Spectral features in galactic cosmic rays

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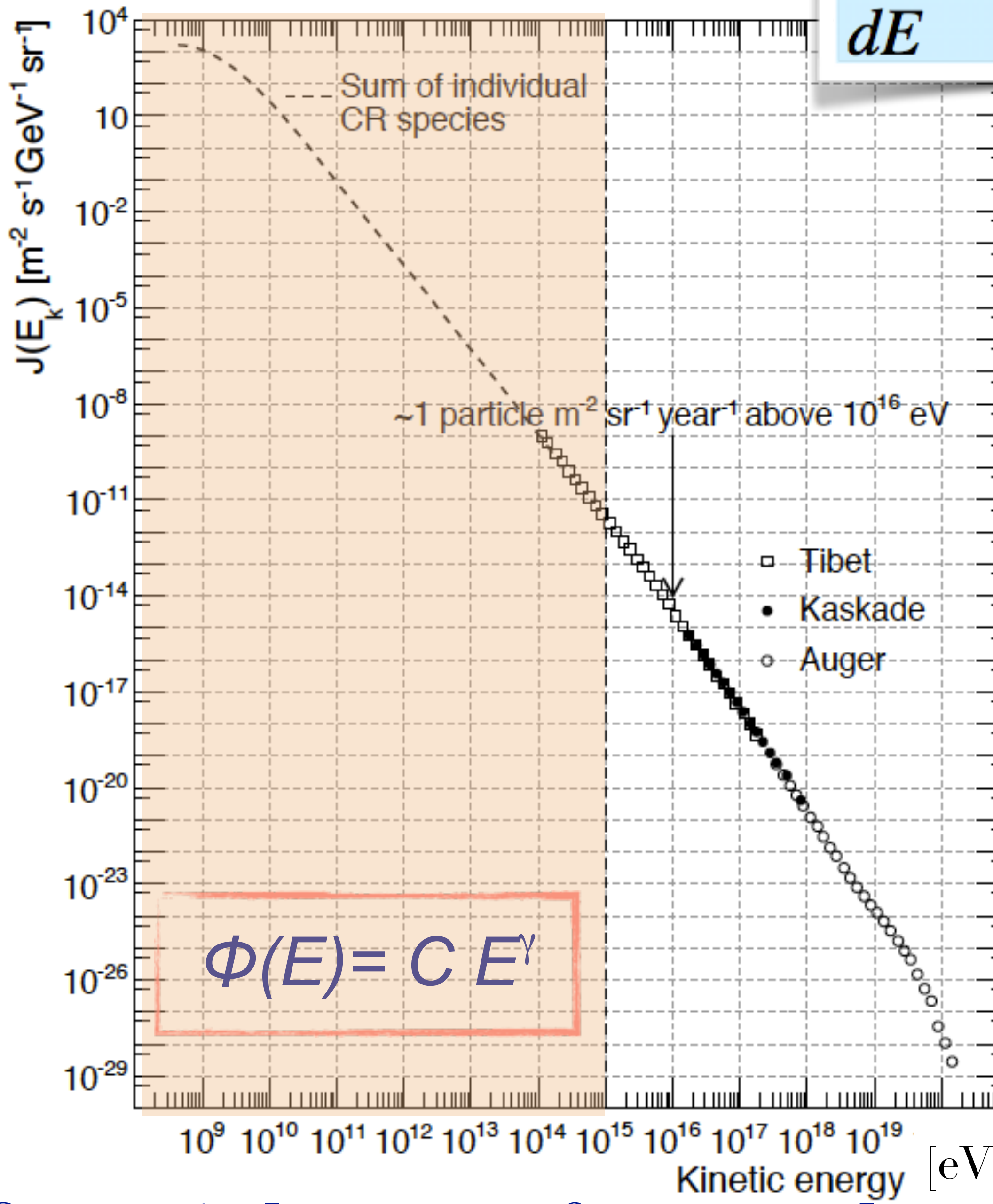
The cosmic ray flux

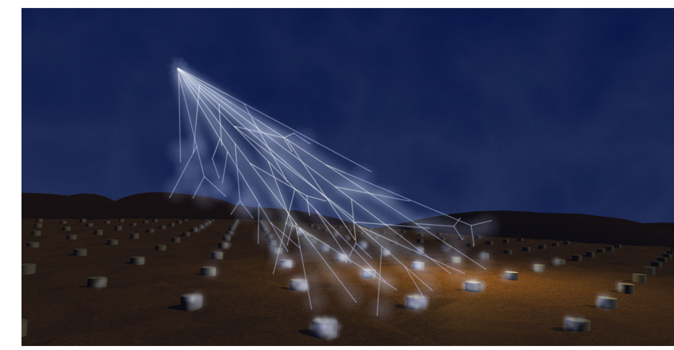
all particle flux

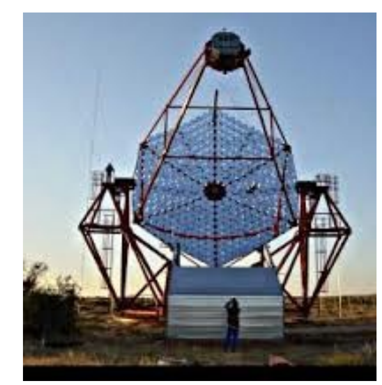
$$\frac{dN}{dE} = [m^{-2} sr^{-1} s^{-1} GeV^{-1}]$$

Direct measurements



Indirect measurements

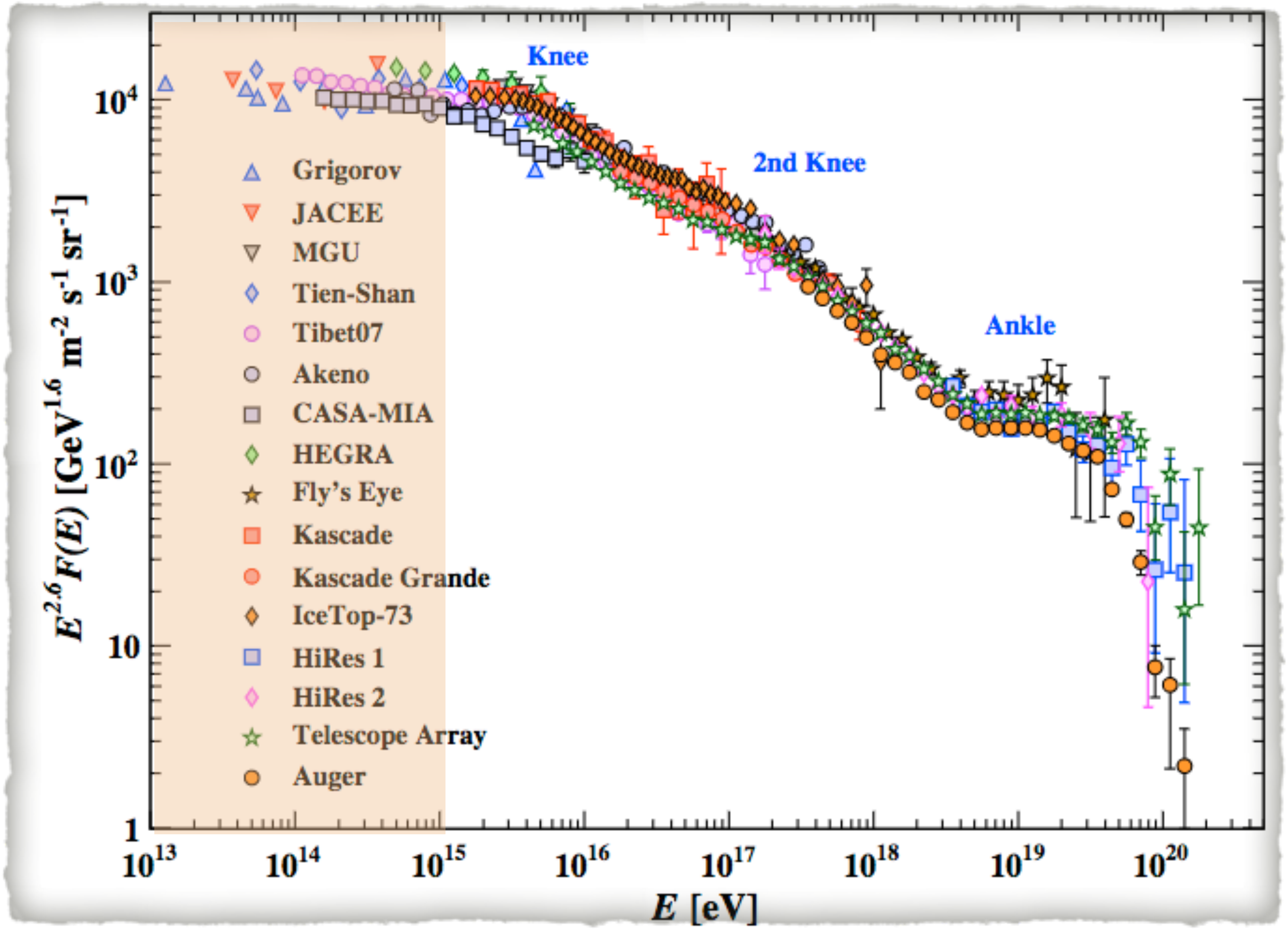




at first sight … a feature-less power law

L. Baldini, arXiv: 1407.7631

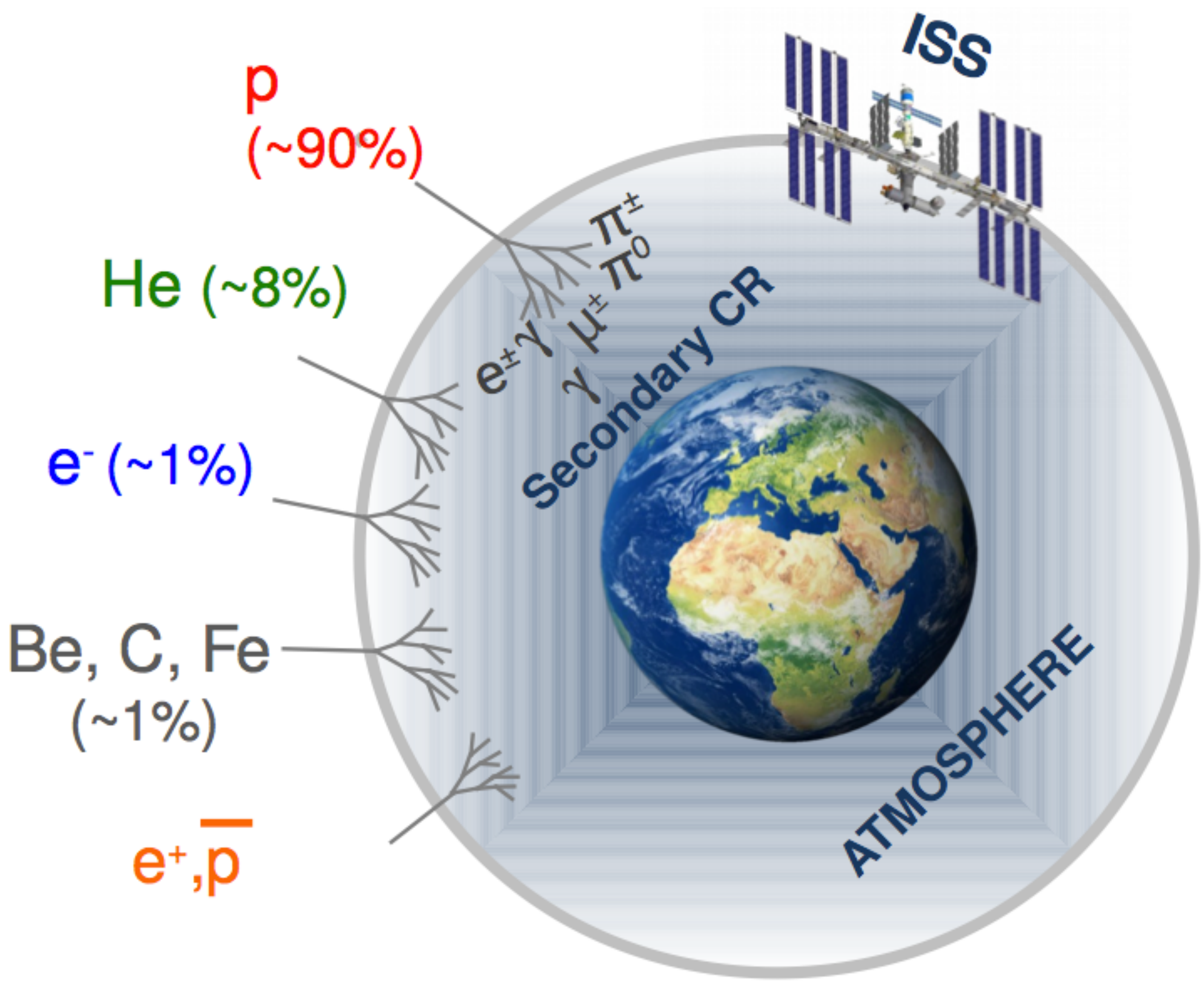
... not so feature-less



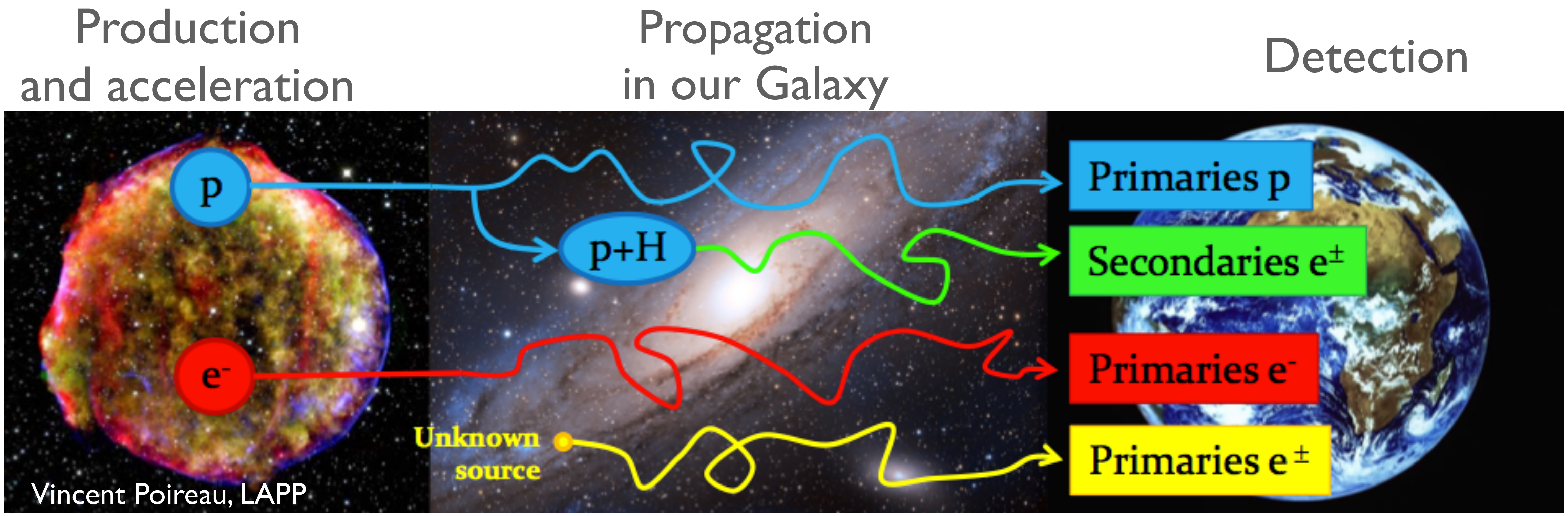
- I will focus on the measurement of CRs in the GeV to TeV range.
- These particles are thought to be of galactic origin.

