Direct cosmic ray measurements: the precision era

Manuela Vecchi
Instituto de Física de São Carlos - Universidade de São Paulo
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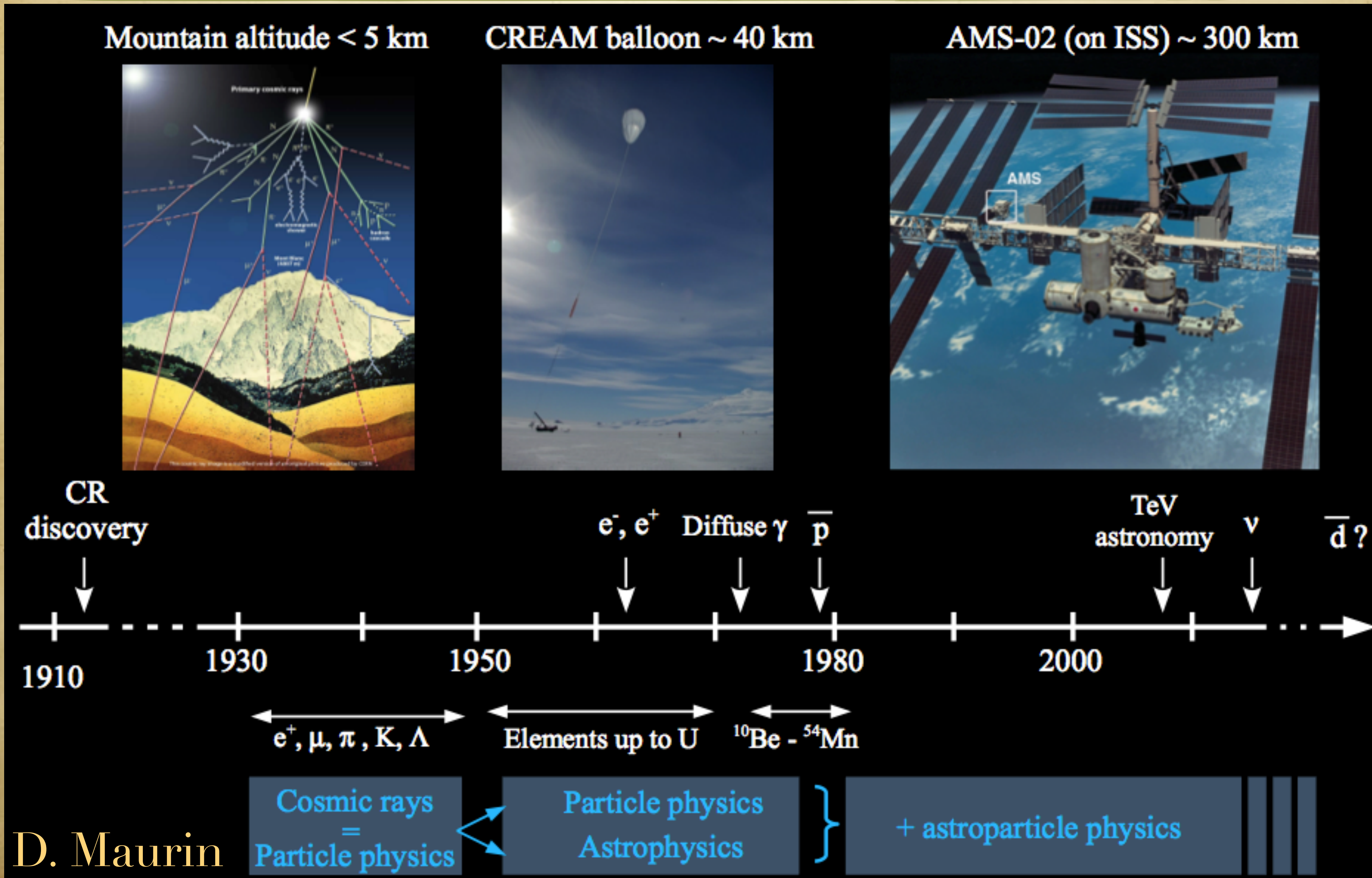
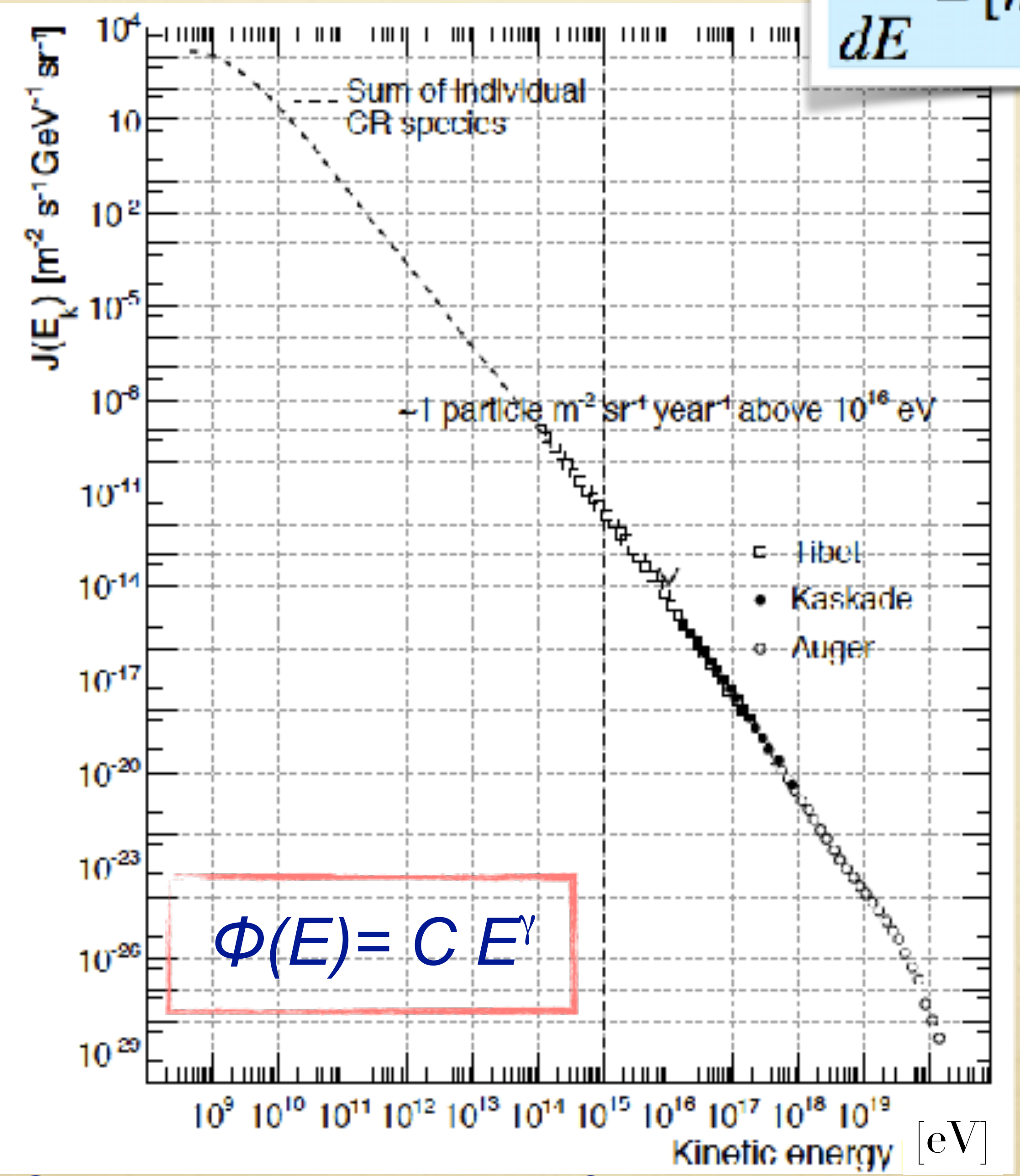
Timeline


Mountain altitude < 5 km
CREAM balloon ~ 40 km
AMS-02 (on ISS) ~ 300 km
AMS
CR discovery
e^-, e^+
Diffuse γ
$\bar{p}$
TeV astronomy
ν
$\bar{d}$?
1910
1930
1950
1980
2000
e^+, μ, π, K, Λ
Elements up to U
^{10}Be - ^{54}Mn
Cosmic rays = Particle physics
Particle physics
Astrophysics
+ astroparticle physics
D. Maurin

Cosmic ray flux

all particle flux

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



at first sight … a featureless power law

L. Baldini, arXiv: 1407.7631

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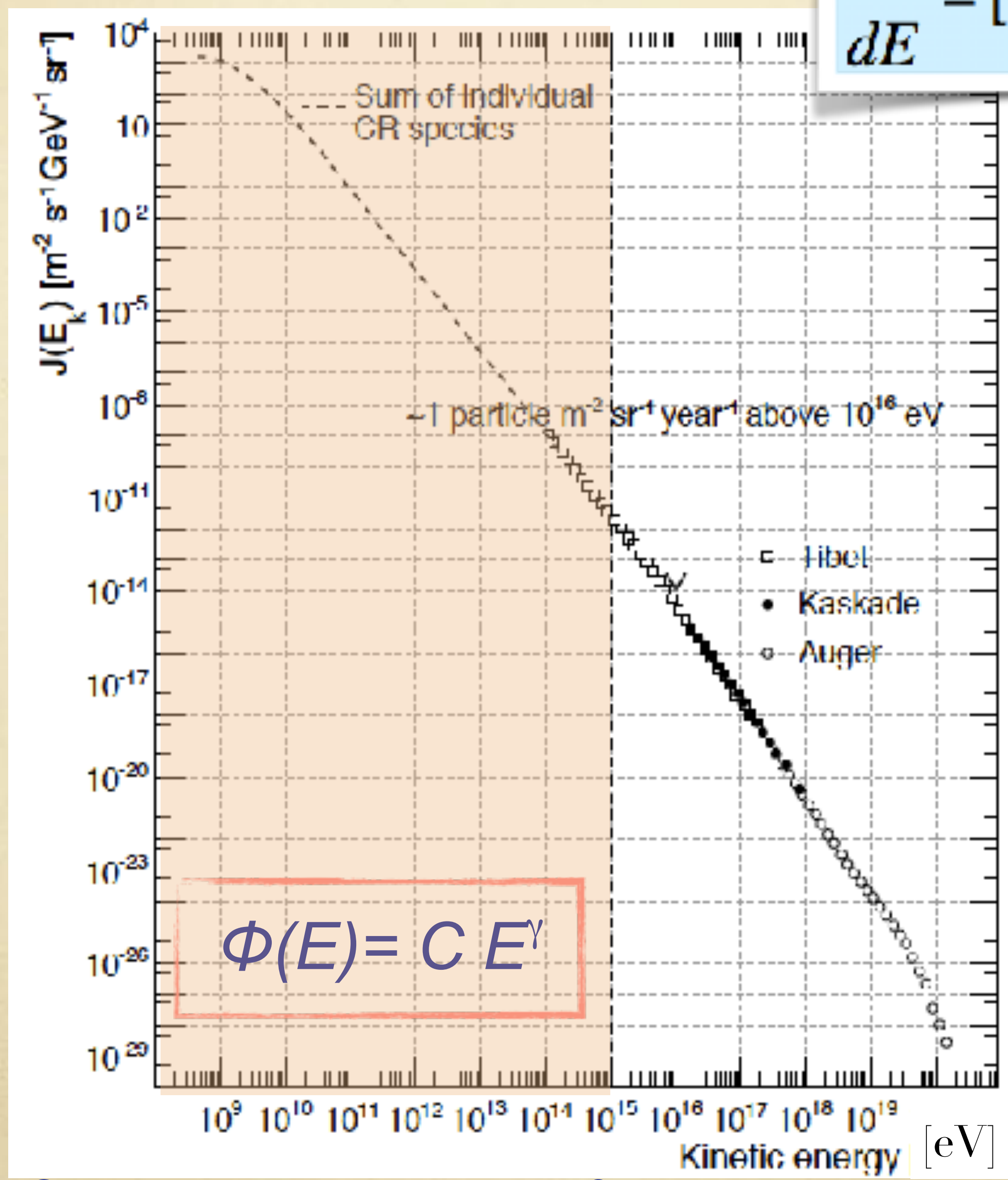
Direct measurements



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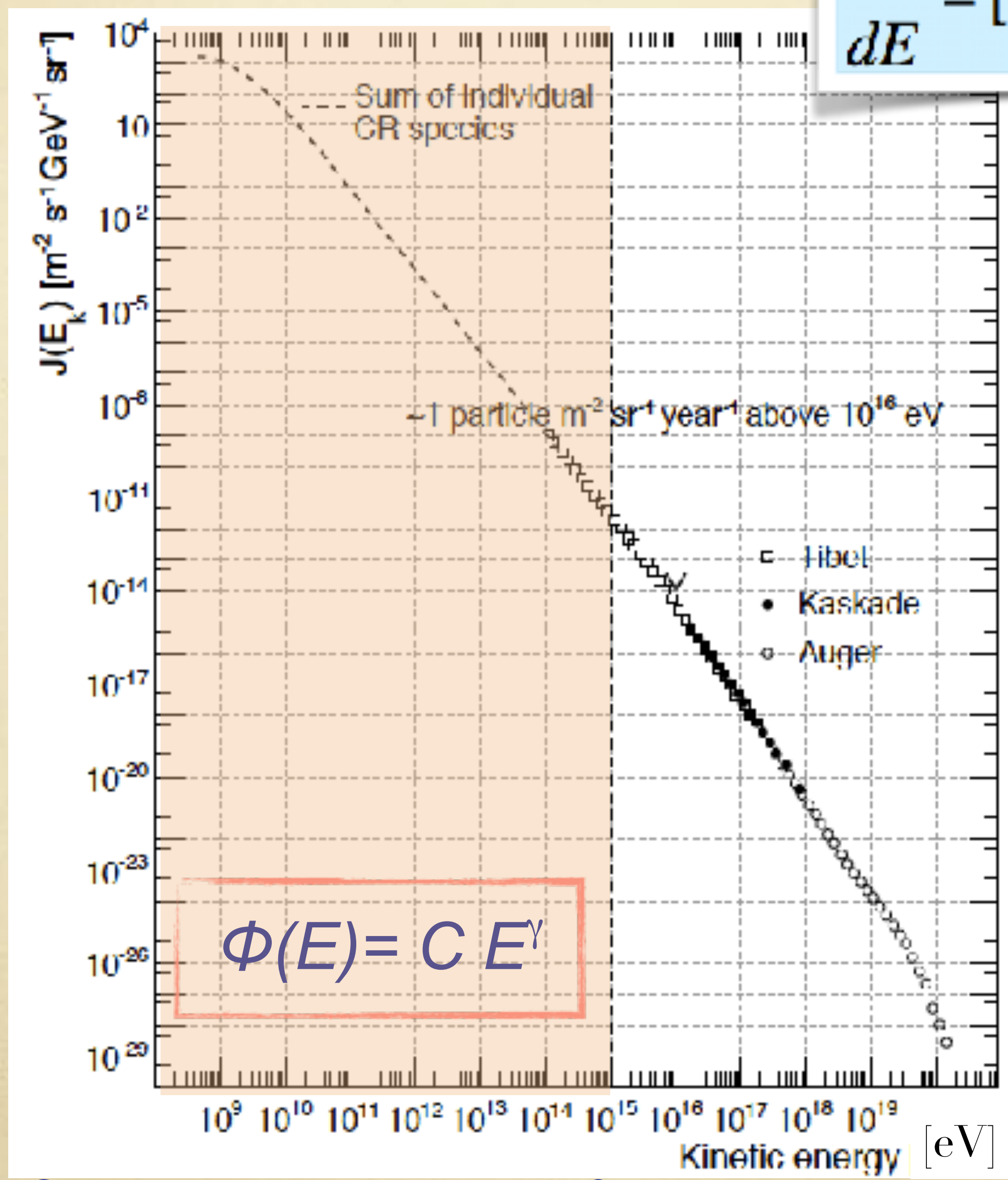

Indirect measurements

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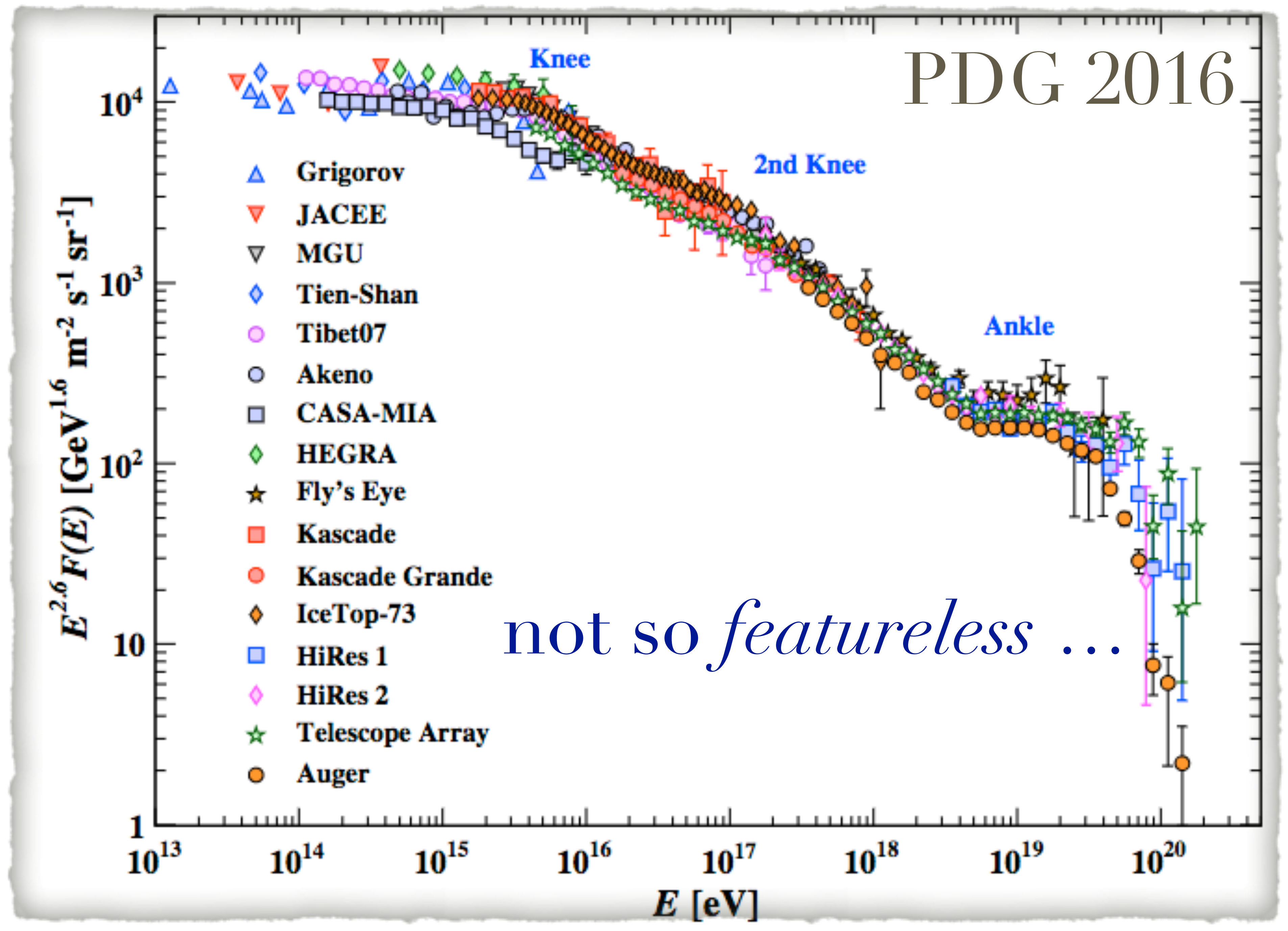
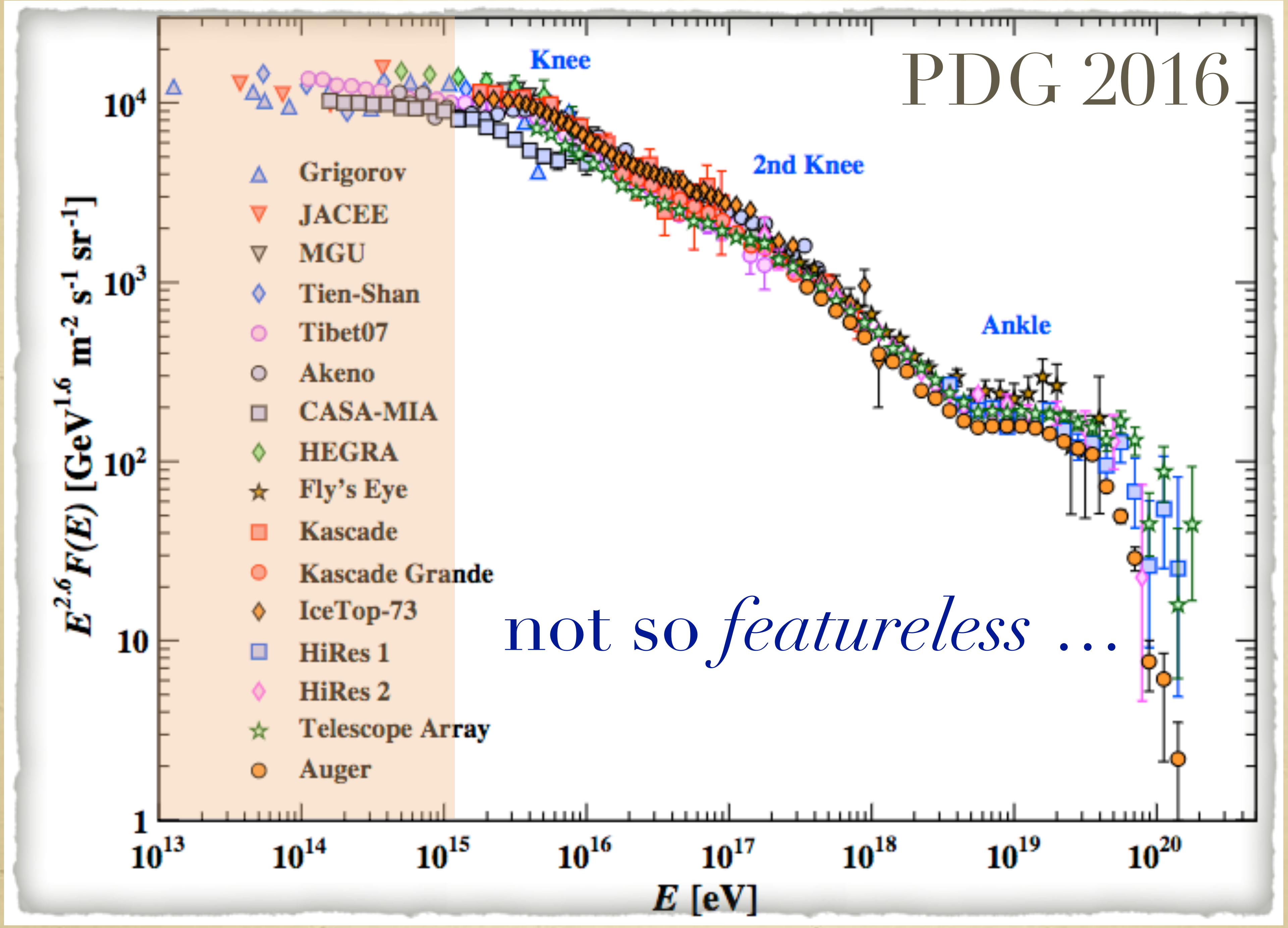


- In this talk I will only focus on the measurement of CRs in the GeV to TeV region, below the knee.
- These particles are thought to be of galactic origin.



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What can we learn by studying cosmic rays below the knee ?

galactic astrophysics

solar physics

primordial antimatter

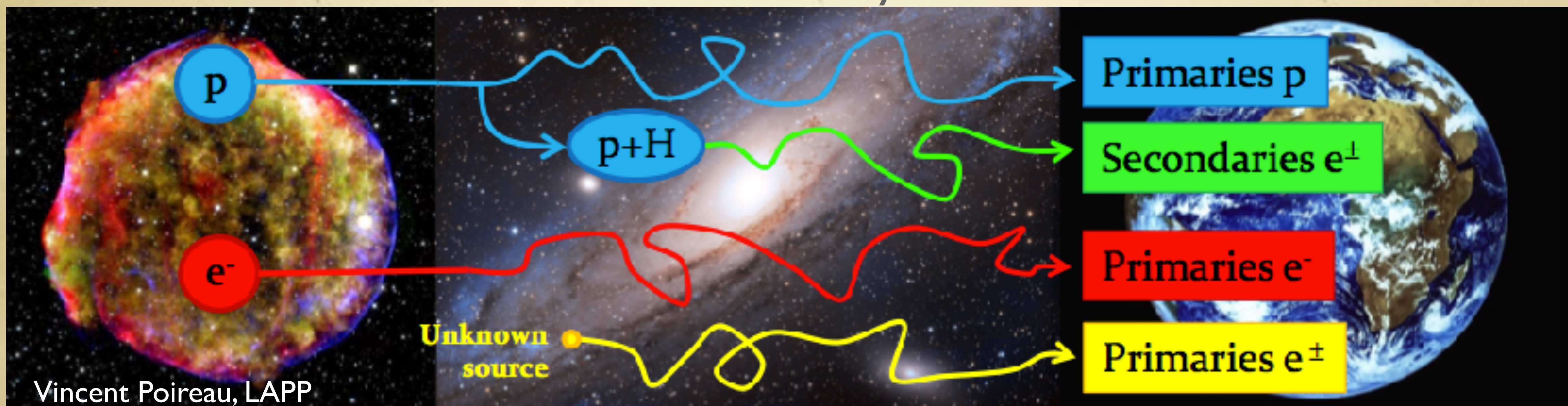
what is the universe made of ?

nuclear composition

be ready for unexpected ...

