Origin and evolution of light elements

light elements have fragile nuclei
they break up in thermonuclear reactions

high abundance of Li, Be, B on
galactic cosmic rays

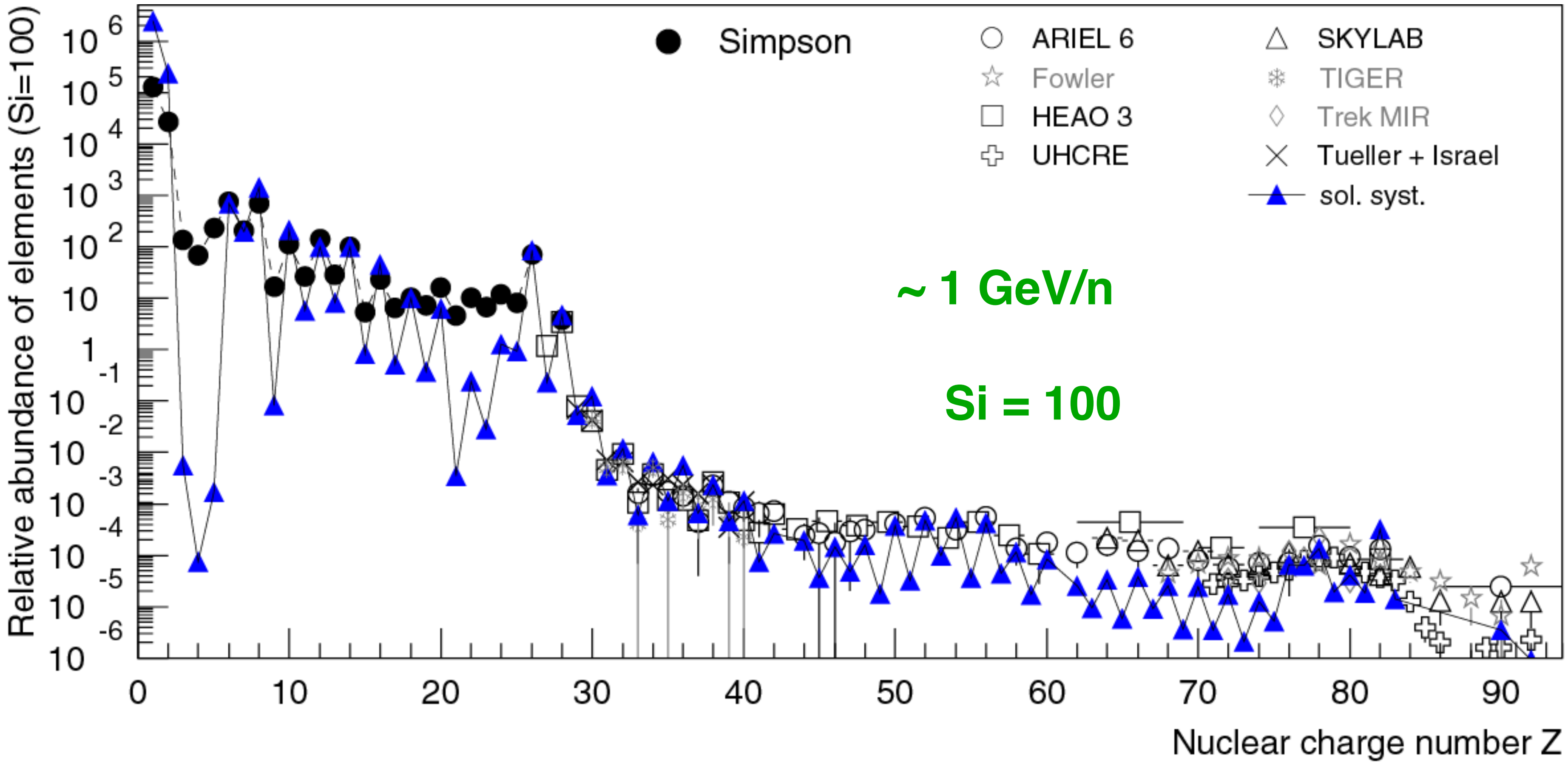
CRs are accelerated in strong shock fronts
of SNR and they propagate in diffusive
process through galaxy
close to Sun: solar modulation

Table 9.1. *Destruction of light nuclei in stellar interiors*

^{2}D	destroyed by	$(p,\gamma)\,^{3}$He	for $T >$	0.5×10^{6} K
^{6}Li	" "	$(p,\alpha)\,^{3}$He	for $T >$	2×10^{6} K
^{7}Li	" "	$(p,\alpha)\,^{4}$He	for $T >$	2.5×10^{6} K
^{9}Be	" "	$(p,\alpha)\,^{6}$Li; $(p,\mathrm{D})\,^{8}\mathrm{Be} \rightarrow 2\,^{4}$He	for $T >$	3.5×10^{6} K
^{10}B	" "	$(p,\alpha)\,^{7}\mathrm{Be}\,(EC)\,^{7}$Li	for $T >$	5.3×10^{6} K
^{11}B	" "	$(p,\alpha)\,^{8}\mathrm{Be} \rightarrow 2\,^{4}$He	for $T >$	5×10^{6} K
^{3}He	" "	$(^{3}\mathrm{He},\alpha)\,^{4}\mathrm{He} + 2\,^{1}$H	for $T >$	$\sim 10^{7}$ K

