Properties of Cosmic Rays $E < 10^{14}$ eV

most important properties:

1) energy spectra are power laws

$\rightarrow \frac{dN}{dE} \propto E^{-\gamma} \qquad \gamma \approx 2{,}7$

$\Rightarrow$ non-thermal origin

$\left(\frac{dN}{dE} \sim e^{-\kappa E} \right)$

2) below ~ 1 GeV/n energy spectra deviate from power laws

Cosmic-ray energy spectra

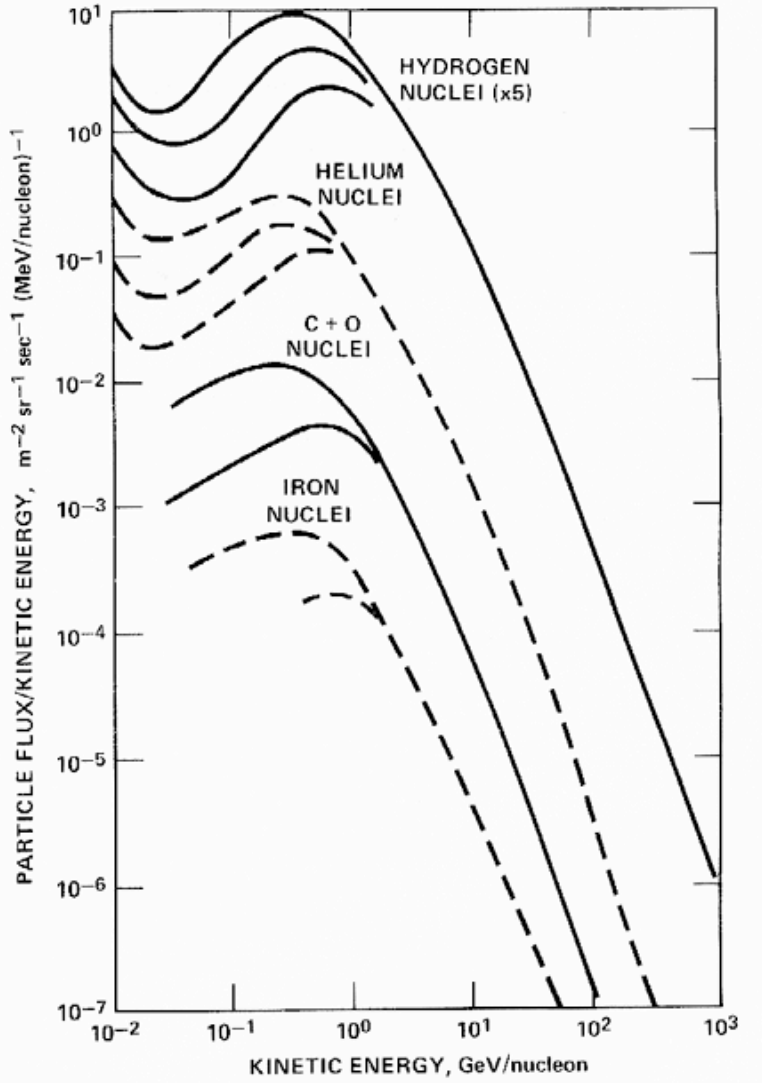
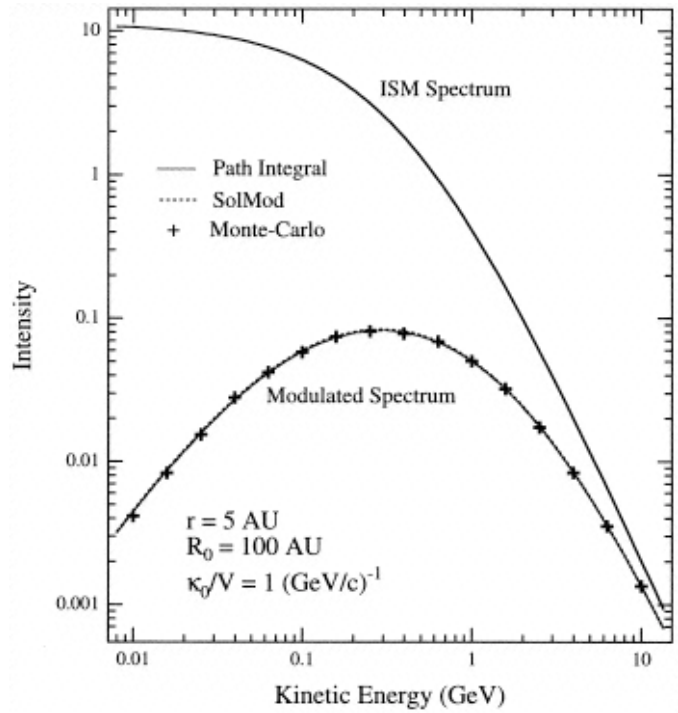


Figure 2-7.– *Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity. (Taken from* Physics Today, *Oct. 1974, p. 25.)*



Protons (Hydrogen)

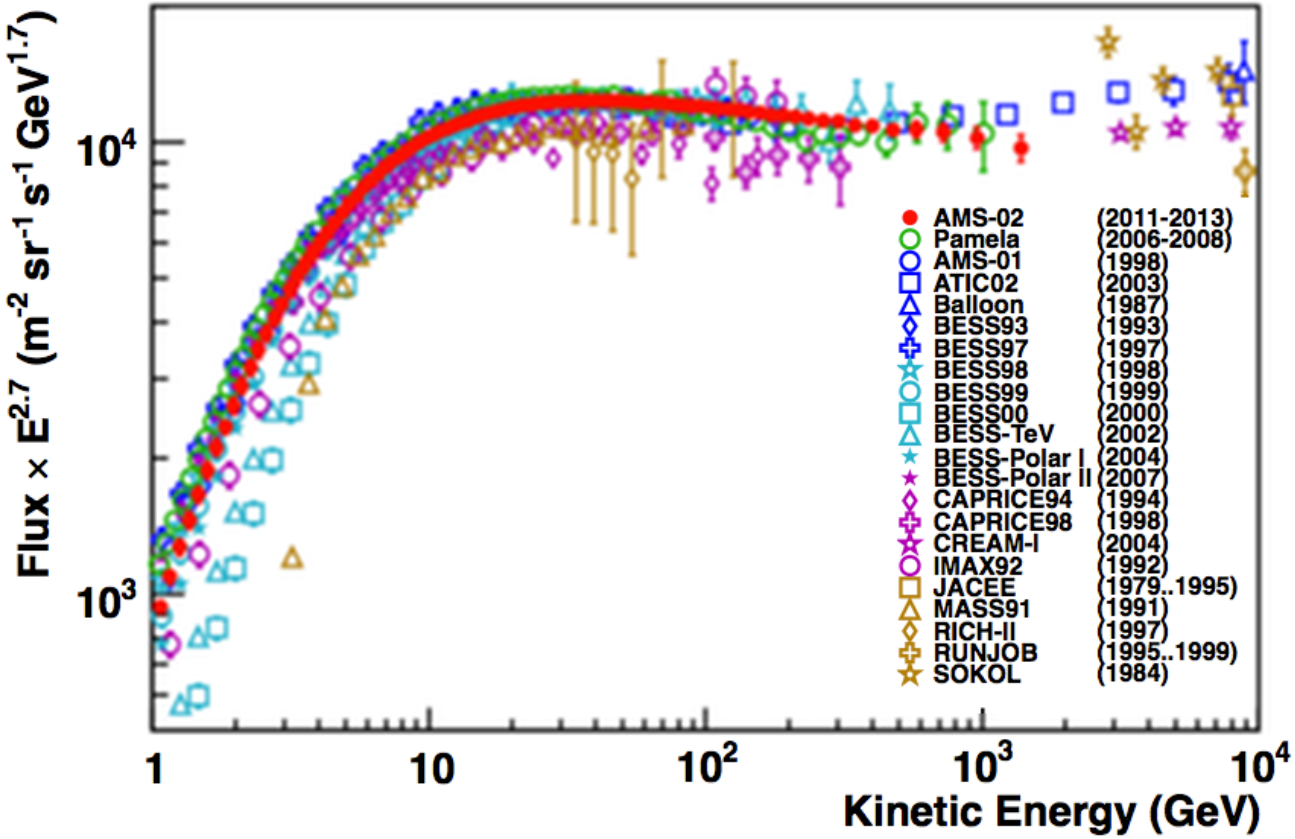
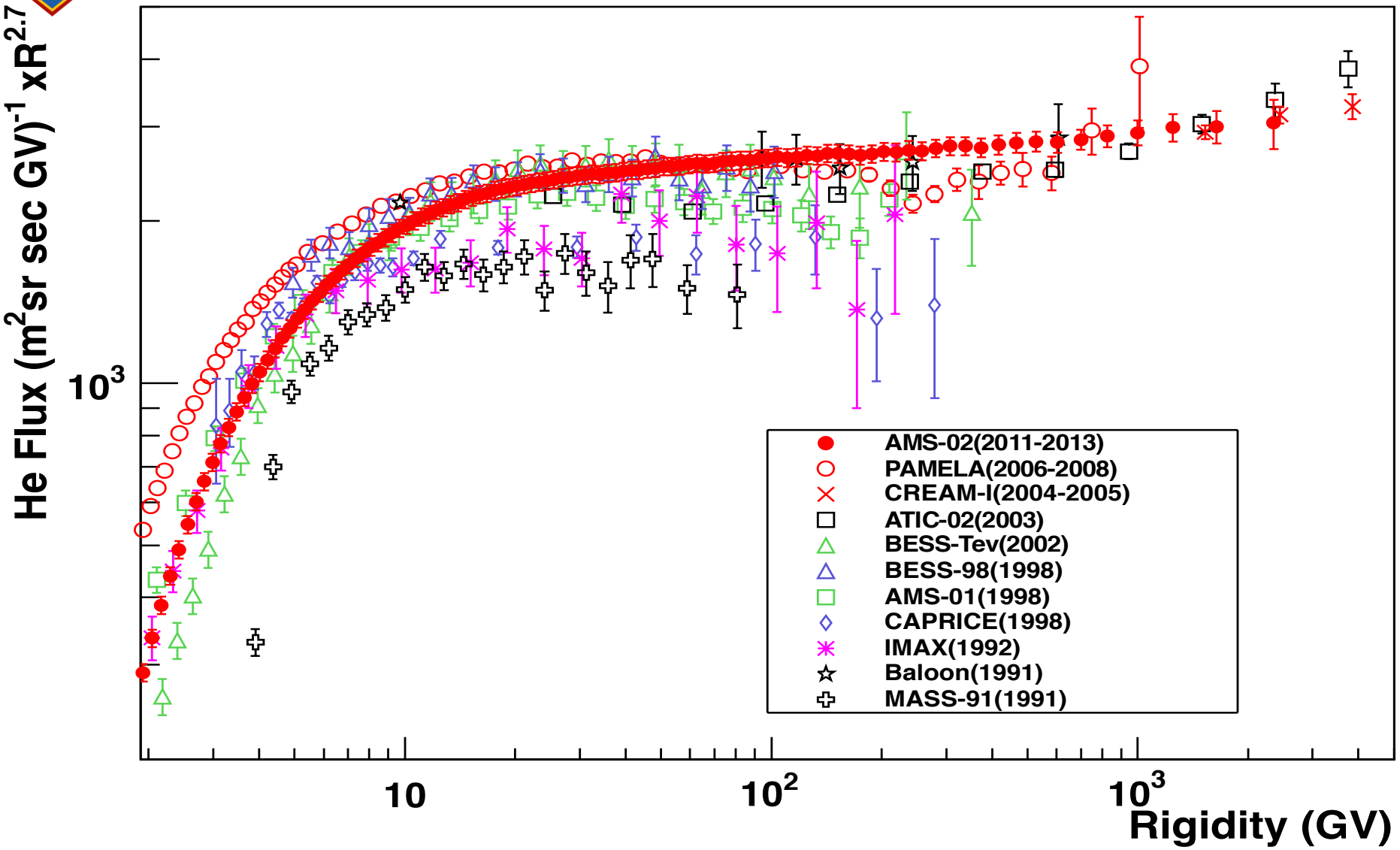


