Galactic Cosmic Rays: Detection techniques & Results review

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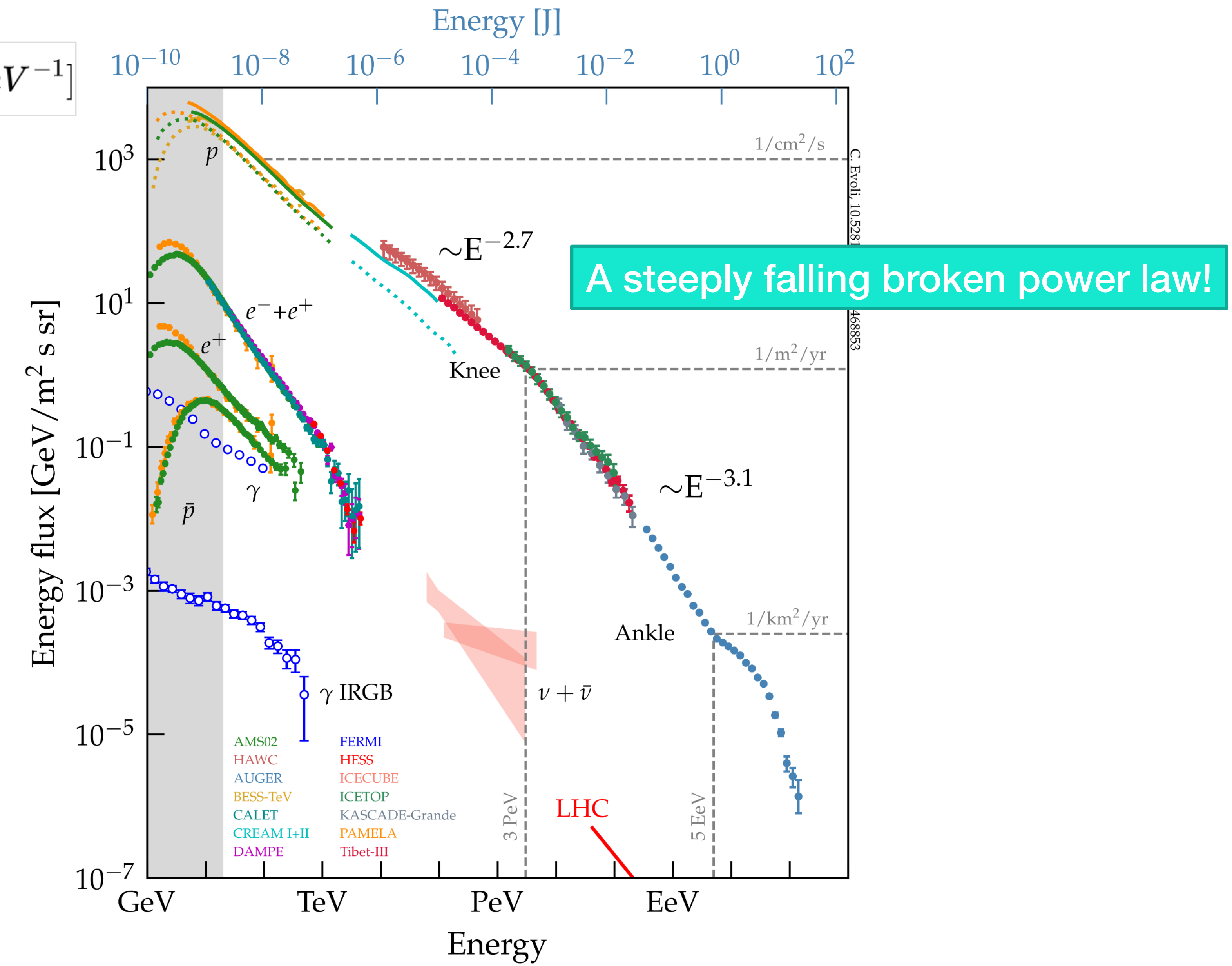
Outline

- Galactic Cosmic Rays: flux and composition
- Space-based detectors in a nutshell
- Cosmic-ray antiparticles
- Cosmic-ray nuclei

Disclaimer: I a member of the AMS-02 Collaboration
and this review is biased towards my
scientific interests and expertise.

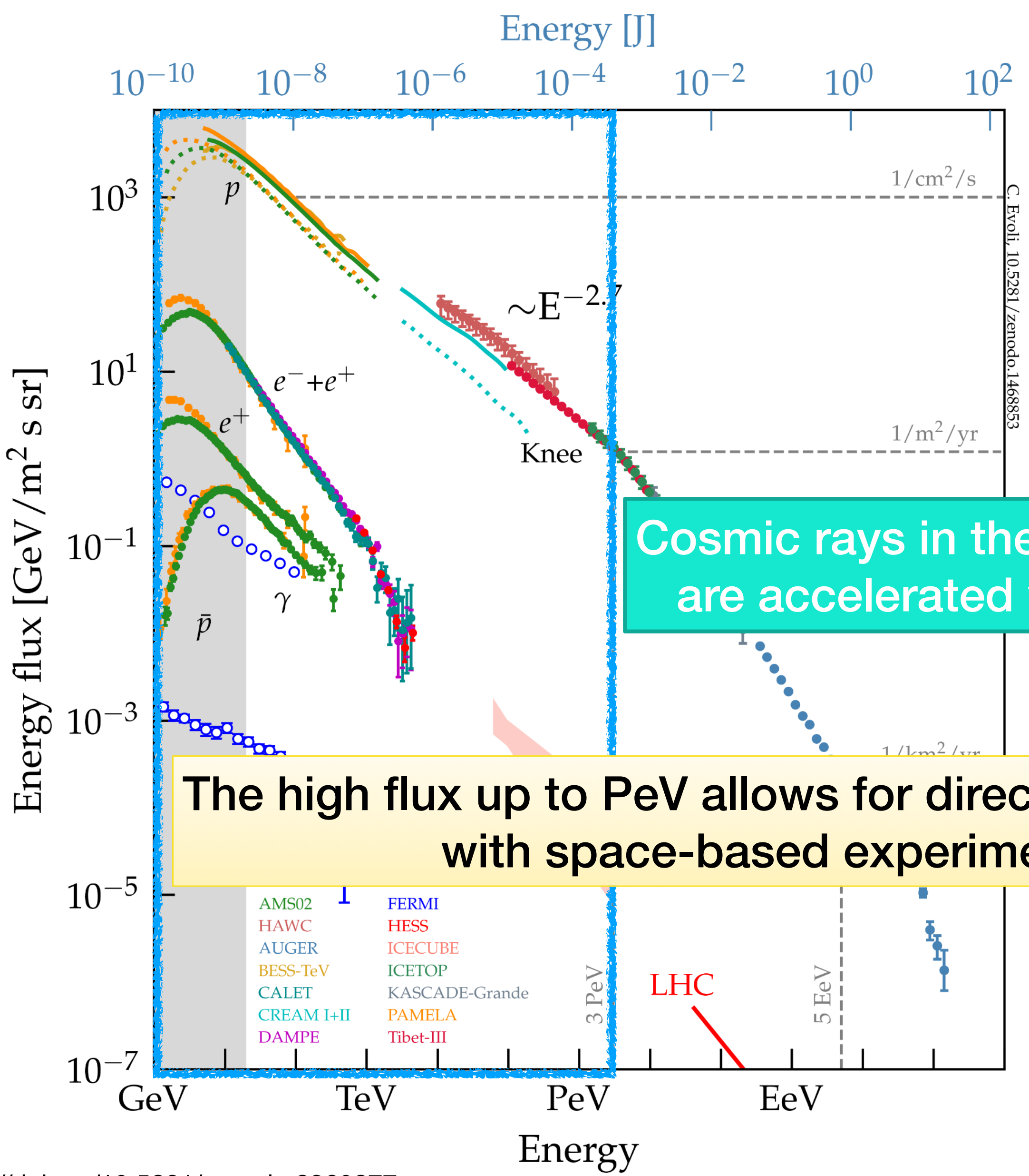
The cosmic-ray spectrum

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



Source: Evoli, Carmelo. 'The Cosmic-ray Energy Spectrum'. https://doi.org/10.5281/zenodo.2360277.

The cosmic-ray spectrum



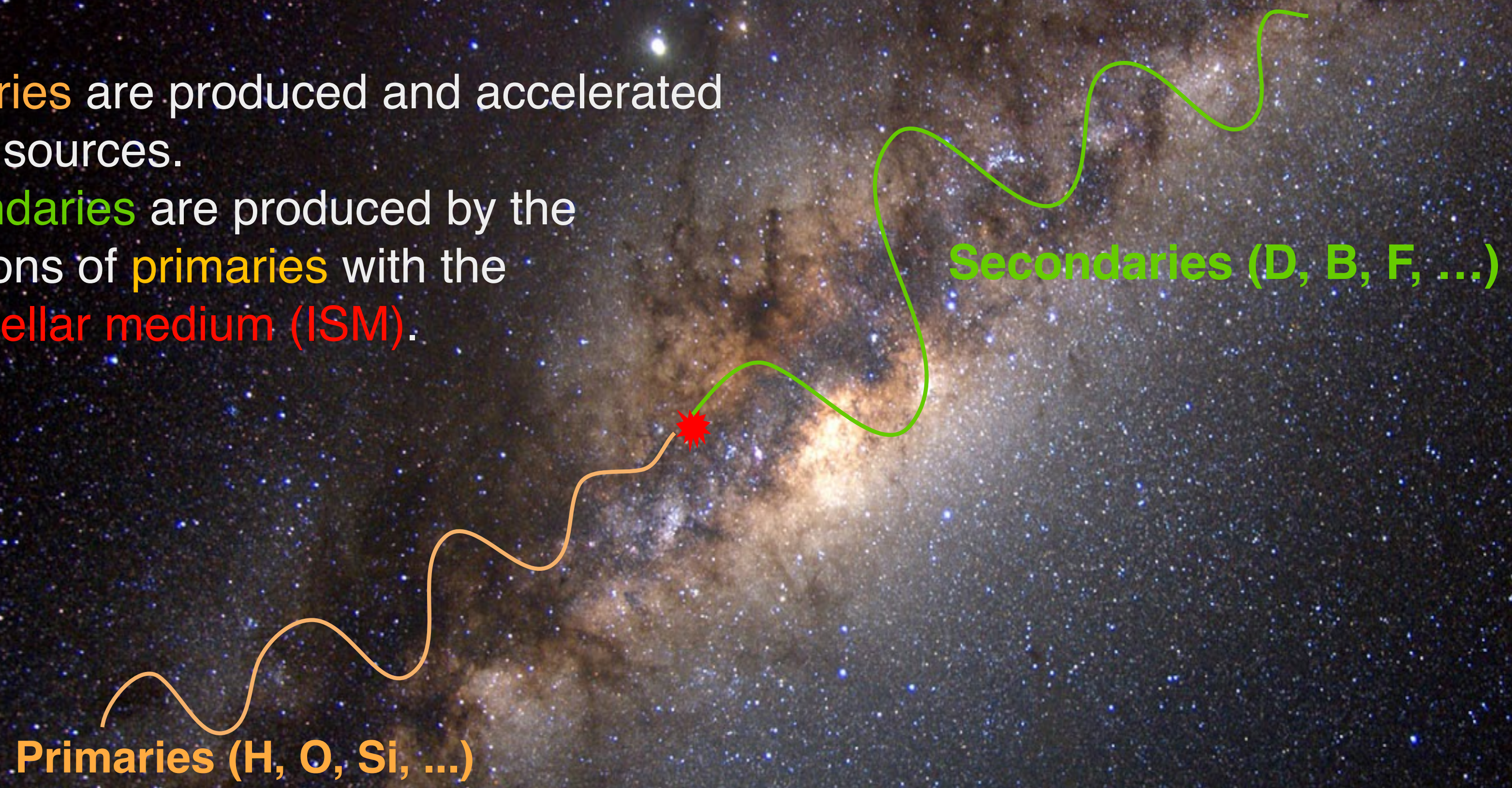
Cosmic rays in the GeV to PeV range are accelerated within our galaxy

The high flux up to PeV allows for direct measurements with space-based experiments.

Source: Evoli, Carmelo, https://doi.org/10.5281/zenodo.2360277.

Two classes of cosmic-ray species

Primaries are produced and accelerated at the sources.
Secondaries are produced by the collisions of primaries with the interstellar medium (ISM).

