International Symposium on
Sixty years of Subnuclear Physics in Bologna

The Alpha Magnetic Spectrometer Experiment on ISS

7 November 2018

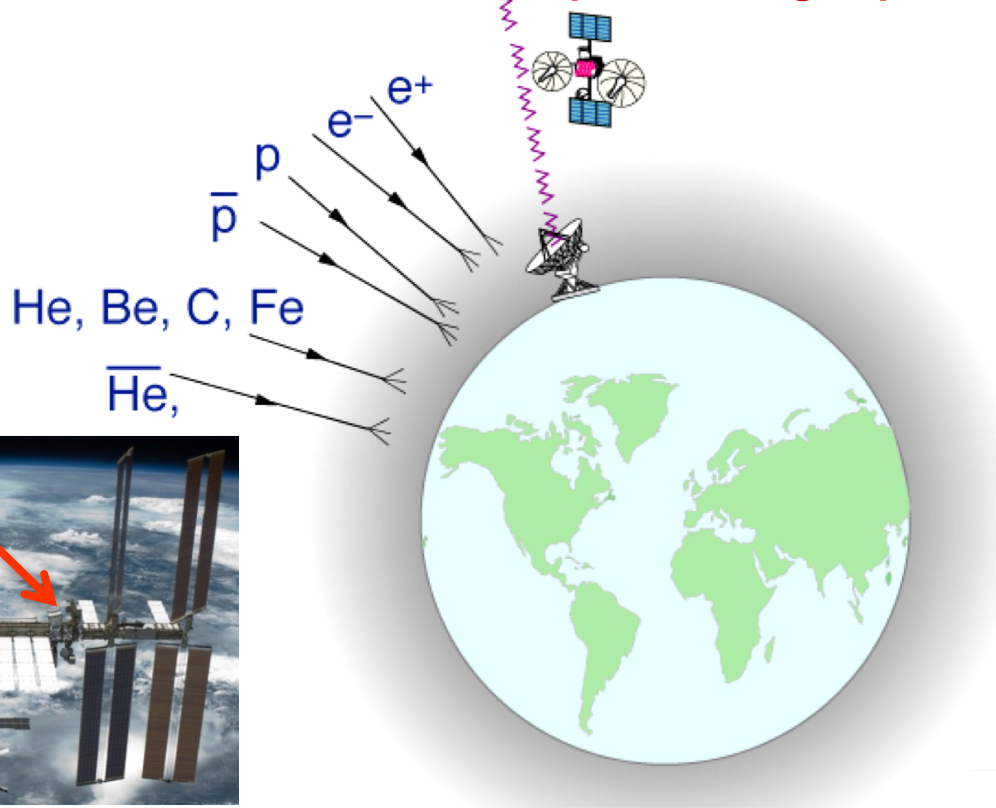
A. Contin

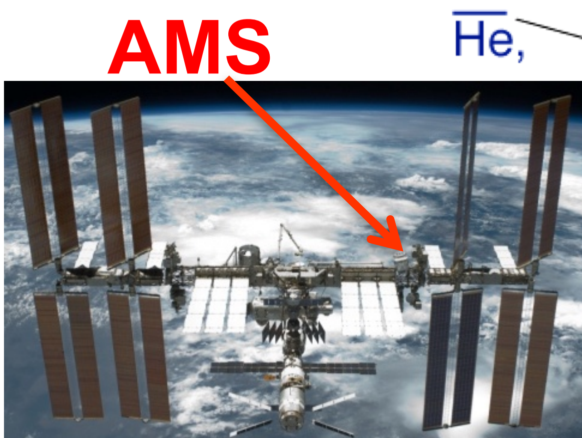
Fundamental Science on the International Space Station (ISS)

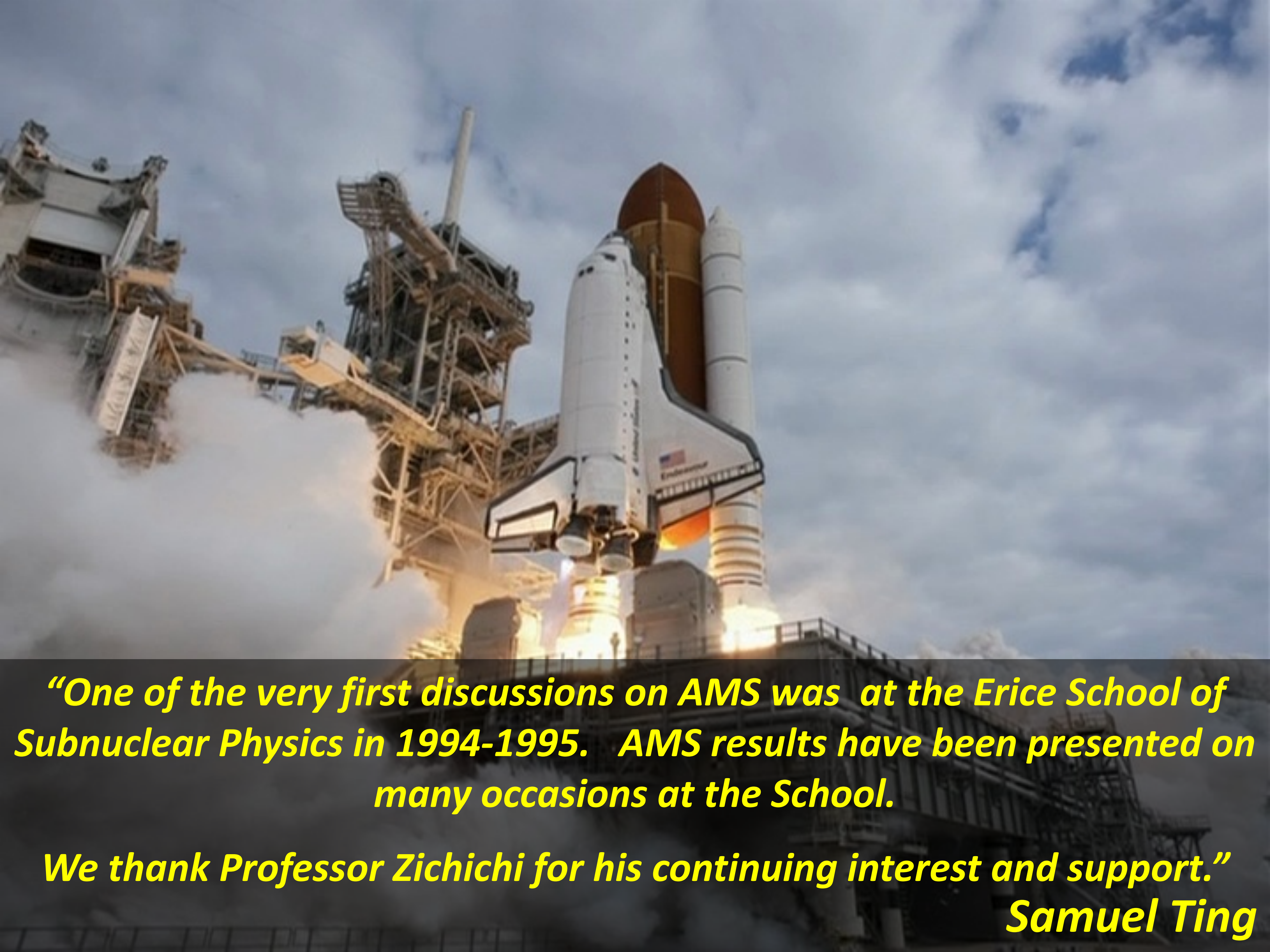
There are two kinds of cosmic rays traveling through space

1- Neutral cosmic rays (light rays and neutrinos):
Light rays have been measured (e.g., Hubble) for over 50 years.
Fundamental discoveries have been made.

2- Charged cosmic rays: A new region in science. Using a magnetic spectrometer (AMS) on ISS is the only way to provide precision long term (20 years) measurements of high energy charged cosmic rays.
AMS is often referred to as the "Hubble telescope for charged particles".

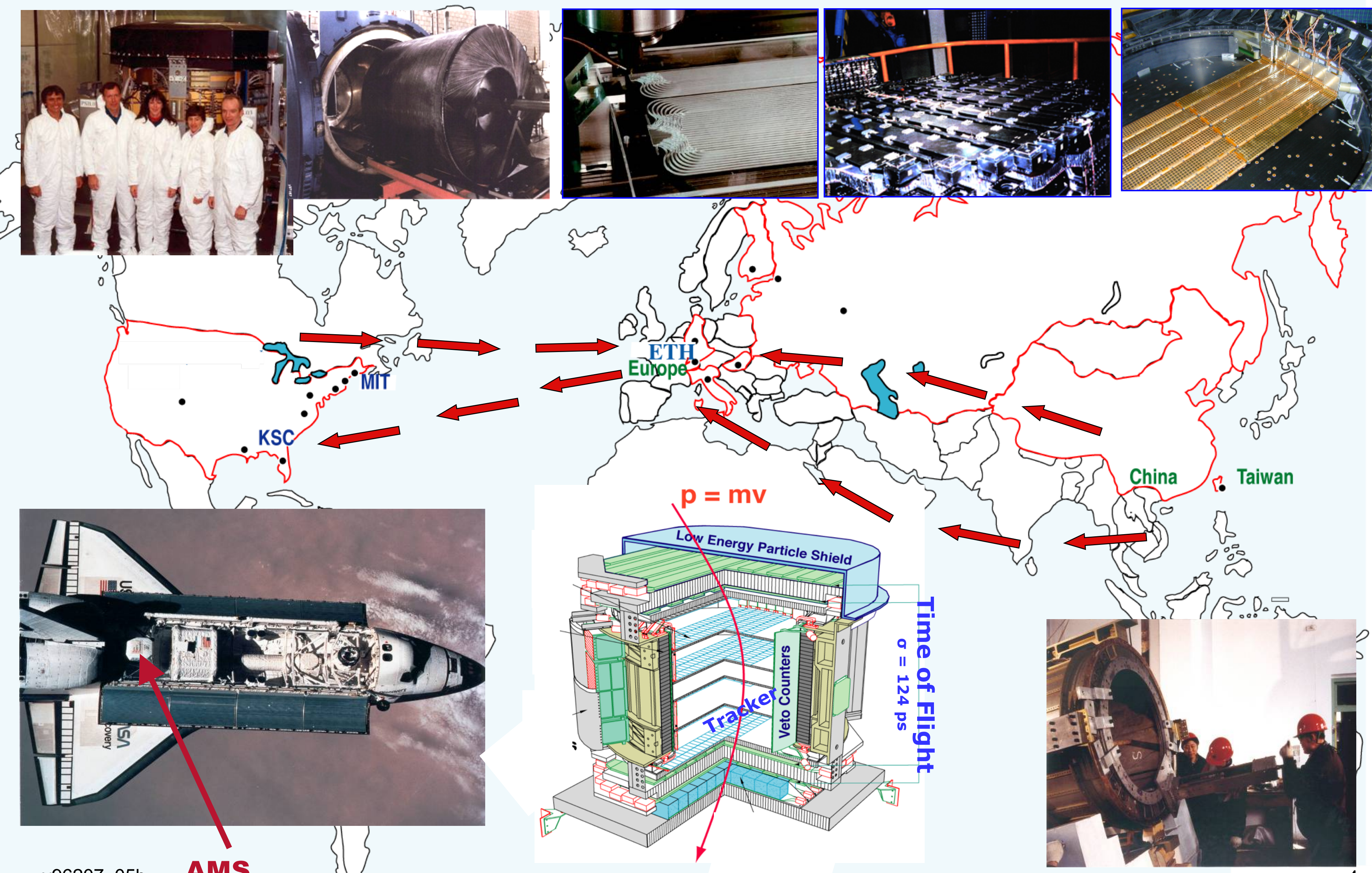





“One of the very first discussions on AMS was at the Erice School of Subnuclear Physics in 1994-1995. AMS results have been presented on many occasions at the School.
We thank Professor Zichichi for his continuing interest and support.”
Samuel Ting

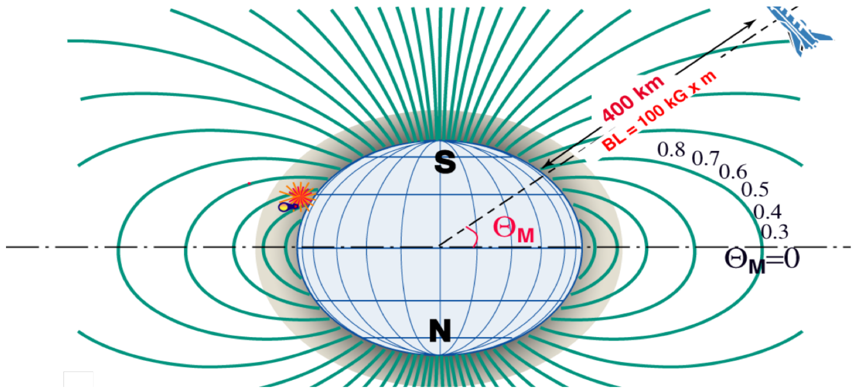
First flight AMS-01

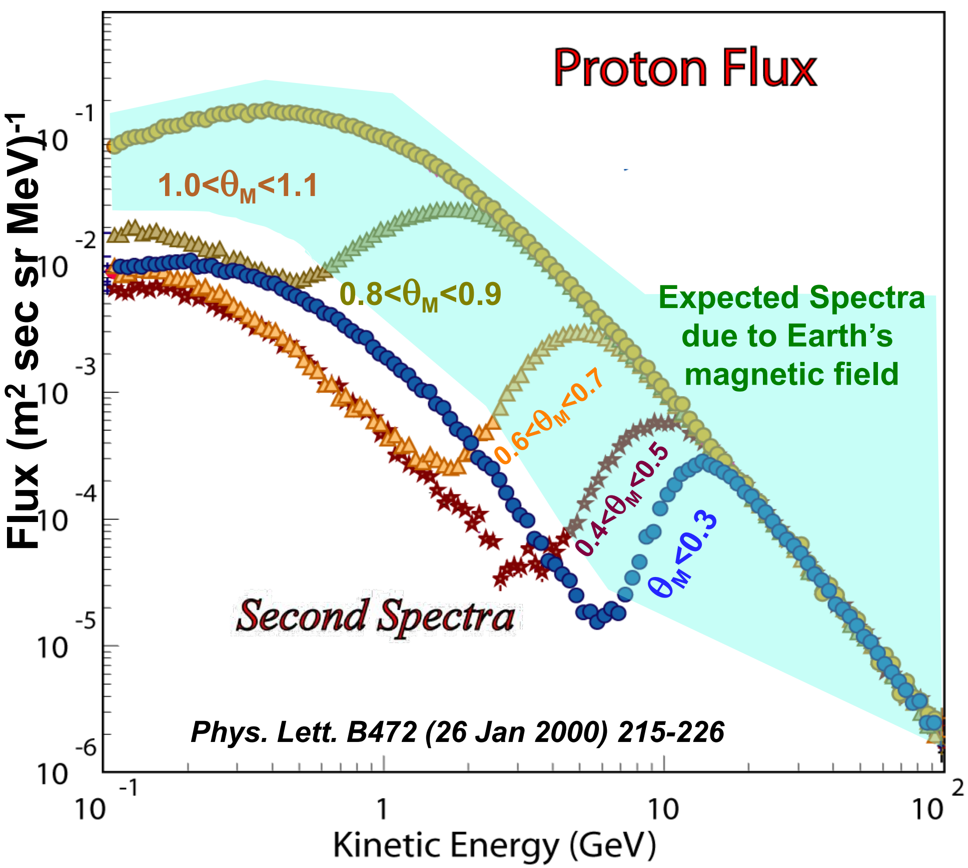
Approval: April 1995, Assembly: December 1997, Flight: 10 days in June 1998



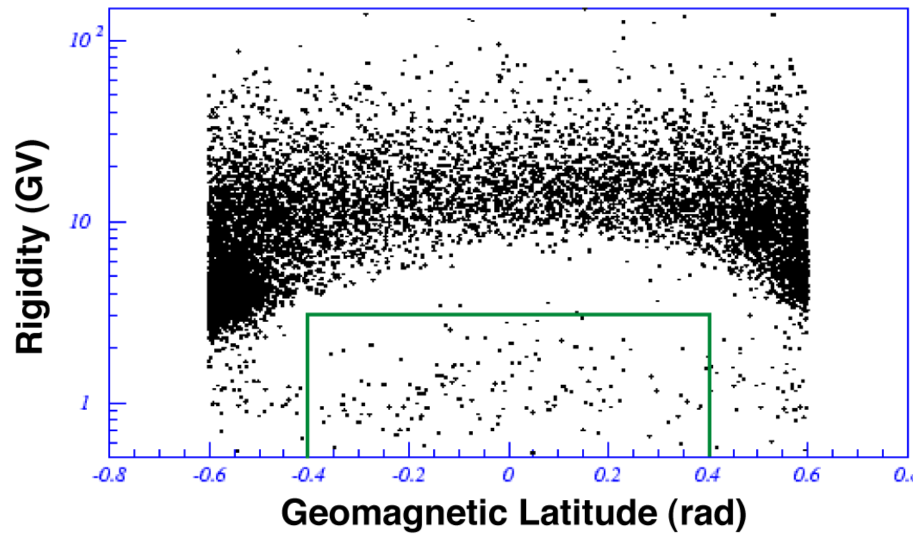
AMS-01 (1998) 10 Days Engineering Flight

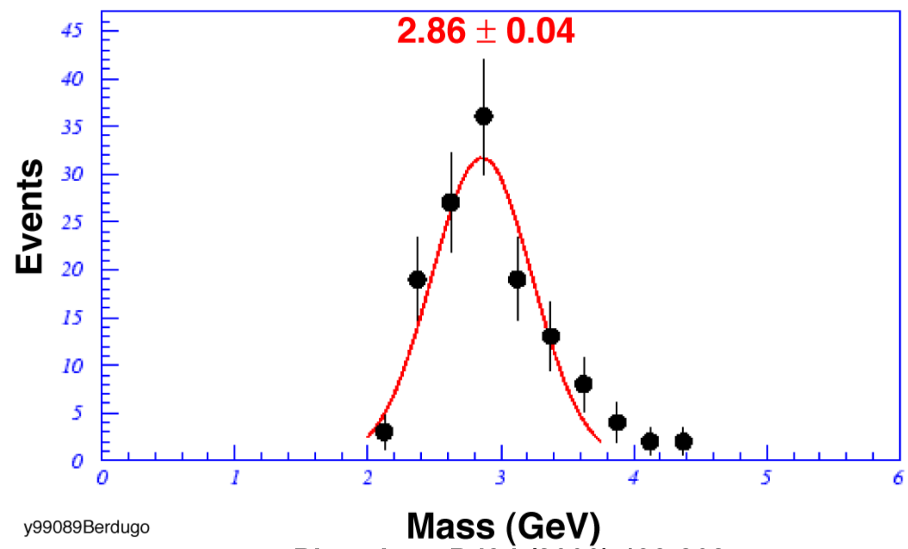
The existence of two Spectra in proton flux





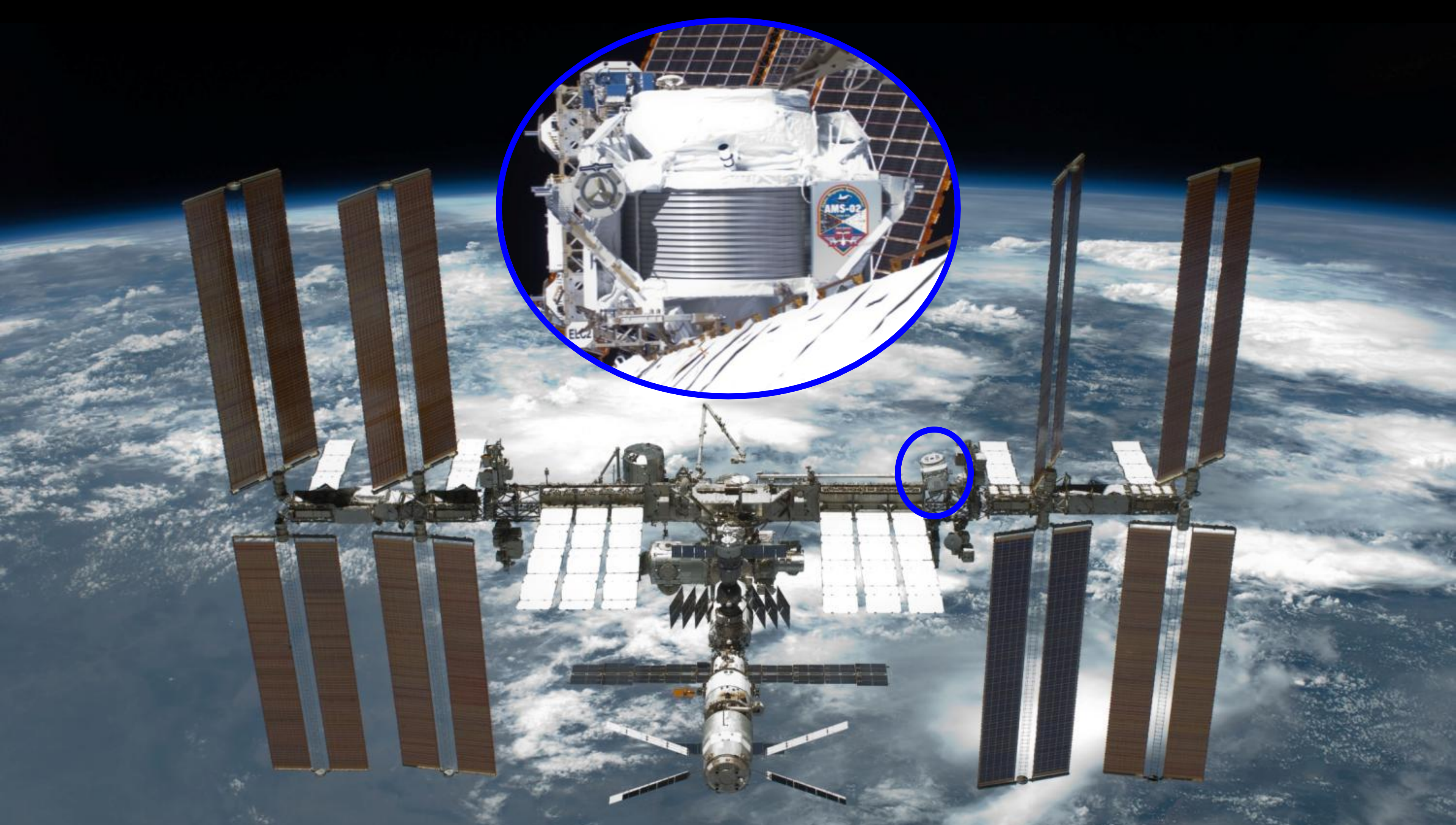
He^4 and He^3 isotopes are completely separated in space





Phys. Lett. B494 (2000) 193-202

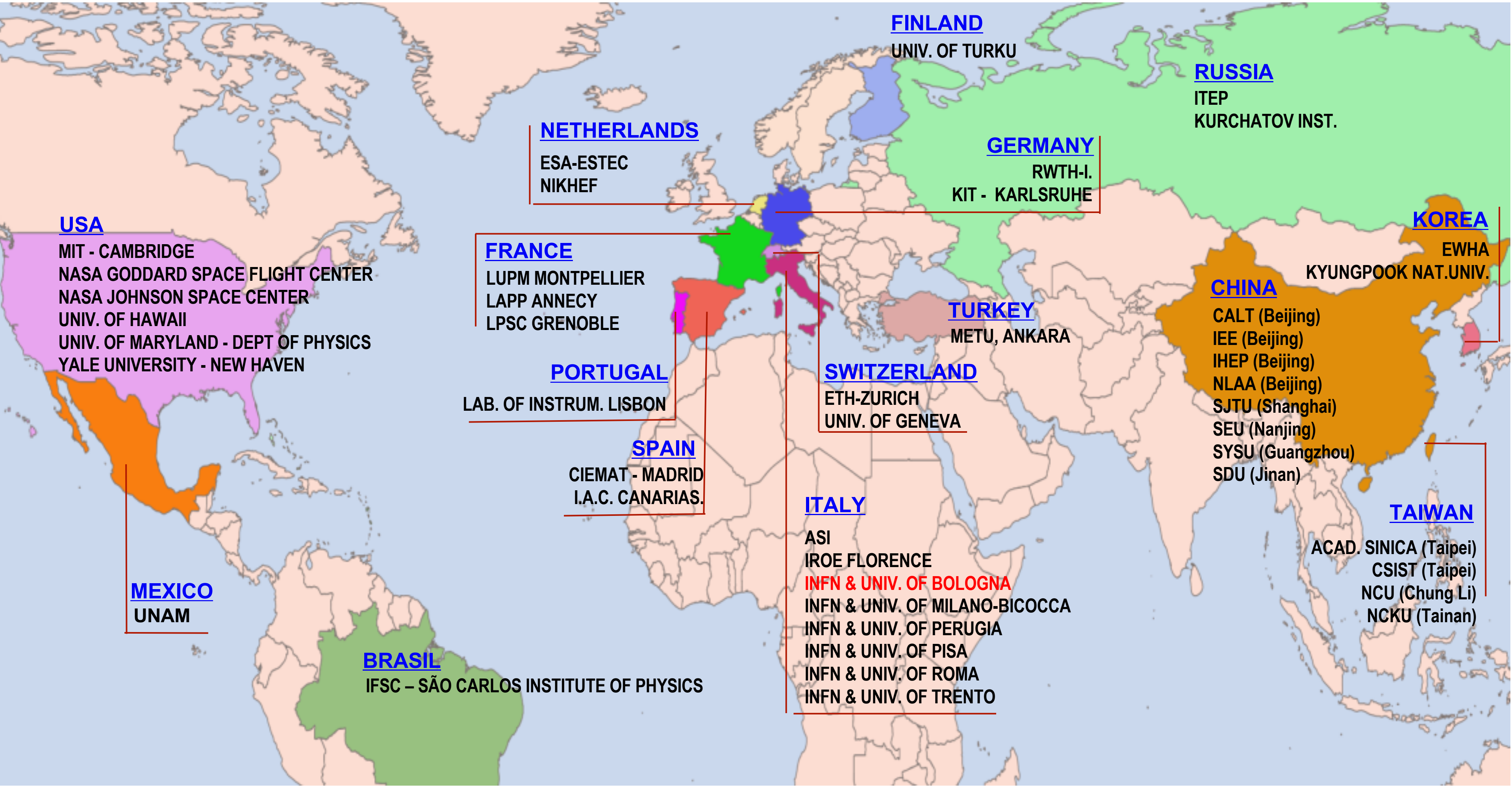
Alpha Magnetic Spectrometer (AMS-02)



In 7 years, over 128 billion charged particles have been measured by AMS

AMS is an International Collaboration

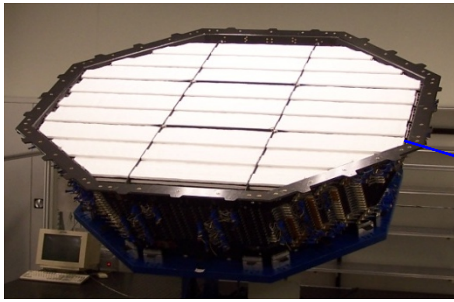
The detectors were constructed in Europe and Asia and assembled at CERN.