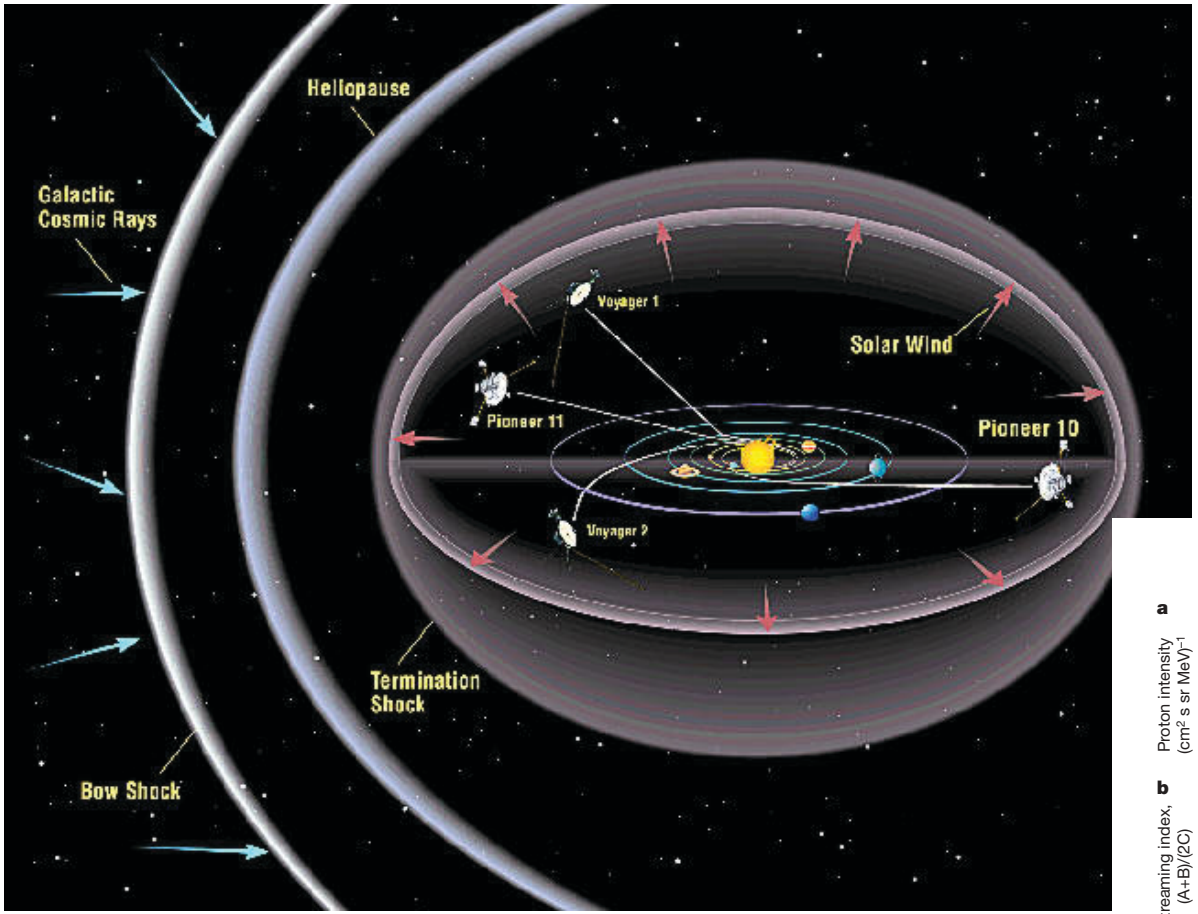
Fig. 6: The average proton flux over the two years of AMS-02 observation as a function of kinetic energy (E) multiplied by $E^{2.7}$ together with the previous experimental data [17]–[34].

AMS, ICRC 2013

Helium


He Flux (m^{2}sr sec GV)$^{-1}$ xR$^{2.7}$
10^3
10
10^2
10^3
Rigidity (GV)
AMS-02(2011-2013)
PAMELA(2006-2008)
CREAM-I(2004-2005)
ATIC-02(2003)
BESS-Tev(2002)
BESS-98(1998)
AMS-01(1998)
CAPRICE(1998)
IMAX(1992)
Baloon(1991)
MASS-91(1991)

Galactic Cosmic Rays and the Heliosphere



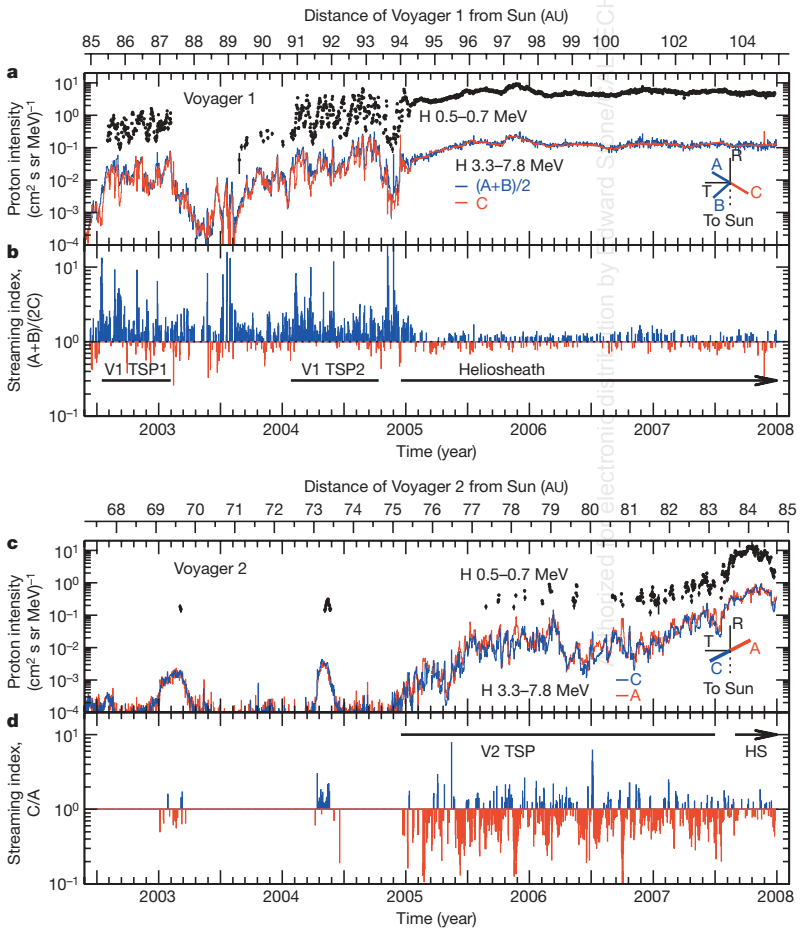


Figure 1 | Daily-averaged intensities and streaming of energetic termination shock particles that are accelerated at nearby regions of the shock. Voyager 1 and Voyager 2 crossed the shock and entered the heliosheath on 2004.96 (16 December 2004) at heliographic coordinates of (34.3°, 173°) and on 2007.66 (30 August 2007) at (−27.5°, 216°), respectively. Insets, telescope (A, B and C) viewing directions projected into the R–T plane, where −R is towards the Sun and T is azimuthal. Error bars on black filled circles, ±1s.d.

Proceedings of ICRC 2001: 3769 © Copernicus Gesellschaft 2001

ICRC 2001

Solar modulation of the galactic cosmic ray spectra since the Maunder minimum

G. Bonino[1], G. Cini Castagnoli[1], D. Cane[1], C. Taricco[1], and N. Bhandari[2]

[1]Dipartimento di Fisica Generale, Universit di Torino and Istituto di Cosmogeofisica, CNR, To rino, Italy
[2]Physical Research Laboratory, Ahmedabad, India

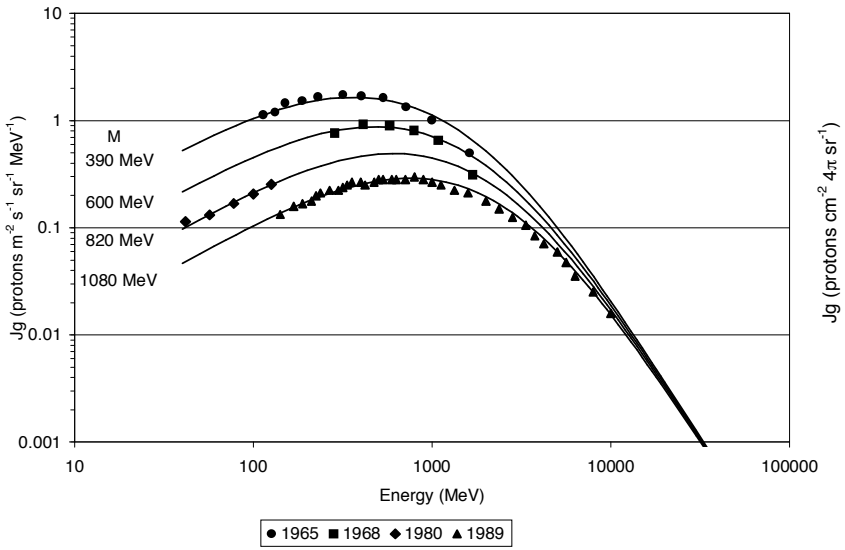


Fig. 1. Differential cosmic-ray spectra obtained from Eq. (1) for different values of the solar modulation parameter M = 390, 600, 820, 1080 MeV corresponding to the measurements performed with balloons or spacecrafts during 1965, 1968, 1980 and 1989 respectively.

