N_i are the abundances of nuclei of type "i"

$$\frac{dN_i}{dt} = \nabla (D \nabla N_i)$$ diffusion

$$- \frac{\partial}{\partial E}(b_i \cdot N_i)$$ energy loss (e.g. Bethe Bloch)

$$- n \cdot v \cdot \sigma_i N_i$$ losses through inelastic scattering in ISM

$$- \frac{N_i}{\gamma \tau_i}$$ losses through radioactive decay

$$+ Q_i$$ source term (acceleration)

$$+ \sum_{j>i} n \cdot v \cdot \sigma_{ij} N_j$$

production through interactions of heavy nuclei in ISM

$$+ \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

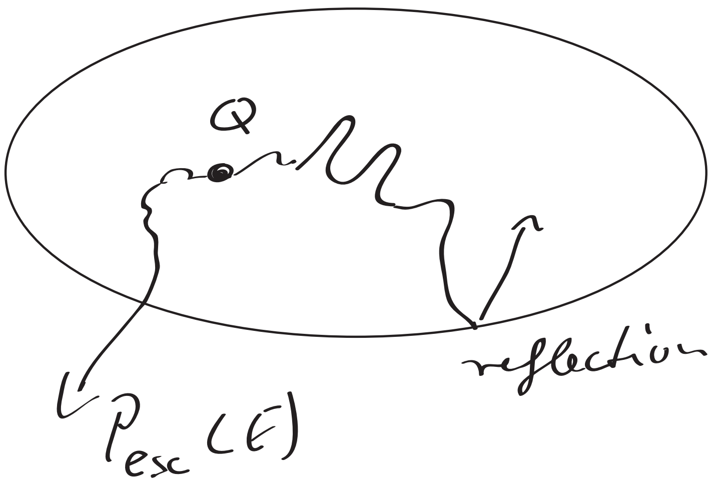
production through decay of heavy nuclei

complete solution of diffusion equation is practically impossible, too many unknown parameters

→ therefore, simplifications

diffusion coefficient $D \sim 10^{28} \frac{cm^2}{s}$

A simple model: Leaky Box model



free propagation of CRs in closed volume (galaxy)

energy-dependent escape probability $P_{esc}(E)$ (constant in time)

$$\frac{dN_i}{dt} = -\frac{N_i}{\tau_{esc}} - \frac{\partial}{\partial E}(b_i \cdot N_i) - n v \sigma_i N_i - \frac{N_i}{\gamma \tau_i}$$

$$+ \overline{Q}_i + \sum_{j>i} n v \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma \tau_{ij}}$$

if we do not have significant energy losses, spallation etc.

$$\rightarrow N_i(E) = N_{i,0}\, e^{-\frac{t}{\tau_{esc}}}$$

$\Rightarrow \tau_{esc}$ corresponds to the average time the CR-particles spend in the volume (galaxy)

Traversed matter / column density

in equilibrium $\frac{dN_i}{dt} = 0$

$$\frac{N_i}{\tau_{esc}(E)} = \cancel{-\frac{\partial}{\partial E}(b_i N_i)}_{E > 1\,\mathrm{GeV}} - \left(\bar{n} \cdot v \cdot \sigma_i + \frac{1}{\gamma \tau_i}\right) N_i + \bar{Q}_i$$

$$+ \sum_{j>i} \left(\bar{n}\, v\, \sigma_{ij} + \frac{1}{\gamma \tau_{ij}}\right) N_j$$

model

from nuclear physics

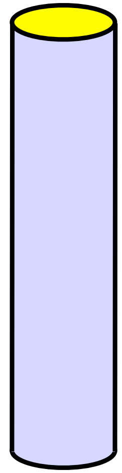
Pathlength of cosmic rays

VOLUME 29, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 1972

Composition of Cosmic-Ray Nuclei at High Energies*

Einar Juliusson, Peter Meyer, and Dietrich Müller
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 26 May 1972)

We have measured the charge composition of cosmic-ray nuclei from Li to Fe with energies up to about 100 GeV/nucleon. A balloon-borne counter telescope with gas Cherenkov counters for energy determination was used for this experiment. Our first results show that, in contrast to low-energy observations, the relative abundances change as a function of energy. We find that the ratio of the galactic secondary nuclei to primary-source nuclei decreases at energies above about 30 GeV/nucleon.

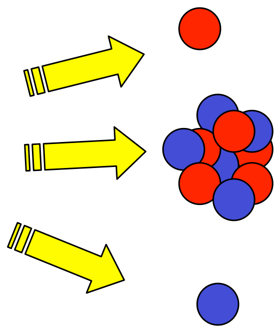


g/cm^2

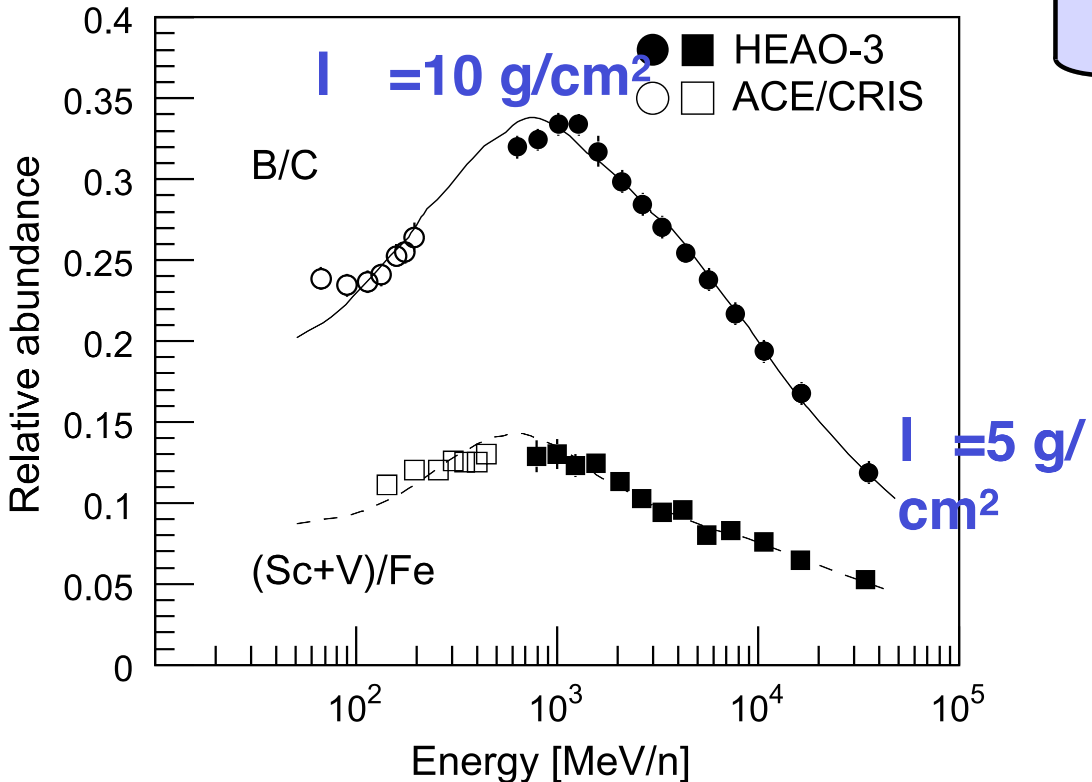
primary/secondary-ratio

spallation

C → B + n + p



$$\lambda(E) \propto E^{-0.6}$$



N. Yanasak, ApJ 563 (2001) 768

TRACER: propagation of cosmic rays

Leaky-Box Propagation Parameters

- Continuity equation:

$$N_i(E) = \frac{1}{\Lambda_{esc}(E)^{-1} + \Lambda_i^{-1}} \times \left(\frac{Q_i(E)}{\beta c \rho} + \sum_{k>i} \frac{N_k}{\lambda_{k \to i}} \right)$$

- Source Spectrum:

$$Q_i(E) = n_i \cdot E^{-\alpha}$$

- Escape Path Length:

$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

- Spallation Path Length:

