The AMS-02 RICH Detector: Status, Latest Results, and Physics Prospects

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On behalf of the AMS-02 Collaboration

(Zhejiang University & CIEMAT)

RICH 2025
XII International Workshop on Ring Imaging Cherenkov Detectors
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The Alpha Magnetic Spectrometer

Installed in May 2011 on the International Space Station and has been operating continuously since then. It has collected more than 250 billion cosmic ray events so far.

International Space Station (ISS)

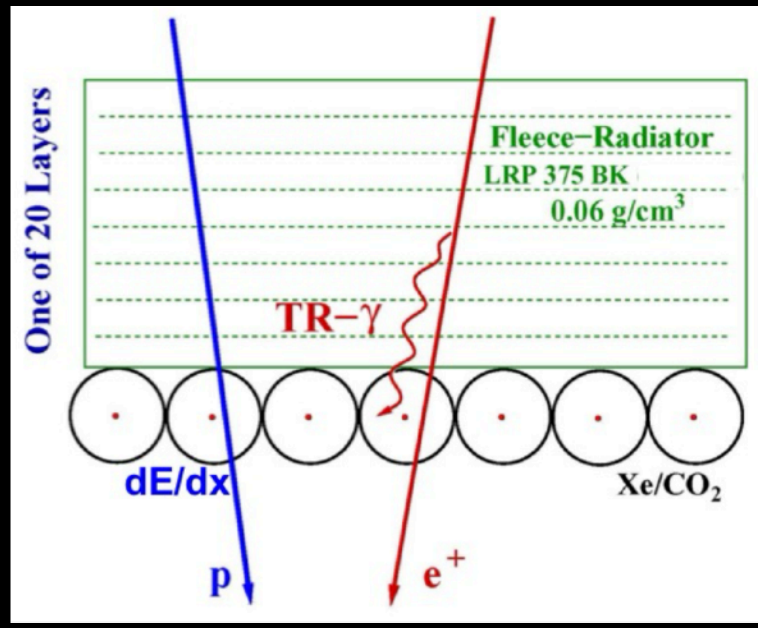
Altitude ~ 400 km
Inclination 51°
Period 93 min
Construction 1998 - …
Dimensions 73 × 109 m²
Weight 420 t

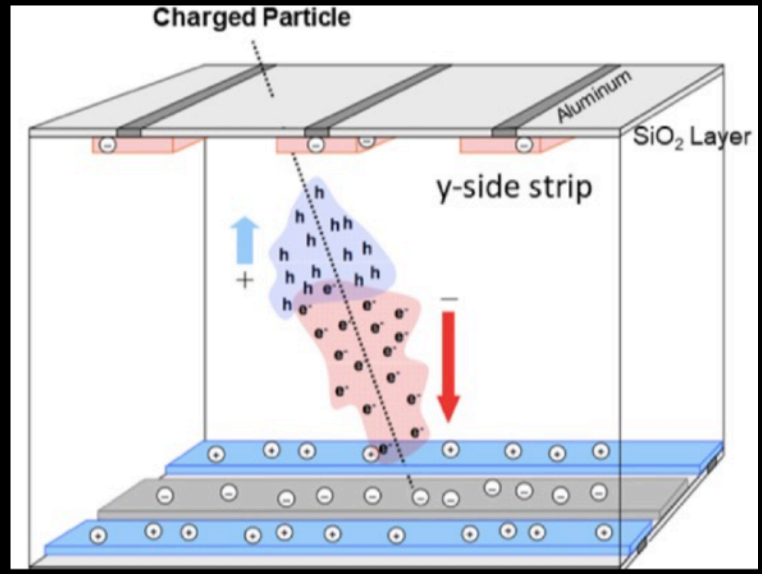
AMS in Figures

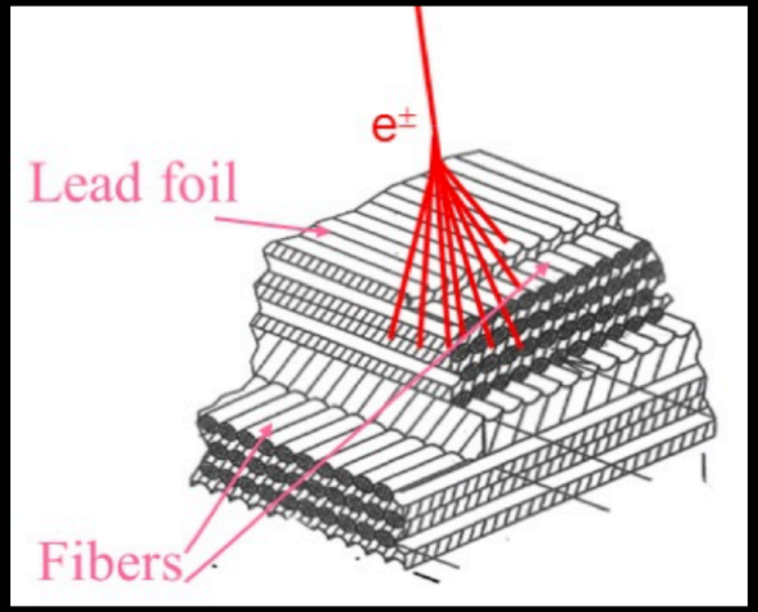
Weight	Size	Magnetic Field Intensity	Launched
7.5 t	5×4×3 m³	0.14 T	16/05/2011 08:56 AM EDT

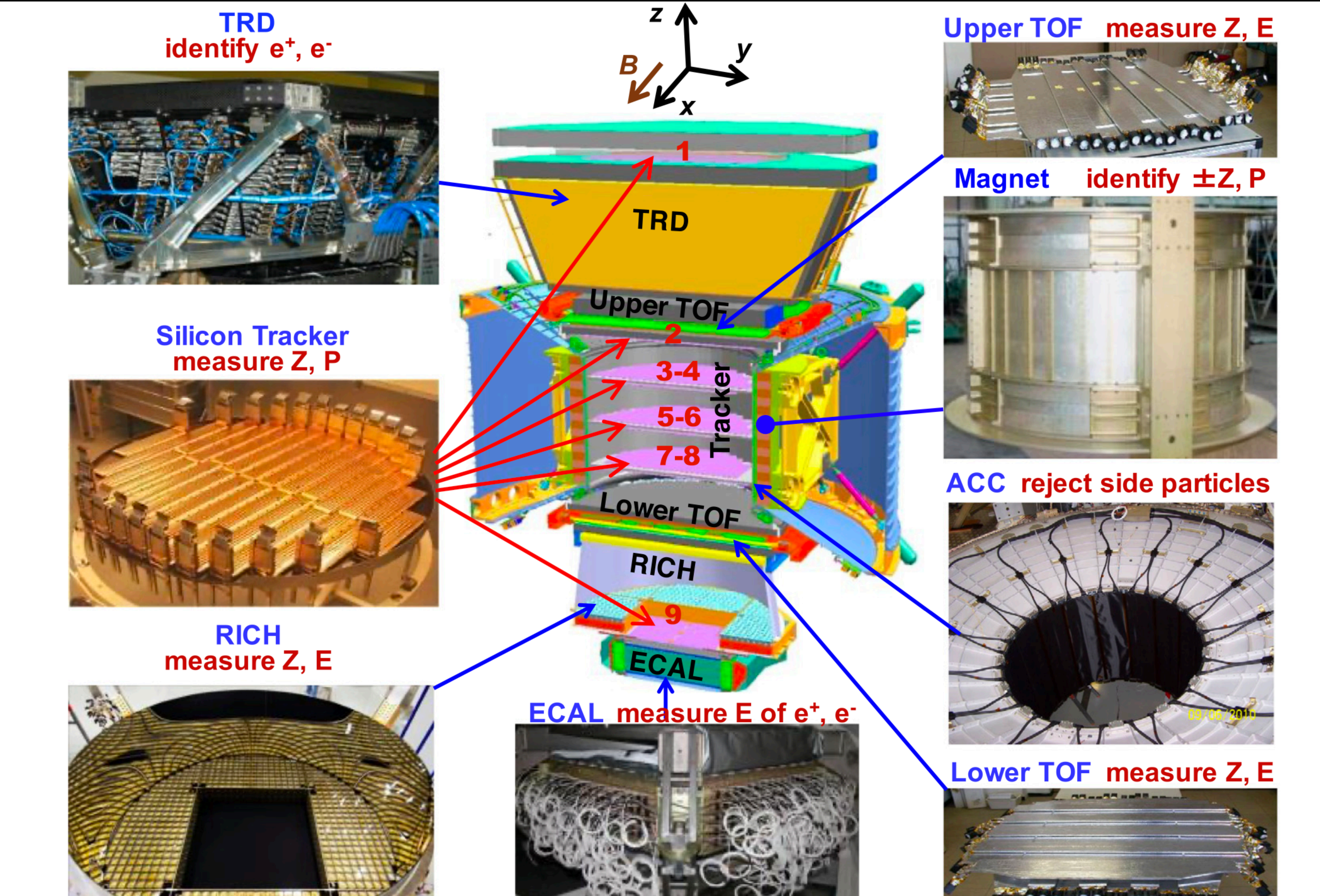
AMS: a TeV precision magnetic spectrometer in space

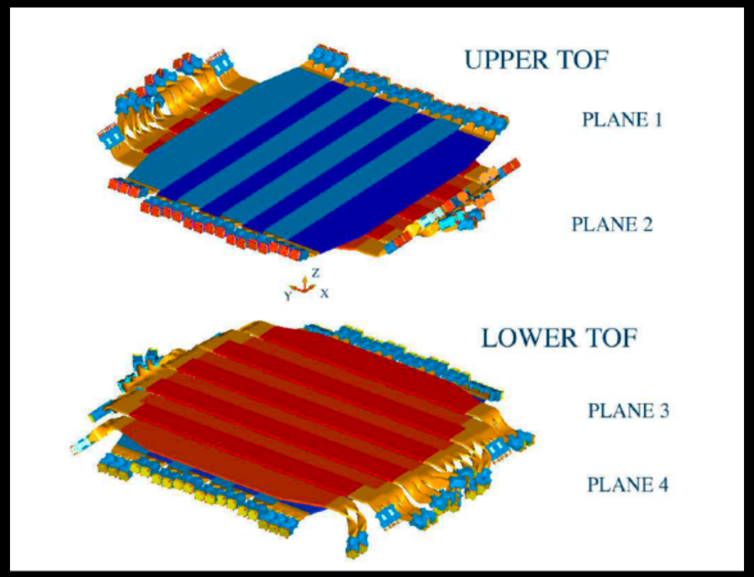
Multiple independent measurement of cosmic ray particle's charge (±Z) and energy (β, p, E) in the GeV to TeV region.

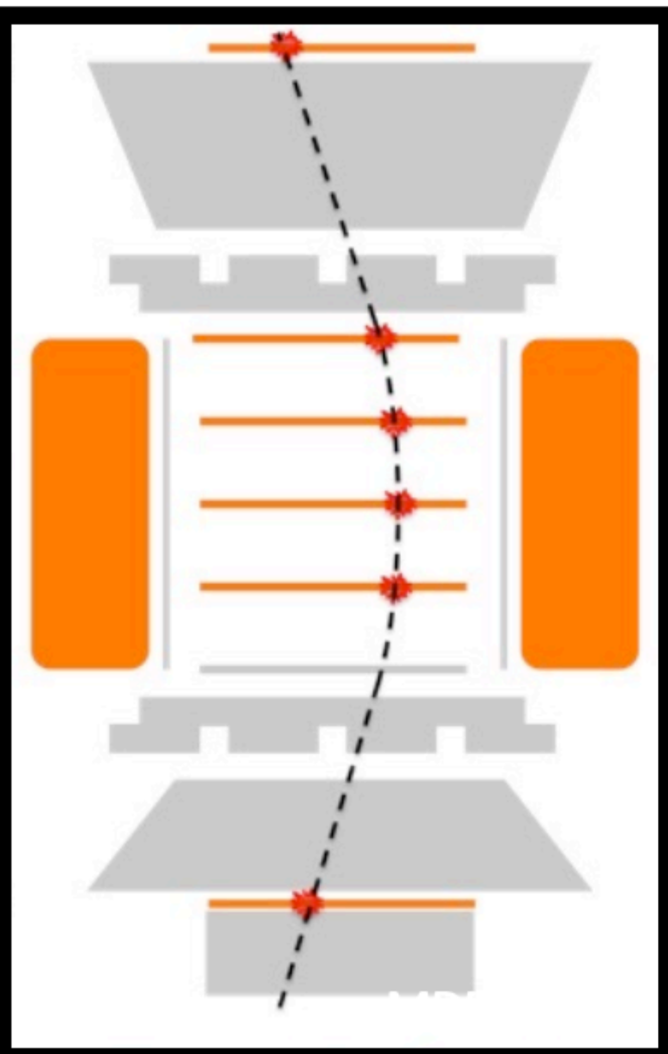


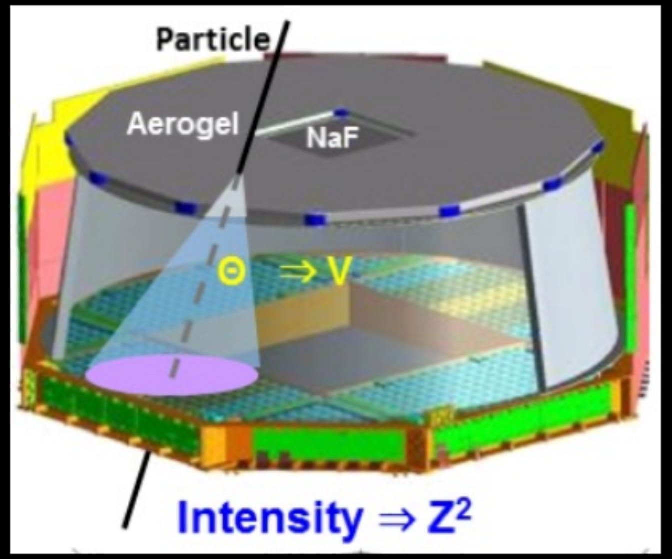






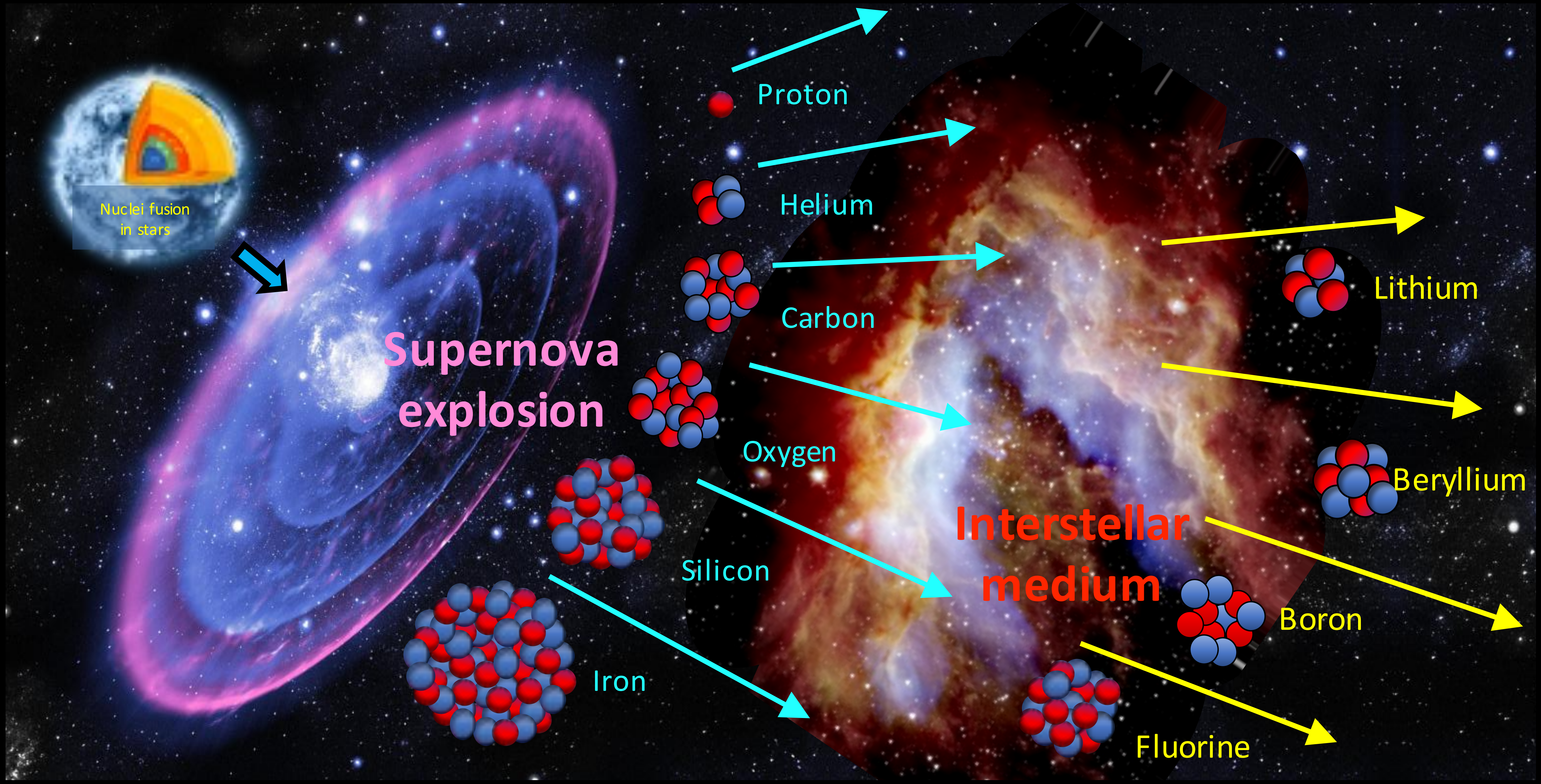


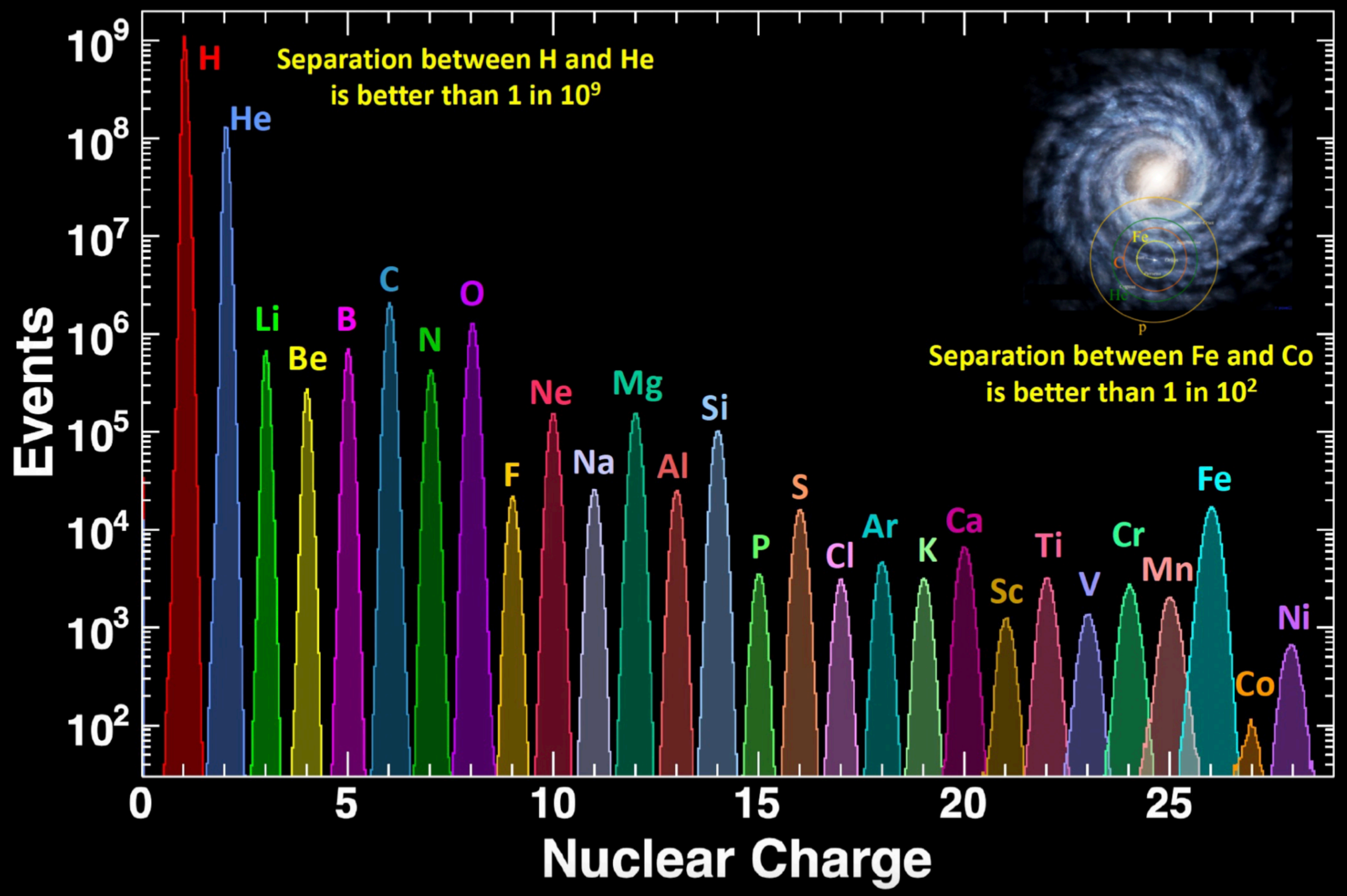




AMS: Physics Goals

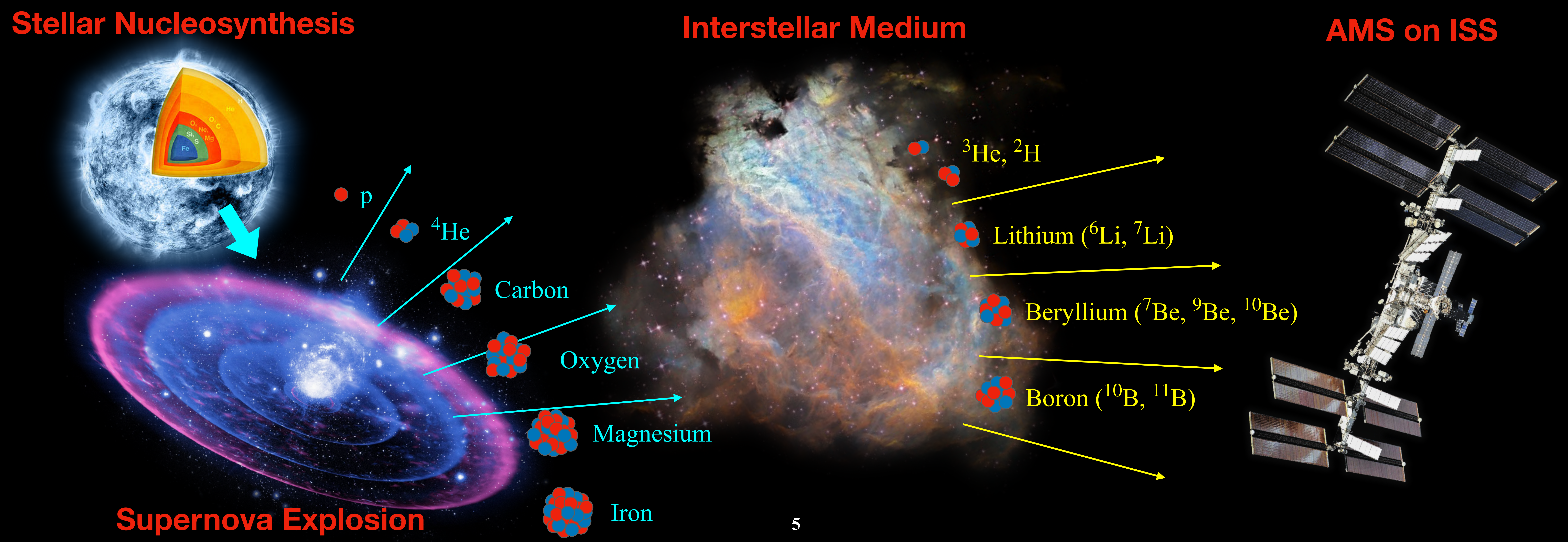
- Search for possible signs of antimatter and dark matter, by identifying excesses in rare cosmic ray components beyond expected astrophysical backgrounds.
- Precision measurement of the spectra of primary and secondary cosmic rays, which is essential for understanding their origin, acceleration, and propagation in our Galaxy.





AMS: Physics Goals

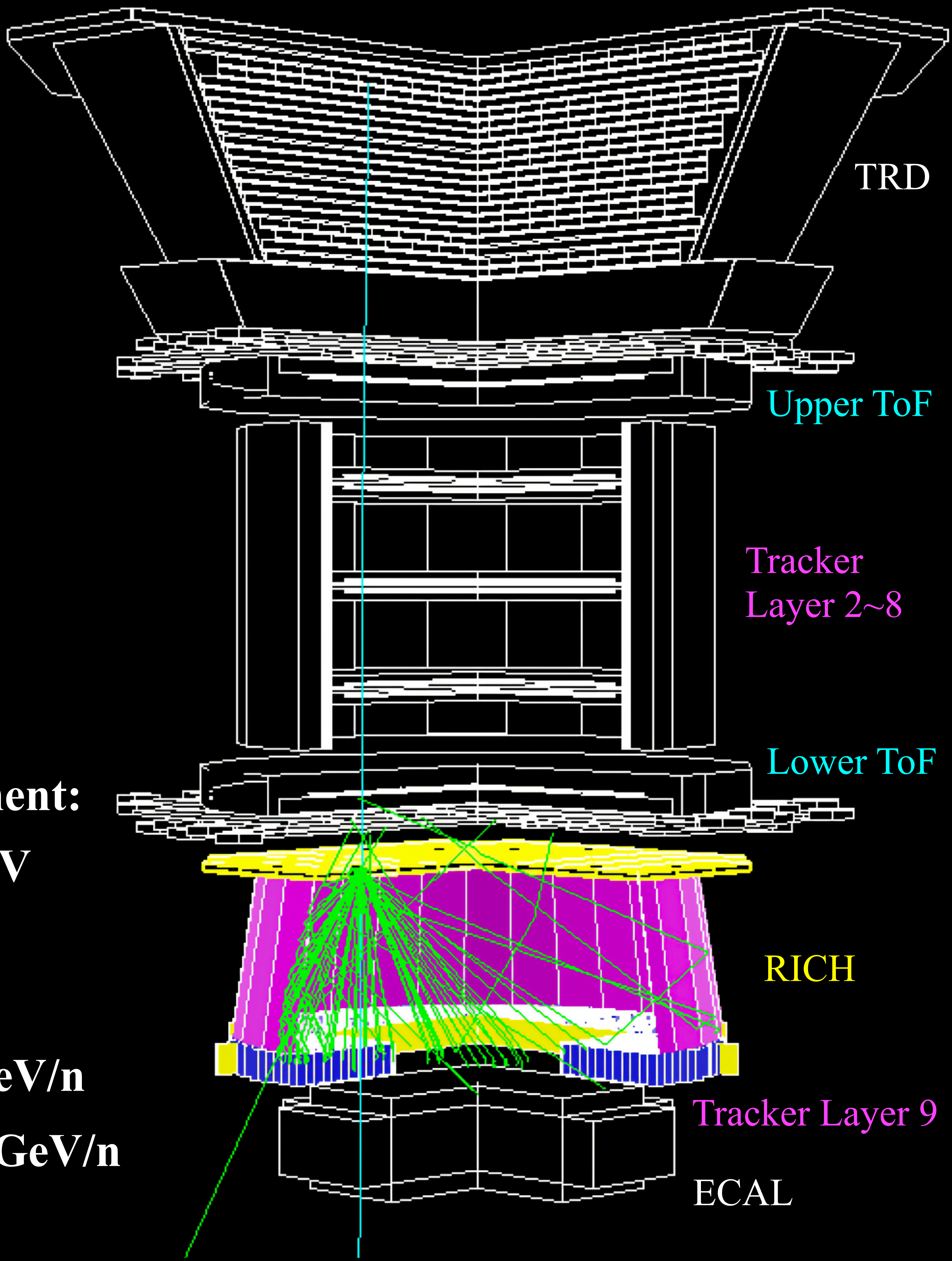
- Search for possible signs of antimatter and dark matter, by identifying excesses in rare cosmic ray components beyond expected astrophysical backgrounds.
- Precision measurement of the spectra of primary and secondary cosmic rays, which is essential for understanding their origin, acceleration, and propagation in our Galaxy.
- Measurement of the isotopic composition of light nuclei, which provides additional important information on cosmic ray propagation models.



AMS-02: Isotope Identification

$$m = ZR/\beta\gamma$$

$$\frac{\sigma(m)}{m} = \frac{\sigma(R)}{R} \oplus \gamma^2 \frac{\sigma(\beta)}{\beta}$$



- **Charge Z Measurement:**

Tracker, **ToF**, **RICH**

- **Rigidity $R = p/Z$ Measurement:**

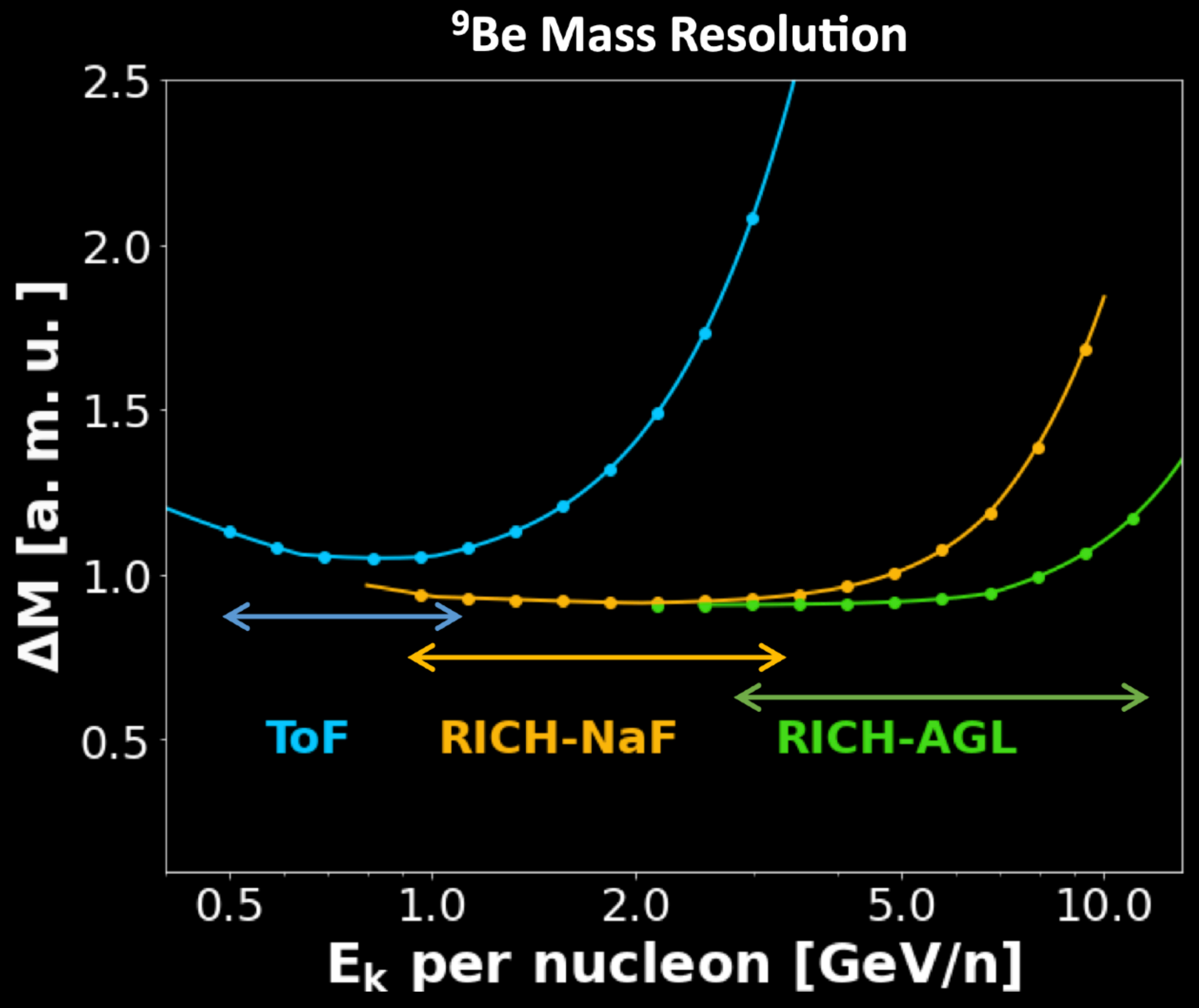
Tracker, $\Delta R/R \sim 10\,\%$ **at 10 GV**

- **Velocity β Measurement:**

ToF, at E_{kn} range 0.5 to 1.2 GeV/n

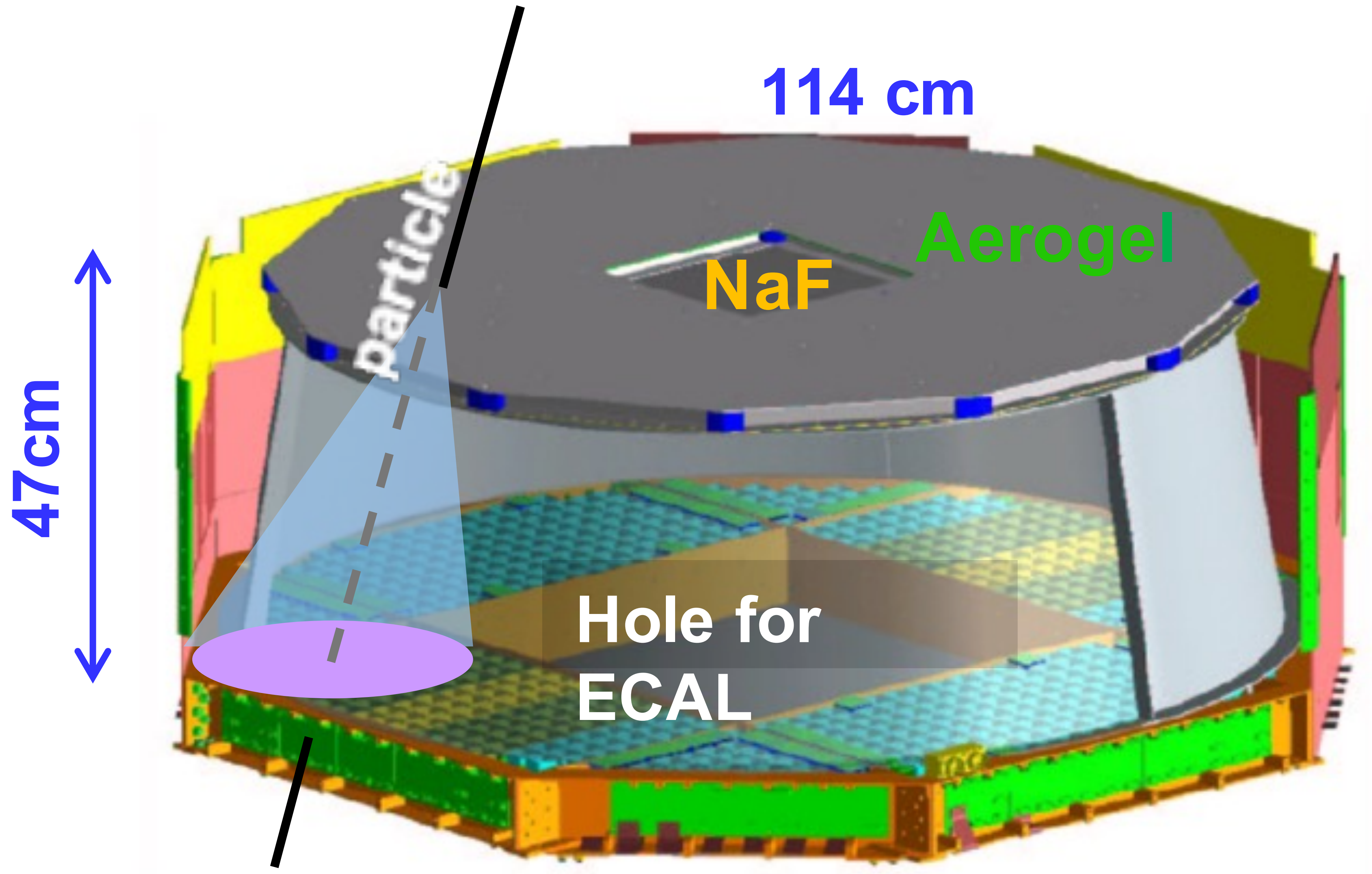
RICH, at E_{kn} range 0.8 to 12 GeV/n

	E_{kn} range (GeV/n)	$\Delta\beta/\beta$ (Z=2, β=1)	$\Delta\beta/\beta$ (Z=4, β=1)
TOF	(0.5, 1.2)	~2%	~1.5%
RICH-NaF (n=1.33)	(0.8, 4.0)	~0.25%	~0.15%
RICH-AgI (n=1.05)	(3.0, 12)	~0.07%	~0.05%



AMS-02 RICH: Detector Layout

- The AMS-02 RICH detector is placed at the lower part of the spectrometer, between the lower TOF planes and the ECAL.
- The detector follows a proximity focusing design and consists of a layer of radiator material, a conical reflector and a detection plane.



