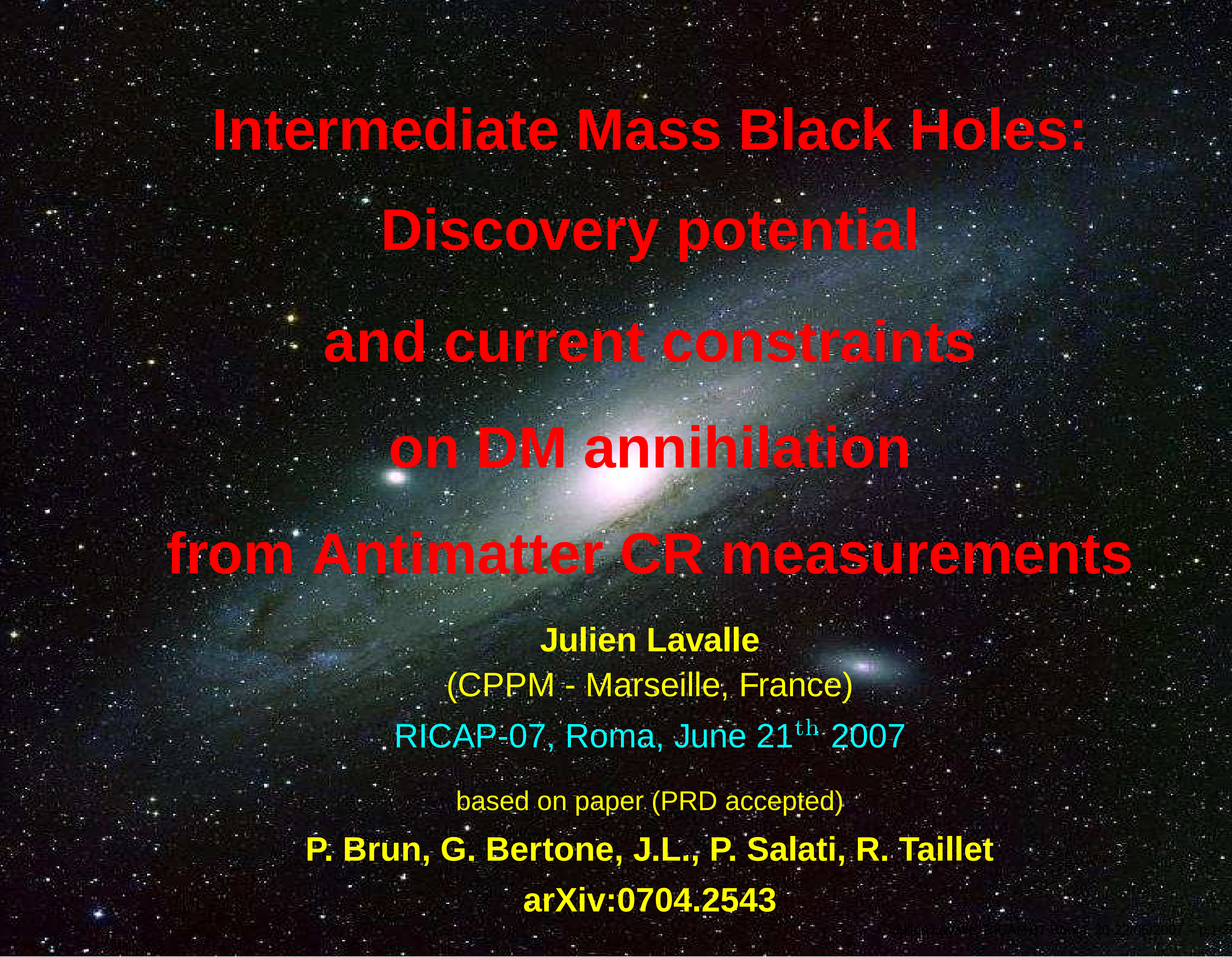

Intermediate Mass Black Holes: Discovery potential and current constraints on DM annihilation from Antimatter CR measurements

Julien Lavalle
(CPPM - Marseille, France)

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based on paper (PRD accepted)

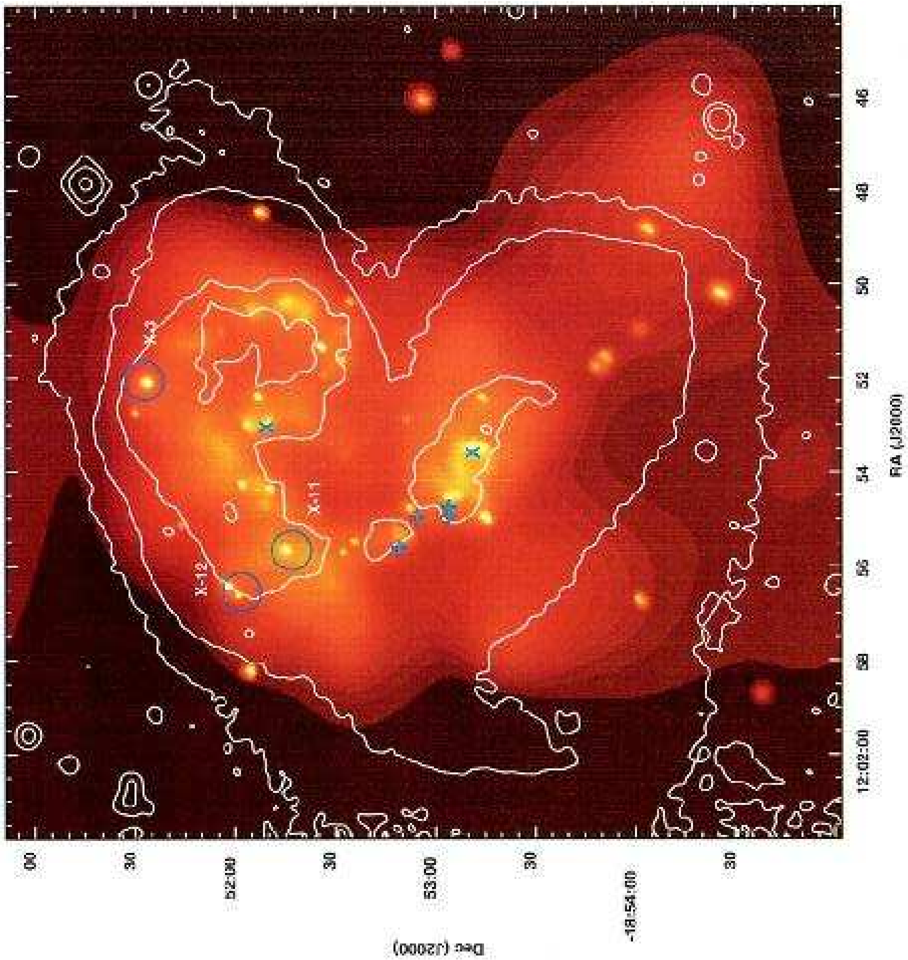
P. Brun, G. Bertone, J.L., P. Salati, R. Taillet

arXiv:0704.2543

What the hell is an IMBH ?

(review in Miller & Colbert - astro-ph/0308402)

- IMBH: black hole with mass between stellar BH and supermassive BH ($20 \leq M_{IMBH}/M_{\odot} \leq 10^6$)
- Hints provided by detection of ultra-luminous X-ray sources (ULX) not associated with AGN
- Theoretically interesting because could be seeds for SMBHs that seemed to have formed early in the universe (1 Gyr)
- IMBHs may originate from remnants of 0-metallicity pop III stars, or from primordial (H_2) gas cooling in early-forming halos.



IMBH and dark matter profile

The slow formation of a BH induces conservation of adiabatic invariants. The consequence is the compression of the density close to the BH (Gondolo & Silk, 1999). Given $\rho \propto r^{-\gamma}$

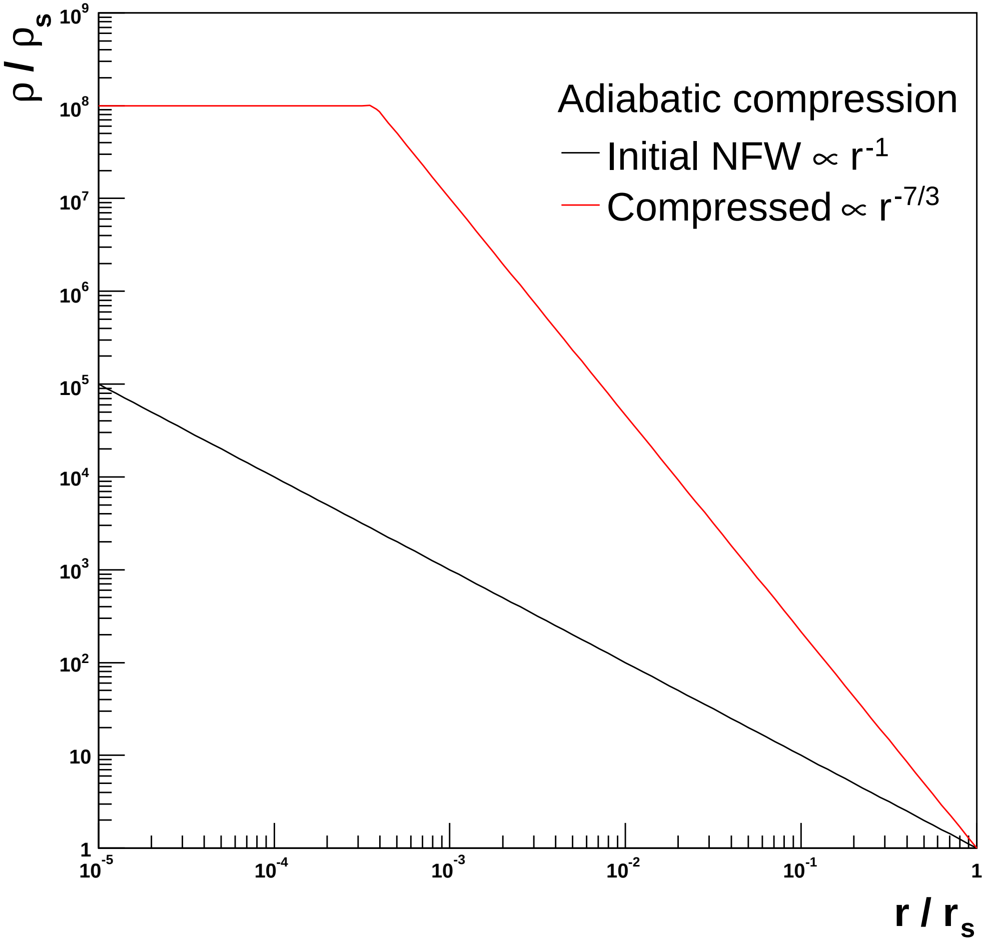
$$\boxed{\gamma_{in} \quad \longrightarrow \quad \gamma_{fin} = \frac{9-2\gamma_{in}}{4-\gamma_{in}}}$$

