Charged Cosmic Rays: Experimental Status

News from the dark, LapTh, Annecy, nov. 22-24, 2021

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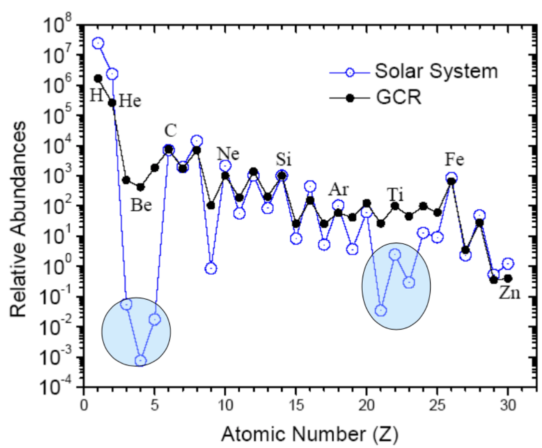
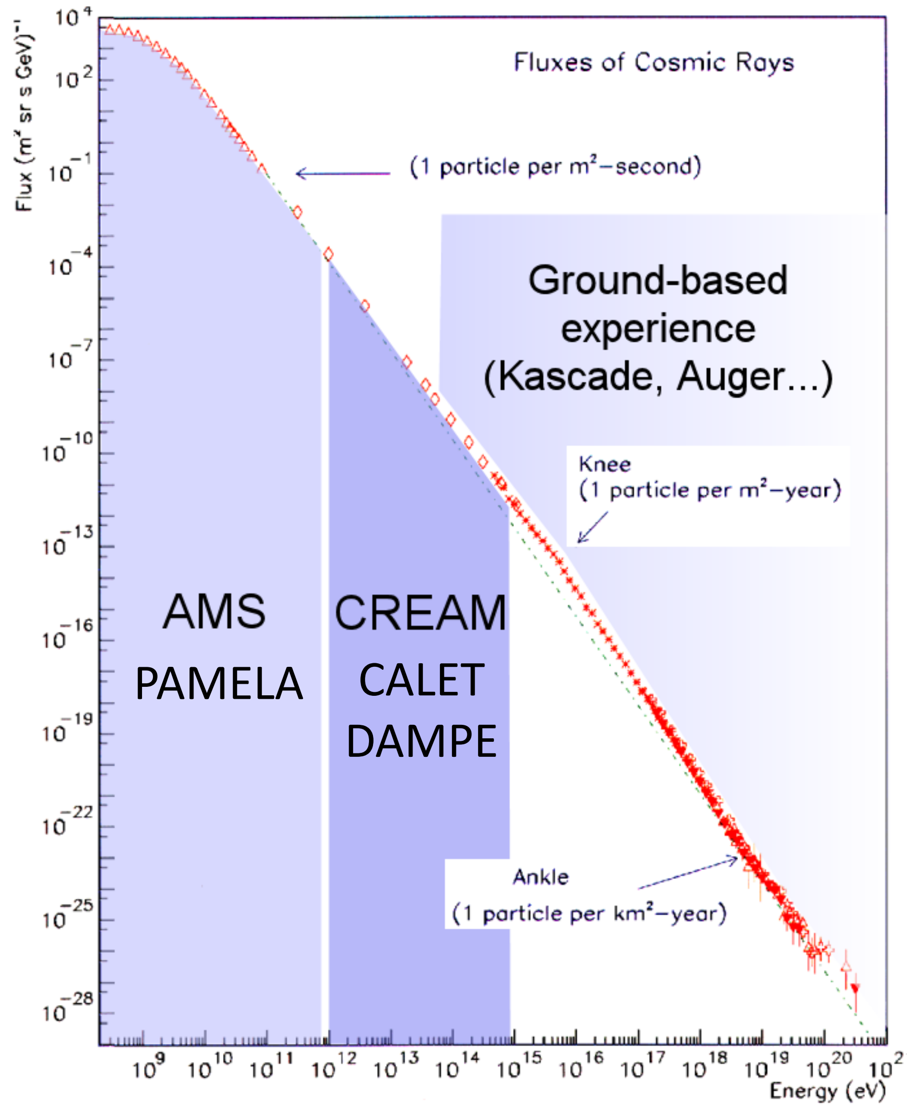
Detection of Charged Cosmic rays

- For E < 10^{15} ev, cosmic rays absorbed in the upper layers of atmosphere but large fluxes:
  - Direct detection in upper atmosphere or from space.
  - Identification of CR/Energy measurement with particle physics detectors.

  ➡ Precise description of the different components in cosmic rays:



  ➡ Rare components in CR positrons, antiprotons, ... and DM searches



Recent and current CR experiments

Balloon

MASS (1989-1991)
IMAX (1992)
CAPRICE (1994-1998)
HEAT (1994-1995)
BESS (1994-2000)
ATIC (2000-2007)
TRACER (2006)
CREAM (2004-2010)

Space

Voyager (1976-...)
HEAO3 (1979-1981)
AMS01 (1998)
PAMELA (2006-2016)
FERMI (2008-...)
AMS02 (2011-...)
CALET (2015-...)
DAMPE (2015-...)
ISSCREAM (2017-2019)

Magnetic Spectrometer
« Calorimeter »

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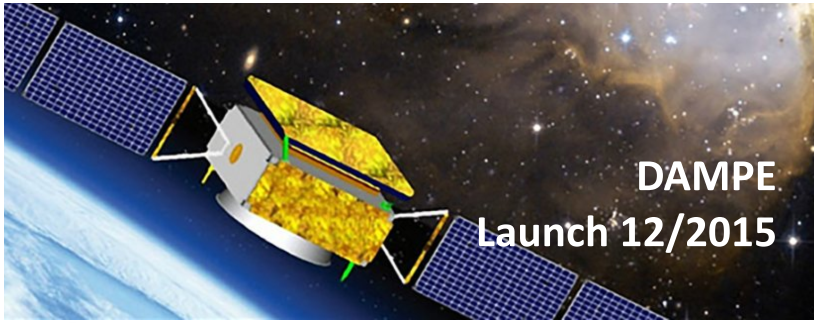
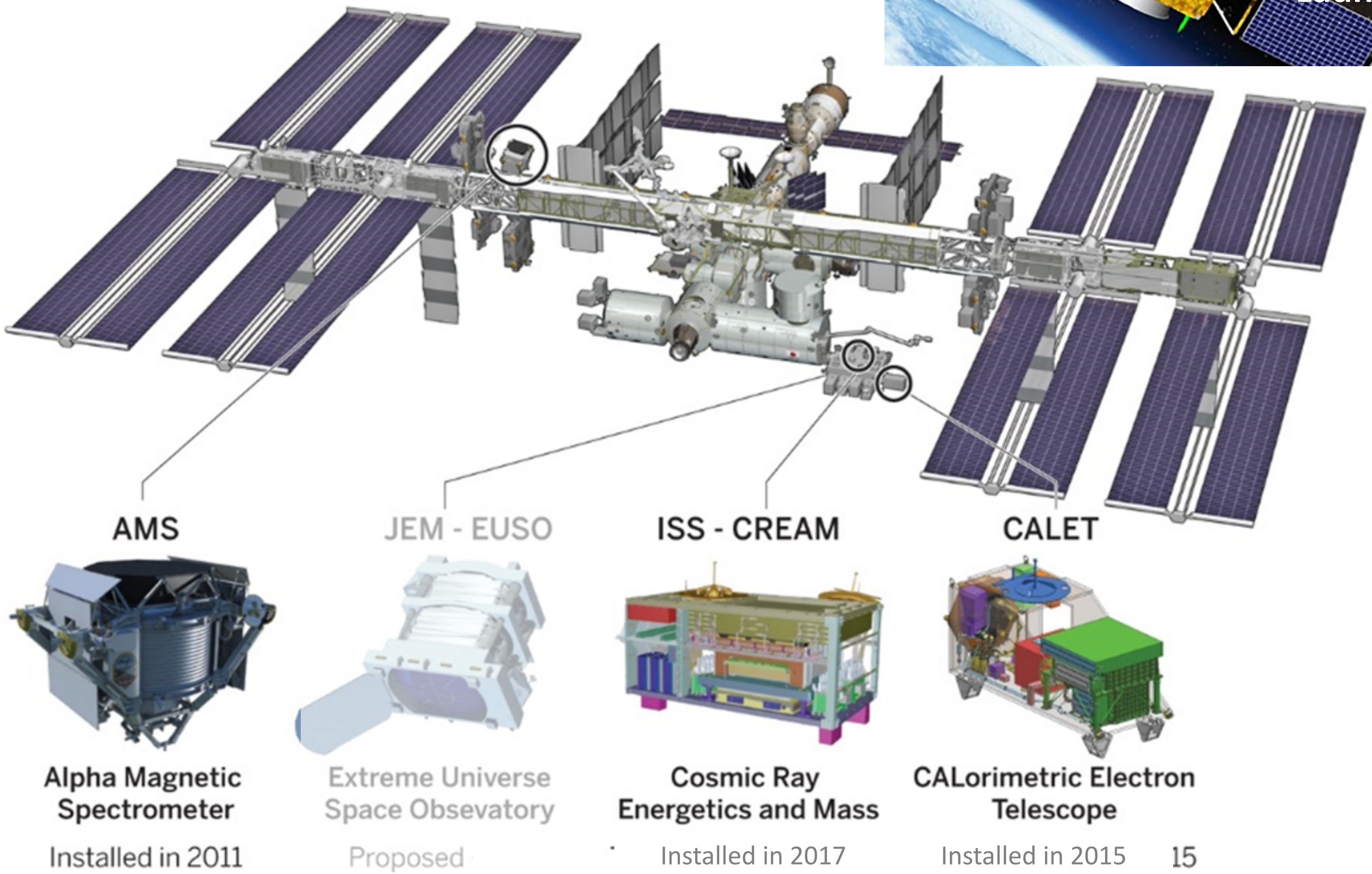
Magnetic Spectrometer
« Calorimeter »

CR detection from space



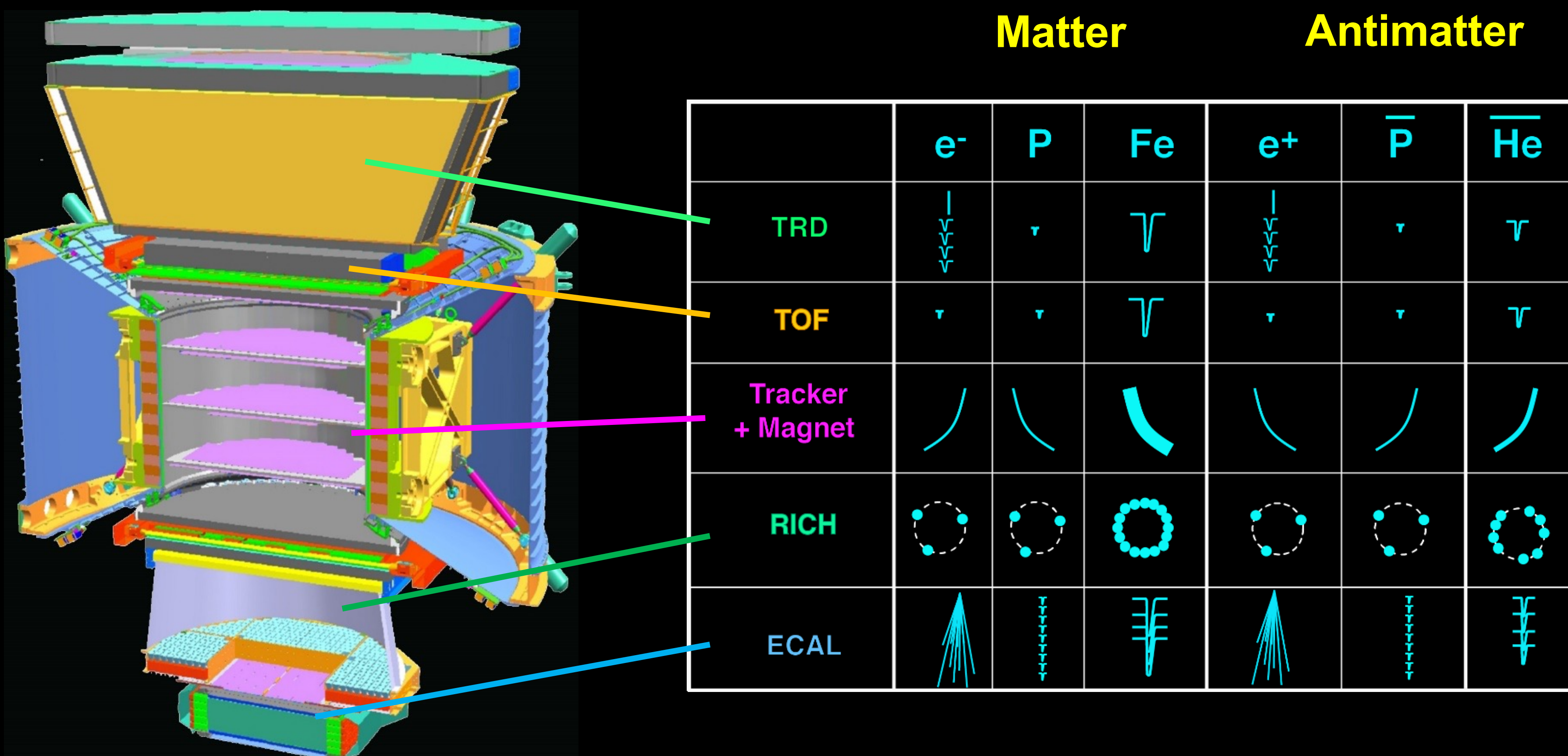


Recent and current CR experiments

- Magnetic Spectrometer (i.e. PAMELA, AMS):
  - ✓ Allows to identification of charge sign: e^+/e^-, $\bar{p}$, $\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$...
  - ✓ Accurate and precise rigidity ($R = \frac{pc}{Ze}$) measurement. Critical points are the alignment of the tracker planes and precise knowledge of the magnetic field.
  - ✓ Combined with precise velocity measurements, can measure the isotopic CR composition.
  - ✗ Rigidity range limited by the bending power and tracker resolution.
- Calorimeter (i.e. DAMPE, CALET, ISSCREAM):
  - ✗ No charge identification, only measure $e^+ + e^-$ or $p + \bar{p}$
  - ✗ Energy measurment from deposit energy in the calorimeter, mild resolution for nuclei, calibration depends on hadronic shower model/ simulation, beam tests critical.
  - ✓ Compact detector, large acceptance, can reach larger energy.


AMS installed on the
ISS on May 19, 2021
ELC2

AMS is a unique magnetic spectrometer in space

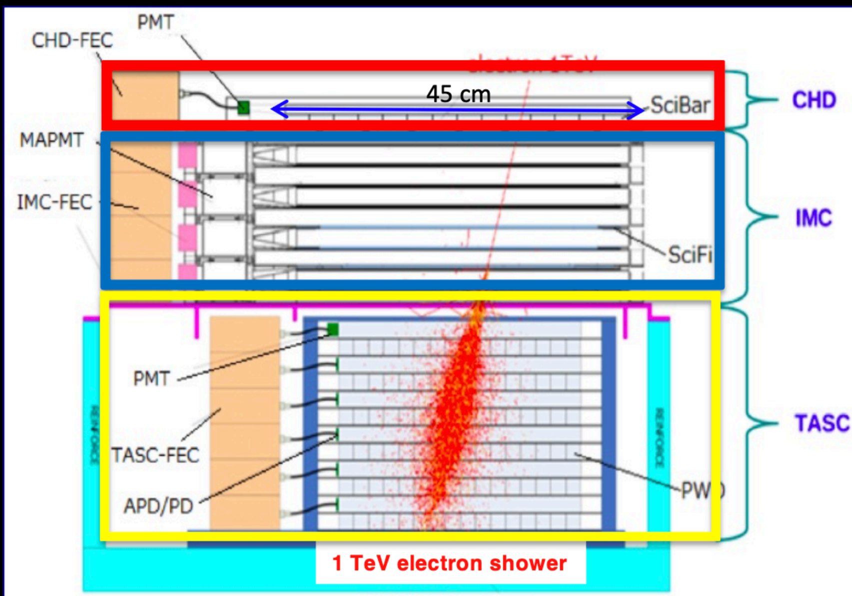


Cosmic rays are defined by:

- Energy (E in units of GeV)
- Charge (Z - location on the periodic table: H Z=1, He Z=2, …)
- Rigidity (R=P/Z in units of GV)

CALET

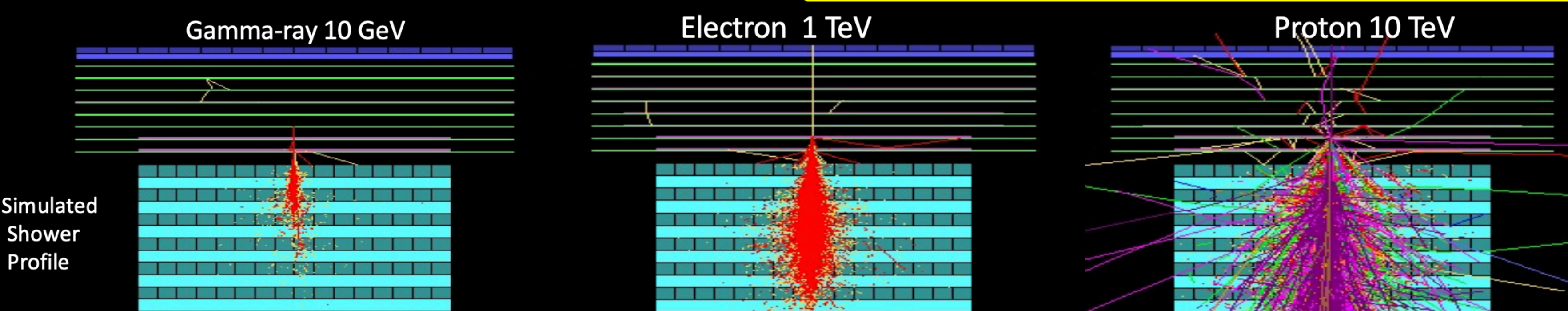
Field of view: ~ 45 degrees (from the zenith)   Geometrical Factor: ~ 1,040 cm²sr (for electrons)   Thickness: 30 X_0, **1.3** λ_I



CHD – Charge Detector
- 2 layers x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

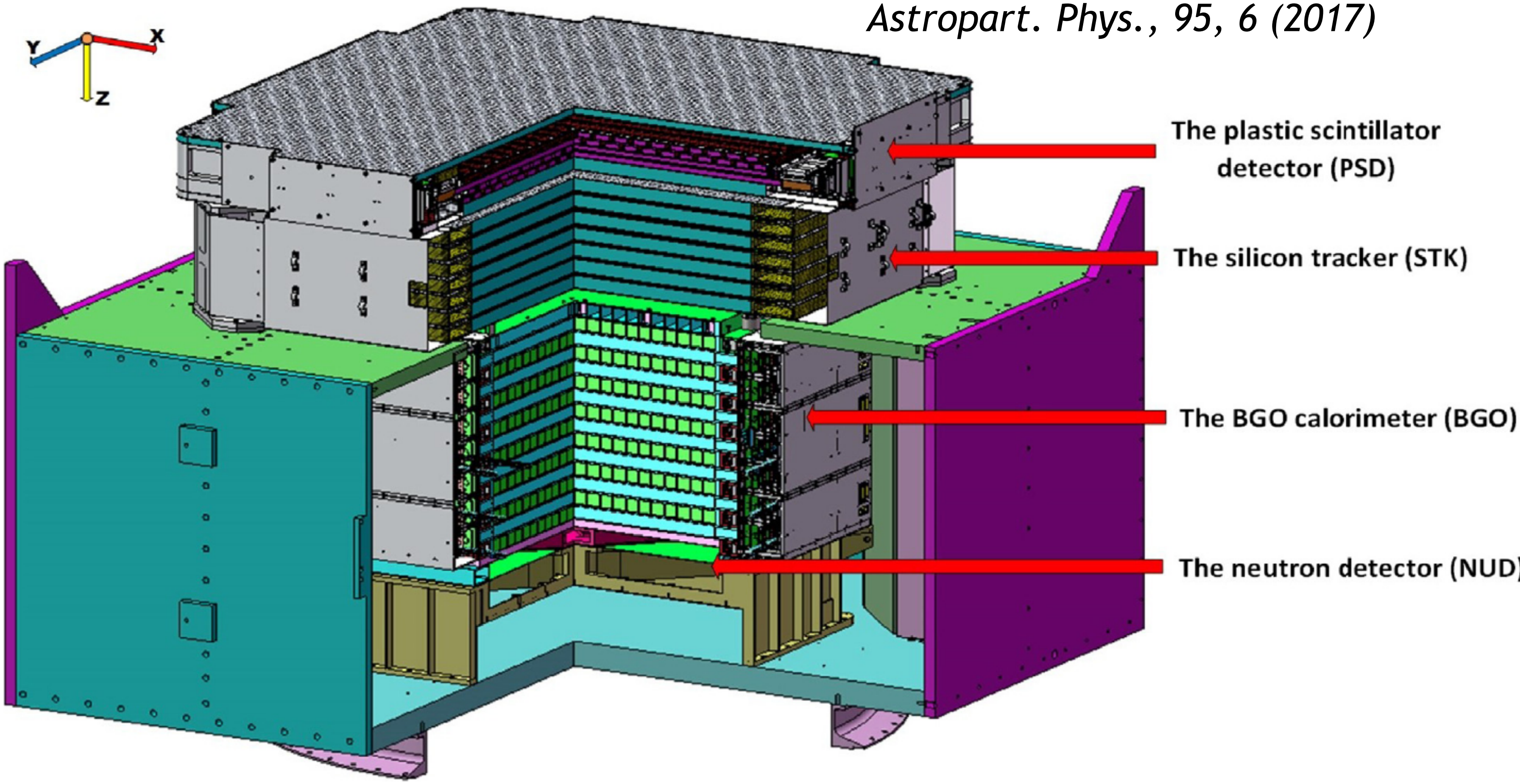
IMC – Imaging Calorimeter
- Scifi + Tungsten absorbers: 3 X_0 at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs
- **Energy resolution:** ~2 % (>10GeV) for e , γ ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}



DAMPE instrument

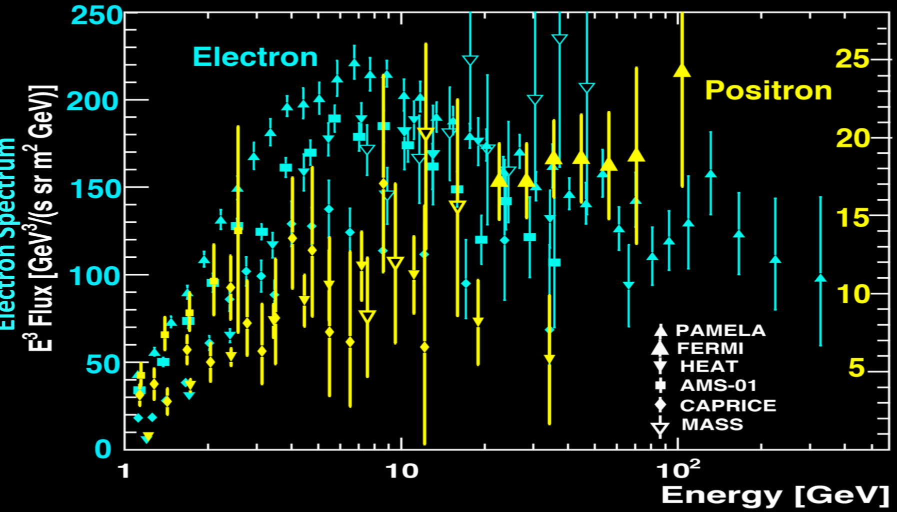
Astropart. Phys., 95, 6 (2017)



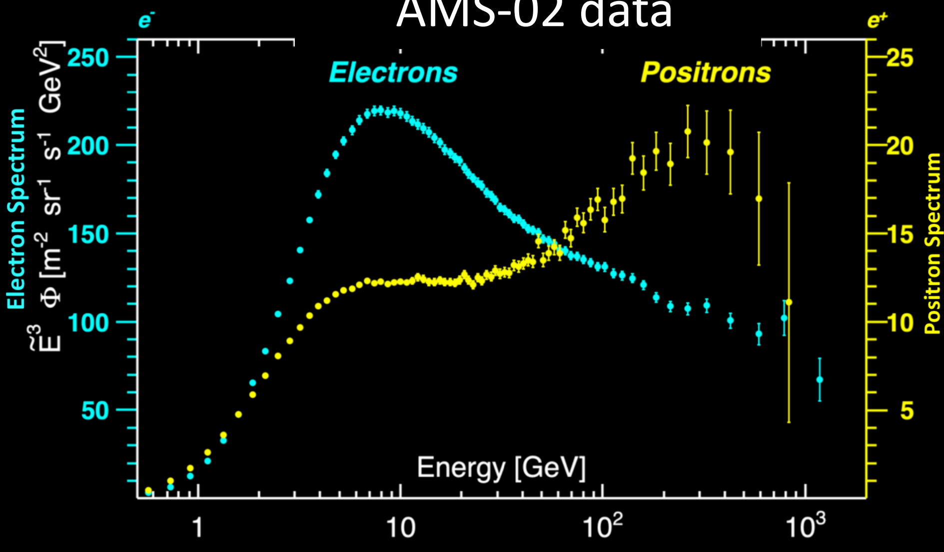
- PSD: charge measuresument via dE/dx and ACD for photons
- STK: track, charge, and photon converter
- BGO: energy measurement, particle (e-p) identification
- NUD: Particle identification

Positrons and electrons fluxes

BEFORE AMS-02



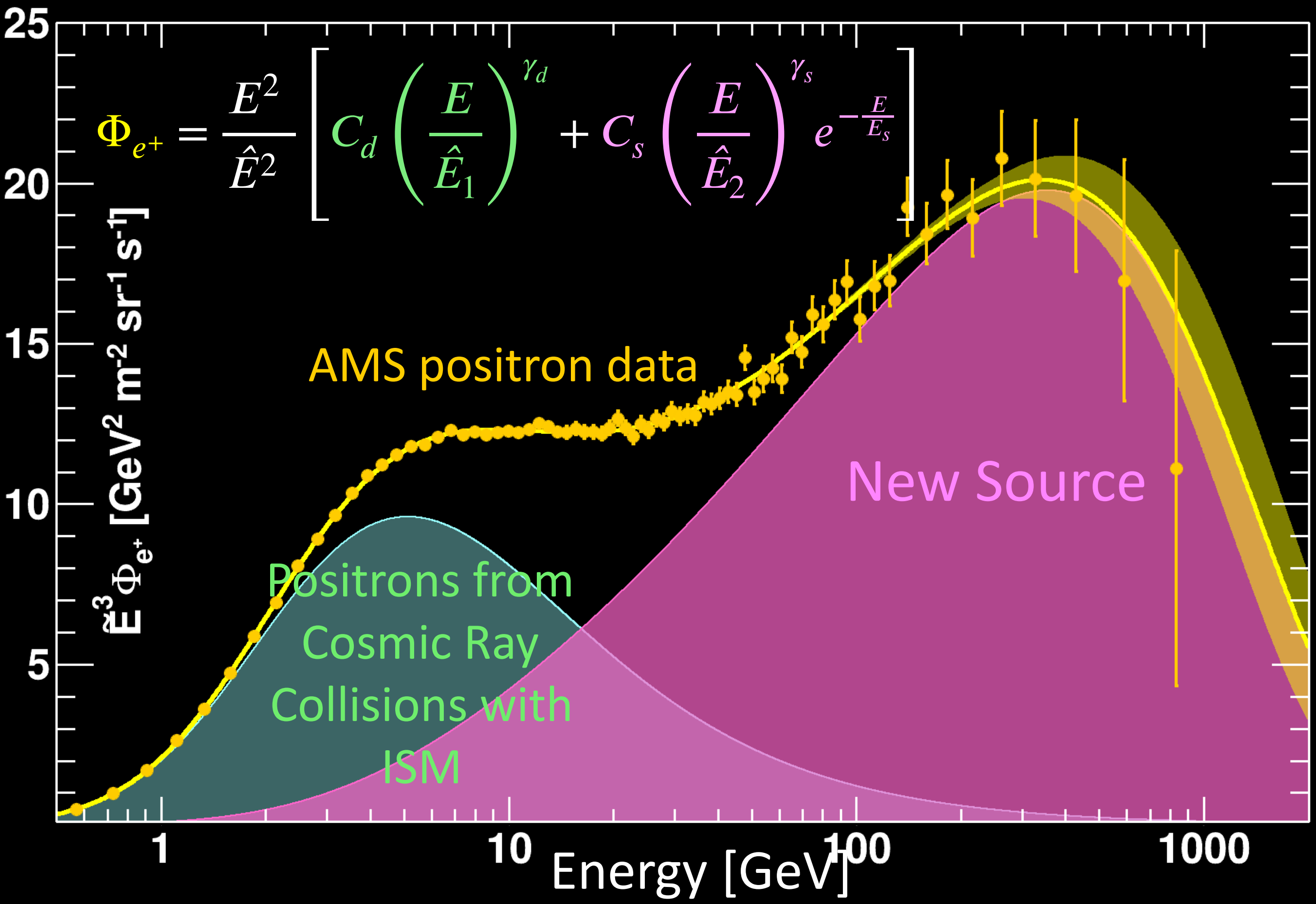
AMS-02 data



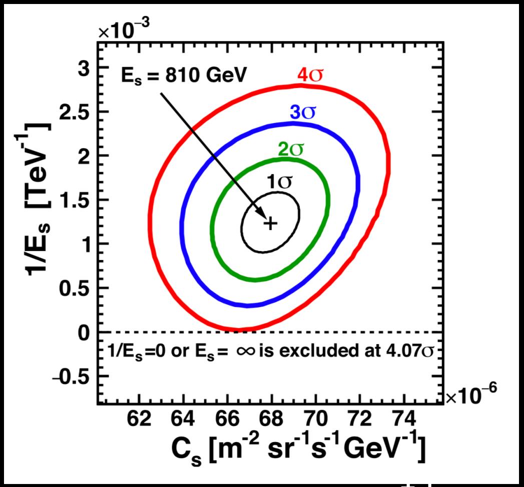
Electrons and positrons spectra have totally distinct behavior:

- Electron mainly produced at sources.
- Positron from collision of CR with ISM but need for additional source for positron

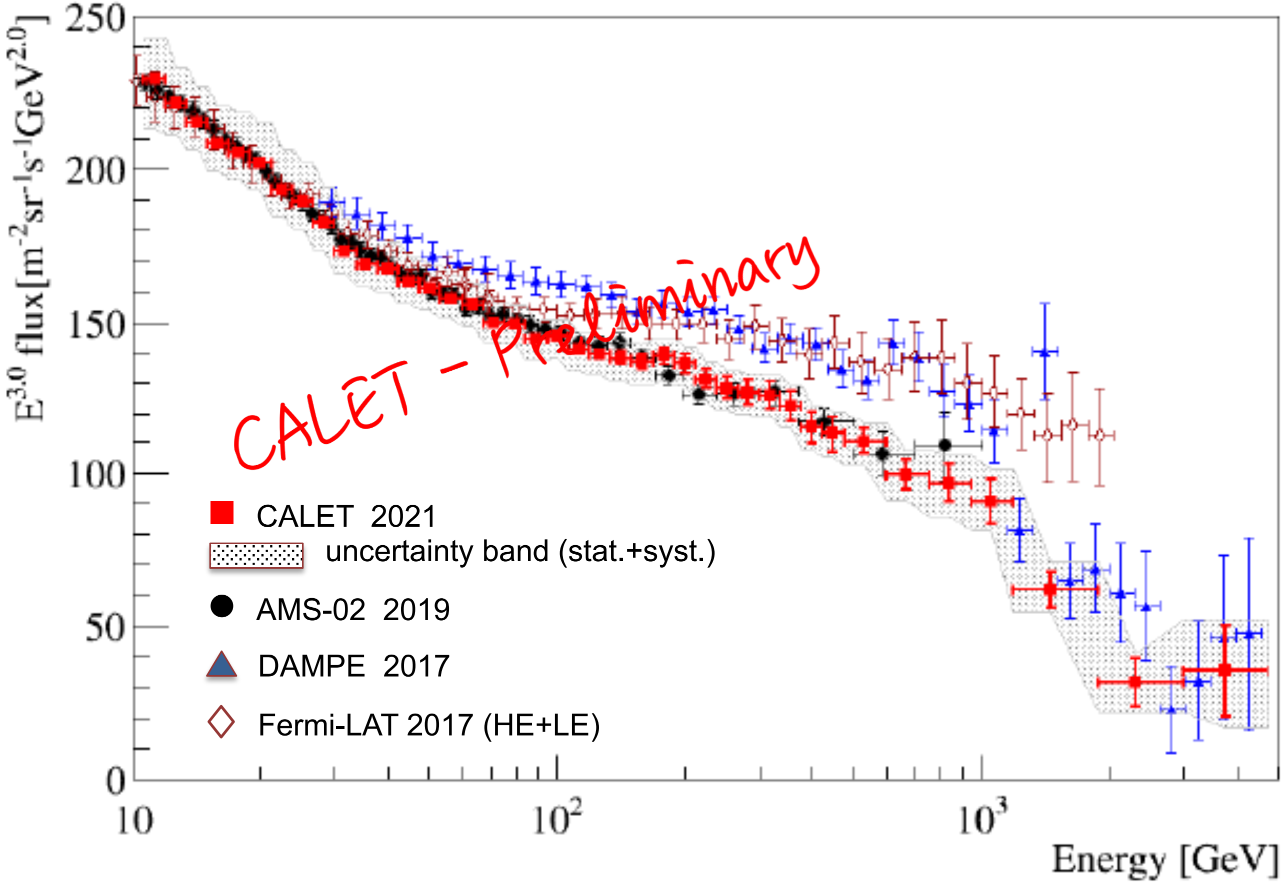
AMS Positron Flux



Source term exhibits an exponential cutoff at 810 GeV with **4σ** significance.



All-electron ($e^+ + e^-$) Flux



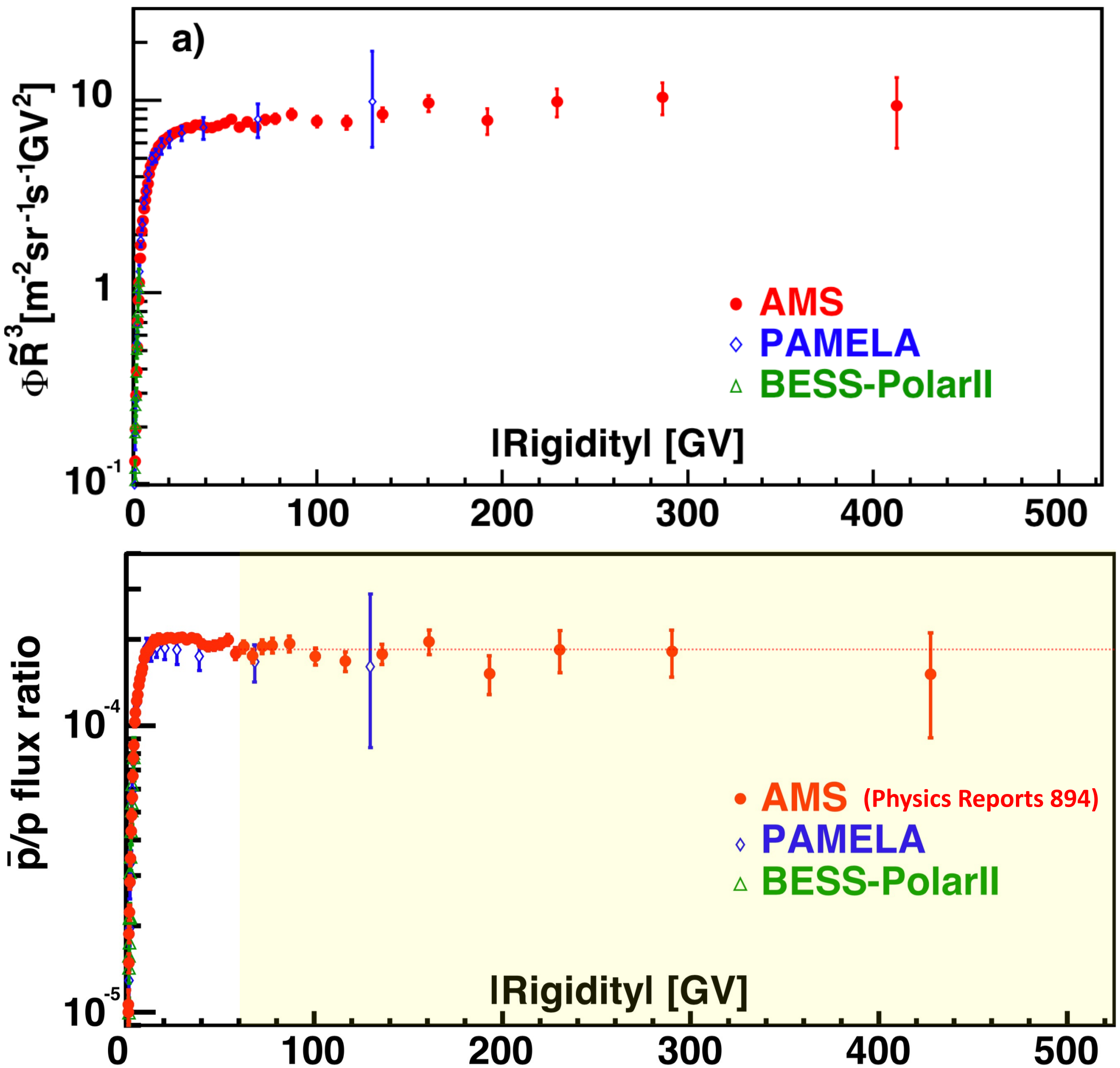
- CALET observes flux suppression above 1 TeV consistent with DAMPE within errors
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning

- CALET results appear to be consistent with AMS-02 below 1 TeV.
- The differences from Fermi-LAT and DAMPE over the allowance for error indicate the presence of unknown systematics in the energy region from 50 GeV to 1 TeV.

