Cosmic rays: direct measurements

ROBERTA SPARVOLI
ROME "TOR VERGATA" UNIVERSITY
AND INFN, ITALY

CRIS 2018 – Entering the era of Multi-Messenger Astronomy
Portopalo di Capo Passero (SR), 18-22 June 2018.

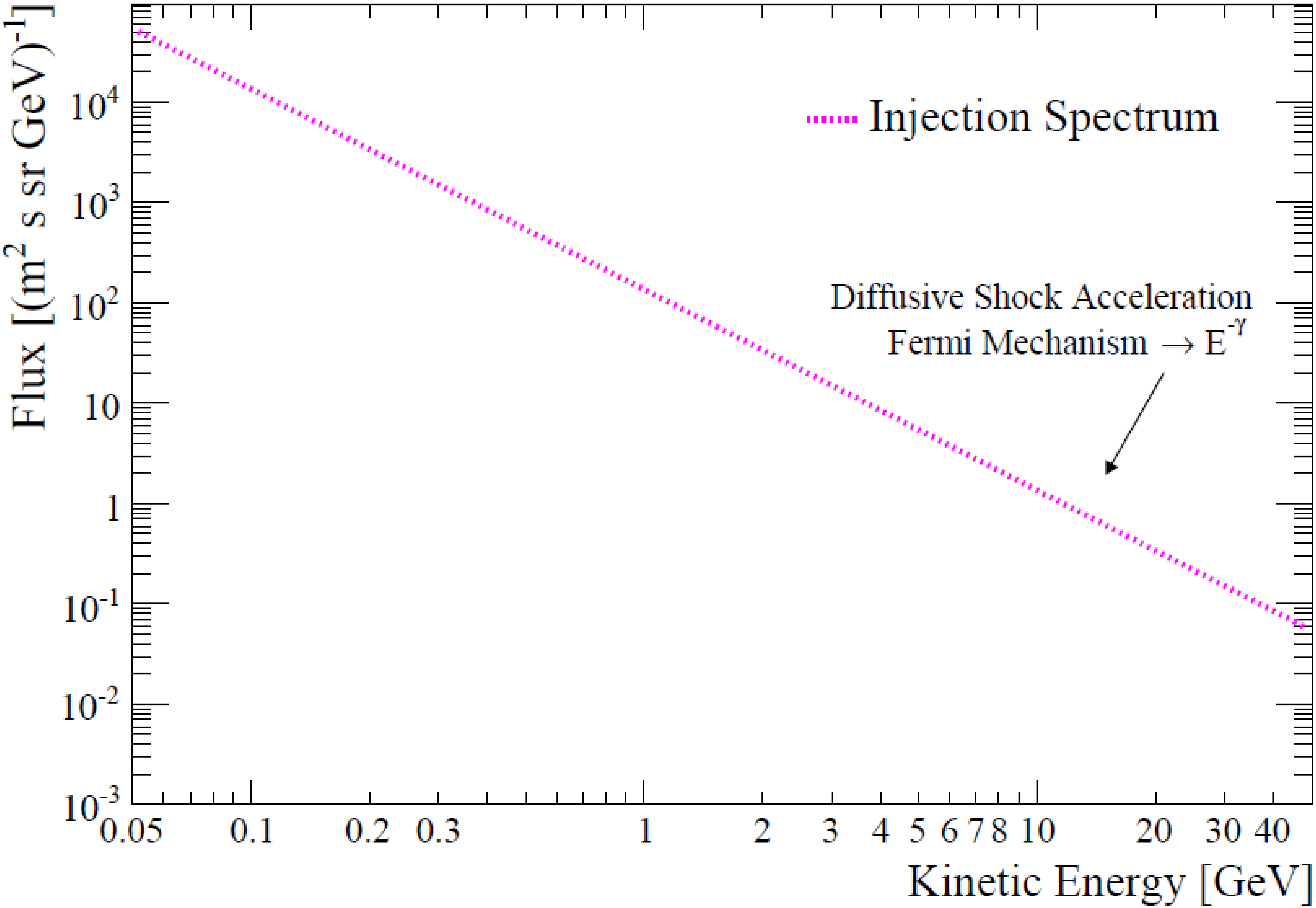
Galactic cosmic rays: open questions

- **What is the origin of Galactic cosmic rays (GCR)?**
  - Which are the possible astrophysical sources? Can they be detected individually?
  - What can we learn about the source properties from GCR elemental composition?
  - Does the GCR elemental composition change with energy?

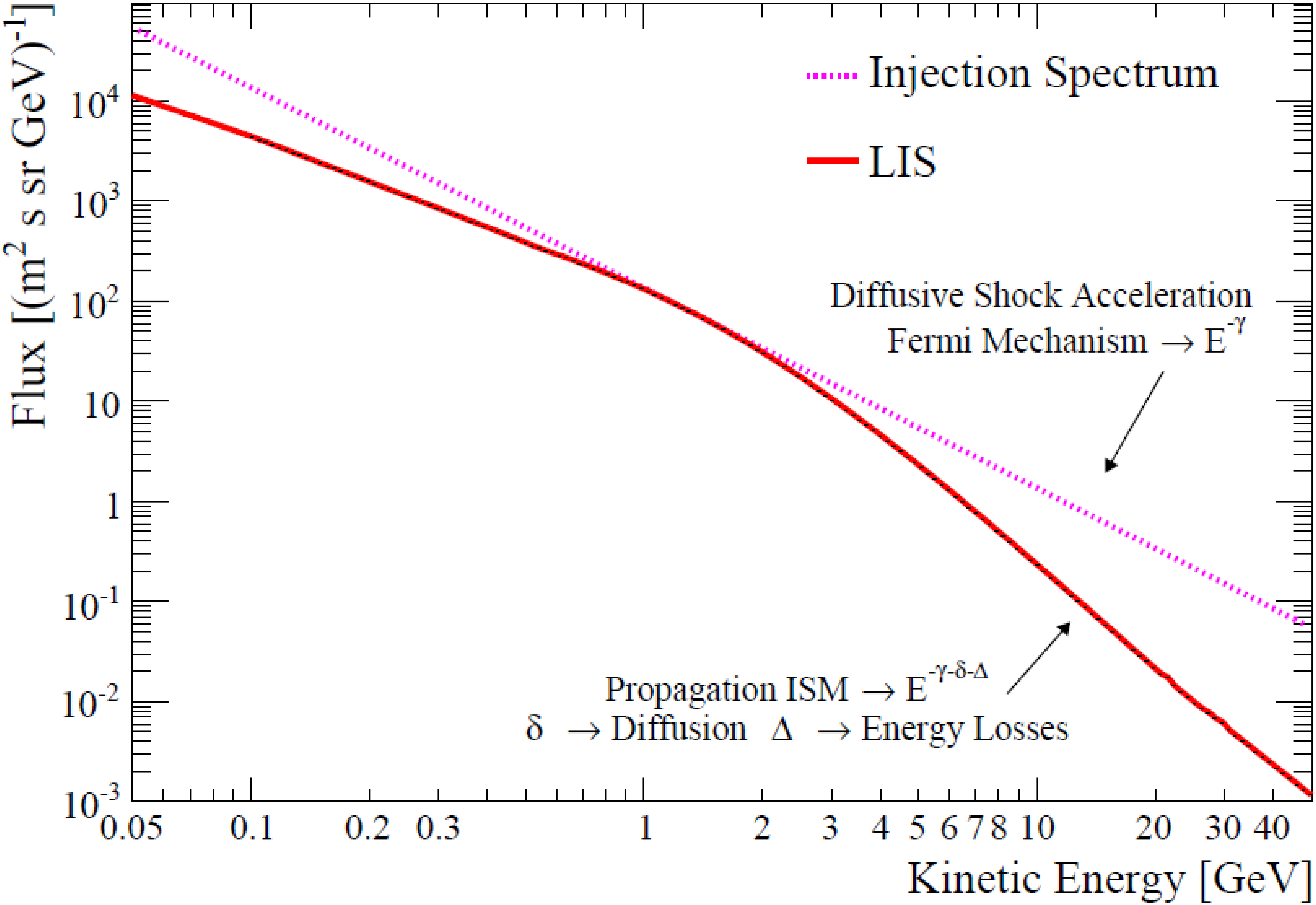
- **How do the Cosmic Accelerators work?**
  - Stochastic acceleration in strong shocks in SN remnants
  - Diffusive shock acceleration occurs in isolated SNR or inside superbubbles ("collective effects") ?
  - Is the "knee" due to a limit in SNR acceleration? Does it depend on the particle rigidity?
  - Are there different astrophysical sites associated with different energy/element regimes?

- **CRs propagation in the Galaxy**
  - What is the energy dependence of the confinment time of CR in the Galaxy?
  - Is there a residual path length at high energy?

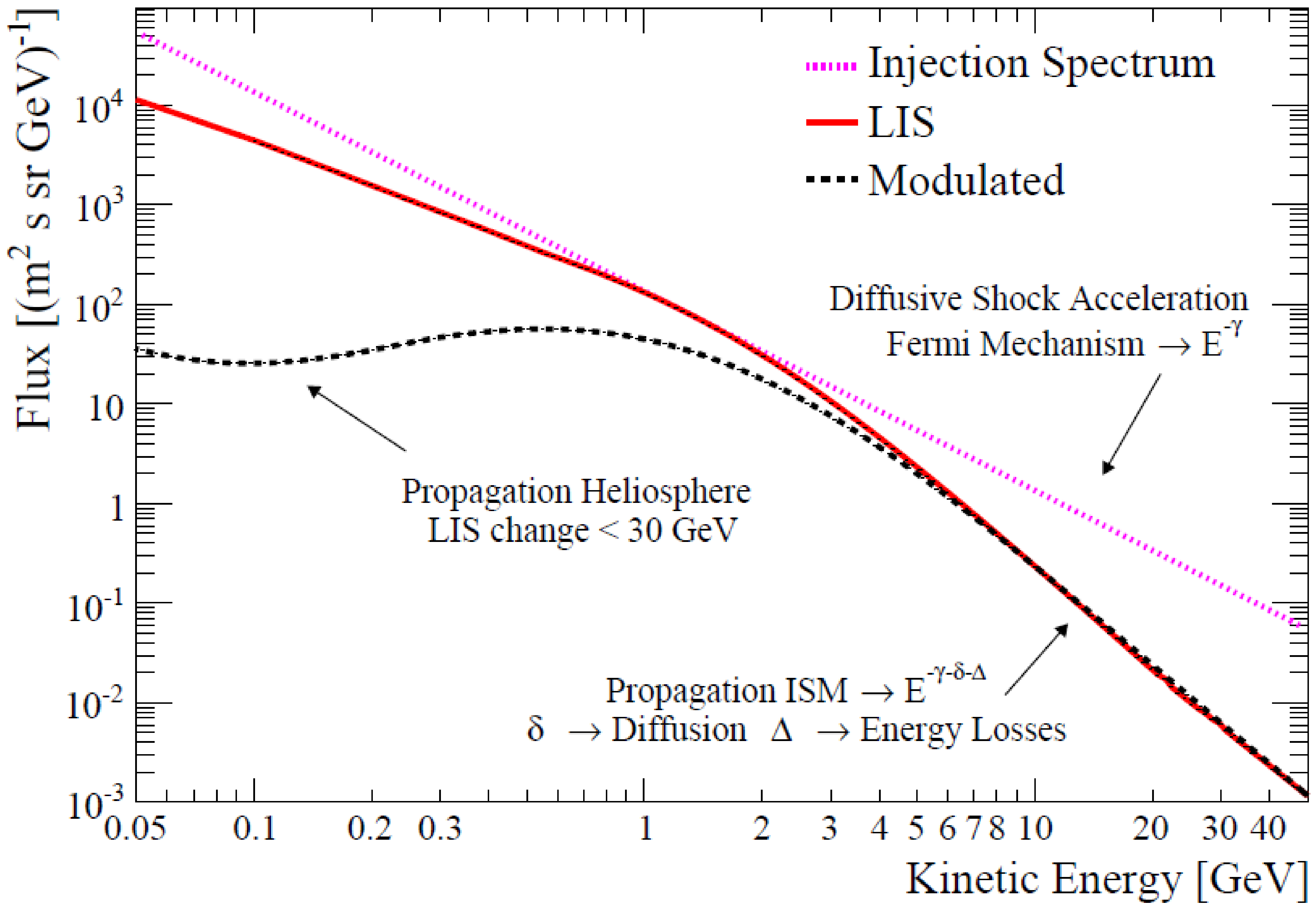
- **Are there signatures of new/exotic physics?**
  - Are there anti-matter regions in the universe?
  - What is the nature of Dark Matter? Which possible signatures in CR spectra?



Flux [(m^2 s sr GeV)^-1]
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
0.05
0.1
0.2
0.3
1
2
3
4
5
6
7
8
10
20
30
40
Kinetic Energy [GeV]
Injection Spectrum
Diffusive Shock Acceleration
Fermi Mechanism → E^-γ



Injection Spectrum
LIS
Diffusive Shock Acceleration
Fermi Mechanism → $E^{-\gamma}$
Propagation ISM → $E^{-\gamma-\delta-\Delta}$
δ → Diffusion Δ → Energy Losses
Flux [(m² s sr GeV)⁻¹]
Kinetic Energy [GeV]
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
0.05
0.1
0.2
0.3
1
2
3
4
5
6
7
8
10
20
30
40



Flux [(m^2 s sr GeV)^-1]
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
0.05
0.1
0.2
0.3
1
2
3
4
5
6
7
8
10
20
30
40
Kinetic Energy [GeV]
Injection Spectrum
LIS
Modulated
Diffusive Shock Acceleration
Fermi Mechanism → E^-γ
Propagation Heliosphere
LIS change < 30 GeV
Propagation ISM → E^-γ-δ-Δ
δ → Diffusion Δ → Energy Losses

Main physics research lines

-- **The High Energy Frontier** (Sources, Acceleration)

-- **The Composition Frontier** (source material, dust/gas, nucleosynthesis, selection effects)

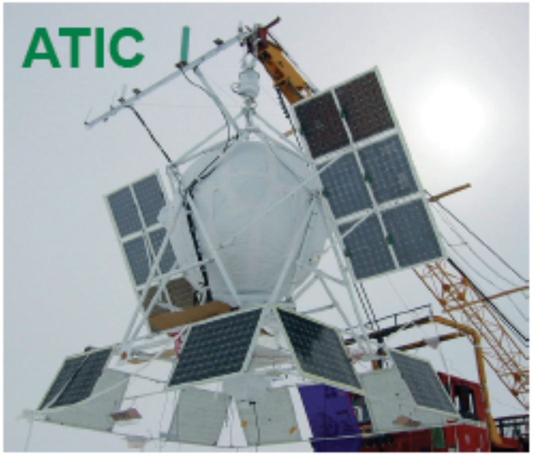
-- **The Anti-matter Frontier** (dark matter limits, anti-matter limits, non-SNR contributions, nearby sources)

According to the physics line, different platforms and detections techniques have been adopted.

Existing platforms

- **Balloon experiments** (CREAM, ATIC, BESS-Polar, TRACER, TIGER, SUPER-TIGER…)
- **Satellite experiments** (PAMELA, FERMI, NUCLEON, DAMPE, …)
- **ISS experiments** (AMS, CALET, ISS-CREAM, …)

Long Duration Balloons (LDB)



In the last decade, direct measurements of VHE cosmic rays have been performed by several instruments flown on NASA Long-Duration Balloons.

Cosmic Ray Energetics And Mass

H.S. Ahn[a], T. Anderson[b], L. Barbier[c], A. Barrau[d], R. Bazer-Bachi[e], J.J. Beatty[f], P. Bhoyar[a], G. Bigongiari[g], T. J. Brandt[f], M. Buénerd[d], N.B. Conklin[b], S. Coutu[b], L. Derome[d], M. A. DuVernois[h], J. Eaton[a], O. Ganel[a], M. Geske[b], J. H. Han[a], A. Haquea, J.A. Jeon[i], K.C. Kim[a], M.H. Kim[a], M. H. Lee[a], S. E. Lee[a], J. T. Link[c,j], L. Lutz[a], P. Maestro[g], A. Malinin[a], M. Mangin-Brinet[d], A. Menchaca-Rocha[k], P.S. Marrocchesi[g], J.W. Mitchell[c], S.I. Mognet[b], G. Nai, J. Nam[i], S. Nam[i], S. Nutter[l], O. Ofoha[a], I.H. Park[i], N.H. Park[i], A. Putze[d], S.S. Ryu[a], E.S. Seo[a,m], B.P. Smith[a], S. Swordy[n], A. Vartanyan[a], S.P. Wakely[n], P. Walpole[a], J. Wu[a], J. Yang[i], J. H. Yoo[a], Y.S. Yoon[a,m], R. Zei[g]

a) Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA
b) Department of Physics, Penn State University, University Park, PA 16802, USA
c) Astrophysics Space Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
d) Laboratorire de Physique Subatomique et de Cosmologia, Grenoble, France
e) Center d'Etude Spatiale des Rayonnements, UFR PCA-CNRS-UPR 8002, Toulouse, France
f) Department of Physics, Ohio State University, Columbus, OH 43210, USA
g) Department of Physics, University of Siena & INFN, Via Roma 56, 53100 Siena, Italy
h) School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, US
i) Department of Physics, Ewha Womans University, Seoul 120-750, Republic of Korea
j) CRESST/USRA, Columbia, MD 21044
k) Instituto de Fisica, Universidad Nacional Autonoma de Mexico, Mexico
l) Department of Physics, Northern Kentucky University, Highland Height, KY 41099, US
n) Kavli Institute for Cosmological Physics, University of Chicago, US

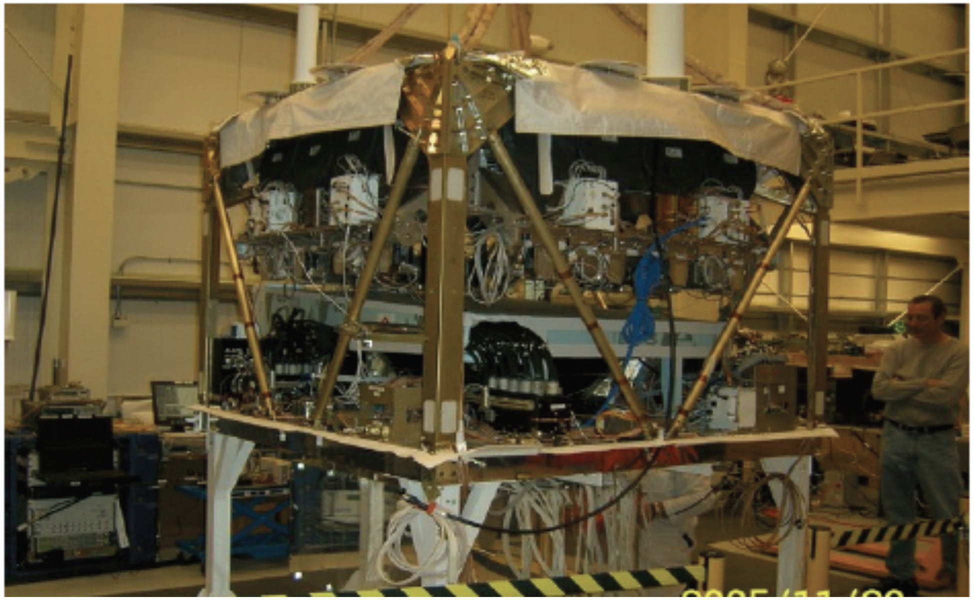
COLUMBIA SCIENTIFIC BALLOON FACILITY

NASA

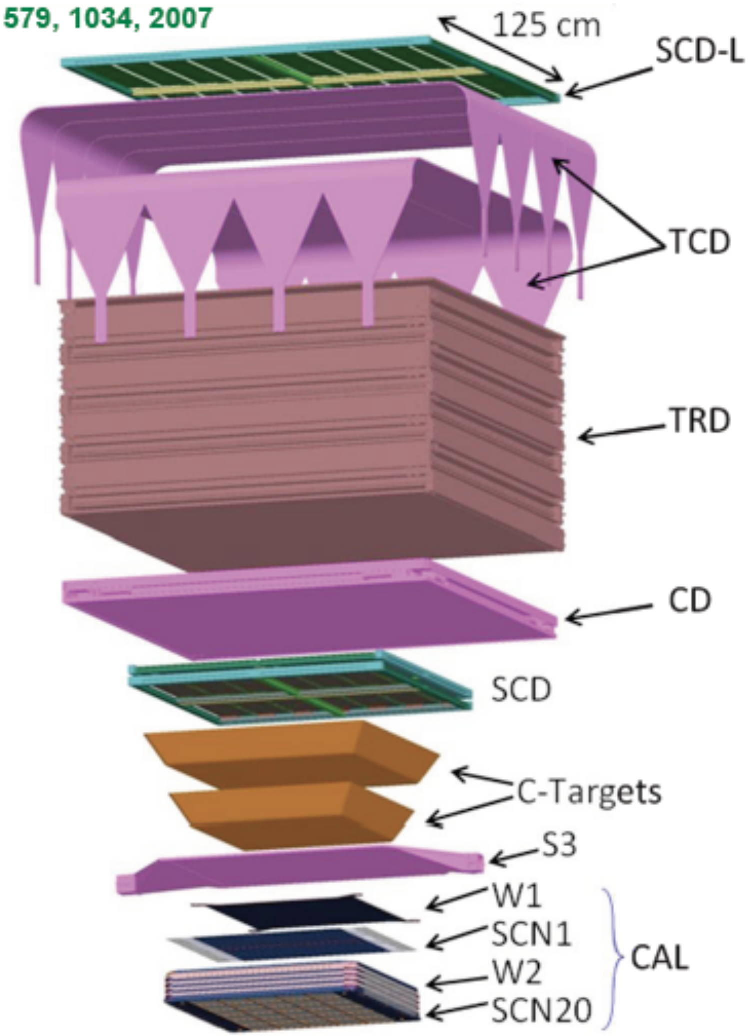
PNRA

CREAM instrument

- ➢ 3 independent charge measurements
- Timing-based Charge Detector (TCD)
- Pixelated Silicon Detector (SCD)
- Cerenkov counter (CD) and Camera (w/o TRD)
- ➢ 2 independent energy measurements + tracking
- Transition Radiation Detector (Z > 3)
- Tungsten Sci-Fi calorimeter (Z ≥ 1)
- ➢ GF ~ 0.3 m^2 sr for Z=1,2; ~ 1.3 m^2 sr for Z>3



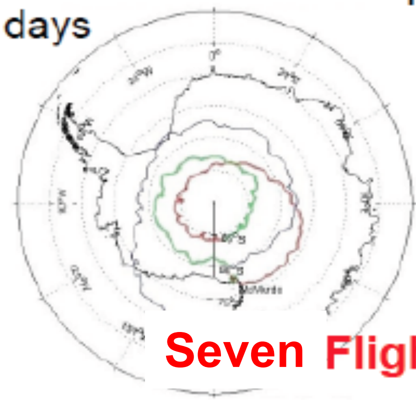
Ahn et al., NIM A, 579, 1034, 2007



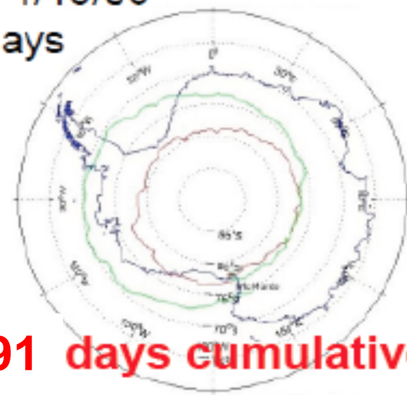
Exploded view: configuration with TRD

CREAM flights

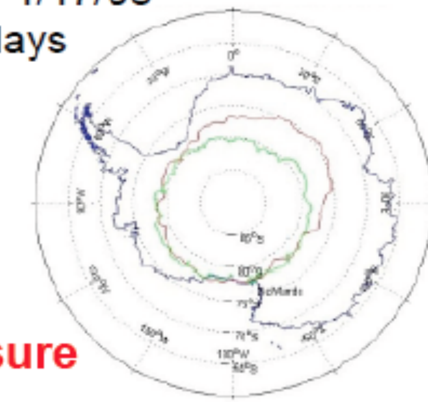
CREAM-I
12/16/04 – 1/27/05
42 days



CREAM-II
12/16/05-1/13/06
28 days

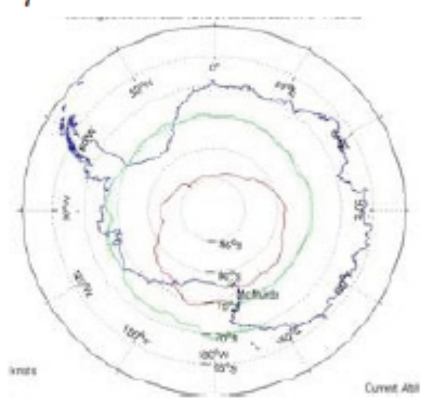


CREAM-III
12/19/07-1/17/08
29 days

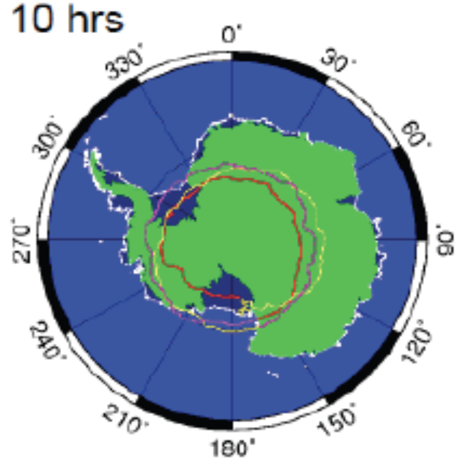


Seven Flights: 191 days cumulative exposure

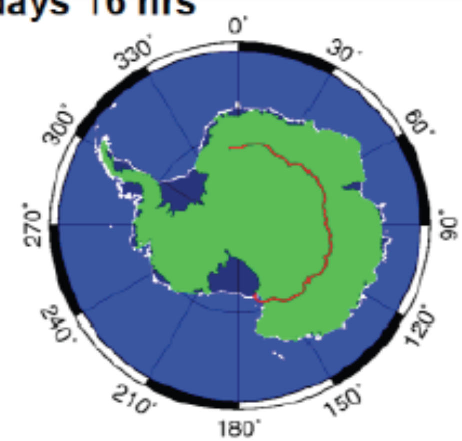
CREAM-IV
12/19/08 - 1/7/09
19 days 13 hrs



CREAM-V
12/1/09 – 1/8/10
37 days 10 hrs

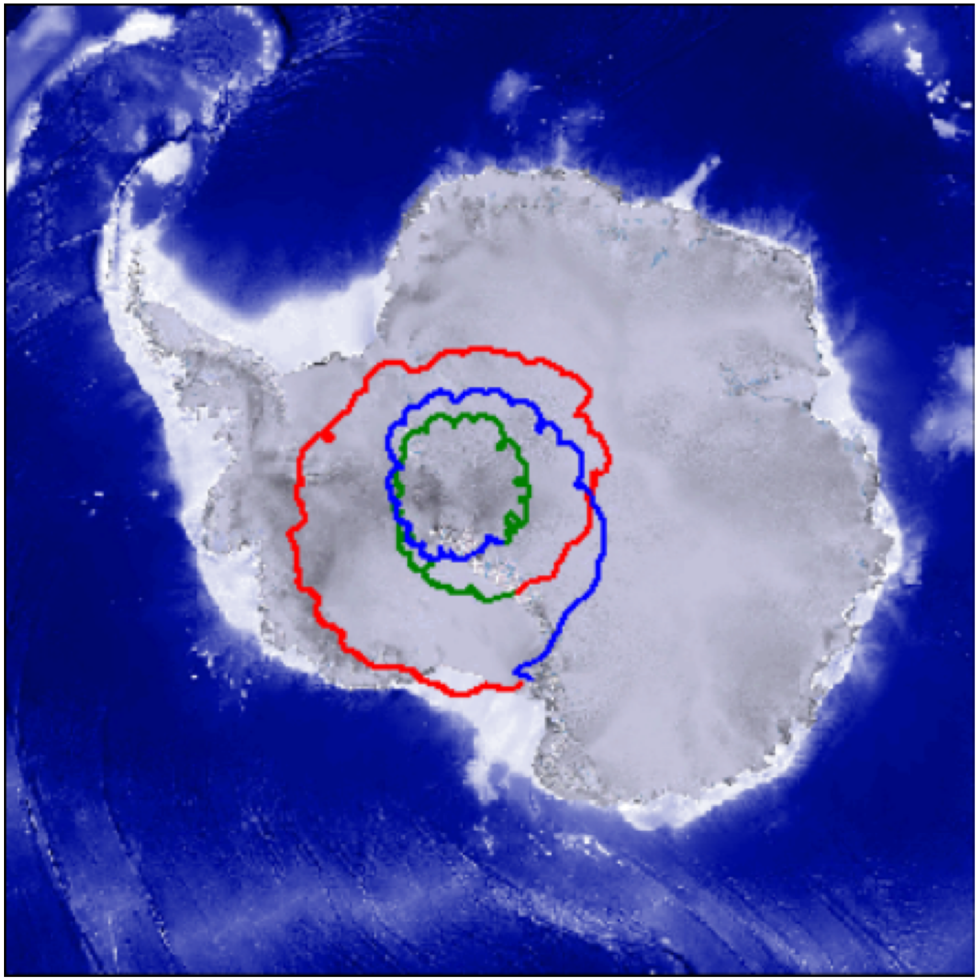


CREAM-VI
12/21/10 – 12/26/10
5 days 16 hrs



7° CREAM- «Baccus» Flight

11/28/2016 - 12/28/2016



The BESS program

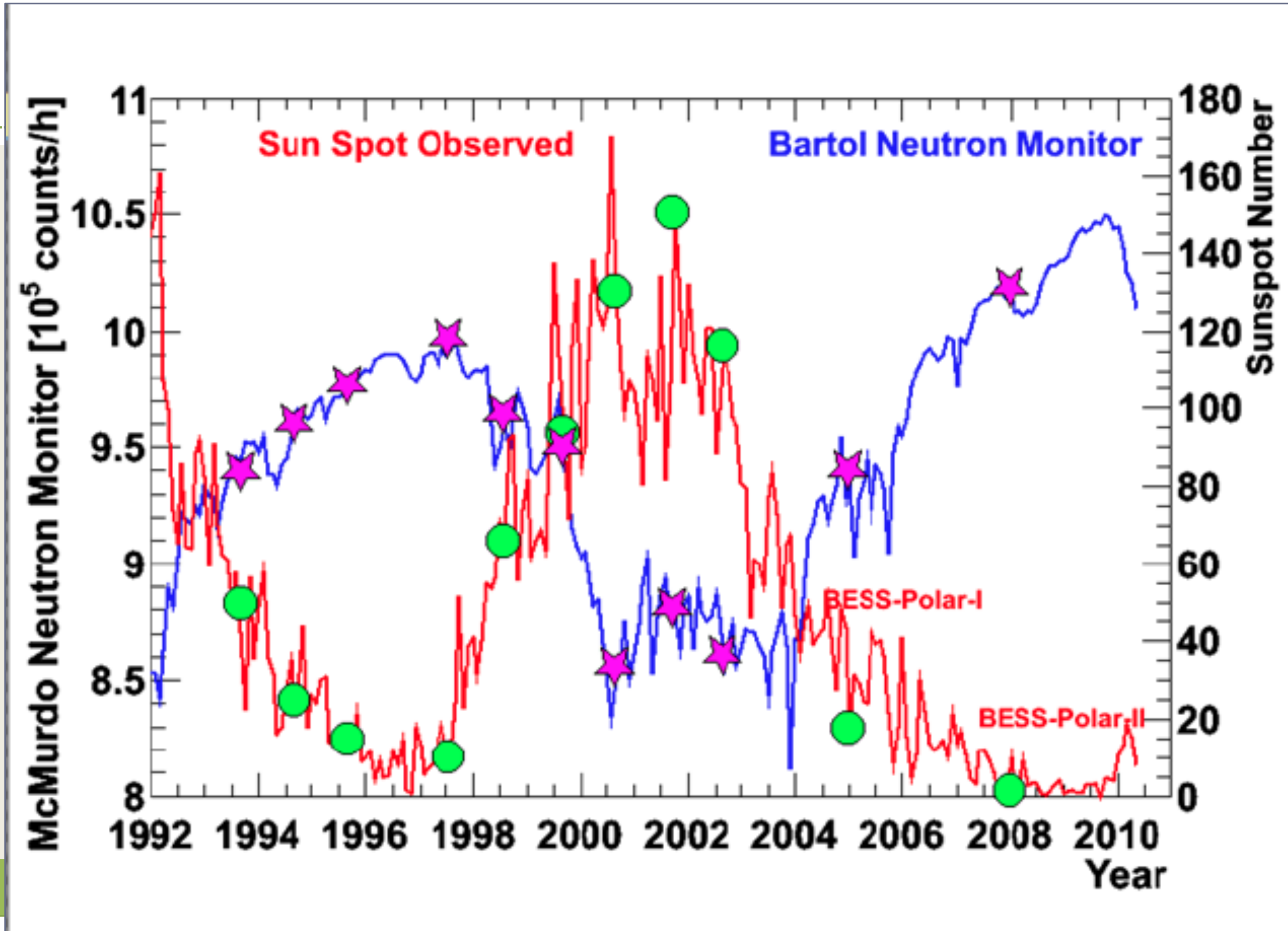
- The BESS program had **11 successful flight campaigns since 1993 up to 2008.**
- Aim of the program is **to search for antimatter (antip, antiD) and to provide high precision p, He, μ spectra**.

