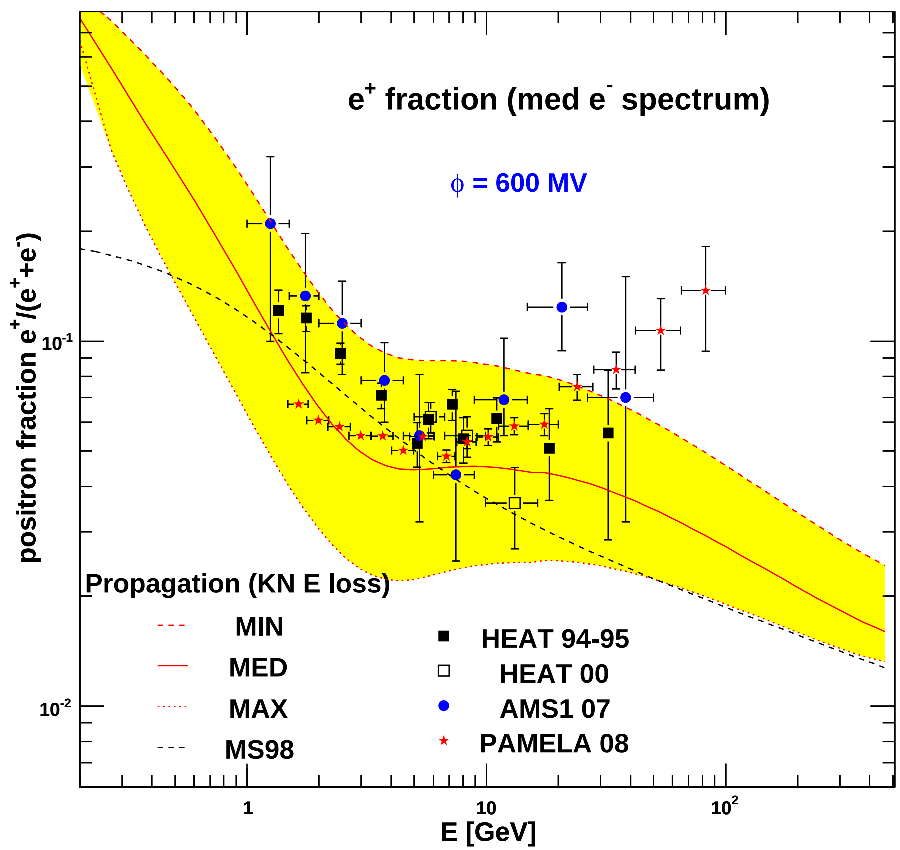
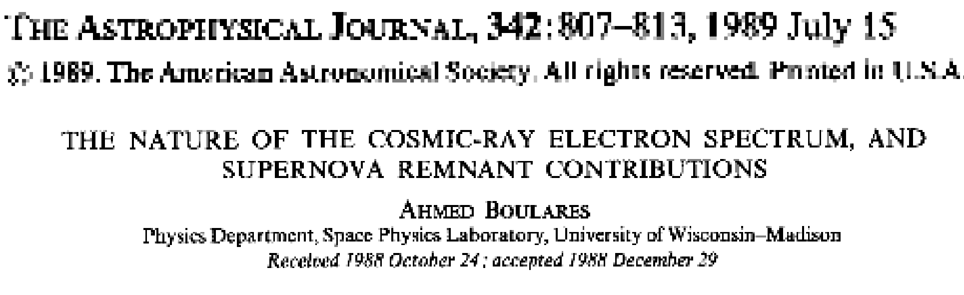




PAMELA excess: standard candidates?


THE ASTROPHYSICAL JOURNAL, 342:807–813, 1989 July 15
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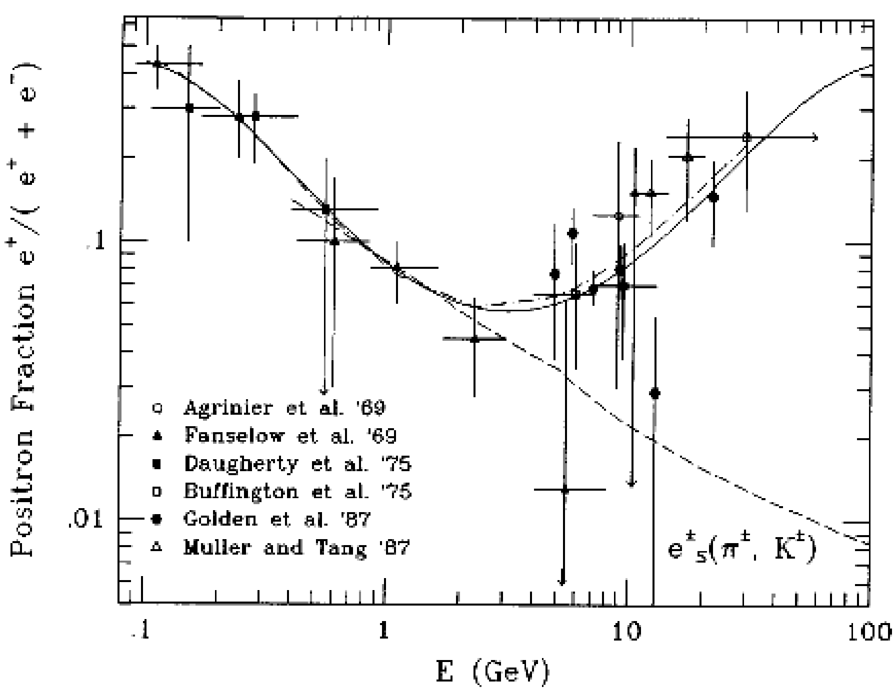
THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

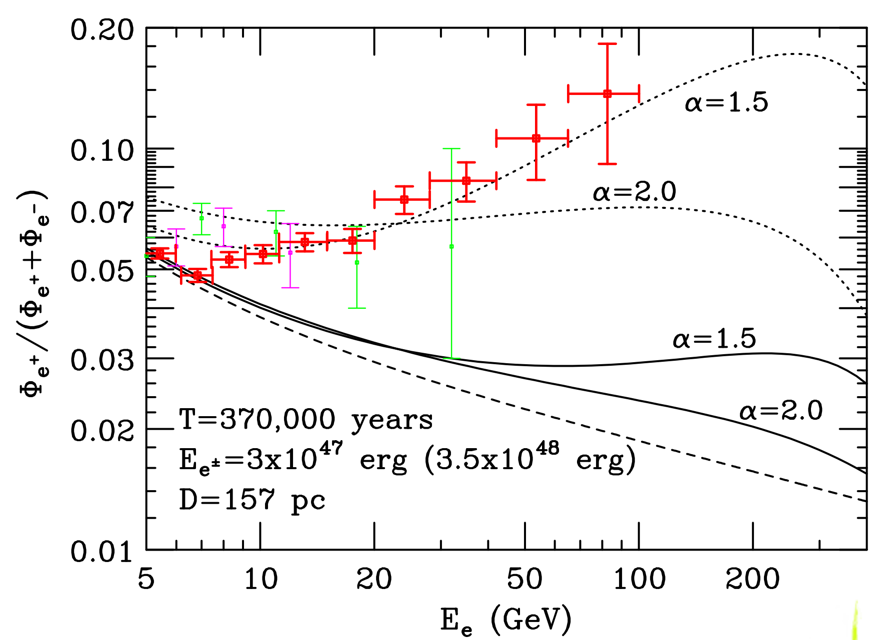
AHMED BOULARES
Physics Department, Space Physics Laboratory, University of Wisconsin–Madison
Received 1988 October 24; accepted 1988 December 29

Among other works:
Aharonian et al (1995)
Zhang & Cheng (2001)
Profumo (2009)
Blasi (2009)

BOULARES

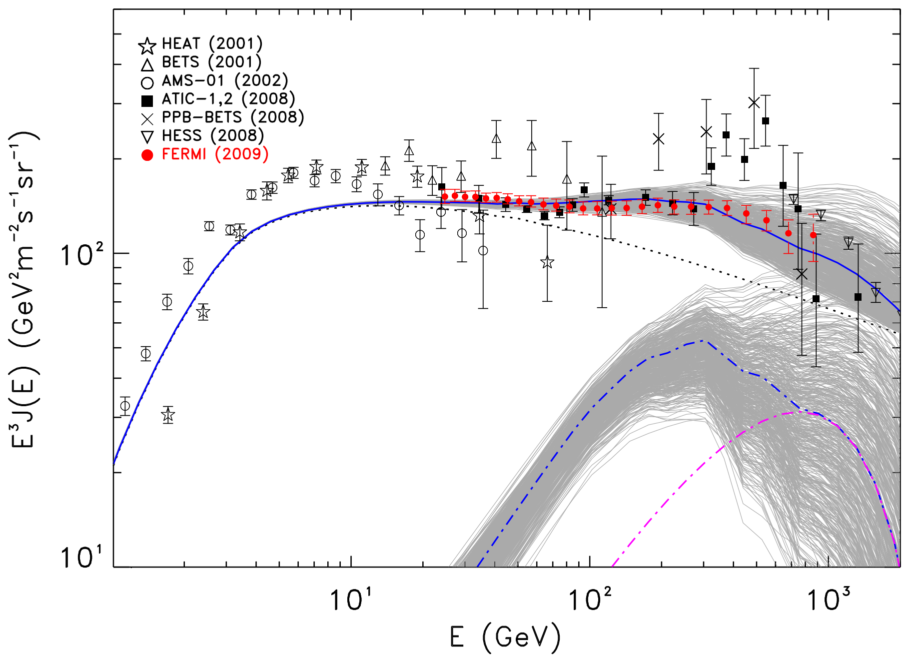


Hooper et al arXiv:0810.1527



PAMELA excess: standard candidates?

Fermi Collab + Grasso et al (2009)



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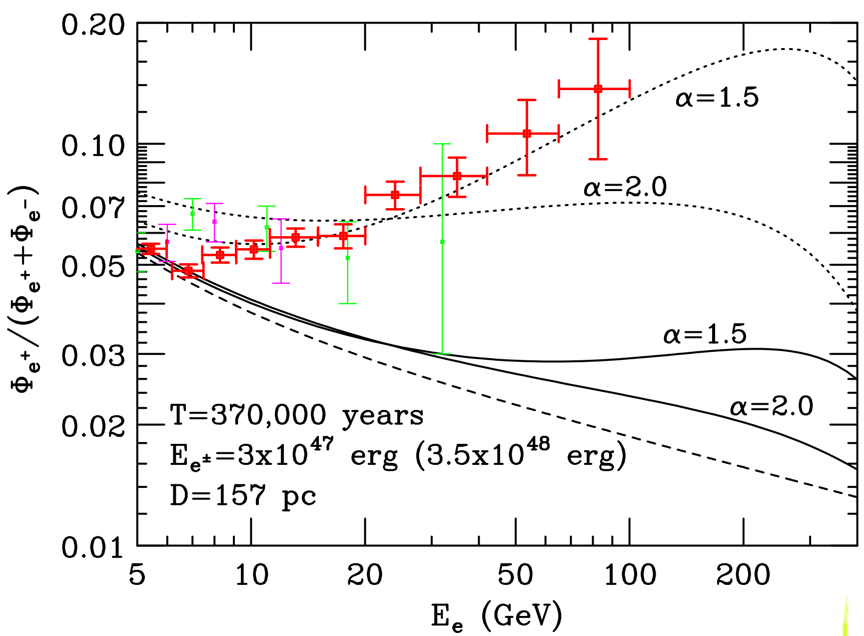