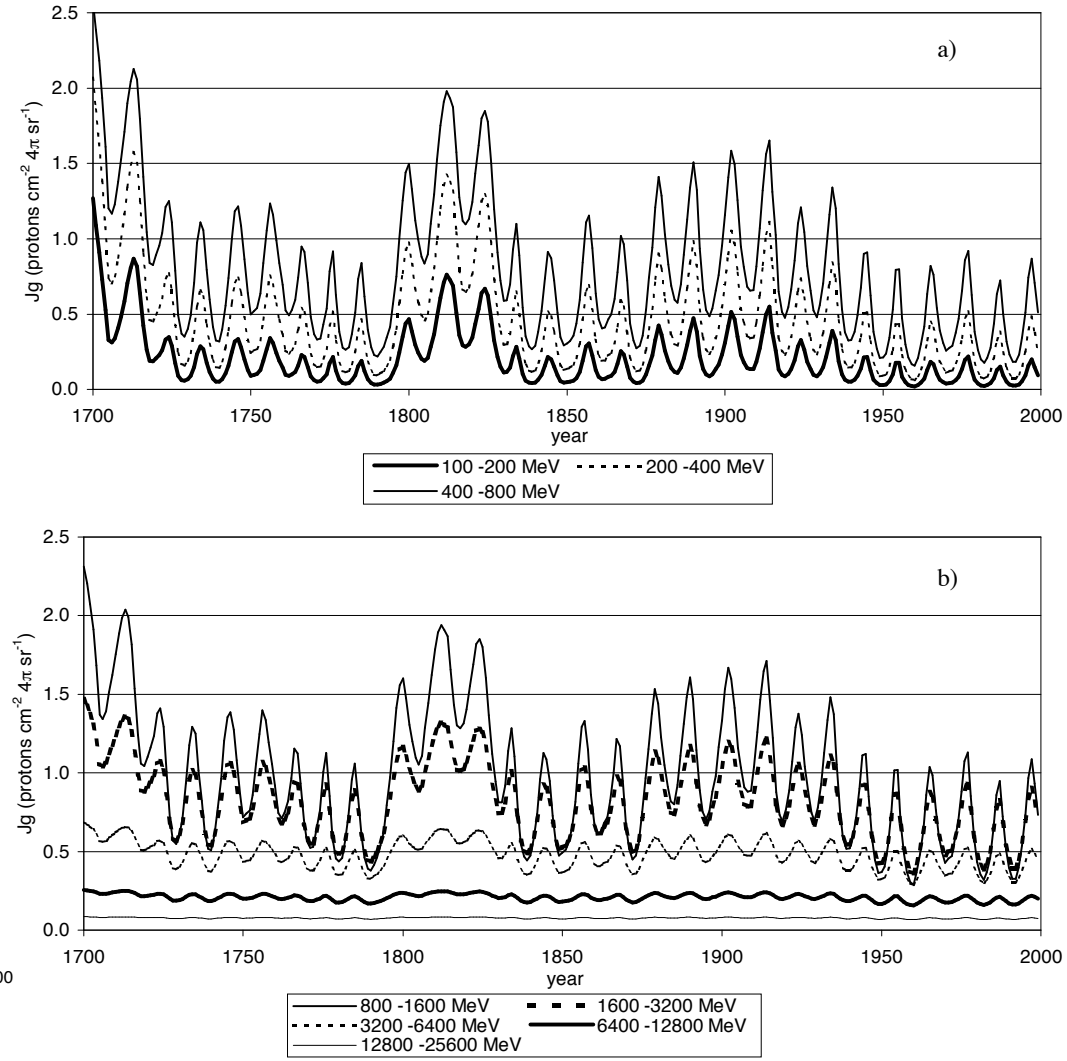


Fig. 2. Proton flux $J_G(t)$: a) for the kinetic energy intervals ΔT = 100-200 MeV, 200-400 MeV, 400-800 MeV; b) for ΔT = 800-1600 MeV, 1600-3200 MeV, 3200-6400 MeV, 6400-12800 MeV, 12800-25600 MeV.