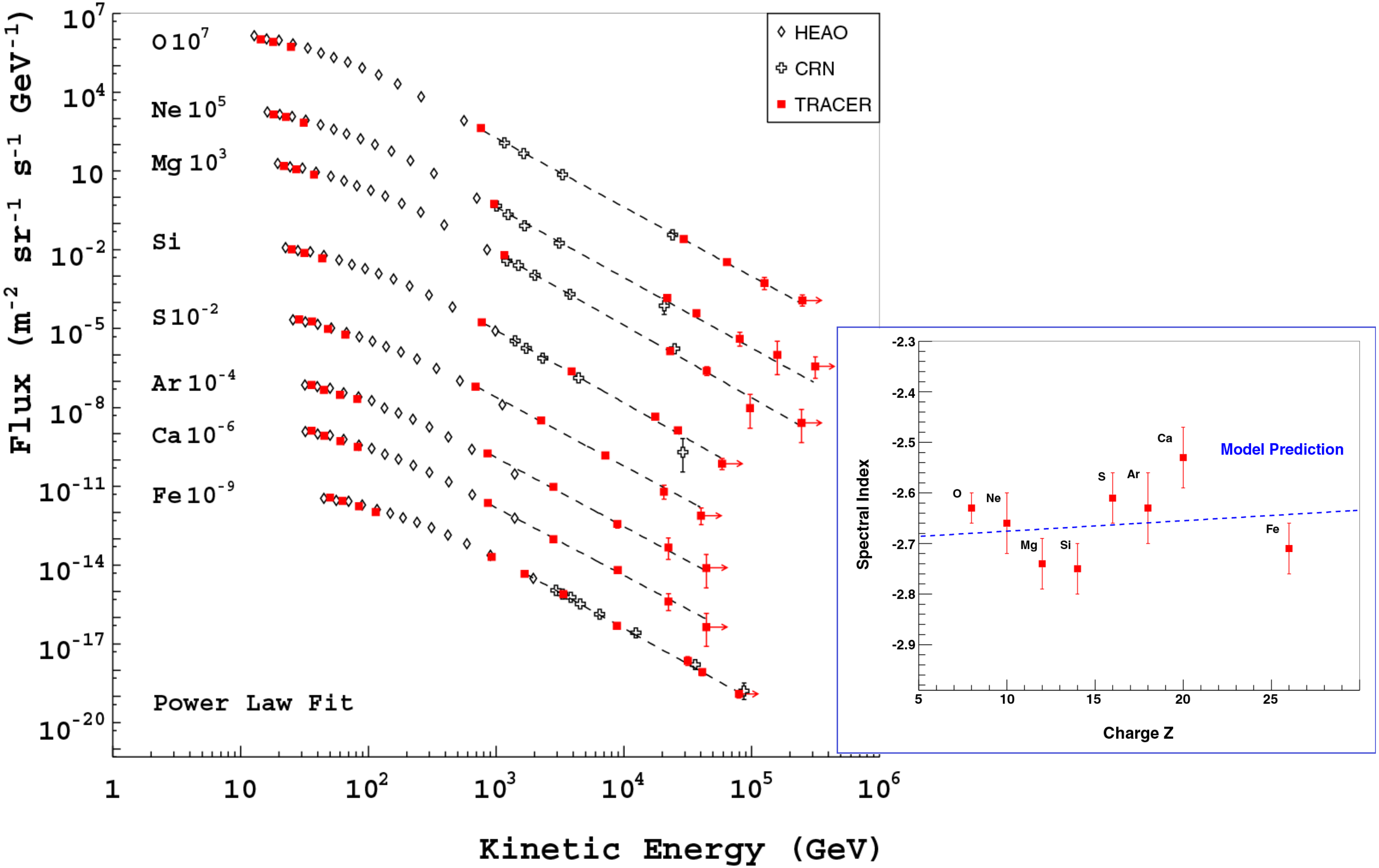
Relative abundance of elements at Earth

cosmic rays - solar system

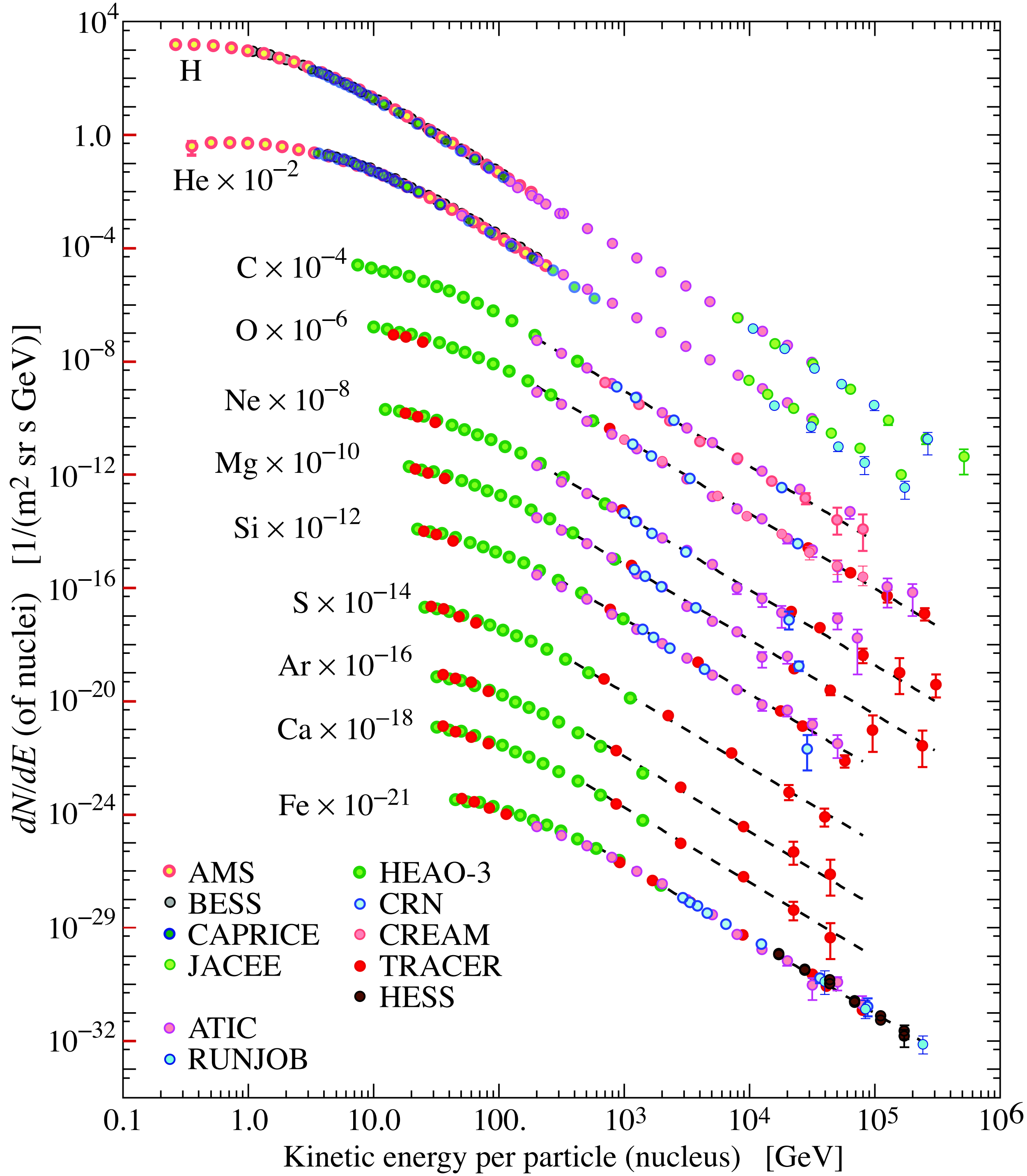


JRH, Adv. Space Res. 41 (2008) 442

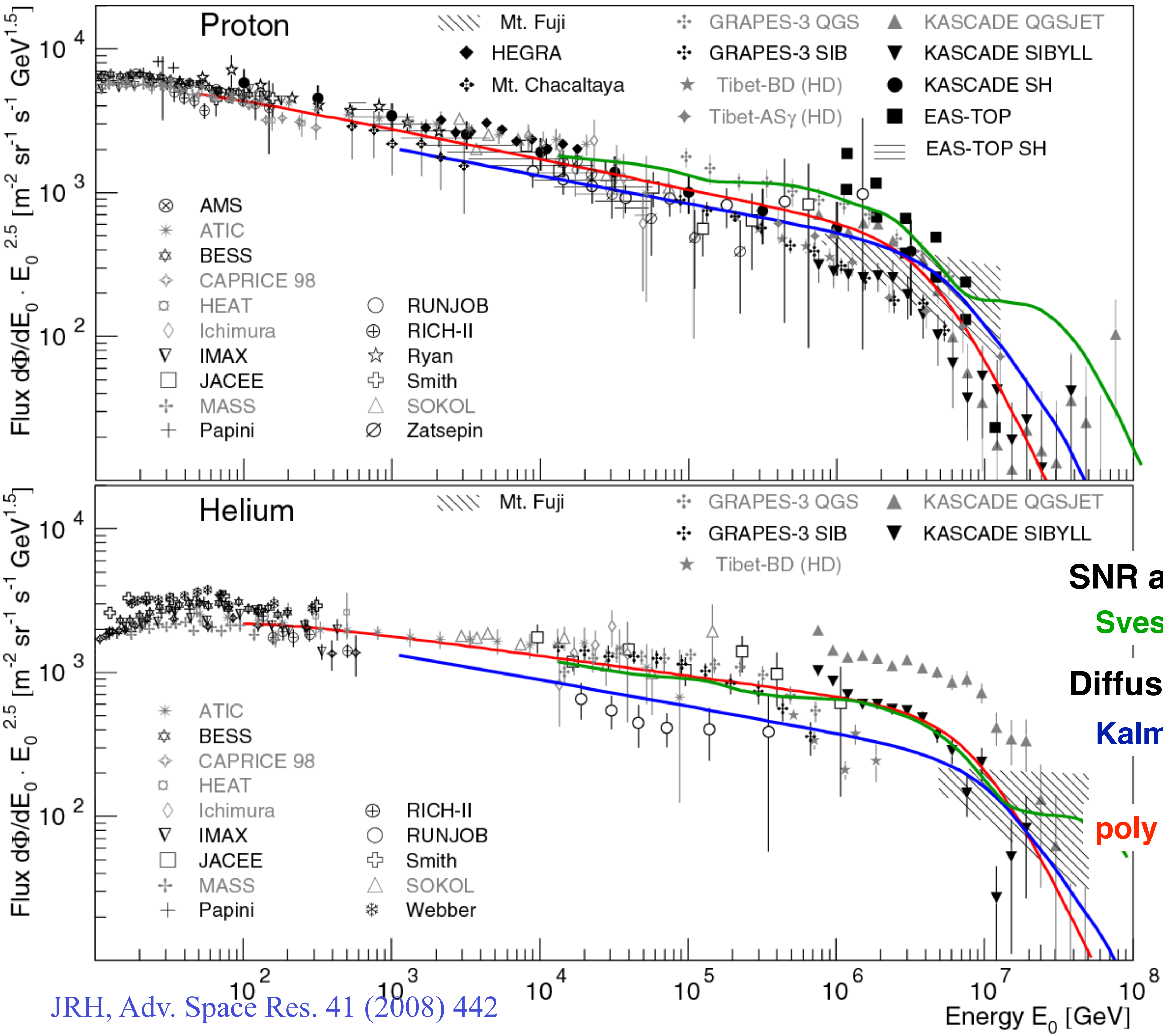
TRACER Energy Spectra for individual elements



