Review on direct measurements of Cosmic Rays

May 22nd, 2018
Vulcano Workshop, Vulcano, Italy

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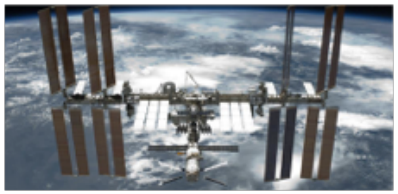
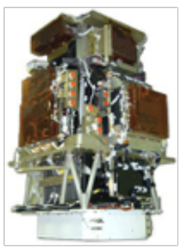
THE SPECTRUM OF COSMIC RAYS

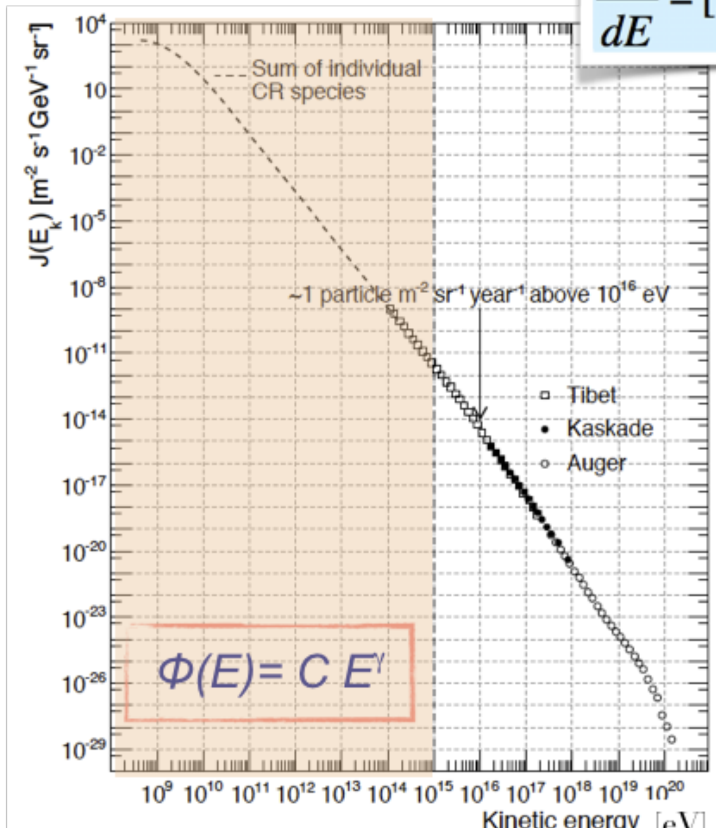
all particle flux

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

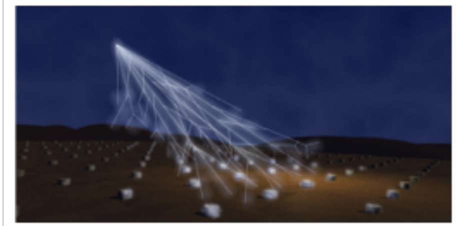
Direct measurements

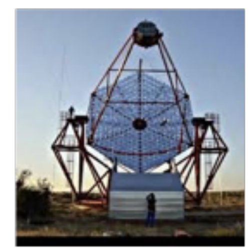






Indirect measurements



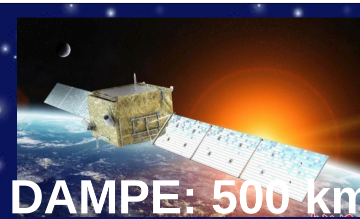


at first sight … a featureless power law

L. Baldini, arXiv: 1407.7631

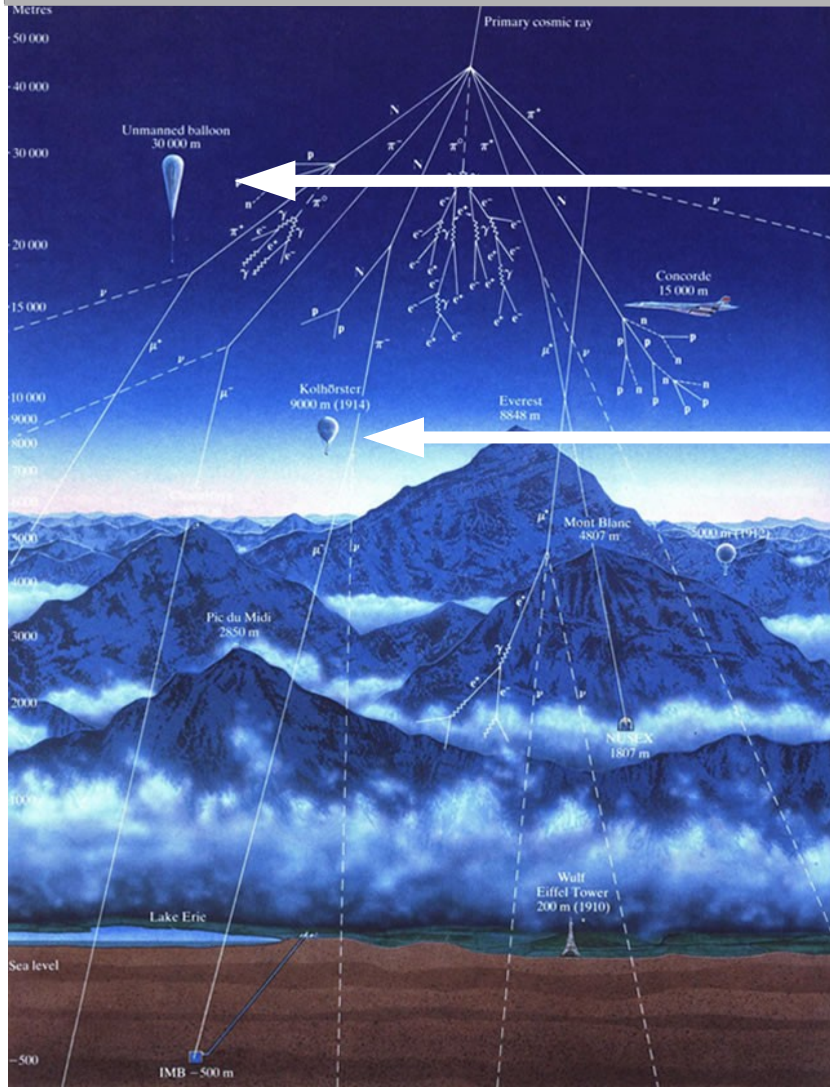
ISS: 400 km
AMS-02
CALET
ISS-CREAM

PAMELA: 350-600 km



DAMPE: 500 km

Fermi: 550 km



Modern balloons
~30 km

Kolhörster
9 km

CREAM launch,
McMurdo

Antares
KM3NeT

IceCube,
South Pole

See A. Capone, M. Circella, C. Kopper

Auger Observatory,
Argentina

See V. de Souza today

PHYSICS QUESTIONS IN DIRECT COSMIC RAY MEASUREMENTS

- What is the origin of galactic cosmic rays and how do they propagate to us?
- Do we understand the diffuse galactic gamma-ray emission from cosmic ray interactions or is there room for new physics (e.g. Dark Matter)
- What is the nature of the elusive Dark Matter? Do we see annihilation/decay signals in cosmic rays? → Antimatter! Photons, neutrinos.
- Is there primordial antimatter left in our Universe?

PHYSICS QUESTIONS IN DIRECT COSMIC RAY MEASUREMENTS

- **What is the origin of galactic cosmic rays and how do they propagate to us?**
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} **Magnet!**

The “conventional scenario” of galactic cosmic rays

Cosmic ray fluxes below the knee can be described by a single power law, the spectral index being the result of the following processes:
-production
-acceleration
-propagation

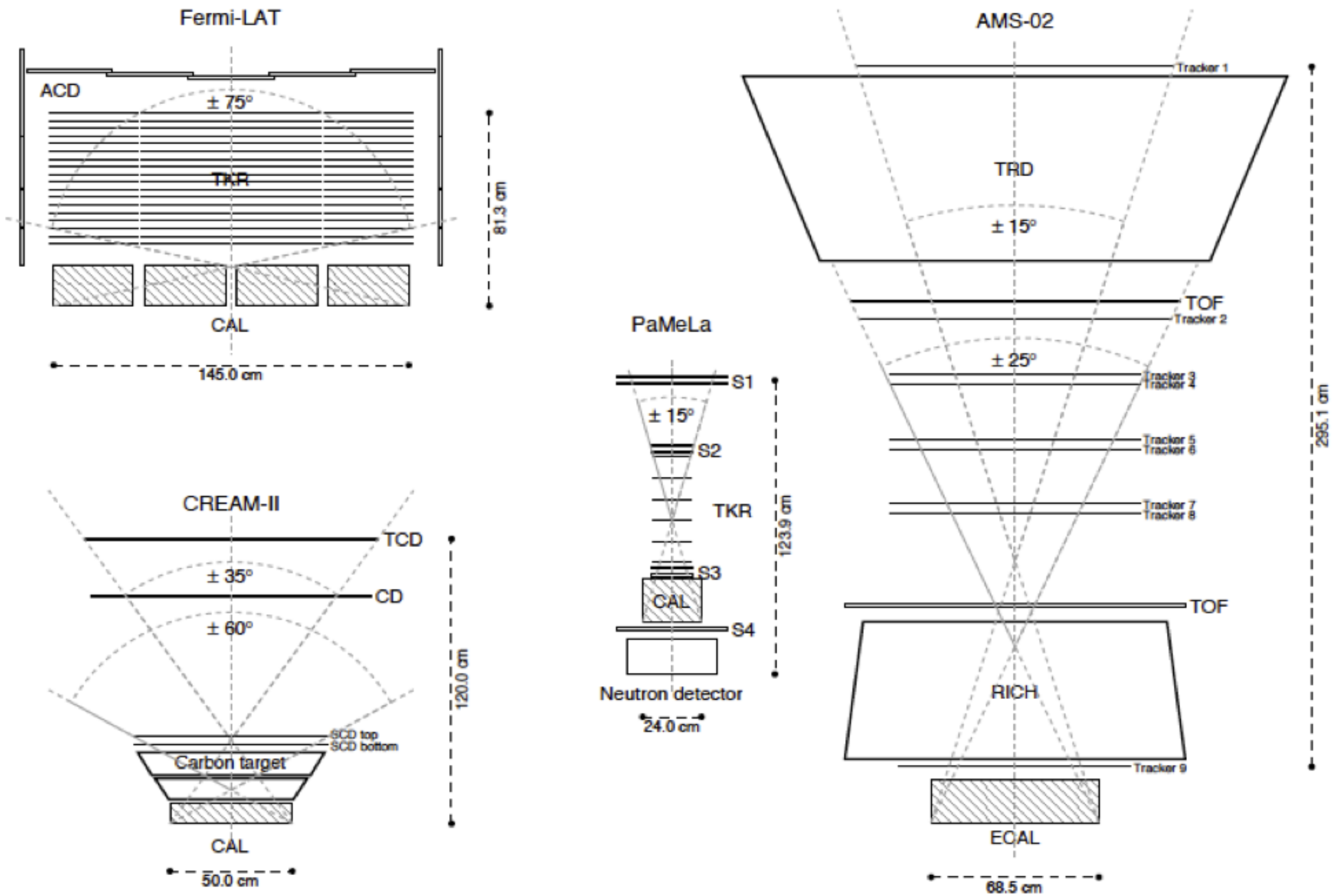
Primary cosmic ray fluxes have universal (species independent) spectral indices.

Antimatter component is purely of secondary origin (no sources of CR antimatter).

Precise measurements provided by the current generation of CR detectors (PAMELA, AMS-02, Fermi-LAT,CREAM,CALET,DAMPE…) have been providing new insight to the physics of cosmic rays, by challenging the previous statements.

P. Serpico ICRC2015
L. Drury ICRC2017
see also G. Morlino today
see also F. Aharonian today

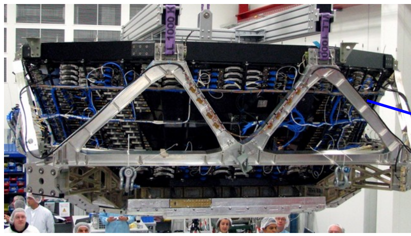
SOME RECENT SPACEBORNE DETECTORS



L. Baldini, arXiv: 1407.7631

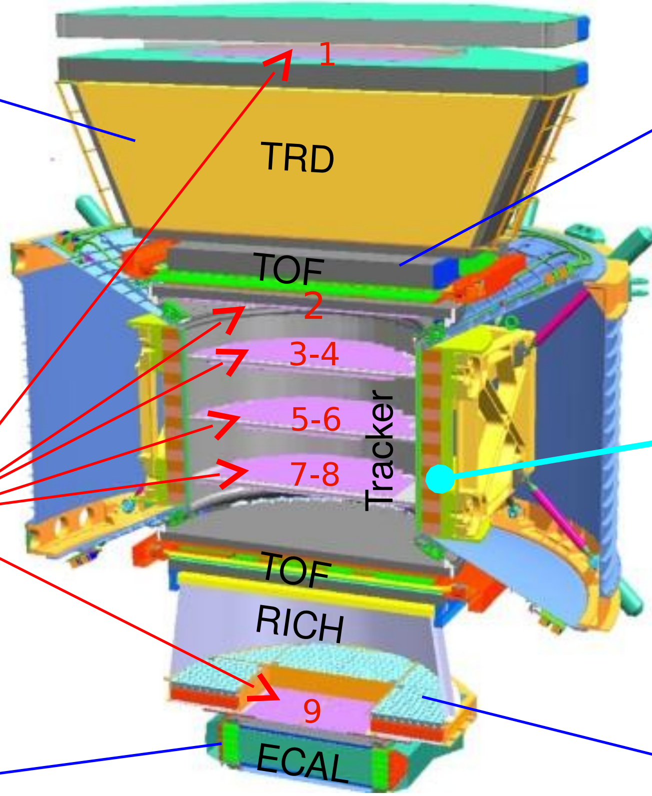
AMS-02: A TeV PRECISION SPECTROMETER

Transition Radiation Detector
Identify e^+, e^-

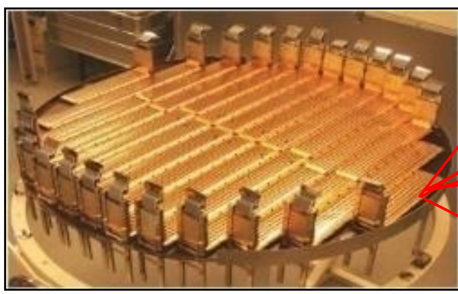


Particles and nuclei are defined by their charge (Z) and energy (E) or rigidity (R=p/Z)

