Properties of CRs $E < 10^{19}$ eV

most important properties:

1) energy spectra are power laws

$$\frac{dN}{dE} \propto E^{-\gamma} \qquad \gamma \approx 2.7$$

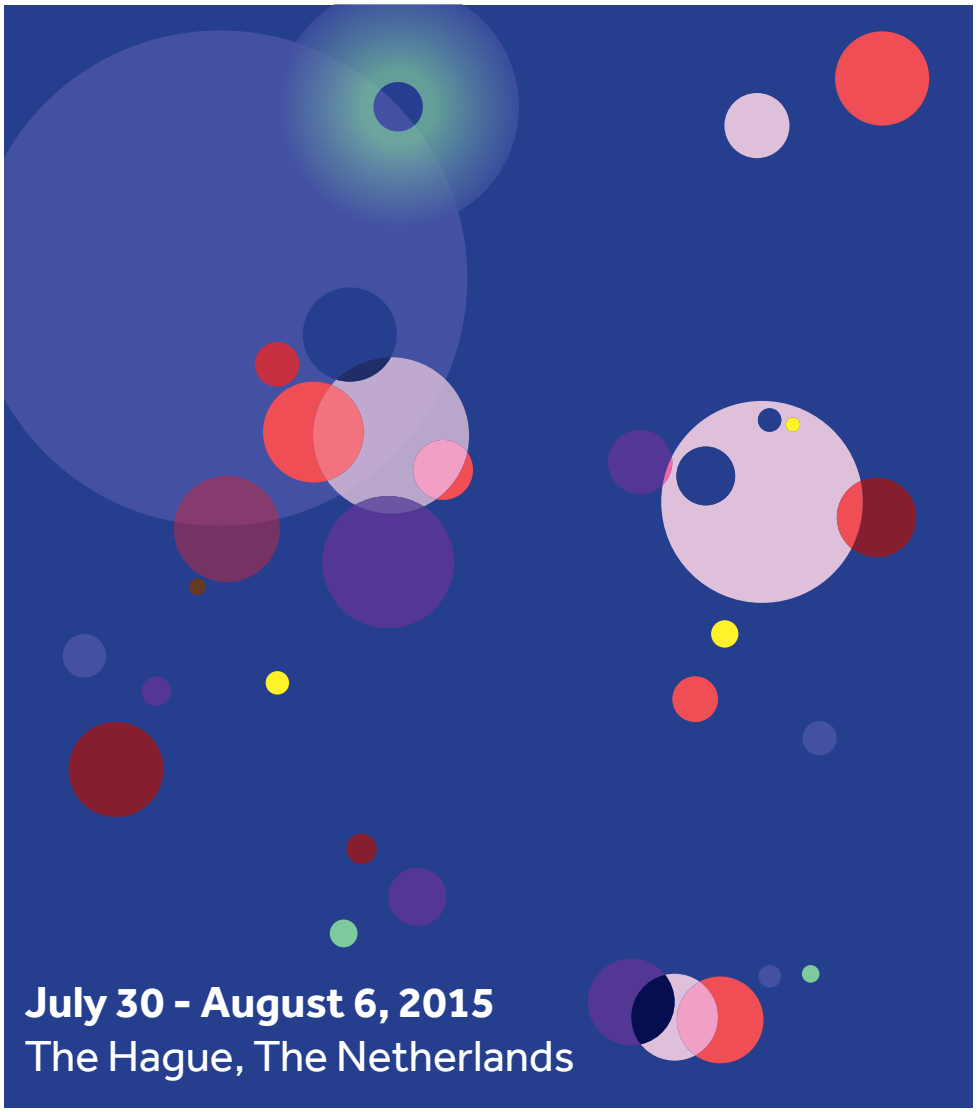
$\Rightarrow$ non-thermal origin $\left(\frac{dN}{dE} \propto e^{-\alpha E}\right)$

2) below $\sim$ 10 GeV/n energy spectra deviate from power laws

$\rightarrow$ solar modulation of cosmic rays

charged particles of extra-solar origin (galactic origin) drift against the solar wind towards Earth / solar system

ICRC The Astroparticle Physics Conference



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The Astroparticle Physics Conference
34th International Cosmic Ray Conference
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The Hague, The Netherlands

www.icrc2015.nl

Cosmic-ray energy spectra

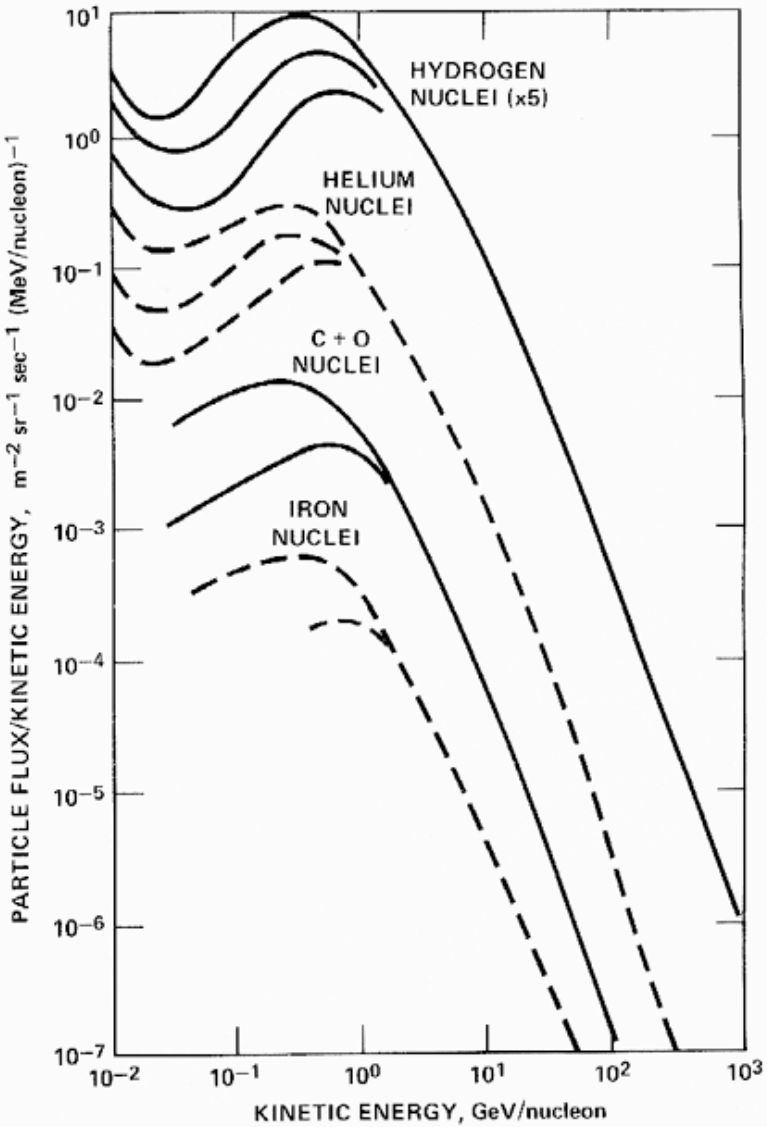
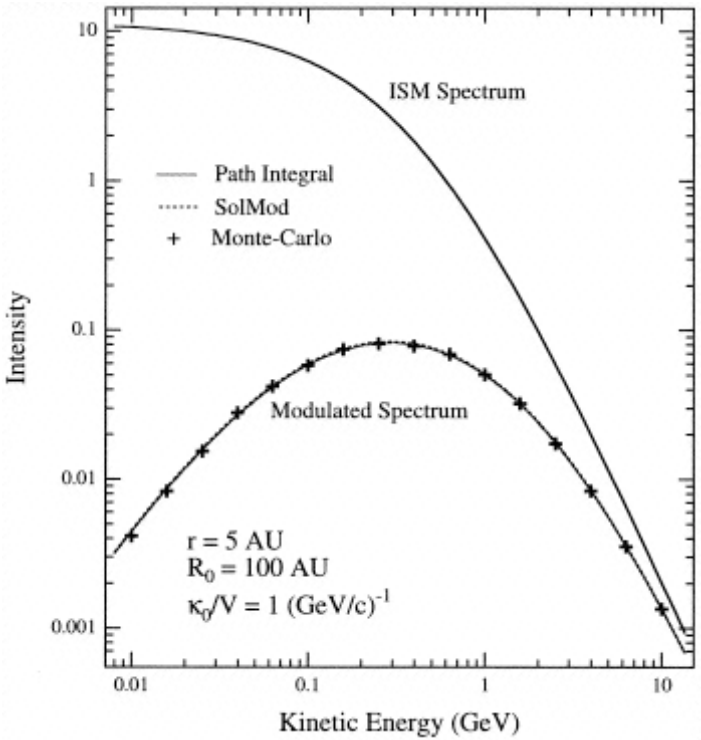
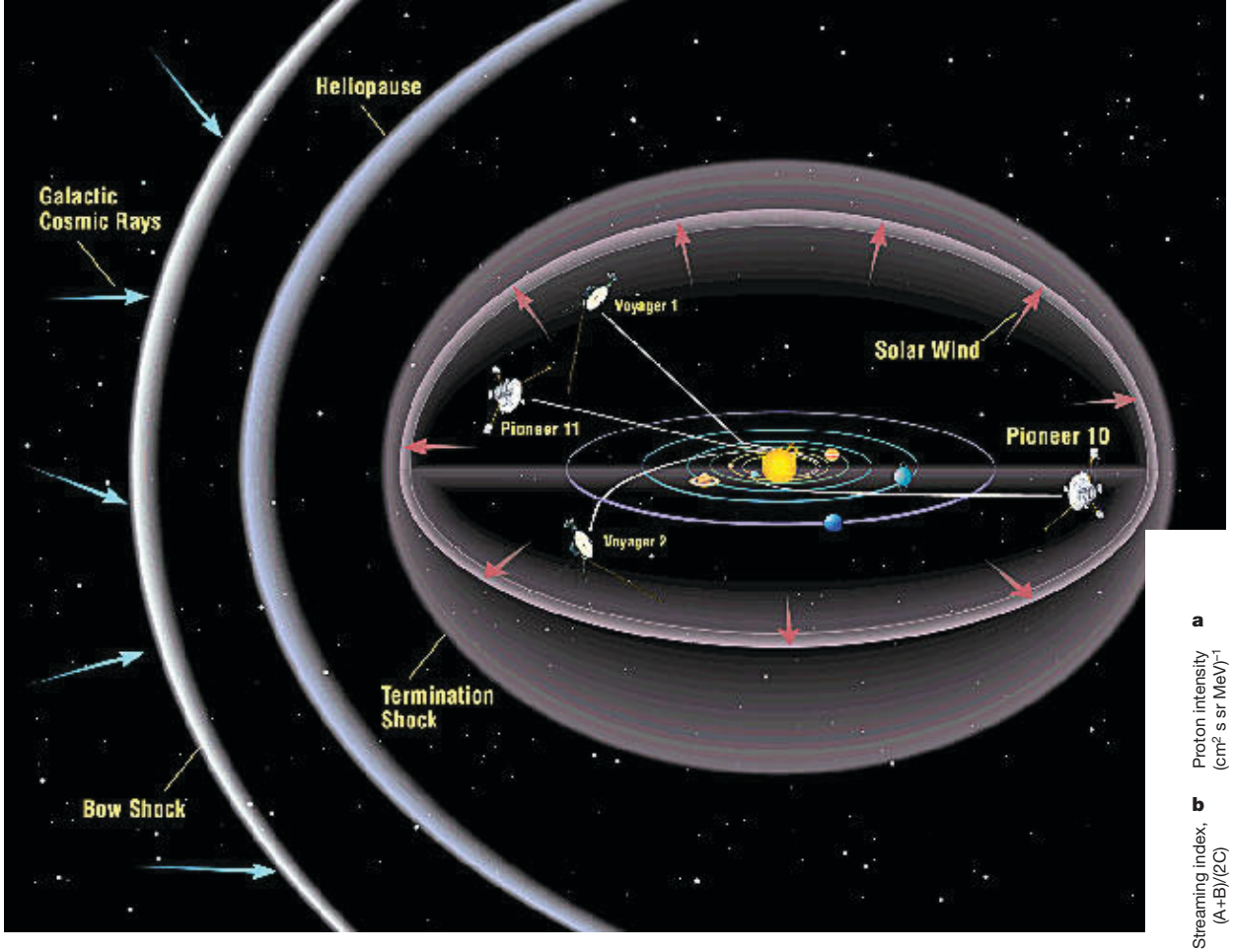


Figure 2-7.– *Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes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



Galactic Cosmic Rays and the Heliosphere



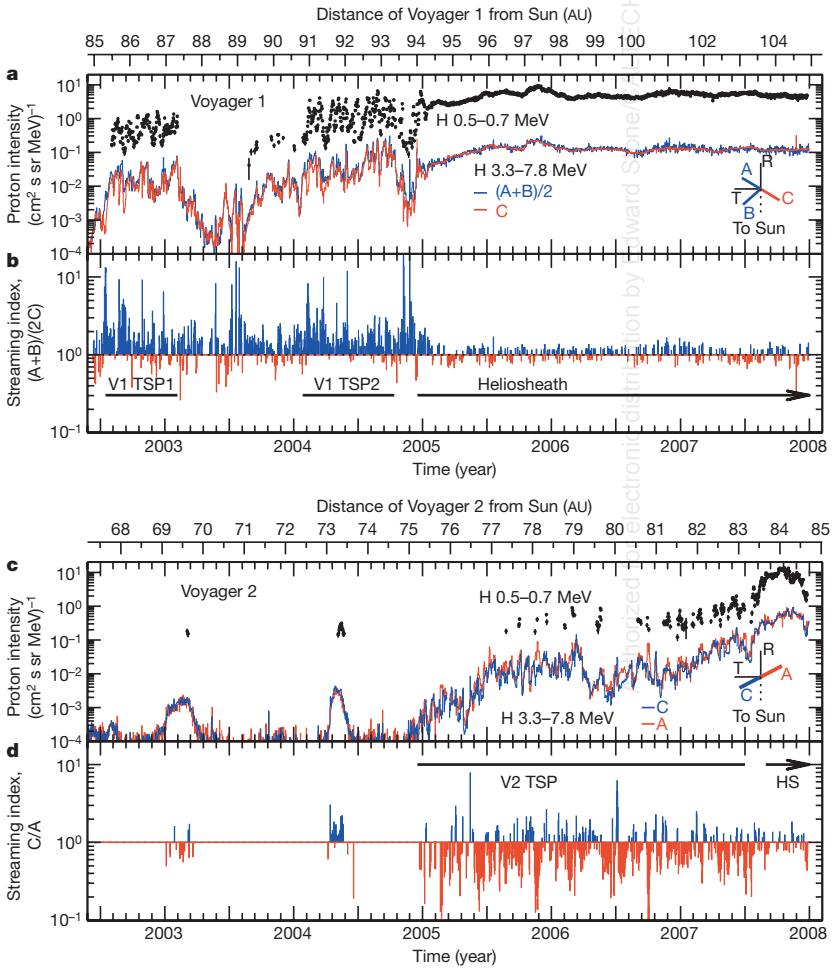
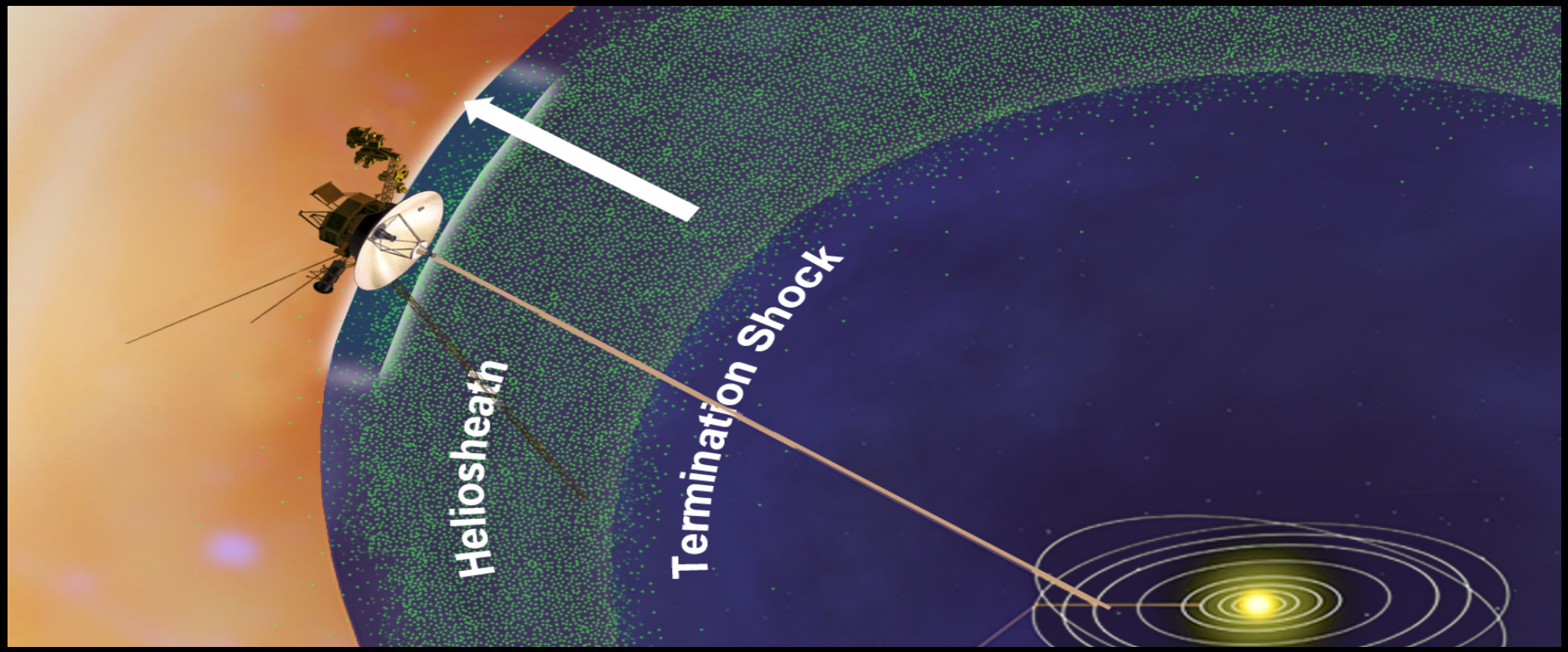


Figure 1 | Daily-averaged intensities and streaming of energetic termination shock particles that are accelerated at nearby regions of the shock. Voyager 1 and Voyager 2 crossed the shock and entered the heliosheath on 2004.96 (16 December 2004) at heliographic coordinates of (34.3°, 173°) and on 2007.66 (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.

