A Decade of Cosmic Rays Investigation by the PAMELA experiment

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On behalf of the PAMELA collaboration

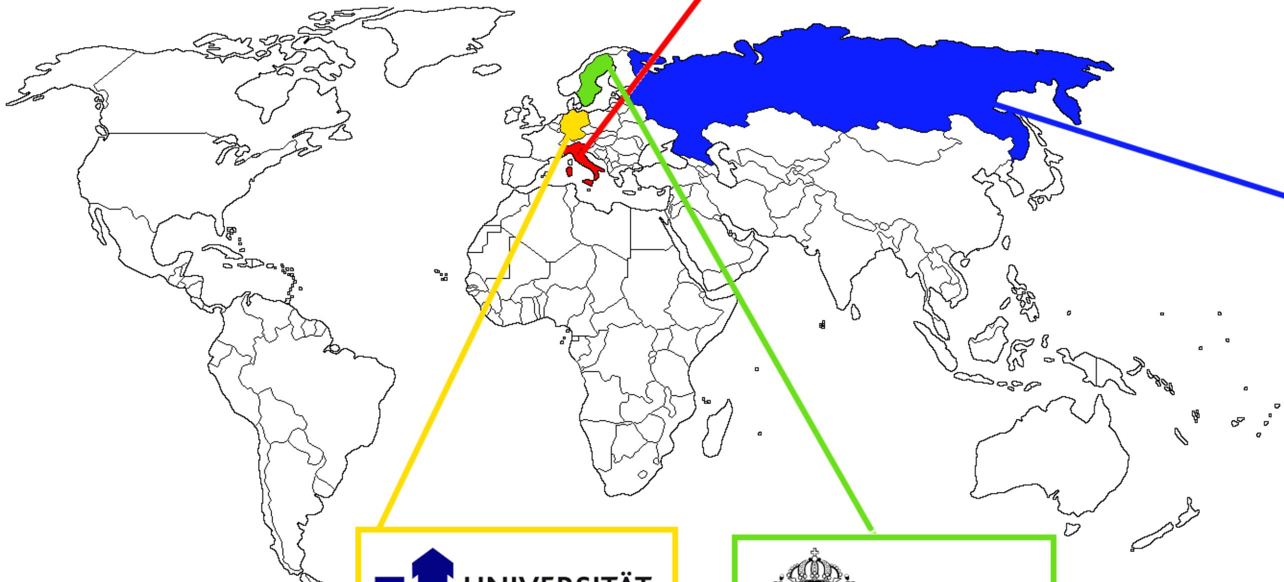
Villa Mondragone, Monte Porzio Catone
15 June 2016

Naples Bari Florence Frascati Rome Trieste CNR, Florence

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Università di Roma Tor Vergata

Consiglio Nazionale delle Ricerche



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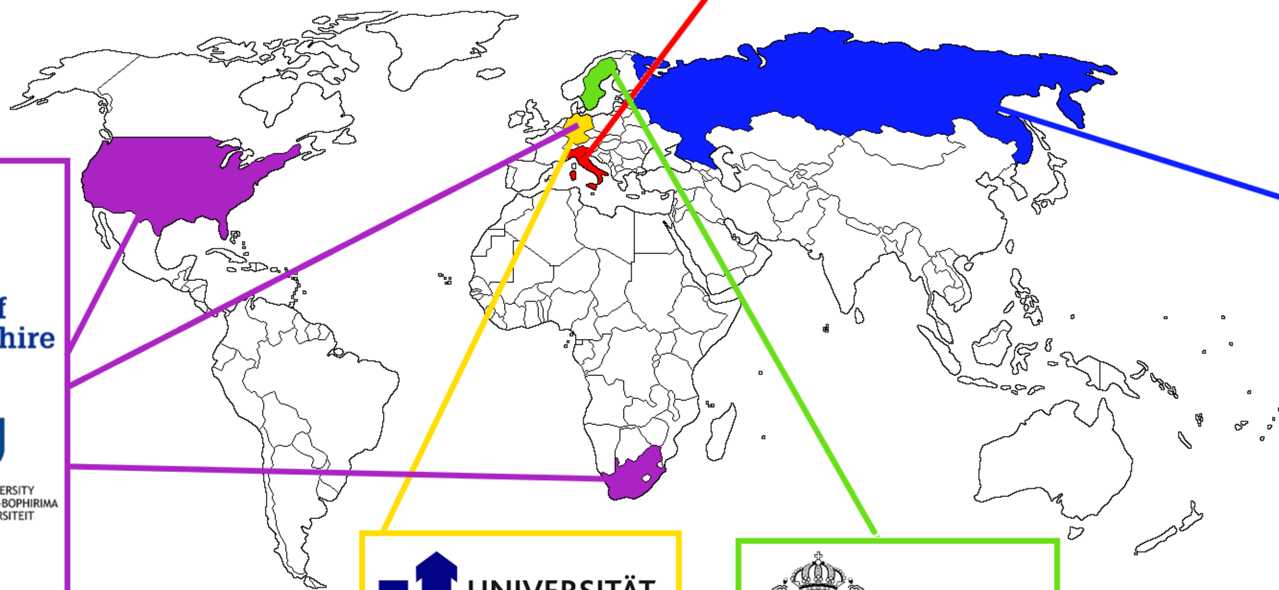

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University of New Hampshire

Christian-Albrechts-Universität zu Kiel

NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT

External collaboration

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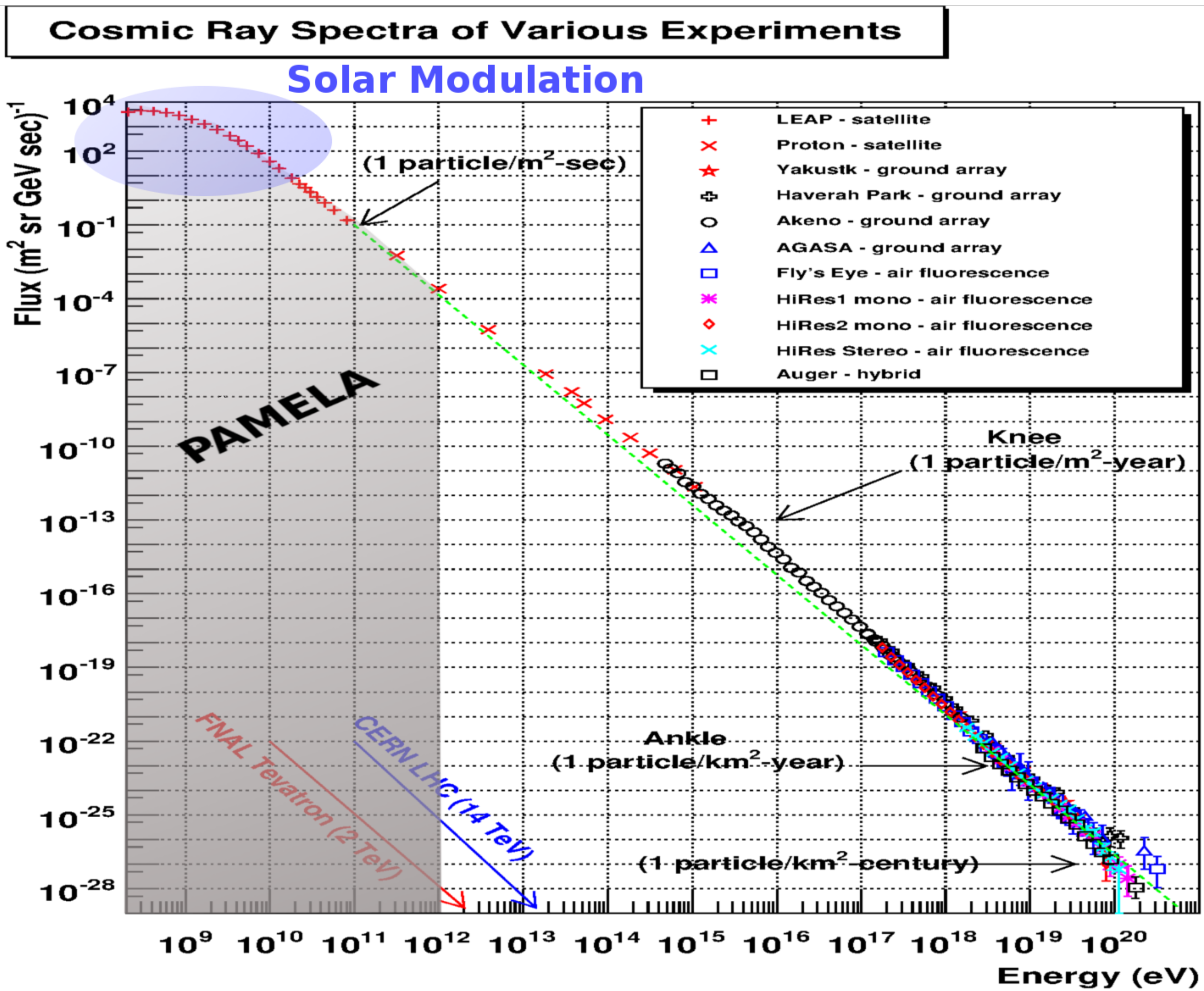
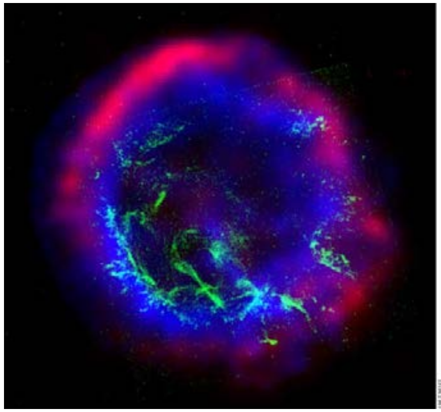

Cosmic Ray Spectra of Various Experiments
Solar Modulation
Flux (m^2 sr GeV sec)$^{-1}$
(1 particle/m^2-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
PAMELA
Knee
(1 particle/m^2-year)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
Energy (eV)

Scientific goals

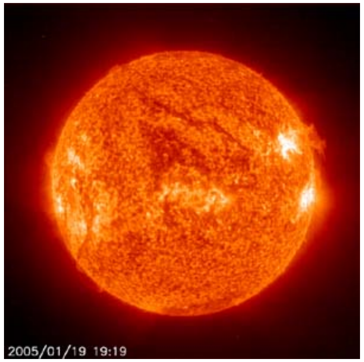
- Search for dark matter annihilation

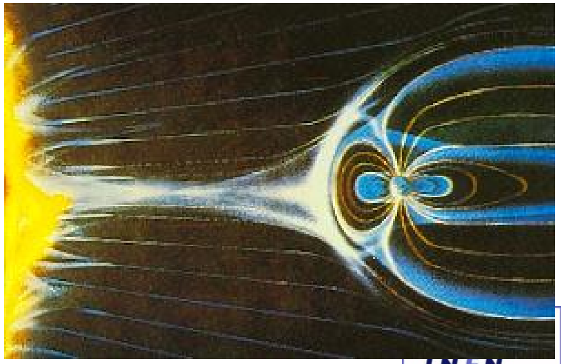
- Search for antihelium (primordial antimatter)
- Search for new Matter in the Universe (Strangelets?)

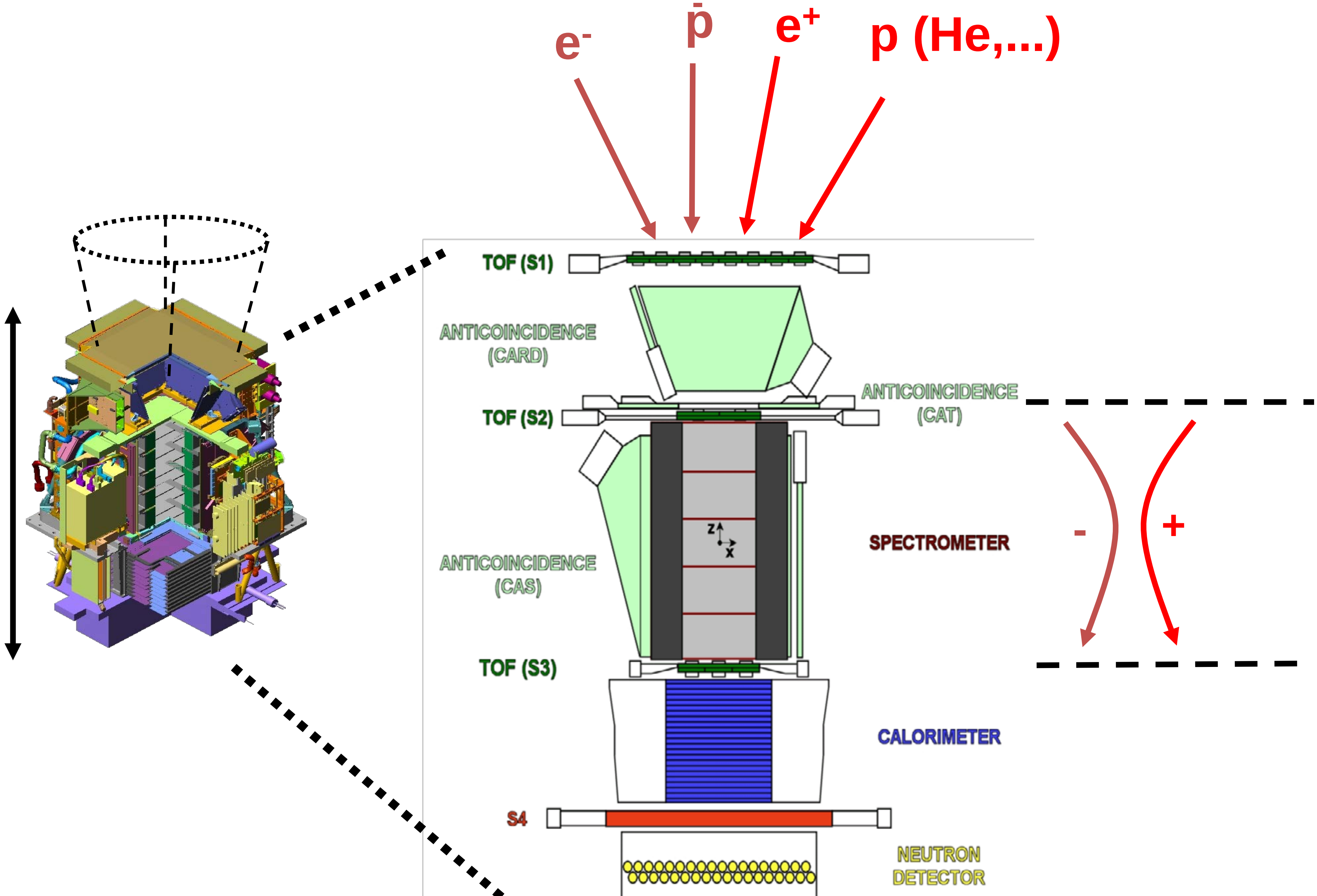


- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)

- Study solar physics and solar modulation
- Study terrestrial magnetosphere

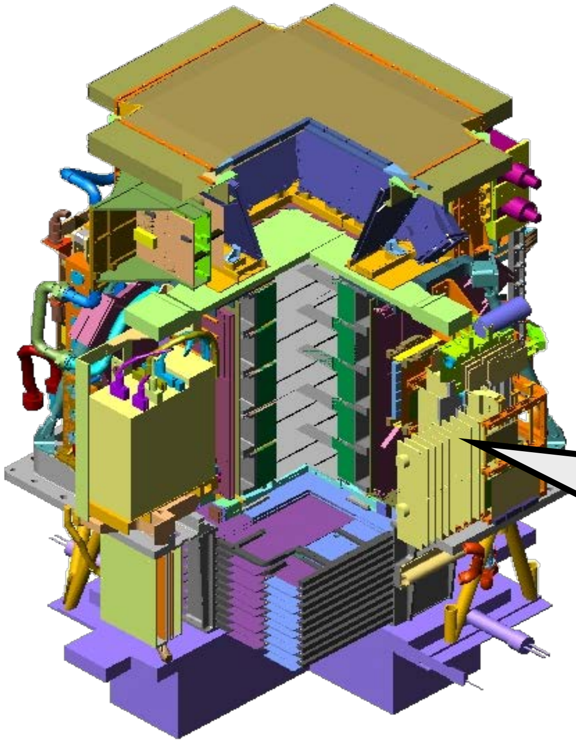






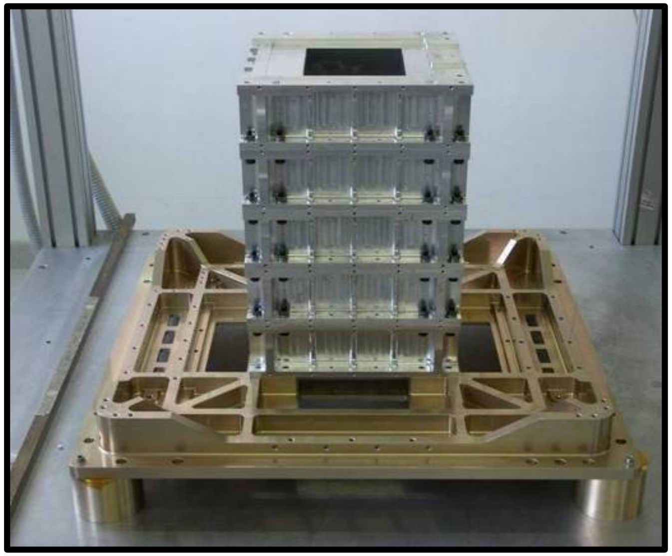
e-
p̄
e+
p (He,...)
TOF (S1)
ANTICOINCIDENCE (CARD)
TOF (S2)
ANTICOINCIDENCE (CAT)
ANTICOINCIDENCE (CAS)
SPECTROMETER
-
+
TOF (S3)
CALORIMETER
S4
NEUTRON DETECTOR

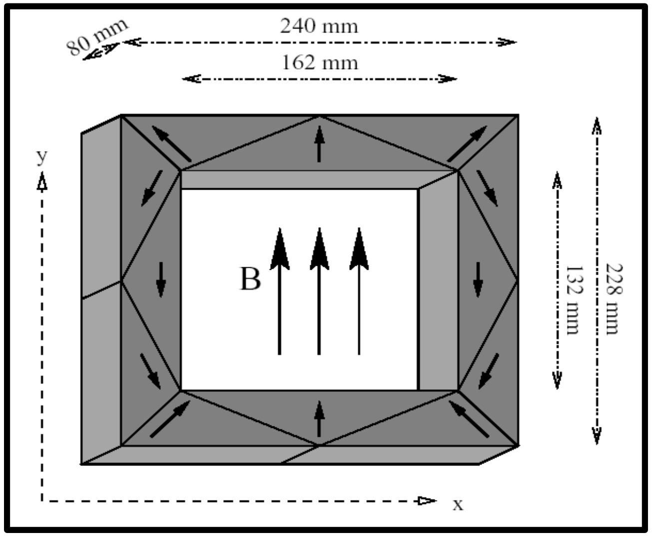
The magnet



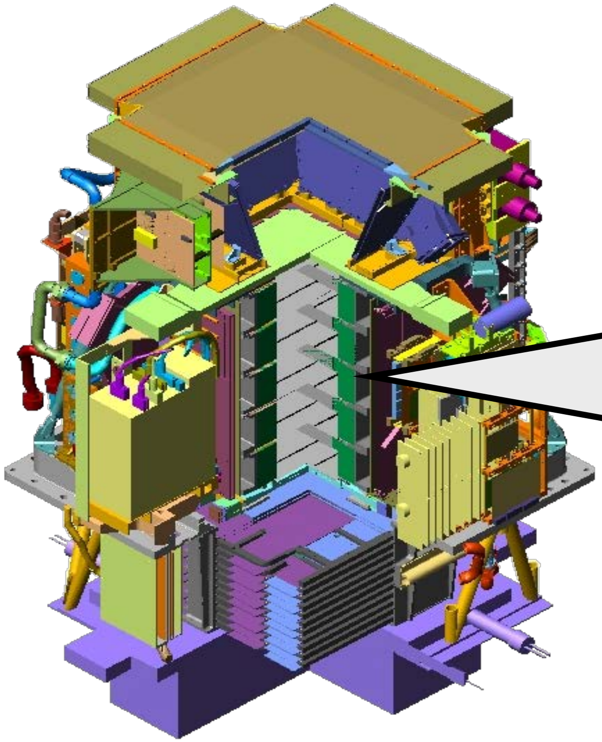
Characteristics:

- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions (162 x 132 x 445) cm^3
  → **GF ~ 21.5 cm^2sr**
- Magnetic shields
- 5mm-step field-map on ground:
  - **B=0.43 T (average along axis),**
  - **B=0.48 T (@center)**





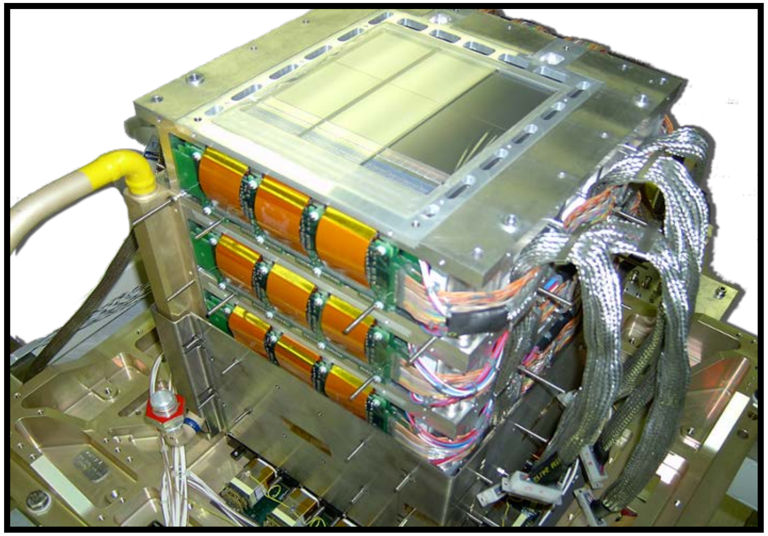
The tracking system

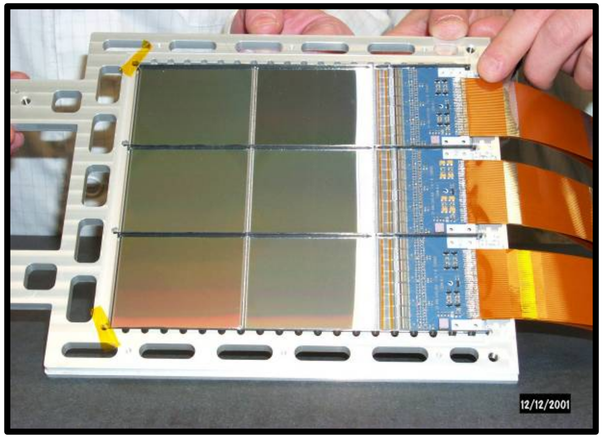


Main tasks:
- **Rigidity measurement**
- **Sign of electric charge**
- **dE/dx (ionisation loss)**

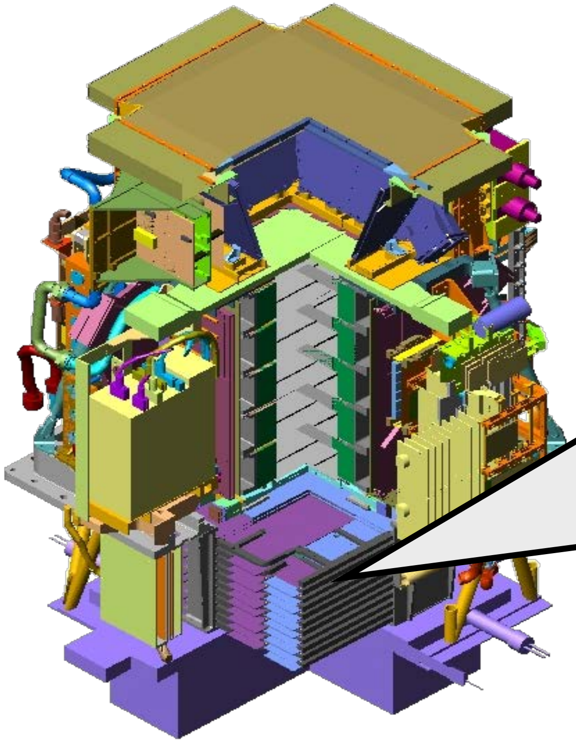
Characteristics:
- **6 planes double-sided (x&y view) microstrip Si sensors**
- 36864 channels
- Dynamic range: 10 MIP

Performance:
- **Spatial resolution: ~3 μm (bending view)**
- **MDR ~1 TV/c (from test beam data)**





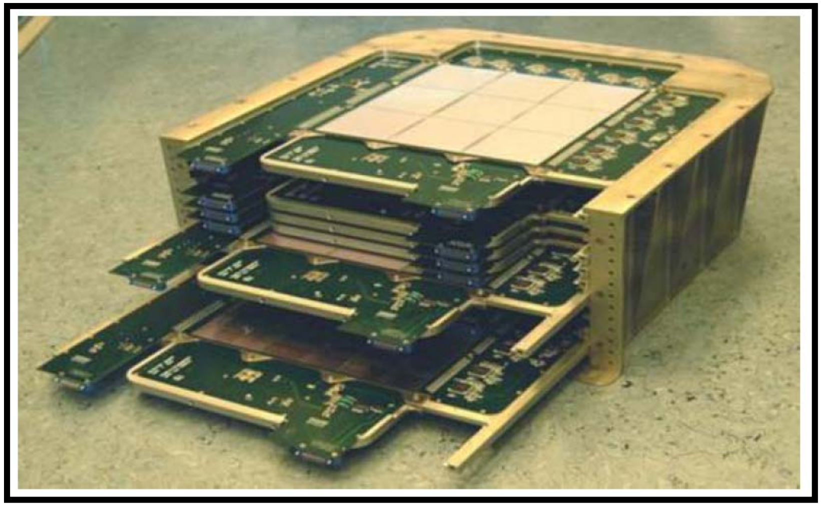
The electromagnetic calorimeter



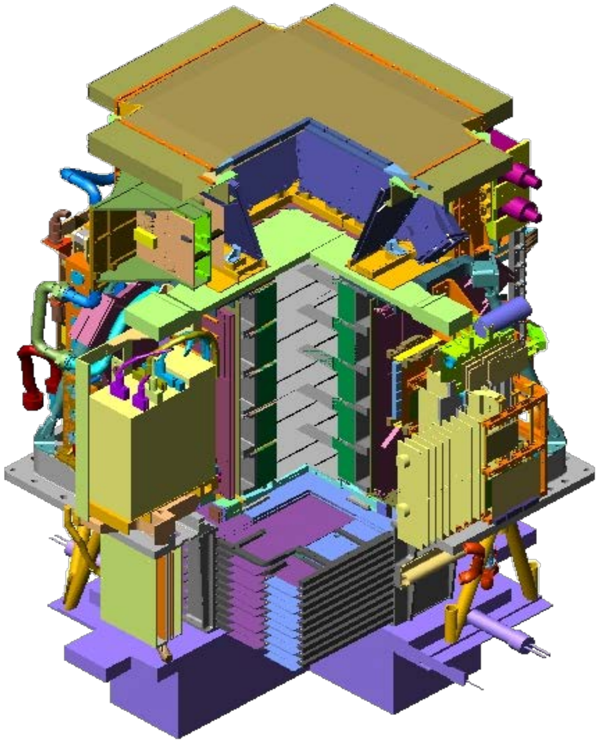
Main tasks:
- **lepton/hadron discrimination**
- **$e^{+/-}$ energy measurement**

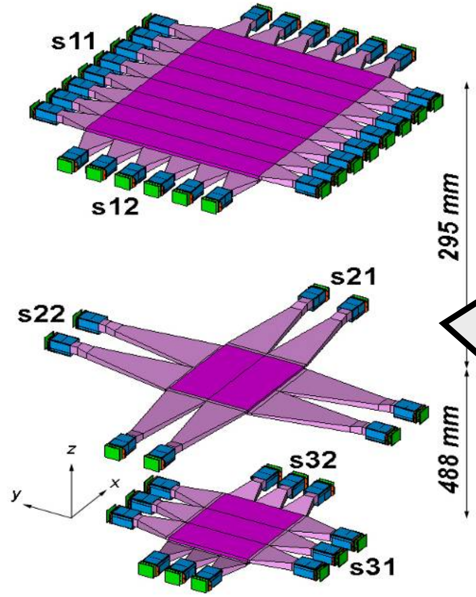
Characteristics:
- **44 Si layers (x/y) + 22 W planes**
- **16.3 X_o / 0.6 λ_L**
- 4224 channels
- Dynamic range: 1400 mip
- **Self-trigger mode (> 300 GeV; GF~600 cm^2 sr)**

Performance:
- p/e^+ selection efficiency ~ 90%
- p rejection factor ~10^5
- e rejection factor > 10^4
- **Energy resolution ~5% @ 200 GeV**



The time-of-flight system





Main tasks:

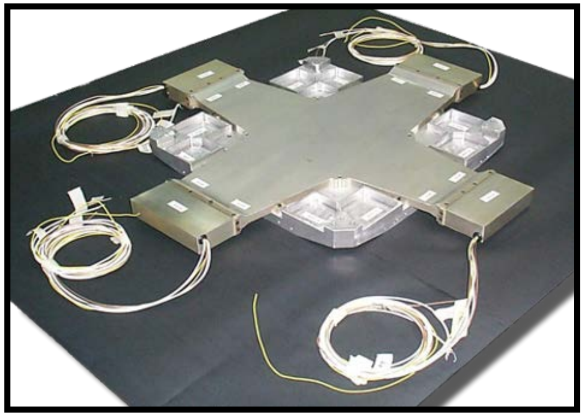
- First-level trigger
- Albedo rejection
- dE/dx (ionisation losses)
- Time of flight particle identification (<1GeV/c)

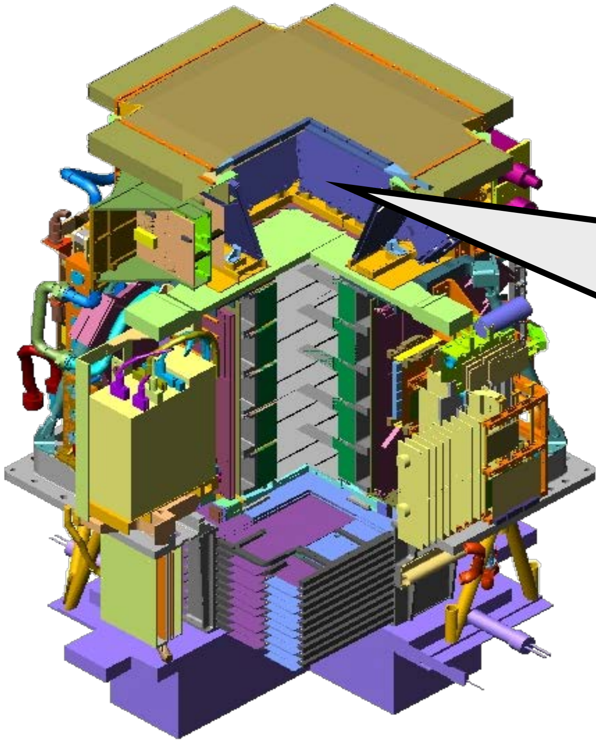
Characteristics:

- 3 double-layer scintillator paddles
- x/y segmentation
- Total: 48 channels

Performance:

- σ(paddle) ~ 110ps
- σ(ToF) ~ 330ps (for MIPs)





The anticounter shields

Main tasks:

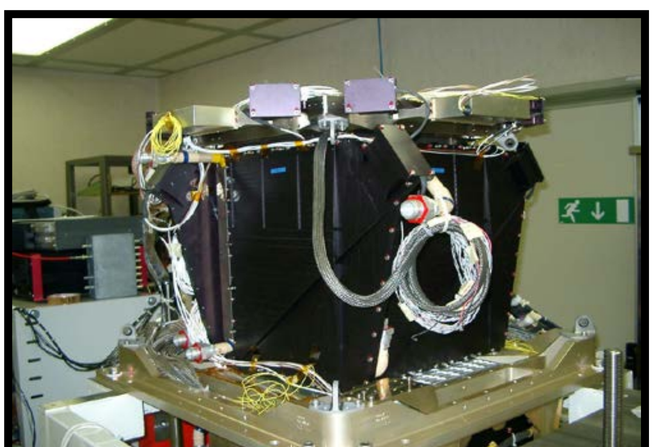
- **Rejection of events with particles interacting with the apparatus** (off-line and second-level trigger)

Characteristics:

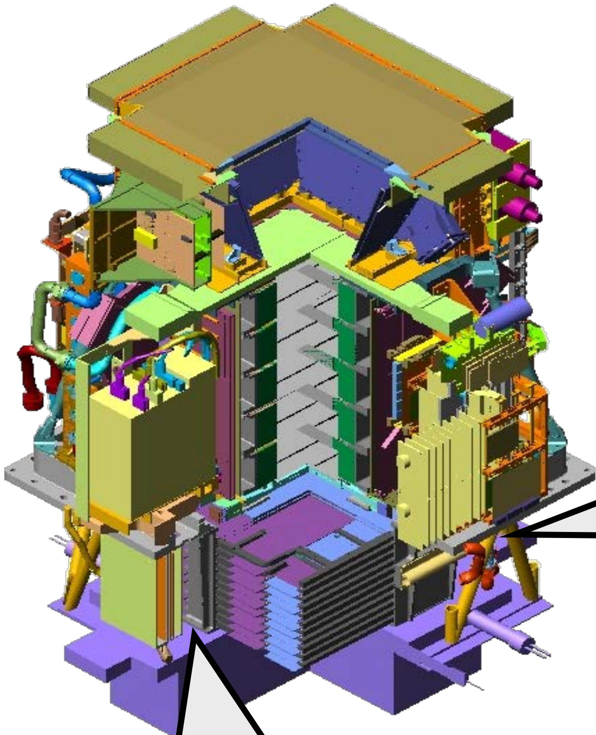
- **Plastic scintillator paddles, 8mm thick**
- 4 upper (CARD), 1 top (CAT), 4 side (CAS)

Performance:

- MIP efficiency > 99.9%

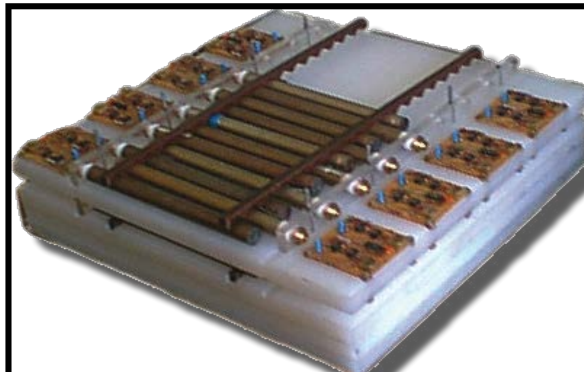


Neutron detector



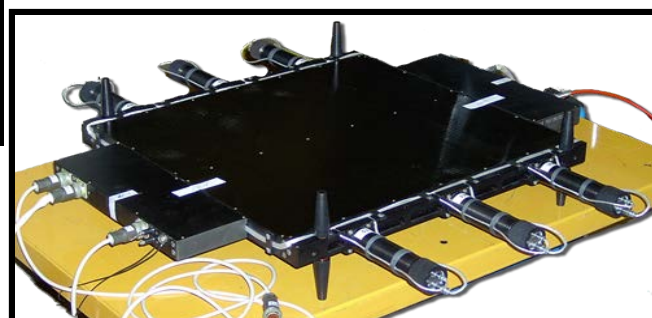
Main tasks:
- **e/h discrimination at high energy**

Characteristics:
- **36 ^{3}He counters**:
  $^{3}He(n,p)T$ - Ep=780 keV
- 1cm thick polyethylene + Cd moderators
- n collected within 200 μs time-window

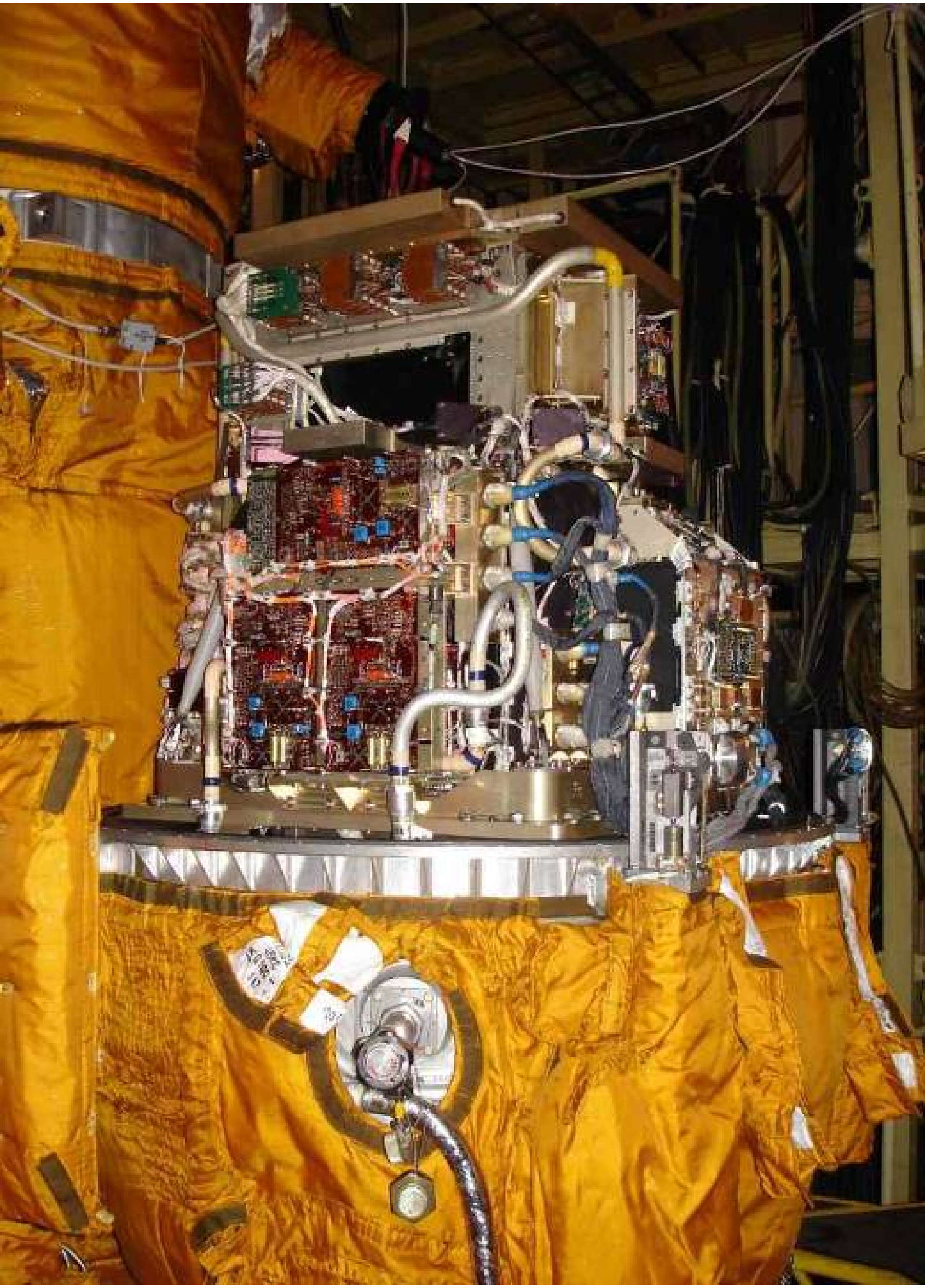
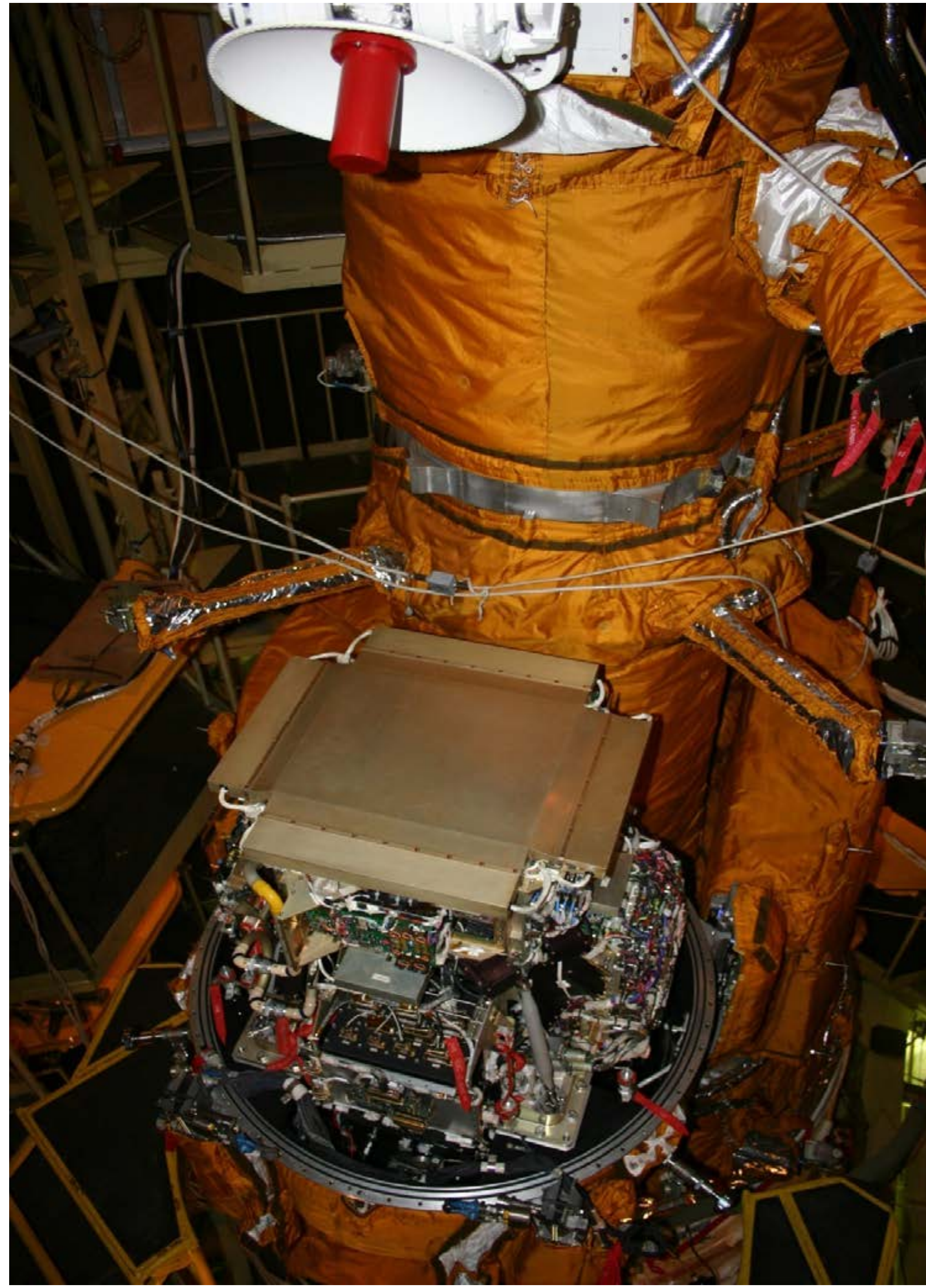