Time of Flight
Z, E

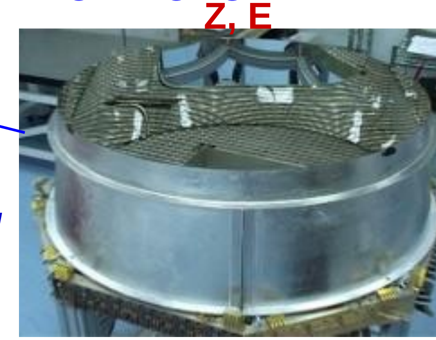


Silicon Tracker
Z, R

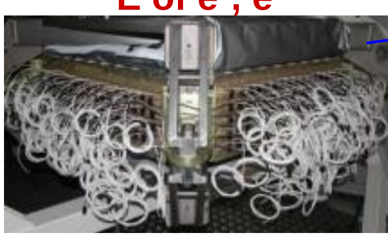


Magnet
±Z, R

Ring Imaging Cherenkov
Z, E



Electromagnetic Calorimeter
E of e^+, e^-



Charge and energy are measured independently by many detectors

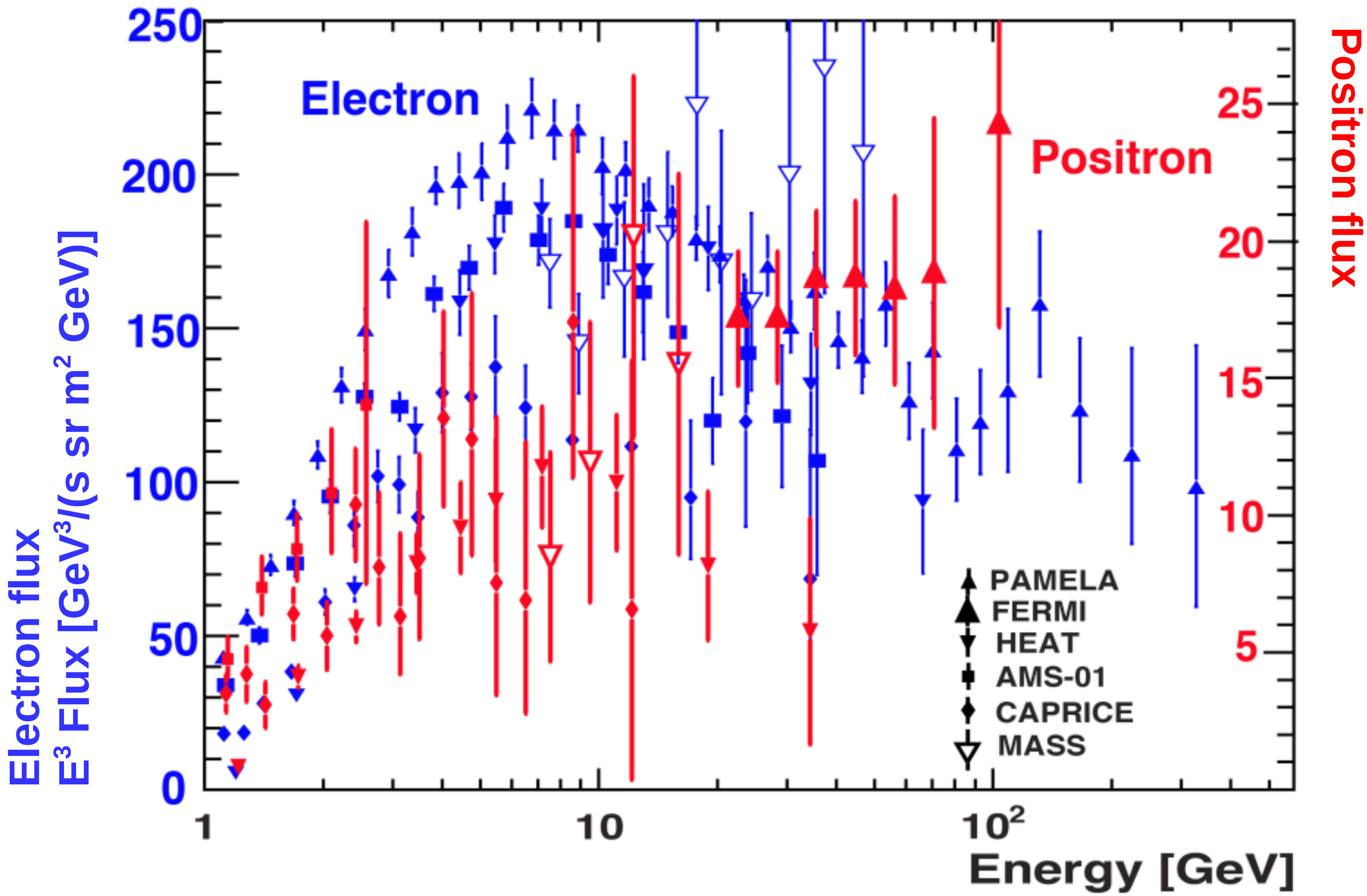
SOME HIGHLIGHTS FROM SPACE: POSITRONS

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

It took AMS 2 years to perform this measurement

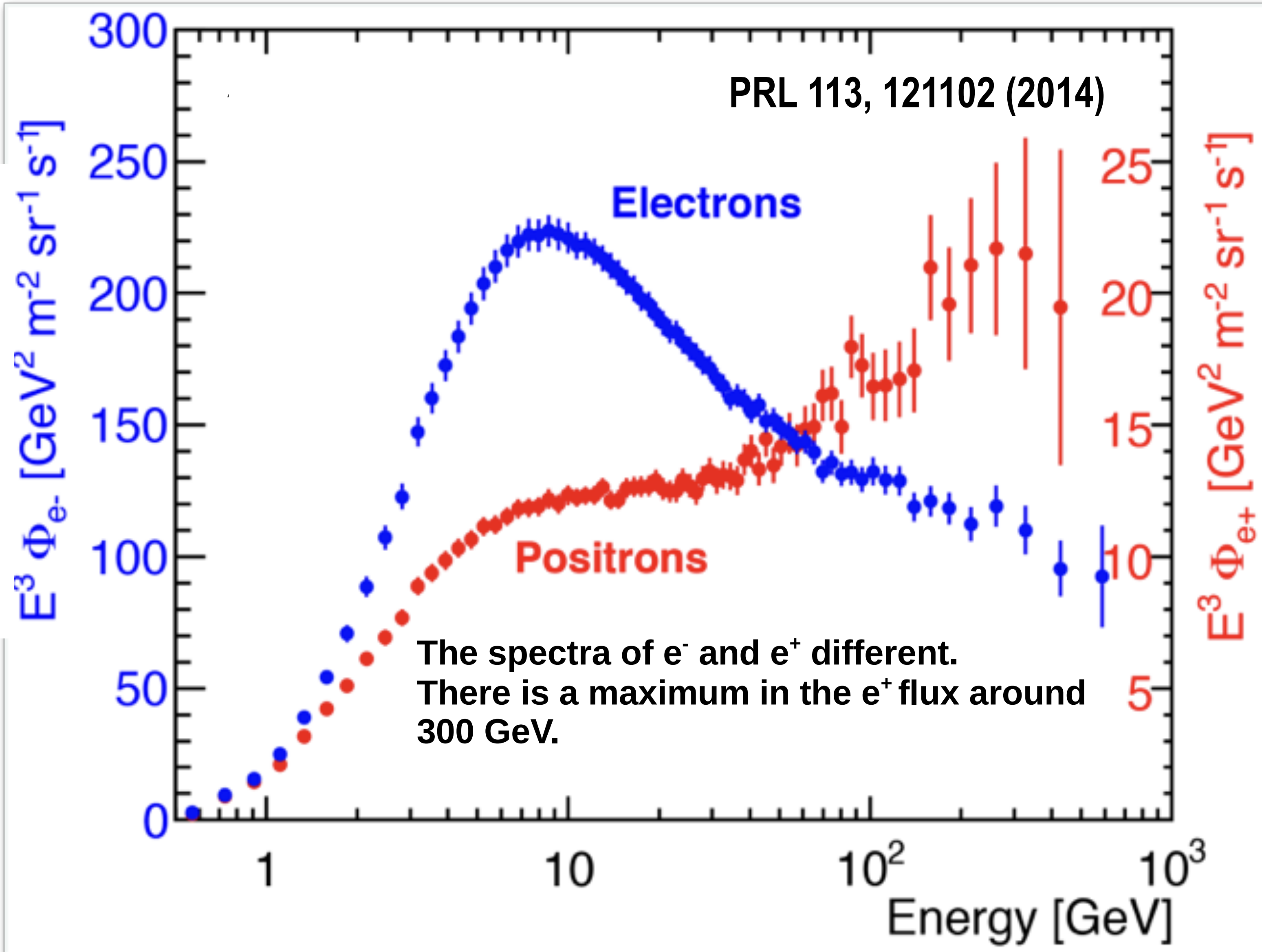
Major challenge:
selection purity → proton background, charge confused electrons.

ELECTRONS AND POSITRONS…. *a few years ago*



ELECTRONS AND POSITRONS WITH AMS

Electron flux



Positron flux

The data are consistent with a symmetric contribution in e^+ and e^-.

Interpretation of the positron data

The data are consistent with a symmetric contribution in e^+ and e^-.

Could be explained by:

- **Dark Matter annihilation**
  → *O*(100) papers
- **Astrophysical point sources like pulsars**
  → *O*(100) papers
- **Secondary e^+ production**
  → a few papers

SOME HIGHLIGHTS FROM SPACE: ANTIPROTONS

There is only 1 antiproton for 10,000 protons.

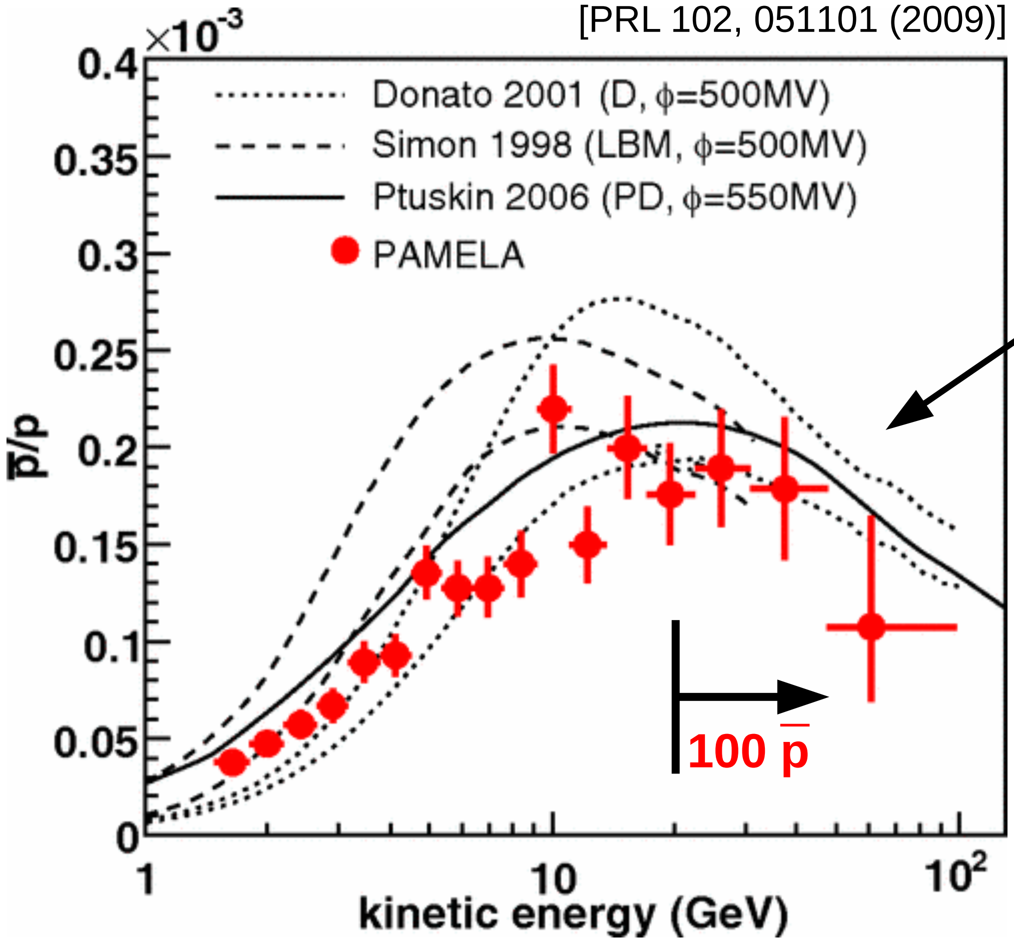
→ A percent precision experiment requires a background rejection close to 1 in a million.

It took AMS 5 years to perform this measurement.

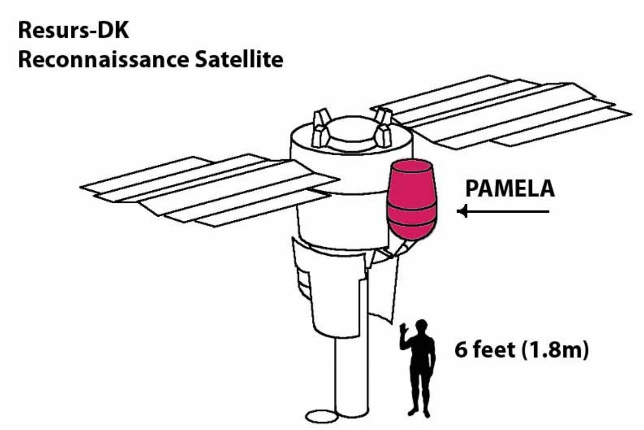
Major challenge:
purity of selection and tracker unfolding.