In August 2012, Voyager 1 entered the LISM

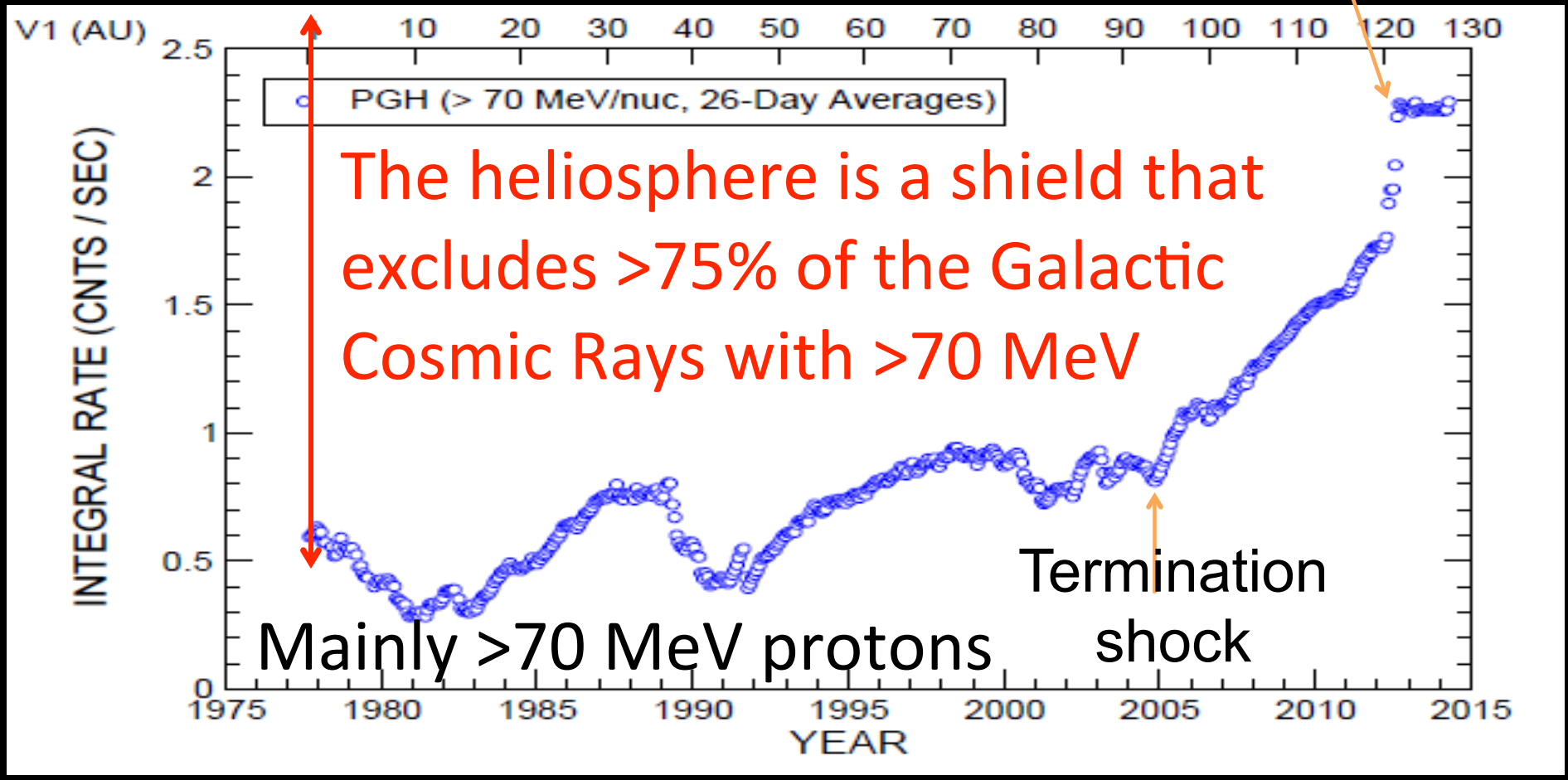


For the first time, GCR were measured in their unmodulated state

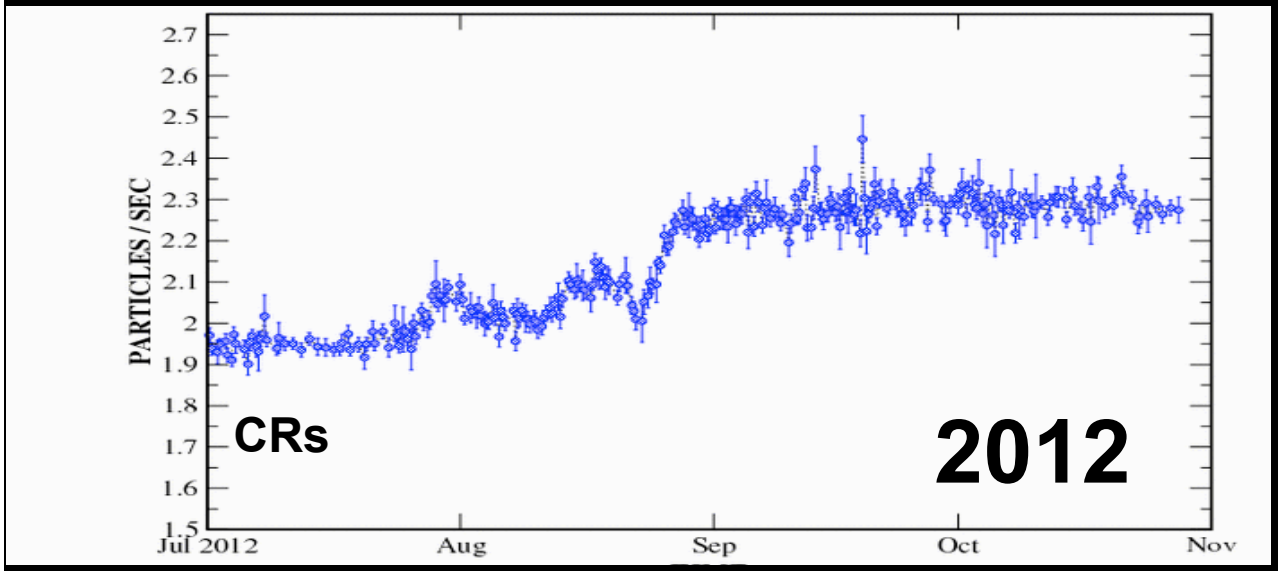
#875 Stone

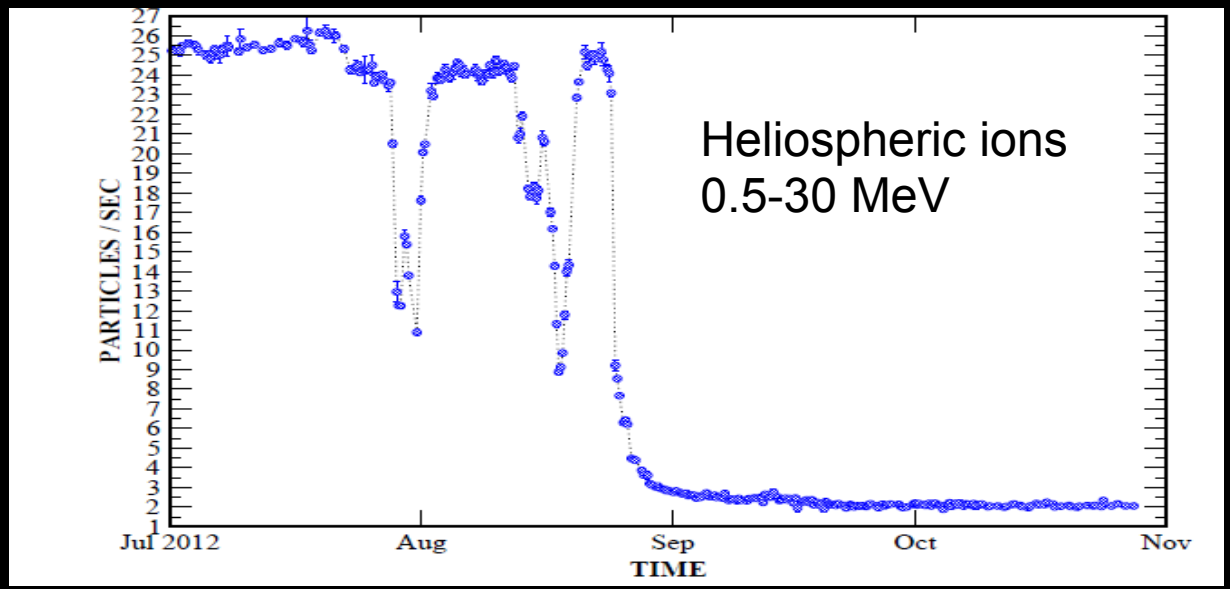
Galactic Cosmic Rays

August 25, 2012
Interstellar Space



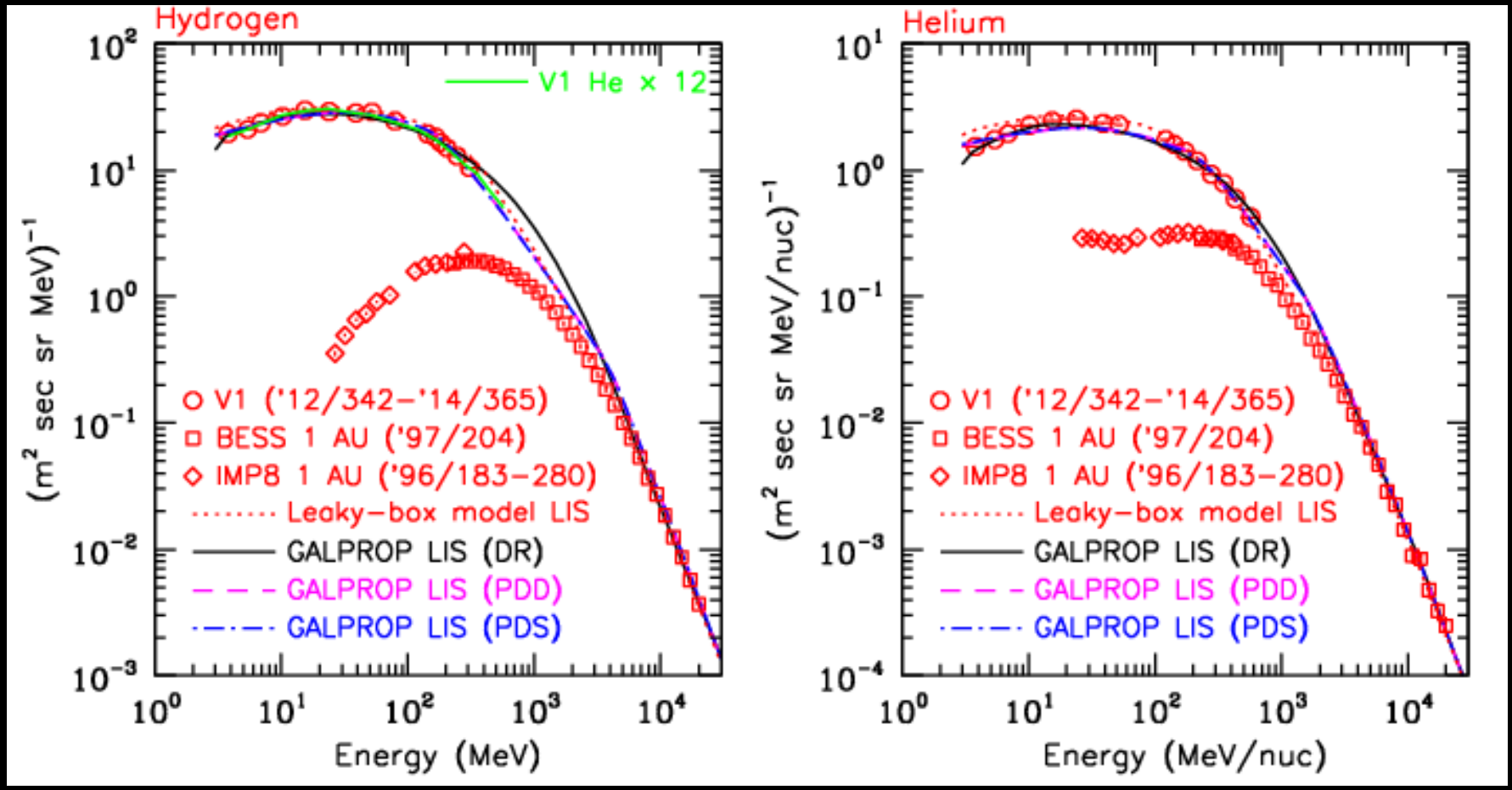
Cosmic Rays >70 MeV from outside





Cosmic rays from outside increased at same time as ions from inside escaped

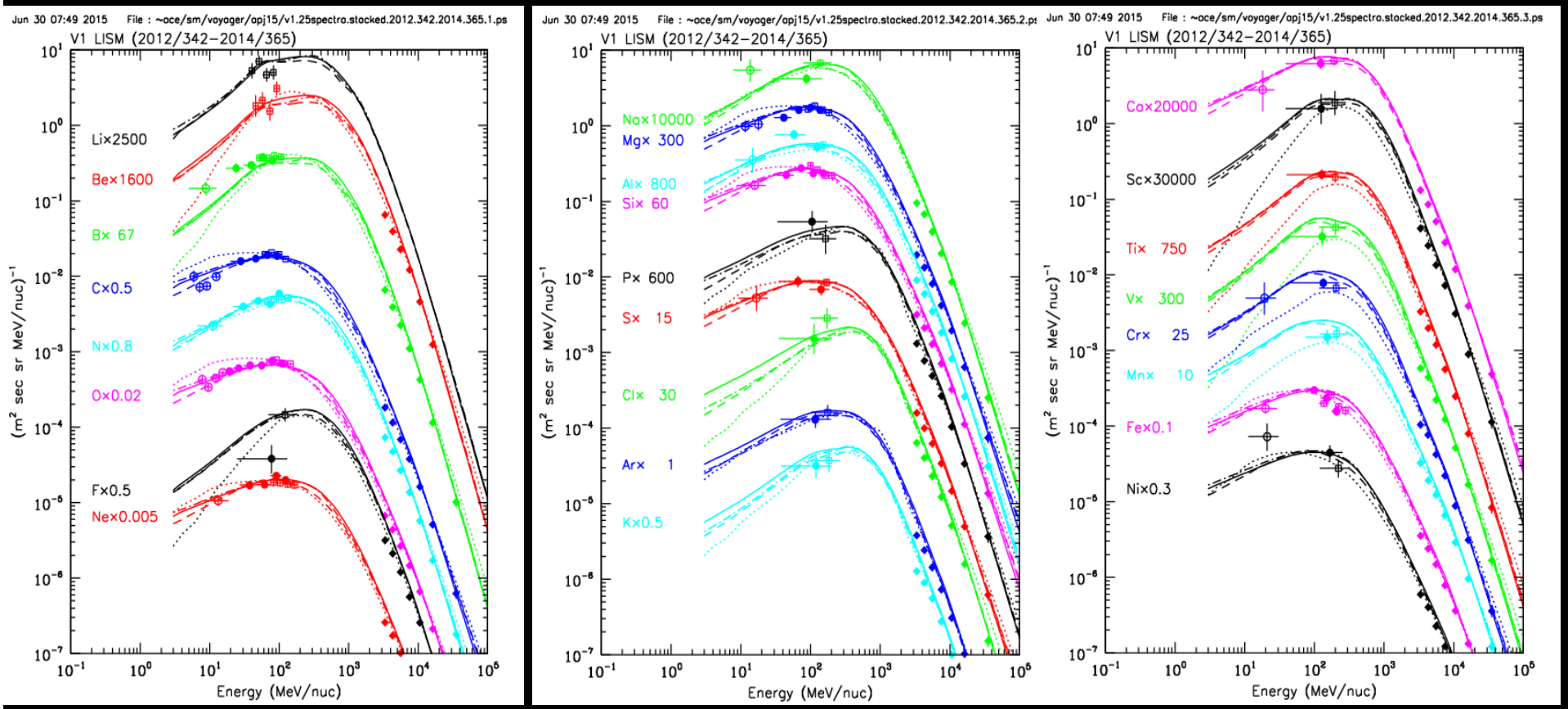
The transition was complex over ~30 days and ~0.3 AU



Similar spectra with H/He=12 from 3-300 MeV/n
No low energy turn-up: no recent nearby source
H and He spectra broad peak at the same energy/n implying spectra are not affected by solar modulation. Supports idea that Voyager is in LISM.

