Measurements of Cosmic Proton Flux through Neutron Monitors Using Deep Learning in the AMS-02 Era

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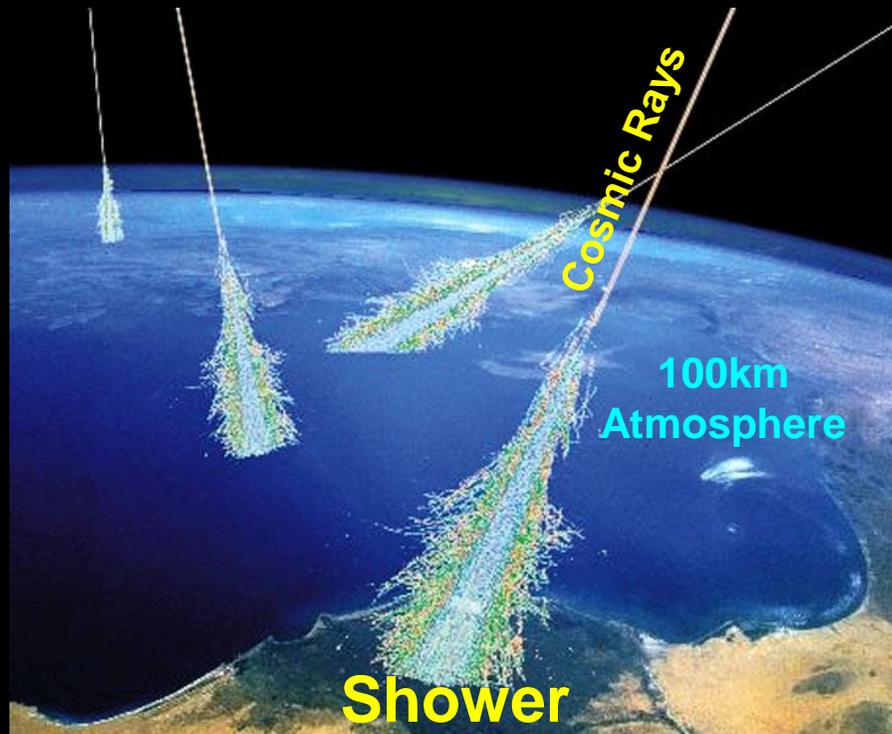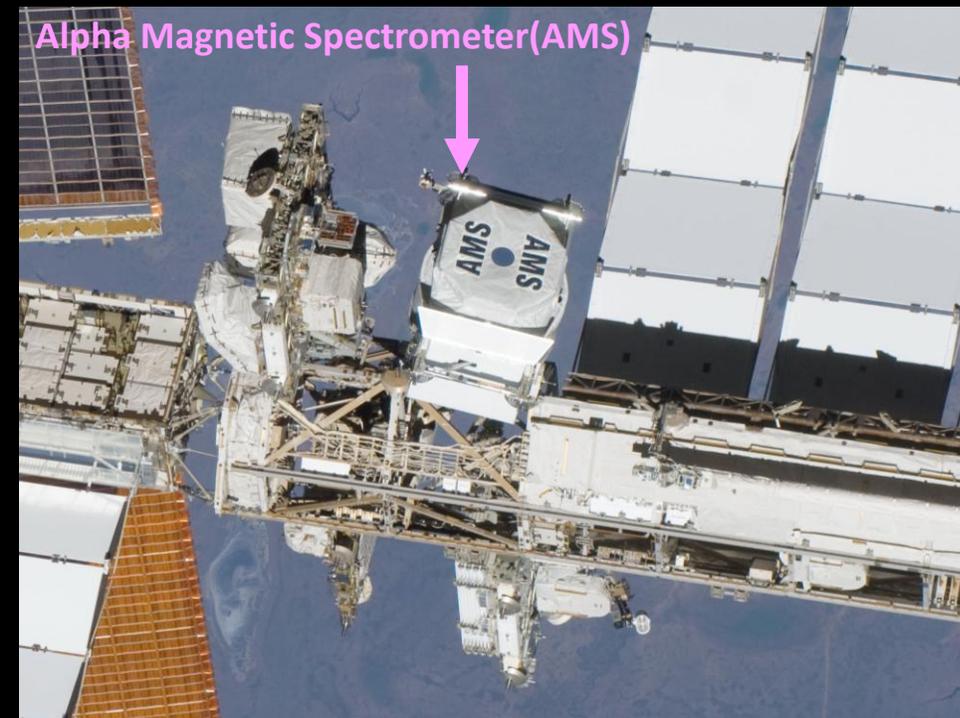
Cosmic rays are high-energy particles from space. They are one of the key messengers from our Galaxy that we can detect directly

