

# Antimatter in Galactic Cosmic Rays

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Congressino del Dipartimento di Fisica Generale  
Torino, 16 aprile 2010

# Theoretical Astroparticle Physics Group

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## Research interests:

Neutrino Physics and Astrophysics  
Particle Dark Matter: Models & Phenomenology  
Astrophysics of Cosmic Rays  
Dark energy, Early Universe

# Plan of my talk

Introduction to galactic cosmic rays and their propagation

Antimatter in the Milky Way:

1. Astrophysical sources
2. Exotic (Dark Matter) sources

- ANTIPROTONS
- POSITRONS
- ANTIDEUTERONS

Concluding remarks and perspectives

# GALACTIC COSMIC RAYS (GCRs)

are charged particles diffusing in the galactic magnetic field  
Observed at Earth with  
 $E \sim 10 \text{ MeV/n} - 10^3 \text{ TeV/n}$

## 1. SOURCES

### PRIMARIES:

directly produced in their sources

### SECONDARIES:

produced by spallation reactions of primaries on the interstellar medium (ISM)

## 2. ACCELERATION

SNR are considered the powerhouses for CRs  
They can accelerate particles up to  $10^2 \text{ TeV}$

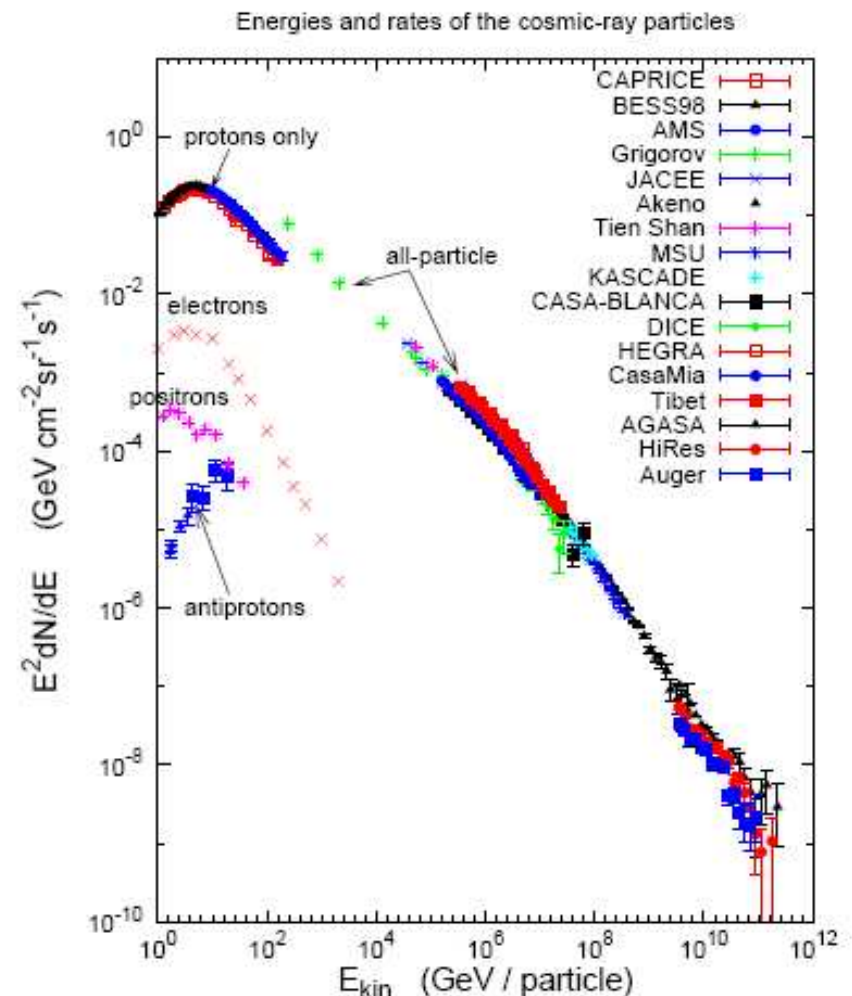
## 3. PROPAGATION

CRs are diffused in the Galaxy by the inhomogeneities of the galactic magnetic field.

During propagation they interact with the ISM (spallation) and loose/gain energy with different mechanisms

Charged GCRs: nuclei & isotopes  
antinuclei  
leptons  
Neutral GCRs: gamma rays  
neutrinos

Gaisser astro-ph/0608553

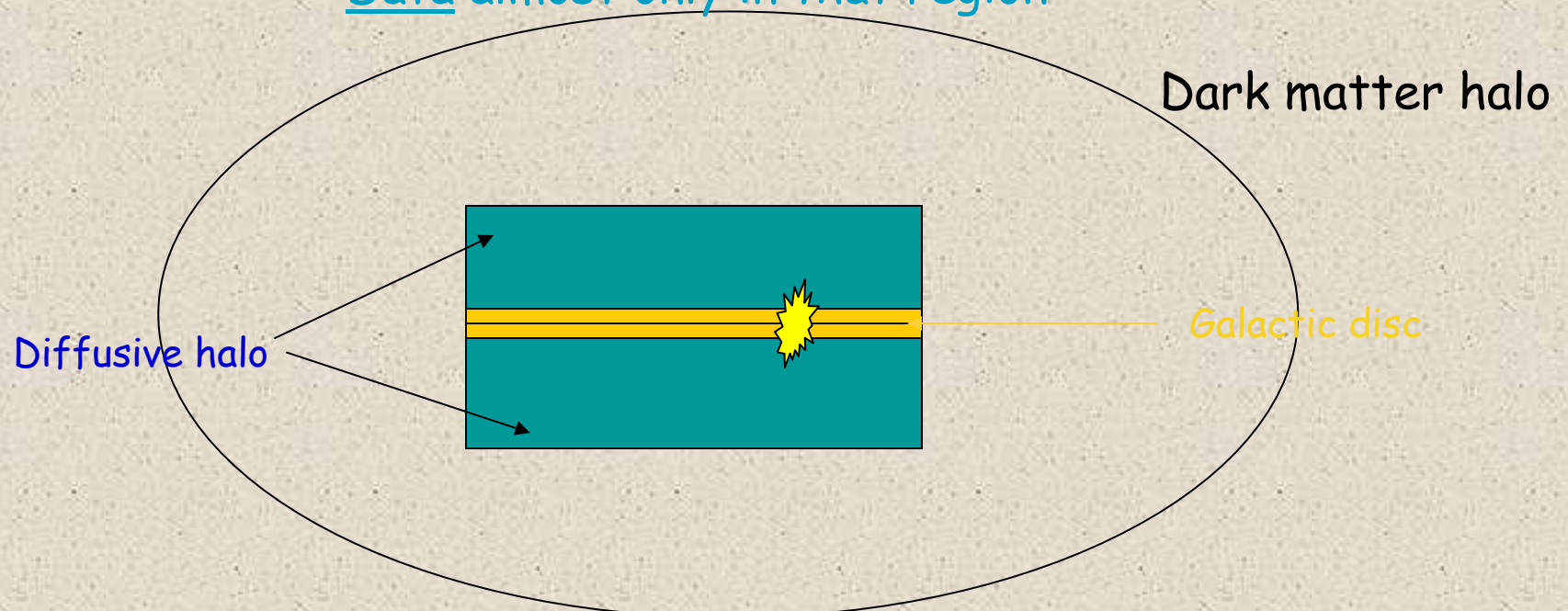


# PROPAGATION OF CRs IN THE MW

## 2-zones DIFFUSION MODEL

Maurin, FD, Taillet, Salati 2000; Maurin, Taillet, FD 2002; Strong & Moskalenko, 1998