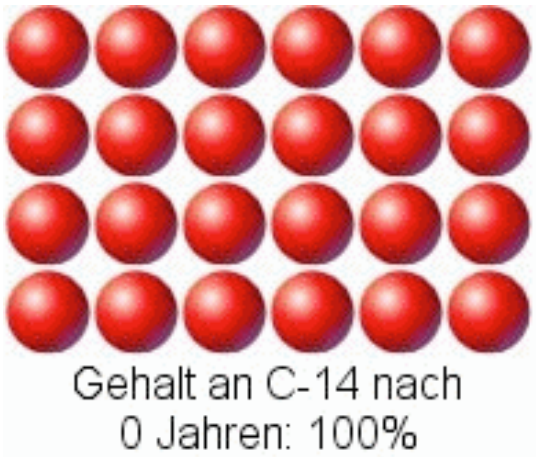
Carbon 14 method

formation of ^{14}C

$^{14}N + {}^{1}n \rightarrow {}^{14}C + {}^{1}p$

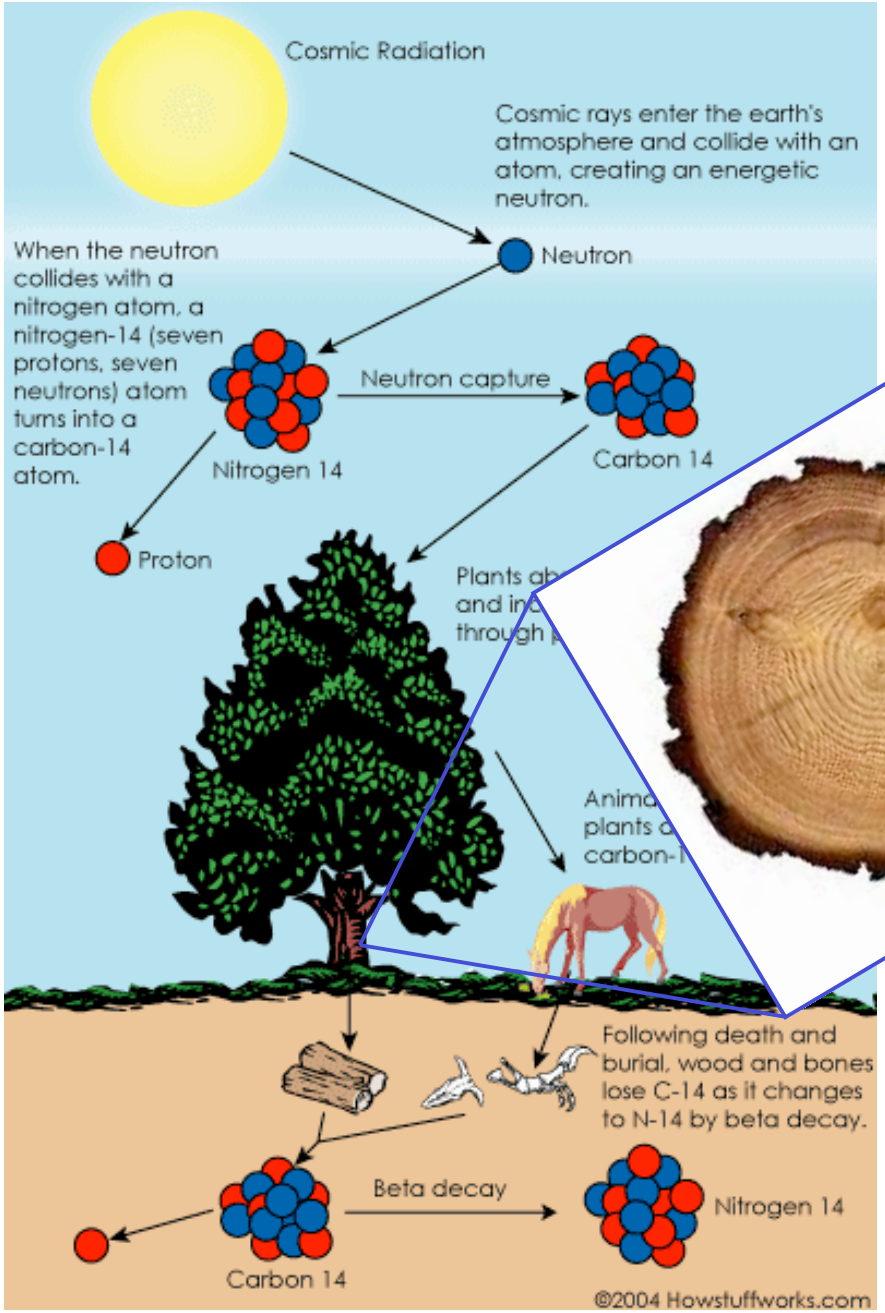
decay of ^{14}C

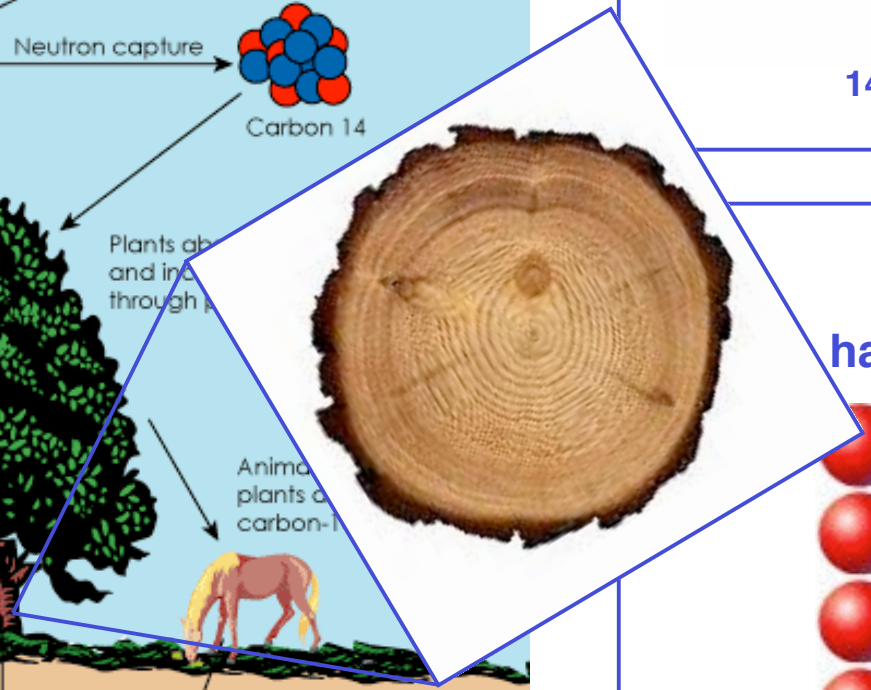
half life time 5730 years



$^{14}C \rightarrow {}^{14}N + e^{-}$

Carbon 14 method





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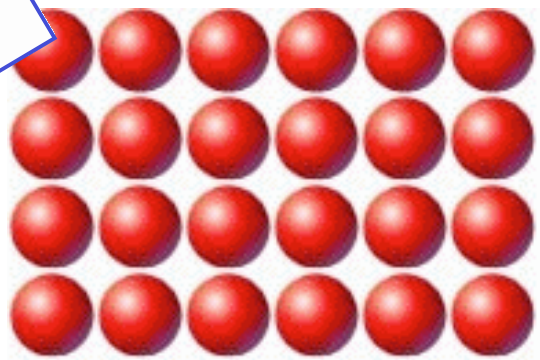
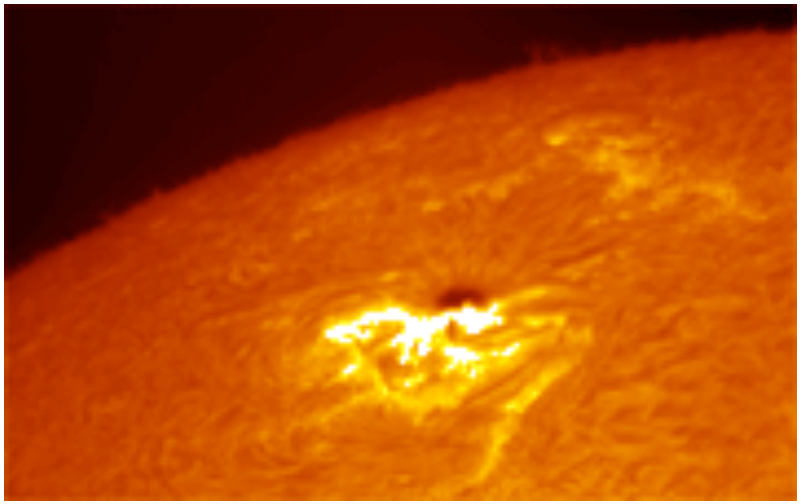
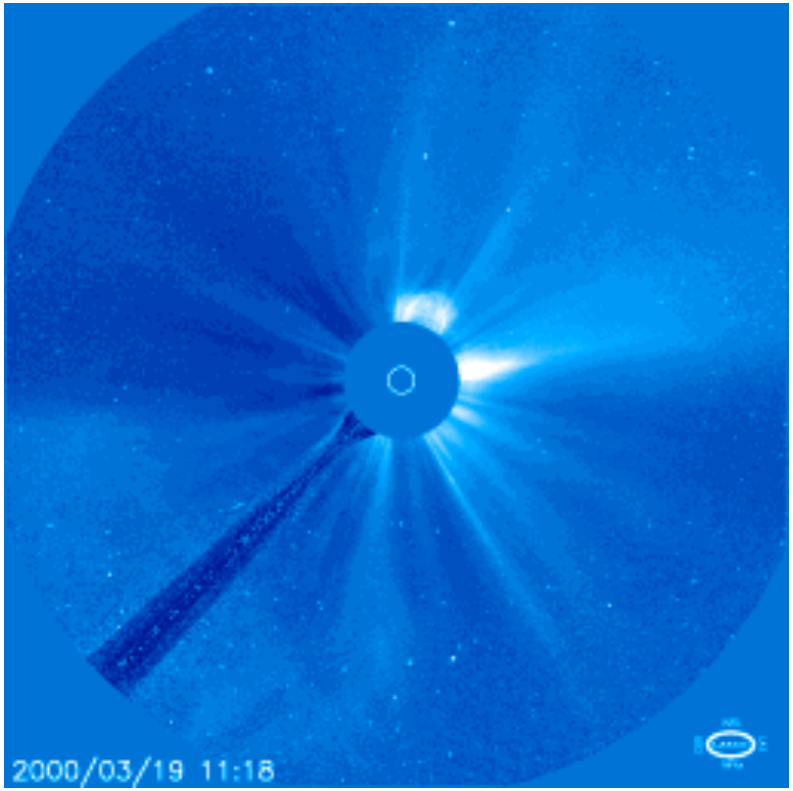