Cosmic rays in the Milky Way

Production and acceleration | Propagation in our Galaxy | Detection



Primary cosmic rays:

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

$$p + p_{\text{ism}} \to \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

Secondary cosmic rays:

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

Some things we believe(d) about CRs

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

P. Serpico ICRC2015
L. Drury ICRC2017

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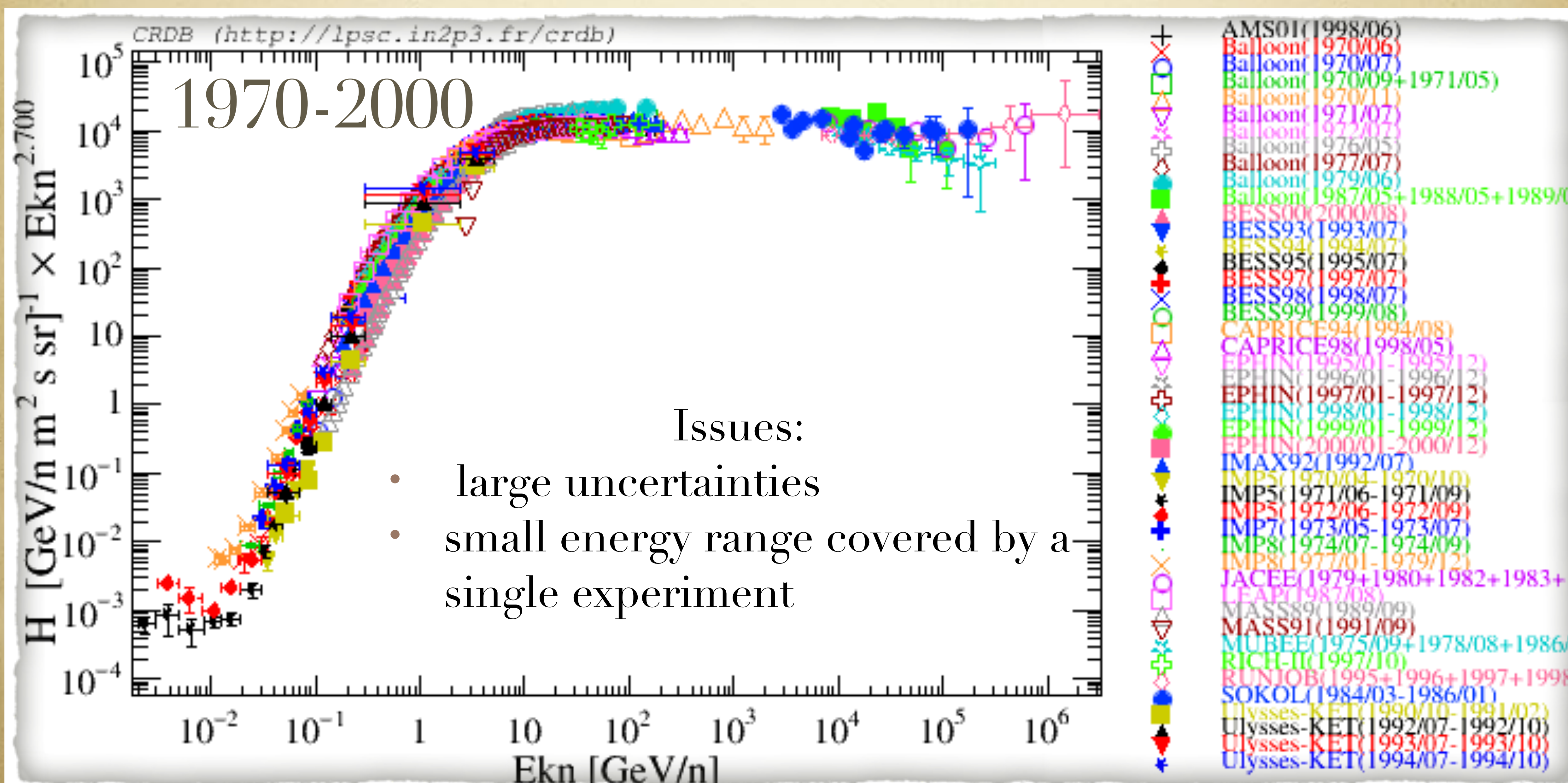
Precise measurements provided by the current generation of CR detector have been providing new insight to the physics of cosmic rays

P. Serpico ICRC2015
L. Drury ICRC2017

Cosmic ray proton measurements

until a few decades ago...

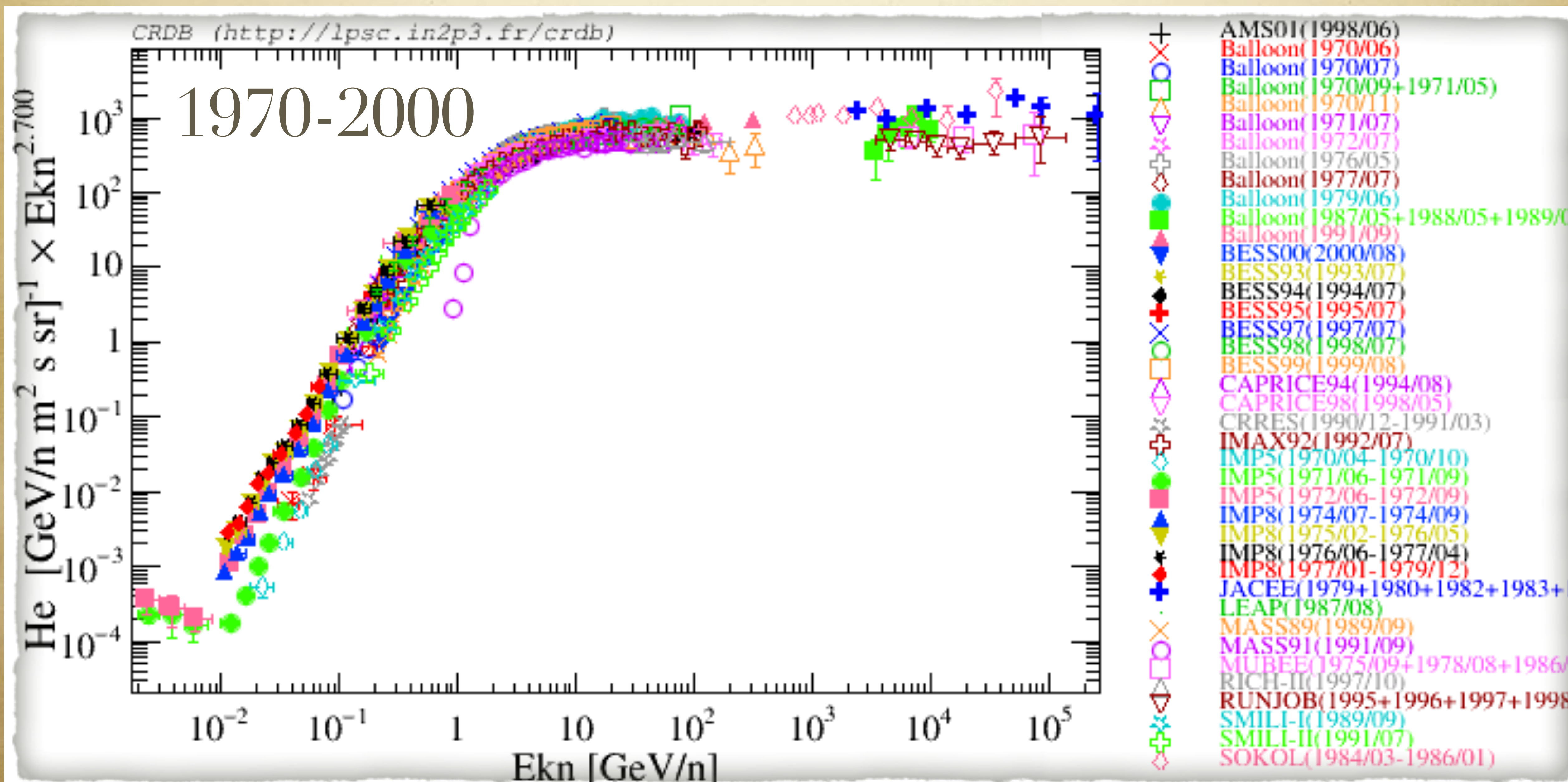


Issues:

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

Cosmic ray helium measurements

until a few decades ago...



Cosmic ray helium measurements

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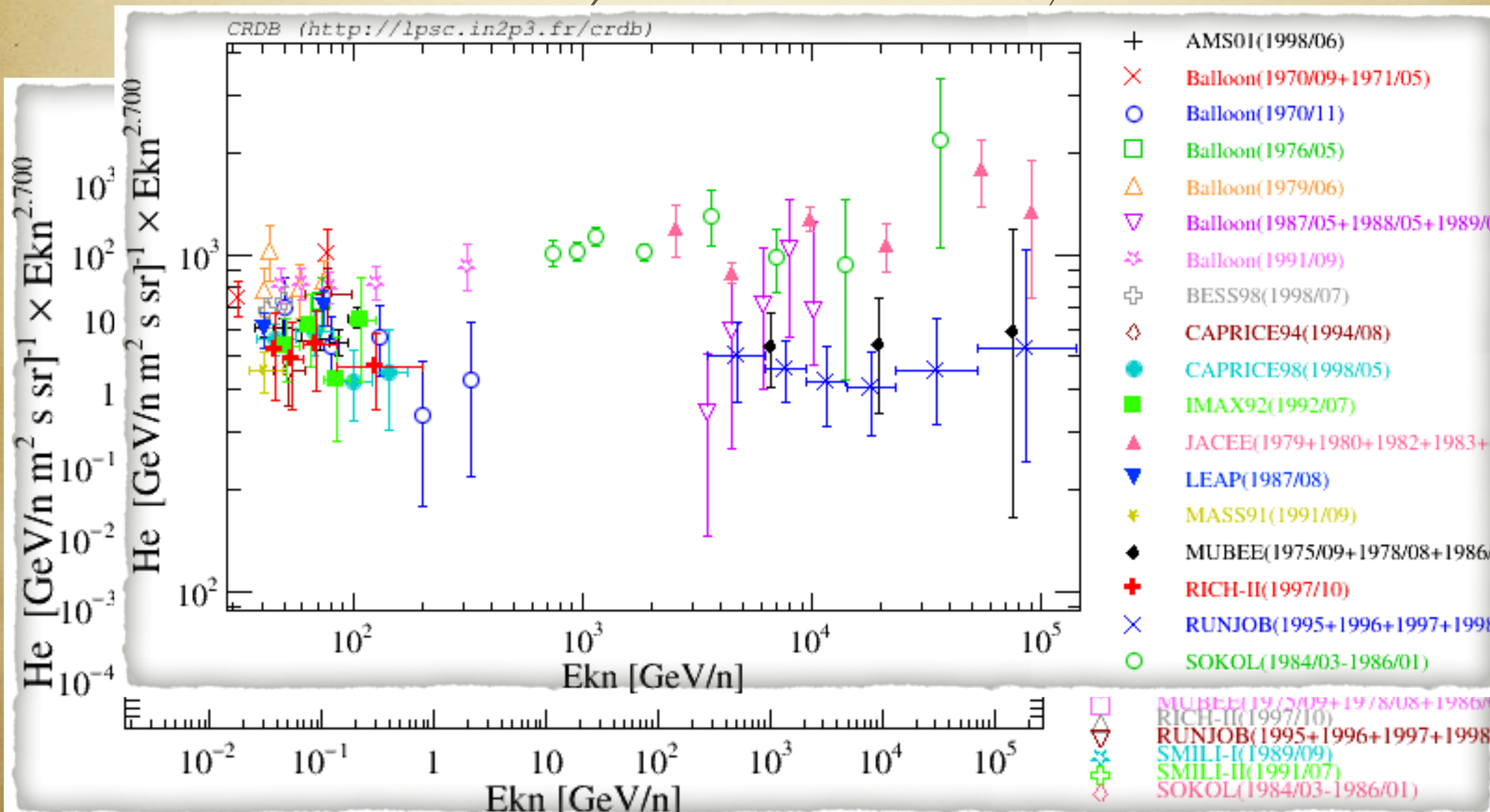
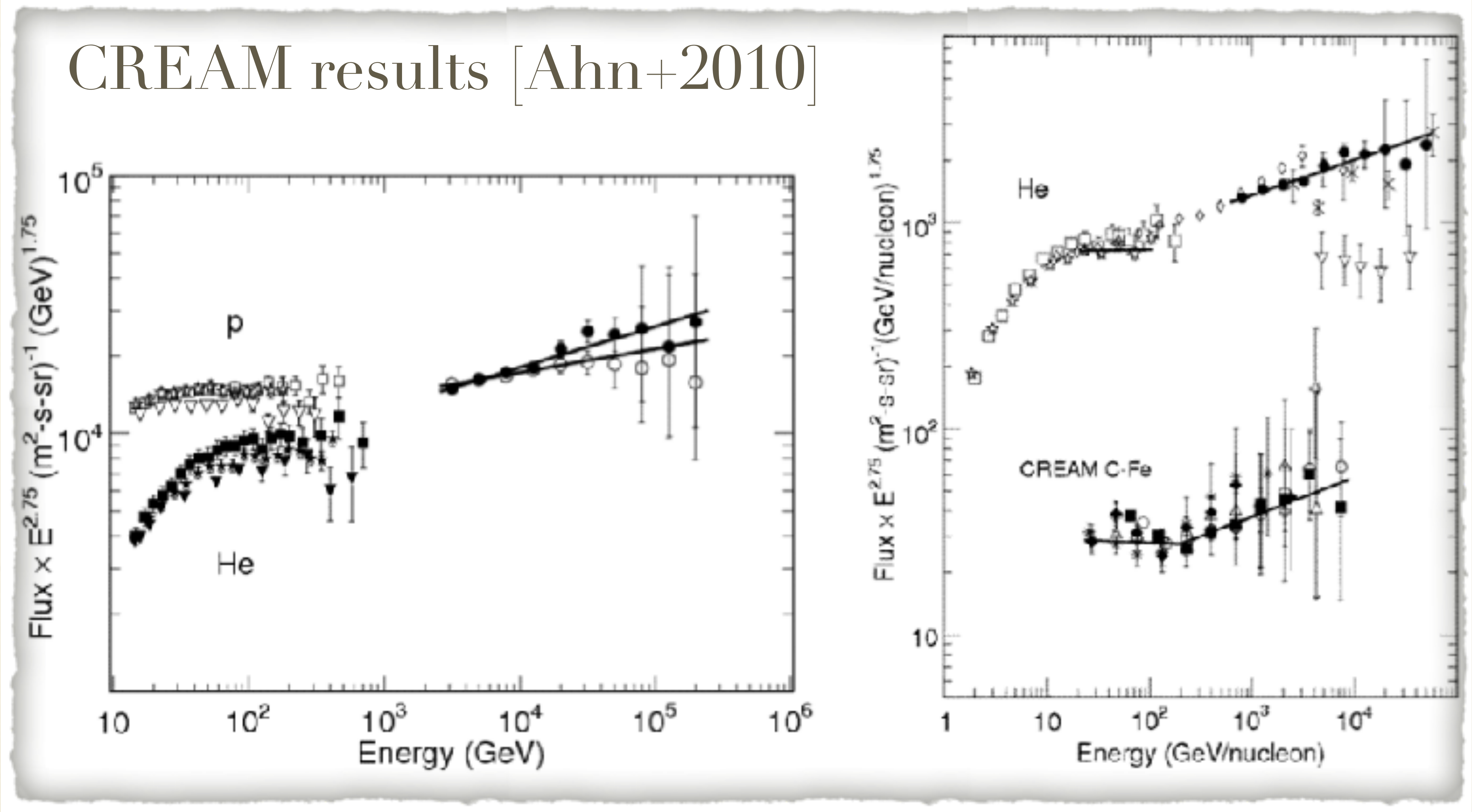


hints of surprises …

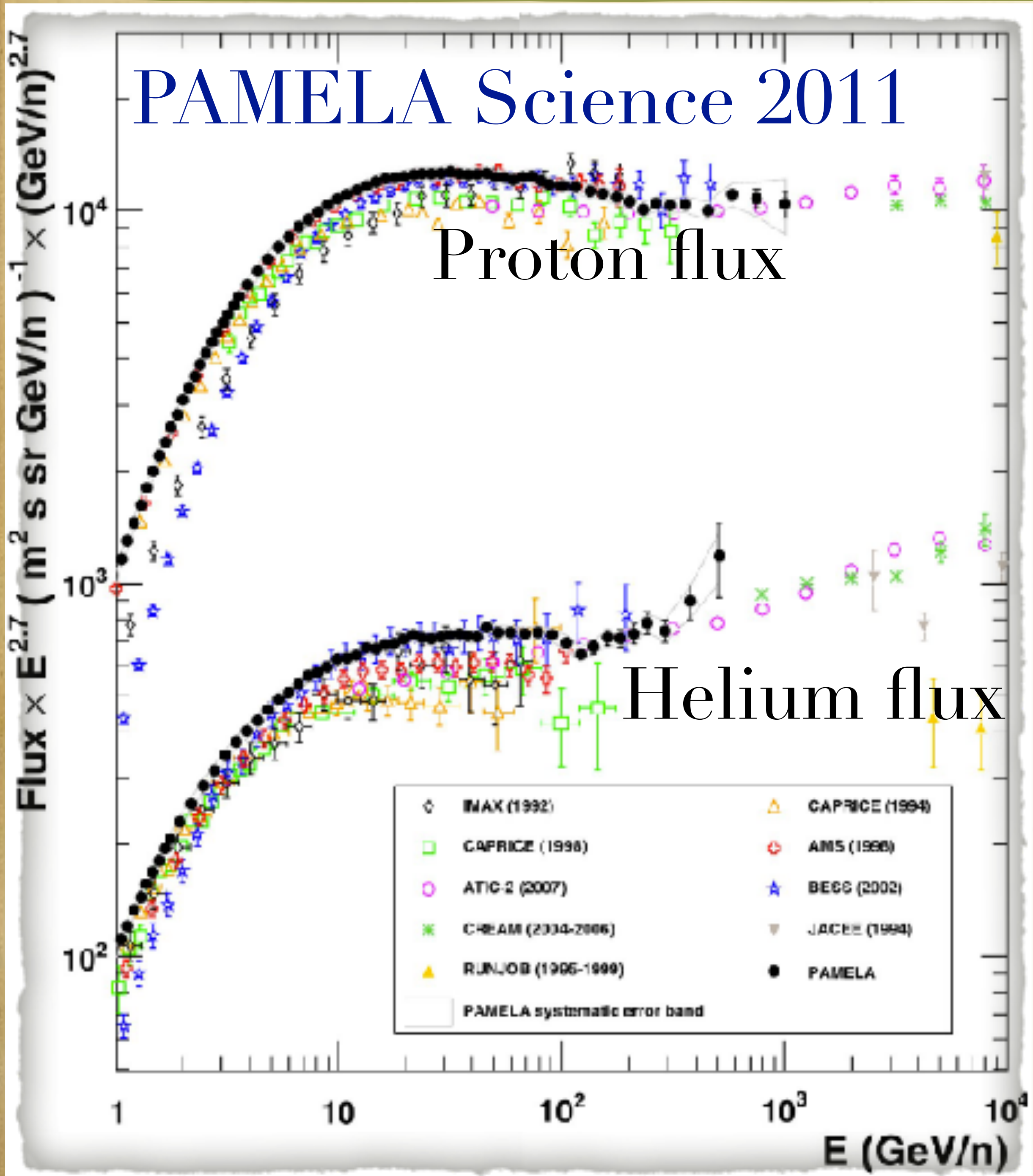
- When the GeV-TeV region became to be explored with sufficient precision … hints of possible features emerged in p, He but also in heavier nuclei and antimatter !



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 surprise: broken PL below the knee



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

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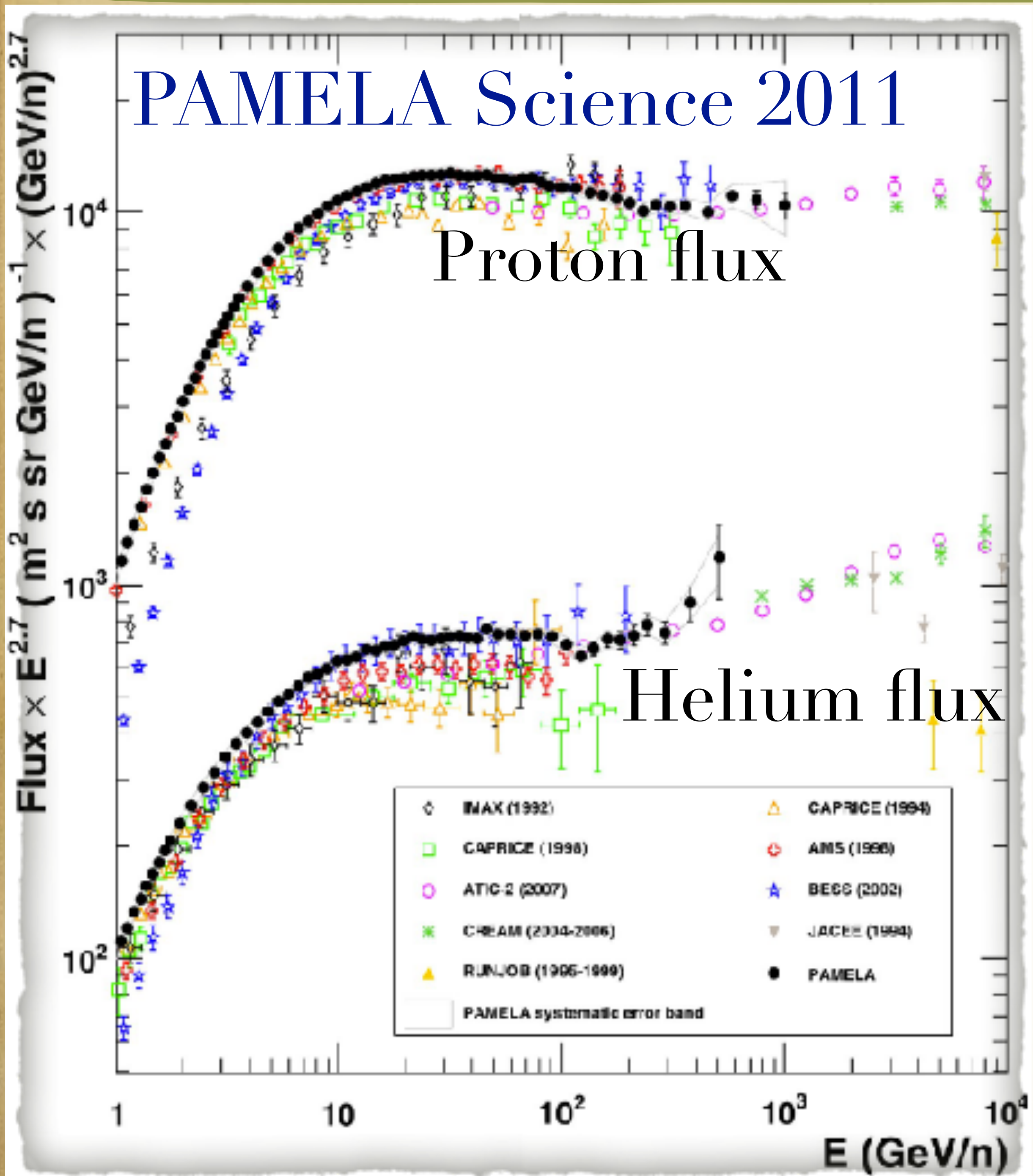
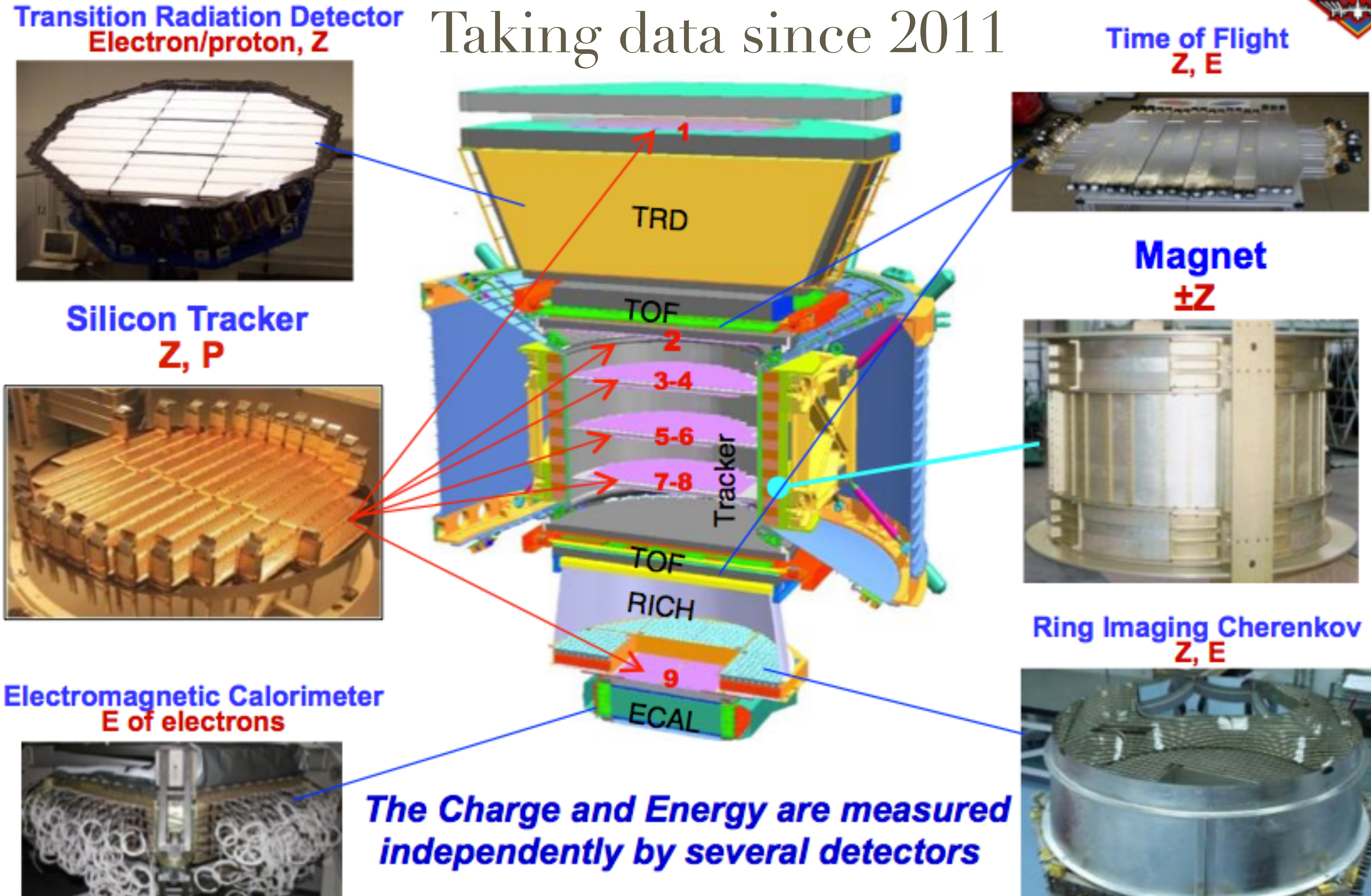