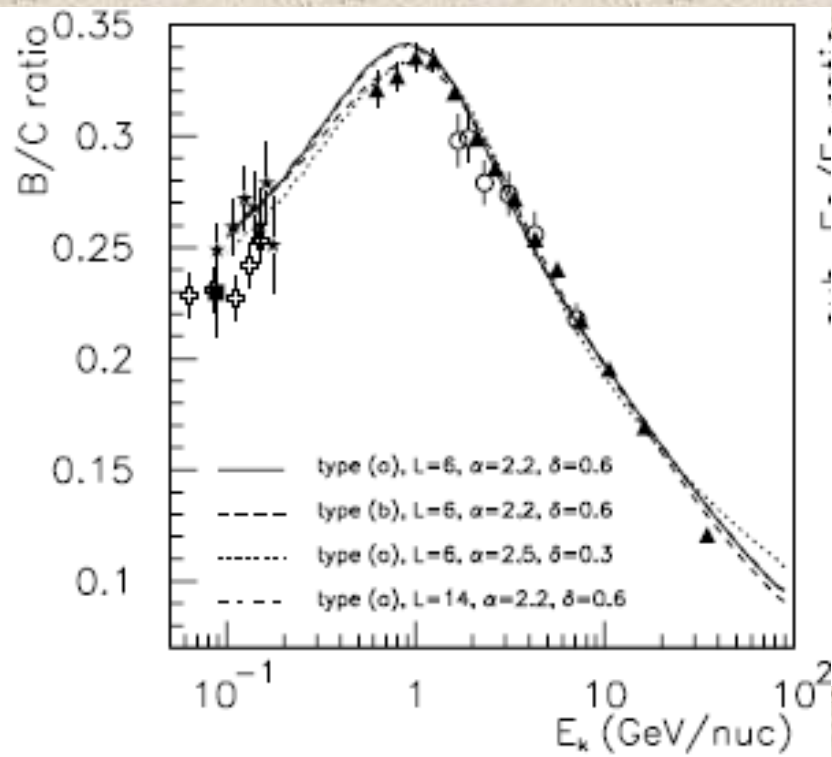
- Several free parameters
- Competing effects in the GeV/n (low-energy) region
- Difficult to disentangle single effect/parameter (degeneracy)
- Data almost only in that region



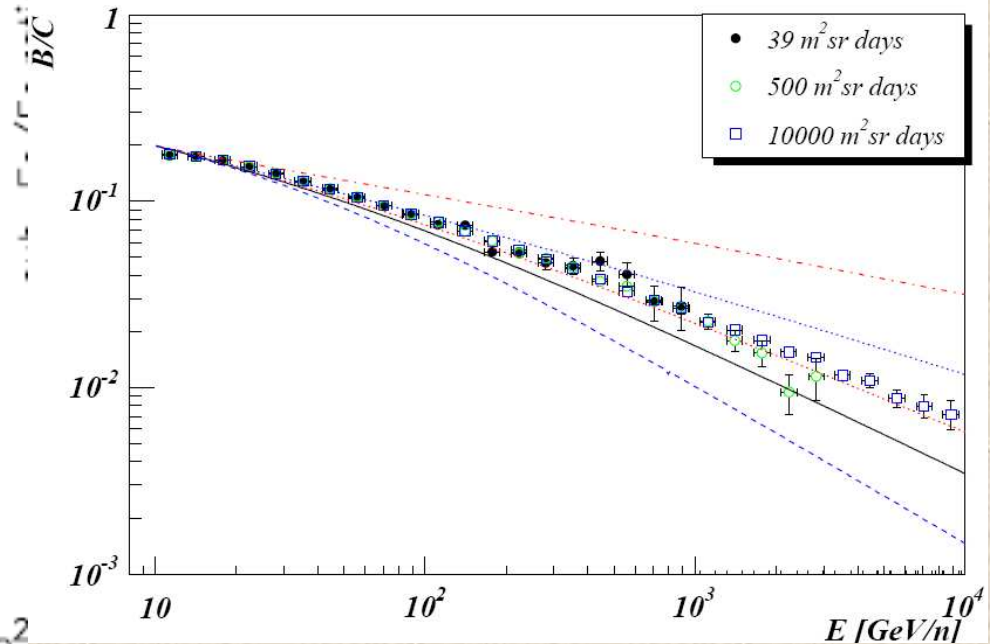
# TESTING PROPAGATION MODELS

Maurin, FD, Taillet, Salati ApJ 2000

Maurin, FD, Taillet, Salati ApJ 2000



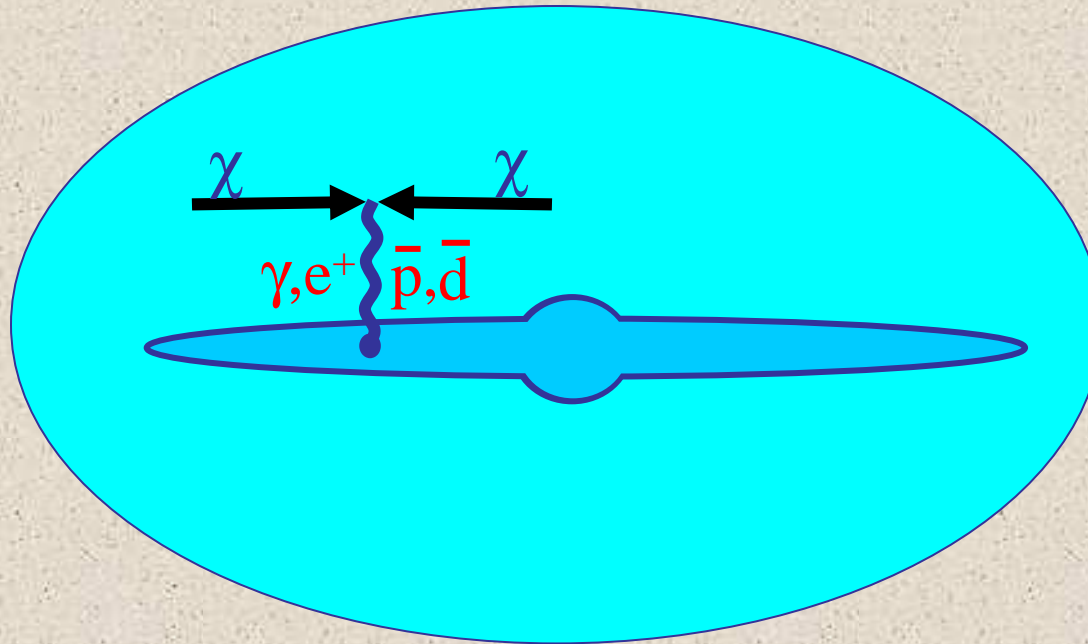
A. Castellina, FD Astropart. Phys. 2005



B/C == BORON/CARBON  
A kind of "standard candle" ...  
Very good prediction of the data!

