Overview of Galactic Cosmic Rays

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"Nuclear physics for Galactic Cosmic Rays in the AMS-02 era"
Grenoble, 03.12.2012

Enrico Fermi!

On the Origin of the Cosmic Radiation, Phys. Rev. 75, 1169–1174 (1949)

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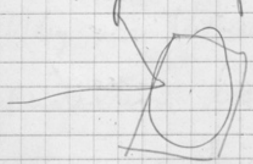
Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields



Non relativistic case

$$MV^2$$

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain

$$M(-2vV+2V^2)$$

Average gain order

$$MV^2$$

Relativistic: order

$$w\beta^2$$

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Notations

Absorption mean free path $\Lambda = 10^{26}$ cm

Absorption time $T = 3\times 10^{15}$ years

Scattering mean free path λ

Scattering " " time τ

Time - energy relationship

$$w = Mc^2 e^{\frac{t}{\tau}\beta^2} \qquad \beta = \frac{V}{c} \simeq 10^{-4}$$

$$t = \frac{\tau}{\beta^2}\log\frac{w}{Mc^2}$$

Prob. distribution in ~~time~~ age

$$e^{-\frac{t}{T}}\frac{dt}{T} = \text{prob of age } t$$

$$= -d\,e^{-\frac{t}{T}}$$

$$e^{-\frac{t}{T}} = \left(\frac{Mc^2}{w}\right)^{\frac{\tau}{T\beta^2}}$$

$$\text{prob} = \frac{\tau\,(Mc^2)^{\tau/T\beta^2}}{T\beta^2}\,\frac{dw}{w^{1+\frac{\tau}{T\beta^2}}}$$

Follows

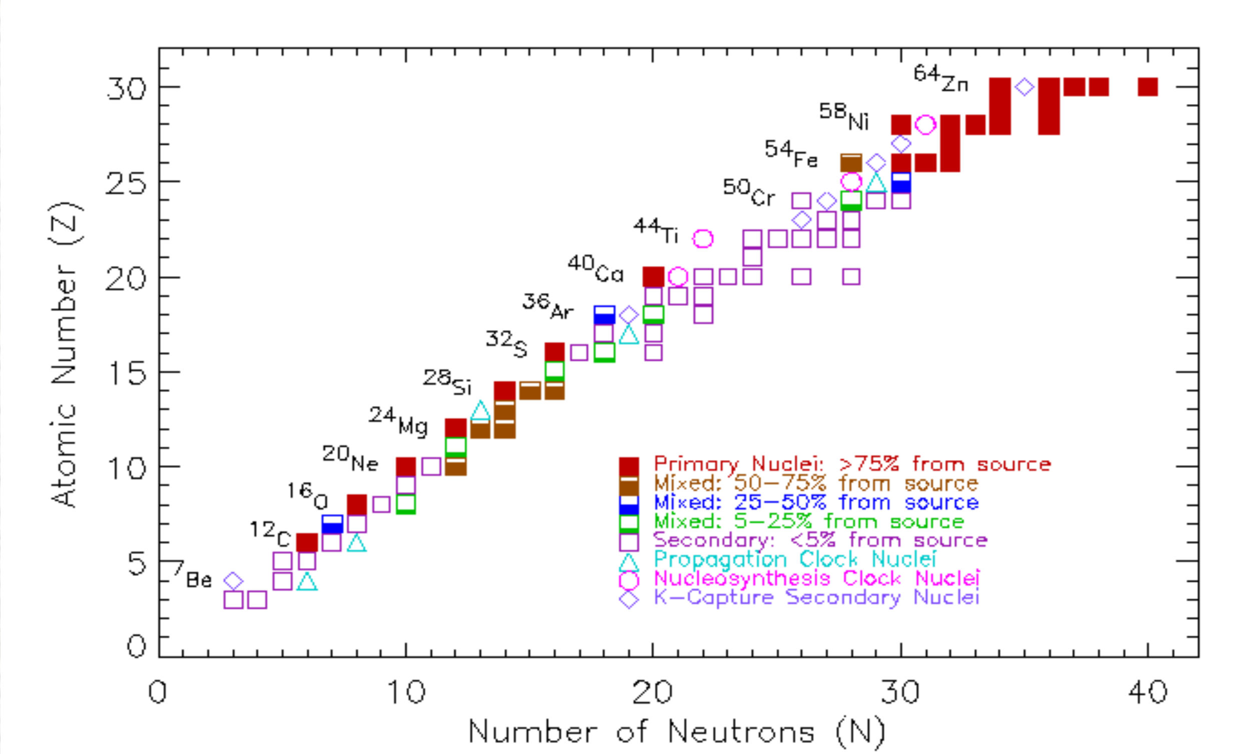
$$1+\frac{\tau}{T\beta^2} = 2.9 \qquad \frac{\tau}{T\beta^2} = 1.9$$

GALACTIC COSMIC RAYS (GCRs)

charged particles diffusing in the galactic magnetic field
Observed at Earth with E~ 10 MeV/n – 10^3 TeV/n

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+; …



Gaisser astro-ph/0608553

CRs production and propagation history

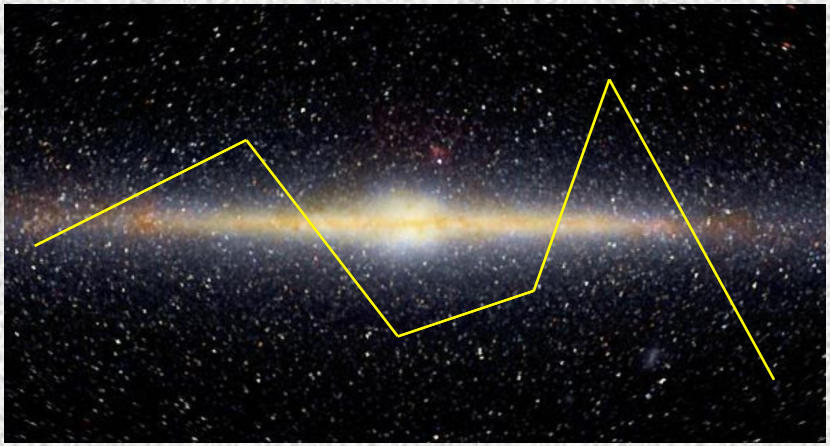
Charged nuclei - isotopes – antinuclei - leptons

1. Synthesis and acceleration

* Are SNR the accelerators?
* How are SNR distributed?
* What is the abundance at sources?
* Are there exotic sources out of the disc?

2. Transport in the Milky Way

* Diffusion by galactict B inhom.
* electromagnetic losses
  - ionization on neutral ISM
  - Coulomb on ionized plasma
* Convection
* Reacceleration



4. Solar Modulation

* Force field approximation?
* Charge-dependent models?

