Propagation of cosmic rays

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T. Delahaye, A. Putze, L. Derome, N. Fornengo...

Three points:

- Physics of propagation
- Indirect detection through antimatter
- Clumps/boost factors

Context

dark matter particles can annihilate and create other particles
→ indirect detection

neutral : neutrinos and gamma-rays
charged : electrons, positrons, protons, antiprotons

e.g.

$$\chi + \chi \rightarrow \bar{p} + X$$

To be able to perform indirect detection, one must be able to tell the signal from the background.

$$p + p \rightarrow \bar{p} + X$$

Antimatter particles have a lower background and should be easier to detect in cosmic rays.

Context

In the context of Dark Matter indirect detection, three main uncertainties :

- existence/properties of the dark matter particle ?
- distribution in space and in velocity space ?
- propagation of the annihilation products

Propagation is important for two reasons :

- to predict the signal (antiprotons, positrons from DM annihilation)
- to understand the background (primaries + secondaries from spallation)

The two studies must be done in a consistent way !

- same propagation model with same physical effects
- same parameters

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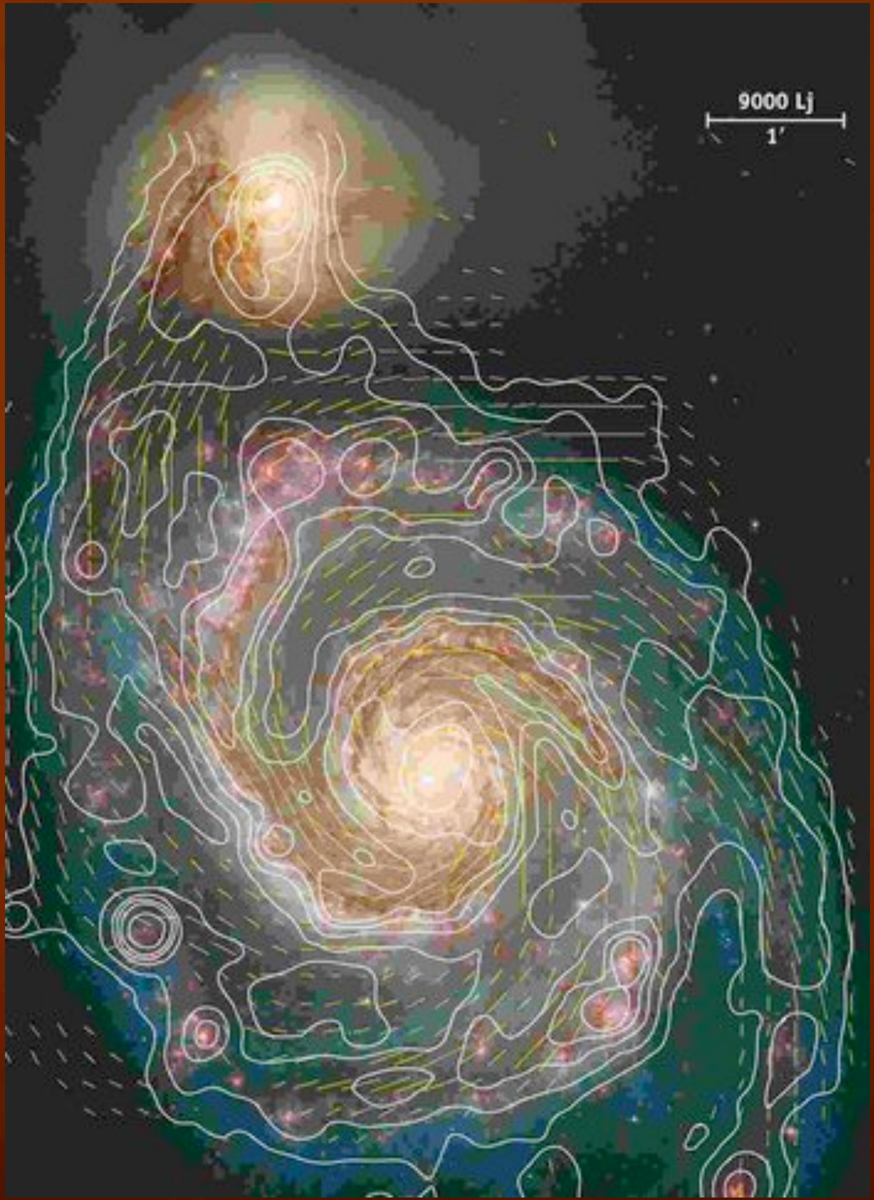
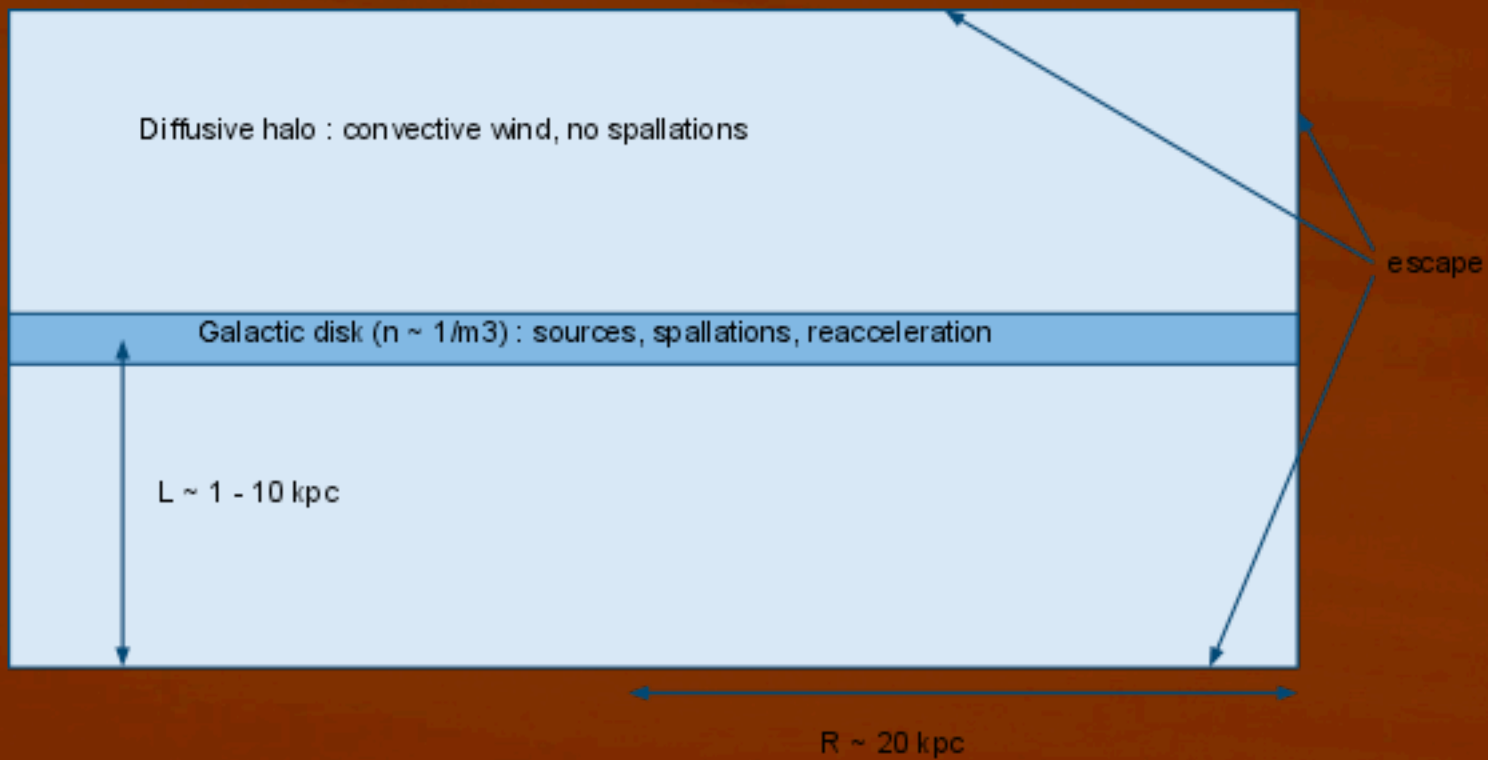
Propagation of charged particles (positrons, antiprotons) is determined by the structure of the Galactic magnetic field.