Predictions for various  
experimental configurations

# Dark Matter Indirect Detection



We look for an "exotic" contribution from DARK MATTER PAIR ANNIHILATION in a purely astrophysics background of:

1. Gamma rays
2. Positrons
3. Antiprotonis
4. Antideuterons
5. Neutrinos



ASTROPHYSICS of COSMIC RAY

# Gamma rays and Antimatter searches



Pamela - 06/2006

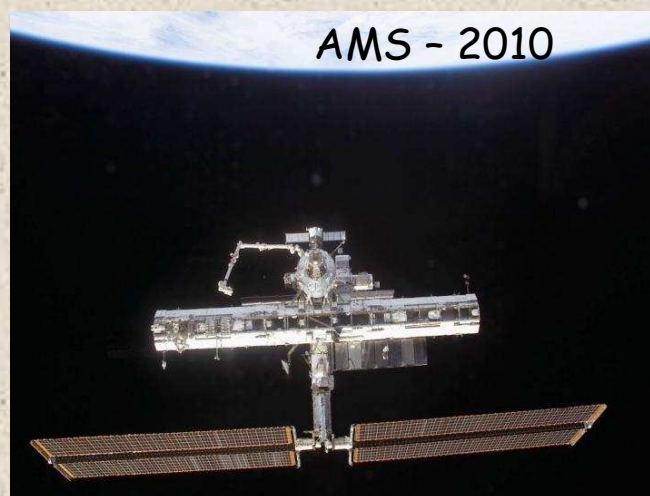
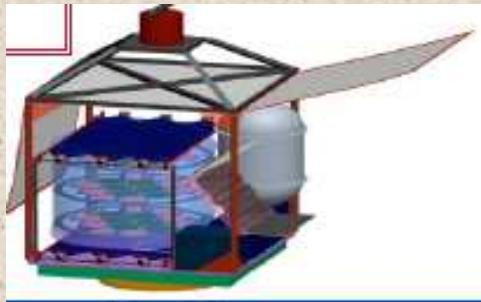


Bess - 2007



Glasc - 2008

GAPS - 2013?



Agile, 04/2007

# ANTI-PROTONS IN COSMIC RAYS

FD et al. ApJ (2001); Bergström, Edsjö, Ullio, ApJ (1999);  
Bieber et al. PRL (1999); Moskalenko et al., ApJ (2002)

$P_{CR} + H_{ISM}$   
 $P_{CR} + He_{ISM}$   
 $\alpha_{CR} + H_{ISM}$   
 $\alpha_{CR} + He_{ISM}$



secondary antiprotons  
act as a background when looking  
for exotic component

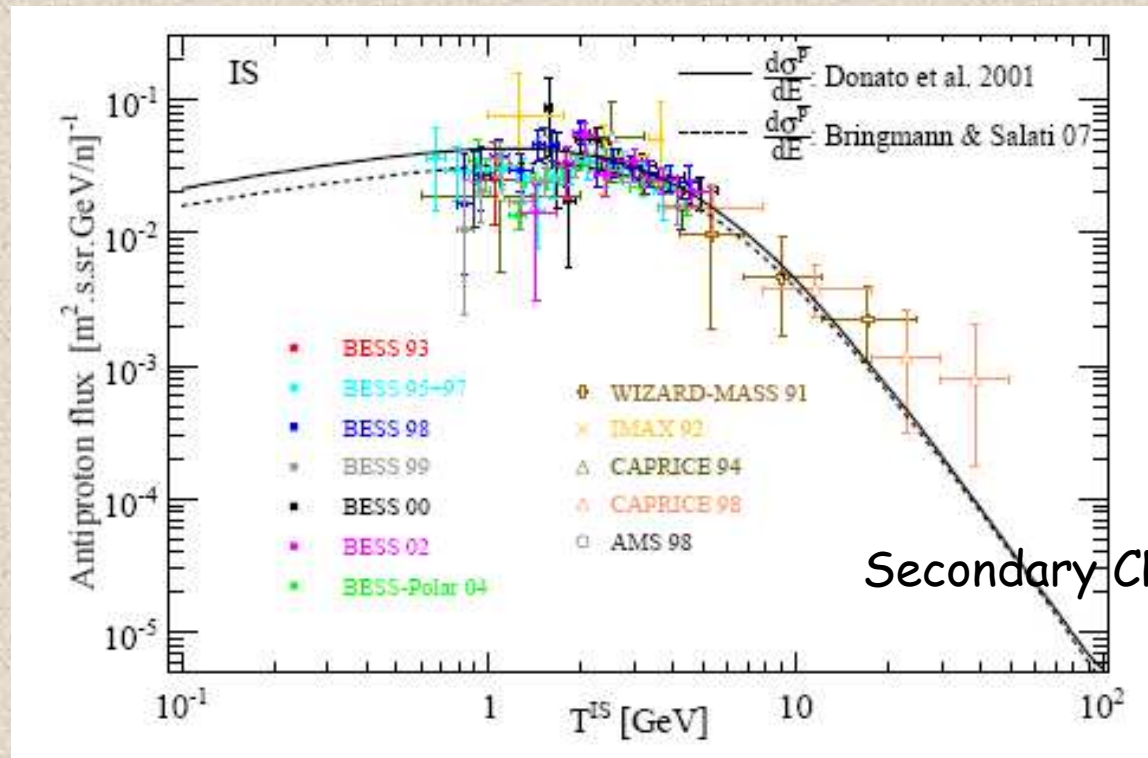
To calculate the **secondary** antiproton flux:

- p and He in CRs *(measured fluxes)*
- Nuclear cross sections *(data + MonteCarlo)*
- Diffusion model *(diffusive models)*

+ eventually, exotic, **primary** contribution from DM annihilation.....

# Antiprotons data

FD, Maurin, Brun, Delahaye, Salati PRL 2009



Demodulated data cover  $\sim 0.7 \div 40 \text{ GeV}$

All experiments from balloons (residual atmosphere) except **AMS98**  
Pamela: preliminary data 3-10 GeV, and expected in  $0.08 \div 190 \text{ GeV}$