- A modification of the BESS instrument, **BESS-Polar**, is similar in design to previous BESS instruments, but is completely new with an ultra-thin magnet and configured to minimize the amount of material in the cosmic ray beam, so as to allow the lowest energy measurements of antiprotons.

- BESS-Polar has the largest geometry factor of any balloon-borne magnet spectrometer currently flying (0.3 m^2-sr).

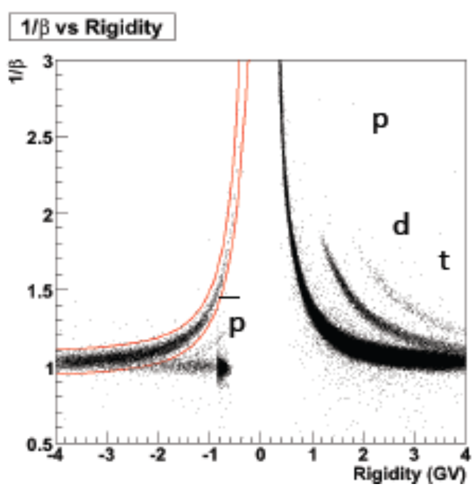
BESS-Polar I and II

Long duration flights of total **38 days** with two circles around the Pole

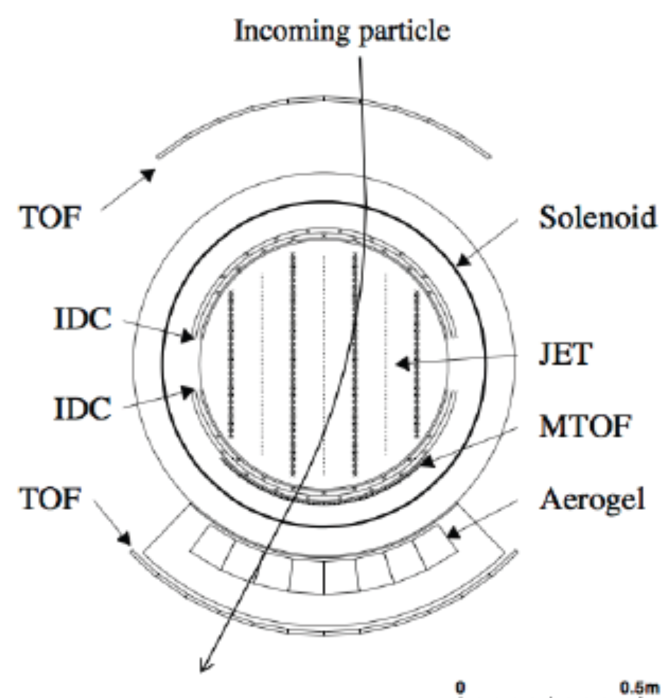


Antiproton flux: BESS-Polar

- Original BESS (Balloon-borne Experiment with a Superconducting Spectrometer) was flown 9 times between 1993 and 2002.
- New BESS-Polar instrument flew from Antarctica in 2004 (8.5 days) and 2007 (24.5 days).
- Measures charge, charge-sign, momentum velocity and mass of the particles
- "JET" drift chamber with 52 points on trace, $\sigma \sim 100\ \mu m$ MDR 240 GV
- Time-of-flight system (TOF)
- Silica-aerogel Cherenkov detector



- NASA/Goddard Space Flight Center T.Hams, J.W.Mitchell, M.Sasaki, R.E. Streitmatter
- KEK S. Haino, M. Hasegawa, A. Horikoshi, Y.Makida, S. Matsuda, M. Nozaki, J.Suzuki, K.Tanaka, A. Yamamoto, K.Yoshimura
- The University of Tokyo J.Nishimura, K. Sakai, R. Shinoda
- Kobe University K. Abe, A. Kusumoto, Y. Matsukawa, R. Orito
- University of Maryland K.Kim, M.H. Lee, S.Lee, E.S. Seo
- ISAS/JAXA H. Fuke, T. Yoshida
- University of Denver J. Ormes, N. Thakur



TIGER
2001-2004

Trans-
Iron
Galactic
Element
Recorder

Measurement of the Relative Abundances of the Ultra-Heavy Galactic Cosmic-Rays ($30 \leq Z \leq 40$) with TIGER

Washington University in St. Louis
B.F. Rauch, W.R. Binns, J.R. Cummings, M.H. Israel, J.T. Link, L.M. Scott

California Institute of Technology
S. Geier, R.A. Mewaldt, S.M Schindler, E.C. Stone

Goddard Space Flight Center
L.M. Barbier, E.R. Christian, J.W. Mitchell, G.A. de Nolfo, R.E. Streitmatter

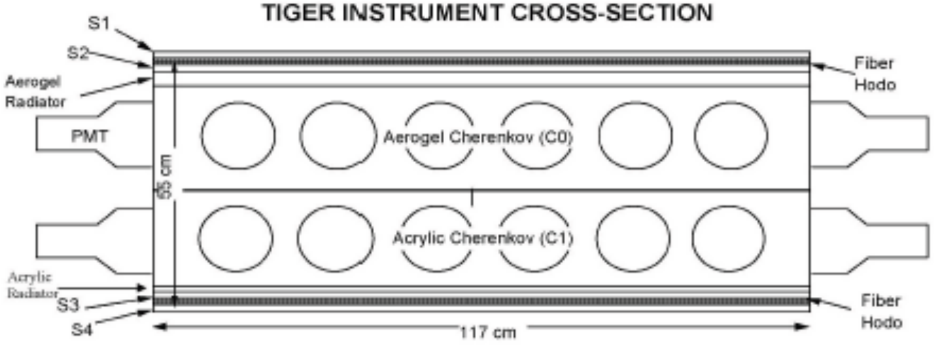
University of Minnesota
C.J. Waddington

2 antarctic flights

Dec. 2001 - Jan. 2002 32 days

Dec. 2003 - Jan. 2004 18 days

TIGER instrument (2001 & 2003)



TIGER is composed of plastic scintillators, Cherenkov detectors with two different indices of refraction, and a scintillation fiber hodoscope.

Scintillator ~ dE/dx ~ (Z^2/β^2)x(logarithmic increase w. energy)

Cherenkov ~ $Z^2(1-1/n^2\beta^2)$

Acrylic n = 1.5 → threshold 325 MeV/nuc

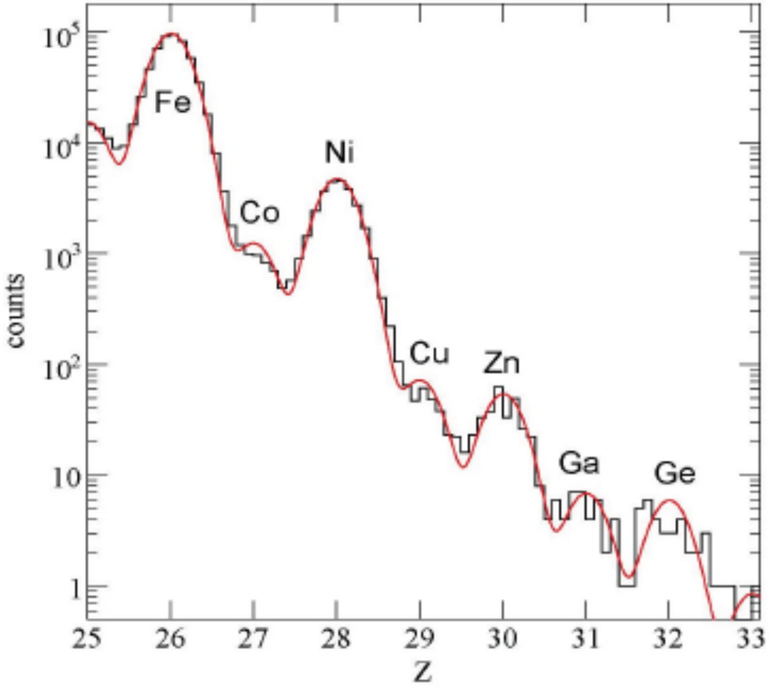
Aerogel n = 1.04 → threshold 2.5 GeV/nuc

Between 325 MeV/nuc and 2.5 GeV/nuc determine charge and energy from Scintillator and Acrylic Cherenkov.

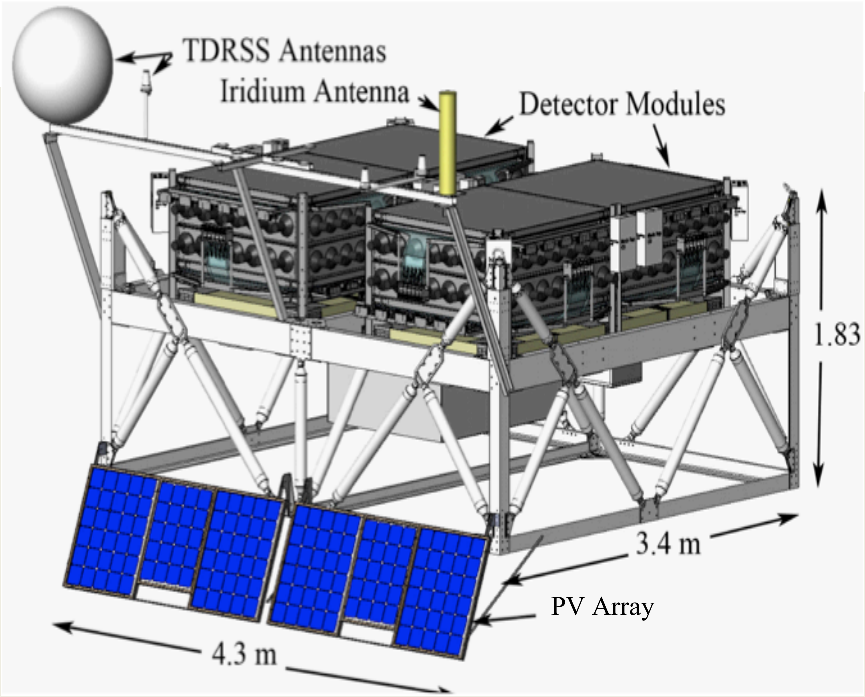
Above 2.5 GeV/nuc determine charge from the two Cherenkov (and from Scintillaor and Aerogel Cherenkov.

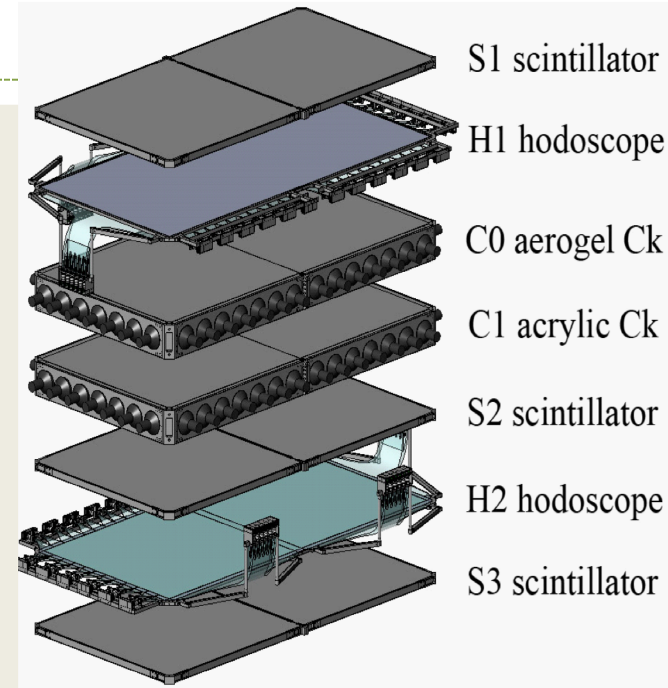
- TIGER is a 1 m^2 electronic instrument measuring the elemental composition of the rare GCR's heavier than iron.
- Obtained best measurement to date of abundances of $_{31}$Ga, $_{32}$Ge, & $_{34}$Se.

Combined 2001 and 2003 TIGER Data with Maximum Likelihood Fit



SuperTIGER Instrument



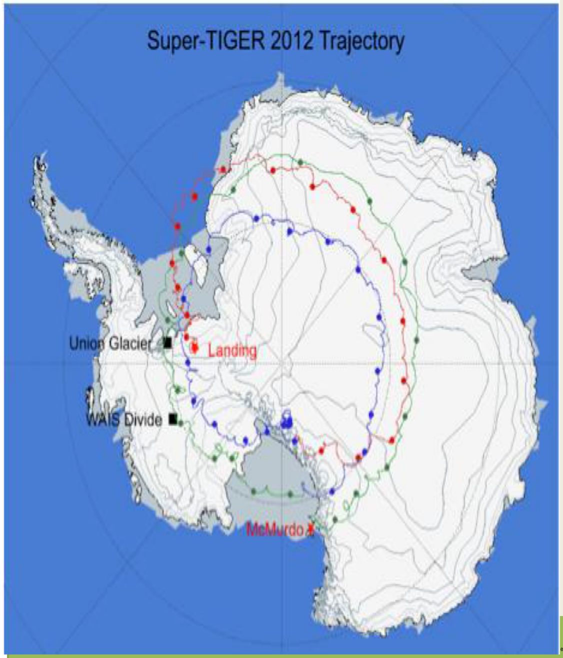


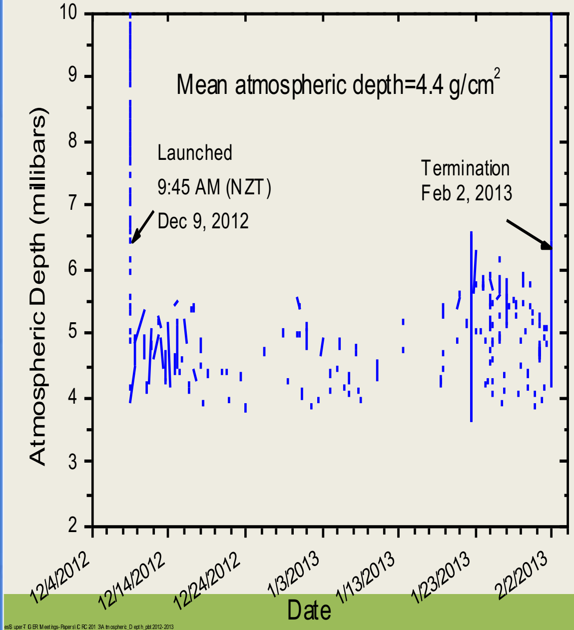
- acceptance ~8.3 m^2sr
- 2 identical modules, each consists of
  - 2 Scintillating Fiber Hodoscopes (H1, H2)
  - 3 layers of Plastic Scinitillator (S1, S2, S3)
  - Aerogel Cherenkov Counter (C0, n=1.043)
  - Acrylic Cherenkov Counter (C1, n=1.49)

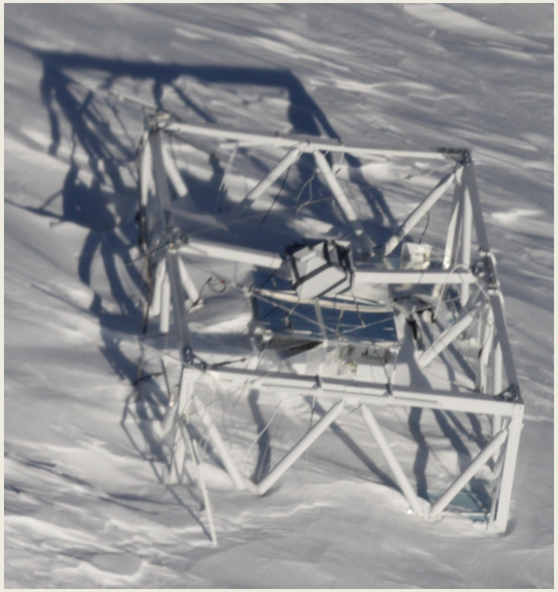
- Hodoscope: determines particle trajectory
- Charge determination combination of
  - S and C1 (below C0) or
  - C0 and C1 (above C0)

SuperTIGER Balloon Flight

- SuperTIGER flew for 55 days, 1 hour, and 34 minutes, December 9, 2012-February 2, 2013 (NZ).
- Collected over 50 million cosmic-ray events (~44 total days of data, 82% high-priority telemetry)
- SuperTIGER Recovery site 82.24°S latitude and 81.91°W longitude, 1625 km from McMurdo. Very successful recovery this past season.
- **Next flight ? More than 16 attempts failed in Winter 2017 !!**

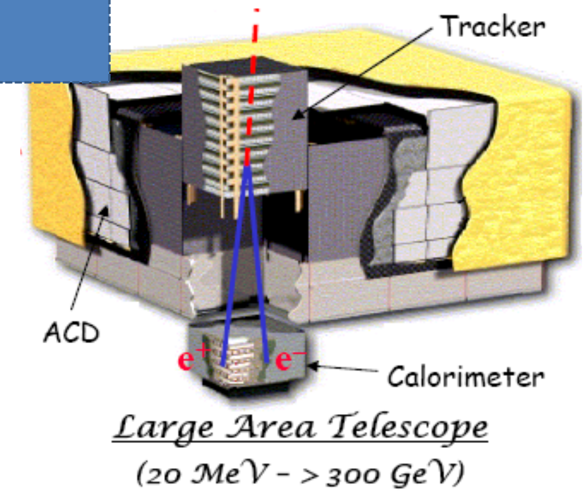






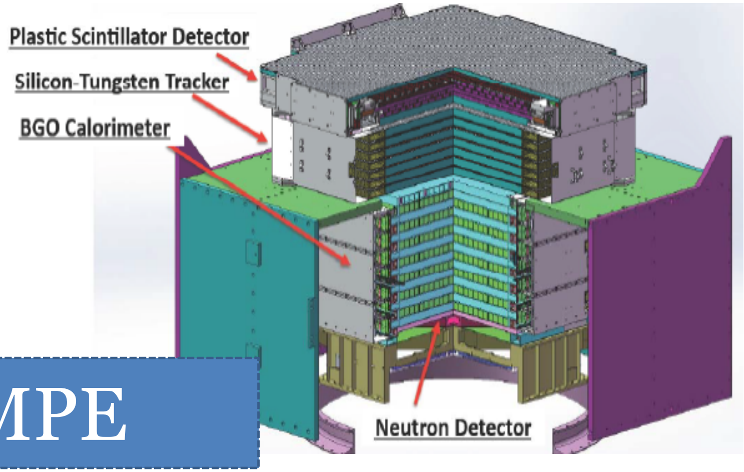
Satellite experiments

FERMI



NUCLEON

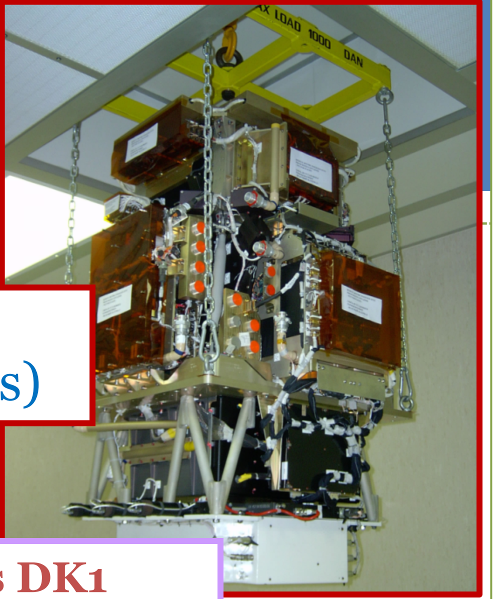
PAMELA



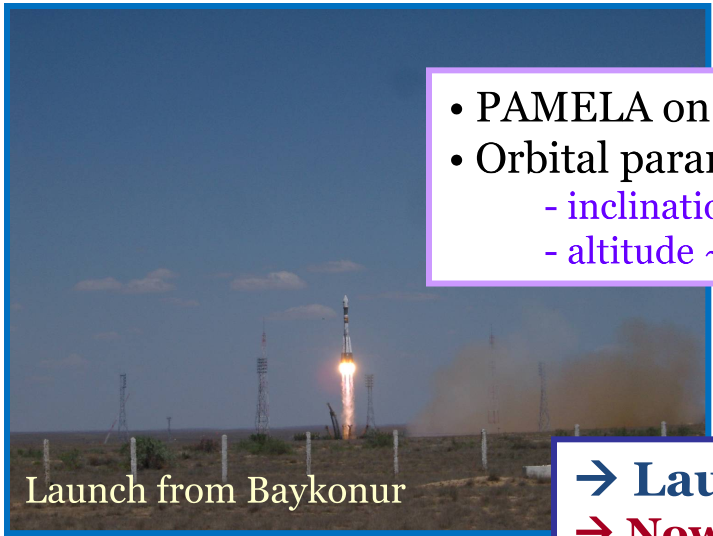
DAMPE

PAMELA

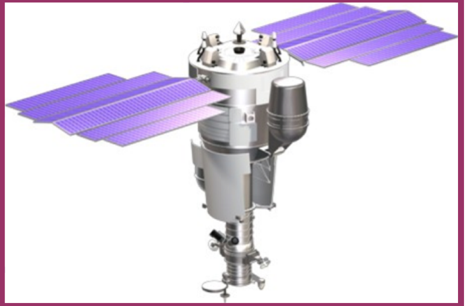
Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics



- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)



- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70° (low energy)
  - altitude ~ 360-600 km (elliptical) , then 500 km

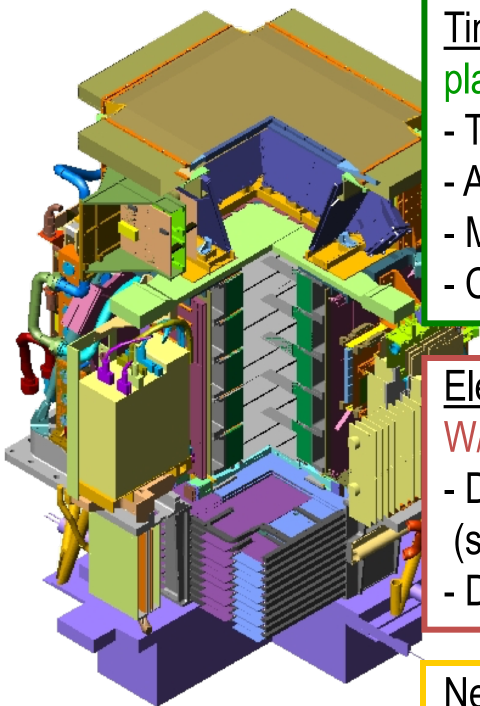


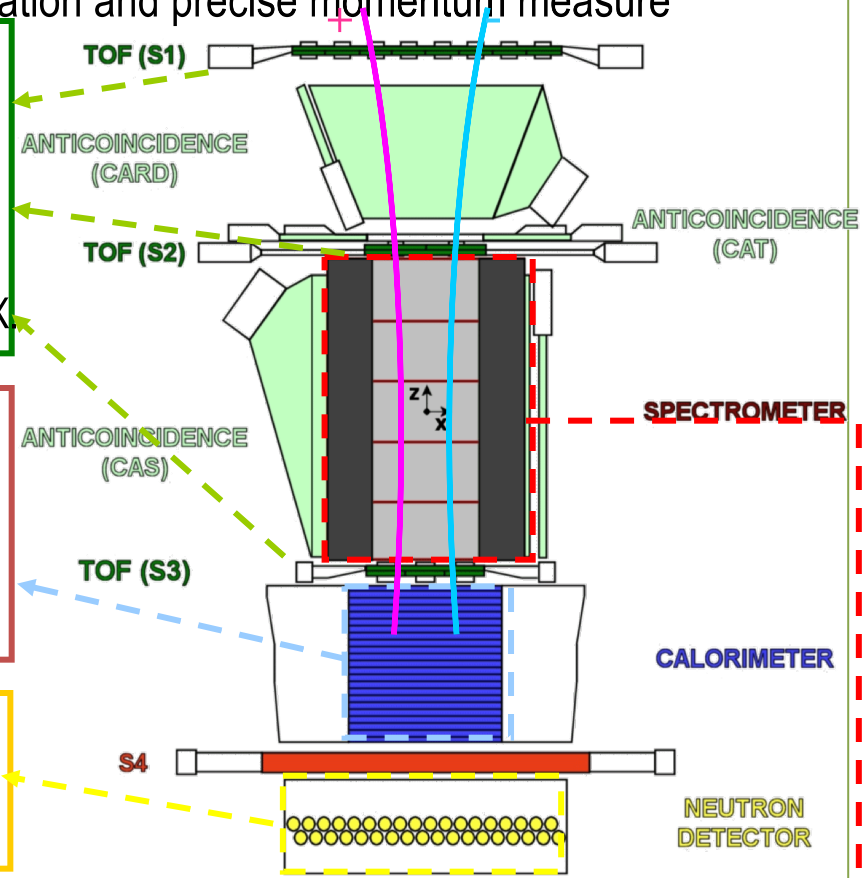
→ **Launched on 15th June 2006**

→ **Now switched off after 10 years of operation!**

PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure





Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

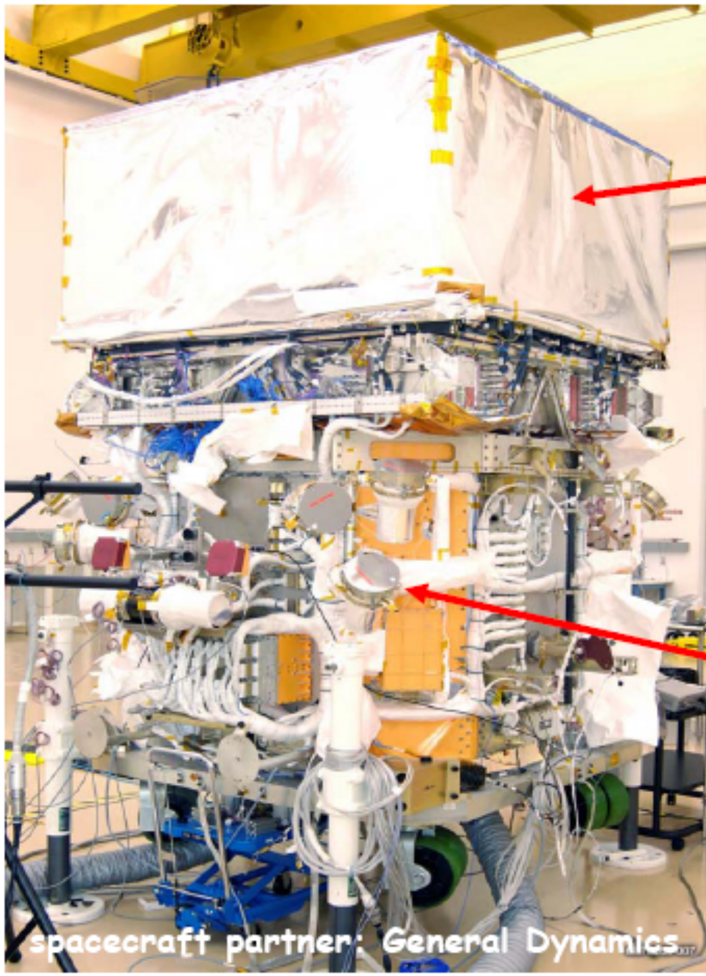
Neutron detector
36 He3 counters
- High-energy e/h discrimination

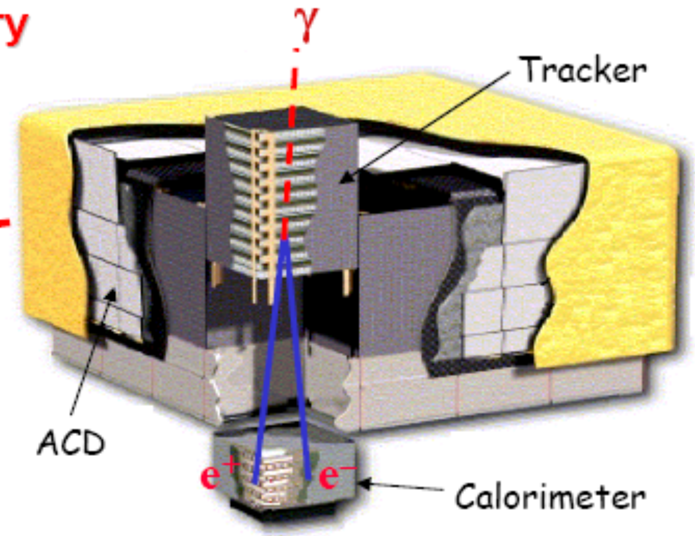
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

FERMI OBSERVATORY

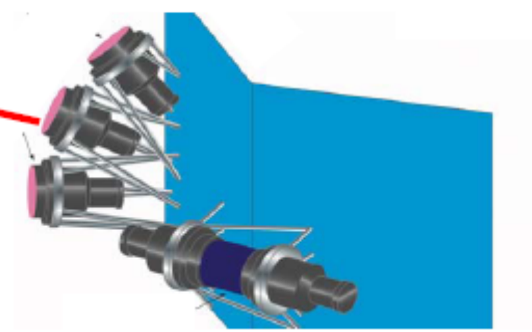
spacecraft and two instruments (LAT and GBM) now integrated and functioning as a single observatory





Large Area Telescope

(20 MeV – > 300 GeV)



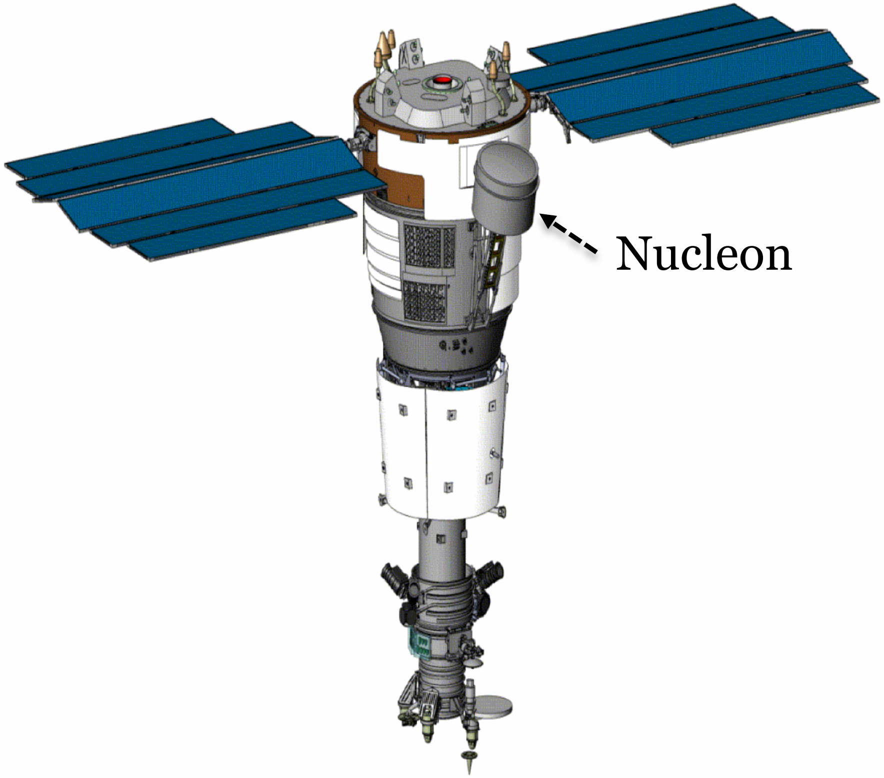
Glast Burst Monitor

(10 keV – 25 MeV)

Launch!

- Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT
- Just celebrated **10 years**!
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination.
- *Prolonged life-time due to GW multi-messenger observations.*

NUCLEON



Resurs-P n.2

- Energy spectra of CR nuclei and chemical composition (Z=1-30) in energy range 100 GeV - 1 PeV
- Electrons 100 GeV – 3 TeV

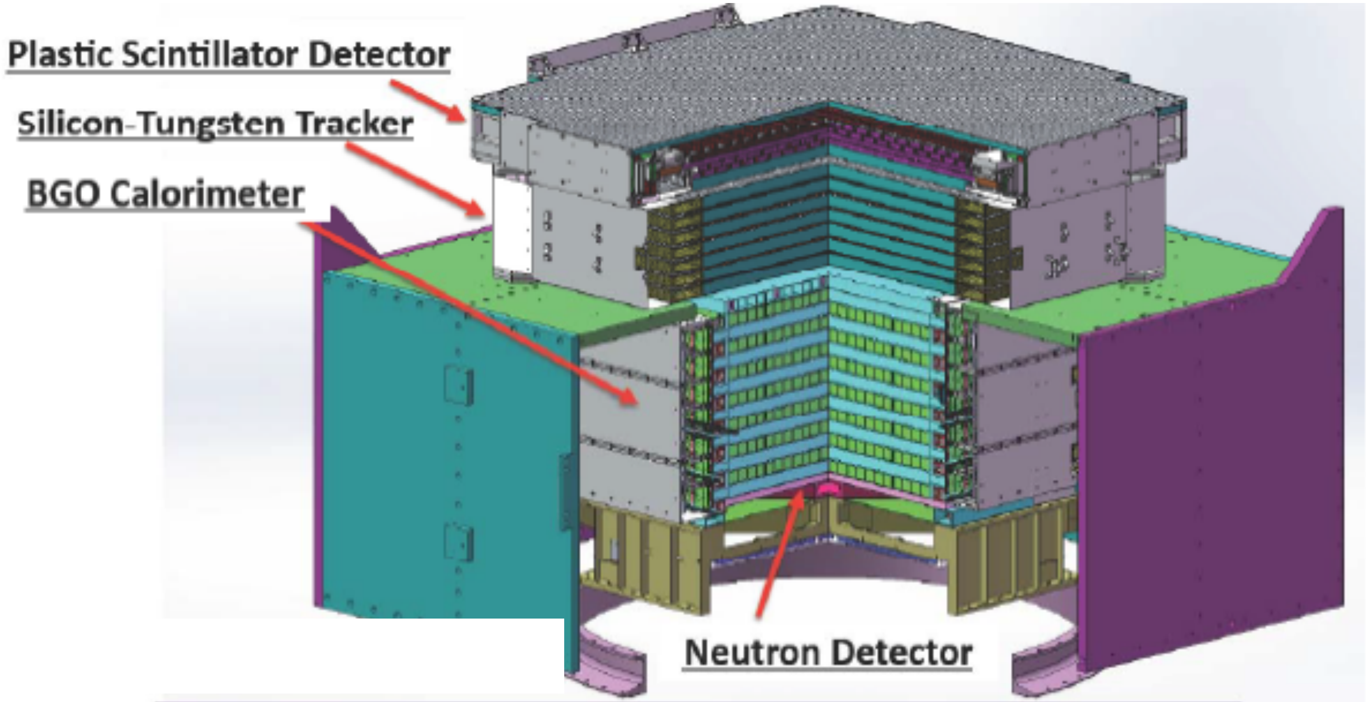
G.F = 0.2 m^2sr for nuclei and 0.06 m^2sr for electrons.

Planned exposition time = 5 years.

The Resurs-P n.2 satellite was launched on **26 December 2014 by Sojuz-2.1b**.

DAMPE: launched in December 2015

DAMPE: Dark Matter Particle Explorer.
Project of **Chinese Academy of Sciences**, in collaboration with **Italy** (INFN) and the **University of Geneva** for the construction of the tracker Si.
Precursor of HERD.



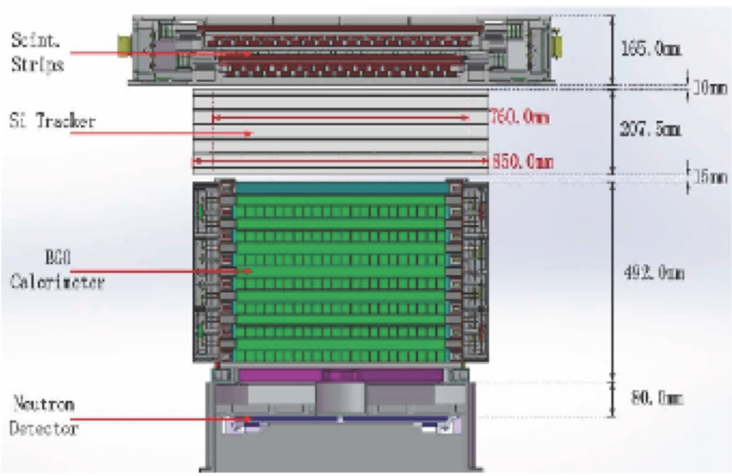
W converter + thick calorimeter (total 33 X_0) + precise tracking + charge measurement ➡ high energy γ-ray, electron and CR telescope

DAMPE

Dark Matter Explorer Satellite

- Large geometric factor instrument (0.3 m^2 sr for p and nuclei)
- Precision Si-W tracker (40μm , 0.2°)
- Thick calorimeter (32 X_0 , σ_E/E better than 1% above 50 GeV for e/γ , ~35% for hadrons)
- “Mutiple” charge measurements (0.2-0.3 e resolution)
- e/p rejection power > 10^5 (topology alone, plus neutron detector)

	DAMPE
e/γ Energy res.@100 GeV (%)	1.5
e/γ Angular res.@100 GeV (°)	0.1
e/p discrimination	10^5
Calorimeter thickness (X_0)	32
Geometrical accep. (m^2sr)	0.29



Comparison with AMS-02 and FERMI

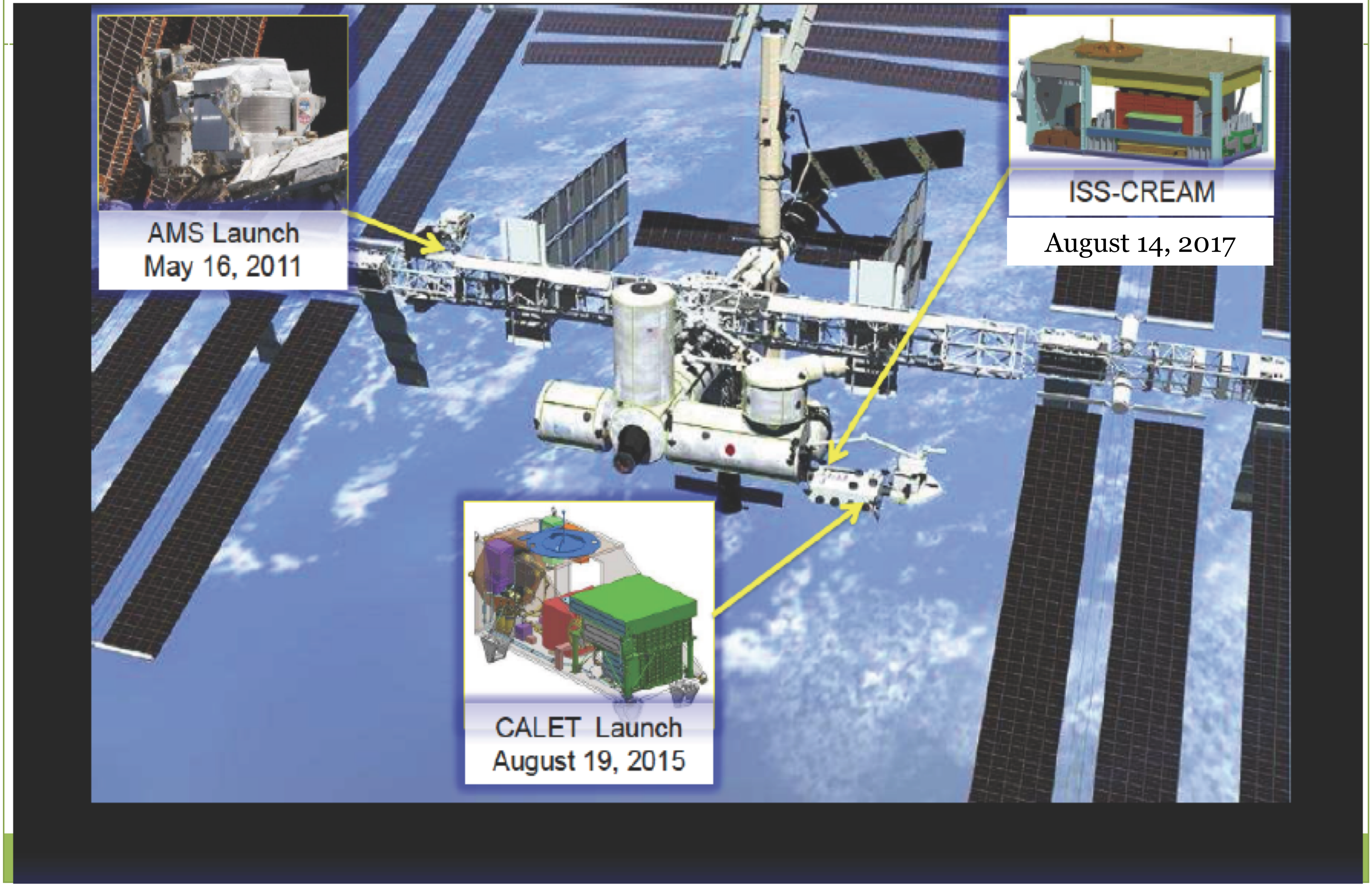
	DAMPE	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	1.5	3	10
e/γ Angular res.@100 GeV (°)	0.1	0.3	0.1
e/p discrimination	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	32	17	8.6
Geometrical accep. (m^2sr)	0.29	0.09	1

[I. De Mitri, LNGS 2015]

- **Satellite ≈ 1900 kg, payload ≈1300kg**
- **Power consumption ≈640W**
- **Lifetime > 3 years**
- **Launched by CZ-2D rockets**

- **Altitude 500 km**
- **Inclination 97.4°**
- **Period 95 minutes**
- **Sun-synchronous orbit**

Experiments on the ISS



ALPHA MAGNETIC SPECTROMETER

→Search for primordial anti-matter

→Indirect search of dark matter

→High precision measurement of the energetic spectra and composition of CR from GeV to TeV

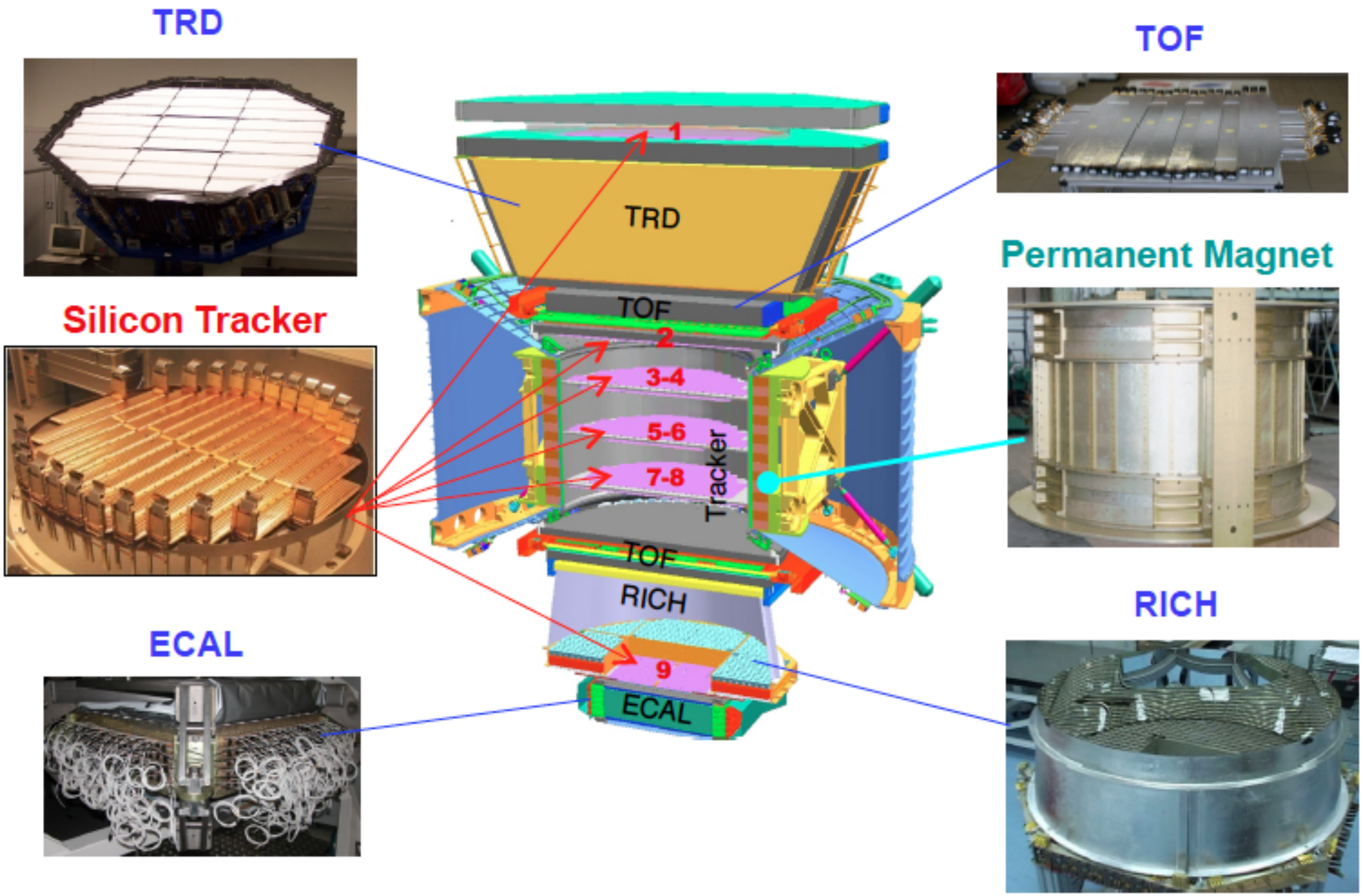
AMS-01: 1998 (10 days) - PRECURSOR FLIGHT ON THE SHUTTLE

AMS-02: **Launched May 16th, 2011 and since May 19th, 2011, safely on the ISS.** Four days after the Endeavour launch the experiment has been installed on the ISS and then activated.

COMPLETE CONFIGURATION FOR >10 YEARS LIFETIME ON THE ISS

» 500 physicists, 16 countries, 56 Institutes

The AMS-02 detector



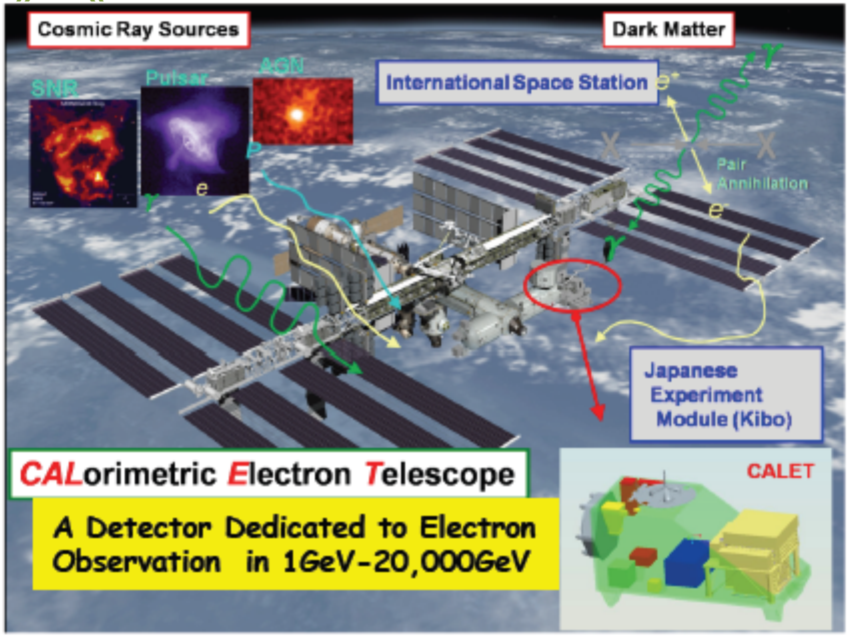
CALET: launched 19th August 2015 !!

Calorimeter (CALET/CAL)
- Electrons: 1 GeV - 20 TeV
- Gamma-rays: 4 *GeV - 10 **TeV
  (Gamma-ray Bursts: > 1 GeV)
- Protons and Heavy Ions:
  10's of GeV – 1,000** TeV
- Ultra Heavy (Z>28) Nuclei :
  E> 600 MeV/nucleon

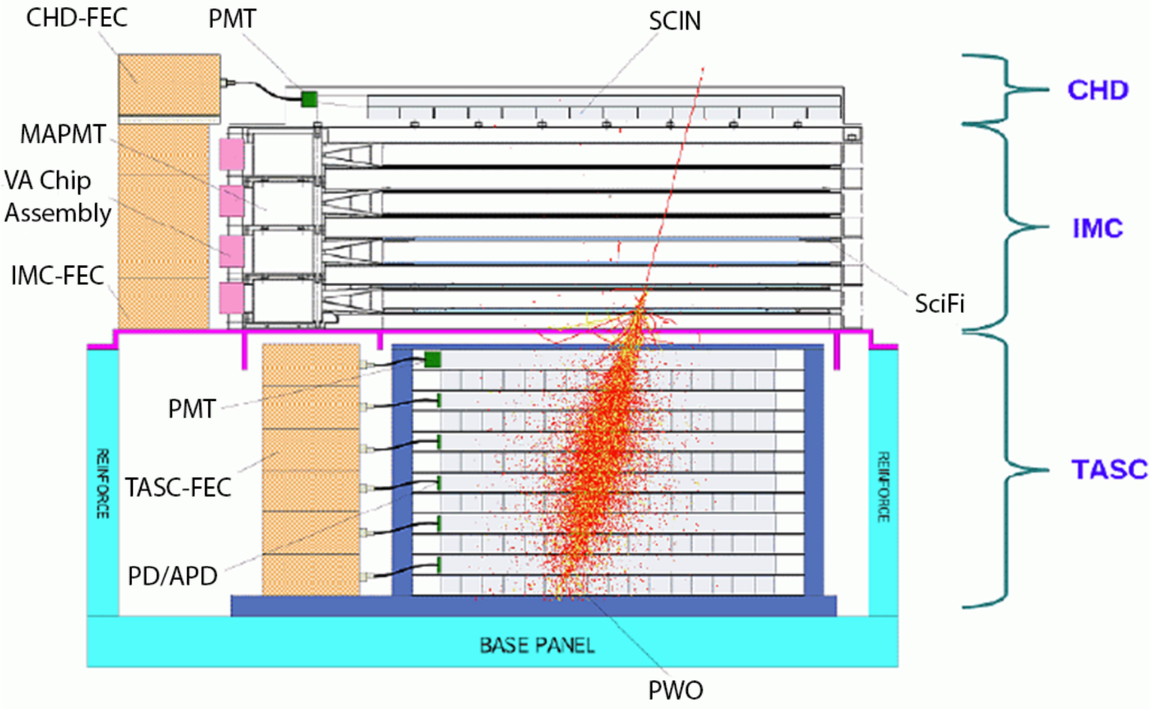
(* 50% efficiency, ** statistical dependent)

Gamma-ray Burst Monitor (CGBM)
- X-rays/Soft Gamma-rays:
  7keV - 20MeV

K.Yamaoka Poster:1007



Science Objectives	Observation Targets
Nearby Cosmic-ray Sources	Electron spectrum in trans-TeV region
Dark Matter	Signatures in electron/gamma energy spectra in 10 GeV - 10 TeV region
Origin and Acceleration of Cosmic Rays	p-Fe over several tens of GeV, Ultra Heavy Nuclei
Cosmic -ray Propagation in the Galaxy	B/C ratio up to several TeV /n
Solar Physics	Electron flux below 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays in 7 keV - 20 MeV



CALET collaboration: JAPAN, USA, ITALY

Charge Detector (Charge Z=1-40)

1 Layer of 14 Plastic Scintillators (32 x 10 x 450 mm^3)

Imaging Calorimeter (Particle ID, Direction)

Total Thickness of Tungsten (W) : 3 X_0

Layer Number of Scifi Belts : 8 Layers ×2(X,Y)

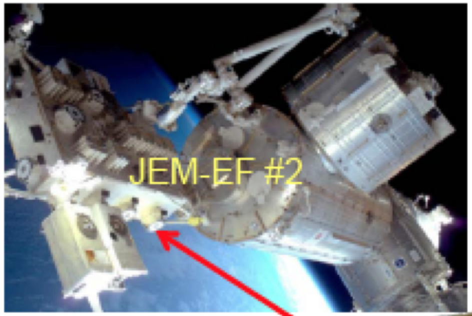
Total Absorption Calorimeter (Energy Measurement, Particle ID)

PWO 20 mm x 20 mm x 320 mm

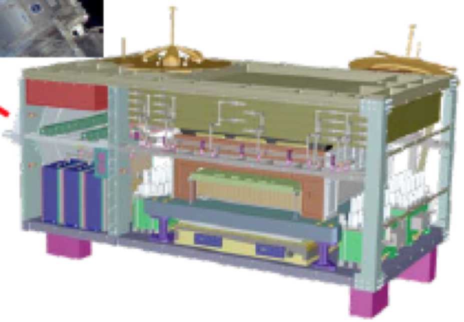
Total Depth of PWO : 27 X_0 (24 cm)

ISS-CREAM: CREAM for the ISS

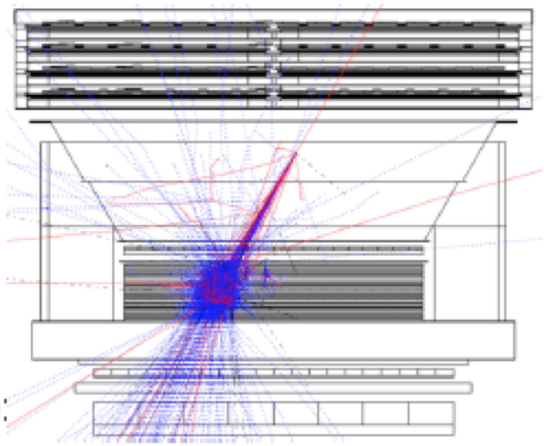
E. S. Seo et al, Advances in Space Research, **53**/10, *1451*, 2014



ISS-CREAM:
launched 14/08/2017



Mass: ~1400 kg
Power: ~ 550 W
Nominal data rate: ~350 kbps



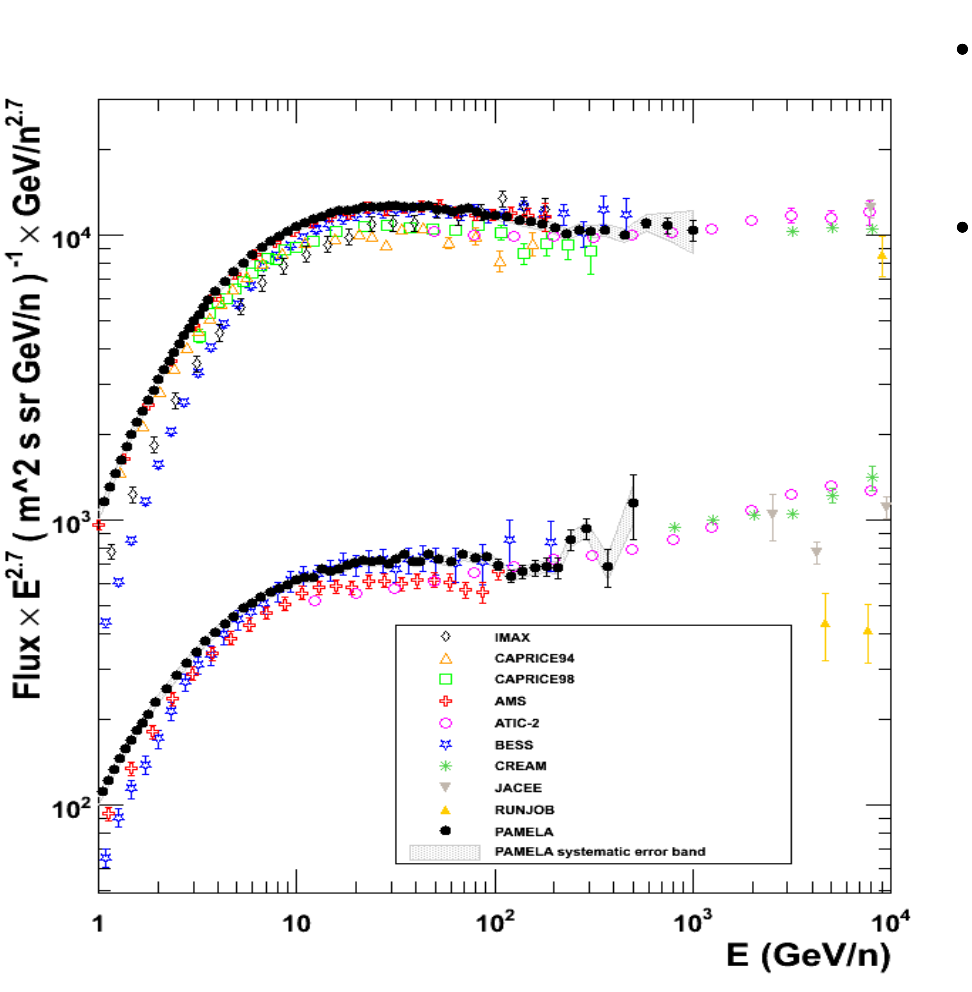
- Building on the success of the balloon flights, the payload is being transformed for accommodation on the ISS (NASA's share of JEM-EF).
  - Increase the exposure by an order of magnitude
- ISS-CREAM will measure cosmic ray energy spectra from 10^{12} to $>10^{15}$ eV with individual element precision over the range from protons to iron to:
  - Probe cosmic ray origin, acceleration and propagation.
  - Search for spectral features from nearby/young sources, acceleration effects, or propagation history.

Review of the current measurements

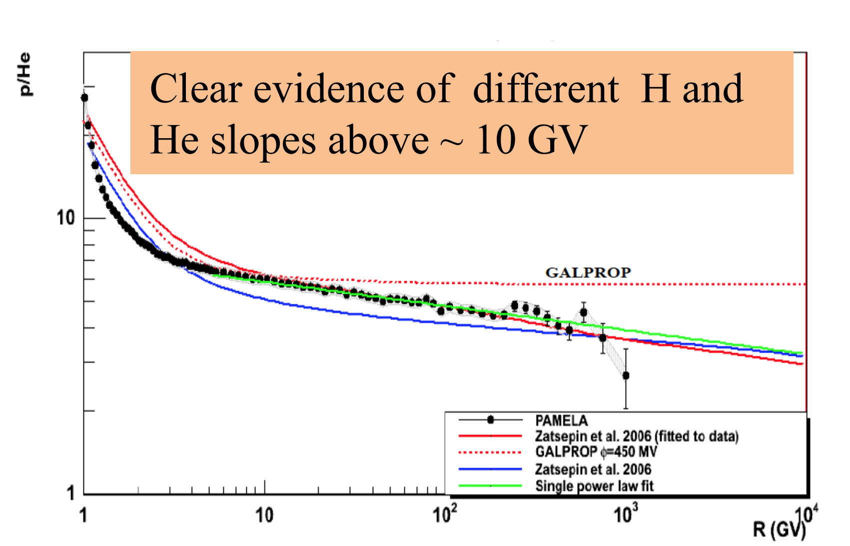
- Primary cosmic rays: Proton, Helium, Carbon, Oxygen, sub-Fe nuclei
- Secondary cosmic rays: B/C, Li, Be, B
- Composition studies
- Electrons and positrons
- Antiparticles & c.

