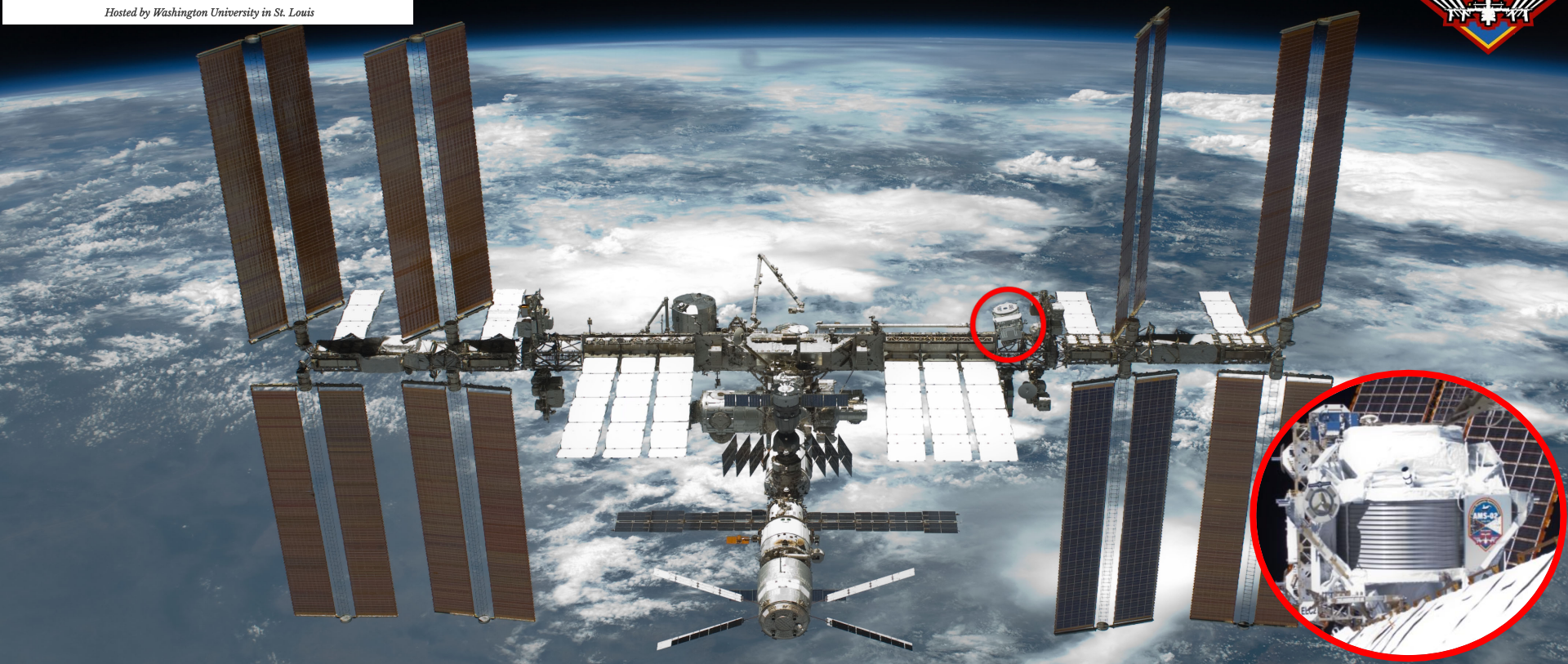


XV International Conference on
Interconnections between
Particle Physics and Cosmology

June 6-10, 2022

Hosted by Washington University in St. Louis

AMS Physics Results



Matteo Duranti

INFN Sez. Perugia

on behalf of the AMS Collaboration



Outline

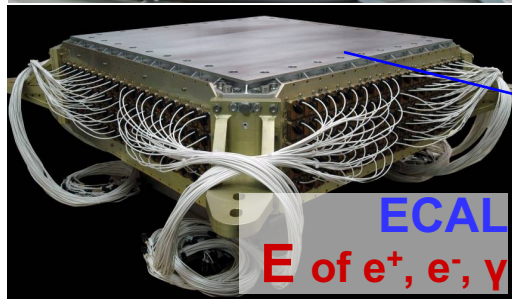
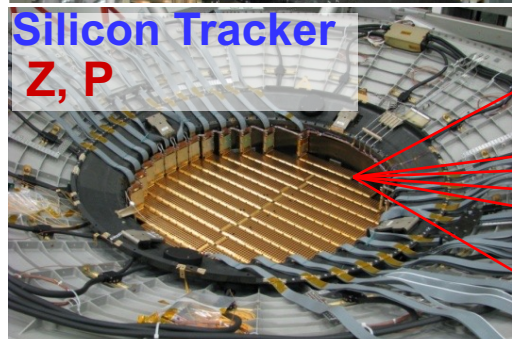
- the instrument
- physics results
- the future...



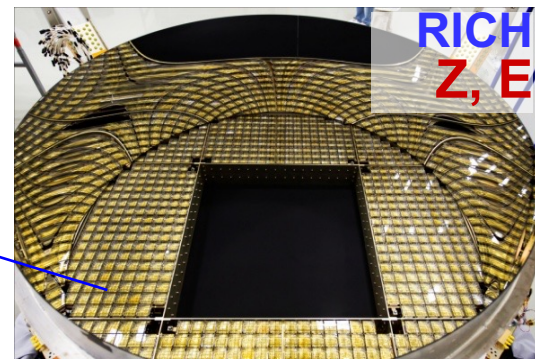
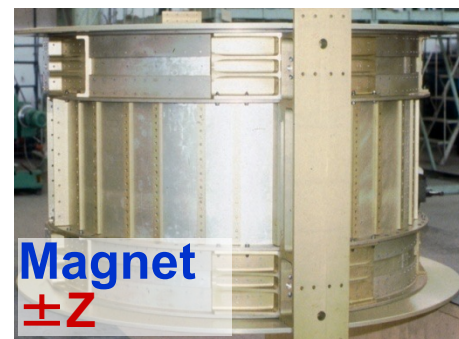
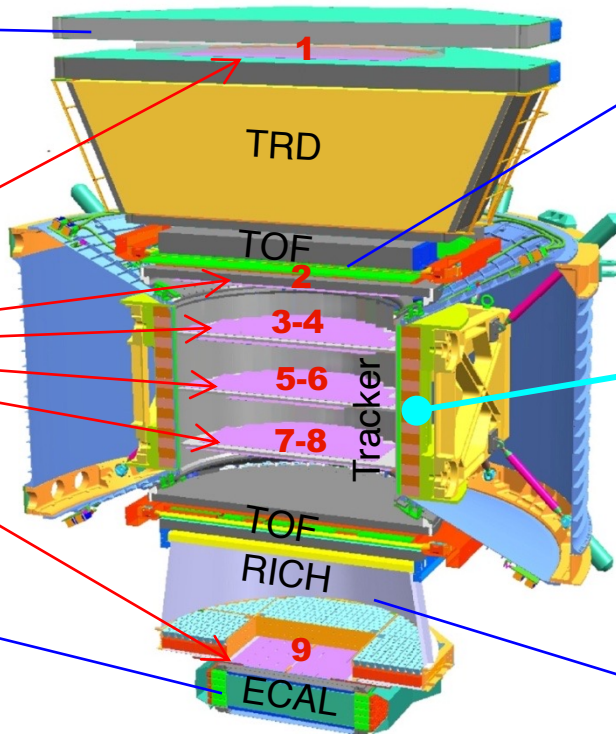
The instrument



A precision, multipurpose, TeV spectrometer



Z, P are measured independently by the Tracker, RICH, TOF and ECAL





2010: AMS-02 assembled





201 I: AMS launch - @ JSC, Texas

Houston, JSC – 16 May, 2011
07:56 AM

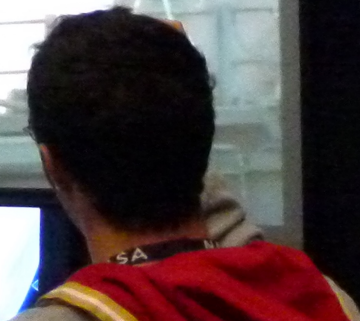
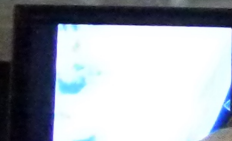
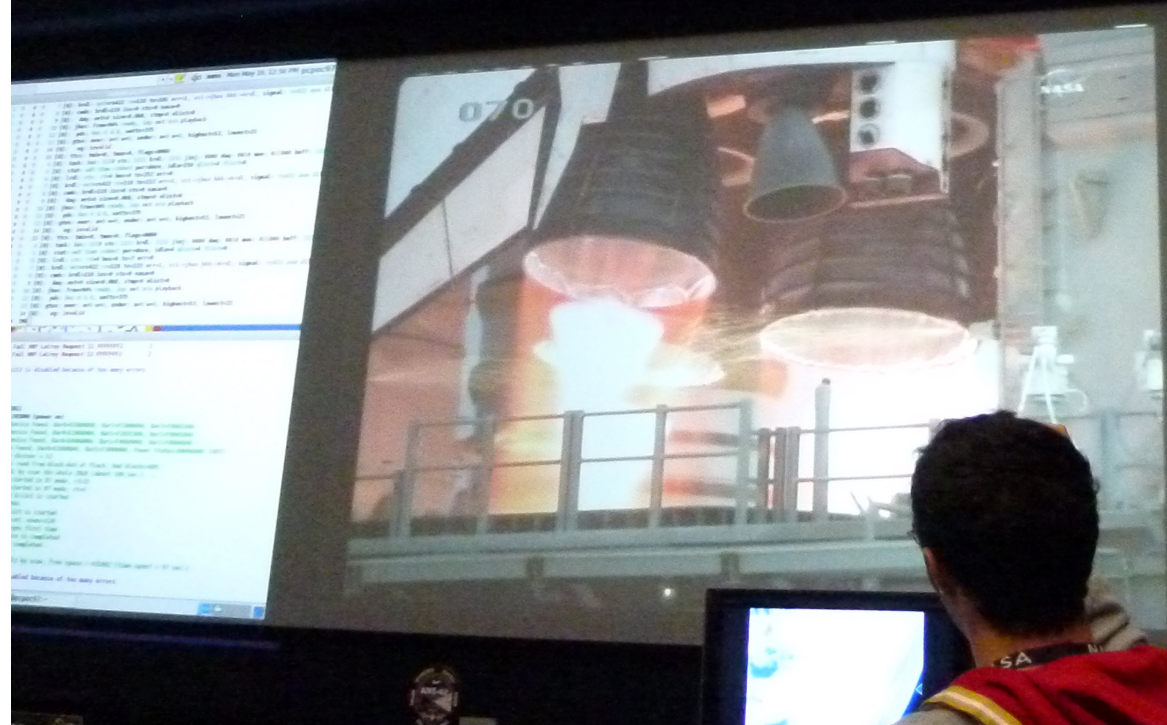


MET

000:00:00:01+

SBND MILA->PDL
SBND PDL->MILA
SBND MILA->TORS

00:00:59-
00:02:29-
00:07:29-





2011: AMS launch - @ KSC, Florida

- Total weight:
2008 t
- AMS weight:
7.5 t

Cape Canaveral, KSC -
16 May, 2011, 08:56 AM





AMS mission



May 16th 2011



May 19th 2011

AMS has collected

203,924,102,396

cosmic ray events

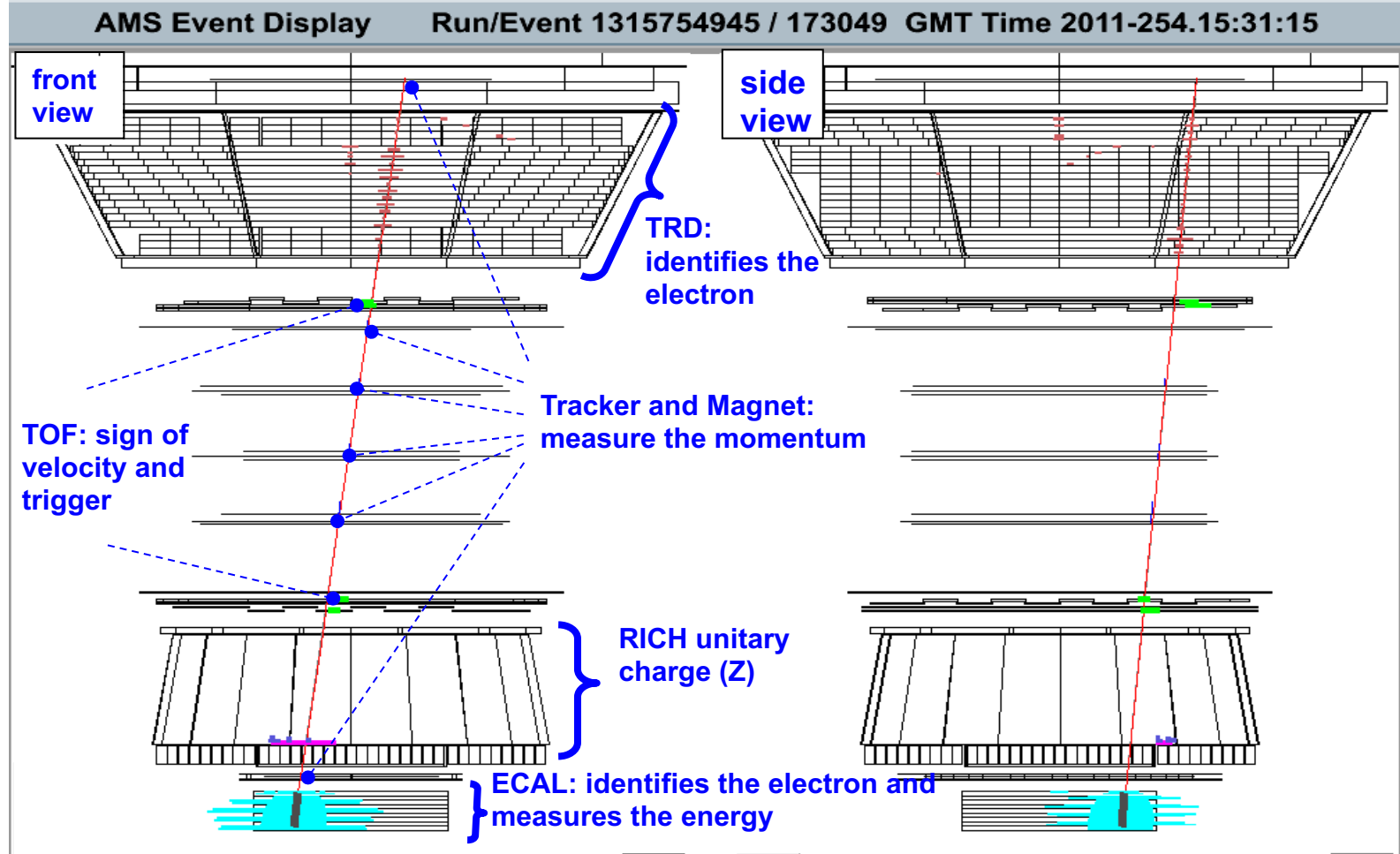
Last update: June 2, 2022, 6:12 PM

AMS-02 time on ISS since May 19th, 5:46 a.m. EDT:

4032 DAYS 8 HOURS 59 MINUTES 38 SECONDS

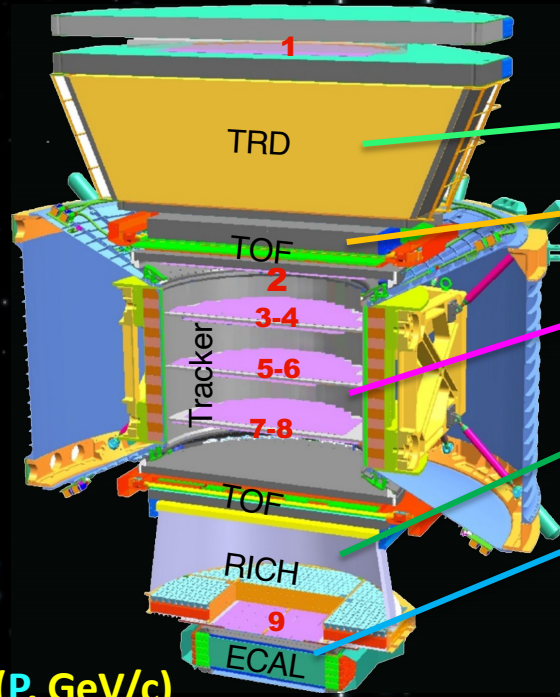


ISS Data – 1.03 TeV Electron





Particle identification



| | e^- | P | Fe | e^+ | \bar{P} | \bar{He} |
|------------------|-------|---|----|-------|-----------|------------|
| TRD | | | | | | |
| TOF | | | | | | |
| Tracker + Magnet | | | | | | |
| RICH | | | | | | |
| ECAL | | | | | | |

AMS measures :

- Momentum (P , GeV/c)
- Charge (Z)
- Rigidity ($R=P/Z$, GV)
- Energy (E , GeV/A)
- Flux (signals/(s sr m² GeV))