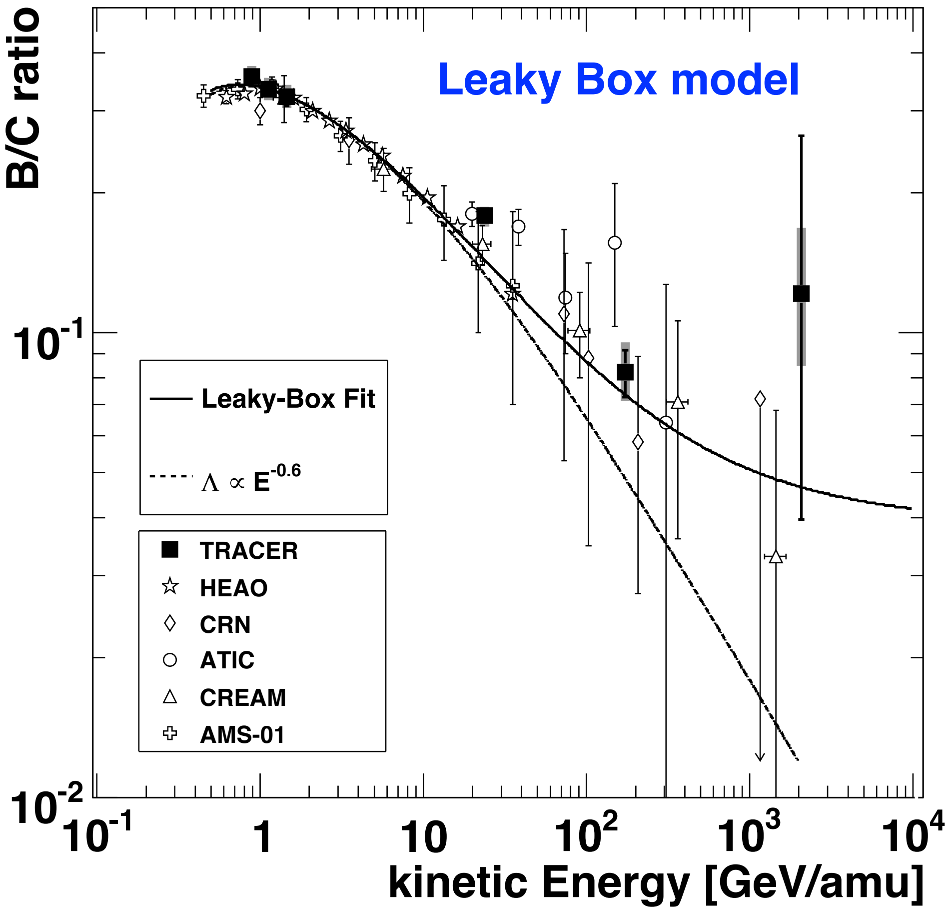
$$\Lambda_i = \frac{m}{\sigma(A)}$$

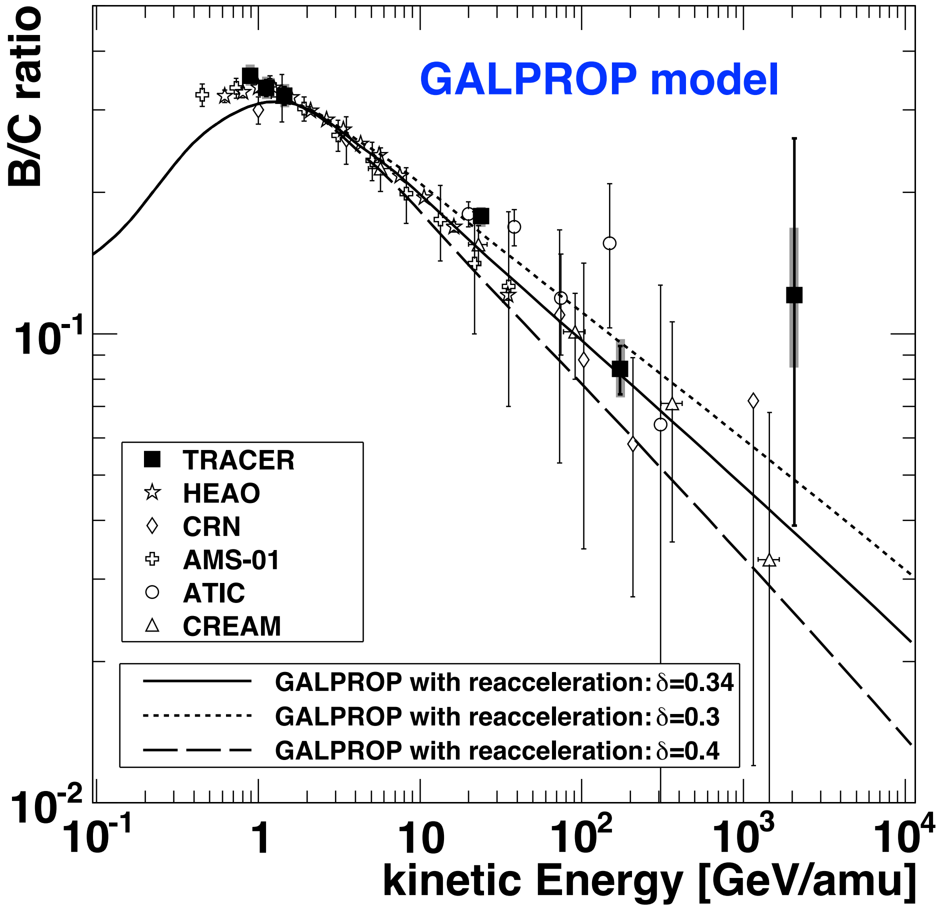
Boron to Carbon ratio

$$\frac{N_B}{N_C} = \frac{\lambda_{\to B}^{-1}}{\Lambda_{esc}(E)^{-1} + \Lambda_B^{-1}}$$

A. Obermeier et al., ICRC 2011

TRACER: propagation of cosmic rays





Escape Path Length:

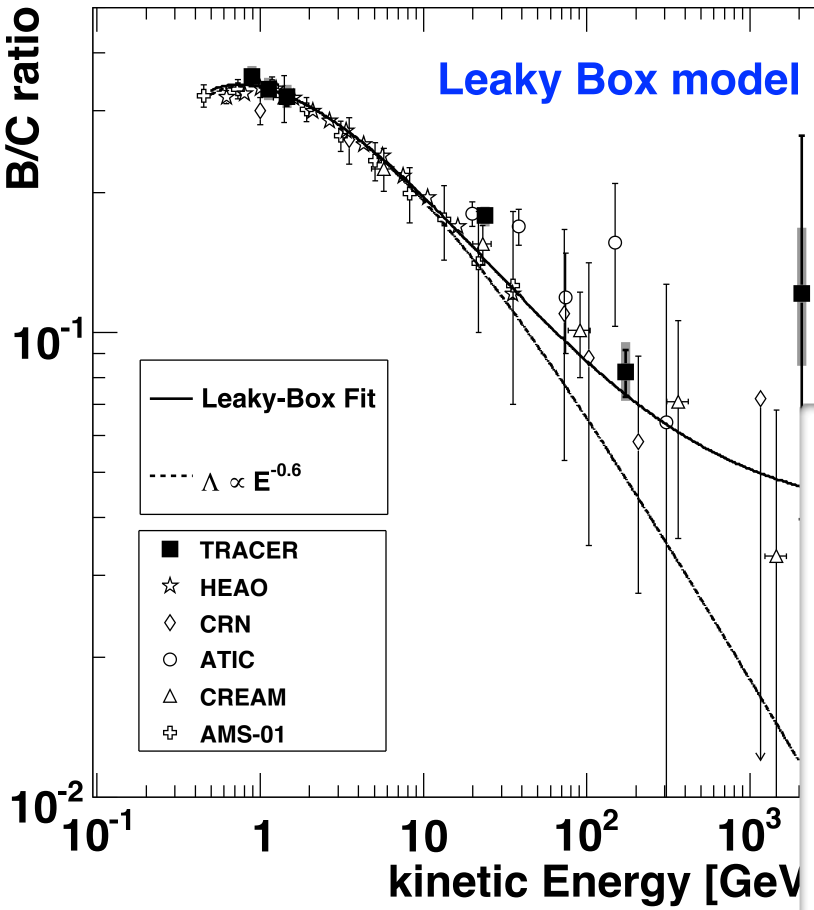
$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

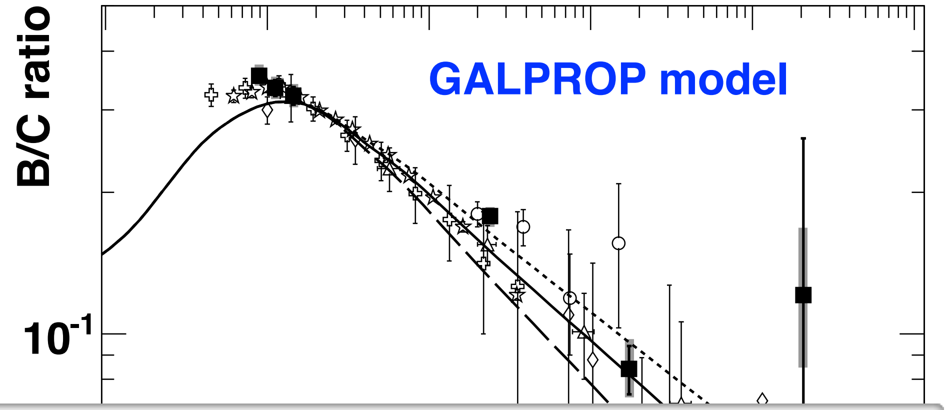
- Propagation index: $\delta = 0.64 \pm 0.02$.
- Residual path length: $\Lambda_0 = 0.7 \pm 0.2$ g/cm^2.