ANTIPROTON/PROTON RATIO … WITH PAMELA

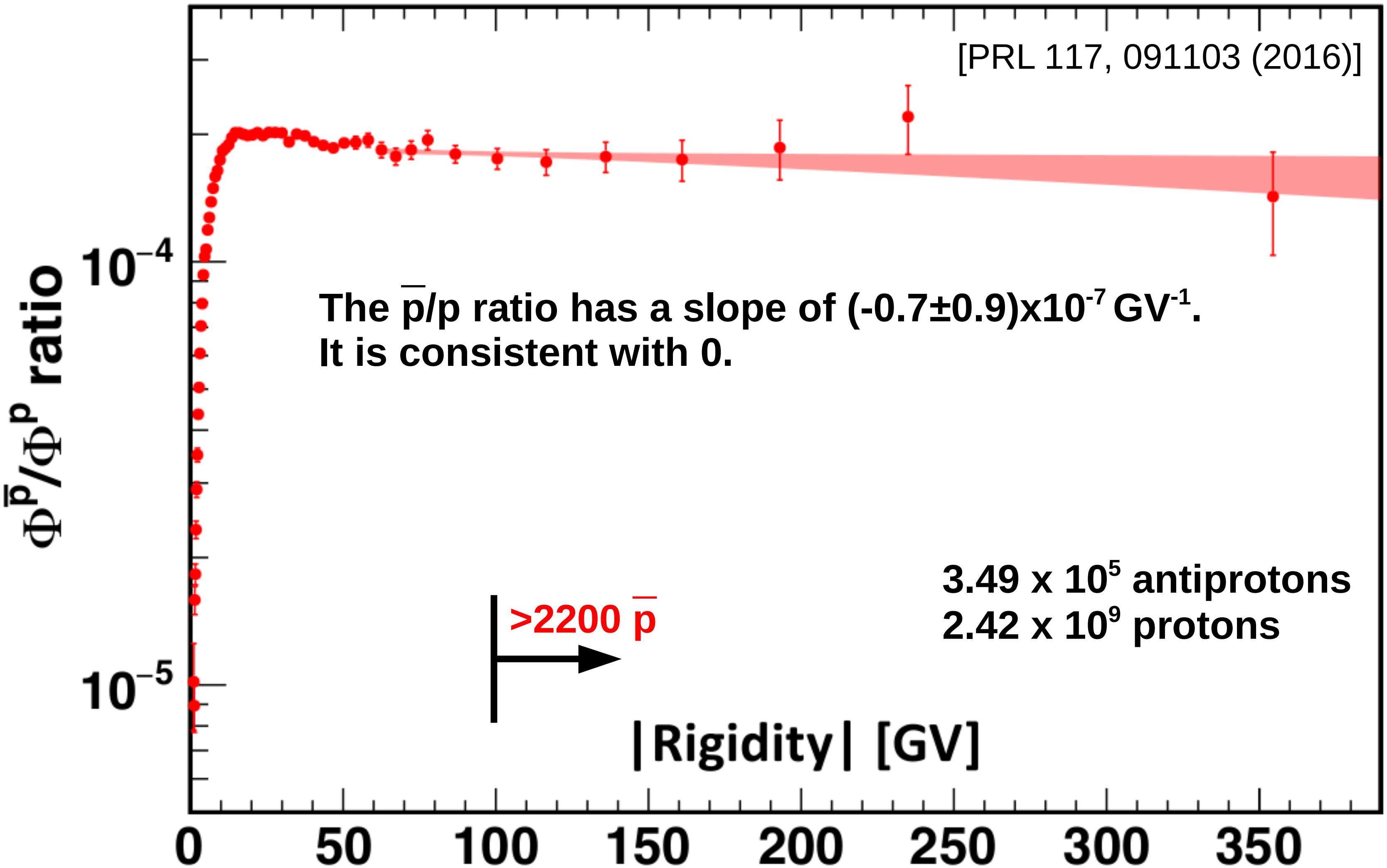
[PRL 102, 051101 (2009)]



Model expectation for secondary $\bar{p}$ production.



THE ANTIPROTON/PROTON RATIO IS FLAT

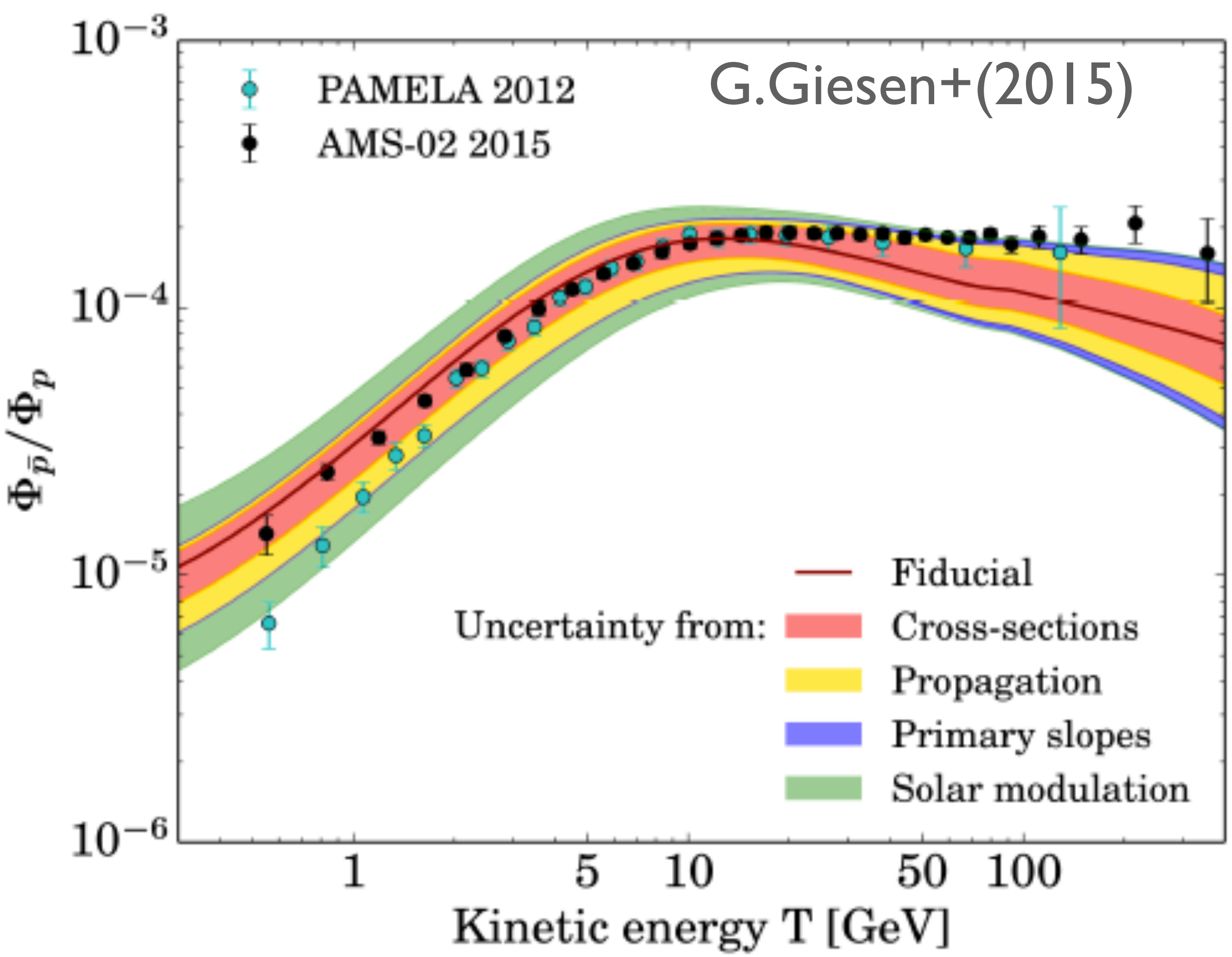


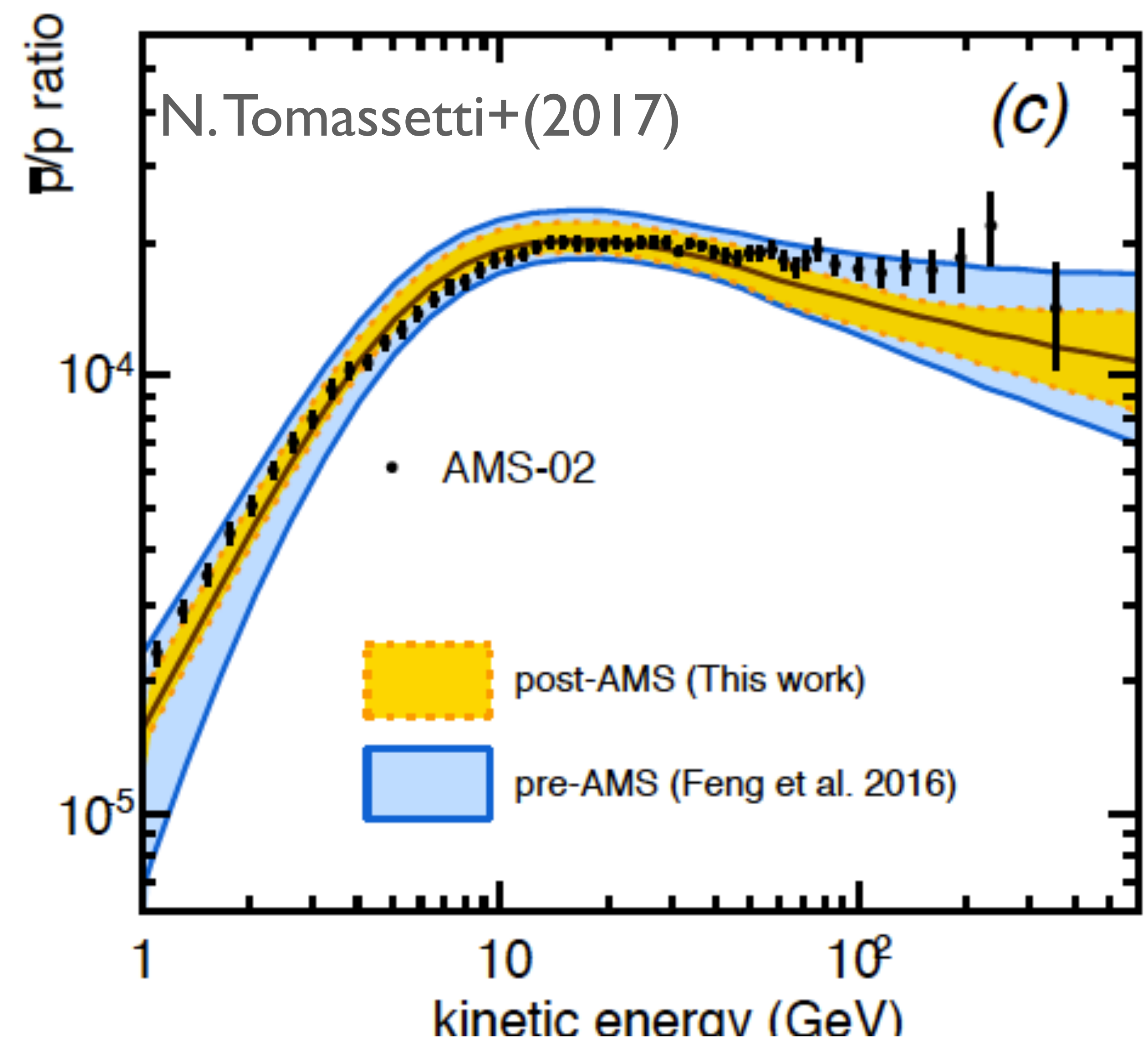
Interpretation of anti-p data

Anomaly in antiprotons ?

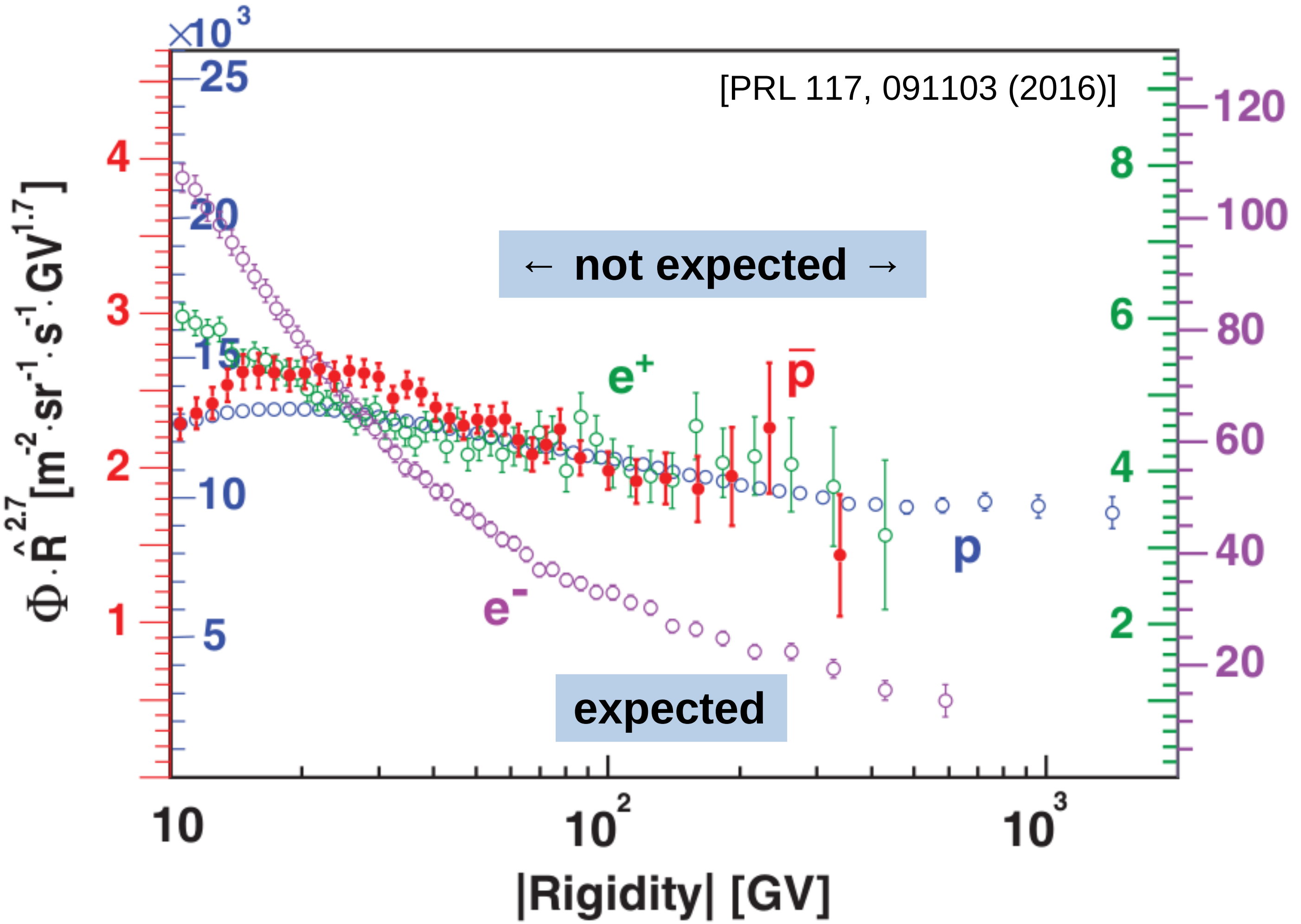
be careful …

Uncertainties in the astrophysical background predictions are reducing with the new results of AMS-02, however the x-section uncertainties in some cases are 20-50% or higher. Stay tuned …





RIGIDITY DEPENDENCE OF ELEMENTARY PARTICLES



The rigidity dependence of e^+, $\bar{p}$, p is identical from 60-500 GV.

What we are learning from cosmic rays antimatter:

-There is an excess of positrons.

Positron measurements are inconsistent with pure secondary hypothesis. We do need a nearby source to reproduce the data. We have many ideas how to explain this, including pulsars and dark matter.

-Excess of antiprotons ?