We define the **intrinsic effective volume**:

$$\xi_{bh} \equiv \int_{V_{dm}} d^3\vec{x} \left(\frac{\rho_{bh}}{\rho_0}\right)^2$$

such that the **intrinsic luminosity** is:

$$\begin{aligned} L_{bh} \quad &= \quad \{S = \frac{\delta < \sigma v >}{4\pi}\left(\frac{\rho_0}{m}\right)^2\} \times \xi_{bh} \\ &\propto \quad < \sigma v >^{2/7} \times m_\chi^{-9/7} \end{aligned}$$

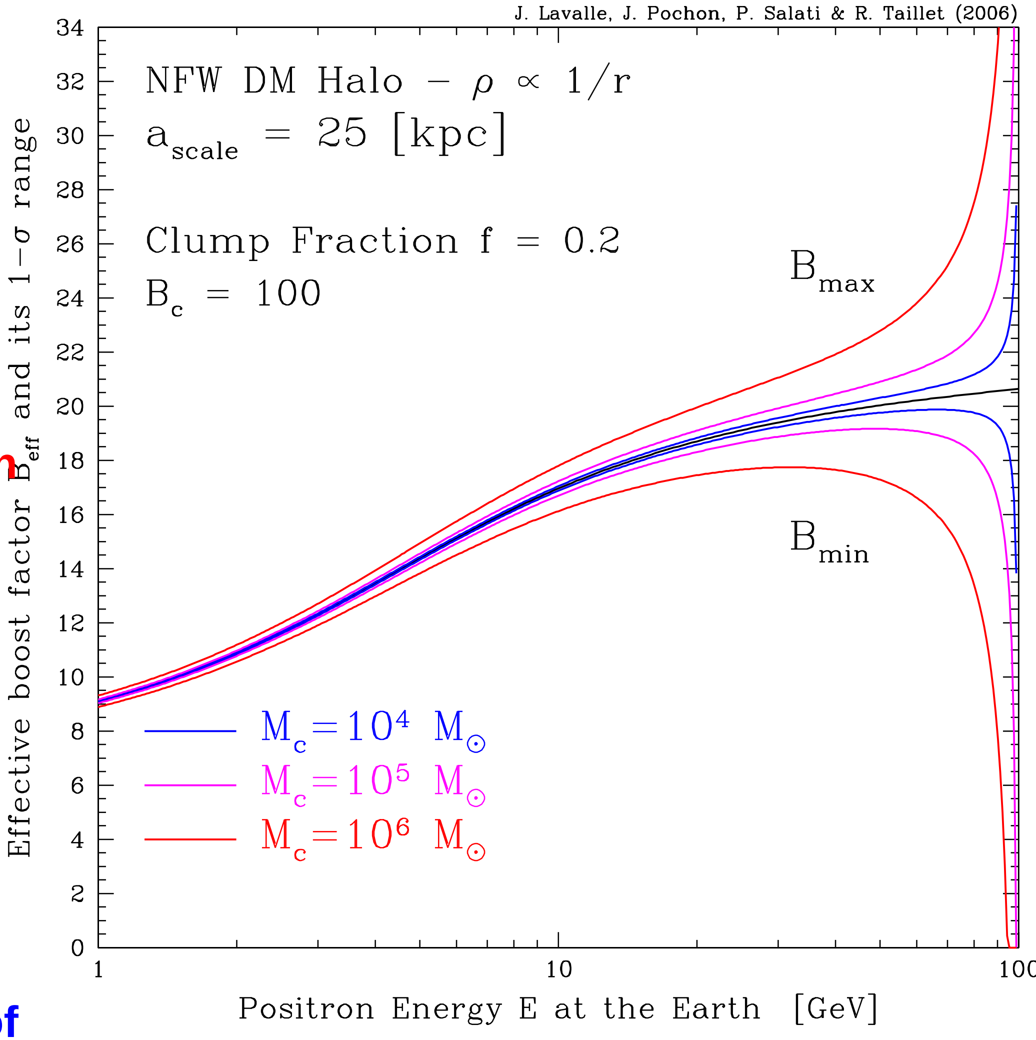


Many-object configuration → boost factors !!!

Boost factors for Antimatter CRs

Boost factor 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).
- **Precise properties and location of each object unknown** → **statistical uncertainties must be infered**
- Variance depends on the number of clumps within the volume bounded by propagation length λ_D: increases when the population when λ_D decreases ($\sim 1/\sqrt{N_{\rm eff}}$).
- **Need of full phase space distribution of objects**



Connecting primary fluxes to statistical properties

A general expression for the primary flux from a single clump is given by:

$$\phi_i(\vec{x}_\odot, E) = S \times \xi_i \times G_i(\vec{x}_i, E_S)$$

- 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)
  $\xi_i \equiv \int_{V_i} d^3\vec{x} \left(\frac{\rho_i(\vec{x})}{\rho_\odot}\right)^2$
- Propagation (CCRs) or dilution (γ-rays):

$$\begin{aligned} G_{i,\gamma}(E_\gamma) &\propto \frac{f(E_\gamma)}{|\vec{x} - \vec{x}_\odot|^2} \times P_V(\vec{x}_i) \\ G_{i,\mathrm{CR}}(E) &\propto \int dE_S \mathcal{G}(E, \vec{x}_\odot \leftarrow E_S, \vec{x}_i) \times \\ & \quad P_V(\vec{x}_i) \times f(E_S) \end{aligned}$$

In a many clump scenario, ϕ_i **is a stochastical variable** !
PDFs of ξ and G translate to the PDF of ϕ.

$$\begin{aligned} \frac{dP}{d\phi} &= \frac{dP_V}{dV} \times \frac{dP_\xi}{d\xi} \\ \phi_{\mathrm{tot}} &= N \times <\phi> = N \times <\xi> \times <G> \end{aligned}$$

The effective boost factor

The mean boost factor (averaged on the IMBH phase space distribution) reads:

$$\boxed{B_{eff}(E) \simeq 1 + < N_{\rm BH} > \times < \xi > \times \frac{J_1}{I_2}}$$

which is independant of M_{cl}, with :

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

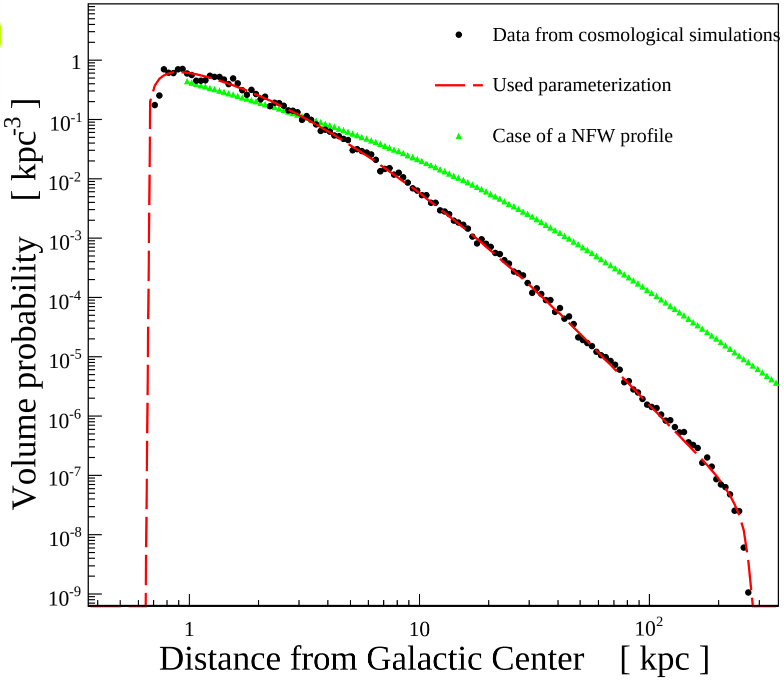
$$J_n \equiv \int_E^\infty dE_S \int_{slab} d^3\vec{x}_S \frac{dP_V}{dV}(\vec{x}_S) \times G^n(\vec{x}', E_S \rightarrow \vec{x}_\odot, E) Q(\vec{x}_S, E_S)$$

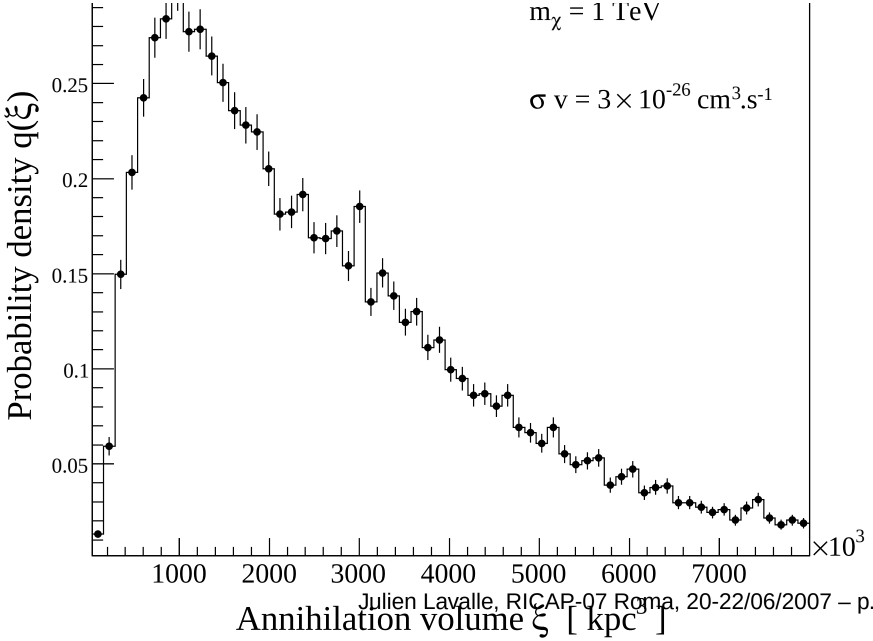
ENERGY-DEPENDENT AND NOT EQUAL TO THAT OF GAMMA-RAYS

The Bertone, Zentner and Silk model (astro-ph/0509565).....