D. Müller et al., ICRC 2007



Energy spectra of main elements in cosmic rays



SNR acceleration:

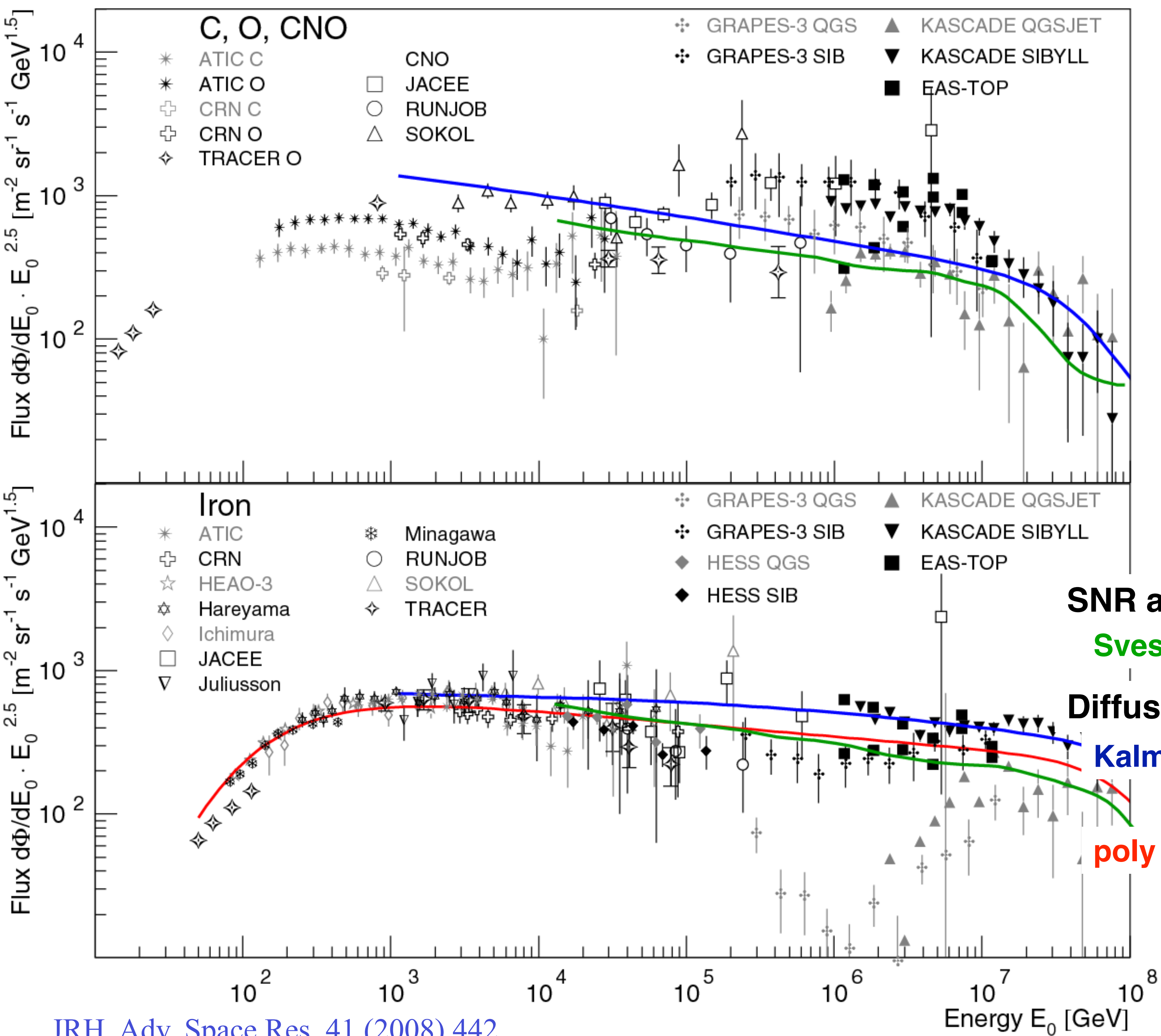
Sveshnikova⁺⁺ 2003

Diffusion:

Kalmykov+JRH 2007

poly gonato ~Z

JRH, Adv. Space Res. 41 (2008) 442



SNR acceleration:

Sveshnikova++ 2003

Diffusion:

Kalmykov+JRH 2007

poly gonato ~Z

JRH, Adv. Space Res. 41 (2008) 442

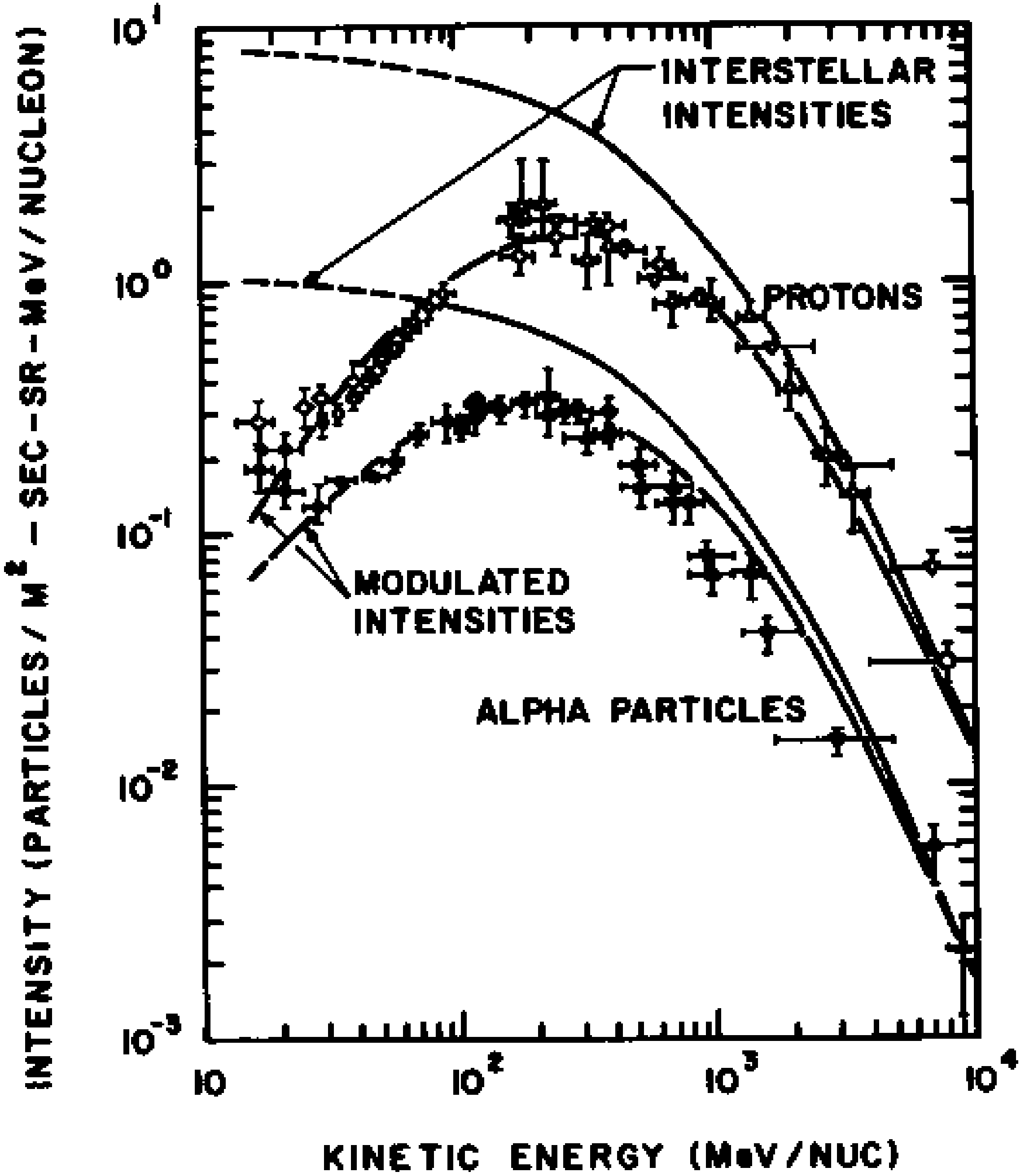


Fig. 9.3. Proton and α-particle spectra of primary cosmic rays and their demodulated versions. After Goldstein *et al*. (1970). Courtesy Reuven Ramaty.