A single instrument covering the whole energy range was solving the puzzle

AMS: A TeV precision, multipurpose spectrometer

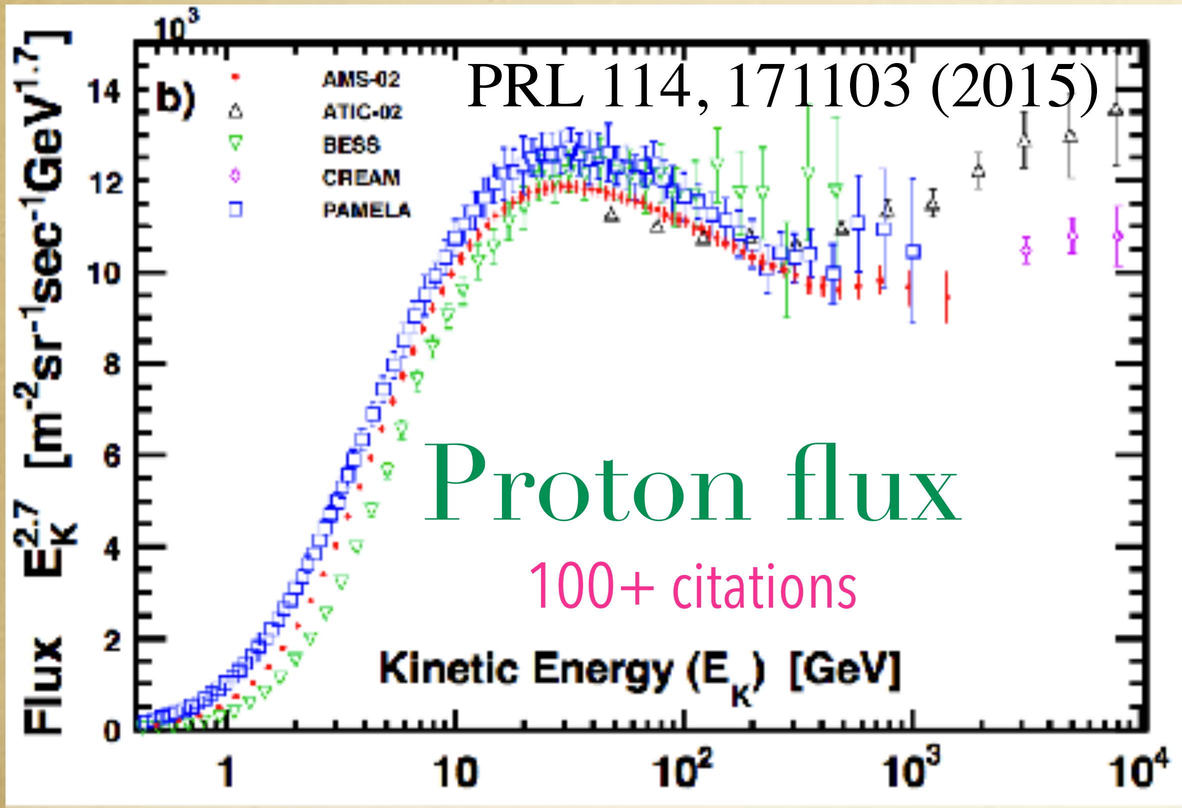
Taking data since 2011



The Charge and Energy are measured independently by several detectors

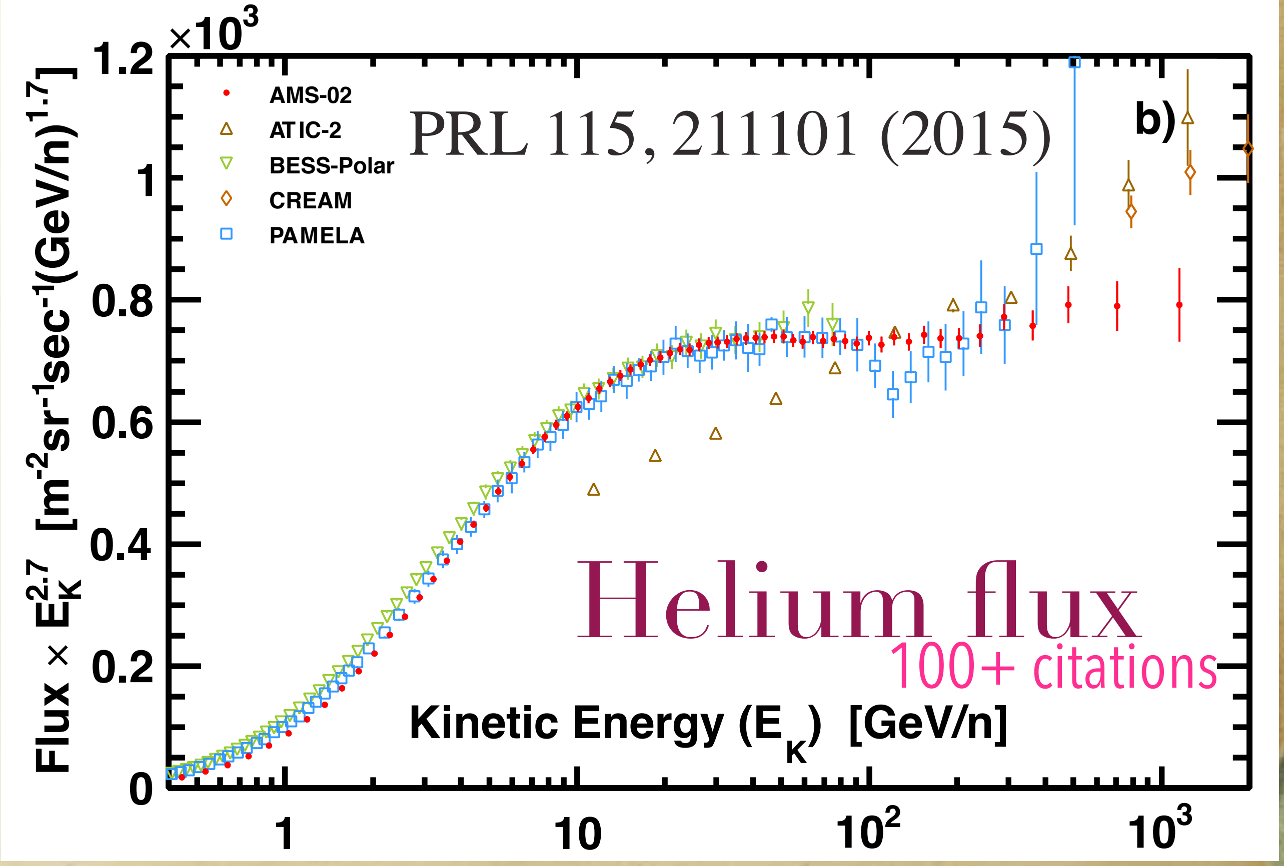
AMS-02 proton and helium result

happy ending



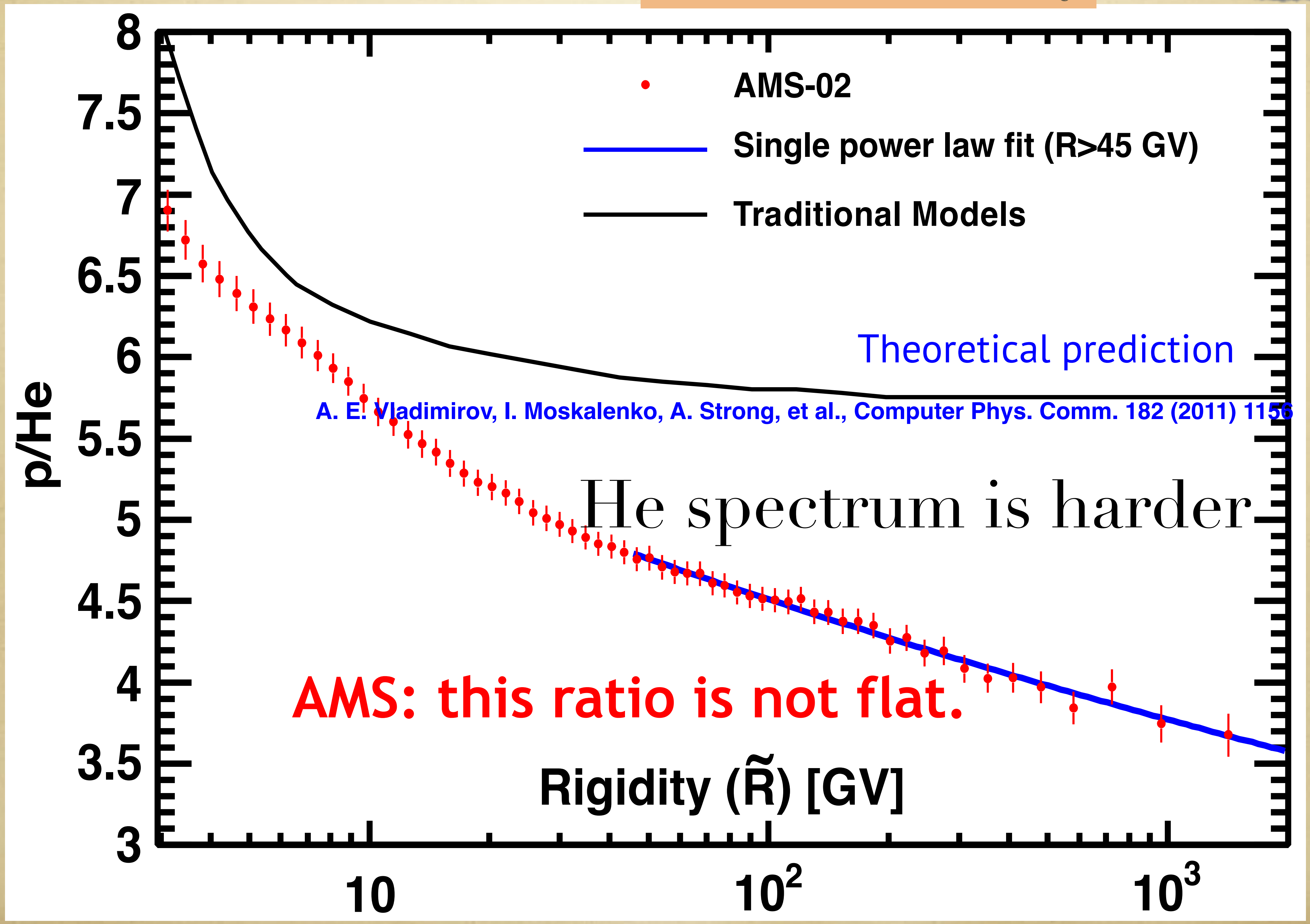
- Based on 300 million events (2011-2013)
- The proton flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.

- 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.



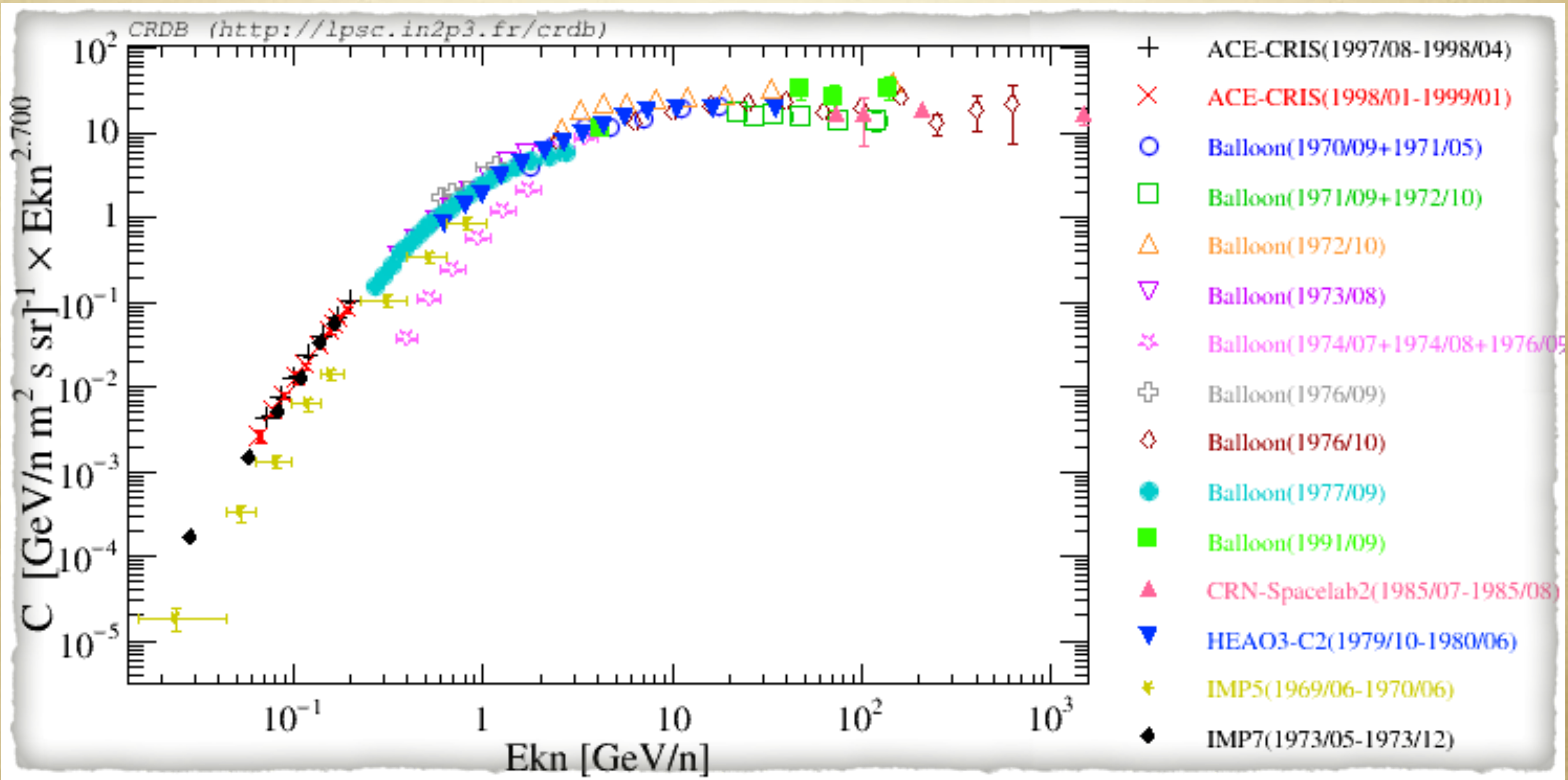
2nd anomaly: p/He flux ratio

non-universality

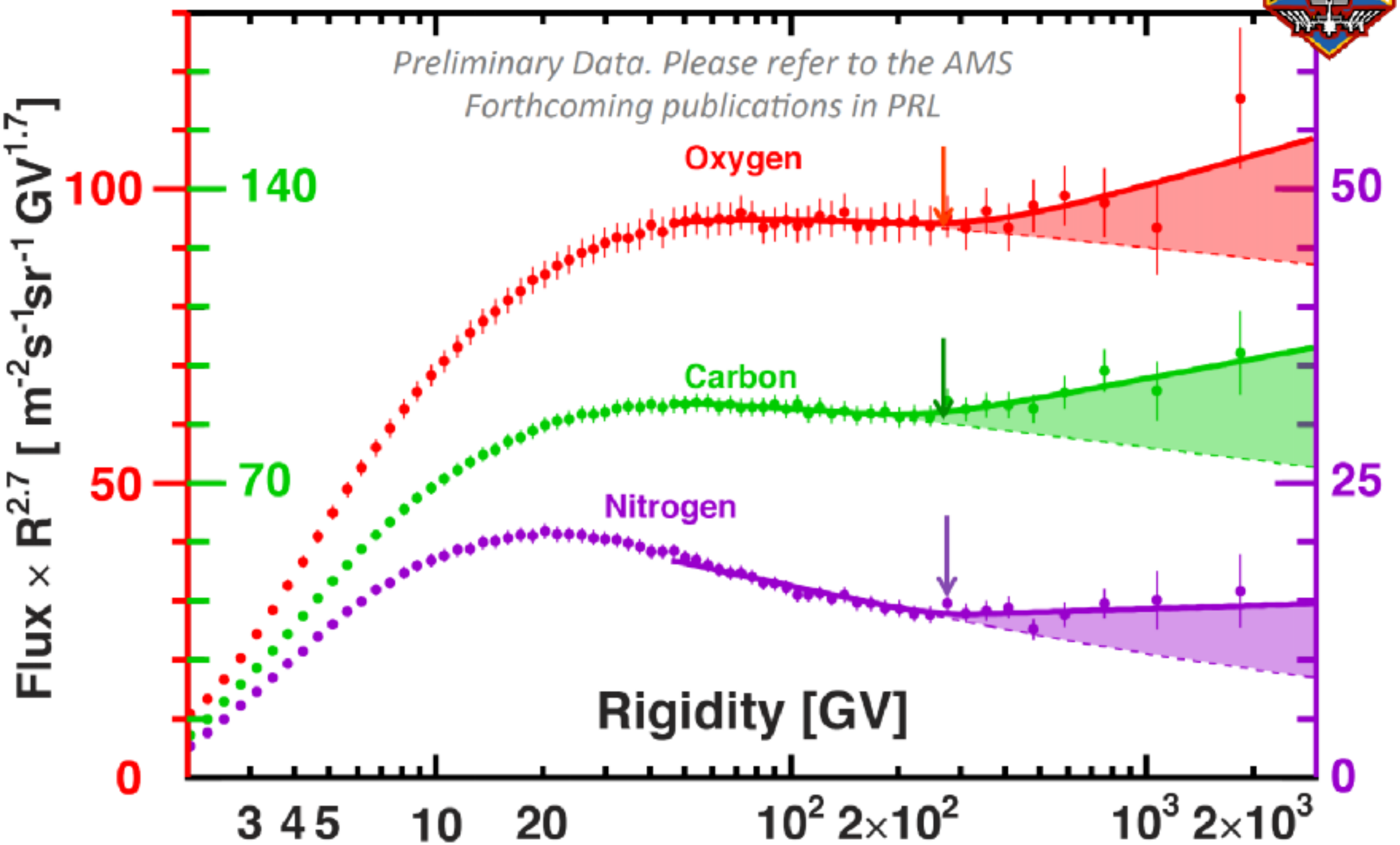


Cosmic ray carbon measurements

until a few decades ago...



The spectra of oxygen, carbon and nitrogen do not follow the traditional single power law.



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Some things we believe(d) about CRs

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The observational improvements occurred during the past decade show the first cracks in the simplest model for cosmic ray origin/propagation.

A simple model to understand CRs

The leaky-box model (LBM) uses the simple picture of particles injected by sources distributed uniformly over some volume (box) and escaping from this volume with an escape time independent of position, and a uniform distribution of gas and radiation fields.

- Diffusive shock acceleration mechanisms provide a single power law for the source term **Q(E) ~ E^{-2}**
- The leakage term only depends on energy and includes diffusion and convection terms **τ(E) ~ $E^{-0.3-0.7}$**

$$\frac{\partial \Phi}{\partial t} + \frac{\Phi}{\tau_{\rm diff}(E)} = Q$$

In the steady state:

$$\Phi = Q(E)\,\tau_{\rm diff}(E)$$

Source term

Propagation term

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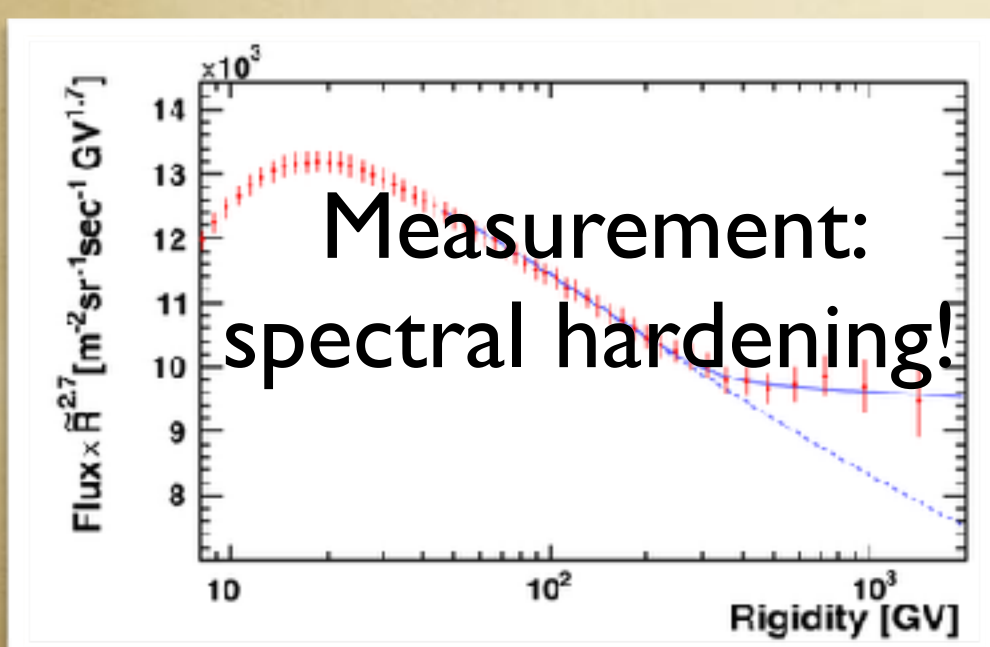


Measurement: spectral hardening!

Q and τ cannot both be described a single power law!

Possible scenarios to reproduce current data:

- Drop the single power-law behaviour in Q(E)
- Drop the single power-law behaviour in $\tau(E)$
- Drop the homogeneity of $\tau(E)$
- Drop the homogeneity of Q(E)
- …

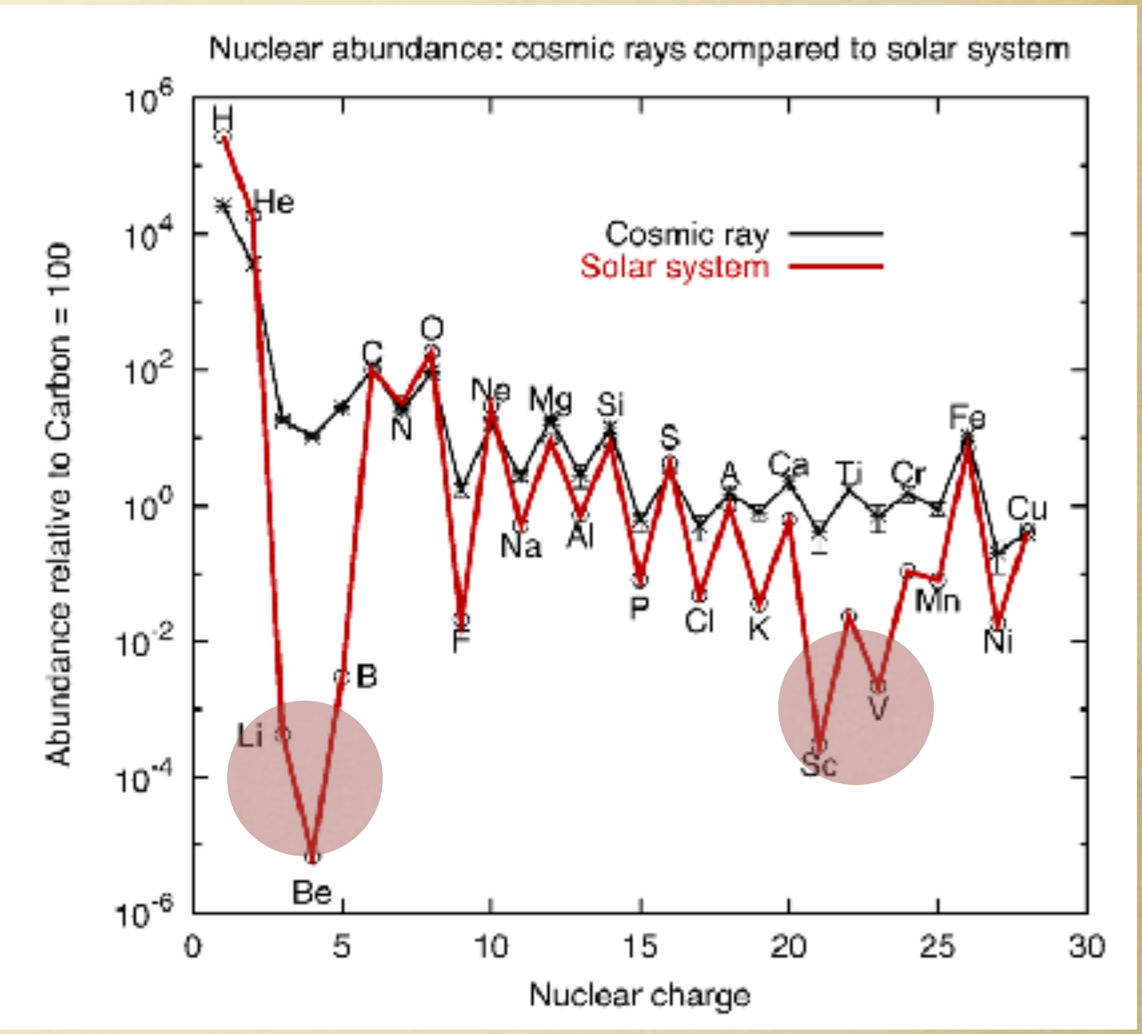
N. Tomassetti, Astrophys. J. 752, L13 (2012)[arXiv:1204.4492].
P .Blasi, E. Amato, P. Serpico, Phys. Rev. Lett. 109, 061101 (2012)[arXiv:1207.3706]
T. Stanev, P. L. Biermann & T. K. Gaisser,A&A 274, 902 (1993)