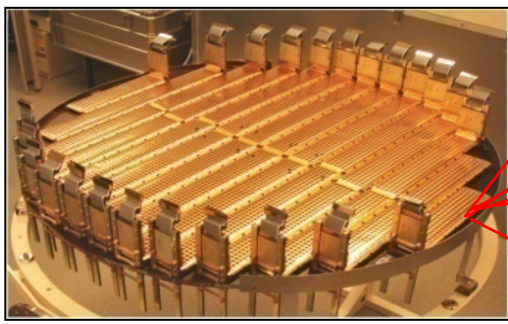

AMS
300,000 electronics channels
650 processors
5m x 4m x 3m
7.5 tons

AMS: A TeV precision, multipurpose spectrometer

TRD
Identify e^+, e^-

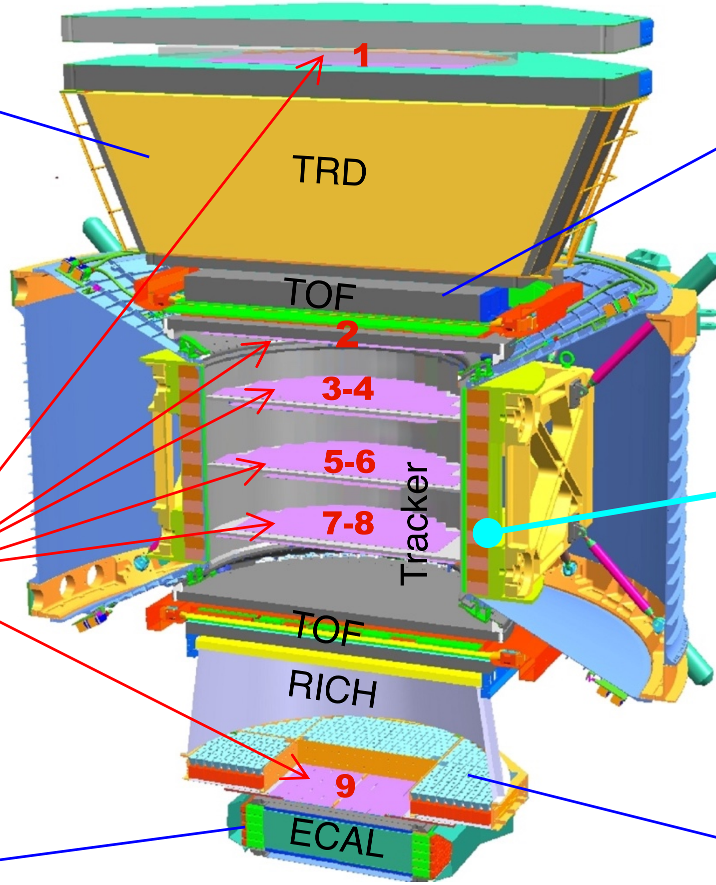


Silicon Tracker
Z, P

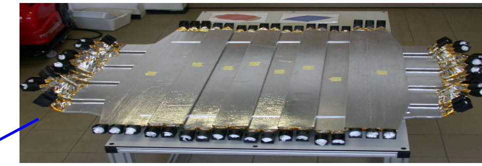


ECAL
E of e^+, e^-, γ

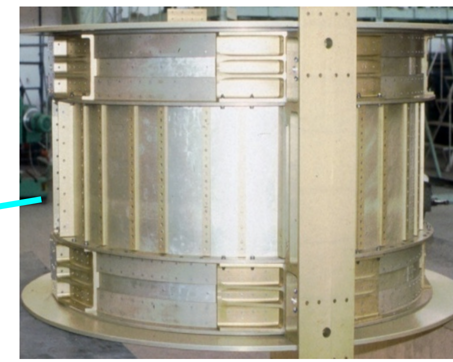
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



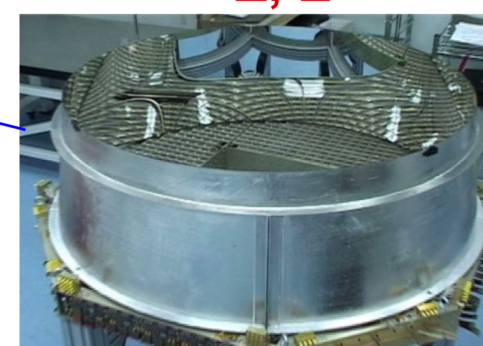
TOF
Z, E



Magnet
±Z



RICH
Z, E

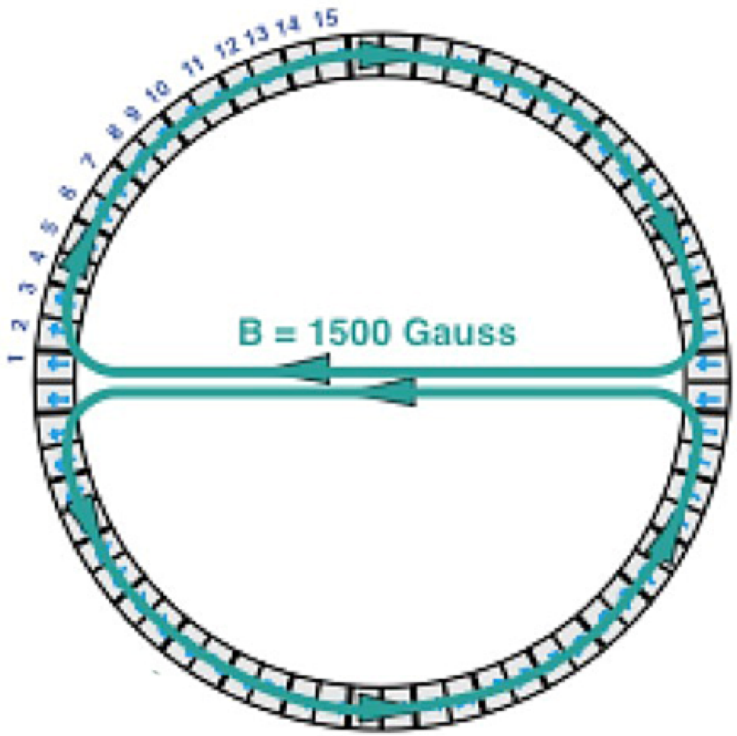


Z, P or R (=P/Z) are measured independently by the Tracker, RICH, TOF and ECAL

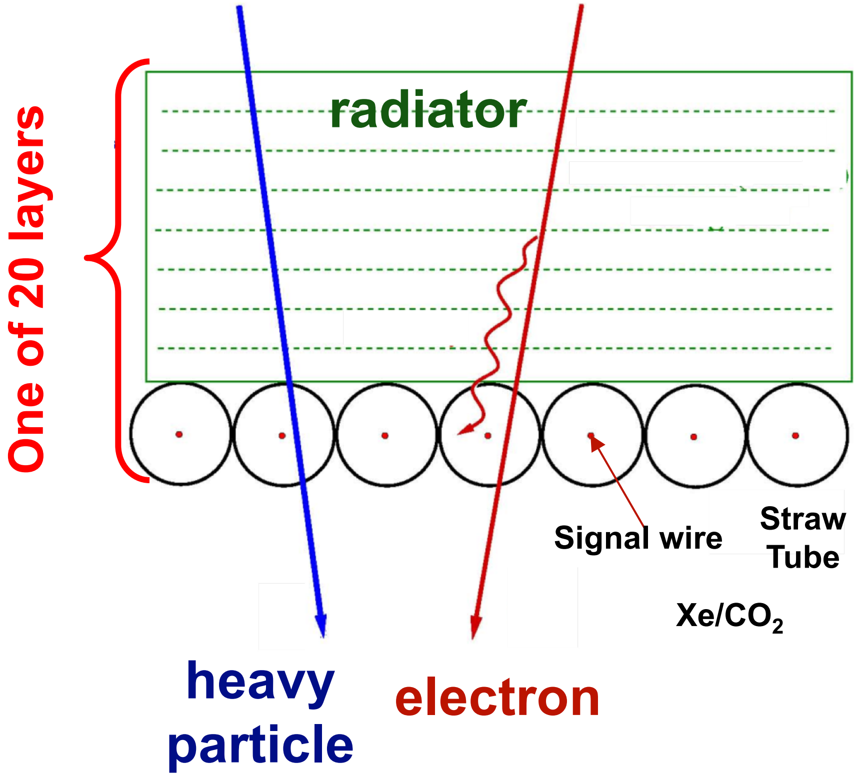
Magnet System: 10 Magnets were made

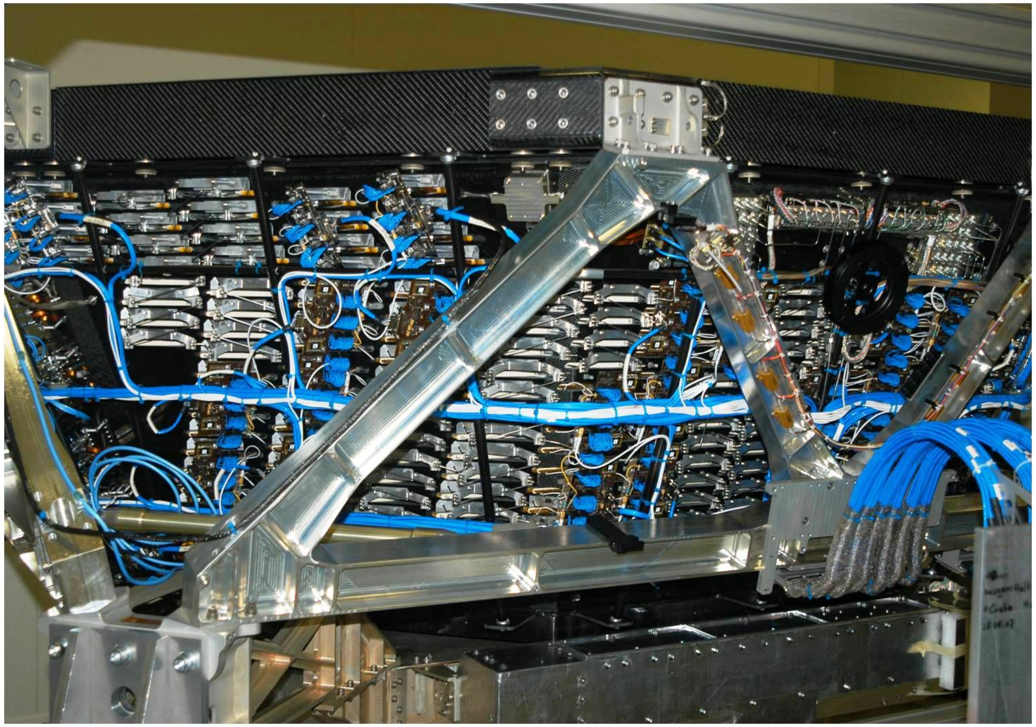
Seven magnets to understand the field calculation, leakage and dipole moment

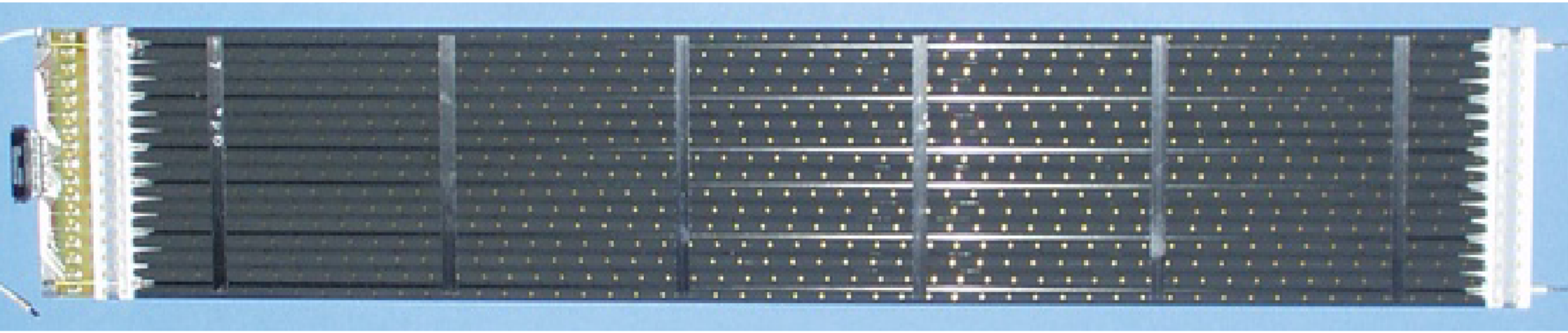
Three full-size magnets for 1) space qualification, 2) destructive testing and 3) flight



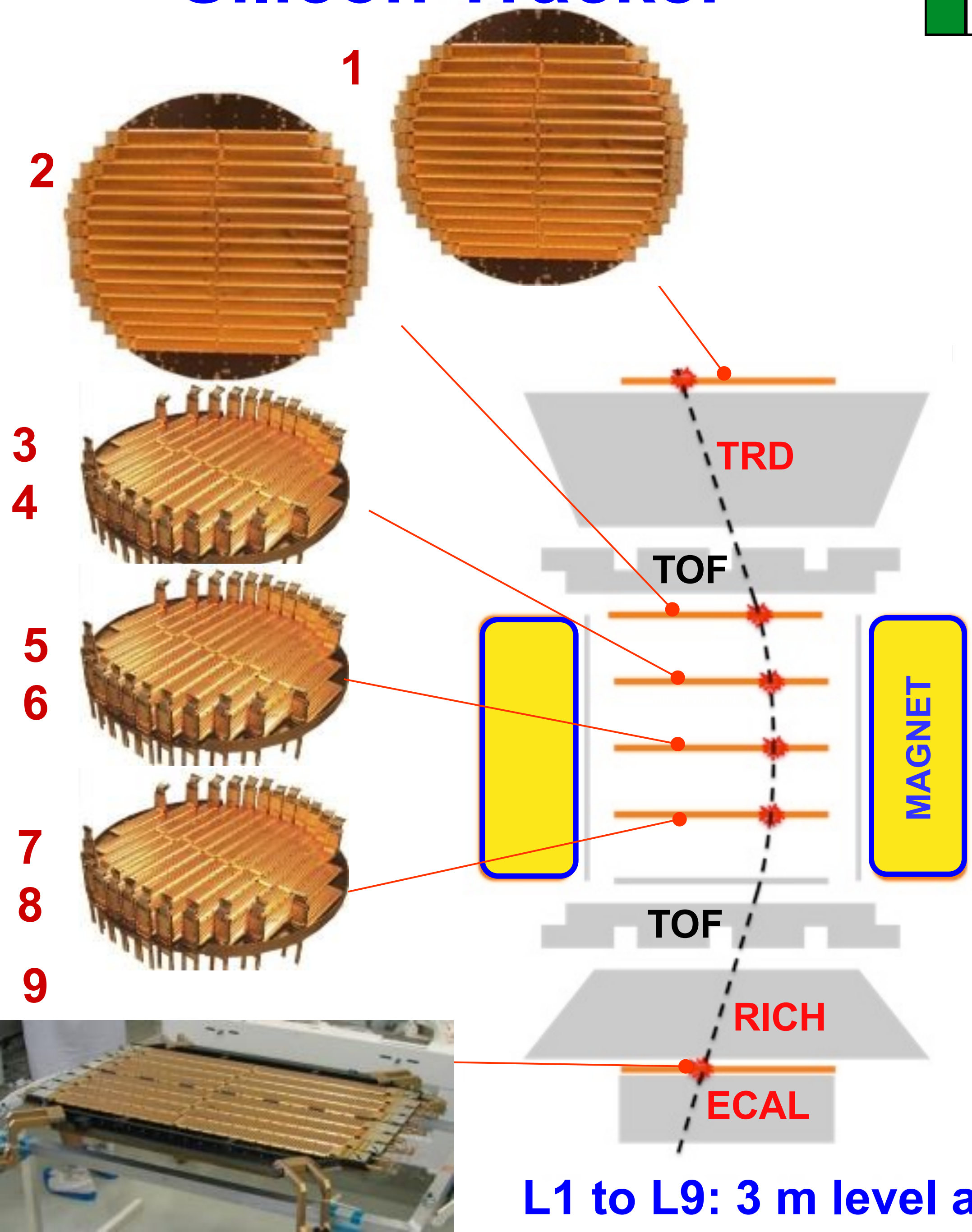
Transition Radiation Detector (TRD): identifies Positrons and Electrons

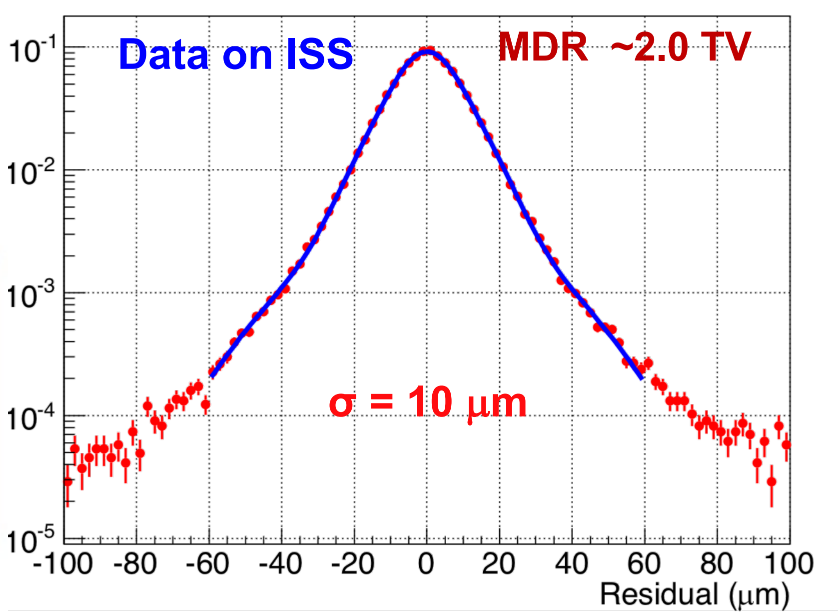






Silicon Tracker

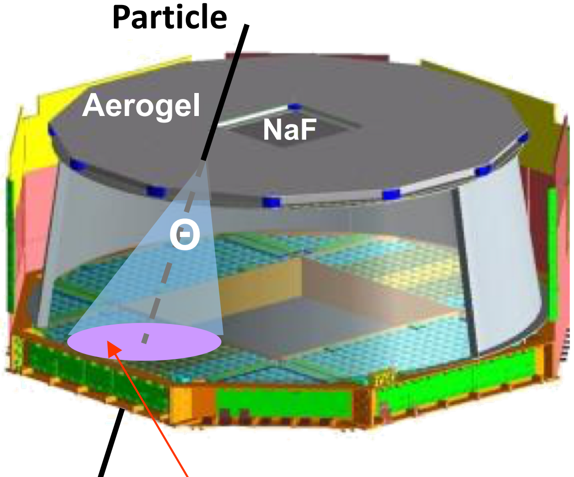




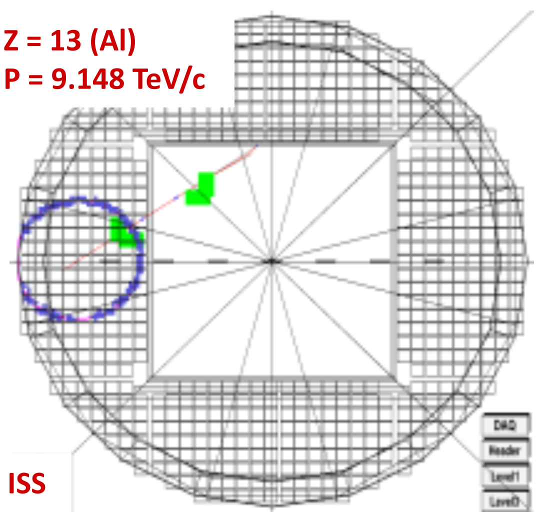
L1 to L9: 3 m level arm

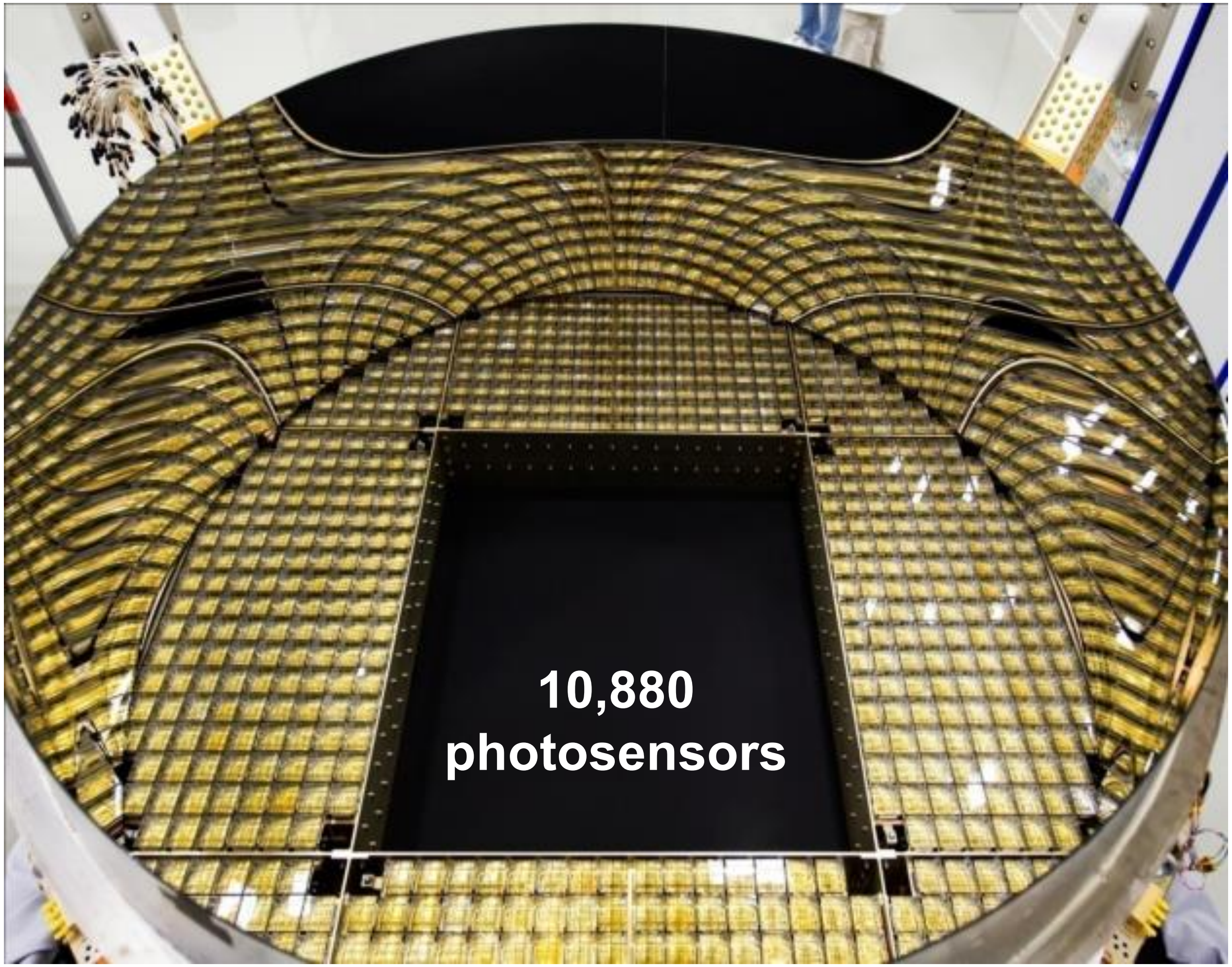
Ring Imaging CHerenkov (RICH)

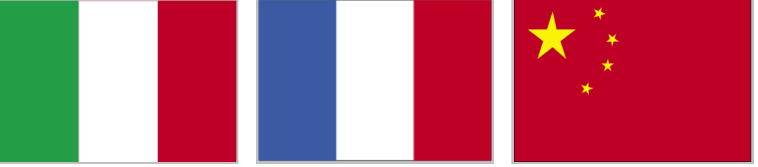
Measurement of Nuclear Charge and its Velocity to 1/1000



Intensity ⇒ Z^2 $\Theta \Rightarrow V$







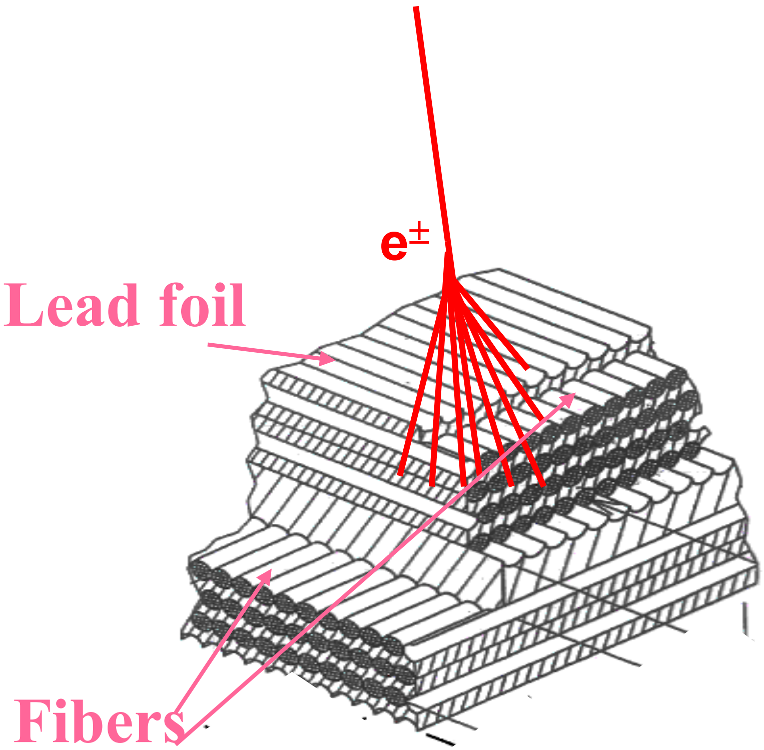
Electromagnetic Calorimeter

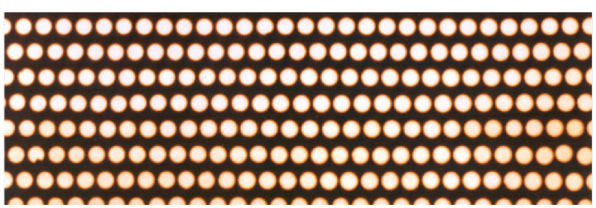
provides a precision, 17 X_0, TeV, 3-dimensional measurement of