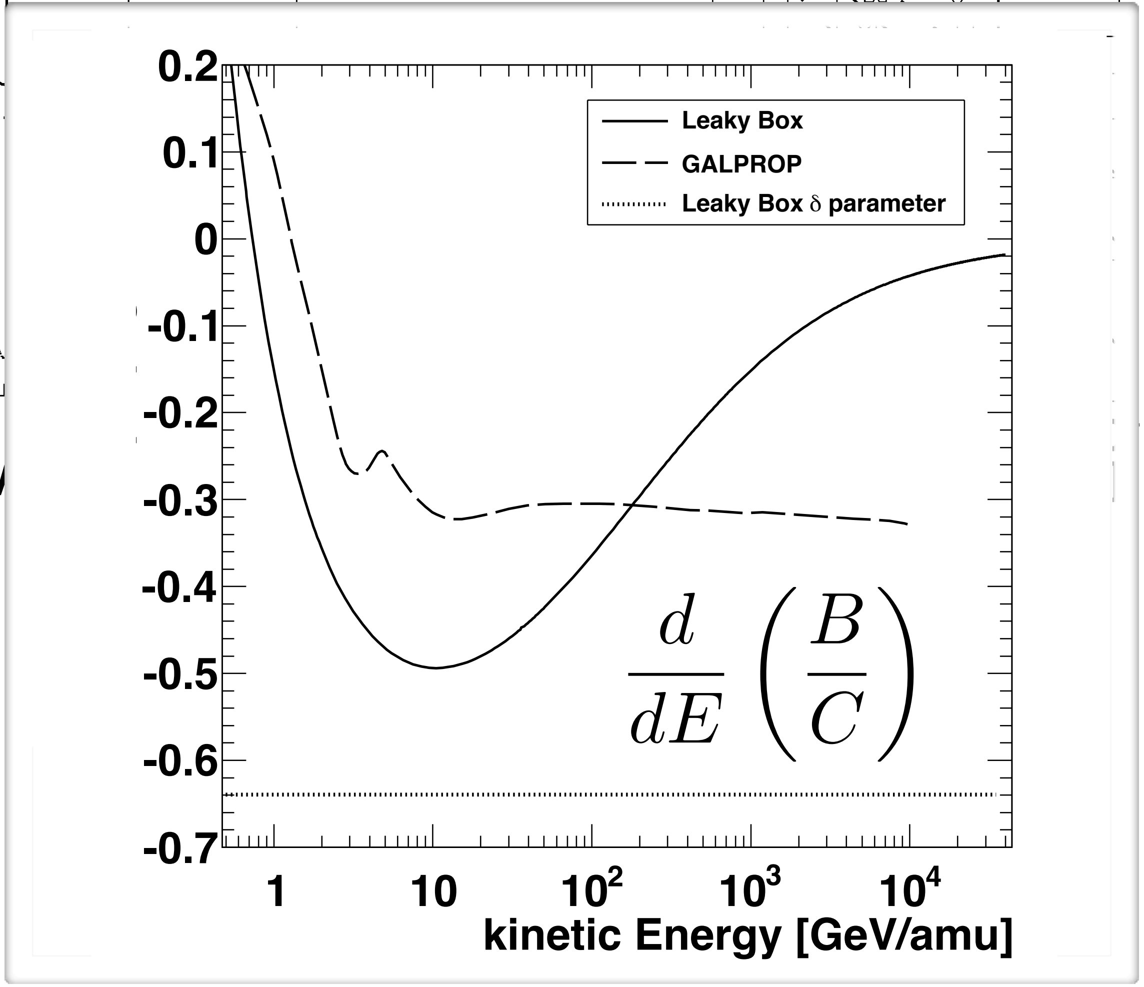
- Diffusion Index: $\delta = 0.34$.
- **Source index:** $\alpha = 2.34$.

A. Obermeier et al., ApJ 752 (2012) 69

TRACER: propagation of cosmic rays



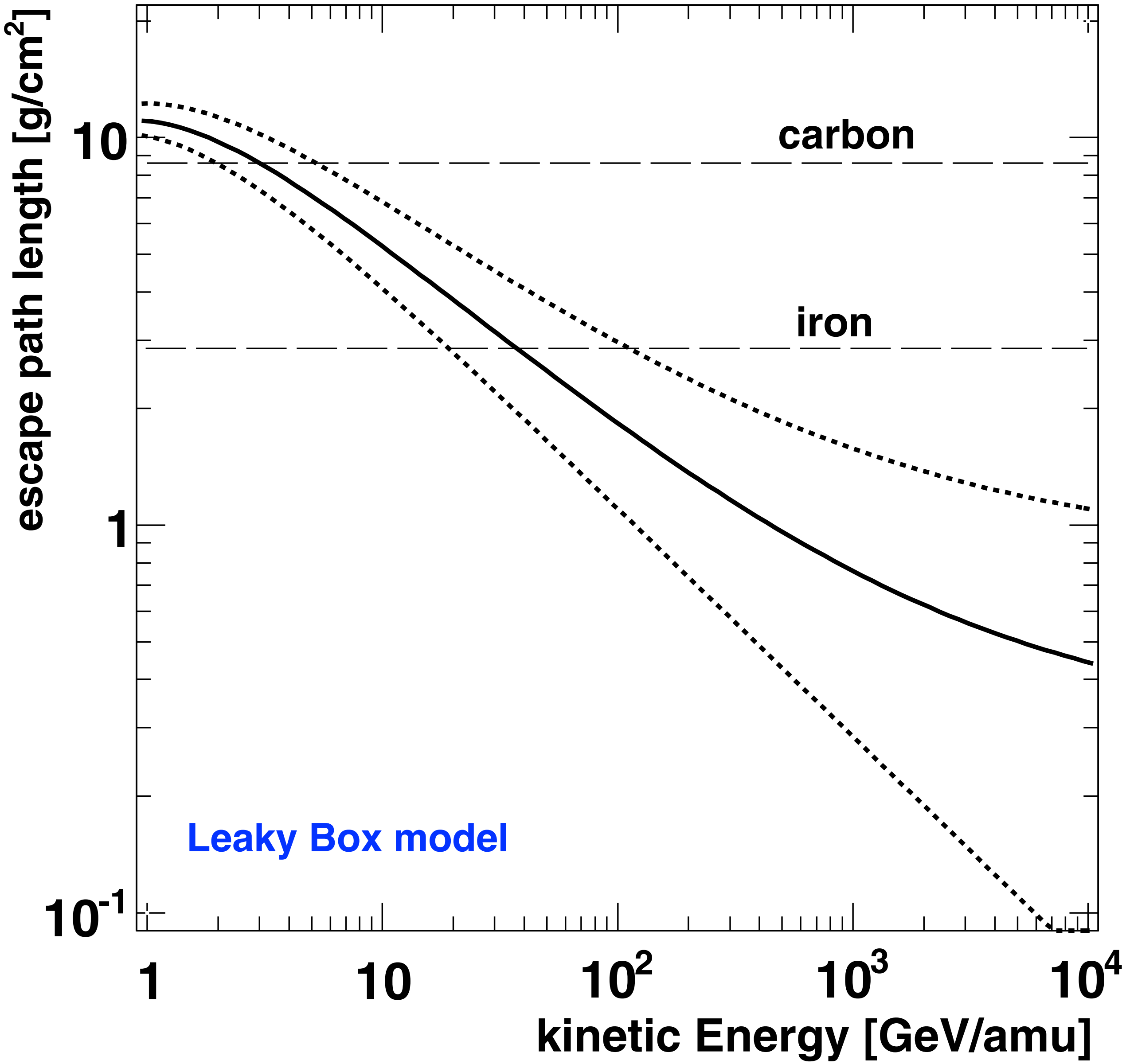




$$\Lambda(R) = \frac{26.7\beta}{(\beta R)^{\delta} + (0.714 \cdot \beta R)^{-1.4}} + \Lambda_0 \text{ g/cm}^2,$$

