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

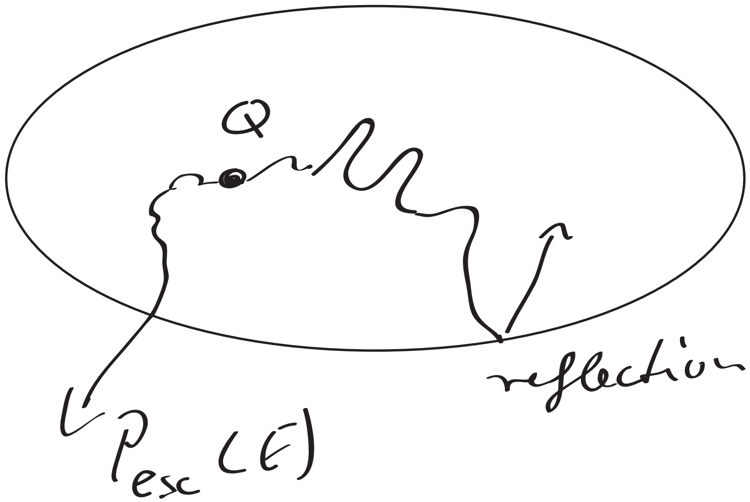
$$+ \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$ production through decay of heavy nuclei

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)

$$\frac{dN_i}{dt} = -\frac{N_i}{\tau_{esc}} - \frac{\partial}{\partial E}(b_i \cdot N_i) - n v \sigma_i N_i - \frac{N_i}{\gamma \tau_i}$$
$$+ Q_i + \sum_{j>i} n v \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma \tau_{ij}}$$

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

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

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

Traversed matter / column density

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

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

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

from nuclear physics

Pathlength of cosmic rays

VOLUME 29, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 1972

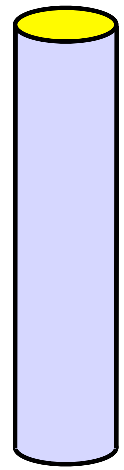
Composition of Cosmic-Ray Nuclei at High Energies*

Einar Juliusson, Peter Meyer, and Dietrich Müller

Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637

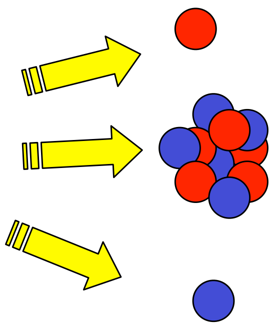
(Received 26 May 1972)

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.