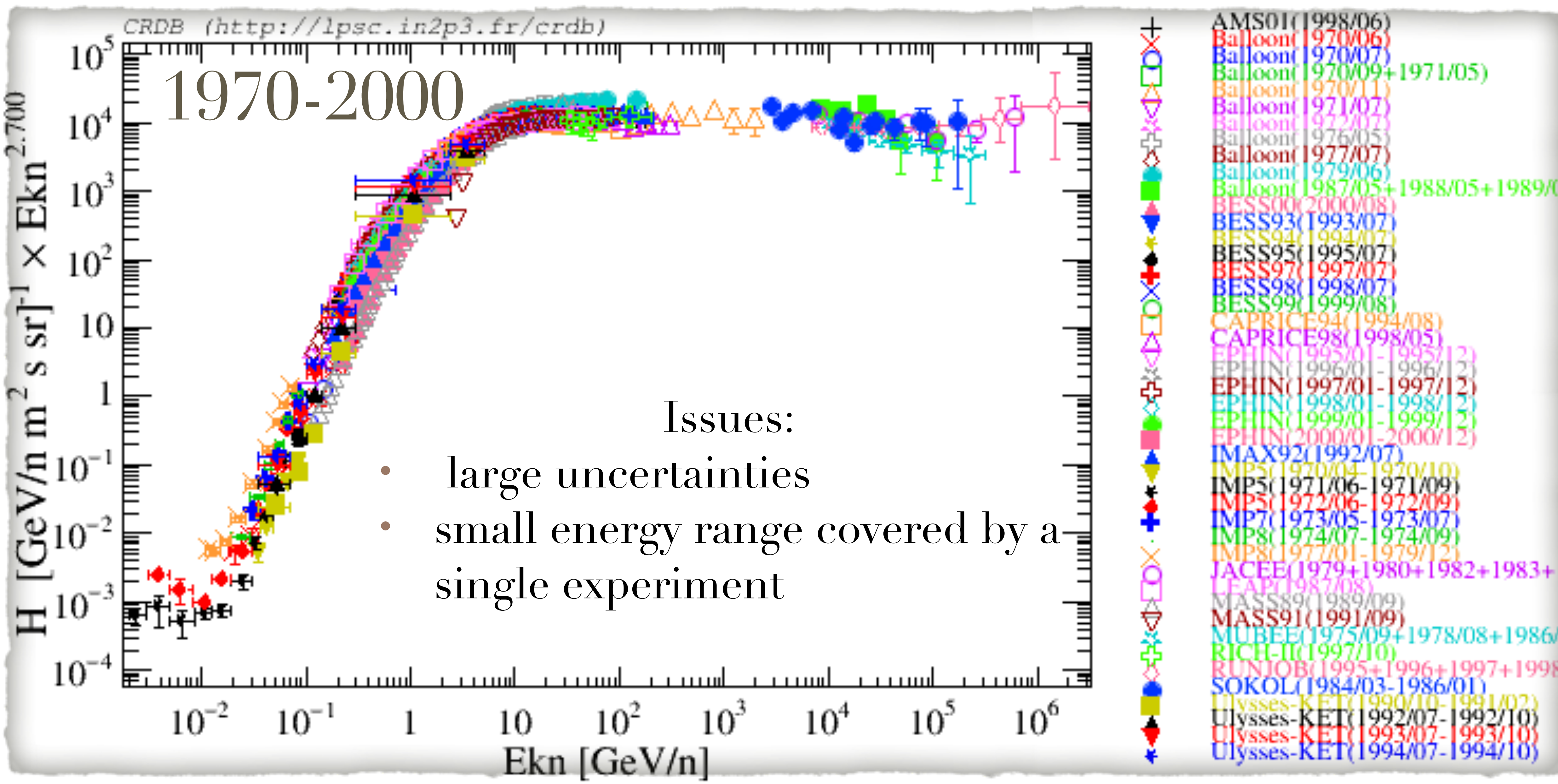
A flat antiproton-to-proton ratio is unexpected, however it is not sure there is an anomaly. The astrophysical background is affected by large uncertainties that may reduce in view of latest CR data, but x-section uncertainties are ~20-50%.
Be ready for surprises …

-The spectra of protons, positrons and antiprotons have identical rigidity dependence above 60 GV.

Currently very few ideas.

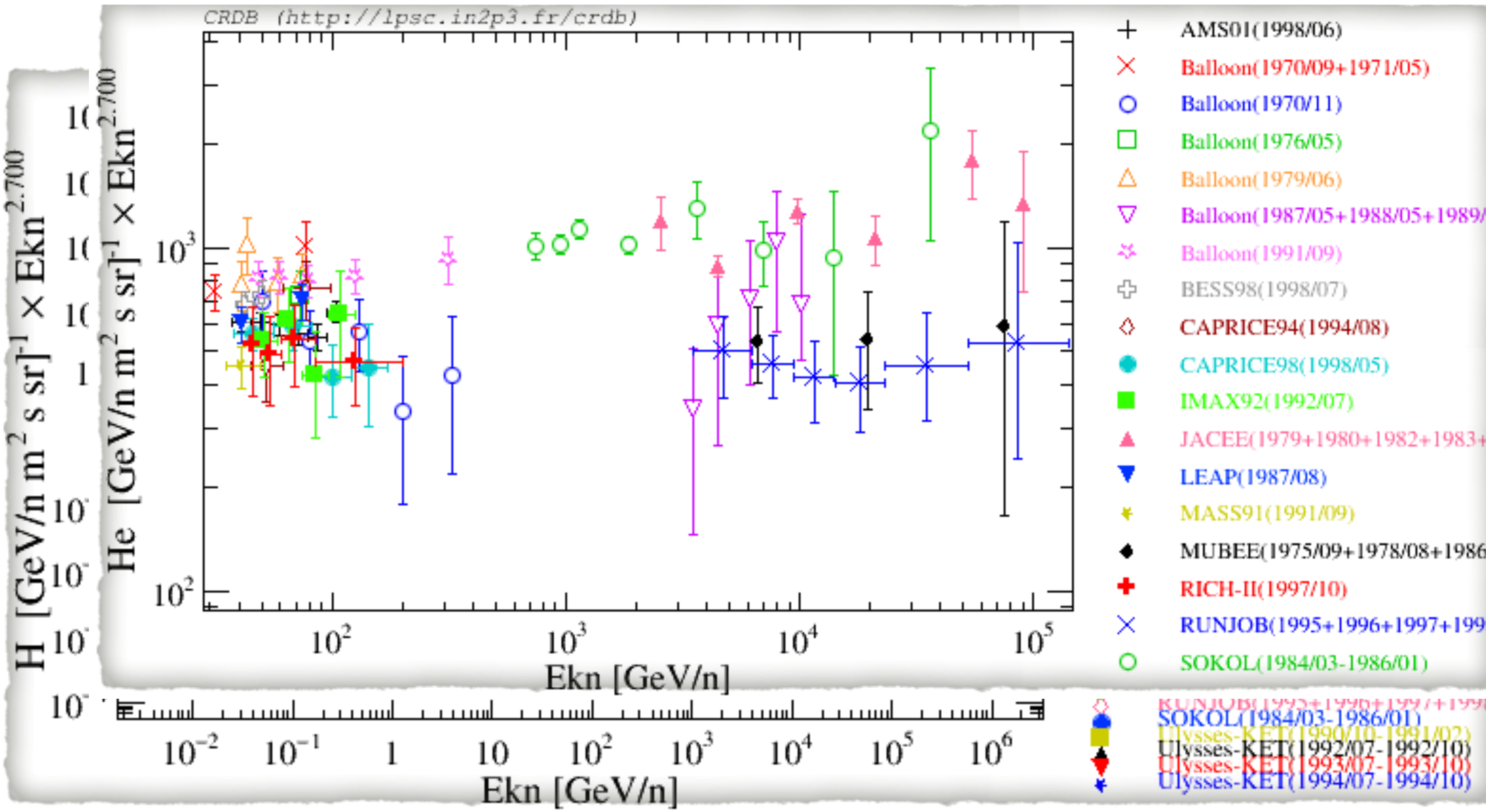
Cosmic ray proton and helium fluxes

until a few decades ago…



Issues:

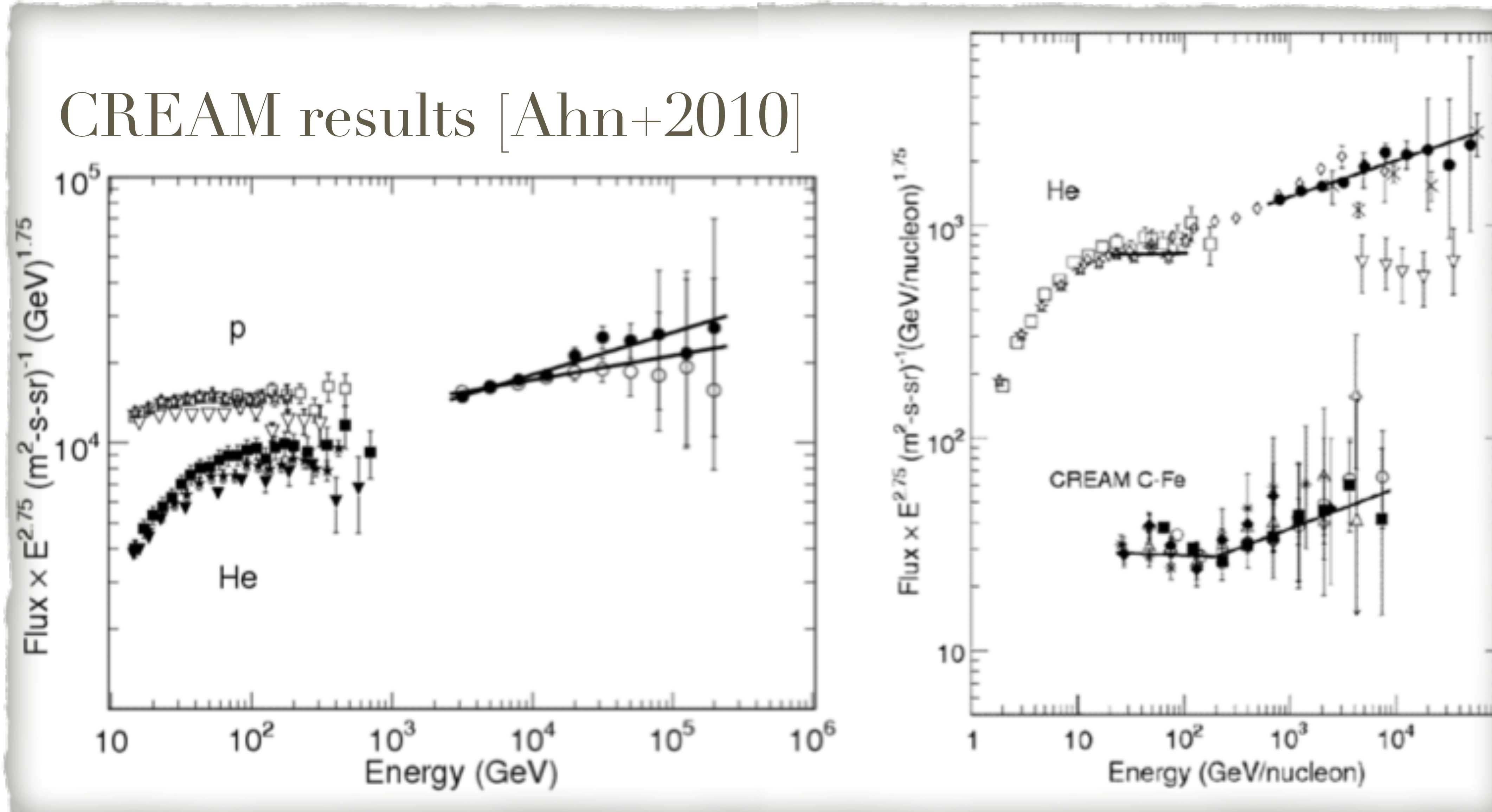
- large uncertainties
- small energy range covered by a single experiment



CRDB (http://lpsc.in2p3.fr/crdb)
He [GeV/n m^2 s sr]^-1 × Ekn^2.700
Ekn [GeV/n]
AMS01(1998/06)
Balloon(1970/09+1971/05)
Balloon(1970/11)
Balloon(1976/05)
Balloon(1979/06)
Balloon(1991/09)
BESS98(1998/07)
CAPRICE94(1994/08)
CAPRICE98(1998/05)
IMAX92(1992/07)
LEAP(1987/08)
MASS91(1991/09)
RICH-II(1997/10)
SOKOL(1984/03-1986/01)
H [GeV/n m^2 s sr]^-1 × Ekn^2.700
Ekn [GeV/n]
SOKOL(1984/03-1986/01)
Ulysses-KET(1992/07-1992/10)
Ulysses-KET(1993/07-1993/10)
Ulysses-KET(1994/07-1994/10)

hints of surprises …

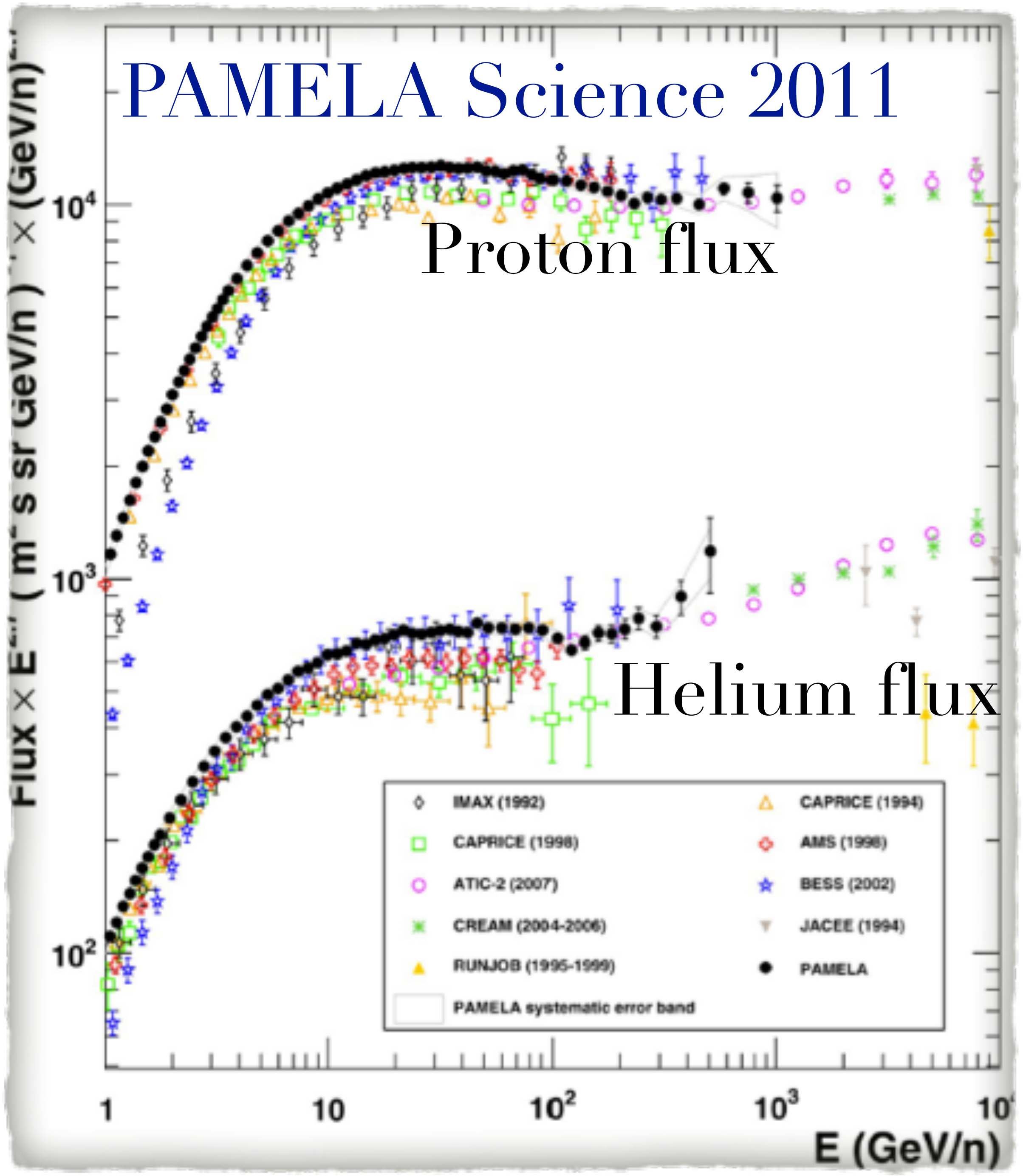
- When the GeV-TeV region became to be explored with sufficient precision … hints of possible features emerged in p, He but also in heavier nuclei and antimatter !