Radiator

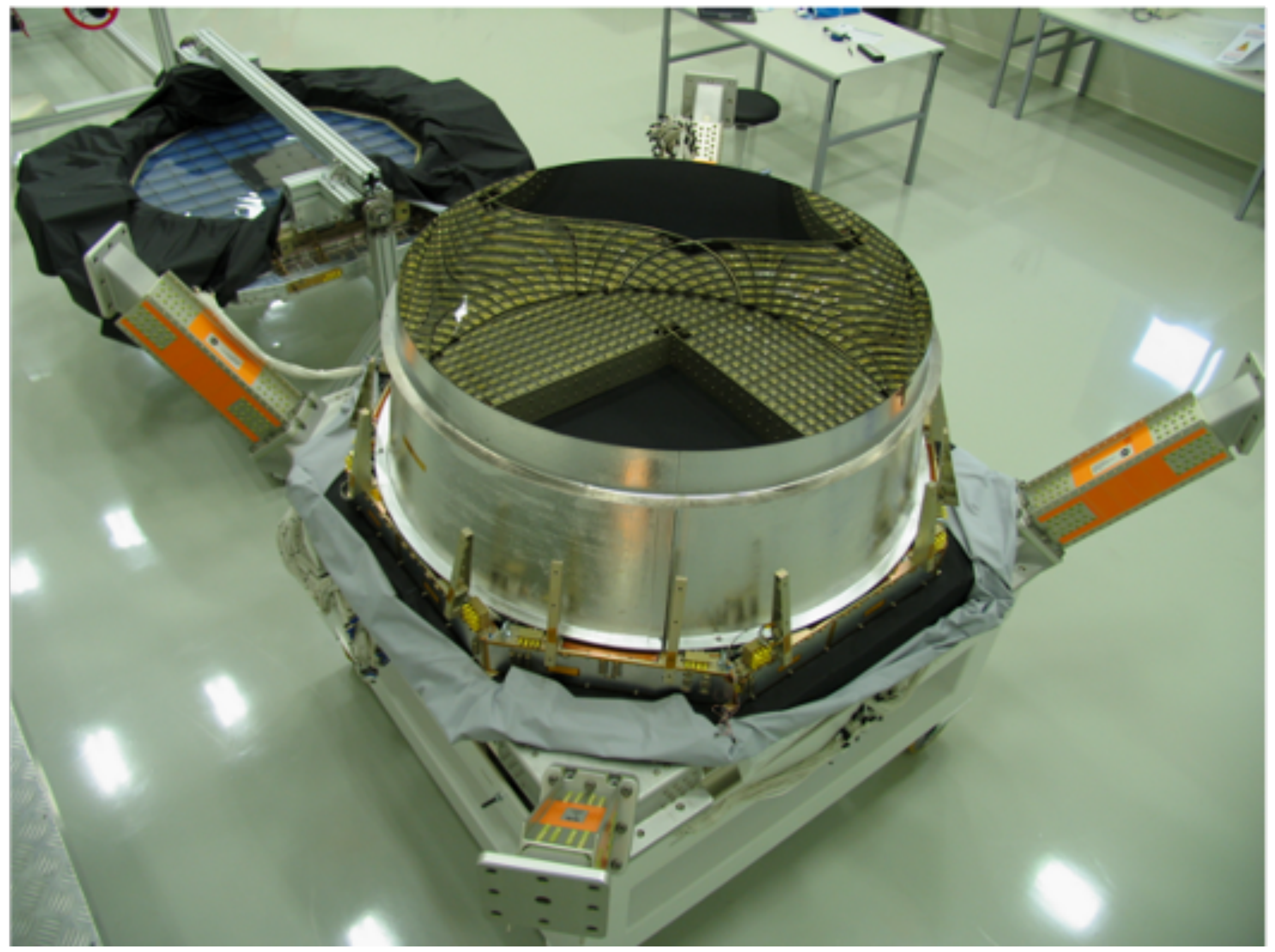
- Dual radiator configuration (Silica Aerogel and Sodium Fluoride)

Mirror

- Reflect photon to increase acceptance, high reflectivity

PMT

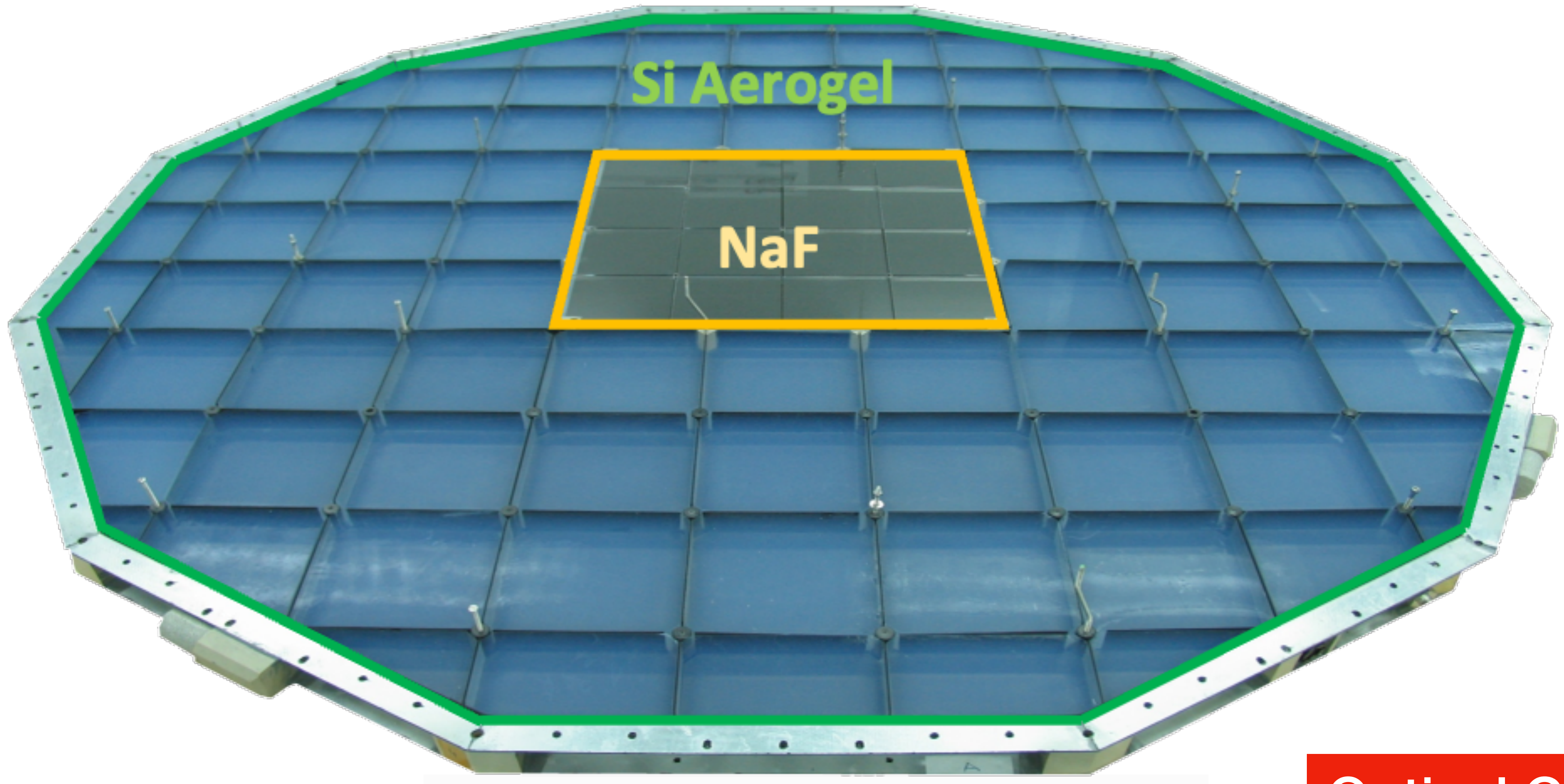
- High granularity PMT arrays with light-guides

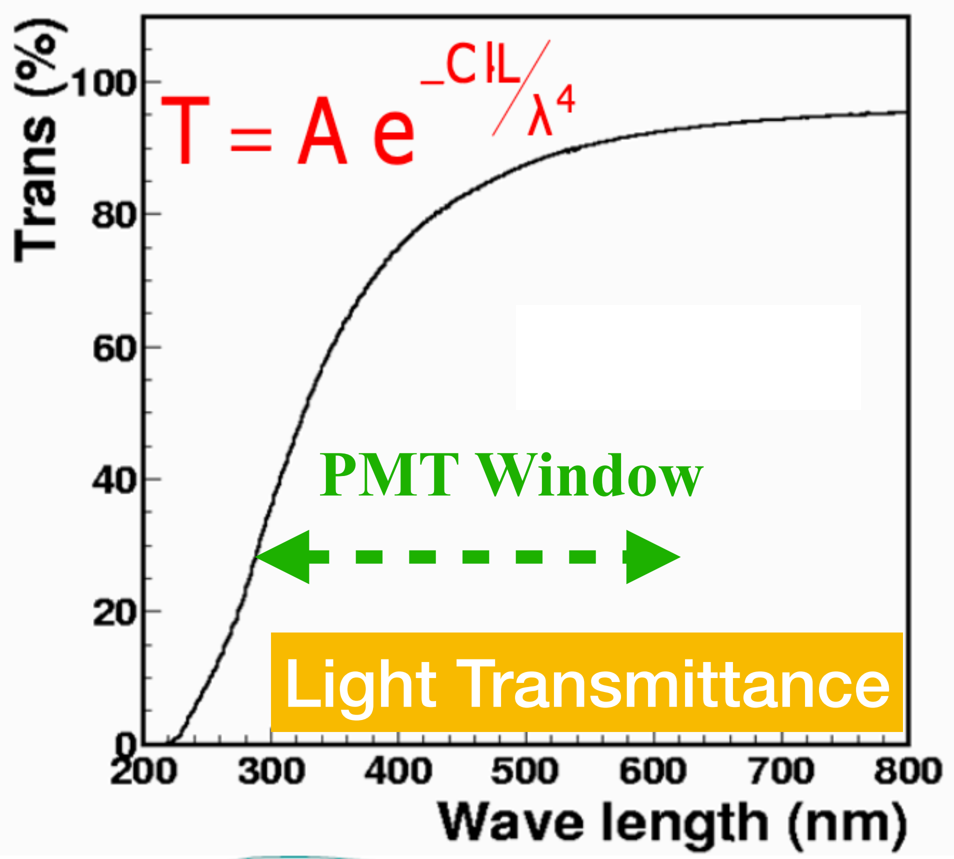


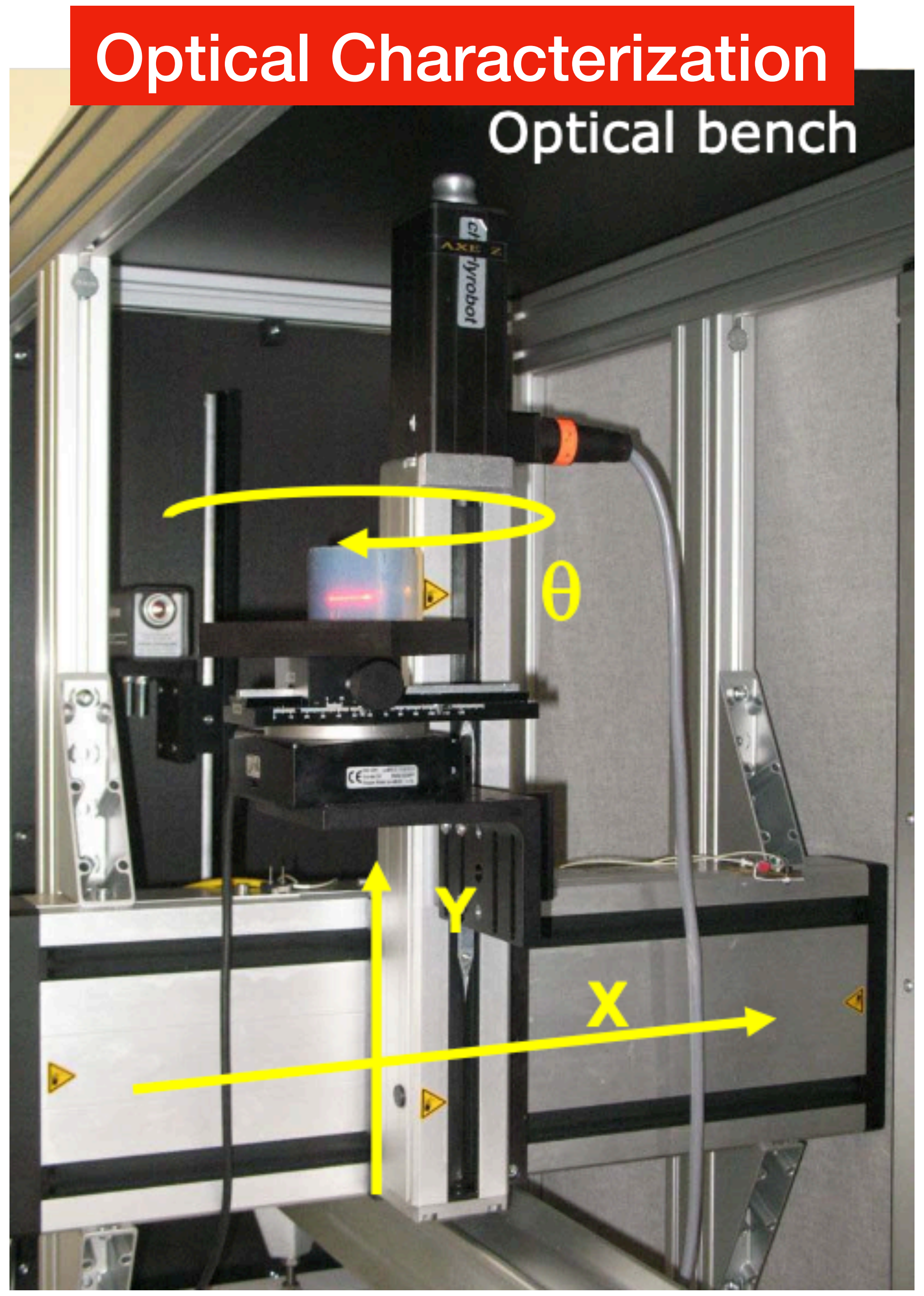
AMS RICH

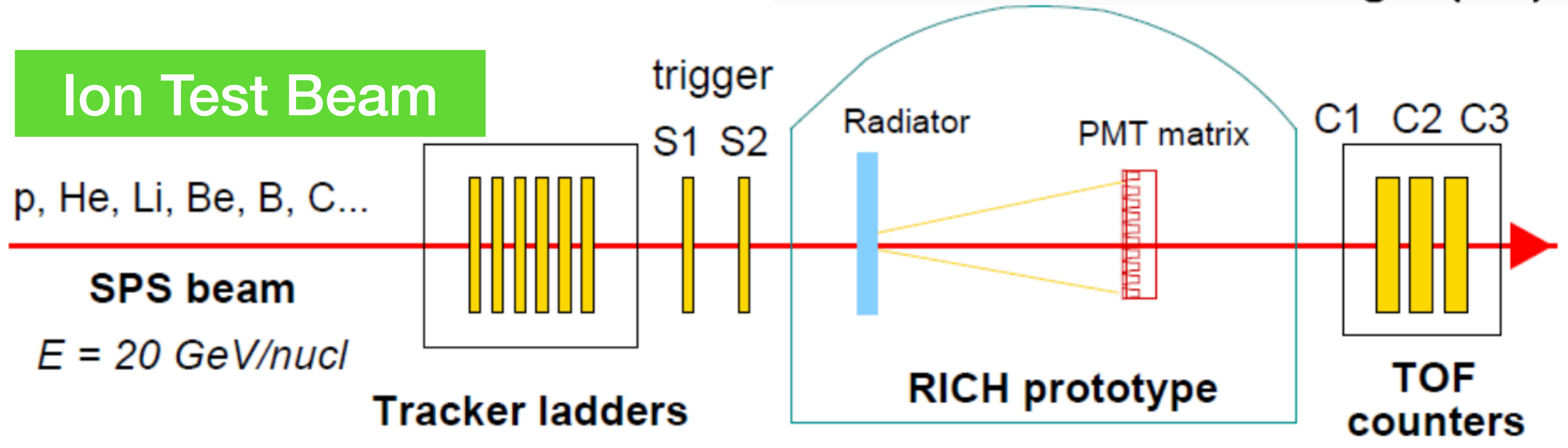
Weight ~ 200 kg
Power 100 W
Acceptance 0.4 m^2 sr
PMTs 680, 4×4 multi-anodes
Granularity 8.5 × 8.5 mm^2

AMS-02 RICH: Radiator









AEROGEL	
Number of Tiles	92
Thickness (mm)	25
Size (mm^2)	113 × 113
Refractive Index	1.05
Clarity (μm^4/cm)	0.0055
Max Opening Angle (deg)	17.8
Threshold Velocity (v/c)	0.952

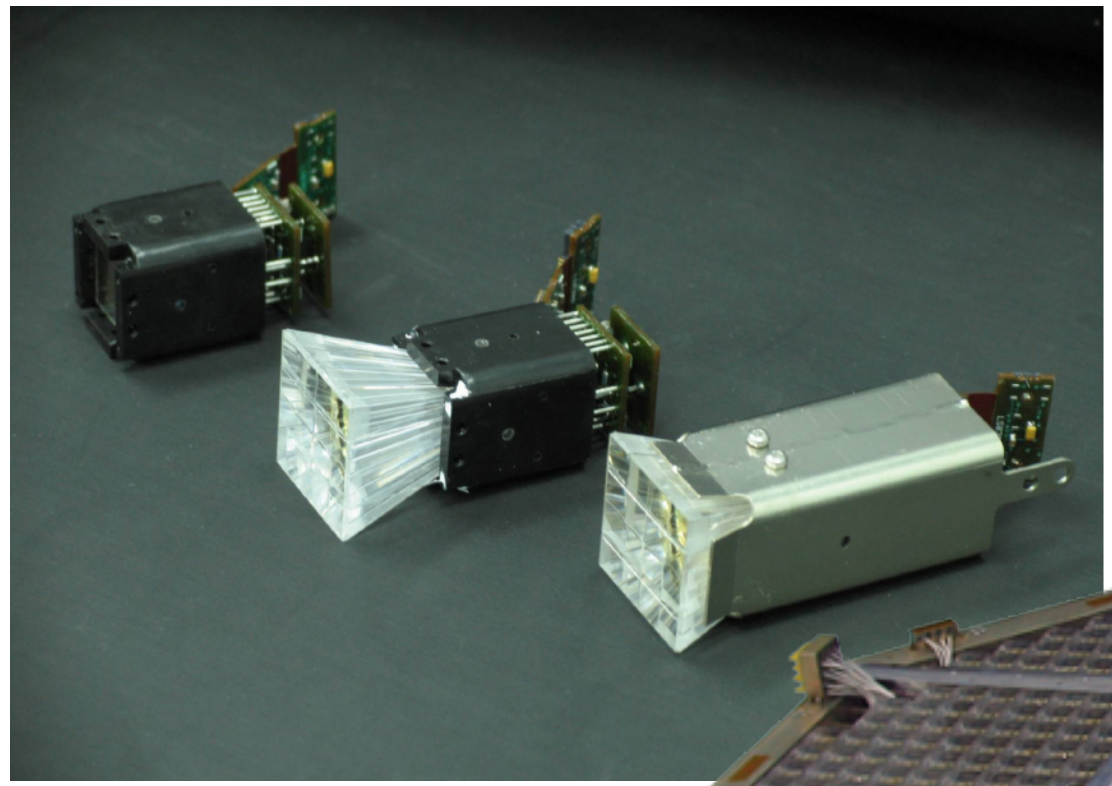
SODIUM FLORIDE	
Number of Tiles	16
Thickness (mm)	5
Size (mm^2)	85 × 85
Refractive Index	1.33
Max Opening Angle (deg)	41.5
Threshold Velocity (v/c)	0.752

AMS-02 RICH: Conical Mirror, Detection Plane

Conical Mirror

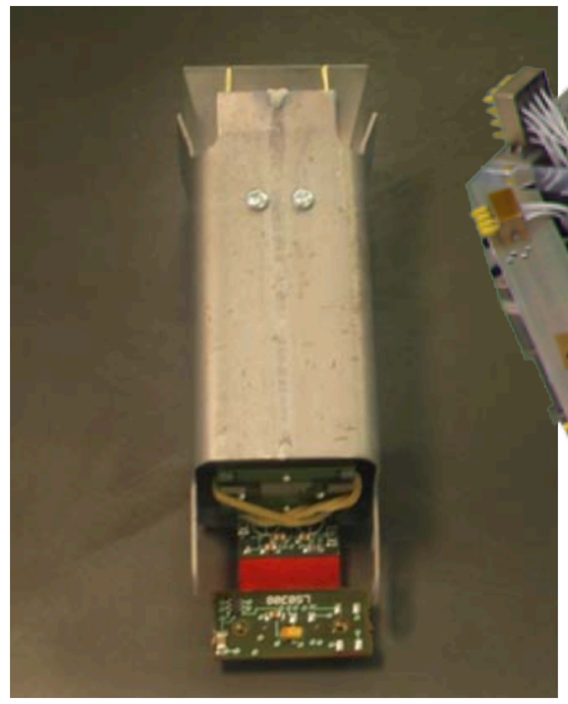
Conicity	200 μm
Centering	100 μm
Reflectivity	≥85% (at λ = 420 nm)
Roughness	≤150 nm
Slope Error	<1 mad
Top Radius	60.1 cm
Bottom Radius	67.0 cm
Height	46.32 cm

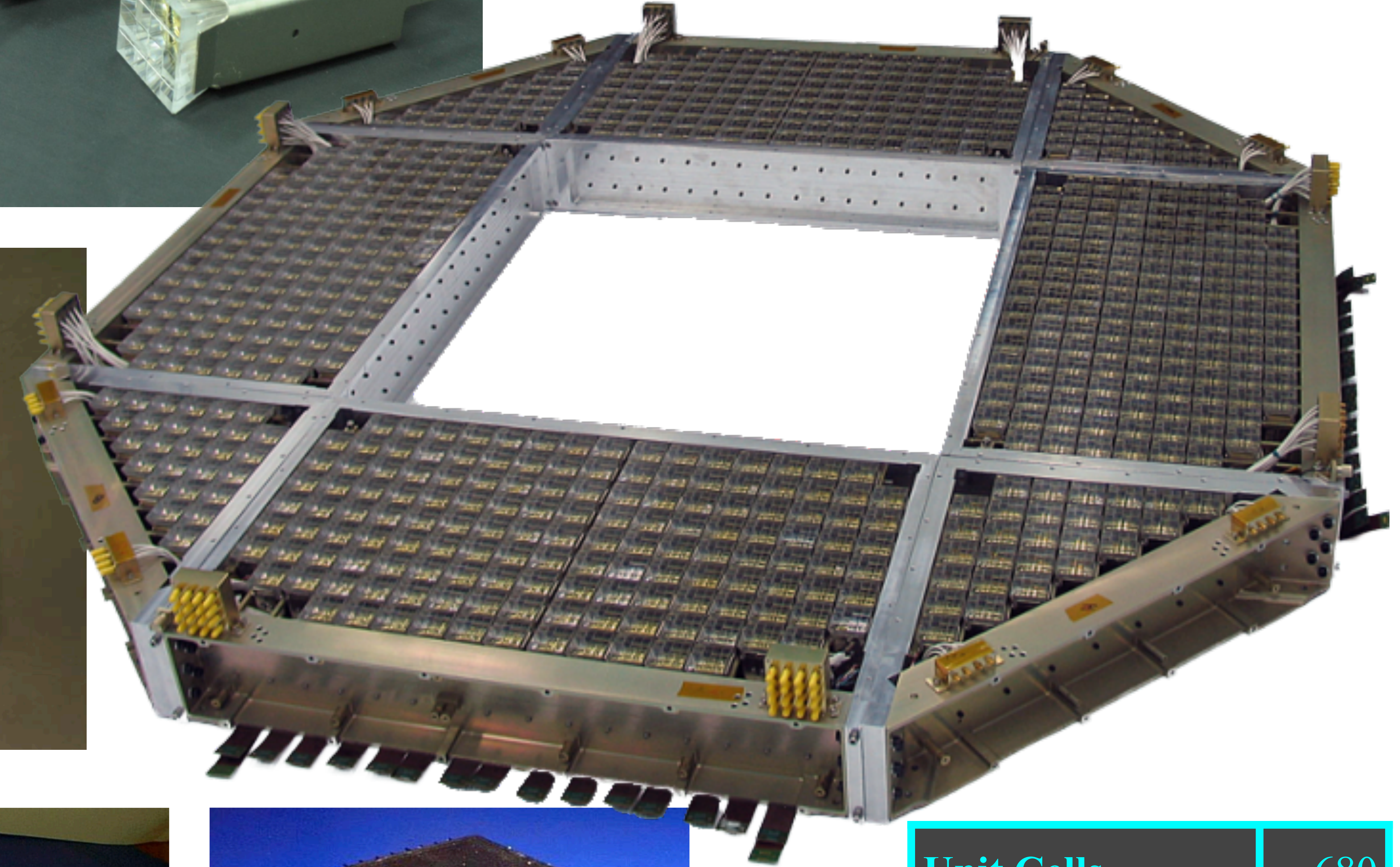
Detection Plane

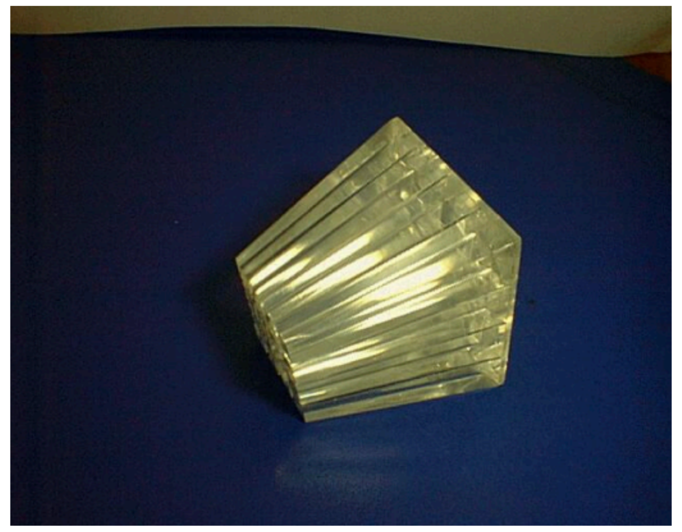


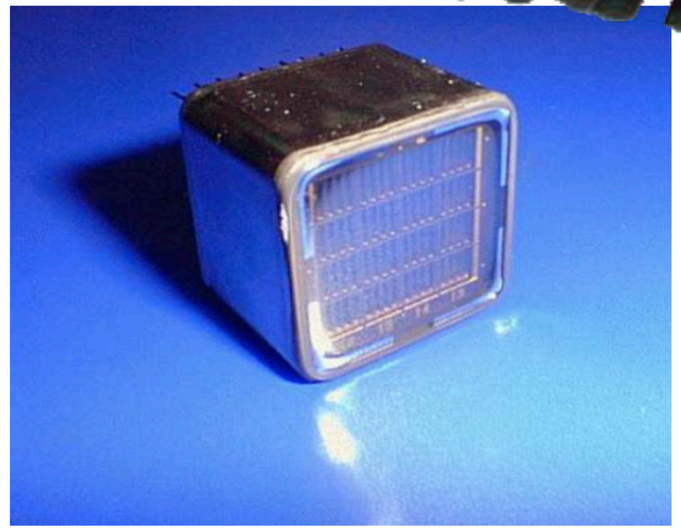
680 PMT Hamamatsu R7900-M16 (multianode 4x4)

10880 channels with a granularity of 8.5×8.5 mm^2



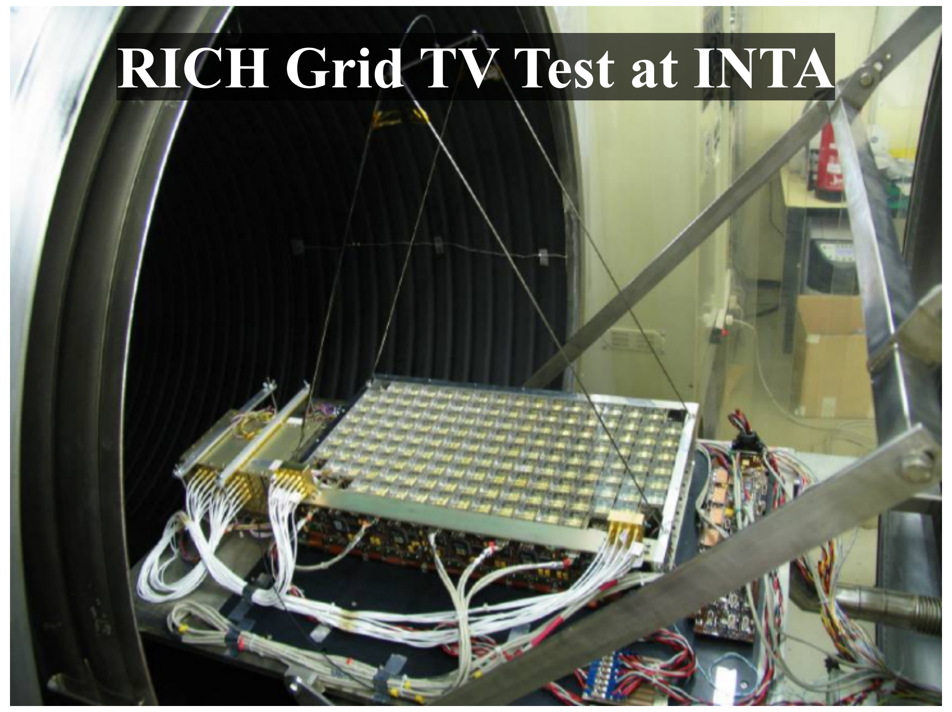




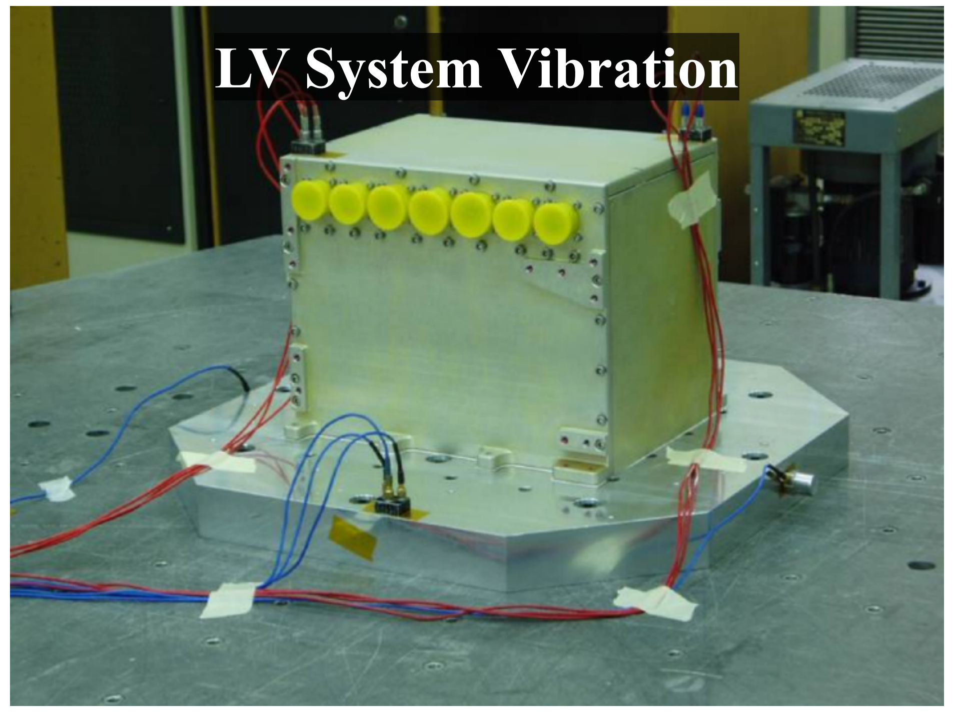


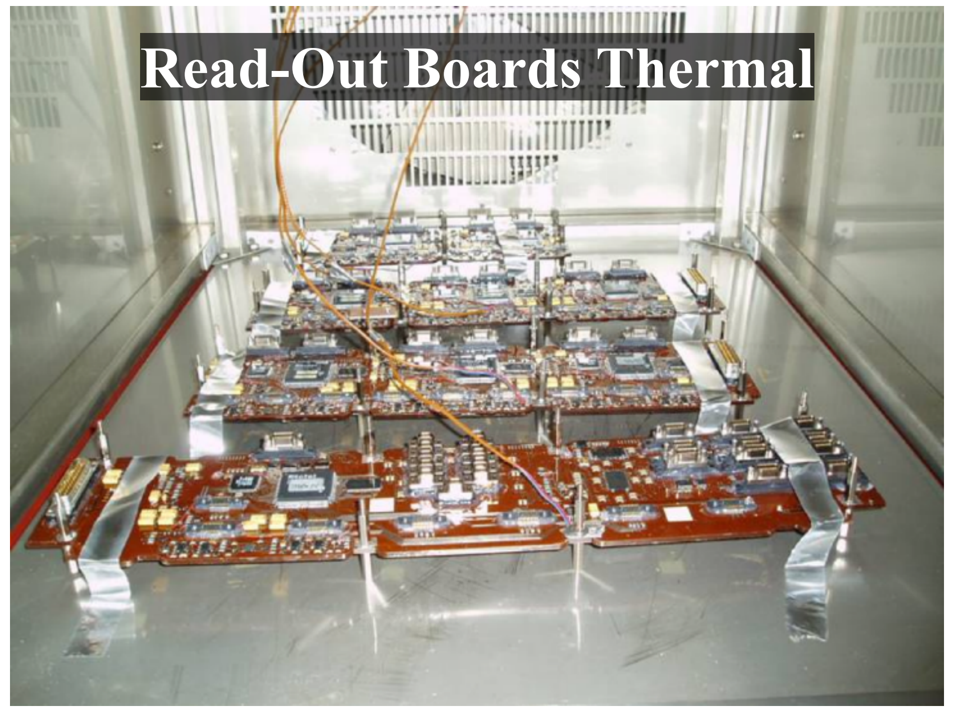
Unit Cells	680
Read-out Lines	92
HV Lines	160
Thermal Sensors	96

