Dark Matter and CHARGED cosmic rays

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The International School for AstroParticle Physics (ISAPP) 2013, Djurönäset: Dark Matter Composition and Detection, July 29 to August 6, 2013

Plan of my lectures

- What are COSMIC RAYs (CRs)
- Why CRs and Dark Matter (DM)
- Theory and phenomenology of galactic CRs
- Signals from DM in antiprotons, antideuterons, positrons
- CR Backgrounds to DM signals

What are cosmic rays

CHARGED (GALACTIC) COSMIC RAYS

<u>are charged particles (nuclei, isotopes, leptons, antiparticles) diffusing in the galactic magnetic field</u>
<u>Observed at Earth with E~ 10 MeV/n – 10^3 TeV/n</u>

1. **SOURCES**
   - PRIMARIES: directly produced in their sources
   - SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM)

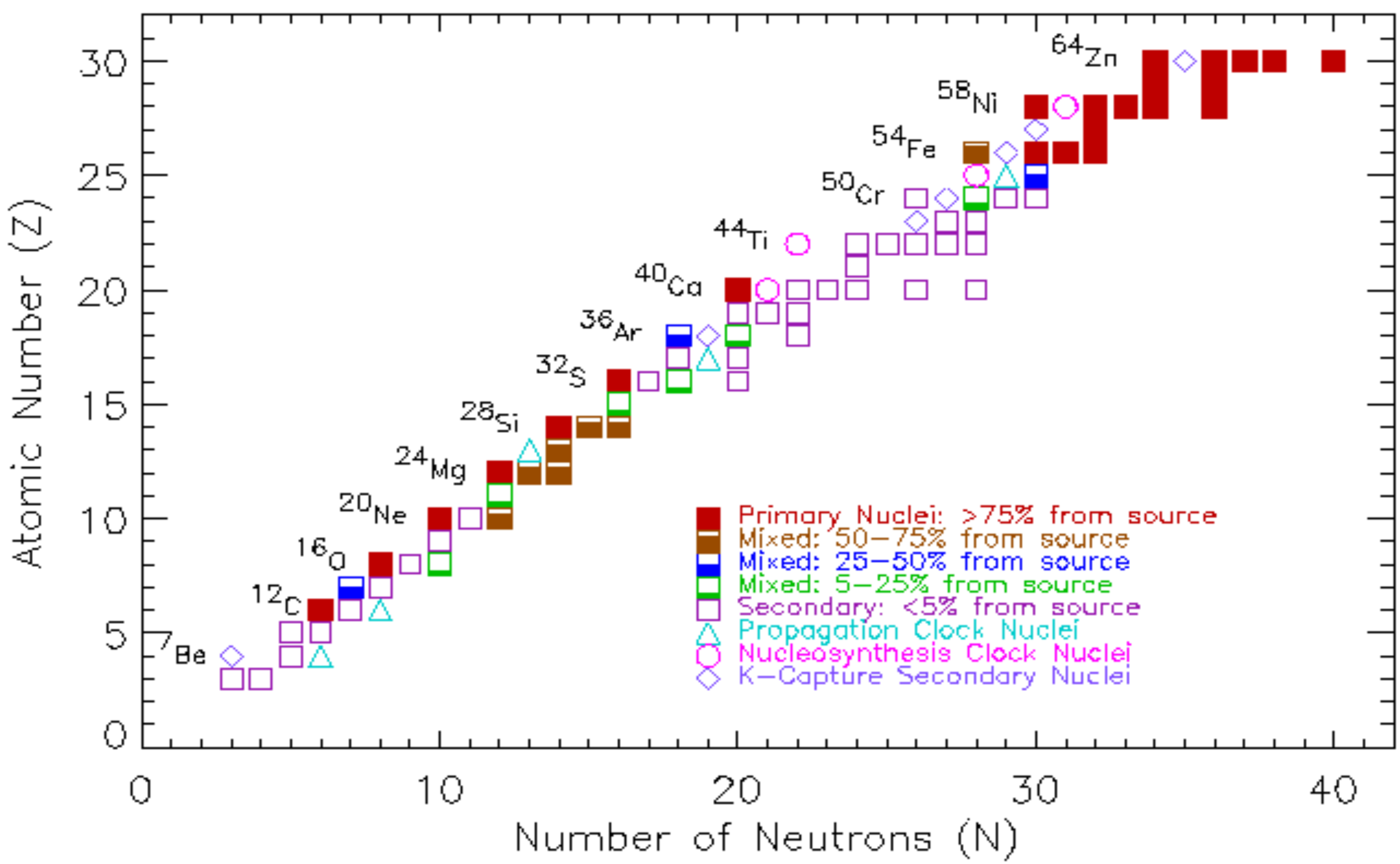
2. **ACCELERATION**
   SNR are considered the powerhouses for CRs. They can accelerate particles up to 10^2 TeV

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

\+ loose/gain energy with different mechanisms

Primaries = present in sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
e^+, p^+, d^+ from Dark Matter annihilation

Secondaries = NOT present in sources, thus produced by **spallation** of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe; e^+, p^+, d^+; ...



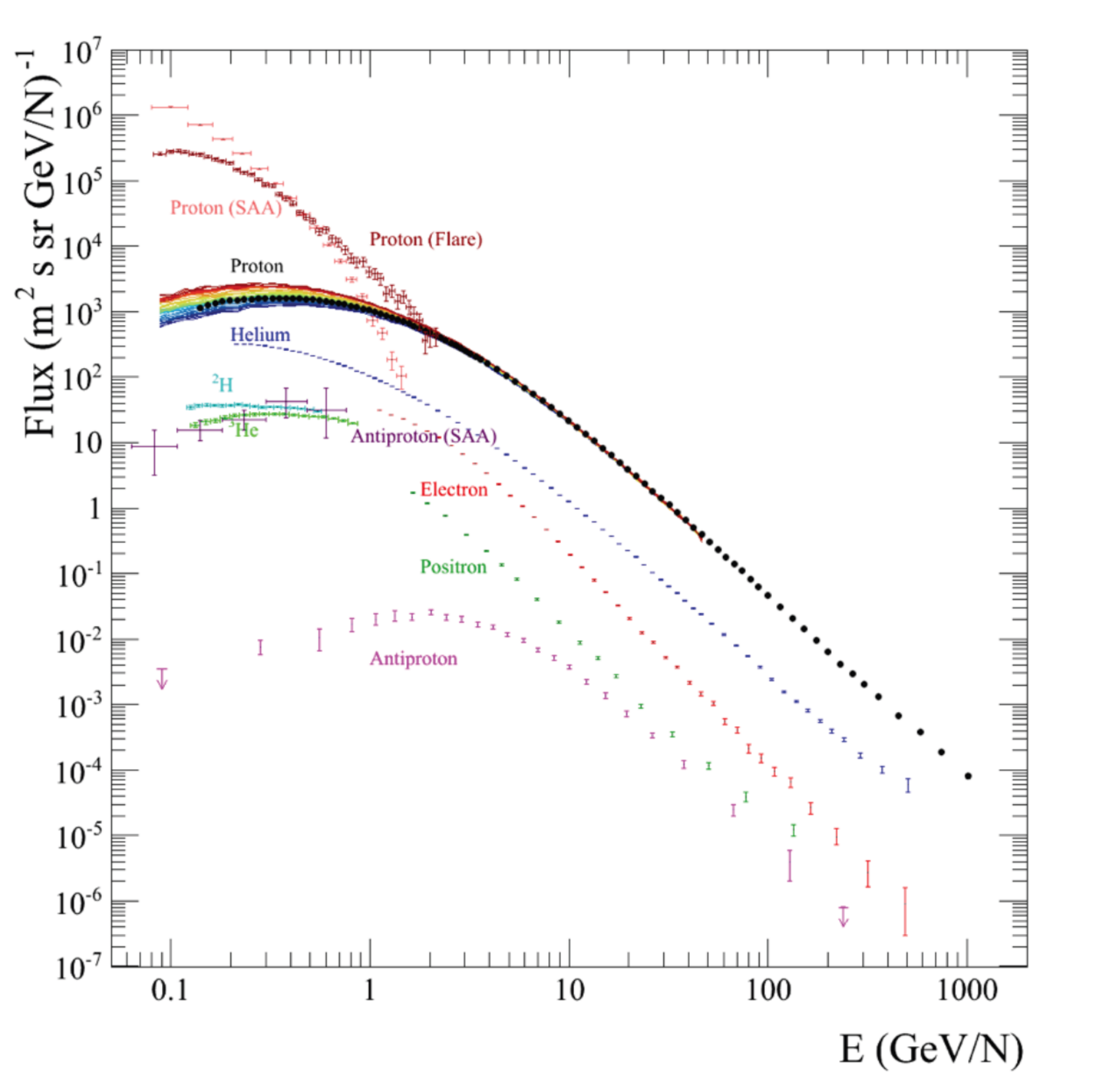
CR discovery: Victor F. HESS 1912

1912 VF Hess embarked on 7 flights onboard hot-air balloon.
August 7, 1912 reached 5200m height!

In the data he collected, the radiation was increasing with the altitude: the opposite of what expected for radiation originating in the Earth crust.

There is a "rain" of particles pervading the sky, called cosmic rays (CRs).

All particle spectra (from Pamela experiment)



Credits: Valerio Formato & Mirko Boezio, Pamela Collaboration, 2013

Why Cosmic Rays

and

Dark Matter?