# Antiproton/proton: data and models

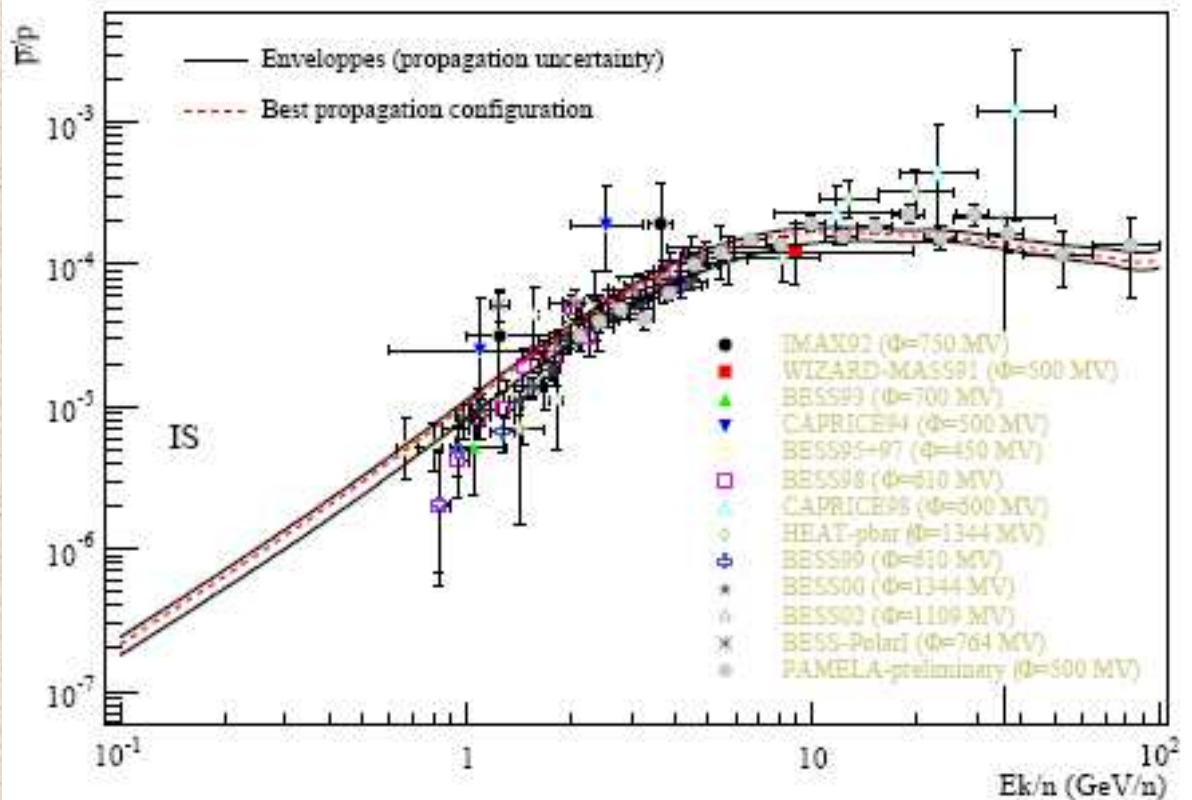
Theoretical calculations with the semi-analytical DM,  
compatible with stable and radioactive nuclei

Donato et al. PRL 2009

PROTON flux:  
 $\Phi = A\beta^{-P1}R^{-P2}$

•  $T < 20$  GeV: Bess 1997-2002  
(Shikaze et al. Astropart. Phys. 2007)

•  $T > 20$  GeV, our fit (Bess98,  
BessTeV&AMS):  
{24132; 0; 2.84}



NO need for new phenomena (astrophysical / particle physics)

## LEPTONS : POSITRONS & ELECTRONS

Primary  $e^-$ : from SNRs & pulsars

Primary  $e^+$ : pulsars

Secondaries  $e^-$  &  $e^+$ : nuclear reactions

+ eventually, exotic, primary contribution from DM annihilation.....

# Propagation of secondary positrons

Delahaye, Lavallo, Lineros, FD, Fornengo, Salati, Taillet A&A 2009

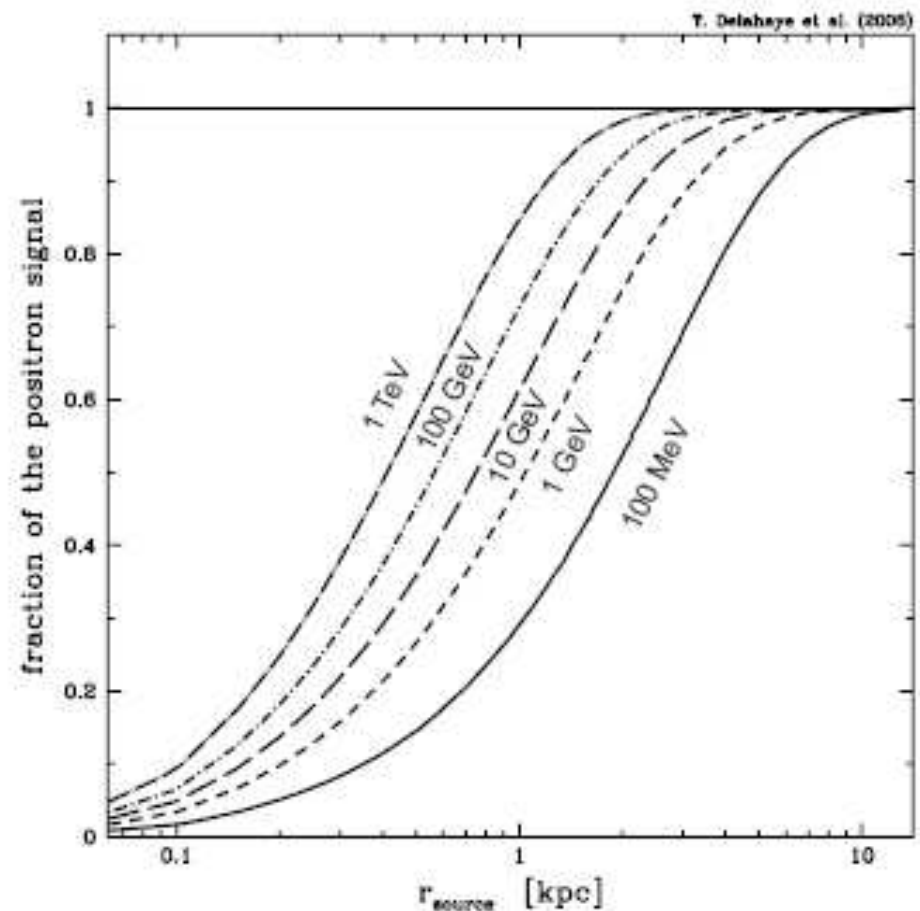
Spallation of proton and helium nuclei on the ISM (H, He)

- $p+H \rightarrow p+\Delta^+ \rightarrow p+\pi^0$  &  $n+\pi^+$  (mainly below 3 GeV)
- $p+H \rightarrow p+n+\pi^+$
- $p+H \rightarrow X + K^\pm$

Diffusive semi-analytical model:  
Thin disk and confinement halo  
Free parameters fixed by B/C