1. the directions to ± 1 degree

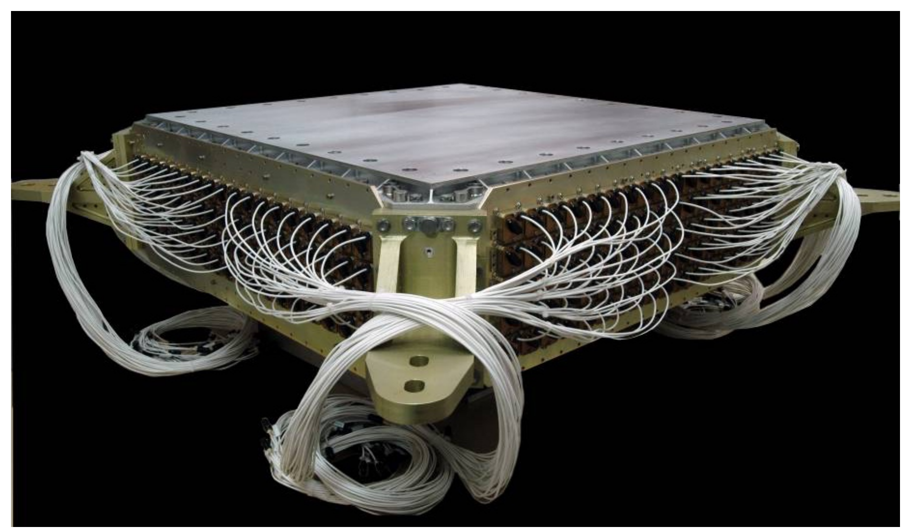
2. the energy resolution of 2%

3. Distinguishes electrons and positrons from protons, helium, …by a factor of 10,000

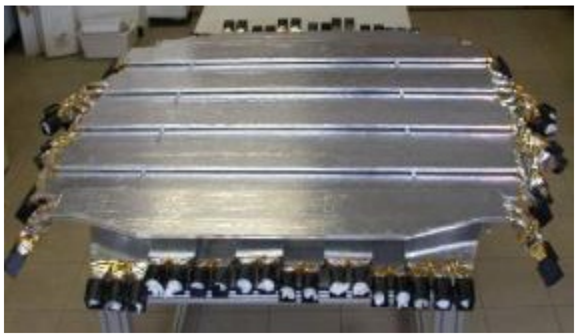




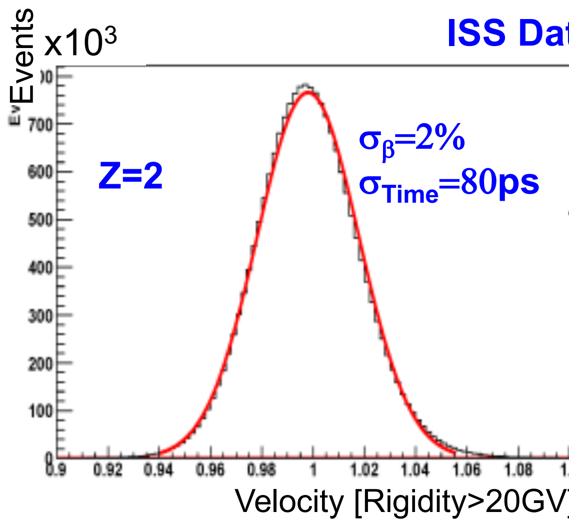
50 000 fibers, $\phi = 1$ mm
distributed uniformly
inside 600 Kg of lead

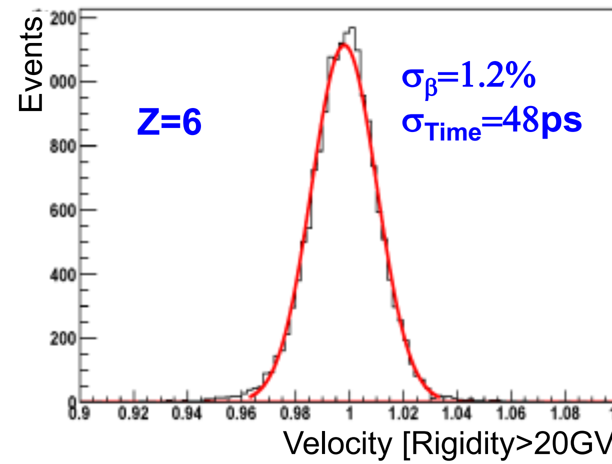


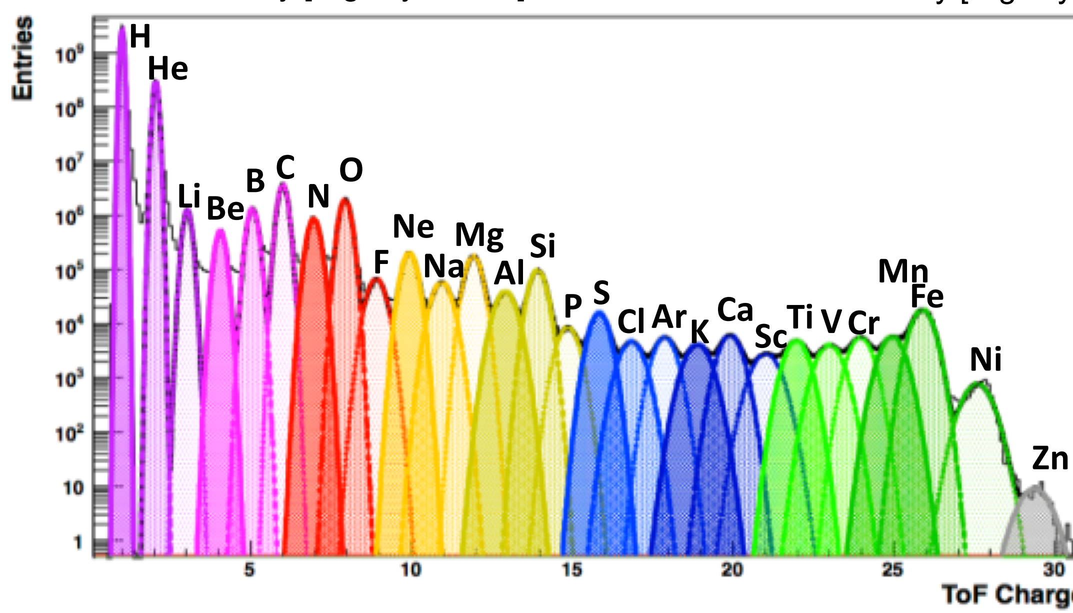
Time of Flight



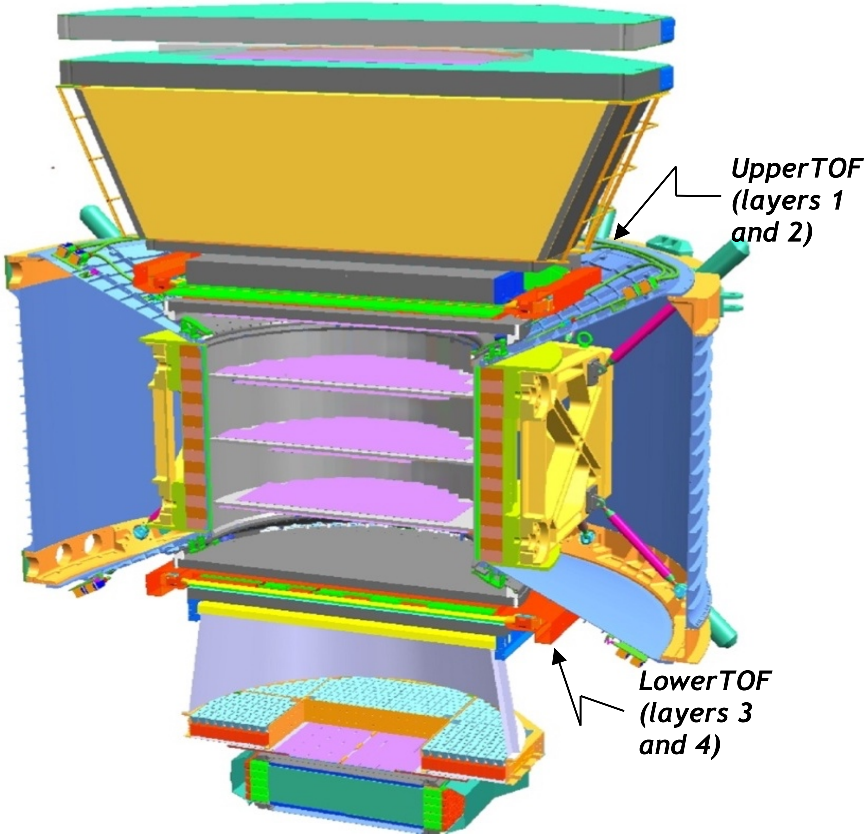
ISS Data on Velocity and Charge

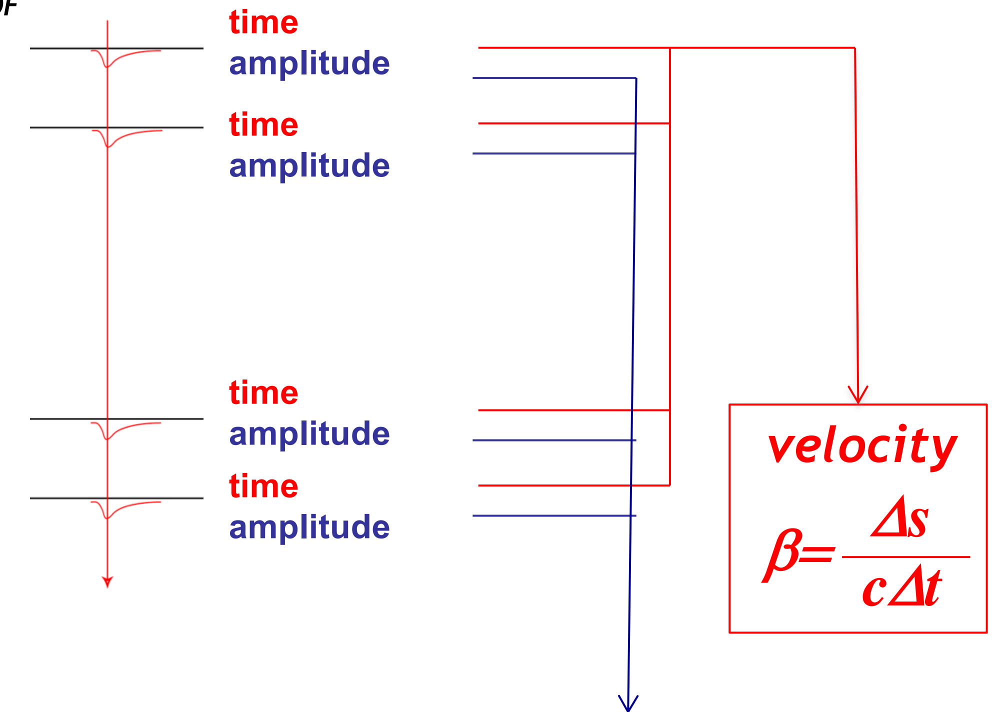






Principles





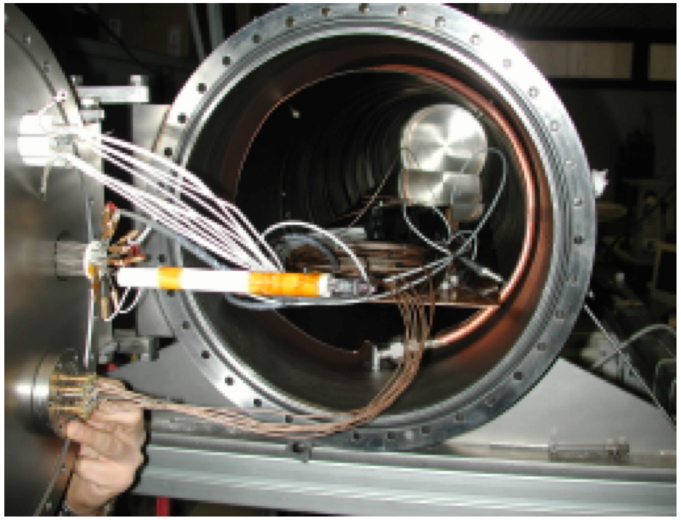
charge

$Z = \sqrt{ampl}$

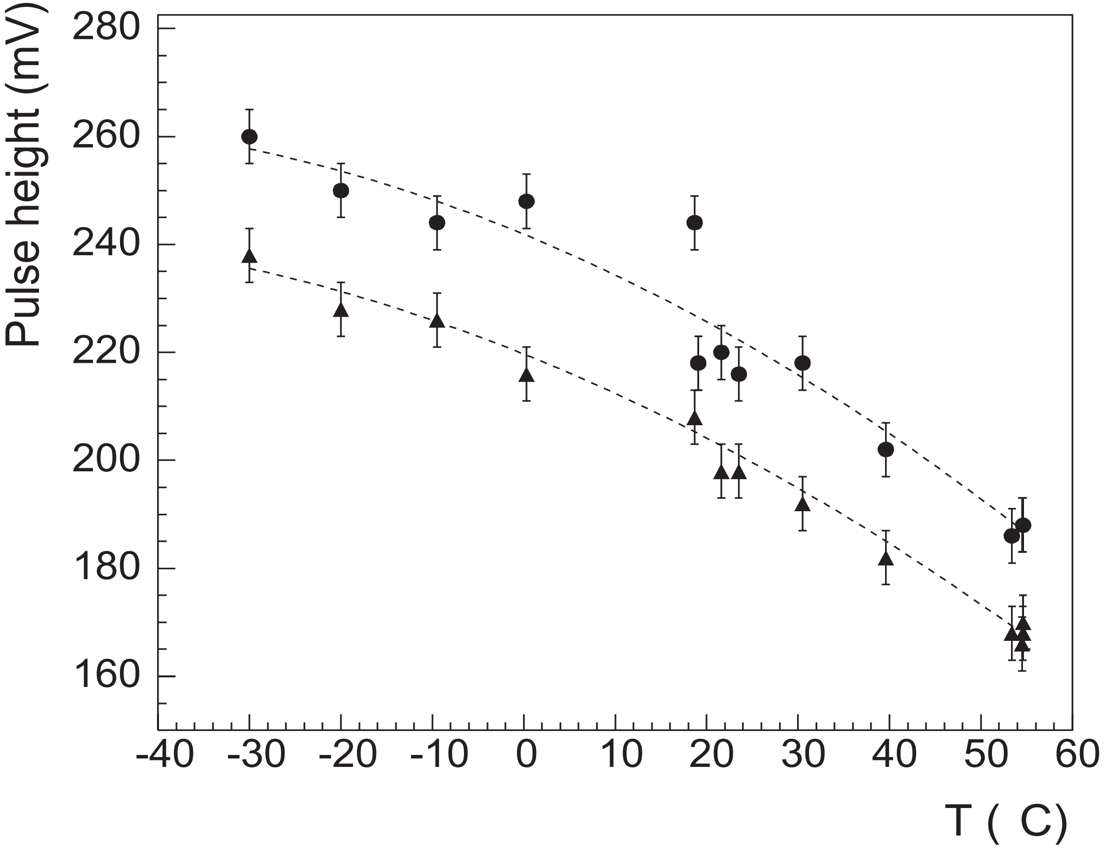
Purpose

- *To start the data acquisition to the experiment.*
- *To distinguish at the trigger level protons from higher charge nuclei.*
- *To measure the time of flight of the particles traversing the detector with a resolution sufficient to distinguish upward from downward going particles at a level of at least 10^{-9}.*
- *To measure the absolute charge of the particle.*

Thermal behavior

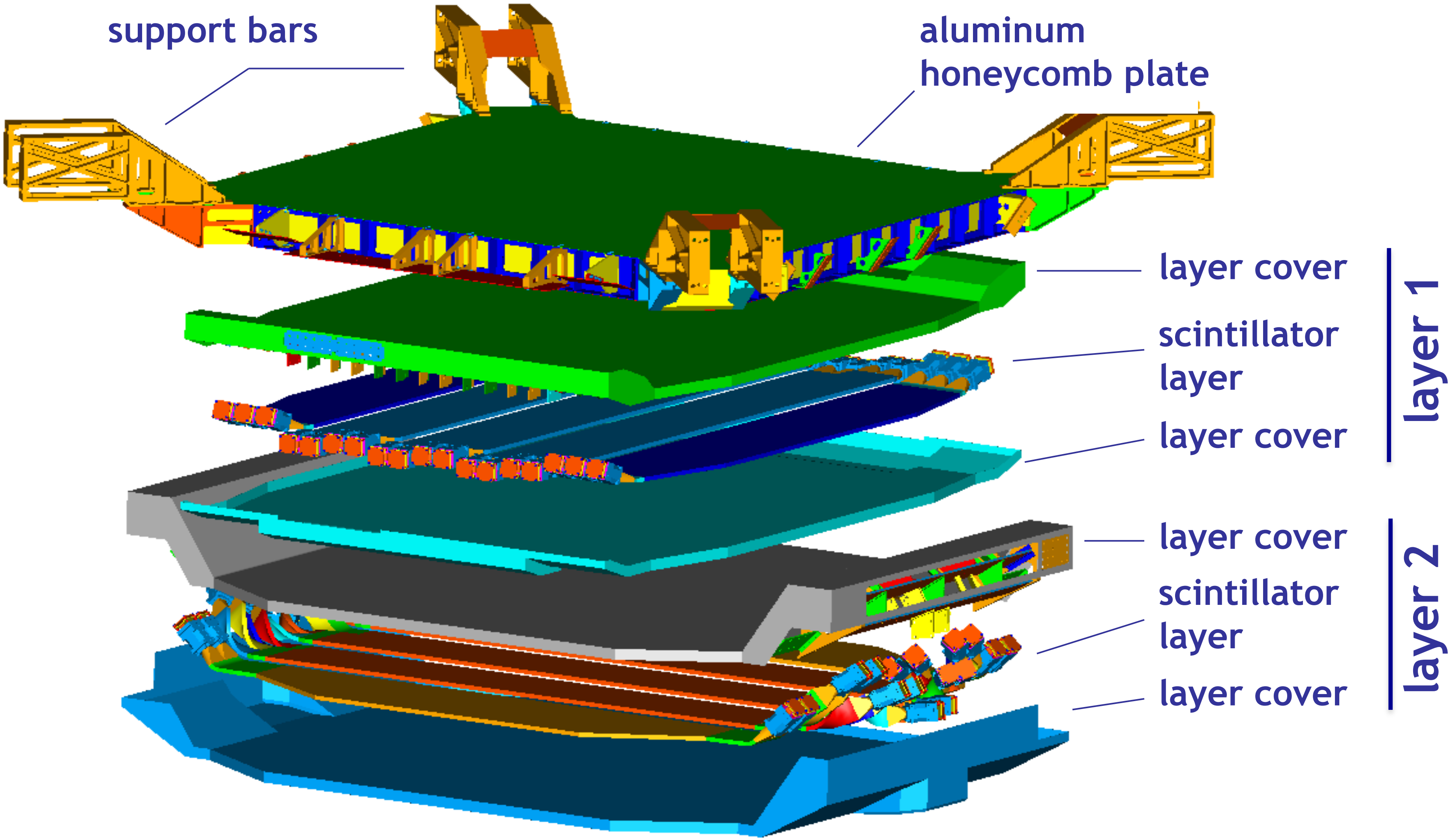


PMTs have been tested in the thermal vacuum chamber in Bologna



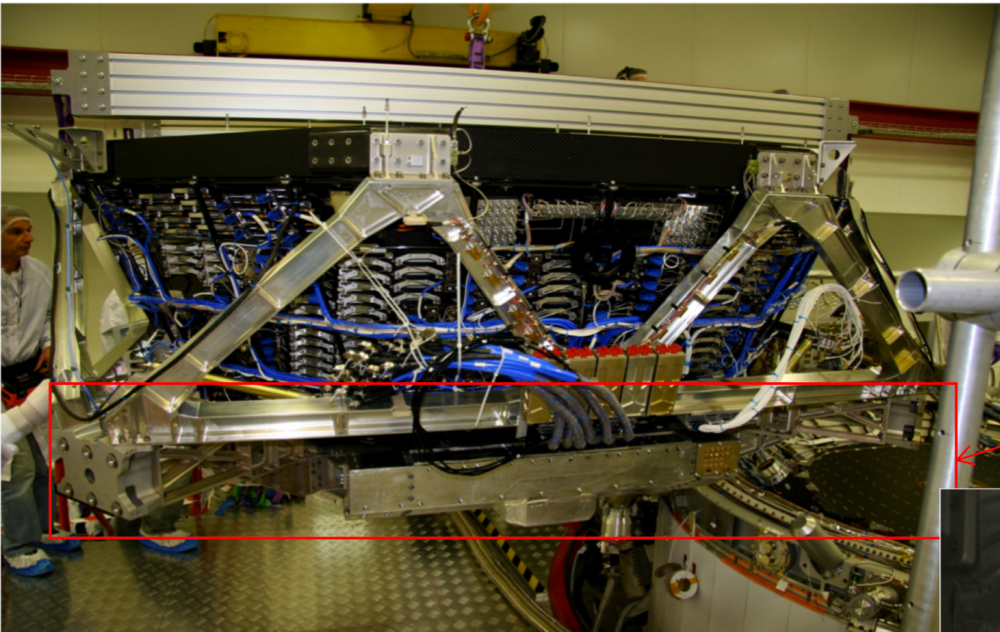
Trigger efficiency may vary with temperature.
Operations at high temperatures may damage the photocathode (evaporation).