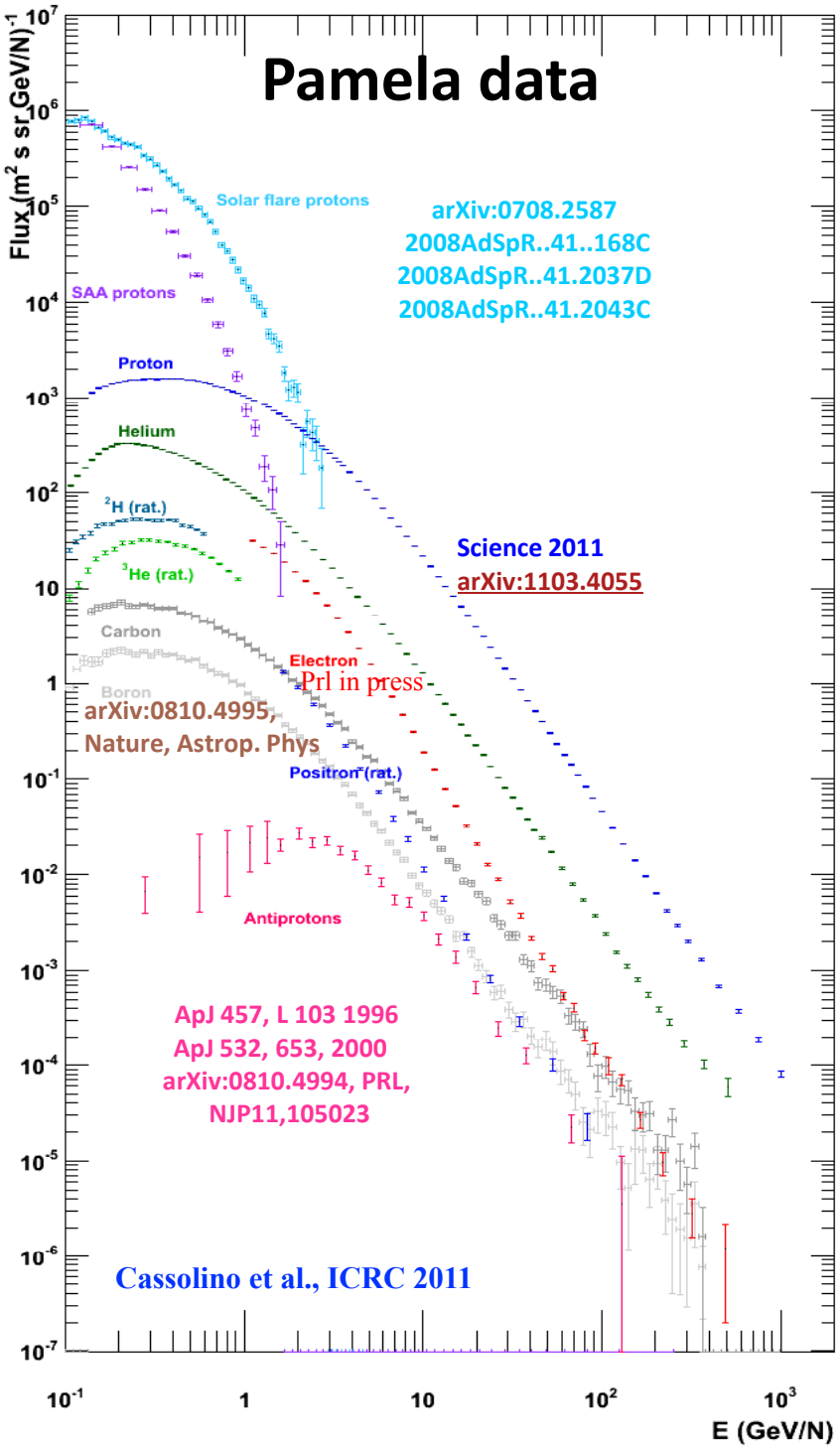
Gehalt an C-14 nach 0 Jahren: 100%

$^{14}C \rightarrow {}^{14}N + e^{-}$

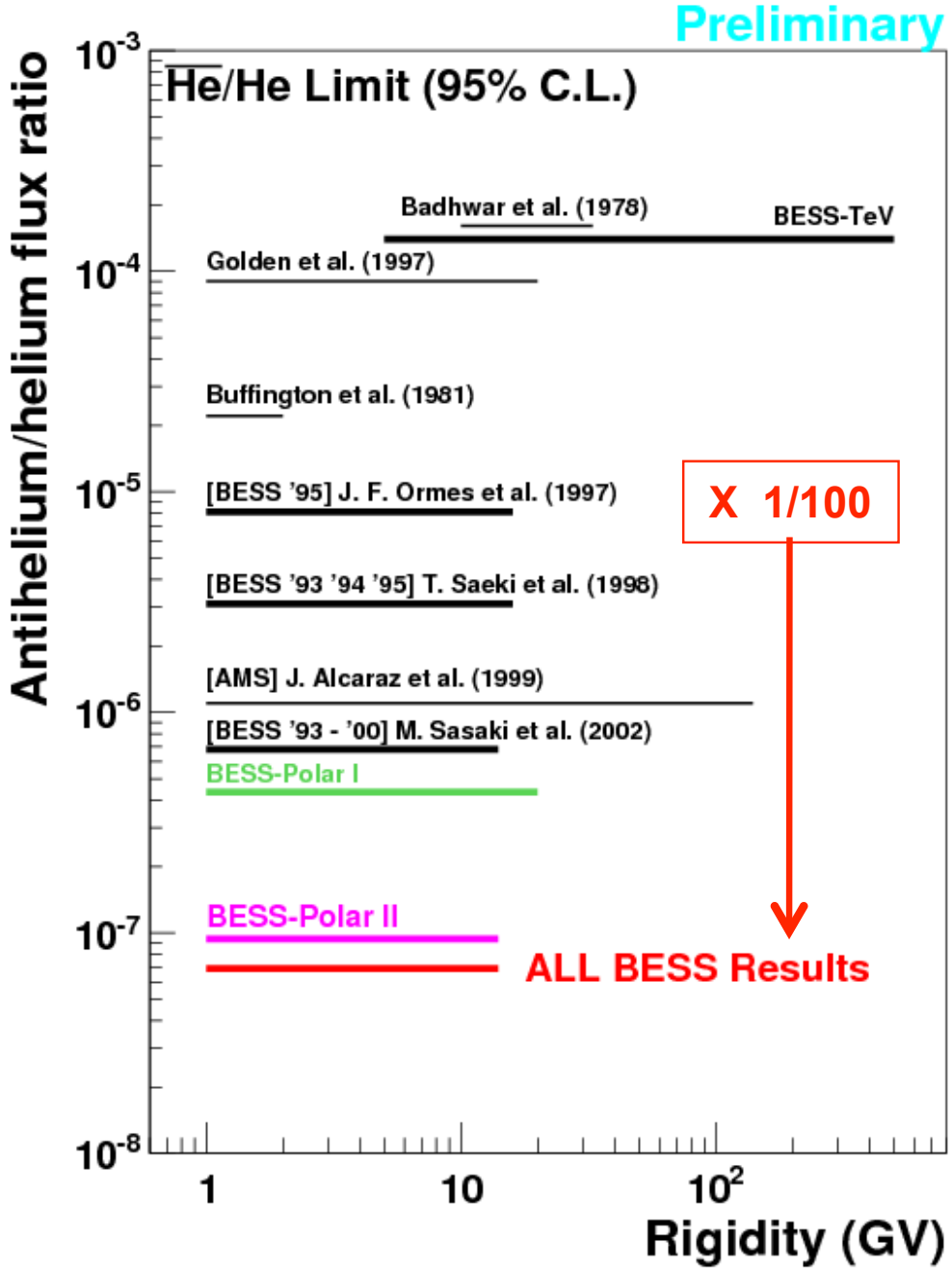
Solar flares

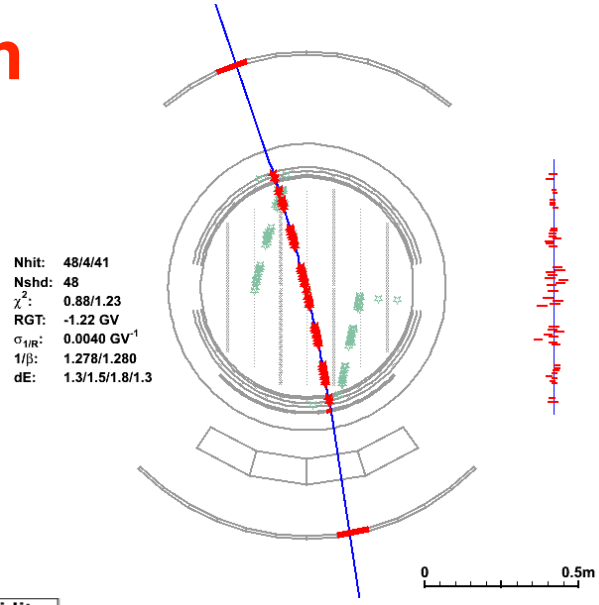


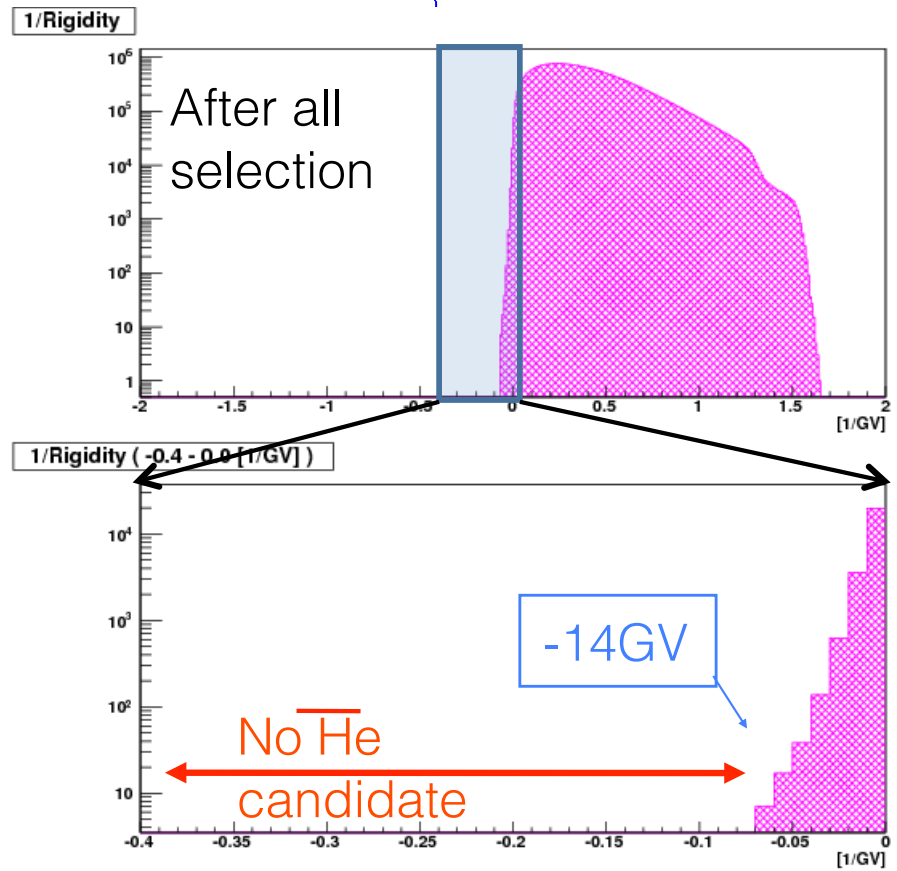




BESS-Polar: Search for antihelium



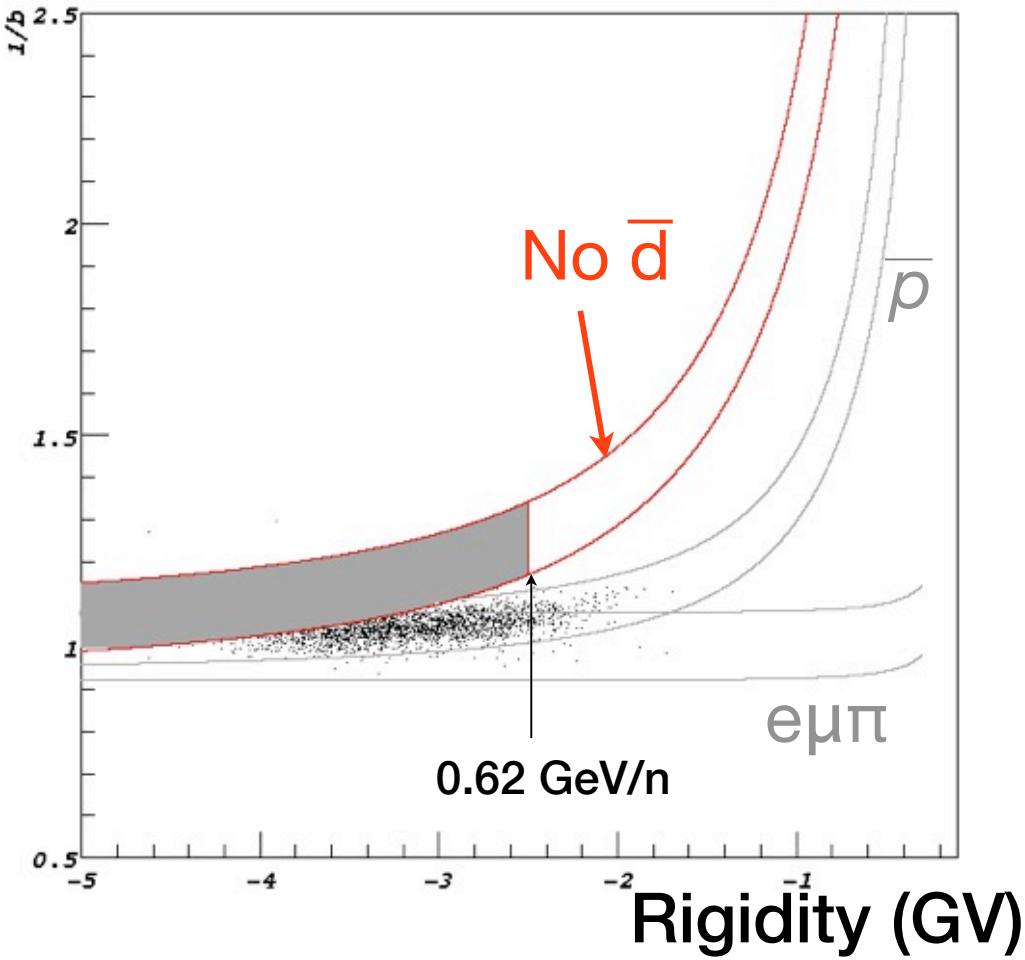




Search for cosmic-ray antideuterons with BESS-Polar

#1259
Yoshimura

Negative curvature



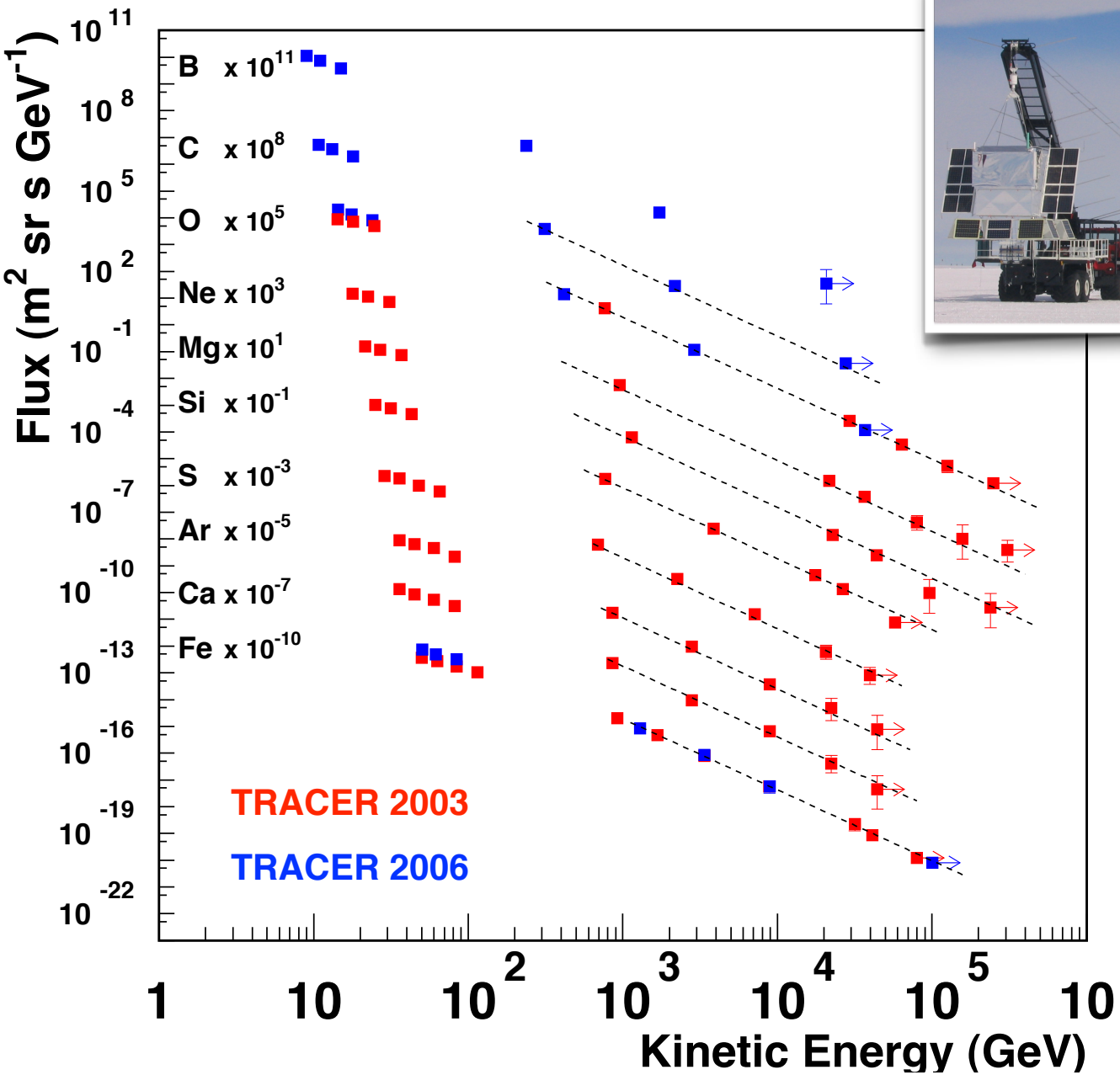
Apply the same selection as deuteron selection.

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)

