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Summary of AMS-02 results and interpretation

Rapporteur talk to the parallel session “AMS-02 experiment on the ISS”

Manuela Vecchi

Kapteyn Astronomical Institute, the University of Groningen, the Netherlands

Session program

Tue 09/07

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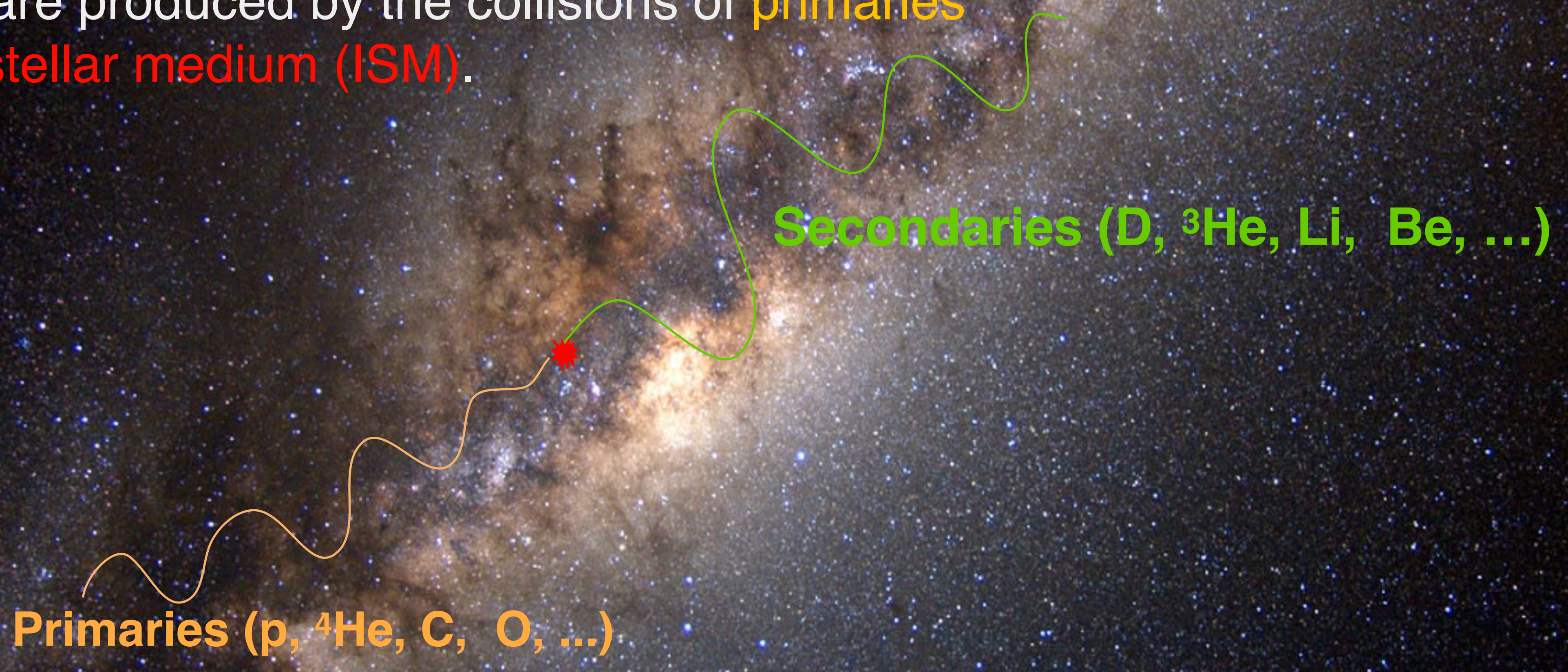
Time	Title	Speaker	Location	Slot
15:00	**The AMS-02 experiment on the International Space Station**	*Mercedes Paniccia*	*Pazienza, Aurum*	15:00 - 15:10
	Unique Properties of Primary Cosmic Rays measured by the Alpha Magnetic Spectrometer	*Meeran Zuberi*	*Pazienza, Aurum*	15:10 - 15:30
	Unique Properties of Secondary Cosmic Rays: Results from the Alpha Magnetic Spectrometer	*Nikita Belyaev*	*Pazienza, Aurum*	15:30 - 15:50
16:00	**Spectra of Cosmic Rays escaping from star clusters**	*Giovanni Morlino*	*Pazienza, Aurum*	15:50 - 16:10
	On the origin of the spectral features observed in the cosmic ray spectrum	*Sarah Recchia*	*Pazienza, Aurum*	16:10 - 16:30
17:00	**The role of electron capture decay in the precision era of Galactic cosmic-ray data**	*Marta Borchiellini*	*Pazienza, Aurum*	17:00 - 17:15
	Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer	*Diego Gomez Coral*	*Pazienza, Aurum*	17:15 - 17:35
	Unique Properties of Daily Proton Fluxes up to 100 GV	*Francesco Faldi*	*Pazienza, Aurum*	17:35 - 17:55
18:00	**The Layer 0 upgrade of the AMS-02 experiment on the ISS: status and perspectives**	*yaozu jiang*	*Pazienza, Aurum*	17:55 - 18:10
	Summary of the AMS results and their interpretation	*Manuela Vecchi*	*Pazienza, Aurum*	18:10 - 18:30

Apologies in advance for the biases and lack of completeness due to limited time.

Cosmic rays

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



The “conventional” paradigm for galactic CRs

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It was able to describe the data up to a few decades ago …

- The bulk of cosmic rays below the knee (i.e. $E<10^{15}$ eV) are accelerated in galactic SuperNova Remnant via Diffusive Shock Acceleration processes, which lead to **single power-law fluxes**, the spectral index being the result of the acceleration and propagation mechanisms.
- SuperNova Remnant accelerate all the species in the same way, so the fluxes of **primary species have universal (species-independent) spectral indices**.
- **Antimatter** component of cosmic rays is **secondary**, generated by collisions of primary species in the ISM.

We will see during this talk how these assumptions must be revisited in view of AMS-02 precise data

Primary CR species

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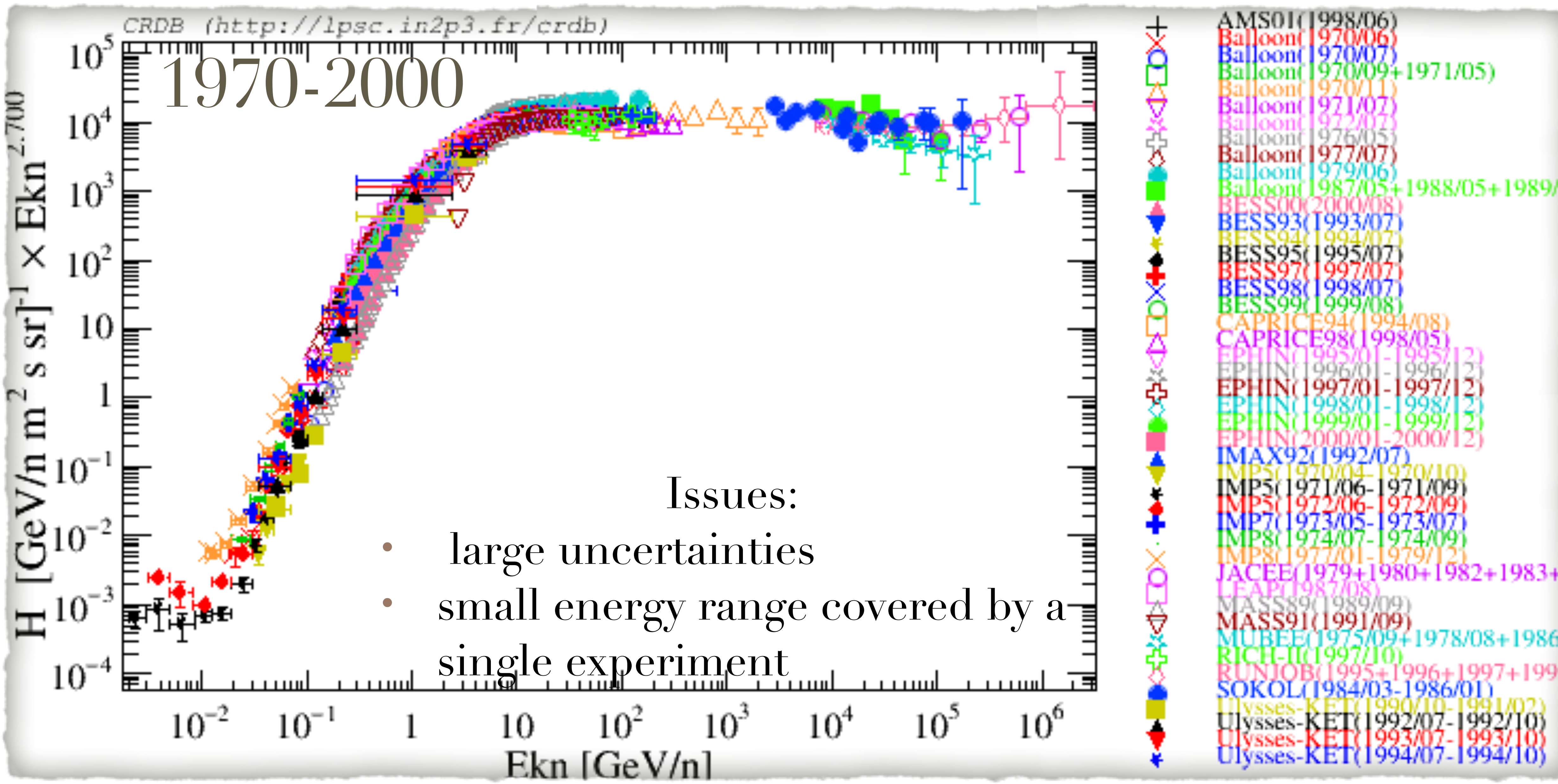
- The flux of CRs is shaped by the physical phenomena occurring at the **source** and during their **propagation**.
- Primary CRs include H, He, O, and Fe …
- In the simplest scenario, the source and the diffusion provide universal spectral indices for primary species:

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

  - q(R) is the source term (a power-law in rigidity)
  - K(R) is the diffusion coefficient (a power-law in rigidity)

Cosmic-ray proton measurements

Protons are the most abundant component of cosmic rays



Issues:

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

Cosmic-ray helium measurement

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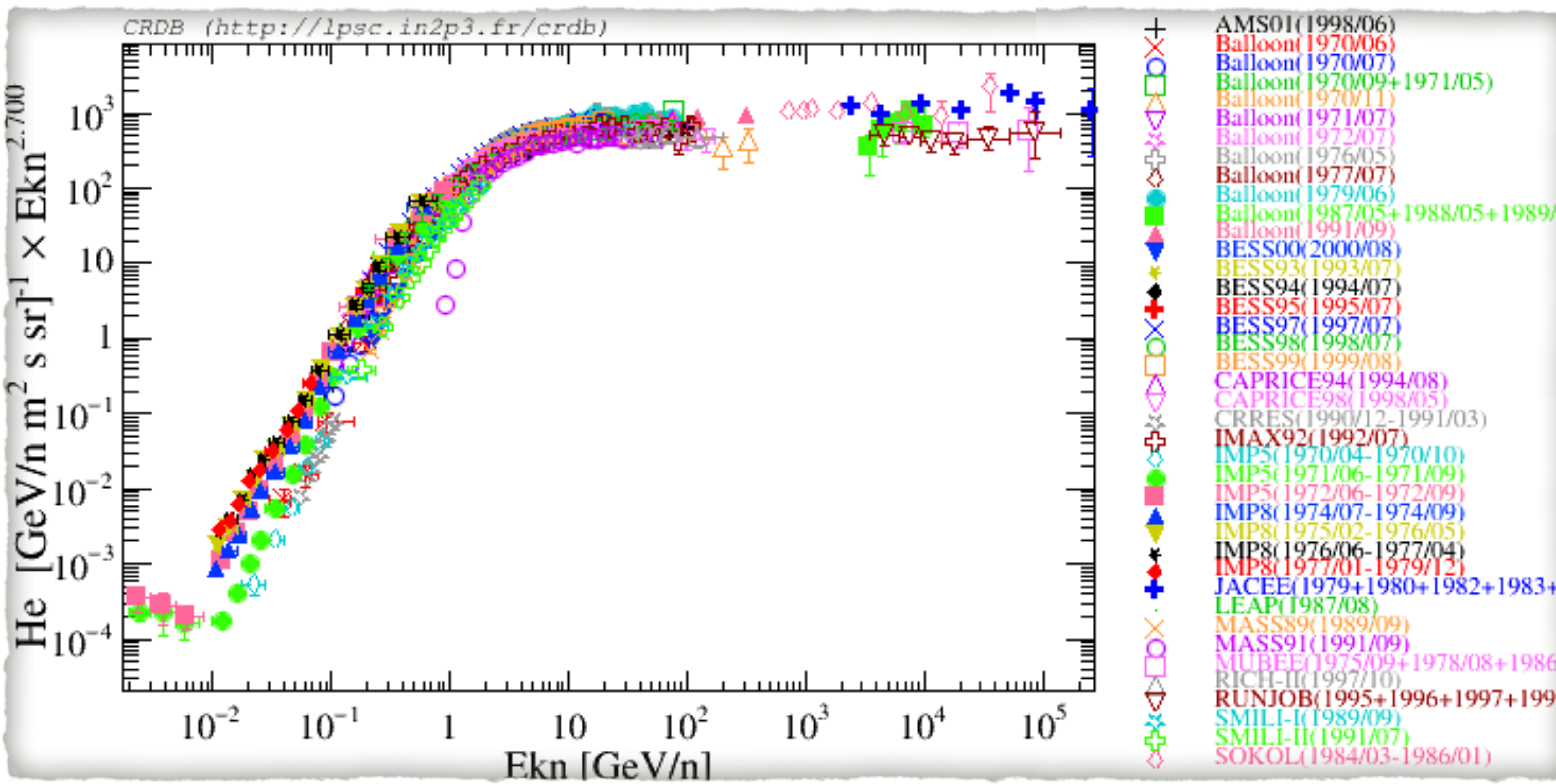
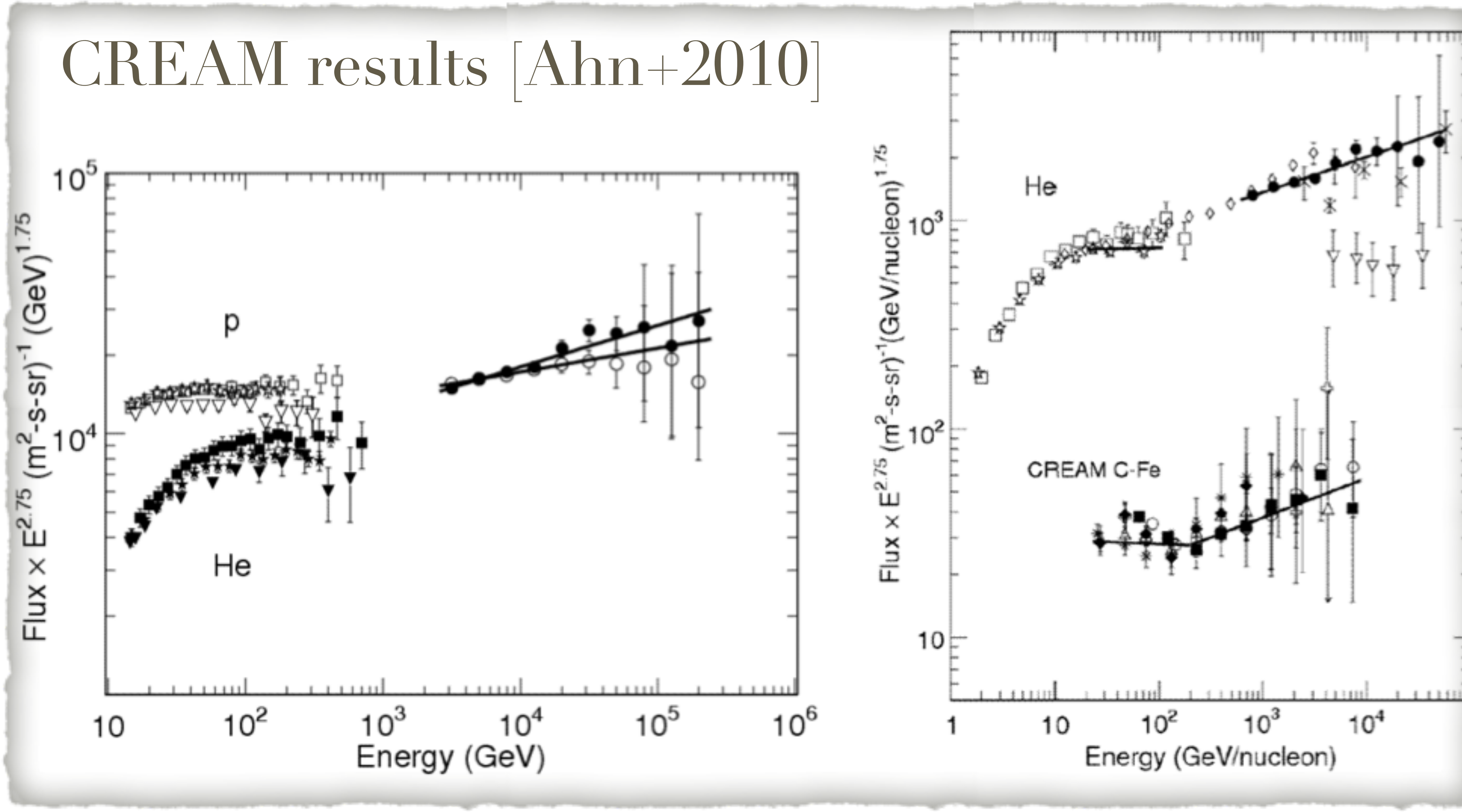
until a few decades ago…



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 !

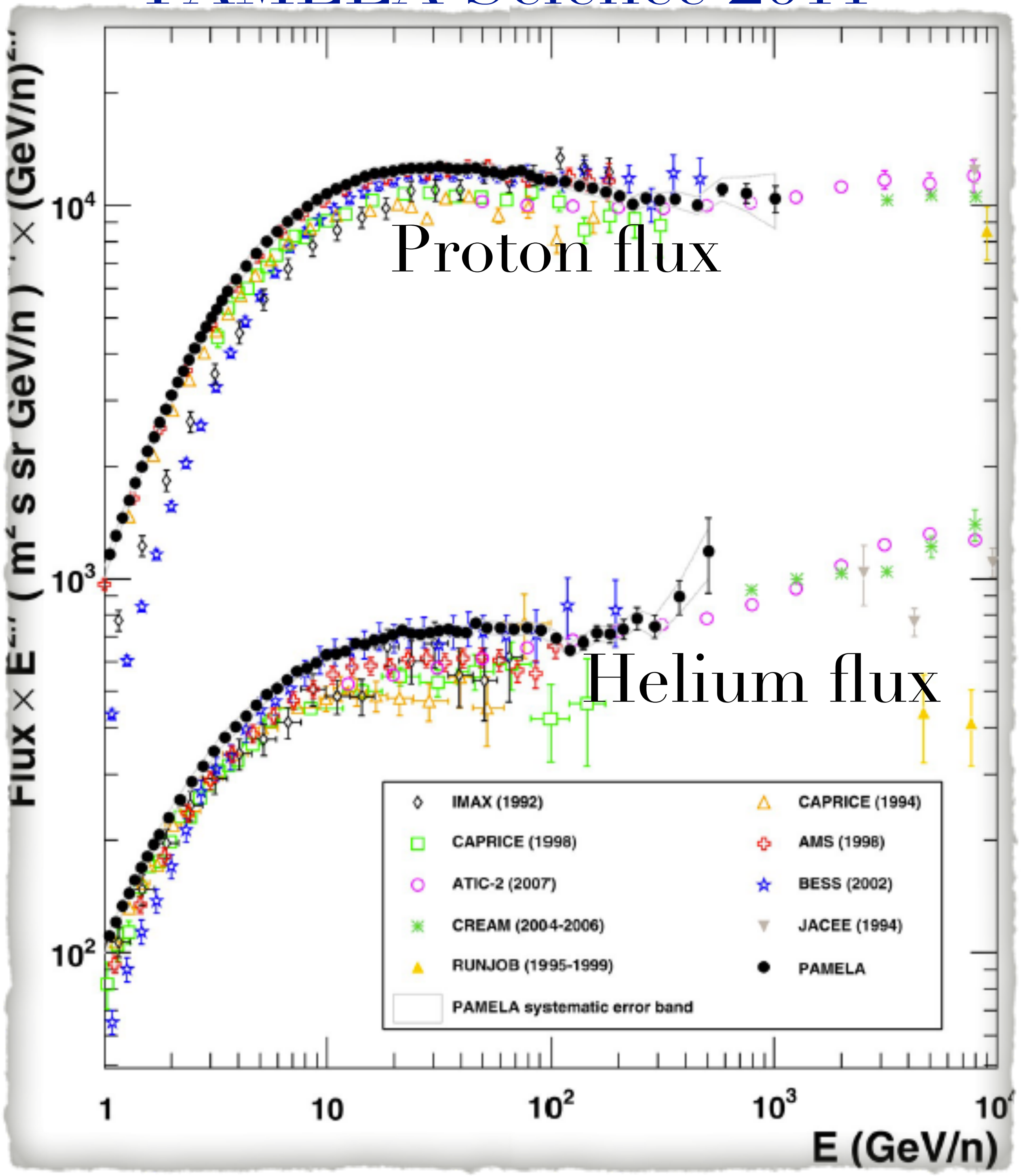


Change in spectral index suggested around 200 GeV/n

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

surprise: broken PL below the knee

PAMELA Science 2011

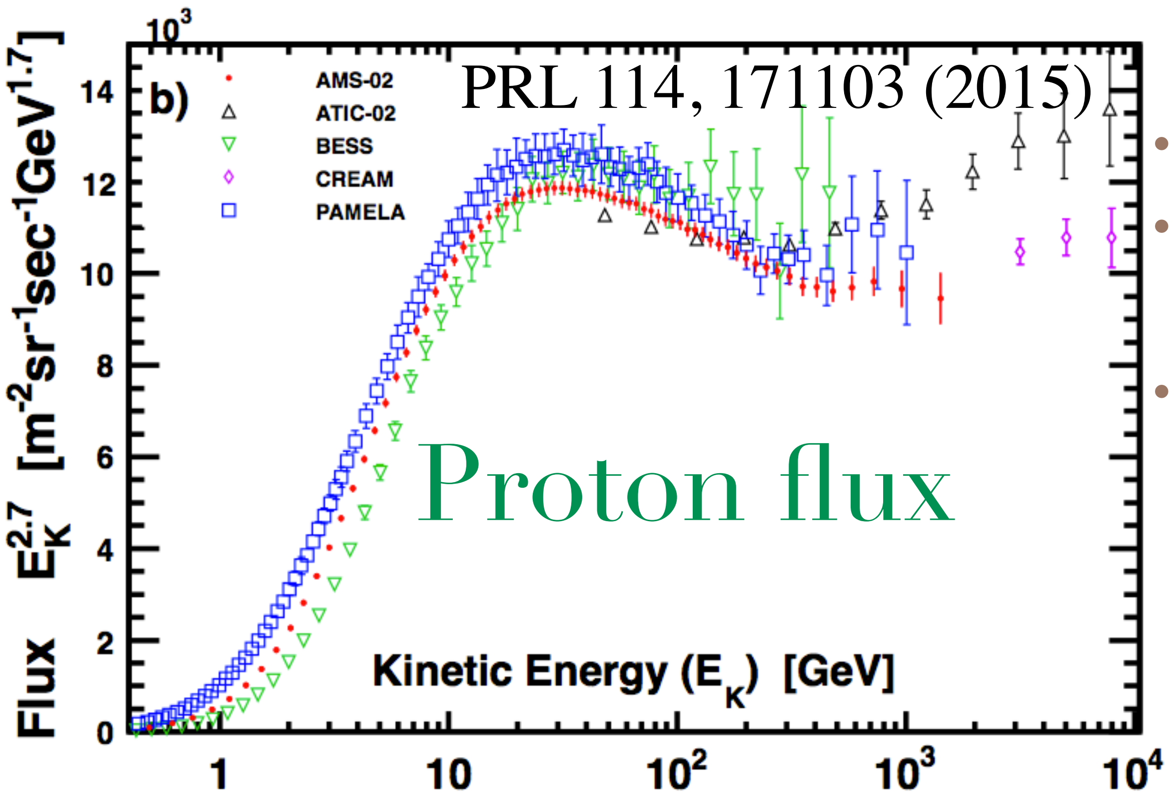


A single instrument covering the whole energy range was solving the puzzle.