Mechanical structure

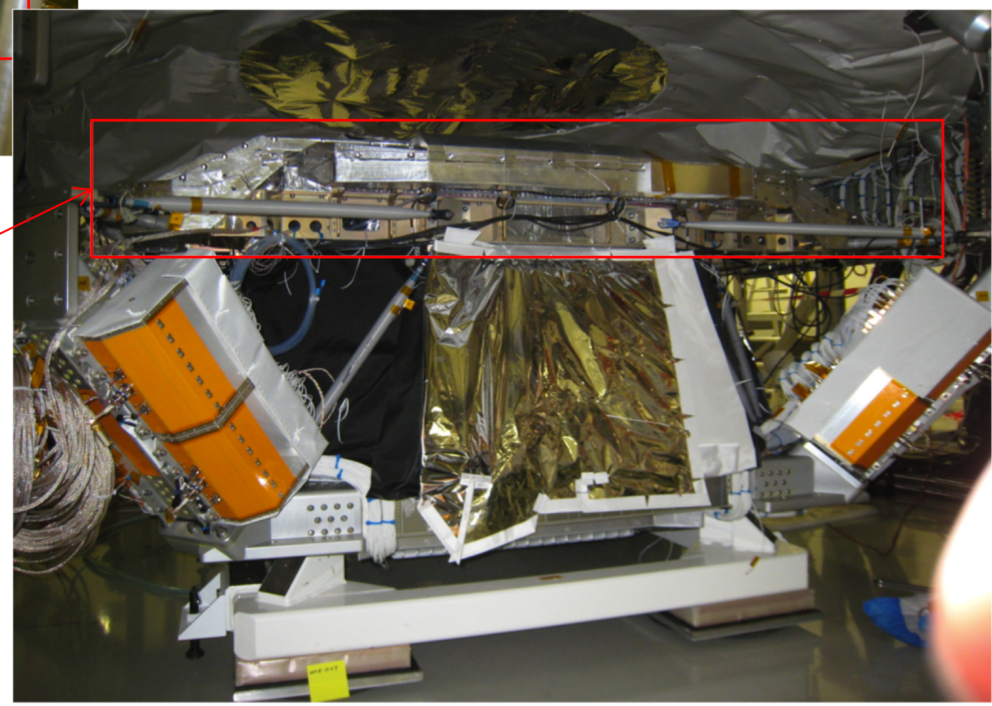


Vibration resistant up to 13 g

Detector integration in May 2010



UTOF

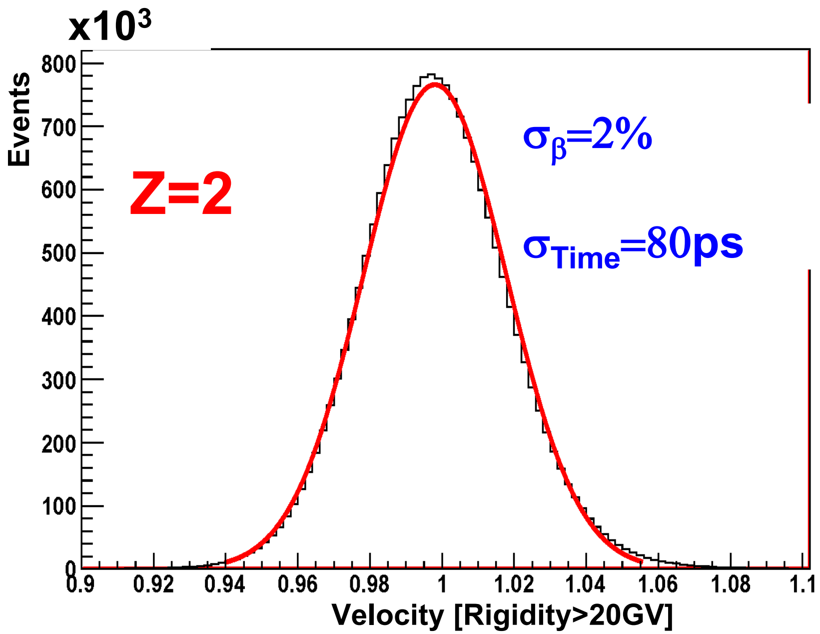


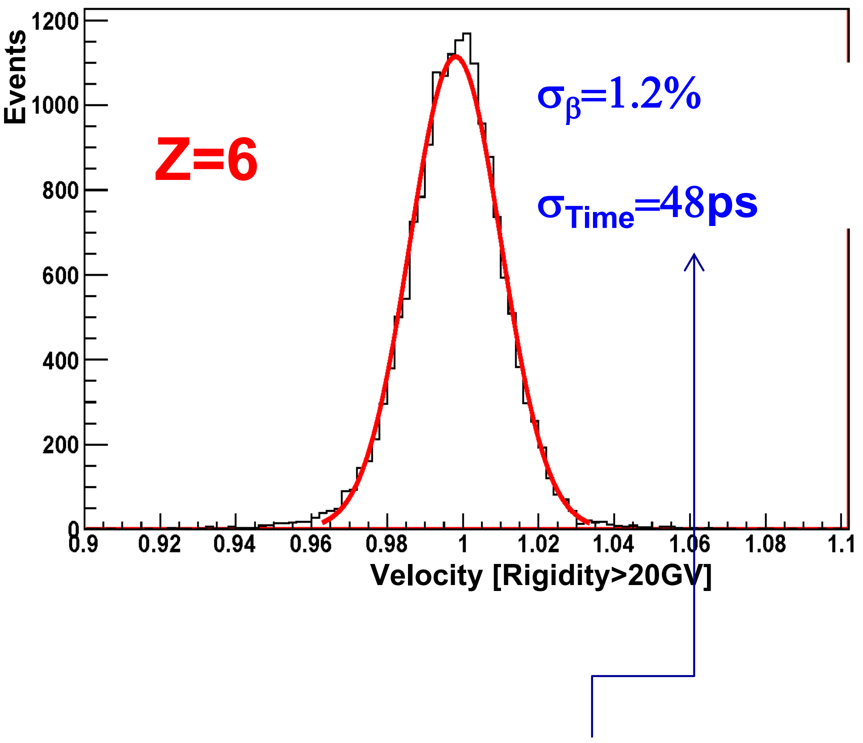
LTOF

LTOF+RICH+ECAL

Beta measurement

Time resolution improves with Z



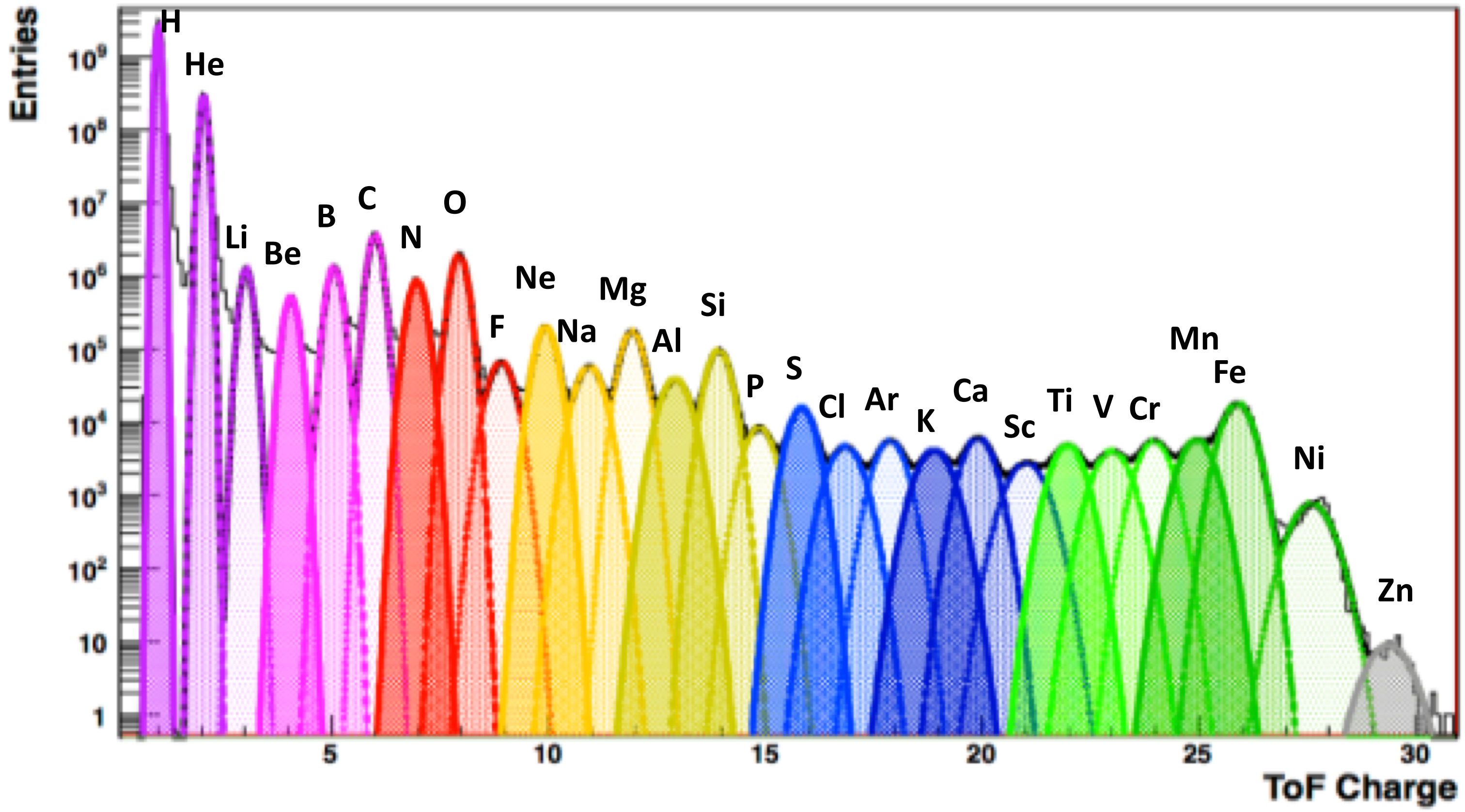


Electronics resolution

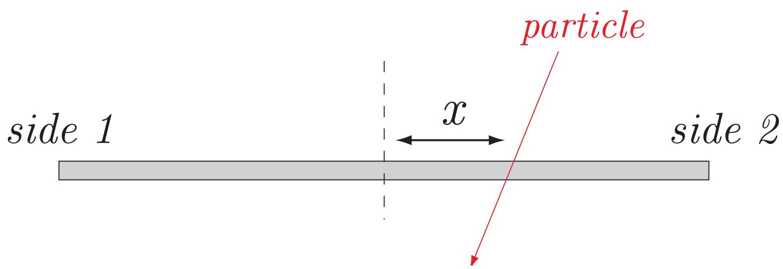
Charge measurement

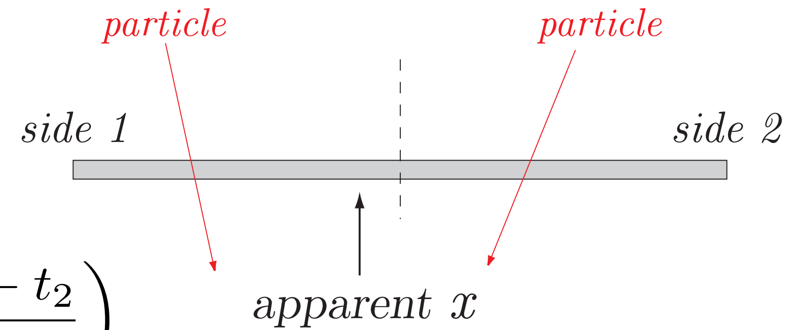
After careful calibration with space data using the redundancy of the AMS-02 apparatus

overall resolution: 2% ×Z

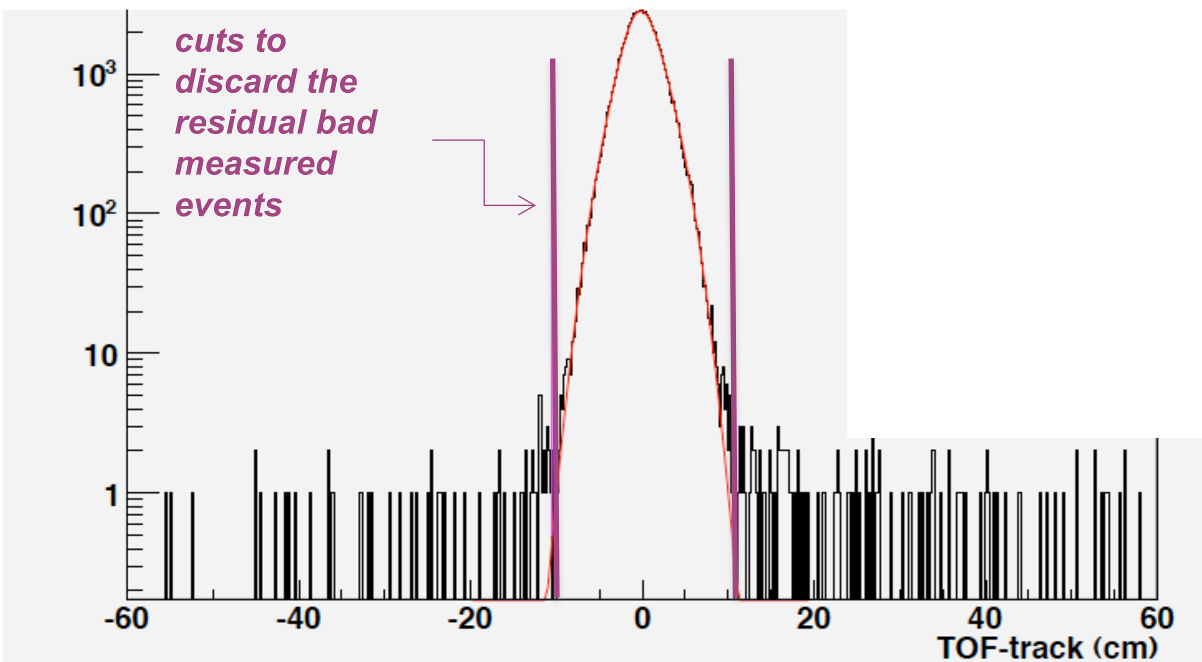


Background rejection





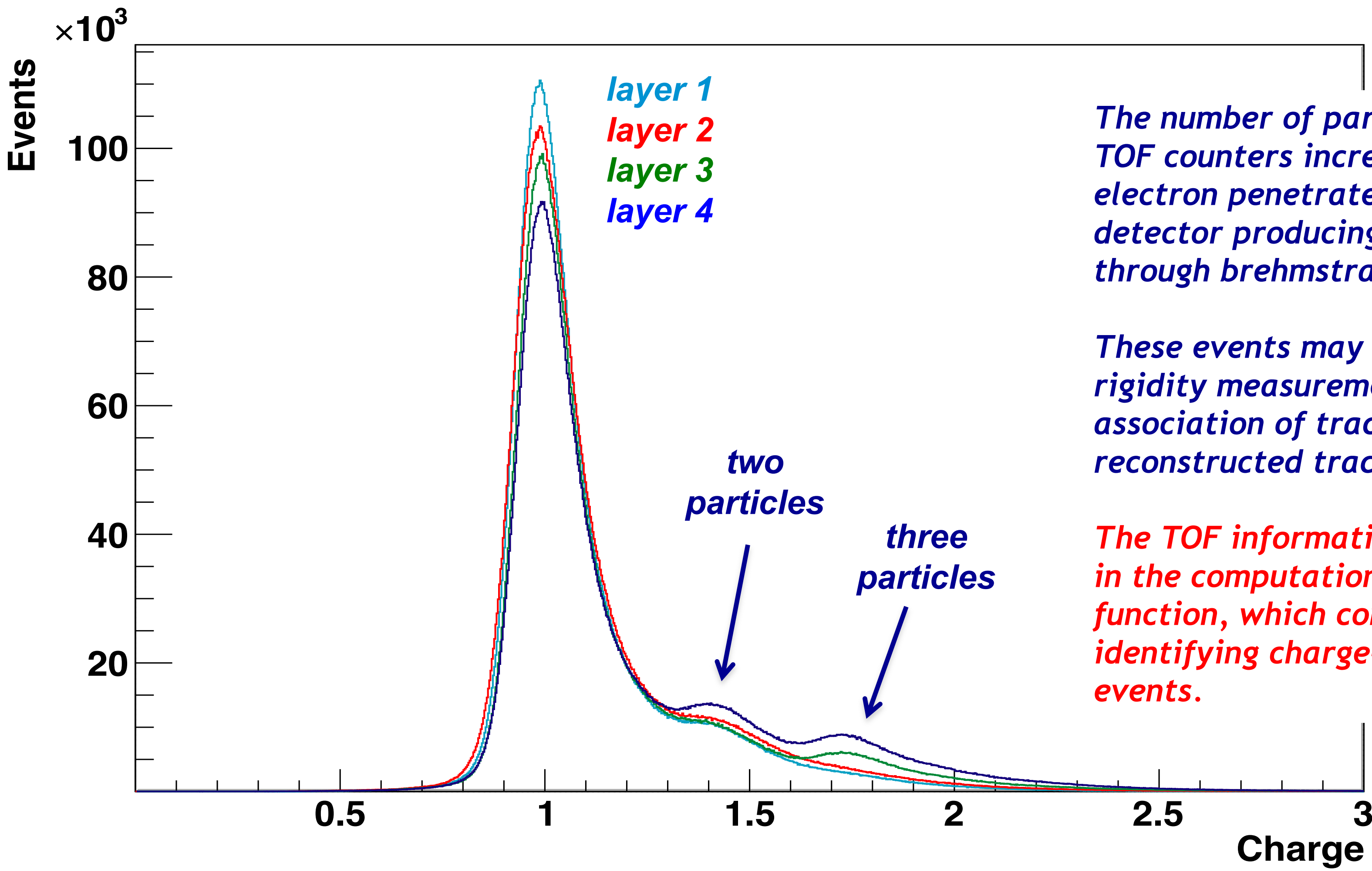
$$x = v_{\text{light}} \left(\frac{t_1 - t_2}{2} \right)$$



Difference between the longitudinal coordinate measured by one paddle in the TOF system and the longitudinal coordinate of the hit point of the reconstructed track

Event tagging

Apparent charge of electrons selected by TRD and ECAL



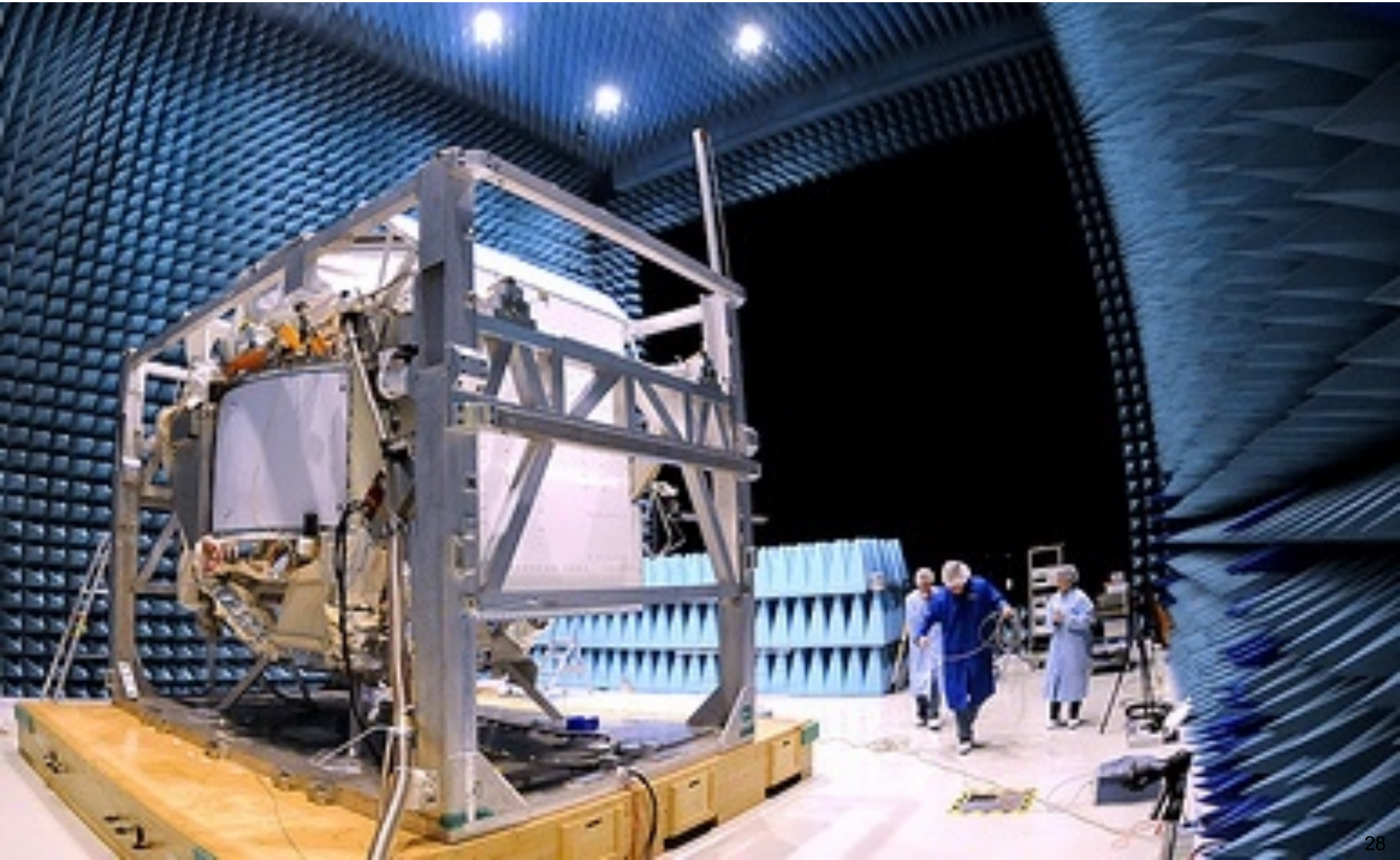
The number of particles hitting the TOF counters increases as the electron penetrates deeper in the detector producing more particles through brehmstrallung.

These events may suffer of a bad rigidity measurement due to wrong association of tracker hits to the reconstructed track.

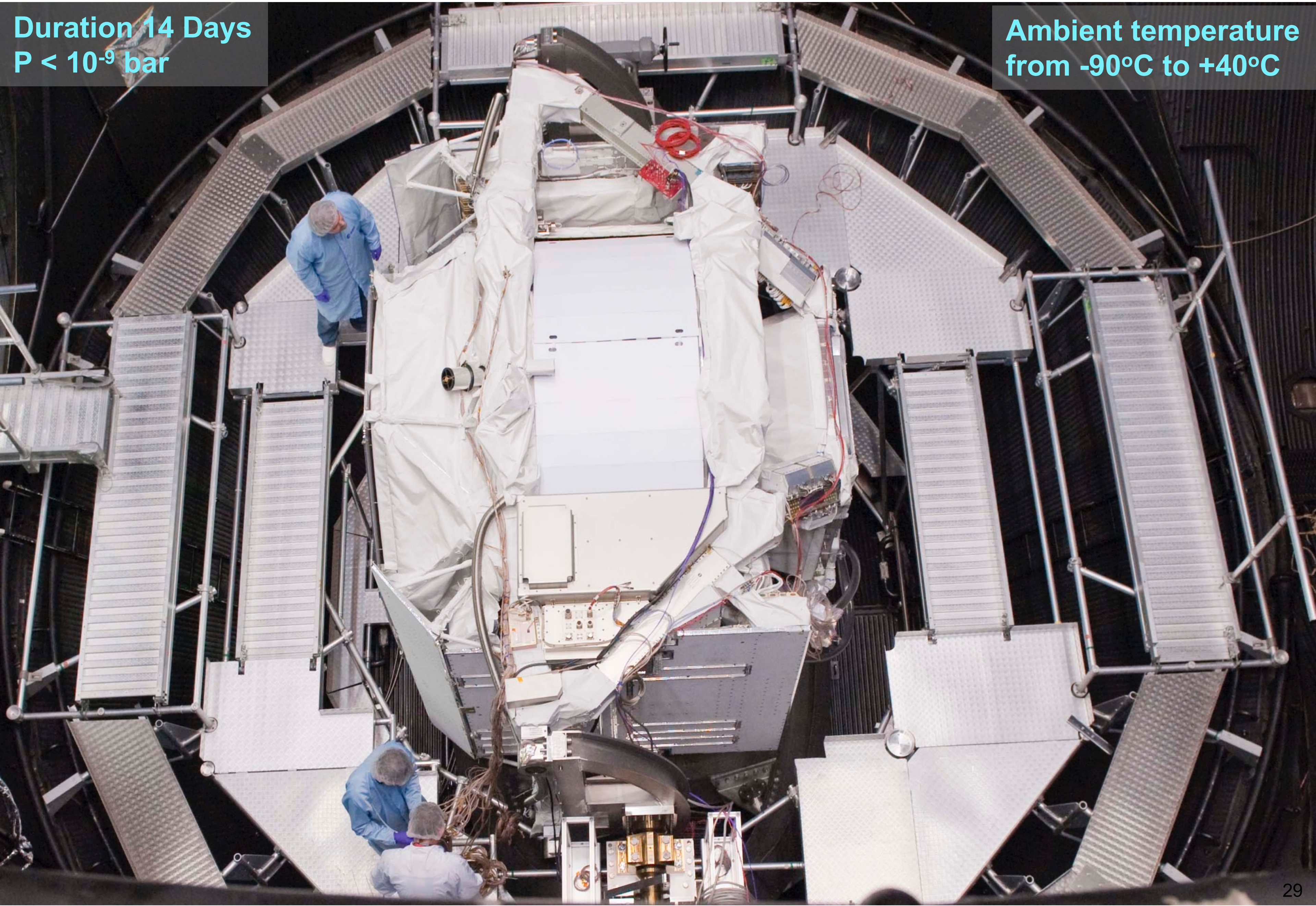
The TOF information can be used in the computation of a likelihood function, which contribute in identifying charge-confusion events.

TOF system – Bologna team

AMS in the ESA Electromagnetic Interference (EMI) Chamber, March 2010, ESTEC, Noordwijk, the Netherlands

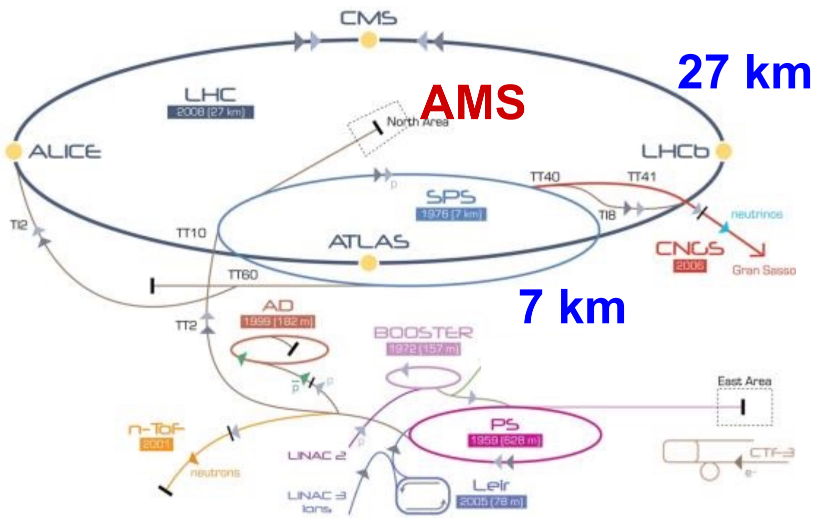


AMS in the ESA TVT Chamber, April 2010, ESTEC

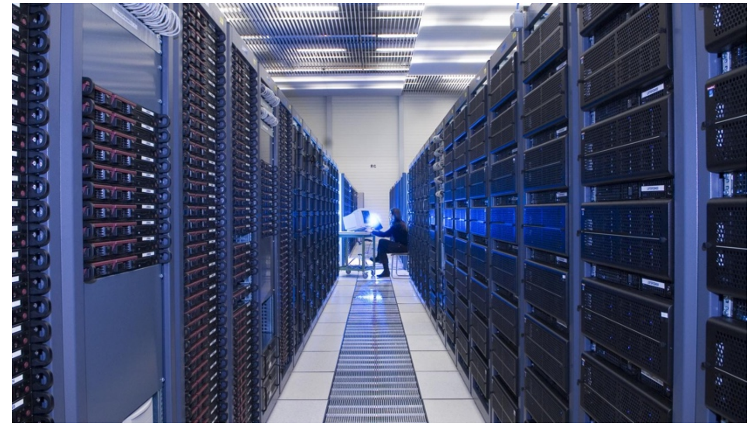


Calibration of the AMS Detector

Test beam at CERN SPS:
p, e$^{\pm}$, π$^{\pm}$, 10−400 GeV

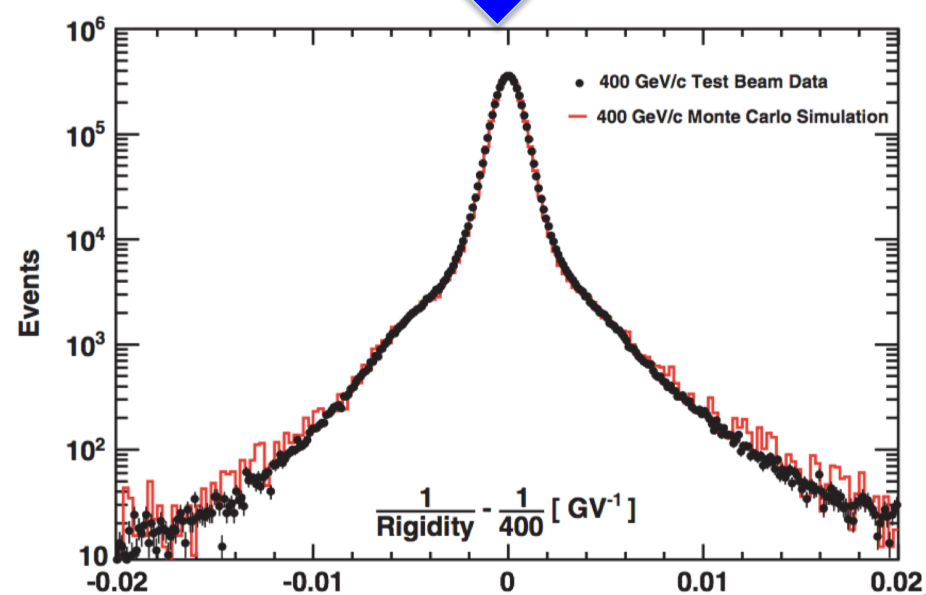


10,000 CPU cores provided by CERN



Computer simulation:
Interactions, Materials, Electronics

2000 positions



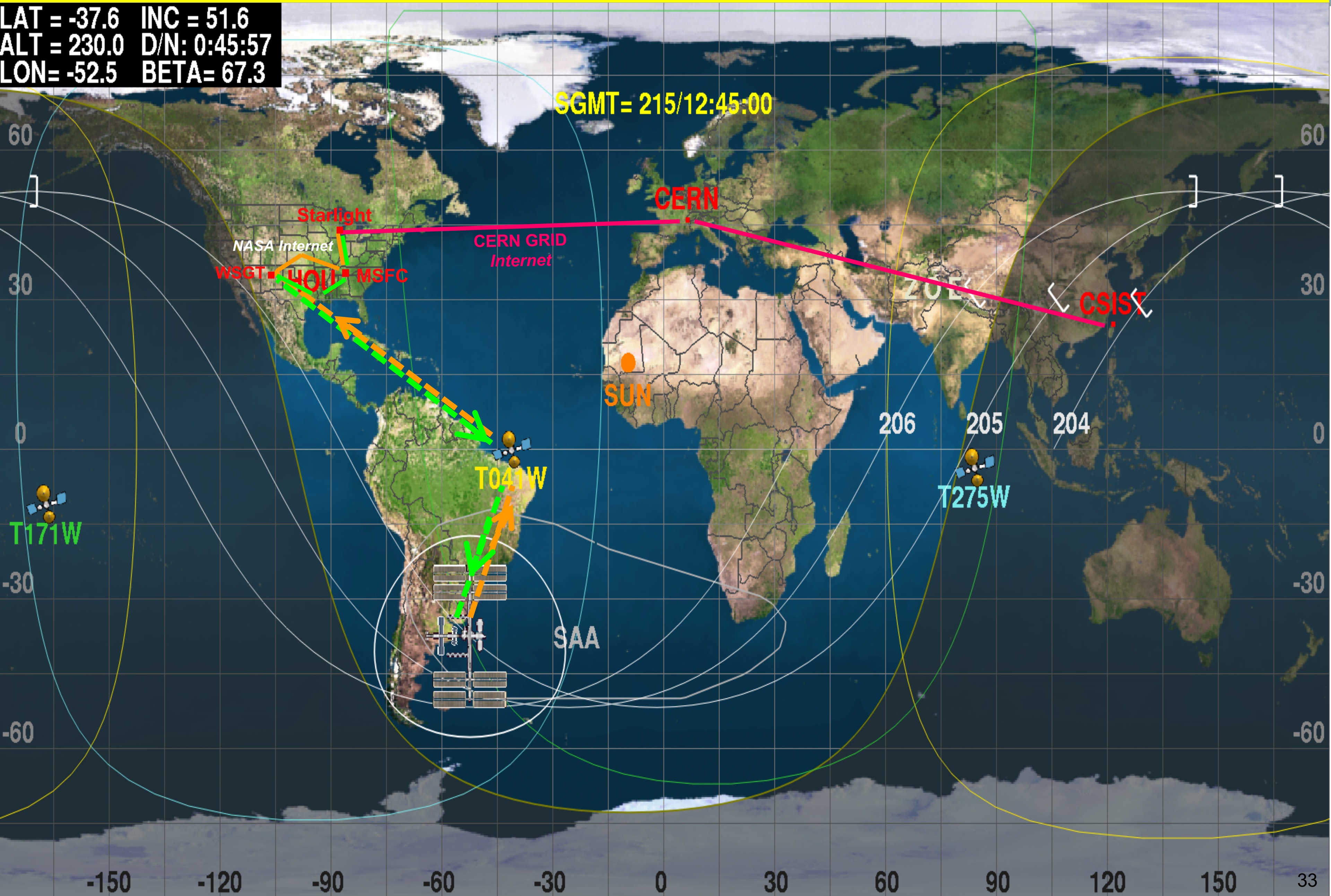
May 16, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t