Regular component + stochastic component, probably associated with turbulence

→ fluctuations of the magnetic field on every scale
→ energy-dependent **diffusion** : diffusion is more efficient at high energy

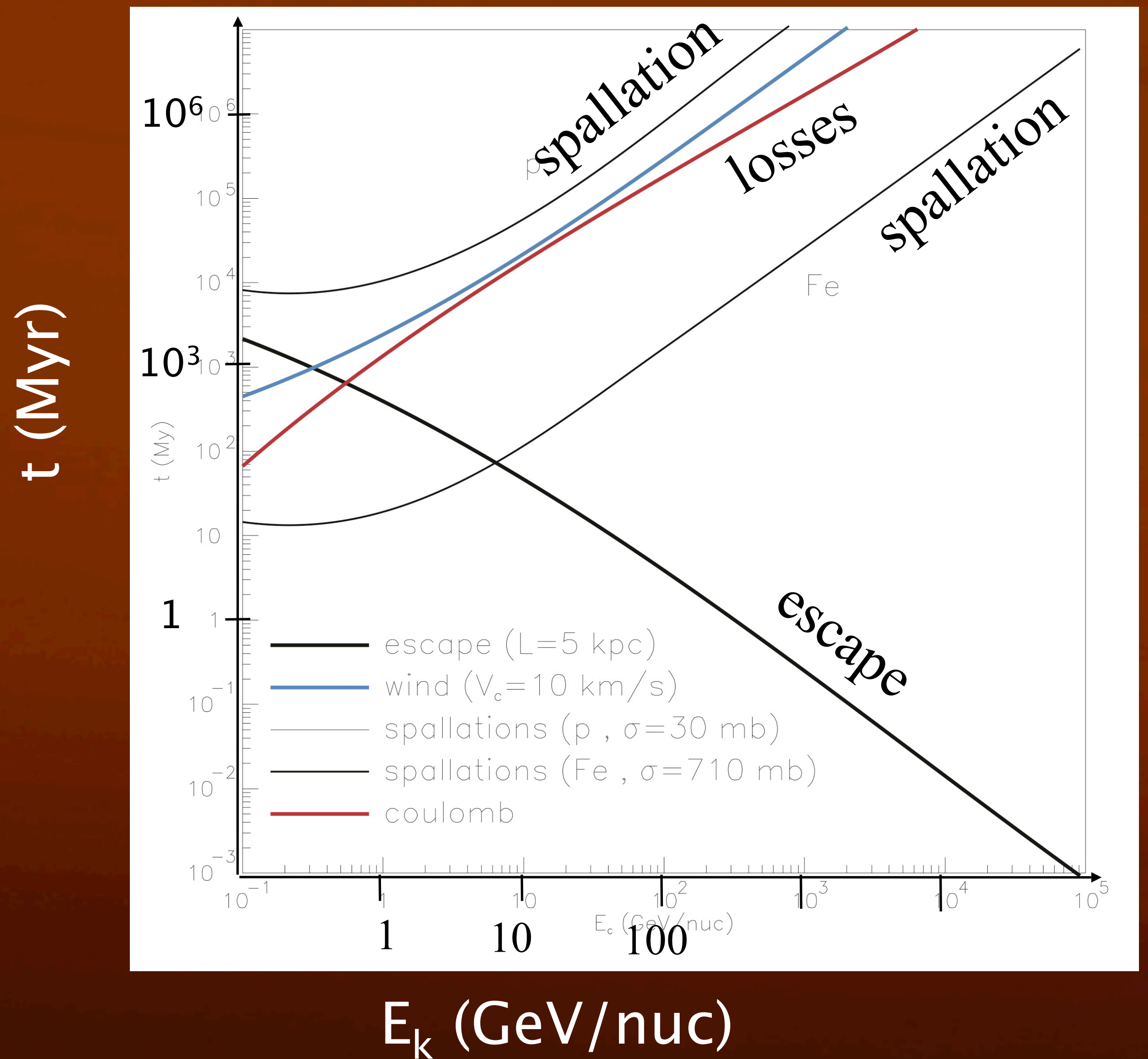




solve a diffusion equation, taking into account:

- diffusion (diffusion coefficient ? anisotropic ? inhomogeneous ?)
- escape (boundary conditions, geometry of diffusion volume)
- spallations (creation/destruction, cross-sections, interstellar medium)
- Sources (distribution, spectra)
- energy losses
- diffusive reaccerelation
- galactic wind (convection)
- inelastic non annihilating reactions (for antiprotons)

caracteristic times



Propagation

Different approaches to model propagation:

Leaky Box : escape time, distribution of grammages

Diffusion equation :

- numerical resolution (GALPROP, Strong & Moskalenko)
- semi-analytical resolution (USINE, Maurin et al.)