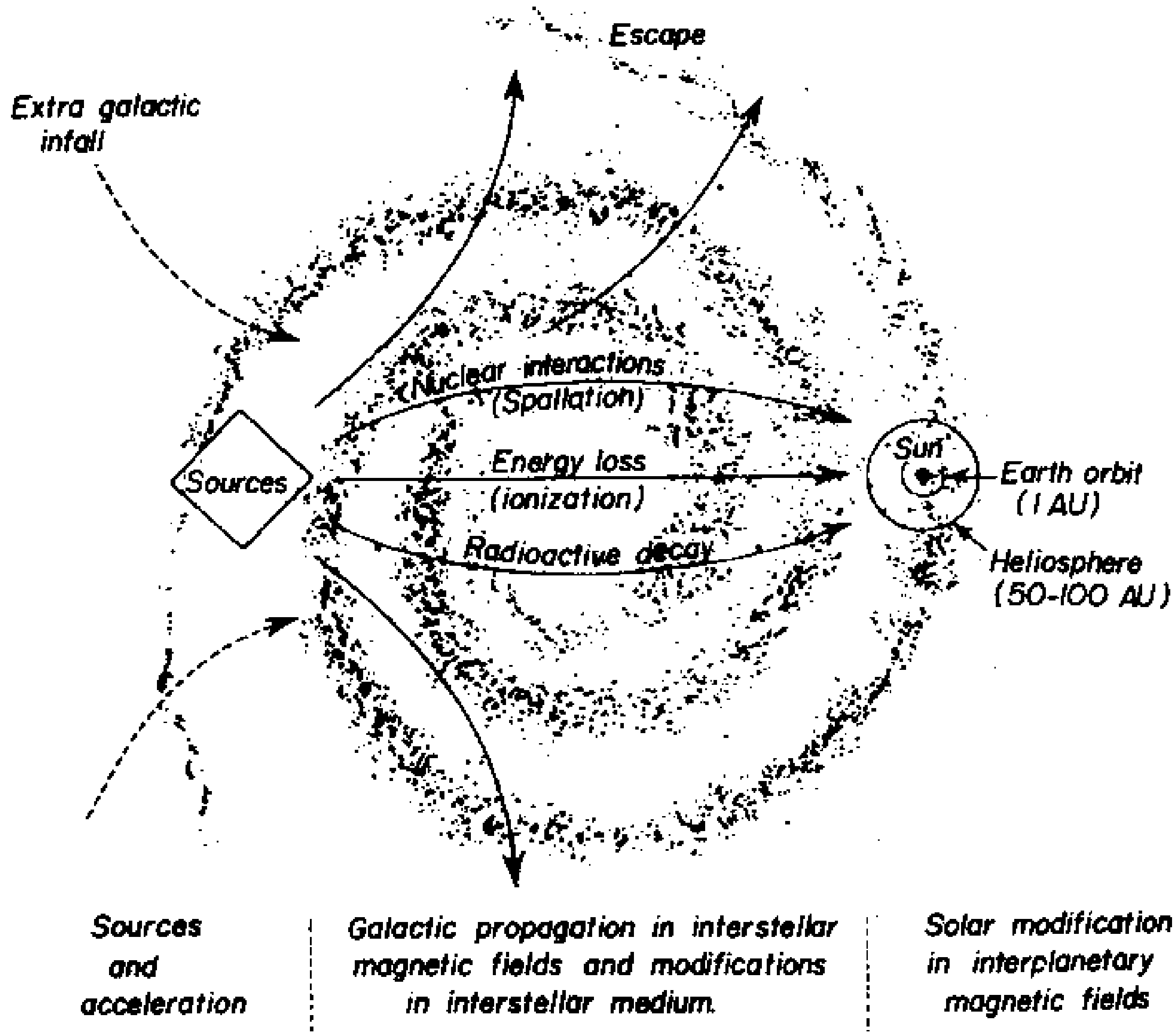


Fig. 9.2. Schematic view of the life history of a cosmic ray from acceleration in the source through propagation in the Galaxy to observation above the Earth's atmosphere. Adapted from Rolfs and Rodney (1988).

Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

production through spallation of heavy neulcei

production through decay of heavy nuclei transport equation of cosmic rays

"radioactive clocks" from ^{10}Be decay:

CRs travel ~ $17 \cdot 10^6$ through Galaxy

spallation of CNO elements → Li, Be, B

→ path length of CRs in Galaxy

B/C - ratio decreases with energy

→ path length decreases with energy

⇒ Leaky Box model $\Lambda_{esc}(E) = C \cdot E^{-\delta} + \Lambda_0$

path length decreases from ~10 g/cm^2 at 1 GeV

to a few g/cm^2 at 10^3 GeV/amu

„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

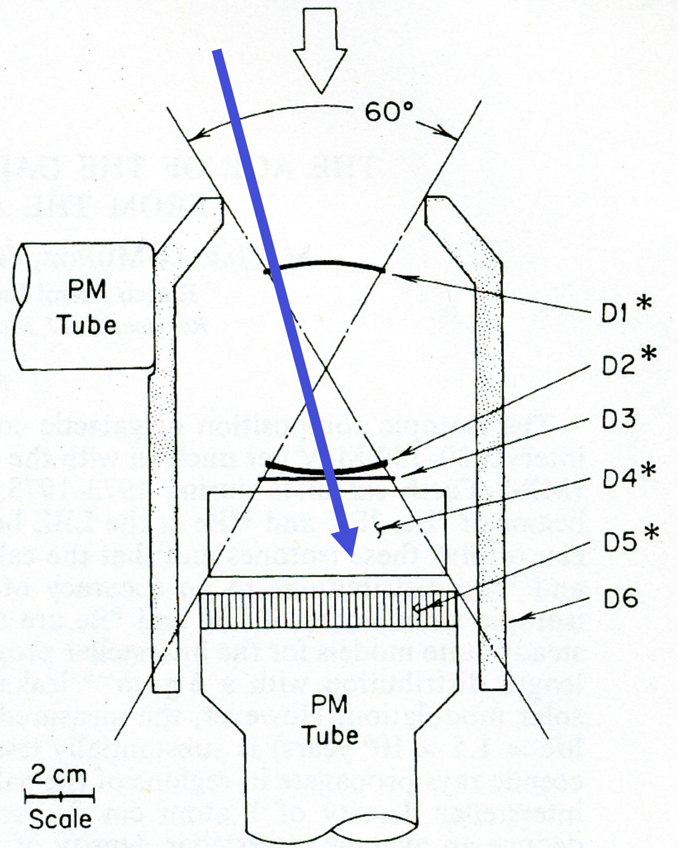
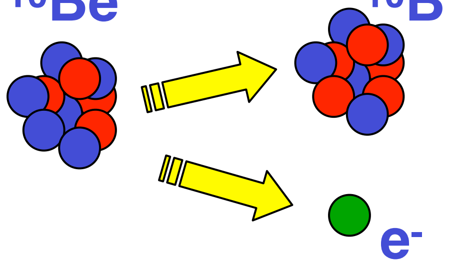


Fig. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (T1) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness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



τ = 17*10^6 a

The Astrophysical Journal, 217:859–877, 1977 November 1

Pathlength of cosmic rays

VOLUME 29, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 1972

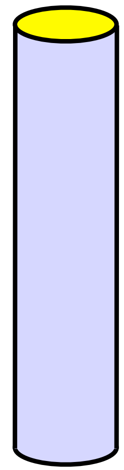
Composition of Cosmic-Ray Nuclei at High Energies*

Einar Juliusson, Peter Meyer, and Dietrich Müller
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637

(Received 26 May 1972)

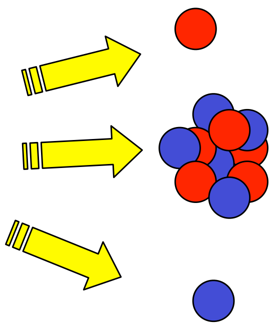
We have measured the charge composition of cosmic-ray nuclei from Li to Fe with energies up to about 100 GeV/nucleon. A balloon-borne counter telescope with gas Cherenkov counters for energy determination was used for this experiment. Our first results show that, in contrast to low-energy observations, 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/cm²