Change in spectral index suggested around 200 GeV/n

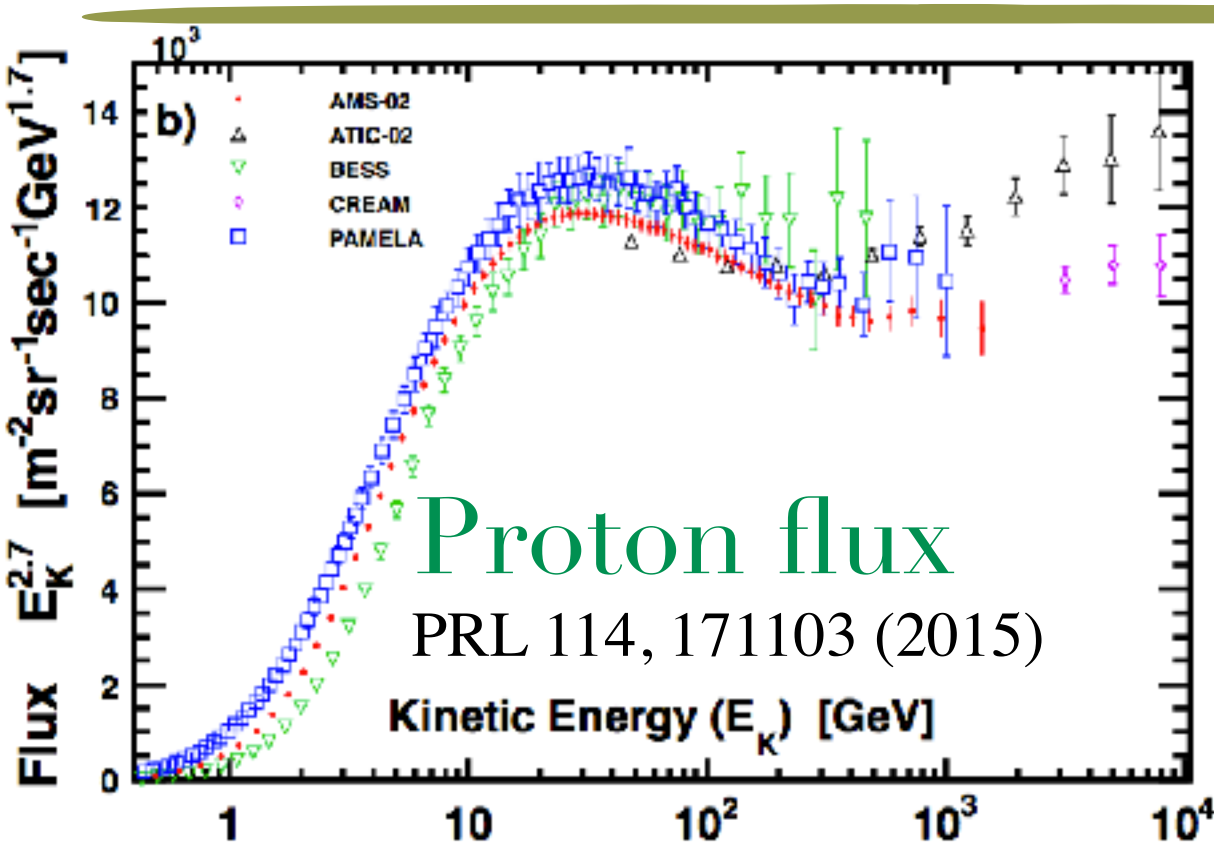
Both the energy range and the flux uncertainties prevented a clear claim for a break in p.He spectra

1st Evidence for a broken power law in CR fluxes



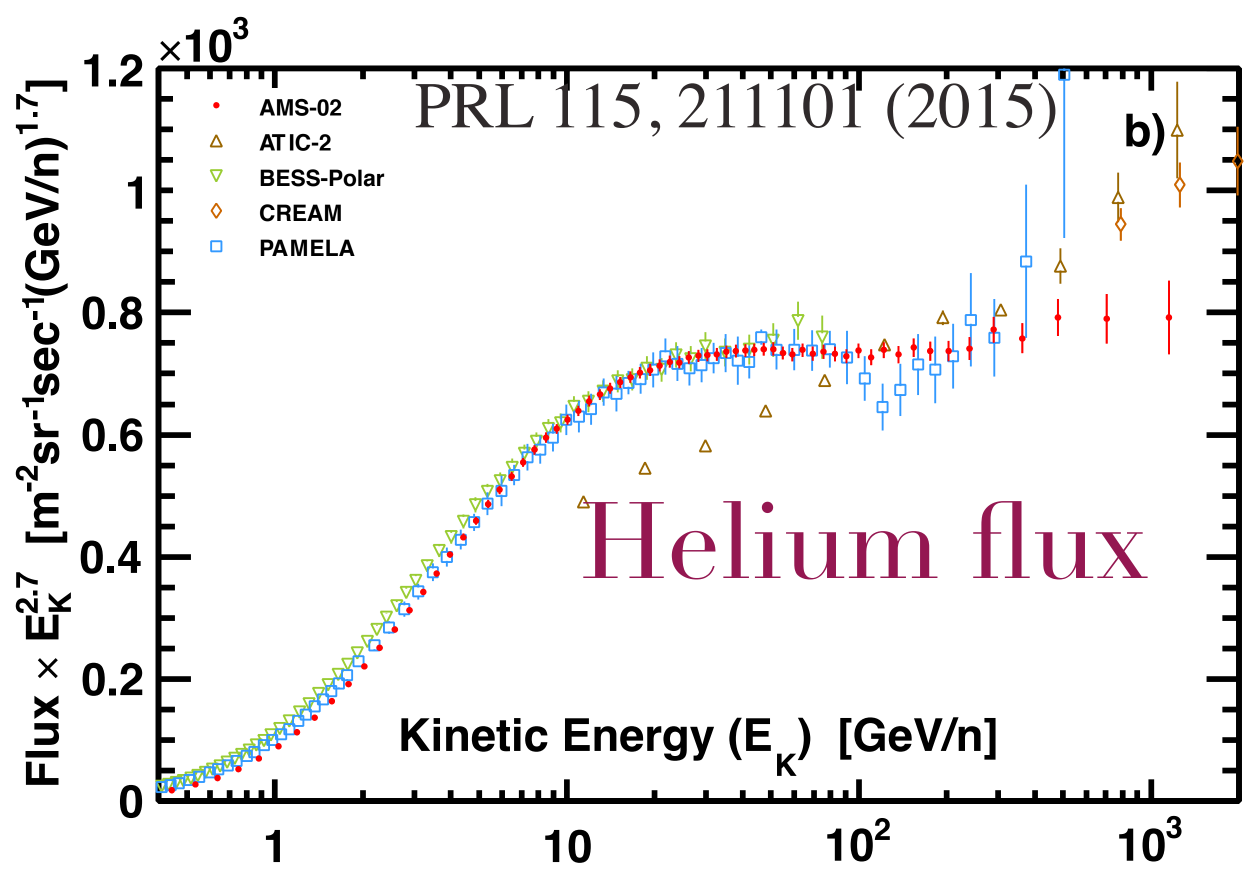
A single instrument covering the whole energy range was solving the puzzle

Proton and helium flux



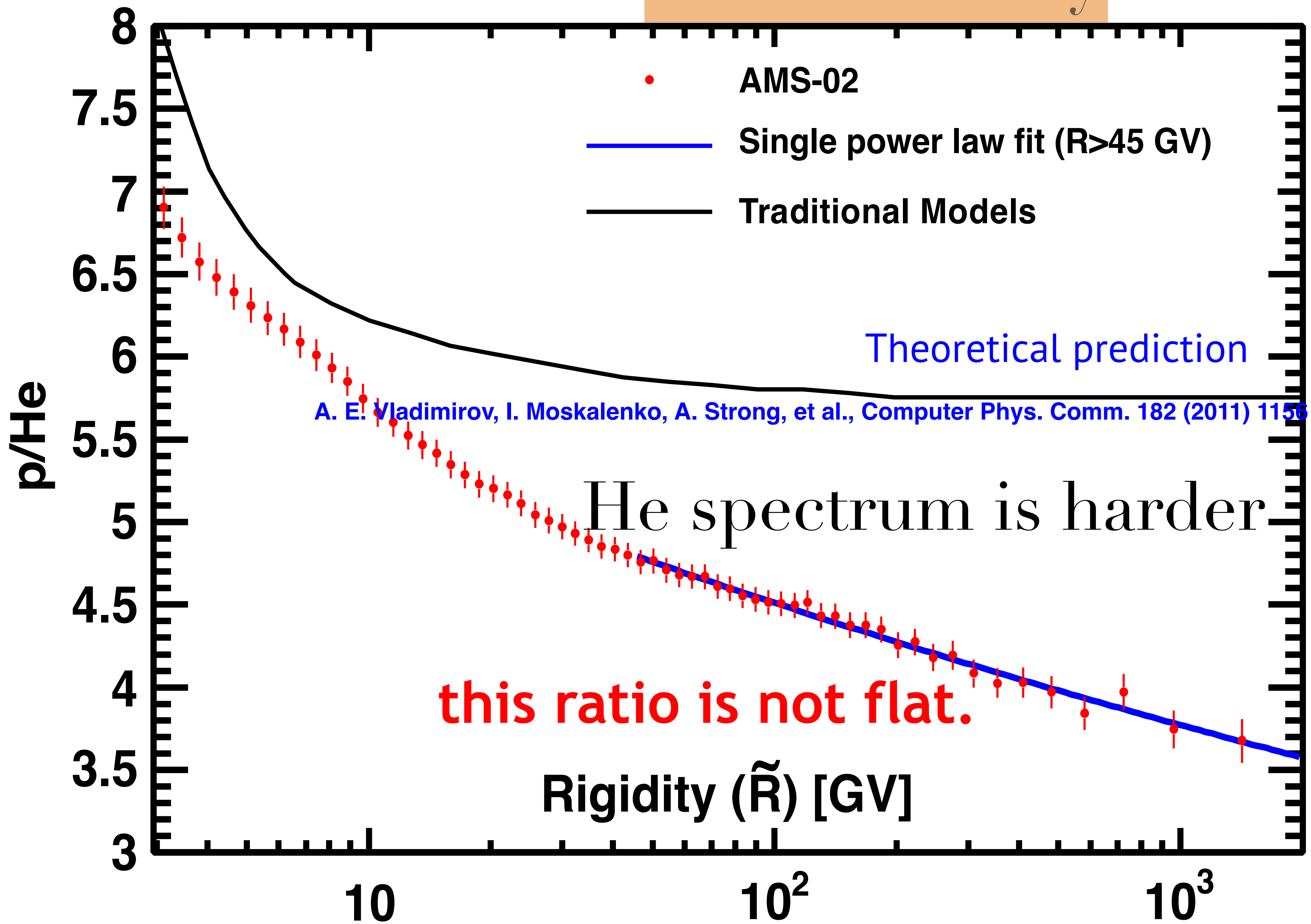
- Based on 300 million events (2011-2013)
- The proton flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.

- 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.

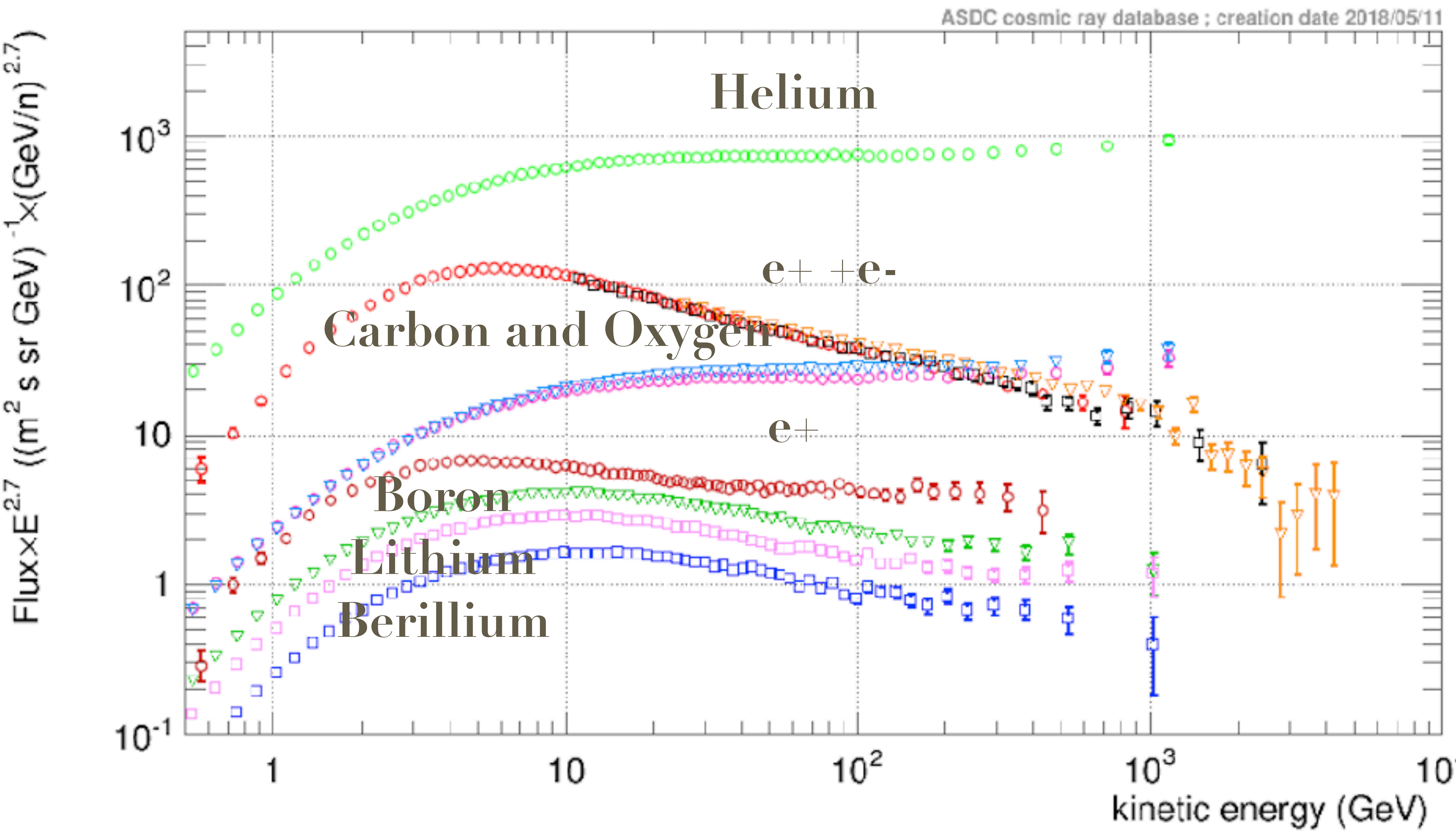


p/He flux ratio

non-universality



Latest Cosmic ray measurements (since 2014)