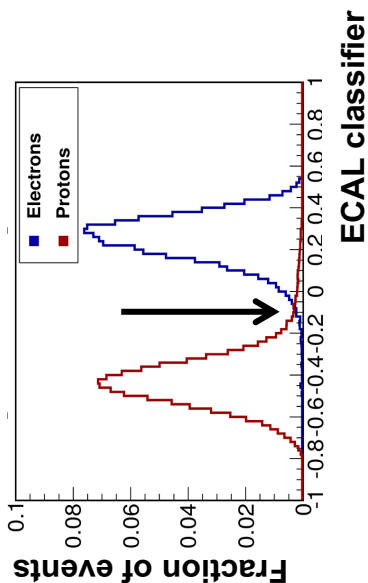
| | | | | | | | | | | | | | | | | | | |
|-----------------------------------|---------------------------------|--------------------------------|-------------------------------------|---------------------------------|----------------------------------|----------------------------------|---------------------------------|----------------------------------|------------------------------------|-----------------------------------|-----------------------------------|--------------------------------------|---------------------------------|--|-----------------------------------|--|---------------------------------------|-----------------------------|
| 1 H Hydrogen 1.008 | | | | | | | | | | | | | | | | | 2 He Helium 4.003 | |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.012 | | | | | | | | | | | | | | | | | 10 Ne Neon 20.180 |
| 11 Na Sodium 22.990 | 12 Mg Magnesium 24.305 | | | | | | | | | | | | | | | | | 18 Ar Argon 39.948 |
| 19 K Potassium 39.098 | 20 Ca Calcium 40.078 | 21 Sc Scandium 44.956 | 22 Ti Titanium 47.88 | 23 V Vanadium 50.942 | 24 Cr Chromium 51.996 | 25 Mn Manganese 54.938 | 26 Fe Iron 55.933 | 27 Co Cobalt 58.933 | 28 Ni Nickel 58.693 | 29 Cu Copper 63.546 | 30 Zn Zinc 65.39 | 31 Ga Gallium 69.732 | 32 Ge Germanium 72.61 | 33 As Arsenic 74.922 | 34 Se Selenium 78.09 | 35 Br Bromine 79.904 | 36 Kr Krypton 84.80 | |
| 37 Rb Rubidium 84.458 | 38 Sr Strontium 87.62 | 39 Y Yttrium 88.909 | 40 Zr Zirconium 91.224 | 41 Nb Niobium 92.906 | 42 Mo Molybdenum 95.94 | 43 Tc Technetium 98.907 | 44 Ru Ruthenium 101.07 | 45 Rh Rhodium 102.906 | 46 Pd Palladium 106.42 | 47 Ag Silver 107.868 | 48 Cd Cadmium 112.411 | 49 In Indium 114.818 | 50 Sn Tin 118.71 | 51 Sb Antimony 121.760 | 52 Te Tellurium 127.6 | 53 I Iodine 126.904 | 54 Xe Xenon 131.29 | |
| 55 Cs Cesium 132.905 | 56 Ba Barium 137.327 | 57-71 Lanthanides | 72 Hf Hafnium 178.49 | 73 Ta Tantalum 180.948 | 74 W Tungsten 183.85 | 75 Re Rhenium 186.207 | 76 Os Osmium 190.23 | 77 Ir Iridium 192.22 | 78 Pt Platinum 195.08 | 79 Au Gold 196.967 | 80 Hg Mercury 200.59 | 81 Tl Thallium 204.383 | 82 Pb Lead 207.2 | 83 Bi Bismuth 208.980 | 84 Po Polonium [209] | 85 At Astatine [209.987] | 86 Rn Radon [222.018] | |
| 87 Fr Francium [223.020] | 88 Ra Radium [226.025] | 89-103 Actinides | 104 Rf Rutherfordium [261] | 105 Db Dubnium [262] | 106 Sg Seaborgium [266] | 107 Bh Bohrium [264] | 108 Hs Hassium [265] | 109 Mt Meitnerium [268] | 110 Ds Darmstadtium [269] | 111 Rg Roentgenium [272] | 112 Cn Copernicium [277] | 113 Uut Ununtrium [unknown] | 114 Fl Flerovium [289] | 115 Uup Ununpentium [unknown] | 116 Lv Livermorium [293] | 117 Uus Ununseptium [unknown] | 118 Uuo Ununoctium [unknown] | |



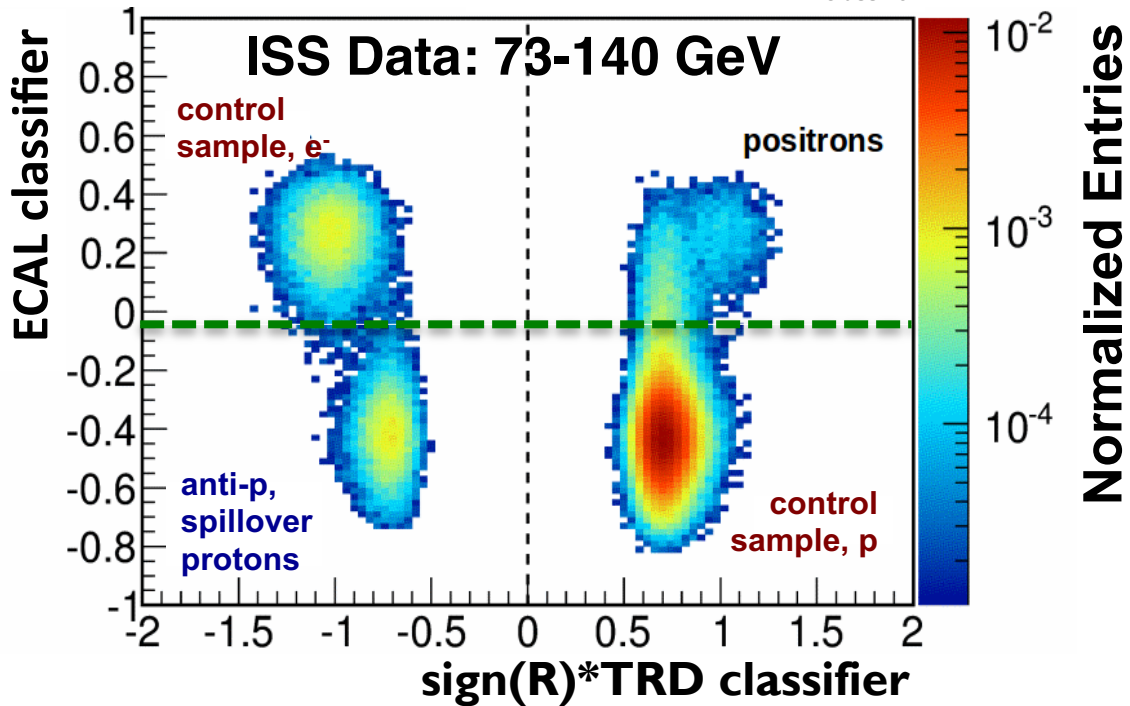
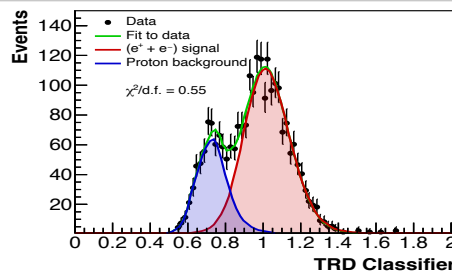
e/p discrimination

One important lesson from the AMS experiment is the importance of the redundancy: use one detector to create control sample for another one.

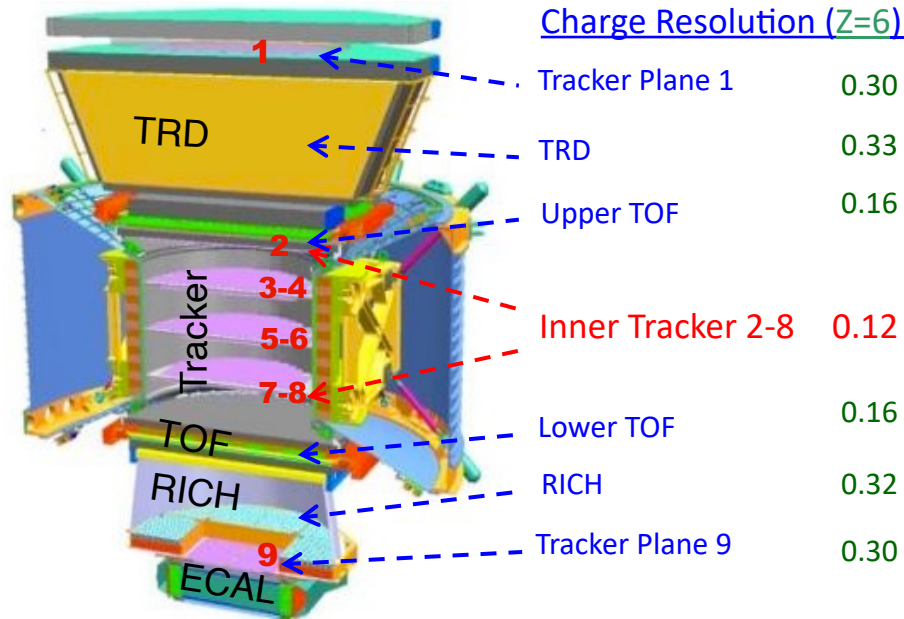
Study of the difference (i.e. Boosted Decision Tree, BDT) between hadrons and EM particles in 19 variables describing 3D shower shape



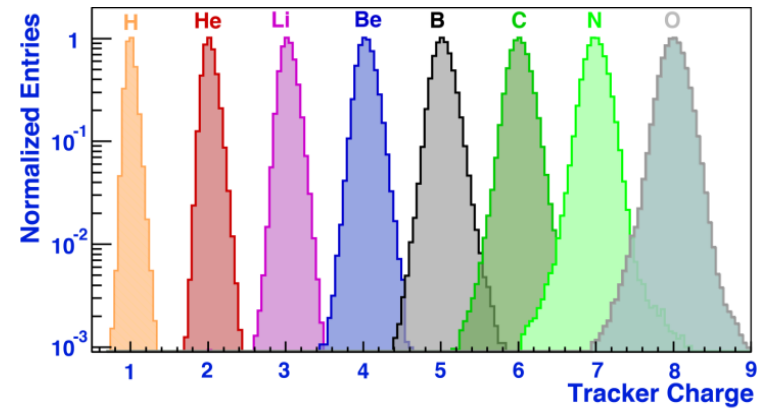
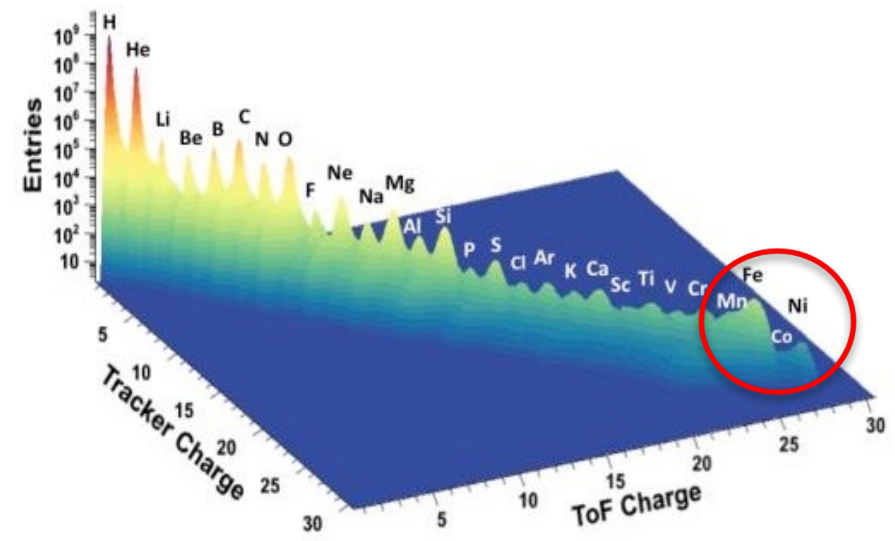
Study of the difference (i.e. likelihood) between dE/dx and TR in 20 layers of fleece radiator + straw tubes



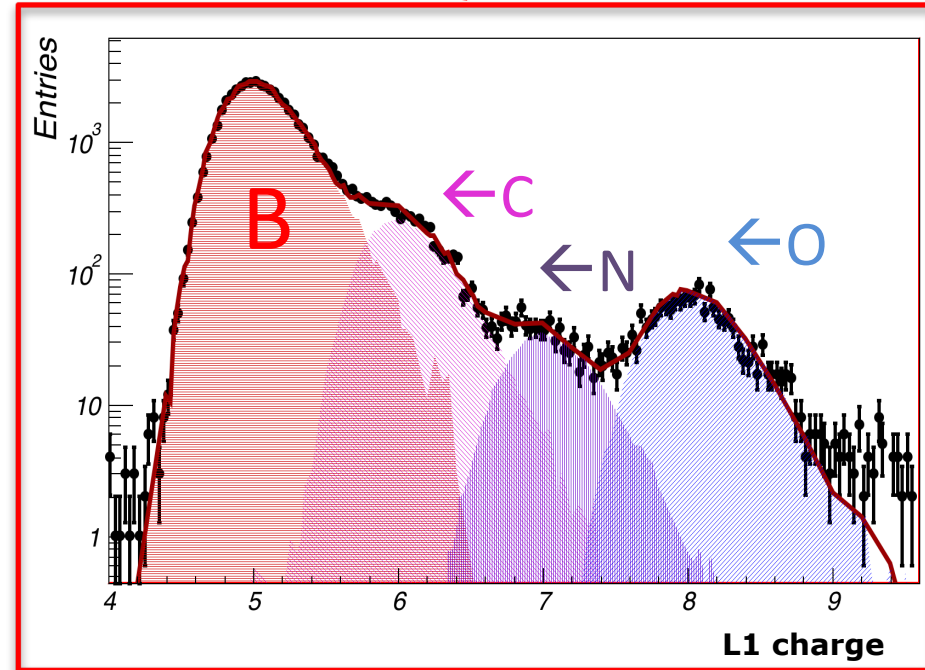
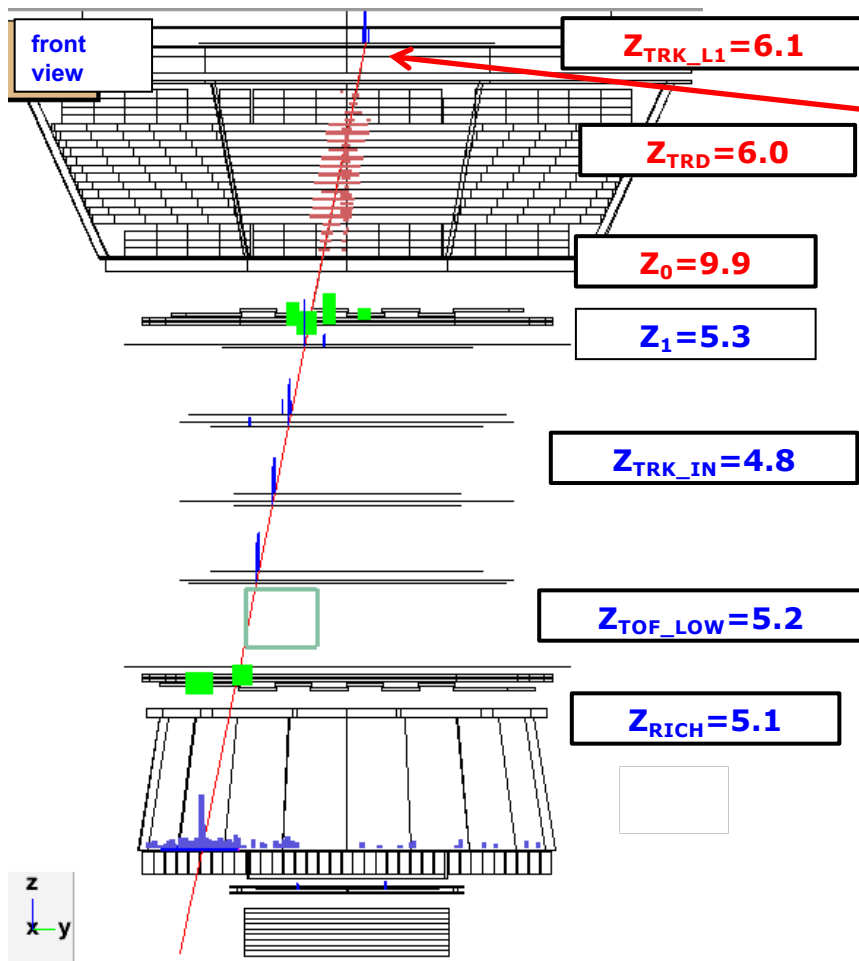
Charge measurement



Charge Resolution ($Z=6$)