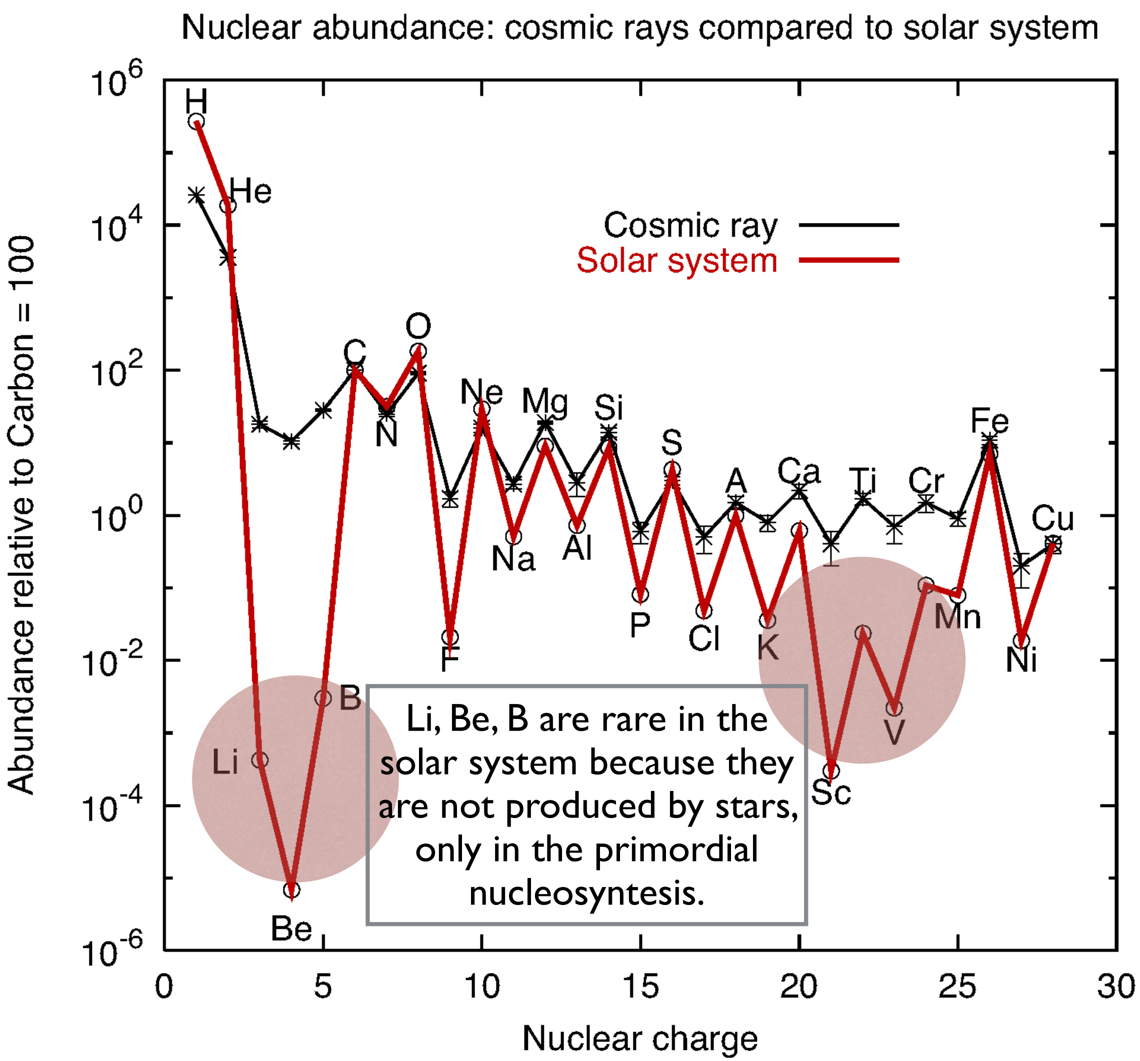


Secondary-to-primary flux ratios, such as B/C or F/Si, are key observables to constrain the propagation processes in the Galaxy.

Slide E. F. Bueno

Chemical composition

Up to the PeV region, we can perform direct detection of CRs and we can measure the composition of cosmic rays.



- Cosmic ray composition is fairly similar to that of the solar system.
- However, Li, Be,B (Z=3-5) as well as sub-iron elements (Z=21-25) are more abundant in CRs than in the solar system.
- This is due to fragmentation of primary CR nuclei (C,N,O) and Fe in the interstellar medium.

How to detect cosmic rays ?

Cosmic rays are made of charged massive particles.

Cosmic ray detectors are particle detectors.

All particle detectors are based on the same fundamental principle: the transfer of part or all of the energy to the detector mass where it is converted into something detectable.

Wide energy range: 10^{9} - 10^{21} eV
Wide range of dimensions:
On balloon/space: O(m^2)
At ground: O(0.01-1000 km^2)

astroparticles detectors

Almost every space-based detector has at least one of them.
Let's see a bit more in detail.

01	Energy	• Calorimeters • Spectrometers (momentum) • Fluorescence
02	Velocity	• Cherenkov detectors • Transition Radiation Detectors • Time of flight
03	Mass	• Cherenkov detectors • Energy loss by ionization • Transition Radiation Detectors
04	Arrival direction	• Cherenkov detectors • Fluorescence • Calorimeters • Energy loss • GW: interferometers

See review L. Baldini 2014, arxiv: 1407.7631

Magnetic spectrometers

- **Purpose**: Measure the momentum and charge of cosmic rays.
- **Function**: Use a magnetic field to bend the trajectories of charged particles. The degree of bending is related to the particle's momentum and charge, allowing for precise measurements of particle's rigidity $R=pc/Ze$.
- **Applications**:
  - Measure the CR antimatter component
  - Measure the spectra of various cosmic rays, including protons, electrons, positrons and nuclei.

Pro: The best detection technique to precisely identify CR antimatter.
Con: The momentum resolution decreases with increasing momentum.

Electromagnetic calorimeters

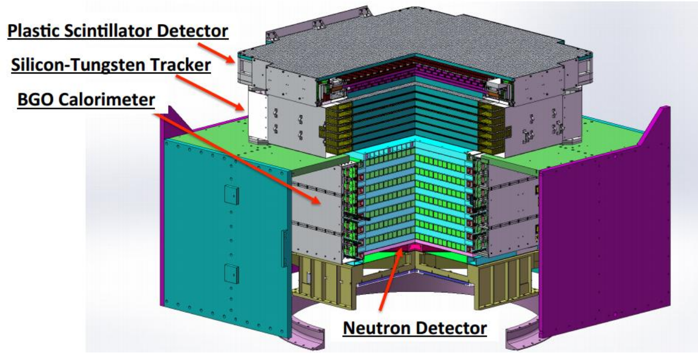
- **Purpose**: Measure the energy of incoming particles (both CRs and photons).
- **Function**: Absorb the particles (and the EM shower) and measure the total energy deposited, providing information on the energy spectrum of cosmic rays and high-energy photons.
- **Applications**:
  - Measure the energy of particles
  - Reconstruct the arrival direction of photons
  - Perform lepton-hadron separation (key to identify positrons)

Pro: They can measure the energy of both CRs and gamma rays.
Con: Limited particle identification capabilities for nuclei (wrt magnetic spectr.)

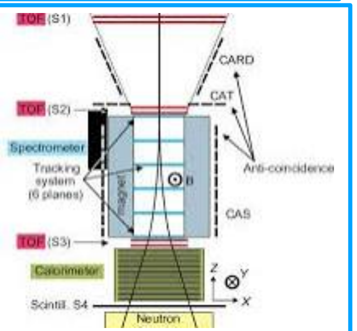
Current generation space-based CR detectors

See M. Pohl arxiv:2502.18025 for a recent review

- Name: AMS-02
- Taking data since: 2011
- Magnetic spectrometer: MDR 2 TeV (p)
- Magnetic field (0.14T): antimatter!
- ECAL: 17 Xo



- Name: DAMPE
- Taking data since: 2015
- Magnetic spectrometer: no
- ECAL: 31.5 Xo

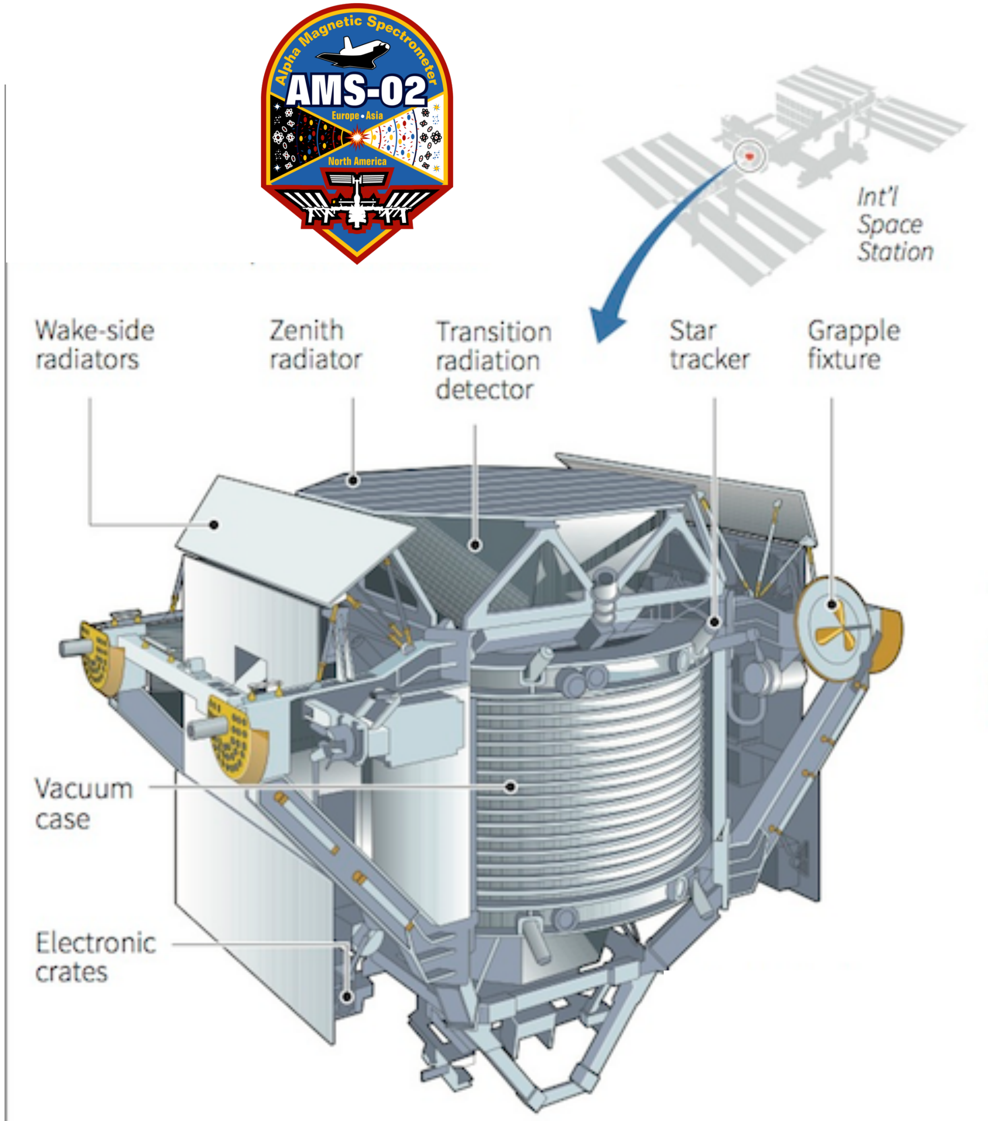


- Name: PAMELA
- Taking data since: 2006-2016
- Magnetic spectrometer: MDR 1.2 TeV
- Magnetic field: antimatter!
- ECAL: 16.3 Xo

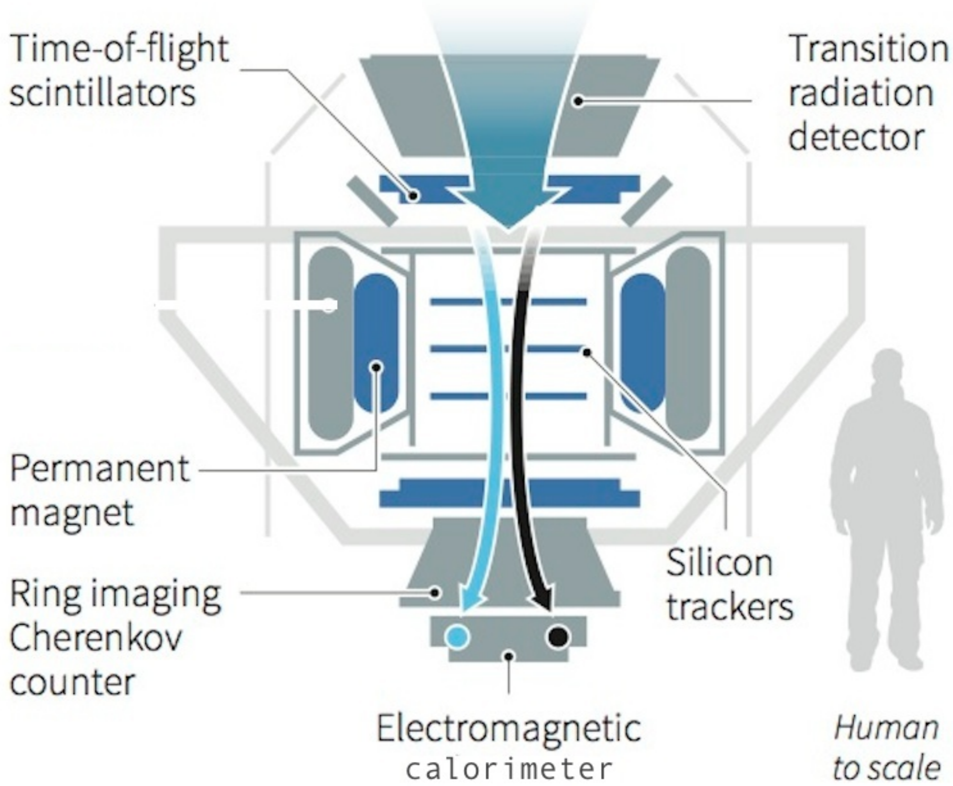
- Name: CALET
- Taking data since: 2015
- Magnetic spectrometer: no
- ECAL: 30 Xo

