Direct detection of galactic cosmic rays

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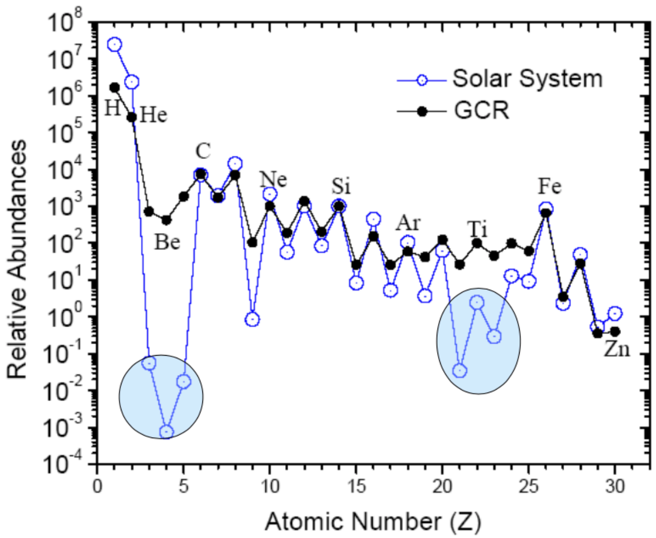
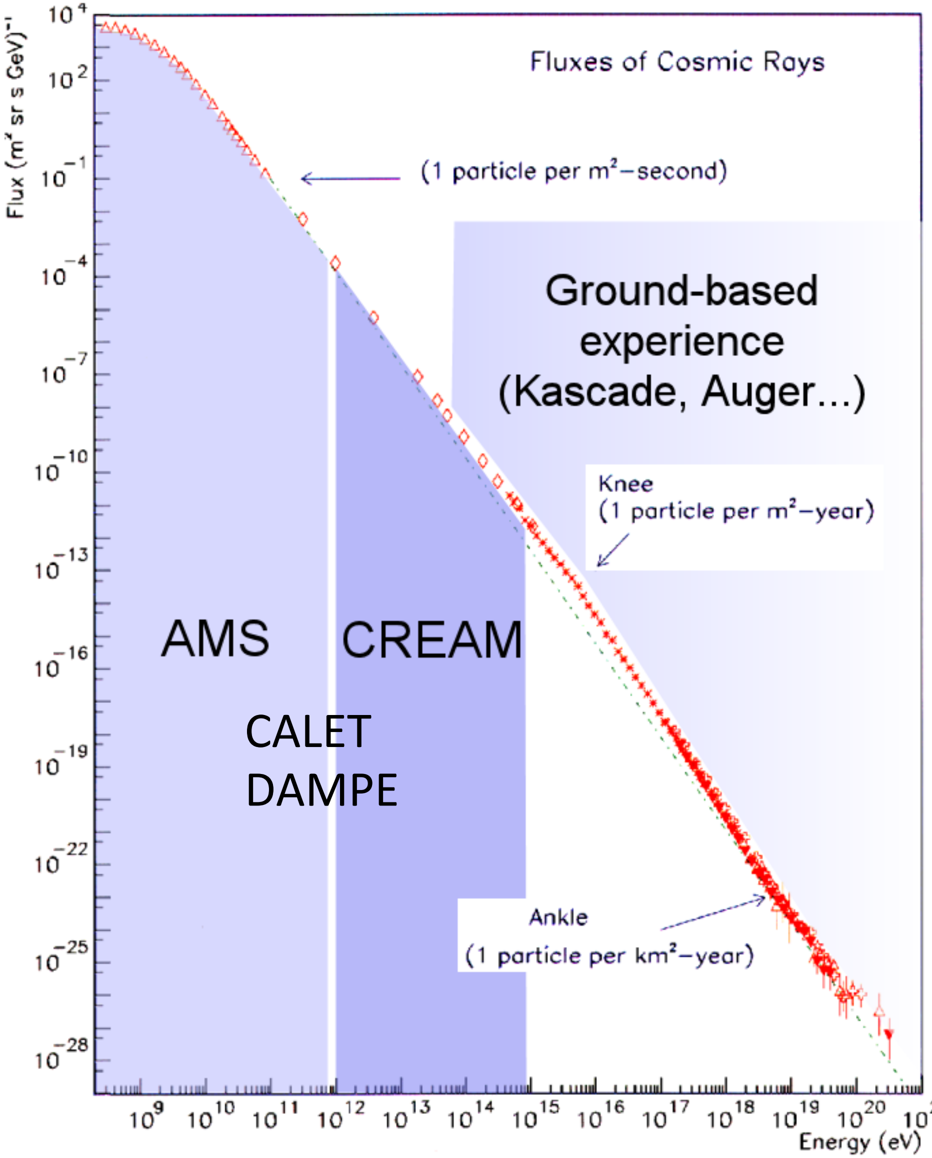
Detection of Galactic Cosmic rays

- E < 10^{15} ev : Cosmic rays are absorbed in the upper layer of atmosphere but the flux is large
  - Direct detection above atmosphere.
  - 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

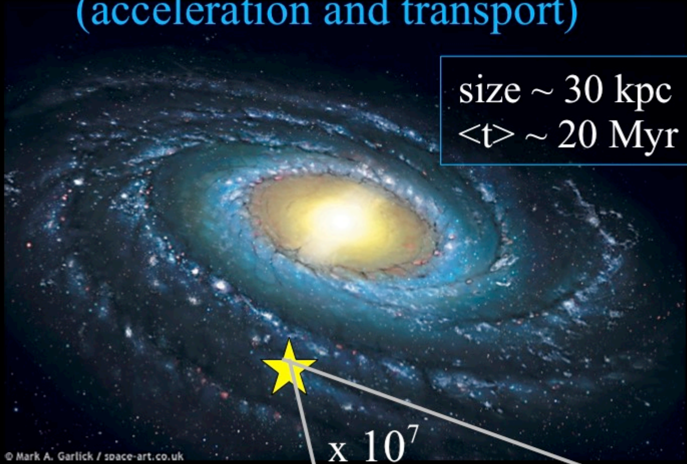


An unexpected journey: across the Earth atmosphere

From David Maurin

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)



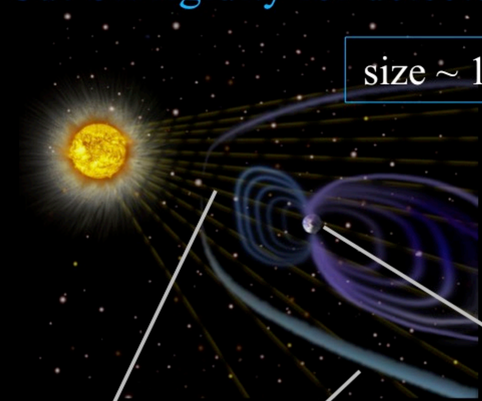
size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

3. Earth magnetic shield

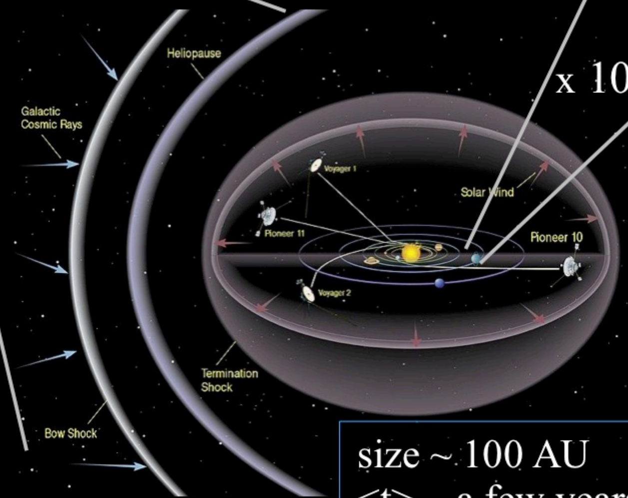
→ Cut-off rigidity for detectors

size ~ 10^4 km



x 10^5

x 10^2

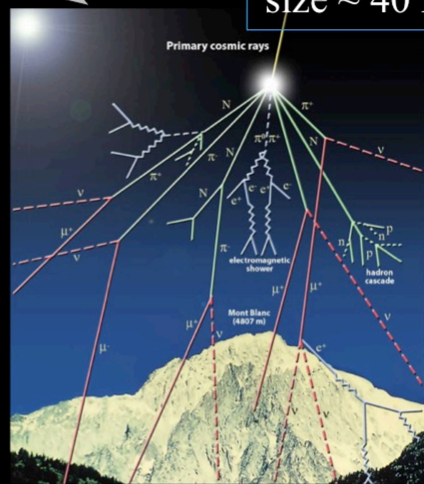


size ~ 100 AU
<t> ~ a few years

2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

size ~ 40 km



4. Atmospheric showers

→ Ground-based detection
→ Solar activity monitoring
[N.B.: Čerenkov flash ~ 10^{-8} s]

Recent GCR experiments

Spectrometer
Calorimeter

balloons

- MASS (1989-1991)
- IMAX (1992)
- CAPRICE (1994-1998)
- HEAT (1994-1995)
- BESS (1994-2000)
- ATIC (2000-2007)
- TRACER (2006)
- CREAM (2004-2010)
- HELIX (2018?)

space

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

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space

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- CALET (2015-...)
- DAMPE (2015-...)
- ISSCREAM (2017-...)

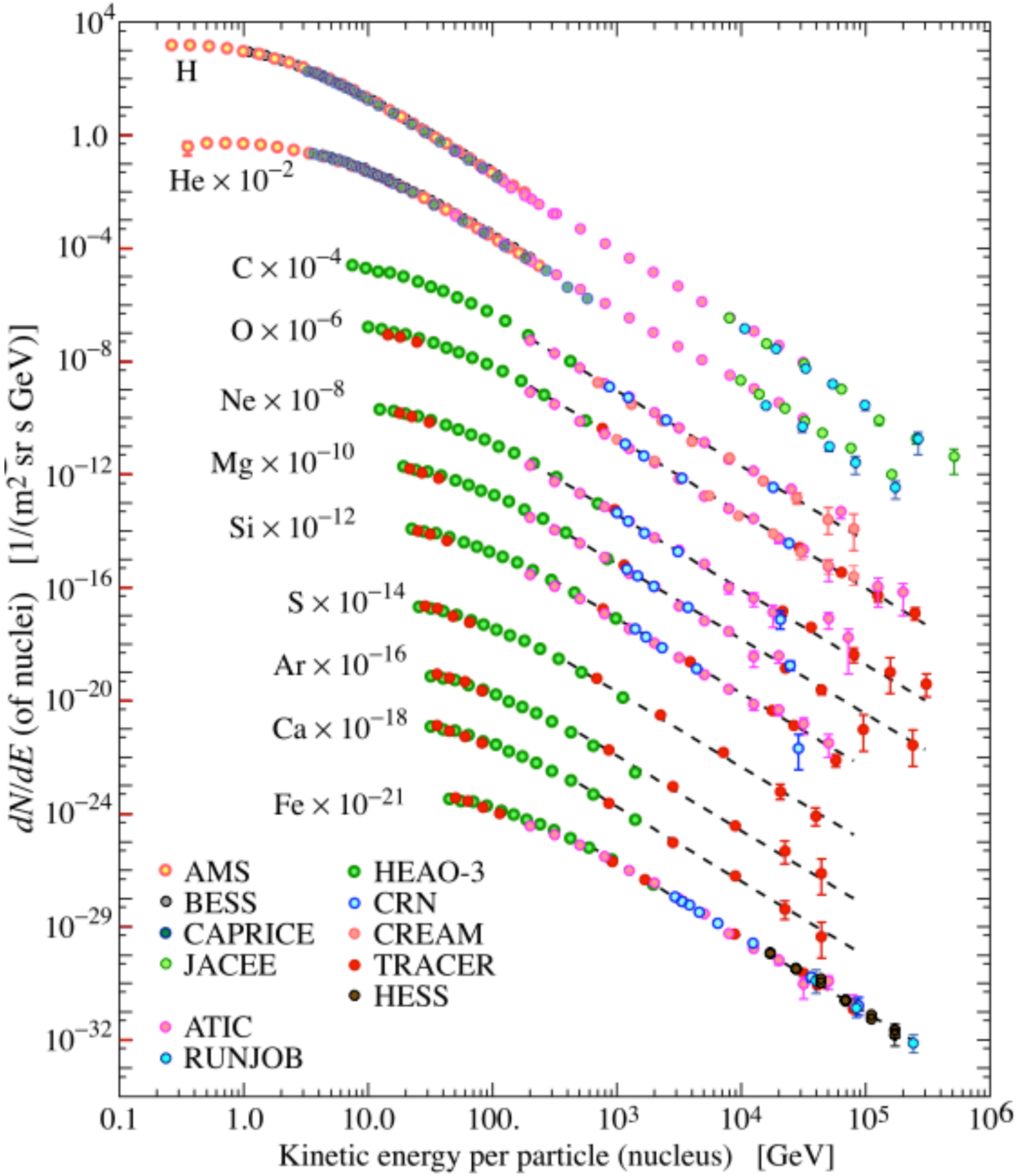
Galactic CRs status ~10 years ago

Main properties:

- Featureless and universal power-law energy spectra above 2 GeV/n
- Abundances for primary species related to Solar system ones.
- Abundances of secondary species explained by nuclear interaction on ISM.

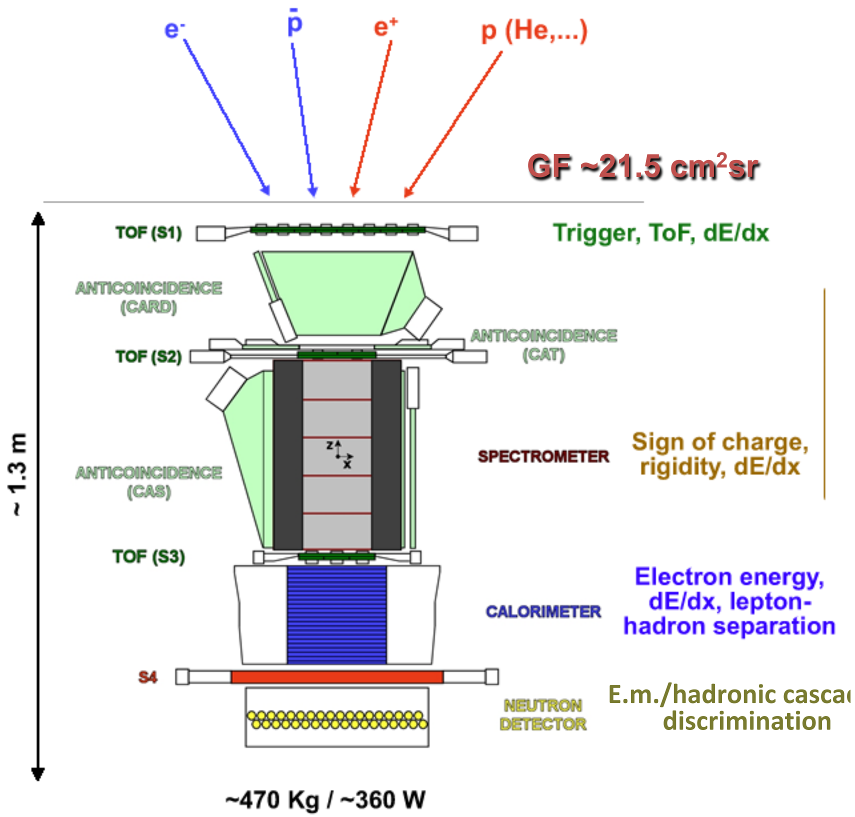
→ Global features could be well described by diffusion model with universal power-law injection in the sources

→ Recent data, reaching an unprecedented precision are challenging this “simple” picture.