G. Bernard, T. Delahaye, P. Salati & R. Taillet, A&A 544, A92 (2012) [1204.6289]
W. Liu, P. Salati and X. Chen, Res. Astron. Astrophys. 15, 1 (2015) [1405.2835].
N. Tomassetti and F. Donato, ApJ 803, 2, L15 (2015) [1502.06150]

and many other interesting papers …

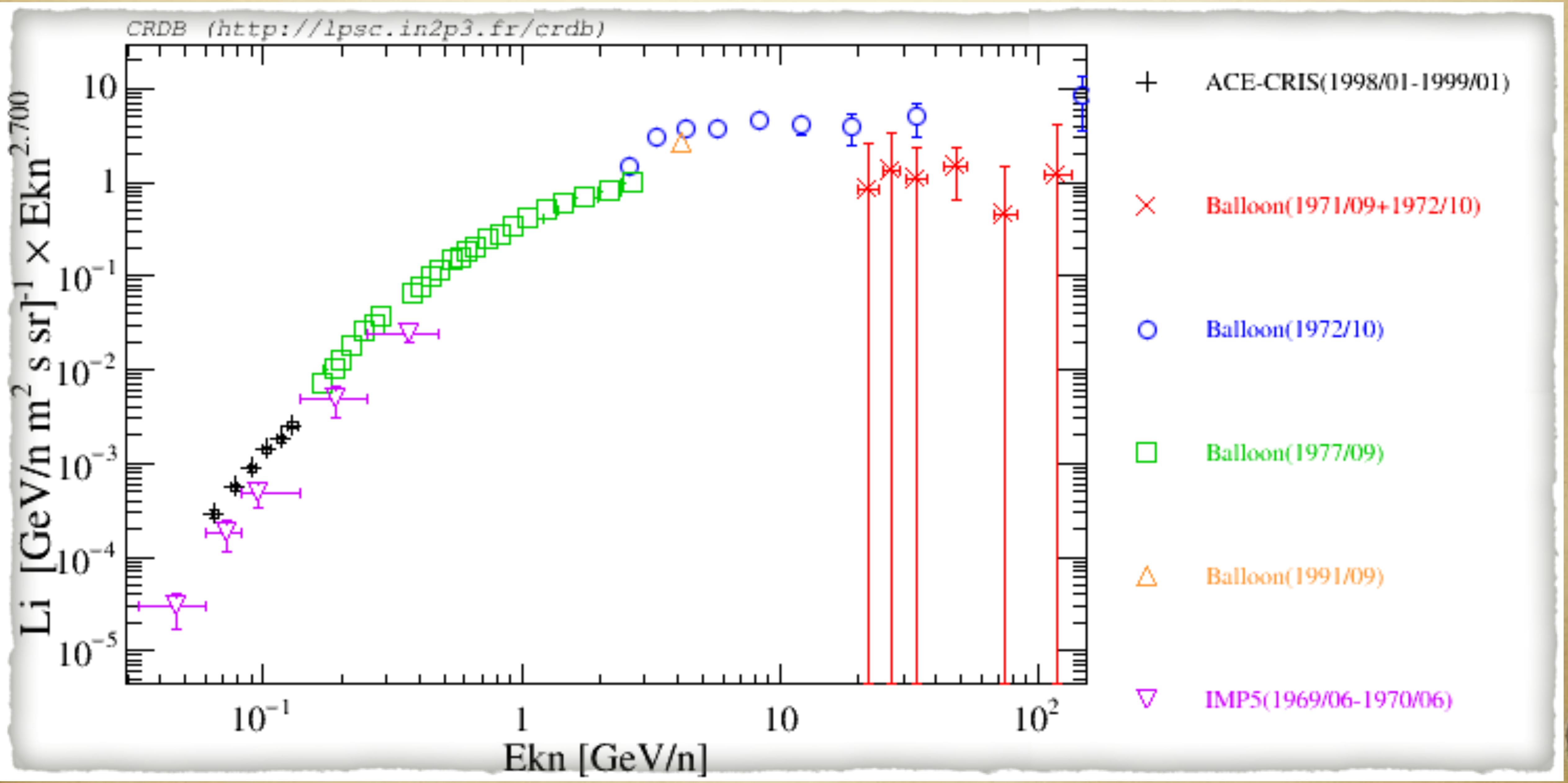
Secondary cosmic rays

- Fragile nuclei such as Li, Be, B are marginally present in stellar environments, while abundant in CRs.
- Their presence in CRs is interpreted as result of spallation of “primary” nuclei during their propagation in the interstellar medium.
- While CRs are sensitive to both acceleration and propagation effects, the secondary-to-primary flux ratios are used to constrain the propagation, being insensitive to injection.



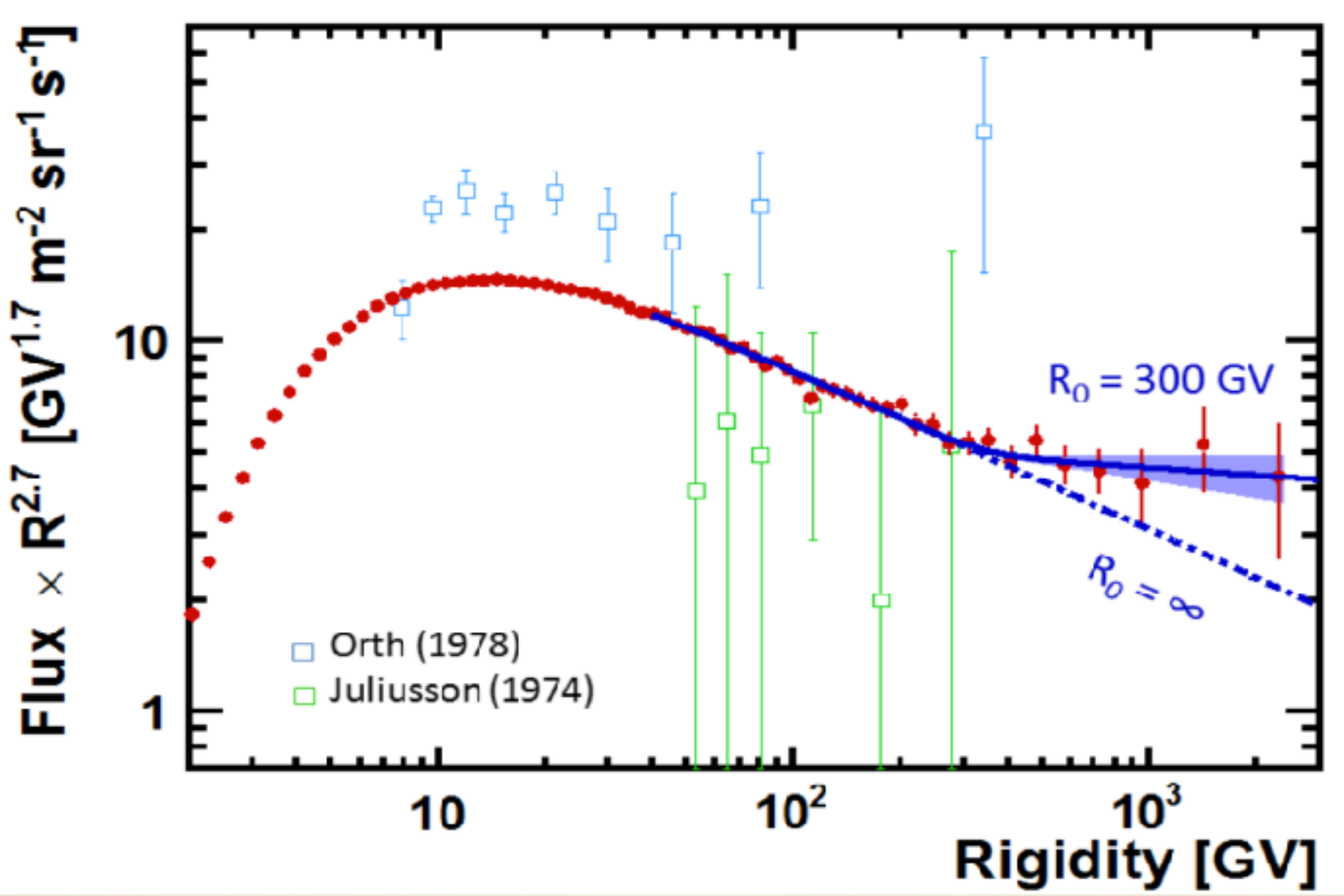
Cosmic ray lithium measurements

until recently...



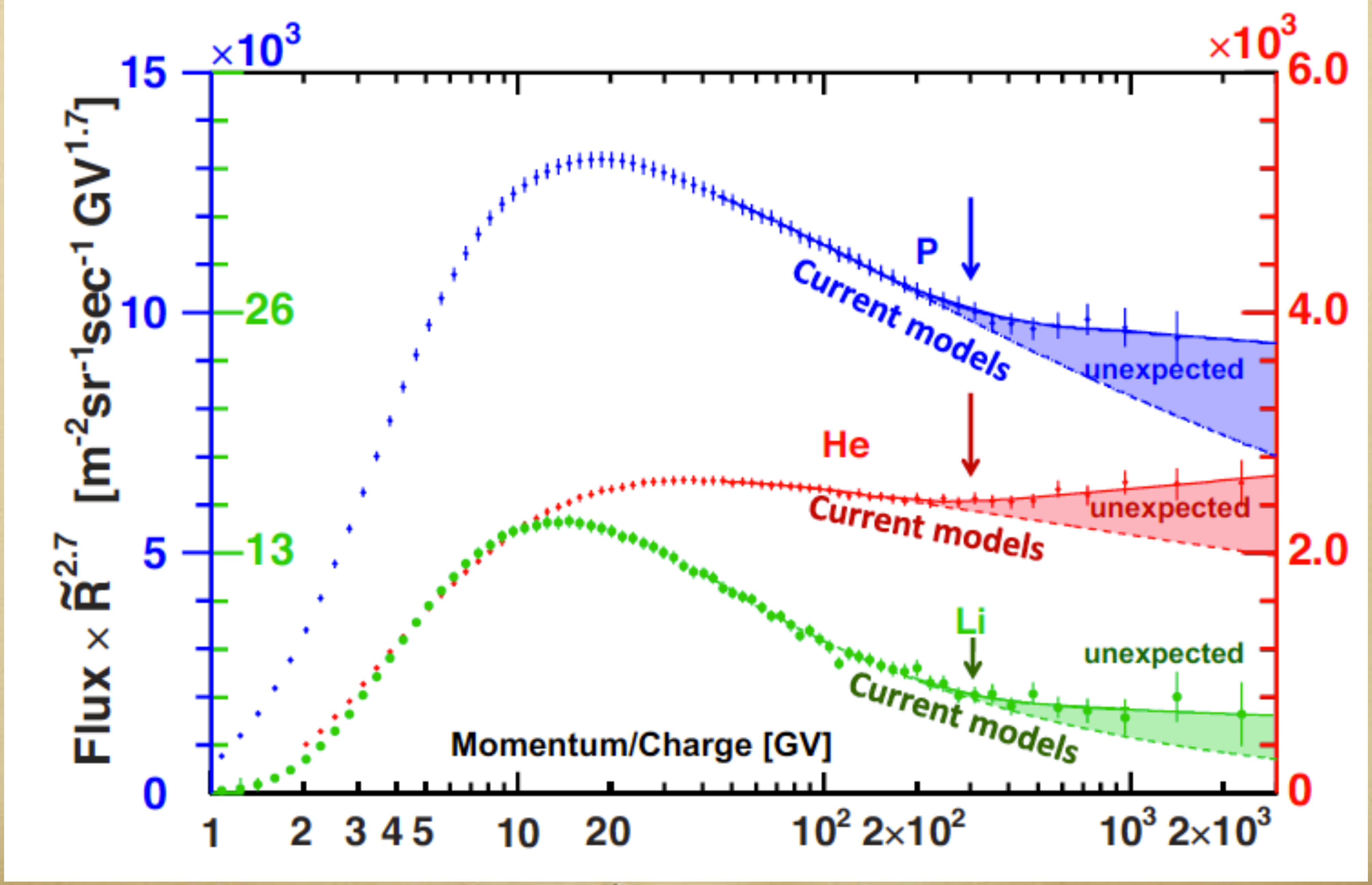
3rd anomaly: Lithium flux

- Up to now it was assumed that CR lithium has pure secondary origin.
- AMS data show that either cosmic ray lithium has a also a primary origin or the propagation of cosmic rays is rigidity-dependent.



Summary on light nuclei

The spectra of protons, helium and lithium cannot be described by a single power law. They all change their behaviour at the same energy.



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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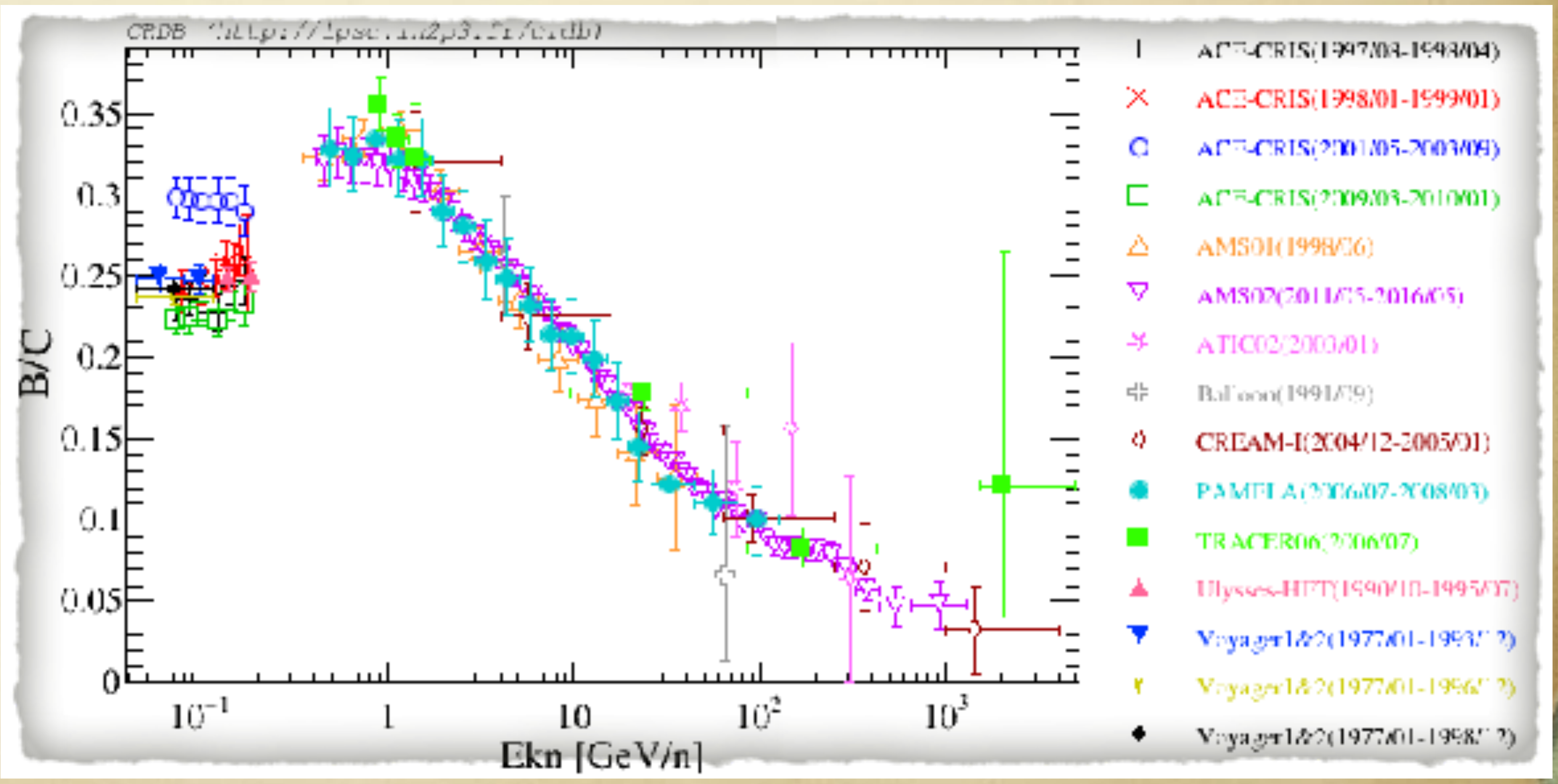
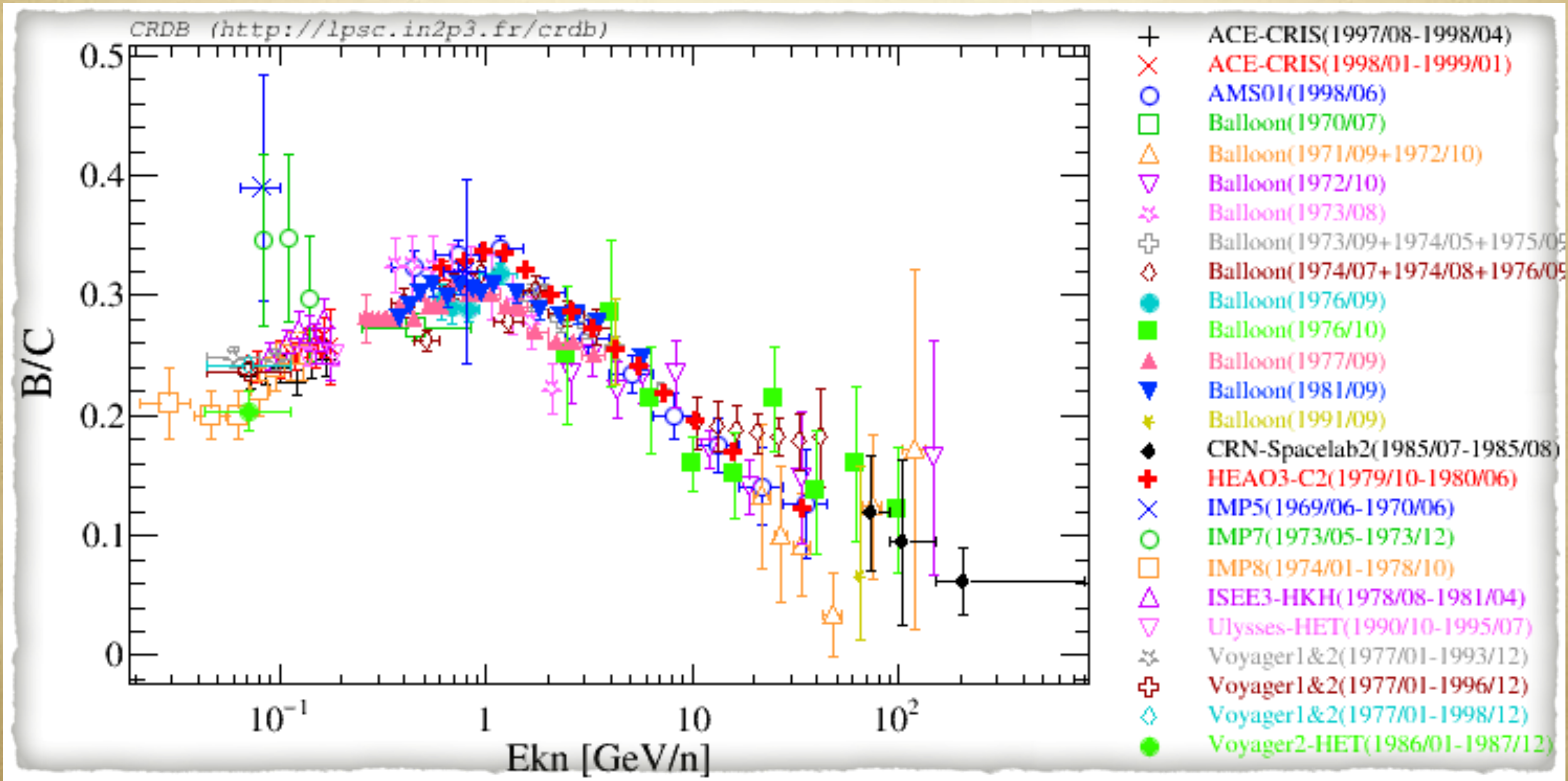


Testing break models

- Spectral hardening at high energy observed in primaries like Proton and Helium.
- Precise measurement of Li, Be, B flux are key observables to study the origin of the hardening:
  - 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

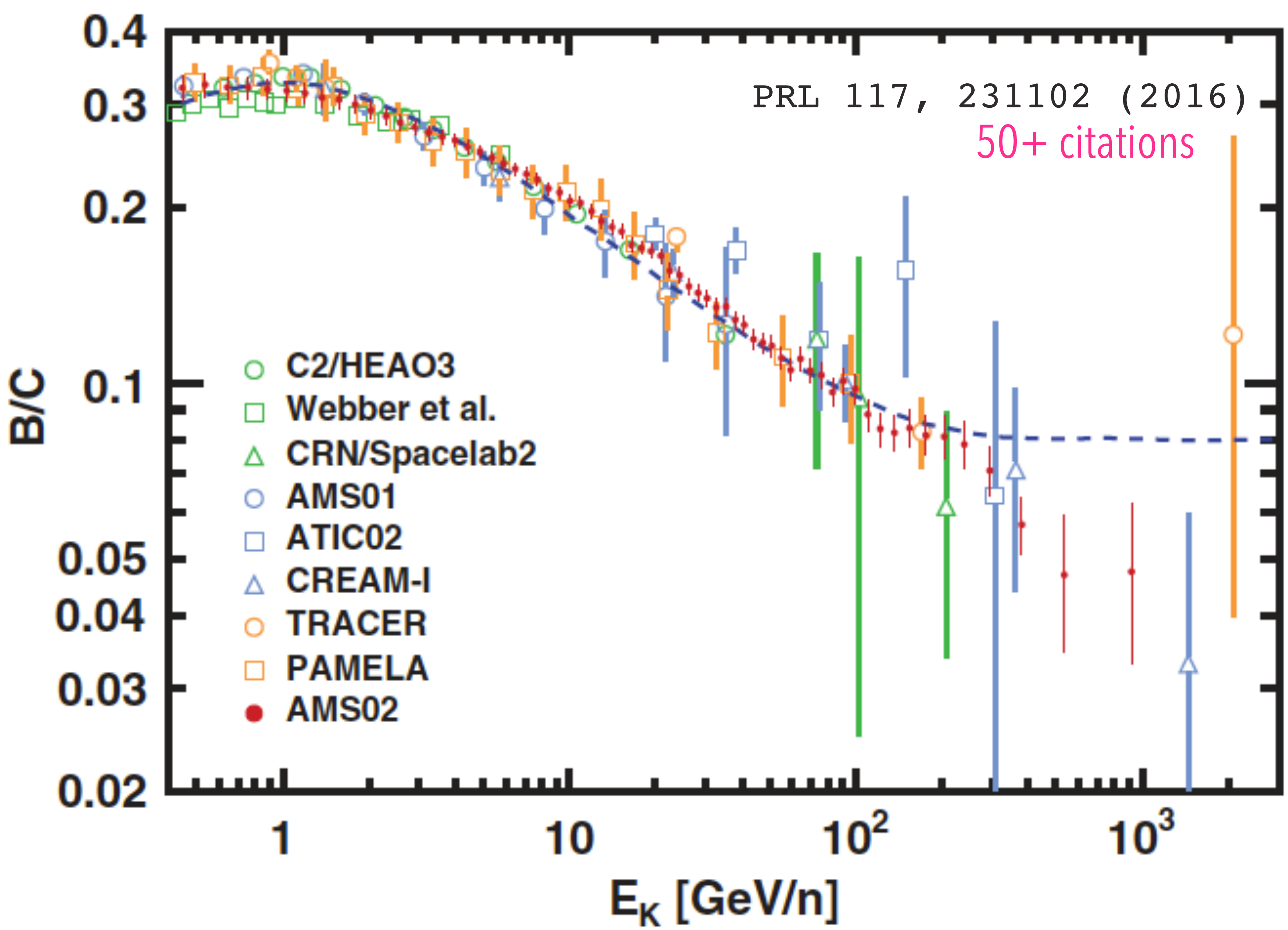
Cosmic ray boron-to-carbon measurements

until a few decades ago...



