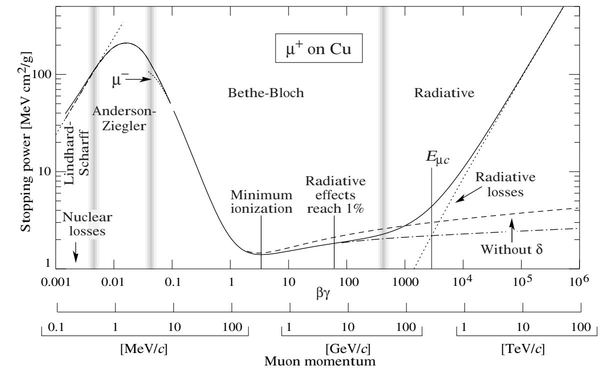
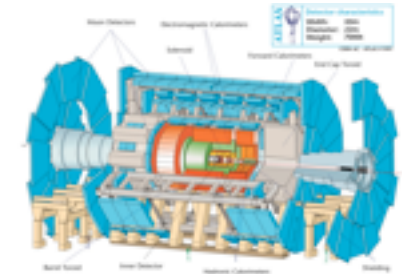
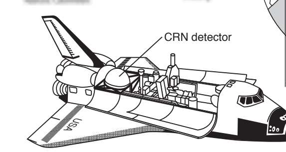
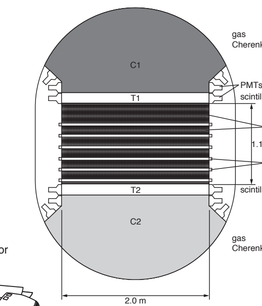
Particles and the Cosmos

Sascha Caron
Jörg R. Hörandel



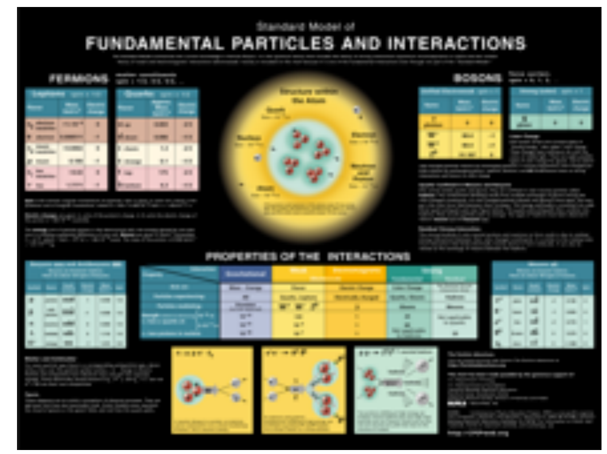






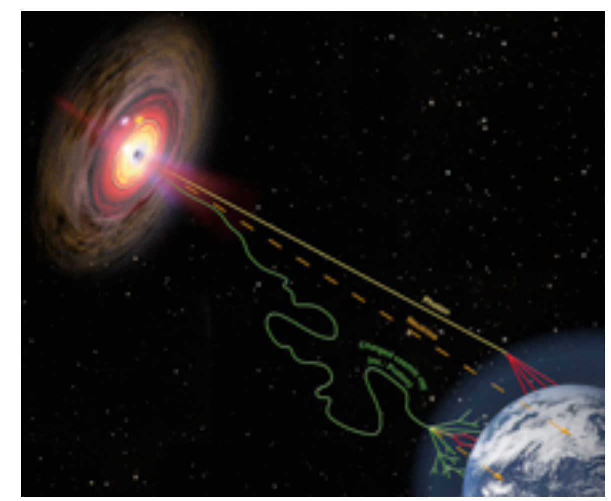
Experimental methods (JRH)

06.09.2017 1. Interactions with matter
13.09.2017 2. Detectors
20.09.2017 3. Observables and experiments



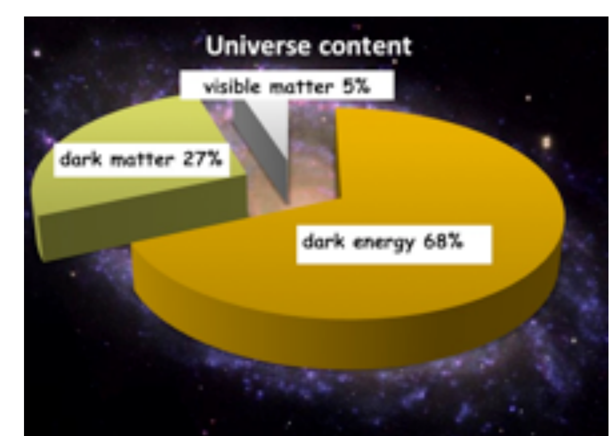
Standard model (SC)

27.09.2017 4. Particles, QED, Feynman rules
04.10.2017 5. Hadrons and QCD
11.10.2017 6. Hadrons and QCD
18.10.2017 7. Weak interactions, CP violation
25.10.2017 8. Higgs mechanism



Astroparticle physics (JRH)

22.11.2017 9. Cosmic rays, direct measurements
24.11.2017 10. Sources, acceleration
29.11.2017 11. Cosmic rays, air showers
01.12.2017 12. Gamma rays
06.12.2017 13. Neutrinos

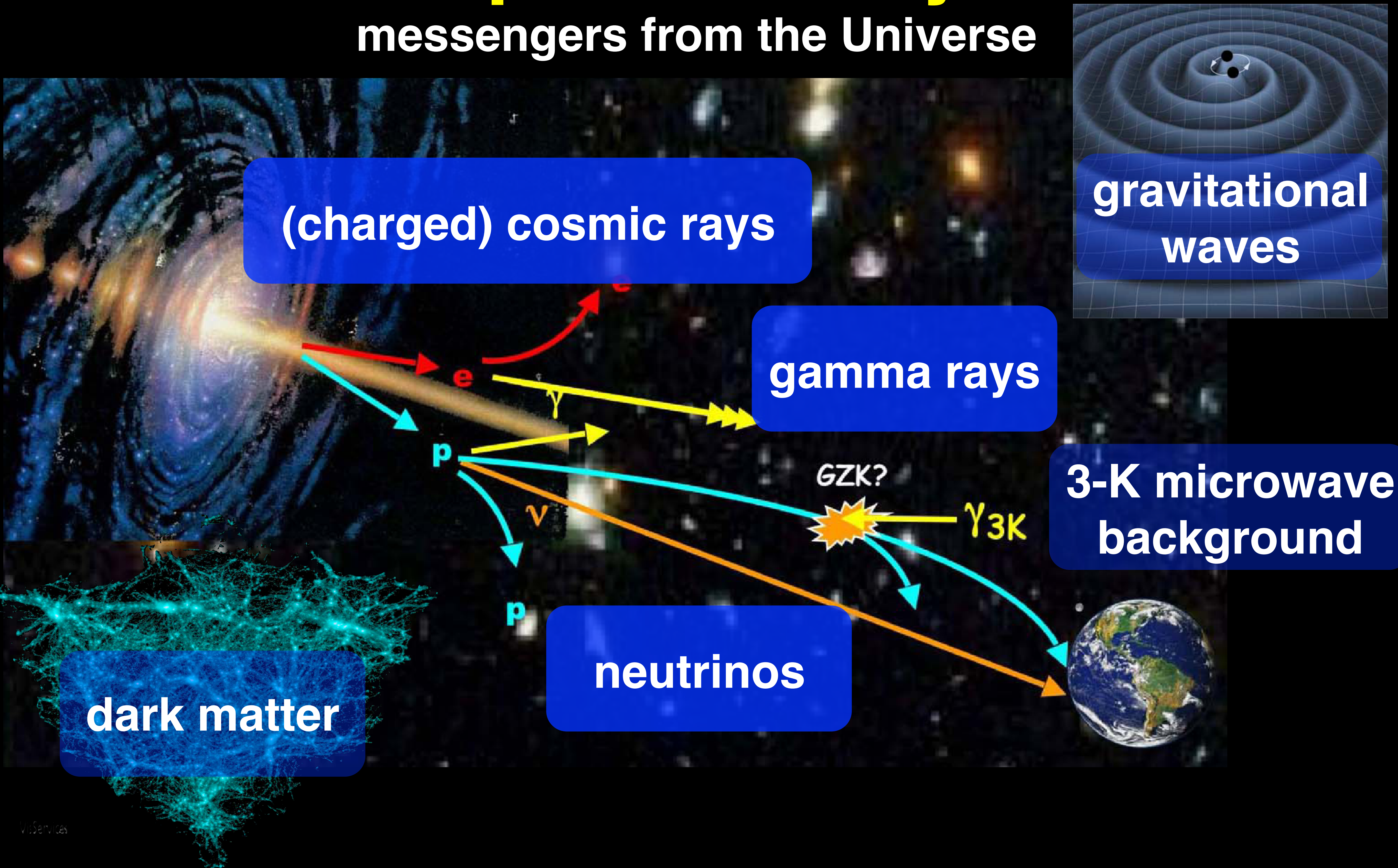


Beyond the Standard Model, Dark Matter (SC)

13.12.2017 14. Lambda CDM, Big-bang nucleosynthesis
20.12.2017 15. Dark matter
10.01.2017 16. Beyond-the-standard-model reasons

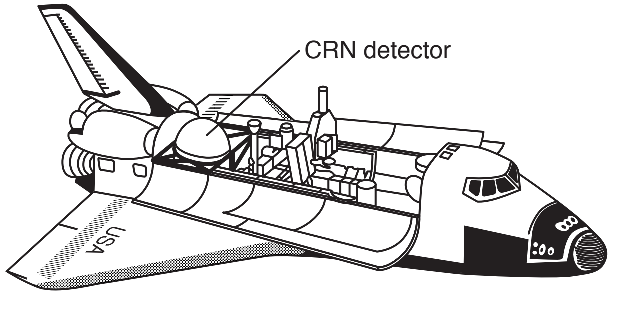
Astroparticle Physics

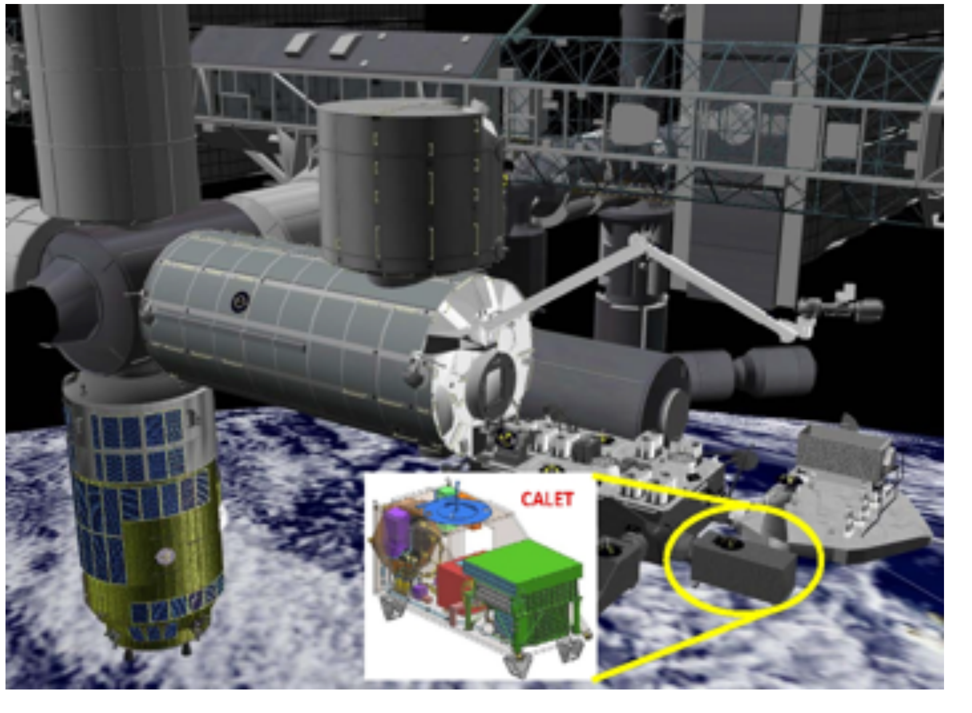
messengers from the Universe



Detectors for direct measurements of Cosmic Rays above the atmosphere

•Silicon detector	IZI, A, E	isotopes
•Magnet spectrometer	+/- Z, E	anti-particles
•Calorimeter	IZI, E	elements
•Cherencov detector	IZI, E	elements
•Transition radiation detector	IZI, E	elements





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

most important properties:

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

1. **energy spectra are power laws**
   --> non-thermal origin $\left(\frac{dN}{dE} \propto e^{-\kappa E}\right)$

2. **below ~10 GV energy spectra deviate from power laws**
   --> solar modulation, charged particles of extra-solar origin (galactic origin) drift against the solar wind towards Earth/solar system

   magnetic rigidity $R = \dfrac{p \cdot c}{Z \cdot e}$

3. **in first approximation all elements exhibit about the same slope**
   spectral index $\gamma \approx -2.7$

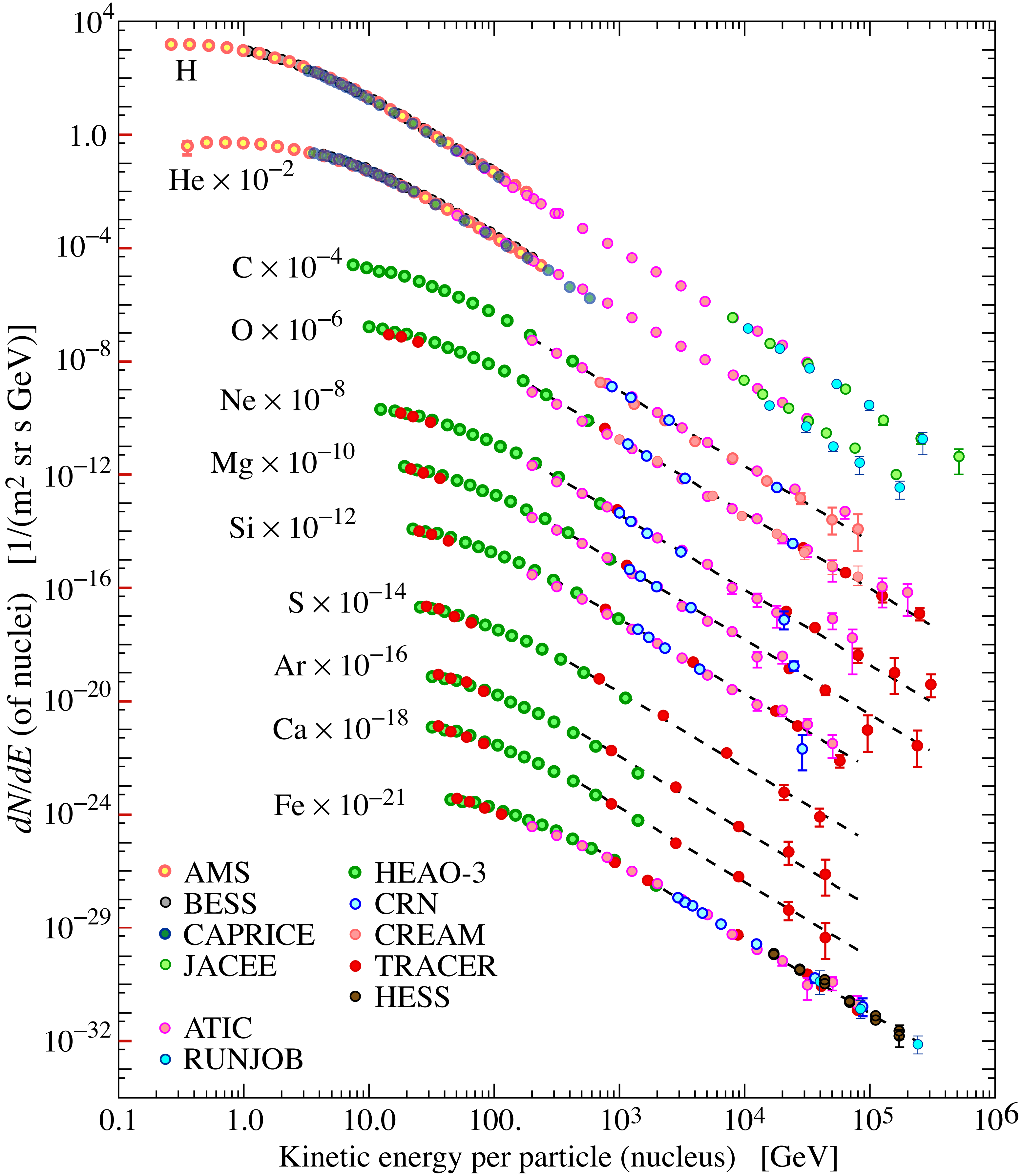
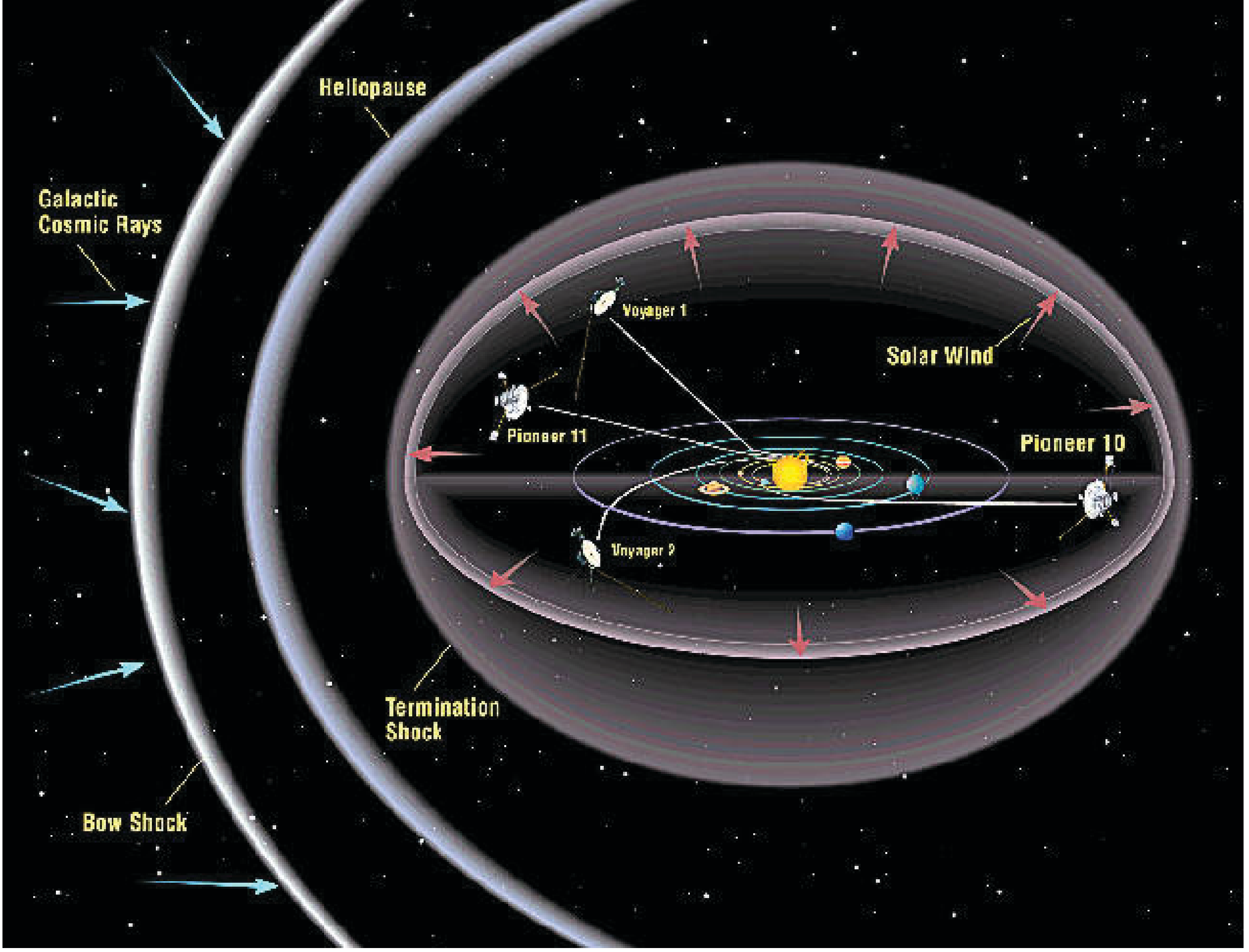
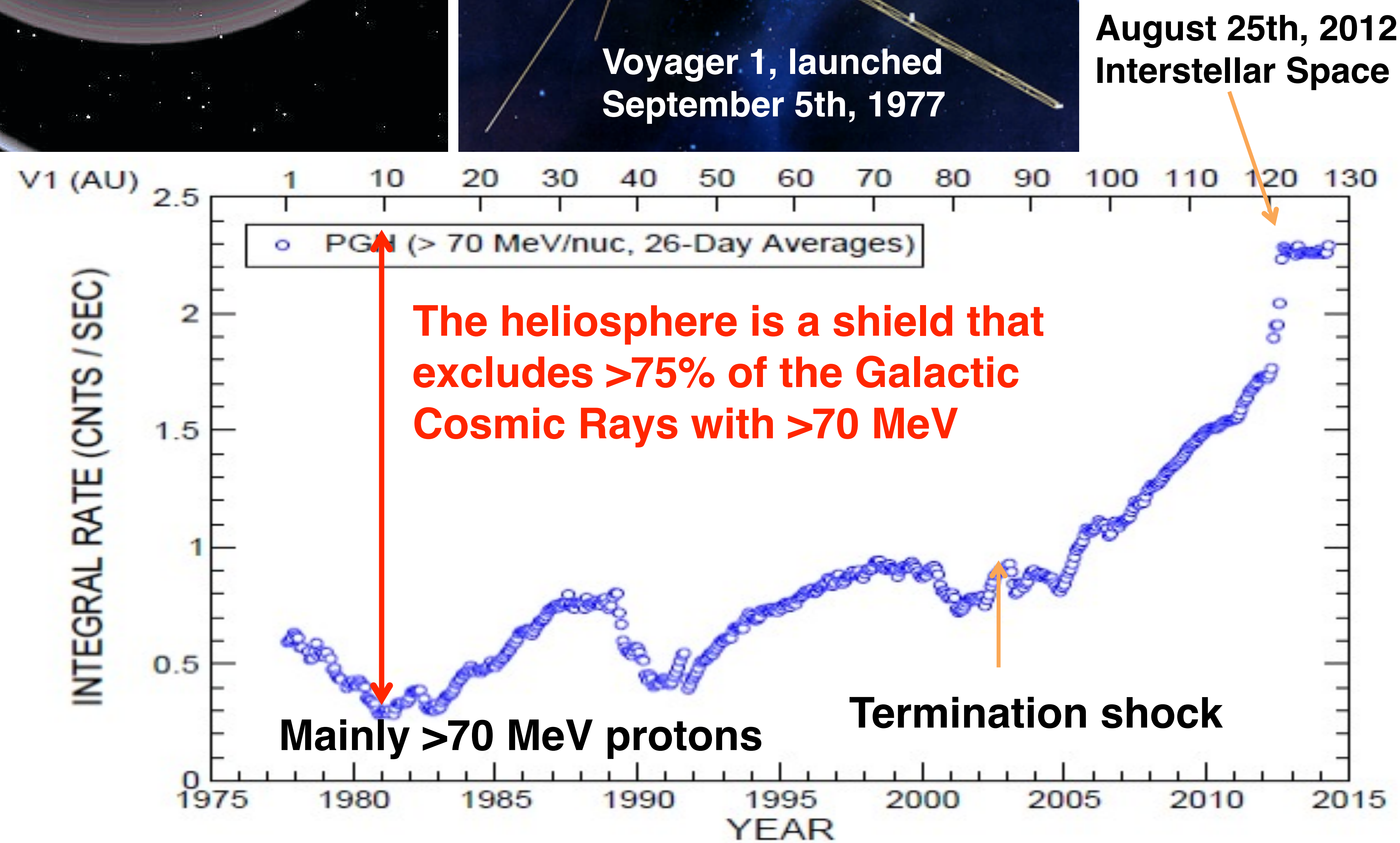


Figure 24.1: Major components of the primary cosmic radiation from Refs. [1–12
The figure was created by P. Boyle and D. Muller. Color version at end of book.