Original idea in Zhao and Silk (astro-ph/0501625)

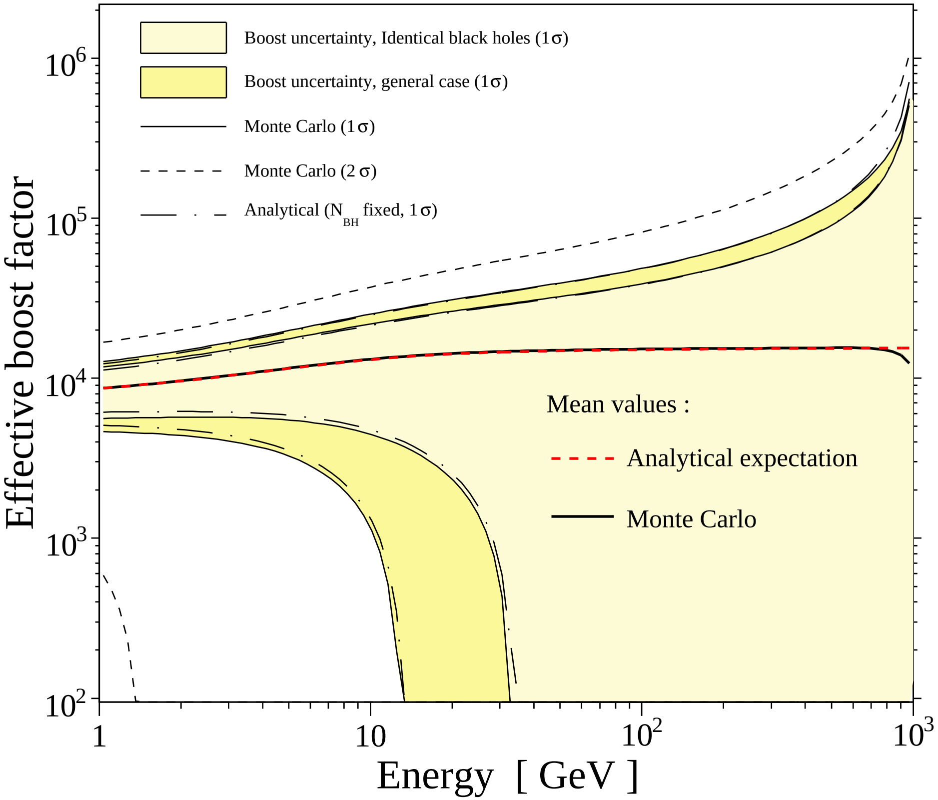
- Intermediate mass black holes (IMBHs) may populate the halo ($\sim$ 100 within the Galaxy)
- **Widely studied and optimistic for γ-rays and neutrinos (Bertone et al, 2005-2007)**
- Simulation results used to predict their space distribution and features (Koushiappas & Zentner, 2006)
- **What predicitons for antimatter CRs ?**
- In the following, we apply our recipe to this problem



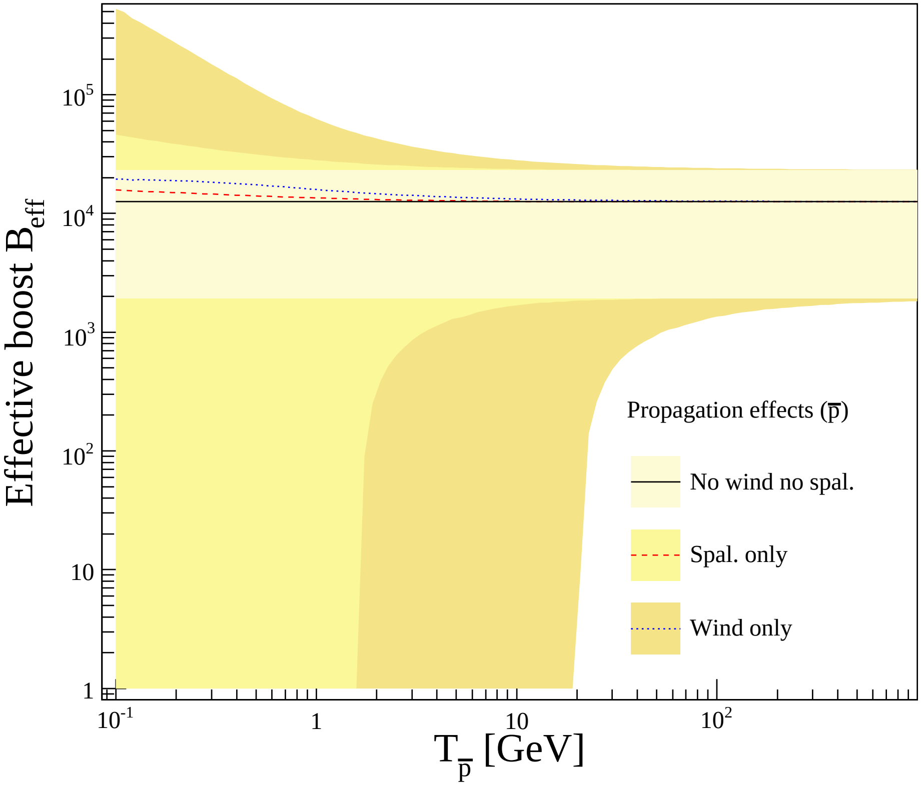


Boost factors for $e^+/\bar{p}$

Positrons (energy loss, diffusion)



Antiprotons (diffusion, wind, spallations)



WIMP models

SUPERSYMMETRY

- bino (140 GeV) ($\bar{b}b, \tau^+\tau^-$)
- higgsino (108 GeV) (W^+W^-, Z^0Z^0)

EXTRA-DIMENSIONS

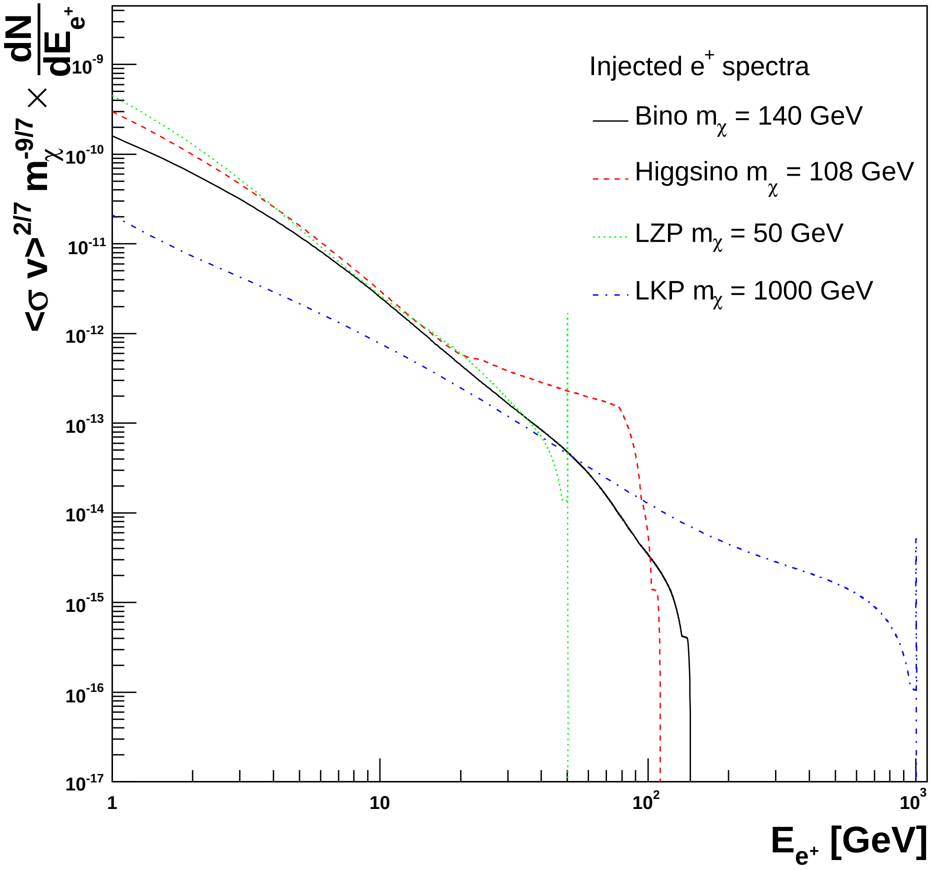
- LZP (50 GeV) ($\bar{q}q, \bar{\nu}\nu, l^+l^-$)
- LKP (1000 GeV) ($\bar{q}q, l^+l^-, \bar{\nu}\nu$)

