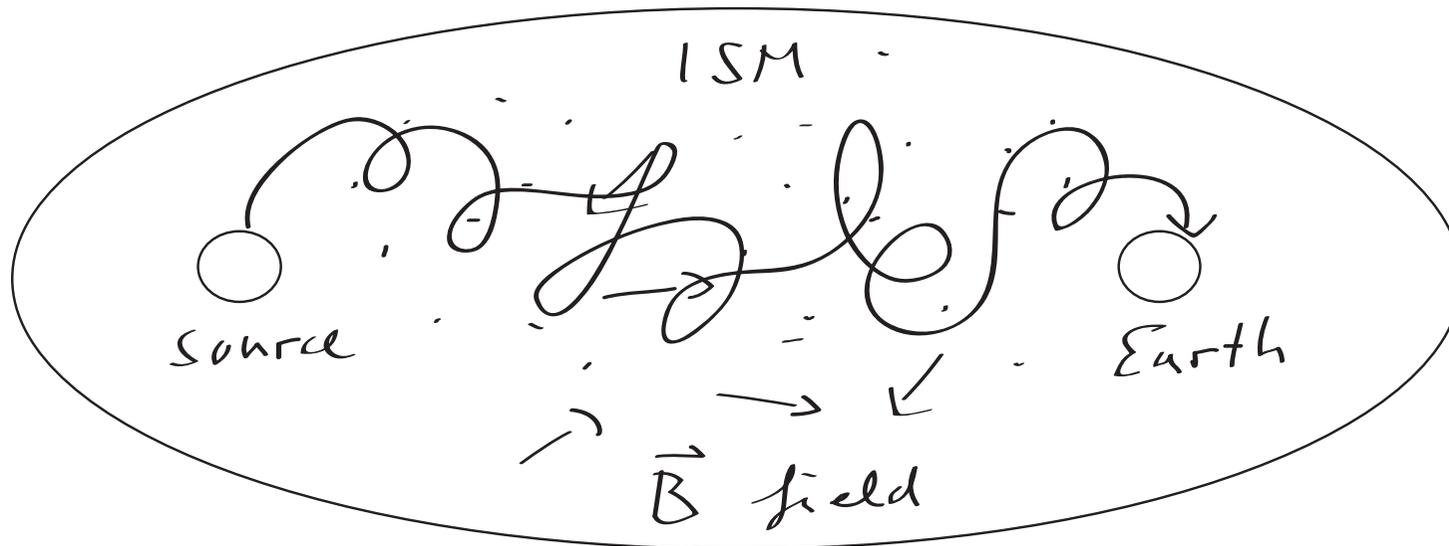


Propagation of Cosmic Rays in the Interstellar Medium (ISM)

objective: quantitative understanding
start with qualitative picture

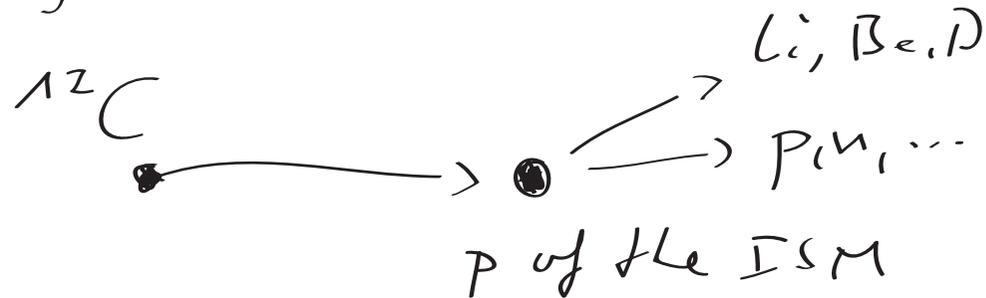


ISM in galactic disc $\sim 1 \text{ H atom/cm}^3$

$$B \sim 3 \mu\text{G} \Rightarrow \epsilon_B = \frac{B^2}{2\mu_0} \approx 0.2 \frac{\text{eV}}{\text{cm}^3}$$

What happens during propagation?

e.g. C nucleus



such nuclear interactions are called spallation reactions

Li, Be, B are rare elements in sol. syst.
(primordial nucleosynthesis)

the production during CR-propagation is significant, they are produced from abundant nuclei C, N, O

Diffusion or Leaky Box model

during transport of particles through Galaxy
we have to consider a number of effects

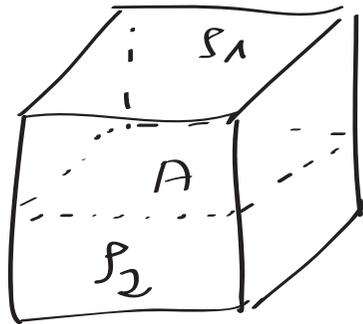
- deflection at B-fields
- energy losses through ionization
- inelastic reactions with ISM
- fragmentation of nuclei, spallation
- radioactive decay
- synchrotron radiation

CR particles diffuse through Galaxy

=> diffusion model

evolution of particle density $N(E, x, t)$
is described by transport equation

diffusion of gases



remove wall \rightarrow diffusion

$$\frac{\Delta m}{\Delta t} = -D \cdot A \cdot \frac{d\rho}{dx}$$

mass flow per unit time

diffusion coefficient $\left[\frac{\text{cm}^2}{\text{s}} \right]$

area

density gradient

current density $\vec{j} = \frac{\Delta m}{A \cdot \Delta t} \cdot \frac{N_A}{M}$

particle number density $n = \frac{\rho \cdot N_A}{M}$

$$\Rightarrow \vec{j} = -D \frac{dn}{dx}$$

① $\vec{j} = -D \text{grad } n$ 1st law of Fick

② $\frac{\partial n}{\partial t} + \text{div } \vec{j} = 0$ conservation of the number of particles

① + ② $\Rightarrow \frac{\partial n_i}{\partial t} = -\text{div}(-D \nabla n_i) \quad \text{div } \vec{A} = \nabla \cdot \vec{A}$
 $= \nabla \cdot (D \nabla n_i)$ 2nd law of Fick

N_i are the abundances of nuclei of type "i"

$$\frac{dN_i}{dt} = \nabla \cdot (D \nabla N_i) \quad \text{diffusion}$$
$$- \frac{\partial}{\partial E} (b_i \cdot N_i) \quad \text{energy loss}$$

(e.g. Bethe Bloch)

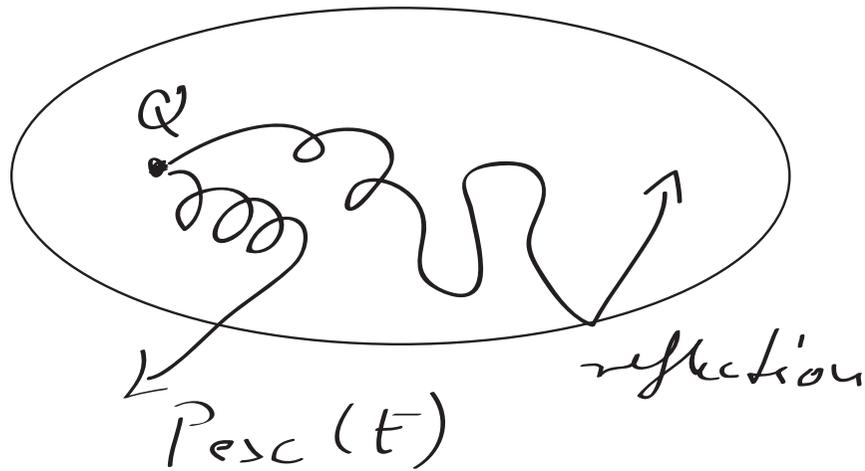
$$- n \cdot v \cdot \sigma_i \cdot N_i \quad \text{losses through inelastic scattering in ISM}$$
$$- \frac{N_i}{\tau_i} \quad \text{losses through radioactive decay}$$
$$+ Q_i \quad \text{source term (acceleration)}$$
$$+ \sum_{j>i} n \cdot v \cdot \sigma_{ij} N_j \quad \text{production through interactions of heavy nuclei in ISM}$$
$$+ \sum_{j>i} \frac{N_j}{\tau_{ij}} \quad \text{production through decay of heavy nuclei}$$