Main tasks:
- **Neutron detector trigger**

Characteristics:
- **Plastic scintillator paddle, 1 cm thick**

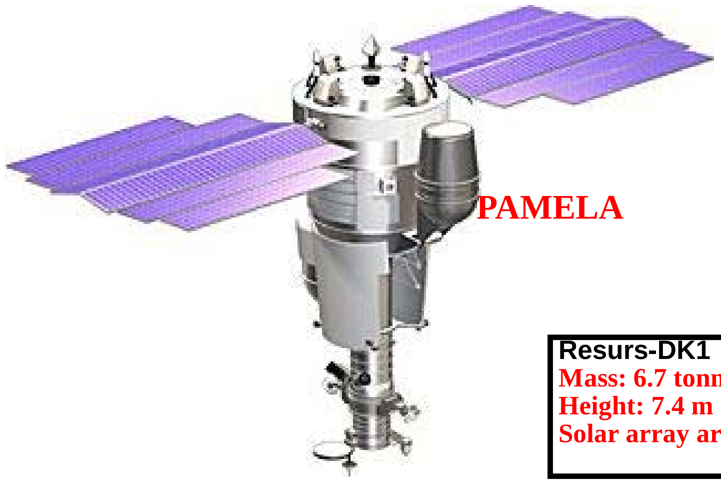


Shower-tail catcher

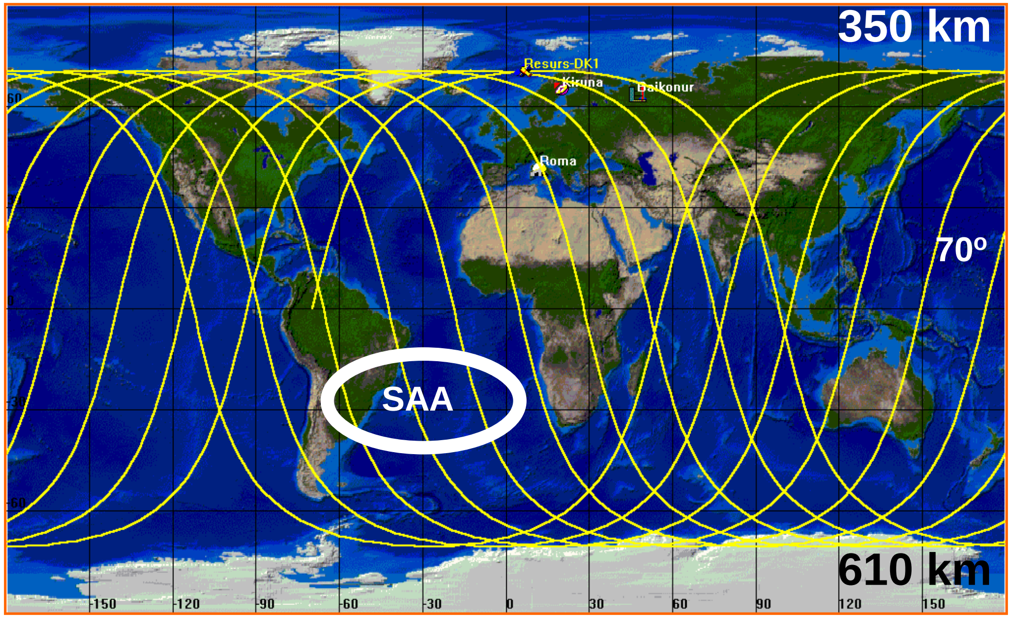



Launch: 15th June 2006, 0800 UTC

Resurs-DK1 satellite + orbit



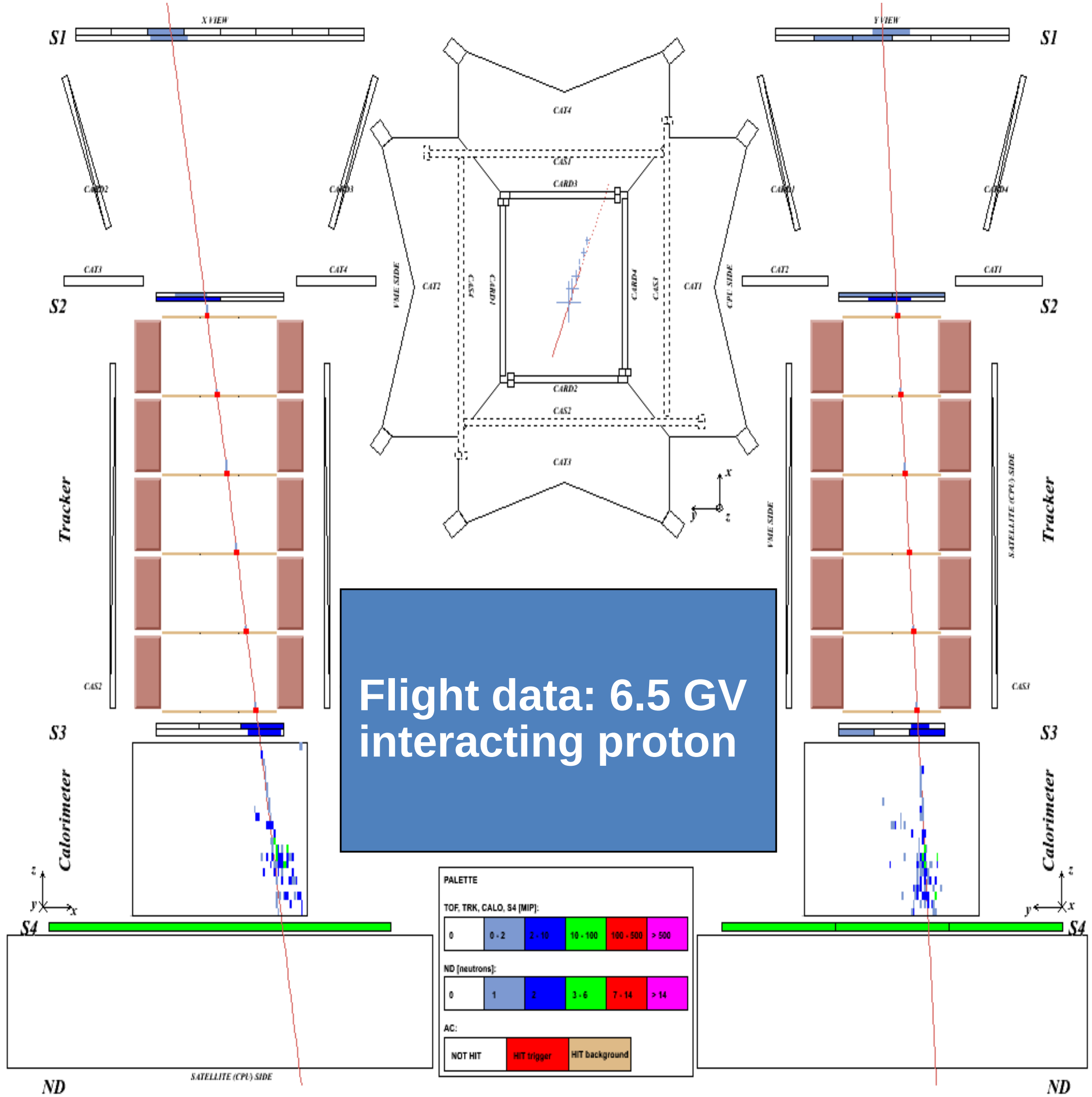
Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



~90 mins

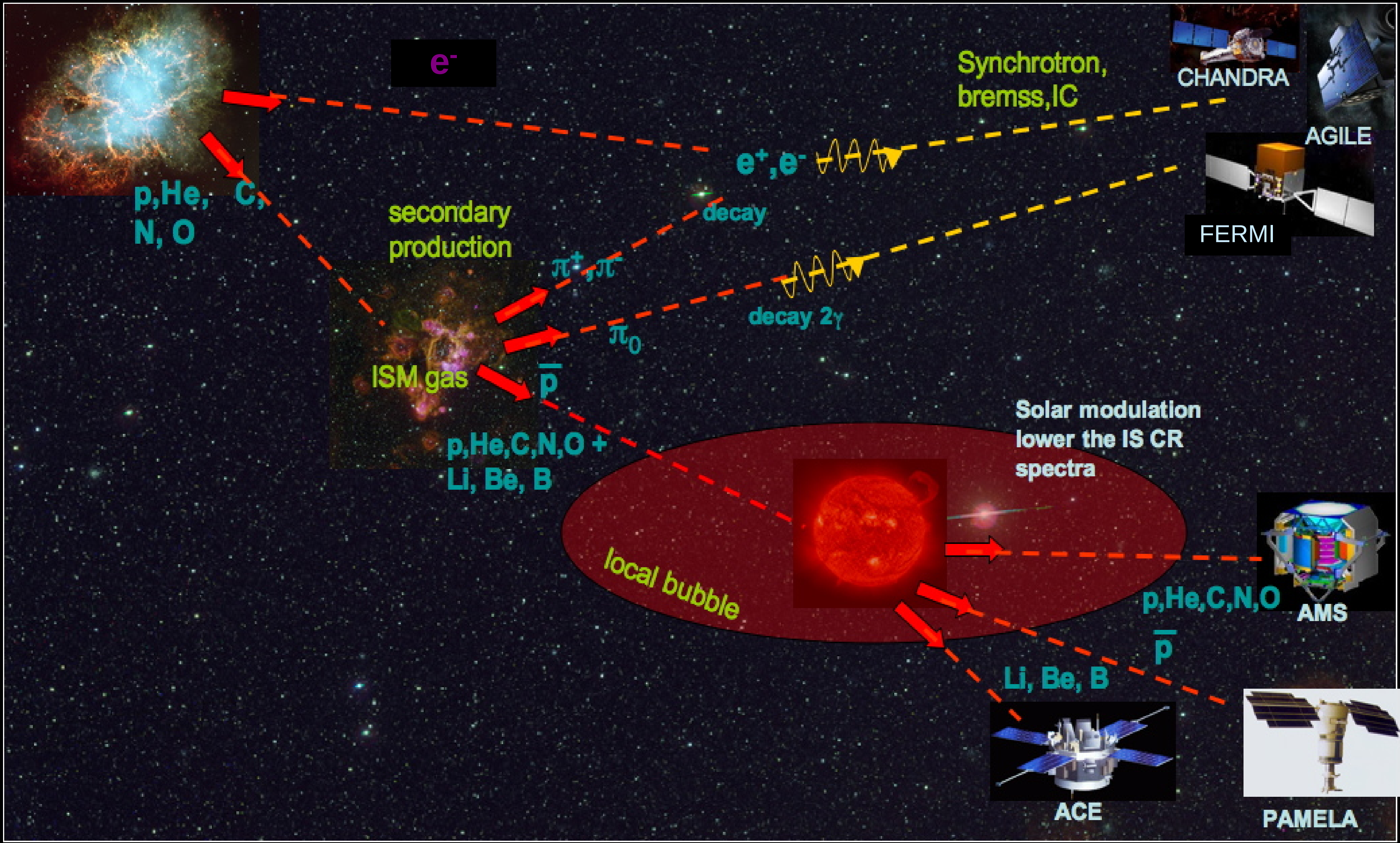
- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day
- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km) – from 2010 circular orbit (70.0°, ~600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

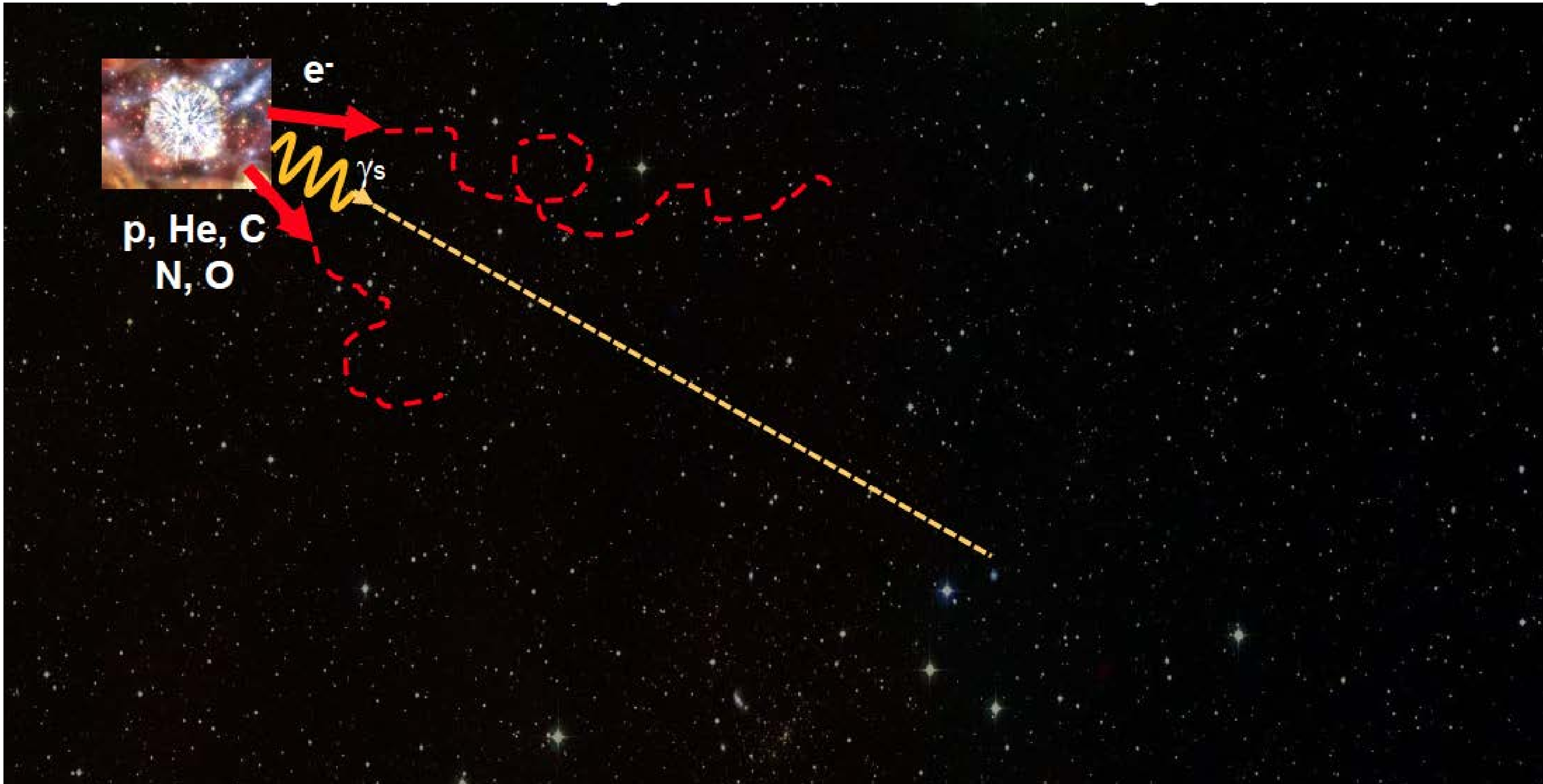
Proton Event from July 9, 2006 data



Flight data: 6.5 GV interacting proton

COSMIC RAYS PRODUCTION MECHANISMS

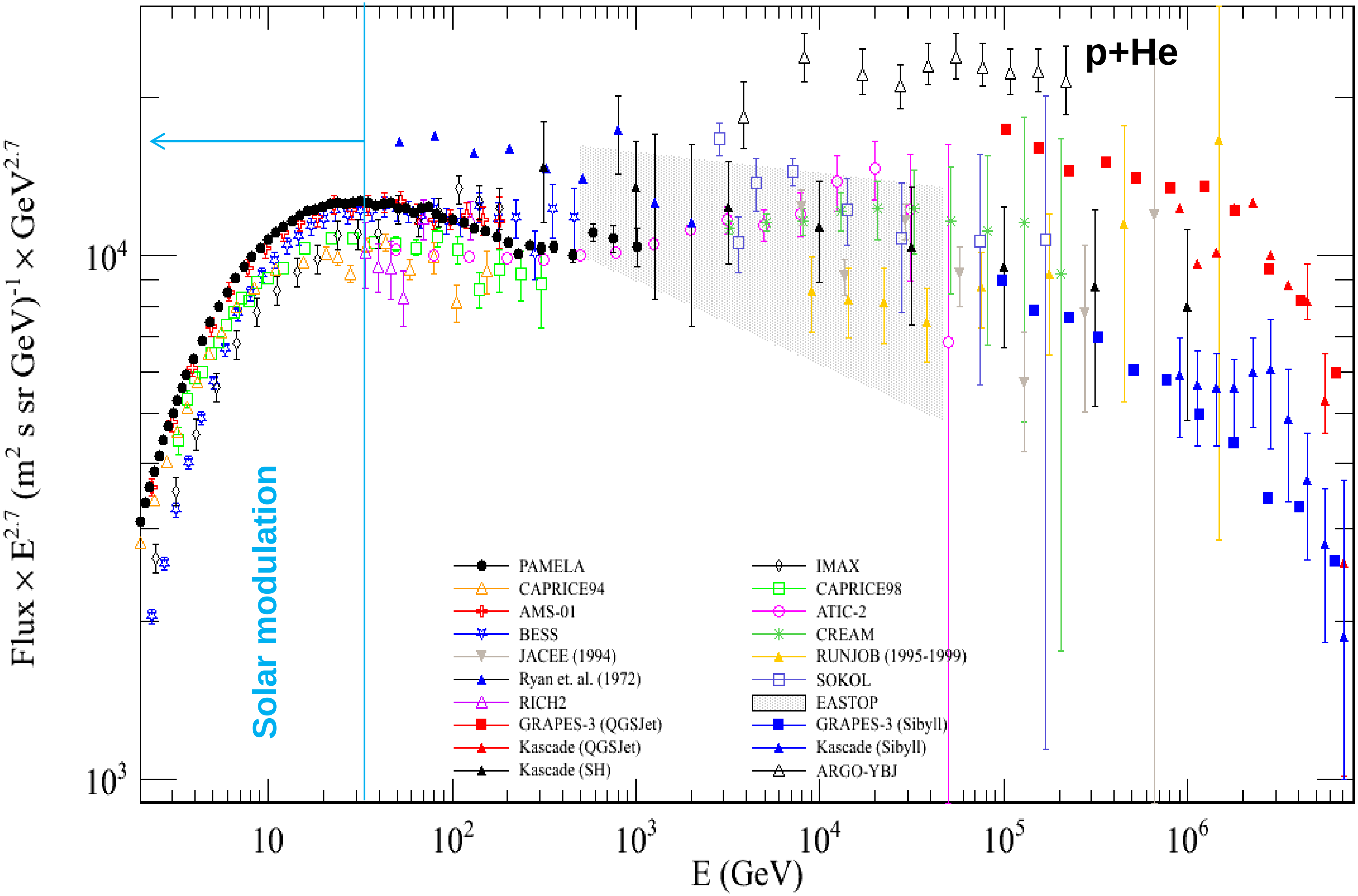




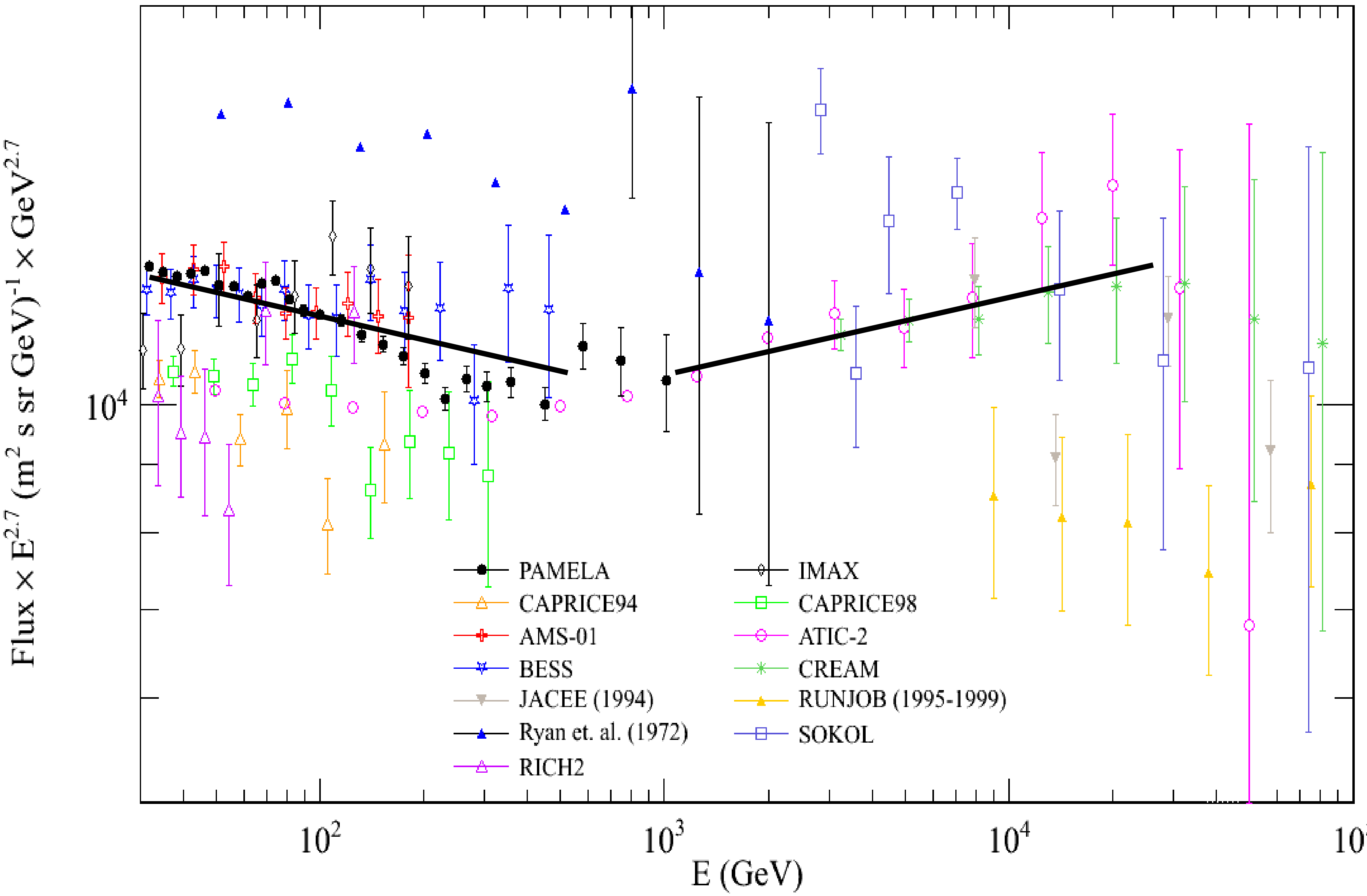
Absolute fluxes of primary GCRs

Protons, helium nuclei, light nuclei, electrons

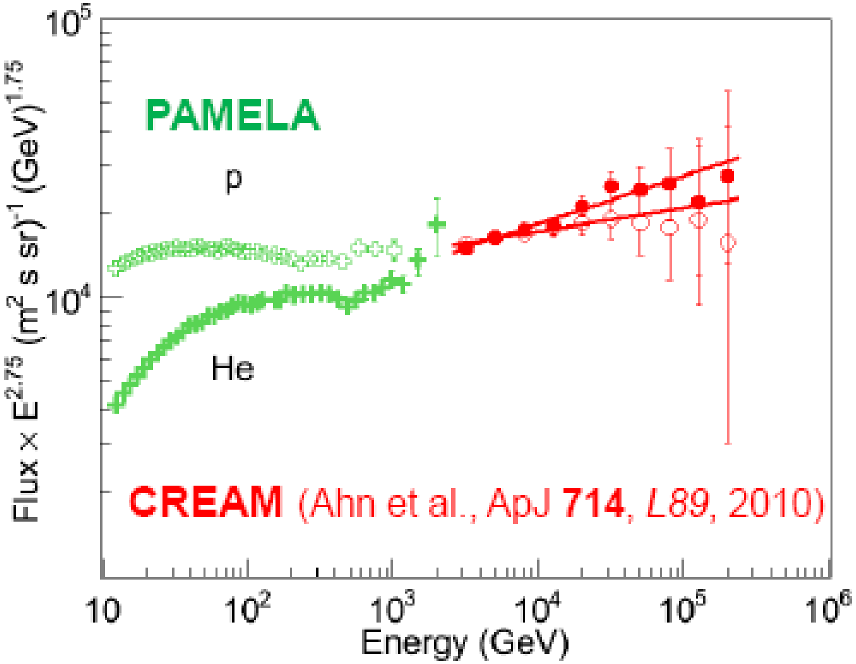
Proton (Hydrogen) Spectrum

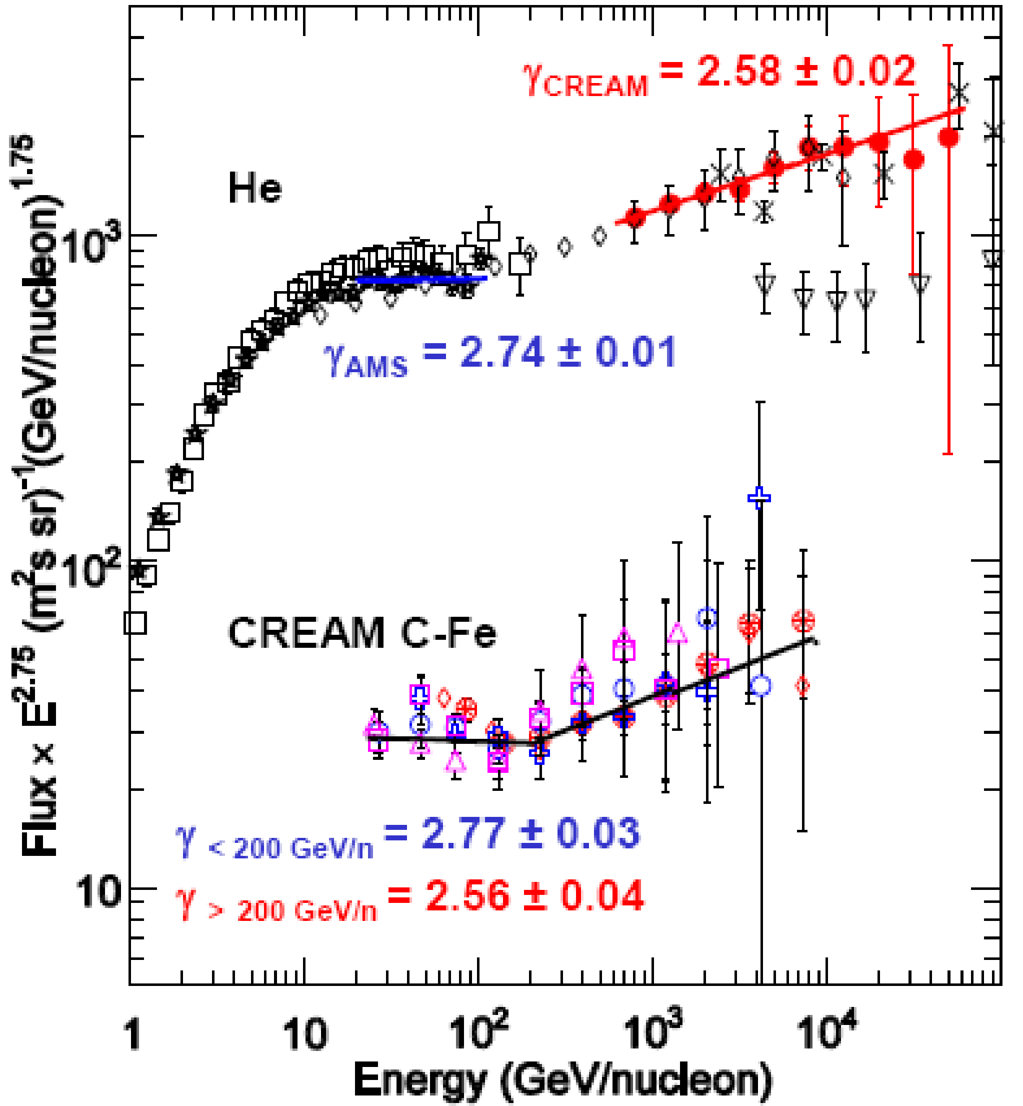


Proton (Hydrogen) Spectrum



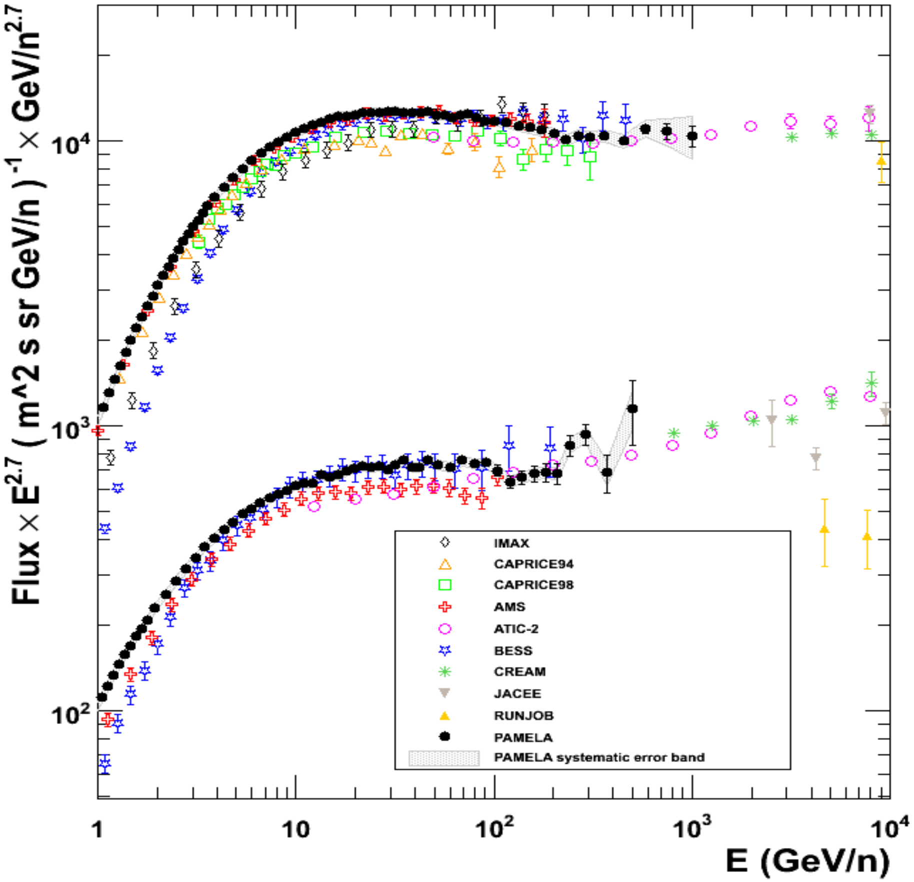
CREAM absolute fluxes @ high energy





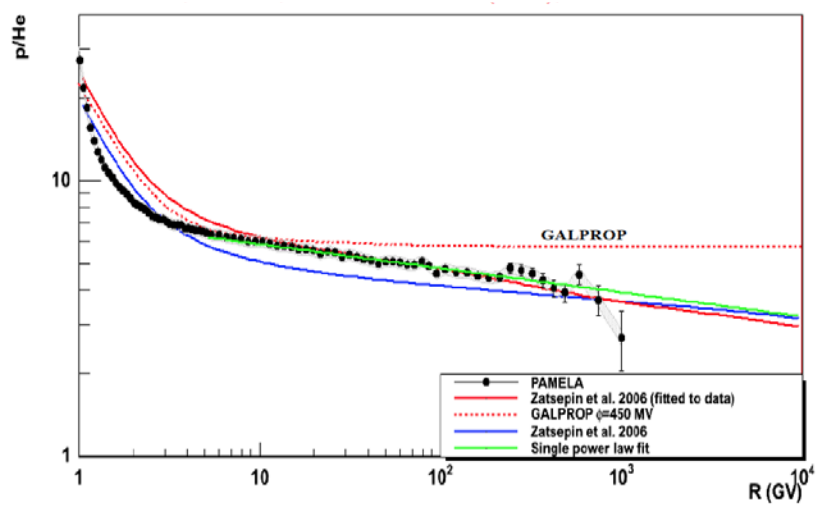
H. S. Ahn et al., 714 (2010) L89

Proton and Helium Nuclei Spectra & H/He ratio



- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV Δγ~0.2÷0.3 SPL is rejected at 98% CL

Origin of the hardening?
(e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)
- At the sources: multi-populations, etc.?
- Propagation effects?



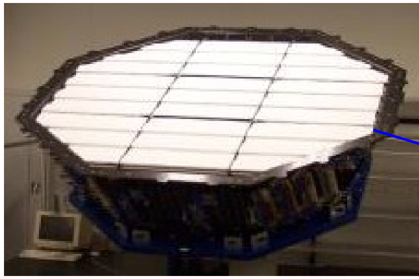
Clear evidence of different H and He slopes above ~ 10 GV

Adriani et al., Science 332 (2011) 6025

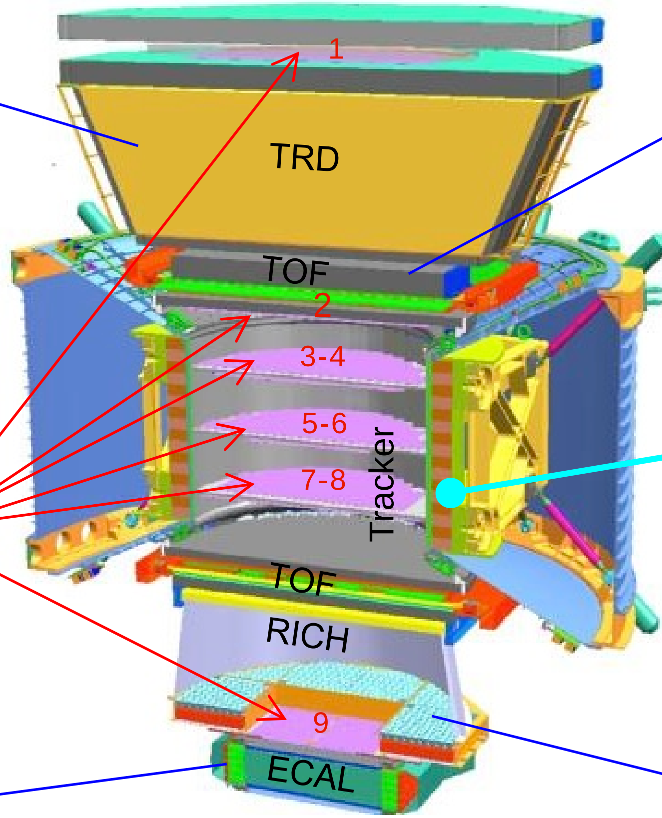
Igor's talk

AMS : A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify electrons

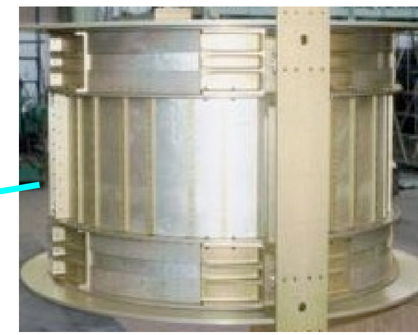


Particles are defined by their charge (Z) and energy (E) or momentum (P)

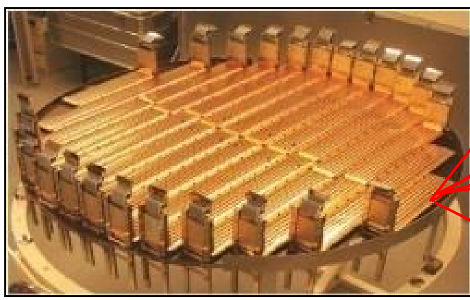


Time of Flight
Z, E

Magnet
±Z

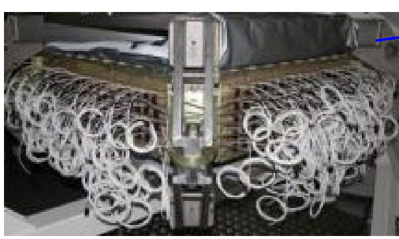


Silicon Tracker
Z, P



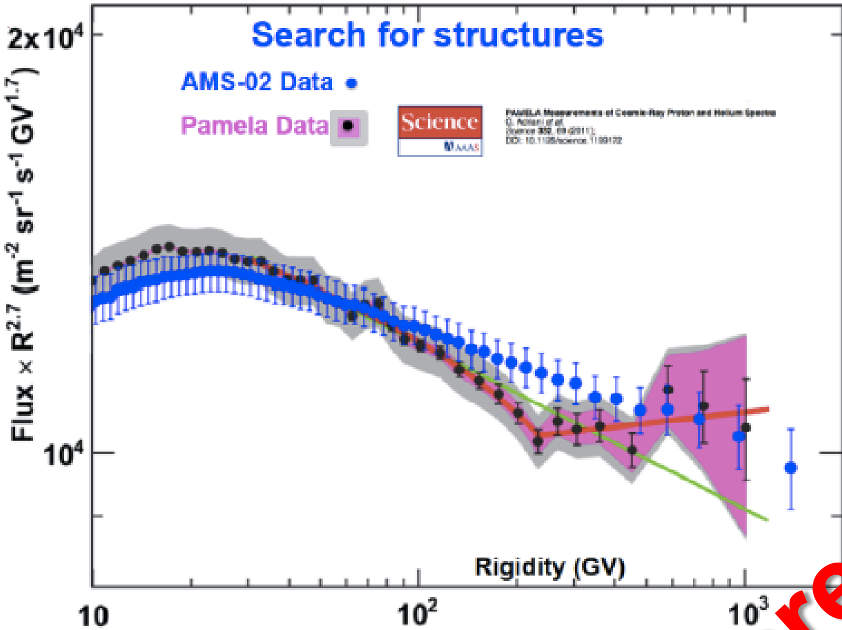
Ring Imaging Cherenkov
Z, E

Electromagnetic Calorimeter
E of electrons

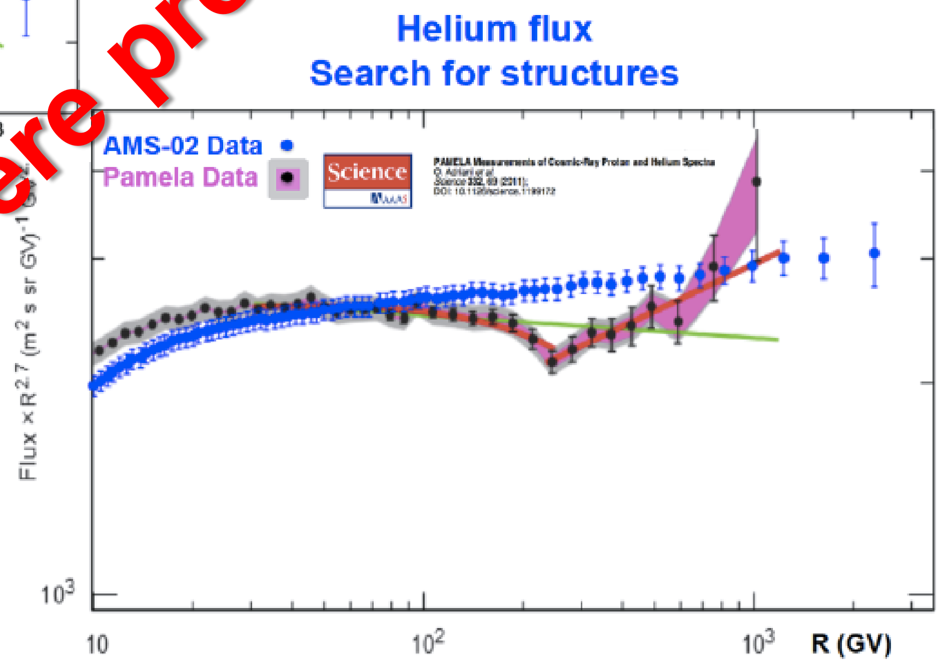


The Charge and Energy (momentum) are measured independently by many detectors

AMS-02 ICRC Comparison with PAMELA



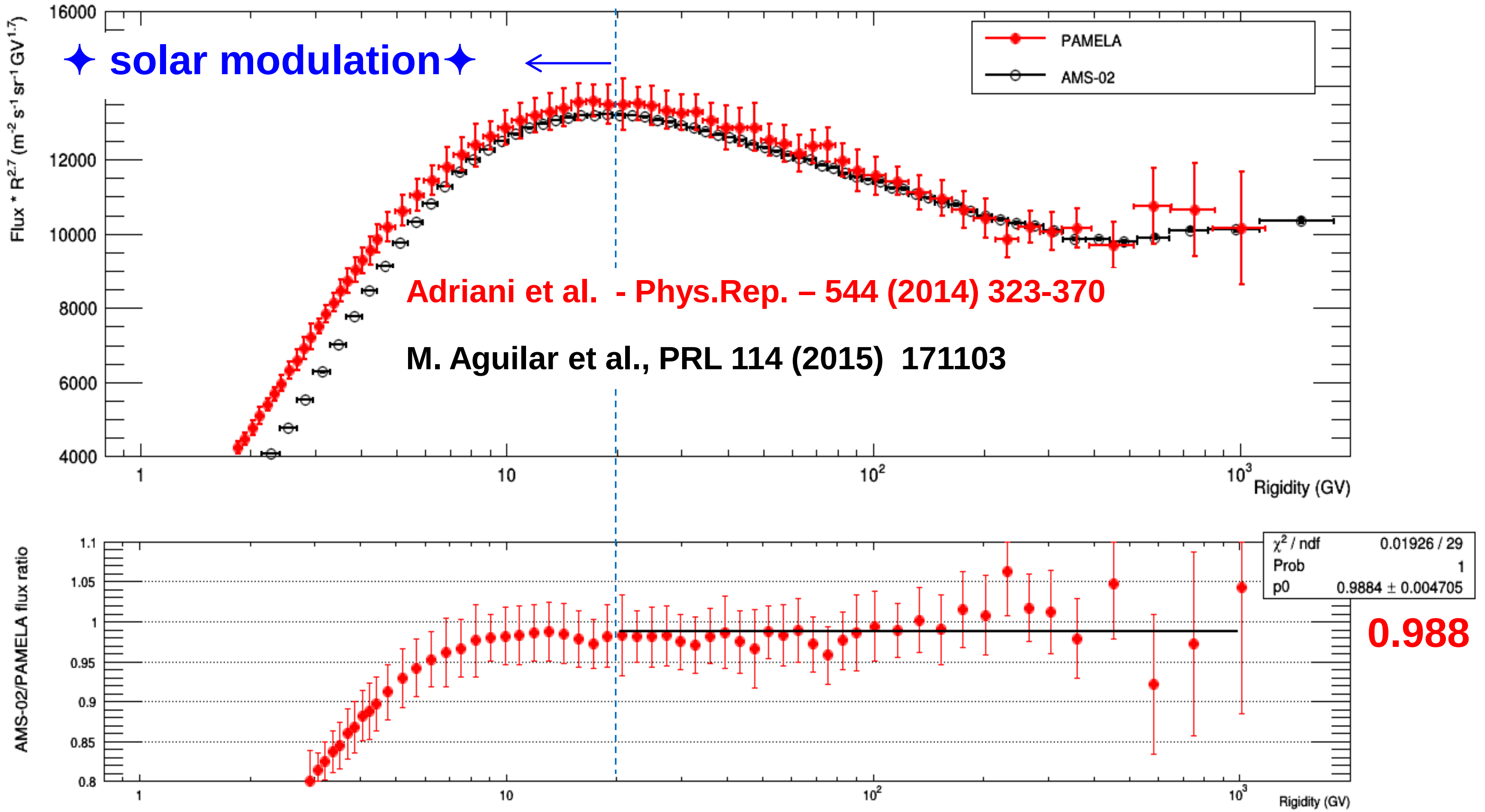
They were preliminary!!!