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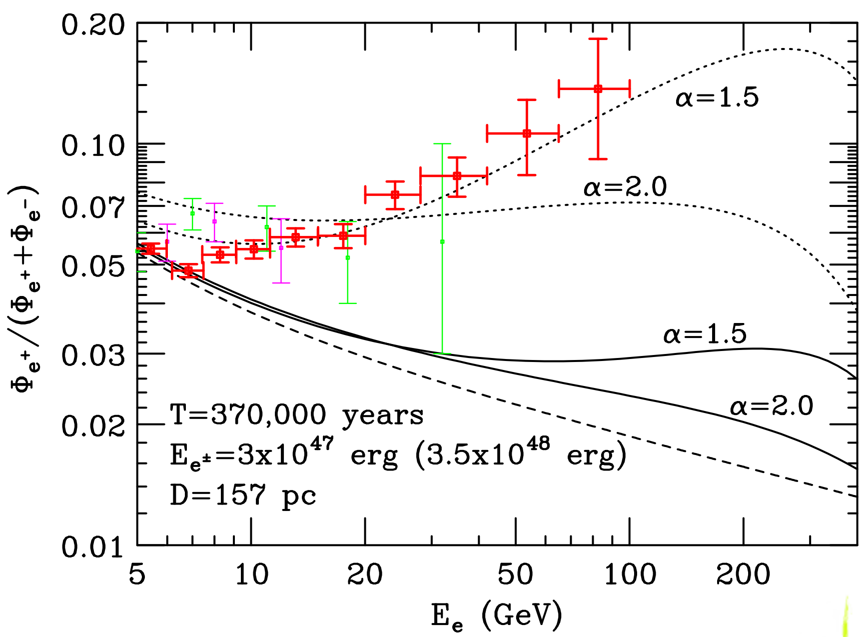


Dark matter: generic predictions (smooth halo)

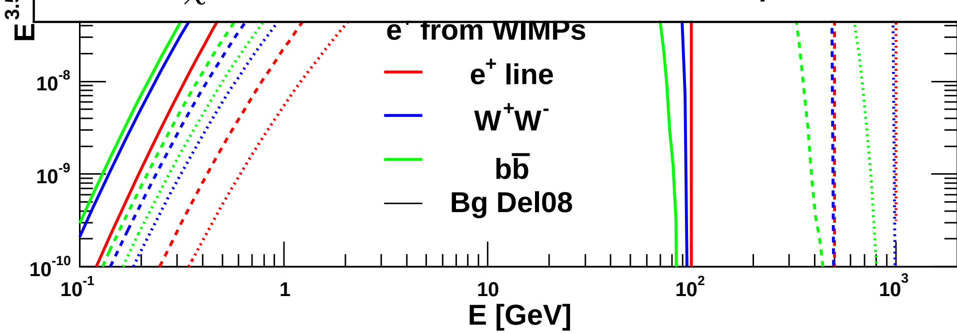
For $\chi\chi \to e^+e^-$ (limit $E \to m_\chi = 100$ GeV). From PAMELA, the excess is $\lesssim 5 \times \phi_{\rm bg}(100~{\rm GeV})$.

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

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

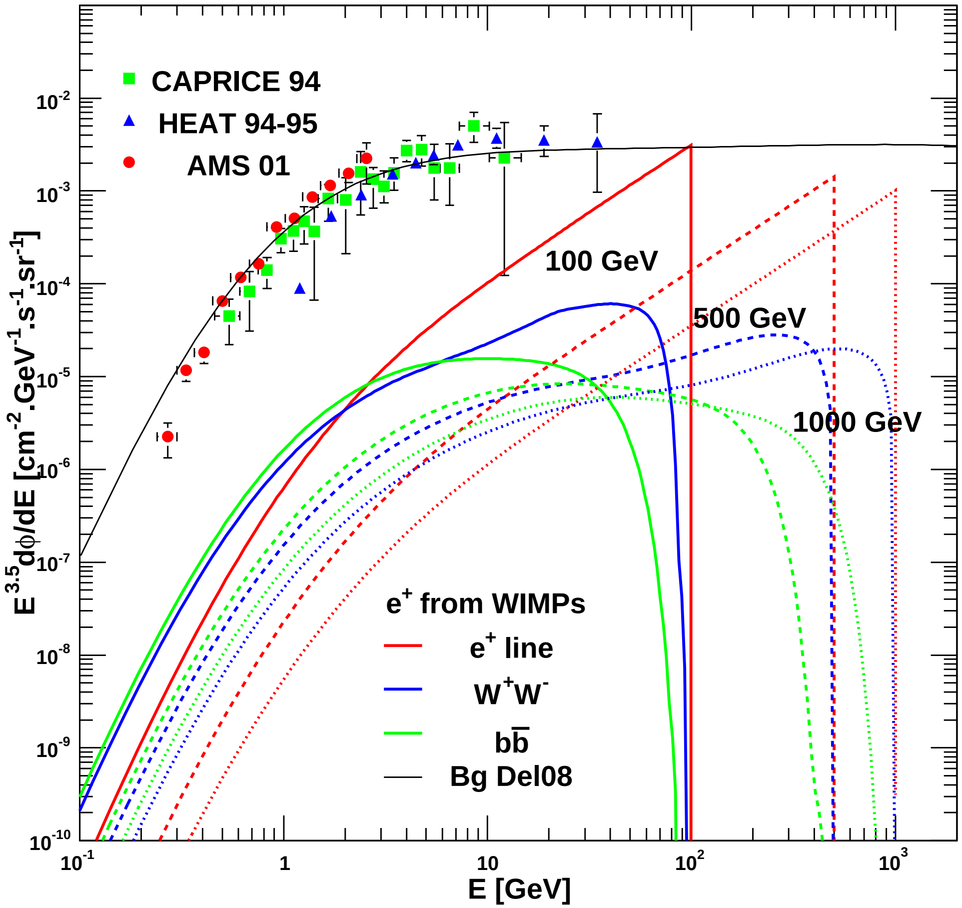
$$\simeq 3 \cdot 10^{-10} \left(\frac{\tau}{10^{16}{\rm s}}\right)\left(\frac{\rho_\odot}{0.3~{\rm GeV/cm^3}}\right)\left(\frac{100~{\rm GeV}}{m_\chi}\right)^4\left(\frac{\langle\sigma v\rangle}{3\cdot 10^{-26}{\rm cm^3/s}}\right)$$

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



$b\bar{b}$	250	500	1000

Dark matter: generic predictions (smooth halo)



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

PAMELA excess: dark matter?

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

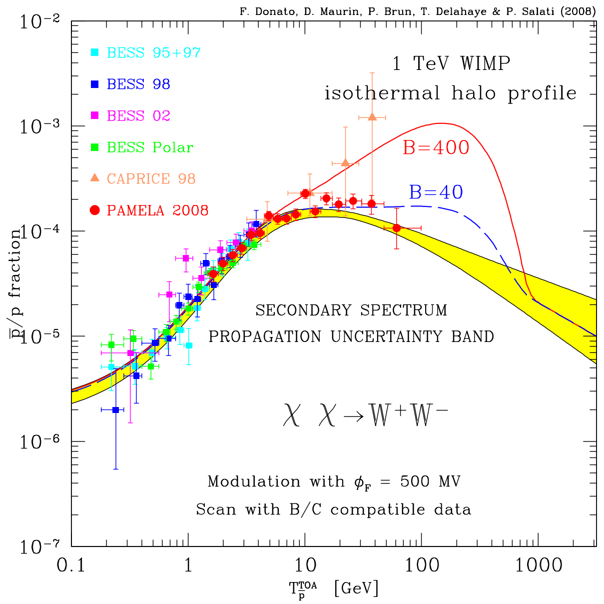
If dark matter annihilates into quarks or heavy bosons

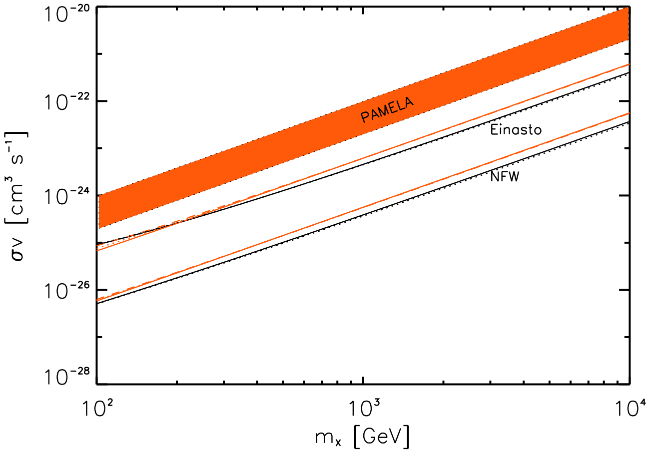
- gamma-rays (next slide)
- antiprotons
  (cf Donato et al arXiv:0810.5292)

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.



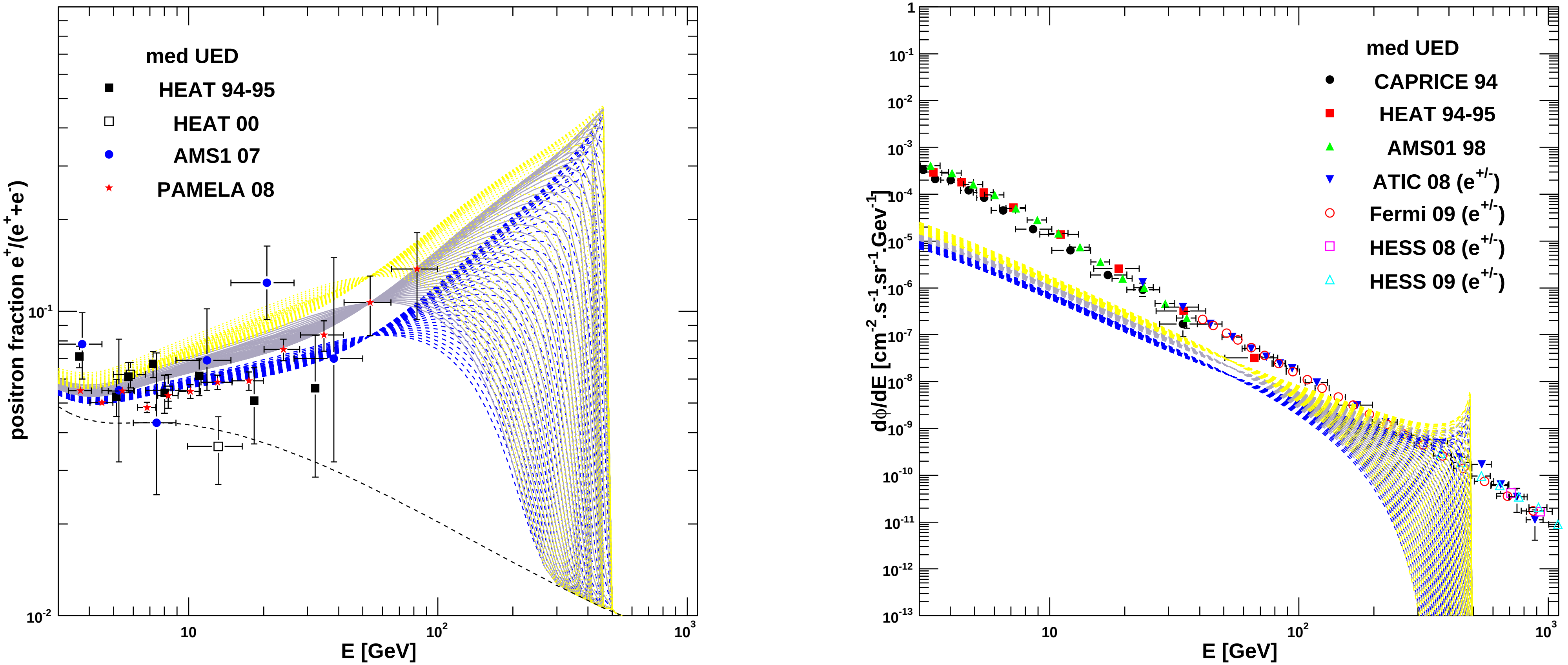


PAMELA excess: nearby dark sources?