$$\frac{\partial N}{\partial t} - \vec{\nabla}\left[D\vec{\nabla}N - \vec{V}_c N\right] - \frac{\vec{\nabla}\cdot\vec{V}_c}{3}\frac{\partial}{\partial E}\left(\frac{p^2 N}{E}\right) = \frac{\partial}{\partial E}\left[-\frac{1+\beta^2}{E}K_{pp}N + \beta^2 K_{pp}\frac{\partial N}{\partial E}\right] + Q(E)$$

Note : USINE will be publicly released within a few months

Diffusion parameters

Diffusion coefficient

$$D = D_0 \beta \left(\frac{\mathcal{R}}{1\ \mathrm{GV}} \right)^{\delta}$$

Height of diffusive halo

$$L$$

Alfvèn velocity (reacc.)

$$V_a$$

Gal. wind velocity (convection)

$$V_c$$

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Related to the kind of magnetic turbulence : no consensus

Diffusion parameters

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Height of diffusive halo

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Alfvèn velocity (reacc.)

$$V_a$$

Gal. wind velocity (convection)

$$V_c$$

Related to the amplitude of turbulence

Diffusion parameters

Diffusion coefficient

$$D = D_0 \beta \left(\frac{\mathcal{R}}{1\ \mathrm{GV}} \right)^{\delta}$$

Height of diffusive halo L

Alfvèn velocity (reacceleration) V_a

Galactic wind velocity (convection) V_c

Mean grammage is determined by L/D $\langle x \rangle \sim \Sigma \frac{vL}{D}$ ~ 10 g cm^{-2}

$$\Sigma \sim 10^{-3}\,\mathrm{g} \cdot \mathrm{cm}^{-2}$$

If the galactic disk was flattened, it would look like a sheet of usual paper, crossed about 10 000 times by every cosmic ray nucleus

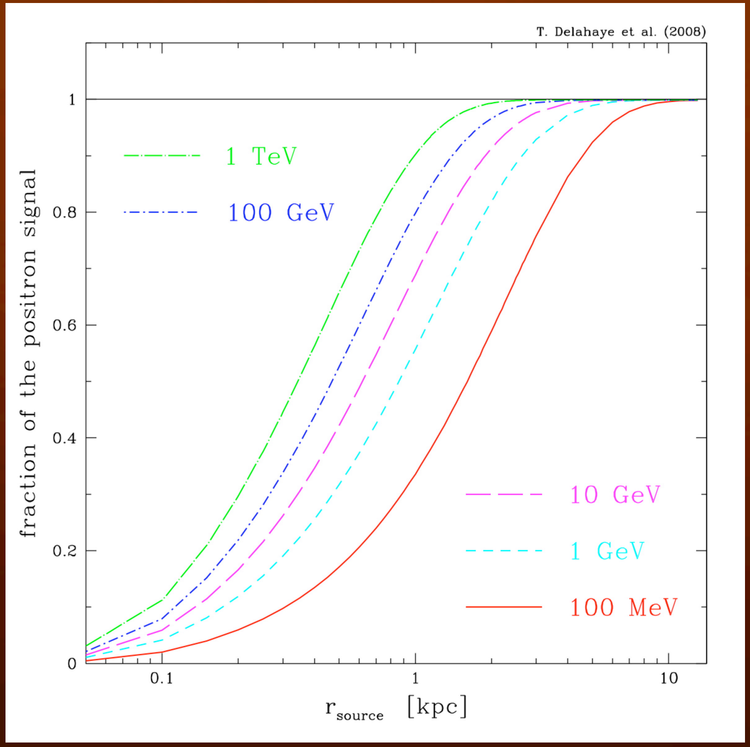
Mean grammage is determined by L/D

$$\langle x \rangle \sim \Sigma \frac{vL}{D}$$ ~ 10 g cm^{-2}

$$\Sigma \sim 10^{-3}\,\mathrm{g} \cdot \mathrm{cm}^{-2}$$

General facts about propagation

- The range of propagation is limited by escape, spallation and decay
- Propagation of nuclei and antiprotons can be studied at a given energy per nucleon, as a first approximation
- Propagation of positrons is dominated by energy losses



Propagation

The propagation parameters can be determined (or at least constrained) by the study of cosmic ray nuclei:

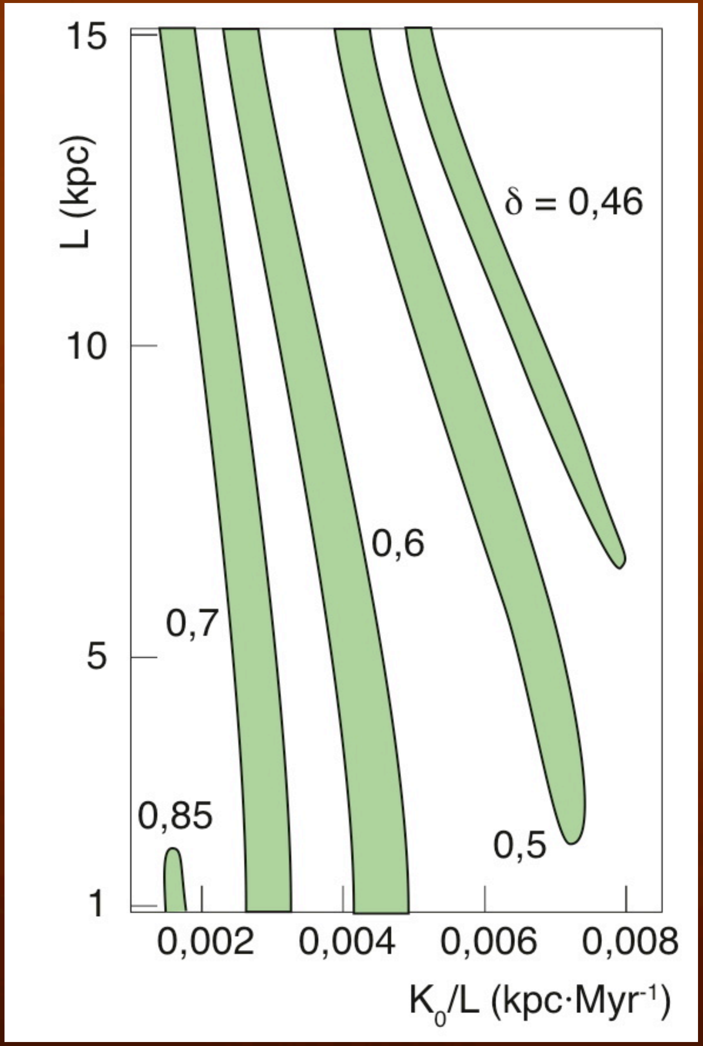
For a given set of parameters,

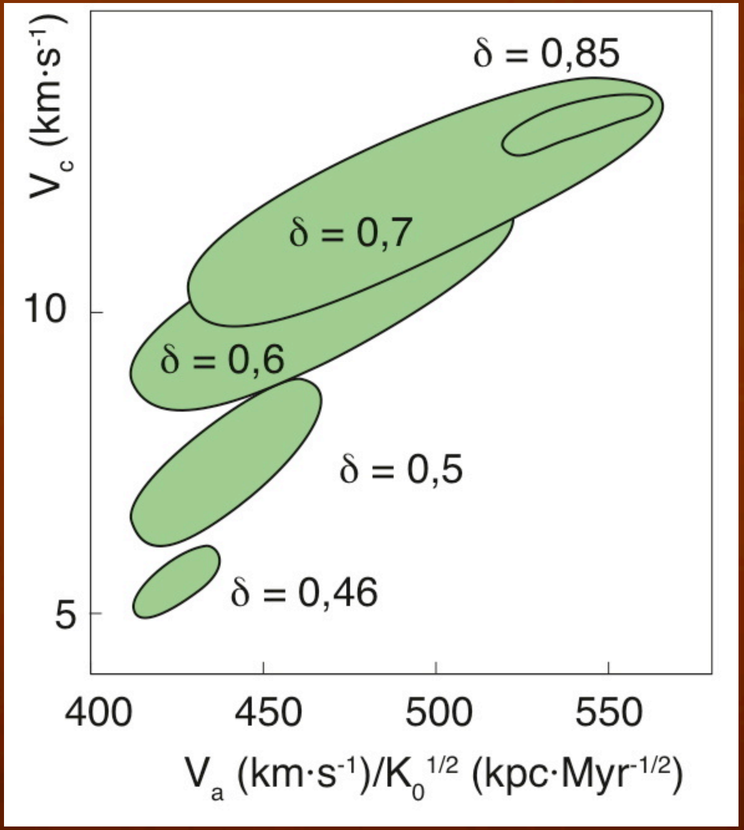
- compute B/C
- compare to data
- keep if good

Astrophysical uncertainties (assuming the model is correct):

- distribution of sources
- distribution of interstellar matter
- energy losses (Lavalle & Delahaye 2010)
- nuclear cross-sections

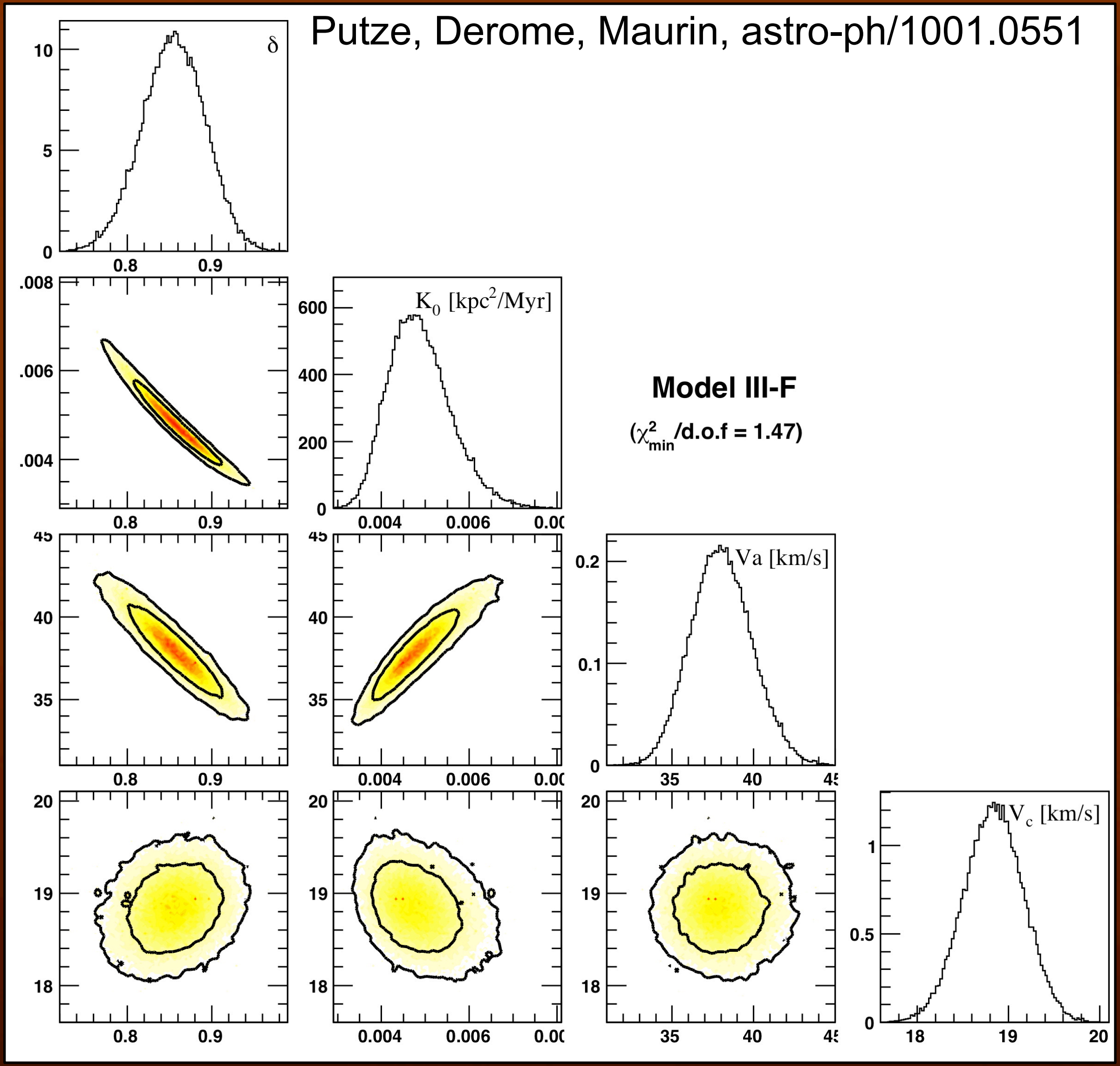
Results from a systematic exploration of the parameter space, using B/C





