Cosmic Ray Physics

Jorge Casaus on behalf of the CIEMAT Cosmic Ray Group

Direct Detection Experiments on Space Platforms

Active:

● **AMS (Alpha Magnetic Spectrometer on the International Space Station ISS),** in operation since May 19th 2011, expected to continue during the ISS lifetime (2030+)

In preparation:

● **HERD (High Energy cosmic Radiation Detection facility for the China Space Station CSS),** planned for operation starting in 2028 for about 10 years

Possible Future Projects:

● **AMS-100**

● **ALADInO**

Personnel

Scientific Personnel:

Seniors: **J. Casaus (AMS, HERD, R&D), C. Delgado (AMS), F. Giovacchini (AMS, HERD, R&D), M. Velasco (AMS, HERD)**

Emeriti: **M. Aguilar (AMS), C. Maña (AMS)**

Students: **I. Rodríguez (2026), F. Hernández (2028), A. Aceituno (2029)**

Technical Personnel:

Mechanics Engineers: **C. Díaz (HERD, R&D), M. Polo (HERD)**

Mechanics Technician: **A. Castro (HERD, R&D)**

Electronics Engineers (Tech. Dept.): **J. Marín (HERD, R&D), G. Martínez (HERD), Ll. Freixas (R&D)**

Funding

Spain – AEI:

Project: **Participation in the AMS Experiment on the ISS, in the HERD Experiment for the CSS, and R&D Activities for Future Detectors in Space**

Funding Agency: MICINN (PID2022-137810NB-C21)

Duration: **2023-2026(7) (AMS Science Activities, HERD Prototype, R&D)**

Funding: **506,250 €**

PI: **Jorge Casaus**; co-PI: **Carlos Mañá**

Spain – AEI:

Project: **Participation in the AMS Experiment**

Funding Agency: MICINN (PCI2023-145945-2)

Duration: **2023-2026(7) (Contribution to AMS Operation and Computing)**

Funding: **300,080 €**

PI: **Jorge Casaus**

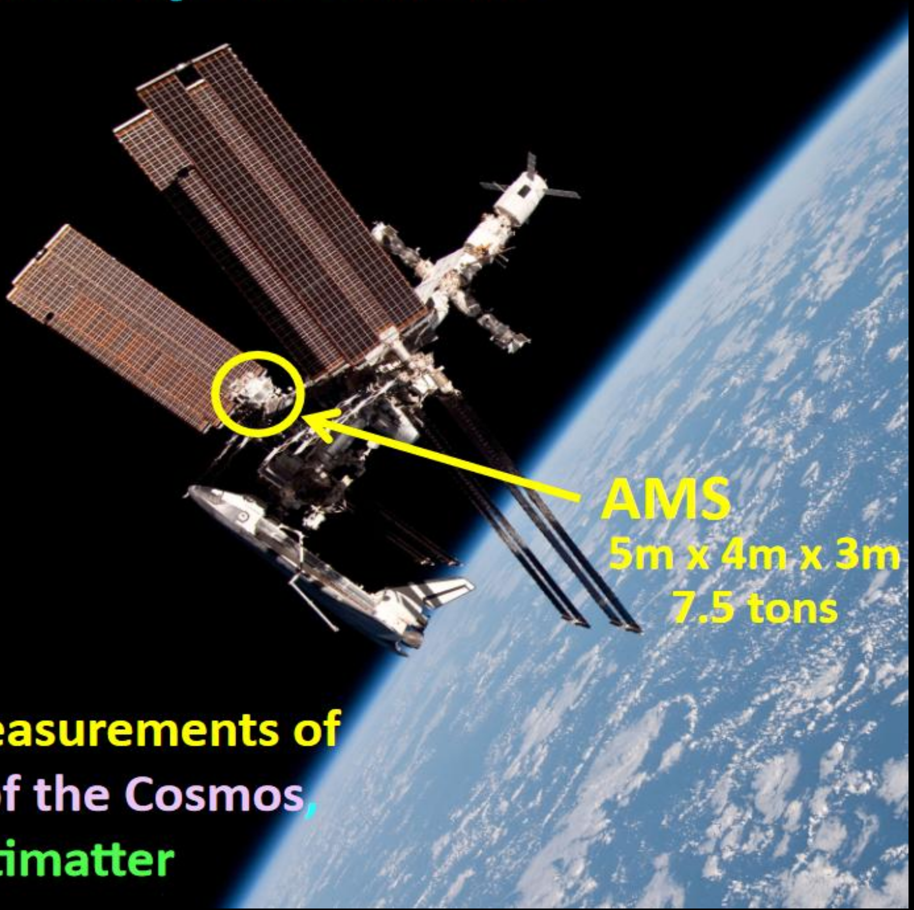
AMS: direct detection of cosmic rays from the International Space Station

AMS installed on the ISS in May 2011

Near Earth Orbit:

- altitude 400 Km
- inclination 52°
- period 92 min

Continuous operations through the ISS lifetime (at least 2030)



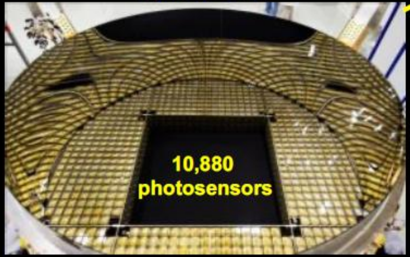
AMS provides precision, long-duration measurements of charged cosmic rays to study the Origin of the Cosmos, the physics of Dark Matter and Antimatter

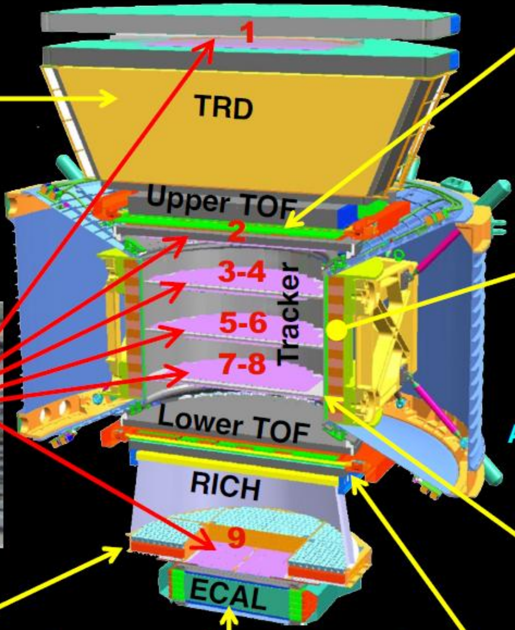
AMS is a space version of a precision detector used in accelerators

Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





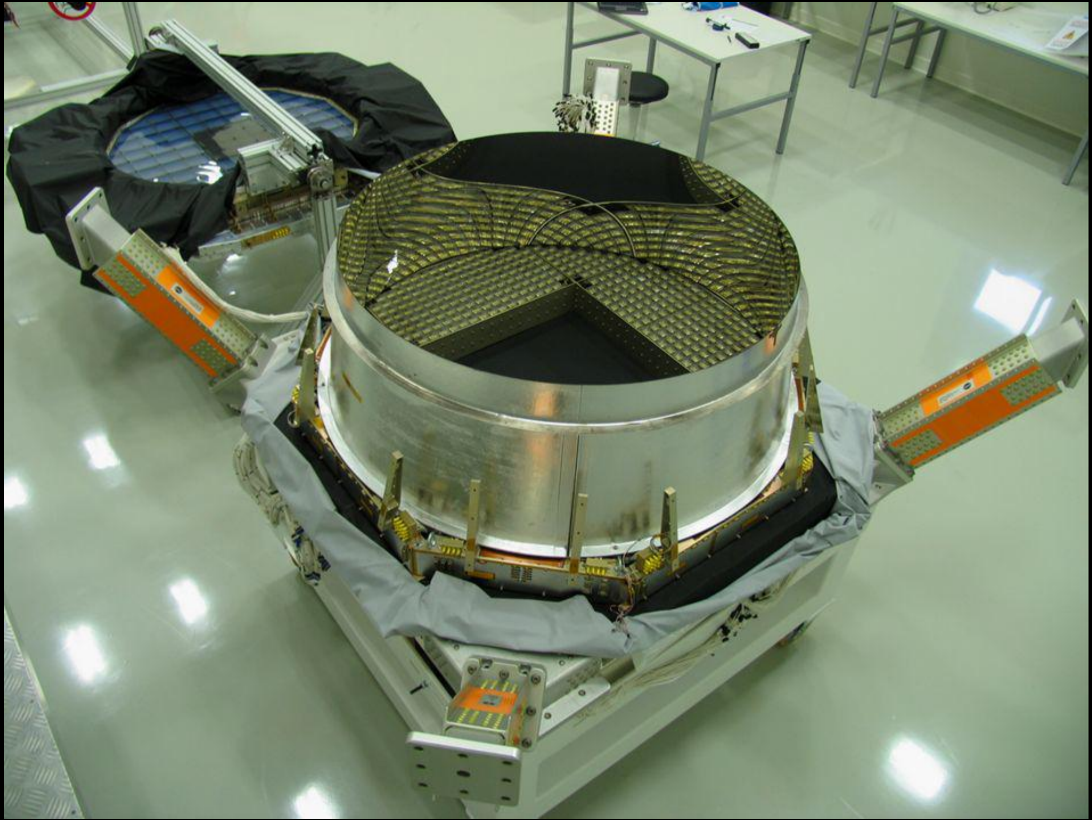
Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

Upper TOF measure Z, E

Magnet identify ±Z, P

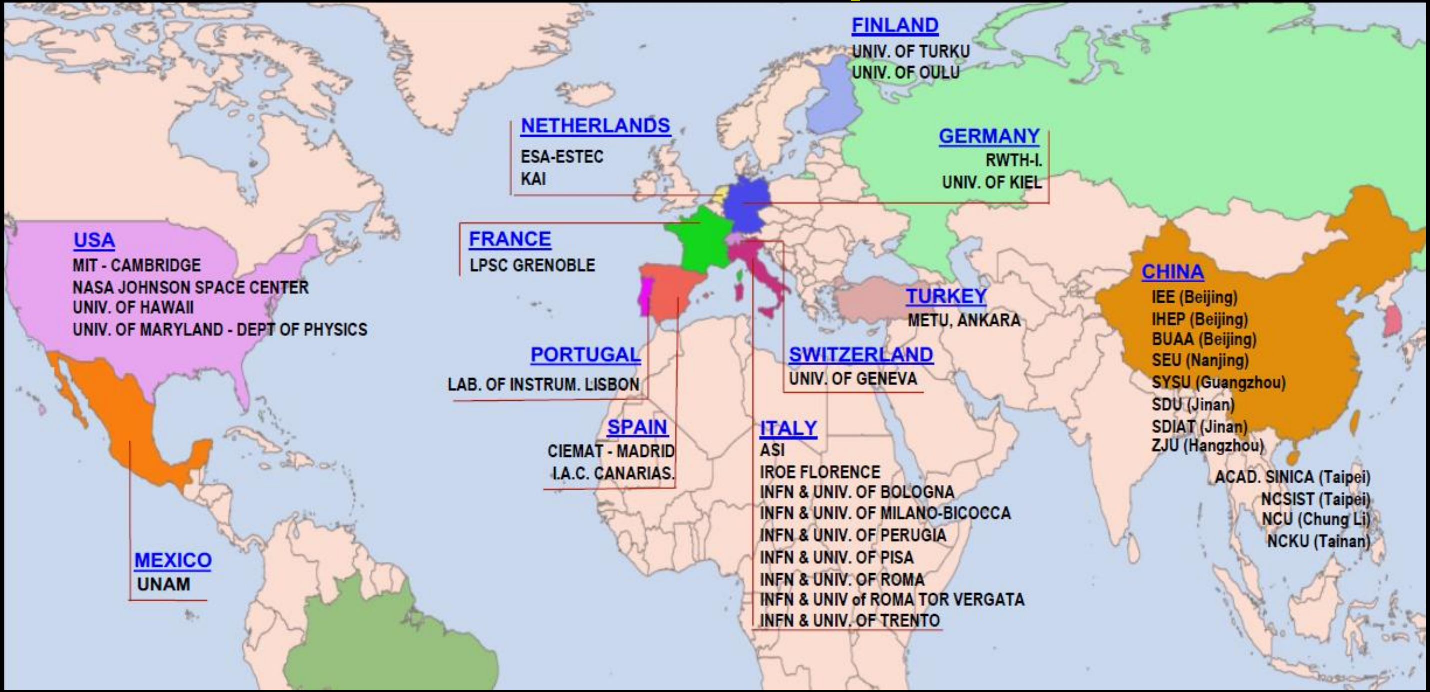
Anticoincidence Counters (ACC)
reject particles from the side

Lower TOF measure Z, E



CIEMAT made a major contribution in the design and construction of the RICH detector, and is responsible for the RICH operations from the AMS-POCC at CERN and the offline reconstruction software

AMS is an international collaboration with 250 members from 44 institutions from Europe, Asia, and America



After 15 years of operation on the ISS AMS has collected more than 260 billion cosmic rays

Main analysis topics at CIEMAT:

- **Cosmic Rays nuclei fluxes and ratios (p, He,…Fe)**
(11 PRL, 6 selected as Editors' Suggestion, 4 Featured in Physics)

- **Cosmic Rays isotopic composition (D, ^{3}He, Li)**
(3 PRL, 3 selected as Editors' Suggestion, 1 Featured in Physics)

- **Flux Anisotropy in e+, e-, protons and light nuclei fluxes**
(in 3 PRL, selected as Editors' Suggestion)

- **Time evolution of electron and positron fluxes**
(2 PRL, 1 of them selected as Editors' Suggestion, Featured in Physics, and Physics Viewpoint)

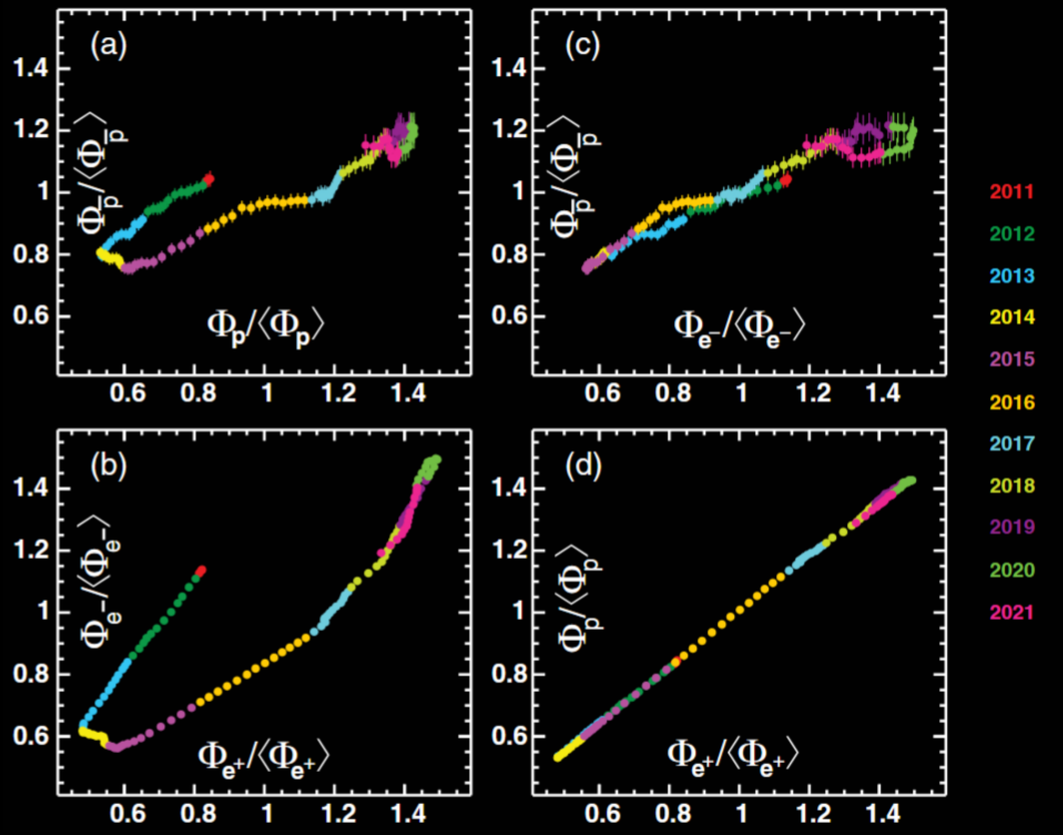
AMS Publications in *Physical Review Letters*