V1 spectra for 2012/342-2014/365 for Li – Ni together with high-energy HEAO-3-C2 data (>= 3.35 GeV/nuc). Models are constrained by the new Voyager observations and by the HEAO observations. All calculations of ionization rate and energy density use the models, starting at 3 MeV/n.

#702 Cummings



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

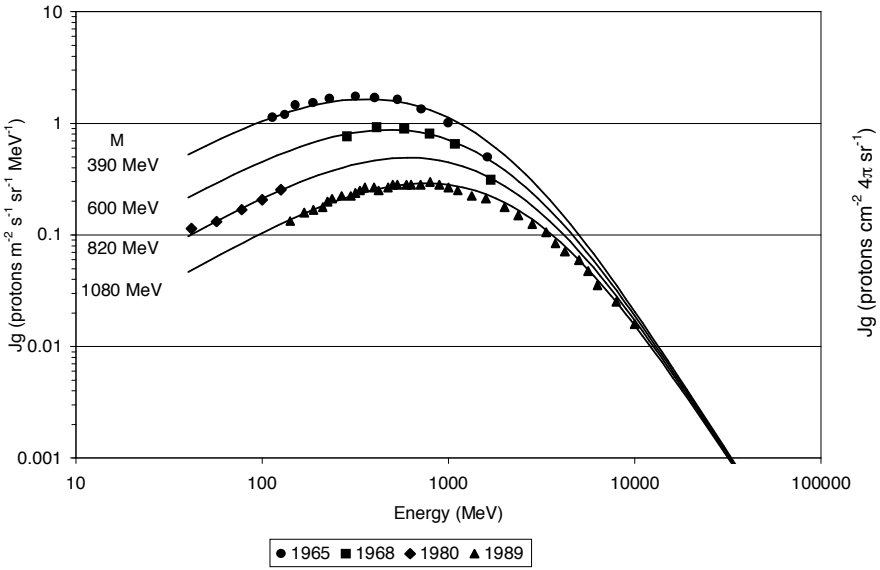


Fig. 1. Differential cosmic-ray spectra obtained from Eq. (1) for different values of the solar modulation parameter M = 390, 600, 820, 1080 MeV corresponding to the measurements performed with balloons or spacecrafts during 1965, 1968, 1980 and 1989 respectively.

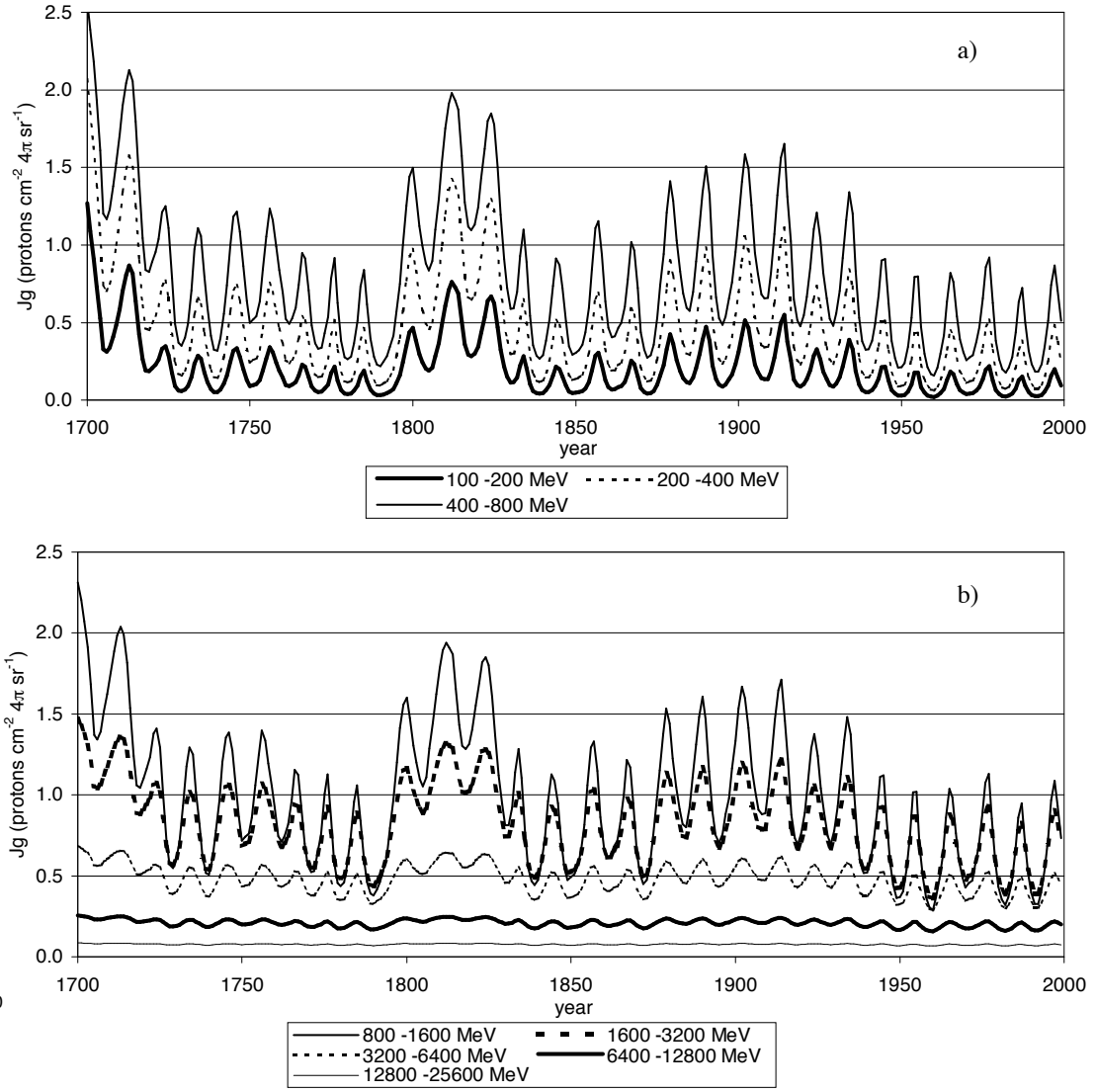


Fig. 2. Proton flux $J_G(t)$: a) for the kinetic energy intervals ΔT = 100-200 MeV, 200-400 MeV, 400-800 MeV; b) for ΔT = 800-1600 MeV, 1600-3200 MeV, 3200-6400 MeV, 6400-12800 MeV, 12800-25600 MeV.