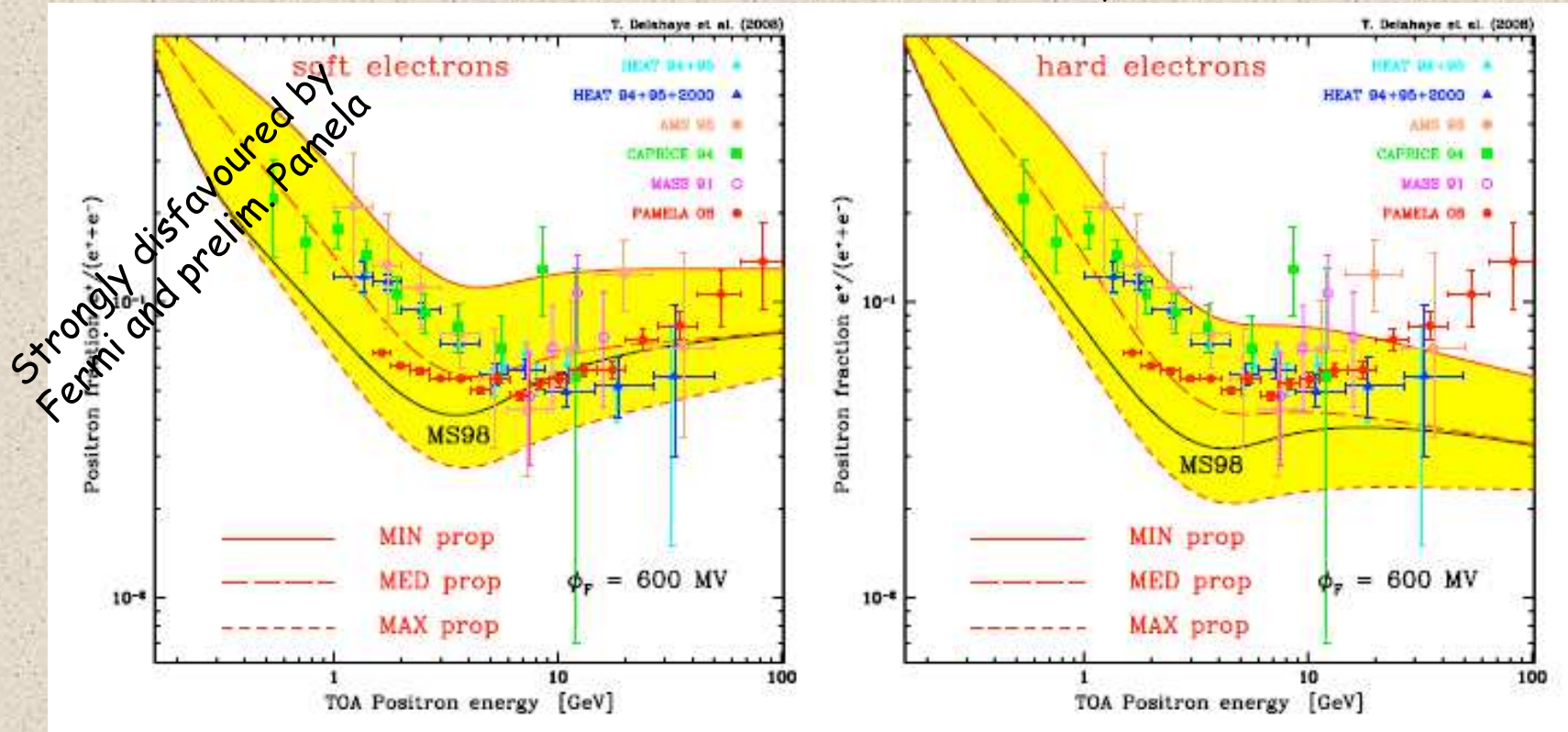
Above few GeV:  
only spatial diffusion and energy losses

**Energetic positrons  
are quite local**



# Positron/electron: data and predictions

Delahaye et al. A&A 2009



Yellow band: secondary positrons & propagation uncertainties

Hard electrons fit to data:  $\gamma=3.34$

There is no "standard" predicted flux (dashed is B/C best fit)

# Primary $e^+$ & $e^-$ from pulsars and SNR

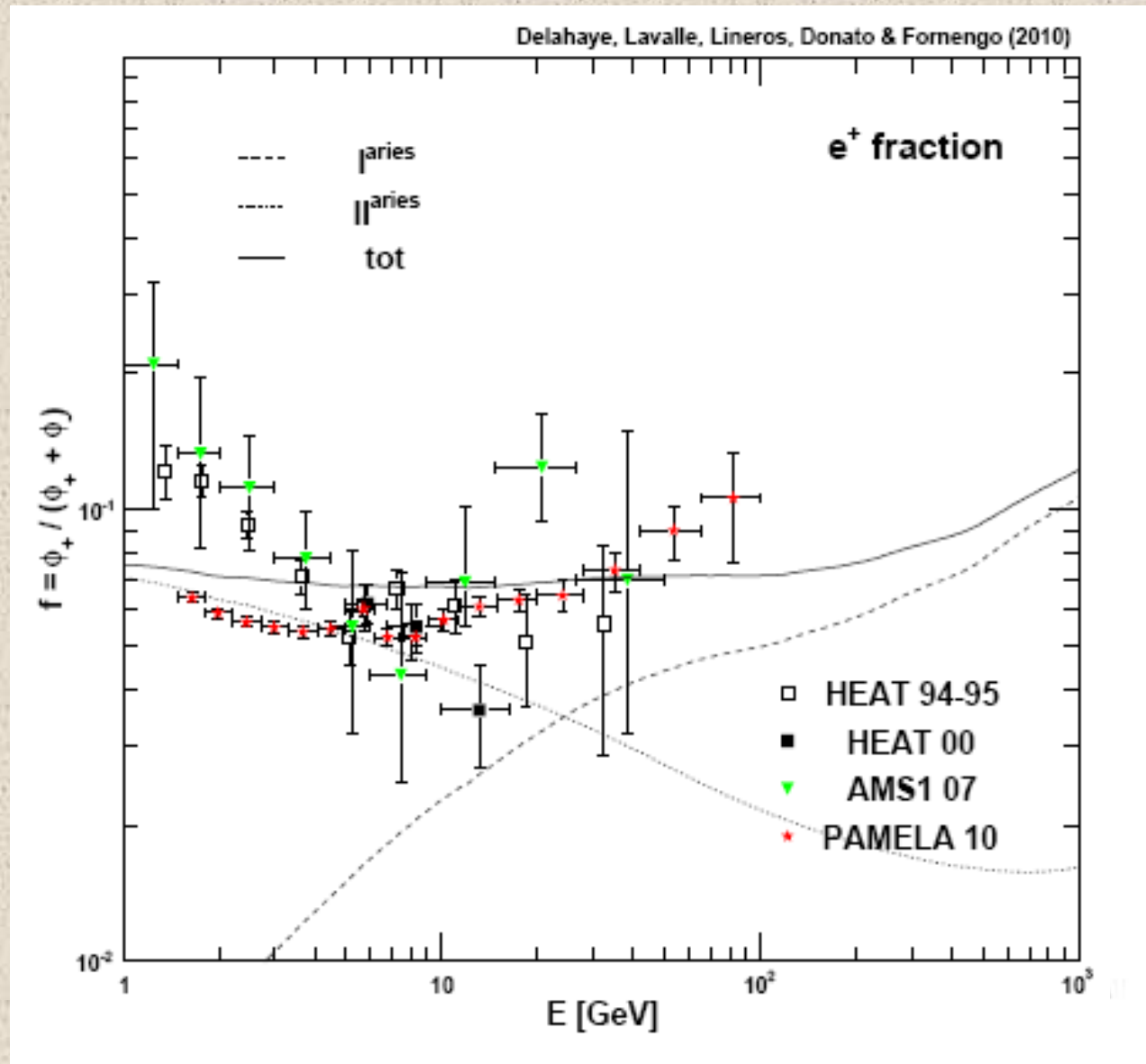
Delahaye, Lavallo, Lineros, FD, Fornengo arxiv:1002.1910