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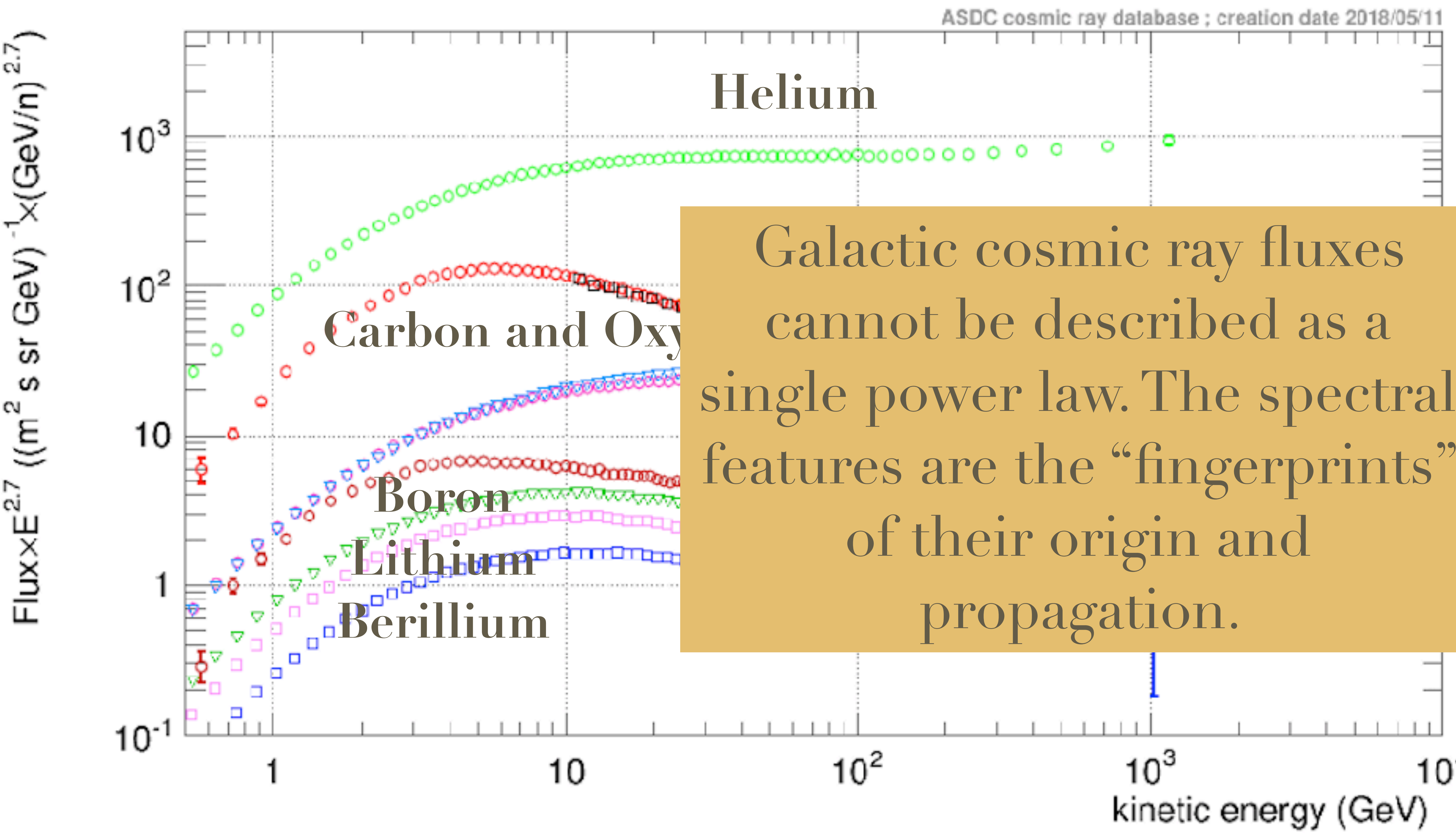
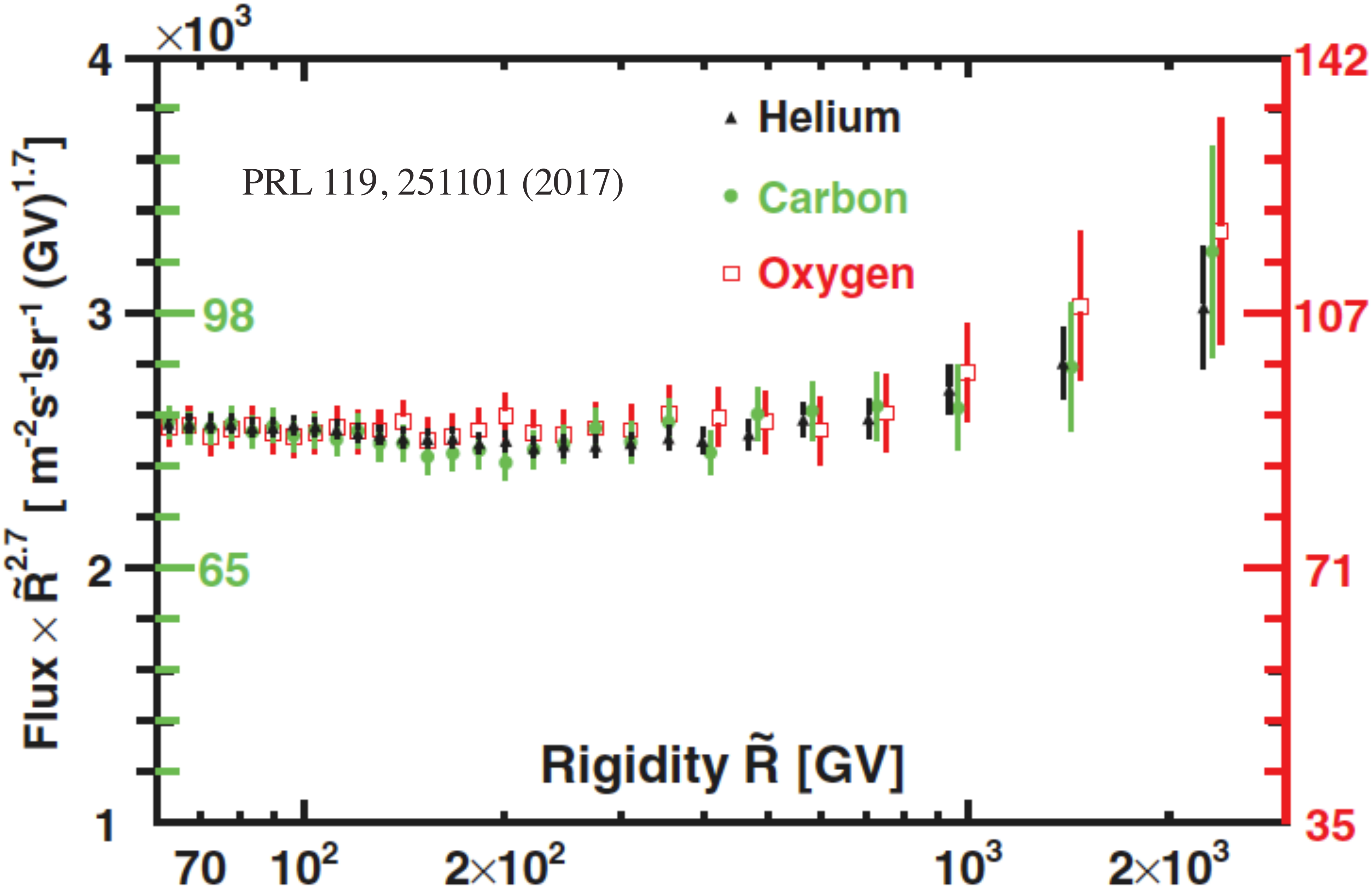


Galactic cosmic ray fluxes cannot be described as a single power law. The spectral features are the "fingerprints" of their origin and propagation.

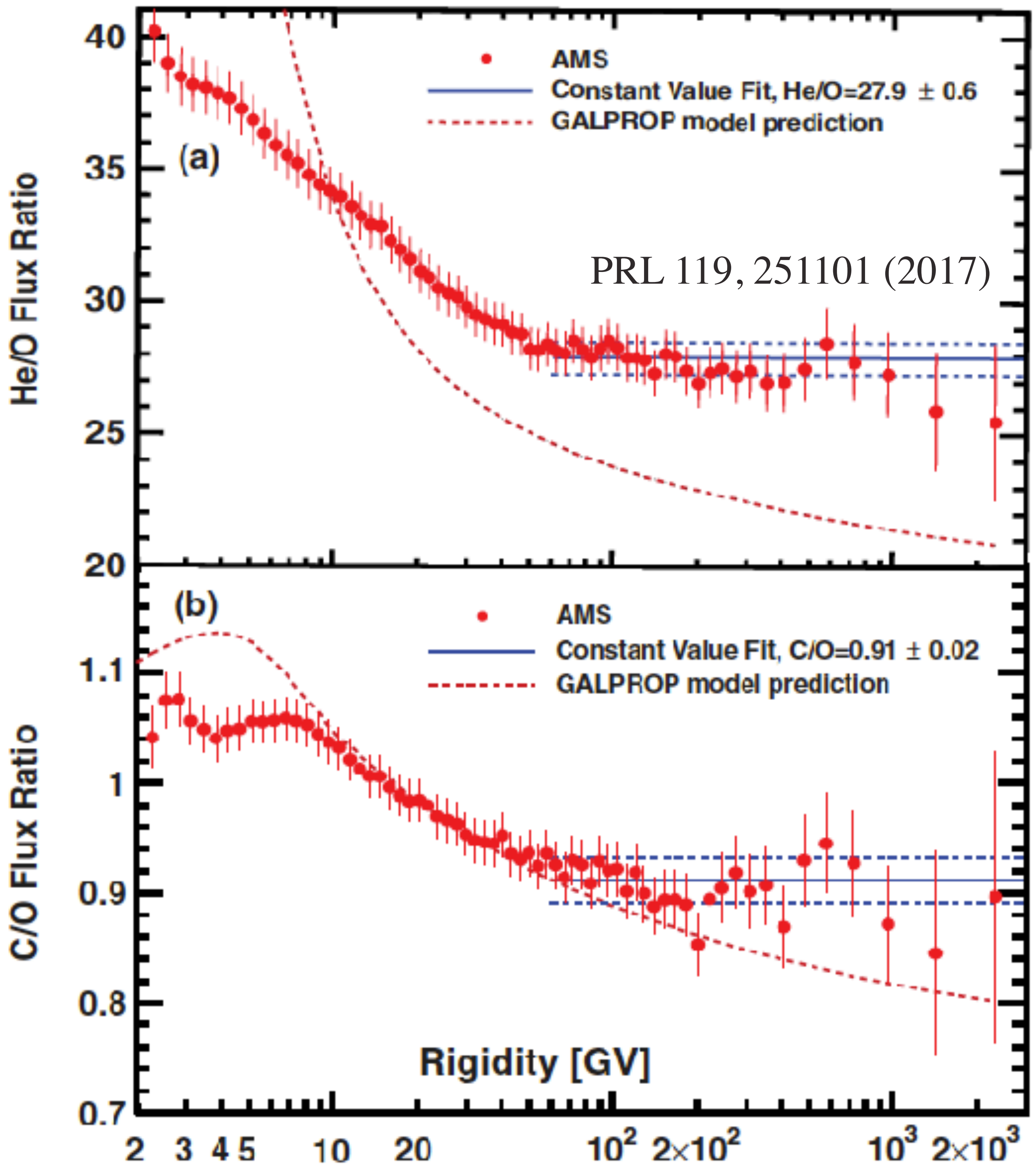
Identical rigidity dependence of He,C and O

They all deviate from a single power law above 200 GV and harden in an identical way.