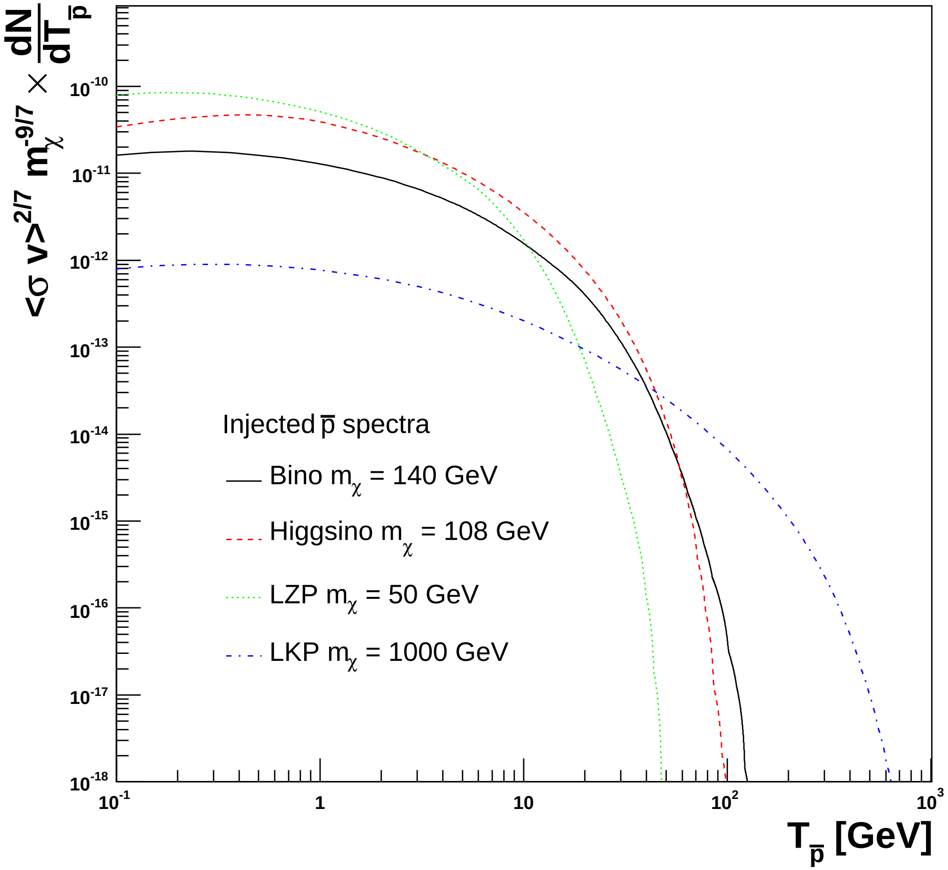
Injected spectra × annihilation rates

Positrons

$$\propto <\sigma v>^{2/7} \times m_\chi^{-9/7}$$

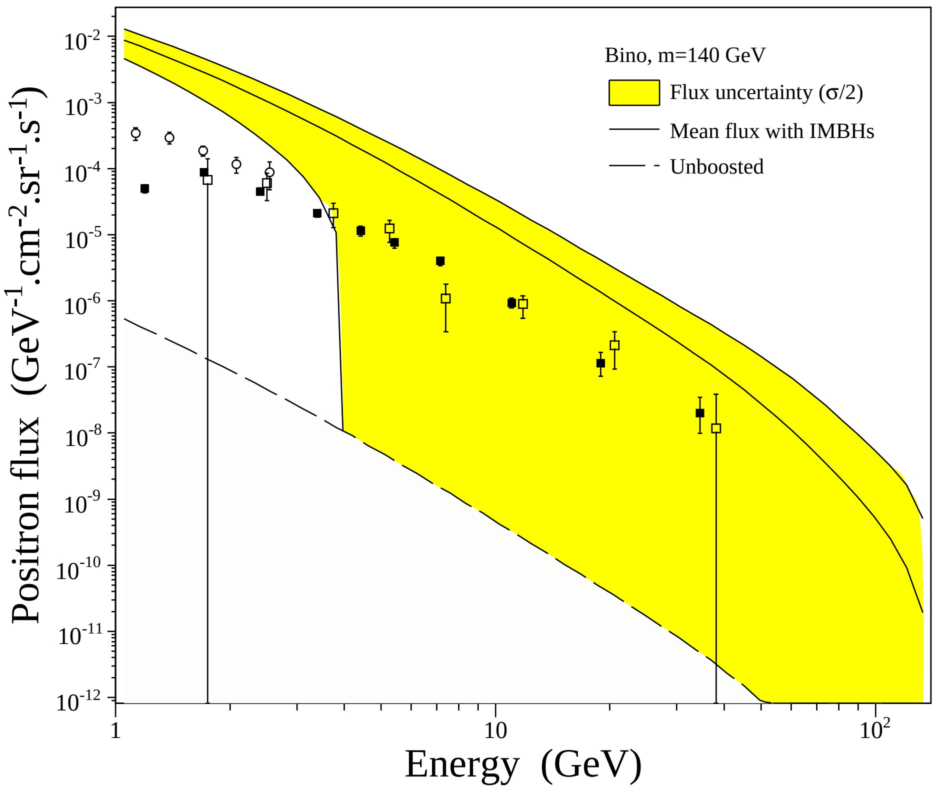
Antiprotons



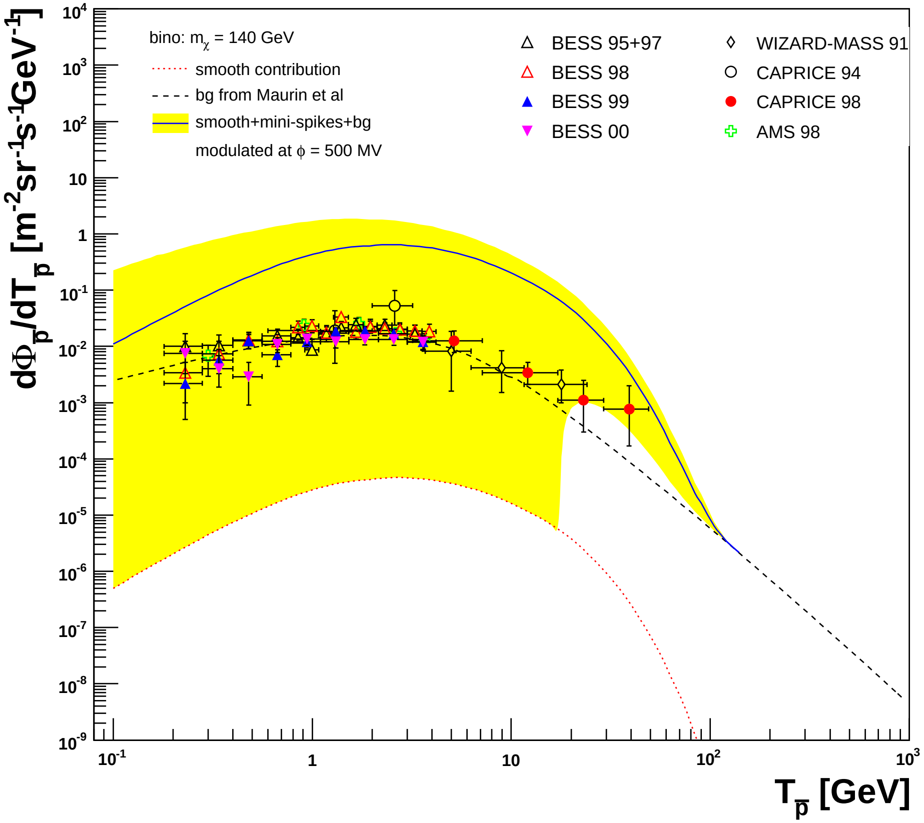


$e^+/\bar{p}$ ***fluxes for a 140 GeV bino-neutralino***

Positrons



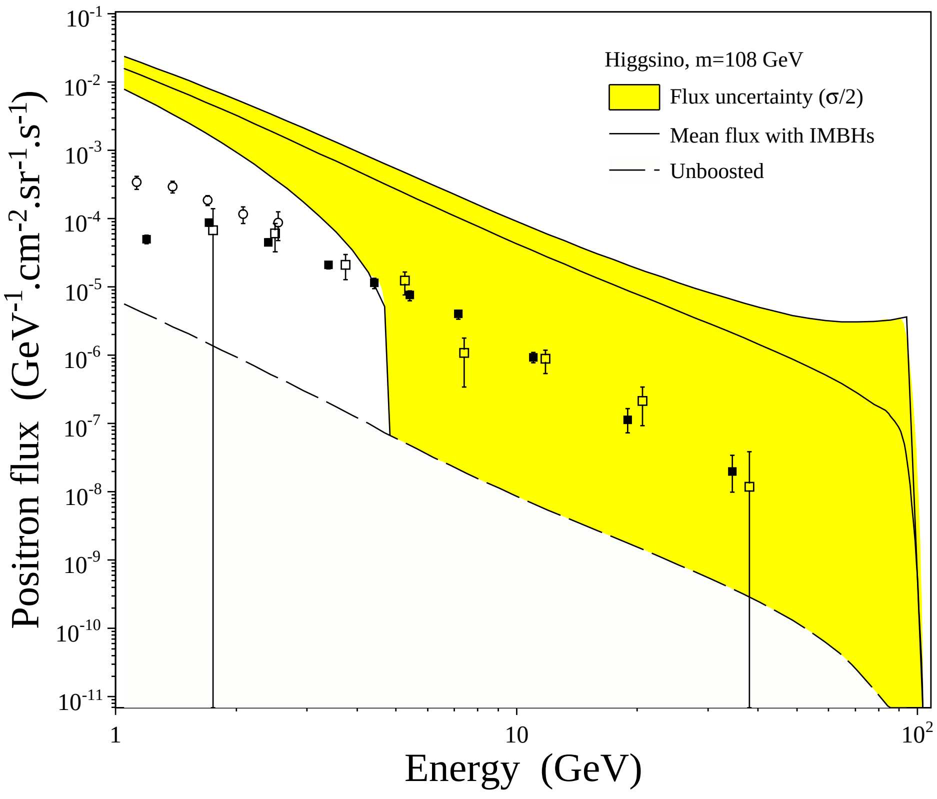
Antiprotons

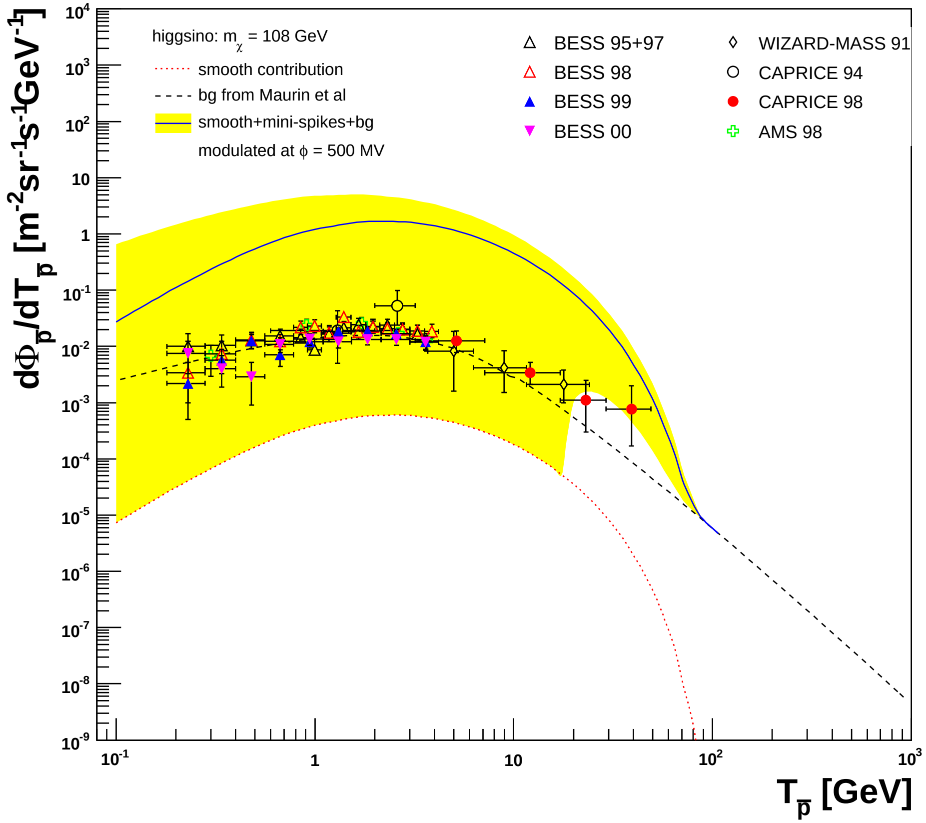


$e^+/\bar{p}$ ***fluxes for a 108 GeV higgsino-neutralino***

Positrons

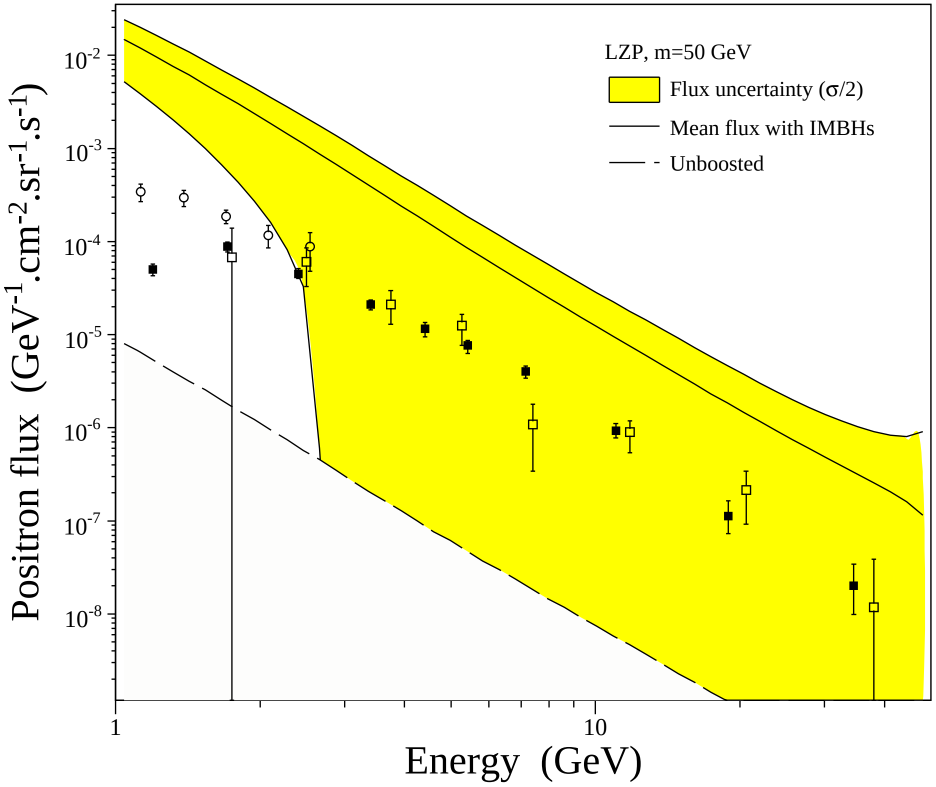
Antiprotons



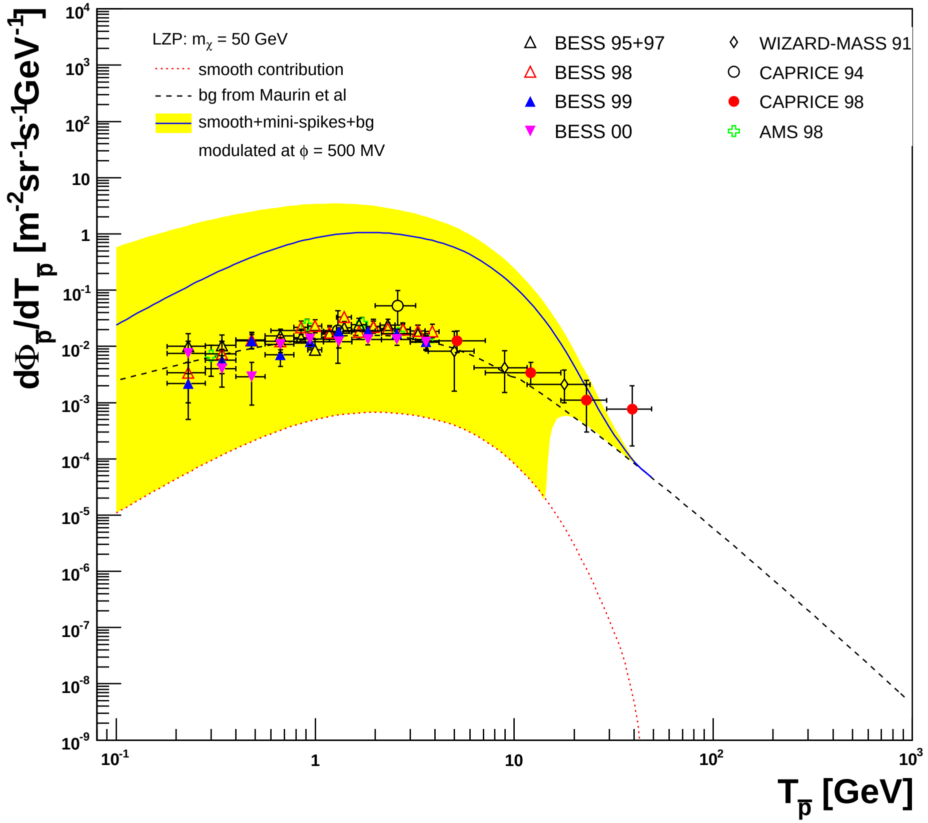