8,666 citations to date

1)	Phys. Rev. Lett. 110, 141102 (2013)	Editors' Suggestion. Viewpoint in *Physics*. Highlight of 2013. Ten-Year Editors' Suggestion retrospective
2)	Phys. Rev. Lett. 113, 121101 (2014)	Editors' Suggestion
3)	Phys. Rev. Lett. 113, 121102 (2014)	Editors' Suggestion. Featured in *Physics*.
4)	Phys. Rev. Lett. 113, 221102 (2014)	
5)	Phys. Rev. Lett. 114, 171103 (2015)	Editors' Suggestion
6)	Phys. Rev. Lett. 115, 211101 (2015)	Editors' Suggestion
7)	Phys. Rev. Lett. 117, 091103 (2016)	
8)	Phys. Rev. Lett. 117, 231102 (2016)	Editors' Suggestion
9)	Phys. Rev. Lett. 119, 251101 (2017)	
10)	Phys. Rev. Lett. 120, 021101 (2018)	Editors' Suggestion. Featured in *Physics*.
11)	Phys. Rev. Lett. 121, 051101 (2018)	
12)	Phys. Rev. Lett. 121, 051102 (2018)	Editors' Suggestion
13)	Phys. Rev. Lett. 121, 051103 (2018)	
14)	Phys. Rev. Lett. 122, 041102 (2019)	Editor's Suggestion
15)	Phys. Rev. Lett, 122, 101101 (2019)	
16)	Phys. Rev. Lett. 123, 181102 (2019)	Editors' Suggestion
17)	Phys. Rev. Lett. 124, 211102 (2020)	Editors' Suggestion. Featured in *Physics*.
18)	Physics Reports 894, 1 (2021)	
19)	Phys. Rev. Lett. 126, 041104 (2021)	Featured in *Physics*.
20)	Phys. Rev. Lett. 126, 081102 (2021)	Editors' Suggestion
21)	Phys. Rev. Lett. 127, 021101 (2021)	
22)	Phys. Rev. Lett. 127, 271102 (2021)	
23)	Phys. Rev. Lett. 128, 231102 (2022)	
24)	Phys. Rev. Lett. 130, 161001 (2023)	Editors' Suggestion. Viewpoint in *Physics*.
25)	Phys. Rev. Lett. 130, 211002 (2023)	Featured on *Phys.org*
26)	Phys. Rev. Lett. 131, 151002 (2023)	APS Press Announcement
27)	Phys. Rev. Lett. 132, 261001 (2024)	Editors' Suggestion. Featured in *Physics*.
28)	Phys. Rev. Lett. 134, 051002 (2025)	Editors' Suggestion. Viewpoint in *Physics*. APS Press Announcement
29)	Phys. Rev. Lett. 134, 051001 (2025)	APS Press Announcement
30)	Phys. Rev. Lett. 134, 201001 (2025)	Editors' Suggestion. Featured in *Physics*. APS Press Announcement

Temporal Structures in e+ Spectra and Charge-Sign Effects in GCR

The AMS results over an 11-year solar cycle show that positron fluxes have distinctly different time variations from electron fluxes and similar to protons

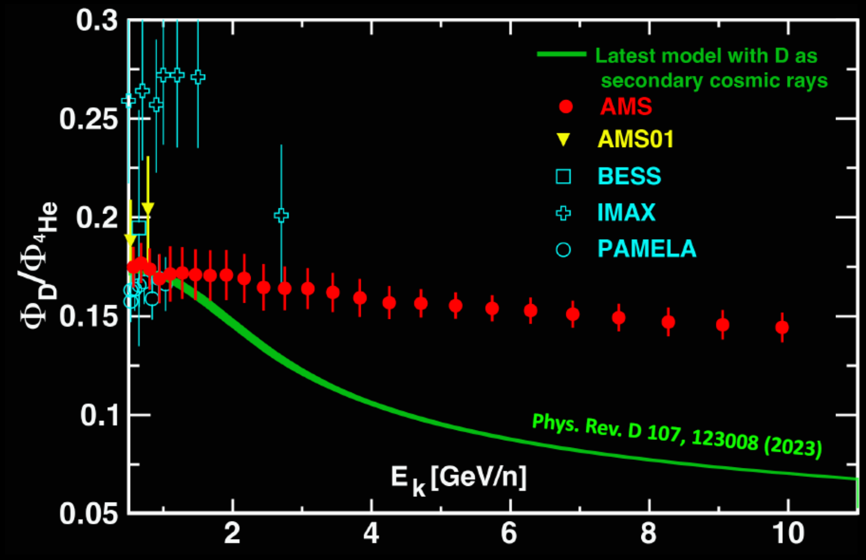


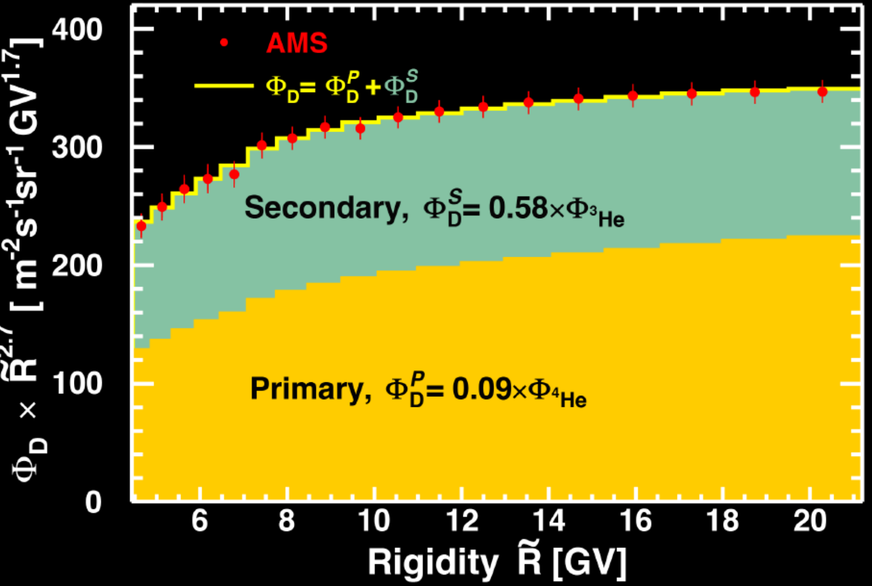
M. Aguilar et al., AMS Collaboration, *Temporal Structures in Positron Spectra and Charge-Sign Effects in Galactic Cosmic Rays*
Phys. Rev. Lett. 131, 151002 (2023)

Origin of Cosmic Deuterons

The AMS results disagree with the latest model with D as secondary cosmic rays

Deuterons have a significant primary component

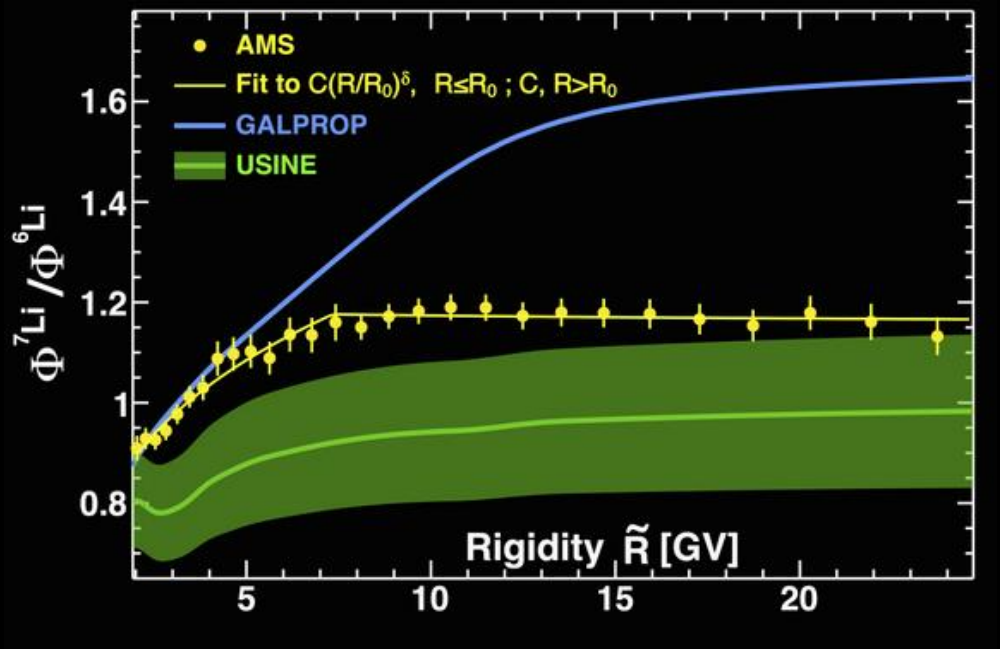




M. Aguilar et al., AMS Collaboration, *Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer*
Phys. Rev. Lett. 132, 261001 (2024)

Origin of Cosmic Lithium

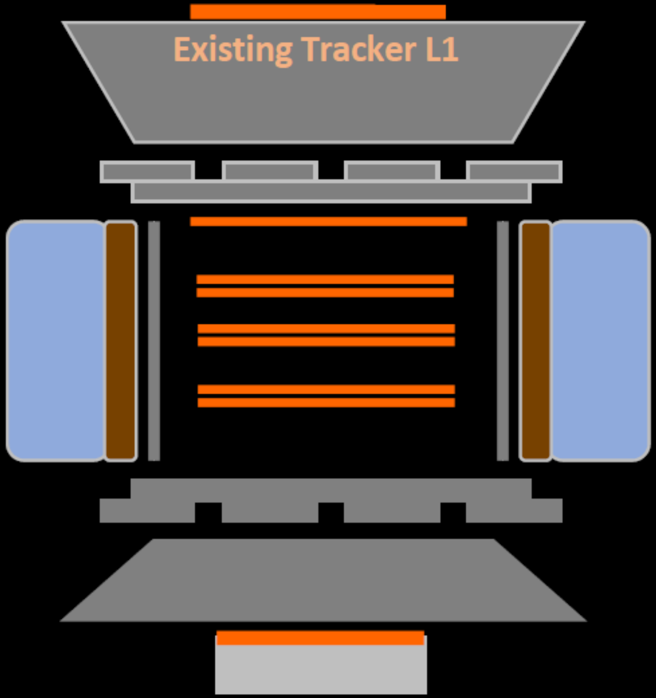
The AMS results observation supports the secondary origin of lithium in cosmic rays and excludes the existence of a sizable primary component in the ^{7}Li flux.



M. Aguilar et al., AMS Collaboration, *Properties of Cosmic Lithium Isotopes Measured by the Alpha Magnetic Spectrometer*
[Phys. Rev. Lett. 134, 201001 (2025)]

AMS 2011-2026

Continuous data-taking



AMS 2026-2030+

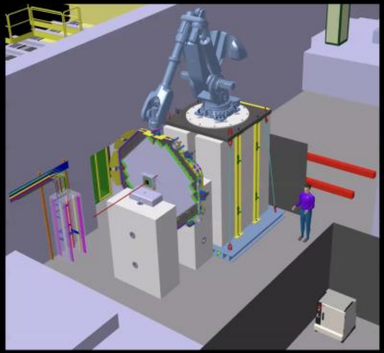
New 4+4m^2 Silicon Tracker Planes

Acceptance increased to 300%

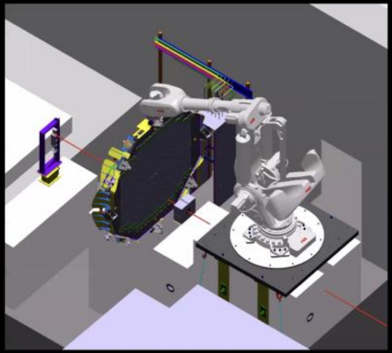
AMS L0 Flight Hardware Integration & Metrology @CERN

Detector mapping performed at several steps during integration and a final one after all tests and before test beam

North Area Installation



Virtual Environment



April 20th, 2026: Vibration test
May 11th, 2026: Thermal Vacuum Test
June 8th, 2026: EMI Test
June 26th, 2026: NASA/DOE visit
July 20th, 2026: Test Beam @SPS

08/2026: Ready for Delivery to NASA KSC
03/2027: Launch on SpaceX-36

AMS Upgrade confirmed on the NASA flying manifest

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
2101 NASA Parkway
Houston, Texas 77058-3696

January 29, 2026

ttn of: OA-26-004

Professor Samuel Ting
Principal Investigator, Alpha Magnetic Spectrometer
Massachusetts Institute of Technology
Laboratory for Nuclear Science
77 Massachusetts Ave
#26-306A
Cambridge MA 02139

Dear Professor Ting:

The Alpha Magnetic Spectrometer (AMS) continues to be a cornerstone of the International Space Station's (ISS) research portfolio, and we recognize the importance of maintaining its operational integrity and maximizing its use through ISS End of Life. After a comprehensive assessment of NASA's resources, the ISS Program has concluded that it can support continuing with the AMS Tracker Layer 0 (TL0) Project for launch on SpaceX-36. In order to minimize disruptions to delivery of critical ISS supplies, the ISS Program can only offer Northrop Grumman NG-25 as the flight opportunity for any pressurized cargo. Please also note that the ISS Flight Program remains dynamic thus any changes which may jeopardize NASA's ability to launch critical supplies will necessitate prioritization decisions, potentially affecting research activities including this AMS TL0 effort. With the understanding of these constraints, please consider the AMS TL0 effort re-authorized effective immediately.

We appreciate your continued leadership and collaboration in advancing this critical scientific endeavor. Please let us know if you require additional details with respect to this decision.

Sincerely,

Dina Cotella
For Dana Weigel

Dana J. Weigel
Manager, International Space Station Program

https://www.commerce.senate.gov/2026/3/commerce-committee-advances-nasa-reauthorization-act-and-weather-act

Commerce Committee Advances NASA Reauthorization Act and Weather Act

March 4, 2026

WASHINGTON, D.C. – Today, the U.S. Senate Committee on Commerce, Science, and Transportation unanimously advanced two bipartisan measures: the NASA Authorization Act of 2026 and the Weather Research and Forecasting Innovation Reauthorization Act of 2026.