Let’s put everything together and let’s study an example: the AMS-02 detector

The Alpha magnetic spectrometer



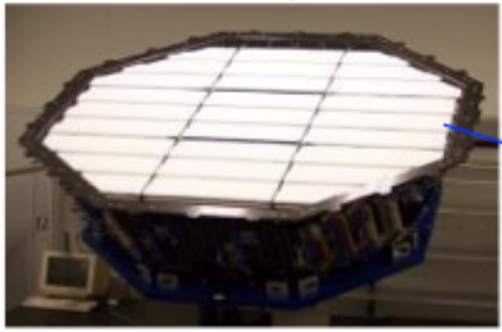
Sources: CERN; NASA; ESA



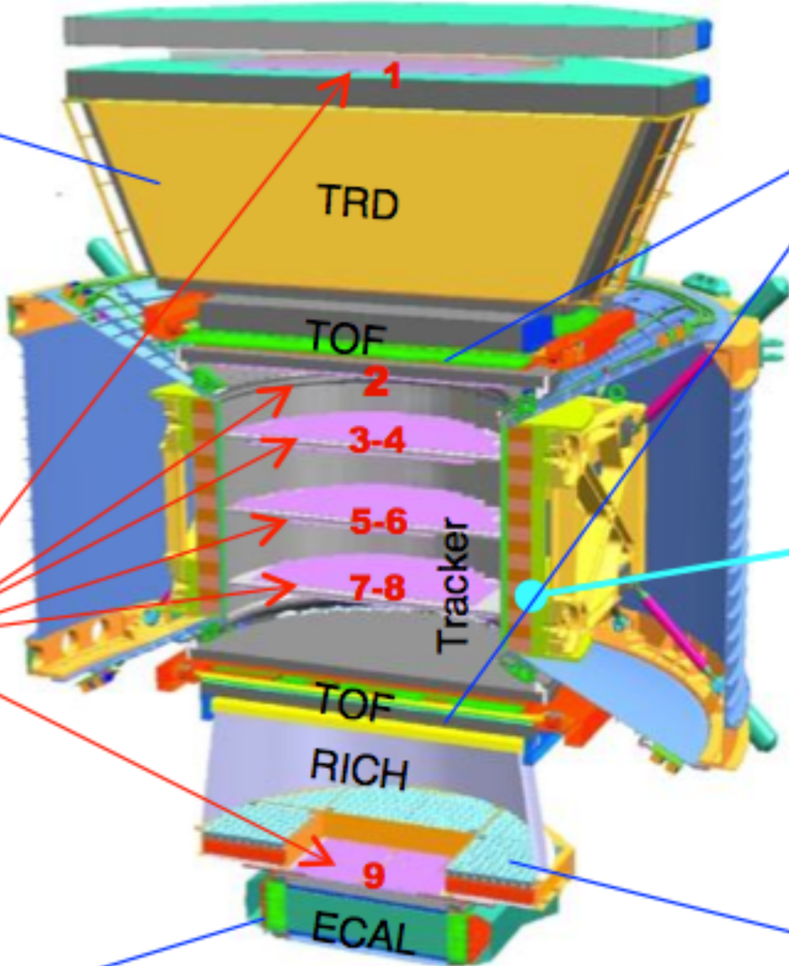
- Size: 5m X 4m X 3m
- Weight: 7.5 Tons
- Power consumption: less than 2.5 kW

AMS: A TeV precision, multipurpose spectrometer

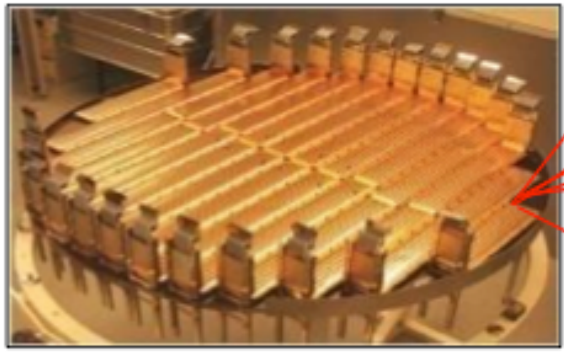
Transition Radiation Detector
Electron/proton, Z



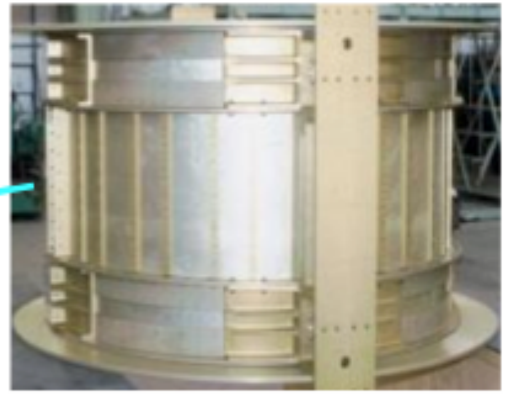
Time of Flight
Z, E



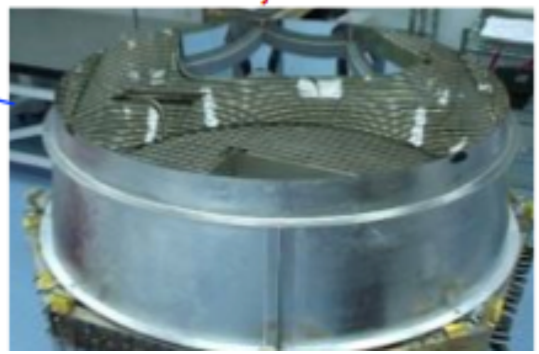
Silicon Tracker
Z, P



Magnet
±Z



Ring Imaging Cherenkov
Z, E



Electromagnetic Calorimeter
E of electrons

The Charge and Energy are measured independently by several detectors

The conventional model for galactic CRs

It was able to describe the data up to a decade ago … not anymore!

- Cosmic rays are accelerated at SuperNova Remnants up the knee (10^{15} eV).
- The CR fluxes below the knee (10^{15} eV) can be described by a single power-law.
- The fluxes of primary species have universal (species-independent) spectral indices.
- Antimatter component of cosmic rays is purely secondary.

Cosmic-ray antimatter

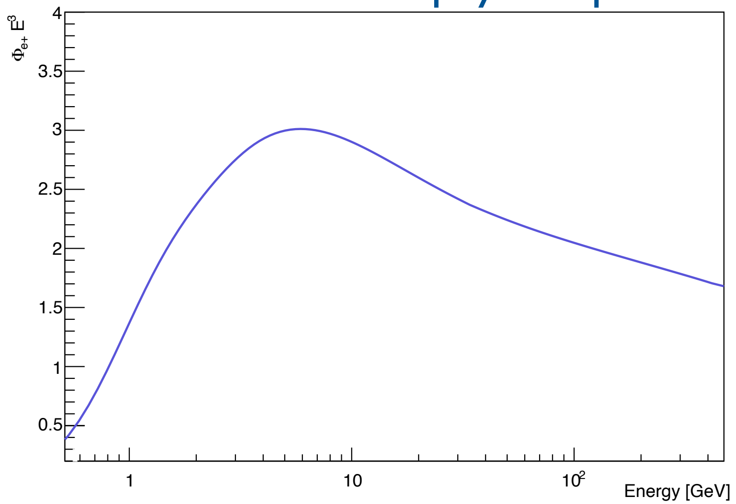
Antimatter in cosmic rays

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$_{ISM}$).

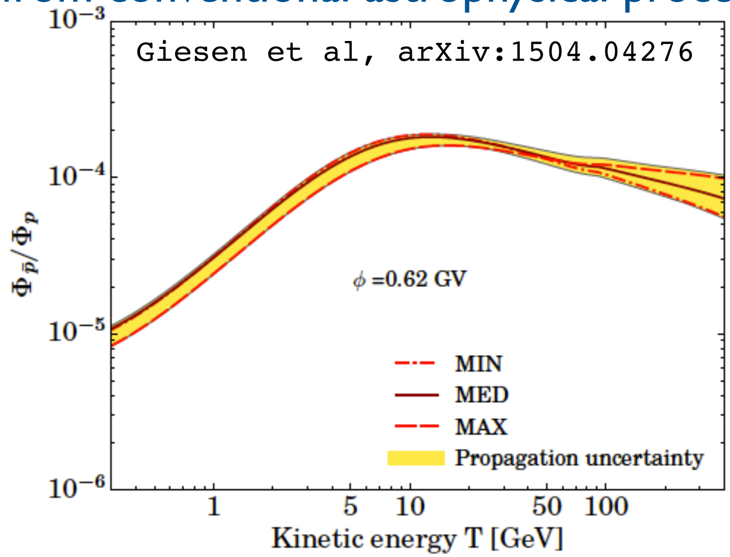
$$p + p_{\text{ism}} \to \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

- Tiny 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



The positron fraction

Defined as : $$F = \frac{\Phi_{e+}}{\Phi_{e+} + \Phi_{e-}} = \frac{N_{e+}}{N_{e+} + N_{e-}}$$

- Acceptance and efficiencies simplify in the ratio
- A ratio of number of counts

Challenge :

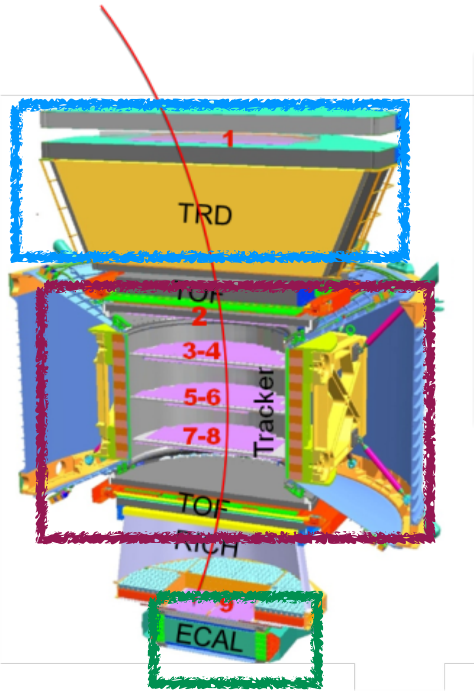
- **Proton rejection of the order of 10^6 is required**

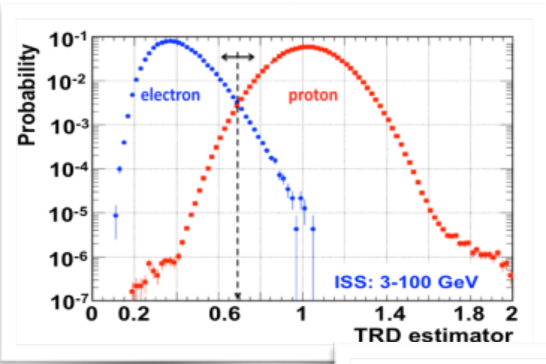
What we do expect :

- Positrons are secondaries, produced in protons interactions with the Interstellar medium.

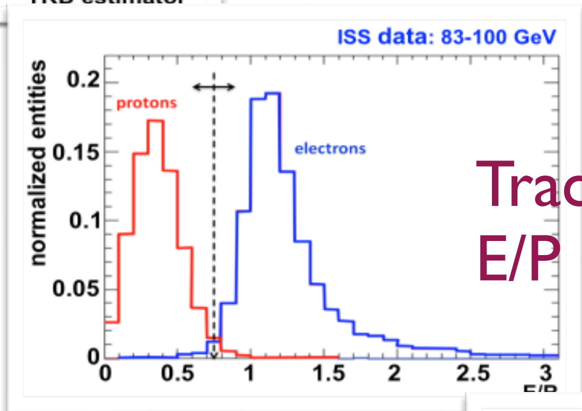
- **If positrons are ONLY secondaries, the positron fraction is expected to decrease with energy.**