Physics of Dark Matter, Antimatter, the Origin of the Cosmos, and new phenomena through the precision, long-duration measurement of charged cosmic rays
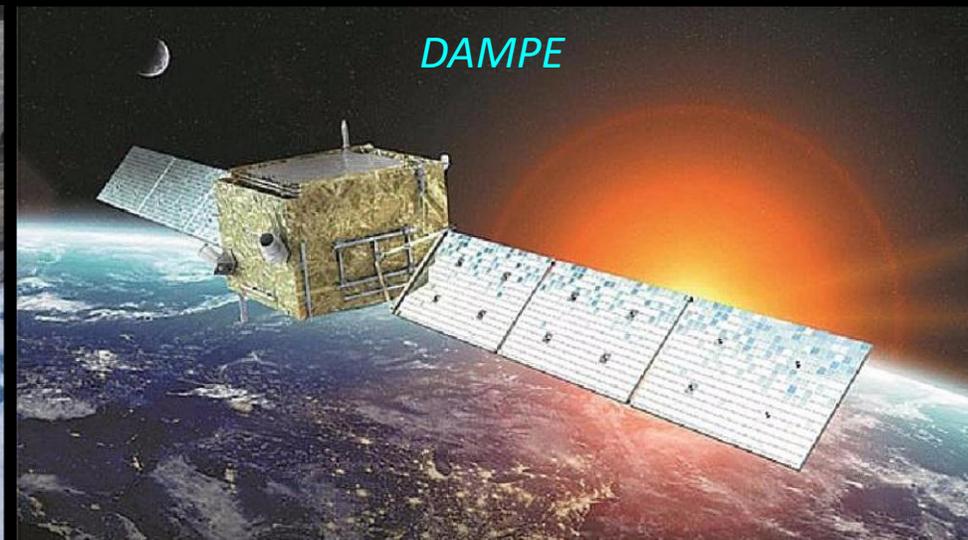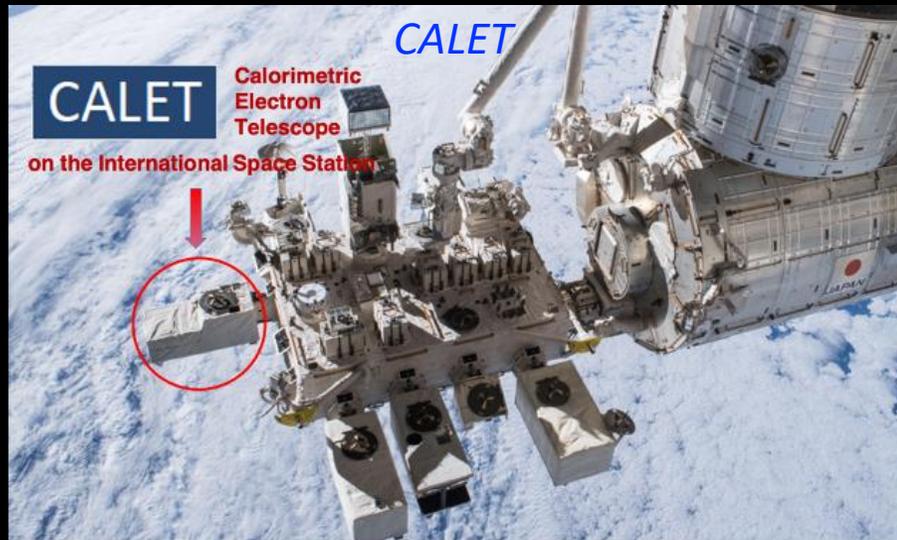
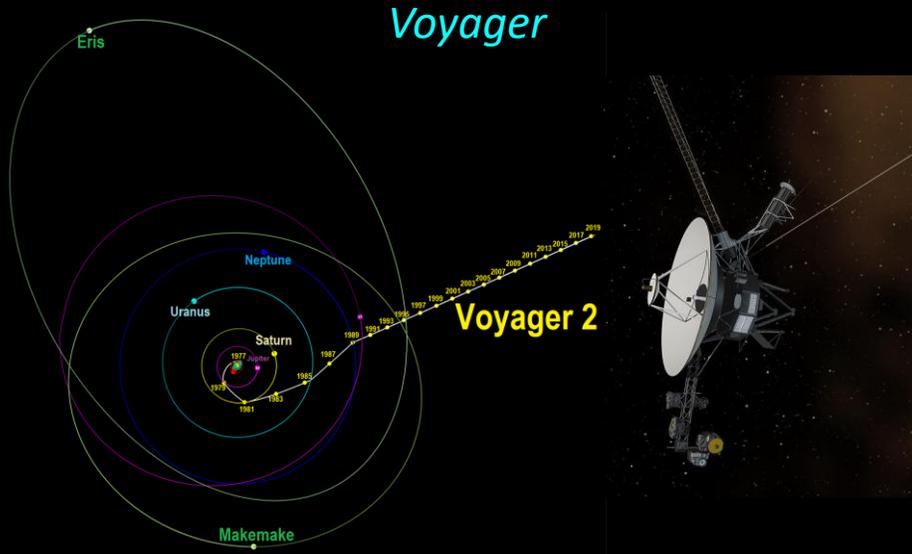Charged cosmic rays are absorbed by the 100 km of Earth's atmosphere.
Their properties ($\pm Z, P$) cannot be studied on the ground.

To measure cosmic ray charge and momentum requires a magnetic spectrometer in space.

Cosmic Rays

100km Atmosphere

Shower

Alpha Magnetic Spectrometer(AMS)

AMS

Examples of Current Non-magnetic, Calorimeter Experiments in Space

Voyager

Fermi-LAT

CALET

DAMPE

Solar Modulation of Cosmic Rays

Cosmic ray flux is anticorrelated to the solar activities:

AMS

AMS provides very precise proton spectra, covering a wide rigidity range.