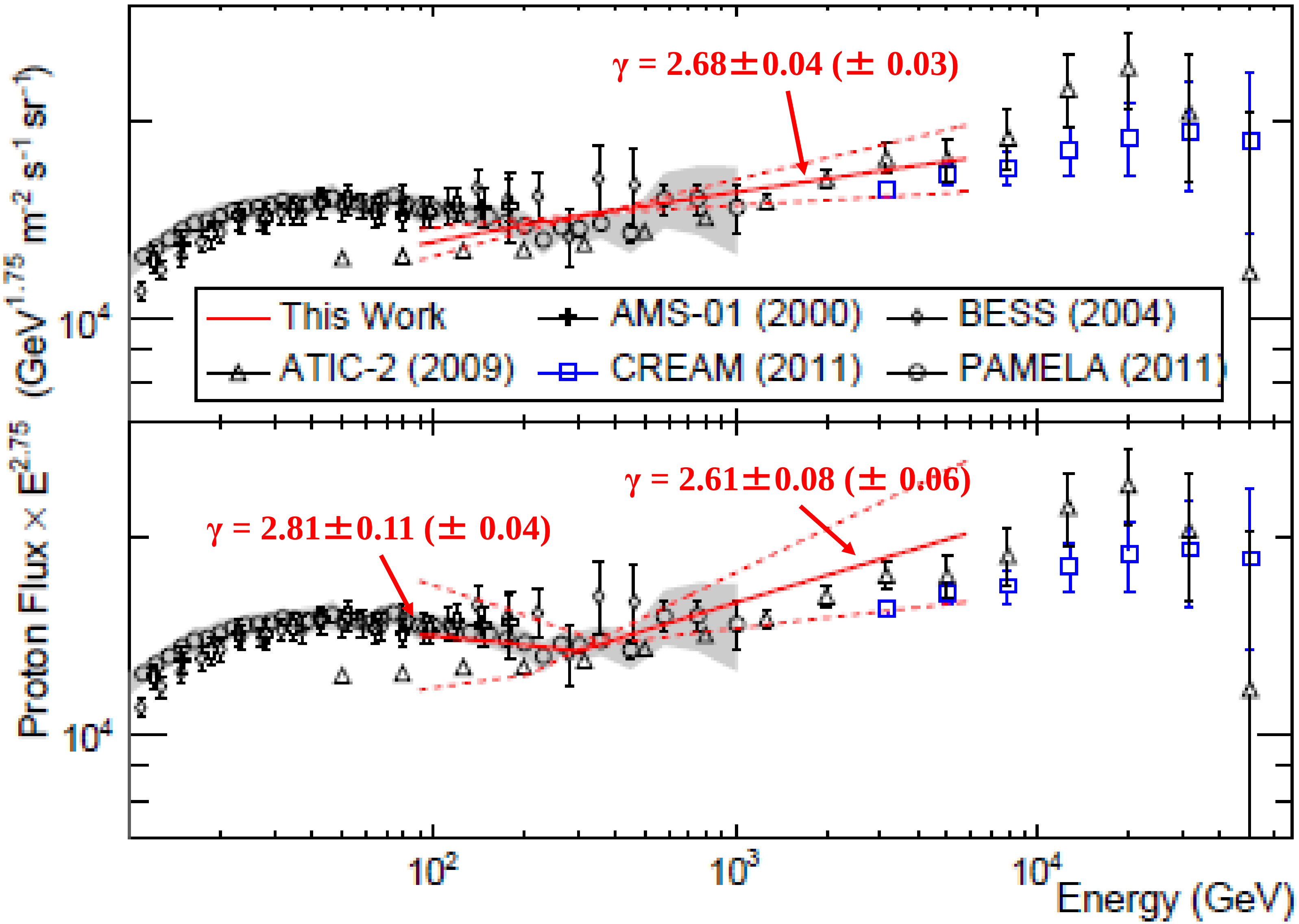
AMS-02 ICRC 2013

PAMELA vs AMS02

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



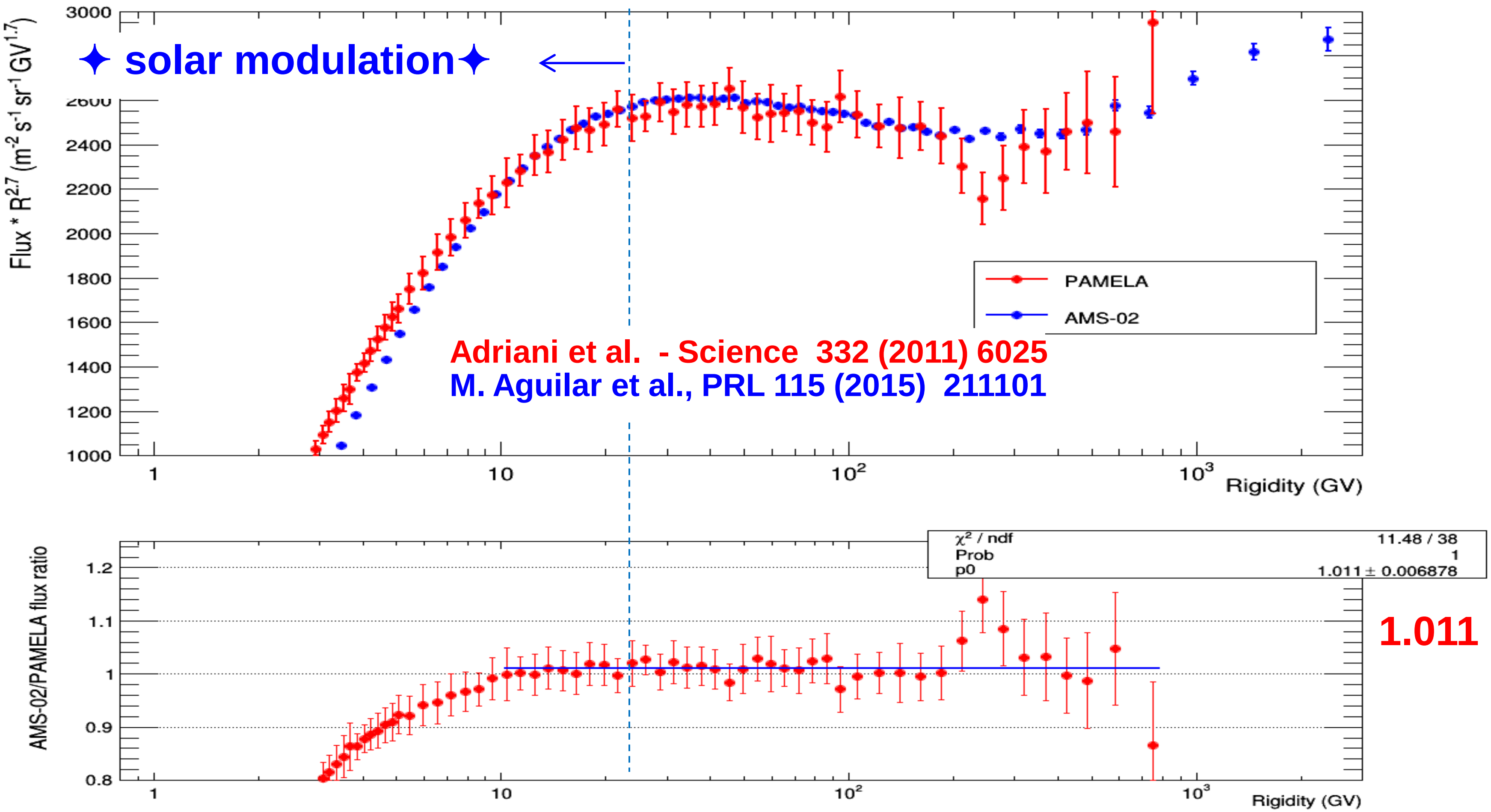
Inferred cosmic-ray p spectrum from Fermi



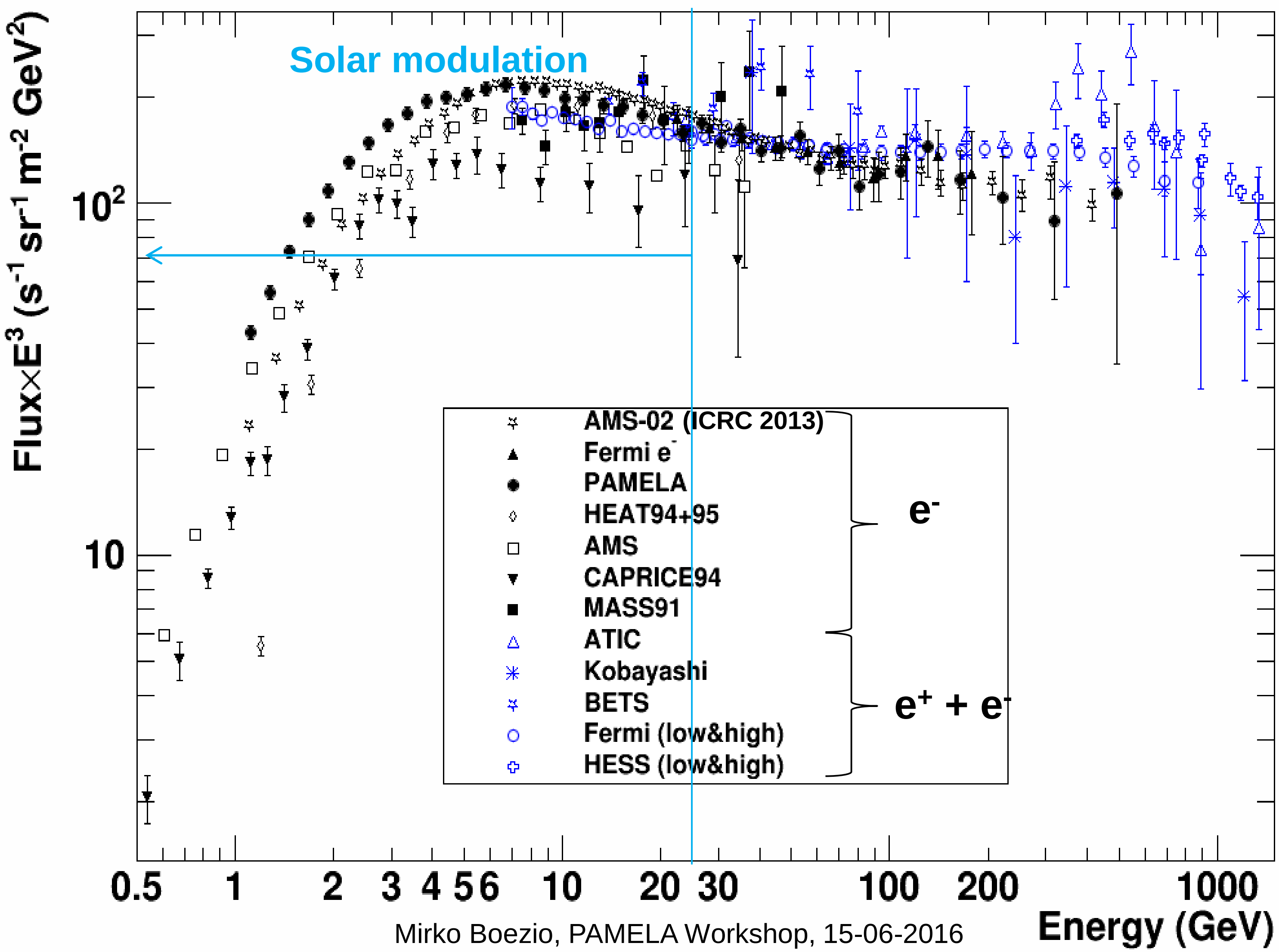
M. Ackermann et al., PRL 112 (2014) 151103

PAMELA vs AMS02

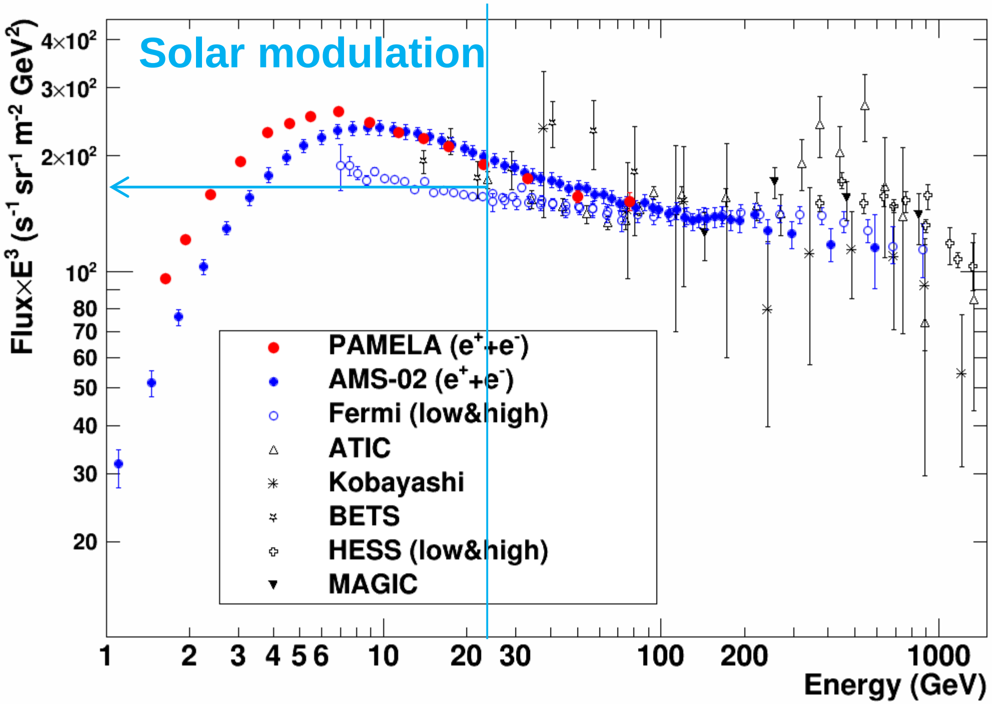
PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

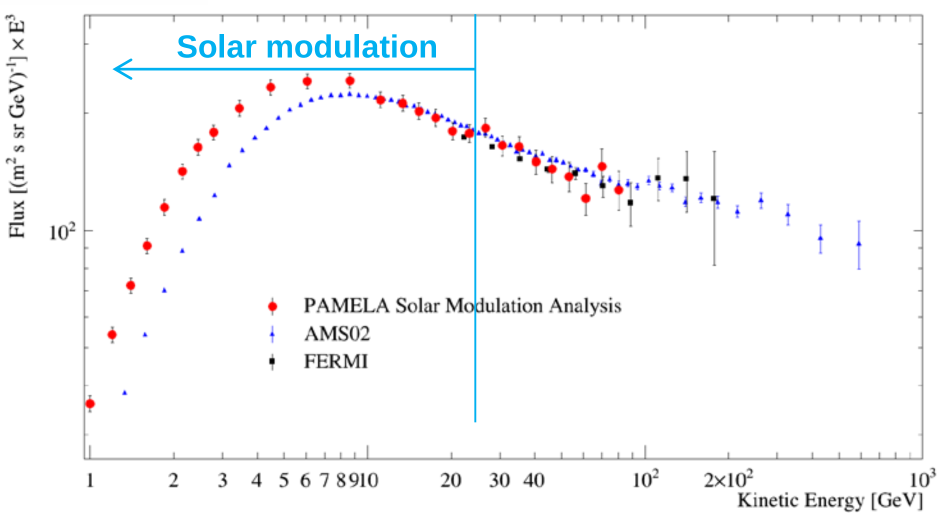


Electron Spectrum



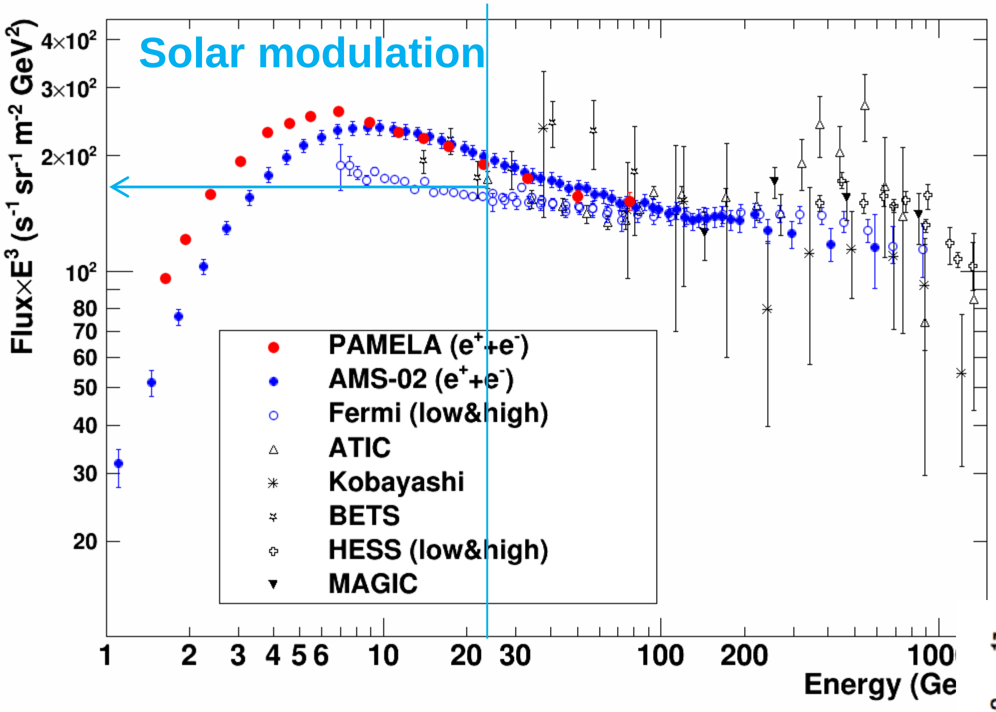
AMS-02, Fermi & PAMELA (e^-+e^+) and e^- spectra

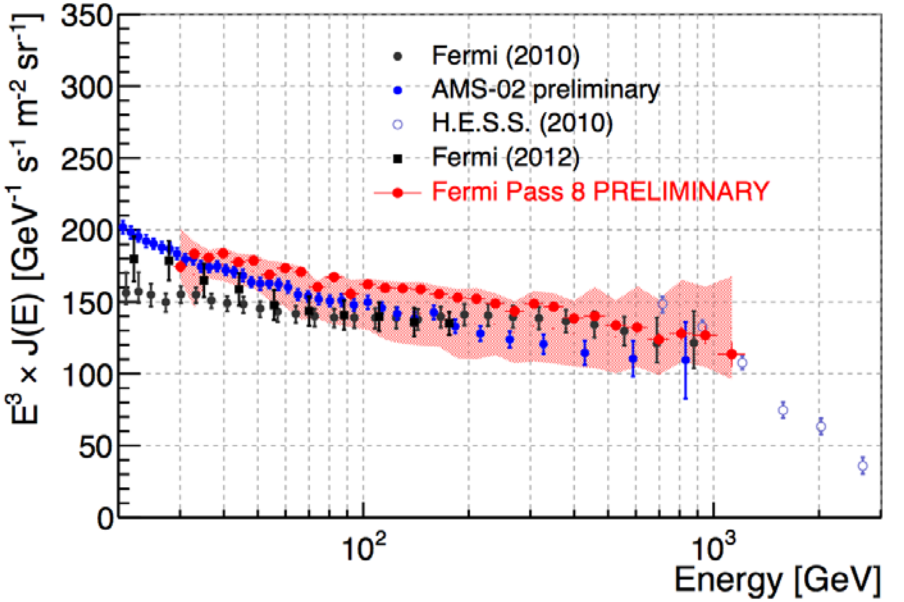


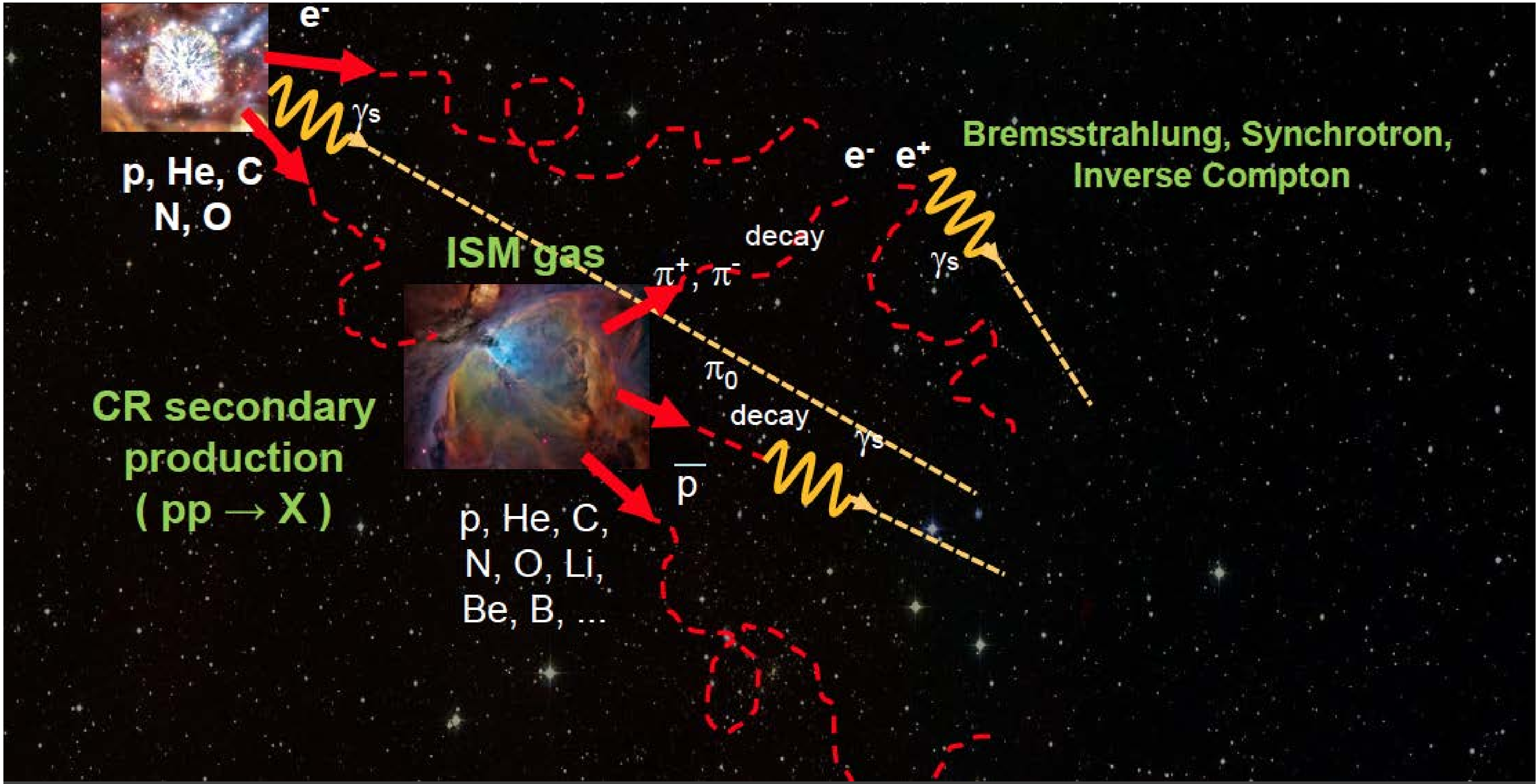


O. Adriani et al., ApJ 810 (2015) 142

AMS-02, Fermi & PAMELA (e^-+e^+) spectra



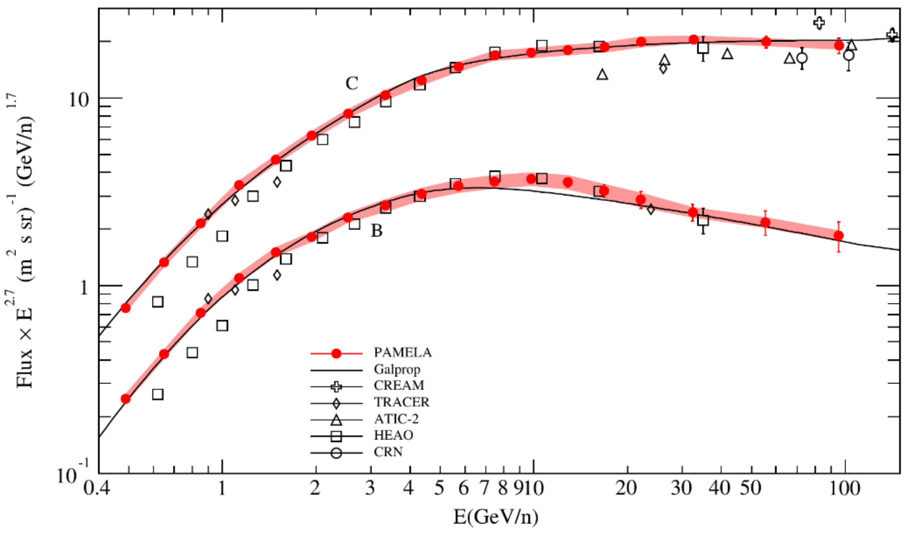




Secondary cosmic rays

Antiparticles (antiprotons, positrons), secondaries from homogeneously distributed interstellar matter (light nuclei)

Boron and carbon fluxes and B/C



- Tracking performance:
  - σ_x = 14 μm, σ_y = 19 μm
  - MDR = 250 GV
- Modelization of cosmic-ray propagation in the Galaxy

O. Adriani et al., ApJ 791 (2014), 93

Boron and carbon fluxes and B/C

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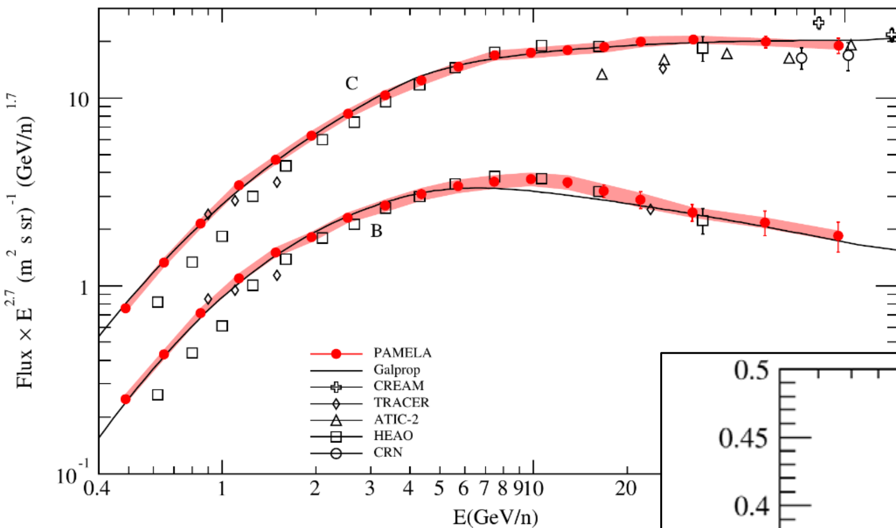
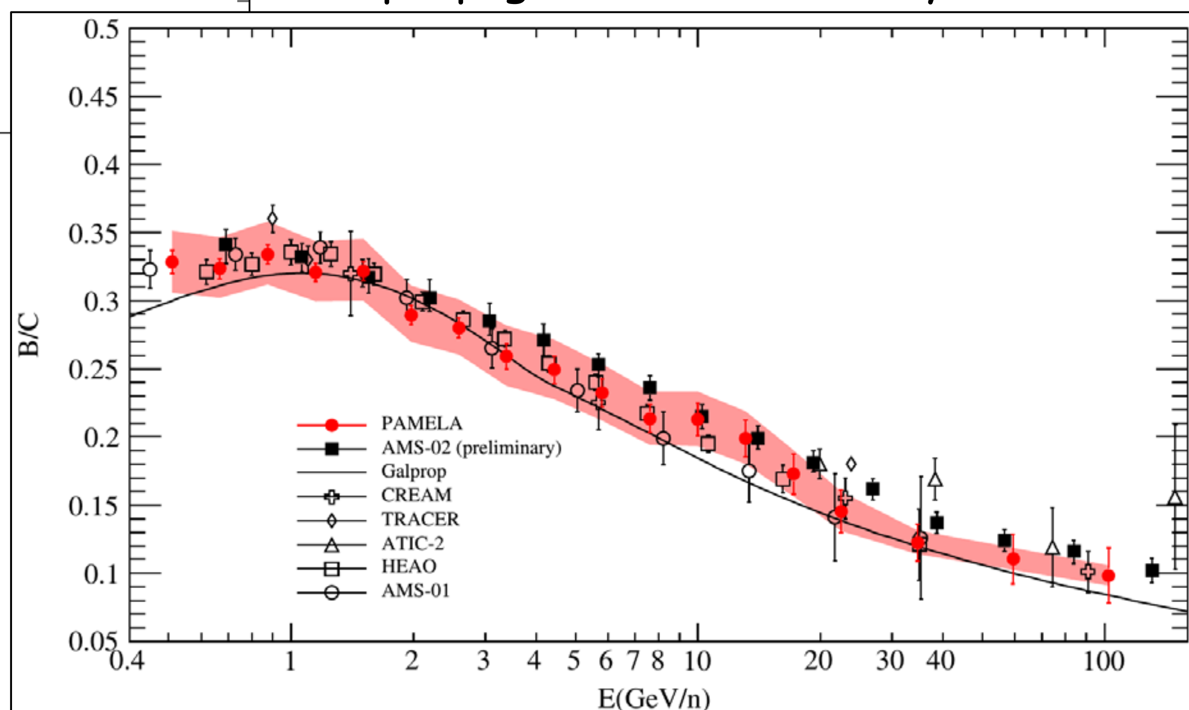
- Modelization of cosmic-ray propagation in the Galaxy

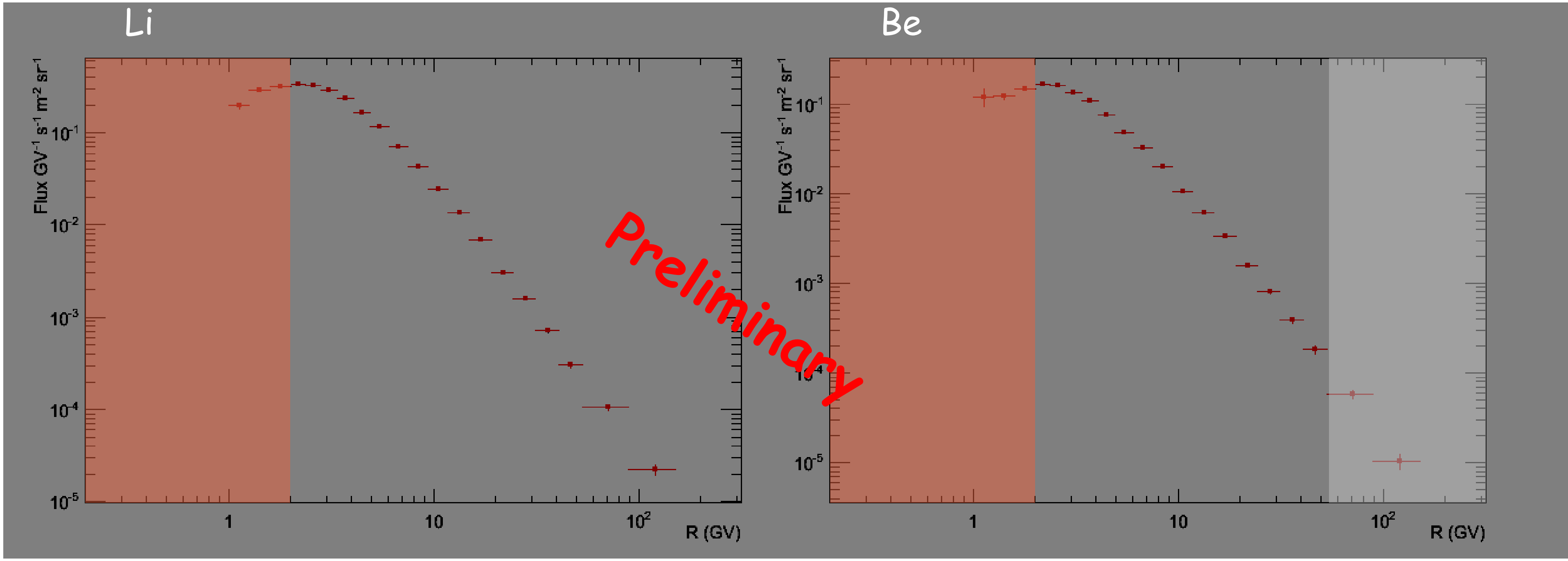




O. Adriani et al., ApJ 791 (2014), 93

Igor's talk

Lithium and beryllium fluxes

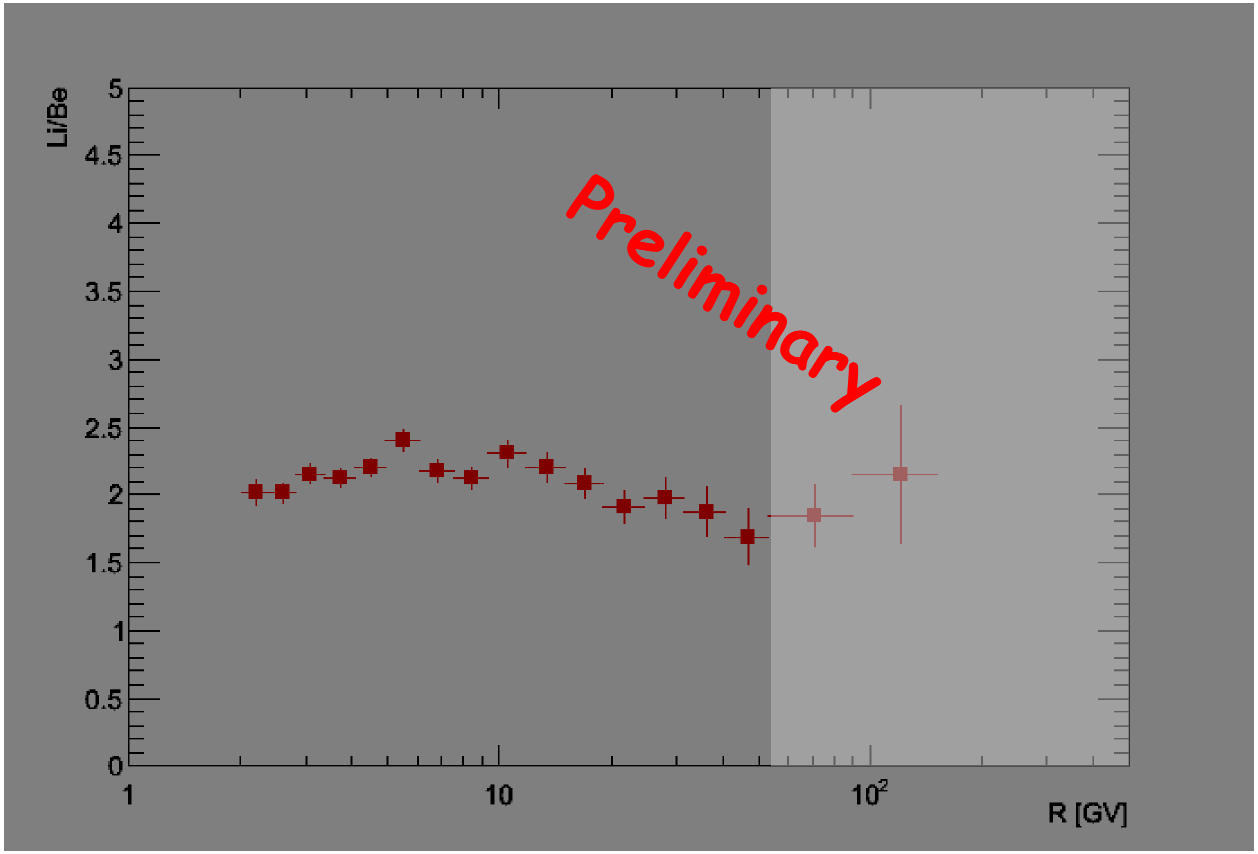


•Shaded red area: particle slow-down effects (still to be corrected)

•Shaded grey area: relevant MDR effects for Be (due to saturated clusters) (still to be corrected)

•No MC corrections
•Not unfolded
•Only statistical errors

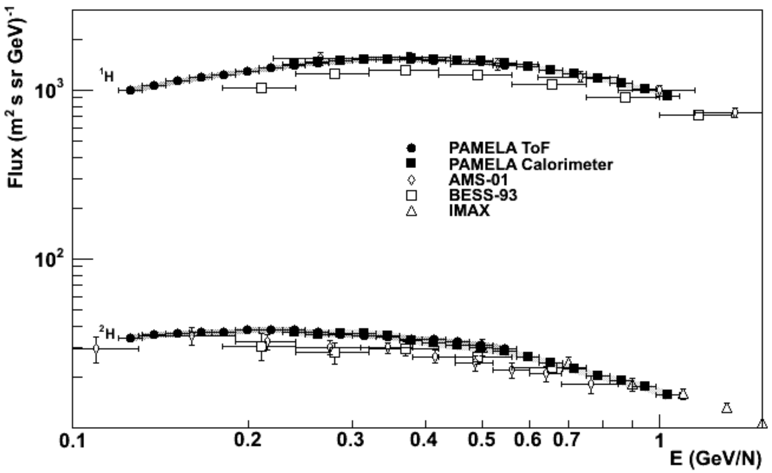
Li/Be Ratio

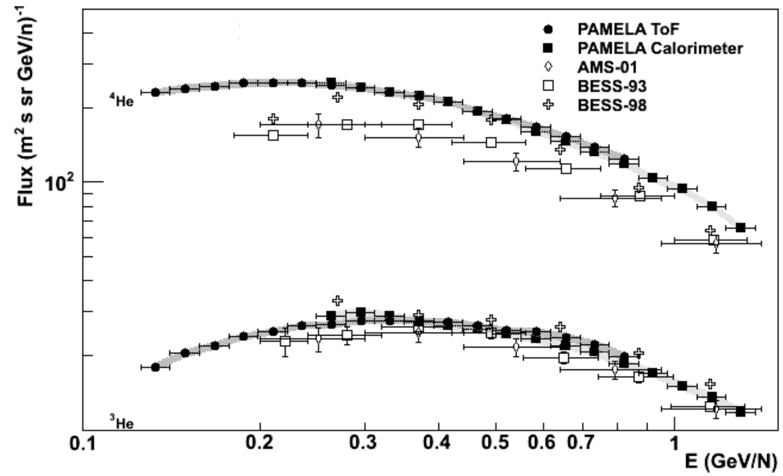


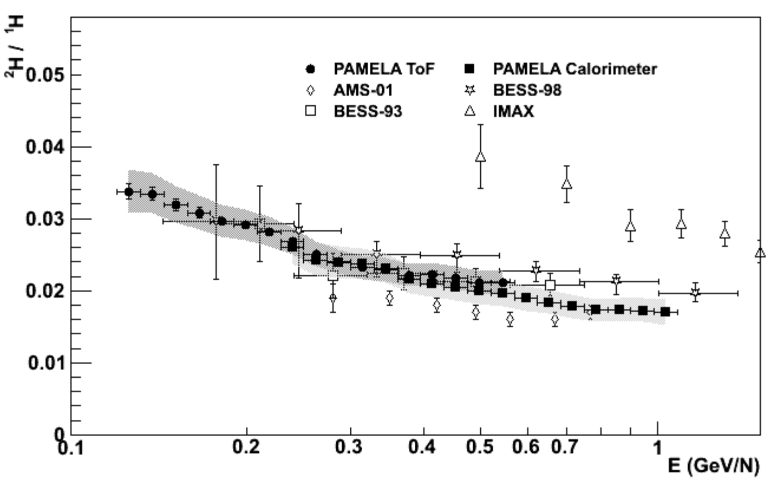
- Shaded grey area: relevant MDR effects for Be (due to saturated clusters) (Still to be corrected)

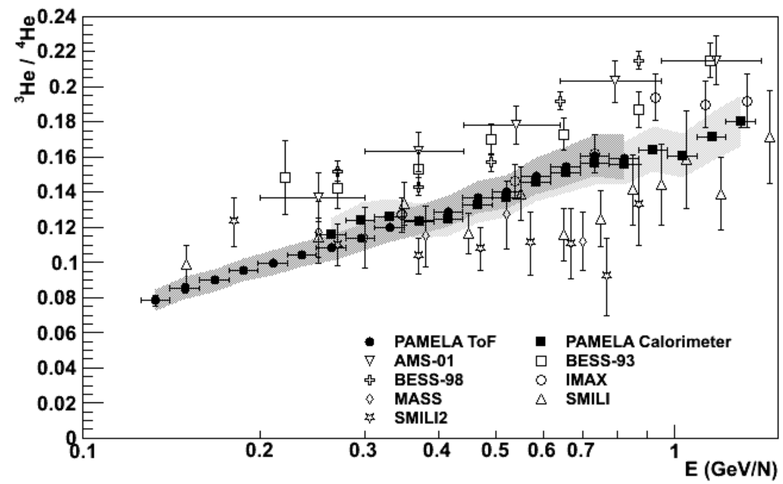
- No MC corrections
- Not unfolded
- Only statistical errors

Hydrogen and helium isotopes







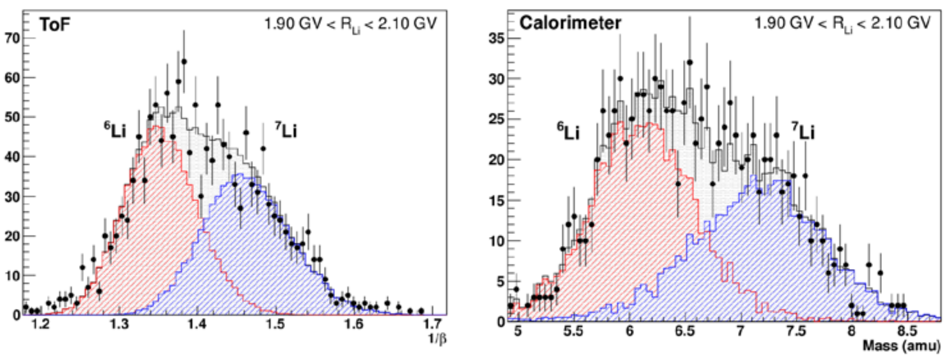


O. Adriani et al., ApJ 770 (2013) 2
O. Adriani et al., ApJ 818 (2016) 68

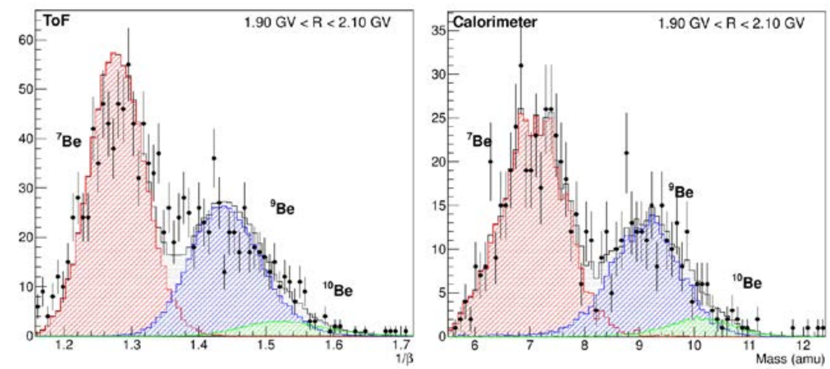
Lithium and Beryllium Isotopes

β (ToF) vs. Rigidity or Multiple dE/dx (Calorimeter) vs. rigidity

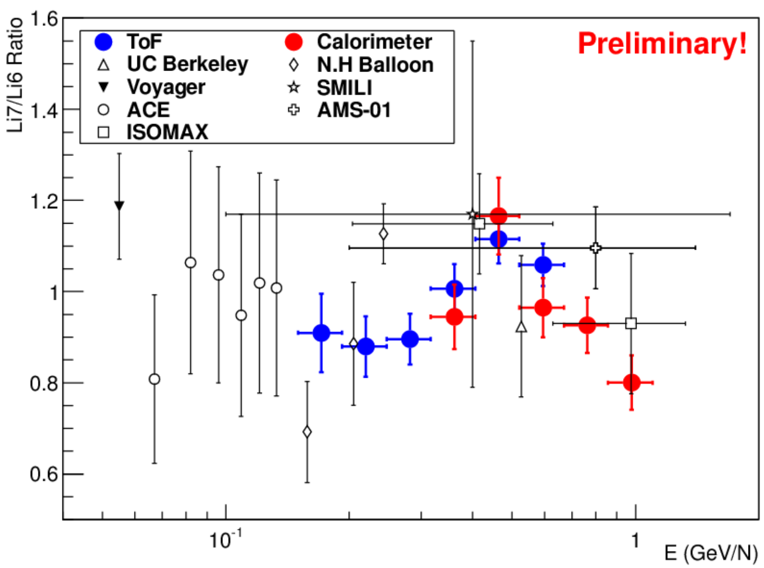
Lithium



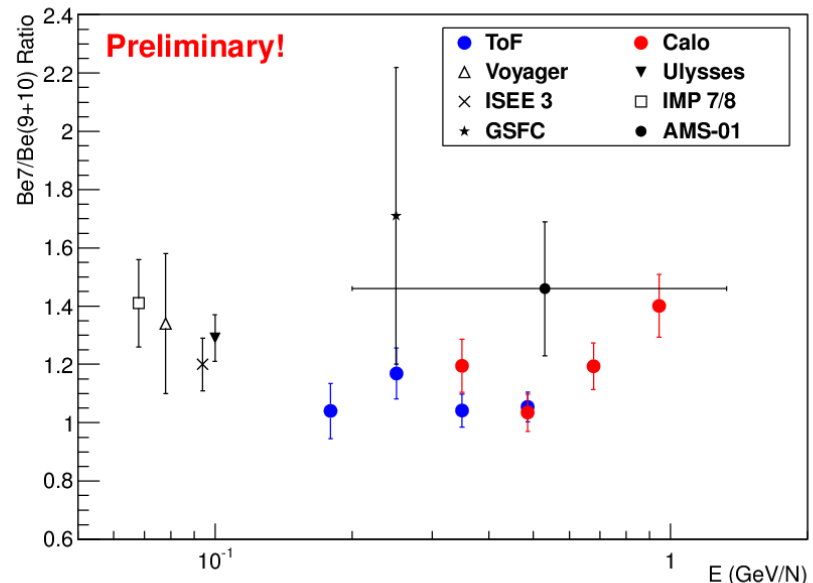
Beryllium



Ratio ^{7}Li / ^{6}Li



^{7}Be / (^{9}Be + ^{10}Be)



Mirko Boezio, PAMELA Workshop, 15-06-2016

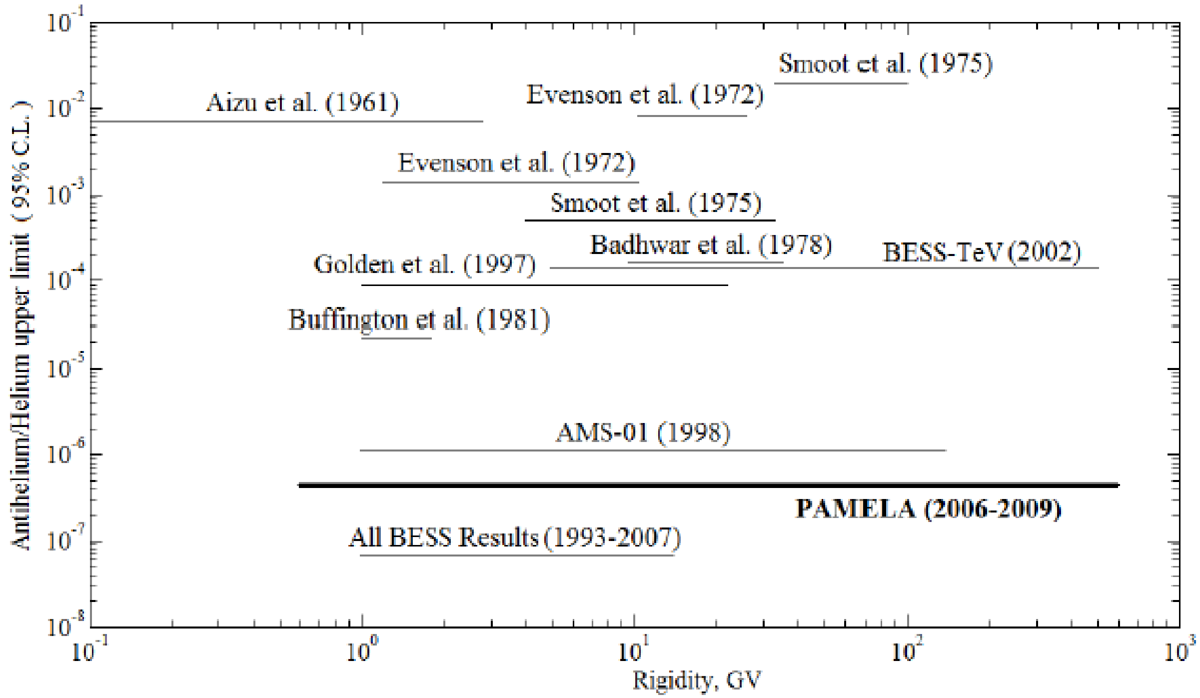
Astrophysics and cosmology compelling issues

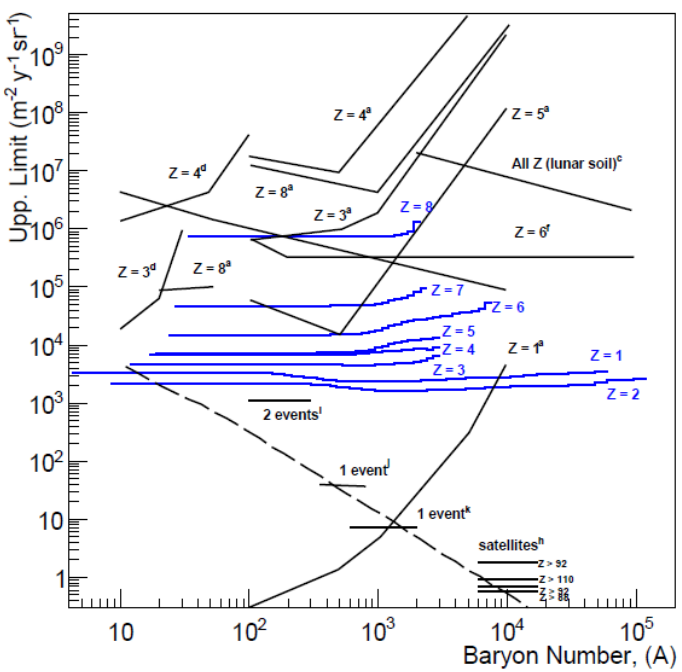
- *Origin and propagation of the cosmic radiation*
- *Nature of the Dark Matter that pervades the Universe*
- *Apparent absence of cosmological Antimatter*

$\overline{\text{He}}$/He and search for SQM

No antiHe detected in a sample of 6.330.000 events with |Z|>=2,from 0.6 to 600 GV.