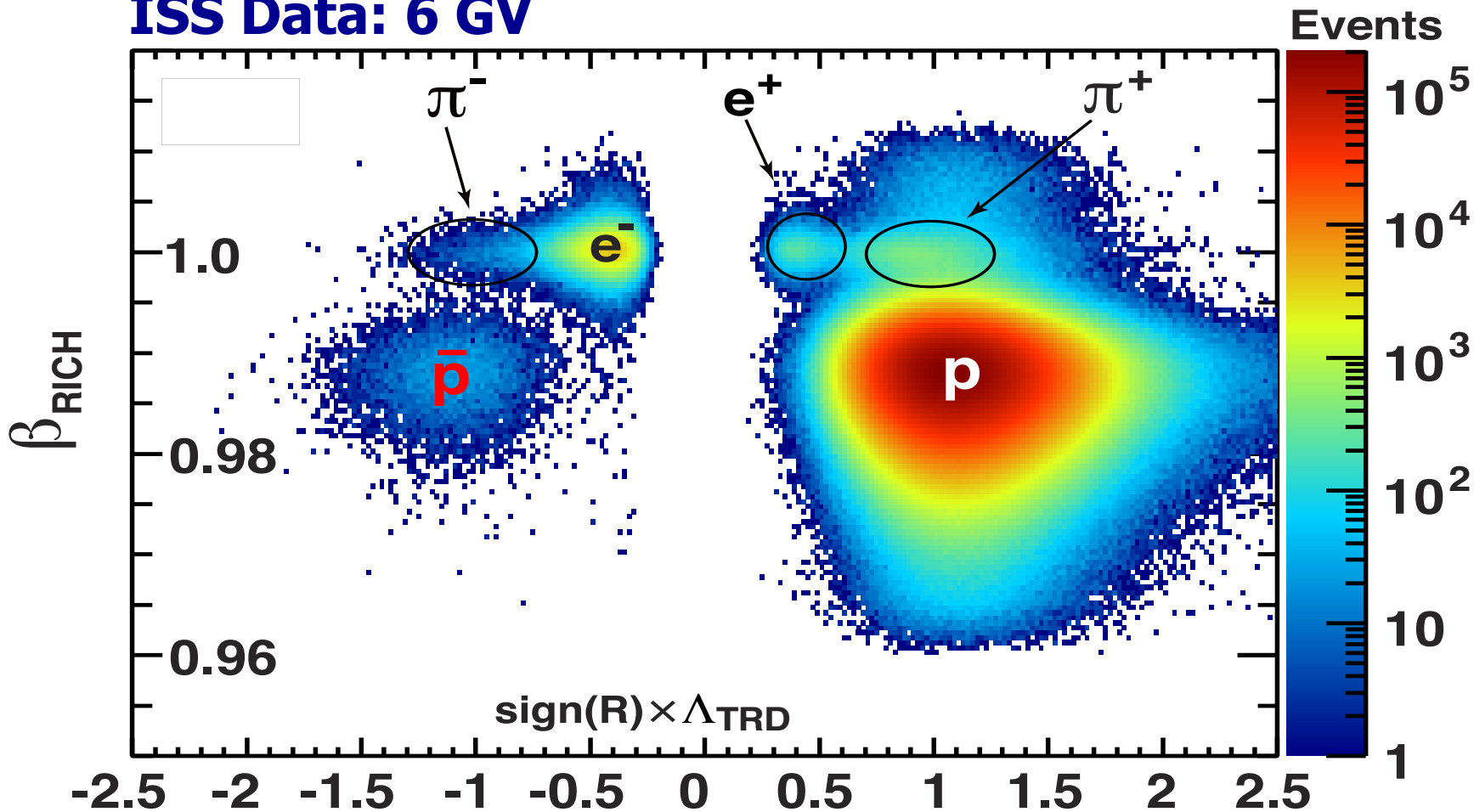
Control of fragmentation inside the detector





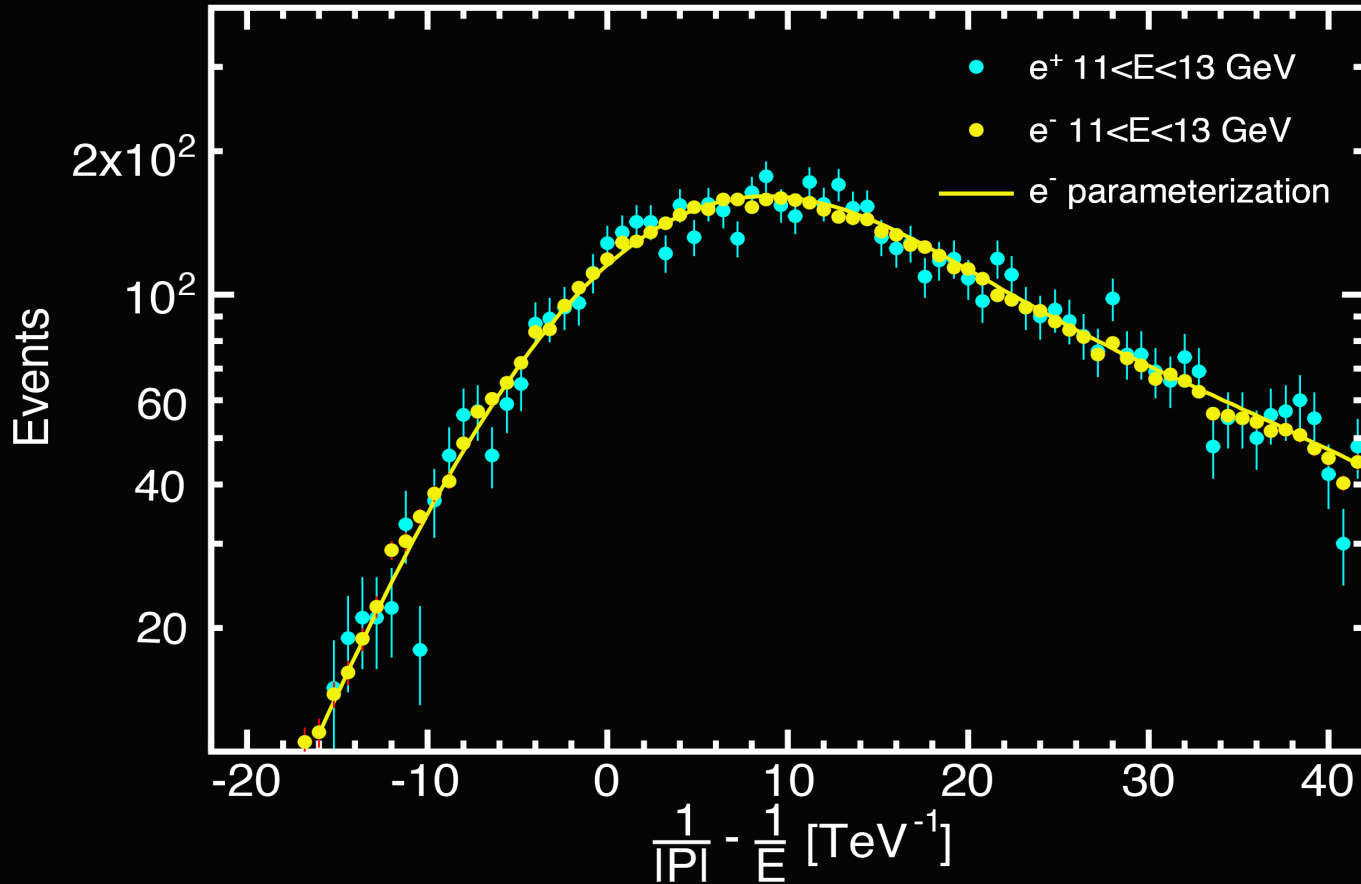
Mass separation (i.e. isotopical measurement)

ISS Data: 6 GV





Momentum Scale Verification



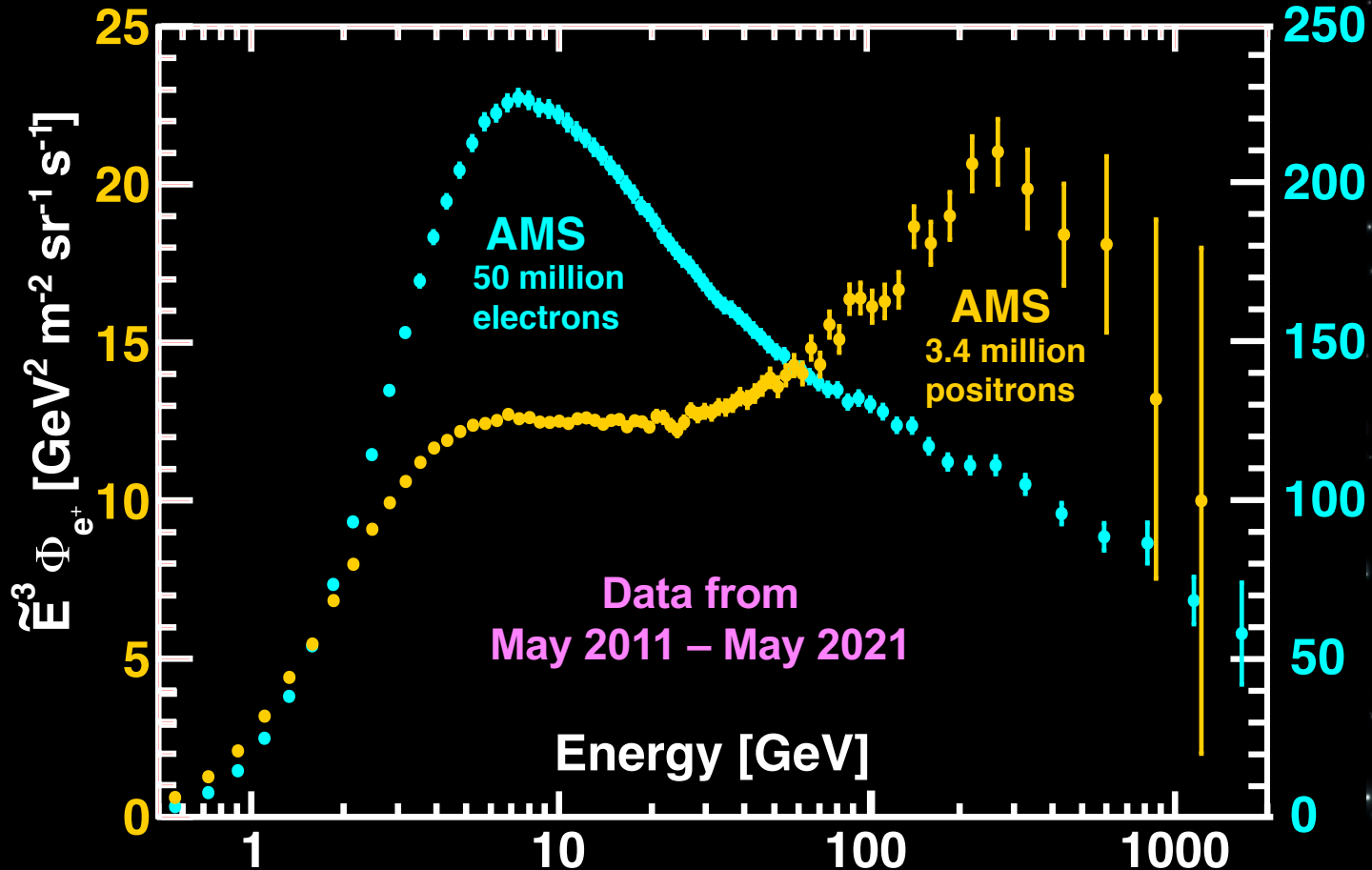
The accuracy of the momentum is determined to be $1/(30,000 \text{ GeV})$ i.e. at 1 TeV the uncertainty is 3%



Physics Results

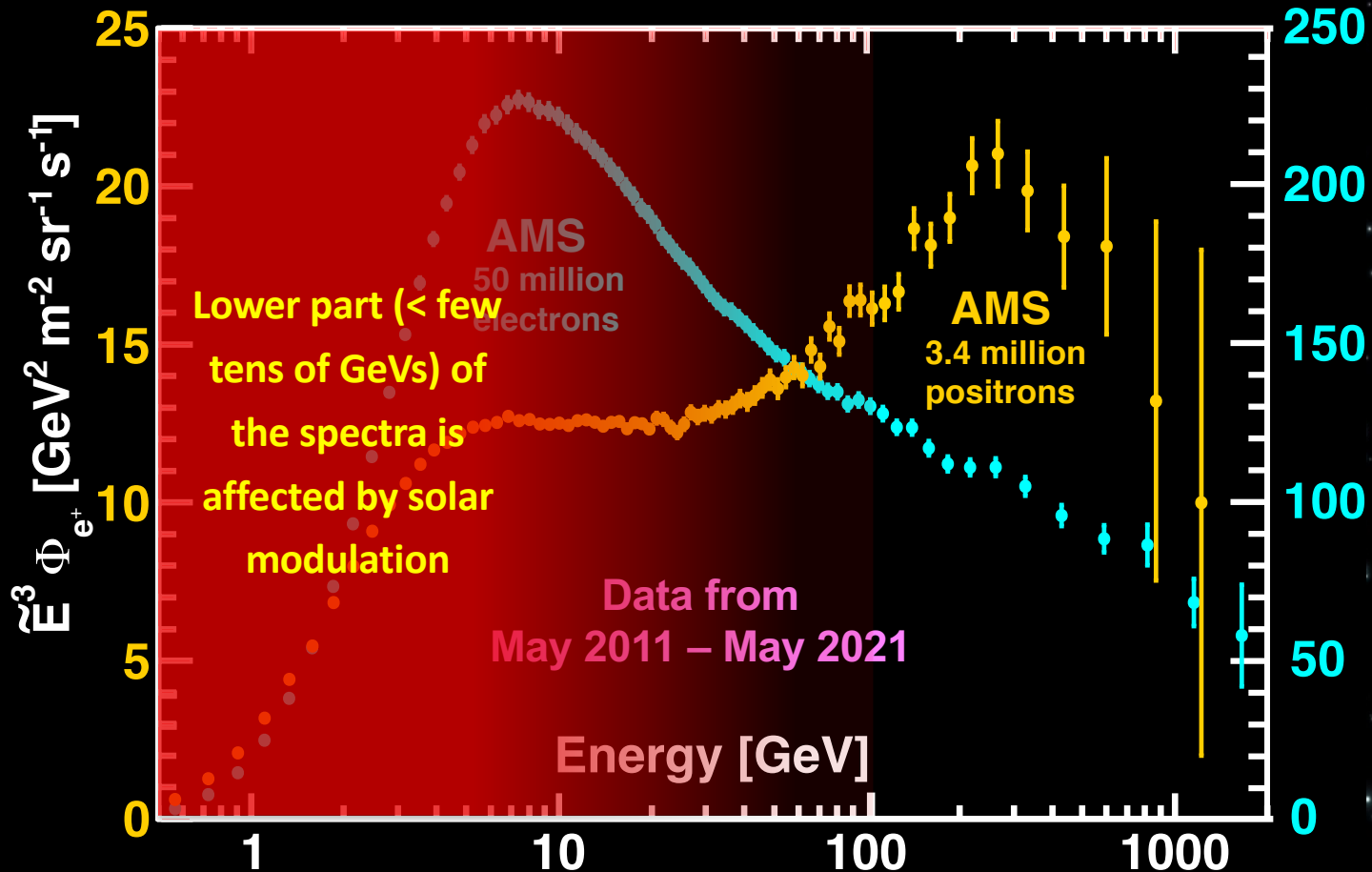


Study of Positrons & Electrons





Study of Positrons & Electrons



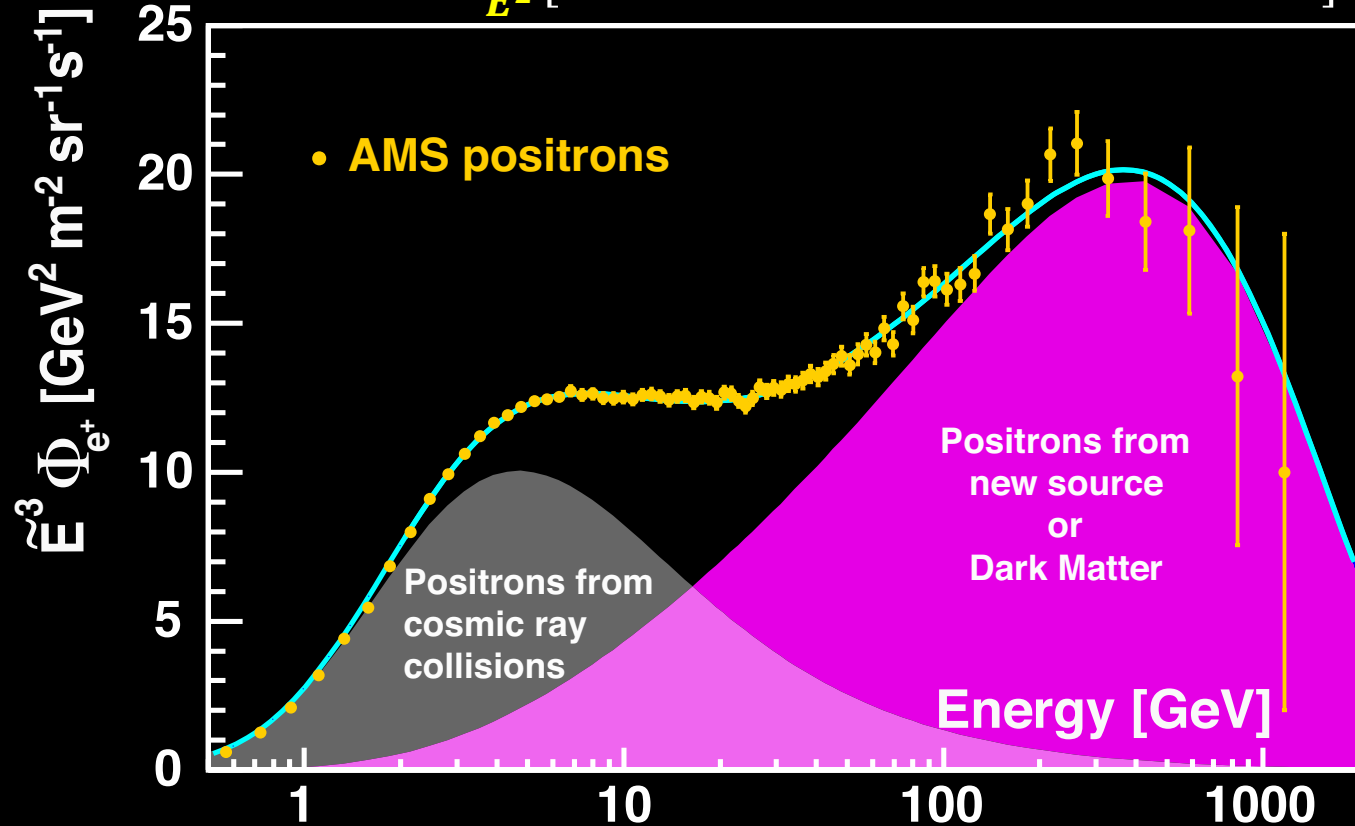


Study of Positrons

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_s .