Galactic Cosmic Rays and the Heliosphere





Proceedings of ICRC 2001: 3769 © Copernicus Gesellschaft 2001

ICRC 2001

Solar Modulation of Cosmic Rays

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

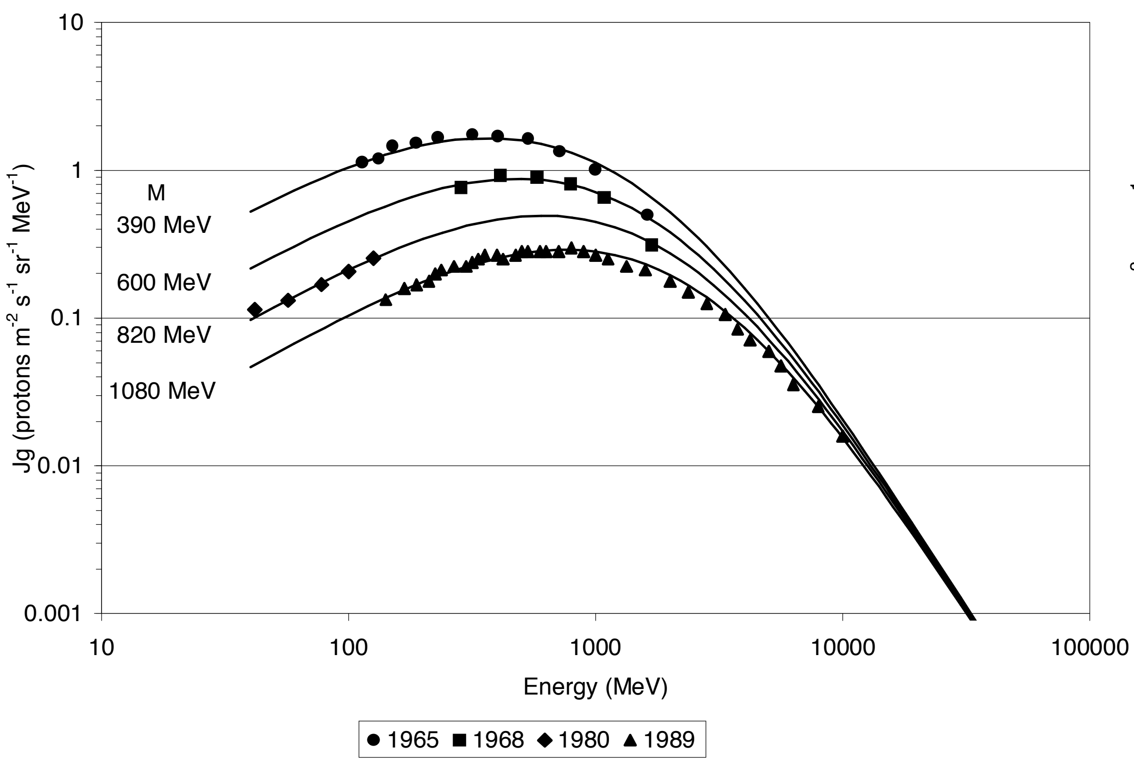
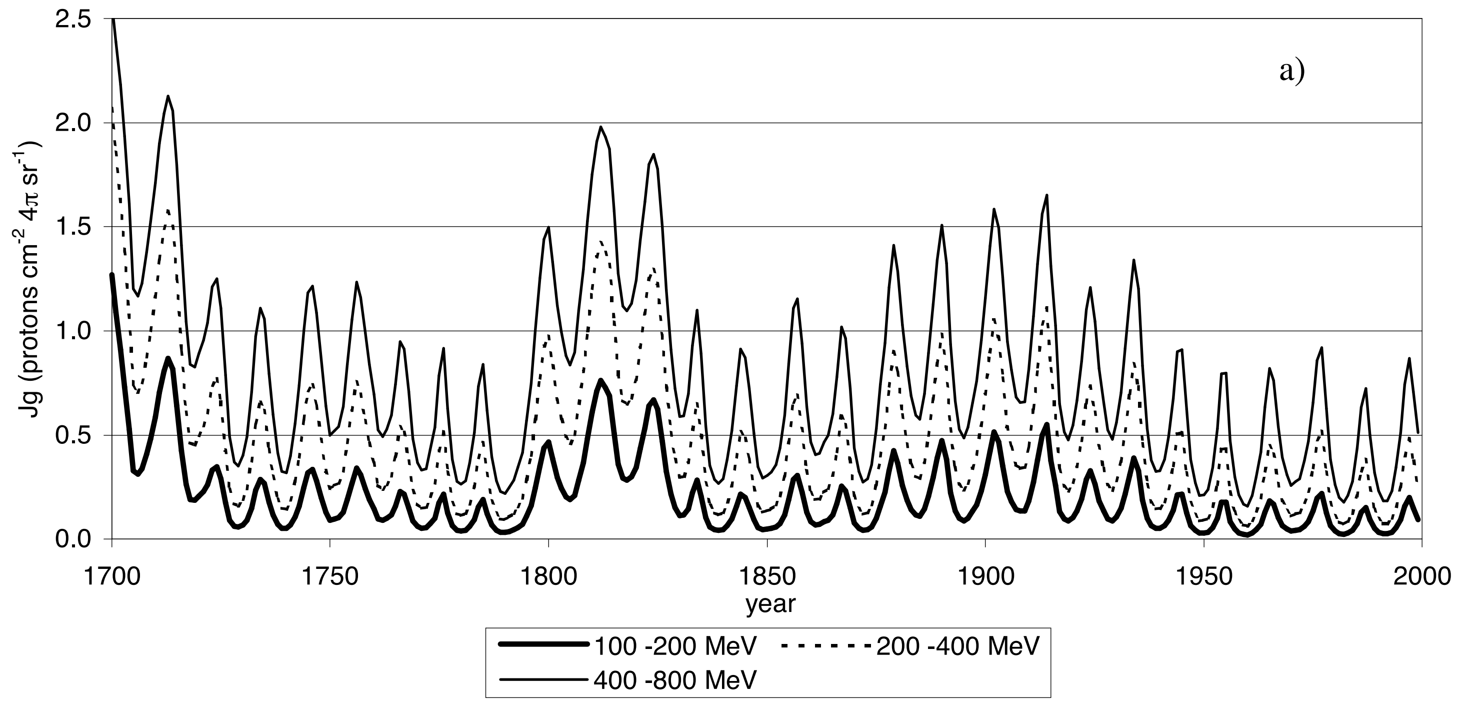


Fig. 1. Differential cosmic-ray spectra obtained from Eq. (1) for different values of the solar modulation parameter M = 390, 600, 820, 1080 MeV corresponding to the measurements performed with balloons or spacecrafts during 1965, 1968, 1980 and 1989 respectively.



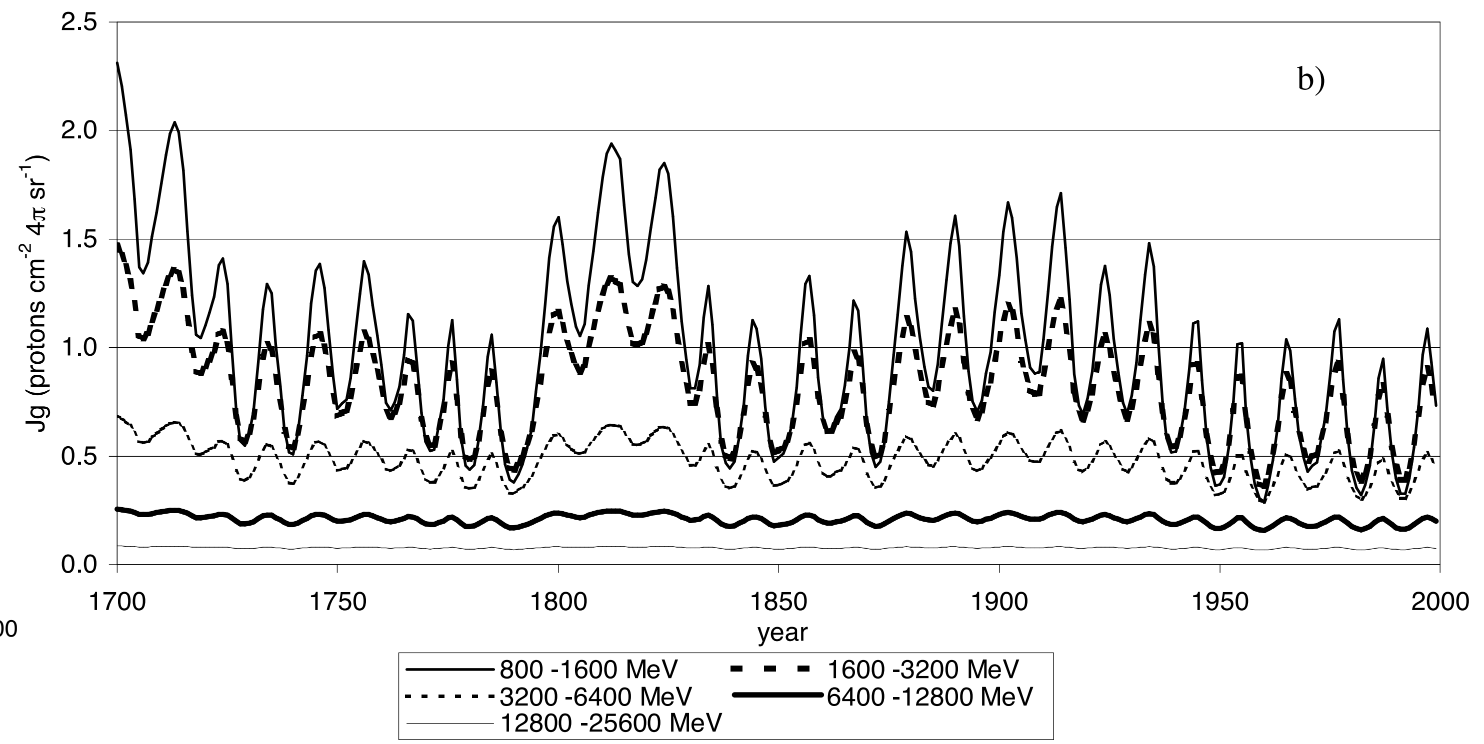
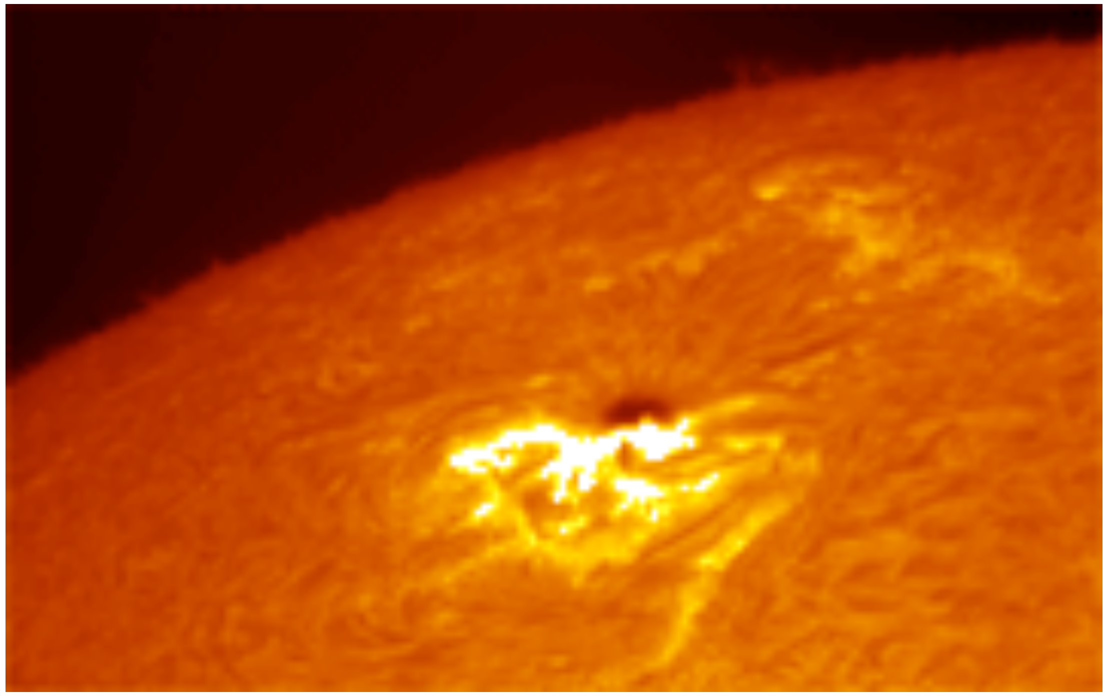
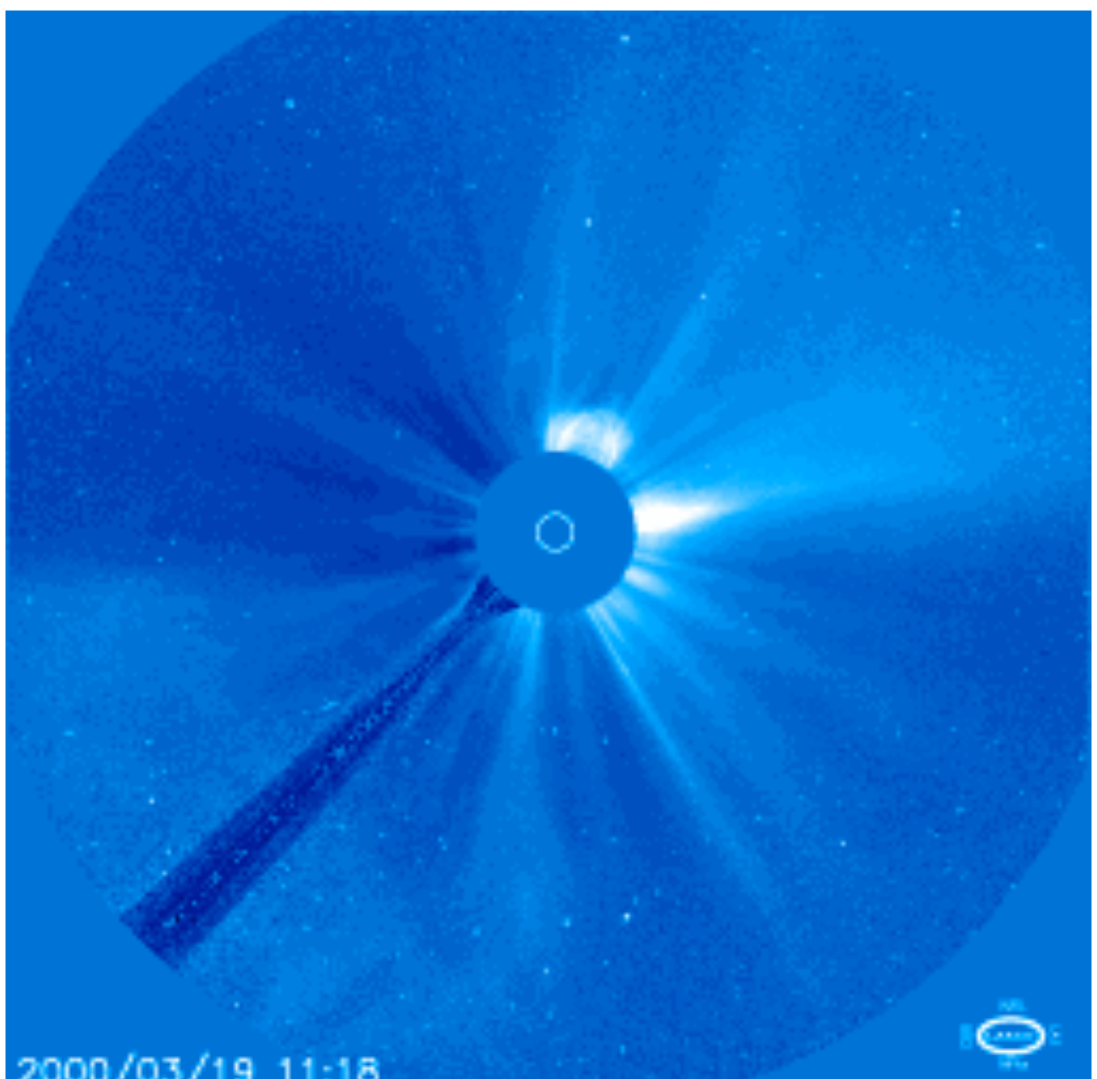
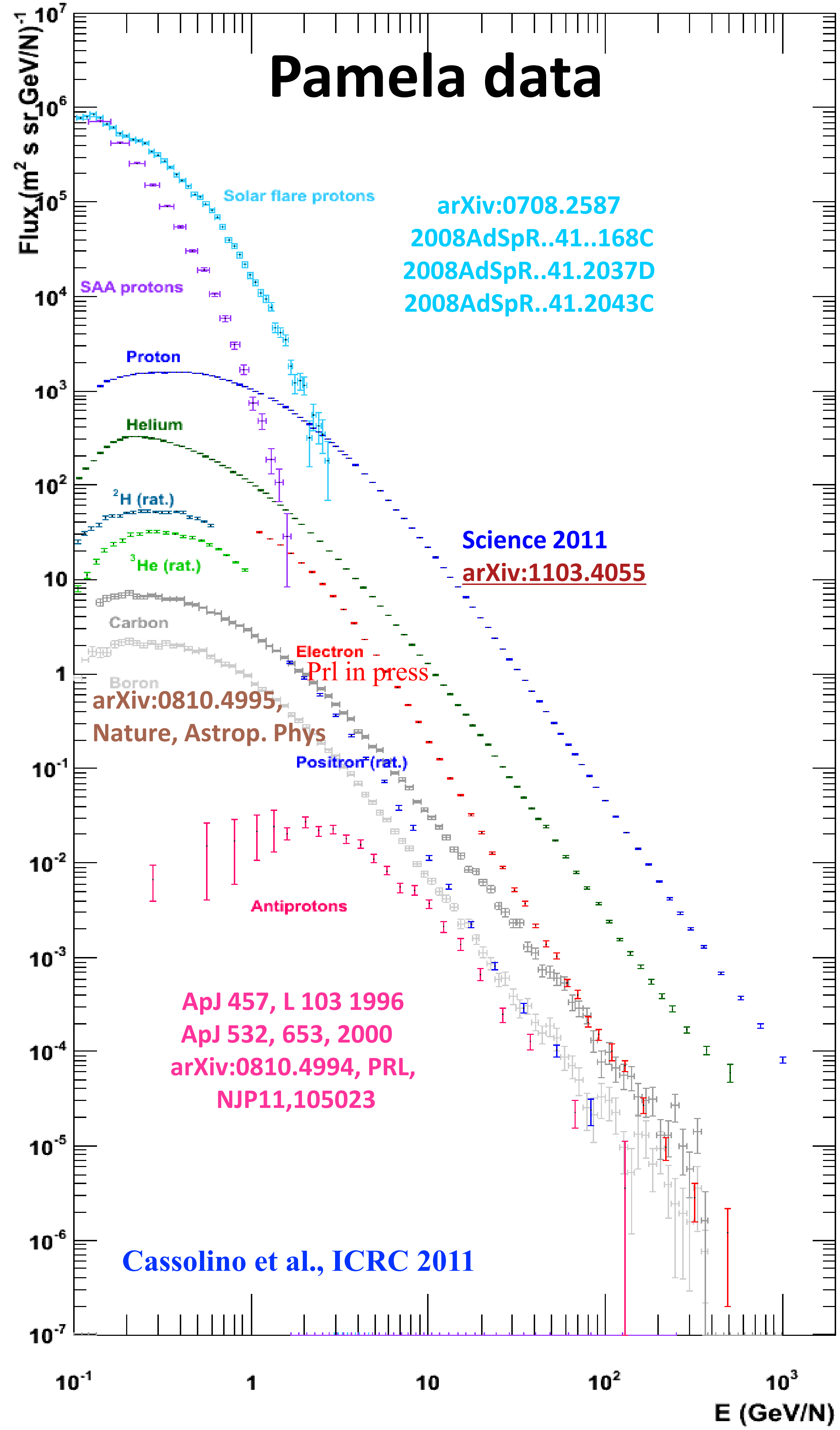


Fig. 2. Proton flux $J_G(t)$: a) for the kinetic energy intervals ΔT = 100-200 MeV, 200-400 MeV, 400-800 MeV; b) for ΔT = 800-1600 MeV, 1600-3200 MeV, 3200-6400 MeV, 6400-12800 MeV, 12800-25600 MeV.