Dark point sources (IMBHs, big clumps) ...

but conventional scenarios **excluded by EGRET+Fermi**

Single DM object wandering around



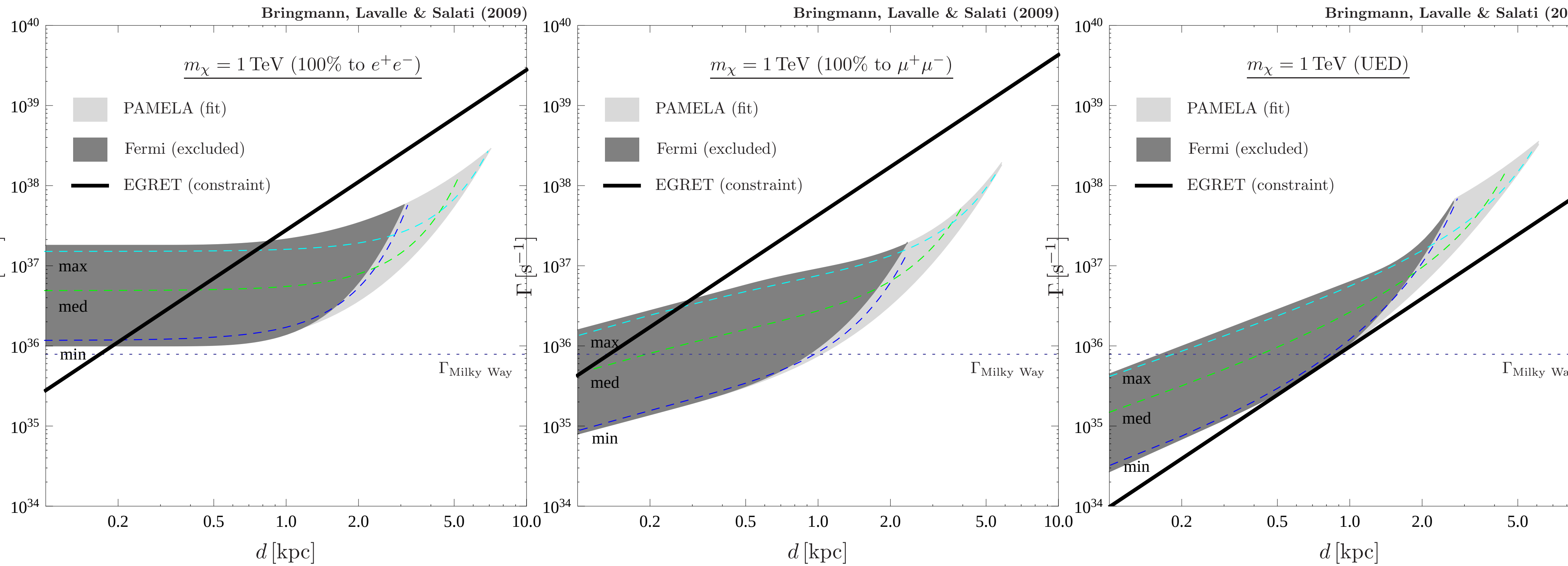
Bringmann, Lavalle & Salati arXiv:0902.3665

PAMELA excess: nearby dark sources?

Dark point sources (IMBHs, big clumps) ...

but conventional scenarios **excluded by EGRET+Fermi**

Any single DM object wandering around



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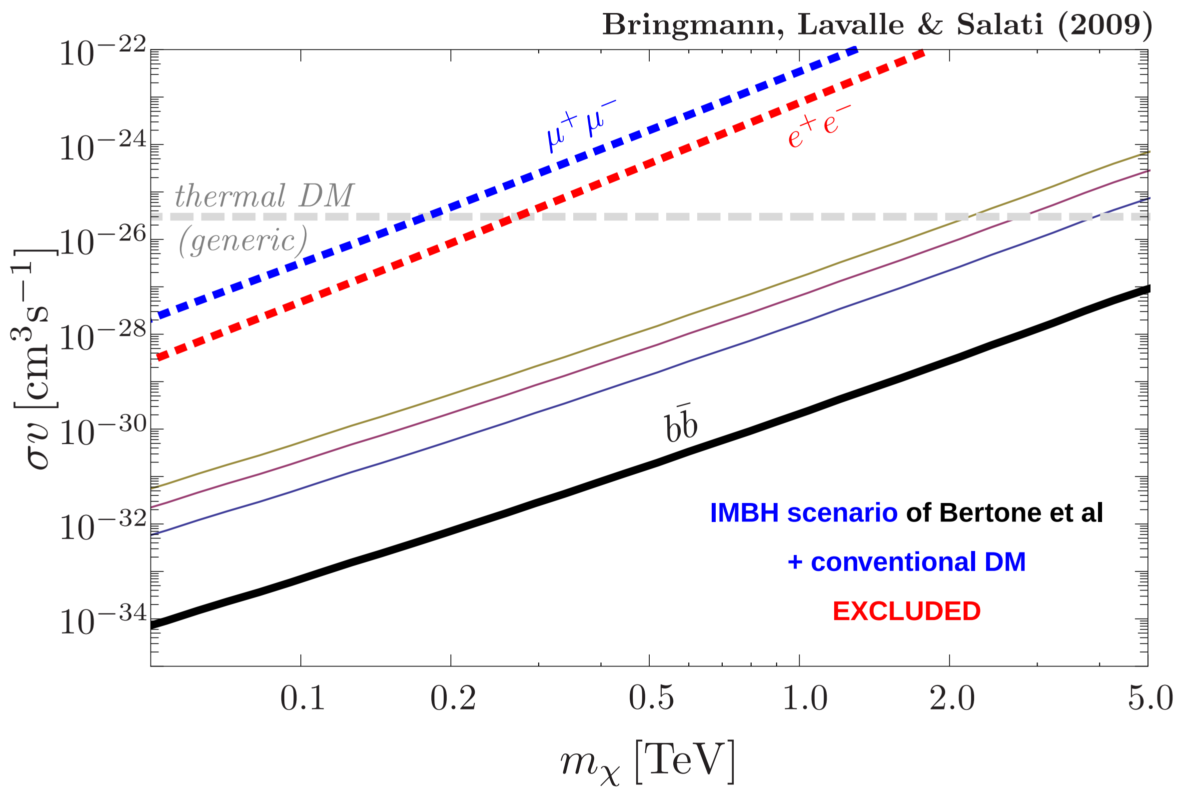
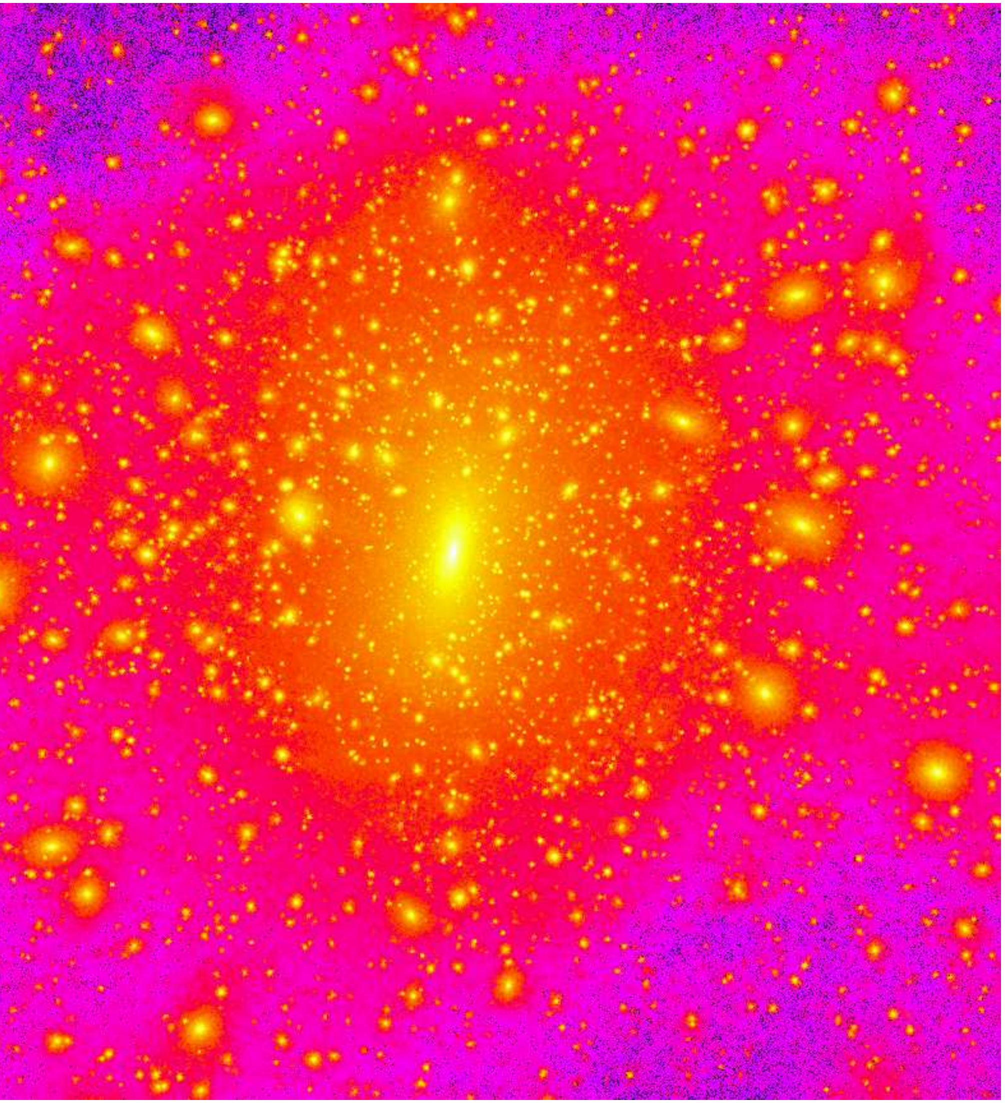