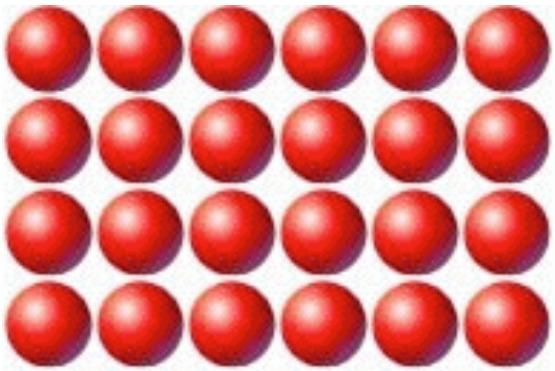
Carbon 14 method

formation of ^{14}C

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

decay of ^{14}C

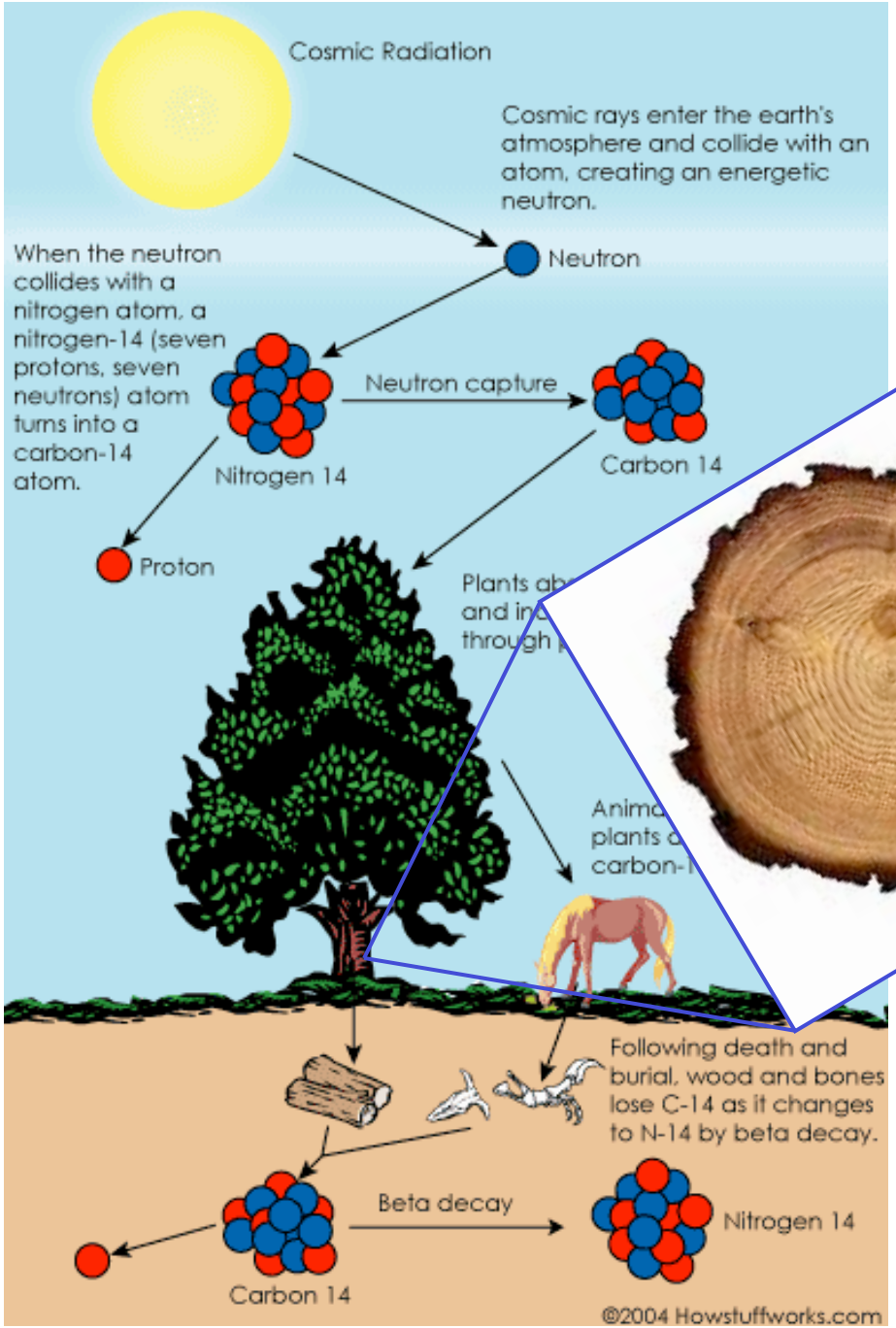
half life time 5730 years



Gehalt an C-14 nach
0 Jahren: 100%

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

Carbon 14 method

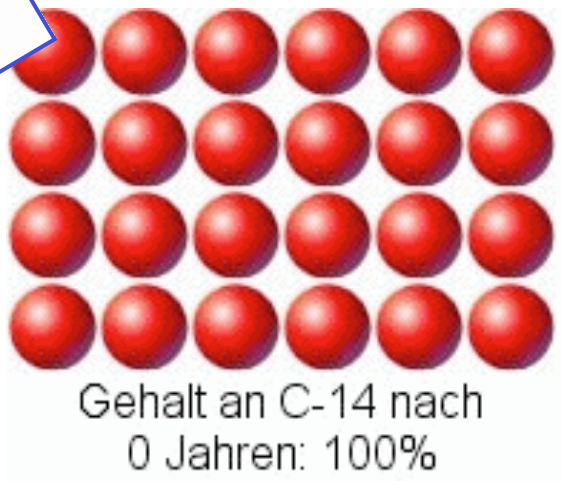


formation of ^{14}C

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

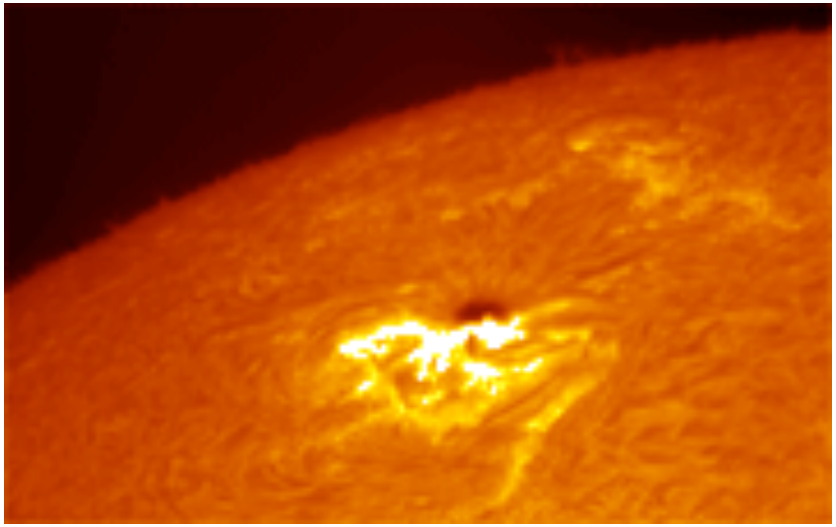
decay of ^{14}C

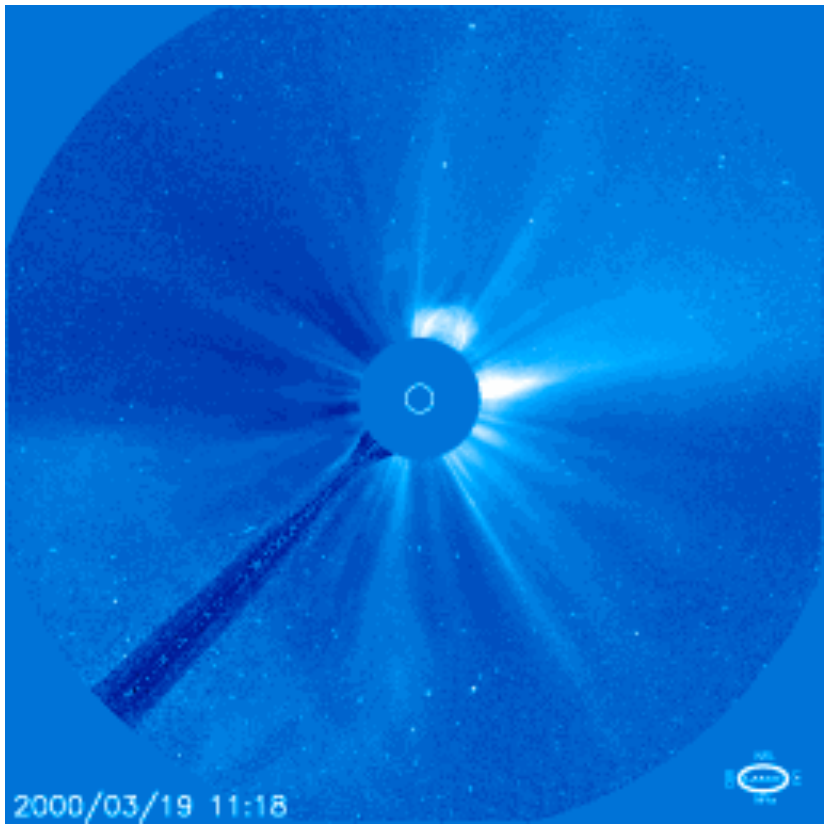
half life time 5730 years

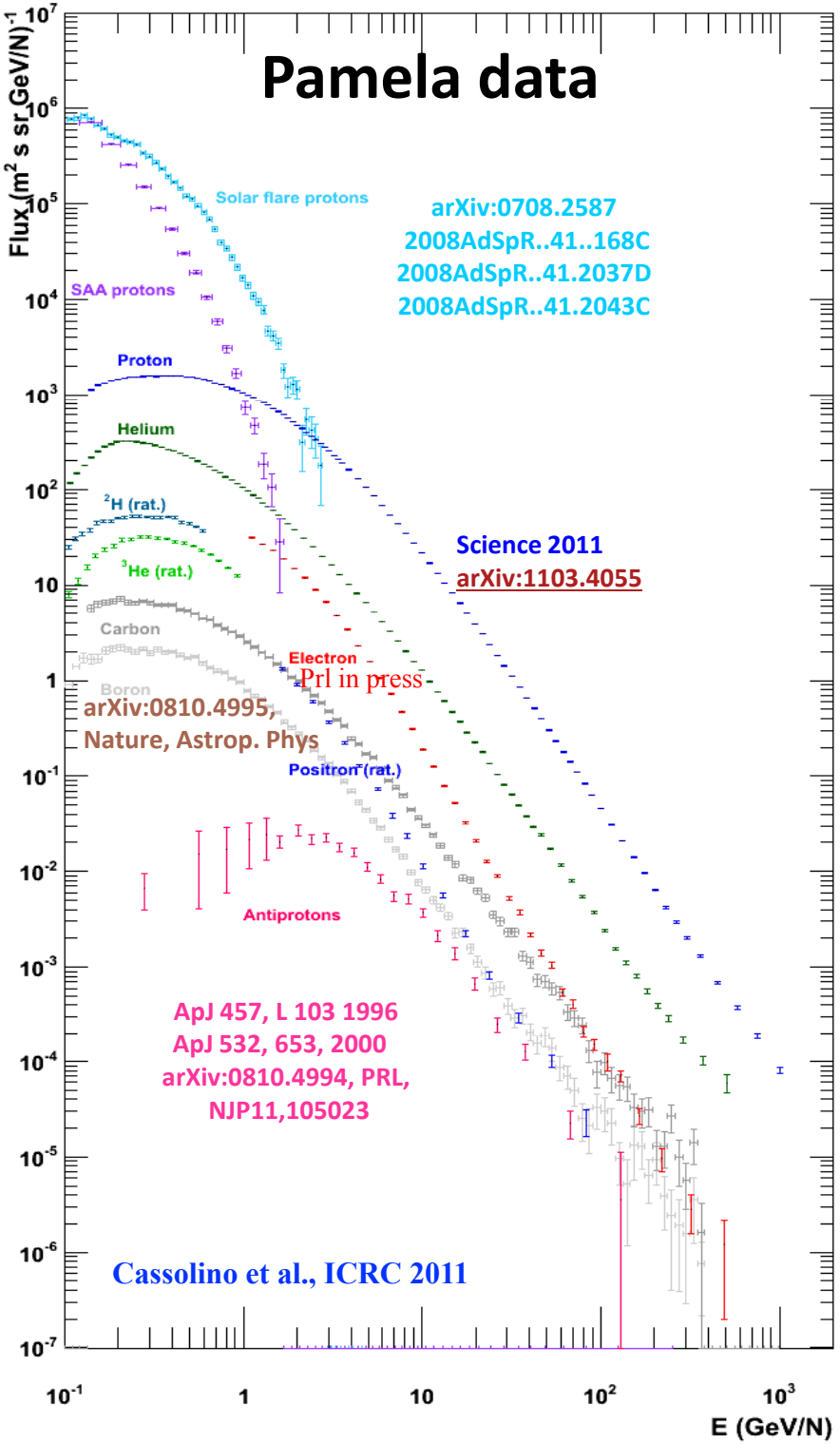


$^{14}C \rightarrow {}^{14}N + e^{-}$

Solar flares

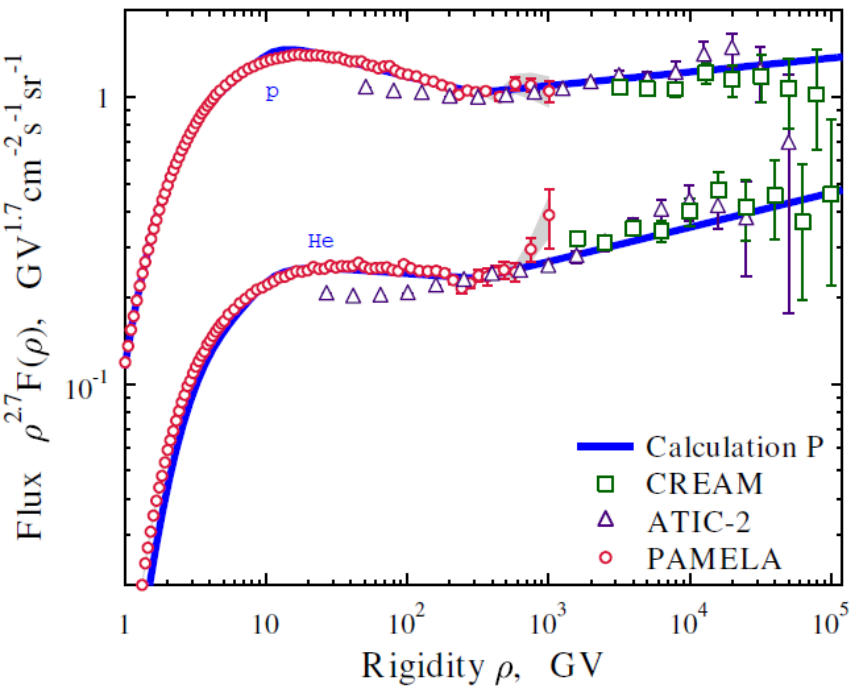






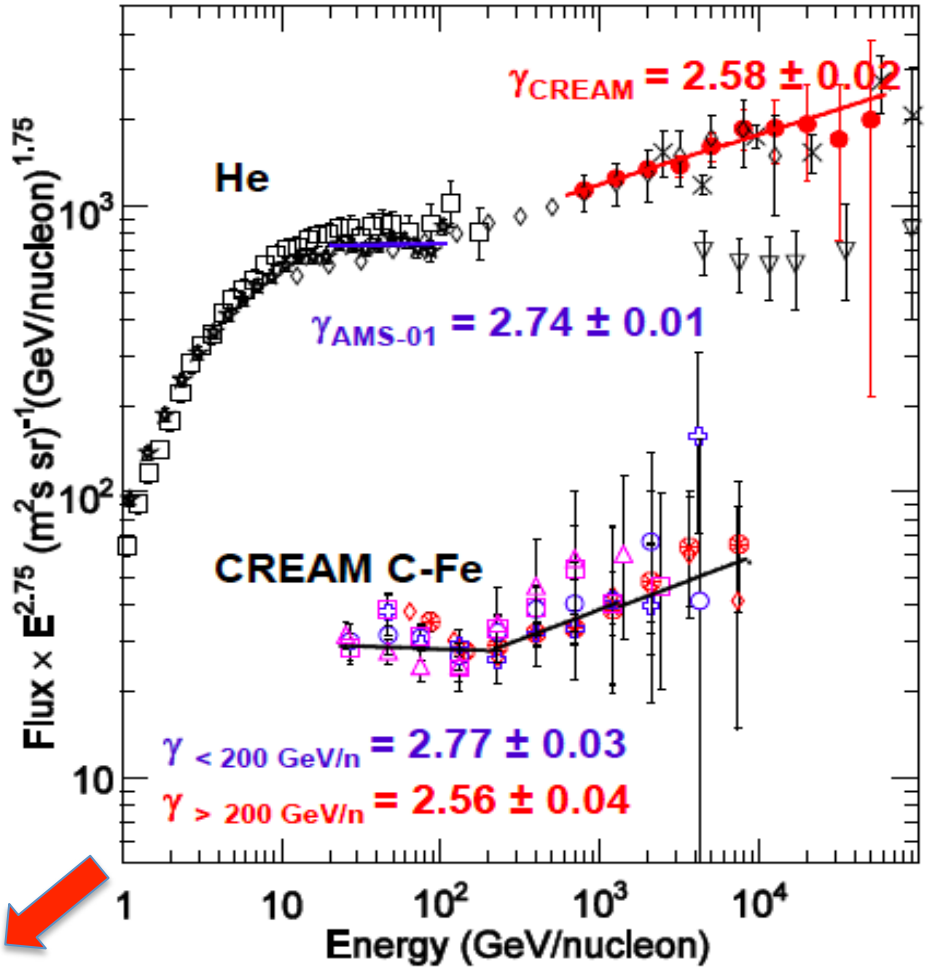
Direct measurements of proton and He spectra

❑ **PAMELA detected a spectral break in PROTON and HE spectra at R ~ 240 GV**



A single power-law seems inadequate to fit the spectra

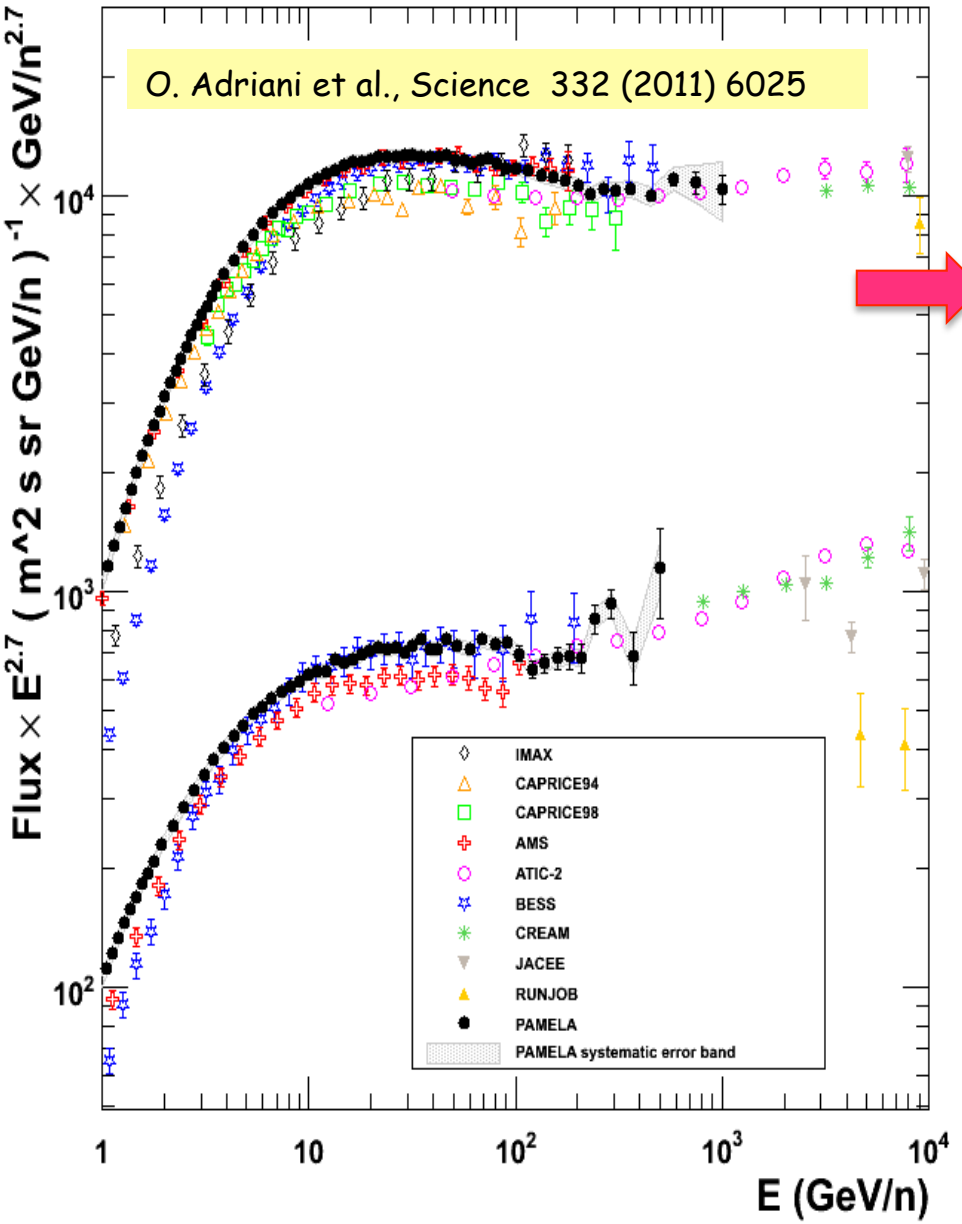
❑ **The break also appears in the spectra of NUCLEI measured by CREAM up to several TeV/n**



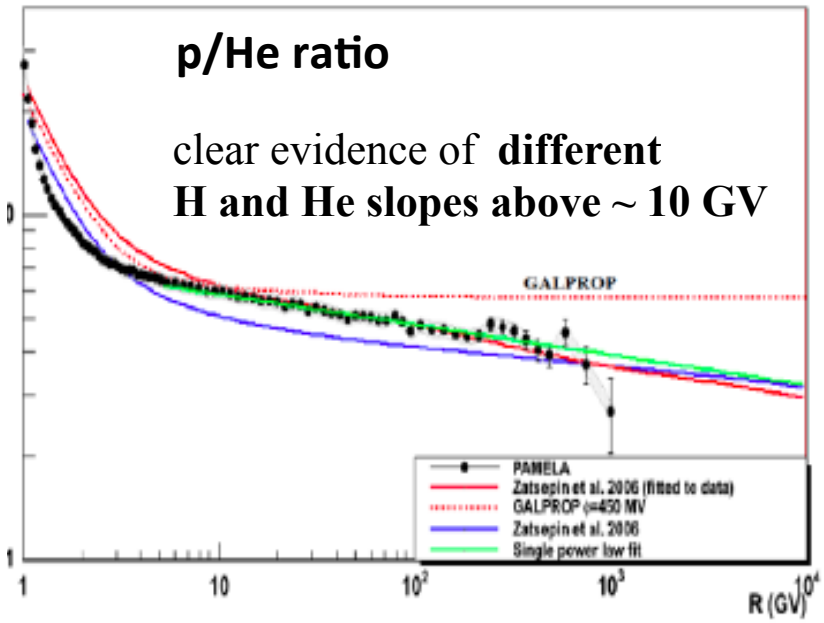
The slope of Z>2 NUCLEI at high energy looks similar to He and different from protons

Ahn et al. ApJ 714, L89, 2010
Yoon et al. ApJ **728**, *122*, 2011

PAMELA: Proton and Helium Nuclei Spectra & H/He ratio



- **First high-statistics and high-precision measurement over three decades in energy**
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV
    $\Delta\gamma \sim 0.2 \div 0.3$
    Single power-law rejected at 98% CL