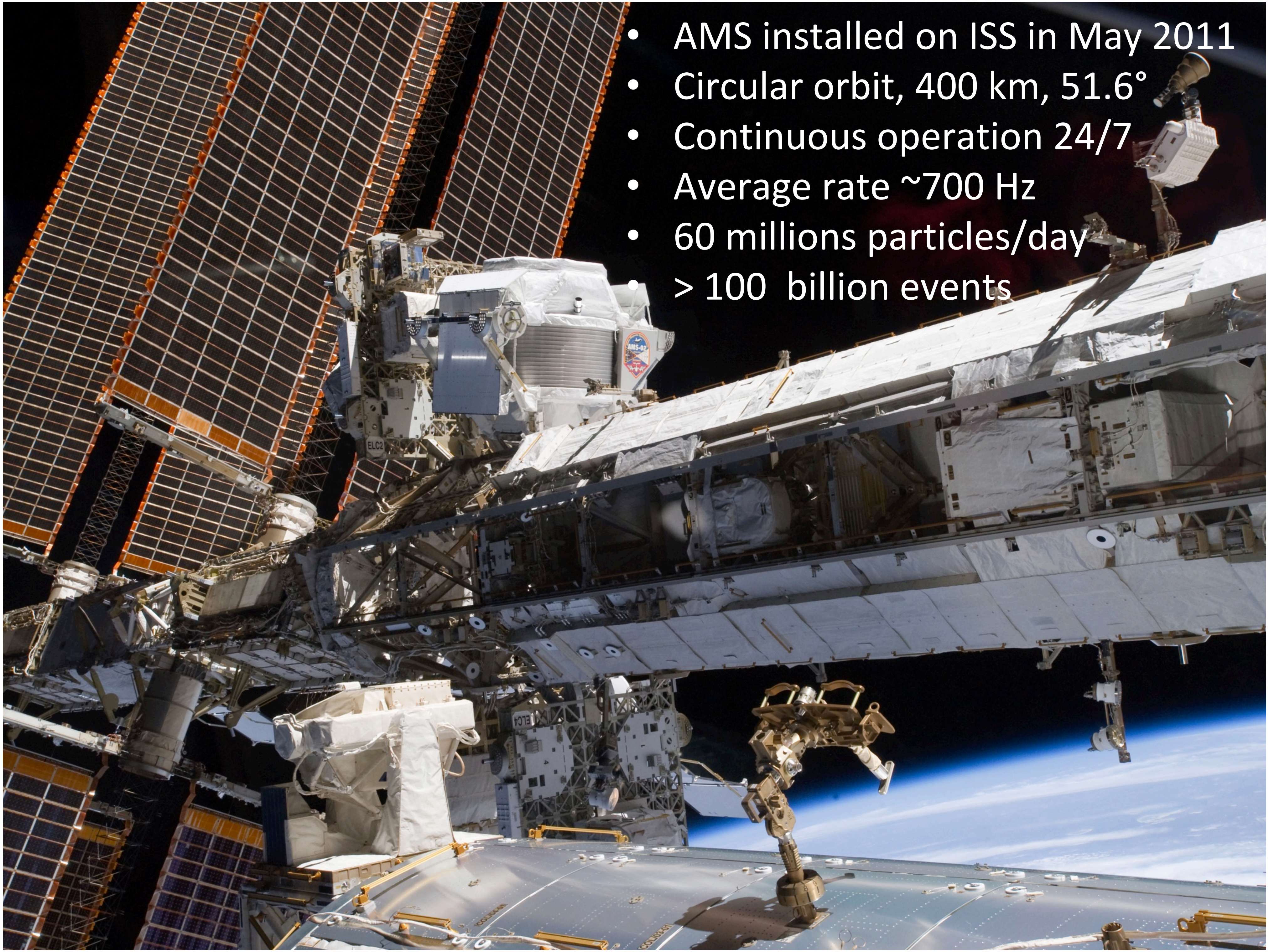
PAMELA Detector

- 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

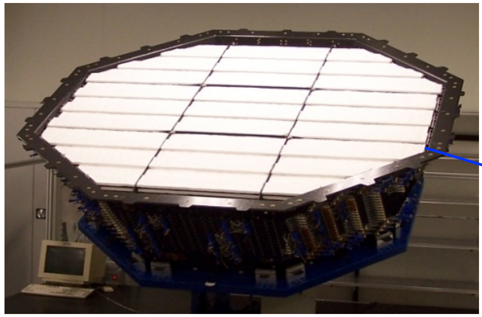
- AMS installed on ISS in May 2011
- Circular orbit, 400 km, 51.6°
- Continuous operation 24/7
- Average rate ~700 Hz
- 60 millions particles/day
- > 100 billion events



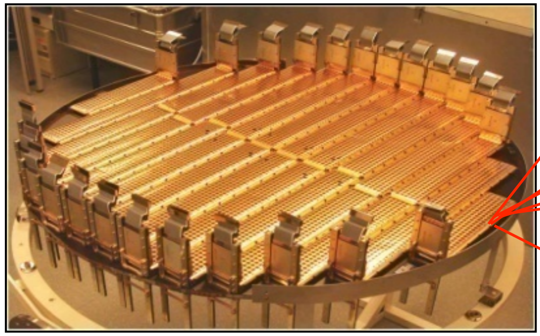
AMS

A TeV precision, multipurpose spectrometer in space.

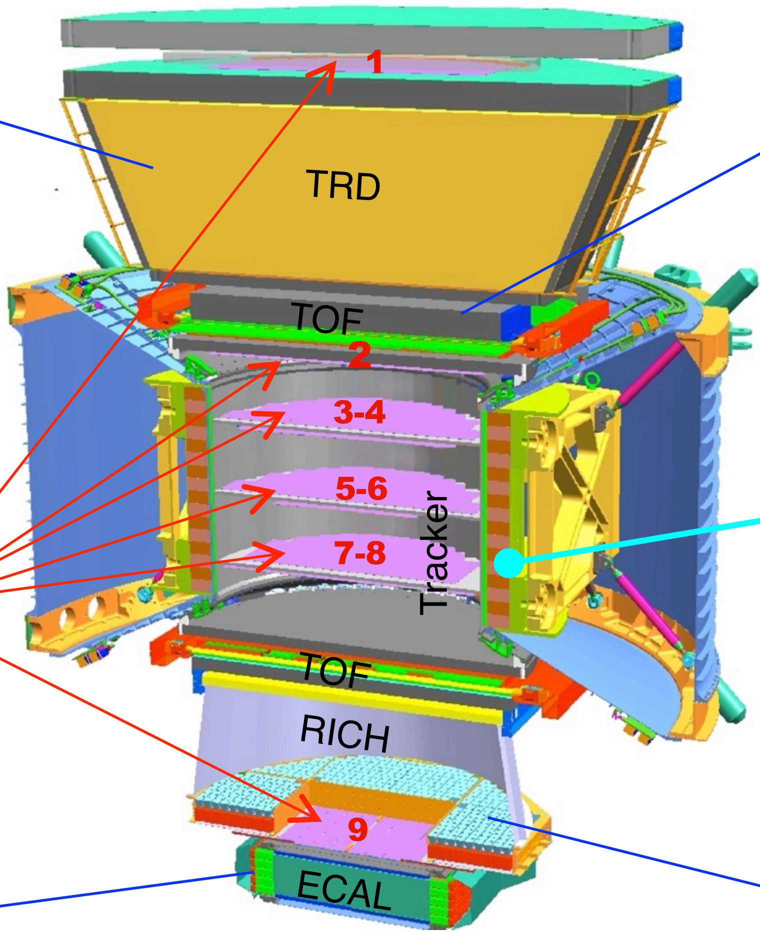
TRD
Identify e^+, e^-



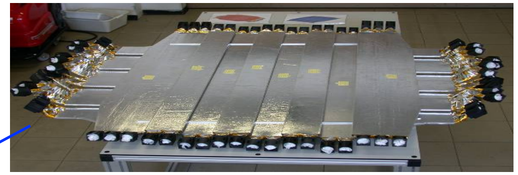
Silicon Tracker
Z, P



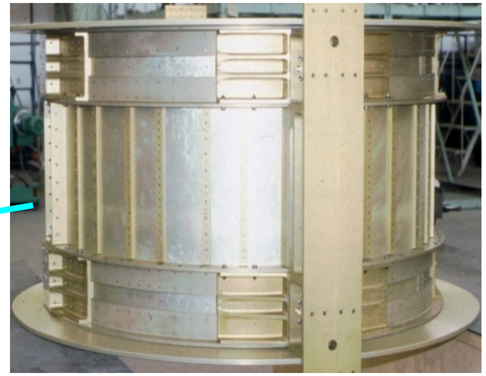
ECAL
Identify e^+,e^-
E of e^+, e^-, γ



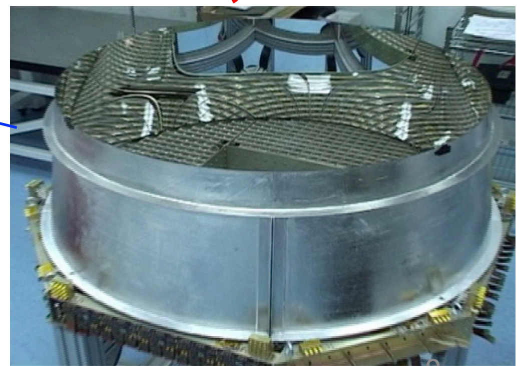
TOF
Z, Beta



Magnet
±Z



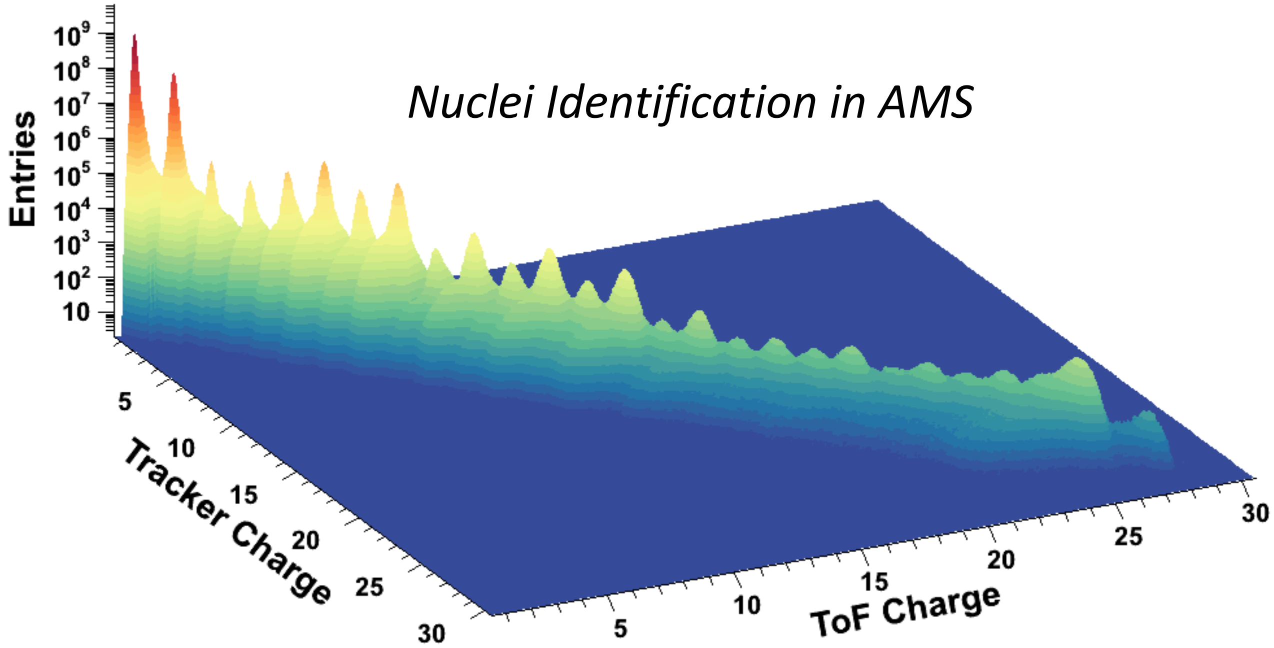
RICH
Z, Beta



5m x 4m x 3m **7.5 tons**

GF ~ 5000 cm^{2}sr

Cosmic-Ray Nuclei



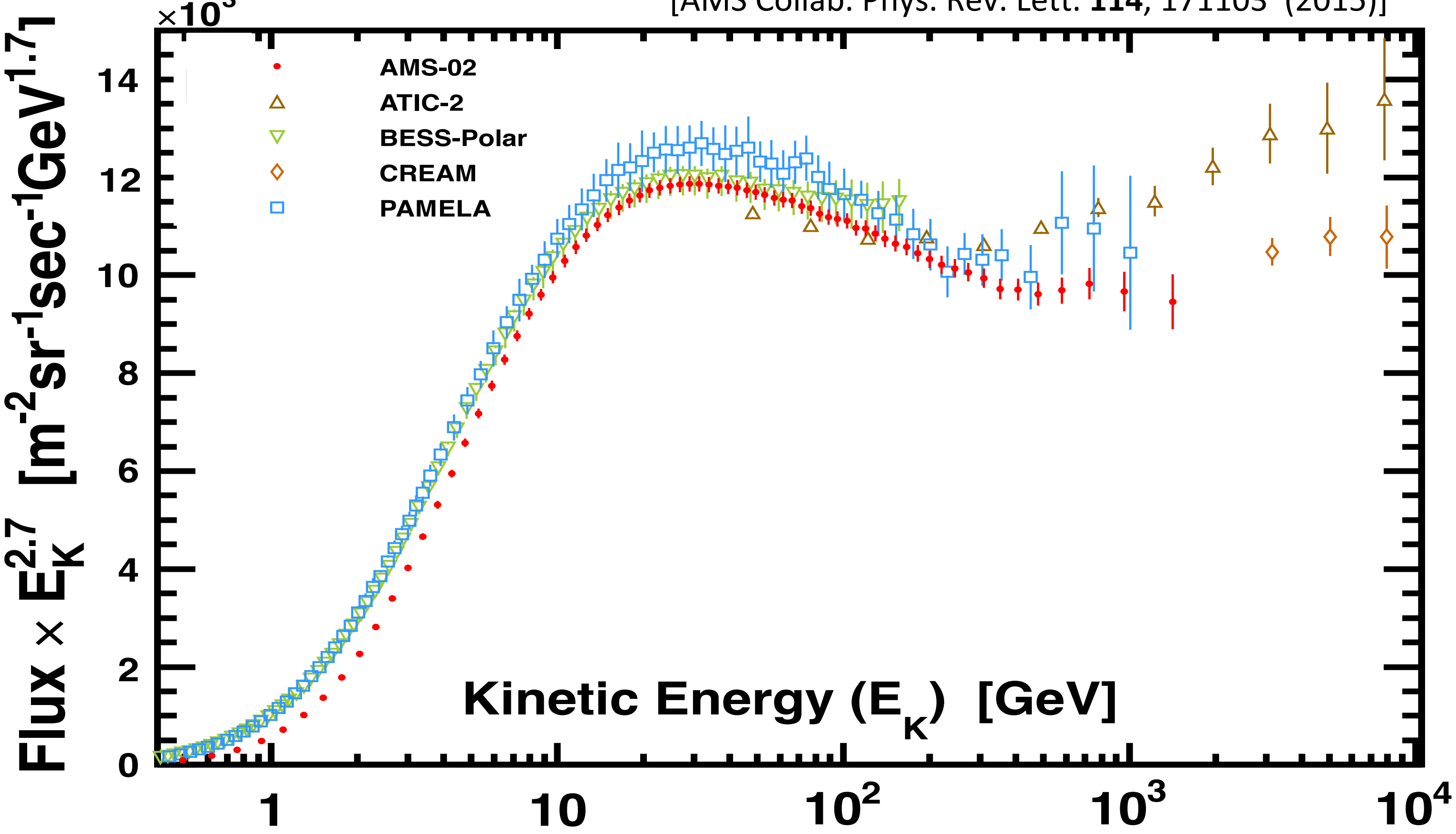
Each cosmic-ray nucleus provides specific information:

- 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 mandatory to assess background (e^+,pbar,…) and expected signal for DM searches.

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)]



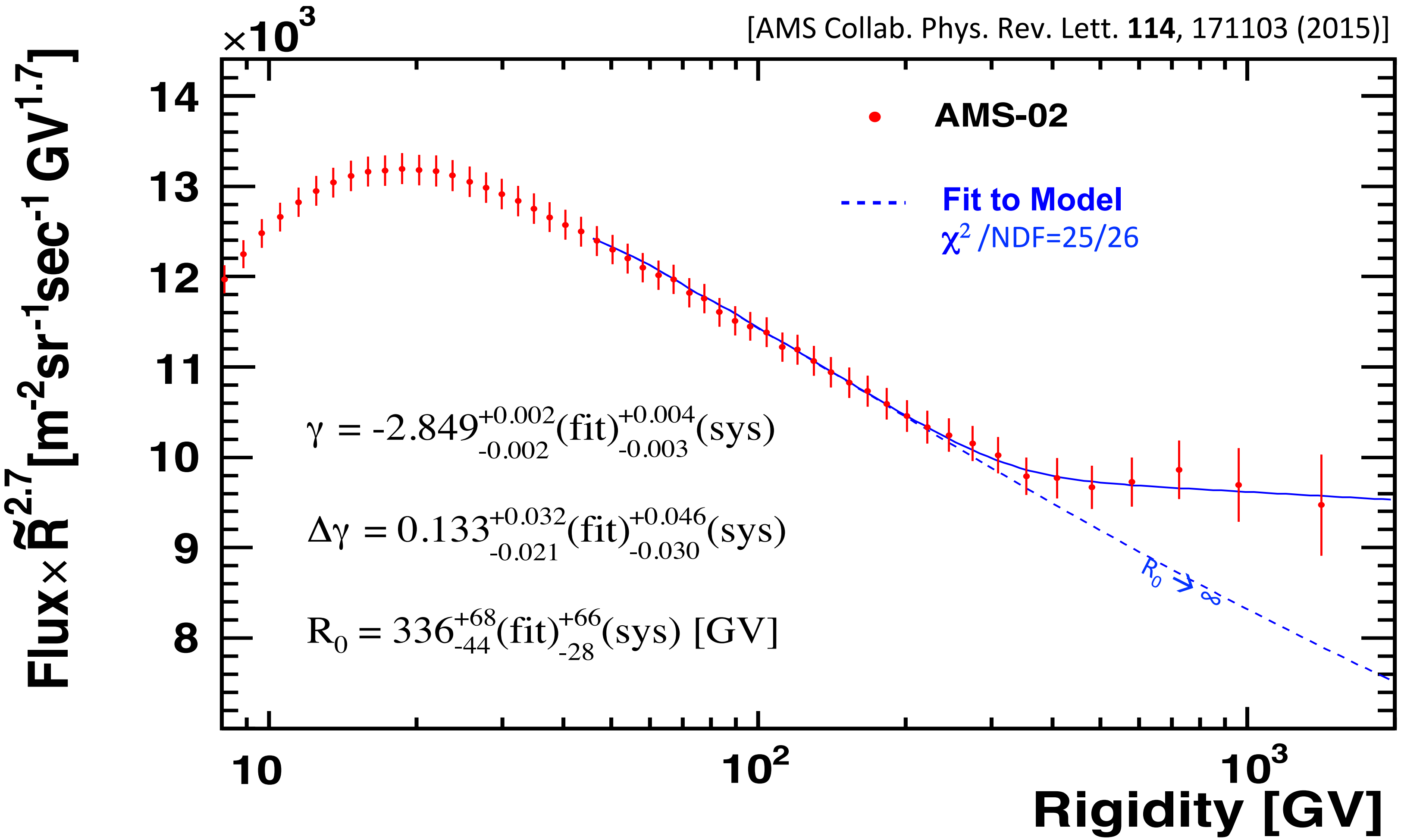
→ Hardening of the proton flux around 300 GeV.
→ Precision of AMS data allowed to characterize the shape of the transition.