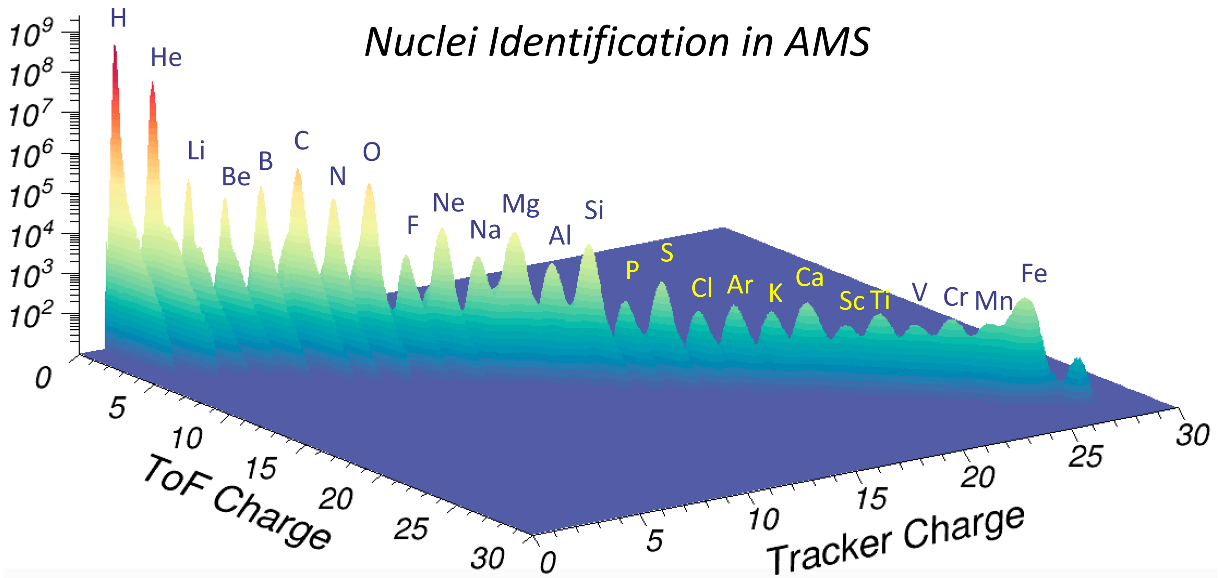
$\bar{p}$ flux and $\bar{p}/p$

Phys. Rep. **894**, 1 (2021)

- Precise $\bar{p}$ measurement up to 525 GV from AMS.
- Starting from 60 GV, the $\bar{p}/p$ flux ratio is constant.
- Interpretation of these data in terms of dark matter is a matter of debate in the community…



Cosmic-Ray Nuclei

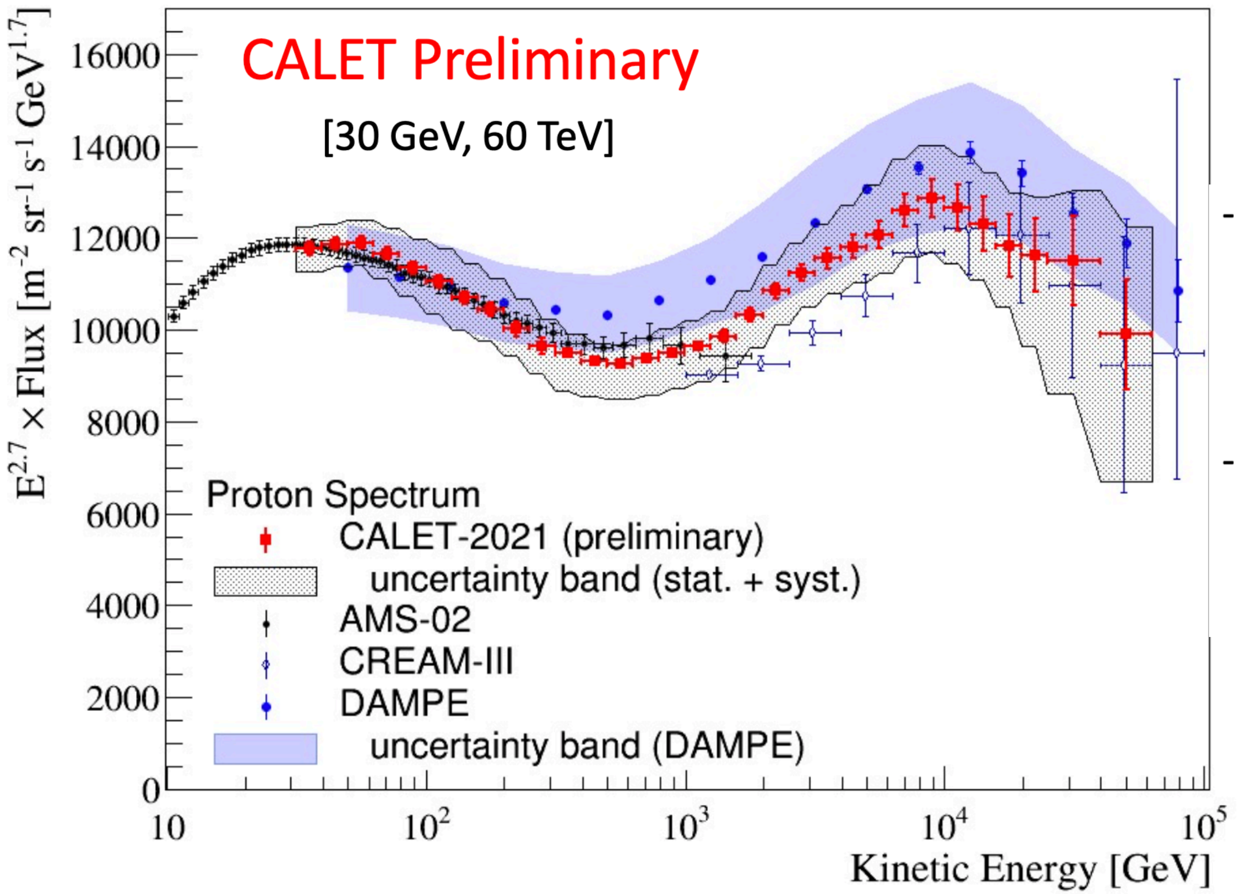


Each cosmic-ray nucleus provides specific information:

- Protons and Helium are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the spectrum is important to understand the origin, acceleration, and propagation of cosmic rays.
- Li, Be, B, F, … are produced by the spallation of cosmic rays in the interstellar medium: The flux of these secondaries or secondary/primary ratios (like B/C) are key measurements to understand propagation.
- Other primary (C, O,..) can be used to test the universality of propagation/acceleration.
- Precise knowledge of both primary fluxes and propagation mechanisms is essential to assess background (e^+, $\bar{p}$,…) and expected signal for DM searches.

Proton Flux

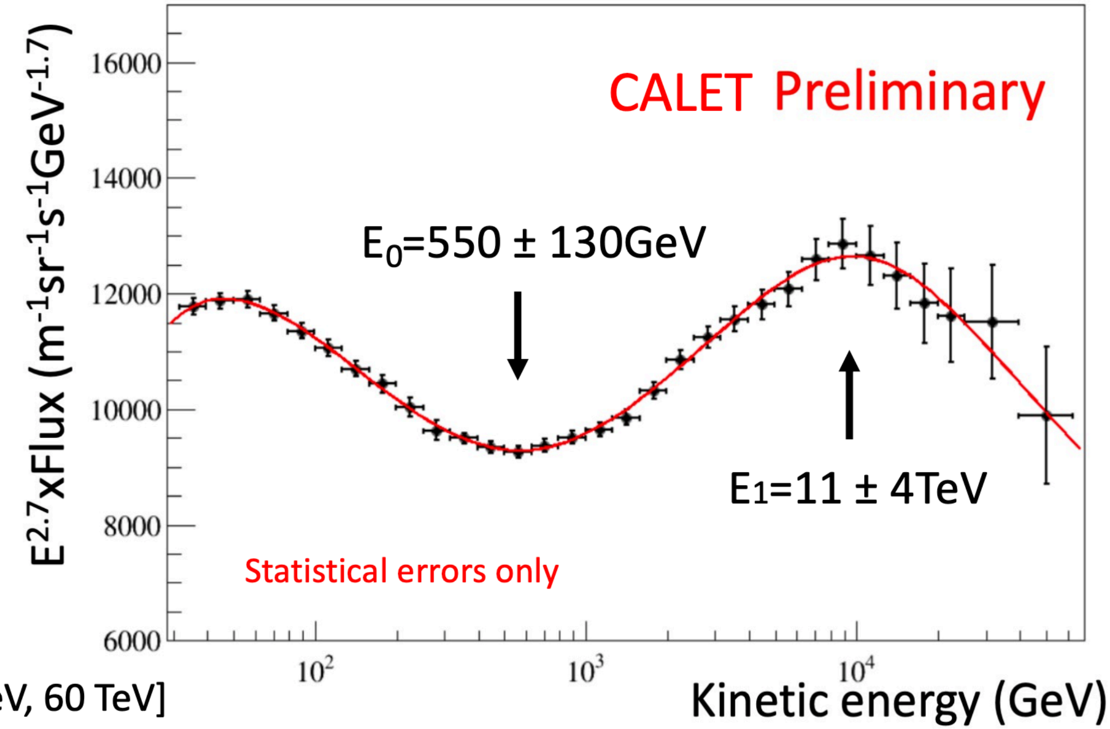
CALET proton flux presented at ICRC21 compared to AMS-02 and DAMPE results:



- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band).

Proton Flux

Fit of spectral breaks from CALET data:



(*) free S parameter in DBPL fit

$\chi^2 = 2.9/22$

C	$(5.1\pm2.1)\times10^{-1}$
p_0	9.1 ± 26
P_1	-6.6 ± 470
γ	-2.9 ± 0.3
S (*)	2.1 ± 2.0
Δγ	$(4.4\pm3.8)\times10^{-1}$
E_0	$(5.5\pm1.3)\times10^{2}$
$\Delta\gamma_1$	$(-4.4\pm3.0)\times10^{-1}$
E_1	$(1.1\pm0.4)\times10^{4}$

[30 GeV, 60 TeV]

Fitting a Double-Broken Power Law (DBPL):

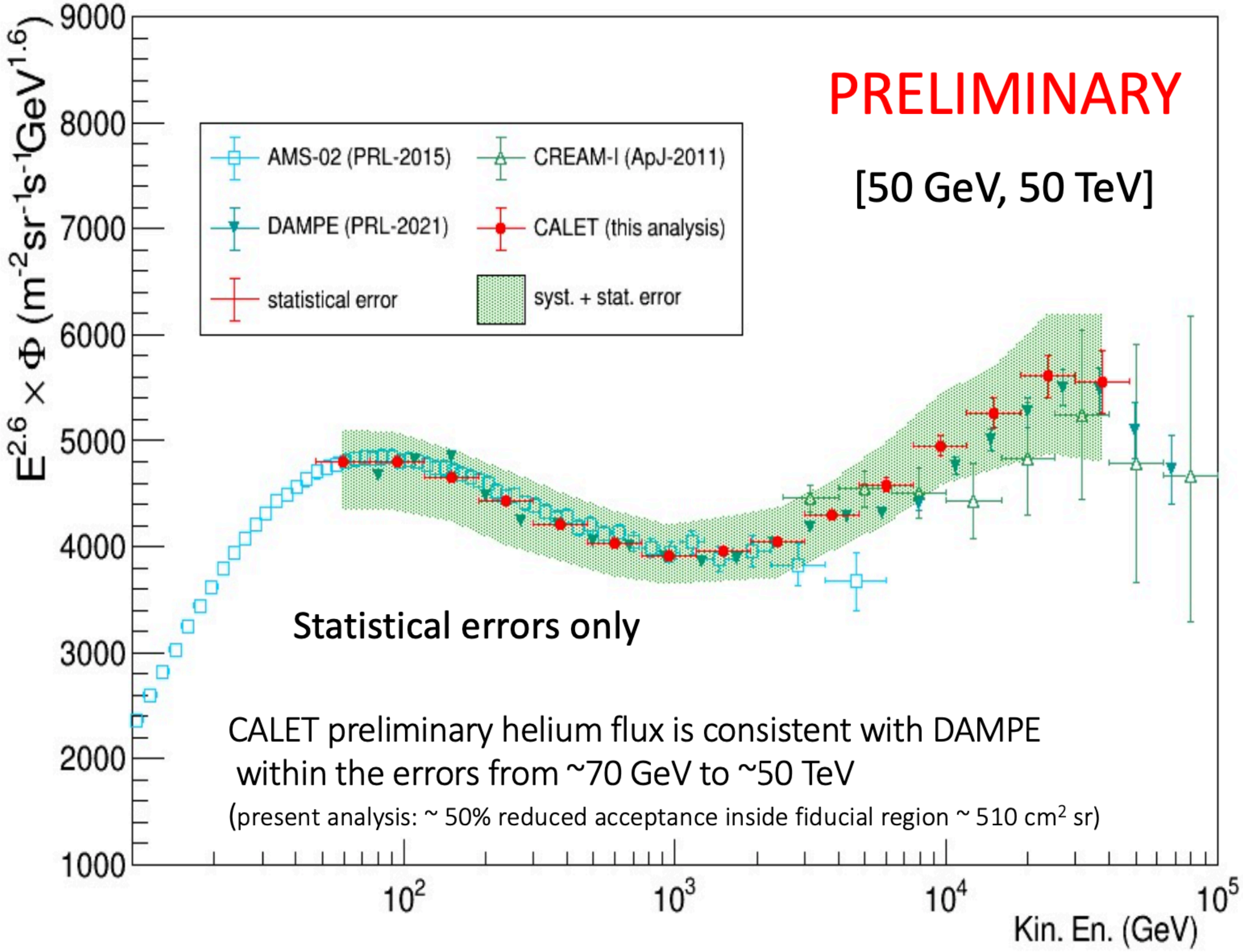
$$\Phi = E^{2.7} \times C \left(1 - \frac{p_1}{E} - \frac{p_2}{E^2}\right)\left(\frac{E}{45\ \mathrm{GeV}}\right)^{\gamma} \left[1 + \left(\frac{E}{E_0}\right)^{\frac{\Delta\gamma}{s}}\right]^{s} \left[1 + \left(\frac{E}{E_1}\right)^{\frac{\Delta\gamma_1}{s}}\right]^{s}$$

spectral hardening

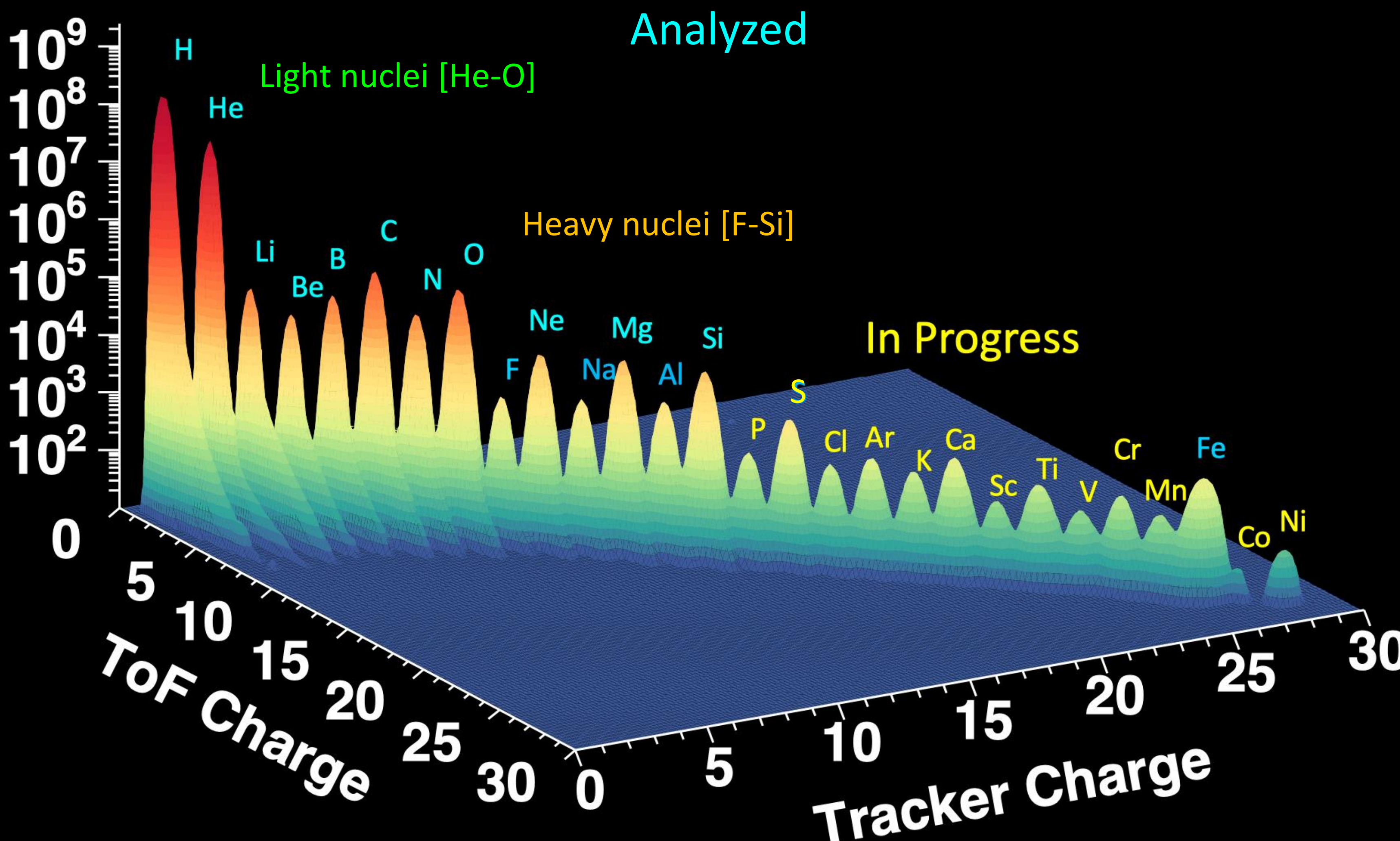
spectral softening

Helium Flux

CALET helium flux presented at ICRC21 compared to AMS-02 and DAMPE and CREAM results:

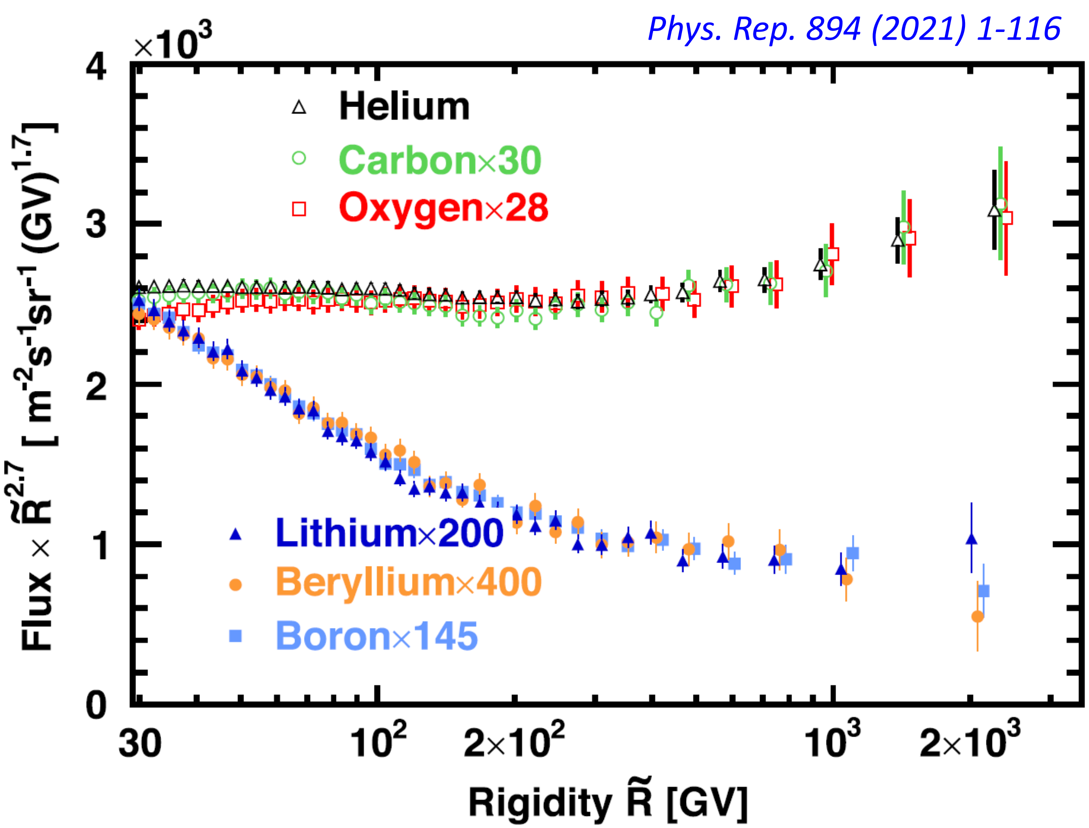


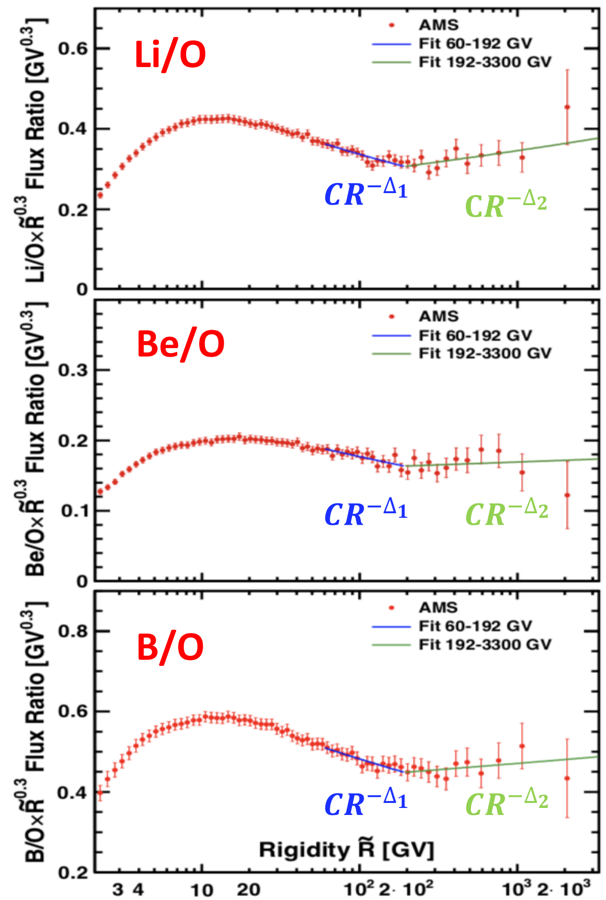
Nuclei cosmic rays detected by AMS



Latest AMS Measurements of Light Nuclei in Cosmic Rays

Above 200 GV, primary and secondary cosmic ray deviate from a single power law

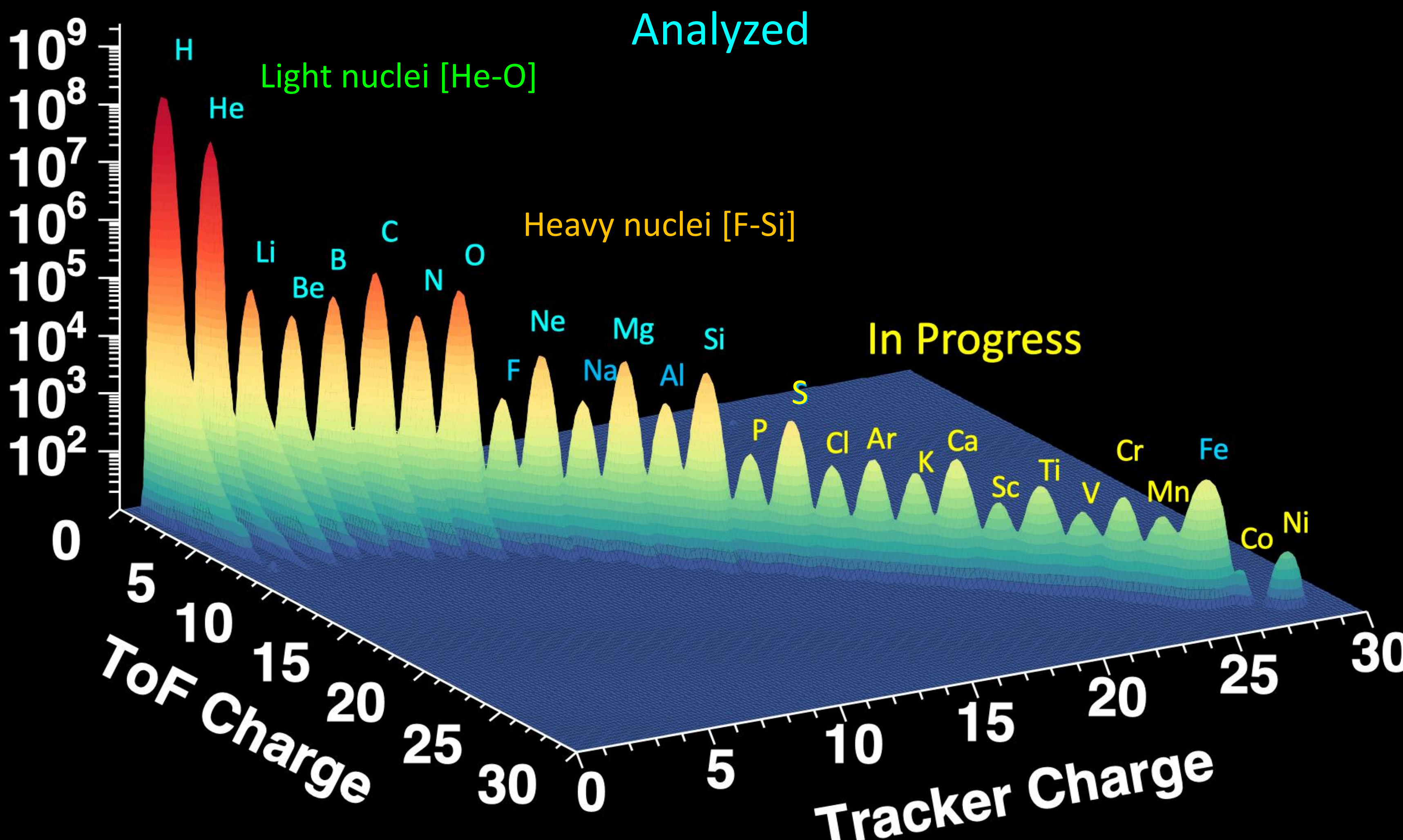




Secondary cosmic ray harden more than primary

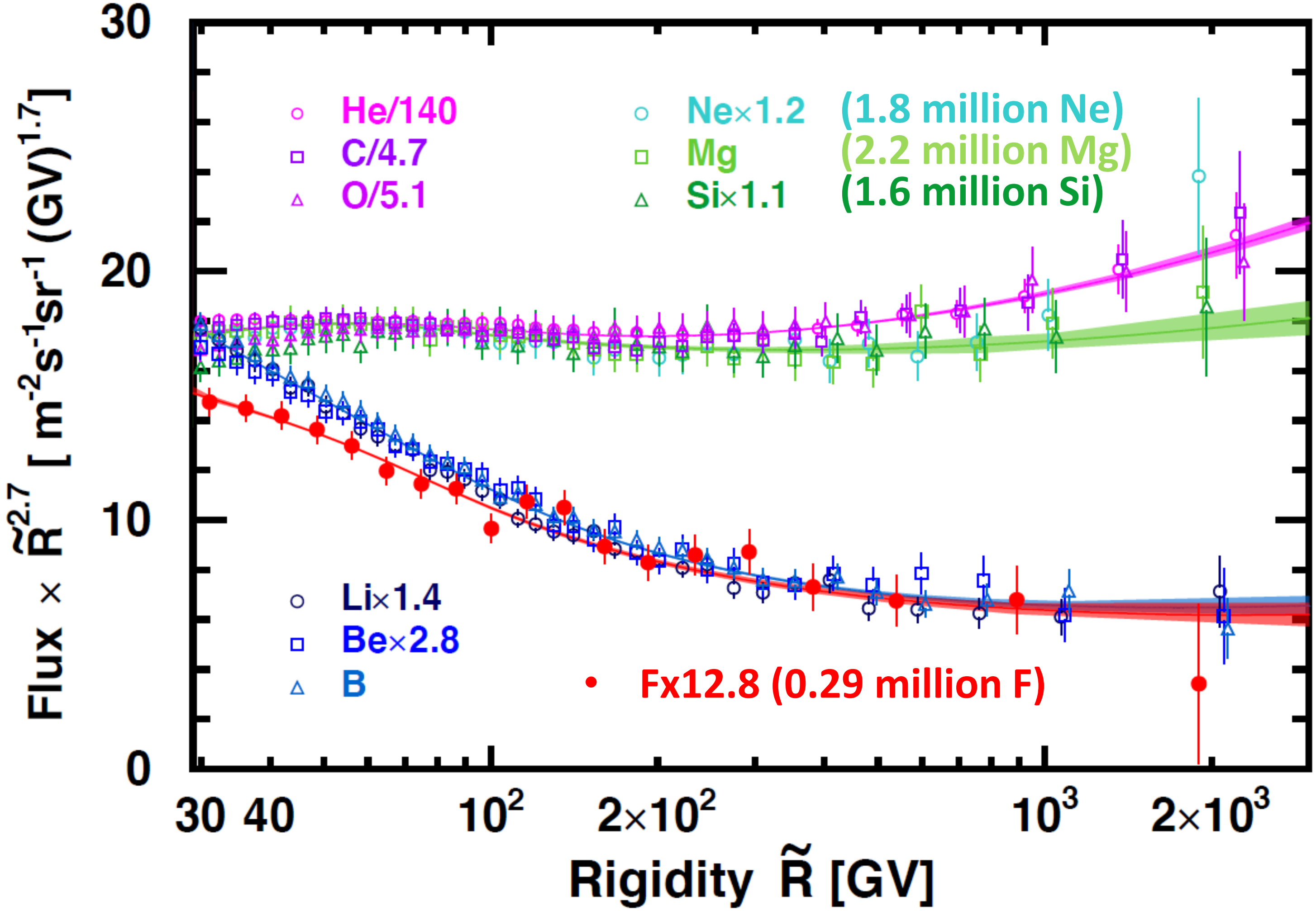
Average hardening $\Delta = \Delta_2 - \Delta_1 = 0.140 \pm 0.025$ (significance 5.6 σ)

Nuclei cosmic rays detected by AMS



F, Ne, Mg, Si fluxes from AMS02

PRL 124, 211102 (2020) *PRL 126, 081102 (2021)*



AMS F/Si

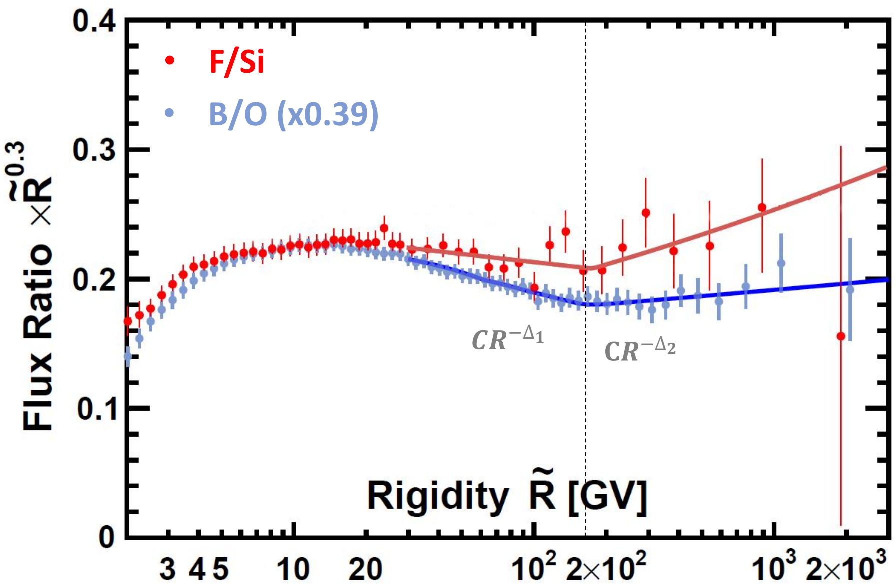
Heavier secondary-to-primary flux ratios (F/Si)

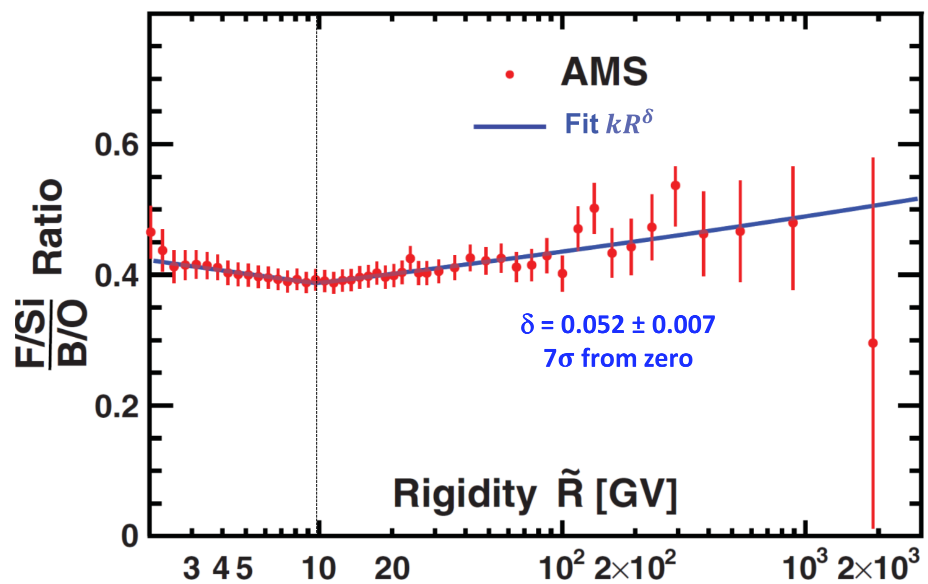
Traditionally the light secondary-to-primary ratio B/O (or B/C) is used to describe the propagation properties of all cosmic rays.

F/Si flux ratio hardens above 175 GV

Average hardening $\Delta = \Delta_2 - \Delta_1$ = 0.15 ± 0.07

Above 10 GV, the (F/Si)/(B/O) ratio can be described by a single power law with δ=0.052±0.007





The propagation properties of heavy cosmic rays are different from those of light CRs.

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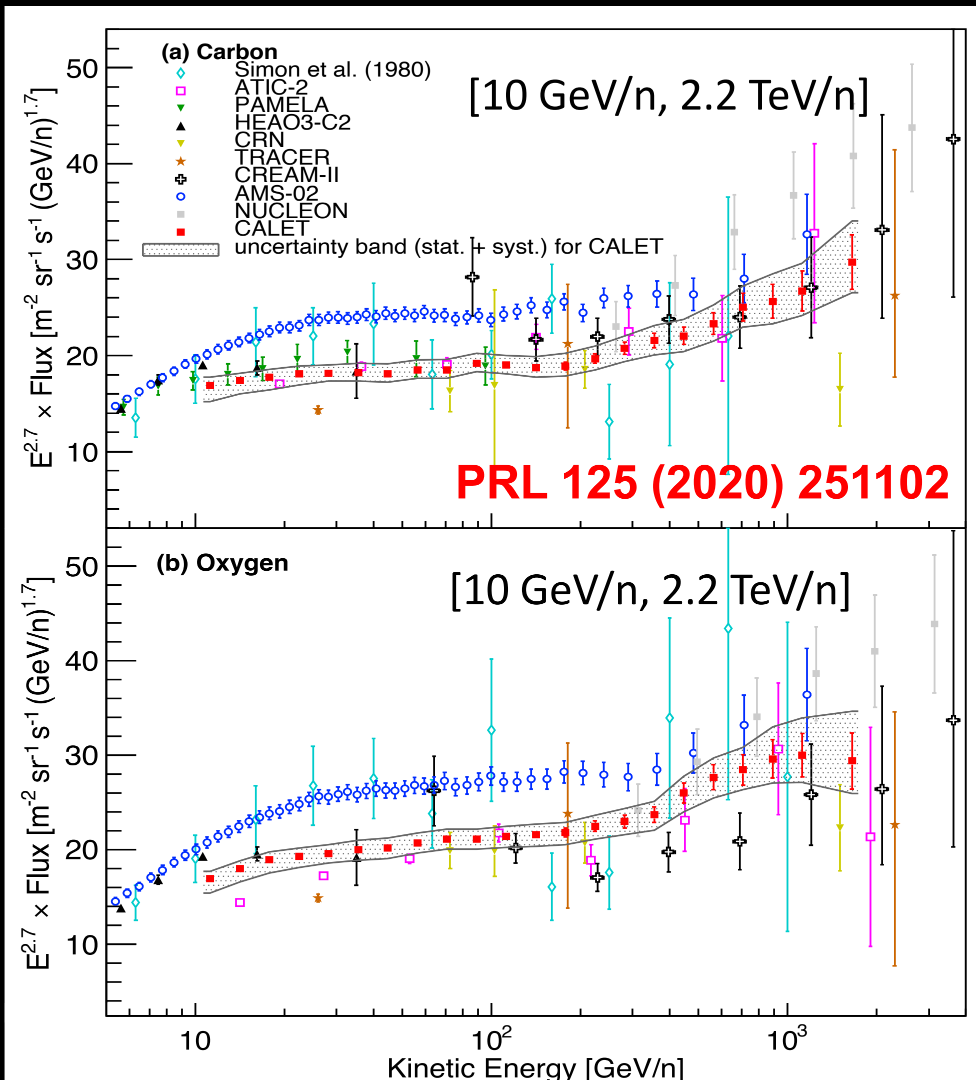
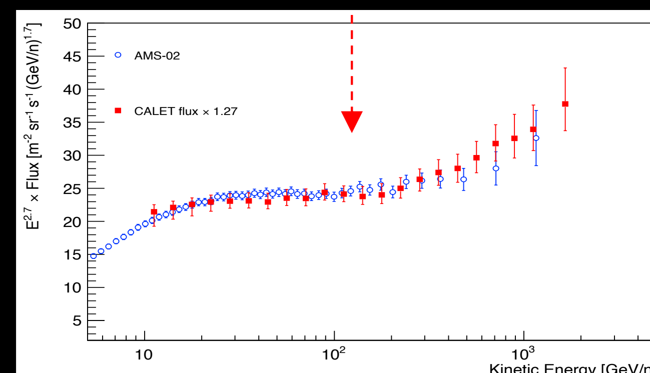
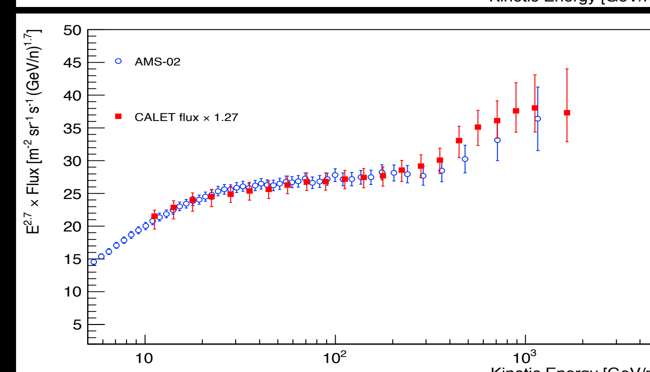
Carbon and Oxygen Fluxes from CALET



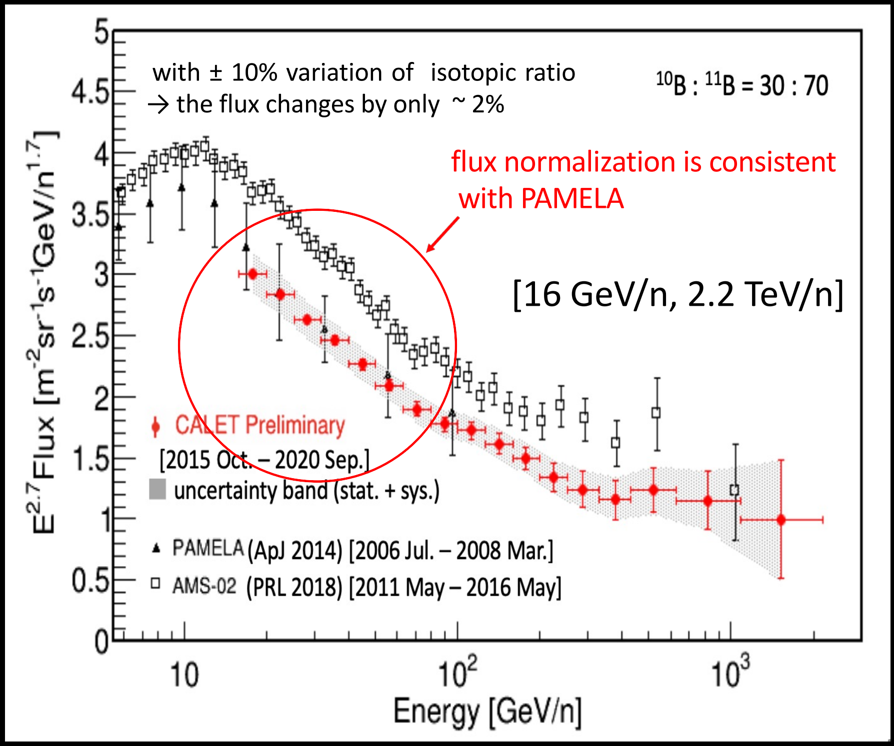
- CALET Carbon flux consistent with PAMELA. PAMELA did not publish oxygen flux.
- The spectra show a clear hardening around 200 GeV/n
- Similar shapes to AMS but the absolute normalization is significantly lower (~27%)