May 19: AMS installation completed at 5:15 AM.
Data taking started at 9:35 AM

Communications for AMS on ISS

To prevent damage to AMS, we need to know the conditions within 4 hours

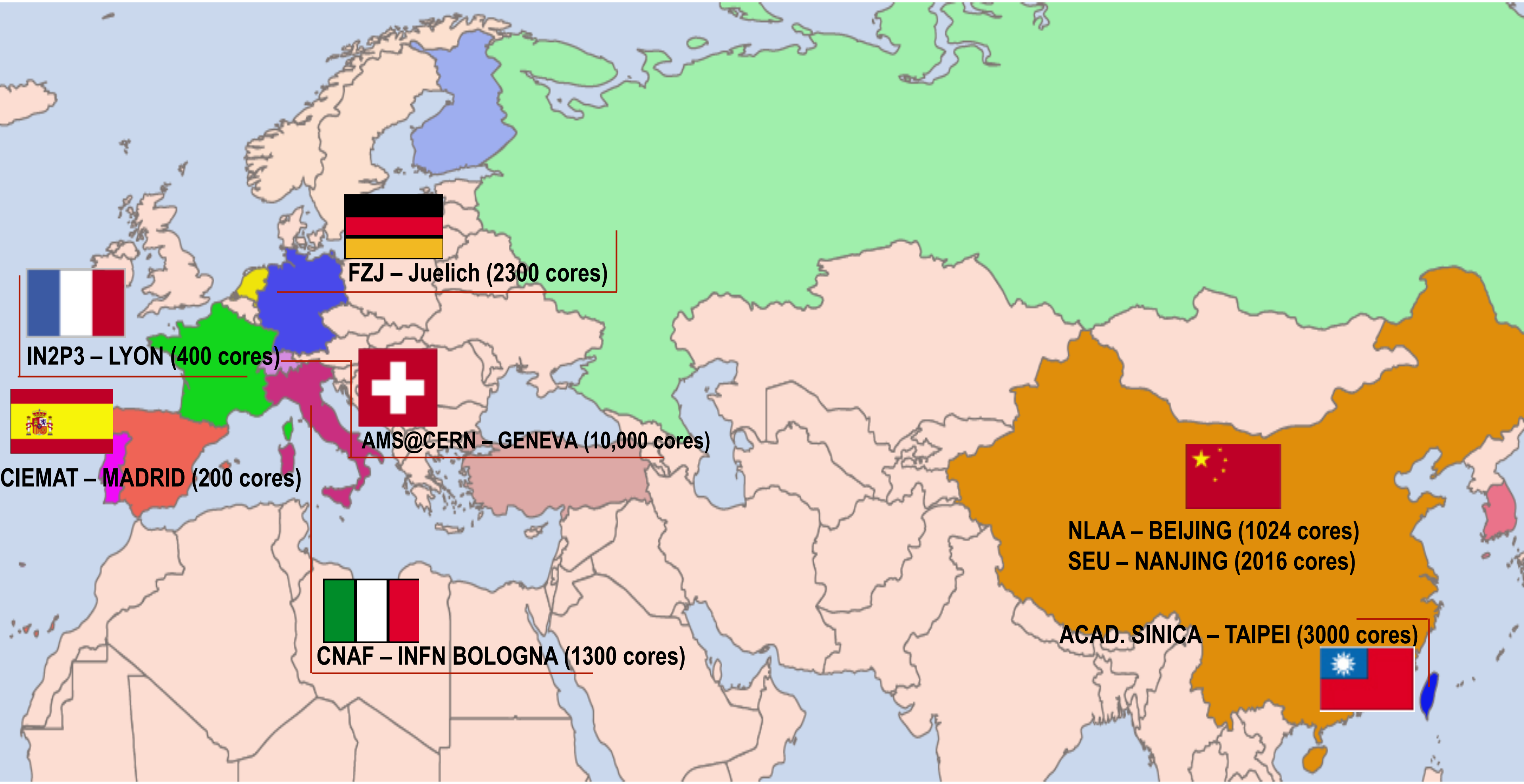


AMS POCC at CERN

The AMS Flight Control Team in the POCC is in constant communication with the ISS Flight Control Team at the JSC.

Analysis is conducted at the AMS Science Operations Center (SOC) at CERN and in the regional centers around the world.

Each physics topic is analysed by at least two independent groups

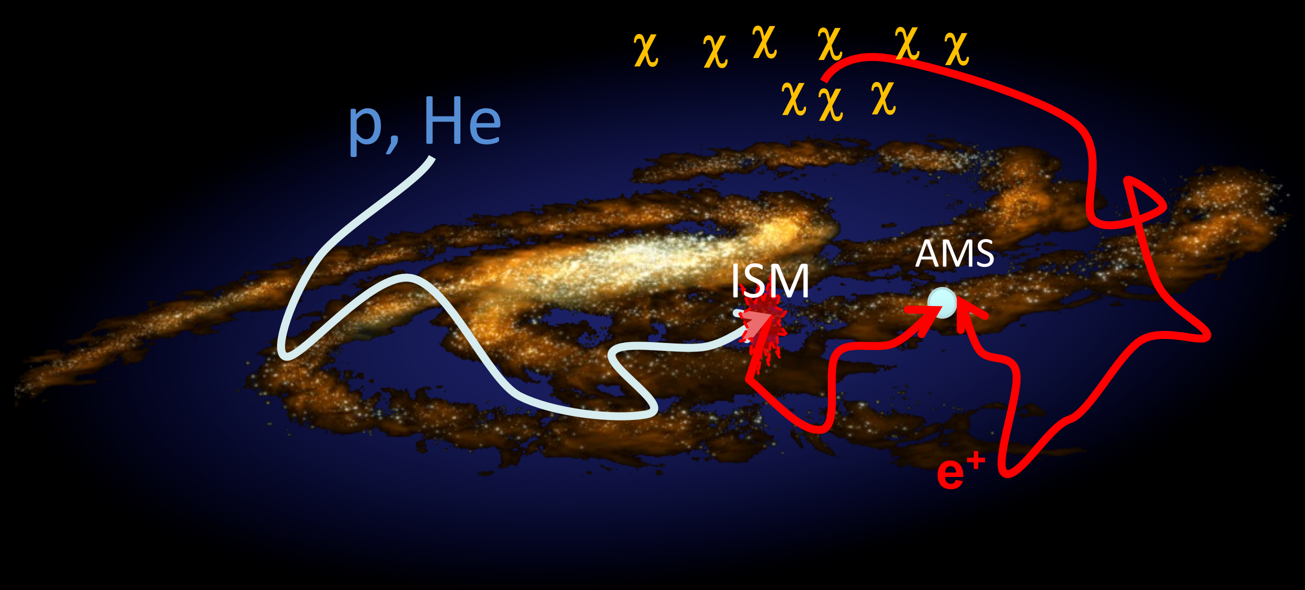


Dark Matter

Collision of Cosmic Rays with Interstellar Matter (ISM) produces e^+

Dark Matter annihilation also produces light antimatter: e^+

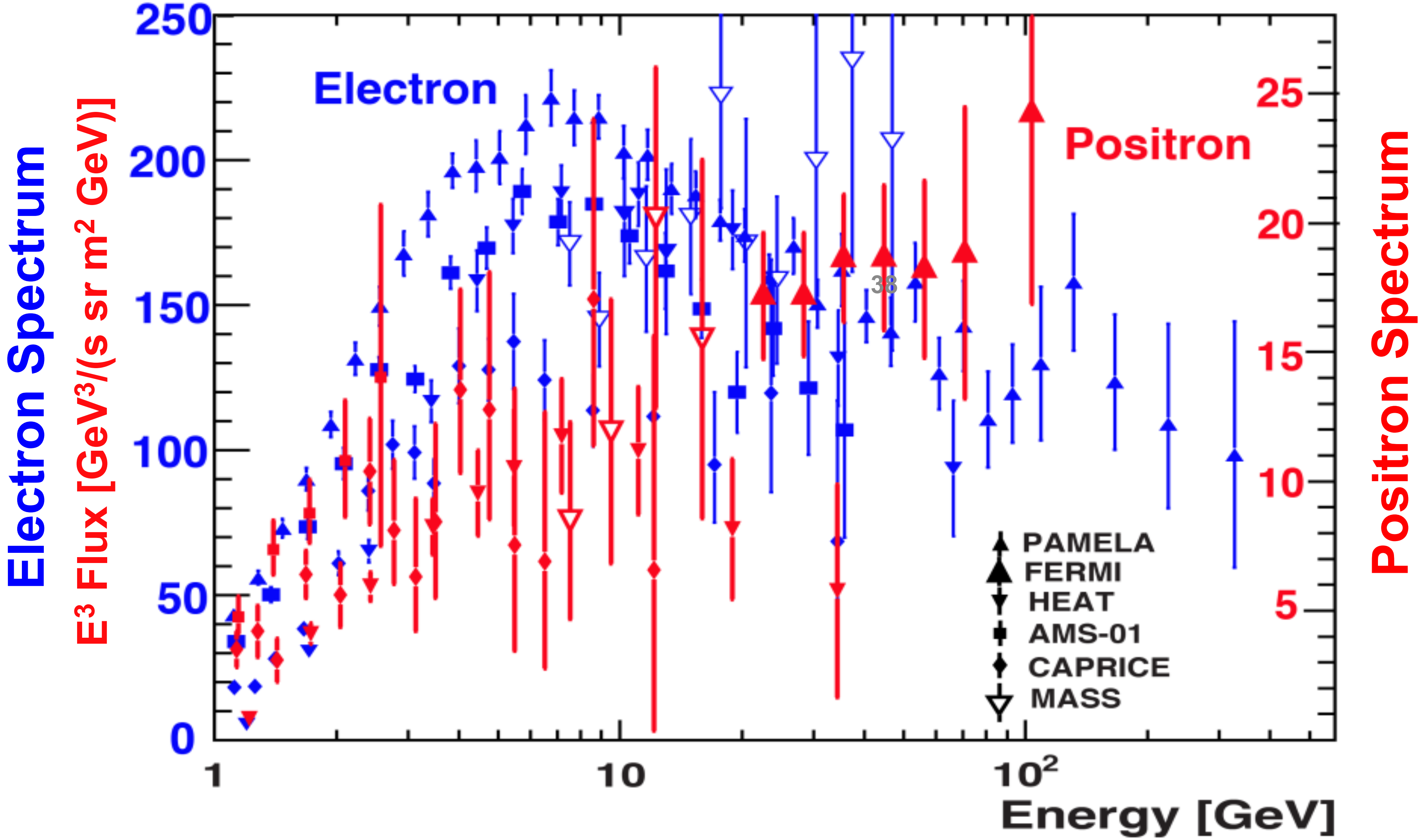
The excess of e^+, from Dark Matter annihilations can be measured by AMS



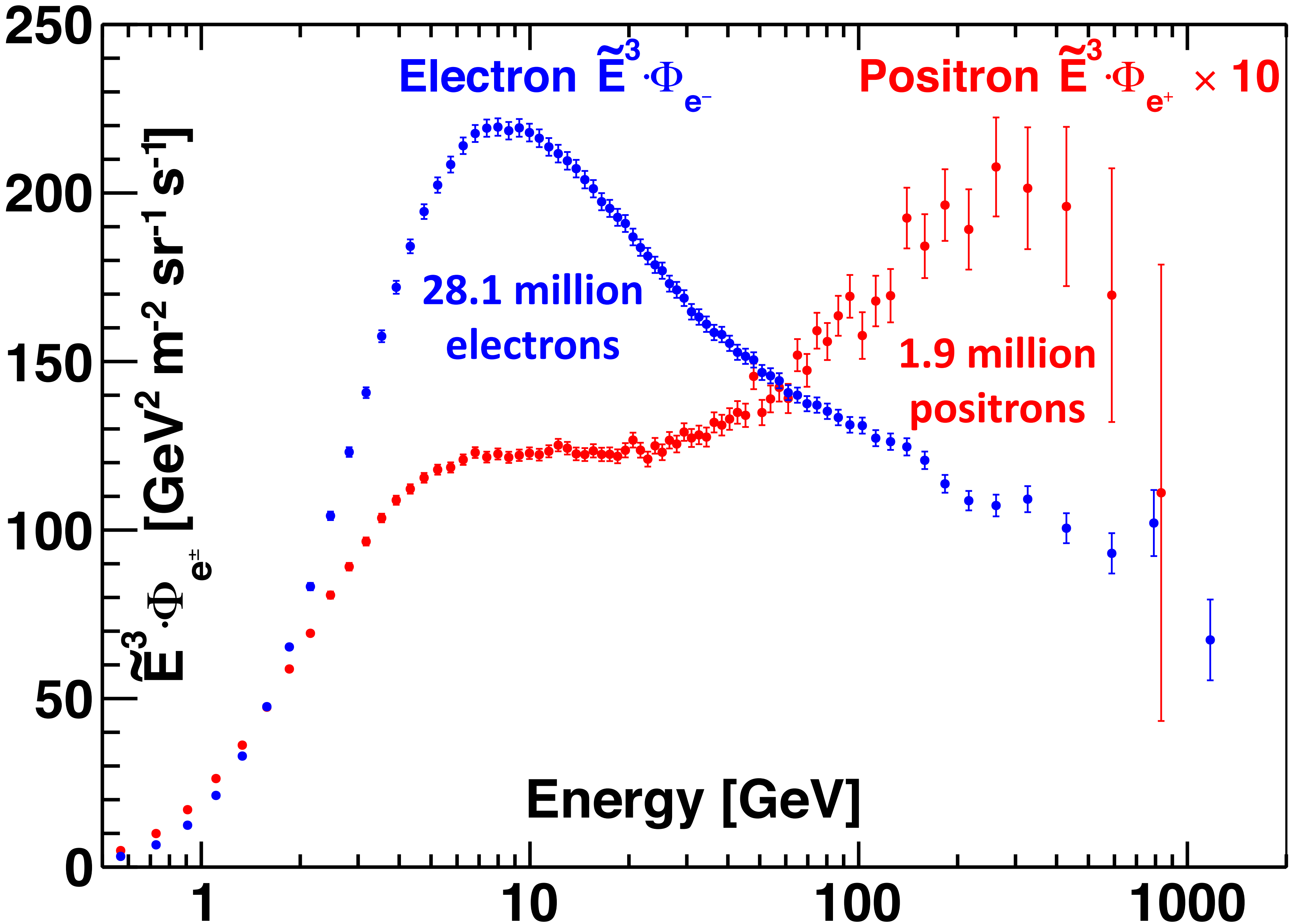
M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsistent.
3. The data has created many theoretical speculations.



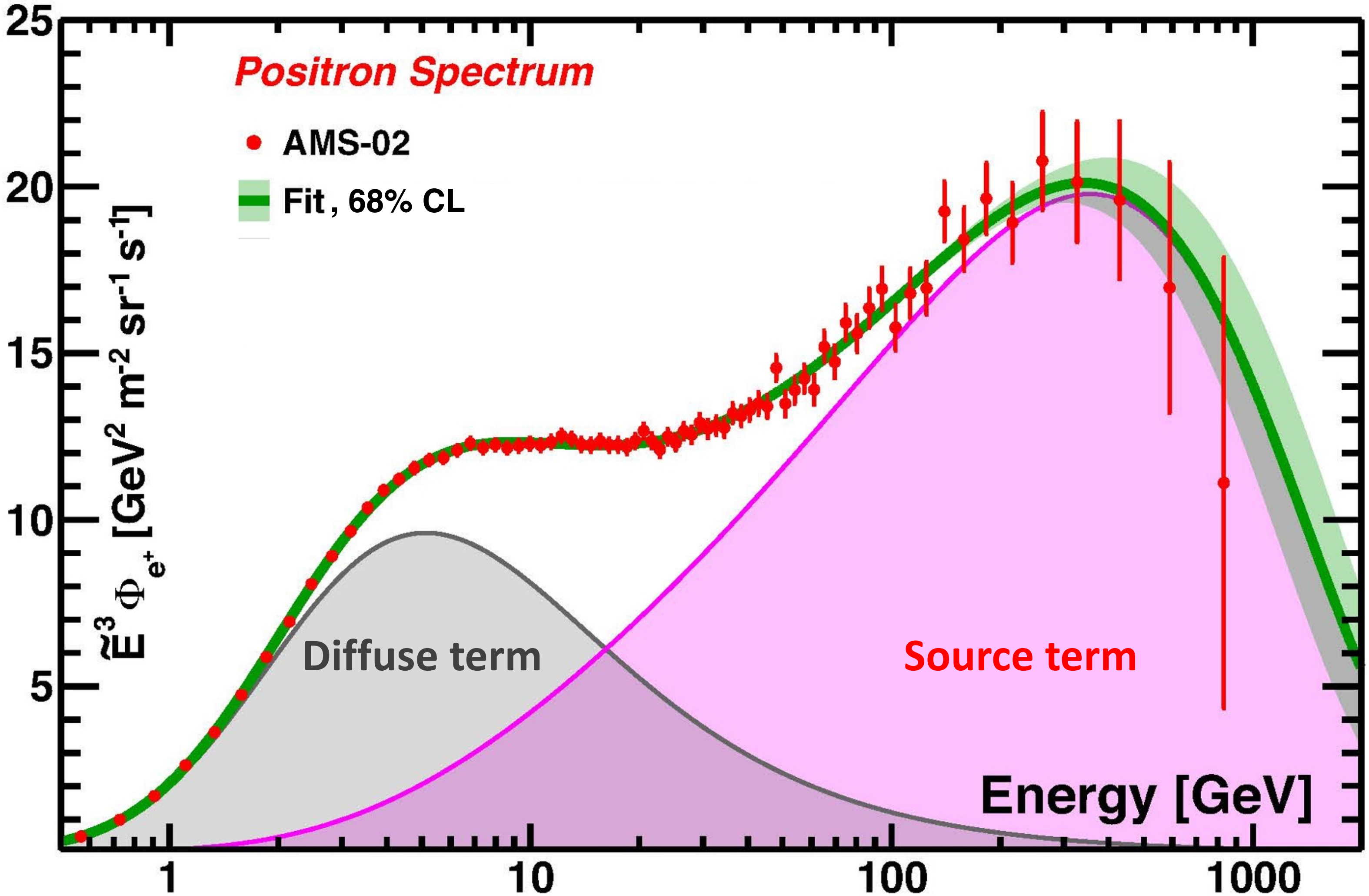
Distinct features of the positron flux and of the electron flux



(c) In the entire energy range the positron flux is well described by the sum of a diffuse term associated with positrons produced in the collision of cosmic rays, which dominates at low energies and a new source term of positrons, which dominates at high energies

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

Diffuse term   Source term



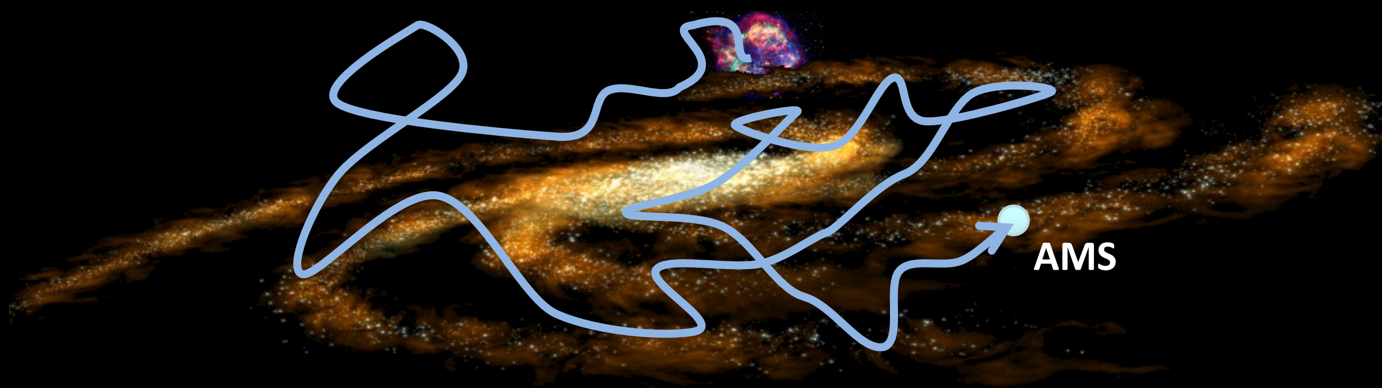
Origins of Cosmic Positrons

1. At low energies positrons originate from the collisions of cosmic rays.

2. At high energies positrons predominately originate either from dark matter collisions or from new astrophysical sources, not from the collisions of cosmic rays.

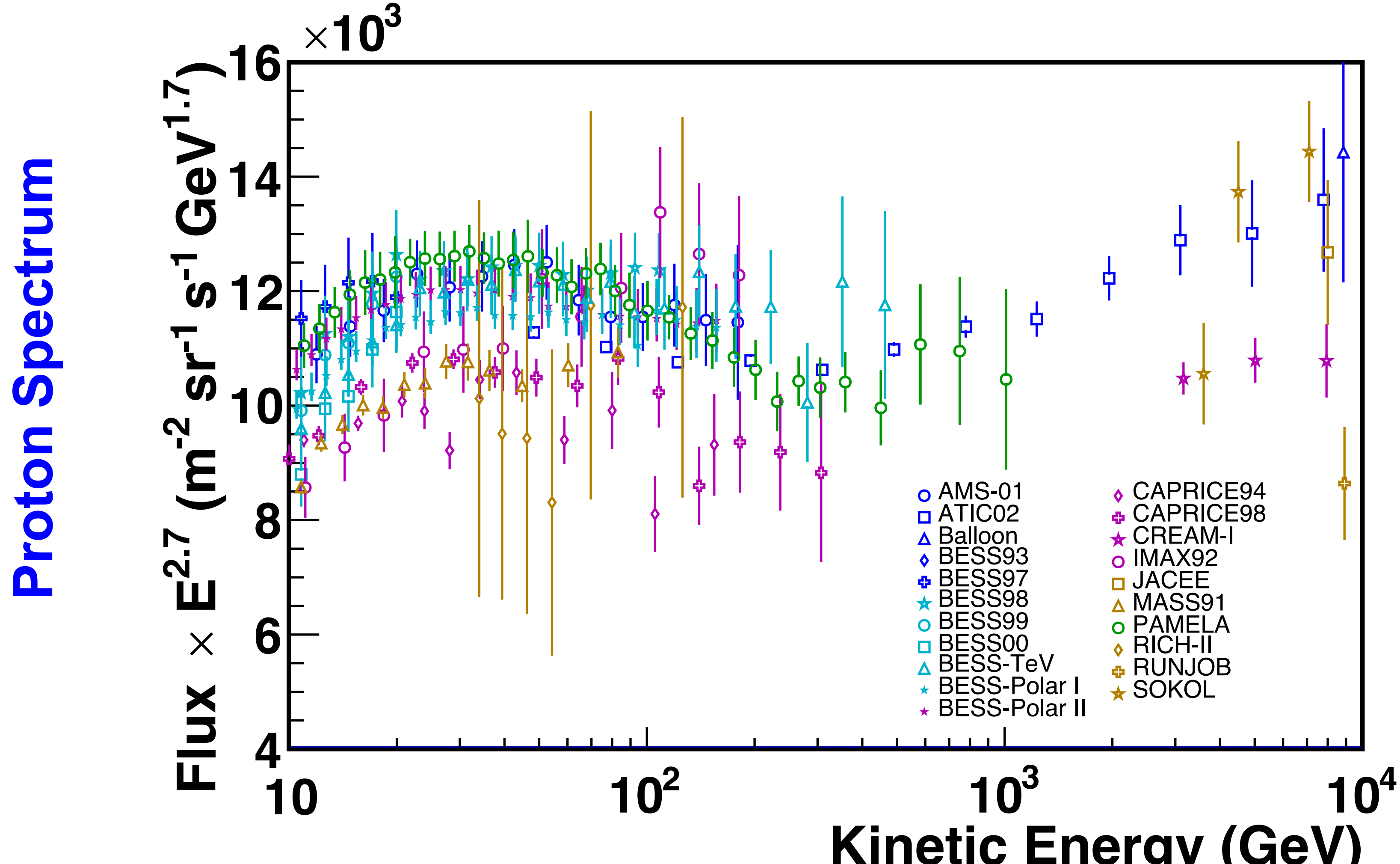
Traditionally, there are two prominent classes of cosmic rays:

Primary Cosmic Rays (p, He, C, O, …)
are produced at their source and travel through space and are directly detected by AMS. They carry information on their sources and the history of travel.