Proton Flux Measurement

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

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

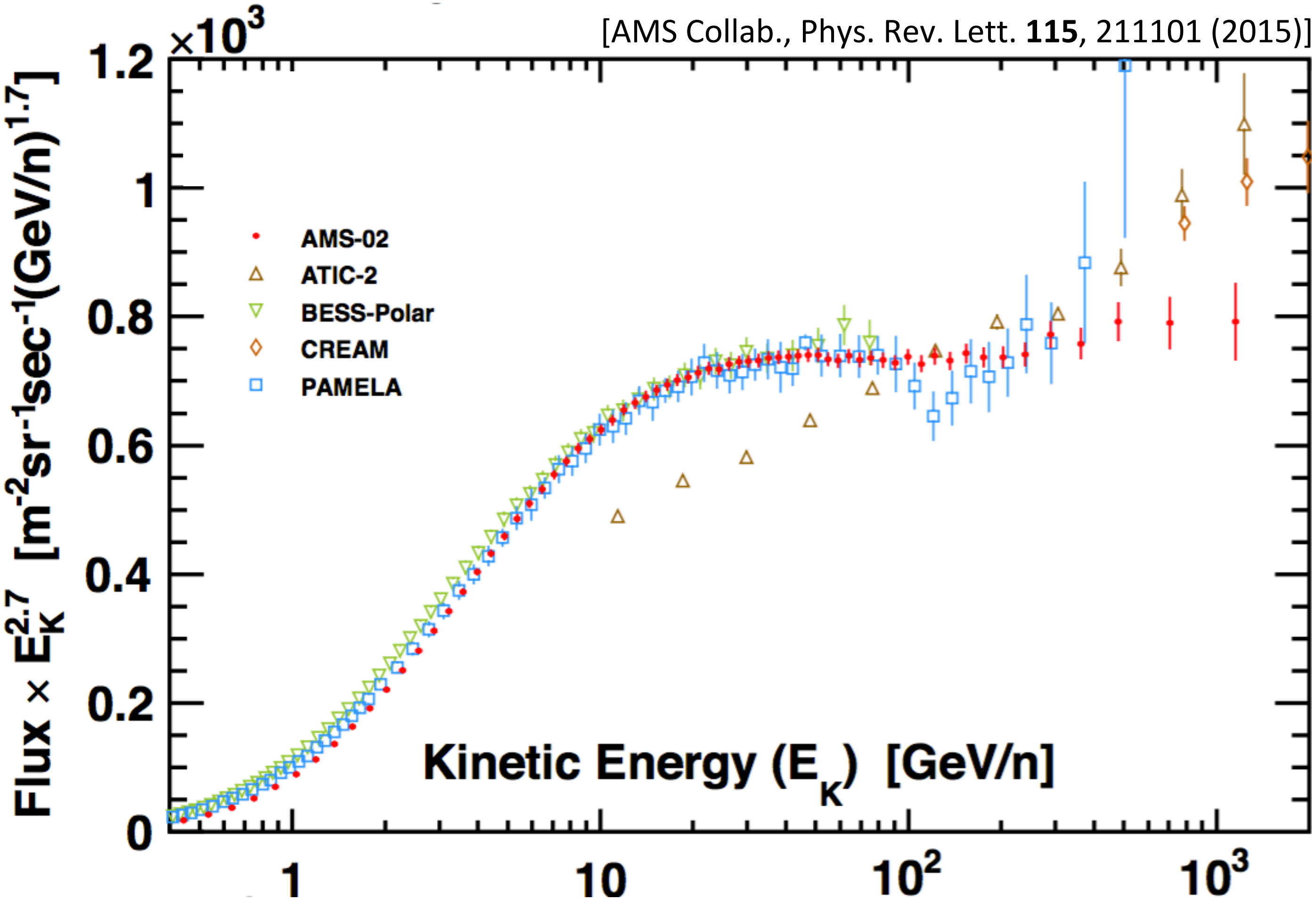
[AMS Collab. Phys. Rev. Lett. **114**, 171103 (2015)]



Helium flux measurement

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

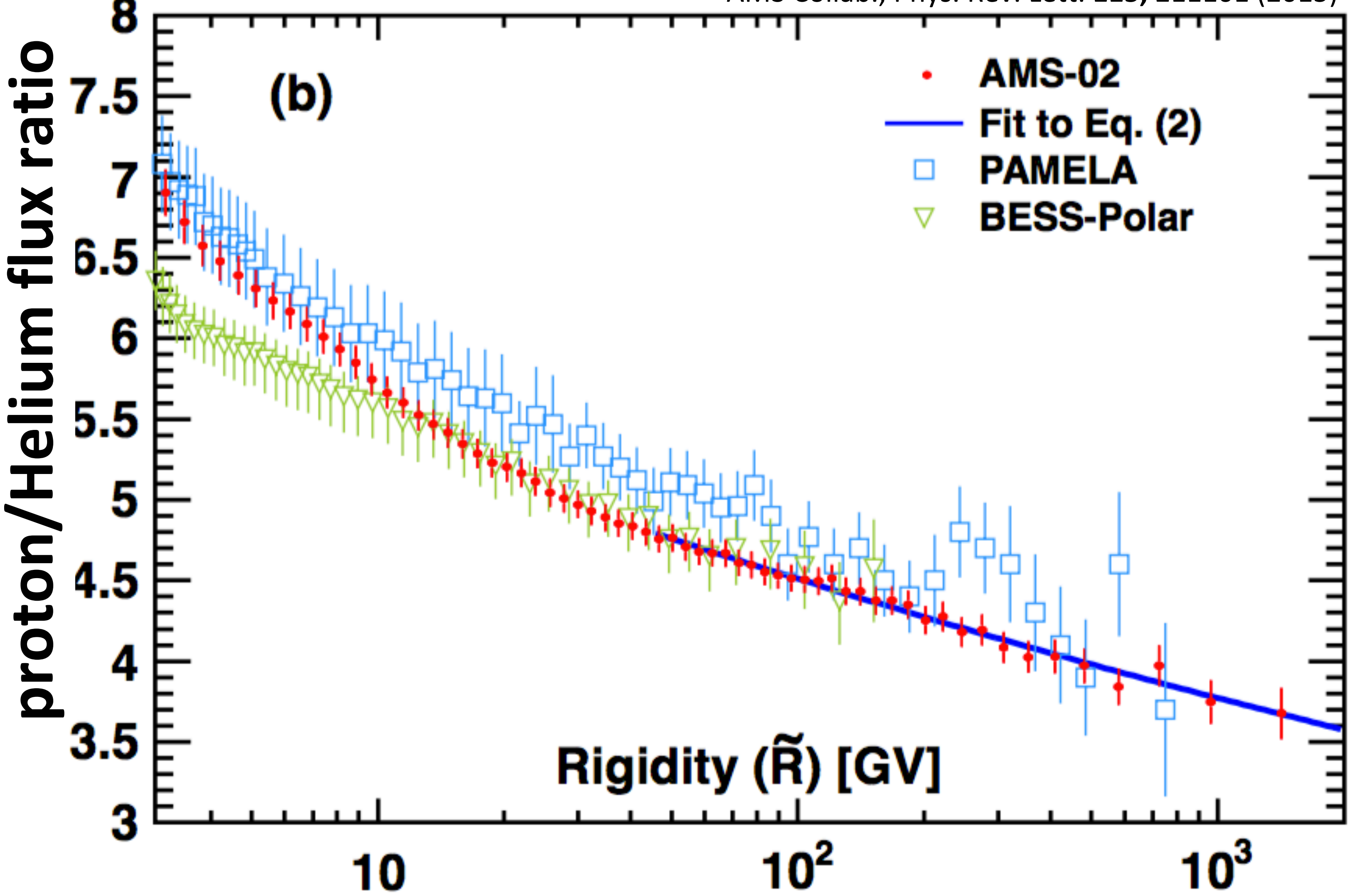
[AMS Collab., Phys. Rev. Lett. **115**, 211101 (2015)]



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

p/He ratio

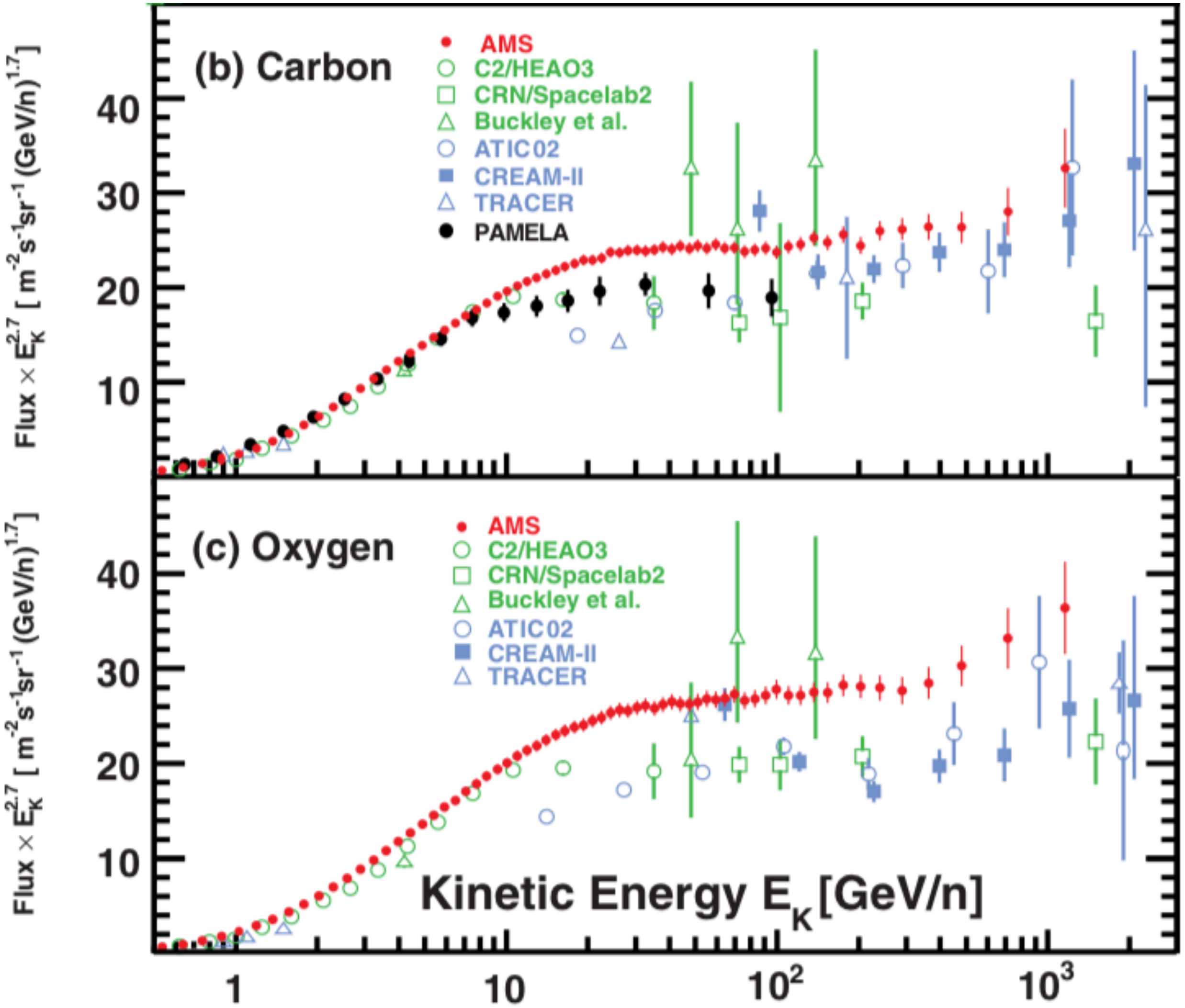
AMS Collab., Phys. Rev. Lett. **115,** 211101 (2015)



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

Carbon and Oxygen

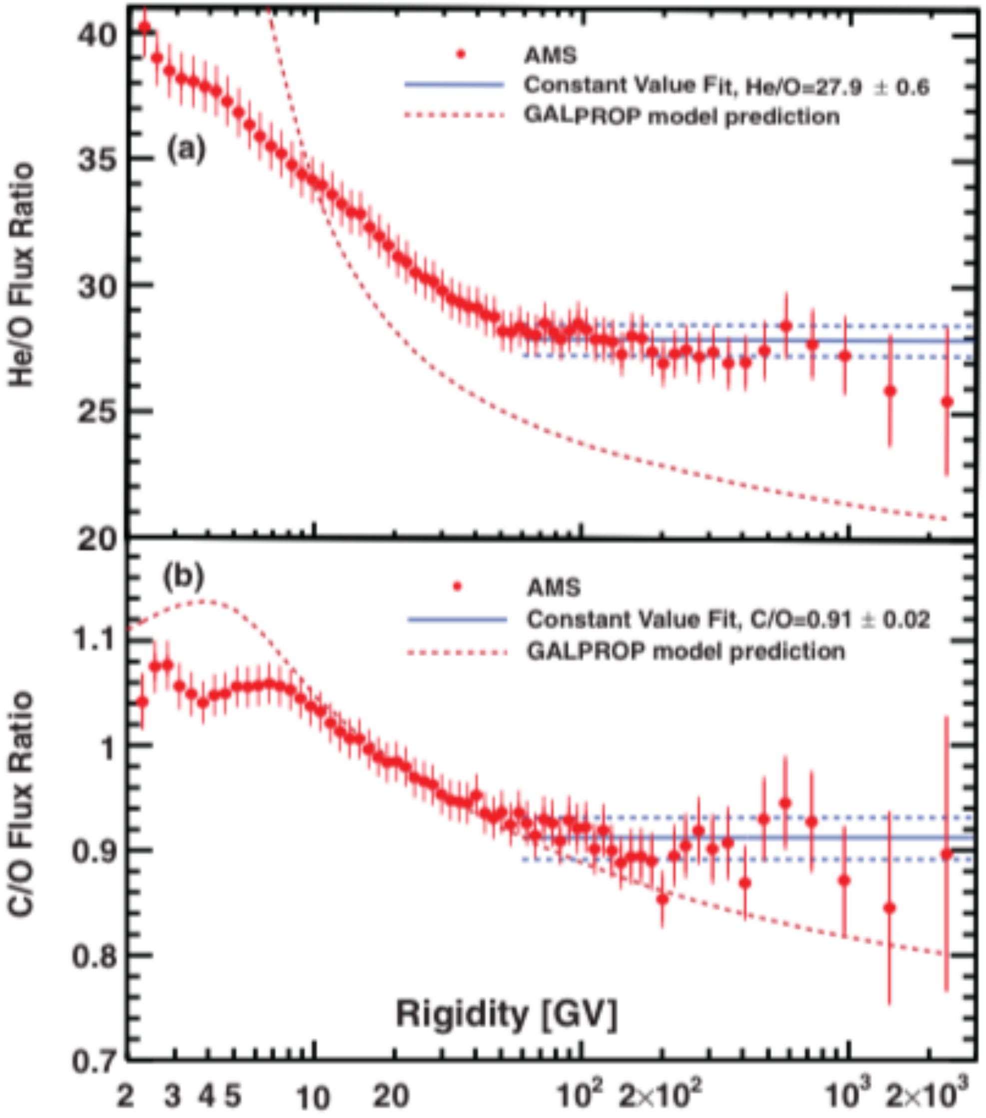
AMS Collab, Phys. Rev. Lett. **119**, 251101 (2017)



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

Carbon and Oxygen

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



Precise measurement of primary/primary ratios :

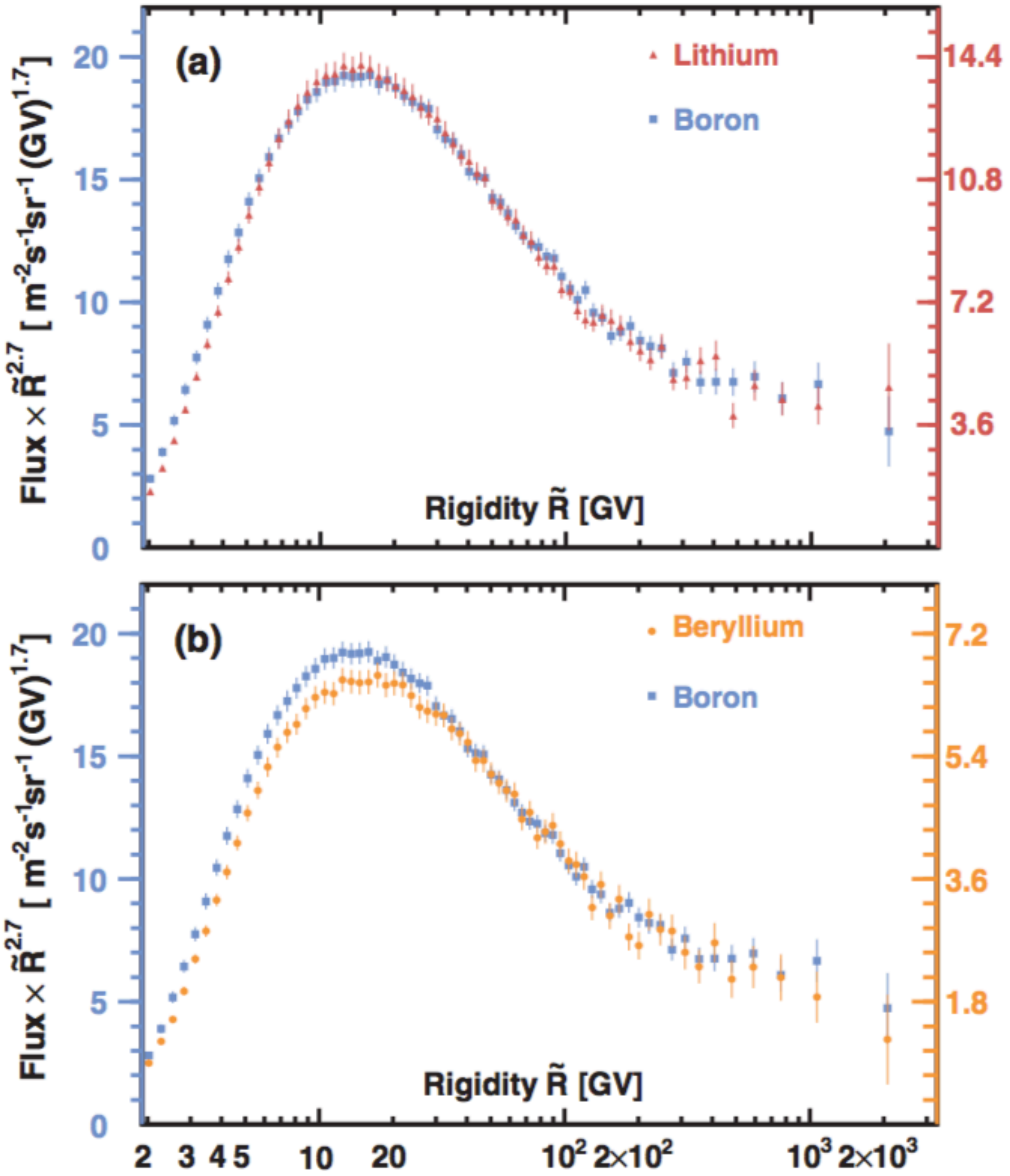
Universality of primary fluxes ?