Solar flares

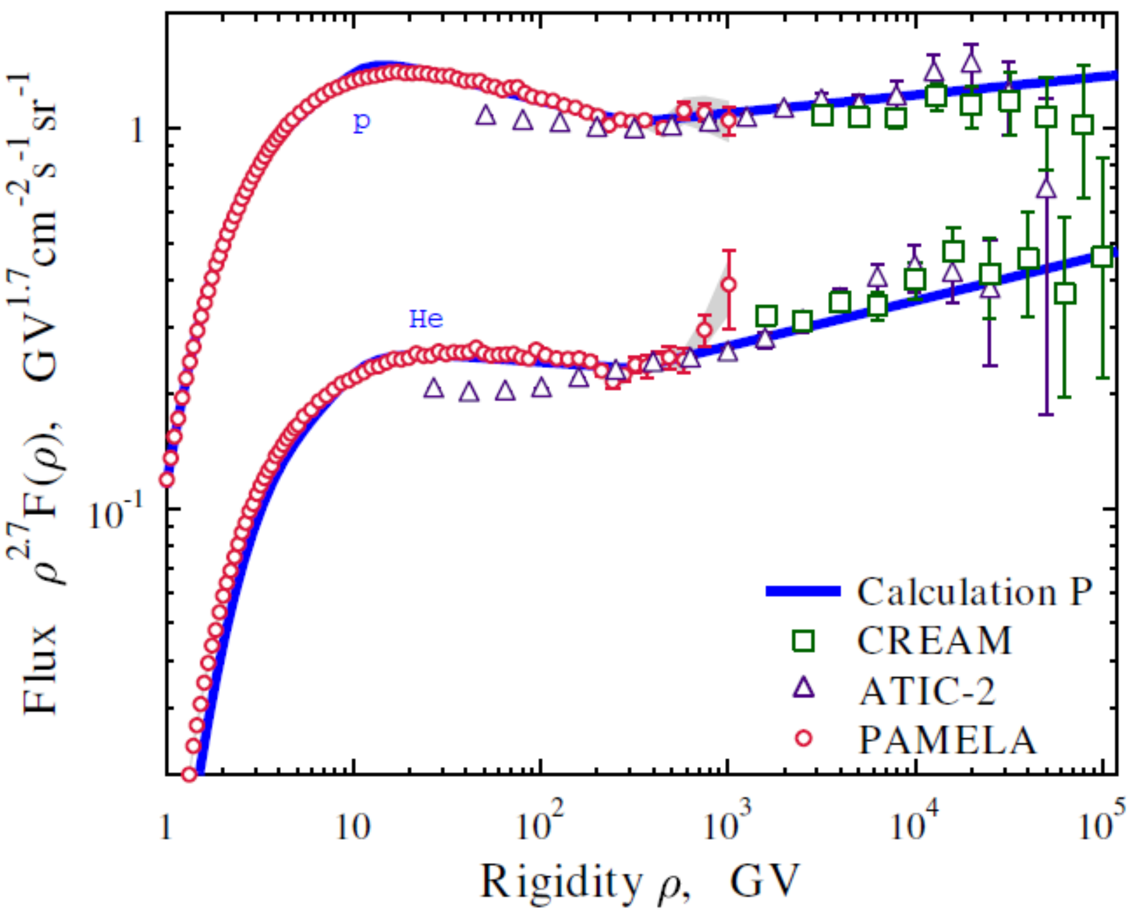






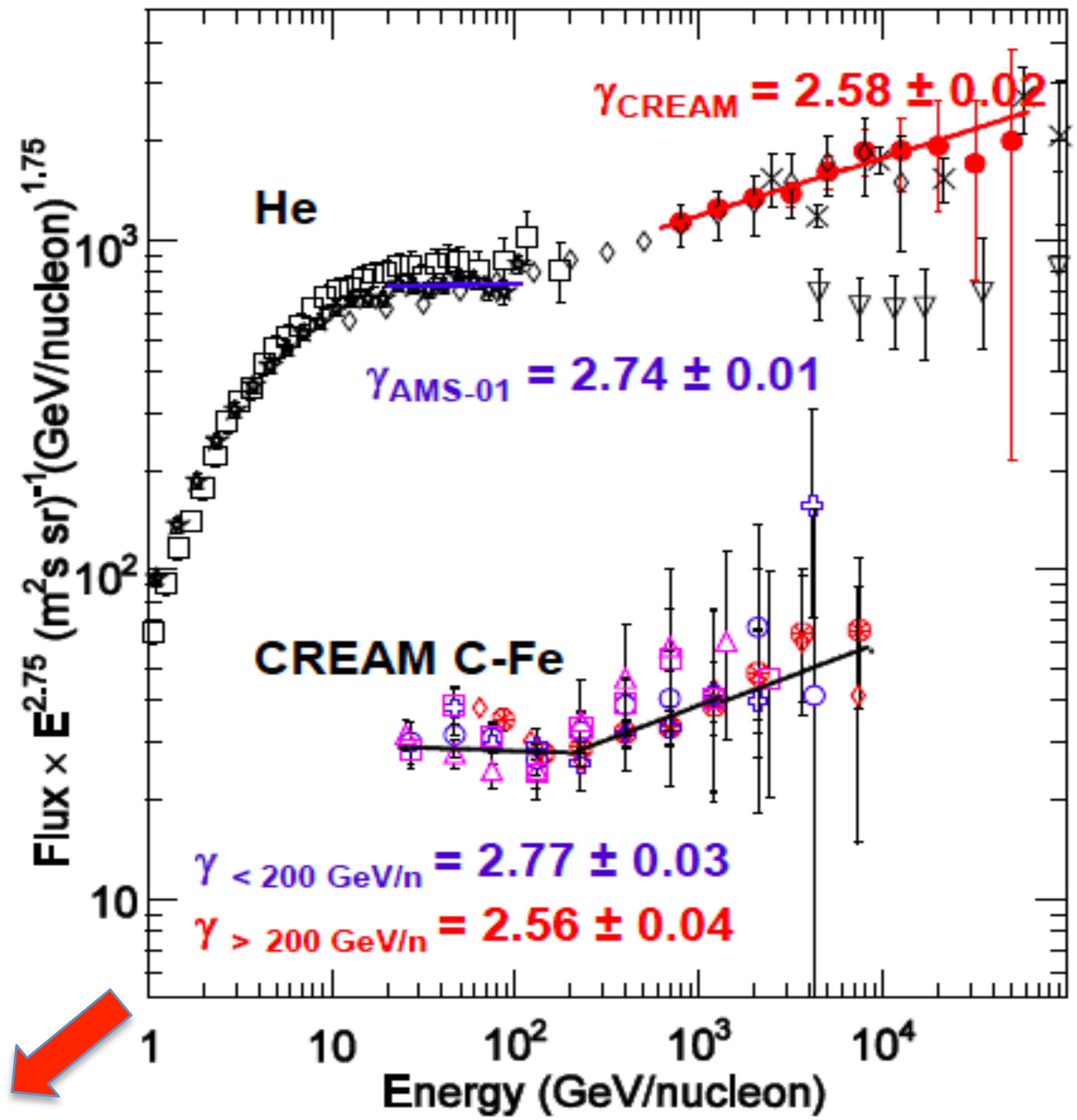
Direct measurements of proton and He spectra

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



<u>A single power-law seems inadequate to fit the spectra</u>

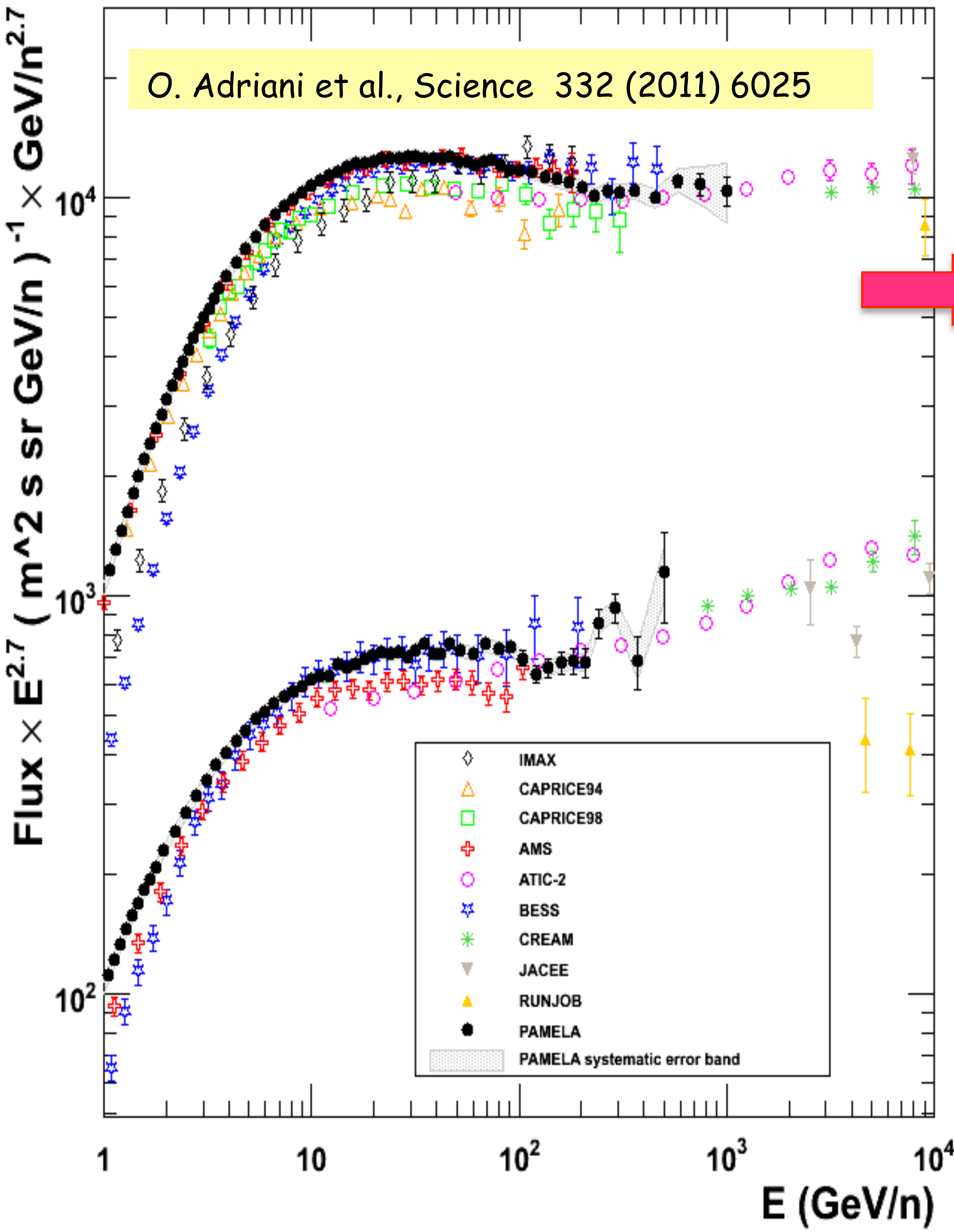
- The break also appears in the spectra of NUCLEI measured by CREAM up to several TeV/n



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

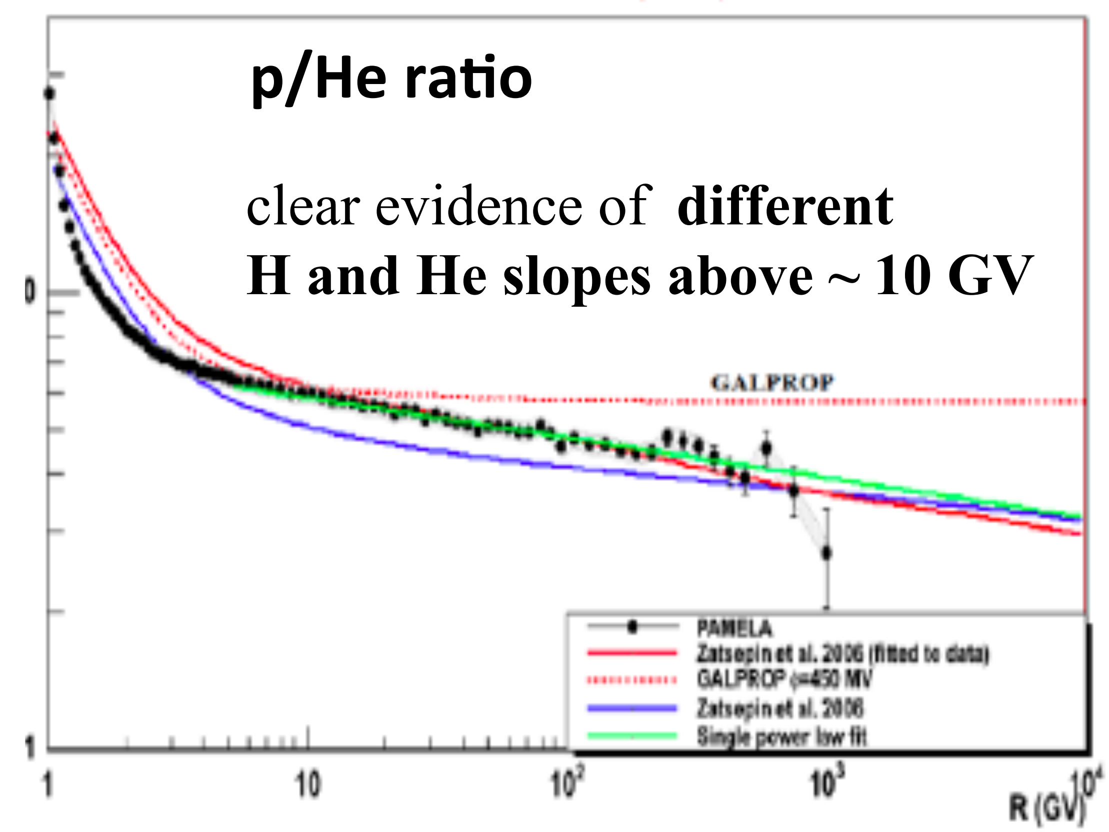
Ahn et al. ApJ 714, L89, 2010
Yoon et al. ApJ **728**, *122*, 2011

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 $\Delta\gamma$~0.2÷0.3

  Single power-law rejected at 98% CL

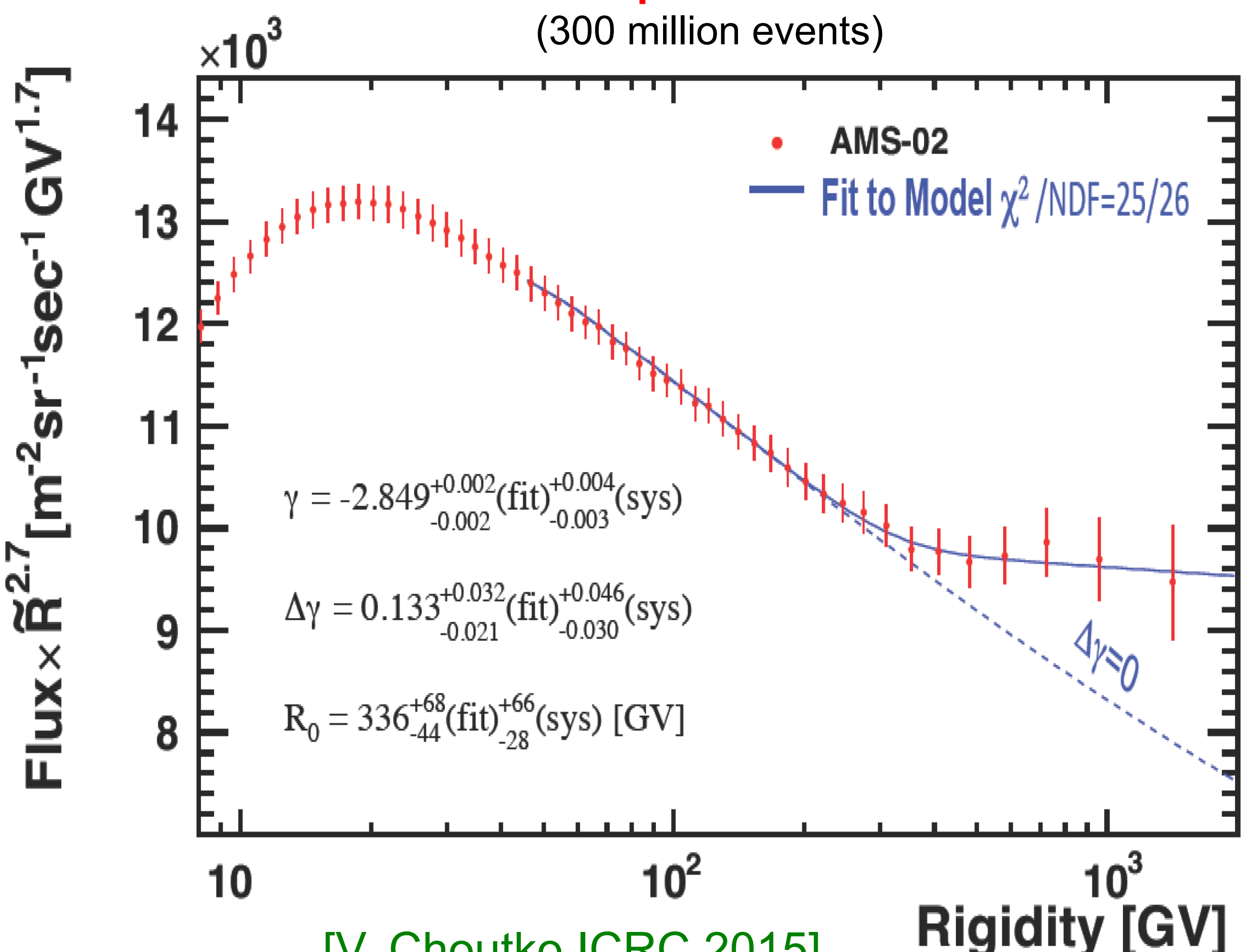


Proton and He fluxes measured by AMS-02

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:

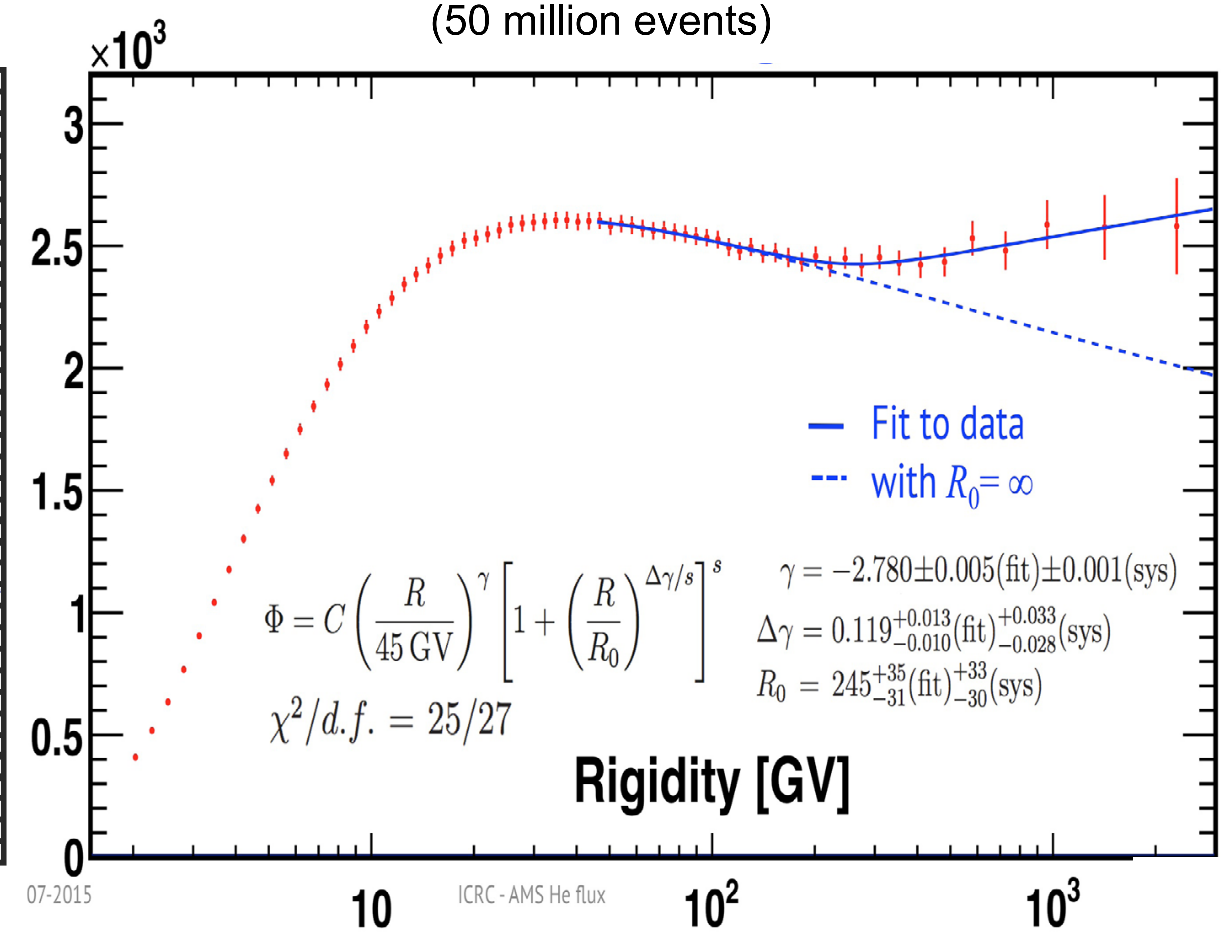
$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux
(300 million events)



[V. Choutko ICRC 2015]

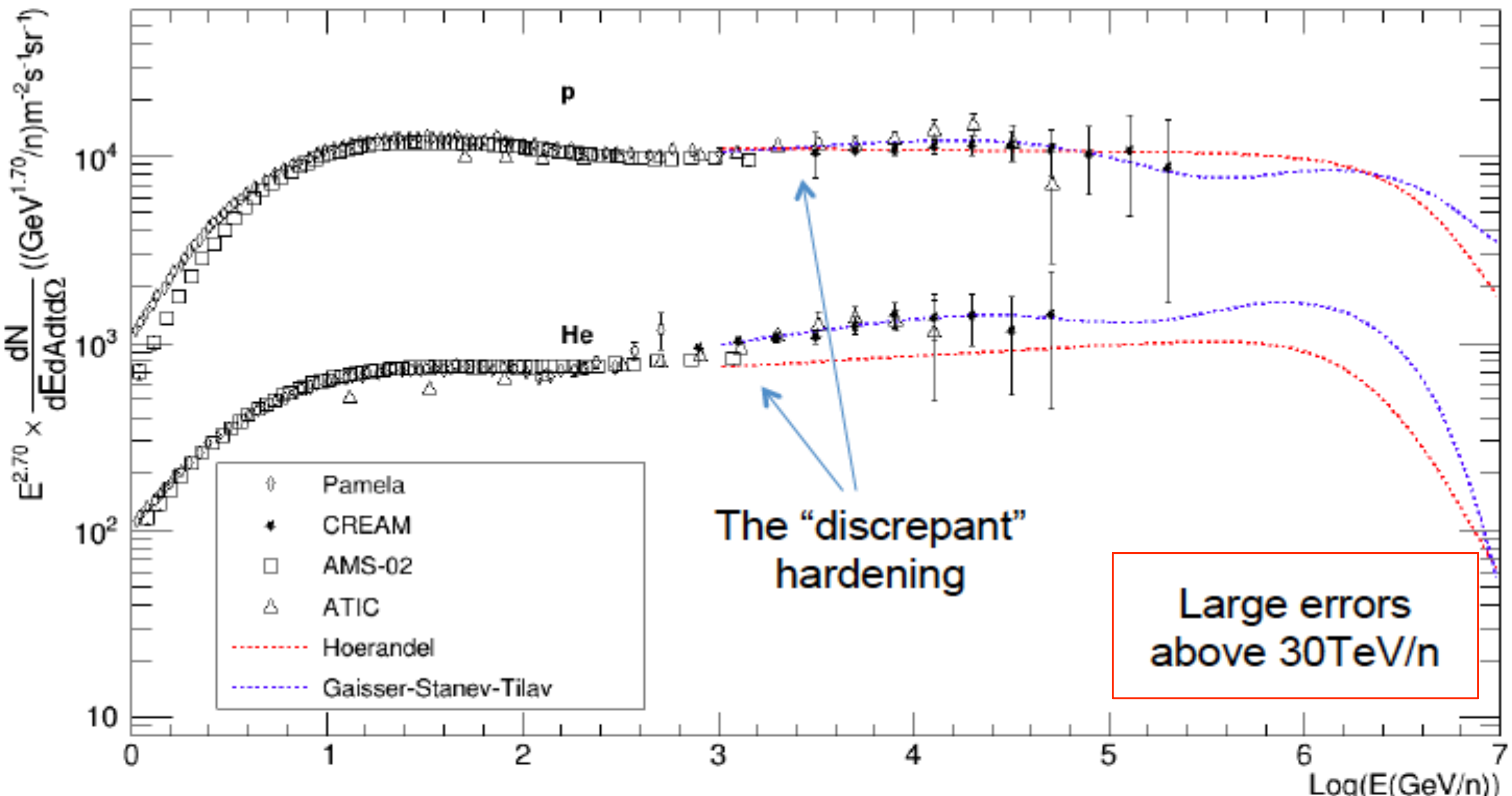
AMS He flux
(50 million events)