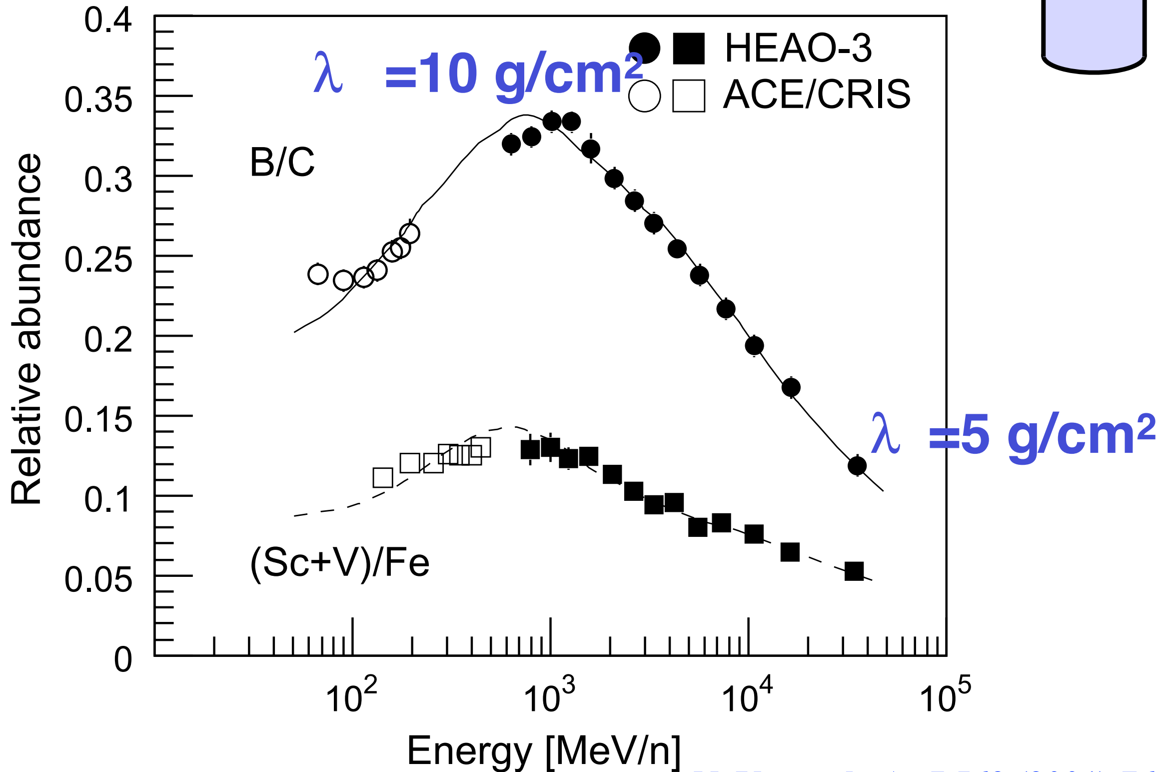
spallation

C → B + n + p



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

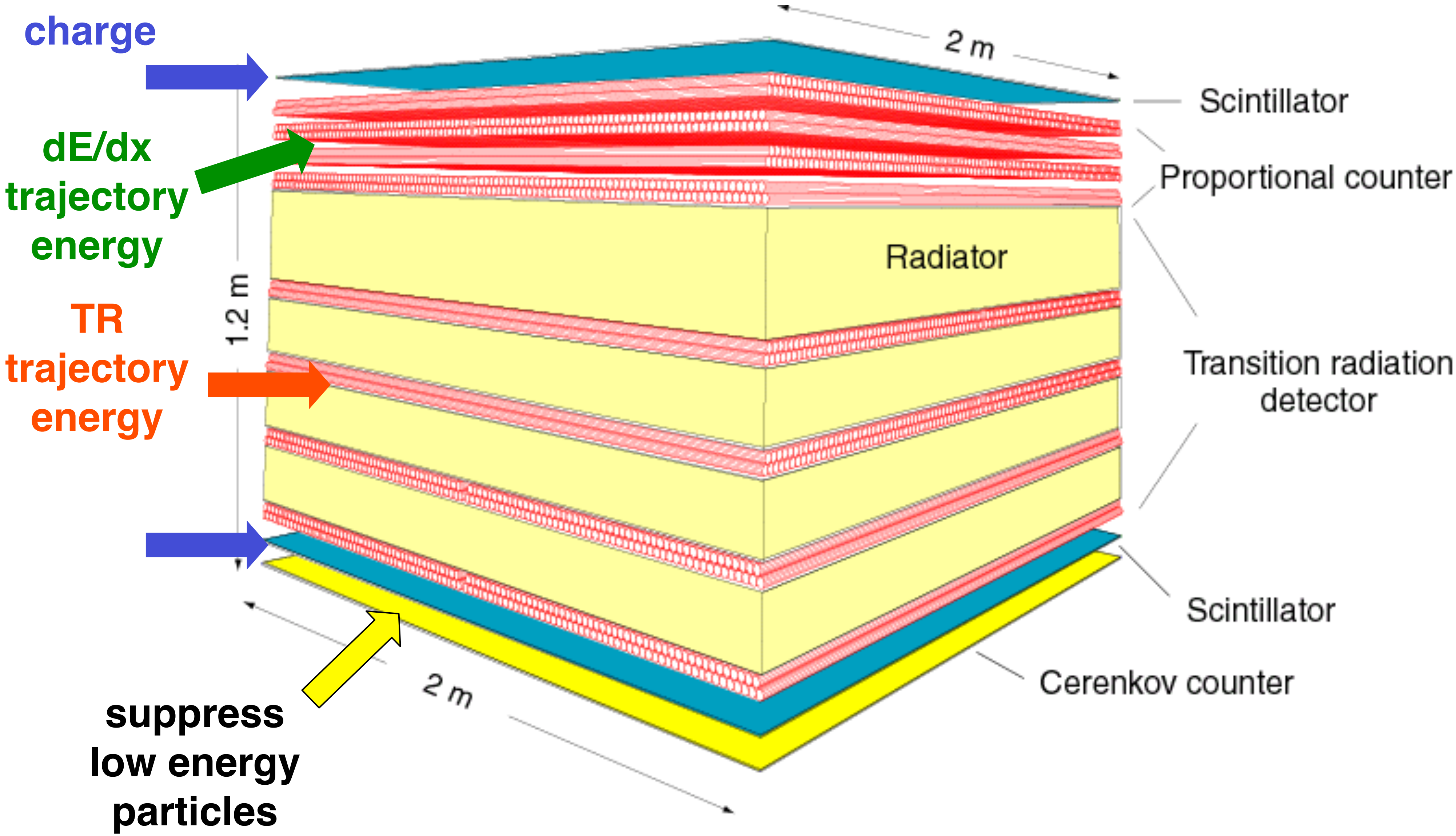
primary/secondary-ratio



N. Yanasak, ApJ 563 (2001) 768


TRACER - Mc Murdo, Antarctica, 2003

Transition Radiation Array for Cosmic Energetic Rays



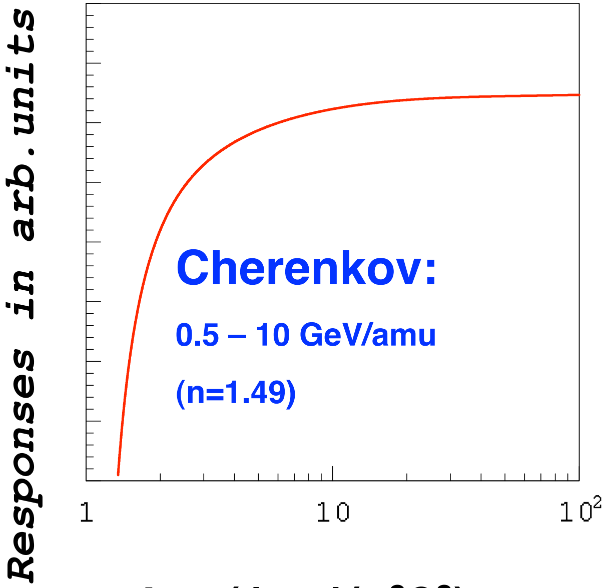
Geometric factor: 5 m² sr

1600 proportional tubes total

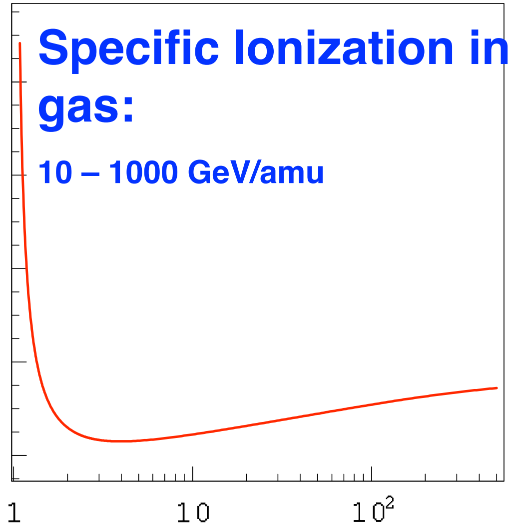
Transition Radiation Array for Cosmic Energetic Radiation