TRACER: Energy spectra for individual elements



P. Boyle et al., ICRC 2011

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

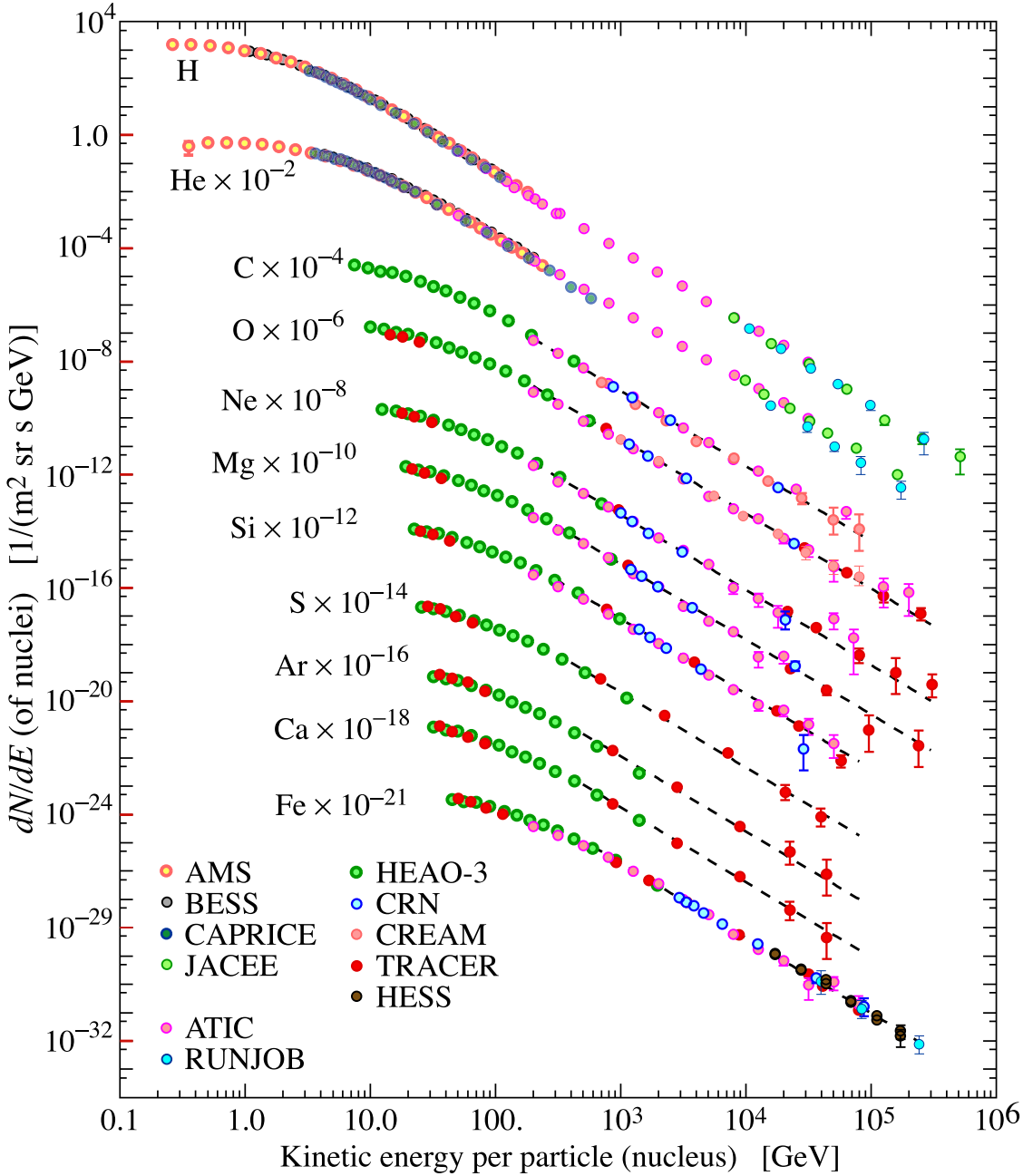


Figure 24.1: Major components of the primary cosmic radiation from Refs. [1–12 The figure was created by P. Boyle and D. Muller. Color version at end of book.

→ solar modulation of cosmic rays

charged particles of extra solar origin (galactic origin) drift against solar wind towards Earth

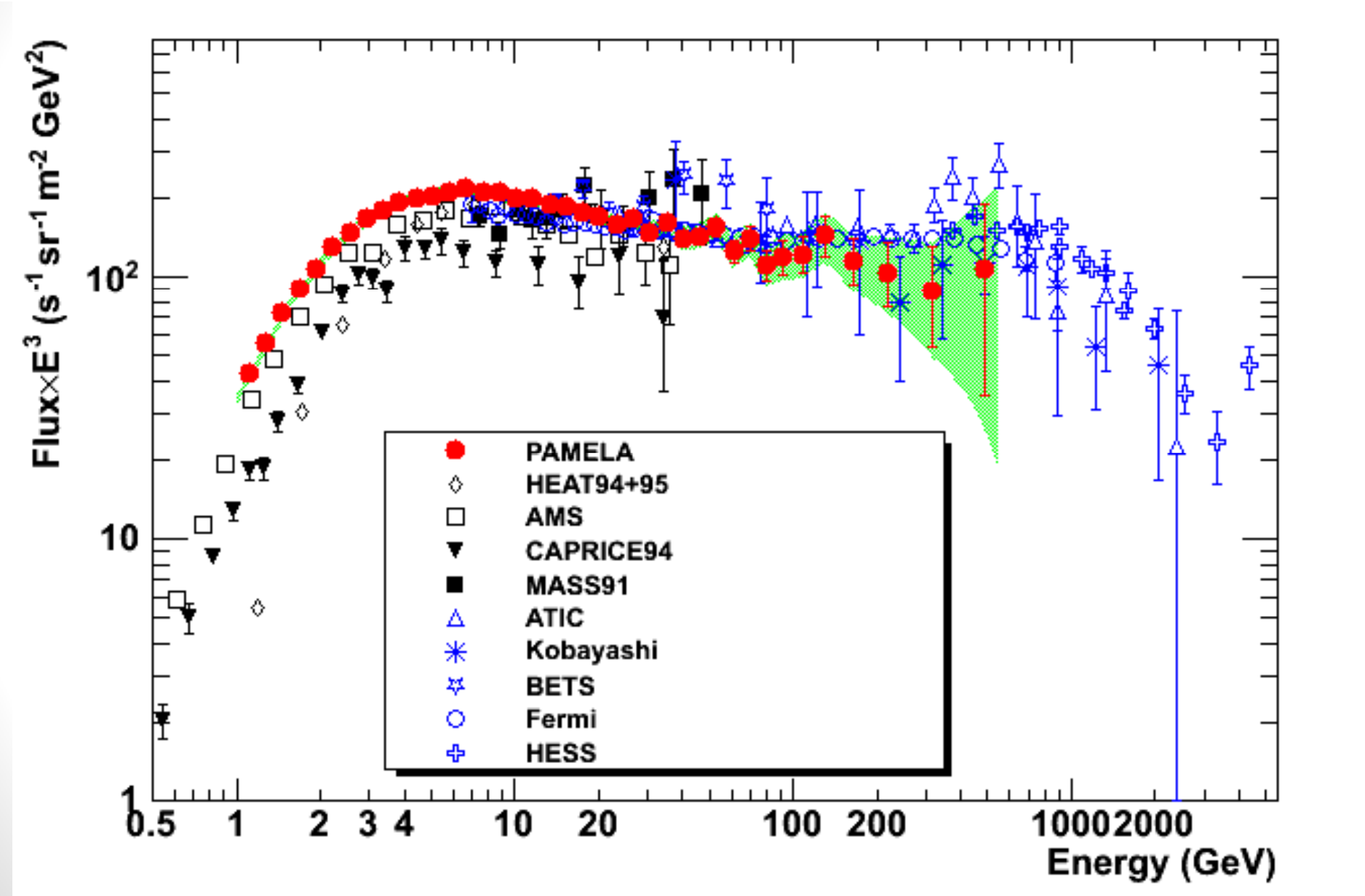
3) in first approximation all elements exhibit about the same slope