[S. Haino ICRC 2015]

Proton and Helium:

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

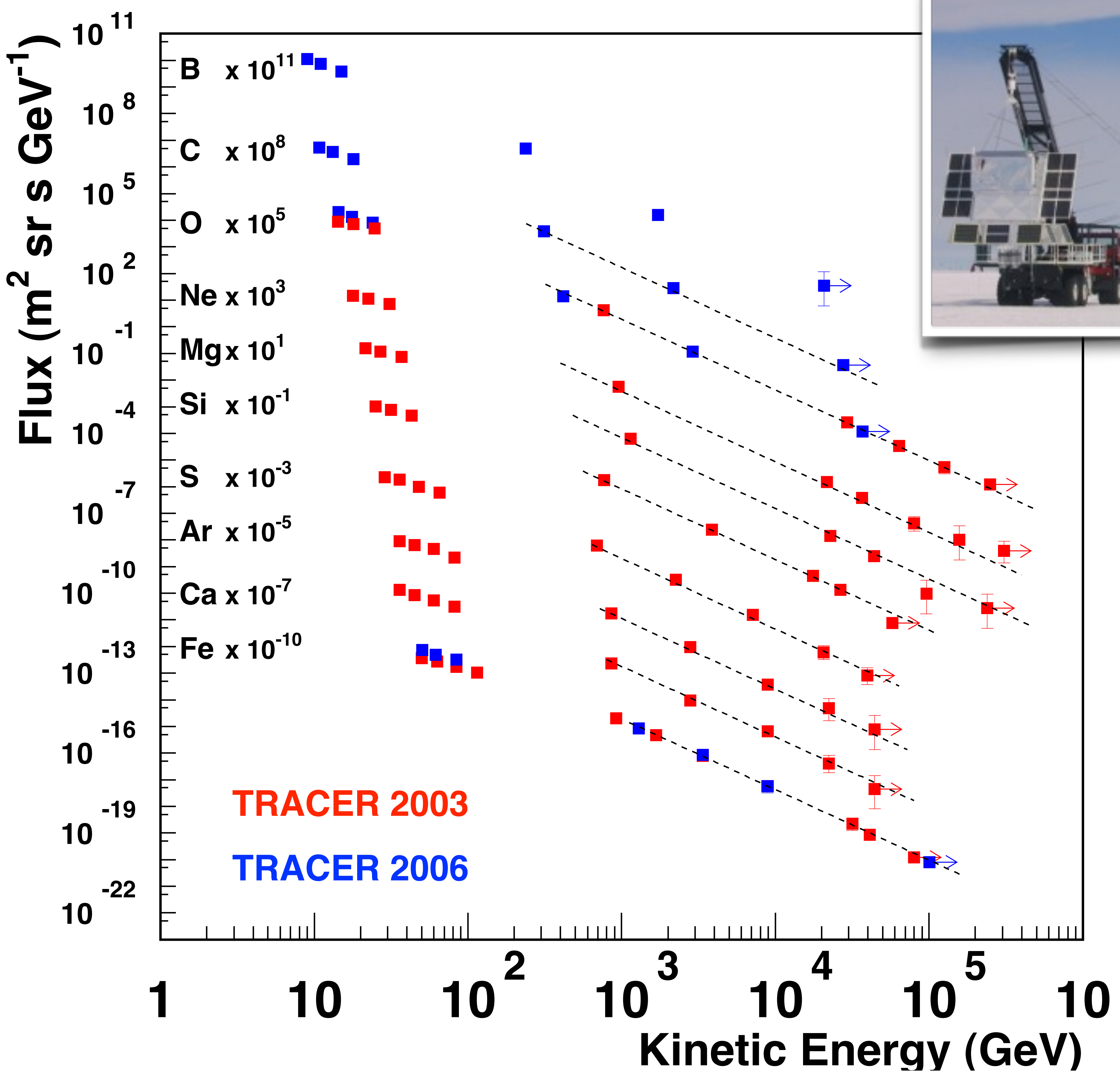


fitted slope of p, He spectra above 230 GV

	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

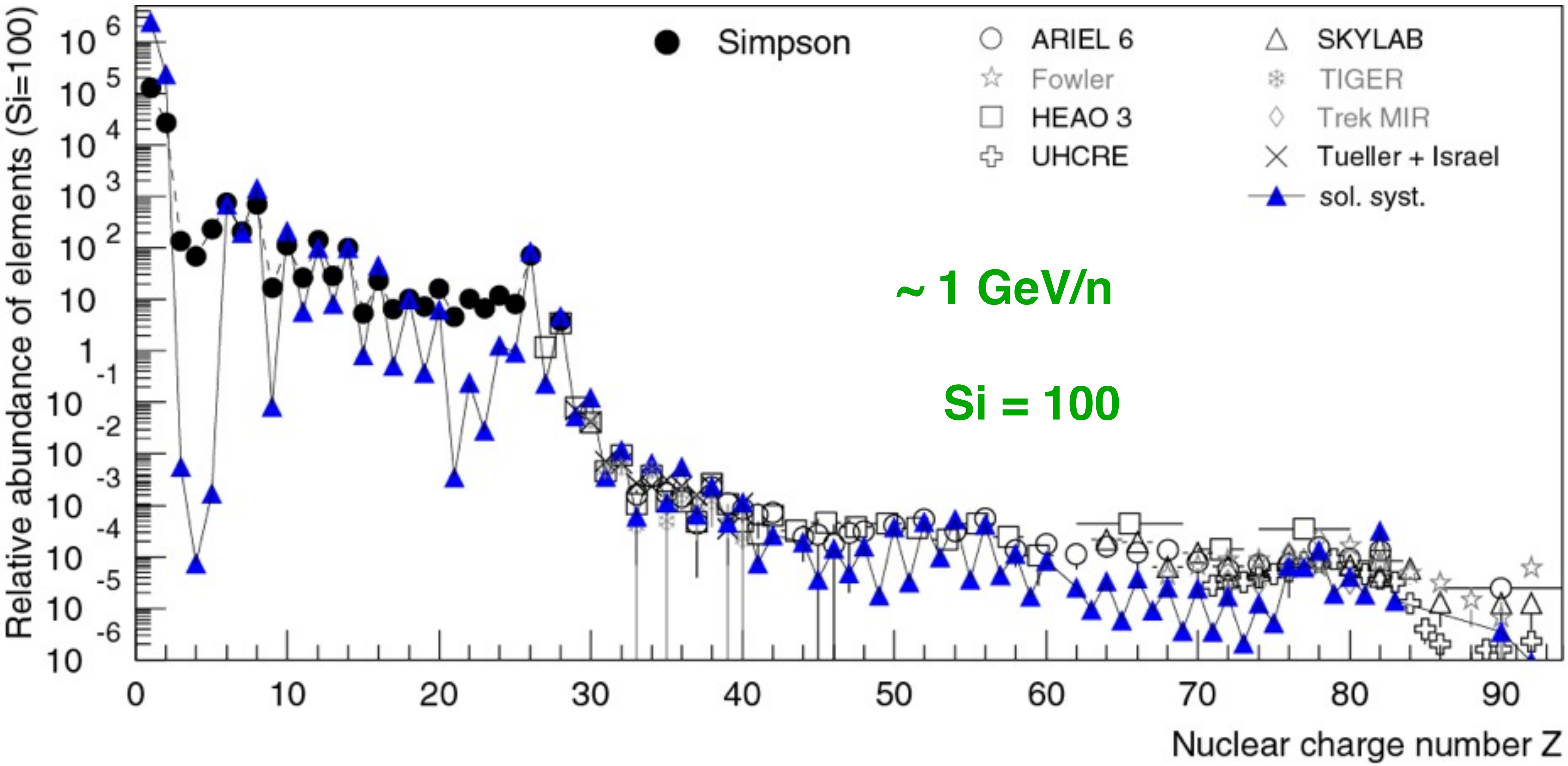
TRACER: Energy spectra for individual elements



P. Boyle et al., ICRC 2011

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

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

$\left.\begin{array}{l}\text{~89\% p} \\ \text{9\% He} \\ \text{1\% heavy nuclei}\end{array}\right\}$ ~1 GeV/n

~1% electrons/positrons
<0.1% gamma rays

some remarks:

1. even-odd effect
   --> due to high binding energy of ee-nuclei

2. elements Li, Be, B are more abundant in CRs than in solar system
   --> propagation in Galaxy

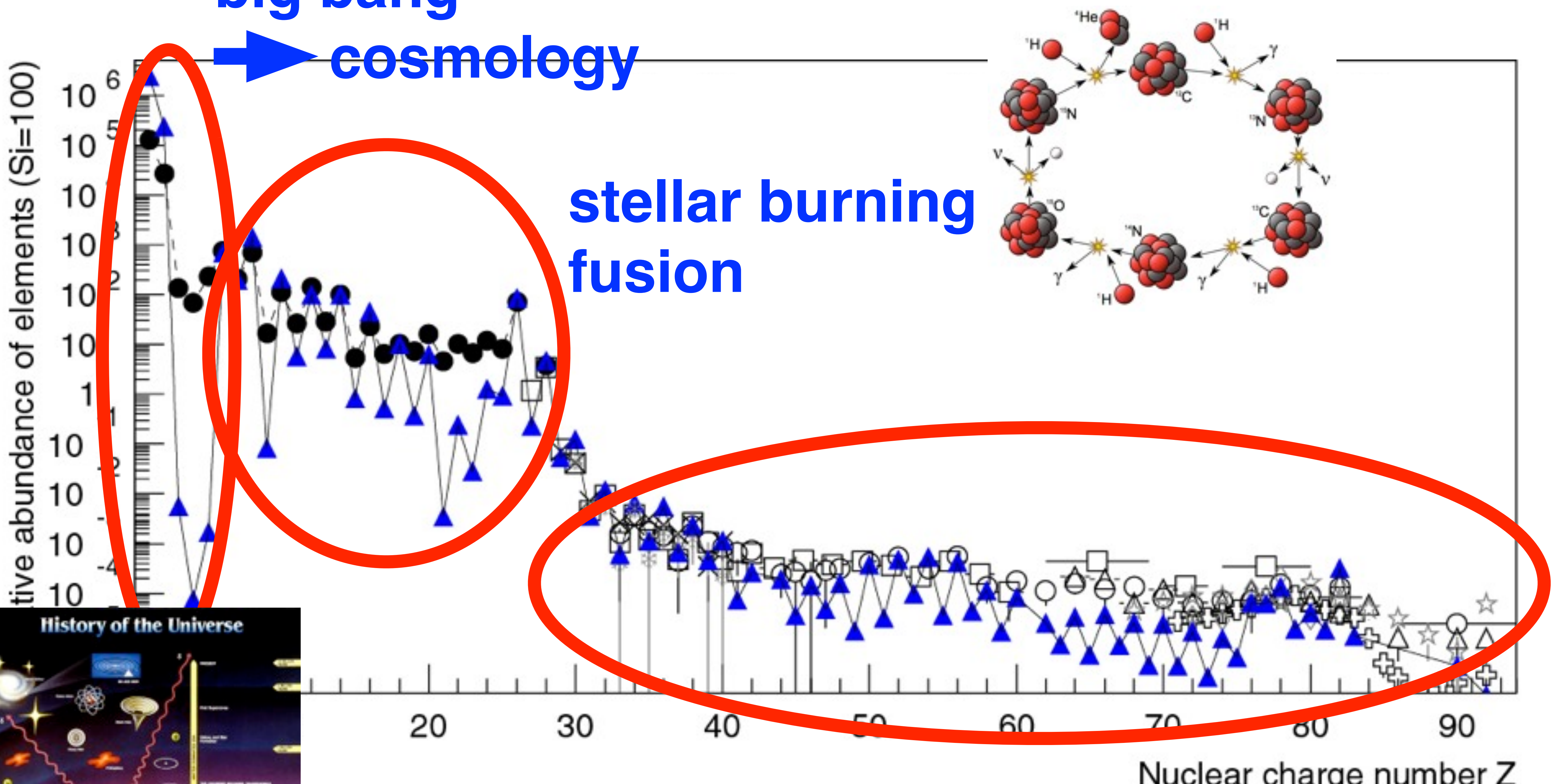
3. same effect for sub-Fe elements (~Ca - Fe)

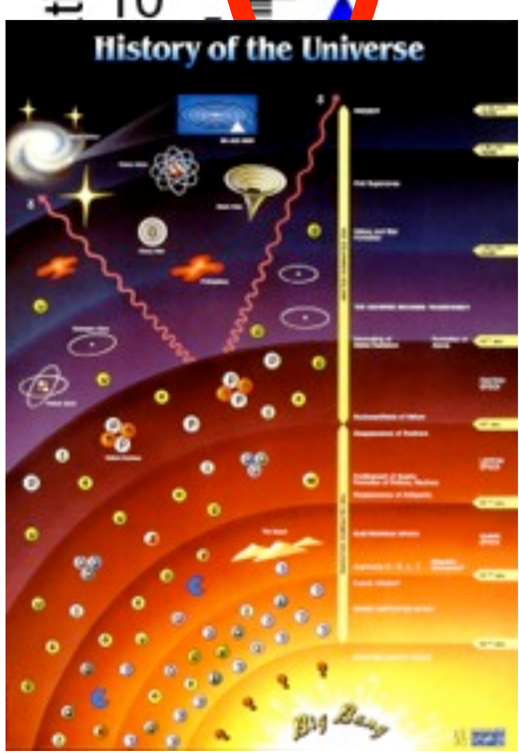
4. p + He are less abundant in CRs as compared to solar system

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

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

--> total energy flux $n_{CR} = I_{CR} \cdot \langle \epsilon_{CR} \rangle \left[\frac{eV}{\mathrm{m}^2 \cdot \mathrm{s}} \right]$

--> total energy density

$$\epsilon_{CR} = I_{CR} \frac{\langle \epsilon_{CR} \rangle}{\langle v_{CR} \rangle} \left[\frac{\mathrm{eV}}{\mathrm{cm}^3} \right]$$

~1 eV/cm³ energy density of cosmic rays (in Galaxy)

comparable with e.g.:

energy density of visible star light $\epsilon_{st} \approx 0.3 \frac{\mathrm{eV}}{\mathrm{cm}^3}$

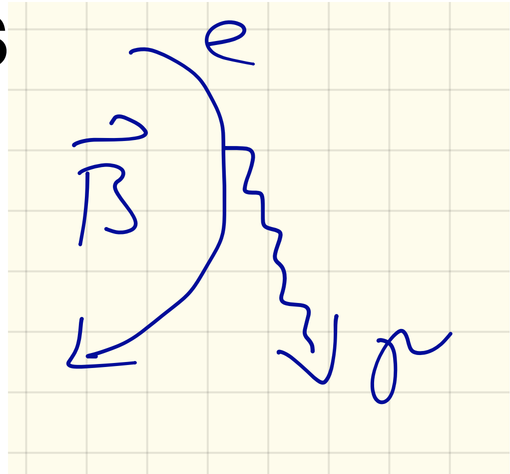
energy density of B-field in Galaxy

$B = 3\ \mu\mathrm{G}$ $\quad \epsilon_B = \frac{B^2}{2\,\mu_0\,\mu_r} = 0.22 \frac{\mathrm{eV}}{\mathrm{cm}^3}$

6.electrons(+positrons): ~1% of nuclear cosmic rays energy spectrum is steeper

$$\frac{dN}{dE} \propto E_e^{-3.3}$$

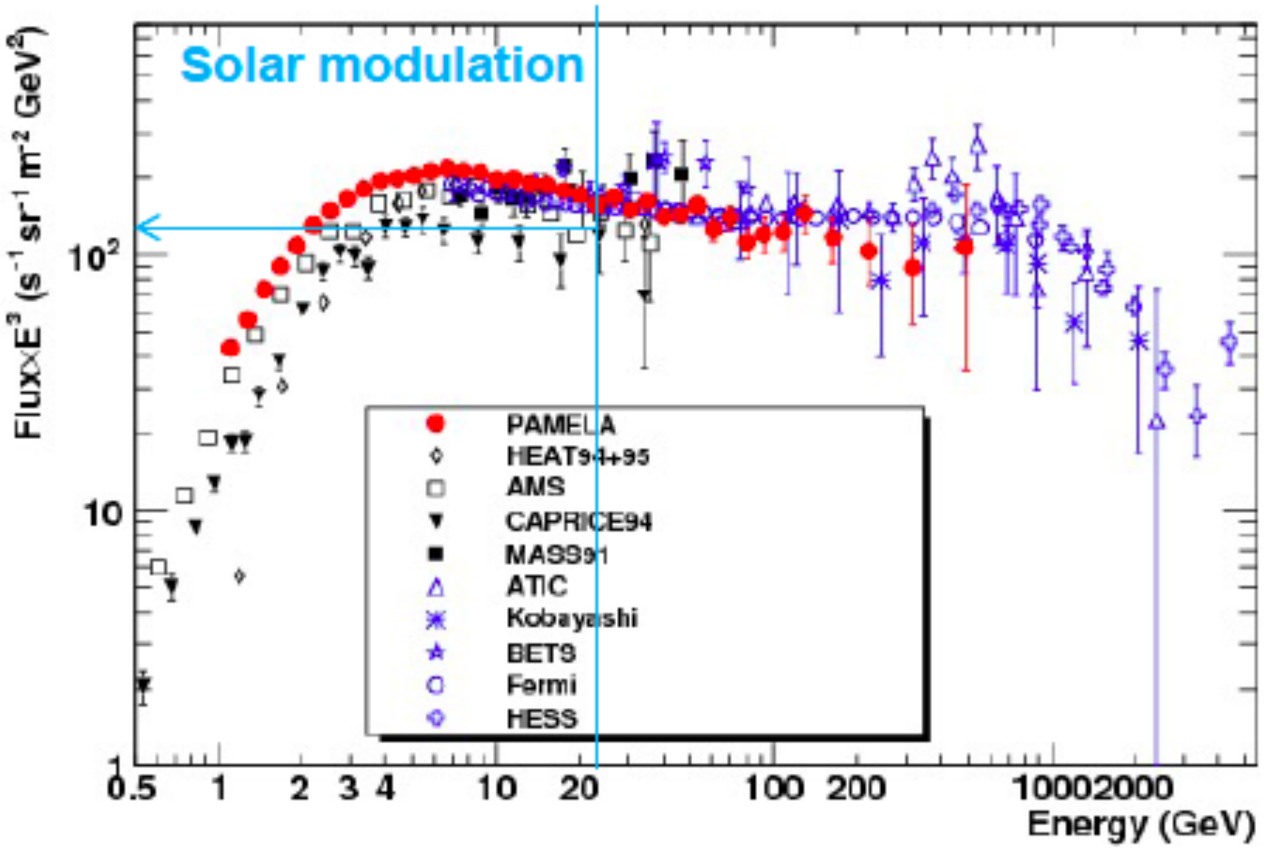
reason: losses through synchrotron radiation at high energies



$$-\left(\frac{dE}{dt}\right) = \frac{4}{3}\sigma_T \cdot c\frac{B^2}{2\mu_0}\left(\frac{v}{c}\right)^2\gamma^2$$

Longair II, 232

PAMELA Results: Electrons

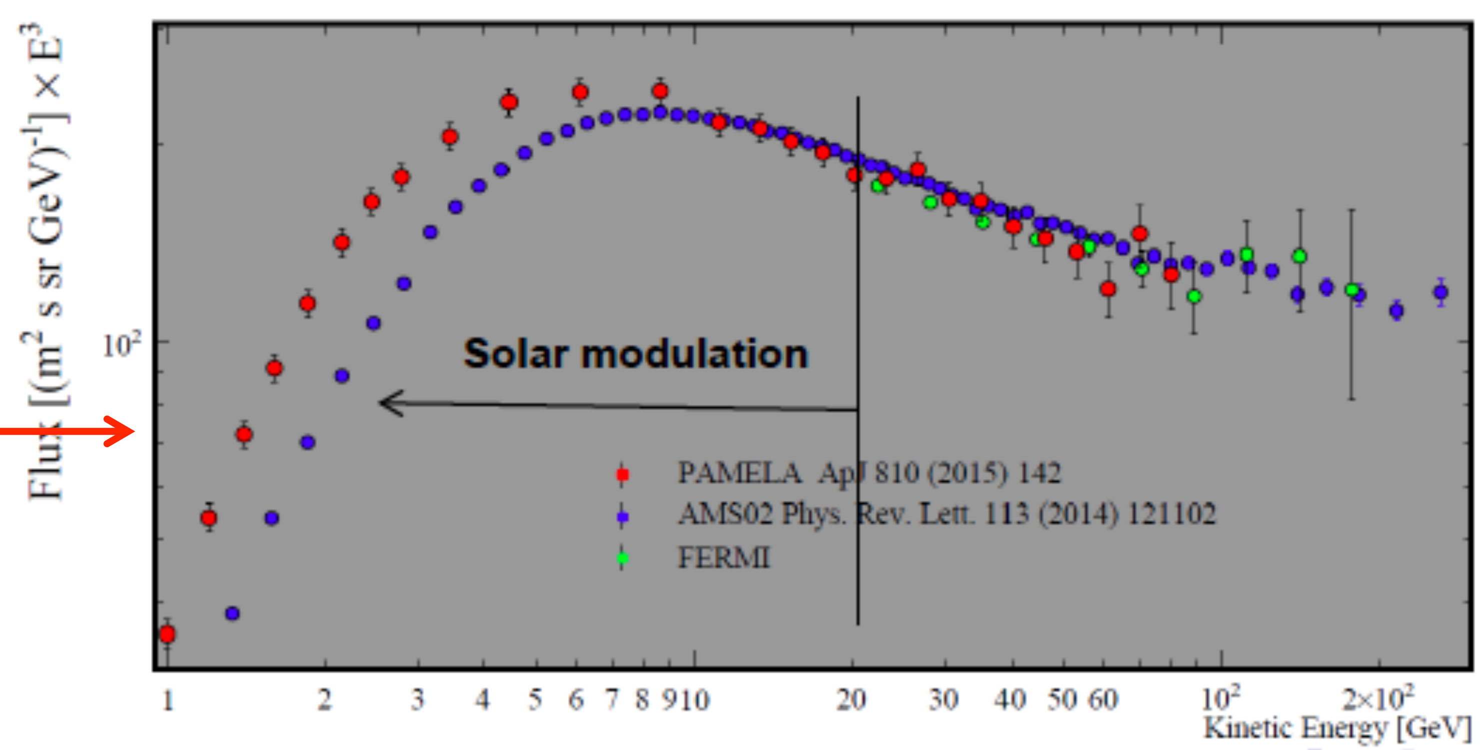


O. Adriani et al., PRL 106, 201101

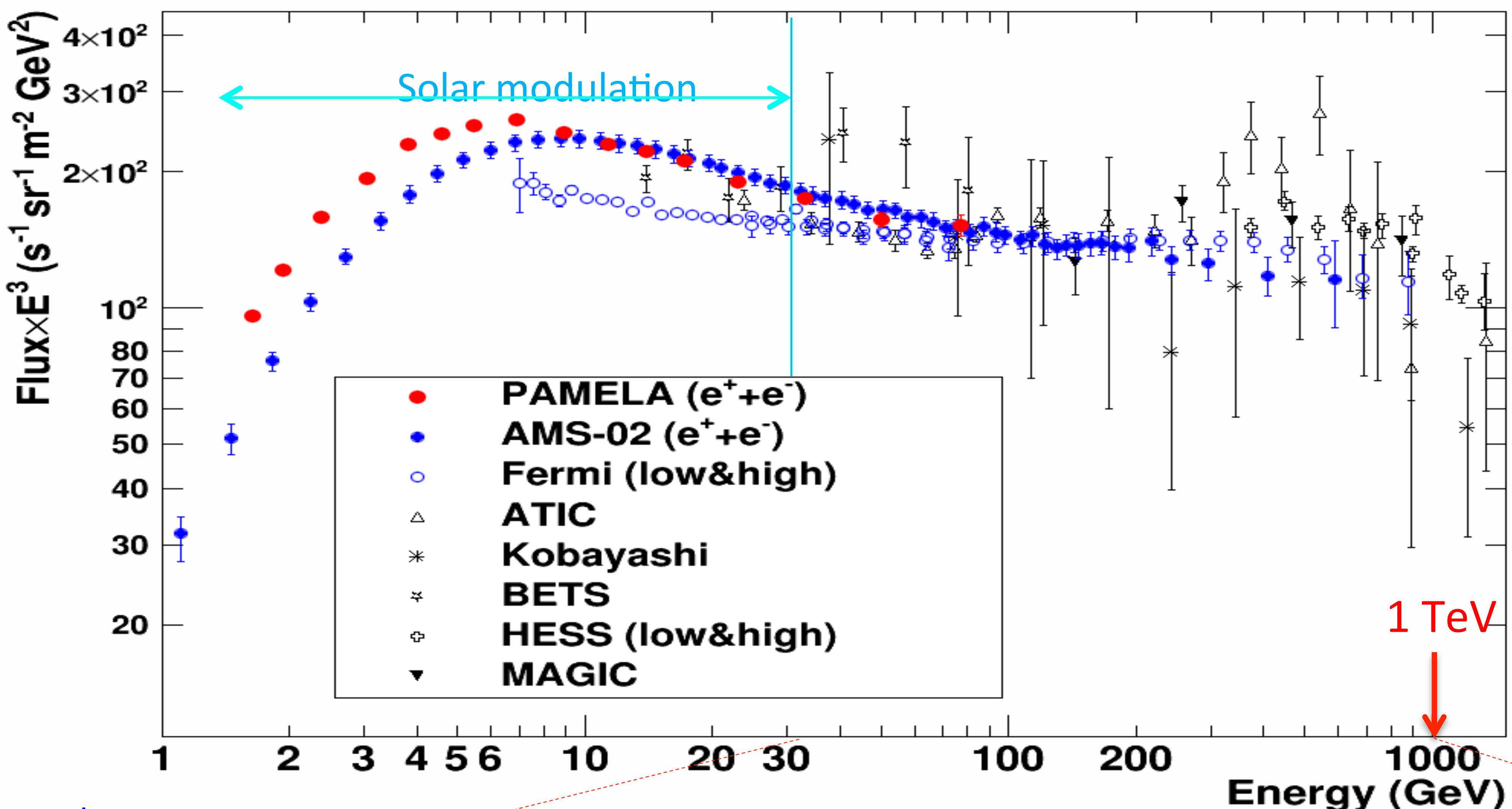
- PAMELA electron spectrum (published data to 625 GeV)
- AMS-02 electrons to 700 GeV