$e^+/\bar{p}$ ***fluxes for a 50 GeV LZP***

Positrons

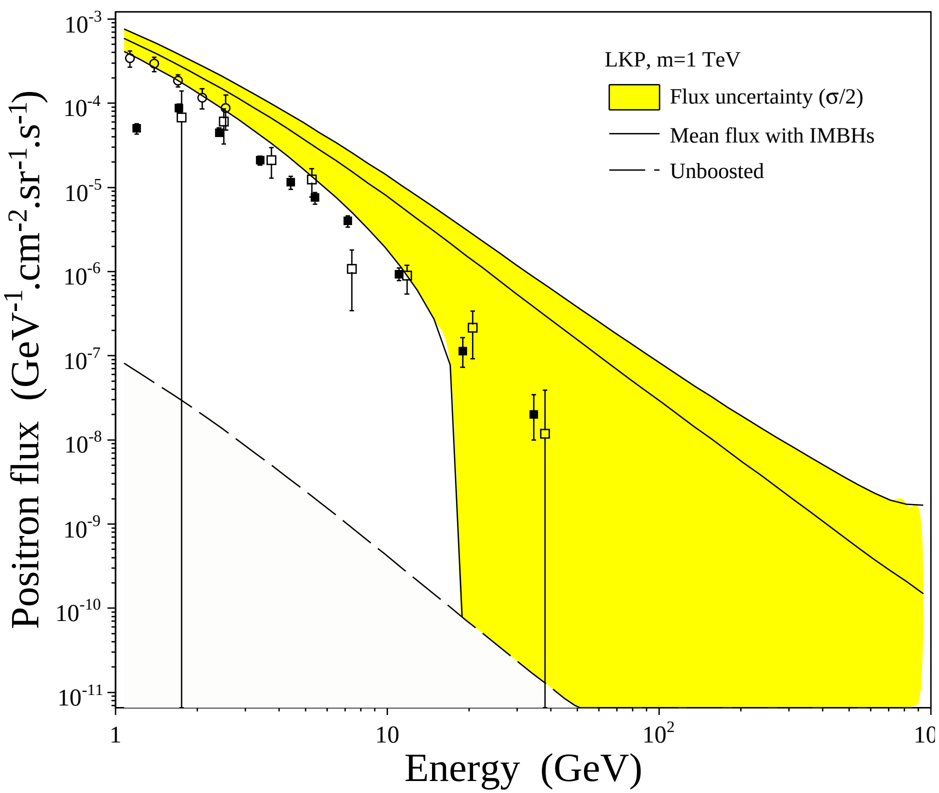


Antiprotons

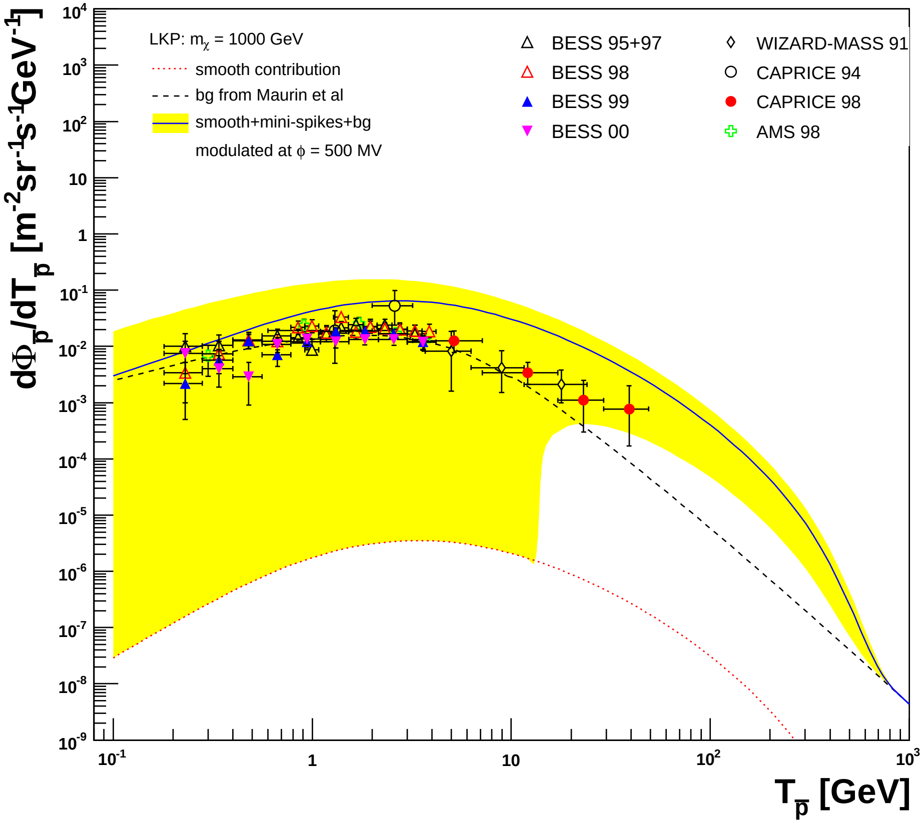


$e^+/\bar{p}$ fluxes for a 1 TeV LKP

Positrons



Antiprotons



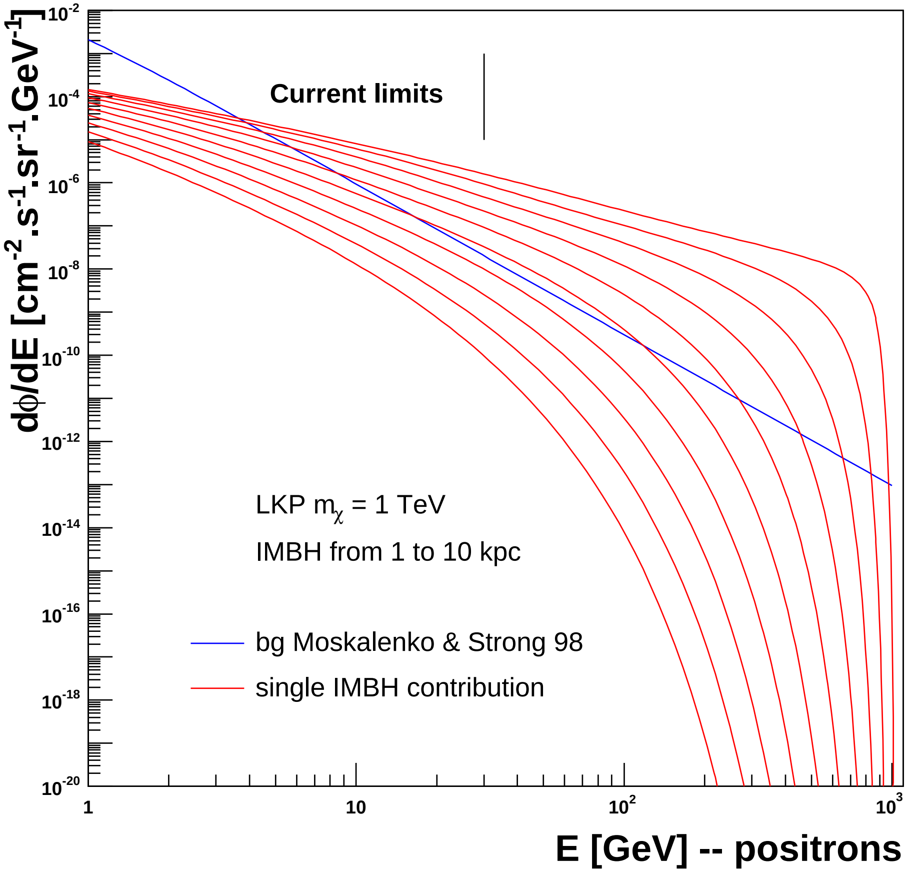
Relevant points

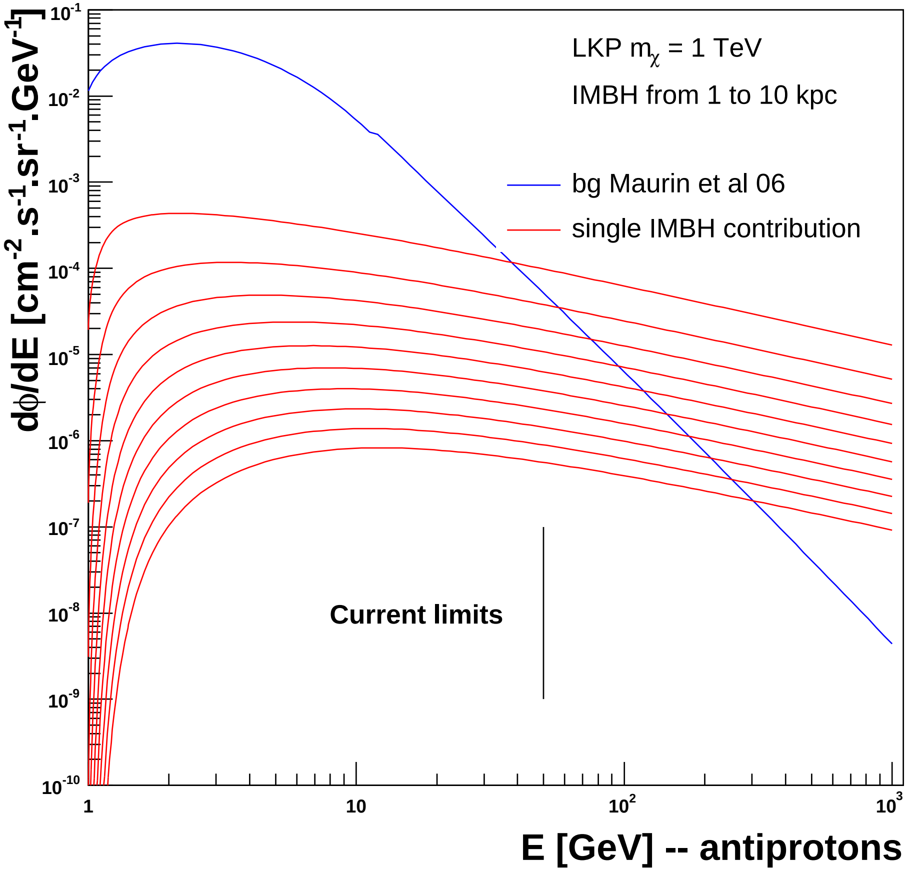
Keys for interpretation

- **Uncertainties due to propagation effects studied in Bringmann & Salati (2007)**
- **Low energy positron data sensitive to far away regions: integrate a large number of IMBHs (energy loss dominant)**