LEPTON-HADRON SEPARATION





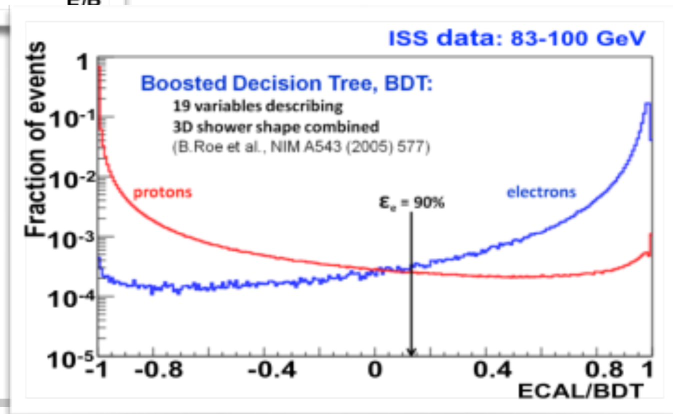
Transition Radiation Detector



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

Acc(p) ~ 0.5 m^2sr
Acc(e) ~ 0.04 m^2sr

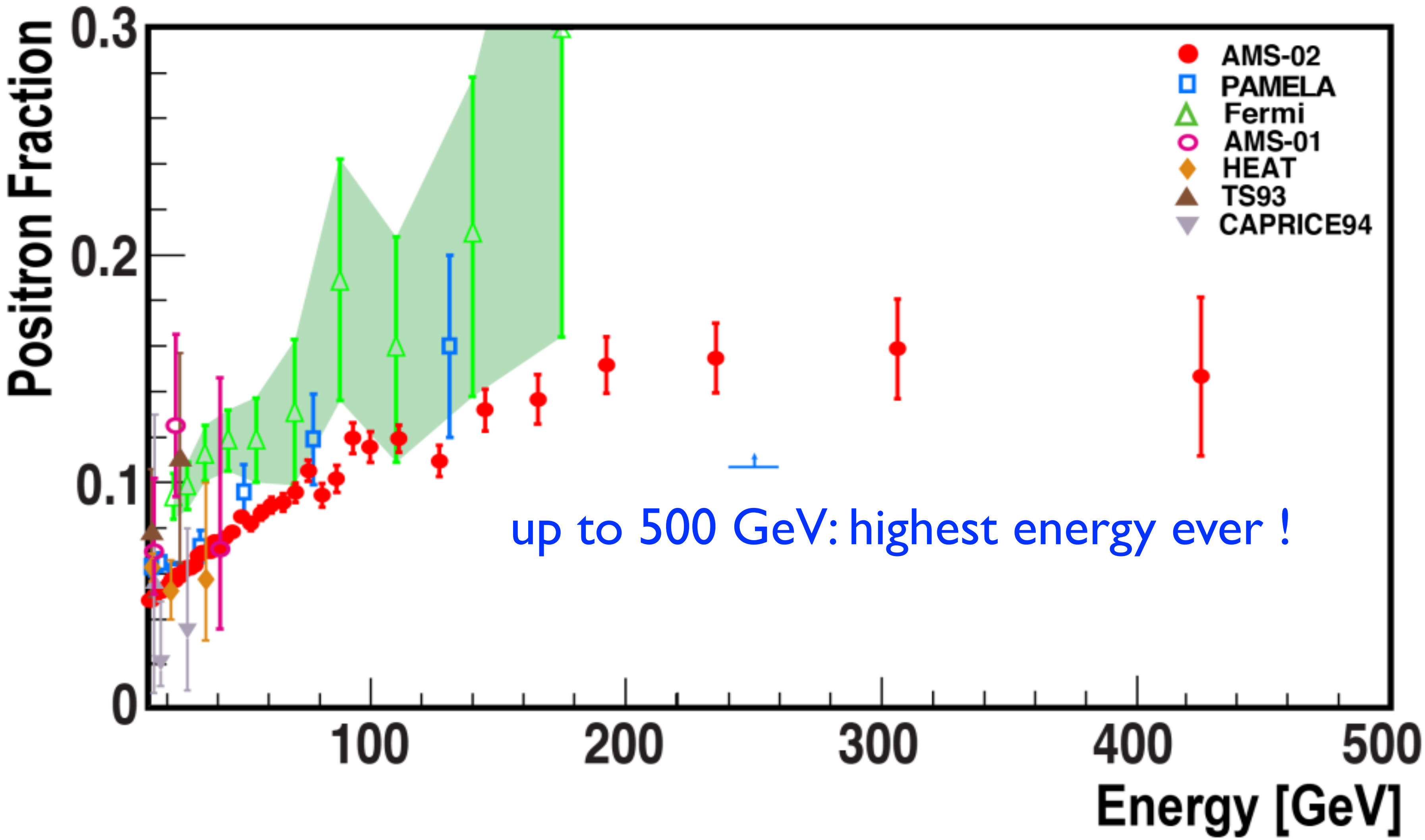
ECAL estimator: based on shower shape



PRL 113, 121101 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

10.9 million e+ and e- events

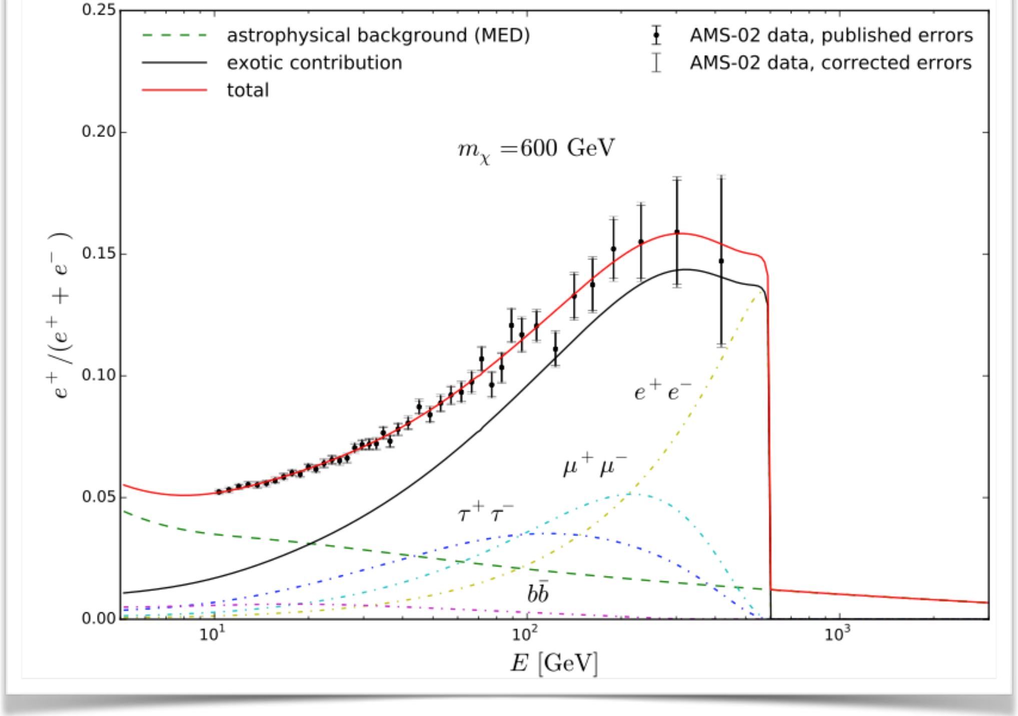


up to 500 GeV: highest energy ever !

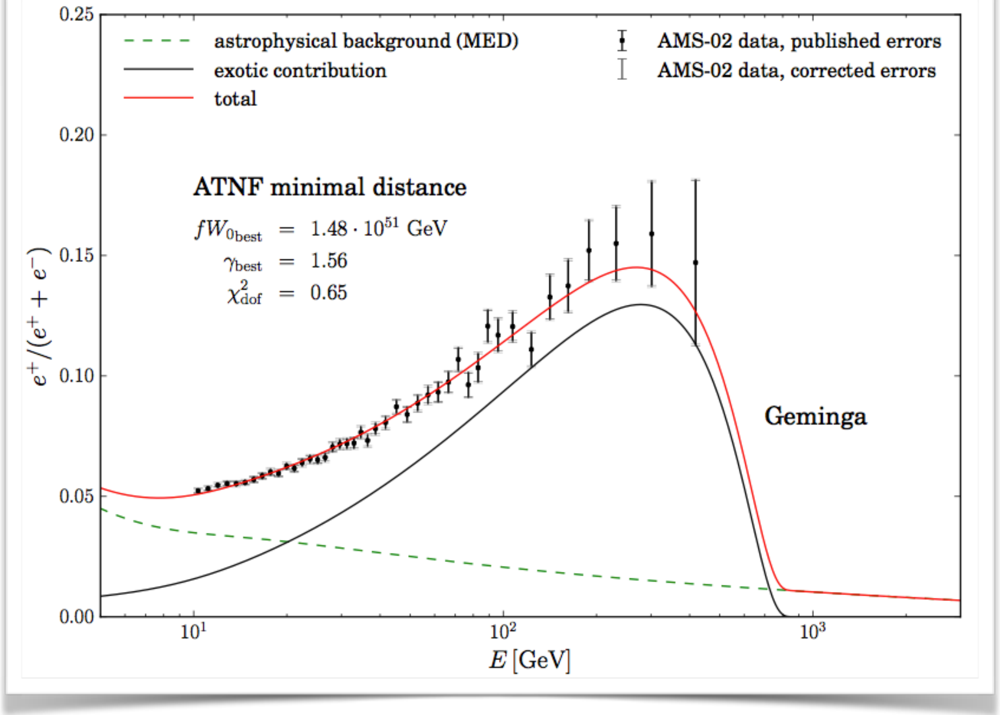
INTERPRETATION OF THE AMS-02 POSITRON DATA

M. Boudaud et al, A&A 575, A67 (2014)

Positron fraction from DM annihilation



Positron fraction from a single pulsar



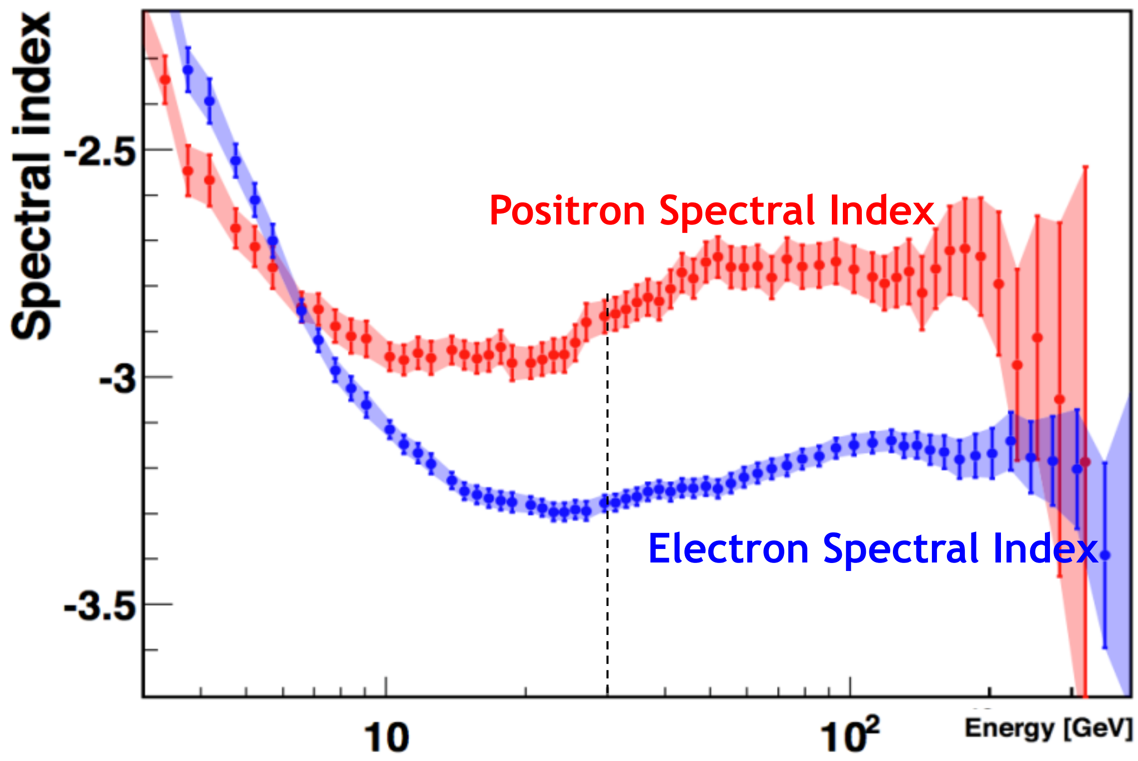
- AMS-02 data are consistent with Dark Matter interpretation, given:
  - A large enhancement of the annihilation cross section
- Young nearby pulsars or SNR can also fit the positron fraction

SPECTRAL INDEX

PRL 113, 121102 (2014)

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

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



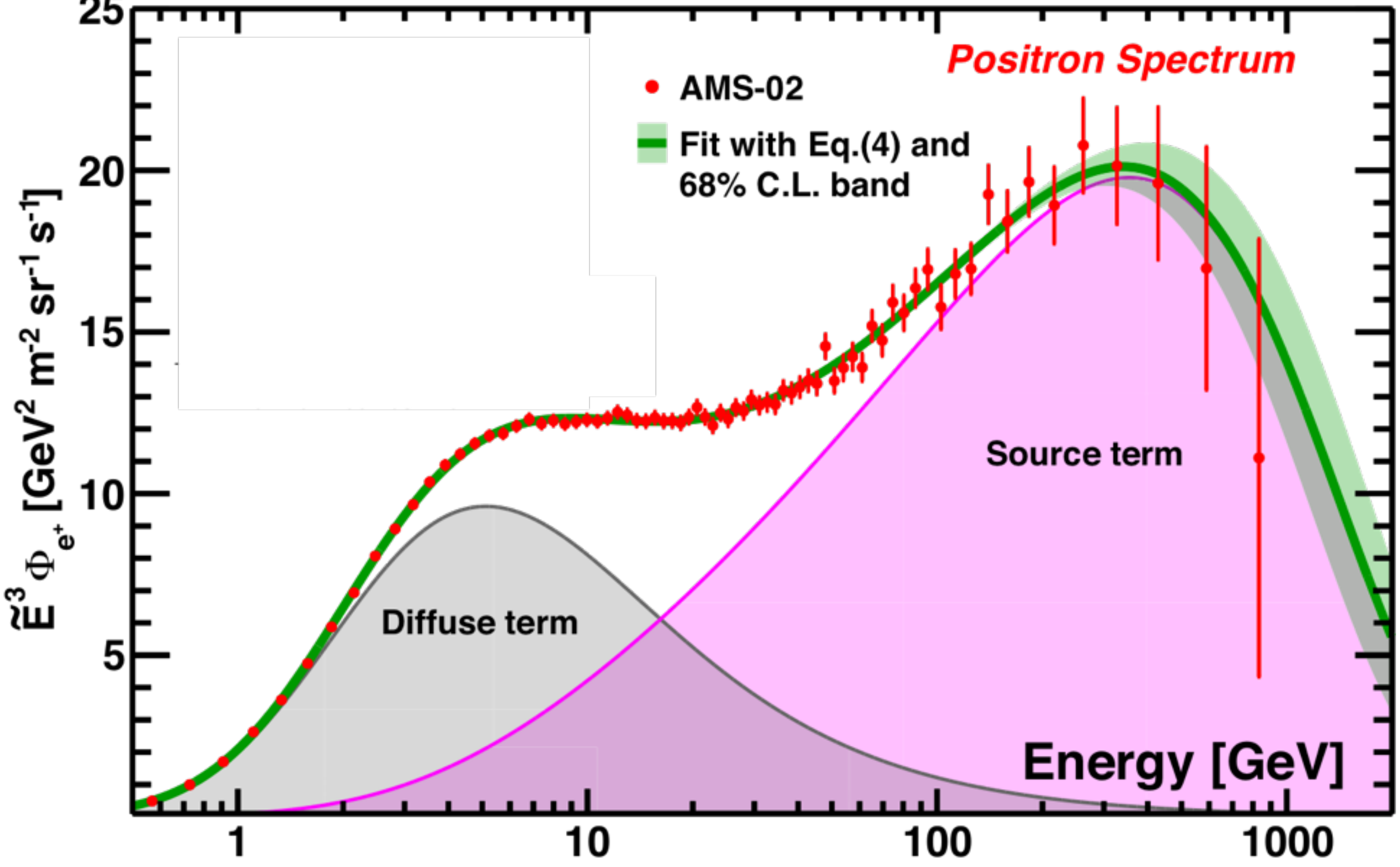
- The spectral indices of electrons and positrons are different
- Both spectra cannot be described by single power laws
- Change of behaviour at ~30GeV

The rise in the positron fraction is actually due to an excess of positrons, not the loss of electrons (the positron flux is harder).