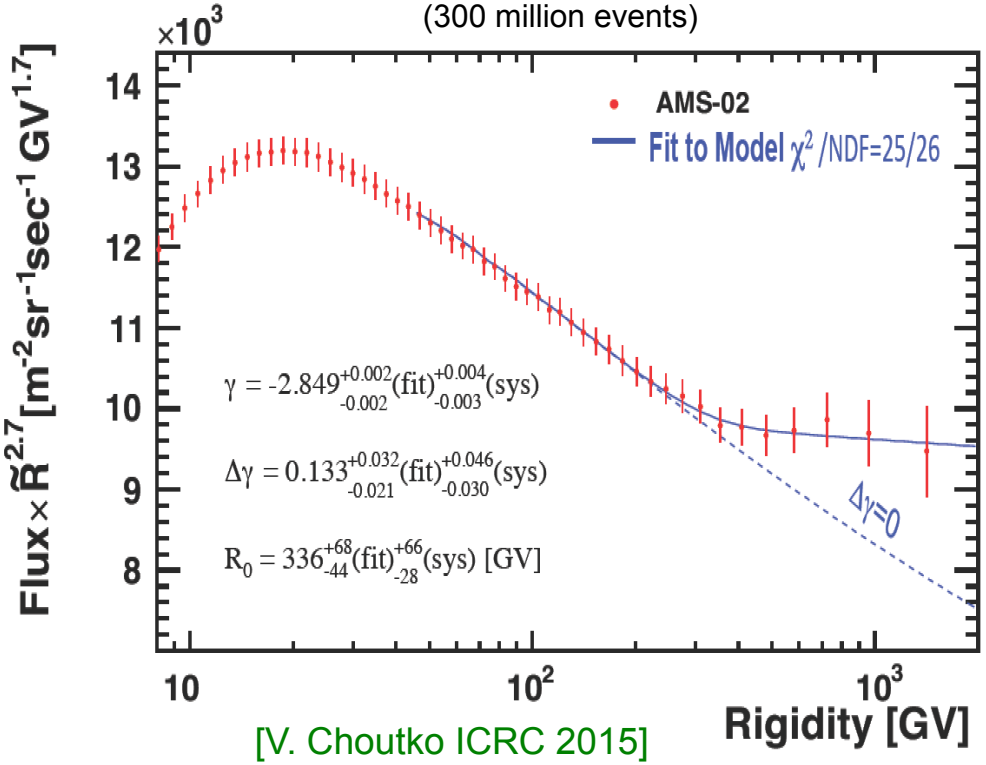
Proton and He fluxes measured by AMS-02

Two power laws with a characteristic transition rigidity R_0 and a smoothness parameter s are used by AMS-02 to fit the measured H and He spectra:

$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux

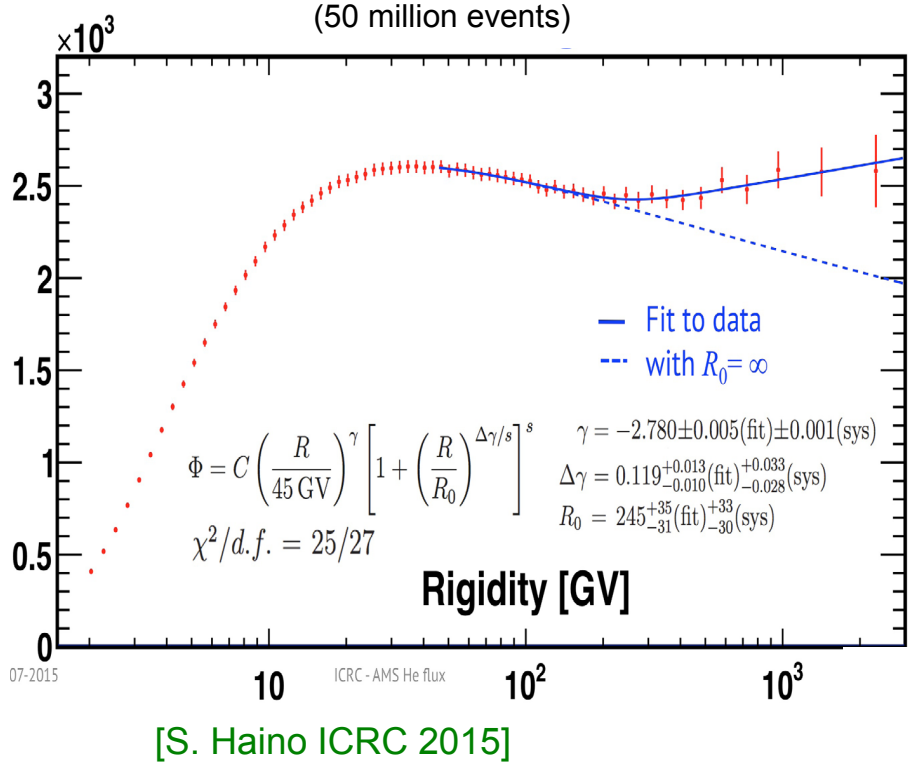
(300 million events)



[V. Choutko ICRC 2015]

AMS He flux

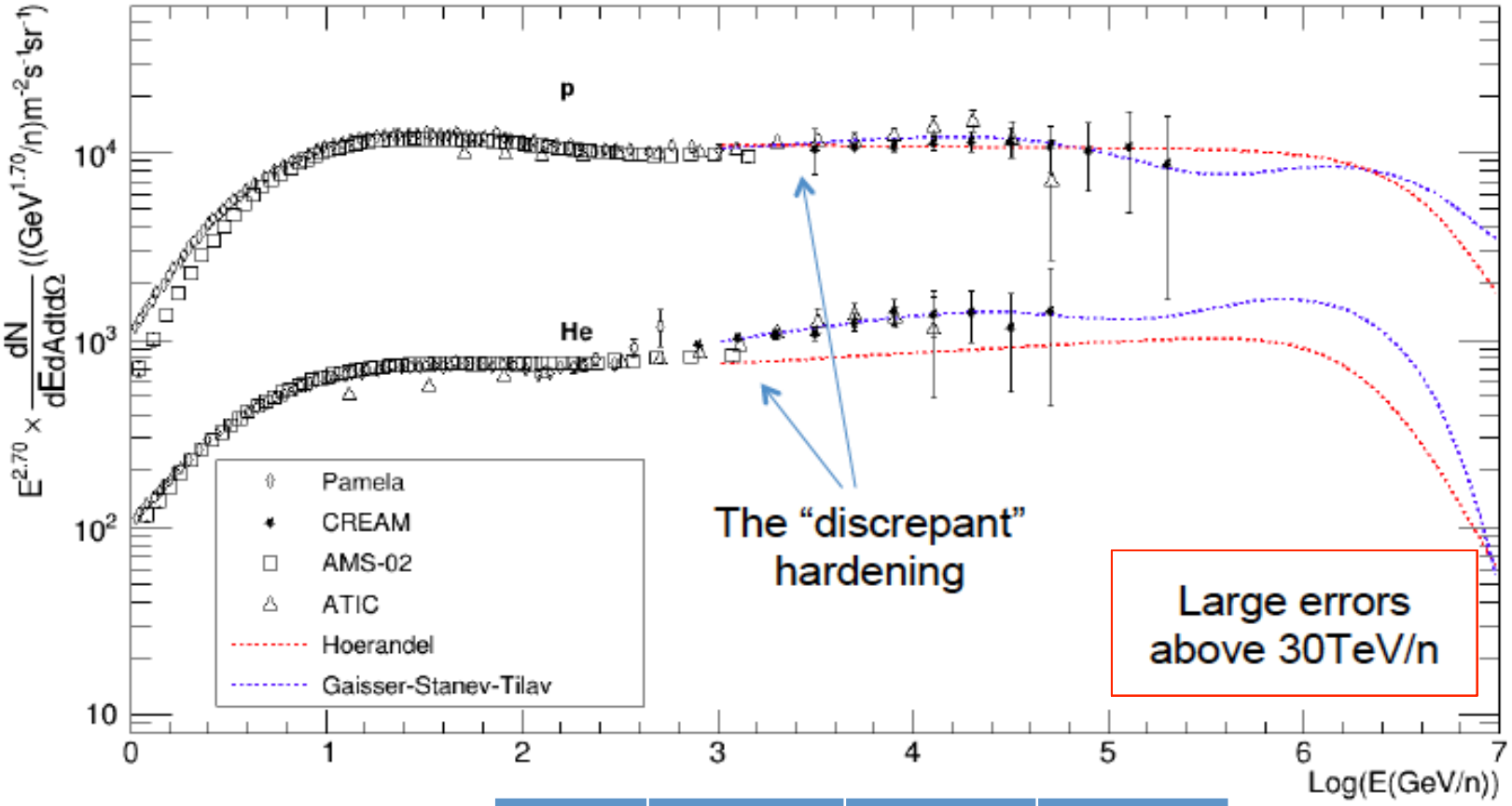
(50 million events)



[S. Haino ICRC 2015]

Proton and Helium:

✧ need to extend precision measurements to the multi-TeV region



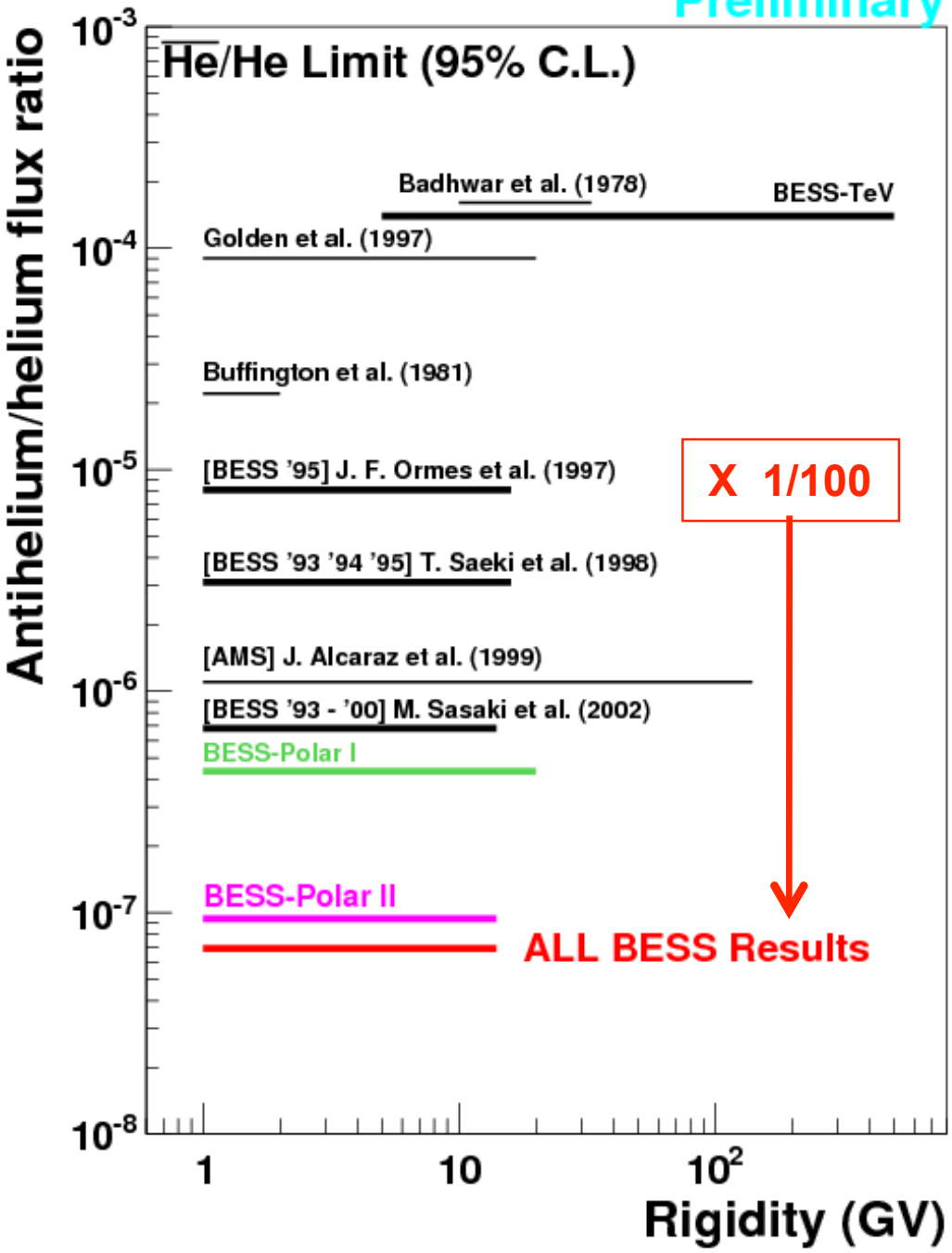
fitted slope of p, He spectra above 230 GV

	fit range p (He)	γ_p	γ_{He}
CREAM(*)	2.5 -250 TeV	-2.66±0.02	-2.58 ±0.02
PAMELA	> 230 (250) GV	-2.706±0.07	-2.604±0.08
AMS-02	> 330 (250) GV	-2.702±0.01	-2.639±0.01

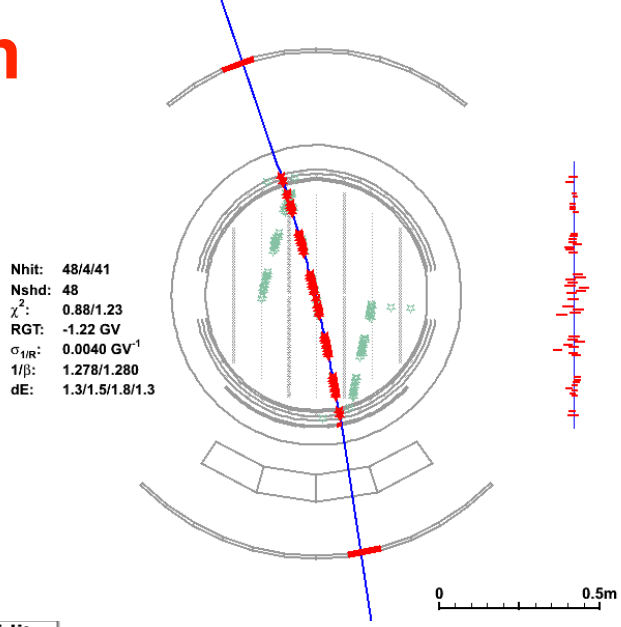
(*) Ahn et al., ApJ **714**, *L89*, 2010