$e^+$  and  $e^-$ : pair production in the strong PULSAR magnetosphere  
Polar cap (disfavoured by recent Fermi data) and outer gap models

- High energy  $e^-$  are accelerated by the strong pulsar electric field
- $e^-$  synchrotron radiate gamma rays
- $e^+/e^-$  are produced by pair conversion in strong magnetic fields of the PSR or scattering off of thermal X-rays

SNR (SuperNovae Remnants) accelerate  $e^-$  (in the ISM) by means of  
1<sup>o</sup> order Fermi acceleration mechanism

# Our predictions and lepton data

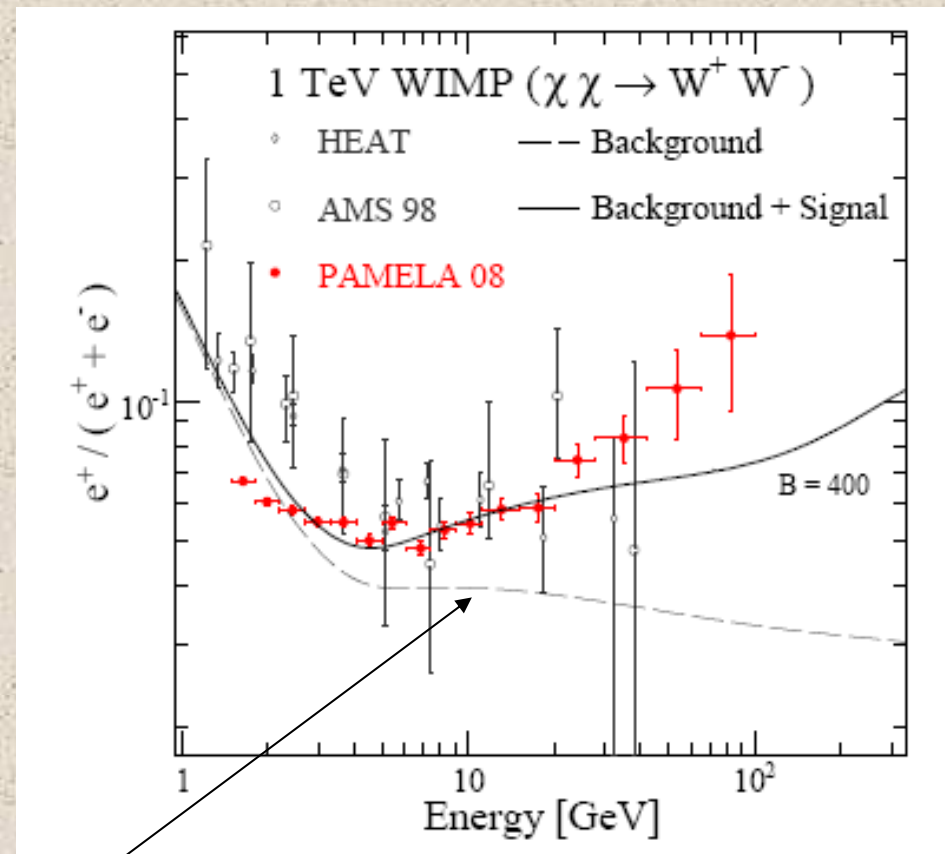


# Constraints on Dark Matter contribution from positron/electron data

Donato et al. PRL 2009

Example:  $m=1$  TeV,  $WW$   
fit improves, but highest points  
in  $E$  not explained

High boost factor required ☹



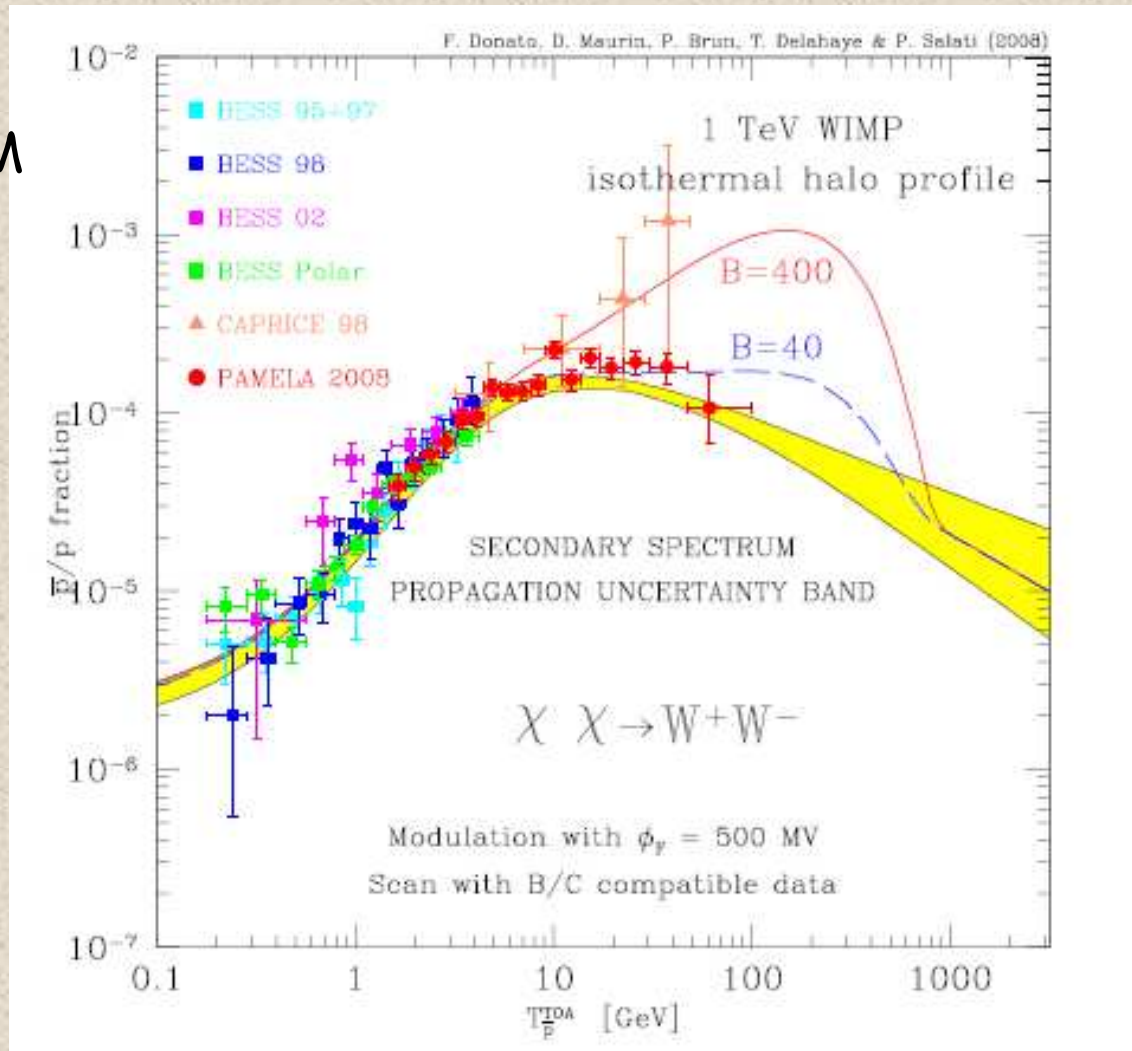
ONLY Secondary positrons  
Best fit propagation parameters

# Effect on antiprotons

The same example: 1 TeV DM candidate

B=400 largely excluded by Pamela!