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

→ therefore, simplifications

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

A simple model: Leaky Box model



free propagation of CRs in closed volume (Galaxy)

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

$$\frac{dN_i}{dt} = -\frac{N_i}{T_{esc}} - \frac{\partial}{\partial E} (b_i \cdot N_i) - n \cdot v \cdot \sigma_i \cdot N_i - \frac{N_i}{\delta \tau_i} + \bar{Q}_i + \sum_{j>i} n \cdot v \cdot \sigma_{ij} \cdot N_j + \sum_{j>i} \frac{N_j}{\delta_j \tau_{ij}}$$

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

$$\frac{N_i}{\tau_{esc}(E)} = - \frac{\partial}{\partial E} (\cancel{\lambda_i} N_i) - (\bar{n} \cdot v \cdot \sigma_i + \frac{1}{\delta \tau_i}) N_i + Q_i$$

$E > 1 \text{ GeV}$

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

\uparrow model
 \uparrow from nuclear physics

Pathlength of cosmic rays

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

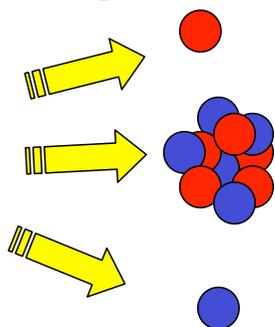
(Received 26 May 1972)

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/cm²

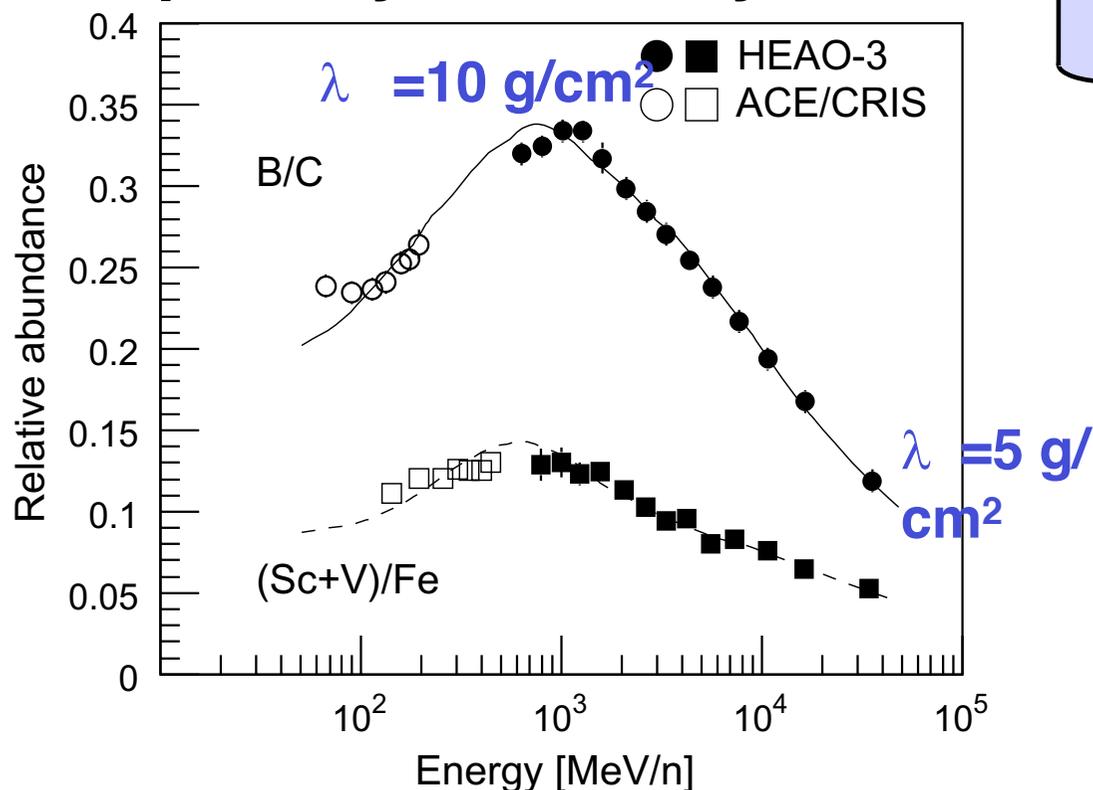


spallation



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

primary/secondary-ratio



N. Yanasak, ApJ 563 (2001) 768

TRACER: propagation of cosmic rays

Leaky-Box Propagation Parameters

- ▶ Continuity equation:

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

- ▶ Source Spectrum:

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

- ▶ Escape Path Length:

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

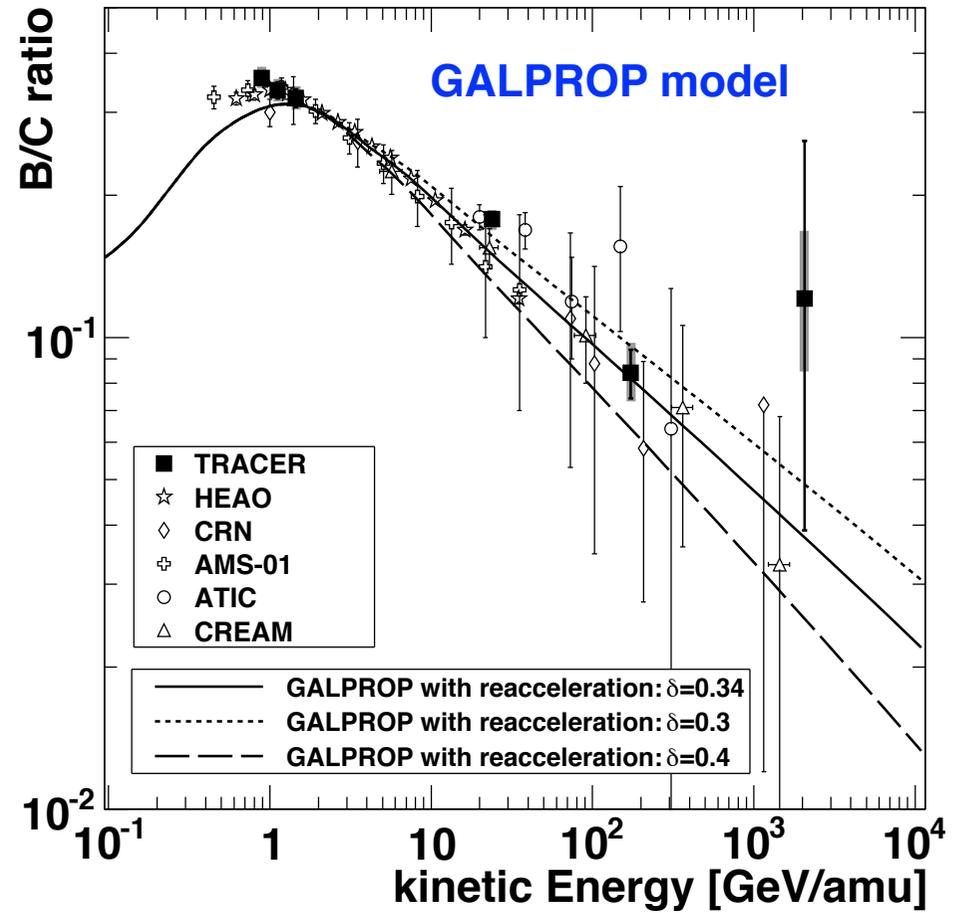
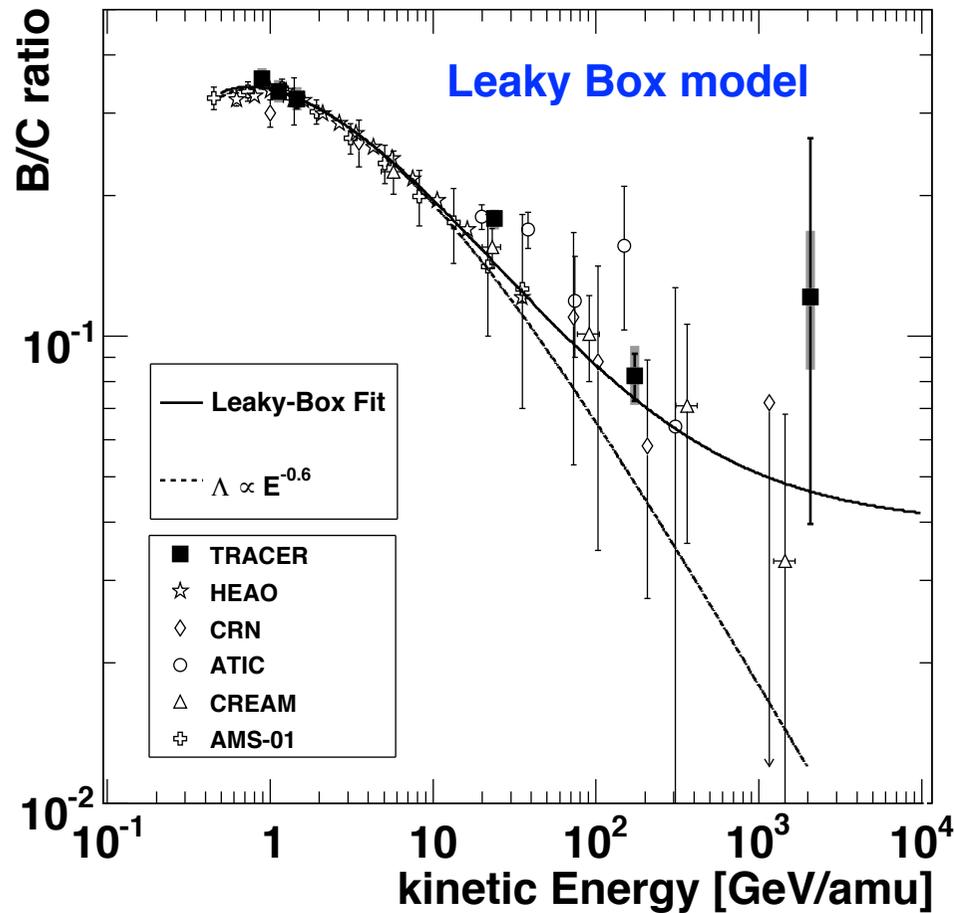
- ▶ Spallation Path Length:

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

Boron to Carbon ratio

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

TRACER: propagation of cosmic rays



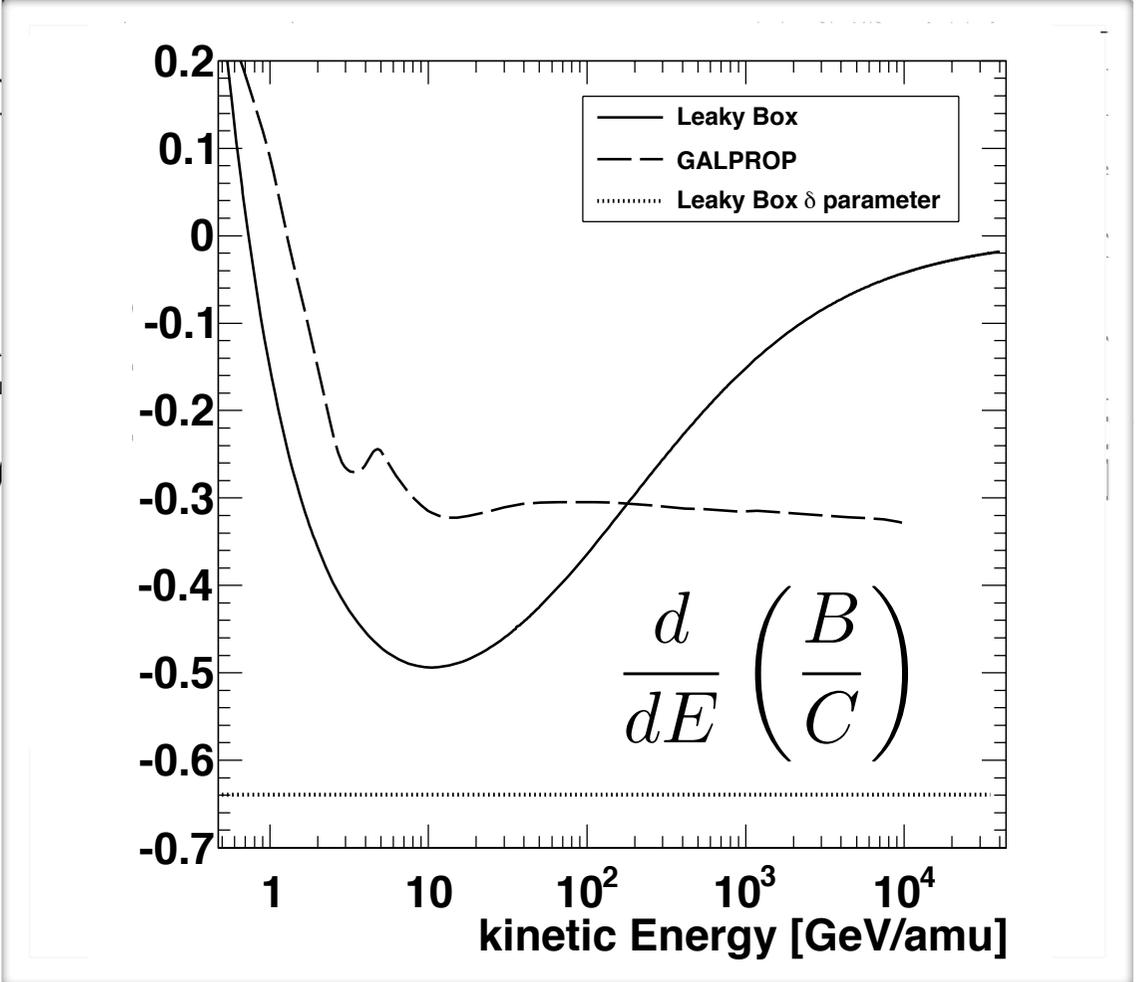
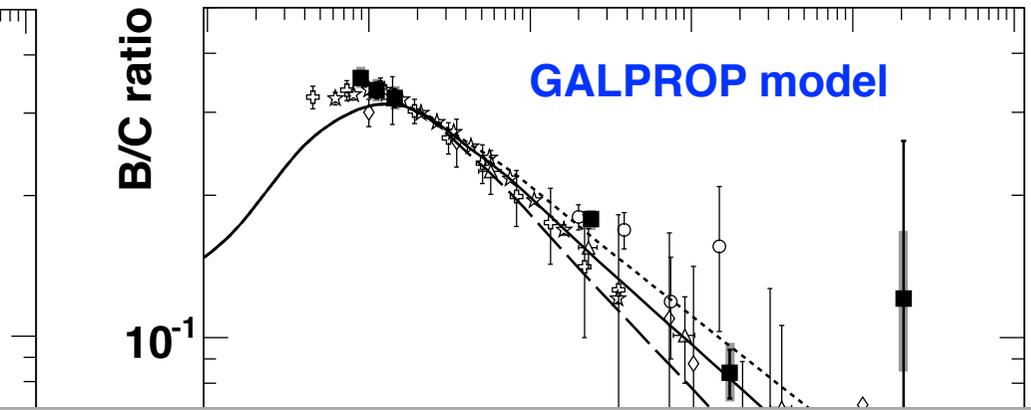
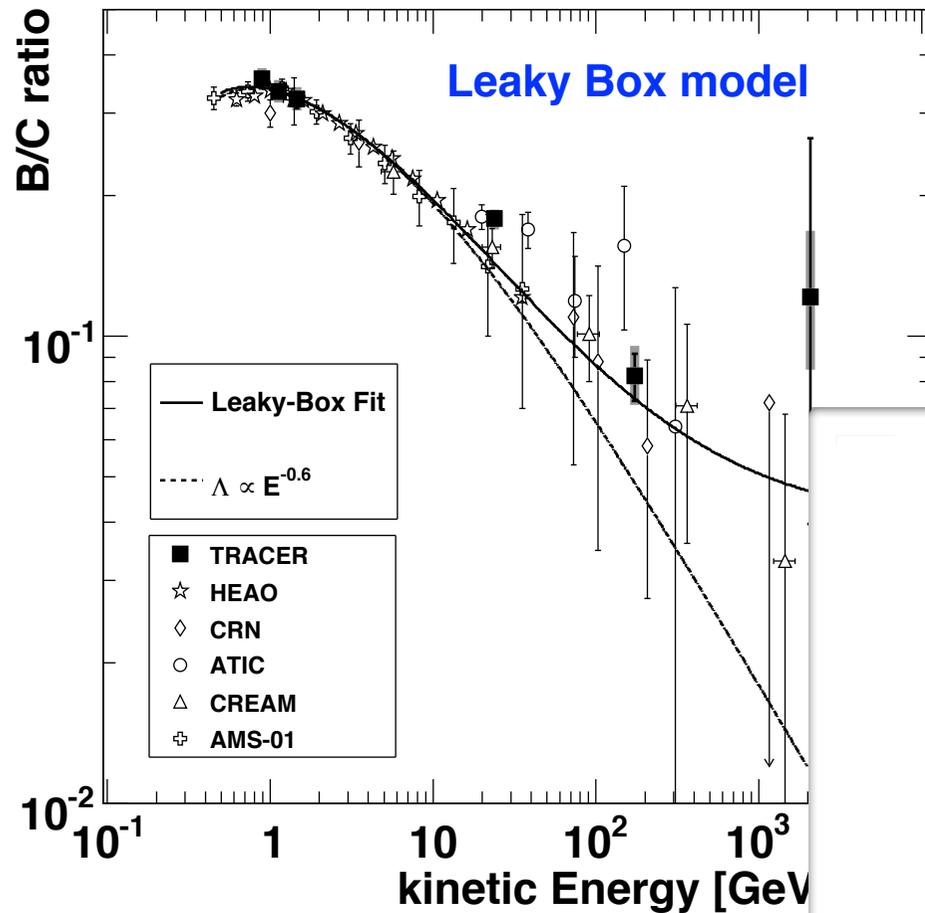
Escape Path Length:

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

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

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

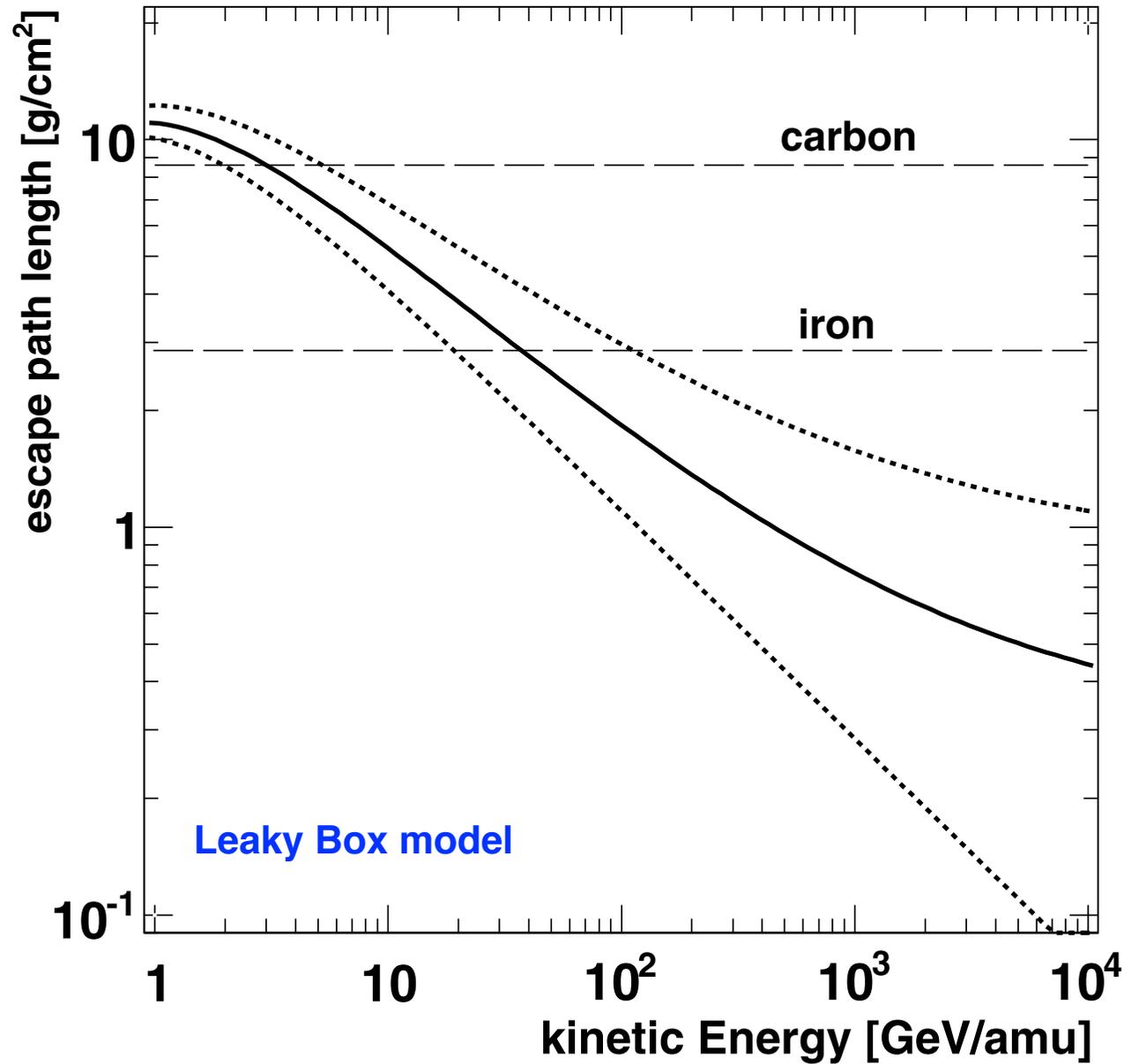
TRACER: propagation of cosmic rays



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

TRACER: propagation of cosmic rays

path length of
cosmic rays in
Galaxy



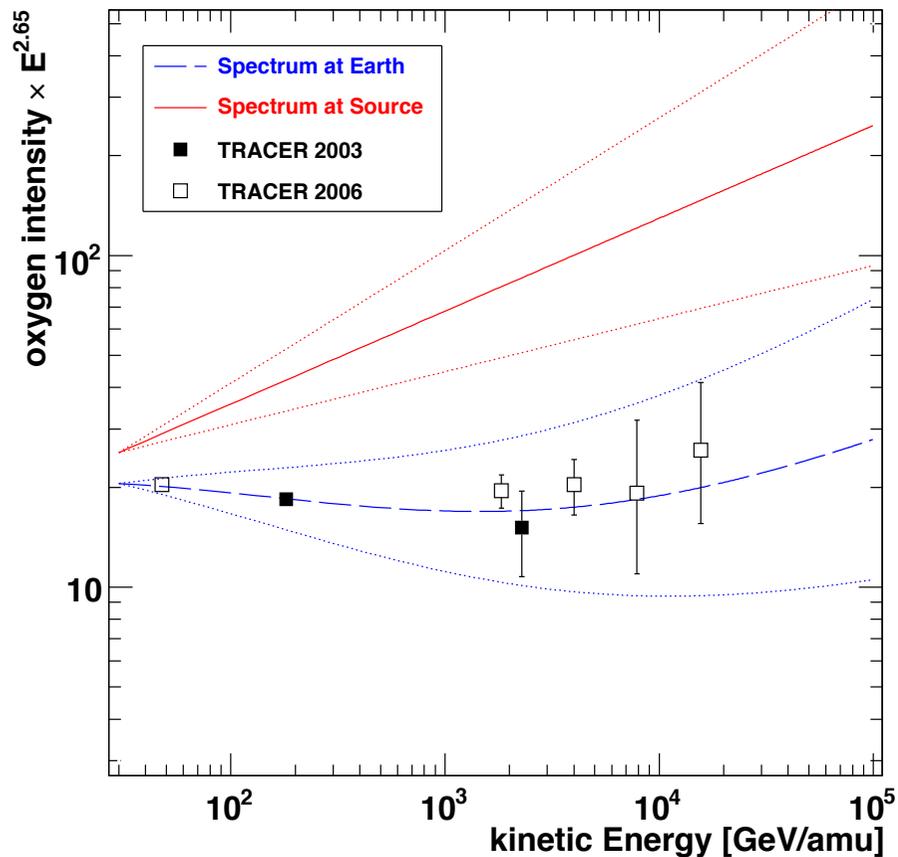
$$\Lambda(R) = \frac{26.7\beta}{(\beta R)^\delta + (0.714 \cdot \beta R)^{-1.4}} + \Lambda_0 \text{ g/cm}^2,$$

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

TRACER: propagation of cosmic rays

The Source Spectrum

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



- ▶ 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: $\alpha = 2.34$

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

$$\Rightarrow \lambda_{esc} = v \cdot \mathcal{S} \cdot \tau_{esc} \approx 10^7 / \text{cm}^2 \frac{v}{c} \left(\frac{41}{R} \right)^5 \quad R > 4V$$

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

$$\mathcal{S} \approx 0,6$$

$$\lambda_{esc} \approx 10 \text{ g/cm}^2 - 1 \text{ g/cm}^2$$

All CR species travel through the same column
density before they escape from the galaxy

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

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

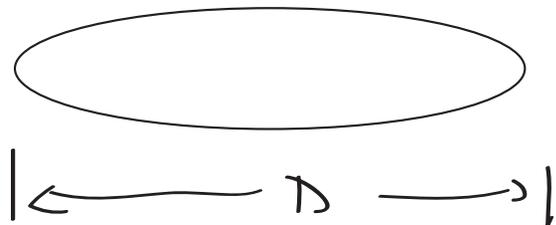
$$\lambda_{\text{int}}(\text{Fe}) \approx 2,3 \text{ g/cm}^2 \quad \leq \lambda_{\text{esc}}$$

\Rightarrow less interactions for protons than for Fe nuclei

$$\begin{aligned} \text{Galactic disc } n &\sim 1 \text{ H atom/cm}^3 \\ &= 1,67 \cdot 10^{-24} \frac{\text{g}}{\text{cm}^3} \end{aligned}$$

