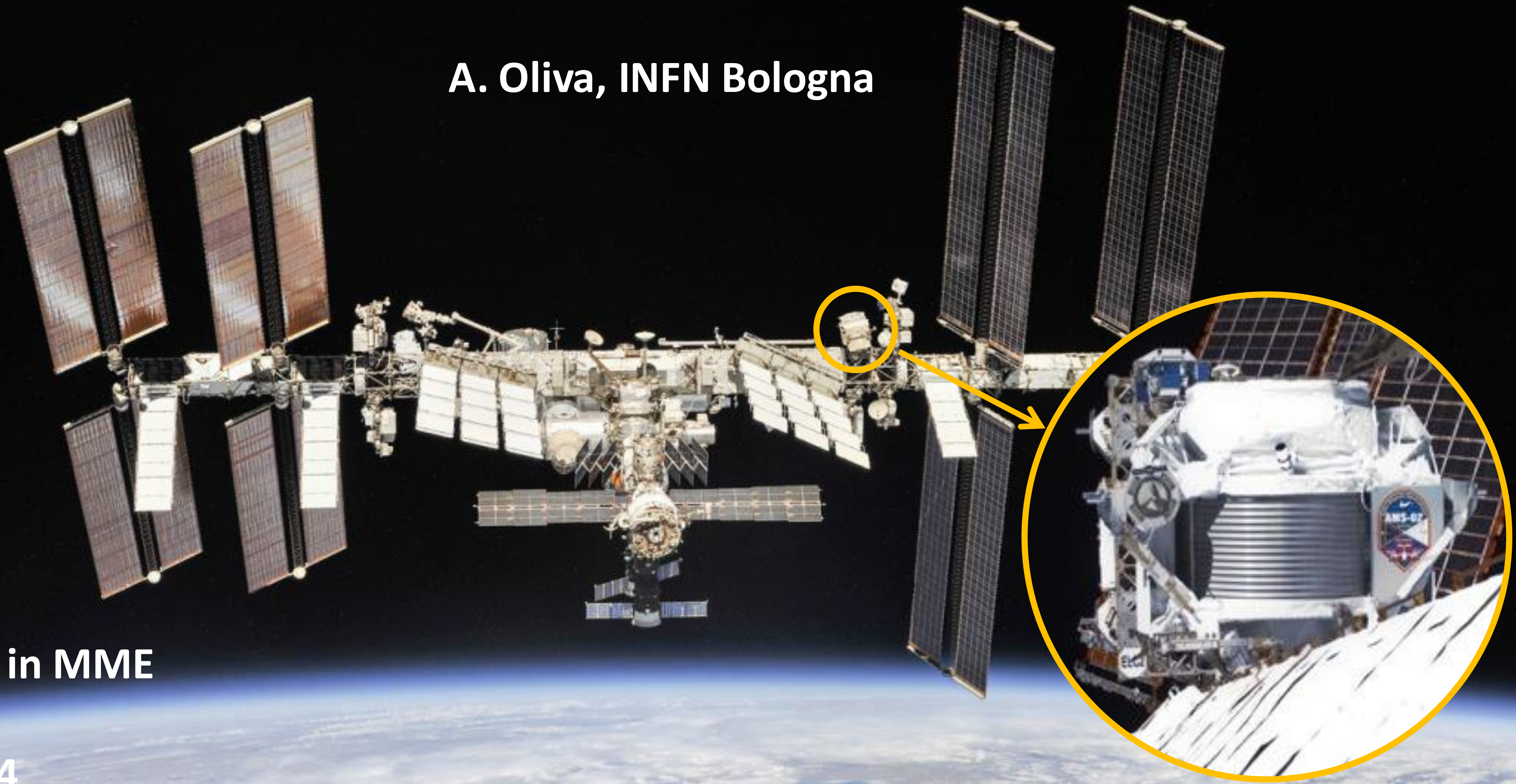
Overview and Latest Results of the Alpha Magnetic Spectrometer on the International Space Station

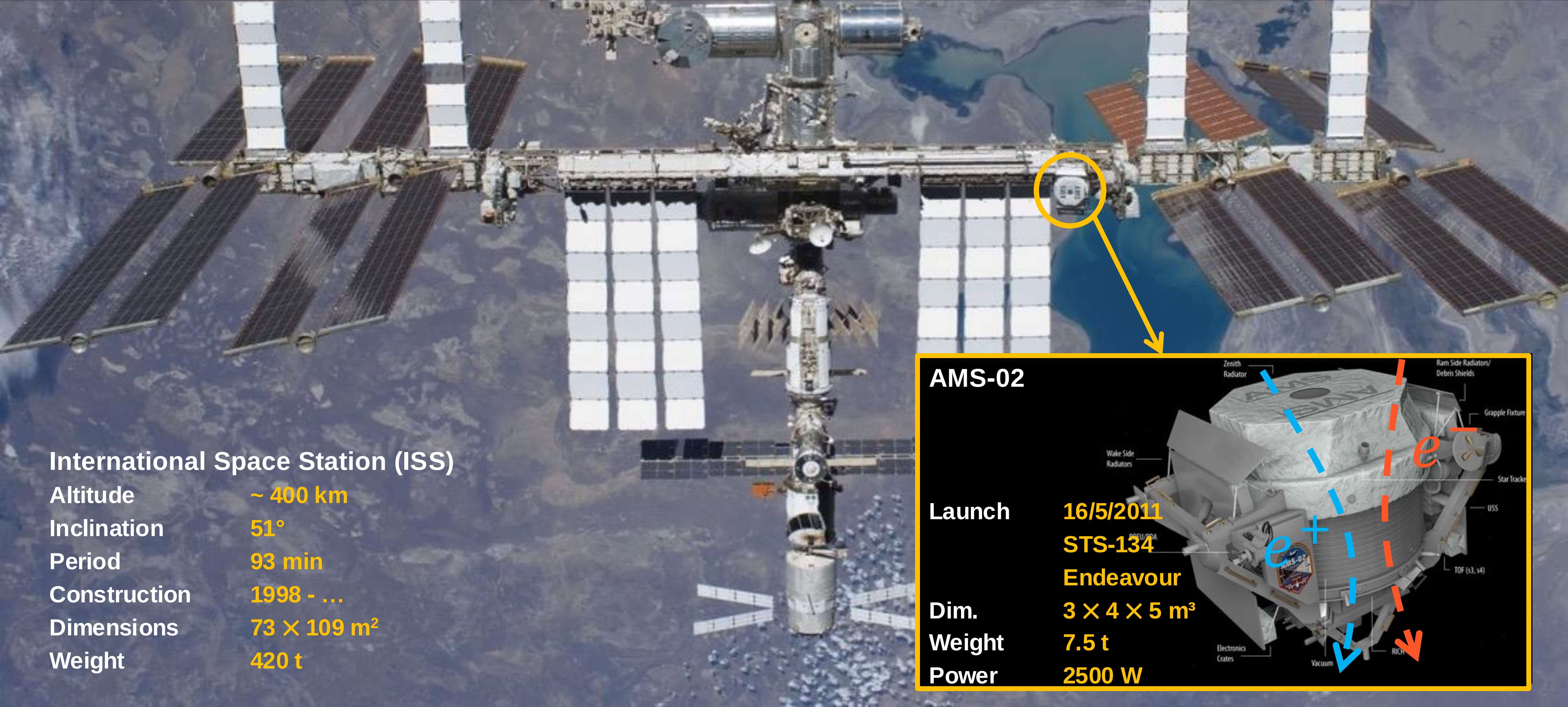
A. Oliva, INFN Bologna



CRs and νs in MME
APC, Paris
13/12/2024

AMS-02: The Alpha Magnetic Spectrometer

Installed in May 2011 on the ISS, AMS takes data continuously since then.
In more than 13 years of operations AMS-02 collected >240 billion cosmic rays.



International Space Station (ISS)

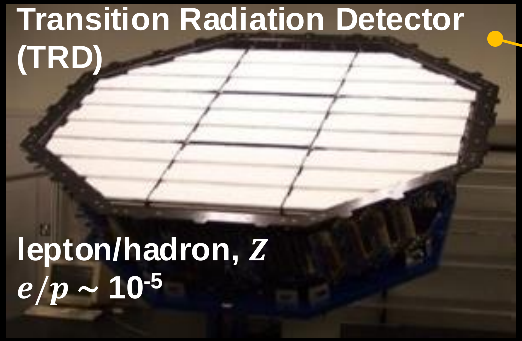
Altitude	~ 400 km
Inclination	51°
Period	93 min
Construction	1998 - …
Dimensions	73×109 m^2
Weight	420 t

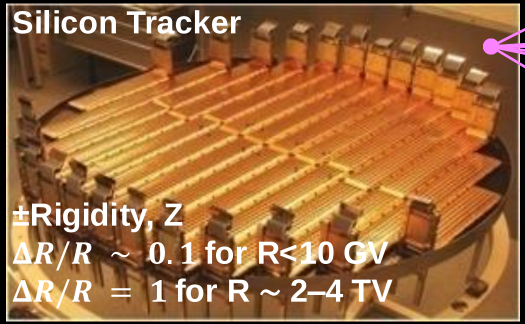
AMS-02

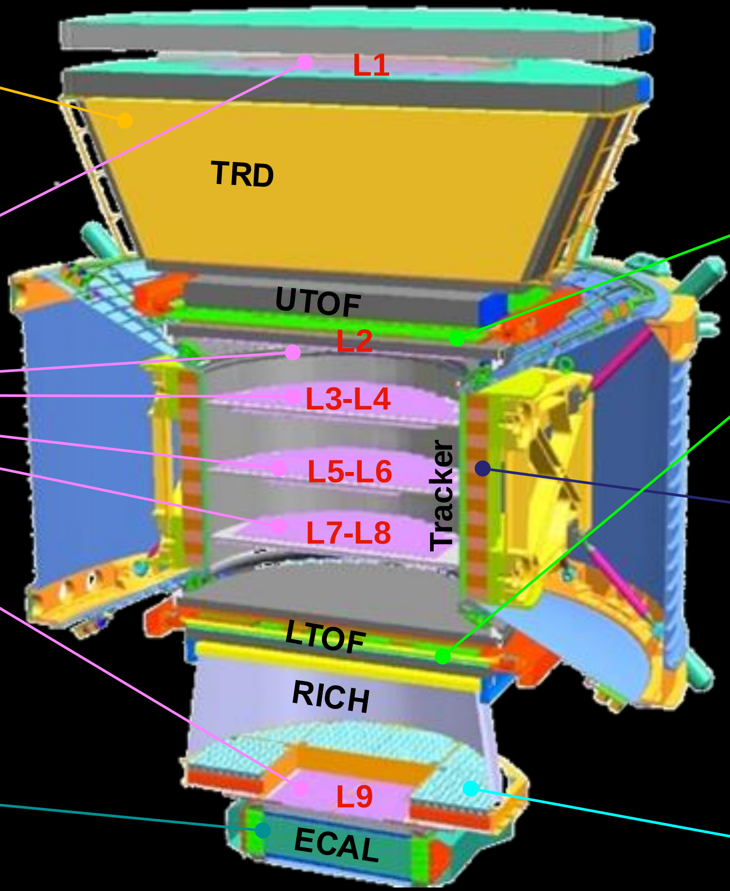
Launch	16/5/2011
	STS-134
	Endeavour
Dim.	$3 \times 4 \times 5$ m^3
Weight	7.5 t
Power	2500 W

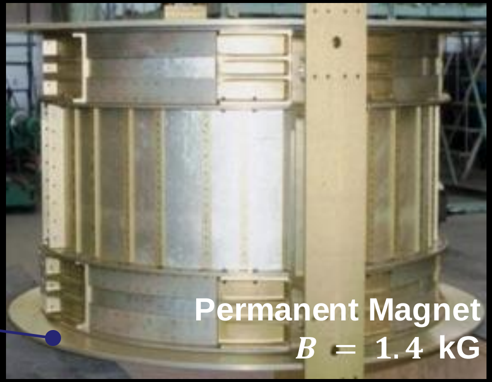
AMS-02: A TeV Multi-Purpose Spectrometer

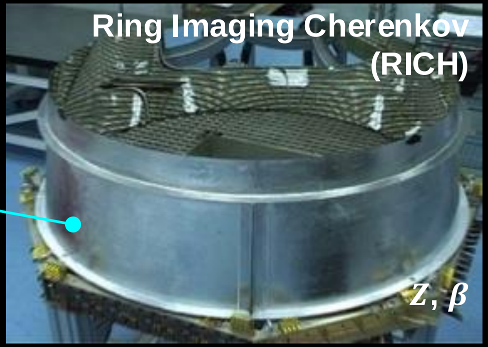
AMS-02 separates **hadrons** from **leptons**, **matter** from **antimatter**, **chemical** and **isotopic** composition from fraction of GeV to multi-TeV.







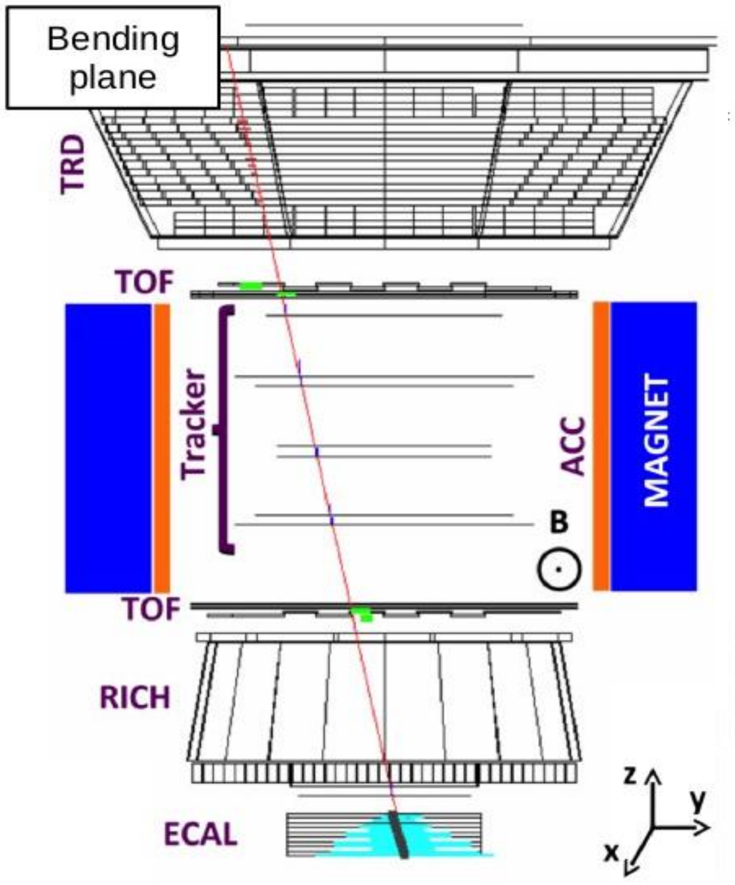


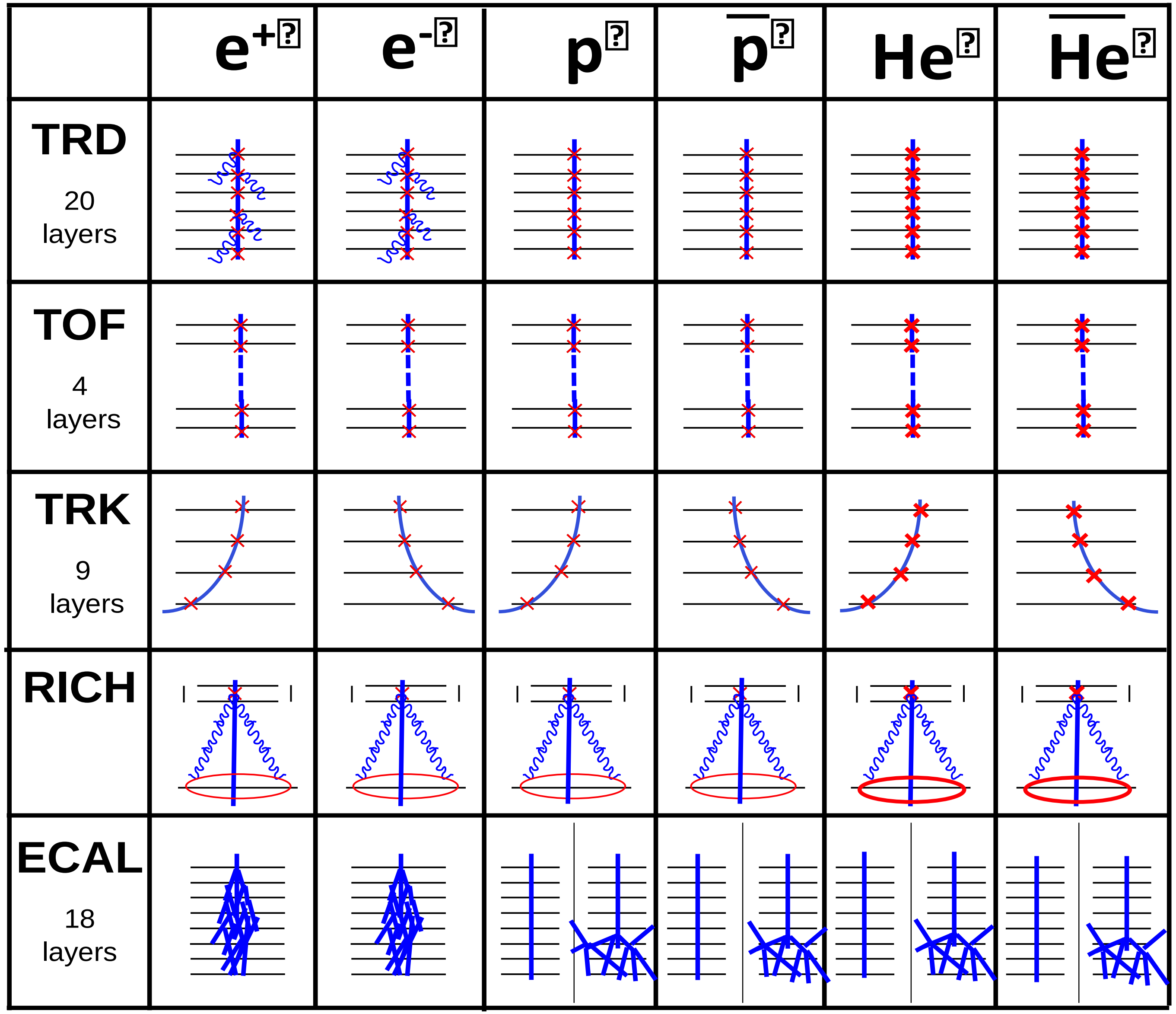


Multiple measurements of charge (Z), energy (β, p, E) and charge sign (±).