TRACER: propagation of cosmic rays

path length of cosmic rays in Galaxy



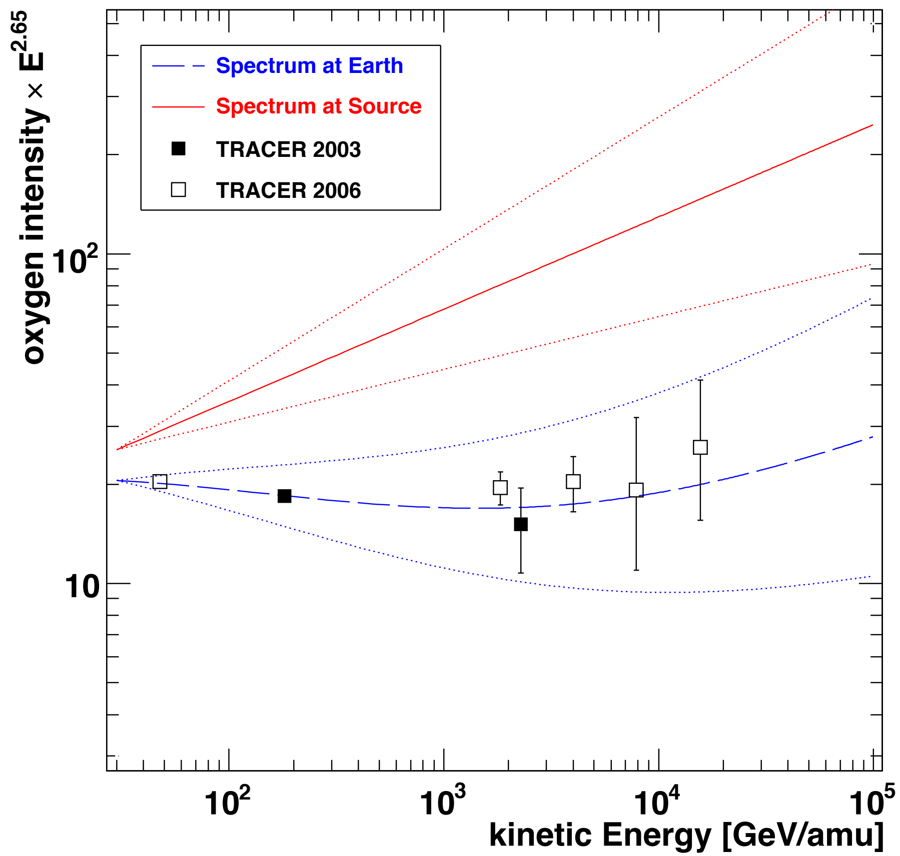
$$\Lambda(R) = \frac{26.7\beta}{(\beta R)^{\delta} + (0.714 \cdot \beta R)^{-1.4}} + \Lambda_0 \text{ g/cm}^2,$$

A. Obermeier et al., ApJ 752 (2012) 69

TRACER: propagation of cosmic rays

The Source Spectrum

- Fit to TRACER oxygen data.
- $\delta = 0.64$, $\Lambda_0 = 0.7$ g/cm^2



- Free parameter: α.
- Source spectrum: power law.

Result

- Source index: $\alpha = 2.37 \pm 0.12$.

- Agrees with previous results.
- Model predicts spectrum at Earth may not be a power law (Λ_0).

GALPROP: $\alpha = 2.34$

A. Obermeier et al., ApJ 752 (2012) 69

investigation of a number of species / isotopes and there energy dependence

$$\Rightarrow \quad \lambda_{esc} = v \cdot \rho \cdot \tau_{esc} \approx 10 \, \frac{g}{cm^2} \, \frac{v}{c} \left(\frac{4}{R} \right)^{\delta} \qquad R > 4V$$

rigidity $\quad R = \frac{p \cdot c}{Z \cdot e}$

$$\delta \approx 0{,}6$$

$$\lambda_{esc} \approx 10 \, g/cm^2 - 5 \, g/cm^2$$

All CR species travel through the same column density $\sim 10 \, g/cm^2$ before they escape from the galaxy

Remark: the same column density means different numbers of interactions for different species

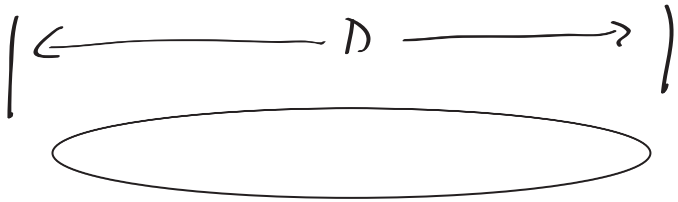
$\lambda_{int}(p) \approx 55\ g/cm^2 \qquad \gg \lambda_{esc}$

$\lambda_{int}(Fe) \simeq 2{,}3\ g/cm^2 \qquad \leq \lambda_{esc}$

$\Rightarrow$ less interactions for protons as compared to Fe nuclei galactic disc: $n \sim 1$ H atom$/cm^3$

$$= 1{,}67 \cdot 10^{-24}\ g/cm^3$$

$$\frac{\lambda_{esc} = 10\ g/cm^2}{1{,}67 \cdot 10^{-24}\ g/cm^3} \approx 6 \cdot 10^{22}\ m$$



$$D_{Galaxy} \approx 9 \cdot 10^{20}\ m$$

$\mathcal{O}(100)$ crossings of galaxy to accumulate $10\ g/cm^2$

$$\tau_{CR} \sim \frac{6 \cdot 10^{22}\ m}{3 \cdot 10^{8}\ m/s} \sim 6 \text{ Mio years!}$$

Radioactive isotopes and "age" of cosmic rays

use secondary radioactive isotopes from spallation reactions

e.g. ^{10}Be : $\tau = \gamma \cdot \tau_0 = 3{,}9 \cdot 10^6\,a$

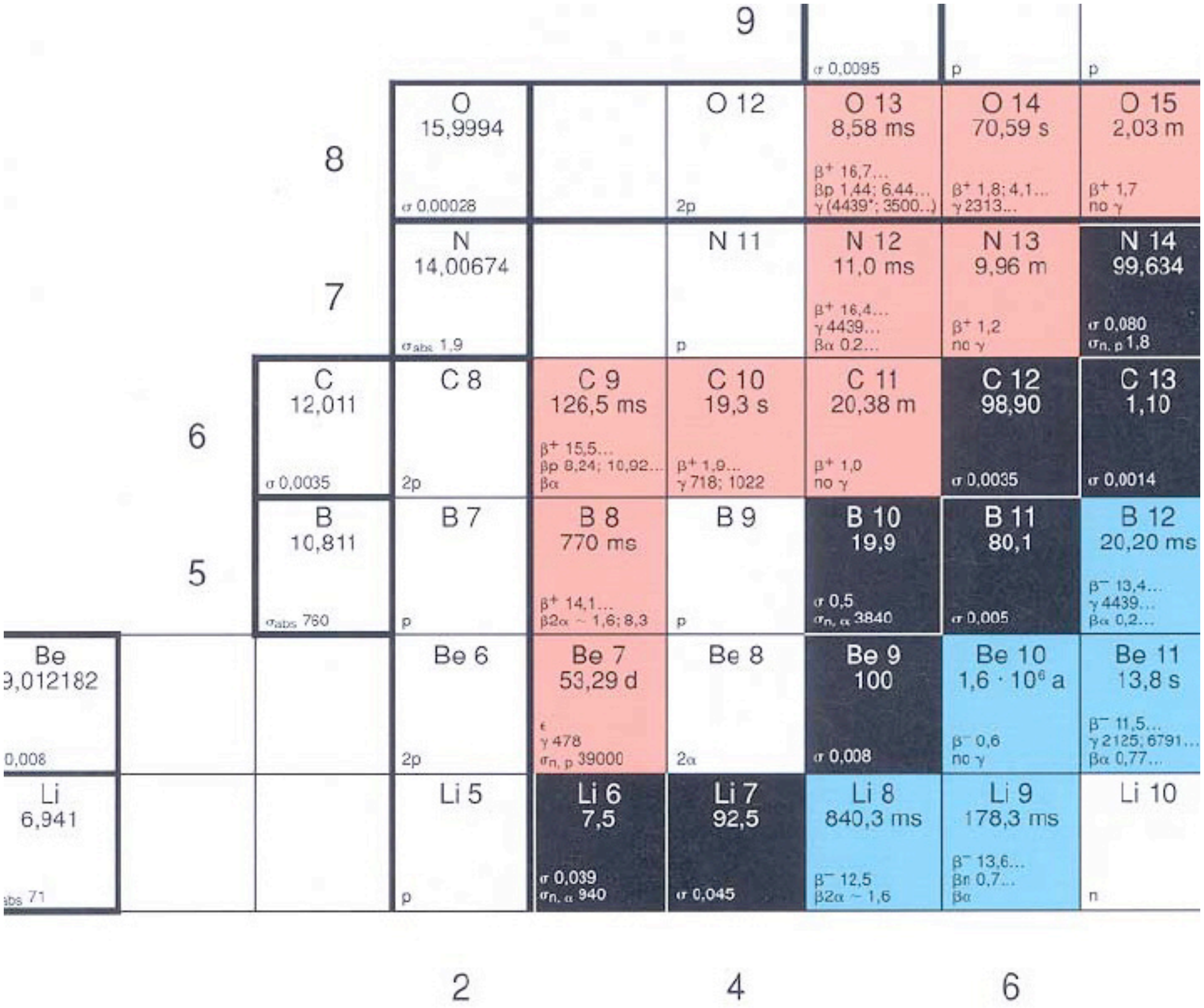
$$^{10}Be \to {}^{10}B + \beta^- + \bar{\nu}_e$$