Boron-to-Carbon flux ratio

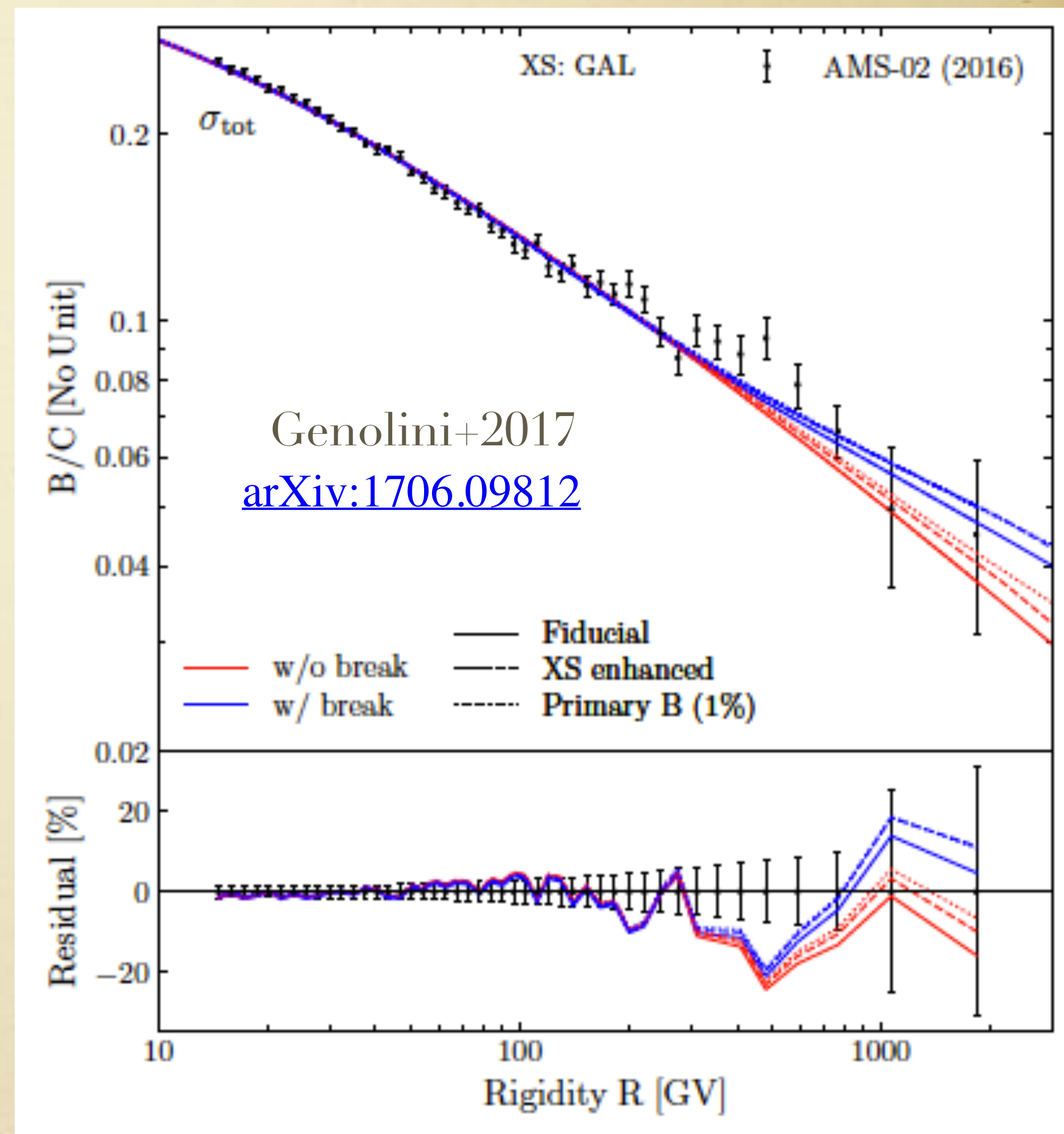
The Boron-to-Carbon flux ratio shows no significant structures, disfavouring several CR models predicting a rise at high energies.



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 in favor of 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.



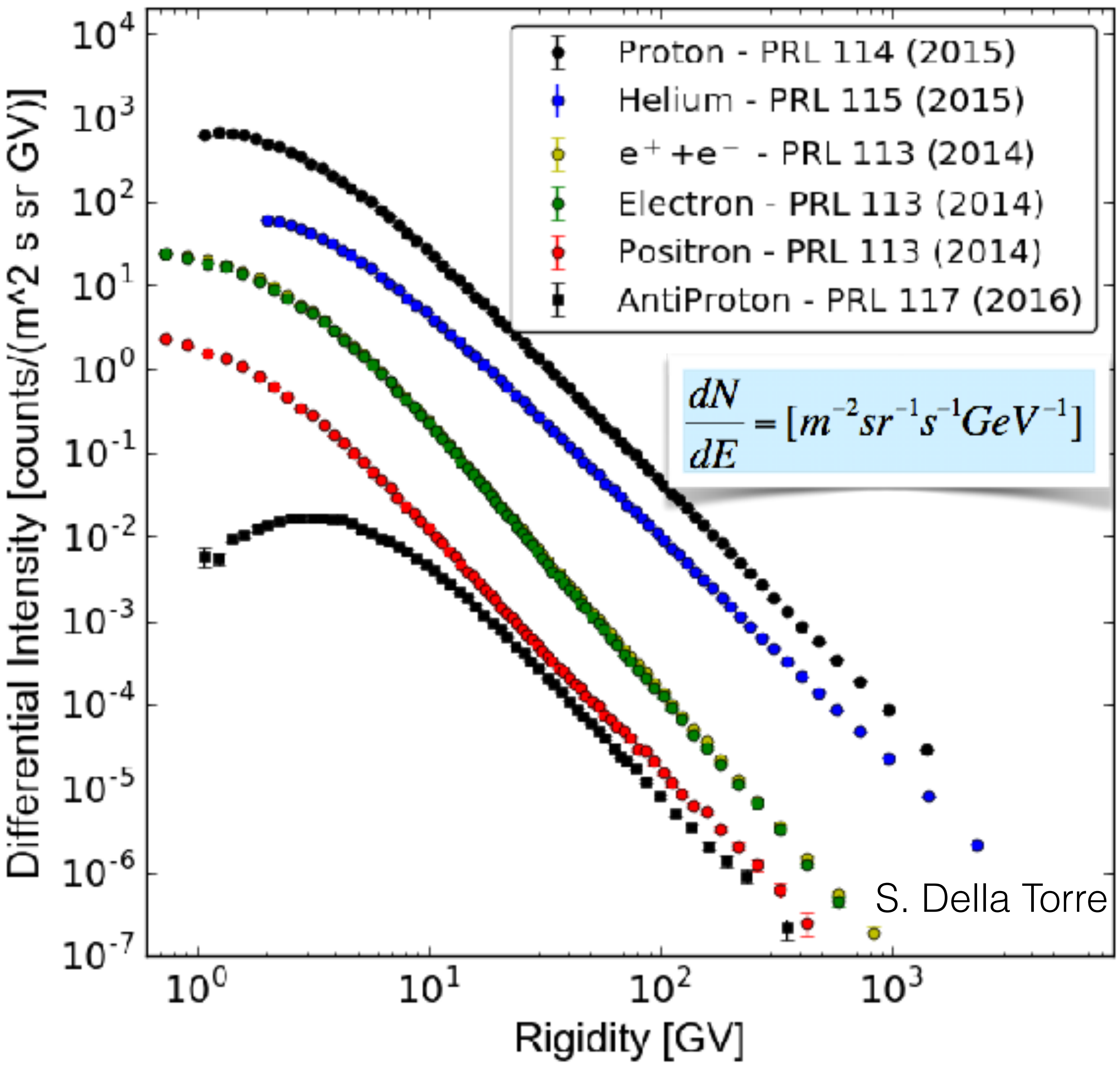
Genolini+2017
arXiv:1706.09812

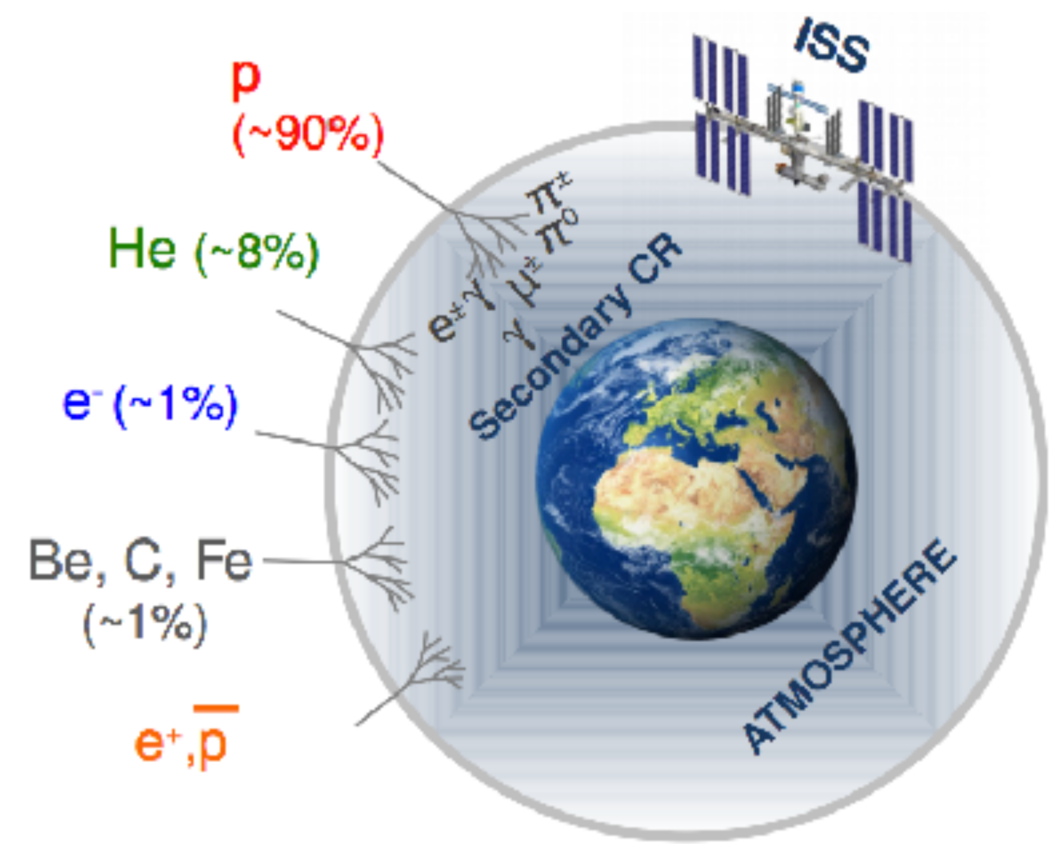
accepted in PRL

Summary on CR nuclei

- More than 100 years after their discovery, CR physics is a lively field of research, driven by new experimental results.
- The observational improvements occurred during the past decade show the first cracks in the simplest model for cosmic ray origin/propagation.
- PAMELA and AMS-02 brought the CR physics to a new precision level in the GeV to TeV energy region.
- Transition in the spectral index of primary nuclei (p, He, C, O) observed around 200 GV. Lithium is also a source of surprise.
- Precise measurement of B/C together with other secondary-to-primary ratios provides important clues to understand the nature of spectral breaks.

Cosmic ray fluxes measured by AMS-02





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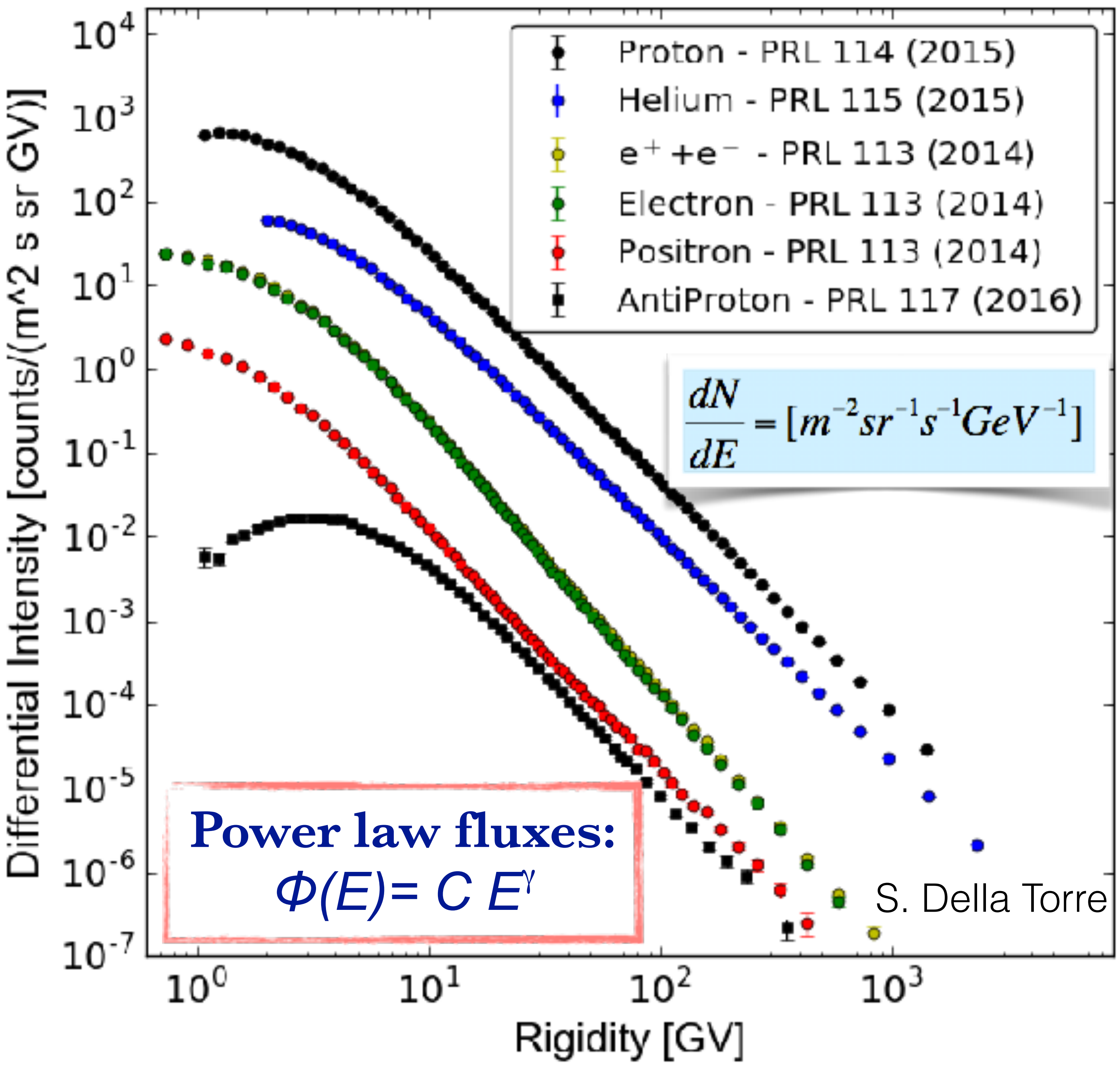
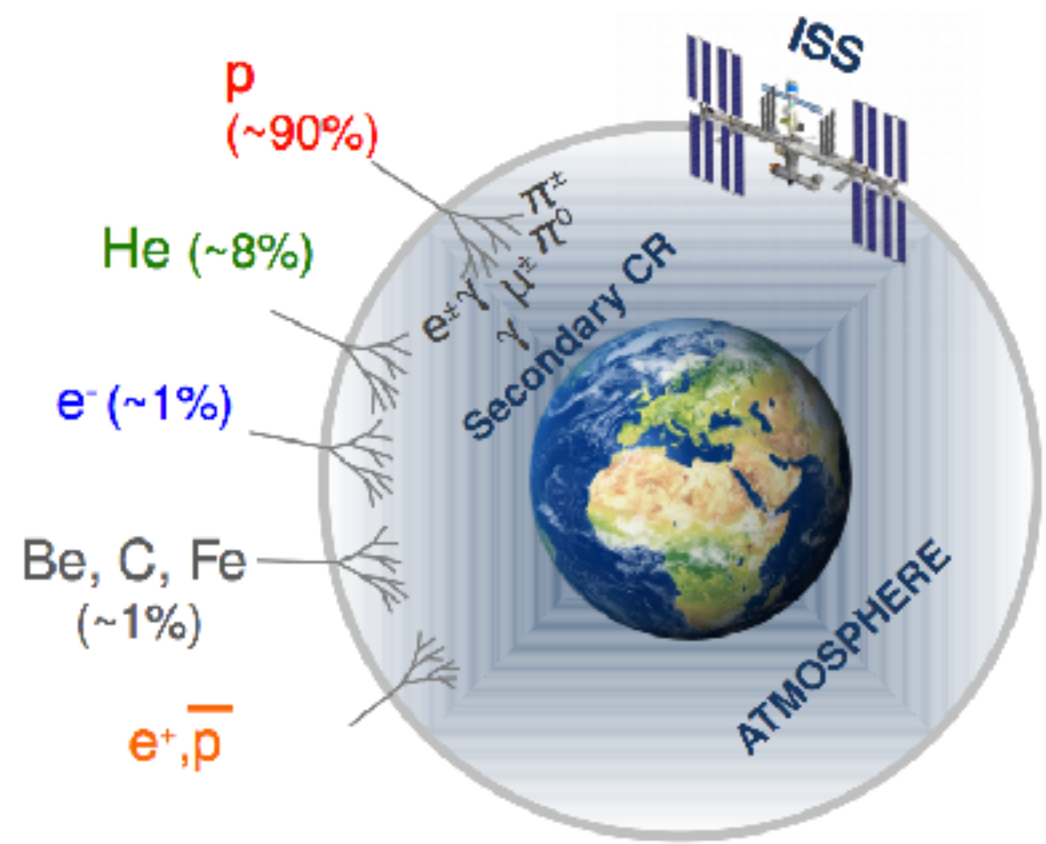




CR electrons, positrons and antiprotons

Why should we care ?

- Electrons and positrons constitute together about 1% of cosmic radiation.
- They are important probes about CR propagation in the galaxy. Given their low mass they suffer severe energy losses during the propagation in the ISM, setting upper limits to the age and the distance of the sources: a window to the nearby universe !
- Measurements performed by balloon-borne or satellite experiments show excess of positrons with respect to the expectations from conventional production mechanisms above 30 GeV, that implies the existence of a nearby source of positrons, whose nature is still under debate.

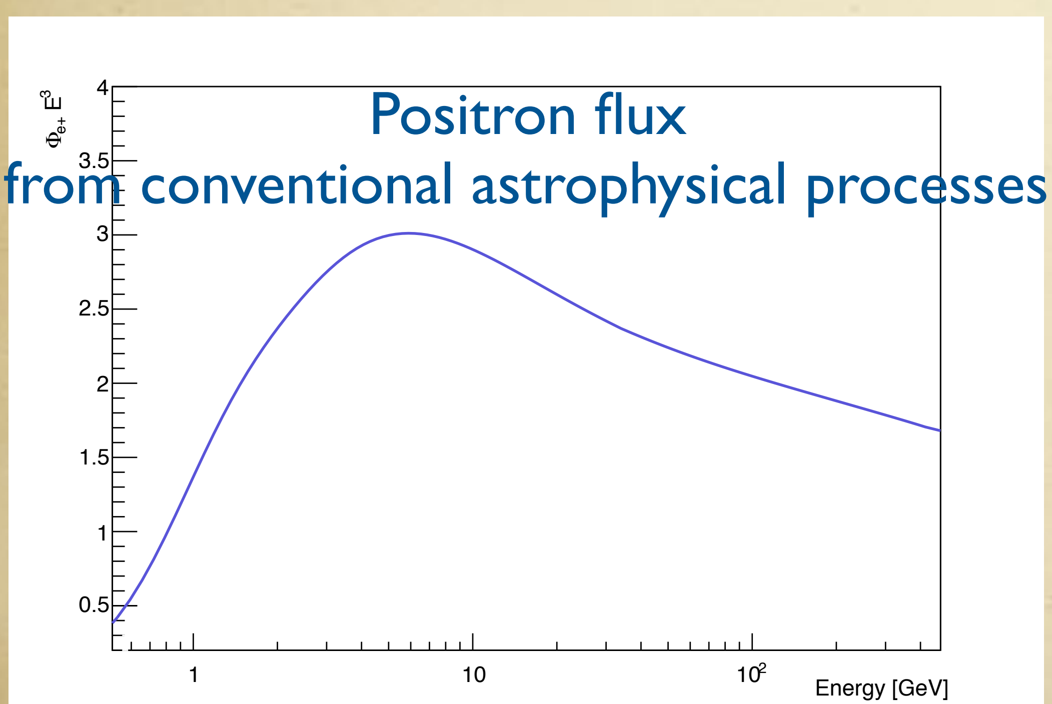
Antimatter in cosmic rays

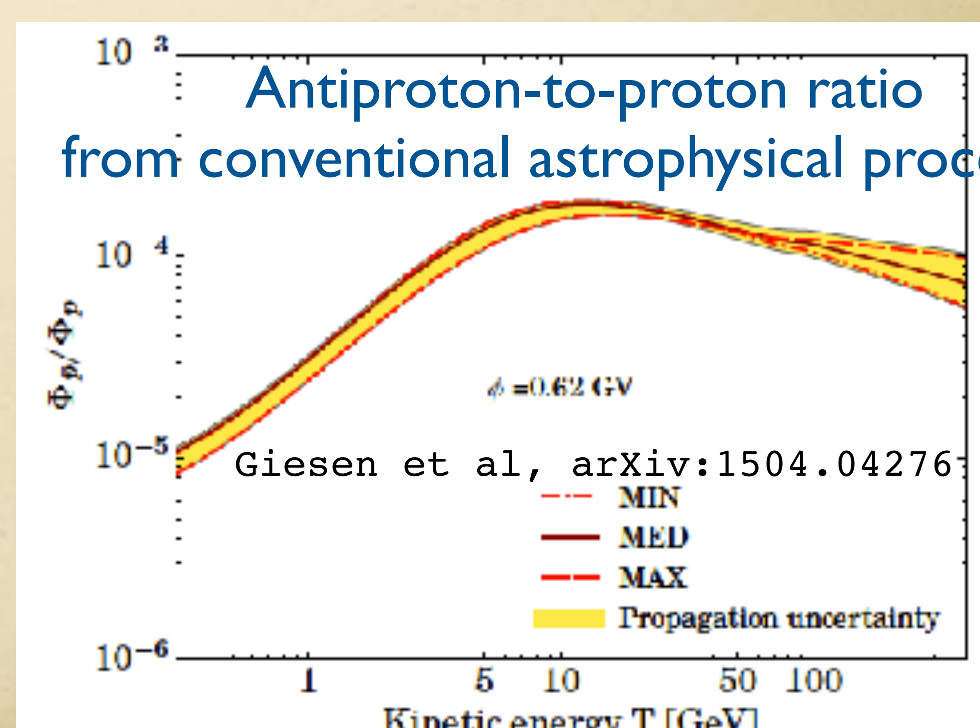
Positrons and antiprotons are known to be secondary particles produced as a consequence of the interaction of primary cosmic rays with the interstellar medium (p+p$_{ISM}$, p+He$_{ISM}$, He+He$_{ISM}$).

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

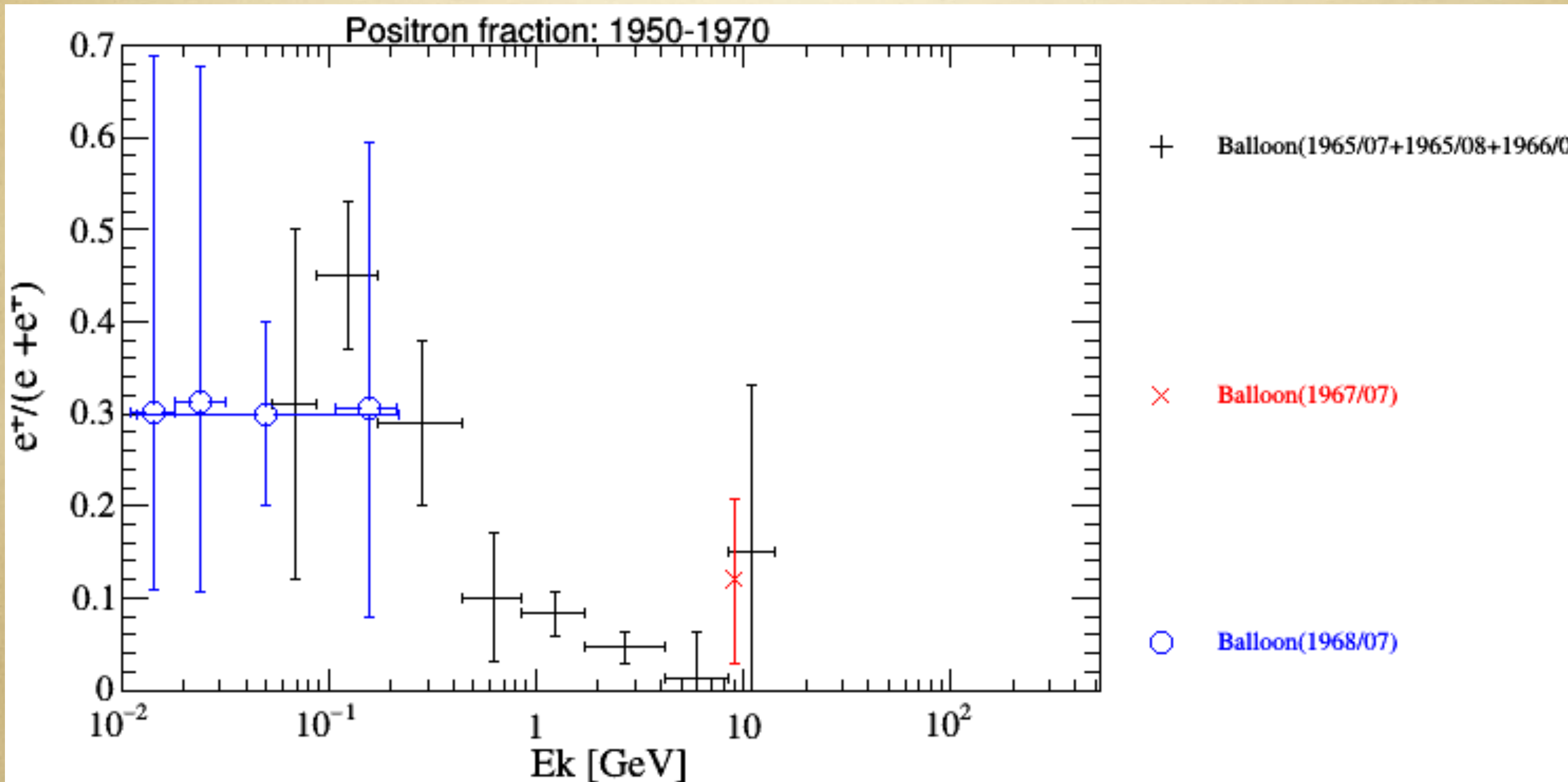
- Subdominant component: in the GeV-TeV region the e+/e- ~ 0.1, while anti-p/p ~ 10^{-4}

- 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.