A TeV Multi-Purpose Spectrometer

600 GeV electron





e/p separation
charge, $|Z|$

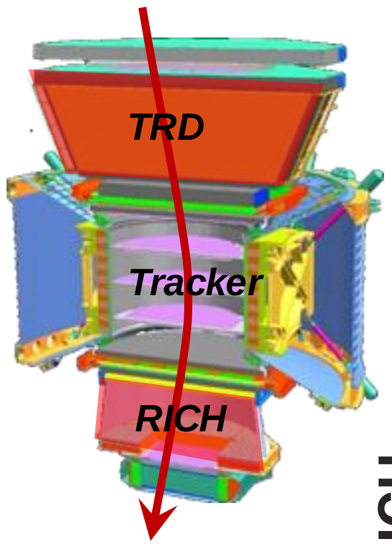
trigger
velocity, β
charge, $|Z|$

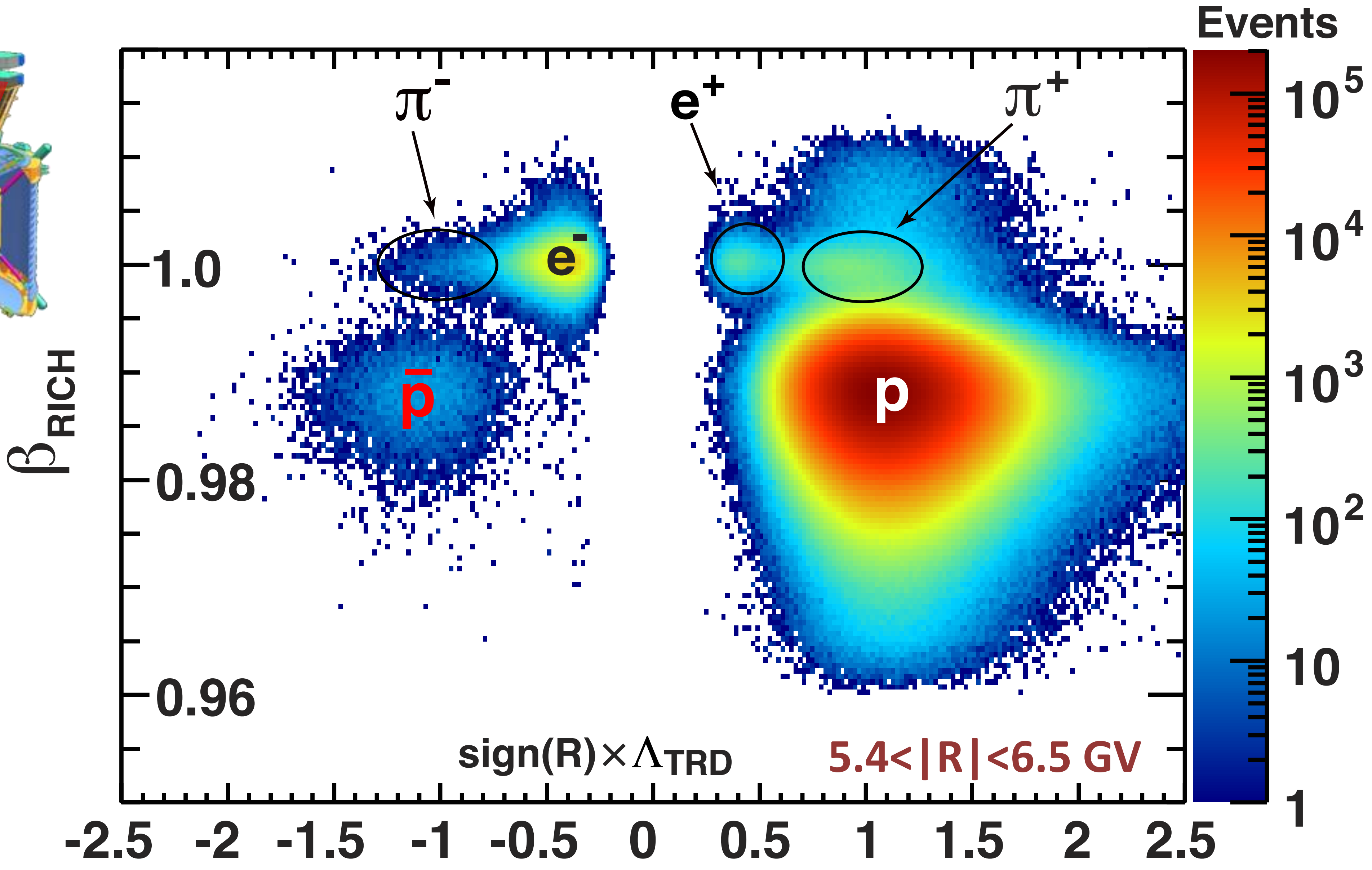
rigidity, p/Z
sign, $\pm$
charge, $|Z|$

velocity, β
charge, $|Z|$

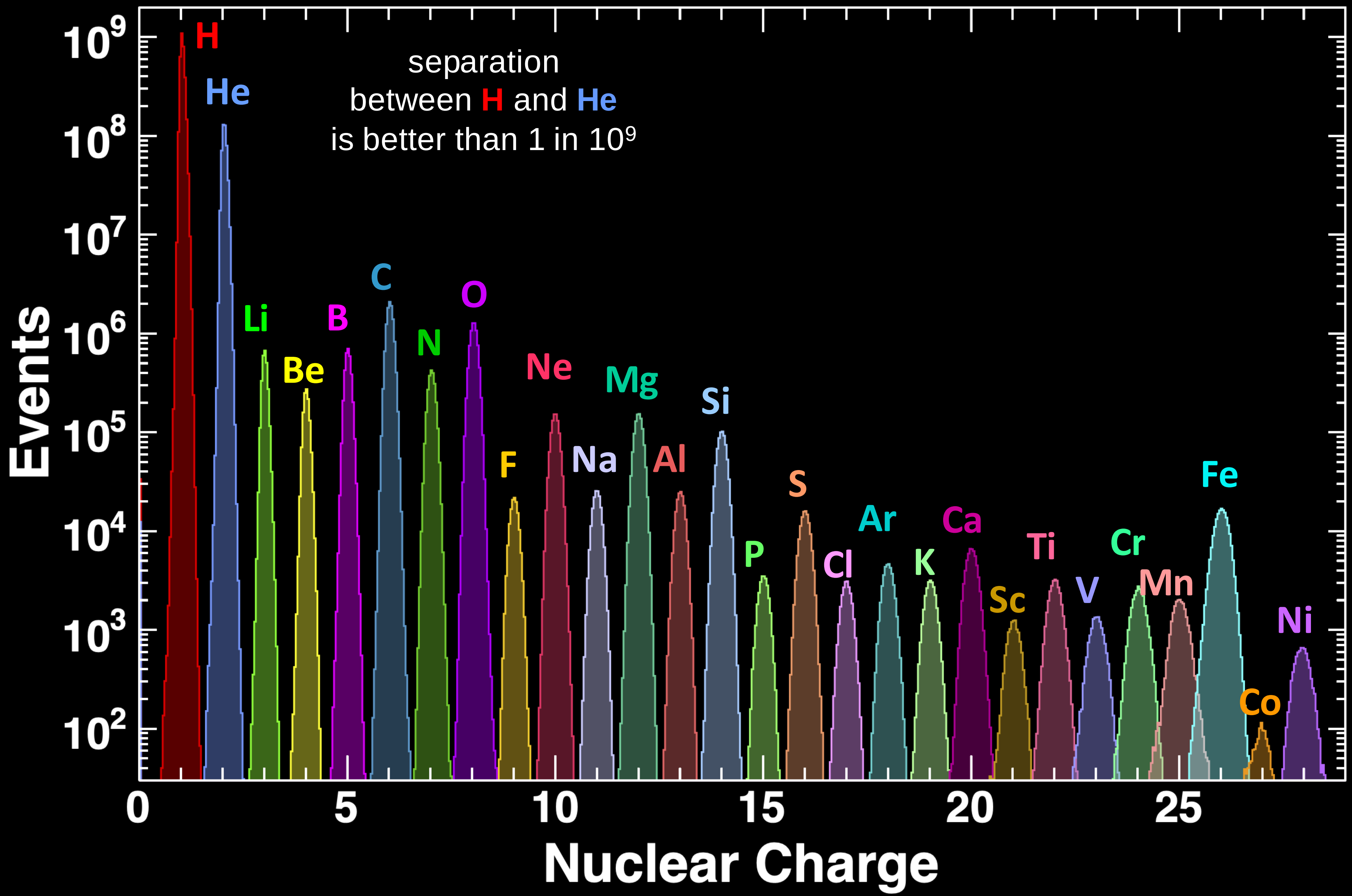
$e^{\pm}$,γ energy
e/p separation
EM-trigger

Light Elements Identification





Chemical Composition



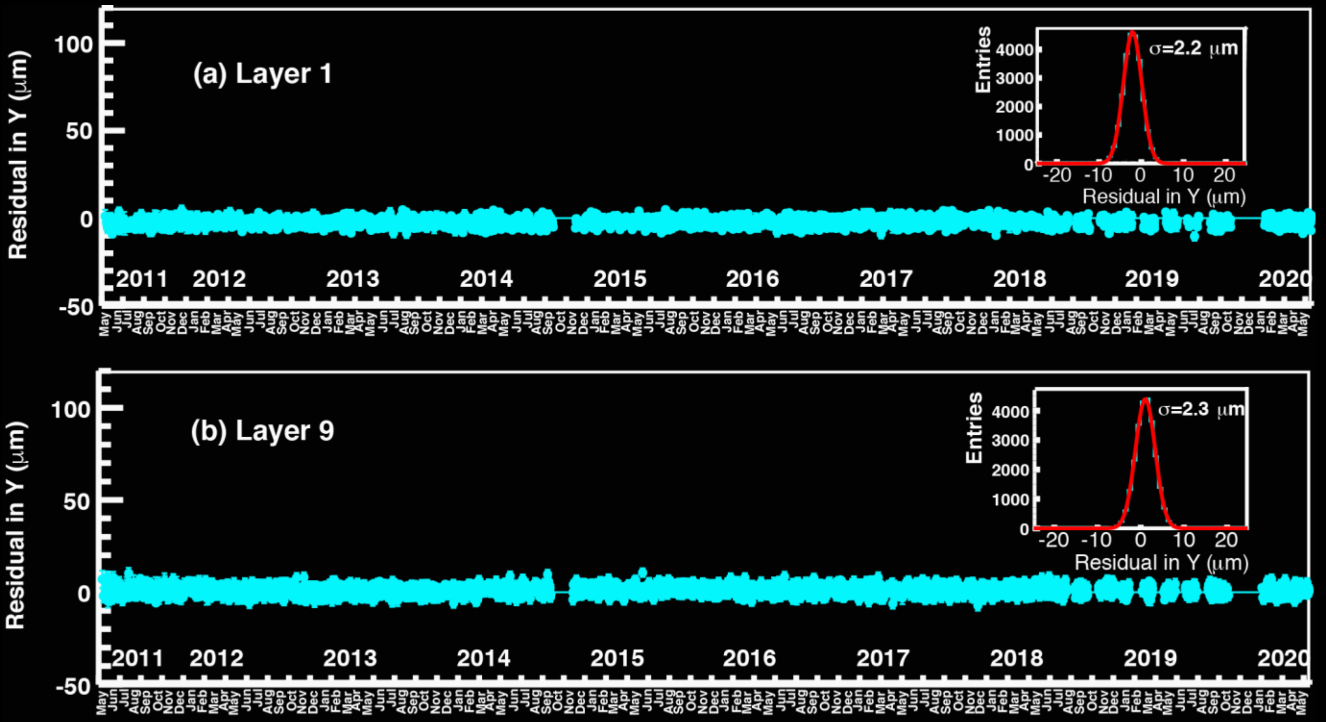
separation between Fe and Co is better than 1 in 10^2

With the unprecedented statistics of ~240 billion events we have precise spectroscopy of all cosmic ray nuclei.

In-Flight Momentum Scale and Sign Determination

Alignment

Position of inner layers L2-L8 monitored with lasers to an accuracy below 1 μm.

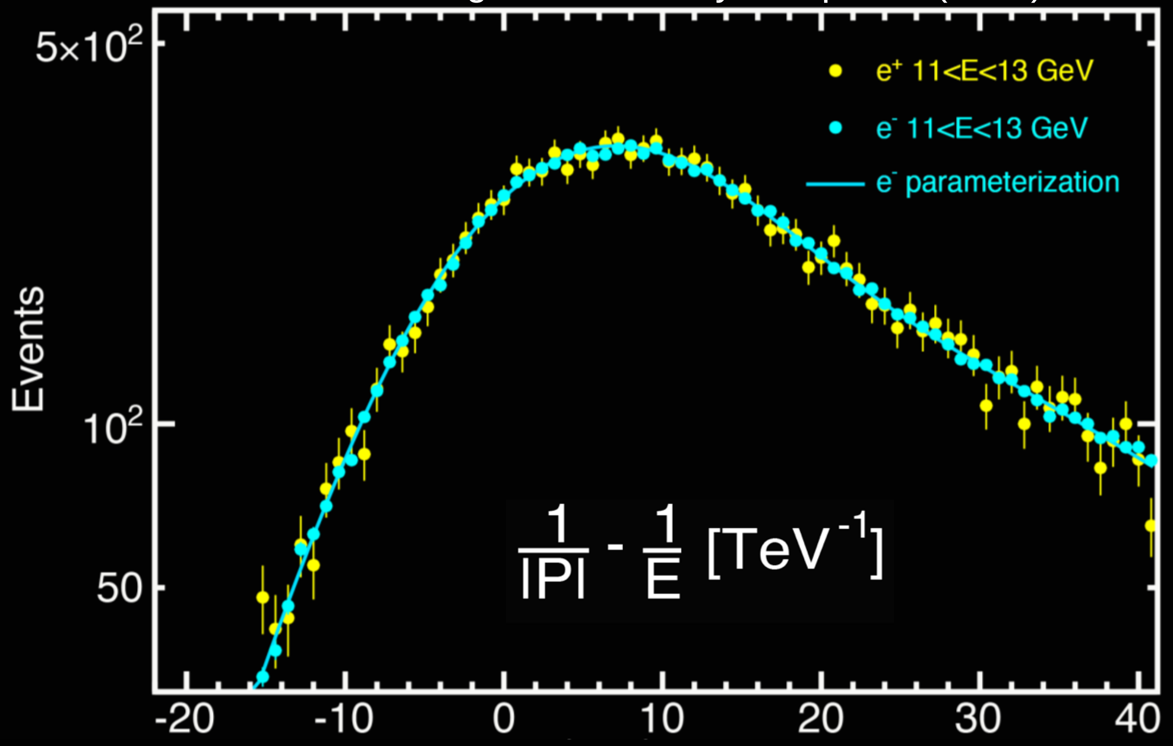


Position of outer layers L1 and L9 monitored every 2 minutes by cosmic rays with an accuracy up to 2 μm over 13 years.

Momentum Scale

Comparison of momentum from Tracker (P) and Energy (E) from ECAL for samples of positrons and electrons.

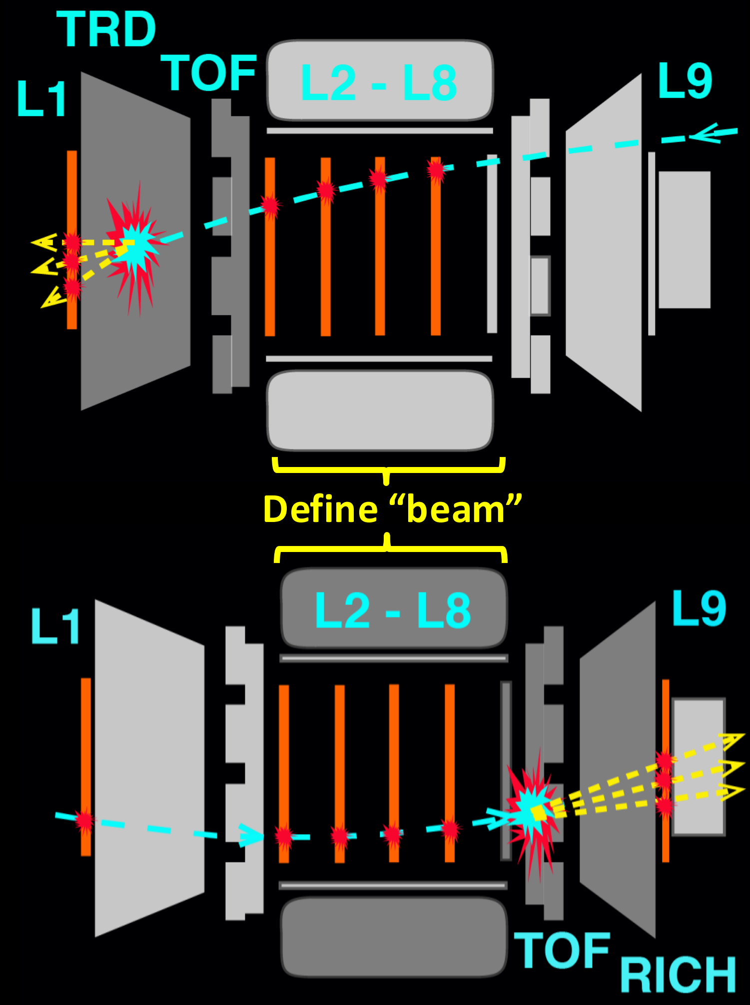
M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.



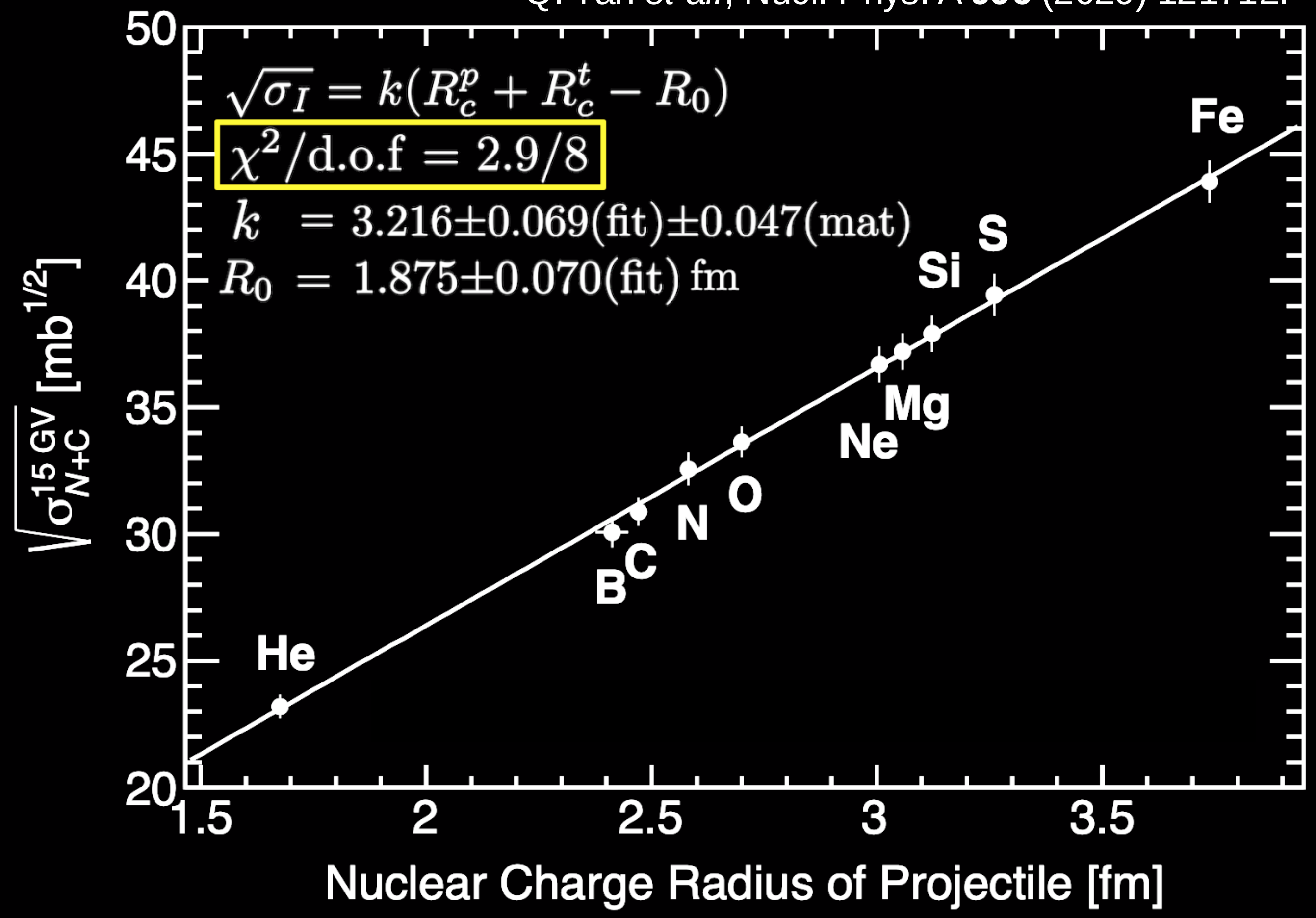
The accuracy of the momentum scale is determined to be 1/(34 TeV) i.e., at 1 TeV the uncertainty is less than 3%.

In-Flight Nuclear Cross Section Measurement

The absolute value of the cosmic ray fluxes is controlled by the direct measurement of nuclear inelastic cross-section with cosmic rays with AMS material (mainly C, Al).

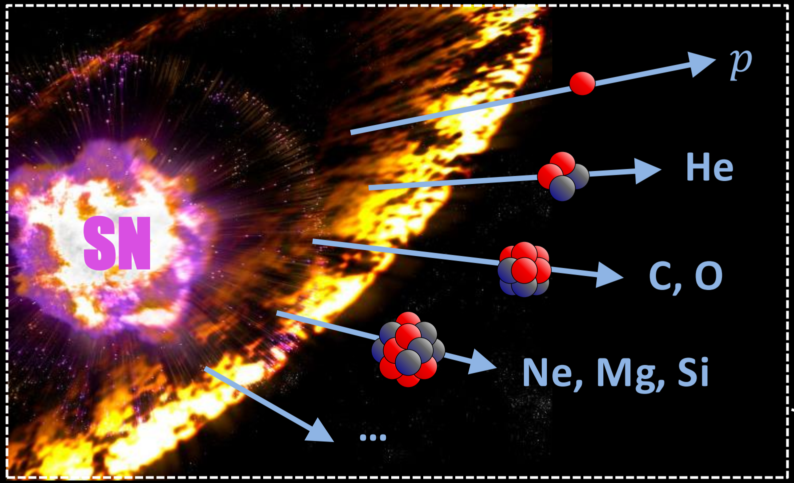


Q. Yan *et al.*, Nucl. Phys. A **996** (2020) 121712.

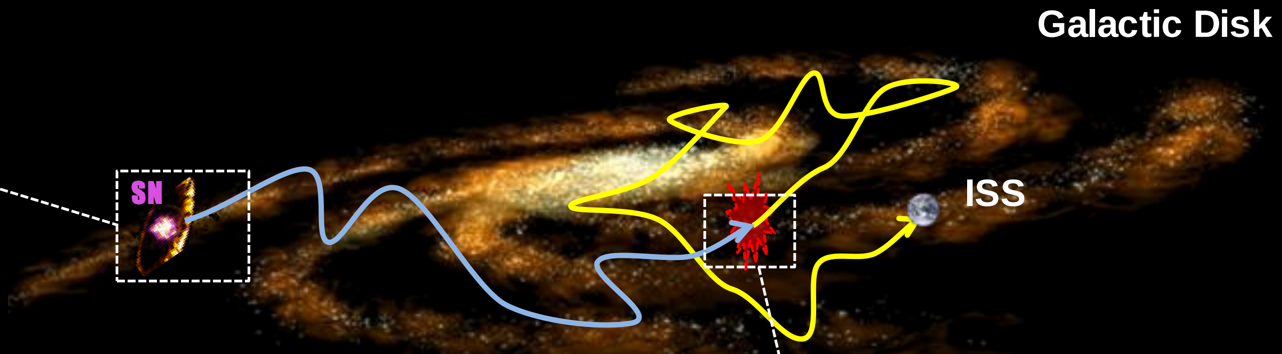


AMS has made nuclei Interaction cross-section measurements (N+C) in a wide rigidity range from a few GV to TV allowing for the precise control of the flux normalization.

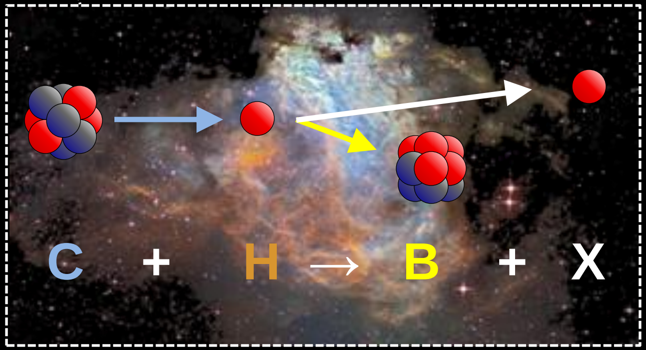
Primary and Secondary CRs



Primary GCRs (e^-, p, He, C, O, Ne, Mg, Si, ..., Fe) are thought to be mostly produced during the lifetime of stars and accelerated by astrophysical processes (as supernovae shocks) in our Galaxy.



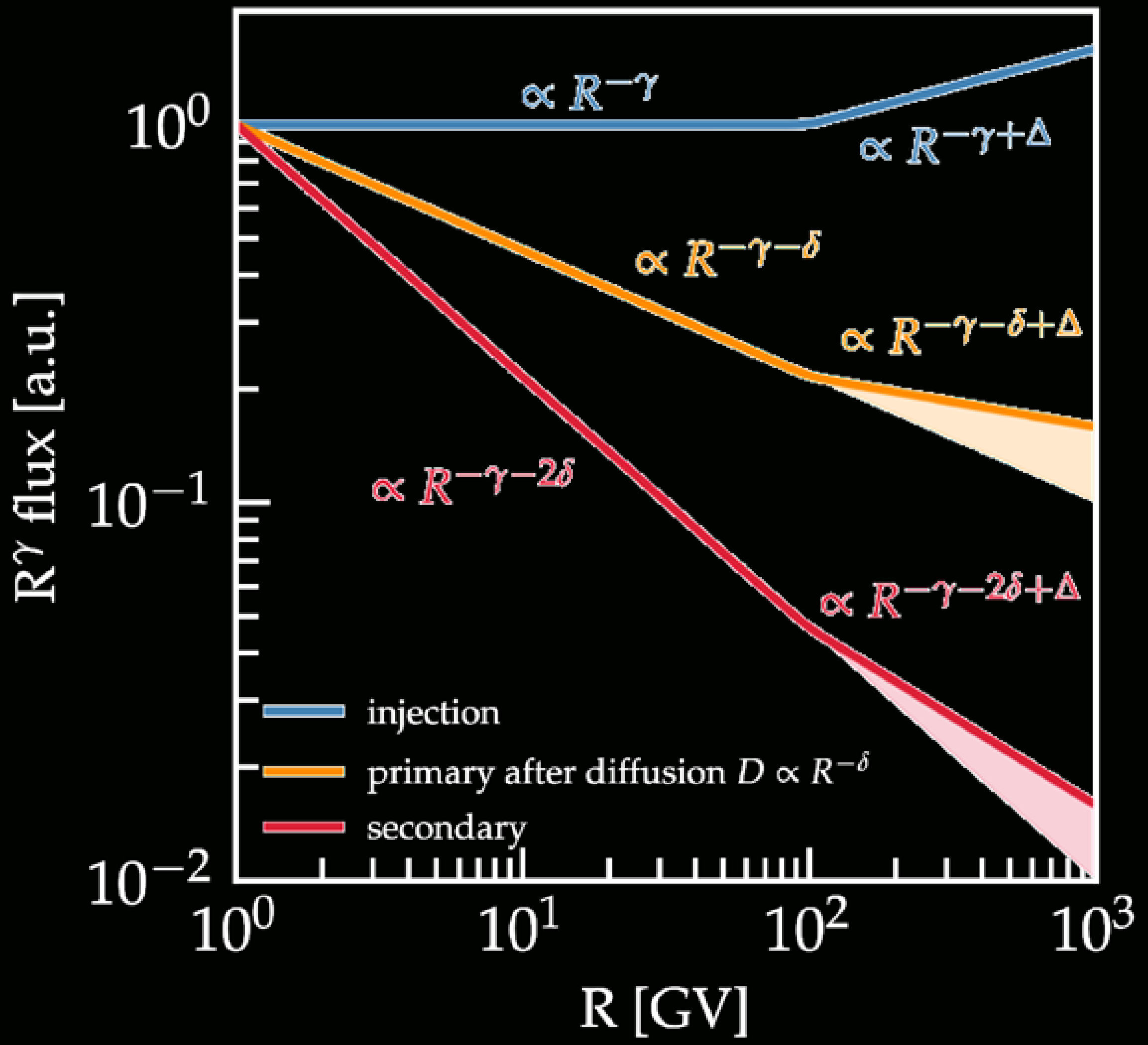
Secondary GCRs (e^+, $\bar{p}$, Li, Be, B, F, sub-Fe, …) are mostly produced from collision of primaries with the interstellar medium.