Cosmic ray composition

We can perform direct measurements of CRs below the knee, before they interact with the atmosphere.



Cosmic rays in the Milky Way



Primary cosmic rays:

- Produced directly in the source
- Known sources ($E < 10^{16}$ eV): SNRs
- Primary cosmic rays include e^-, p, He, C, …

Secondary cosmic rays:

- Produced in the interaction of primaries in the interstellar medium
- Secondary cosmic rays include e^-, e^+, anti-p, B, …

A simplified description of CR fluxes

The flux of primary particles is shaped by the physical phenomena occurring at the **source** and during their **propagation**.

$$\Phi_P \propto \frac{q}{K} \propto R^{-\alpha-\delta}$$

The flux of secondary particles is shaped by the physical phenomena occurring during the propagation of the parent nuclei.

$$\Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta}$$

The secondary to primary flux ratios are extremely sensitive to propagation parameters and they are almost insensitive to the injected primary spectrum.

$$\frac{\Phi_S}{\Phi_P} \propto R^{-\delta}$$

The propagation is traditionally studied with the B/C flux ratio, but other secondary species (also Li and Be) have recently been measured with high precision by AMS-02.

Conventional model

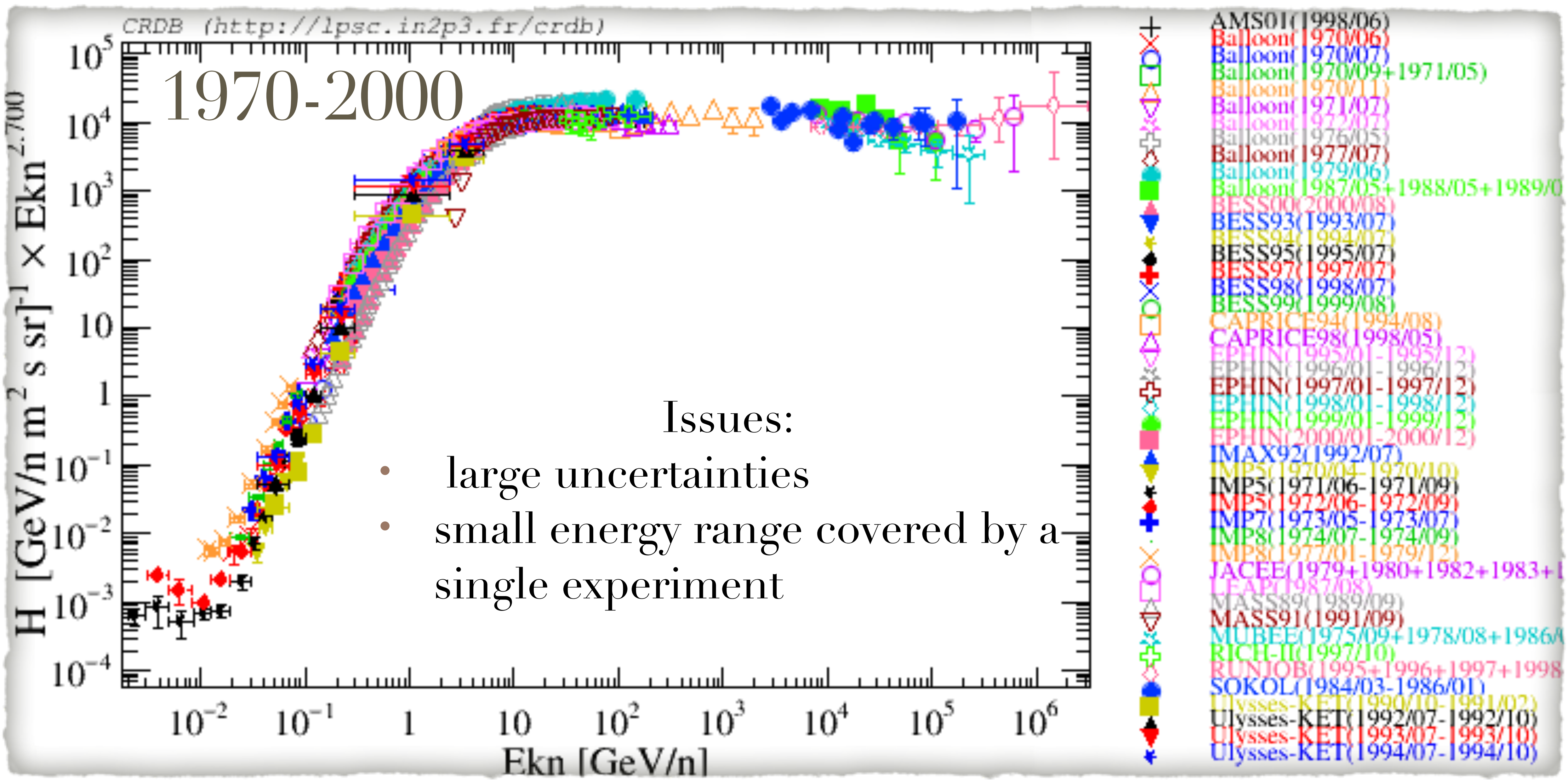
- Cosmic ray fluxes below the knee ($E<10^{15}$ eV) can be described by a single power law, the spectral index being the result of the following processes:
  - production
  - acceleration
  - propagation
- Primary cosmic ray fluxes have universal (species independent) spectral indices.
- Antimatter is purely of secondary origin (no sources of CR antimatter).

Precise measurements provided by the current generation of CR detectors have been providing new insight to the physics of cosmic rays

Cosmic ray particles and nuclei

Cosmic ray protons

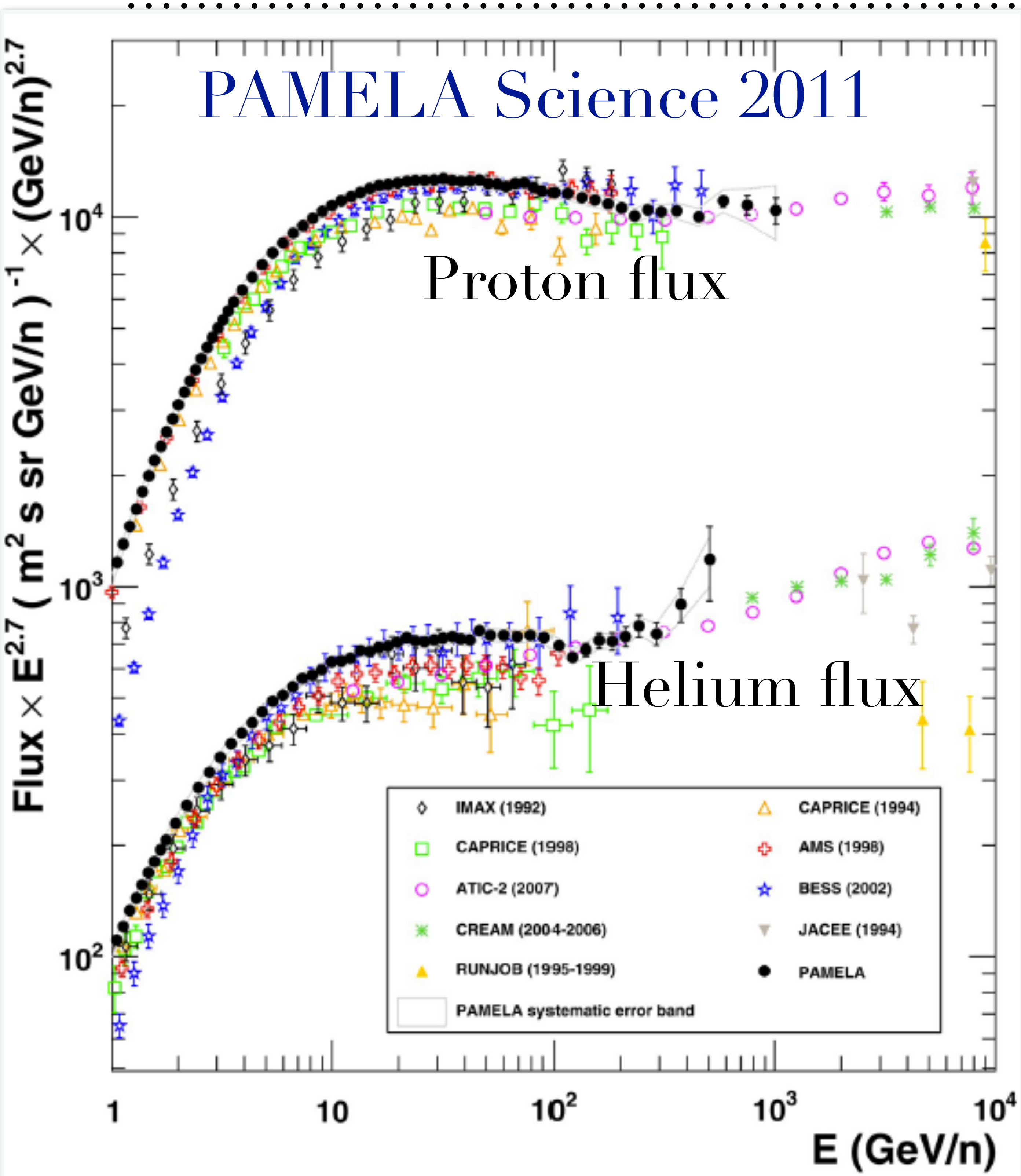
until a few decades ago...



Issues:

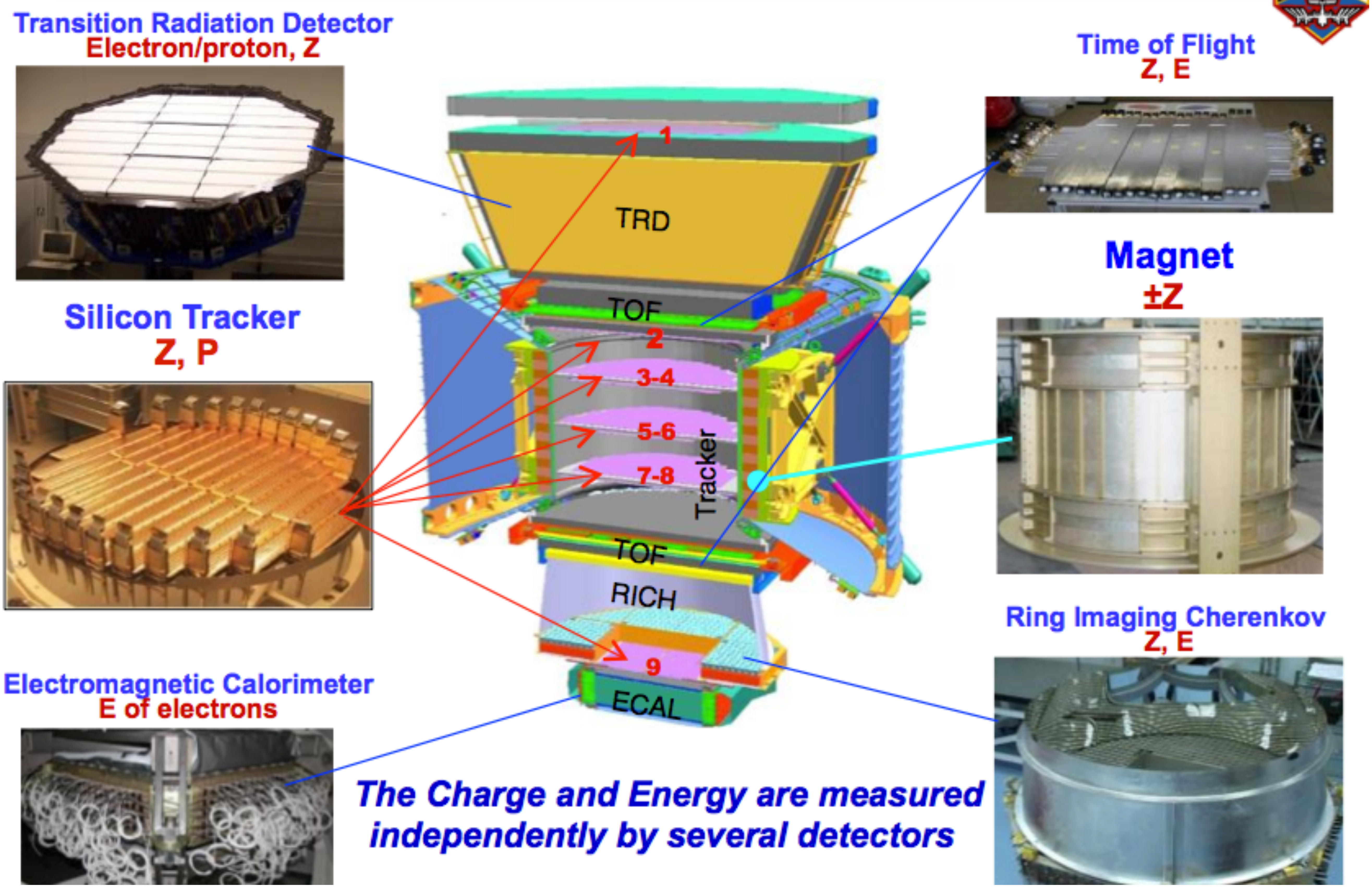
- large uncertainties
- small energy range covered by a single experiment