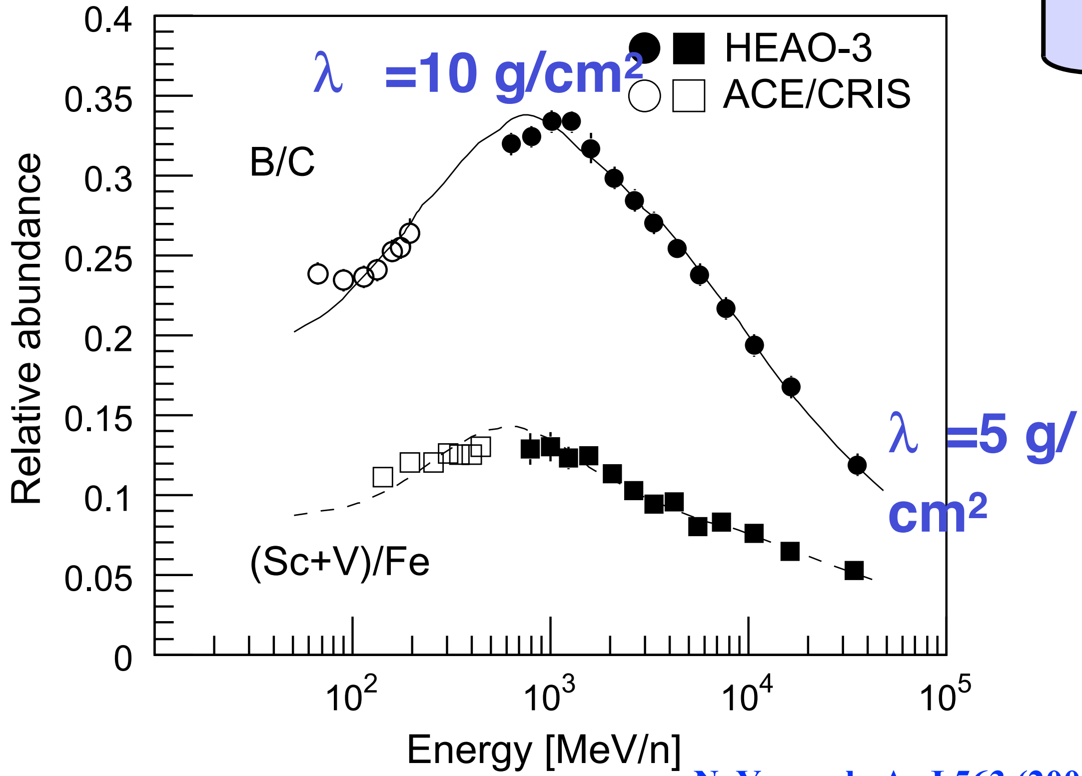
spallation

C → B + n + p



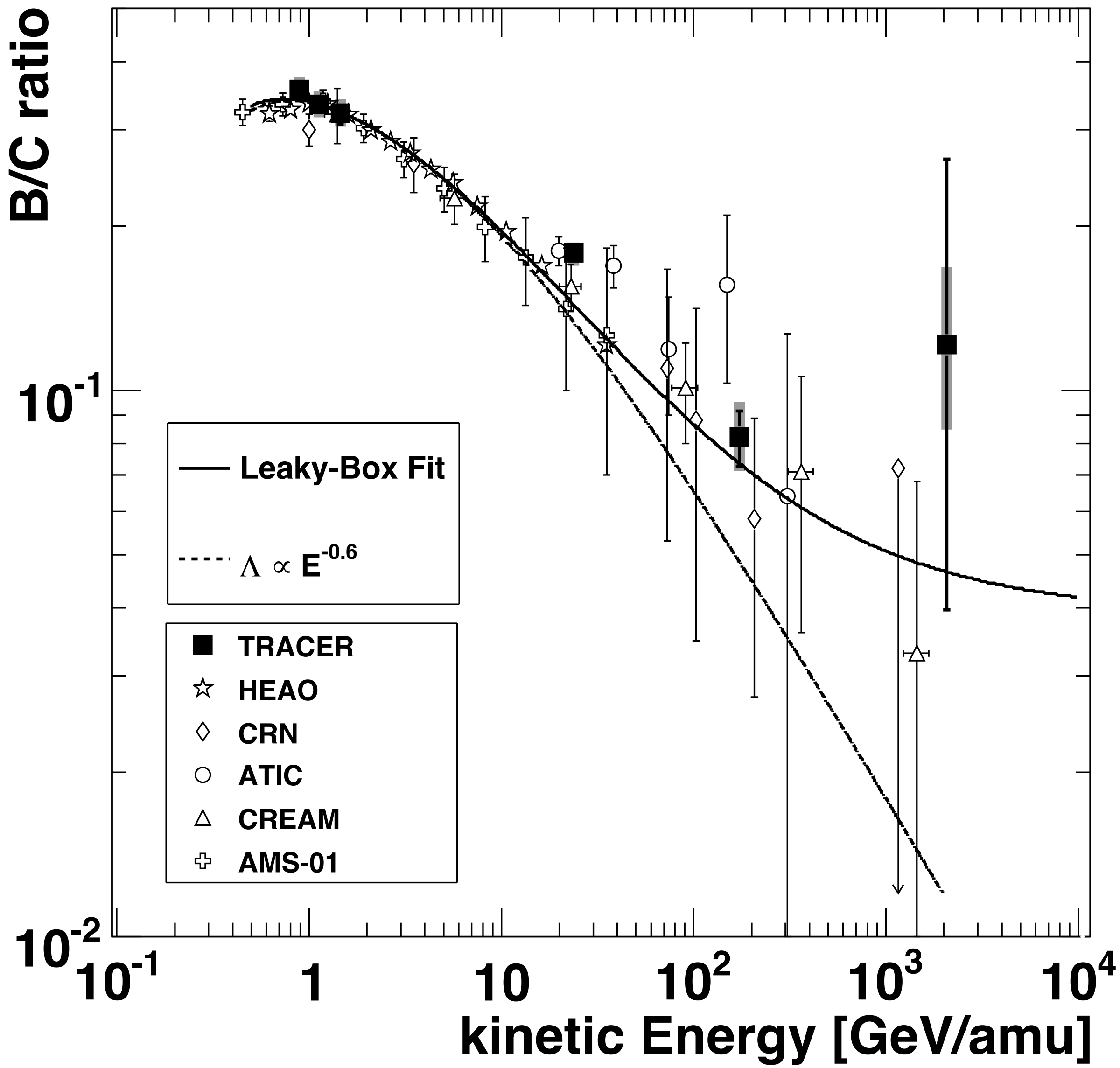
$$\lambda(E) \propto E^{-0.6}$$

primary/secondary-ratio



N. Yanasak, ApJ 563 (2001) 768

B/C ratio



residual path length model

Escape Path Length:

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

$$\frac{N_B}{N_C} = \frac{\lambda^{-1}_{\to B}}{(CE^{-\delta} + \Lambda_0)^{-1} + \Lambda_B^{-1}}$$