Widest energy range ever reached





- **No anomalous A/Z particle has been found** (for Z <8) in the rigidity range
  $1 < R < 1.0 \times 10^3$ GV
  and mass range
  $4 < A < 1.2 \times 10^5$

- Upper limit as a function of Baryon Number (A) set

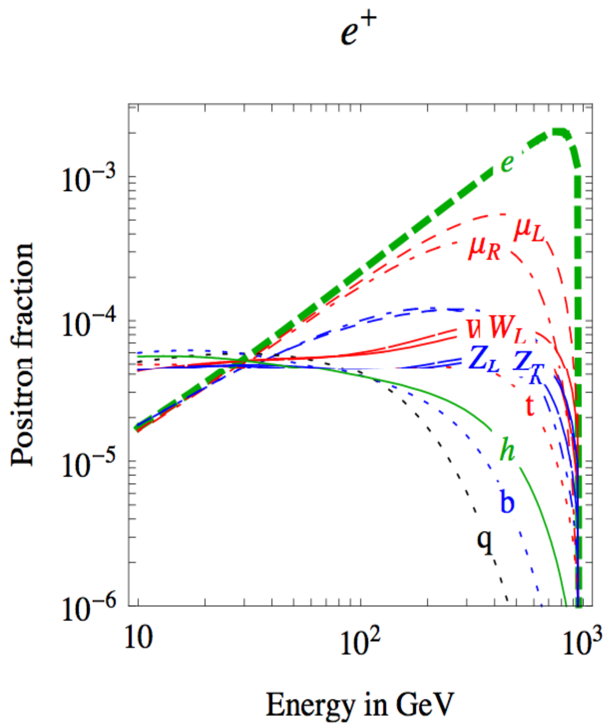
O. Adriani et al., PRL 115 (2015) 111101

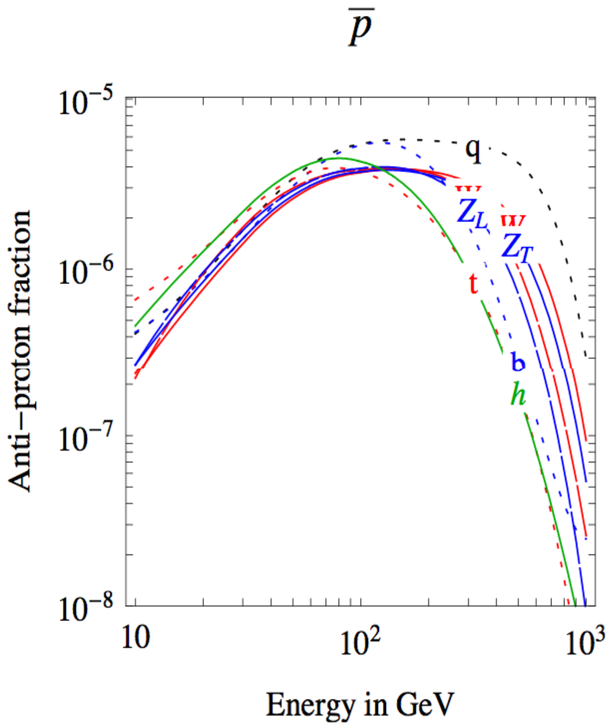
DM annihilations

Resulting spectrum for positrons and antiprotons
M_{WIMP}= 1 TeV

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels





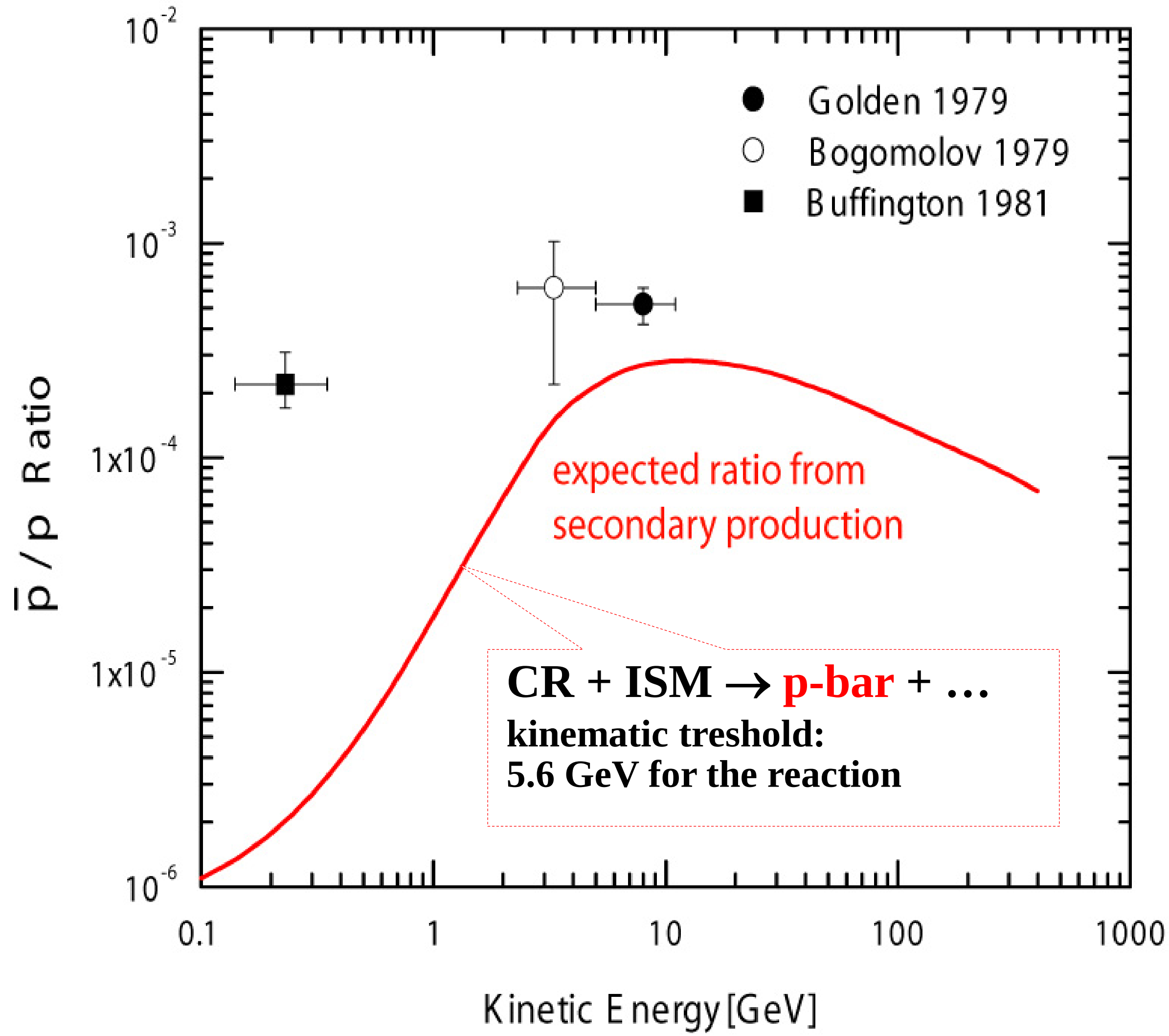
Tim's talk

First Detection in the Cosmic Rays

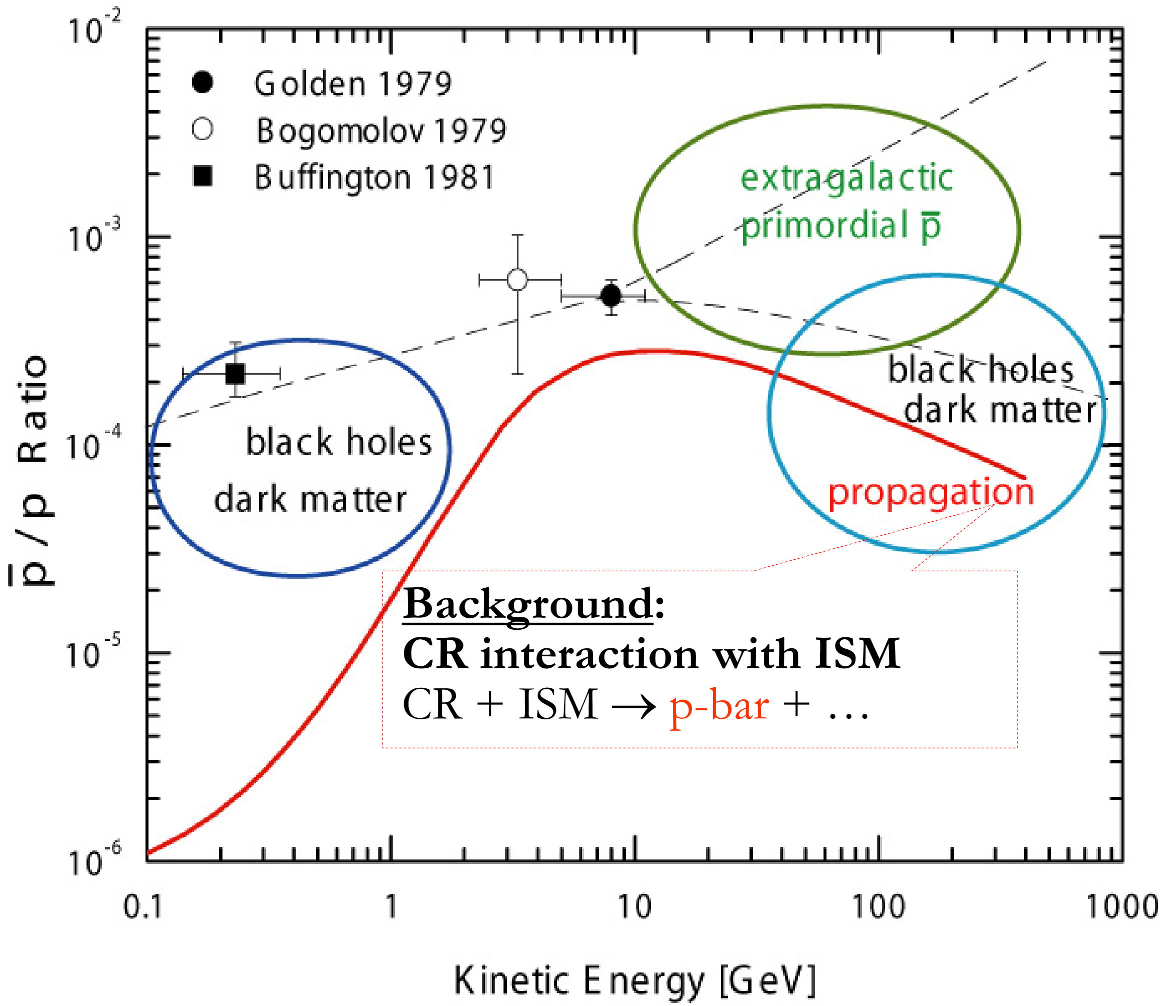
- First detection of positrons in the cosmic radiation in 1964 by J.A. De shong, R.H. Hildebrand & P. Meyer Phys. Rev. Let. **12** (1964) 3

- First detection of antiprotons in the cosmic radiations in 1979 by R.L. Golden et al. Phys. Rev. Let. **43** (1979) 1196, and by E. Bogomolov et al., 16^{th} ICRC (1979), Tokyo, Japan

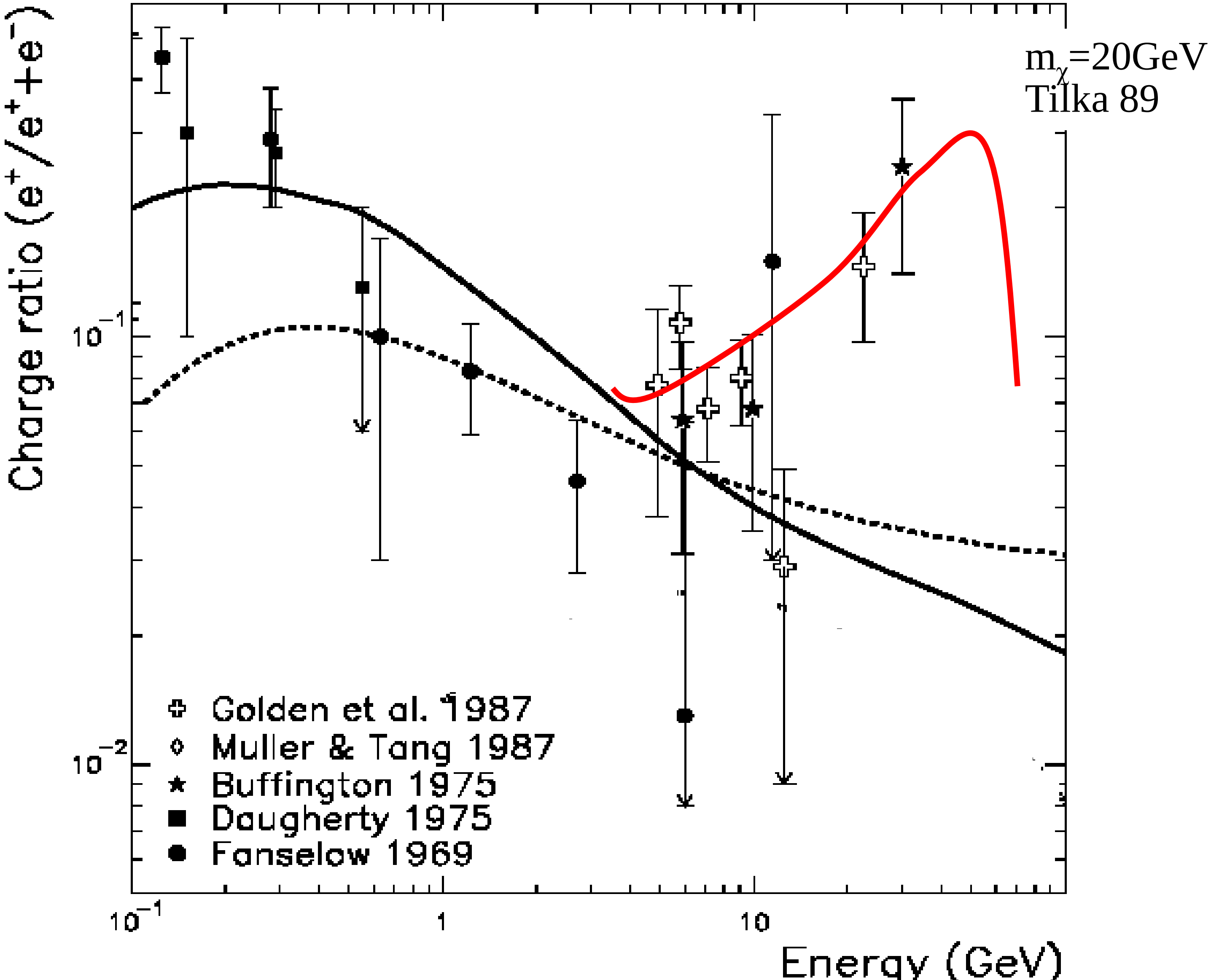
The first historical measurements on galactic antiprotons



The first historical measurements of the p̄/p - ratio and various Ideas of theoretical Interpretations

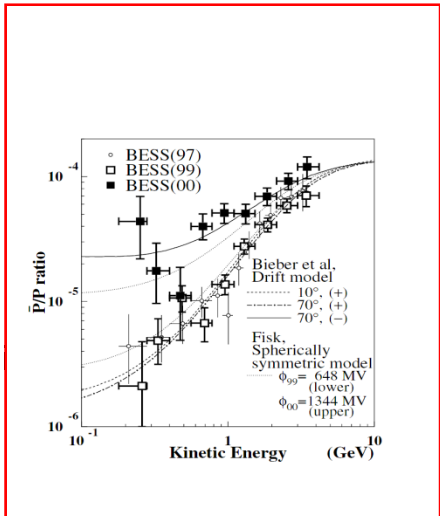


Balloon data : Positron fraction before 1990

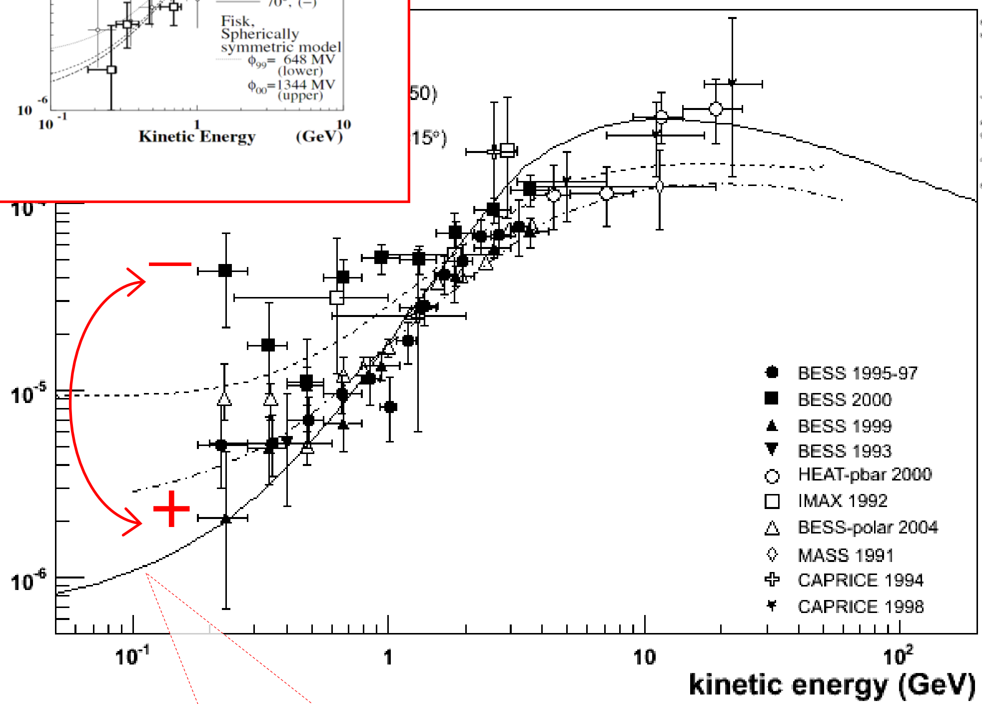


CR antimatter

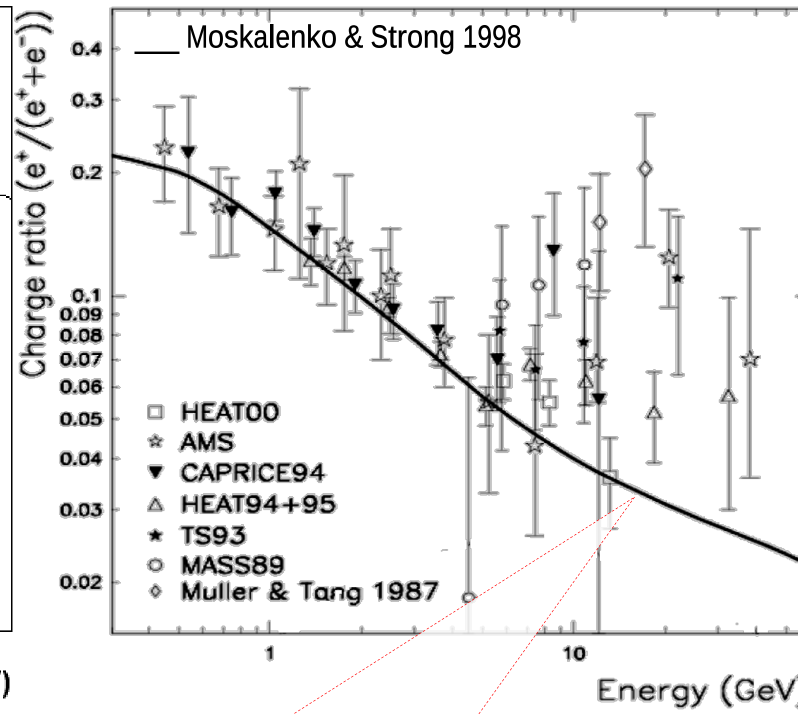
Status in 2006



Antiprotons



Positrons



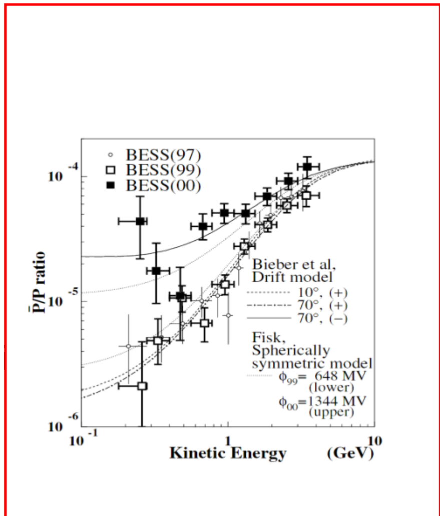
CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

$$pp \rightarrow \bar{p}ppp$$

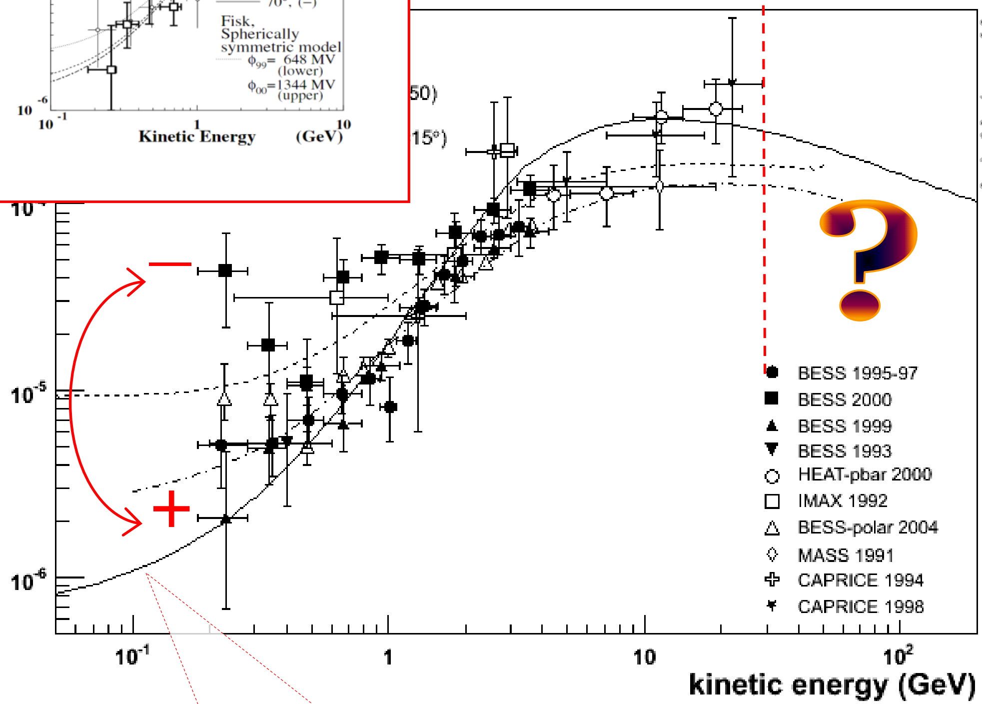
CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x
CR + ISM → π^0 + x → $\gamma\gamma$ → **$e^{\pm}$**

CR antimatter

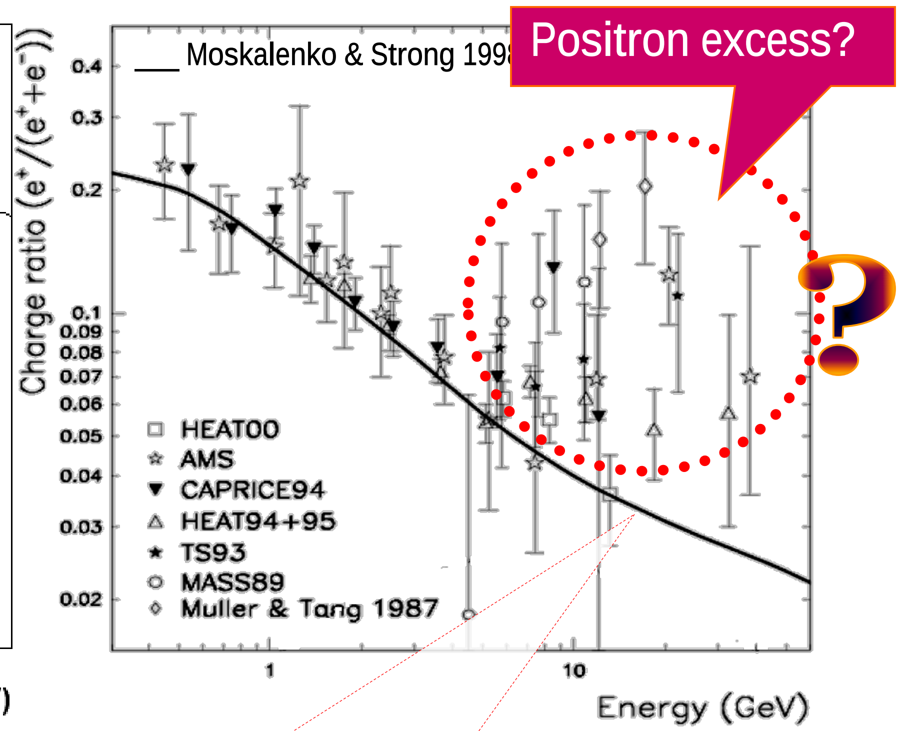
Status in 2006



Antiprotons



Positrons



CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

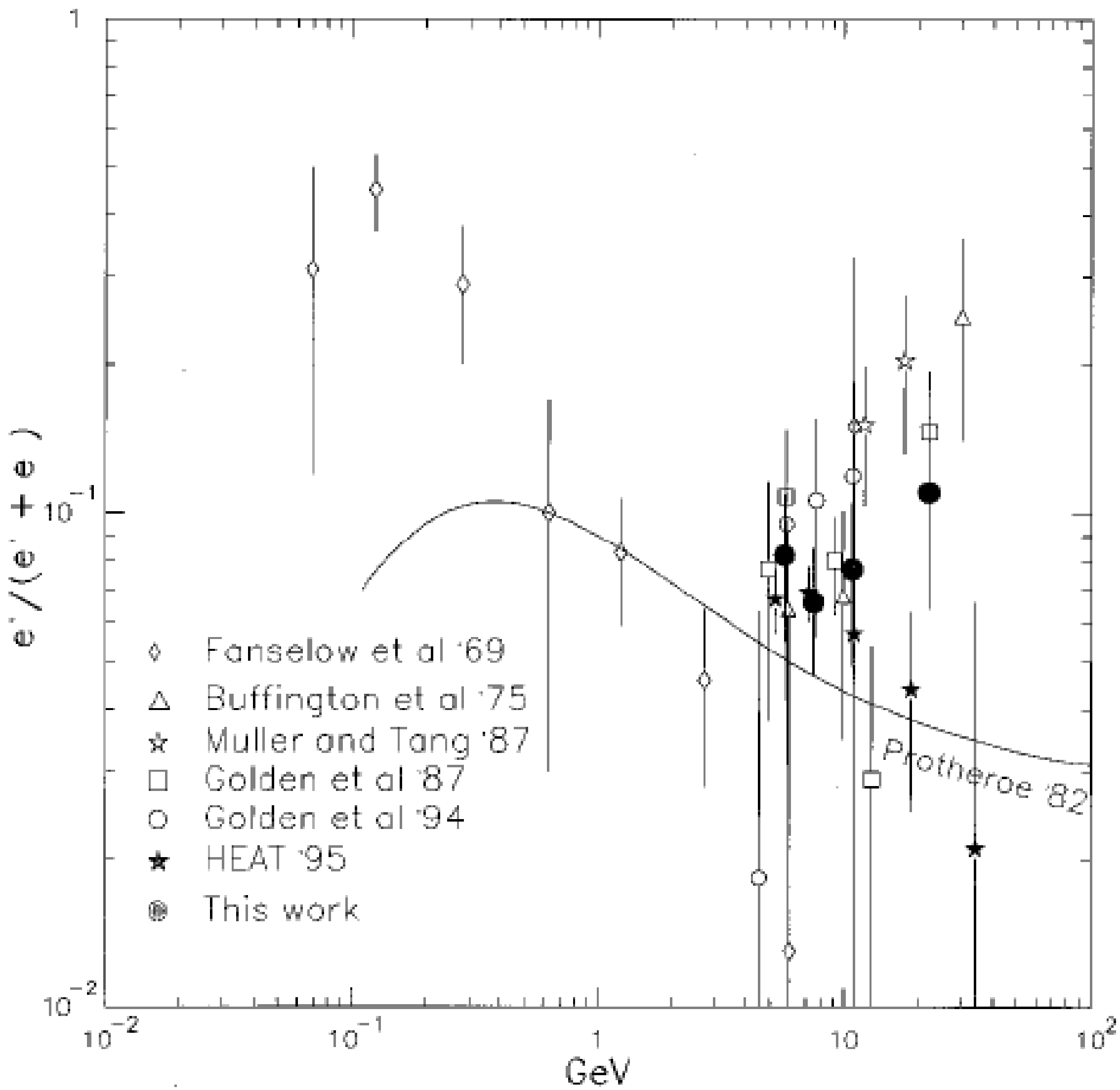
$$pp \rightarrow \bar{p}ppp$$

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x
CR + ISM → π^0 + x → $\gamma\gamma$ → **$e^{\pm}$**

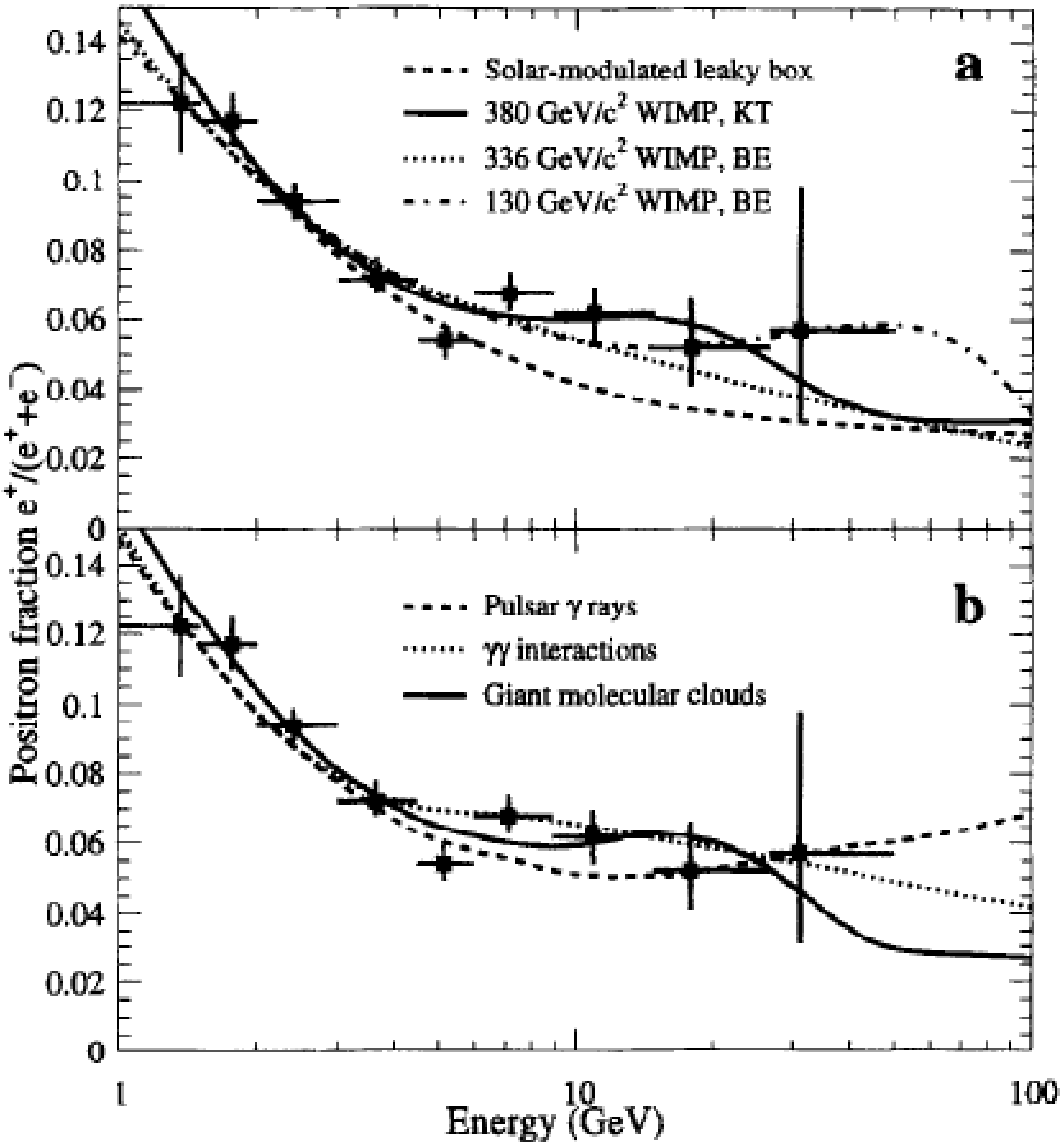
Interlude: positron fraction history

R. Golden et al., ApJ 457 L103 (1996)

"It may be pointed out that our results do not exhibit the trend shown by Barwick et al. (1995) [HEAT94], in which the positron fraction decreases with energy."