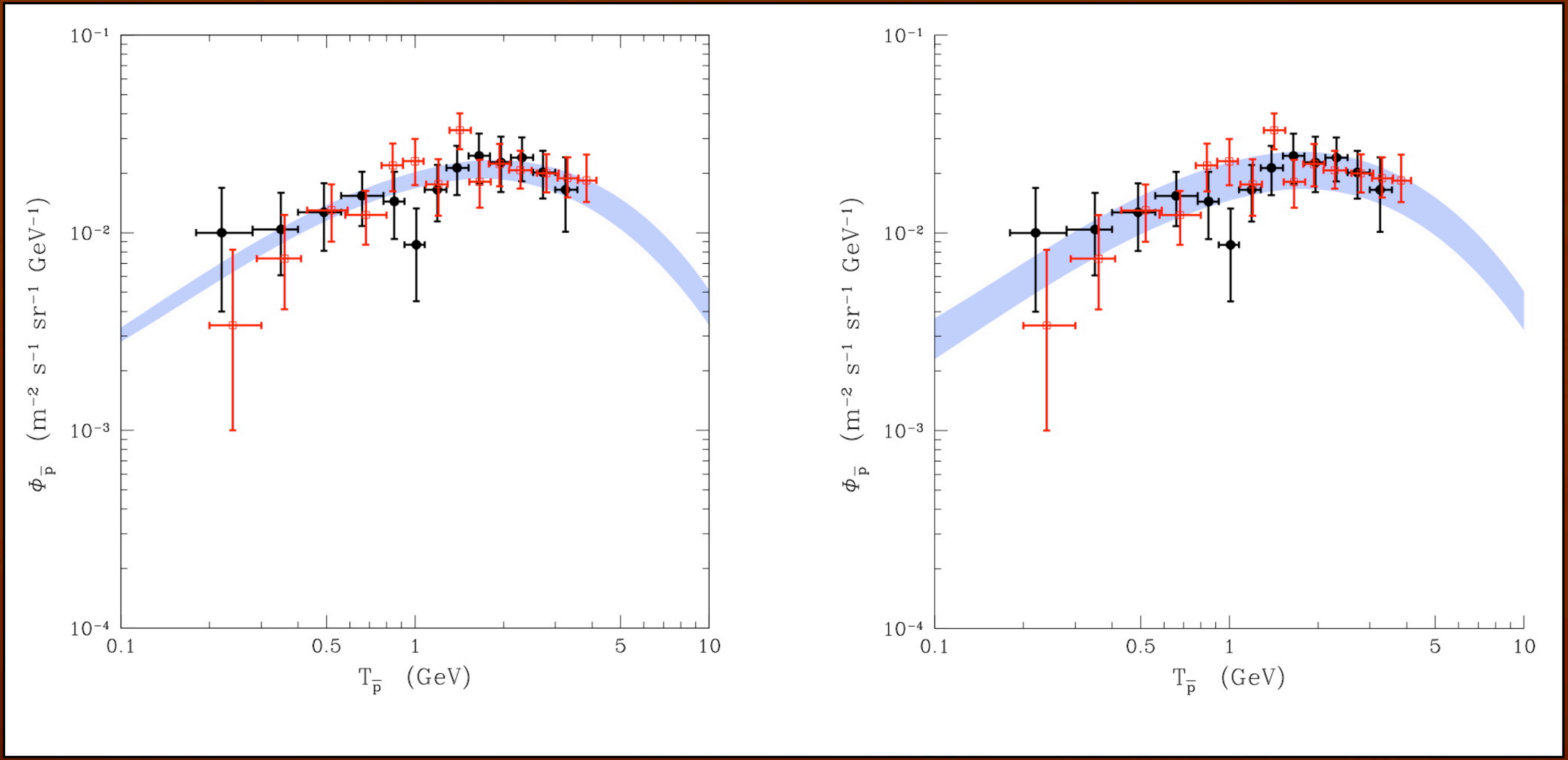
Maurin et al. 2001

Results from a Monte Carlo Markov Chain analysis (MCMC)



Putze et al. 2010

Results for secondary antiprotons (background)