Direct measurement of the composition of cosmic rays from 0.5 to 10,000 GeV/amu with single elemental resolution

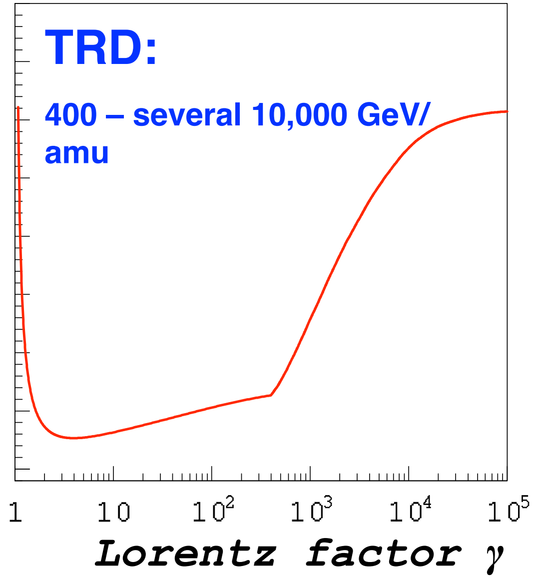
Combined responses for energy measurements over 4 decades:



$L \sim (1 - 1/n^2\beta^2)$



$dE/dx \sim 1/\beta^2 \ln(E)$

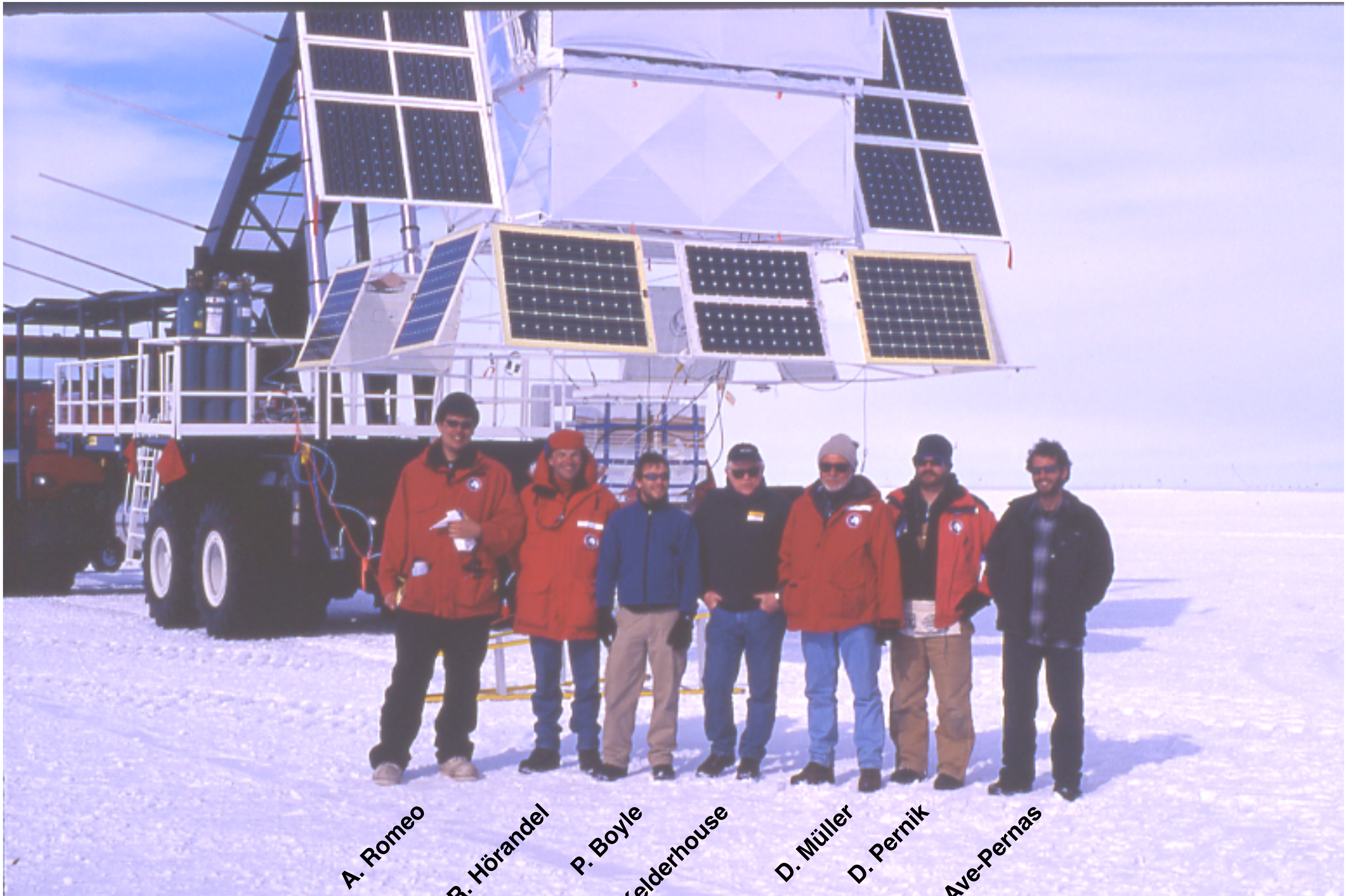


TR = dE/dx + x-rays

all signals scale with Z^2

$5 m^2$ sr - currently the largest cosmic-ray detector on balloons

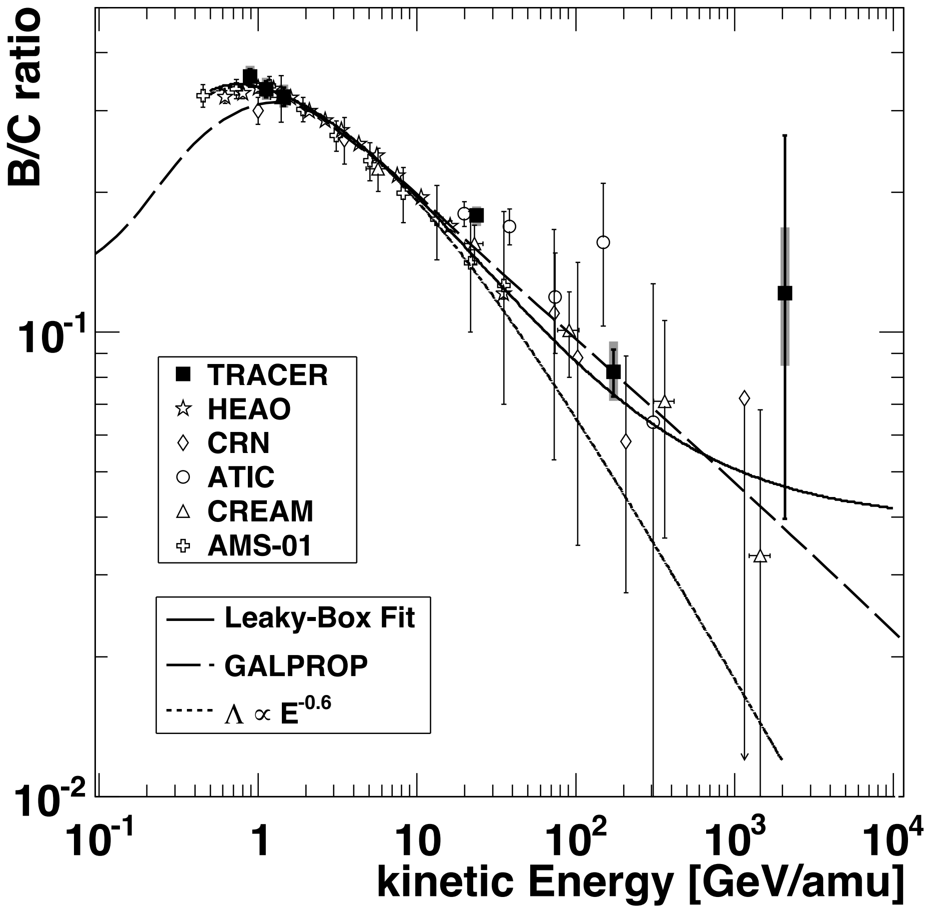
TRACER - Mc Murdo, Antarctica, 2003



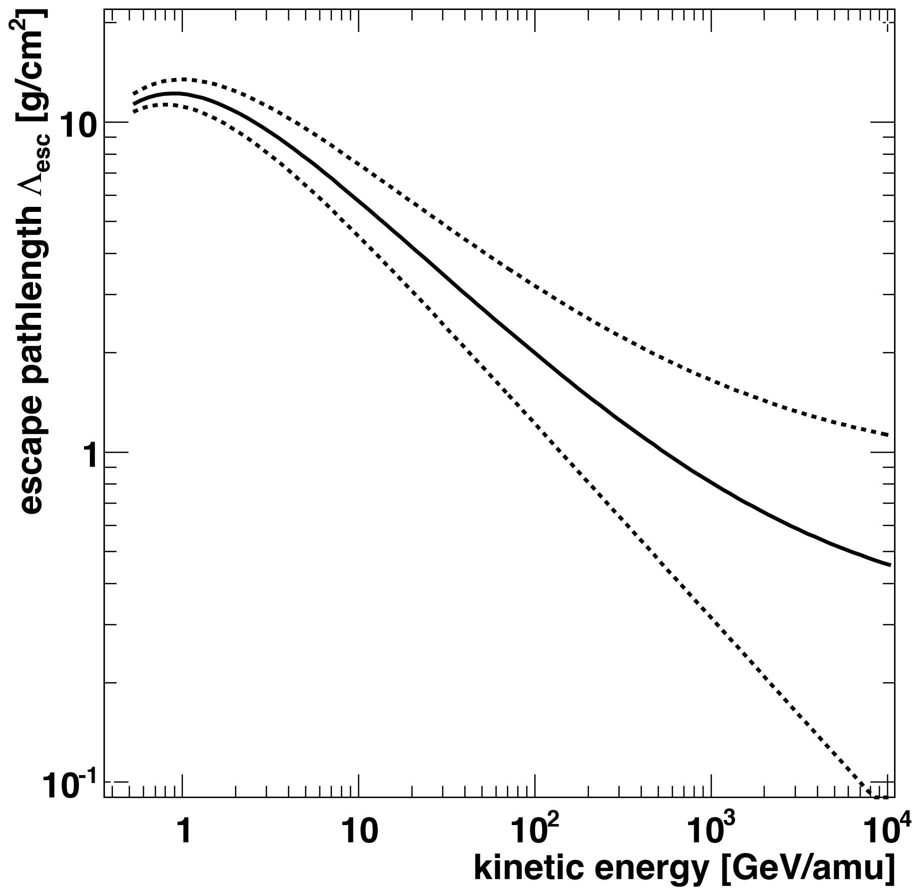
SOUTHERN OCEAN
FALKLAND ISLANDS (UK)
South Orkney Is.
Scotia Sea
ARGENTINA
Weddell Sea
South Shetland Is.
Larsen Ice Shelf
Ronne Ice Shelf
CHILE
Antarctic Penin.
Alexander I.
ANTARCTICA
KERGUELEN (Fr.)
HEARD & MCDONALD ISLANDS (Austr.)
Amery Ice Shelf
Vinson Massif 4897 m
South Pole
Thurston I.
Mt. Kirkpatrick 4528 m
Ross Ice Shelf
Roosevelt I.
Ross Sea