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)

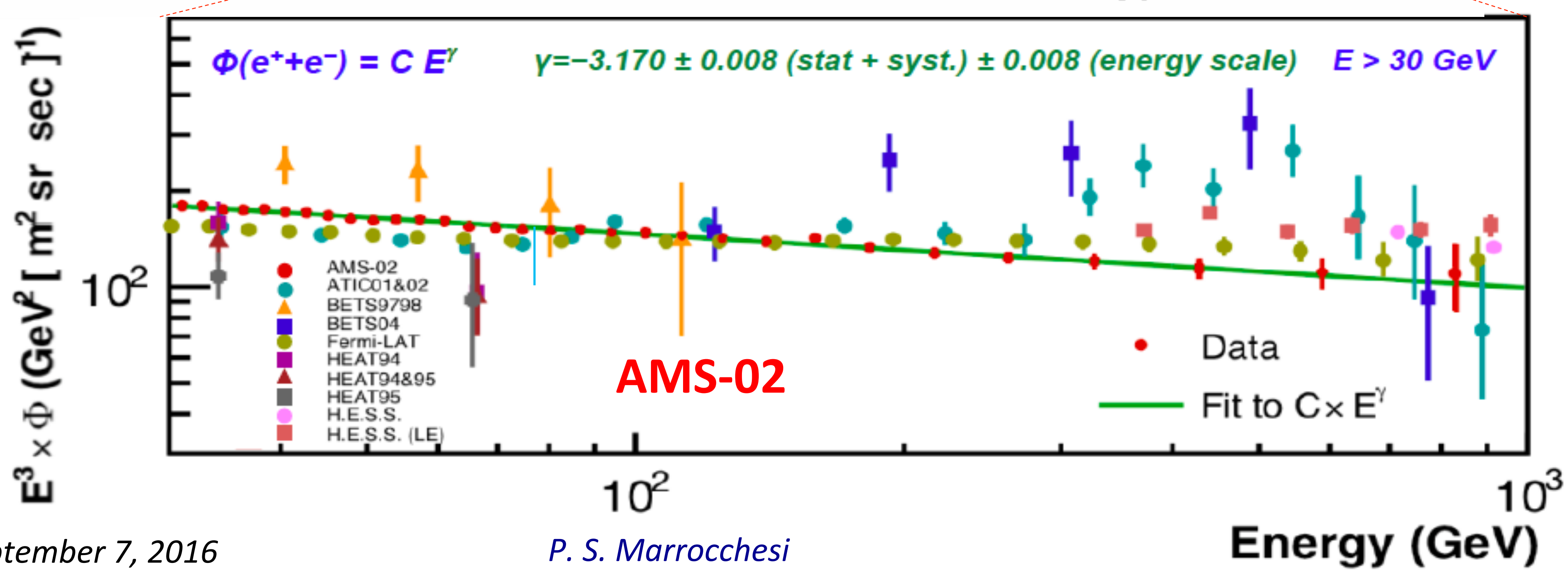


e^-+e^+ spectrum:

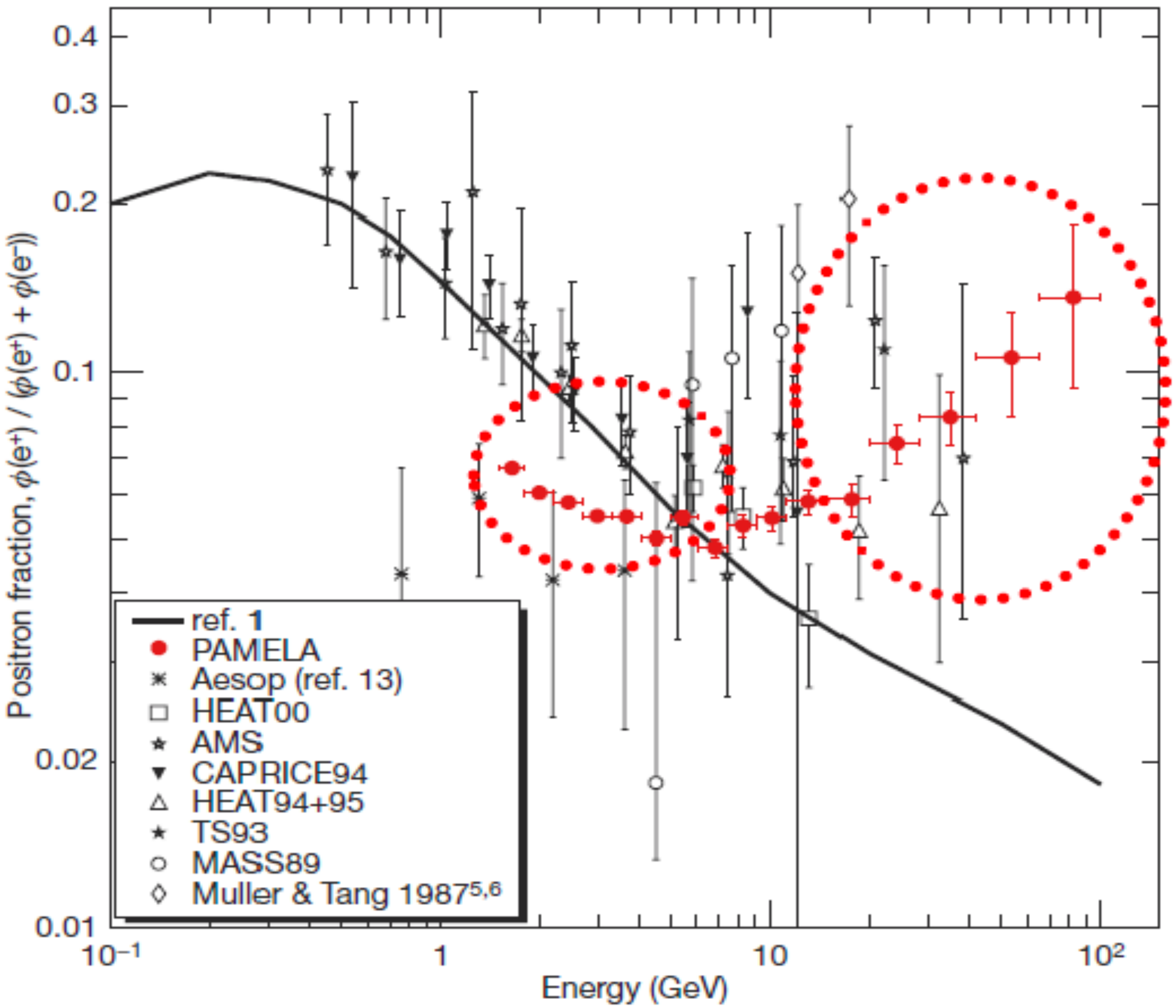
AMS-02 to 1 TeV

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

Vol 458 | 2 April 2009 | doi:10.1038/nature07942

August 2009

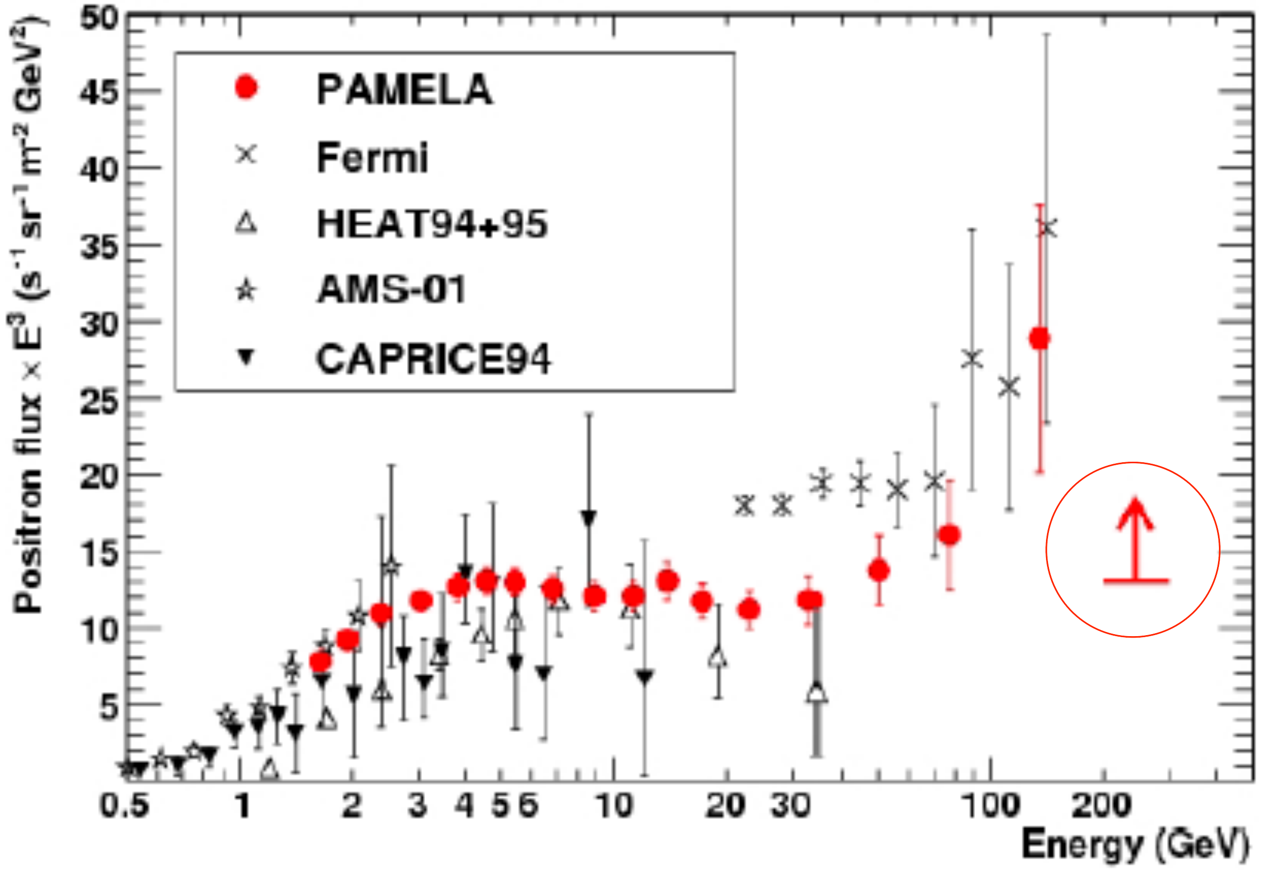
LETTERS

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

O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, M. P. De Pascale, G. De Rosa, N. De Simone, V. Di Felice, A. M. Galper, L. Grishantseva, P. Hofverberg, S. V. Koldashov, S. Y. Krutkov, A. N. Kvashnin, A. Leonov, V. Malvezzi, L. Marcelli, W. Menn, V. V. Mikhailov, E. Mocchiutti, S. Orsi, G. Osteria, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. Simon, R. Sparvoli, P. Spillantini, Y. I. Stozhkov, A. Vacchi, E. Vannuccini, G. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa & V. G. Zverov

Citations: 1338

PAMELA Results: Positrons



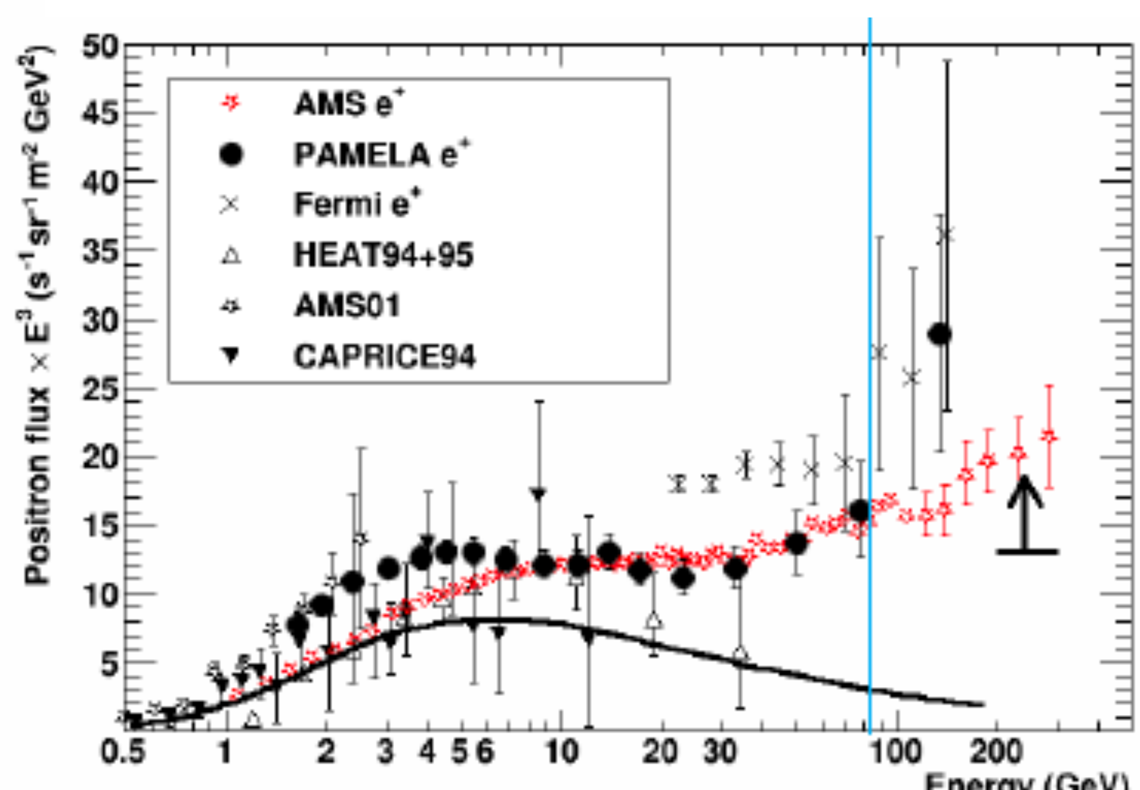
PHYSICAL REVIEW LETTERS

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

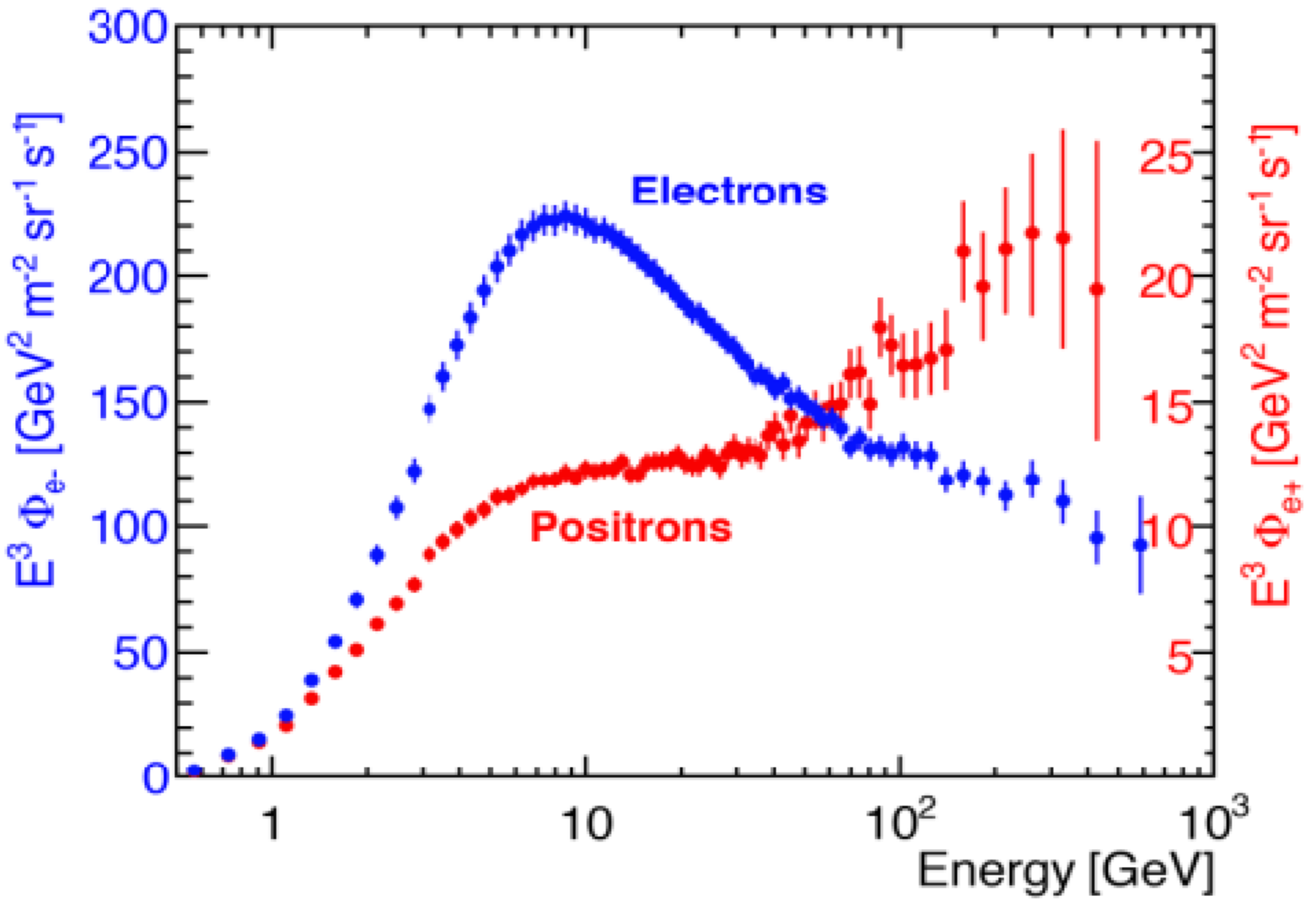
- PAMELA positron spectrum to 300 GeV

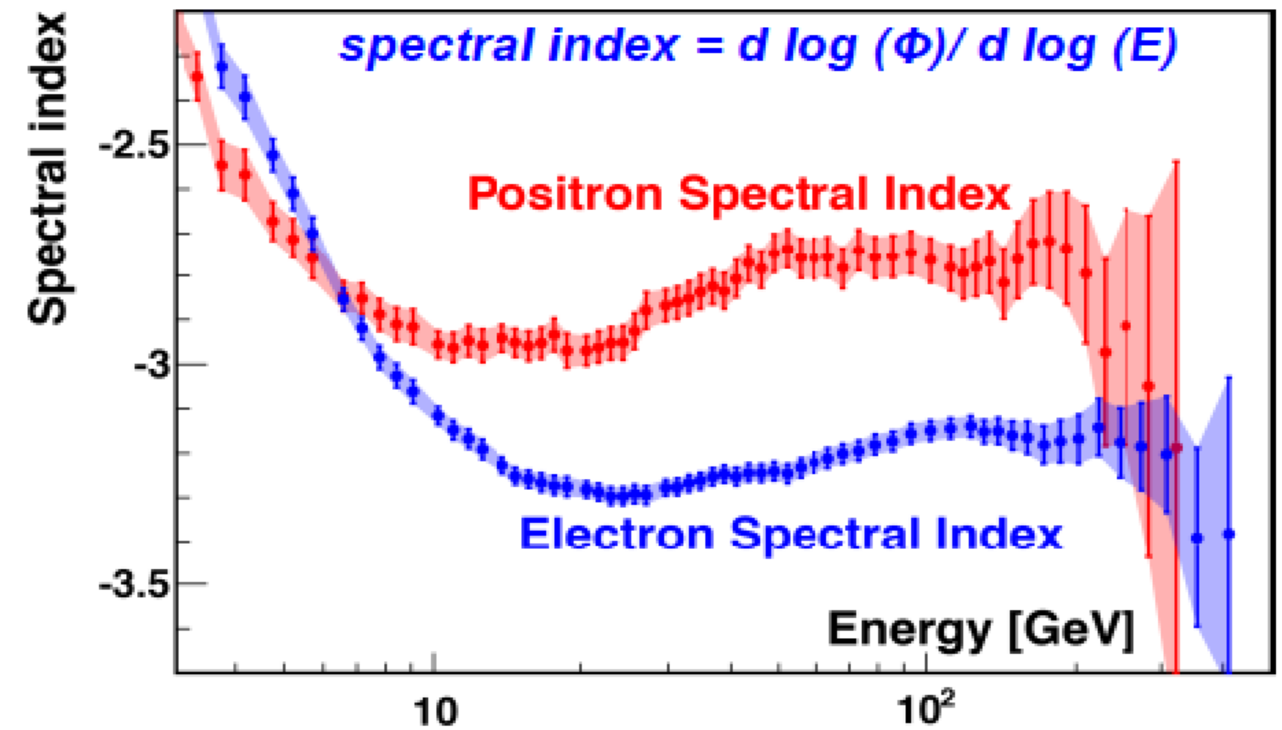
- AMS-02 positrons to 500 GeV

Results confirmed by AMS-02!