- **Low energy antiproton data sensitive to close regions: integrate a small number of IMBHs (no energy loss, but convective wind and spallations at low energy)**
- **Low energy positron data seem to disfavour any candidate but – heavy – LKPs. Not statistically significant ($\lesssim 1\sigma$) effect).**
- **LKPs affect the high energy antiproton spectrum (no data at the moment)**
- **...The closest IMBH contribution dominates over the others !**

How far the closest IMBH ?

For a single IMBH with $\xi = <\xi> \sim 10^6$ kpc^3 located close to the GC plane.





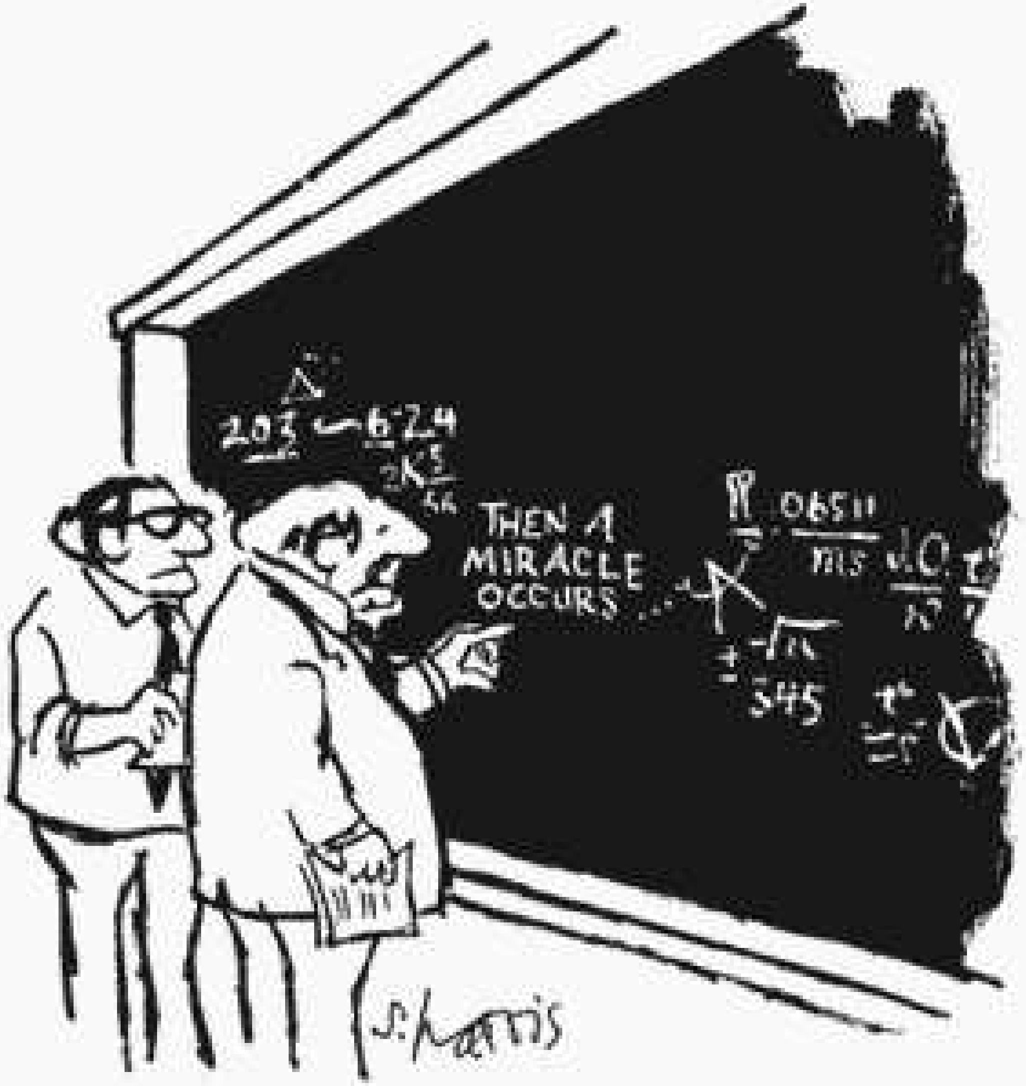
Compare with background expectations (close to data)