However, these measurements are not continuous in time.

As shown in the right plot, there are clear data gaps, mainly caused by detector studies and upgrades.

Cristina Consolandi (AMS Collaboration) ICRC 2025

Indirect measurements of cosmic ray spectrum

Before entering the atmosphere:
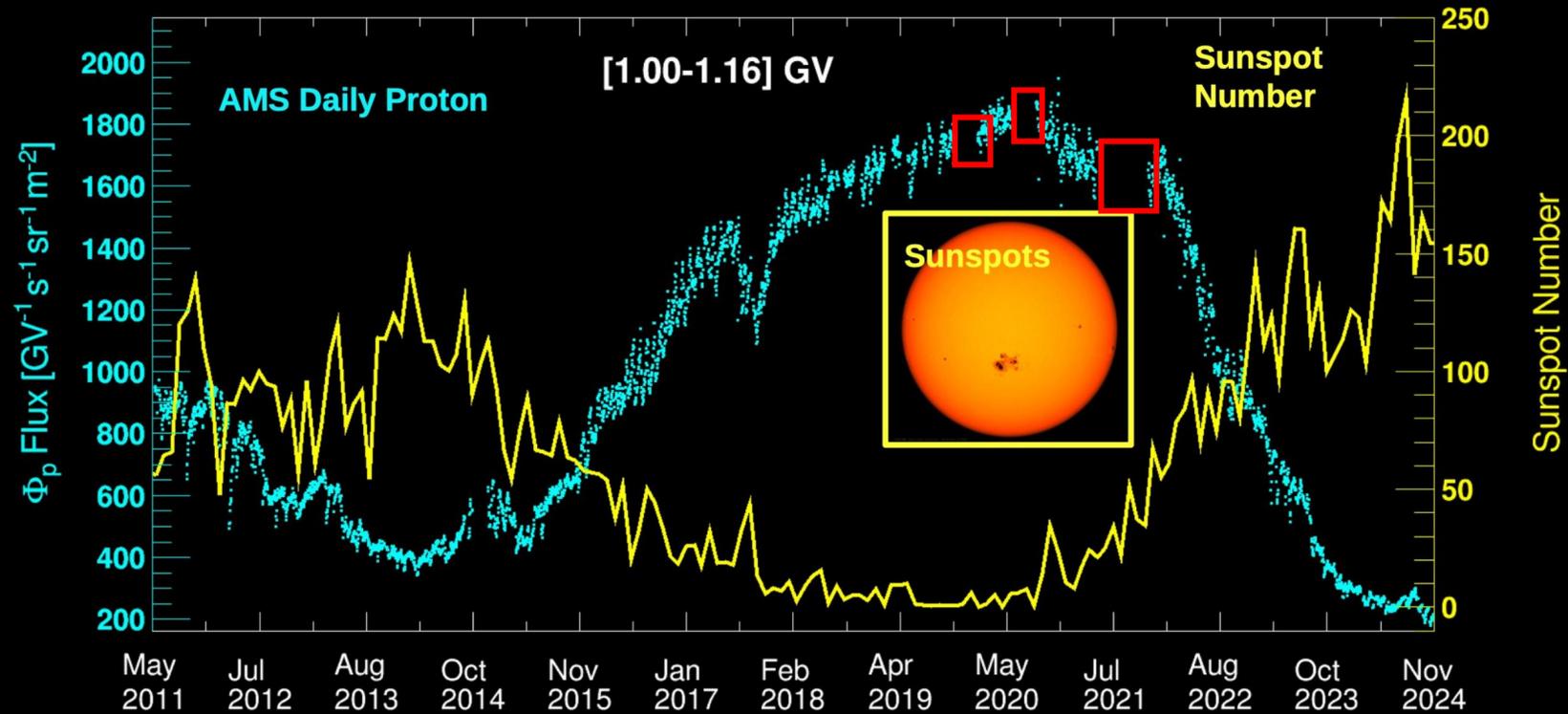
The geomagnetic field shields low-energy cosmic rays. Only cosmic rays with rigidity greater than the geomagnetic cutoff can penetrate into the atmosphere.

After entering the atmosphere:

Cosmic rays collide with atoms and molecules in the atmosphere, producing many secondary particles. Ground-based detectors observe cosmic rays by detecting these secondary particles. Experiments such as Neutron Monitors and the Global Muon Network are currently conducting such measurements.