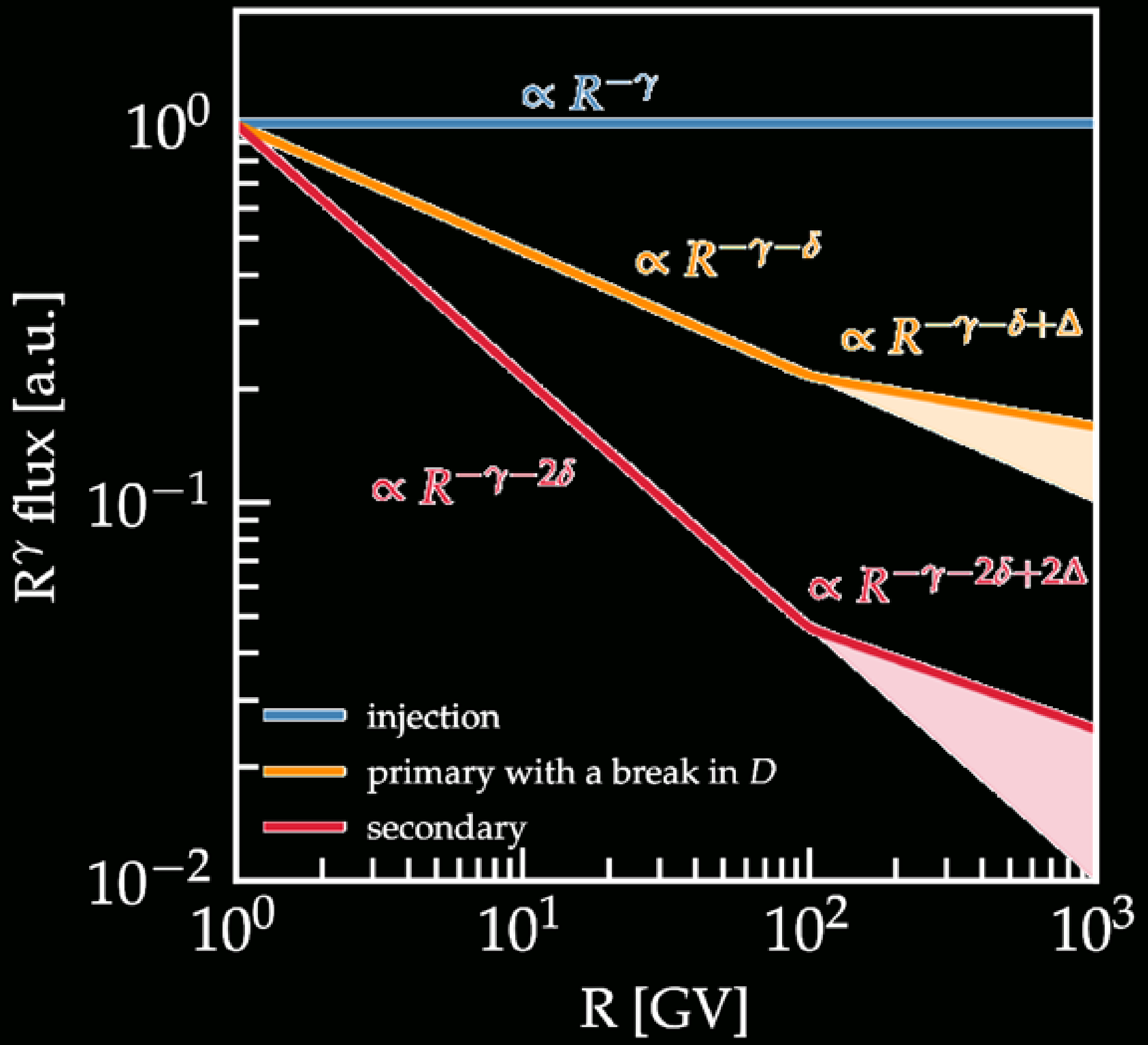


Measurements of primary and secondary cosmic ray fluxes help the understanding the origin and propagation of cosmic rays in the Galaxy.

Cosmic Ray Propagation

From C. Evoli (2019).

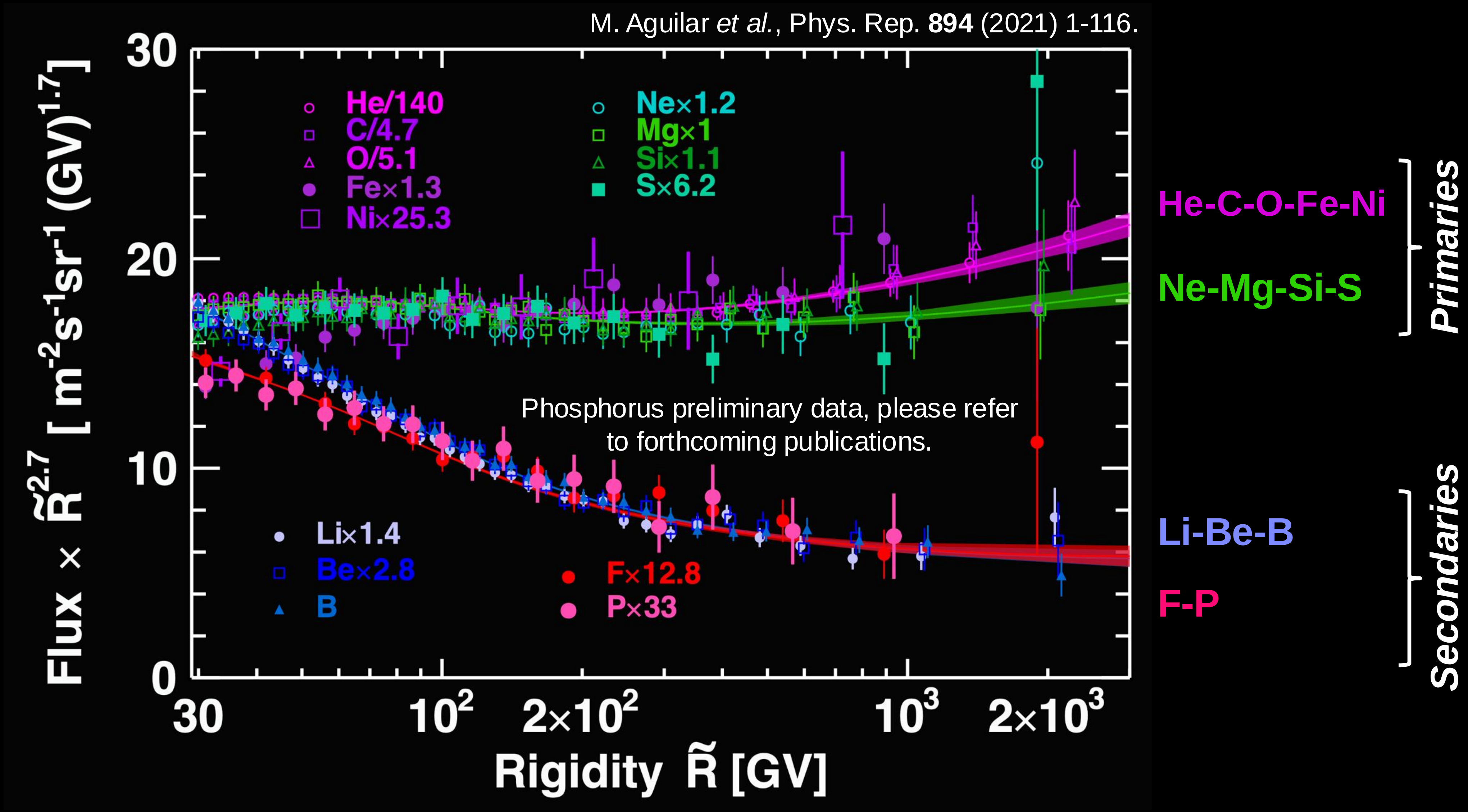




If the hardening in CRs is related to the **injected spectra** at their source, then **similar hardening** is expected both for secondary and primary CRs.

If the hardening is related to **propagation properties** in the Galaxy, then a **stronger hardening** is expected for the secondary with respect to the primary CRs.

Primary and Secondary Species with AMS-02

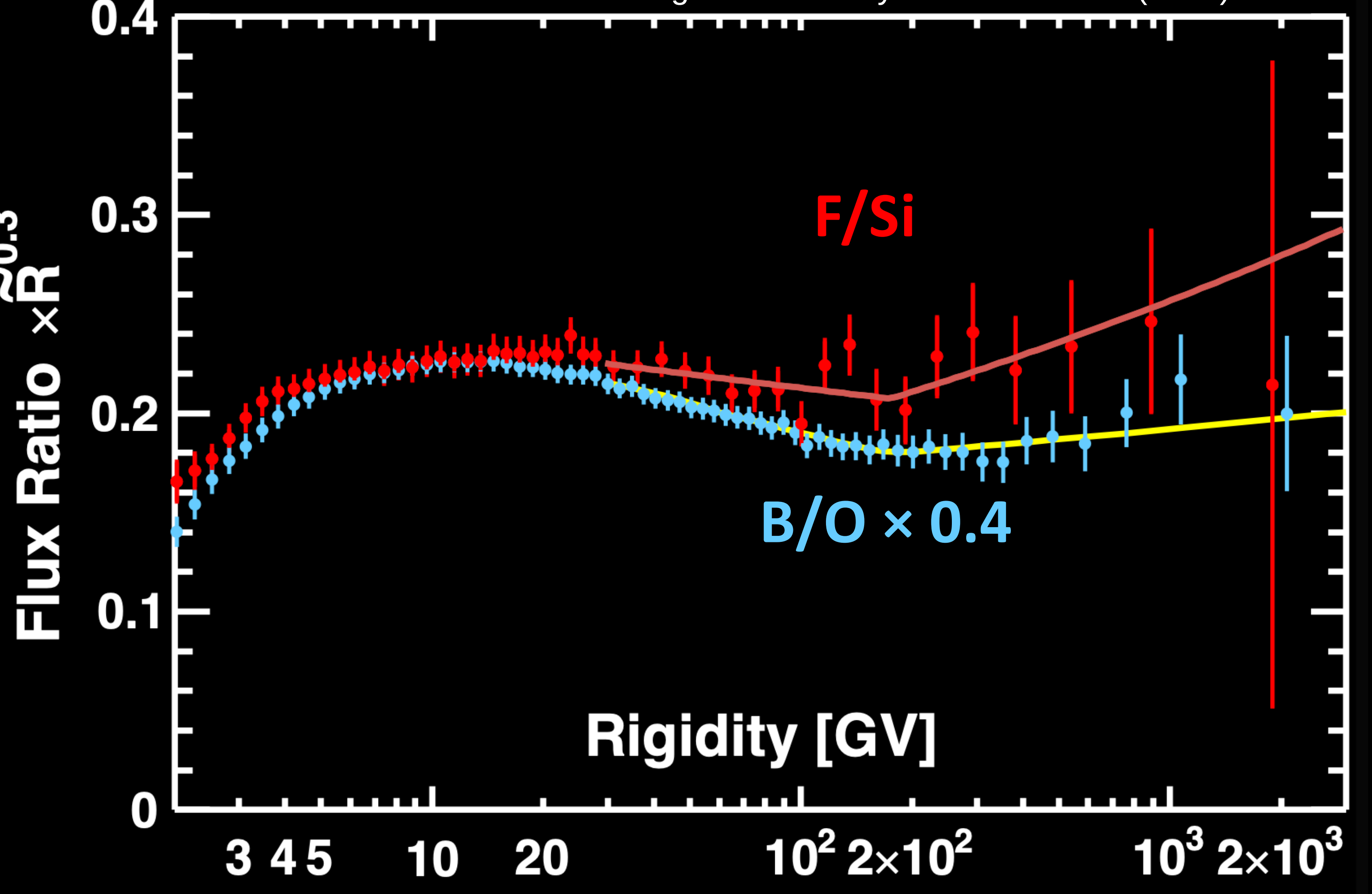


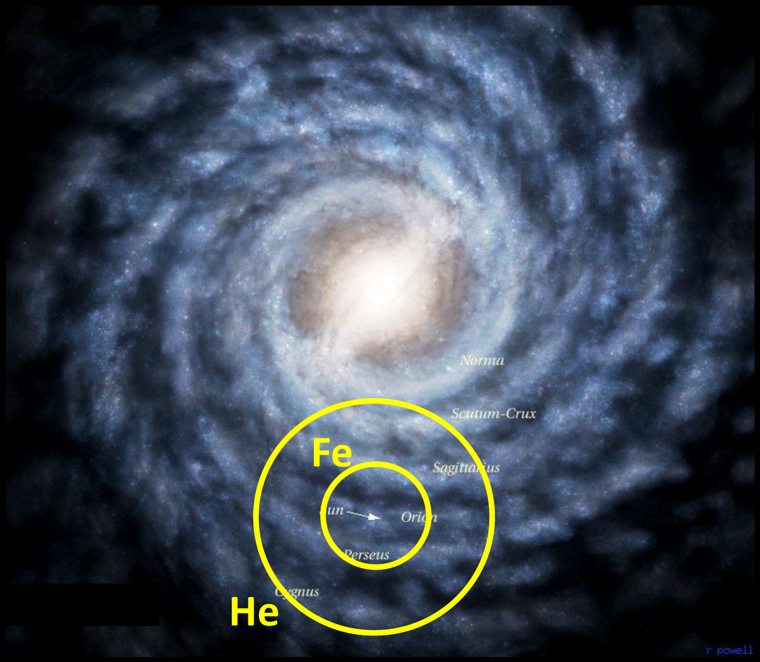
- All cosmic rays (both primary and secondaries) show a **spectral hardening at about 200 GV**.
- **Secondary harden more than primaries** favouring the existence of a propagation feature.
- There are different behaviours in the primaries and secondaries (proton spectrum is peculiar, …).

Secondary/Primary Ratios

Secondary/primary ratio show are directly connected with cosmic ray diffusion.
The study of ratios at different Z tests diffusion in different galactic volumes.

M. Aguilar et al. Phys. Rev. Lett. **126** (2021) 081102.

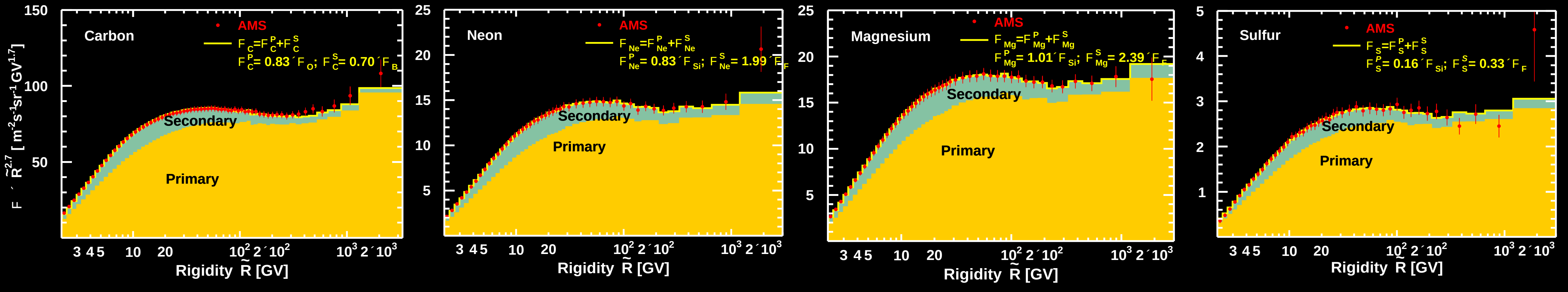




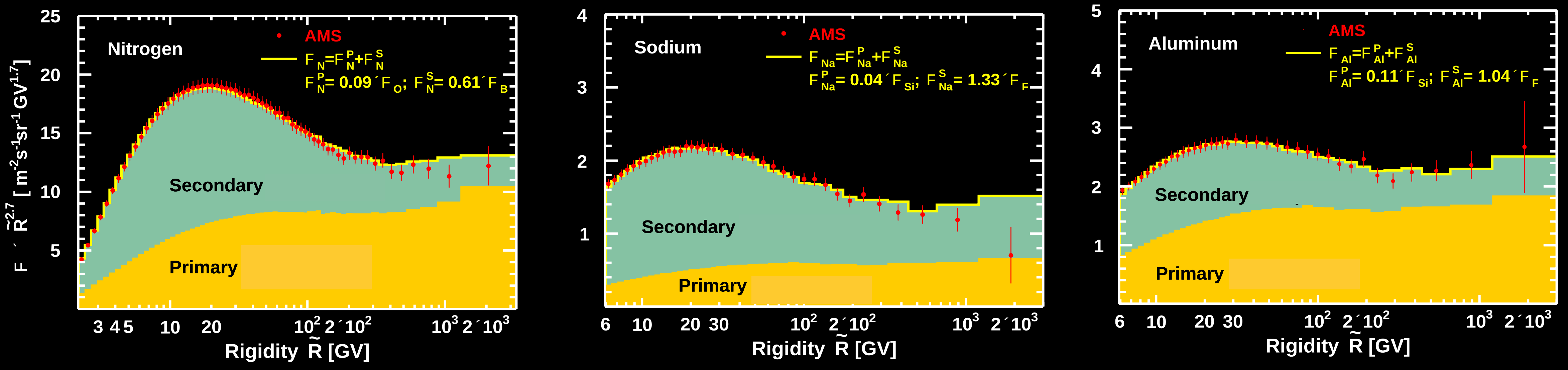
Above 175 GV, the F/Si ratio exhibits a hardening compatible with the one of B/O ratio.
The ratio (F/Si)/(B/O) can be fitted with a power law with no feature at 200 GV.

Model Independent Primary/Secondary Composition with AMS

The composition fits are based on assumed pure primary (O, Si) and secondary (B, F) fluxes.

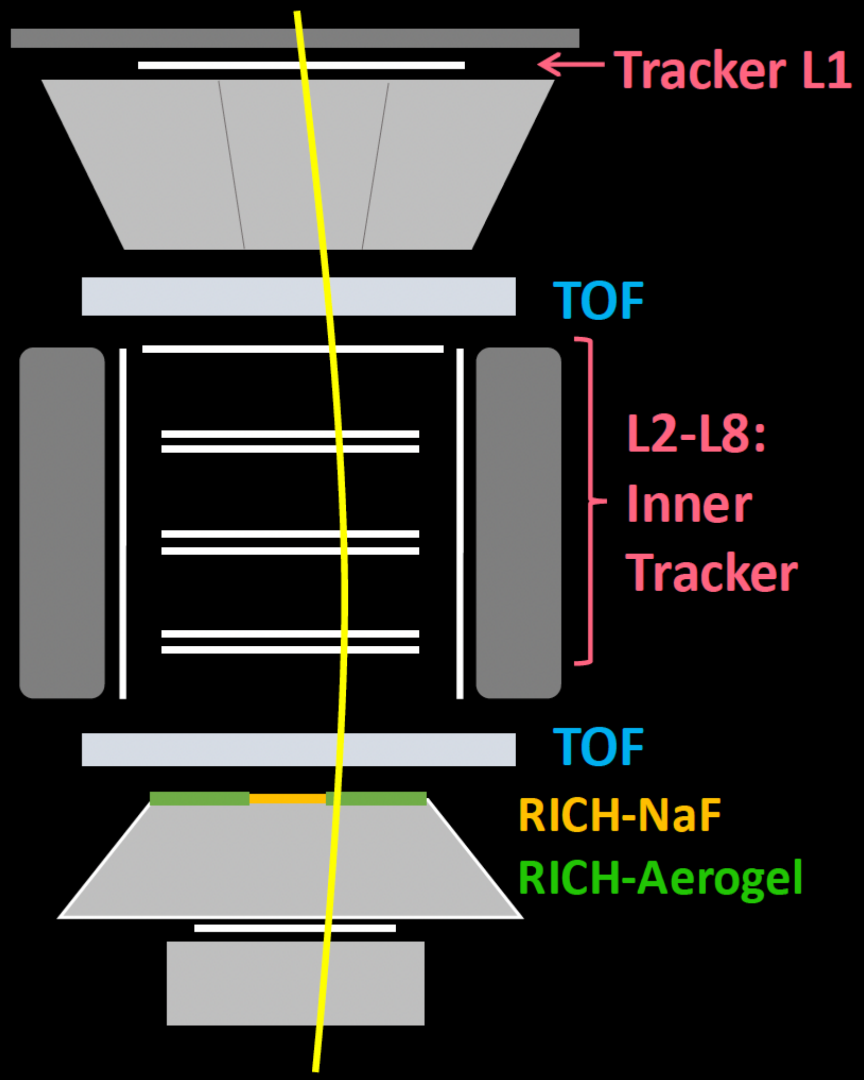


Even-Z nuclei are dominated by primaries



Odd-Z nuclei have more secondaries than even-Z

Isotopic Composition



- AMS mass resolution depends on rigidity ($R = P/Z$) and velocity (β) resolutions:

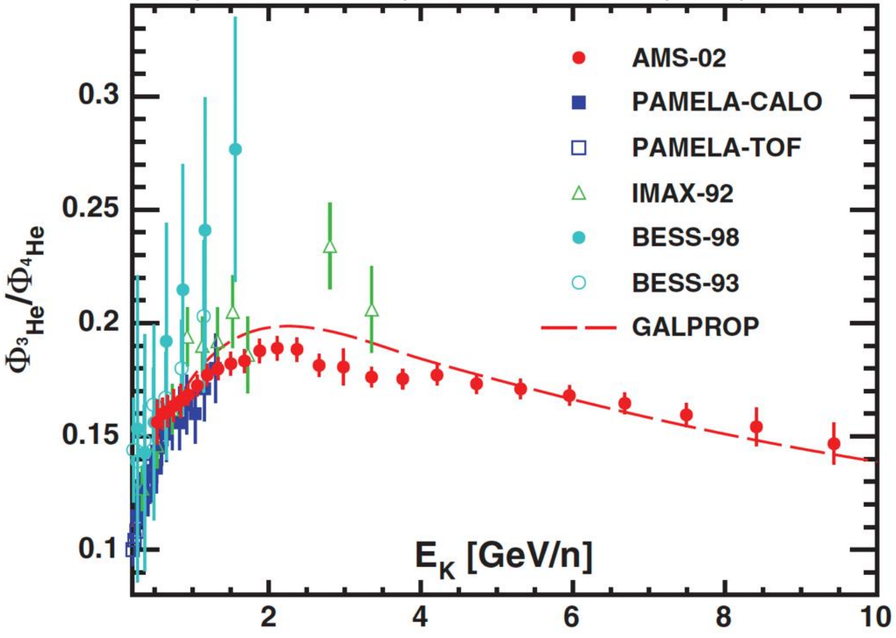
$$\frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\frac{1}{1-\beta^2} \cdot \frac{\Delta\beta}{\beta}\right)^2}$$

- R measurement :
  - Tracker, $\frac{\Delta R}{R} \sim 9\%(Z = 1), 10\%(Z = 4)$ below 20 GV
- β measurements:

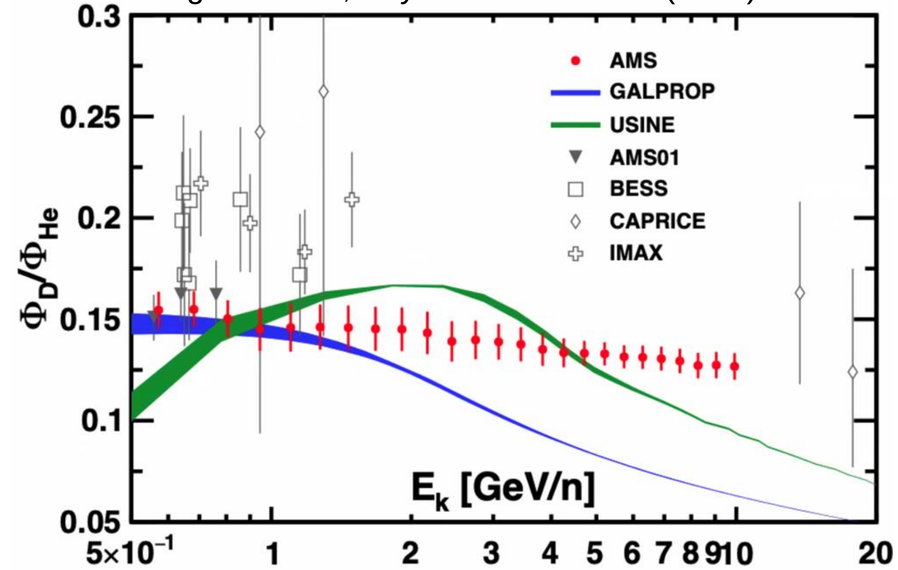
	E_k/n range (GeV/n)	$\Delta\beta/\beta$ $(Z = 1)$	$\Delta\beta/\beta$ $(Z = 4)$
TOF	(0.4, 1.2)	$\sim 4\%$	$\sim 1.5\%$
RICH-NaF	(0.8, 4.0)	$\sim 0.35\%$	$\sim 0.15\%$
RICH-Aerogel	(3.0, 12)	$\sim 0.12\%$	$\sim 0.05\%$

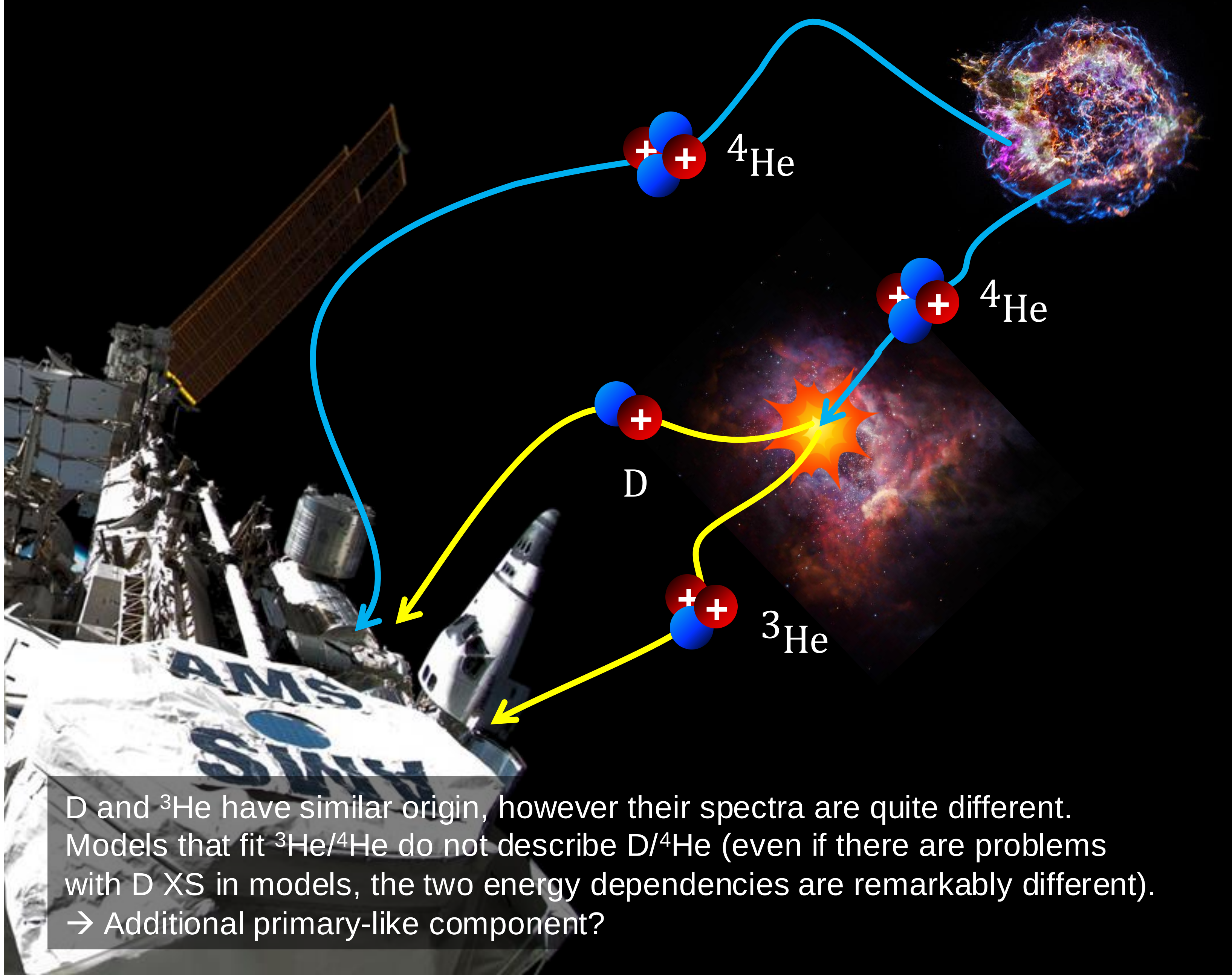
Secondary/Primary Ratios with Light Isotopes

M. Aguilar et al., Phys. Rev. Lett. **123** (2019) 181102.



M. Aguilar et al., Phys. Rev. Lett. **132** (2024) 261001.

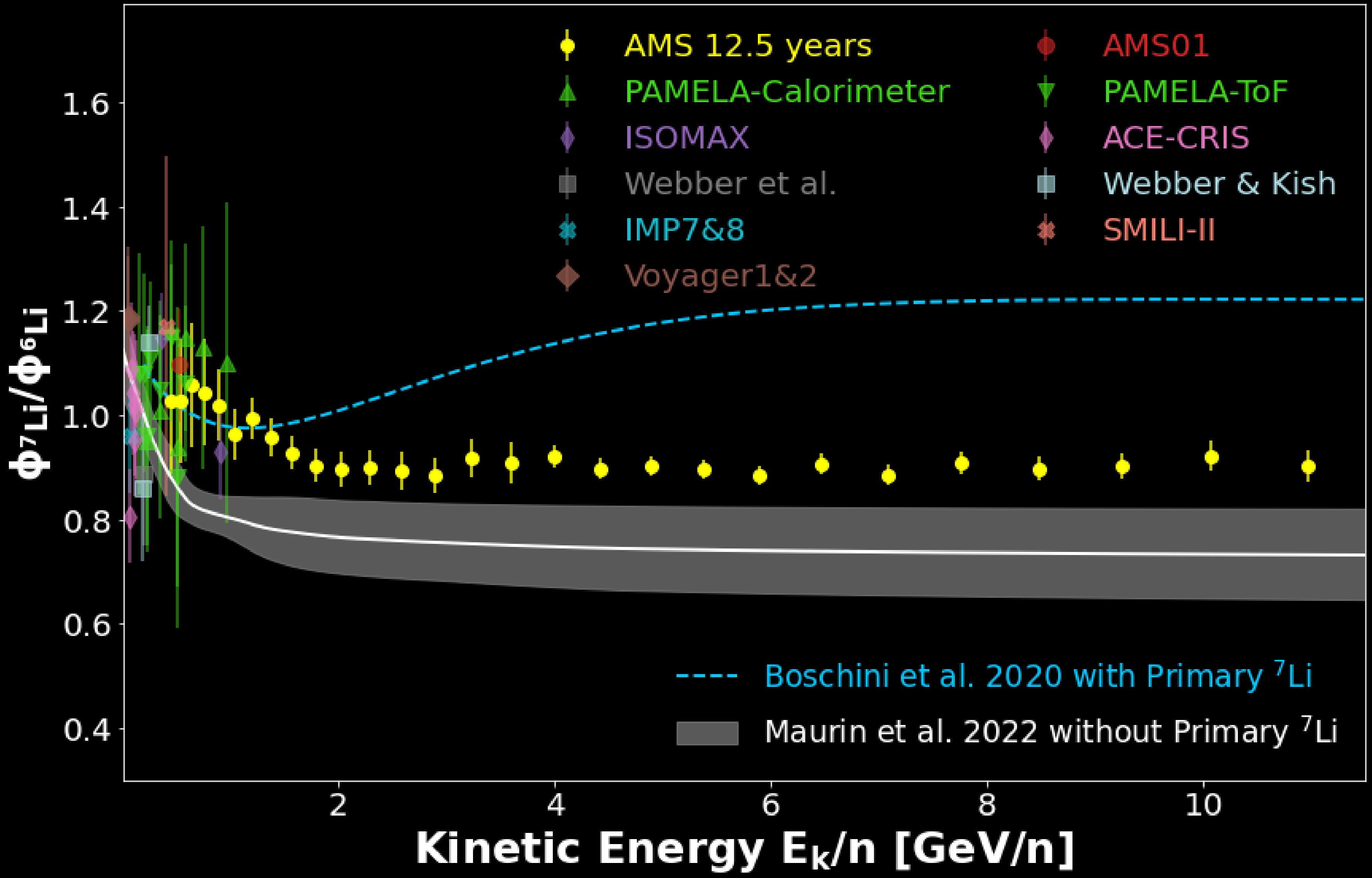




D and ^{3}He have similar origin, however their spectra are quite different.
Models that fit ^{3}He/^{4}He do not describe D/^{4}He (even if there are problems with D XS in models, the two energy dependencies are remarkably different).
→ Additional primary-like component?

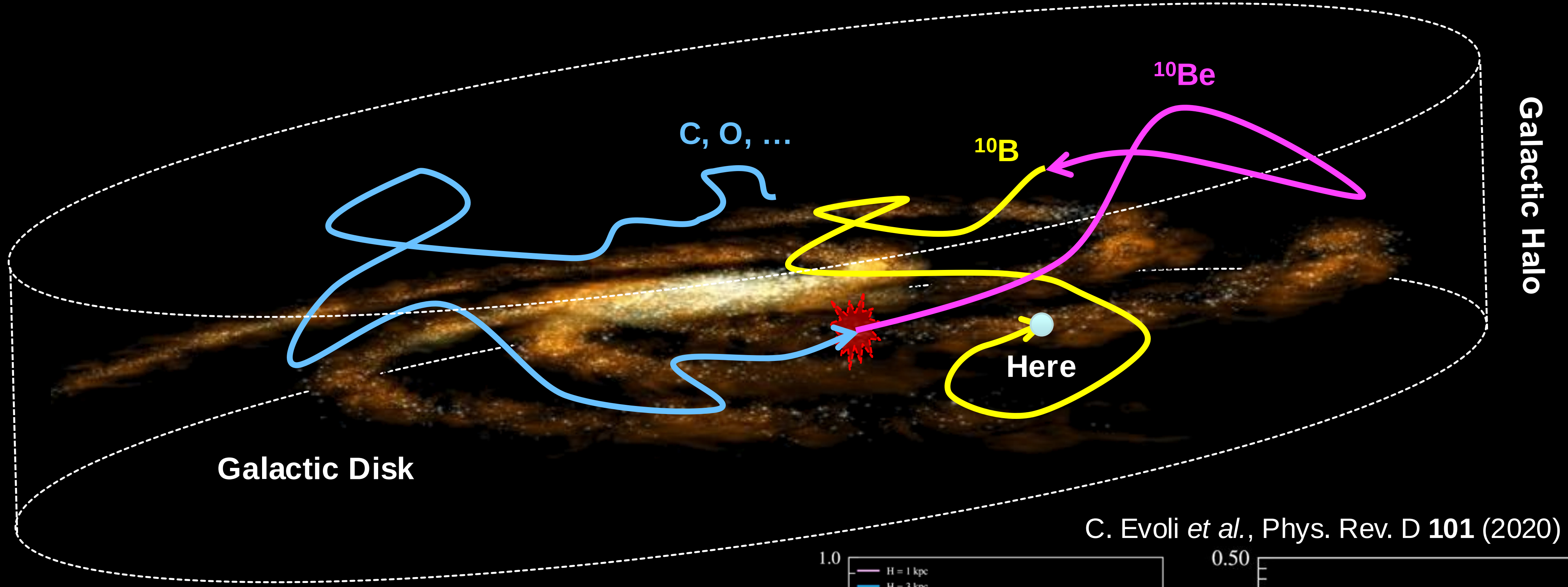
Testing Lithium Isotopes Origin

Submitted to Phys. Rev. Lett.

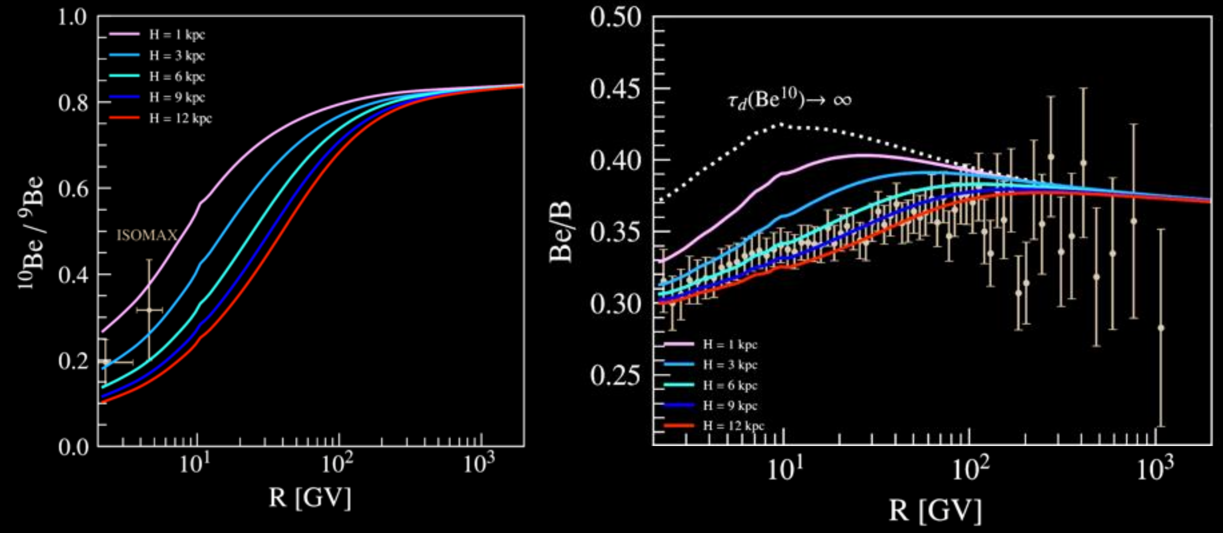


AMS data disfavors models with presence of 7Li primary component.

Unstable Secondary Cosmic Rays



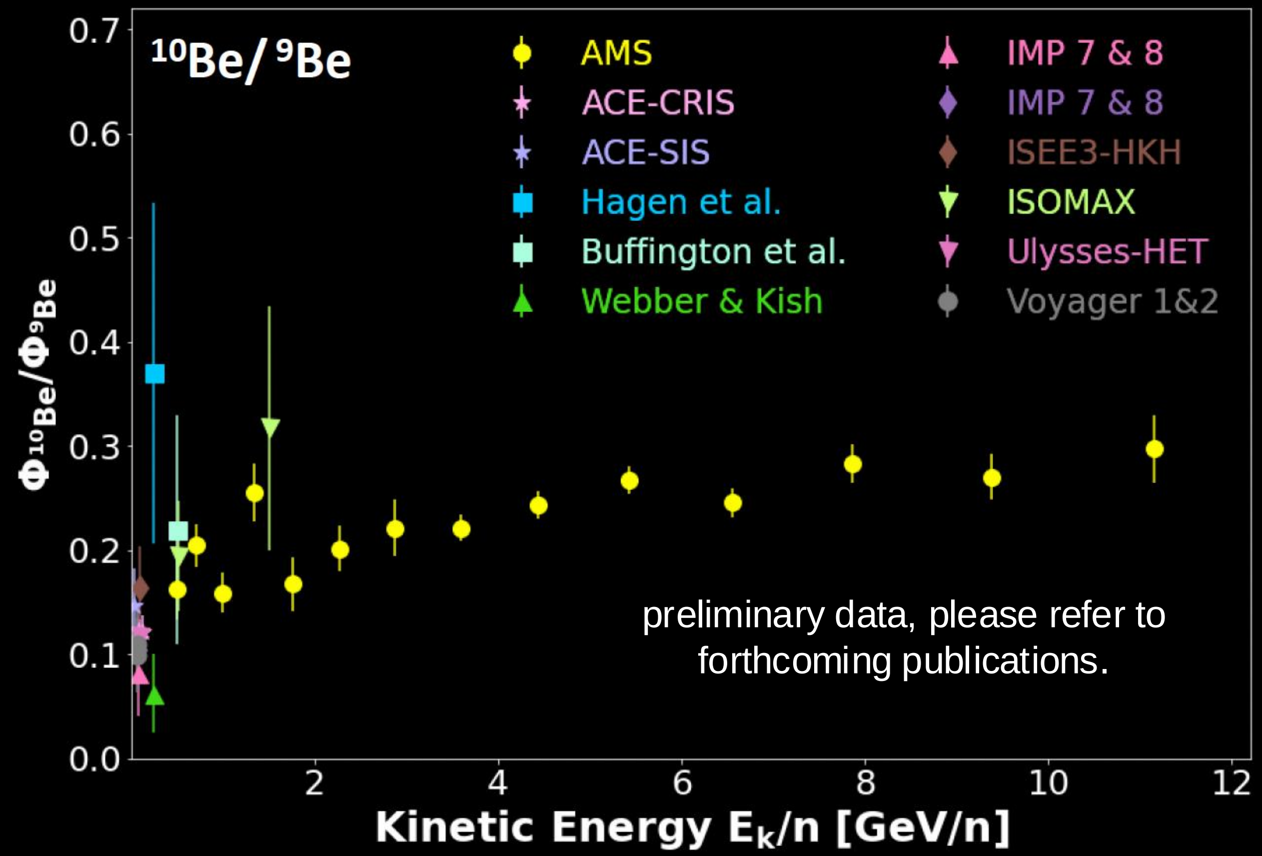
C. Evoli *et al.*, Phys. Rev. D **101** (2020) 023013.

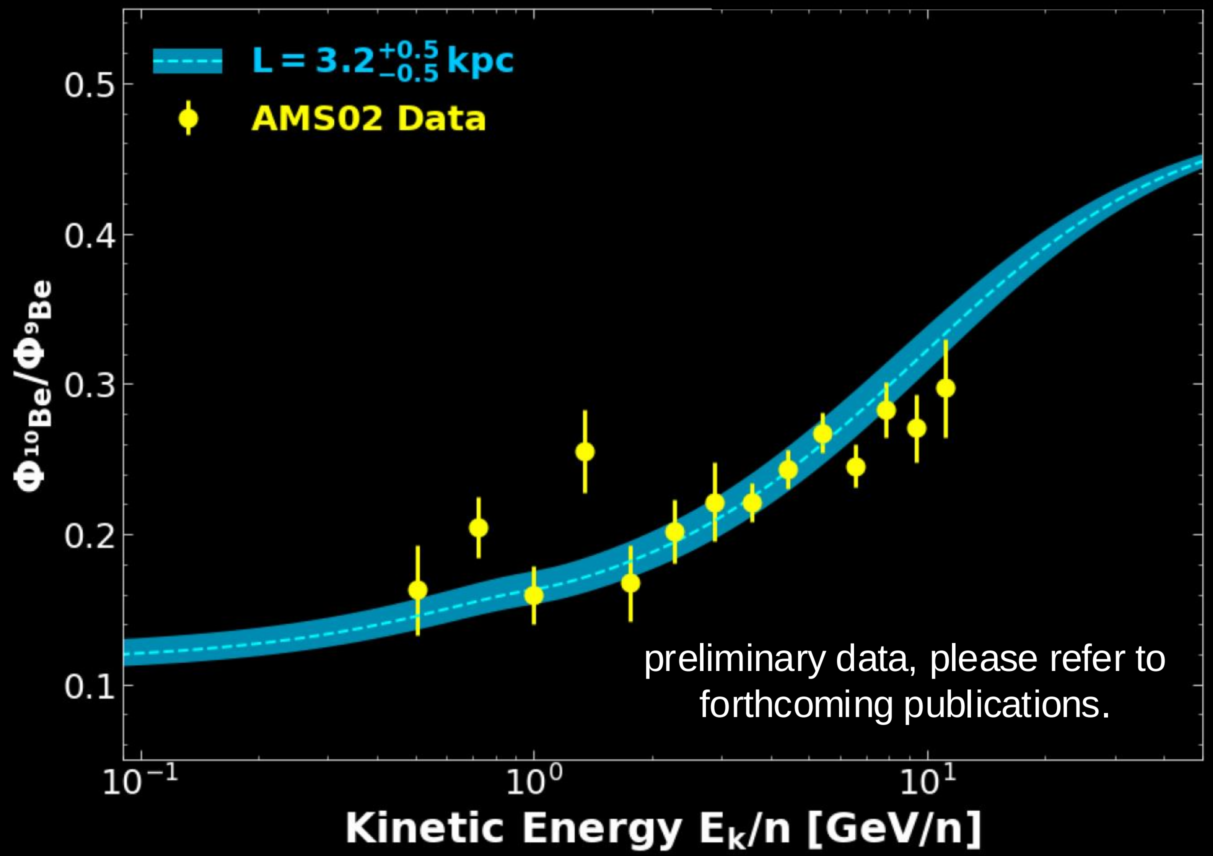


The secondary ^{10}Be β-decays ($^{10}\mathrm{Be} \to {}^{10}\mathrm{B} + e^- + \bar{\nu}_e$) with a half-life of $t_{1/2}$ = 1.4 My.
Differently from spallation production, happening only on the galactic disk, ^{10}Be may decay anywhere.
Therefore, the amount of ^{10}Be (and ^{10}B) with respect to other secondaries, depends to the **galactic halo size**.