equilibrium between production and decay of ^{10}Be

$$\frac{^{10}Be}{^{7}Be + {}^{9}Be + {}^{10}Be} \sim 0{,}1 \quad \text{at production}$$

if $\tau_{esc} \gg \tau_0$ $\Rightarrow$ expect observed

Chart of the nuclides



„Age“ of galactic cosmic rays

THE AGE OF THE GALACTIC COSMIC RAYS DERIVED FROM THE ABUNDANCE OF ^{10}Be*

M. GARCIA-MUNOZ, G. M. MASON, AND J. A. SIMPSON†
Enrico Fermi Institute, University of Chicago
Received 1977 March 14; accepted 1977 April 21

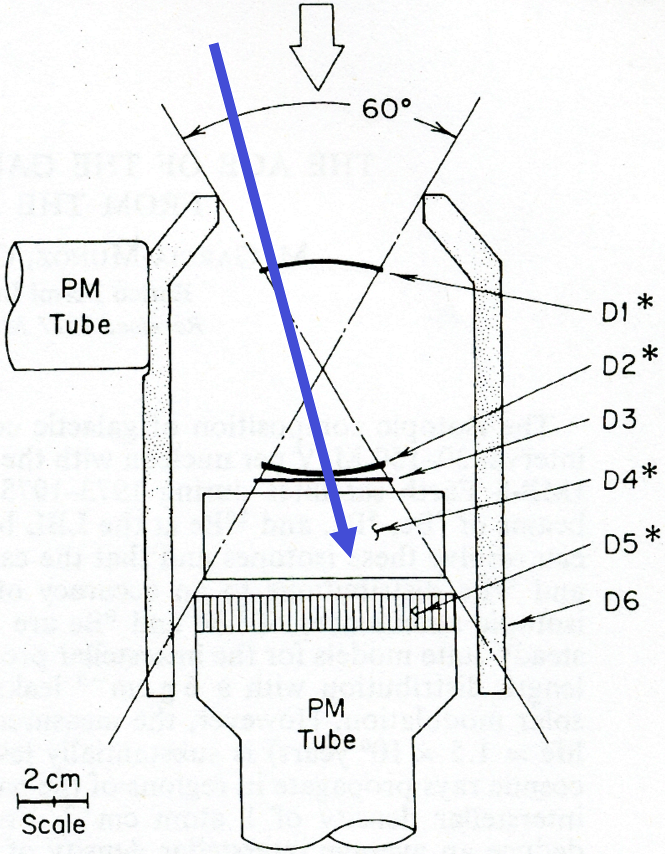
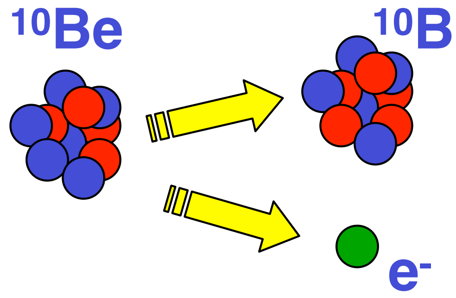


FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (T1) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness 3.98 g cm^{-2}, and D6 is a plastic scintillation guard counter viewed by a photomultiplier tube. Asterisks denote detectors whose output is pulse-height analyzed.

Residence time in Galaxy

$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^-$ (t =2.4 10^6 a)



$$\tau_{esc} = 17 \cdot 10^6 \text{ a}$$

THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

ratio of ^{10}Be $< 0{,}1$

measurements yield

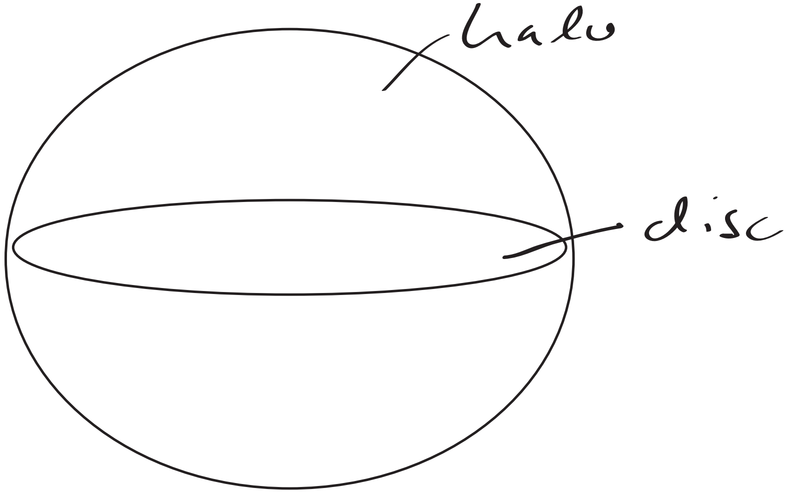
$$\frac{^{10}Be}{^{7}Be + ^{9}Be + ^{10}Be} \approx 0{,}028 \quad \text{in CRs}$$

$$\Rightarrow \tau_{esc} = 17 \cdot 10^{6}\,a$$

from this, we can derive an average density

$$\tilde{\rho} = \frac{\lambda_{esc}}{v \cdot \tau_{esc}} = \frac{10\,g/cm^2}{3 \cdot 10^{10}\,\frac{cm}{s} \cdot 17 \cdot 10^{7} \cdot 86400 \cdot 365\,s}$$

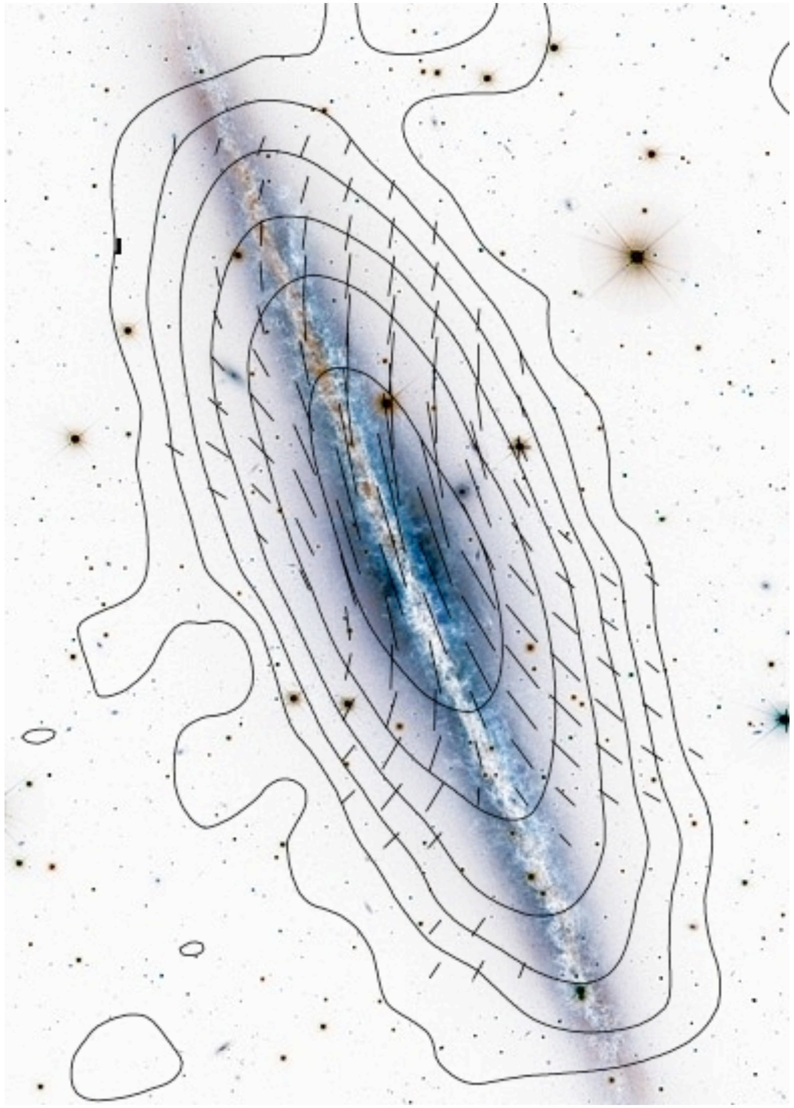
$$= 0{,}3 \text{ H atoms}/cm^3$$



CR particles spend a significant fraction of their residence time in the galactic halo (lower density)