Bringmann, Lavalle & Salati arXiv:0902.3665

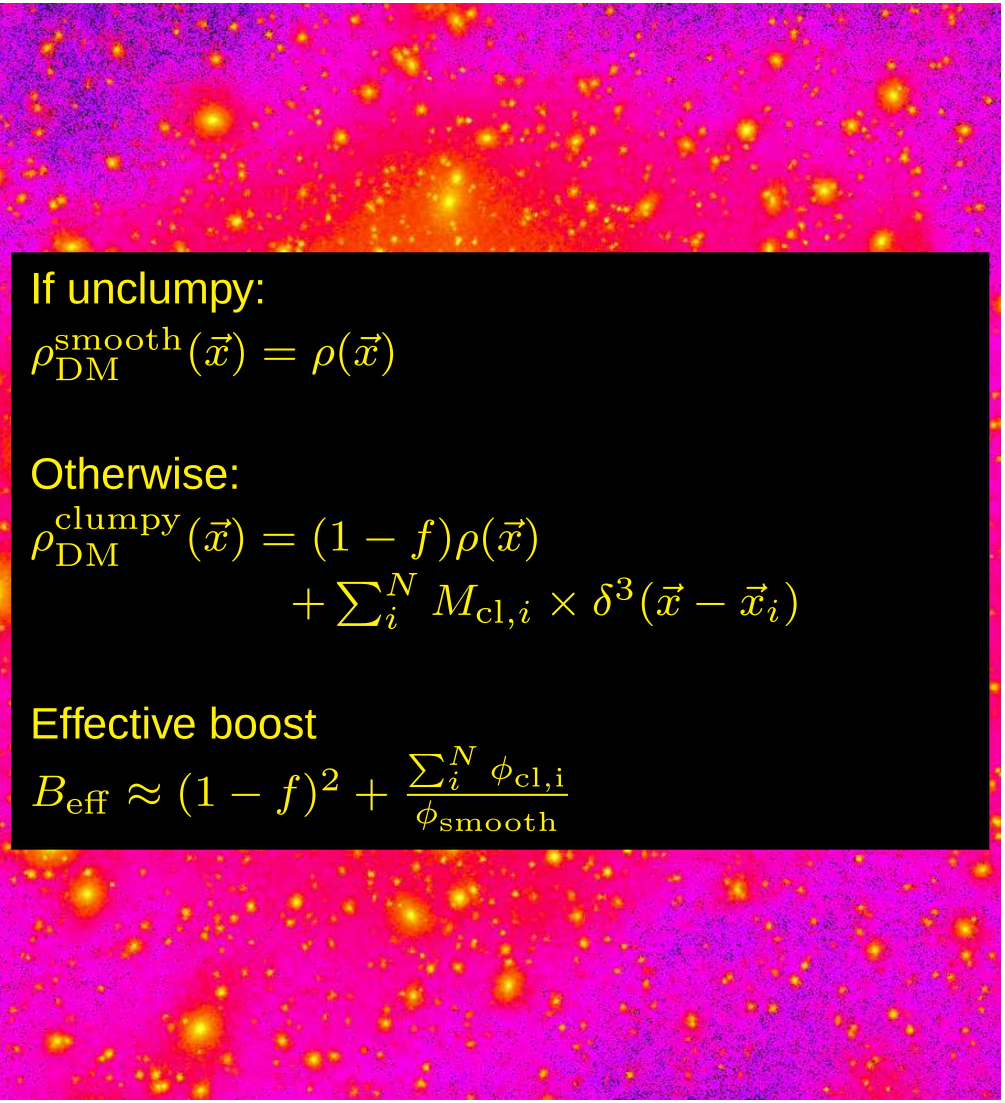
Inhomogeneous halo and boosted annihilation rate



(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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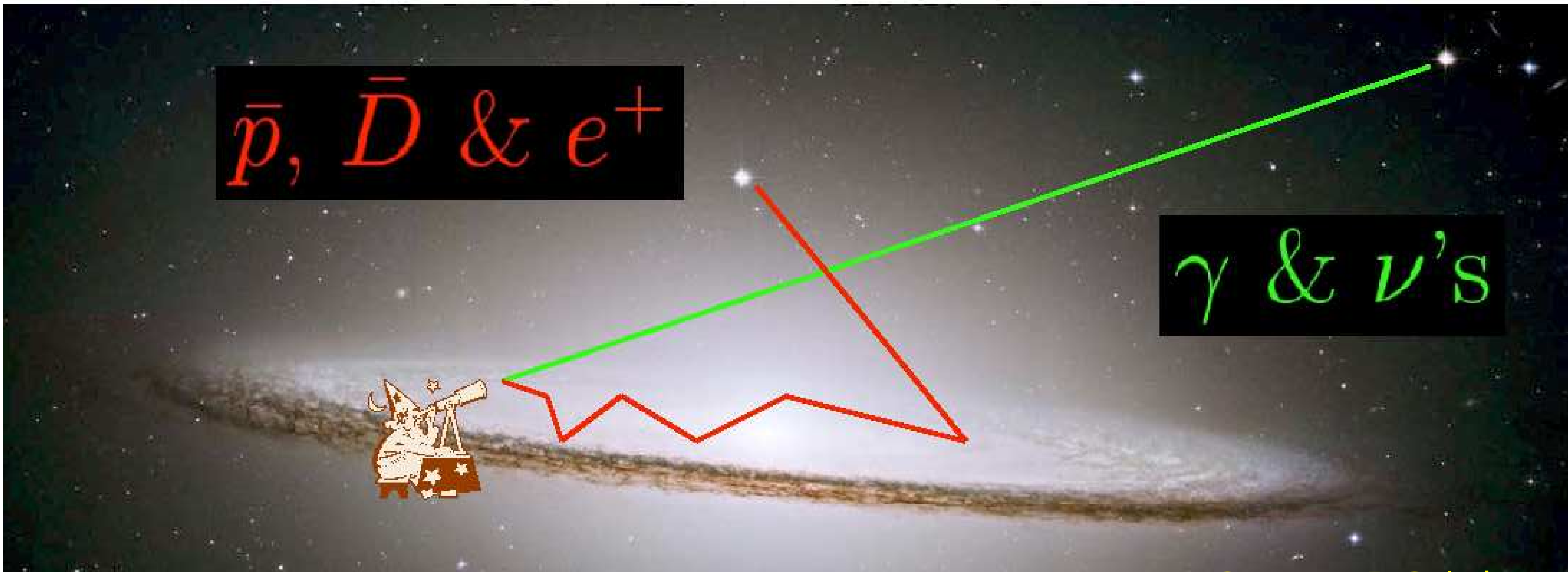
Gamma-rays versus antimatter cosmic rays



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

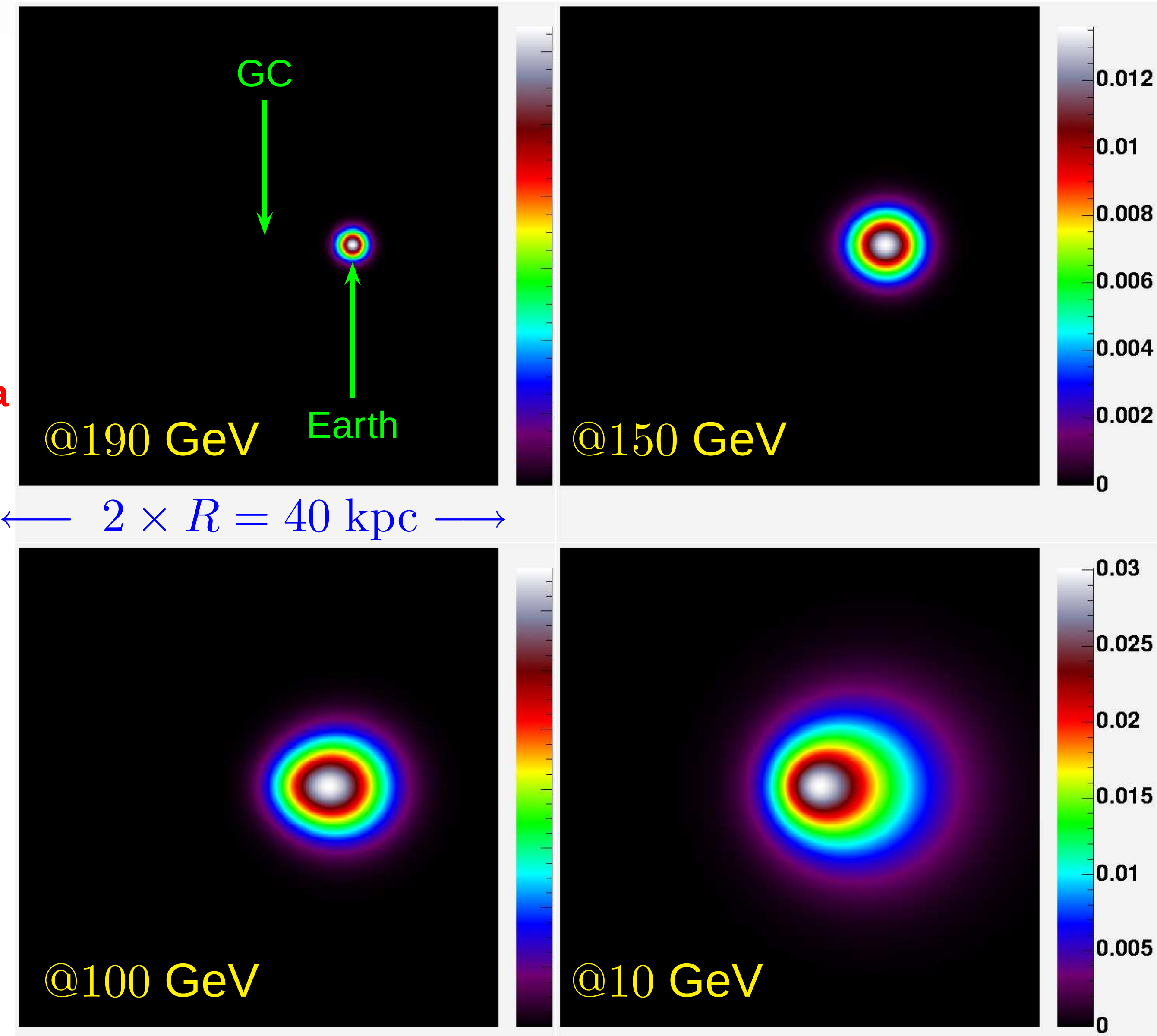
Inject a 200 GeV e^+ with $Q(r) = \rho^2(r) \propto r^{-2}$ ...

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

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

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

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

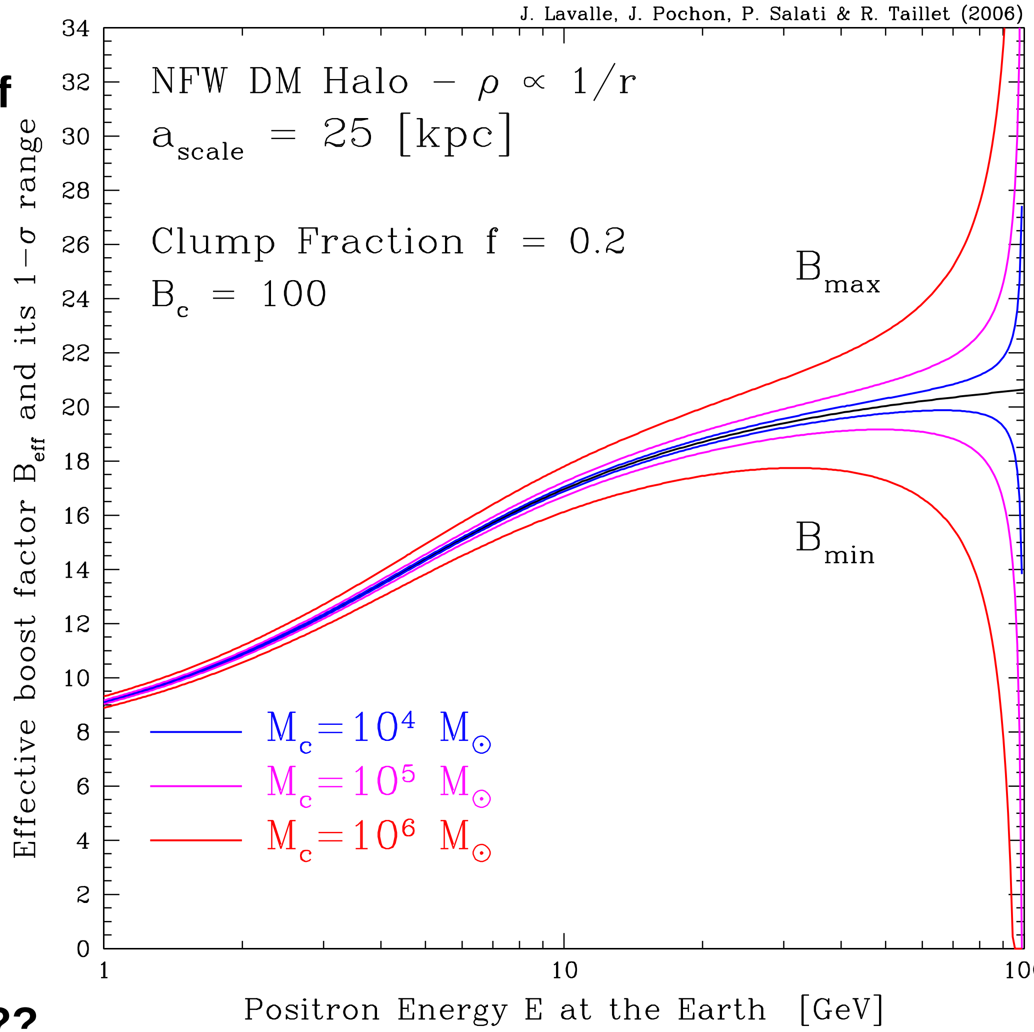
PDFs allow to compute mean values and associated statistical variances for some physical quantities