AMS-02 RICH: Space Qualification

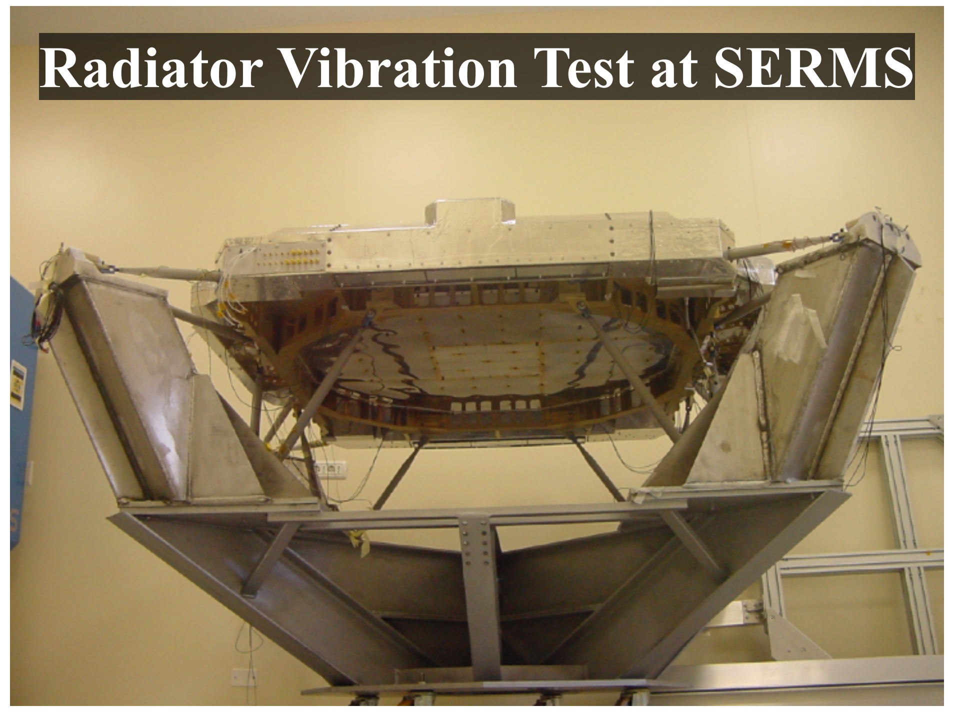

RICH Grid TV Test at INTA

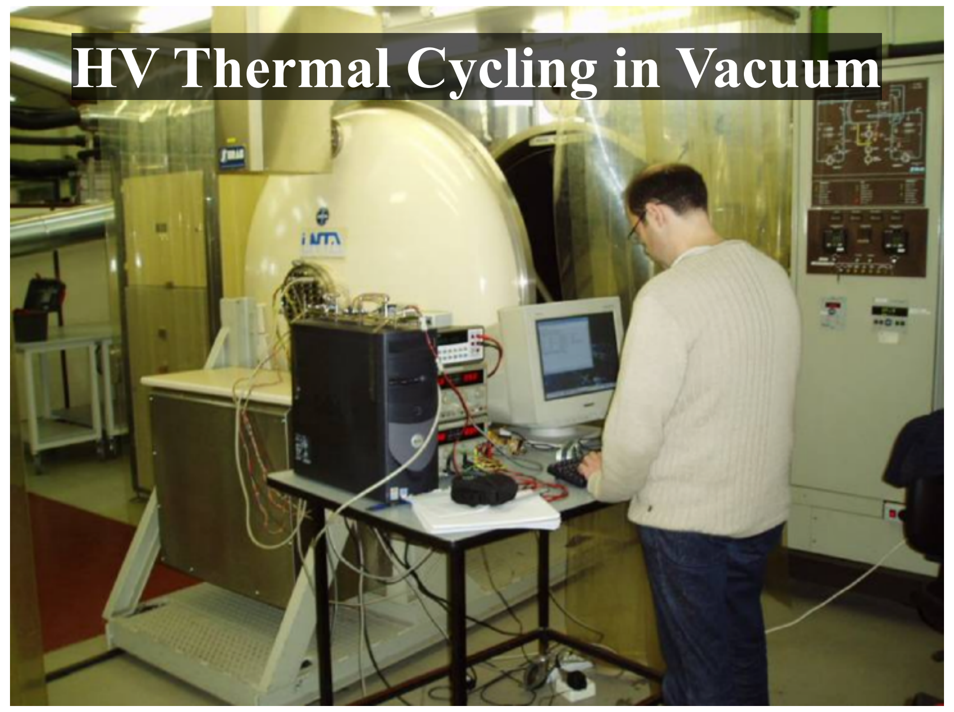

RICH EMI Test at INTA

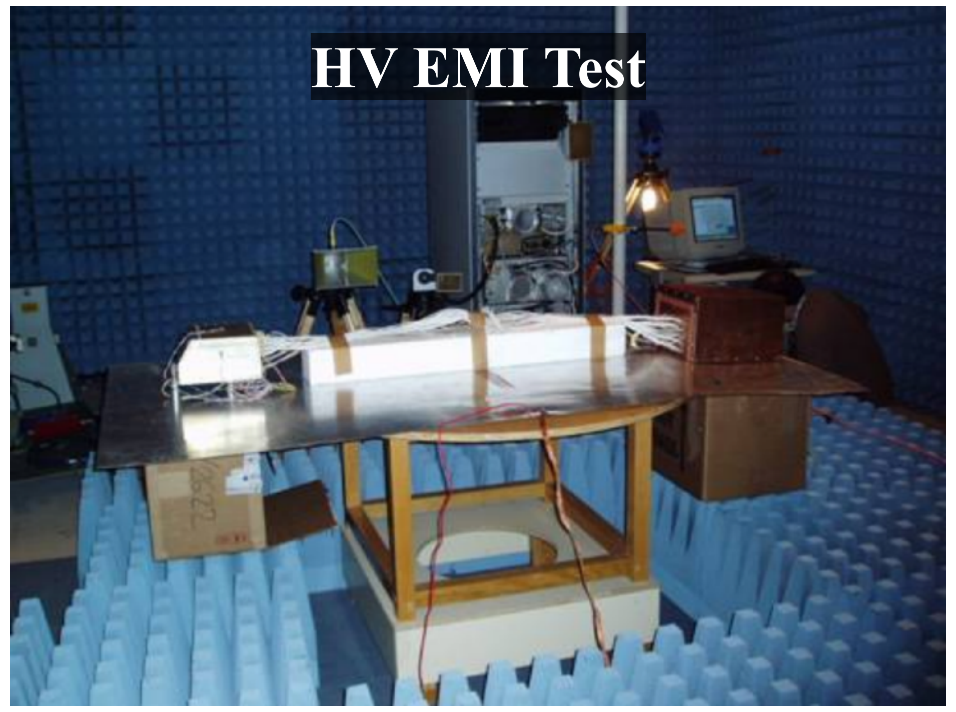

LV System Vibration

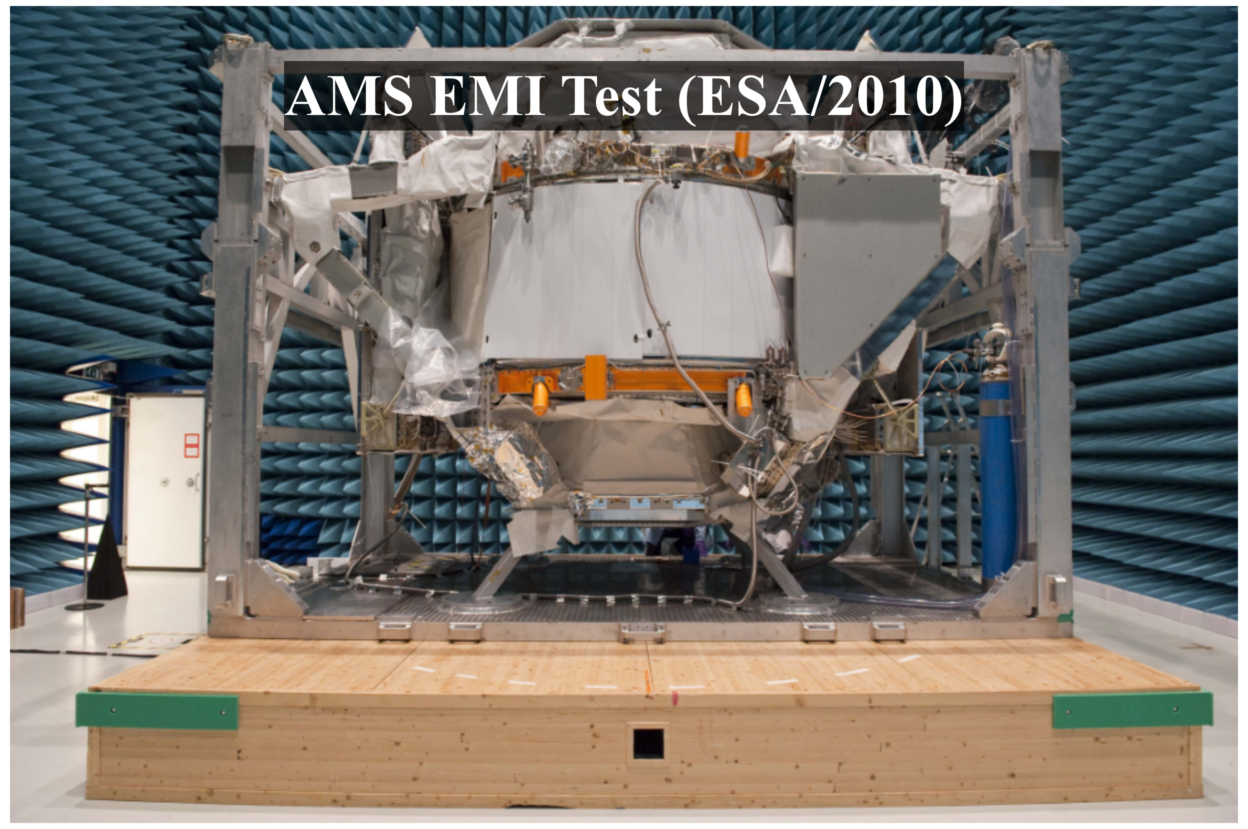

Read-Out Boards Thermal

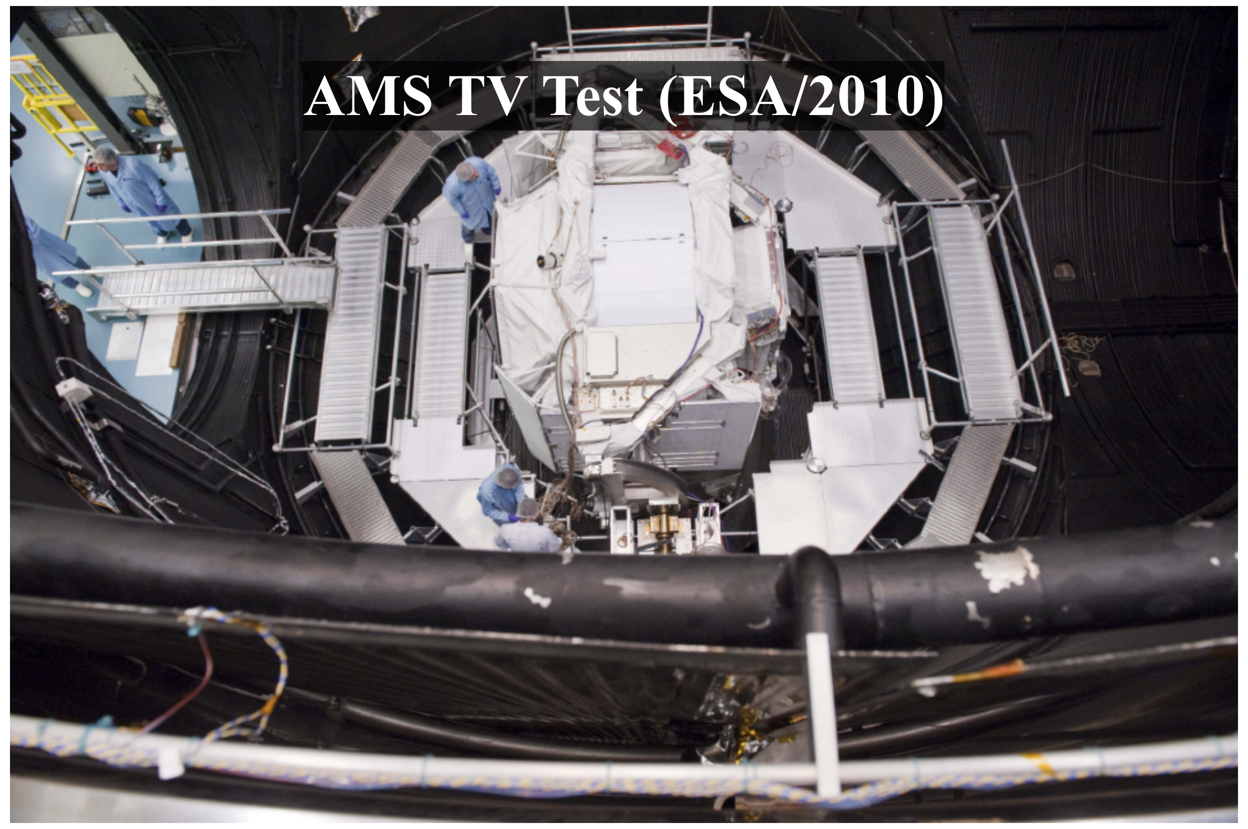

RICH Vibration Test at INTA


Radiator Vibration Test at SERMS


HV Thermal Cycling in Vacuum


HV EMI Test

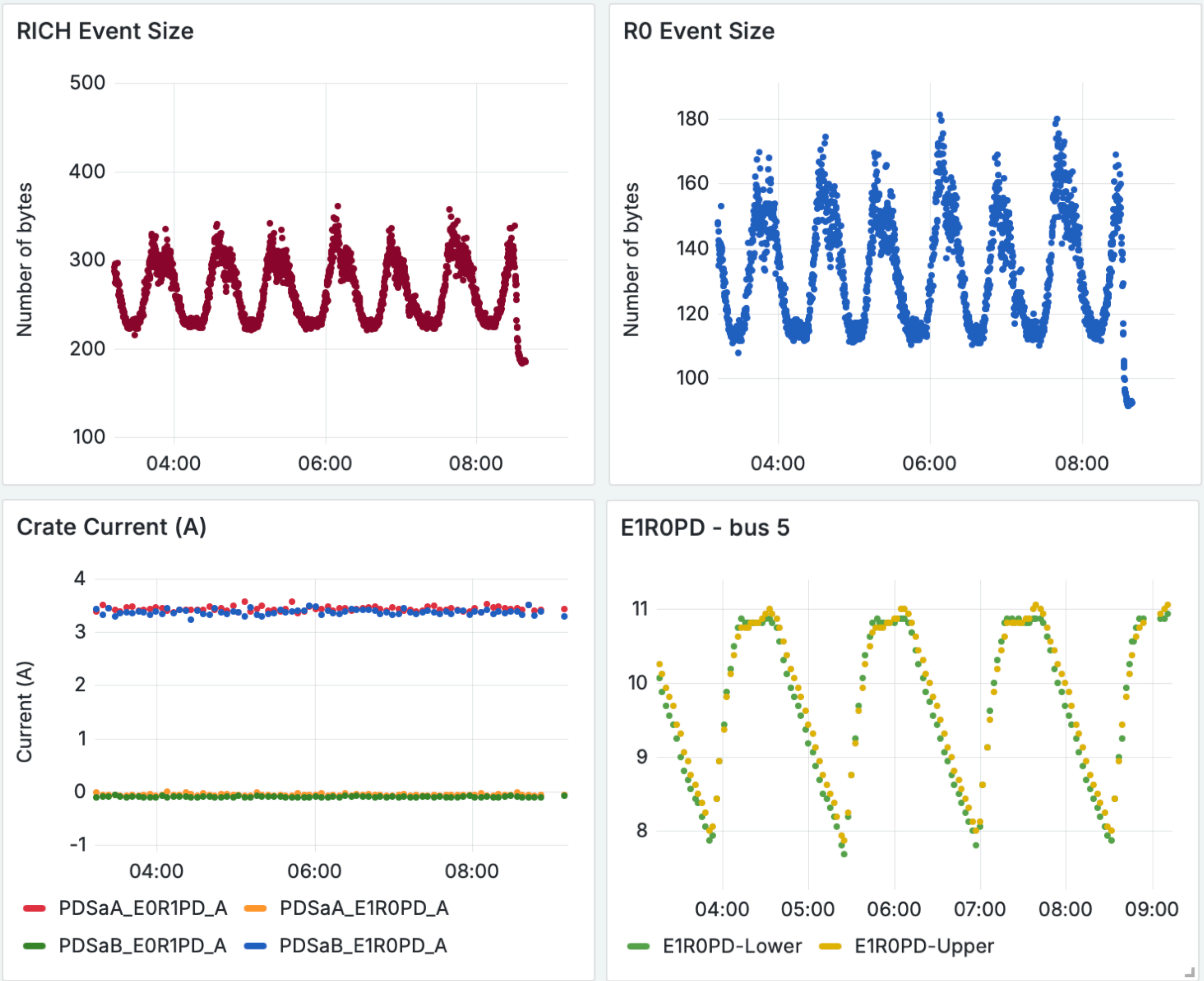

AMS EMI Test (ESA/2010)


AMS TV Test (ESA/2010)


Launch (16/05/2011)

AMS-02 RICH: Monitoring and Operation

- The detector is continuously running
- RICH critical parameters are constantly monitored 24/7 at CERN AMS Payload Control Center (POCC) to ensure detector integrity and optimal performances
- More than 14 years of data taking in nominal configuration
- More than 95% of the channels are working nominally



AMS-02 RICH: Reconstruction

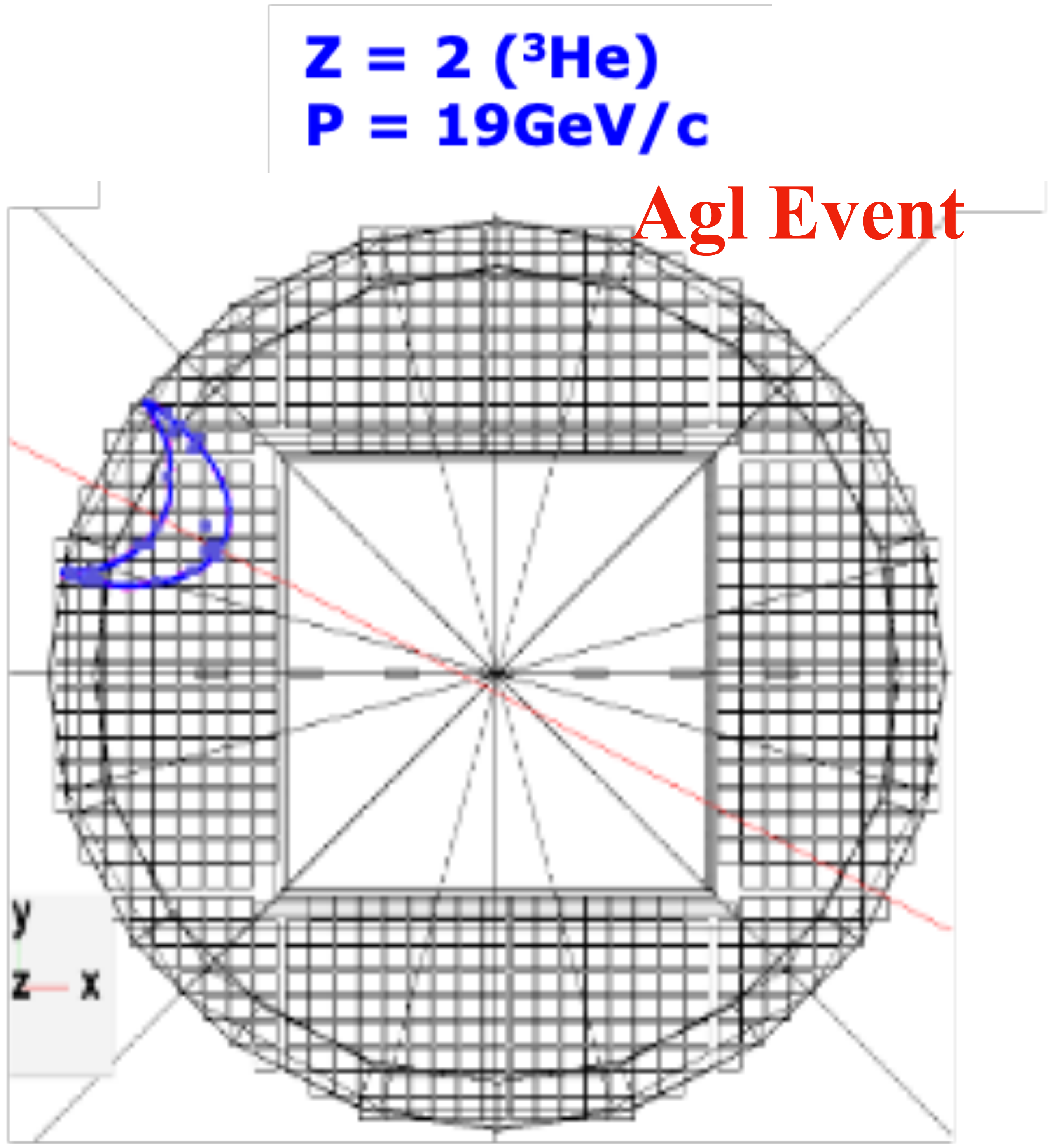
RICH is used for the reconstruction of particle's Velocity and Charge:

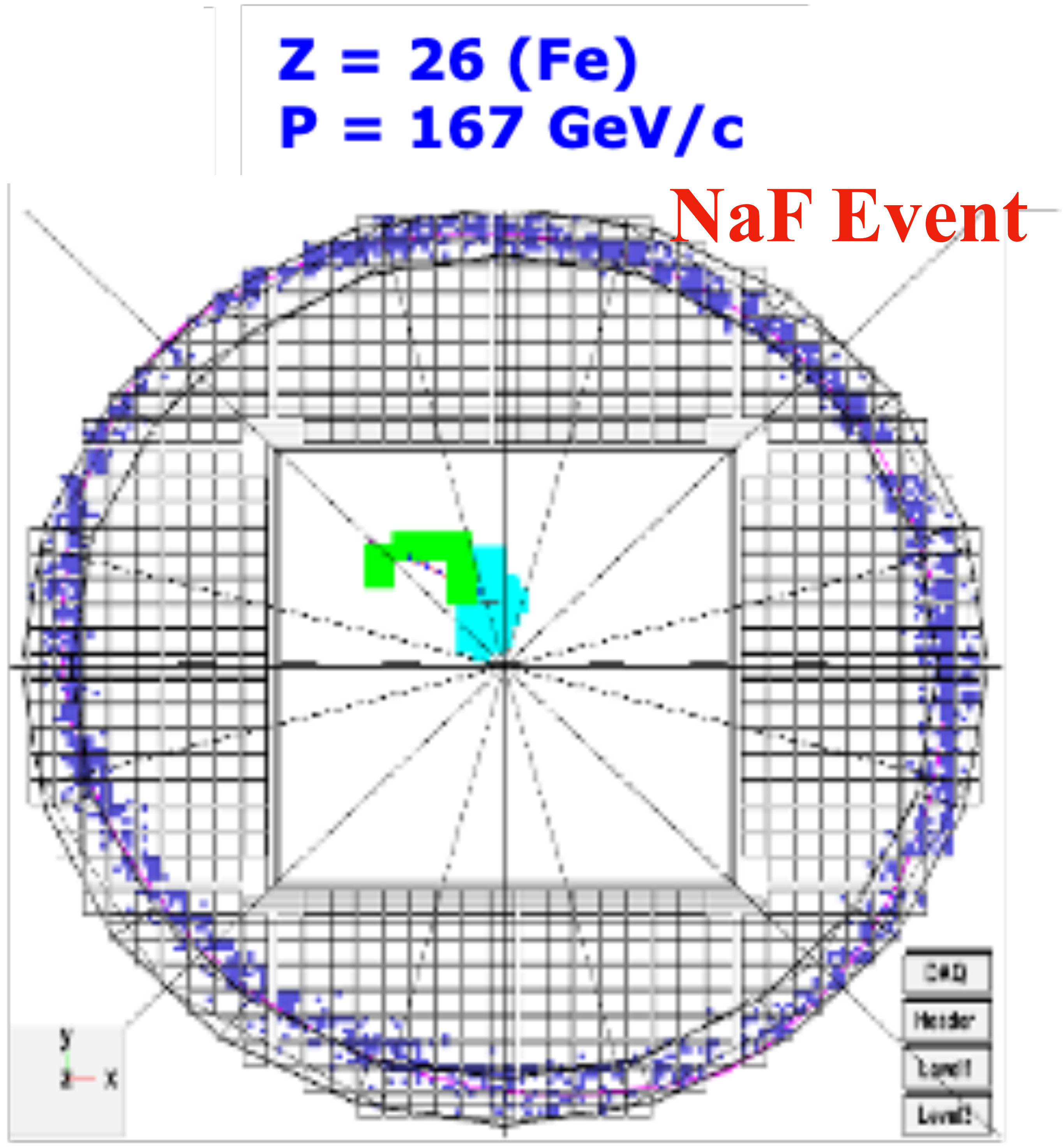
Velocity Reconstruction

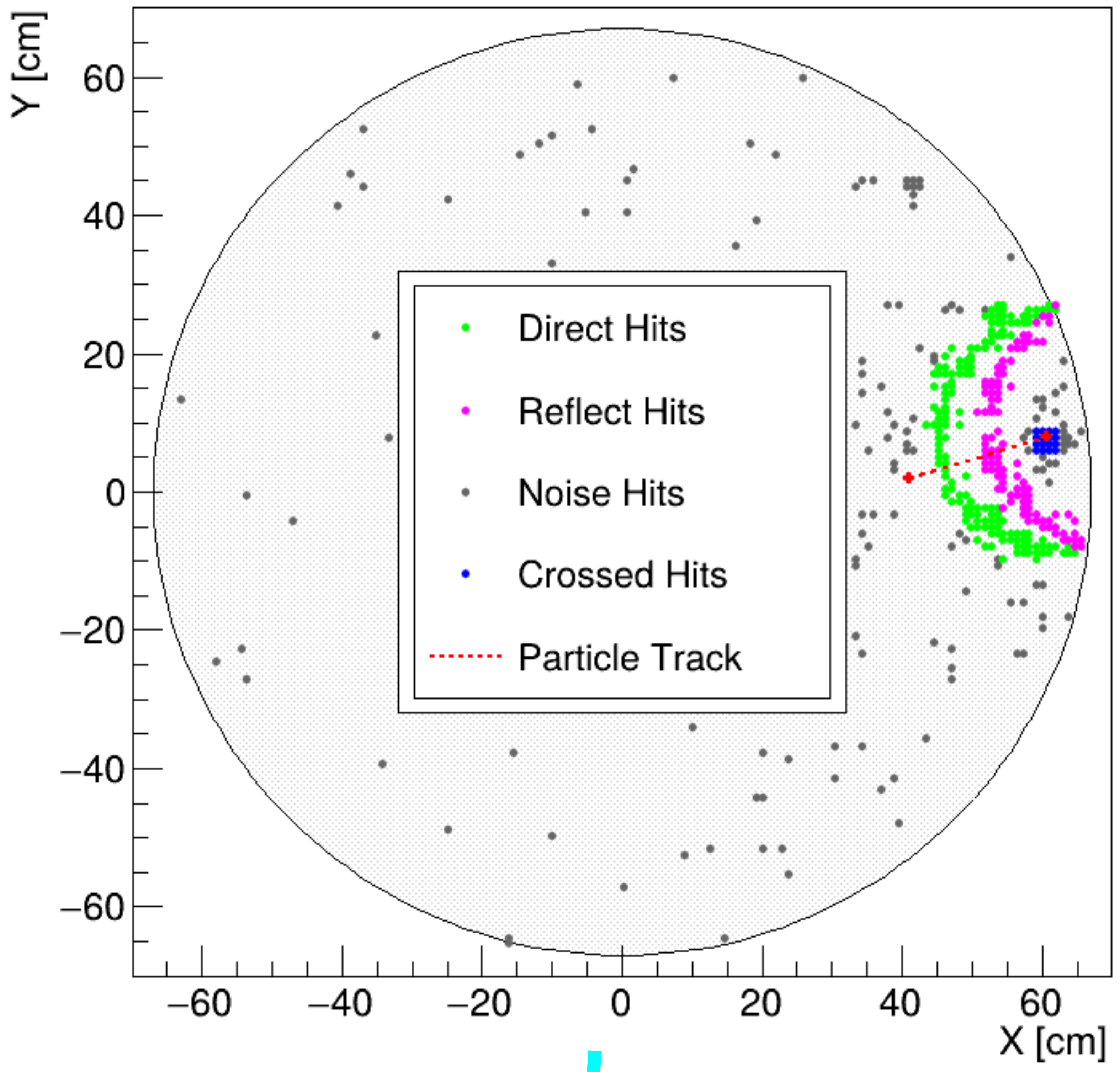
- Each detected photon hit is used to reconstruct a possible Cherenkov angle, which is then combined across the event to estimate the velocity β

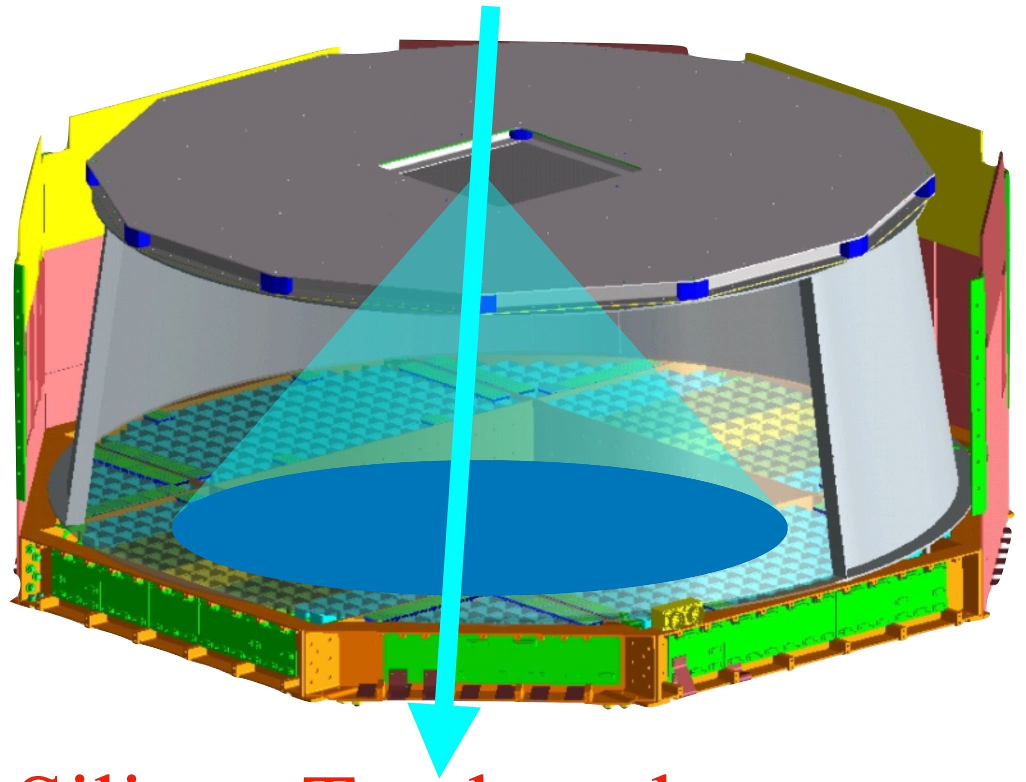
Charge Reconstruction

- Once β is known, the particle charge is estimated by counting the number of photon along the Cherenkov Ring with the formula $N_{\text{p.e.}} \propto Z^2 \sin^2(\theta_C)$









The Silicon Tracker above provides tracking for ring reconstruction

AMS-02 RICH: On-Orbit Alignment

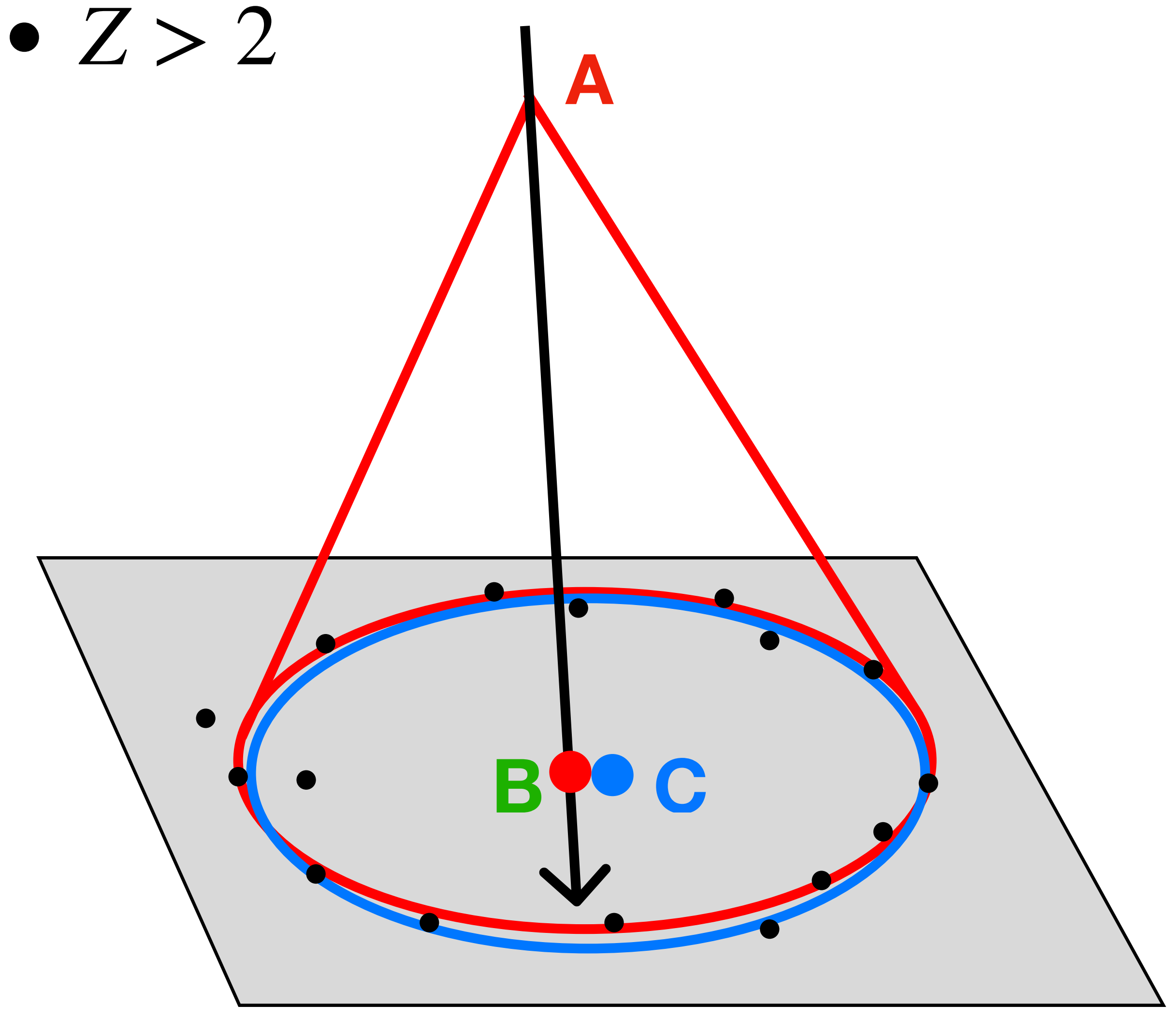
Due to the space shuttle launch vibration and the thermal expansion and contraction in space, the relative position of RICH with respect to Tracker may be mis-aligned.