The first unexpected feature



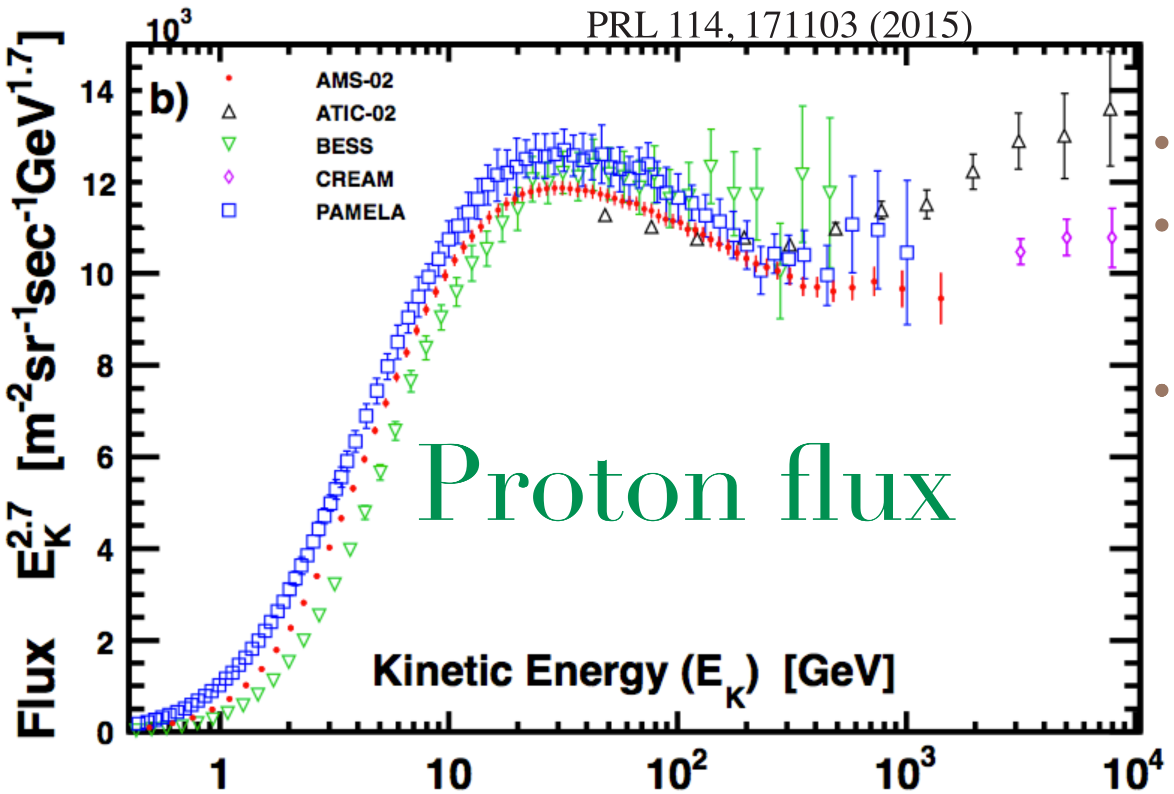
PAMELA:
A single instrument covering the whole energy range was solving the puzzle

AMS: A TeV precision, multipurpose spectrometer



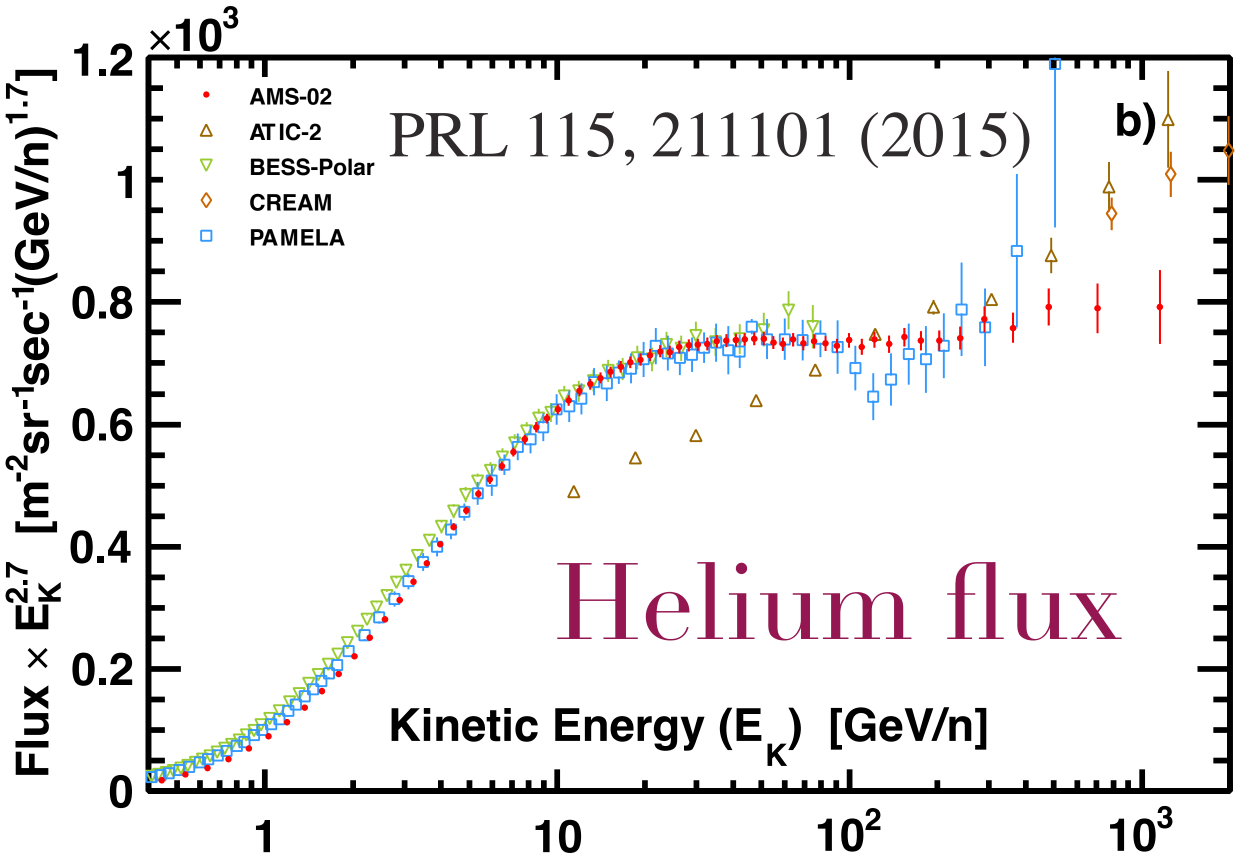
The Charge and Energy are measured independently by several detectors

AMS-02 proton and helium fluxes



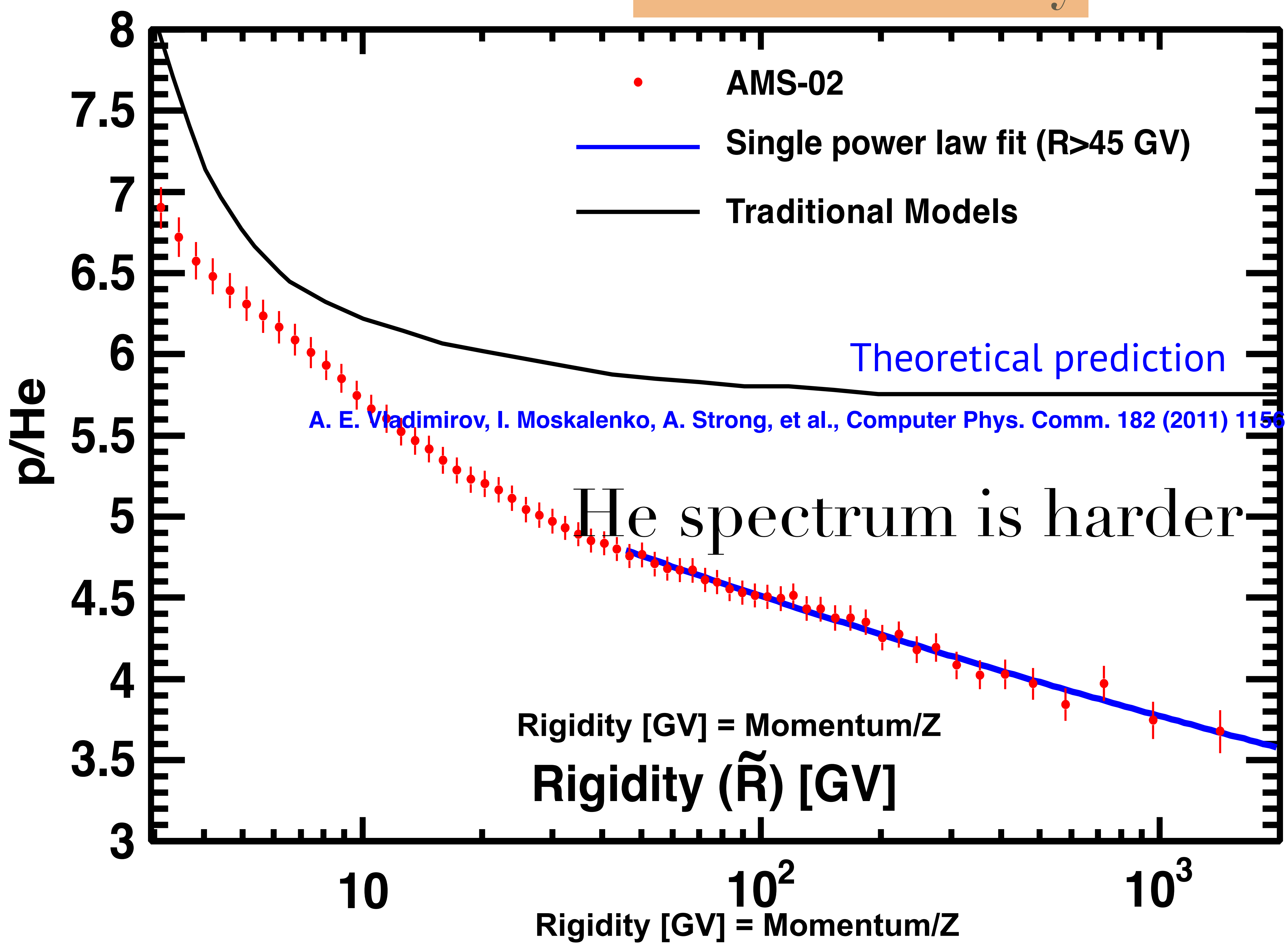
- Based on 300 million events (2011-2013)
- The proton flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.