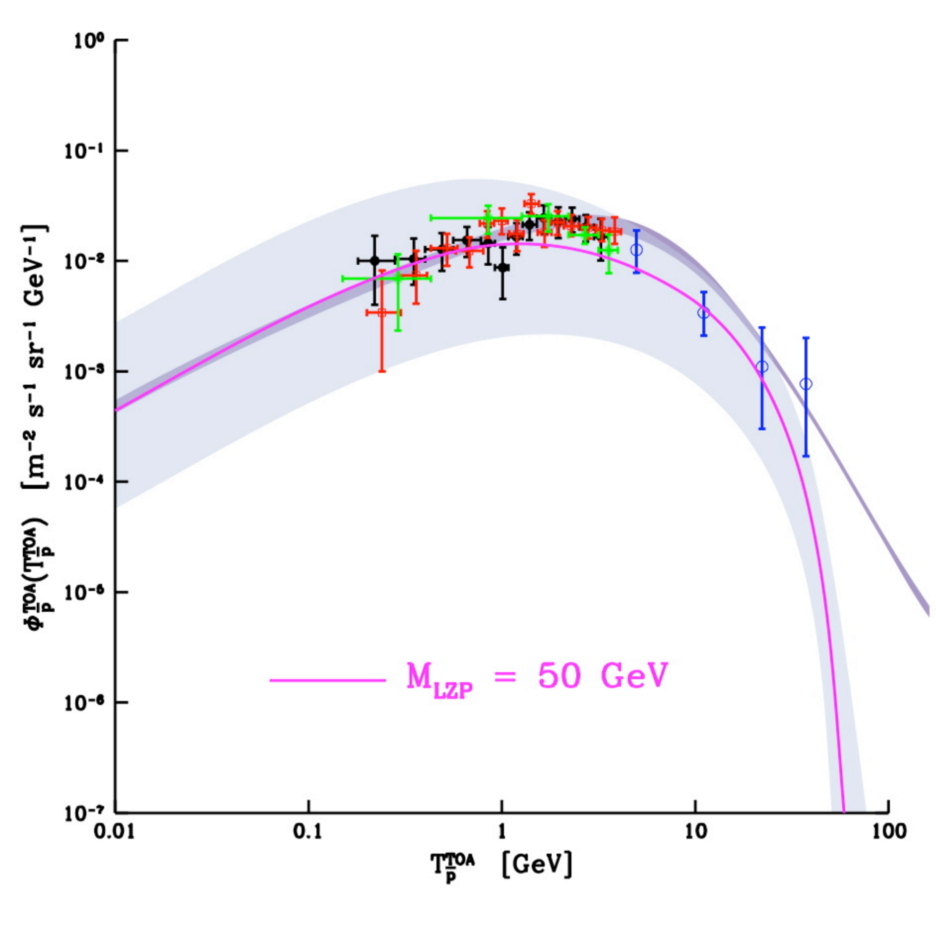


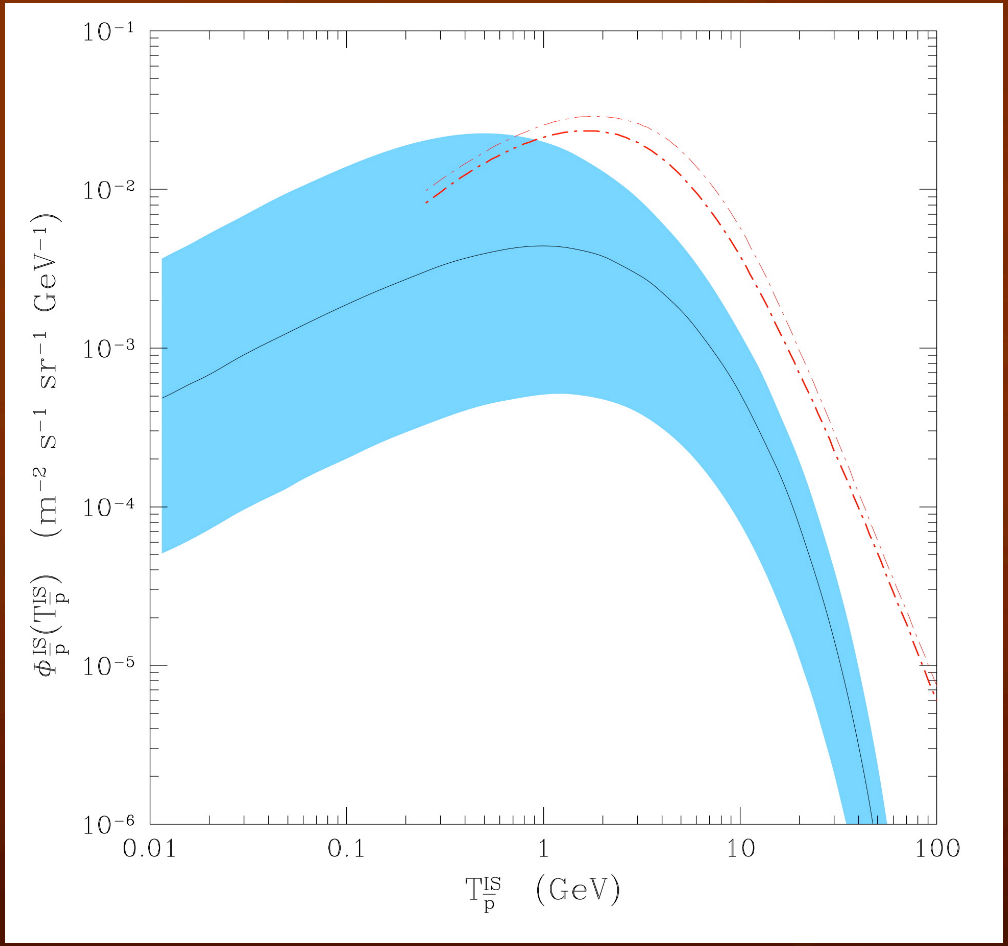
Uncertainty on the parameterizations of nuclear cross sections (but proton flux rather well measured)

Examples of results for antiprotons from exotic sources

Kaluza-Klein, m = 50 GeV/c^2

neutralino m = 300 GeV/c^2





Donato et al. 2004

Very sensitive to L, for two reasons: if L si higher,

- Confinement is more efficient
- More sources in the diffusive halo

Created through decay of pions produced in p-p collisions

Propagation dominated by energy losses (synchrotron & inverse Compton upon CMB/starlight)

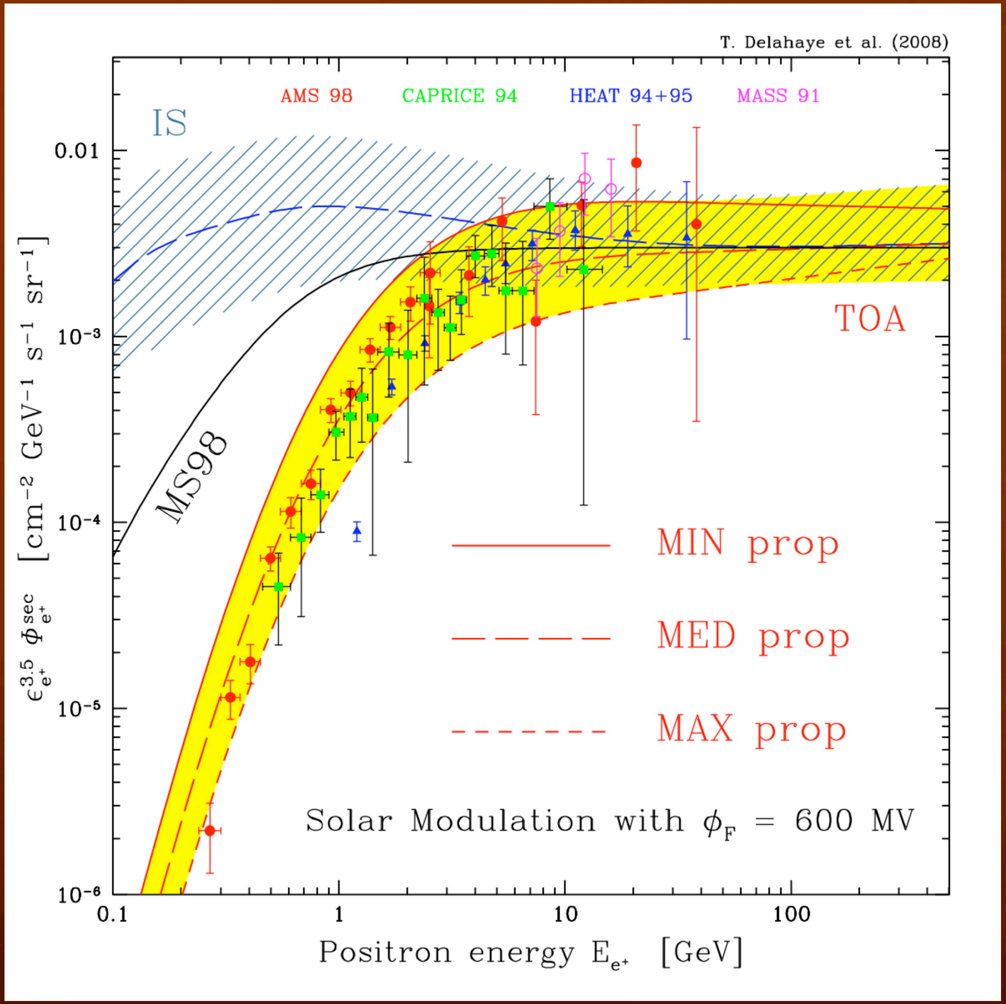
$$\boxed{\frac{dE}{dt} = -\frac{1}{\tau_{\rm loss}} \times \frac{E^2}{E_0}}$$