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

Collisions New Source or Dark Matter



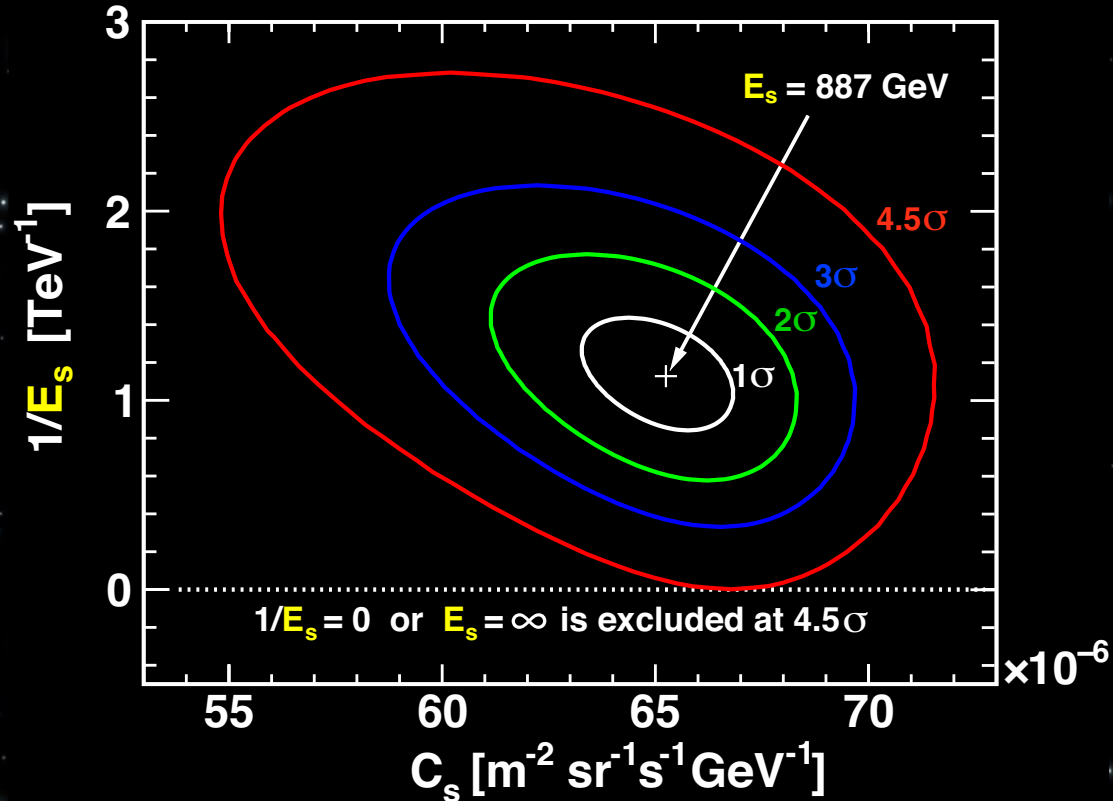


Study of Positrons & Electrons

The finite cutoff energy E_s is established at 4.5σ

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

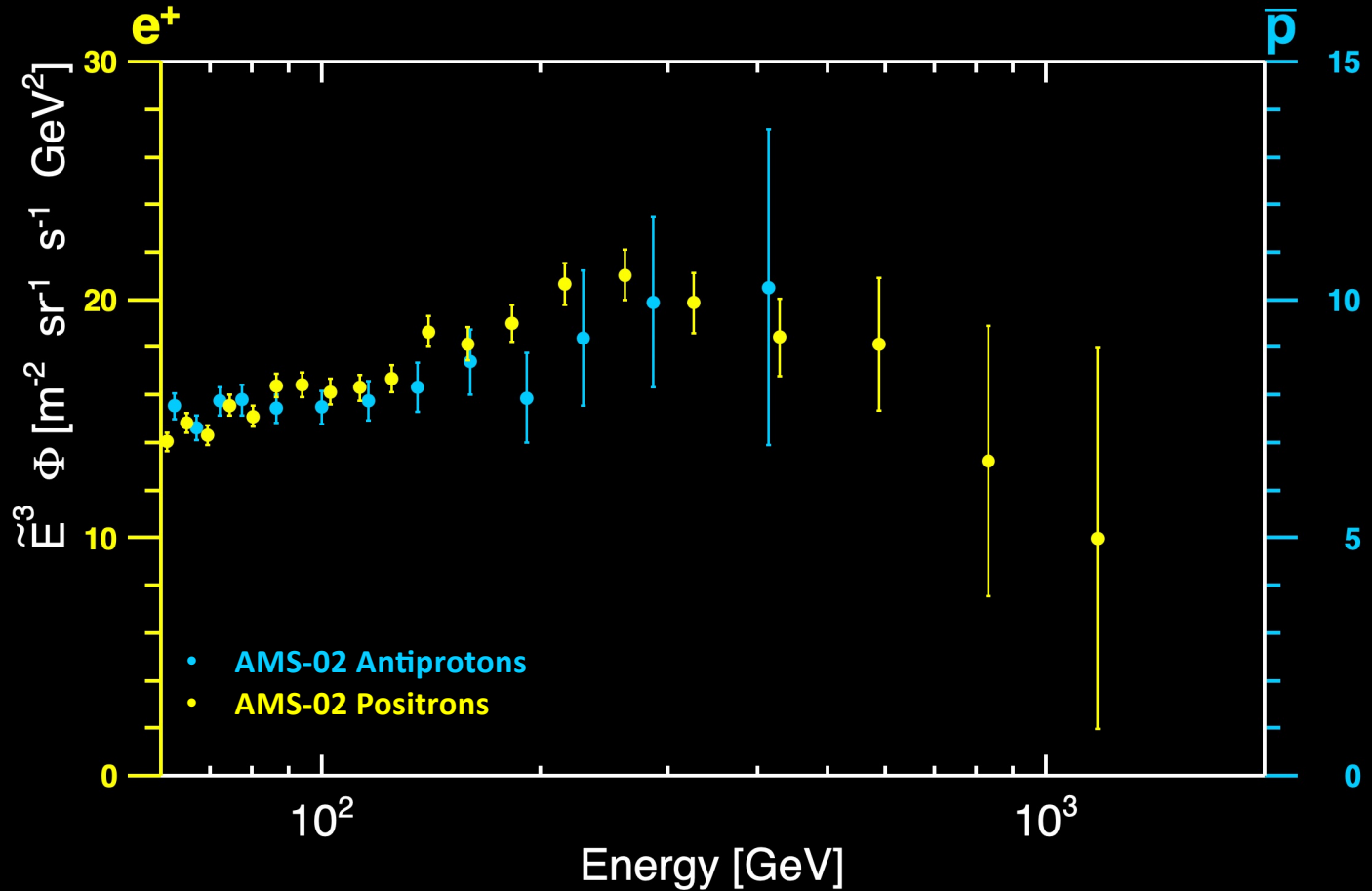
Collisions New Source or Dark Matter





Antiprotons vs positrons

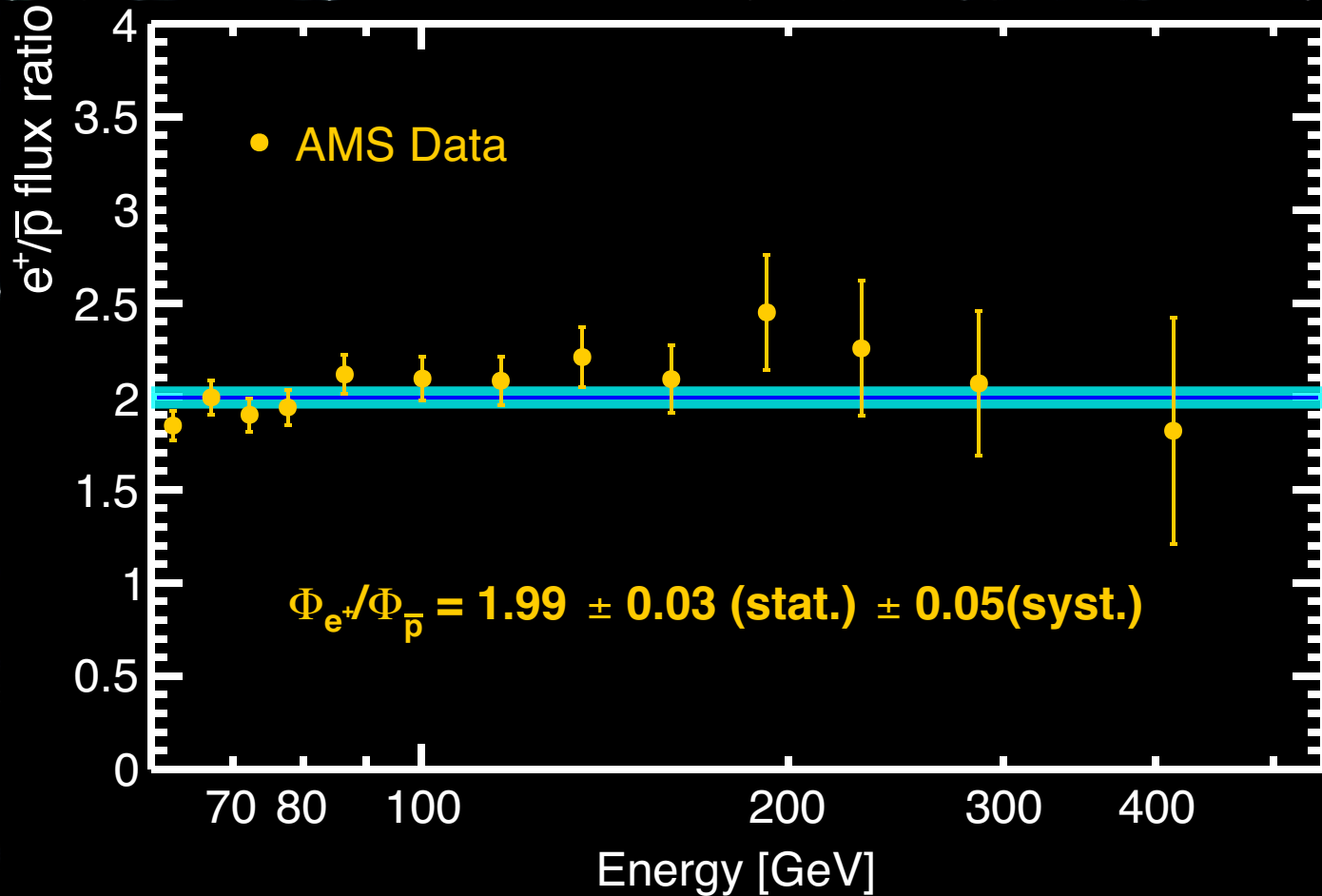
Antiproton data show a similar trend as positrons.





Antiprotons vs positrons

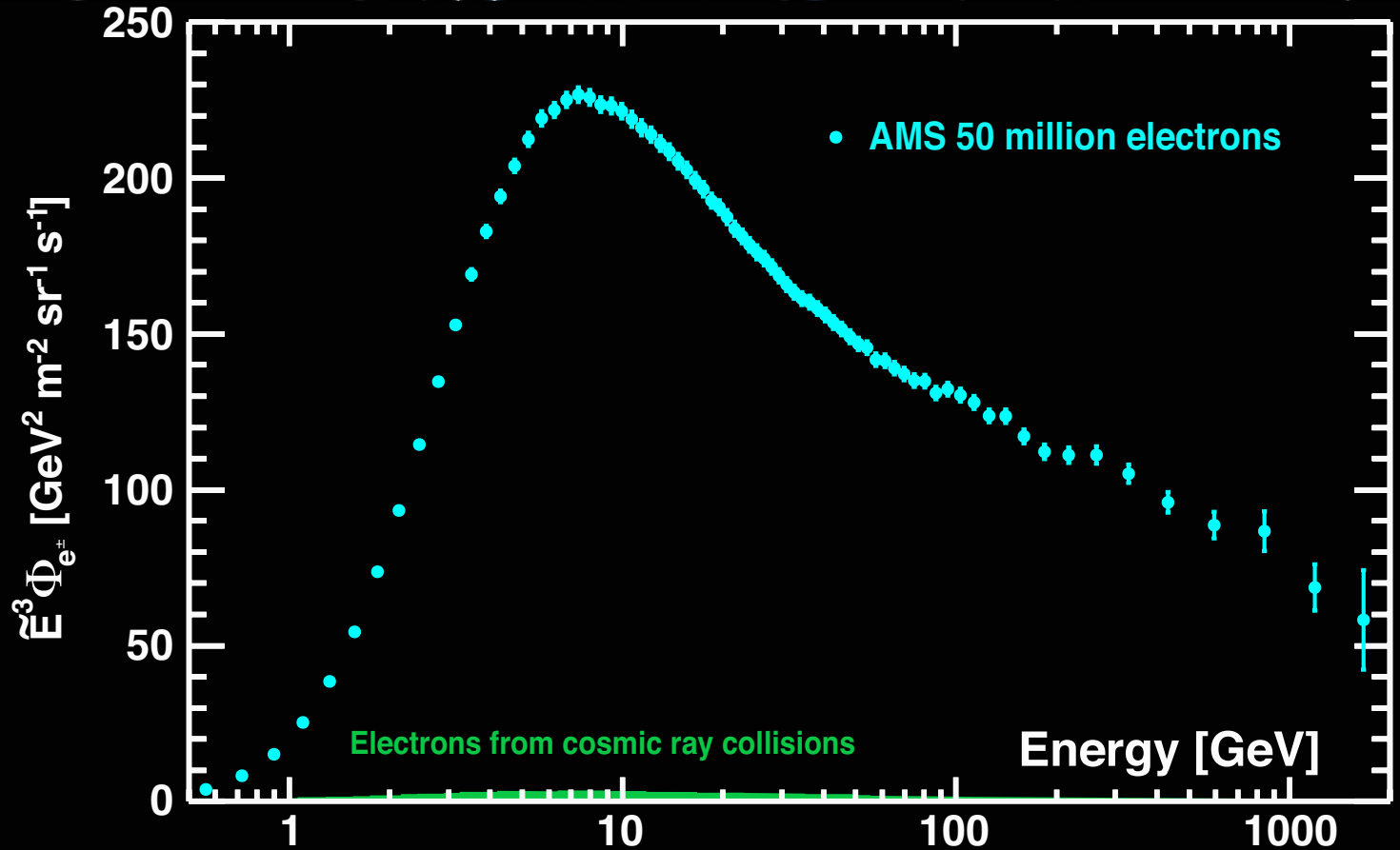
The positron-to-antiproton flux ratio is constant independently of energy. Antiprotons cannot come from pulsars.