spectral index $\gamma \approx 2{,}7$ $\quad \propto E^{-\gamma}$

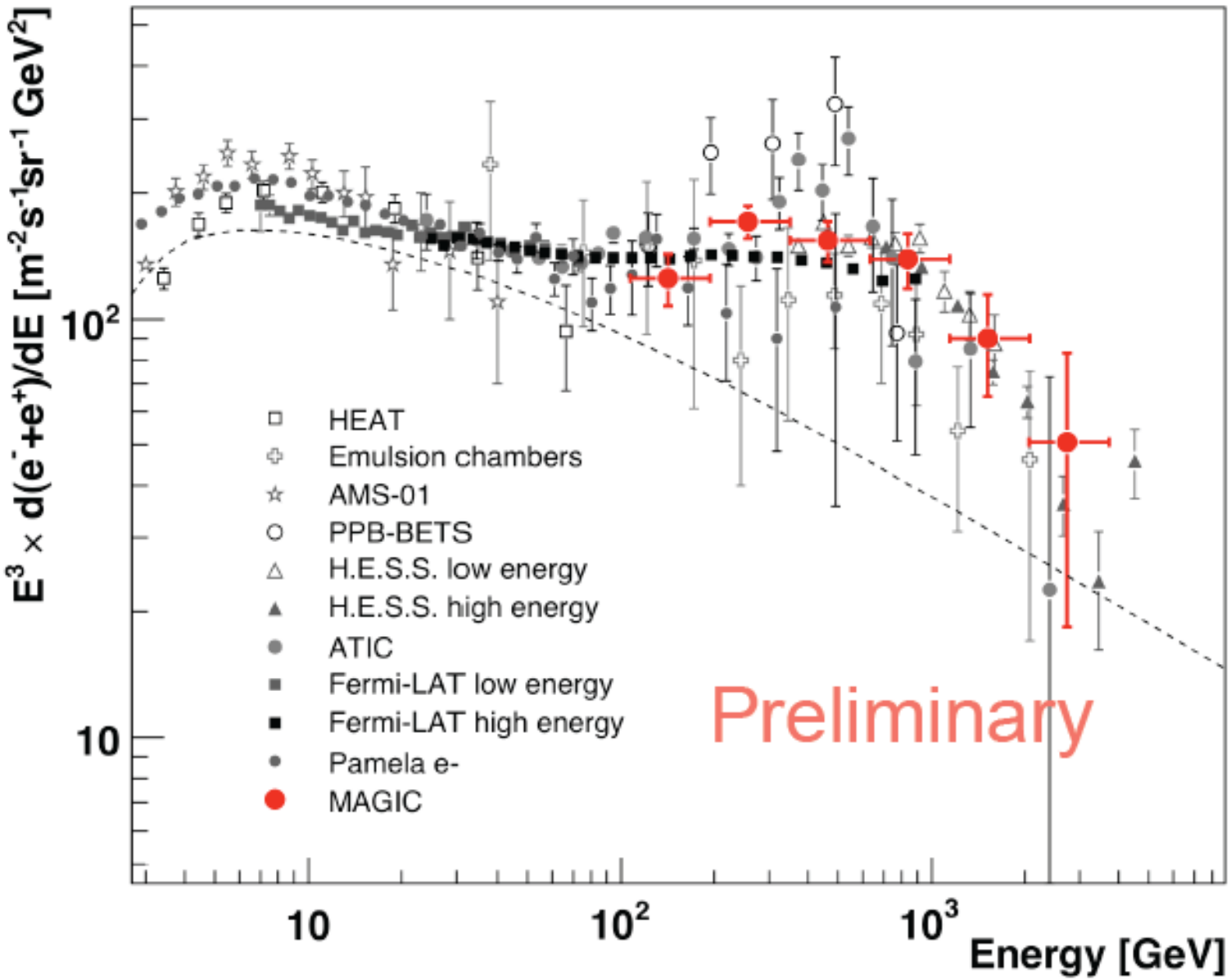
magnetic rigidity

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

e^- only


Flux×E³ (s⁻¹ sr⁻¹ m⁻² GeV²)
10²
10
1
0.5
1
2
3
4
10
20
100
200
1000
2000
Energy (GeV)
PAMELA
HEAT94+95
AMS
CAPRICE94
MASS91
ATIC
Kobayashi
BETS
Fermi
HESS

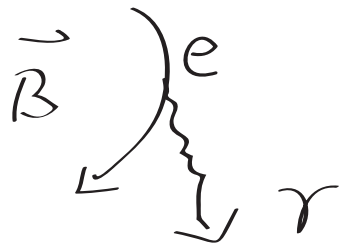
e^- & e^+


$E^3 \times d(e^-+e^+)/dE$ [$m^{-2}s^{-1}sr^{-1}$ GeV^2]
10^2
10
10
10^2
10^3
Energy [GeV]
HEAT
Emulsion chambers
AMS-01
PPB-BETS
H.E.S.S. low energy
H.E.S.S. high energy
ATIC
Fermi-LAT low energy
Fermi-LAT high energy
Pamela e-
MAGIC
Preliminary

4) electrons: ~1% of nuclear cosmic rays

energy spectrum is steeper $\frac{dN_e}{dE_e} \propto E_e^{-3,3}$

reason: losses through synchrotron radiation at high energies



5) energy density of cosmic rays

integrate all-particle energy spectrum

diff. flux $\frac{dI}{dE} \left[\frac{1}{m^2 \cdot s \cdot sr \cdot MeV} \right]$

$$I_{CR} = \int d\Omega \, dE \, \frac{dI}{dE} \quad \left[\frac{1}{m^2 \cdot s}\right]$$

all particle flux

→ total energy flux

$$u_{CR} = I_{CR} \cdot \langle E_{CR} \rangle \quad \left[\frac{eV}{m^2 \cdot s}\right]$$

→ total energy density

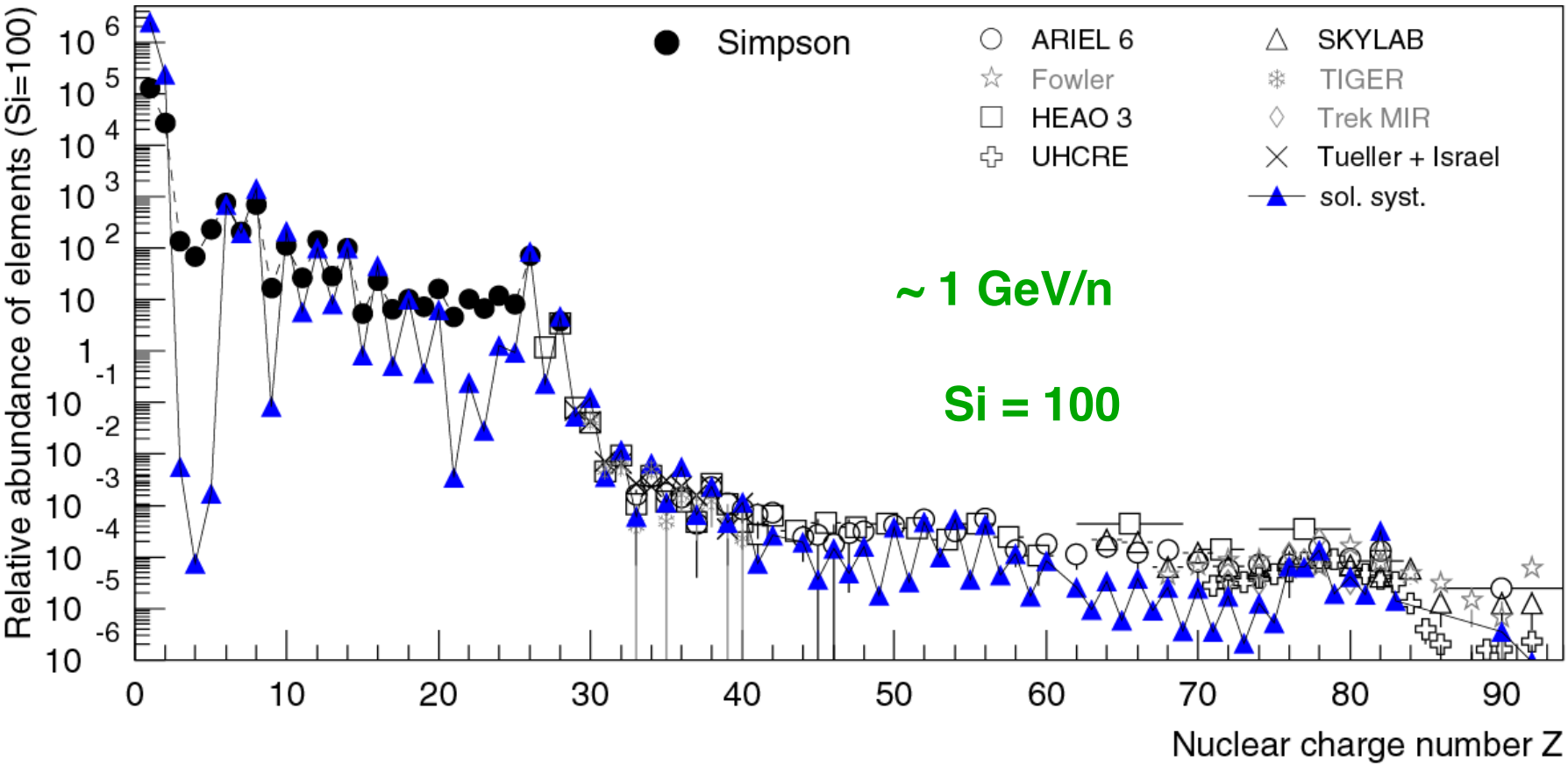
$$\varepsilon_{CR} = I_{CR} \frac{\langle E_{CR} \rangle}{\langle v_{CR} \rangle} \quad \left[\frac{eV}{cm^3}\right]$$

$$\approx 1 \frac{eV}{cm^3}$$ energy density of CRs

comparable with e.g. energy density of visible star light $\varepsilon_{St} \sim 0{,}3 \frac{eV}{cm^3}$

energy density of B-field in galaxy

Relative abundance of elements at Earth



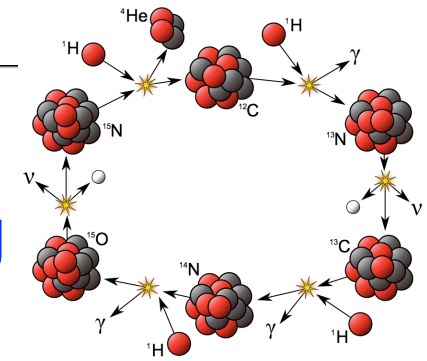
→Cosmic rays are „regular matter“, accelerated to extremely high energies