WIMP INDIRECT SIGNALS

(see lecture by Torsten Bringmann)

Annihilation inside celestial bodies (Sun, Earth):

- ν at ν telescopes as up-going μ's

  (see lecture by David Boersma)

Annihilation in the galactic halo:

- γ-rays (diffuse, monochromatic line), multiwavelength

- e^+, $\bar{p}$, $\bar{D}$ antimatter searched as rare components in cosmic rays (CRs)

ν and γ keep directionality

Charged particles diffuse in the galactic halo

→ ASTROPHYSICS OF COSMIC RAYS!

Theory and phenomenology

of galactic CRs

Enrico FERMI, PR 75 (1949) 1169

« A theory of the origin of cosmic radiation is proposed
according to which cosmic rays are
originated and accelerated primarly in the
interstellar space of the galaxy
by collisions against moving magnetic fields.

One of the features of the theory
is that it yields naturally an inverse power law
for the spectral distribution of cosmic rays [...]. »

FIORENZA DONATO

August 5, 2013

ISAPP 2013 STOCKHOLM BJURÖNÄSET

DARK MATTER AND CHARGED COSMIC RAYS

(follows slides)

Charged particles in the Galaxy may be described by a general DIFFUSION EQUATION for the cosmic ray (CR) differential energy density $N^j = \frac{dn^j}{dE}$ for the species j ($n_j = 4\pi \int dp\, p^2 f_j$). We have that $N^j(E) = \frac{4\pi}{\beta} p^2 f_j$, where $f_j \equiv f_j(t, \vec{r}, \vec{p})$ is the phase space distribution.

The DIFFUSION (or transport) EQUATION is:

$$\frac{\partial N_j}{\partial t} - \vec{\nabla}\left[K\vec{\nabla} N_j(E) - \vec{V}_c N_j(E)\right] - \Gamma_j N_j(E) -$$

$$- \frac{(\vec{\nabla}\cdot\vec{V}_c)}{3} \frac{\partial}{\partial E}\left[\frac{p^2}{E} N_j(E)\right] =$$

$$= q_0 Q_j(E) + \sum_k^{m_k > m_j} \Gamma^{kj} N^k(0) +$$

$$+ \frac{\partial}{\partial E}\left[-b(E) N^j(E) + \beta^2 K_{pp} \frac{\partial N_j(E)}{\partial E}\right]$$

for the species j, and E is the kinetic energy per nucleon:

$$E \equiv \frac{E_{kin}}{\text{nucleon}} \quad (= E_{kin}/A)$$

(which is conserved in spallation reactions) for steady-state $\frac{\partial N_j}{\partial E} = 0$.

- The term $\vec{\nabla}(k \vec{\nabla} N(E))$ describes spatial diffusion on the inhomogeneities of the galactic field. $k(R)$ is the diffusion coefficient as a function of RIGIDITY

$$R = \frac{pc}{ZE}$$

- V_c is the convective velocity, with the adiabatic term $\propto \vec{\nabla} \cdot \vec{V}_c / 3$

- $\Gamma^j = n_{ISM} v_j \sigma_j$ is the destruction of nucleus j on the atoms of the interstellar medium (ISM), mainly H (90%) and He (10%)

- $q_0 Q(E)$ is the SOURCE SPECTRUM (primaries)

- $\sum_k^{m_k > m_j} \Gamma^{kj} N^k(0) = \sum_k^{m_k > m_j} n_{ISM} v_j \sigma^{kj} N^k(0)$ is the production of the nucleus (or species) j by the spallation (nuclear destruction reaction) of the nuclei k, having atomic number k greater than the j-one. This catastrophic loss for nuclei k is a source term for nucleus j: secondaries

- $\frac{\partial}{\partial E}[\quad]$ describes energy loss and gains.

$$b(E) \equiv b_{loss}(E) + \underbrace{b_{gain}(E)}_{\equiv reacc} \equiv b_{loss}(E) + b_{reacc}(E)$$

$$b_{loss}(E) = \left(\frac{dE}{dt}\right)_{ion} + \left(\frac{dE}{dt}\right)_{Coul} + \left(\frac{dE}{dt}\right)_{adiab}$$

$$b_{reacc}(E) = \frac{1+\beta^2}{E} K_{pp}(E)$$

→ SLIDE with the CHARACTERISTIC TIMES for the main processes affecting the propagation of galactic cosmic rays.

In the above diffusion equation we have neglected unstable nuclei, namely isotopes unstable for β-decay or electronic capture.

The main effects, at least at high ($\gtrsim O(10^2)$ GeV/n) energies are SOURCE INJECTION and DIFFUSION. Let's look at them with some details

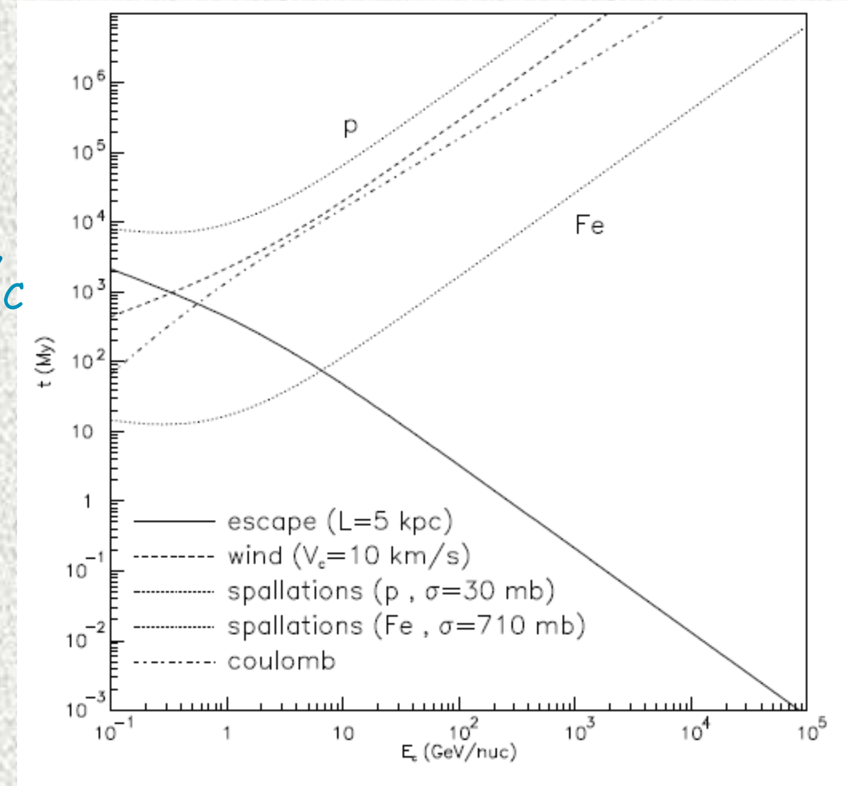
Characteristic times for various processes

For a particle to reach z and come back (diffusion time) : $t_D \approx z^2/K(E)$

At the same time, convection time: $t_C = z/V_C$

A particle in z can come back to the disk only if $t_C < T_D \rightarrow z_{max} = K/V_C$

N. B. The smaller the time, the most effective the process is



For protons: escape dominates > 1 GeV
E<1 GeV, convection and e.m. losses

For iron: Spallations dominate for E<10 GeV/n

THE SOURCE TERM: ACCELERATION IN SUPERNOVAE REMNANTS (SNRs)

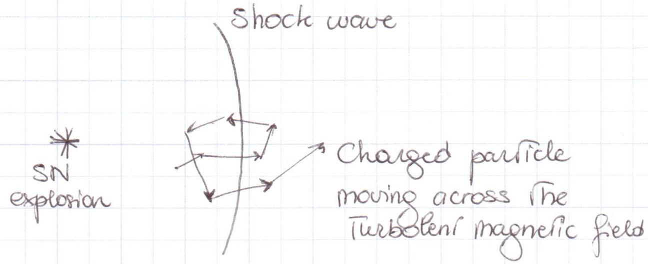
- Supernovae explode with an average rate of 1/(30 years).
- Their released (mechanical) energy is $\sim 10^{51}$ erg.
- The total power required to maintain the observed population of relativistic protons is $\sim 10^{41}$ erg/s

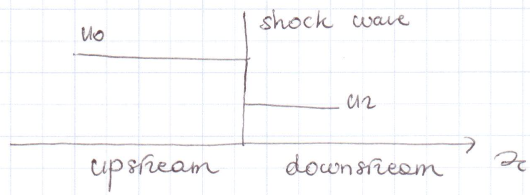
$$10^{41}\ \frac{\mathrm{erg}}{\mathrm{s}} = f \cdot \frac{10^{51}\ \mathrm{erg}}{30\ \mathrm{yr}} \quad \Rightarrow f \approx 10\%$$

$f \approx 10\%$ is the fraction of SN energy which should be converted into relativistic protons in order to provide the observed level of CR protons in the Milky Way.

This argument, together with the lack of other plausible sources, is a strong hint that the power source for CR relies in SNe. However, if CRs were accelerated during the explosion itself, the adiabatic losses suffered by CRs pushing aside the ISM would require an energy budget impossible to reach. The acceleration is therefore believed to take place in the subsequent SNR via diffusive shock acceleration (DSA).