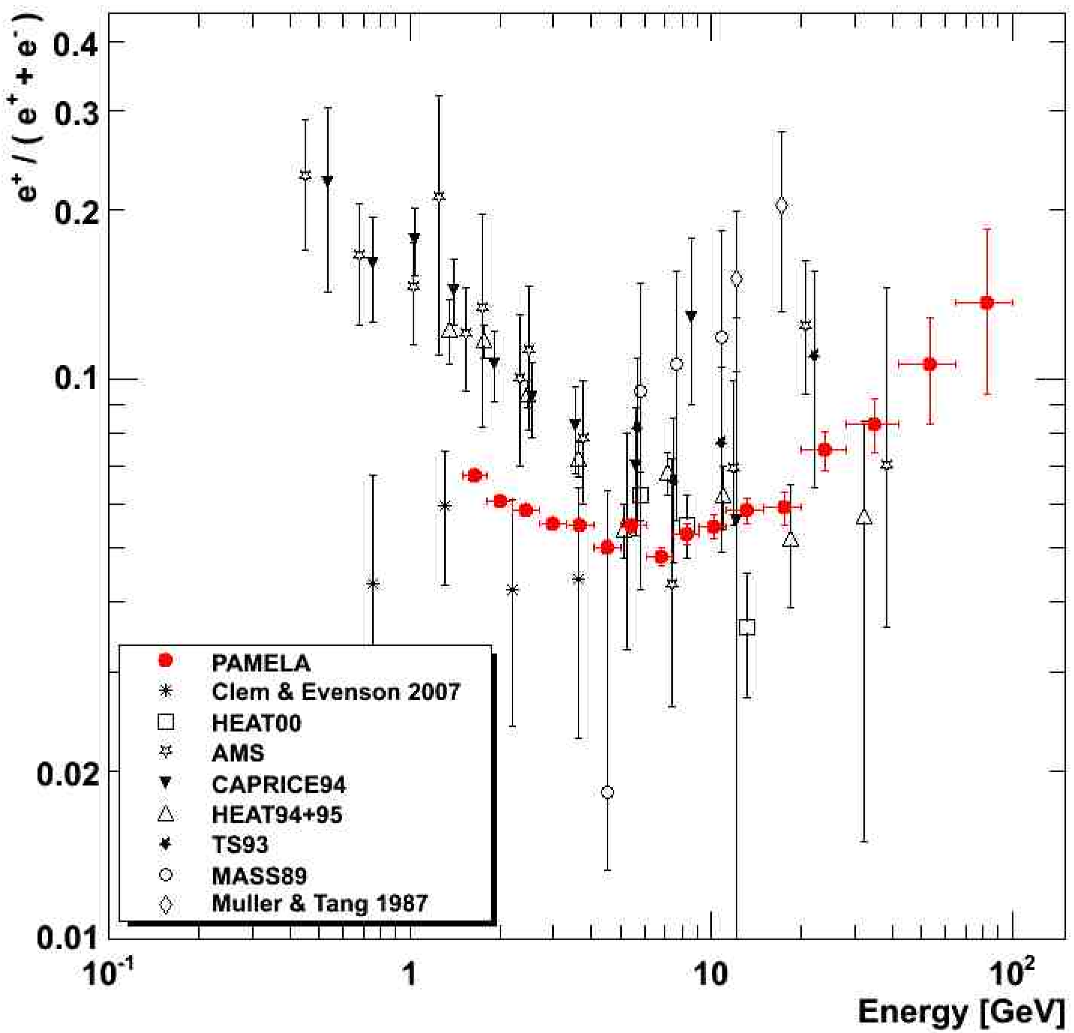


Interlude: positron fraction history

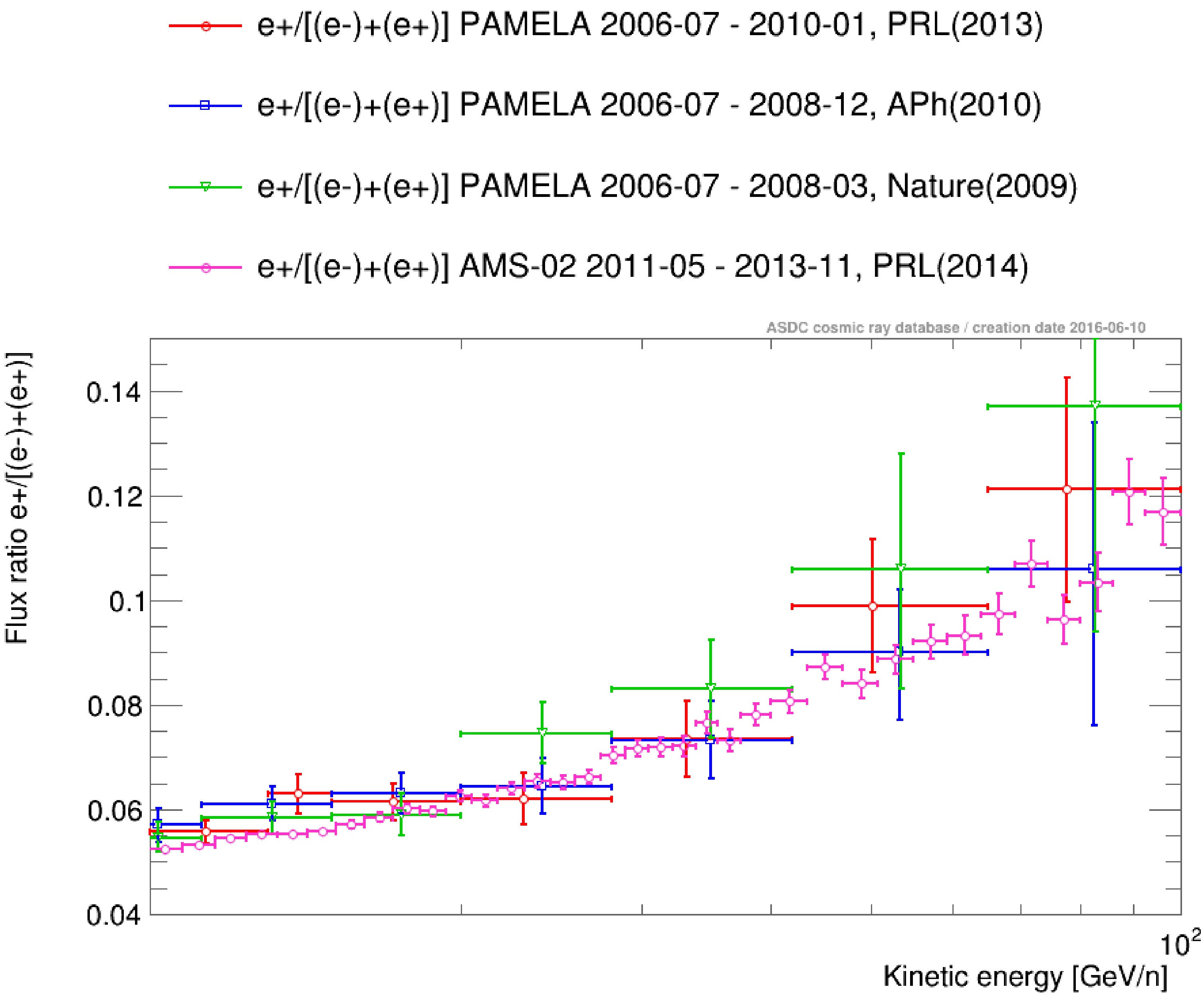


S. Coutu et al., ***Cosmic ray positrons: Are there primary ources?***, *Astropart. Phys. 11 (1999) 429*

PAMELA Positron to Electron Fraction



O. Adriani et al. , Nature 458 (2009) 607



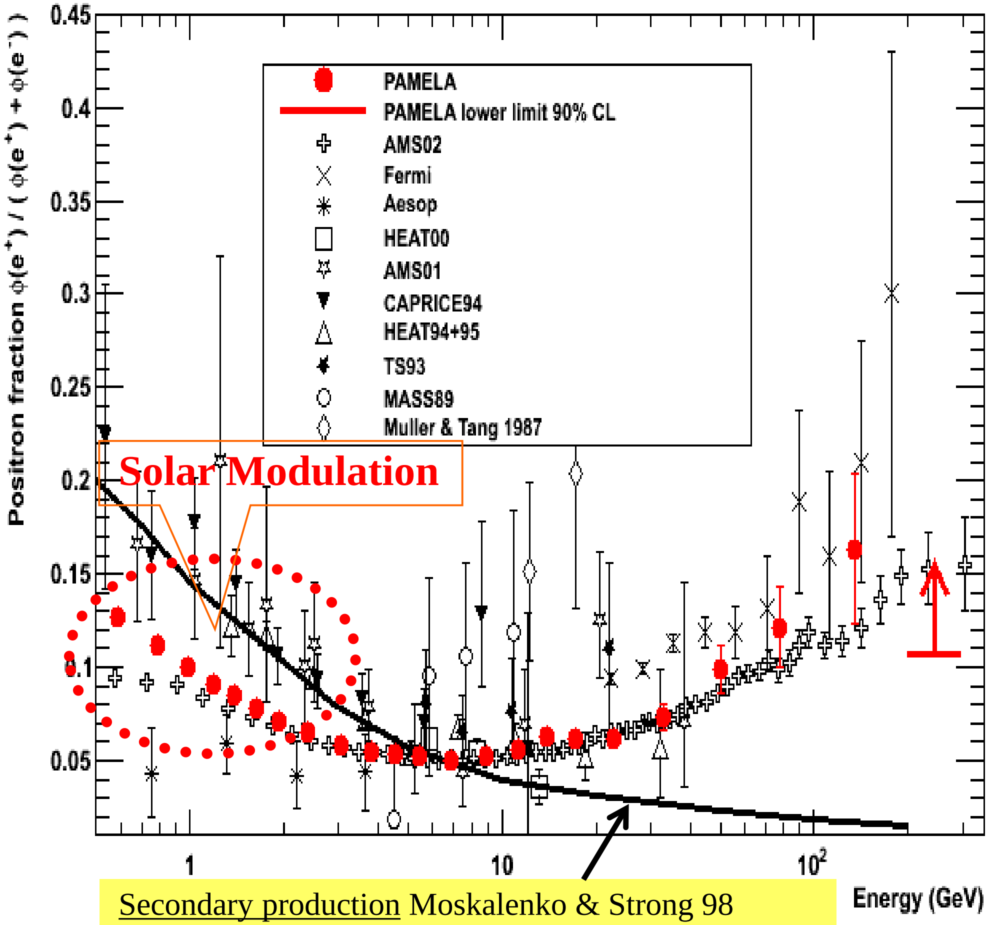
e+/[(e-)+(e+)] PAMELA 2006-07 - 2010-01, PRL(2013)
e+/[(e-)+(e+)] PAMELA 2006-07 - 2008-12, APh(2010)
e+/[(e-)+(e+)] PAMELA 2006-07 - 2008-03, Nature(2009)
e+/[(e-)+(e+)] AMS-02 2011-05 - 2013-11, PRL(2014)
ASDC cosmic ray database / creation date 2016-06-10
Flux ratio e+/[(e-)+(e+)]
0.14
0.12
0.1
0.08
0.06
0.04
10^2
Kinetic energy [GeV/n]

O. Adriani et al. , Nature 458 (2009) 607
O. Adriani et al., Astropart. Phys. 34 (2010) 1
O. Adriani et al. , PRL 111 (2013) 081102

Low energy
→ charge-dependent solar modulation (see later)

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

Positron fraction



Secondary production Moskalenko & Strong 98

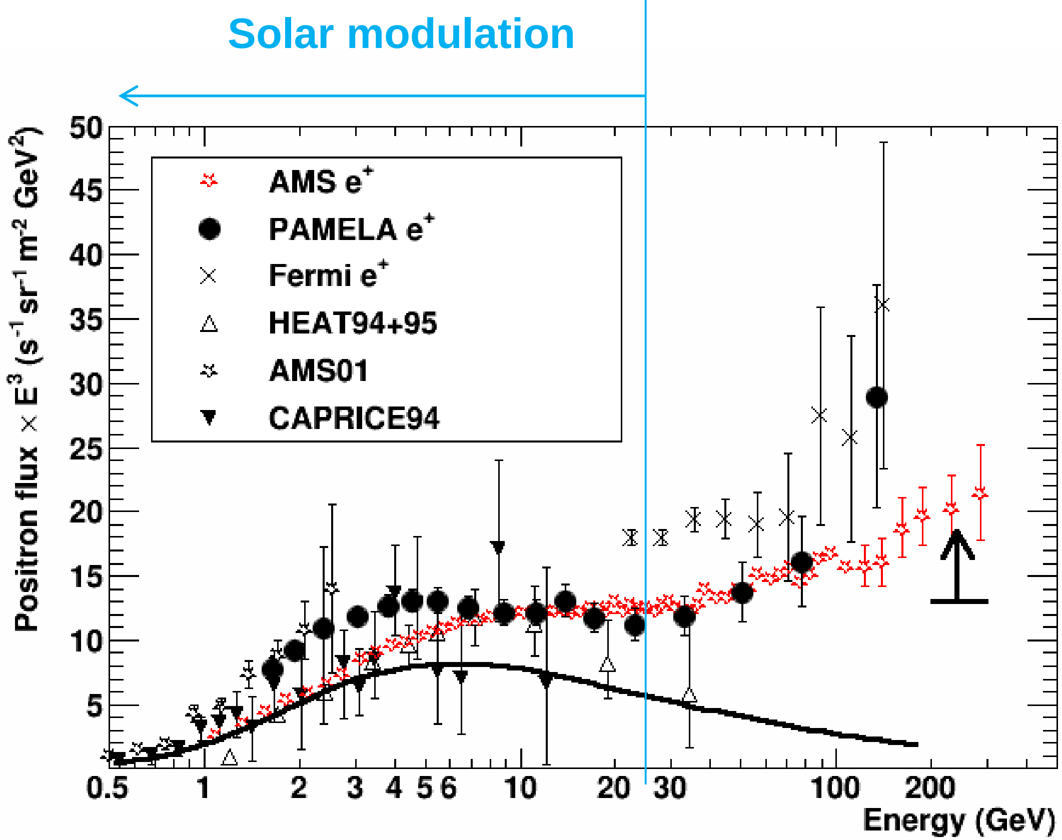
CLEAR evidence for deviation from secondary production

Clear evidence →

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

Positron flux

O. Adriani et al. , PRL 111 (2013) 081102
Editors' Suggestion



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

Implications

A rising positron fraction requires:

1. **An additional component of positrons with spectrum flatter than CR primary electrons**

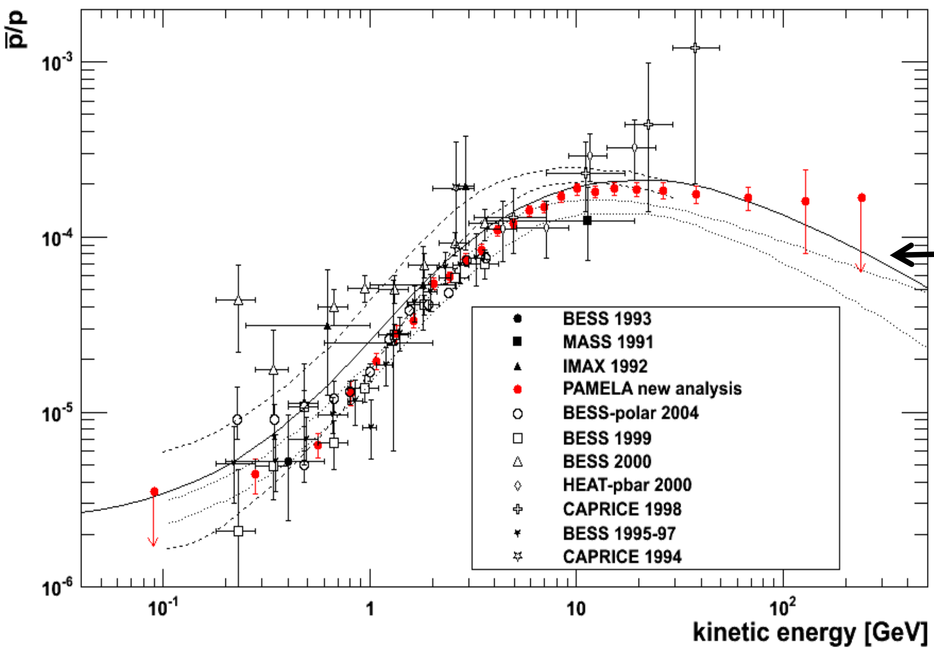
2. **A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)**

3. **Subtleties of Propagation**

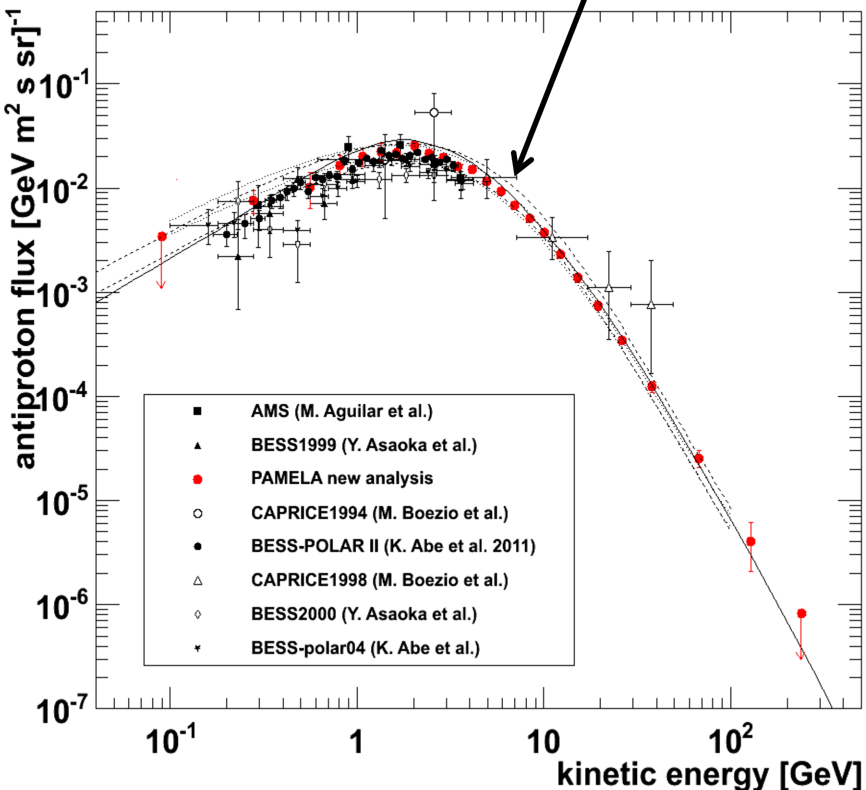
Courtesy by P. Blasi

PAMELA Antiparticle Results: Antiprotons

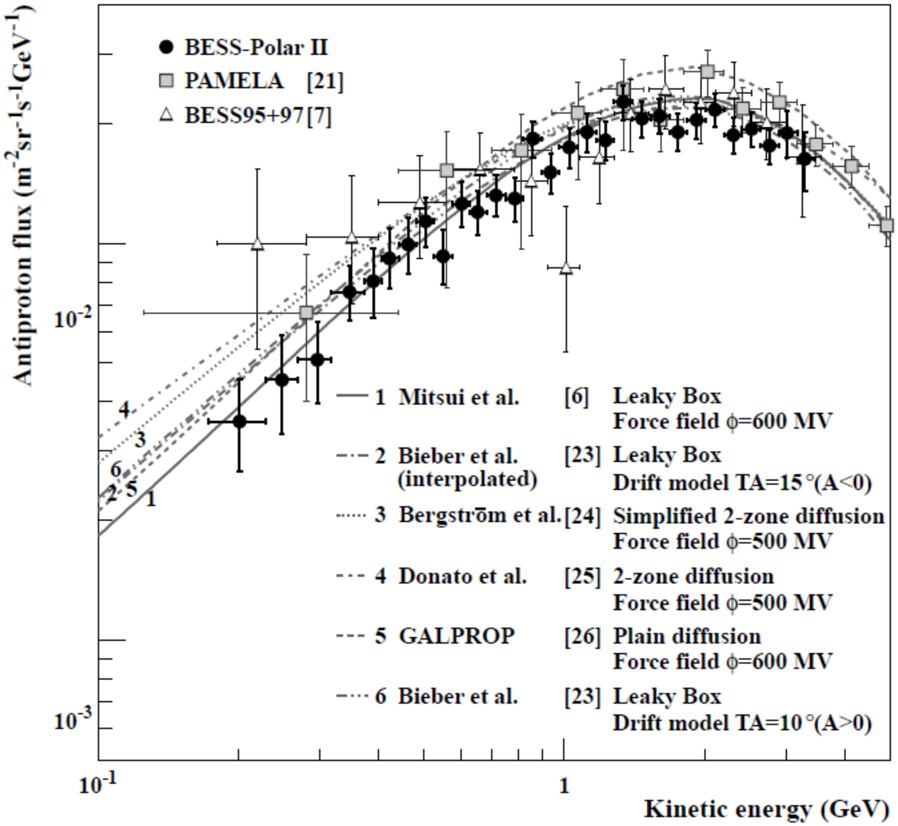
O. Adriani et al,
PRL 102 (2009) 051101, Editors' Suggestion;
PRL 105 (2010) 121101, Editors' Suggestion;
Phys. Rep. (2014).



Secondary production calculations

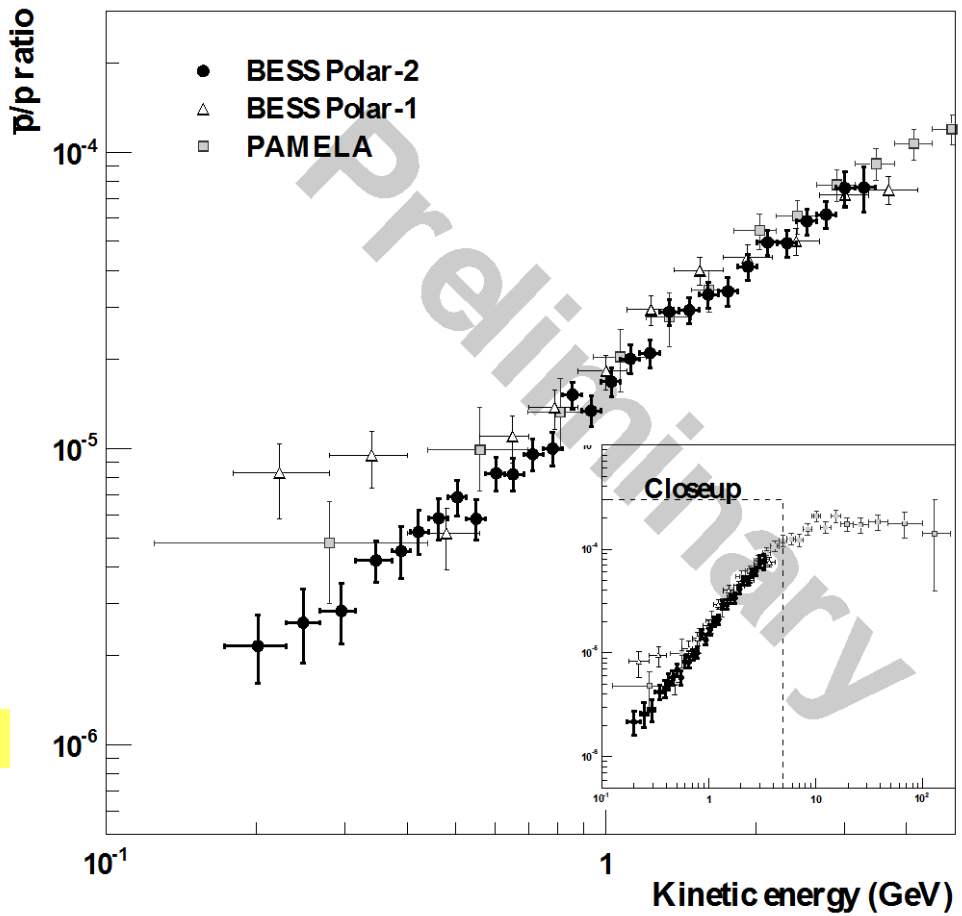


Global picture: PAMELA vs BESS Polar pbar

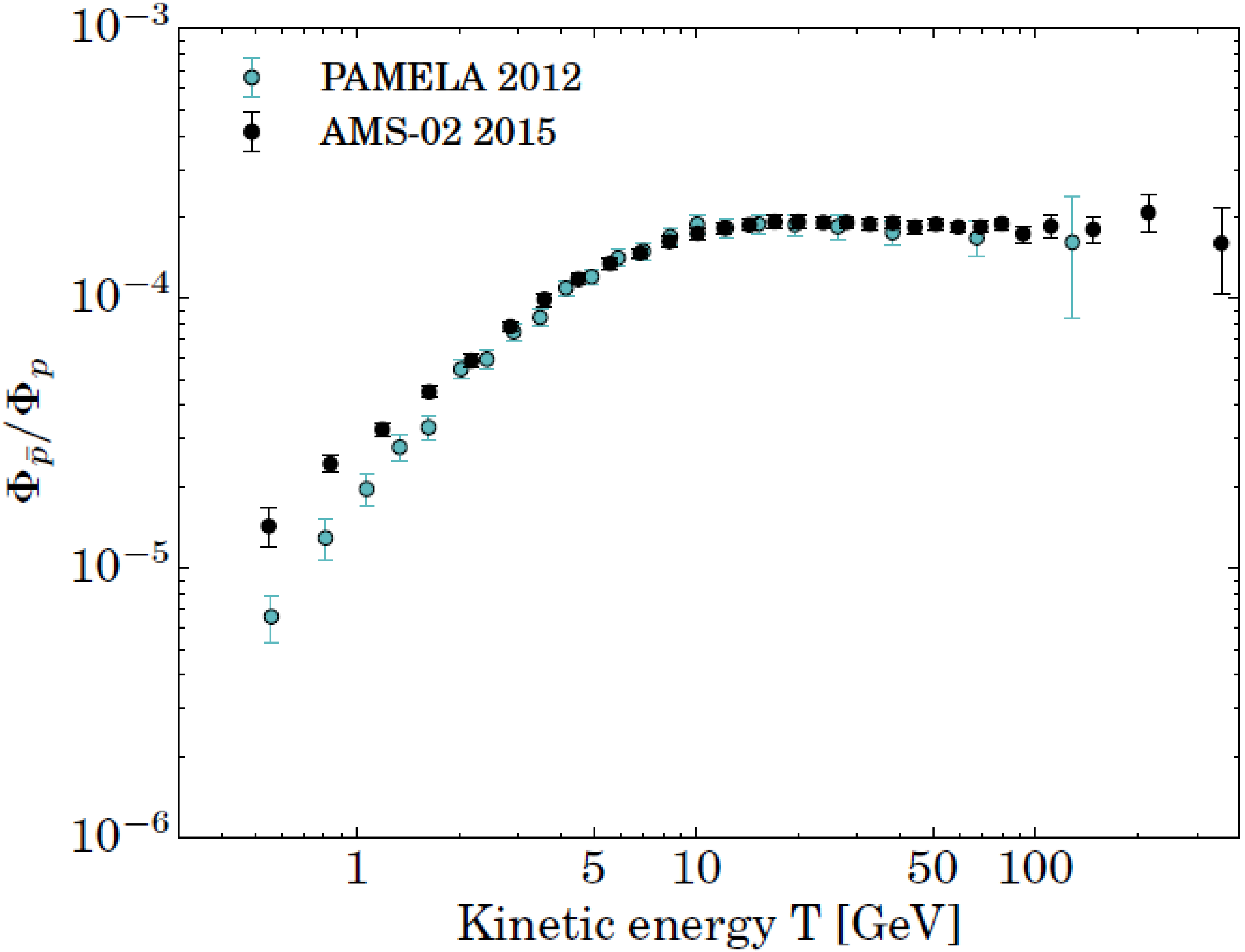


J. W. Mitchell, TeVPA 2013

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

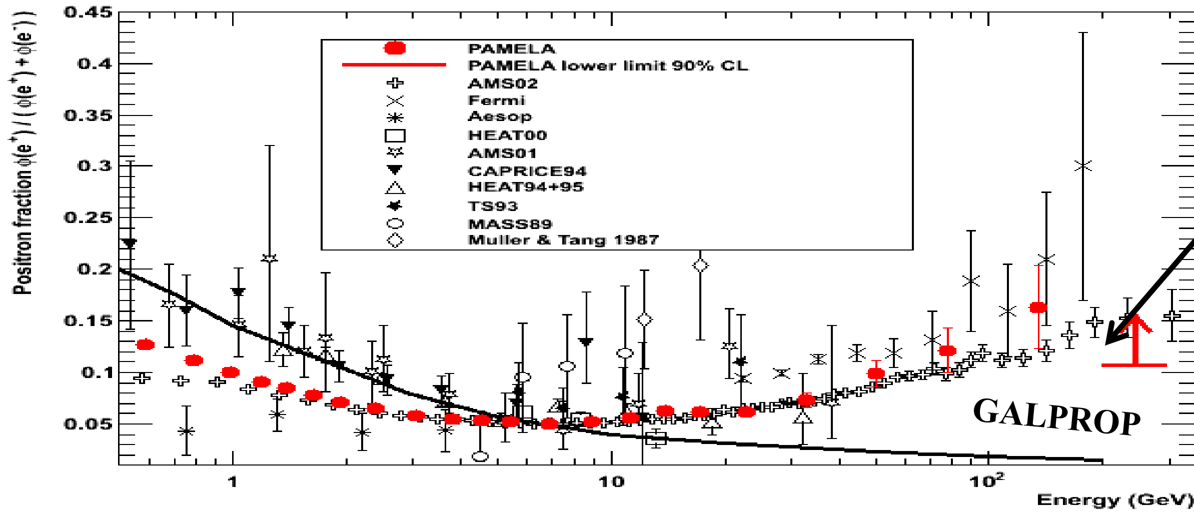


Global picture: PAMELA vs AMS-02 pbar/p ratio

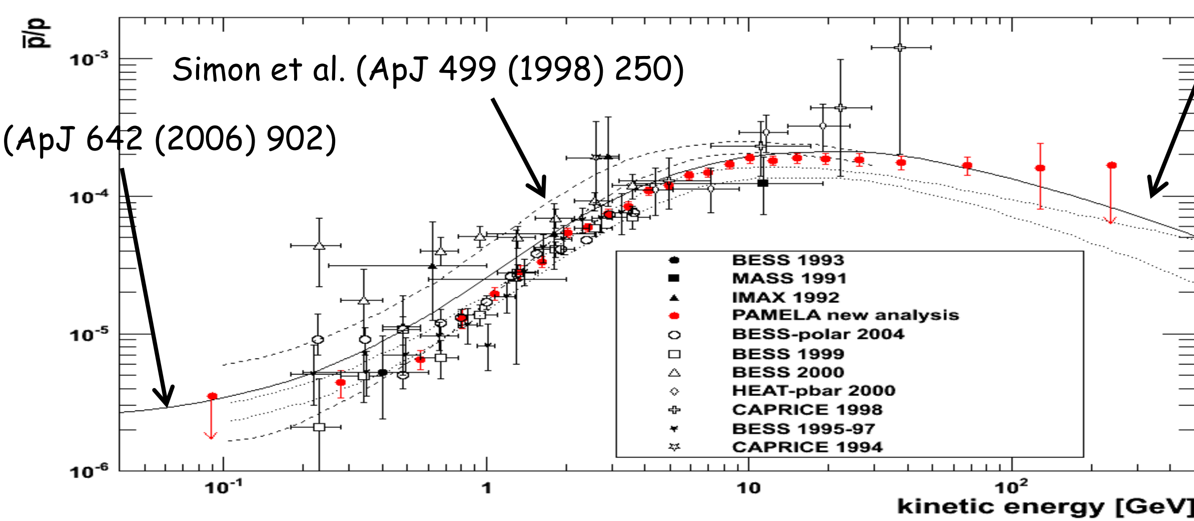


M. Circelli,
Rapporteur talk
ICRC 2015

A Challenging Puzzle for CR Physics



CR Positron spectrum significantly harder than expectations from secondary production



Ptuskin et al. (ApJ 642 (2006) 902)

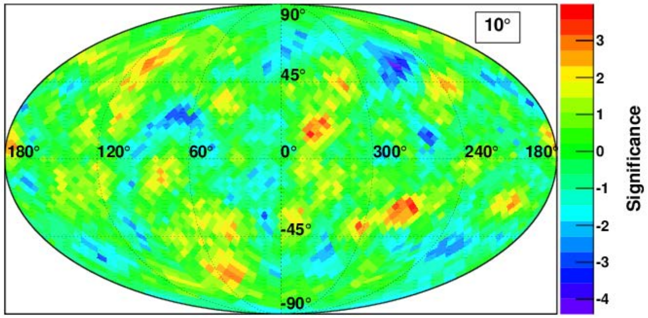
Donato et al. (PRL 102 (2009) 071301)

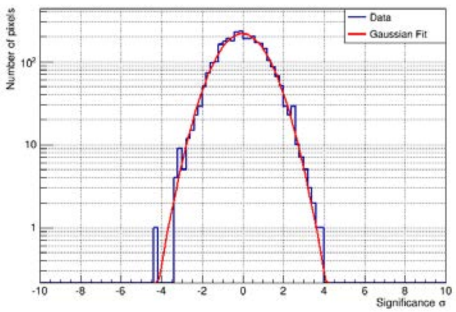
But antiprotons in CRs are in agreement with secondary production

Anisotropy in the e+ and e- data

Positrons - R > 10 GV

Significance map for
backtraced positrons
Background: Protons
Angular scale 10°



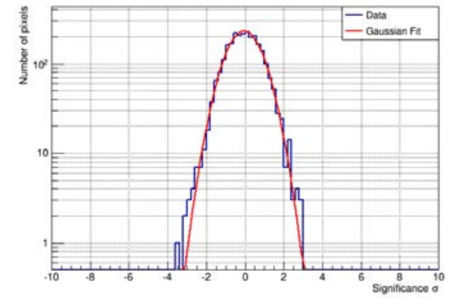


Histogram of calculated significance

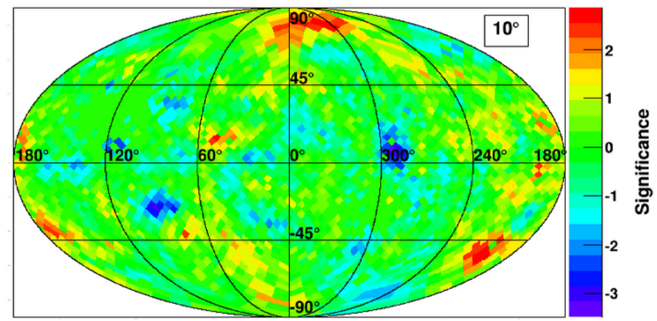
O. Adriani et al., ApJ 811 (2015) 21

Electrons R > 10 GV

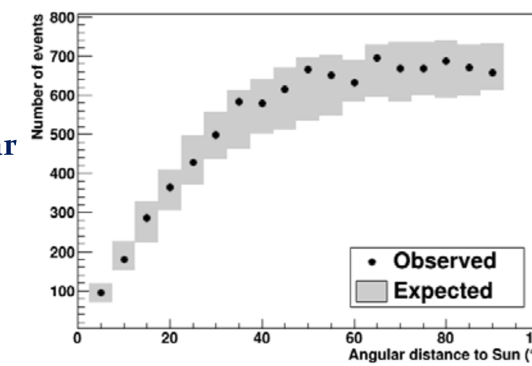
Significance map for
backtraced electrons
Background: Monte Carlo simulations
Angular scale 10°