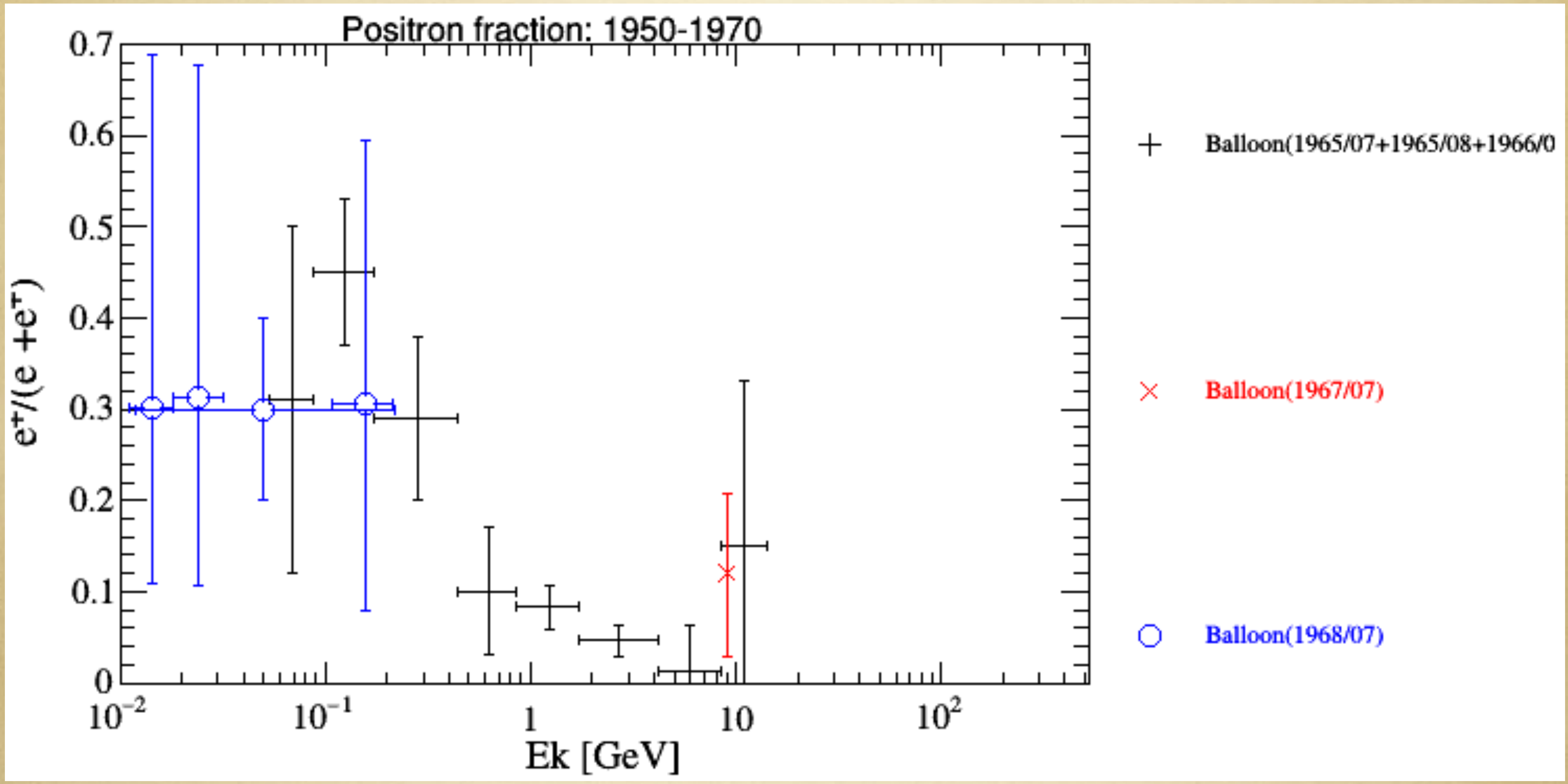


CR positrons data history



Animation by E. F. Bueno
Data from CRDB:https://lpsc.in2p3.fr/cosmic-rays-db/

CR positrons data history



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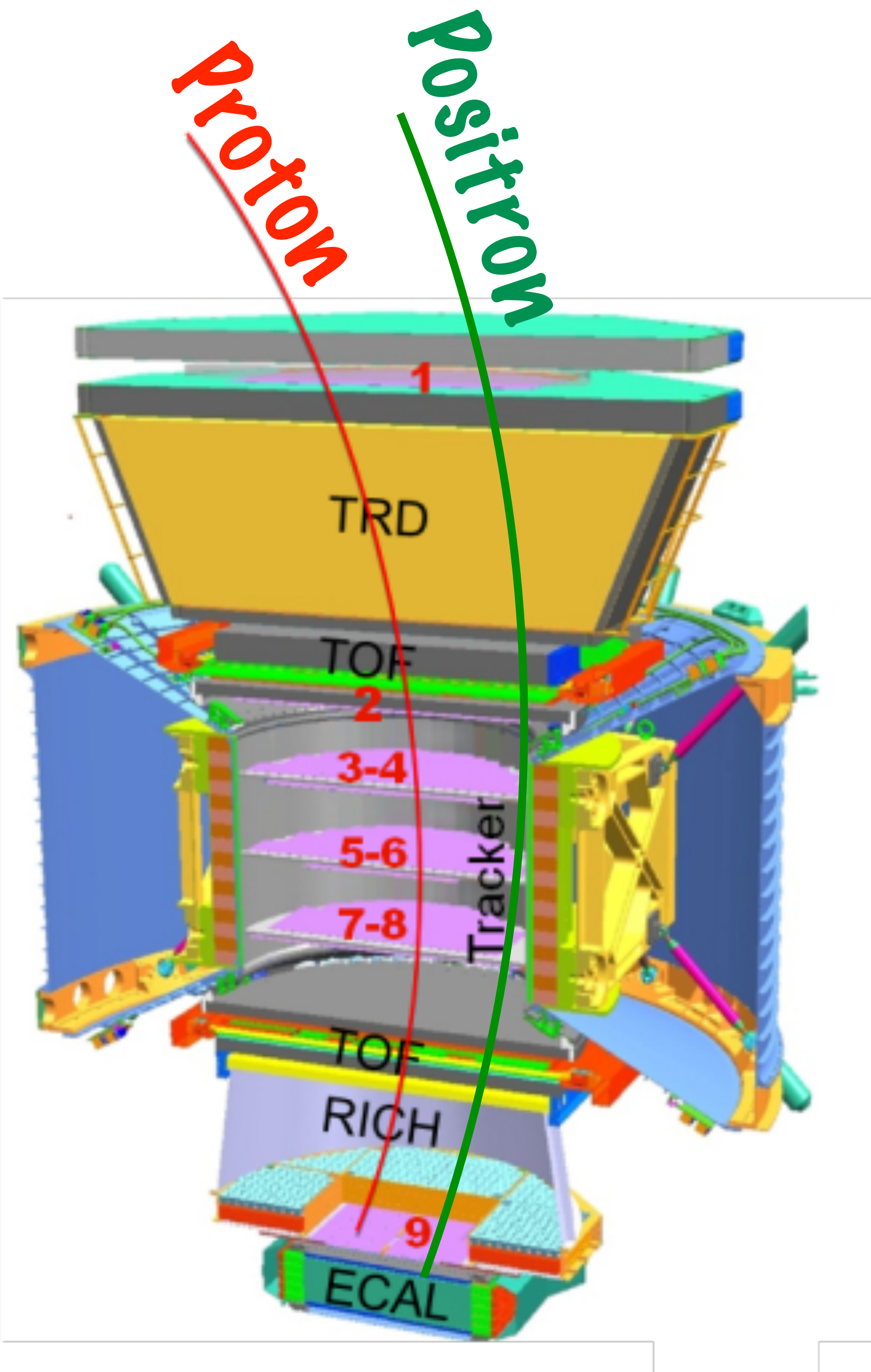
SEARCH FOR PRIMARY ANTIMATTER: POSITRONS



Main background: protons (S/B~10^{-4})
Background is reduced combining complementary detection techniques

Leptons identification

Keys of success :

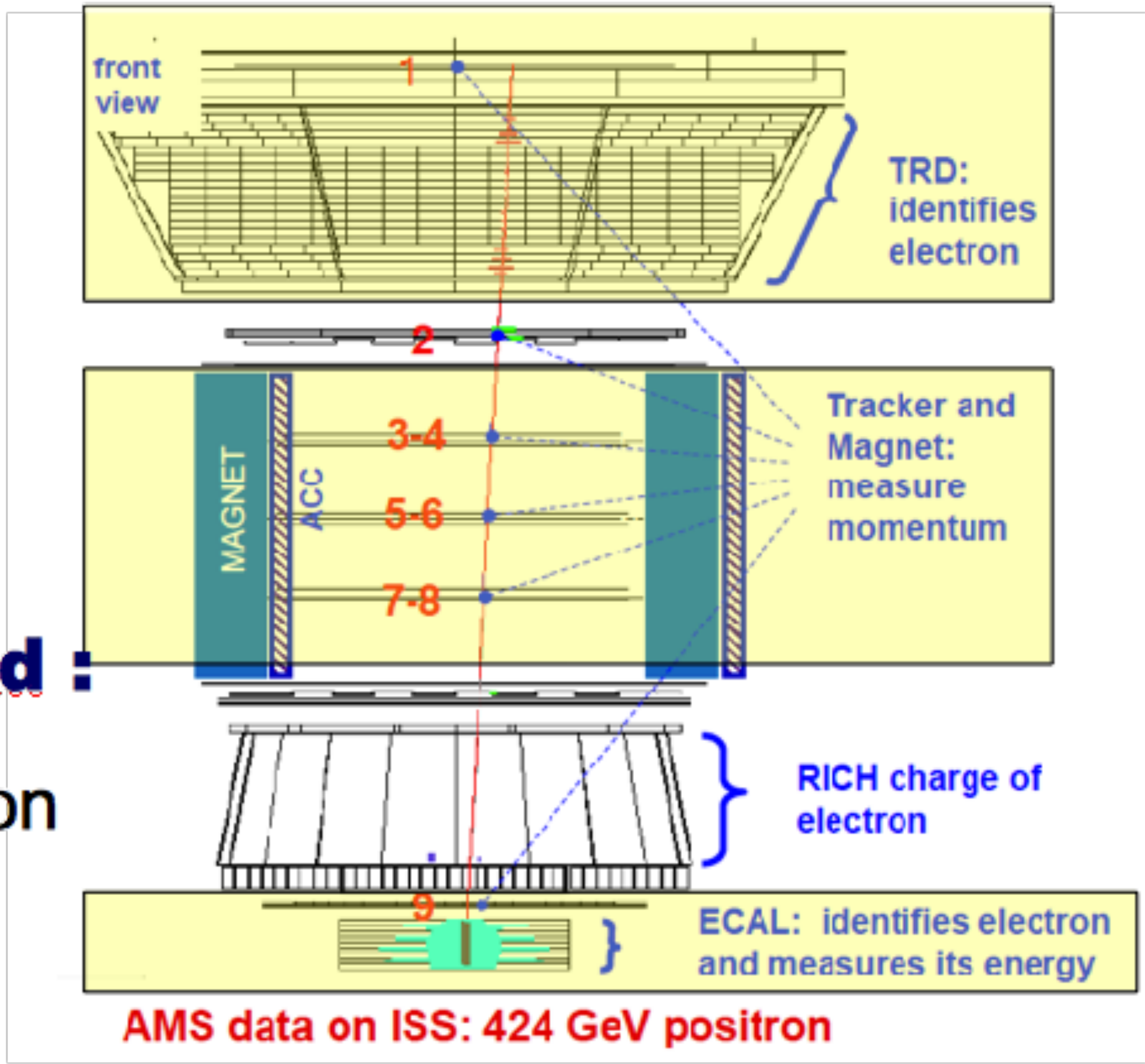
- redundancy of sub-detectors
- ECAL energy resolution
- Large data sample

Main sources of background :

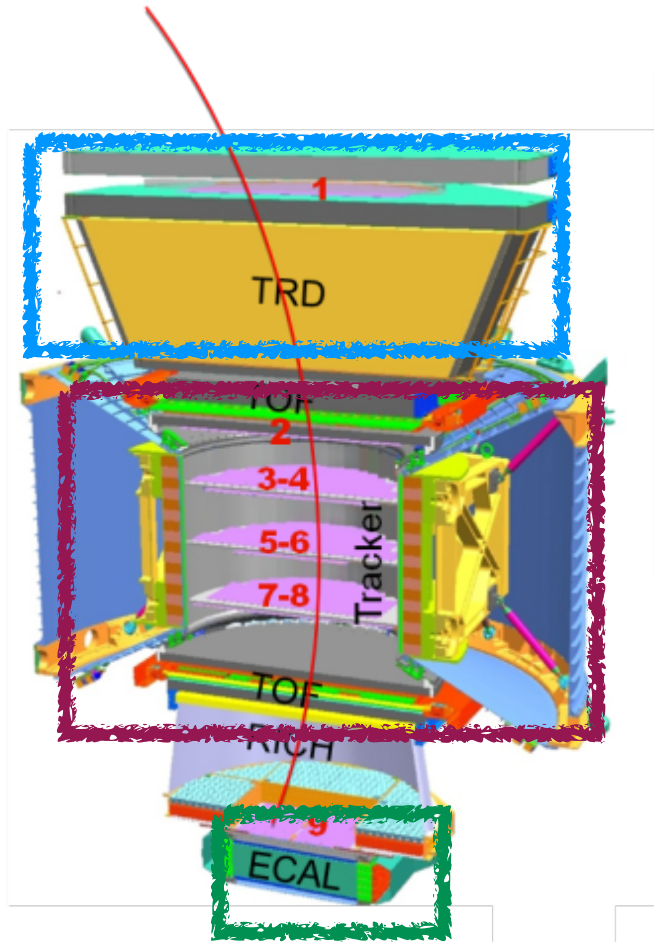
- Lepton/hadron mis-identification

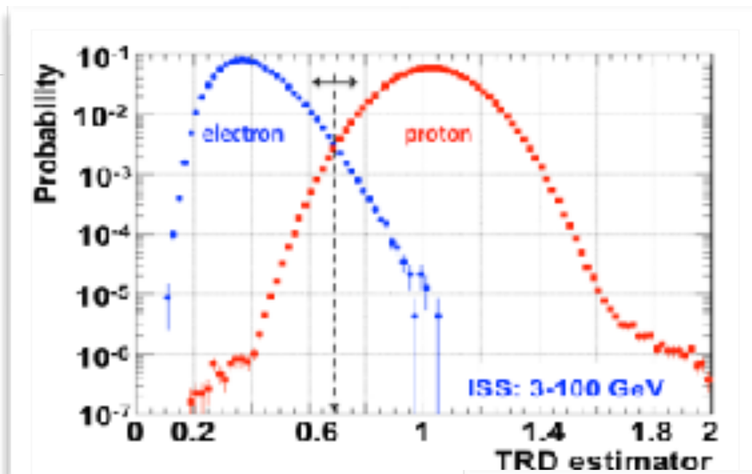
  (*p identified as e+*)
- Charge confusion

  (*e- identified as e+*)

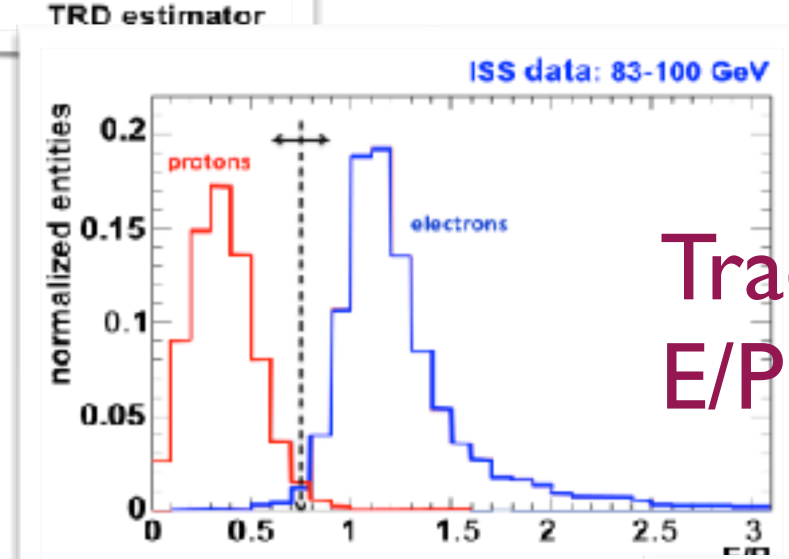


LEPTON-HADRON SEPARATION





Transition Radiation Detector



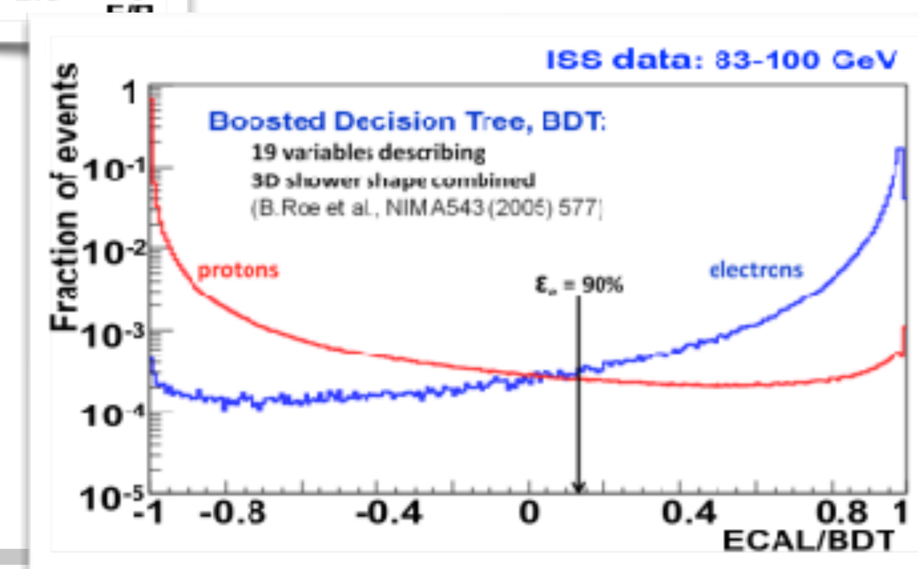
Tracker:

E/P ~ 1 for e^+ and e^-

Acc(p) ~ 0.5 m^2sr

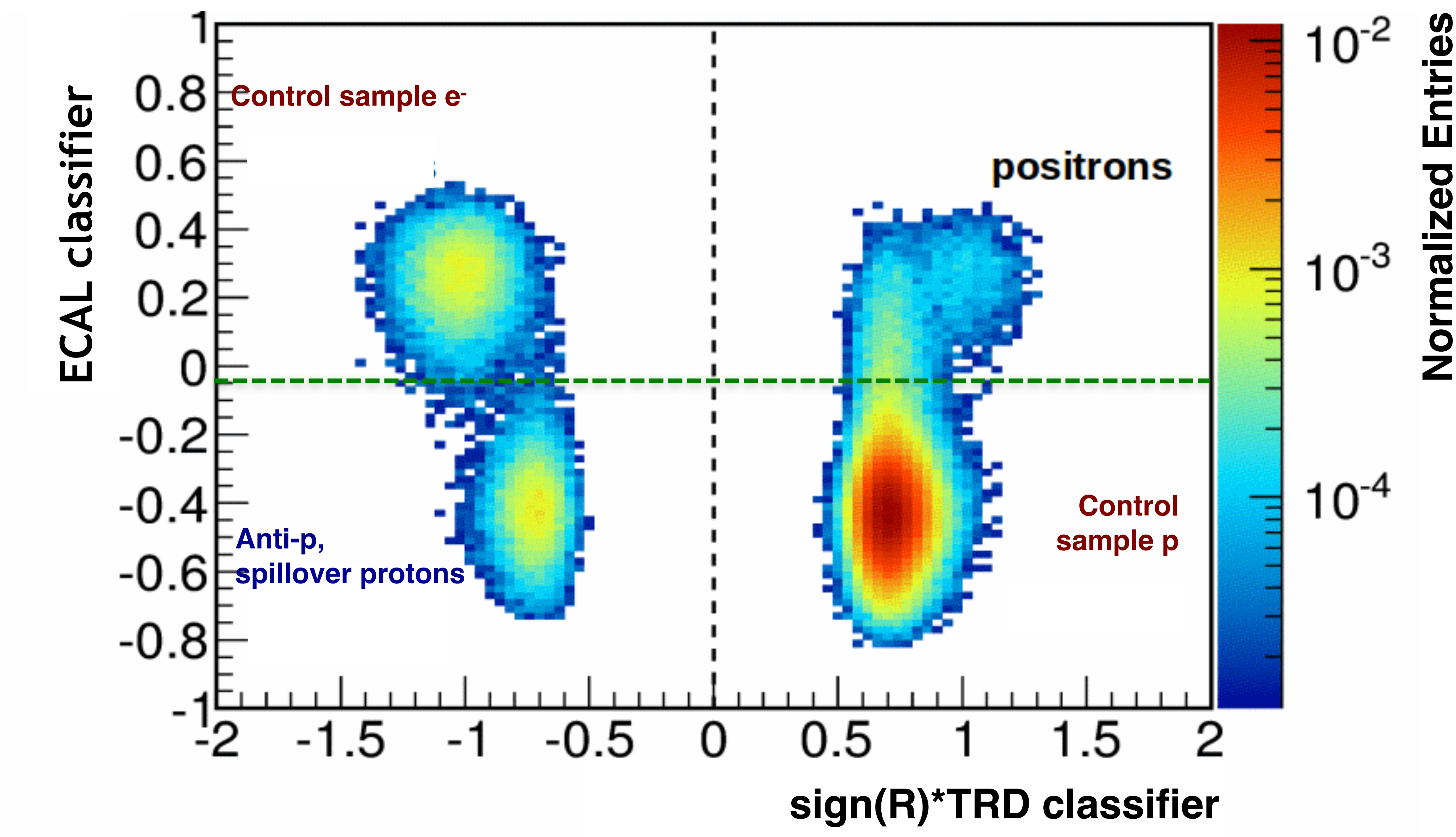
Acc(e) ~ 0.04 m^2sr

ECAL estimator: based on shower shape



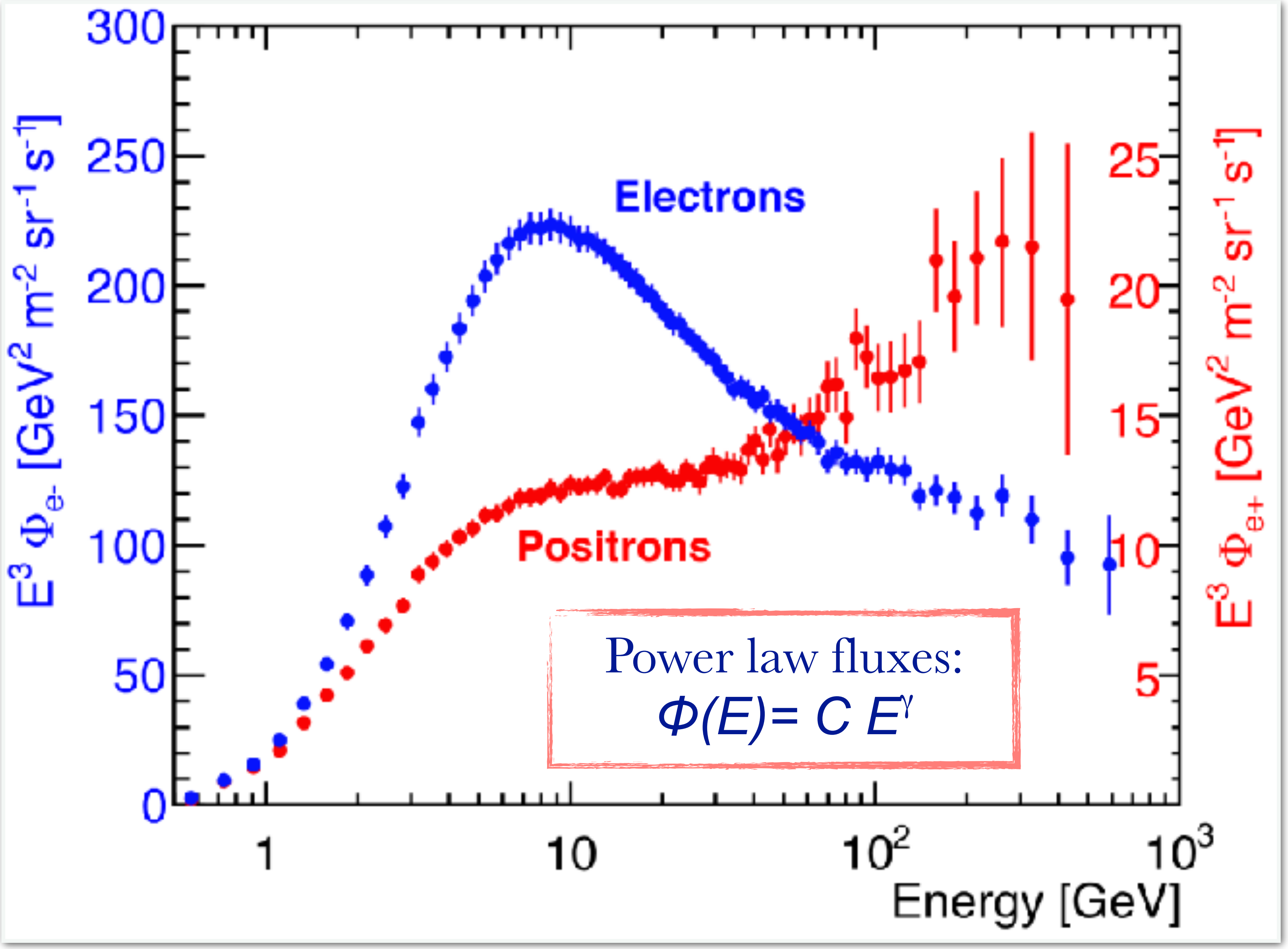
Lepton/hadron separation

ISS Data: 73-140 GeV, Z=1



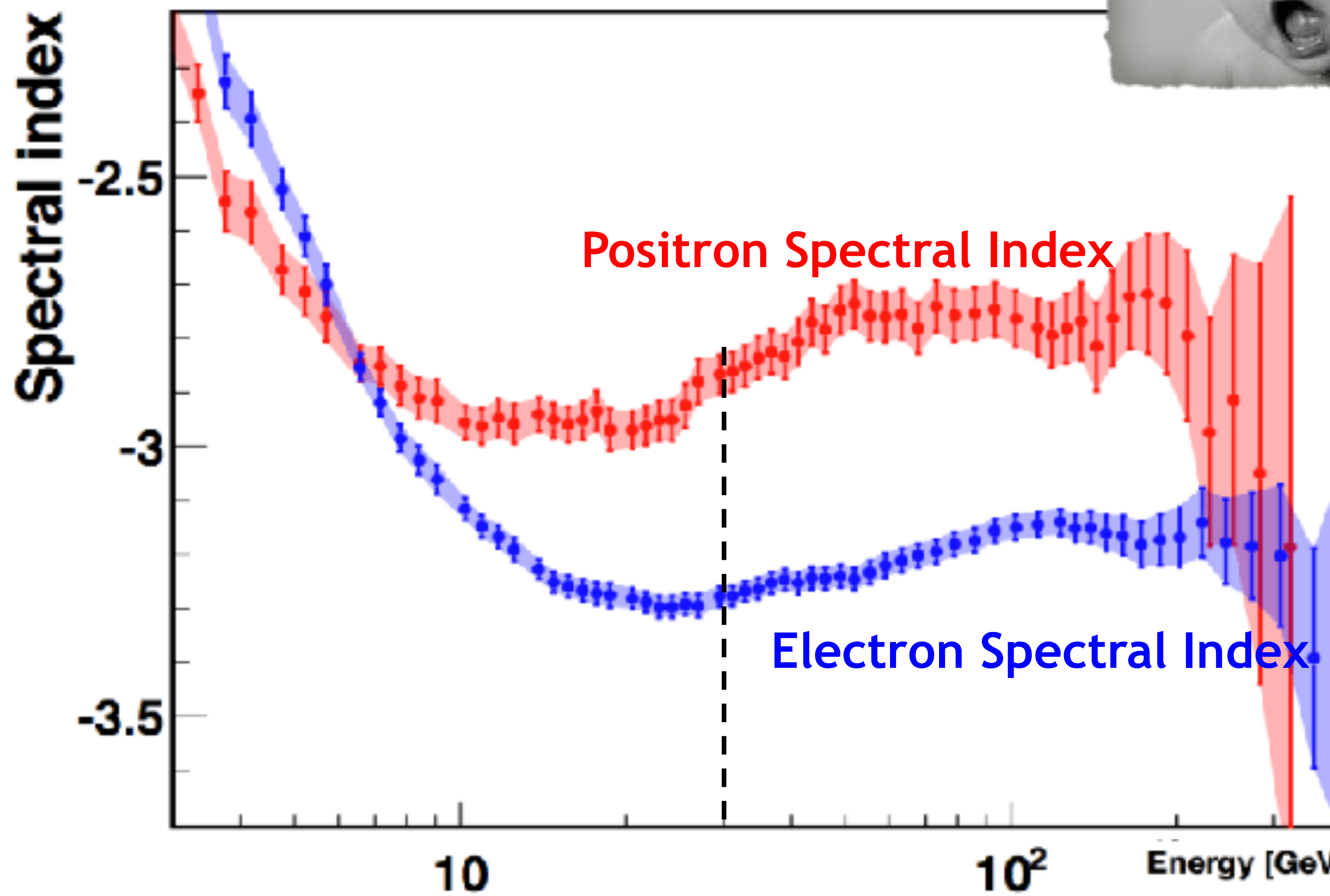
4TH ANOMALY: ELECTRON AND POSITRON FLUX

PRL 113, 121102 (2014) 250+ citations



The electron flux and the positron flux are different in their magnitude and energy dependence.