B=40 marginally allowed

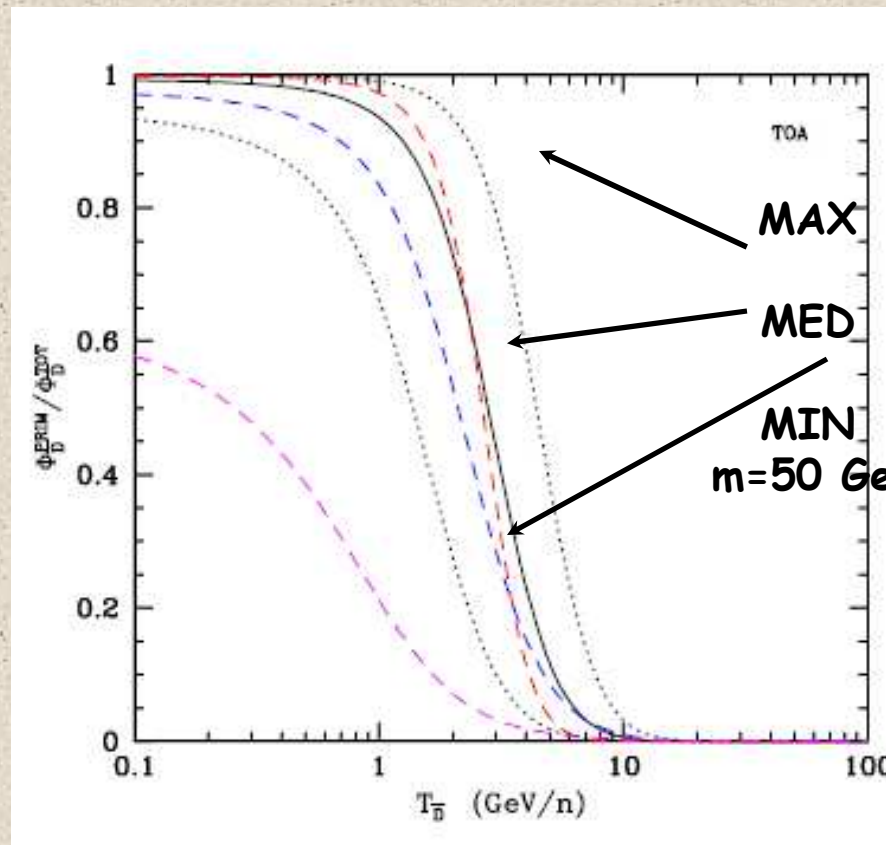


Antiprotons are strong constraints to exotic contributions!

# Antideuterons in Cosmic Rays

FD, Fornengo, Salati PRD 2000; FD, Fornengo, Maurin PRD 2008

Antideuterons may form by the fusion of an antiproton and an antineutron



Dashed: MED

$m=10$

$m=100$

$m=500$

Antideuteron  
Signal-to-  
Background

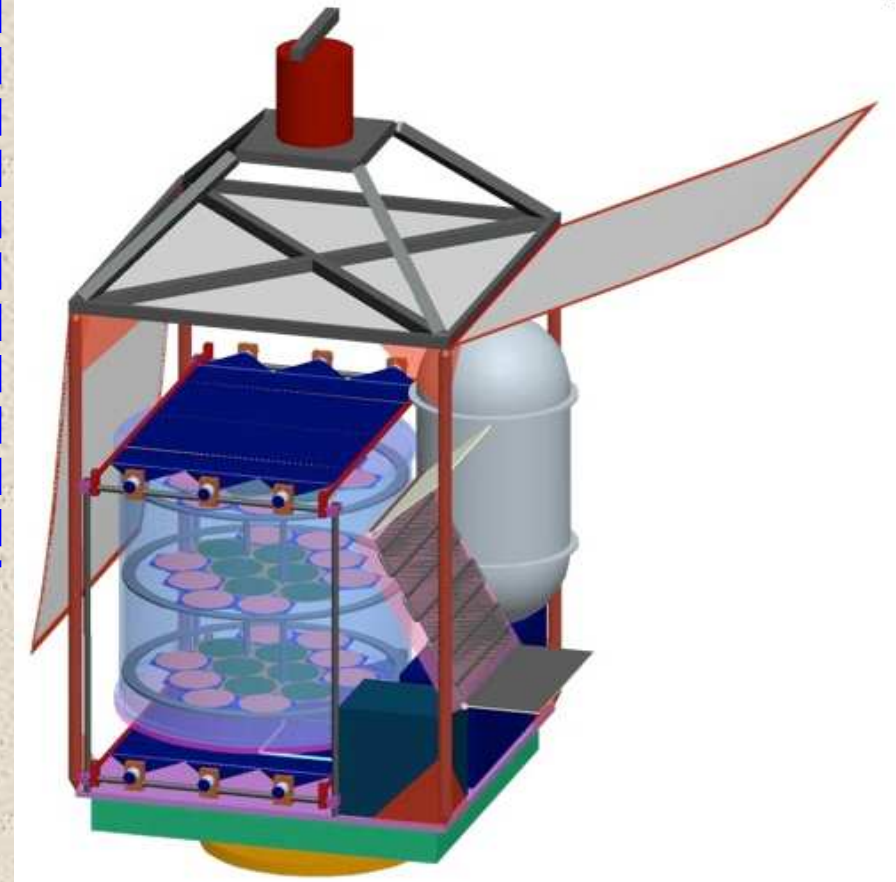
Low energy antideuterons have a high discrimination power