AMS-02: Electron Flux and Positron Flux





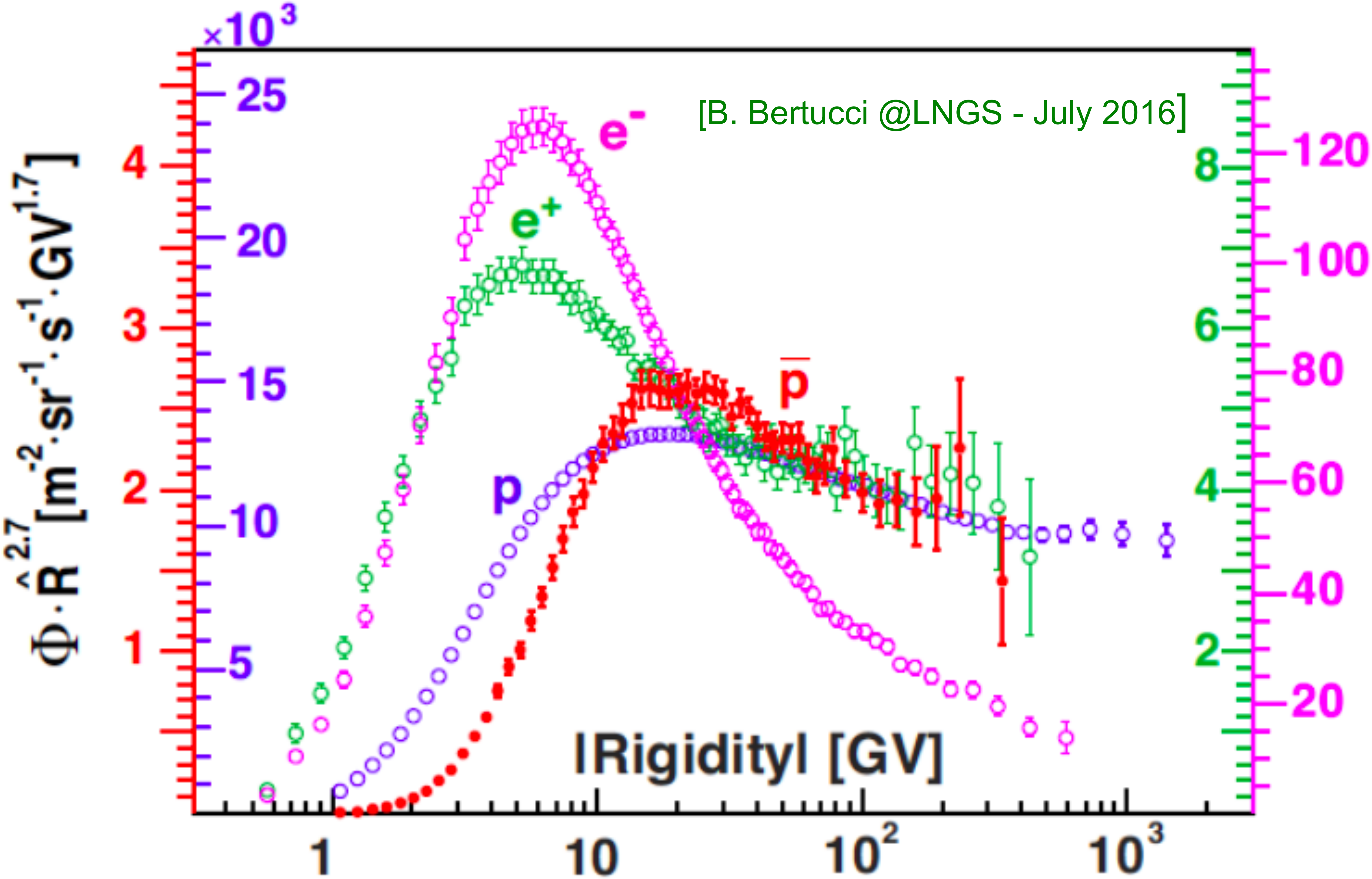
[M. Aguilar et al., PRL 113 (2014) 121102]

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]

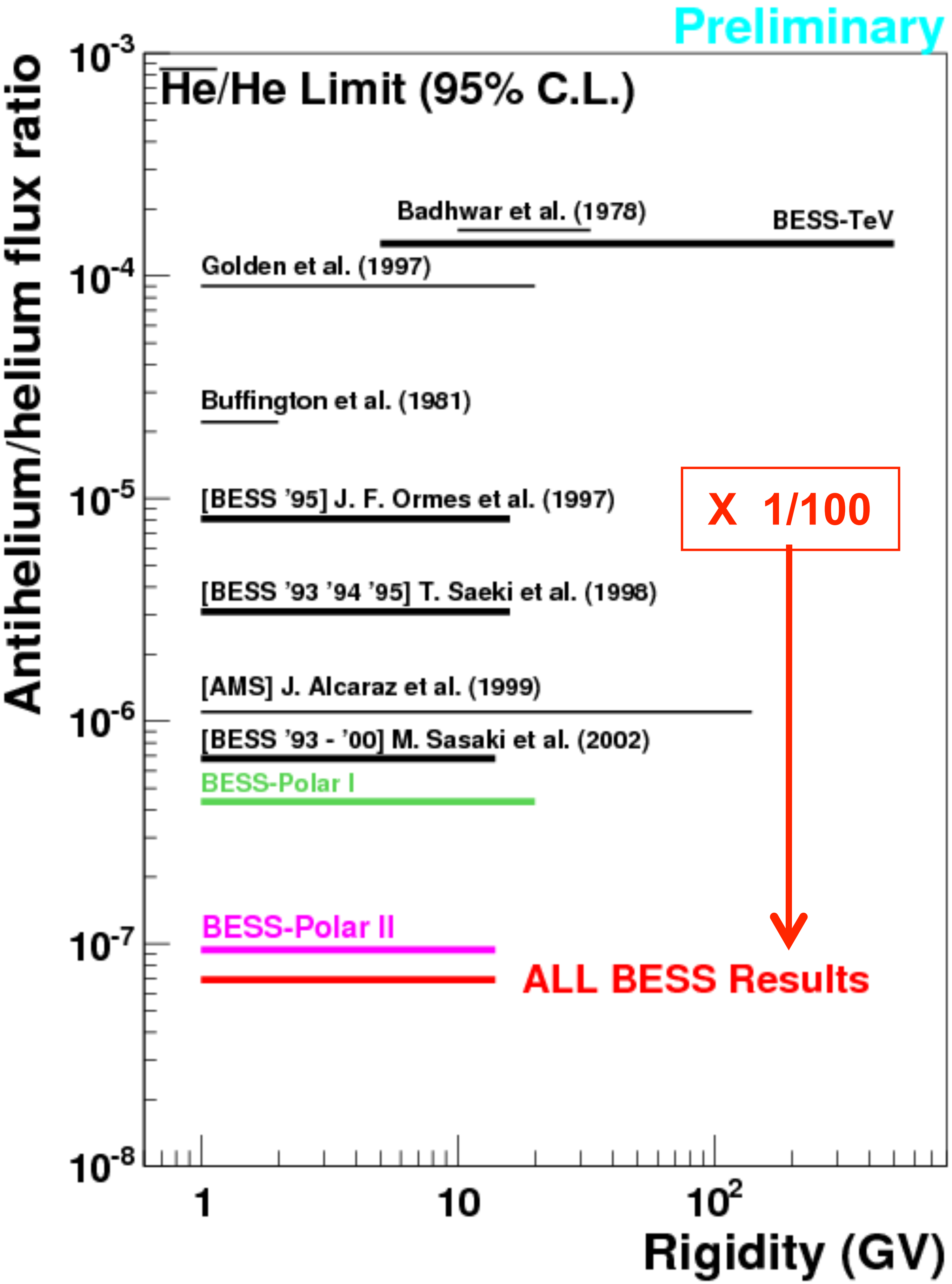
Fluxes of e^+, e^-, p and anti-p as measured by AMS-02

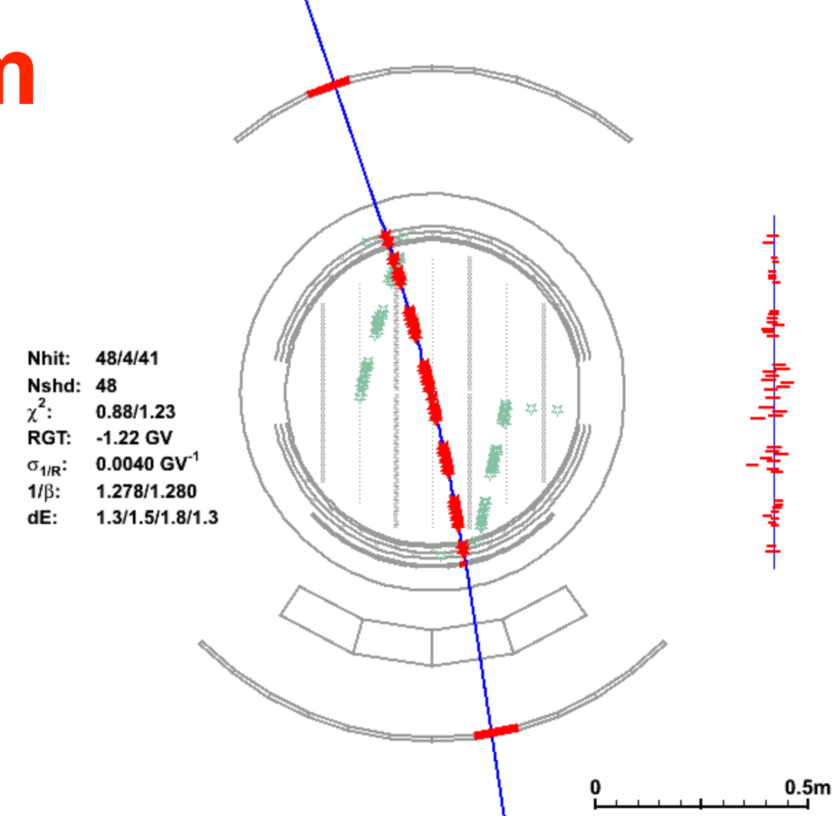


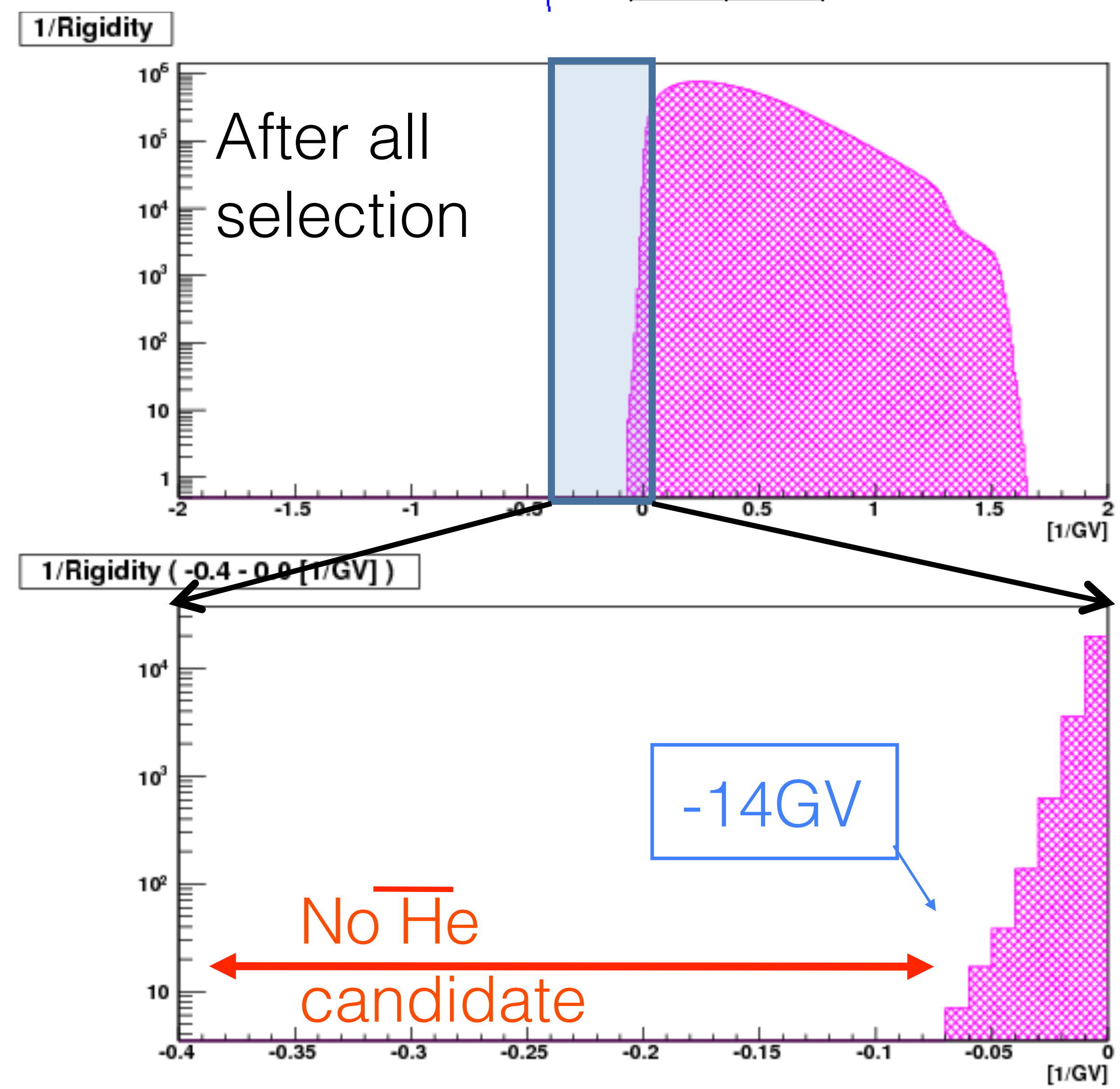
- Above ~60 GV the rigidity dependence of e^+, p and anti-p are **almost identical**
- BUT electrons behave differentlly.

BESS-Polar: Search for antihelium

#1230
Sasaki



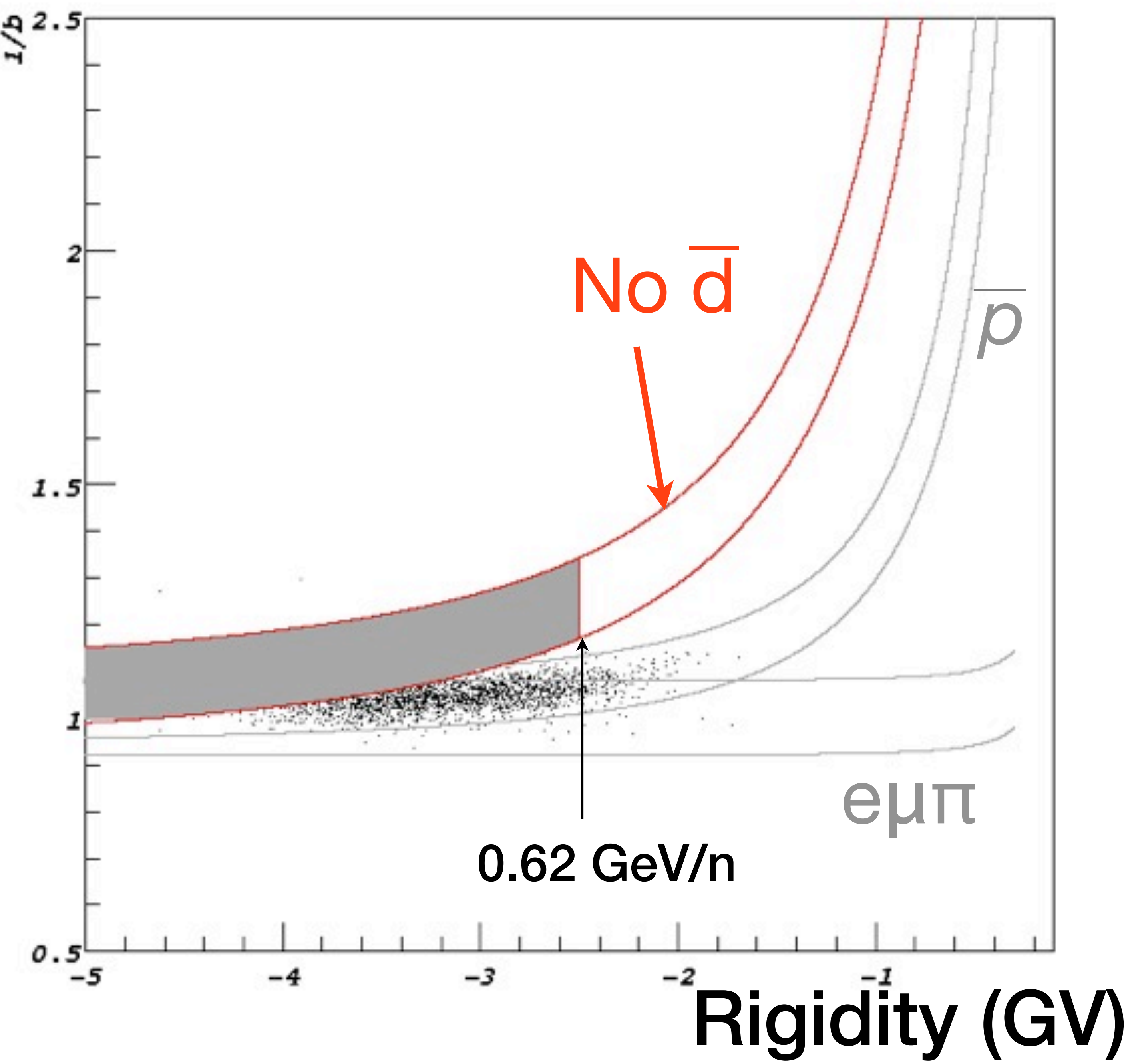




Search for cosmic-ray antideuterons with BESS-Polar

#1259
Yoshimura

Negative curvature



Apply the same selection as deuteron selection.

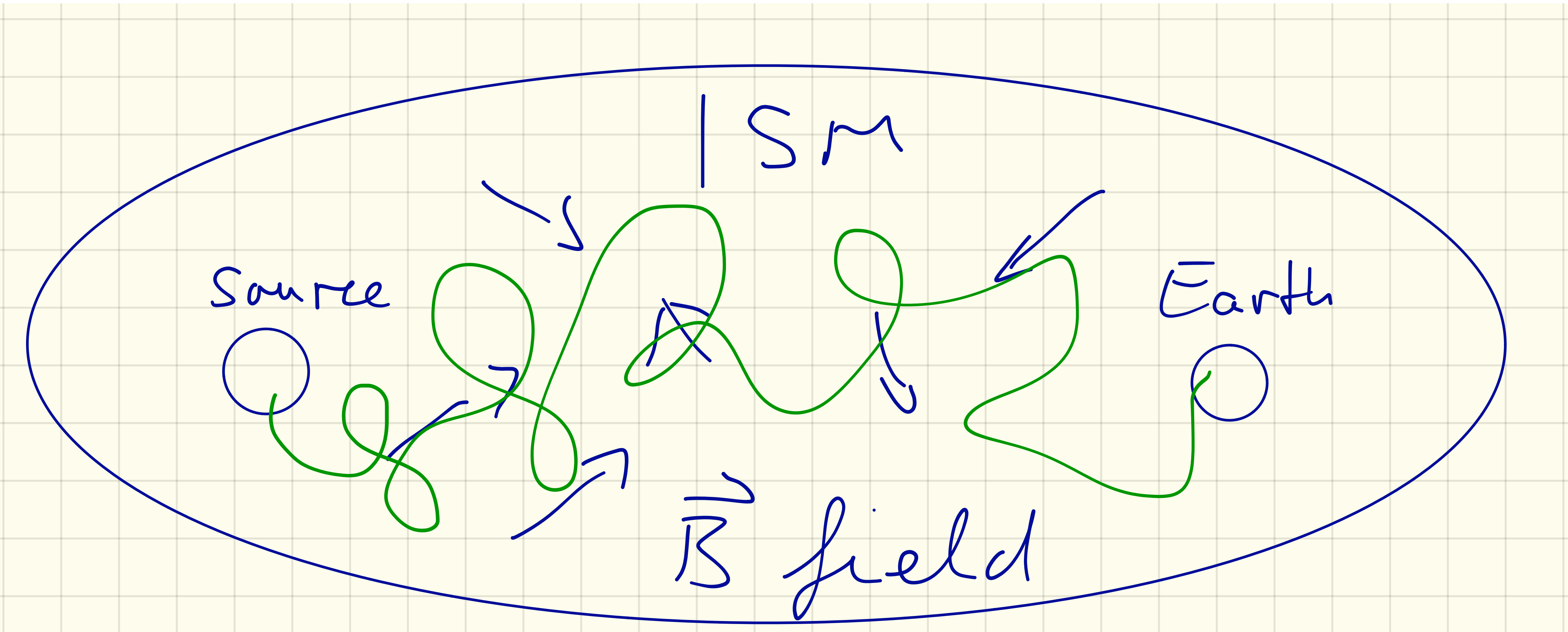
Box has not be fully opened except the BG-free region yet....

NO Antideuteron was found in rigidity below 2.5 GeV/c.