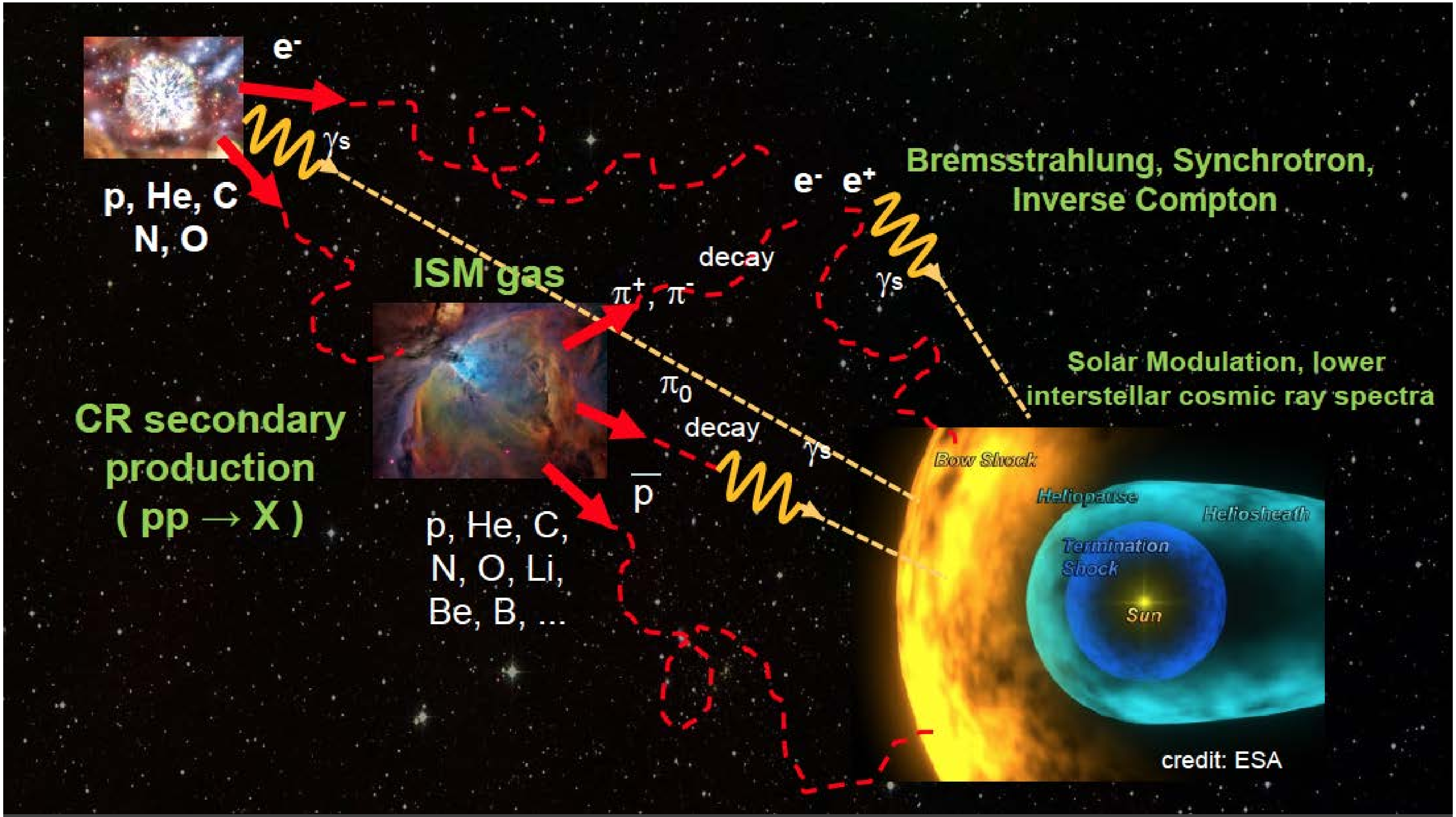
Histogram of calculated significance



Number of events as a function of the angular distance from the Sun direction

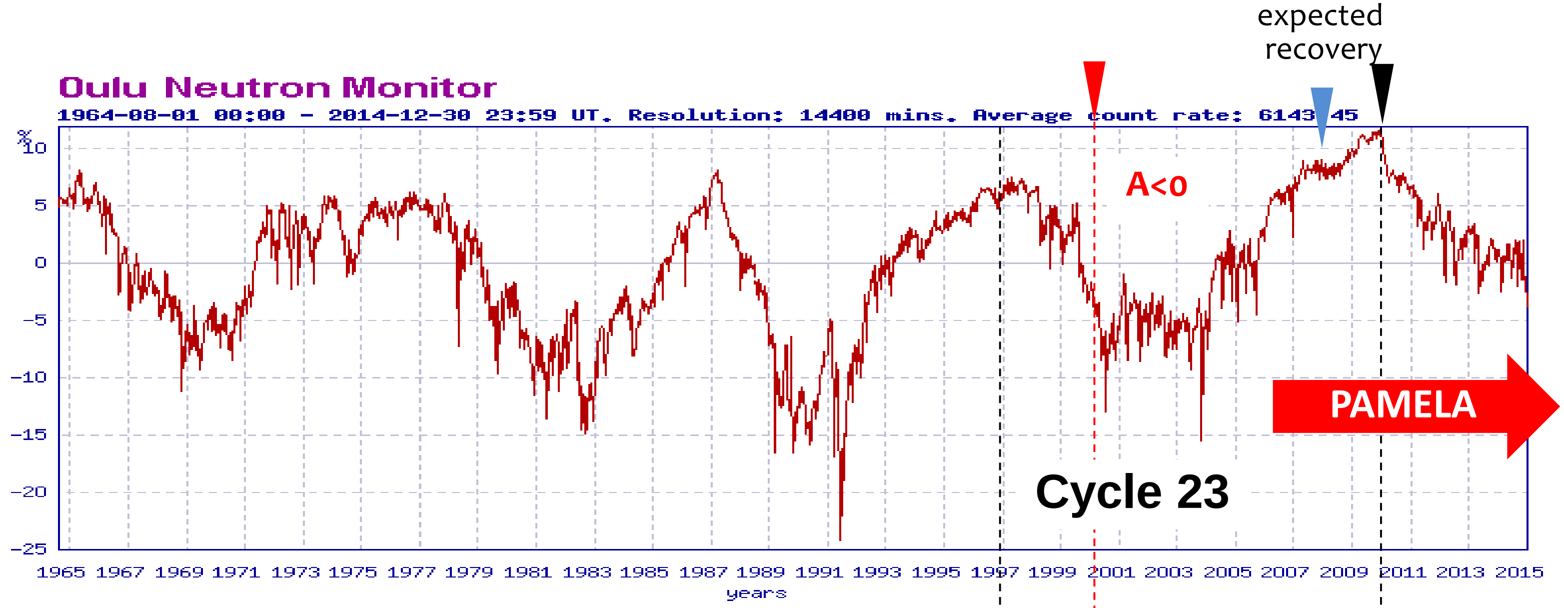


Fiorenza's talk



Cosmic rays in the heliosphere

PAMELA observations during 23° solar cycle

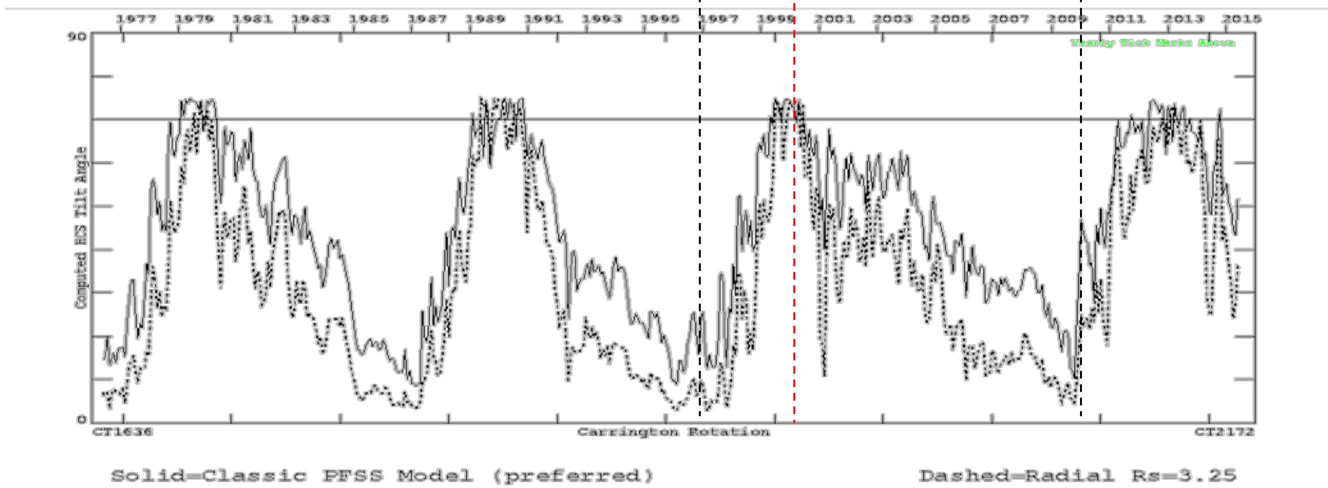


Neutron Monitor counts

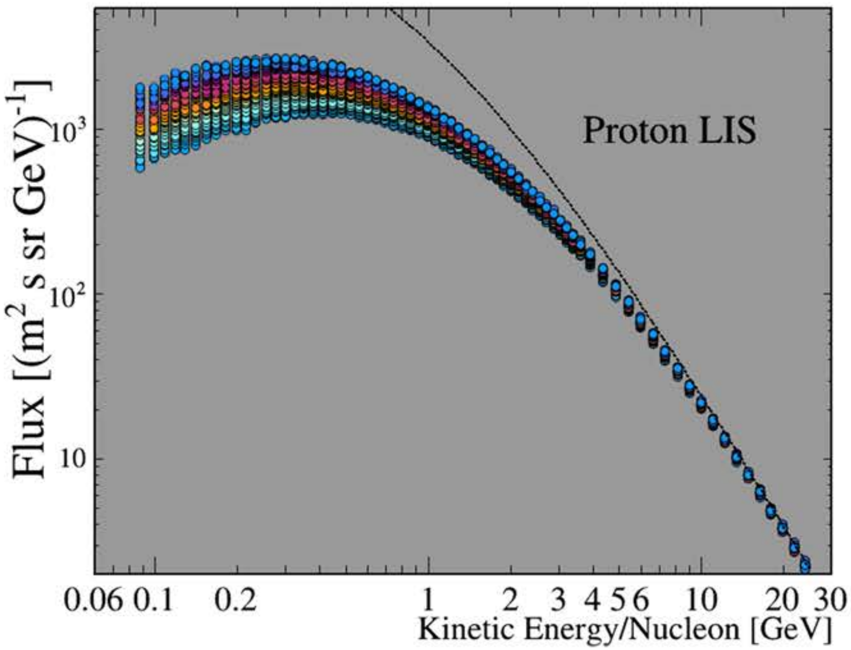
Data from
http://cosmicrays.oulu.fi/

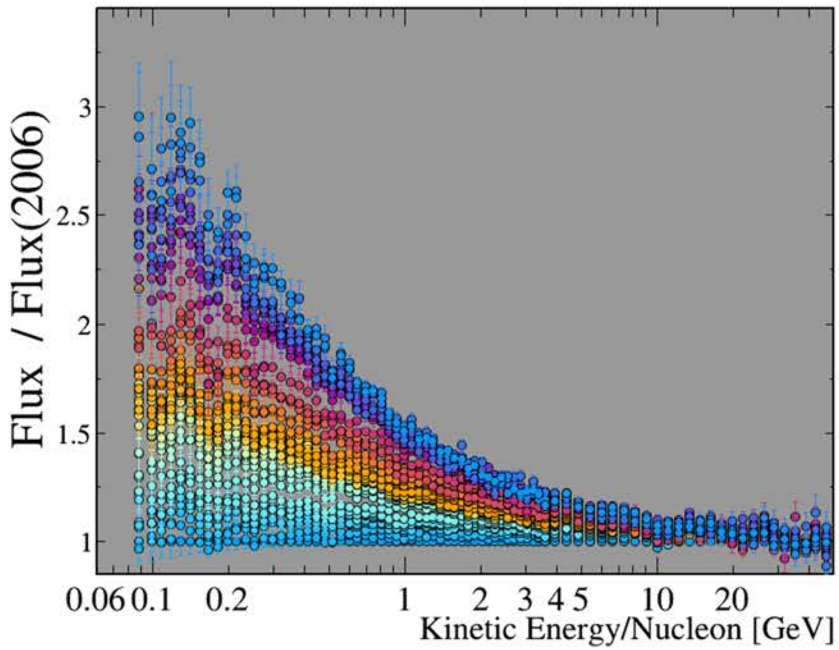
Computed HCS tilt angle

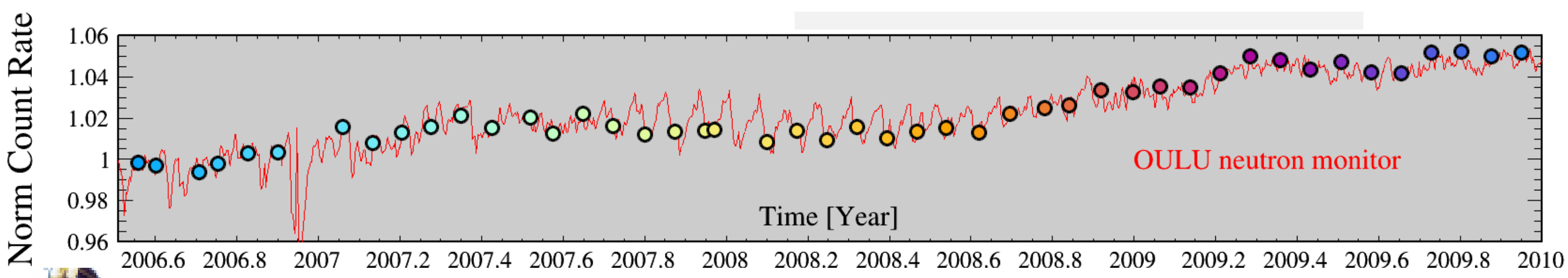
Data from
http://wso.stanford.edu/



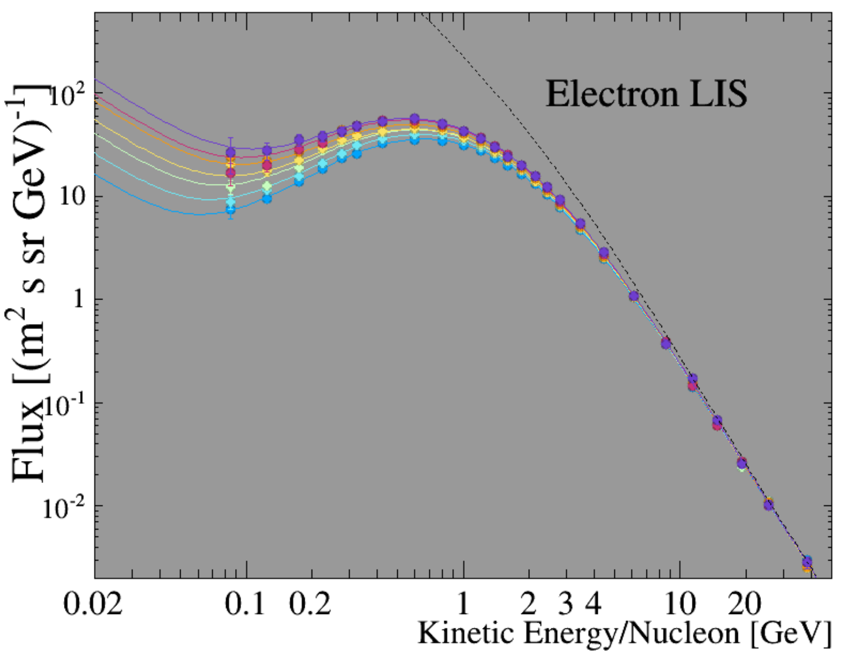
Time dependence – Proton flux

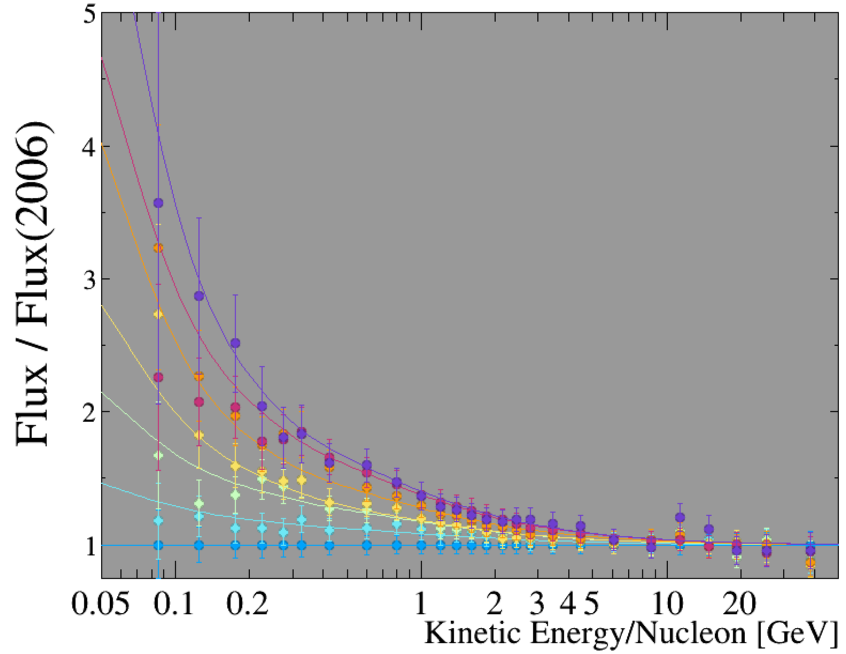


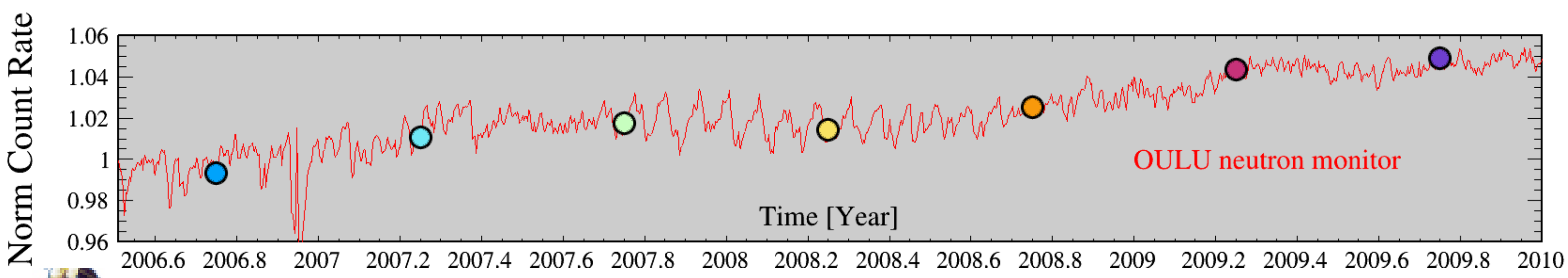




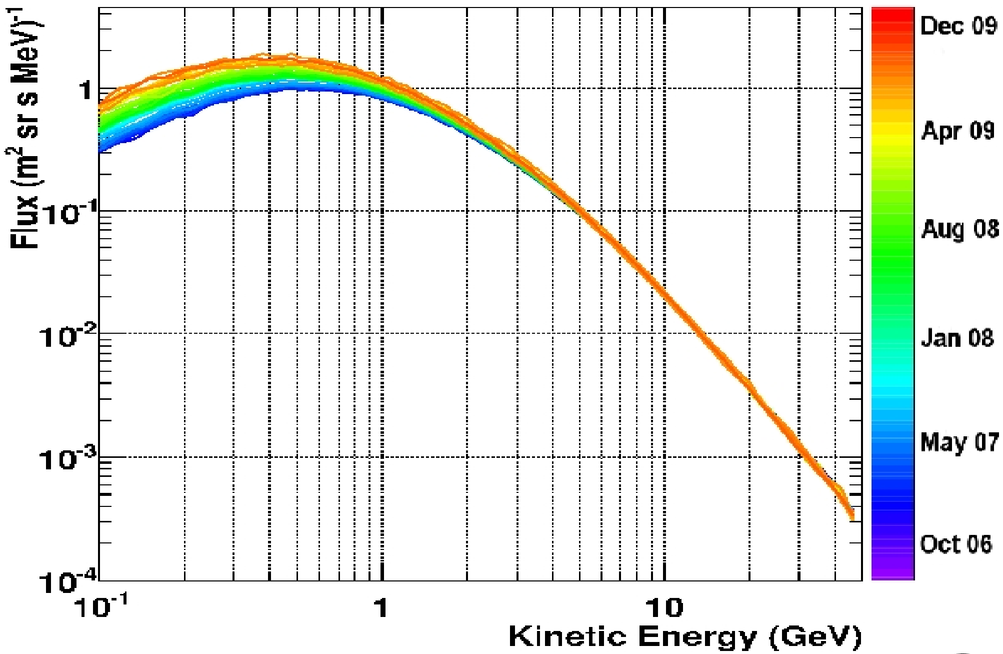
Time dependence – Electron flux



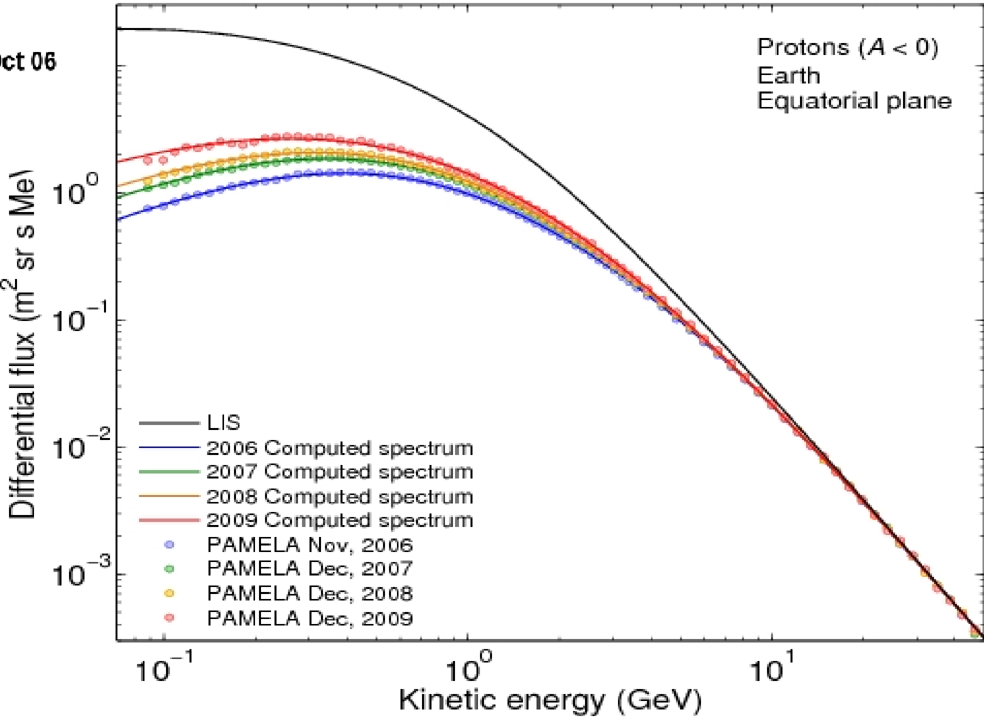




Time Dependance of the Proton Flux



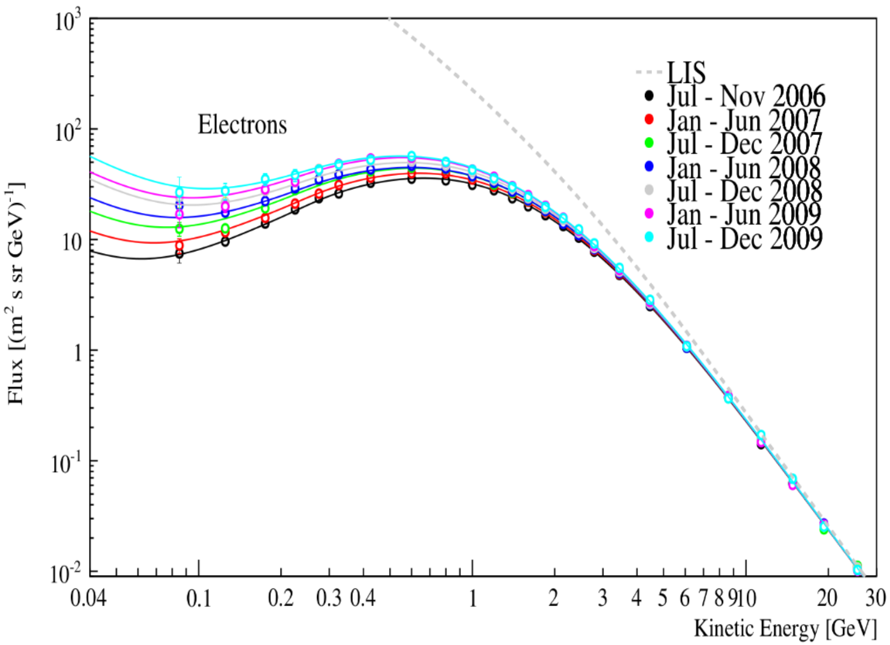
Evolution of the proton energy spectrum from July 2006 to December 2009



The PAMELA proton spectra over four months compared with the computed spectra

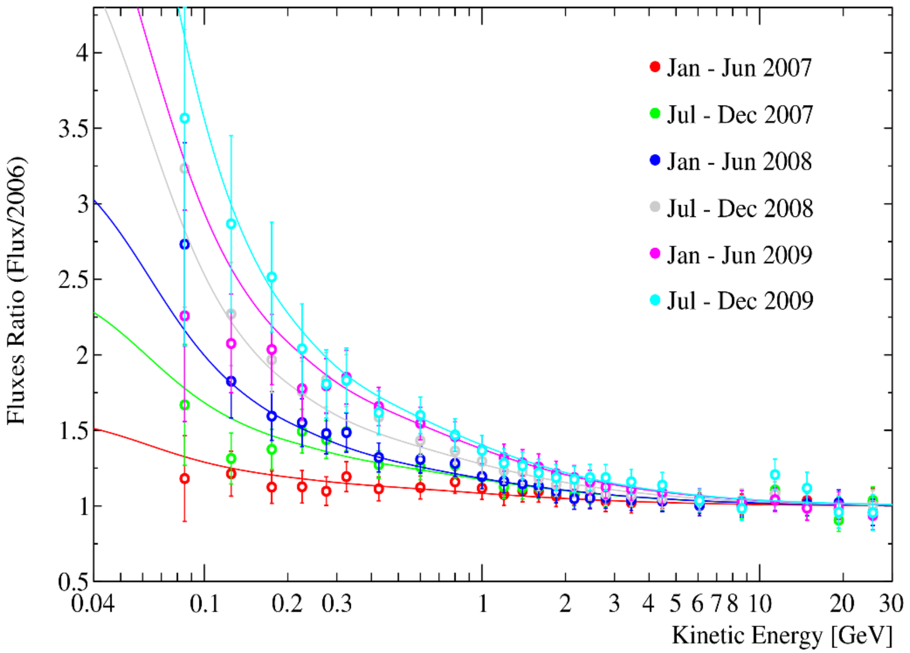
O. Adriani et al., ApJ 765 (2013) 91;
M. S. Potgieter et al., Solar Phys. 289 (2014) 391

Time Dependance of the Electron Flux



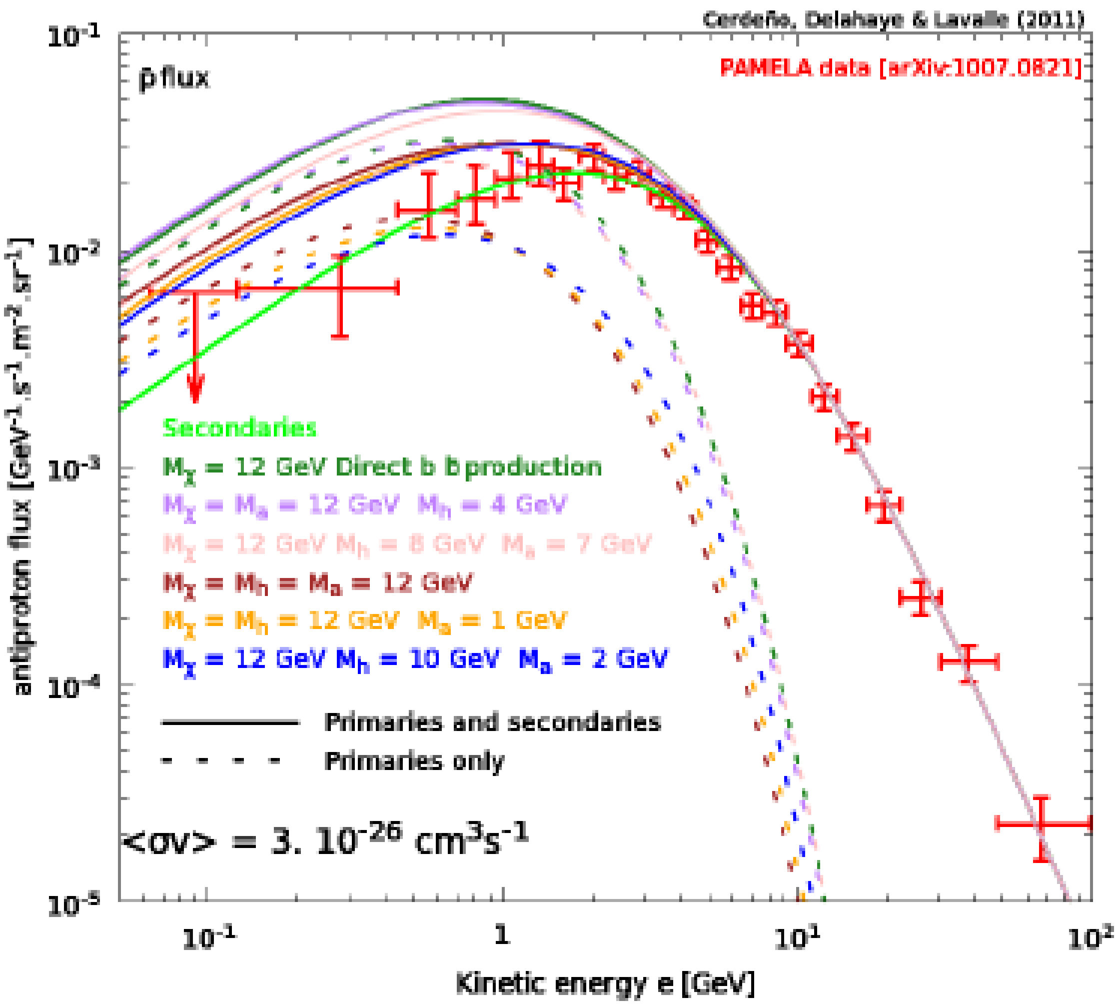
Evolution of the electron (e^-) energy spectrum from July 2006 to December 2009

The ratios between the measured e^- fluxes from January 2007 till December 2009 and the measured fluxes for the period July-November 2006 with the corresponding computed spectra.



O. Adriani et al., ApJ 810 (2015) 142;
M. S. Potgieter et al., 810 (2015) 2, 141

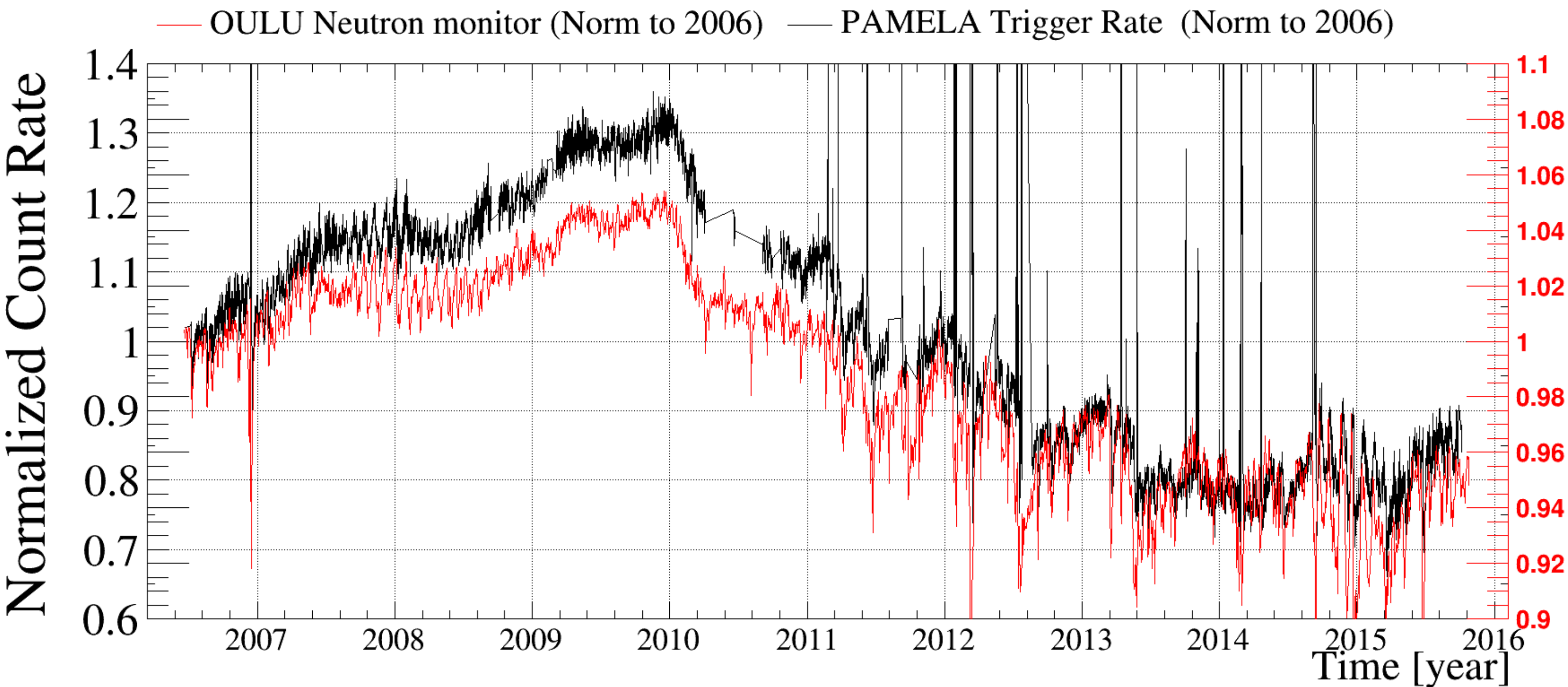
Cosmic-Ray Antiprotons and DM limits



D. G. Cerdeno, T. Delahaye & J. Lavalle, Nucl. Phys. B 854 (2012) 738
Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

See also:
- M. Asano, T. Bringmann & C. Weniger, Phys. Lett. B 709 (2012) 128.
- M. Garny, A. Ibarra & S. Vogl, JCAP 1204 (2012) 033
- R. Kappl & M. W. Winkler, PRD 85 (2012) 123522

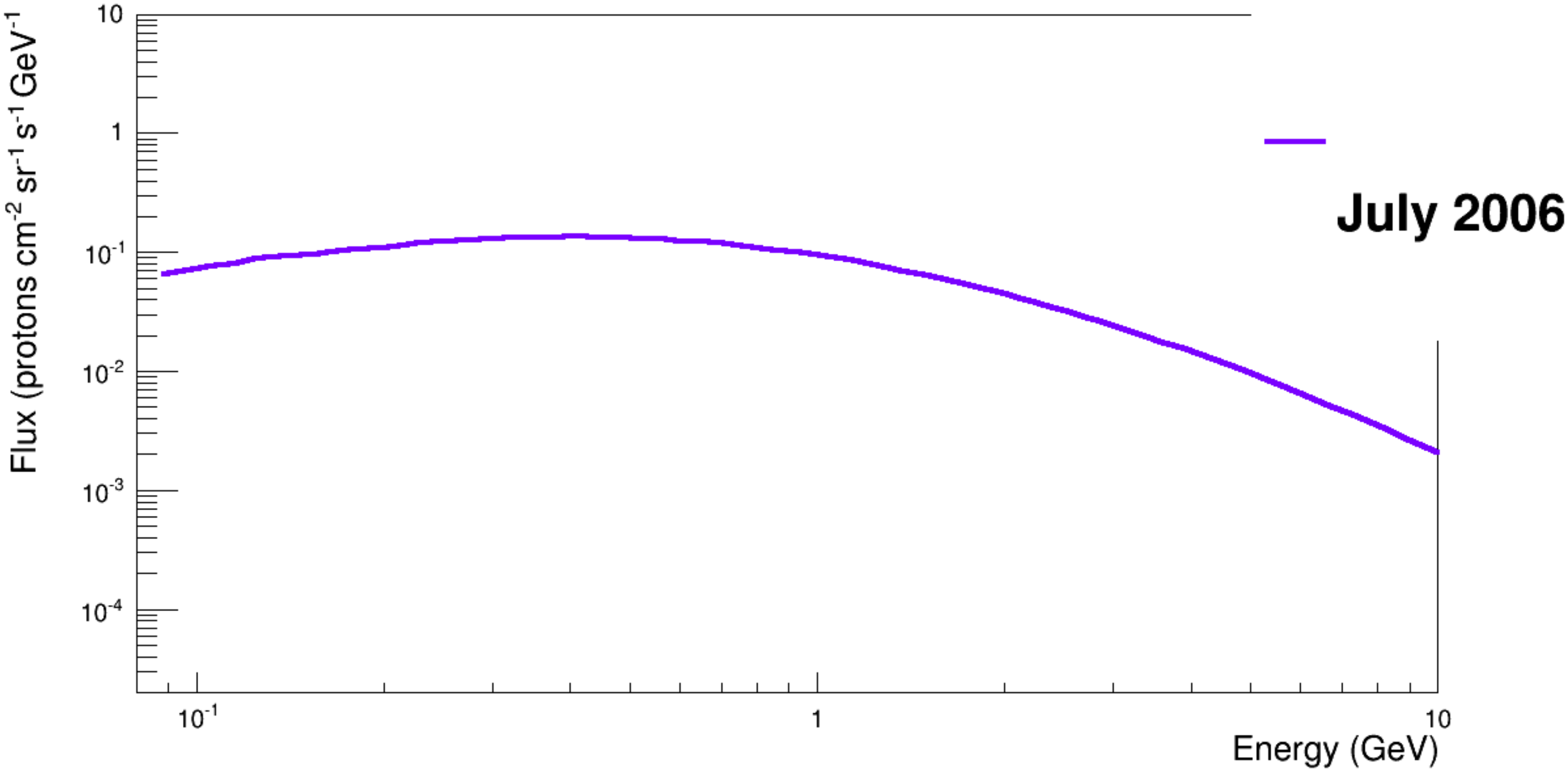
Heliospheric conditions during PAMELA observations



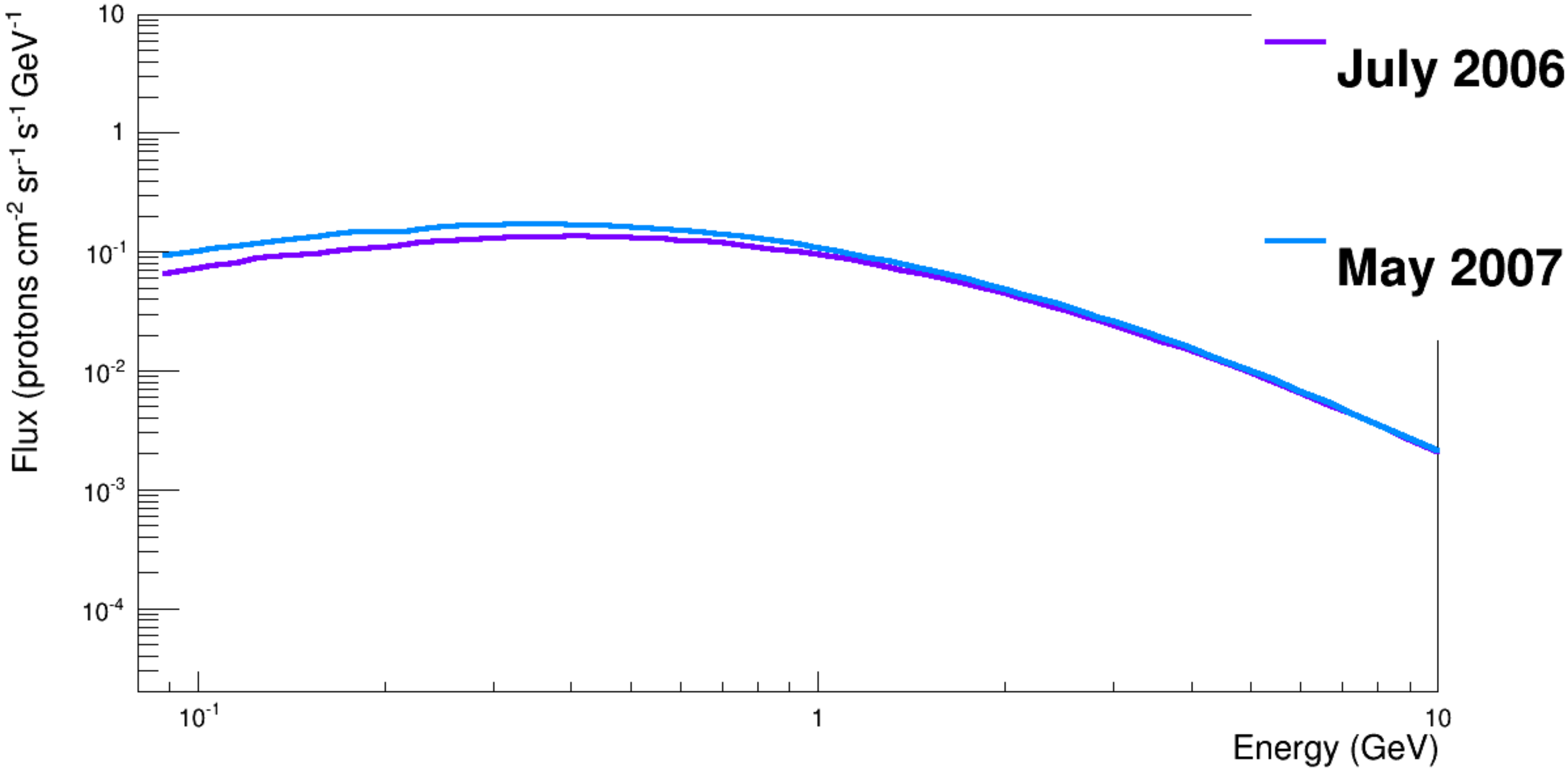
Neutron Monitor counts data from
http://cosmicrays.oulu.fi/

PAMELA observations covers ~ one solar cycle

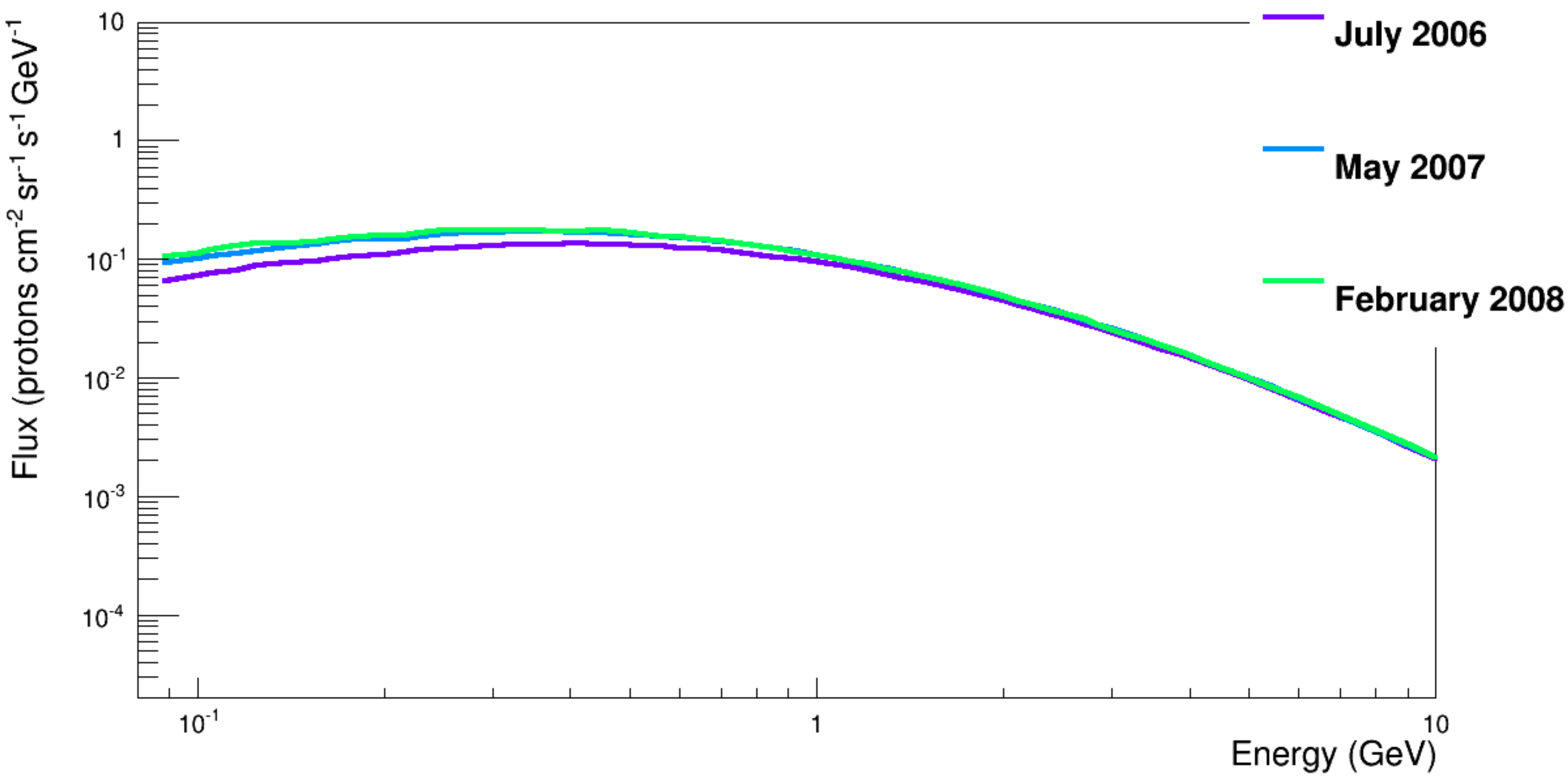
Time dependance of the proton flux July 2006-January 2014



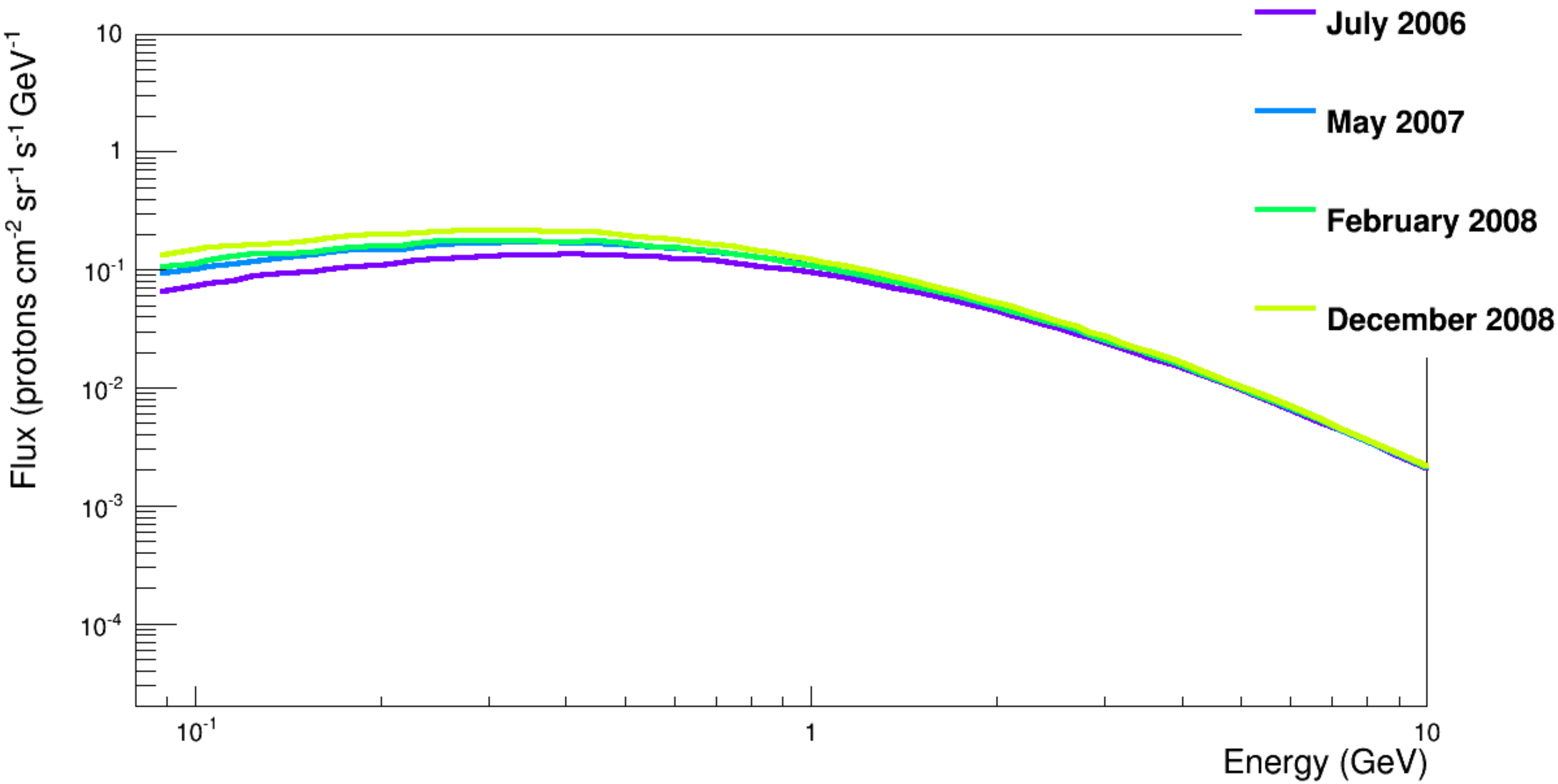
Time dependance of the proton flux July 2006-January 2014



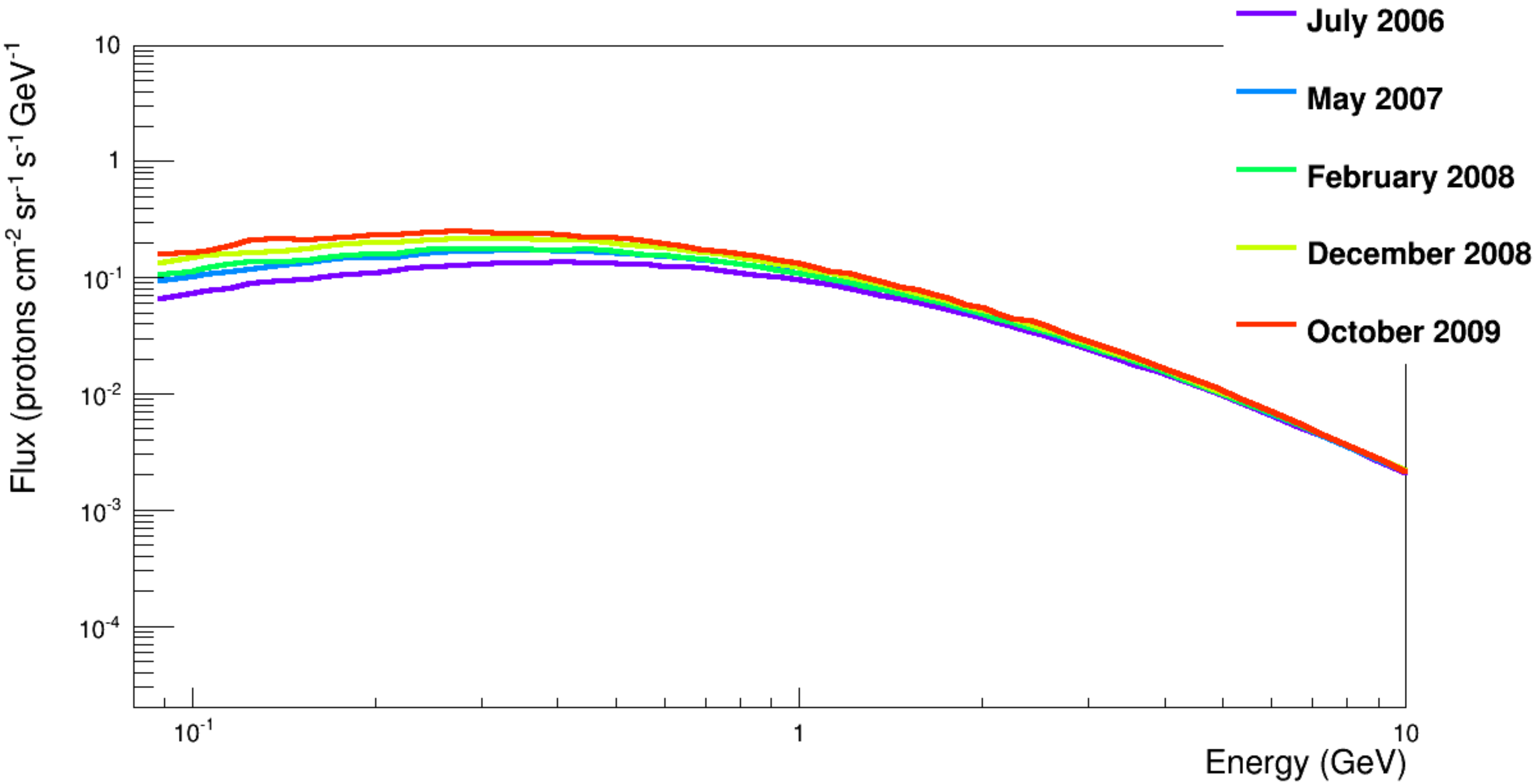
Time dependance of the proton flux July 2006-January 2014



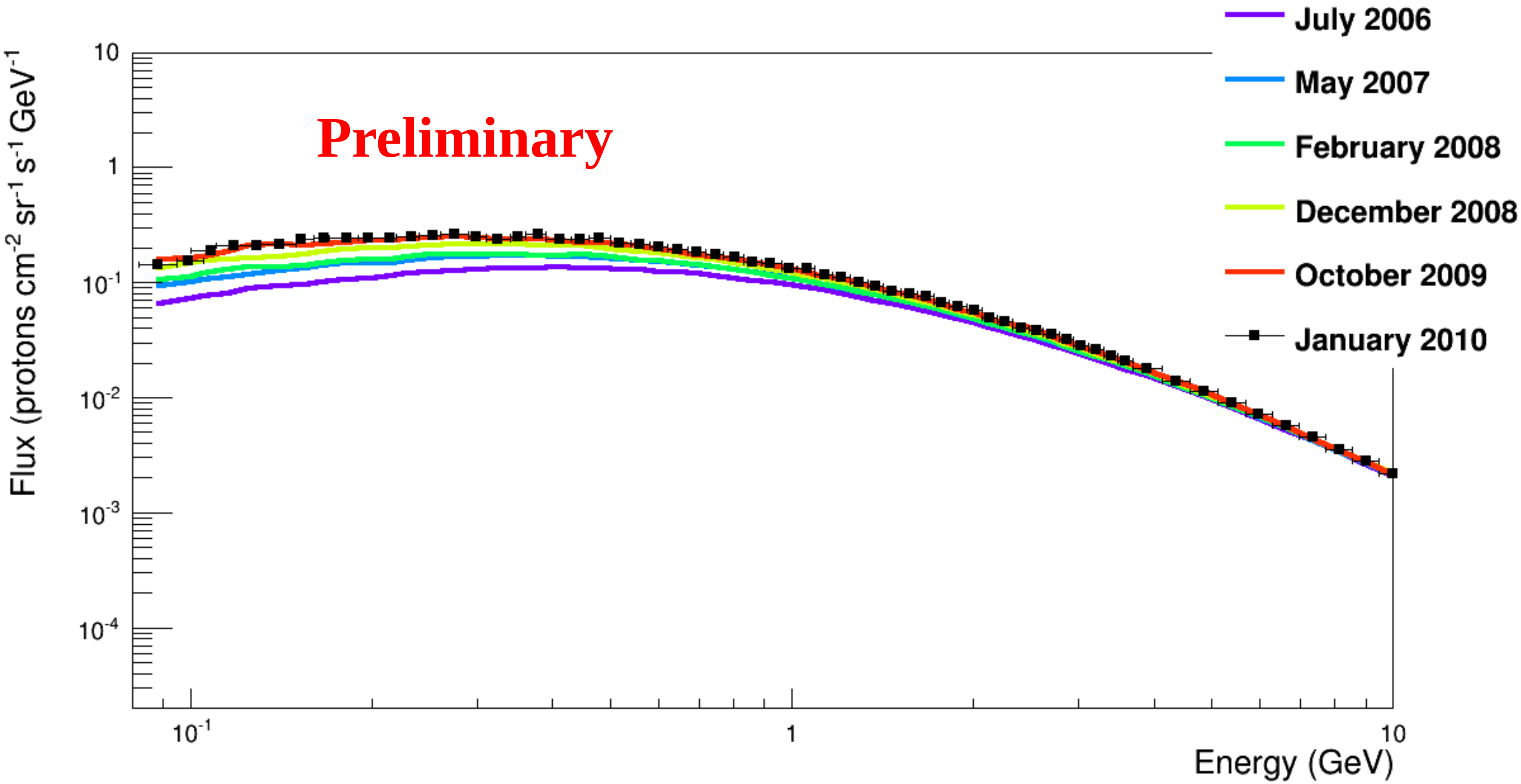
Time dependance of the proton flux July 2006-January 2014