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:

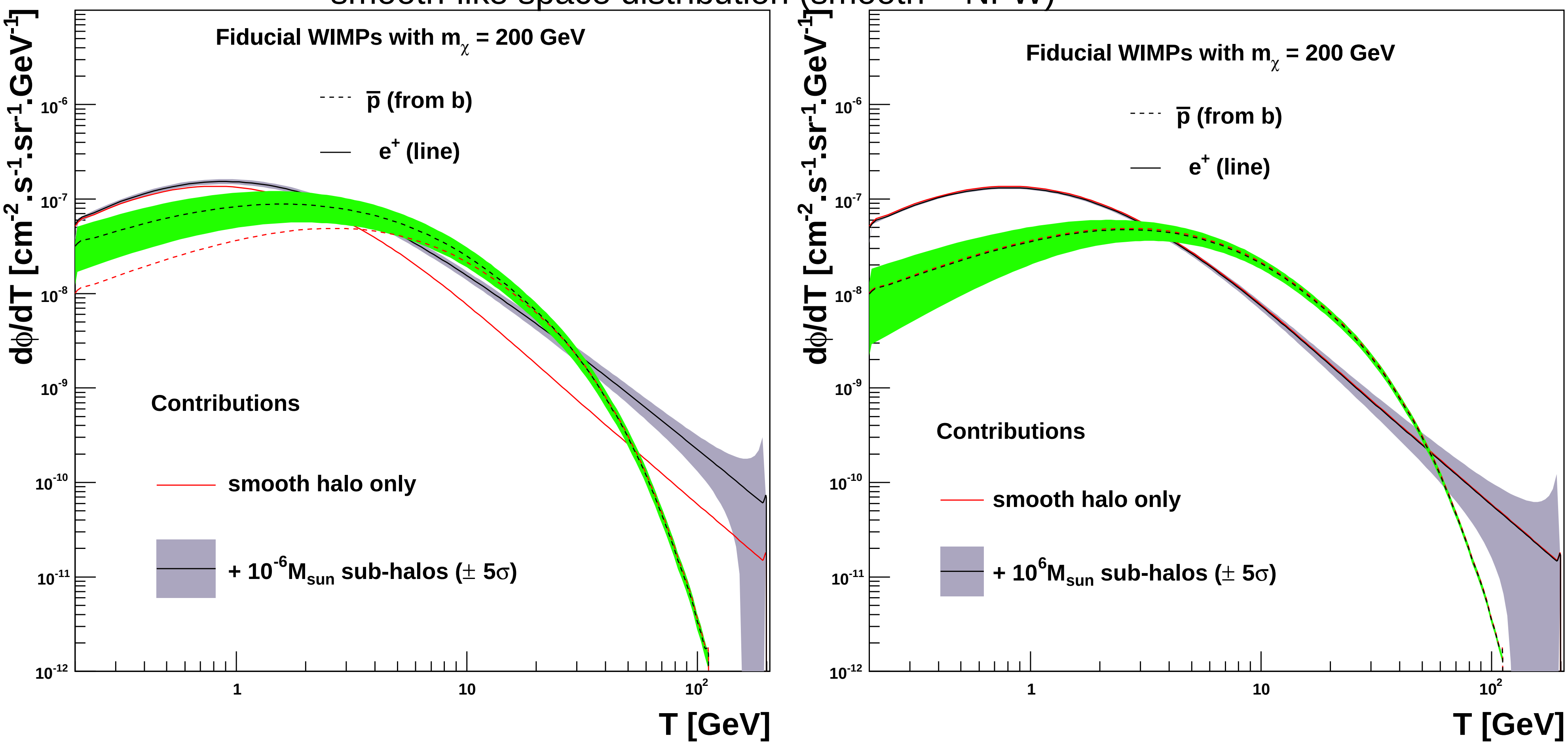
- Long believed to be **simple rescaling of fluxes** ...
- **This picture is wrong**. Due to propagation effects, ***boost* is a non-trivial function of energy** (J.L, Pochon, Salati & Taillet, 2006).
- Variance depends on the number of clumps within the volume bounded by diffusion length λ_D: increases 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)

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)

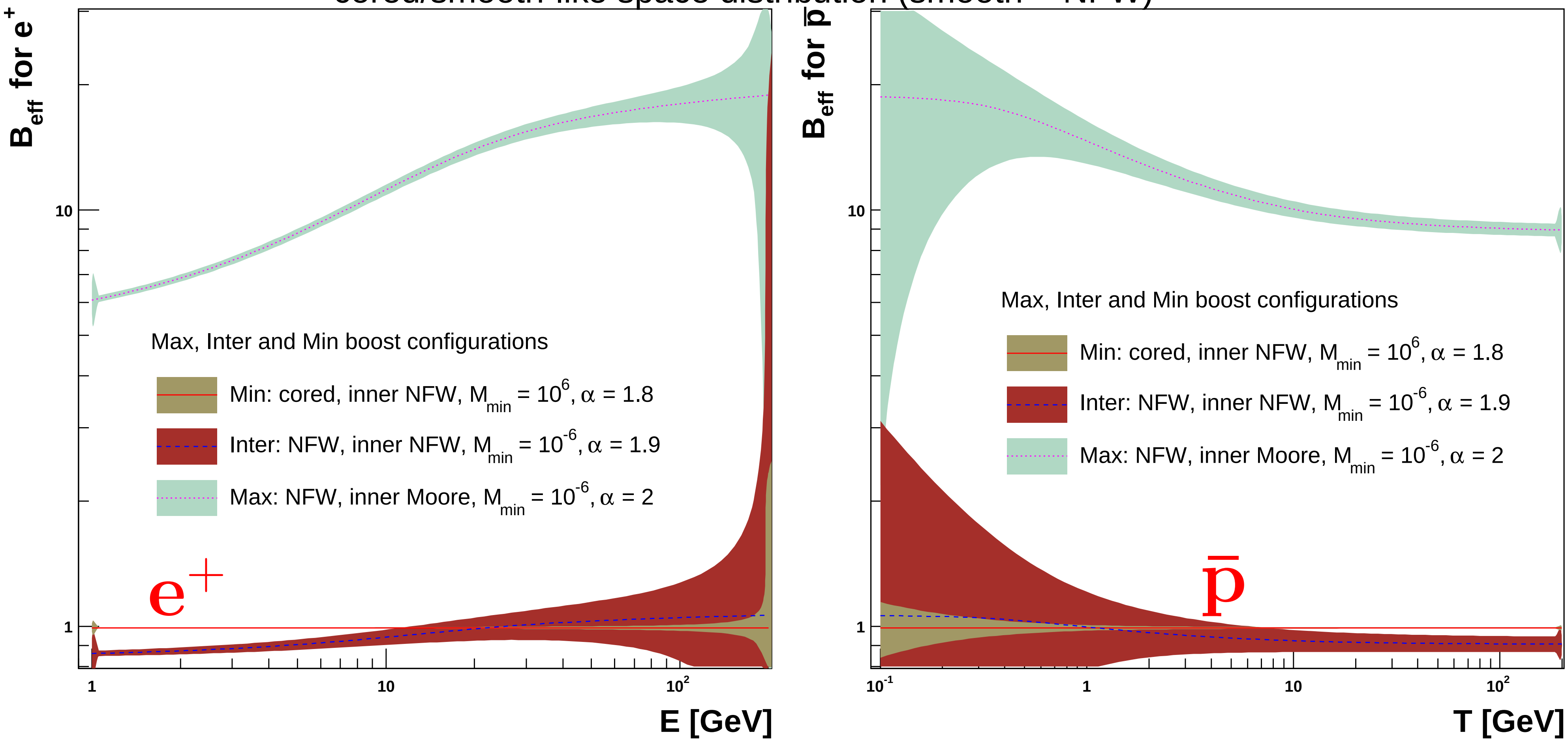


Lavalle, Maurin et al – A&A 429, 427 (2008)

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)



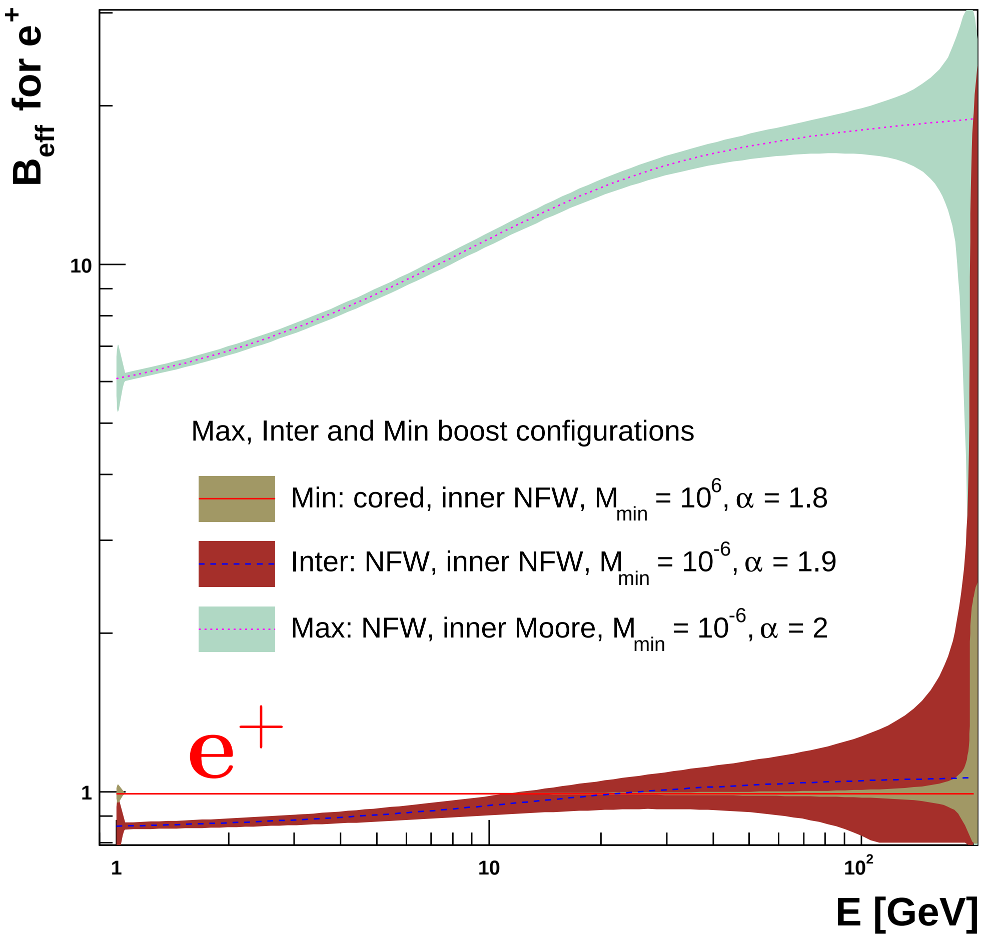
Lavalle, Yuan, Maurin & Bi – A&A 429, 427 (2008)