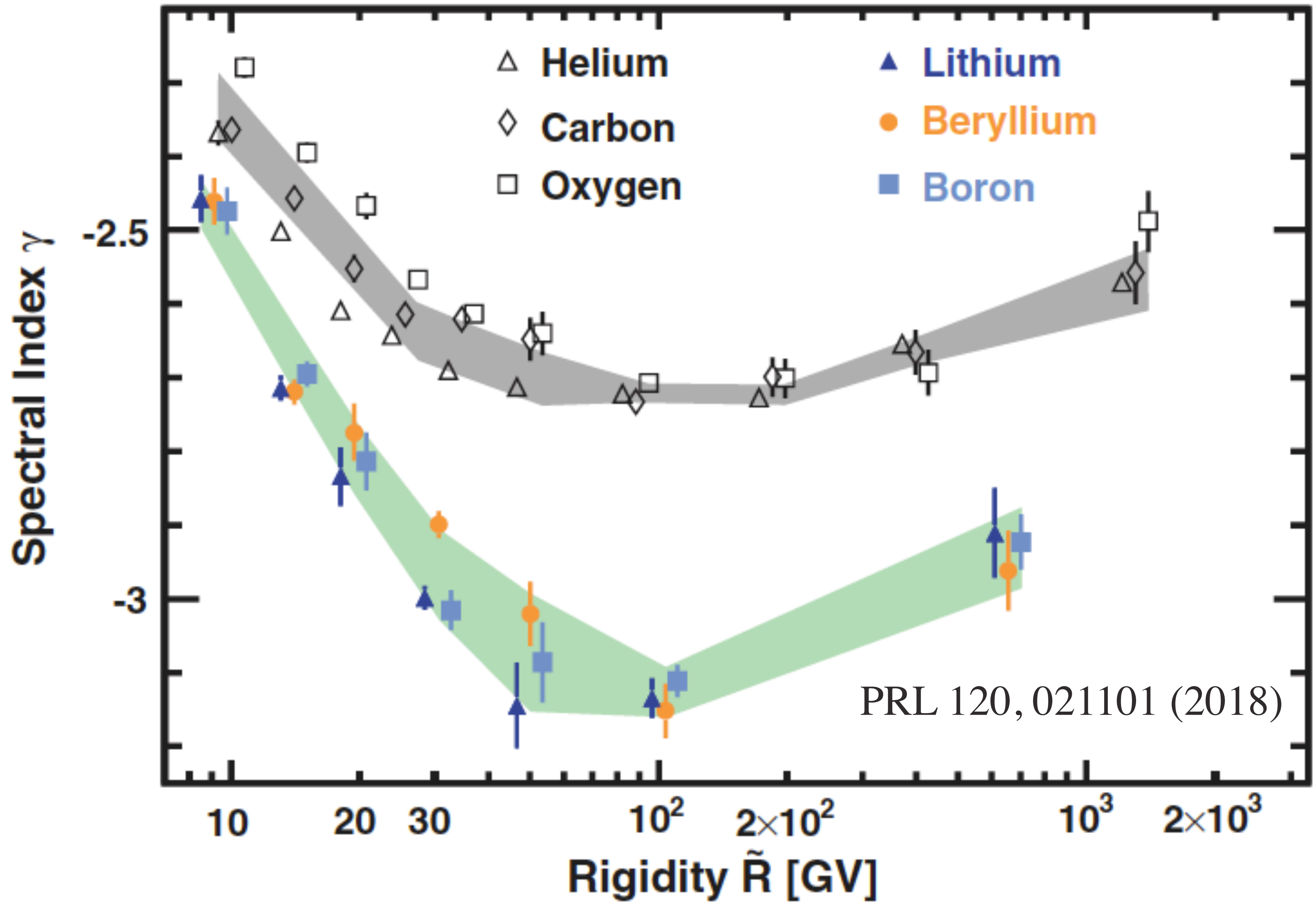


p/C and p/O ratio show identical behaviour as p/He

Primary-to-primary ratios



Summary on spectral breaks



How to investigate the spectral hardening

- Spectral hardening at high energy observed in primaries and secondaries.
- Plausible explanations include:
  - 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

Secondary to primary ratios

Secondary nuclei are only produced via collisions in the ISM

$$\Phi_s = Q_s \tau_{diff} \propto \sigma_{p \to s} \Phi_p \tau_{diff}$$

The secondary to primary flux ratios provide informations about the diffusion process:

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{diff}(E) \propto E^{\delta}$$

Usually studied with B/C

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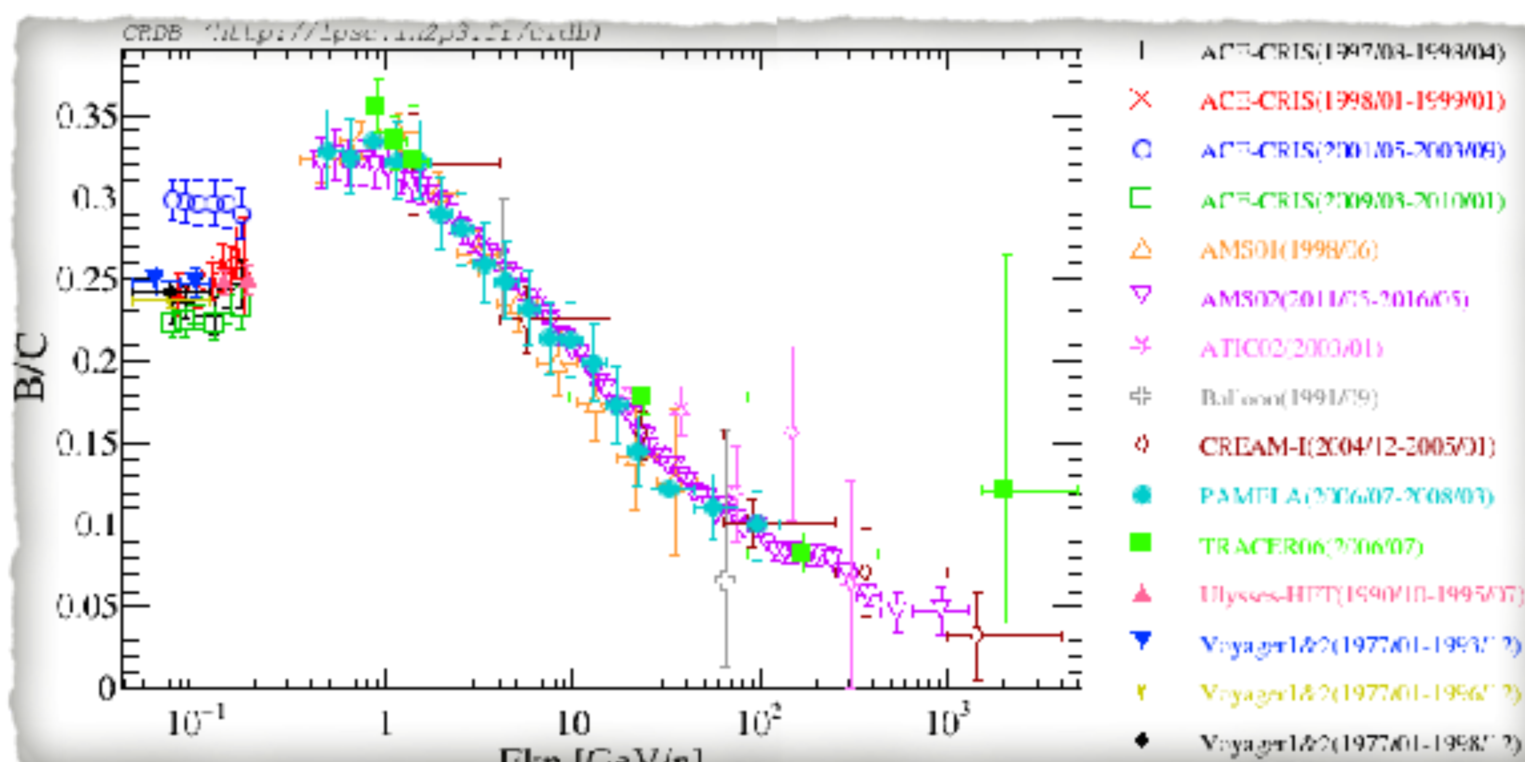
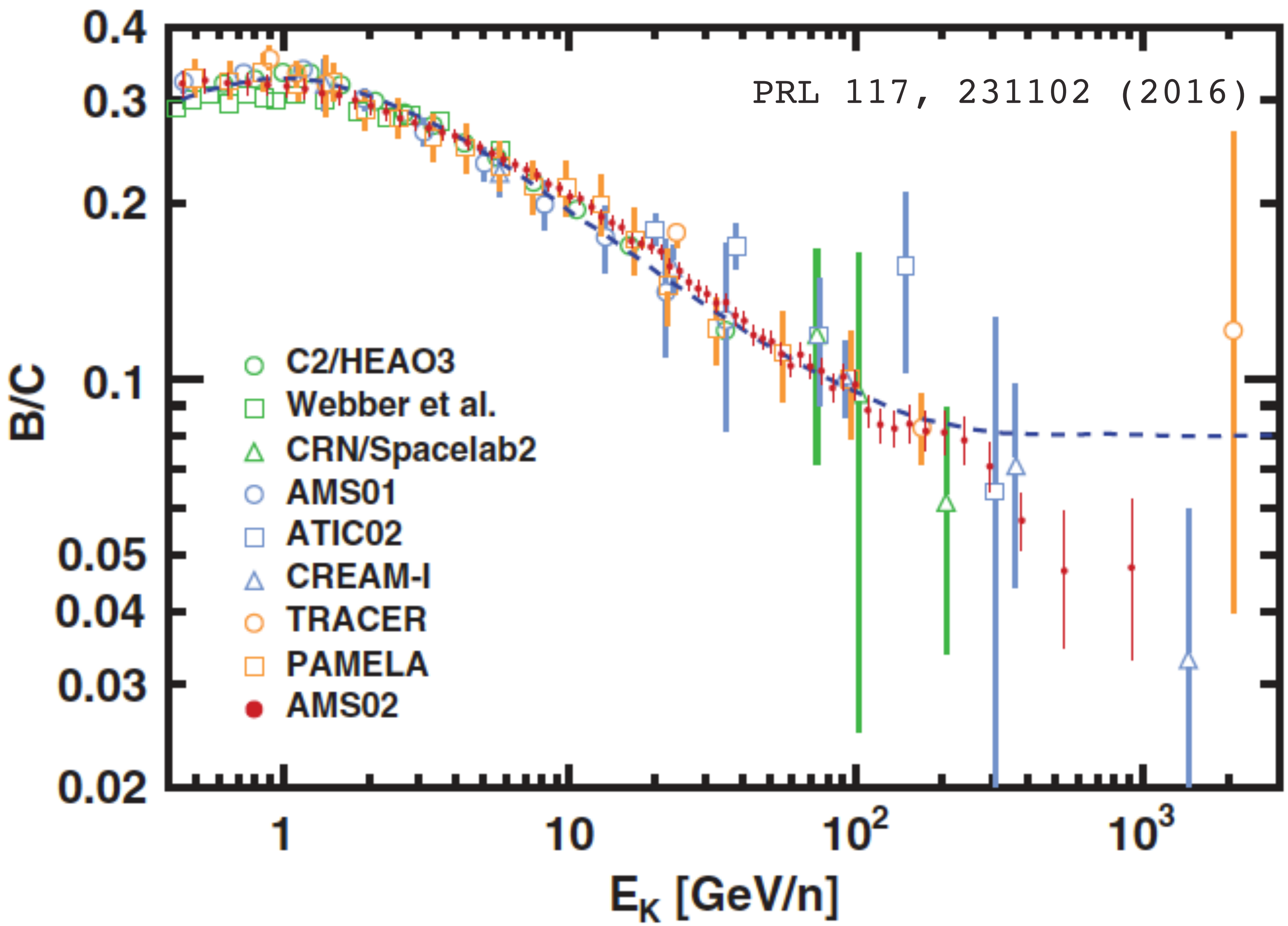


Boron-to-Carbon flux ratio

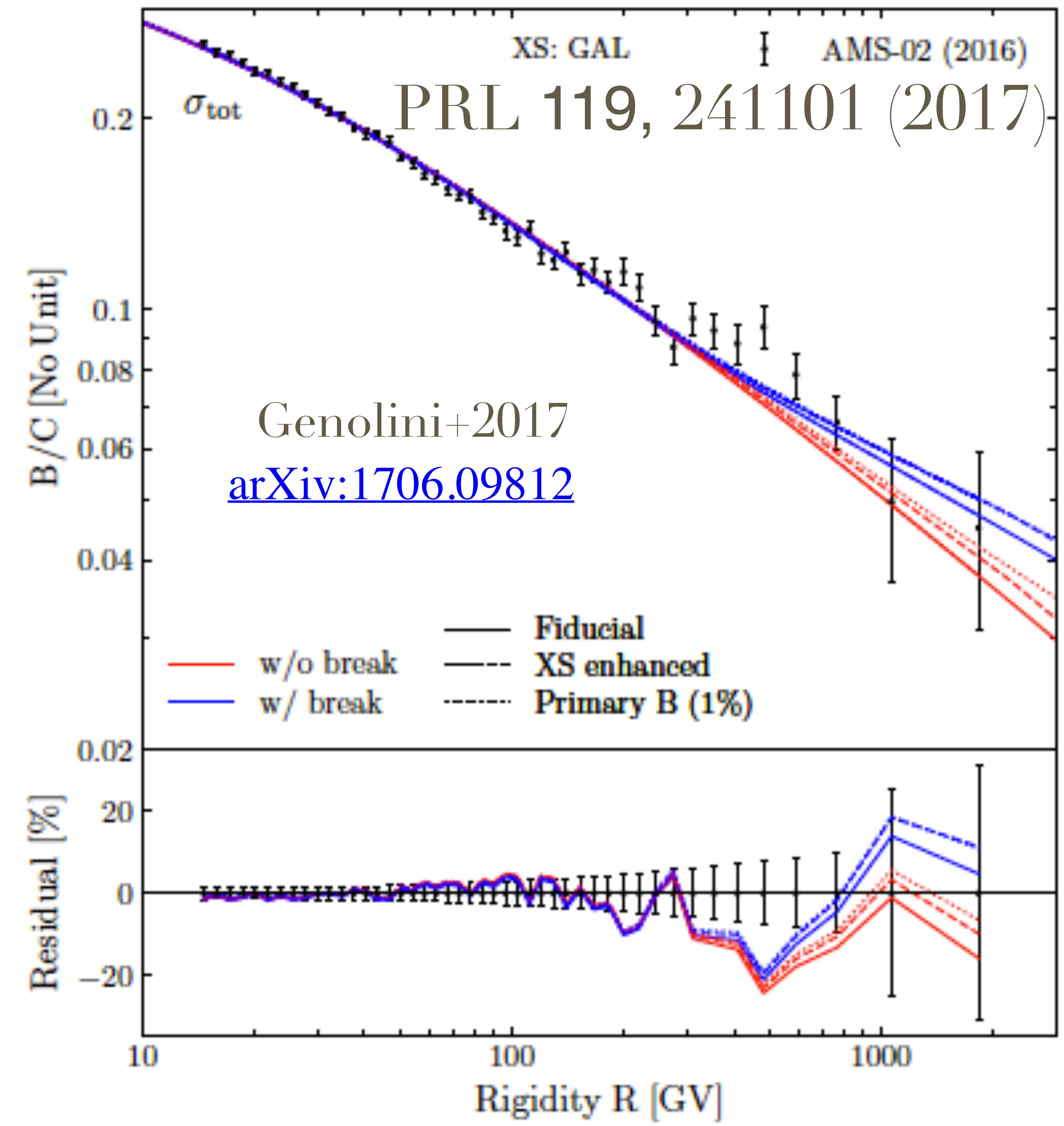
The Boron-to-Carbon flux ratio disfavours several CR models predicting a rise at high energies.