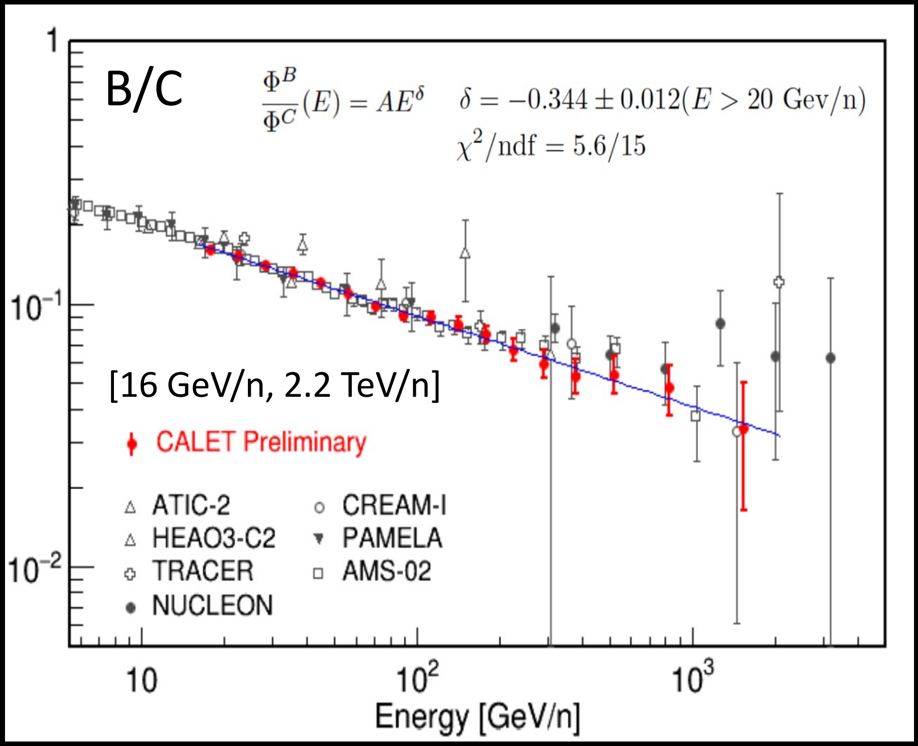




Boron flux and B/C from CALET

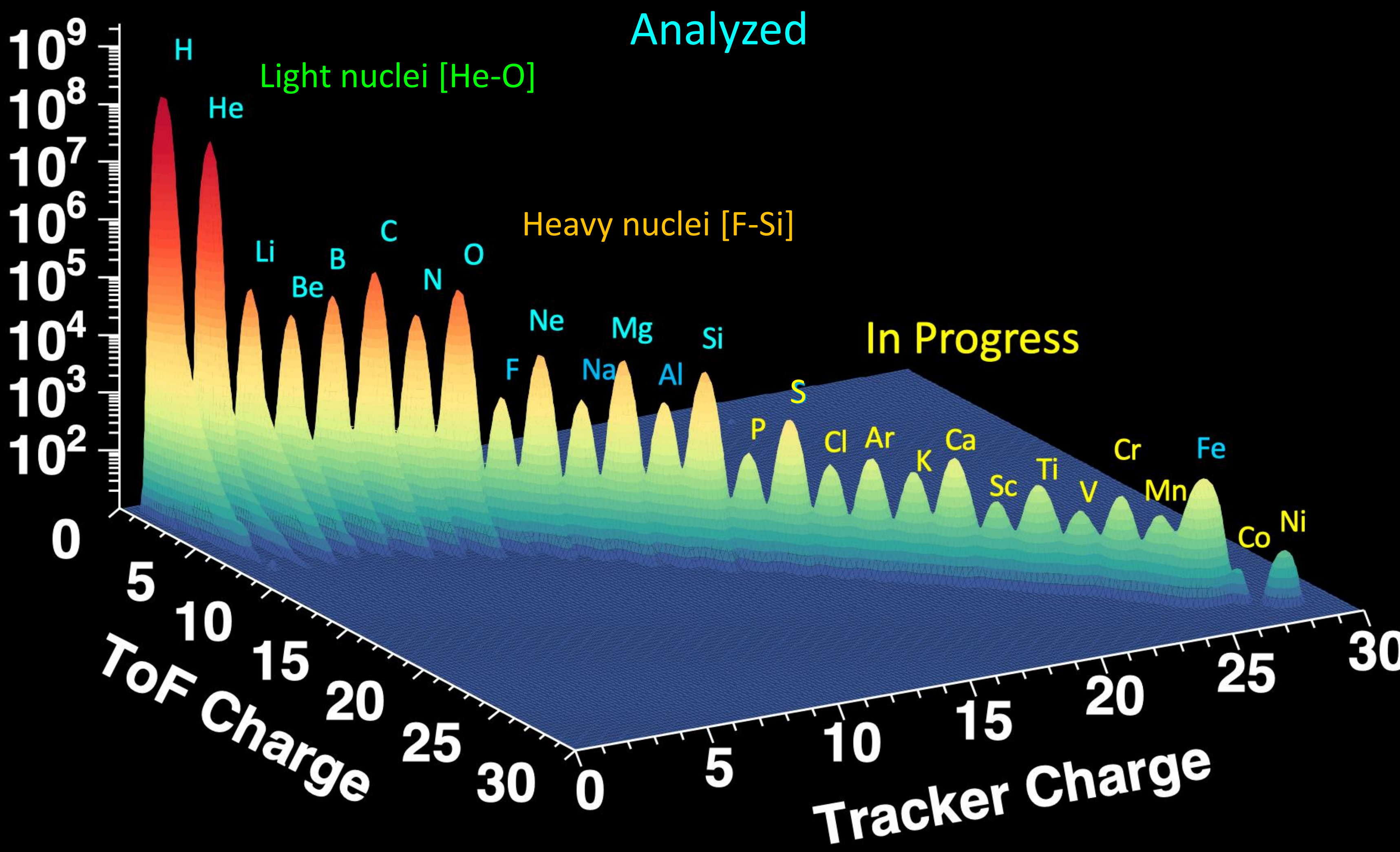
Latest CALET data presented at ICRC21 compared to AMS-02 and previous results:



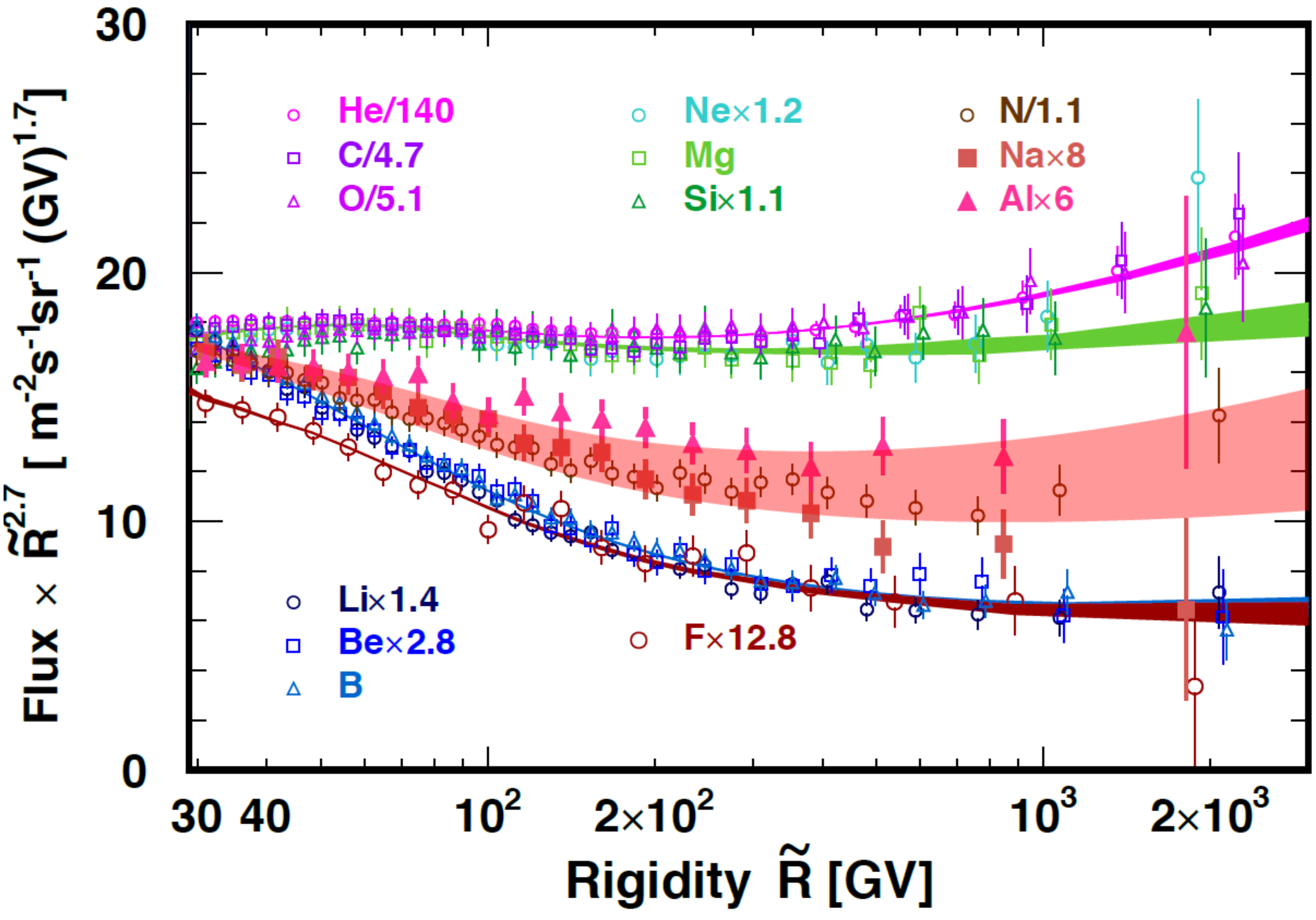


+ Preliminary CALET spectra from Ne to Fe presented at ICRC21.

Nuclei cosmic rays detected by AMS



AMS Nuclei Cosmic Rays fluxes

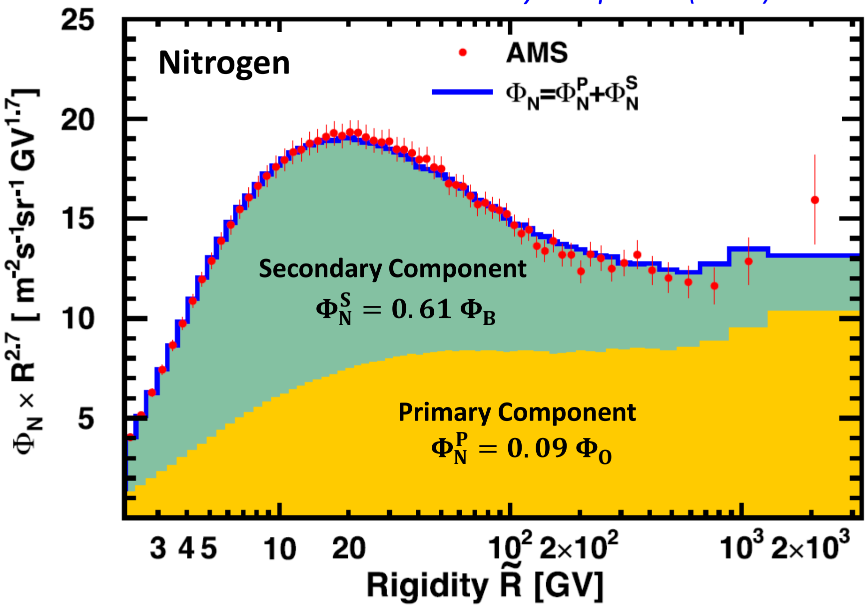


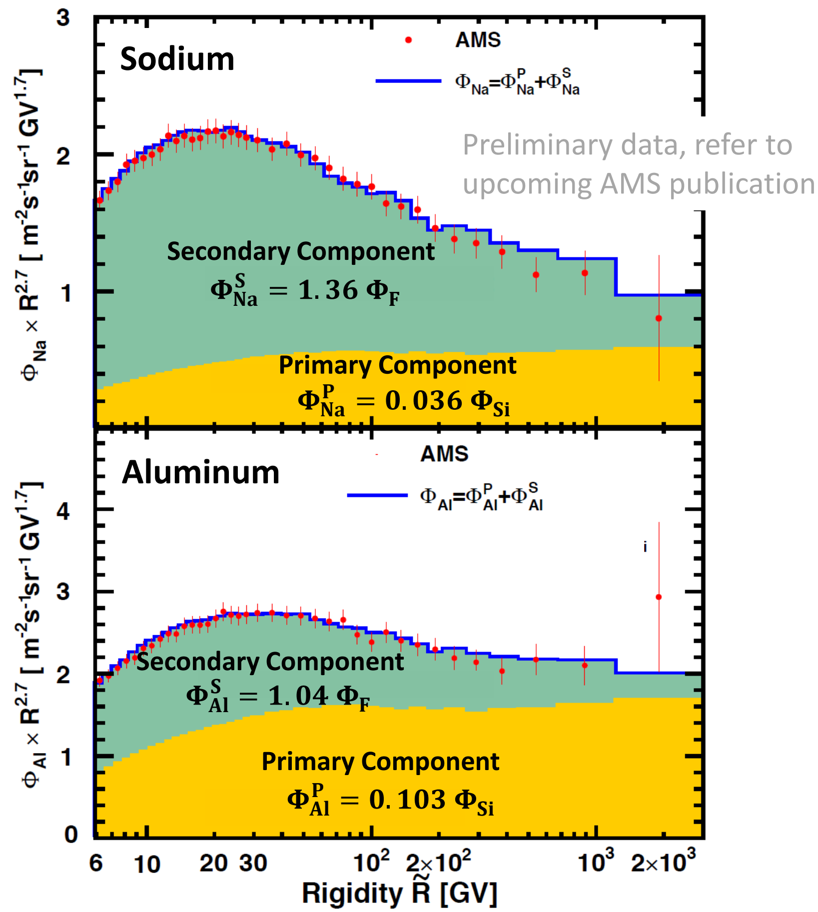
Cosmic Nuclei with both, Primary and Secondary components (N, Na, Al)

3.9 x 10^6 Nitrogen
0.46 x 10^6 Sodium
0.51 x 10^6 Aluminum

N, Na and Al fluxes expressed as sum of primary and secondary

Phys. Rep. 894 (2021) 1-116



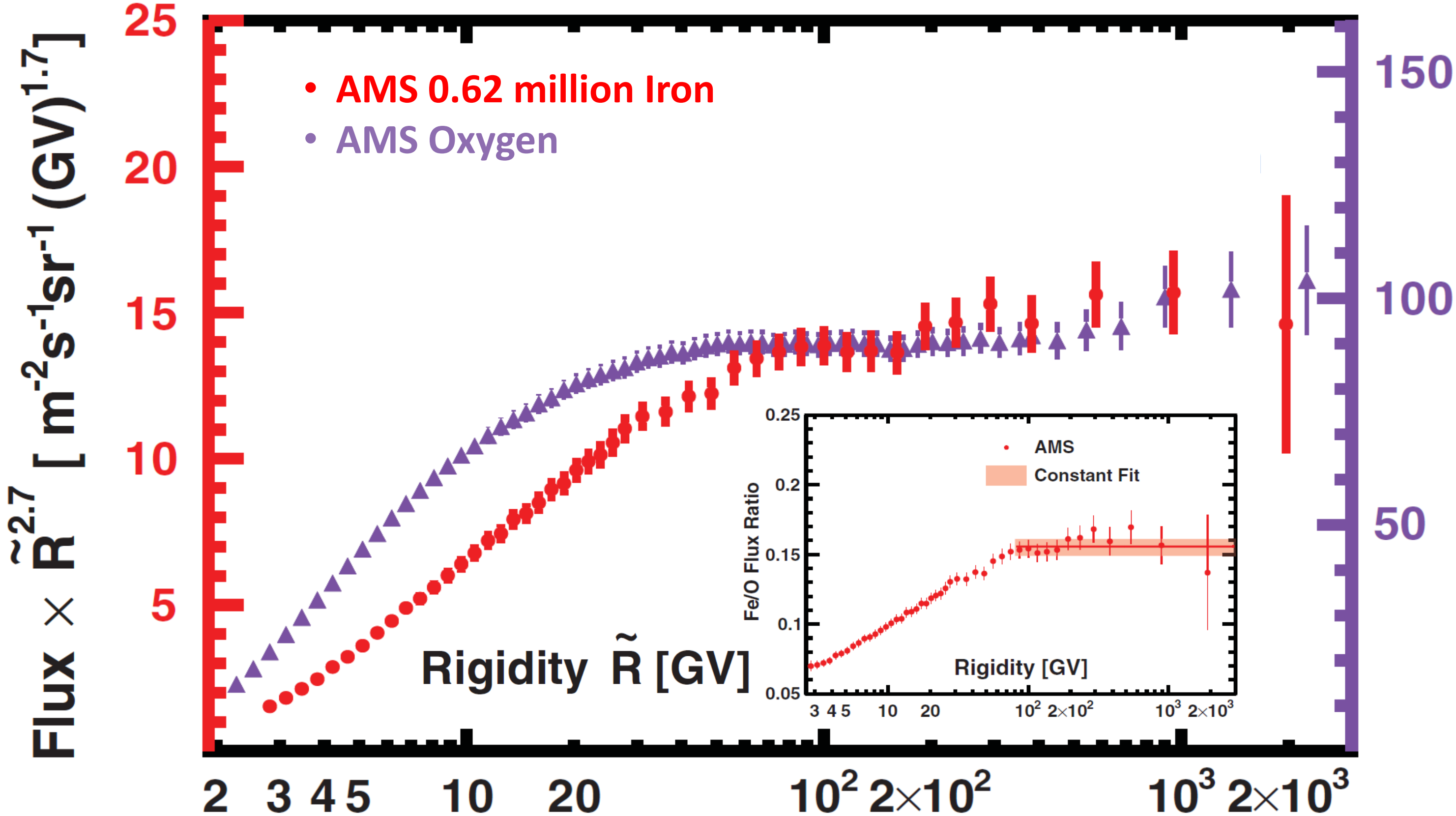


ϕ_N/ϕ_O, ϕ_{Na}/ϕ_{Si}, and ϕ_{Al}/ϕ_{Si} abundance ratios at the source are determined without the need to consider the Galactic propagation of cosmic rays.

Iron nuclei flux

Above 200 GV, Iron flux deviates from a single power law

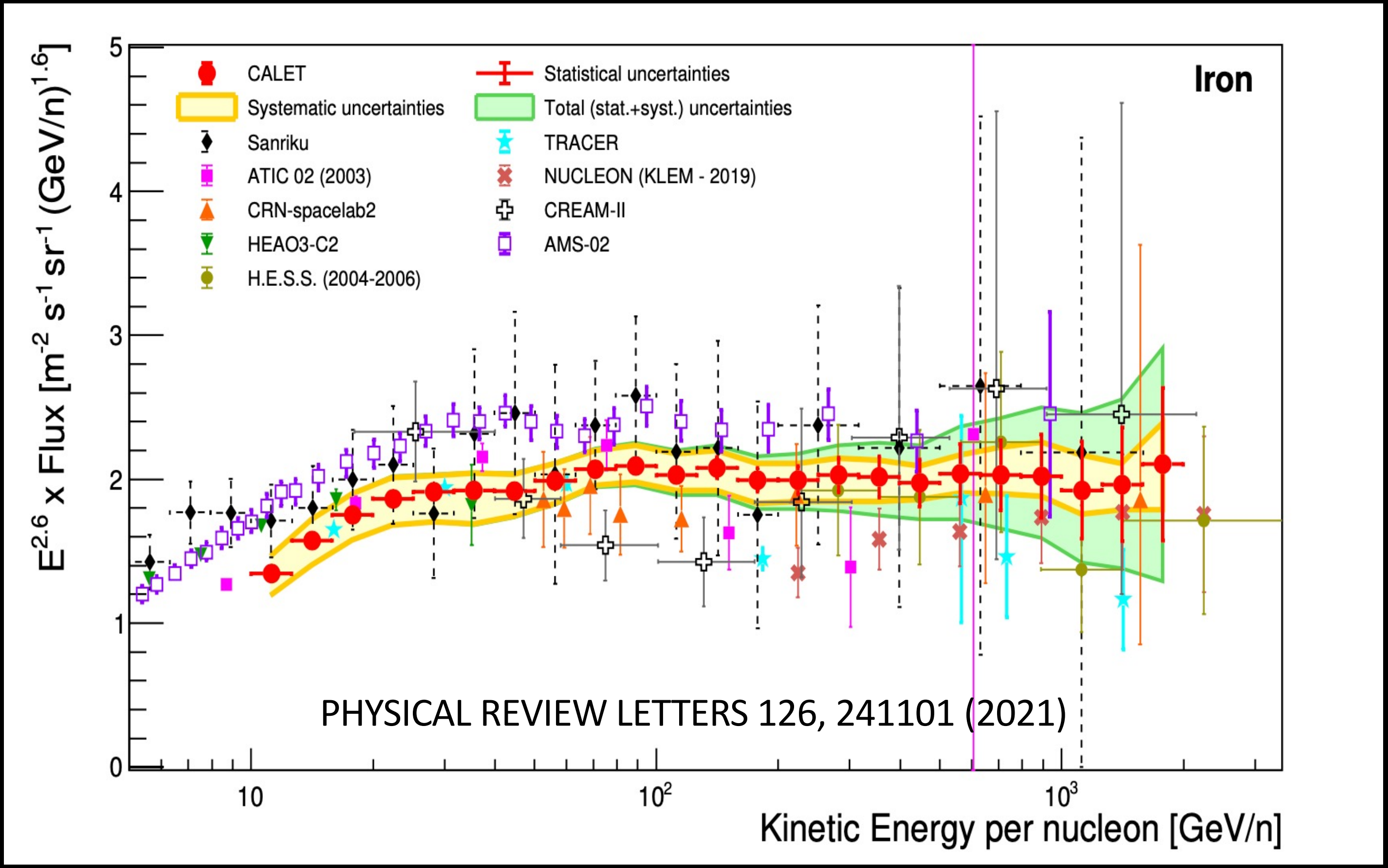
PRL 126, 041104 (2021)



Iron and Oxygen have identical rigidity dependence above 80.5 GV

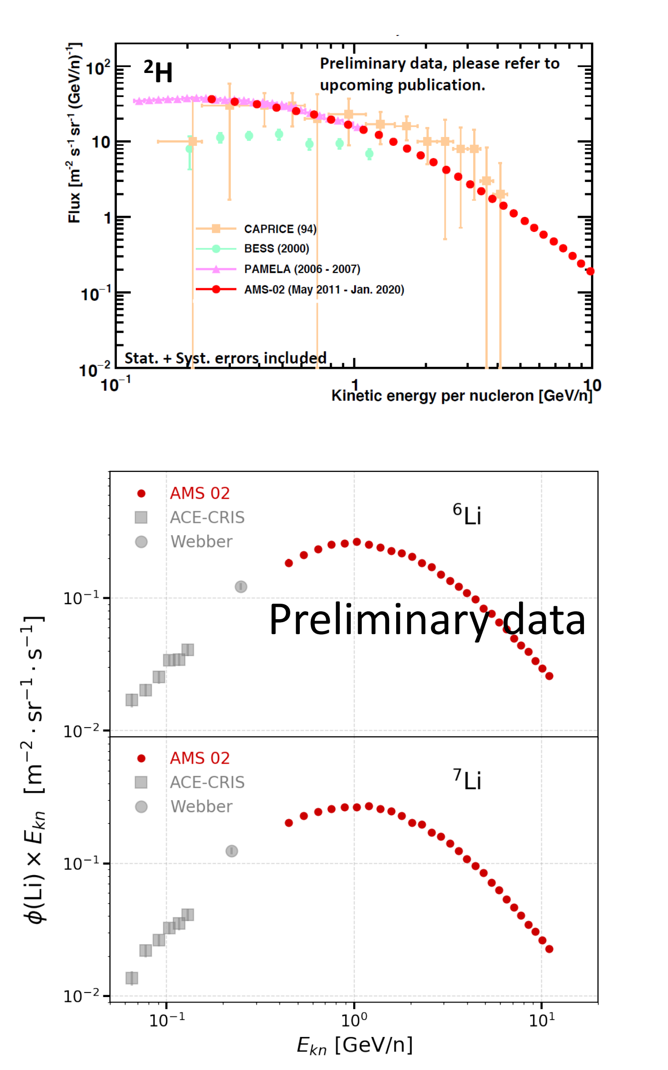
Iron Flux from CALET

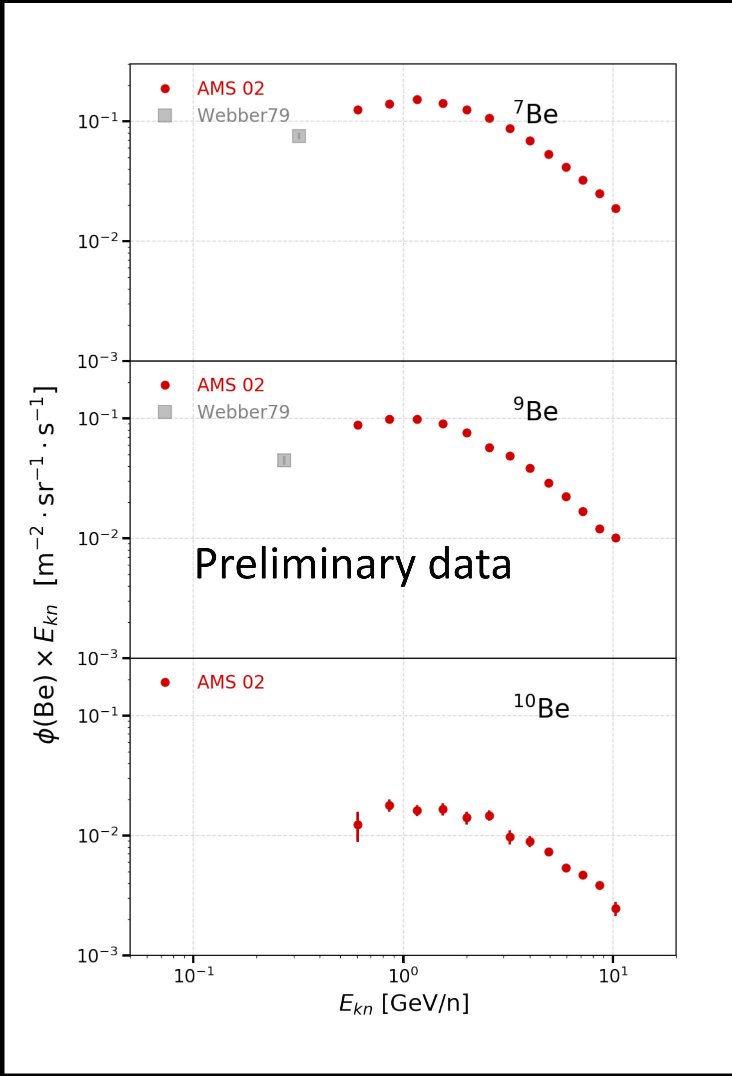
Flux x $E^{2.6}$ vs kinetic energy per nucleon [10 GeV/n, 2 TeV/n] analyzed data: Jan 1, 2016 – May 2020



Isotopes with AMS02

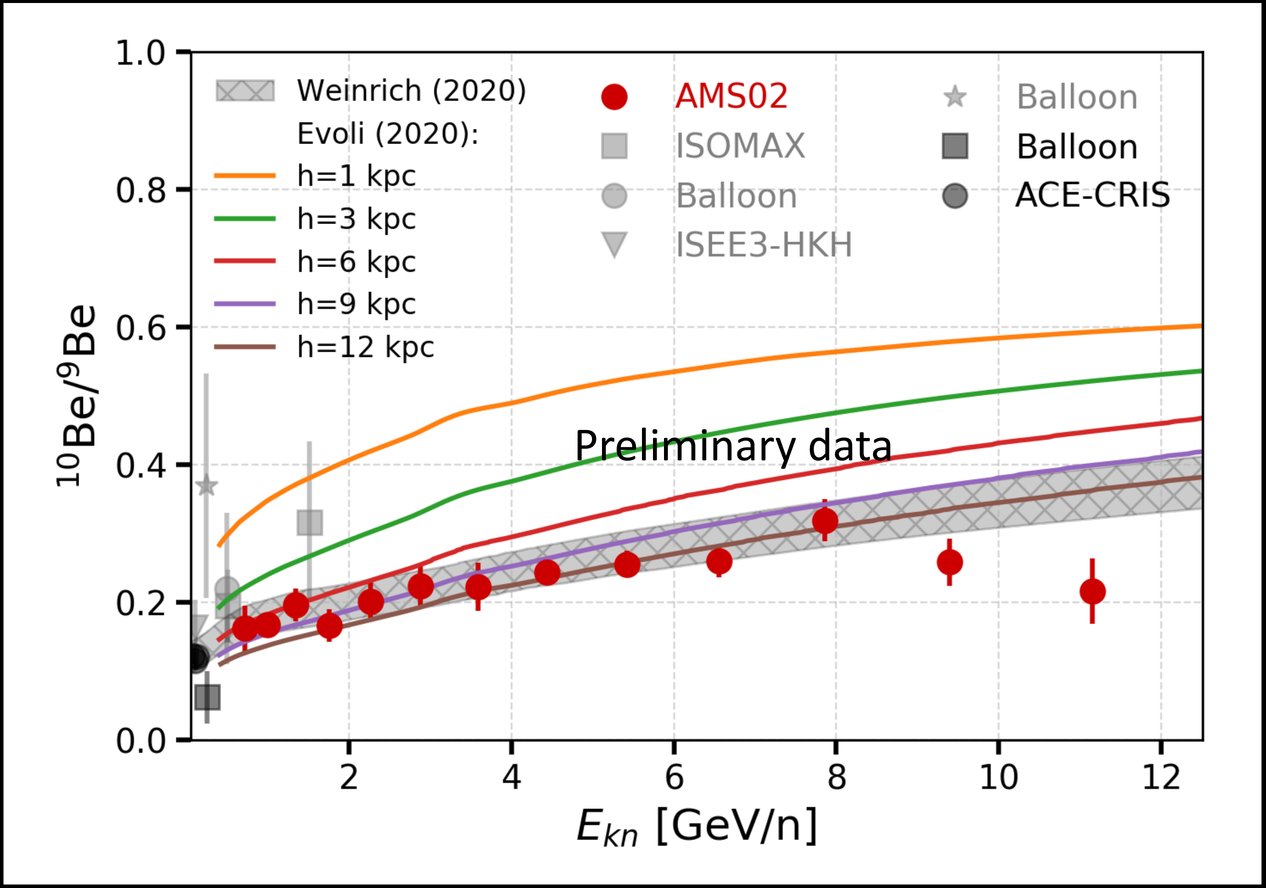
H, Li and Be isotopic fluxes measured by AMS presented at ICRC21:





Beryllium Isotopic Flux ratios vs E_{kn}

AMS 02 ratio compared with recent models from Weinrich (2020) and Evoli (2020).



→ AMS data provide strong constraints on the size of galactic halo size h (~ τ_{diff})

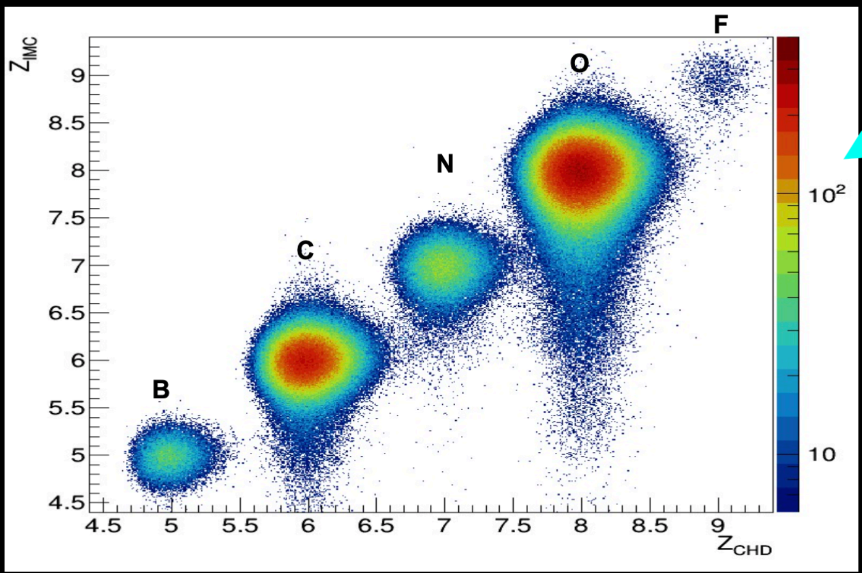
Conclusions

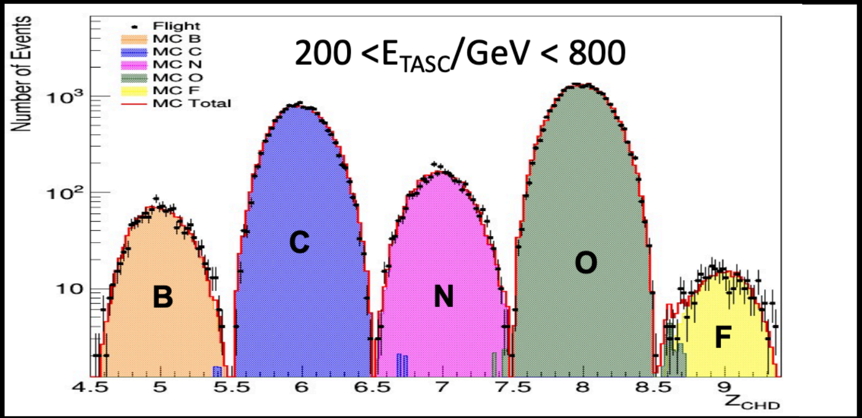
- AMS taking data since May 2011, AMS has recorded more than 180 billion cosmic rays.
- CALET was installed on ISS on August 2015.
- DAMPE was successfully launched on December 2015.
- awaiting ISS-CRREAM first results

$\longrightarrow$ Large set of data new for all component of cosmic rays with an extend energy range, over a long period of time and unprecedented precision.

$\longrightarrow$ New era for cosmic ray physics which can use this unprecedent set of data to challenge source, propagation model and search for exotic components.

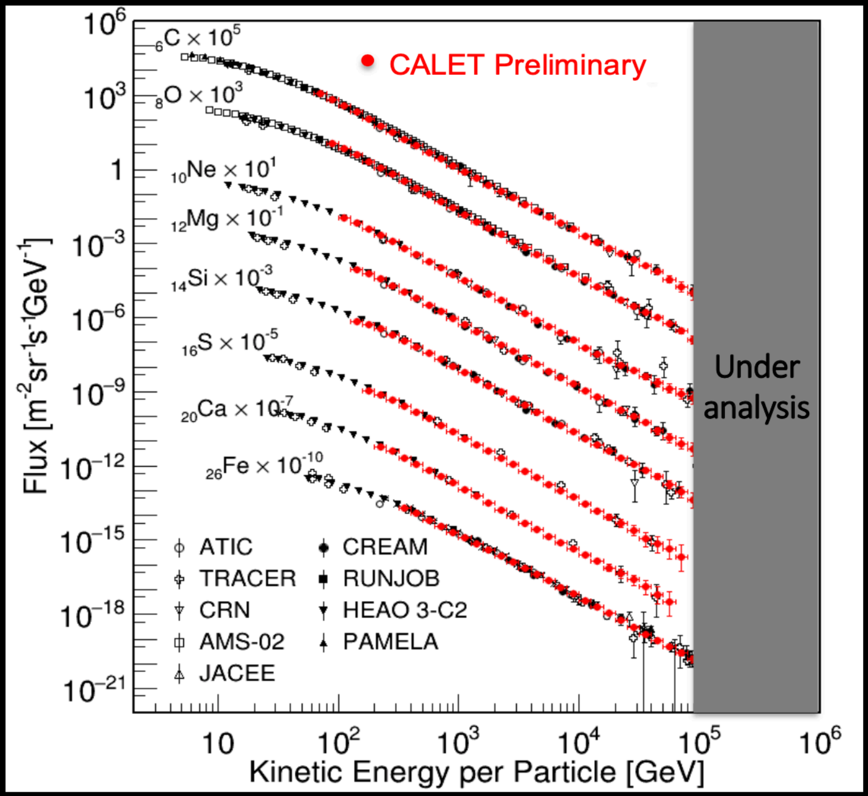
Spectra of cosmic-ray nuclei from C to Fe from CALET