DSA is the 1-st order Fermi acceleration according to which charged particles gain energy being repeatedly reflected back and forth by a shock wave (such as the SNR).





u_0 = shock speed

u_2 = downstream flow speed

v_{DS} = compressed gas dragged along with this speed

$u_2 = u_0 - v_{DS}$

Particles can be lost downstream at any moment, or make several crossings (with low probability)

The DSA may be described by a transport equation, giving:

$$f(p) \propto p^{-3r(r-1)} \qquad r = \text{compression ratio}$$

$r = 4$ for high Mach numbers $\Rightarrow f(p) \propto p^{-4}$ or $Q(E) \propto E^{-2}$

The injection spectrum is a power law:

$$Q(E) \propto E^{-\alpha} \quad , \alpha \in (2.0 \div 2.5)$$

Confirmation of this mechanism comes from γ-rays produced by π^0 decay, π^0 produced by the interactions of the accelerated protons and the ISM. The γ-rays are also produced by leptonic processes, such as bremsstrahlung and inverse Compton scatterings. Recent evidence comes from the observed spectra of the SNRs IC443 and W44 by the Fermi-LAT detector.

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Sezione Formazione

THE DIFFUSION COEFFICIENT

The diffusion on the irregularities of the galactic magnetic field explains the high isotropy of CRs and their confinement in the galaxy. The fluctuations of the magnetic field (MF) are supposed to be small with respect to the average MF ($\delta B \ll B$). The interaction between the waves and the cosmic particle is resonant and maximal when the MF irregularities have their wave number // to the average MF:

$$k_{//} = \pm \frac{s}{r_g \mu}, \quad s \cong \text{cyclotron resonances number},$$

$r_g = R/B$ is the gyroradius, μ is the pitch angle. One finds

$$K_{//}(\vec{r}, R) \simeq \frac{1}{3} \frac{v r_g}{P}$$

with $P = \int \Delta B(k^*)^2 / B^2 dk$ is the normalized power spectrum of the turbolent hydromagnetic fluctuations

$P \propto \int k^{-5/3} dk \propto k^{-2/3}$ for Kolmogorov turbolence

$k \propto \frac{1}{\ell} \propto \frac{1}{r_g}$

so we have that for Kolmogorov spectrum the spatial diffusion coefficient is given by:

$$K(R) = K_{//}(\vec{r}, R) \propto \frac{1}{3} v \, r_g \, k^{2/3} \propto$$

$$\propto \beta \, r_g \, r_g^{-2/3} = \beta r_g^{1/3} \propto \beta R^{1/3}$$

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In general, for a turbolence spectrum shaped as

$$P(k) \propto k^{-(1-\delta)}$$

we have a diffusion coefficient for CRs:

$$K(R) \propto \beta R^{\delta}$$

with $\delta = 1/3$ for Kolmogorov spectrum
$\delta = 1/2$ " Kraichnan spectrum

Since we do not know the properties of the galactic MF – neither the regular nor the irregular part – such that to predicts the coefficients of the $K(R)$, we phenomenologically assume:

$$K(R) = \beta K_0 R^{\delta}$$

with K_0 and δ to be fix by observations of CR spectra.

SOLUTIONS to the diffusive equations

The solution is searched after a geometry for the Galaxy is fixed. It is usually assume cylindrical symmetry

Sources for primary standard and secondary CRs are located in the disk, while diffusion takes part everywhere.
Solutions may of course be fully numerical (i.e. Galprop code) with some minor approximations, one can find analytical solutions for the diffusive equation, except for the energy dependent equation.

Given cylindrical symmetry, we can write:

$$N(r,z) = \sum_{i=0}^{\infty} J_0(\xi_i \rho)\, N_i(z) \qquad \rho \equiv r/R_{gal}$$

where $J_0(\xi_i \rho)$ is the first Bessel function and

$$N_i(z) = \frac{2}{J_1^2(\xi_i)} \int_0^1 \rho\, N(\rho R, z)\, J_0(\xi_i \rho)\, d\rho$$

This development may be inserted in the diffusion equation, which is therefore rewritten as:

$$N_i''(z) - \left(\frac{2h\,\Gamma_{inel}}{k}\delta(z) + \frac{\xi_i^2}{R^2}\right) N_i(z) - \frac{V_c}{k} N_i'(z) = -\frac{q_i^{source}(z)}{k}$$

(where we have assumed a constant galactic wind).

The general solution to this equation takes the form:

$$N(r,z) = \exp\left(\frac{V_c z}{2k}\right) \sum_{i=0}^{\infty} \frac{Q_i}{A_i} \frac{\sinh[S_i[L-z]/2]}{\sinh(S_i L/2)} J_0\left(\xi_i \frac{r}{R_{gal}}\right)$$

where $Q_i = q_0\, Q(E) \cdot q_i^{disk}$ for pure primary
$Q_i = \sum_k^{m_k > m_j} \Gamma_{kj} N_i^k(0)$ for secondary nuclei

$$A_i = 2h\Gamma_{inel} + V_c + kS_i \coth\left(\frac{S_i L}{2}\right)$$

$$S_i = \sqrt{\frac{4\xi_i^2}{R_{gal}^2} + \frac{V_c^2}{k^2}}$$

L = heigth of the diffusive halo

At "high energies":
Primary CRs: $N(E) \sim E^{-\alpha-\delta}$
Secondary CRs: $N(E) \sim E^{-\alpha-2\delta}$

Prim/Sec $\sim E^{-\delta}$ (i.e. Boron/Carbon)

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CHARGED COSMIC RAYS FROM DARK MATTER ANNIHILATION IN THE GALACTIC HALO

Primary sources may also be located in the diffusive halo, and not only in the disk. This is the case, for example, for dark matter particles self-annihilating in the halo of the Milky way. In this case the difference is in the source term, which has the following form:

$$q^j_{DM}(r, z, E) = \langle \sigma v \rangle_{ann} \frac{dN_j}{dE_j} \left(\frac{\rho_\chi(r, z)}{m_\chi} \right)^2$$

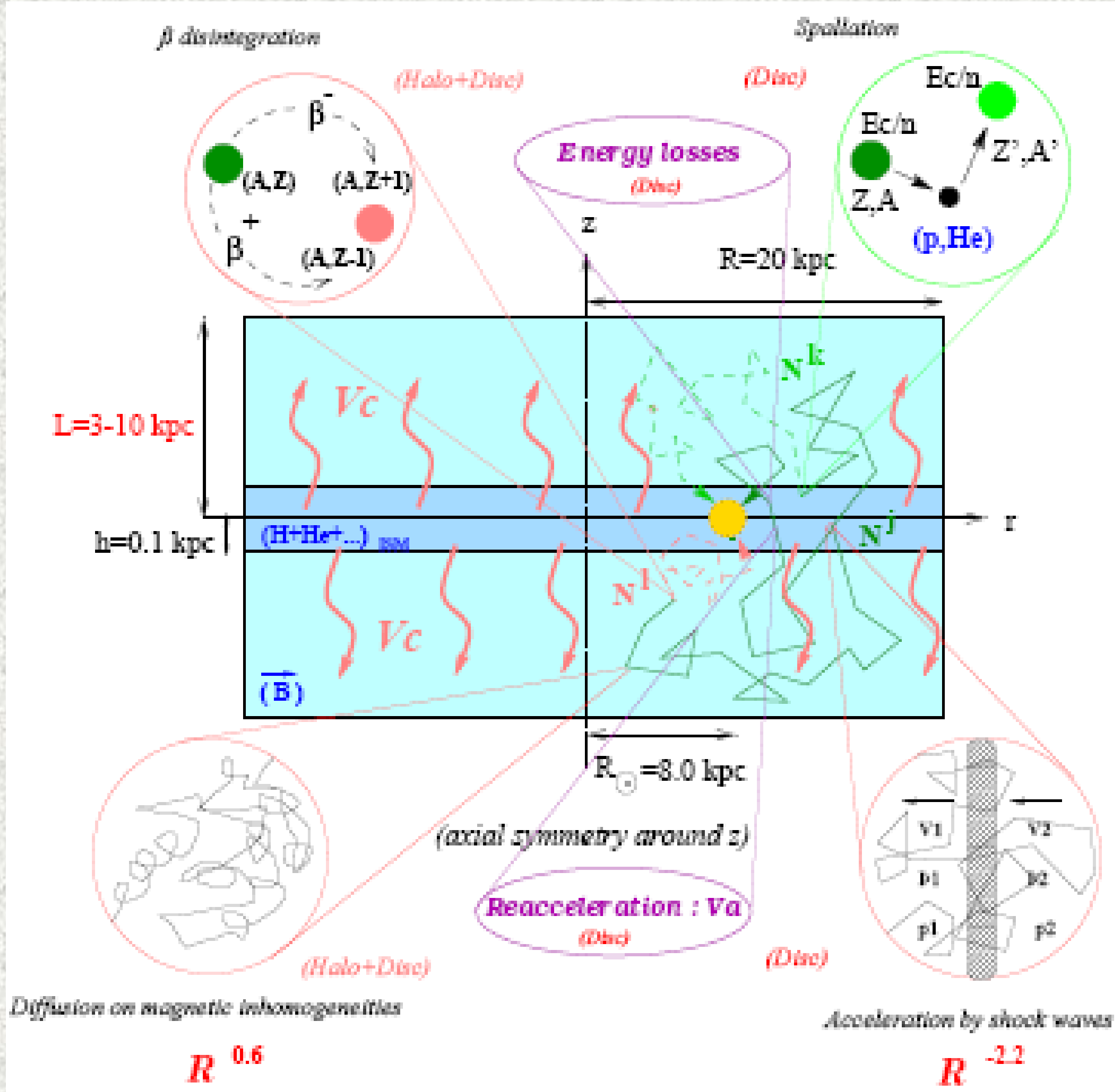
where $\langle \sigma v \rangle$ is the thermally averaged cross section times the velocity of the DM particle, dN_j/dE_j is the production spectrum from one DM annihilation into the species j, m_χ is the WIMP mass and $\rho_\chi(r, z)$ is the DM density distribution in space (i.e. the galactic halo).