Compute the residual between RICH and Tracker Position:

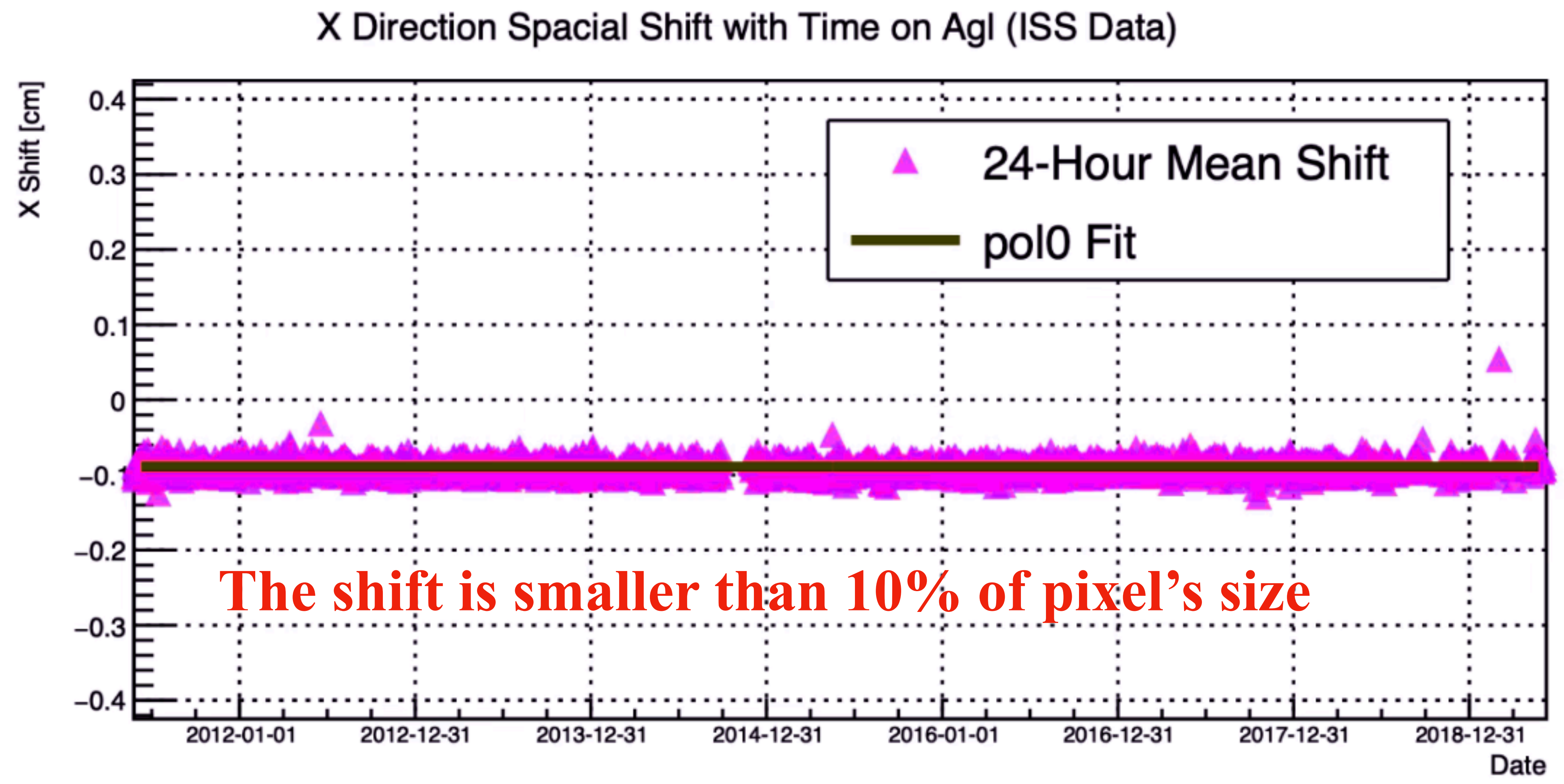
$$\delta = X_{RICH} - X_{Tracker}$$

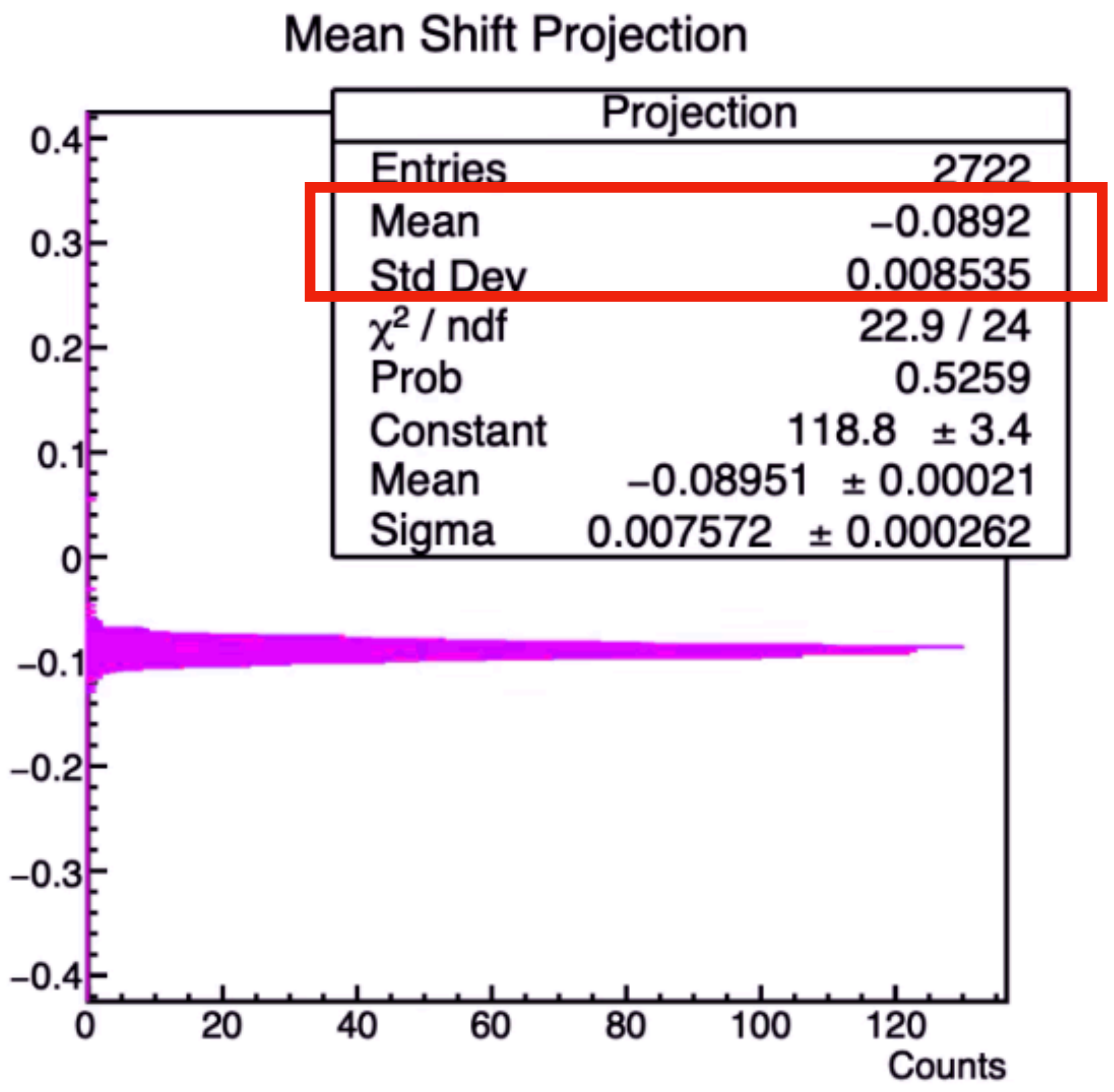
Data Sample:

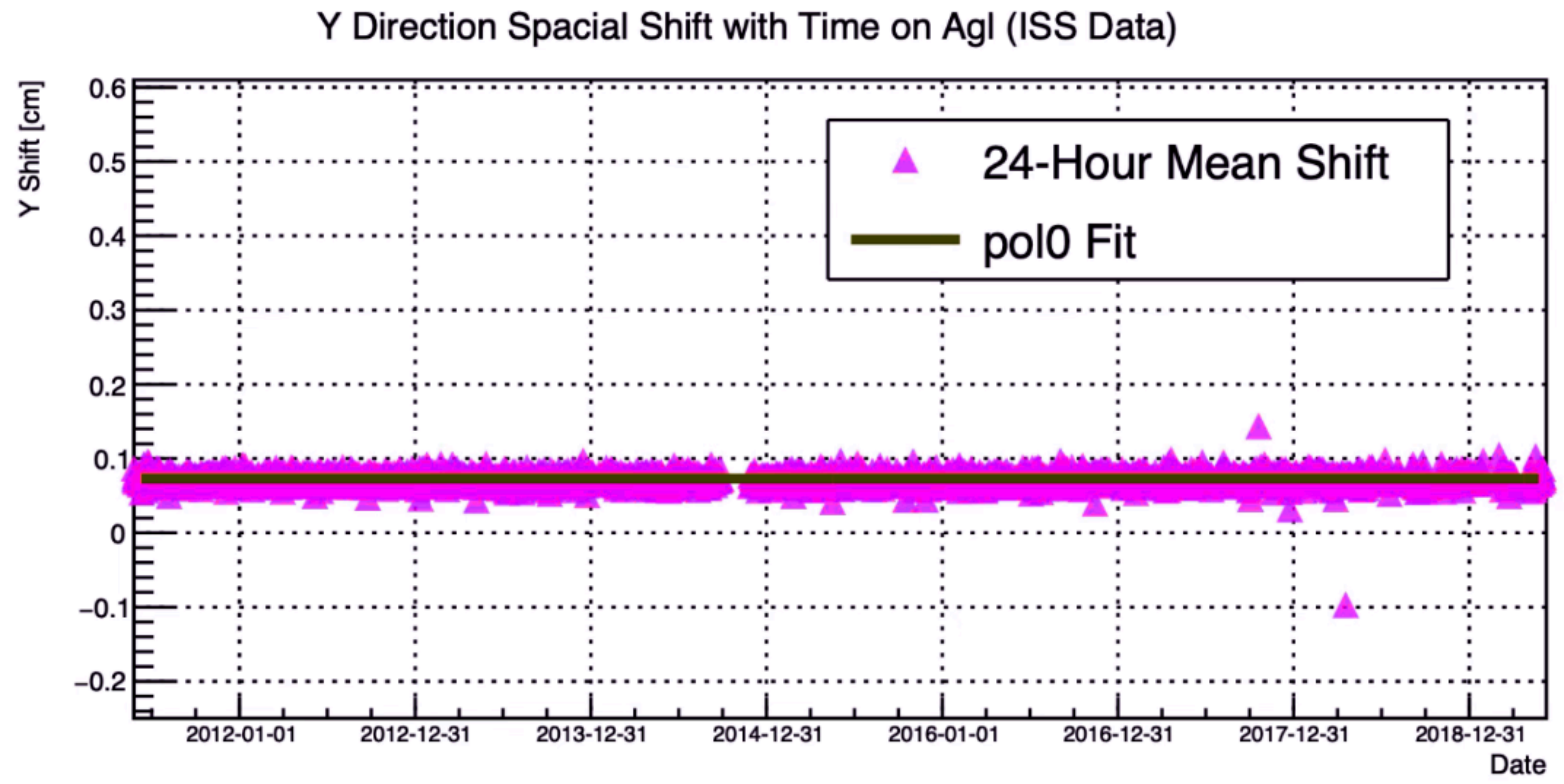
- Vertical incident particles
- $\beta \rightarrow 1$ (Rigidity > 100 GV)
- $Z > 2$

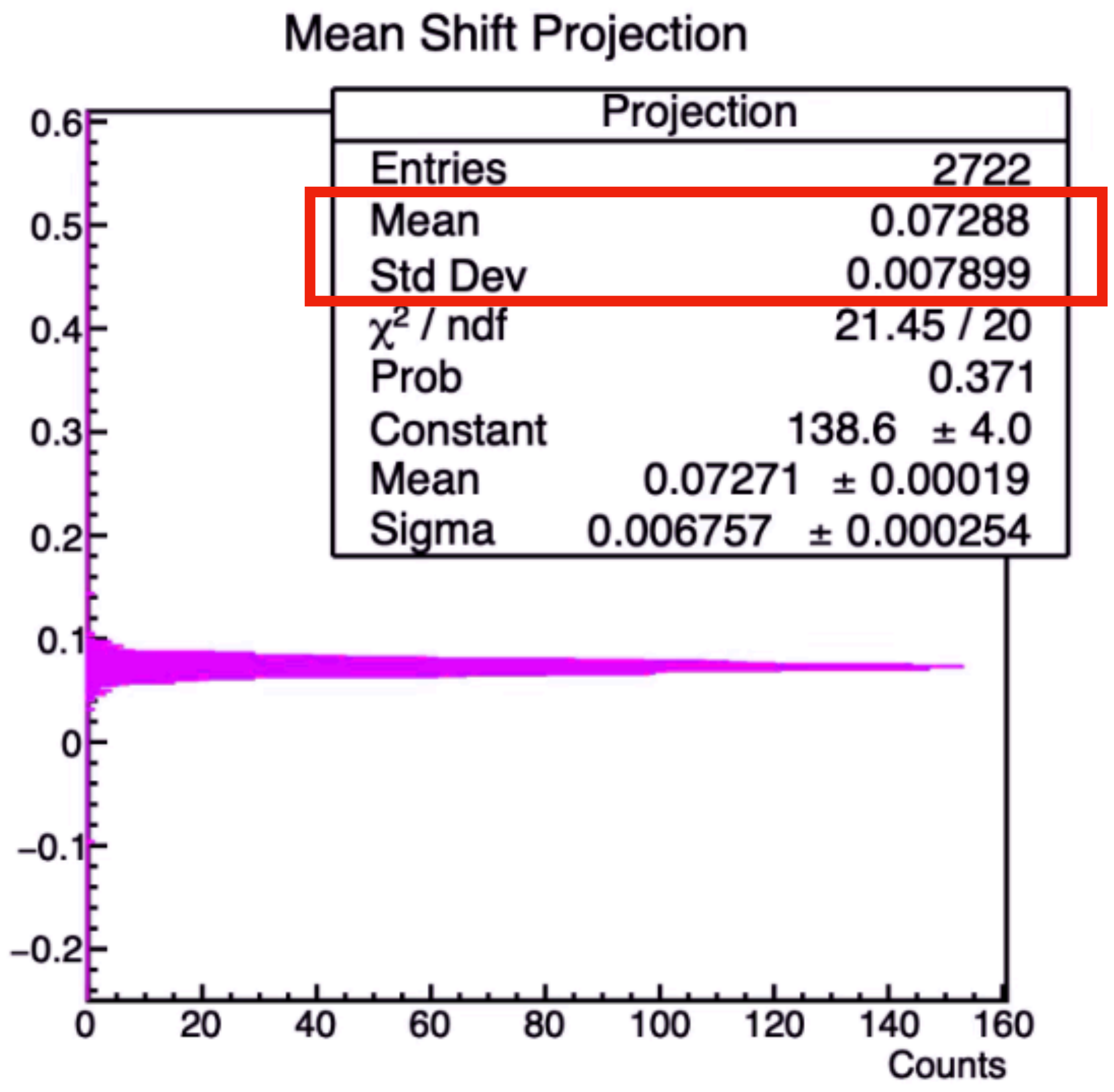


- A: Emission Position
- B: Track Extrapolation Position
- C: Reconstructed Ring Center





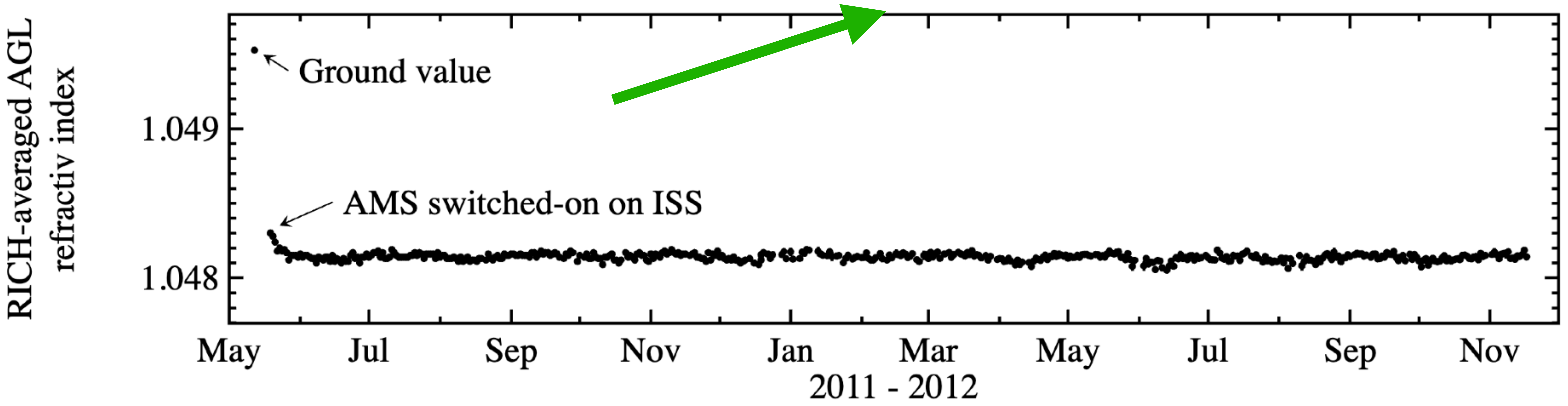




On-Orbit Agl Refractive Index Calibration

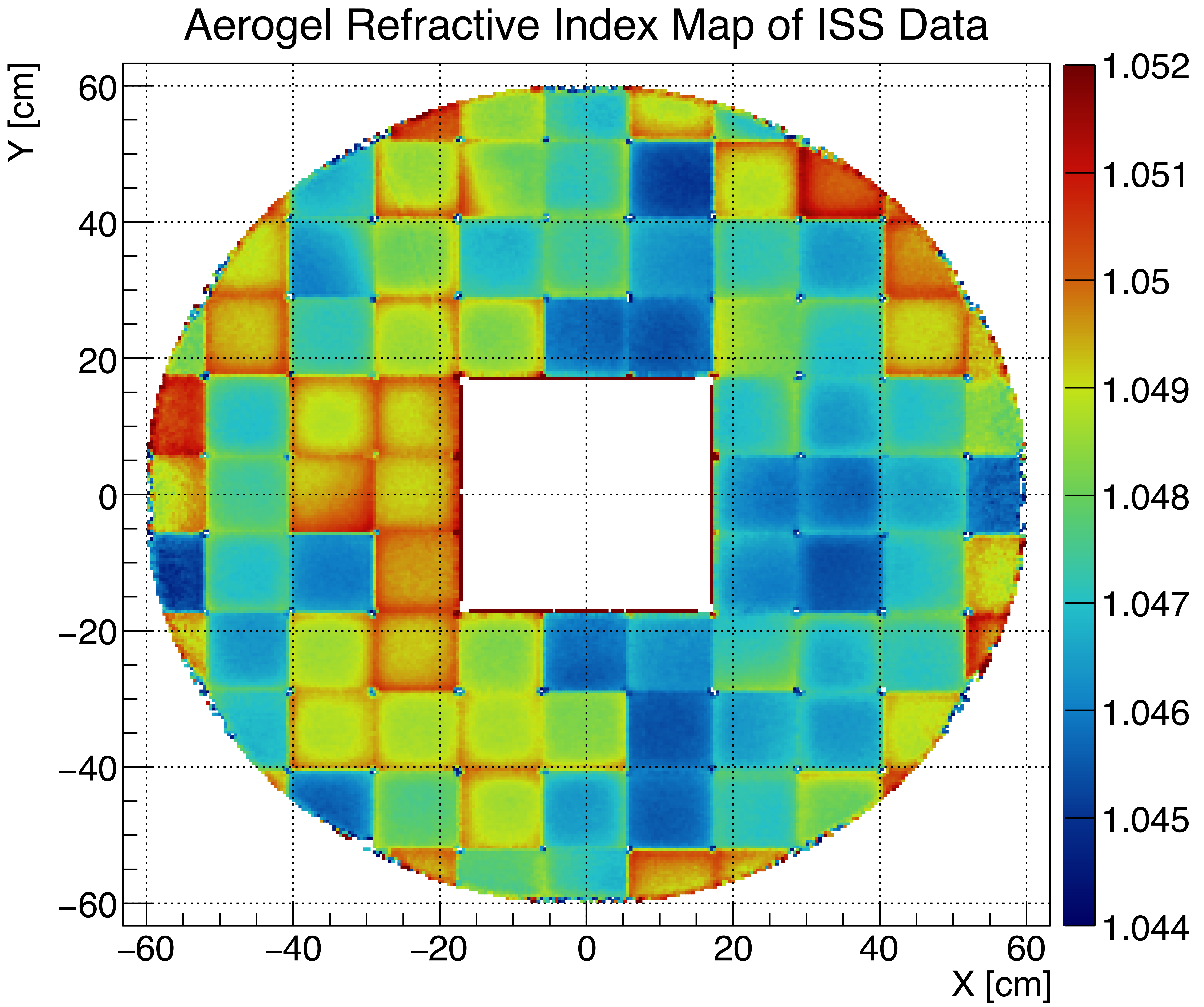
Refractive index differences among tiles as well as its non-uniformities within each Agl tile were measured on ground and used as starting input.

The non-uniformity of the refractive indices must be re-calibrated on-orbit



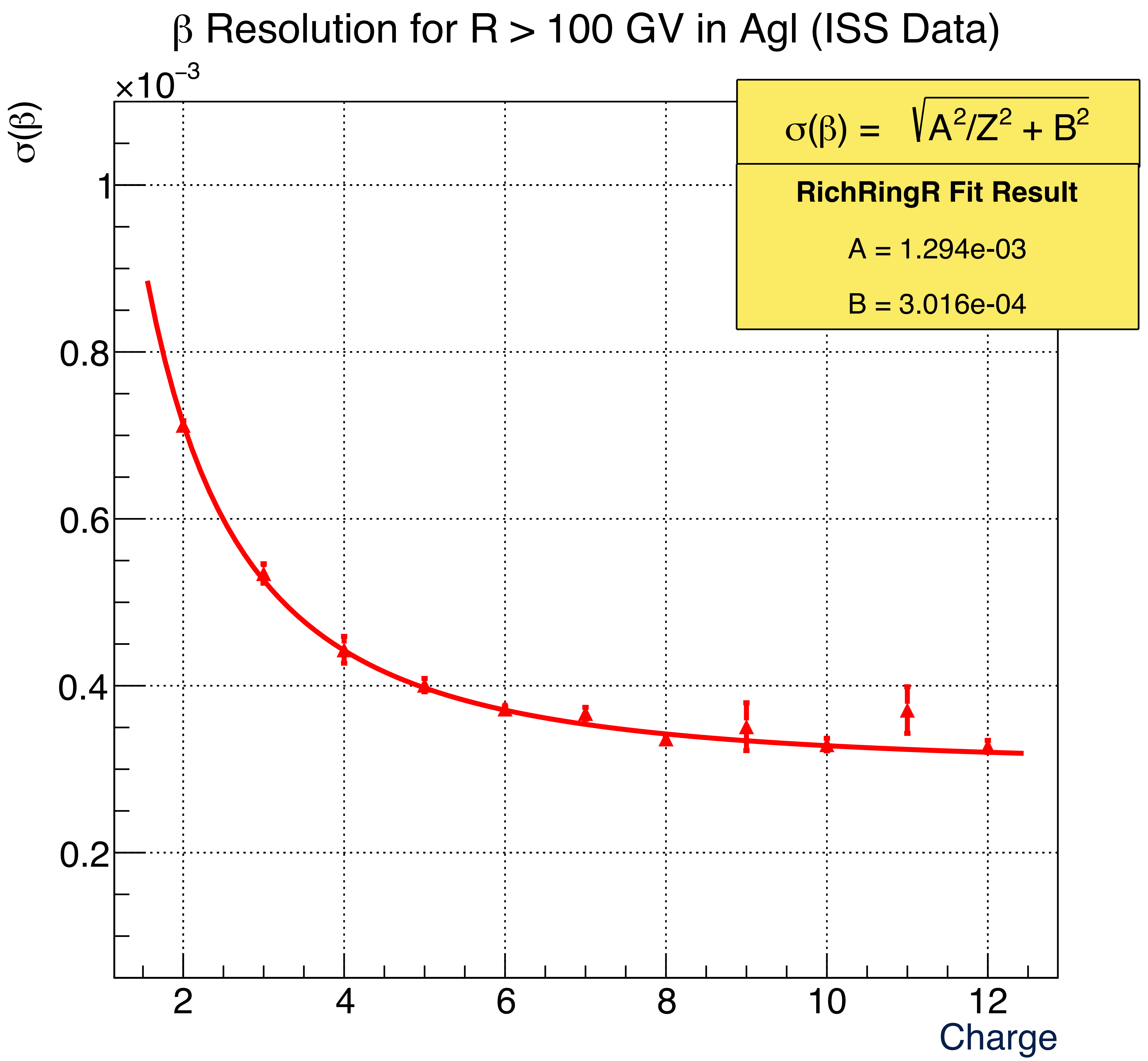
Reconstruct R > 100GV ($\beta \to 1$) Helium events with full opening angle in both radiators, and obtain the refractive index estimation by:

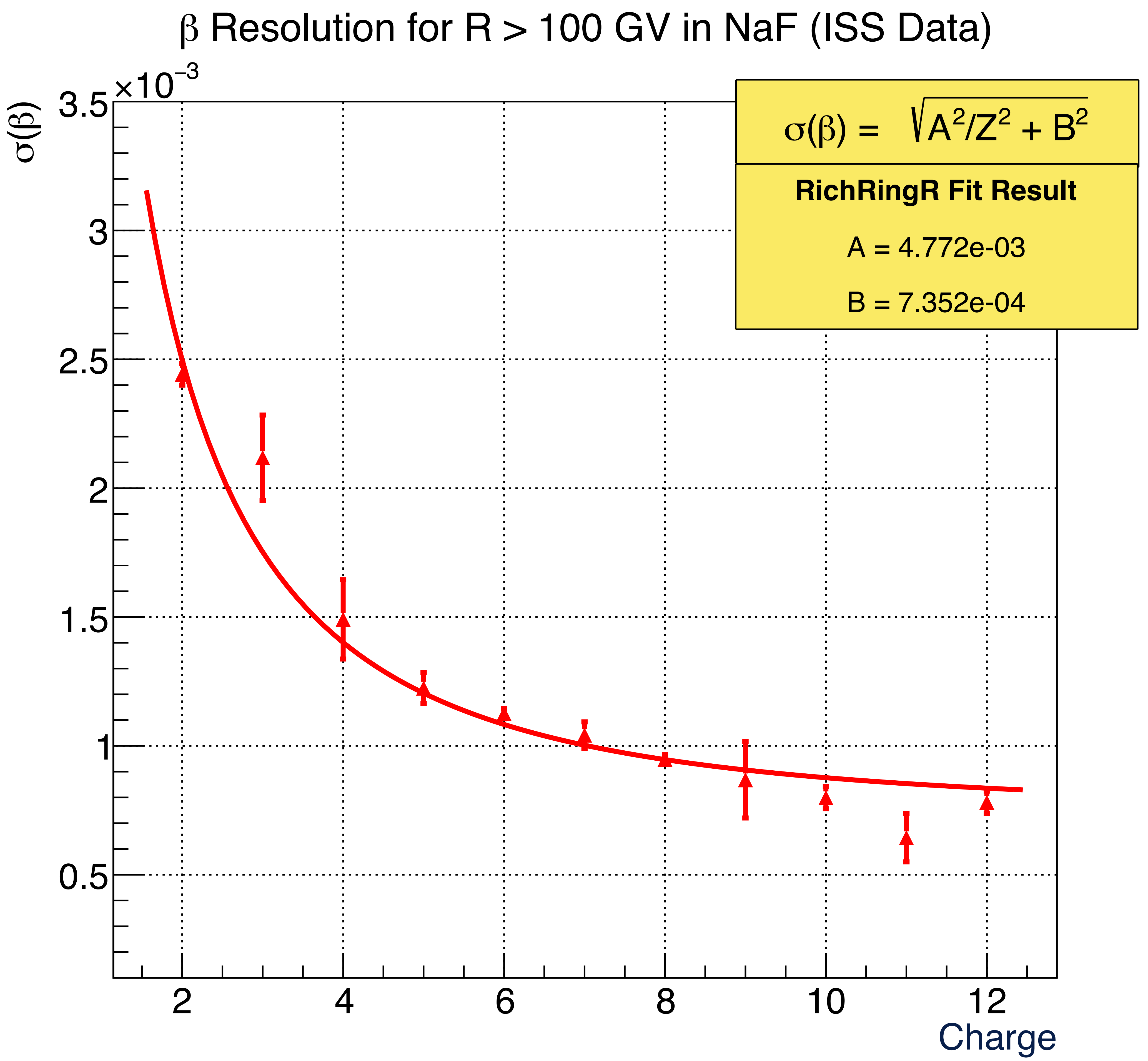
$$\beta = \frac{1}{n(x,y)\cos\theta_C} \quad \Rightarrow \quad n(x,y) = \left\langle \frac{1}{\cos\theta_C} \right\rangle$$



AMS-02 RICH: Performance on the ISS

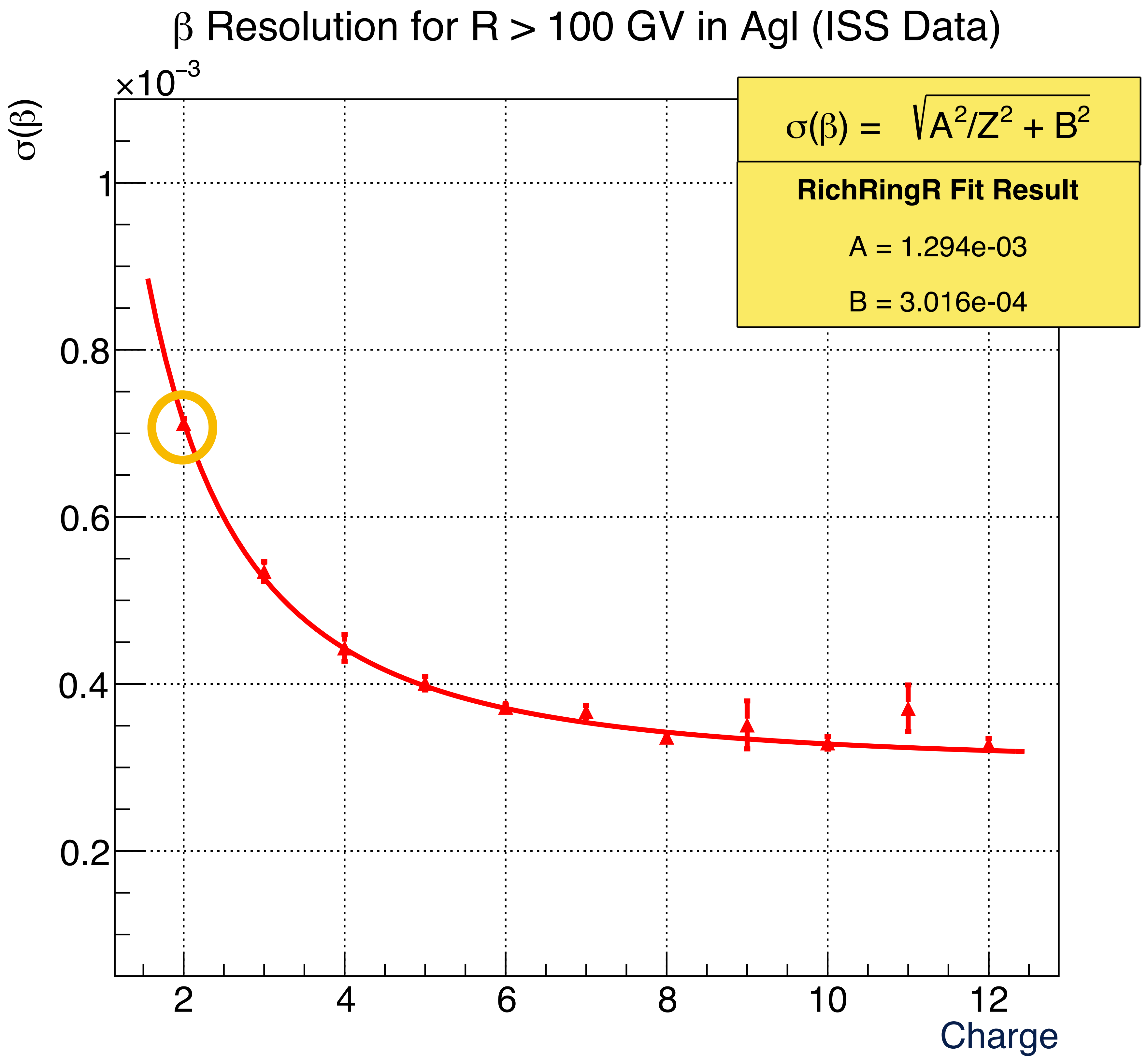
- The Beta resolution in AgI (NaF) is 0.7 (2.4) per mil for Helium, and better than 0.4 (1.4) per mil for higher nuclei with Z > 4.
- The successful application of RICH detection technology enables isotopic separation in an extended energy range mostly unexplored by previous cosmic-ray experiments.

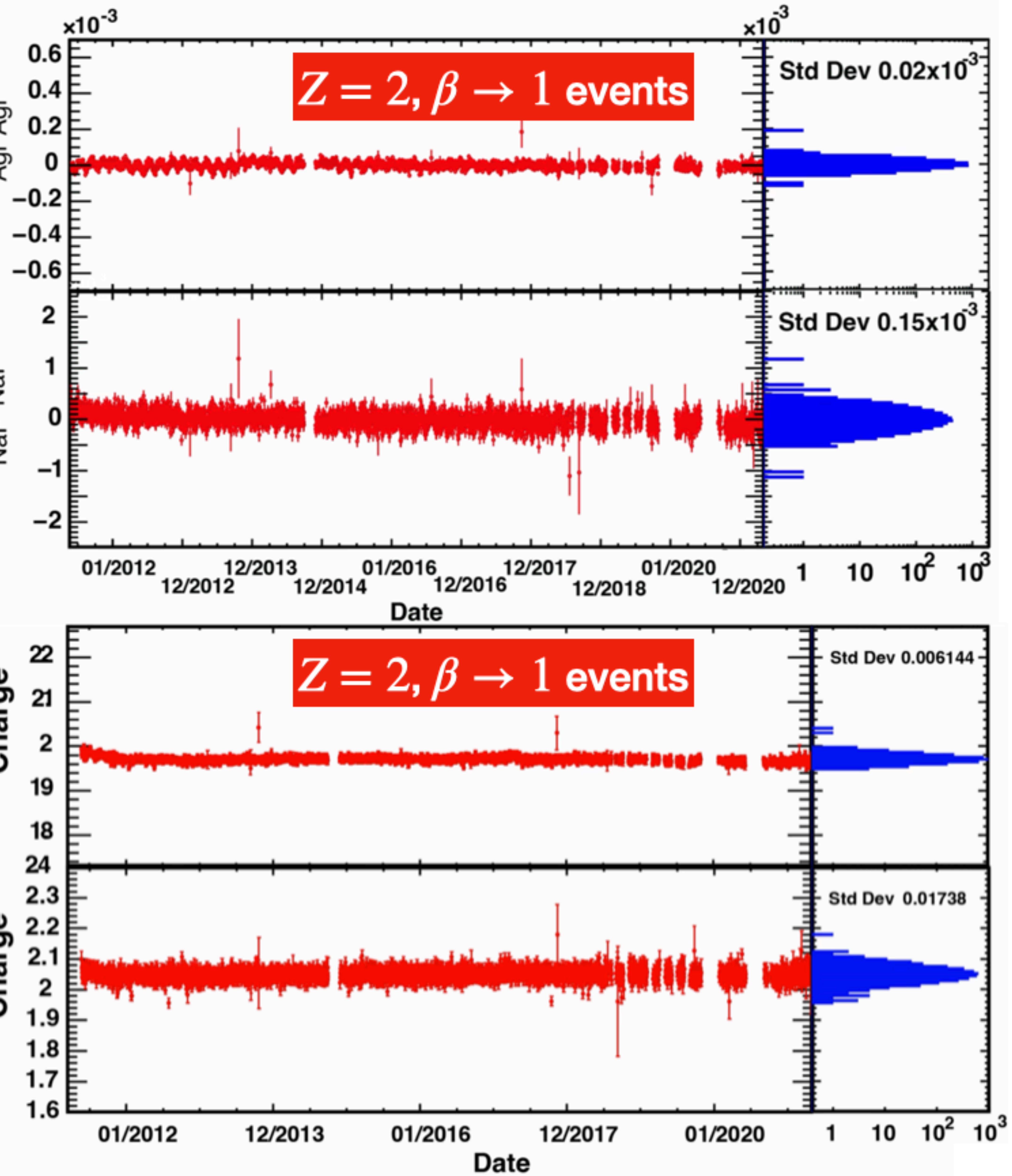




AMS-02 RICH: Measurement Stability

On Aerogel, the β resolution for Helium is about 0.7×10^{-3} with a charge resolution ~0.3.
The fluctuation of β and charge measurement is 10% smaller than their resolution.