Electrons

The contribution from cosmic ray collisions is negligible



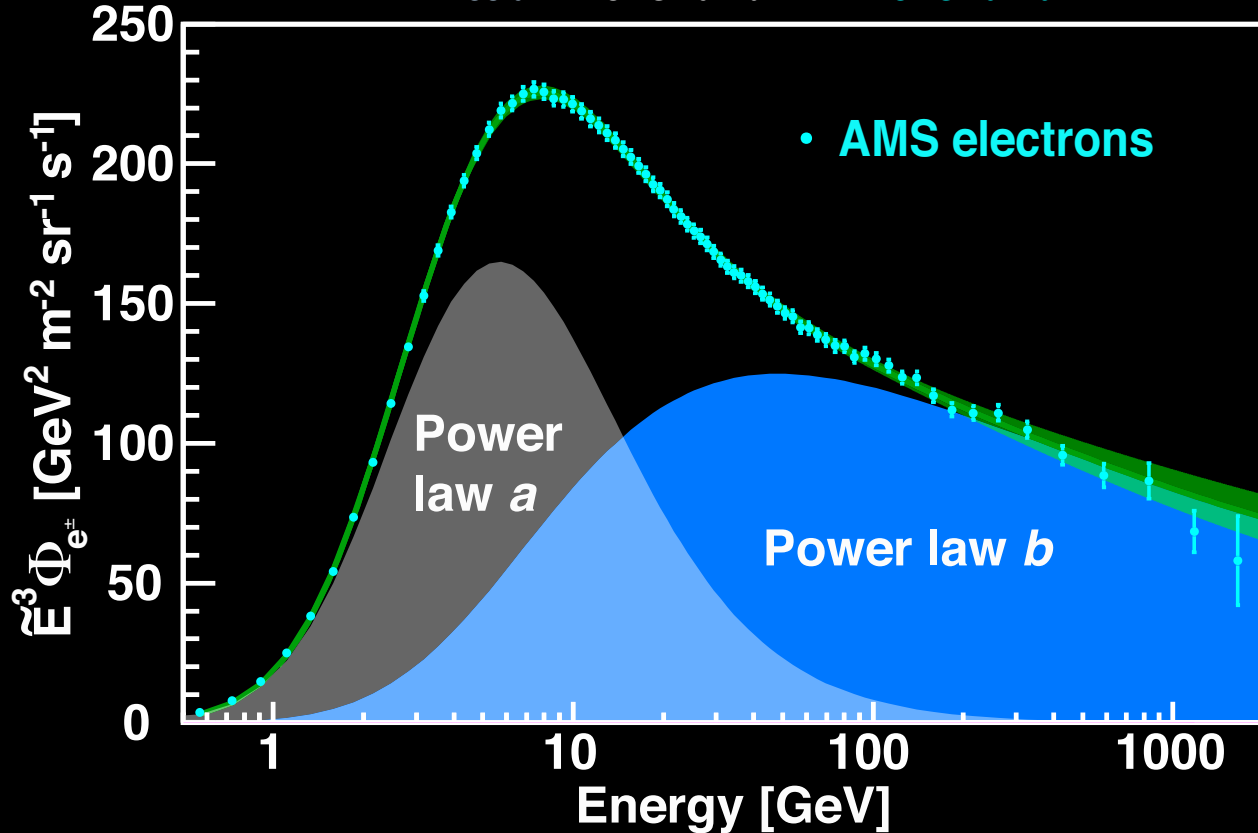


Electrons

Electron spectrum
without source term
disfavored

$$\Phi_{e^-}(E) = S(E) \left[C_a (\hat{E}/E_a)^{\gamma_a} + C_b (\hat{E}/E_b)^{\gamma_b} \right]$$

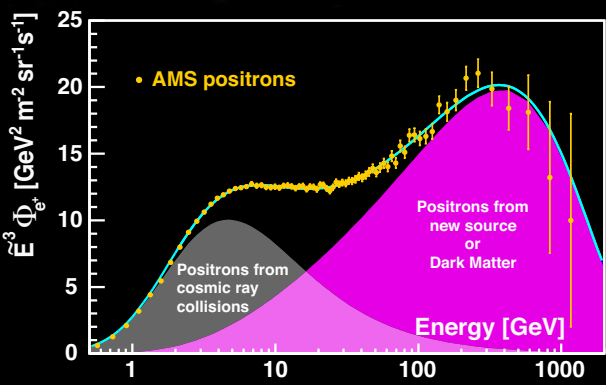
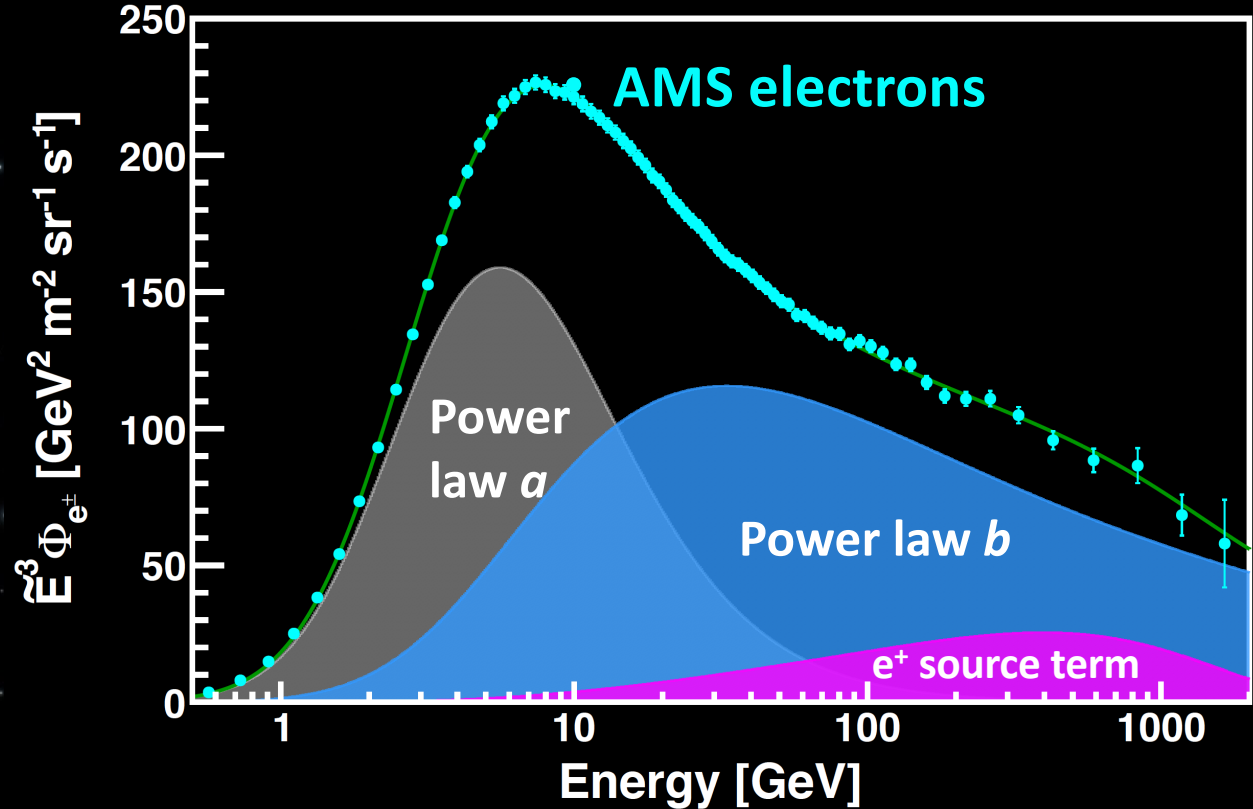
Solar Power law *a* Power law *b*



$$\Phi_{e^-}(E) = S(E) \left[C_a (\hat{E}/E_a)^{\gamma_a} + C_b (\hat{E}/E_b)^{\gamma_b} + f_s C_s^{e^+} (\hat{E}/E_2)^{\gamma_s^{e^+}} \exp(-E/E_s^{e^+}) \right]$$

Solar Power law a Power law b Positron source term

Electron spectrum favors the contribution of the positron-like source term at 2σ level

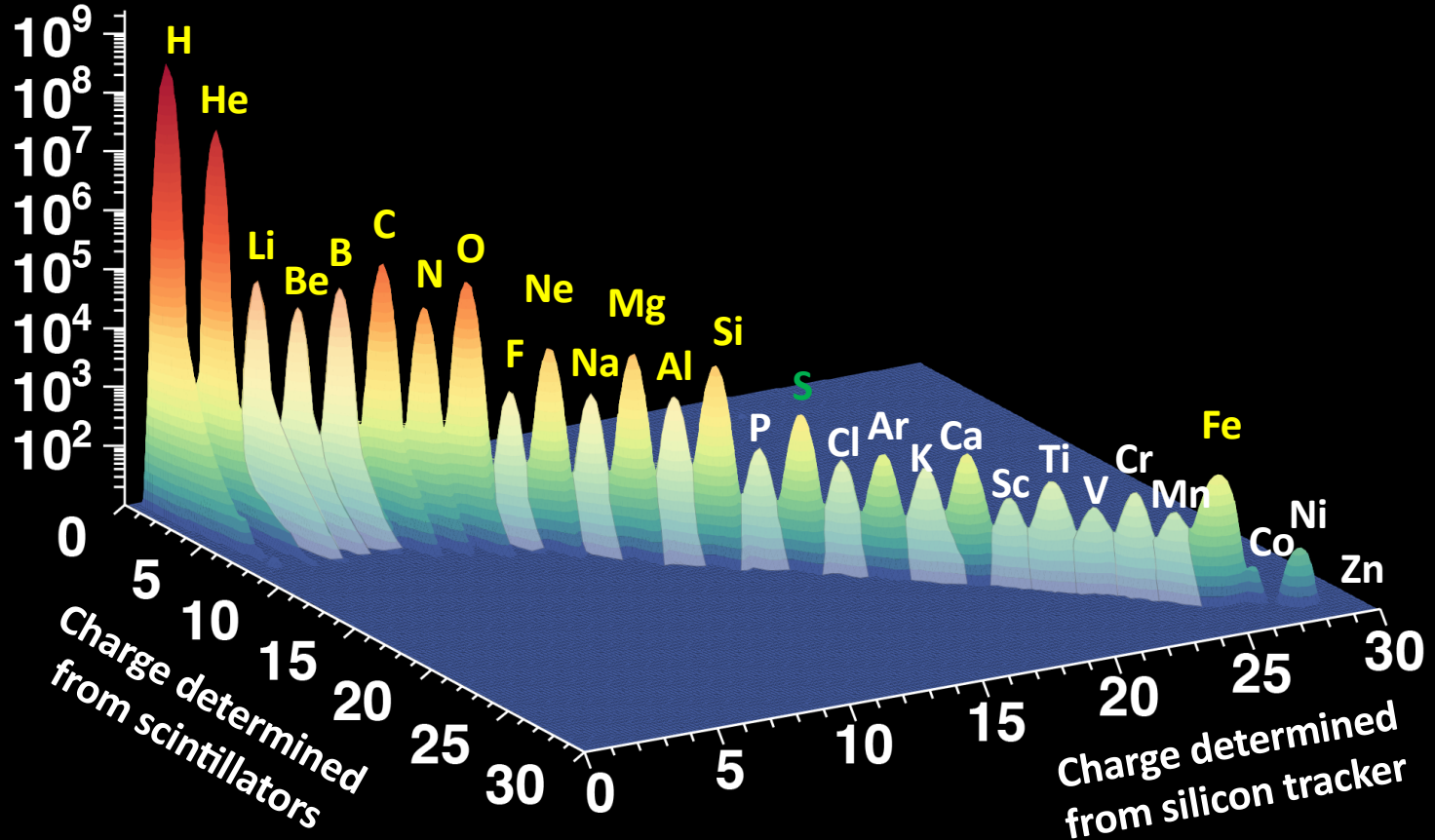




Nuclear matter

In ten years we have studied 15 (16) elements. In the next ten years we will study the other 14 elements.

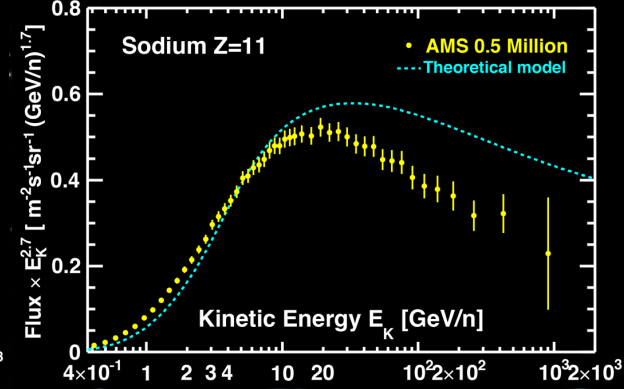
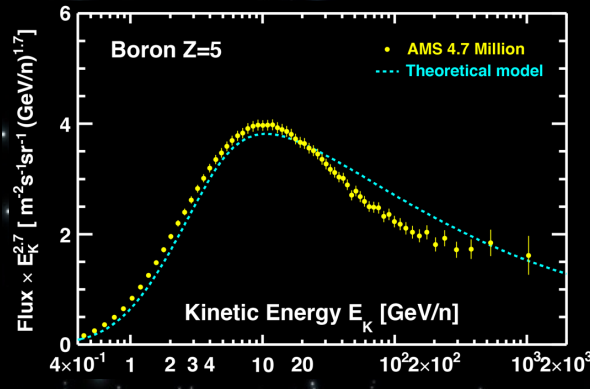
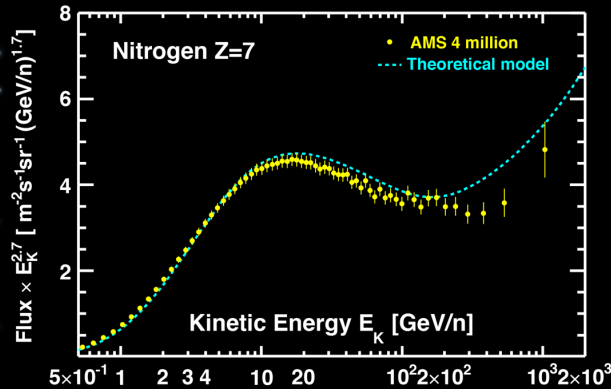
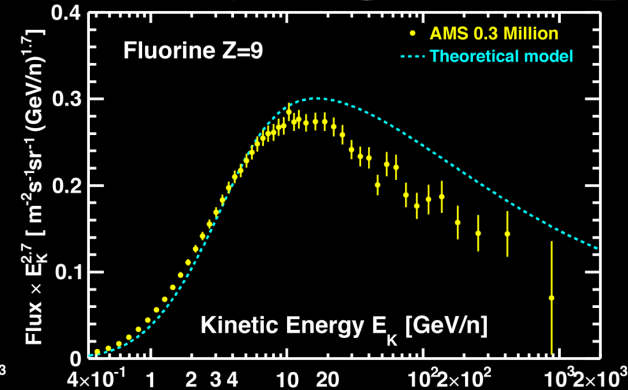
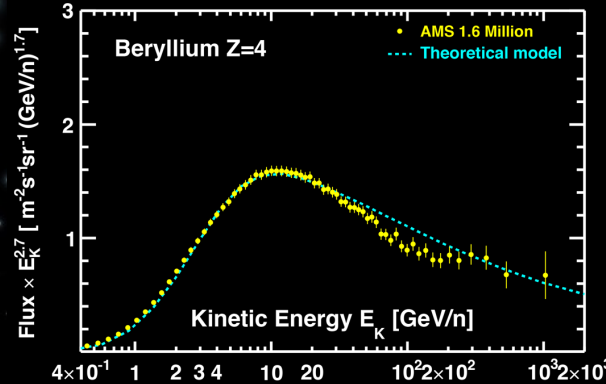
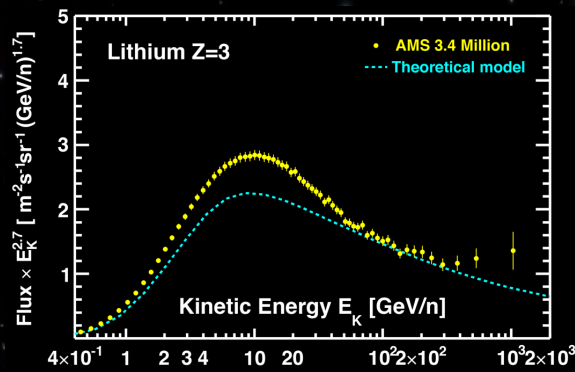
This will provide the foundation for a comprehensive theory of the cosmos