In the 2-zones semi-analitical diffusive model an analitical solution for the space-dependent diffusive equation is still possible.

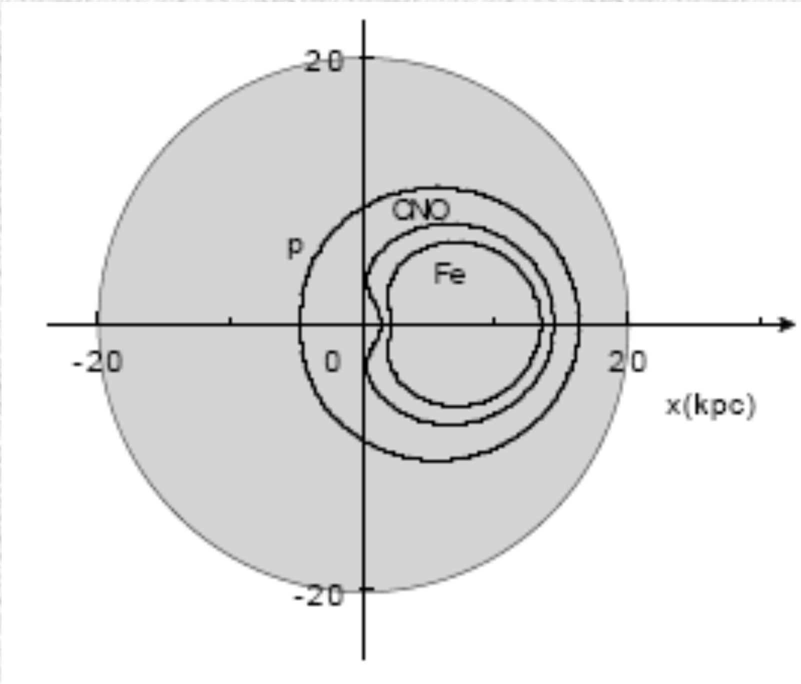
Free parameters of a 2(3) D diffusive model

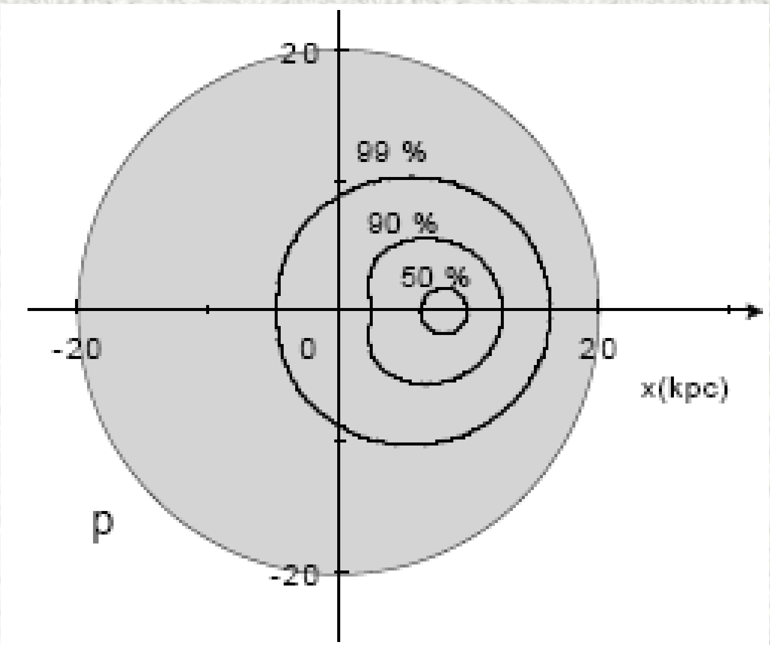
- Diffusion coefficient: $K(R)=K_0\beta R^\delta$
- Convective velocity: V_c
- Alfven velocity: V_A
- Diffusive halo thickness: L
- Acceleration spectrum: $Q(E)=q_0 p^\alpha$

K_0, δ, V_c, V_A, L, (α)



Spatial origin of cosmic rays





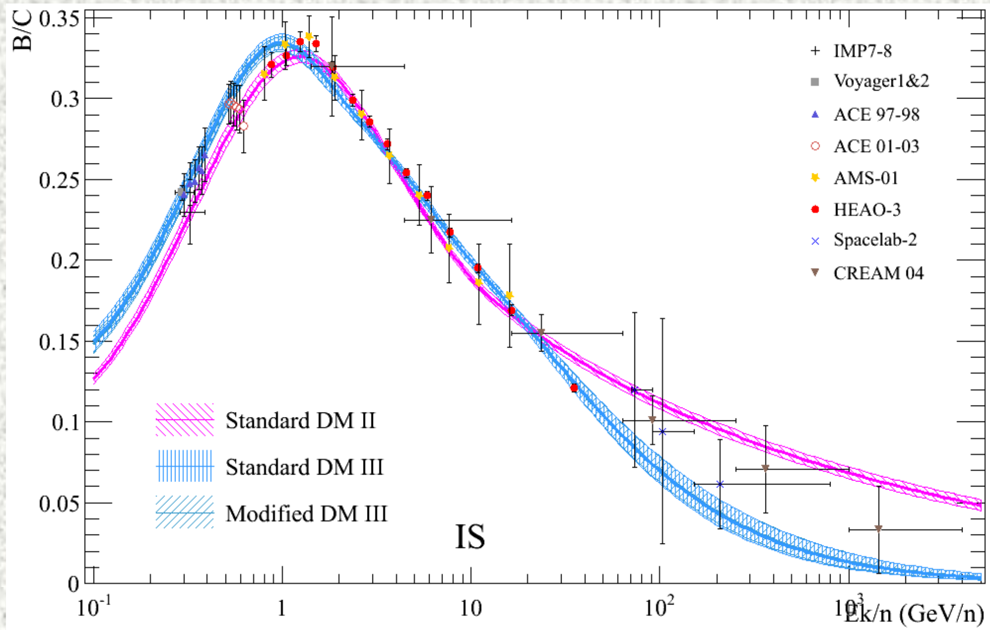
Some species have a local origin: $L_{max} \sim \sqrt{K(E)t}$

Radioactive nuclei: $t_{rad} = \gamma\tau_0 = \gamma \ln 2 \; t_{1/2}$
@ GeV/n, $K_0 \sim 10^{28}$ cm²/s, $t^{10Be} = 1.5$ Myr → $l_{rad} \sim 0.1$ kpc

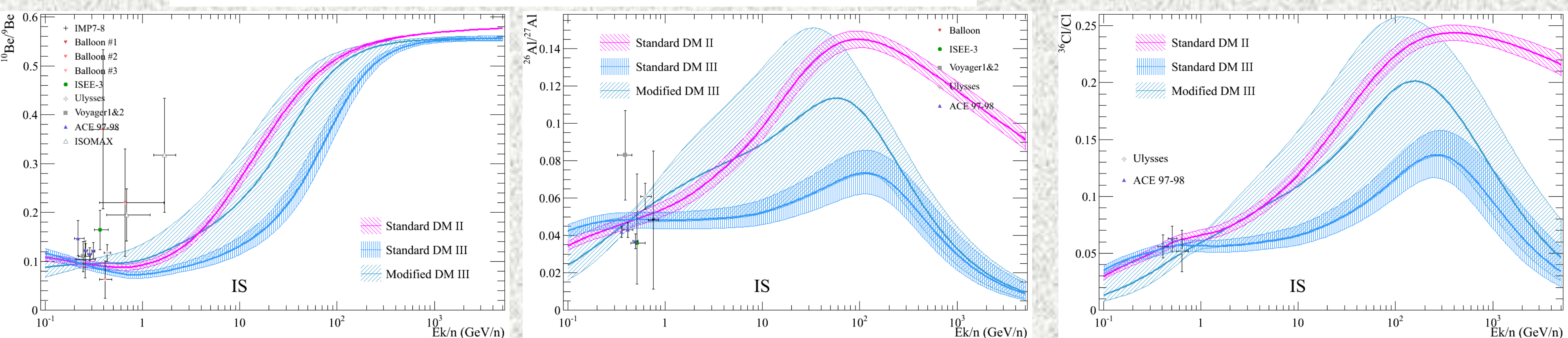
Leptons: $t_{loss} = 300$ Myr (1 GeV)/E
@ E>10 GeV → $l_{e+e-} \sim 1$ kpc

Propagation of CRs: DATA and MODELS

Putze, Derome, Maurin A&A 2010



B/C: still high degeneracies in the propagation models



Antiprotons in CRs
I. Secondary component

Secondary antiprotons in cosmic rays (CR) are produced by spallation reactions on the interstellar medium (ISM)

$$\left.\begin{array}{l} p_{CR} + H_{ISM} \\ p_{CR} + He_{ISM} \\ p_{CR} + H_{ISM} \\ He_{CR} + He_{ISM} \end{array}\right\} \bar{p} + X$$