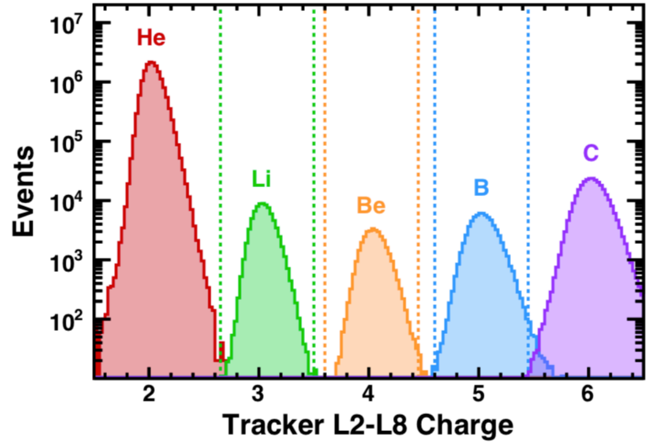
- < ~30 G : Rise linked to the A-dependence of absorption cross-sections
- > 30 GV: expected contribution from secondary component for C and He (computed here in GALPROP, similar results with USINE) but flat measured ratio.

→ Beyond universality of source spectra?

Li, Be, B

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





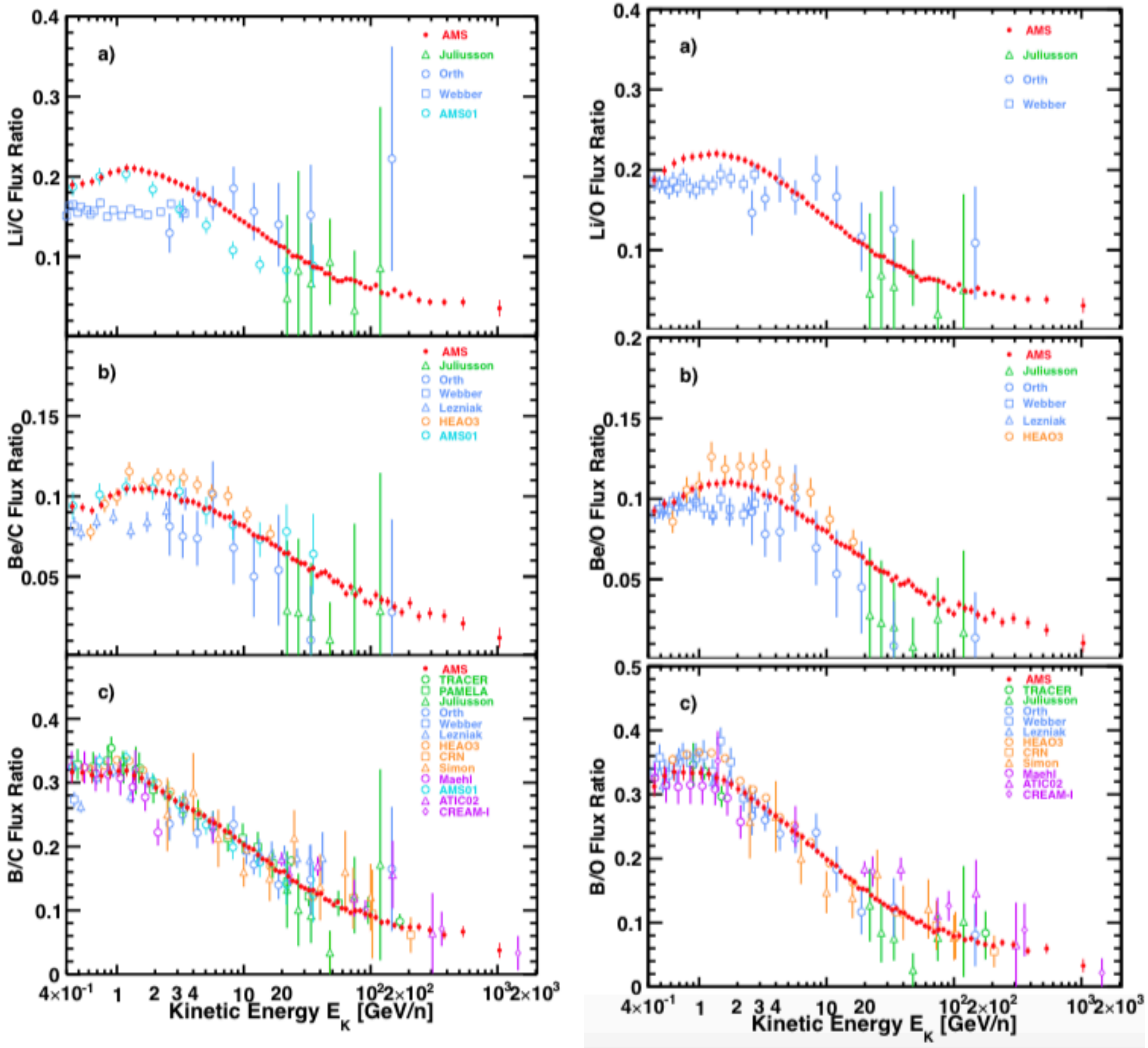
- Li, Be, B produced by spallation processes.
- Sensitive to CR propagation parameters (diffusion, convection, reacceleration…).
- > 20 GV, identical rigidity dependence.
- Low energy < 20 GV, sensitive to radioactive decay:

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

Li, Be, B

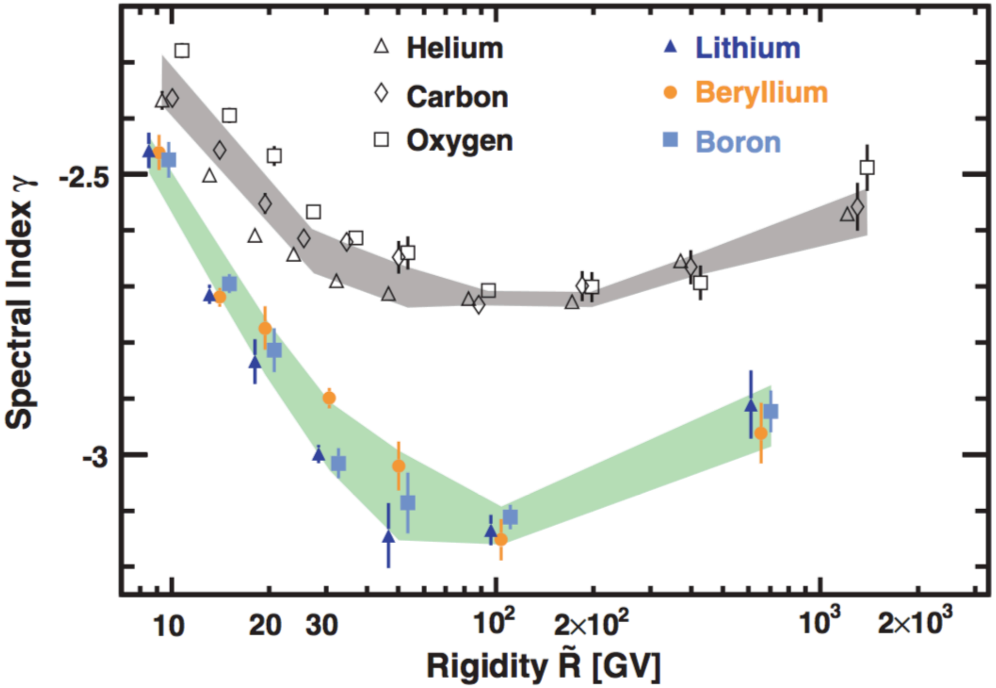
→ Secondary/ primary Ratios

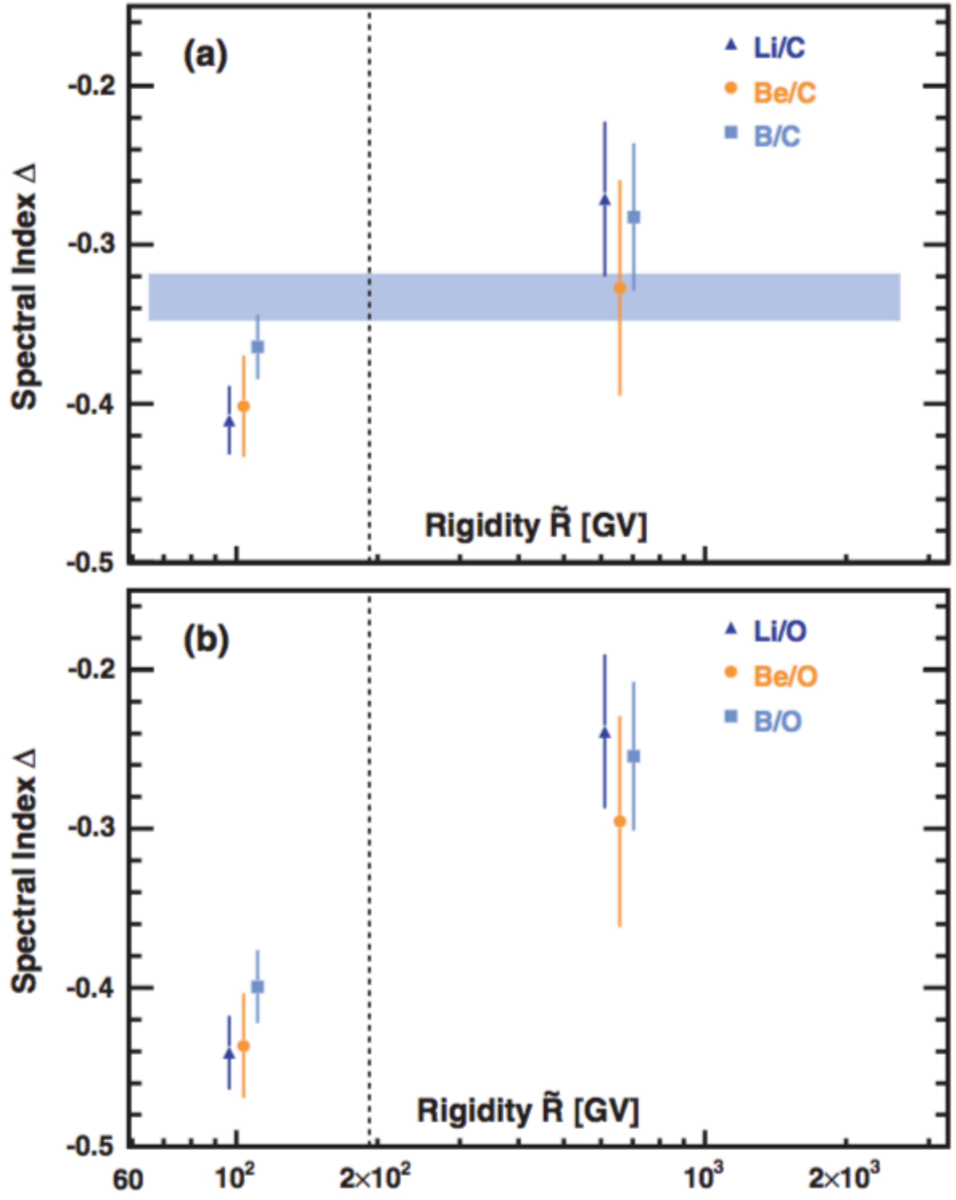
AMS Collab.,Phys. Rev. Lett. **120**, 021101 (2018)



Data can be extracted from CRDB database [lpsc.in2p3.fr/cosmic-rays-db/]
+ UHECR to be included soon

Li, Be, B vs C, O



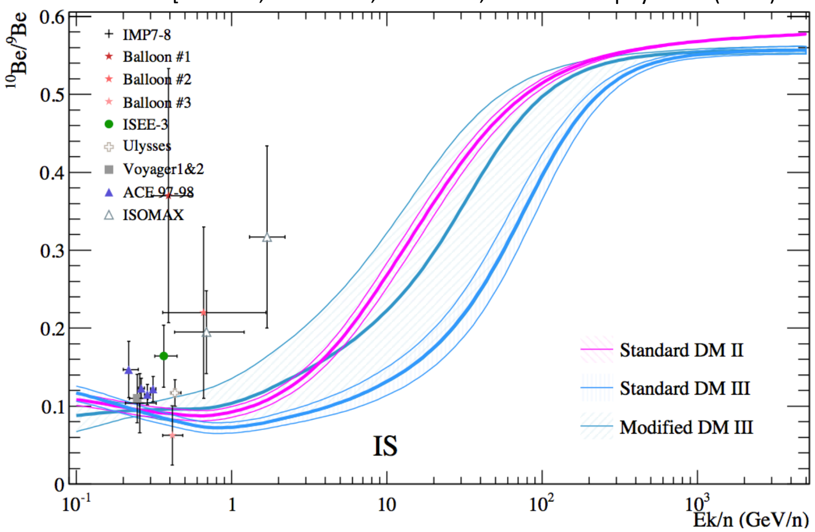


→ Indications for a High-Rigidity Break in the Cosmic-Ray Diffusion Coefficient, Y. Genolini et al, PRL **119**, 241101 (2017)

Isotopic Composition

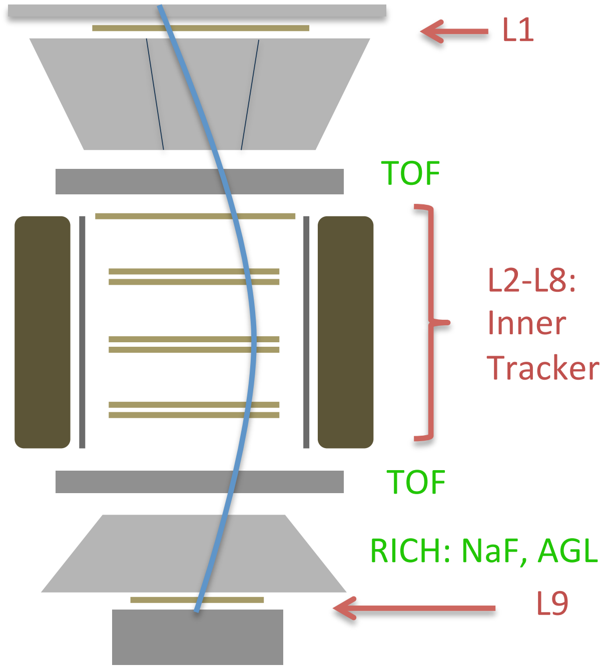
- Key CR observables but few measurements:

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

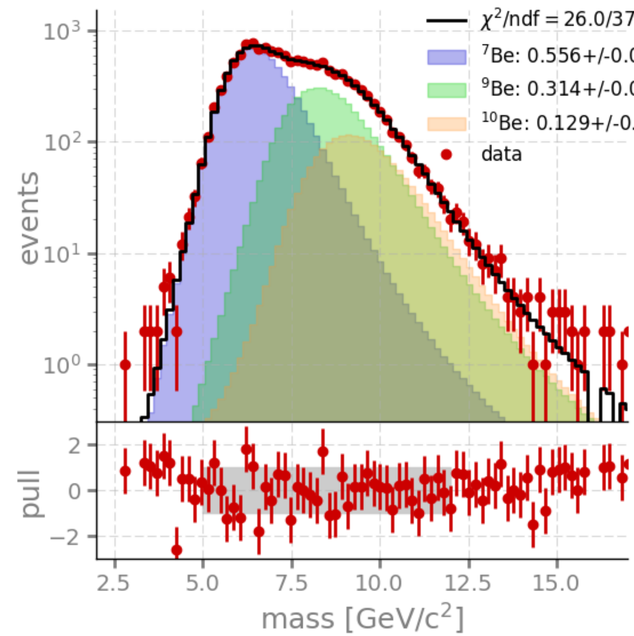


- Quartet (^{1}H, ^{2}H, ^{3}He, ^{4}He) from PAMELA at low energy [PAMELA Coll. Astrophysical Journal, 818 (2016) 68]
- Ongoing analyses of AMS data:
  ^{3}He:^{4}He, ^{6}Li:^{7}Li, ^{10}Be:^{9}Be:^{7}Be