Minimal distance fixed by positron data constraints

Summary and conclusion

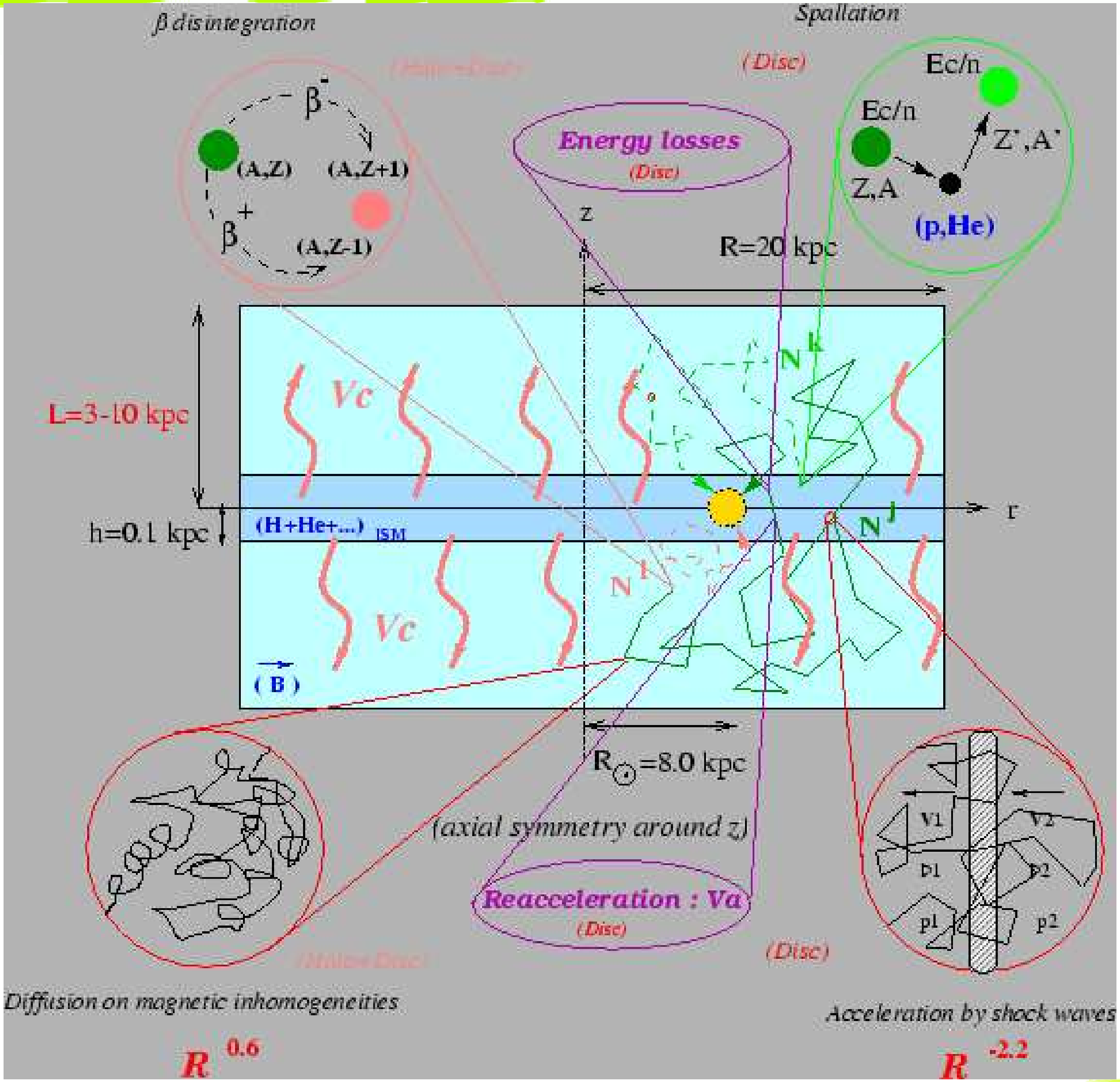
- We explicitely determined how to correctly semi-analitically predict cosmic ray fluxes and errors given inhomogeneity properties
- Antimatter CRs give strong constraints on closest objects, especially positrons
- Higher energy measurements will provide unique tests of validity of the IMBH DM scenario (mainly antiprotons)
- WARNING: better understanding and predictions of backgrounds mandatory (secondaries/primaries)
- PAMELA and future AMS-02 are very powerful in order to kill/discover models of inhomogeneously annihilating DM in the Galaxy
- Complementarity with γ-rays and neutrinos mandatory to check consistency
- We are impatient to know more ...

Backup



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Cosmic ray propagation: The slab picture



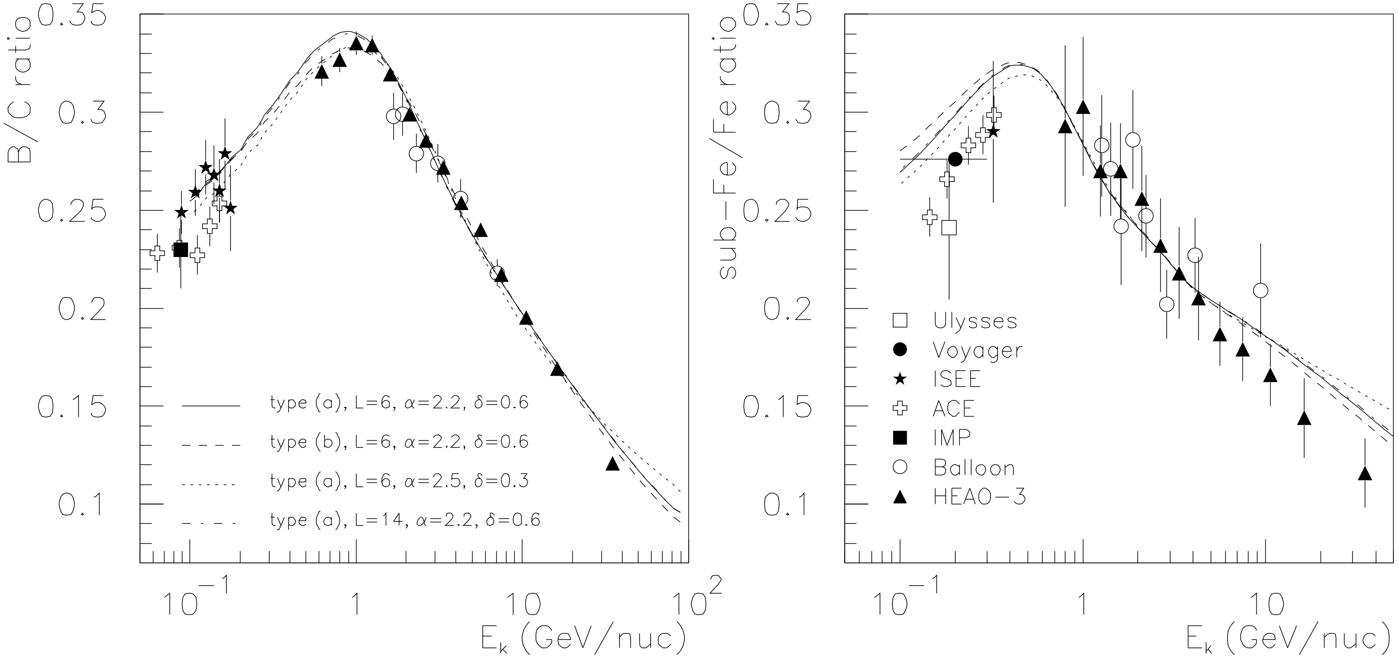
- Diffusive cylindrical halo : $R \sim 20\mathrm{kpc}, \mathrm{L} \sim 3\mathrm{kpc}$ spallation on ISM and diffusion on magnetic inhomogeneities
- Disc ($h \sim 0.1\mathrm{kpc}$) : convection and reacceleration in addition
- Propagation model free parameters: $K(E), L, R, V_C, V_A$