To calculate the **secondary** antiproton flux:

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

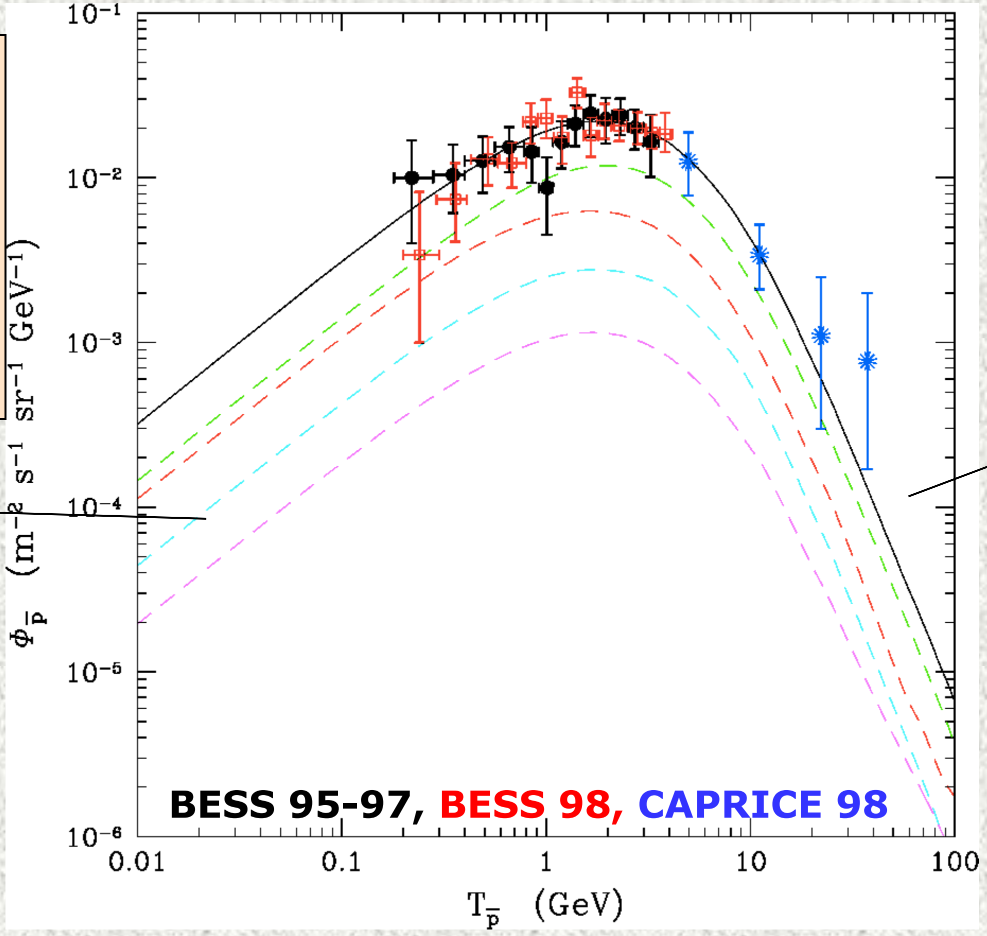
  (The only measured cross section is pp → $\bar{p}$ + X)
- Propagation *(diffusive models)*

SECONDARY ANTIPROTON FLUX and DATA

CR – target

p - H
p - He
He - H
He - He

☀ **Solar Minimum**



Total flux

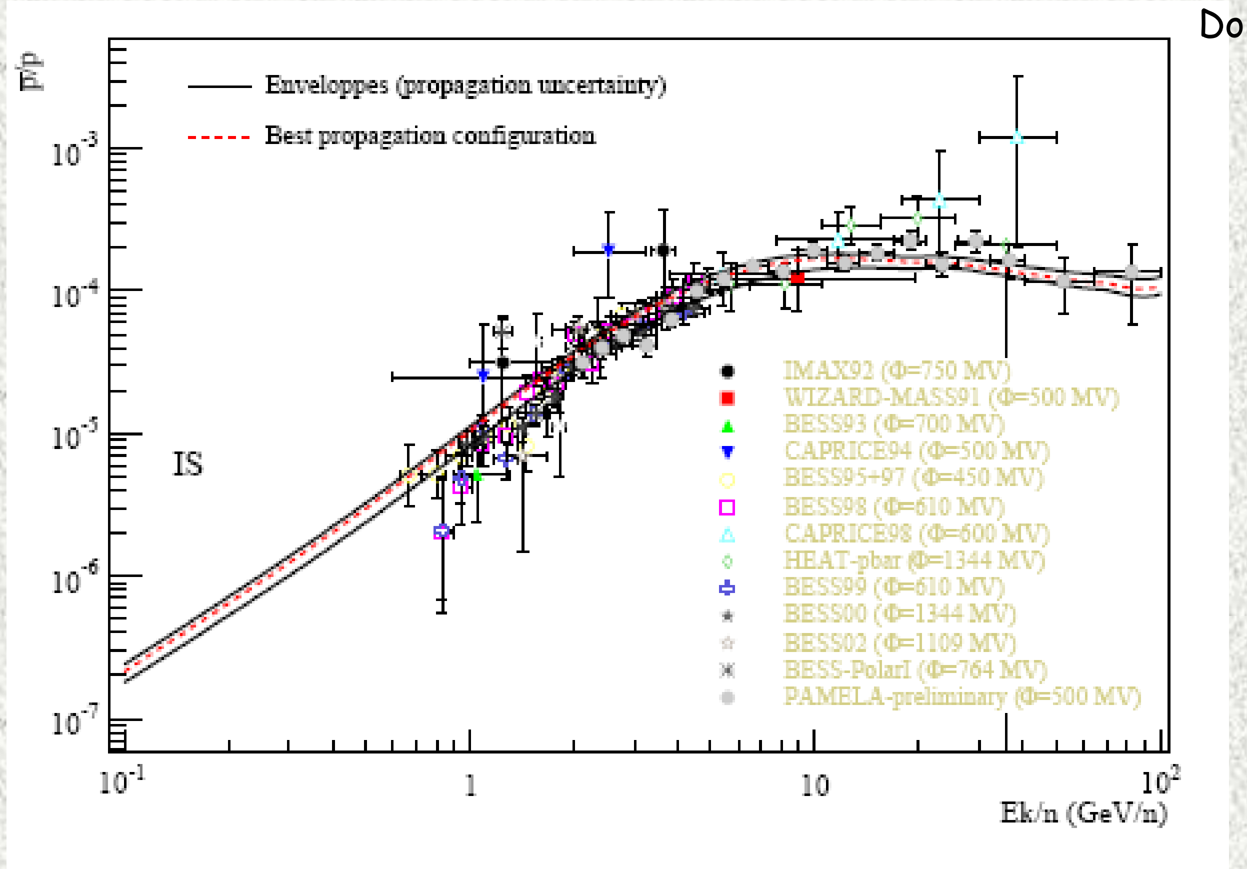
FD et al, 2002

N.B. Propagation parameters: B/C best fit

Antiproton: data and models

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

Donato et al. PRL 2009



<u>NO need for new phenomena (astrophysical / particle physics)</u>

Antiprotons in CRs
II. Primary component from DM

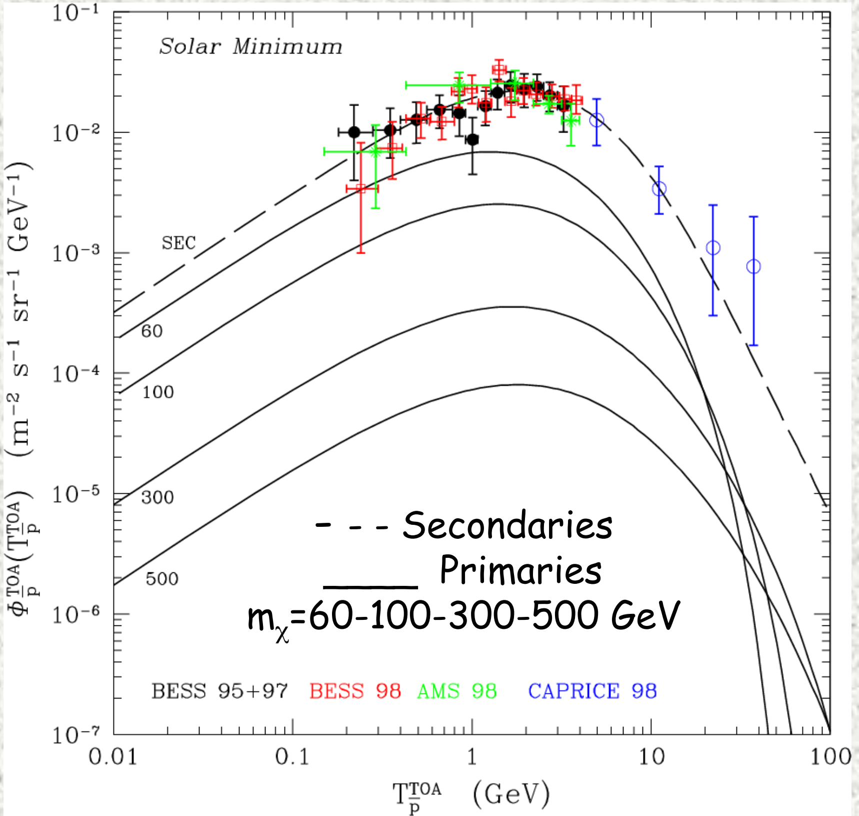
Source:

$$q_{\bar{p}}^{susy}(E_{\bar{p}}) = <\sigma_{ann} v> g(E_{\bar{p}}) \left\{ \frac{\rho_\chi(r,z)}{m_\chi} \right\}^2$$

Annihilation cross section

Production spectrum

χNumber density



Production takes place everywhere in the halo!!