confirmed by observations of diffuse radio emission

synchrotron radiation

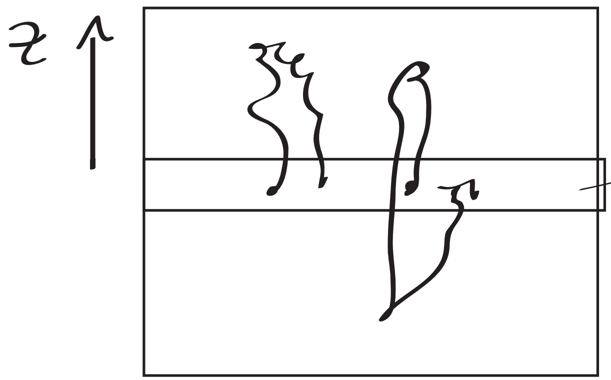


This figure shows the spiral galaxy **NGC 891**, seen almost edge-on, which is believed to be very similar to our Milky Way. It was observed at 8.4 GHz (3.6 cm wavelength) with the Effelsberg 100m telescope. The background optical image is from the CFHT Observatory. The "X-shaped" structure of the magnetic fields indicates the action of a galactic wind. The observed extent of the radio halo is limited by the large energy losses of the cosmic-ray electrons emitting at this wavelength. At lower frequencies (longer wavelengths) the radio waves are emitted by electrons with lower energies for which the energy lossesare smaller, so that larger radio halos are expected.

similar results with ^{26}Al, ^{36}Cl, ^{53}Mn

Leaky Box model is very simple

today mostly: Diffusion halo model



galactic disc with sources

$$D = D(z)$$

numerical models, e.g. GALPROP

Antiparticles in cosmic rays

Is the Universe symmetric with respect to matter-antimatter

-> not in our vicinity ($p\bar{p} \rightarrow \gamma\gamma$)

- maybe in other galaxies?

$\bar{p}$ discovered in CRs in 1979

expect background of $\bar{p}$ from high-energy interactions $pp \rightarrow p\bar{p} + X$

$$E_p > 6\ \mathrm{GeV}$$

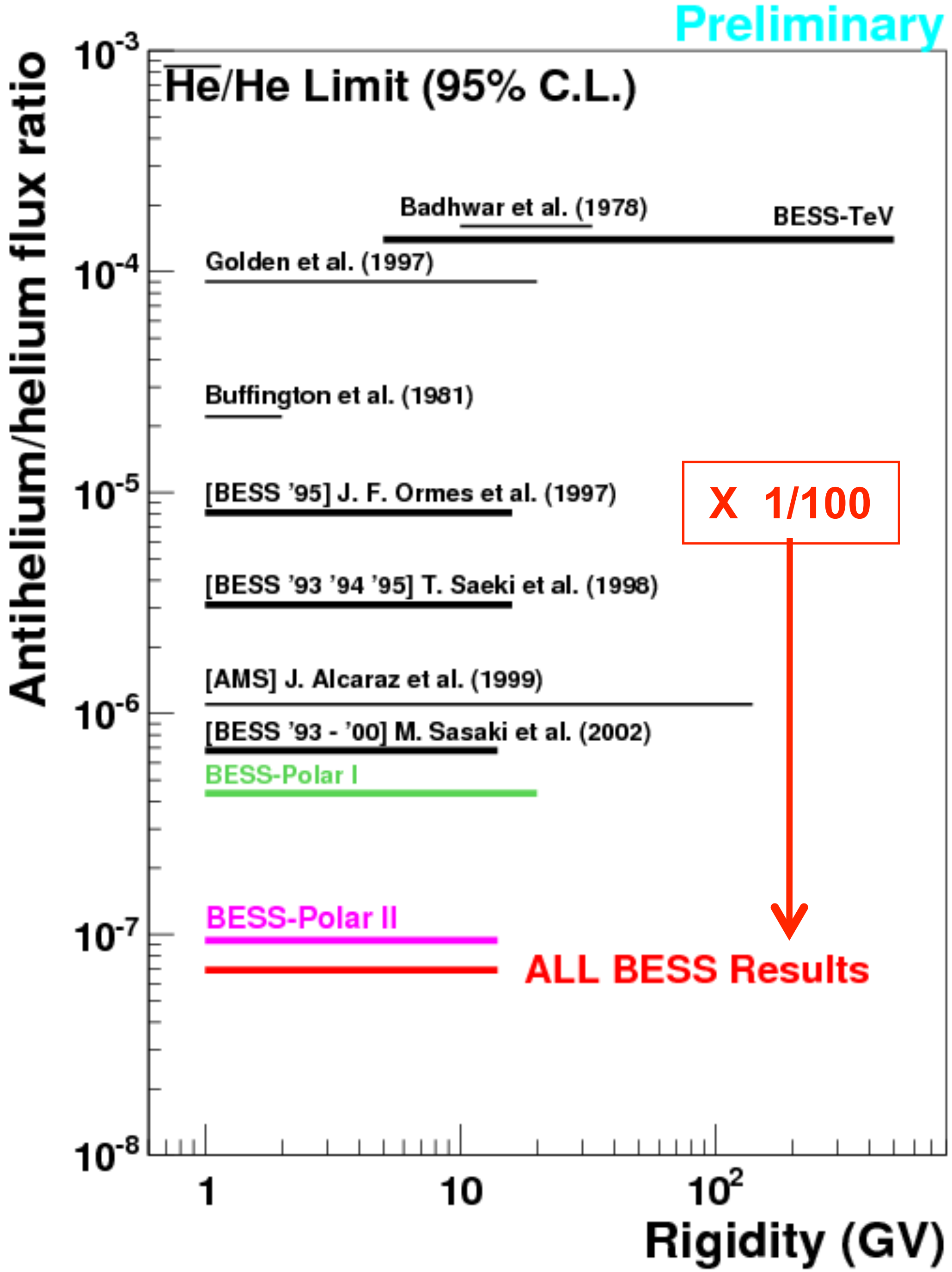
in similar way also e^+ are produced

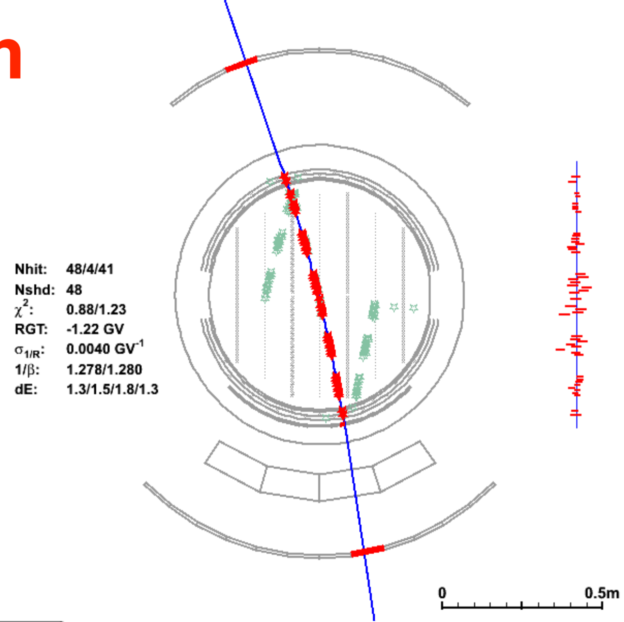
if we observe an excess of antiparticles above the "known" secondary fraction