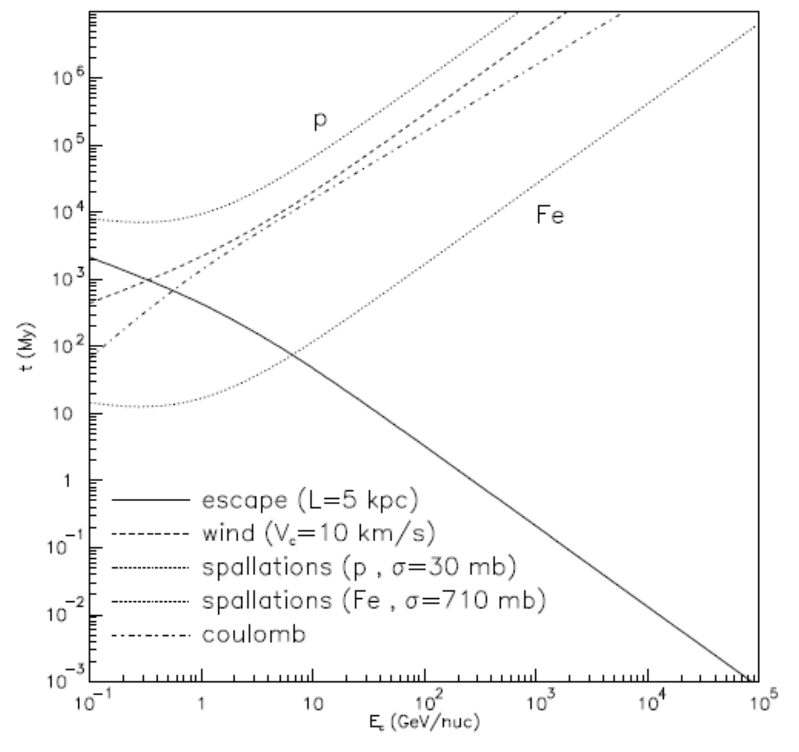
3. Nuclear interactions CRs&ISM:

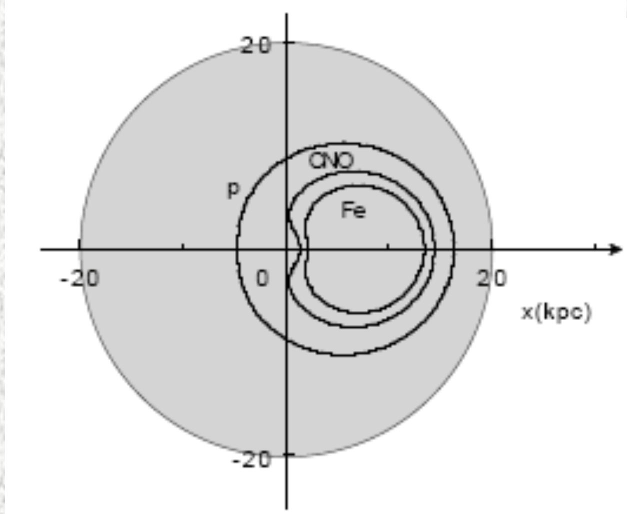
* Production of secondary nuclei
* Destruction of nuclei on the ISM

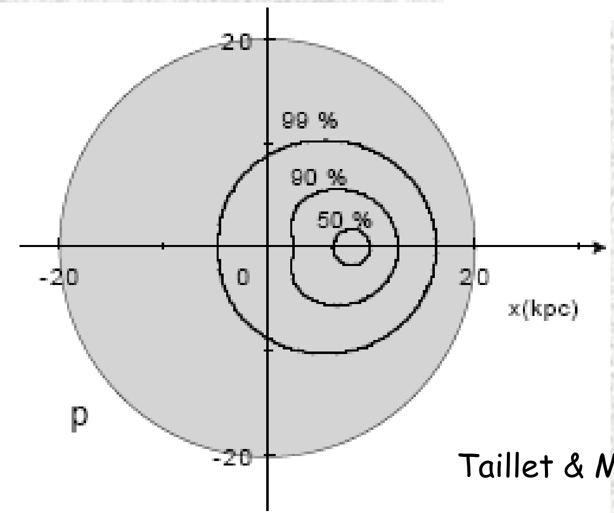
Characteristic times and distances

The smaller the time,
the most effective the process is

Protons: escape E > 1 GeV
convection and e.m. losses E<1 GeV,
Iron: escape E > 1 GeV
Spallations E<10 GeV/n







Fe more local than p

90% p from 5-6 kpc

Taillet & Maurin A&A 2003

Which cosmic ray recent data?

Antimatter: e+, p^-, D^-

→ searching for DM hints

Secondary/Primary nuclei: B/C mainly

→ fixing propagation models in the Galaxy

Primary nuclei: p, He, C, Fe, …

→ testing source properties (hardening?)

Leptons: e- (e^-+e^+)

→ testing the local ISM/SNR environment

Transport equation in diffusion models

Diffusion

Convection

Destruction on ISM

$$-\vec{\nabla}\left[K\vec{\nabla}N^j(E)-\vec{V}_c N^j(E)\right]-\Gamma^j N^j$$

$$-\frac{(\vec{\nabla}.\vec{V}_c)}{3}\frac{\partial}{\partial E}\left[\frac{p^2}{E}N^j(E)\right]=Q^j(E)+$$

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

CR sources: primaries, secondaries (spallations)

Reacceleration

Ionization, Coulomb, Adiabatic losses + Reacceleration

Diffusive models

Jopikii & Parker 1970; Ptuskin & Ginzburg, 1976; Ginzburg, Khazan & Ptuskin 1980; Weber, Lee & Gupta 1992, ...

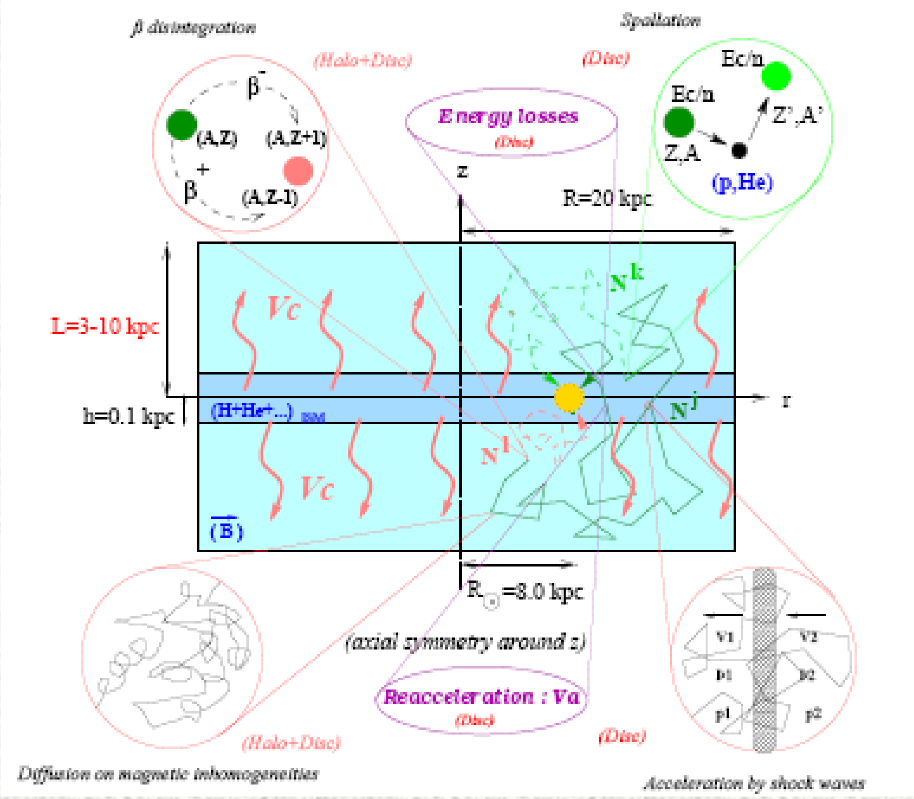
Some recently developped diffusive models:

1. Maurin, FD, Taillet, Salati ApJ 2001; Maurin, Taillet, FD A&A 2002; Putze, Derome, Maurin 2010
2. Strong & Moskalenko ApJ 1998; Moskalenko, Strong, Ormes, Potgieter, ApJ 2002
3. Shibata, Hareyama, Nakazawa, Saito ApJ 2004; 2006
4. Jones, Lukasiak, Ptuskin, Webber ApJ 2001 (Modified Weighted-slab technique)
5. Evoli, Gaggero, Grasso, Maccione JCAP 2008; Di Bernardo et al. Astrop.Ph. 2010