AMS and Neutron Monitor measurements

The time variation of AMS proton flux with rigidity greater than 6.47GV is highly consistent with Neutron Monitor counts.
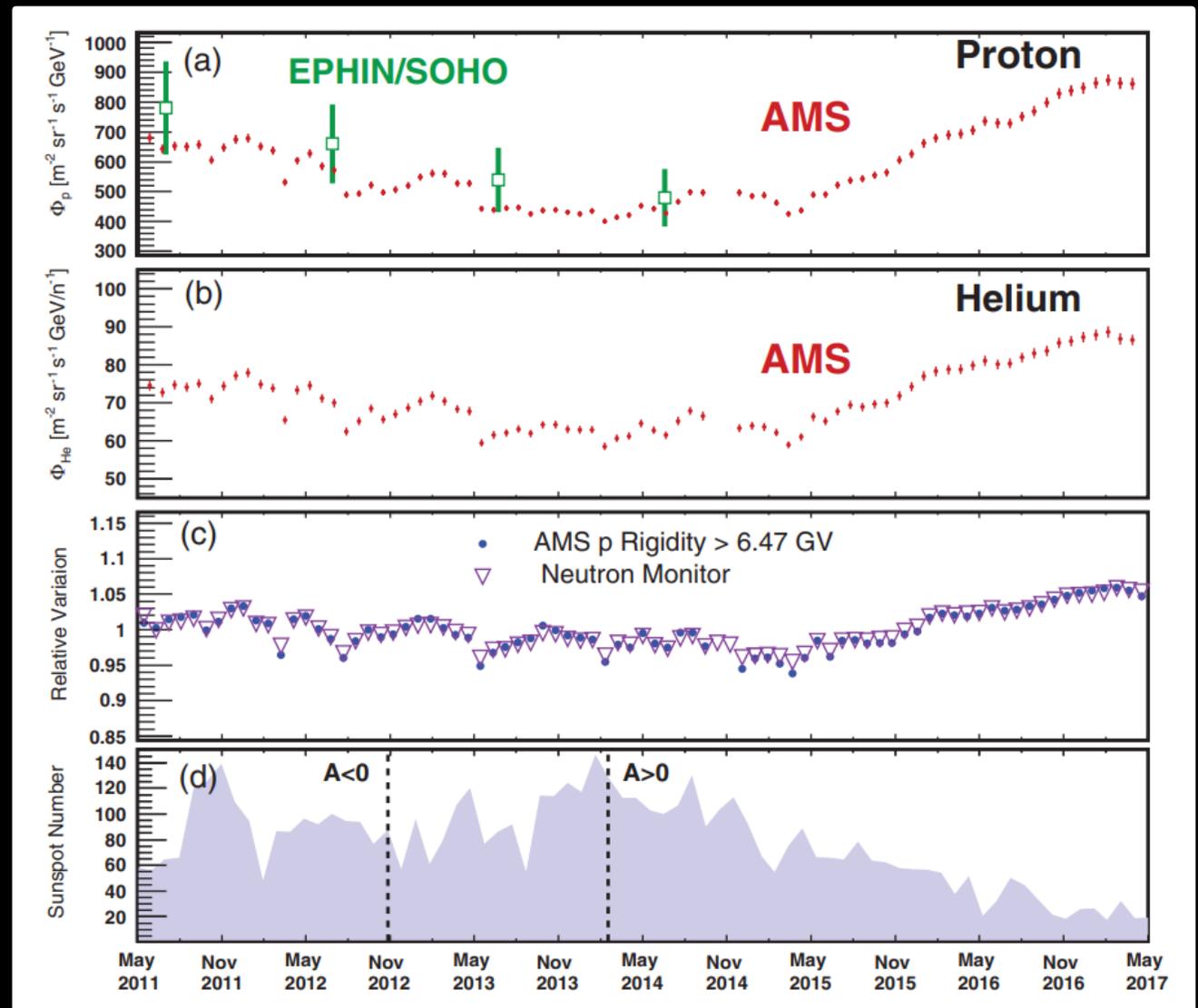
They are both anticorrelated with sunspot number.

It is possible to use Neutron Monitor counts to reconstruct proton flux measured by AMS.

Use Neutron Monitor counts to reconstruct AMS proton flux measurements

Previous studies calculated yield functions
to connect Neutron Monitor measurements
with cosmic-ray fluxes.

Using these yield functions,
cosmic-ray fluxes were reconstructed
from Neutron Monitor ,
with good agreement between about 5 and 15 GV.

These traditional methods are indirect
and model dependent,
which leads to relatively large uncertainties.

Vaisanen, P., Bertucci, B., Tomassetti, N., et al. 2025, Journal of Geophysical Research (Space Physics), 130, e2025JA033805

Our idea – Machine Learning solution

We use a data-driven approach.

During the period when AMS and Neutron Monitors overlap, we train the model to learn the relationship between Neutron Monitor count rates and proton flux measured by AMS.

AMS measurements are used as the ground truth. After the model is trained, we can use Neutron Monitor data alone to calculate proton flux when AMS data are not available.