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

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



$\sigma(100)$ crossings of galaxy
to accumulate 10 g/cm^2

$$\tau_{(12)} \sim \frac{6 \cdot 10^{22} \text{ m}}{3 \cdot 10^8 \frac{\text{m}}{\text{s}}} \sim 6 \text{ Mio years!}$$

Radioactive isotopes and "age" of CRs

or residence time in galaxy

use secondary radioactive isotopes from spallation reactions

e.g. ^{10}Be $\tau \approx \sigma \tau_0 = 3.5 \cdot 10^6 \text{ a}$



equilibrium between production and decay of ^{10}Be

$$\frac{^{10}\text{Be}}{^7\text{Be} + ^9\text{Be} + ^{11}\text{Be}} \sim 0.1 \quad \text{at production}$$

if $\tau_{esc} \gg \tau_0 \Rightarrow$ expect observed ratio of $^{10}\text{Be} < 0,1$

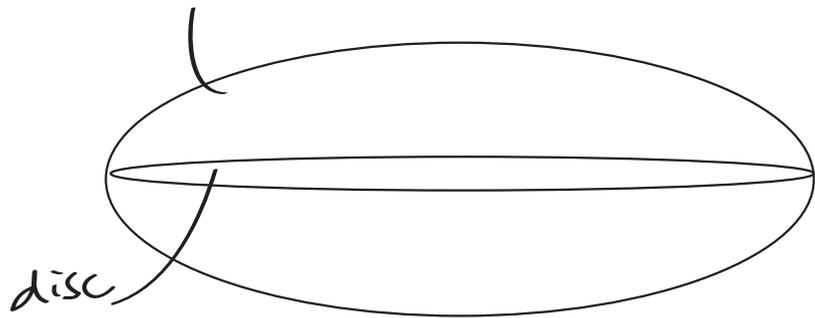
$$\frac{{}^{10}\text{Be}}{{}^7\text{Be} + {}^9\text{Be} + {}^{11}\text{Be}} \approx 0,028 \text{ in CRs}$$

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

from this, we can derive an average density

$$\bar{\rho} = \frac{\lambda_{esc}}{v \cdot \tau_{esc}} = \frac{10 \text{ g/cm}^2}{3 \cdot 10^{10} \frac{\text{cm}}{\text{s}} \cdot 17 \cdot 10^6 \cdot 86400 \cdot 365 \text{ s}}$$

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



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

„Age“ of galactic cosmic rays

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

M. GARCIA-MUNOZ, G. M. MASON, AND J. A. SIMPSON†

Enrico Fermi Institute, University of Chicago

Received 1977 March 14; accepted 1977 April 21

Residence time in Galaxy

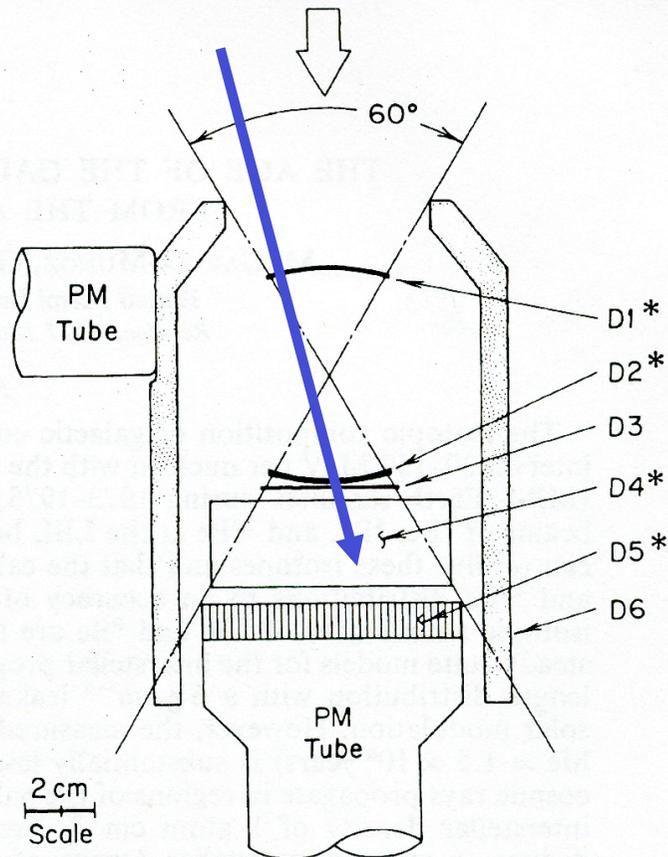
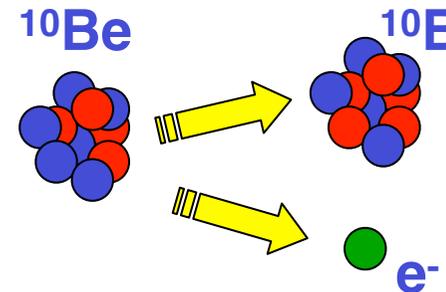