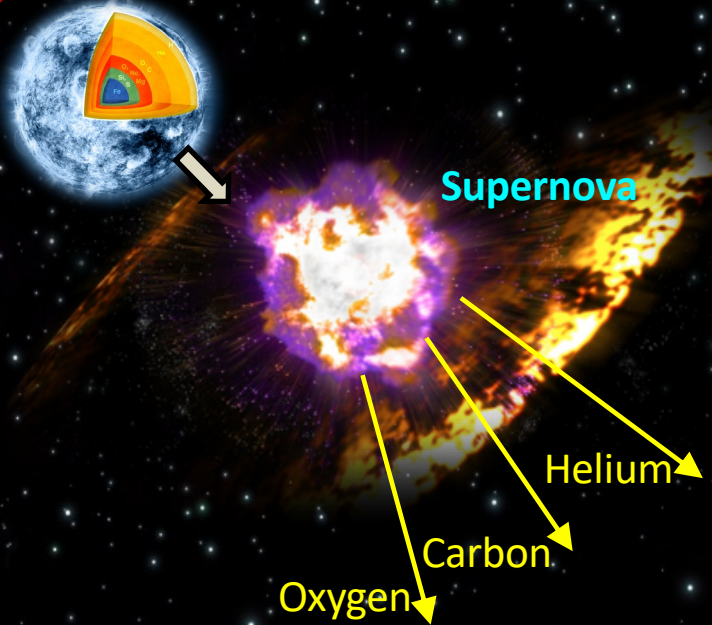


Nuclear matter

The full set of AMS results is challenging all the theoretical models



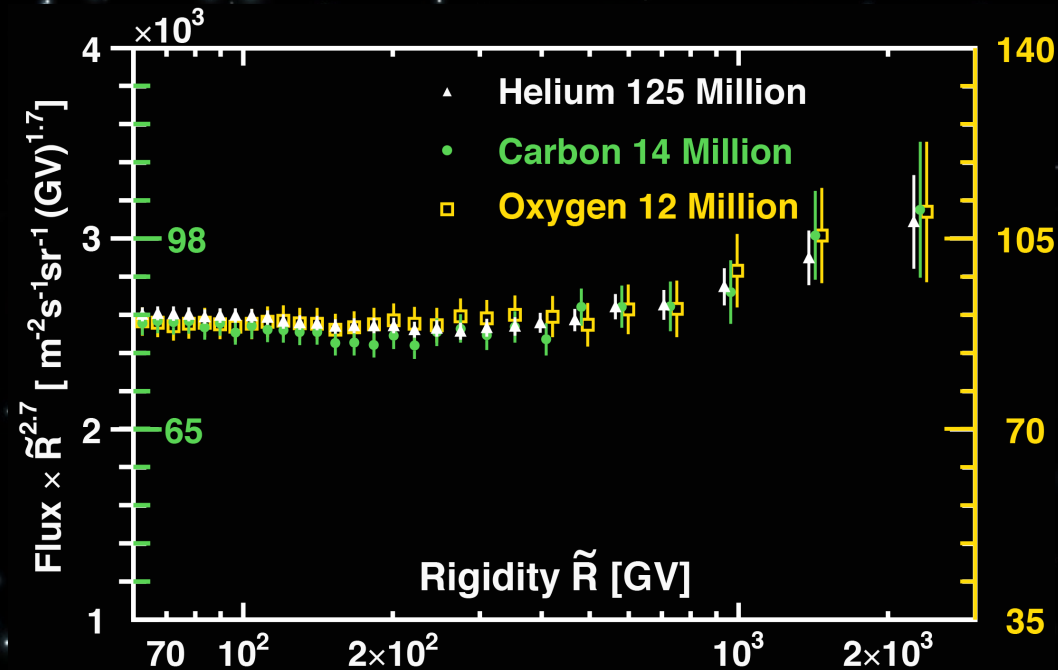
Primary Cosmic Rays



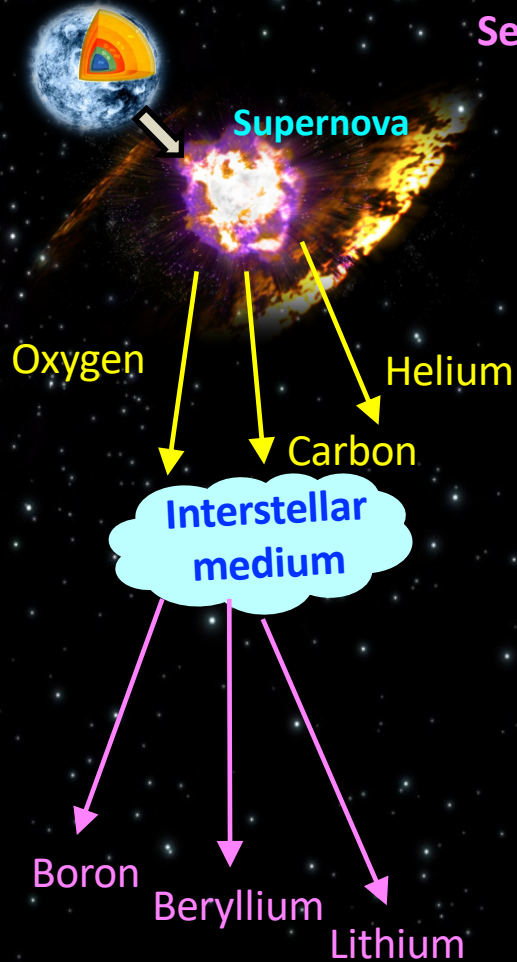
Surprisingly,
the primary cosmic rays
He, C, and O
have identical rigidity (P/Z)
dependence

Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

They are accelerated by the explosion of stars (supernovae).

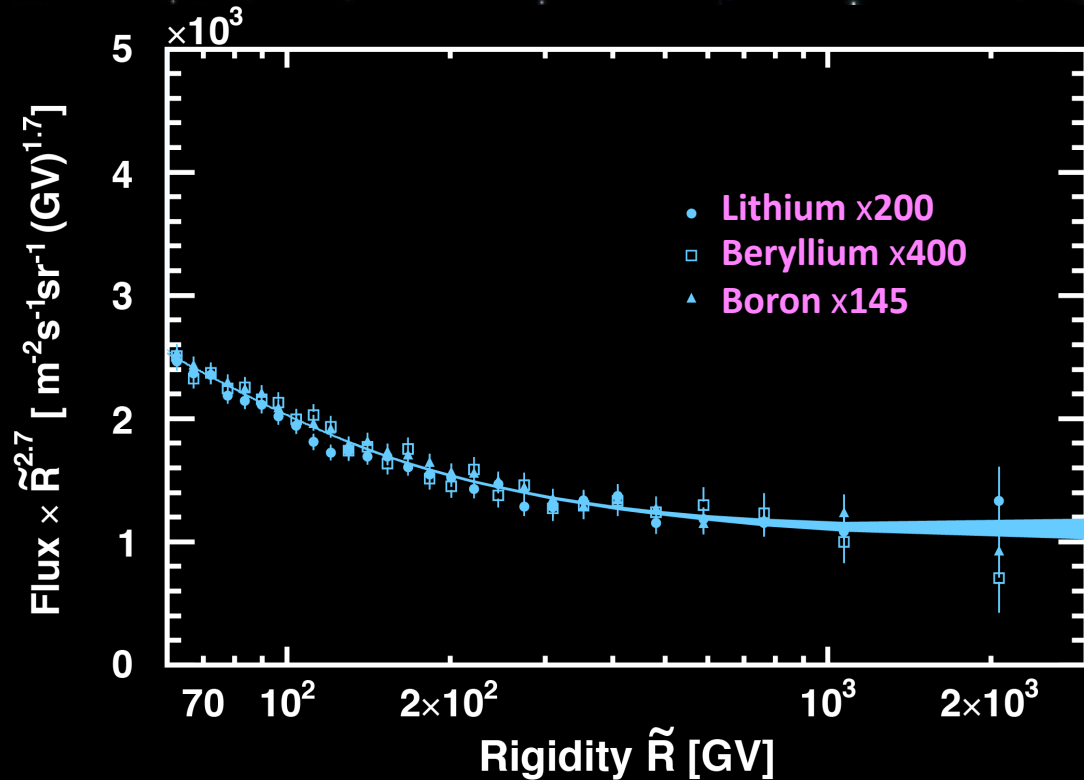


Secondary Cosmic Rays



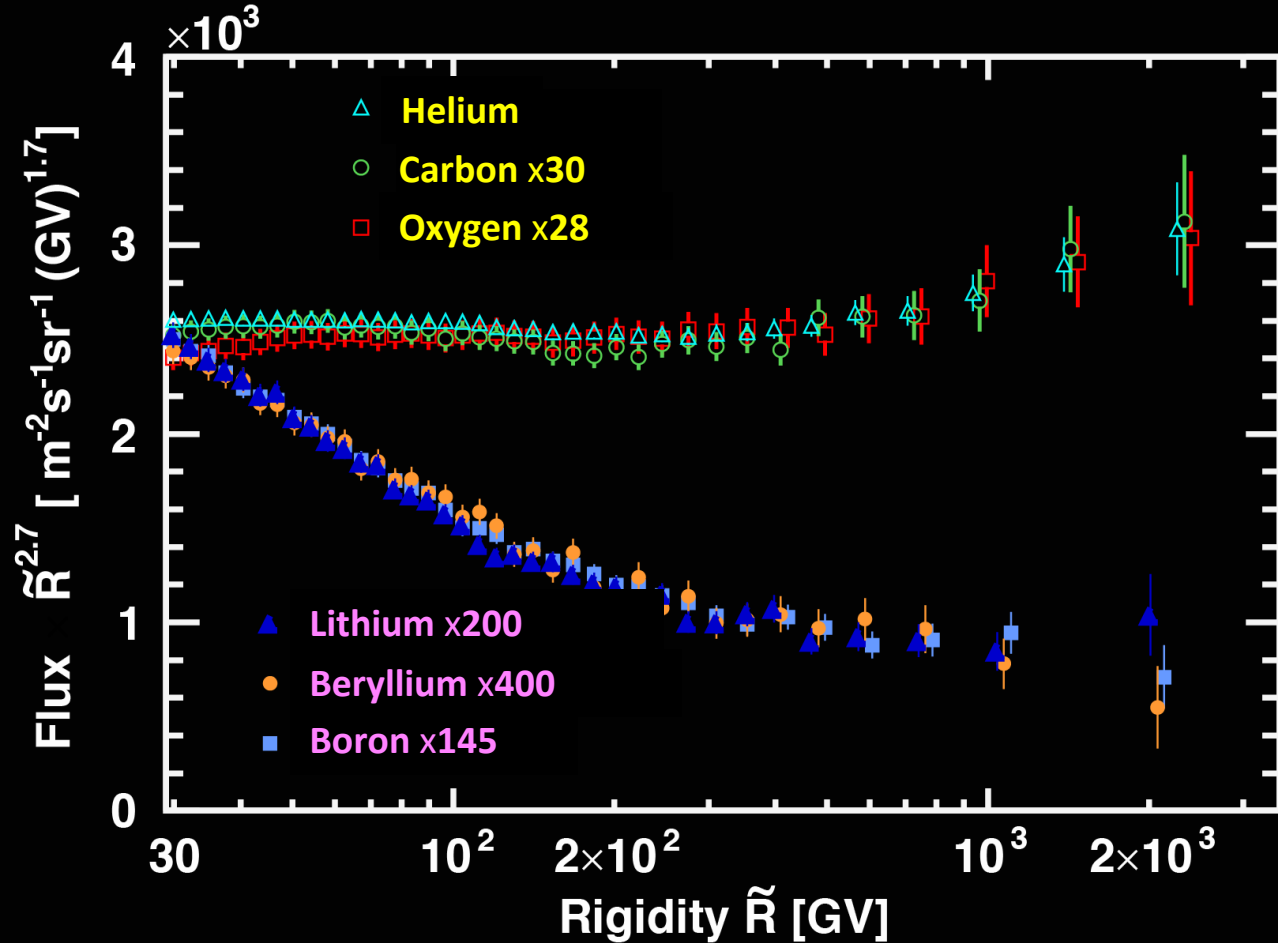
Secondary cosmic nuclei (Li, Be, B, ...) are produced by the collision of **primary cosmic rays** and **the interstellar medium**.

Secondary cosmic rays also have identical rigidity dependence



Primaries vs Secondaries

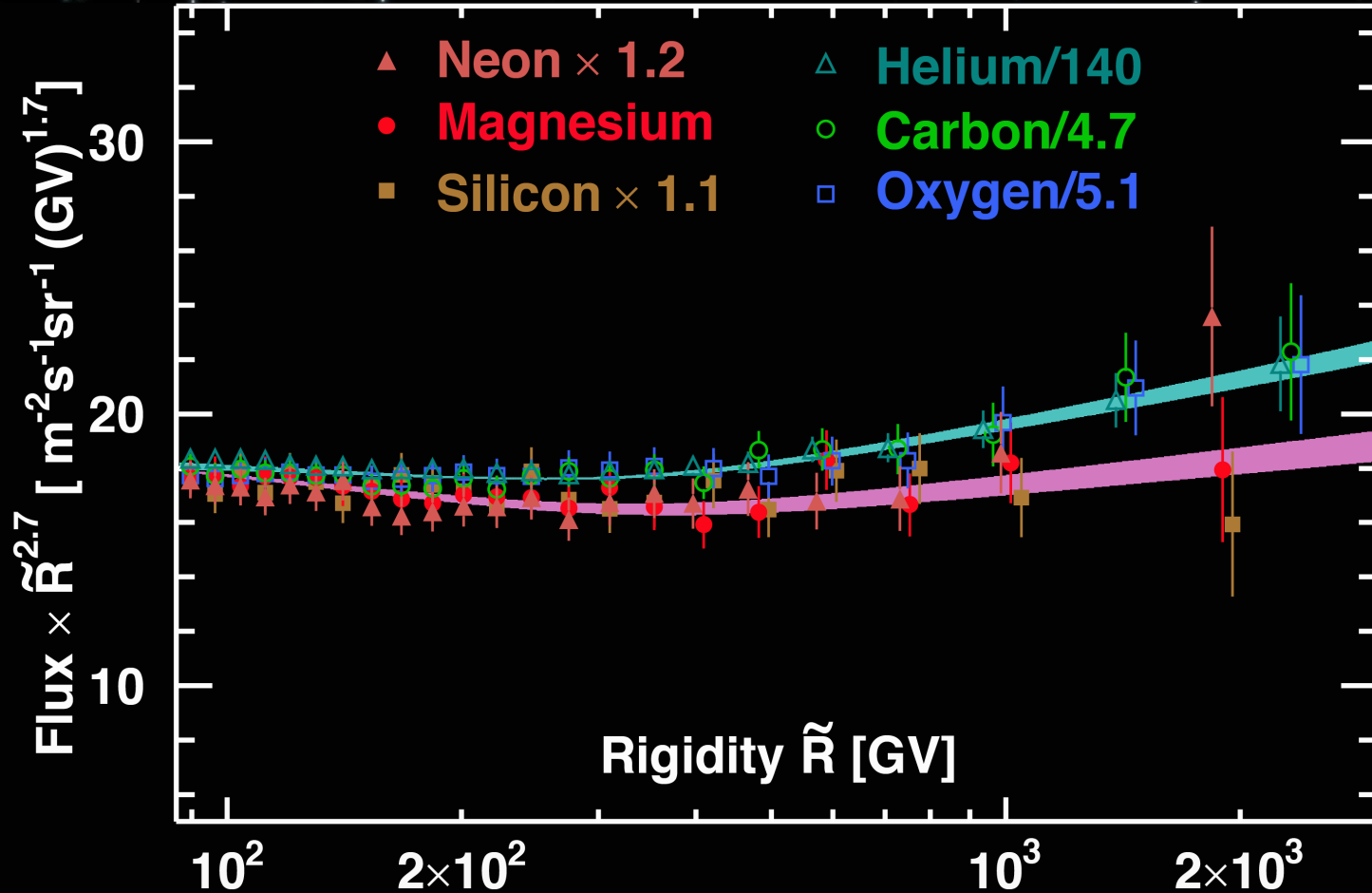
Each has their own rigidity dependence but distinctly different from each other.





Heavier primary cosmic rays

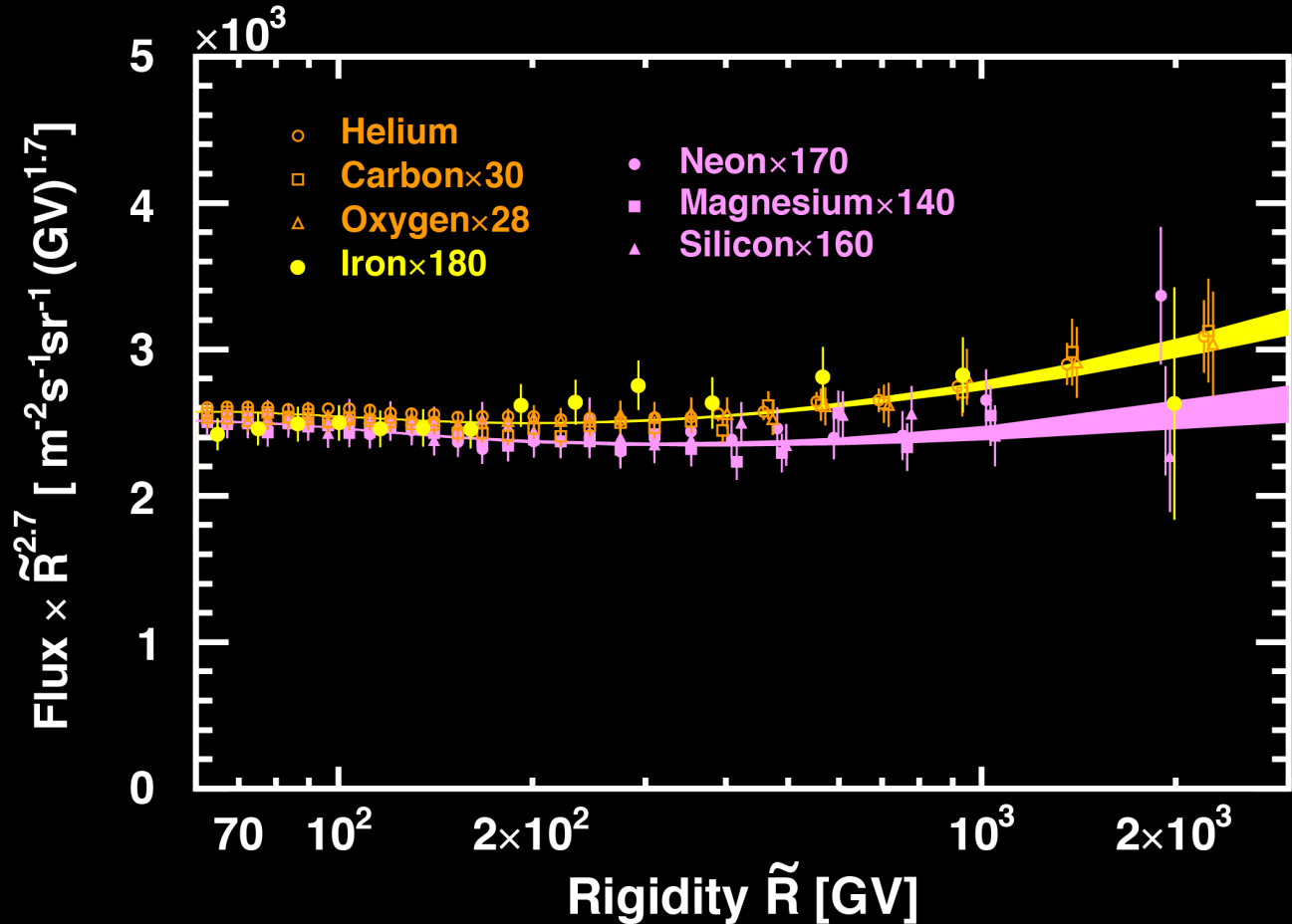
Heavier primary cosmic rays **Ne**, **Mg**, **Si** have their own identical rigidity behavior but different from **He**, **C**, **O**.
Unexpectedly, primary cosmic rays have at least two classes.