Result

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

A. Obermeier, ICRC 2011

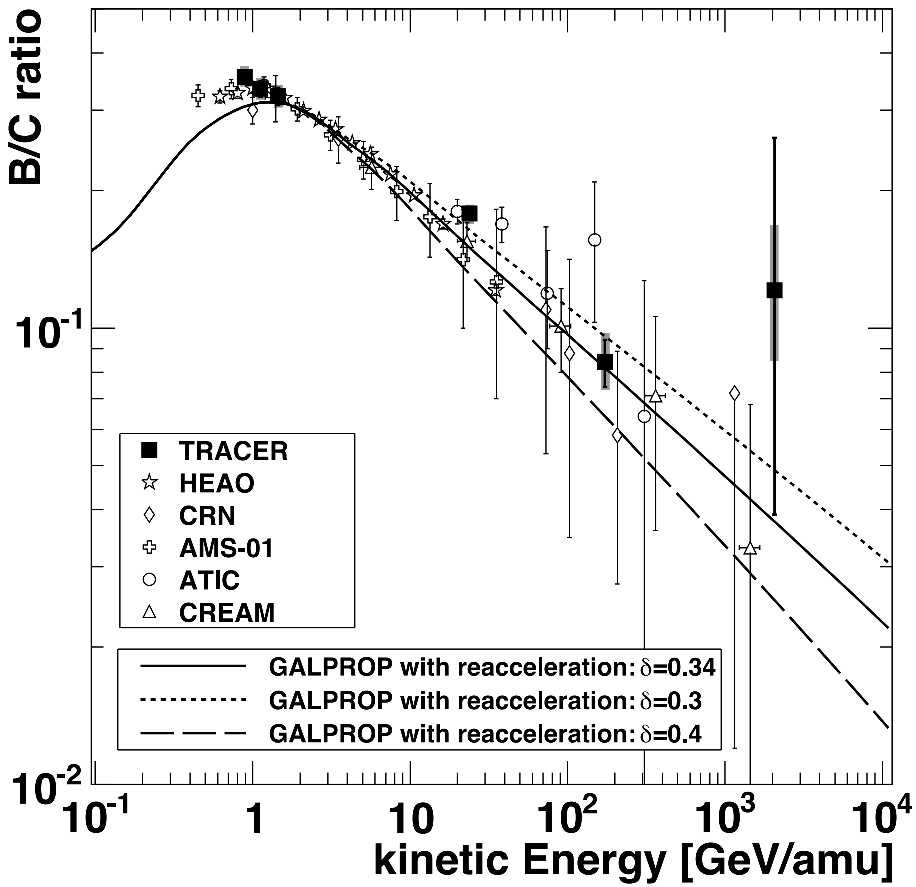
B/C and GALPROP

- Numerical simulation of CR transport equation.
- Diffusion model.

Propagation Parameters

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

Strong et al., Annu. Rev. Nucl. Part. S., 2007, 57:285



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

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

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

$\delta \approx 0{,}6$

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

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

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

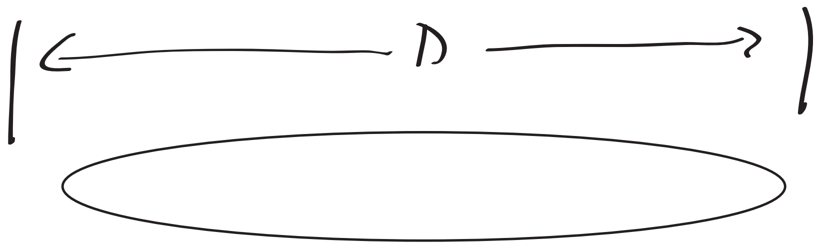
$\lambda_{int}(F) \approx 2{,}3\ g/cm^2 \qquad \leq \lambda_{esc}$

$\Rightarrow$ 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 : $\tau = \gamma \cdot \tau_0 = 3{,}9 \cdot 10^6\,a$