SPECTRAL INDEX

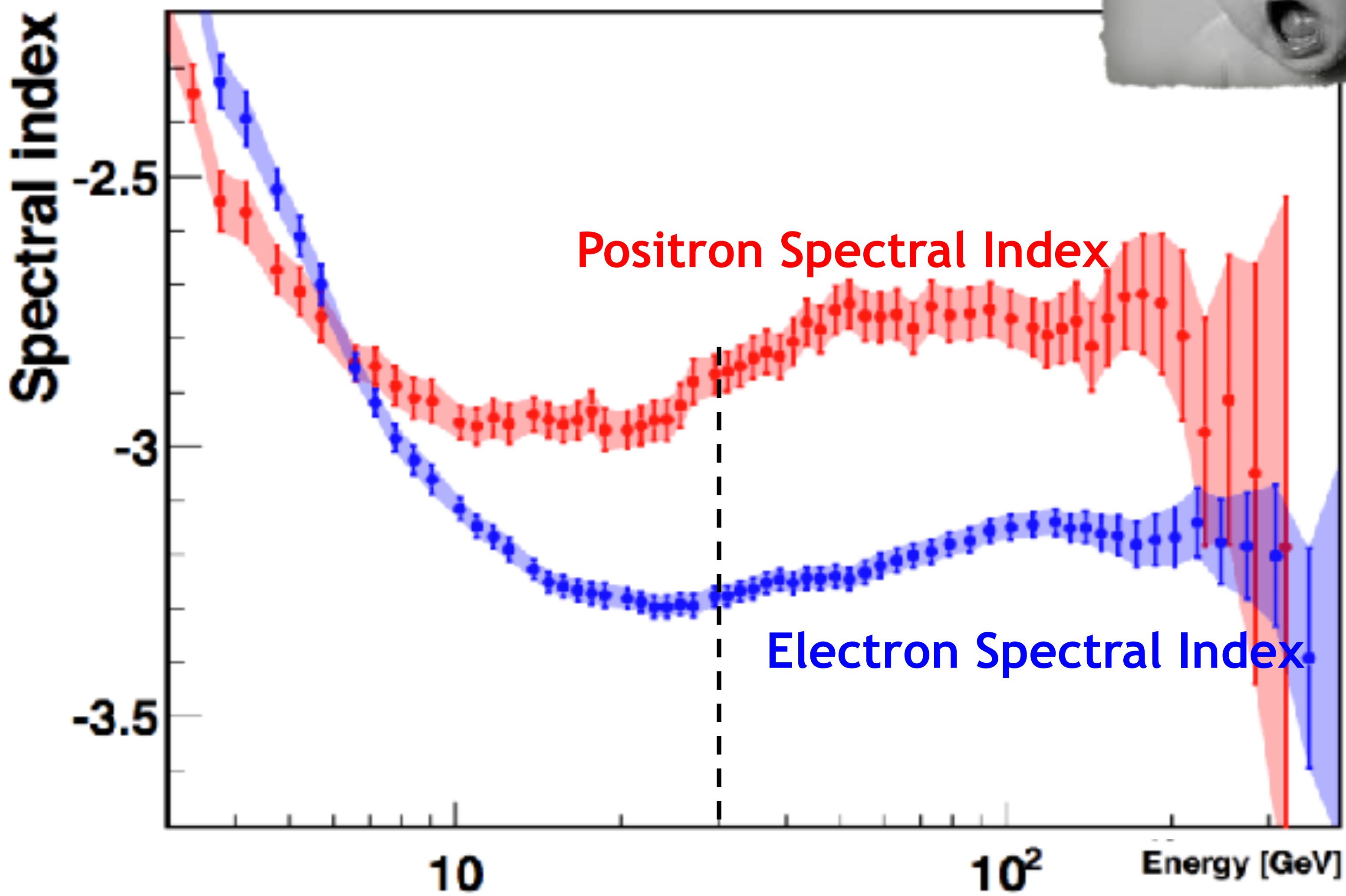


- The spectral indices of electrons and positrons are different
- Both spectra cannot be described by single power laws
- Change of behaviour at ~30GeV

SPECTRAL INDEX

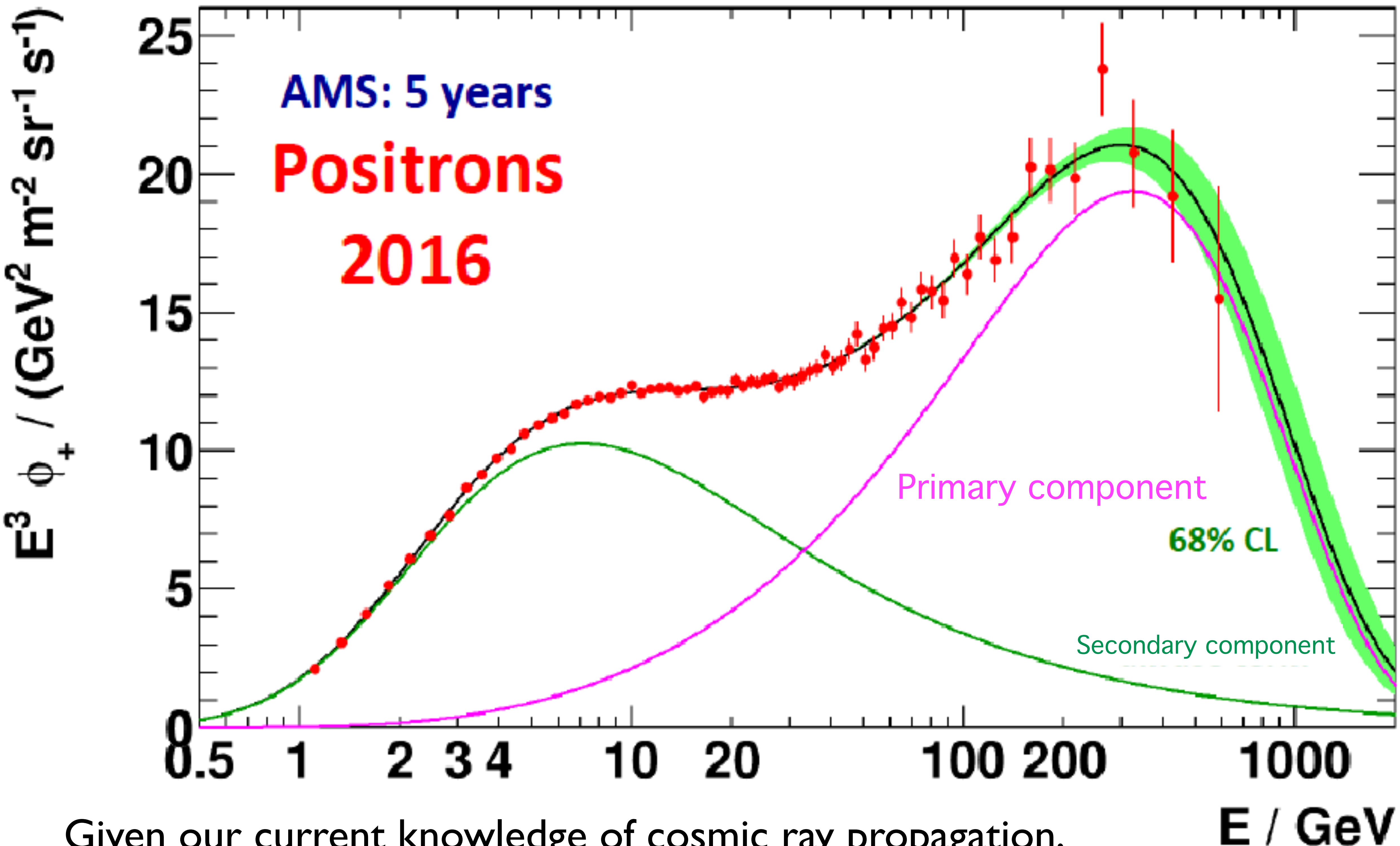
Positron flux: $\Phi(E) = C\,E^{\gamma+}$

Electron flux: $\Phi(E) = C\,E^{\gamma-}$



- The spectral indices of electrons and positrons are different
- Both spectra cannot be described by single power laws
- Change of behaviour at ~30GeV

PRELIMINARY results up to 700 GeV



Given our current knowledge of cosmic ray propagation, positron data are inconsistent with pure secondary hypothesis.

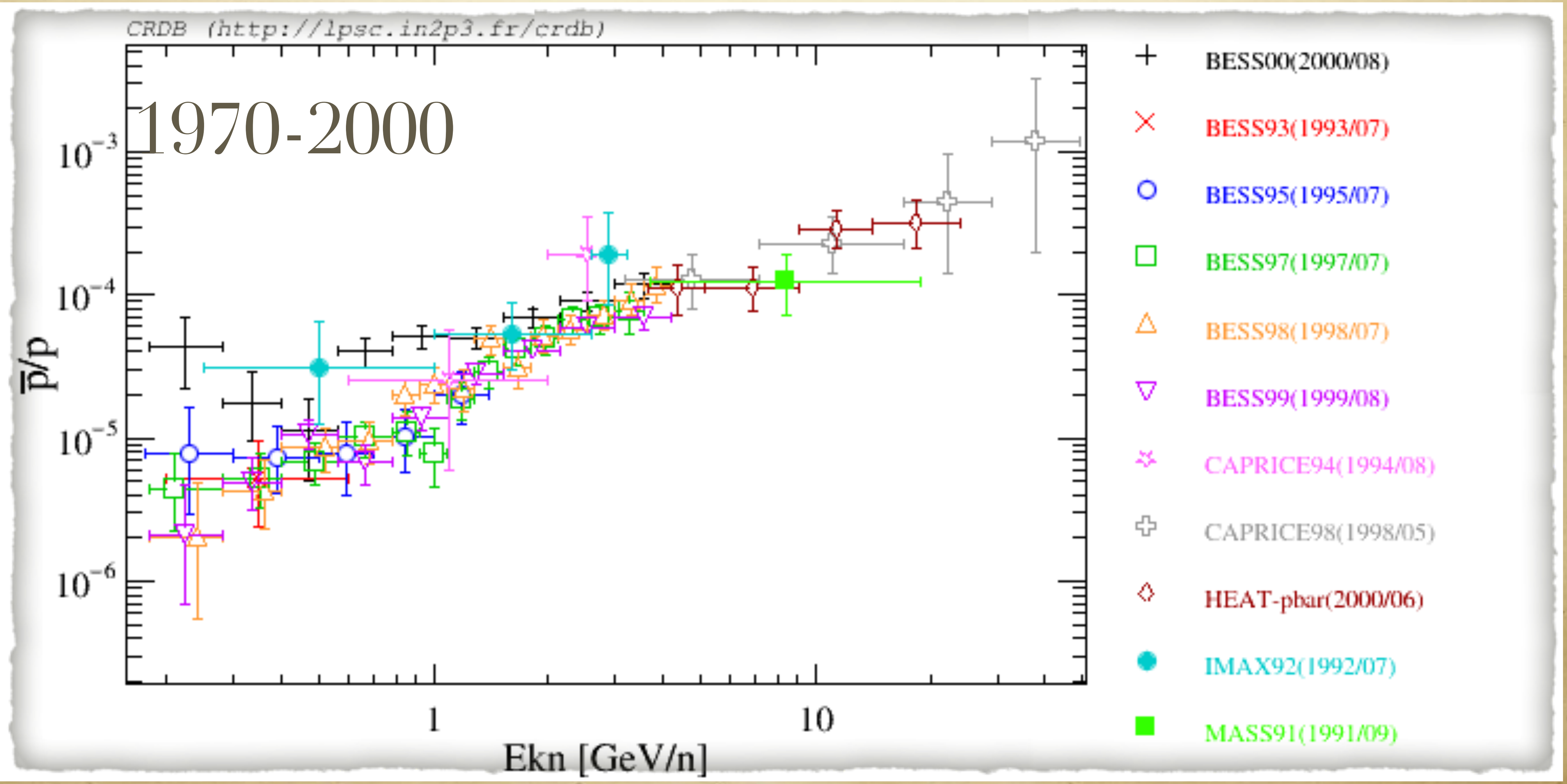
Interpretation of e+ data

- Alternative frameworks [Lipari 2016, Blum+2017 …]
- Pulsars [Abeysekara+2017, Di Mauro+ 2016 …]
- SuperNovae [Blasi2009, Mersch&Sarkar2014 …]
- Dark matter [Profumo+2004, Bergstrom+2009 …]

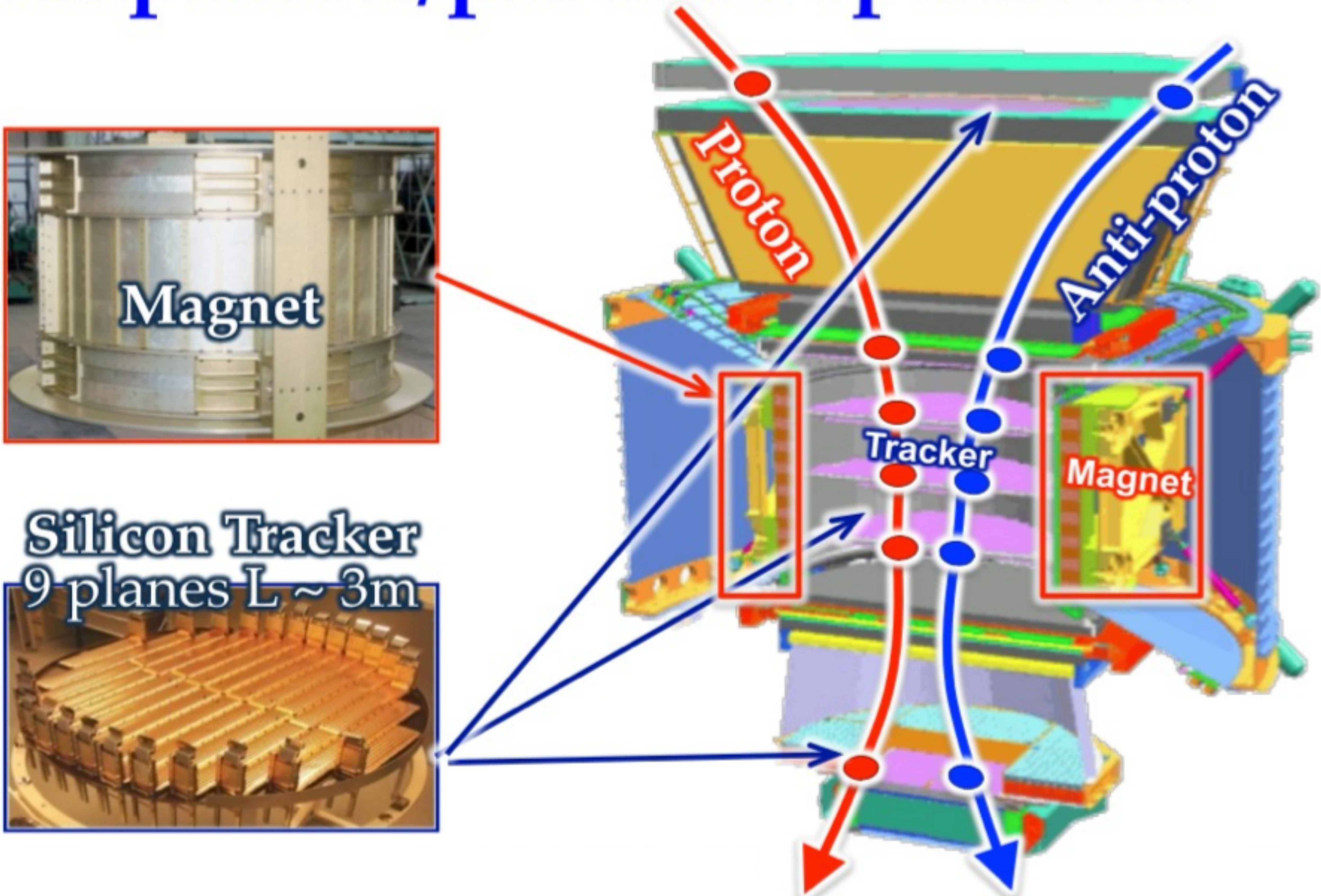
Cosmic ray anti-proton measurements

until a few decades ago…

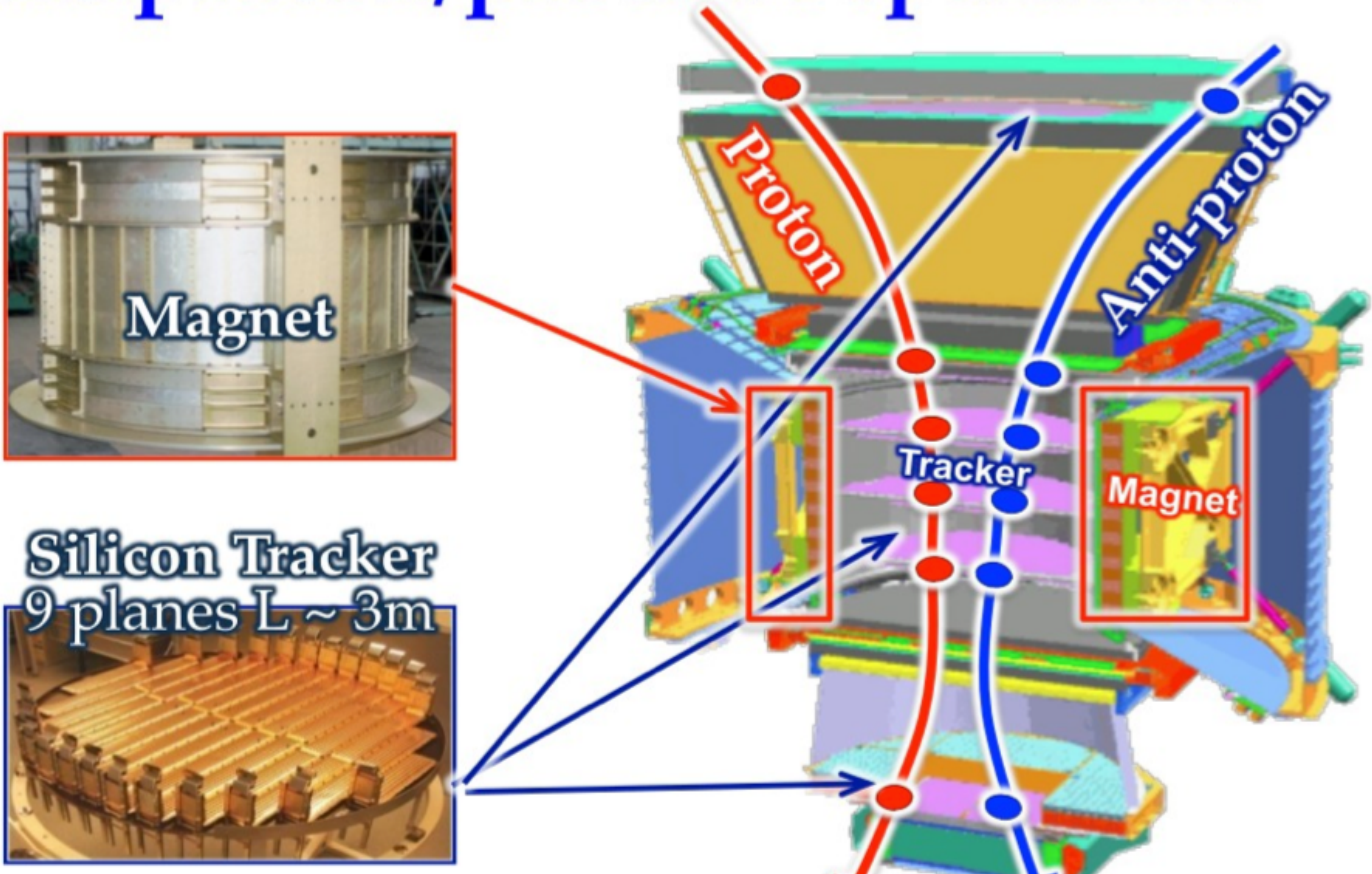
- The CR anti-proton component can only be identified by using magnetic spectrometers together with sufficient MDR and particle identification capabilities. BESS, PAMELA and AMS-02 provided the most precise measurements.