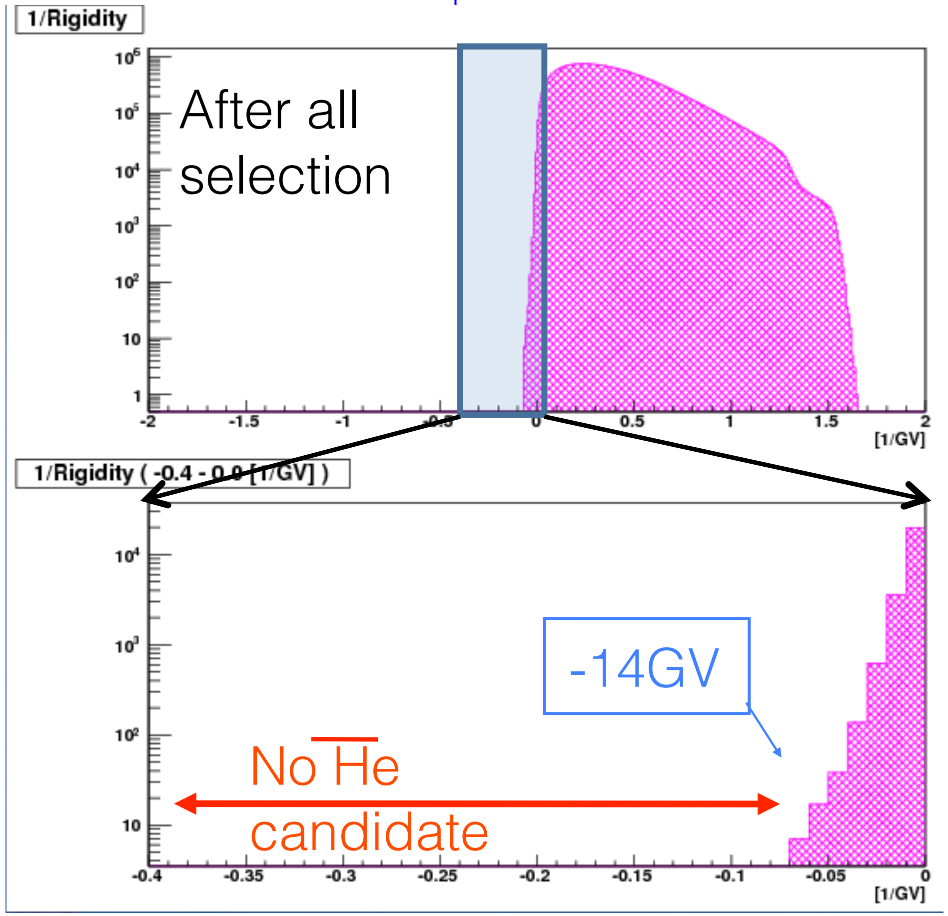
$\Rightarrow$

- from antigalaxies
- DM in galactic halo
- exotic physics

BESS-Polar: Search for antihelium



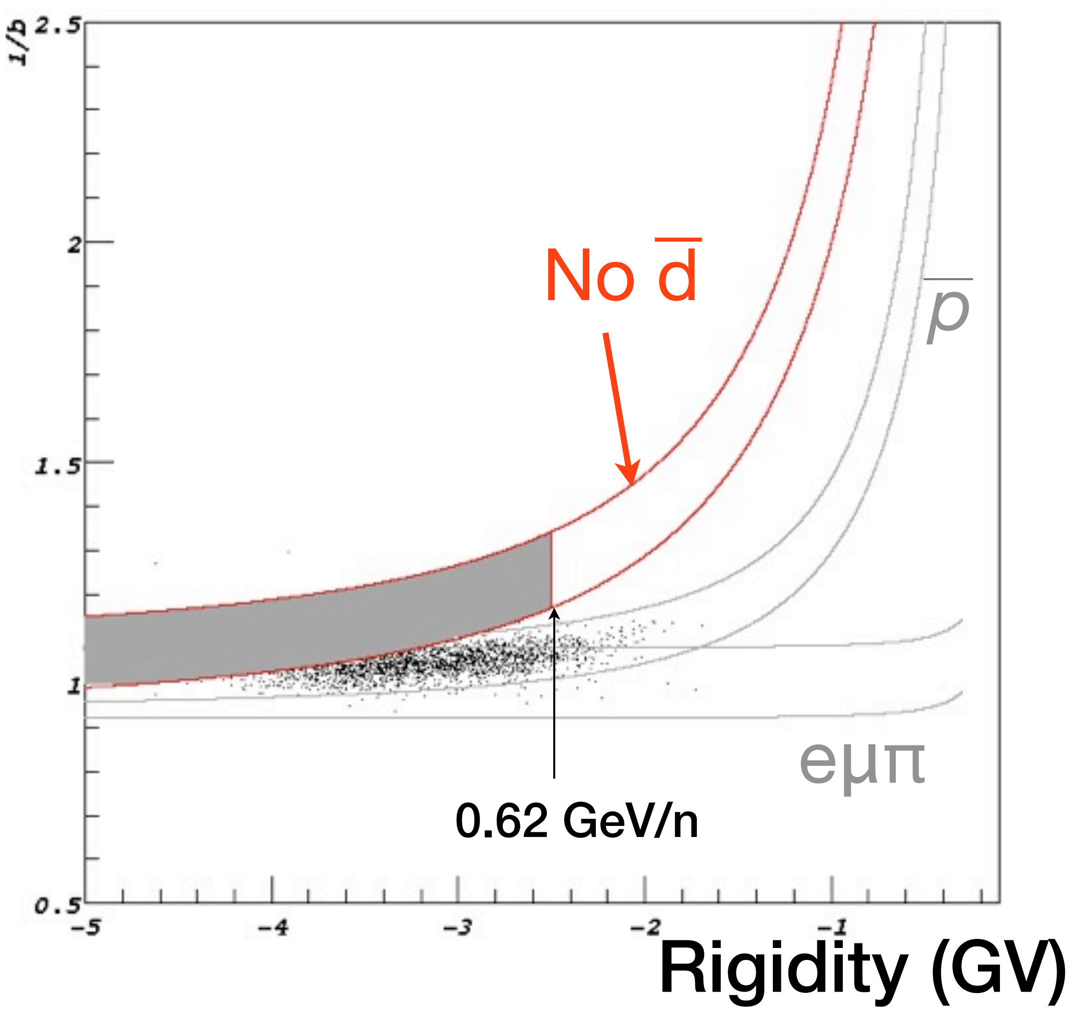




Search for cosmic-ray antideuterons with BESS-Polar

#1259
Yoshimura

Negative curvature



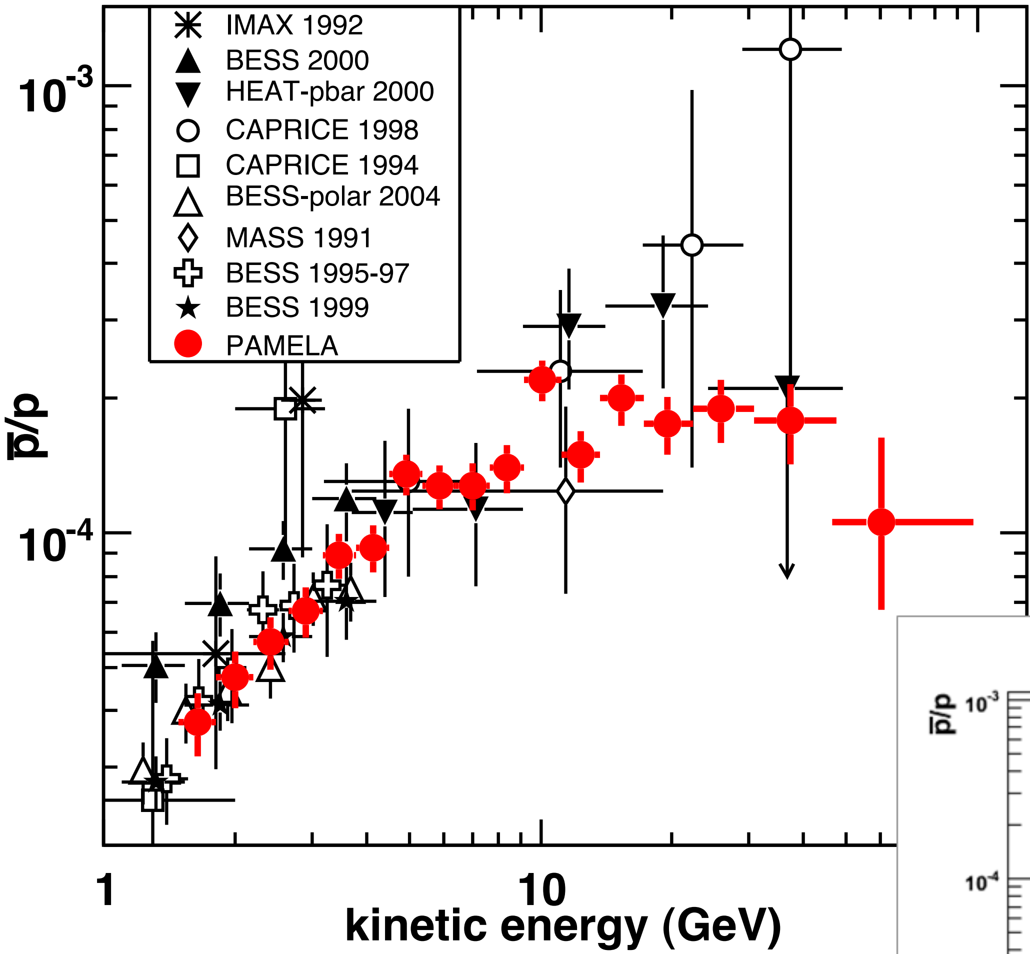
Apply the same selection as deuteron selection.