- Based on 50 million events (2011-2013)
- The helium flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.



p/He flux ratio

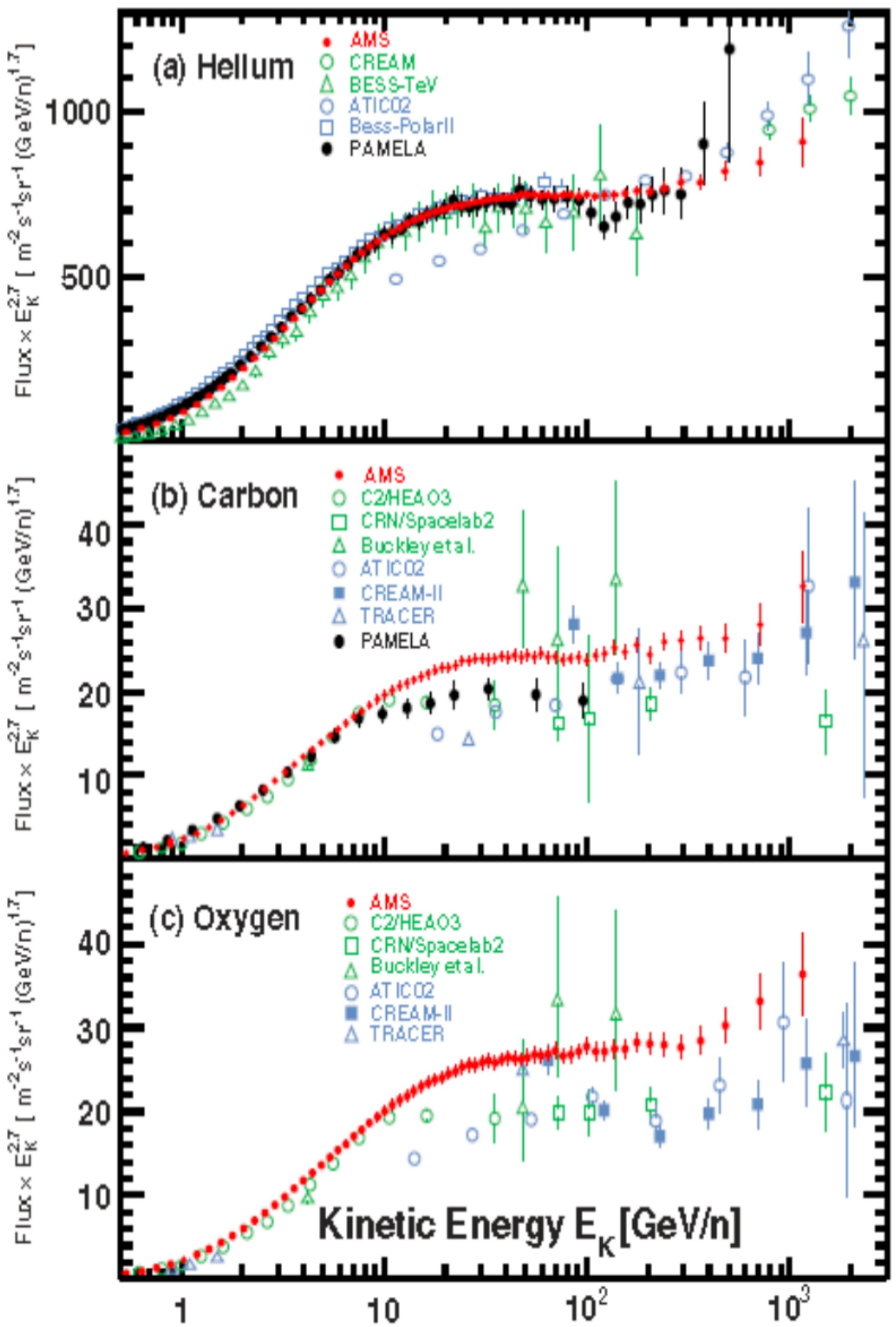
non-universality



Primary and Secondary Cosmic Rays

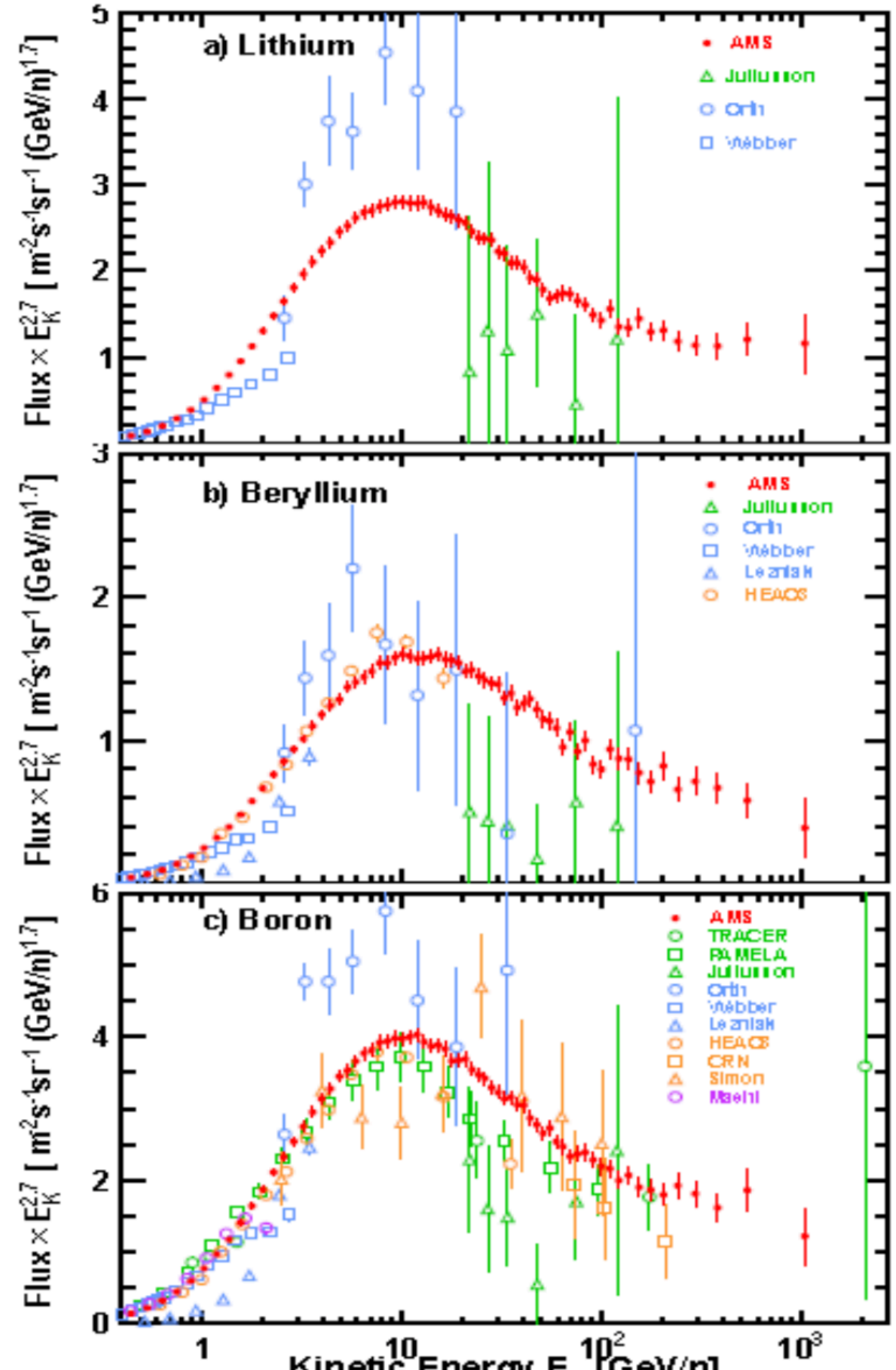
Primary species

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101

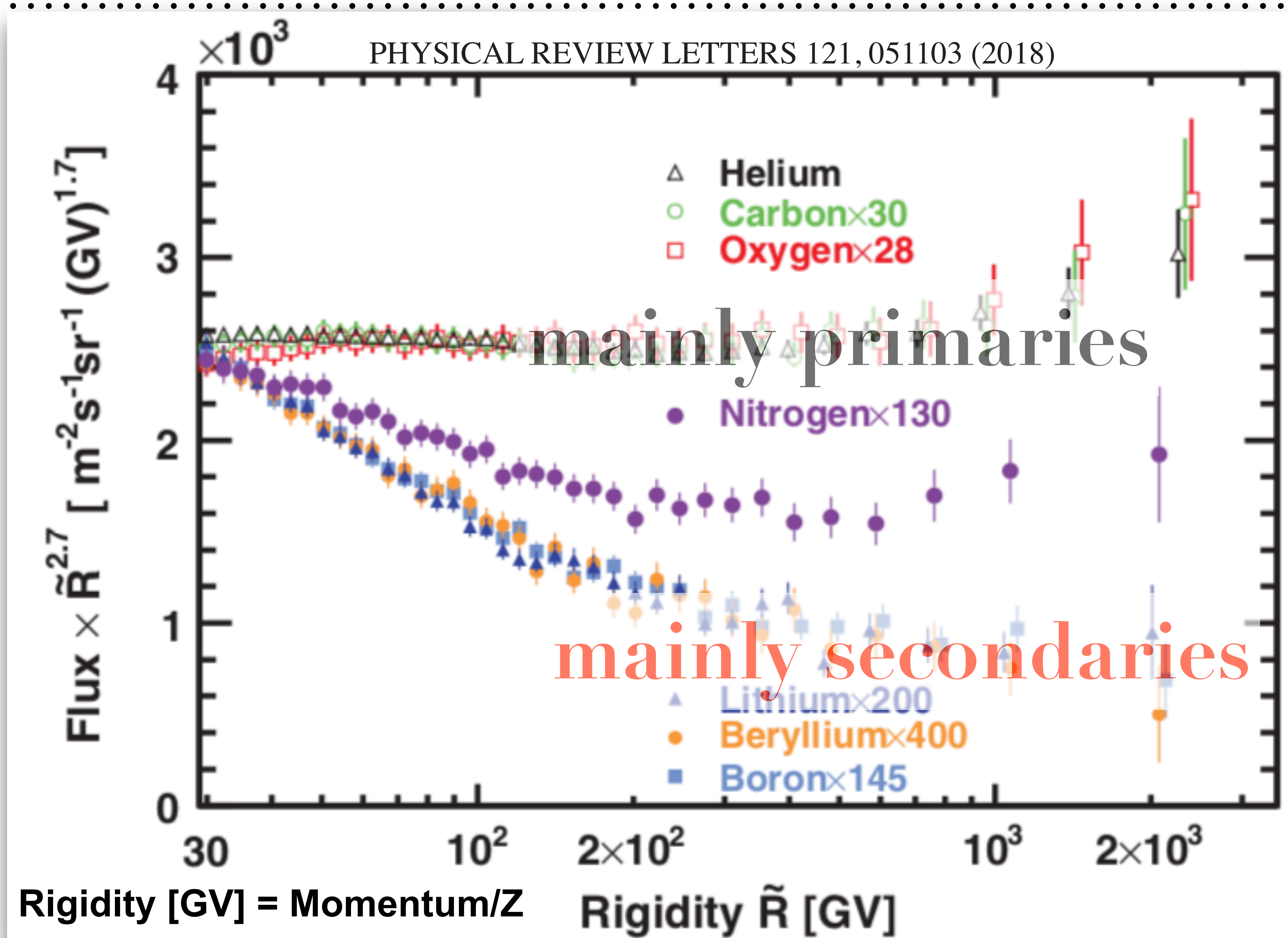


Secondary species

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



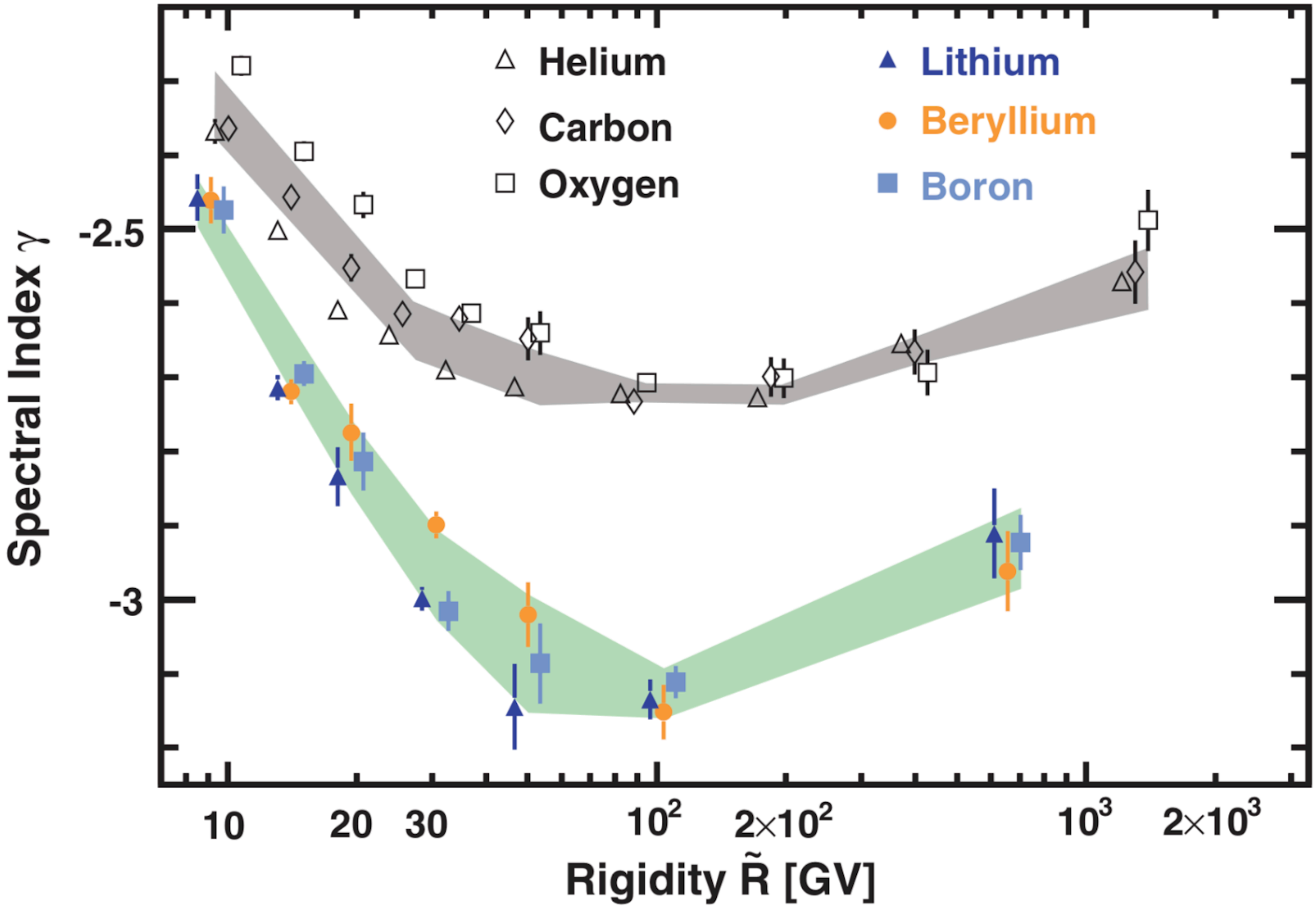
RIGIDITY DEPENDENCE OF NUCLEI



- **He, C, O**: They all deviate from a single power law above 200 GV and harden in an identical way.
- **Li, Be, B**: They all deviate from a single power law above 200 GV and harden more than primaries.
- **N**: The rigidity dependence is distinctly different from the primary and the secondary fluxes.