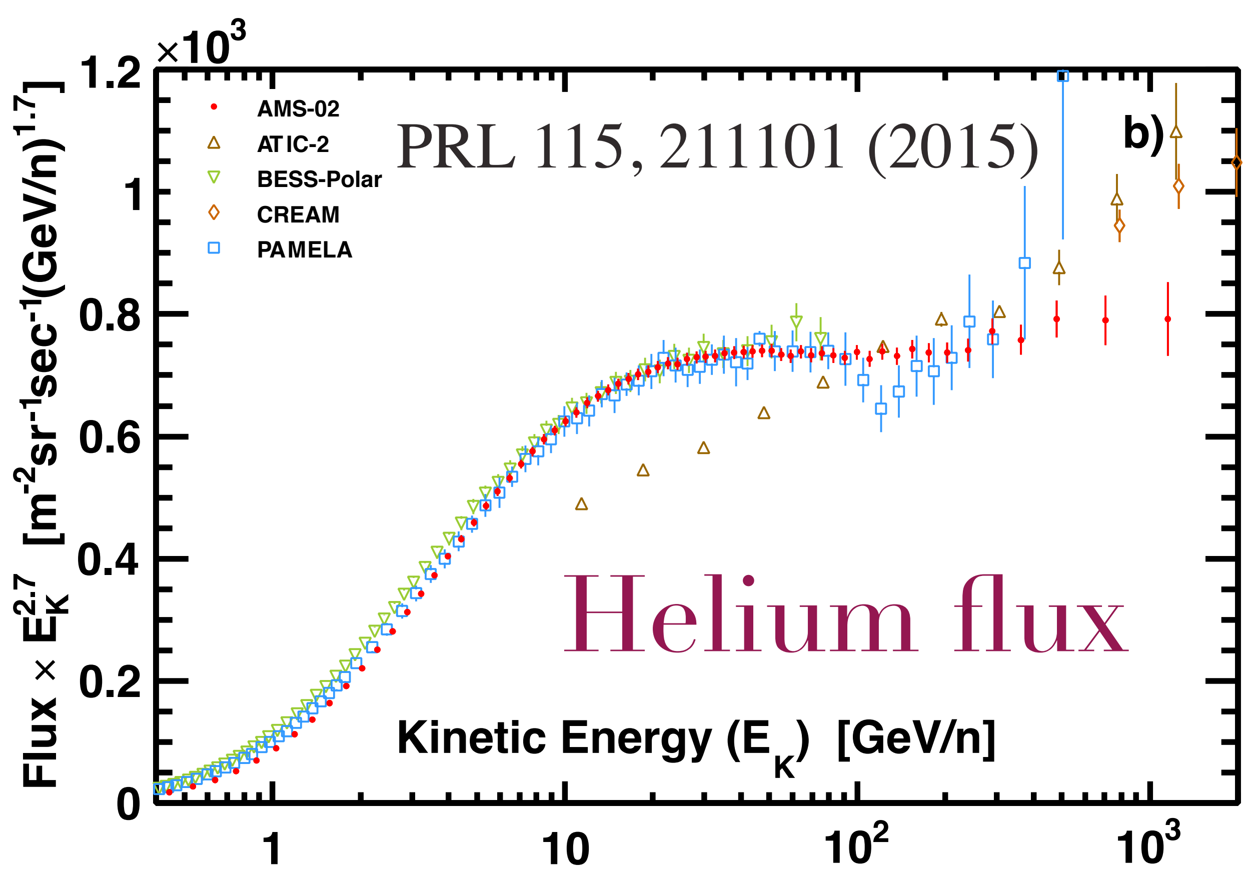
Unambiguous evidence for hardening in both proton and helium flux.

AMS-02 Proton and helium fluxes

See Meeran Zuberi's talk



- 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 300 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 300 GV.

Proton and helium fluxes

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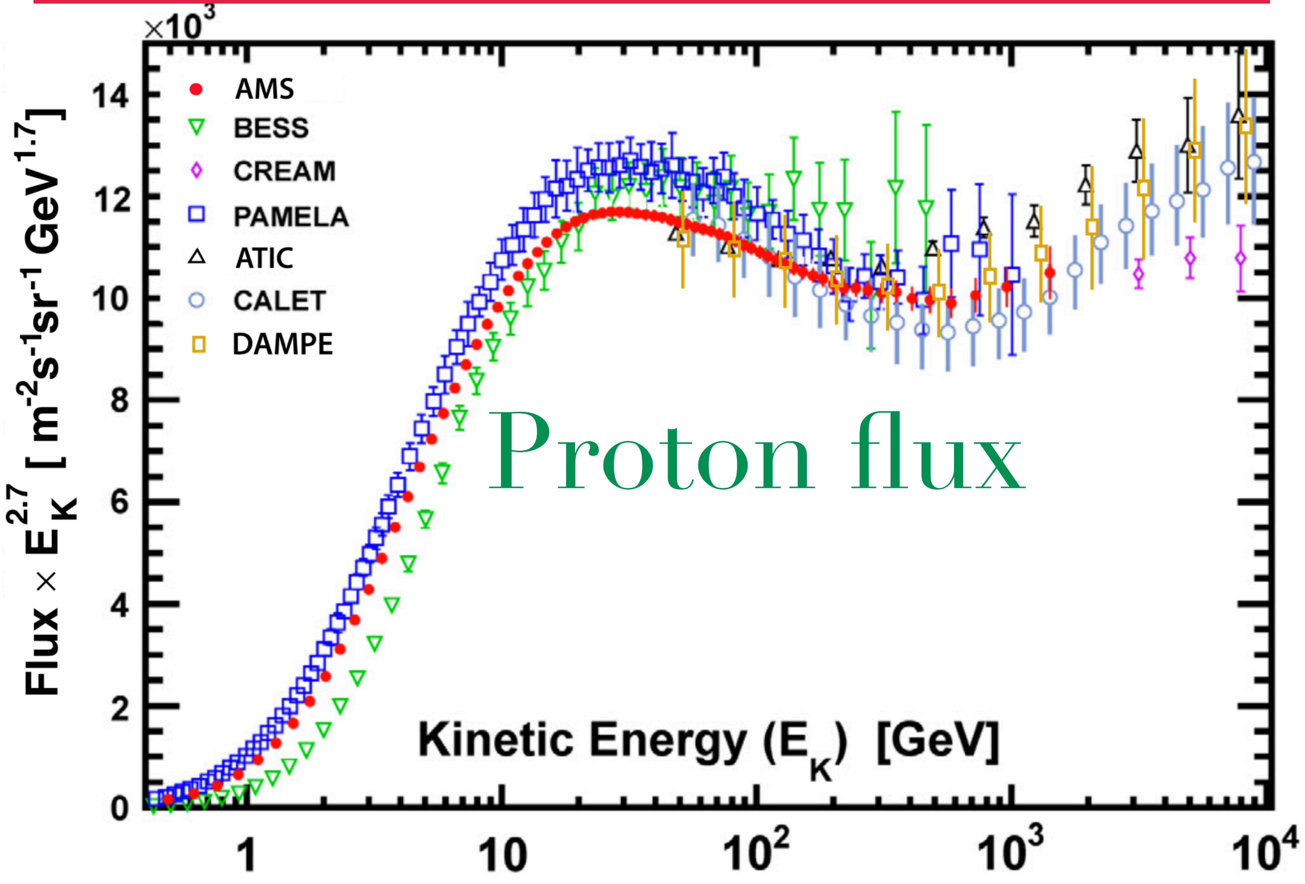
Aguilar *et al*, Physics Report 849 (2021) 1-116



- Based on 1 billion events
- New result in complete agreement with previous but with smaller errors.
- The Spectral hardening can be explained by a change in the rigidity dependence of the diffusion coefficient (see for example Tomassetti 2012, Aloisio&Blasi 2013, Genolini+2017)

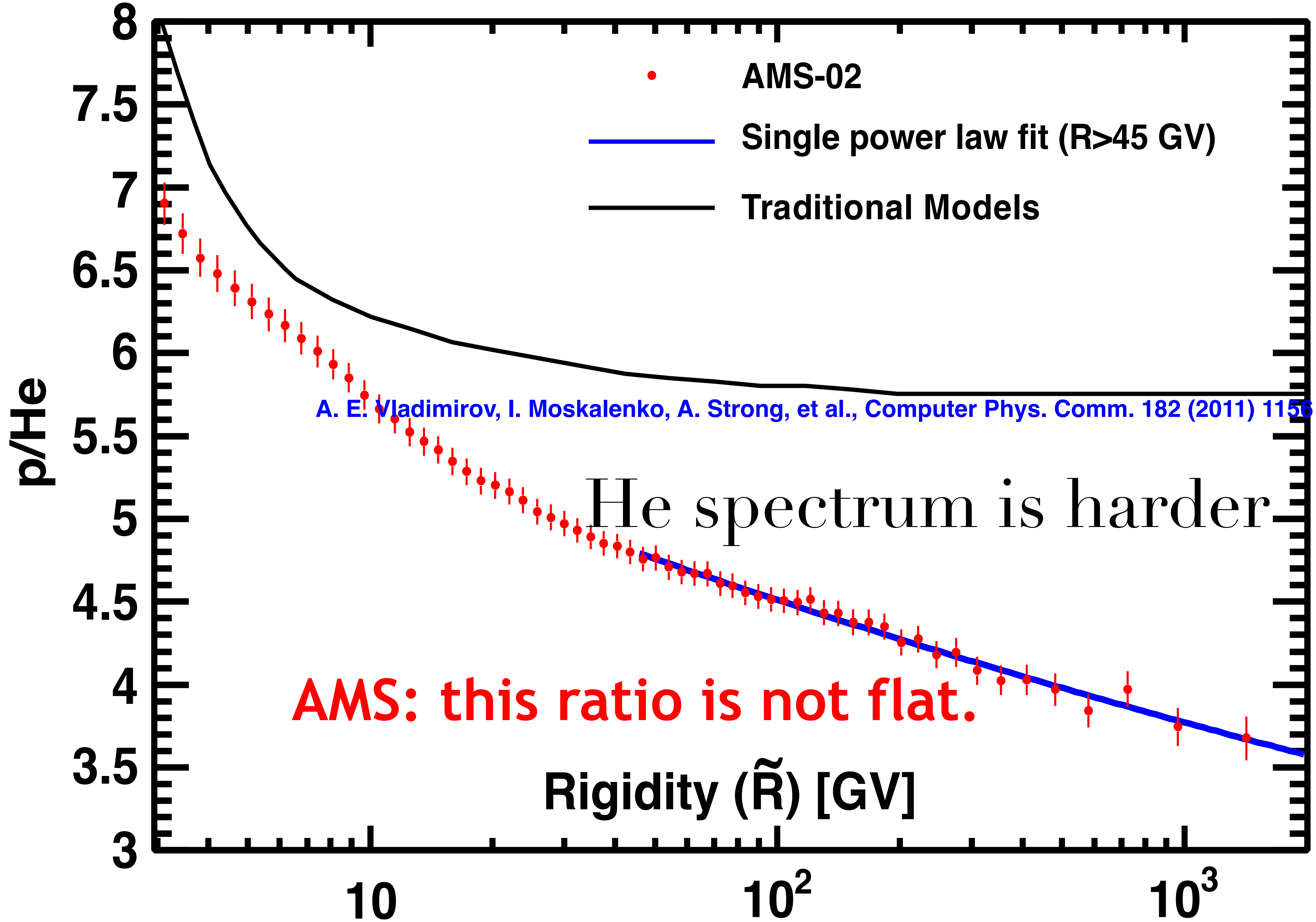
The proton/helium flux cannot be described by a simple power law

$$\Phi = CR^{\gamma}$$

Broken power law

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

Non universality of spectral indices



Star clusters as cosmic-ray factories ?