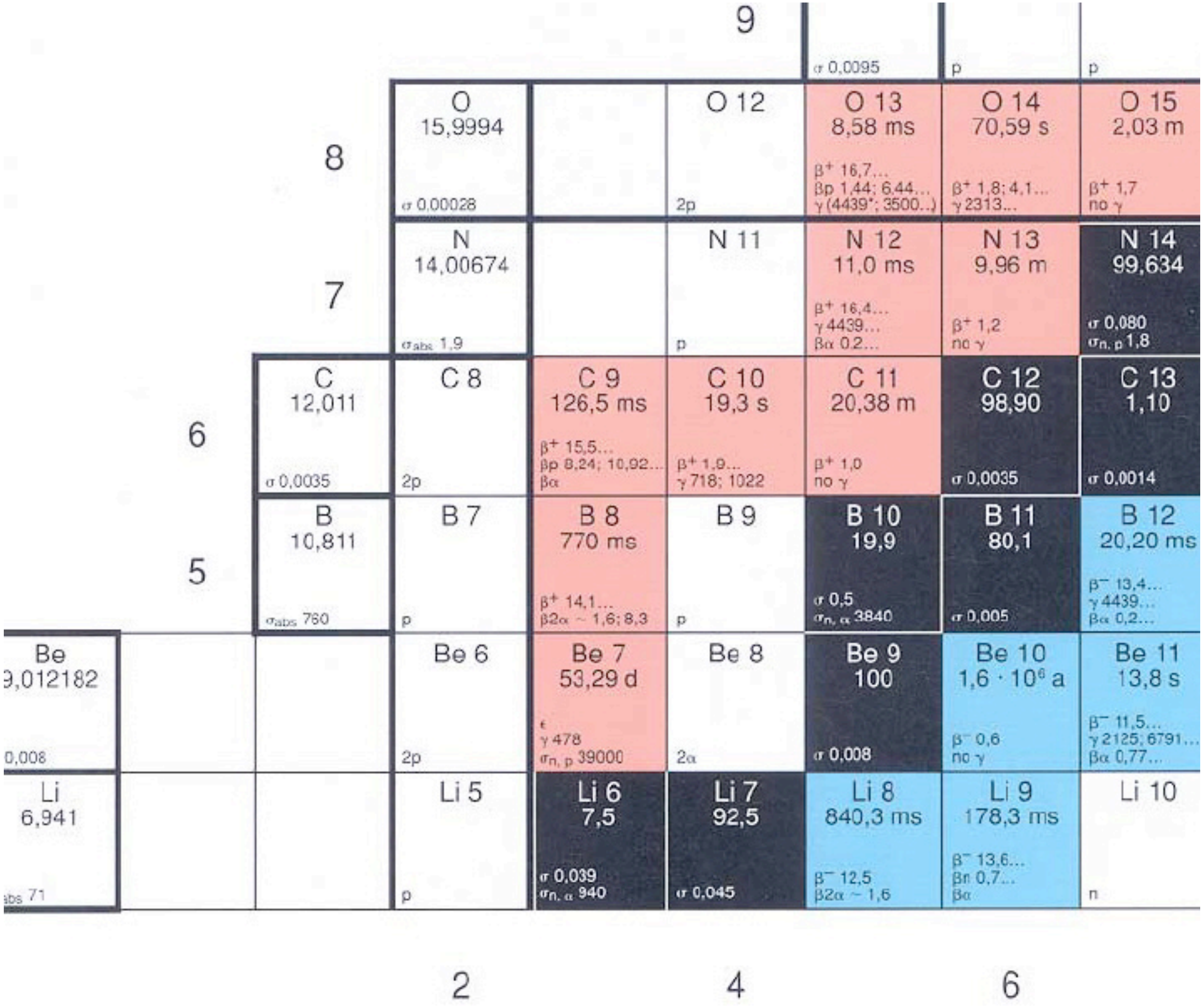
$$^{10}Be \rightarrow {}^{10}B + \beta^- + \bar{\nu}_e$$

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



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

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

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

„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

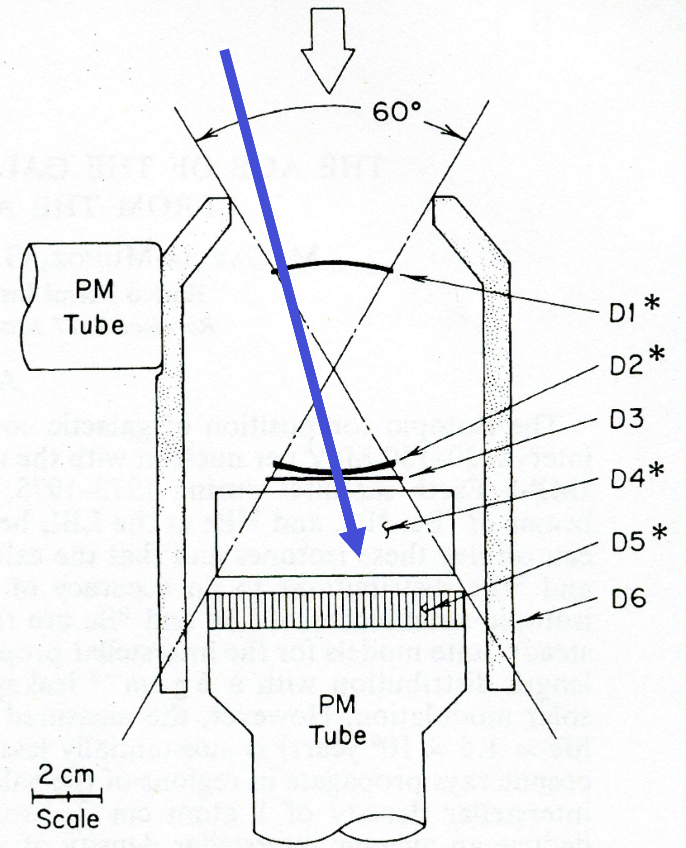
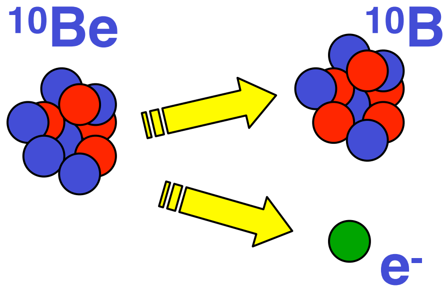


FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (T1) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness 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.