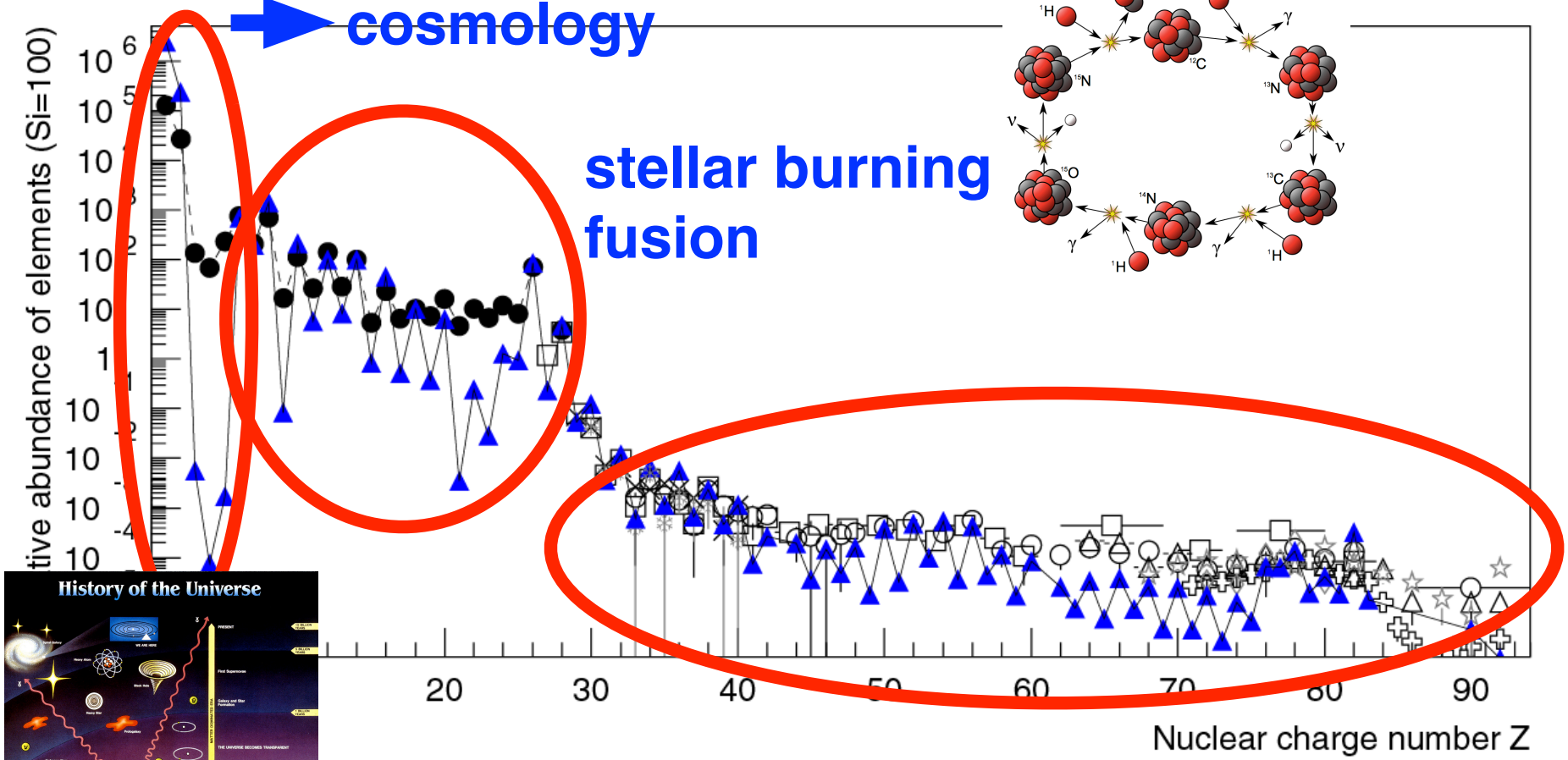
JRH, Adv. Space Res. 41 (2008) 442

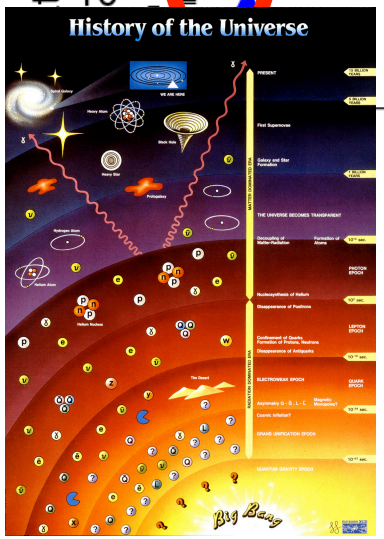
Origin of the Elements

big bang
cosmology

stellar burning
fusion







supernova
explosions

elemental composition of CRs

$\sim 89\%$ p

9% He

1% heavier nuclei

1% e^-

$\lesssim 0{,}1\%$ γ

some remarks

1) even-odd effect
   → due to the high binding energy
   of ee-nuclei

2) elements Li, Be, B are more abundant
   in CRs than in solar system
   → propagation in Galaxy

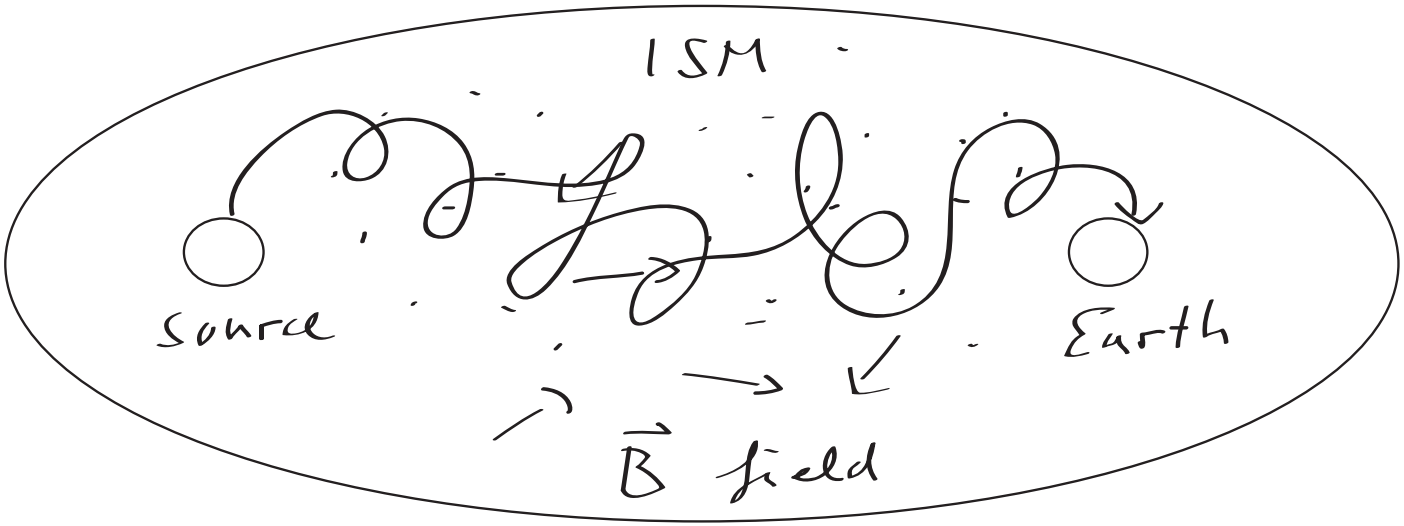
3) same effect for sub-Fe elements
   (~ Ca-Fe)

4) p, He less abundant in CRs as
   compared to sol. syst.

Propagation of Cosmic Rays in the Interstellar Medium (ISM)

objective: quantitative understanding

start with qualitative picture

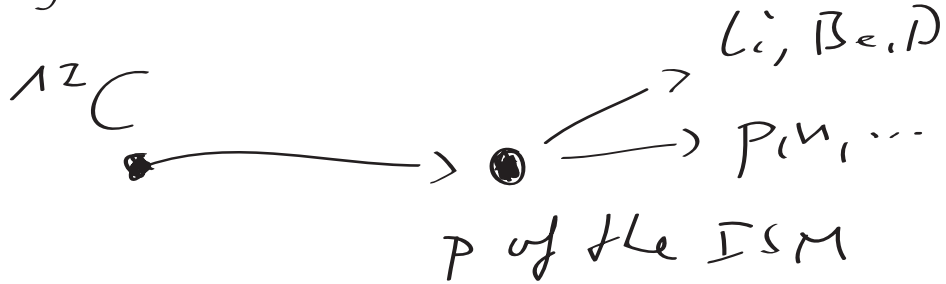


ISM in galactic disc ~ 1 H atom / cm^3

$B \sim 3\,\mu G \Rightarrow \varepsilon_B = \frac{B^2}{2\mu_0} \approx 0{,}2 \; \frac{eV}{cm^3}$

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