Solutions (still analytical in the 2D model) different from secondaries

Antideuterons in CRs
I. Secondary component

- Proton and helium measured fluxes;
  antiproton calculated/measured fluxes

- Production and non-ann (tertiary) cross sections

- Nuclear fusion: coalescence model, one parameter P_{coal}
  the flux depends on $(P_{coal})^3$ (fit to data);
  more realistic: Monte Carlo (few data to tune simulations)

- Propagation in the MW from source to the Earth:
  2-zones semi-analytic diffusion model

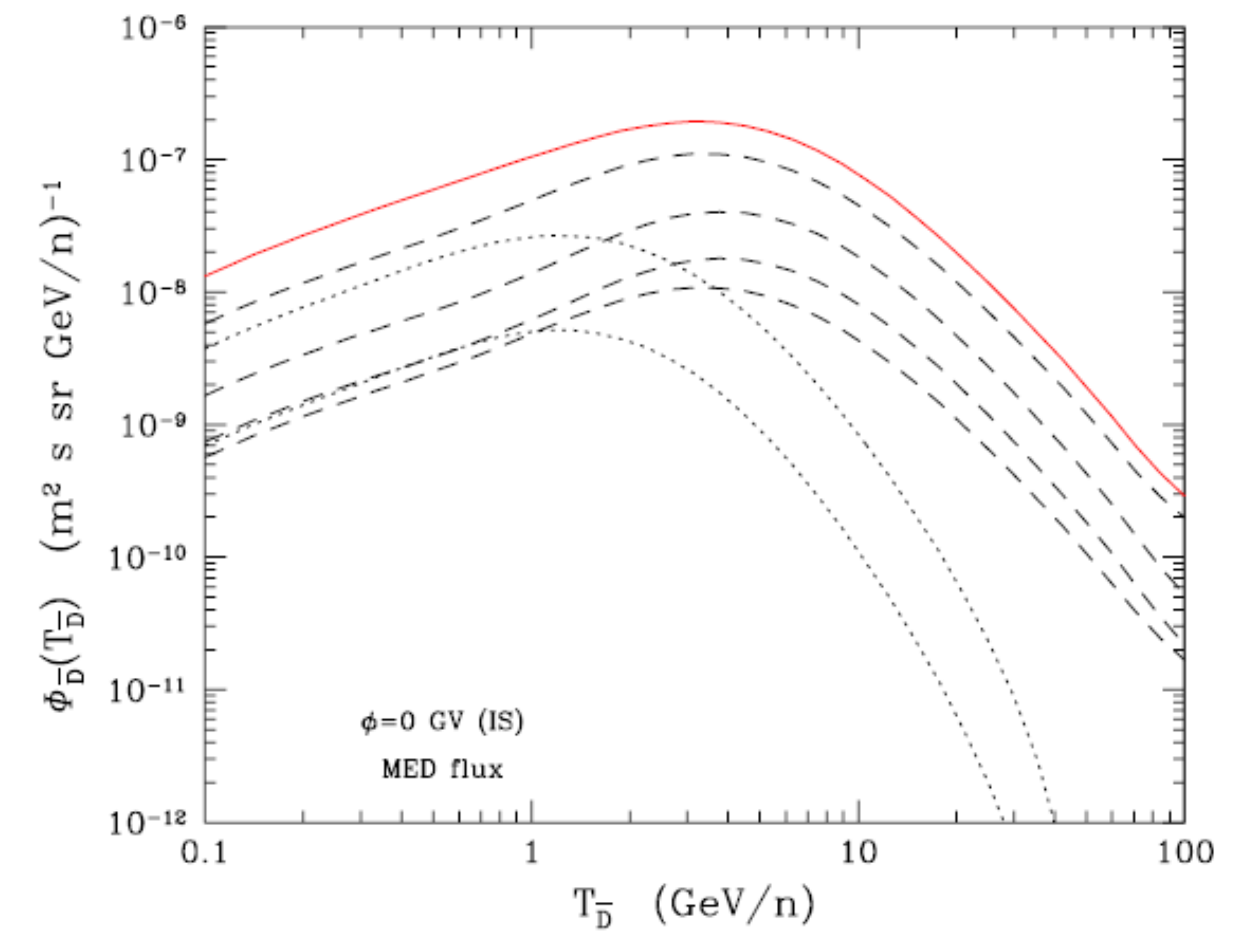
Secondary antideuterons

FD, Fornengo, Maurin arXiv:0803.2460, PRD in press

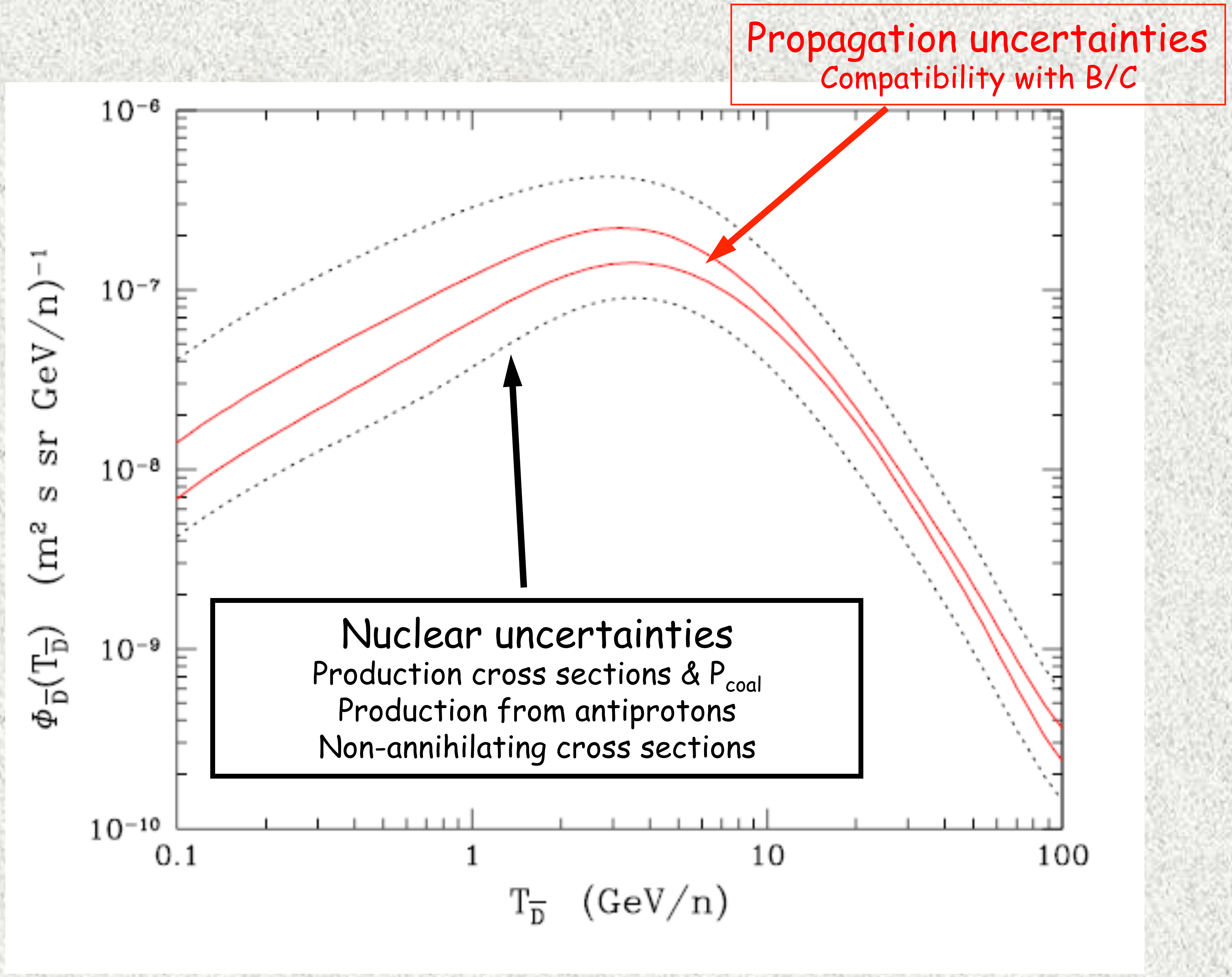
Contributions to Secondaries

p-p
p-He
He-H
He-He

$\bar{p}$ -H
$\bar{p}$ - He



Secondary antideuterons: predictions (and no data!)