$$\boxed{\hat{\tau}_{\rm loss} \sim 10^{16}\,\mathrm{s}}$$

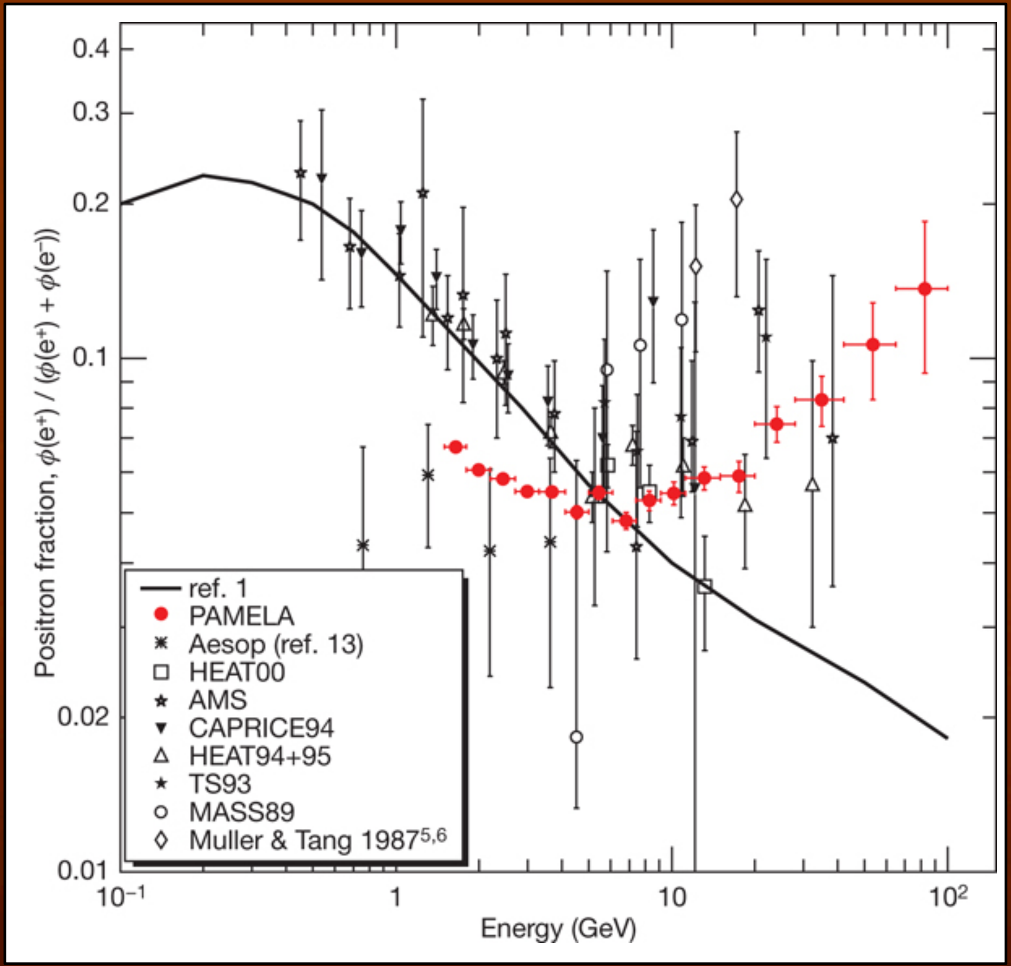
$$\boxed{\hat{\tau} \equiv \tau_{\rm loss} \times \frac{E^{\delta-1}}{1-\delta}}$$