Flux spectral indices

PRL 120, 021101 (2018)



Spectral features in CR nuclei

- Cosmic ray fluxes below the knee cannot be described by a single power law.
- Primary species deviate from a single power law above 200 GV and harden in an identical way.
- Secondary species deviate from a single power law above 200 GV and harden more than primaries.
- Cosmic ray fluxes do not have universal spectral indices.

Plausible explanations

– Hardening of the injected spectrum from the source

[Biermann et al. 2010, Ohira et al. 2011, Yuan et al. 2011, and Ptuskin et al. 2013, Thoudam & Horandel 2013….]

- Same hardening expected for secondaries and primaries
- No hardening of the Sec./Prim. ratio

– Changes in the propagation properties in the Galaxy

[Ave et al. 2009, Tomassetti 2012, and Blasi et al. 2012,…]

- Stronger hardening expected for Secondaries
- Hardening of the Sec./Prim. Ratio

How to investigate the spectral features ?

The CR transport equation describes the spatial and energy evolution of the differential interstellar CR density per unit energy

$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_c\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$

$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = \;q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism}\;+\Gamma_{\beta\to\alpha}\right\}\,\psi_\beta$$

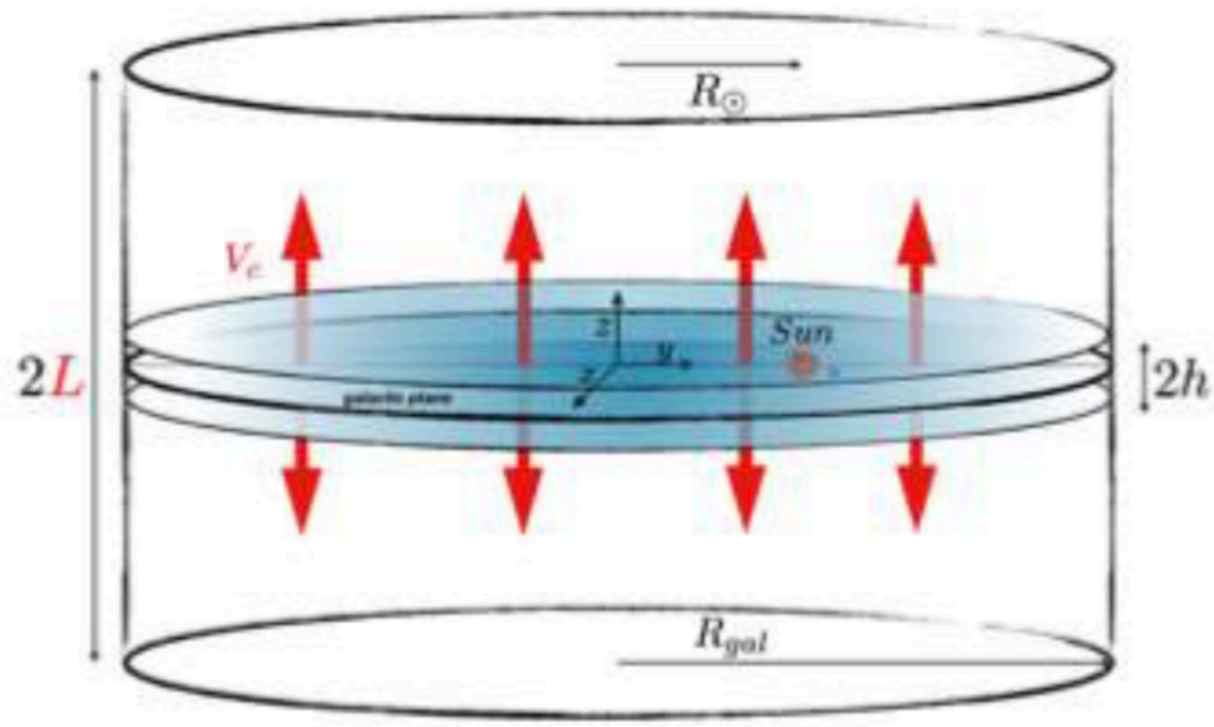
1D model and semi-analytic approach with the USINE code [arxiv:1807.02968]

The description of the galaxy

The magnetic halo confining the CRs is an infinite slab in the radial direction and of half- height L.

The radial boundary has only a minor quantitative impact on other transport parameters when the diffusion coefficient is taken as a scalar function.

The vertical coordinate z is the only relevant spatial coordinate. The sources of CRs and the ISM gas which they scatter off are taken homogeneous in an infinitely thin disk at z = 0, with an effective half-height h = 100 pc.



The diffusion coefficient

The diffusion coefficient describes the scattering of CRs off magnetic turbulence.

We take it as a scalar function, homogeneous and isotropic all over the magnetic slab.

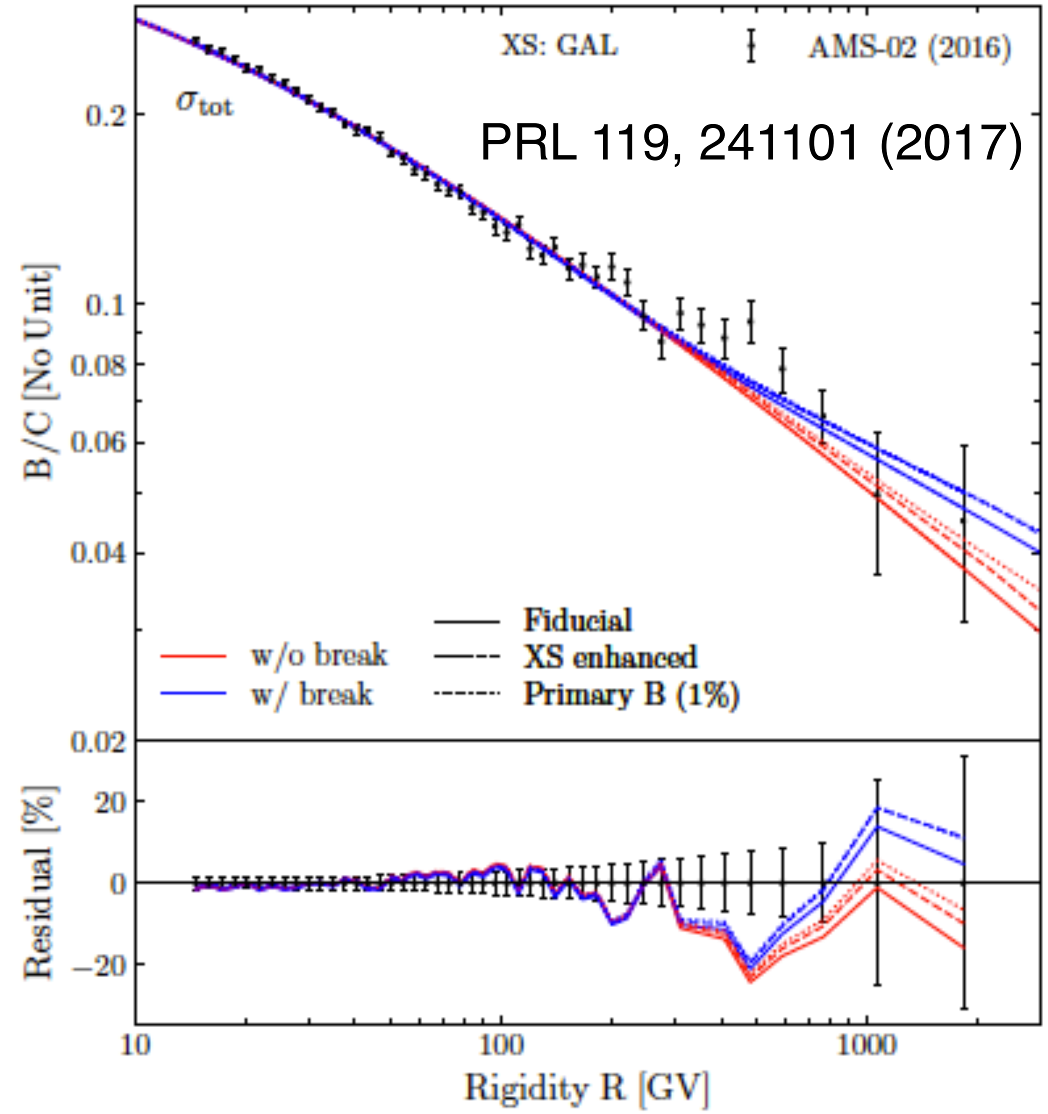
In the conventional model for CR transport it is described as:

$$K(R) = K_0 \beta (R/\mathrm{GV})^{\delta}$$

Indications for a high-rigidity break in the cosmic-ray diffusion coefficient

Yoann Génolini,[1,*] Pasquale D. Serpico,[1,†] Mathieu Boudaud,[2] Sami Caroff,[3] Vivian Poulin,[1,4] Laurent Derome,[5] Julien Lavalle,[6] David Maurin,[5] Vincent Poireau,[7] Sylvie Rosier,[7] Pierre Salati,[1] and Manuela Vecchi[8]

At HE (above ~ 10 GV) we expect the B/C to be dominantly affected by the diffusive propagation and nuclear cross sections.

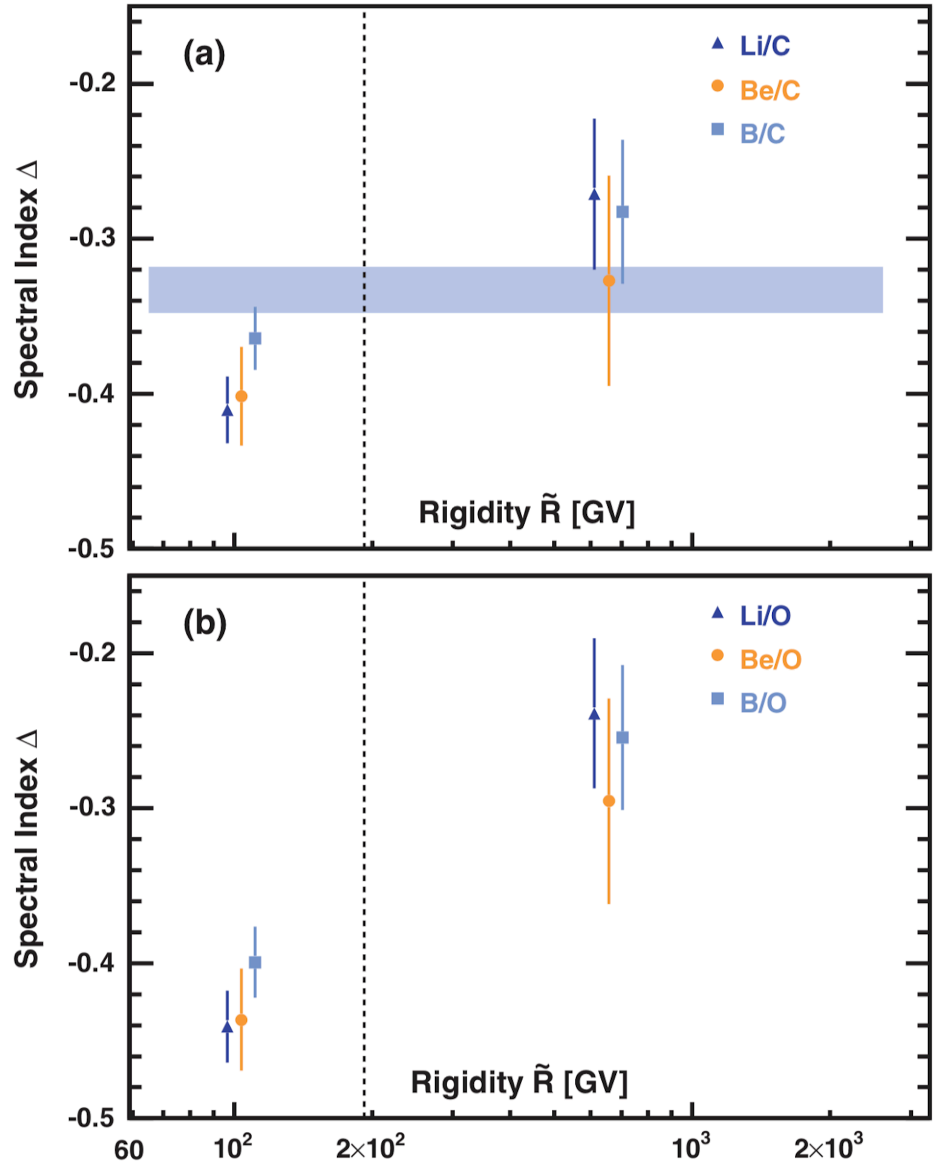


- We analyse the high energy range of the AMS B/C (2016) and find indications for a diffusive propagation origin for the broken power-law spectra found in protons and helium nuclei.
- The result is robust with respect to currently estimated uncertainties in the cross sections.