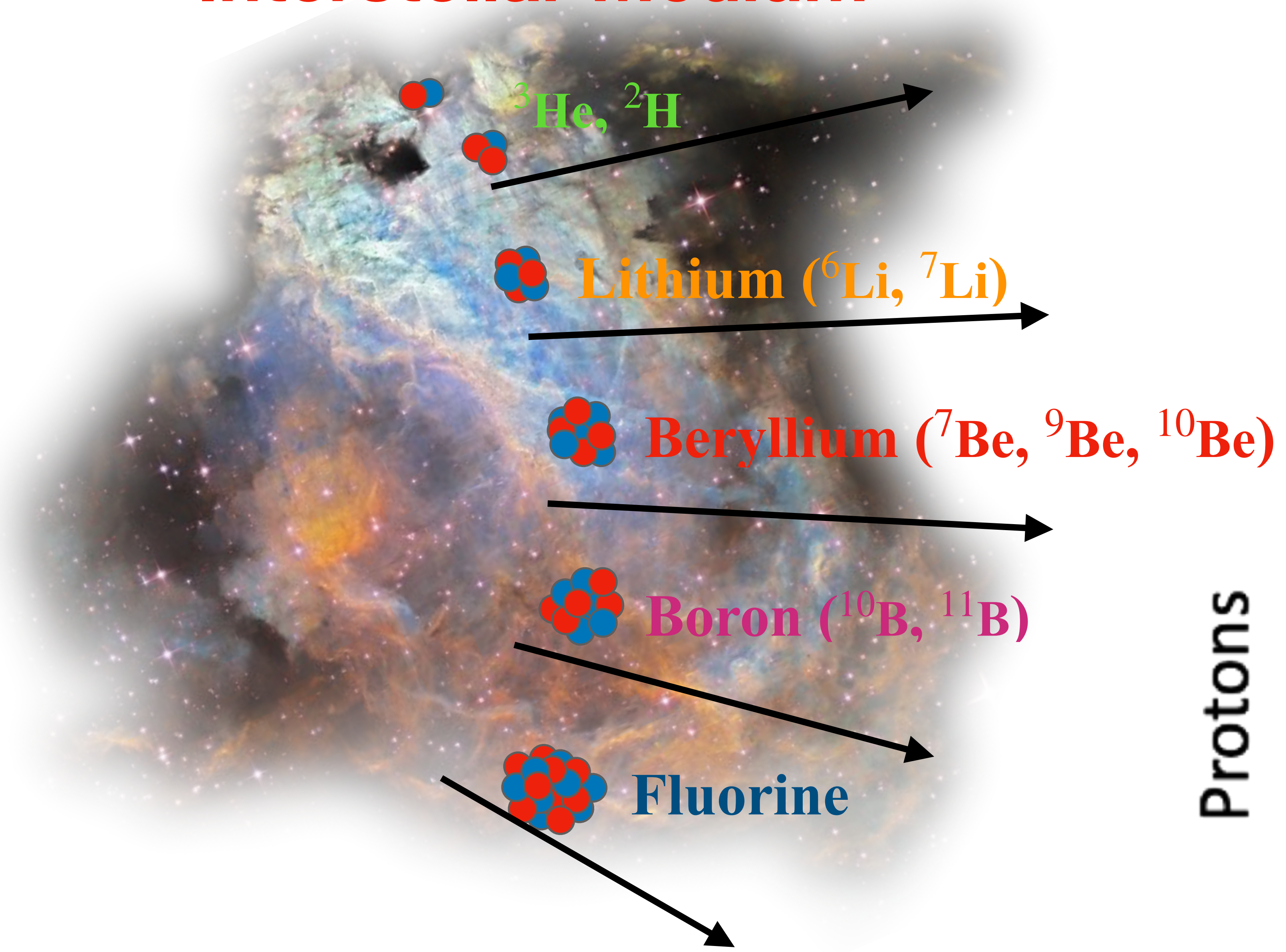


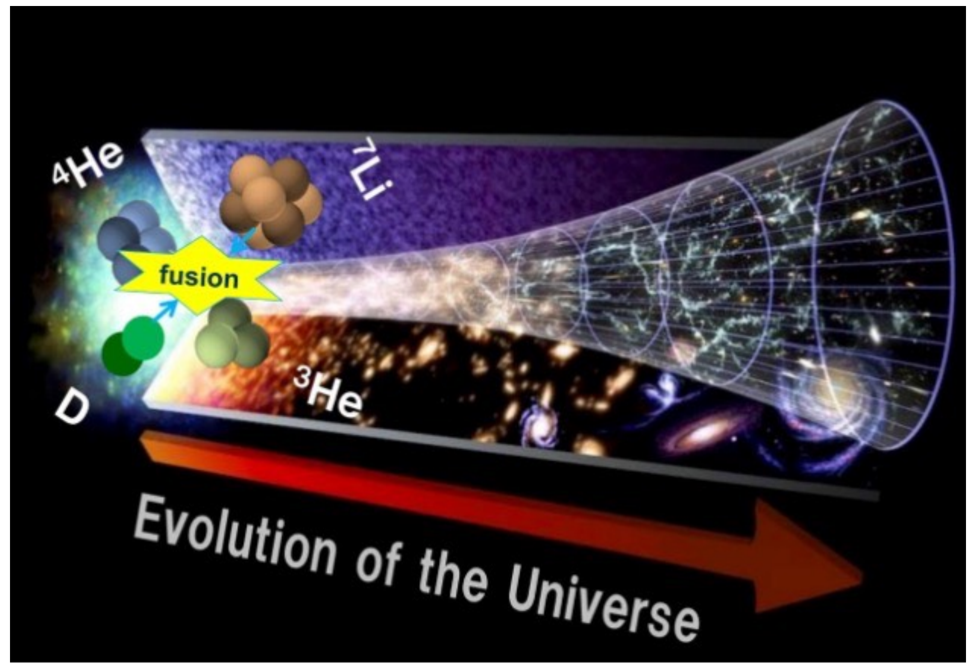


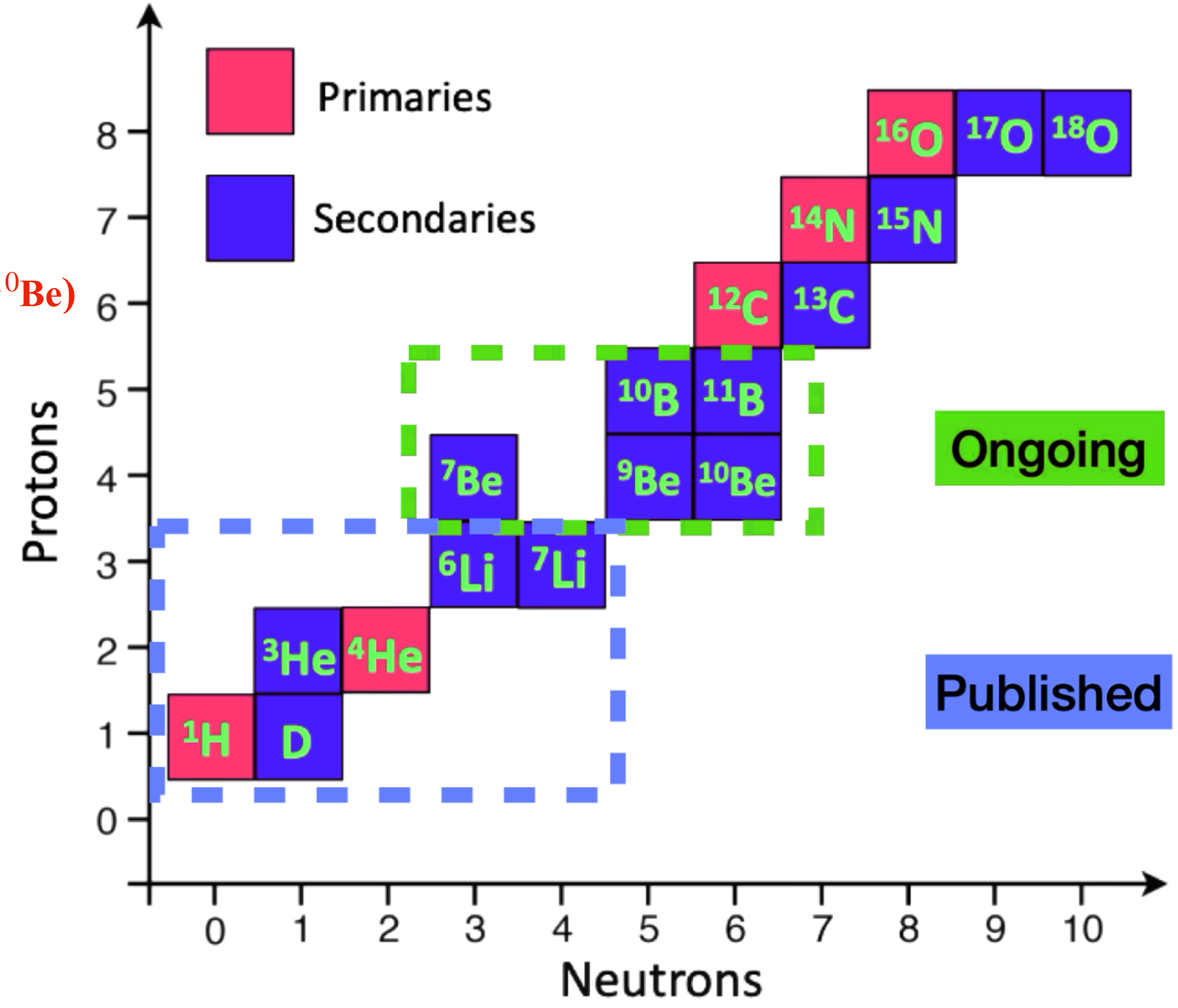
AMS-02 Isotope Physics Topics

- **With the superior performance of velocity resolution, AMS-02 experiment can cover a wide range of cosmic ray isotope measurements.**
- **The light nuclei isotopes are powerful probes to constrain cosmic rays propagation model parameters.**

Interstellar Medium





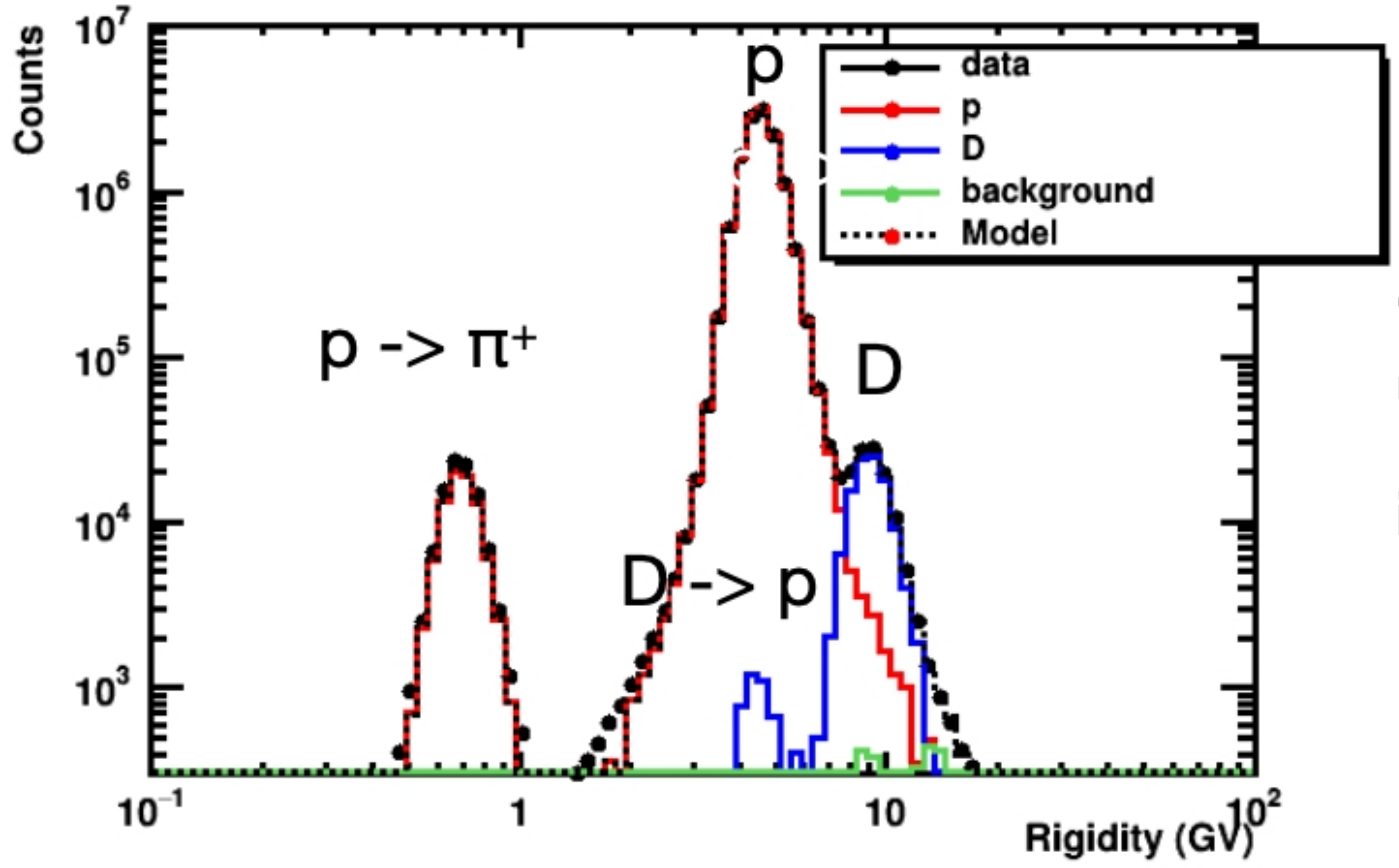


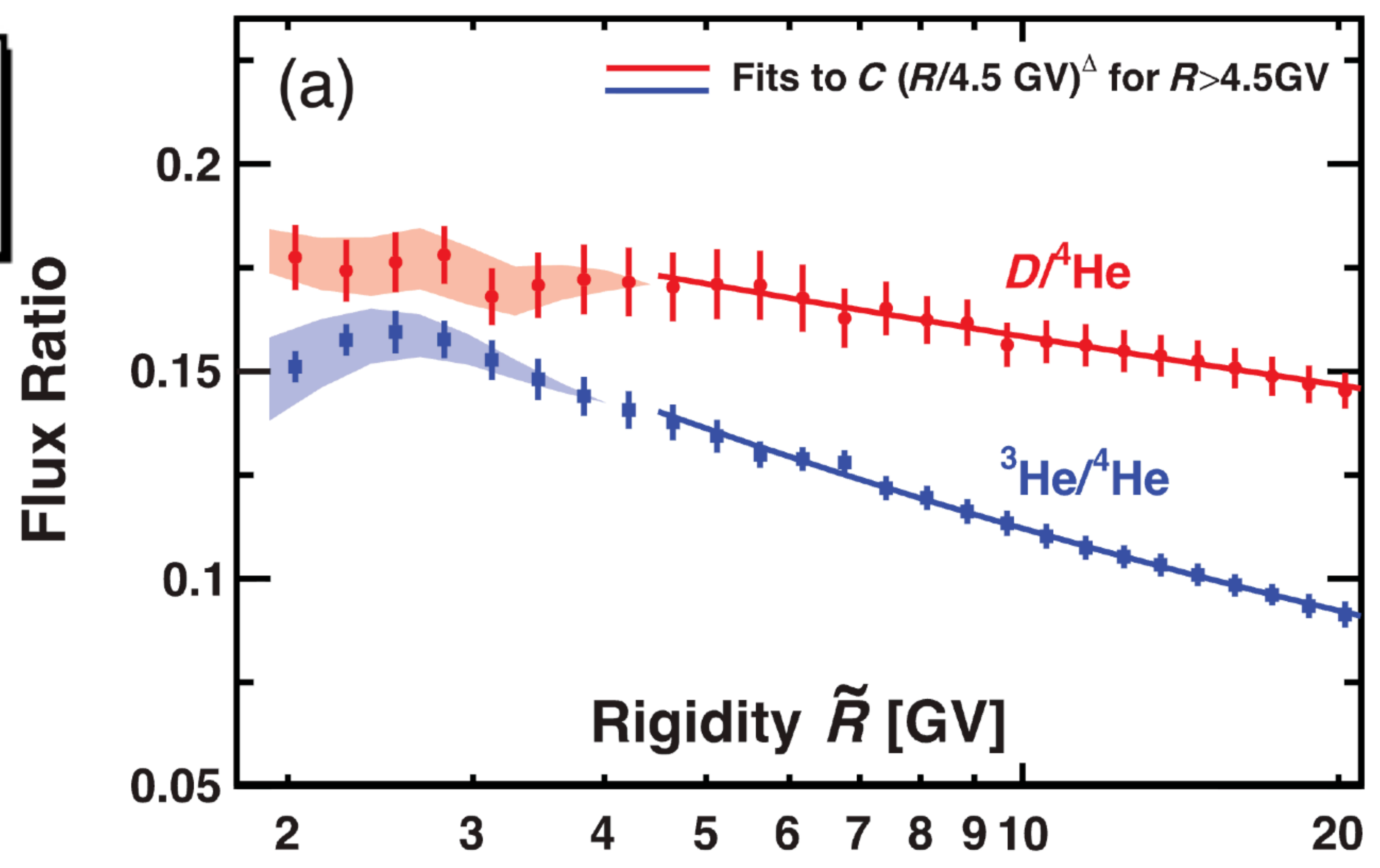
AMS: List of Isotopes Publications

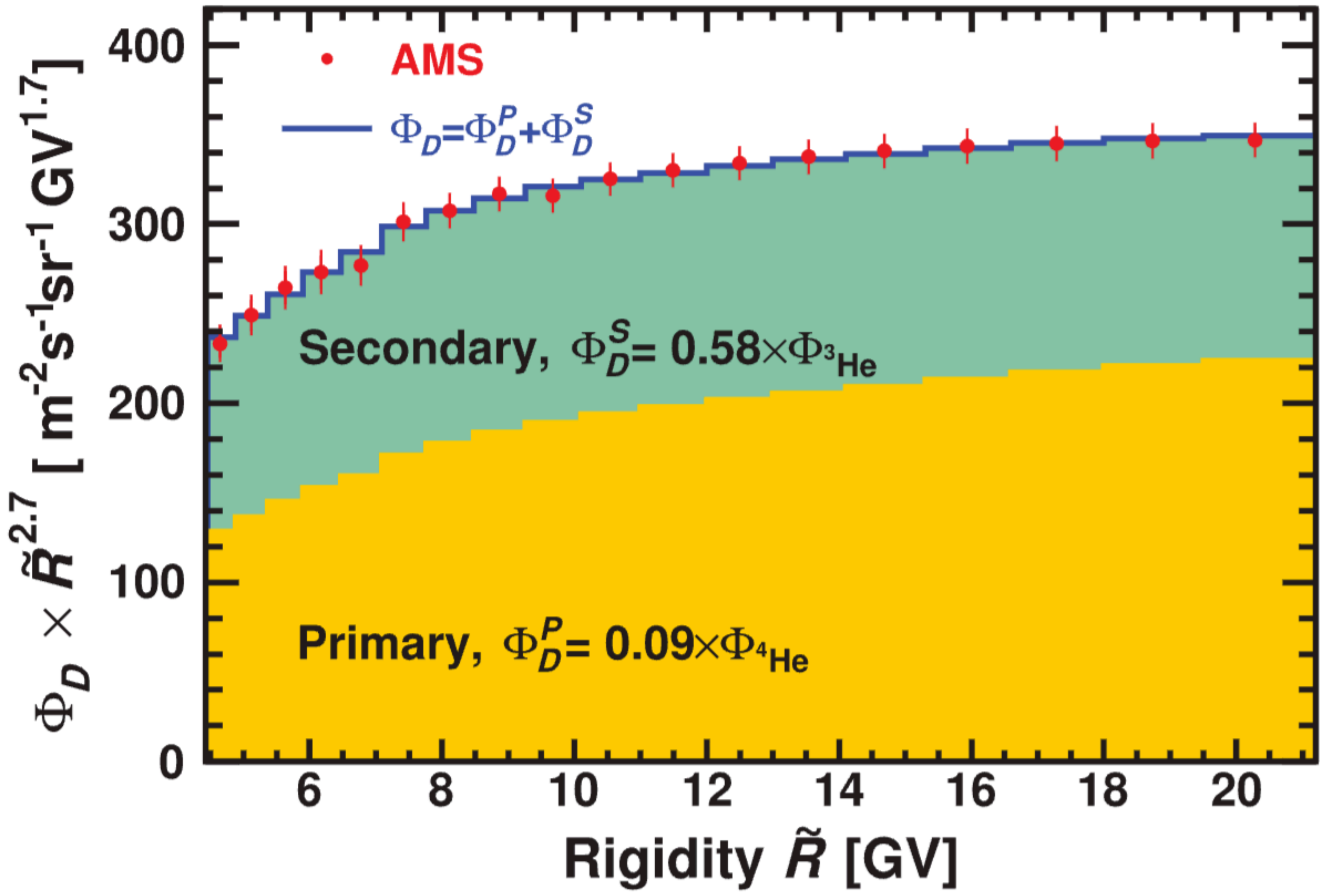
- Properties of Cosmic Lithium Isotopes Measured by the Alpha Magnetic Spectrometer (Phys. Rev. Lett. 134, 201001 (2025))
- Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer (Phys. Rev. Lett. 132, 261001 (2024))
- Properties of Cosmic Helium Isotopes Measured by the Alpha Magnetic Spectrometer (Phys. Rev. Lett. 123, 181102 (2019))

Properties of Cosmic Deuteron

- Deuterons, like ^{3}He, are generally thought to be secondary particles, mainly produced by spallation of 4He in the interstellar medium.
- The unexpected rigidity dependence of D/^{4}He flux ratio indicate that cosmic deuterons have a significant primary-like component.
- Above 4.5 GV, the rigidity dependence of deuteron flux can be well described by a combination of ^{4}He (primary) and ^{3}He (secondary) fluxes;



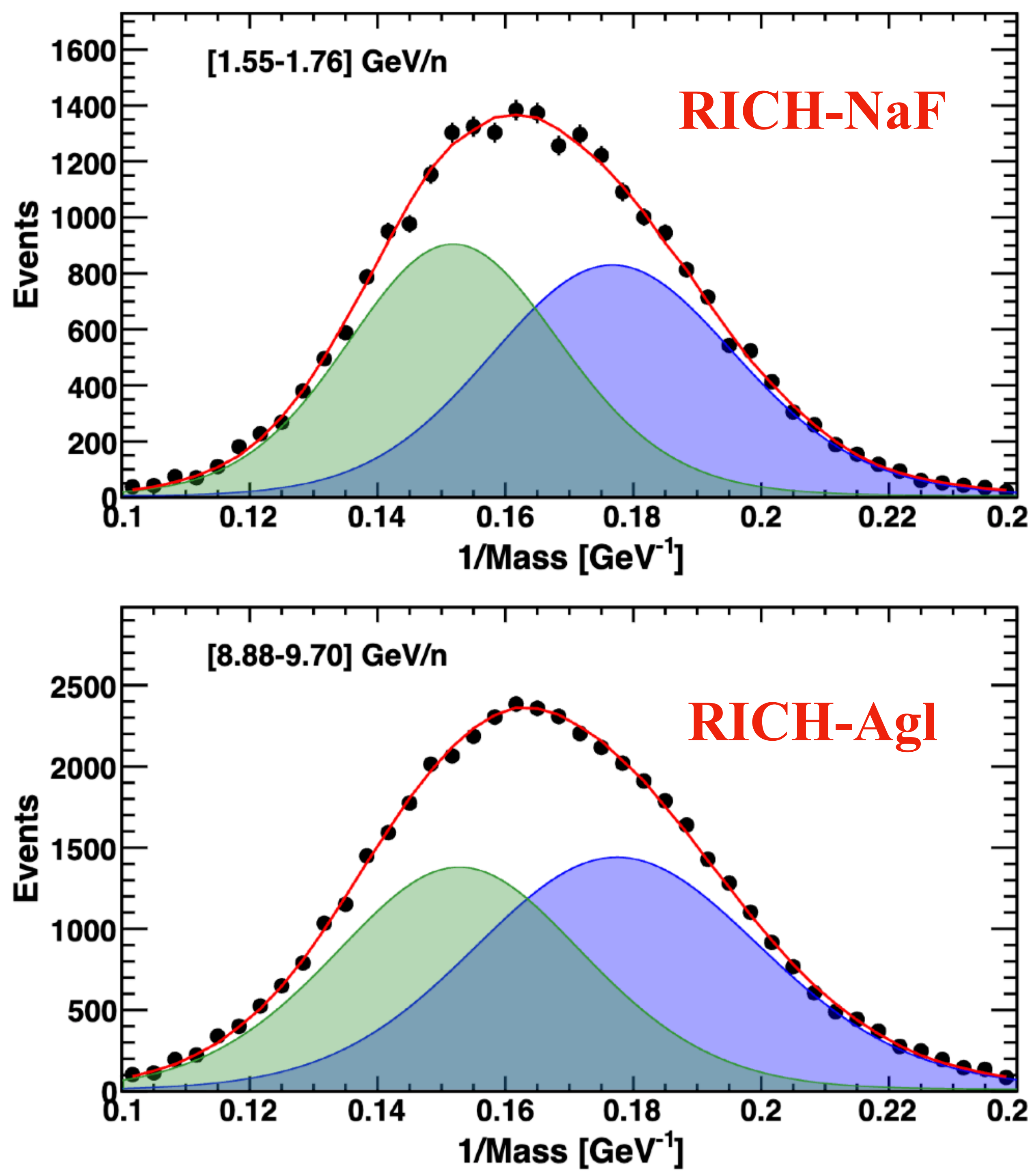




PhysRevLett.132.261001 (2024)
Featured in Physics; Editors' Suggestion

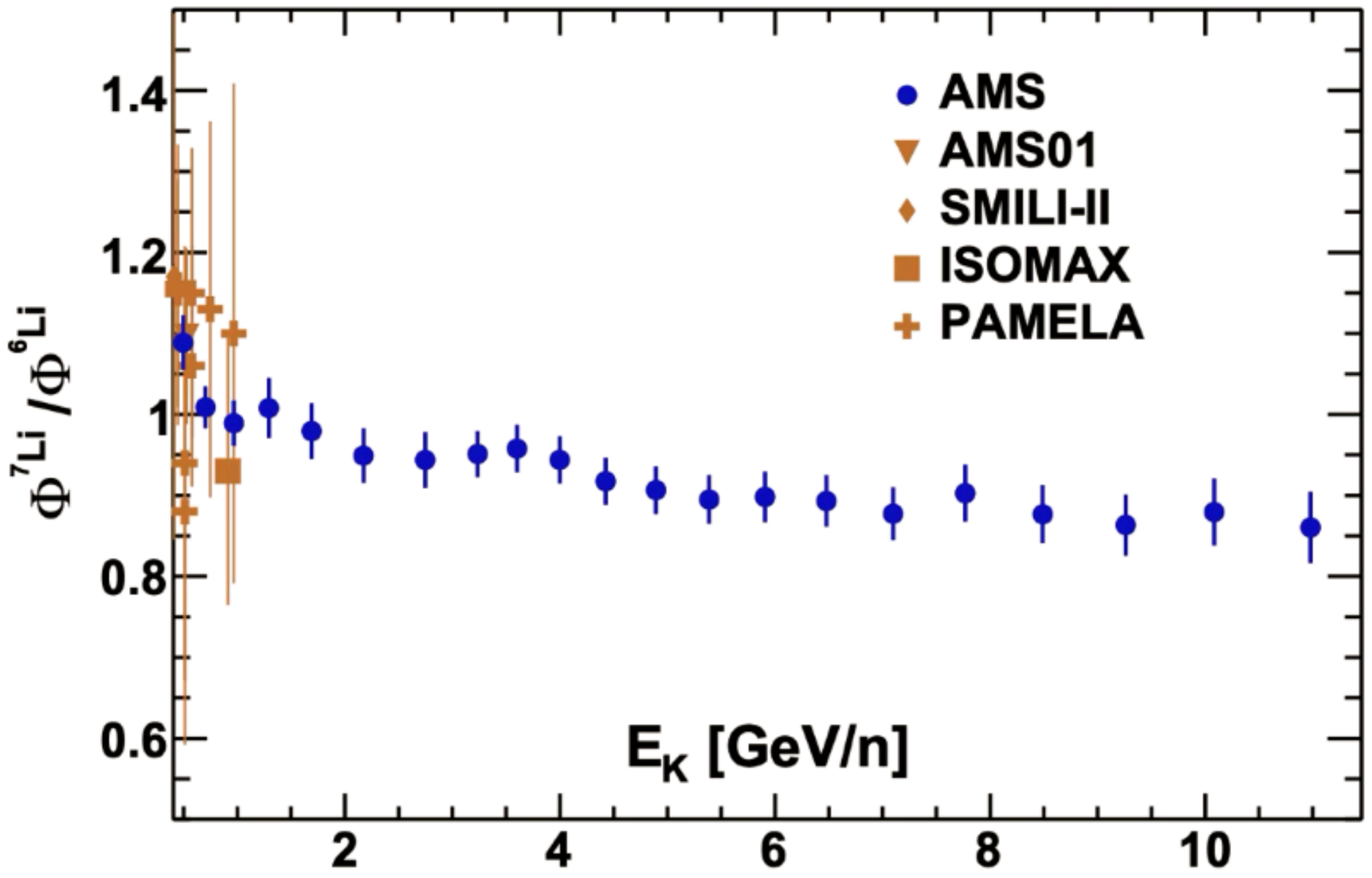
Properties of Cosmic Lithium

- ^{6}Li and ^{7}Li are assumed to be secondary species, mainly produced by the spallation of heavier primary nuclei with the interstellar medium.
- The origin of ^{7}Li is not well understood, which may include primary sources in Big Bang Nucleosynthesis or astrophysical sources.

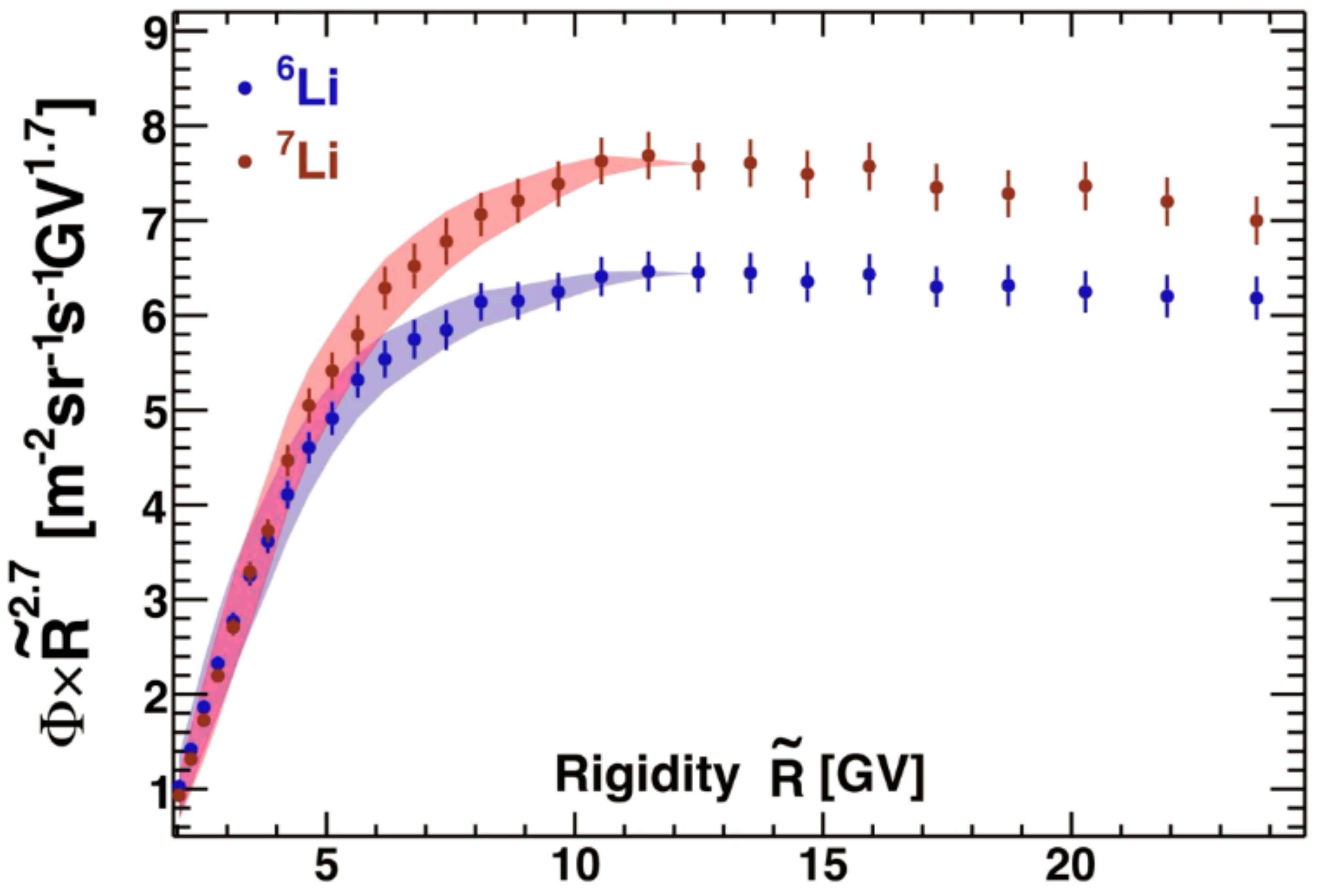


PhysRevLett.134.201001 (2025)
Featured in Physics; Editors' Suggestion

AMS presents the first measurement of ^{7}Li/^{6}Li flux ratio above 1.0 GeV/n, which contradict current propagation models.



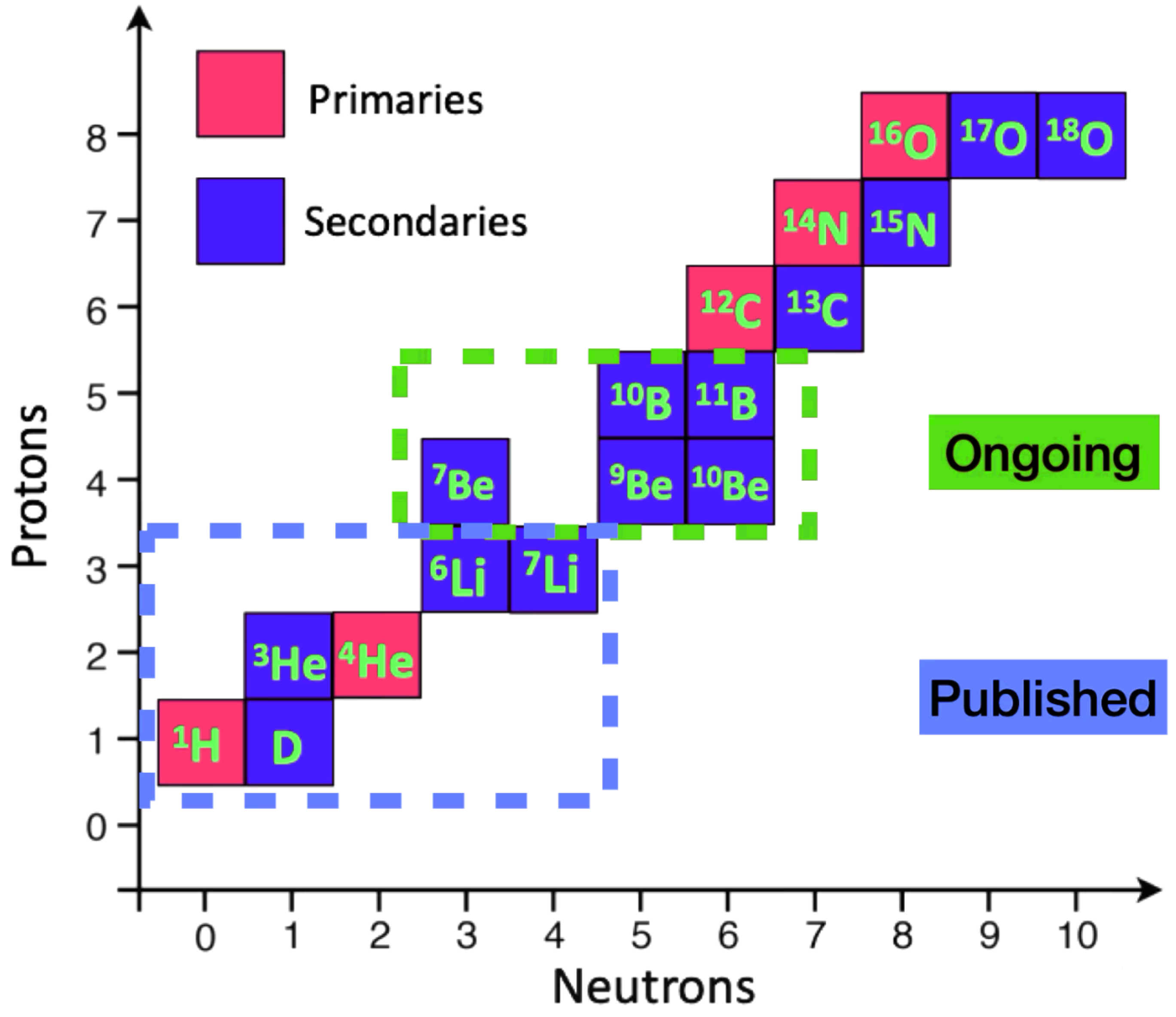
Above ~7 GV, ^{6}Li and ^{7}Li have identical rigidity dependence, which excludes sizable primary ^{7}Li contribution (< 3% at 90% C.L.)