# Antideuterons in Cosmic Rays: GAPS

<http://gamma1.astro.ucla.edu/gaps/index.html>

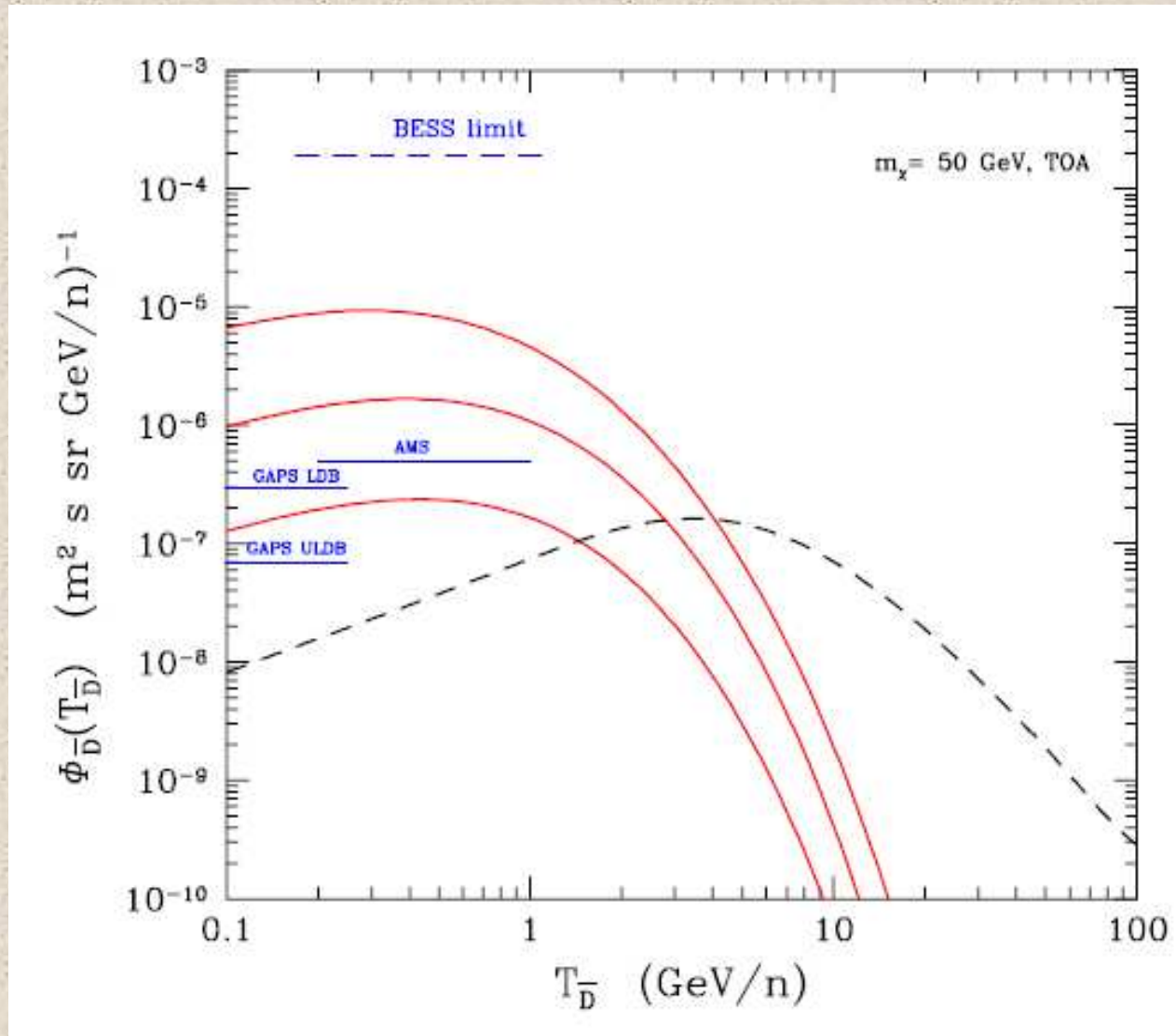
Questo studio ha costituito la motivazione fondamentale per la proposta dell'esperimento GAPS (Usa+) alla NASA.

- Prototipo già testato al KEK (Tokyo)
- Proposal alla NASA per un pallone LDB e ULDB in Antartico



Volo di un prototipo su un piccolo pallone è previsto nel 2011

# ANTIDEUTERONS & future experiments



effMSSM neutralino dark matter can be detected by means of next generation space instruments measuring antideuterons in CRs

## Conclusive remarks:

The search for Dark Matter contributions in rare antimatter cosmic fluxes requires very good knowledge of all astrophysical backgrounds.

Huge theoretical/phenomenological work is needed for modelling the Milky Way as experienced by charged particles, and predict all Measured cosmic rays

Precise and extended data on **B/C** and **light nuclei** are fundamental for fixing propagation models and refine the calculation of astrophysical backgrounds

Better determination of of galactic CR **propagation**:  
ULDB, satellites, AMS/ISS...:  
Strong experimental activity!

# Transport equation in diffusion models

Diffusion

Convection

Destruction on ISM

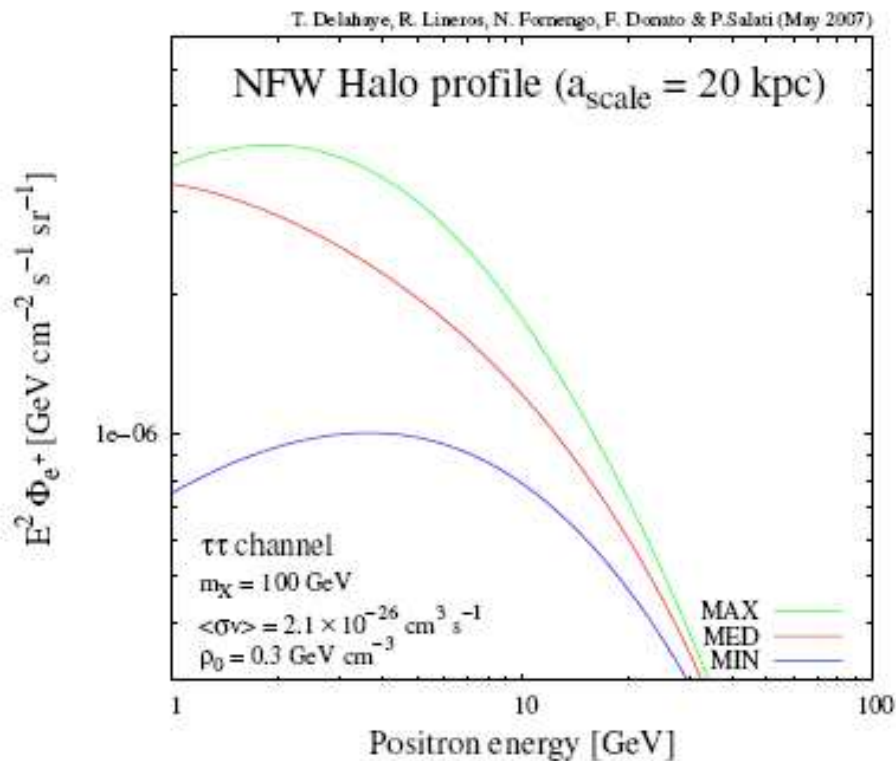
$$\begin{aligned} & -\vec{\nabla} \left[ K \vec{\nabla} N^j(E) - \vec{V}_c N^j(E) \right] - \Gamma^j N^j \\ & - \frac{(\vec{\nabla} \cdot \vec{V}_c)}{3} \frac{\partial}{\partial E} \left[ \frac{p^2}{E} N^j(E) \right] = Q^j(E) + \\ & \frac{\partial}{\partial E} \left[ -b_{\text{tot}}(E) N^j(E) + \beta^2 K_{pp} \frac{\partial N^j(E)}{\partial E} \right] \end{aligned}$$

CR sources: primaries,  
secondaries (spallations)

Reacceleration

Ionization, Coulomb, Adiabatic losses  
+ Reacceleration

# Astrophysical uncertainties on primary positrons



Uncertainties on primaries is 3-5, depending on:

- Energy
- Annihilation mode
- DM distribution in the halo