[see also arxiv:1902.09343, arxiv:1712.00002 for independent analyses]

Experimental confirmation

PRL 120, 021101 (2018)



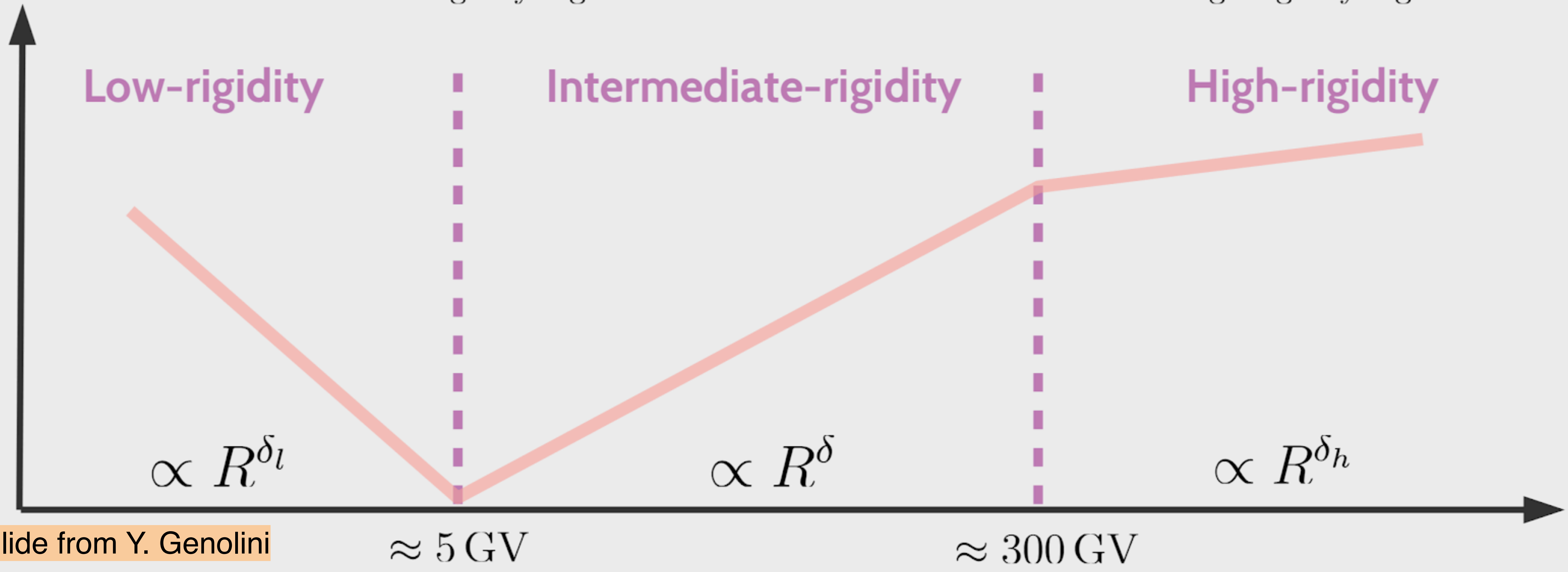
The secondary-to-primary flux ratios (B/C, Li/C etc) deviate from a single power law by 0.13 +/- 0.03. This result supports the interpretation of the hardening in terms of a change in the propagation properties in the Galaxy.

Two-break diffusion coefficient

-> Diffusion is assumed to be ***homogeneous*** and ***isotropic.***

-> We introduce several breaks in the diffusion coefficient:

$$K(R) = \beta^{\eta} K_{10} \underbrace{\left\{ 1 + \left(\frac{R}{R_{\mathrm{l}}} \right)^{\frac{\delta_{\mathrm{l}} - \delta}{s_{\mathrm{l}}}} \right\}^{s_{\mathrm{l}}}}_{\text{low-rigidity regime}} \underbrace{\left\{ \frac{R}{(R_{10} \equiv 10\,\mathrm{GV})} \right\}^{\delta}}_{\text{intermediate regime}} \underbrace{\left\{ 1 + \left(\frac{R}{R_{\mathrm{h}}} \right)^{\frac{\delta - \delta_{\mathrm{h}}}{s_{\mathrm{h}}}} \right\}^{-s_{\mathrm{h}}}}_{\text{high-rigidity regime}} .$$

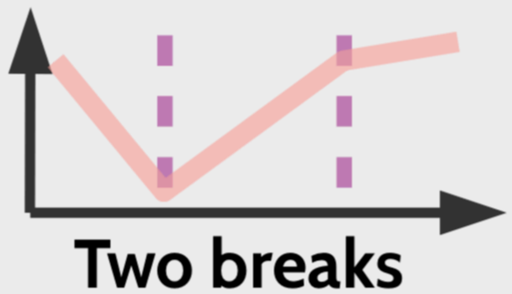


Slide from Y. Genolini

Propagation benchmark models

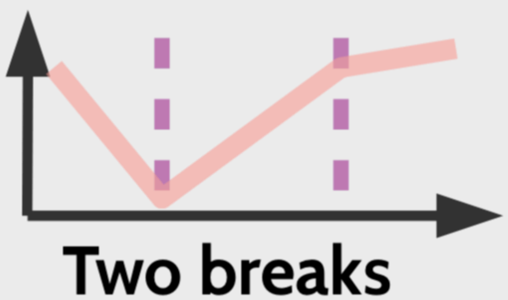
We define three benchmark models:

BIG V_c K_{pp} $K(E)$



6 free parameters

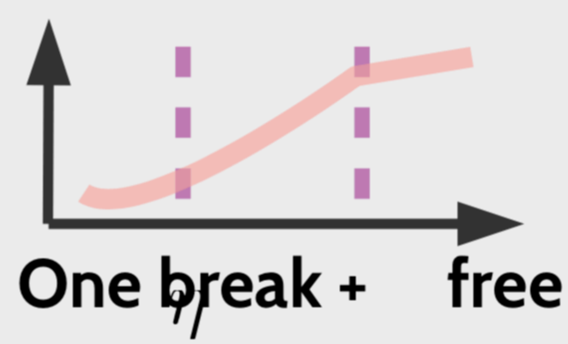
SLIM $K(E)$



4 free parameters

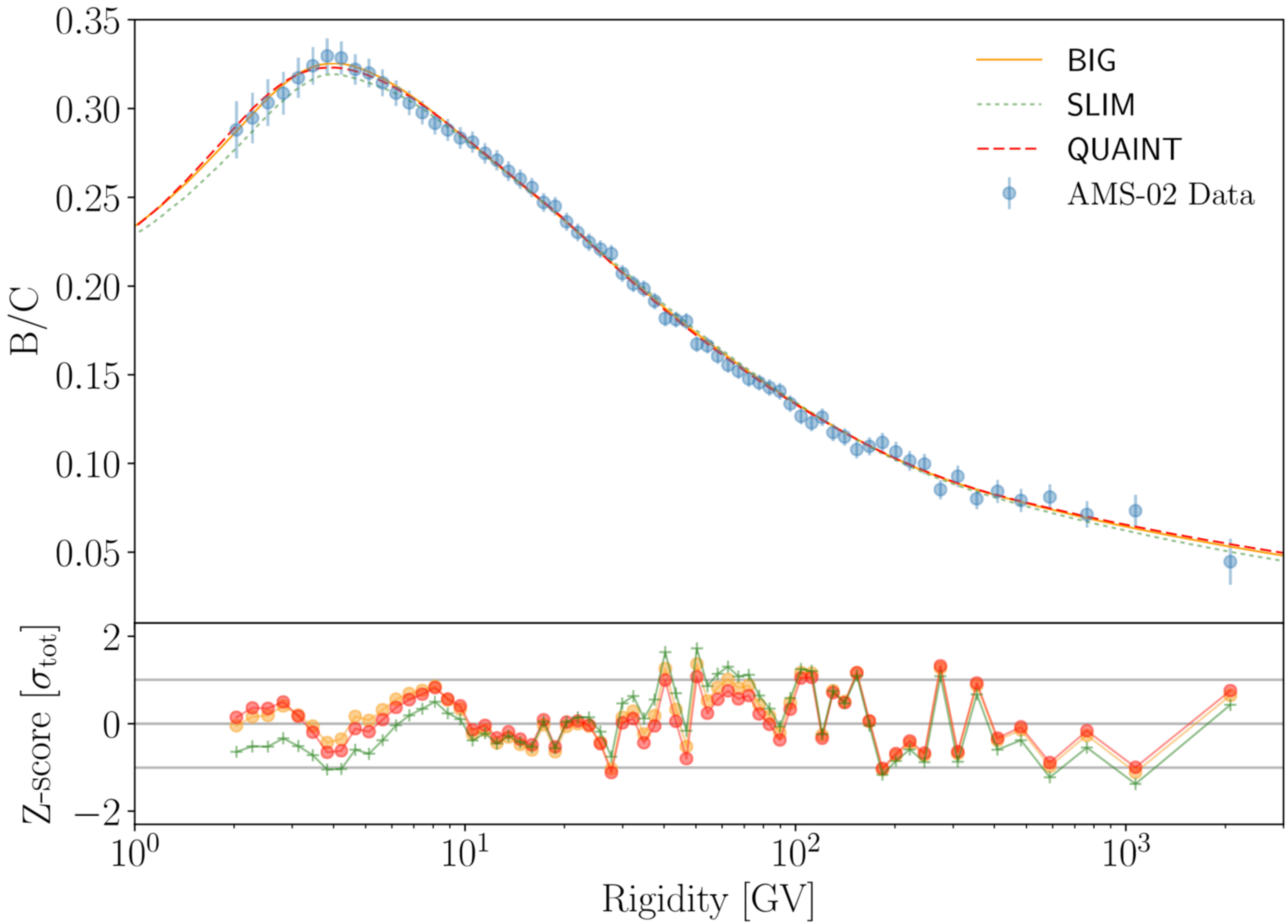
Slide from Y. Genolini

QUAINT V_c K_{pp} $K(E)$



5 free parameters

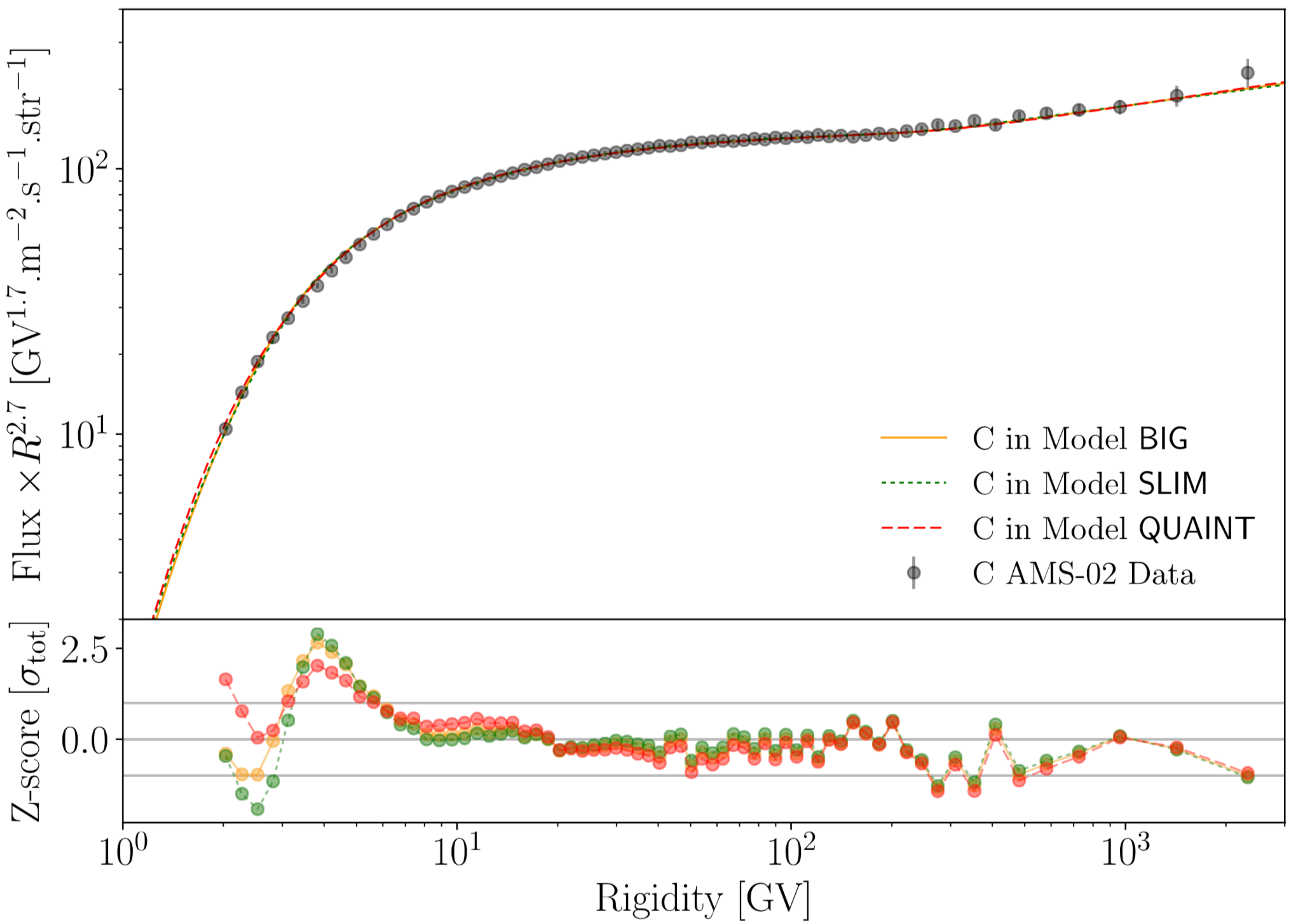
Fit Results



BIG
SLIM
QUAINT
AMS-02 Data
B/C
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Z-score [σ_{tot}]
2
0
−2
10^0
10^1
10^2
10^3
Rigidity [GV]

What about other CR species ?

Excellent fit to He, C and O (primary species) AMS-02 data.
Injection is described by a single power law in rigidity



The source spectral index for the proton flux is steeper.