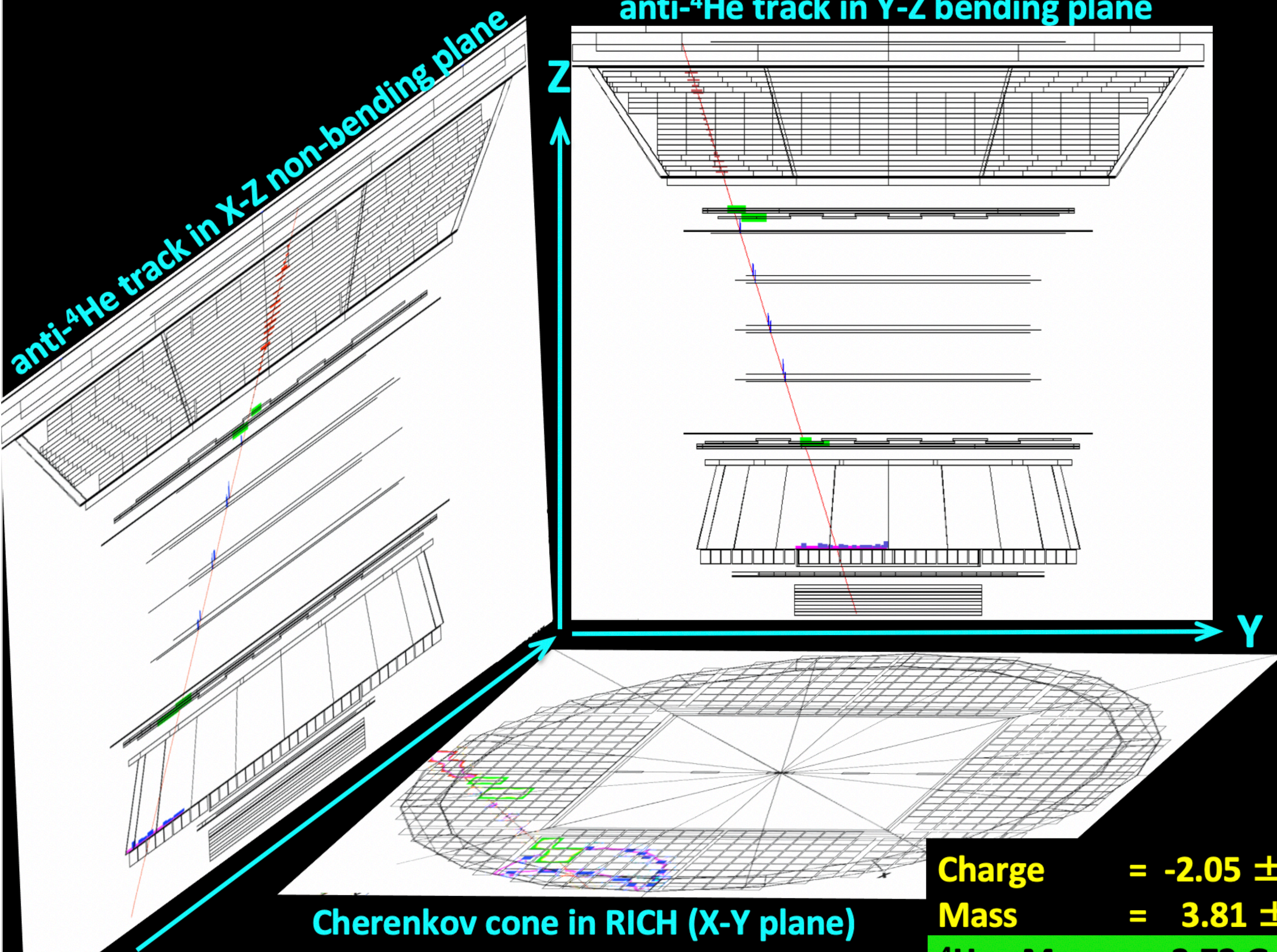


With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

Preliminary Spectra of Carbon – Iron



Observation of anti-He events



Date: 2017-173:06:11:40

Charge = -2.05 ± 0.05

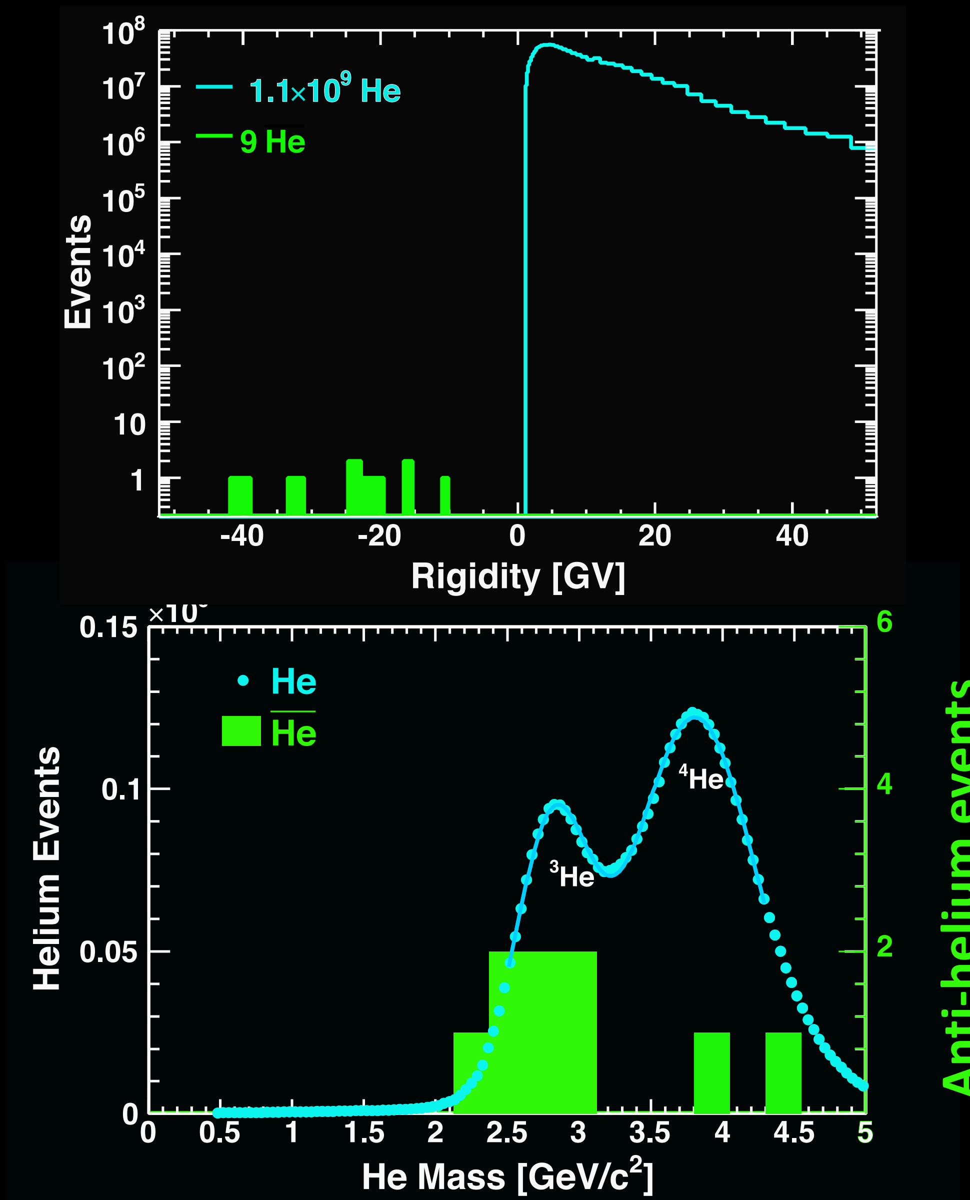
Mass = 3.81 ± 0.29 GeV/c^2

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

Charge = +2

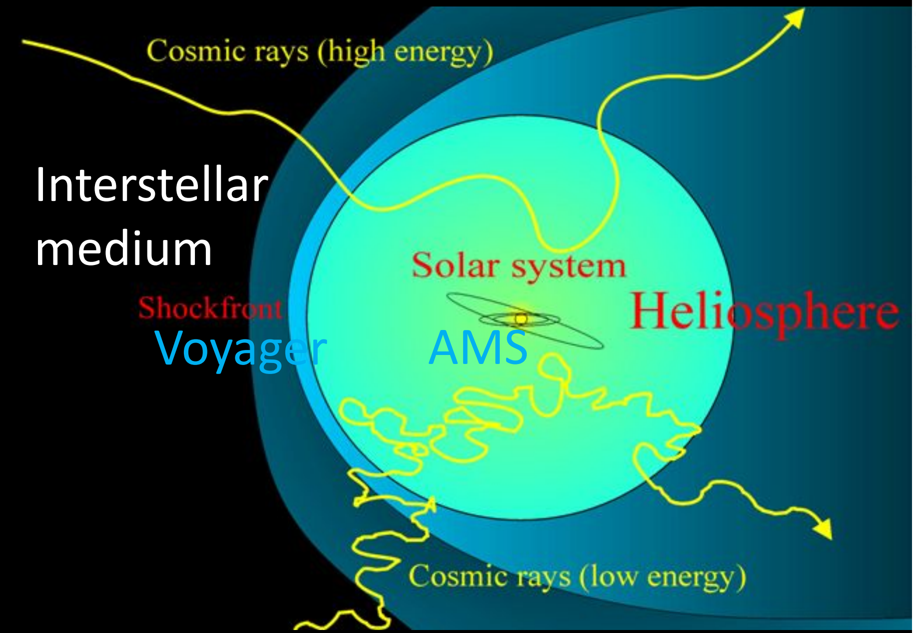
Antihelium candidates

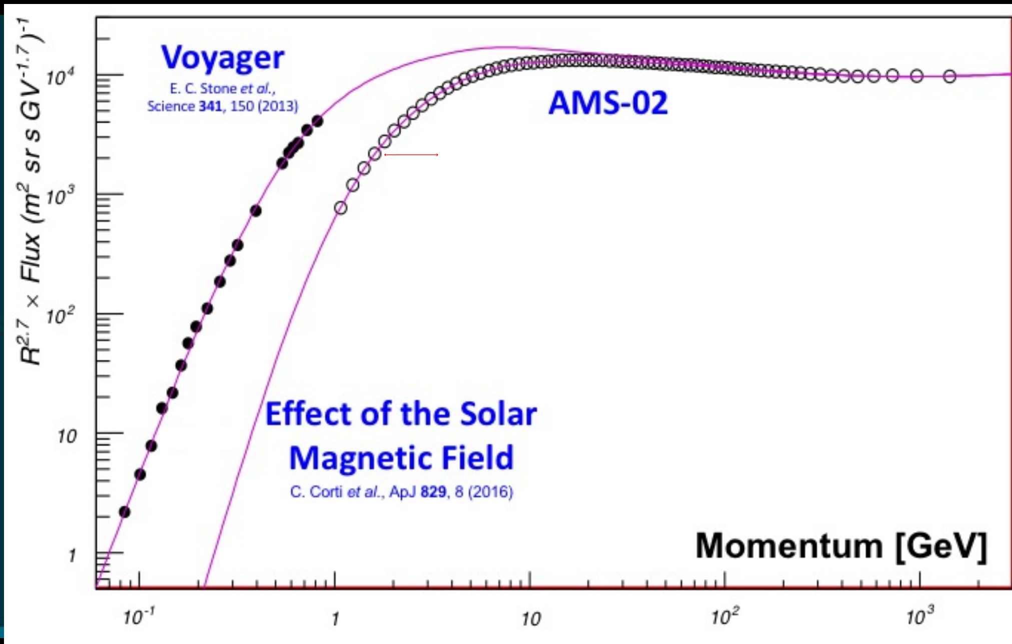
The rate in AMS of antihelium candidates is less than 1 in 100 million helium. At this extremely low rate, more data and understanding of MC at $1/10^9$ level is required to further check the origin of these events.



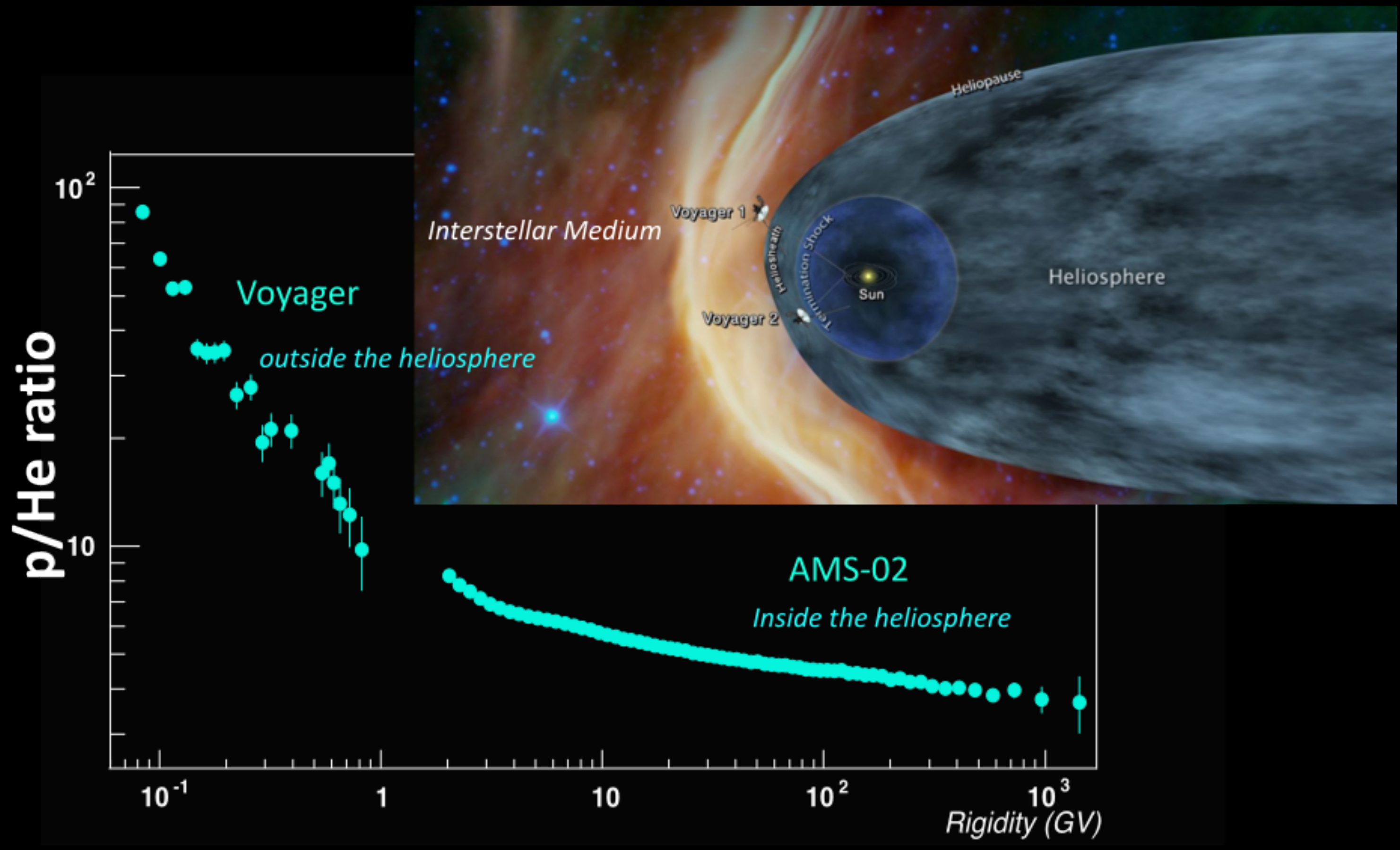
Solar Modulation of cosmic-ray spectra

Low energy cosmic rays from the interstellar medium are "screened" by the heliosphere, emanation of the Sun's magnetic field in the interstellar medium





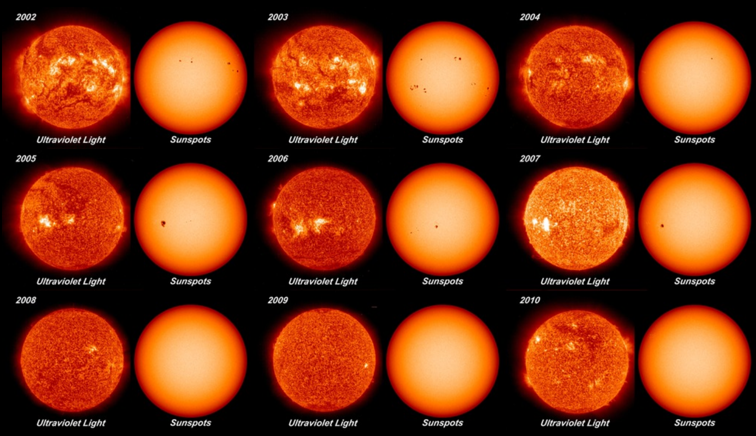
Connecting near-Earth space radiation with Deep Space

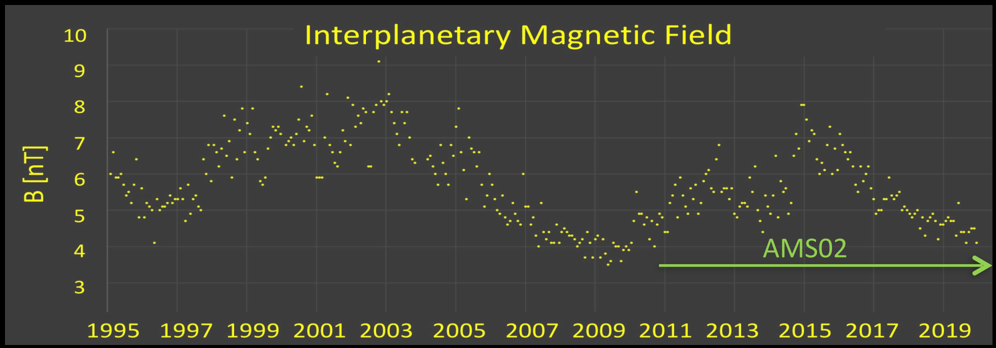


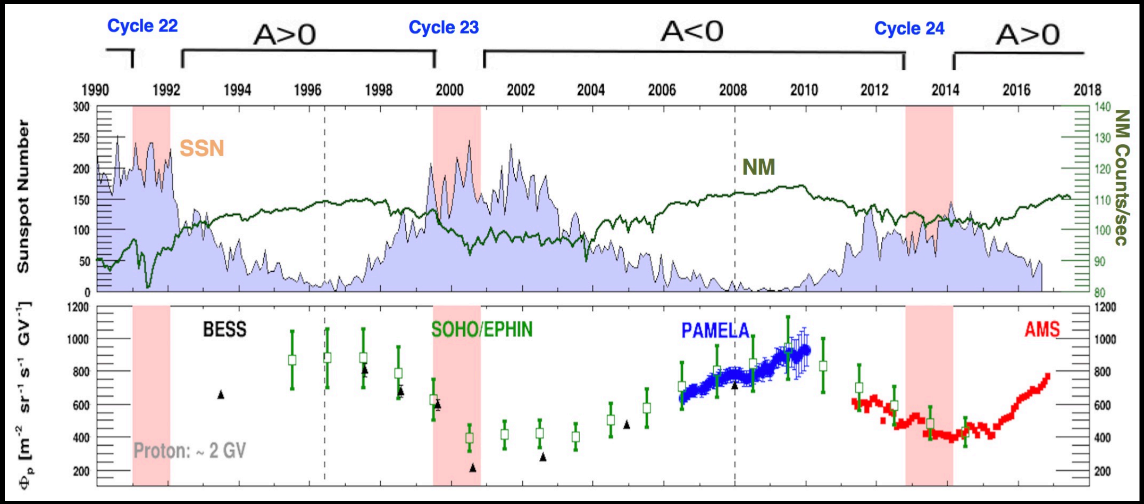
The Solar Cycle

The Sun has an 11-year activity cycle shown by sunspot number (SSN)

The heliosphere changes with time following the solar cycle:

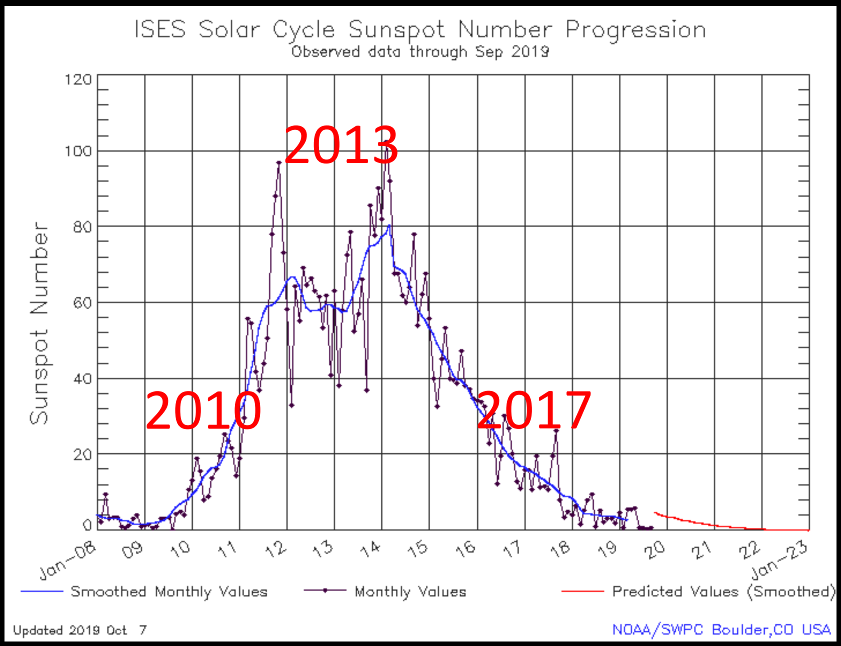


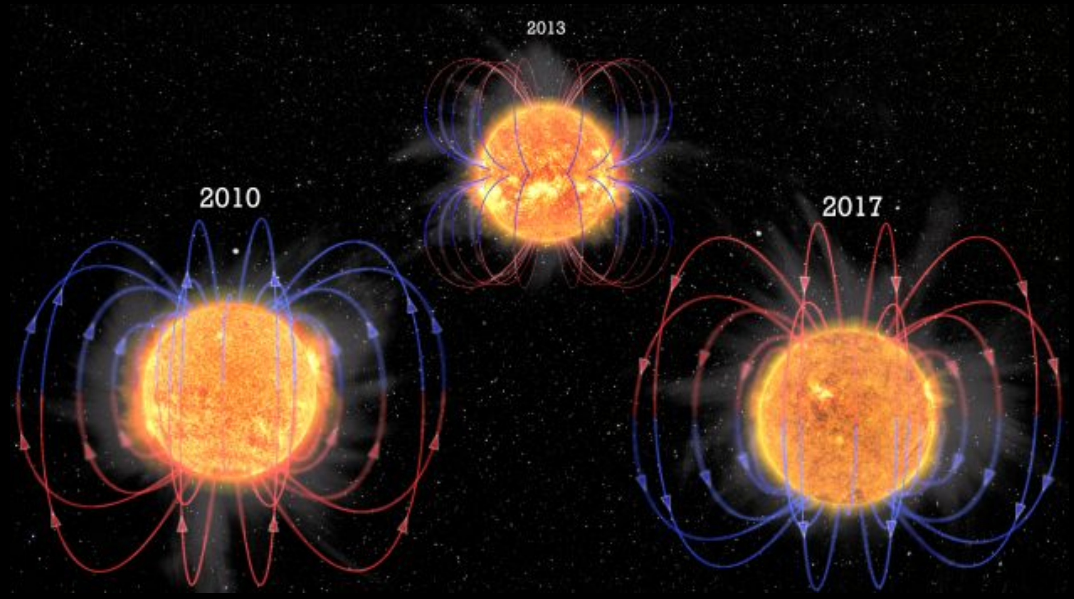




Solar Magnetic field: polarity reversal

At each solar maximum (every 11 years) the polarity of the Sun's magnetic field flips

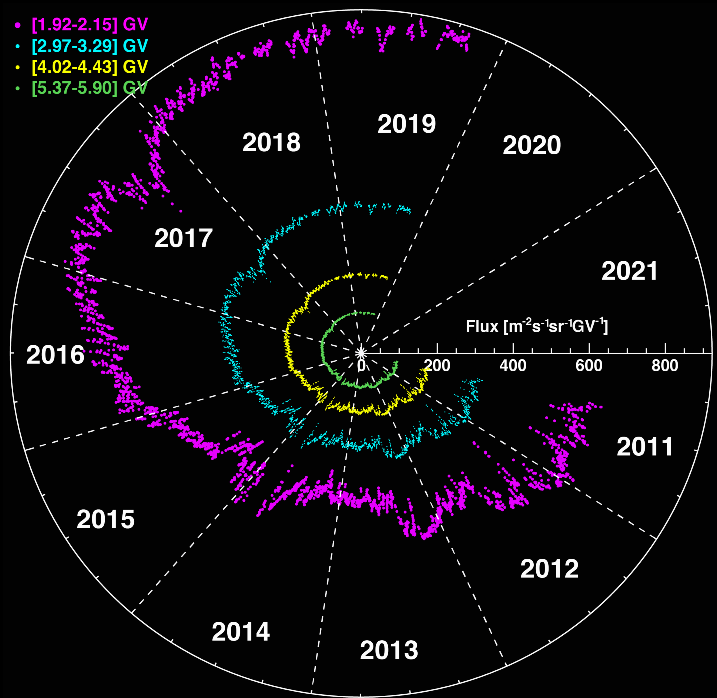




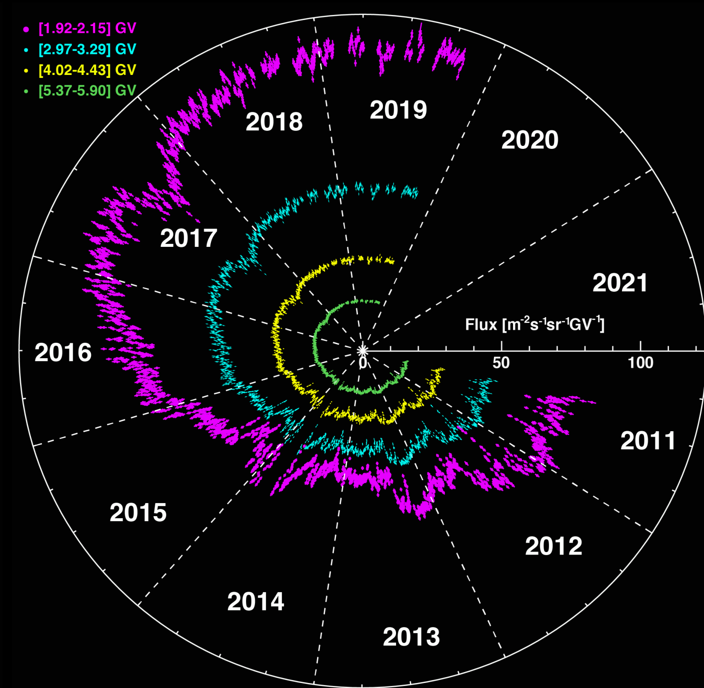
Generates charge-sign dependent effects on solar modulation of cosmic rays

Observation of Fine Time Variations in Proton and Helium Fluxes

AMS Daily Proton Fluxes



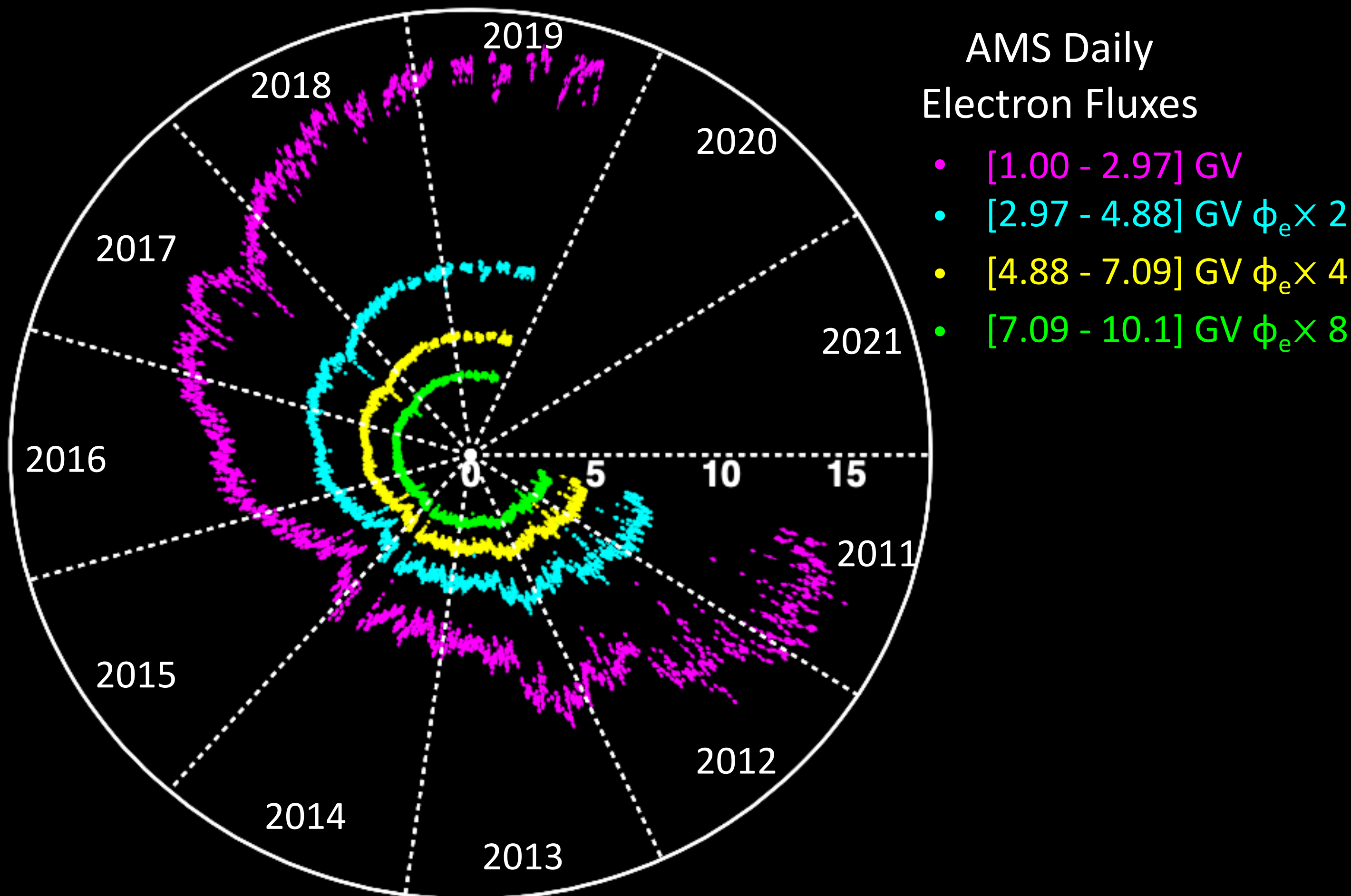
AMS Daily Helium Fluxes



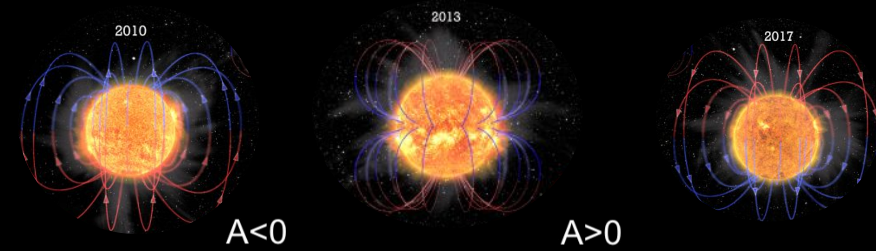
Detailed study of solar effects on cosmic rays are important to assess CR Local Interstellar Spectra

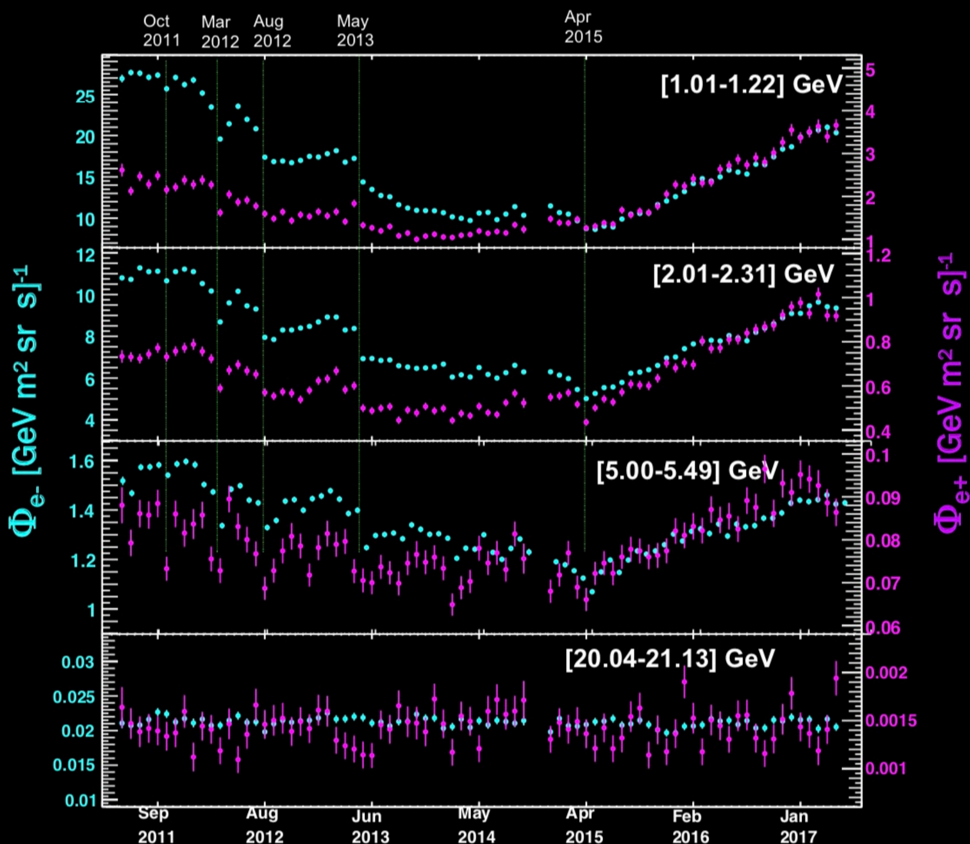
Space radiation measurements are crucial to model radiation hazards for human travel in space

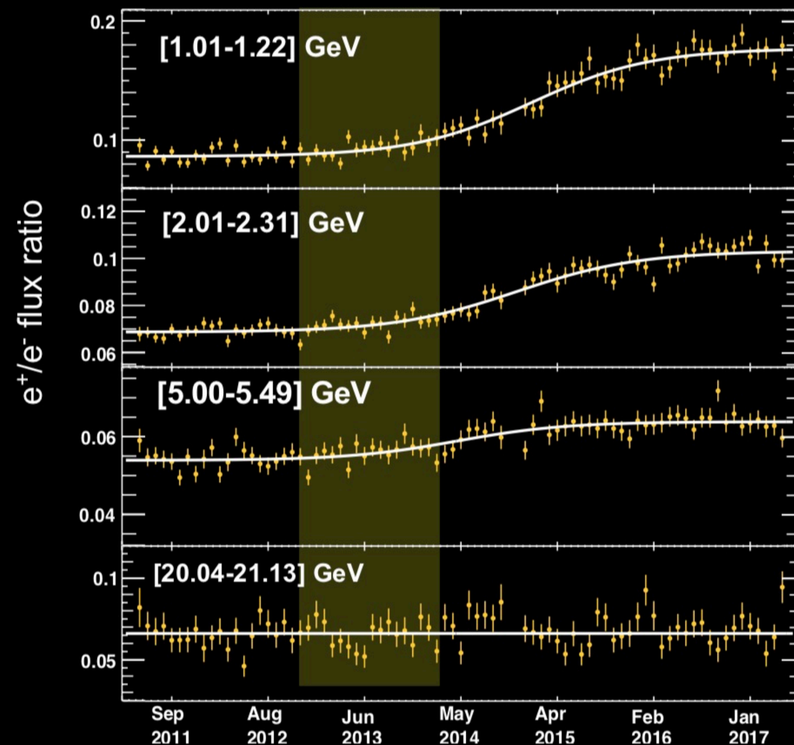
Observation of fine time variations in the electron flux



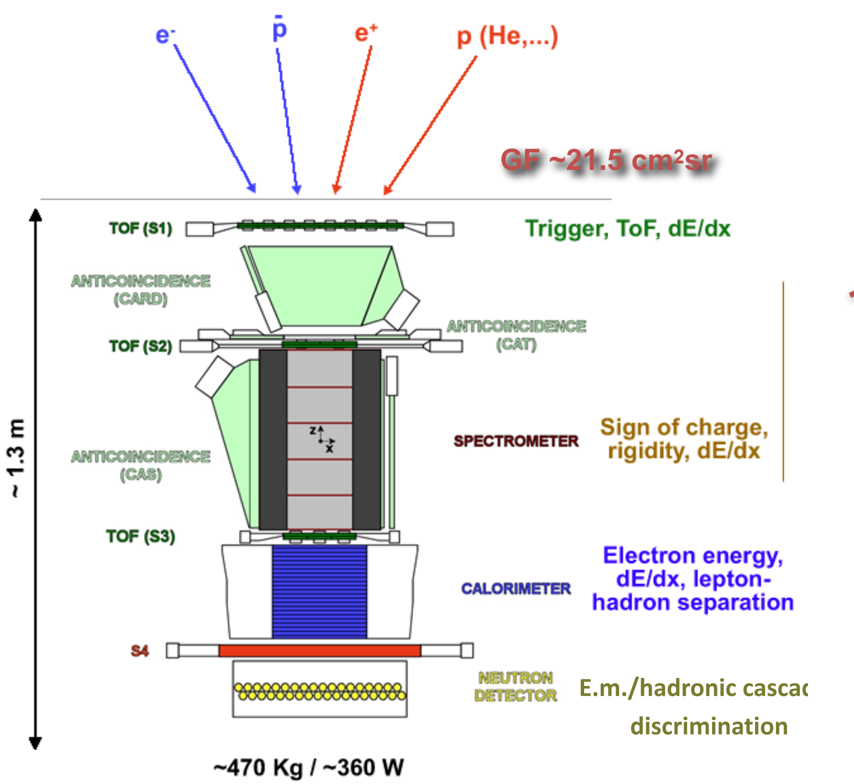
Observation of charge-sign dependent heliospheric effects: e+ and e- monthly fluxes





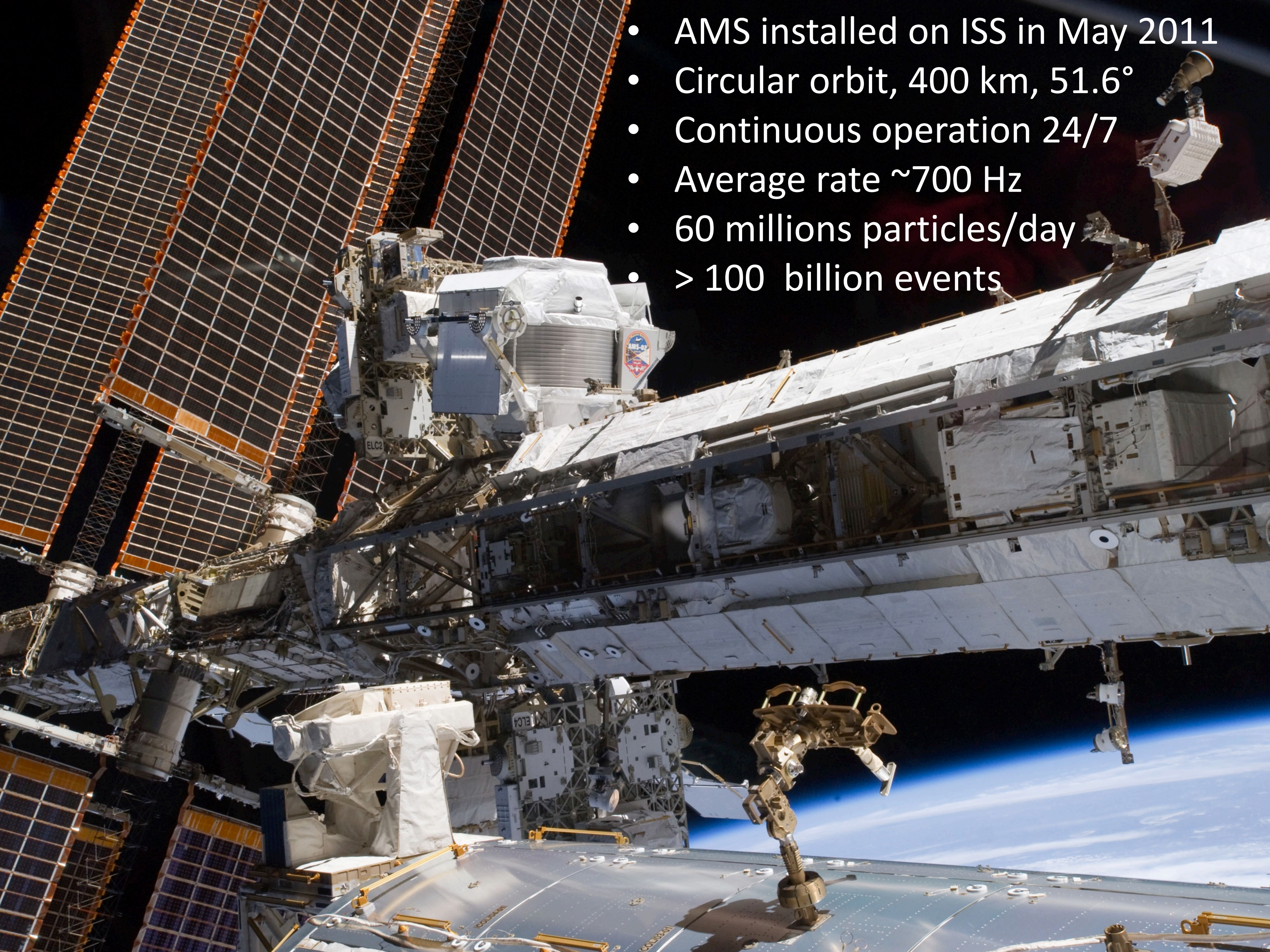


- PAMELA installed on Russian satellite Resurs-DK1, inside a pressurized container.



- Launched in June 2006,
- Circular orbit (70.0°, 600 km).
- Pamela operations terminated in 2016

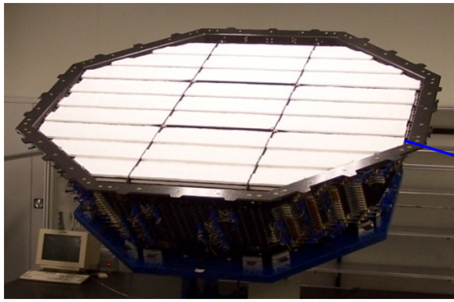
- AMS installed on ISS in May 2011
- Circular orbit, 400 km, 51.6°
- Continuous operation 24/7
- Average rate ~700 Hz
- 60 millions particles/day
- > 100 billion events



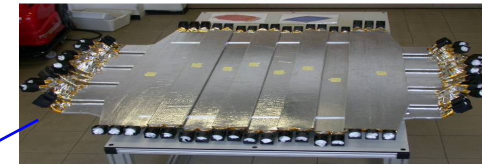
AMS

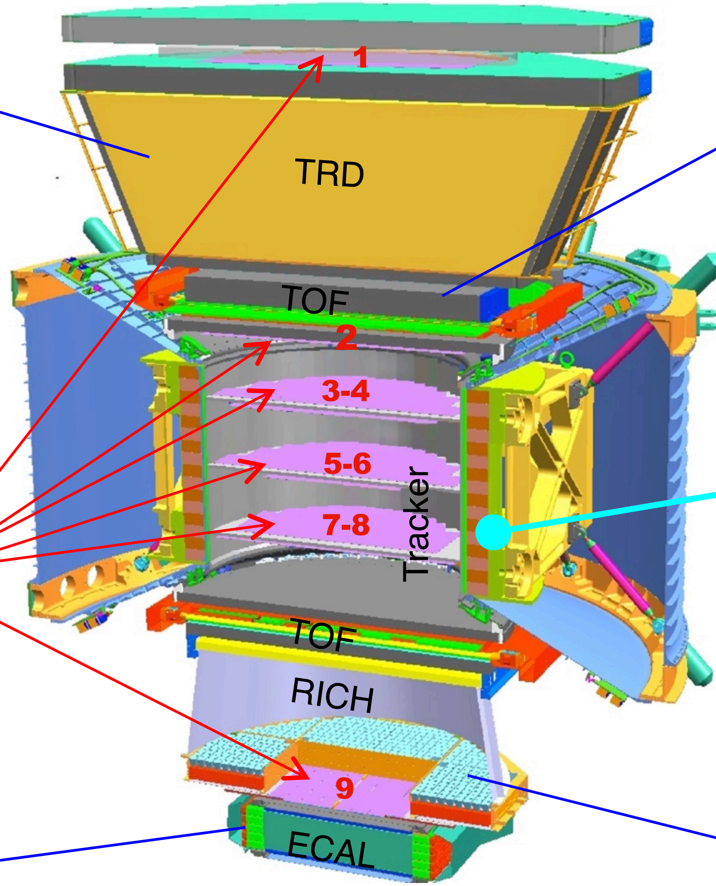
A TeV precision, multipurpose spectrometer in space.