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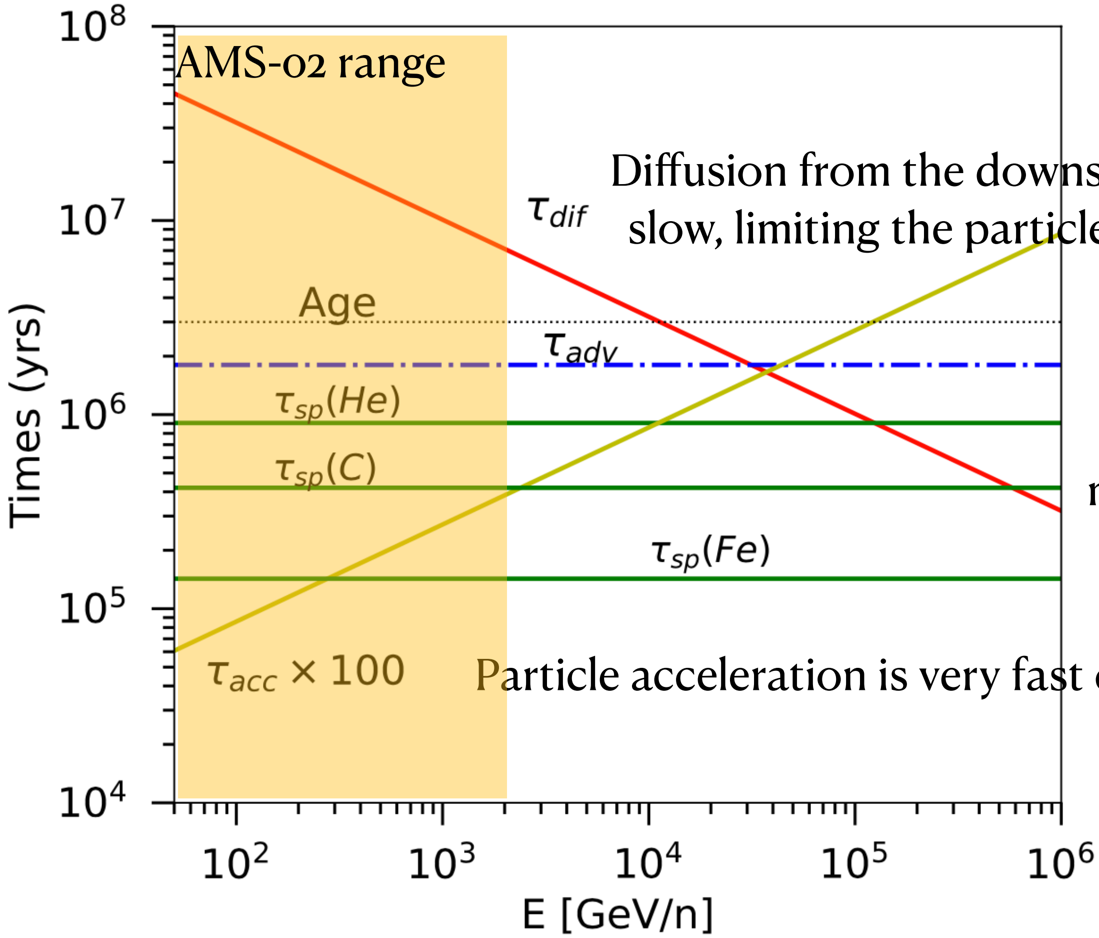
See Giovanni Morlino's talk based on arxiv: 2307.11663

Cosmic ray acceleration at the termination shock of compact star clusters has recently received much attention, mainly because of the detection of gamma ray emission from e.g. Westerlund 1 (Abramowski et al. 2012), Westerlund 2 (Yang et al. 2018), Cygnus cocoon (Ackermann & et al. 2011; Aharonian et al. 2019, Cao et al 2021).



Diffusion from the downstream region is slow, limiting the particles' max energy

Spallation is increasingly important for heavier species, making advection only relevant for He.

Particle acceleration is very fast compared to the age of the cluster

- Focus: the acceleration of nuclei at the termination shock of compact star clusters.

Star clusters as cosmic-ray factories ?

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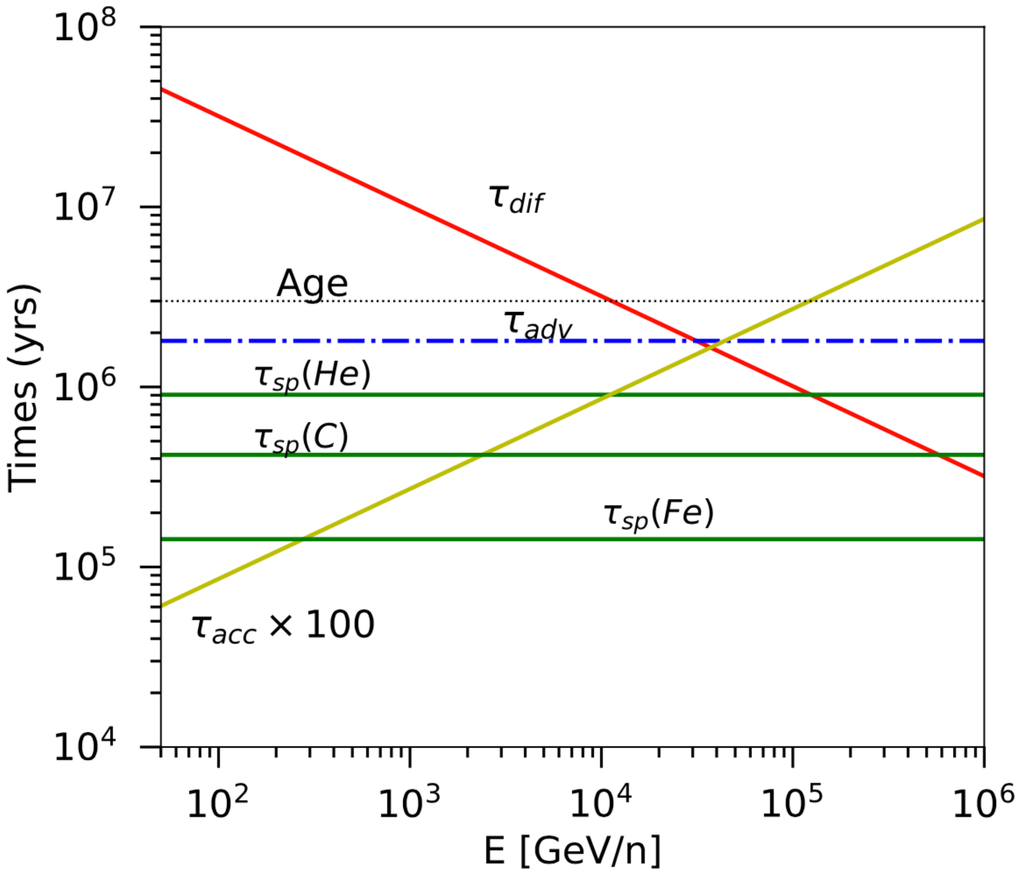
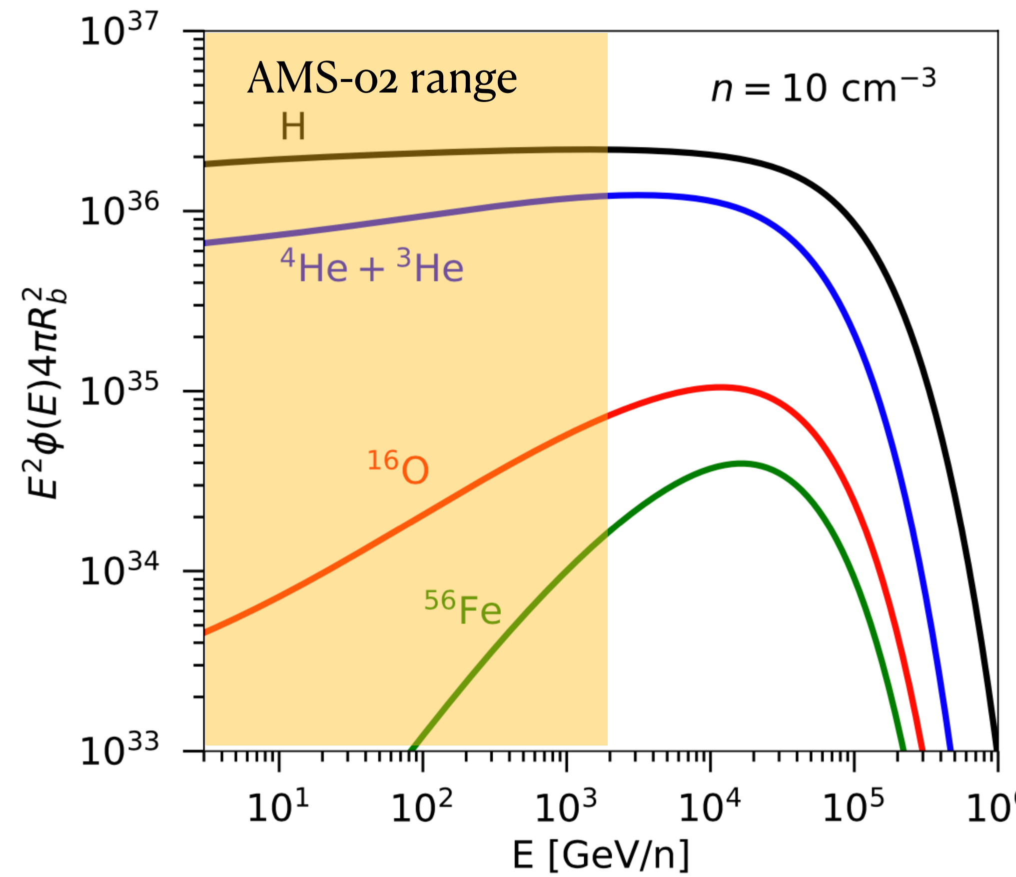