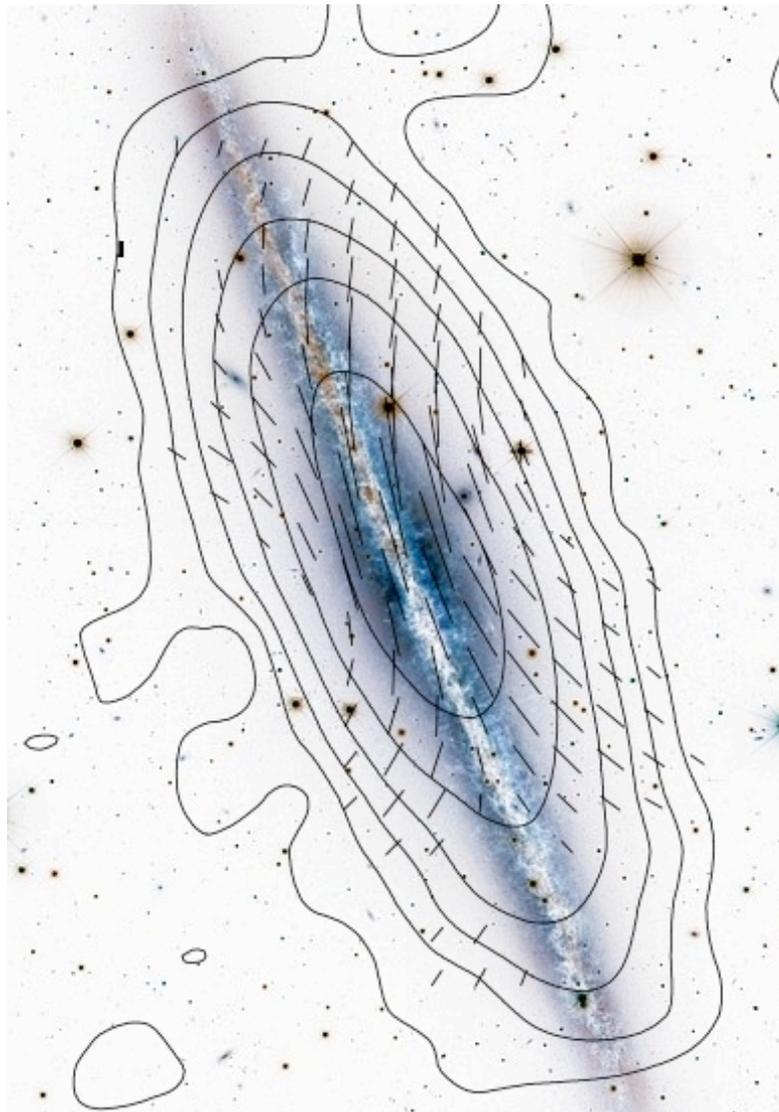
FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm , respectively. D4 is an 11.5 g cm^{-2} thick CsI (T1) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness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



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

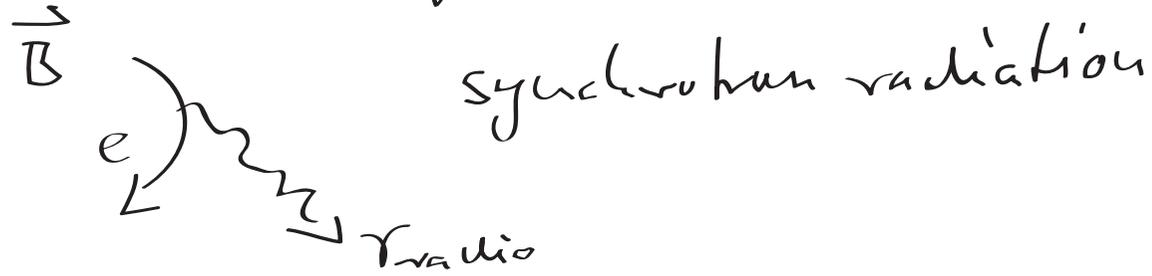
THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

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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 losses are smaller, so that larger radio halos are expected.

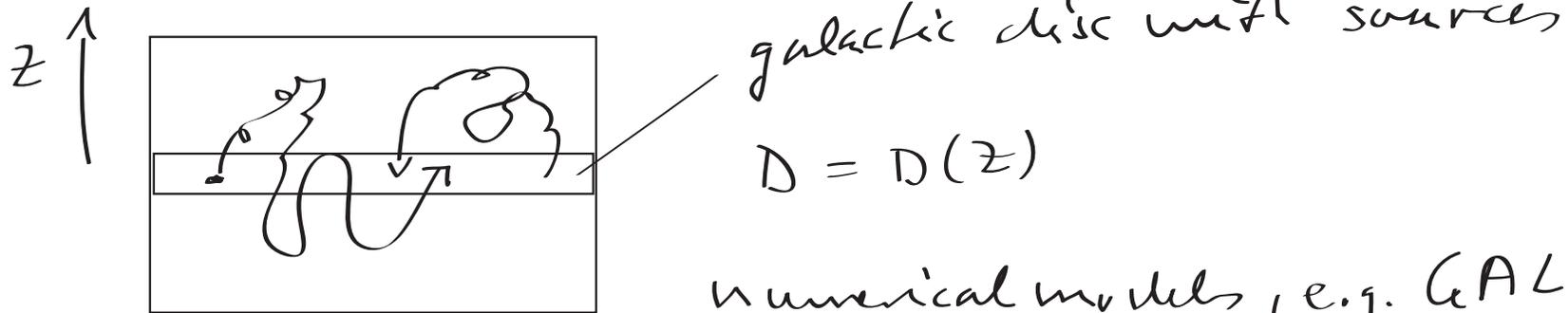
confirmed by observations of diffuse radio emission