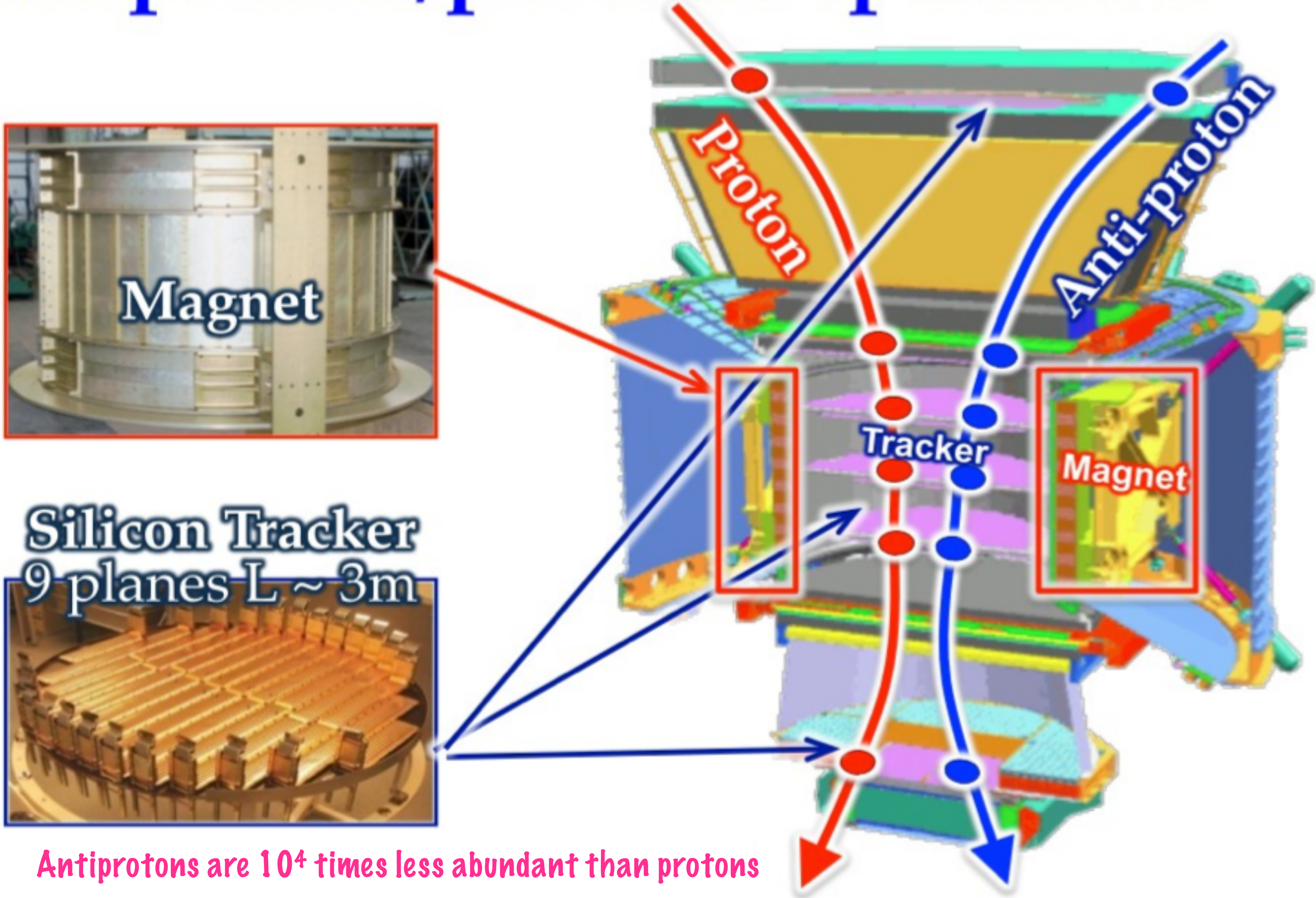
The positron flux

Diffuse term   Source term

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s\left(\hat{E}/E_2\right)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$



Antiproton/proton separation

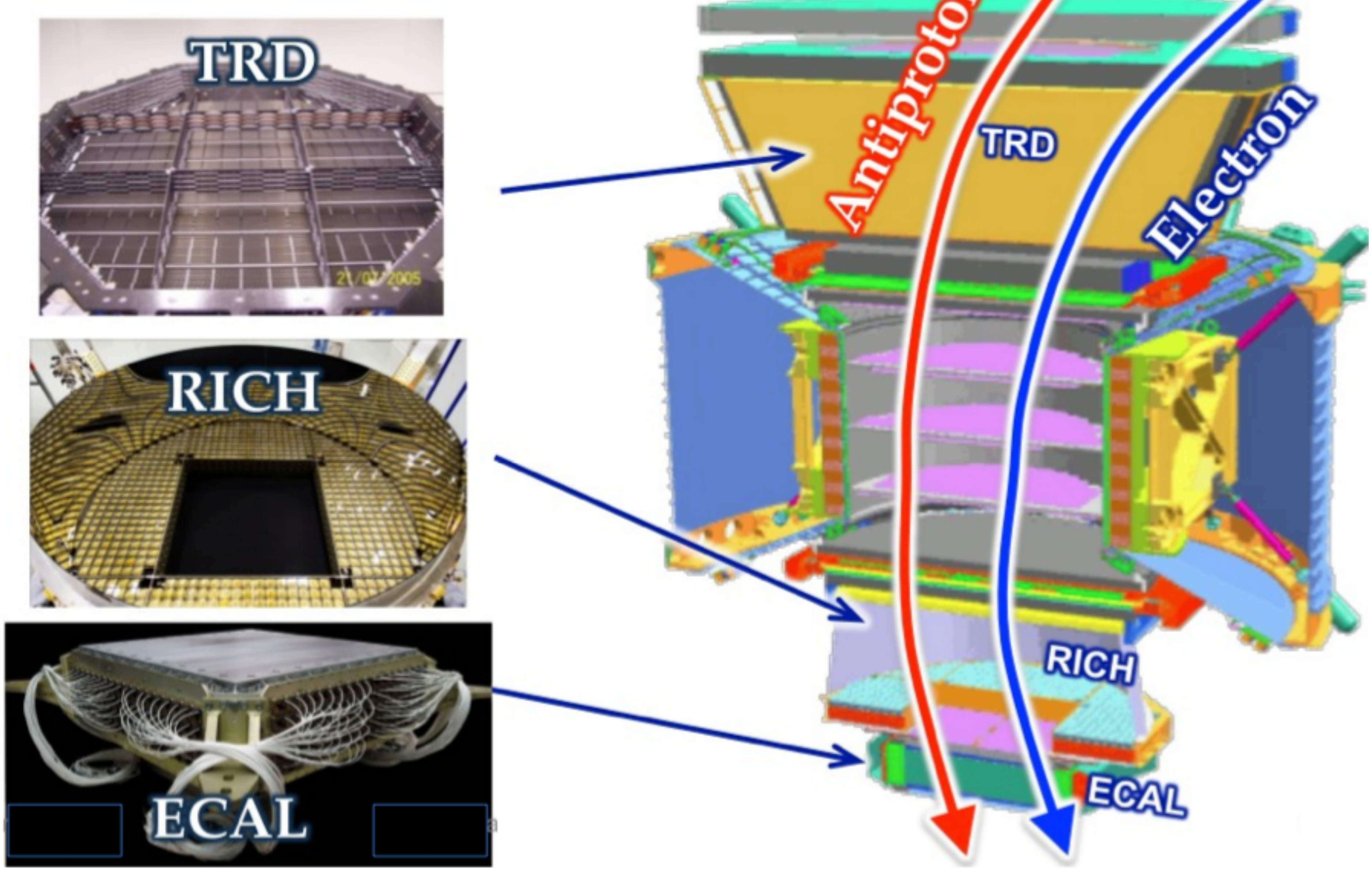


Antiprotons are 10^4 times less abundant than protons

Slide S. Haino

Antiproton/electron separation

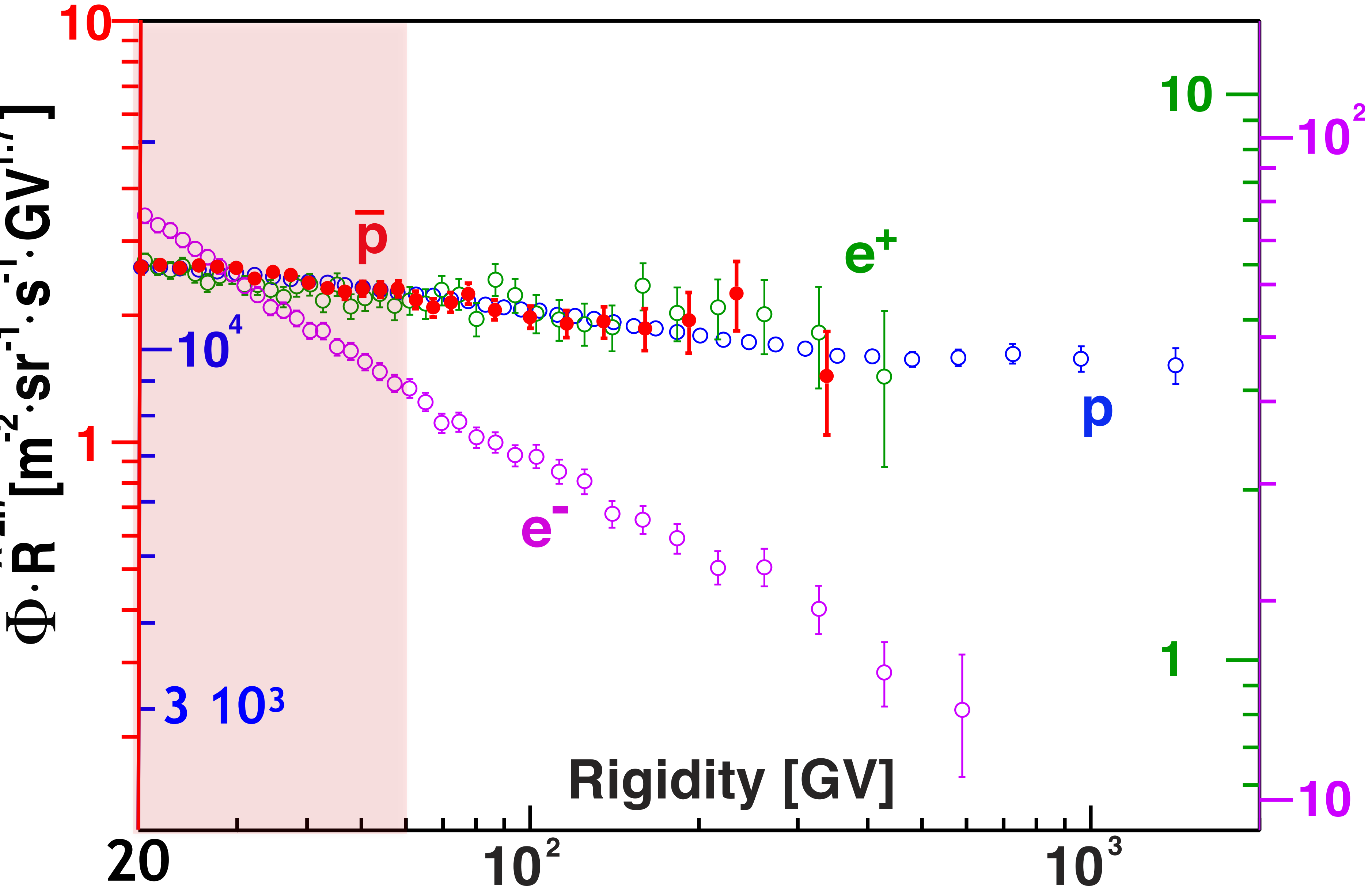
Electrons/kaons/pions can be removed using TRD+RICH+ECAL



Slide S. Haino

Unexpected Result
Spectrum of e+, $\bar{p}$, p
have identical energy dependence above 60 GeV
e- does not

PRL **117**, 091103 (2016)