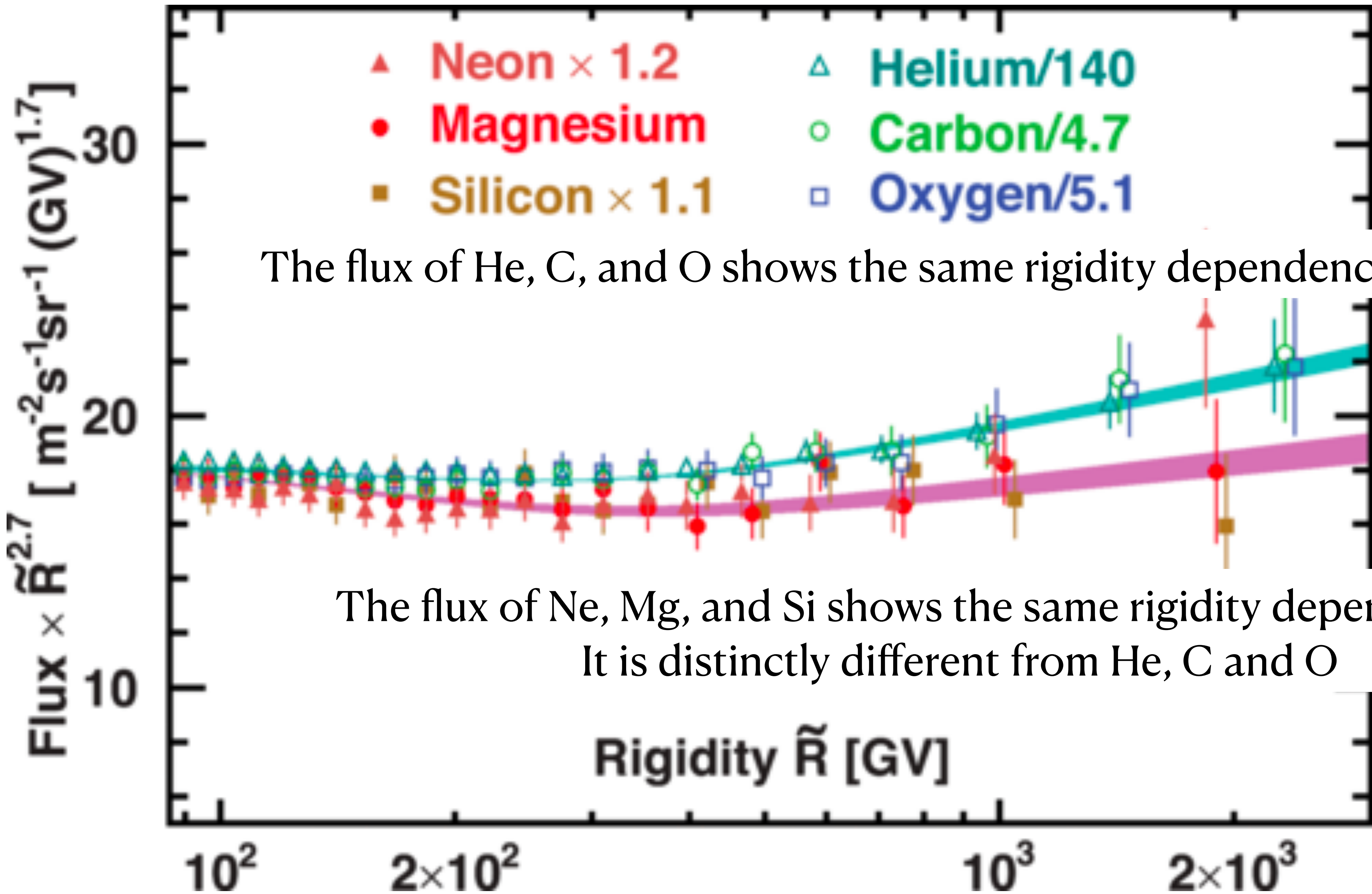


- Focus: the acceleration of nuclei at the termination shock of compact star clusters.
- Main findings: the discrepant harding observed in the p/He flux ratio can be reproduced for a rather generic choice of the mean gas density in the cavity excavated by the cluster wind. These sources do not play a major role in accelerating heavier nuclei.

Rigidity dependence of primary CR fluxes

See Meeran Zuberi's talk

M. Aguilar *et al.* Phys. Rev. Lett. **124**, 211102 2020



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

The flux of He, C, and O shows the same rigidity dependence

The flux of Ne, Mg, and Si shows the same rigidity dependence, but
It is distinctly different from He, C and O

Secondary CR species

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

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

- Secondary species include Li, Be, B and F.

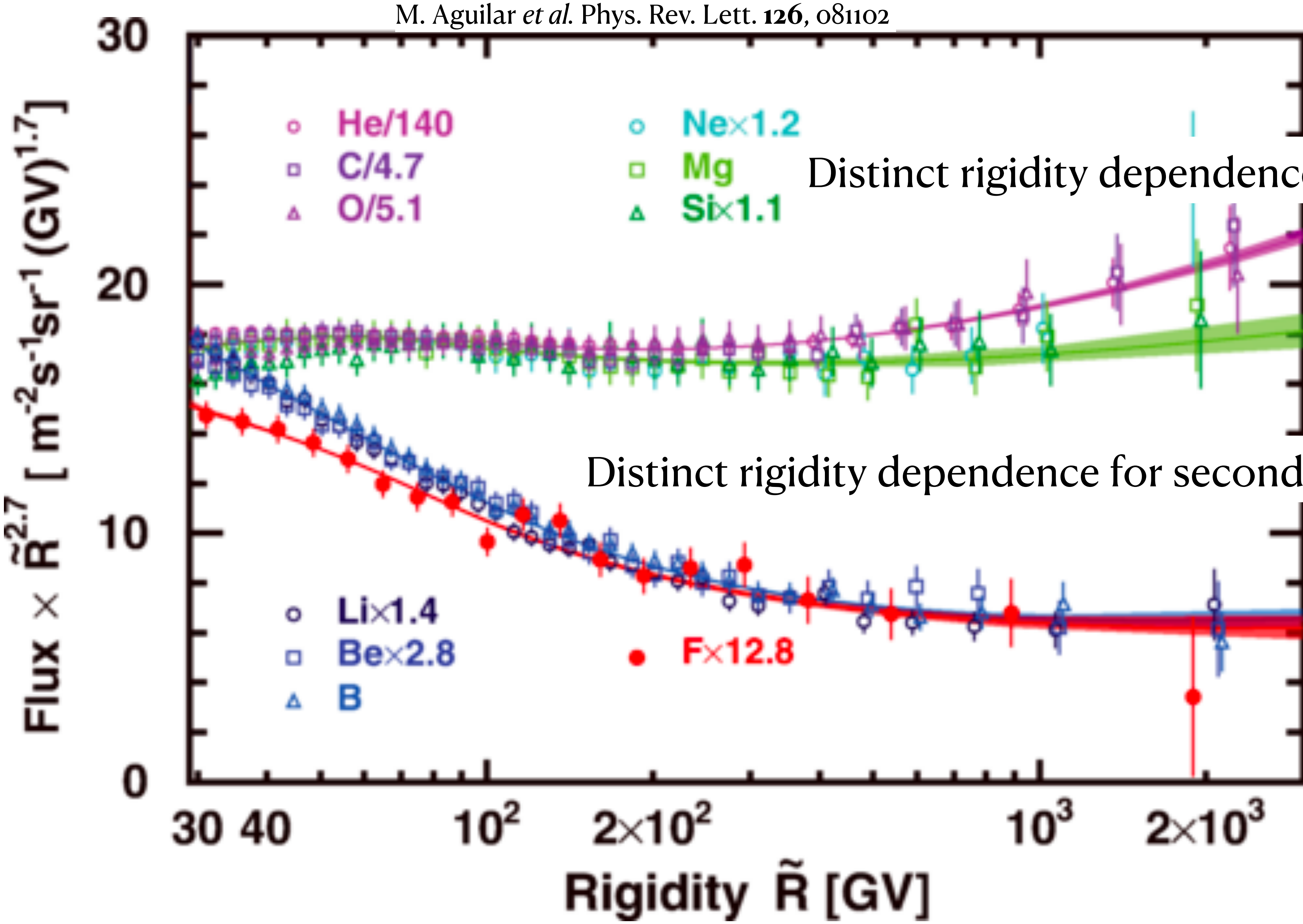
- The secondary-to-primary flux ratios are extremely sensitive to propagation parameters and they are almost insensitive to the injected primary spectrum.

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

Rigidity dependence of primary and secondary CR fluxes

See Nikita Belayev's talk

M. Aguilar *et al.* Phys. Rev. Lett. **126**, 081102



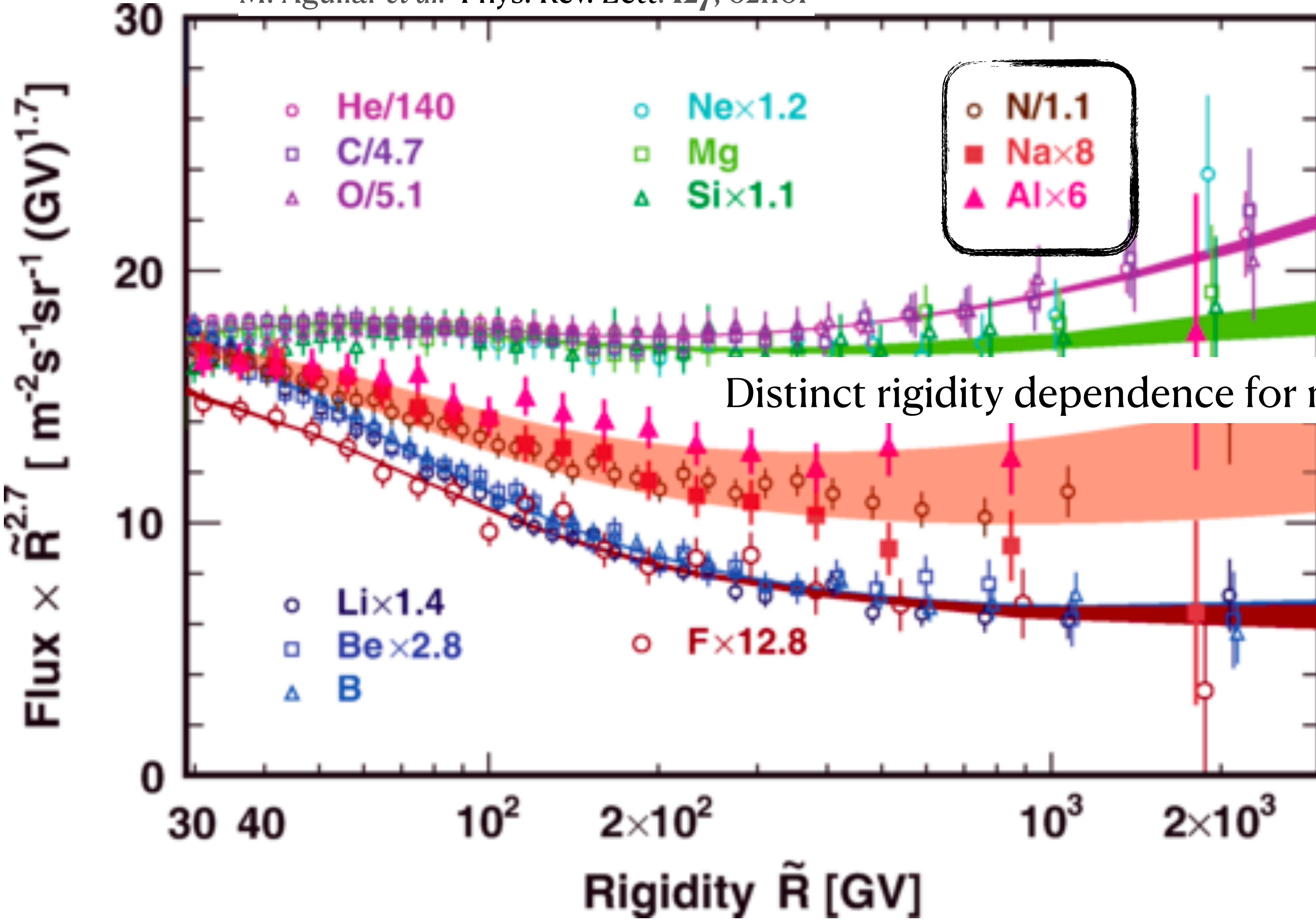
Distinct rigidity dependence for primary species