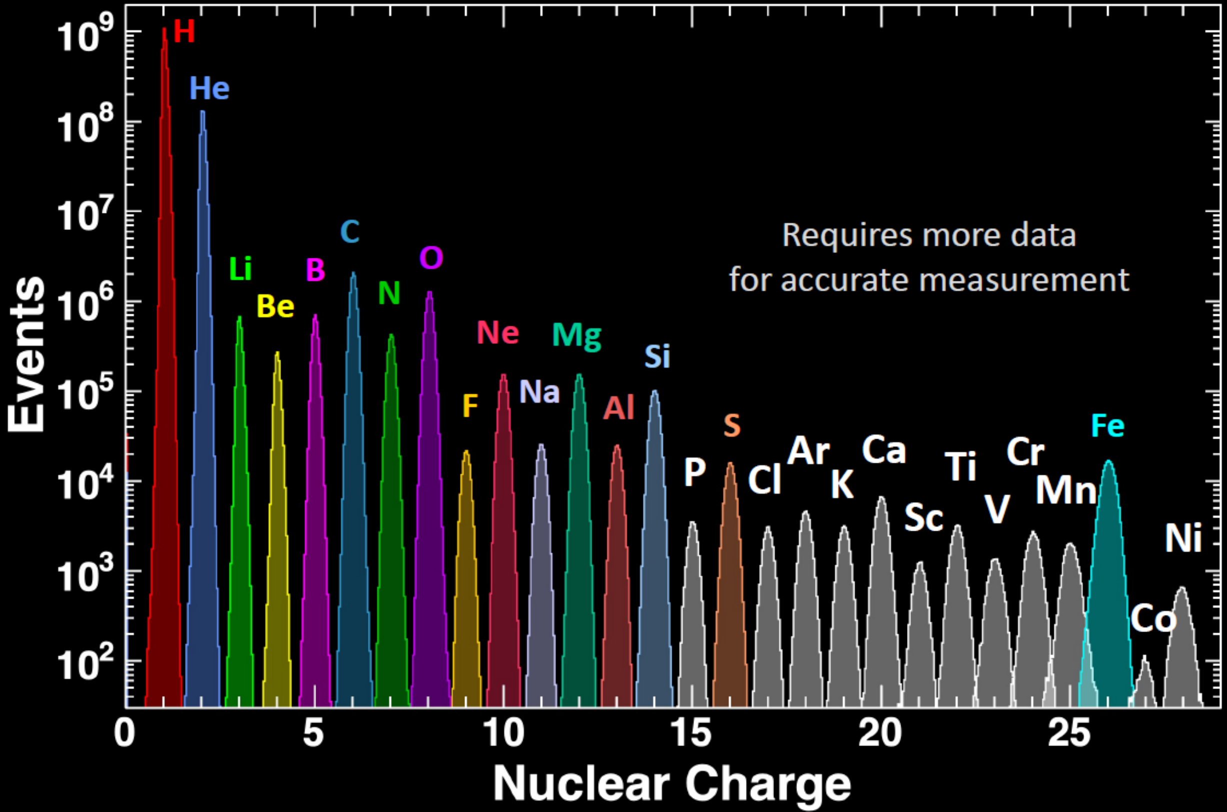
The NASA Authorization Act of 2026

Securing American Dominance in the New Space Race

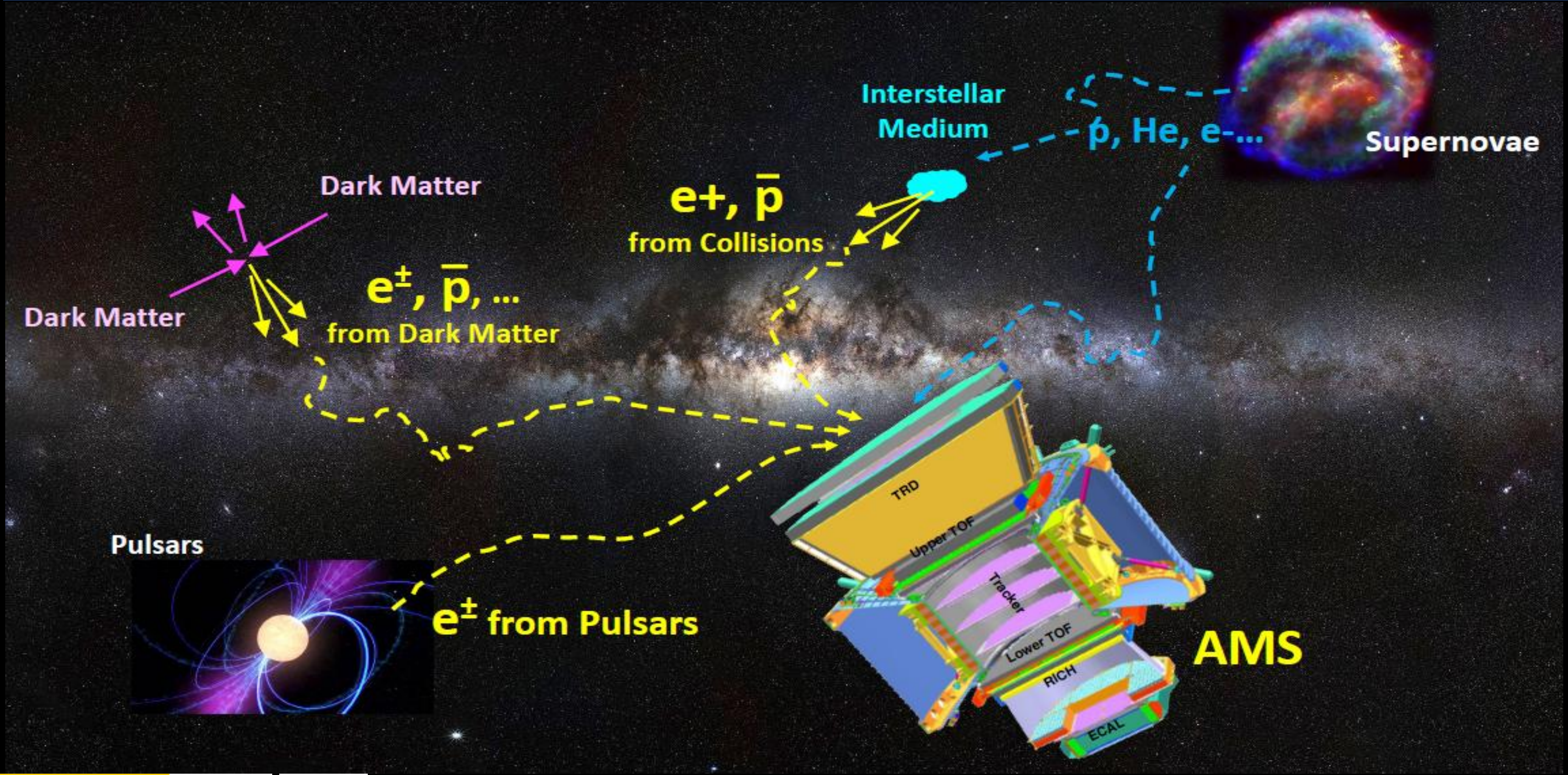
- Directs NASA to establish a permanent Moon Base so we can get there before the Chinese.
- Requires NASA to begin soliciting for two commercial space stations immediately.
- Extends the International Space Station (ISS) to 2032 to avoid a gap in continuous human presence and capabilities in LEO, thus avoiding ceding leadership to China before commercial stations are ready.
- Reasserts American leadership in deep space by advancing the Artemis program as we prepare to return U.S. astronauts to the lunar surface for the first time since Apollo 17, paving the way for the next generation of commercial services beyond Earth's orbit.
- Protects U.S. national security by prohibiting unauthorized cooperation with China, requiring disclosure of foreign financial ties in NASA contracting, and directing comprehensive supply chain risk reviews.

Cosmic Ray Nuclei by 2030

AMS will provide complete and accurate spectra for the
29 elements and provide the foundation for a comprehensive theory of cosmic rays.



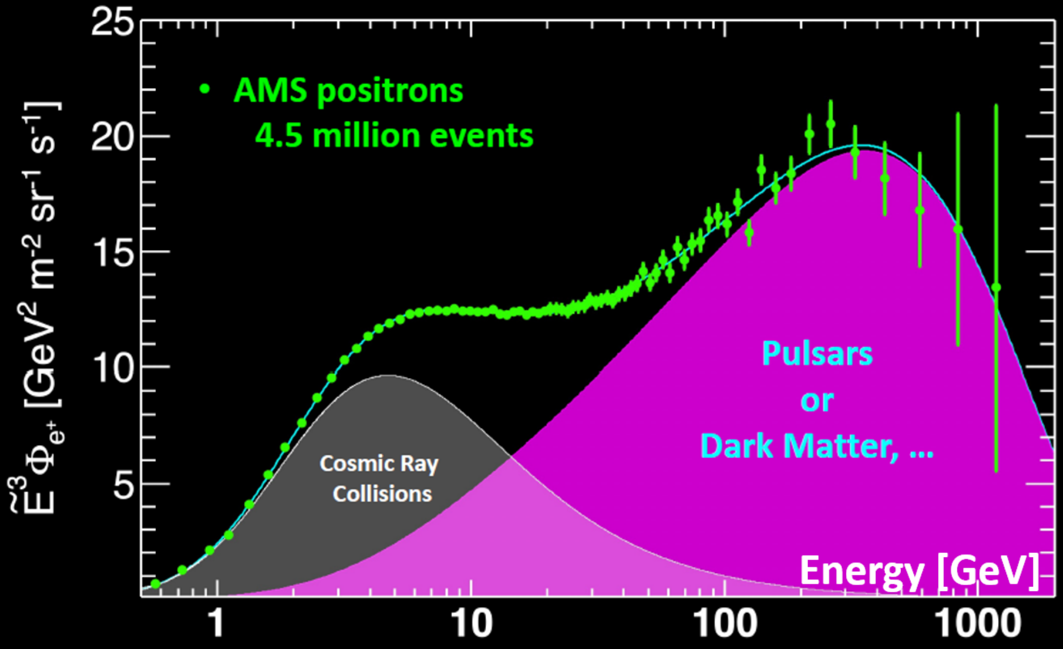
Latest Results on positrons e^+, electrons e^-, antiprotons $\overline{p}$



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

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[\underbrace{C_d(\hat{E}/E_1)^{\gamma_d}}_{\text{Collisions}} + \underbrace{C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)}_{\text{Pulsars or Dark Matter}}\right]$$

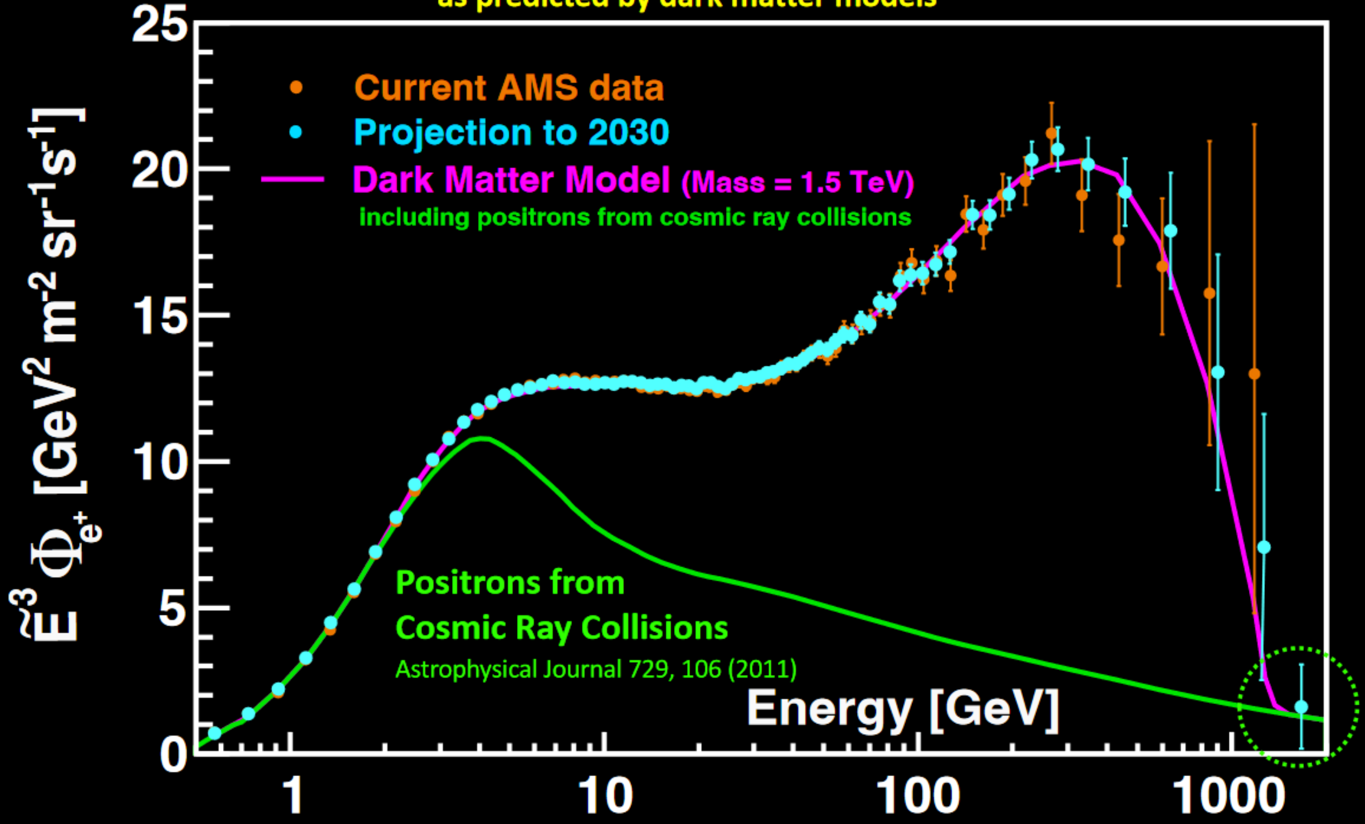
Solar Collisions Pulsars or Dark Matter



The existence of the finite cutoff energy (5.0σ) Is an unexpected observation

Determination of the Origin of Cosmic Positrons by 2030

AMS will ensure that the measured high energy positron spectrum indeed drops off quickly and, at the highest energies, the positrons only come from cosmic ray collisions as predicted by dark matter models

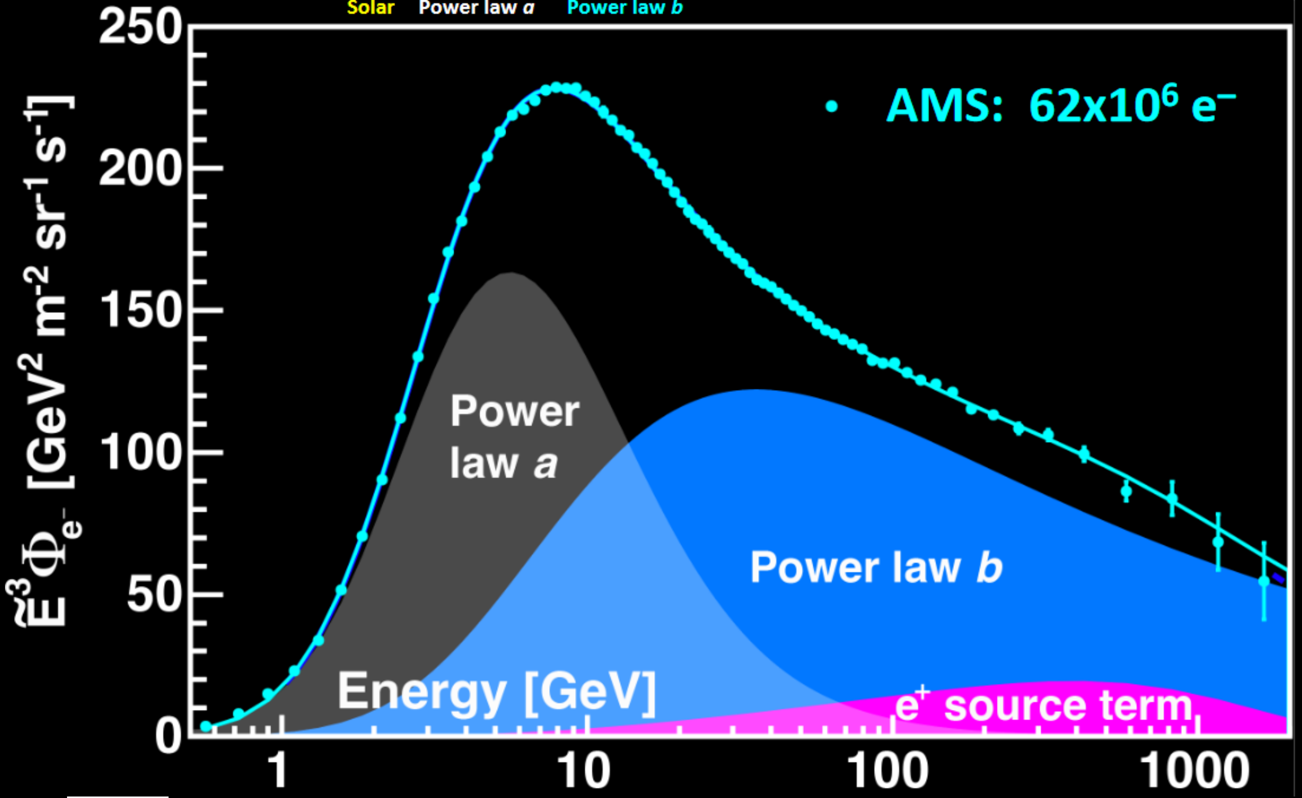


AMS Result on the electron spectrum

The spectrum fits well with two power laws (a, b) and a source term like positrons