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

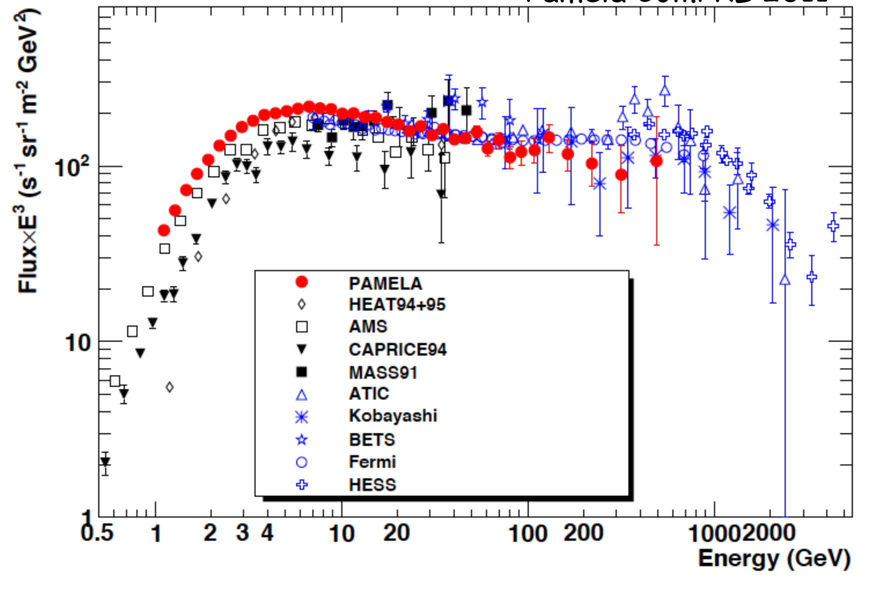
K_0, δ, V_c, V_A, L, (α)

AT LEAST!