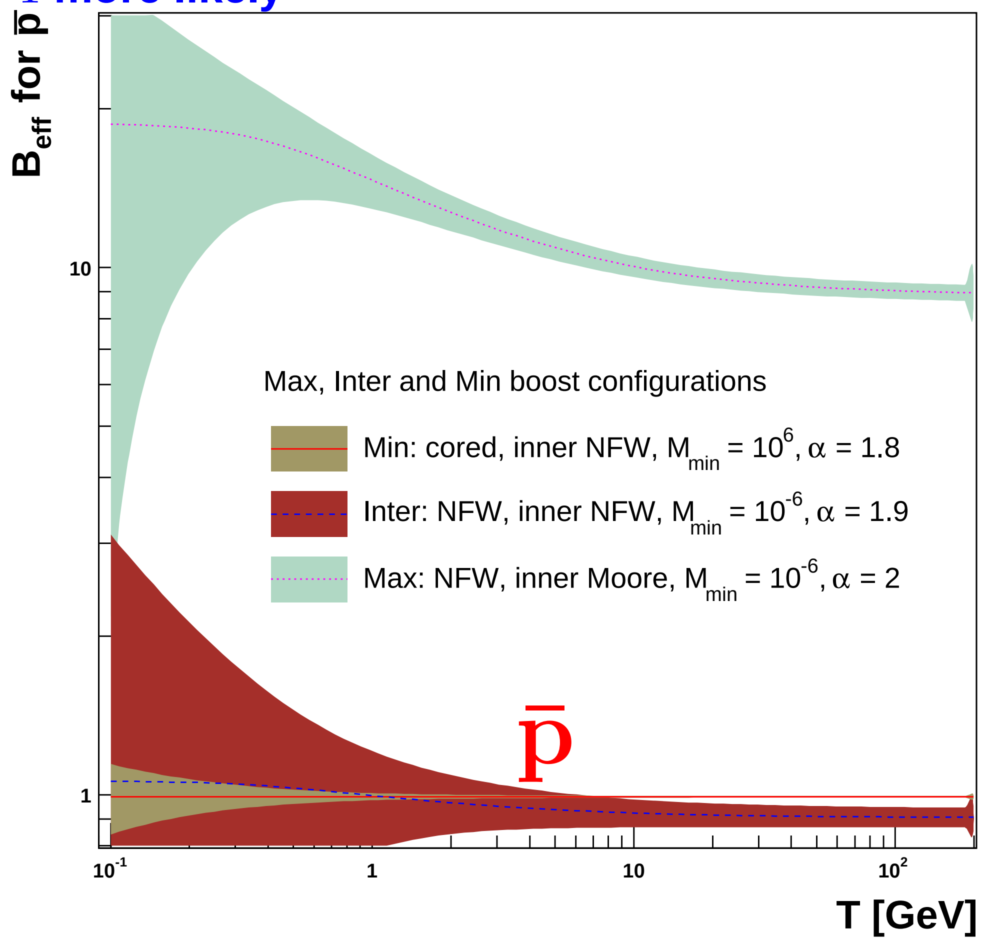
Boost factors for a 200 GeV e^+ line / antiprotons

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)

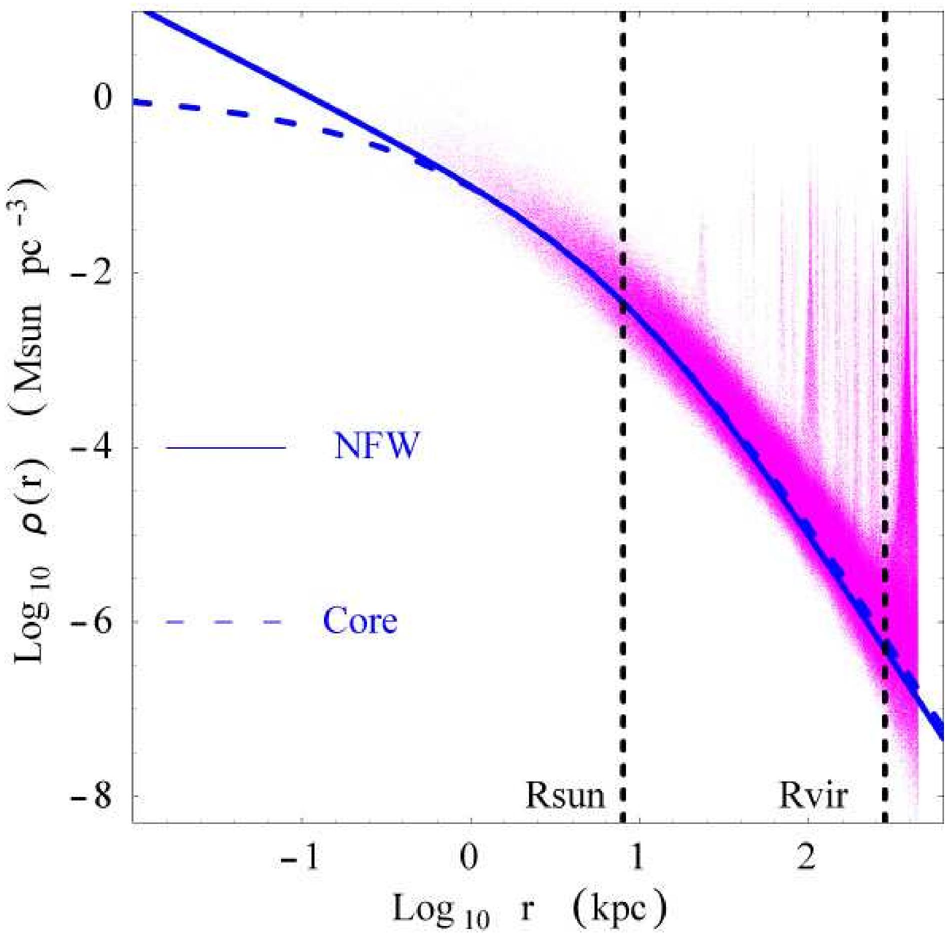
HORIZON:
implementing tools for γ-rays and cosmic rays

(**PRD 78 (2008)**
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^{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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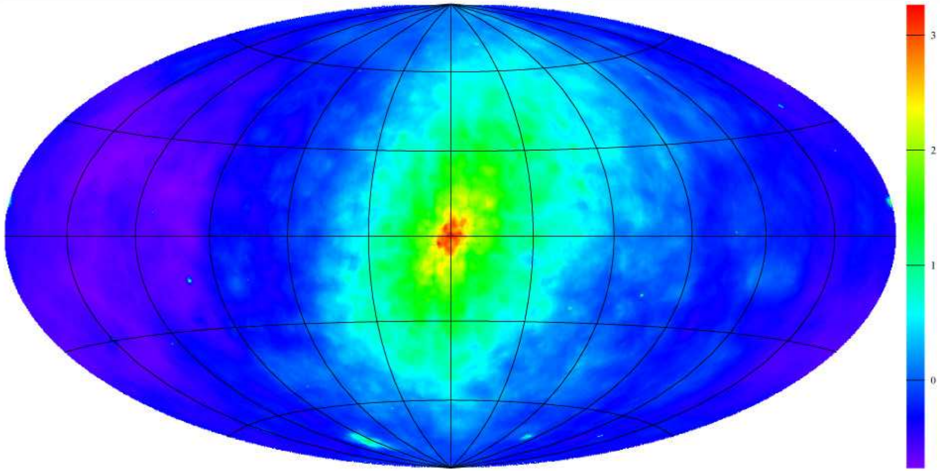