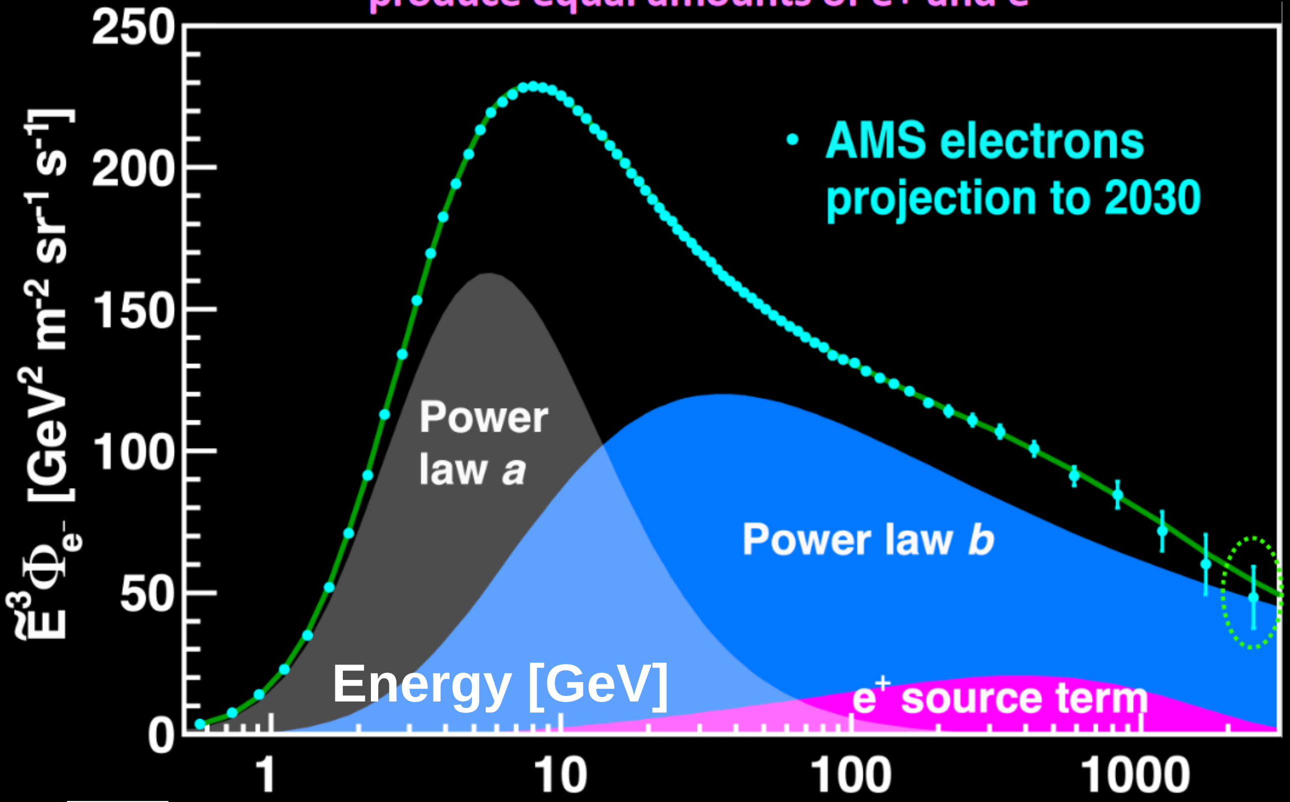
$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left(C_a \hat{E}^{\gamma_a} + C_b \hat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

Solar | Power law a | Power law b | 2.5σ effect

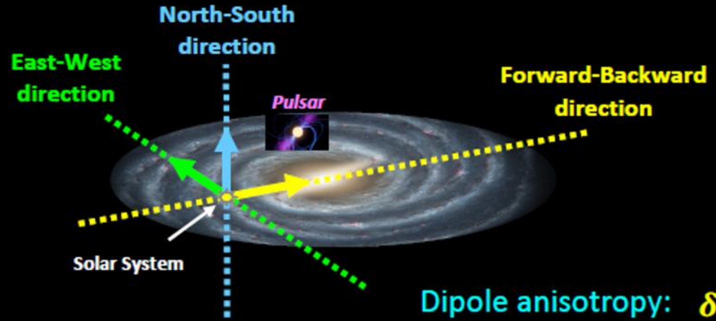


By 2030, the charge-symmetric nature of the high energy source will be established at the 4σ level

New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e−



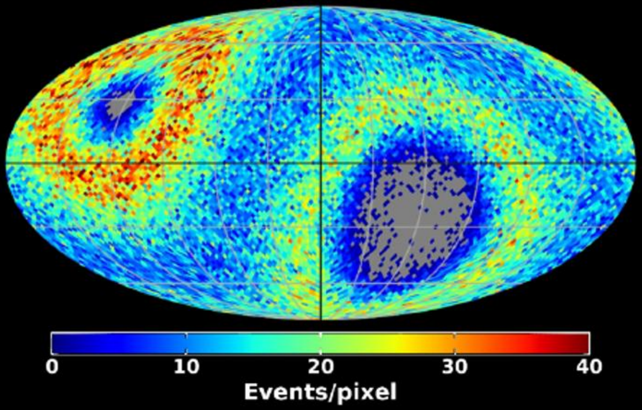
Positron Anisotropy



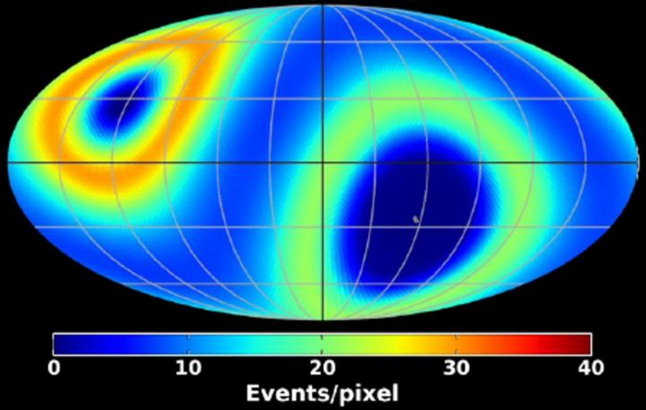
Astrophysical point sources will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

Dipole anisotropy: $\delta = 3\sqrt{C_1/4\pi}$ C_1 is the dipole moment

Positrons

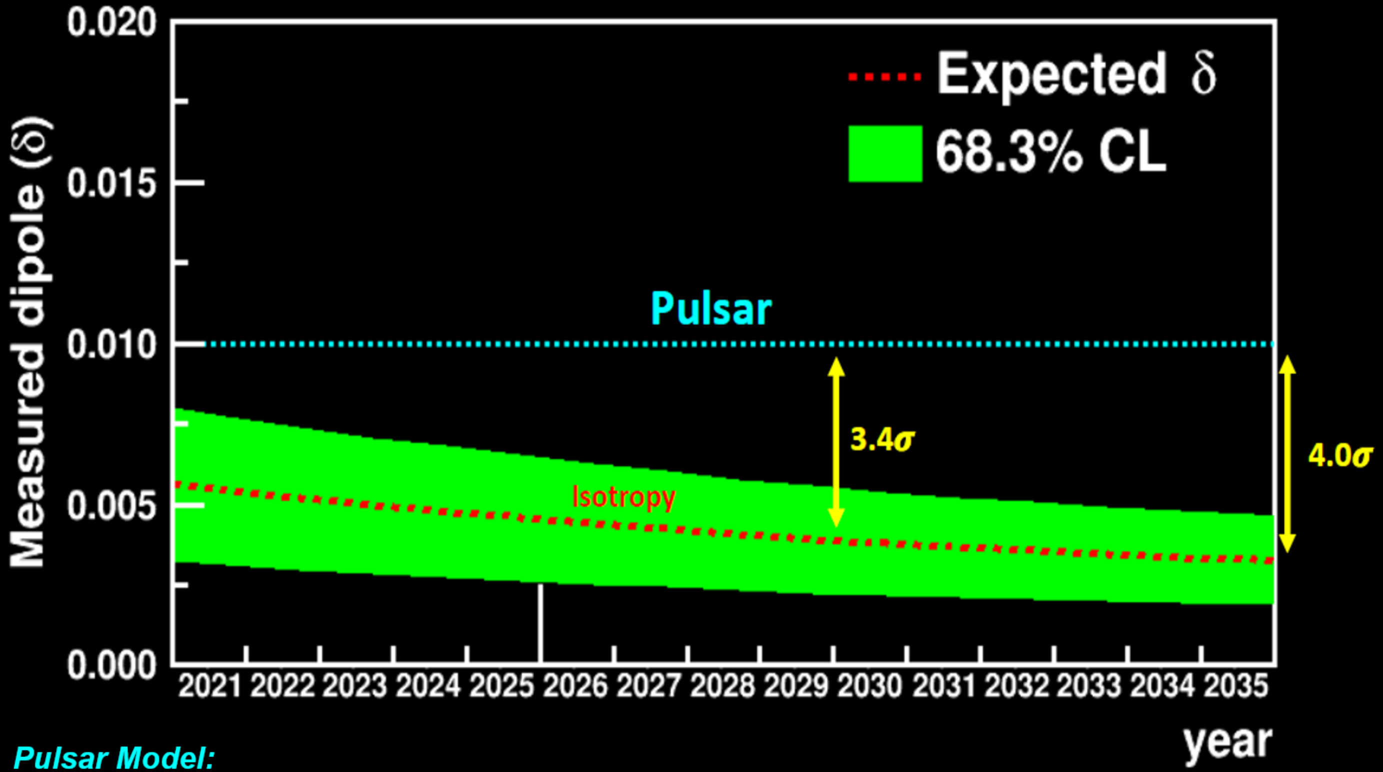


Isotropic map



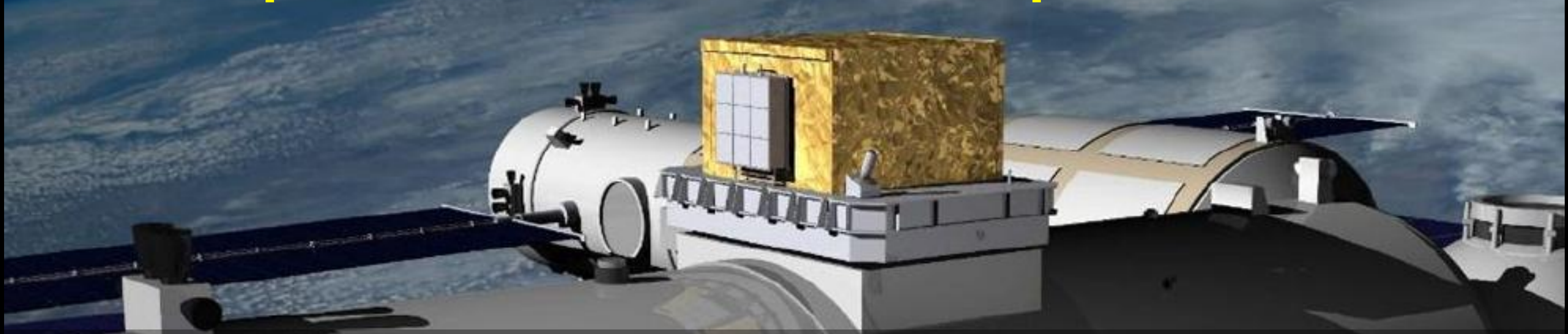
AMS **Currently at 95% C.I.:** for 16 < E < 500 GeV **$\delta_{e+} < 0.0144$**

Future AMS measurement with improved positron statistics will allow us to distinguish dark matter and pulsar origin at the 99.93% C.L. in 2030, and at 99.99% C.L. in 2035



Pulsar Model:
D. Hooper, P. Blasi & P. D. Serpico, **JCAP 0901(2009)**

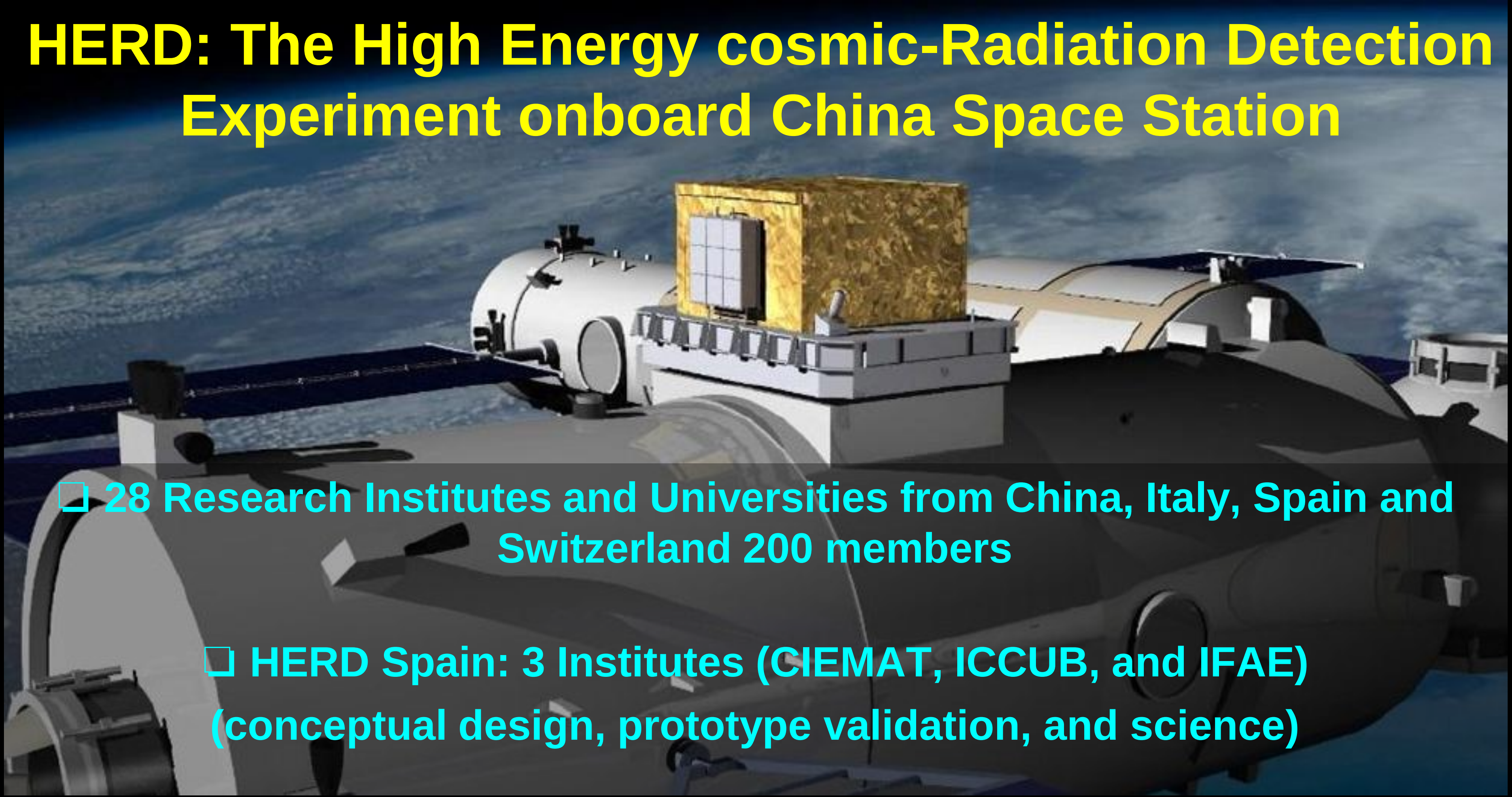
HERD: The High Energy cosmic-Radiation Detection Experiment onboard China Space Station