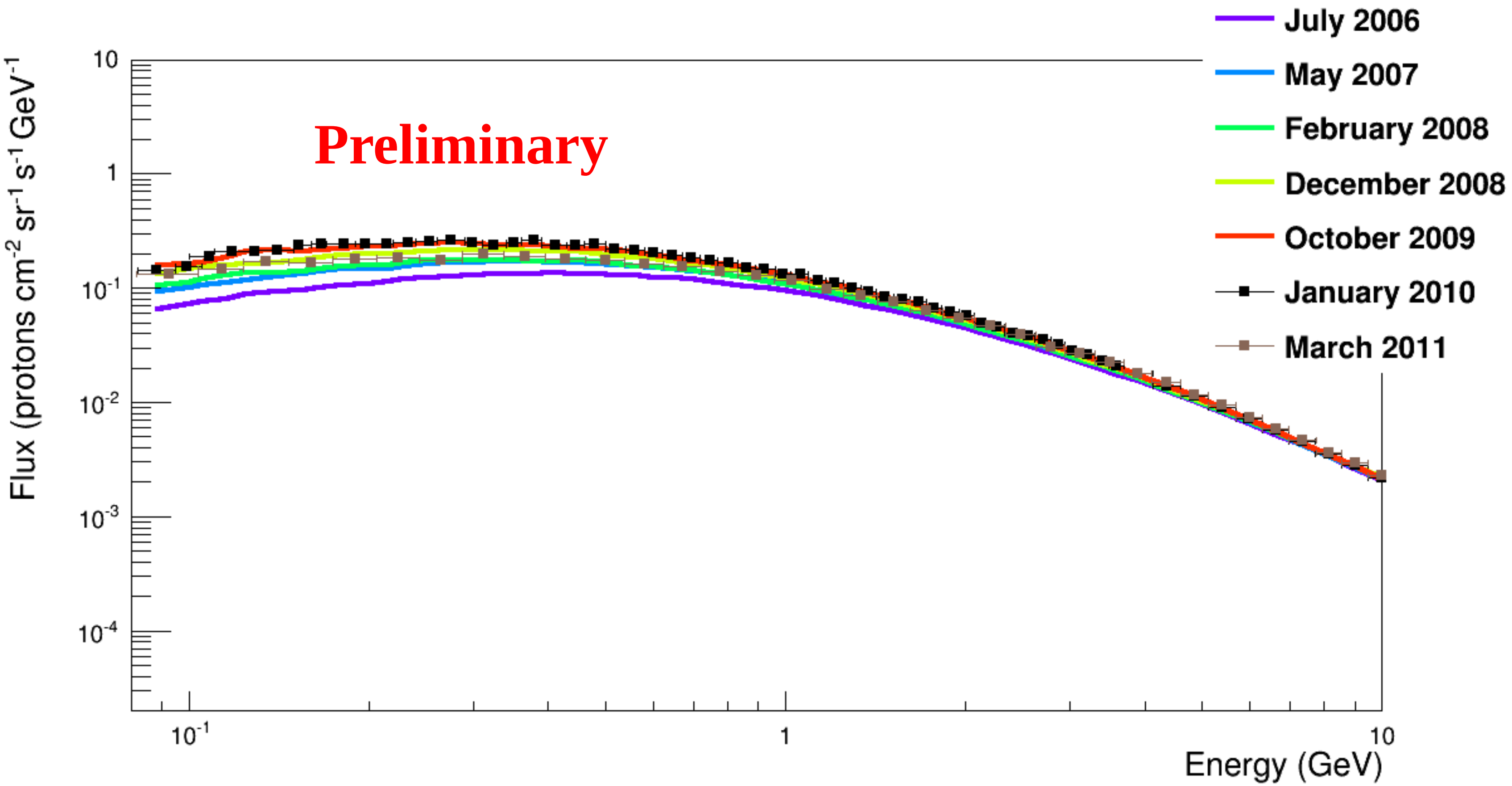
Time dependance of the proton flux July 2006-January 2014



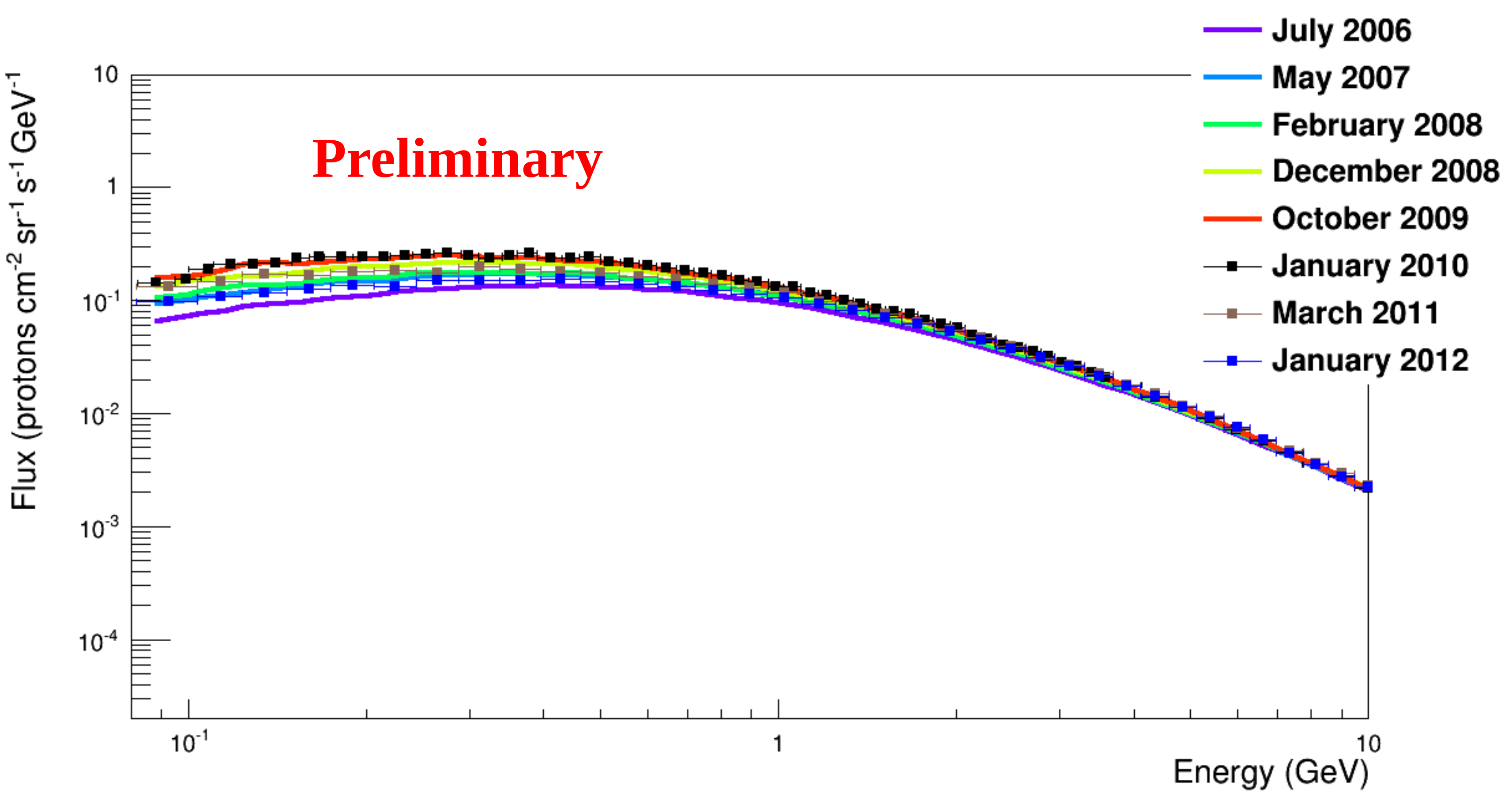
Time dependance of the proton flux July 2006-January 2014



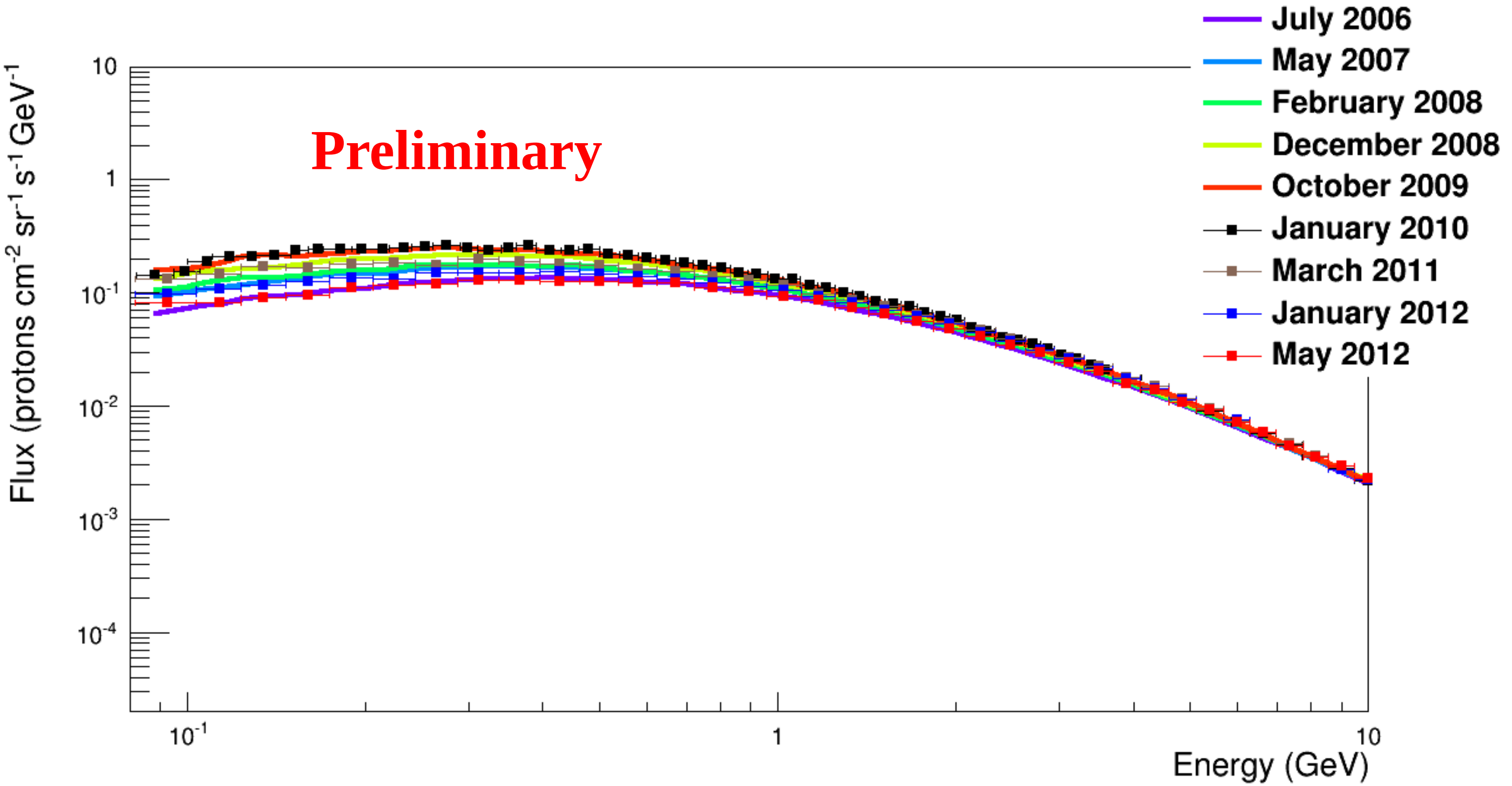
Time dependance of the proton flux
July 2006-January 2014



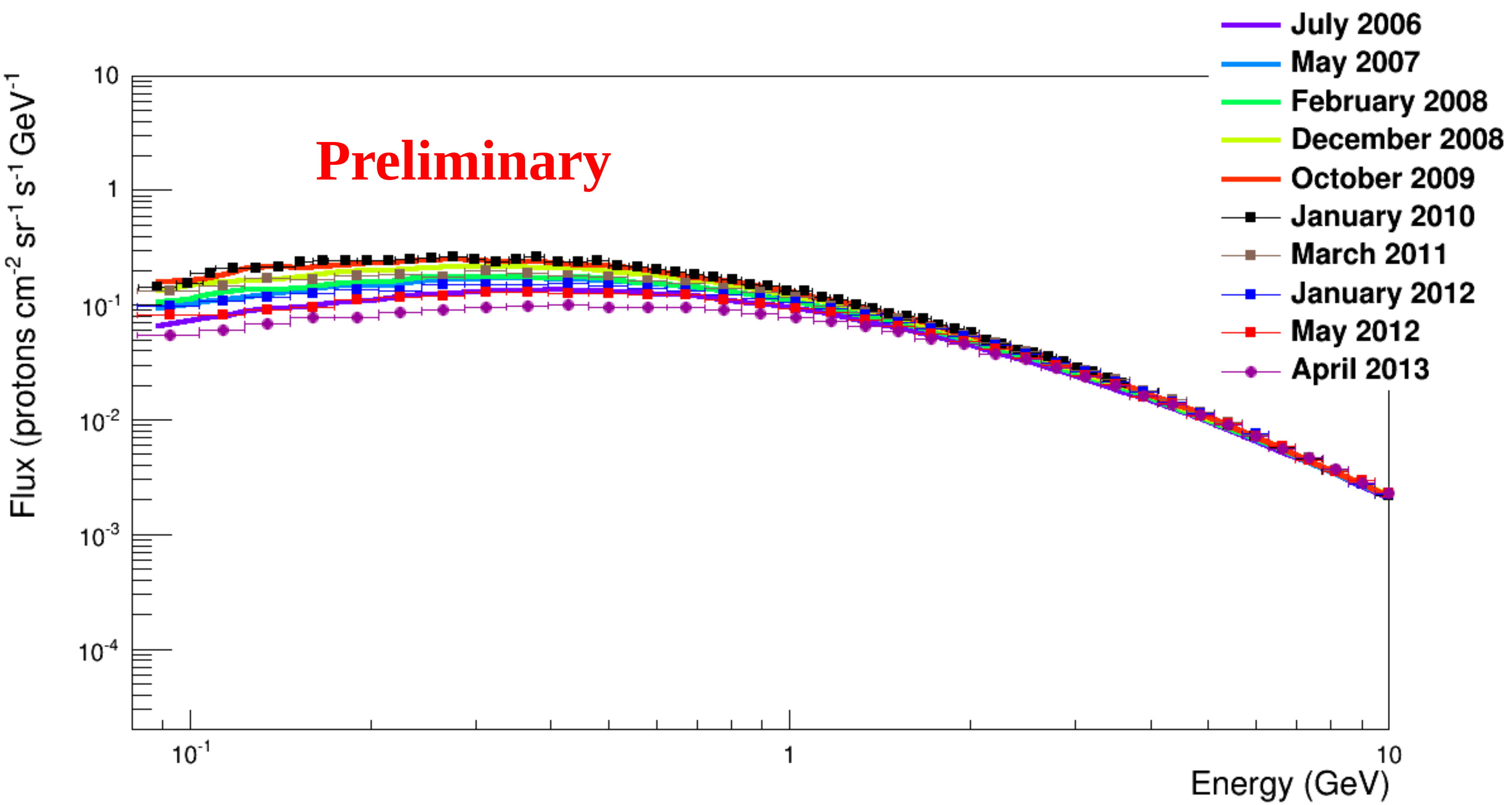
Time dependance of the proton flux July 2006-January 2014



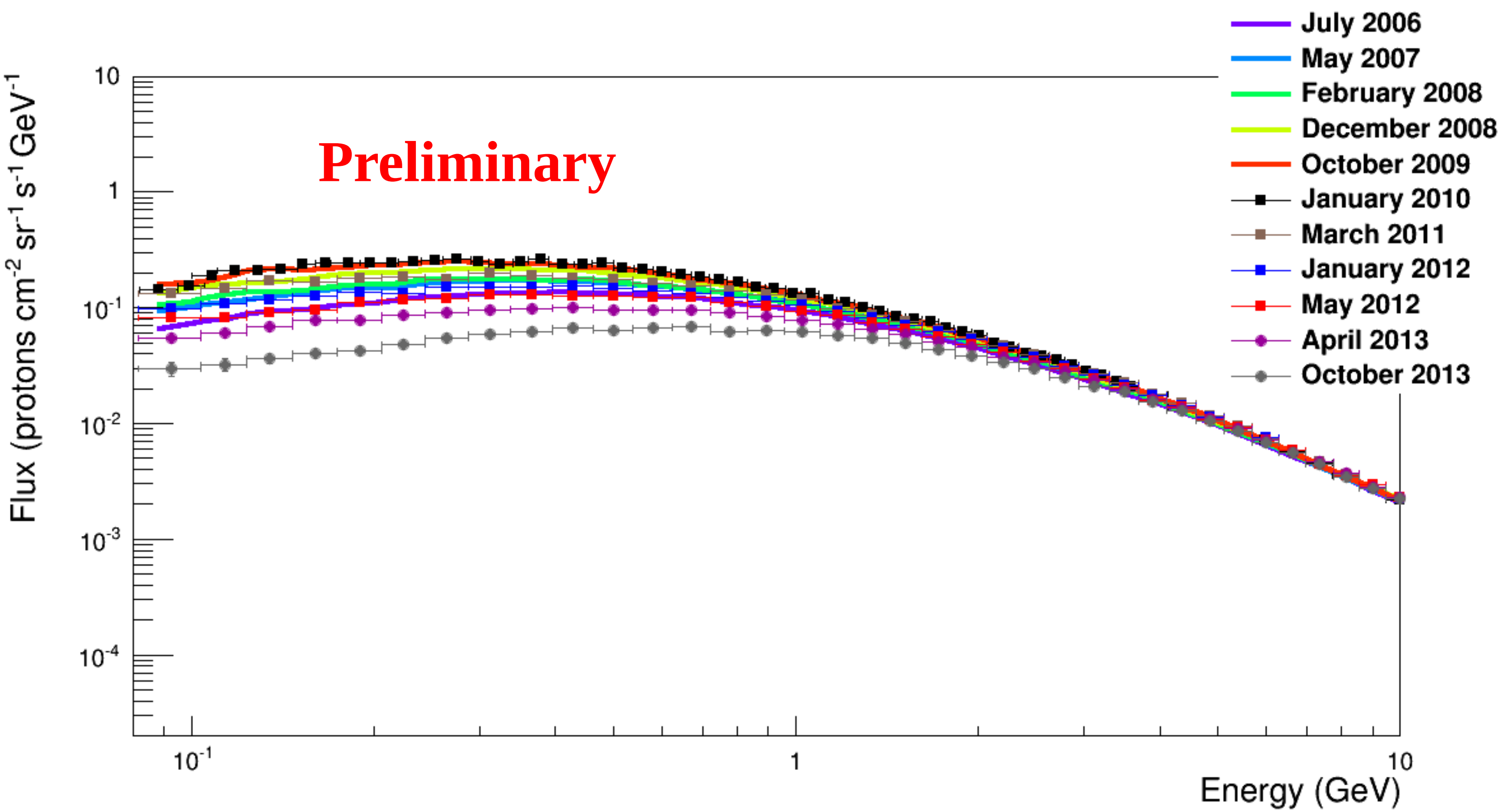
Time dependance of the proton flux July 2006-January 2014



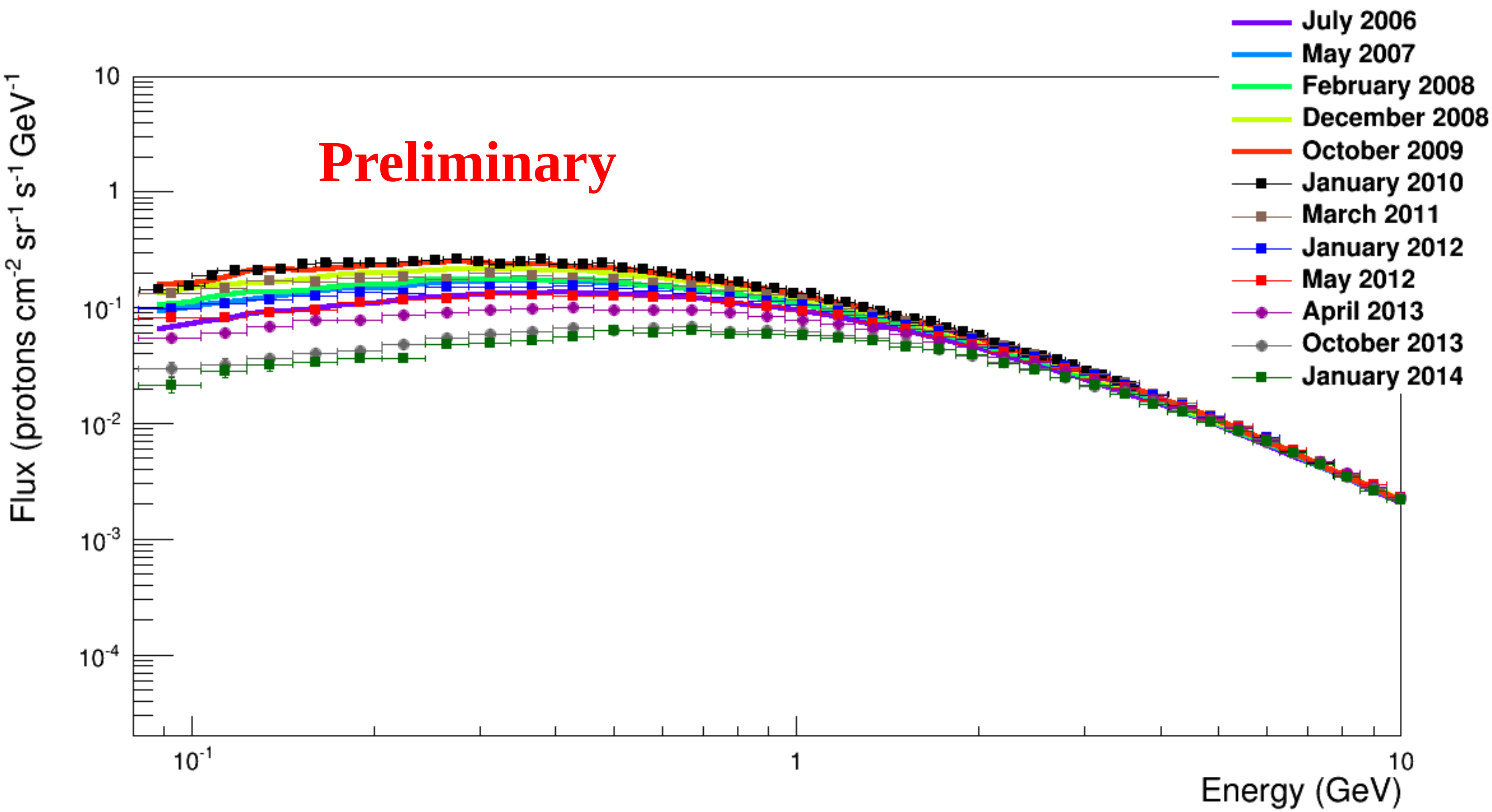
Time dependance of the proton flux July 2006-January 2014

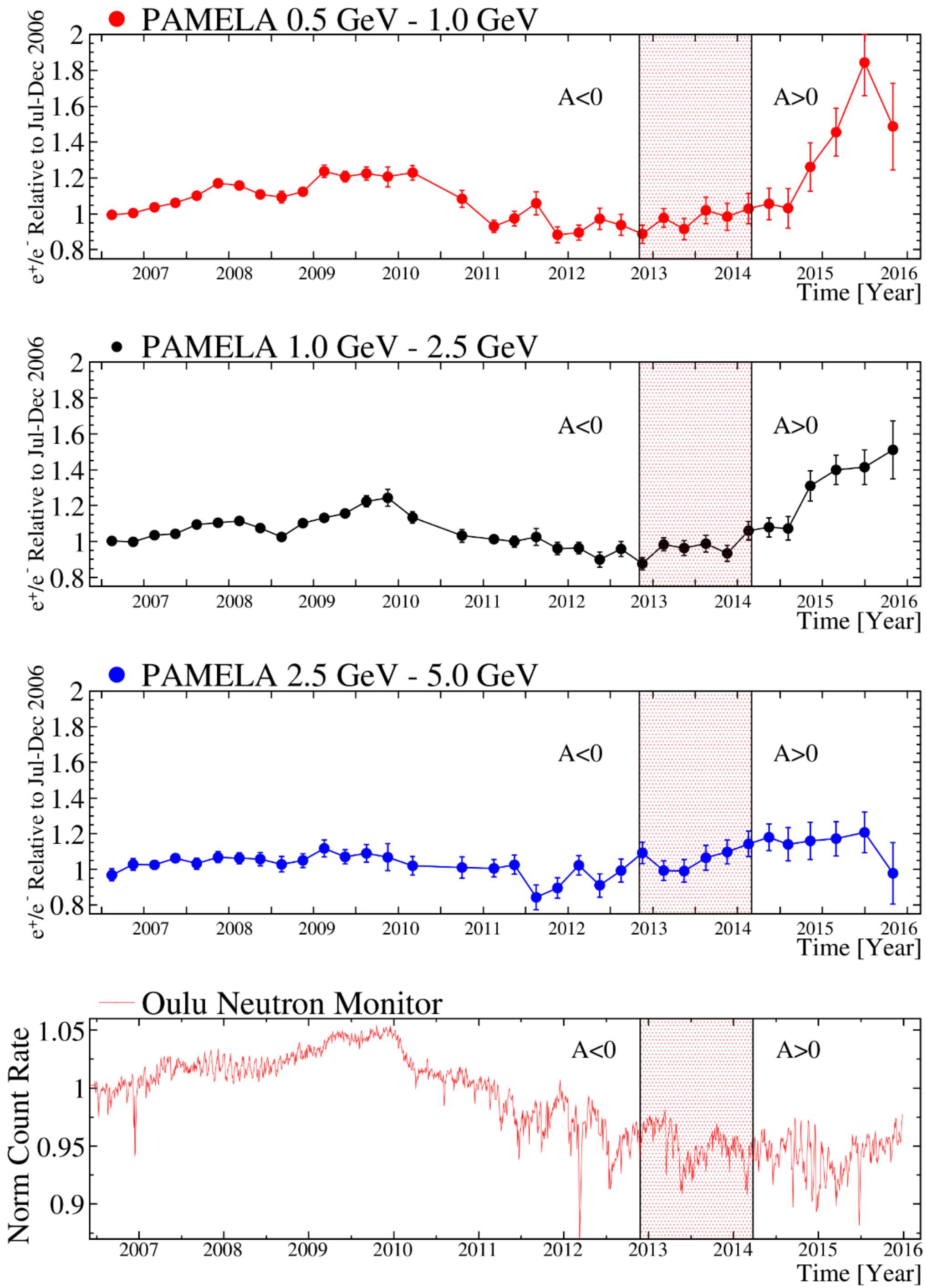


Time dependance of the proton flux July 2006-January 2014



Time dependance of the proton flux July 2006-January 2014

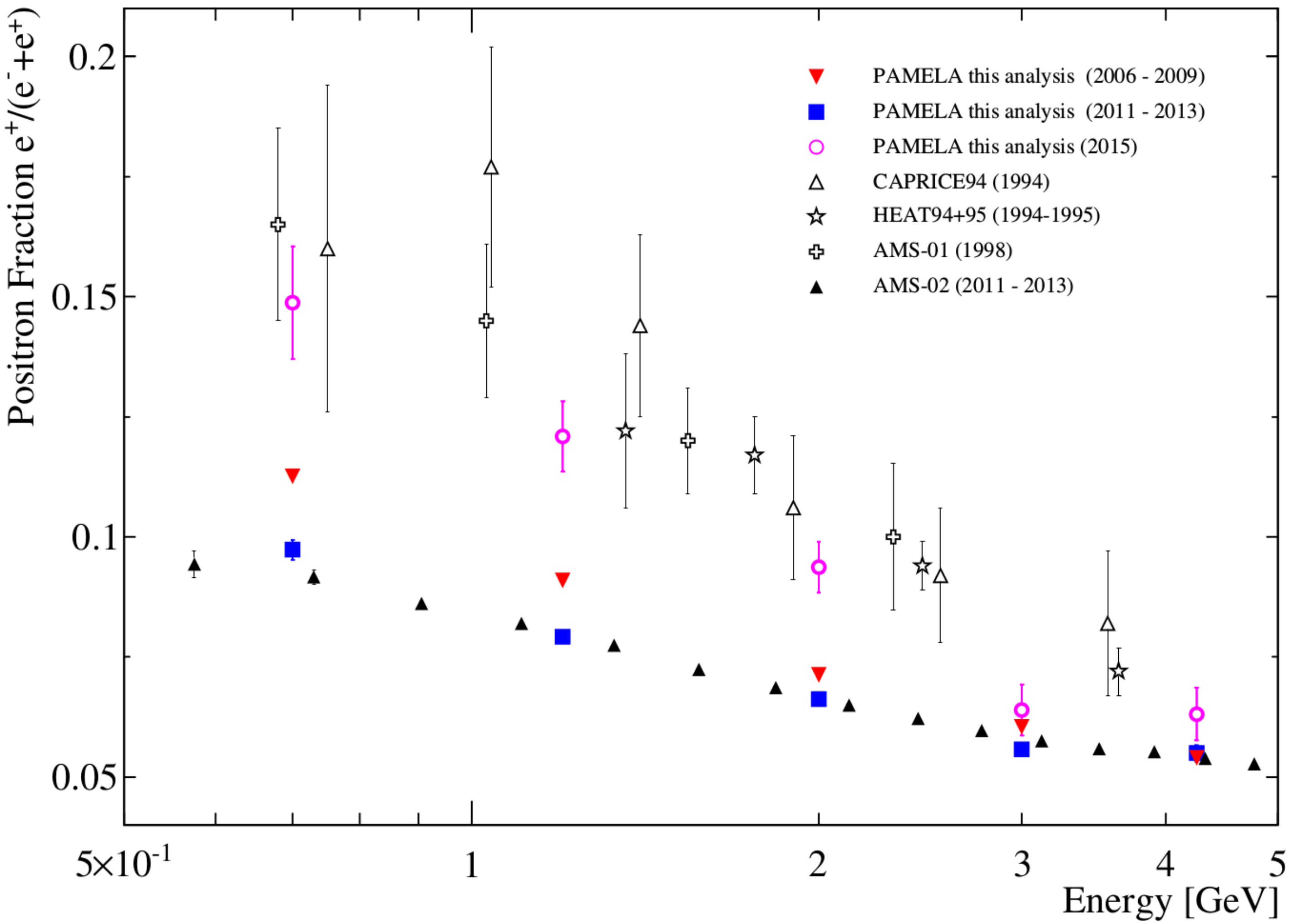




Time dependance of the electron and positron fluxes

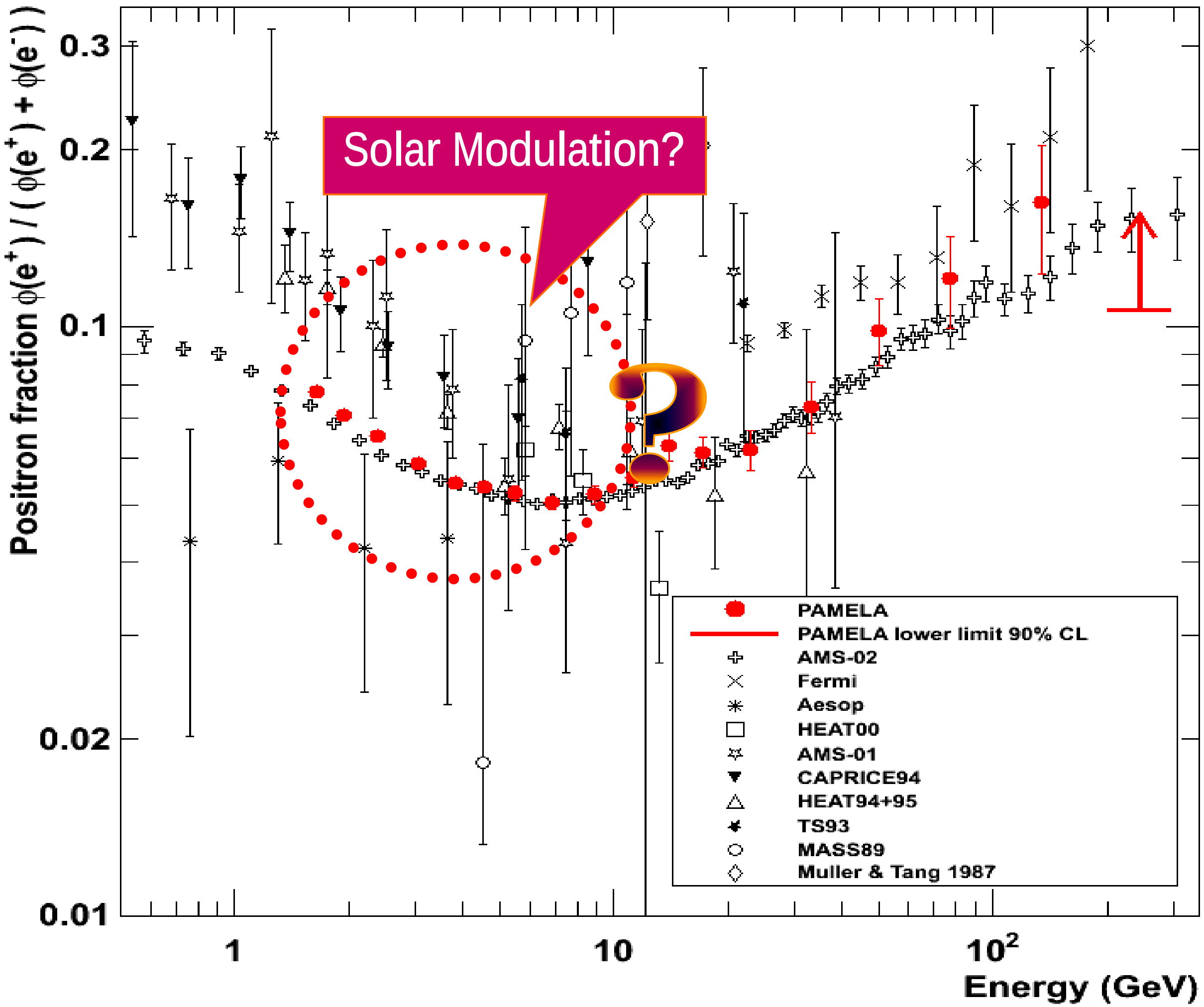
O. Adriani et al., PRL 116 (2016) 241105 (Editors' Suggestion)

Time dependance of the electron and positron fluxes

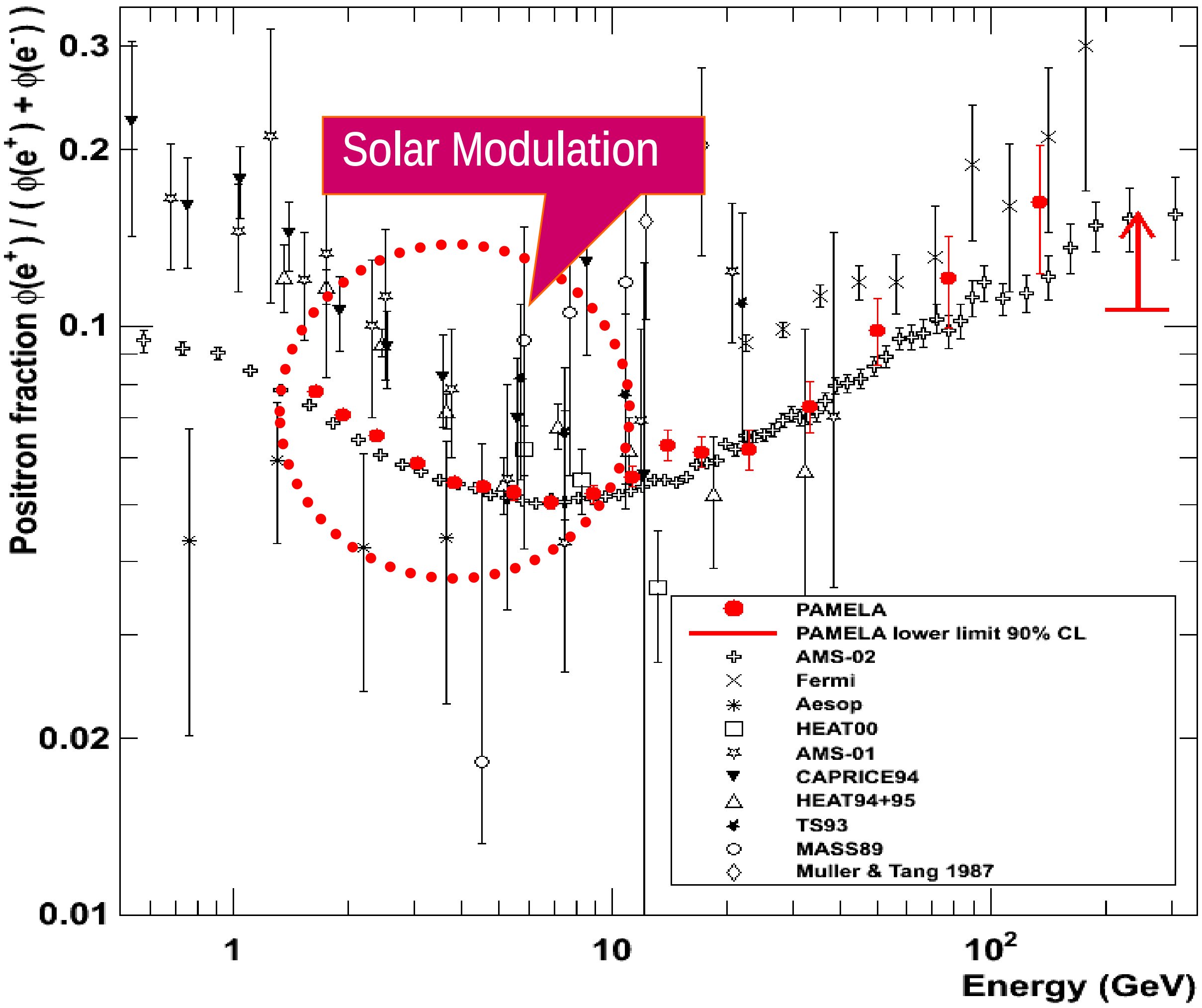


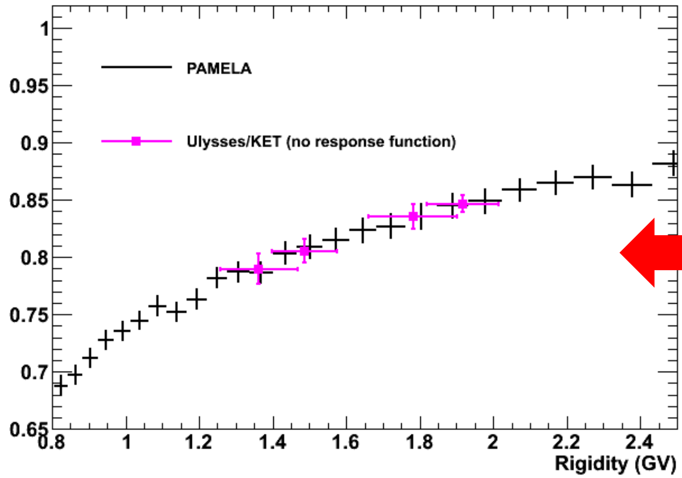
O. Adriani et al., PRL 116 (2016) 241105 (Editors' Suggestion)

Positron to Electron Fraction



Positron to Electron Fraction



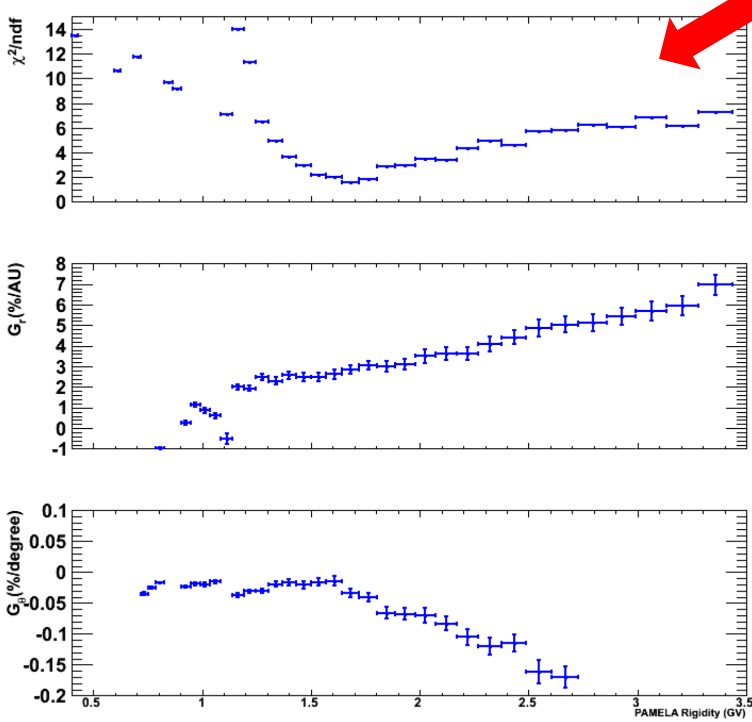


Joint work: Ulysses (1 – 5 AU) and PAMELA (1 AU)

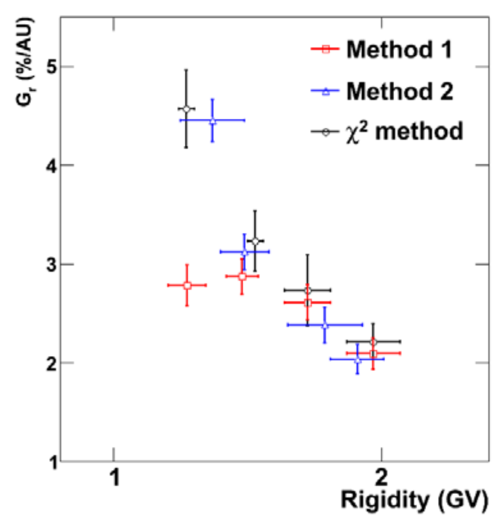
cross-calibration of energy channel of Ulysses thanks to PAMELA precision rigidity measurements

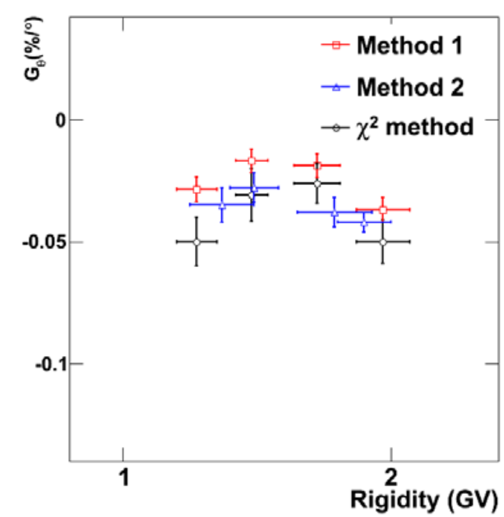
Use of χ^2 minimization to enforce the analysis