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]

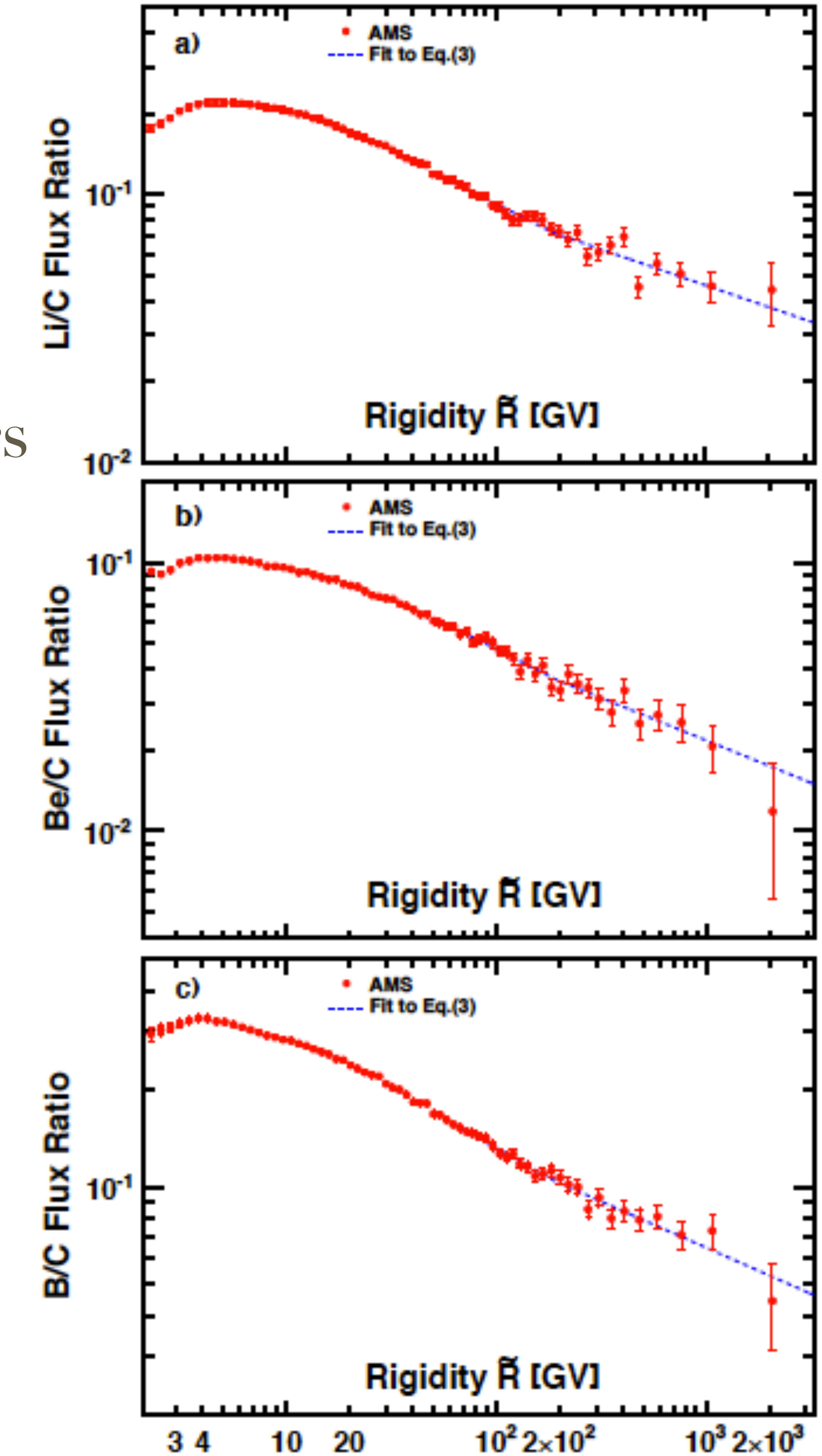
- Using cosmic-ray boron to carbon ratio (B/C) data we find indications for a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He).
- The result is robust with respect to currently estimated uncertainties in the cross sections, and in the presence of a small component of primary boron, expected because of spallation at the acceleration site.
- Reduced errors at high energy as well as further cosmic ray nuclei data definitely confirm this scenario.



Measurement of Li, Be, B

PRL 120, 021101 (2018)

- Based on 5 million nuclei (2011-2016)
- A transition in the spectral index occurs around 200 GV also for secondaries.
- Secondary fluxes harden more than primaries.
- The transition in the spectral index is confirmed.



What we are learning from cosmic ray nuclei:

The observational improvements occurred during the past decade challenge the ‘conventional’ model for cosmic ray origin/propagation.

A new precision level in the GeV to TeV energy region has been reached.

Transition in the spectral index of primary nuclei (p, He, C, O) observed around 200 GV. Li, Be and B fluxes also show a hardening. However, the secondaries harden more than the primaries.

Precise measurement of B/C together with other secondary-to-primary ratios provides important clues to understand the nature of spectral breaks.

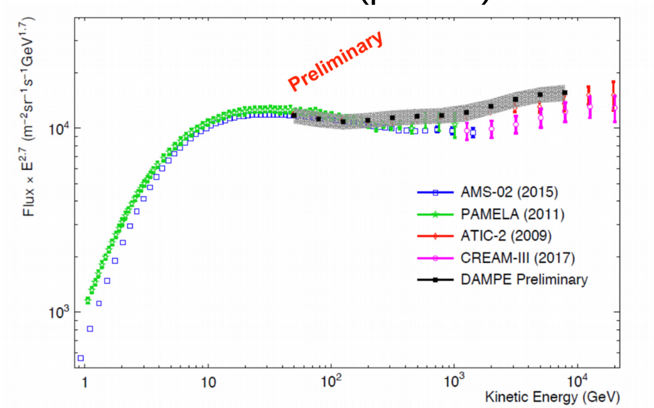
It is now time to combine these high quality data to establish an updated conventional model for CRs below the knee.

- Recent results from CREAM-III and NUCLEON did confirm the scenario up to about 100 TeV but with large uncertainties.
- Current missions like CALET and DAMPE have the needed resolution to check the break region and determine the spectral behaviour up to more than 100 TeV.

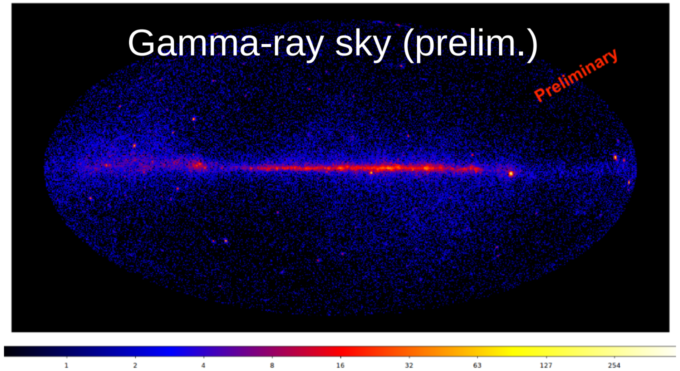
DAMPE AND CALET WITH FIRST RESULTS!

DAMPE

Proton flux (prelim.)

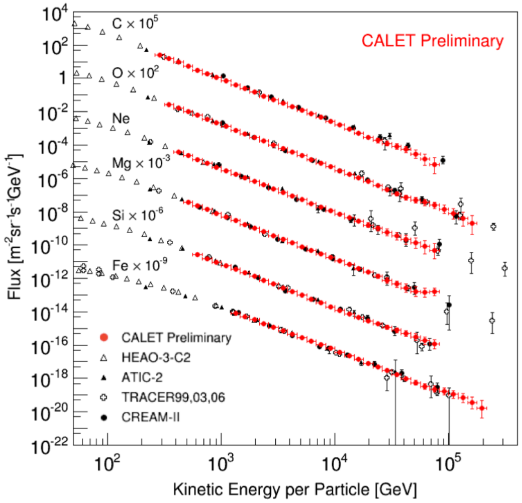


[Yue et al. PoS (ICRC 2017) 1076]



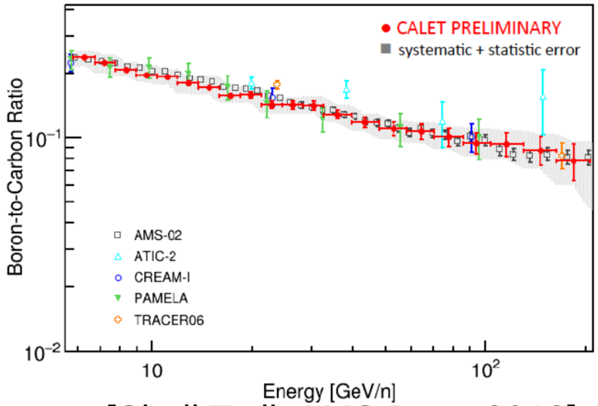
[Lei et al. PoS (ICRC 2017) 616]

CALET



Heavy nuclei (prelim.)

B/C (prelim.)



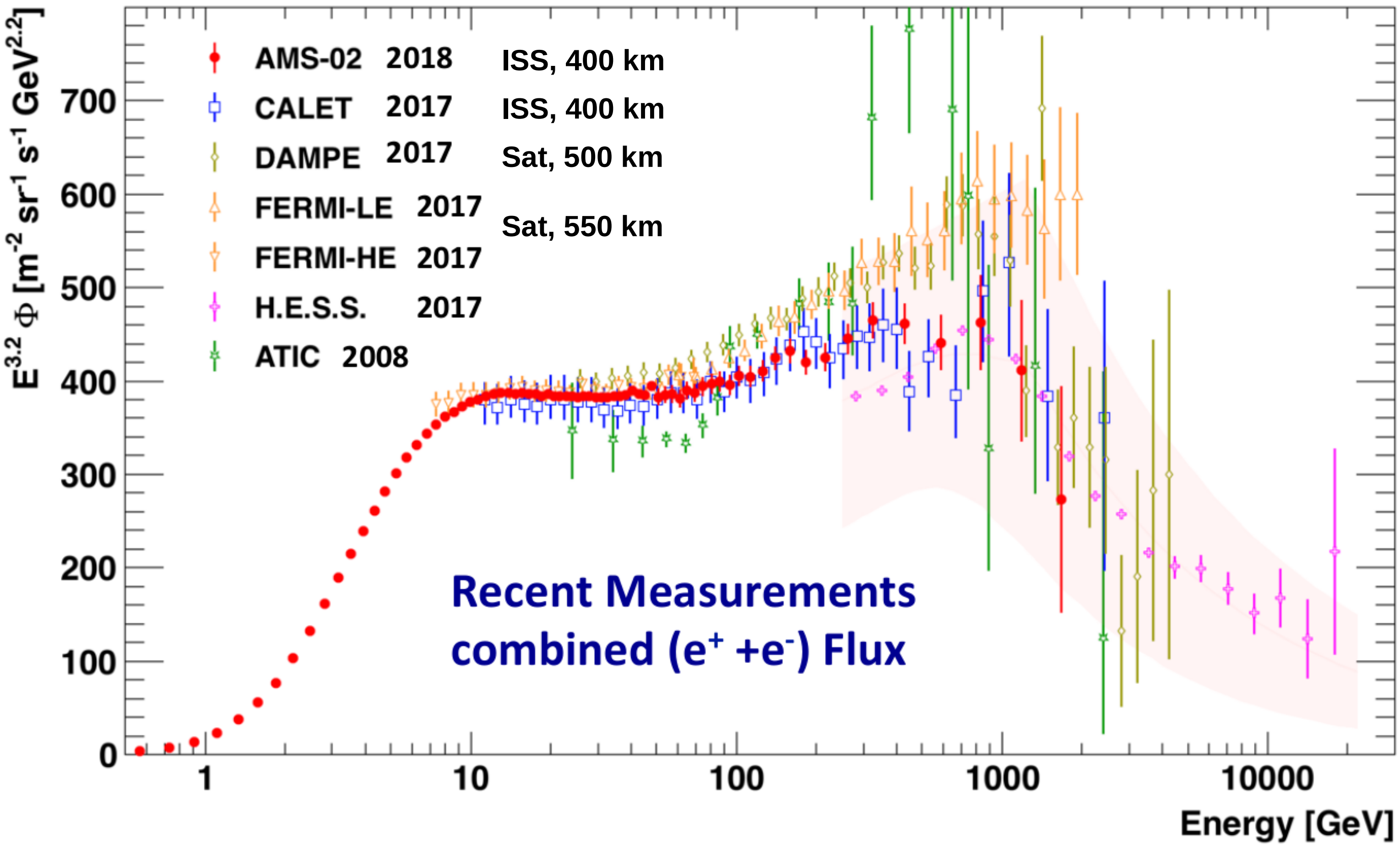
[Shoji Torii, AMS Days 2018]

There is a lot more to come…..

[see also P. S. Marrocchesi @ Vulcano]

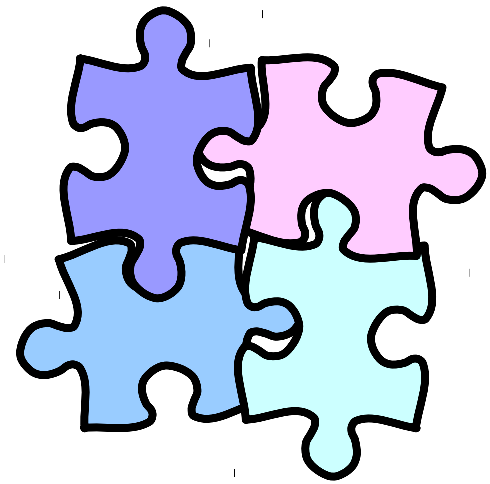
THE COMBINED ($e^+ + e^-$) FLUX

The combined $e^+ + e^-$ flux is a difficult measurement and it is difficult to interprete.
The results of the space experiments are not consistent
They come in two groups: (**AMS** and **CALET**) ↔ (**Fermi** and **DAMPE**)
ISS Satellites



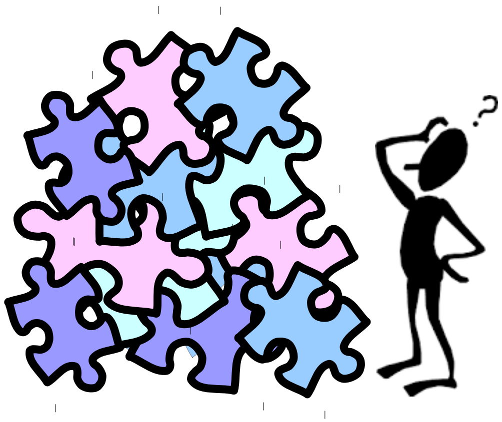
WHERE WE ARE

Few decades ago …



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

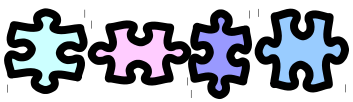
You are here



The accuracy of the data challenges the "standard paradigm".

Future

CALET, DAMPE, ISS-CREAM,...



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

Summary

Direct CR measurements are a gateway to some of the most fundamental questions in our universe, like the understanding of the nature of dark matter and the baryon asymmetry in our Universe. The answers to these questions requires, as a first step, a detailed understanding of cosmic ray sources and transport in our galaxy.

The observational improvements occurred during the past decade brought to light a lot of unexpected features below the knee reveal new physics phenomena that should be incorporated in a coherent model for cosmic ray origin/propagation.

The uncertainties in the isotopic x-sections are still 20-50% or even larger, and this affect the uncertainty on the astrophysical background, that is the fundamental key for discovery of new physics. Indirect search for dark matter with charged cosmic rays is a powerful tool, but so far no clear consensus. Stay tuned for antideuterons ….

The accuracy achieved by PAMELA and AMS-02 measurements brought CR physics to a precision level.

The new experiments are CALET, DAMPE and ISS-CREAM all equipped with powerful calorimeters. They will collect unprecedented statistics and improve our knowledge on CR matter.