- ❑ **HERD is a spaceborne cosmic ray detector and gamma ray observatory to be installed at the CSS in 2028 and operate for a period of 10 years**

- ❑ **indirect search for dark matter, extend of the direct measurement of CRs to higher energies, and gamma-ray monitoring and full sky survey**

HERD: The High Energy cosmic-Radiation Detection Experiment onboard China Space Station



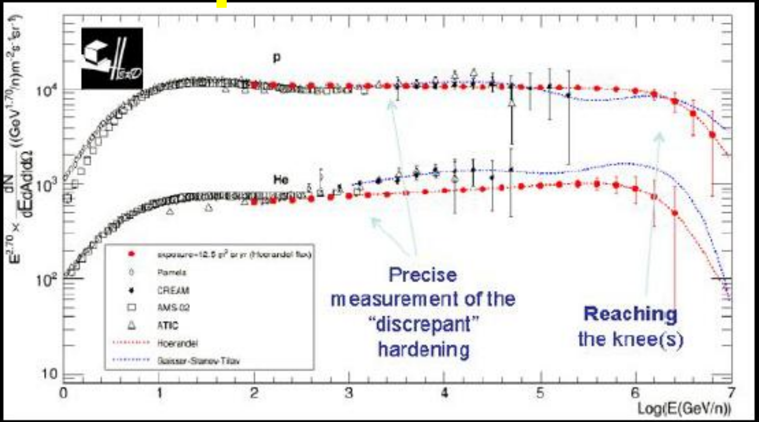
- ❑ 28 Research Institutes and Universities from China, Italy, Spain and Switzerland 200 members

- ❑ HERD Spain: 3 Institutes (CIEMAT, ICCUB, and IFAE) (conceptual design, prototype validation, and science)

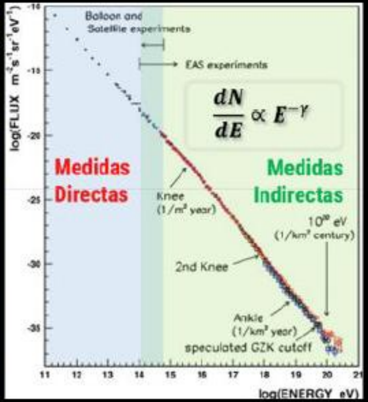
HERD: The High Energy cosmic-Radiation Detection Experiment onboard China Space Station

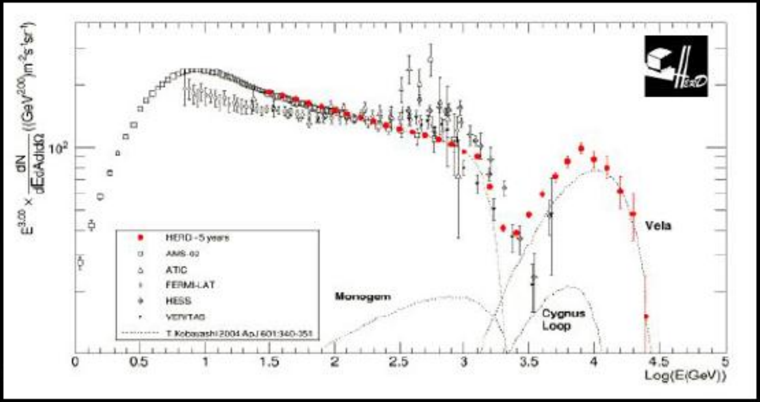
HERD will extend the energy range of direct CR measurements

- Measure the spectra and composition of cosmic rays to 1 PeV
- Search for dark matter signatures in the spectra of high energy electrons and γ-rays up to 100 TeV
- Continuous high energy γ ray sky monitoring

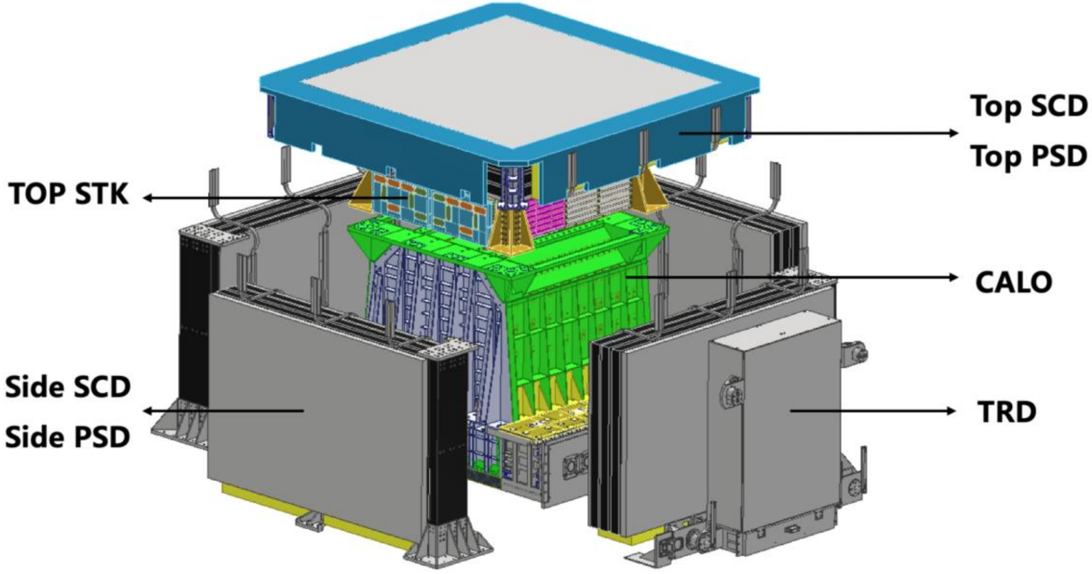


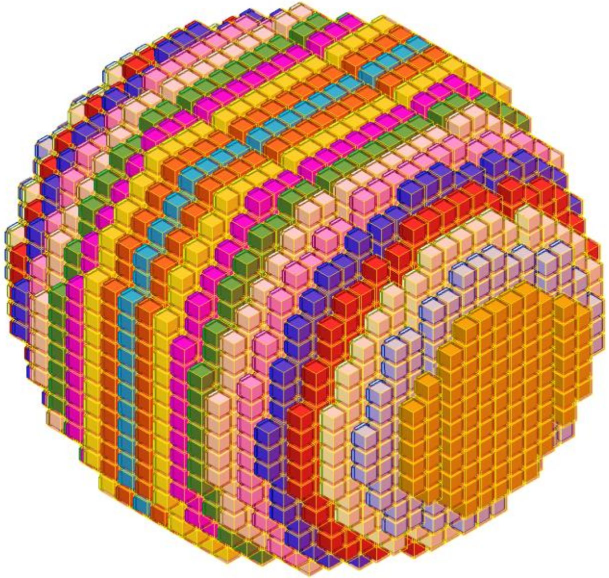
Item	Value
Energy range (e/γ)	10 GeV - 100 TeV (e); 0.5 GeV - 100TeV (γ)
Energy range (CR)	30 GeV - PeV
Angular resolution	<0.6º @1GeV, 0º
Charge measurement	Z=1 to 26
Charge resolution	0.15c.u.@Z=1, 0.2c.u.@Z=6
Energy resolution (e)	<1.5%@200GeV
Energy resolution (p)	<22%@400GeV
e/p separation	>3*10⁵@effi. 90% 100GeV e-
G.F. (e)	>3m²sr @200 GeV
G.F. (p)	>2m²sr @100 TeV





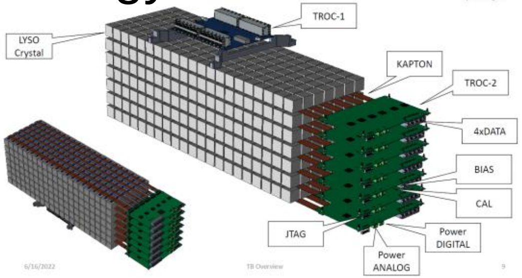
HERD: The High Energy cosmic-Radiation Detection Experiment onboard China Space Station





HERD implements a novel 3D calorimeter concept for space applications developed in the INFN Calocube R&D project participated by CIEMAT since 2015

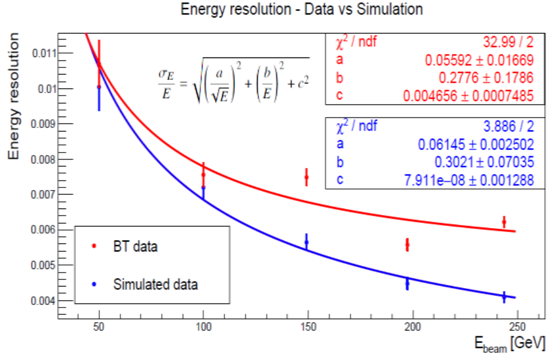
- HERD CALO prototypes have been extensively tested at CERN PS and SPS
- Analysis of the 1,000 LYSO crystal prototype tests at SPS provides electron, proton and ion energy resolutions consistent with specifications

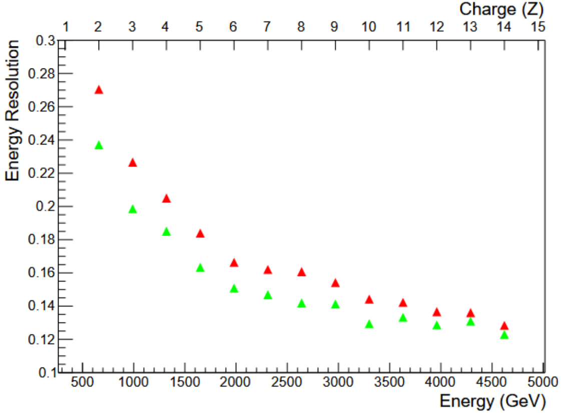


P. Betti et al., [Instruments 2024, 8(1), 5]



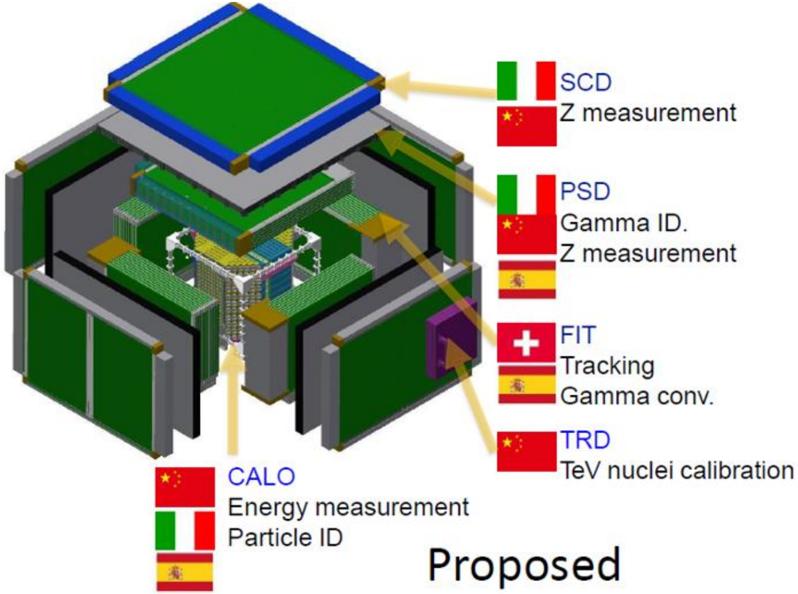

O. Adriani et al., [2025 JINST 20 P02015]

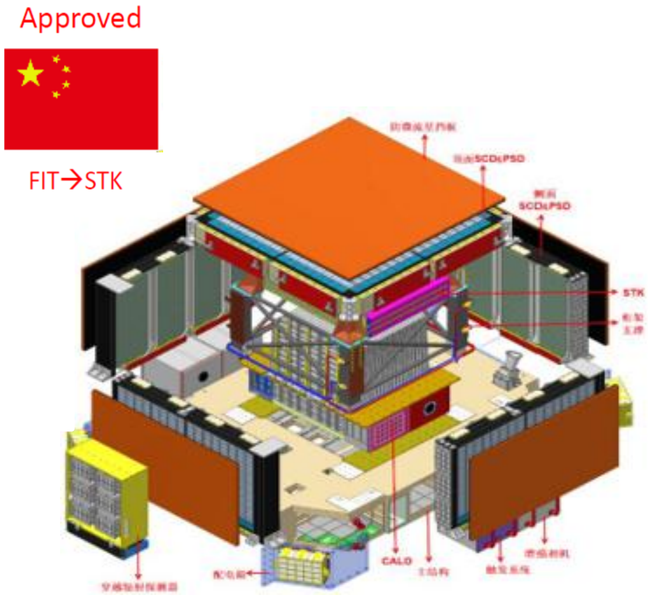




HERD: The High Energy cosmic-Radiation Detection Experiment onboard China Space Station

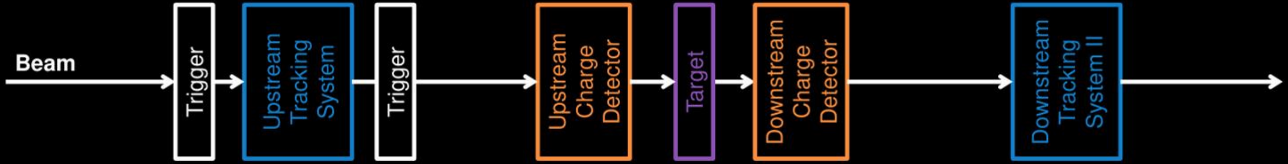
- No European contribution to HERD flight hardware
- Spanish groups involved in the assessment of HERD scientific capabilities and in the future scientific exploitation



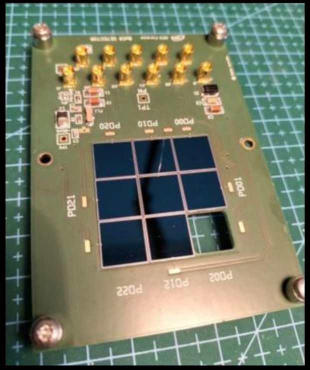


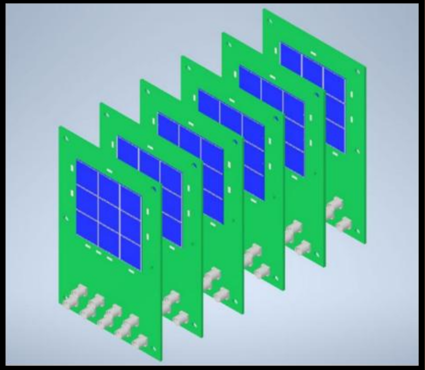
BeER: Beam-monitor with Extreme Range

BeER is a multi-purpose, high-resolution, high dynamic-range charge detector proposed as a technological spin-off of the hardware contributions initially developed for Calocube and later for HERD CALO PD