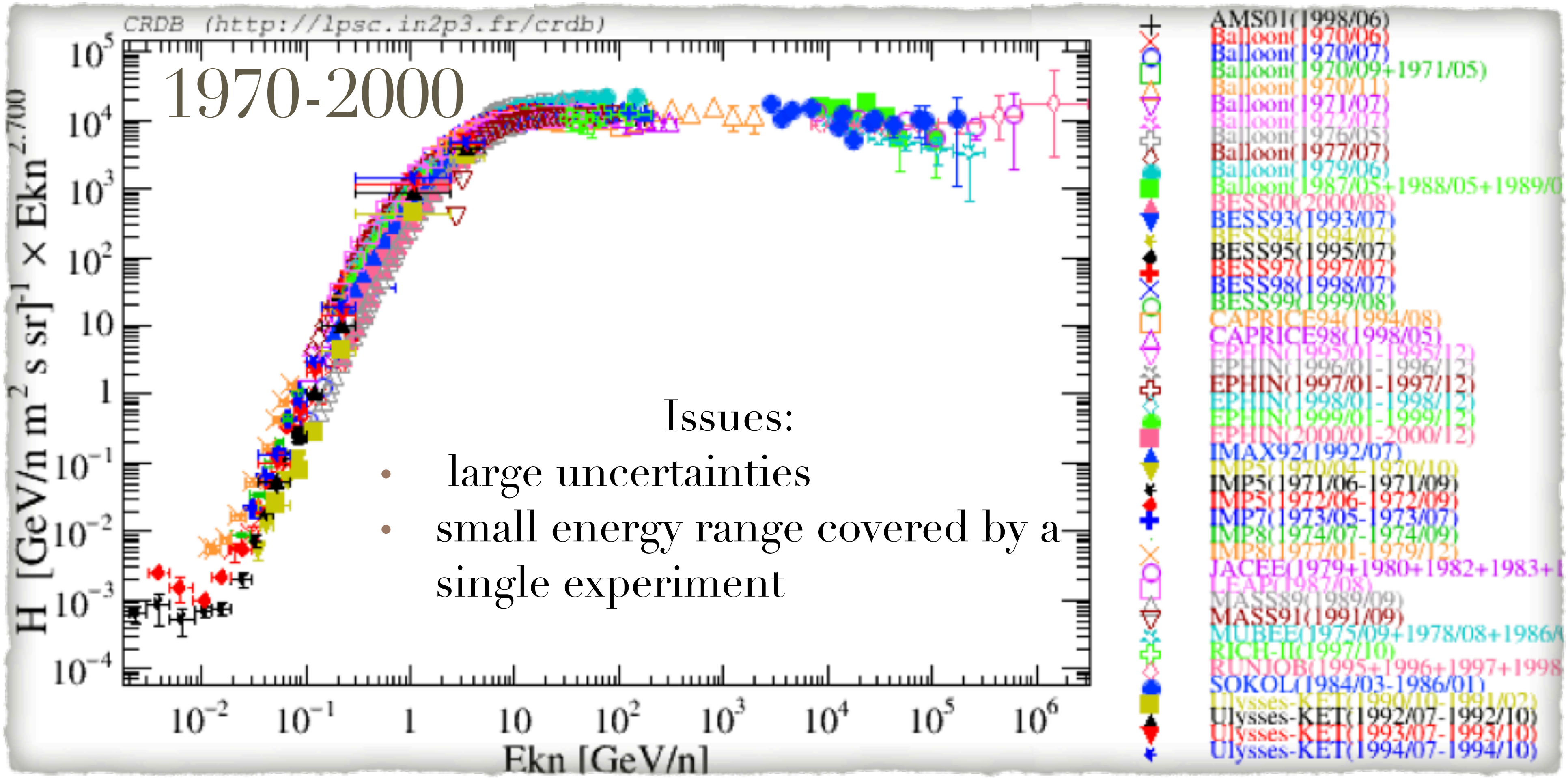
Take away message

- CR positron flux is not consistent with pure secondary hypothesis.
- The CR antiproton flux is surprisingly following the same rigidity dependence of positrons.

Cosmic-ray particles and nuclei

Cosmic-ray protons

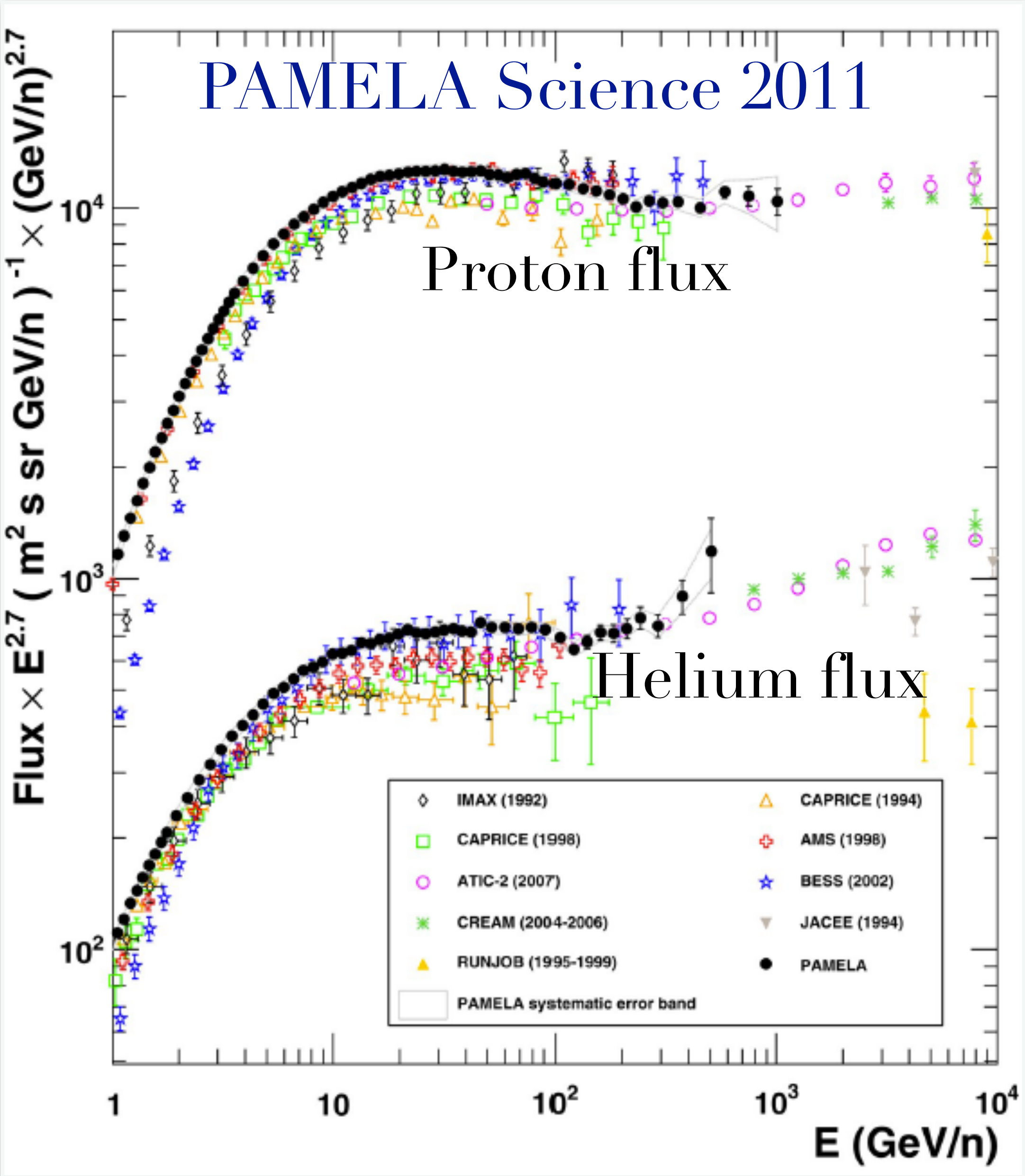
until a few decades ago...



Issues:

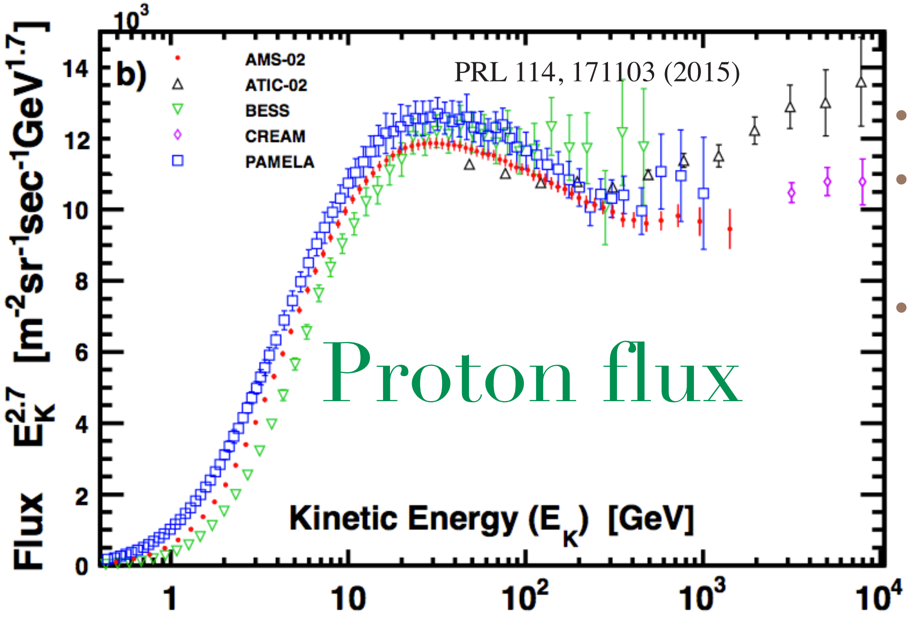
- large uncertainties
- small energy range covered by a single experiment

An unexpected observation



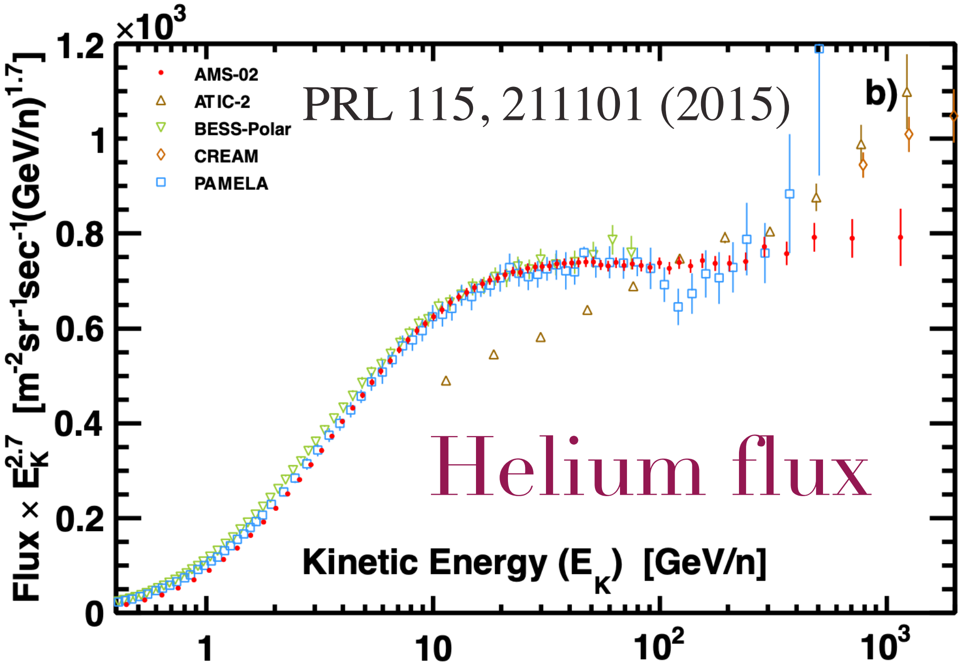
PAMELA:
A single instrument covering the whole energy range was solving the puzzle

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.