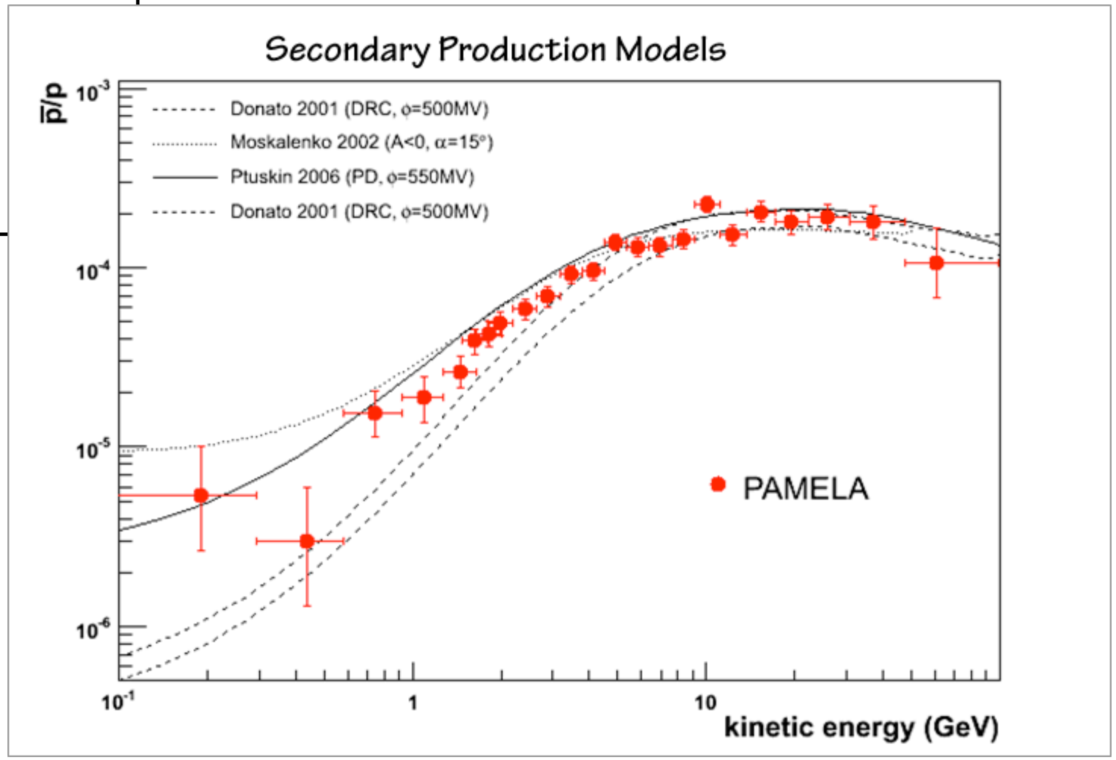
Box has not be fully opened except the BG-free region yet....

NO Antideuteron was found in rigidity below 2.5 GeV/c.

(K.E. ~ 0.62 GeV/nucleon)

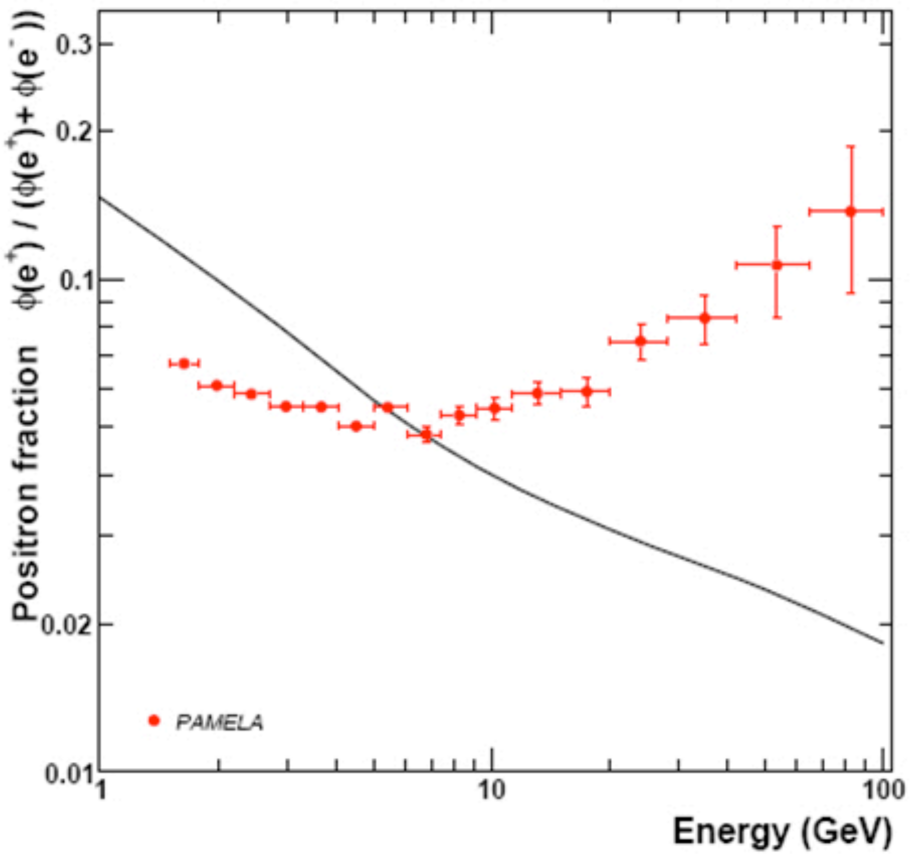
antiproton-proton ratio

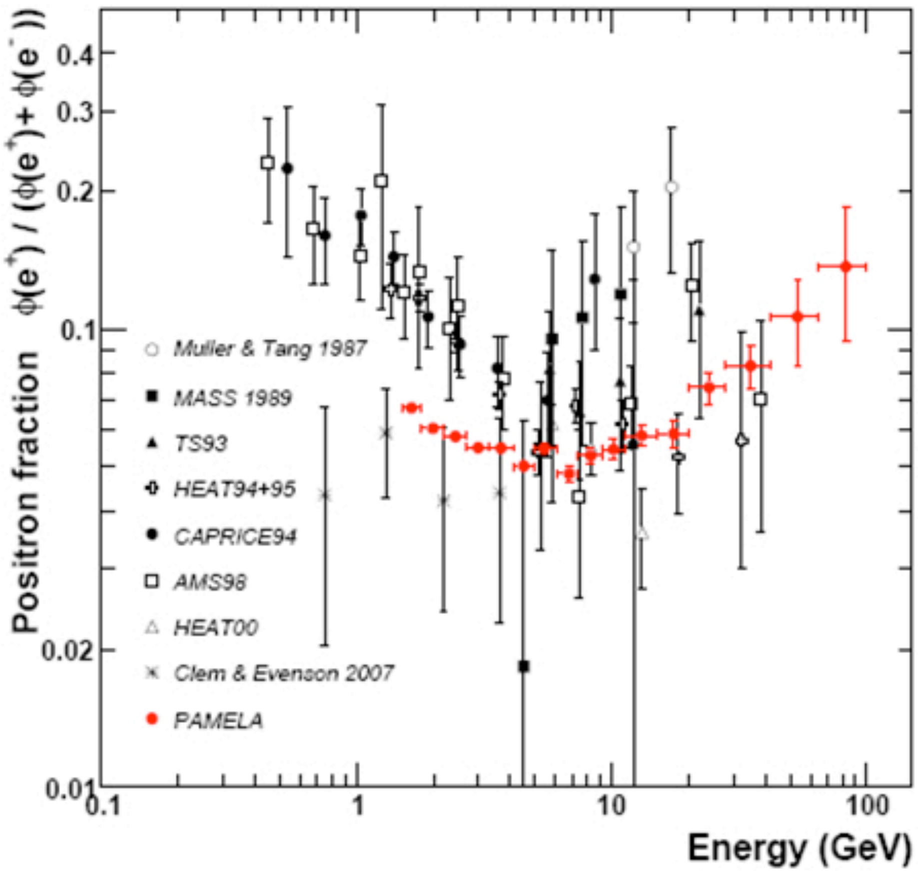




PAMELA, arXiv 0810.4994

electron-positron fraction





O. Adriani et al., Nature 458 (2009) 607