TRD
Identify e^+, e^-

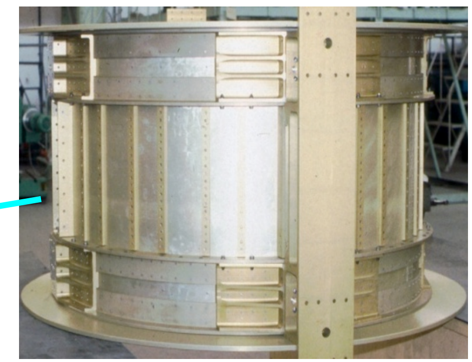


TOF
Z, Beta

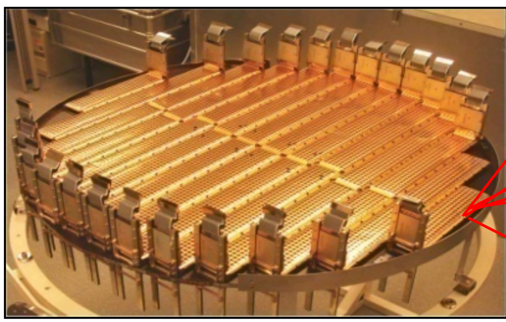




Magnet
±Z

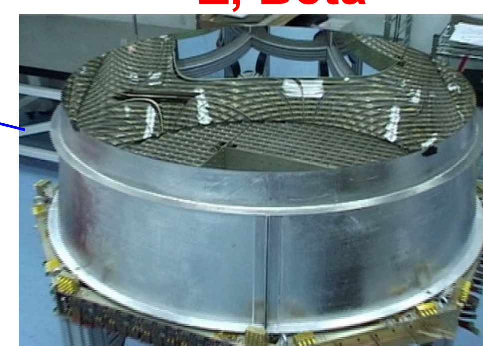


Silicon Tracker
Z, P



ECAL
Identify e^+,e^-
E of e^+, e^-, γ

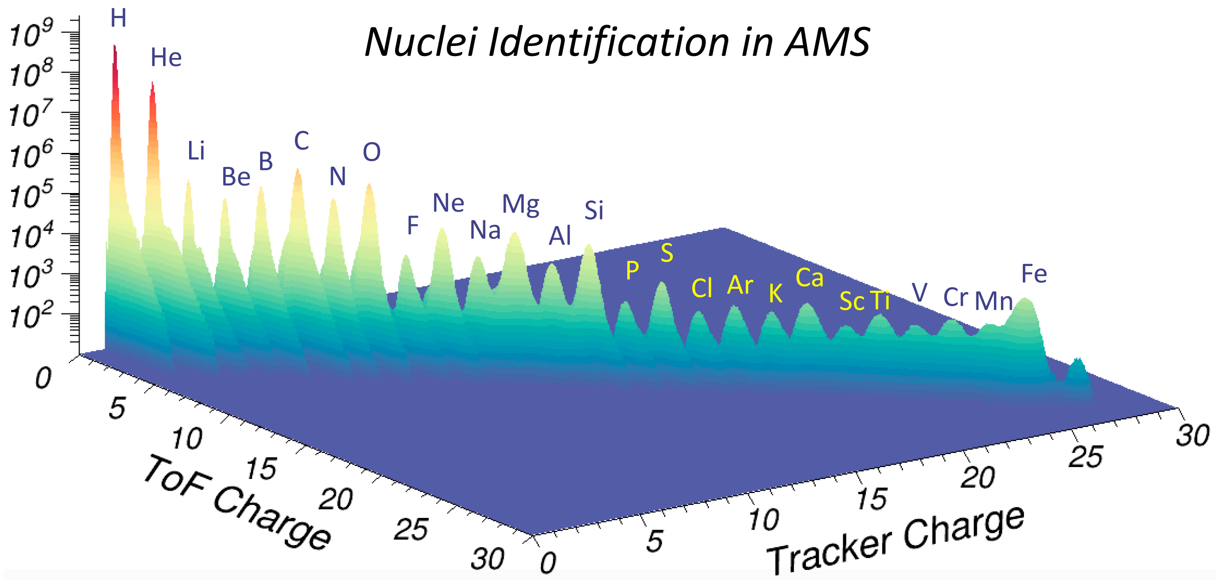
RICH
Z, Beta



5m x 4m x 3m 7.5 tons

GF ~ 5000 cm^2sr

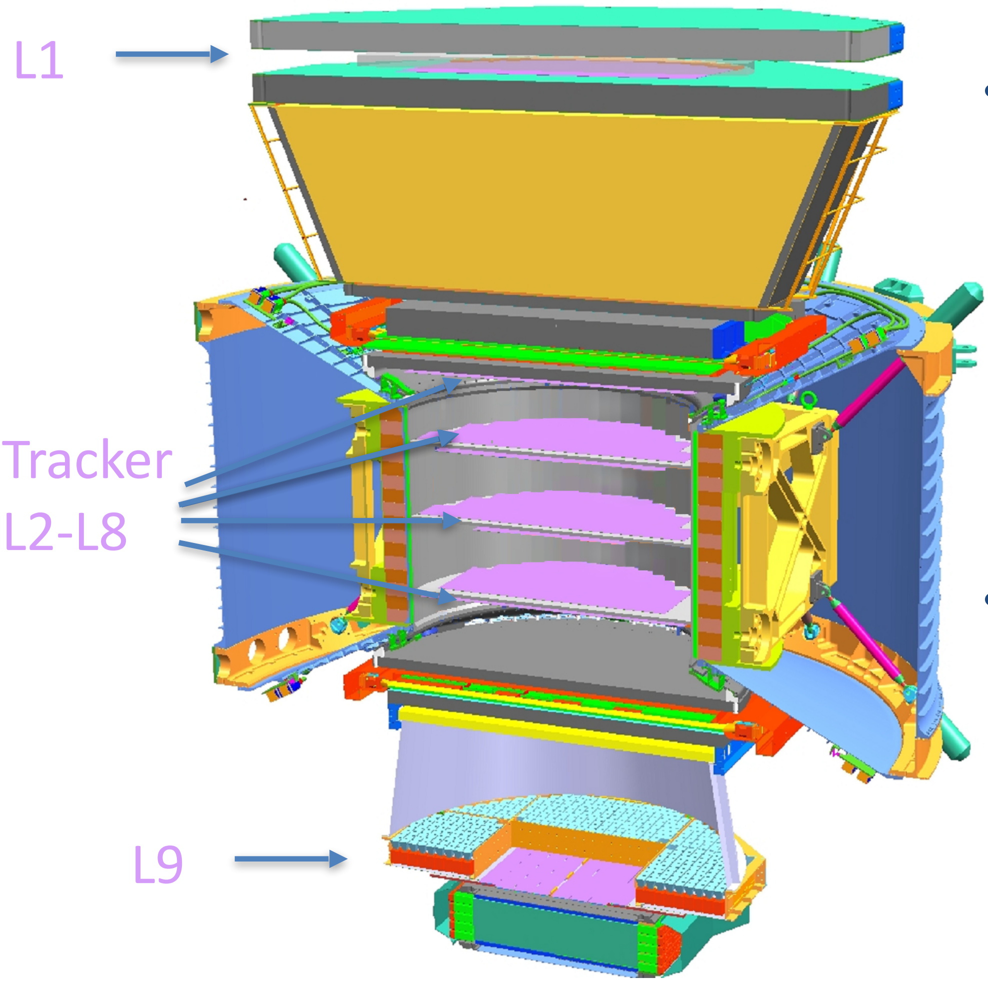
Cosmic-Ray Nuclei



Each cosmic-ray nucleus provides specific information:

- Protons and Helium are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the spectrum is important to understand the origin, acceleration, and propagation of cosmic rays.
- Li, Be, B, … are produced by the spallation of cosmic rays in the interstellar medium: The flux of these secondaries or secondary/primary ratios (like B/C) are key measurements to understand propagation.
- Other primary (C,O,..) can be used to test the universality of propagation/acceleration.
- Precise knowledge of both primary fluxes and propagation mechanisms is essential to assess background (e^+, pbar,…) and expected signal for DM searches.

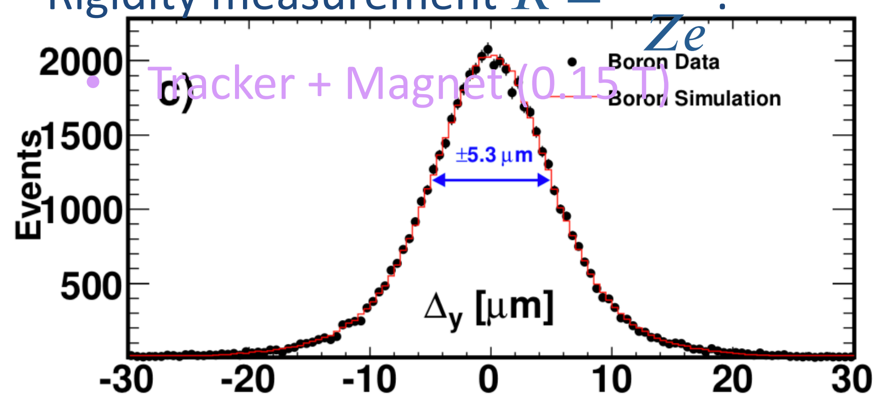
Nuclei fluxes in AMS



- Charge Z measurement:
  - Tracker: 9 layers ($\frac{\Delta Z}{Z} \sim 5\,\%$ per layer)
  - UTOF & LTOF ($\frac{\Delta Z}{Z} \sim 4\%$ per plane)

  → Charge misidentification negligible

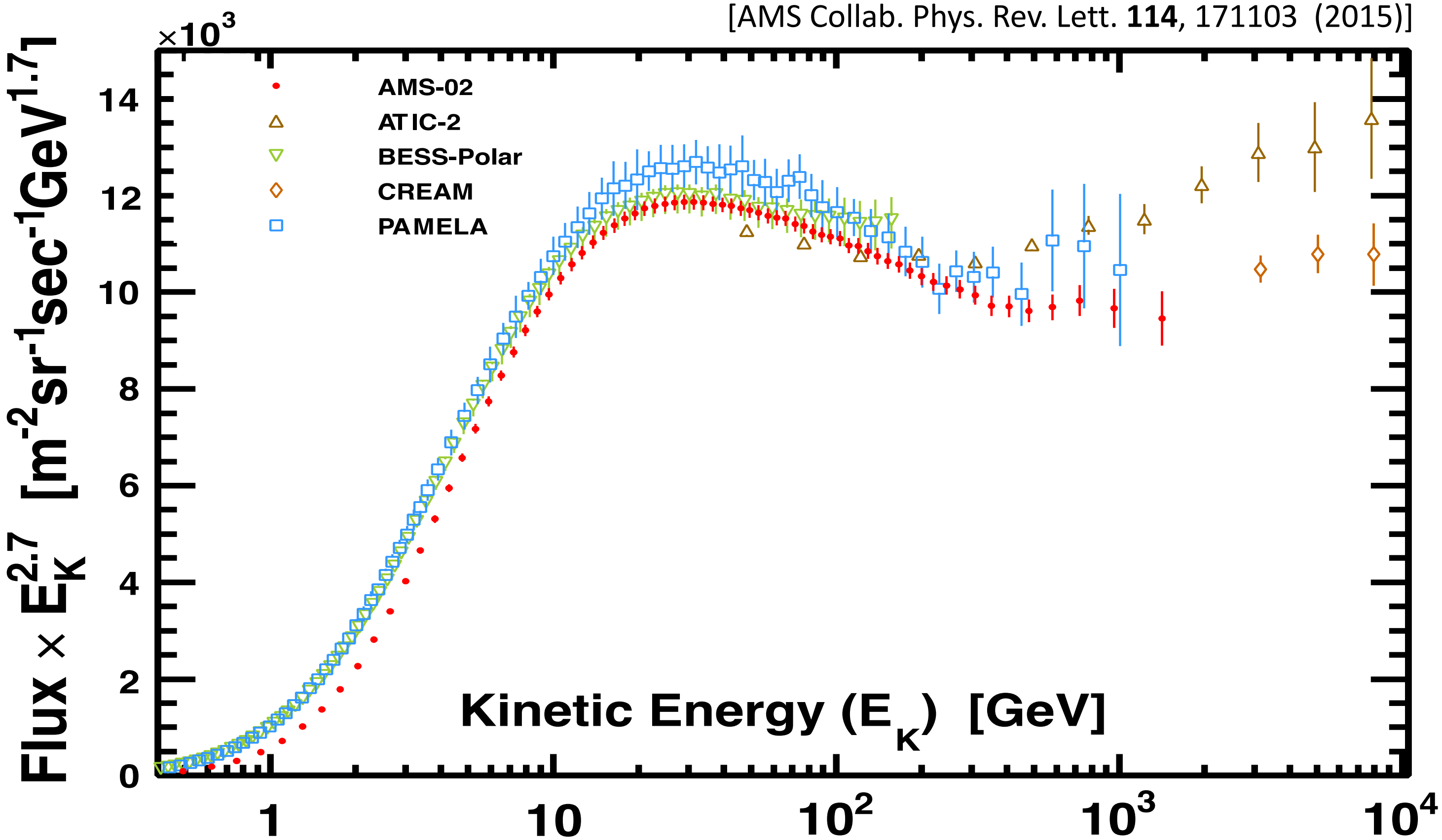
- Rigidity measurement $R = \frac{pc}{Ze}$:
  - Tracker + Magnet (0.15 T)



Proton Flux Measurement

- Proton flux from AMS based on 300 million events released in 2015, compared to PAMELA and recent measurements:

[AMS Collab. Phys. Rev. Lett. **114**, 171103 (2015)]



→ Hardening of the proton flux around 300 GeV.

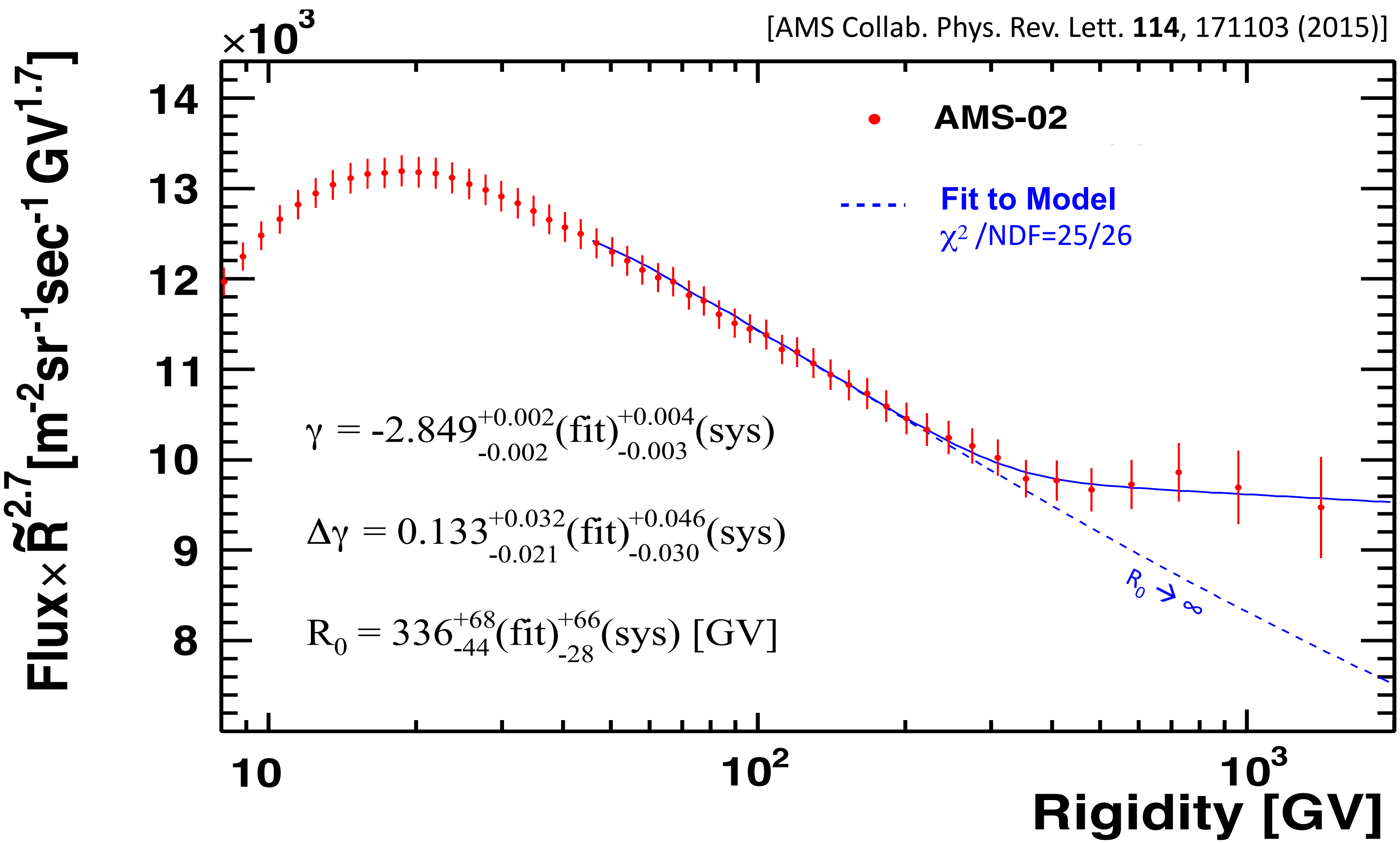
→ Precision of AMS data allowed to characterize the shape of the transition.

Proton Flux Measurement

- Fit of the AMS flux with a double power model with smooth transition:

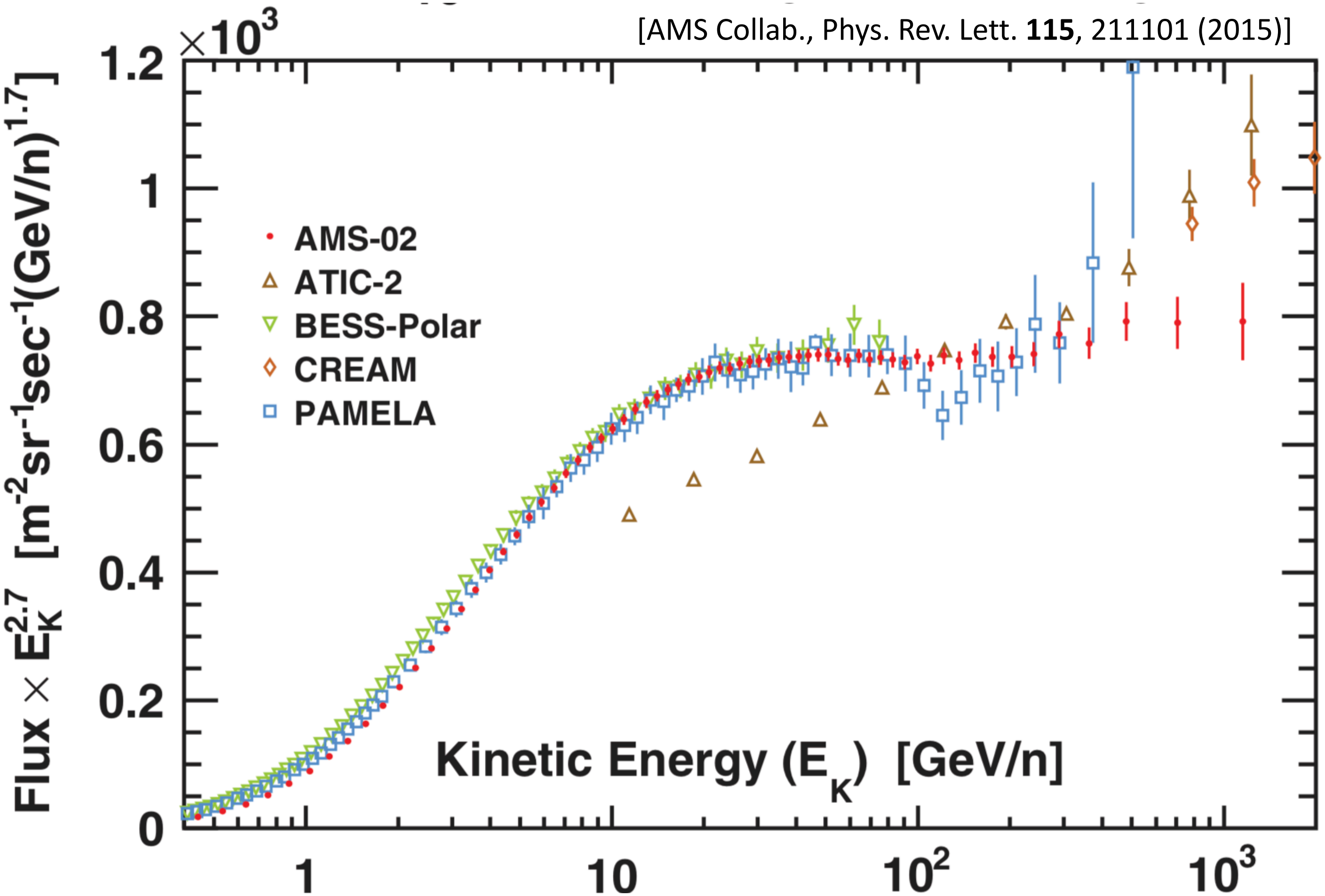
$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

[AMS Collab. Phys. Rev. Lett. **114**, 171103 (2015)]



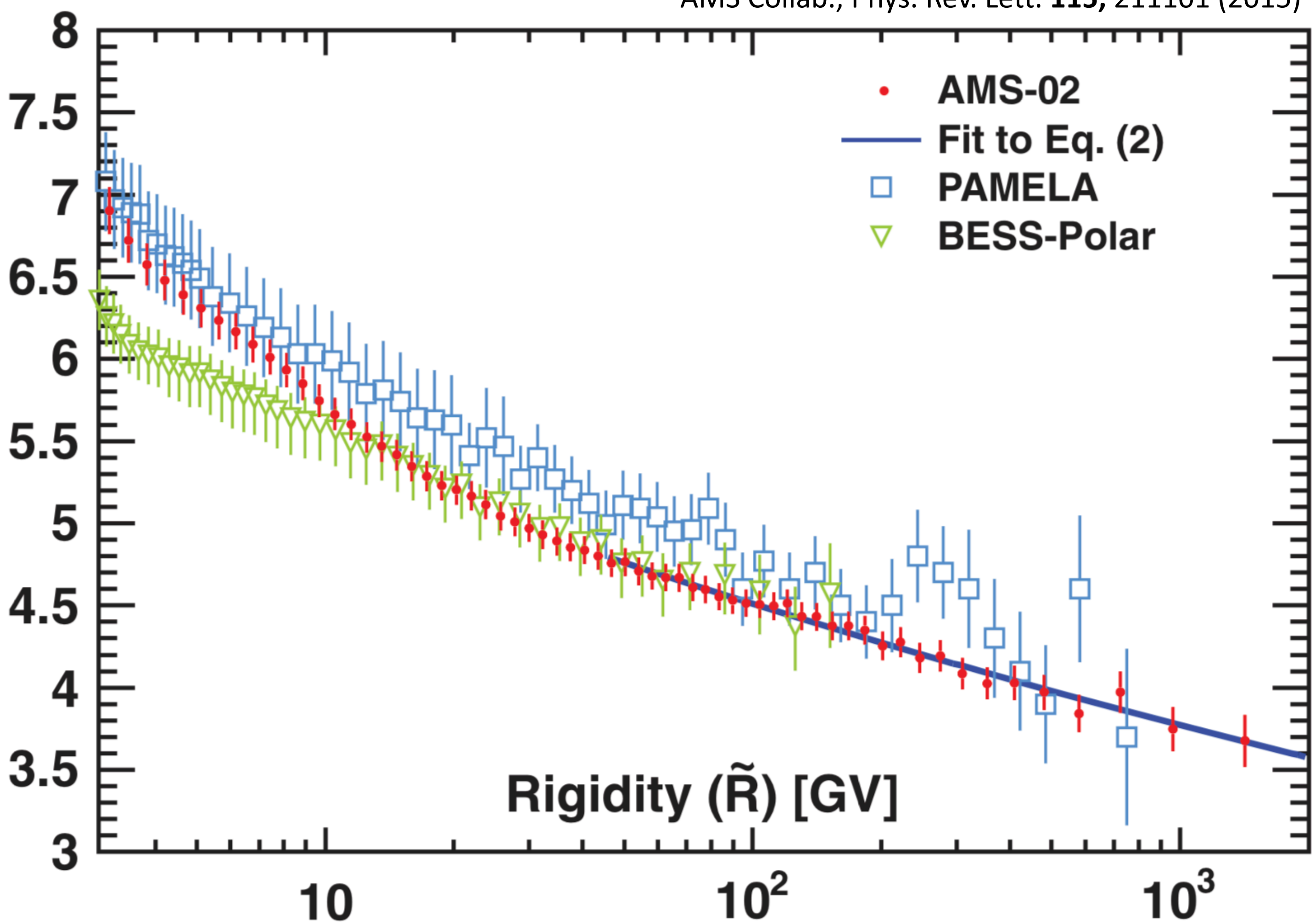
Helium flux from AMS based on 50 million events compared to PAMELA and previous measurements:

[AMS Collab., Phys. Rev. Lett. **115**, 211101 (2015)]



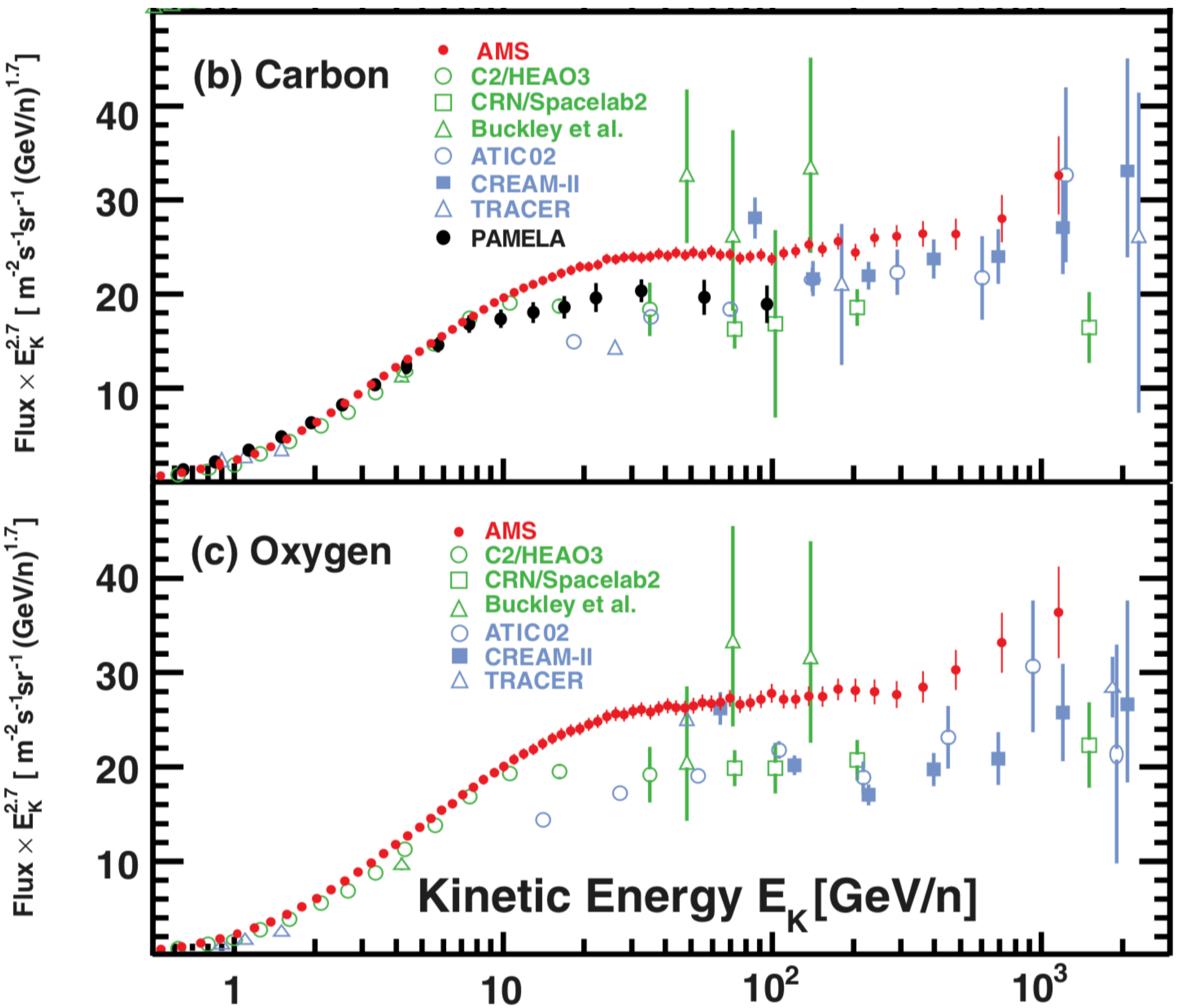
→ Same hardening as for proton in the flux around 300 GeV.

AMS Collab., Phys. Rev. Lett. **115,** 211101 (2015)



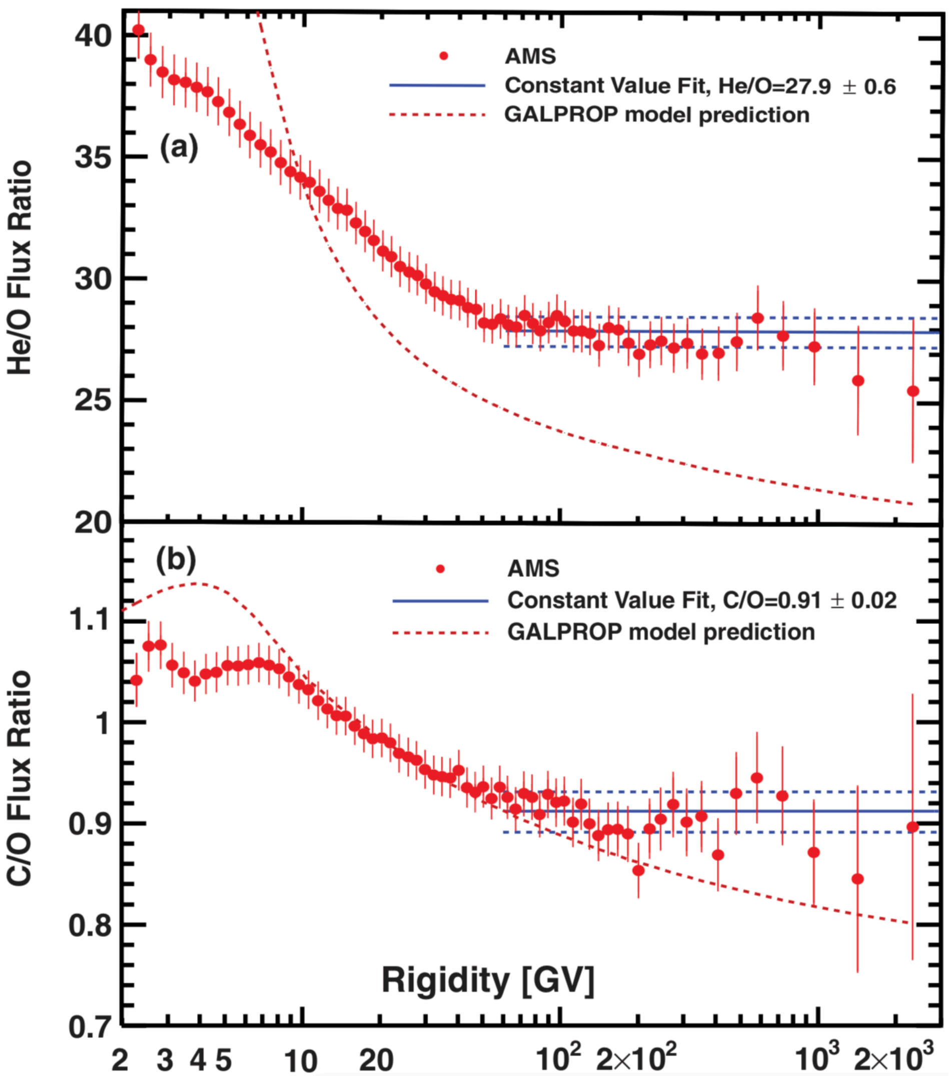
→ The He spectral index is different from that of proton, but the rigidity dependence is similar.

AMS Collab, Phys. Rev. Lett. **119**, 251101 (2017)



→ Deviation from single power law and hardening of the flux above 300 GV

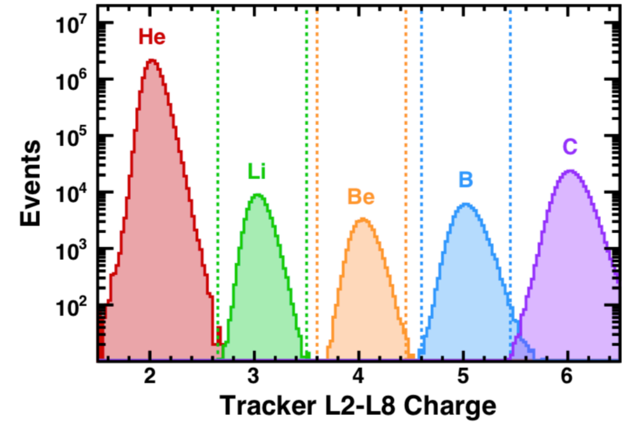
[AMS Collab., Phys. Rev. Lett. **119**, 251101 (2017)]



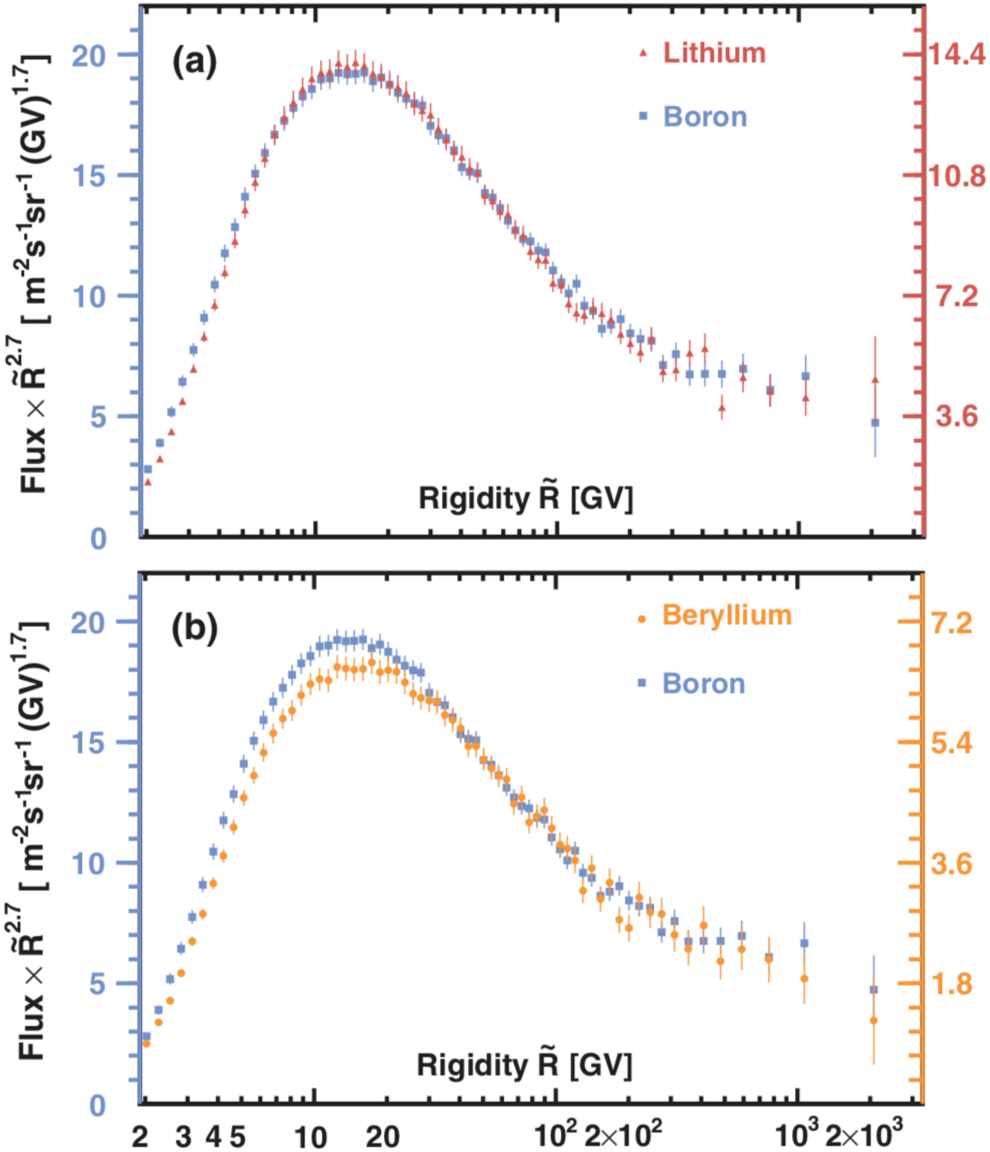
Precise measurement of primary/primary ratios :

Universality of primary fluxes?

- < ~30 GV: Decrease of the He/O and C/O linked to the A-dependence of inelastic cross-sections
- > 30 GV: decrease of the He/O and C/O ratio expected due to the contribution from secondary component for C and He (computed here in GALPROP, similar results with USINE) not seen in data.