Antiproton/proton separation

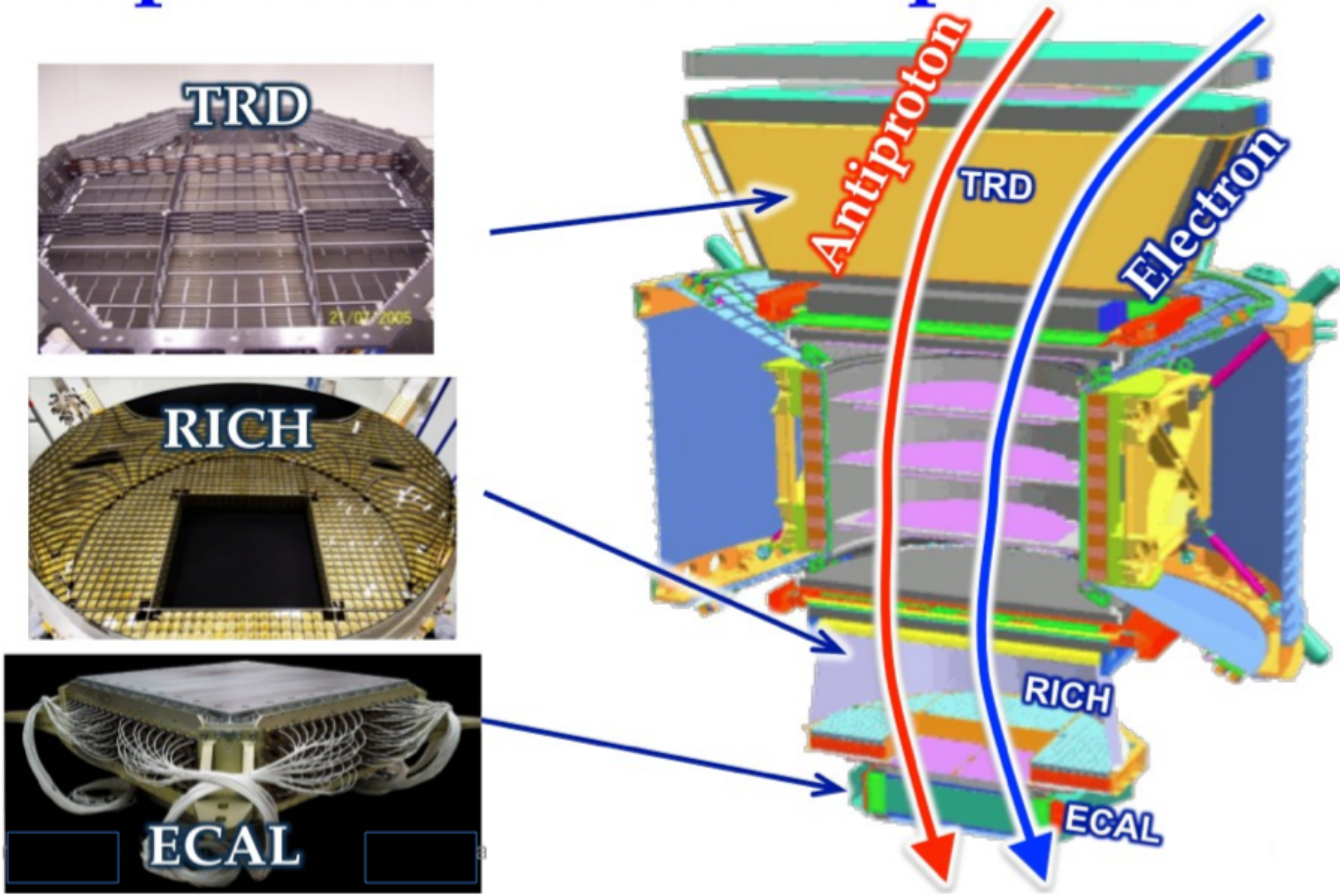


Antiproton/proton separation



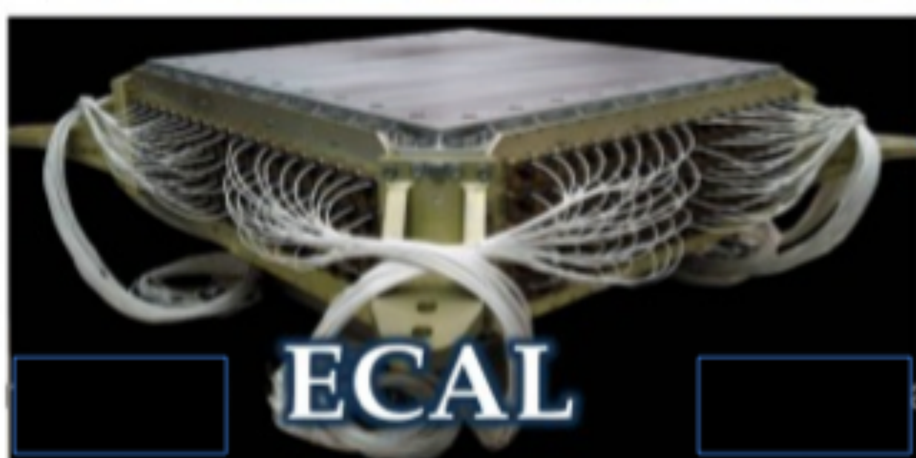
Antiprotons are 10^4 times less abundant than protons

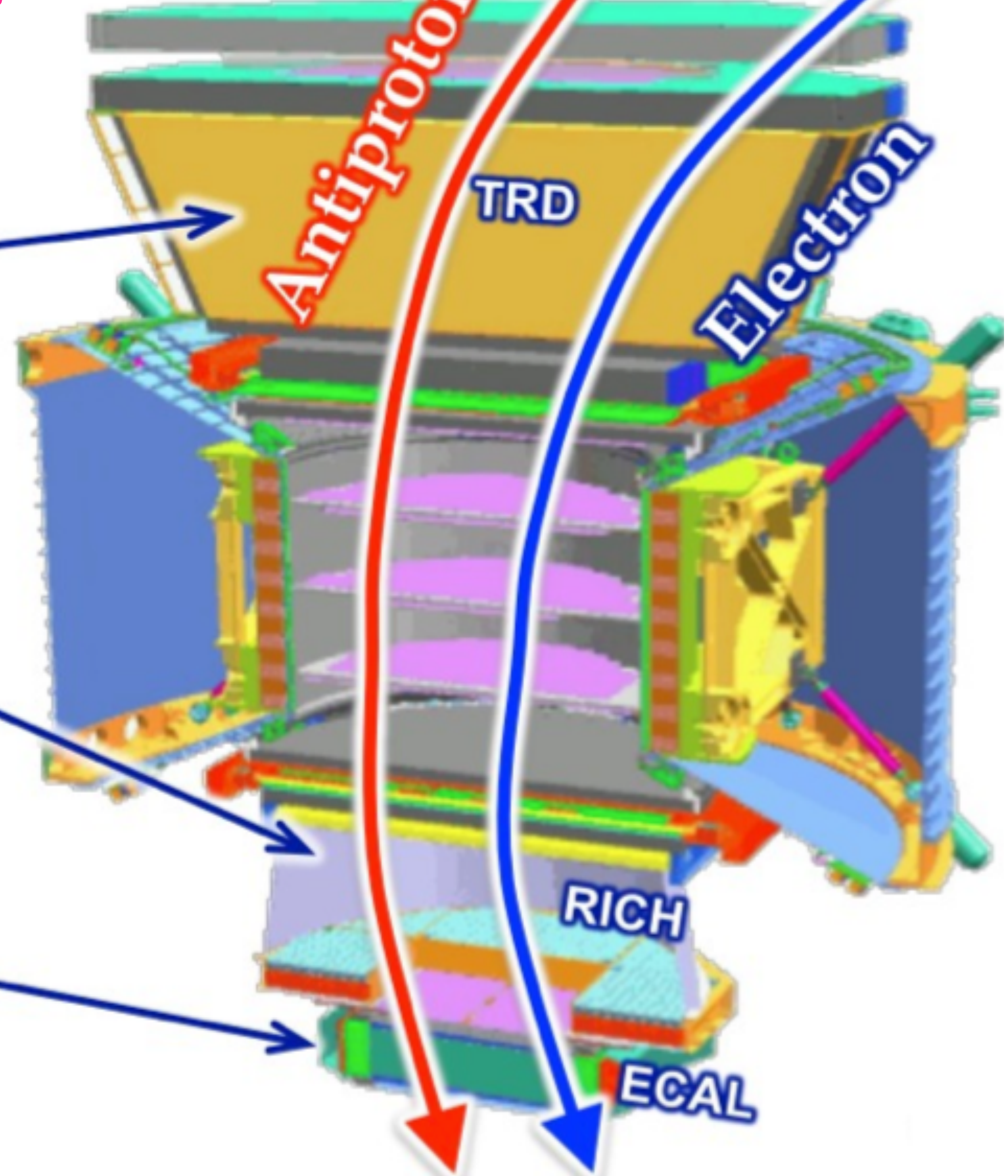
Antiproton/electron separation



Antiproton/electron separation

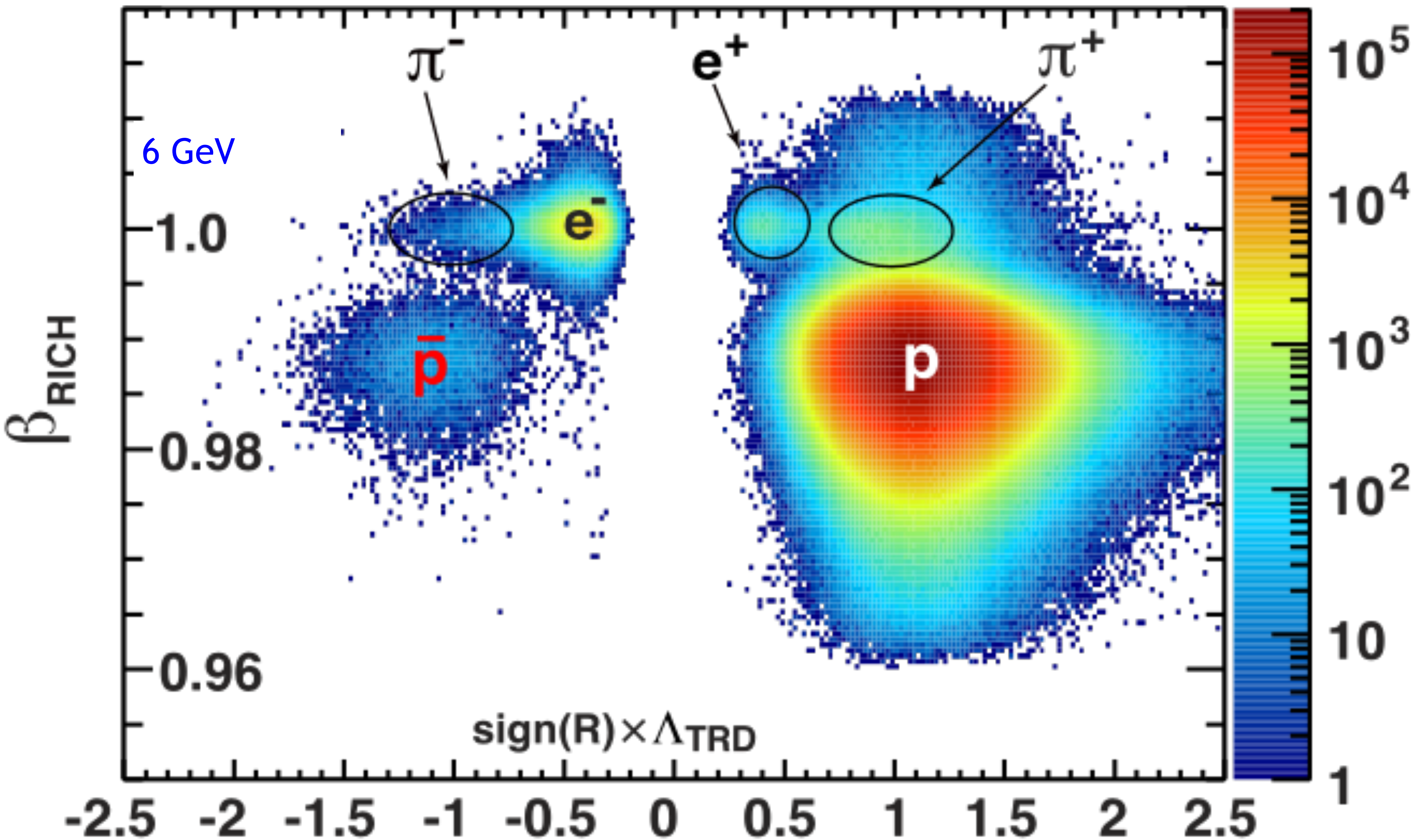
Electrons/kaons/pions can be removed using TRD+RICH+ECAL





Antiproton Flux and Properties of Flux Ratios of Elementary Particles in Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station

RICH Detector
measures velocity with an accuracy 1 in 1000

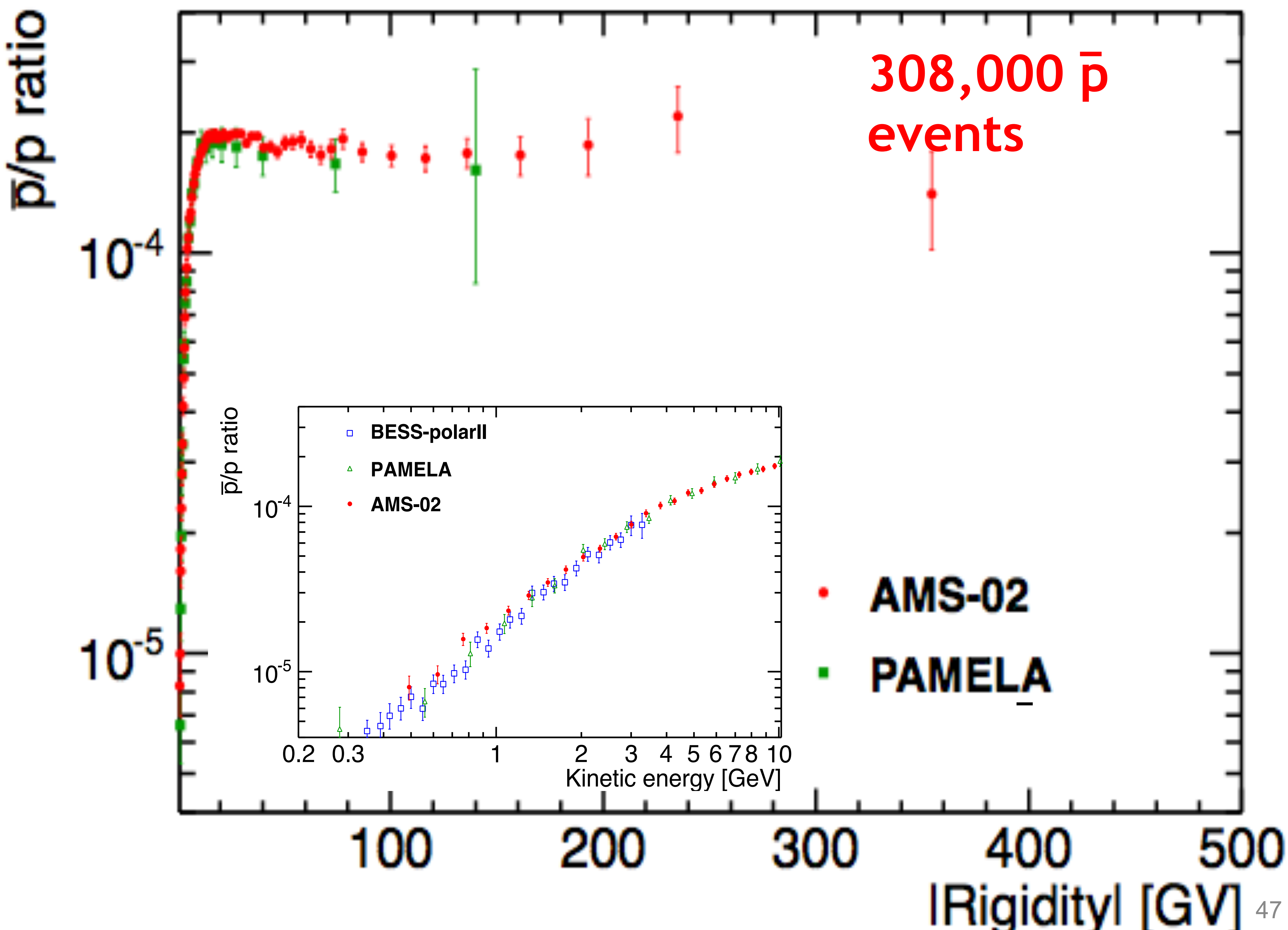


TRD Detector + Tracker

TRD separates e^+, e^- from p, $\bar{p}$ with an accuracy of 1 in 10000

AMS results on the p̅/p ratio

50+ citations

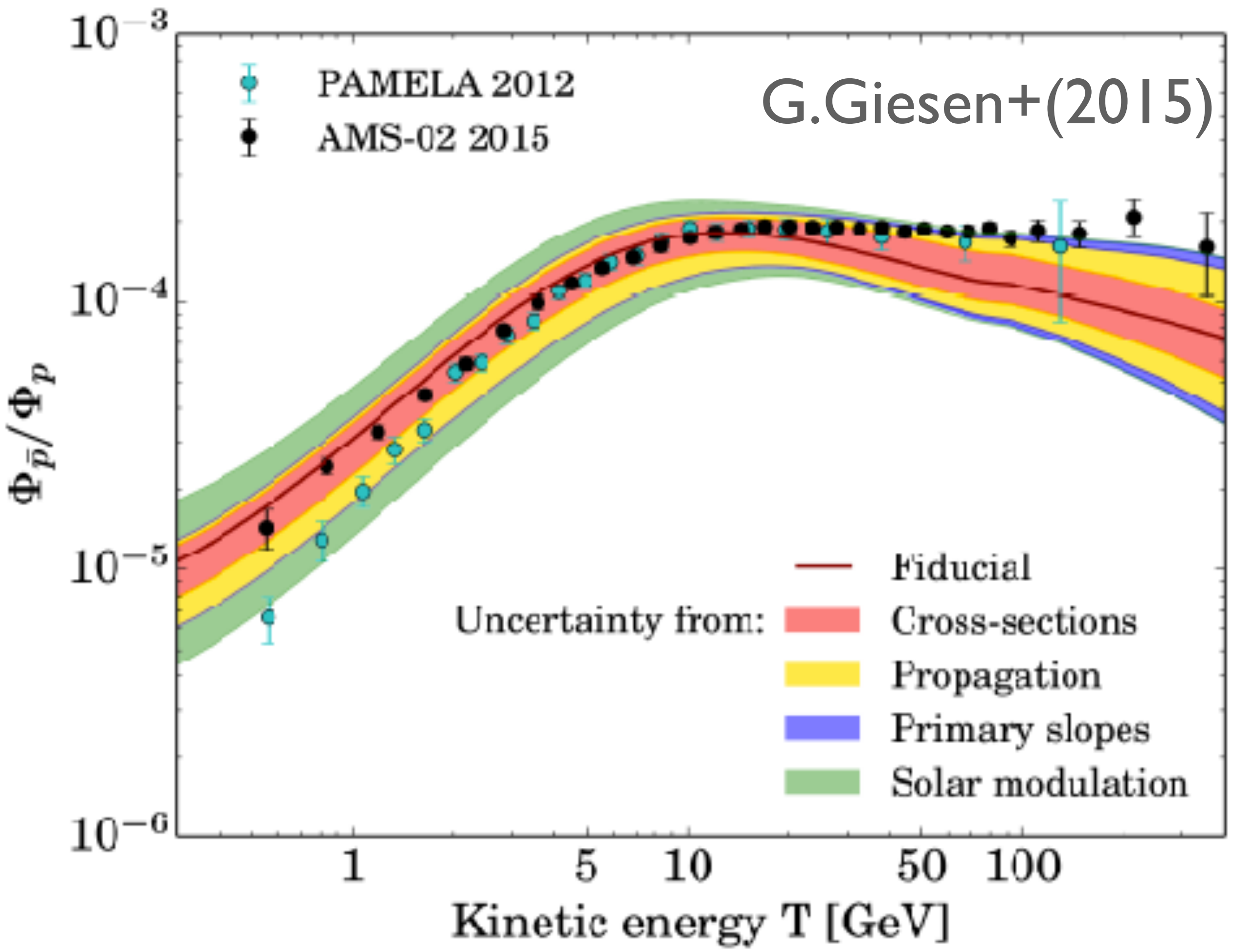


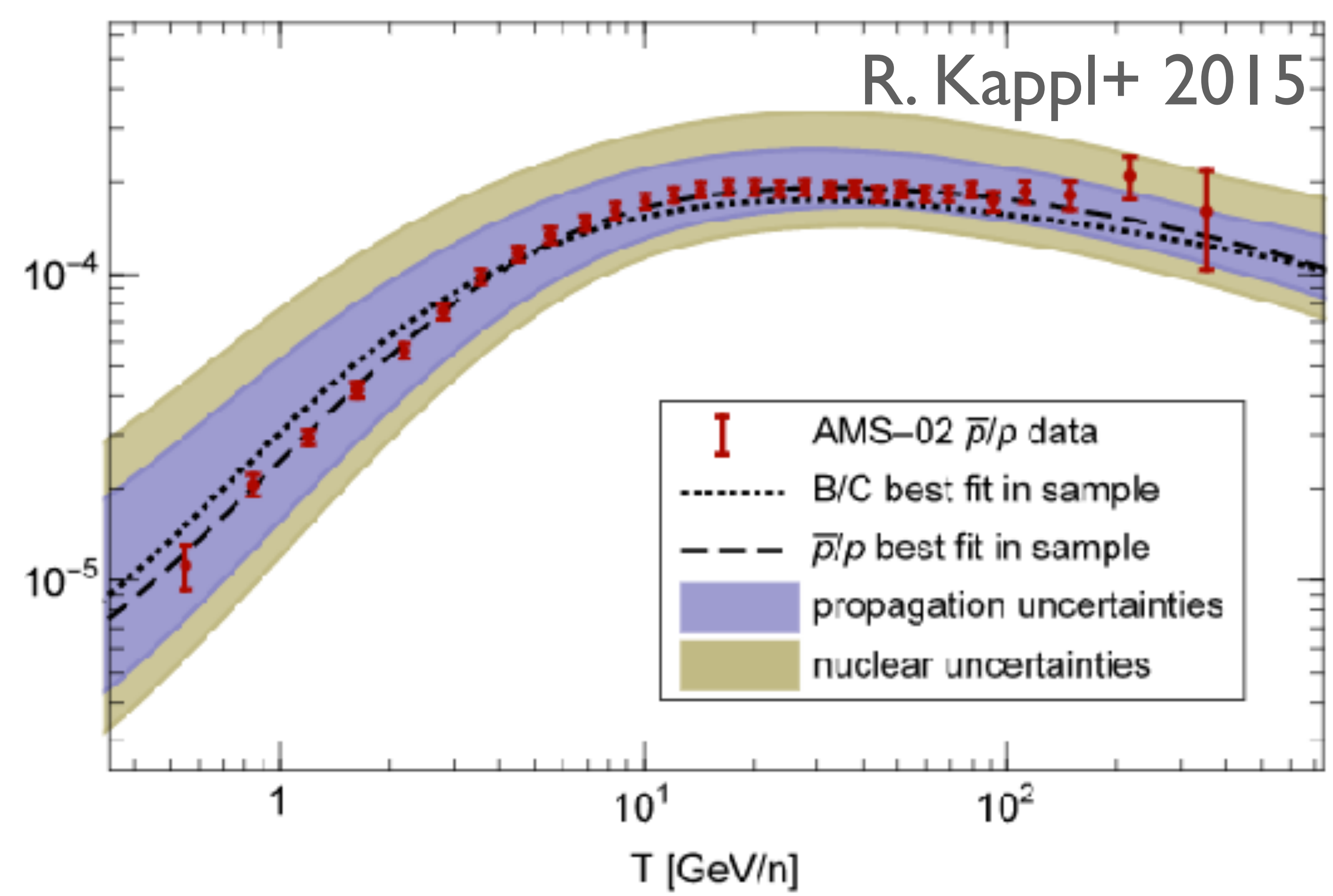
PRL **117**, 091103 (2016)

Interpretation of anti-p data

Anomaly in antiprotons ? Not yet …

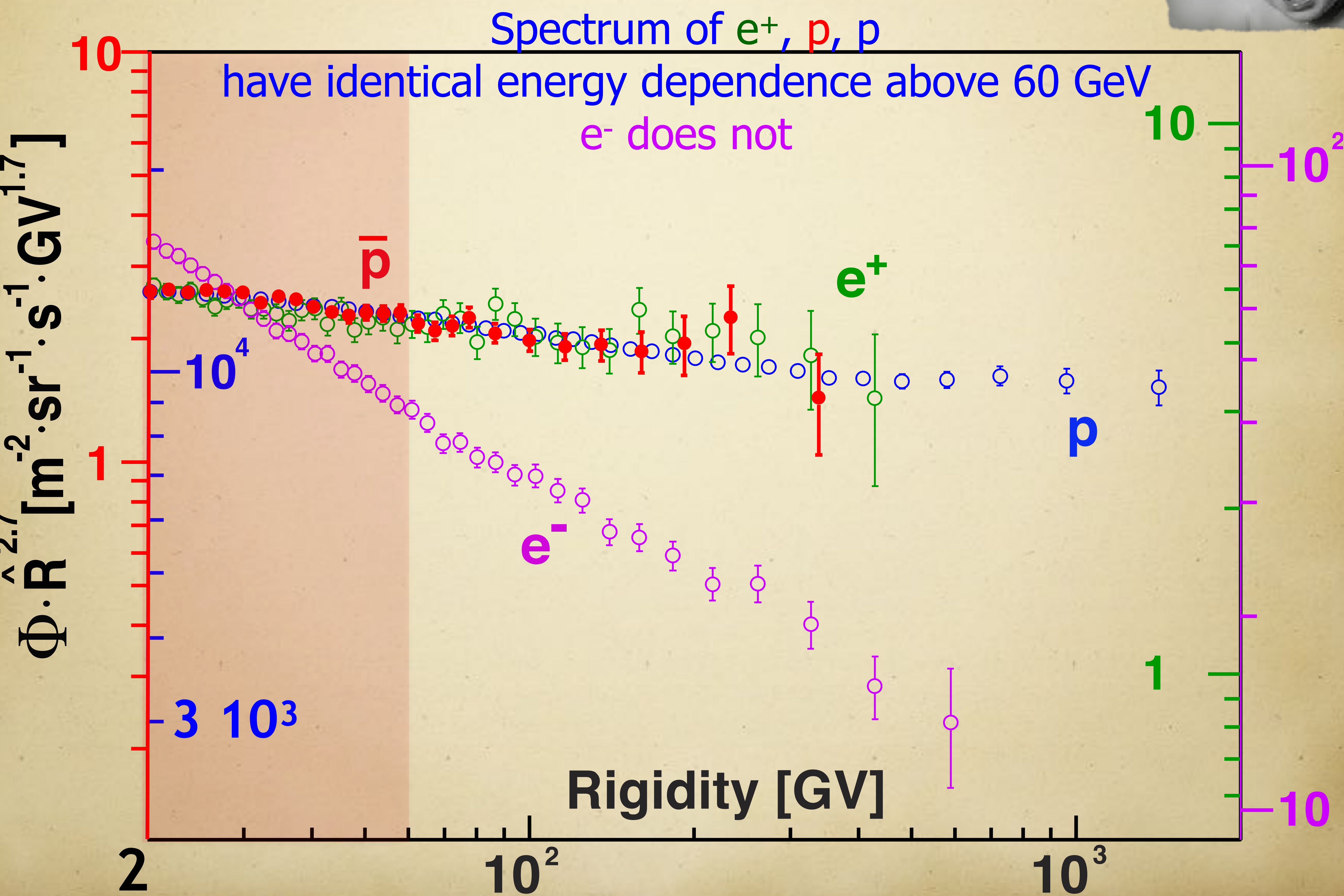
Updated secondary production and its uncertainties not in tension with antiproton-to-proton ratio





PRL **117**, 091103 (2016)

Surprise :)



Conclusions

- More than 100 years after their discovery, CR physics is a lively field of research, driven by new experimental results.
- The observational improvements occurred during the past decade show the first cracks in the simplest model for cosmic ray origin/propagation.
- PAMELA, Fermi-LAT and AMS-02 brought CR physics to a new precision level in the GeV to TeV energy region.
- AMS-02 is taking data since May 2011.AMS-02 is currently the only space experiment equipped with a magnet … unique access to CR antimatter component.
- Indirect search for dark matter as well as the search for primordial antimatter can also be performed, still a lot to be done.
- Despite a huge effort of the community, currently we do not have a “standard framework” that fits all observables.
- More data and more precision will help to understand the main class of solution for spectral breaks.
- Multi-messenger astronomy is an extra tool to provide useful insights to the scientific community.