Distinct rigidity dependence for secondary species

$$\Phi_S \propto \frac{\Phi_P}{\tau_{esc}(E)} \propto R^{-\alpha-2\delta}$$

Rigidity dependence of CR fluxes

M. Aguilar *et al.* Phys. Rev. Lett. **127**, 021101



Distinct rigidity dependence for mixed species

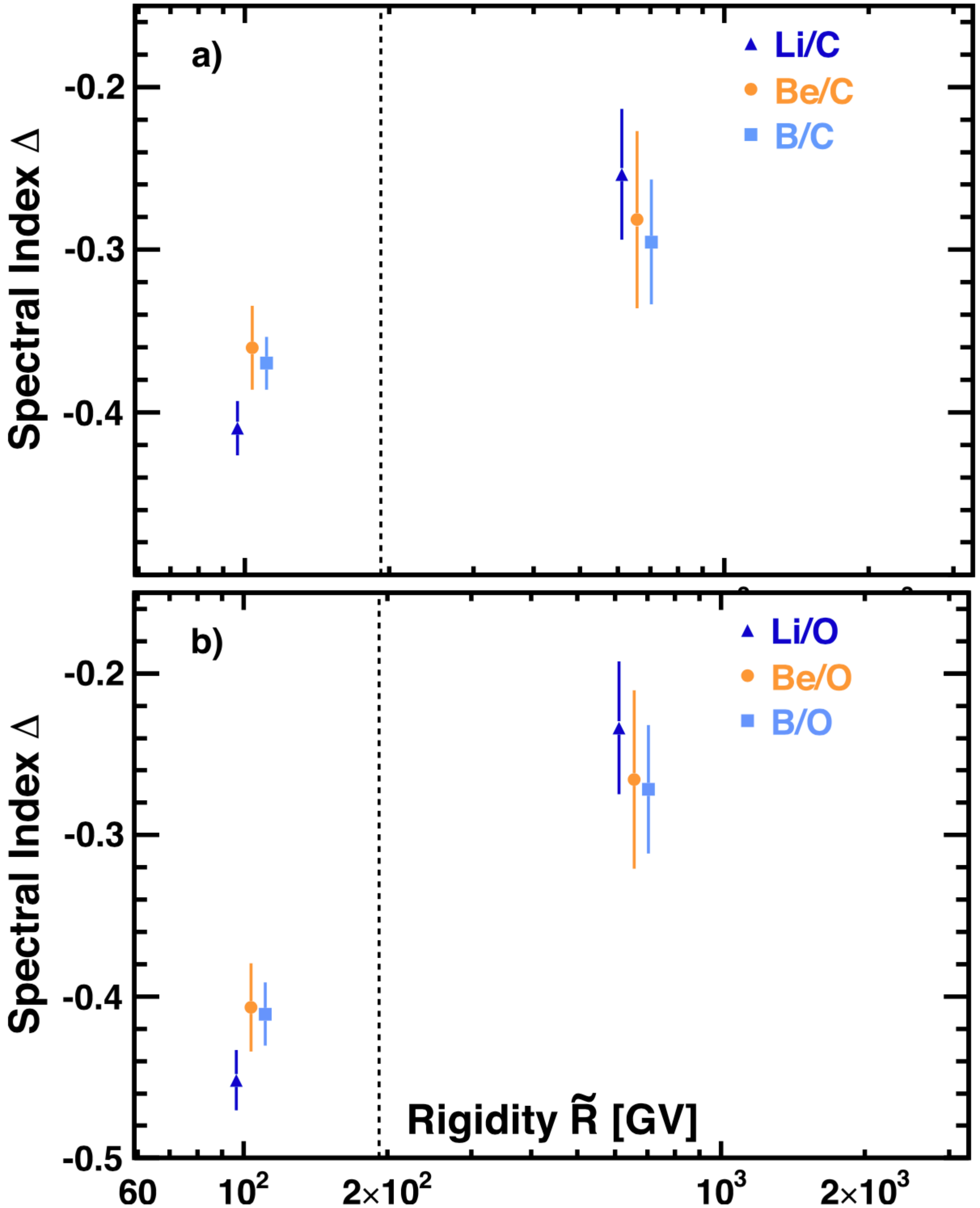
Secondary-to-primary flux ratios

$$\frac{\Phi_B}{\Phi_C} \propto R^{\Delta}$$

- AMS provides evidence for a break in the B/C (and similar flux ratios).
- The first evidence of a diffusive origin of this spectral feature was provided by Génolini et al PRL 2019

See Nikita Belayev's talk

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



A new look at the galactic CR "paradigm"

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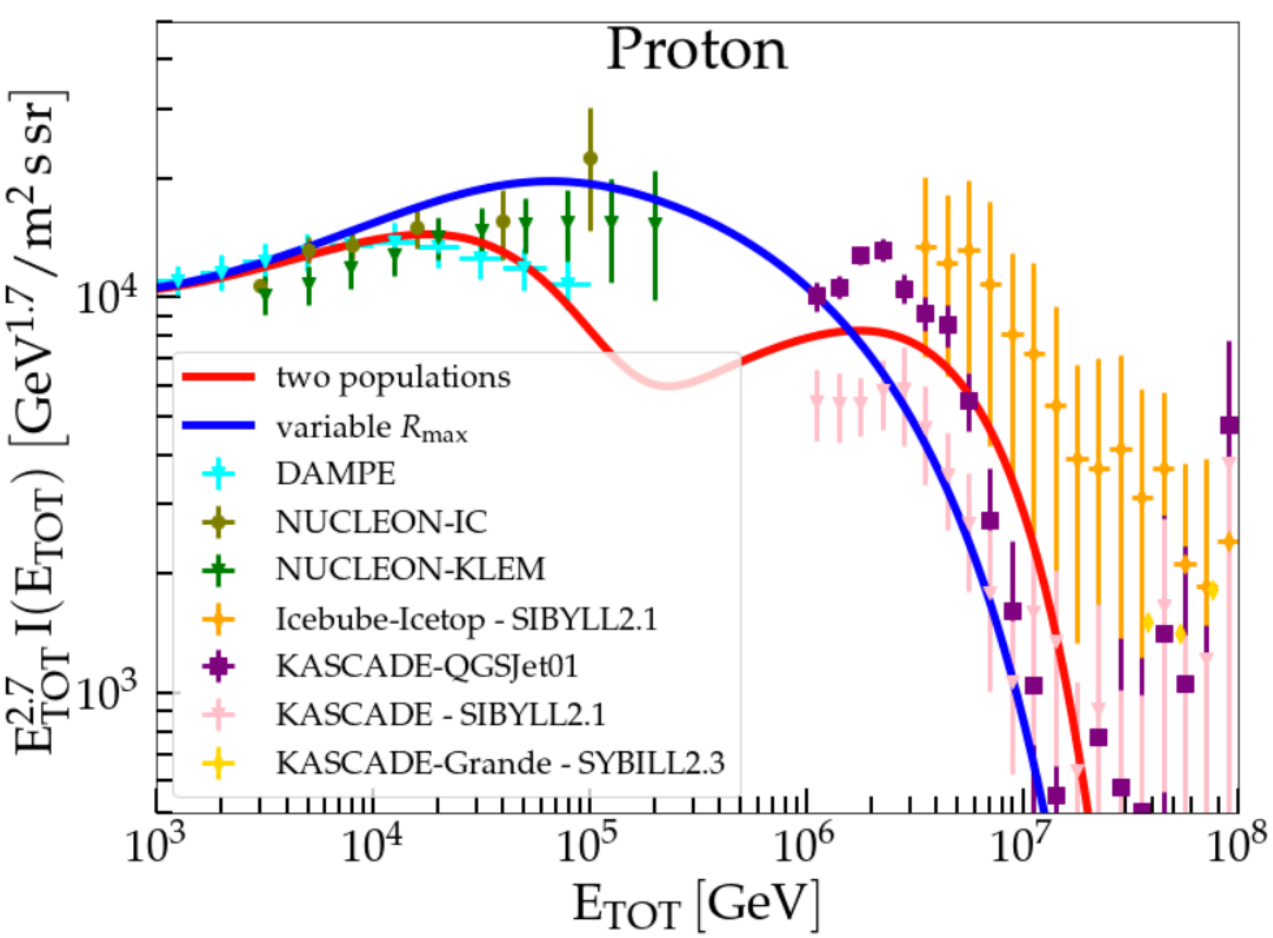
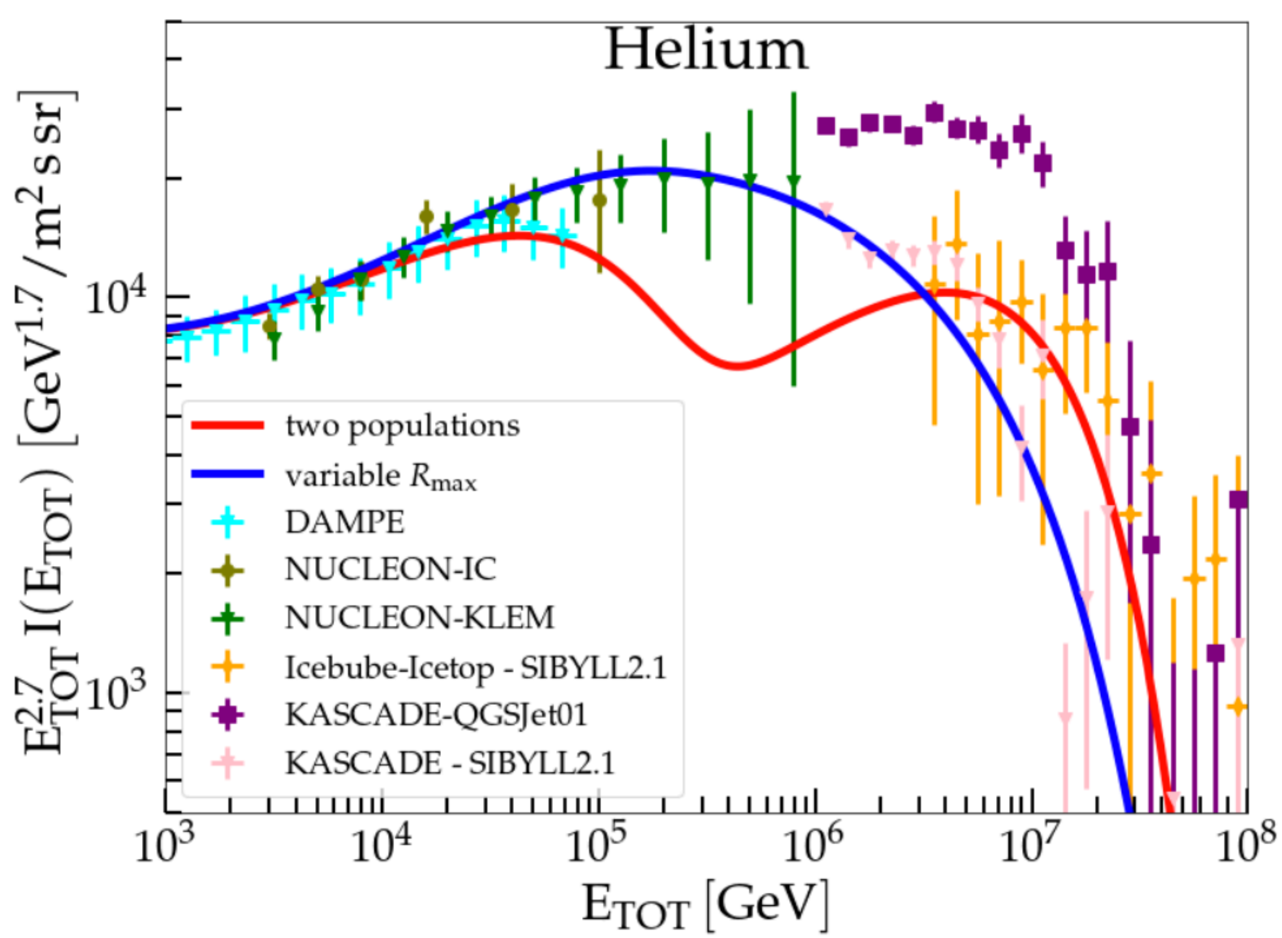
See Sarah Recchia's talk based on arxiv: 2312.11397

Pillars:

- The spectral features at multi TV may reflect the maximum CR rigidity reached in the bulk of SNRs, while only a few sources are PeVatrons.
- The GD plays an important role in the propagation of cosmic rays, where particles experience weak scattering along magnetic field lines, parallel to the Galactic Plane (GP) > at TV energies the CR spectrum is shaped by energy-independent propagation in the GP rather than in the halo.