Preliminary Measurement $^{10}Be/^{9}Be$ with AMS-02

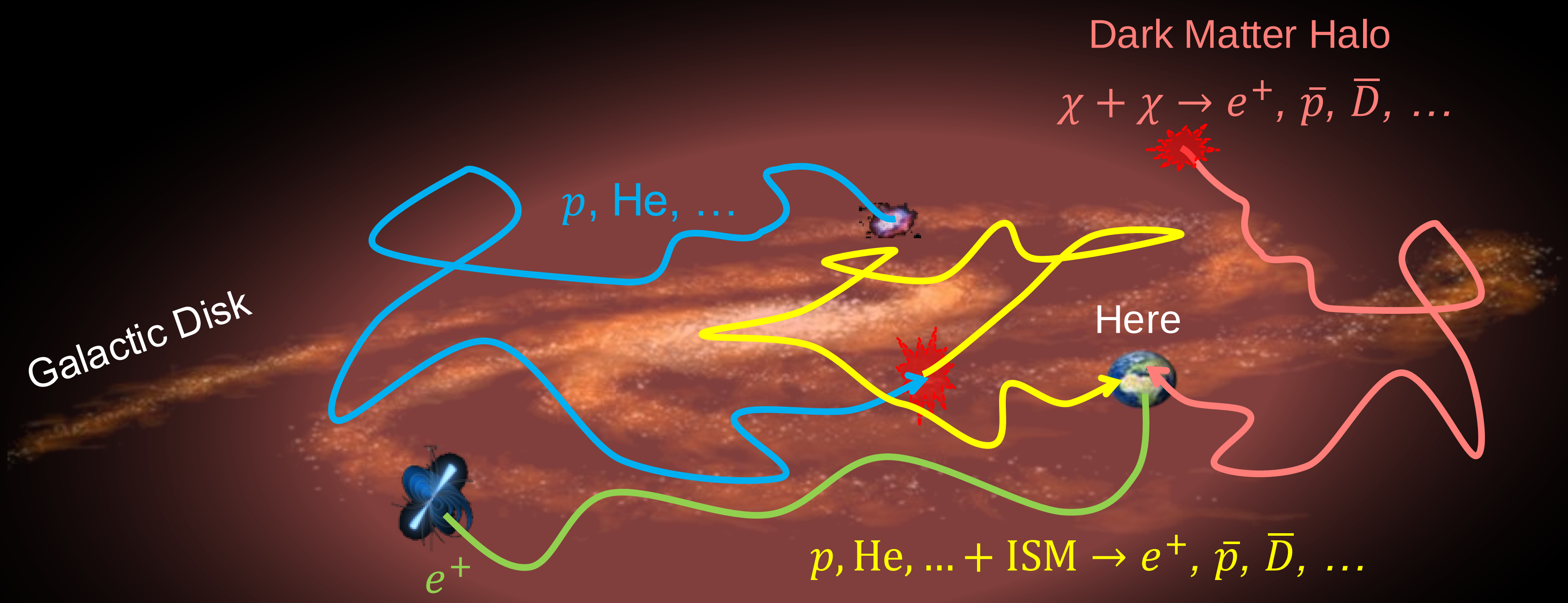
F. Giovacchini, ECRS 2024.

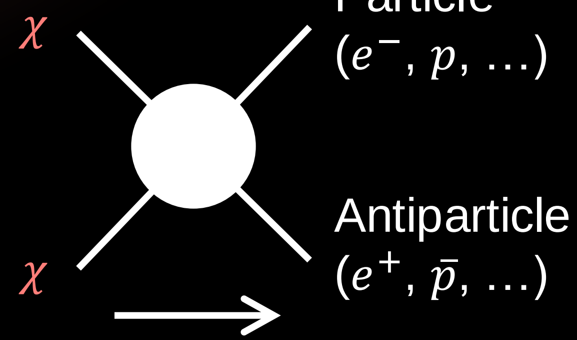




- The precision on the Galactic halo size L from the AMS data is about ~0.5 kpc.
- Error on L is dominated by the **uncertainty on spallation cross-sections** ~1 kpc (D. Maurin *et al.,* A&A **667** (2022) A25).
- Good news there, SHINE/NA-61 took data with SPS nuclei beam for the measurement of nuclear fragmentation XS.

Indirect Dark Matter Search with Cosmic Ray Antimatter





We assume that antimatter in cosmic rays is composed by:

- **Secondary production** of cosmic rays' collisions with interstellar medium.
- **Sources** (pulsar, …).
- **Dark matter annihilation.**

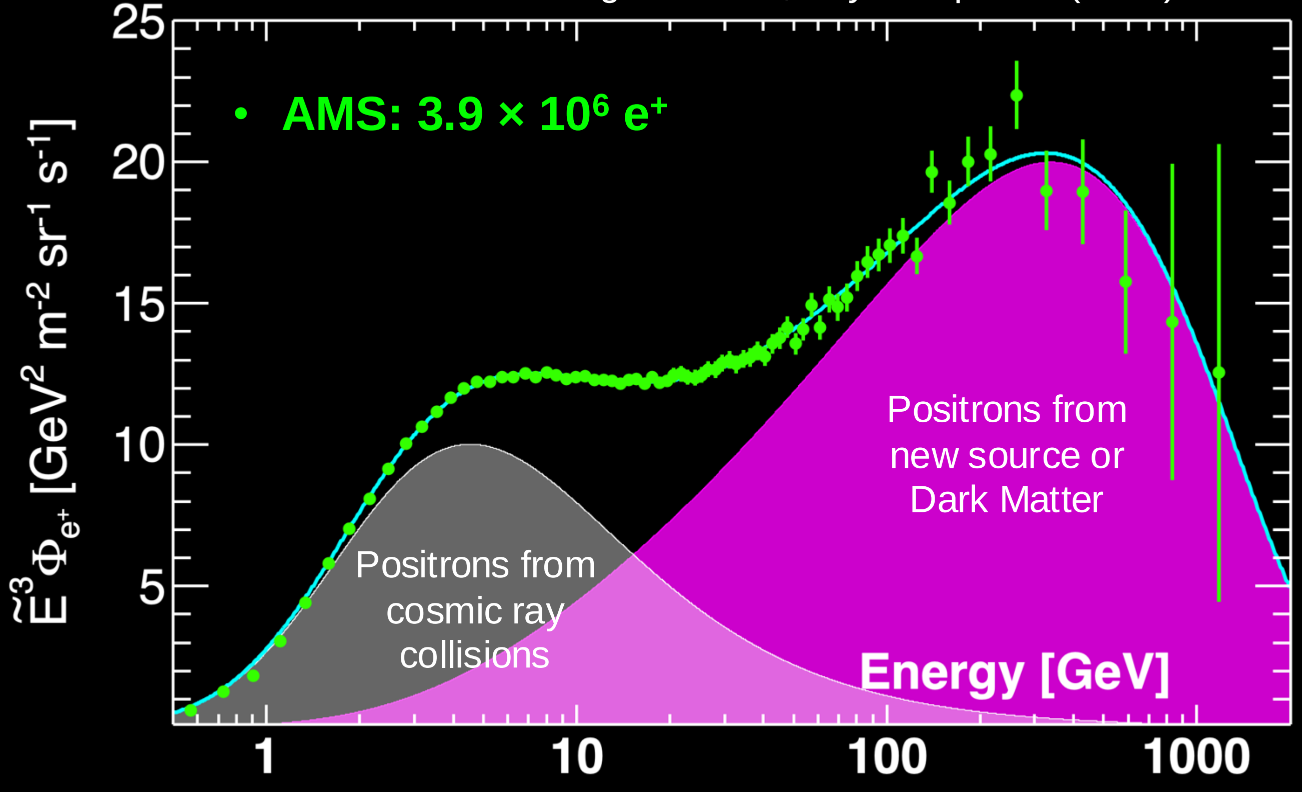
Positron Flux

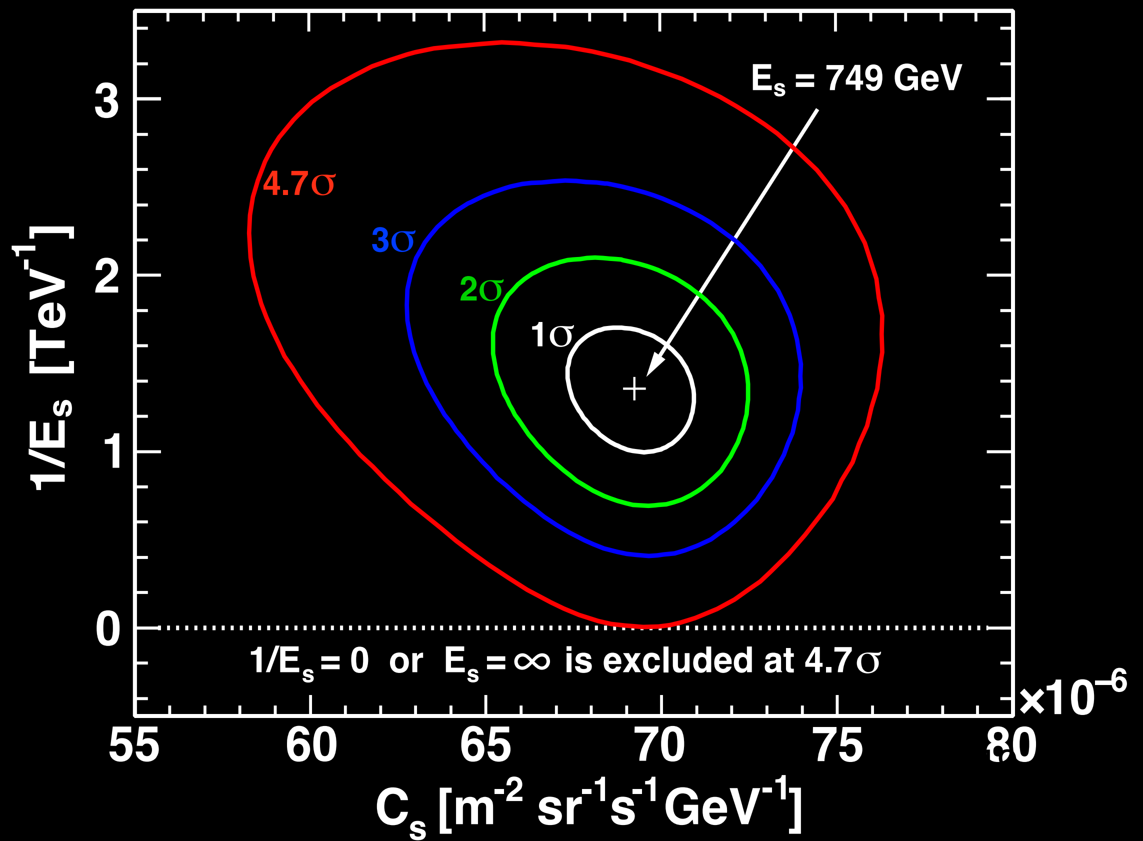
The positron flux is modeled with the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter both with a cutoff energy E_S.

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

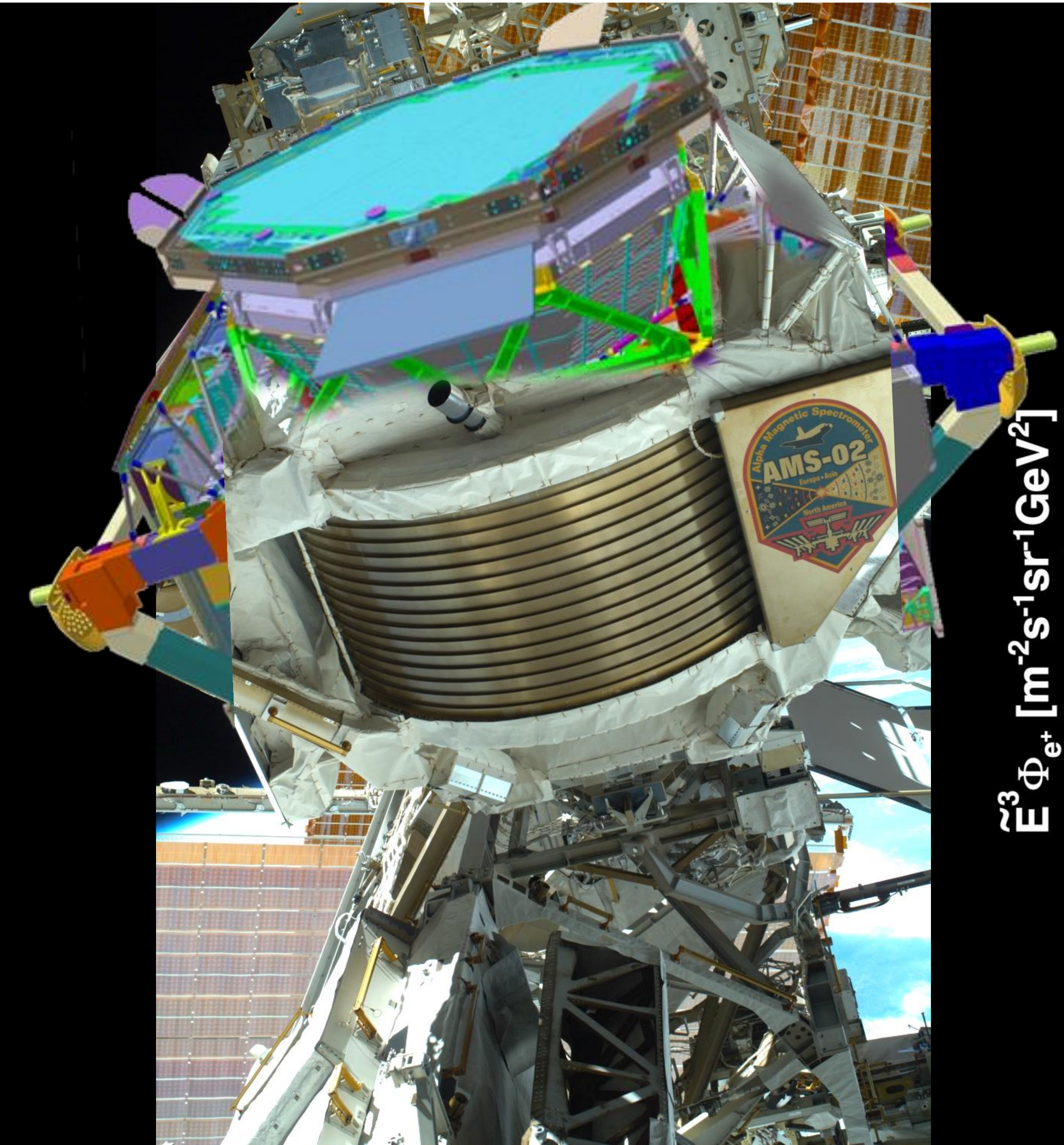
Solar Collisions Pulsars or Dark Matter

M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.

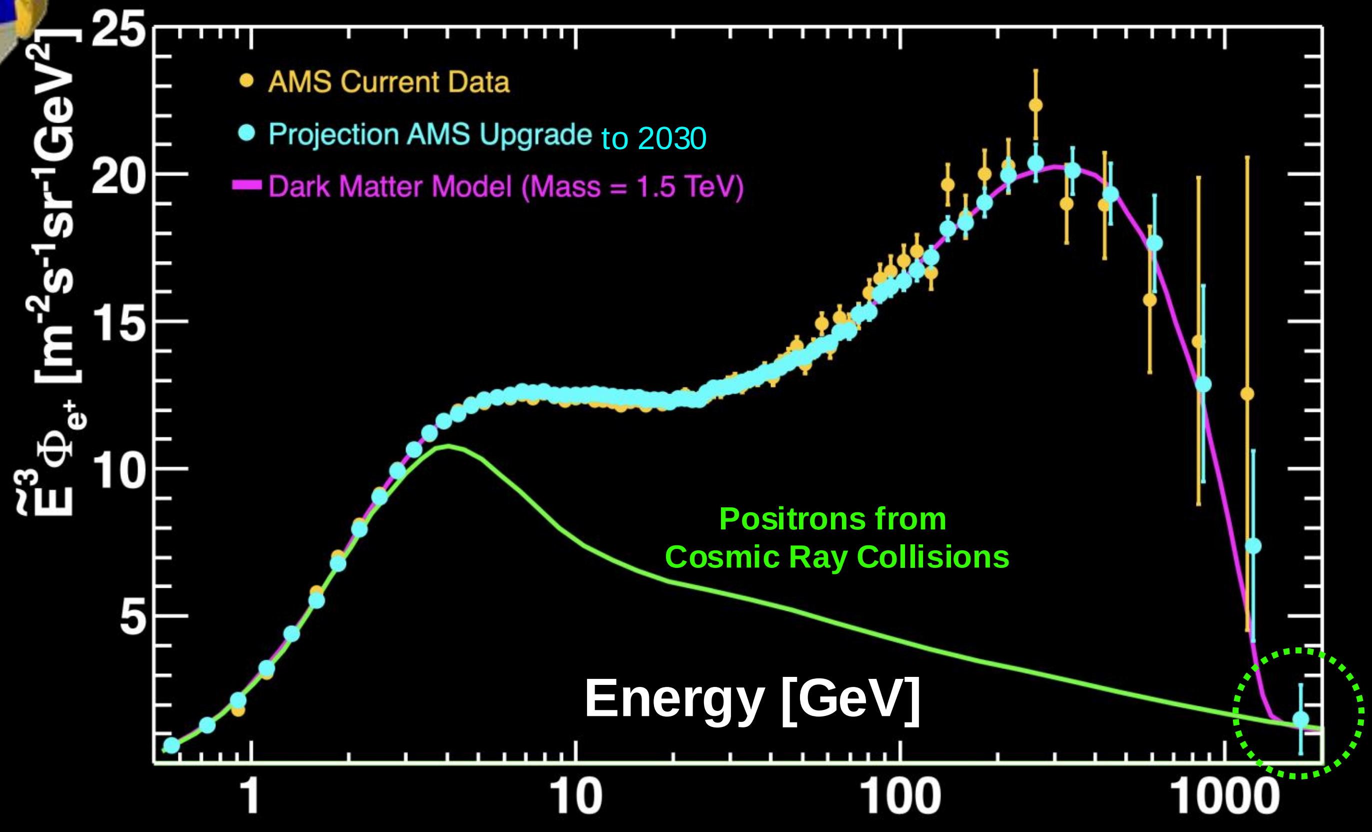




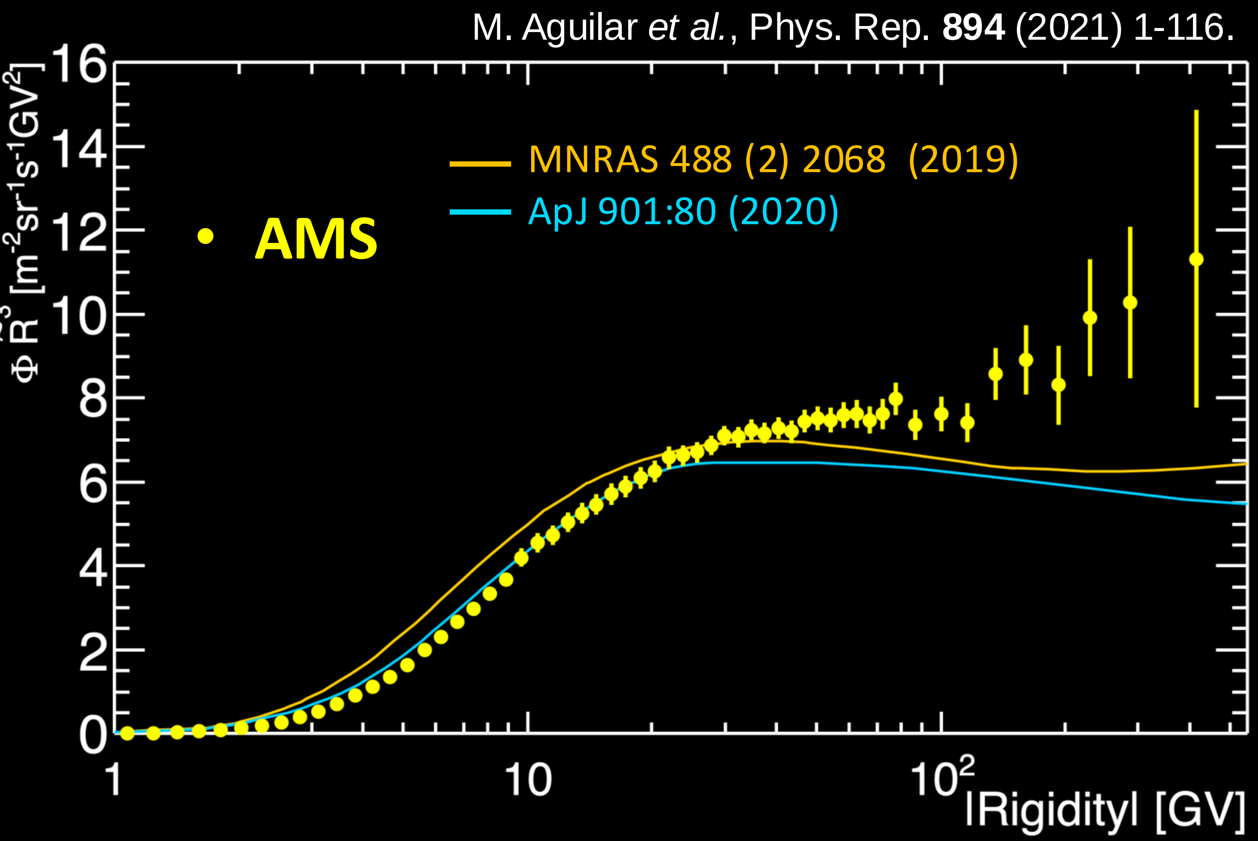
The AMS-02 Upgrade

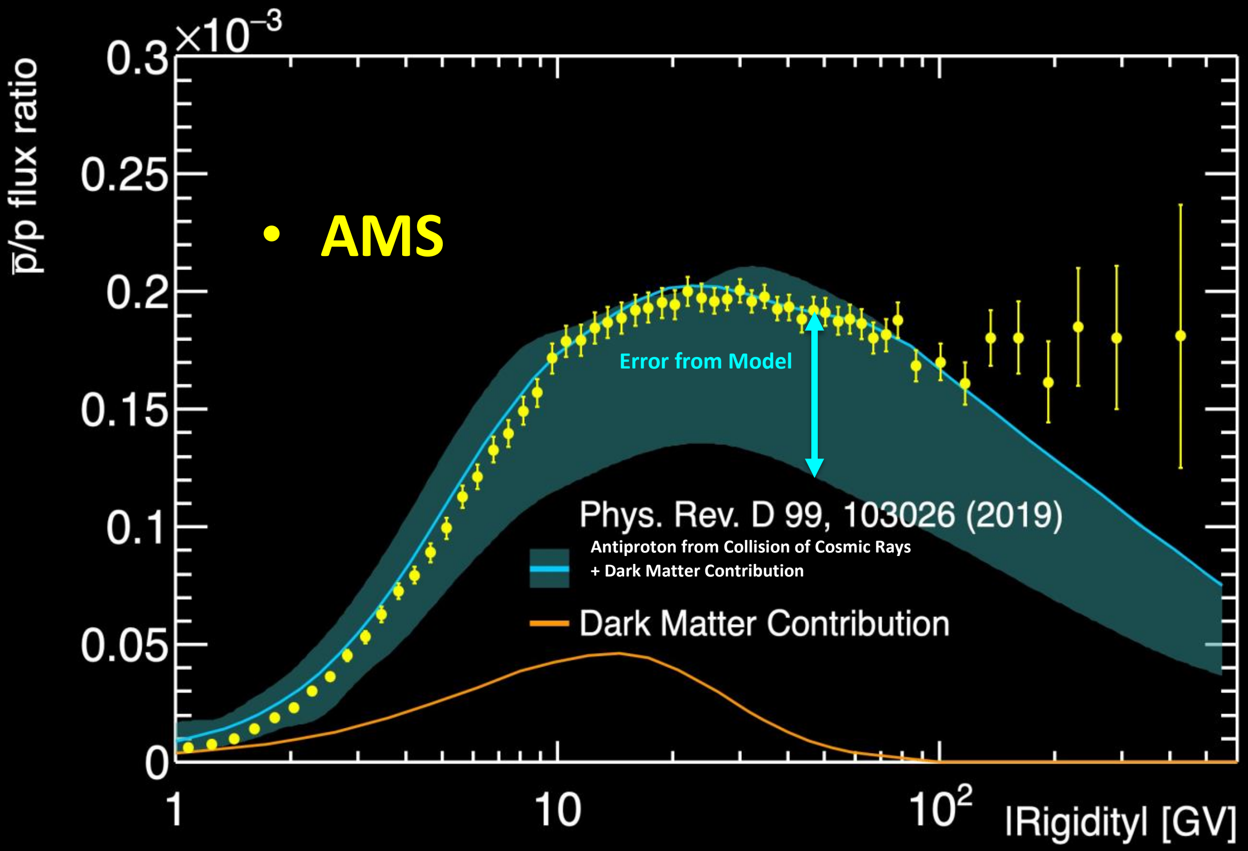


- A large (2.6m diagonal) layer with silicon sensors on both sides to be added on top of AMS.
- Set to be installed on AMS in **2026**.
- The upgrade will allow to collect high energy positrons (and many other particles) with a **3-fold rate**.
- This will allow to study the difference between sources and secondary production models for positrons.