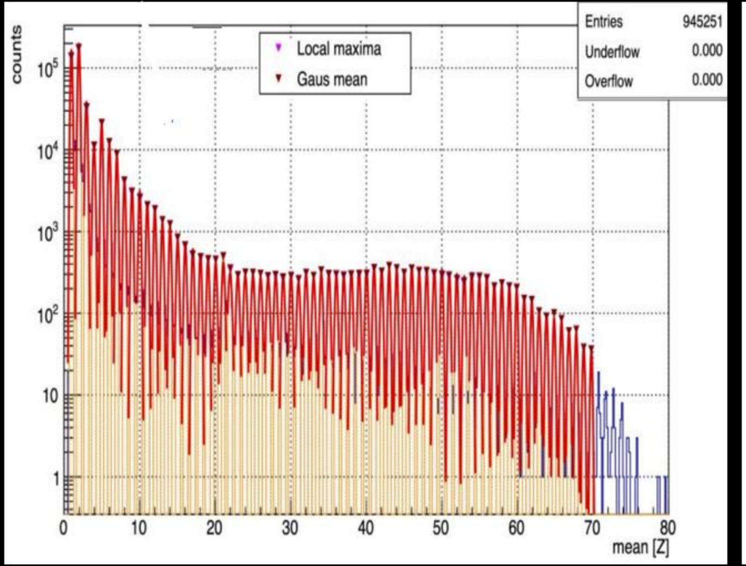
Charge detector



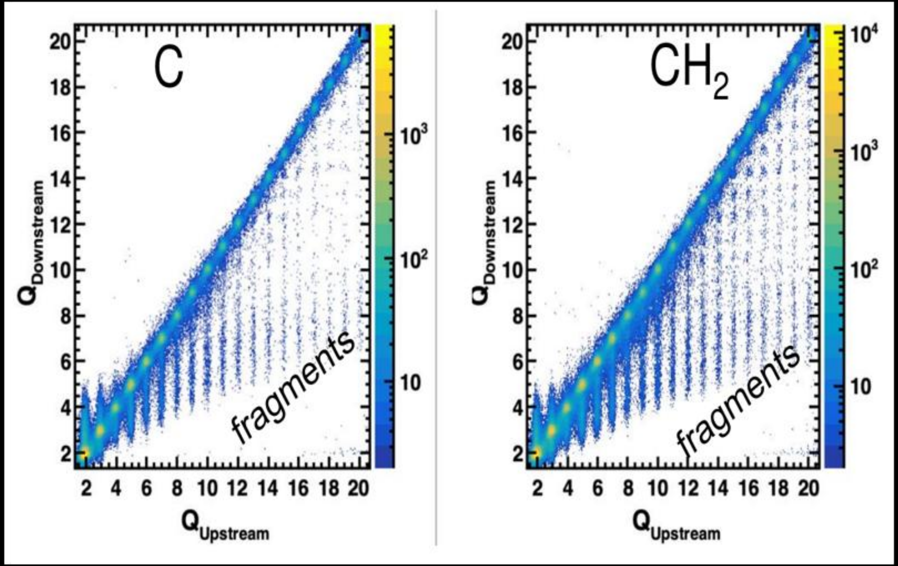


- Geometrical configuration:
  6 layers, 3×3 PDs ($9.2 \times 9.2\ mm^2$)
- Read-out electronics
  developed by CIEMAT and INFN
- Charge resolution
  $\Delta Z/Z$ better than 0.3 up to Z~80

Upstream Charge Identification



Downstream Charge Identification

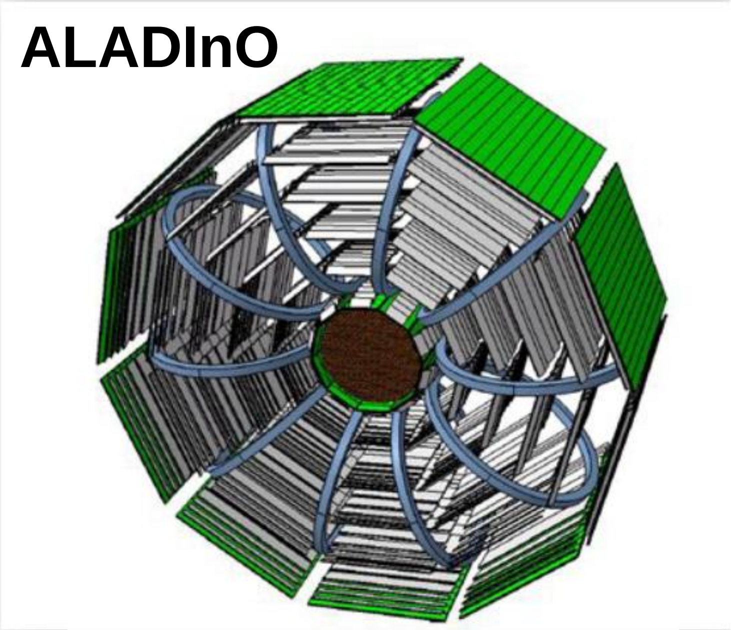


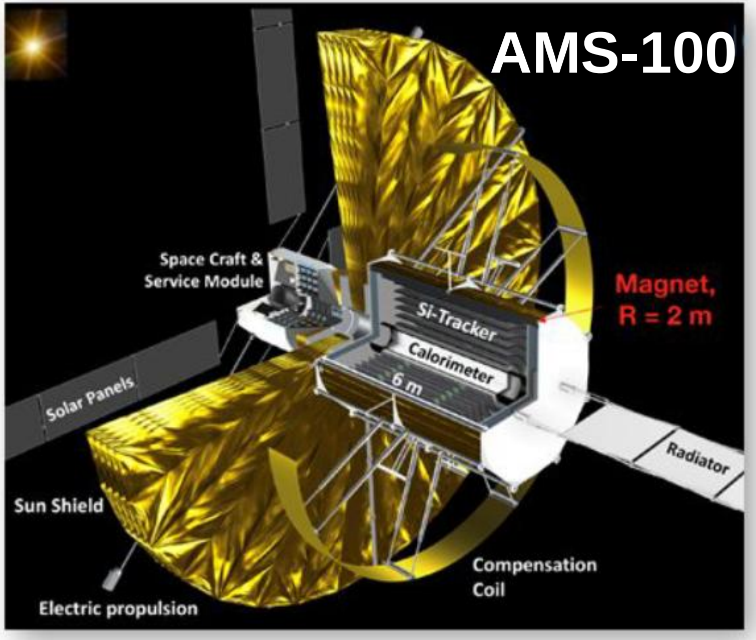
- BeER can be used as a self working detector for heavy ion observation or added to general purpose CR experiment

- BeER also provides the opportunity for precise measurements of nuclei cross-section needed to improve the understanding of CR propagation in the Galaxy

Next generation Magnetic Spectrometers in Space

ALADInO and AMS-100 to be installed in L2, share the heritage of AMS and HERD to provide 10-100 increased sensitivity

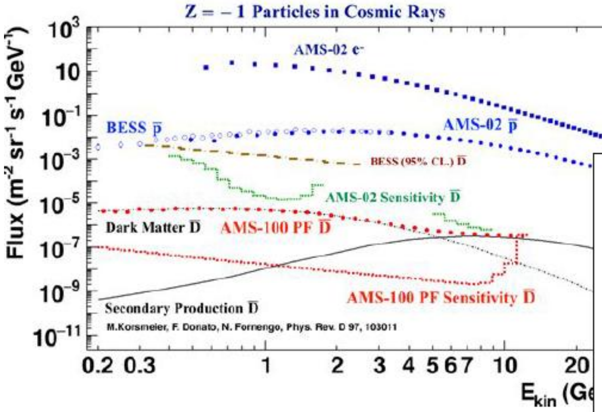


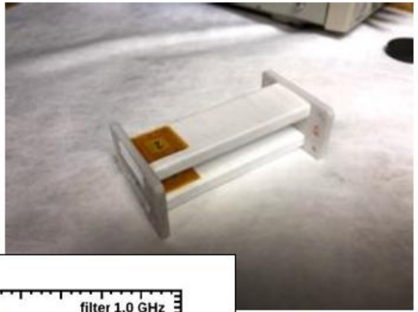


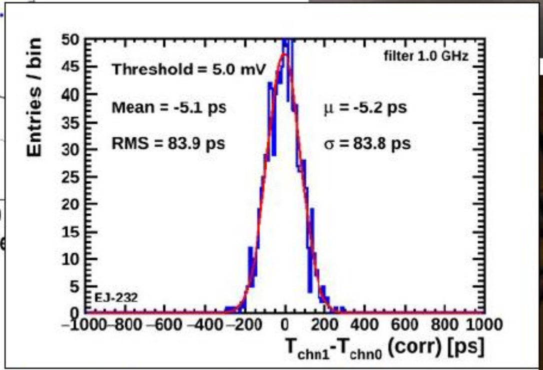
Pathfinder mission next decade final scientific mission: ~2040-50

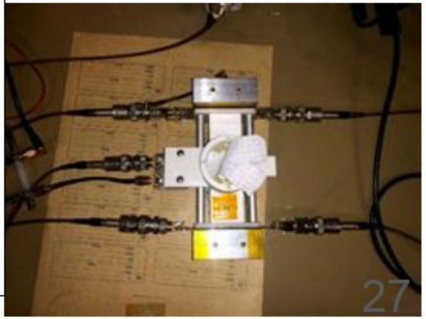
Precise ToF measurements for future Magnetic Spectrometers in Space

- Precise ToF system for isotope identification in a wide energy range
- Development of a ToF based on SiPM with better time resolution than current state-of-the-art ground based detectors (PANDA, MEG II)
- First results already provide a 20% improvement (~42 ps)



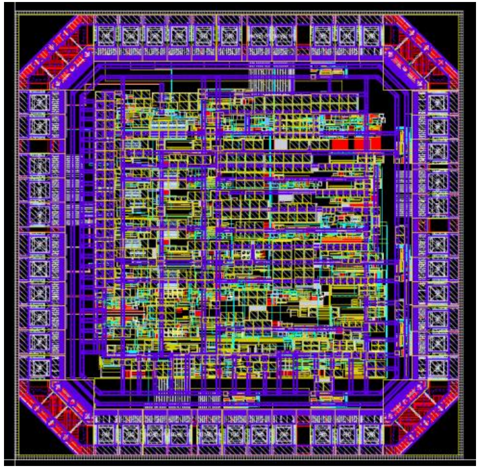


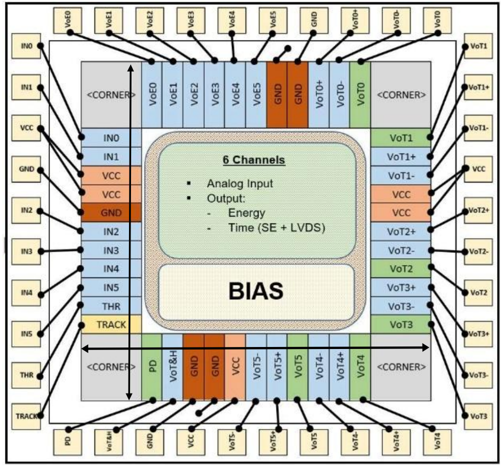




Precise ToF measurements for future Magnetic Spectrometers in Space

- **Development of a test ASIC** with 6 input channels implementing different configurations to study and optimize the time resolution (under test)





- **Evaluation of the optimal read-out** circuit architecture expected in 2025.
- **A second version of the ASIC**, designed on an optimized technology, to be sent to the foundry in 2026.
- **Conversations with FBK** to procure SiPM arrays for evaluation
- **Cryogenic and TVT tests** to study the performance in real conditions (under study)

Current responsibilities

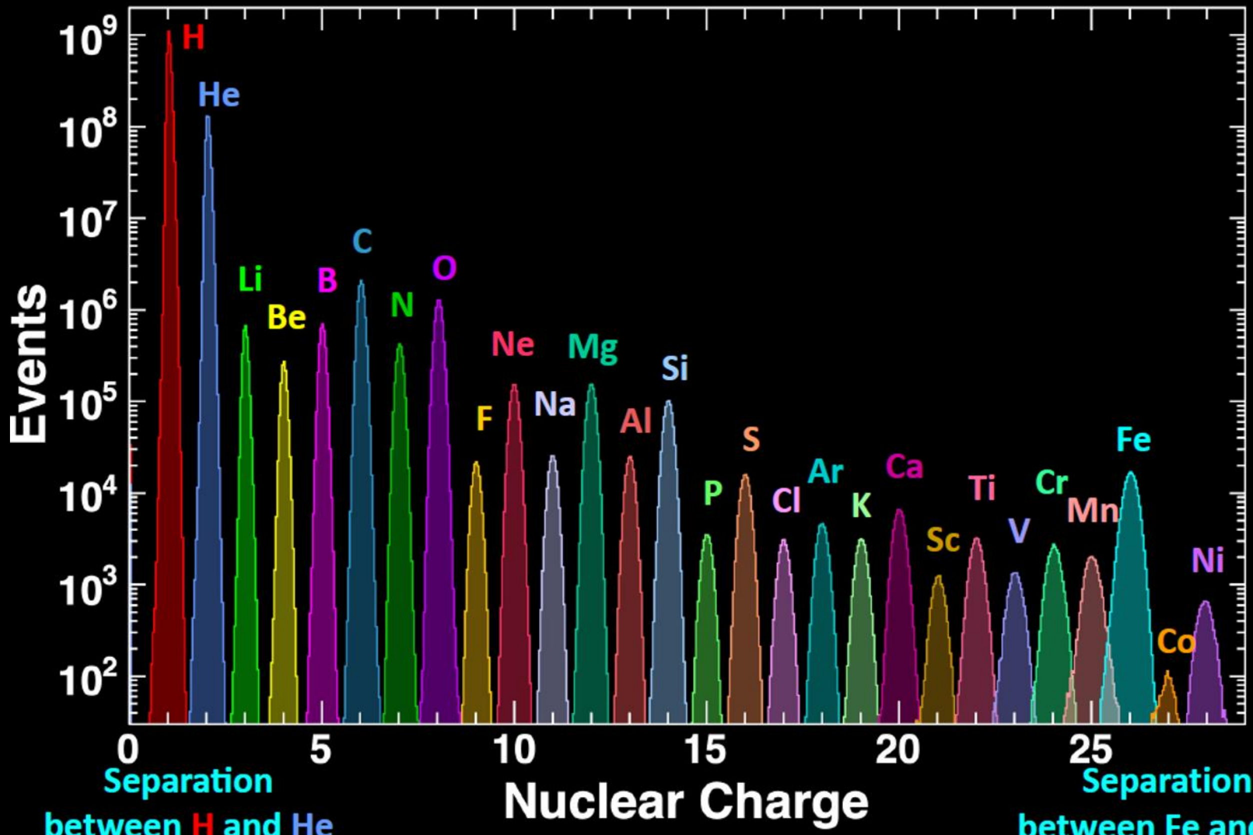
- **AMS**:
  - RICH Operation & Control Coordinator (FG – 2011-)
  - RICH Offline Software Coordinator (CD – 2011-)
  - Spanish National Coordinator (JC – 2020-)
  - Anisotropy Analysis Working Group Convener (MAV – 2024-)
  - Finance Board Representative (CM – 2020-)
- **HERD**:
  - Trigger Working Group co-Coordinator (JC – 2020-)
  - Institute Leader Board Member (JC – 2020-)
  - Science Committee Member (JC – 2025-)

- **AMS** measurements provide new insights on cosmic-ray origin, acceleration and propagation mechanisms, and require a comprehensive model that reproduces these observations
- With the upgrade, **AMS** will explore the heavy secondaries in the sub-Fe group, the heavy primaries beyond Fe, and improve the accuracy of the positron, electron, and antiproton measurements at high energy
- **HERD** is the next generation space calorimetric experiment to be deployed at the CSS by 2028 for a 10-year mission which will extend the range of direct CR measurements to the knee of the spectrum
- The new generation of **space magnetic spectrometers** proposed for the next decade(s) will improve the current sensitivity by a factor 10-100.