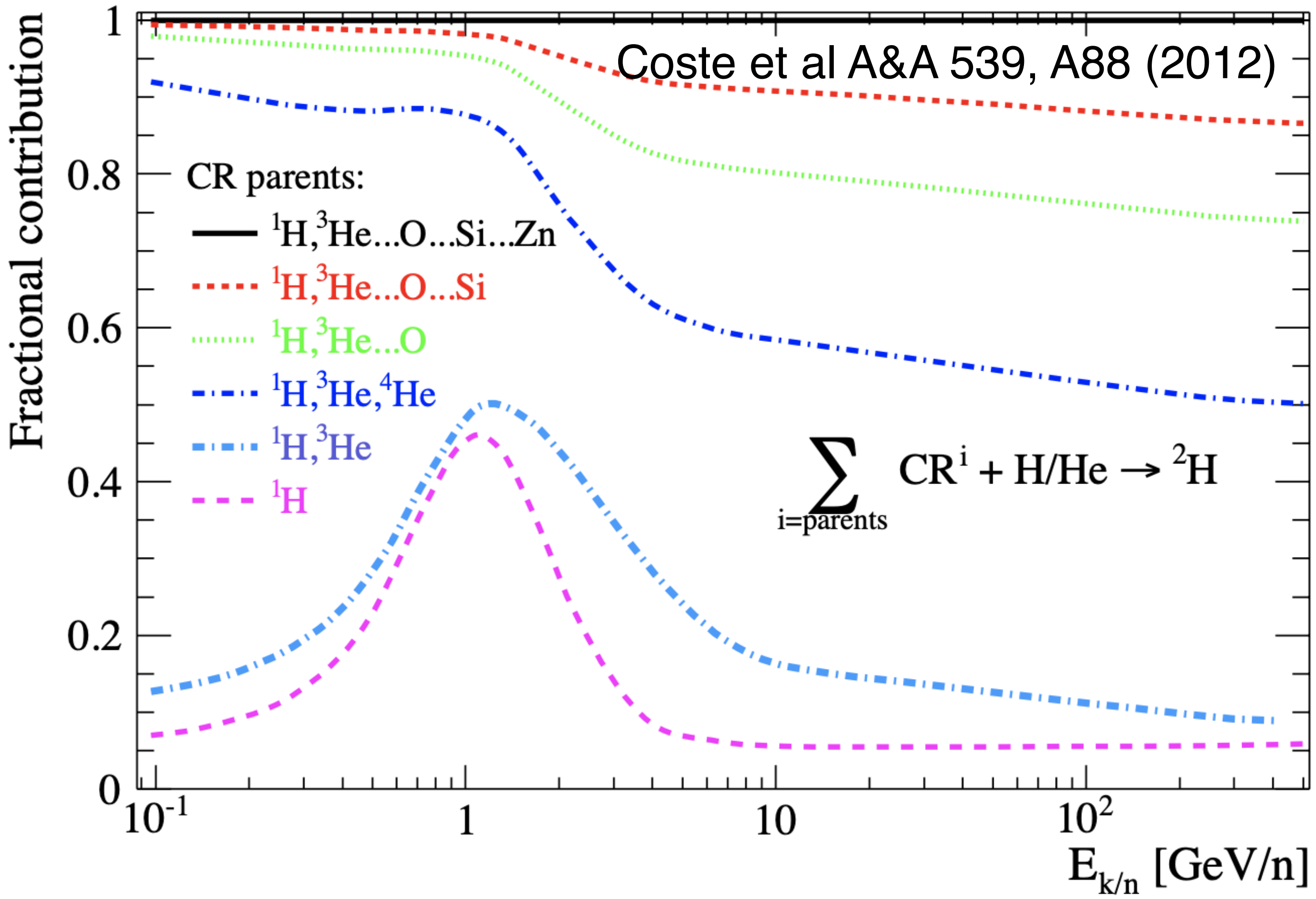




Deuterons in cosmic rays

See Diego Gomez Coral's talk based on Aguilar *et al* PRL 2024

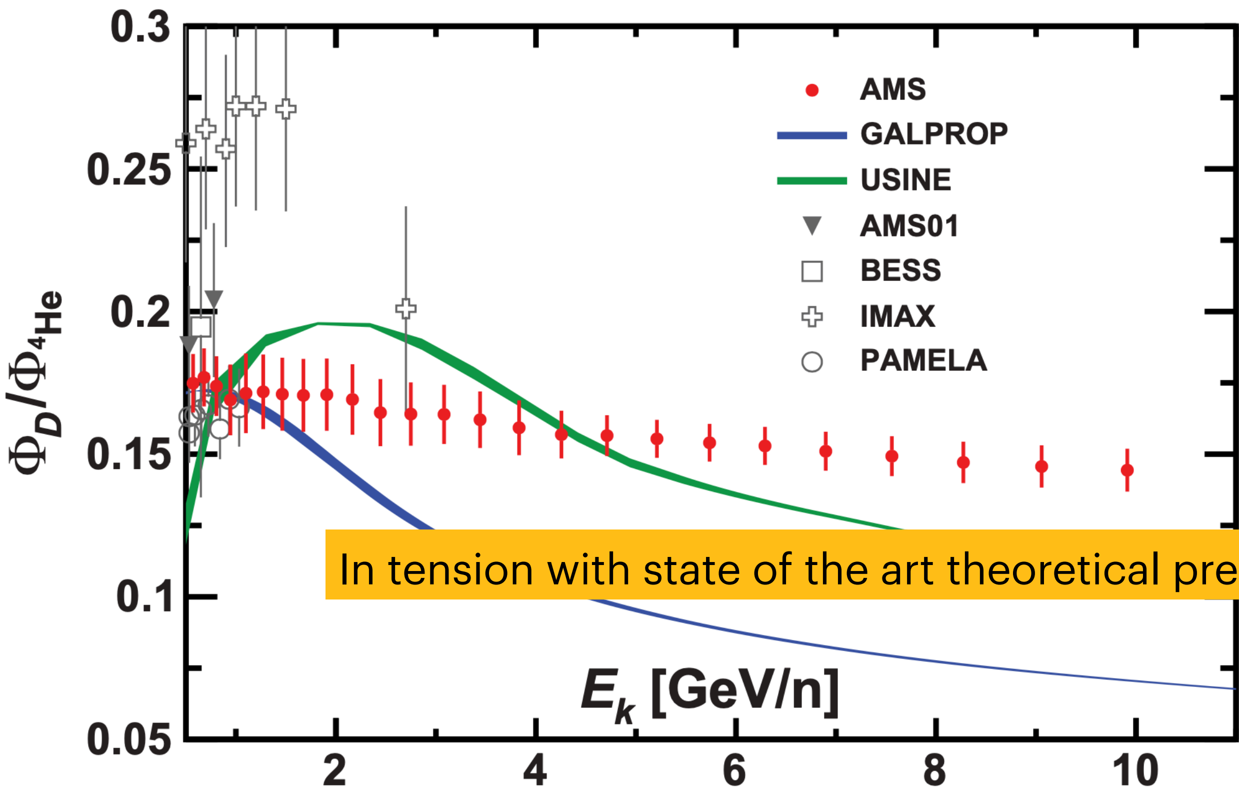
- Deuterons constitute the most abundant secondary species in galactic cosmic rays.
- The main contribution to their production comes from cosmic-ray H, ^{3}He, and ^{4}He interacting with the Interstellar Medium.



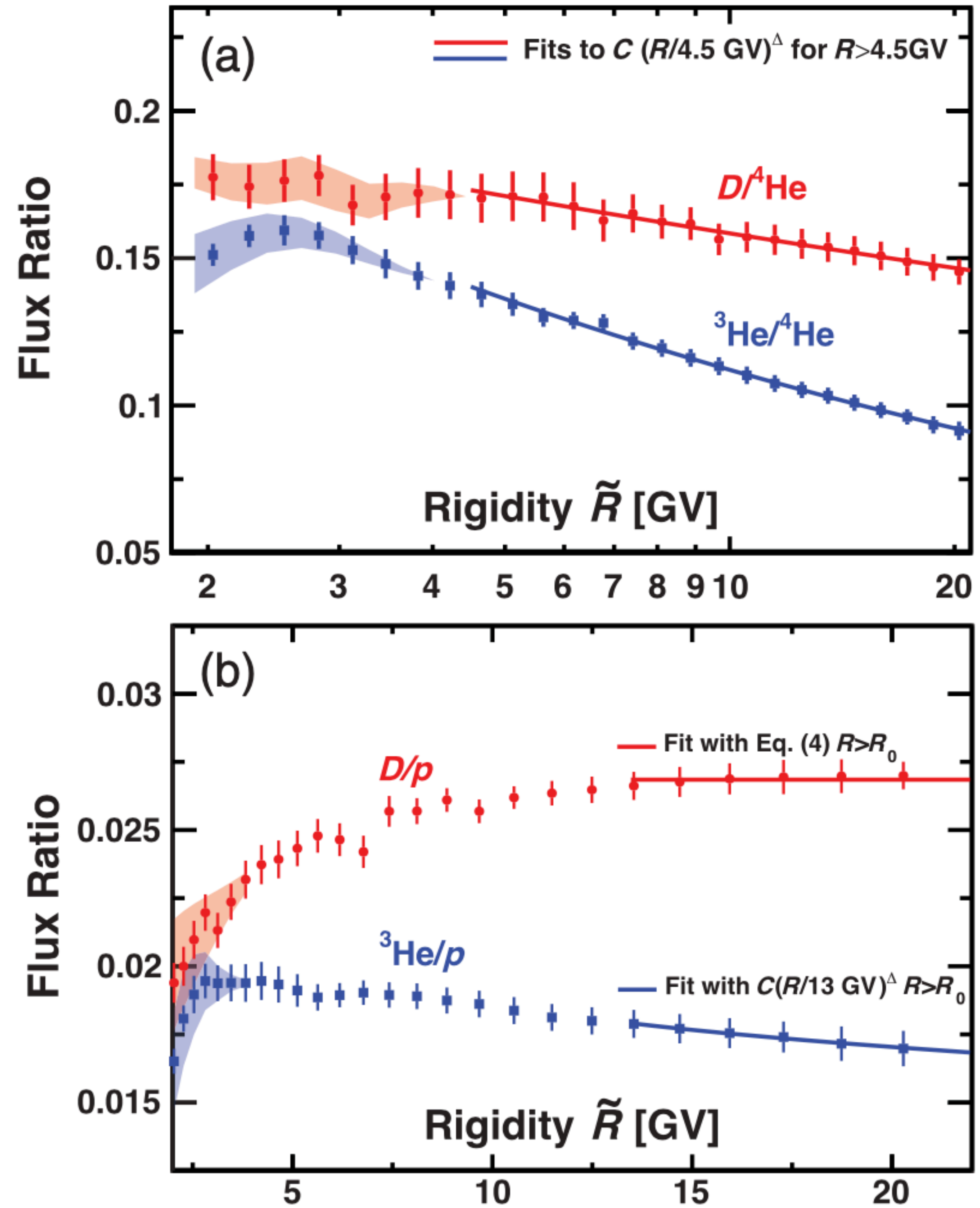
The cosmic-ray deuteron flux

See Diego Gomez Coral's talk based on Aguilar *et al* PRL 2024

- Measurement from 1.9 to 21 GV, based on 21 million deuterons.
- D/^{4}He flux ratio can be described as a single power law whose spectral index is different wrt ^{3}He/^{4}He.
- D/p flux ratio is constant wrt rigidity.



In tension with state of the art theoretical predictions..