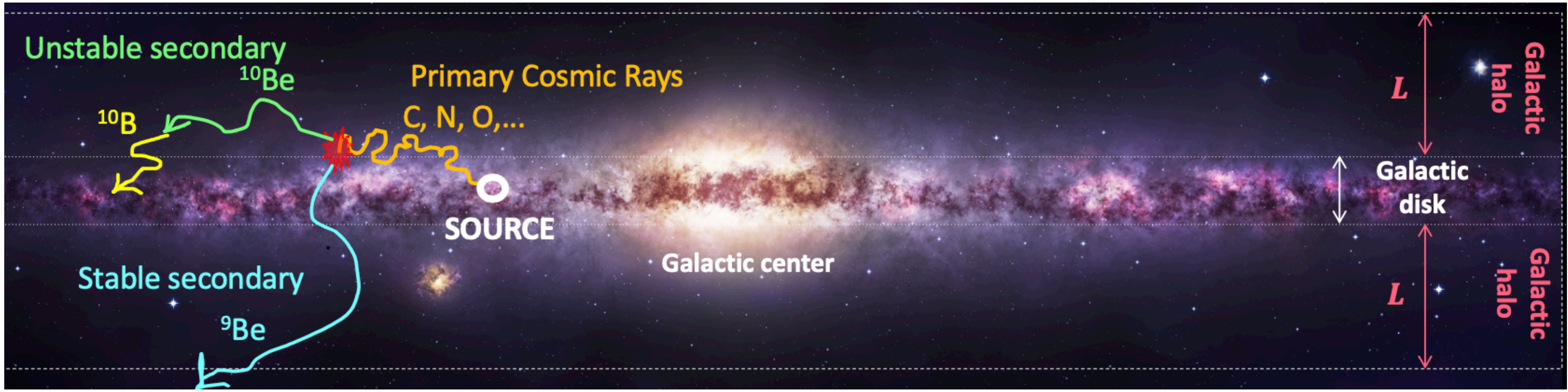


Properties of Cosmic Beryllium

Beryllium nuclei are also secondary cosmic rays, which include three isotopes: stable ^{7}Be and ^{9}Be, and unstable ^{10}Be.

Stable secondaries as ^{9}Be propagate in the entire galactic halo, while ^{10}Be decay to ^{10}B before reaching the boundary of the Galaxy (half-life $T_{1/2} \approx 1.38$ Myr).





The ratio of unstable-to-stable secondary cosmic rays ^{10}Be/^{9}Be measures the Galactic halo size L.

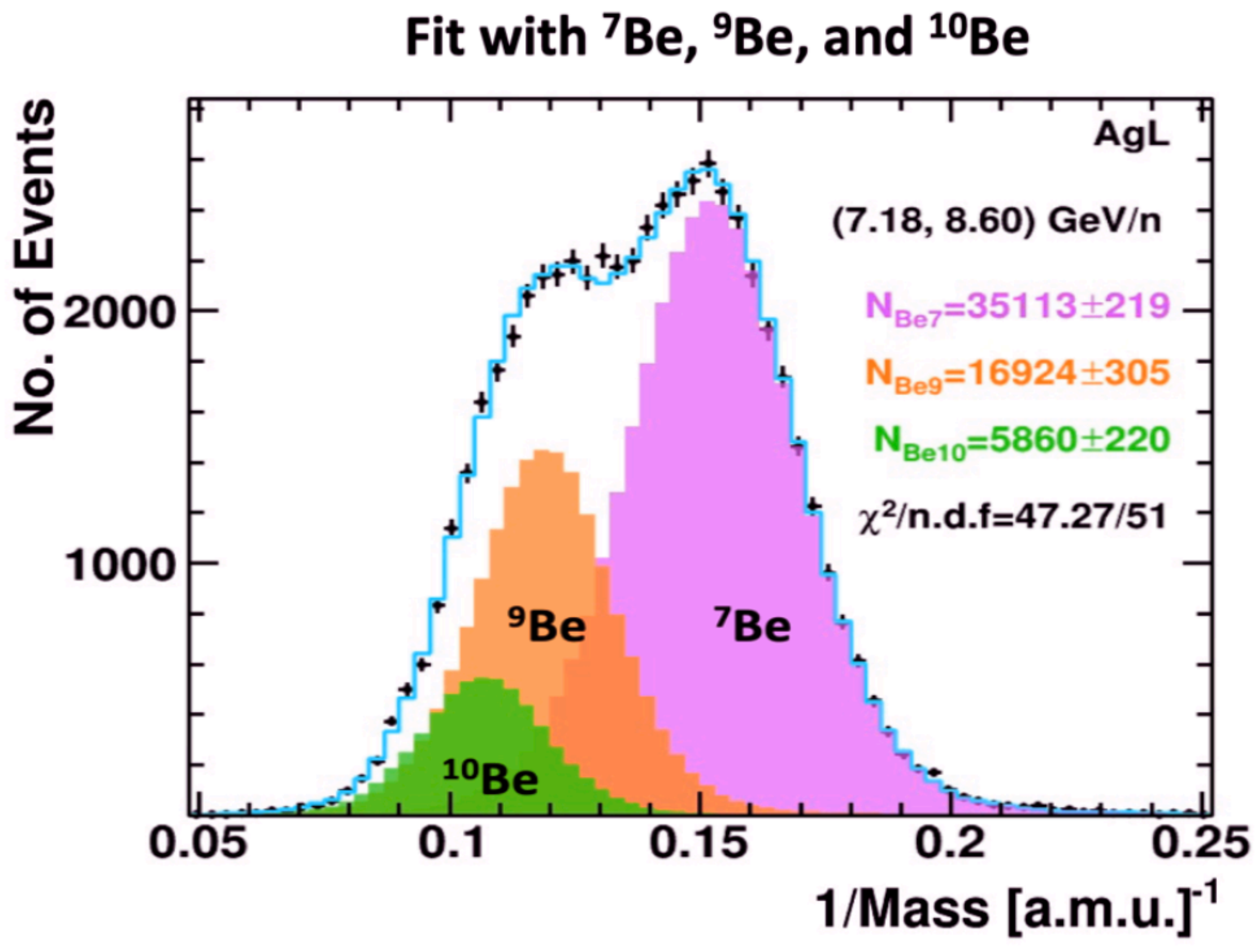
L determines the galactic cosmic ray propagation volume and constrains the cosmic rays' residence time in the galaxy.

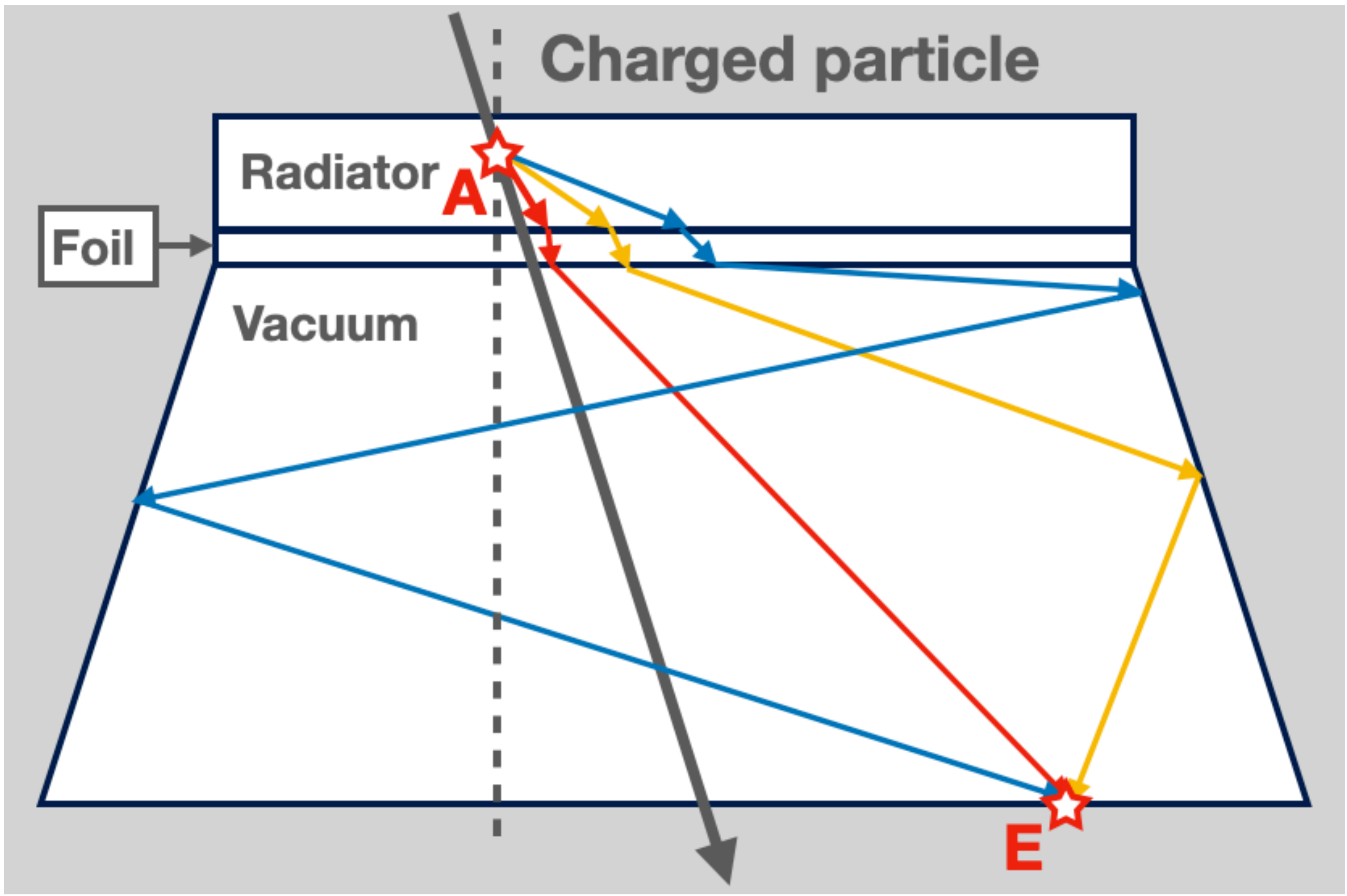
^{10}Be is often called as a cosmic ray radioactive clock.

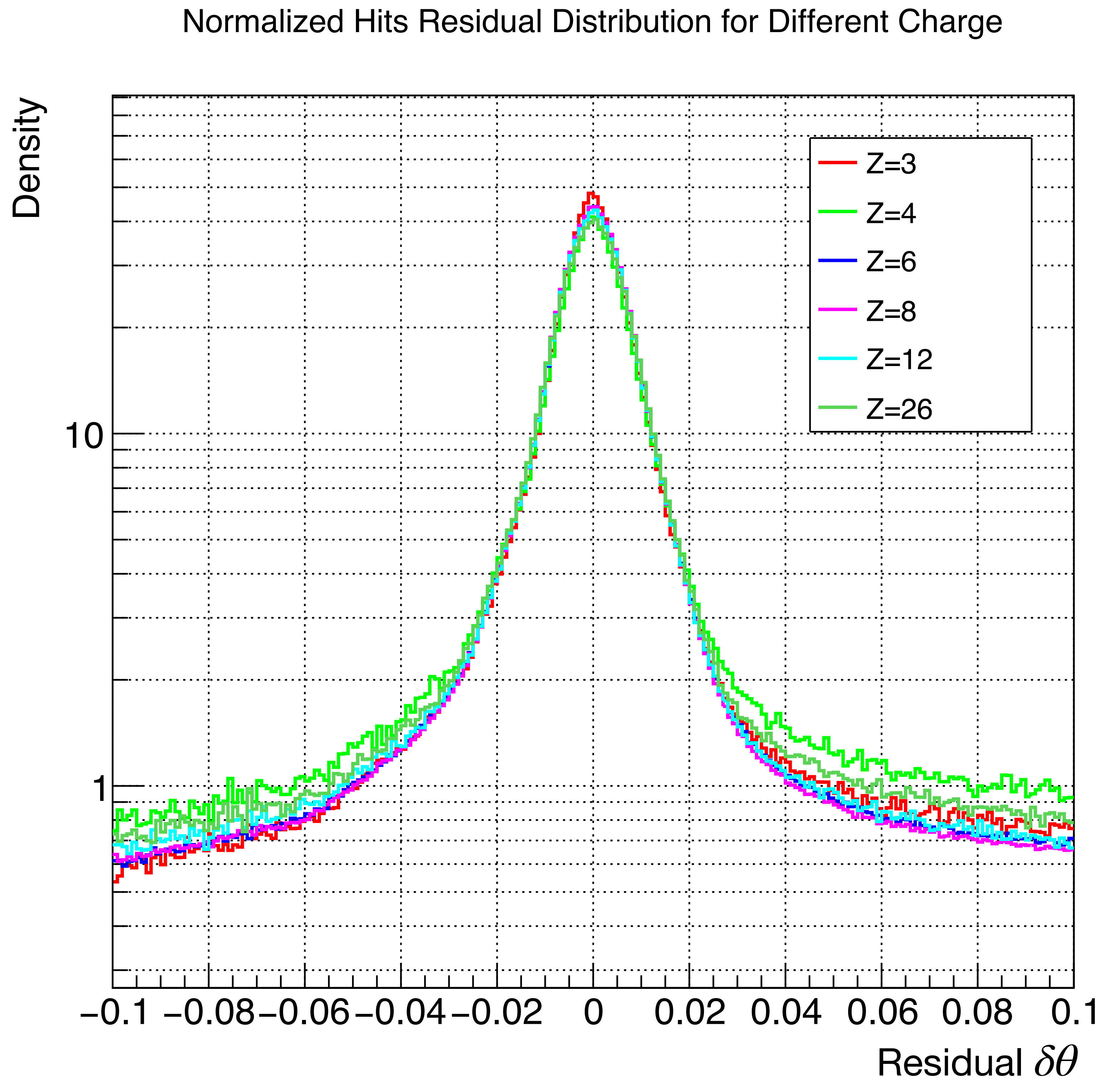
AMS-02 RICH: Performance on the ISS

- **With increasing charge Z, the demand for stronger mass separation power becomes critical.**
- **AMS Collaboration has developed independent reconstruction algorithms aiming to improve the mass separation with the RICH.**

- **A new independent reconstruction method introduces detailed ray tracing to model *refraction* and *reflection* effects in RICH, in order to match the detected photon accurately.**
- **A dedicated *probability density function* is also implemented to accurately capture the hit residuals in the *Maximum-Likelihood Estimation*.**

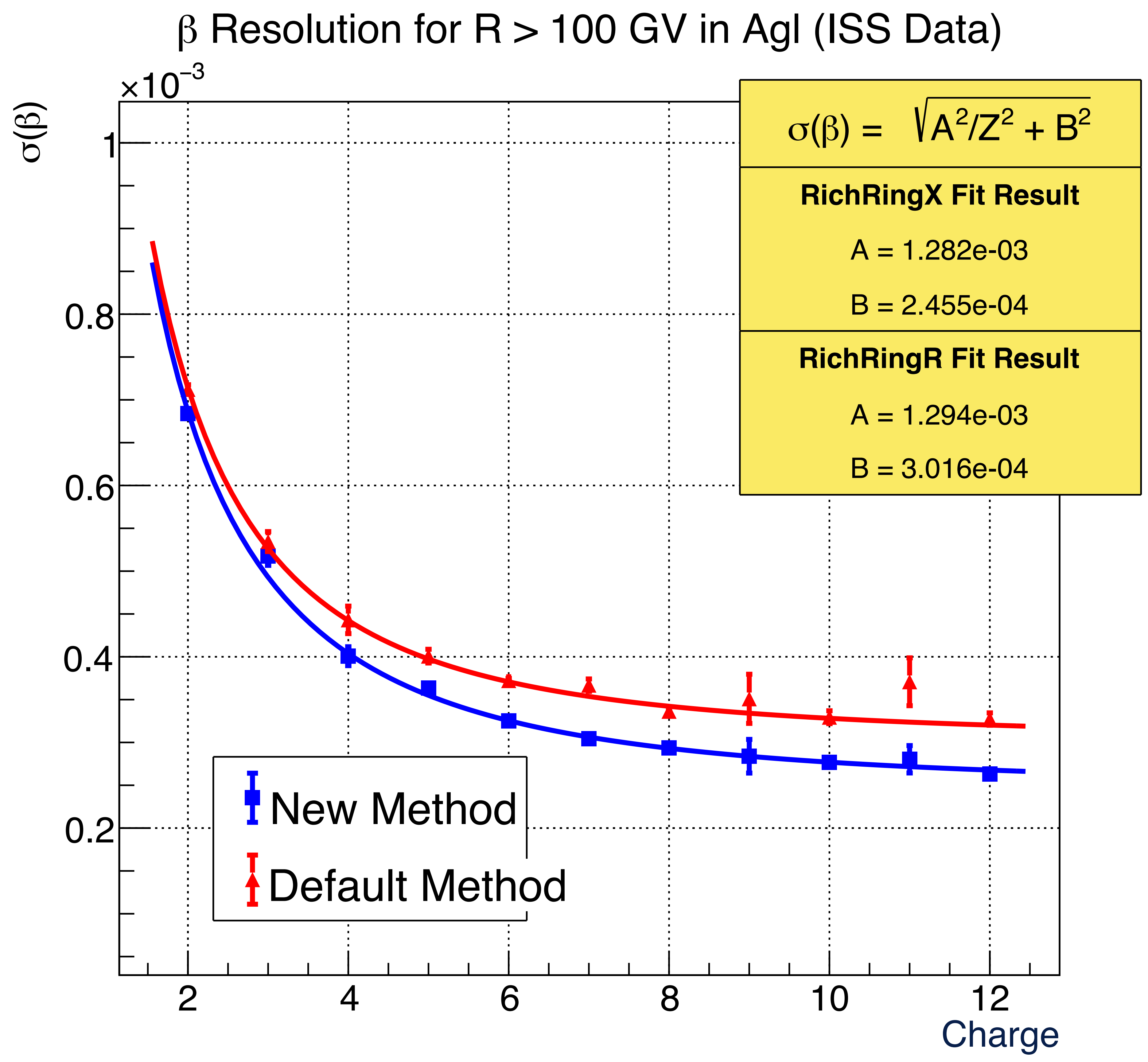






AMS-02 RICH: Performance on the ISS

- The new beta resolution in Agl is 0.4 per mil for Beryllium, and 0.35 per mil for Boron.
- The consistency among different reconstructed β could be used to reduce the β tails in the detector response and improve data to MC agreement.
- The ongoing development of new algorithms may further enhance mass separation power of Be and B isotopes.

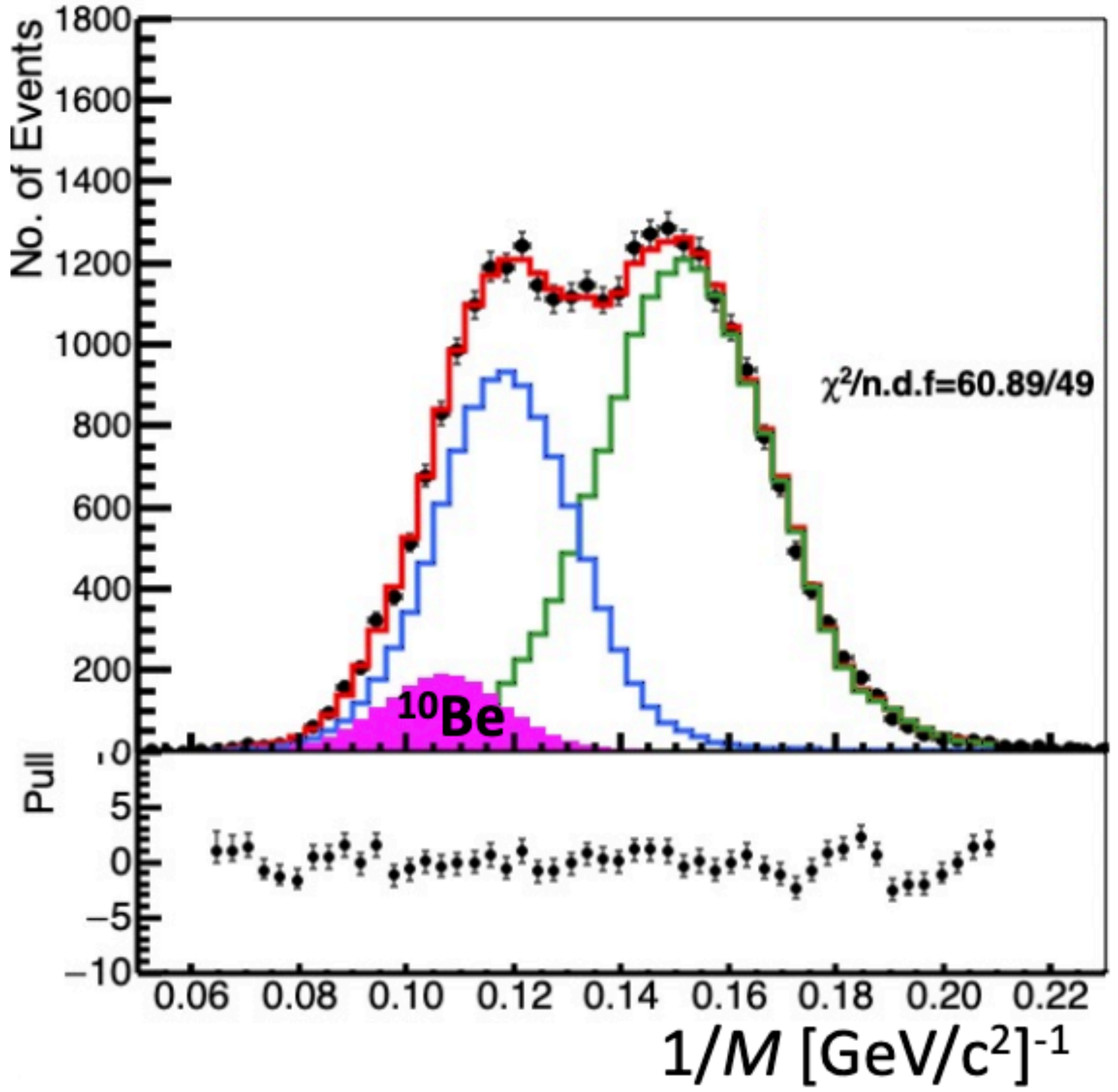


Properties of Cosmic Beryllium

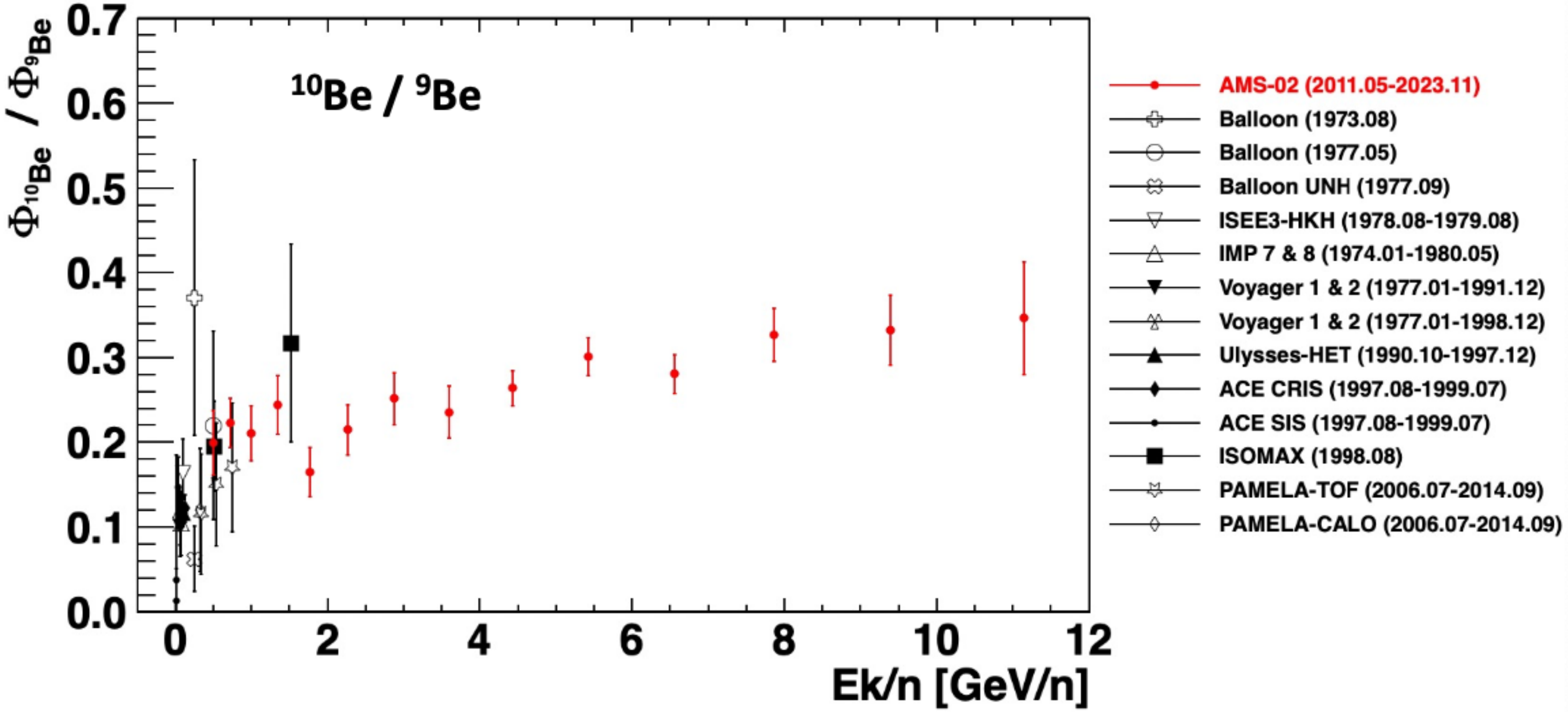
By fitting the inverse mass templates of three Be isotopes, the individual number of events and fluxes can be obtained.

We have obtained preliminary result of the ratio, and the systematics are under careful study.

$\beta > 1.002 \times \beta_{\mathrm{cutoff}}^{^{10}\mathrm{Be}}$



$N_{^{10}\mathrm{Be}} = 1908 \pm 148$



Stay tuned for our forthcoming publication on Beryllium!

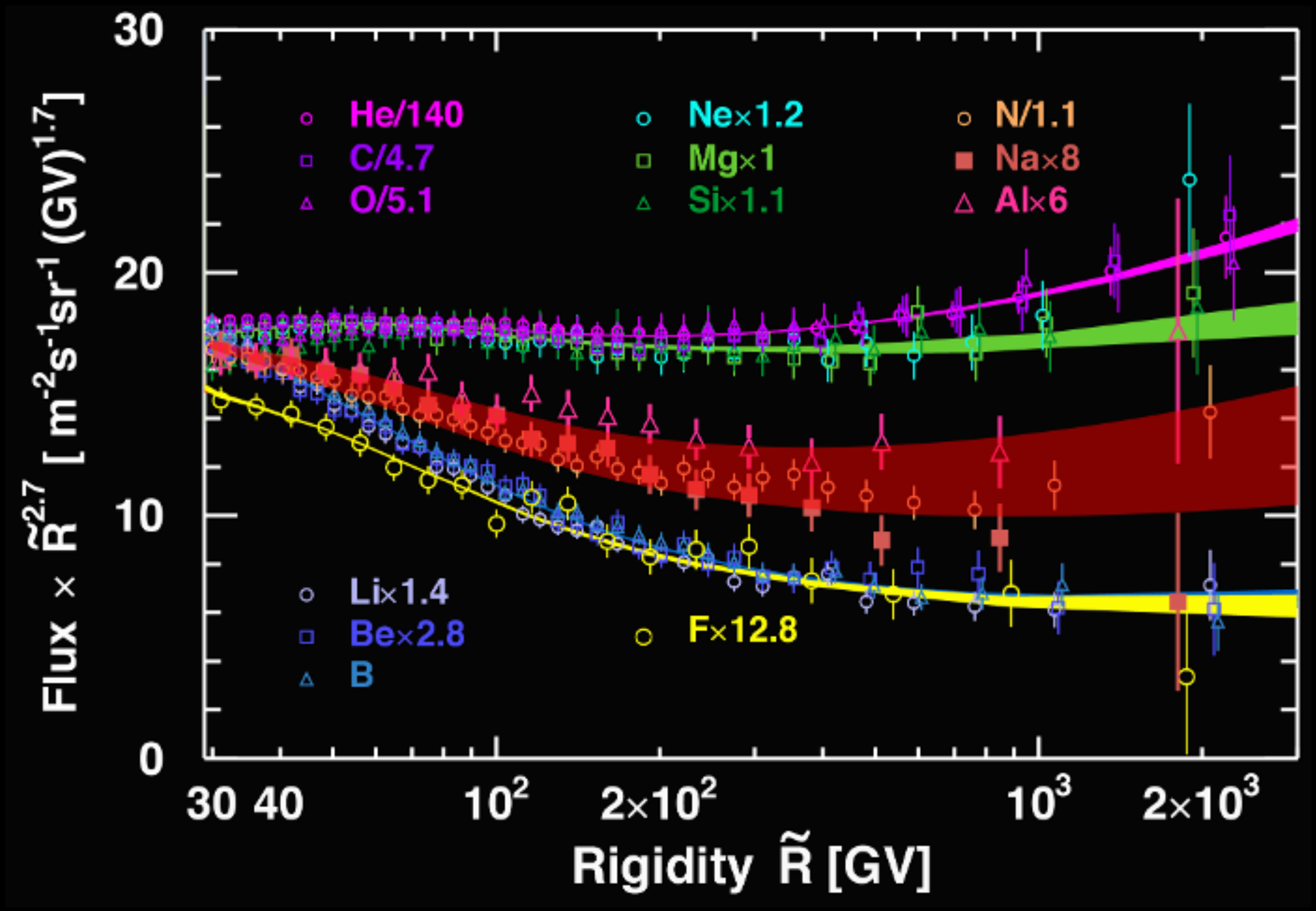
Conclusions

- **The AMS-02 RICH detector has been operating continuously on the ISS since 2011, proving great contribution to AMS physics.**
- **Continuous monitoring and calibration ensure its long-term stability and reliability, and superior β resolution and mass separation power is achieved.**
- **Latest isotope results (D, He, Li) demonstrate the unique capability of AMS-02 to probe cosmic-ray origin, acceleration, and propagation.**
- **Based on ray-tracing and maximum-likelihood, a reconstruction algorithm is being developed aiming for better velocity resolution at higher charge.**
- **Ongoing Beryllium isotope analysis will provide the first high precision measurement of cosmic-ray residence time using $^{10}Be/^{9}Be$.**

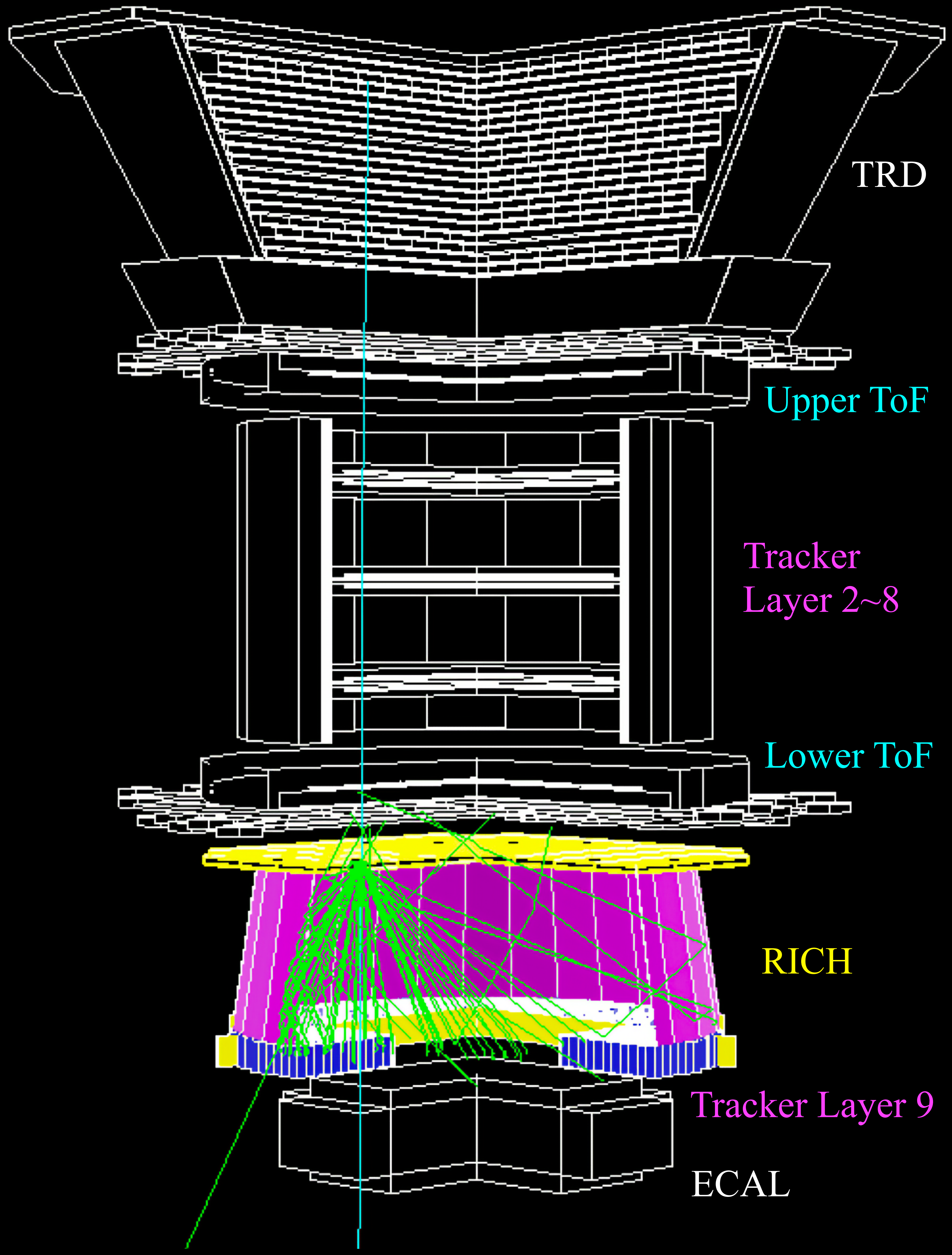
Thank you!

AMS: Physics Goals

- To search for possible signs of antimatter and dark matter, by identifying excesses in rare cosmic ray components beyond expected astrophysical backgrounds.
- To precisely measure the spectra of primary and secondary cosmic rays, which is essential for understanding their origin, acceleration, and propagation in our Galaxy.