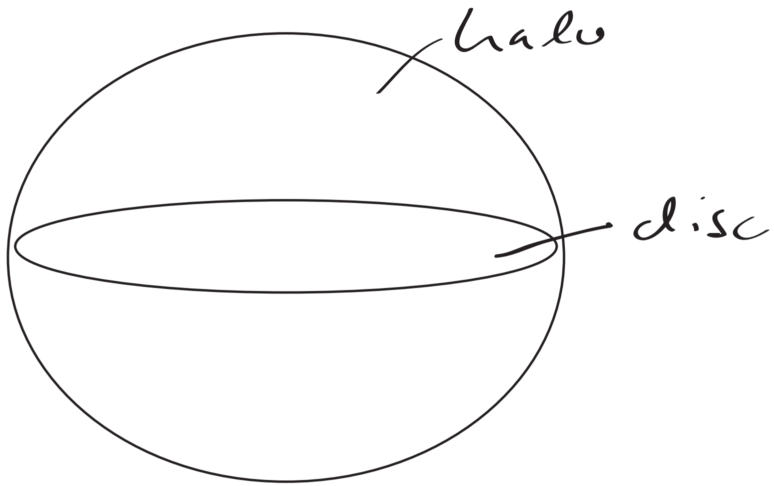
Residence time in Galaxy

^{10}Be → ^{10}B + e$^-$ (τ =2.4 10^6 a)



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

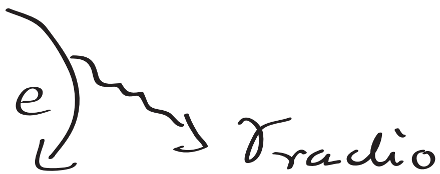
THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

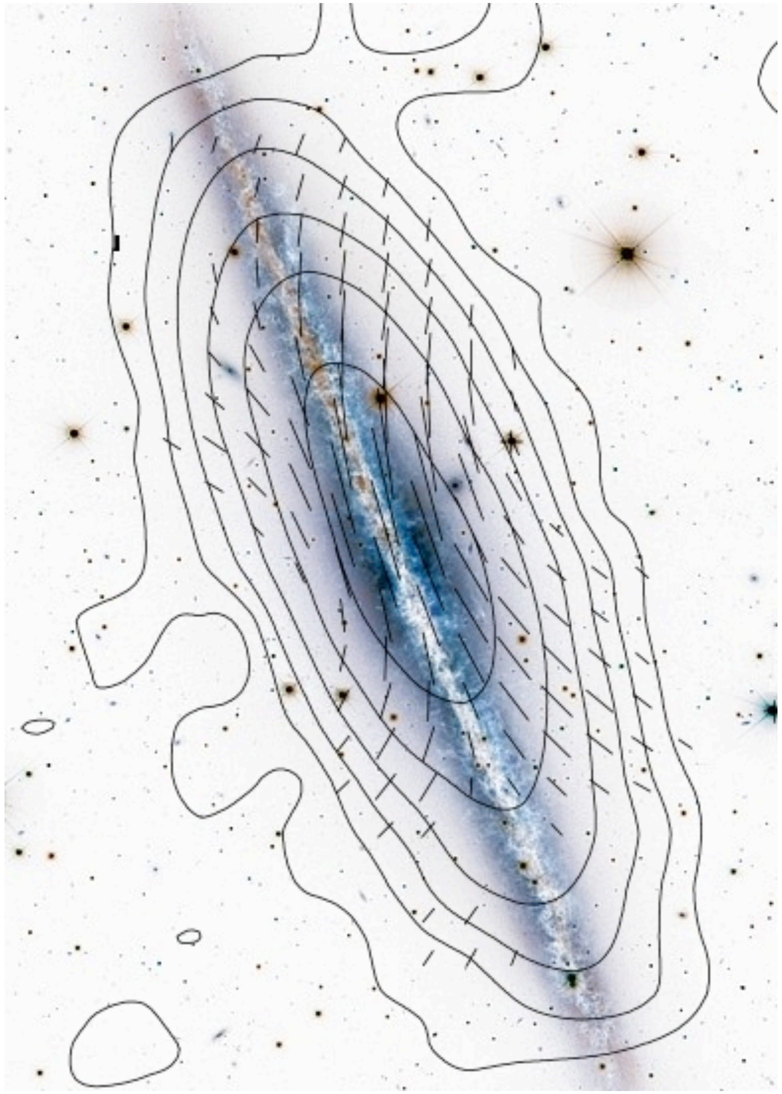


CR particles spend a significant fraction of their residence time in the galactic halo (lower density)