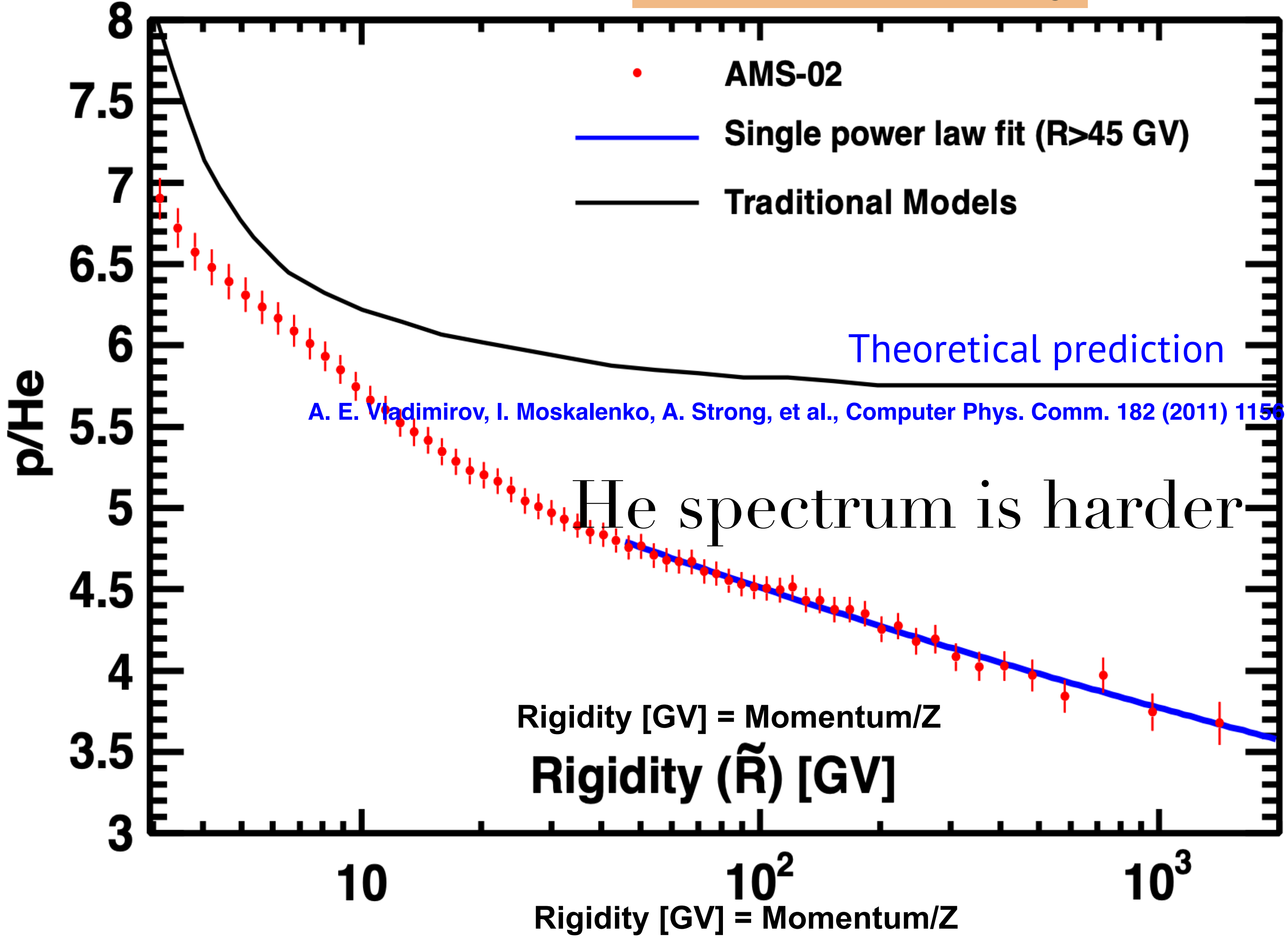
- Based on 50 million events (2011-2013)
- The helium flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.



Result confirmed by later measurement with higher statistics *Phys.Rept.* 894 (2021) 1-116

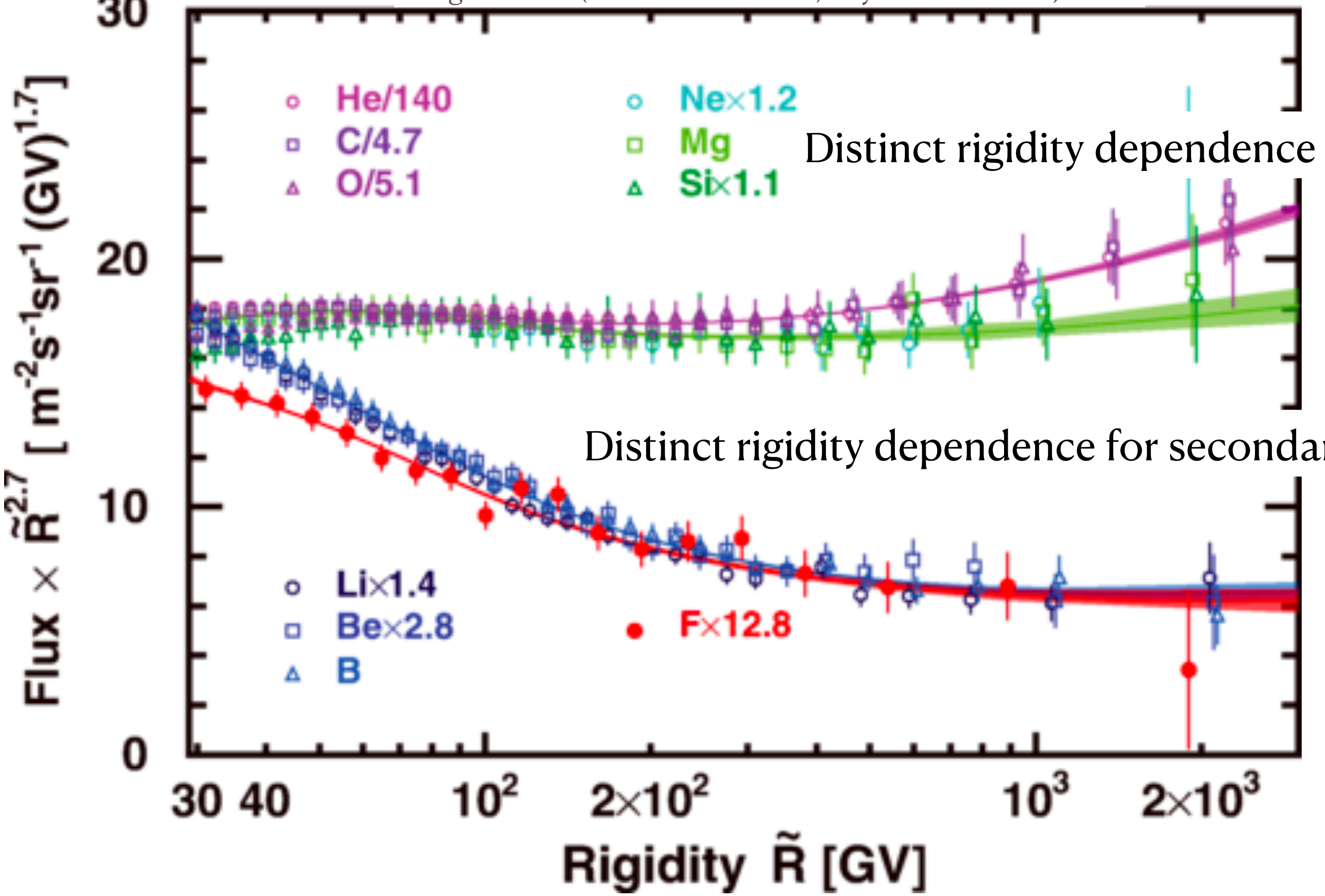
p/He flux ratio

non-universality



Rigidity dependence of *primary and secondary* CR fluxes

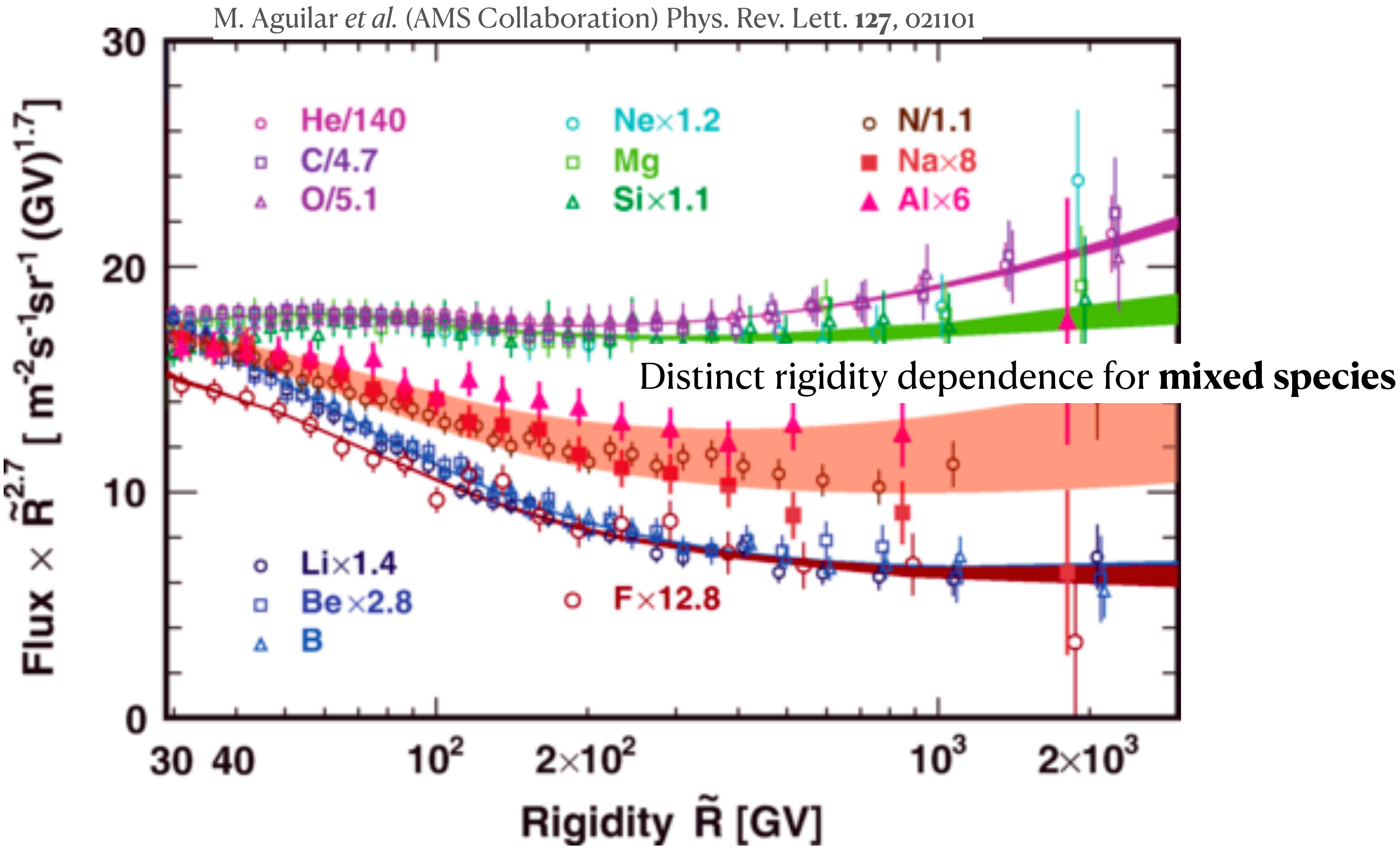
M. Aguilar *et al.* (AMS Collaboration) Phys. Rev. Lett. **126**, 081102



Distinct rigidity dependence for primary species

Distinct rigidity dependence for secondary species

Rigidity dependence of CR fluxes for all species

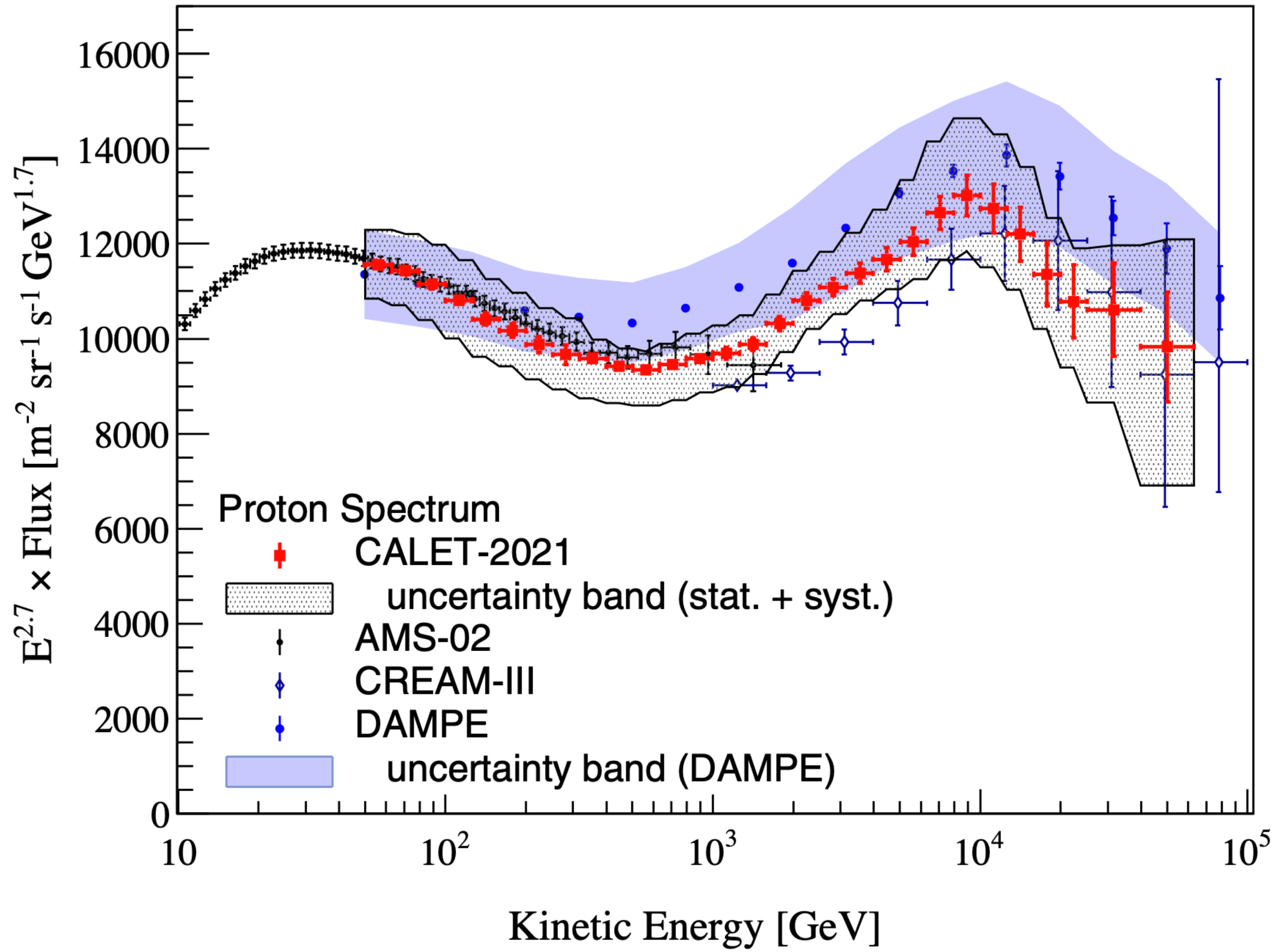


Takeaway message (2)

- Cosmic-ray fluxes below the knee cannot be described by a single power law: the precision of AMS-02 data brought to light a number of unexpected signatures in CR fluxes.
- Primary species deviate from a single power law above 200 GV and harden in an identical way. Two classes (He,C,O and Ne, Mg, Si).
- 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.