- Balloon HELIX project dedicated to isotopic measurement in the range 1-10 GeV/n



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



Propagation du rayonnement cosmique

Large ensemble de donnés → changement de paradigme :

- Avant AMS : Contraintes sur les modèles de propagation ajustées sur des données dominées par le seul rapport B/C avec des erreurs de l'ordre de 10%
- Mesures récentes :
  - précision de l'ordre du %, description détaillée des systématiques
  - large gamme d'énergie du GeV au TeV
  - Large ensemble de noyaux : Li, Be, B, C et O (N en préparation)
  - Flux et rapports
- Sensibilité très forte à certains paramètres du modèle :
  - Section efficaces nucléaires d'absorption et de production (Point critique !)
  - Paramètres des sources
  - Description de la diffusion (basse énergie, 2 zones, brisure à haute énergie)

→ Nouvelles méthodologies pour implémenter l'ensemble des incertitudes

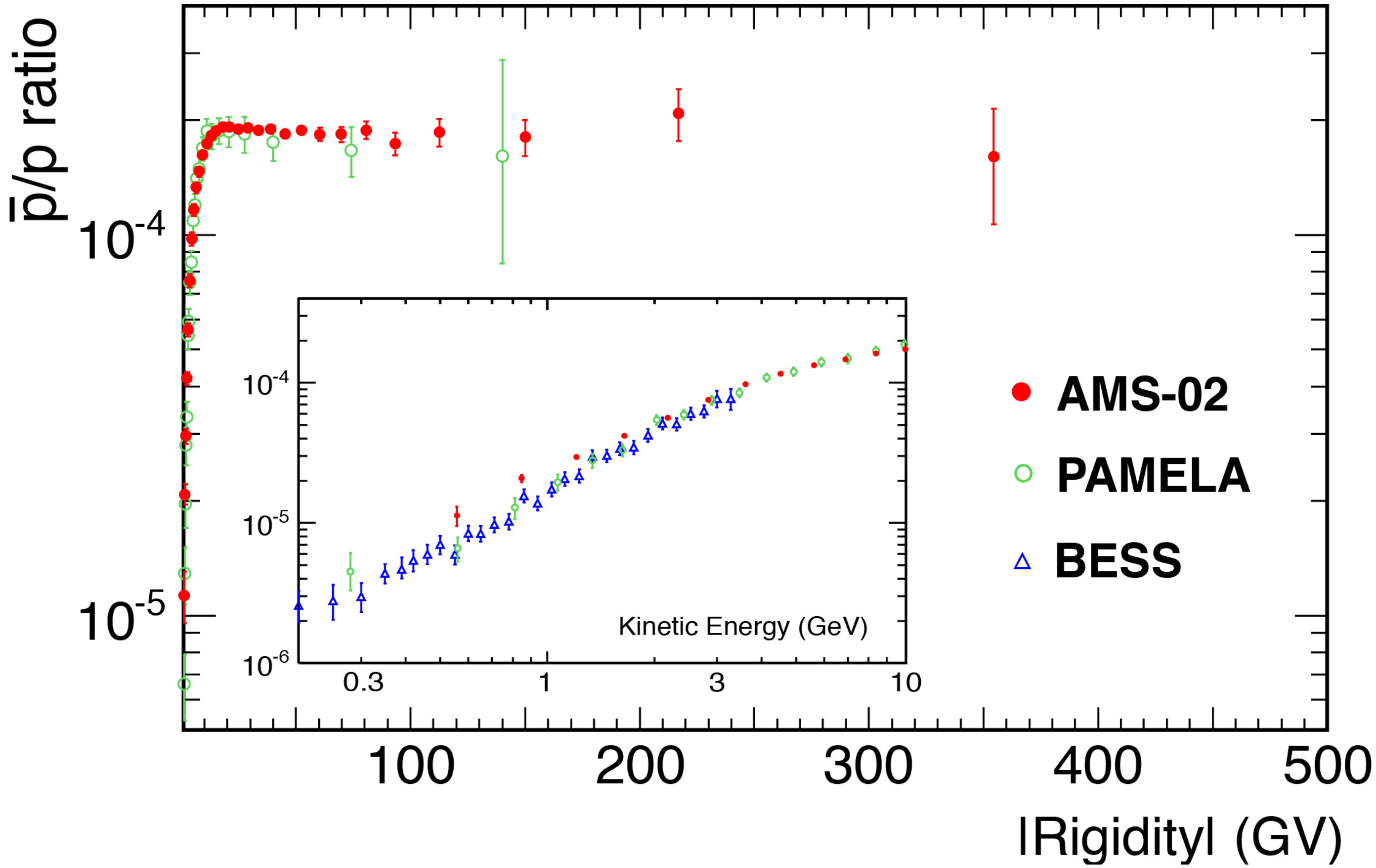
→ Besoin de nouvelles mesures de section efficaces (voir Y. Génolini et al.)

→ En France, activité structurée autour d'une collaboration LAPP, LAPTh, LPSC, LUPM, (projet CR&MN porté par D. Maurin et soutenu par IN2P3)

Antiproton/Proton

Measurement by AMS of the antiproton flux and the antiproton-to-proton flux ratio from 1 to 450 GV based on 3.5×10^5 antiprotons

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



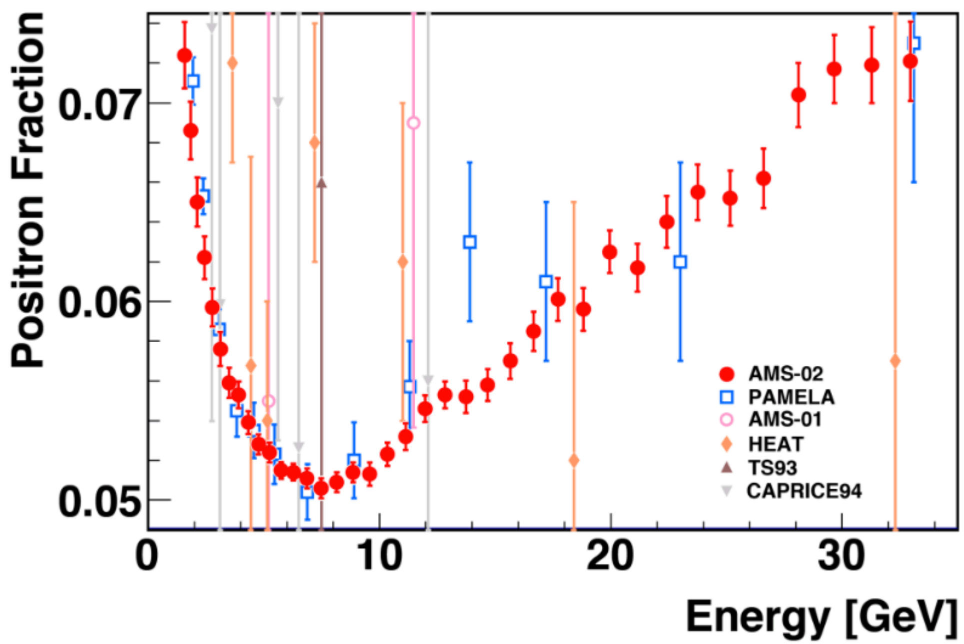
→ Flat Antiproton/proton ratio at high energy in tension with pure secondary component in standard propagation model

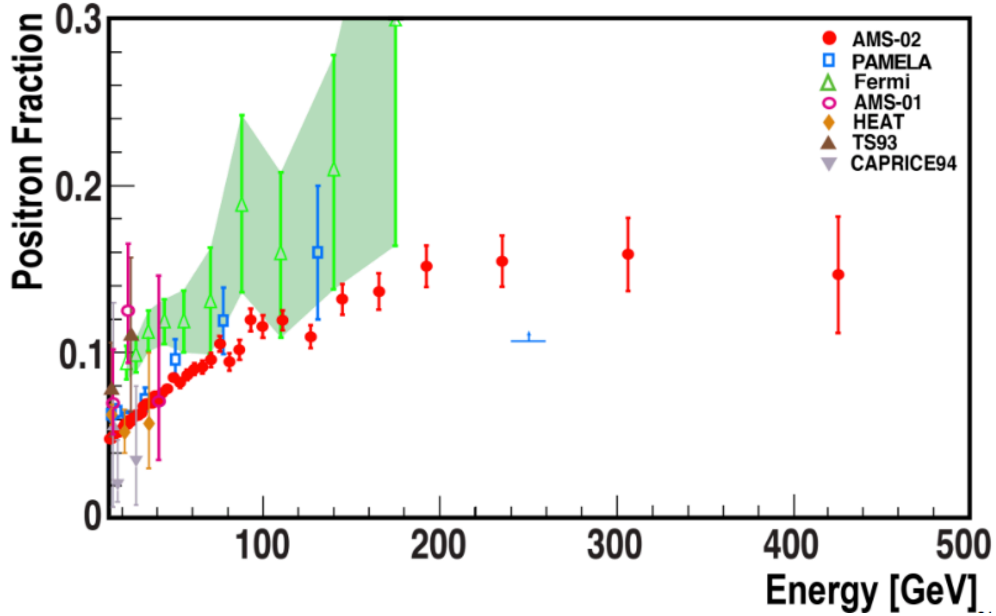
Positron Fraction

- 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:
  - reaches its minimum at 8 GeV,
  - steadily increases from 10 to ~250 GeV, no fine structures.
  - At 275±32 GeV the fraction reaches its max.

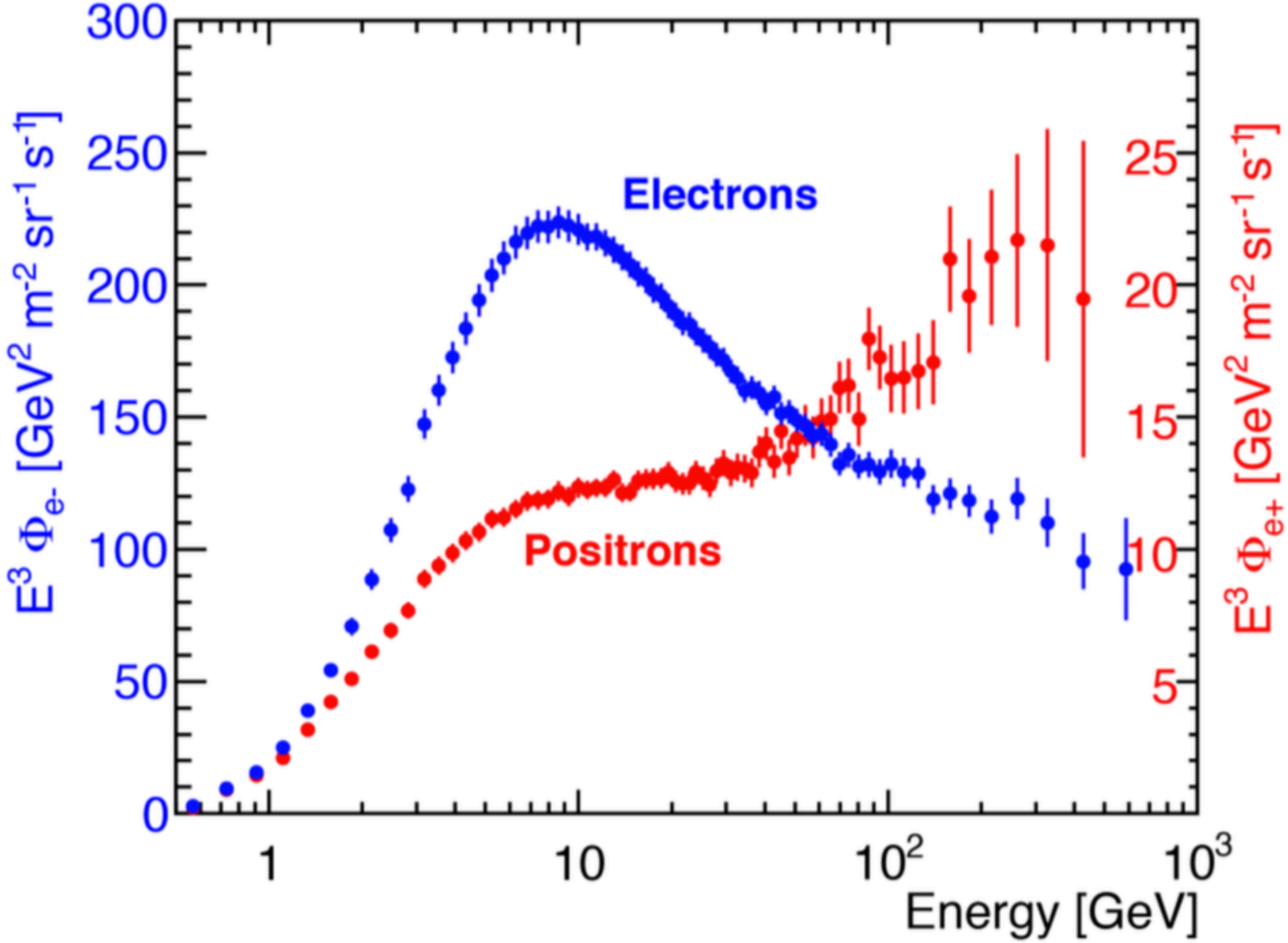
[AMS Collab. Phys. Rev. Lett. 113 (2014)]





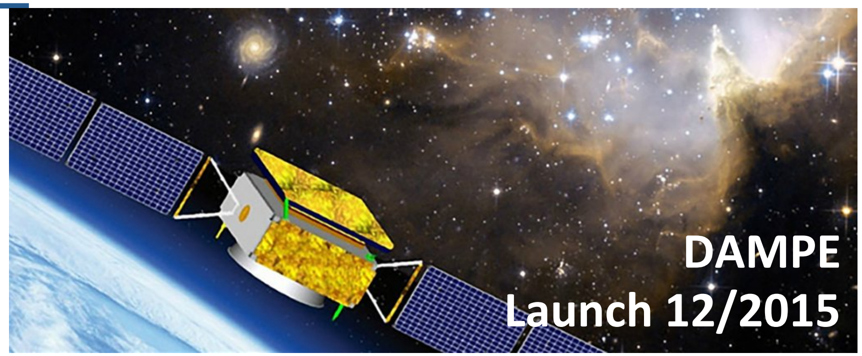
Electron and Positron Fluxes from AMS

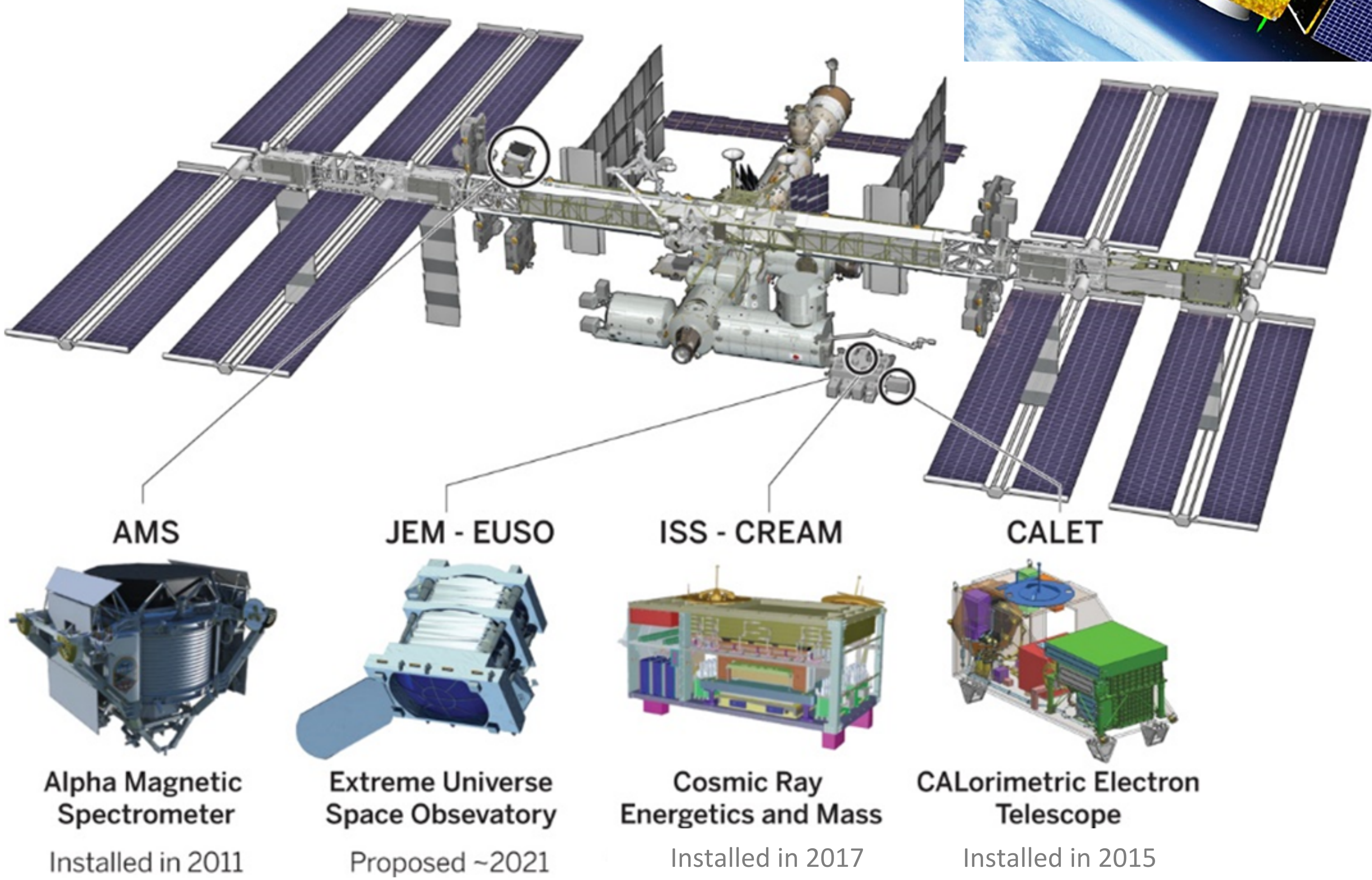
[AMS Collab. Phys. Rev. Lett. 113 (2014)]