confirmed by observations of diffuse radio emission

synchrotron radiation



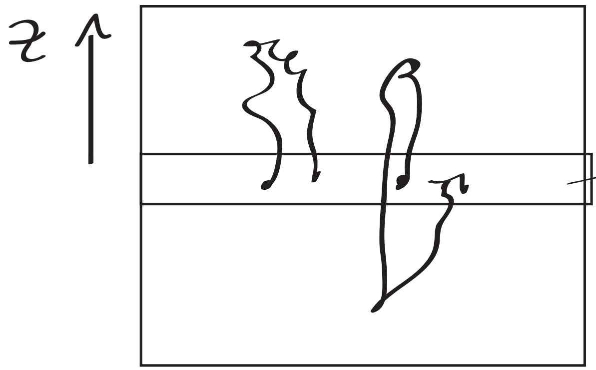


This figure shows the spiral galaxy **NGC 891**, seen almost edge-on, which is believed to be very similar to our Milky Way. It was observed at 8.4 GHz (3.6 cm wavelength) with the Effelsberg 100m telescope. The background optical image is from the CFHT Observatory. The "X-shaped" structure of the magnetic 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 ($p\bar{p} \to \gamma\gamma$)

- maybe in other galaxies?

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

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

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

in similar way also e^+ are produced

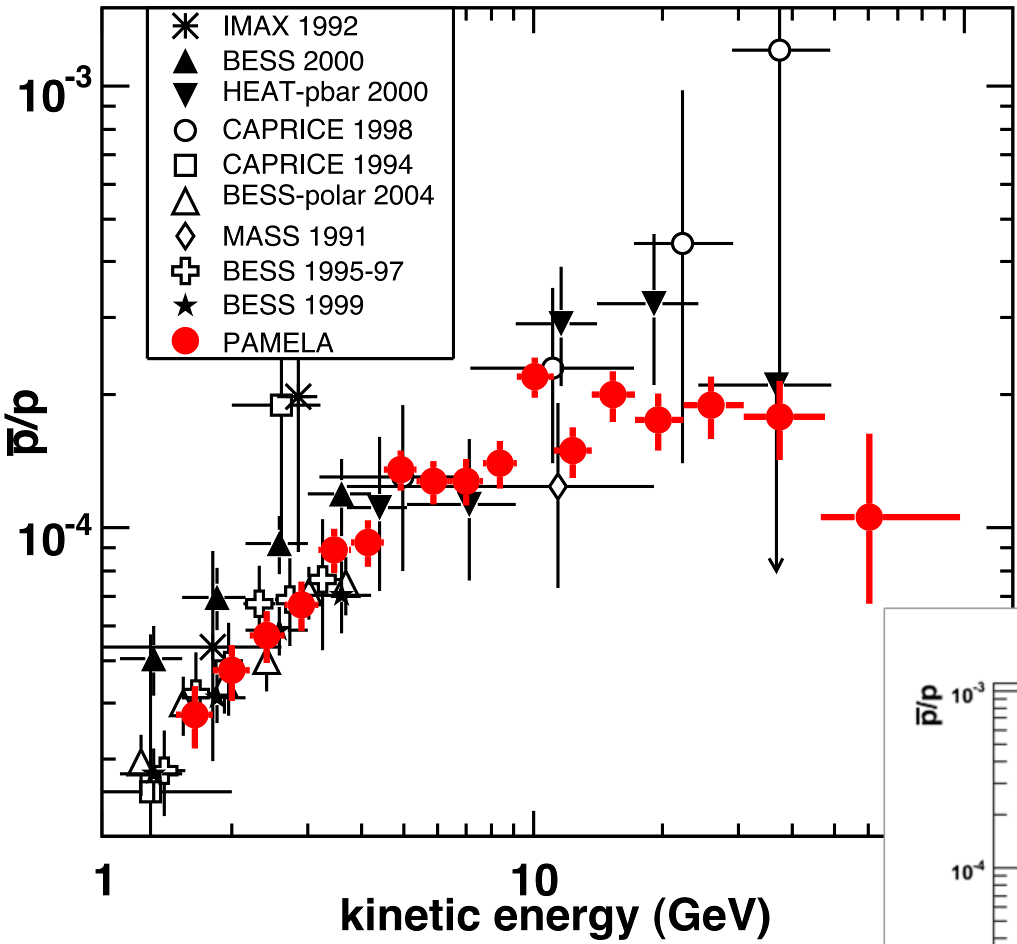
if we observe an excess of antiparticles above the "known" secondary fraction