INDIAN OCEAN
SOUTHERN OCEAN
Balleny Is.
PACIFIC OCEAN
MACQUARIE I. (Austr.)
CAMPBELL IS. (N.Z.)
AUCKLAND IS. (N.Z.)
ANTIPODES IS. (N.Z.)
AUSTRALIA
NEW ZEALAND
60°
70°
80°
100°
120°
140°
160°

Cosmic-ray propagation

B/C ratio



path length



A. Obermeier et al., ICRC (2011)

A. Obermeier, PhD thesis, RU Nijmegen (2011)

Light element production

two processes CR's + ISM

- fusion reactions

$$\alpha + \alpha \to {}^6Li + p + n$$

$${}^7Li + p$$

$${}^7Be\ (EC)\ {}^7Li + n$$

- spallation reactions (dominant)

$$C, N, O + p, \alpha \to {}^{6,7}Li,\ {}^9Be,\ {}^{10,11}B$$

constant production rate

$$\frac{dN_L}{dt} = N_{CNO} \int \bar{\sigma}_{CNO}(E)\, \phi(E)\, dE \approx N_{CNO} \langle \tilde{\sigma} \rangle \phi$$

abundance relative to H

$$\frac{L}{H} = \frac{CNO}{H} \langle \bar{\sigma} \rangle \phi_p T = 4 \cdot 10^{-12} \left(\frac{T}{10^9 a} \right) \langle \bar{\sigma} \rangle \mathrm{mb}$$