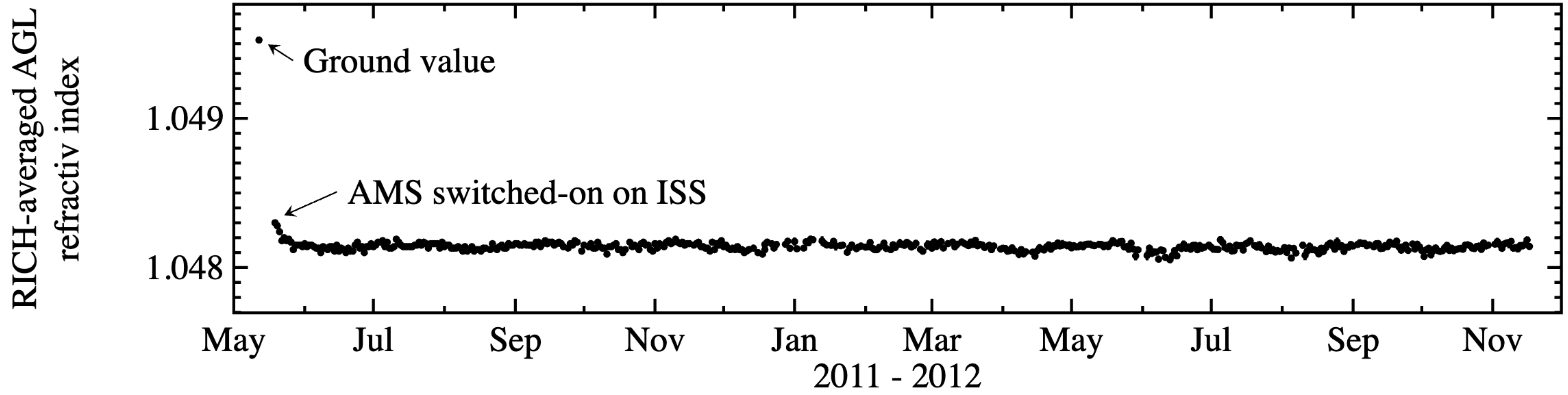


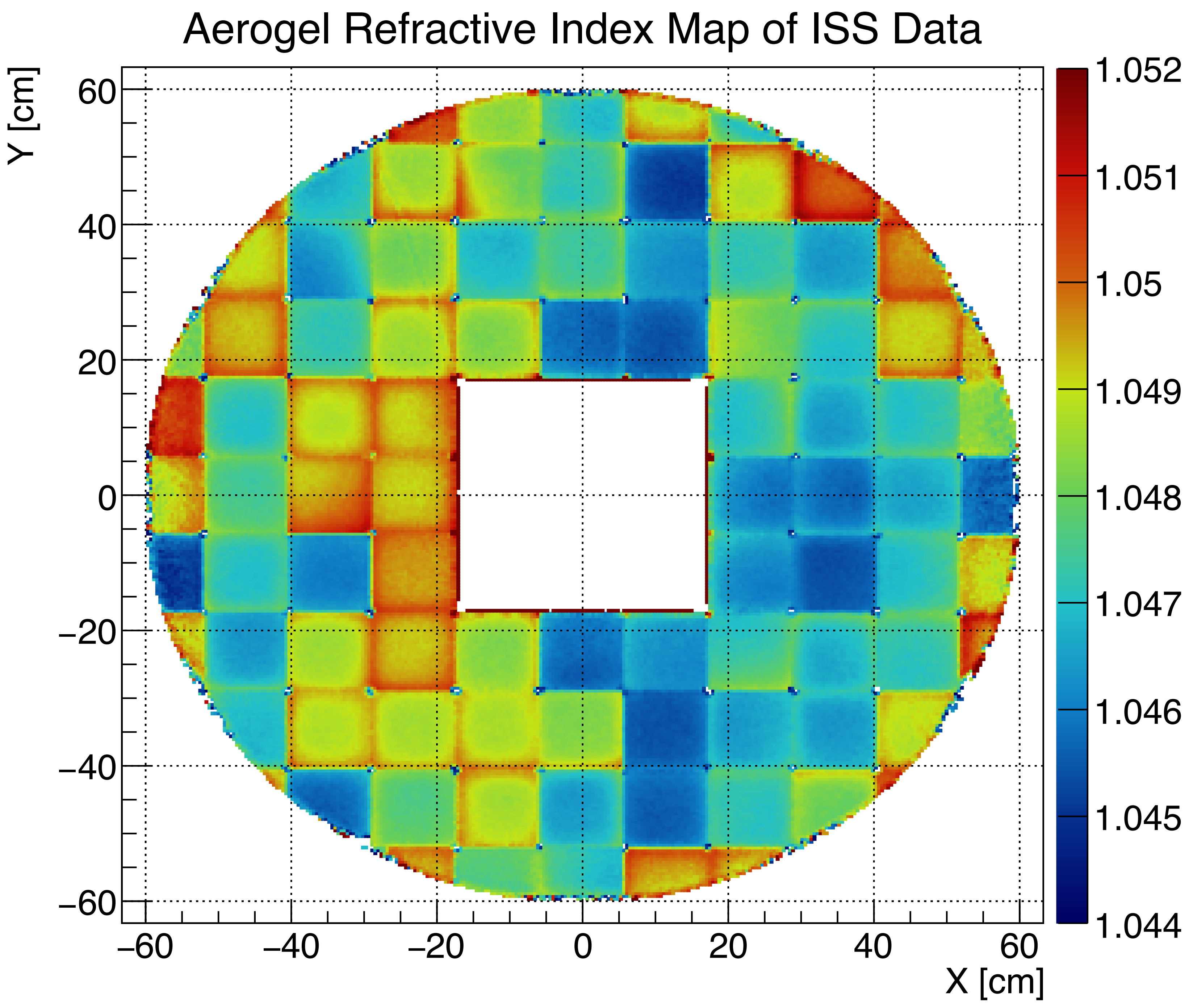
AMS-02 RICH: Detector Layout

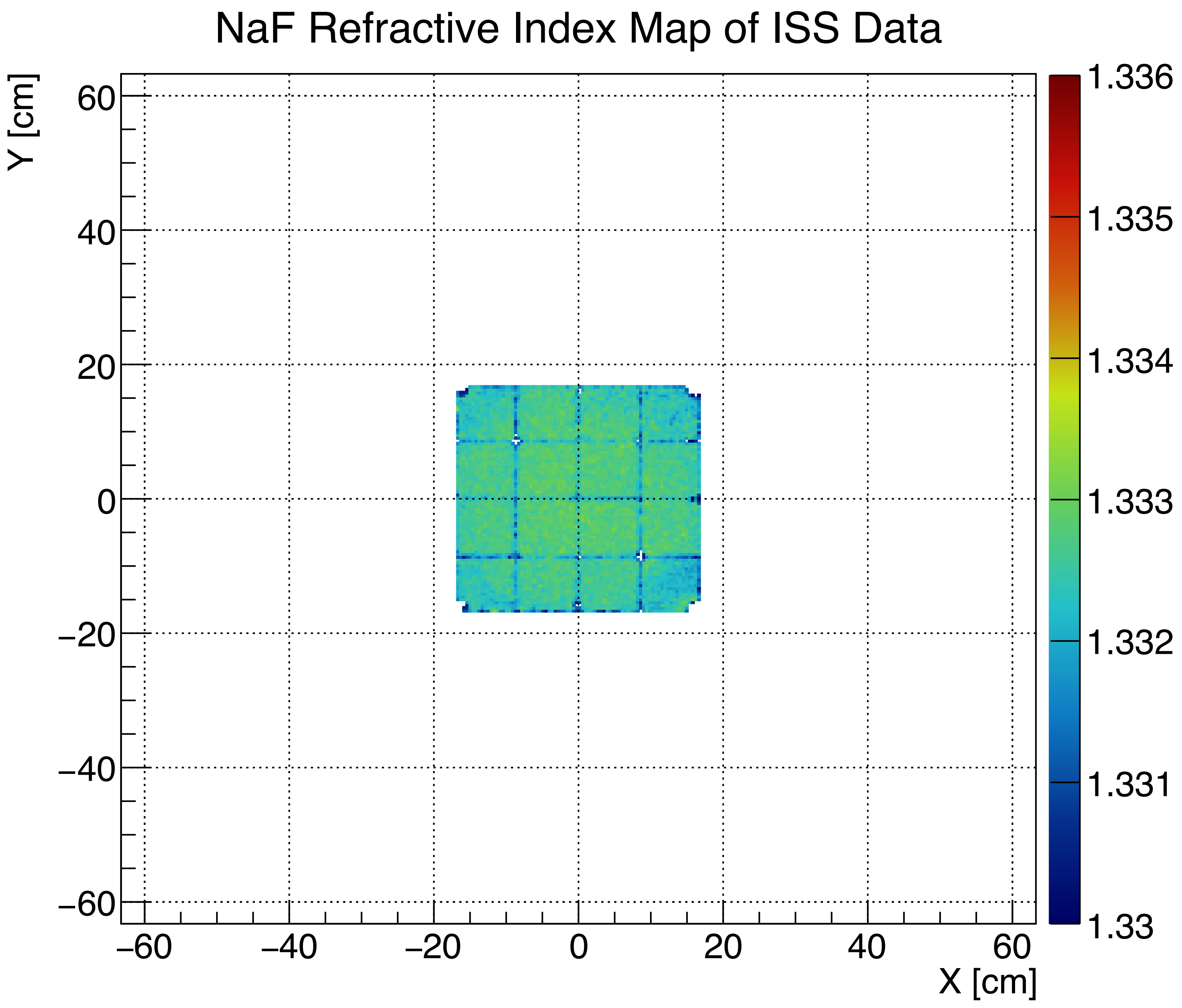


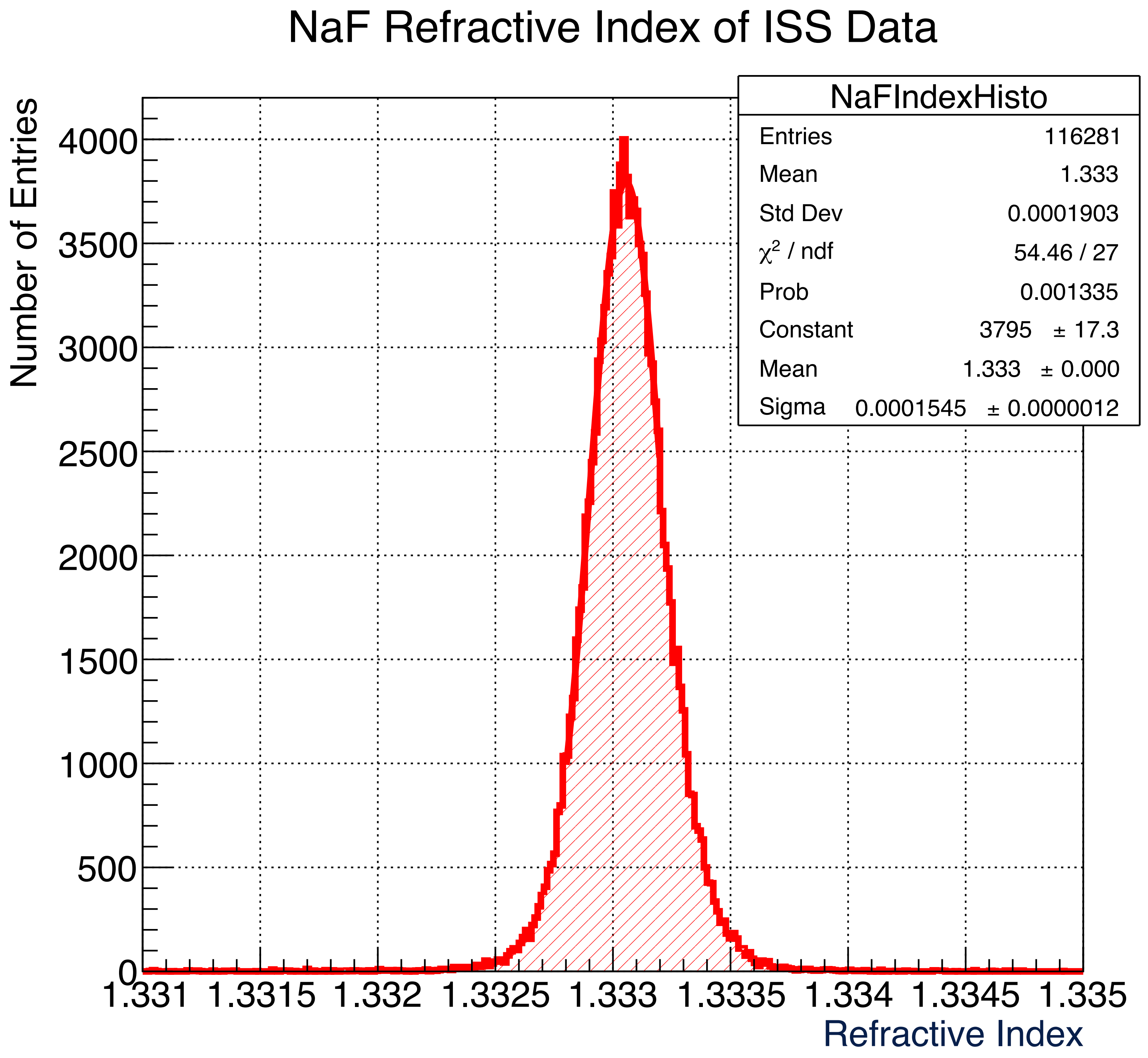
The RICH detector is installed in the lower part of the AMS detector stack. This design choice is made to minimize the energy loss of the particle as it passes through the detector.

AMS-02 RICH: Radiator Index Calibration



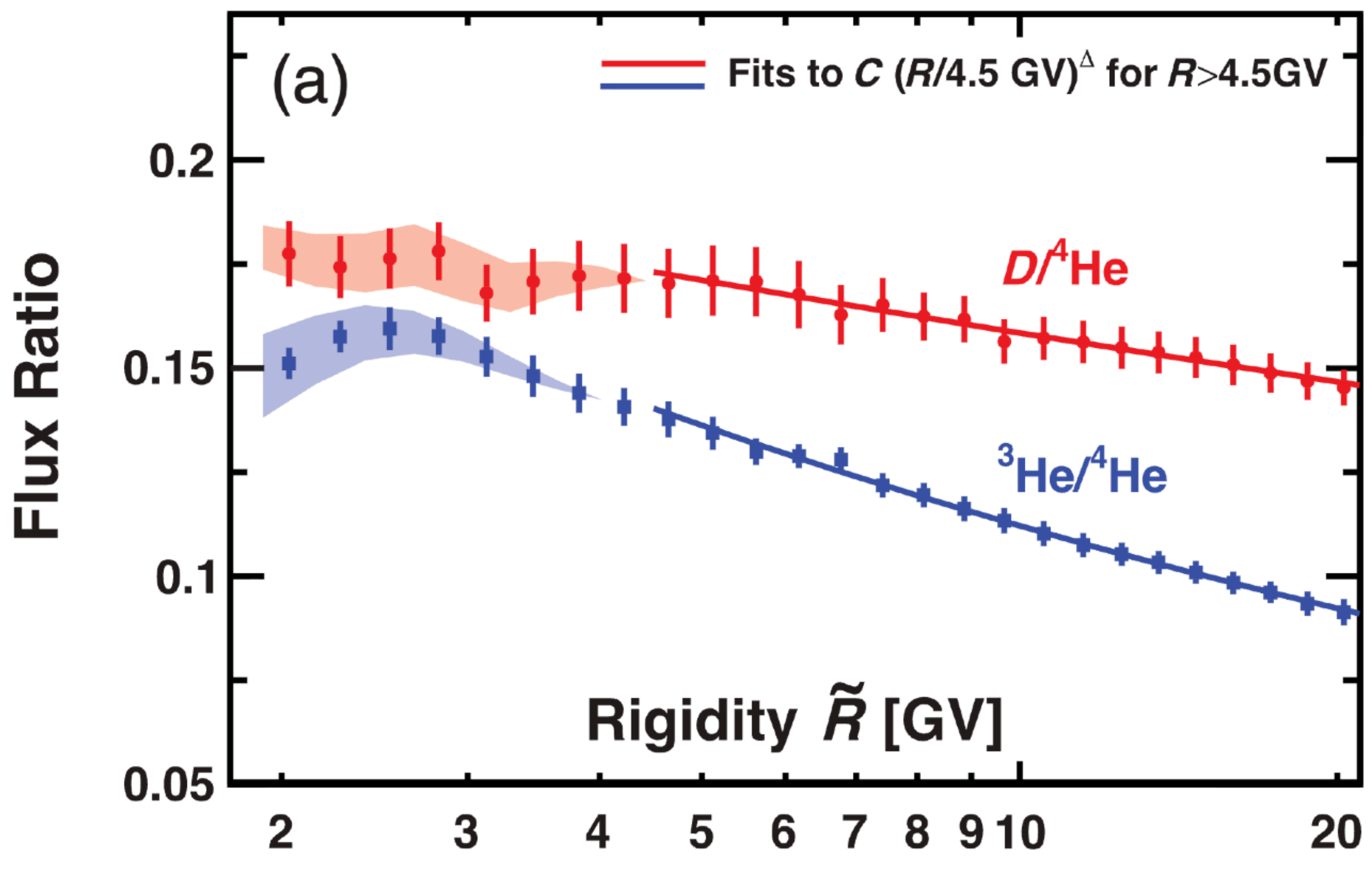


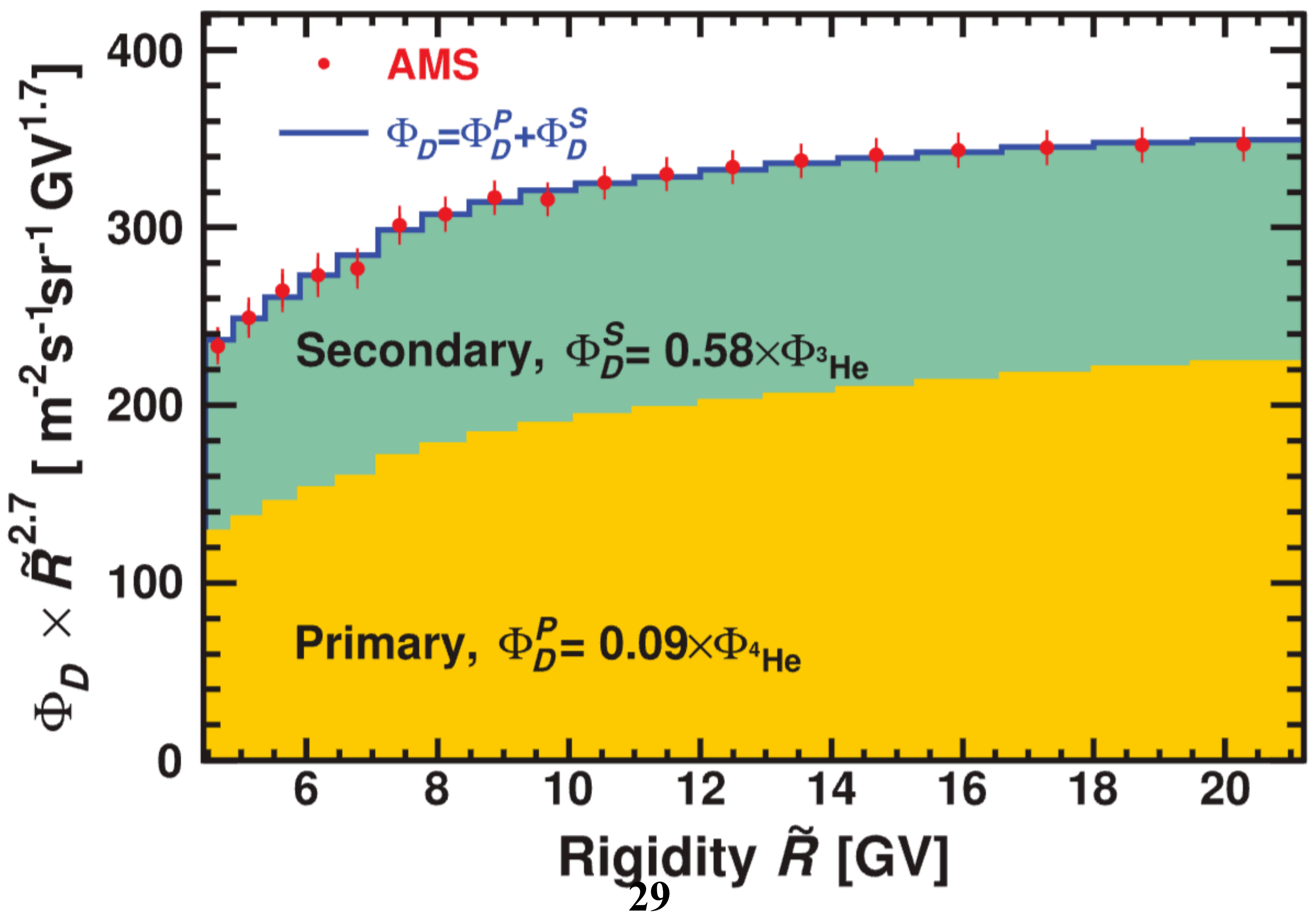


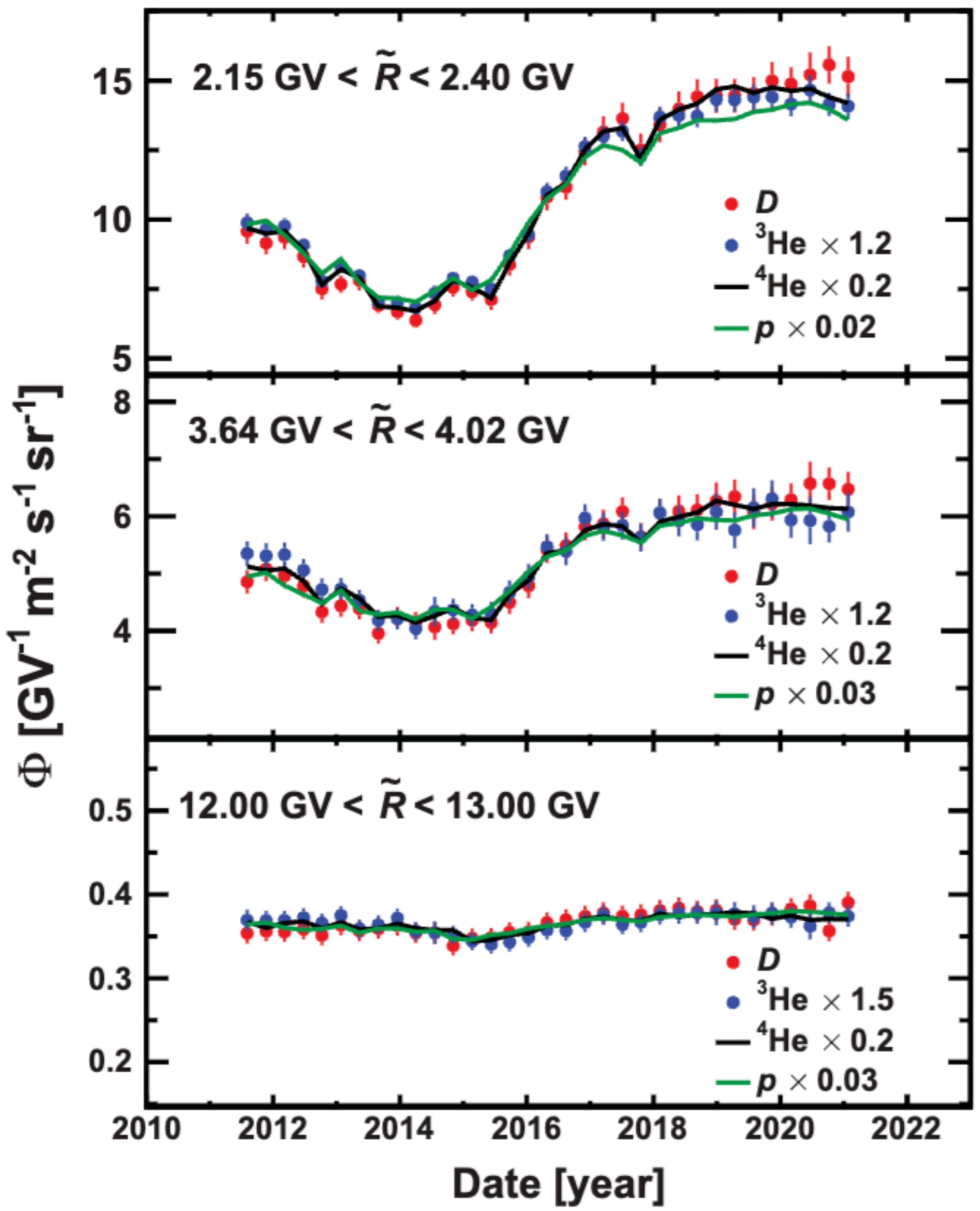


Properties of Cosmic Deuteron

- Deuterons are thought to overwhelmingly originate from interactions of He with the interstellar medium, though Big Bang nucleosynthesis also predicts a very small production of deuterons.
- We observed that over the entire rigidity range the deuteron flux exhibits nearly identical time variations with the p, ^{3}He, and ^{4}He fluxes.
- Above 4.5 GV, the rigidity dependence of deuteron flux can be well described by a combination of ^{4}He (primary) and ^{3}He (secondary) fluxes;
- **These unexpected observations indicate that cosmic deuterons have a sizable primary-like component.**



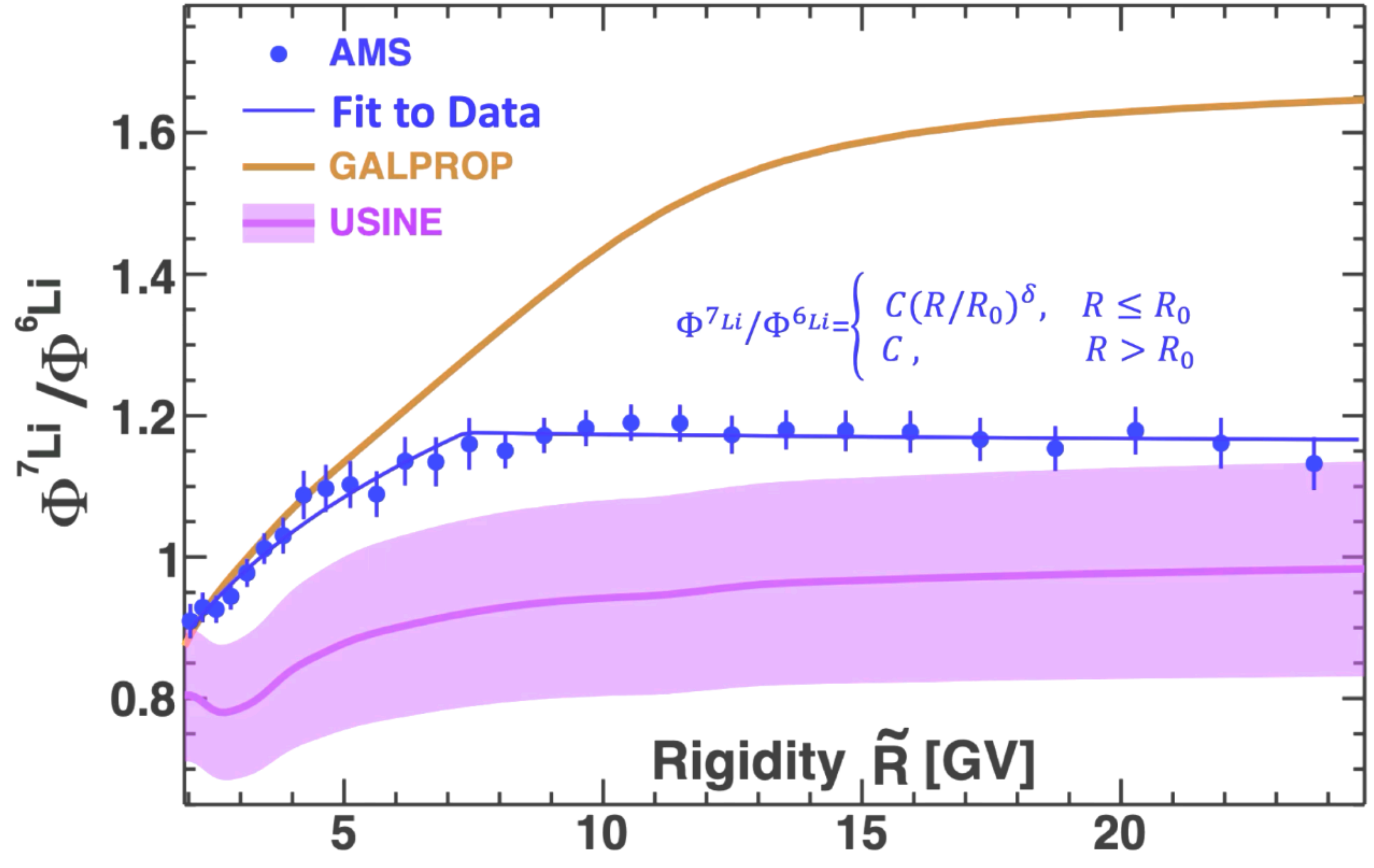




PhysRevLett.132.261001 (2024)
Featured in Physics; Editors' Suggestion

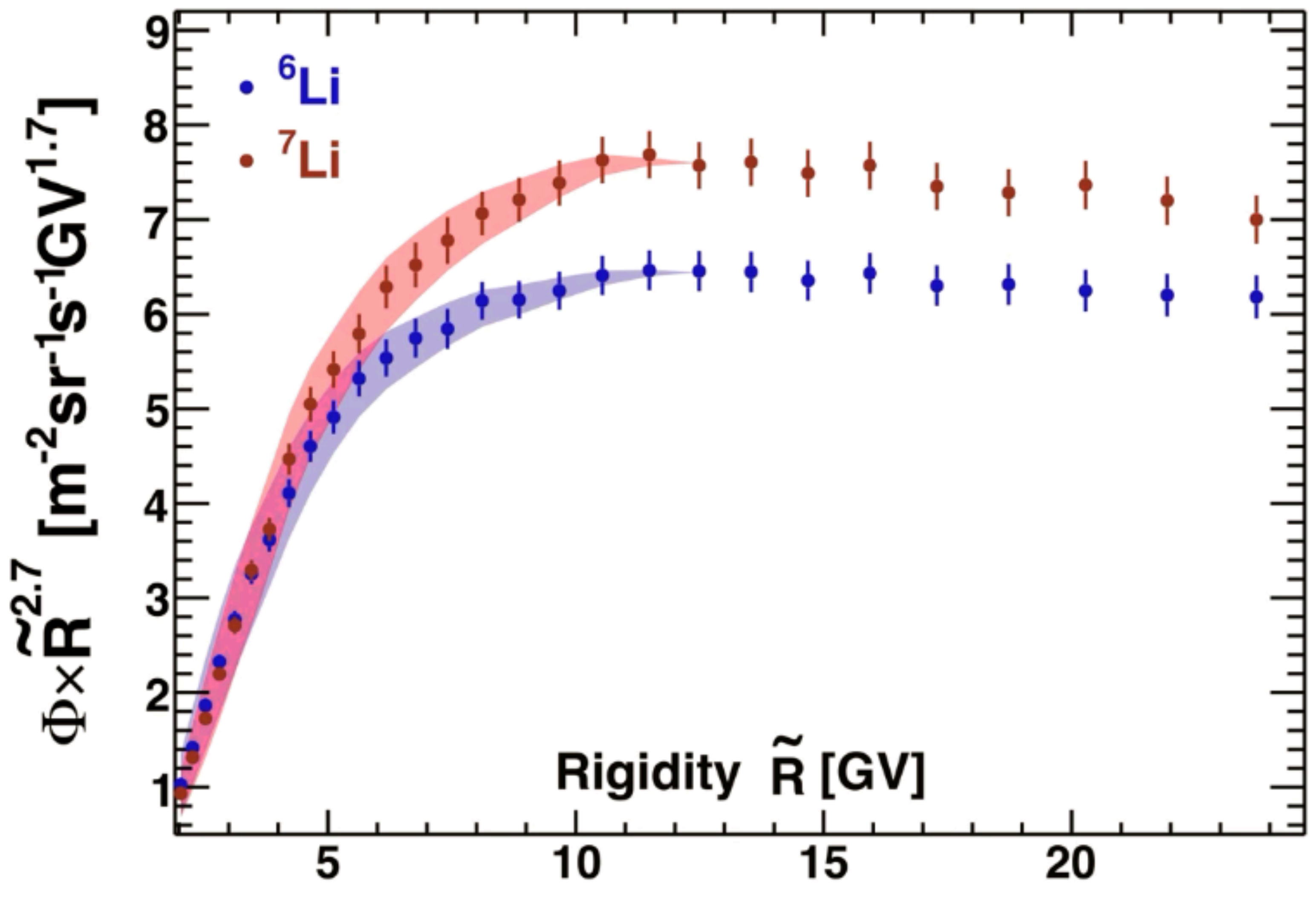
Properties of Cosmic Lithium

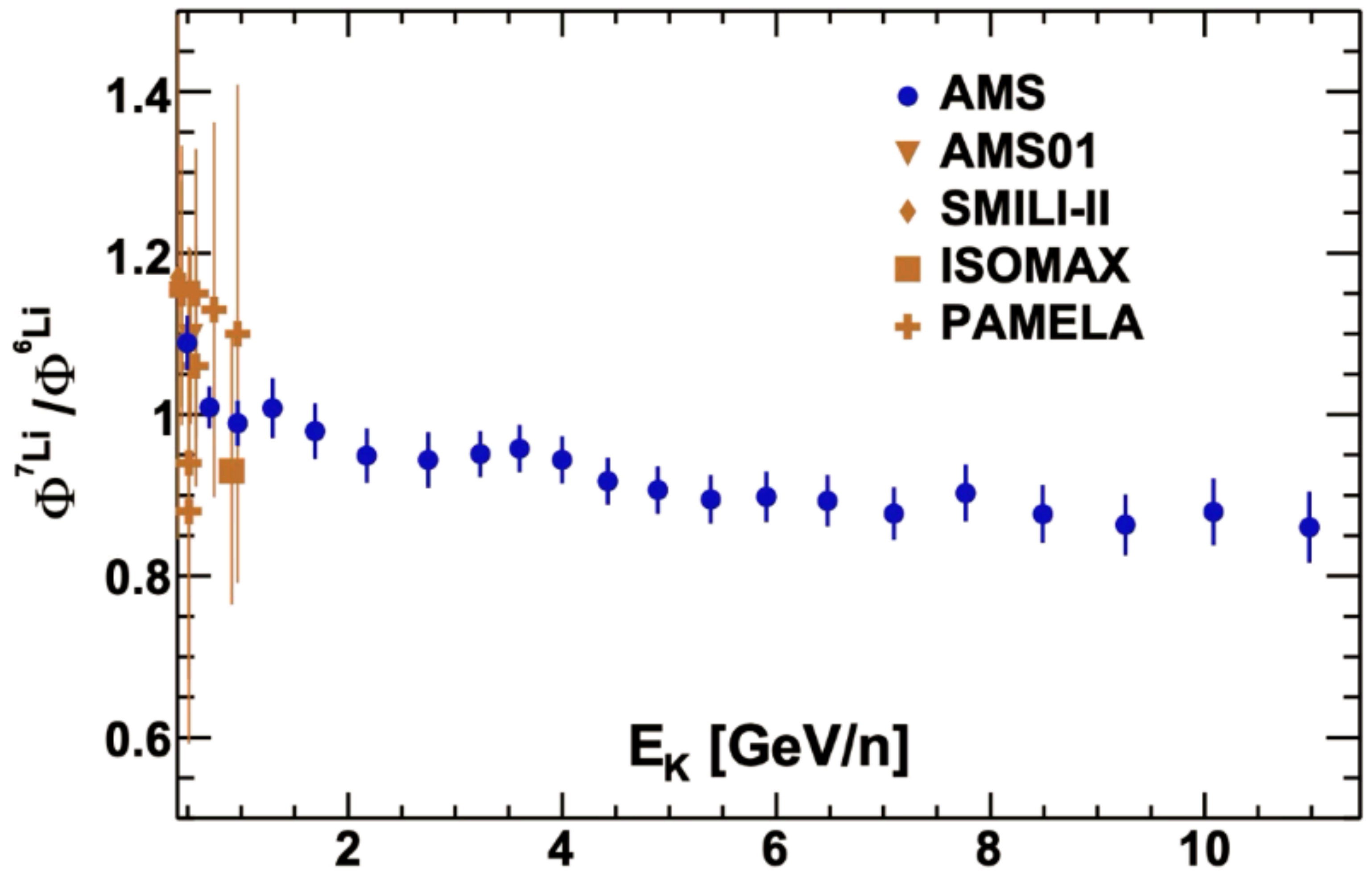
- The AMS measurement of the 7Li/6Li flux ratio lies between the predictions of GALPROP and USINE, highlighting two complementary sources of uncertainty.
- GALPROP tends to overestimate the ratio, due to assuming a primary component in the 7Li flux. On the other hand, USINE underestimates the ratio, due to assuming 6Li and 7Li being mostly secondary.