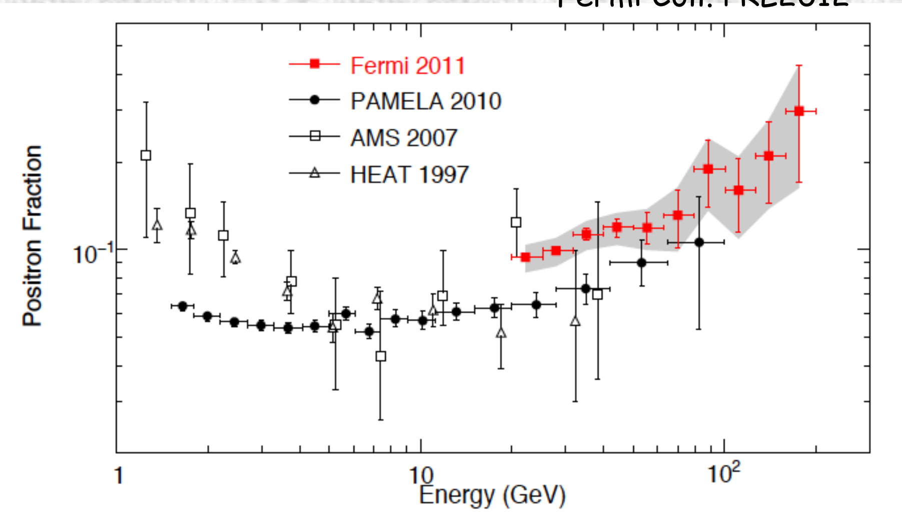


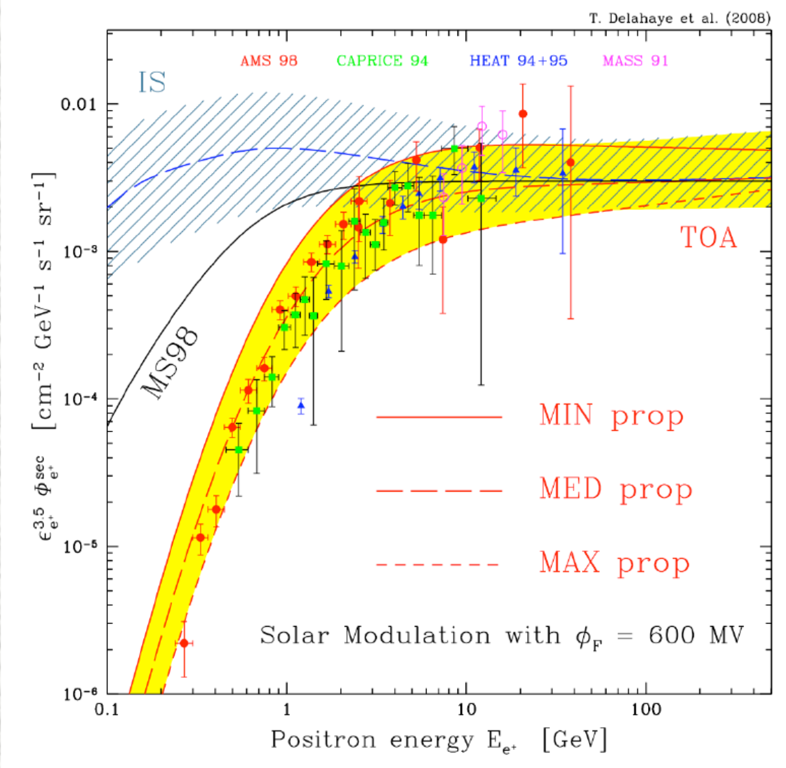
Leptons: absolute fluxes & ratio

Pamela Coll.PRL 2011



Fermi Coll. PRL2012

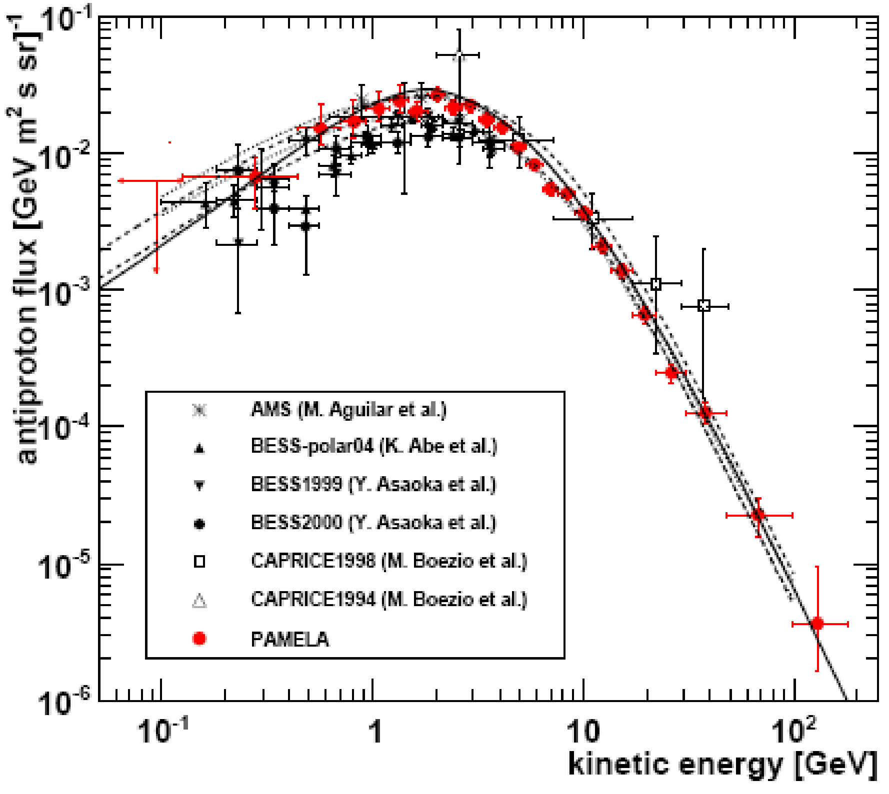


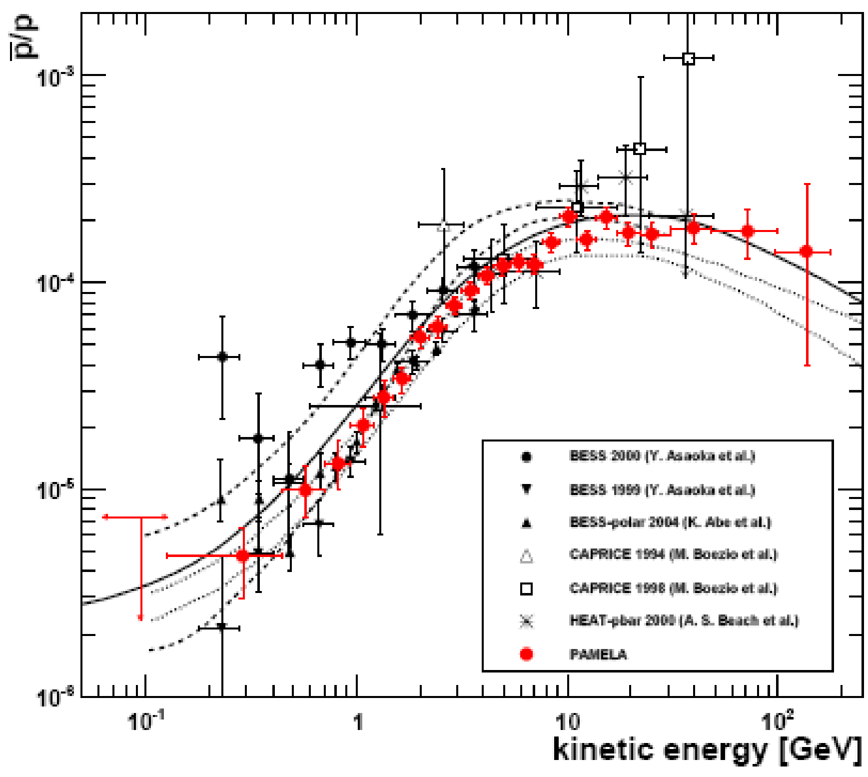


Delahaye et al. A&A 2009

Antiprotons: absolute flux and ratio