- **CIEMAT-FP Strengths**:
  - **Recognized expertise** in cosmic ray direct detection, including hardware development, operation, software, and science
  - Participates in **world-leading projects** and **future proposals**
- **CIEMAT-FP Challenges**:
  - Current difficulties in hiring new technical personnel & young postdocs may limit our visibility in new projects
  - Space is a harsh environment… Geopolitics matters even more than in other areas

BACKUP

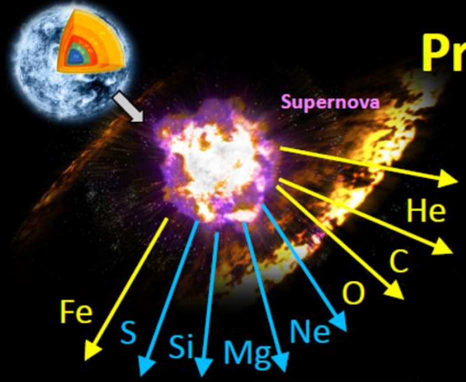
AMS provides precise spectroscopy of charged cosmic rays



Separation between H and He is better than 1 in 10^9

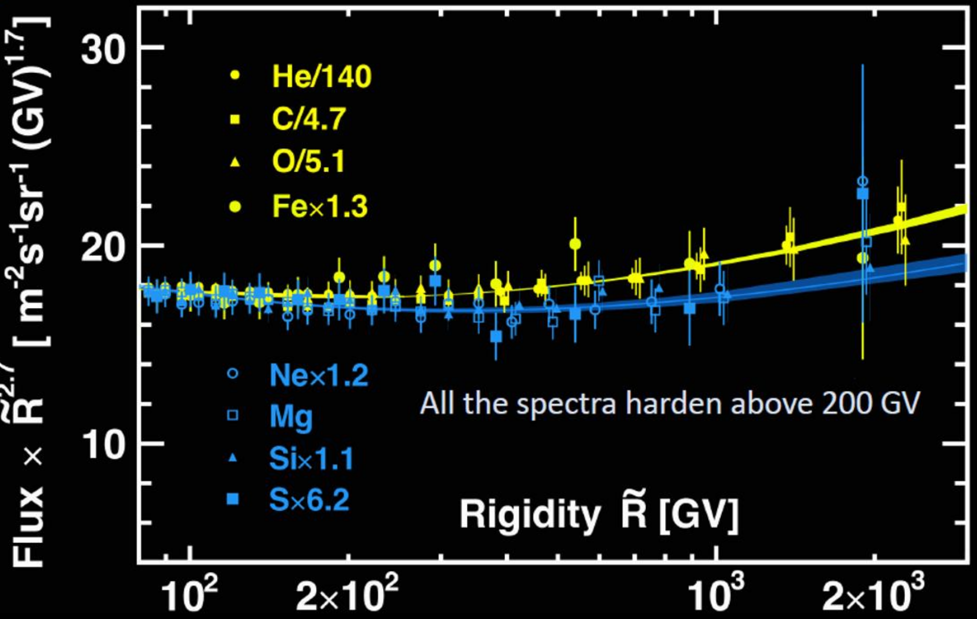
Separation between Fe and Co is better than 1 in 10^2

Primary Cosmic Rays

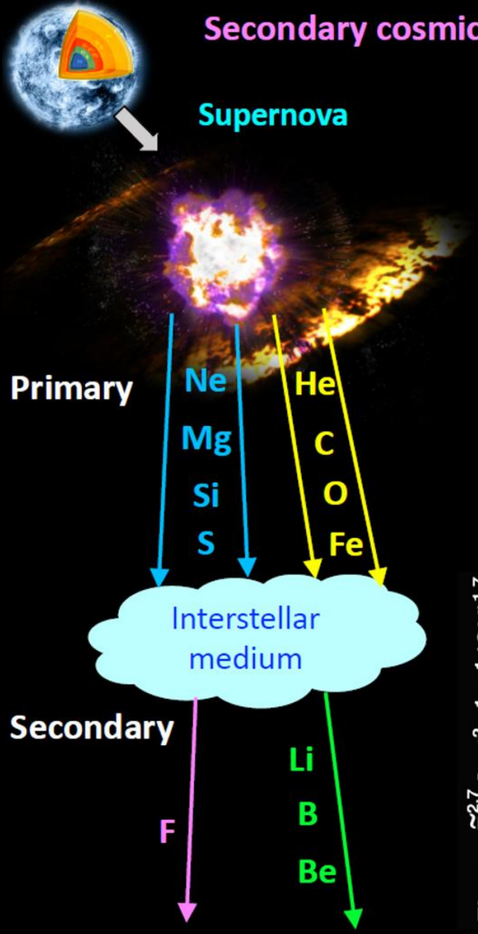


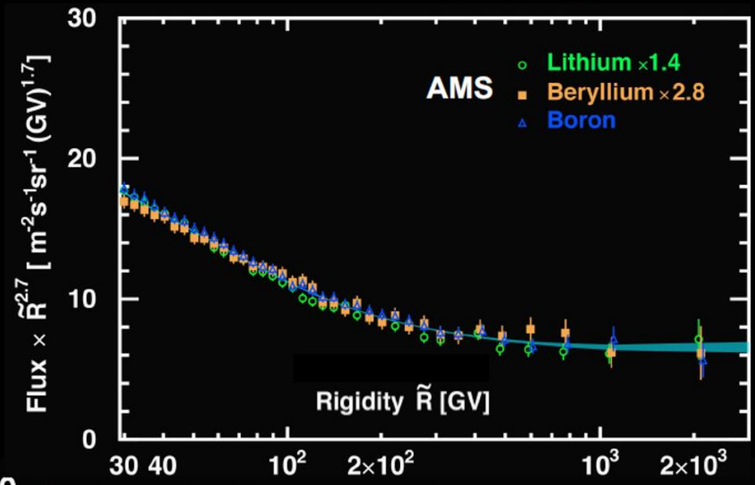
Primary elements (He, C, ..., Fe) are produced during the lifetime of stars.
They are accelerated by the explosion of stars (supernovae).

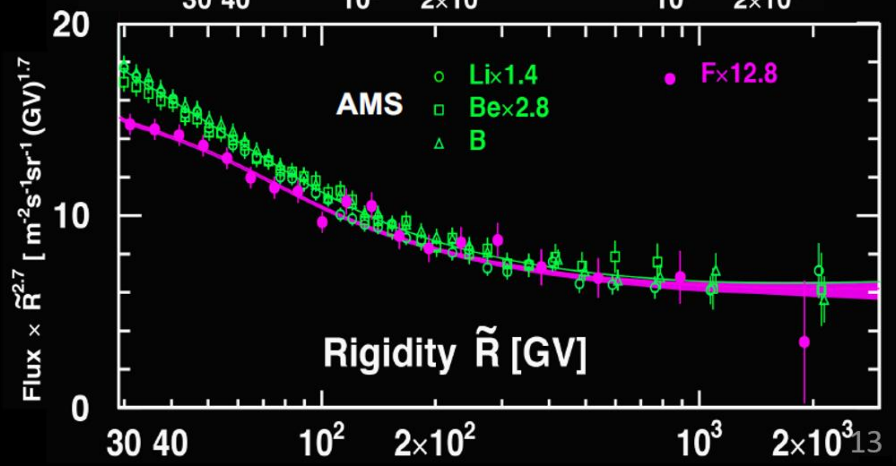
Primary cosmic rays have at least two classes.



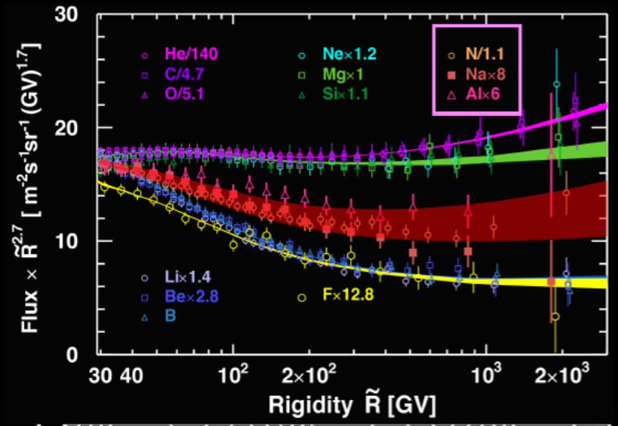
Secondary cosmic rays also have two classes of rigidity dependence

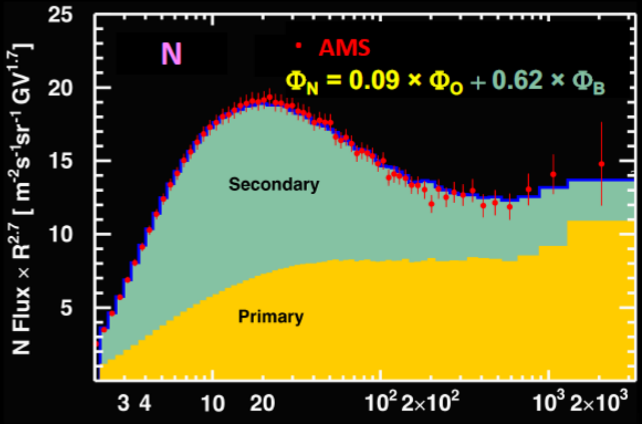


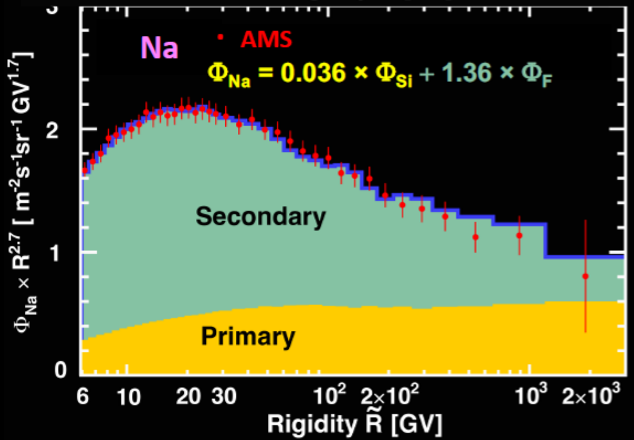


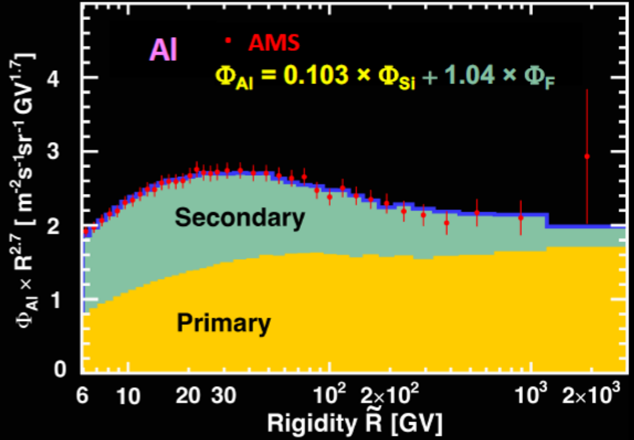


A third group of cosmic rays N-Na-Al
partially primary, partially secondary

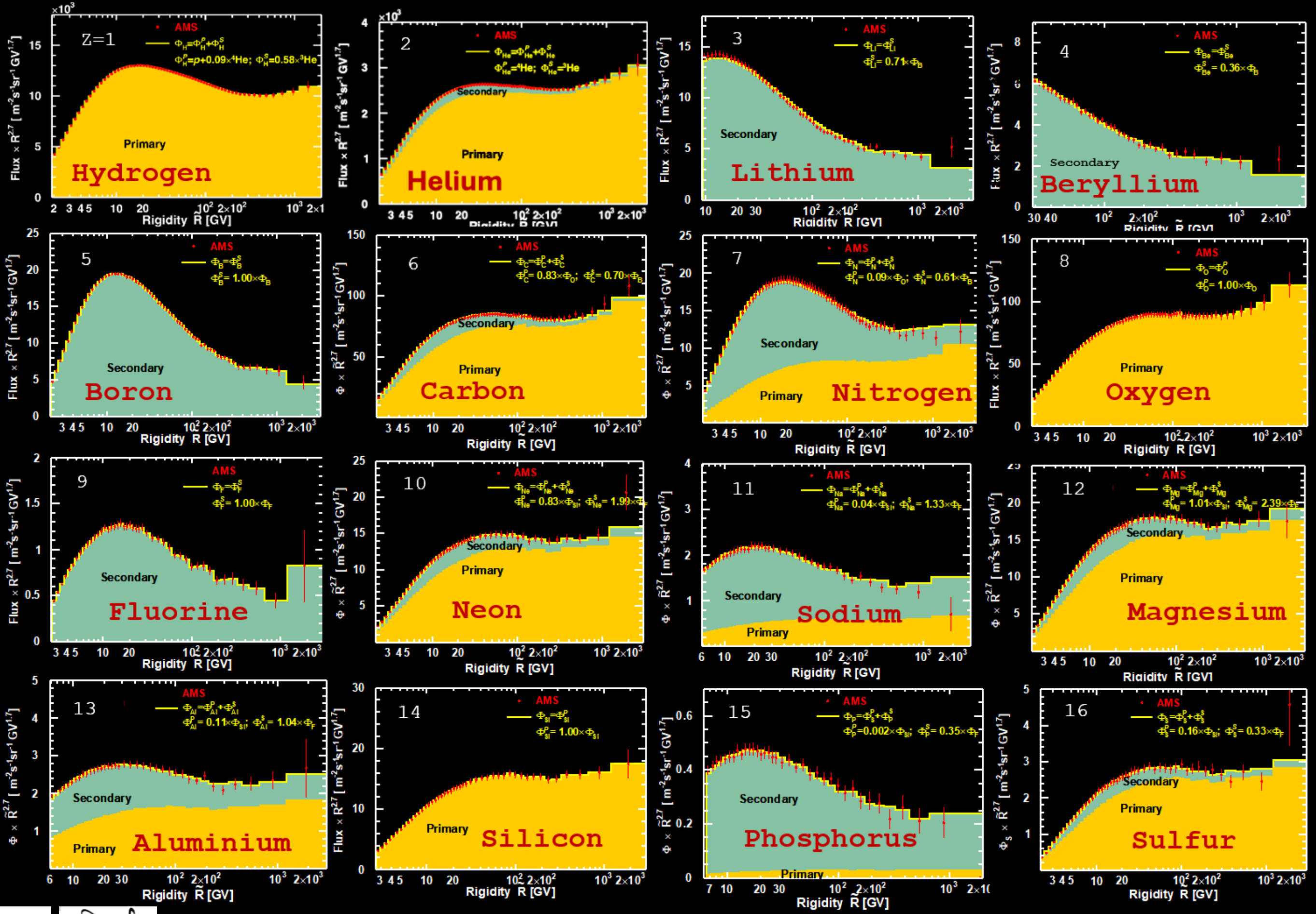








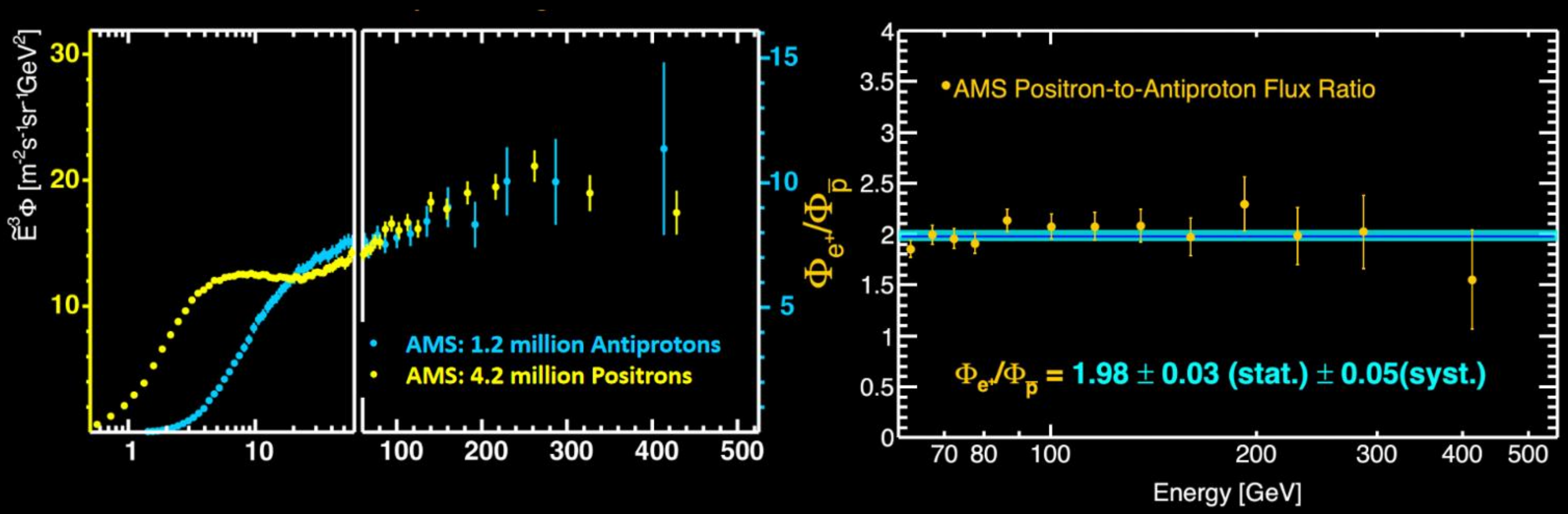
Primary and Secondary Composition of Cosmic Rays