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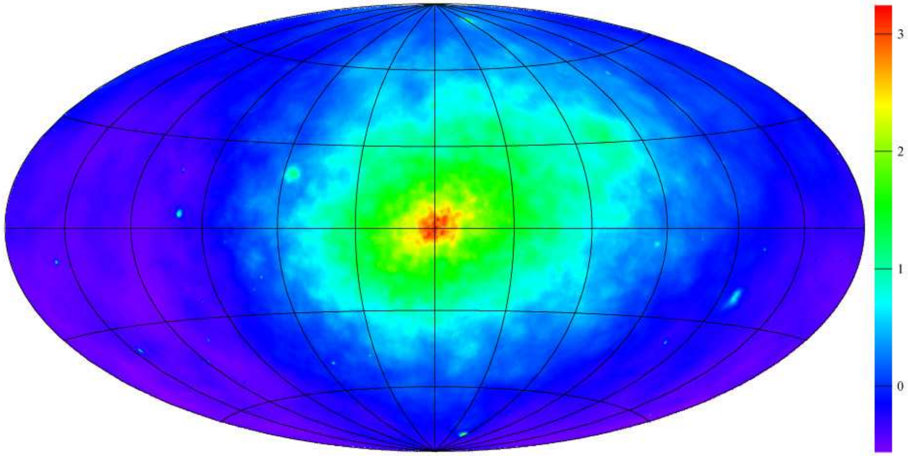
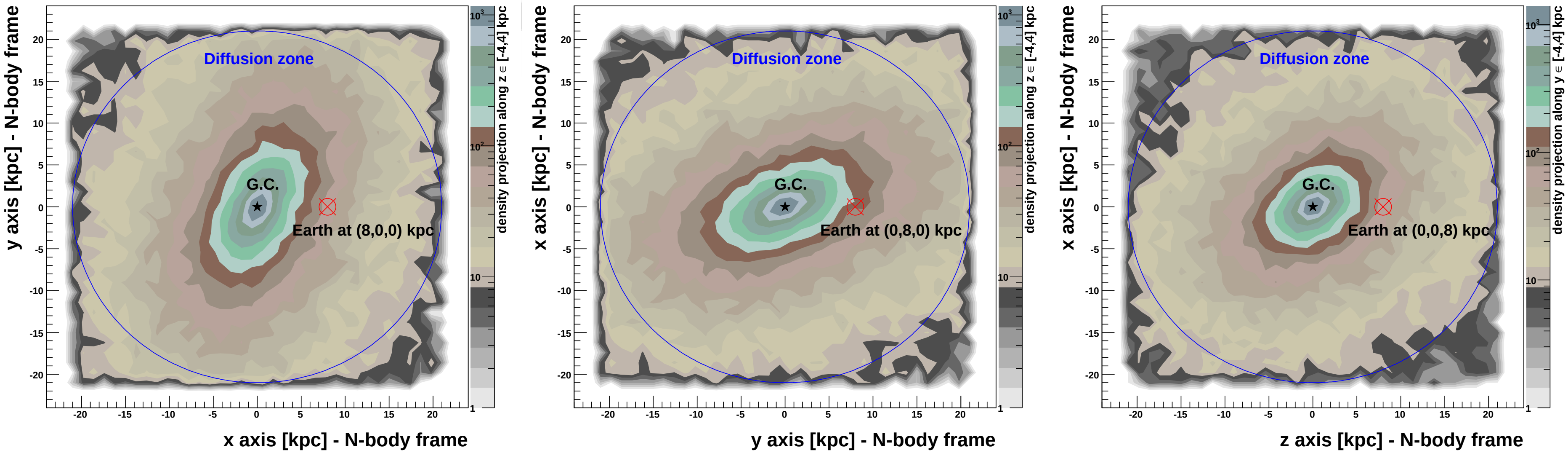
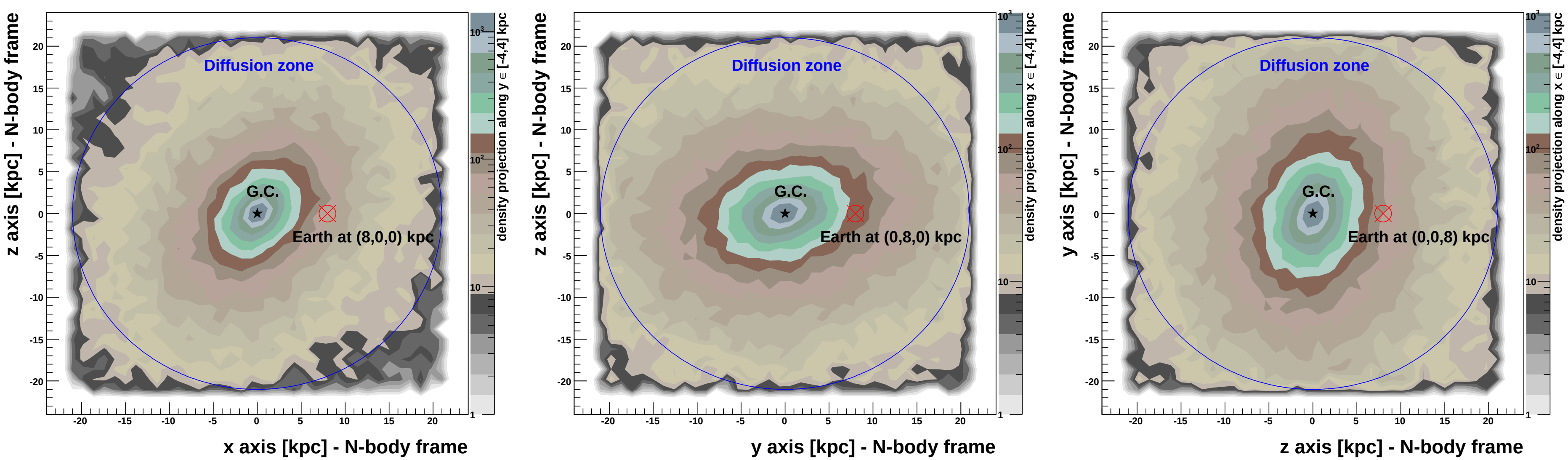


HORIZON: implementing tools for γ-rays and cosmic rays



Earth at different positions (8 kpc)



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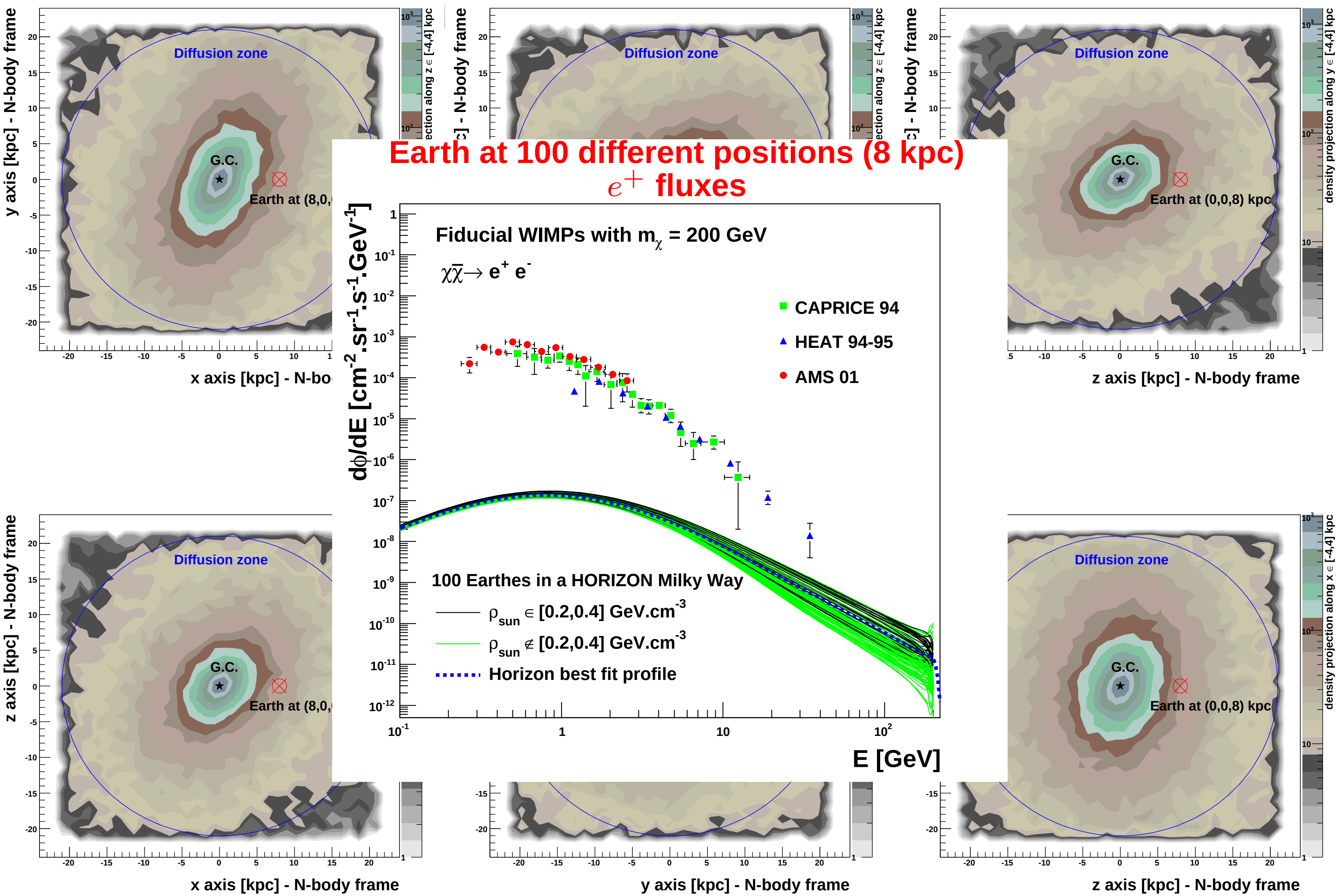

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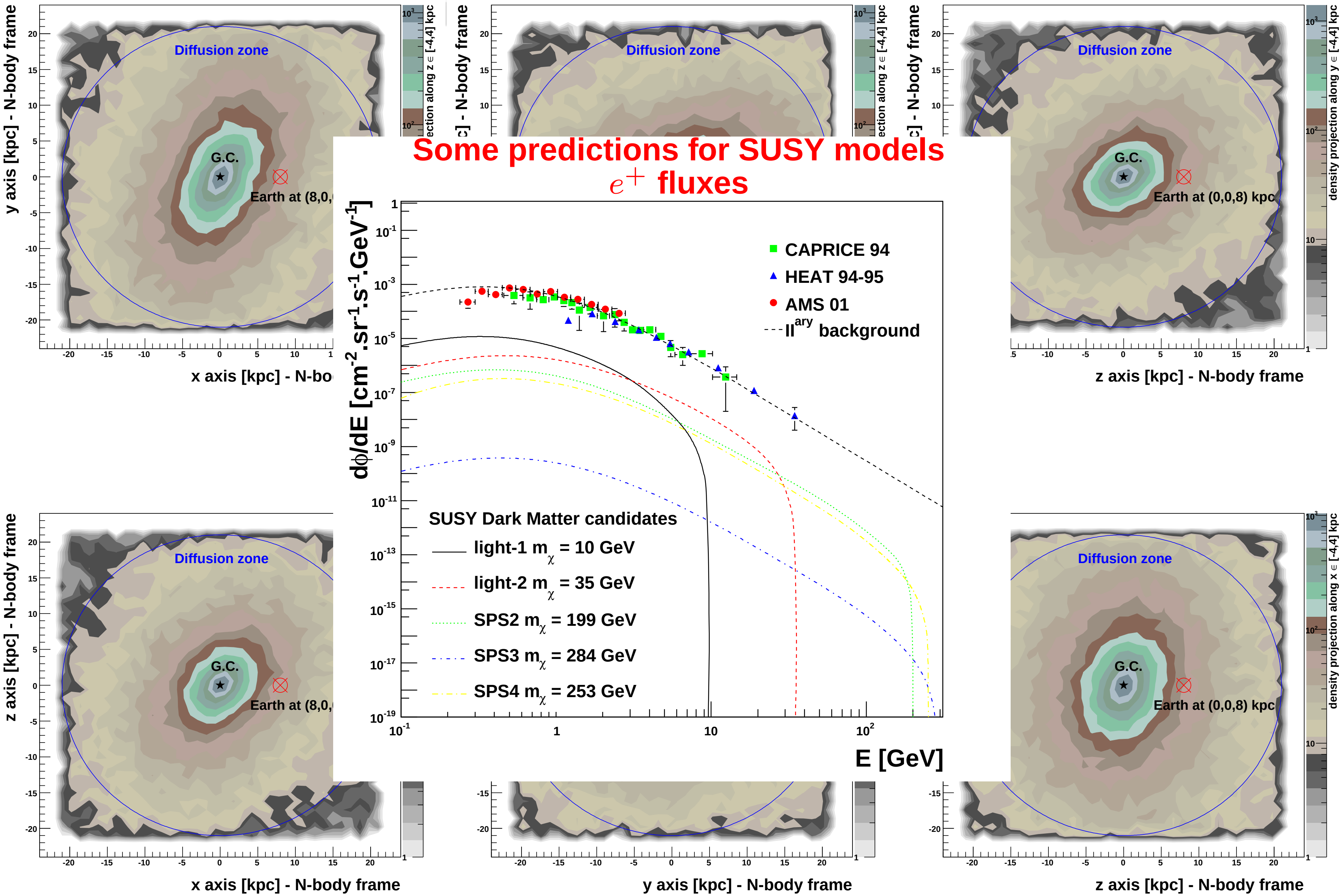
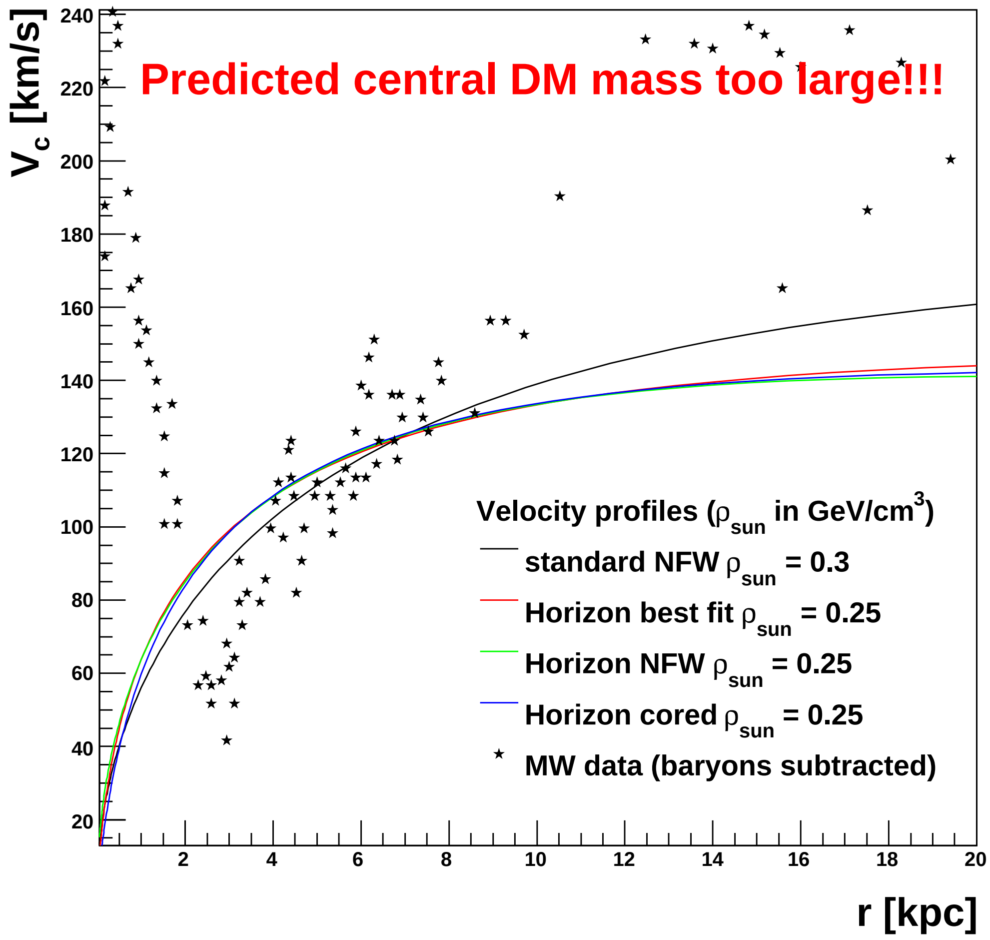