ANTIDEUTERONS from RELIC NEUTRALINOS

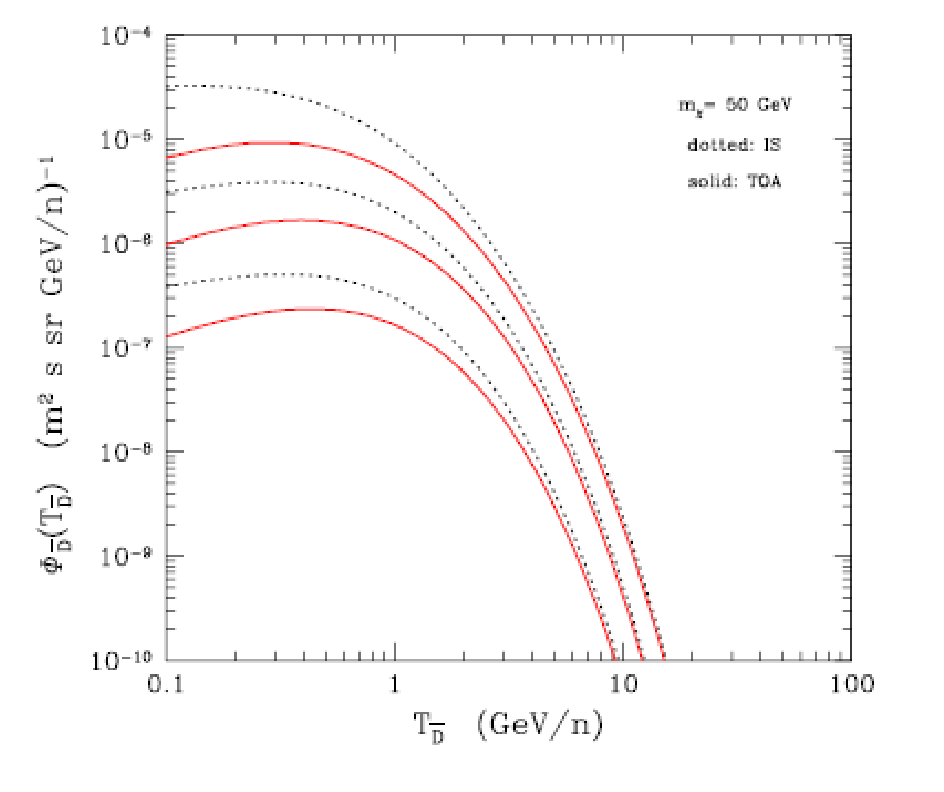
In order for fusion to take place, the two antinucleons must have kinetic energy ~0

Kinematics of spallation reactions prevents the formation of very low antiprotons (antineutrons).
At variance, neutralinos annihilate almost at rest

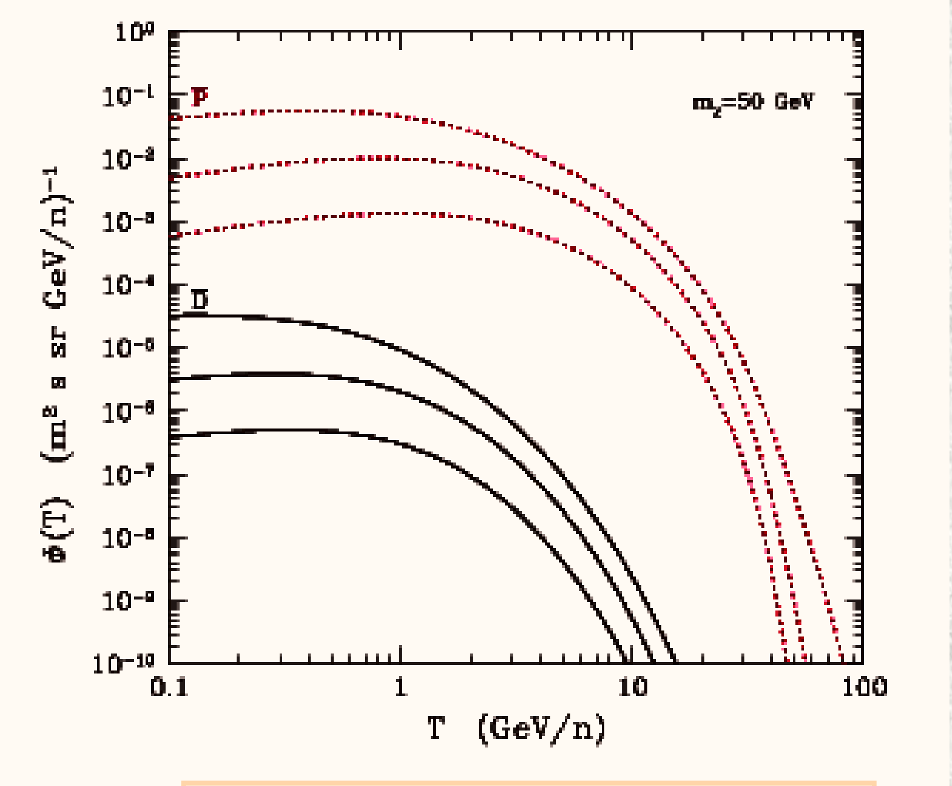
$$\boxed{\frac{dN_{\bar{\mathrm{D}}}}{dE_{\bar{\mathrm{D}}}} = \left(\frac{4\,P_{\mathrm{coal}}{}^{3}}{3\,k_{\bar{\mathrm{D}}}}\right)\left(\frac{m_{\bar{\mathrm{D}}}}{m_{\bar{\mathrm{p}}}\,m_{\bar{\mathrm{n}}}}\right)\sum_{\mathrm{F,h}} B^{(\mathrm{F})}_{\chi\mathrm{h}}\left\{\frac{dN^{\mathrm{h}}_{\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}}\left(E_{\bar{\mathrm{p}}}=\frac{E_{\bar{\mathrm{D}}}}{2}\right)\right\}^{2}}$$

N.B: Up to now, NO ANTIDEUTERON has been detected yet.
Several exprériments are planned: AMS/ISS, BESS-Polar, GAPS …

Antideuterons in CRs
II. Primary component from DM



Propagation uncertainties driven by L
At lower energies, also effect from V_C



Antiprotons & Antideuterons
Propagation Uncertainties

FD, Fornengo, Maurin 2008

Positrons in CRs
I. Secondary component

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)
- $p+H \rightarrow p+n+\pi^+$
- $p+H \rightarrow X + K^{\pm}$

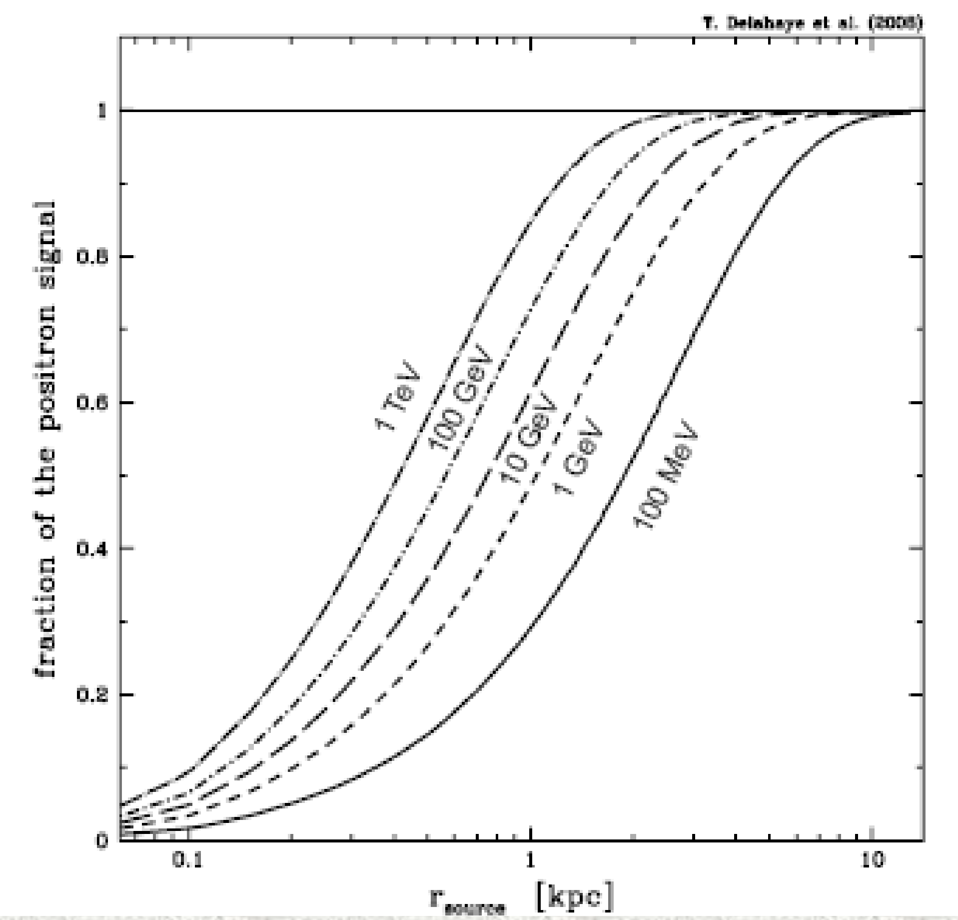
Diffusive semi-analytical model may be employed.