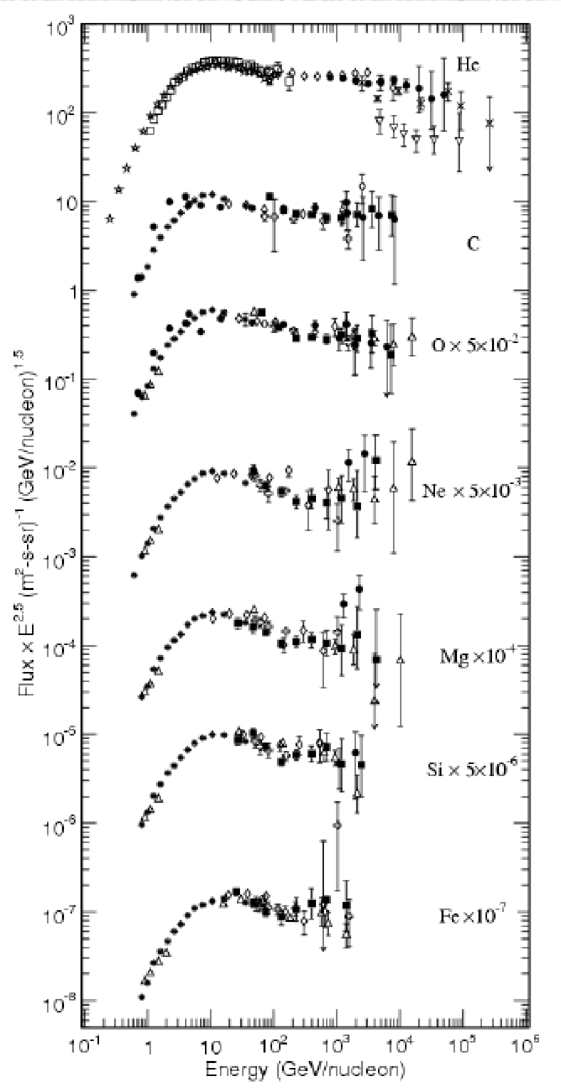
Pamela Coll, PRL 2010; BESS flights



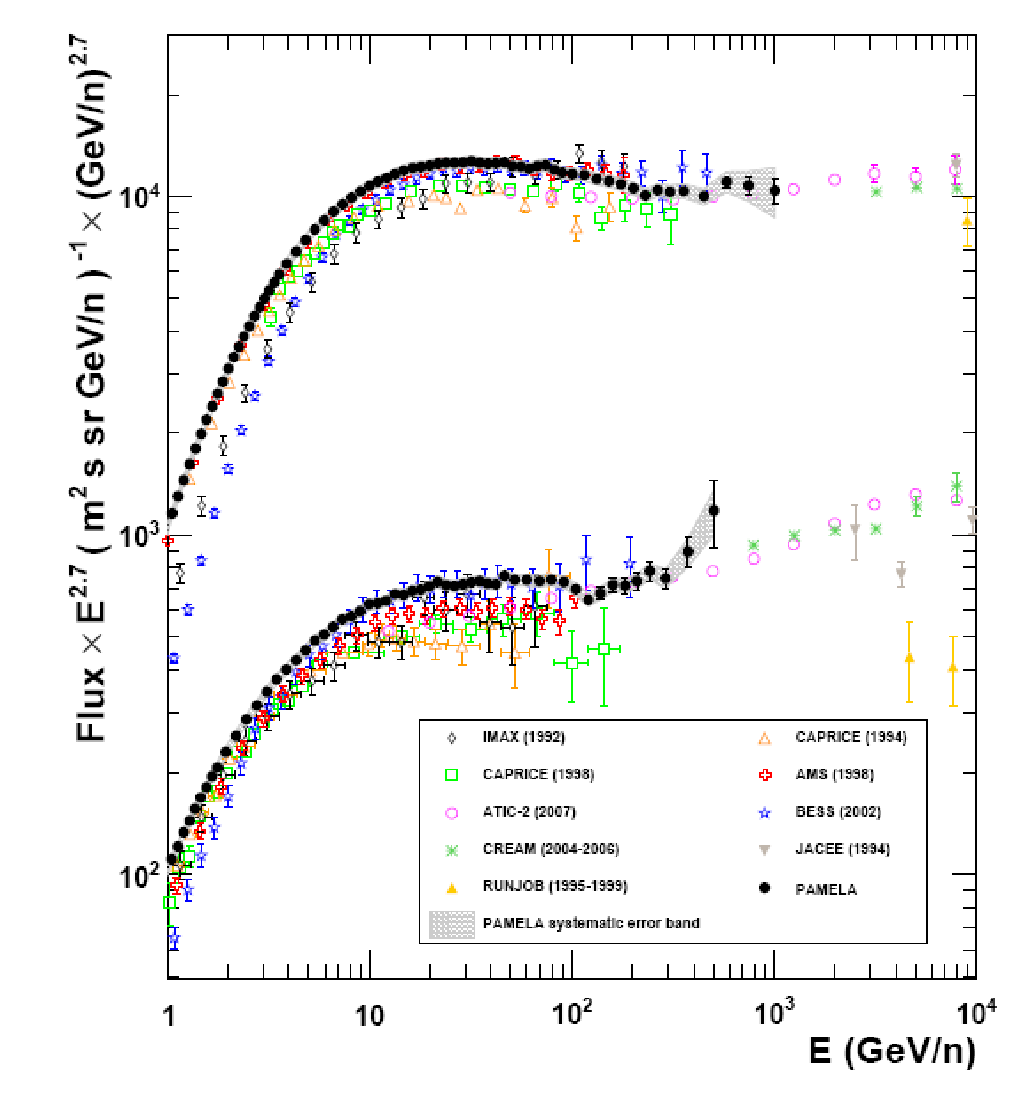


Nuclei from He to Fe

CREAM Coll., ApJL 2010

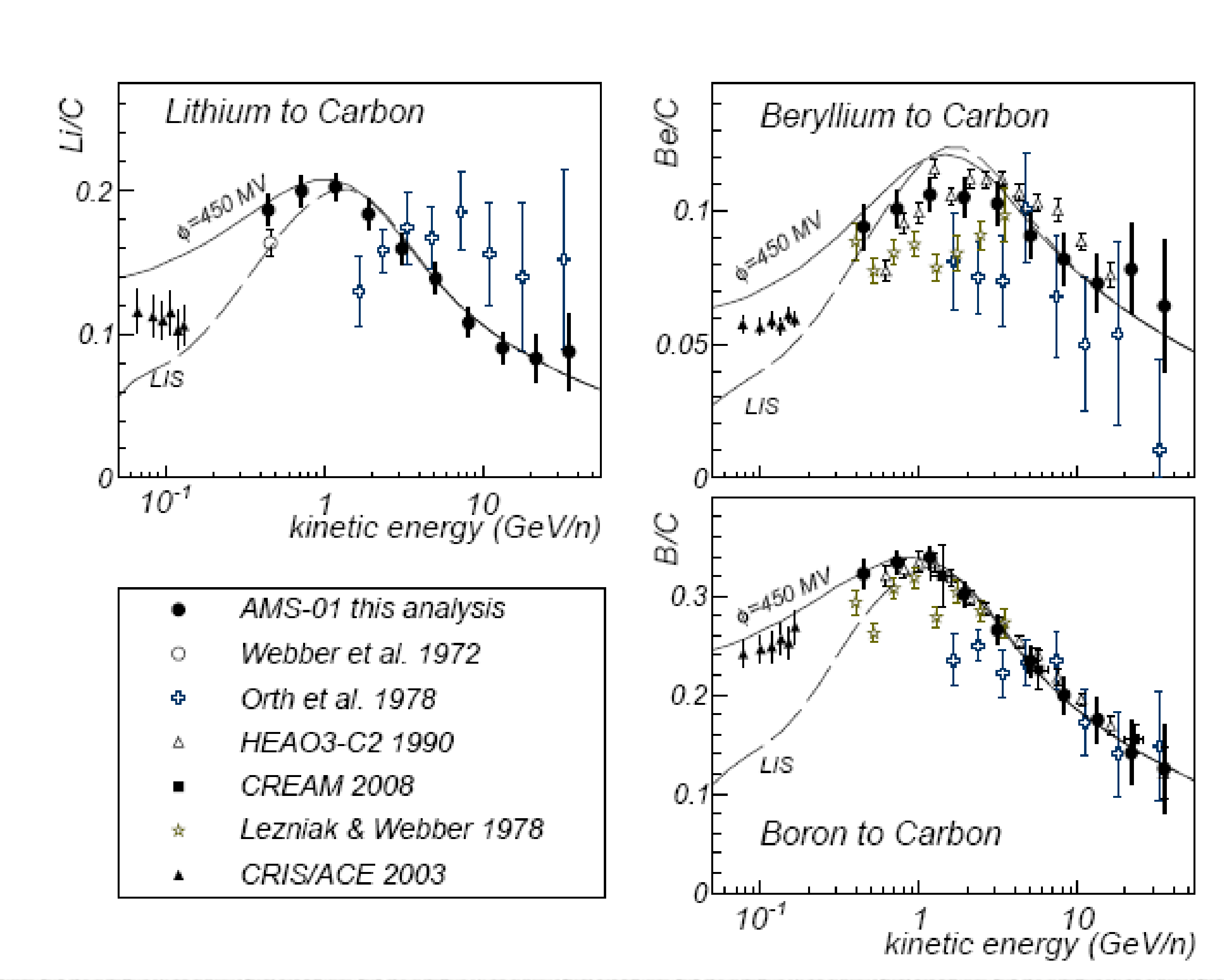


PAMELA Coll., Science 2011



Light nuclei: fluxes and ratios

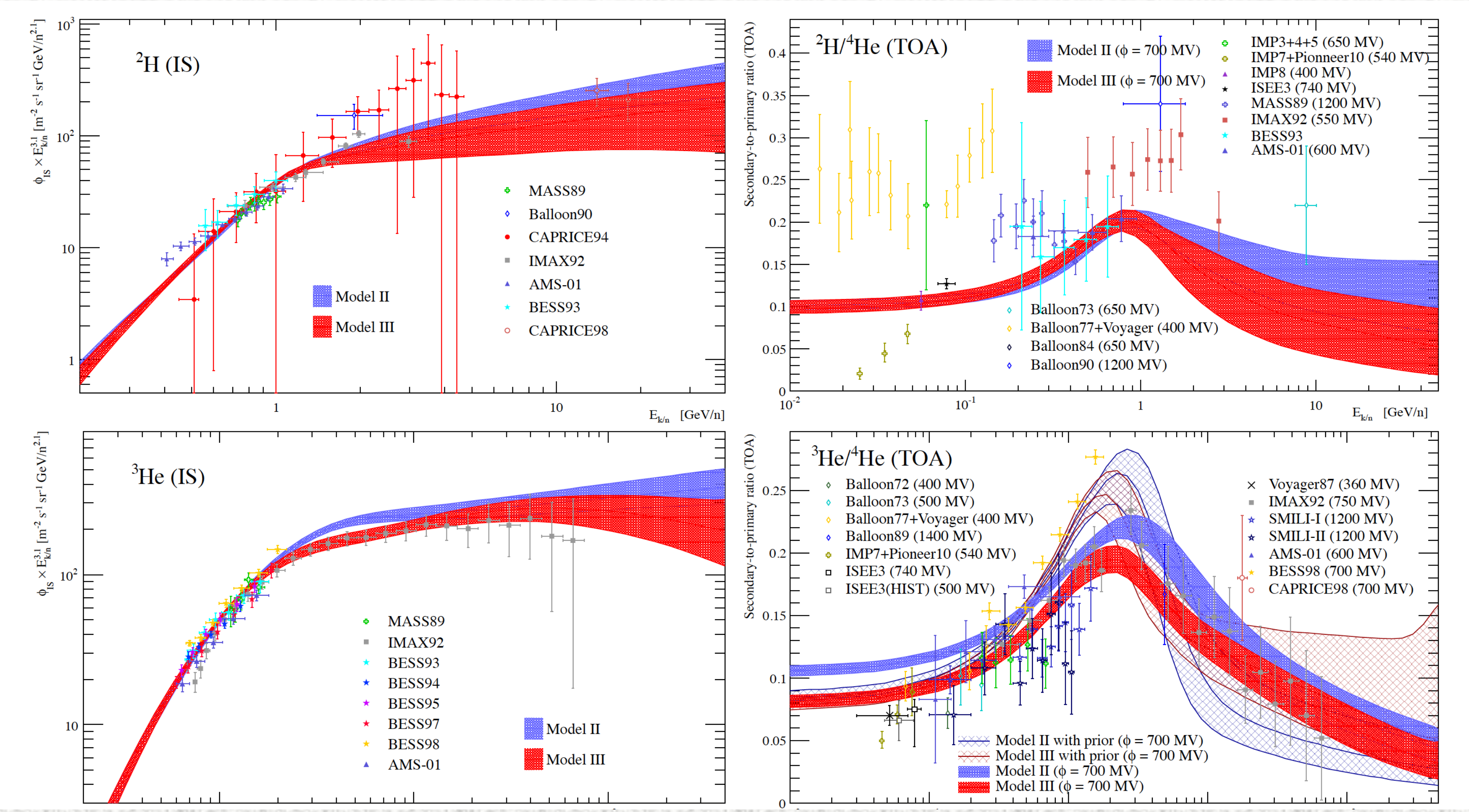
AMS-01 Coll., ApJ 2011



Z<=2 Nuclei