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

CALET – DAMPE - ISSCREAM



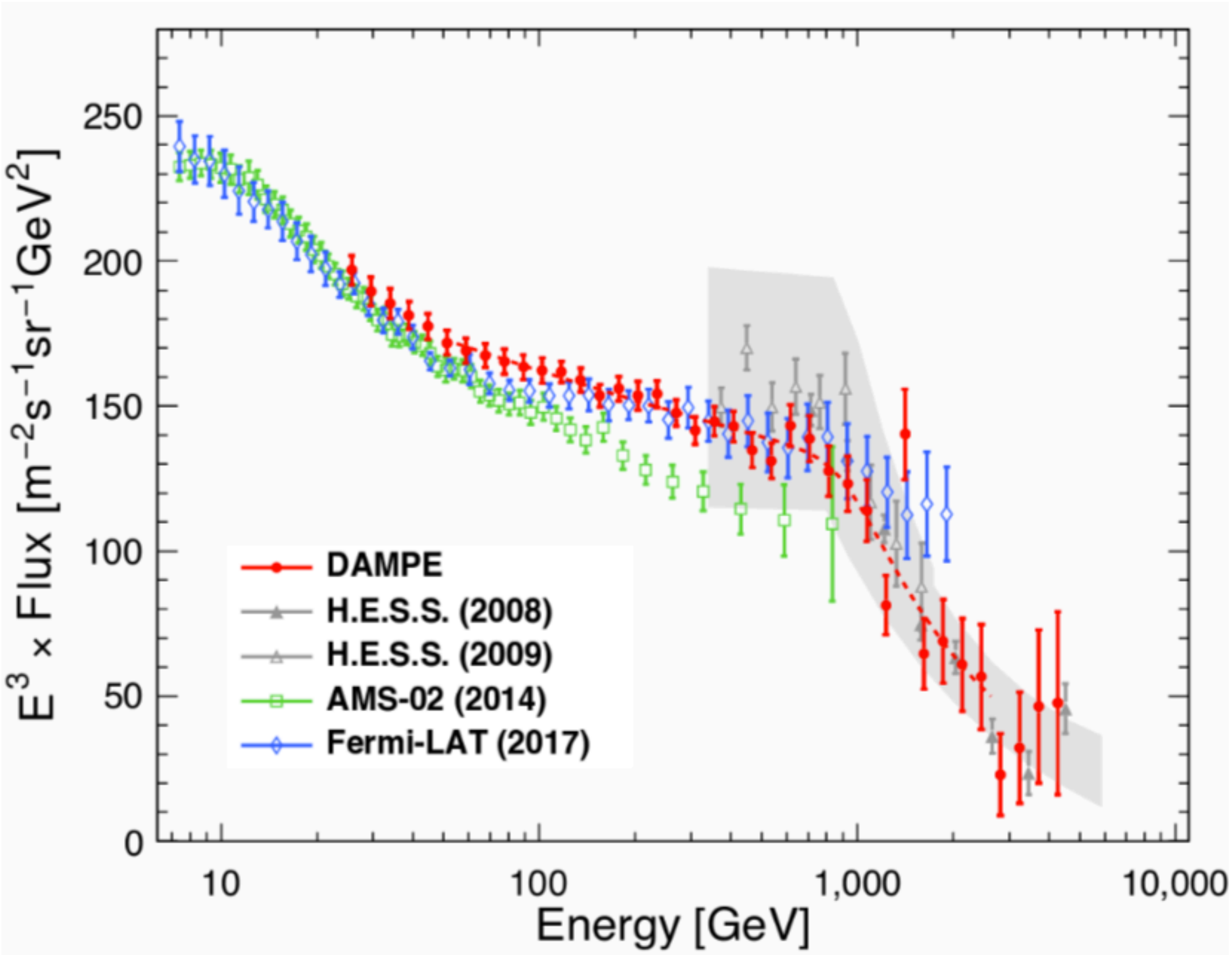


Comparison of Detector Performances for e^++e^-

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)

Dampe $e^{+}+e^{-}$

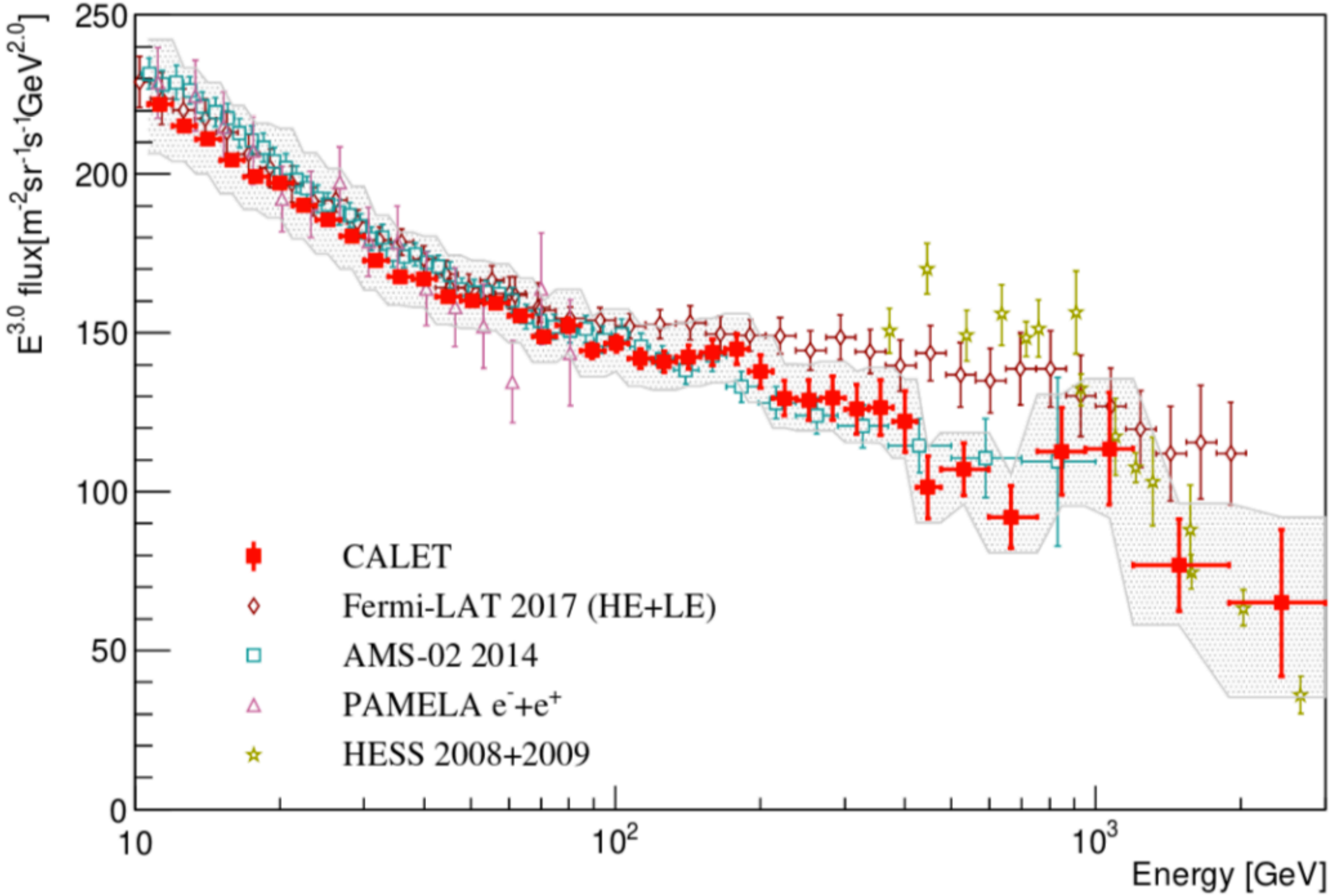
[DAMPE Collab., *Nature* **552**, (2017)]



CALET $e^+ + e^-$

CALET flux released one day after DAMPE

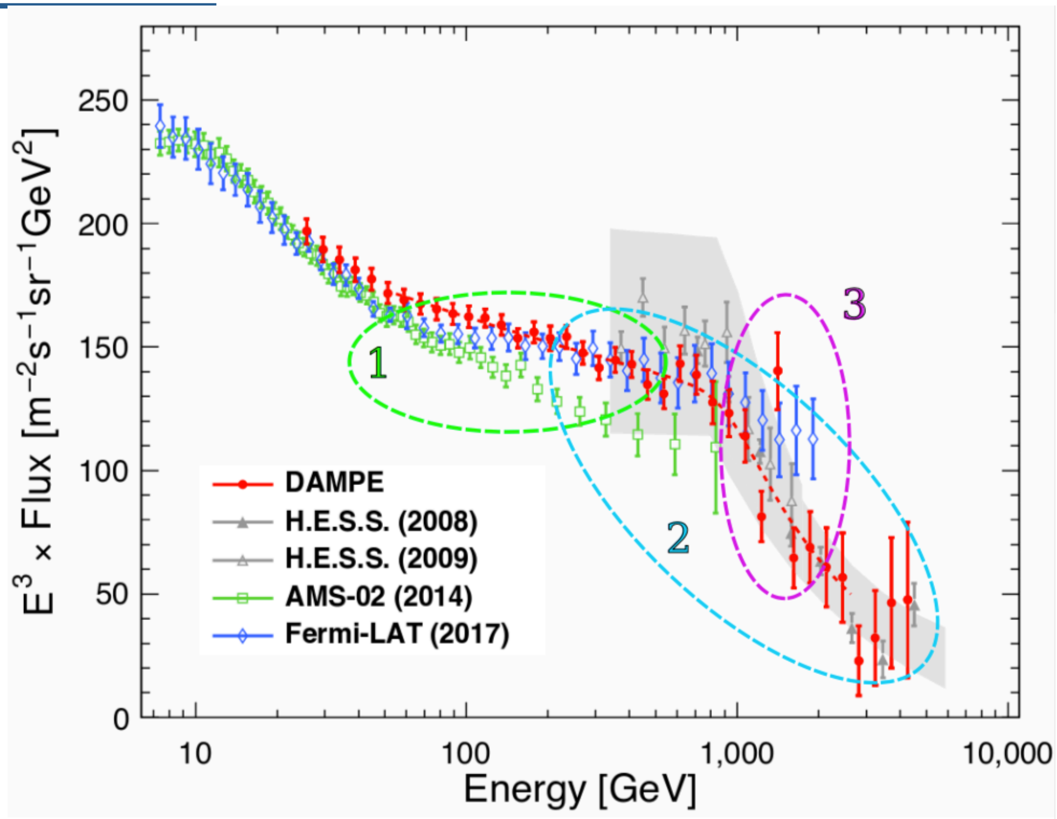
[CALET Collab., PRL. 119 (2017)]



Features in Dampe Flux (From Y. Génolini Moriond talk)

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.



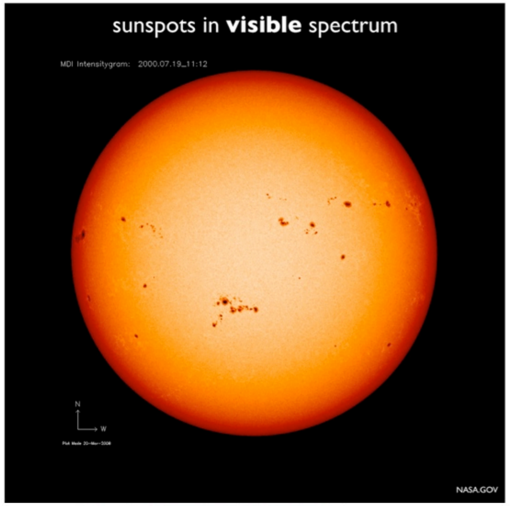
3- « Dampe Peak »

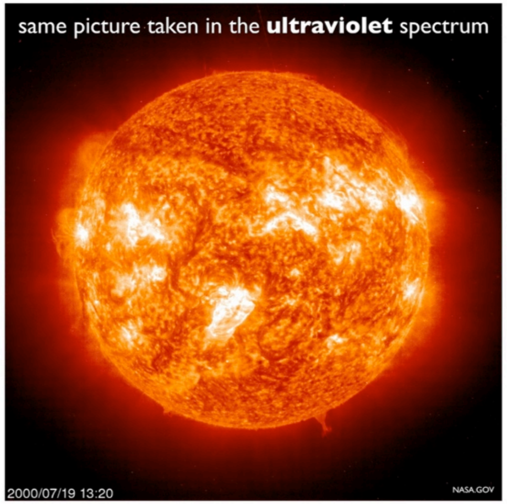
- Low significance
- "Exotic" (DM) or "Astrophysical" (Pulsar) explanations imply fine-tuned physics which can only be probed by a multimessenger approach.

Cosmic ray modulation

- At low Energy (<20GV) 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:

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



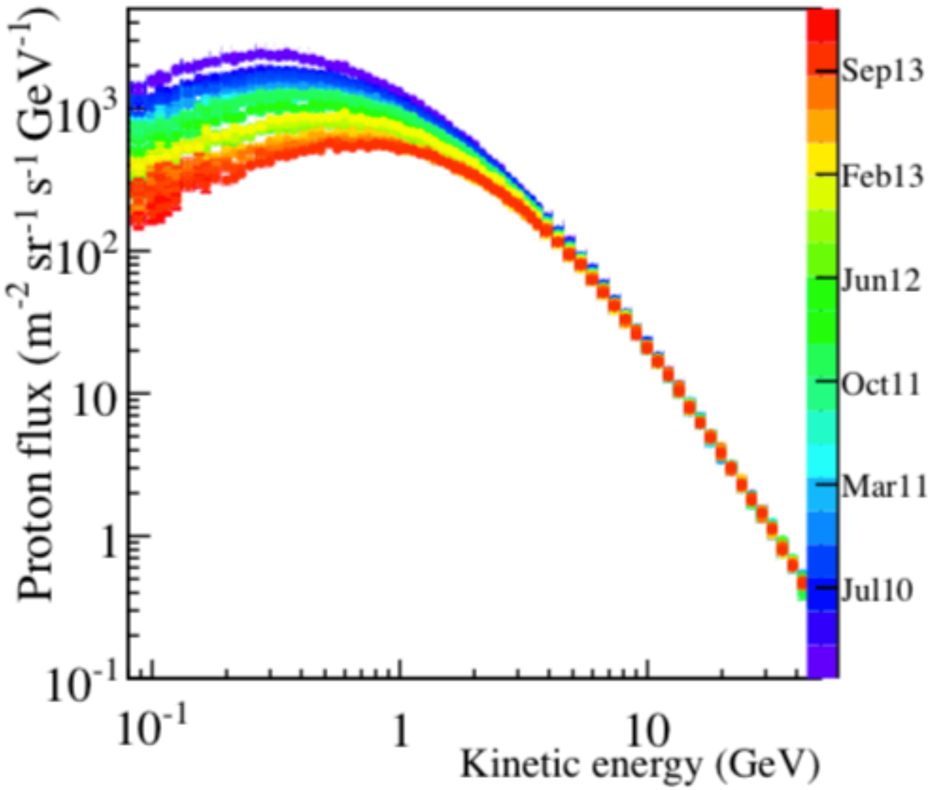


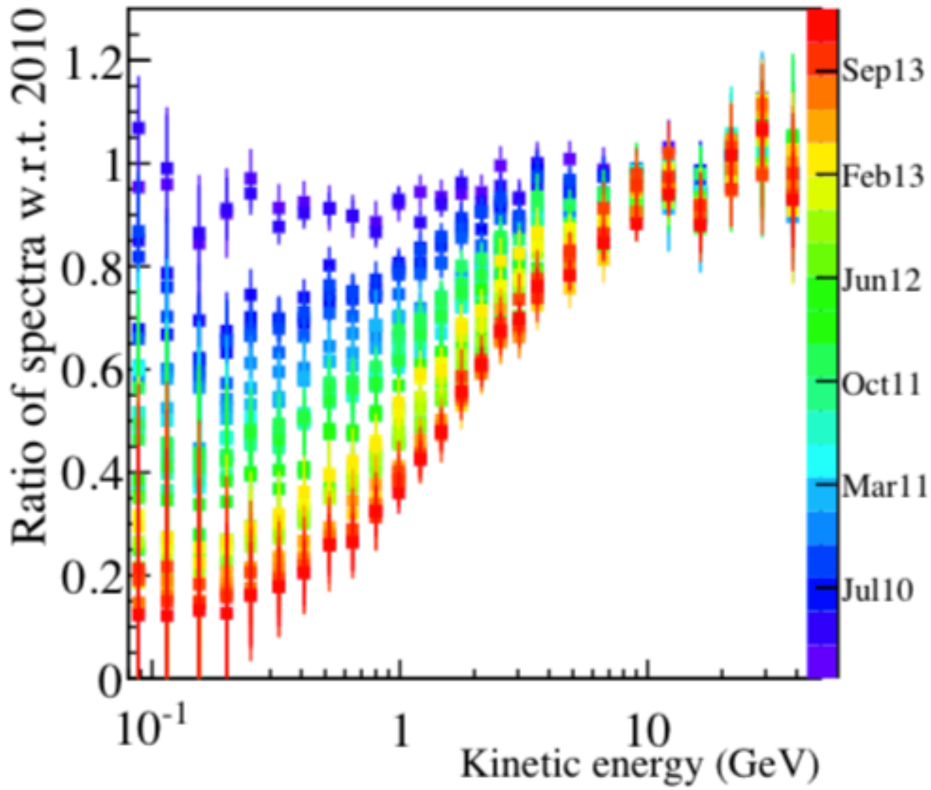
→ Precise measurement of the different components of CR over long period of time with the same detector needed to understand the solar modulation process.