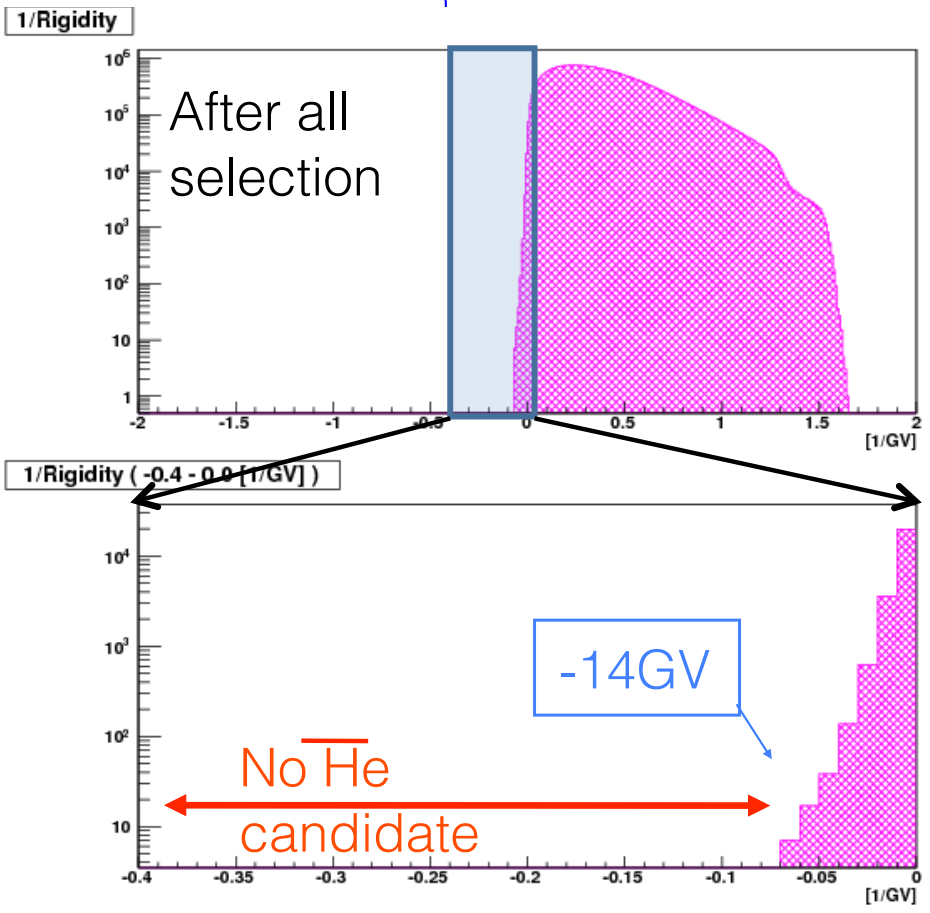
BESS-Polar: Search for antihelium

Preliminary



#1230
Sasaki

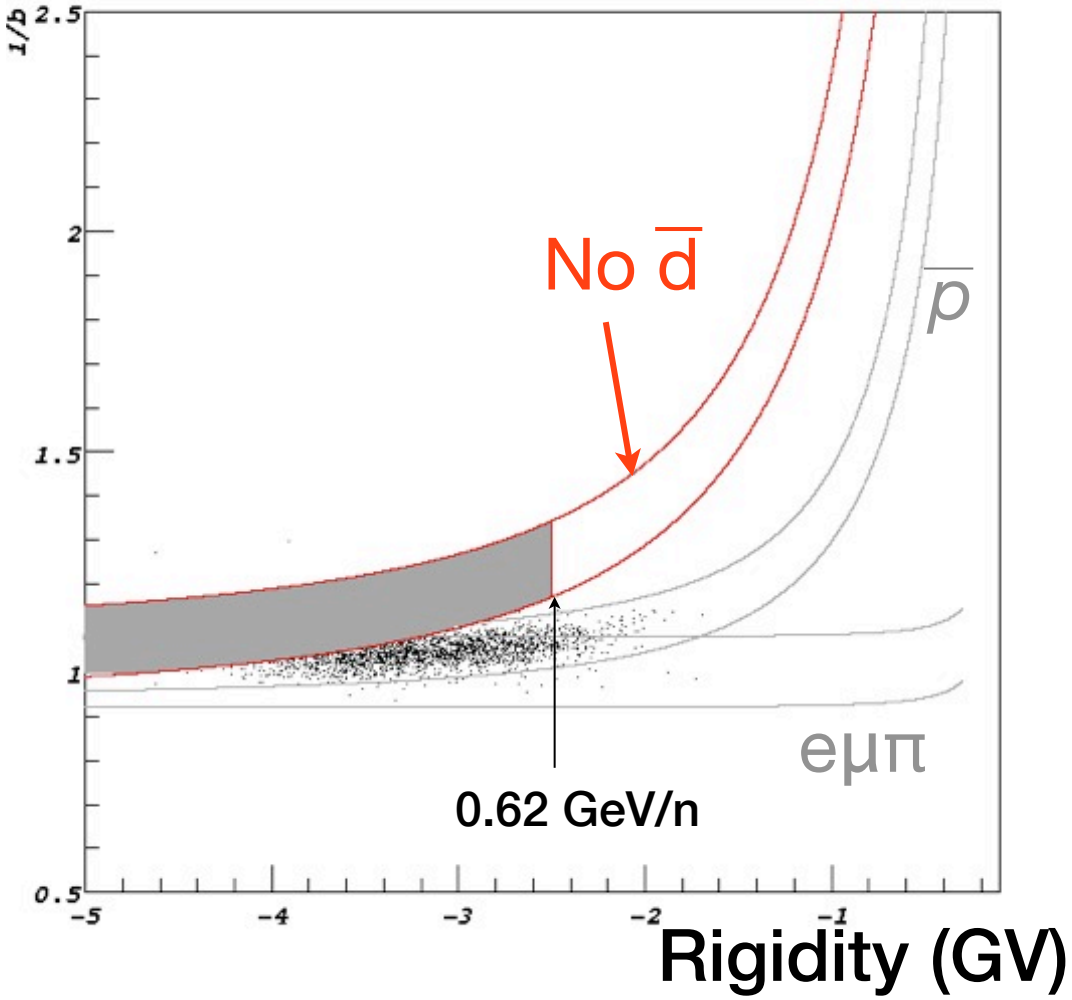




Search for cosmic-ray antideuterons with BESS-Polar

#1259
Yoshimura

Negative curvature



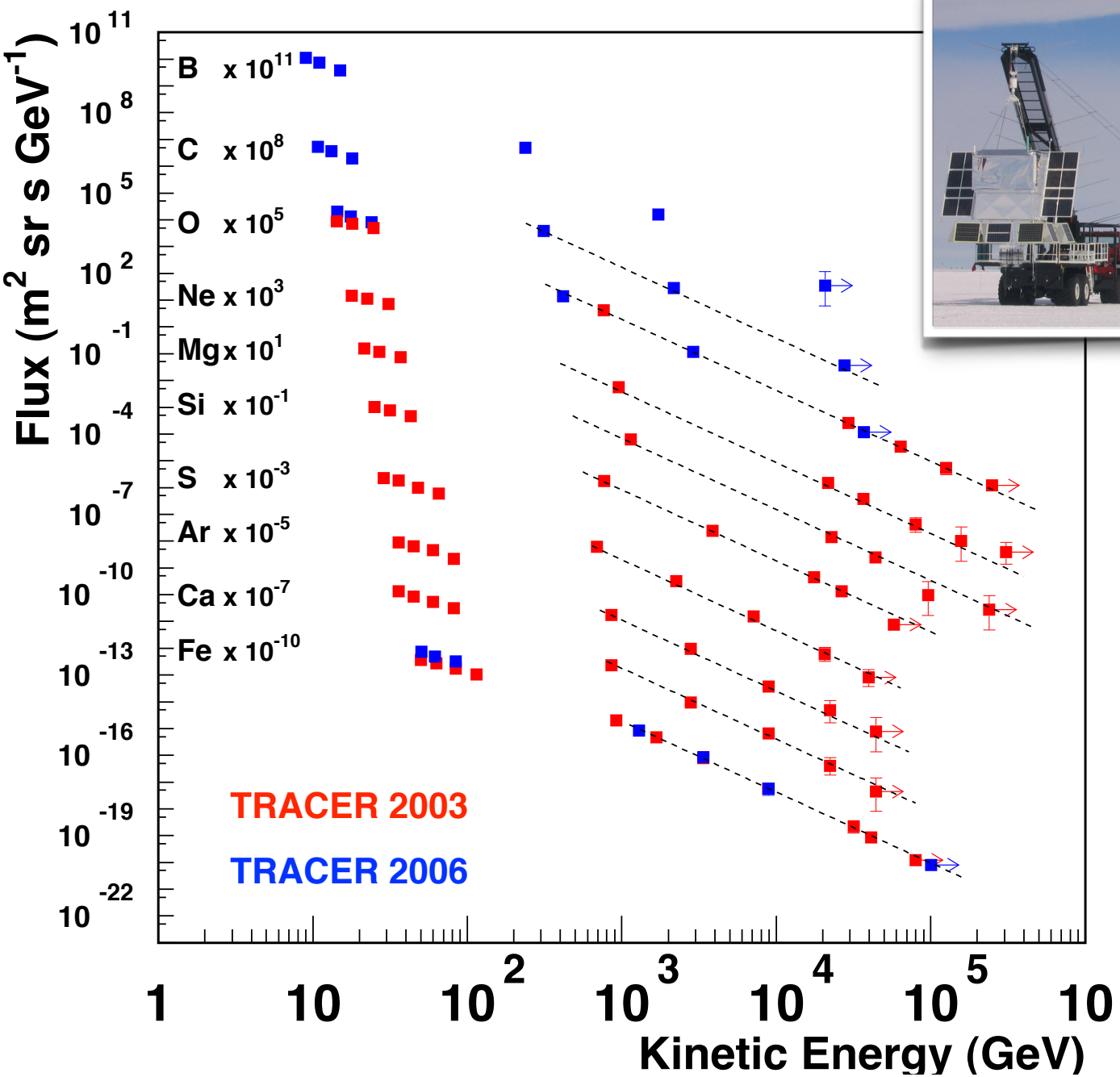
Apply the same selection as deuteron selection.

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

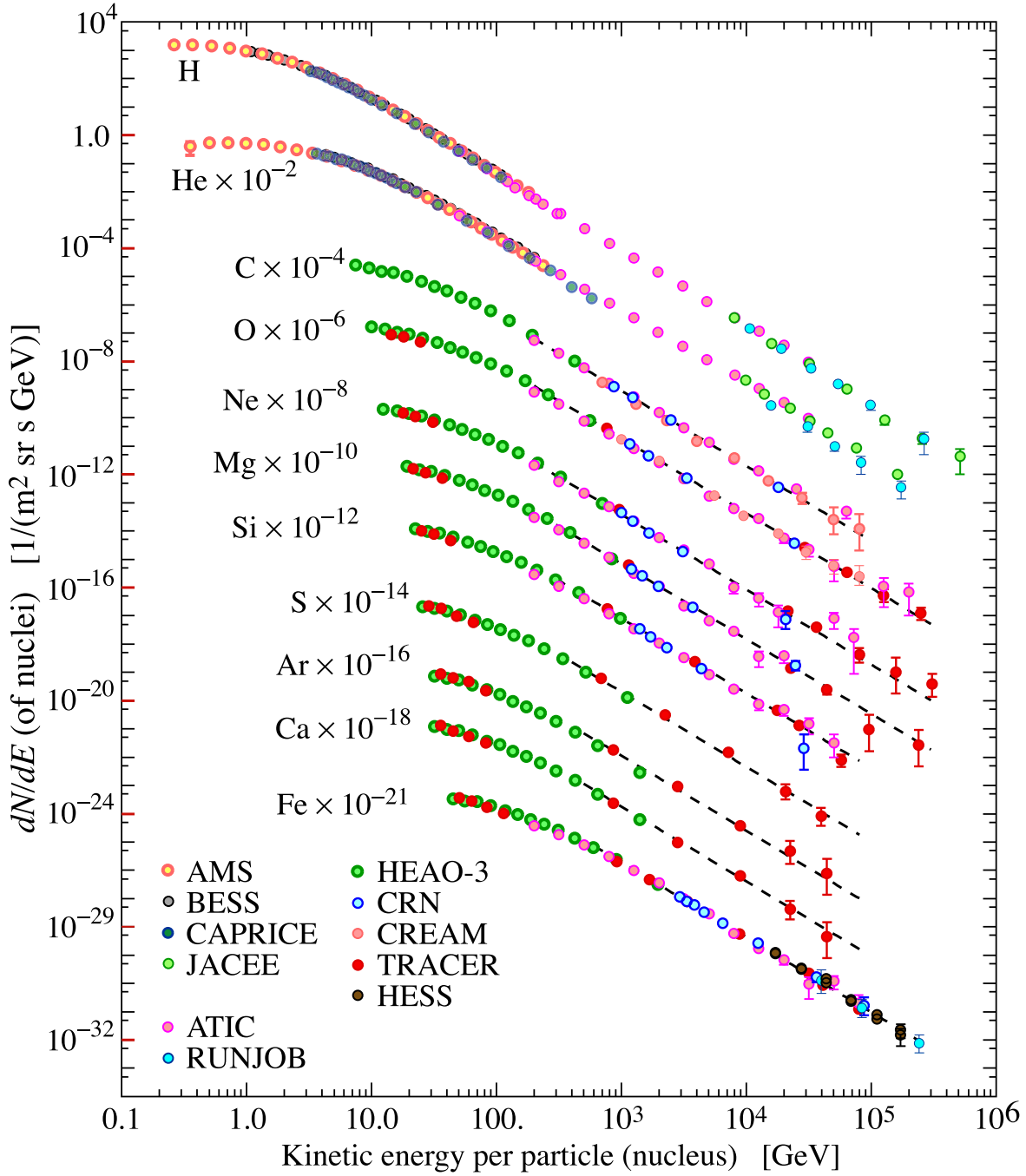


Figure 24.1: Major components of the primary cosmic radiation from Refs. [1–12 The figure was created by P. Boyle and D. Muller. Color version at end of book.

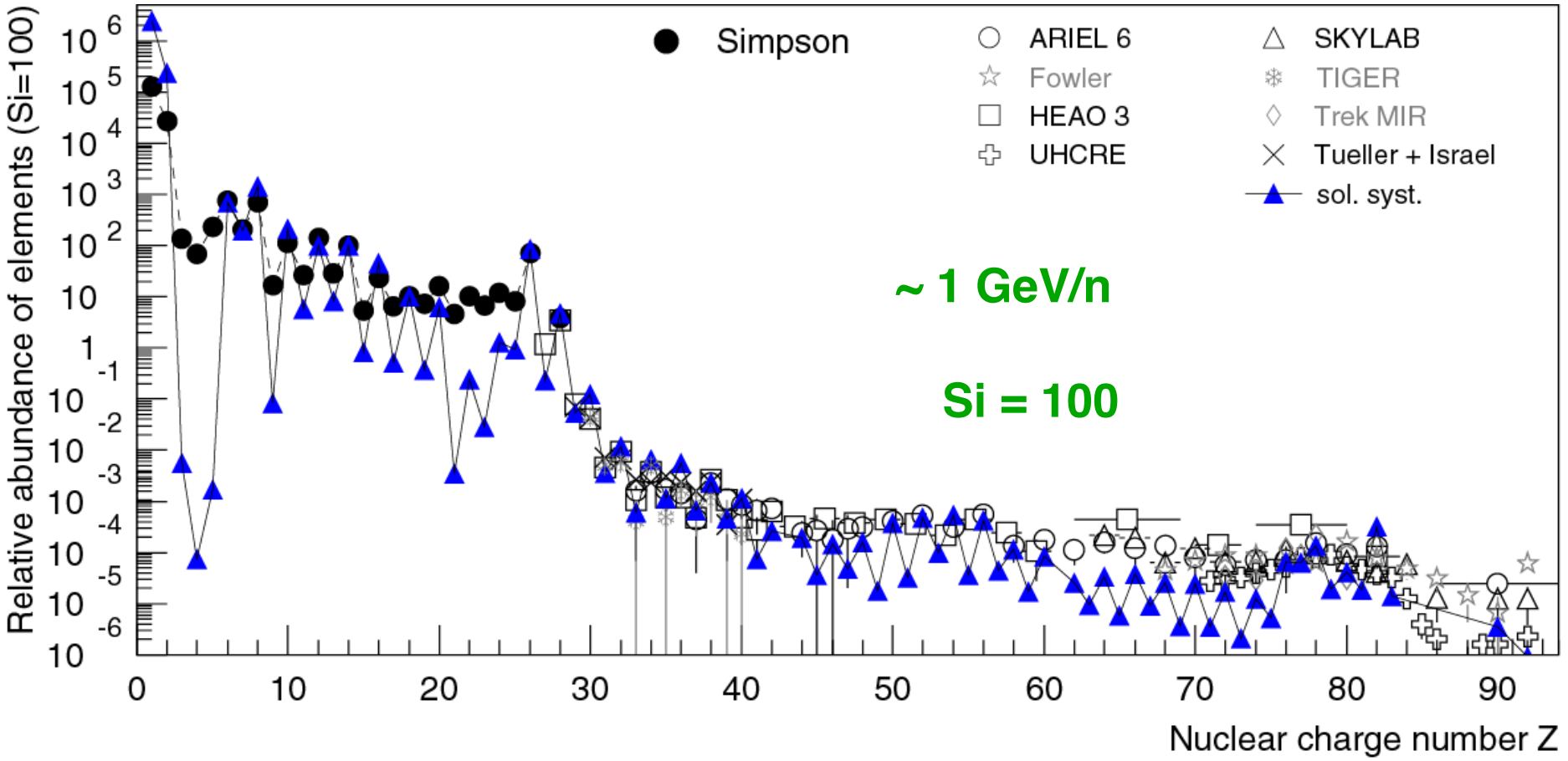
3) in first approximation all elements exhibit about the same slope