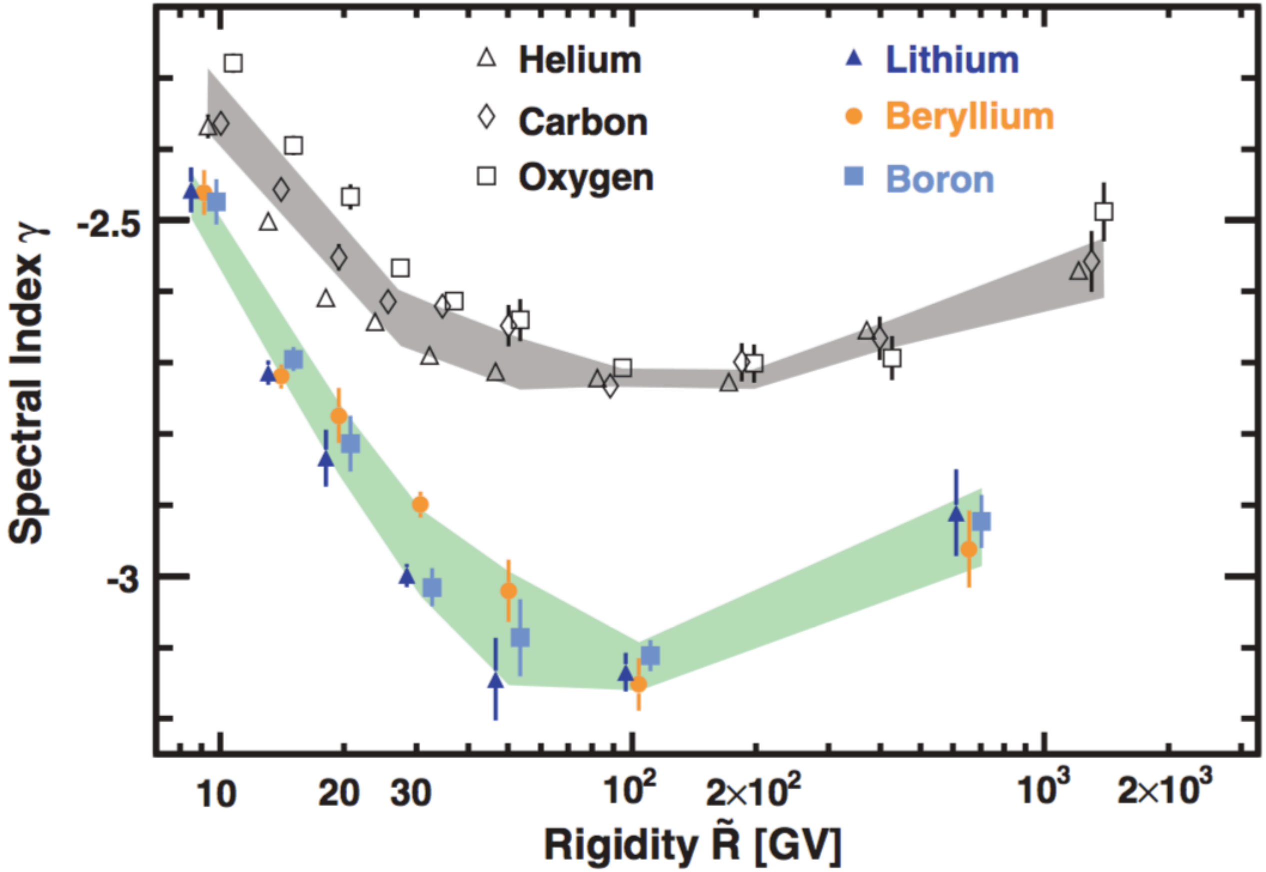
[AMS Collab.,Phys. Rev. Lett. **120**, 021101 (2018)]



- Li, Be, B produced by spallation processes.
- Sensitive to CR propagation parameters (diffusion, convection, reacceleration…).
- > 20 GV, identical rigidity dependence.
- Low energy < 20 GV, sensitive to differences in cross-sections and ^{10}Be radioactive decay:

B (^{10}B from ^{10}Be) > Li > Be (^{10}Be decay)

$$\phi(R) \sim R^{\gamma}$$

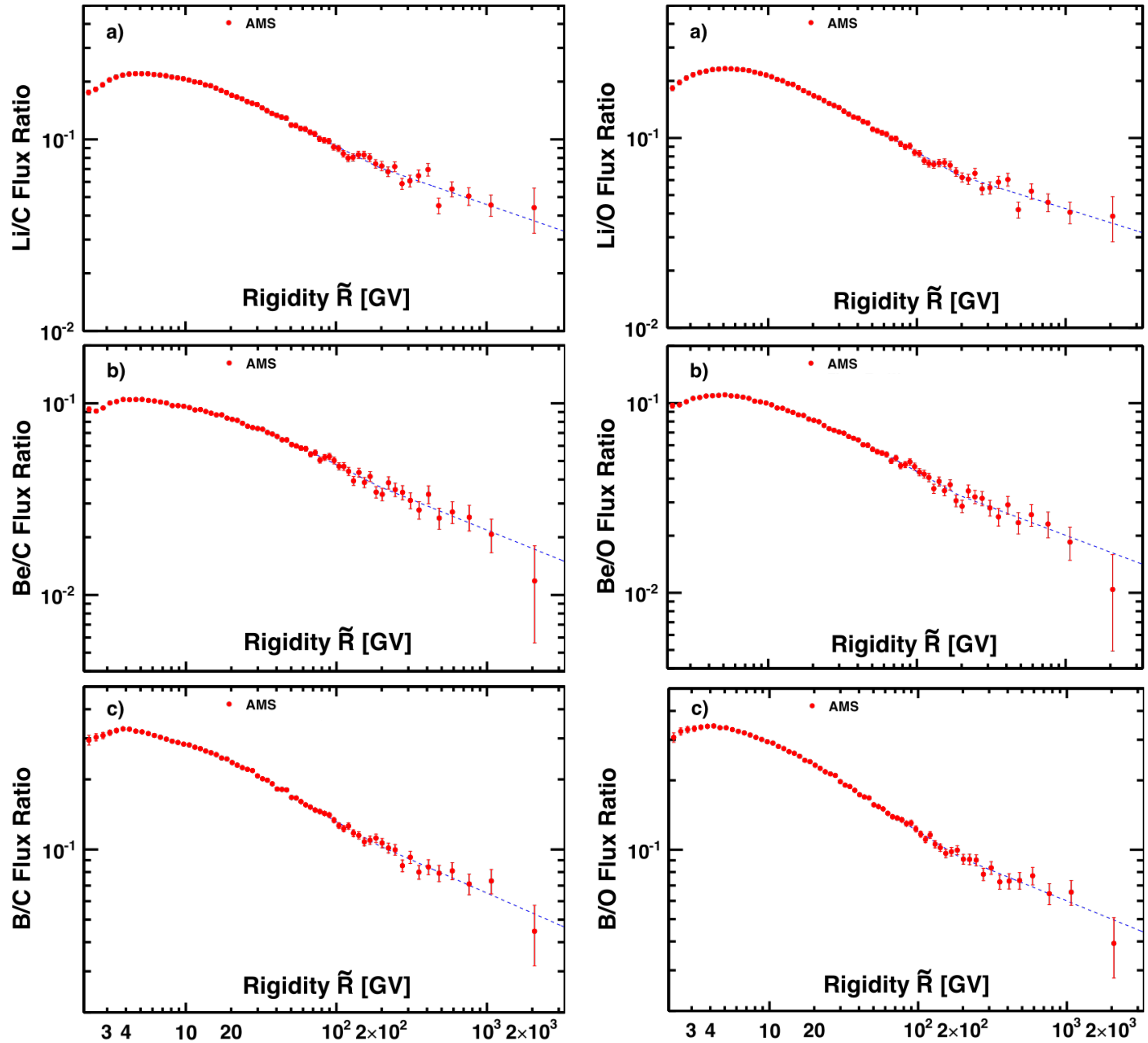


→ Hardening of the Secondaries and primaries component in CR.

Li/C, Be/C, B/C
and
Li/O, Be/O, B/O
ratios between 2 GV and 3 TV

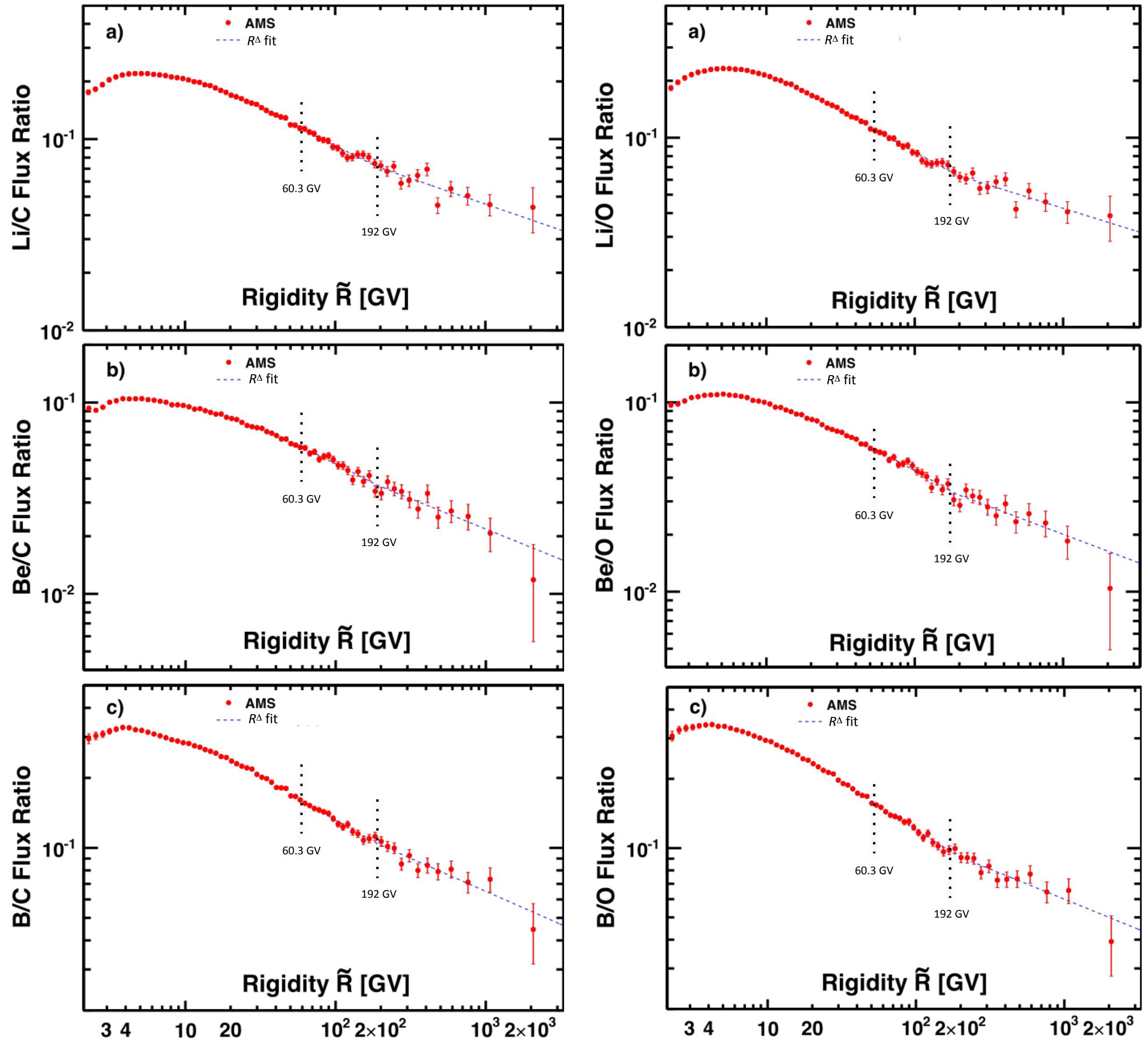
Based on 5 years of AMS data collected from May 2011 to May 2016:

- Li: 1.9 Mevents
- Be: 0.9 Mevents
- B: 2.6 Mevents
- C: 8.4 Mevents
- O: 7.0 Mevents

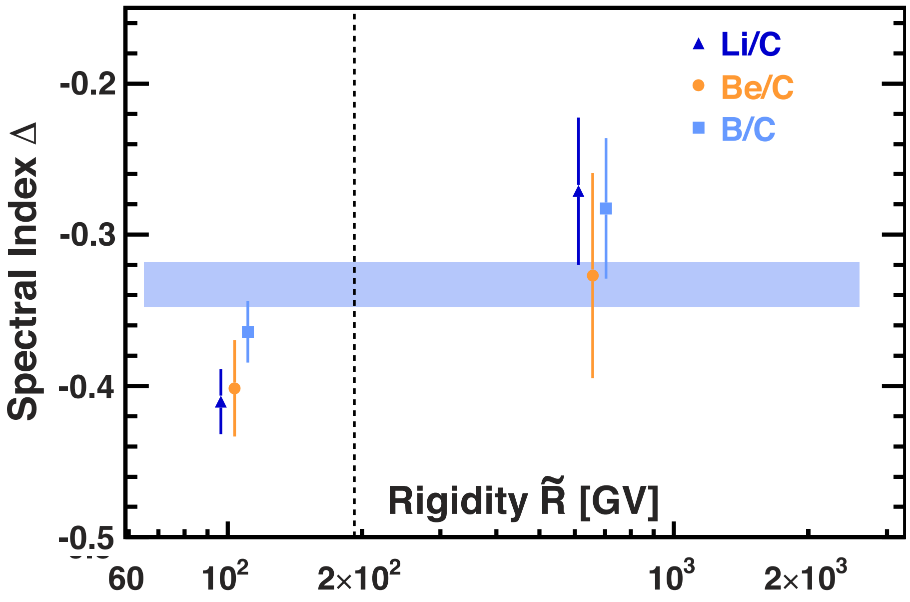


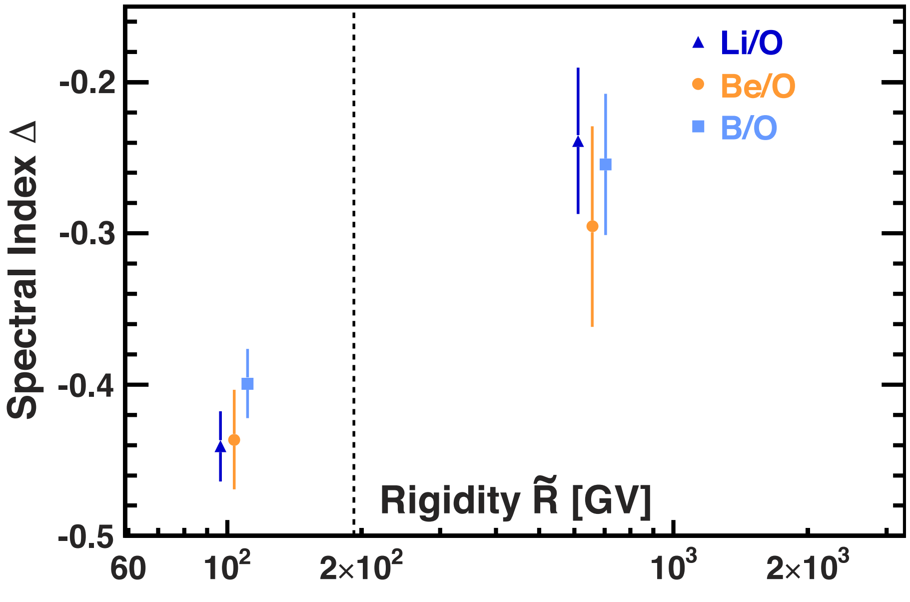
To investigate the rigidity dependence and the origin of the spectral hardening at high rigidity :

R^{Δ} fits for two rigidity intervals:
[60.3 GV–192 GV] and
[192 GV–3300 GV]



R^{Δ} fits for two rigidity intervals [60.3 GV–192 GV] and [192 GV–3300 GV] of Li/C, Be/C, B/C and Li/O, Be/O, B/O:





→ Indications for a hardening on the ratio (average 0.13±0.03)

→ Support the interpretation of the hardening in terms of a change in the propagation properties in the Galaxy.

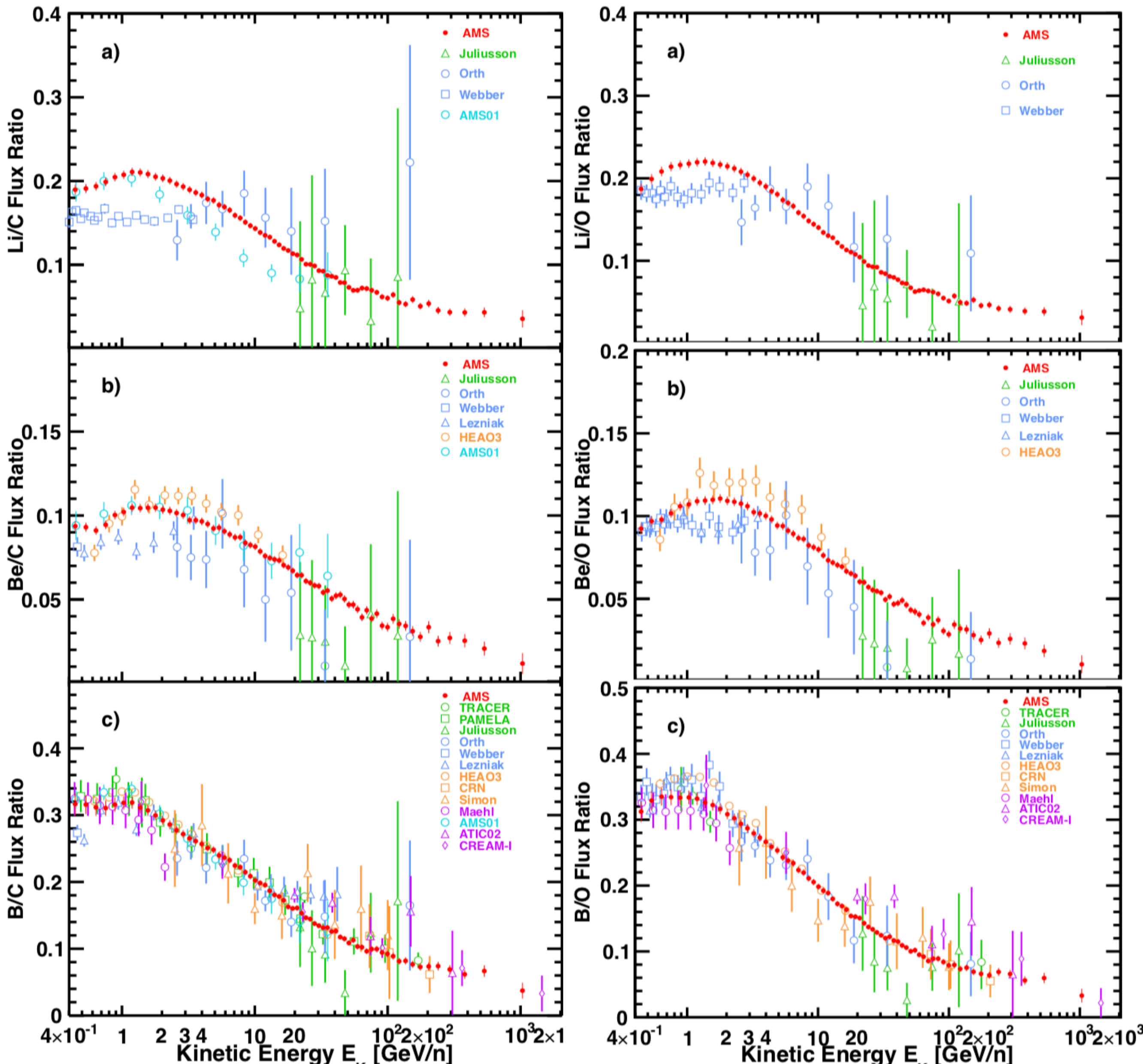
(See also Y. Genolini et al, PRL **119**, 241101 (2017))

[AMS Collab.,Phys. Rev. Lett. **120**, 021101 (2018)]

Secondary/primary Ratios vs E_{kn}.

Precise data from AMS02 to constrain the processes describing the propagation of CR in the Galaxy.

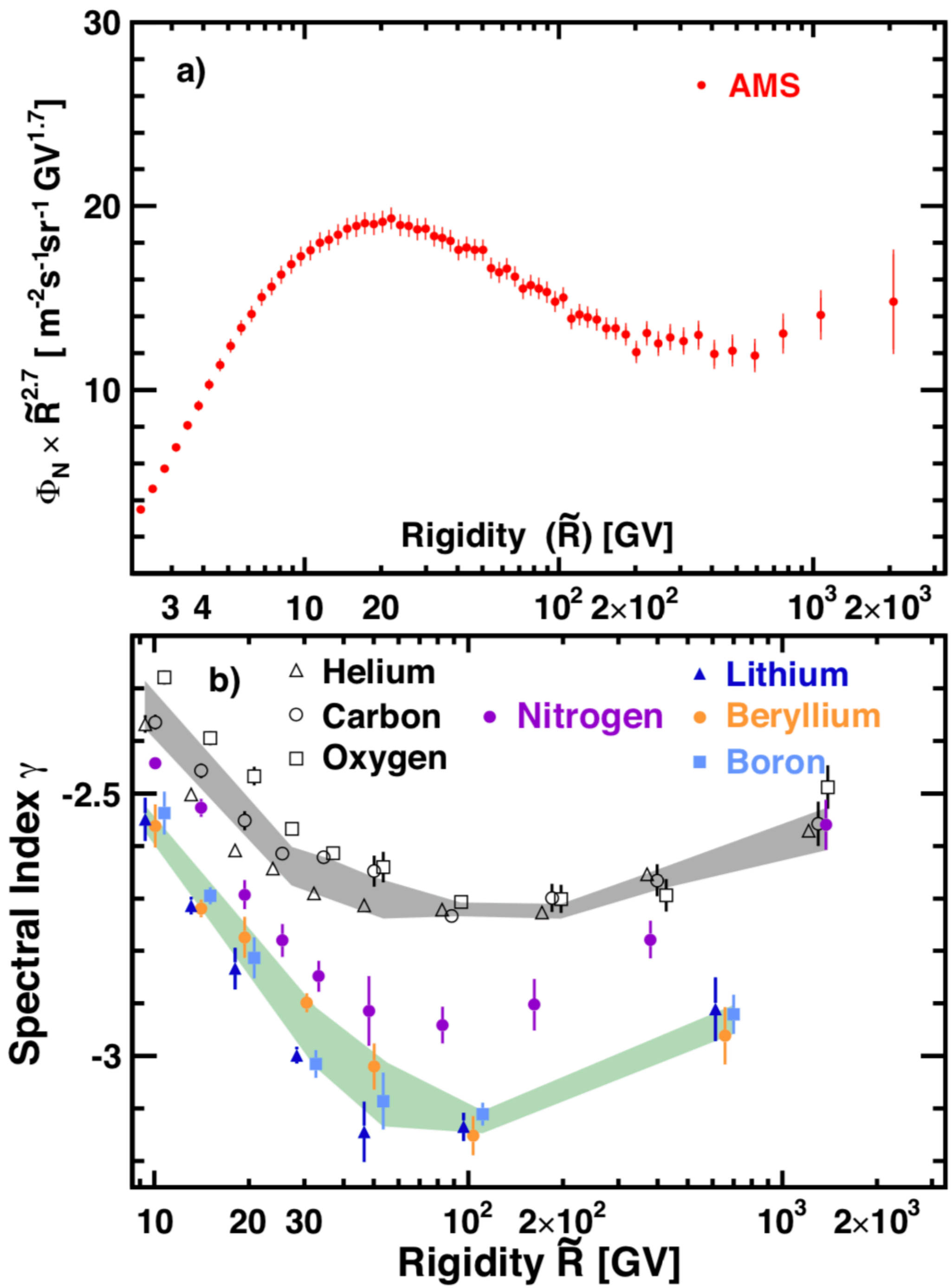
Different ratios can be used to test the universality of the propagation, are complementary since they have different systematics in the model.



[accepted for publication in PRL]

Nitrogen flux measurement from AMS to be published soon.

Spectral index versus rigidity indicates a transition from a secondary-like component to a primary-like shape at high rigidity.



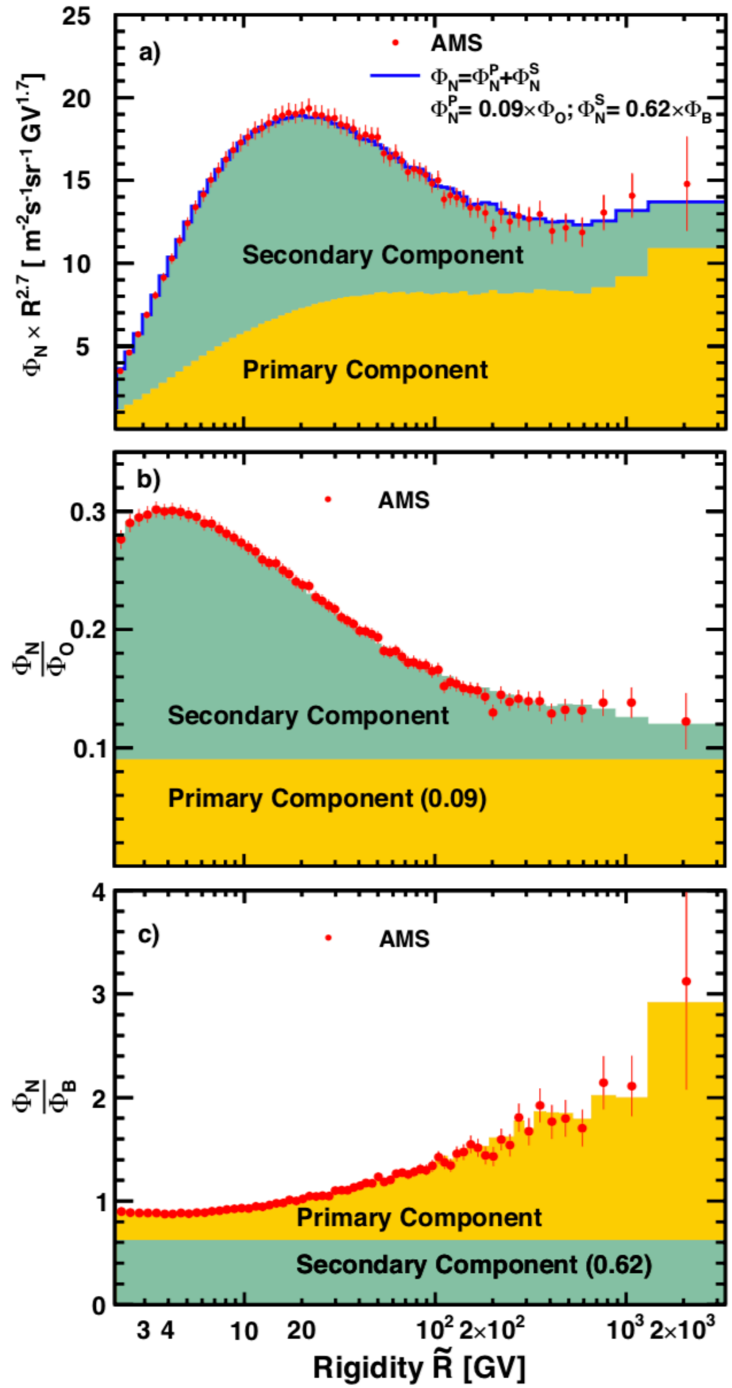
[accepted for publication in PRL]

The AMS nitrogen flux fitted to the weighted sum of the oxygen flux and the boron flux from AMS02 over the entire rigidity range:

$$\chi^2/\mathrm{d.o.f.} = 51/64$$

$$\Phi_\mathrm{N}^\mathrm{P} = (0.090 \pm 0.002) \times \Phi_\mathrm{O}$$

$$\Phi_\mathrm{N}^\mathrm{S} = (0.62 \pm 0.02) \times \Phi_\mathrm{B}$$



Data before AMS: constraints on the propagation models adjusted on data dominated by B/C ratio with errors ~10%

→ Recent measures:

- Precision at the %-level, detailed description of systematics.
- wide range of energy from GeV to TeV
- Large set of nuclei: Li, Be, B, C, N and O
- Fluxes and ratios

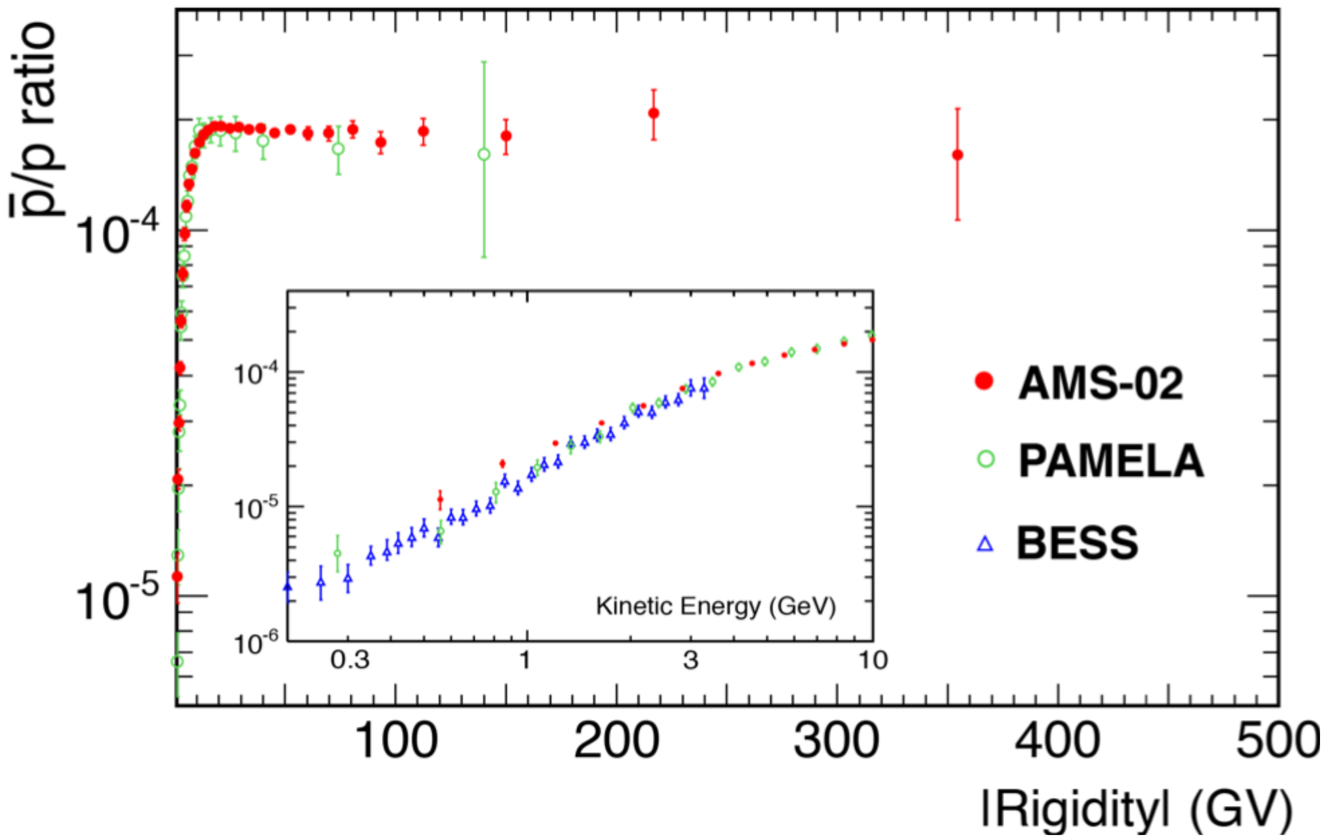
→ Paradigm shift in the propagation modeling:

- Large dependence to many parameters of the model:
  - Inelastic and production cross-sections
  - CR Source settings
  - Description of the diffusion (low energy, 2 zones, high energy break)
- Need for new methodologies to implement all uncertainties
- Need for new cross section measurements (see Y. Genolini et al. Astro-ph:1803.04686)

Antiproton/Proton

Measurement by AMS of the antiproton flux and the antiproton-to-proton flux ratio from 1 to 450 GV based on 3.5 × 10⁵ antiprotons

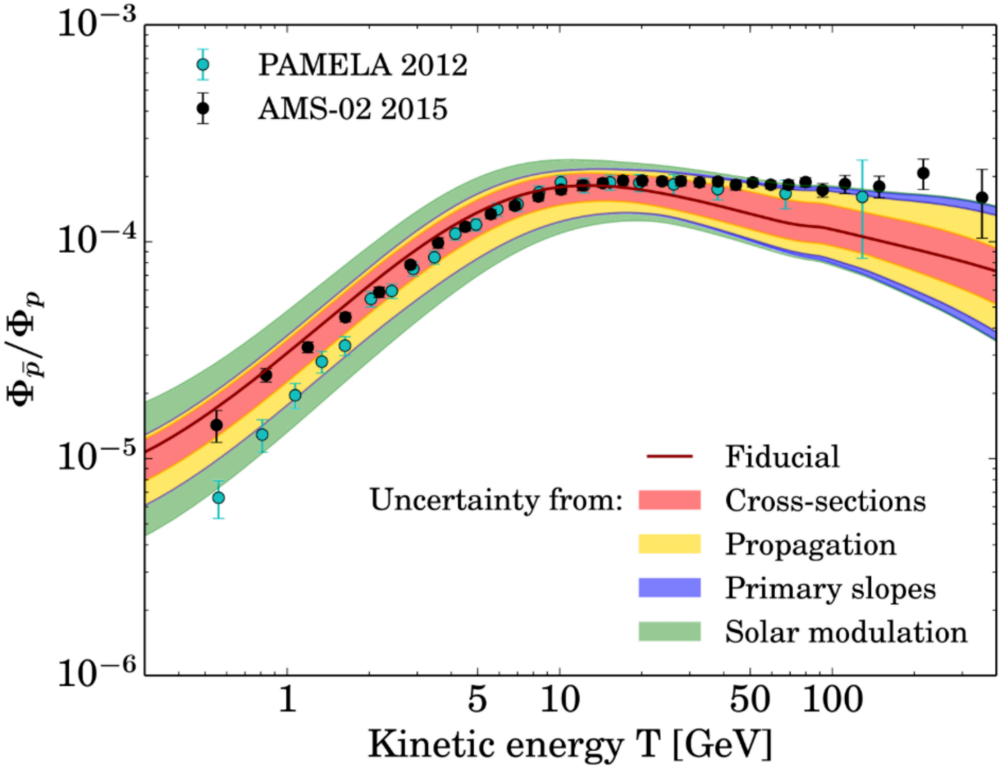
[AMS Collab., PRL 117, 091103 (2016)]



→ Flat Antiproton/proton ratio at high energy in tension with pure secondary component in standard propagation model

Antiproton/Proton and modeling

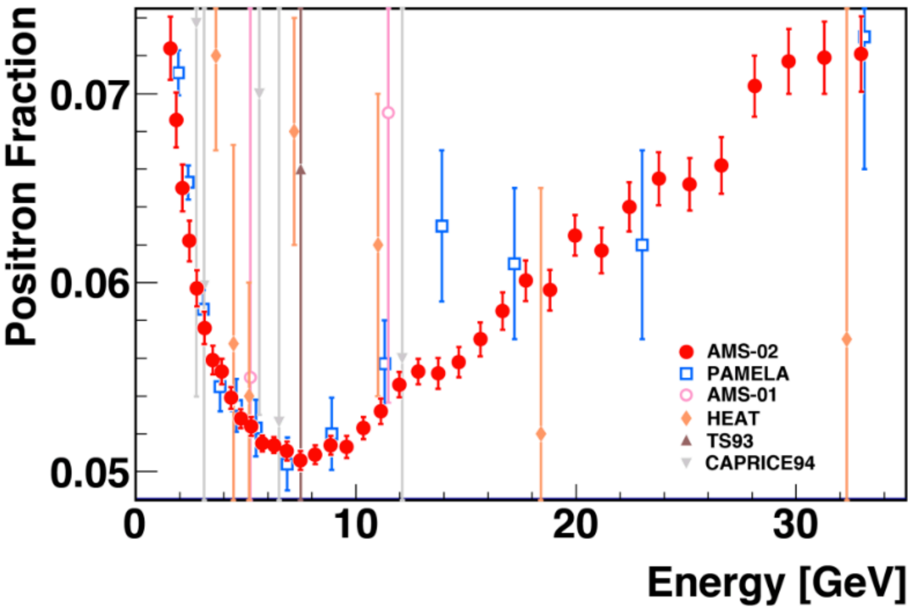
Secondary production of CR antiproton: [G. Giesen, et al. arXiv:1504.04276]



- Large uncertainty in the estimation of secondary antiproton.
- Recent nuclear data from AMS should help to reduce the propagation uncertainty.
- More statistics and work needed on models to know if extra sources are needed to reproduce the flat pbar/p ratio at high energy

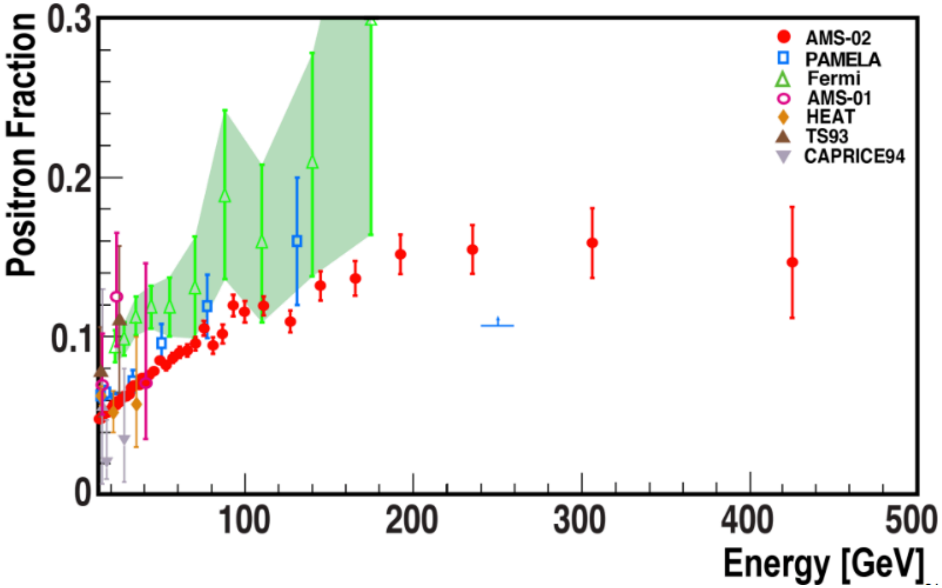
Positron Fraction

[AMS Collab. Phys. Rev. Lett. 113 (2014)]



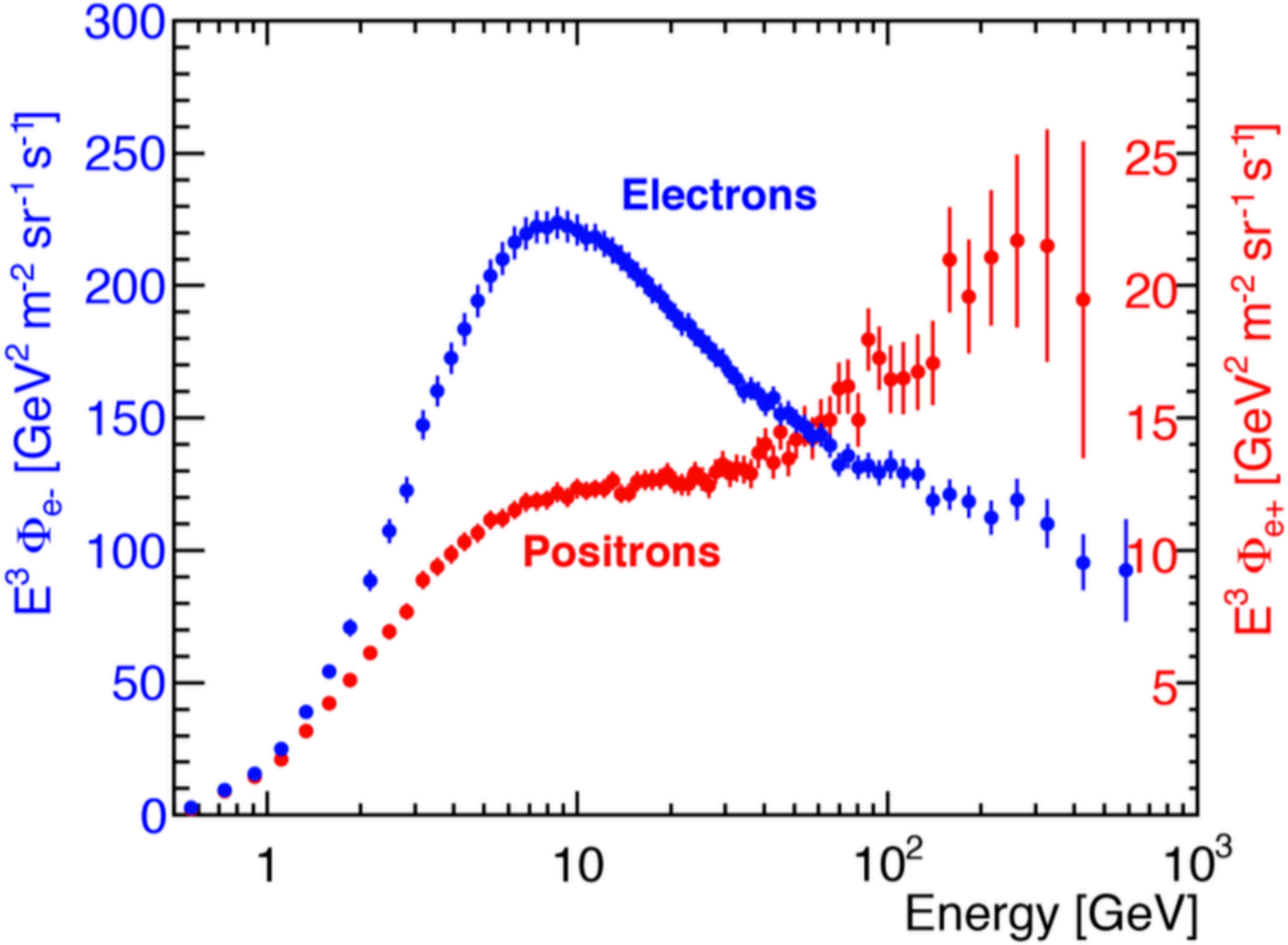
- Conclusive evidence of positron excess published by PAMELA in 2009 and then by Fermi.
- Confirmed with improved precision and extended energy range by AMS:

→ Positron fraction:
  - steadily increases from 10 to ~250 GeV, no fine structures.
  - At 275±32 GeV the fraction reaches its max.