Antiproton Flux

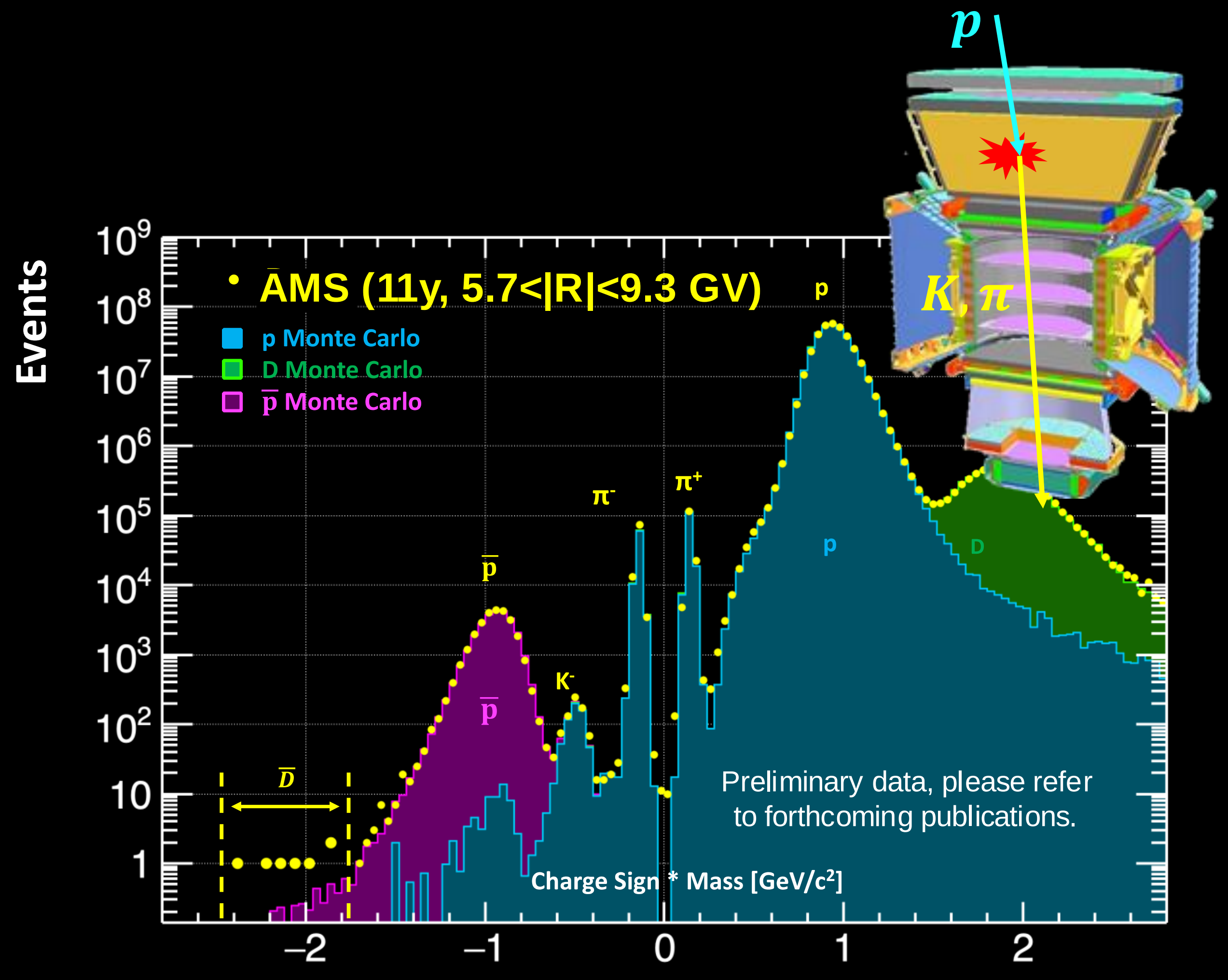


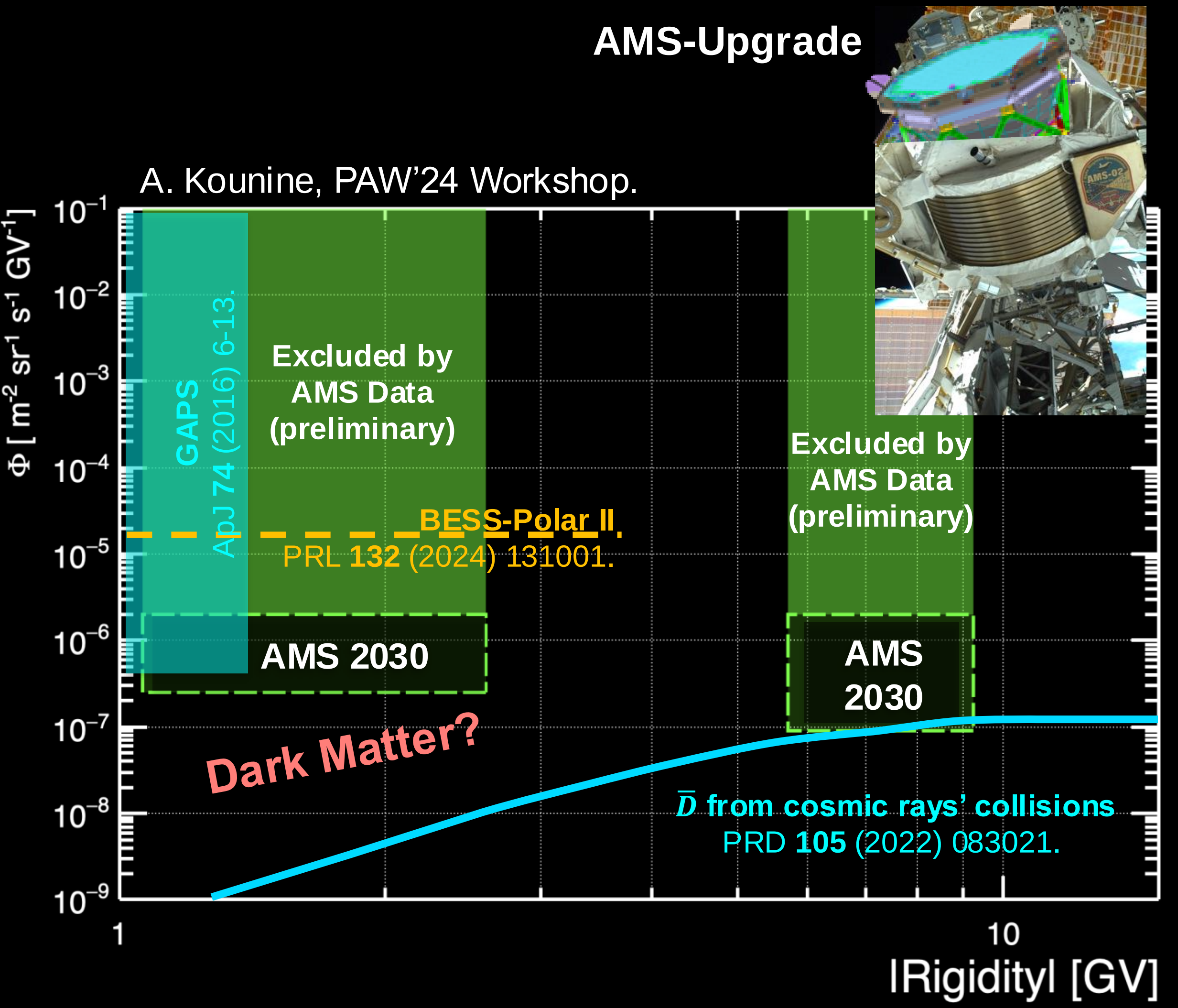


The interpretation of AMS data requires knowledge of the astrophysical background. Uncertainties in the modelling include **production cross section** (AMBER, SMOG-LHC), **cosmic ray propagation in the galaxy**, and **in the heliosphere** (solar modulation).

Antideuteron Search

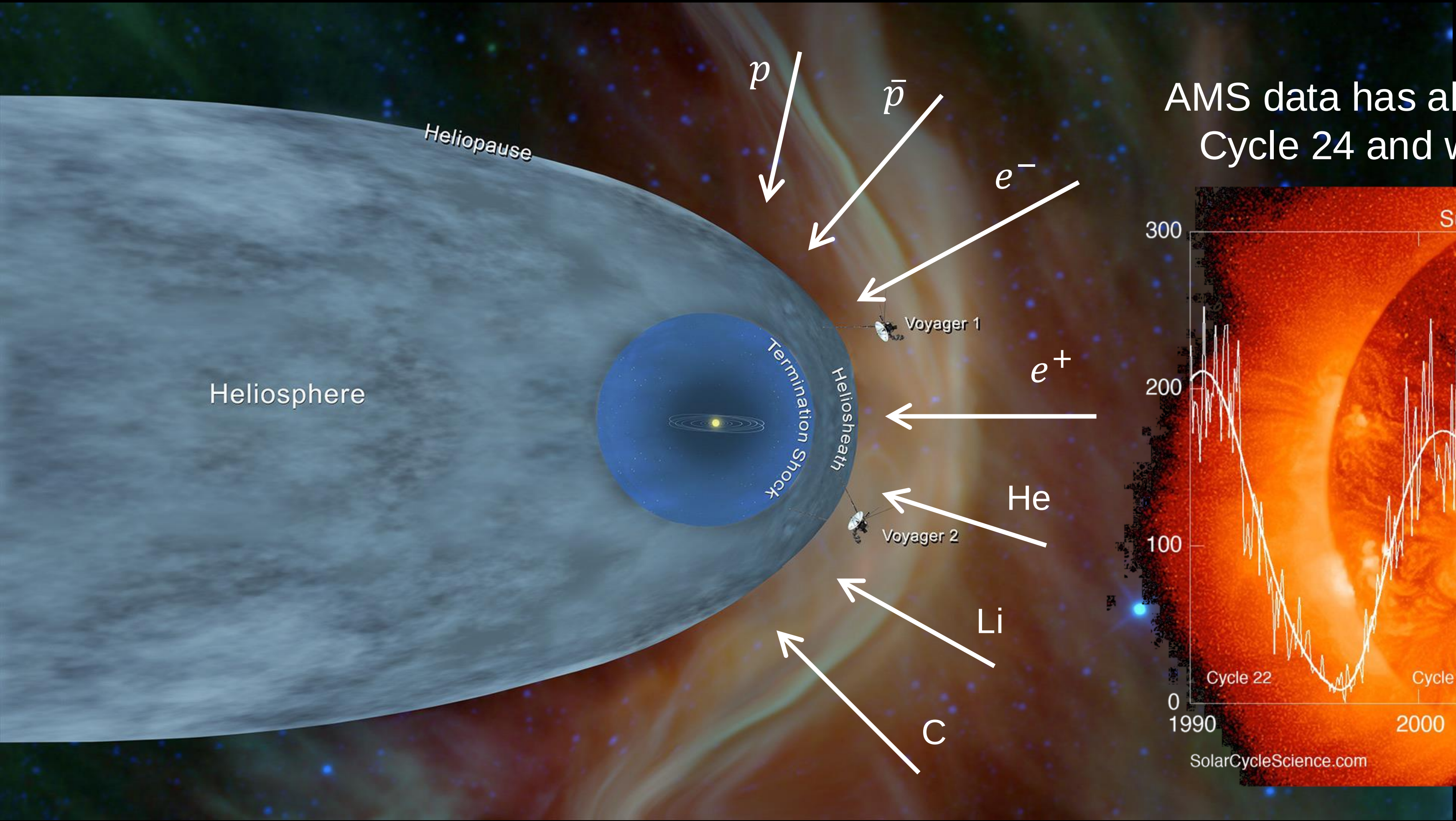
Anti-deuterons have never been observed in space (most stringent limits set from BESS Polar-II in 2024).
Very low background at low energy for indirect search of Dark Matter.
Expected very low flux. High rejection to other species is needed: $\bar{D}/\bar{p} < 10^{-4}, \bar{D}/p < 10^{-9}, \bar{D}/e^{-} < 10^{-6}$.



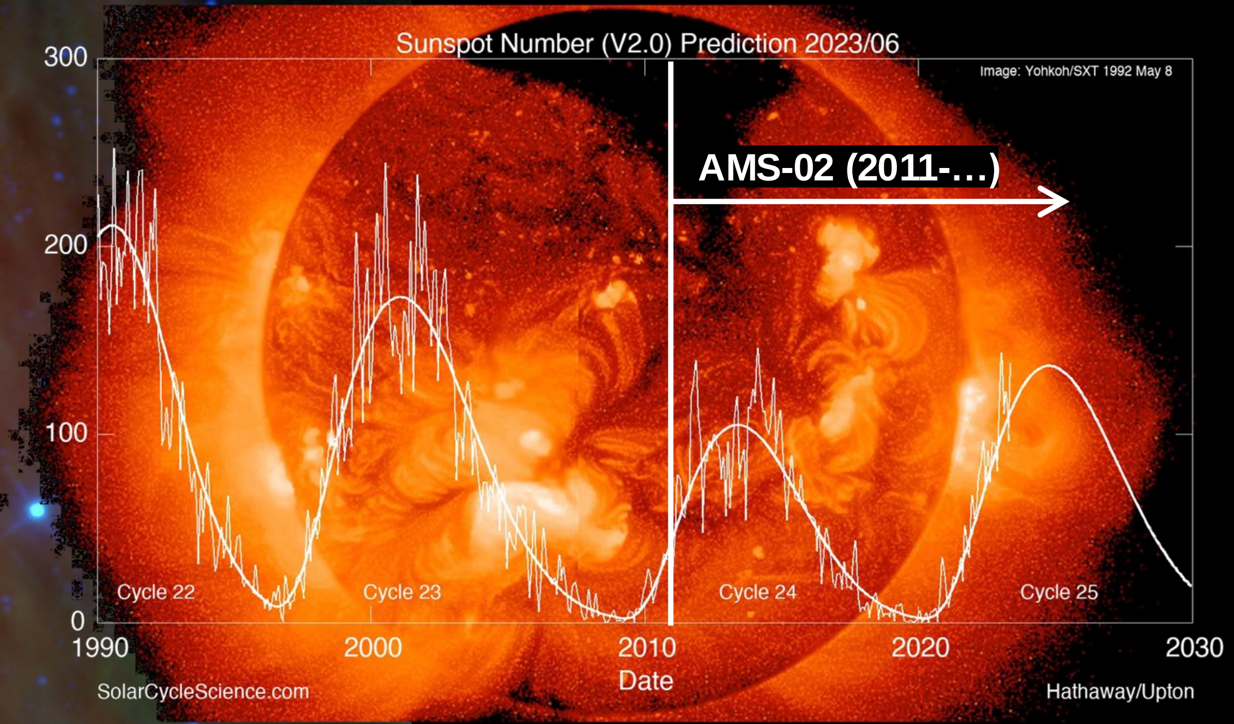


Solar Modulation of Cosmic Rays

GCRs entering the heliosphere are subject to diffusion, convection, adiabatic energy losses and magnetic drift. This is commonly known as Solar Modulation.



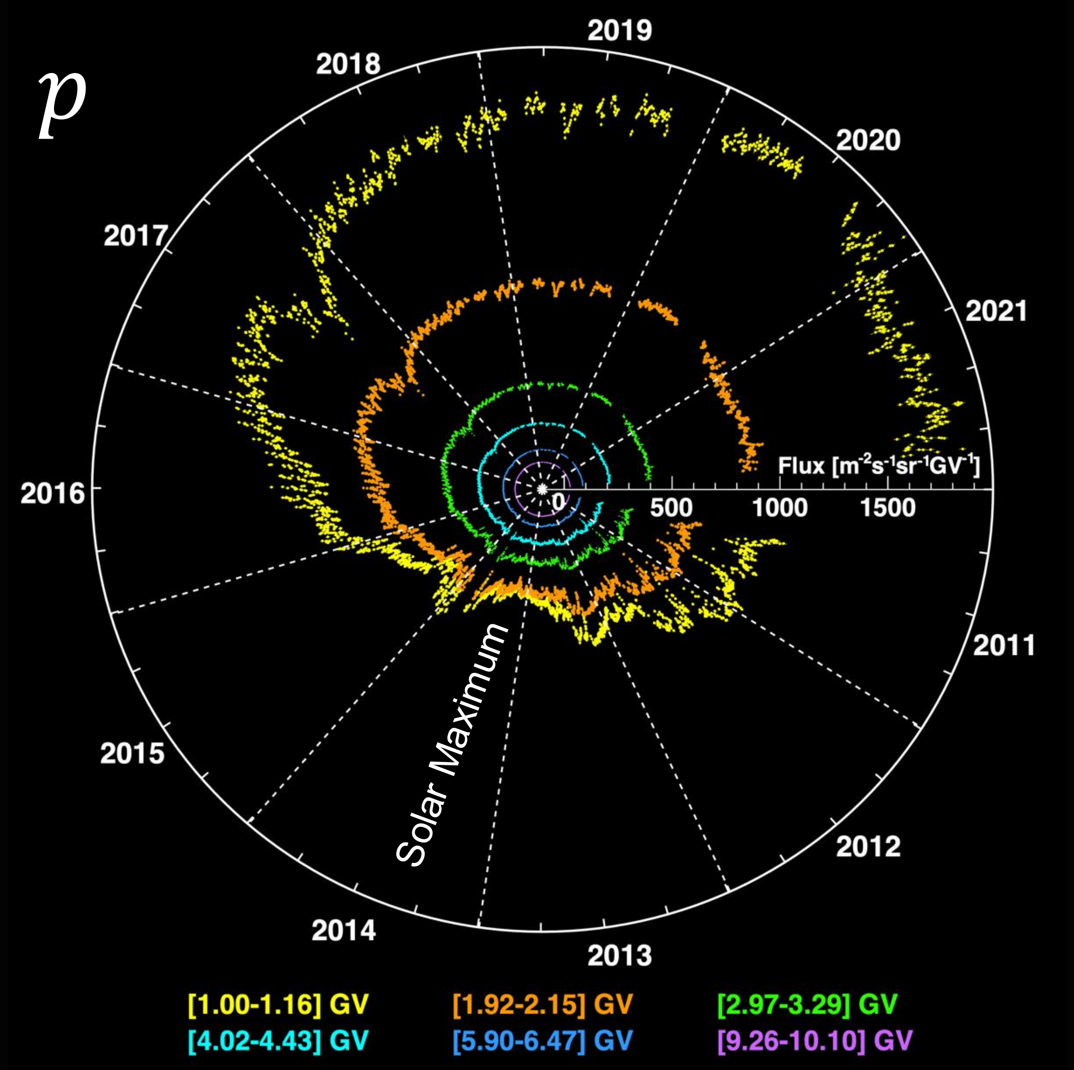
AMS data has already covered almost the full Solar Cycle 24 and will fully cover the Solar Cycle 25.