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

magnetic rigidity

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

Relative abundance of elements at Earth



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

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

4) elemental composition of cosmic rays

~ 89 % p
9 % He
1 % heavy nuclei

} 1 GeV/n

1 % e^-
≤ 0,1 % γ

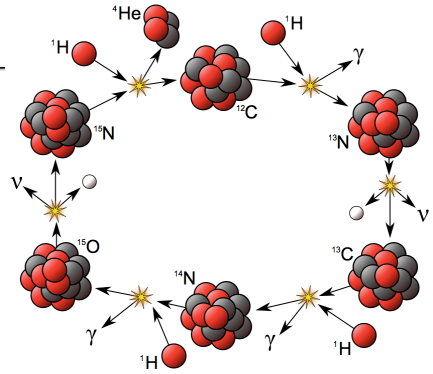
Some remarks

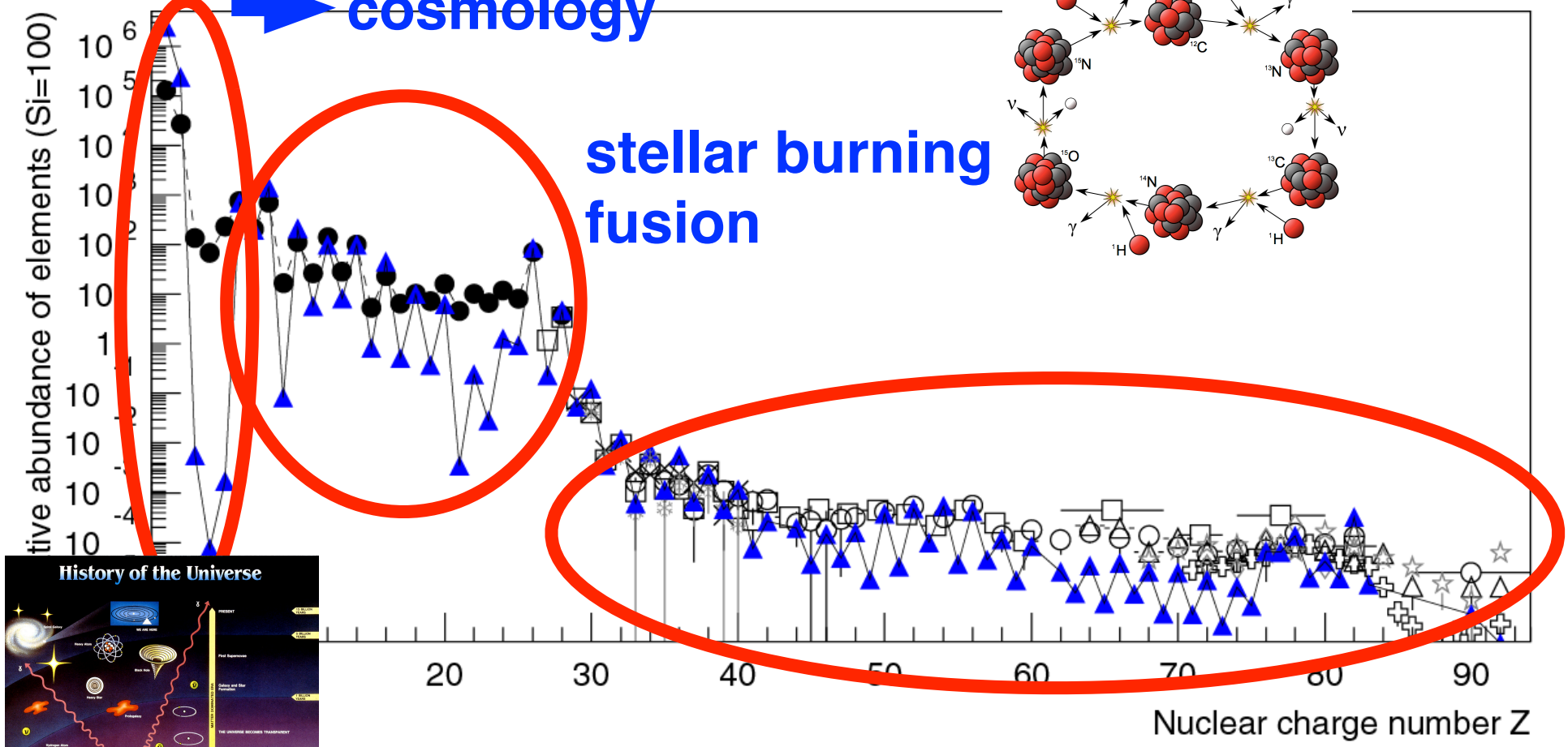
1) even-odd effect
   → due to the high binding energy of ee-nuclei
2) elements Li, Be, B are more abundant in CRs than in solar system
   → propagation in Galaxy
3) same effect for sub-Fe elements (~Ca-Fe)
4) p, He are less abundant in CRs as compared to solar system

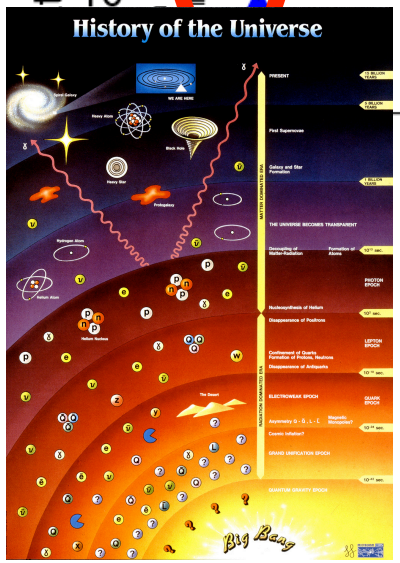
Origin of the Elements

big bang
cosmology

stellar burning
fusion







supernova
explosions

5) energy density of CRs

integrate the all-particle energy spectrum

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

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

→ total energy flux

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

→ total energy density

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

$\approx 1\,eV/cm^3$ energy density of CRs

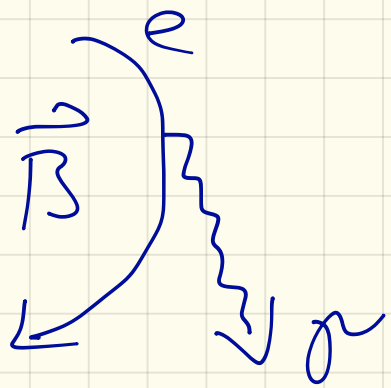
comparable with e.g.
energy density of visible star light $\mathcal{E}_{St} \sim 0{,}3 \frac{eV}{cm^3}$
energy density of B field in Galaxy

6) electrons: ~1% of nuclear cosmic rays

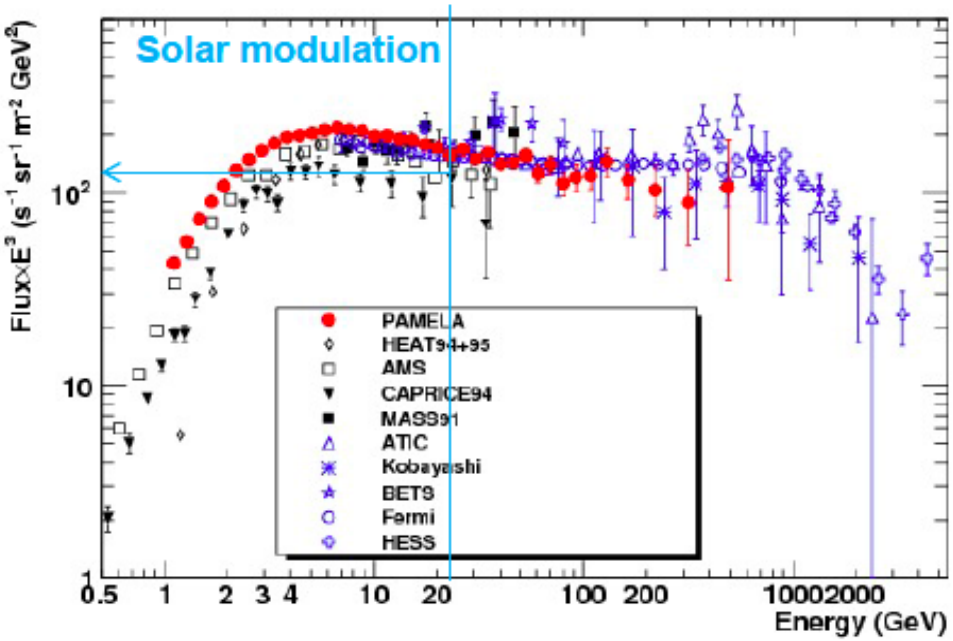
energy spectrum is steeper

$$\frac{dN_e}{dE_e} \propto E_e^{-3,3}$$

reason: losses through synchrotron radiation at high energies



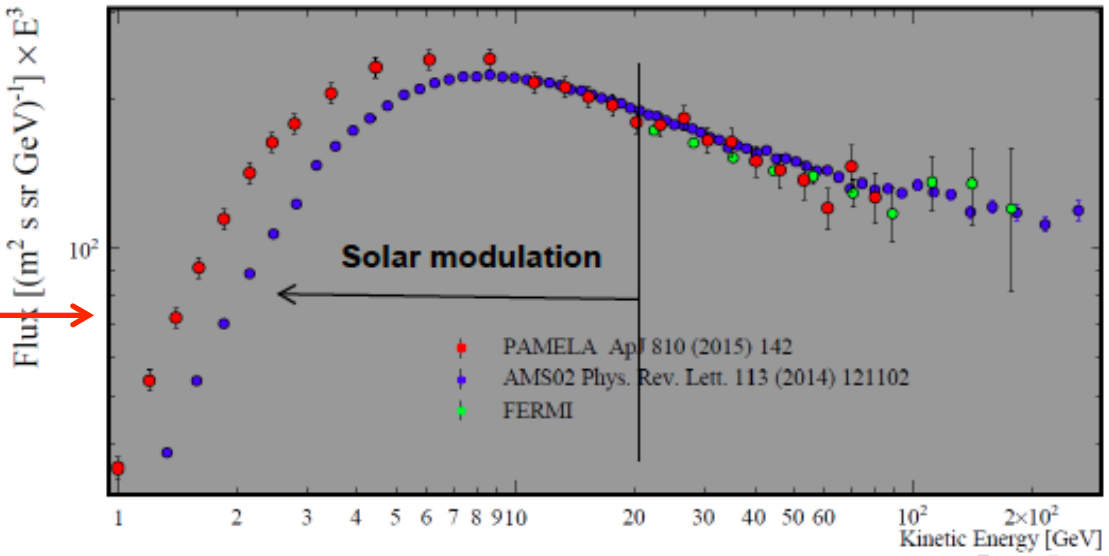
PAMELA Results: Electrons



- PAMELA electron spectrum (published data to 625 GeV)
- AMS-02 electrons to 700 GeV

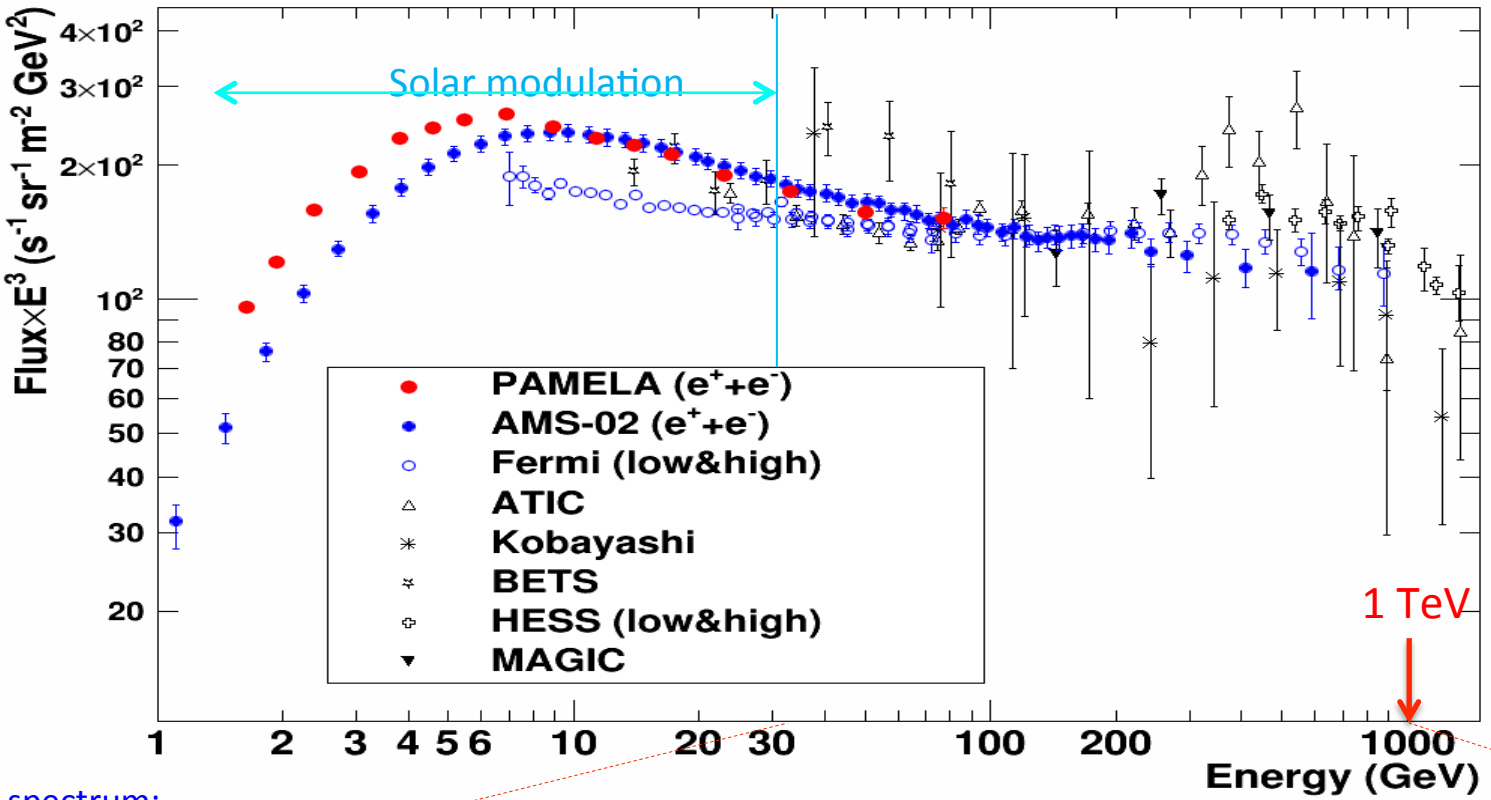
O. Adriani et al., PRL 106, 201101

Study of low energy data (affected by solar modulation)



O. Adriani et al., ApJ 810 (2015) 142

INCLUSIVE (e^-+e^+) spectrum below 1 TeV (AMS-02, FERMI & PAMELA)

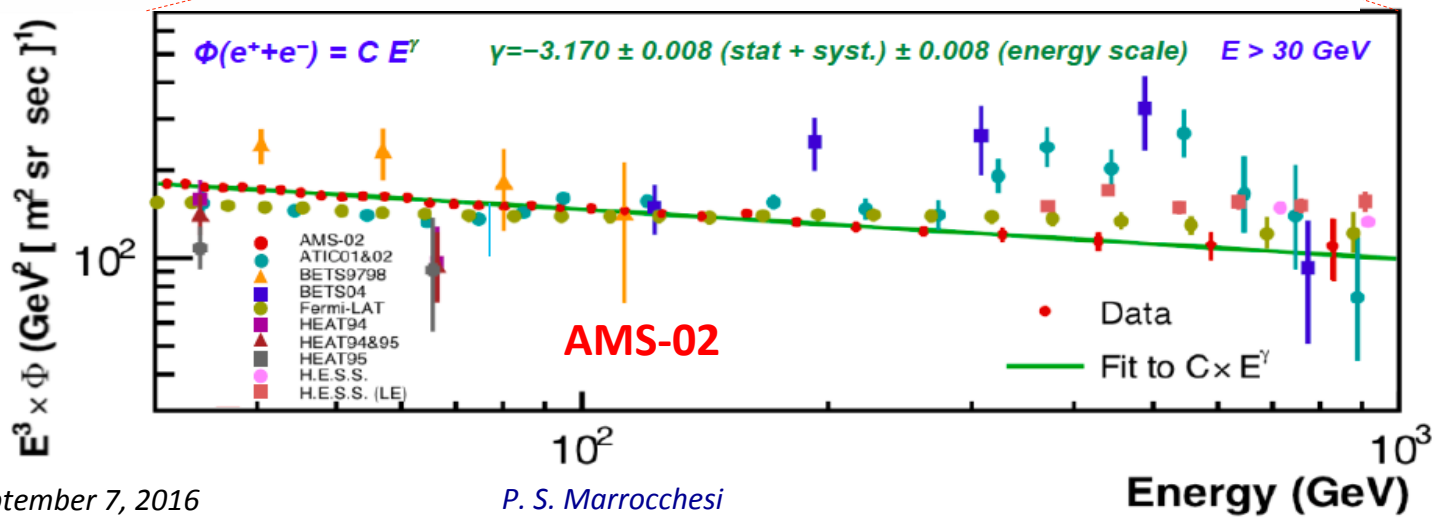


e^-+e^+ spectrum:

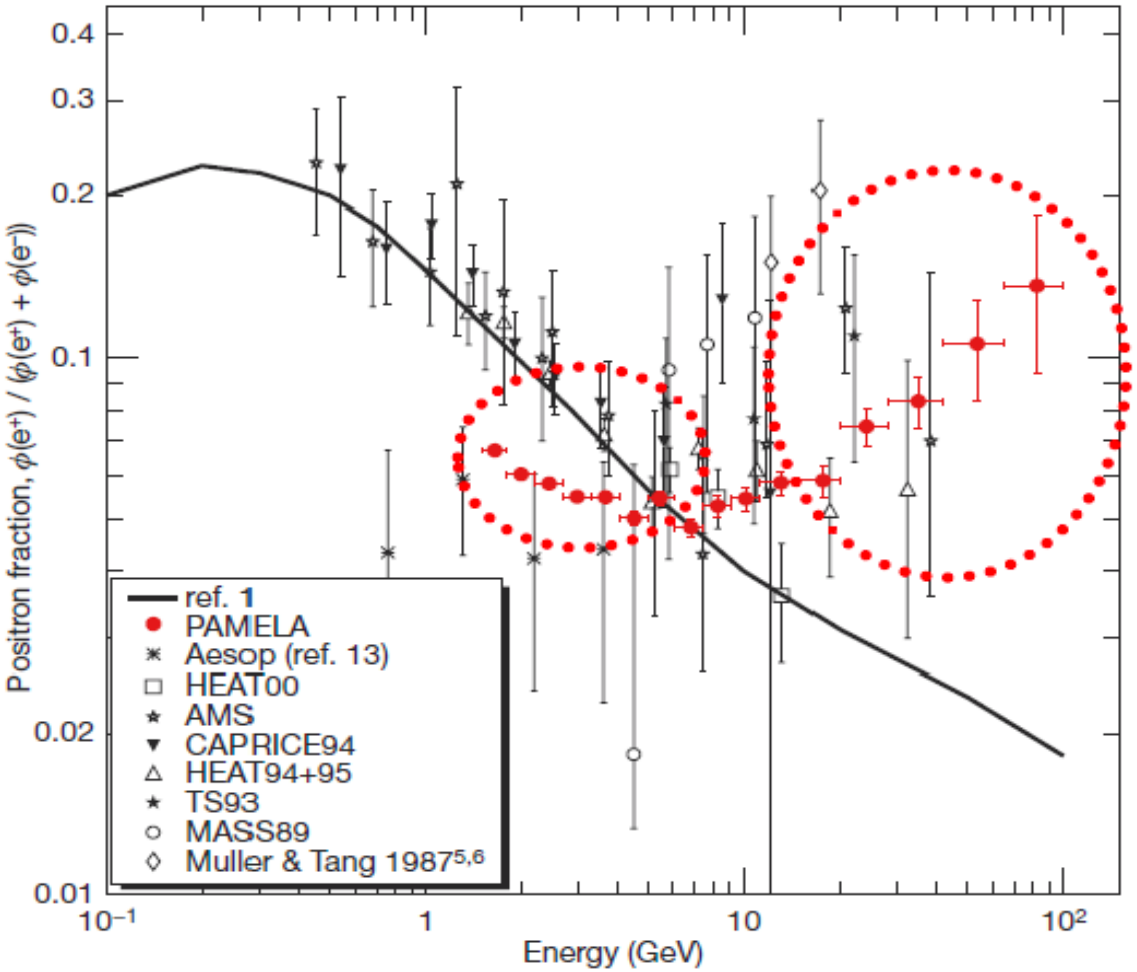
AMS-02 to 1 TeV

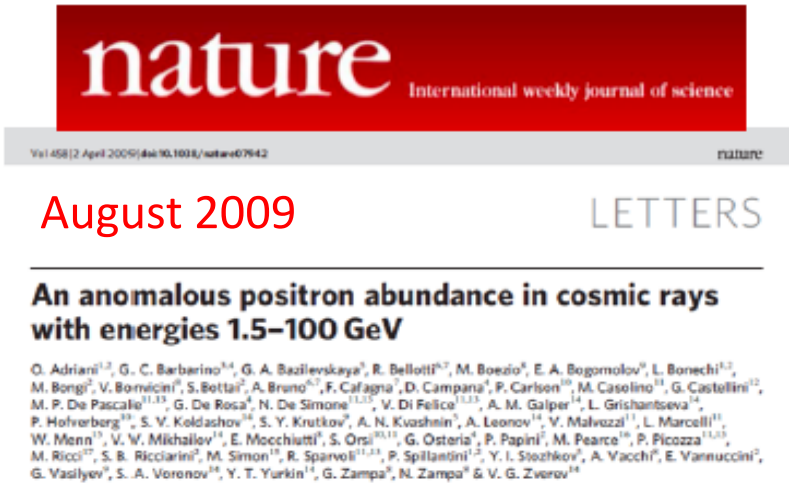
PAMELA (calorimeter only) to 3 TeV (*)

(*) A.V. Karelin et al. Journal of Physics Conf. Series 632 (2015) 01**2014**



PAMELA: first unambiguous evidence of the rise of the positron fraction above 10 GeV




nature International weekly journal of science

August 2009

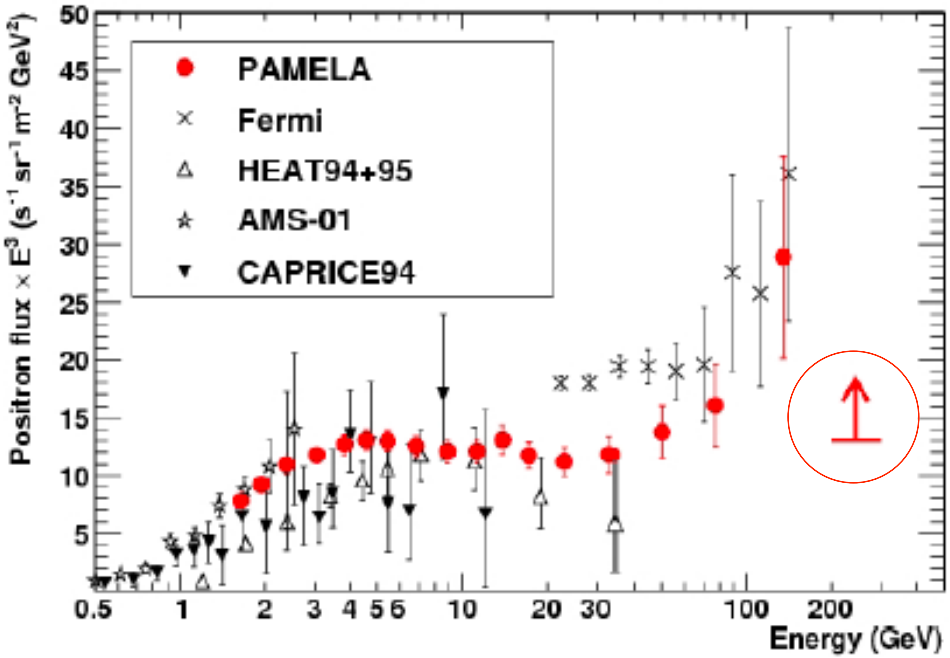
LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[1], V. Bonvicini[8], S. Bottai[1], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[15], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[11,13], G. Osteria[4], P. Papini[1], M. Pearce[10], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[1], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[1], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

Citations: 1338

PAMELA Results: Positrons



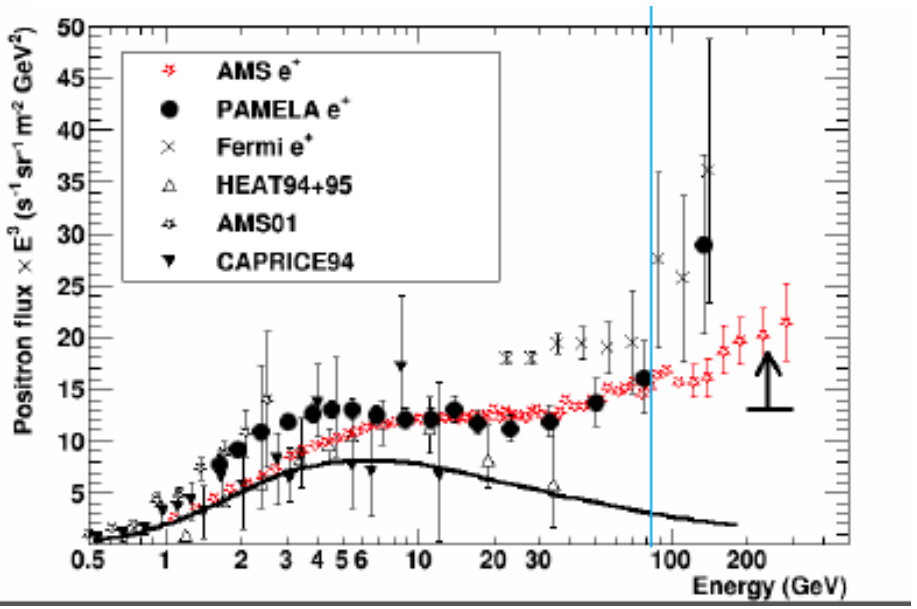
PHYSICAL REVIEW LETTERS

O. Adriani et al. , PRL 106 (2011) 201101

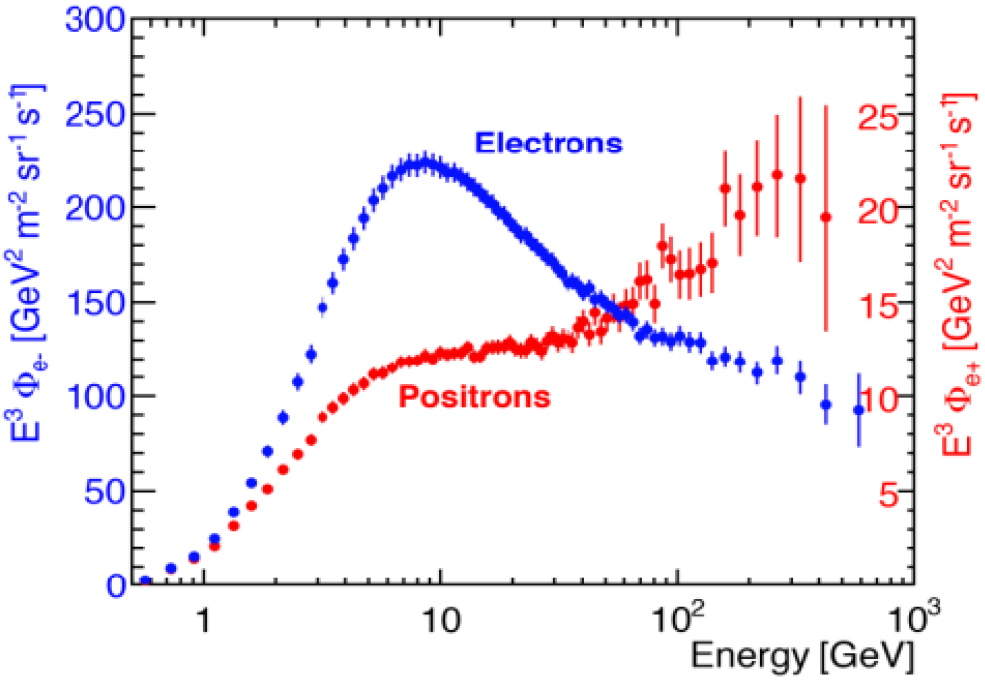
❖ PAMELA positron spectrum to 300 GeV

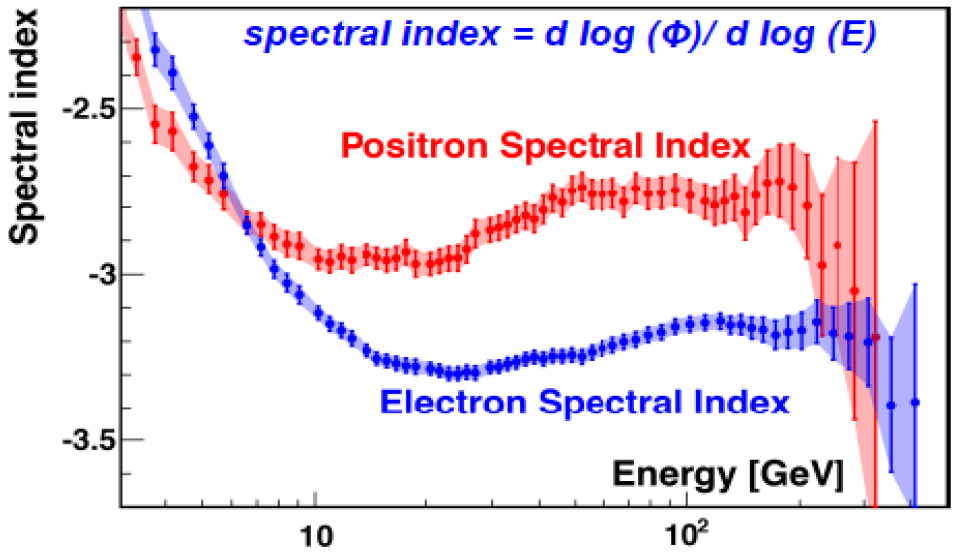
❖ AMS-02 positrons to 500 GeV

Results confirmed by AMS-02!



AMS-02: Electron Flux and Positron Flux





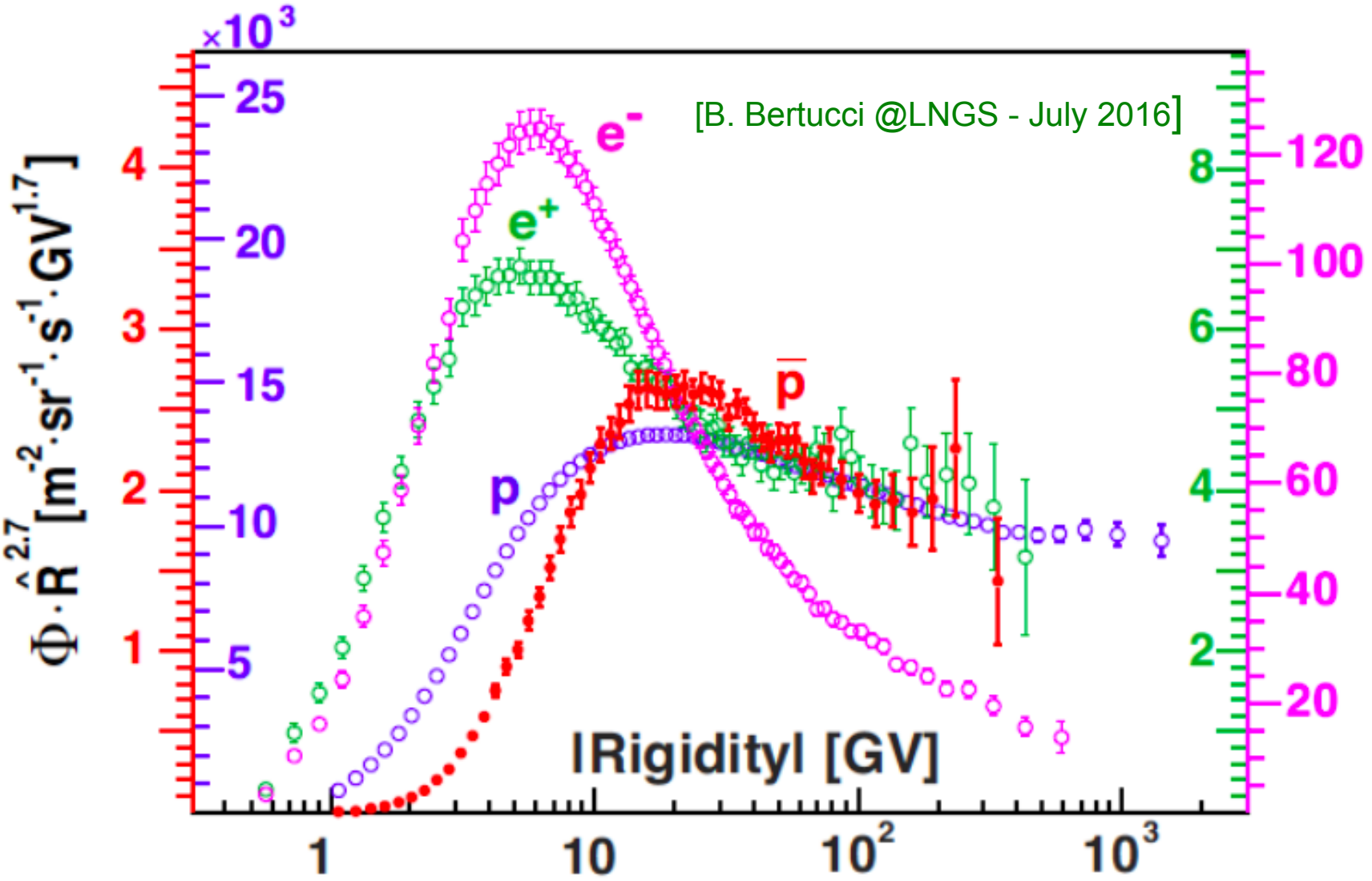
[M. Aguilar et al., PRL 113 (2014) 121102]

Observations:

1. **The electron flux and the positron flux are different in their magnitude and energy dependence.**
2. **Both spectra cannot be described by single power laws.**
3. **The spectral indices of electrons and positrons are different.**
4. **Both change their behavior at ~30GeV.**
5. **The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).**

[S.C.C. Ting, ICRC 2015]

Fluxes of e^+, e^-, p and anti-p as measured by AMS-02



- Above ~60 GV the rigidity dependence of e^+, p and anti-p are **almost identical**
- BUT electrons behave differentlly.