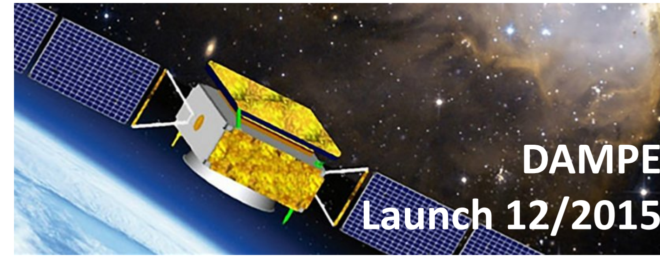
Electron and Positron Fluxes from AMS

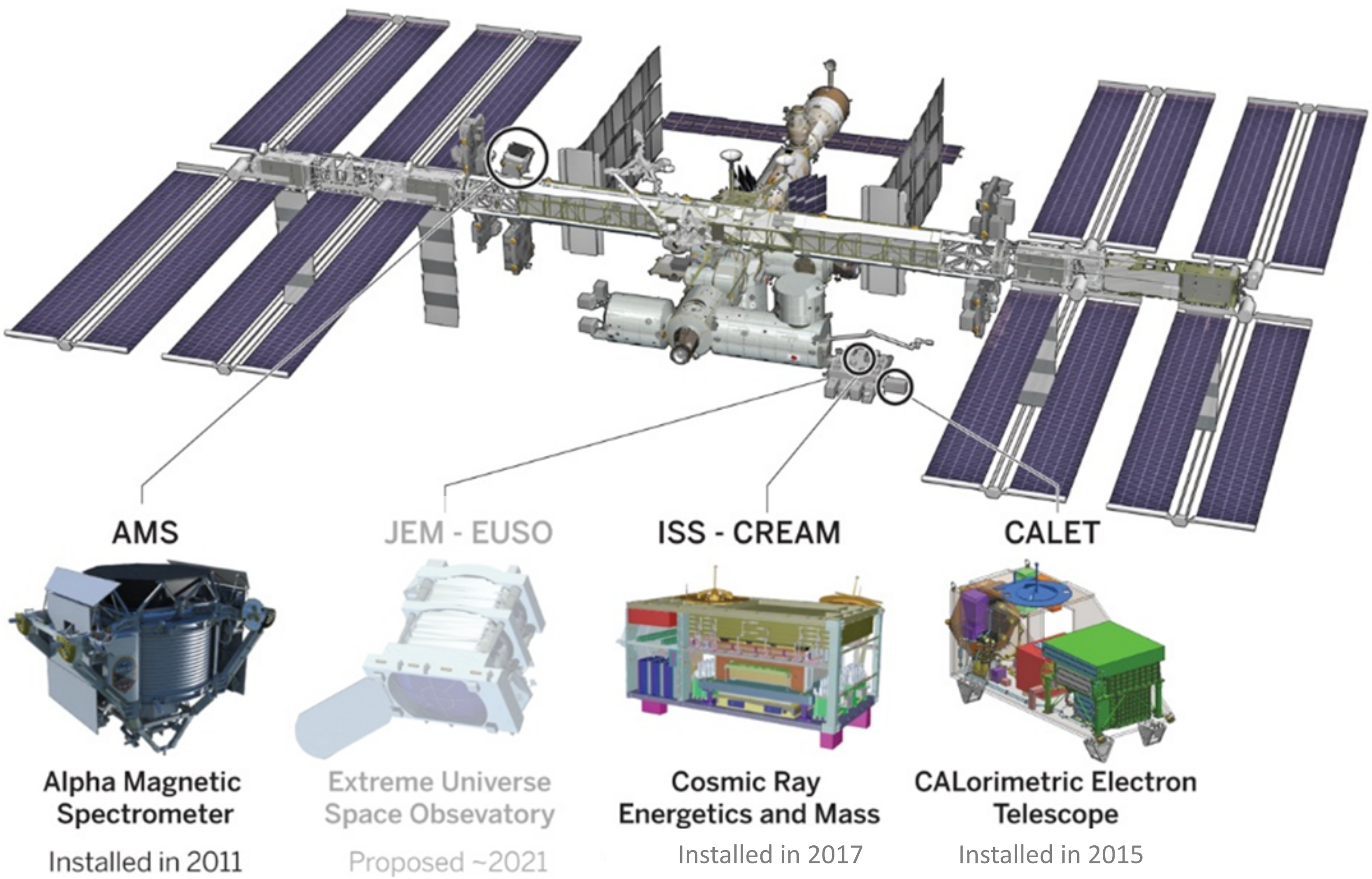
[AMS Collab. Phys. Rev. Lett. 113 (2014)]



→ Shows that the rise of positron fraction is due to positron excess.

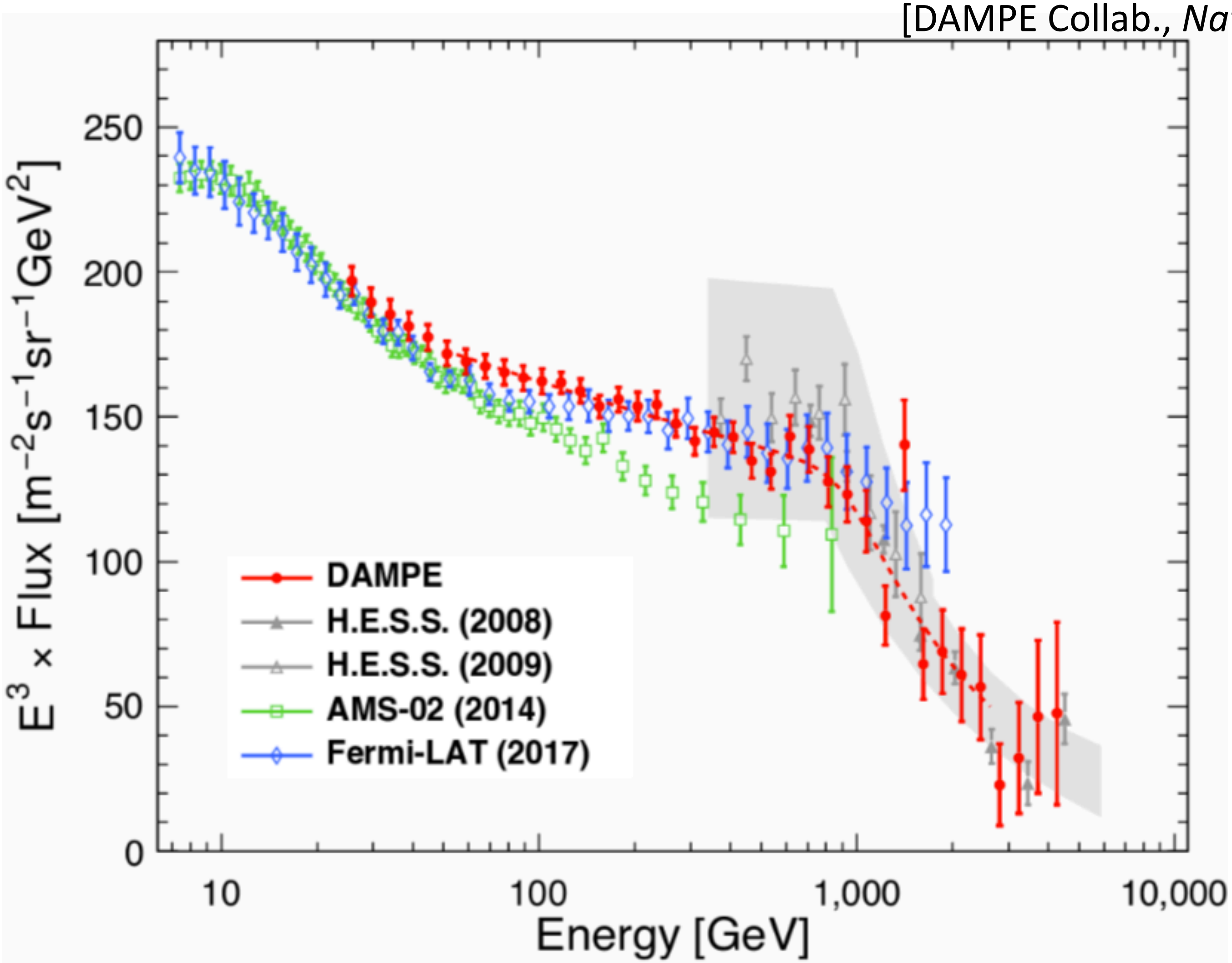
CALET – DAMPE - ISSCREAM





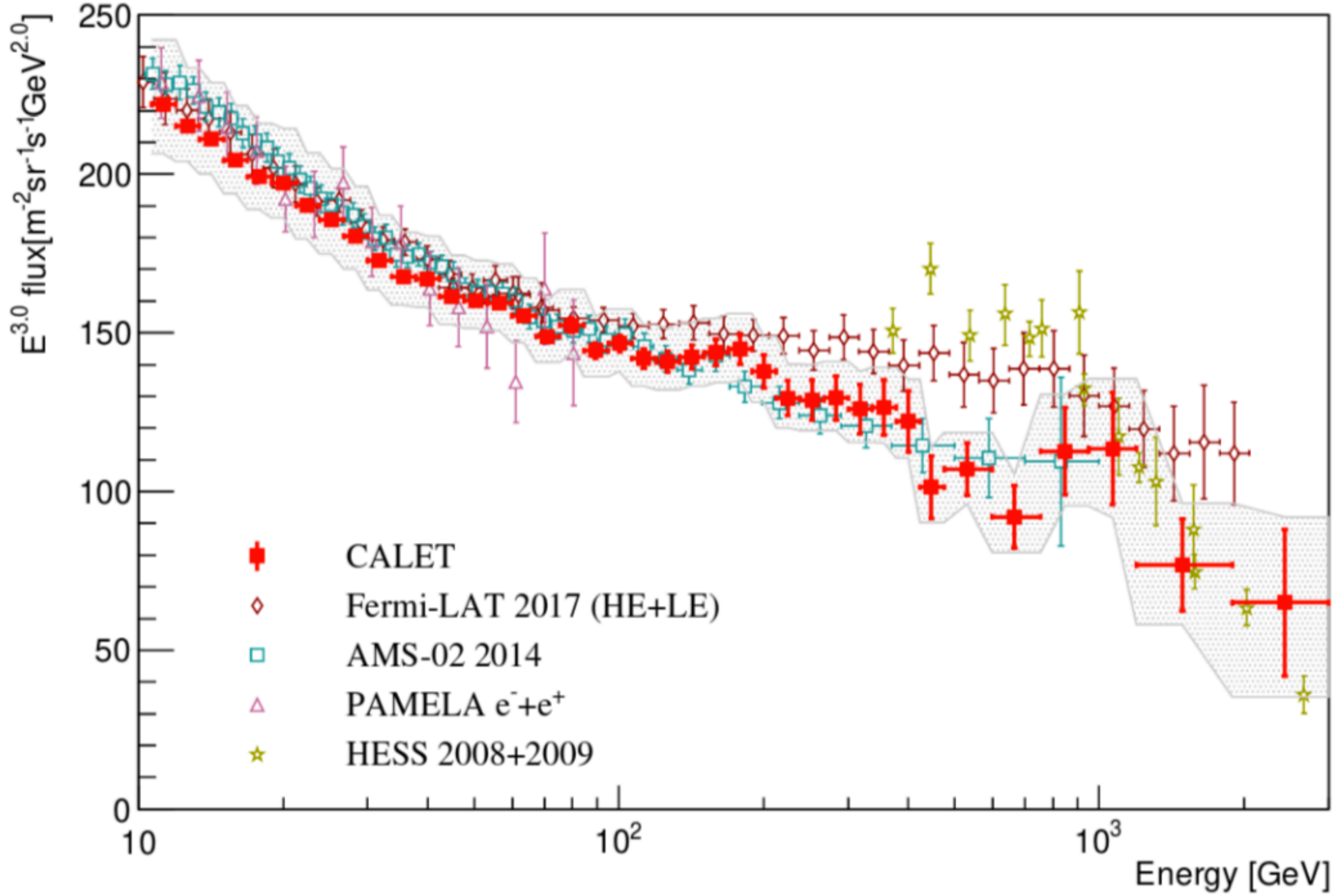
All electron ($e^{+}+e^{-}$) flux from DAMPE released last December:

[DAMPE Collab., *Nature* **552**, (2017)]



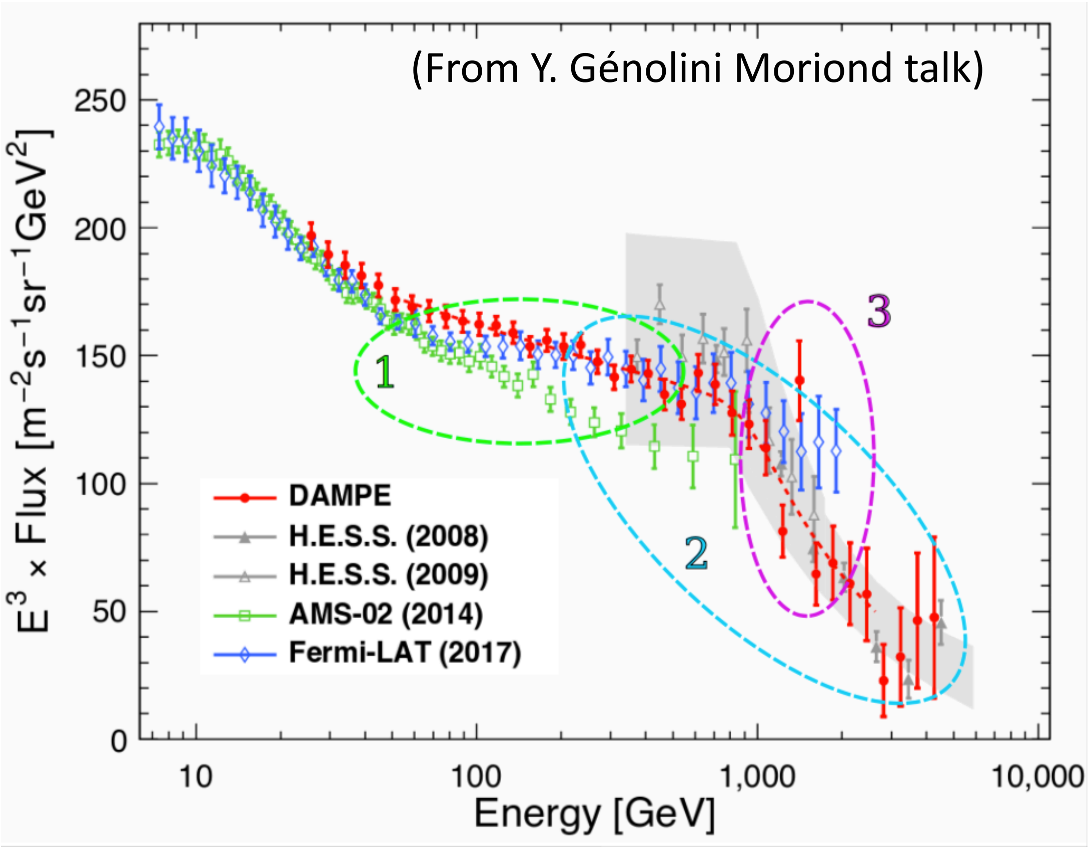
CALET flux released one day after DAMPE

[CALET Collab., PRL. 119 (2017)]



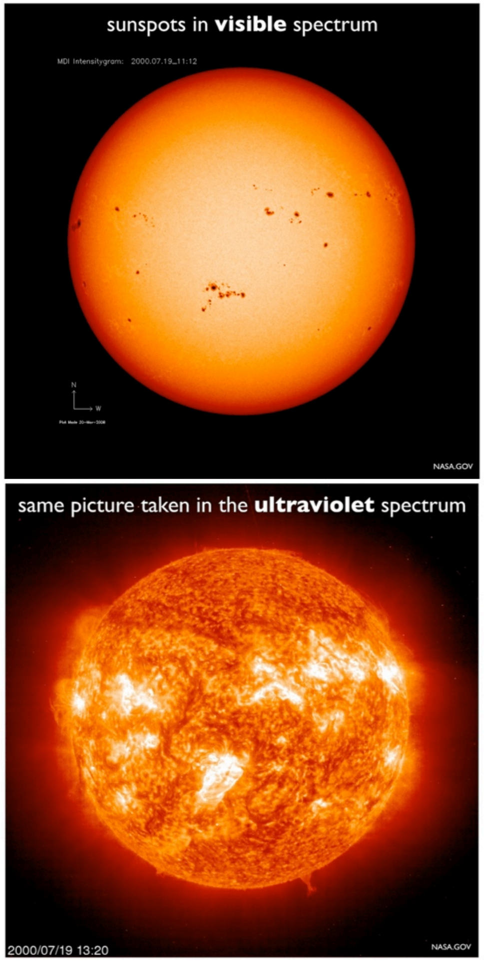
1-DAMPE data in tension with AMS and CALET.
Comment from CALET paper :
"The difference might be partially due to the uncertainty in the absolute energy scale, which would coherently shift the CRE spectrum up or down."

2- First direct detection of the ($e^{+}+e^{-}$) knee.
Can be explained in a two components model with few local (<300pc) and far (continuous) sources : break from local source.
See Fowlie A., 2017. arXiv:1712.05089.



3- « Dampe Peak »
- Low significance
- "Exotic" (DM) or "Astrophysical" (Pulsar) explanations imply fine-tuned physics which can only be probed by a multimessenger approach.

- At low Energy (<20 GV) cosmic ray spectrum affected by its propagation in the Solar cavity and the interaction with the plasma emitted by the sun.
- This produces a modulation of the spectrum which follows 11-year cycle in antiphase with Solar activity (Sunspot number)
- Simplest model for Solar Modulation: Force-Field approximation:

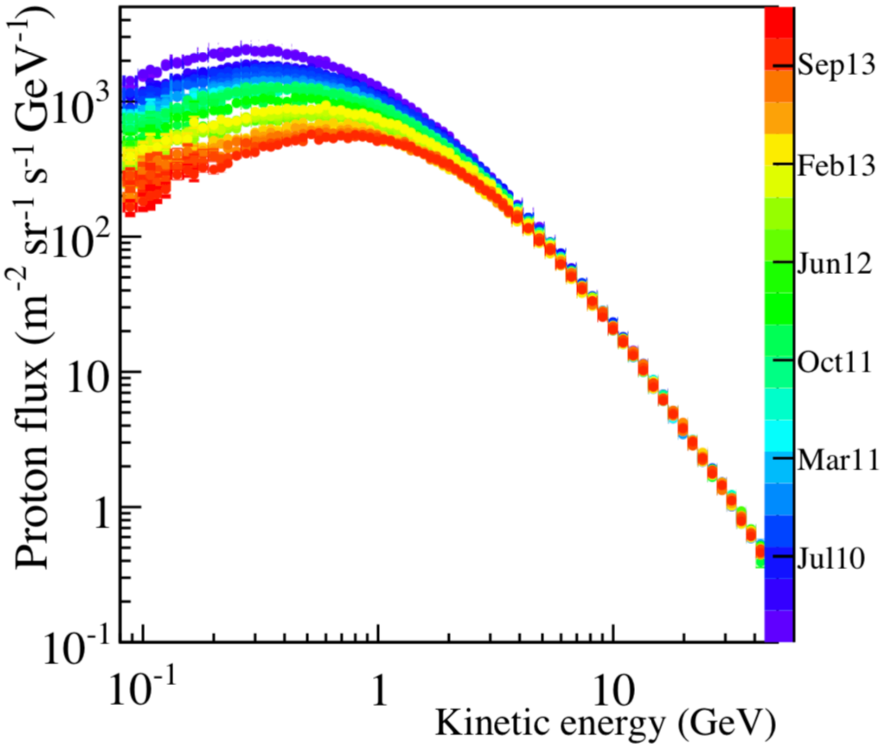


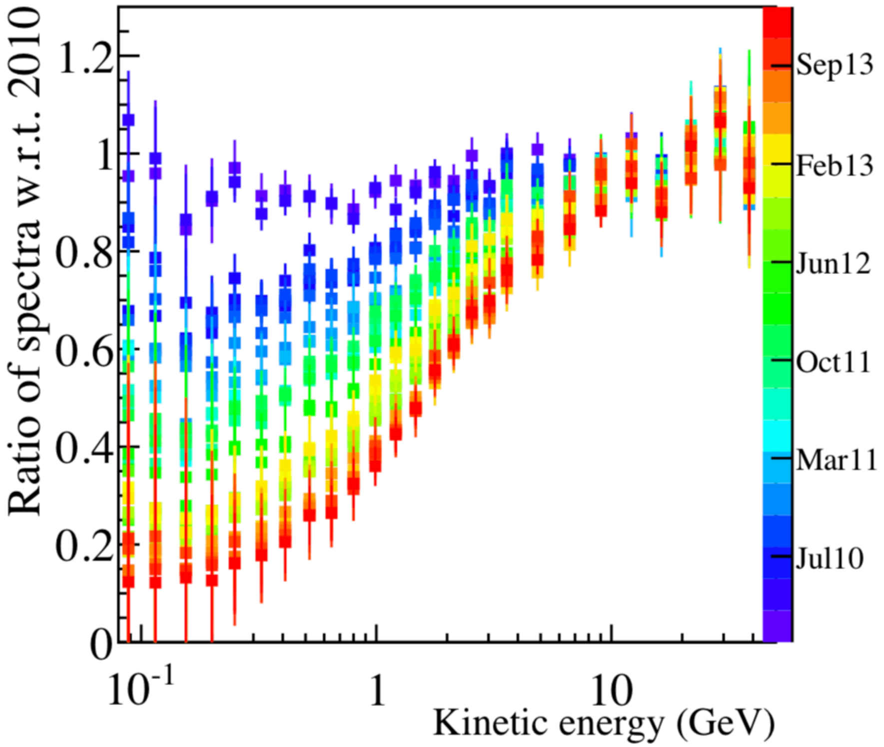
$$J(E,t) = \frac{E^2 - M^2}{(E+\Phi(t))^2 - M^2} J^{IS}(E+\Phi(t))$$

→ Precise measurement of the different components of CR over long period of time with the same detector needed to understand the solar modulation process.

Monthly proton flux from PAMELA:

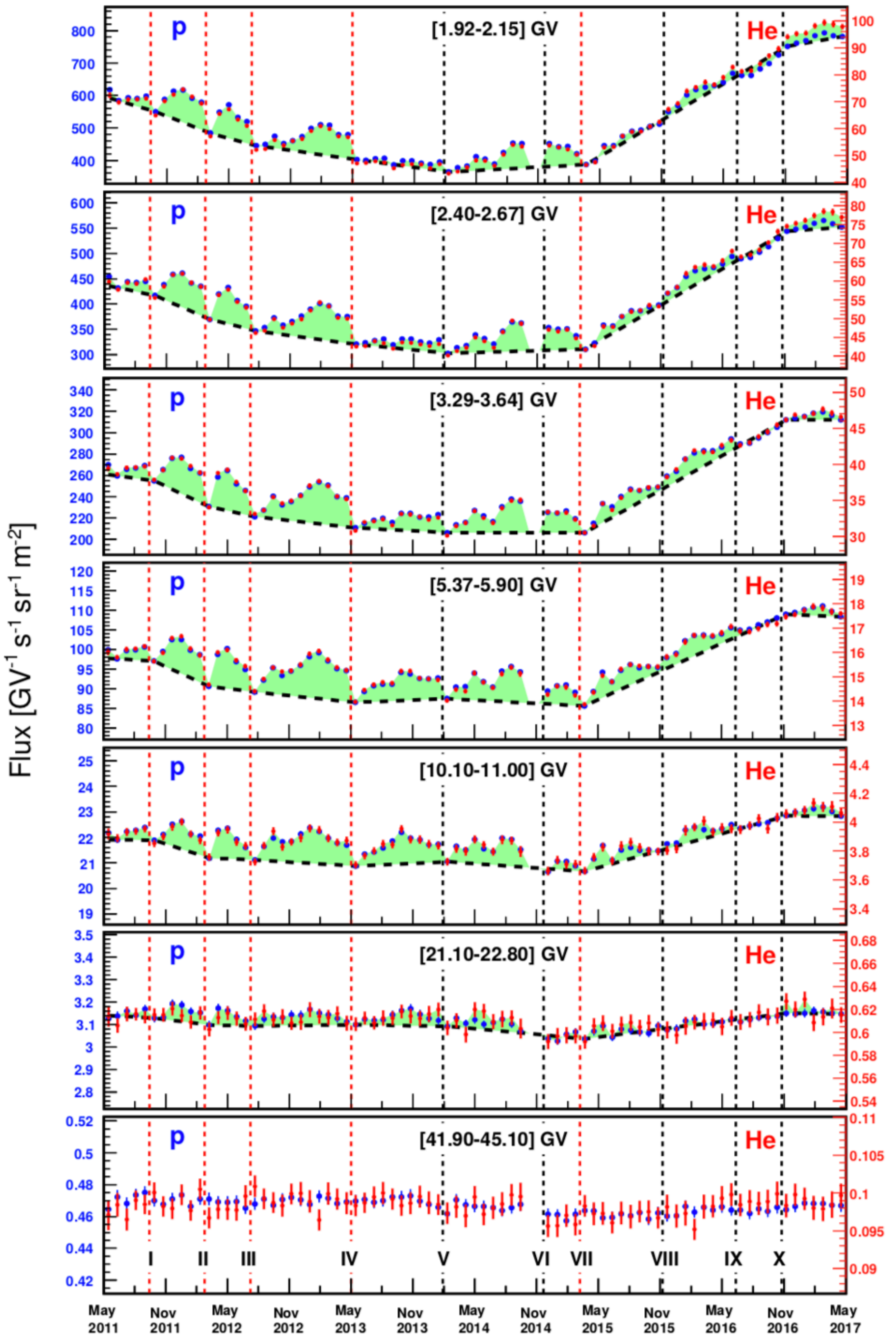
[PAMELA Collaboration, APJ Letter 854 (2018)]

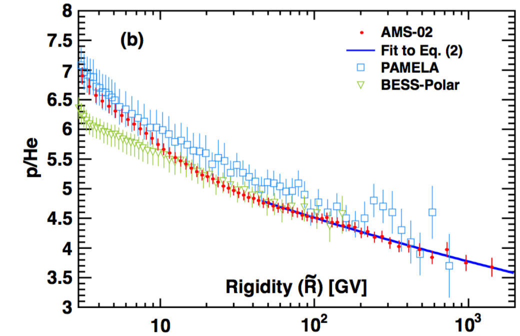




[accepted for publication in PRL]

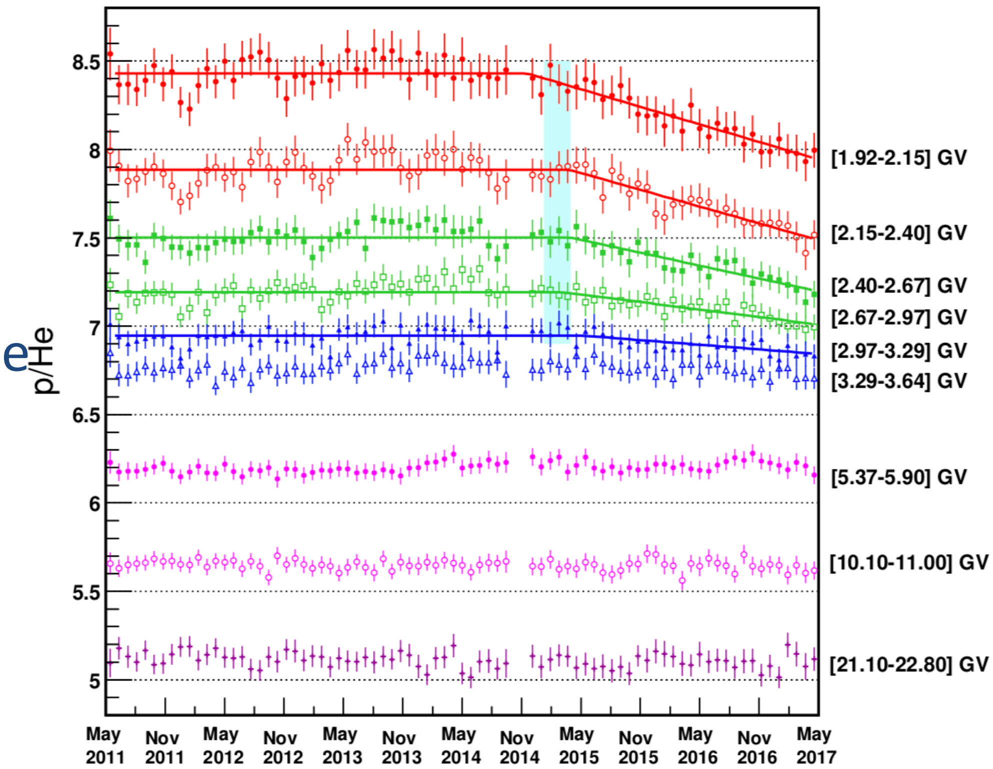
- Accurate monthly proton and helium fluxes over six years during the maximum of Solar Cycle 24.
- Proton and helium fluxes have nearly identical fine structures both in time and relative amplitude.





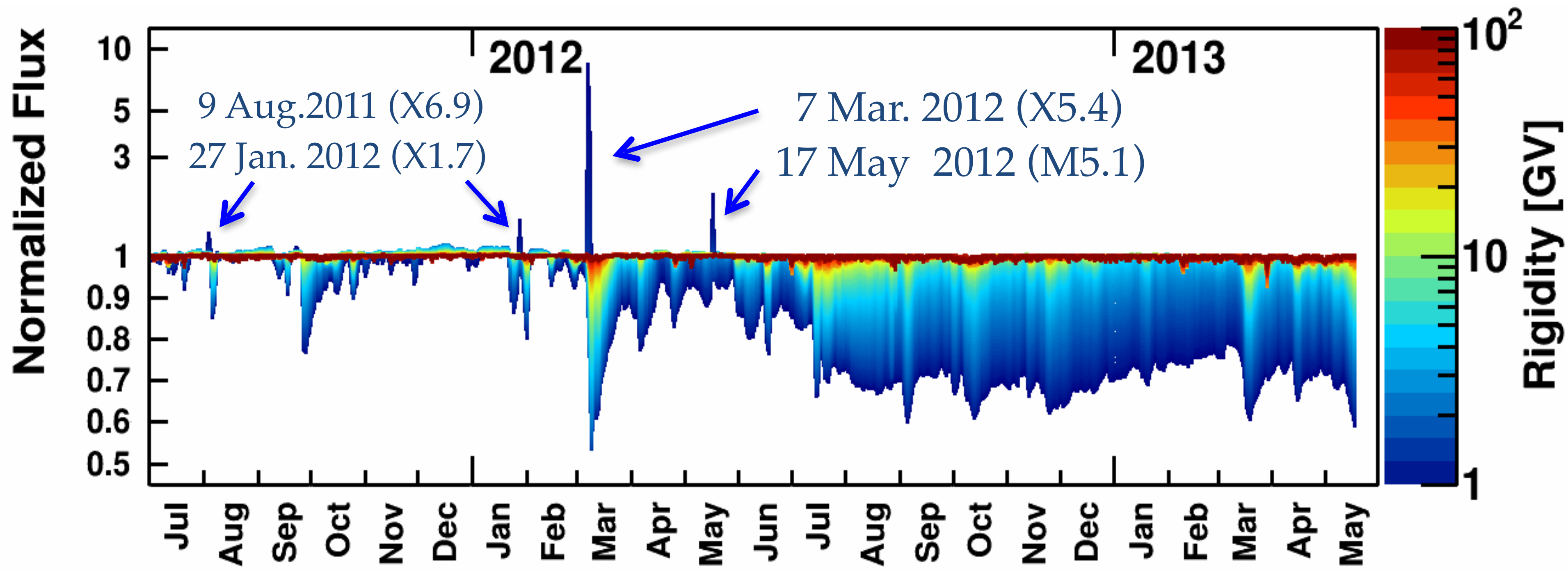
[accepted for publication in PRL]

- Proton and helium fluxes have nearly identical fine structures both in time and relative amplitude.
- p/He flux ratio: long-term decrease in the ratio below 3 GV, also starting one year after Solar Maximum.



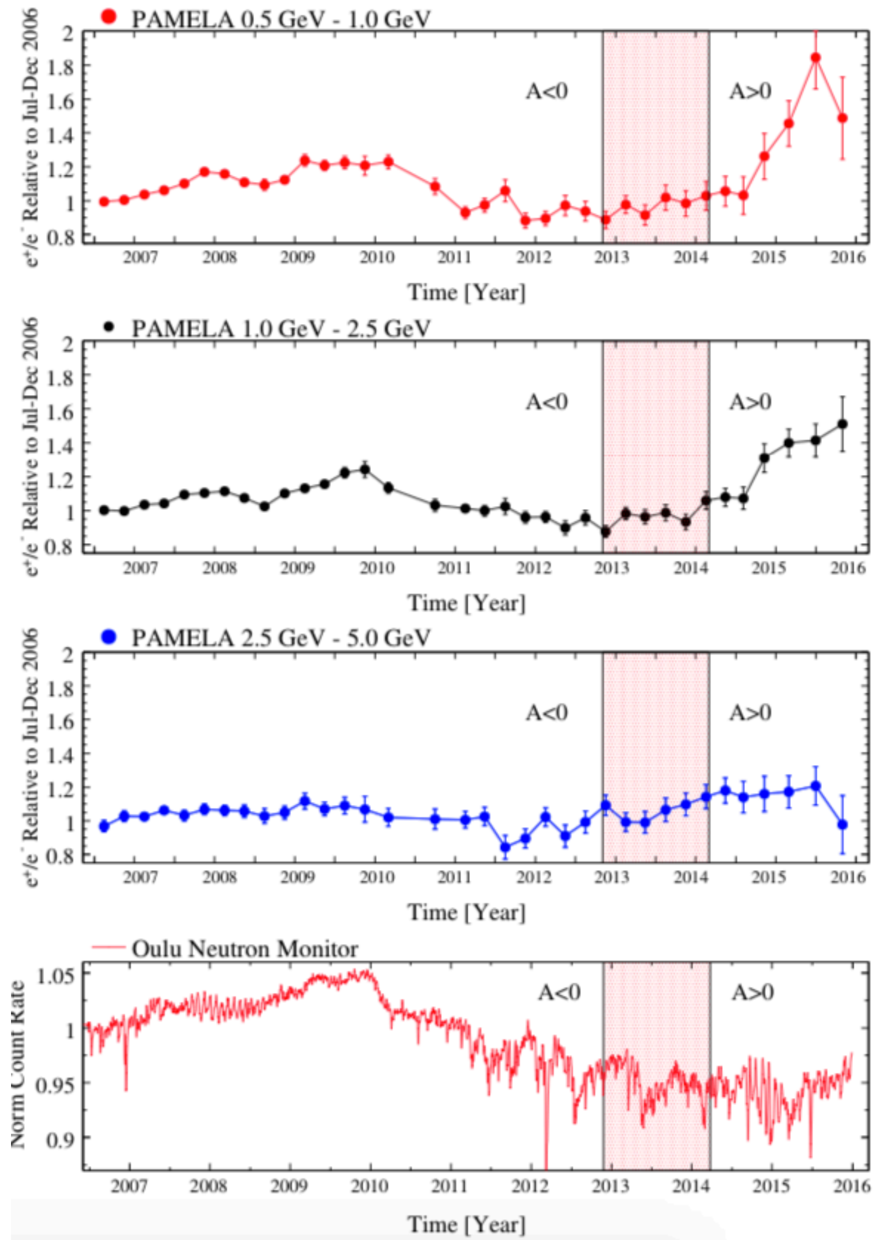
Time fluctuation of proton rate for different rigidities from AMS02 data:

R < ~3 GV : Peaks associated with Solar flares (SEP)



[PAMELA Collab., PRL 116, 241105 (2016)]

- e^+/e^- time dependence from PAMELA provides evidence for charge solar modulation sign dependence at low energy.

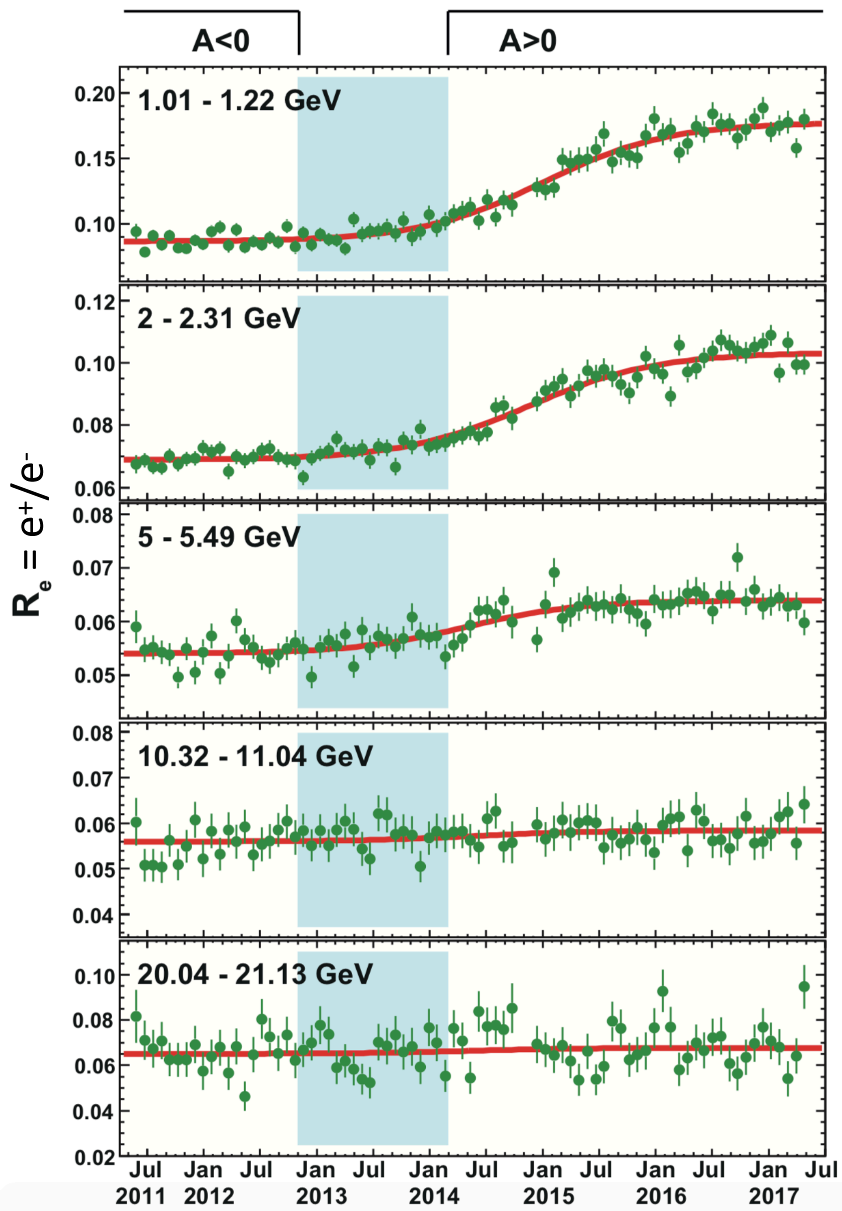


[accepted for publication in PRL]

High precision monthly fluxes of e+ and e- from AMS.

Measurement across the solar polarity reversal show that the ratio exhibits a smooth transition over 830 ± 30 days from one value to another.

The midpoint of the transition shows an energy dependent delay relative to the reversal and changes by 260 ± 30 days from 1 GeV to 6 GeV.