Model assuming a primary component in the ^{7}Li flux

Model assuming secondary origin of ^{6}Li and ^{7}Li

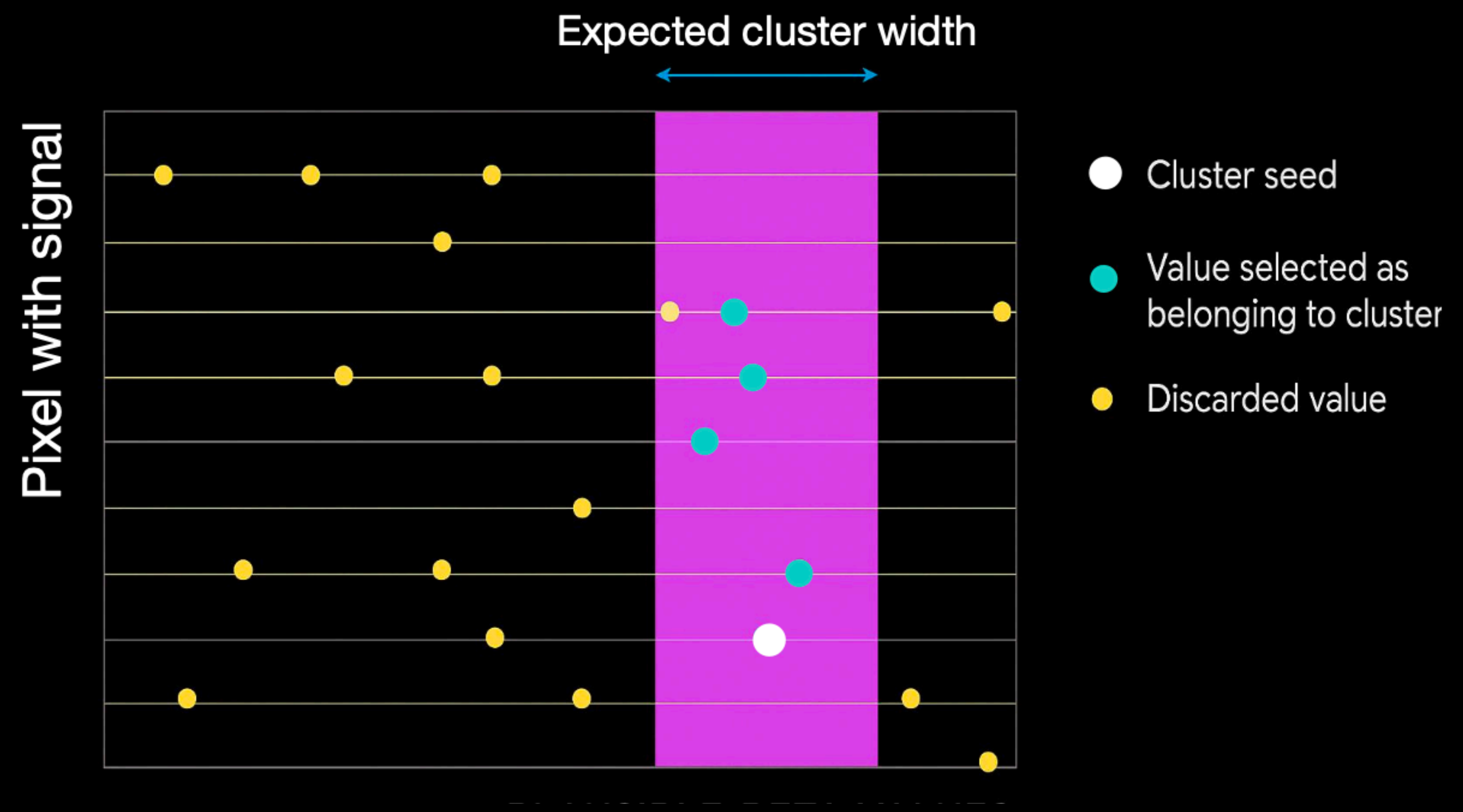




AMS-02 RICH: Clustering Algorithm

I. Compute all possible trajectories for detected photons semi-analytically

II. Use a Gaussian clusterization algorithm to reject background photons and select the right solution for each pixel with signal



III. Obtain the measured beta as the average of the ones in the cluster, weighted by the estimated photons detected on the corresponding pixels.

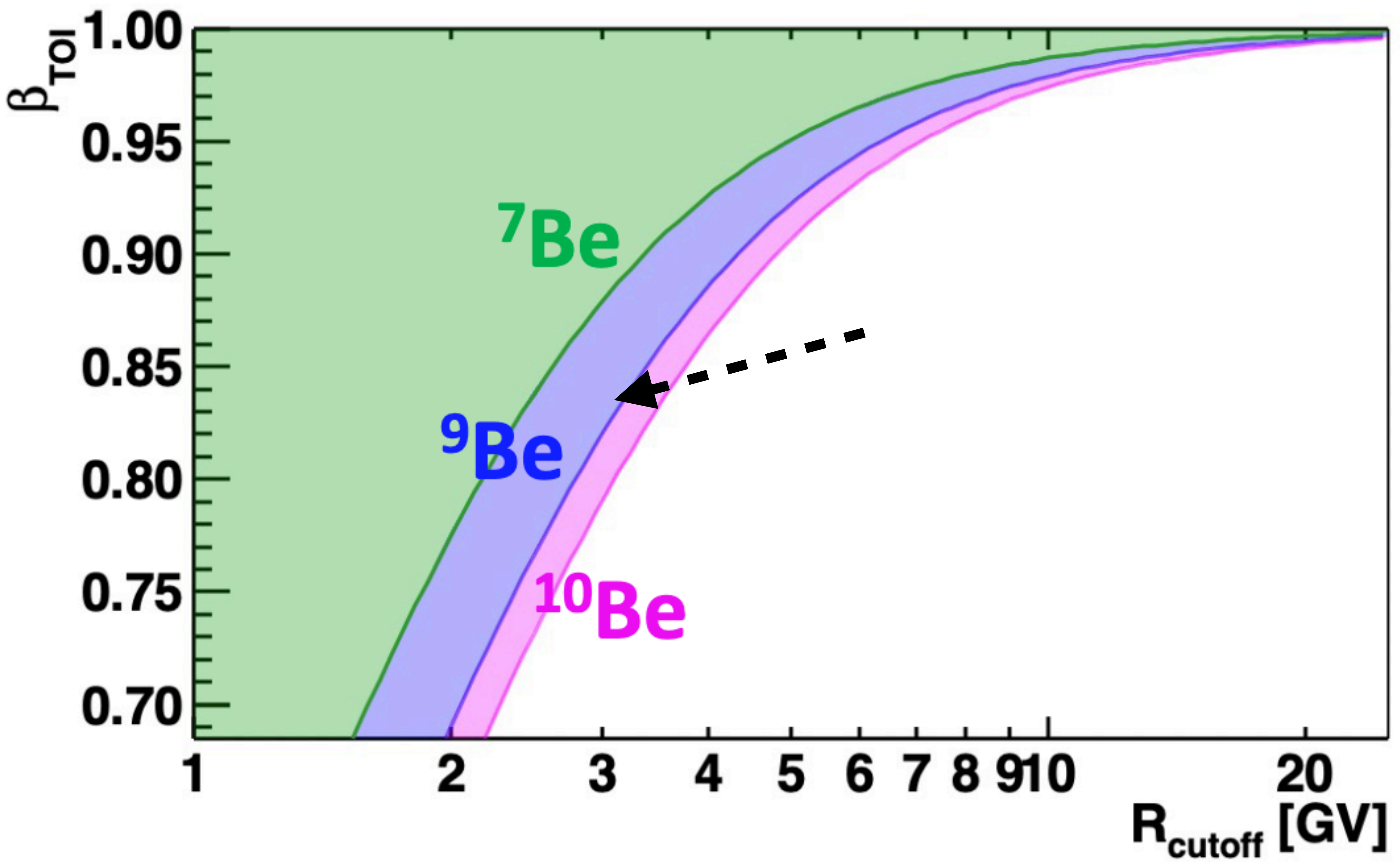
Properties of Cosmic Beryllium

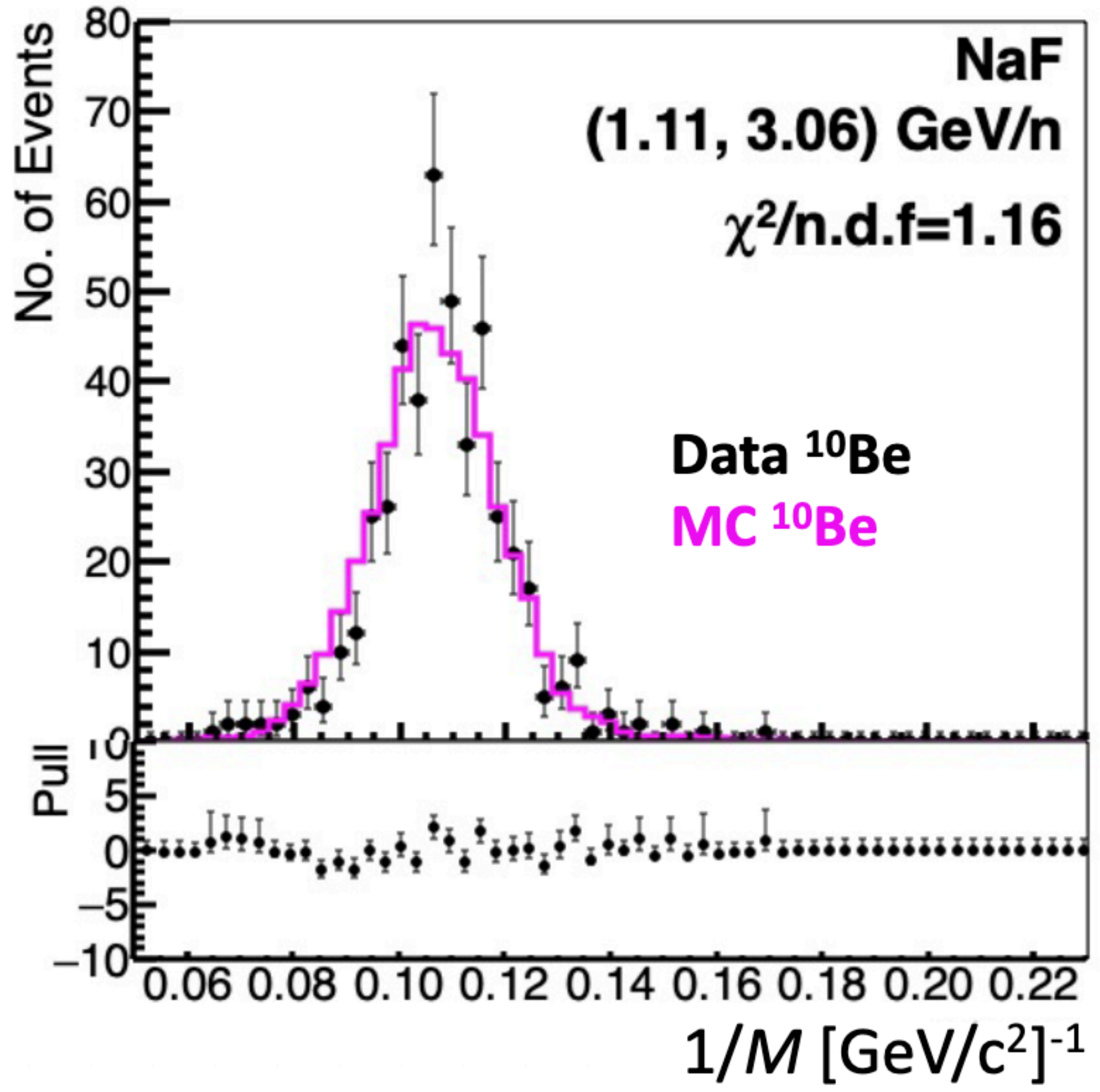
By utilizing the Geomagnetic cutoff, a pure sample of ^{10}Be can be selected in the ISS data by *rigidity to beta conversion*.

$$\beta_{cutoff}(A, Z, R_{cutoff}) = \sqrt{\frac{R_{cutoff}Z}{M^2 + (R_{cutoff}Z)^2}}$$

The inverse mass distribution of selected ^{10}Be sample are in good agreement with Monte Carlo simulation.

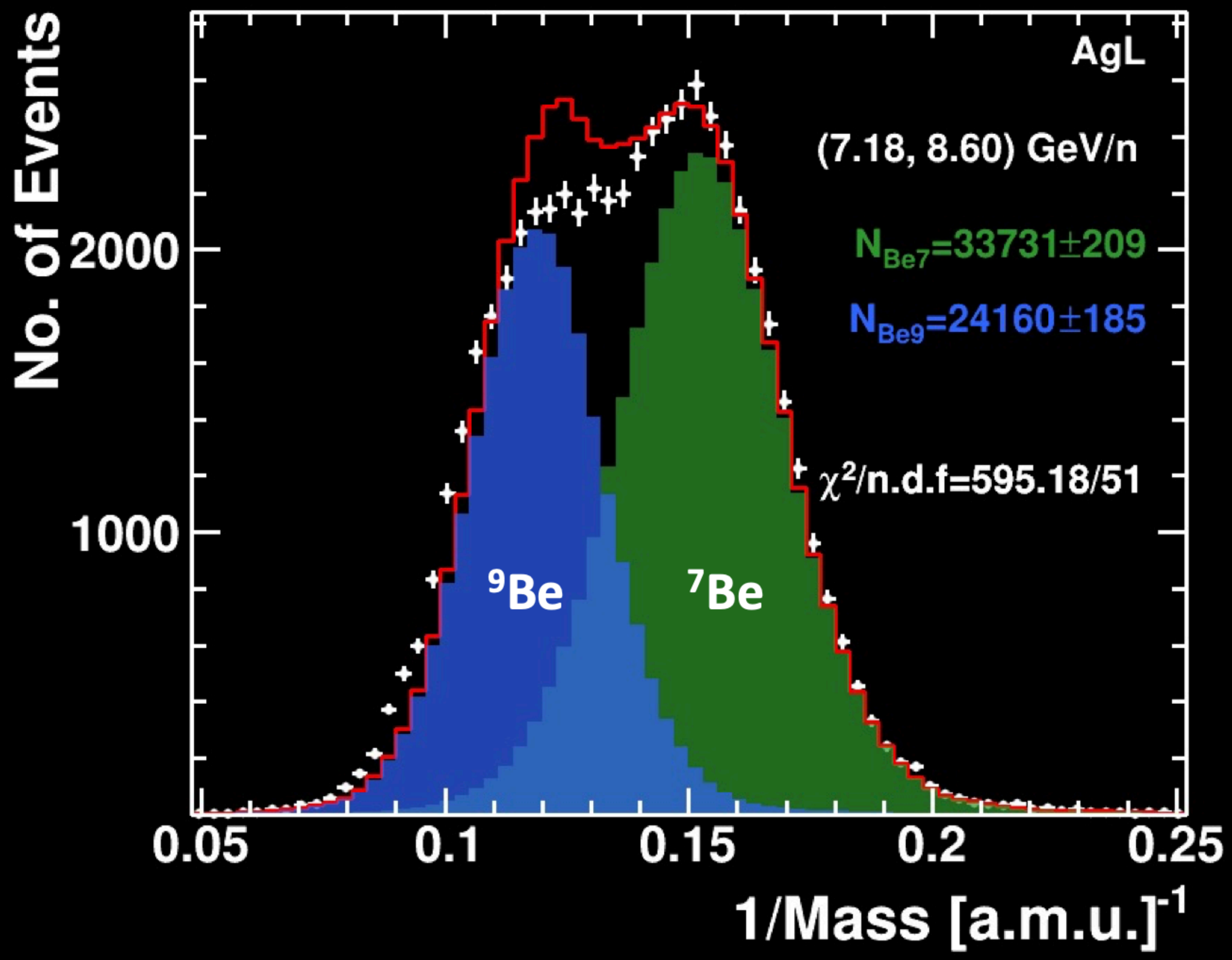
Direct observation of ^{10}Be isotopes by AMS with RICH-NaF measurement.



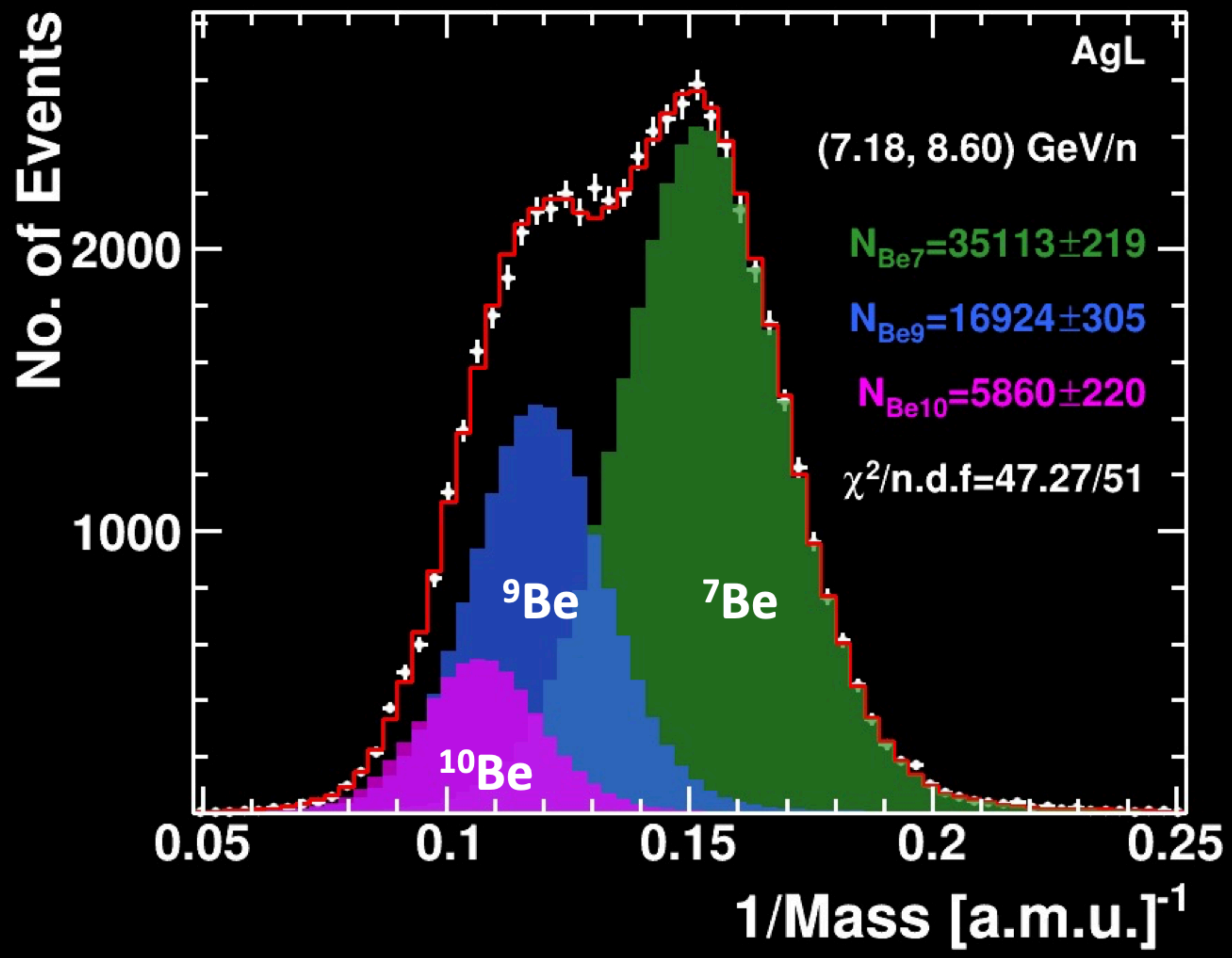


Examples of Mass Template Fit for Be Nuclei

Fit with only ^{7}Be and ^{9}Be



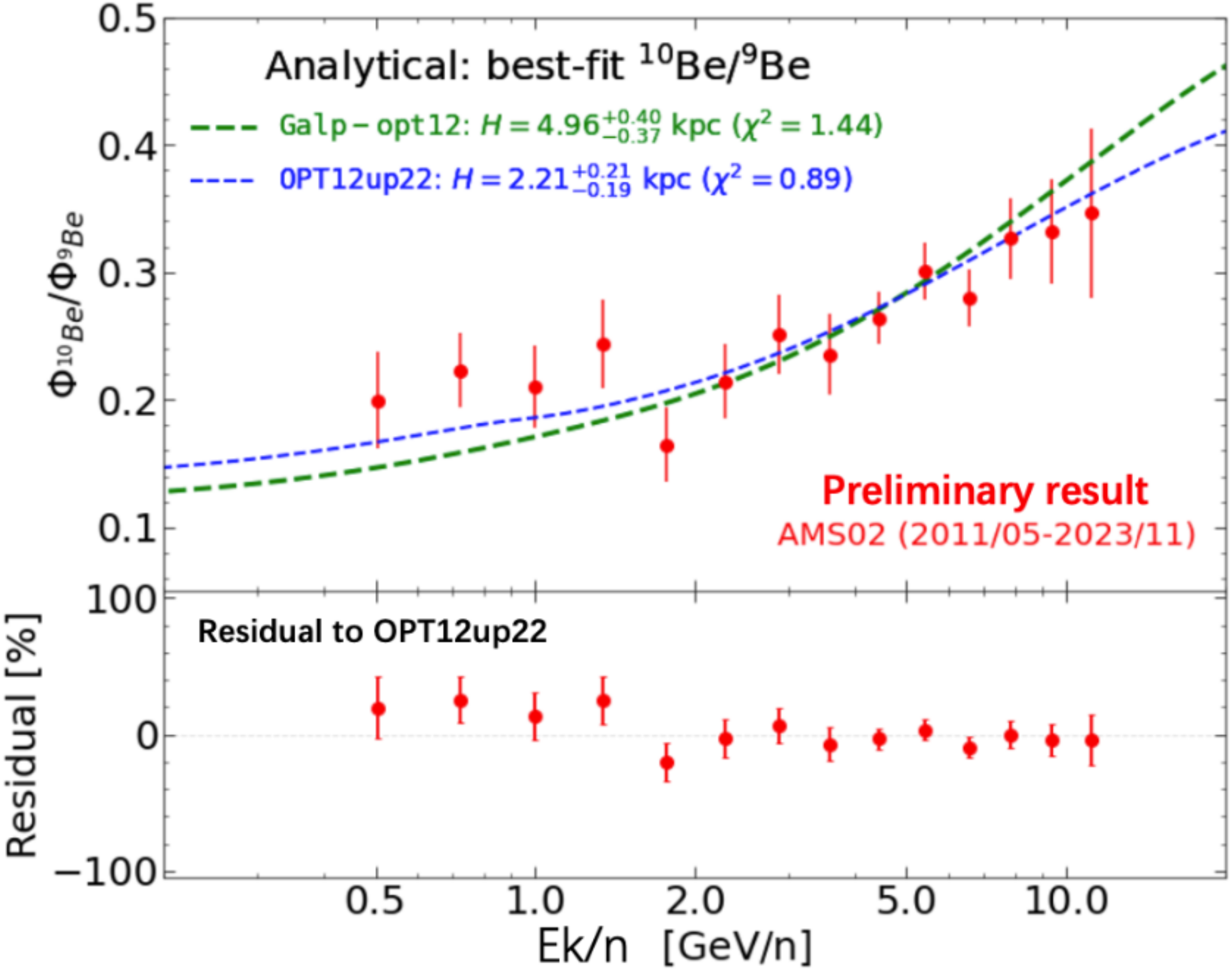
Fit with ^{7}Be, ^{9}Be, and ^{10}Be



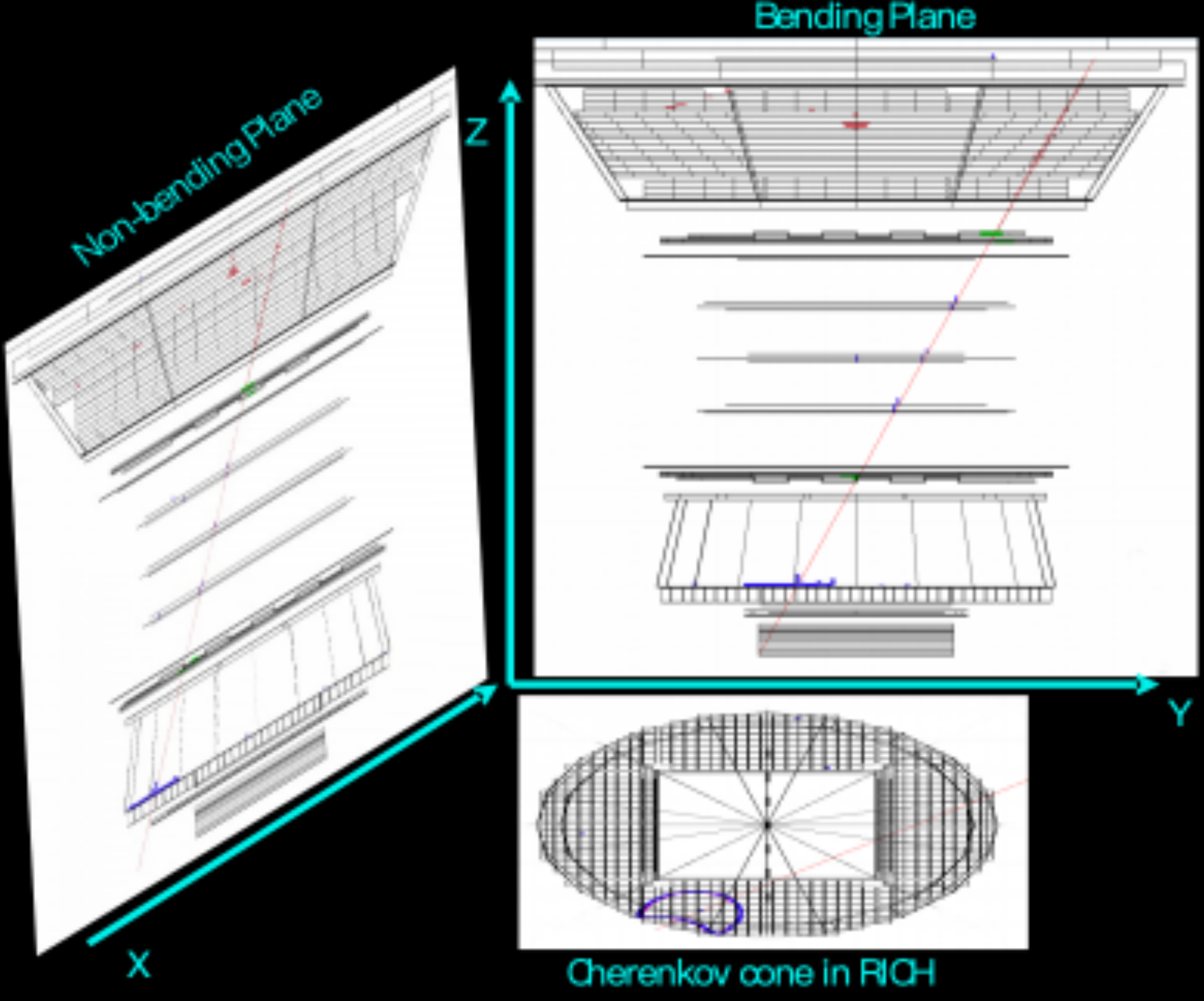
^{10}Be is needed to fit the data

In total, we have analysed 0.7 million beryllium events.

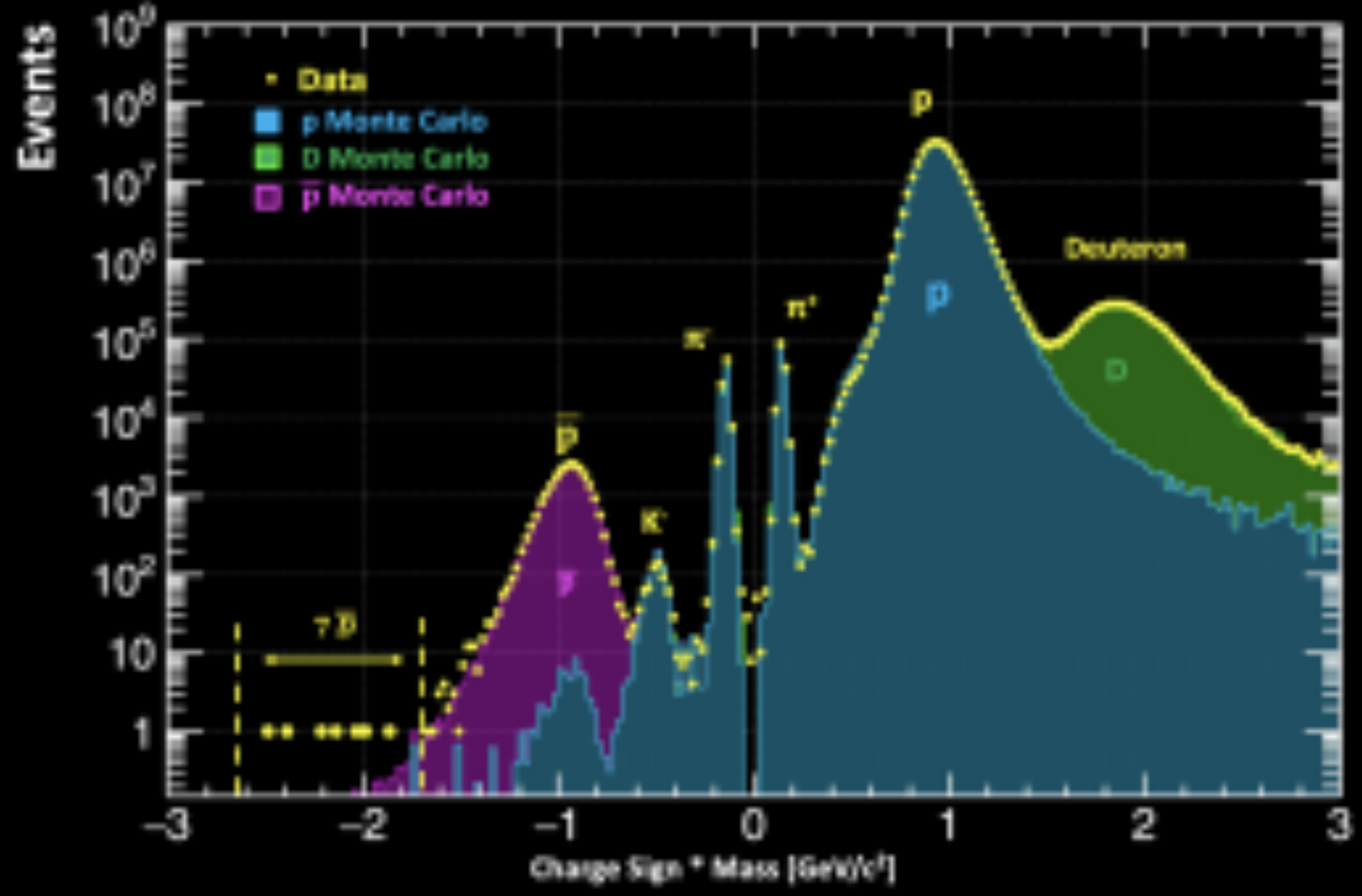
Properties of Cosmic Beryllium



Search for Anti-D candidates



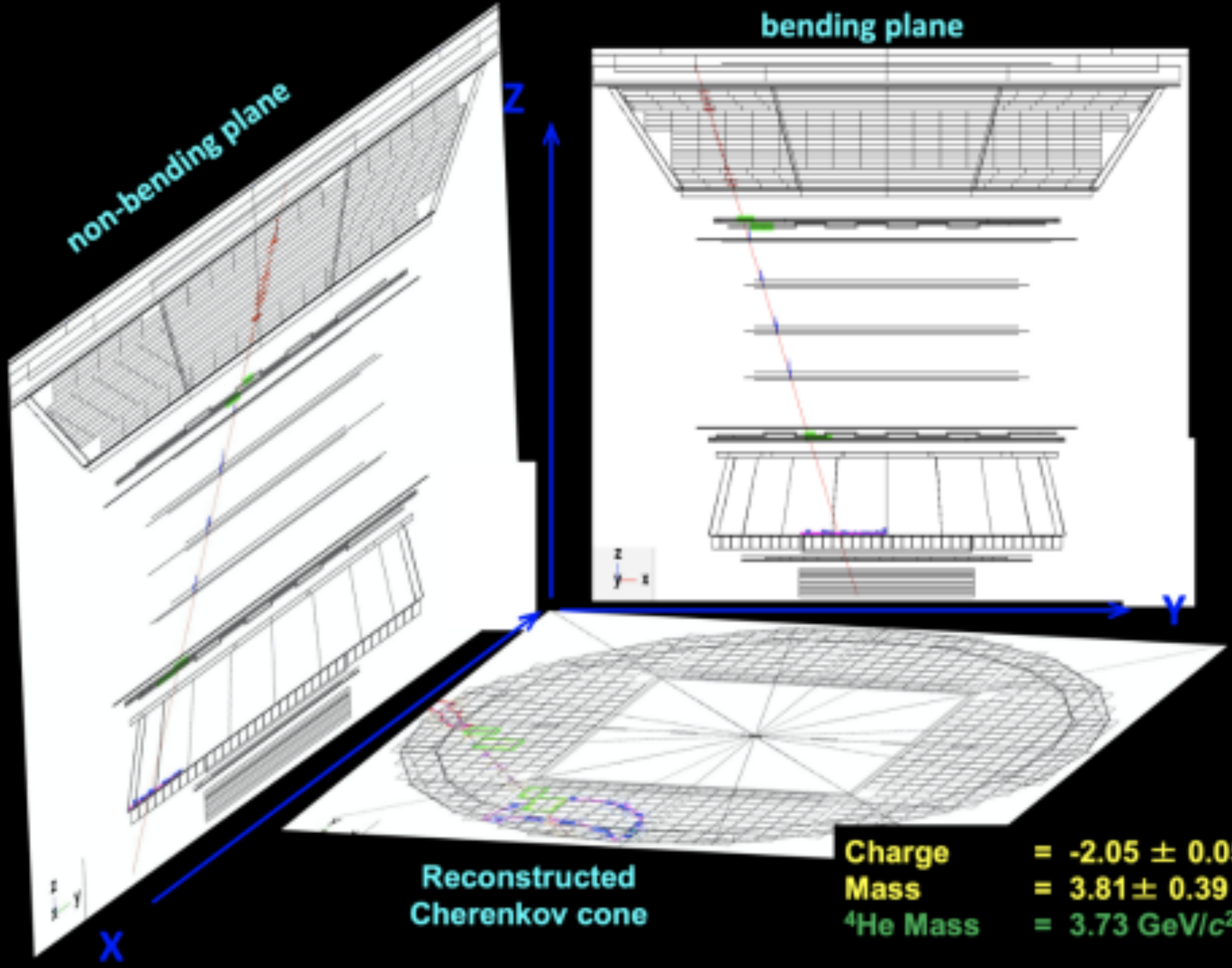
Anti-deuteron Candidate
Charge = -1.02 ± 0.05
Mass = 1.9±0.1 *GeV/c²*



A few antideuteron candidates were selected. Extensive study of the Monte Carlo simulation is on-going to understand the detector effects.

Benefit from continuous data taking through the lifetime of the Space

Search for Anti-He candidates



Charge = -2.05 ± 0.05
Mass = 3.81 ± 0.39 GeV/c^2
^{4}He Mass = 3.73 GeV/c^2

- Few anti-helium candidates were observed with R<50 GV;
- All masses are in the ^{3}He or ^{4}He mass ranges ;
- 1 anti-He in about 100 million helium;
- No bg expected by MC;
- At this level MC simulation are difficult to validate.

➢ Increase acceptance with L)0 upgrade (300%)

AMS Publications in *Physical Review Letters*

8012 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