(K.E. ~ 0.62 GeV/nucleon)

Propagation of CRs in the interstellar medium (ISM)

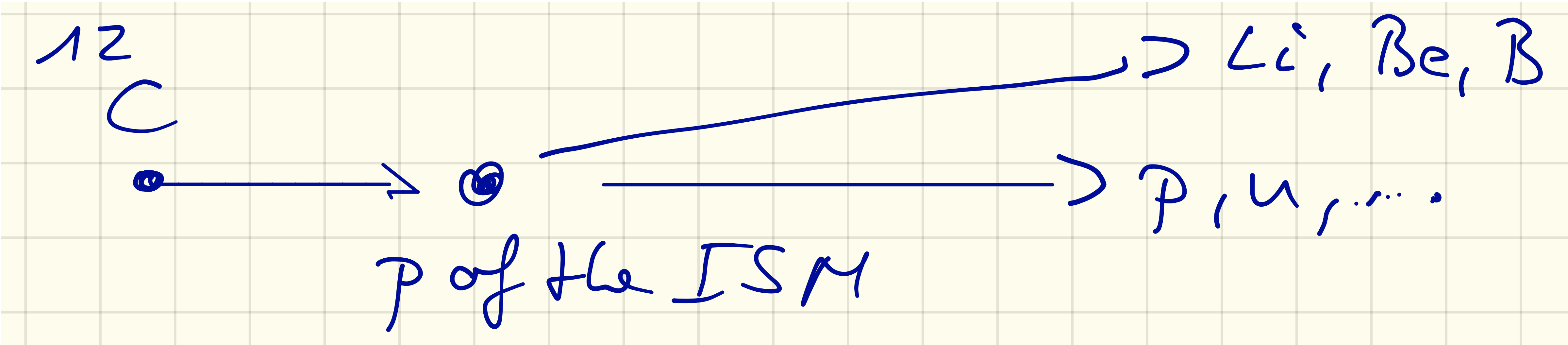
objective: quantitative understanding
start with qulitative picture



ISM in galactic disc: 1 H atom/cm³ $B \approx 3\ \mu\mathrm{G}$

$$\epsilon_B = \frac{B^2}{2\mu_0} \approx 0.22 \frac{\mathrm{eV}}{\mathrm{cm}^3}$$

what happens during propagation?



such nuclear interactions are called spallation reactions

Li, Be, B are rare elements in the solar system (primordial nucleosynthesis)

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

Diffusion or Leaky Box model

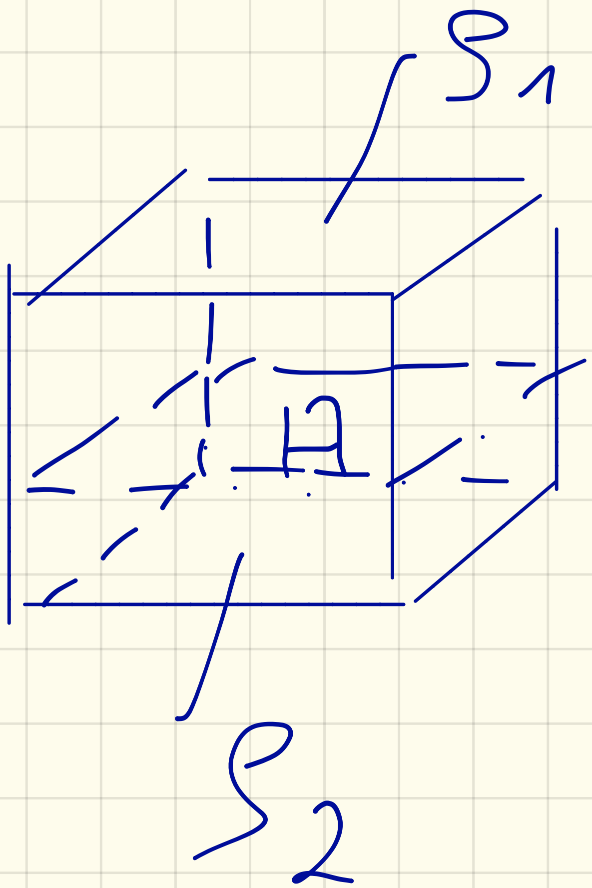
during transport of particles through the Galaxy we have to cosnider a number of effects

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

CR particles diffuse through the Galaxy
--> diffusion model

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

diffusion of gases



remove wall $\longrightarrow$ diffusion

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

mass flow per unit time

area

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

density gradient

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

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

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

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

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

① + ② $\Rightarrow \frac{\partial n_i}{\partial t} = - \mathrm{div} \left(-D \nabla n_i \right)$ $\mathrm{div} \, \vec{A} = \nabla \vec{A}$

$= \nabla \left(D \nabla n_i \right)$ 2nd law of Fick

N_i are the number densities 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 losses (e.g. Bethe Bloch and/or synchrotron losses)

$$- n \cdot v \cdot \sigma_i \cdot N_i$$ losses through inelastic scattering in the ISM

$$- \frac{N_i}{\gamma \tau_i}$$ losses through radioactive decay

$$+ Q_i$$ source term (acceleration)

$$+ \sum_{j>i} n \cdot v \cdot \sigma_{ij} \cdot N_i$$ production through interactions of heavy nuclei in the ISM

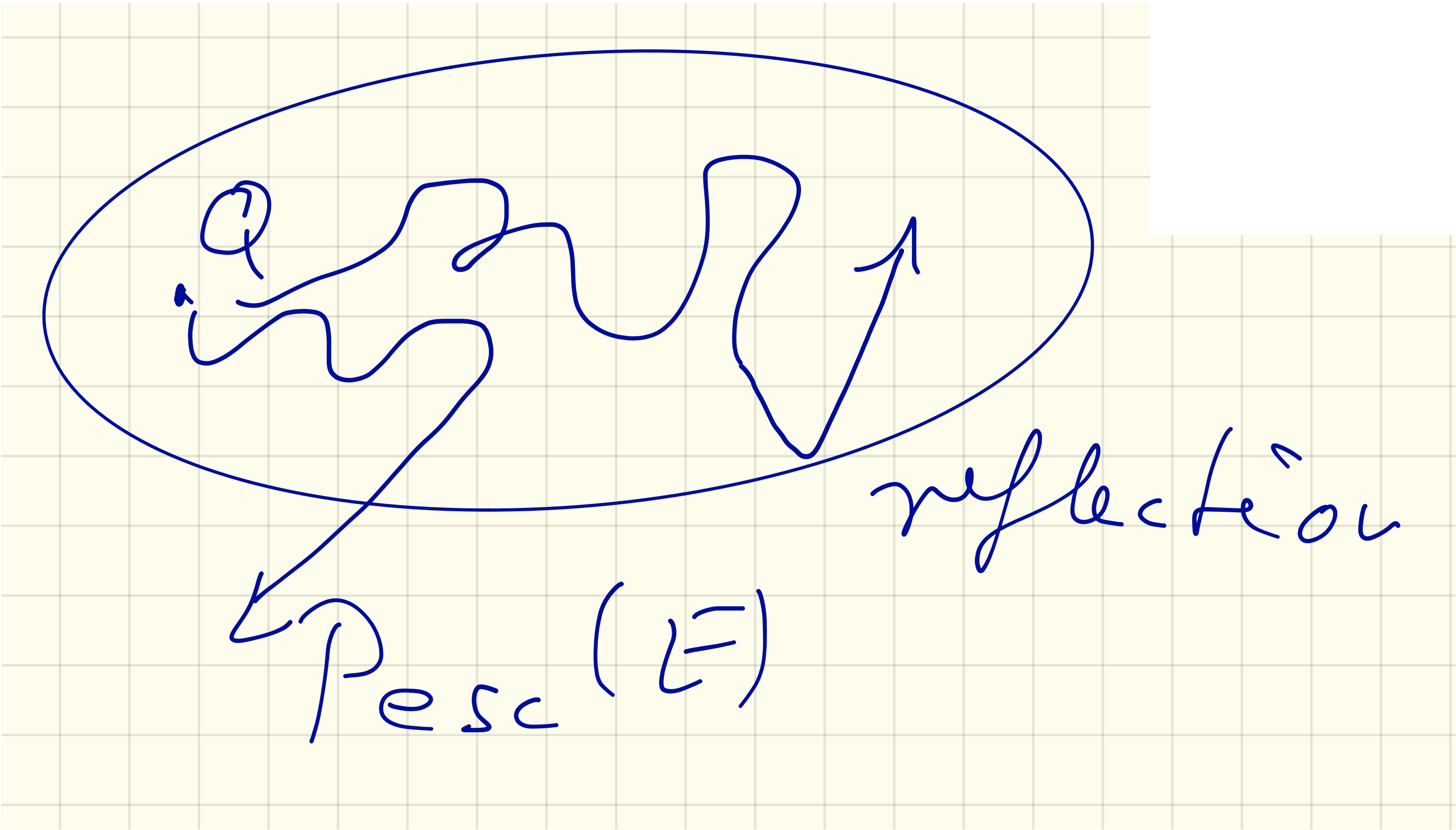
$$+ \sum_{j>i} \frac{N_i}{\gamma_i \tau_{ij}}$$ production through decay of heavy nuclei

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

therefore, simplifications are applied

diffusion coefficient D ~10^{28} cm^2/s

A simplified model: Leaky Box model



free propagation of CRs in a closed volume (Galaxy)

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

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

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

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

τ_{esc} **corresponds to the average time ththe CR particles spend in the volume (Galaxy)**

Traversed matter/column density

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

$$\frac{N_i}{\tau_{esc}} = \cancel{-\frac{\partial}{\partial E}(b_i \cdot N_i)} - \left(n \cdot v \cdot \underline{\sigma_i} + \frac{1}{\gamma \underline{\tau_i}}\right) N_i + \underline{Q_i} + \sum_{j>i} \left(n \cdot v \cdot \underline{\sigma_{ij}} + \frac{1}{\gamma_j \underline{\tau_{ij}}}\right) N_j$$

E>1 GeV **model** **from nuclear physics**

TRACER: propagation of cosmic rays

Leaky-Box Propagation Parameters

- Continuity equation:

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

- Source Spectrum:

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

- Escape Path Length:

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

- Spallation Path Length:

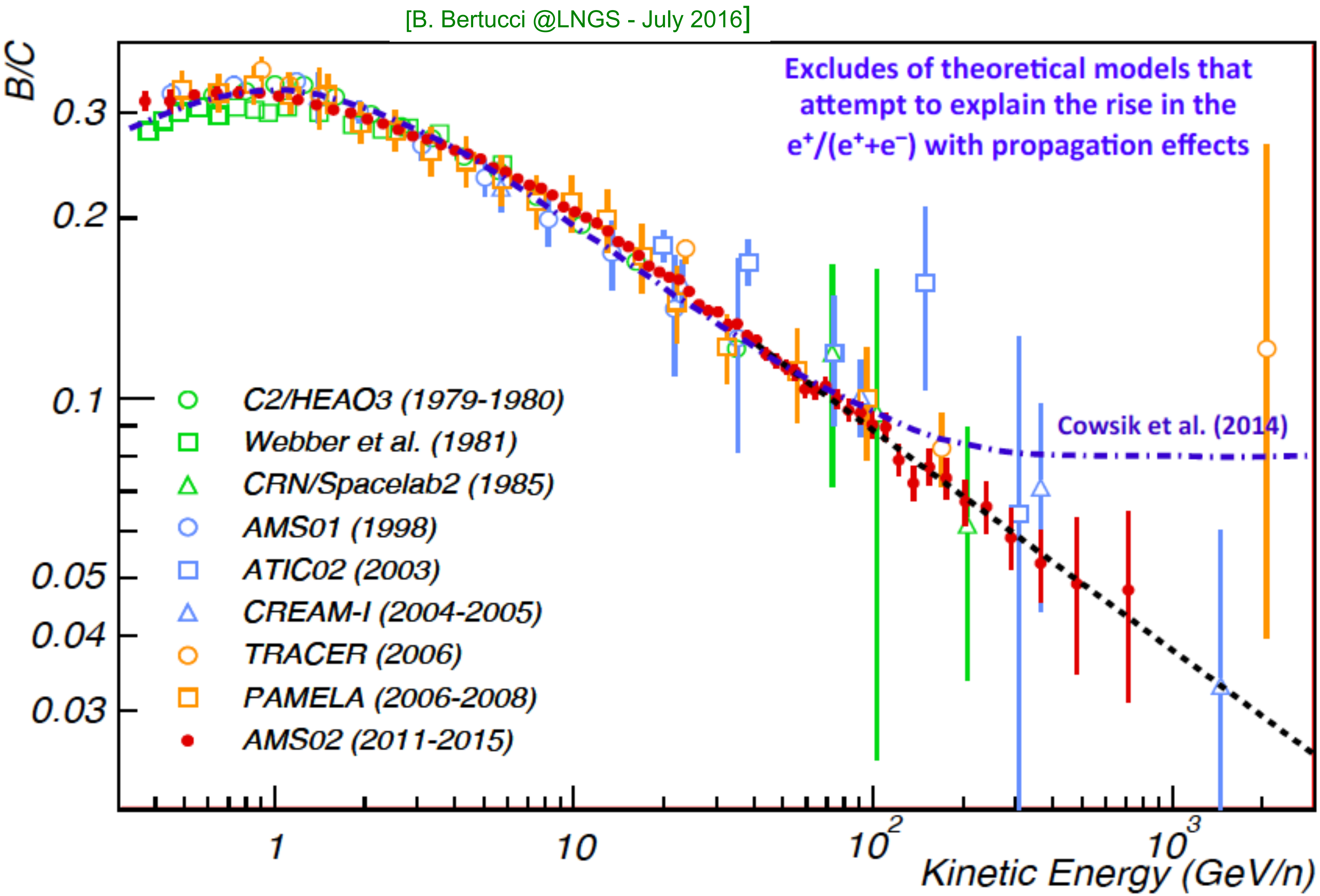
$$\Lambda_i = \frac{m}{\sigma(A)}$$

Boron to Carbon ratio

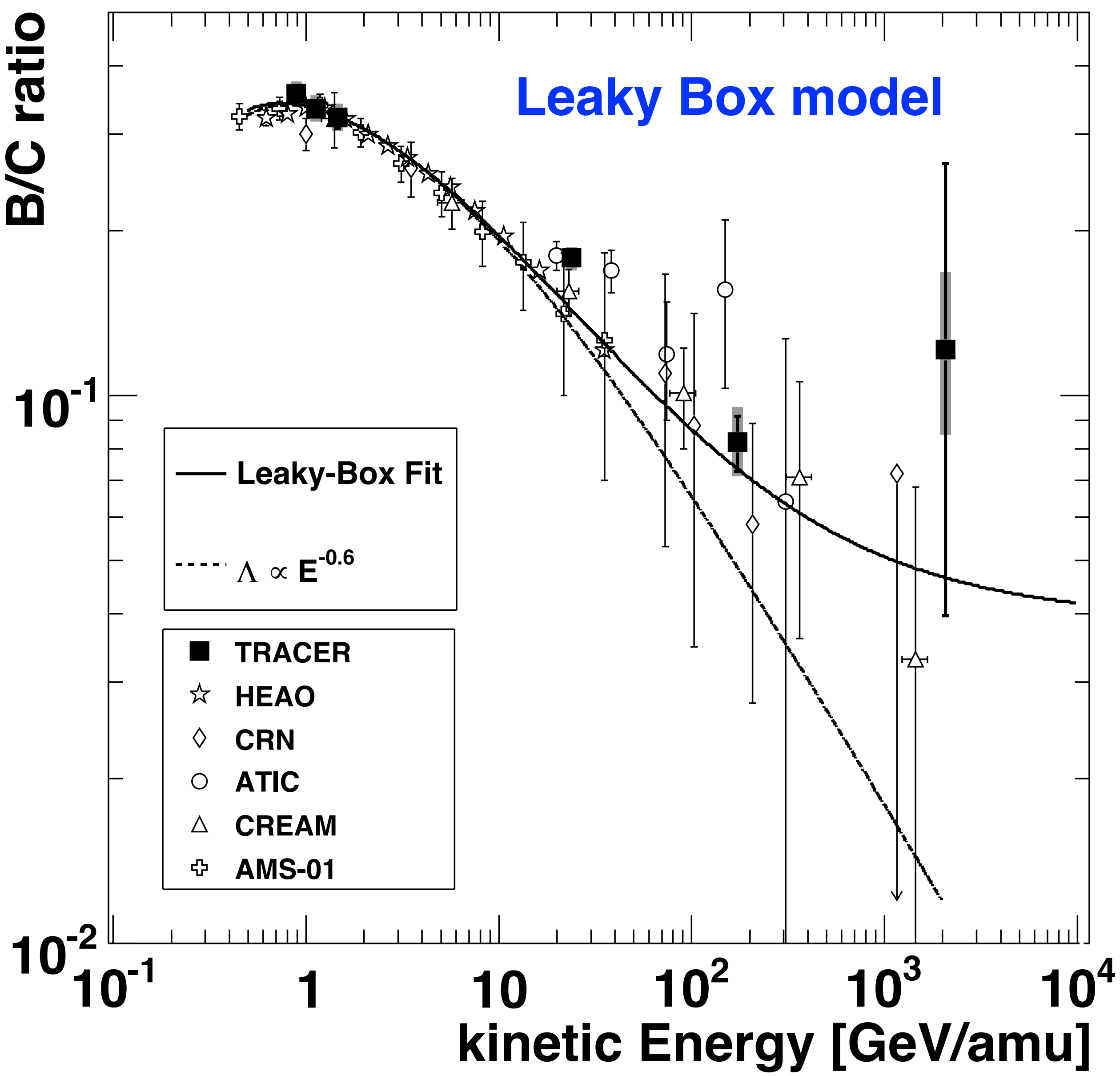
$$\frac{N_B}{N_C} = \frac{\lambda_{\to B}^{-1}}{\Lambda_{esc}(E)^{-1} + \Lambda_B^{-1}}$$

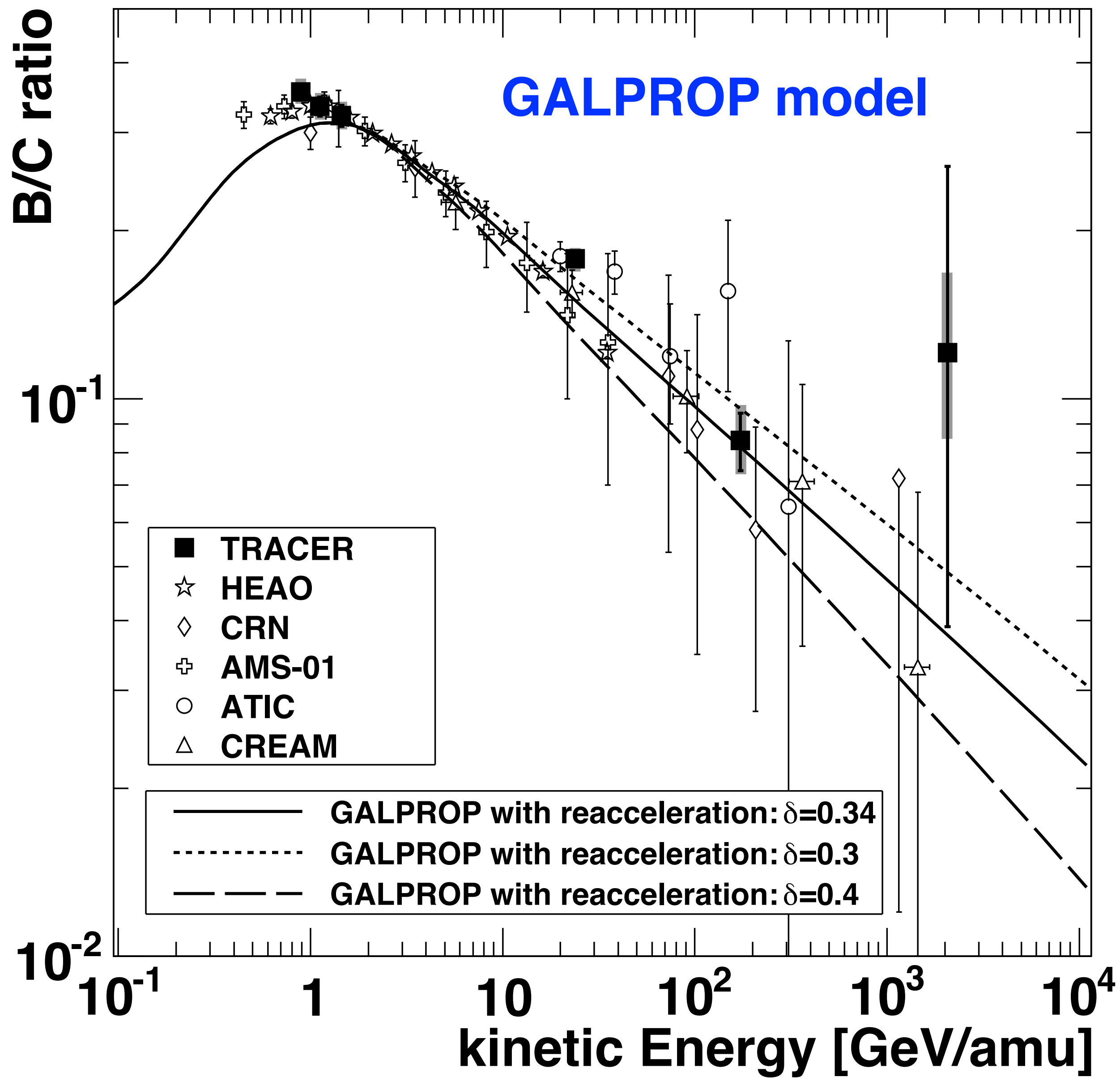
A. Obermeier et al., ICRC 2011

Current B/C measurements (AMS-02 red points)



TRACER: propagation of cosmic rays





Escape Path Length:

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

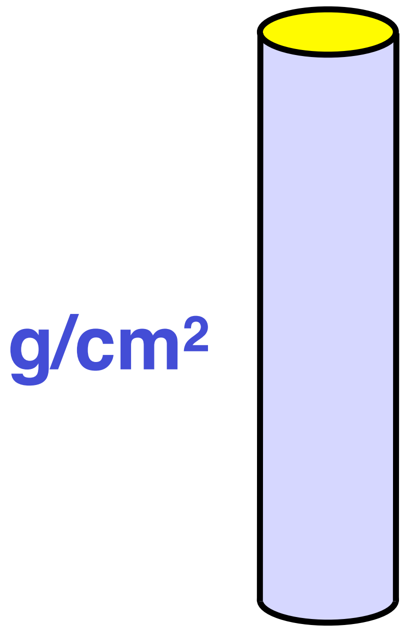
- Propagation index: $\delta = 0.64 \pm 0.02$.
- Residual path length: $\Lambda_0 = 0.7 \pm 0.2$ g/cm^2.