CAVEATS: too simplistic galaxy model?

Rotation curves with baryon contribution (COBE/DIRBE inferred) subtracted
(Englmaier & Gerhard 2006)



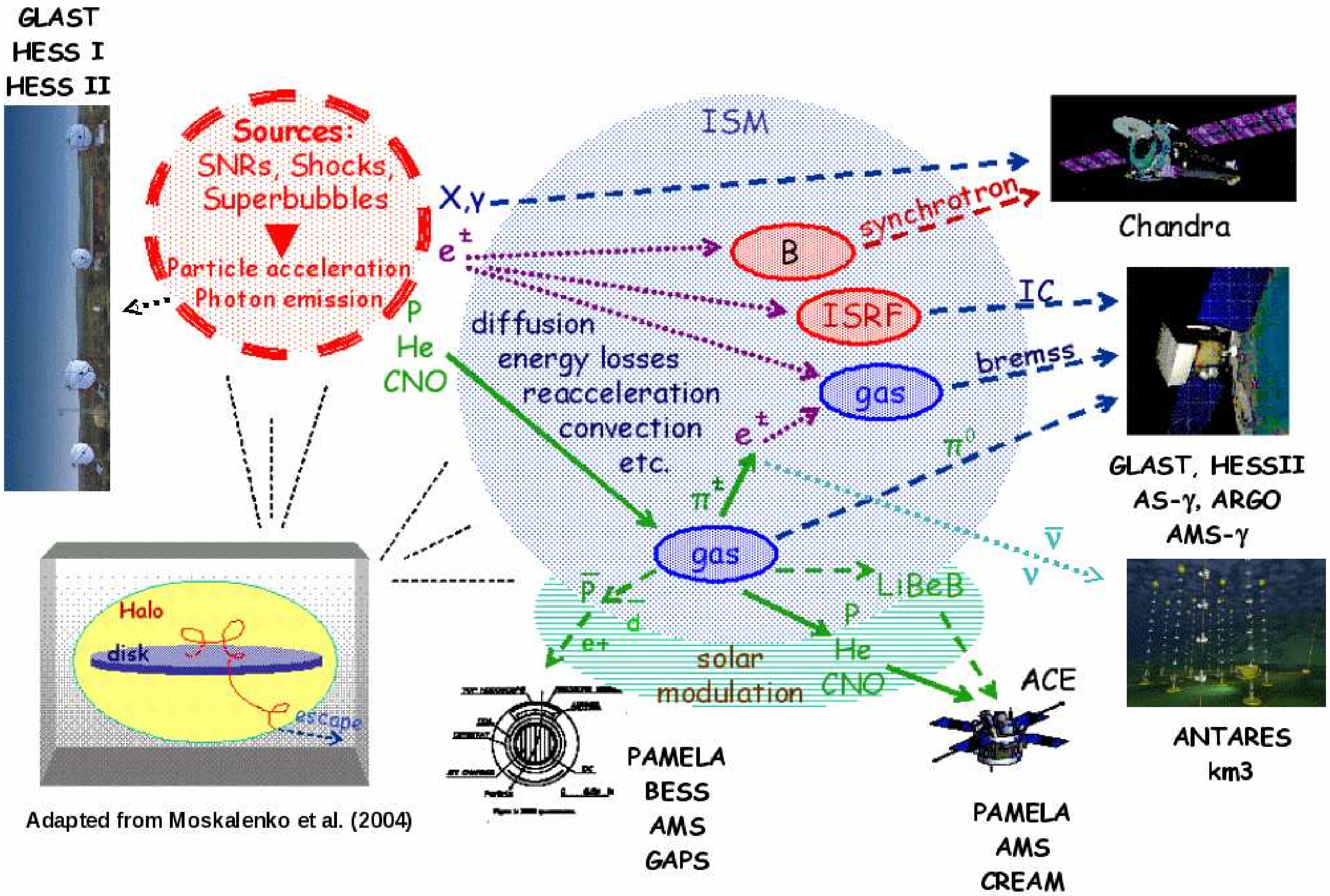
Lavalle, Nezri et al – PRD 78 (2008)

HORIZON: with baryons !!!

Exotic + standard cosmic ray study
Lavalle, Ling, Nezri & Teyssier (in prep)

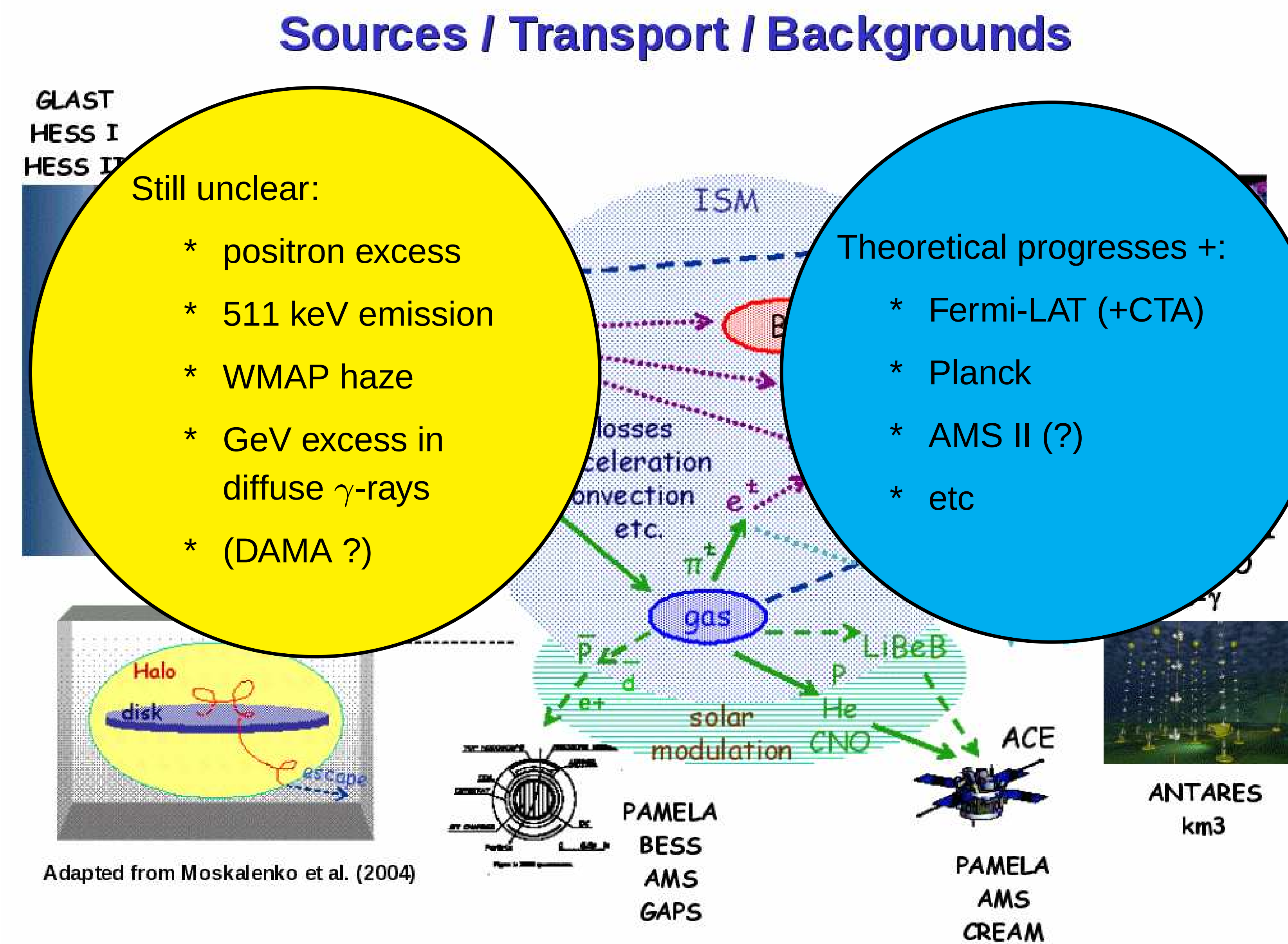
Cosmic Rays:
the necessity/tools to understand the backgrounds

Sources / Transport / Backgrounds



Adapted from Moskalenko et al. (2004)

Cosmic Rays:
the necessity/tools to understand the backgrounds



Still unclear:

* positron excess
* 511 keV emission
* WMAP haze
* GeV excess in diffuse γ-rays
* (DAMA ?)

Theoretical progresses +:

* Fermi-LAT (+CTA)
* Planck
* AMS II (?)
* etc

Summary

- **Dark Matter: a link between LHC physics, astrophysics and cosmology**

On the positron fraction:

- **Standard sources are likely enough**
- **Dark matter may contribute, but needs very specific properties (strong couplings to leptons, Sommerfeld enhancement)**
- **Nearby dark sources or clumpiness enhancement are strongly disfavored**
- **Hard to infer a dark matter origin when astrophysical sources explain the observations easily**
- **Need much better estimates of theoretical uncertainties!!! (sources & propagation)**
- **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! In particular, γ-rays from Dwarph spheroidals or antideuterion cosmic rays ... and LHC!**