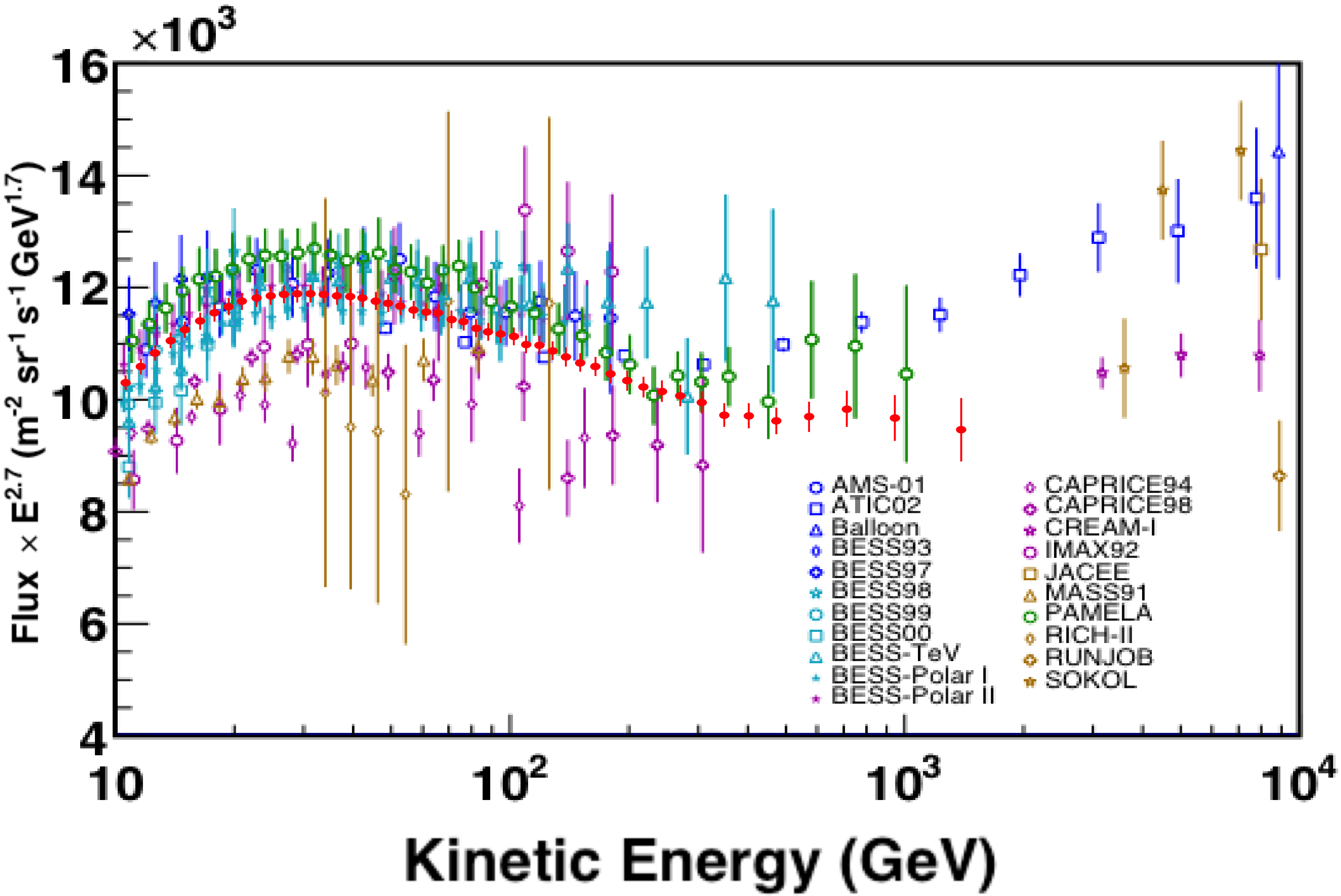


Cosmic Protons

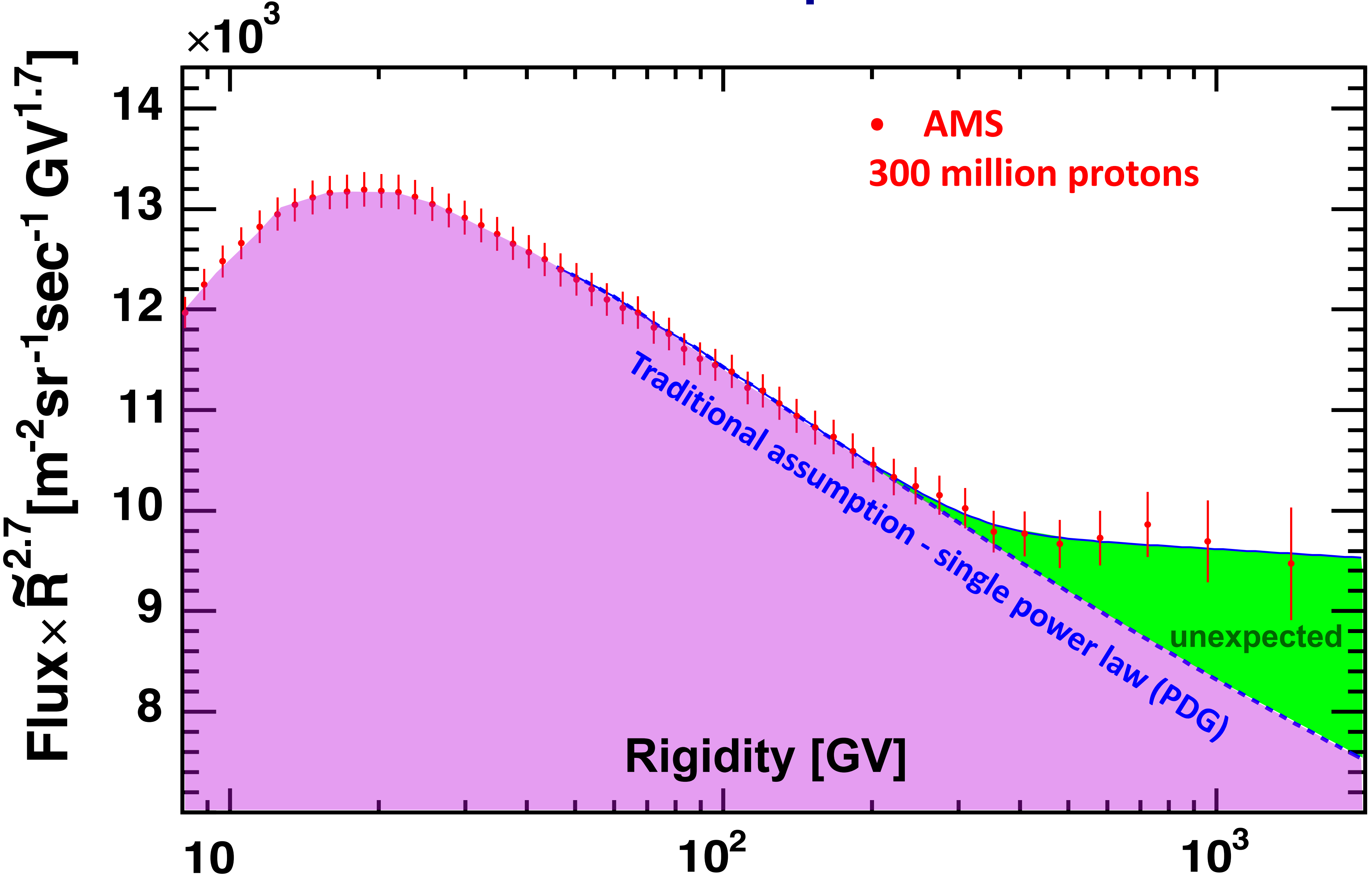
1. **Protons are the most abundant cosmic rays.**
2. **Before AMS there have been many measurements of the proton spectrum.**
3. **In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^{\gamma}$ with γ = -2.7**



AMS Measurement of the proton spectrum

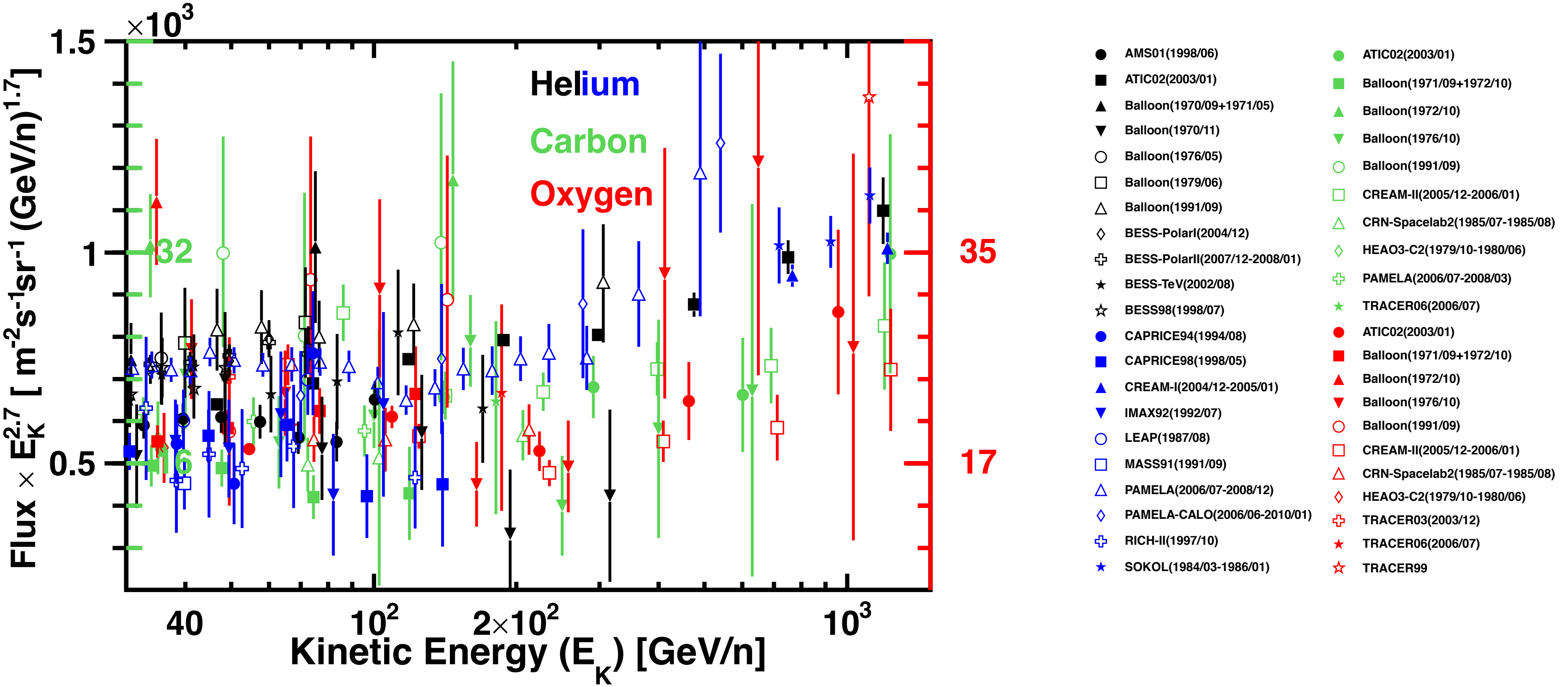


AMS results on the proton flux

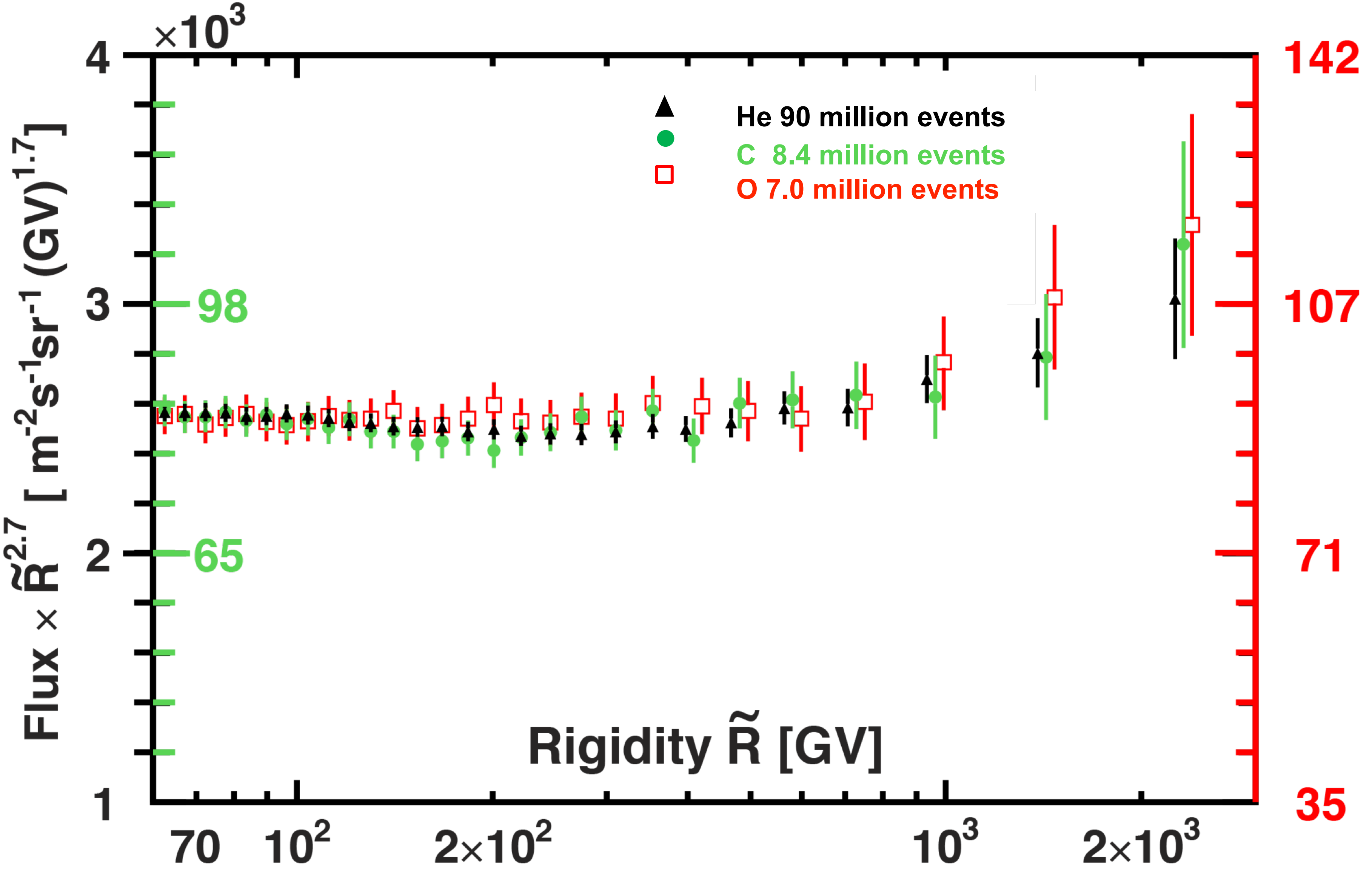


The proton flux **cannot** be described by a single power law = CR^{γ}

Before AMS: results on Primary Cosmic Rays (Helium, Carbon, Oxygen) from balloon and satellite experiments

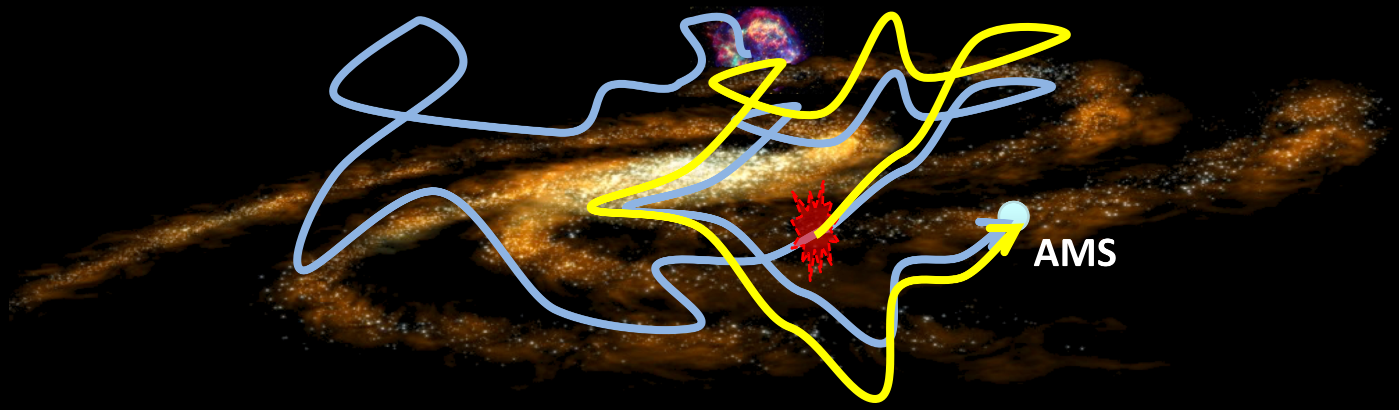


AMS Result: Surprisingly, above 60 GV, these fluxes have identical rigidity dependence.



Traditionally, there are two prominent classes of cosmic rays:

Primary Cosmic Rays (p, He, C, O, …)

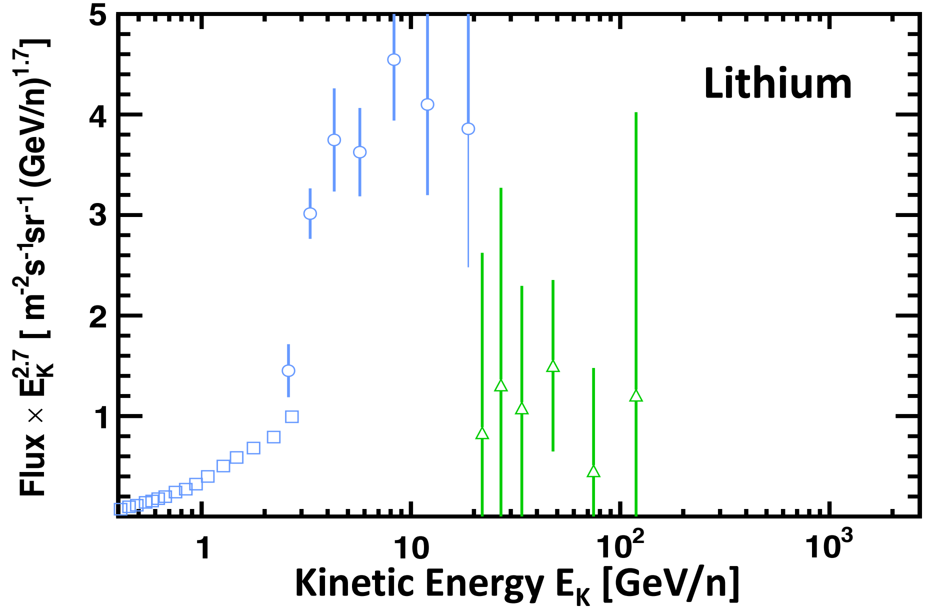


Secondary Cosmic Rays (Li, Be, B, …)

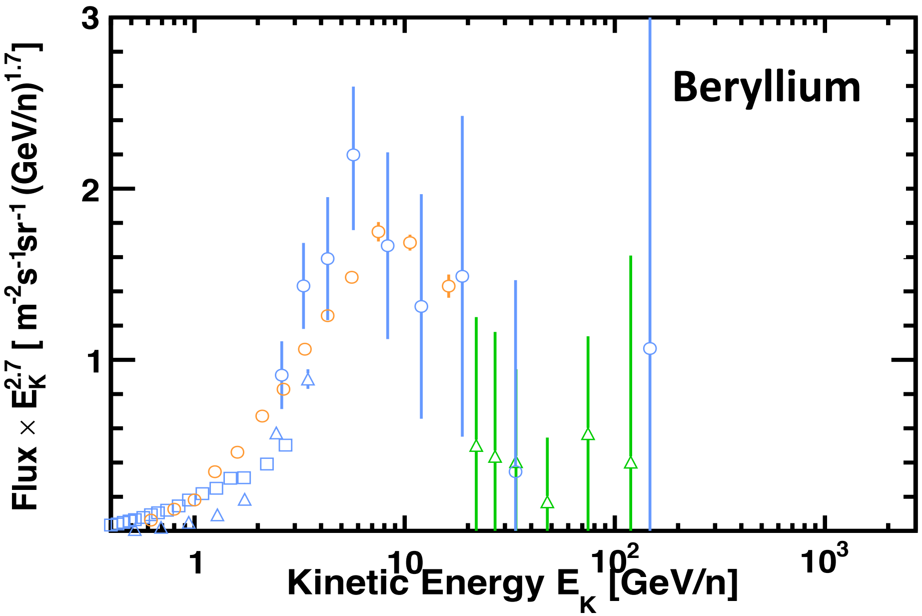
are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.

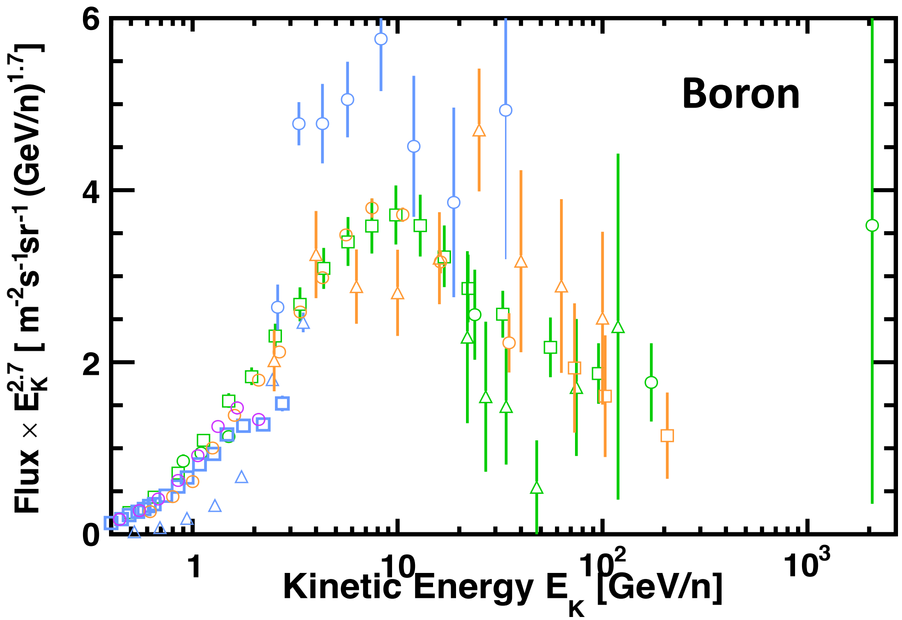
Flux Measurements of Li, Be, B before AMS

- ○ TRACER
- □ PAMELA
- △ Juliusson
- ○ Orth
- □ Webber
- △ Lezniak
- ○ HEAO3
- □ CRN
- △ Simon
- ○ Maehl



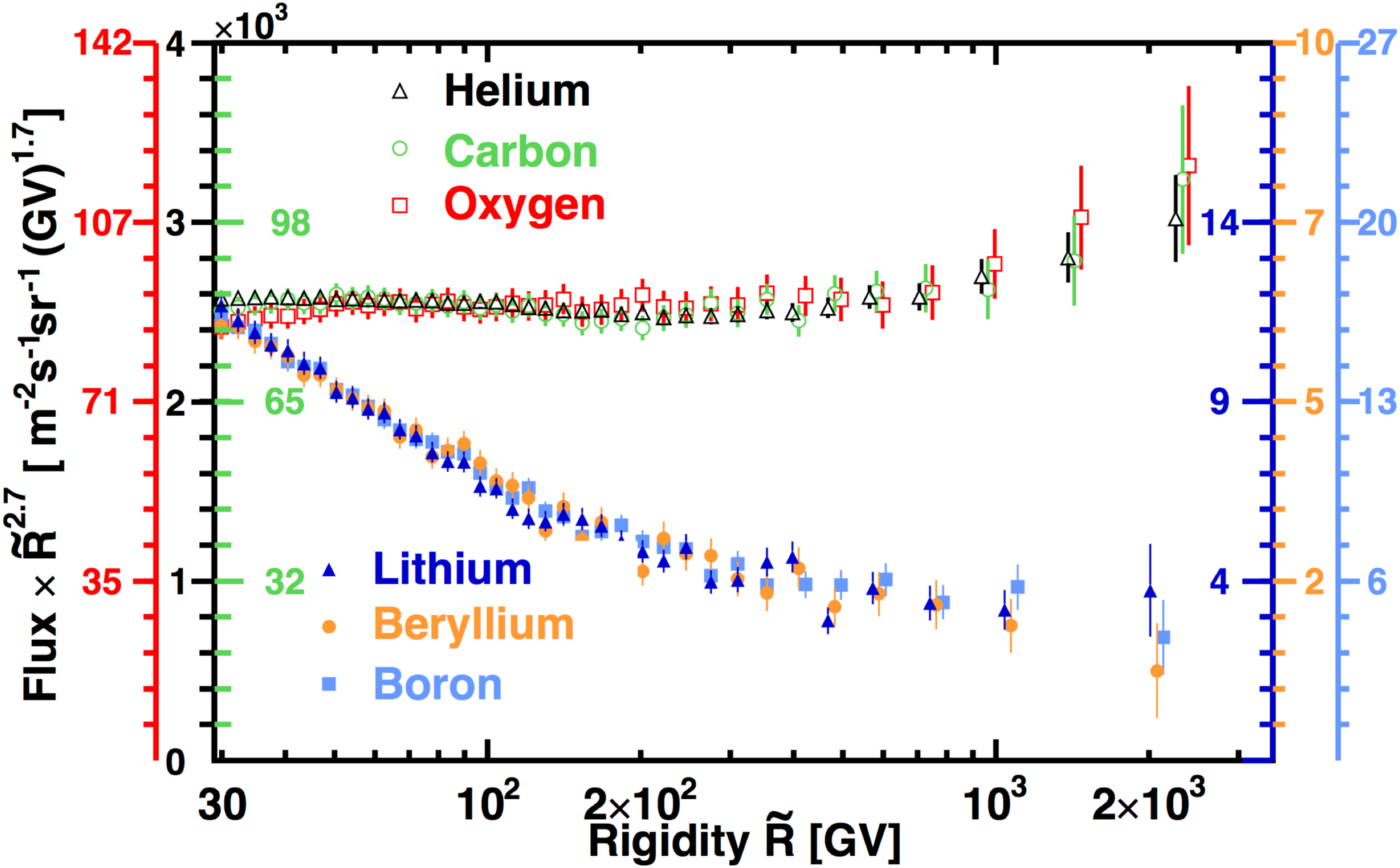
Typically, the error on each flux is larger than 50% at 100 GV