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

leaky box model is very simple

today mostly: diffusion halo model



$$D = D(z)$$

numerical models, e.g. GALPROP

Antiparticles in CRs

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

$$p\bar{p} \rightarrow p\bar{p} + X \quad E_p > 6 \text{ GeV}$$

in a similar way also e^+ are produced

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

⇒ - from anti-galaxies

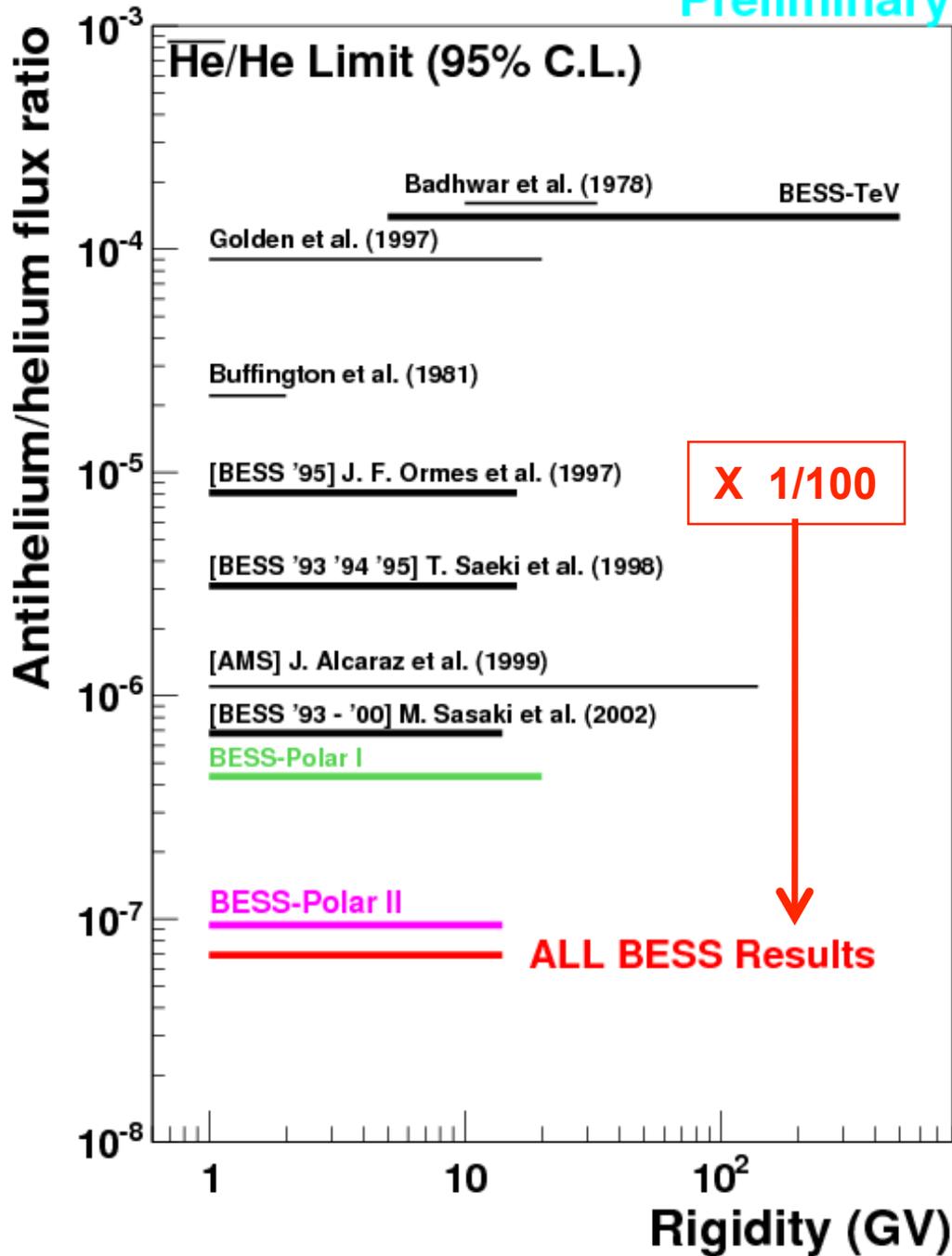
- DM in galactic halo

- exotic physics

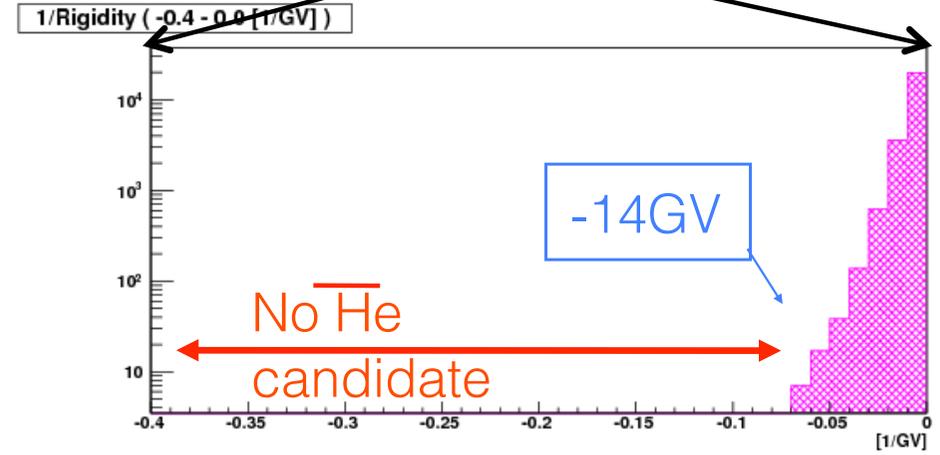
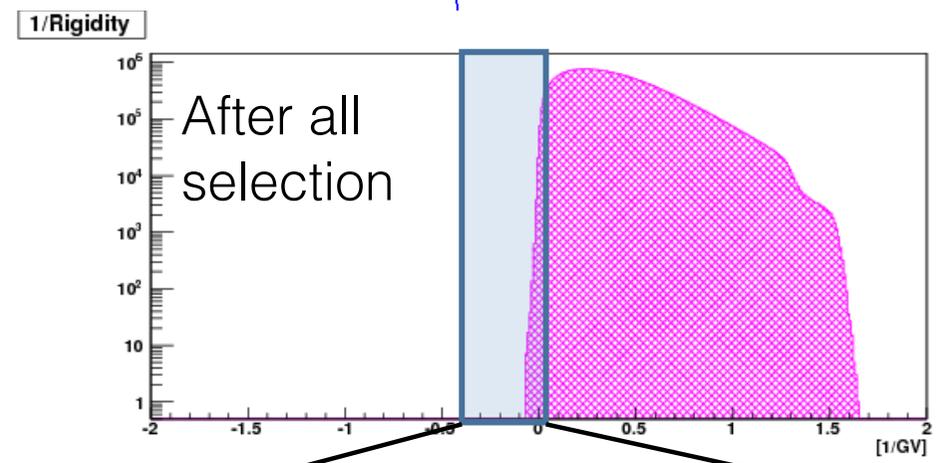
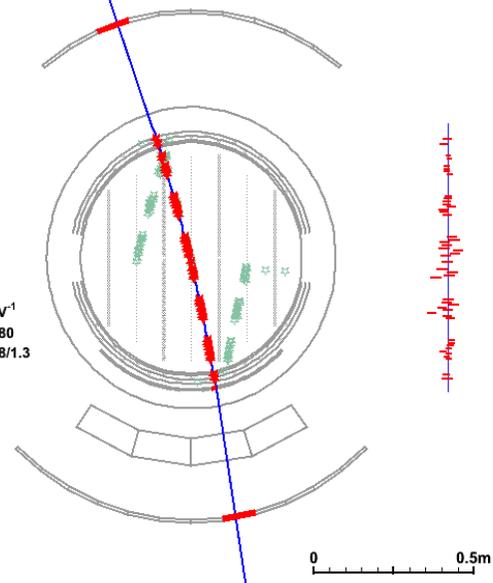
BESS-Polar: Search for antihelium

#1230
Sasaki

Preliminary



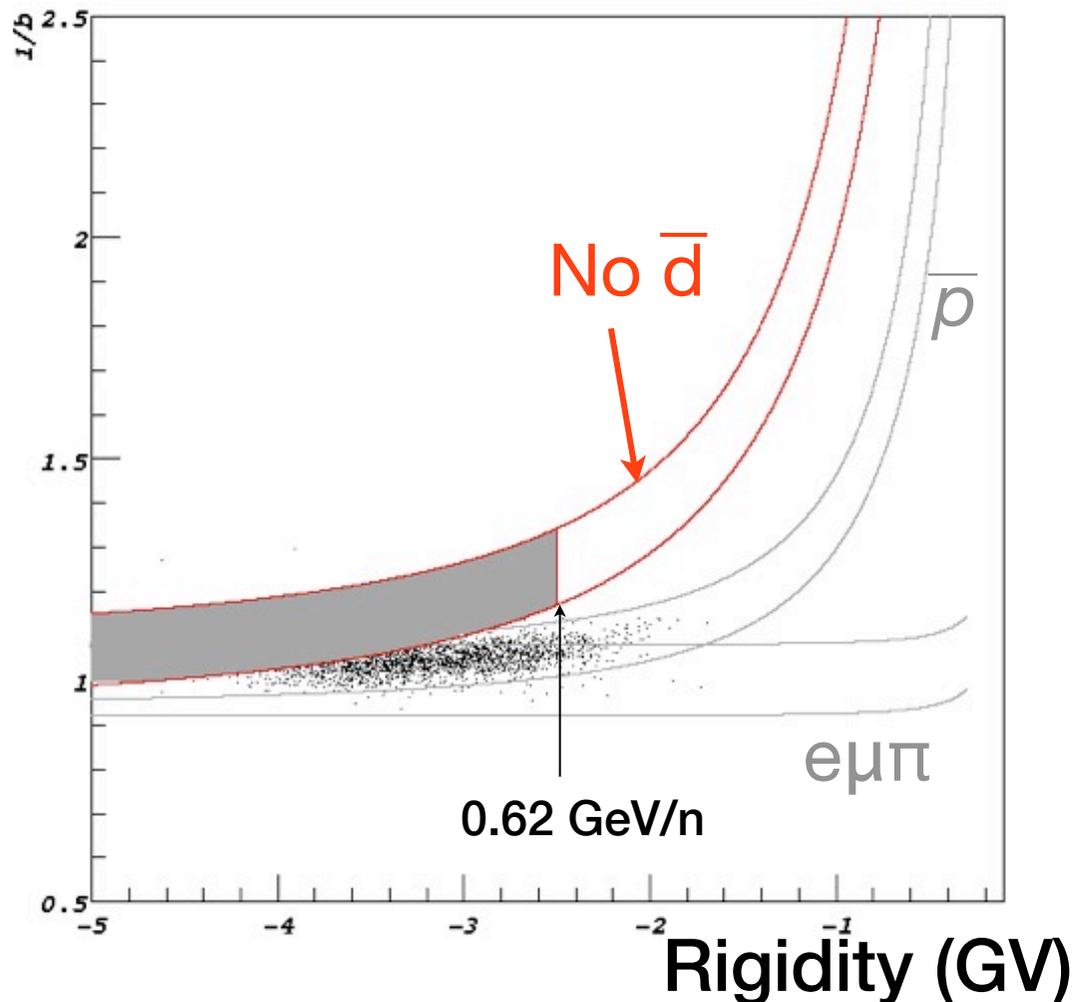
Nhit: 48/441
Nshd: 48
 χ^2 : 0.88/1.23
RGT: -1.22 GV
 $\sigma_{1/R}$: 0.0040 GV⁻¹
1/ β : 1.278/1.280
dE: 1.3/1.5/1.8/1.3