- On the experimental side:
  - Many experiences are currently taking data: FERMI, AMS02, CALET, DAMPE, ISS-CREAM
  - No/few new experimental projects for the next decade
  - Reflections for projects beyond but very exploratory (low level of maturity)
- Many results in recent years and more results to come:
  - Wide dataset with unprecedented accuracy:

    Measurement of H, He, Li, Be, B, C, N, O fluxes and ratios

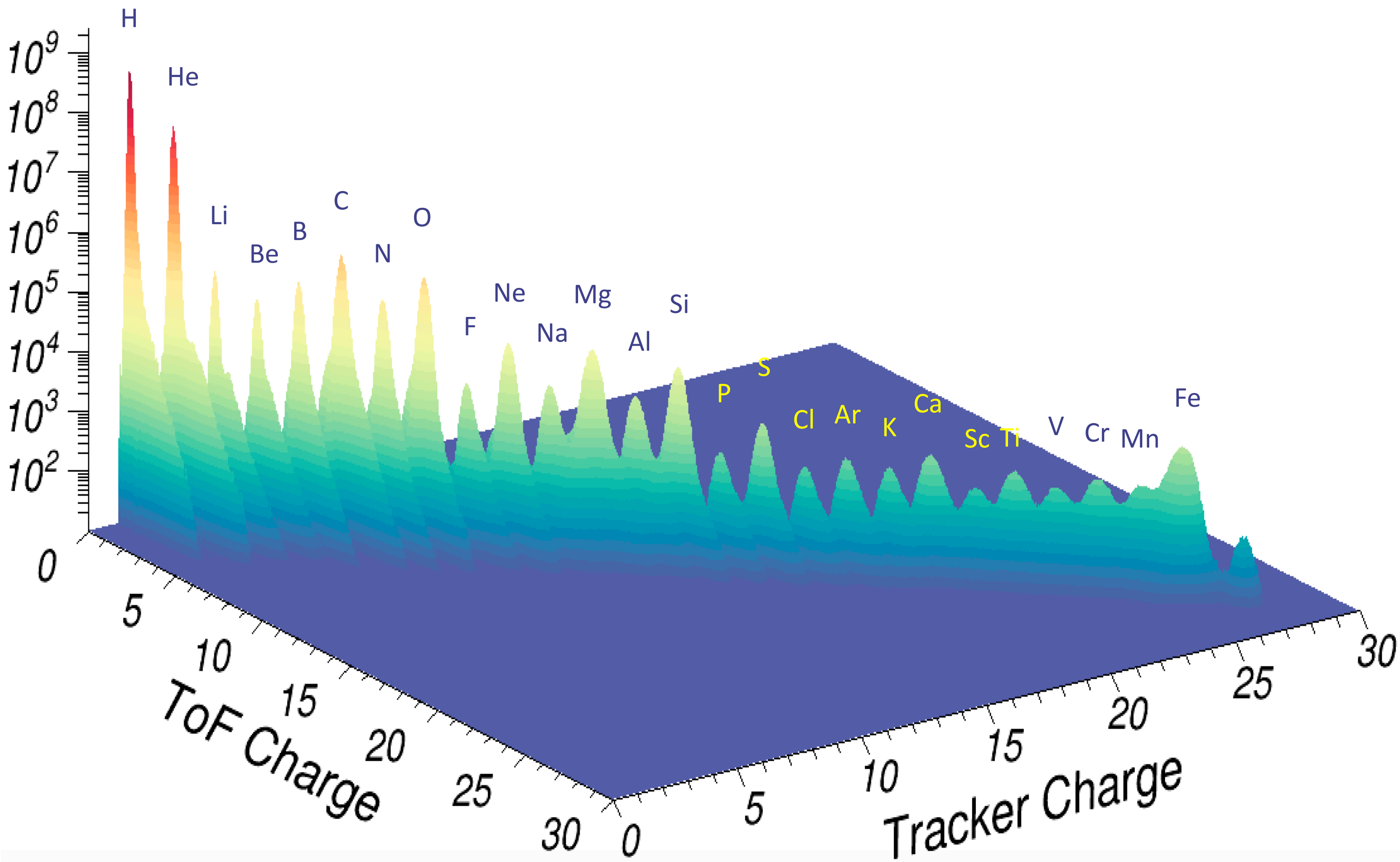
    + Heavier nuclei (to be released in the coming years)

    + Isotopes (to be released in the coming years)

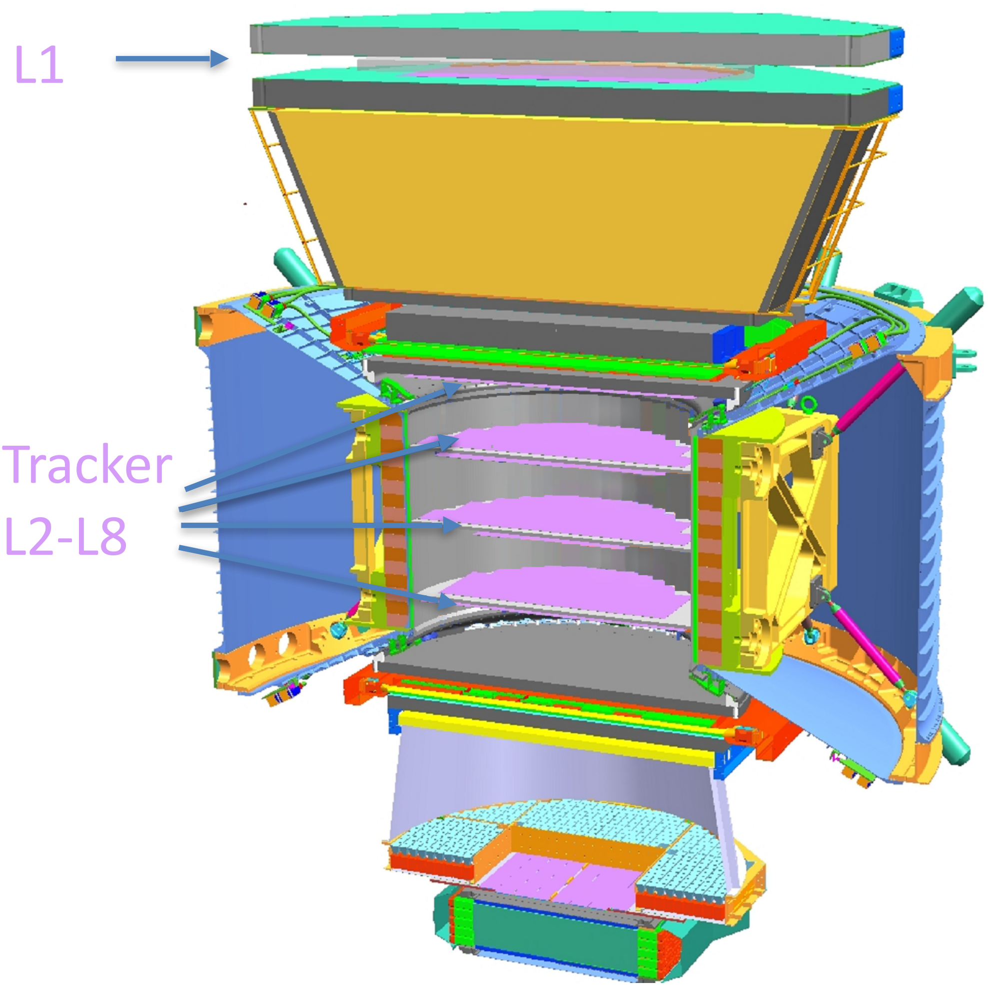
    + Time dependence of the different components of the RC

    + LE ISM p & He fluxes from Voyager

→ Interpretation of all these data in the context of propagation models is an important challenge.


H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0
5
10
15
20
25
30
ToF Charge
0
5
10
15
20
25
30
Tracker Charge

Nuclei flux in AMS



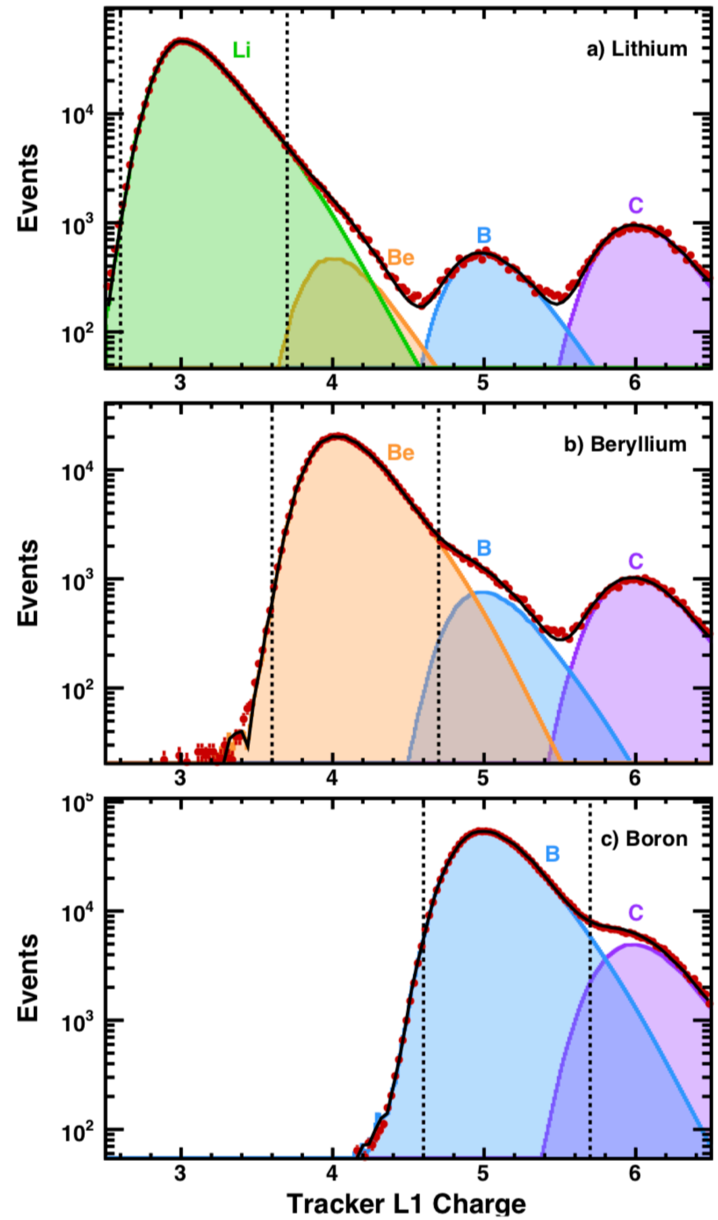
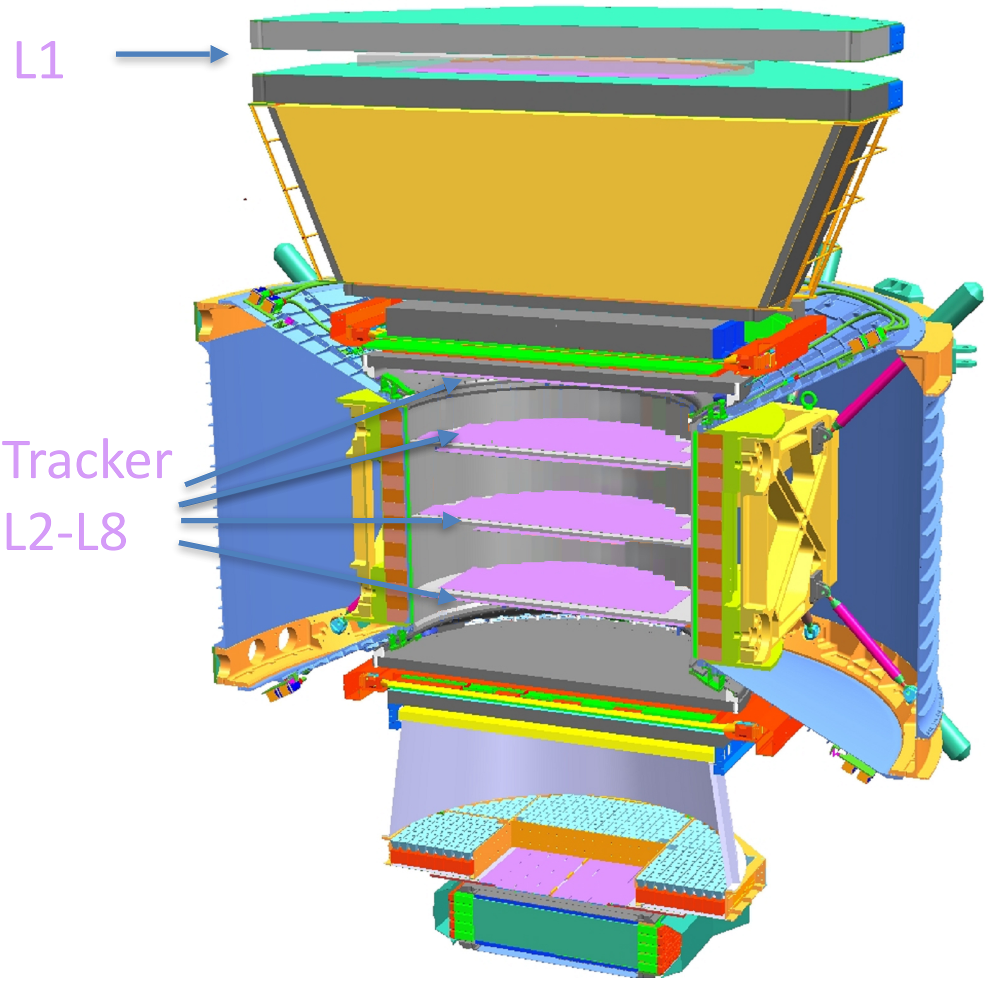
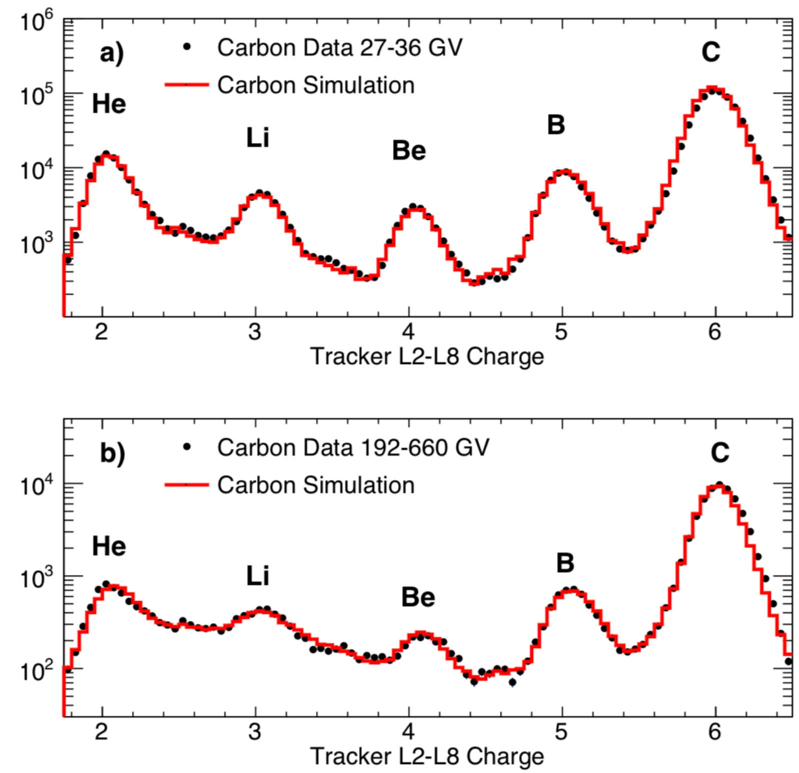


FIG. SM 2. Charge distributions measured by tracker $L1$ for (a) lithium, (b) beryllium, and (c) boron events selected by the inner tracker with rigidity 9 to 11 GV (red circles). The solid black curve shows the fit of the sum of the charge distribution templates for Li (green), Be (orange), B (light blue), and C (violet) to the data. The templates are obtained from a selection of non-interacting samples on $L2$ by the use of the charge measurement from $L1$ and $L3$-$L8$. The charge selection cuts applied on $L1$ are shown as vertical dashed lines.

Nuclei flux in AMS



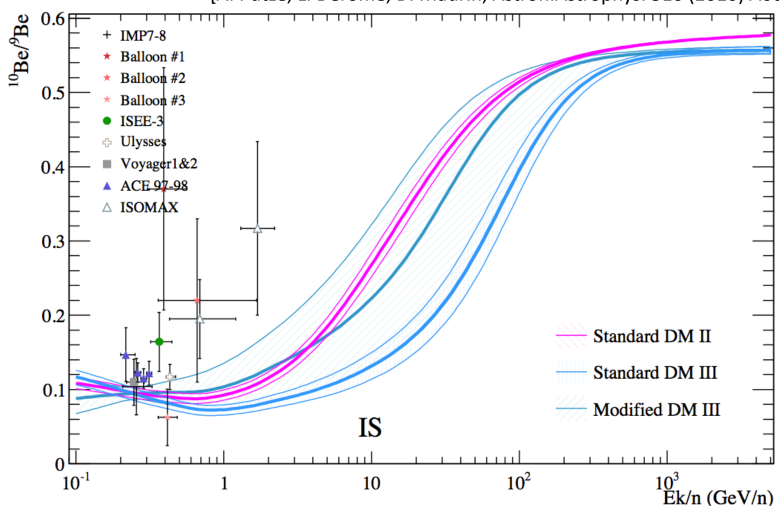


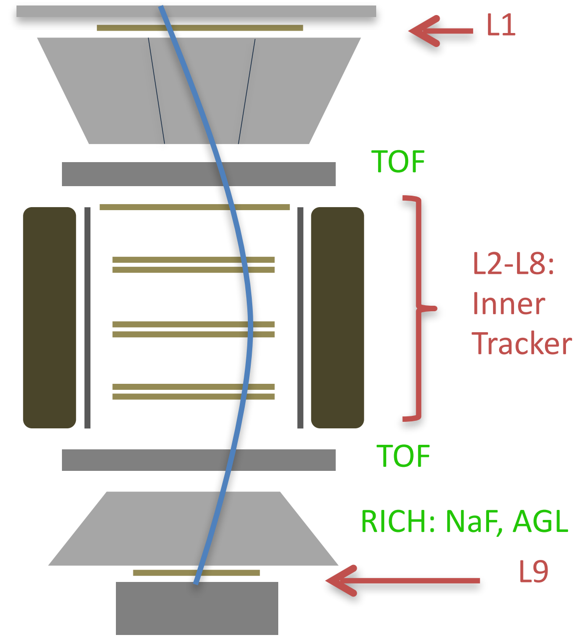
SM 3. The charge distribution measured by the inner tracker ($L2$-$L8$, MDR ~700 GV) for a sample of carbon events selected with tracker $L1$ in the rigidity range (a) from 27 to 36 GV and (b) from 192 to 660 GV. MC distributions (red histograms) are normalized to the non-interacting carbon peak measured in the data (points).

Detector	Energy Range (GeV)	Energy Resolution	e/p Selection Power	Key Instrument (Thickness of CAL)	SΩT (m^2srday)
ATIC1+2 (+ ATIC4)	10 - a few 1000	<3% (>100 GeV)	~10,000	Thick Seg. CAL (BGO: 22 X_0) + C Targets	3.08
PAMELA	1-700	5% @200 GeV	10^5	Magnet+IMC (W:16 X_0)	~1.4 (2 years)
FERMI-LAT	20-1,000	5-20 % (20-1000 GeV)	10^3-10^4 (20-1000GeV) Energy dep. GF	Tracker+ACD + Thin Seg. CAL (W:1.5X_0+CsI:8.6X_0)	60@TeV (1 year)
AMS	1-1,000 (Due to Magnet)	~2-4% @100 GeV	10^4 (x 10^2 by TRD)	Magnet+IMC +TRD+RICH (Lead: 17X_0)	~50(?) (1year)
CALET	1-10,000	~2-3% (>100 GeV)	~10^5	IMC+CAL (W: 3 X_0+ PWO : 27 X_0)	44 (1years)
DAMPE	1-10,000	~1% (>100 GeV)	~10^5-10^6	IMC+CAL+Neutron (W: 2 X_0+ BGO: 32 X_0)	180 (1 years)

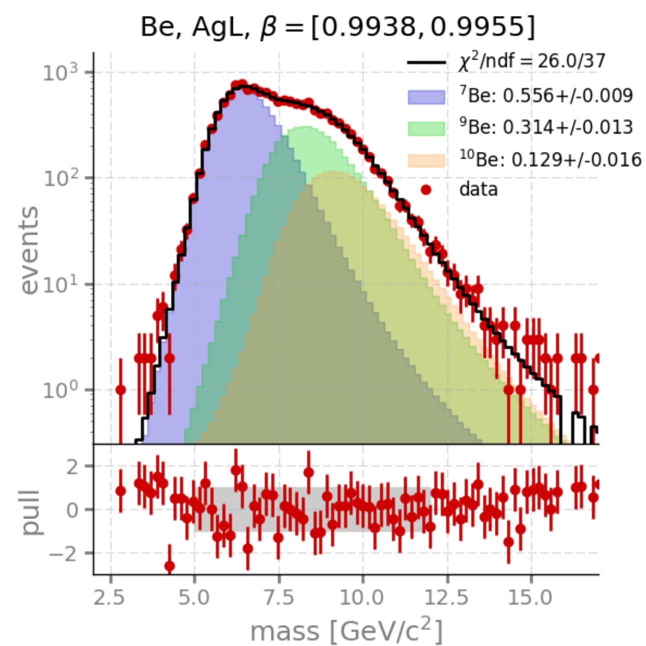
- Key CR observables but few measurements:

[A. Putze, L. Derome, D. Maurin, Astron.Astrophys. 516 (2010) A66]





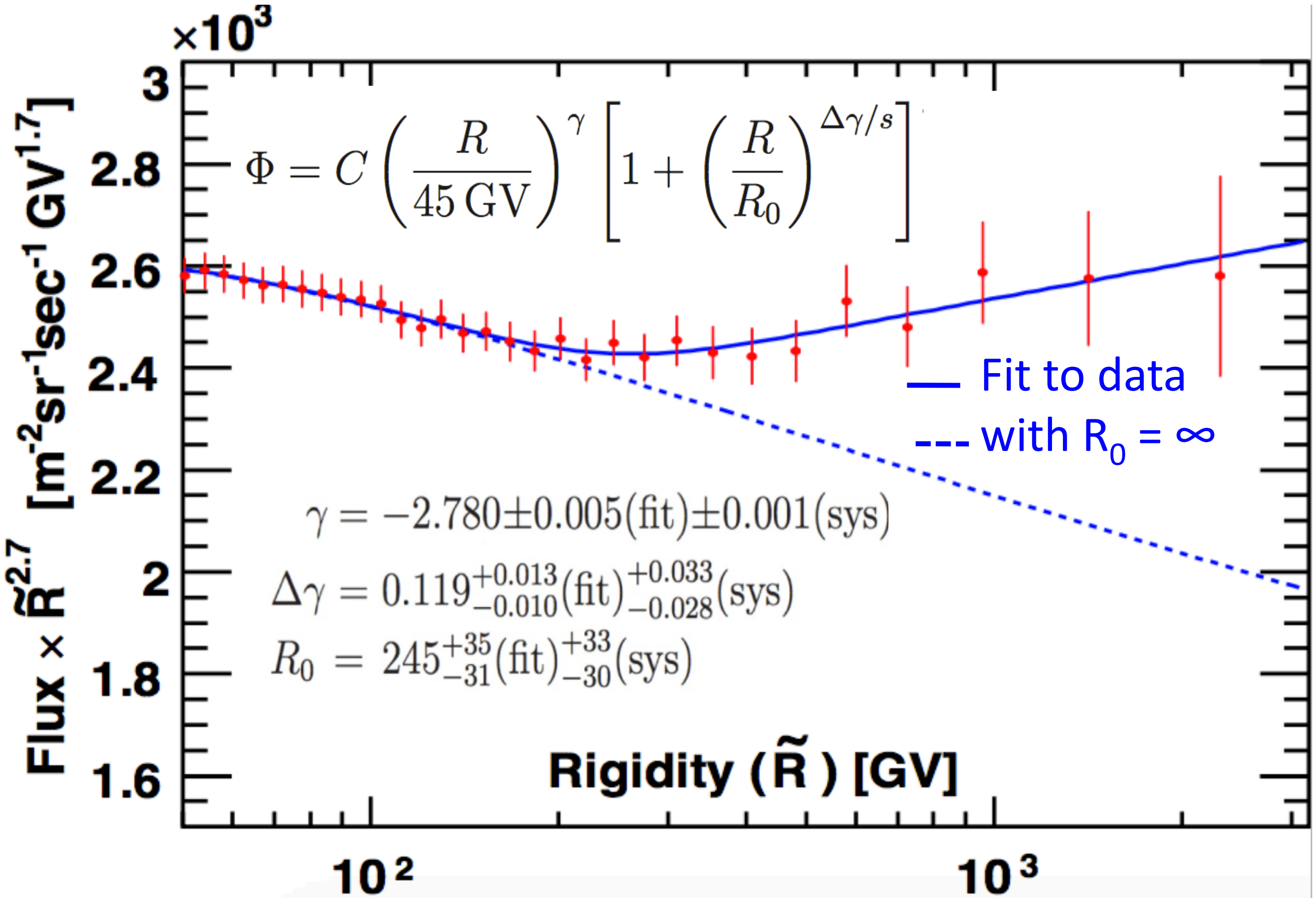
$$M = \frac{RZ}{\gamma\beta} \Rightarrow \frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\gamma^2 \frac{\Delta\beta}{\beta}\right)^2}$$



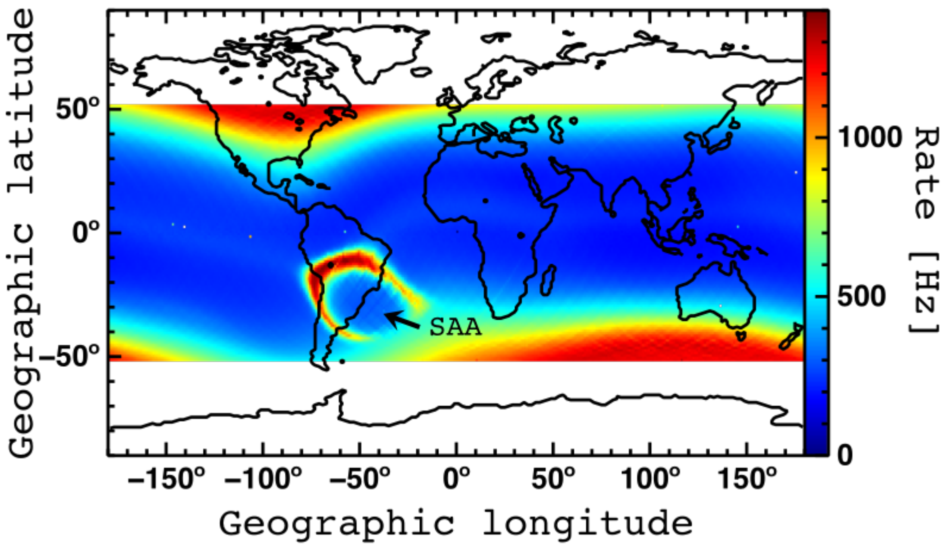
- Quartet (^{1}H, ^{2}H, ^{3}He, ^{4}He) from PAMELA at low energy [PAMELA Coll. Astrophysical Journal, 818 (2016) 68]
- Ongoing analyses of AMS data:
  ^{3}He:^{4}He, ^{6}Li:^{7}Li, ^{10}Be:^{9}Be:^{7}Be
- Balloon HELIX project dedicated to isotopic measurement in the range 1-10 GeV/n

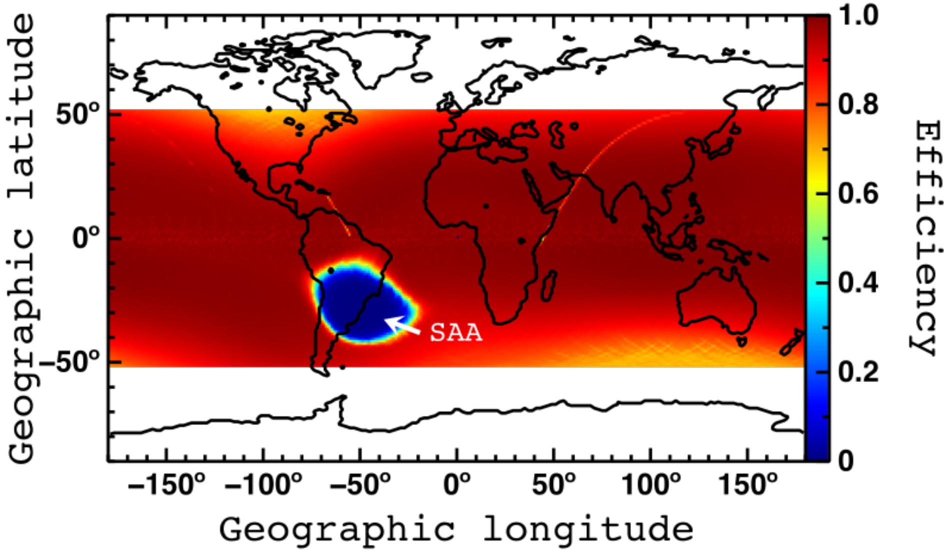
Helium flux measurement

- Fit of the AMS flux with a double power model with smooth transition:

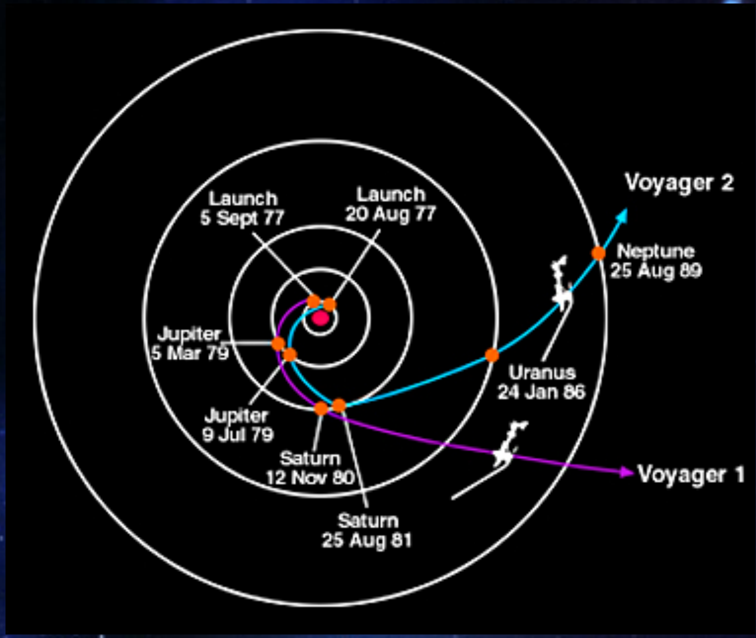


→ Same hardening as for proton in the flux around 300 GeV.





- AMS installed on ISS in May 2011
- Circular orbit, 400 km, 51.6°, 90 mn
- Continuous operation 24/7
- Average rate ~700 Hz
- 60 millions particles/day
- 39 TB raw data/yr
- 200 TB rec. data/yr
- More than 100 milliards of events collected so far



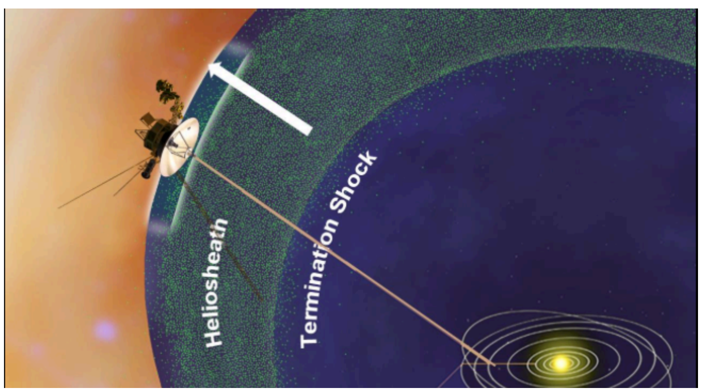
- Voyager 1&2 launched in 1977
- **Used the gravity slingshot method to catapult itself to the furthest planets and eventually beyond the Heliosphere.**
- Payloads still active…**cosmic ray telescopes (CRS) measure the Low energy CR intensity for almost 40 years.**

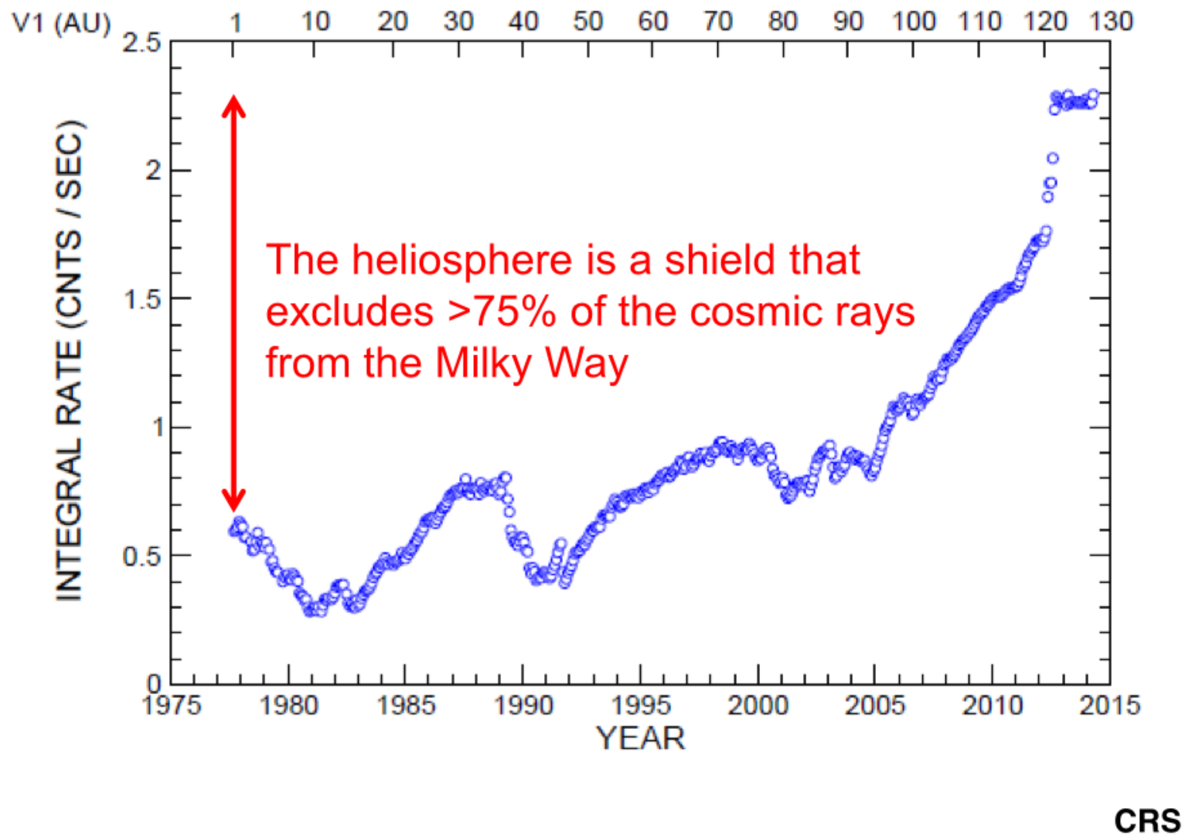
Voyager 1

Measures CR intensity as it travels to the interstellar space:

Variation due to:

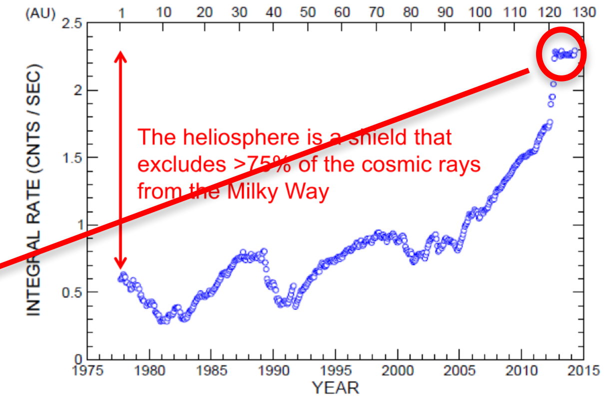
- 11-years cycles due to solar activity
- Global rise as Voyager go out from the sun.

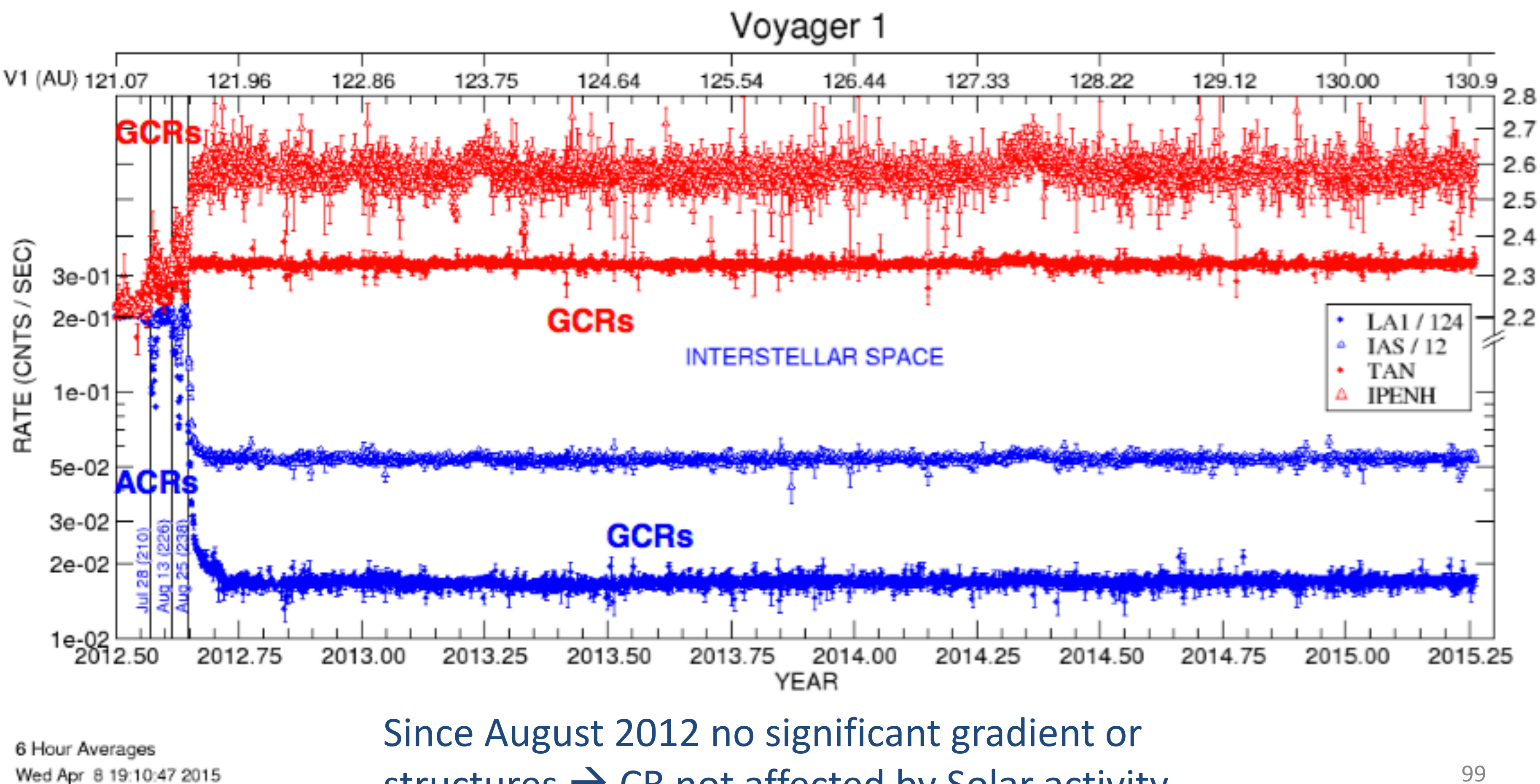




On August 2012, Voyager 1 reached interstellar space at 121 AU.

Voyager 1





Since August 2012 no significant gradient or structures → CR not affected by Solar activity....

Voyager 1

- Voyager1 measured for the first time the IS (unmodulated) CR spectra.
- Also measured electron and higher charge nuclei (not shown)