Proton Spectra

Deep Learning

Neutron Monitor

Neutron Monitor counts preprocessing

Ground-based neutron monitor counts often contain gaps. We applied multiple time-series imputation methods (SAITS[1] and iTransformer[2]) to select more suitable model for data completion.
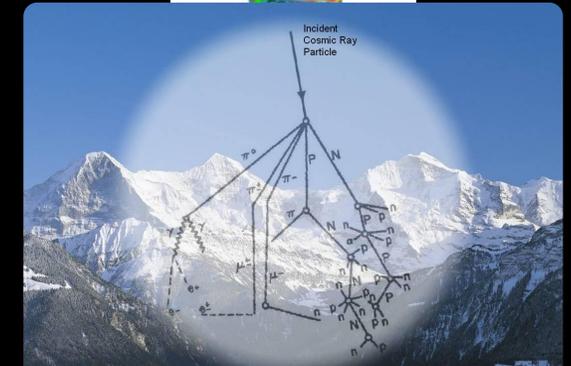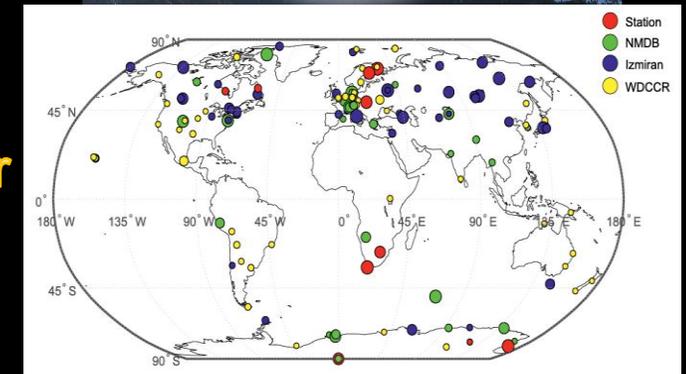
To test the accuracy of preprocessing, we artificially removed some data points and then predicted the missing values to evaluate performance.

The predicted values were consistent with the true values, demonstrating that the method for filling gaps in ground-based data is feasible.

[1]. Du, W., Cote, D., & Liu, Y. (2023). SAITS: Self-Attention-based Imputation for Time Series. Expert systems with applications.
[2]. Liu, Y., Hu, T., Zhang, H., Wu, H., Wang, S., Ma, L., & Long, M. (2024). iTransformer: Inverted Transformers Are Effective for Time Series Forecasting. ICLR 2024.

Model architecture: Convolutional Neural Network (CNN)

Input:

Daily count rates from 18 Neutron Monitor stations

Output:

Daily proton flux in 30 rigidity bins

Trained and validated with AMS data

Purely data-driven and model-independent.

Figure 1. Illustration of the workflow for proton flux calculation and the architecture of the CNN.

Results I: Daily Spectra

From 2014 to early 2015, the cosmic-ray proton spectra are shown.

Comparison with the AMS results indicates that the machine learning can reconstruct the AMS measurements.

By including the time period not measured by AMS, we can clearly observe a 27-day periodicity in the spectra during the solar magnetic polarity reversal period.
The wavelet analysis results shown on the right column describe the temporal evolution of this periodicity.

Results II: Hourly Proton Spectra

Space experiments such as AMS are limited by orbital constraints and cannot provide continuous low-energy measurements;

they can only measure a complete spectrum every 90 minutes.

On the other hand, ground-based neutron monitors are capable of continuous measurements.

For the Forbush Decrease event on March 17, 2015, the hourly variation of the cosmic-ray proton spectrum was measured. Our machine learning model reconstructs the entire variation.

Conclusions

- Machine learning models can accurately calculate the GV cosmic proton fluxes based on ground-based neutron data.

- The proton flux derived from neutron monitor data is more continuous in time, allowing us to recover the cosmic-ray proton, thereby filling the gaps in AMS measurements.
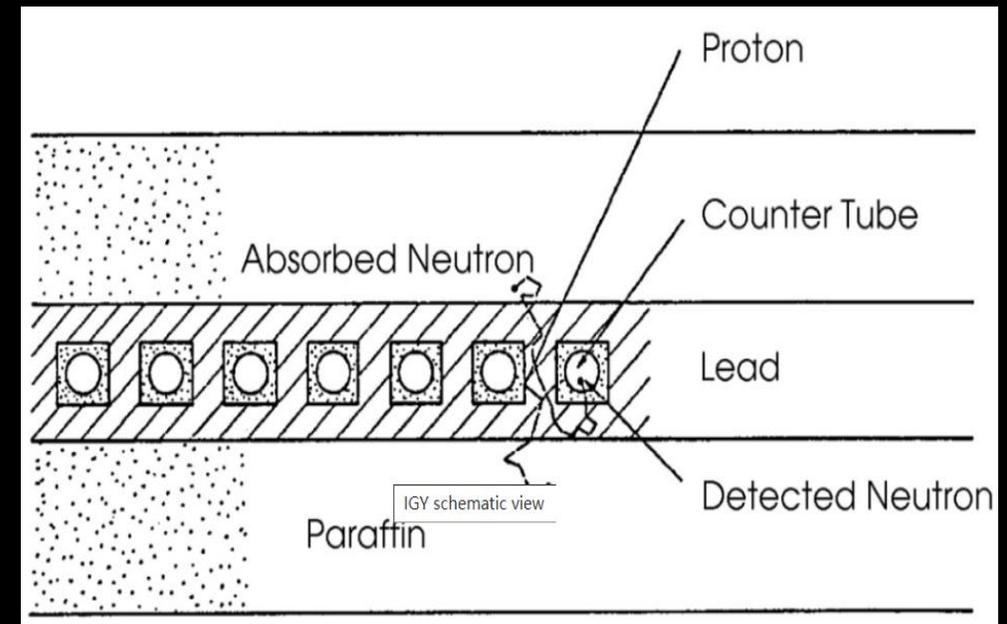
- We can produce hourly proton fluxes. This provides crucial data for studying solar modulation.