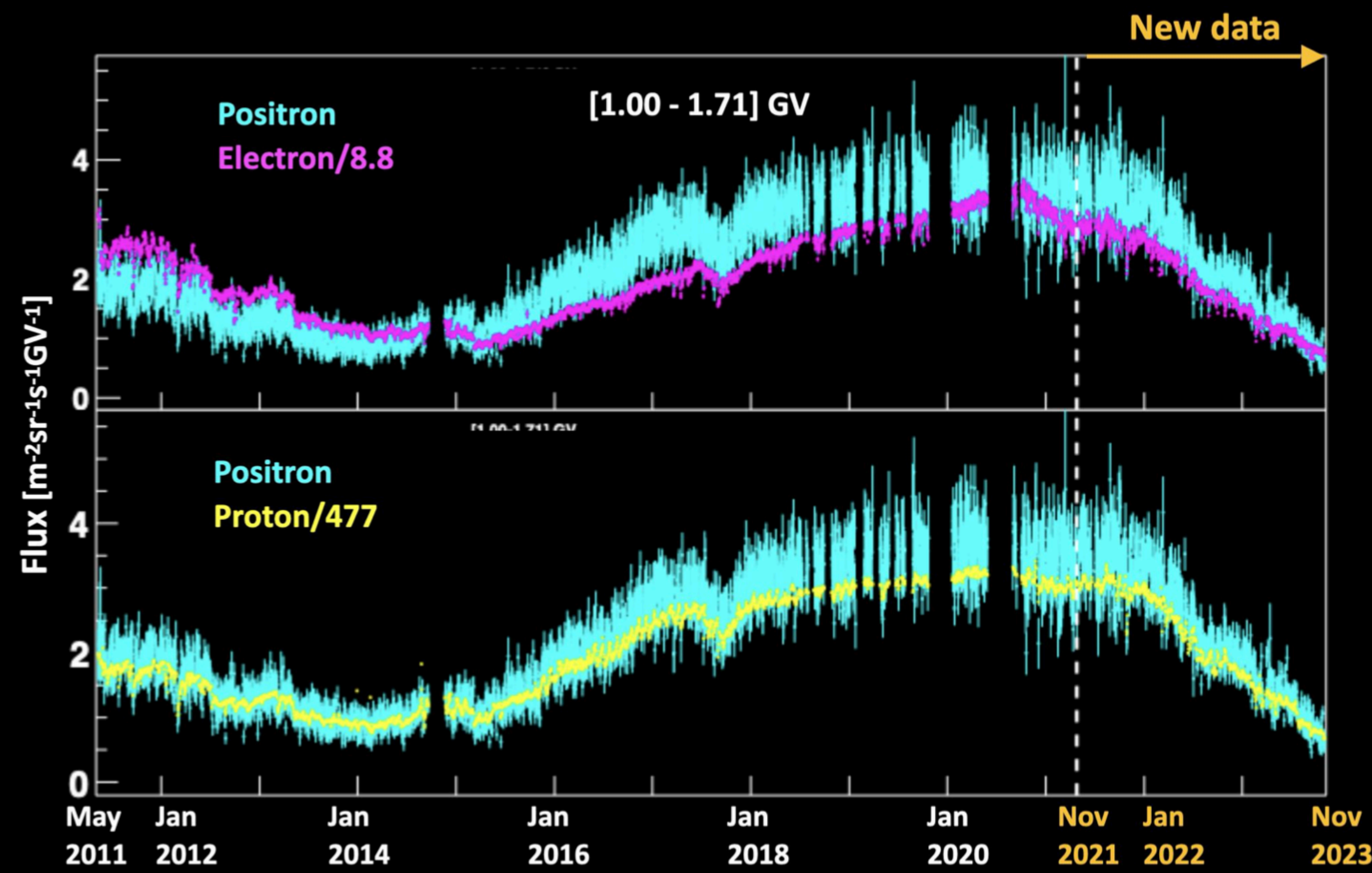


Time dependent fluxes

Daily Positron Flux

See Francesco Faldi’s talk based on PRL 2023

- The positron flux matches the long-term trend of proton flux.
- Similar differences with electron flux, as seen in electron VS proton, are observed for R < 8.5 GV.



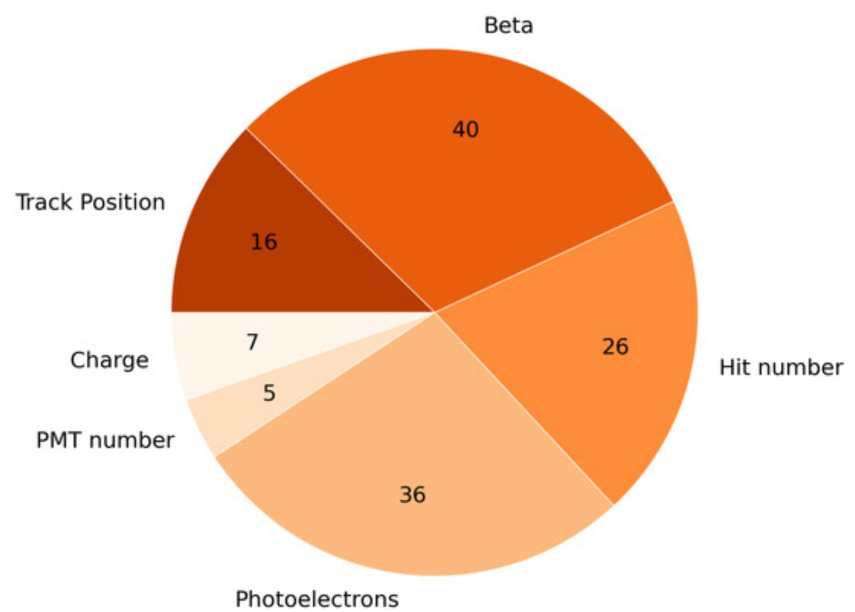
Phys. Rev. Lett. 131, 151002 (2023)

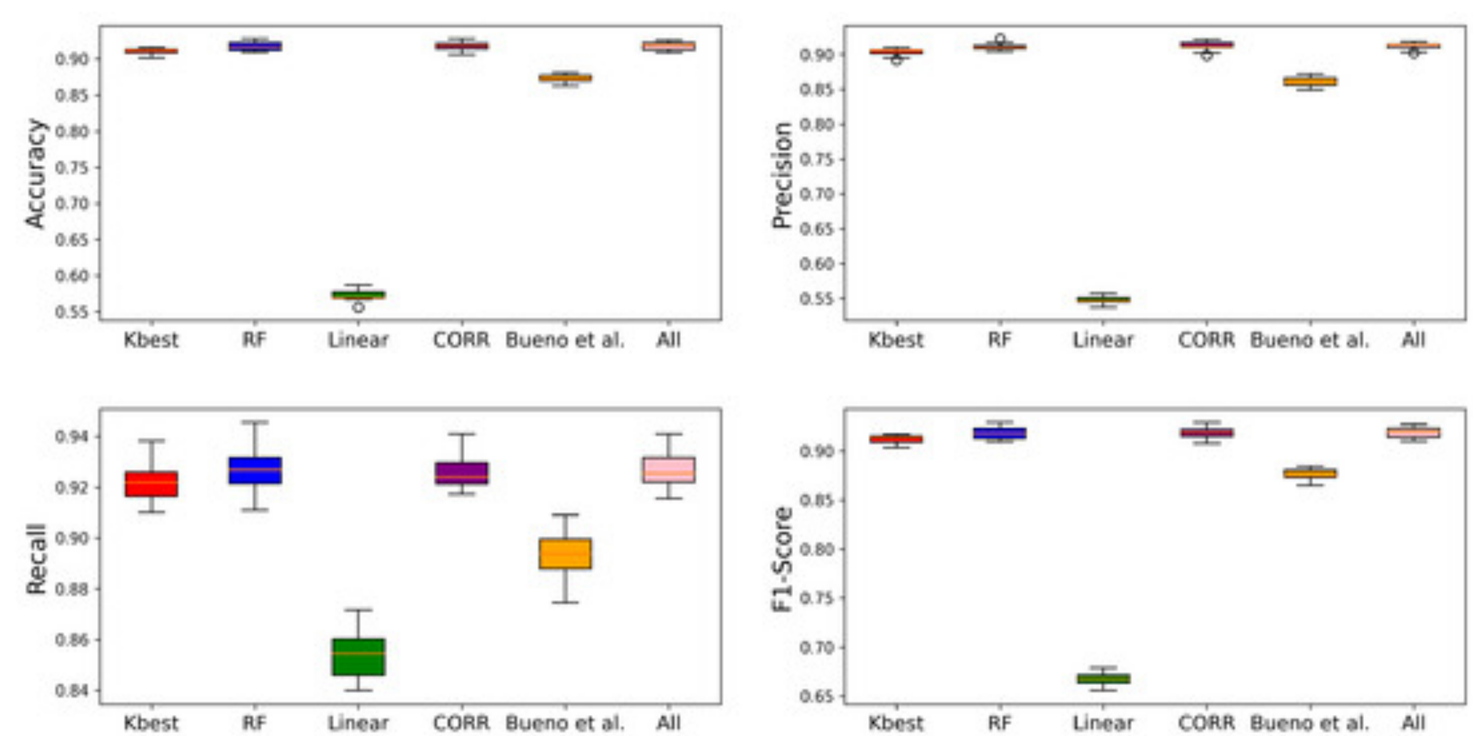
3

Machine learning for CR identification

See Marta Borchiellini's talk, based on Borchiellini et al Particles 2024

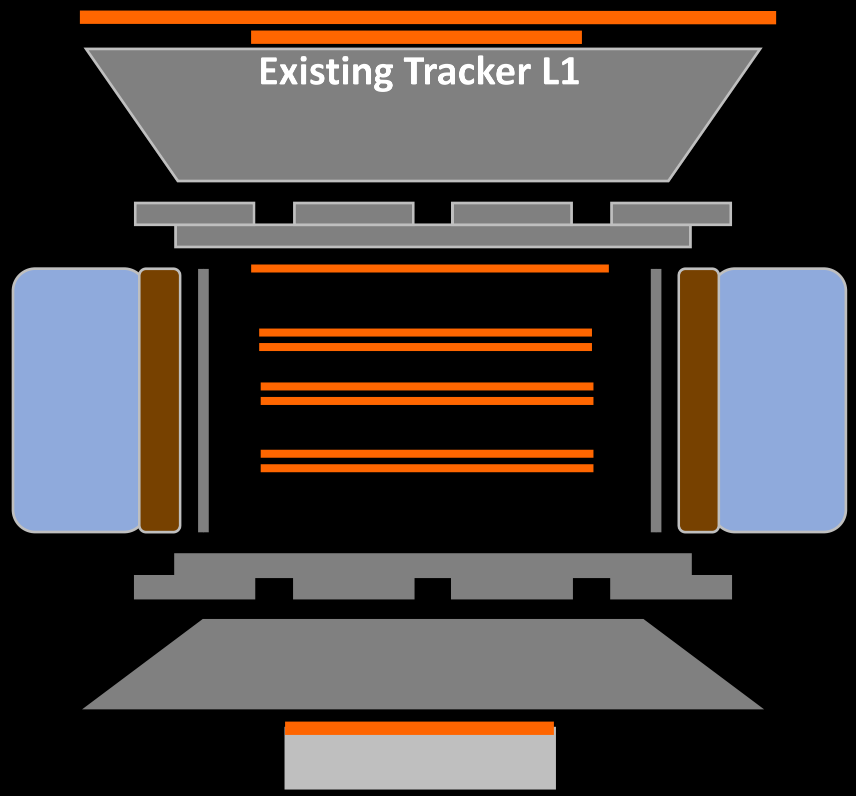
- AI algorithms are widely used to perform particle identification with space-based cosmic-ray experiments.
- Most of the ML algorithms in the literature use Boosted Decision Tree-like algorithm whose inputs are variables, aka features, chosen with physics-driven methods. In this work ML algorithm for feature selection are used.
- Focus: identify positive singly charged cosmic ray isotopes with the AMS-02 RICH detector.
- Findings: Random Forest method stands out as the best-performing algorithm.





The future: the AMS-02 upgrade

See Yaozu Jiang' talk



The White House announced the lifetime of the Space Station will be extended through 2030. To benefit from this extension, AMS is building an Upgrade consisting of a new Silicon Tracker layer to increase the acceptance by 300%.

The results from AMS are unexpected.
AMS will continue to collect data over the life of the Station.
This will change our understanding of the universe.

The most important goal of AMS is to explore the unknown, to search for phenomena in nature that we have never imagined nor had the tools to discover.

Thank you !