Primary cosmic rays: Proton, Helium, Carbon, Oxygen, sub-Fe nuclei

PAMELA: Proton and Helium Spectra & H/He ratio



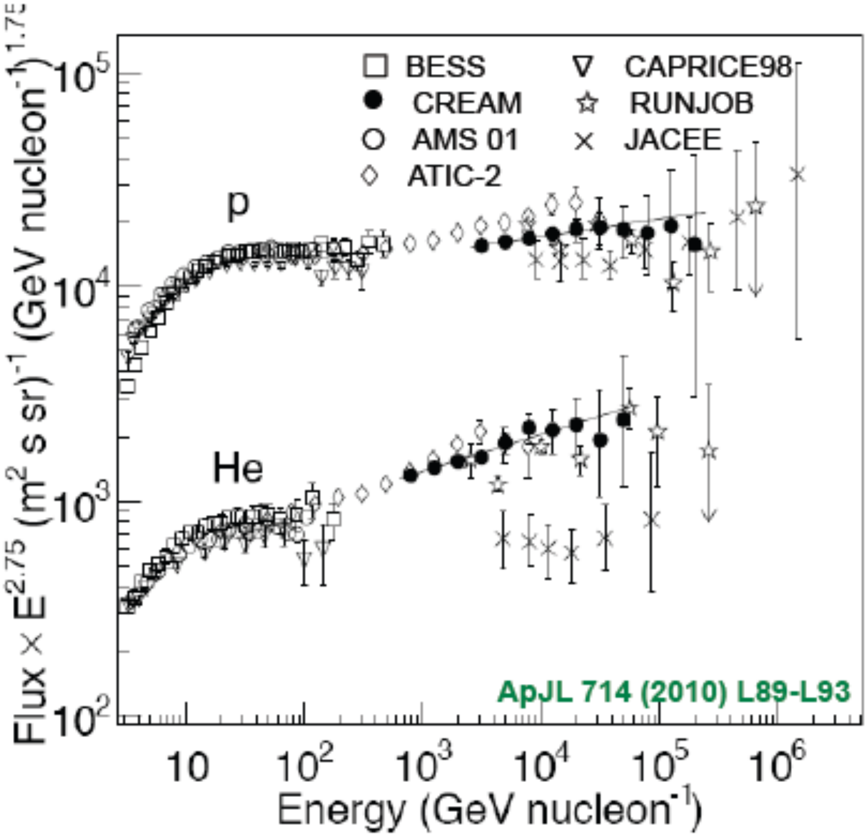
- **First high-statistics and high-precision measurement over three decades in energy**
- **First clear deviations from single power law (SPL):**
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV

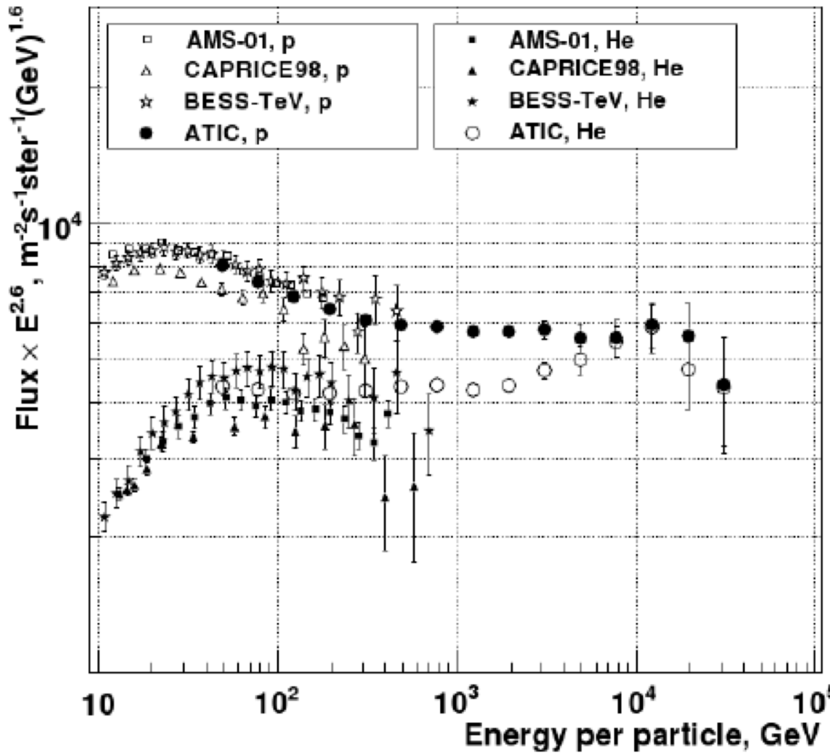


Clear evidence of different H and He slopes above ~ 10 GV

Adriani et al., Science 332 (2011) 6025

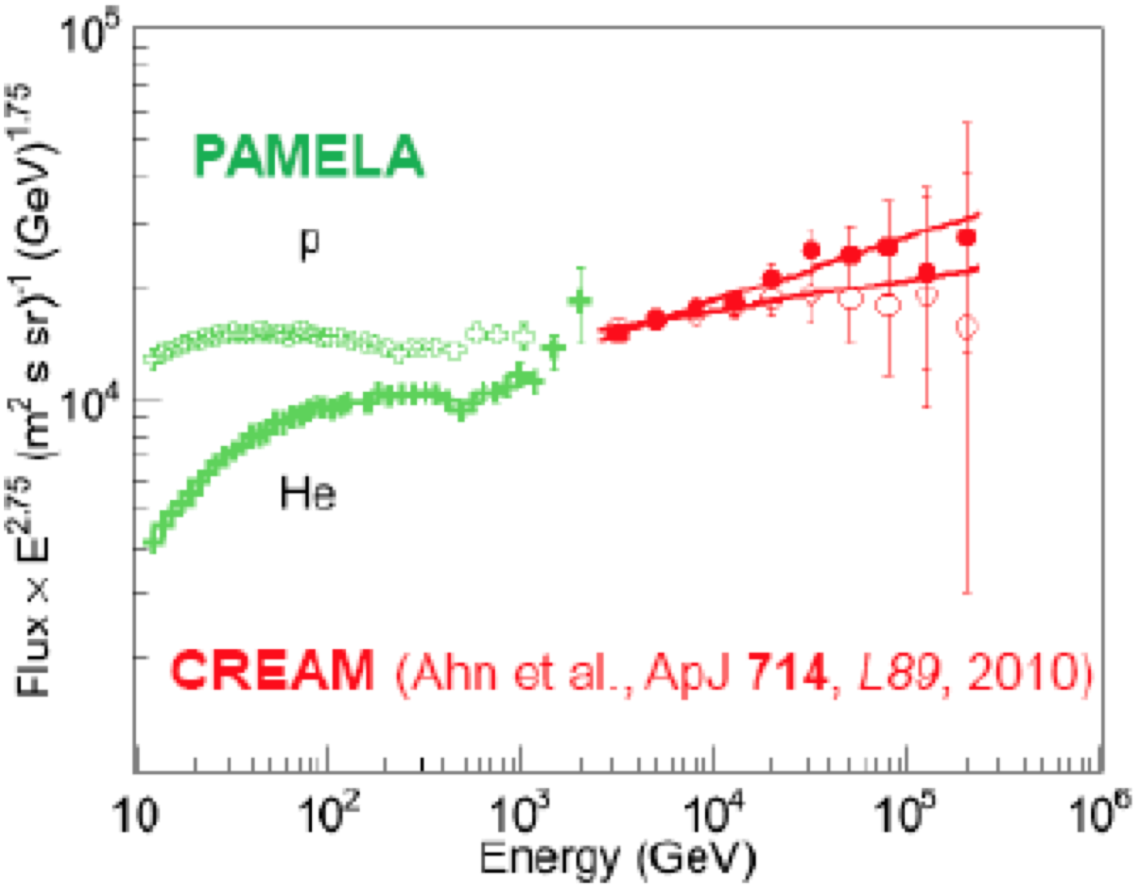
CREAM: Proton and helium spectra





- Proton and helium spectra at TeV are harder than the low-energy spectra.
  ➔Evidence of CRs-shock interaction (Non linear acceleration models) ? (ApJ 540 (2009) 292)
- Proton and helium spectra have different spectral shapes
  ➔ Different types of sources or acceleration mechanisms? (Biermann P. A&A 271 (1993) 649)

PAMELA & CREAM



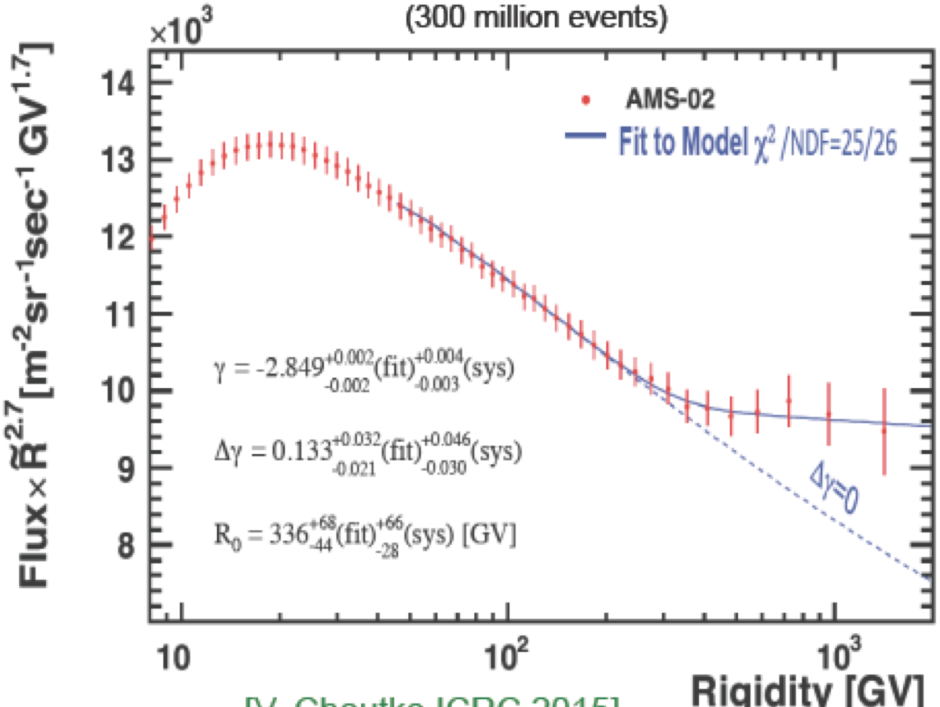
AMS: Proton and helium spectra

Two power laws with a characteristic transition rigidity R_0 and a smoothness parameter s are used by AMS-02 to fit the measured H and He spectra:

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

AMS proton flux

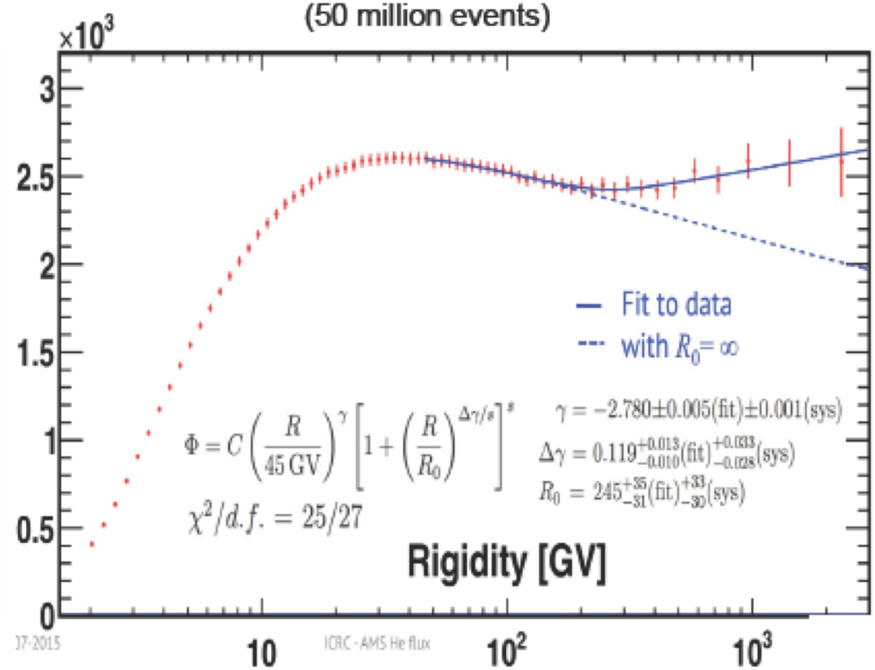
(300 million events)



[V. Choutko ICRC 2015]

AMS He flux

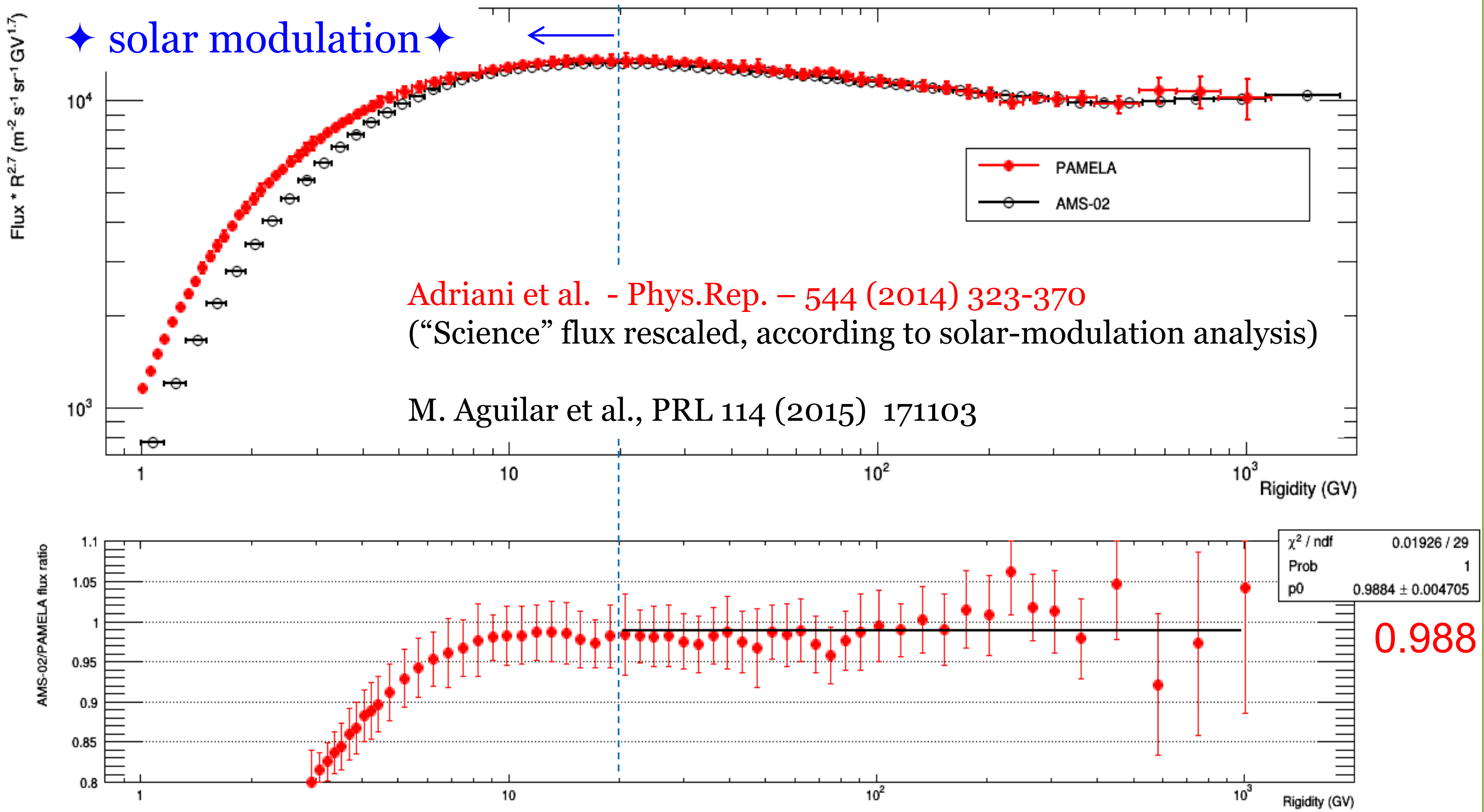
(50 million events)



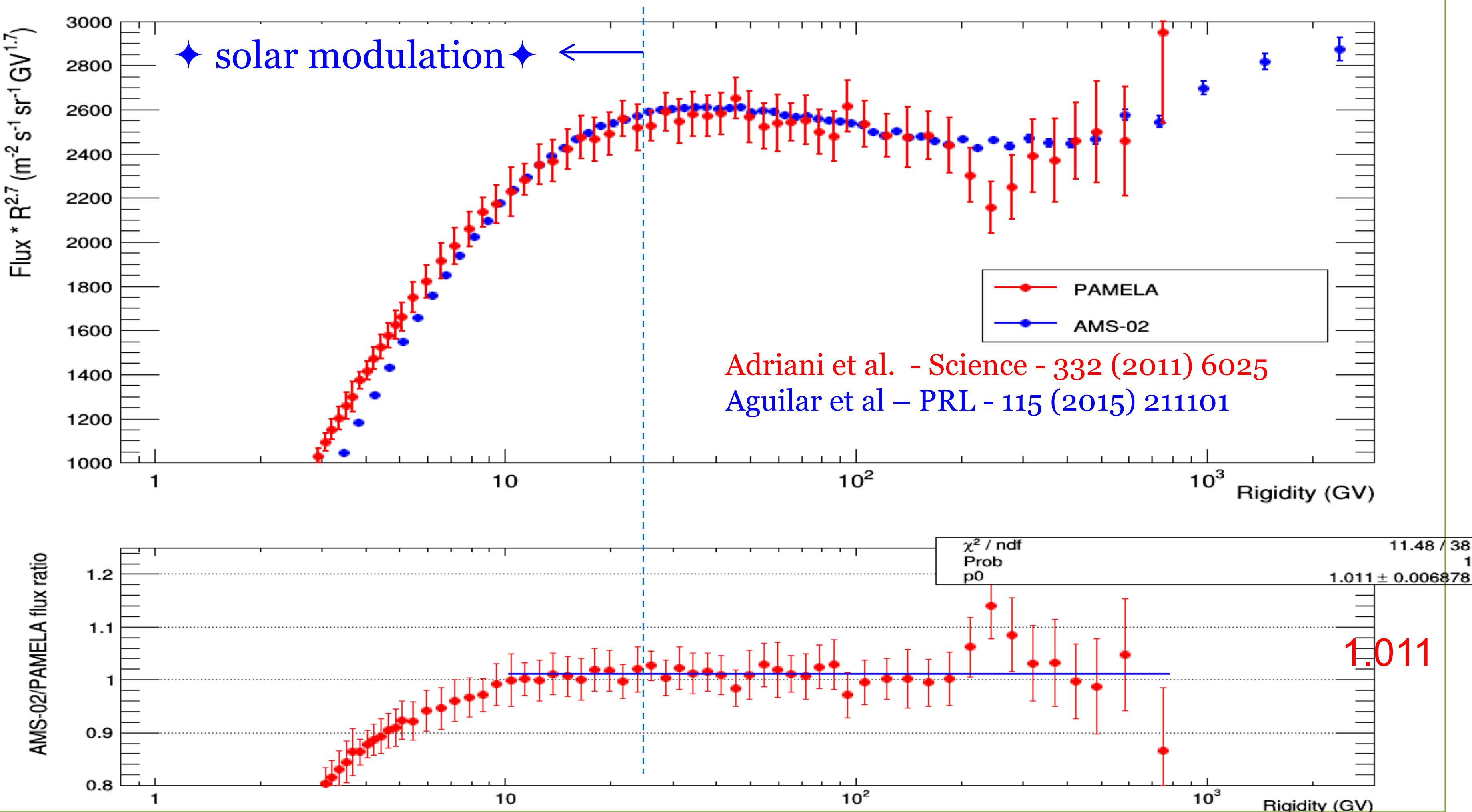
[S. Haino ICRC 2015]

PAMELA vs AMS02: protons

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013



PAMELA vs AMS02: heliums

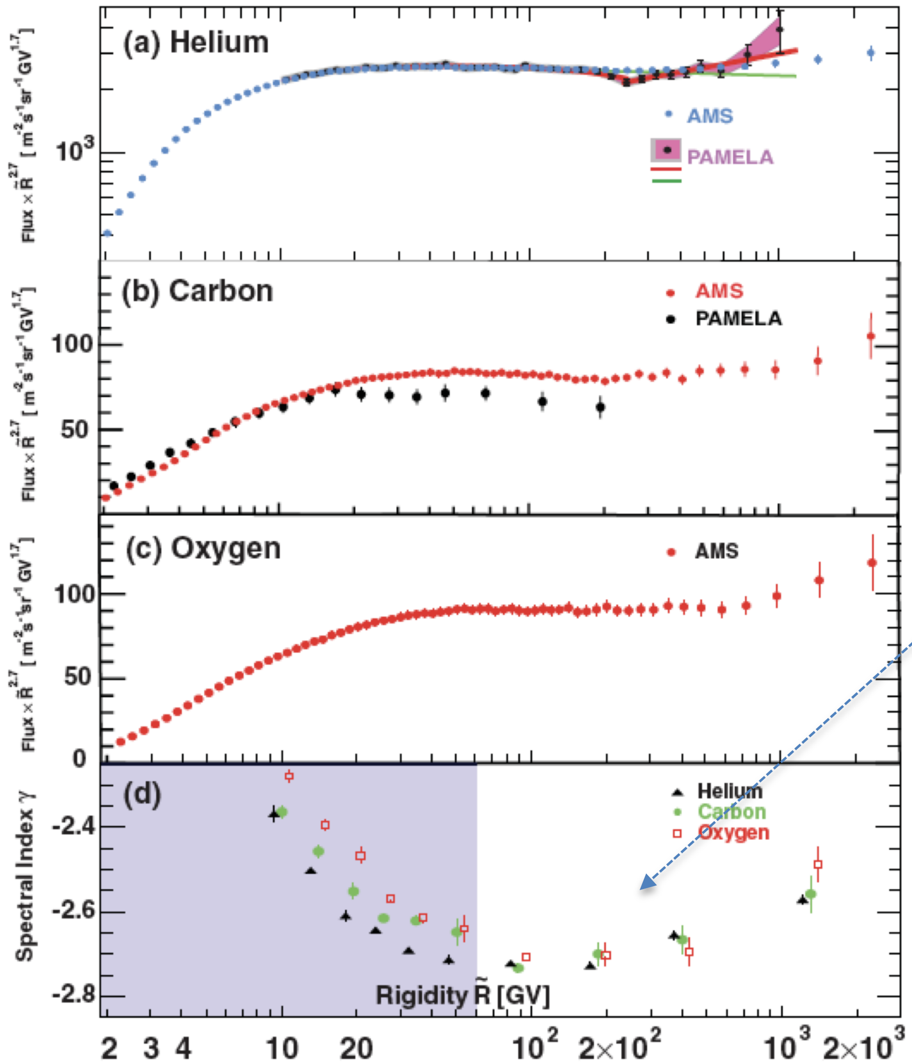


Very good agreement between exps

	fit range proton	γ_p	fit range He	γ_{He}
PAMELA	80-230 GV	-2.844±0.02	80-250 GV	-2.753±0.03
AMS-02	45-330 GV	-2.816±0.006	45-250 GV	-2.743±0.006

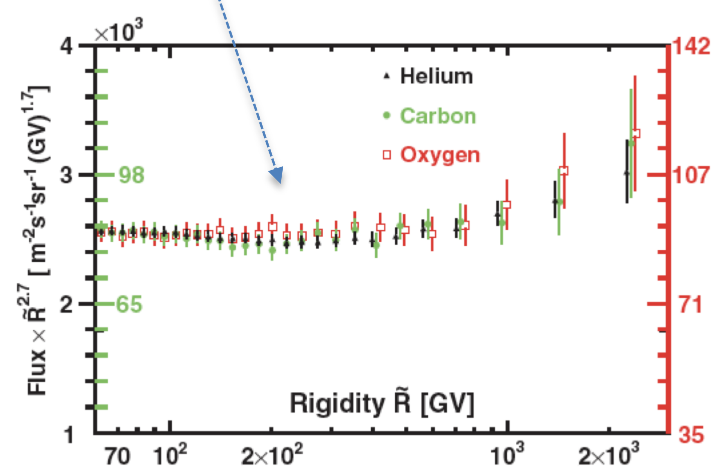
With PAMELA and AMS we entered a hera of high precision measurements !

AMS-02: Helium, Carbon, Oxygen

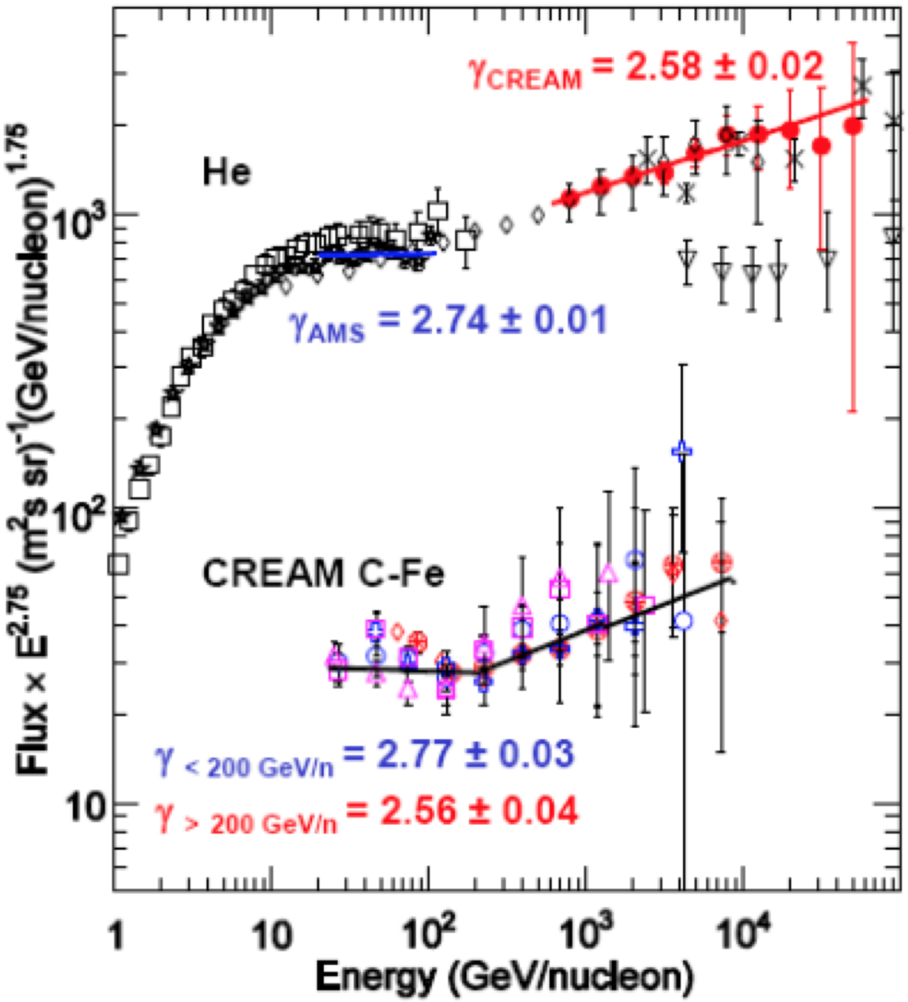


Spectral break occups in the 3 primary components at R above 200 GV!

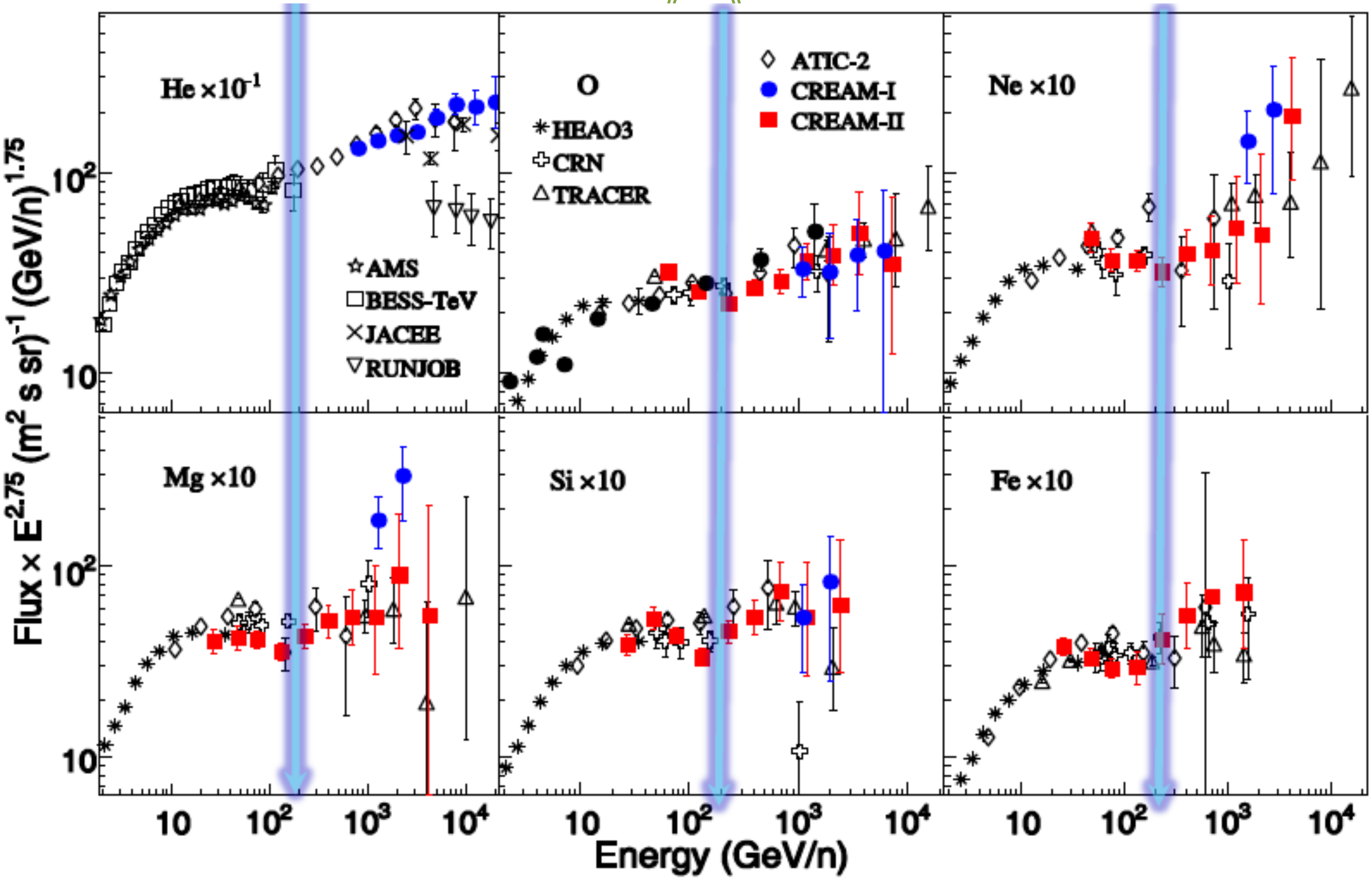
The 3 primary spectral index has the same rigidity dependence above 60 GV.



CREAM: C-Fe nuclei



ATIC, CREAM: He-Fe nuclei



Possible interpretations

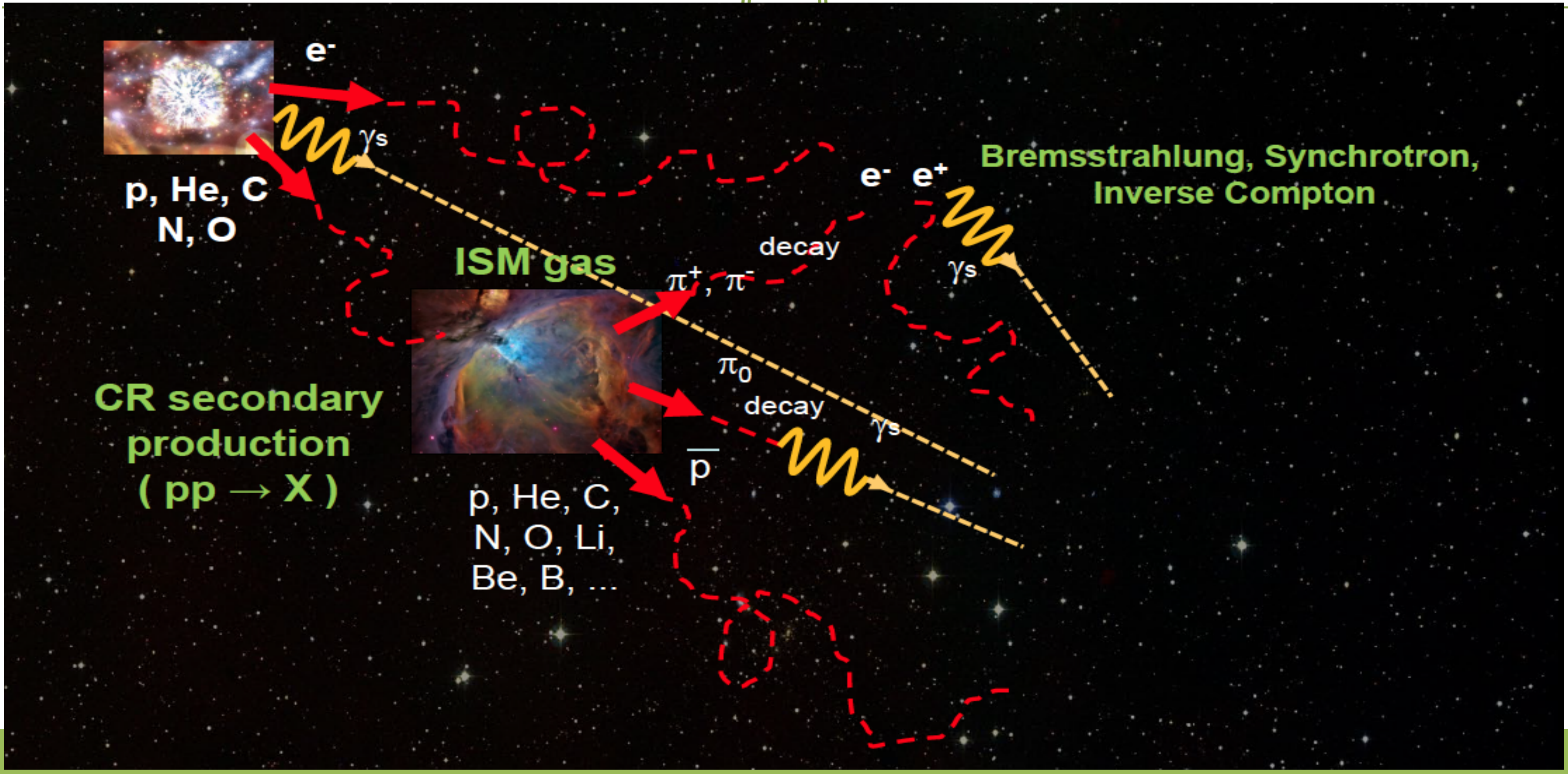
Broken power-law:

- Diffusion effects: **power-law at the source** (then non-linear, rigidity dependent diffusion?)
- Acceleration effects: **features already present at the production site** (acceleration by different sources, re-acceleration?)
- **Local sources**: anisotropy then visible?

Important to look at secondaries!
Extension to MultiTeV region!