Search for cosmic-ray antideuterons with BESS-Polar

#1259
Yoshimura

Negative curvature

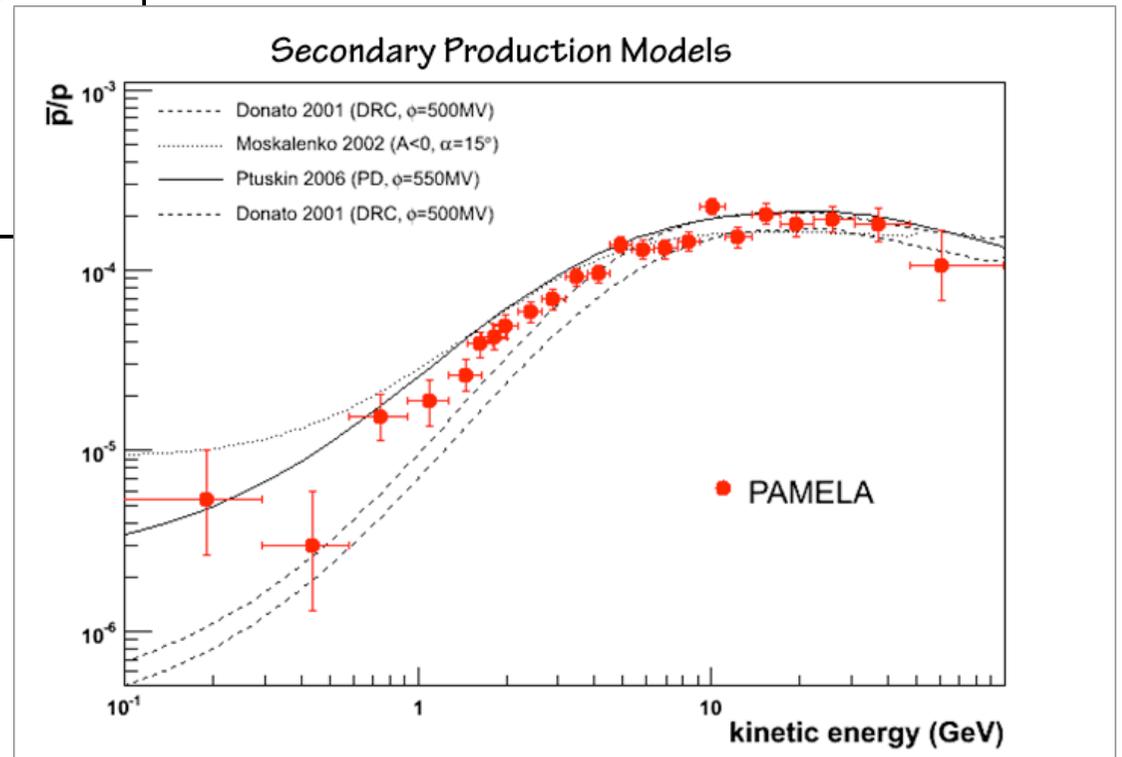
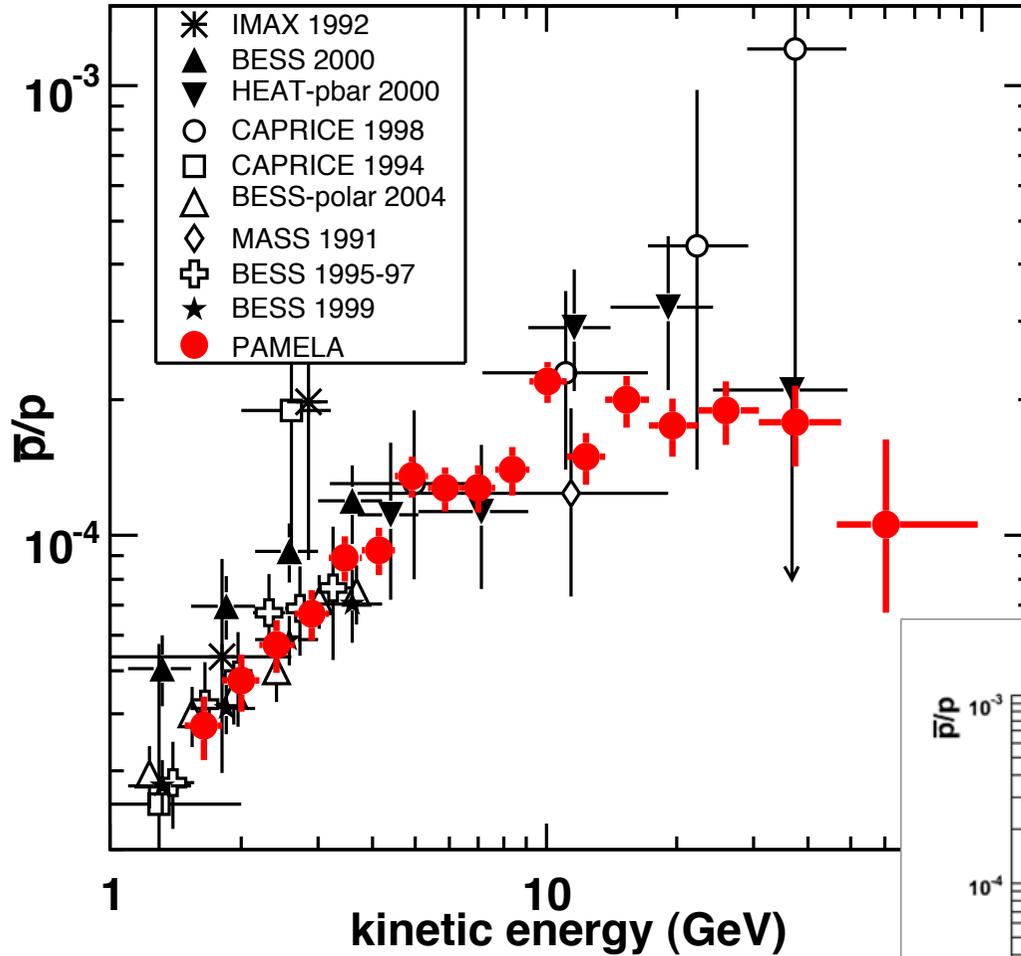


Apply the same selection as deuteron selection.

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. $\sim 0.62 \text{ GeV/nucleon}$)

antiproton-proton ratio



electron-positron fraction