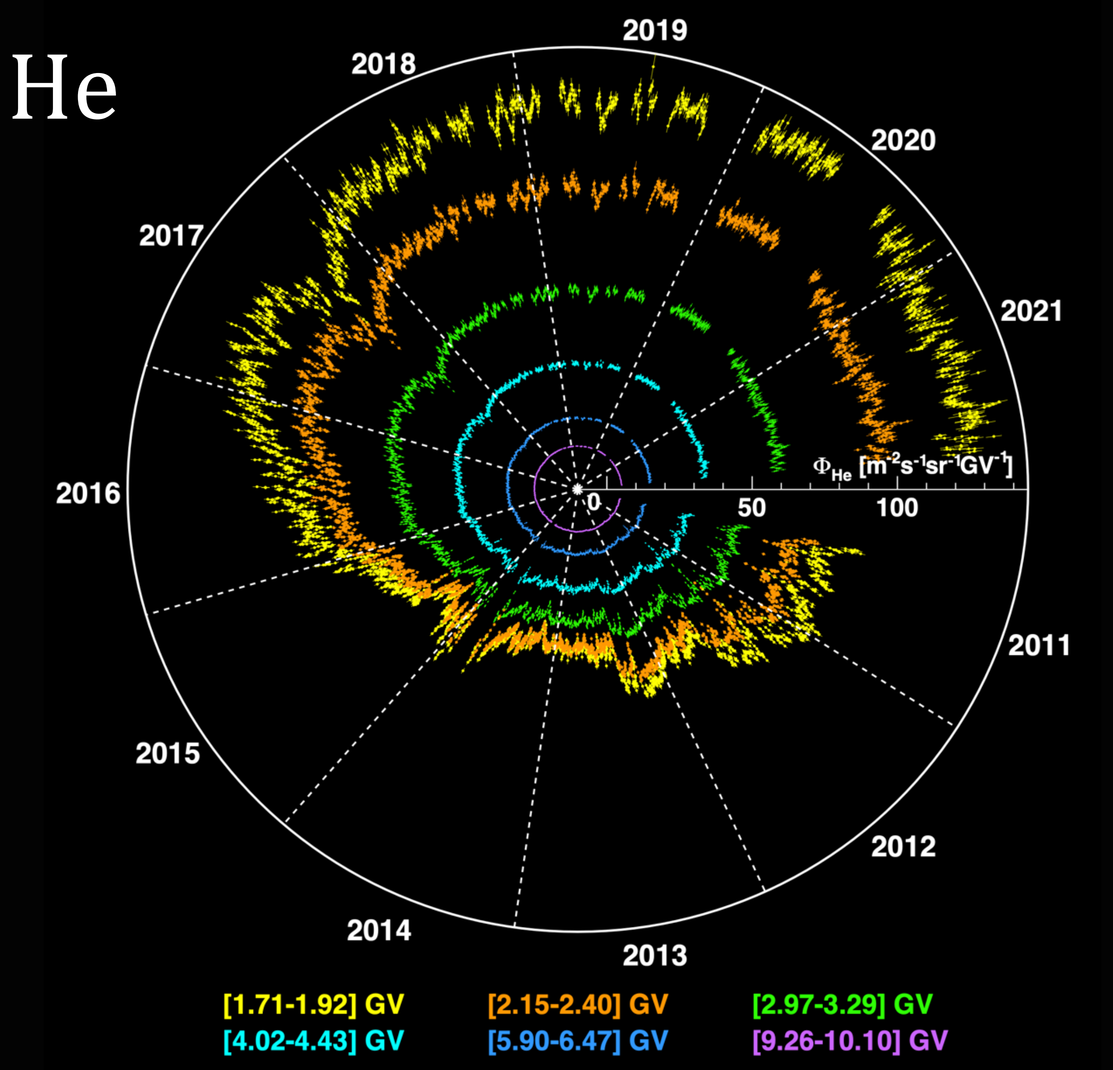
Measuring the effect of solar modulation on different elementary particles ($p, e^-, e^+, \bar{p}$) and nuclei (He, Li, Be, B, C, N, and O) provides information of the propagation of GCRs in the heliosphere.

Proton and Helium Daily Fluxes

M. Aguilar et *al*., Phys. Rev. Lett. **127** (2022) 271102.



M. Aguilar et *al*., Phys. Rev. Lett. **128** (2022) 231102.

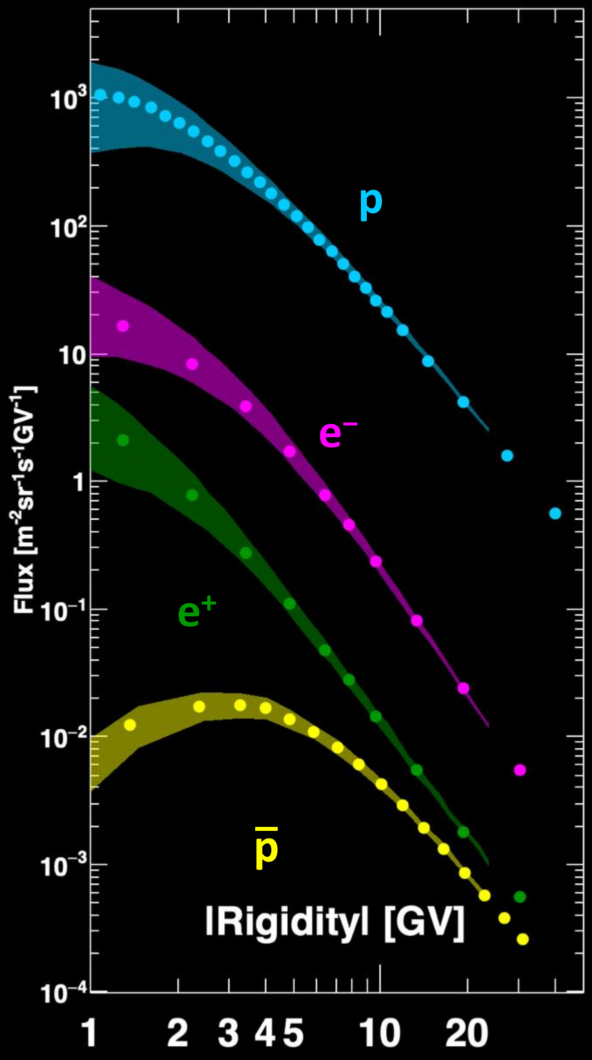


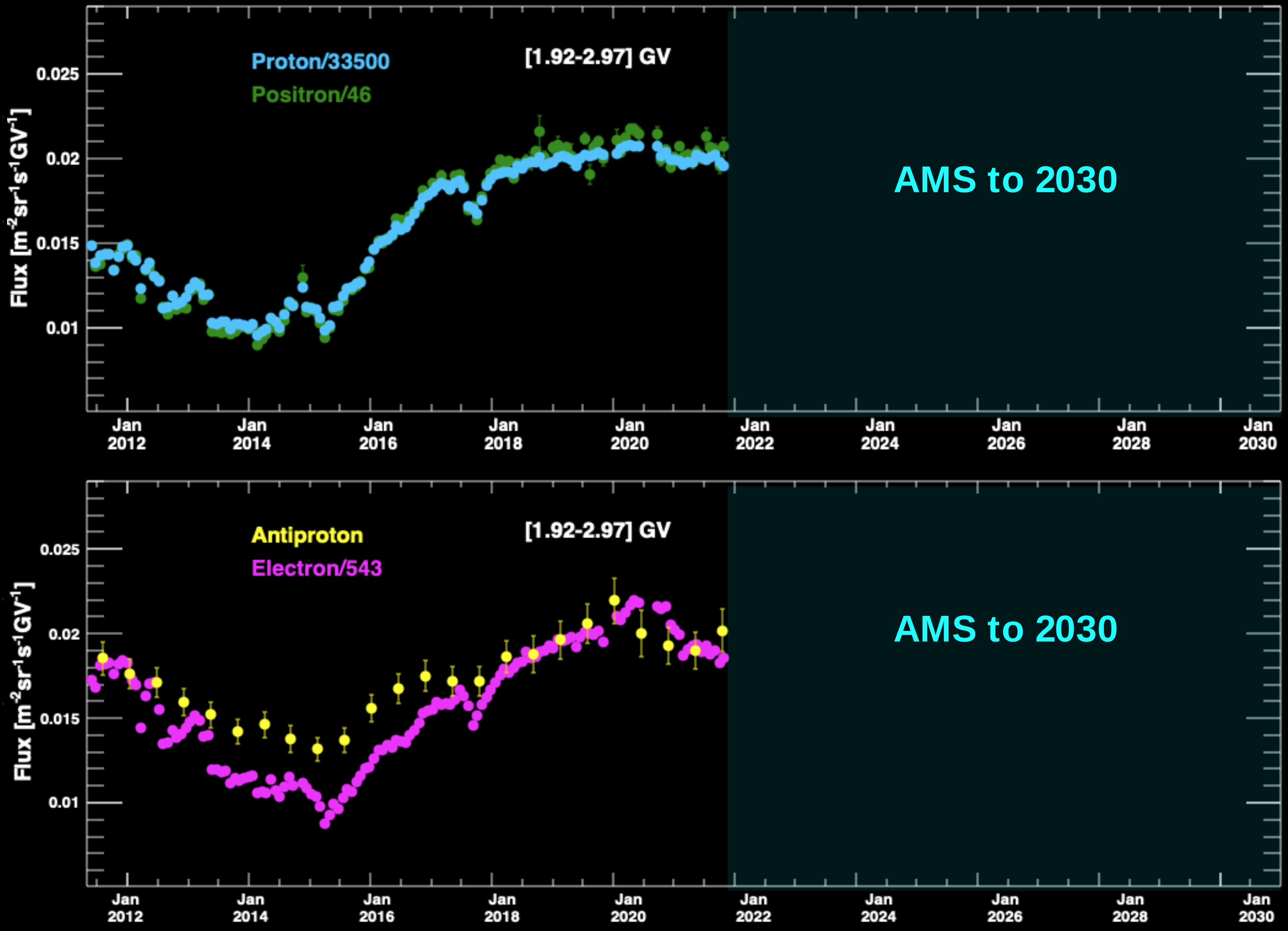
Fluxes are anti-correlated with solar activity, being higher during epoch of low solar activity and lower during epoch of high solar activity. The amplitude of the time structures decreases with increasing rigidity.

Solar Modulation of p, e^-, e^+, and $\bar{p}$

For the first time, the time dependence of p, e^-, e^+, and $\bar{p}$ are studied in detailed (daily and monthly) with the same experiment in an entire 11 years solar cycle over an extended rigidity range.

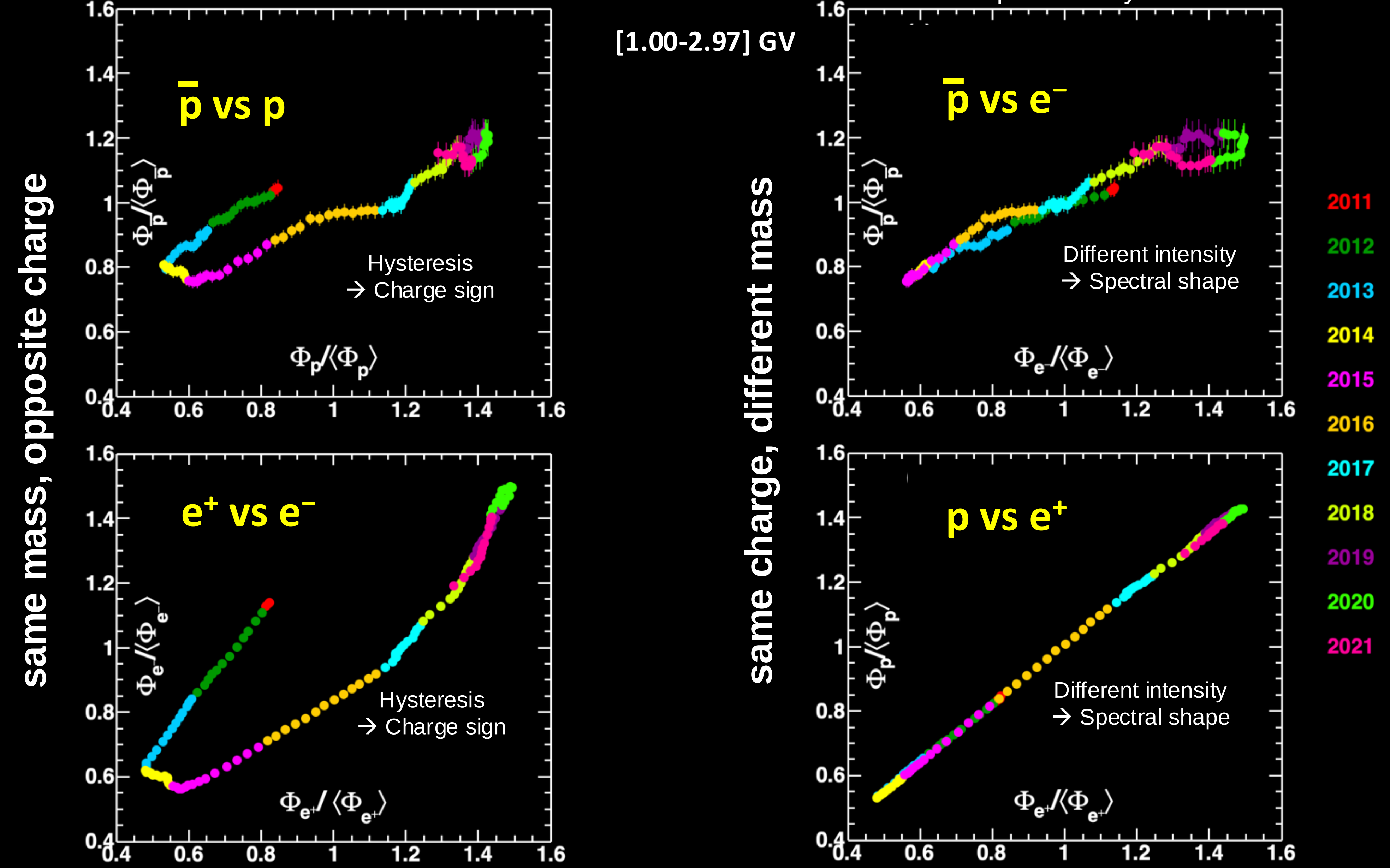
Accepted on Phys. Rev. Lett.





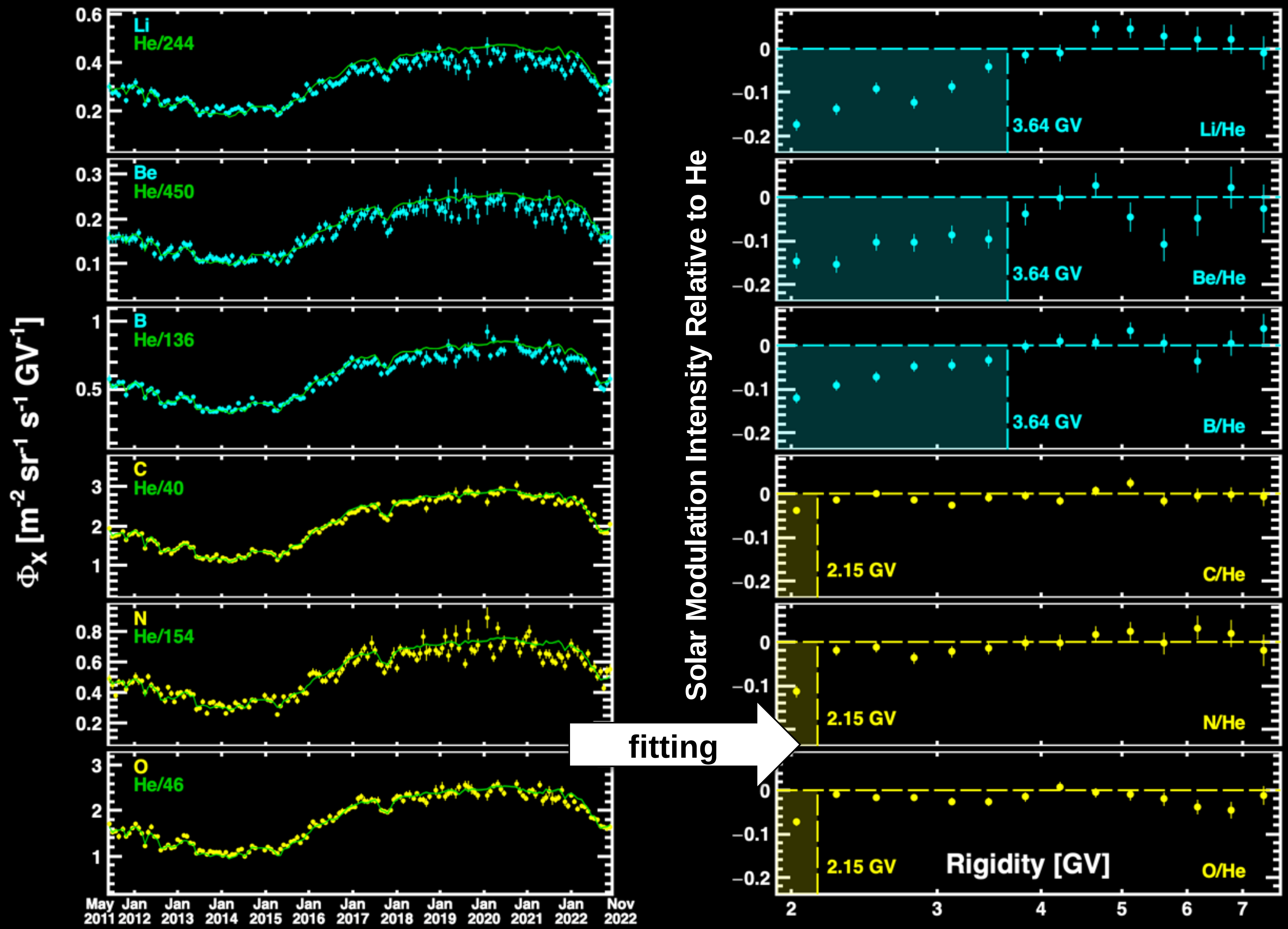
Differences in Solar Modulation between p, e^-, e^+, and $\bar{p}$

Accepted on Phys. Rev. Lett.



Solar Modulation of Light Ions

Phys. Rev. Lett., in Press. Phys. Rev. Lett., in Press.



- Similar solar modulation among all elements with $2 \leq |Z| \leq 8$.
- No hysteresis.
- Li, Be, and B are less modulated than He up to 3,64 GV. C, N, and O are less modulated than He up to 2.15 GV.
- There is a direct correlation between the **spectral shape** and the **solar modulation intensity**.
- Velocity effect is subdominant (as an ex. C, O and Be have similar average <A/Z> ratio and yet different solar modulation).

Conclusions

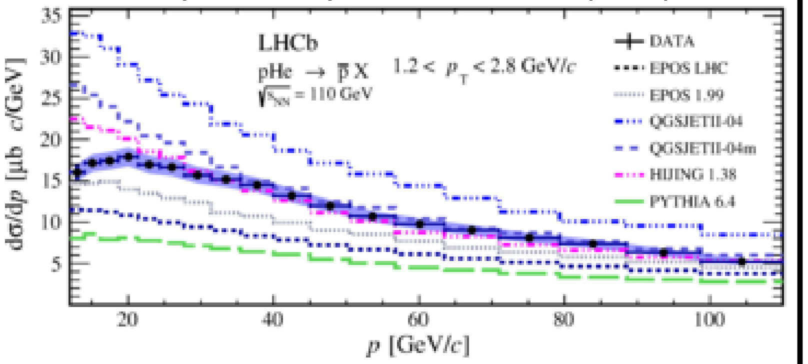
- AMS has been operating in the Space Station since May 2011 performing precision measurements of cosmic rays and revealing new details about origin and propagation of all CRs species.
- With its unprecedented statistics and accuracy, AMS has a unique capability to detect matter and antimatter in cosmic rays and study their properties.
- AMS is the only operating spectrometer in space and will continue to collect and analyze data for the lifetime of the Space Station (now projected to 2030).
- An upgrade of AMS is in production to make the best use of the remaining time on the space station.

Uncertainty in Antiproton Astrophysical Background

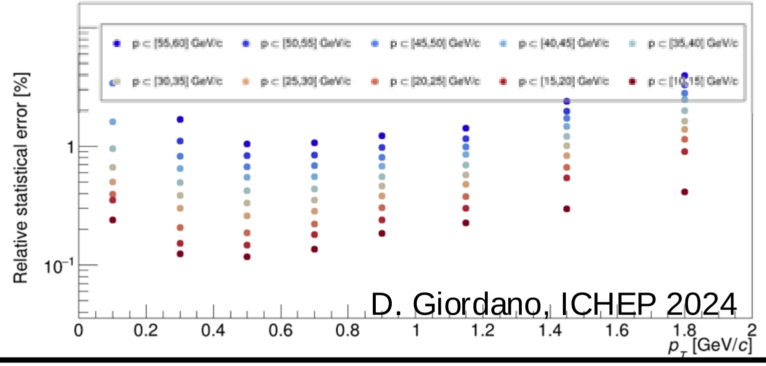
Uncertainty in antiproton production: measurements of the $\bar{p}$ production cross section for $p + p, \mathrm{He} \rightarrow \bar{p}$ are needed.

LHCb/SMOG: $p + \mathrm{He} \rightarrow \bar{p}$ at $\sqrt{s} = 110\ \mathrm{GeV}$ measurement already done.

R. Aaij *et al.*, Phys. Rev. Lett. **121** (2018) 222001.



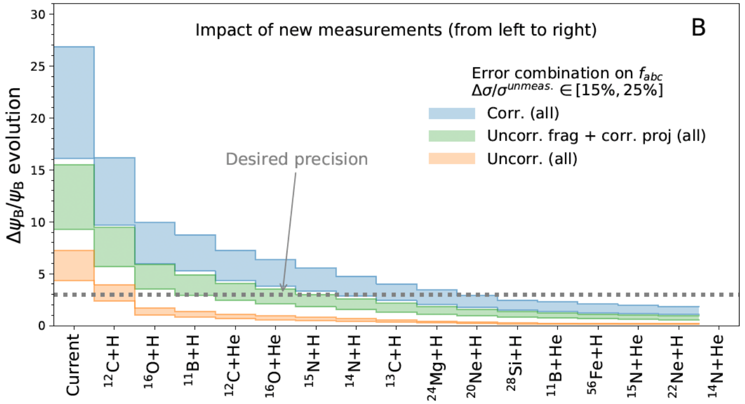
AMBER: Fixed target experiment at SPS (CERN). Data acquired for pp and pHe. Under analysis the pp at $\sqrt{s} = 18.9\ \mathrm{GeV}$.