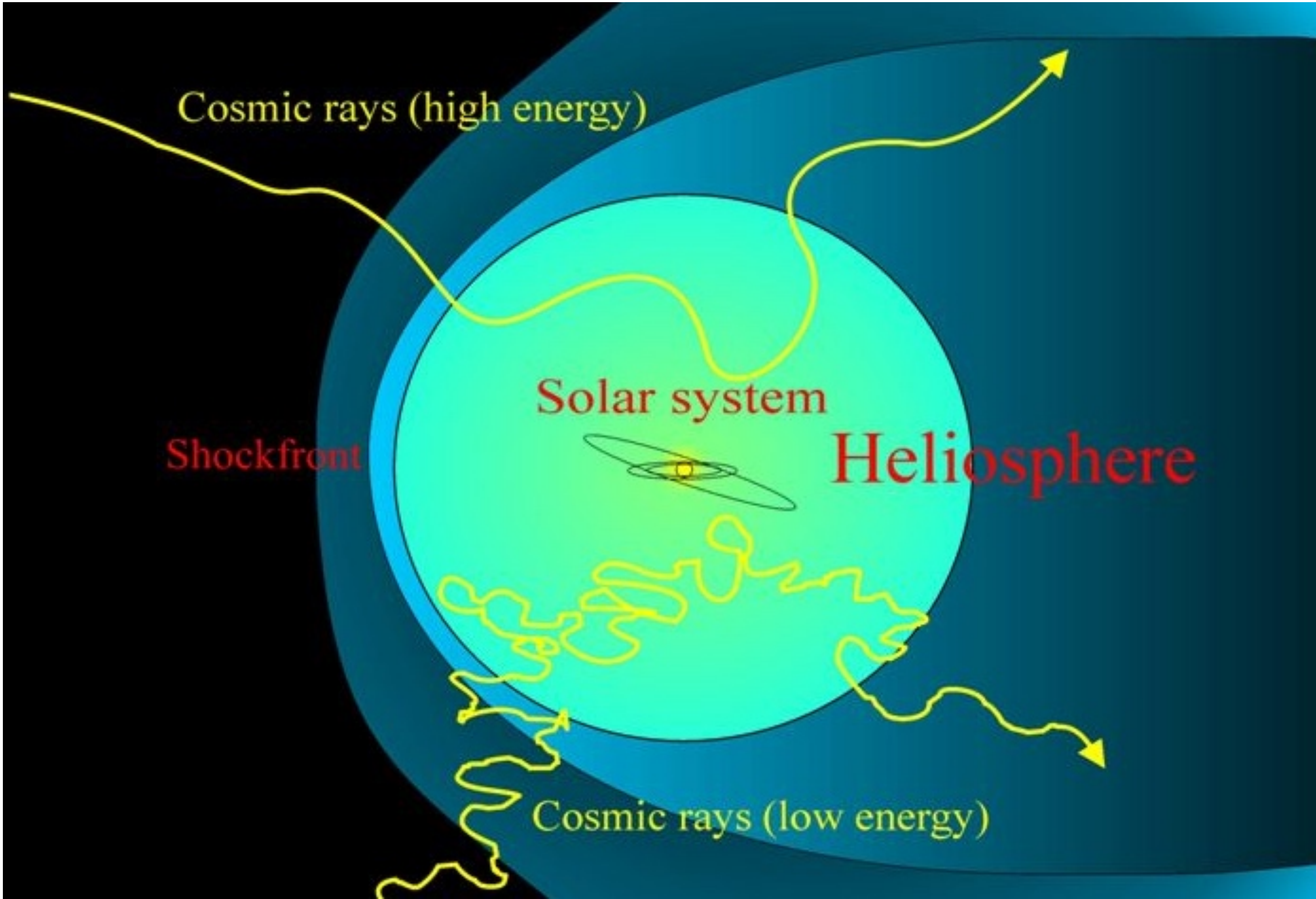


AMS Result:

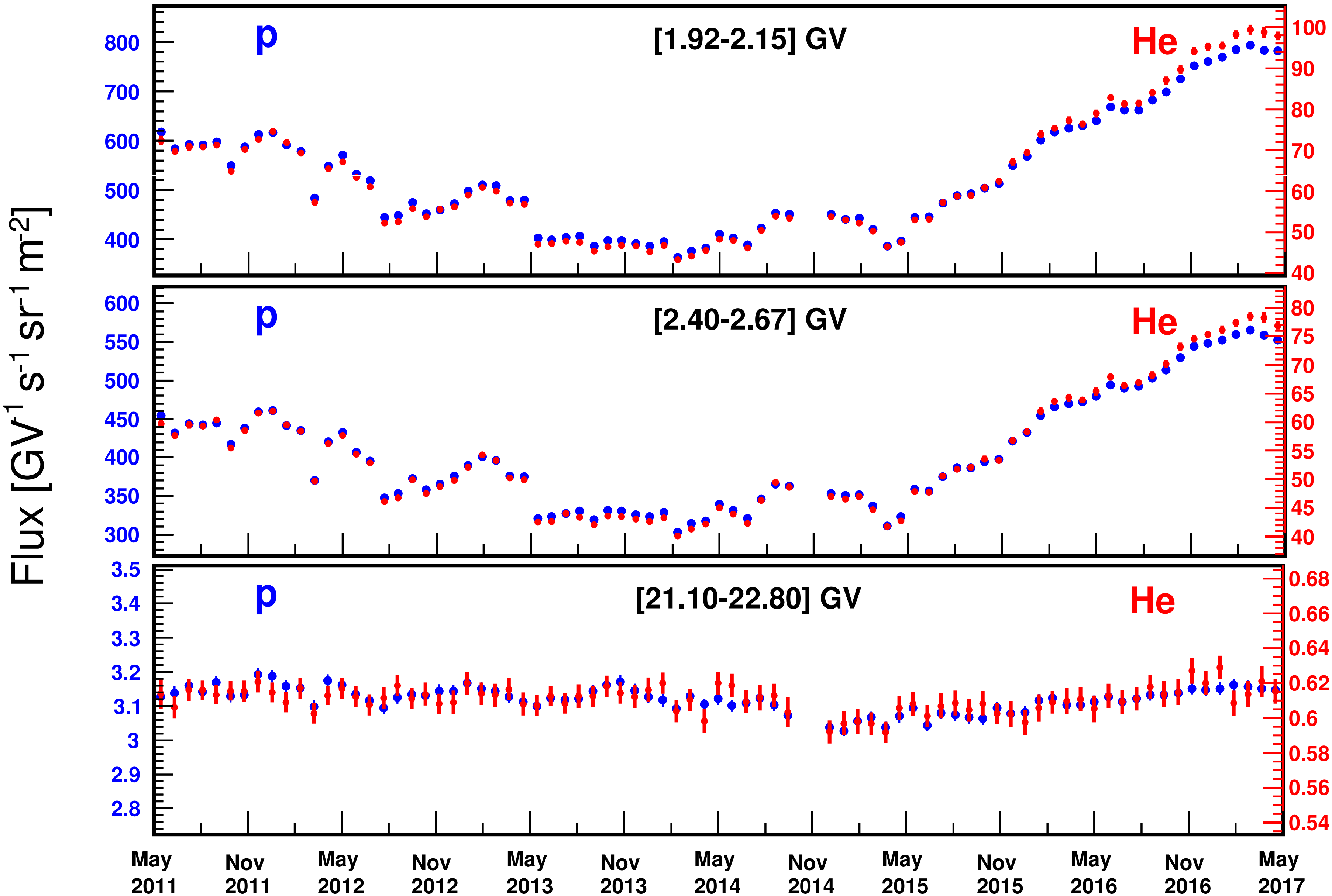
Secondary cosmic rays Li, Be, and B also have identical rigidity dependence but they are different from primaries



Time structures in the p and He fluxes in Solar System



New observation: Identical monthly time variation of the p, He fluxes

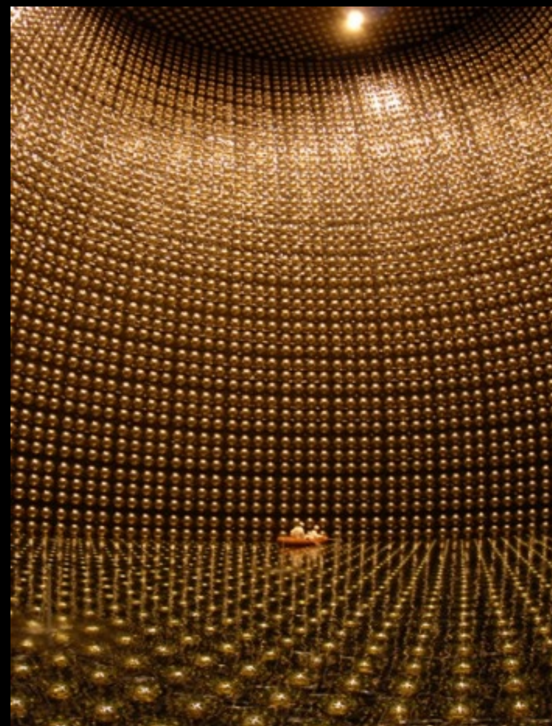


Experimental work on Antimatter in the Universe

Search for Baryogenesis

New symmetry breaking

Proton has finite lifetime

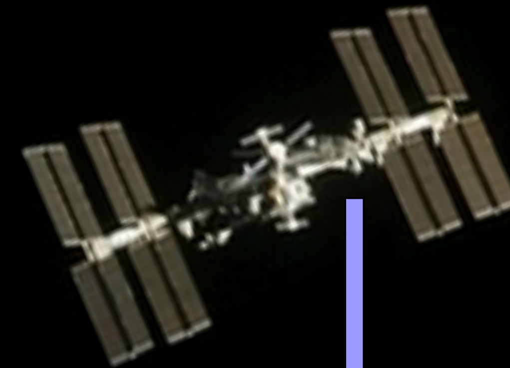


LHC-b, ATLAS,CMS Super Kamiokande

$\tau_p > 6.6 * 10^{33}$ years

No explanation found for the absence of antimatter
(no reason why antimatter should not exist)

Direct search

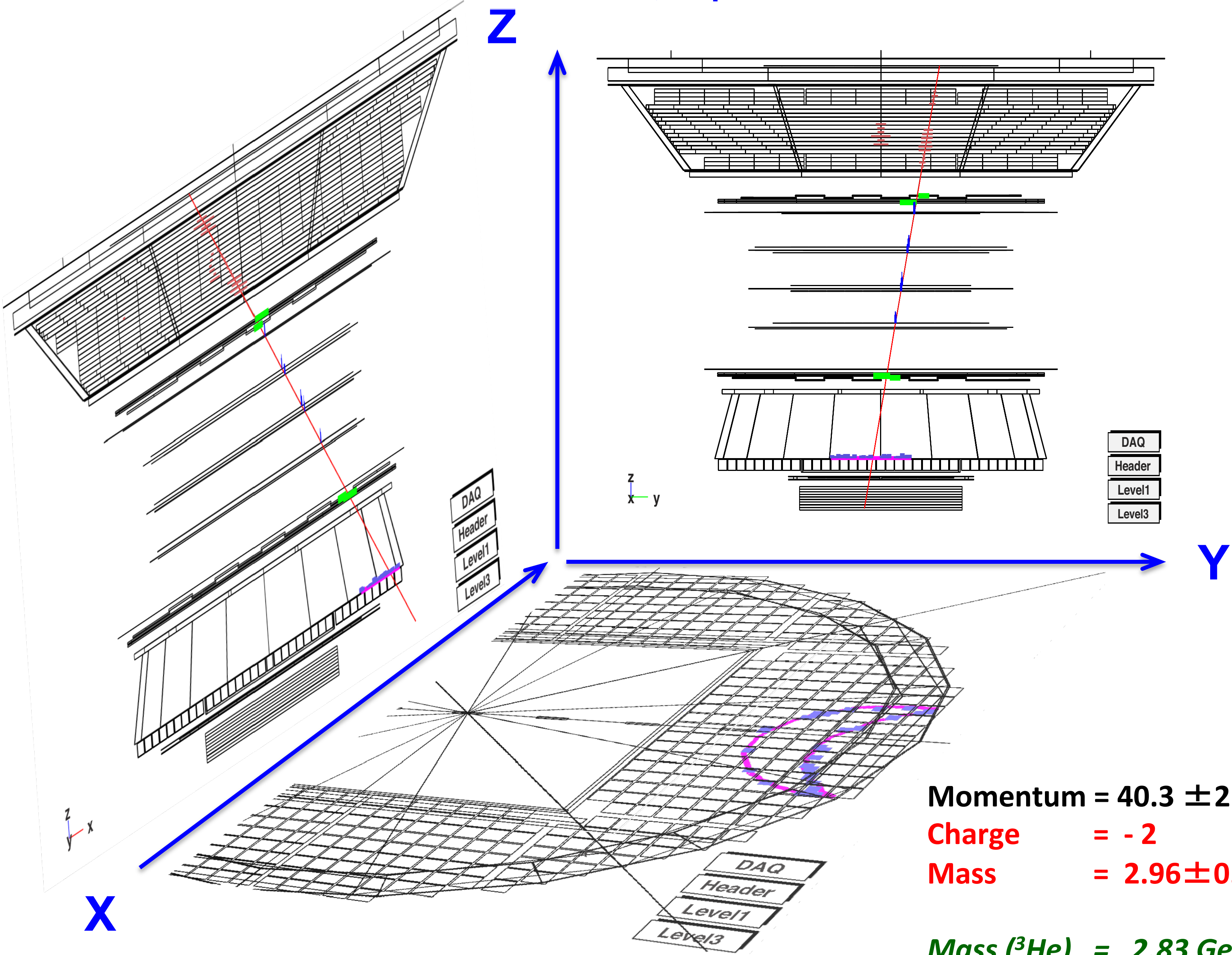


AMS

Increase in sensitivity: x $10^3 - 10^6$
Increase in energy to ~TeV

An anti-Helium candidate:

Presented to DOE, September 2016



Momentum = 40.3 ±2.9 GeV/*c*

Charge = - 2

Mass = 2.96±0.33 GeV/*c*²

Mass (³He) = 2.83 GeV/c ²

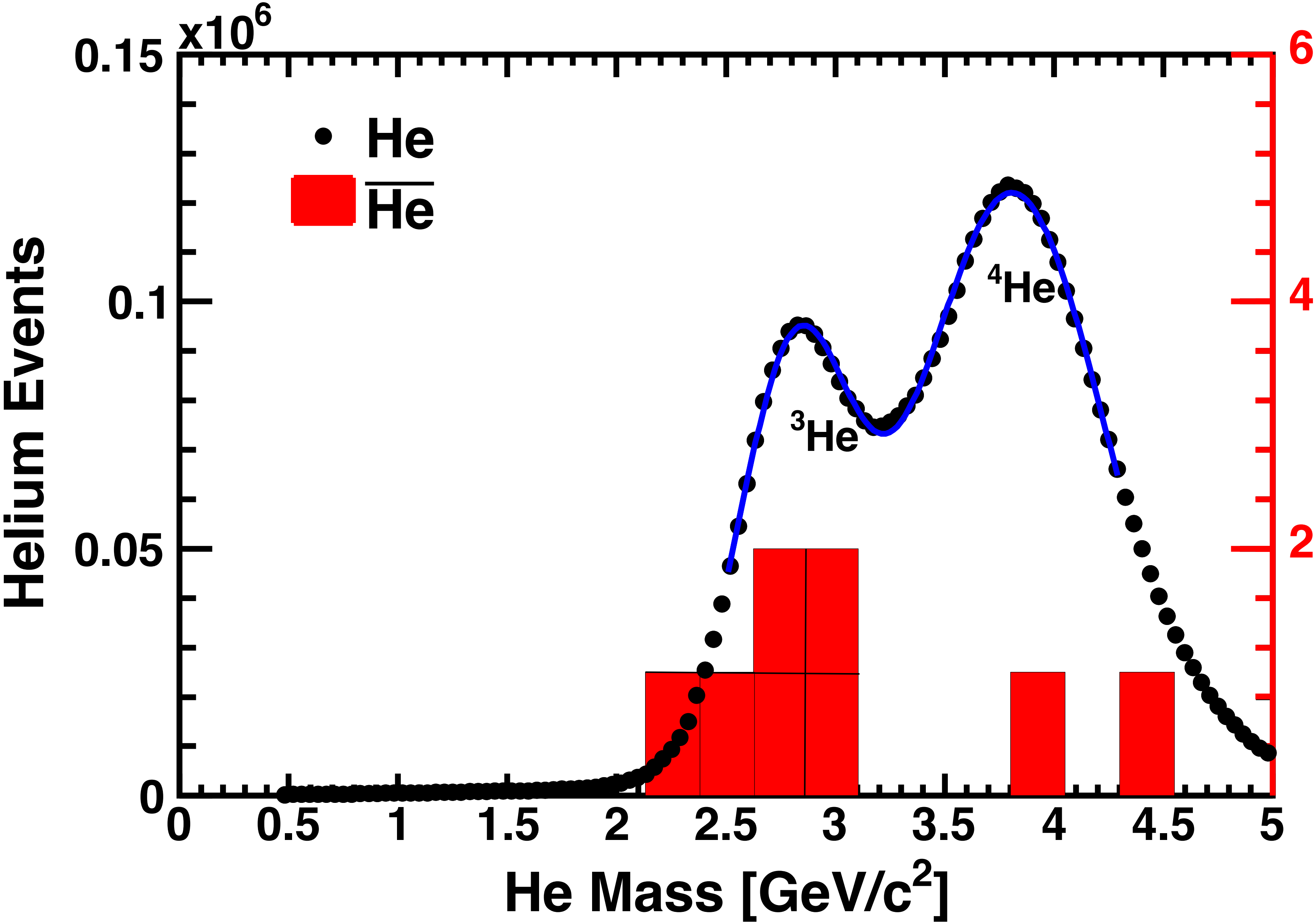
To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$.

All eight events are in the helium mass region.

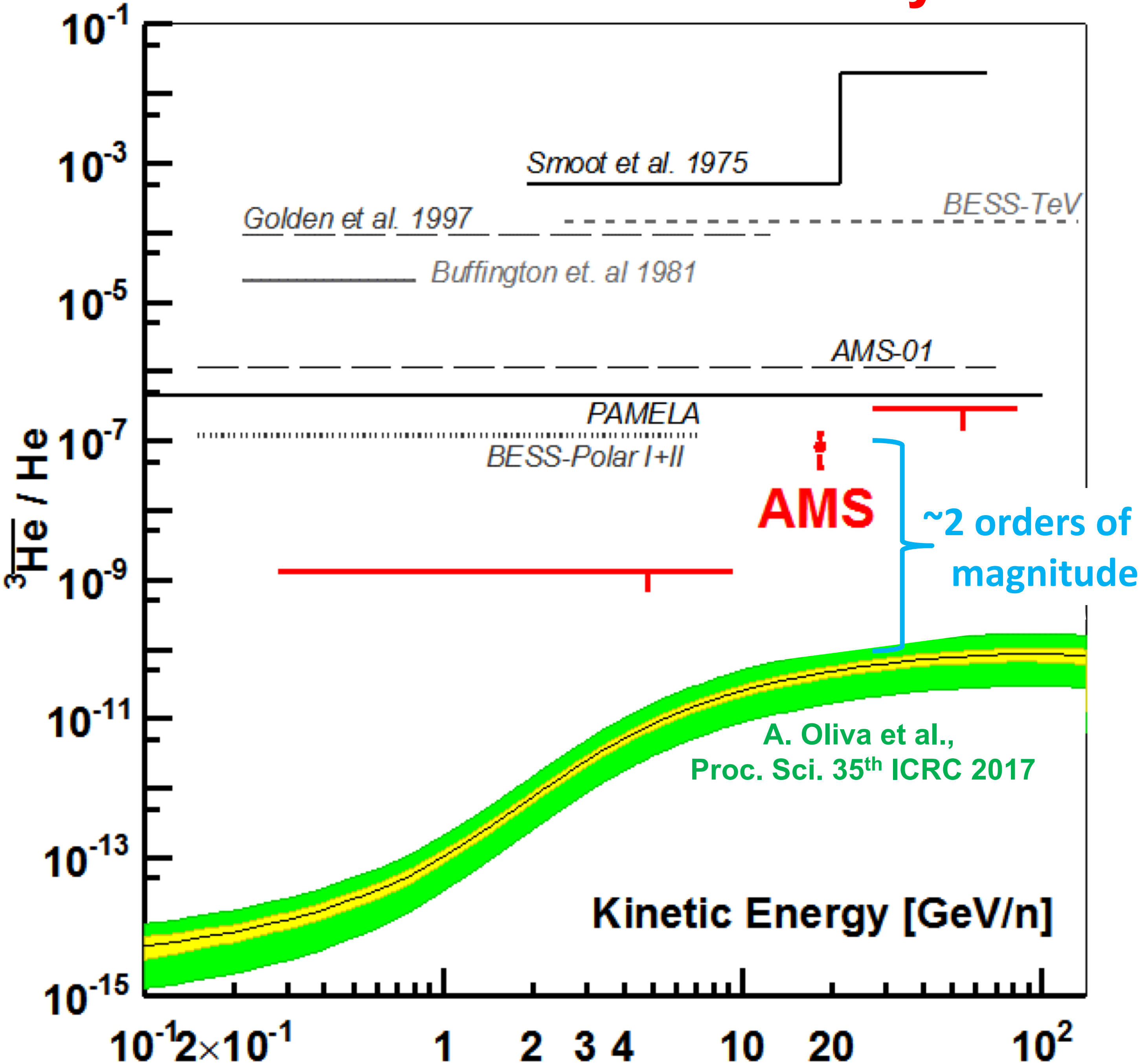
All eight events are clean single-track events without additional hits.

All eight events are in the momentum range < 100 GeV/c (where the momentum resolution is better than 10%).

Mass distribution of the anti-helium events



$^{3}\overline{He}/He$ data and models of cosmic ray collisions



International Recognition of AMS Results
AMS Publications (>2600 inSPIRE citations)

1) M. Aguilar *et. al*., Phys. Rev. Lett. 110 (2013) 141102. Editor's Suggestion, Viewpoint in Physics, Highlight of the Year 2013.
2) L. Accardo *et al*., Phys. Rev. Lett. 113 (2014) 121101. Editor's Suggestion
3) M. Aguilar *et. al*., Phys. Rev. Lett. 113 (2014) 121102. Editor's Suggestion
4) M. Aguilar *et. al*., Phys. Rev. Lett. 113 (2014) 221102.
5) M. Aguilar *et. al*., Phys. Rev. Lett. 114 (2015) 171103. Editor's Suggestion
6) M. Aguilar *et. al*., Phys. Rev. Lett. 115 (2015) 211101. Editor's Suggestion
7) M. Aguilar *et. al*., Phys. Rev. Lett. 117 (2016) 091103.
8) M. Aguilar *et. al*., Phys. Rev. Lett. 117 (2016) 231102. Editor's Suggestion
9) M. Aguilar *et. al*., Phys. Rev. Lett. 119 (2017) 251101.
10) M. Aguilar *et. al*., Phys. Rev. Lett. 120 (2018) 021101. Editor's Suggestion
11) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051101.
12) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051102. Editor's Suggestion
13) M. Aguilar *et. al*., Phys. Rev. Lett. 121 (2018) 051103.

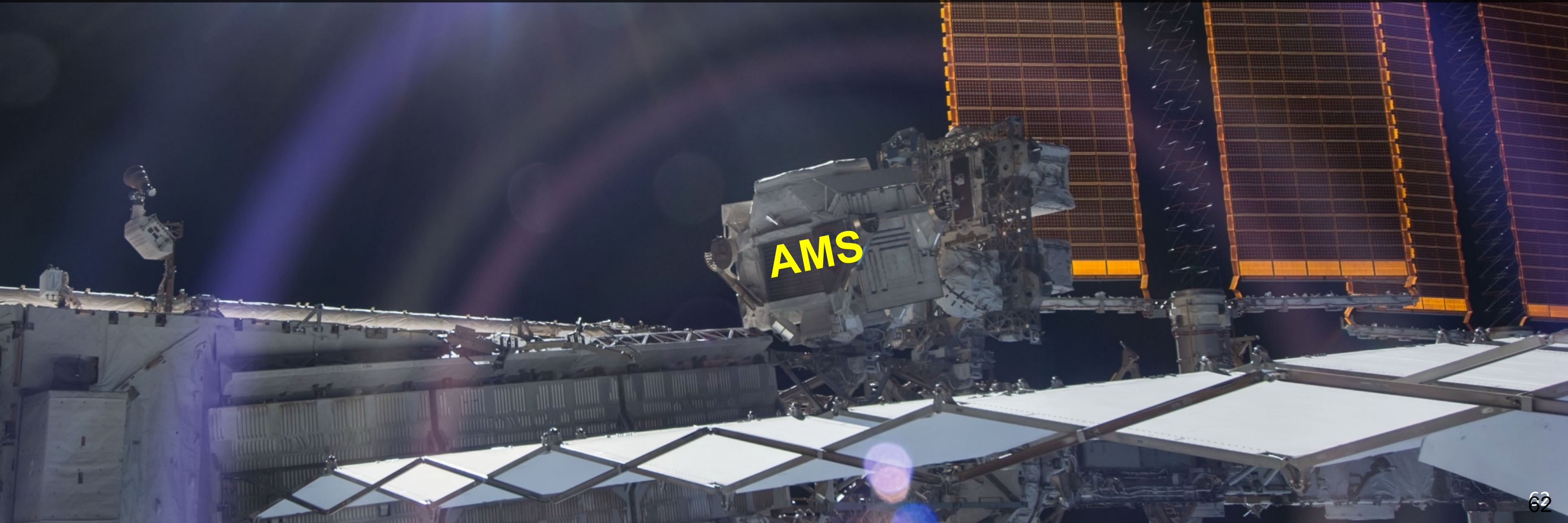
From: "garisto@aps.org" <garisto@aps.org>
Subject: First AMS paper chosen for a ten year retrospective of PRL Editors' Suggestions
Date: April 20, 2017 at 4:49:57 PM GMT+2

Since we began Editors' Suggestions 10 years ago, we have published about 3000 PRLs marked as an Editors' Suggestion.
To mark the 10 year anniversary, each week we are posting a placard (like the one I sent you--a link to the paper and a brief description) on our website for one of those papers. So we are picking just 52 out of the 3000 possible candidates (and each candidate was of course already a PRL paper we chose to highlight). Other papers we have already commemorated in this way include the discovery of element 117, and the observation of gravitational waves by LIGO.