Secondary cosmic rays:

B/C, Li, Be, B



Importance of Li, Be, B

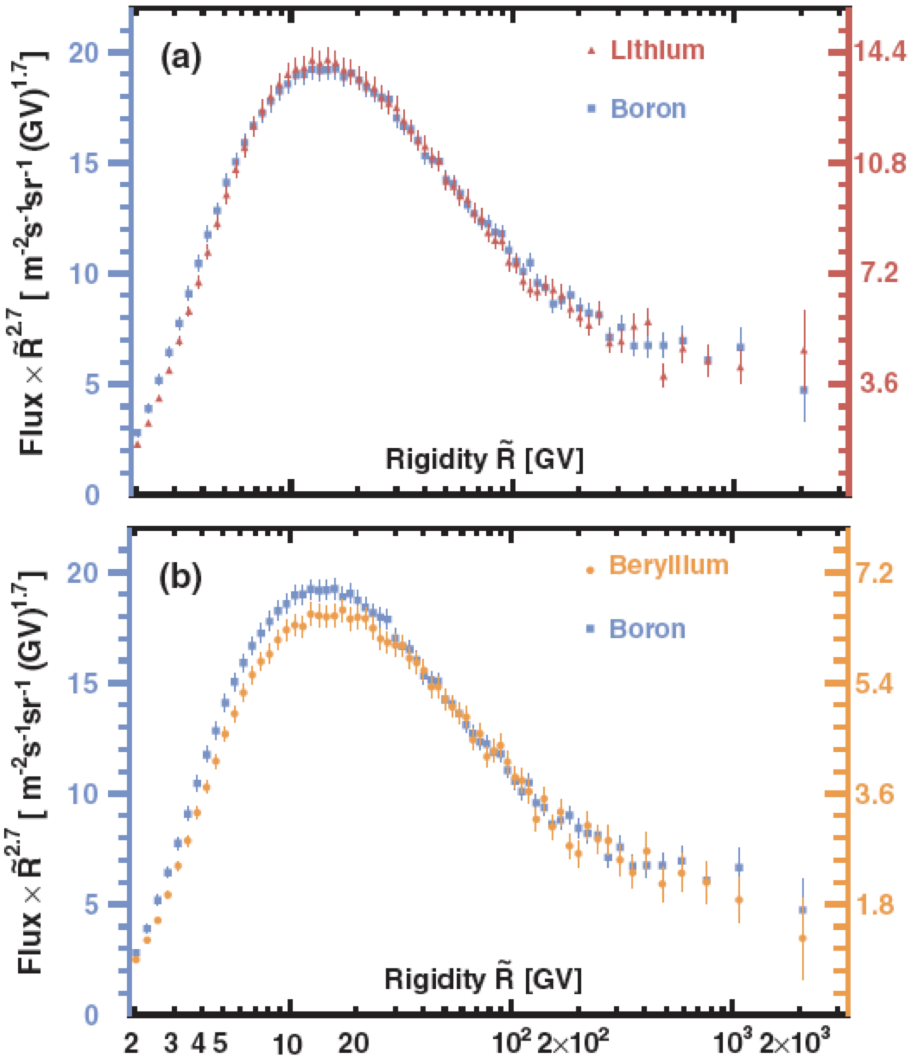
The detailed knowledge of **lithium, beryllium, and boron fluxes** rigidity dependences is important to study the origin of the **hardening in cosmic ray fluxes.**

For example, according to models, if the hardening in cosmic rays is **related to the injected spectra at their source**, then **similar hardening is expected both for secondary and primary cosmic rays**.

However, 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 cosmic rays**.

The theoretical models have their **limitations**, as **none of them predicted the observed spectral behavior of the primary cosmic rays He, C and O.**

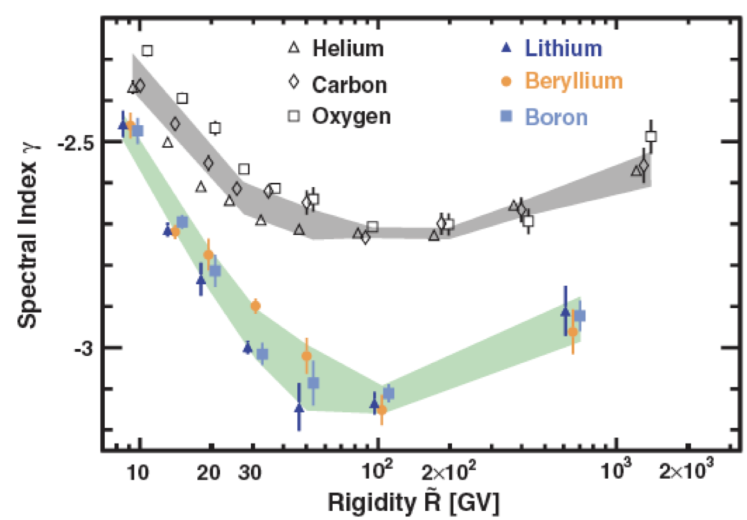
Li, Be, B by AMS



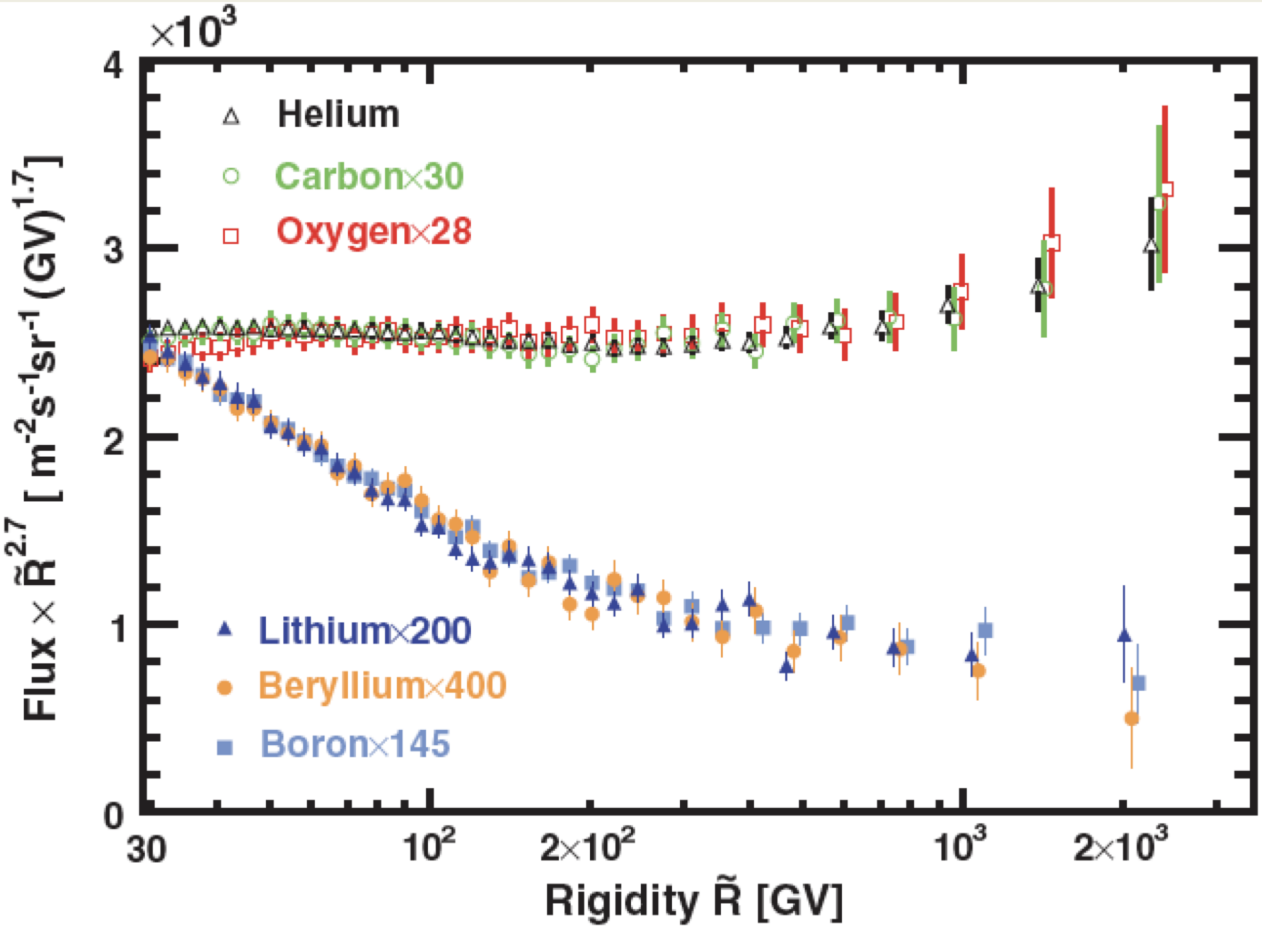
Spectral break **occurs in the 3 secondary components as well, at R above 200 GV**!

The 3 secondary's spectral index **has the same rigidity dependence above 30 GV**.

The rigidity dependence is **distinctly different than for the primaries.**



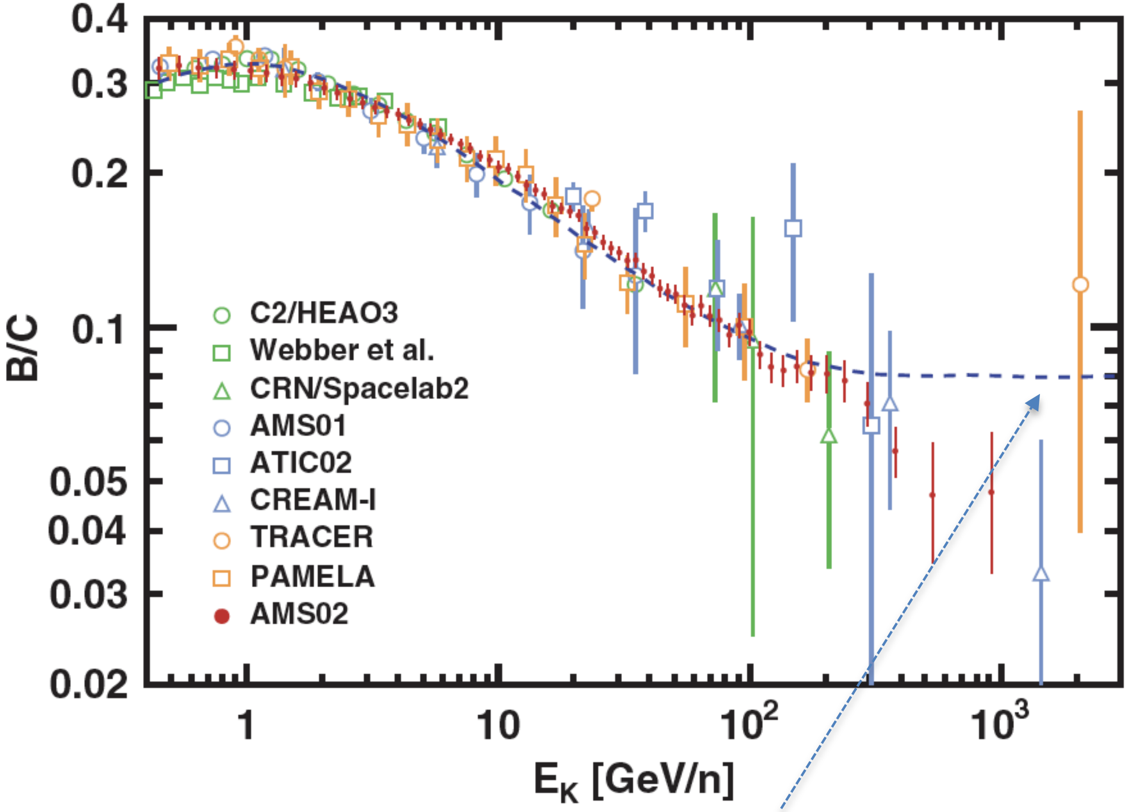
Li, Be, B by AMS



The spectral indices of secondaries **harden by an average of 0.13 more than the primaries**.

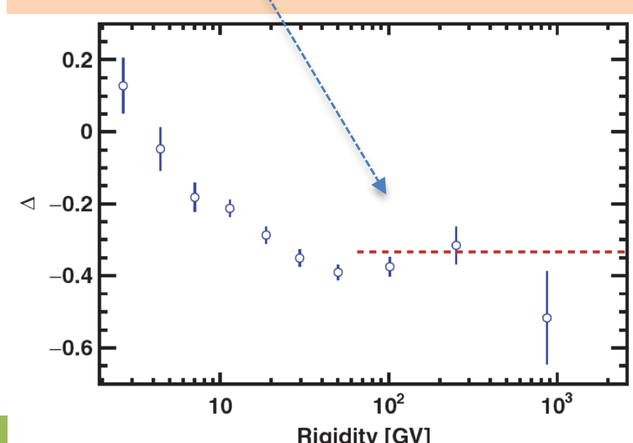
This **additional hardening** is consistent with expectations when the **hardening of cosmic ray fluxes is due to the propagation properties in the Galaxy.**

Boron/Carbon ratio: all data



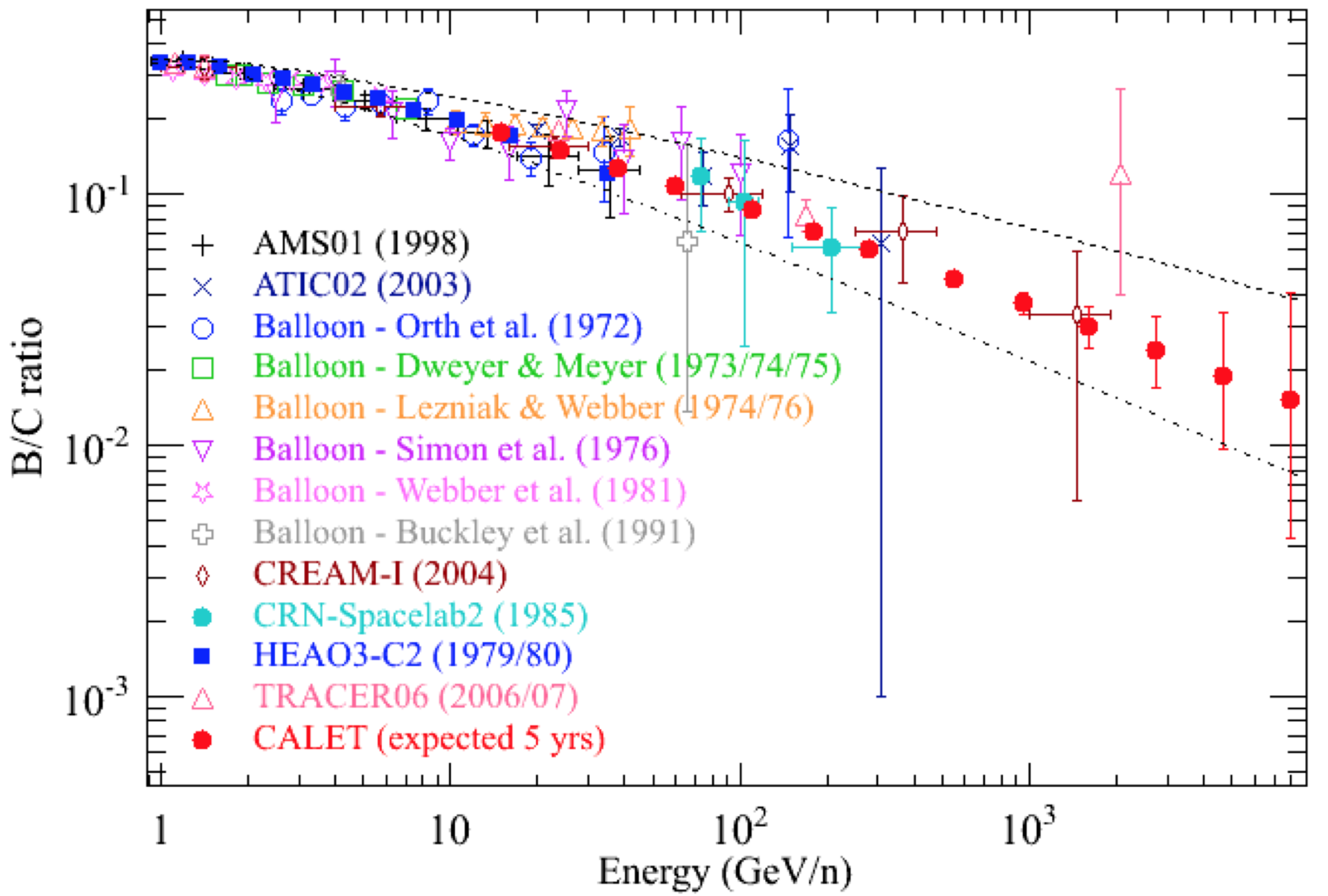
In the B/C ratio no structure at high energy can be seen.

Above 65 GV the AMS B/C ratio can be described by a single power law of $\Delta=-0.333$, in good agreement with the Kolmogorov theory of turbulence which predicts $\Delta=-1/3$ asymptotically.



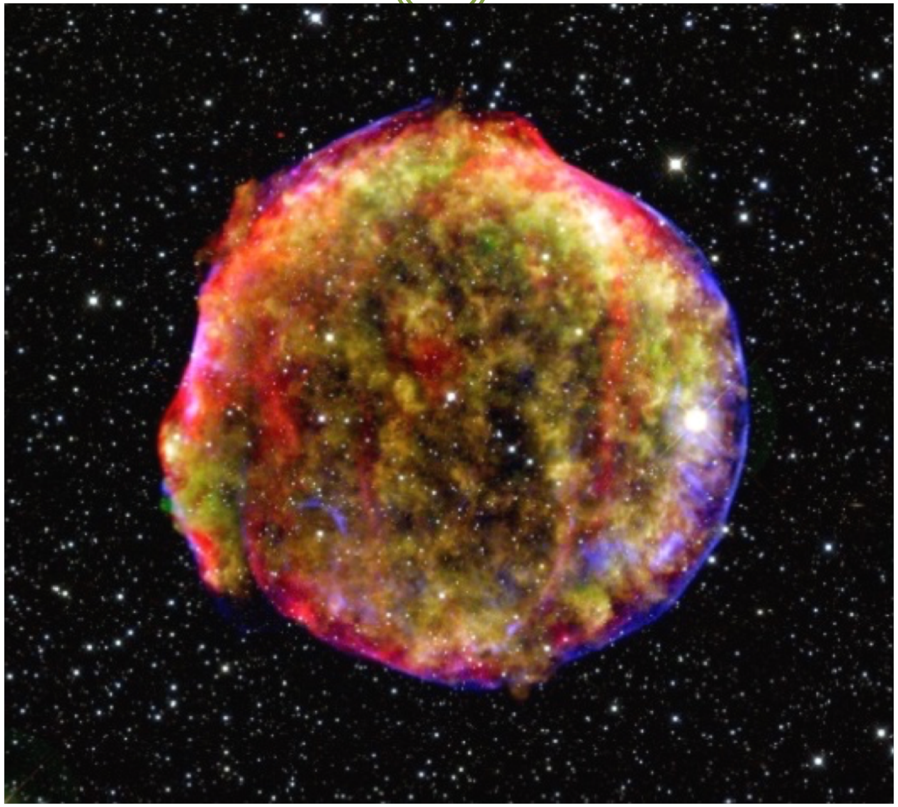
After and He new results, several models were **predicting a deviation from a single power law of B/C.** Independently, such models tried to explain also the <u>positron anomaly.</u>

New data needed at higher energies!



CALET expectations in 5 years

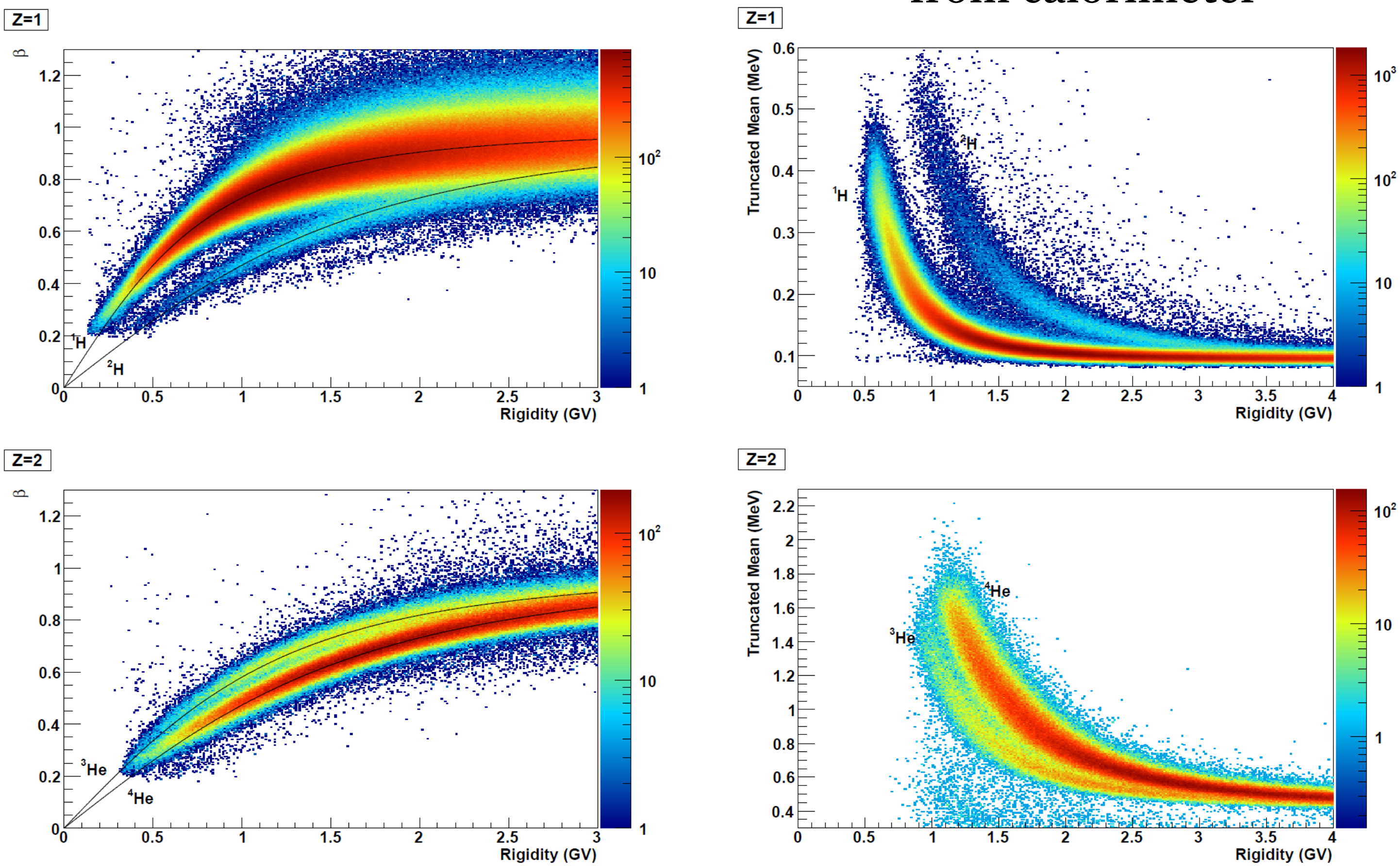
Composition studies



PAMELA: H and He isotopes

β from ToF

Multiple energy deposits from calorimeter



Reduntant identification cababilities

H isotopes

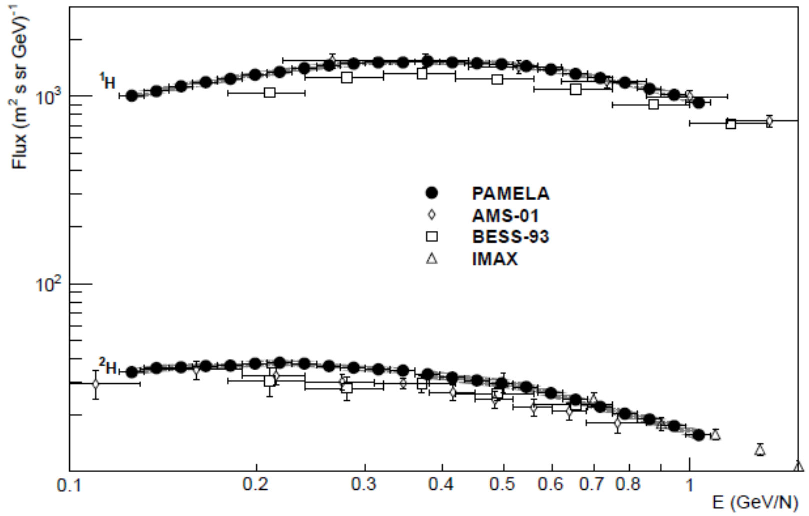
Parameter constraint competitive/complementary to B/C measurement with current instrument precision

Probe different Z/A regime

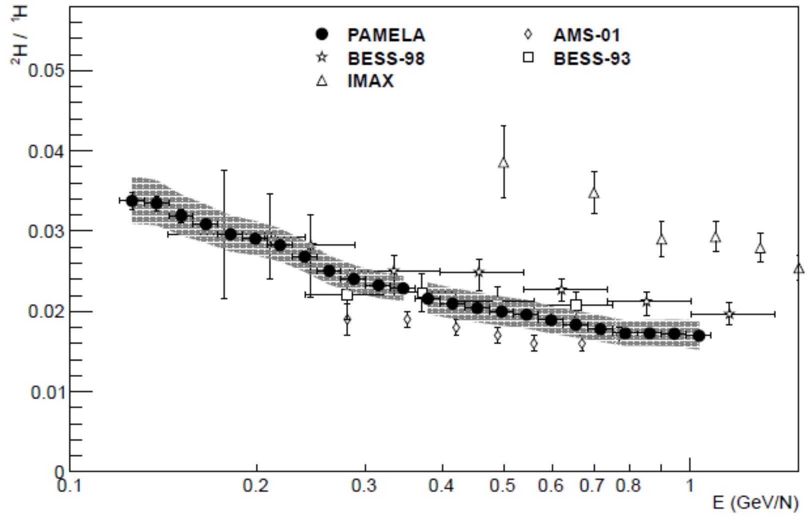
Test «universality» of propagation

(Coste et al. 2012)

Adriani et al – ApJ 218 (2016)



^{1}H → primary



^{2}H → secondary

90% from 4He+1H (40%@1 GeV/n)

He isotopes

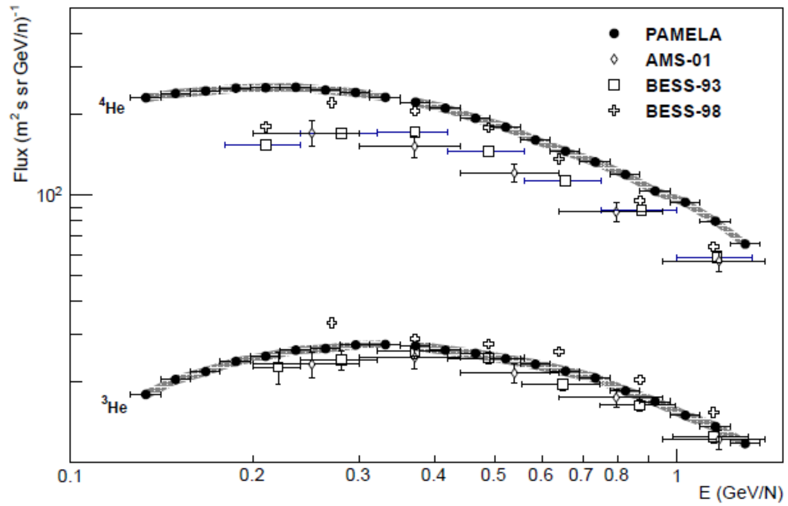
Parameter constraint competitve/complementary to B/C measurement with current instrument precision

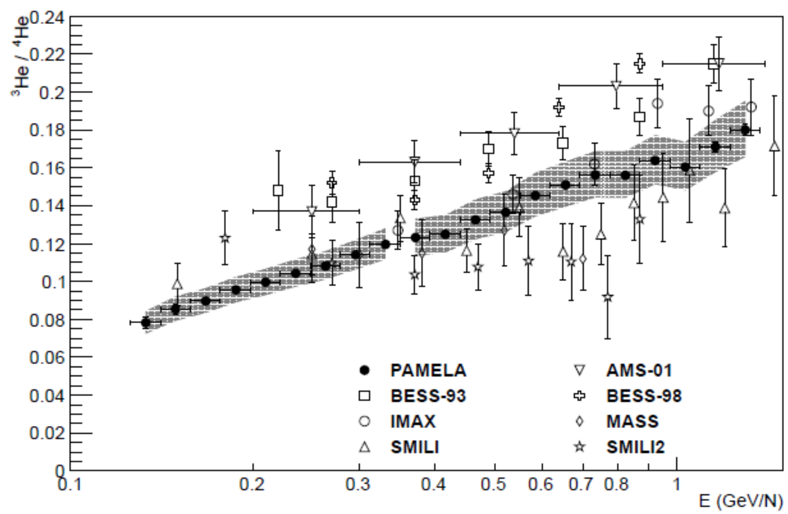
Probe different Z/A regime

Test «universality» of propagation

(Coste et al. 2012)

Adriani et al – ApJ 218 (2016)