Above few GeV: only spatial diffusion and energy losses
At higher energies: only energy losses

Propagation of positrons (electrons): relevance of energy lossses

Energetic positrons are quite local

$$-b^{\rm loss}(\epsilon) = \begin{cases} \dfrac{\epsilon^2}{\tau_E} & \text{Inverse Compton and synchrotron} \\ +\nabla \cdot \mathbf{V}_C \, \dfrac{p^2}{6h\epsilon} & \text{Adiabatic losses} \\ +K_b \, n_H \, \epsilon & \text{Bremsstrahlung} \\ +K_i \, n_H \left\{ 3 \ln\left(\dfrac{E}{m_e}\right) + 19.8 \right\} & \text{Ionisation.} \end{cases}$$



Synchrotron and Inverse Compton* dominate

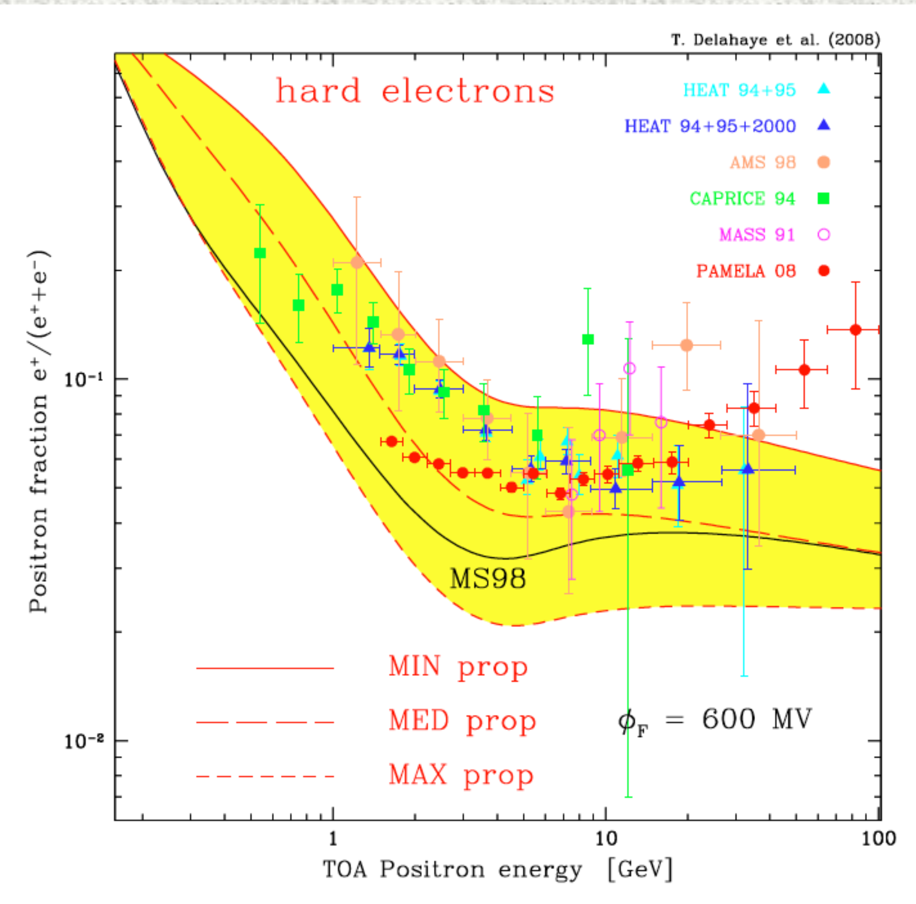
*IC=scattering of e- on photons (starlight, infrared, microwave)

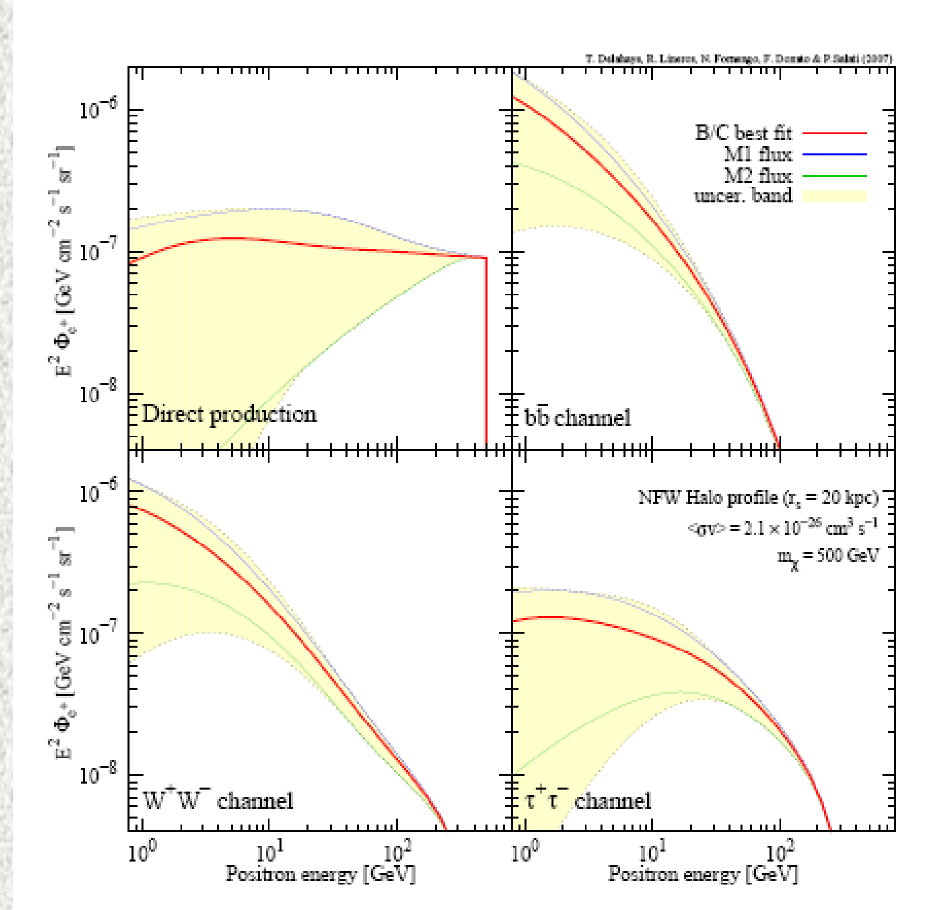
Positrons in CRs
II. Primary component from DM

- Distribution of DM in the Galaxy
- Mass and annihilation cross section: effMSSM
  overall normalization
- Source term g(E): direct production or from secondary decays (from bb,WW,$\tau\tau$, ...) ◊ Pythia MC
- Propagation in the MW from source to the Earth:
  2-zones semi-analytic diffusion model
- Solar modulation: force field approximation
  ϕ= 0.5 MV for solar minimum

Positrons: predictions and data for secondaries and DM primaries

Delahaye et al. PRD 2008





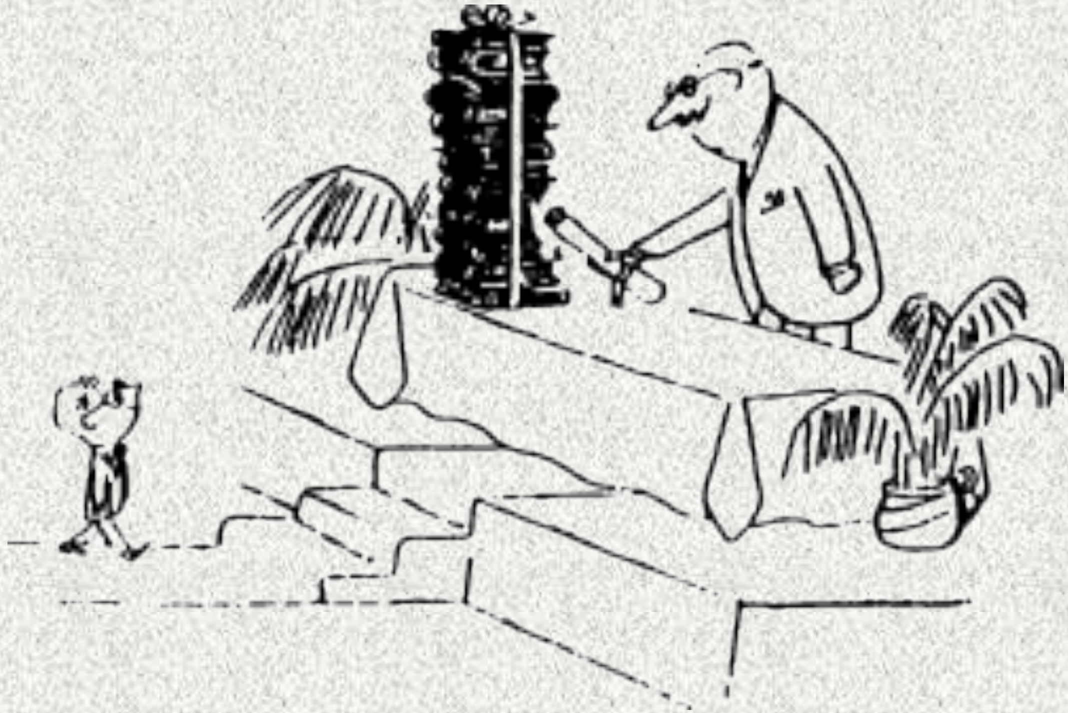
AMS-02 is going to release a bunch of data on nuclei, antiprotons and leptons which will lead to a significant improvement in the understanding of the propagation of CRs in the Galaxy and in gauging the presence of DM in galactic haloes.

Hope this lecture

and the whole ISAPP school

will help you in dealing

a fruitful ISAPP PhD ☺



Backup slides