Cheers,
Robert

The physics of AMS to 2024:

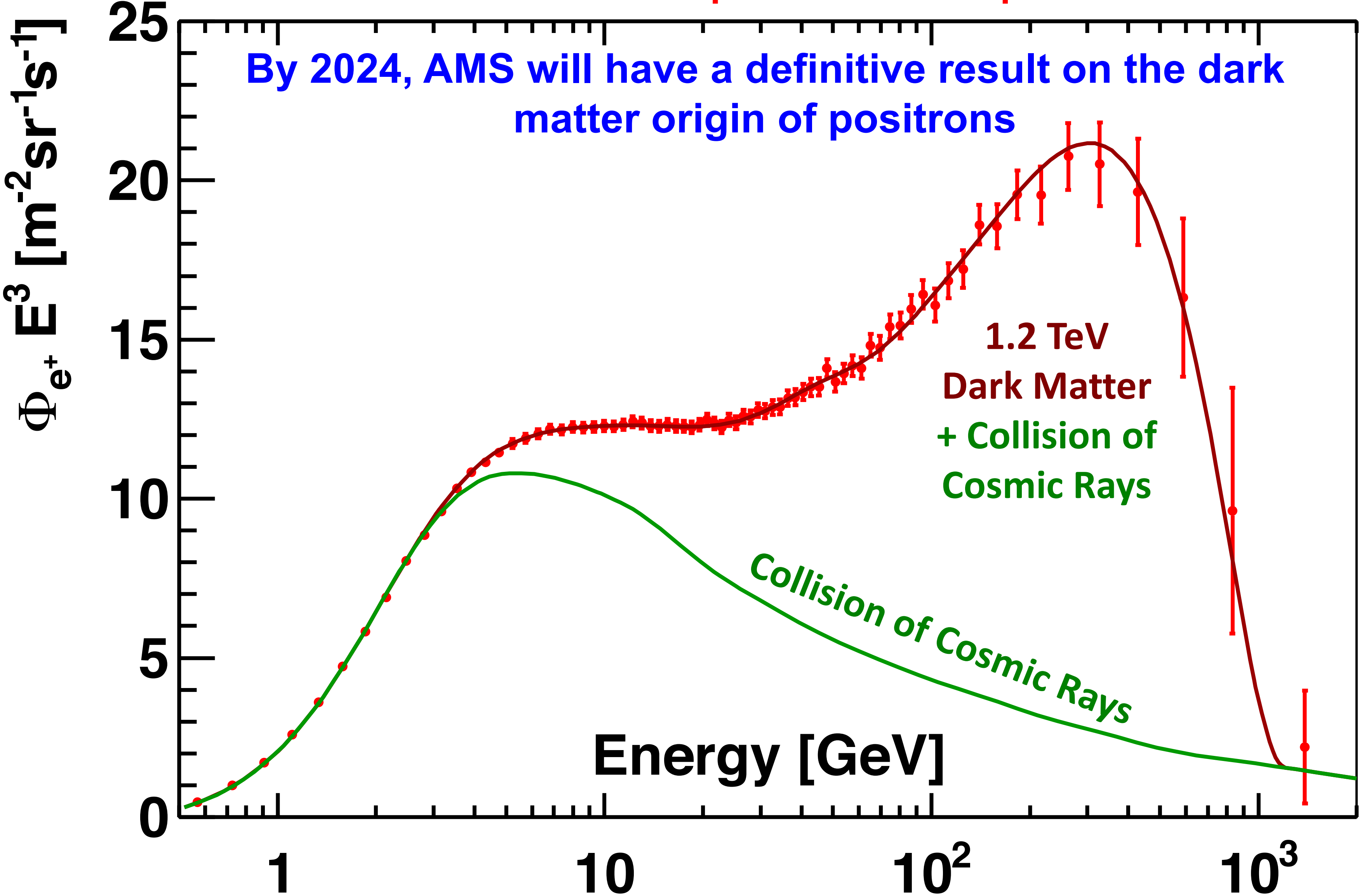
1. Positrons and Dark Matter
2. Anisotropy and Dark Matter
3. Anti-deuterons and Dark Matter
4. Study solar physics of p, He, C, O, …
5. Study high Z cosmic rays to the highest energies
6. Unexpected



The Positron Flux through 2024

Extend the measurements to 2 TeV and double the current statistics

to determine the sharpness of the drop off.



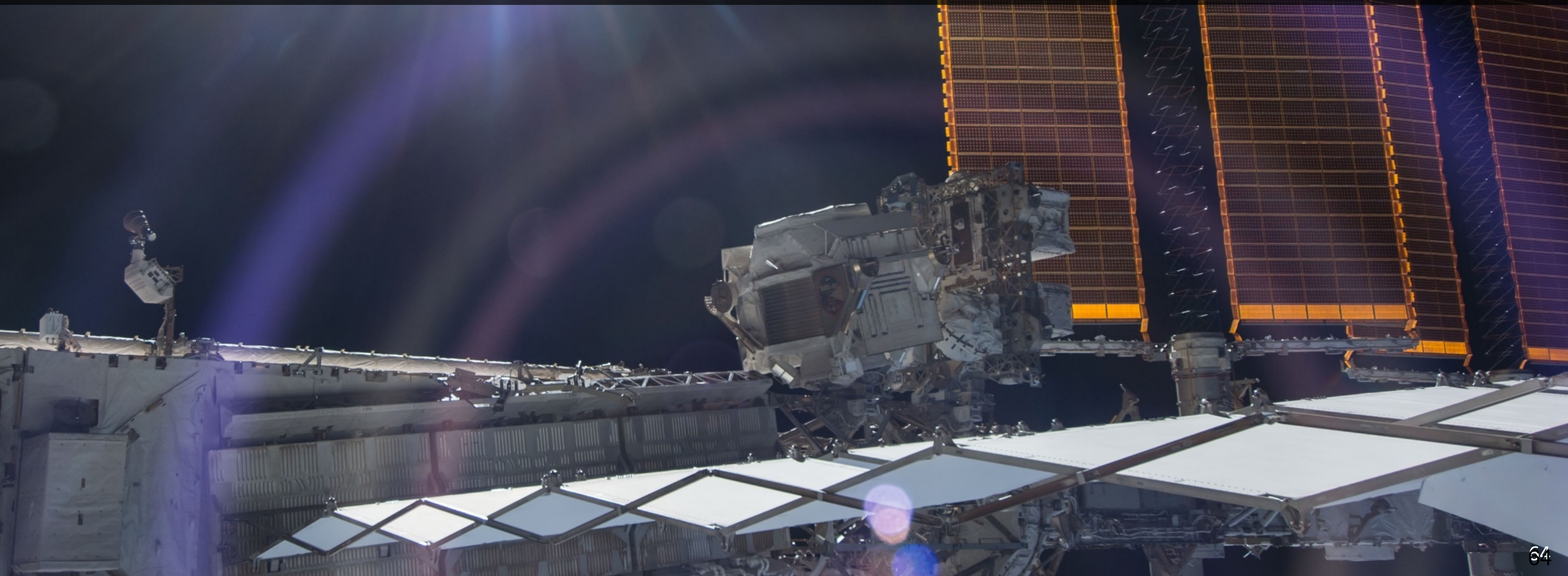
The physics of AMS to 2024:

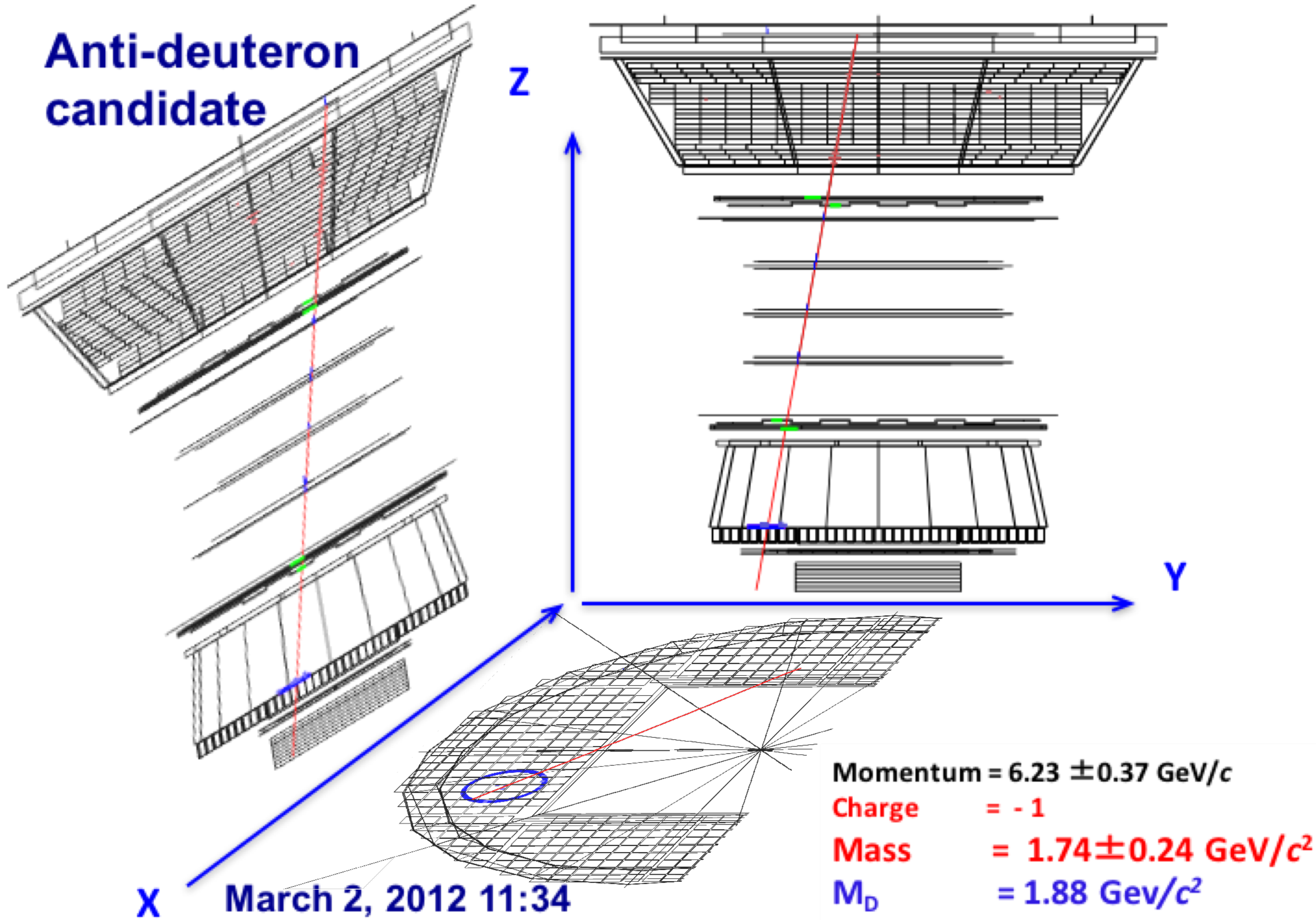
3. Anti-deuterons and Dark Matter

Anti-Deuterons have never been observed in space

By 2024, AMS will have collected more than 200 million deuterons.

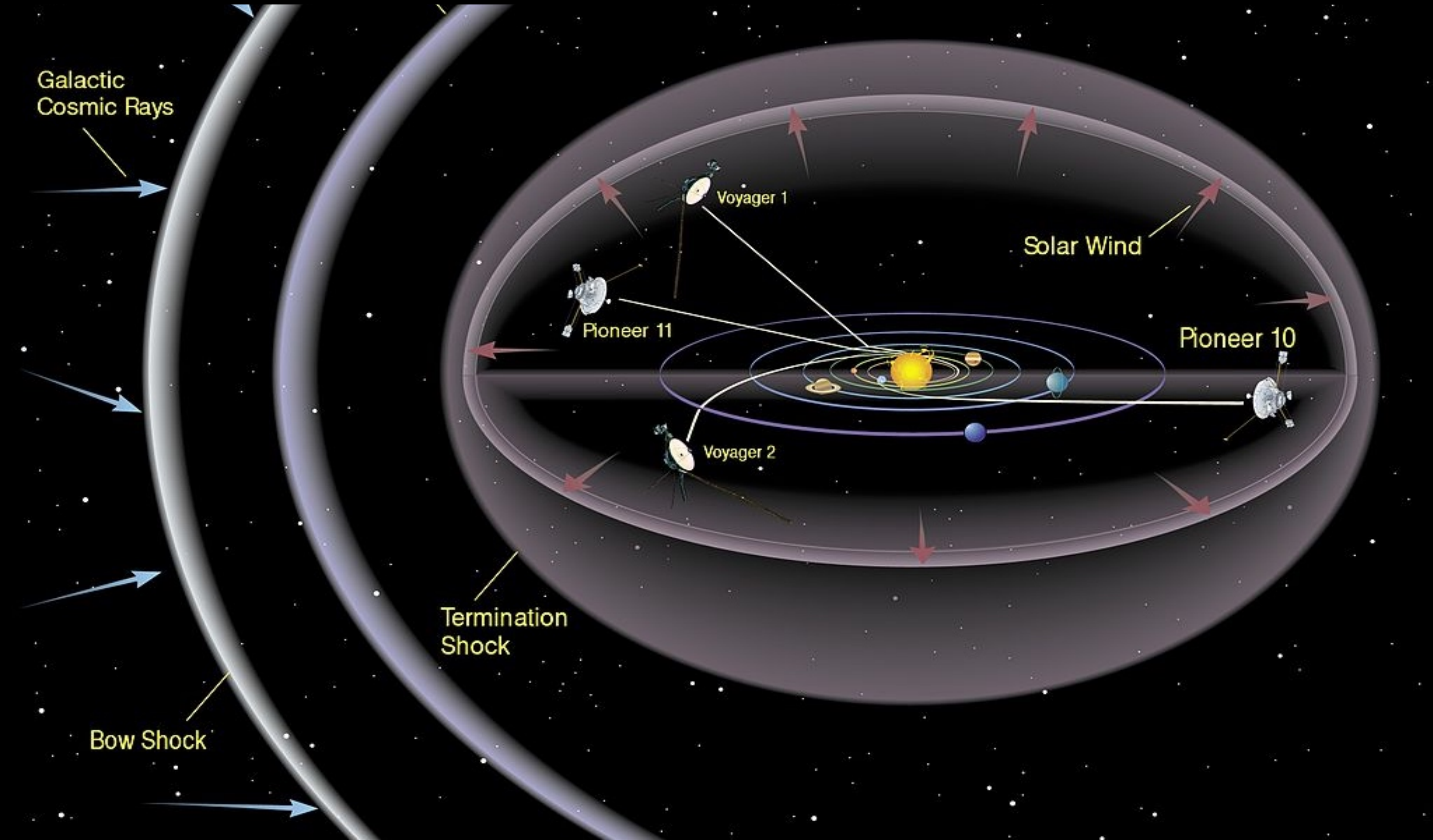
Dark Matter annihilation will produce anti-Deuterons




Anti-deuteron candidate
Z
Y
X
March 2, 2012 11:34
Momentum = 6.23 ±0.37 GeV/c
Charge = - 1
Mass = 1.74±0.24 GeV/c²
M_D = 1.88 Gev/c²

The physics of AMS to 2024:

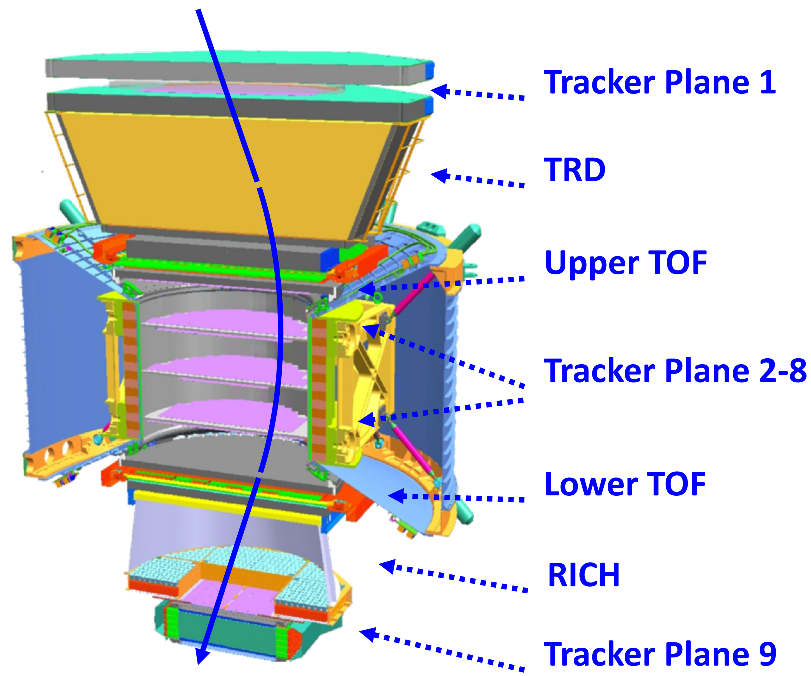
By 2024, AMS will provide an accurate study of the time-variation of nuclei fluxes on a daily basis over a complete solar cycle.

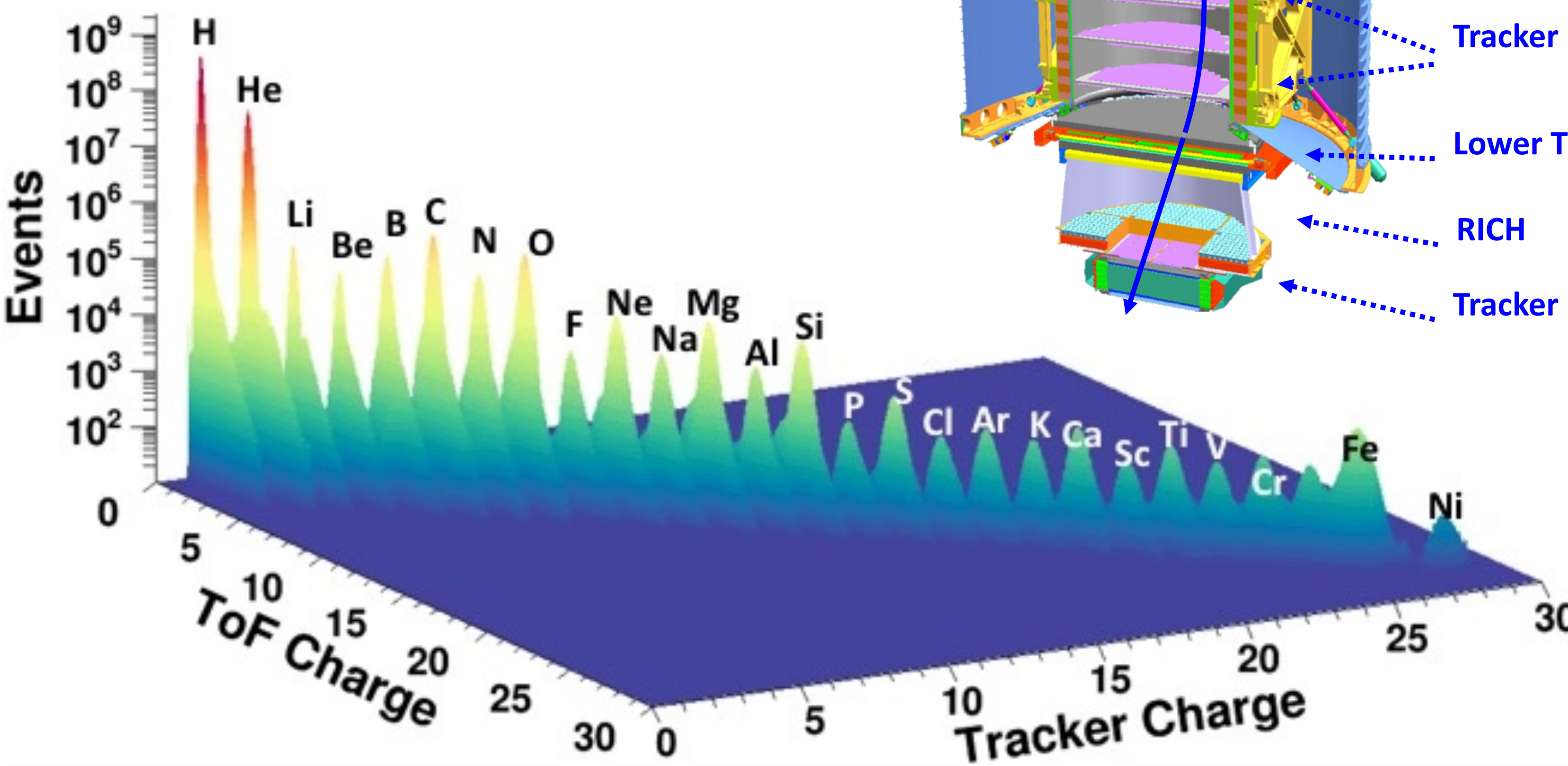


The physics of AMS to 2024:

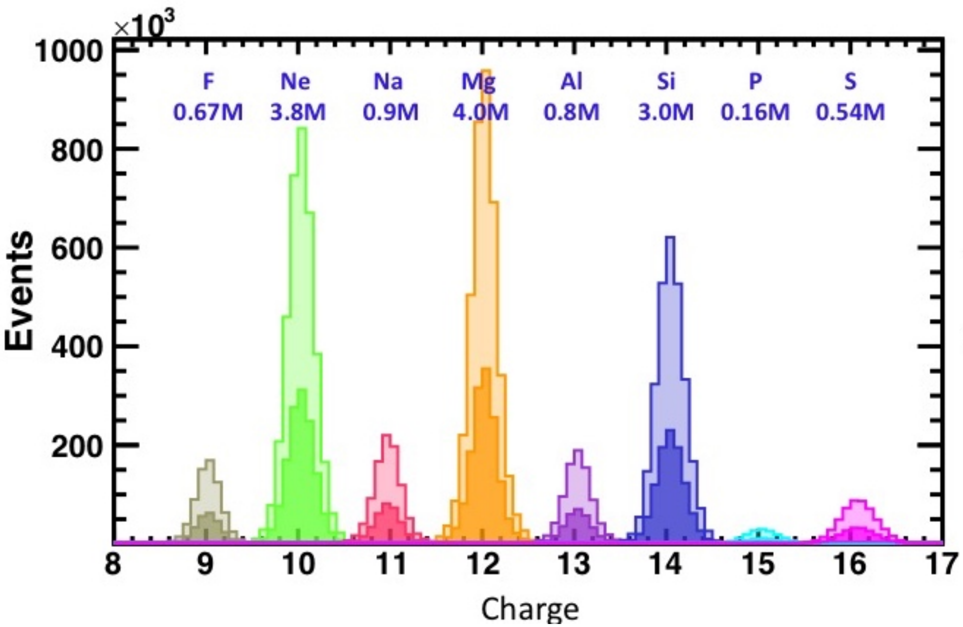
5. Study high Z cosmic rays

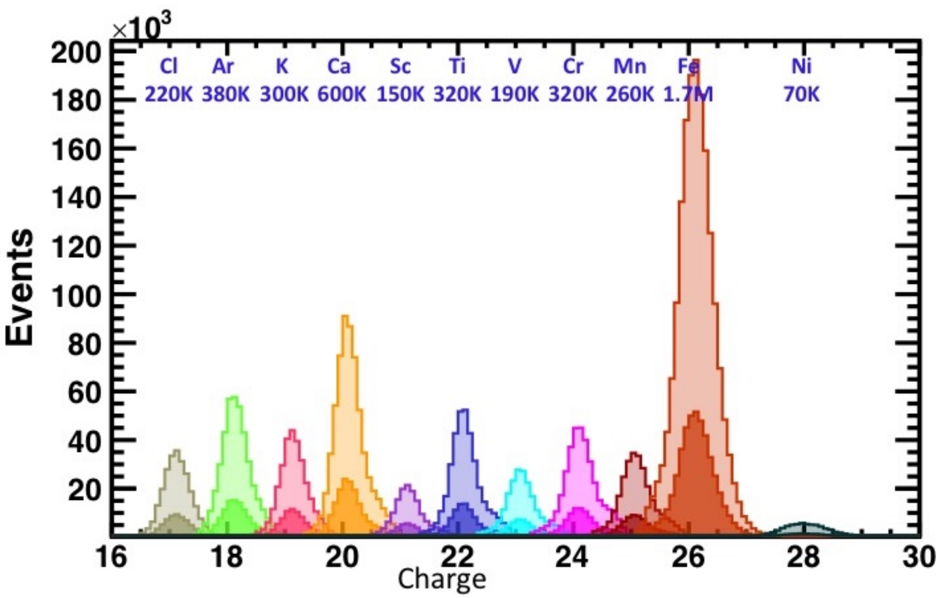
AMS has seven instruments which independently measure Cosmic Nuclei





AMS - Expected events to 2024



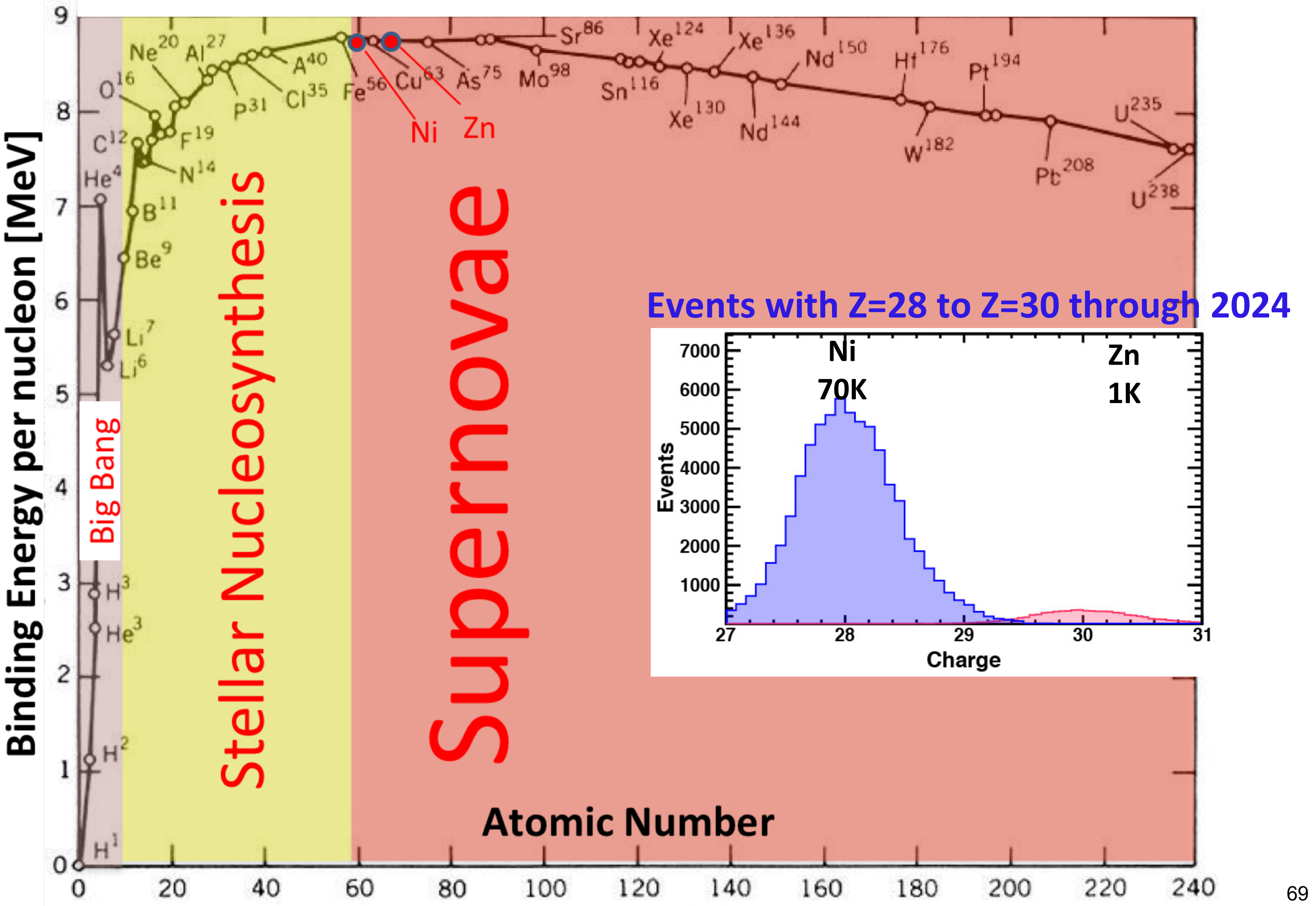


Z=9 to Z=16

Z=17 to Z=28

Darker shading shows events collected to date

V. The lightest elements created by supernova are Nickel and Zinc. AMS will be able to study their properties for the first time and compare them with elements produced by stellar nucleosynthesis.



AMS is the only magnetic spectrometer in space.

None of the AMS results were predicted.

The AMS results on Dark Matter and anti-matter are of historic importance. The current and new results on cosmic rays have, and will continue to, change our understanding of the cosmos.