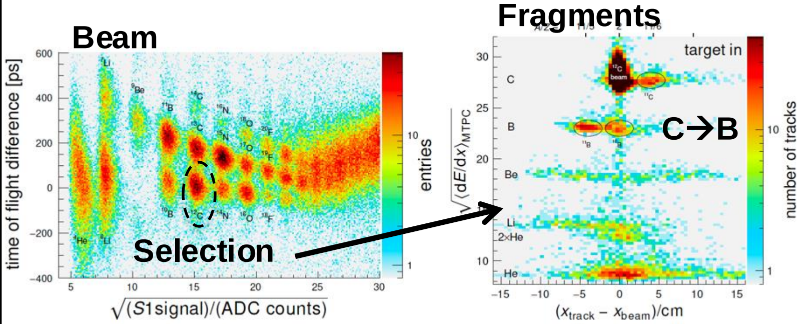
D. Giordano, ICHEP 2024

Uncertainty in galactic propagation: parameters of the galactic propagation (diffusion coefficient, galactic halo size, …) depend on the knowledge of spallation cross section (as C + p → B):

Y. Genolini et al., Phys. Rev. C **109** (2024) 064914.



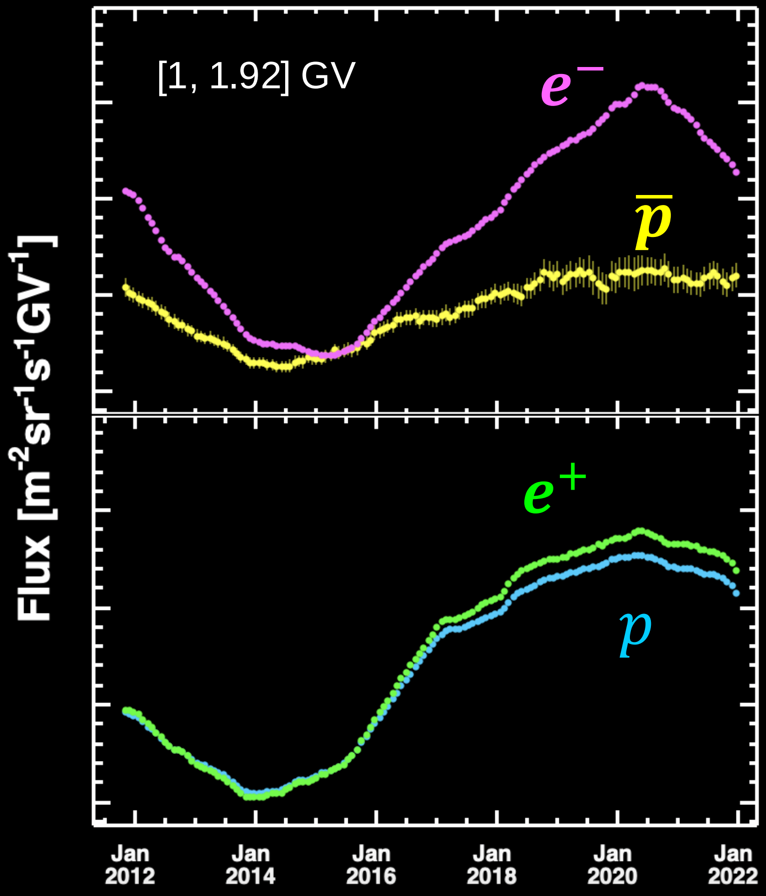
NA61/SHINE: Fixed target experiment at SPS (CERN). Pilot run in 2018.



Uncertainty in solar modulation: direct measurement of $\bar{p}$ as function of time allows the accurate modelling of solar modulation.

AMS-02: measurement of all CR species over a solar cycle.

S. Lu, ICHEP 2024.

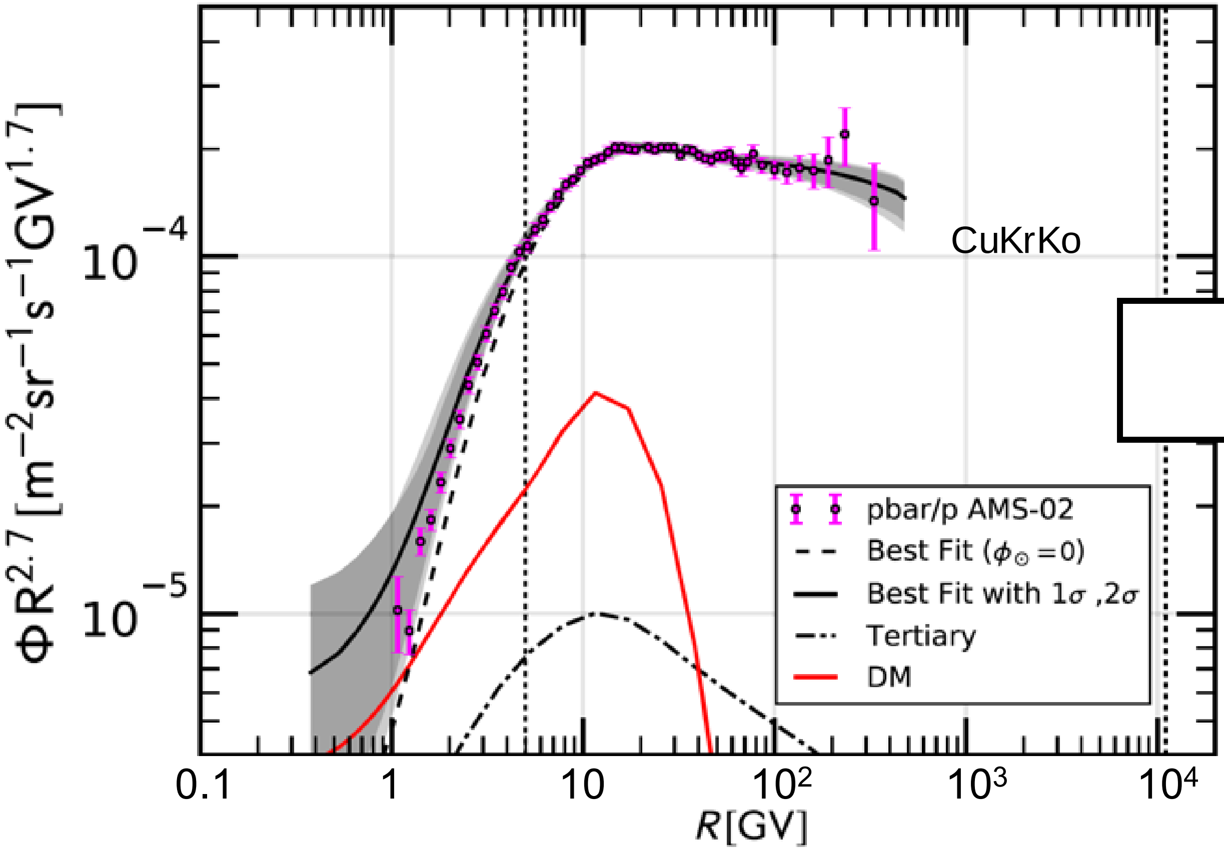


→ Upcoming workshop on this: XSCRC2024 Cross sections for Cosmic Rays @ CERN, 16 – 18 October 2024.

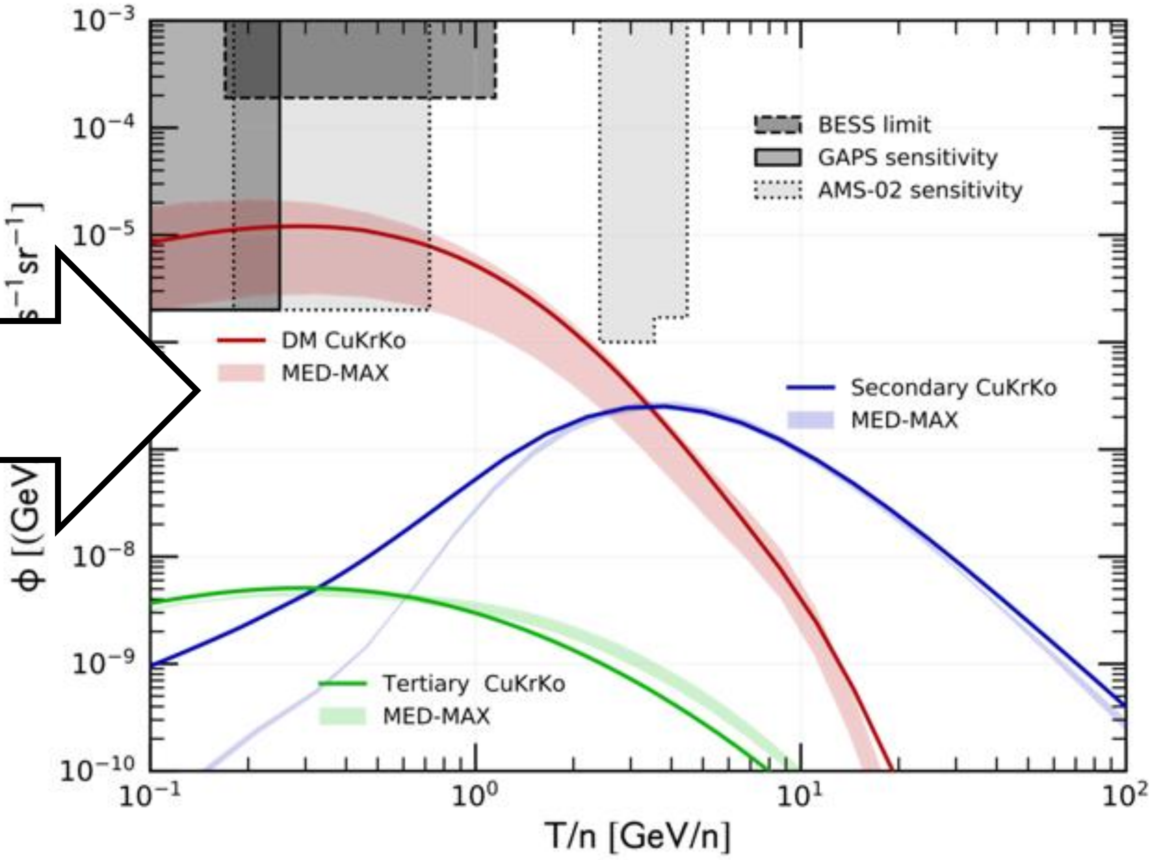
The Antiproton-Antideuteron Connection

Several authors reported an anti-proton excess at low energy at ~ 10 GV in AMS-02 data (with *very* different significances) that can be explained a dark matter signal. This signal can give a detectable anti-deuteron signal.

A. Cuoco *et al.*, Phys. Rev. Lett. 118 (2017) 191102.



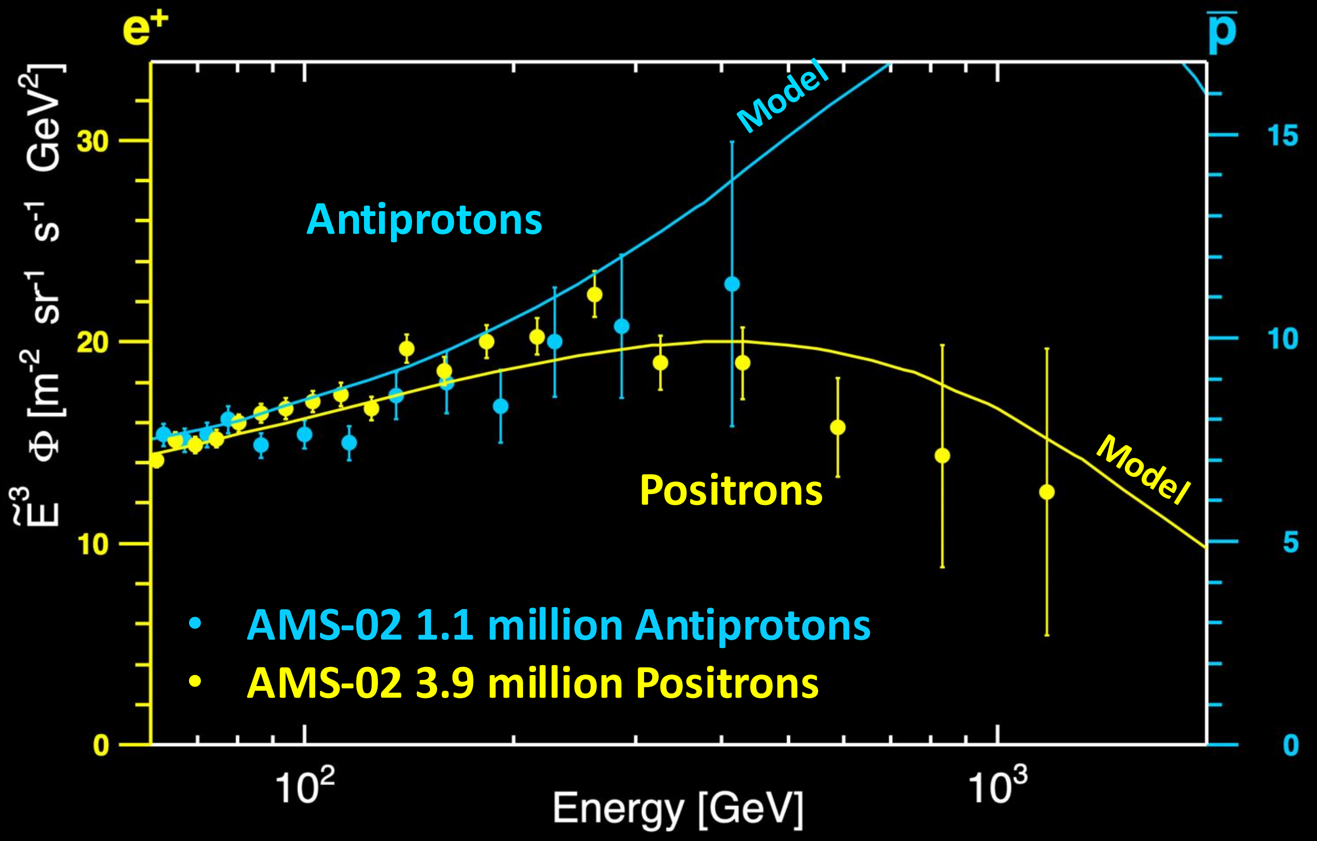
M. Korsmeier *et al.*, Phys. Rev. D 97 (2018) 103011.

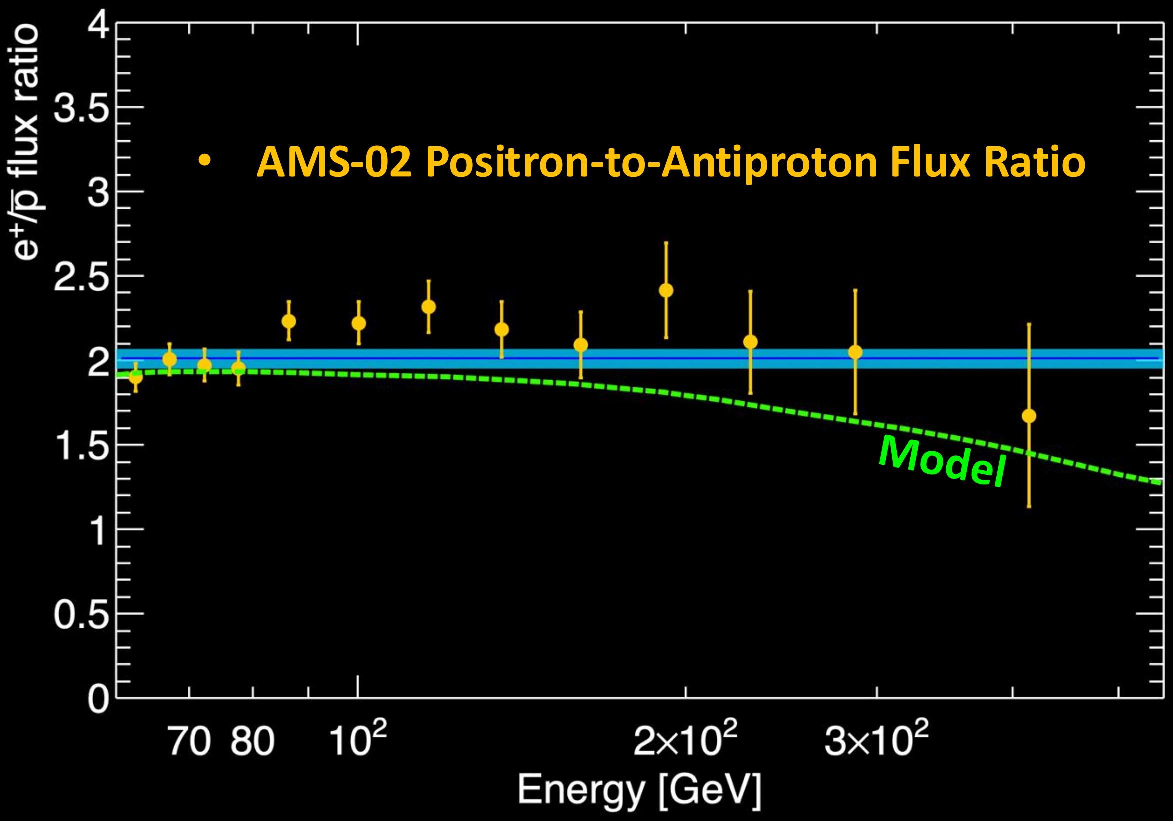


Anti-deuterons (with or without anti-protons) are believed to be a clean channel for indirect dark matter search, their **secondary production is very suppressed at low energy** and can be efficiently produced by dark matter annihilation.
[original idea published in F. Donato *et al.*, Phys. Rev. D 62 (1999) 043003]

AMS Positron and Antiproton Fluxes

Model from P. Mertsch, A. Vittino, S. Sarkar, *Explaining cosmic ray antimatter with secondaries from old supernova remnants*, Phys. Rev. D **104** (2021) 103029.

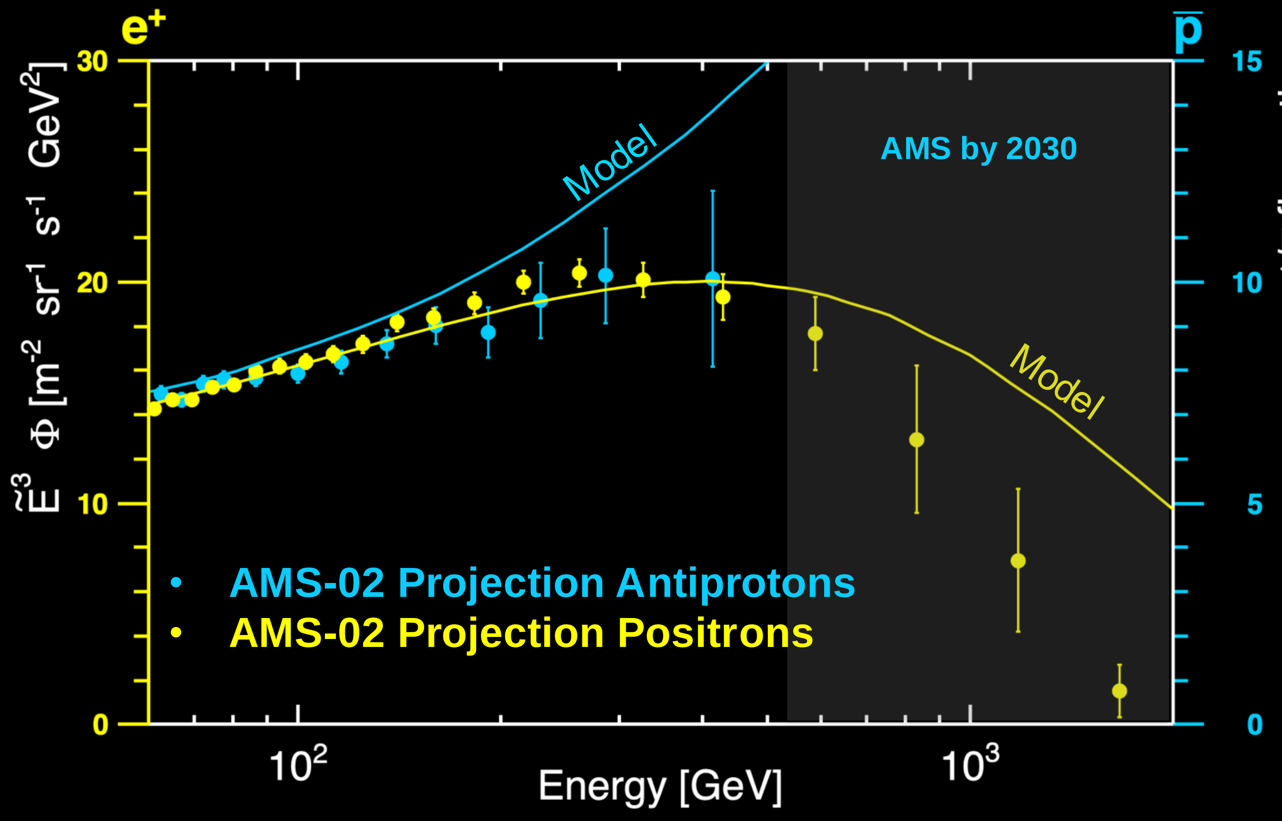


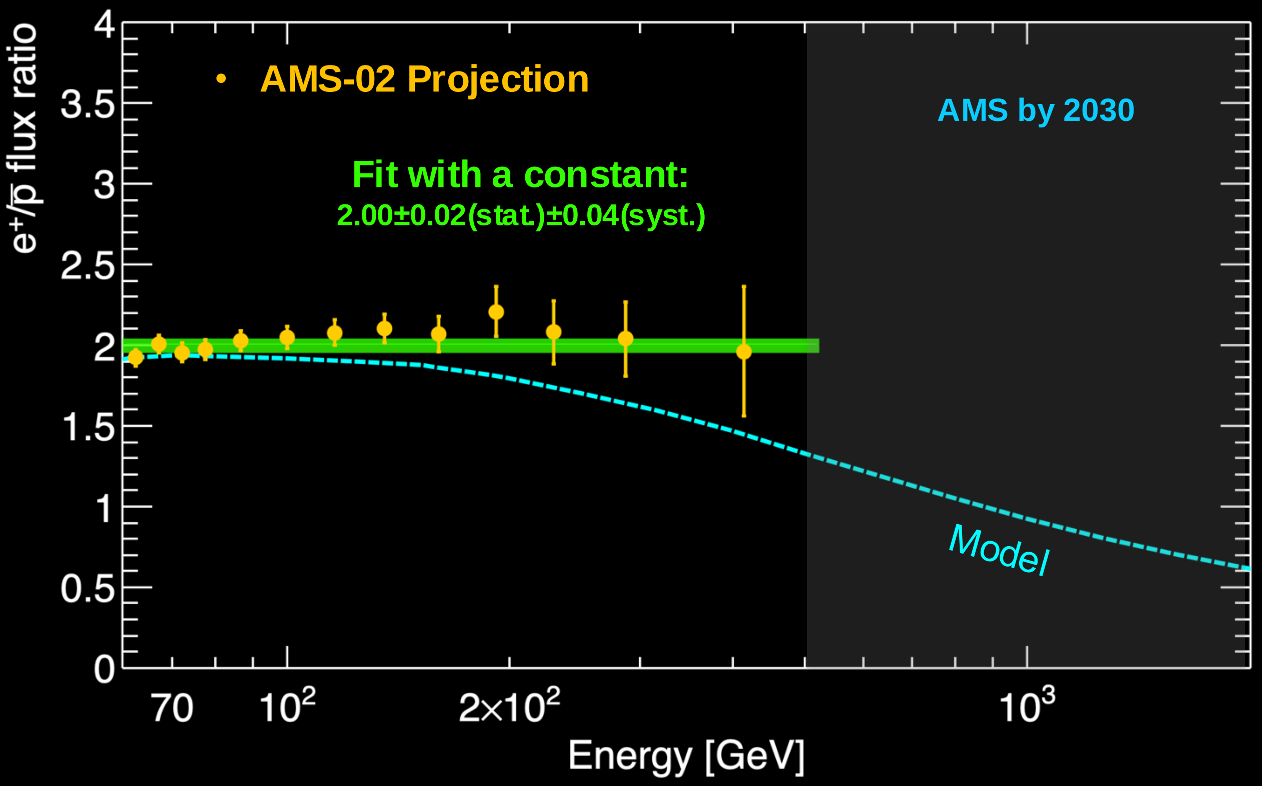


Positrons and **antiprotons** have nearly identical energy dependence.

Projection of AMS Positron and Antiproton Fluxes

Model from P. Mertsch, A. Vittino, S. Sarkar, *Explaining cosmic ray antimatter with secondaries from old supernova remnants*, Phys. Rev. D **104** (2021) 103029.





AMS will significantly improve the measurement of the **positrons** and **antiprotons**.
This will help in separating between different models.