Unique Observation from AMS:

Positron and Antiproton have nearly identical energy dependence

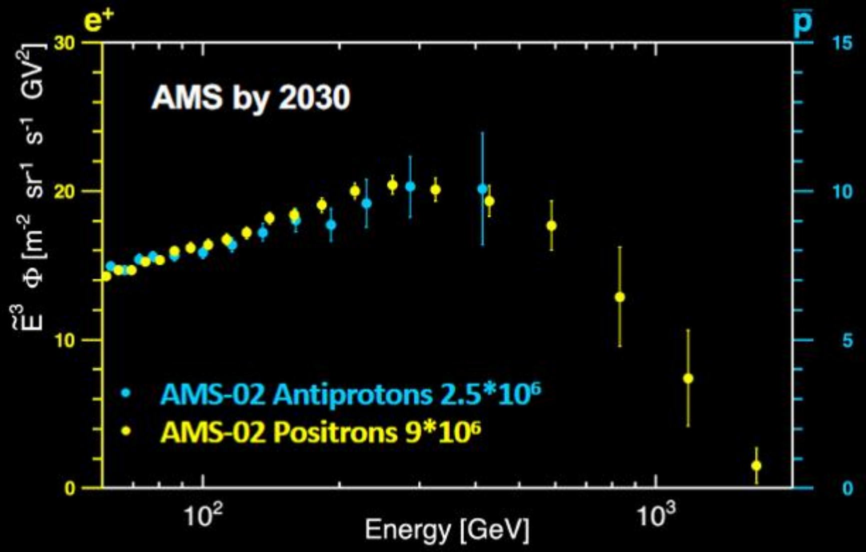
The positron-to-antiproton flux ratio is independent of energy.

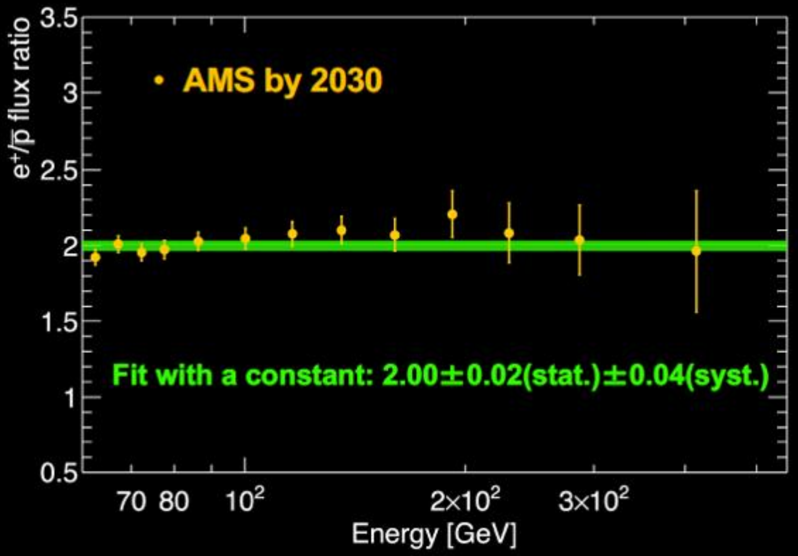


Antiprotons cannot come from pulsars.

By 2030, AMS will greatly improve the accuracy of the antiproton spectra.

The identical behaviour of positrons and antiprotons excludes the pulsar origin of positrons.





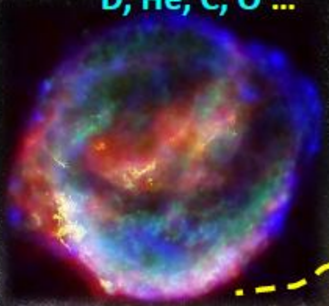
Latest AMS Results on Heavy Antimatter

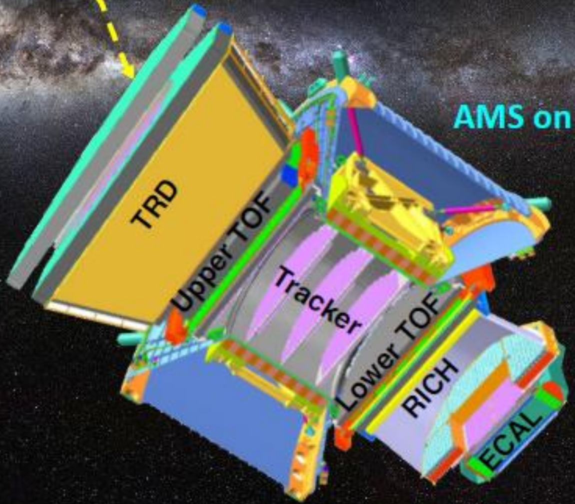
Matter is defined by its mass *M* and charge *Z*.

Antimatter has the same mass *M* but opposite charge –*Z*.

$\overline{\mathrm{D}}, \overline{\mathrm{He}}, \overline{\mathrm{C}}, \overline{\mathrm{O}}$ ...

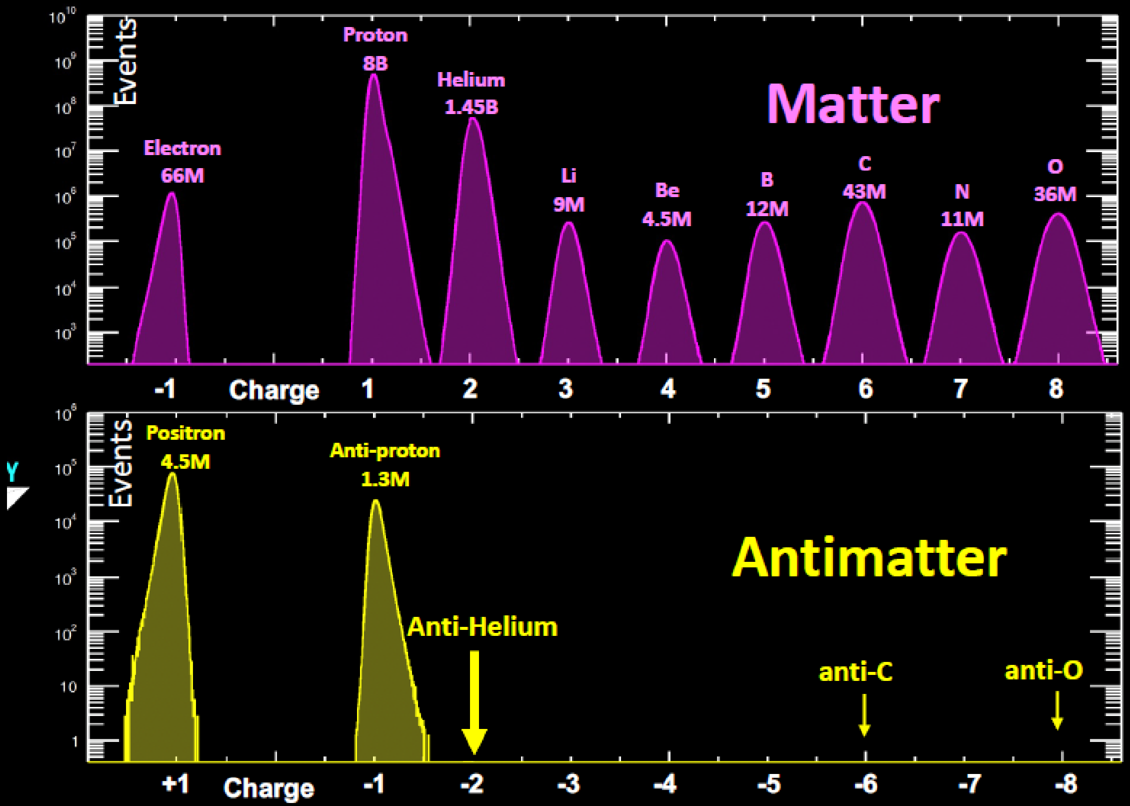
Antimatter Star





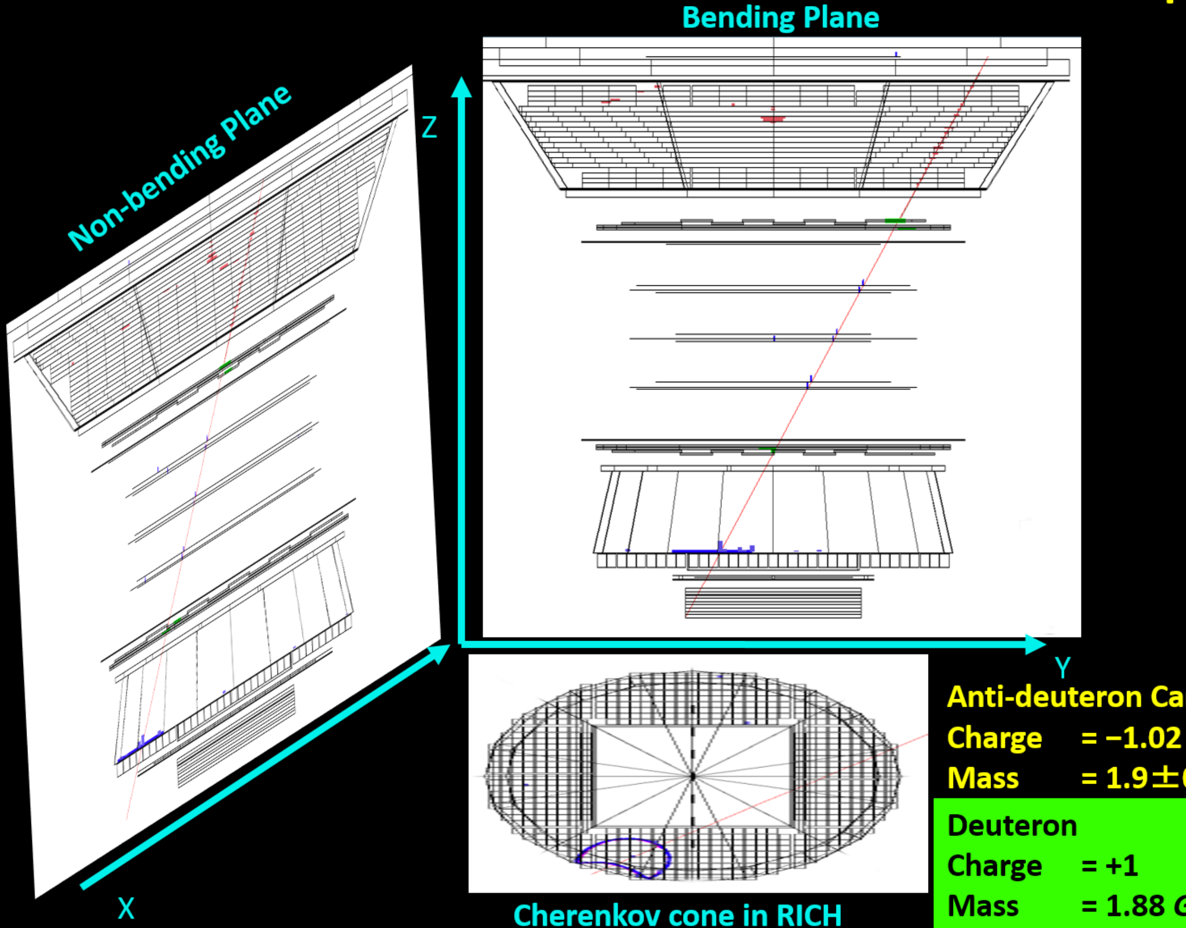
AMS on ISS

Current Matter and Antimatter Statistics



By 2030, AMS will have additional measurement points in the study of antimatter: anti-deuterons, anti-helium, anti-carbon, and anti-oxygen.

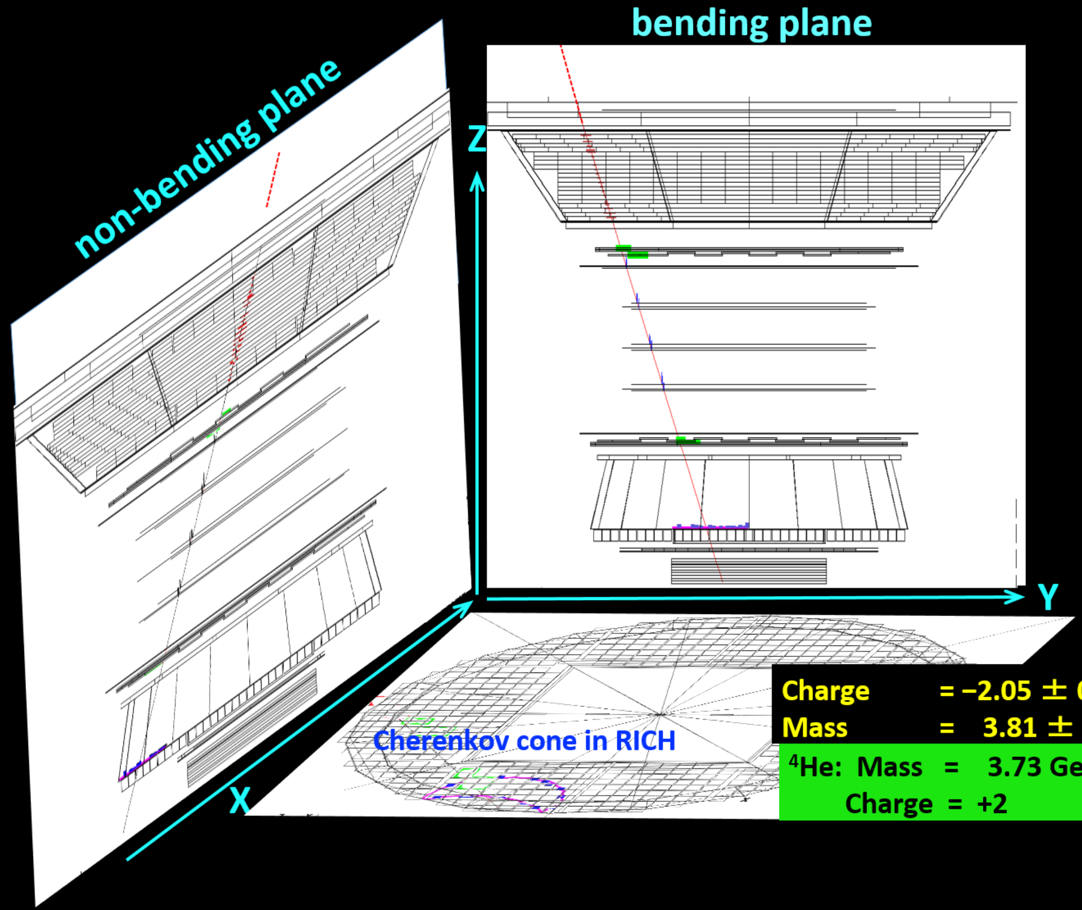
Anti-Deuteron Candidate from ~10^8 D and ~10^{10} p



Anti-deuteron Candidate
Charge = -1.02 ± 0.05
Mass = 1.9 ± 0.1 *GeV/c²*

Deuteron
Charge = +1
Mass = 1.88 *GeV/c²*

Anti-^{4}HeliumCandidate



Charge = −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/c^2

^{4}He: Mass = 3.73 GeV/c^2
Charge = +2