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

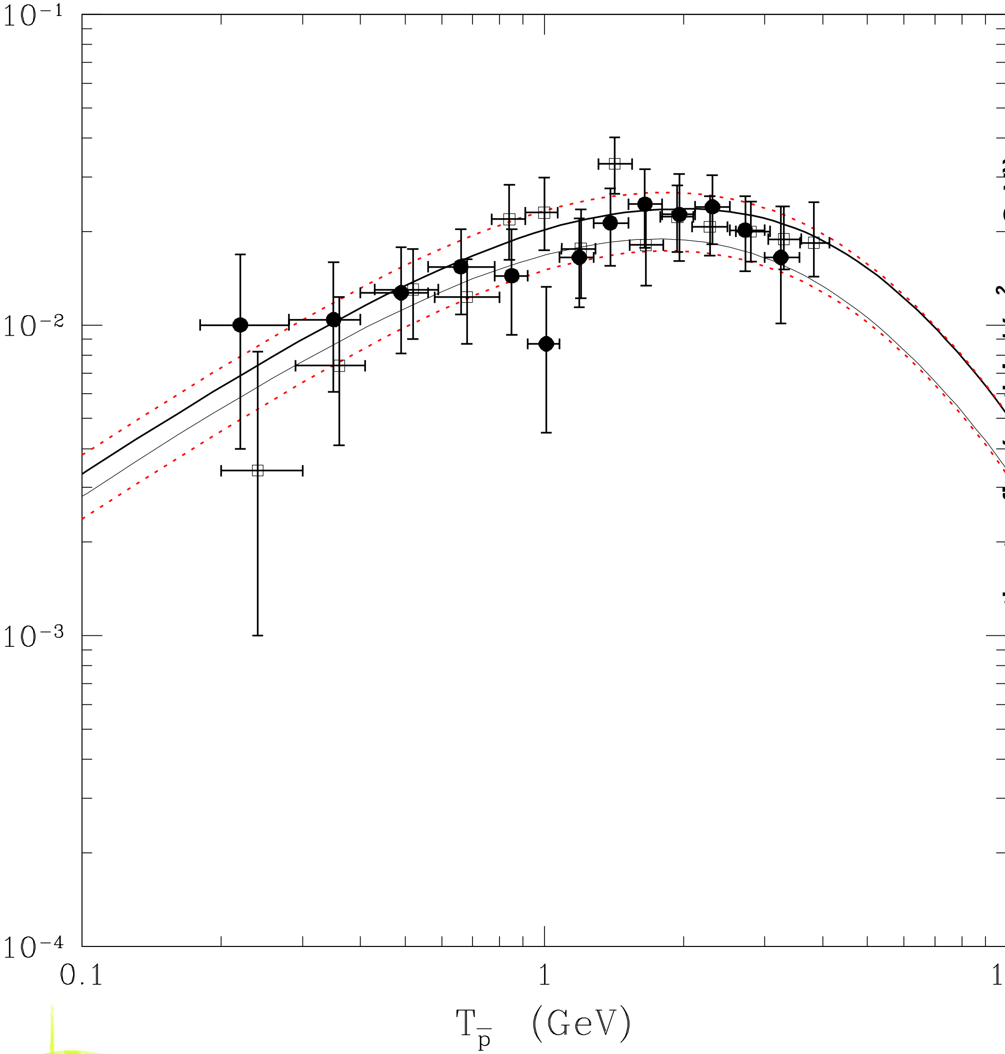
Cosmic ray diffusion: Constraints

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

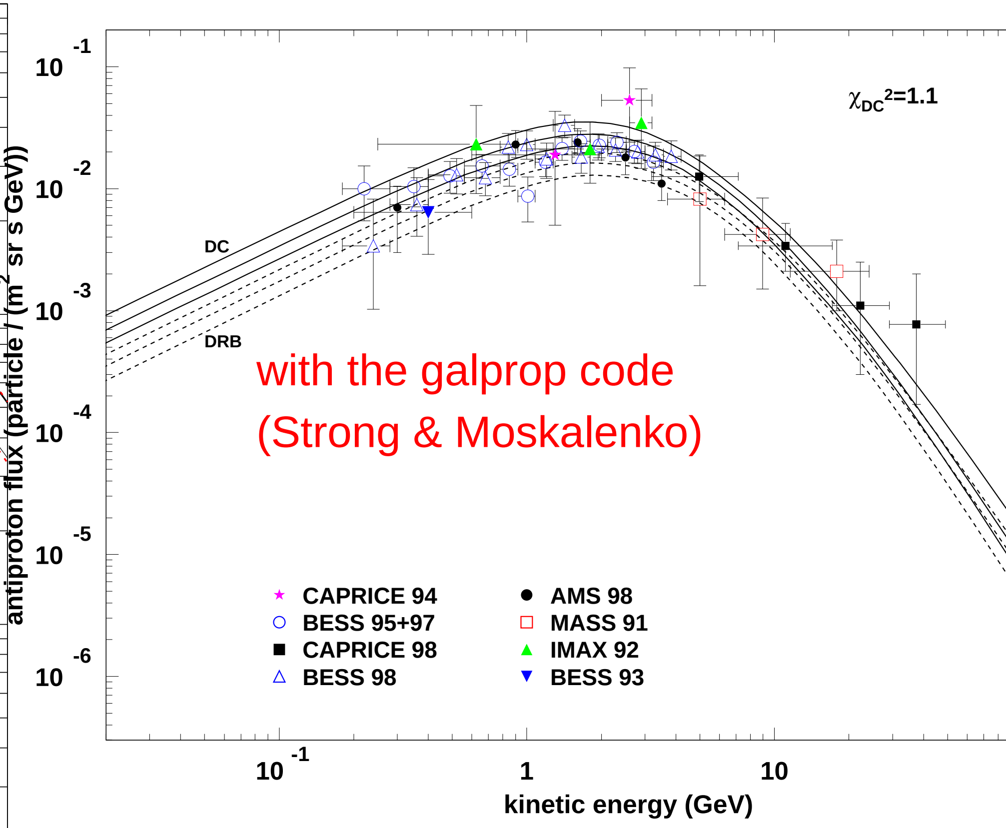
Maurin, Taillet et al., 2002



Example : Systematics for secondary antiprotons



Maurin, Taillet et al., 2002



Lionetto et al., 2005

with the galprop code (Strong & Moskalenko)

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

The diffusion equation for a positron density dn/dE:

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

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

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

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

$$\mathcal{G}_{\odot}^{\bar{p}}(r,z) \quad = \quad \frac{\exp^{-k_v z}}{2\pi K L} \times \qquad (1)$$

$$\sum_{n=0}^{\infty} c_n^{-1} K_0(r\sqrt{k_n^2 + k_v^2}) \sin[k_n L] \, \sin[k_n (L-z)]$$

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

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

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

Where does a e^+ of 200 GeV come from ? ($\rho \propto r^{-1}$)

Simplest view of propagation

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

with $\lambda_D = \sqrt{4K_0\Delta\tilde{t}}$

($\Delta\tilde{t} = f(E_S, E)$ decreases as $E \to E_S$)

→ **Detection volume scaling a**
sphere of radius λ_D

Figures:

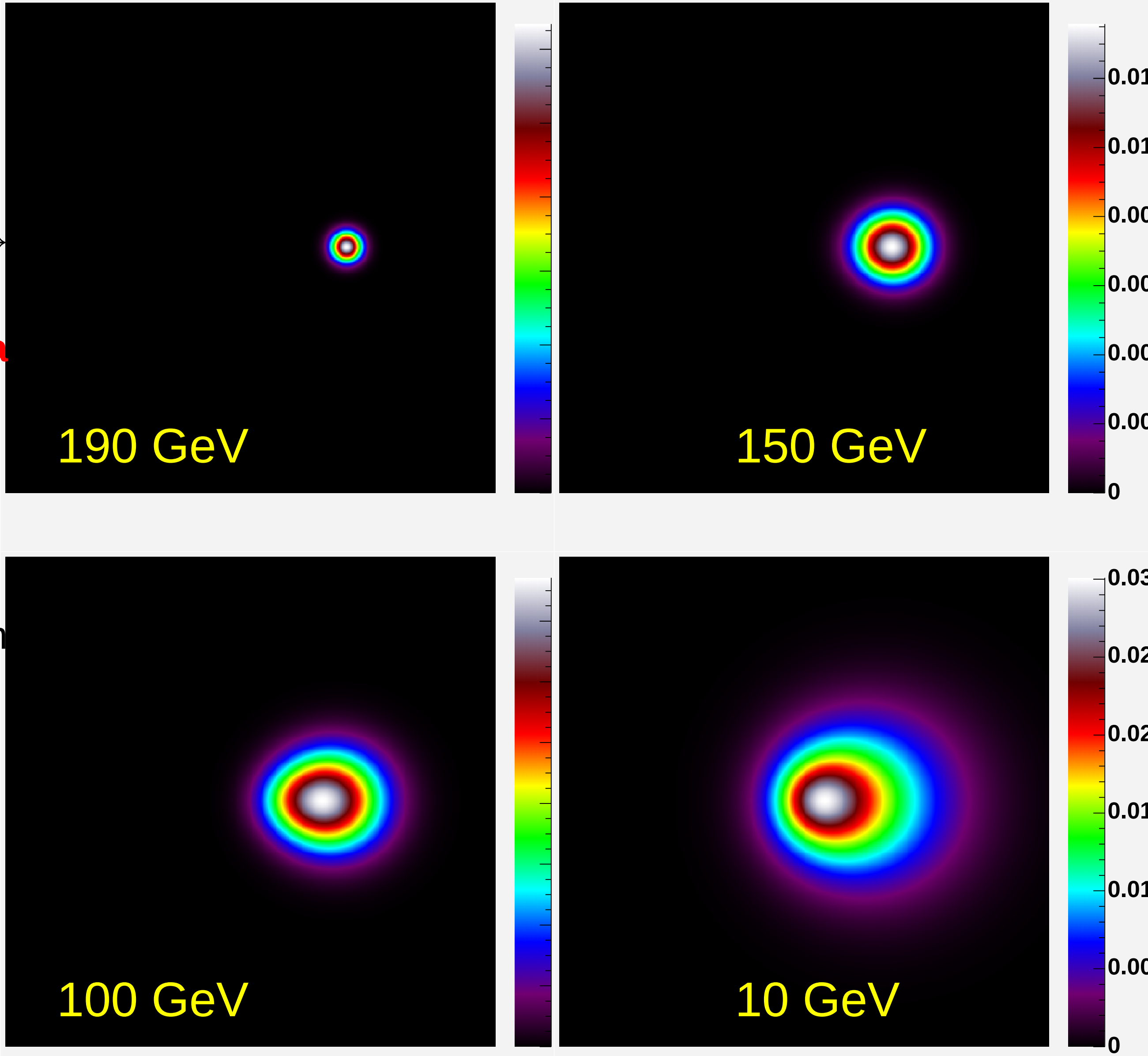
galactic plane at z=0 kpc

square side of 40 kpc (x and y from
-20 to 20)

Earth located at ($x = 8, y = 0$) kpc

2D plots of

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



Probability distribution function for boost (e^+)

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