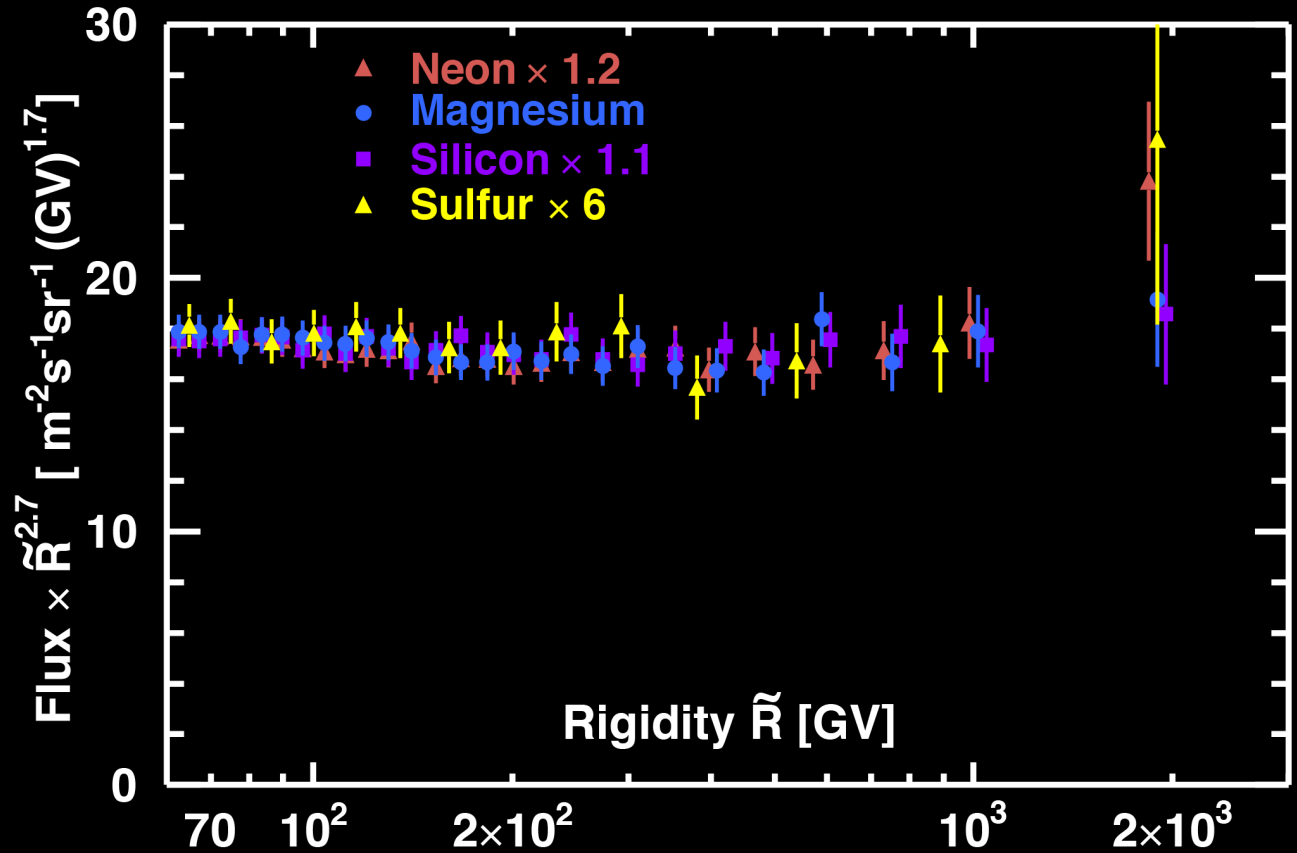


Iron

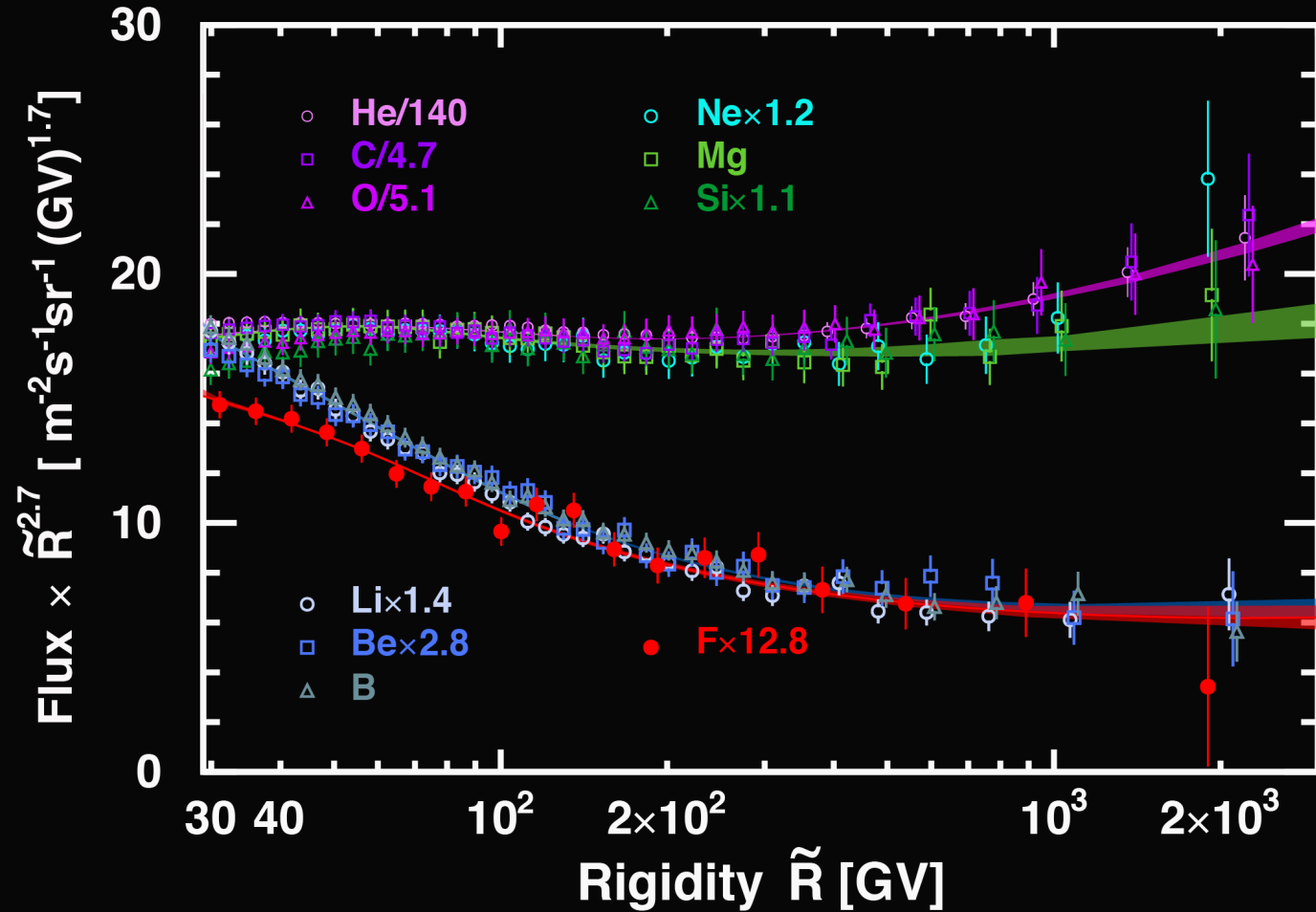
Unexpected Result:
Iron is in the He, C, O primary cosmic ray group instead of the expected Ne, Mg, Si group.



S belongs to the same class as Ne, Mg, and Si



Unexpectedly,
secondary cosmic rays
also have two classes



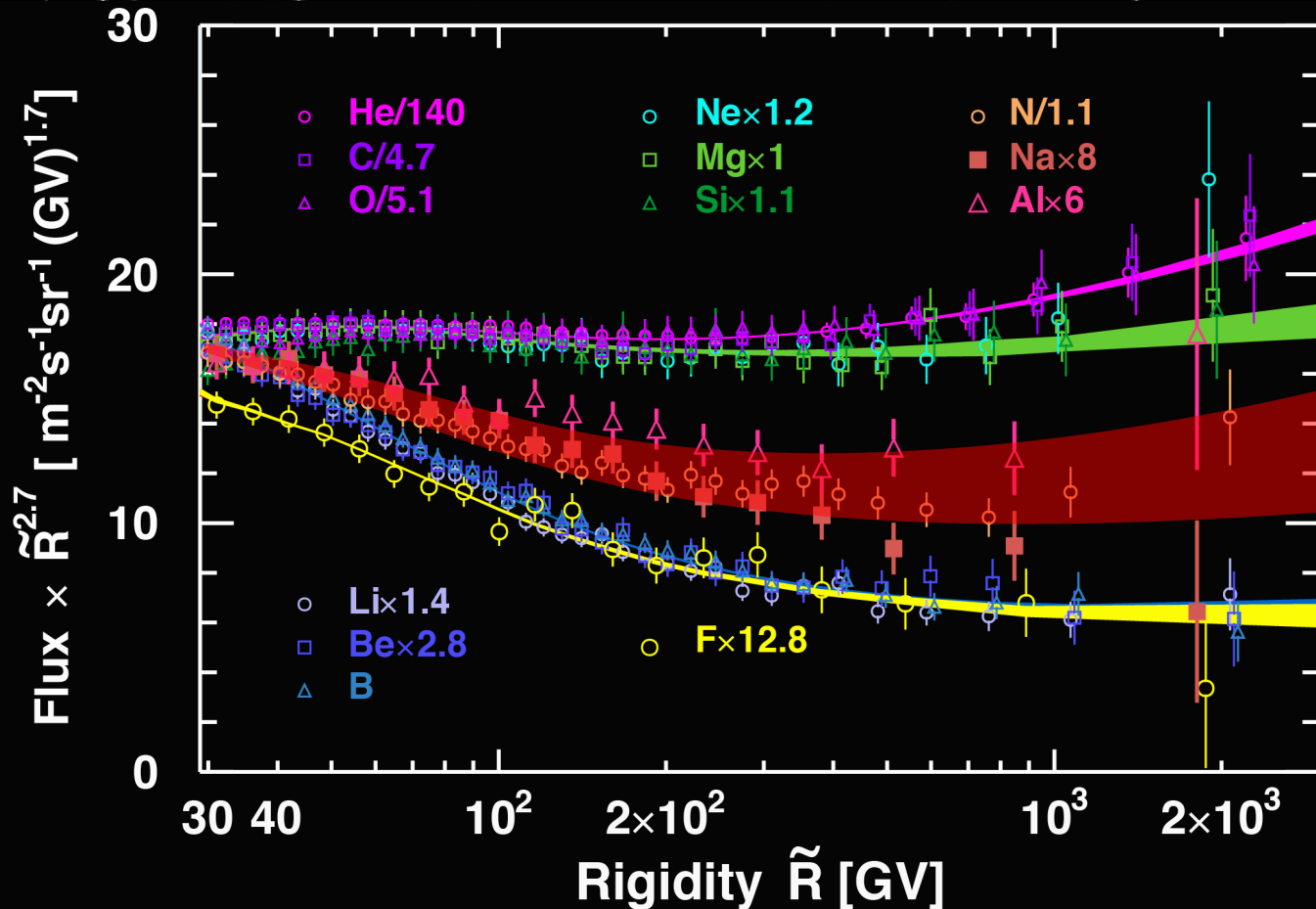


Third group

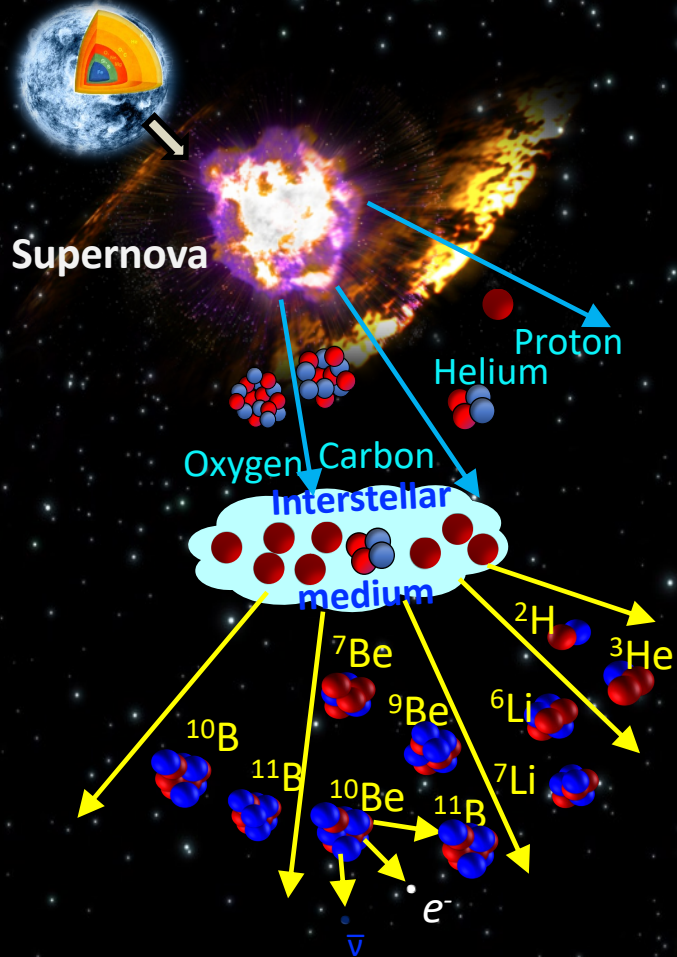
The Third Group of Cosmic Rays:

N, Na, Al

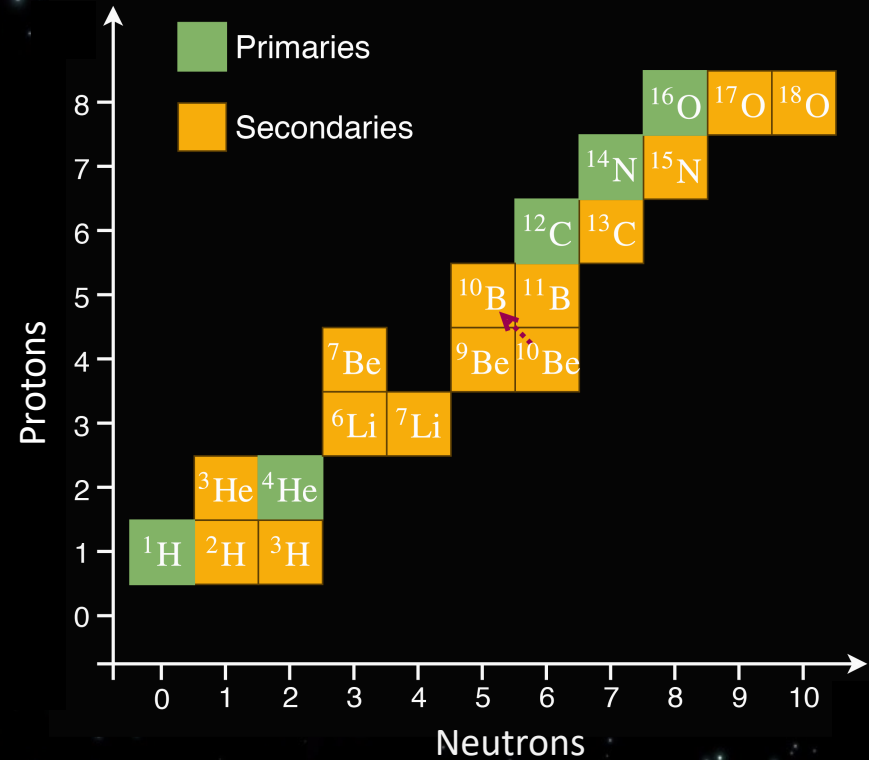
The fluxes are well described as a sum of a primary component + a secondary component



Isotopes



Provides unique information on production and propagation of secondary cosmic rays ($^6,7\text{Li}$, $^9,7\text{B}$) and age of cosmic rays ($^9,^{10}\text{Be}$).