^{4}He → primary + secondary

~10% @2 GeV/n from CNO

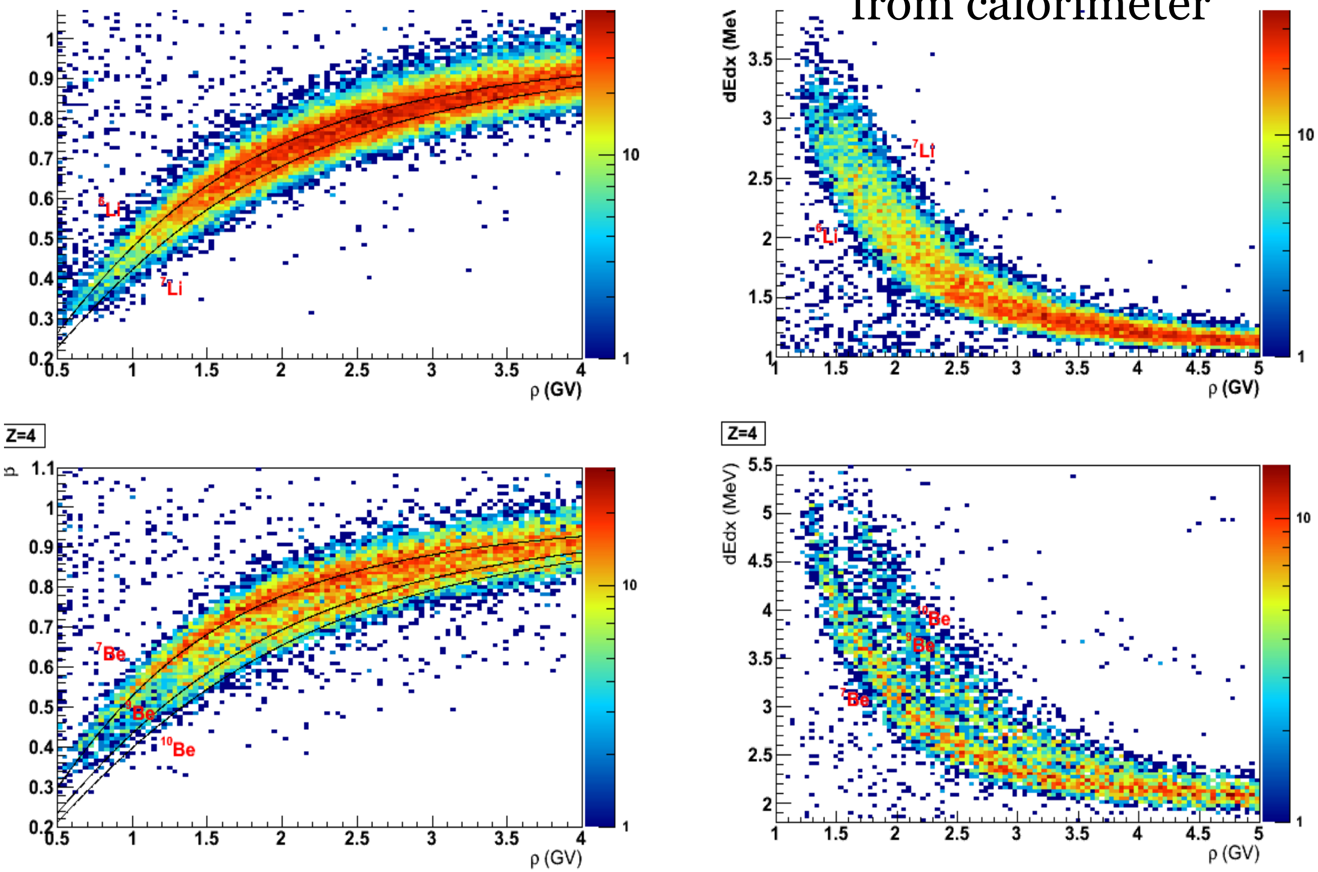
^{3}He → secondary

95% from 4He

PAMELA: Li&Be isotopes

β from ToF

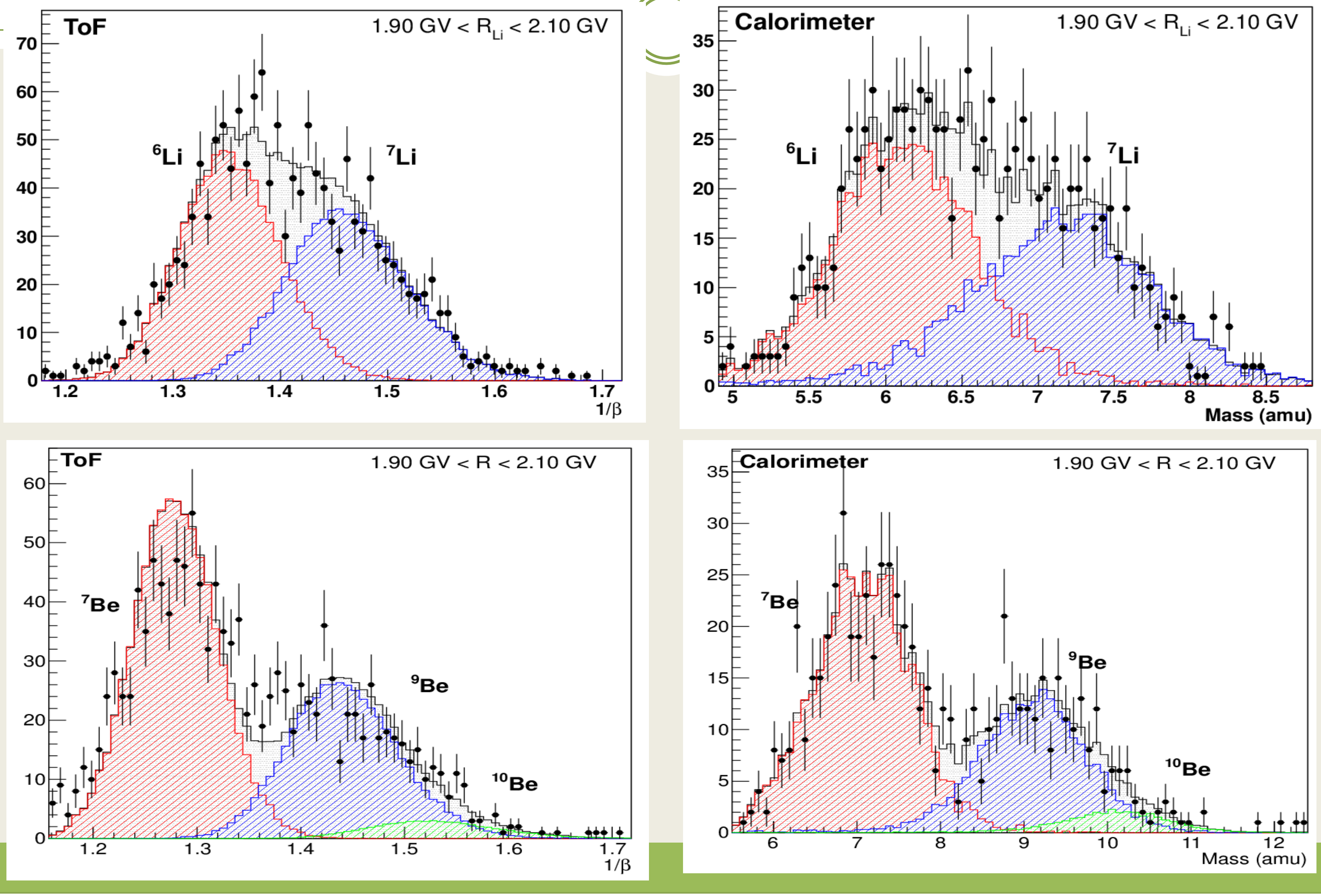
Multiple energy deposits from calorimeter



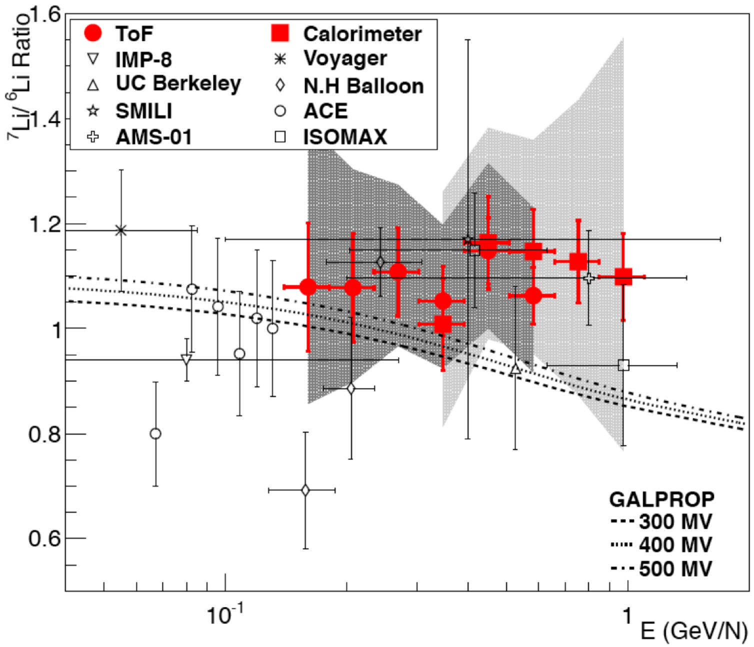
Reduntant identification cababilities

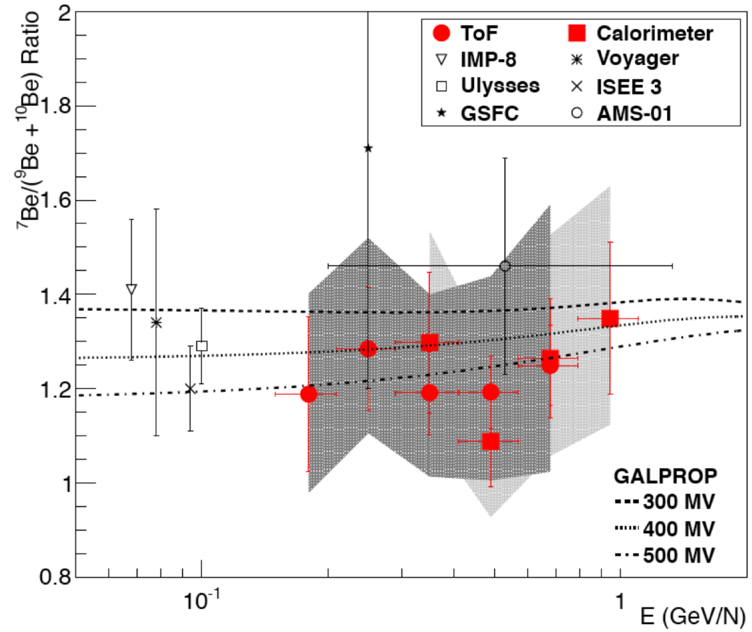
Li and Be isotopes originate mainly from **«secondary»** interaction of high energy C, N and O with the ISM, but also on **«tertiary"** interactions in the ISM (produced by fragmentation of secondary Be and B).

PAMELA: Li & Be isotopes



PAMELA: Li & Be isotope ratios





W. Menn et al., ApJ, in press

In general, good agreement with Galprop simulations. Better for Be, worse for Li at high energies, but models suffer from unprecise cross-sections (expecially for tertiary origin).

TIGER: Ultra Heavy nuclei

Observed elemental and isotopic abundances of GCRs at the TOA are corrected for the effects of fragmentation in the ISM (by means of propagation models) to determine the source abundances, which provide information about:

➢ **the site of acceleration**

- $^{22}Ne/^{20}Ne$ ratio in GCRs is ~5 times (ACE/CRIS, Binns et al. ApJ 634 (2005) 351) higher than the Solar System value.
- Trans-Fe/Fe abundances (TIGER, Rauch et al. ApJ 697 (2009) 2083) show discrepancies with the solar system values ($^{31}Ga/^{32}Ge$ ~1 in GCRs vs. 0.3 in solar system)

These observations :

➔ are consistent with a **CR source mixture of about 20% ejecta of massive stars (including Wolf–Rayet stars and core–collapse supernovae) mixed with 80% material of solar system composition**

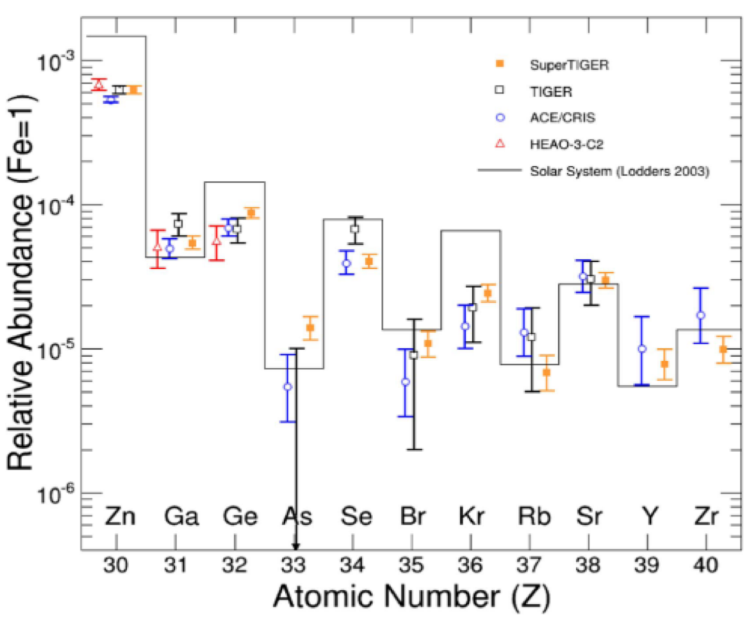
➔ support a model of GCR origin in **OB associations**

↓

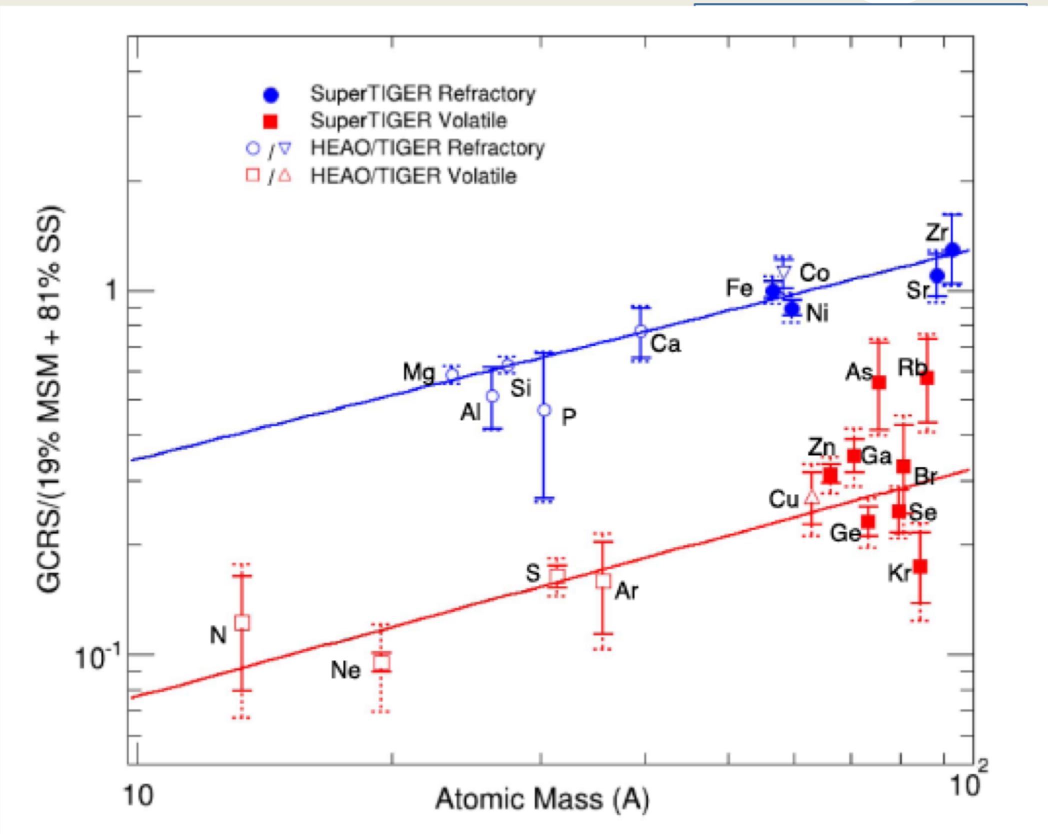
Multiple SN shock acceleration in **superbubbles**

- $E_{max} \approx Zx10^{17}$ eV
- More efficient injection mechanism
- Spectrum hardening at high energy

(Parizot et al. A&A 424 (2004) 747)



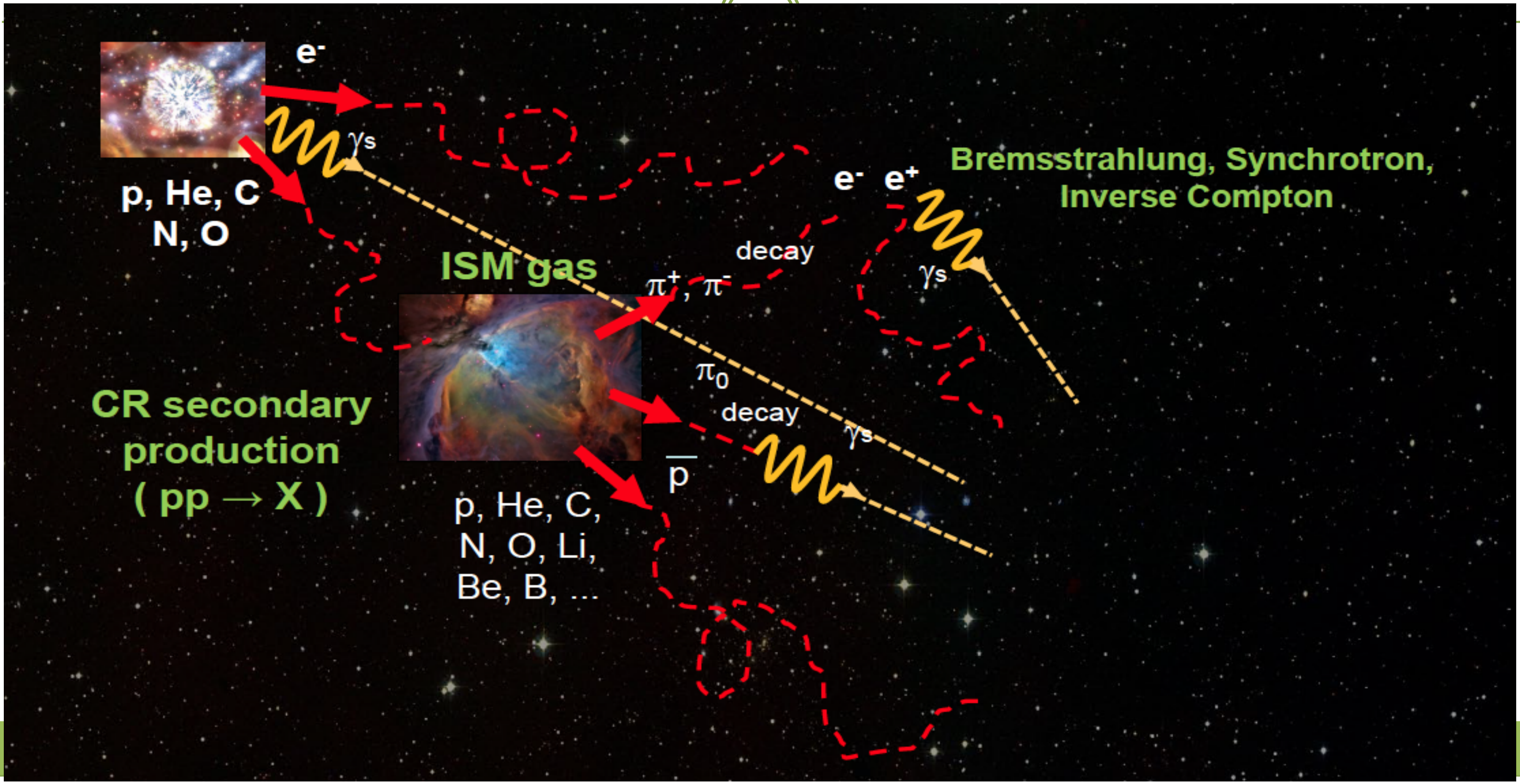
SUPERTIGER: Results



- GCRS calculated using TIGER galactic propagation
- SuperTIGER uncertainties are statistical only
- Lines are from TIGER Rauch et al. ApJ 697, 2083, 2009

CONFIRMATION OF TIGER RESULTS!

Electrons & Positrons



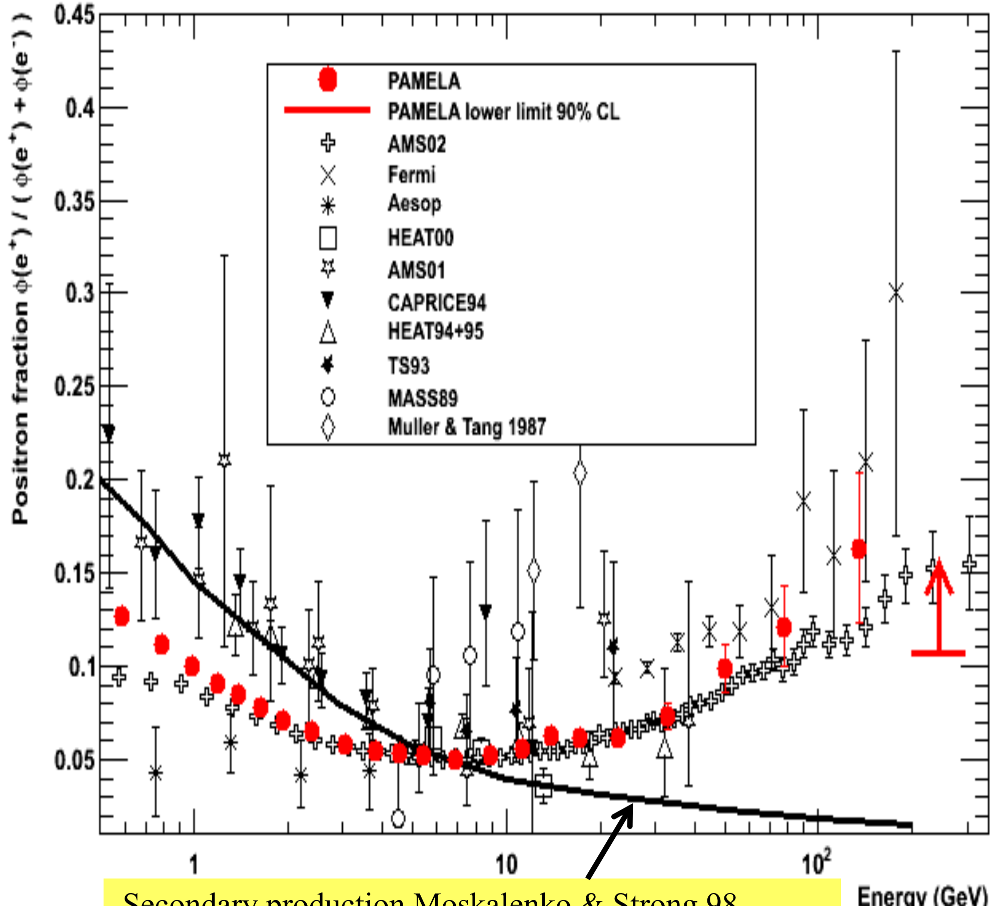
PAMELA: Positron fraction

Adriani et al. , Nature 458 (2009) 607
Adriani et al., AP 34 (2010) 1

Low energy
→ charge-dependent solar modulation

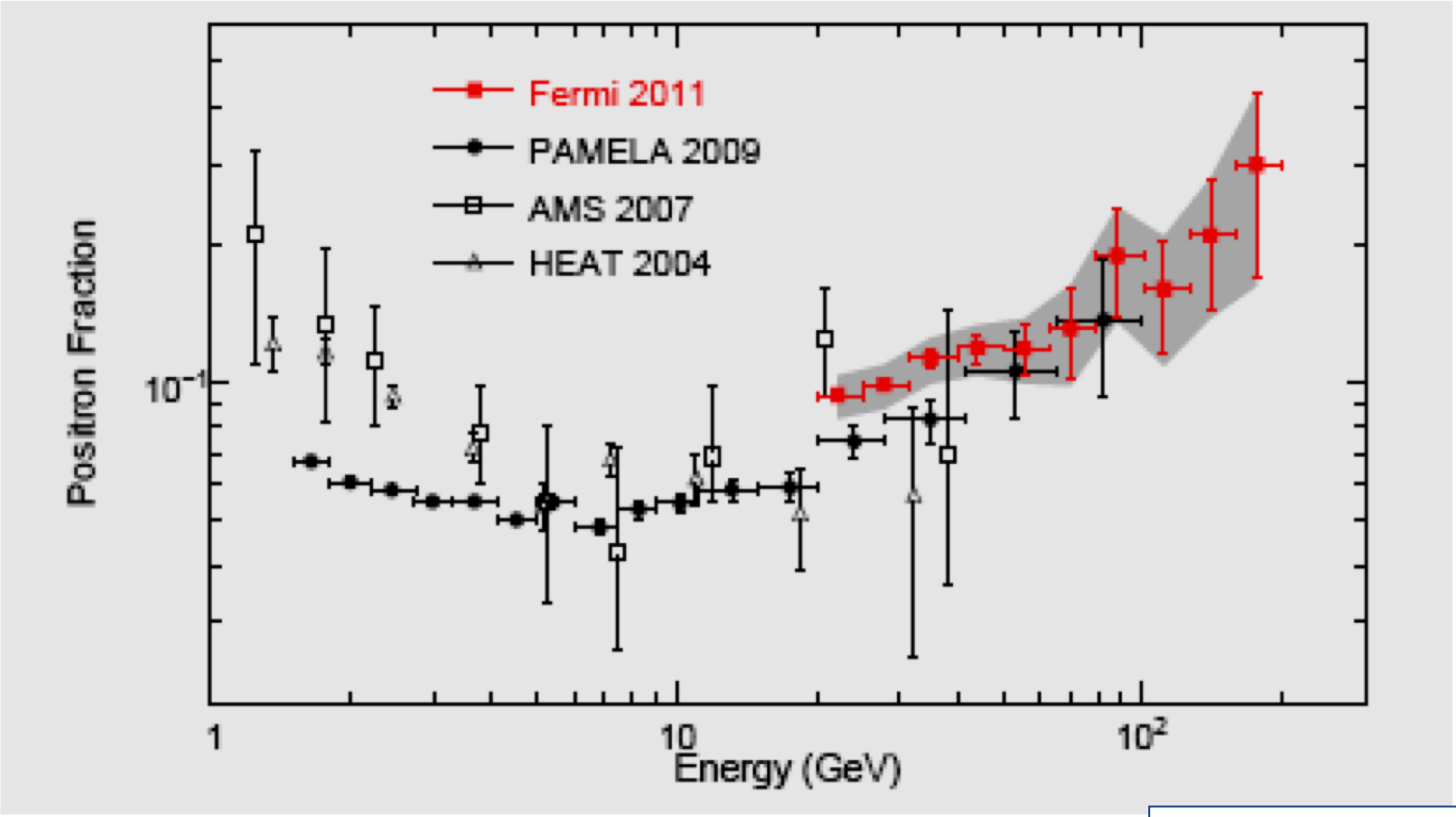
High energy
→ (quite robust) evidence of positron excess above 10 GeV

CLEAR evidence for deviation from secondary production

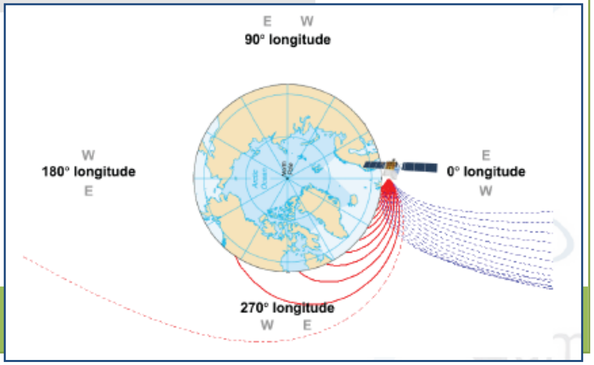


Secondary production Moskalenko & Strong 98

FERMI: Positron Fraction

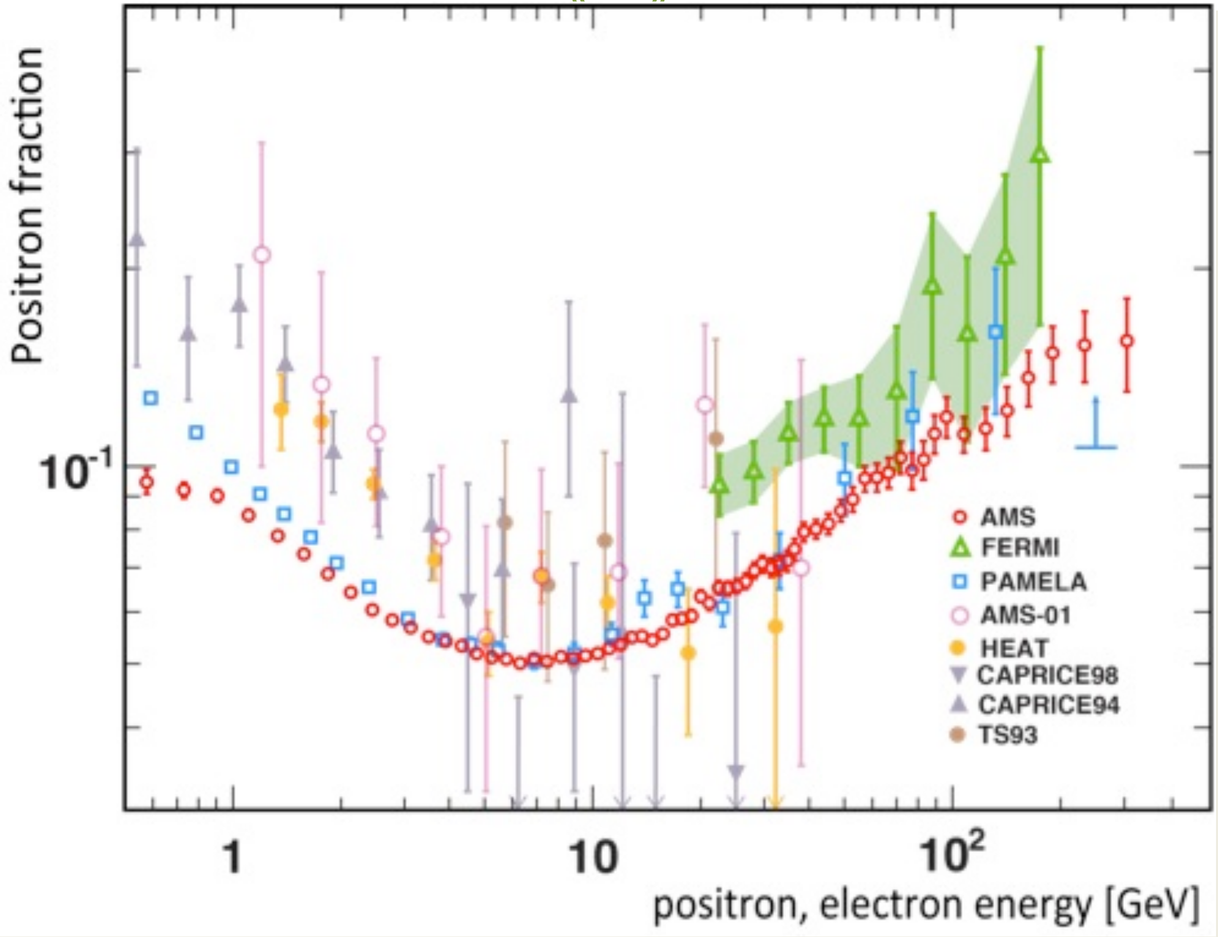


Confirmation of PAMELA positron excess



AMS: Positron fraction

M. Aguilar et al, PRL 110, 2013



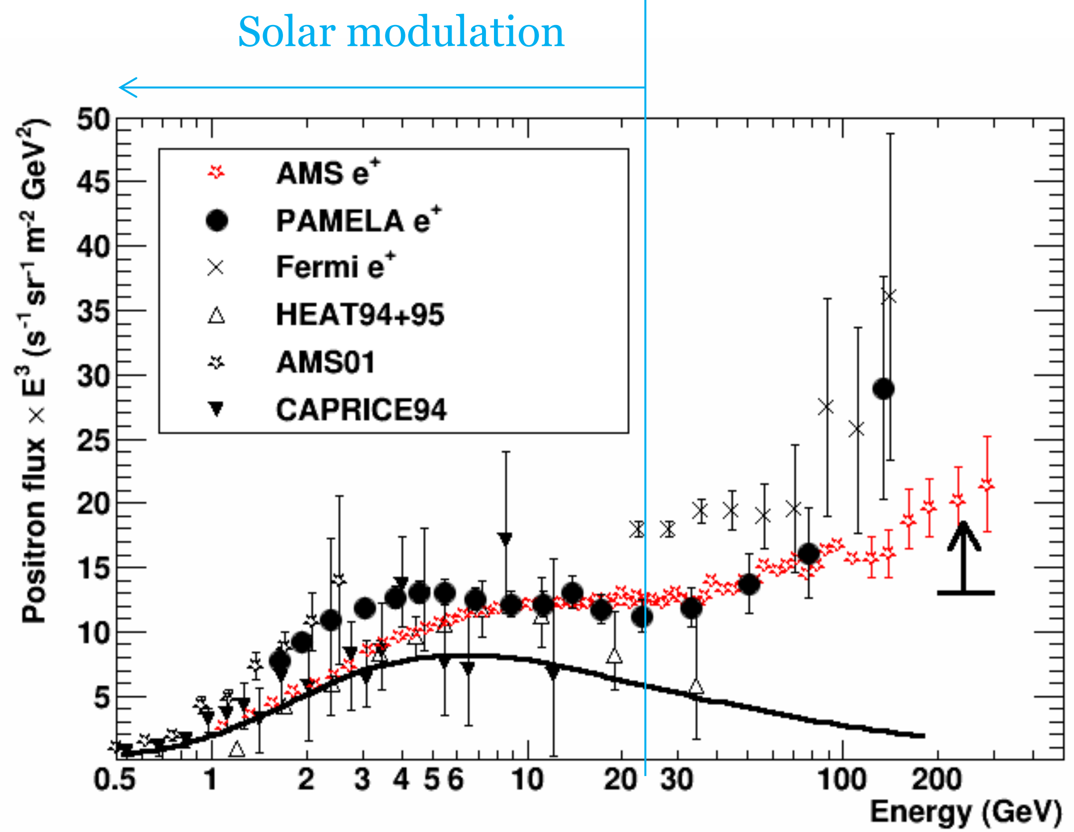
Further confirmation of the positron fraction excess

PAMELA & AMS: Positron flux

Adriani et al. , PRL 111 (2013) 081102

Clear evidence →

The positron fraction increase is due to an harder positron spectrum and not to a softer electron one.



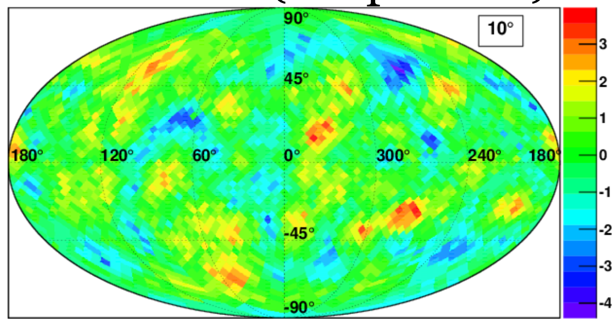
In the highest bin a lower limit has been estimated with 90% confidence level, due to a possible overestimation of the proton contamination.