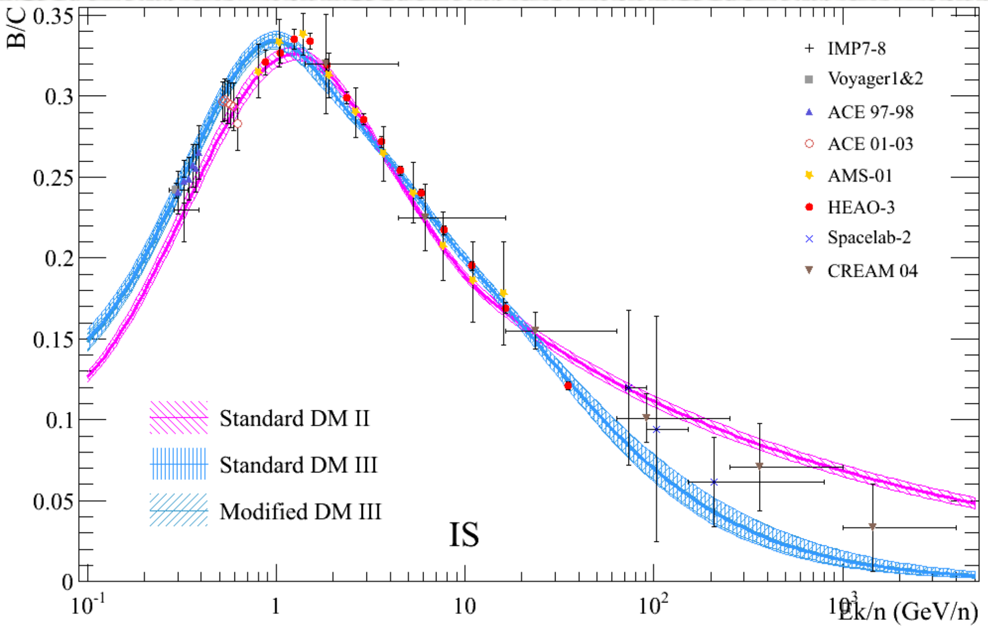
Coste, Derome, Maurin, Putze A&A 2012

^{1}H, ^{2}H, ^{3}He, ^{4}He almost as powerful as B/C
Noticeable effort on reliable cross sections

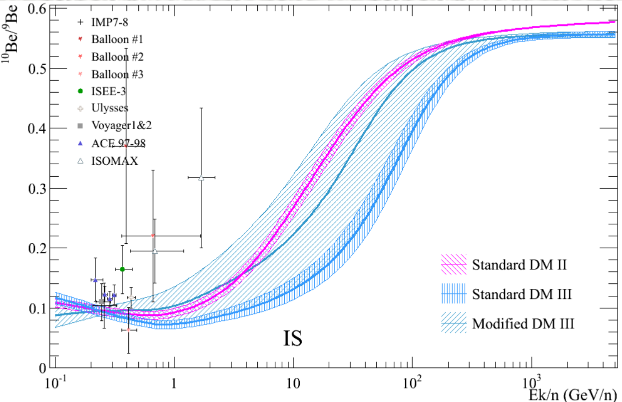


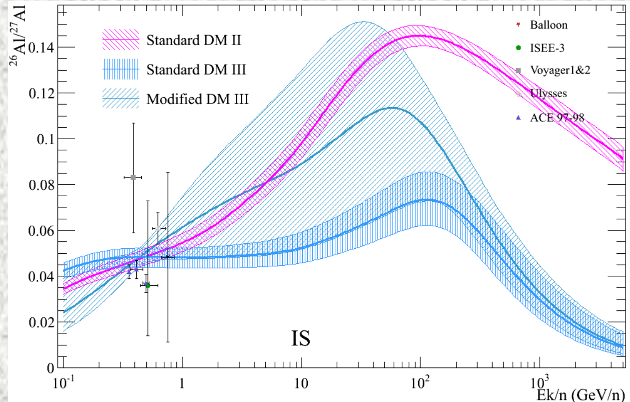
Propagation of CRs: MCMC results on B/C AND radioactive isotopes