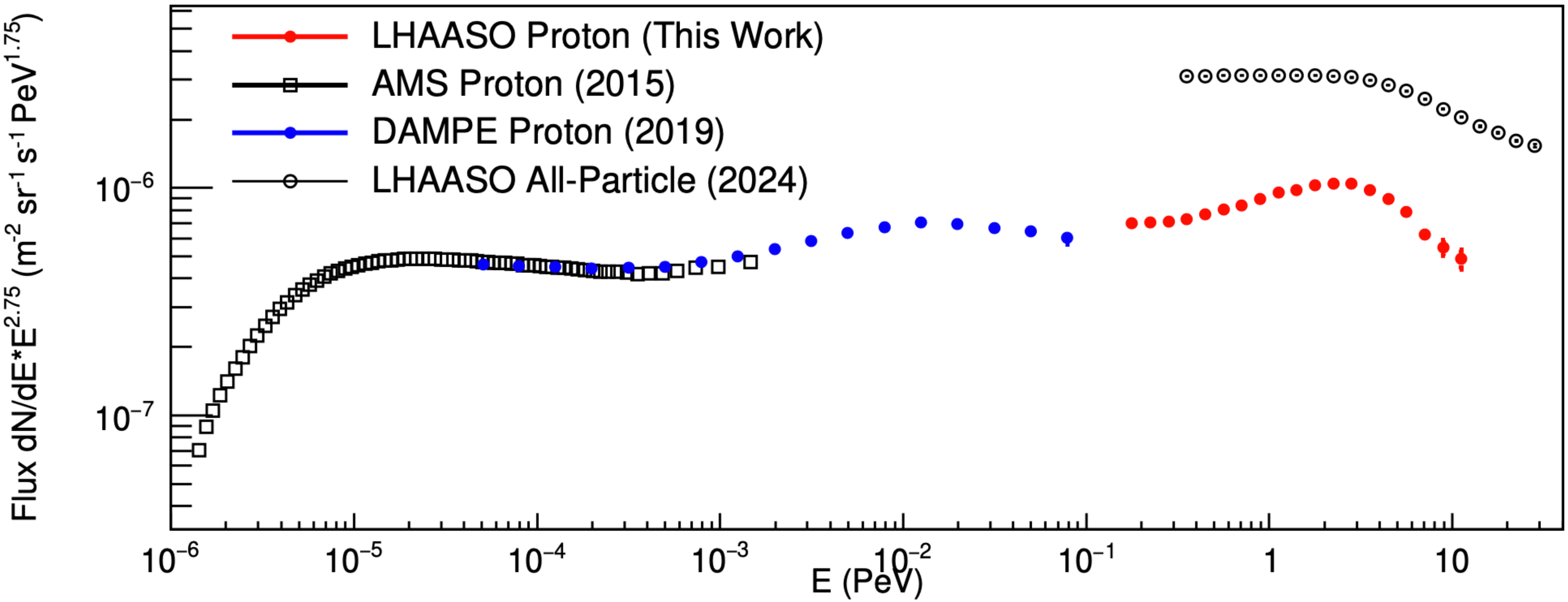
A look at the highest energies

PRL 129, 101102 (2022)



LHAASO proton flux

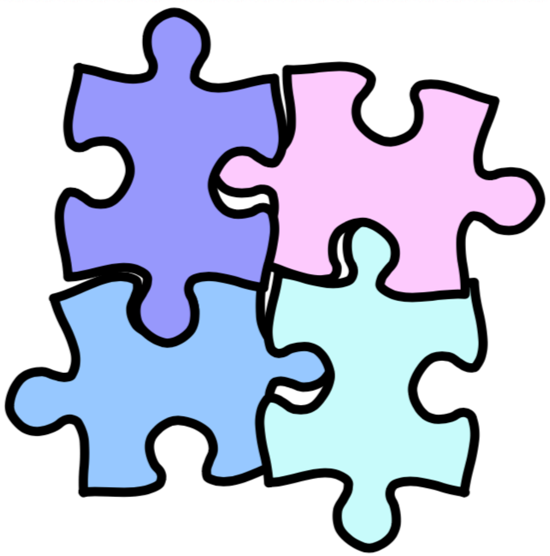
The LHAASO collaboration [ground-based detector]
arXiv: 2505.14447



CR proton measurements from the GeV up to 10 PeV !

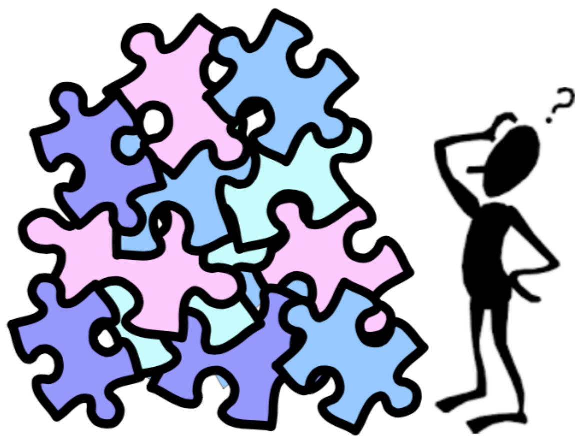
Where we are

Few decades ago …



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

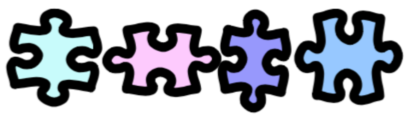
AMS-02 data



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

Beyond AMS-02

CALET, DAMPE, ISS-CREAM,...



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

Credit: Iris Gebauer

Acknowledgements

This work is part of the project "Cosmic ray antideuterons as a probe for new physics" with project number OCENW.KLEIN.387 (Budget Number 11680) of the research programme Grant Open Competition Domain Science, which is financed by the Dutch Research Council (NWO).

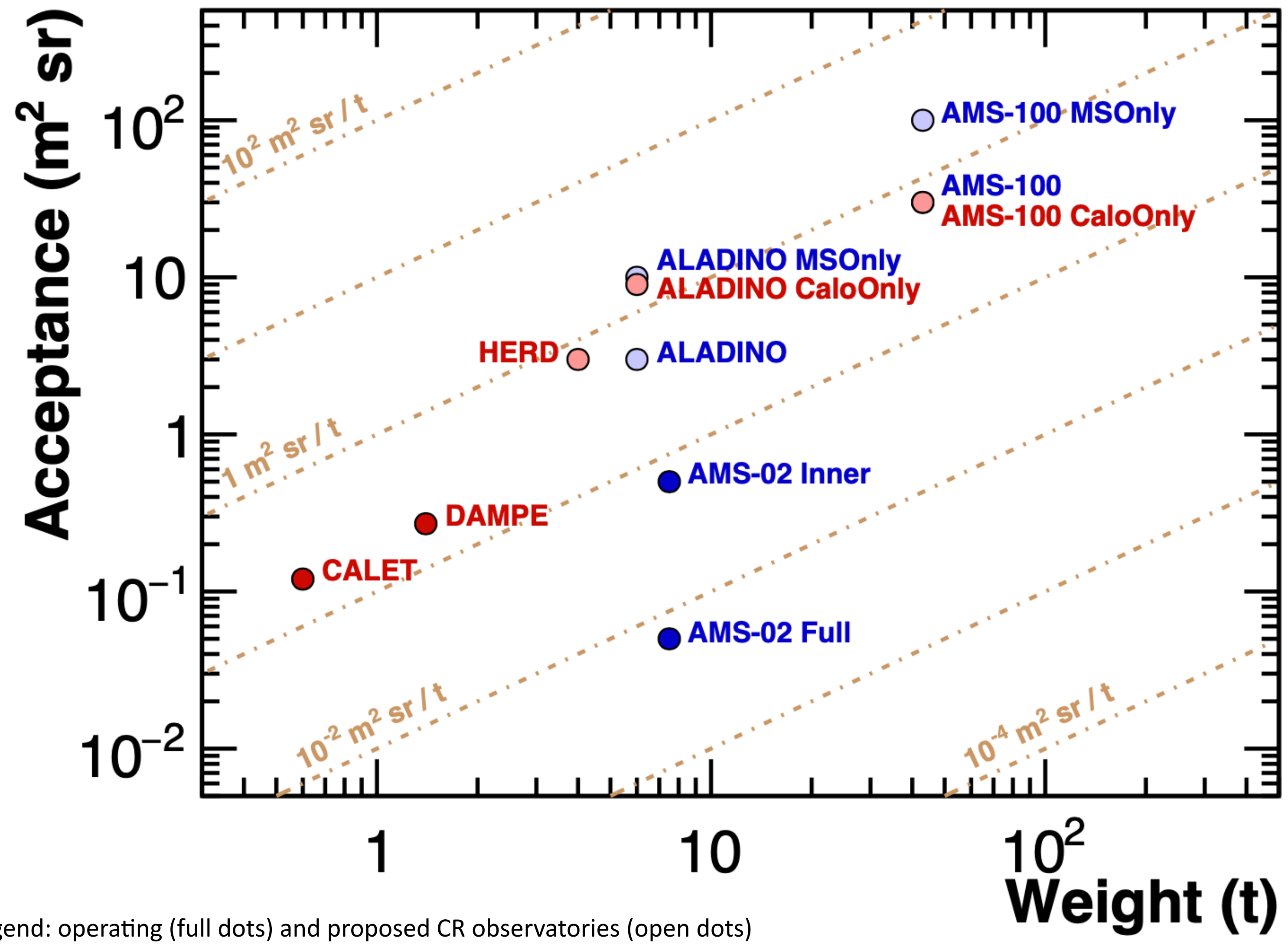
Suggested readings

- L. Baldini, arXiv: 1407.7631
- M. Pohl, arXiv:2502.18025
- S. Gabici et al: arXiv:1903.11584

Backup

Current and future projects

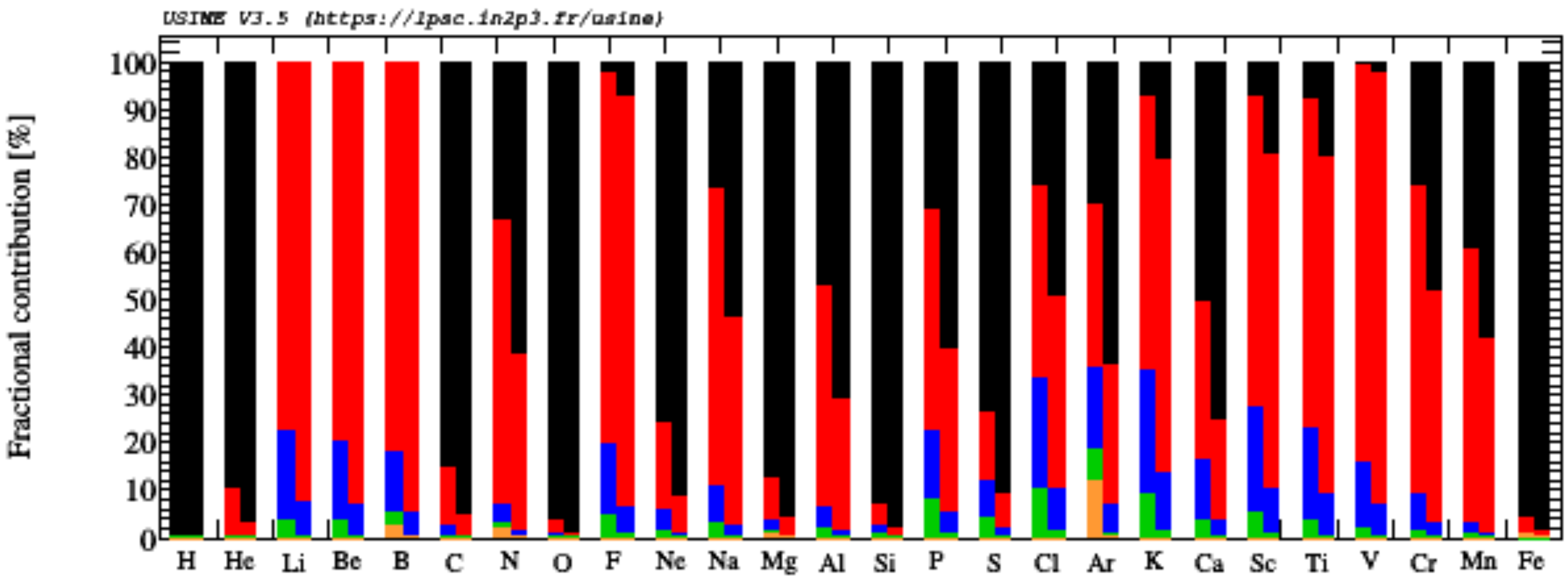
From M. Pohl arxiv:2502.18025



Legend: operating (full dots) and proposed CR observatories (open dots)

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).

Proton and helium spectral indices