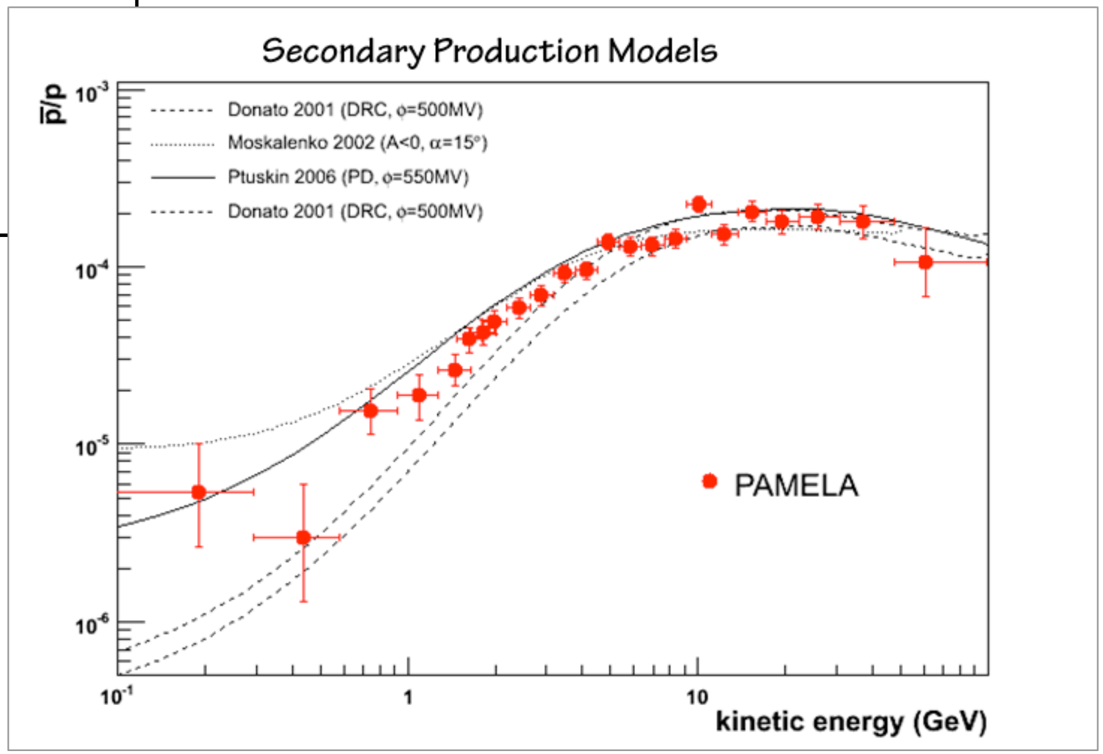
$\Rightarrow$ - from antigalaxies

- DM in galactic halo

- exotic physics

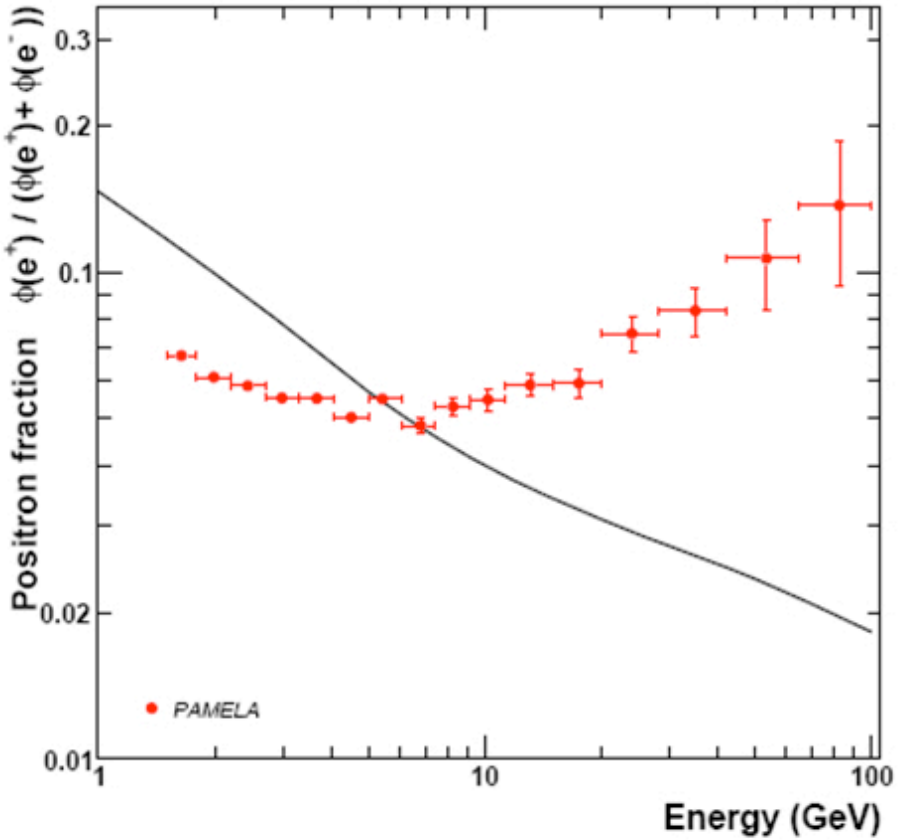
antiproton-proton ratio

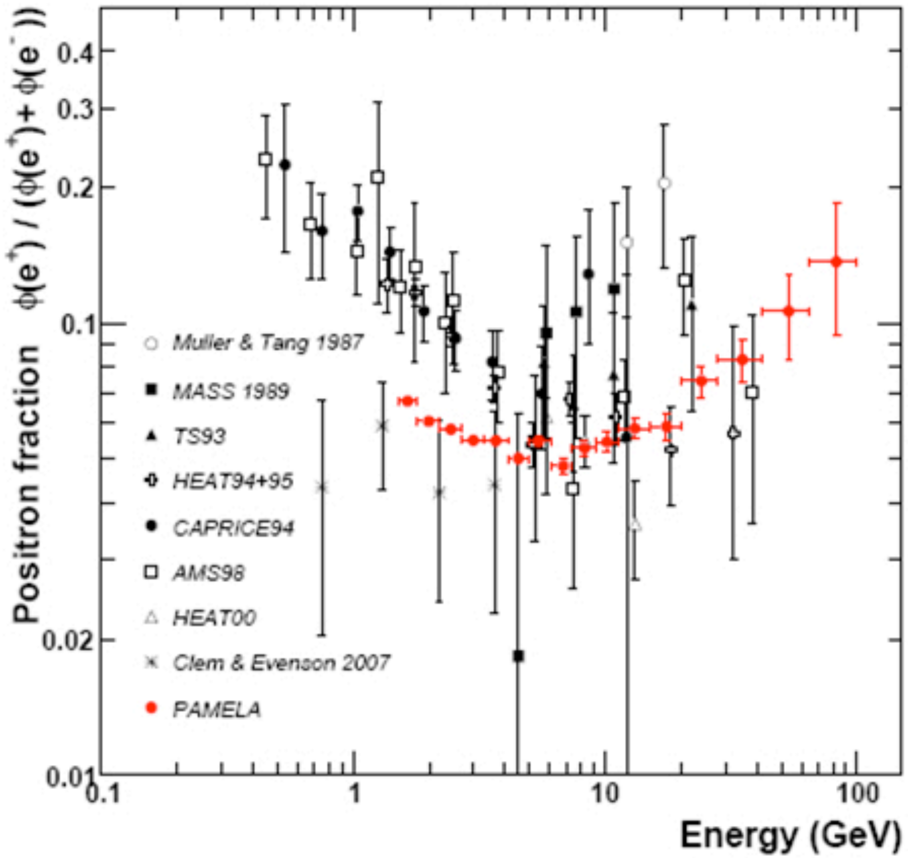




PAMELA, arXiv 0810.4994

electron-positron fraction





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

Sources & acceleration of cosmic rays

energy content of CRs in our galaxy

(Leaky Box model)

$$E_{tot} \simeq \varepsilon_{CR} \cdot V_{gal}$$

$$\simeq \varepsilon_{CR} \cdot \pi \cdot R^2 \cdot d$$

$$\simeq 1 \frac{eV}{cm^3} \cdot \pi \cdot (15\ kpc)^2 \cdot 1\ kpc$$

$$\simeq 2 \cdot 10^{67}\ eV$$

to keep flux of CRs constant,

the sources need to produce

$$L_{CR} \sim \frac{2 \cdot 10^{67} eV}{17 \cdot 10^6 a} \simeq 10^{53} \frac{eV}{s}$$

$1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$

$1\,\mathrm{eV} = 1{,}602 \cdot 10^{-19}\,\mathrm{J}$

$= 1{,}602 \cdot 10^{-12}\,\mathrm{erg}$

$\Rightarrow \; L_{CR} = 1{,}5 \cdot 10^{41}\,\mathrm{erg/s}$

compare, e.g. $L_{\odot} = 3{,}86 \cdot 10^{33}\,\mathrm{erg/s} \quad (3{,}86 \cdot 10^{26}\,\mathrm{W})$

(e/m radiation)

solar wind $\sim 5 \cdot 10^{-3}\,\frac{\mathrm{eV}}{\mathrm{cm}^3}$

Which sources in our Galaxy are able to sustain L_{CR}?