Cosmic ray antiparticles

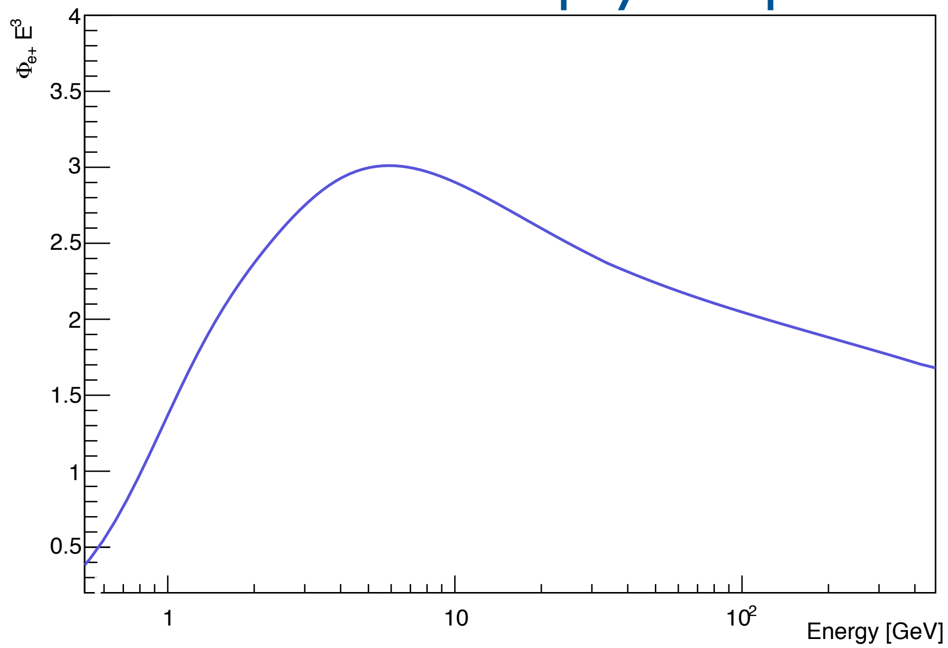
Antimatter in cosmic rays

Positrons and antiprotons are known to be secondary particles produced as a consequence of the interaction of primary cosmic rays with the interstellar medium (p+p$_{ISM}$, p+He$_{ISM}$, He+He$_{ISM}$).

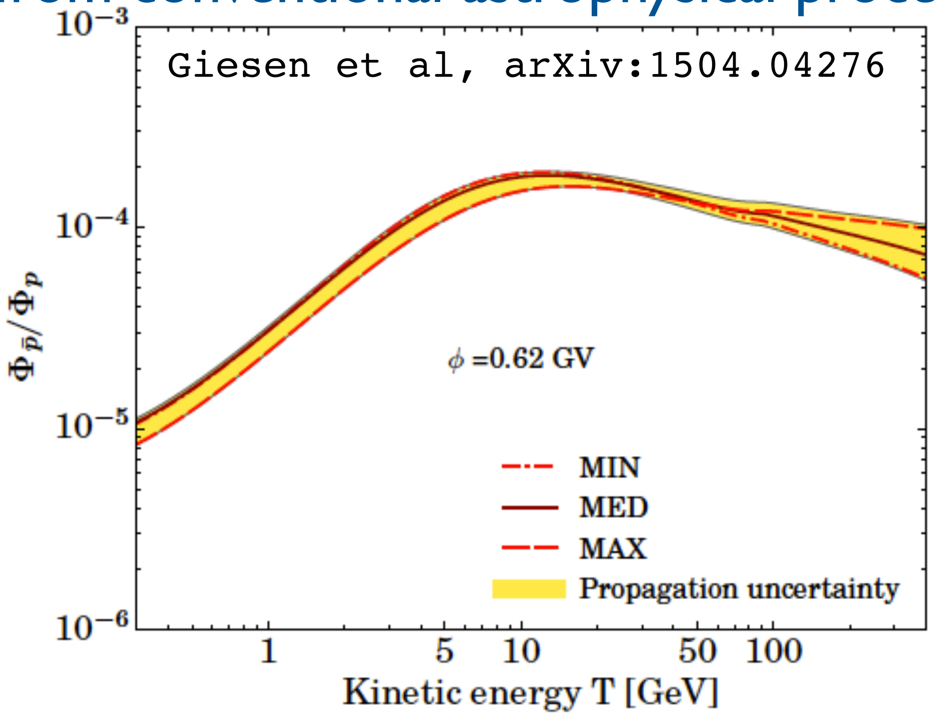
$$p + p_{\rm ism} \rightarrow \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

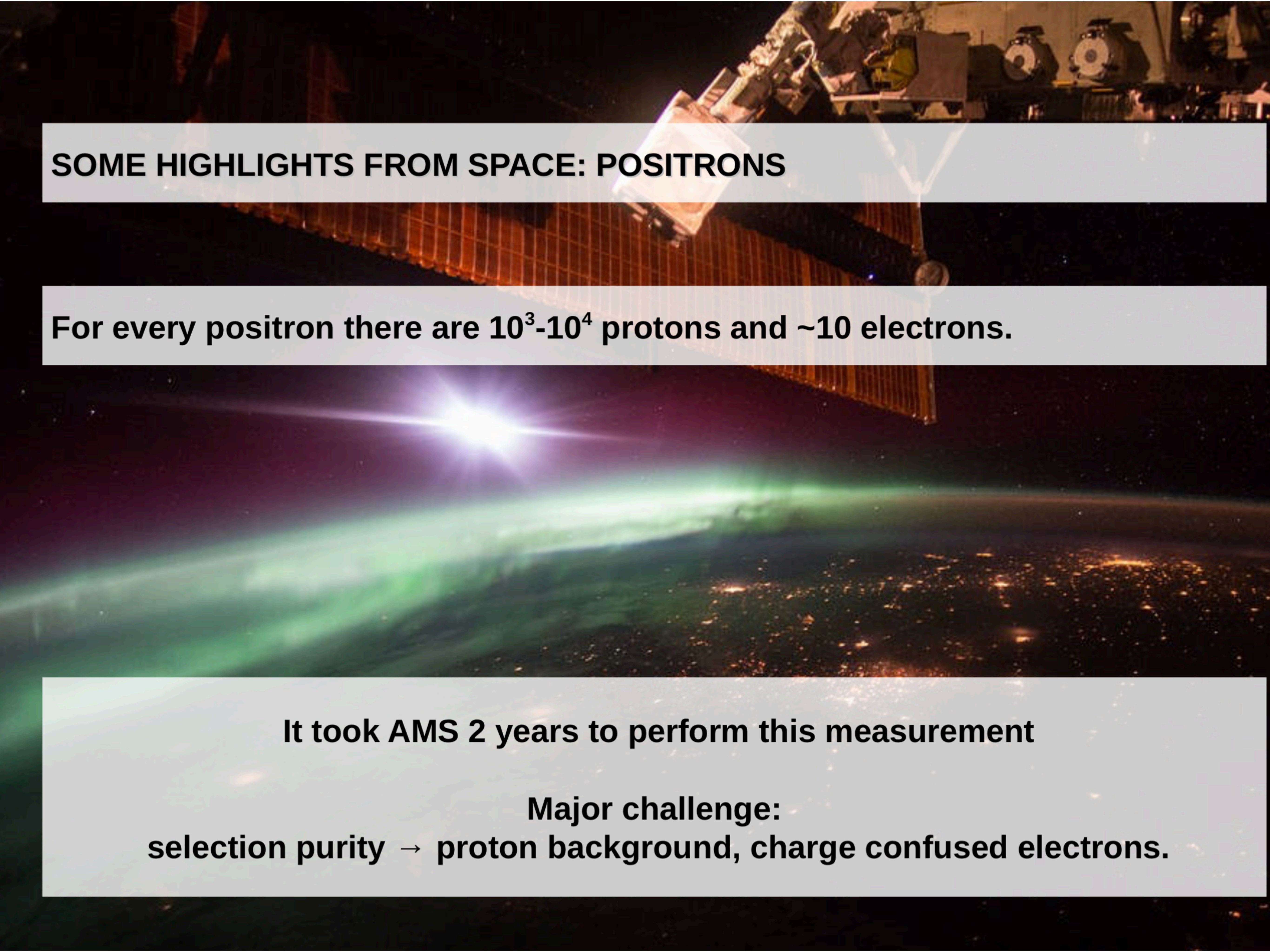
- Subdominant component: in the GeV-TeV region the e+/e- ~ 0.1, while anti-p/p ~ 10^{-4}
- Given their low fluxes, positrons and antiprotons are good candidates for indirect dark matter search: a dark matter signal would appear as a distortion in the expected flux, estimated from conventional mechanisms.

Positron flux from conventional astrophysical processes



Antiproton-to-proton ratio from conventional astrophysical processes





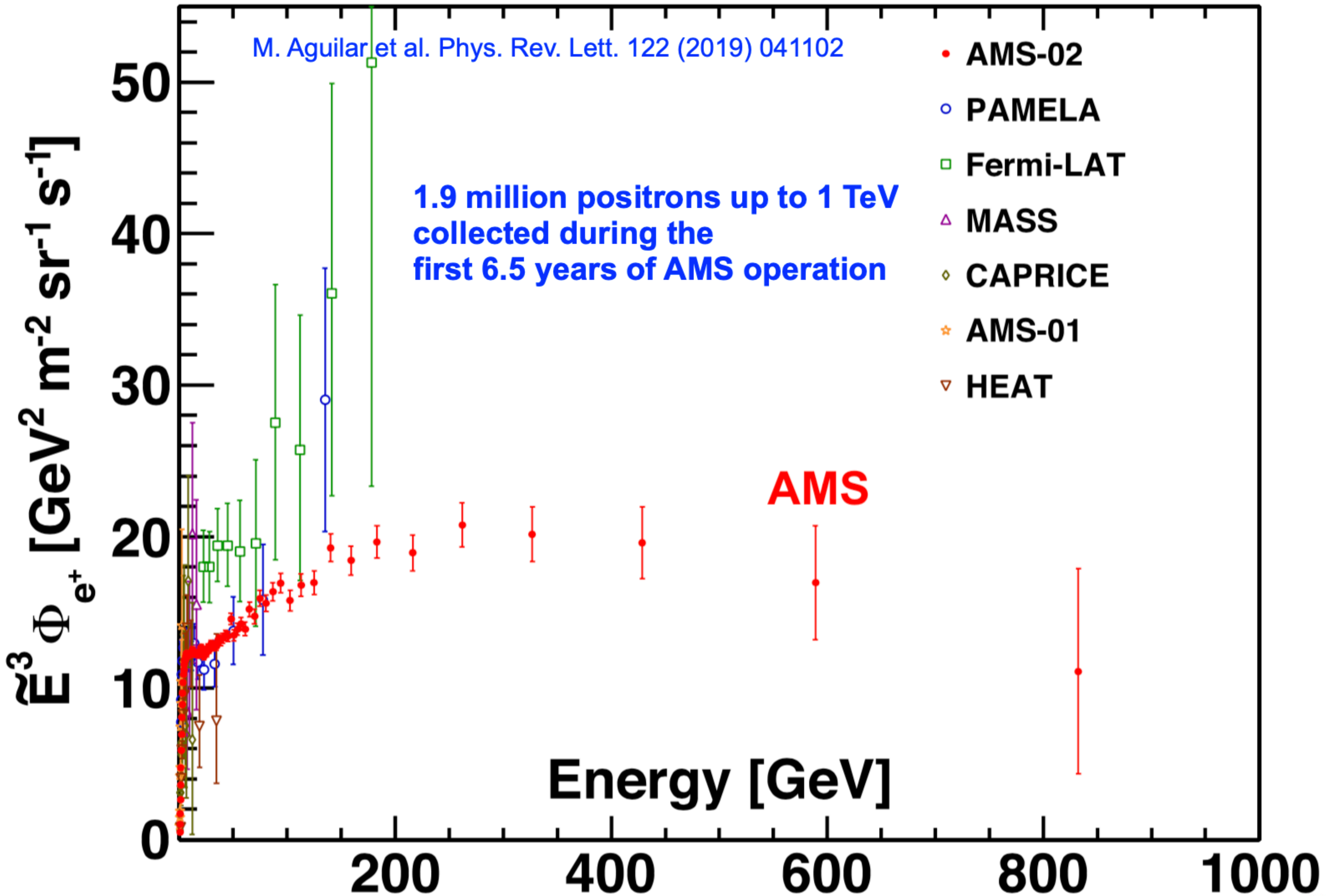
SOME HIGHLIGHTS FROM SPACE: POSITRONS

For every positron there are 10^3-10^4 protons and ~10 electrons.