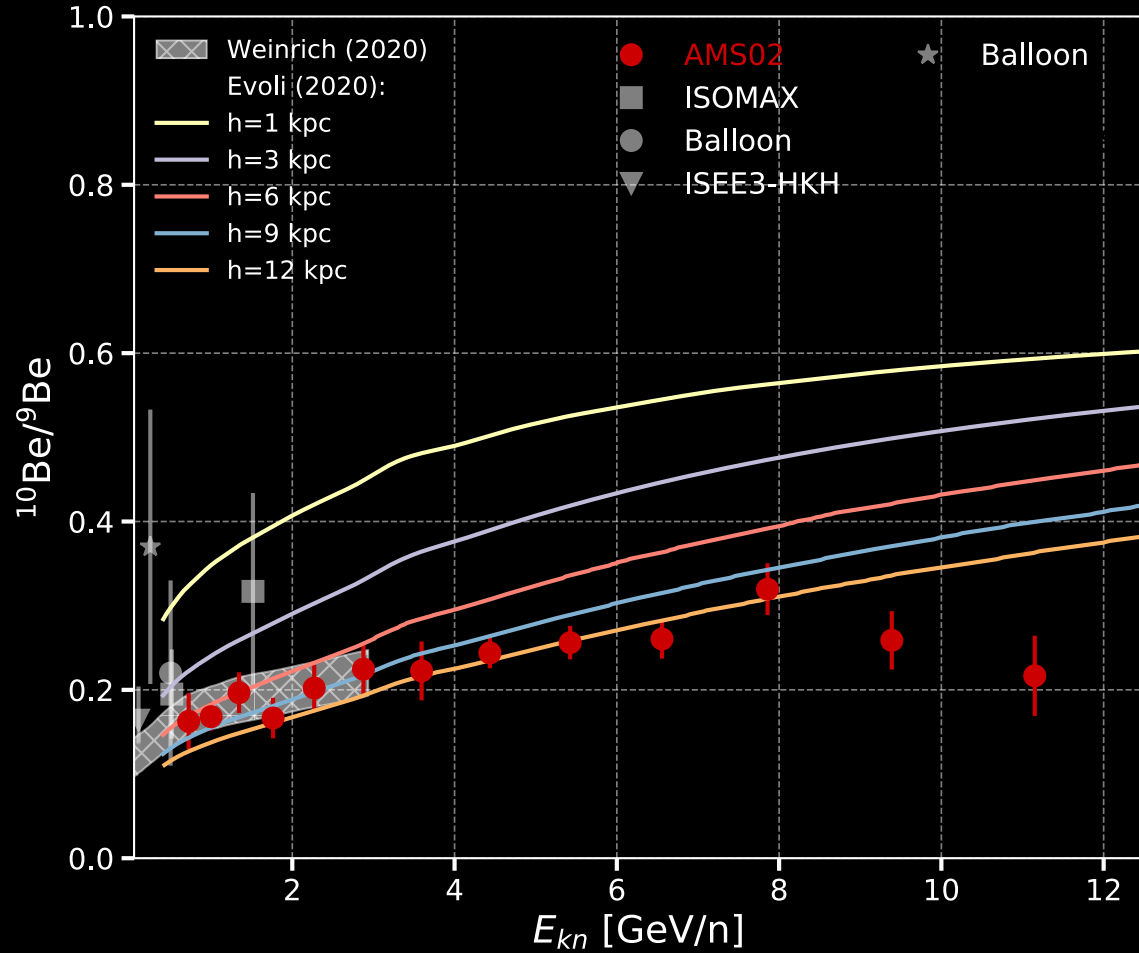




$^{10}\text{Be}/^9\text{Be}$

^9Be stable
 $^{10}\text{Be} \sim 1.4 \cdot 10^6 \text{ y}$

AMS data constrains the halo size h





Time variations: protons

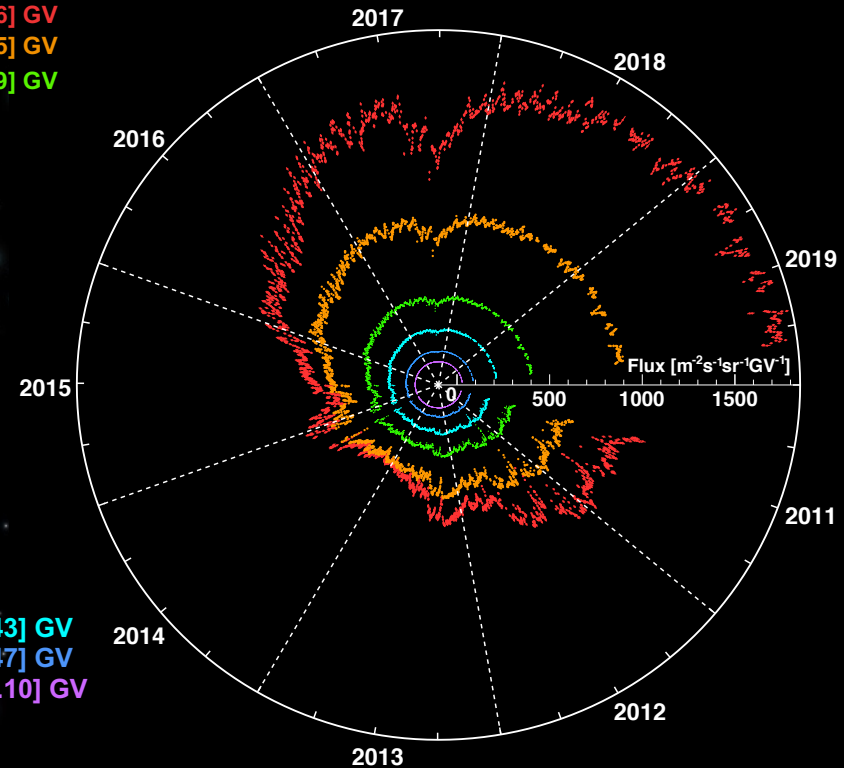
Yearly, Monthly, Daily Proton Flux from 5.5 billion events

Unexpected observation of periodic structures which are momentum dependent

These are new and unique probes of fundamental properties of solar system and provide safety information for interplanetary travel.

[1.00-1.16] GV
[1.92-2.15] GV
[2.97-3.29] GV

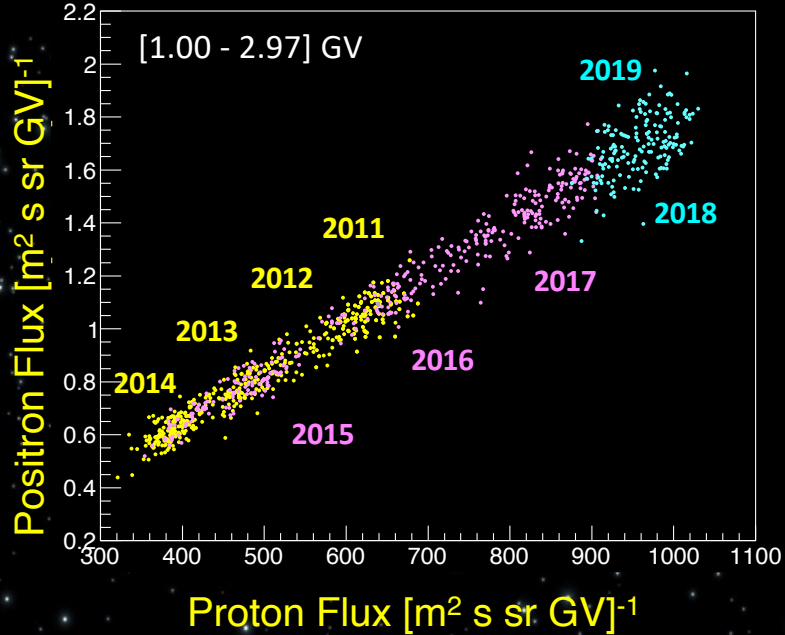
[4.02-4.43] GV
[5.90-6.47] GV
[9.26-10.10] GV





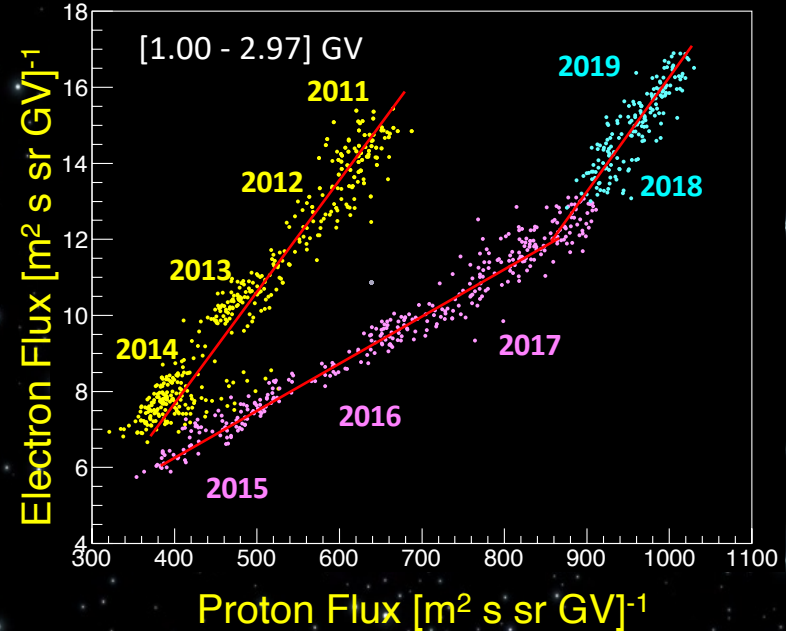
Protons vs electrons and positrons

Positron vs. proton



**Positrons and protons
fluxes have a linear relation**

Electron vs. proton



**The relation between
the electron and proton
fluxes is a surprise**



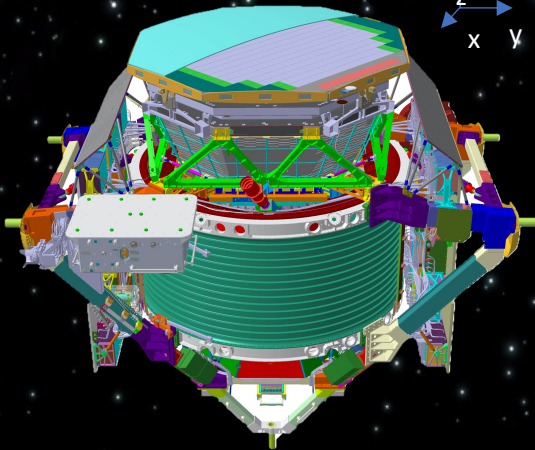
Conclusion

- in the first 10 years AMS-02 produced a wide set of high statistics, high accuracy, unprecedented, cosmic ray measurements
- this set of measurements is challenging the theoretical community for a fully comprehensive model able to explain all the observed features
- AMS will be operated for the full life-time of the ISS (2032?). In case of upgrade, some channels will have a significant boost in statistics/accuracy

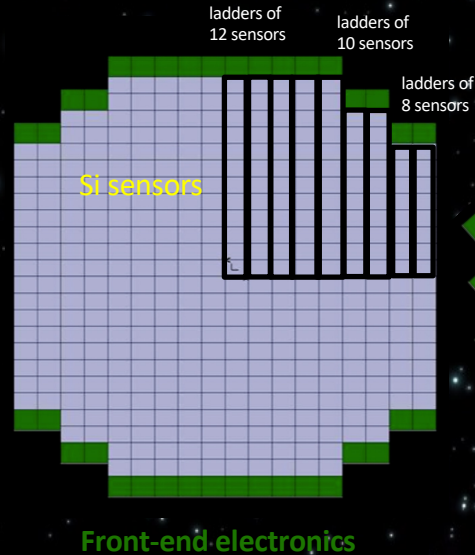


AMS-02 upgrade "LO"

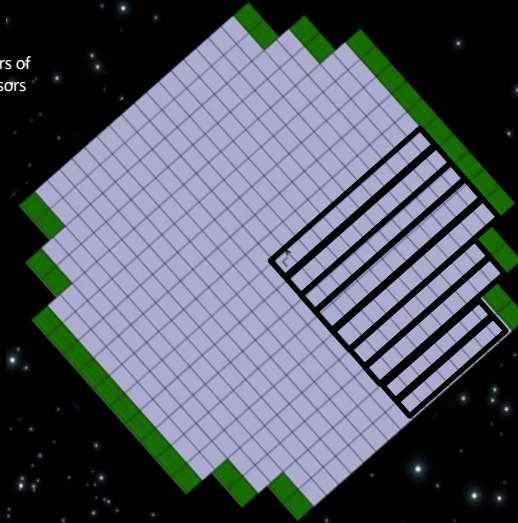
New Silicon Tracker Layer:
one plane, two layers, each ~ 4m²



L0-Y
bending direction
7 micron



L0-U
rotated 45°
10 micron bending
10 micron non-bending



Acceptance increased to 300% (10 years data becomes 30 years data)



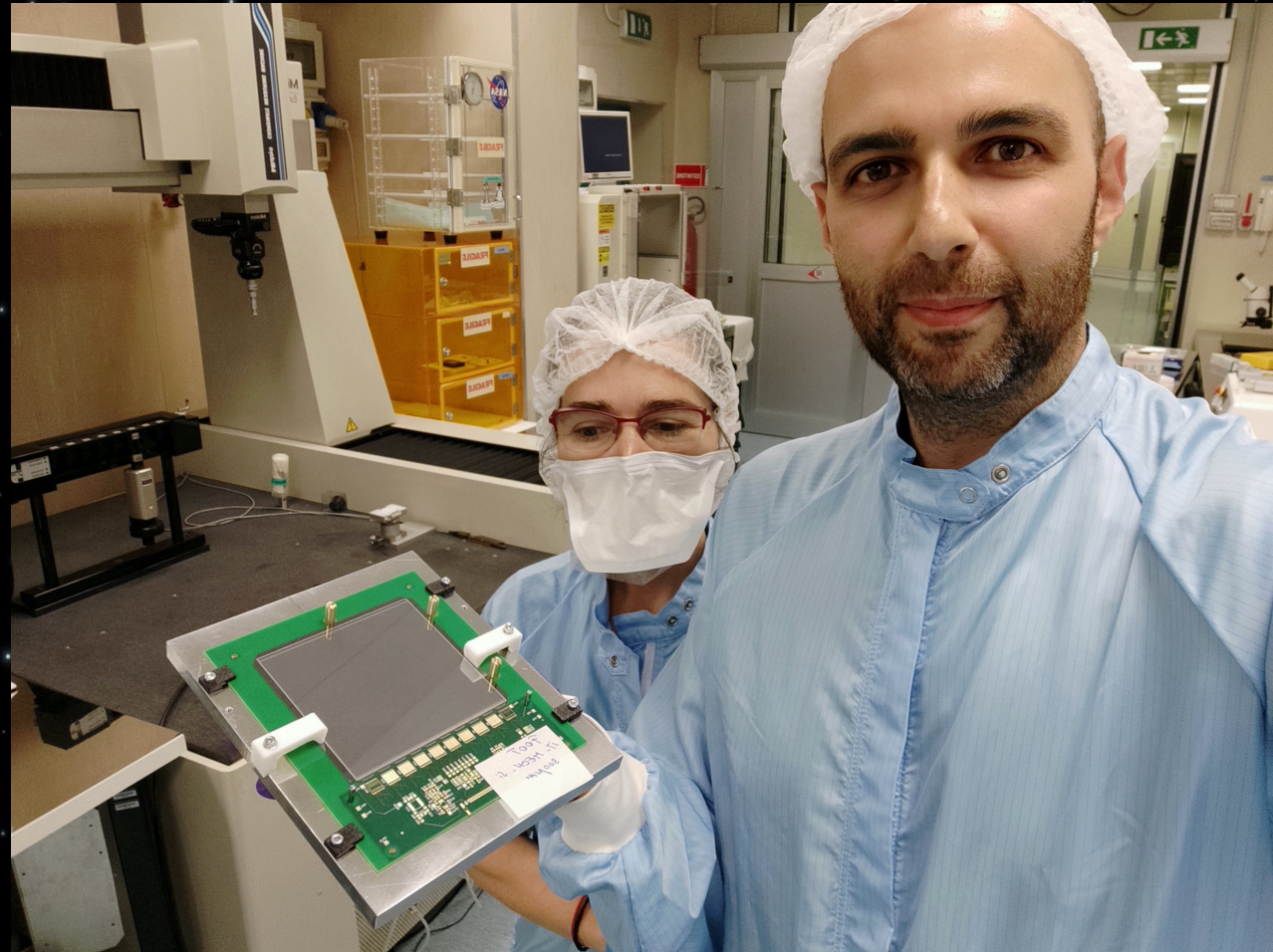
AMS-02 upgrade "LO"

10x10 cm² sensors
(INFN-Perugia, Italy)

new ladder, mech. proto

960 mm, 10 detectors

INFN-PG



Stay tuned...