backup

Neutron Monitors

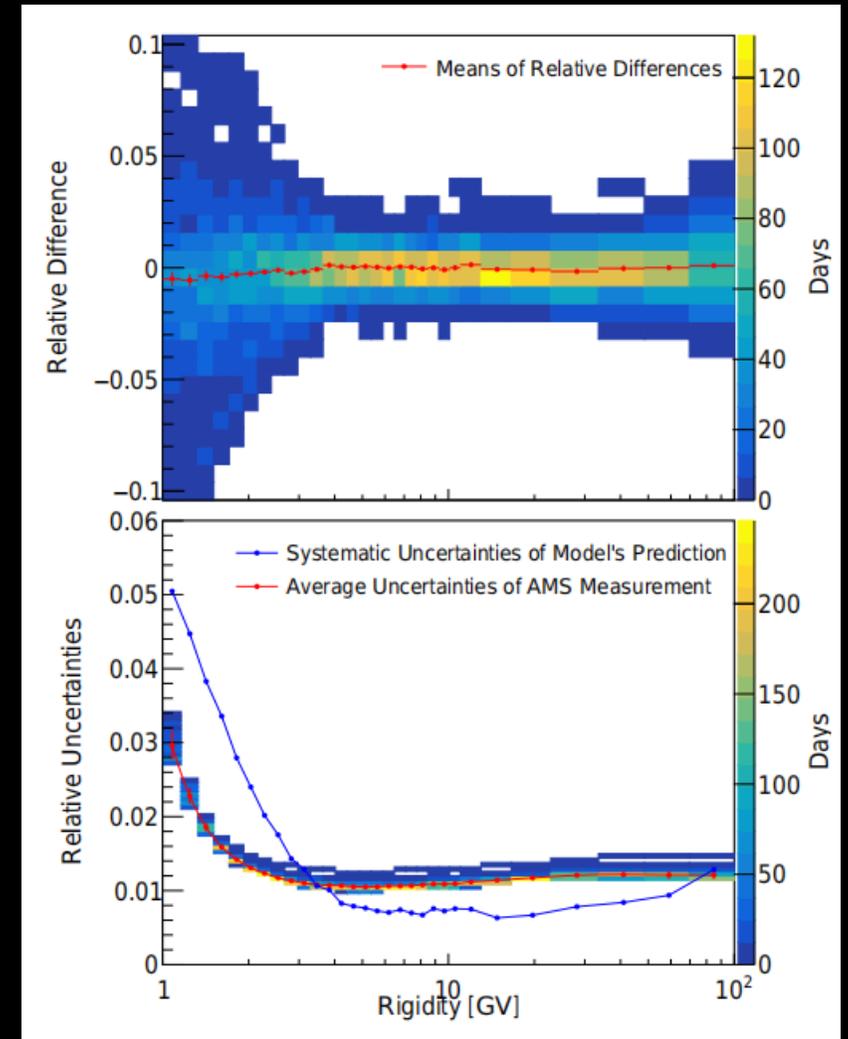- A neutron monitor detects cosmic rays by using lead to produce neutrons from incoming particles, which are then slowed down and counted by gas-filled tubes.

- Neutron monitors operate continuously worldwide and are widely used for long-term cosmic-ray studies.

- However, they detect secondary particles and measure only integral count rates above the local geomagnetic cutoff rigidity.

NMDB

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Validation I: Daily Proton Spectra

- The top plot shows the relative difference between the model and AMS, where red points are the mean values in each rigidity.

- The bottom plot shows the relative uncertainties.

- The colored plot shows the relative uncertainty distribution of the AMS testing sample, while the red points are the mean values.

- The blue points are defined as the standard deviation of the relative difference in each rigidity bin from the top plot.

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Validation II: Monthly Spectra

- Model calculations combined into Bartel Rotation resolution are compared with AMS proton flux measurements.

- Two representative rigidity intervals are consistent with the AMS measurement.

- We define the residual as $(\Phi_{NM\ Prediction} - \Phi_{AMS})/\sigma_{AMS}$;

- The residuals remain small before 2019 and increase afterward. The error bars on the monthly prediction results represent a conservative estimate of the systematic deviation.
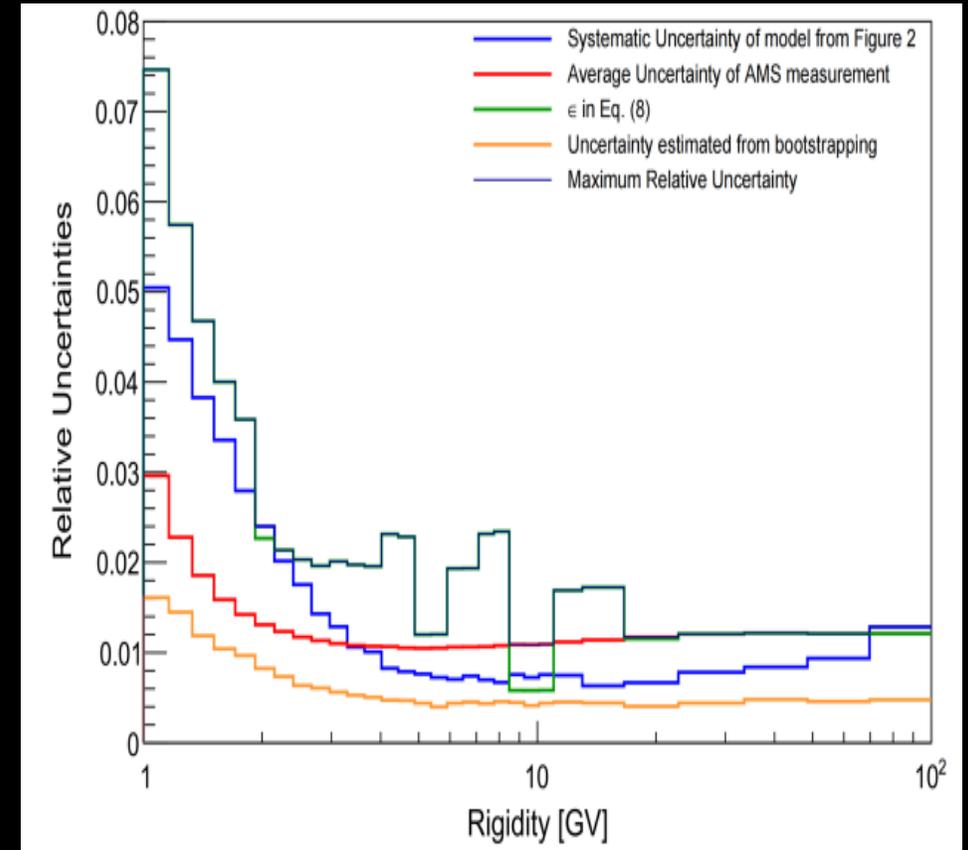
Uncertainties