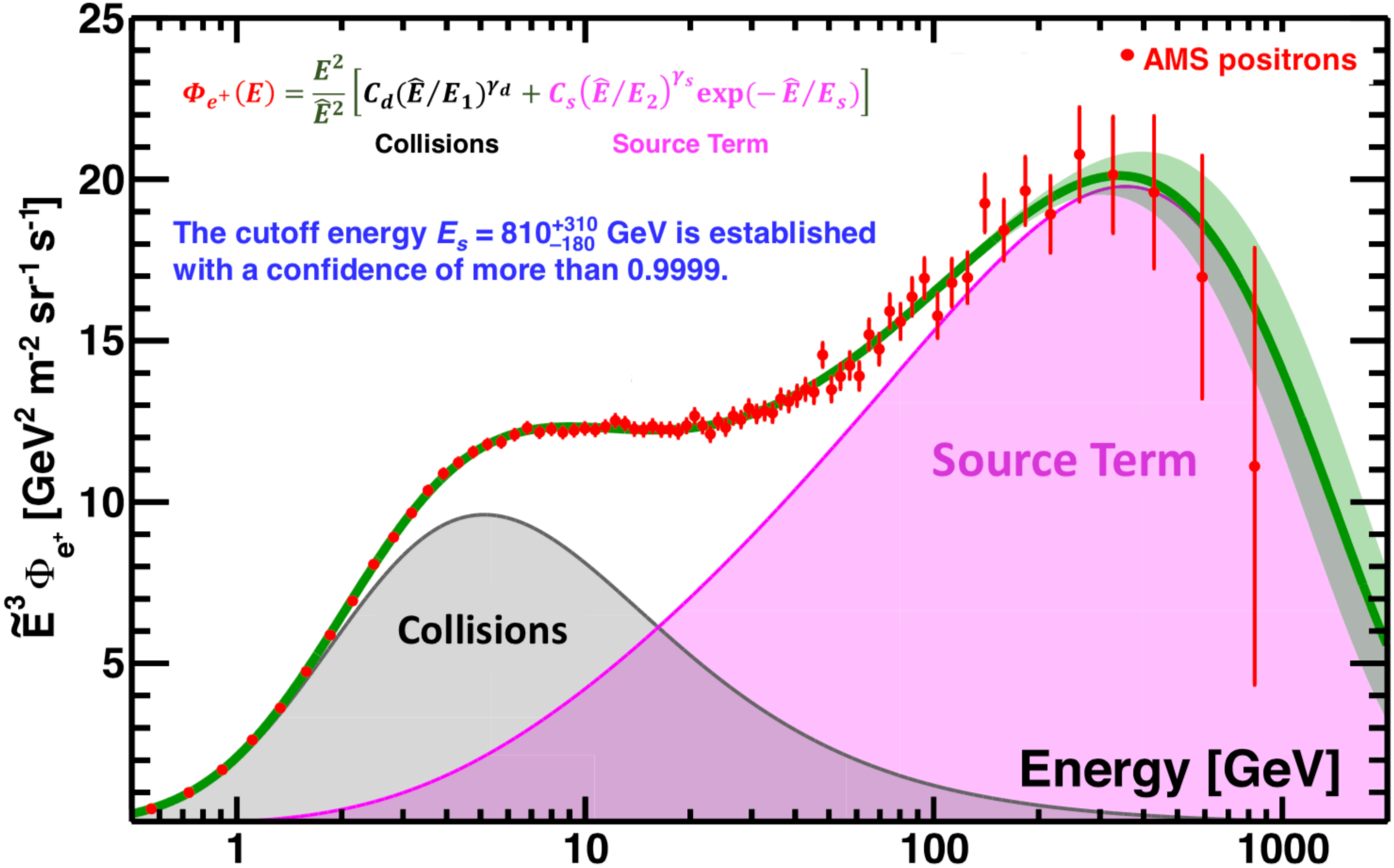
It took AMS 2 years to perform this measurement

Major challenge:
selection purity → proton background, charge confused electrons.

Positron flux



The positron flux is the sum of low-energy part from cosmic ray collisions plus a new source at high-energy.

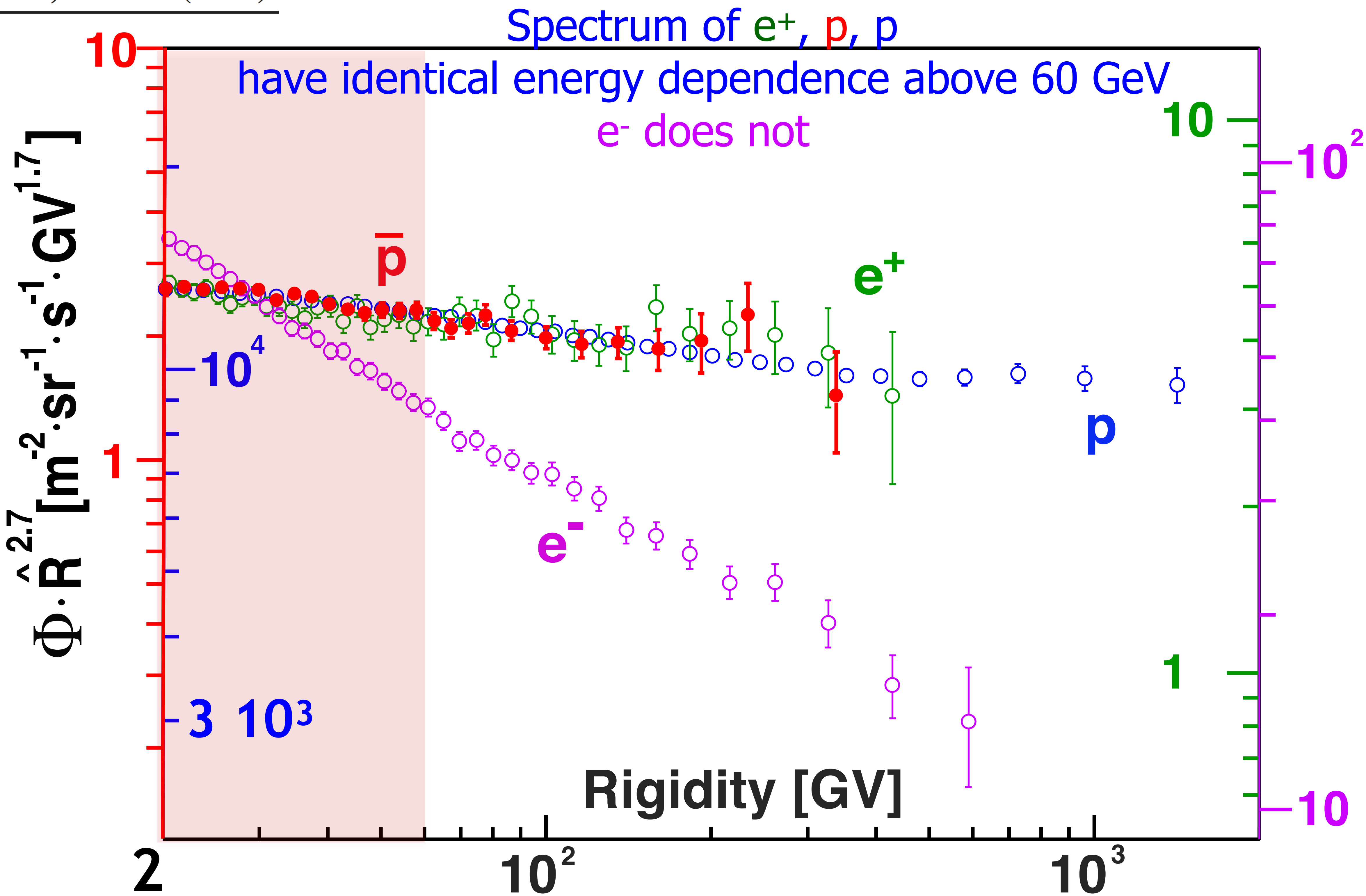


Interpretations of the positron flux

- Astrophysical nearby sources (pulsars or SNR).
- Exotic sources (DM annihilation or decay).
- Unconventional propagation mechanisms (disfavoured by B/C).

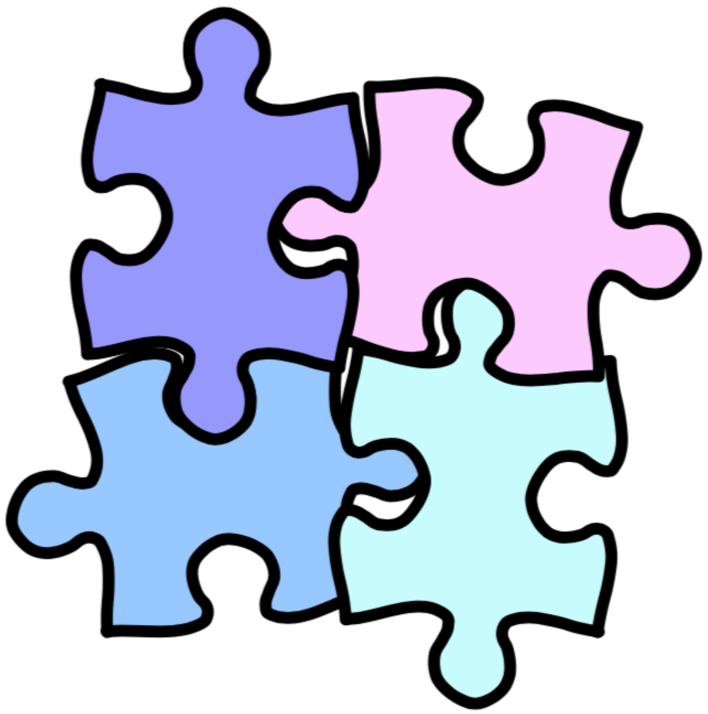
Rigidity dependence of light CRs

PRL **117,** 091103 (2016)



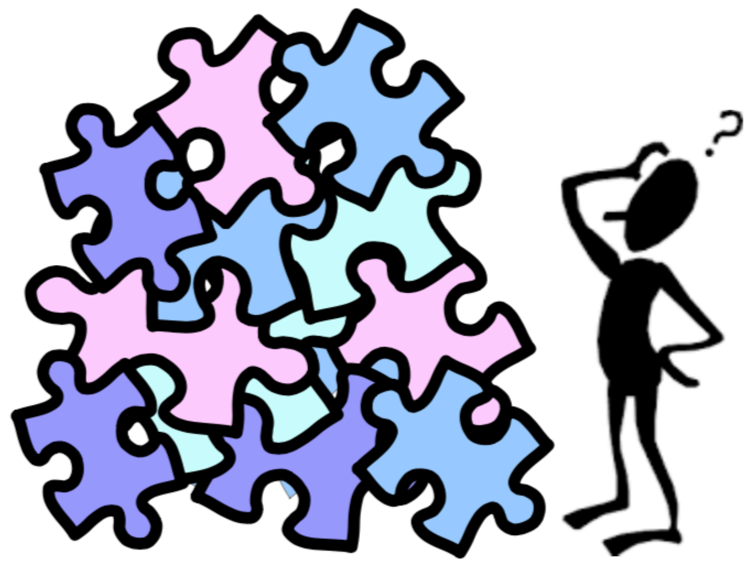
Where we are

Few decades ago …



A “standard paradigm” for cosmic ray transport (with some problems).

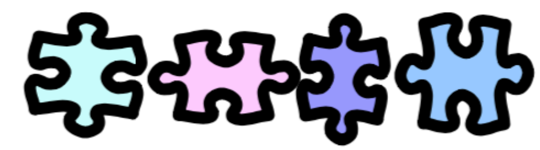
You are here



The accuracy of the data challenges the “standard paradigm”.

Future

CALET, DAMPE, ISS-CREAM,...

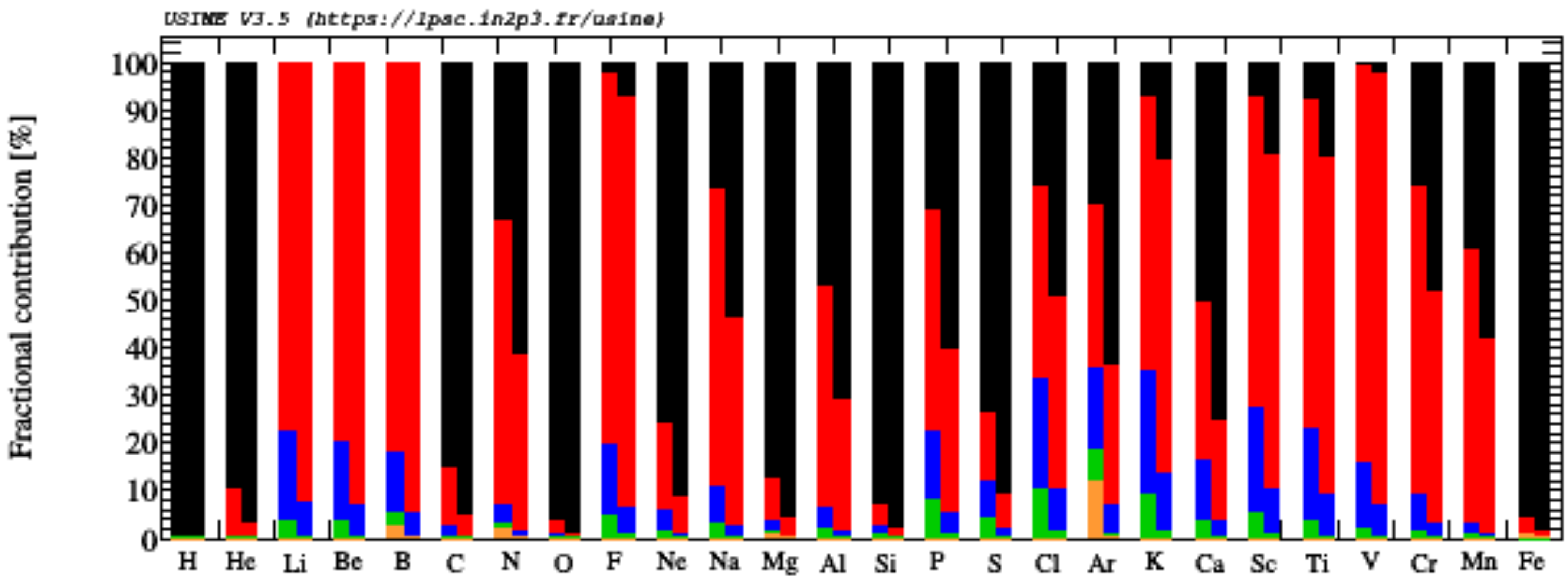


- Statistics!
- High energies!
- New answers and new questions!
- Only matter.

Backup

Secondary CR production

Relative contributions per production process for elemental fluxes (at 50 and 2 TV).



The species with the highest primary content are H, O, Si, and Fe (black), while Li, Be, B, F, and Cl to V have the highest secondary component from both single (red) and multi-step production (blue and green).