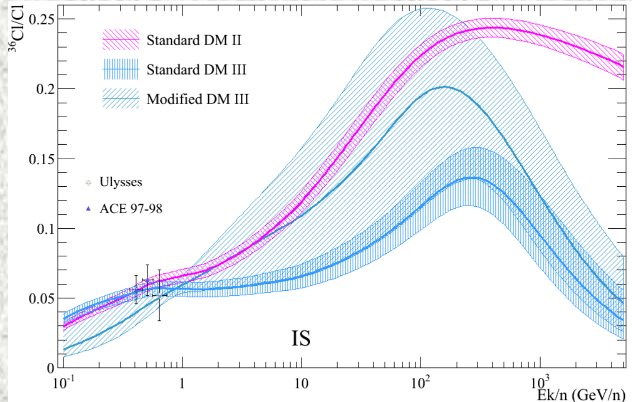
Putze, Derome, Maurin A&A 2010



B/C: high degeneracies in the propagation models



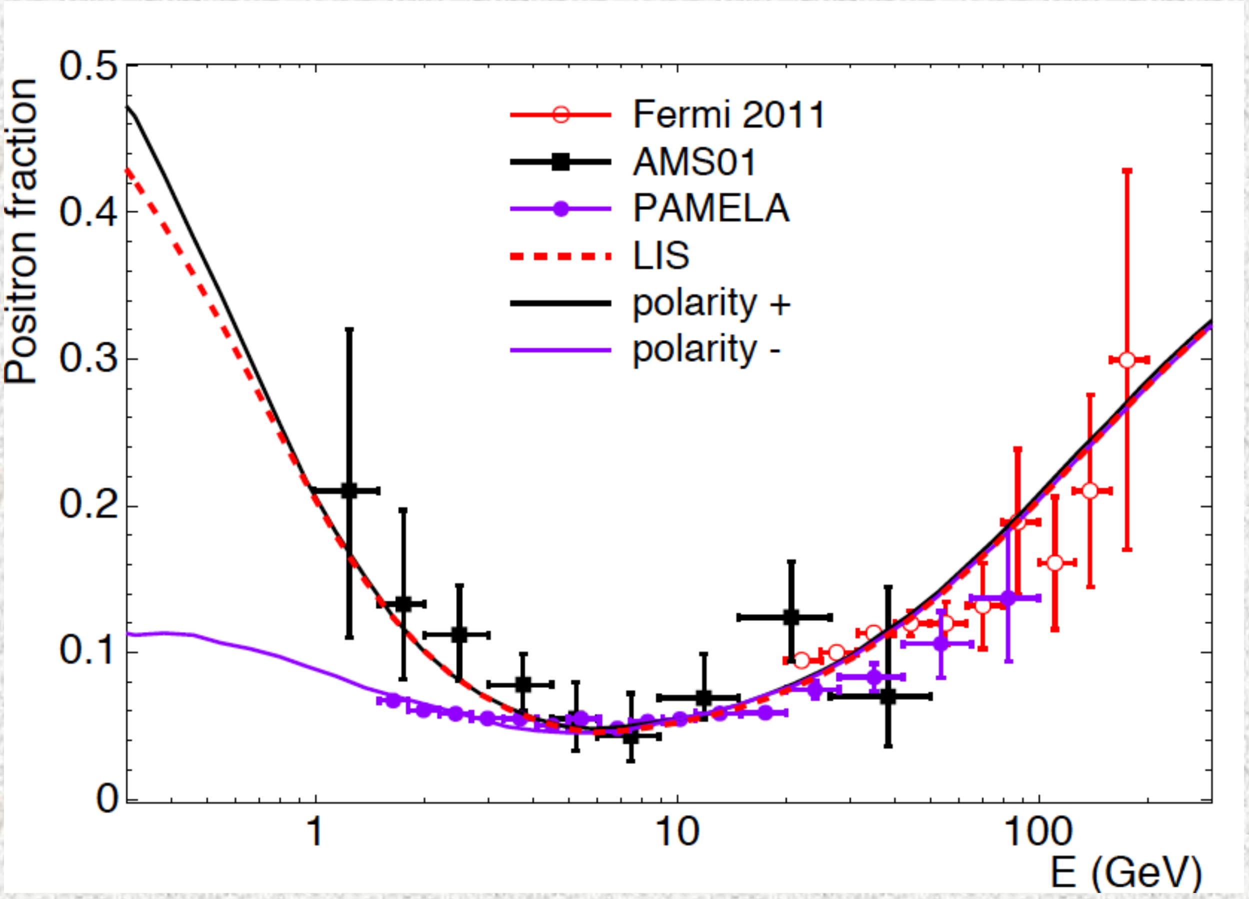




Low-energy positron fraction: new interpretation

Maccione 1211.6905

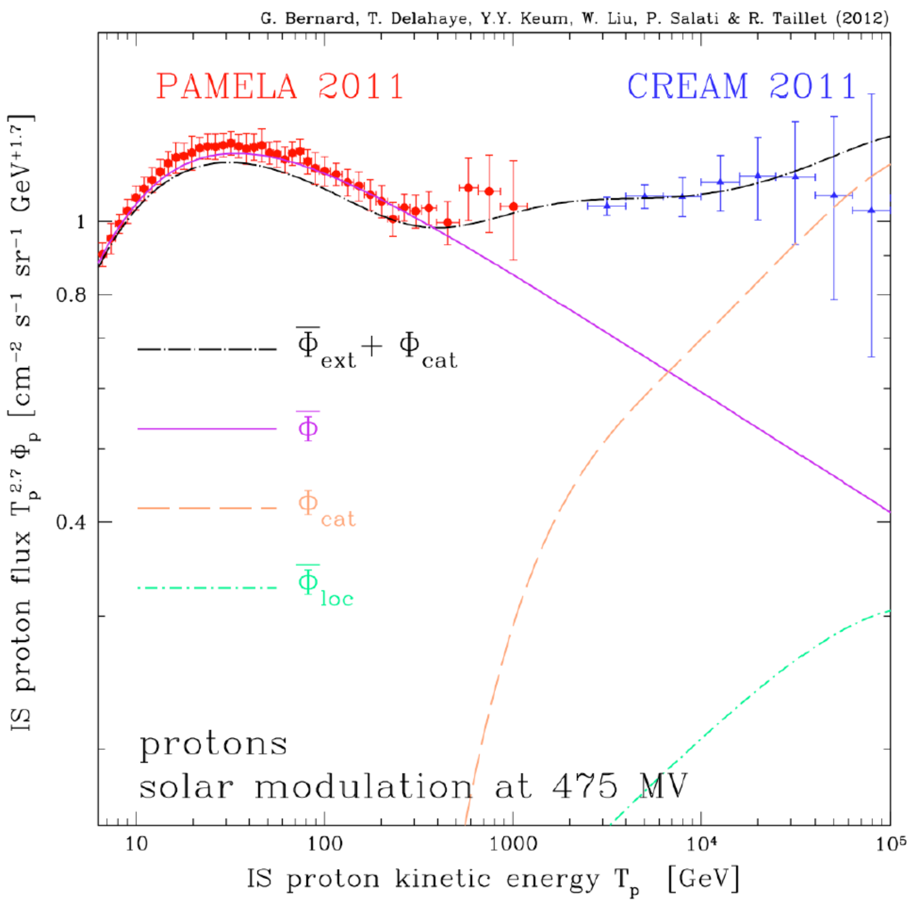
Explained by a charge-sign dependent 4D (3 space+energy) **solar model**