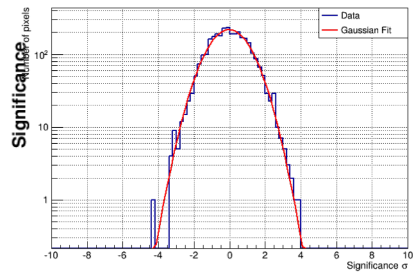
PAMELA:
Anisotropy in e+/e- arrival directions

No evidence for e+/e- anisotropies

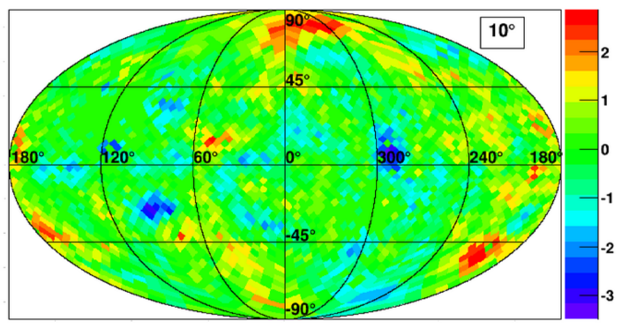
AMS:
Analysis in good progress

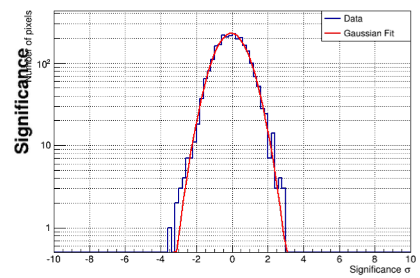
Positrons (bk: protons)





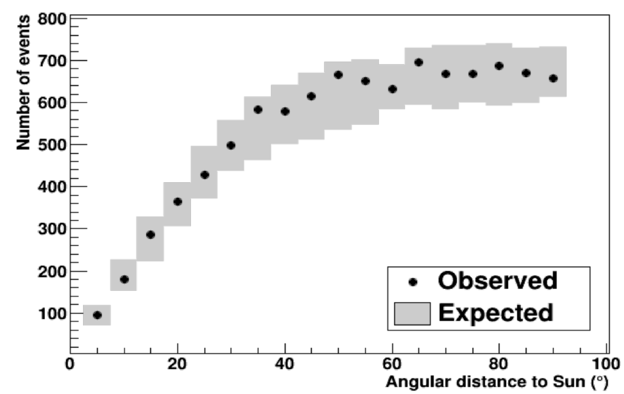
Electrons (bk: MC)



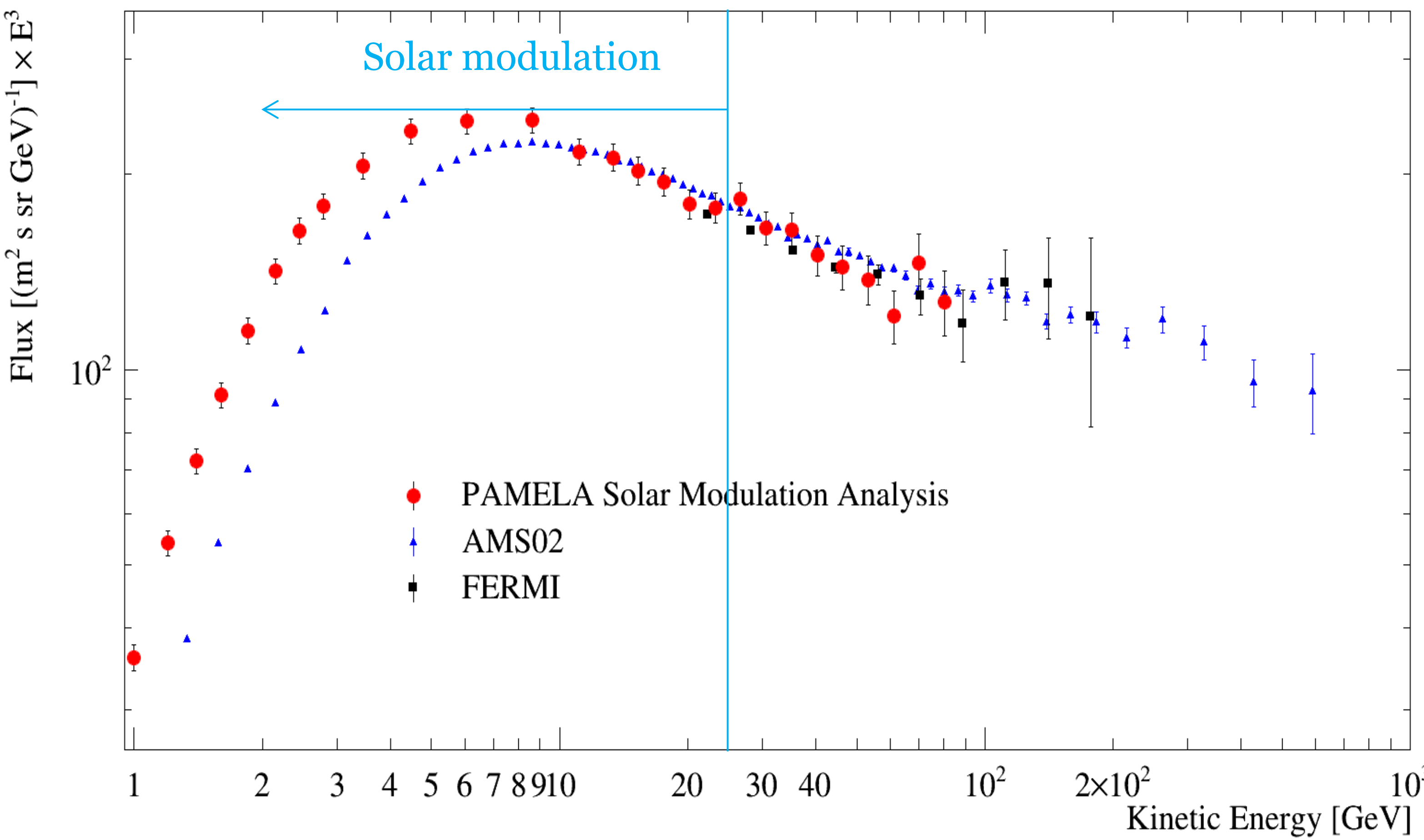


O. Adriani et al., ApJ 811 (2015) 21

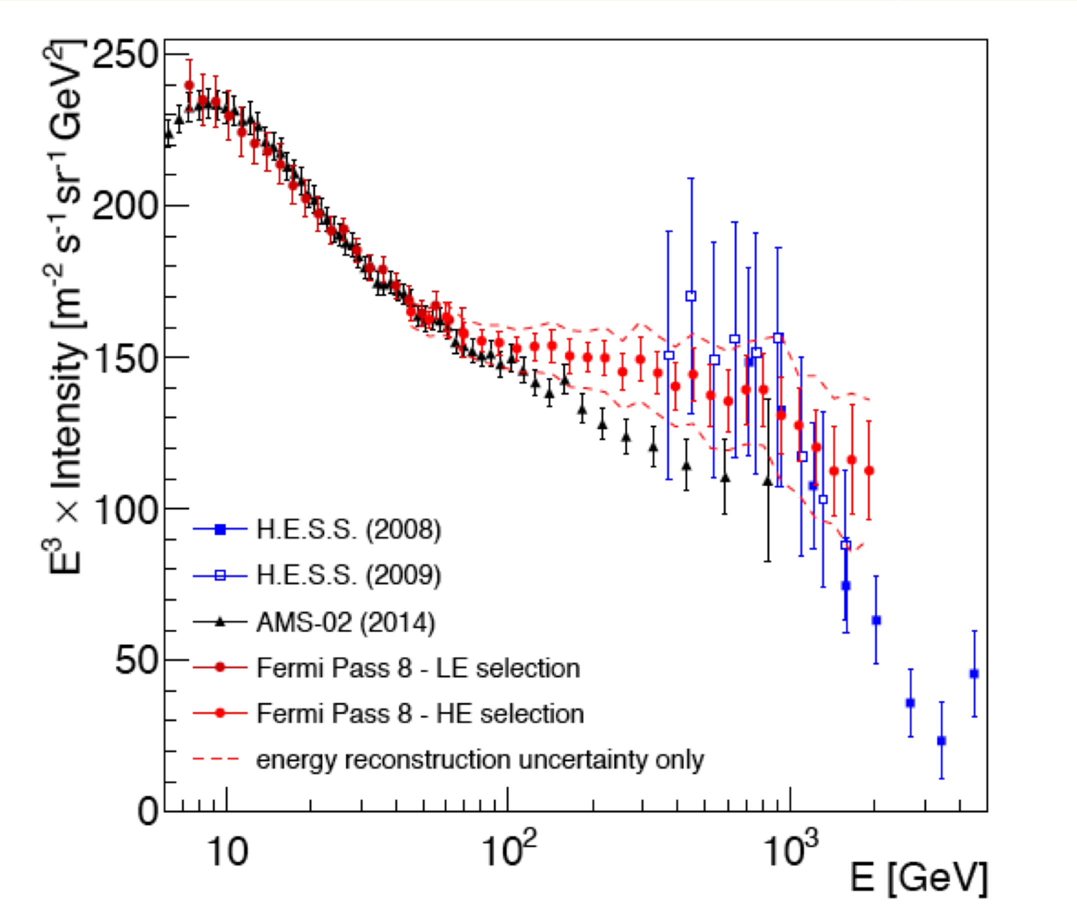
- Significance galactic maps for back-traced positrons and electrons > 10 GeV (angular scale 10°)
- Distribution of angular-distance from the Sun



PAMELA&AMS:
pure electron spectrum



AMS and FERMI: electron+positron flux



AMS flux at high energy:

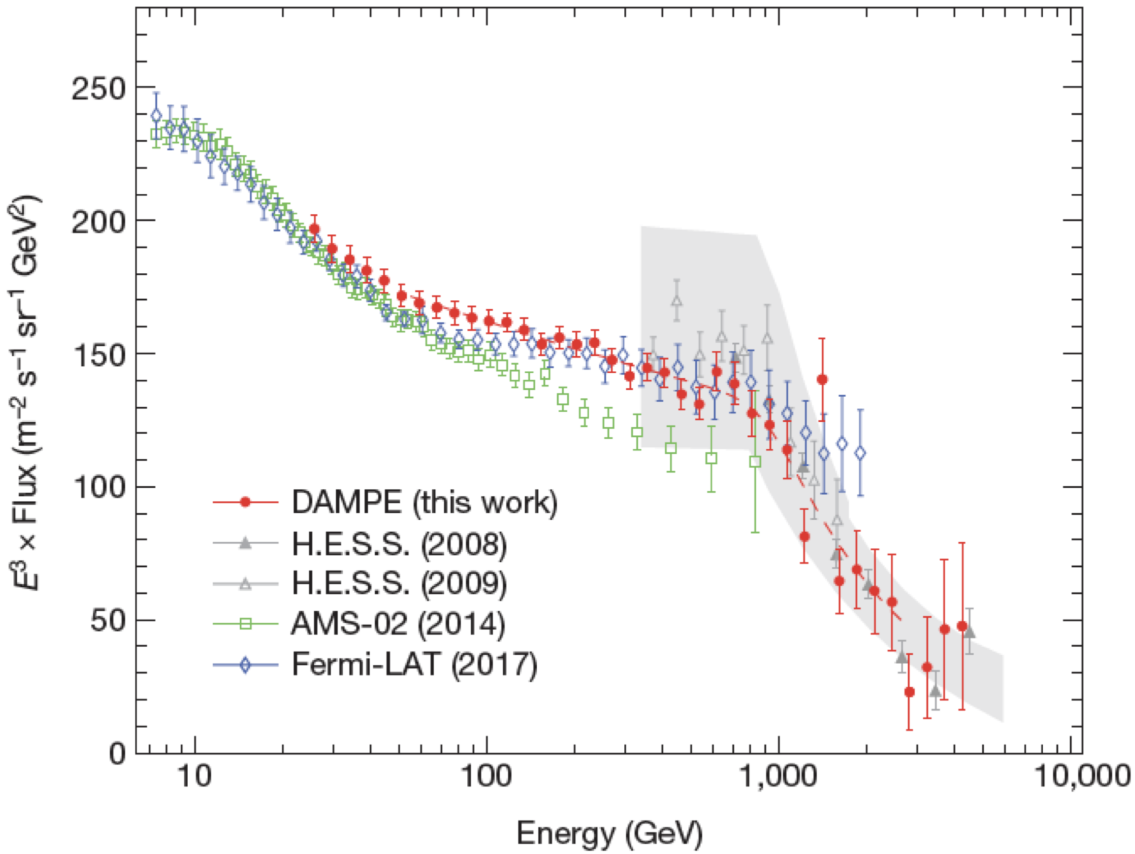
- is **smooth and shows no structures;**
- **single power law > 30 GeV** with spectral index about 3.170

FERMI flux at high energy:

- **broken power-law**
- the break energy is **53 GeV**;
- the spectral indices below and above the break are 3.210 and 3.070, respectively.
- No HESS break at 2.1 TeV.

Abdollahi, S. *et al.* (The Fermi LAT Collaboration). *Phys. Rev. D* **95,** 082007 (2017).

DAMPE all-electron spectrum



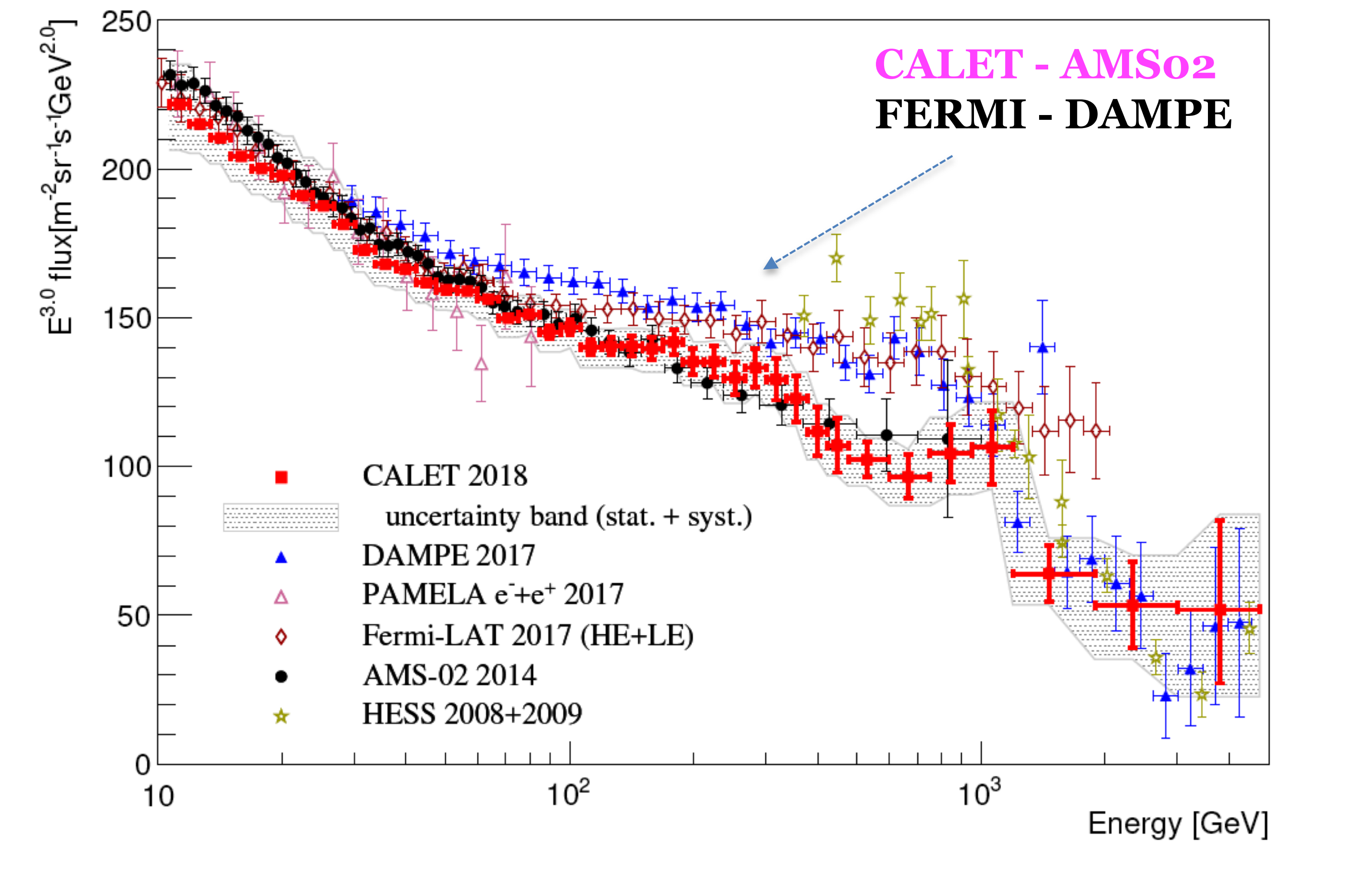
G. Ambrosi et al., Nature 552, 63 (2017).

Spectral hardening at about 50 GeV (agreement with Fermi-LAT).

Data from 55 GeV to 2.63 TeV fit to **a broken power-law model**, with spectral break at ***E* ≈ 0.9 TeV**, with the spectral index changing from $\gamma_1 \approx 3.1$ to $\gamma_2 \approx 3.9$.

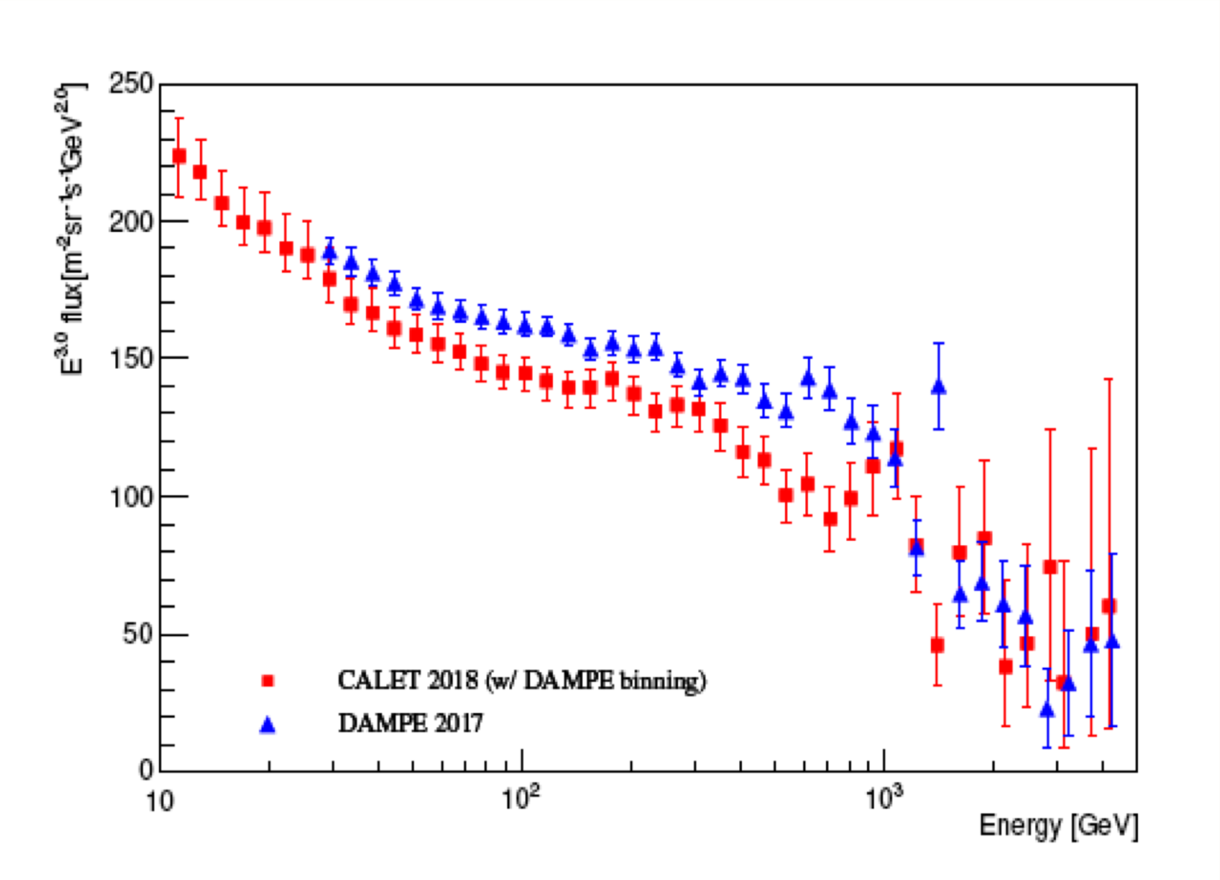
Confirms the previous evidence found by H.E.S.S.

CALET all-electron spectrum



O. Adriani et al, PRL, accepted May 2018

DAMPE - CALET



- Same energy binning;
- Data somehow lower than DAMPE;
- Both single and broken-power law fit possible.

Possible interpretations

Positron excess from astrophysical sources:

- **Pulsars** producing e+e- pairs then accelerated away from the neutron star
- **SNR**
- **Local sources**: 0.1% anisotropy expected at 100 GeV?

Positron excess from exotic sources:

- Though **not excess in antiprotons**, still room for DM exists.

Antiparticles &co.

ANTIPROTONS & ANTIHELIUMS



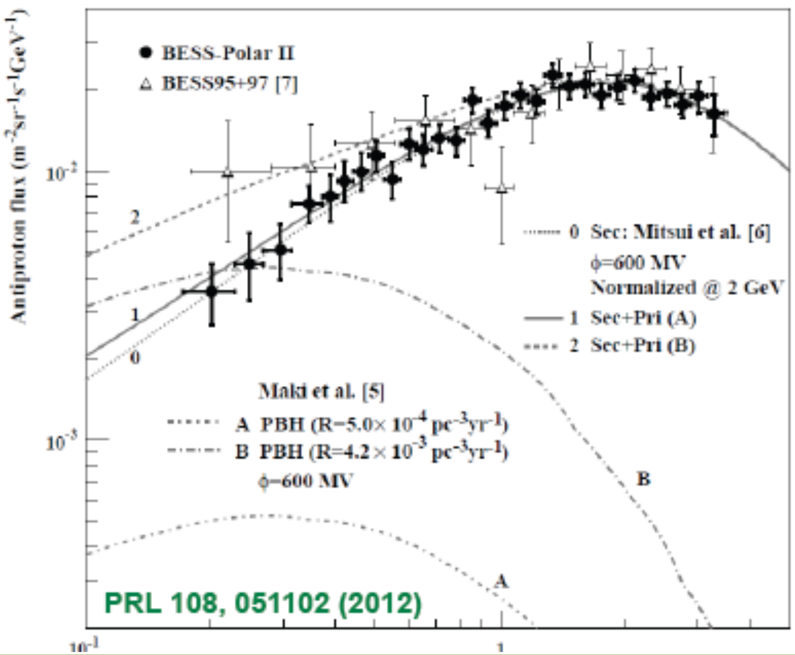
BESS-Polar: Antiproton spectrum

Cosmic-ray antiparticles probe the early Universe

Antiprotons are mainly of secondary origin (i.e. produced in CR interactions with ISM)

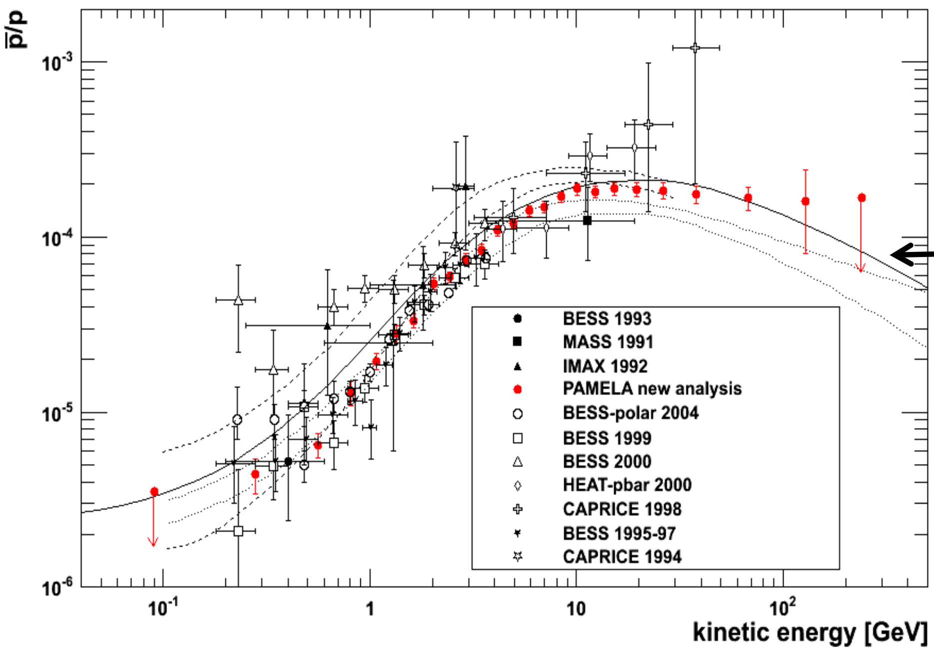
Possible small primary component:

- Evaporation of primordial black holes (PBH)
- Decay of dark-matter particles?



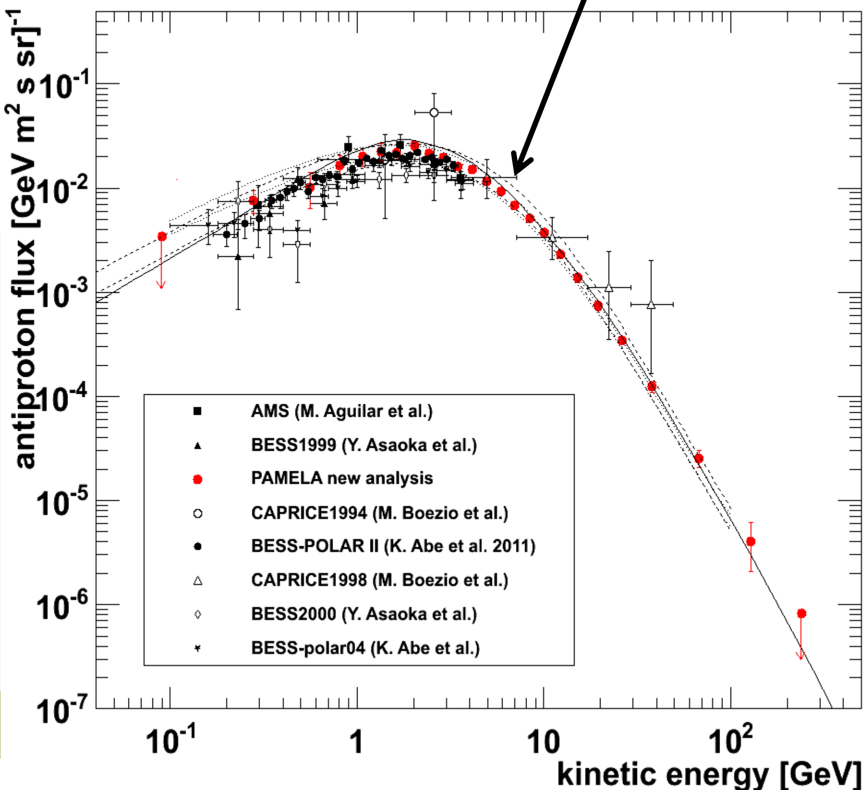
- BESS (95+97) Solar min. data show a possible *flattening of the antiproton spectrum at lower energies* compared to secondary production, suggesting possible excess.
- BESS-Polar I data taken at higher solar activity 851 MV are consistent with secondary production, as expected.
- BESS-Polar II detected 7886 antiprotons at Solar minimum: **no evidence of primary antiprotons from evaporation of primordial black holes.**