$$\boxed{\ell \sim \sqrt{D_0 \hat{\tau}}}$$

Example of results for secondary positrons

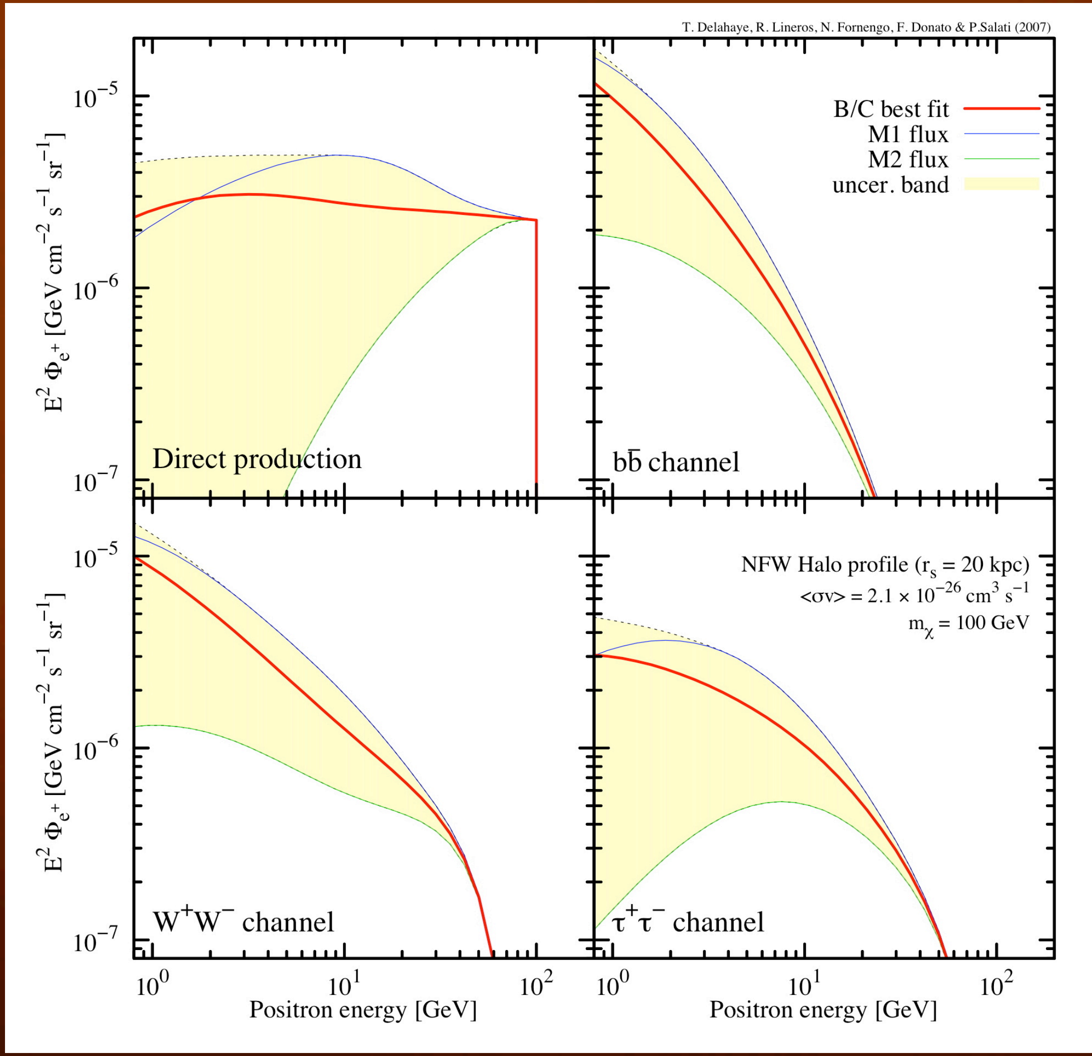


[make nasty remark here … ☺]



Adriani et al., Nature 458 (2009) 607

Results for positrons from DM annihilation



clumpiness

The Dark Matter distribution must be clumpy

$$\boxed{\langle\rho^2\rangle > \langle\rho\rangle^2}$$

→ enhancement of the indirect detection signal (boost factor)

via lactea simulation of a galactic halo

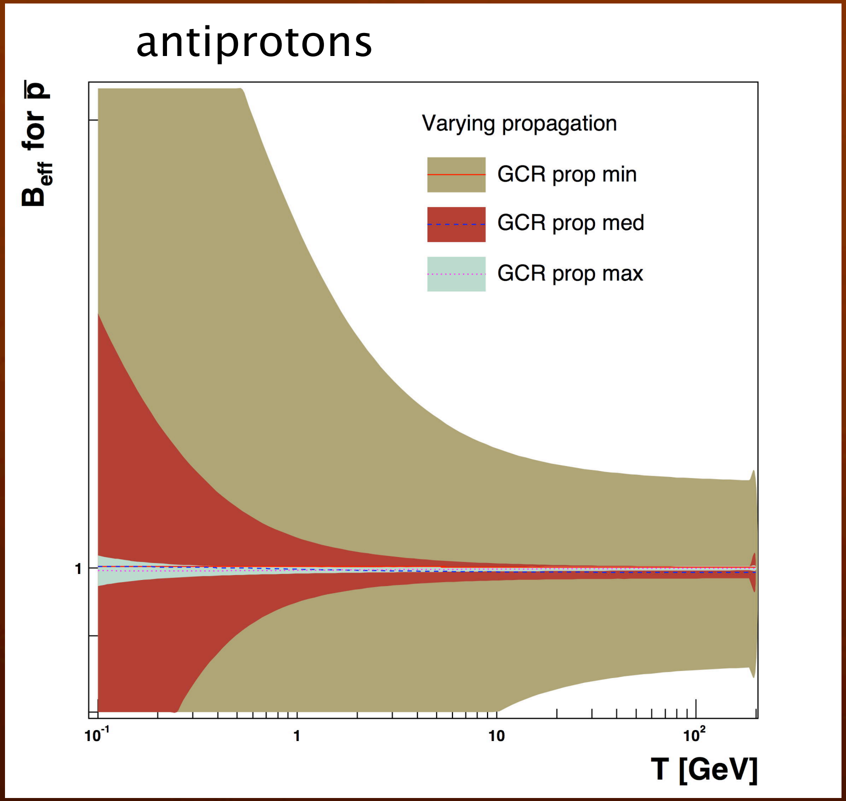
Antimatter from dark matter

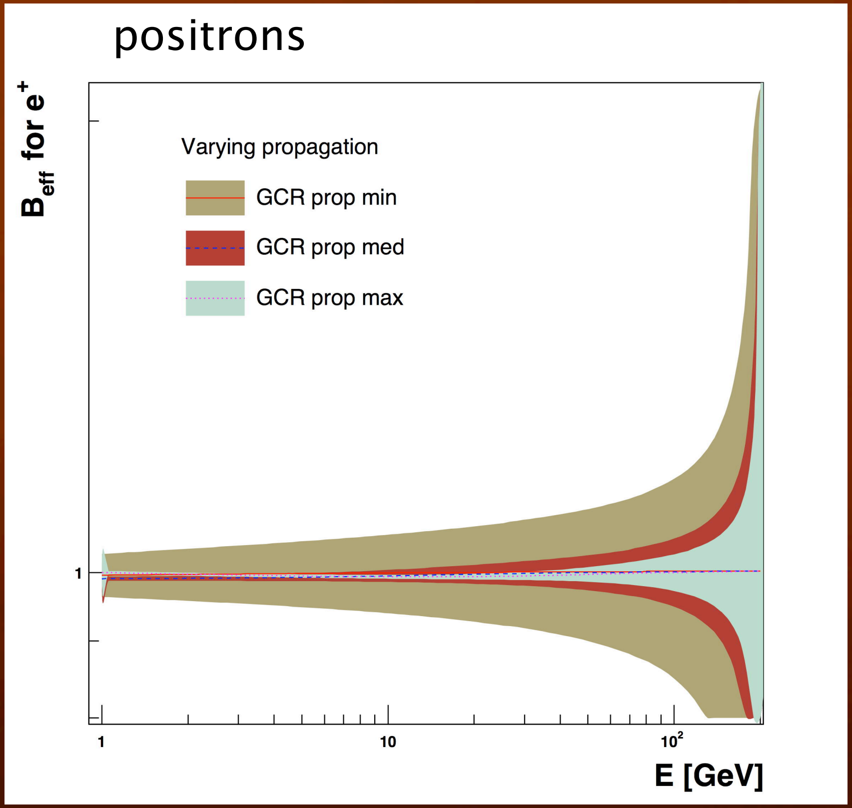
When the diffusion range is short, we are very sensitive to the graininess of the source distribution

→ larger variance of the predicted flux

This shows:

- at low energy for antiprotons
- at high energy for positrons





Lavalle, Yuhan, Maurin & Bi, A&A 479 (2008) 427

Conclusions

- Signal and background must be studied within the same framework
- There is no « standard model » for propagation parameters
- Clumpiness does not simply translates into a boost factor