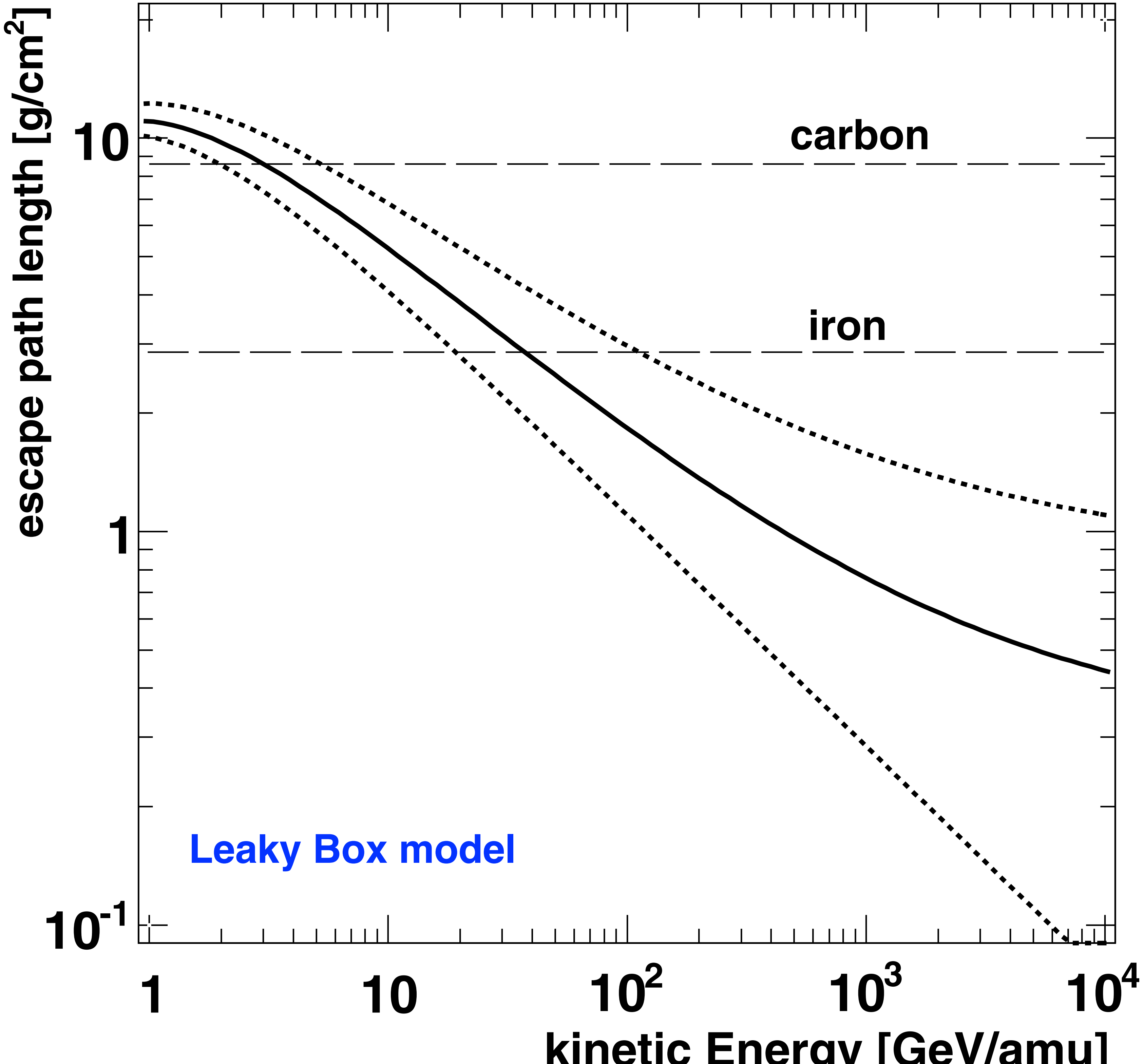
- Diffusion Index: $\delta = 0.34$.
- **Source index:** $\alpha = 2.34$.

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

TRACER: propagation of cosmic rays

path length of cosmic rays in Galaxy





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

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

investigating a number of species/isotopes and their energy dependence

$$\Rightarrow \lambda_{esc} = v \cdot \rho \cdot \tau_{esc} \approx 10 \frac{\mathrm{g}}{\mathrm{cm}^2} \frac{v}{c} \left(\frac{4}{R}\right)^{\delta} \qquad R > 4\ \mathrm{GV} \qquad \delta \approx 0.6$$

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

$$\lambda_{esc} \approx 10\ \frac{\mathrm{g}}{\mathrm{cm}^2} \quad (1\ \mathrm{GeV})$$

$$1\ \frac{\mathrm{g}}{\mathrm{cm}^2} \quad (1\ \mathrm{TeV})$$

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

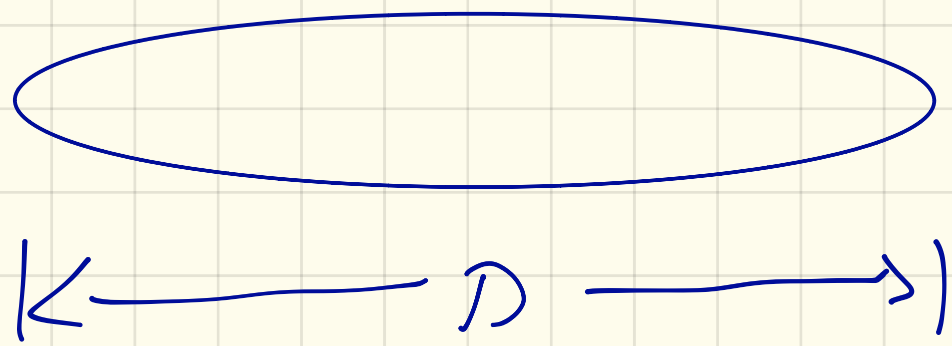
$$\lambda_{int}^{p} \approx 55\ \frac{\mathrm{g}}{\mathrm{cm}^2} >> \lambda_{esc}$$

$$\lambda_{int}^{Fe} \approx 2.3\ \frac{\mathrm{g}}{\mathrm{cm}^2} < \lambda_{esc}$$

less interactions for protons than for Fe nuclei

galactic disc $n \sim 1$ H atom / cm^3 $= 1{,}67 \cdot 10^{-24}\ \frac{g}{cm^3}$

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



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

$\mathcal{O}(100)$ 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 CRs

or residence time of CRs in Galaxy

use secondary radioactive isotopes from spallation reactions

e.g. ^{10}Be $\tau = \gamma \cdot \tau_0 = 3.9 \cdot 10^6 \text{ a}$

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

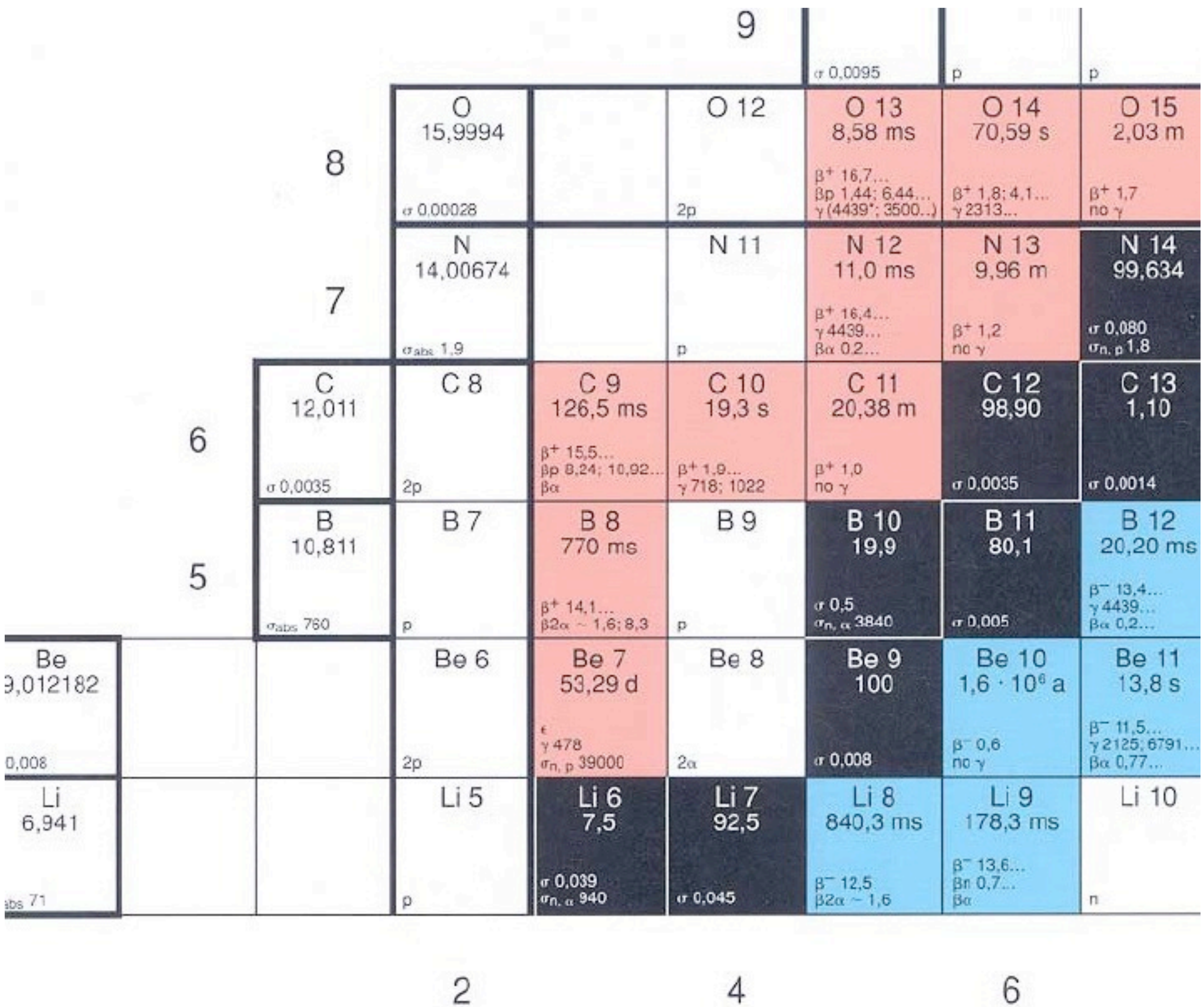
equilibrium between production and decay of ^{10}Be

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

if $\tau_{esc} > \tau_0$ **expect observed ratio of ^{11}Be < 0.1**

$$\frac{^{10}\text{Be}}{^{7}\text{Be} + {}^{9}\text{Be} + {}^{11}\text{Be}} \approx 0.028$$ **in CRs**

Chart of the nuclides



„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

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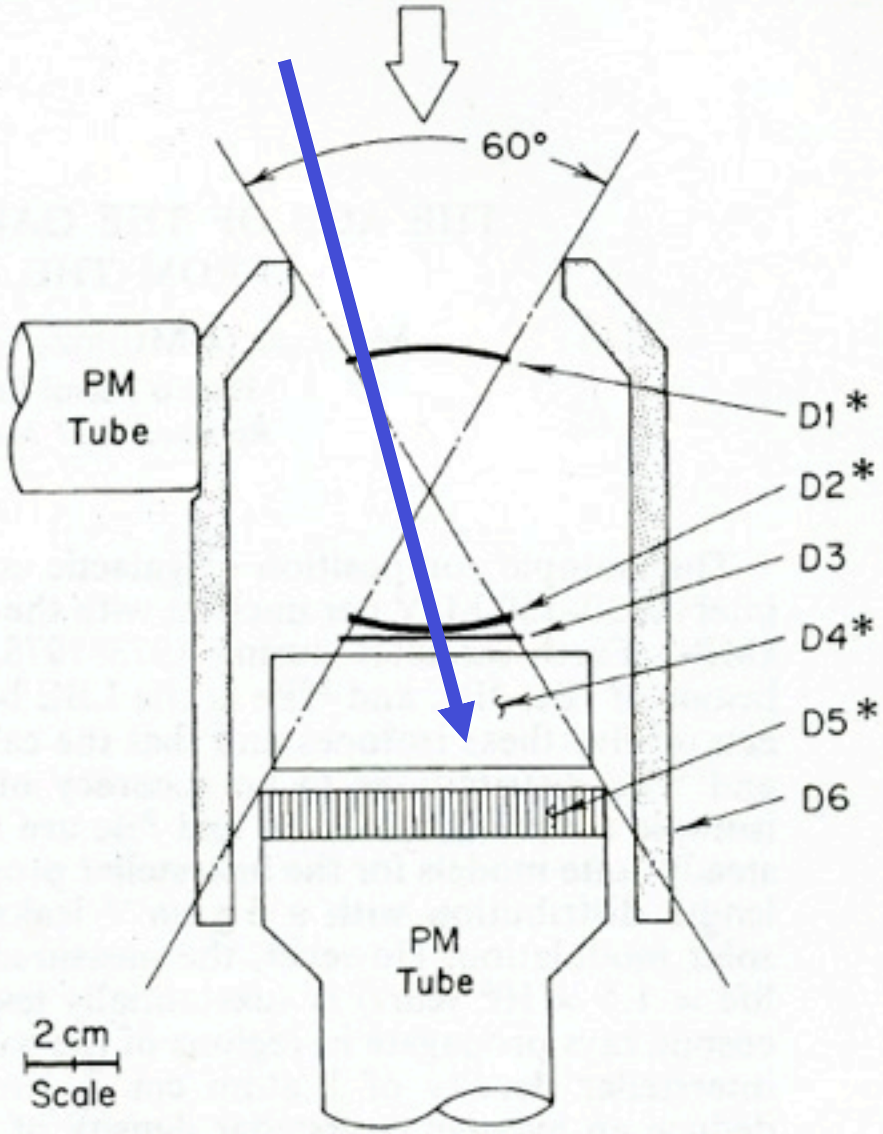
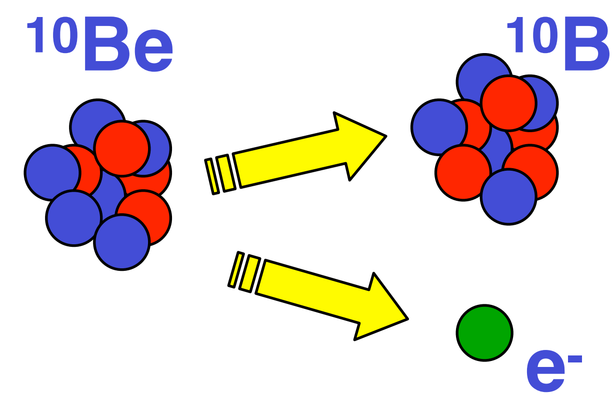


FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (Tl) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness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

$^{10}Be \rightarrow {}^{10}B + e^-$ (t $=2.4\ 10^6$ a)



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

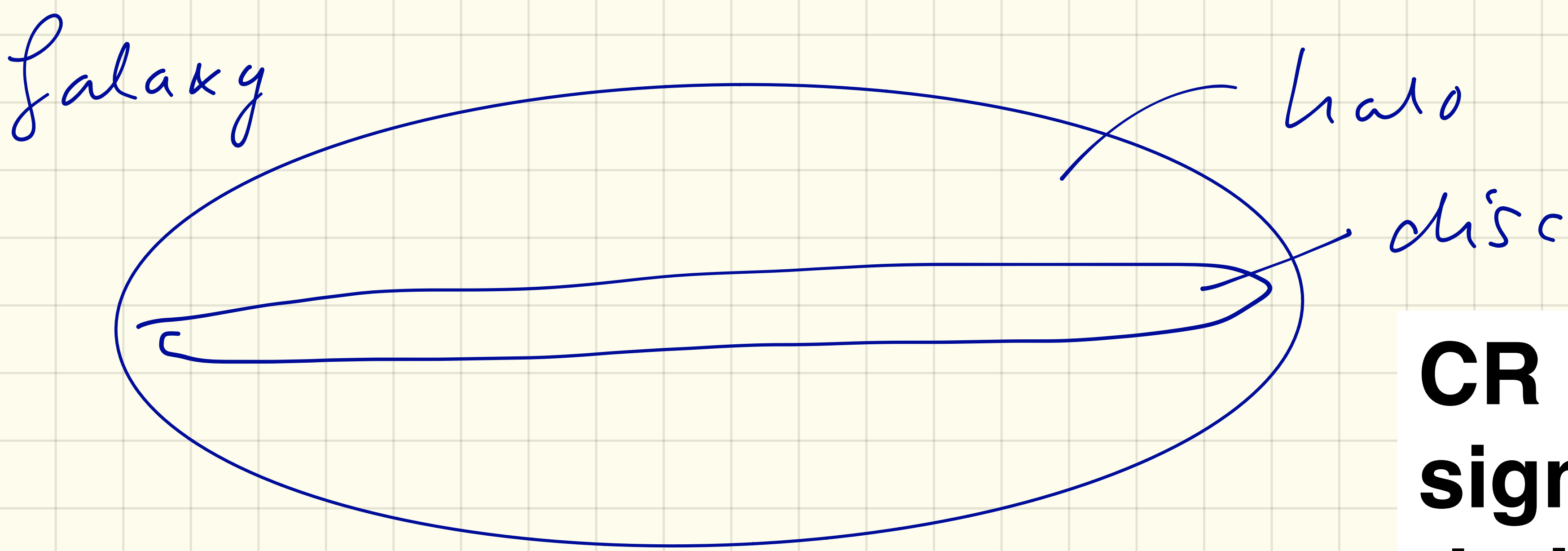
THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

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

from this, we can derive an average density

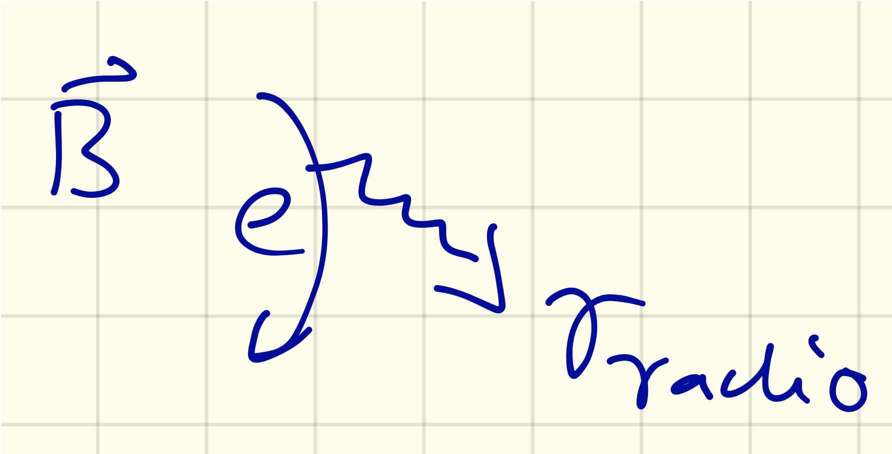
$$\bar{\rho} = \frac{\lambda_{esc}}{v \cdot \tau_{esc}} = \frac{10 \, g/cm^2}{3 \cdot 10^{10} \frac{cm}{s} \cdot 17 \cdot 10^6 \cdot 86400 \cdot 365 \, s}$$

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



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

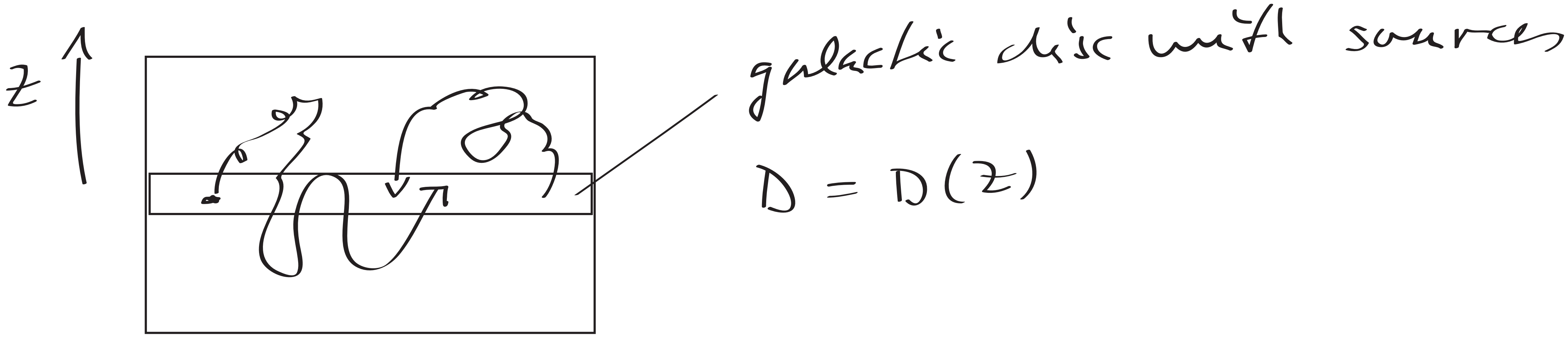
confirmed by observations of diffuse radio emission



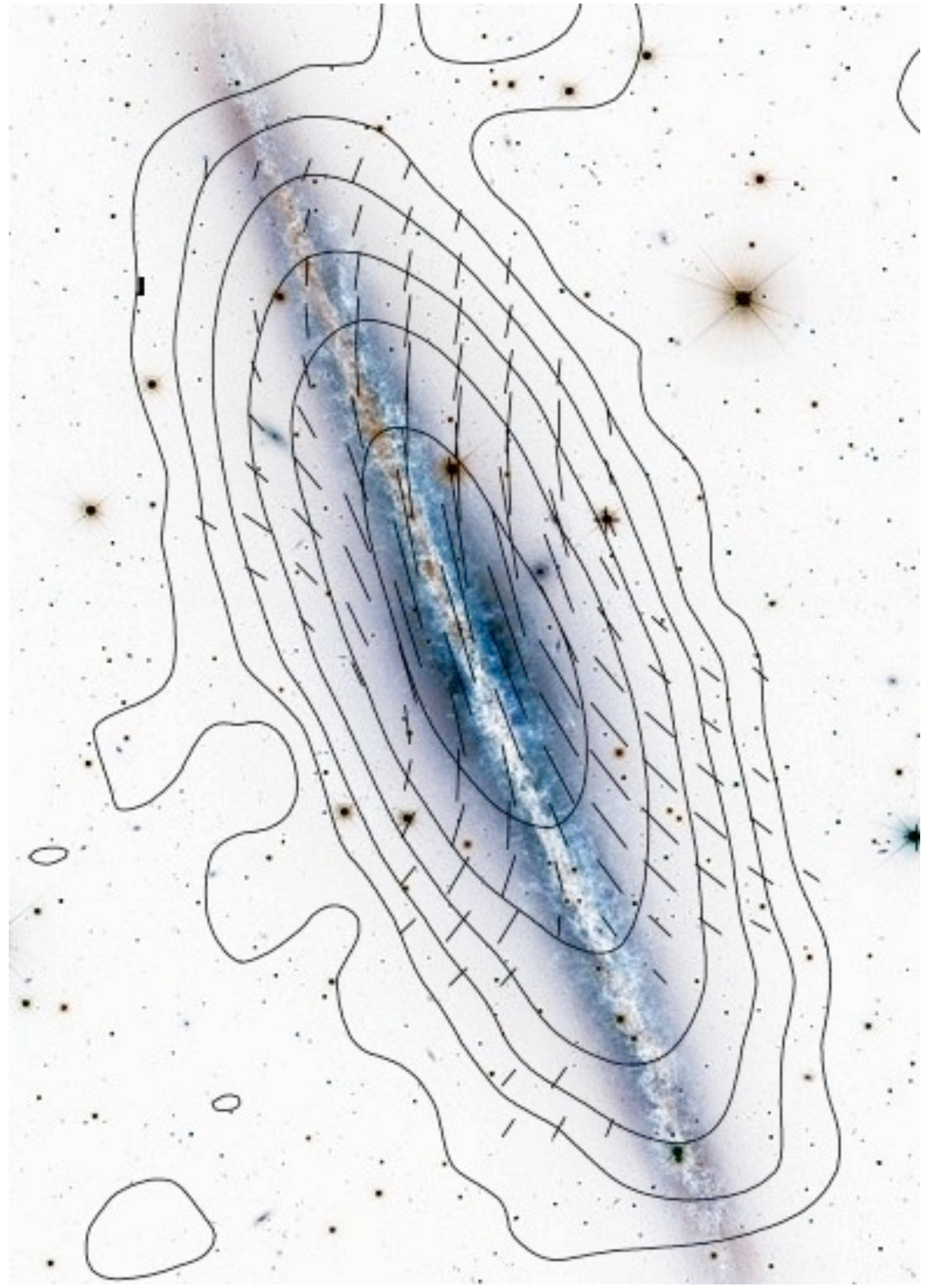
synchrotron radiation

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

Leaky Box model is very simple
today mostly: diffusion halo model



numerical models: e.g. GALPROP



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.