Total uncertainty estimation for the model.

The deep blue line shows the overall model uncertainty, conservatively defined as the maximum of three distinct error sources:
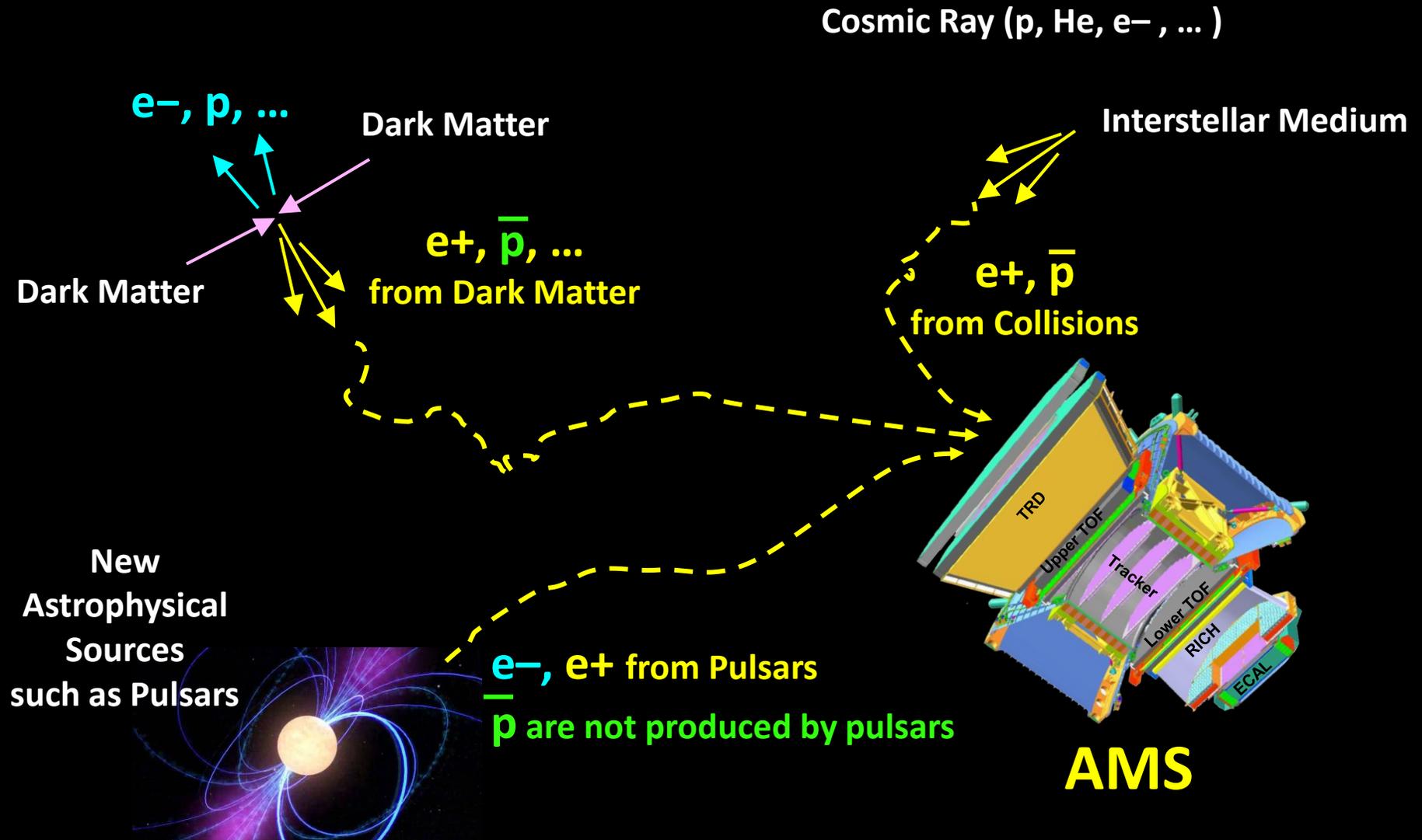
1. systematic uncertainty of the model from the testing sample of pre-2019(blue), which is the AMS daily proton period

2. average uncertainty of AMS measurement (red),

3. Uncertainty estimate from post-2019, which AMS monthly proton flux covers (green).

For comparison, the orange line shows an independent uncertainty obtained by bootstrapping.