Time dependence of the proton flux

Monthly proton flux from PAMELA:

[PAMELA Collaboration, APJ Letter 854 (2018)]

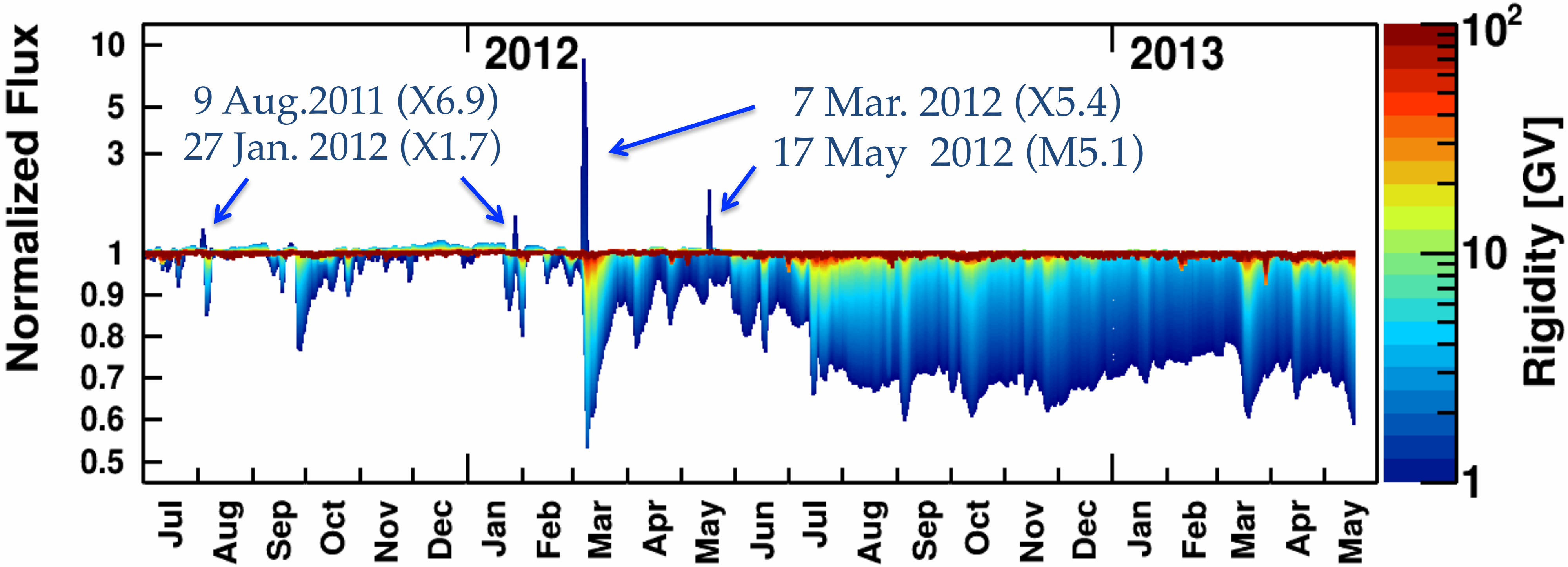




AMS02 - Daily normalized flux

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

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



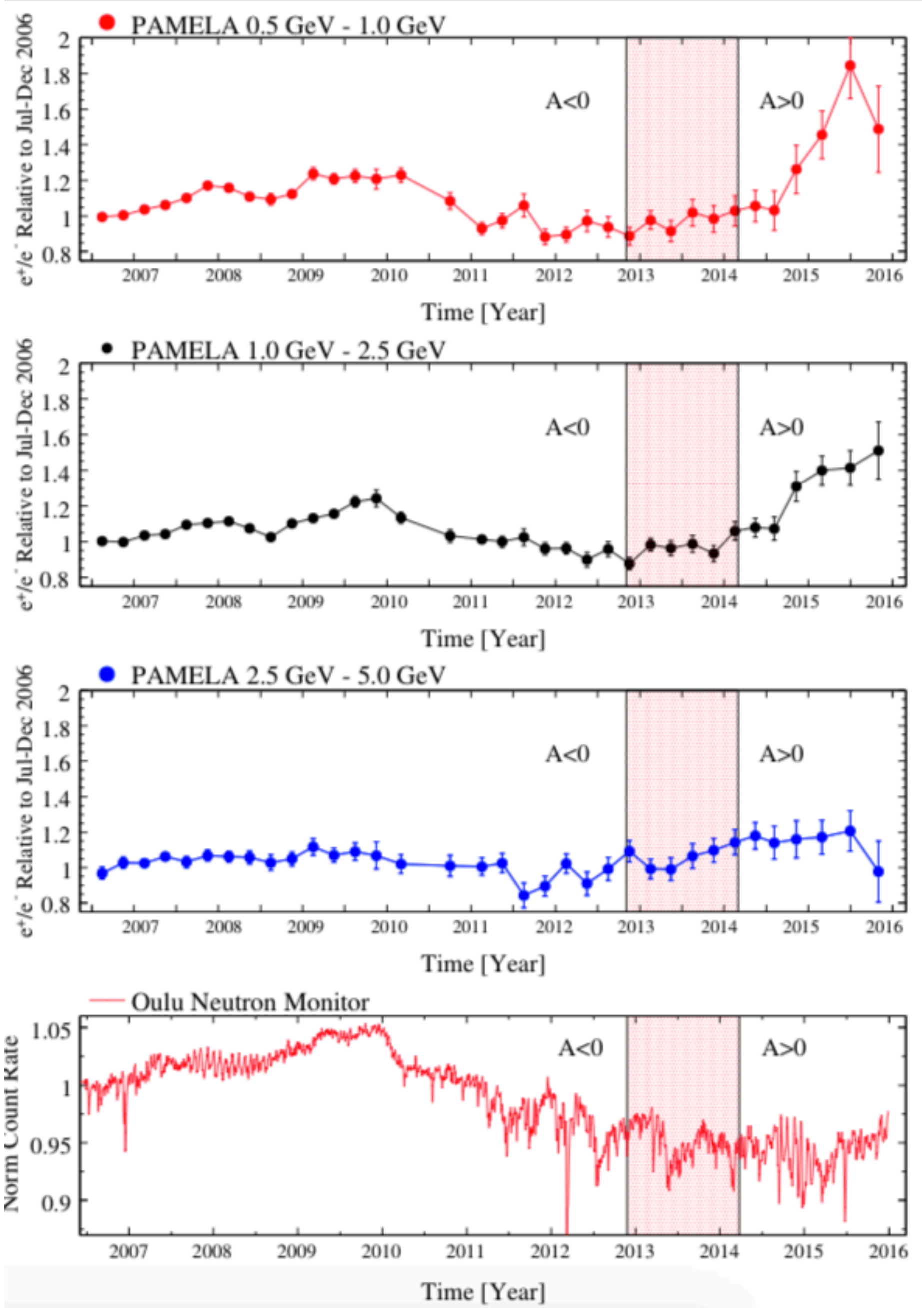
→ p, He time dependence AMS paper submitted

Sign-charge dependence

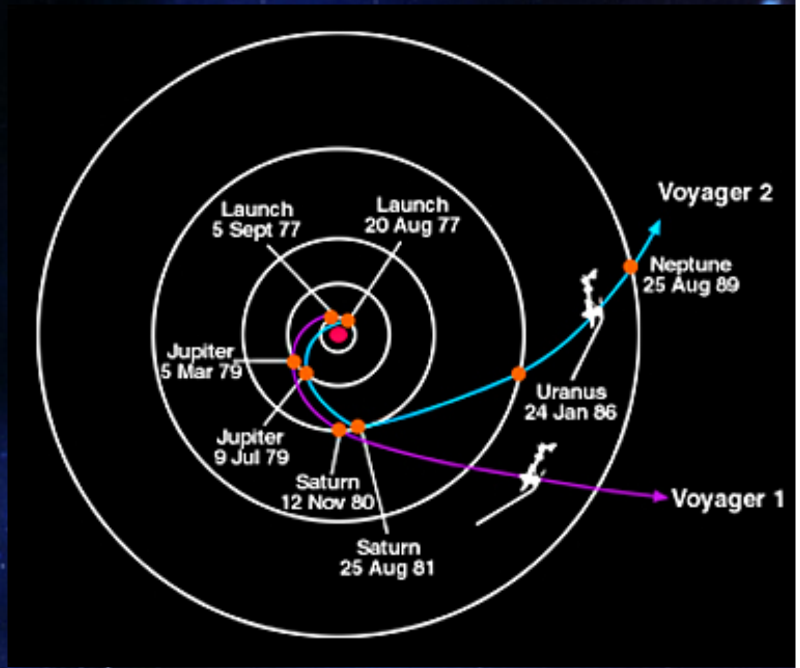
[PAMELA Collab., PRL 116, 241105 (2016)]

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

- Precise measurement for e^+ and e^- during solar magnetic reversal AMS paper submitted.



Voyager



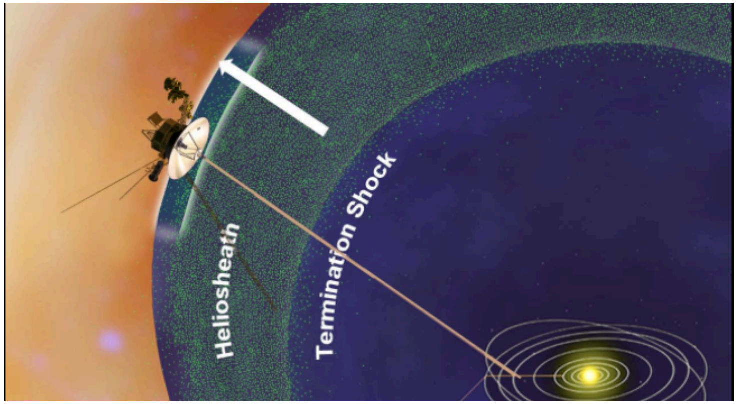
- Voyager 1&2 launched in 1977
- **Used the gravity slingshot method to catapult itself to the furthest planets and eventually beyond the Heliosphere.**
- Payloads still active…**cosmic ray telescopes (CRS) measure the Low energy CR intensity for almost 40 years.**

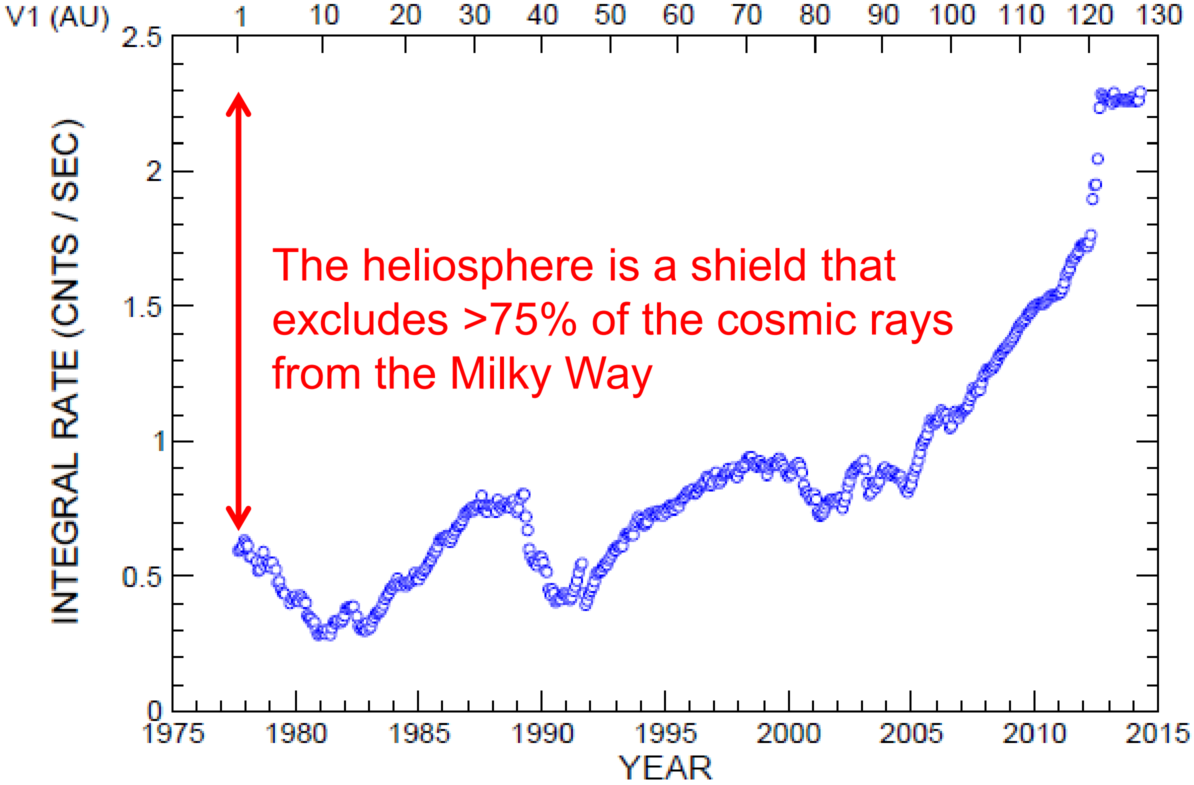
Voyager 1

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.