T age of galaxy

$\sigma(E) \approx$ const. for relevant E

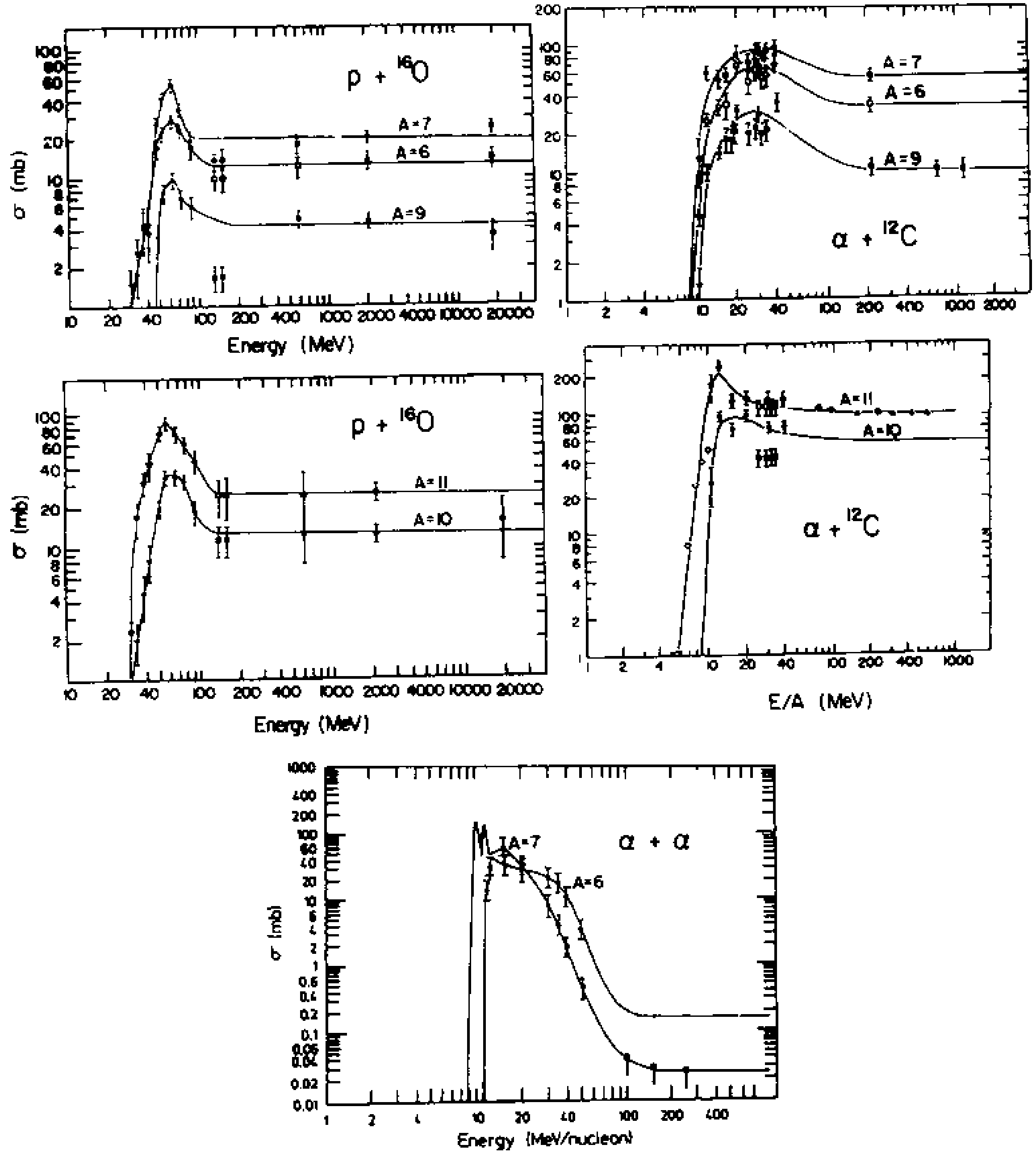


Fig. 9.4. Reaction cross-sections, as a function of energy per nucleon, for the production of light elements for some typical cases. Adapted from Read and Viola (1984). Courtesy Vic Viola.

Galactic chemical evolution of light elements

using instantaneous recycling approximation

$$\frac{d}{ds}(g\,z) = q + \beta R z - z + \frac{N_{CNO}\, \sigma \phi A m_H + z_F F - z_E E}{\psi} \qquad (1)$$

$0 \leq \beta \leq 1$ allows for astration

$\beta = 0$ for complete destruction

A mass number of light element

α-α fusion reactions have been neglected

if SFR is assumed proportional to mass of gas

$$\frac{ds}{dt} = \omega g \qquad \omega = \text{const.}$$

→ abundance of primary element increases linearly with time

$$Z = \omega t$$

or, in general $Z(t) = \int_0^t \omega(t')\,dt' \equiv u$

(1) with u

(2) $$\frac{d}{du}(gZ) = g\left(P + \frac{A}{A_{CNO}}\,\sigma\, Z_{CNO}\,\frac{\phi}{\omega} - \frac{Z}{\alpha'}\right) + \frac{Z_F F - Z_E E}{\omega}$$

P yield from stellar production

$$\alpha' \equiv \frac{\alpha}{1-\beta(1-\alpha)}$$

→ α for complete destruction

→ 1 for no destruction

pure CR spallation products $^6Li, Be, B$

(2) becomes

$$\frac{d}{du}(gZ) + \frac{gZ}{\alpha'} = \frac{A}{A_{CNO}}\, g\, Z_{CNO}\, \sigma \frac{\phi}{\omega} + \frac{Z_F F - Z_E E}{\omega}$$

ϕ proportional to SN rate $\propto$ SFR ψ

$$\frac{\phi/\omega}{(\phi/\omega)_1} = g/g_1 \qquad \text{1 refers to present epoch}$$

simple model $E = F = 0 \qquad g = e^{-u} \qquad Z_{CNO} = P_{CNO} \cdot u$

$$\frac{dZ}{du} + (\alpha'^{-1} - 1) Z = \frac{A}{A_{CNO}}\, \sigma\, P_{CNO} \frac{\phi_1}{\omega_1}\, u\, e^{-(u-u_1)}$$

$$= k \left(\frac{\sigma\phi}{\omega}\right) u \; e^{u_1 - u}$$

$$z = k \left(\frac{\sigma \phi}{\omega}\right)_1 e^{u_1} \frac{e^{-u}\left[e^{v'} - (1+v')\right]}{(2-1/\alpha')^2}$$

with $k = \dfrac{A}{A_{CNO}}\, p_{CNO}$

$$v' = (2 - 1/\alpha')u \simeq \frac{u}{2} \quad \text{for } \alpha' = \frac{2}{3}$$

$\Rightarrow$ limiting behaviours

$$z \propto \frac{1}{2} u^2 \qquad u \to 0$$

$$\propto \frac{e^{-(u-v')}}{(2-1/\alpha')^2} \qquad u \to \infty$$

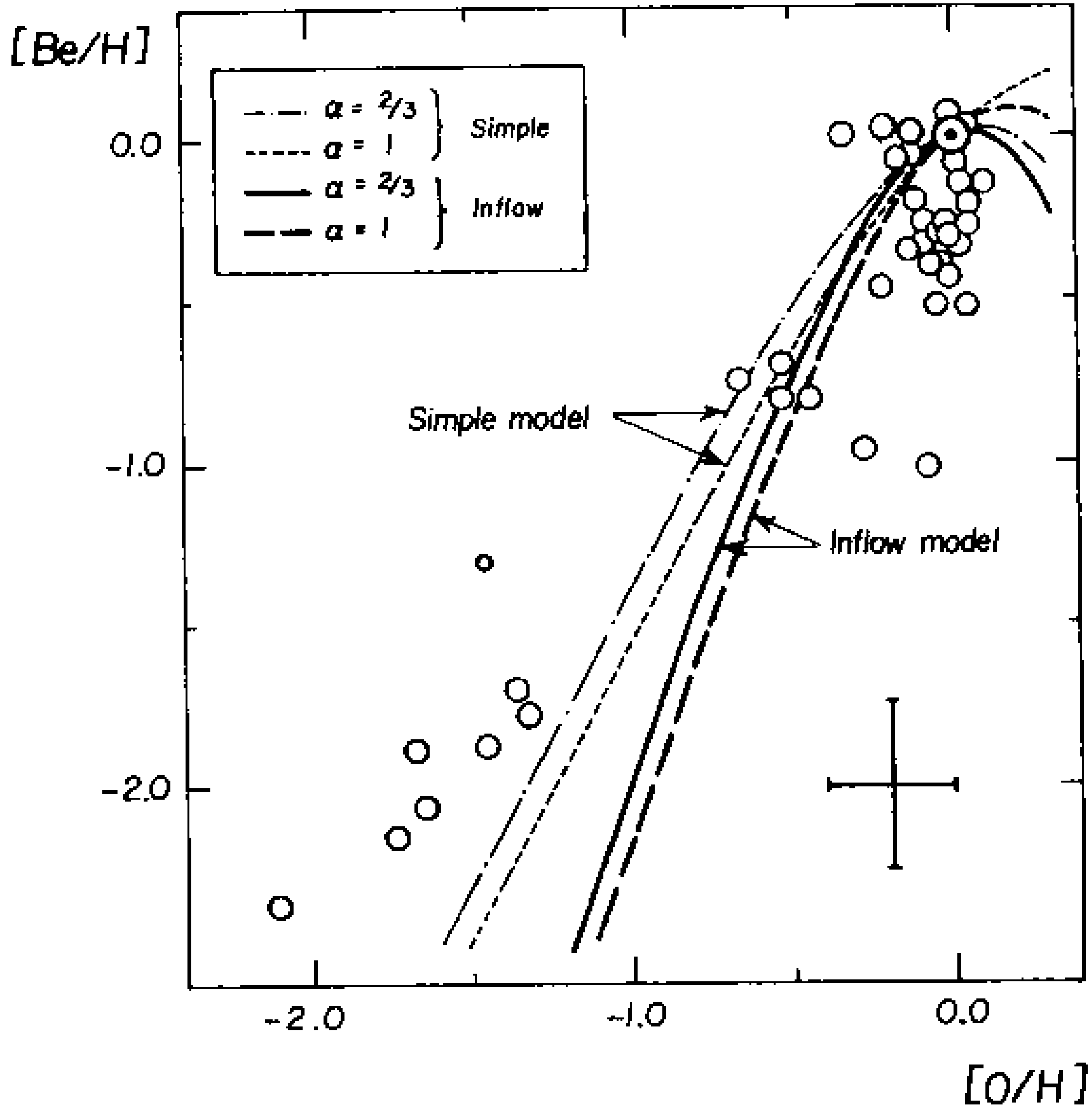


Fig. 9.6. Beryllium abundance as a function of oxygen abundance, according to models (curves) and observations (open circles) by Gilmore *et al.* (1992). (α in the key is actually the quantity called α' in the text.) After Pagel (1994). With kind permission from Kluwer Academic Publishers.