Dark matter

Cosmic Ray (p, He, e− , …)

e−, p, …

Dark Matter

Interstellar Medium

Dark Matter

e+, p̄, …
from Dark Matter

e+, p̄
from Collisions

TRD

Upper TOF

Tracker

Lower TOF

RICH

ECAL

New
Astrophysical
Sources
such as Pulsars

e−, e+ from Pulsars

p̄ are not produced by pulsars

AMS

Features of Dark Matter

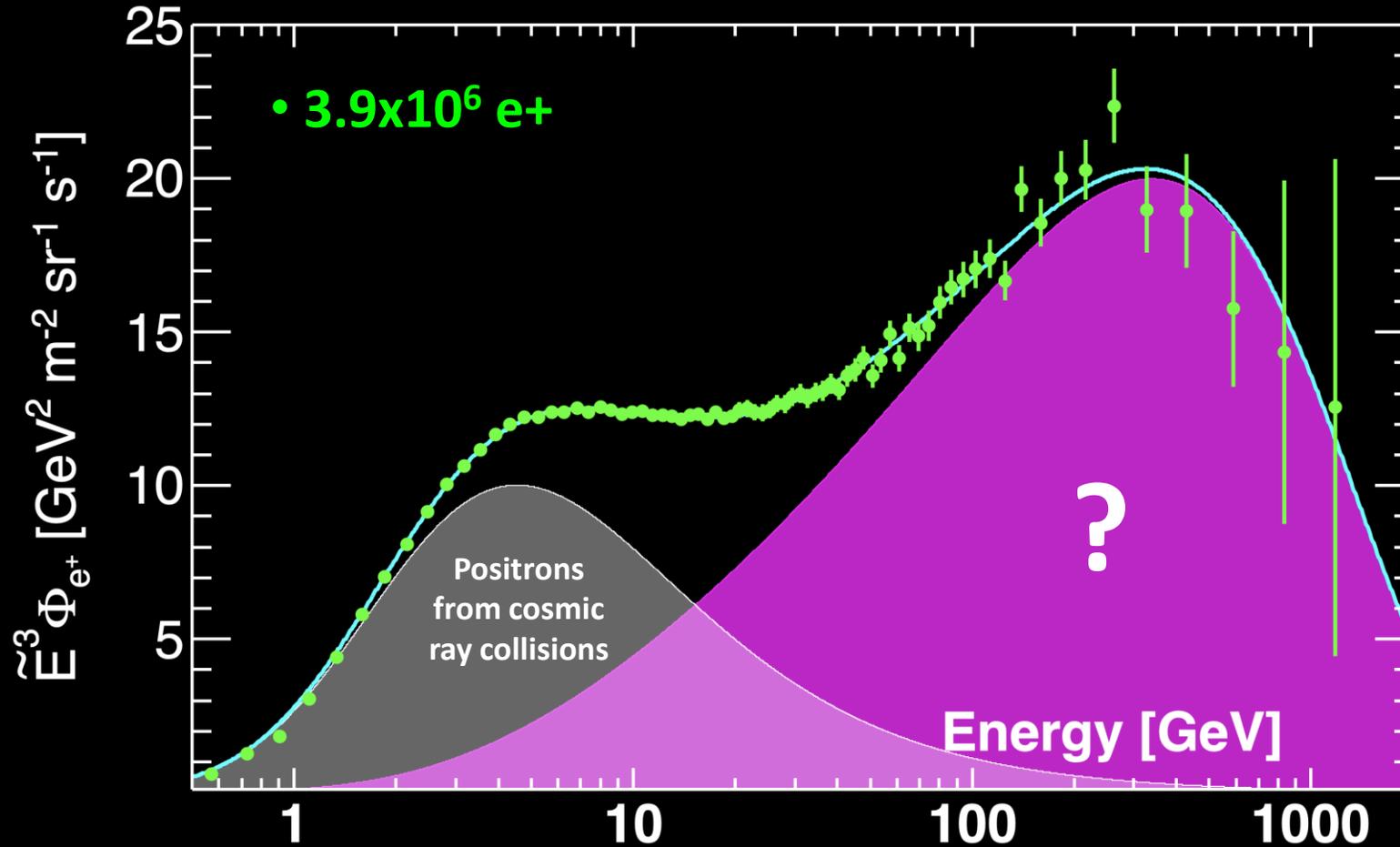Sharp drop in positron spectrum at high energy (energy-momentum conservation)

Similar spectral shape of positrons and antiprotons

Isotropic distribution of position arrival directions

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.

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

Solar   Collisions   ?

• 3.9×10^6 e+

Positrons from cosmic ray collisions

?

Energy [GeV]

$\tilde{E}^3 \Phi_{e^+}$ [GeV^2 m^{-2} sr^{-1} s^{-1}]

The existence of the finite cutoff energy is a new and 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