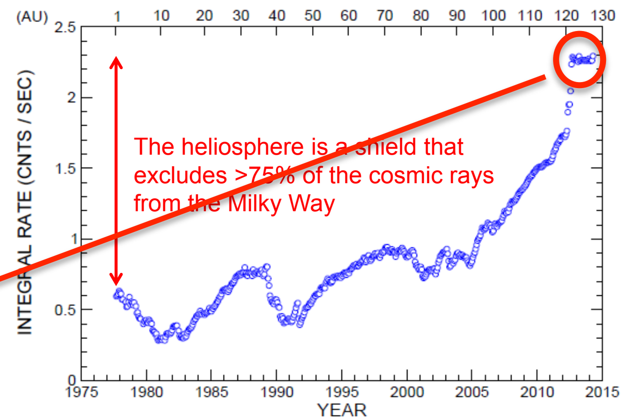


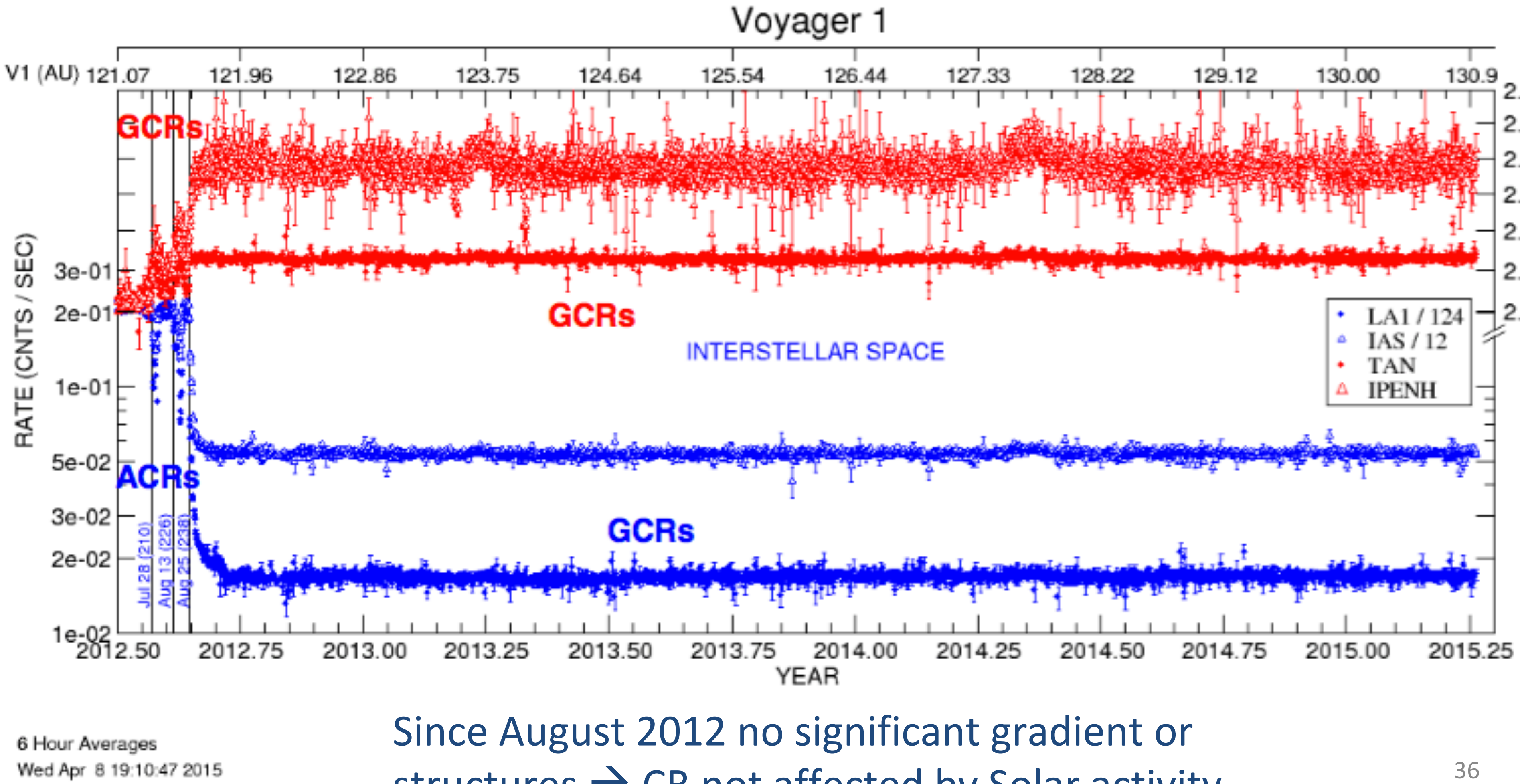


CRS

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

Voyager 1

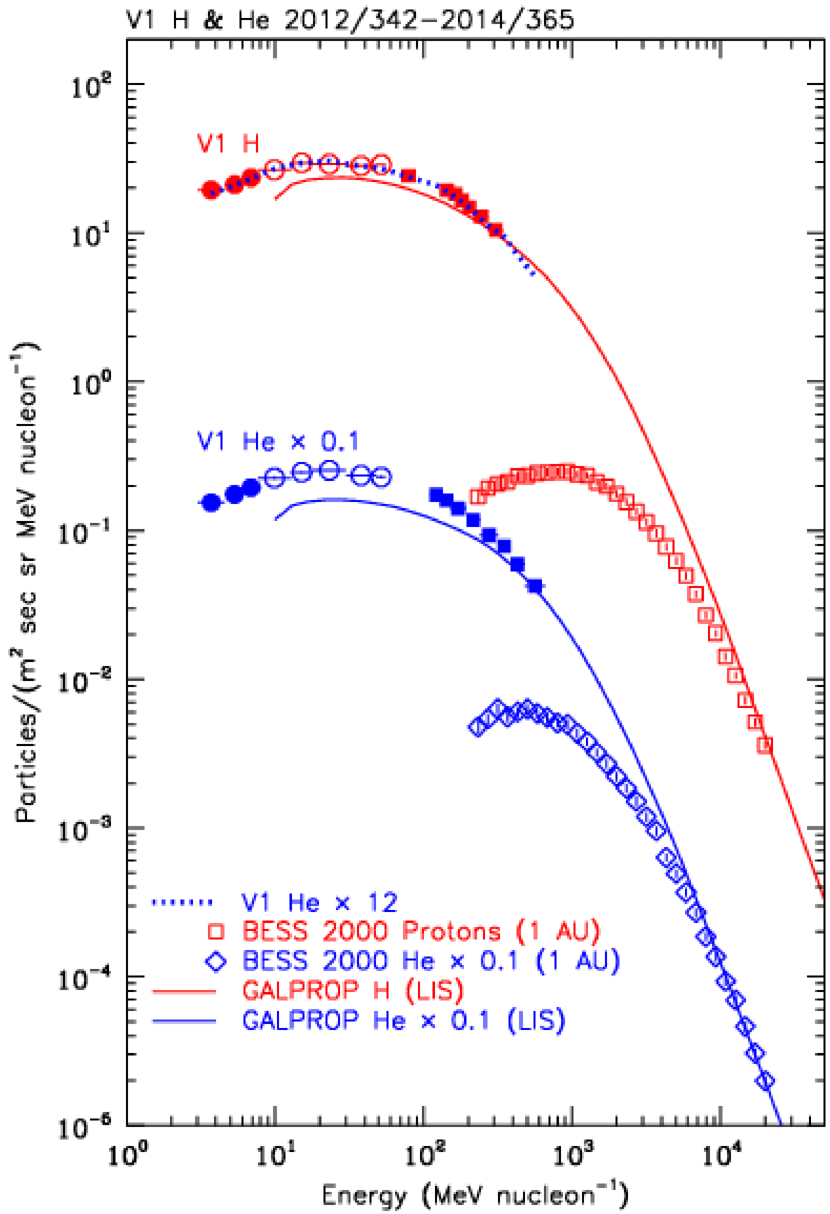




Since August 2012 no significant gradient or structures → CR not affected by Solar activity….

Voyager 1

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



Conclusions

- Du coté expérimental:
  - Nombreuses expériences en cours de prise de données. FERMI, AMS02, CALET, DAMPE, ISS-CREAM
  - Pas/peu de nouveaux projets expérimentaux pour la prochaine décennie
  - Réflexions pour des projets au delà mais reste très exploratoire (niveau de maturité faible)
- De très nombreux résultats ces dernières années et encore des résultats à venir:

  → Large ensemble de données avec une précision inégalée.

  Mesure des flux d'H, He, Li, Be, B, C, N, O et des rapports

  \+ Noyaux plus lourds (résultats à venir)

  \+ Isotopes (résultats à venir)

  \+ Dépendance en temps des différentes composantes du RC

  → L'exploitation de l'ensemble de ces données dans le cadre des modèles de propagation est un défit important. Fort potentiel en France autour du LAPTh, LAPP, LPSC, LUPM

GCR propagation

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 and O (N from AMS02 in preparation)
- Fluxes and ratios

→ Paradigm shift:

- Strong sensitivity to many parameters of the model:
  - Nuclear absorption and production cross-sections
  - Source settings
  - Description of the diffusion (low energy, 2 zones, high energy break)
- New methodologies to implement all uncertainties
- Need new cross section measurements (see Y. Genolini et al. Astro-ph: 1803.04686)
- In France, LAPP, LAPTh, LPSC, LUPM collaboration (CR & MN project supported by D. Maurin and supported by IN2P3)

Conclusions

- 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)

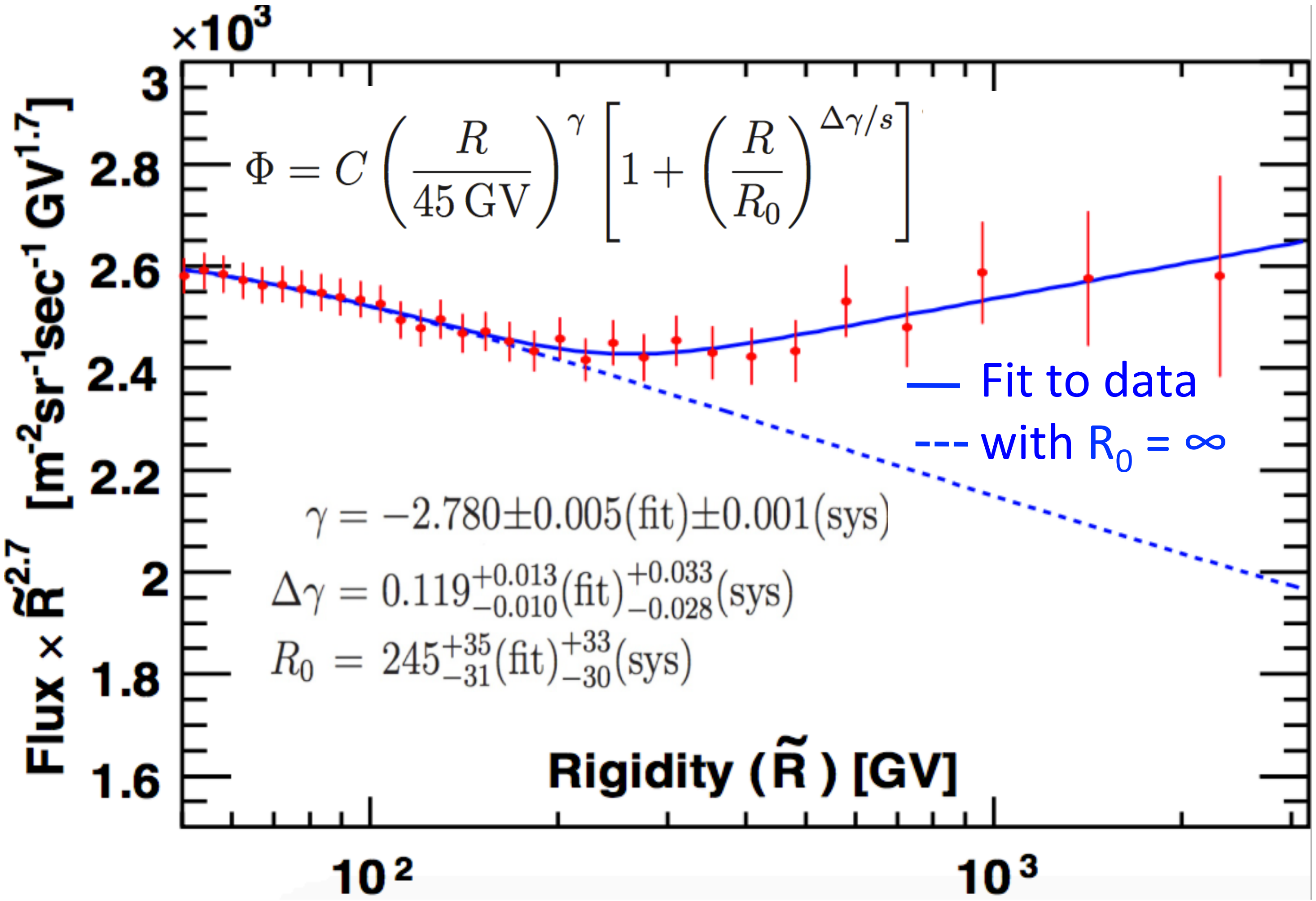
    + Time dependence of the different components of the RC

    + LE ISM p & He fluxes from Voyager

→ Interpretation of all these data in the context of propagation models is an important challenge. High potential in France around the LAPTh, LAPP, LPSC, LUPM collaboration.

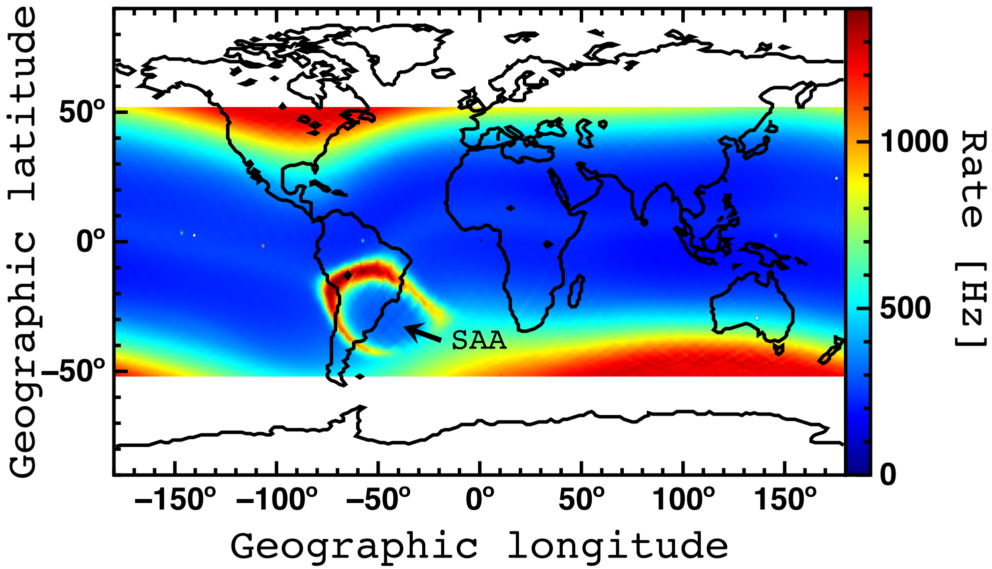
Helium flux measurement

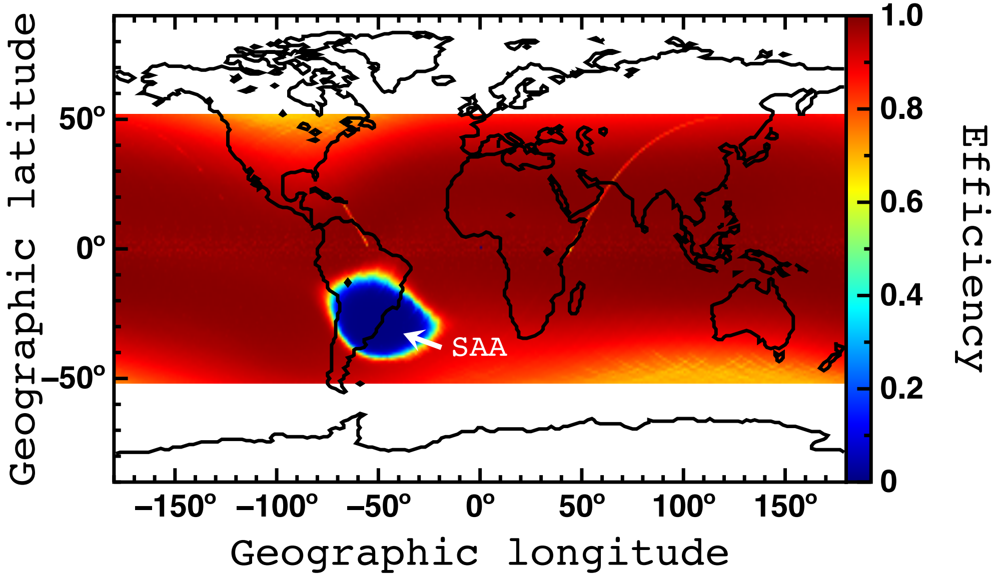
- Fit of the AMS flux with a double power model with smooth transition:



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

In flight operations

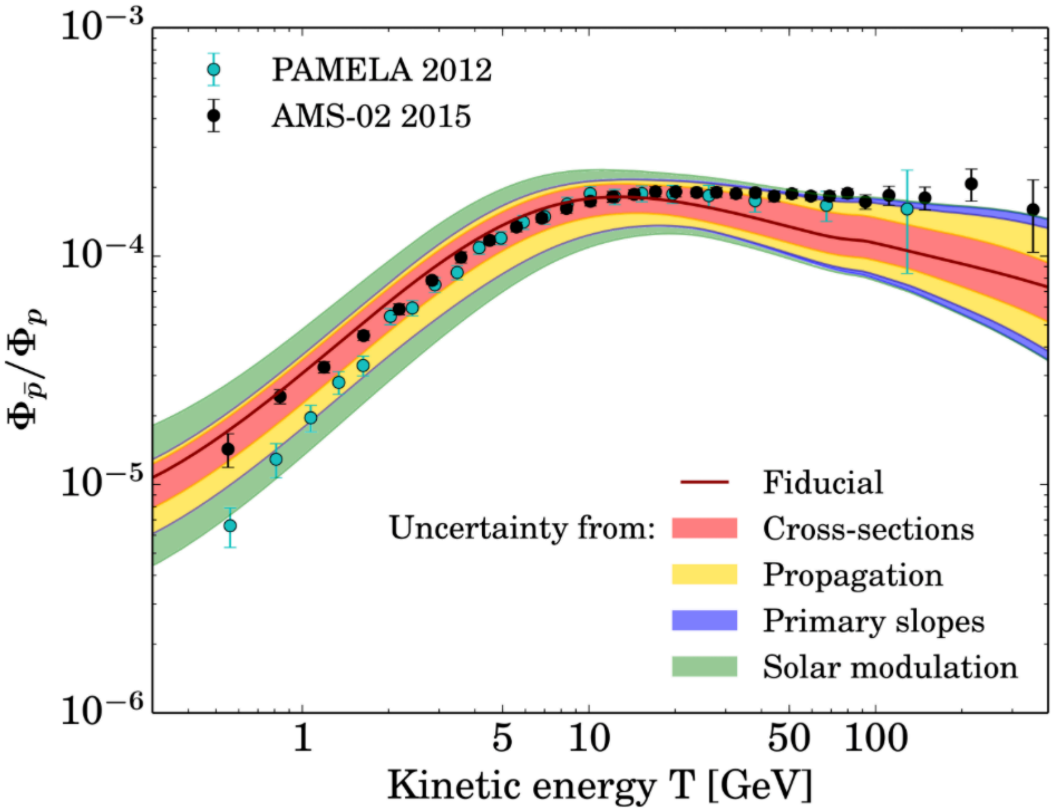




- AMS installed on ISS in May 2011
- Circular orbit, 400 km, 51.6°, 90 mn
- Continuous operation 24/7
- Average rate ~700 Hz
- 60 millions particles/day
- 39 TB raw data/yr
- 200 TB rec. data/yr
- More than 100 milliards of events collected so far

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

Propagation du rayonnement cosmique

Large ensemble de donnés → changement de paradigme :

- Avant AMS : Contraintes sur les modèles de propagation ajustées sur des données dominées par le seul rapport B/C avec des erreurs de l'ordre de 10%
- Mesures récentes :
  - précision de l'ordre du %, description détaillée des systématiques
  - large gamme d'énergie du GeV au TeV
  - Large ensemble de noyaux : Li, Be, B, C et O (N en préparation)
  - Flux et rapports
- Sensibilité très forte à certains paramètres du modèle :
  - Section efficaces nucléaires d'absorption et de production (Point critique !)
  - Paramètres des sources
  - Description de la diffusion (basse énergie, 2 zones, brisure à haute énergie)

→ Nouvelles méthodologies pour implémenter l'ensemble des incertitudes

→ Besoin de nouvelles mesures de section efficaces (voir Y. Génolini et al.)

→ En France, activité structurée autour d'une collaboration LAPP, LAPTh, LPSC, LUPM, (projet CR&MN porté par D. Maurin et soutenu par IN2P3)

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