PAMELA : Antiprotons

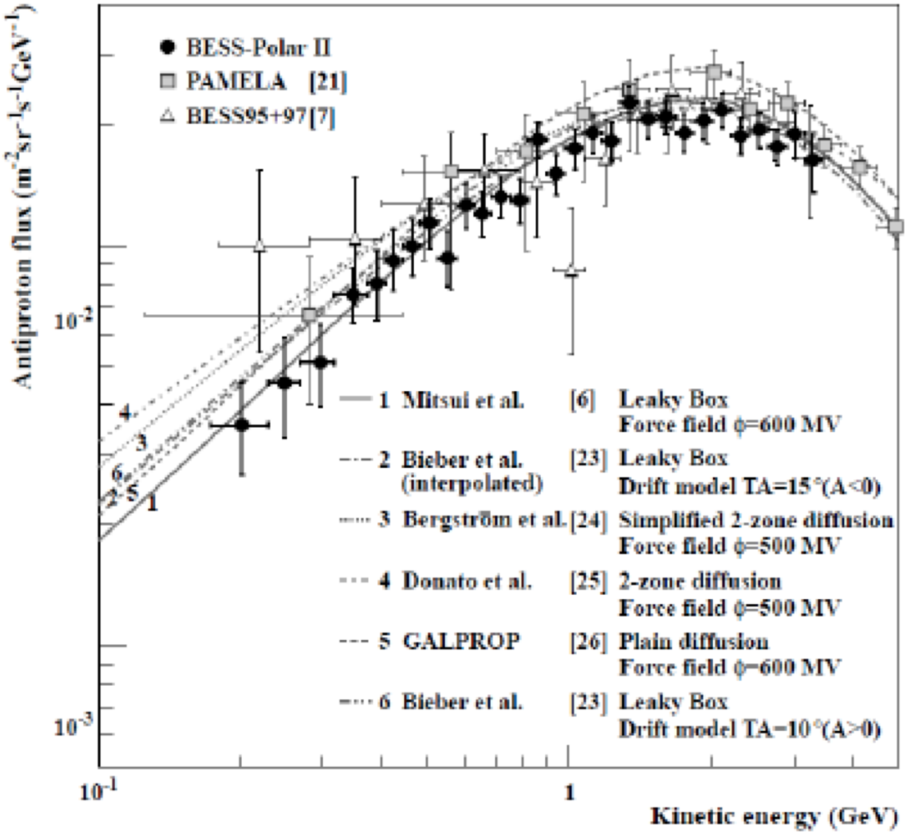


O. Adriani et al,
PRL 102 (2009) 051101;
PRL 105 (2010) 121101;
Phys. Rep. (2014).

Secondary production calculations

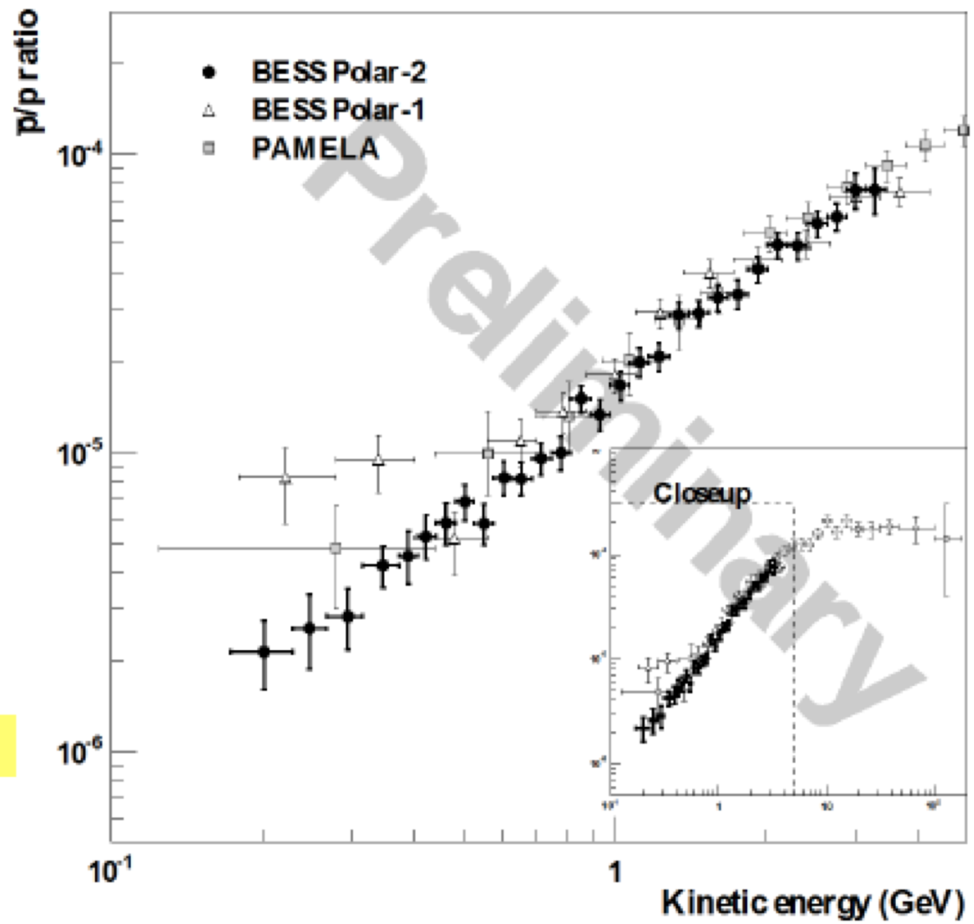


BESS-Polar & PAMELA : Antiprotons

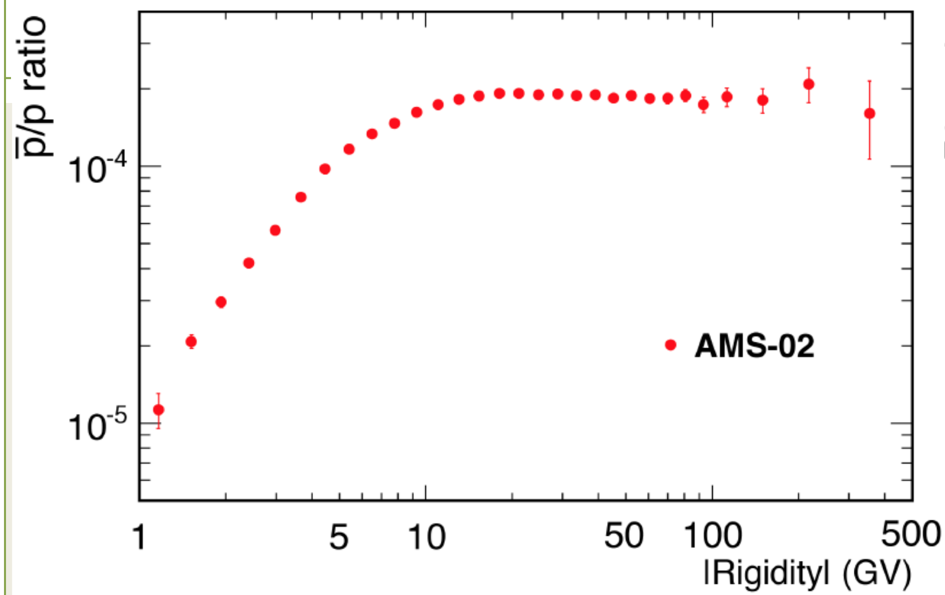


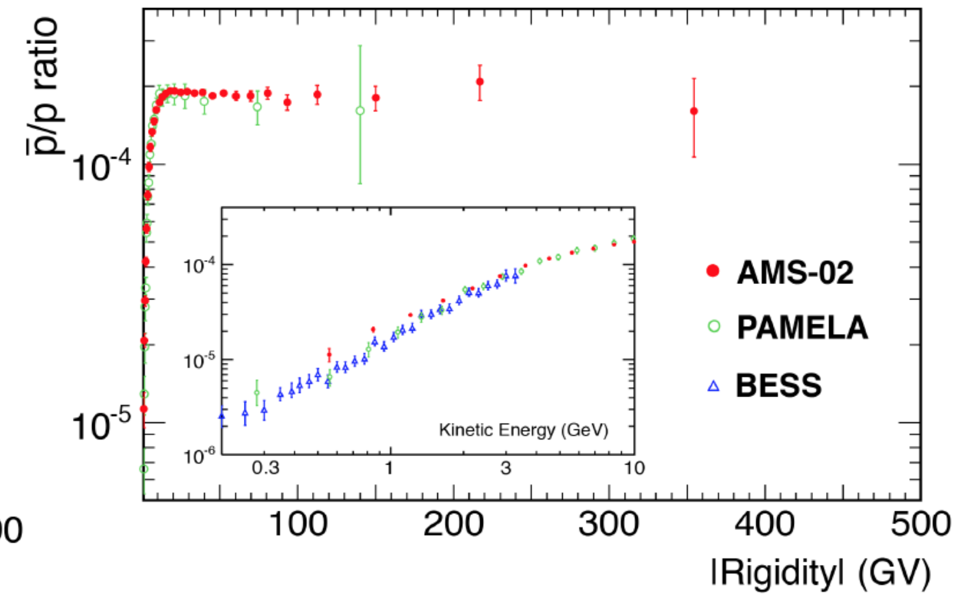
J. W. Mitchell, TeVPA 2013

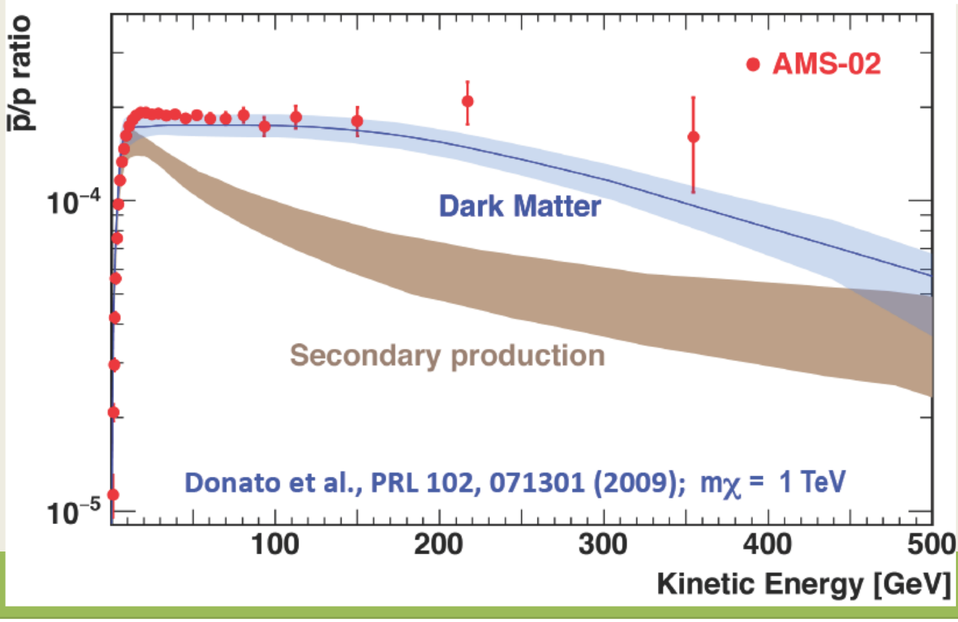
K. Abe et al., PRL 108 (2012) 051102



AMS: Antiproton/proton ratio







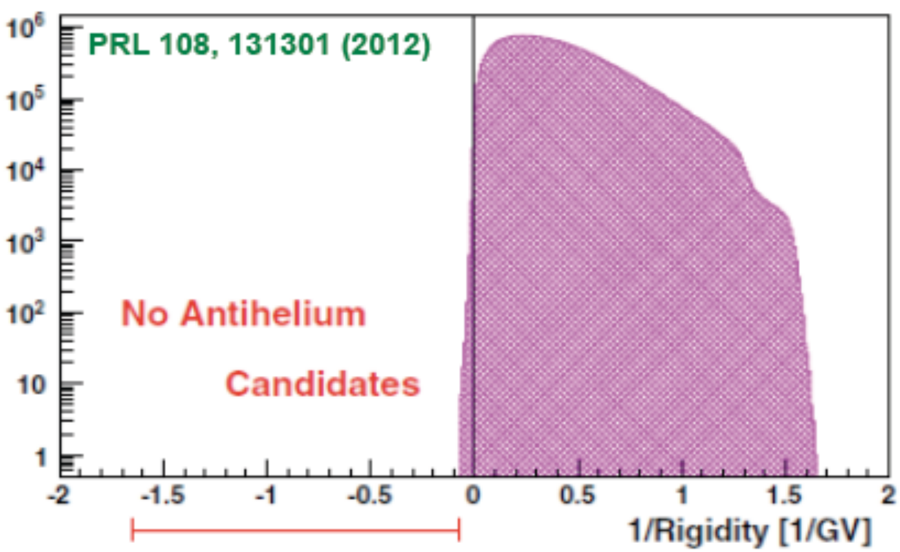
Flat p-bar/p ratio at high energy **can be explained in terms of secondary production** by new propagation models (i.e. taking into account spectral breaks, and updated cross-sections data)

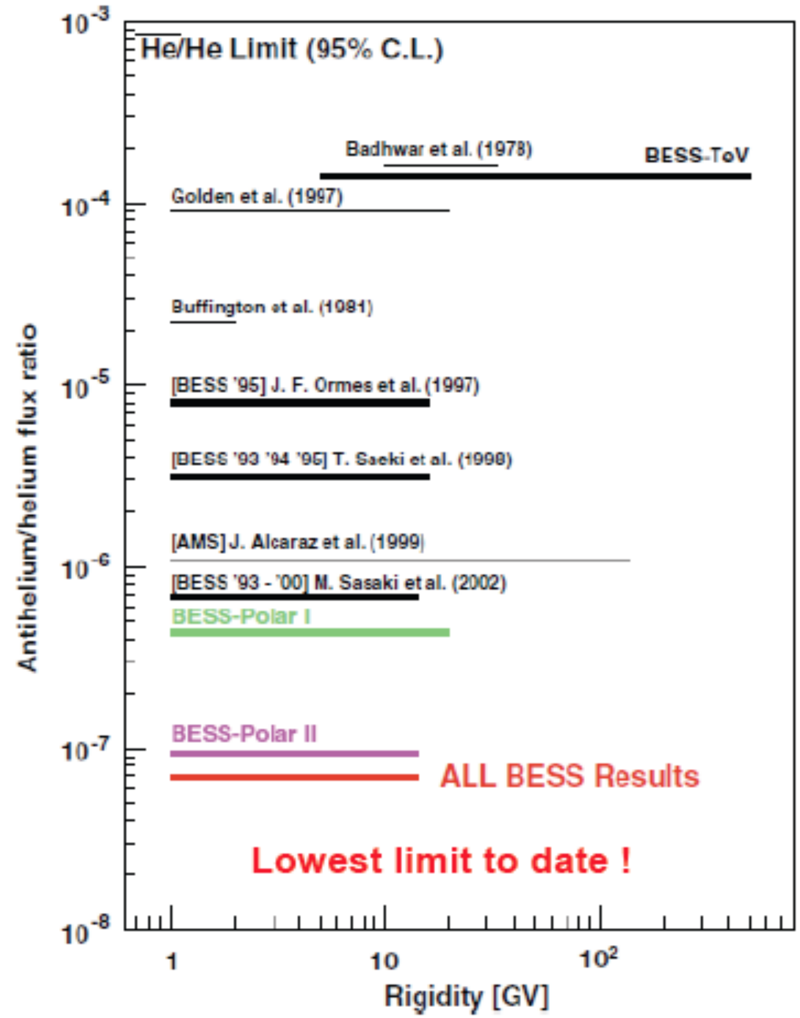
BESS-Polar: Search for antihelium

Asymmetry of particles and antiparticles is one of the fundamental problems in cosmology.

Small antimatter domains from which primordial antinuclei could reach the Earth are not excluded.

(A. D. Dolgov, Nucl. Phys. B, Proc. Suppl. 113, 40)



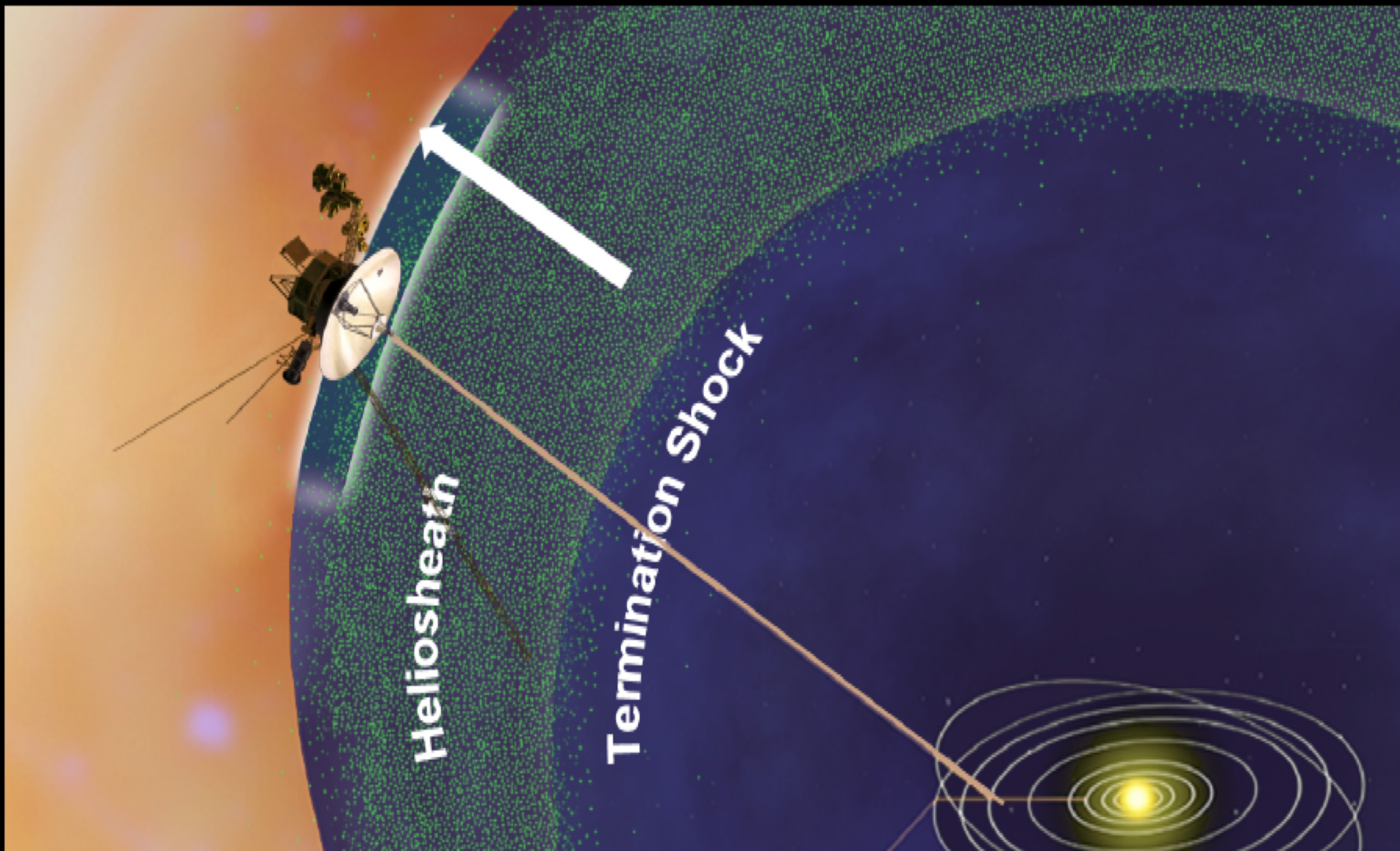


8.4×10^6 |Z|=2 nuclei identified by BESS-Polar I

4.0×10^7 |Z|=2 nuclei identified by BESS-Polar II

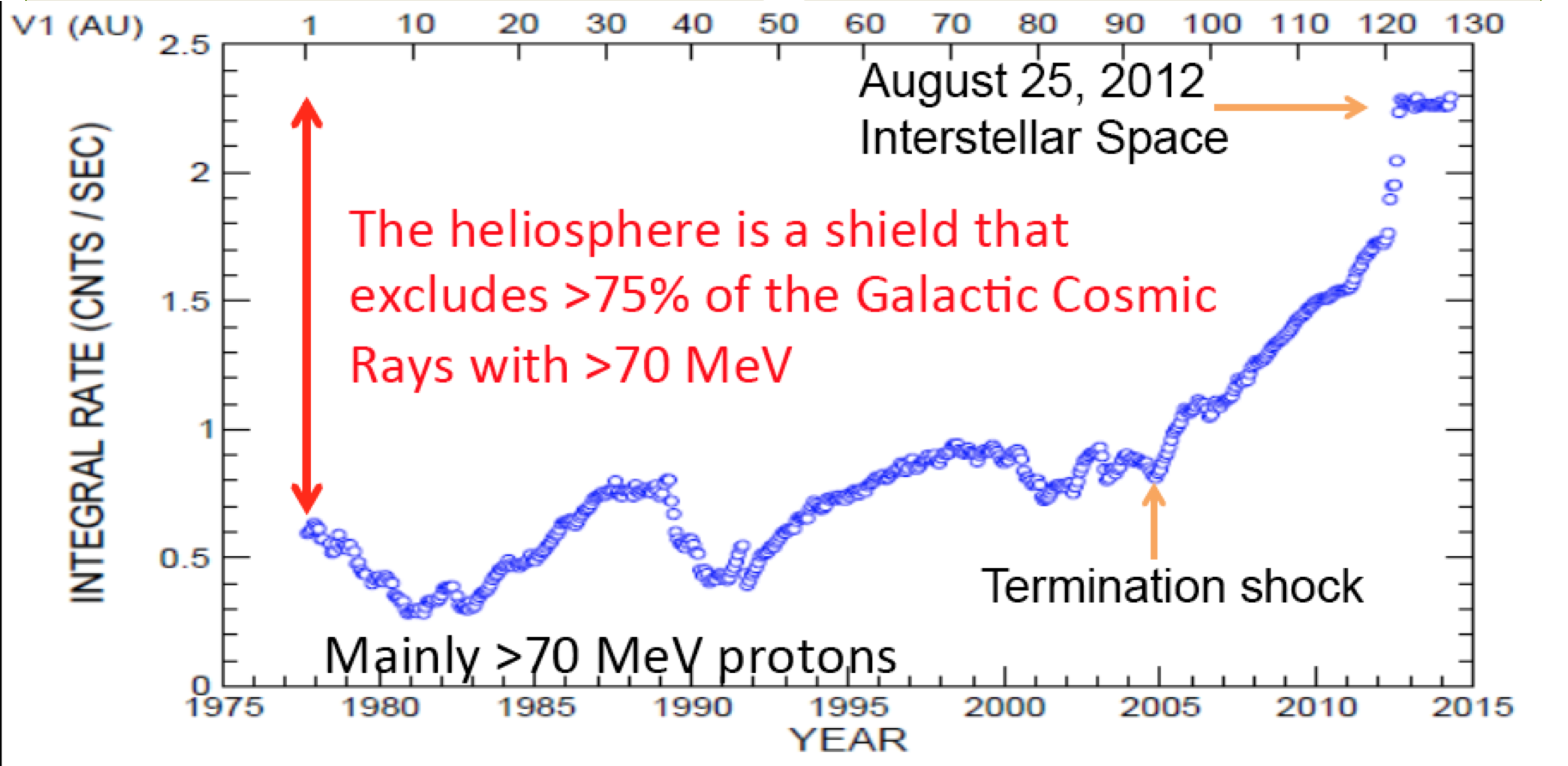
No antiHe candidates were found

In August 2012, Voyager 1 entered the LISM

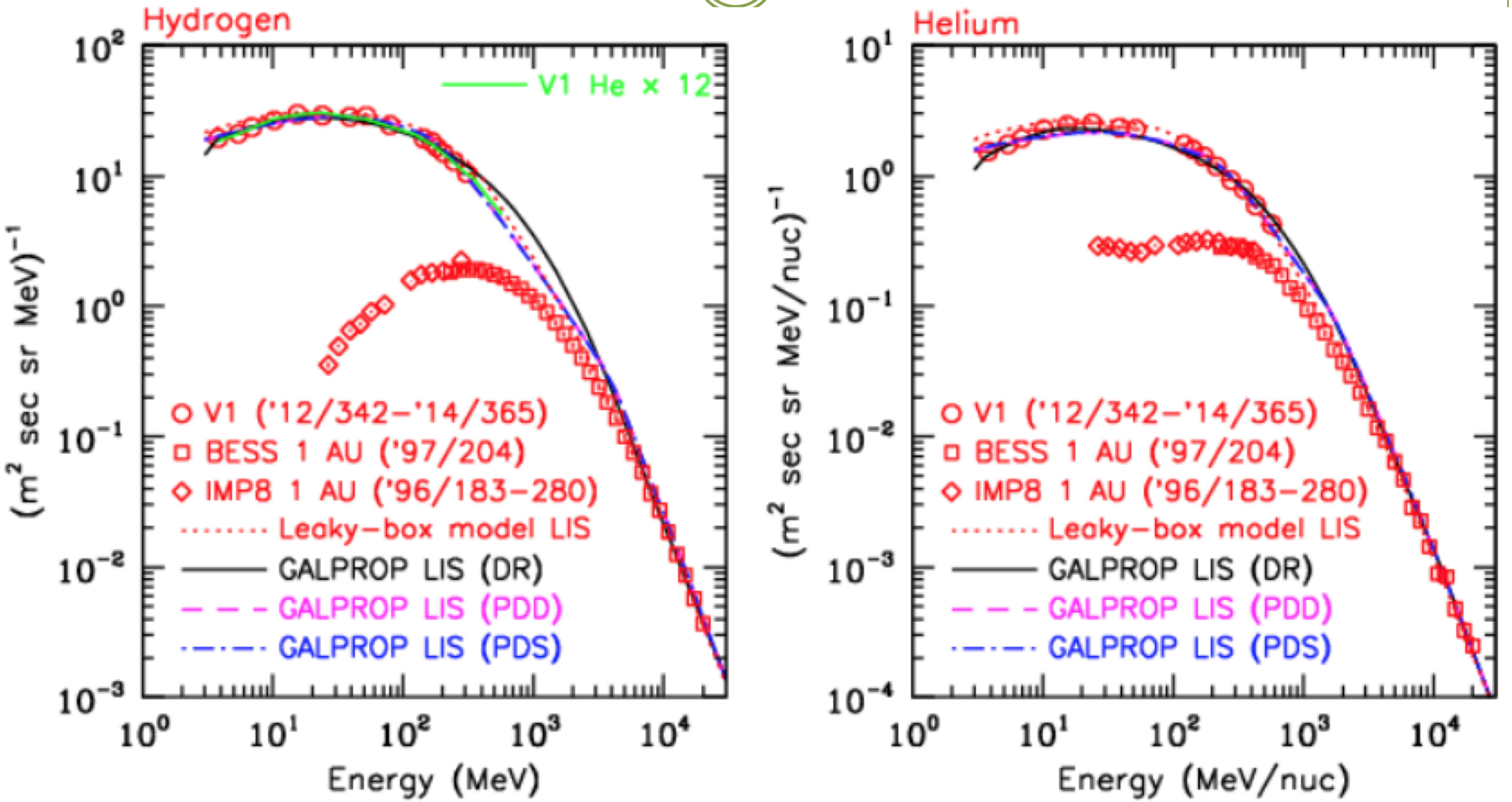


For the first time, GCR were measured in their unmodulated state

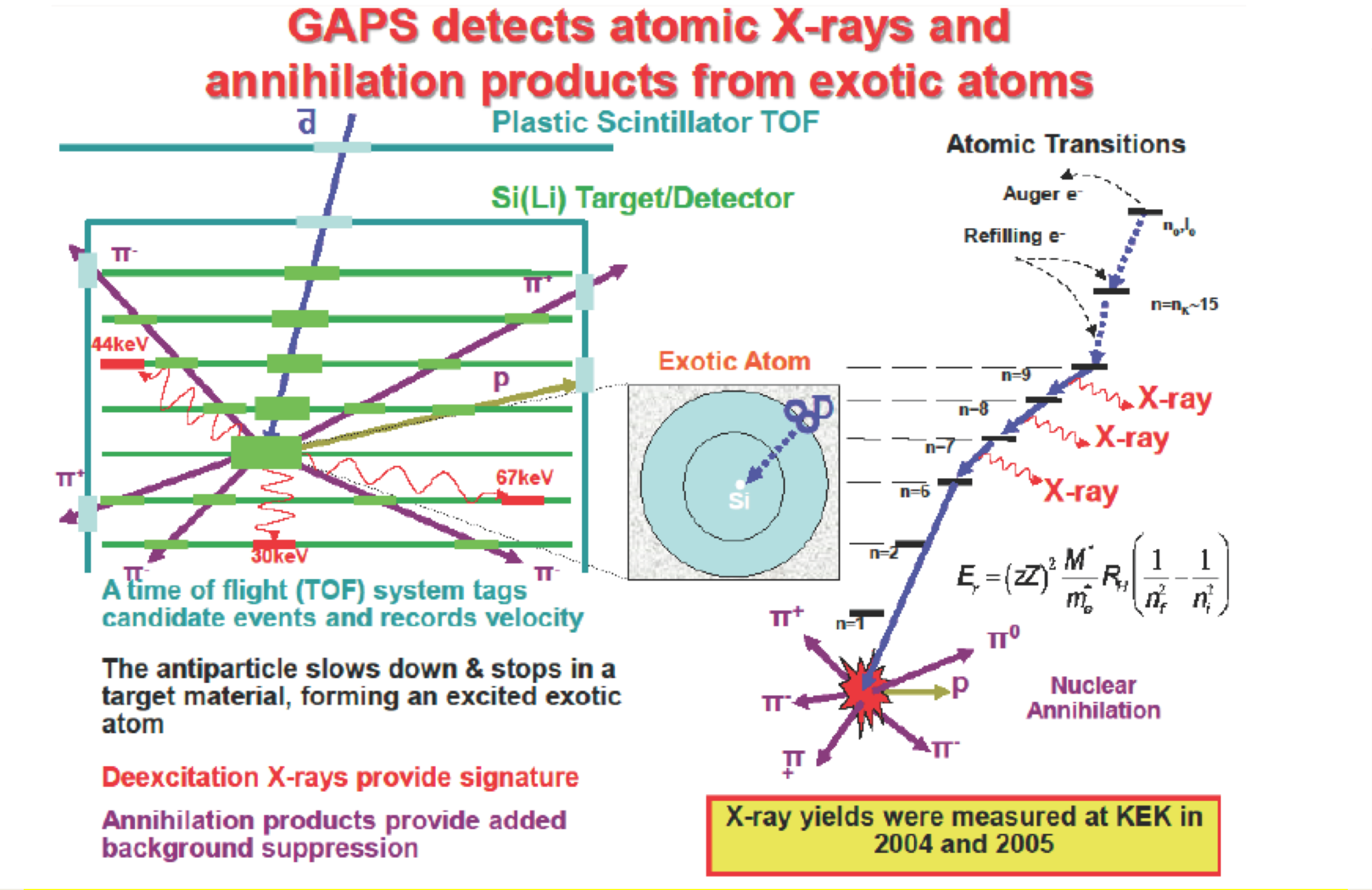
Travel of Voyager: GCR



VOYAGER: H and He in the LISM



The future: GAPS experiment



A balloon-borne detector approved by NASA: launch 2020-2021

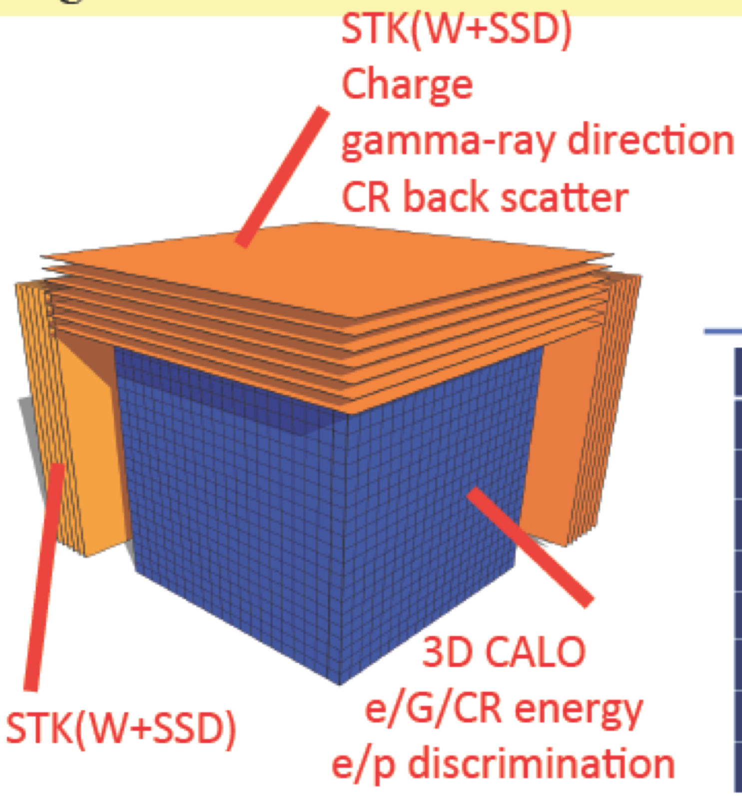
GAPS science summary

- *Antideuterons* as DM signatures
    - no astrophysical background at low energy
    - **complementary** to direct/indirect searches and collider experiments
    - search for: light DM, heavy DM, gravitino DM,
      LZP in extra-dimensions theories, (evaporating PBH)
- *Antiprotons* as DM and PBH signatures
    - precision flux measurement at ultra-low energy (E < 0.25 GeV)
    - **complimentary** to direct/indirect searches and collider experiments
    - **~ 10 times more statistics** @ 0.2 GeV, compared to BESS/PAMELA
    - search for: light DM gravitino DM,
      LZP in extra-dimensions theories, evaporating PBH
- *Expected to launch from Antarctica in 2020/2021*

- **1 LDB flight (~35 days) -> precision antiproton flux measurement**
  ~1500 antiprotons in GAPS $E < 0.25$ GeV, while 30 for BESS, 7 for PAMELA at $E \sim 0.25$ GeV
- **2 LDB flights (~70 days) -> improved antideuteron statistics**
  Antideuteron sensitivity: ~3.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at $E < 0.25$ GeV
- **3 LDB flights (~105 days) -> Antideuteron sensitivity: <2.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at $E < 0.25$ GeV**

The future: HERD

About a factor 10 increase in statistics respect to existing experiments with a weight 2.3 T ~1/3 AMS



Expected performance of HERD

γ/e energy range (CALO)	tens of GeV-10TeV
nucleon energy range (CALO)	up to PeV
γ/e angular resol.	0.1°
nucleon charge resol.	0.1-0.15 c.u
γ/e energy resolution (CALO)	<1%@200GeV
proton energy resolution (CALO)	20%
e/p separation power (CALO)	$<10^{-5}$
electron eff. geometrical factor (CALO)	3.7 m^2sr@600 GeV
proton eff. geometrical factor (CALO)	2.6 m^2sr@400 TeV

Experiment	e+ | e- (present data)	e++e- (Energy range)	CR nuclei (Energy range)	charge Z	gamma	Type	Launch
PAMELA	e^+ < 300 GeV e^- < 625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	e^+ < 500 GeV e^- < 700 GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014/12/26 Dec 26
CALET	-	1 GeV-10 TeV (extendable -> 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	~ 2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	~ 2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) GeV–10 TeV	up to PeV	TBD	10(s) GeV–10 TeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	2020-2021

Conclusions

High energy line

A new vision appears from the current data:

- H and He spectra **harden with energy** (>230 GV);
- H and He spectra **are different**;
- He, C, O also **harden with energy** (>230 GV) with same spectral index;
- Li, Be, B **behave the same, with same spectral index but harder than primaries;**
- Hi-Z spectra **show a hardening of the spectral index w.r.t. protons.**

Composition line

- Source matter **must be** a composition of old ISM with newly synthetized matherial, in percentage 80%-20% (sites of acceleration rich in massive stars, like OB associations)

Conclusions

Antimatter line

- Positrons **show enhancement** in the E>10 GeV region (new e+ e- source)
- **No antiproton excess** observed both at low and high energy (several DM models and exotics ruled out), despite <u>some room seems to be left in AMS data;</u>
- **Controversary data** above 300 GeV for the all-electron spectrum and at the HESS cutoff;
- **No heavier anti-nucleus** observed (very stringent limits)

The new instruments just taking data such as CALET, DAMPE, ISS-CREAM, NUCLEON, as well as space instruments continuing to operate and new balloon flights of existing instruments, promise a robust future for cosmic ray research.