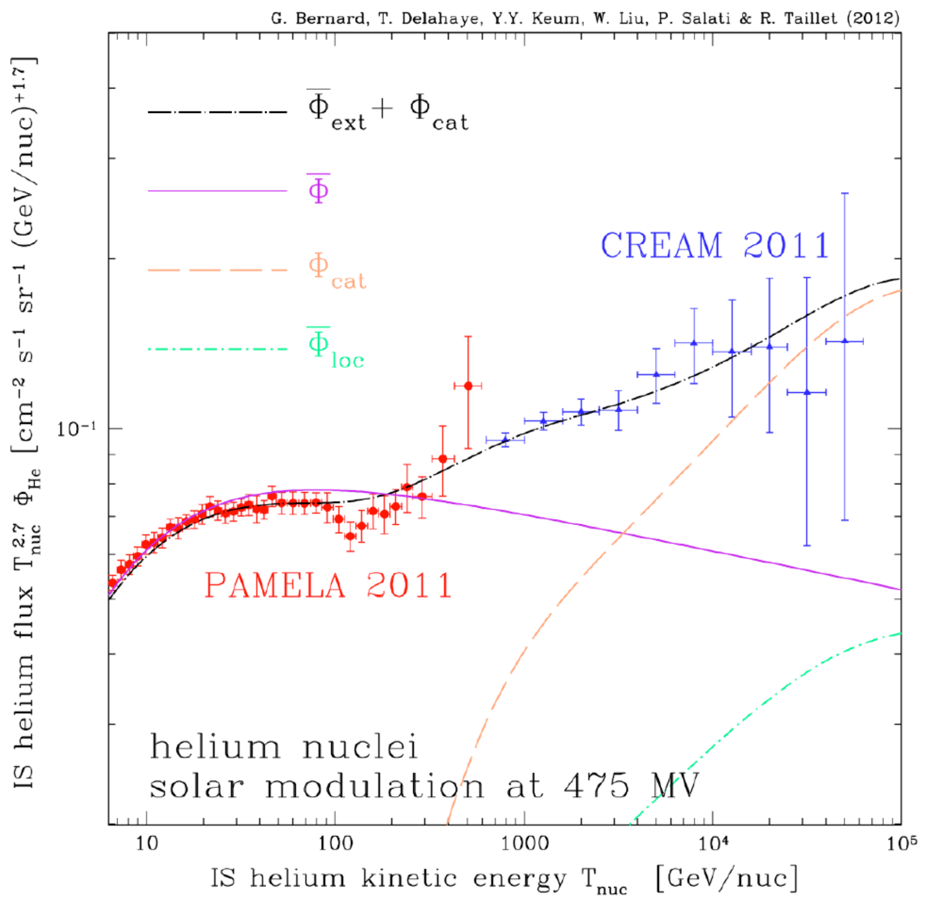


Observed primary features: new interpretations

Bernard et al. 1207.4670

Hardening due to local (~2 kpc) catalog SNRs and PSRs

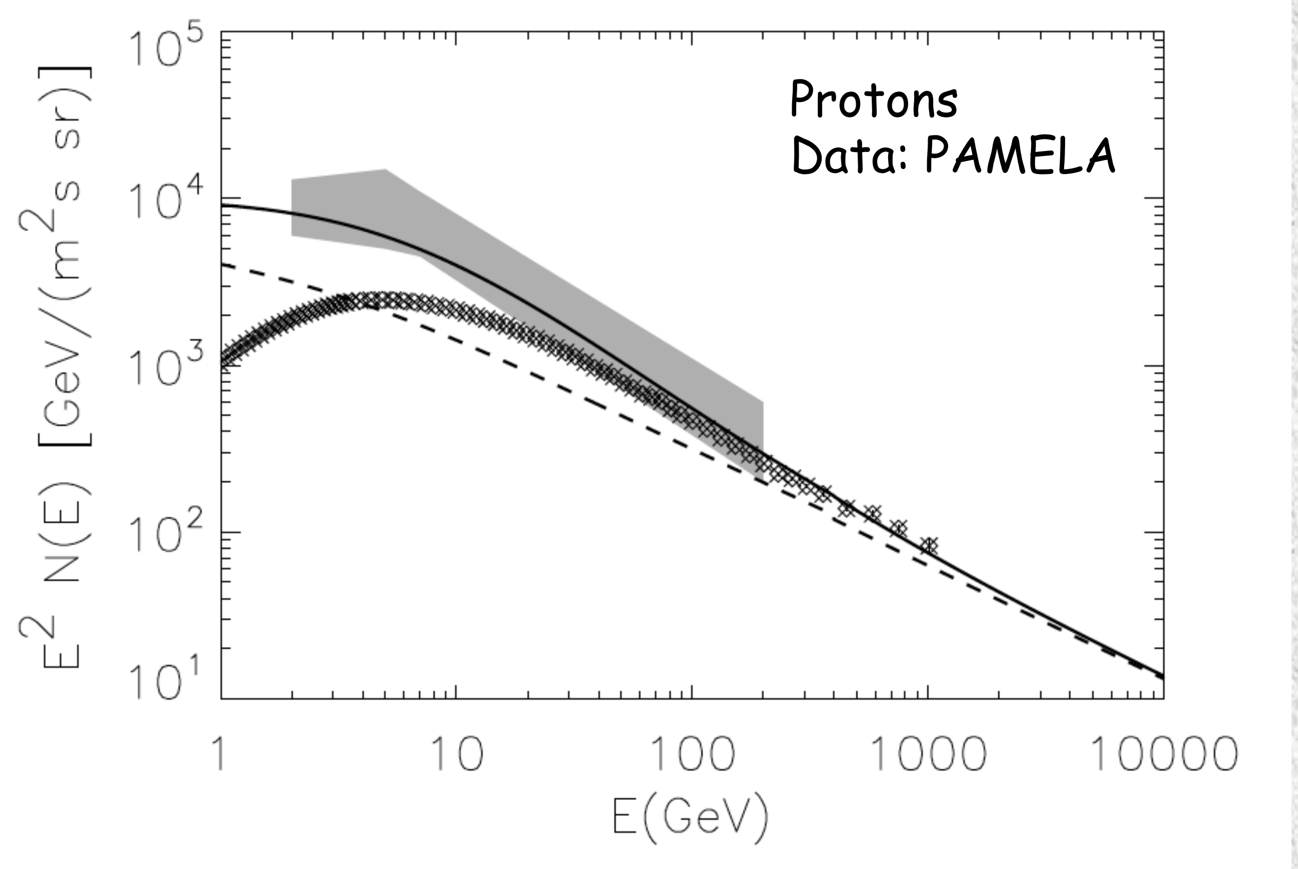




Observed primary features: new interpretations

Blasi, Amato, Serpico PRL 2012

Departure from power law spectra ("breaks") as a consequence of basic processes.
@ 10 GeV: transition from transport dominated by advection with v_A to diffusion due to turbulence of the same CRs
@ 200 GeV: transition to diffusion due to external agents (SNR bubbles)

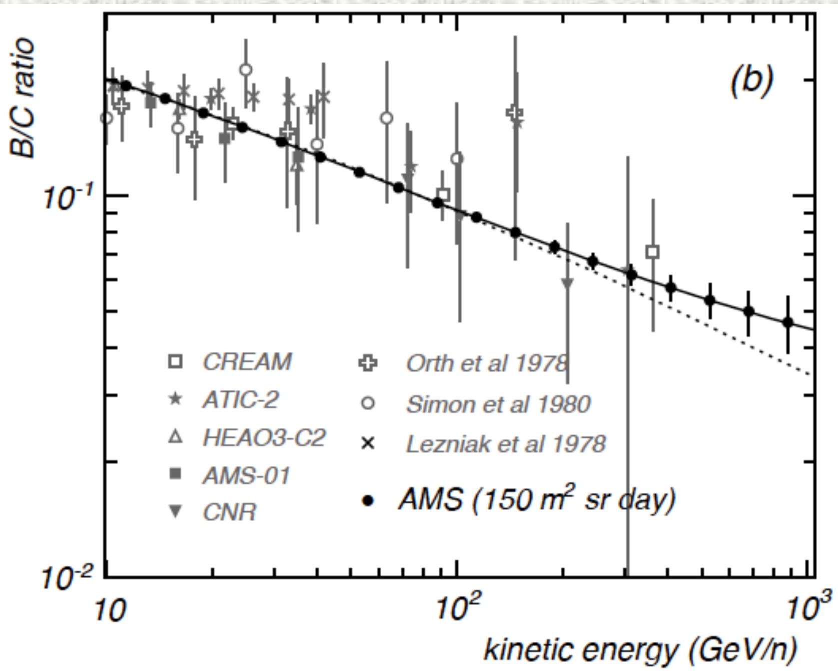


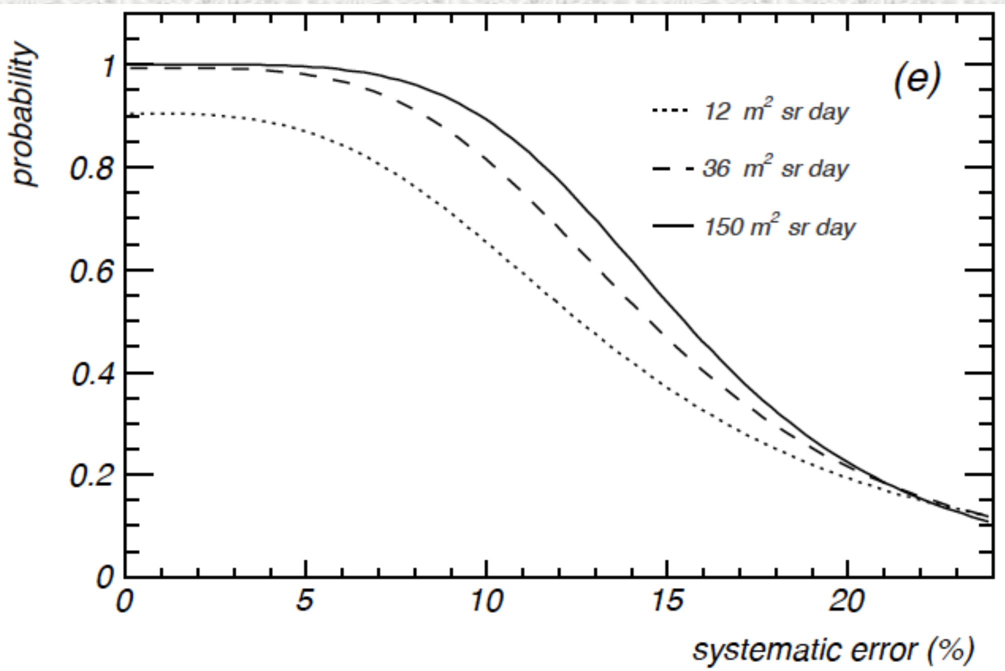
Secondaries in sources: predictions for AMS-02

Tomassetti & FD, A&A 2012

Secondary nuclei in SNRs – due to both re-acceleration and/or hadronic interactions - imply a hardening of the spectra.

Degeneracy with δ. AMS-02 can break it (see talk by N. Tomassetti)





Where do we stand with CRs? I

Despite huge modeling uncertainties:

We can predict many cosmic species with accuracy!

- **Supernovae** remnants are almost certainly the engines
- **Diffusive** models are probably realistic, even if oversimplified-
- The spectrum of the **magnetic turbulence** is fixed within a factor of 2
- The galactic disk seems sandwiched in a magnetic **halo** few kpc thick
- Some **minor effects** are present and necessary

A significant AMBIGUITY is left:

1. Among the **galactic models**
2. Given a model, among the **free parameters**

Where do we stand with CRs? II

Despite the success to qualitatively reproduce CR data we need:

- More refined models for **solar modulation**:
  - Charge-dependence; solar polarity; realistic wind treatment
  - Use of data from solar probes

    (see session tomorrow!)

- More data on **nuclear cross sections**.
  - needed for different nuclei and isotopes at various energies

    (see session after this talk)

All these items touch the Dark Matter induced antimatter cosmic fluxes

(see P. Salati's talk tomorrow)

Few open points (out of many!)

- Many data sets are not compatible
- Magnetic turbulence spectrum
- Isotropic/non isotropic diffusion? Anisotropy of CRs
- Demonstration that SNR are the accelerators
- Confirmation & understanding of slope changing in primaries

→ Multiwavelength correlations

AMS-02 is expected to bring to CR astrophysics a

breakthrough

by measuring nuclei & isotopes, hadrons & leptons, primaries and secondaries, over large energy band,

in different solar activity levels