Bernd's talk

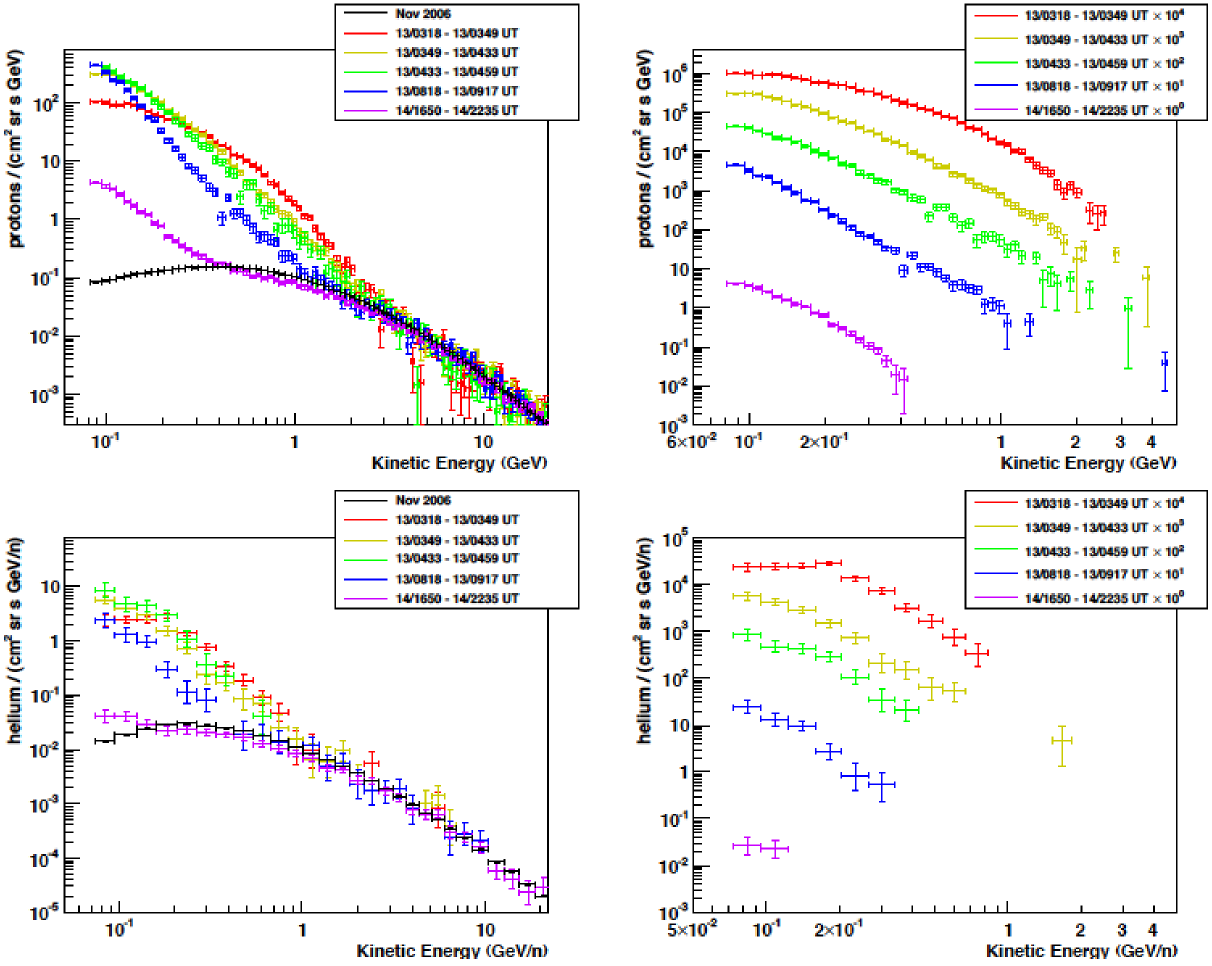


Results



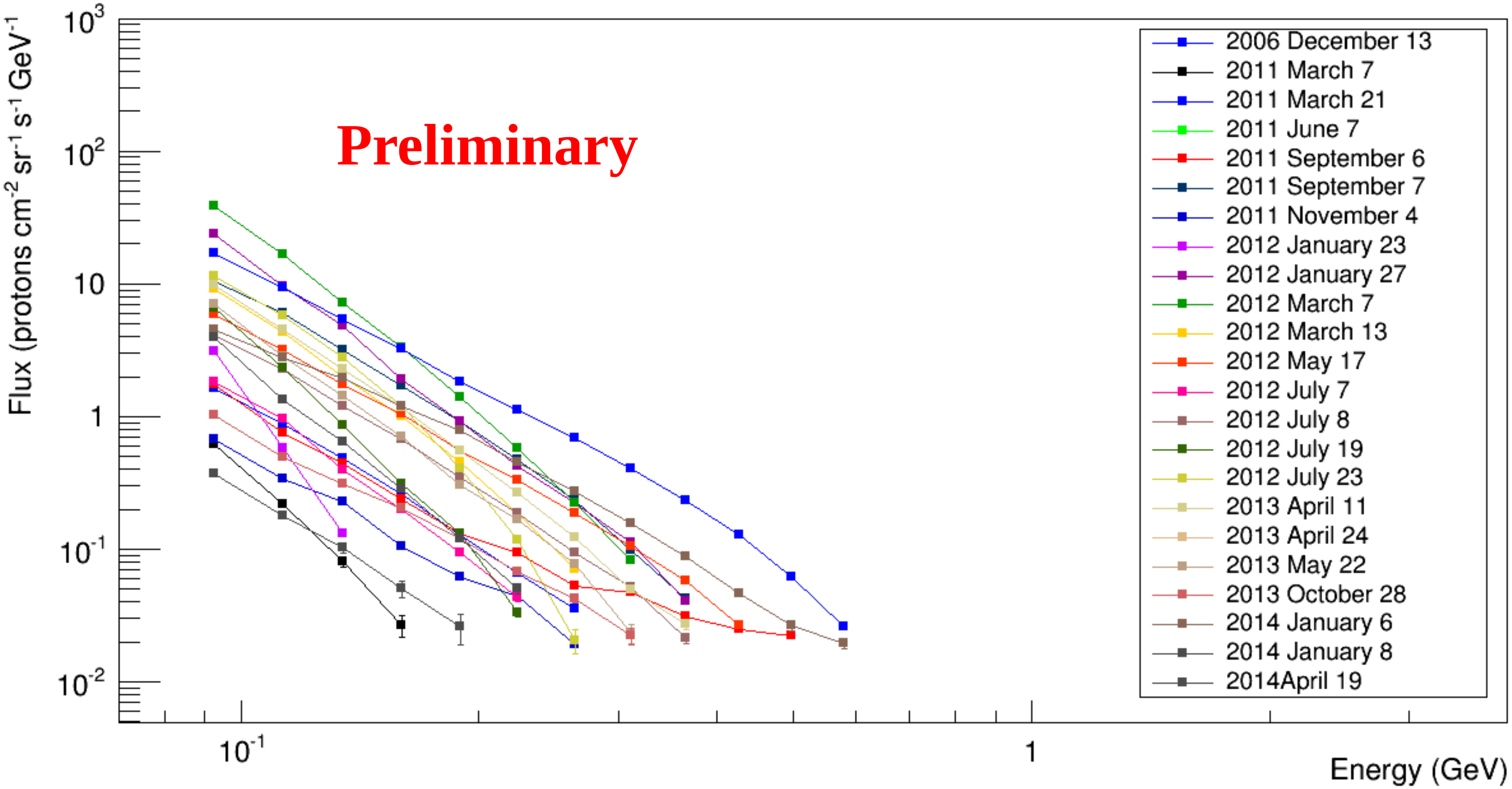


SEP events (SEP from 2006 Dec. 13th)



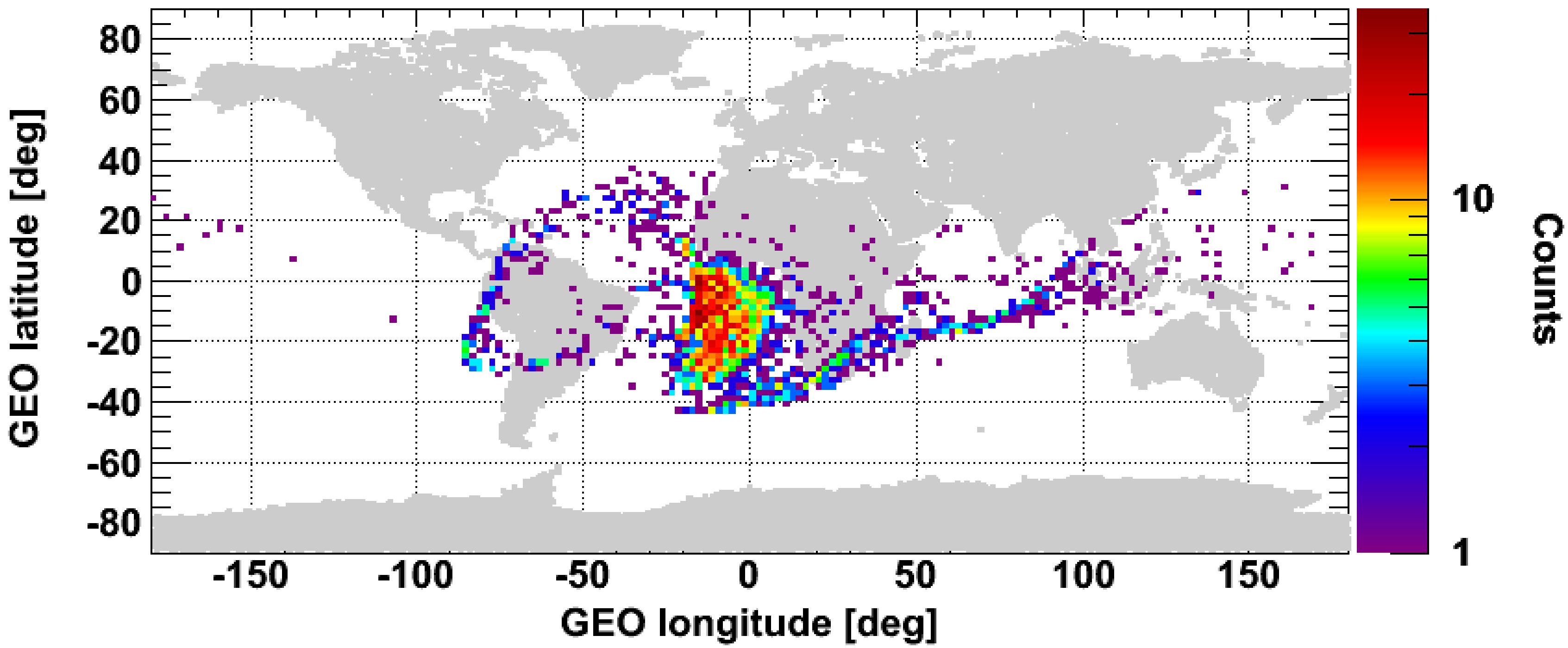
Adriani et al. - ApJ 742 102, 2011

Preliminary PAMELA Solar Energetic Proton Spectra

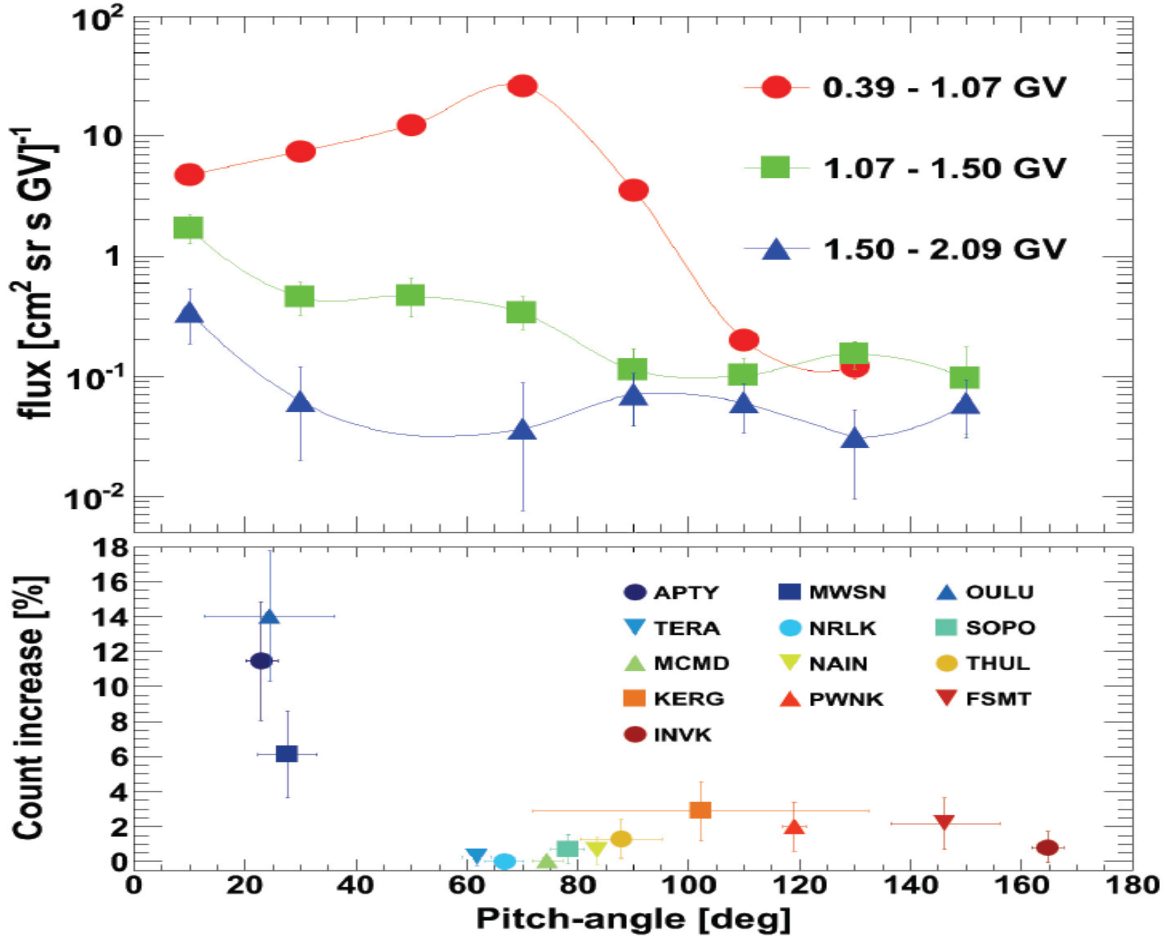


Bernd's talk

2012 May 17th event as observed by PAMELA



Nasa Press Release 31 May 2012:Science Nugget: Catching Solar Particles Infiltrating Earth's Atmosphere
http://www.nasa.gov/mission_pages/sunearth/news/particles-gle.html



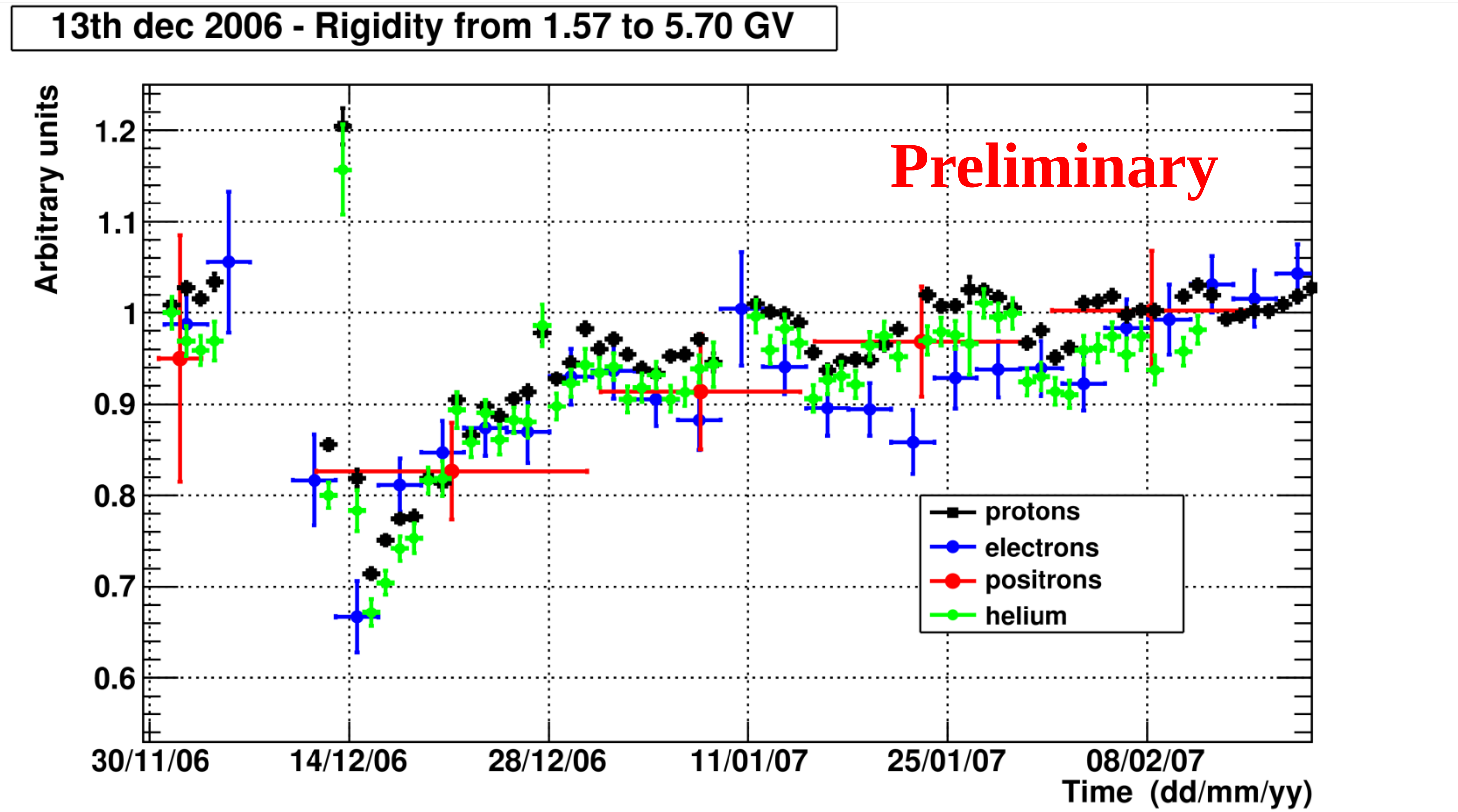
During 2012 May 17th event PAMELA observed 2 energy components with different pitch angle distribution:

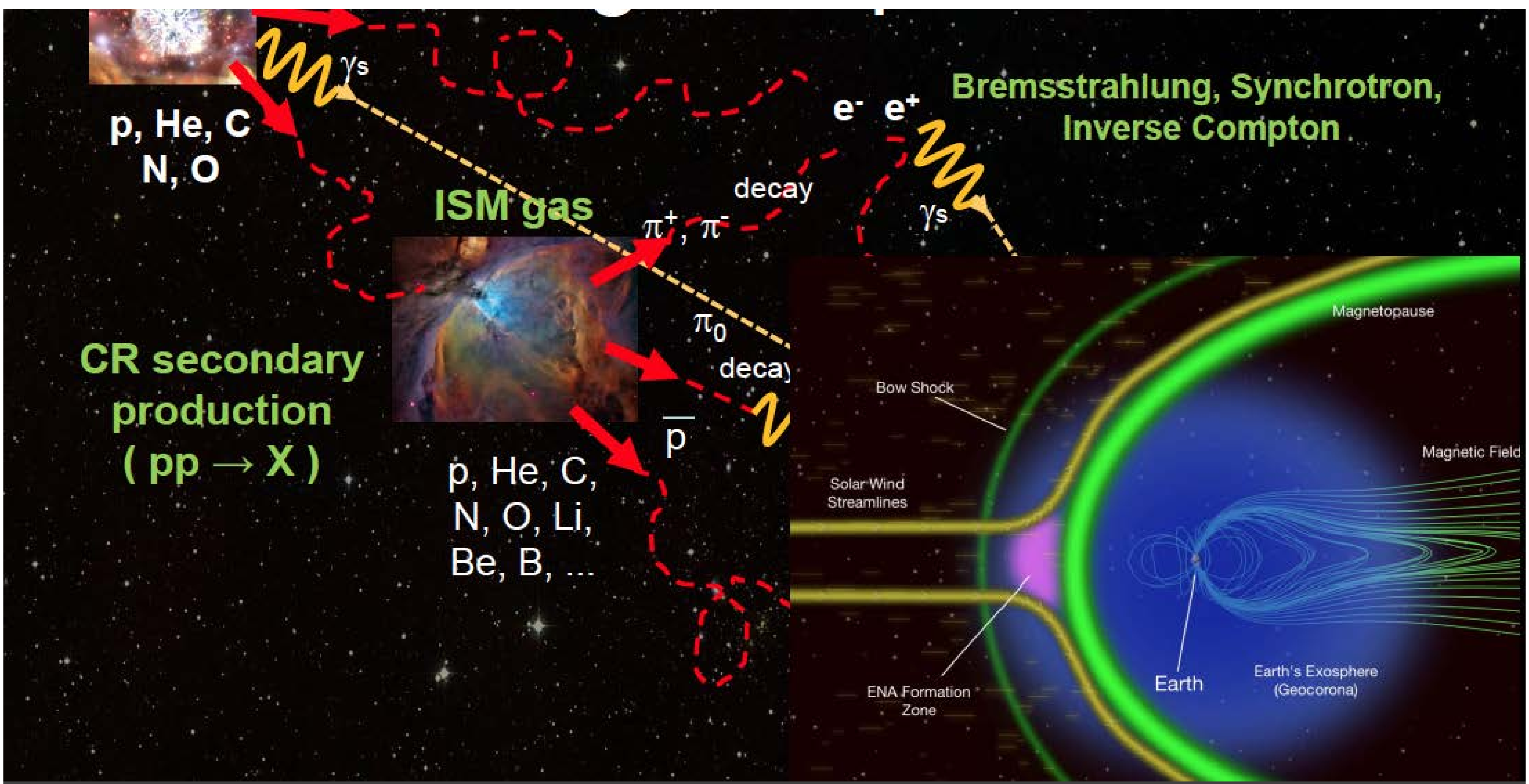
- **High rigidity component** consistent with NM where particles are field aligned → Beam width **~40-60º** (not scattered)
- **Low rigidity component** shows significant scattering for pitch angles **~90º**

Adriani et al., ApJL 801 (2015) L3

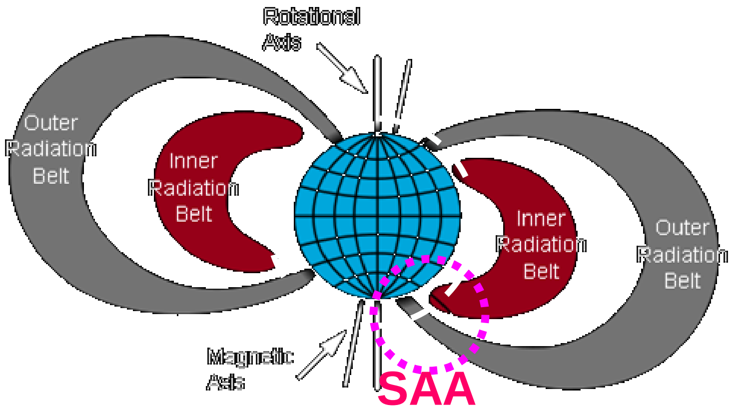
Multiparticle observation of Forbush decrease

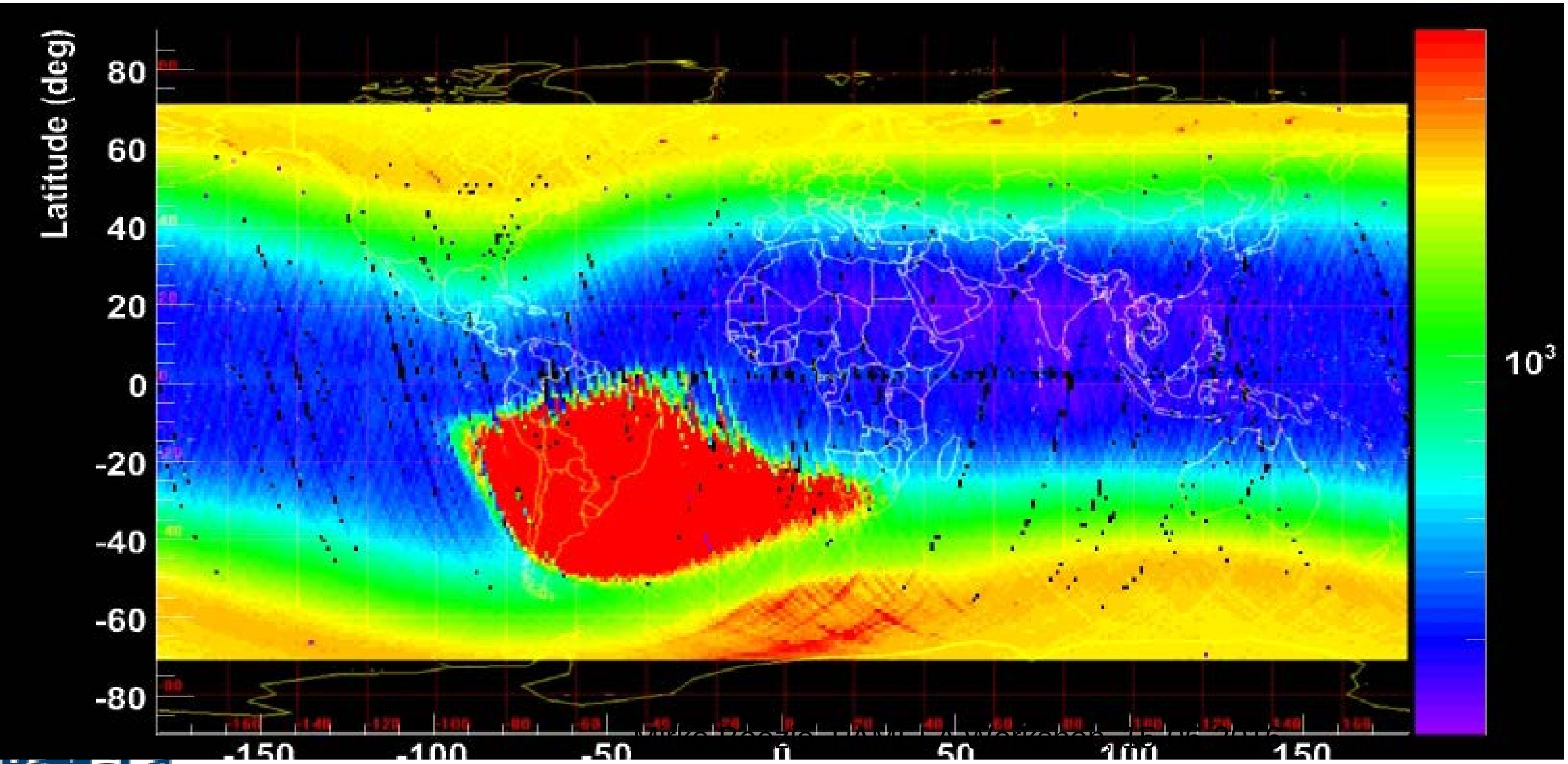
- Similar intensity
- No significant charge dependent effects
- No significant velocity dependent effects

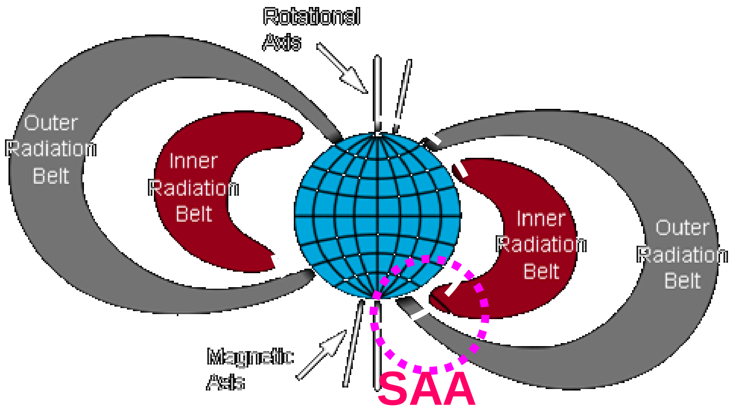


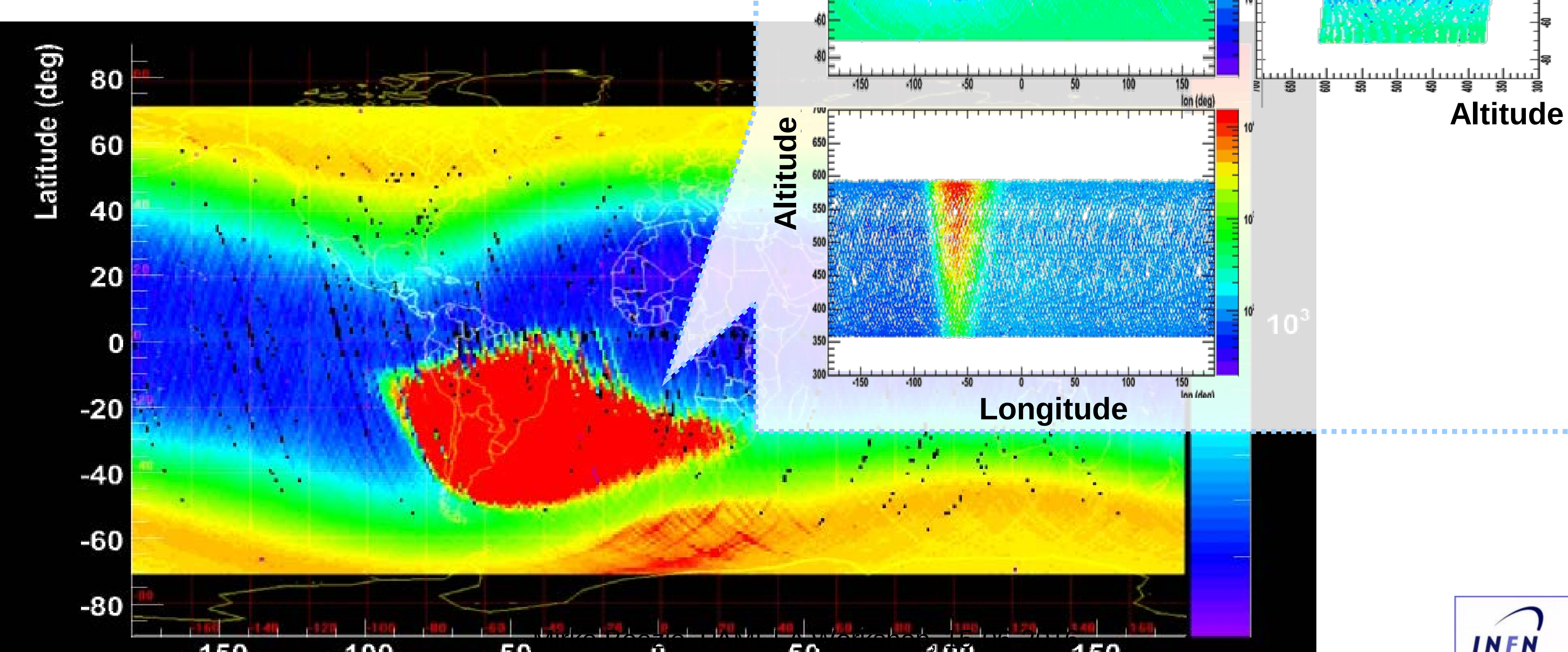


Cosmic rays in the magnetosphere

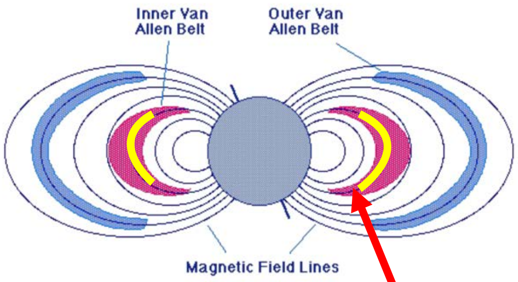

Rotational Axis
Outer Radiation Belt
Inner Radiation Belt
Inner Radiation Belt
Outer Radiation Belt
Magnetic Axis
SAA

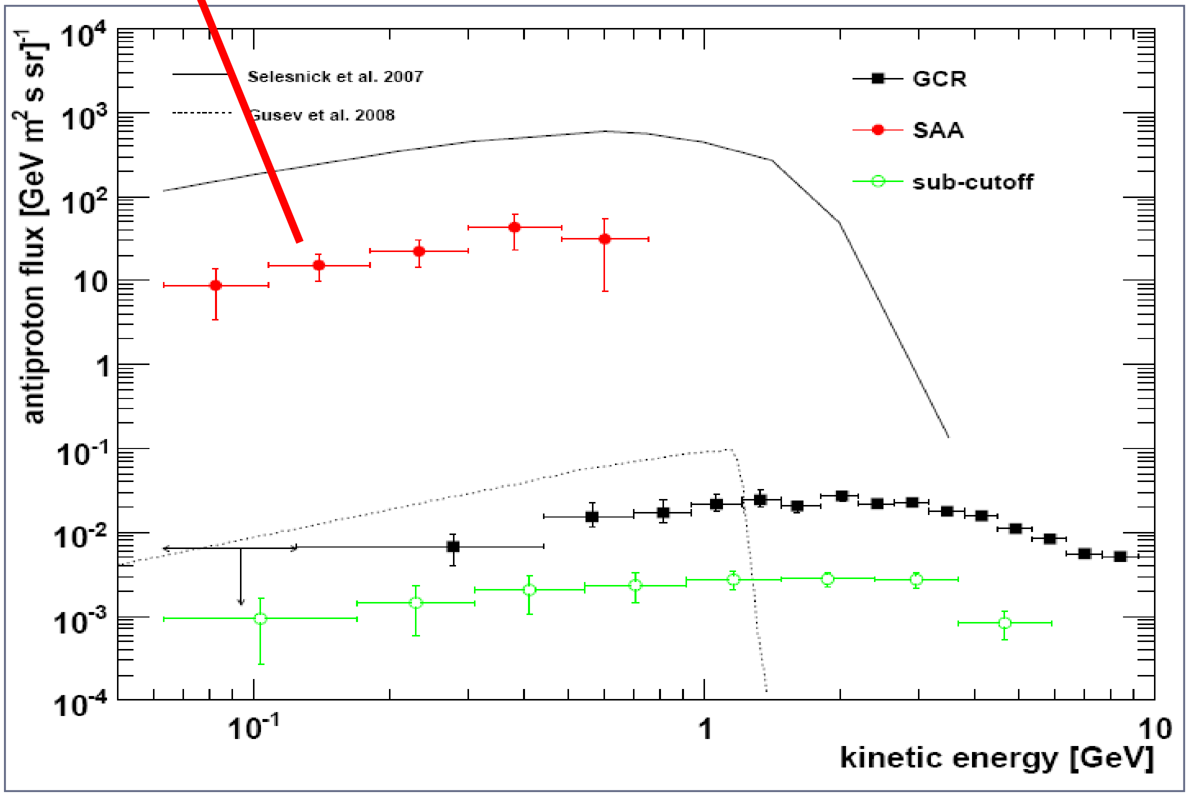

Latitude (deg)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
10^3


Rotational Axis
Outer Radiation Belt
Inner Radiation Belt
Inner Radiation Belt
Outer Radiation Belt
Magnetic Axis
SAA


Latitude (deg)
Latitude
Altitude
Longitude
Altitude

Geomagnetically trapped antiprotons

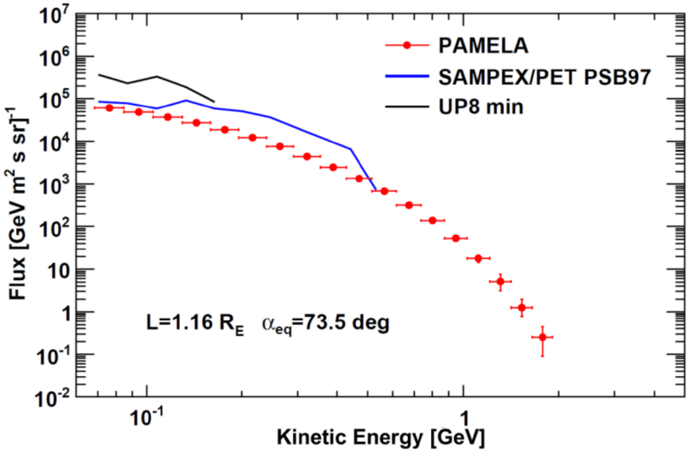




- First measurement of p-bar trapped in the inner belt
- **29 p-bars** discovered in SAA and **traced back to mirror points**
- p-bar flux exceeds GRC flux by **3 orders of magnitude,** as expected by models

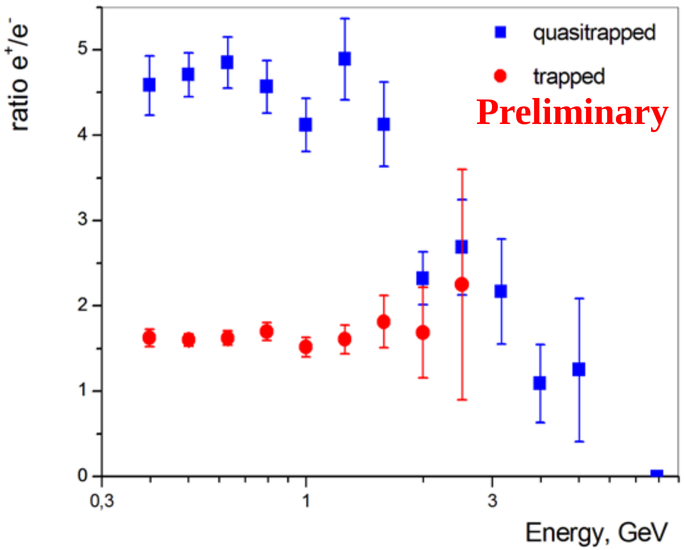
O. Adriani et al., ApJL 737 (2011), L29

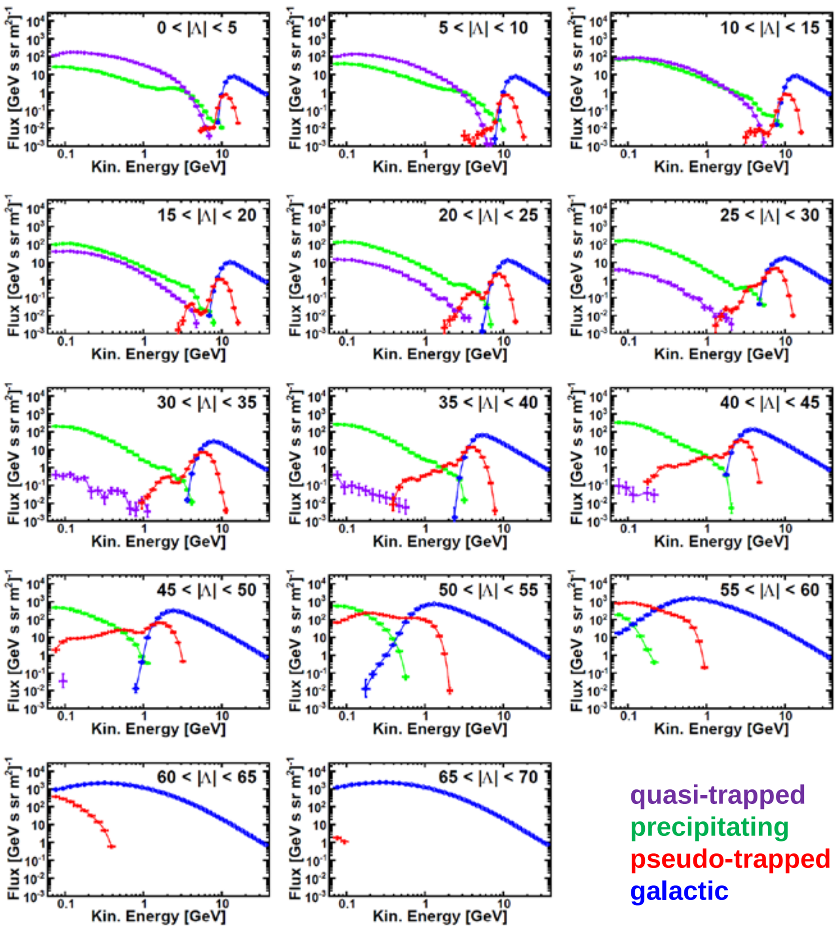
Geomagnetically trapped and albedo particles



Comparison with trapped proton empirical models

O. Adriani et al., ApJL 799 (2015) L4





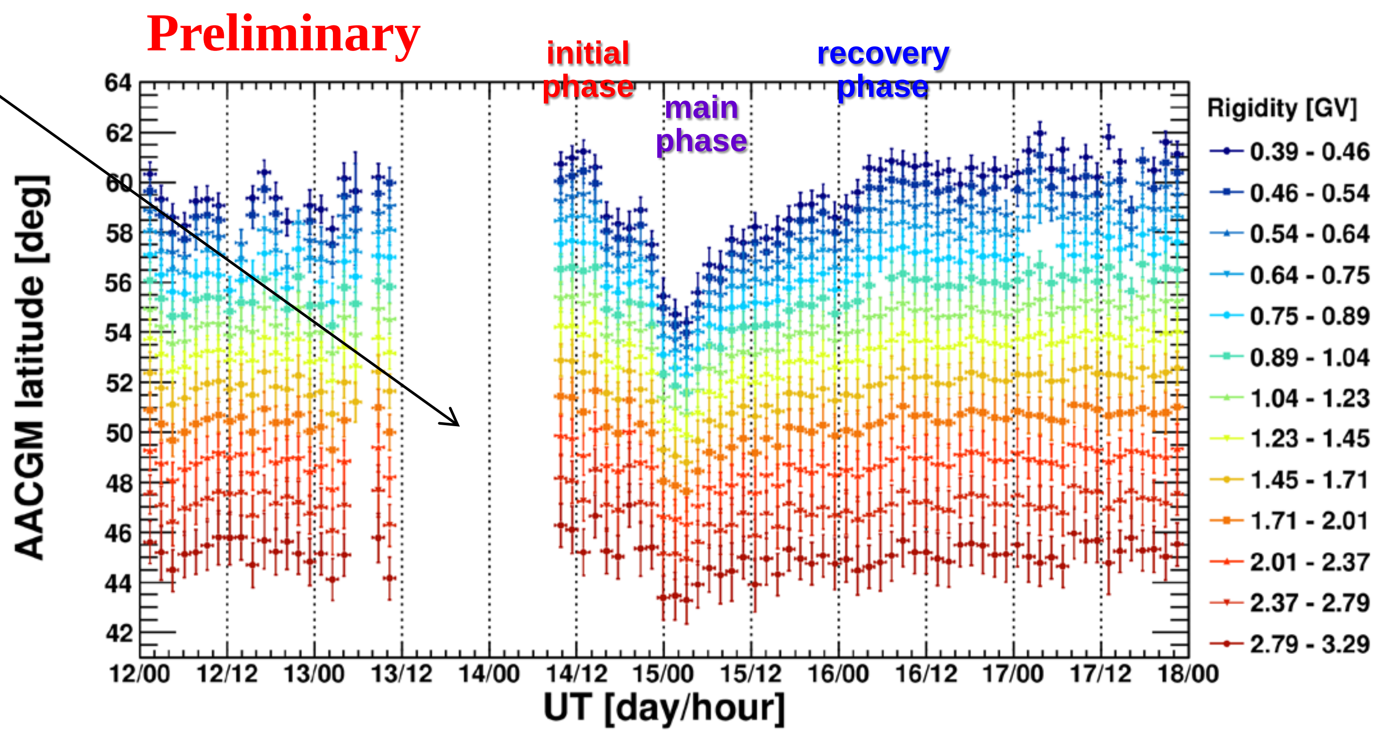
Re-entrant albedo proton spectra vs latitude |Λ|

O. Adriani et al., JGR A120 (2015) 3728

Measured cutoff latitudes

Data missing from 10:00 UT on Dec 13 until 09:14 UT on Dec 14 because of an onboard system reset of the satellite

Time profile of the geomagnetic cutoff latitudes measured by PAMELA for different rigidity bins



O. Adriani et al., Space Weather 14 (2016) 210, featured as a Research Spotlight on https://Eos.org

PAMELA overall results

- Results span 4 decades in energy and 13 in fluxes

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The PAMELA Mission: Heralding a new era in precision cosmic ray physics

O. Adriani [a,b], G.C. Barbarino [c,d], G.A. Bazilevskaya [e], R. Bellotti [f,g], M. Boezio [h], E.A. Bogomolov [i], M. Bongi [a,b], V. Bonvicini [h], S. Bottai [b], A. Bruno [f,g], F. Cafagna [g], D. Campana [d], R. Carbone [d,h], P. Carlson [j,k], M. Casolino [l], G. Castellini [m], M.P. De Pascale [l,n,1], C. De Santis [l,n], N. De Simone [l], V. Di Felice [l], V. Formato [h,o], A.M. Galper [p], U. Giaccari [d], A.V. Karelin [p], M.D. Kheymits [p], S.V. Koldashov [p], S. Koldobskiy [p], S.Yu. Krut'kov [i], A.N. Kvashnin [e], A. Leonov [p], V. Malakhov [p], L. Marcelli [n], M. Martucci [n,q], A.G. Mayorov [p], W. Menn [r], V.V. Mikhailov [p], E. Mocchiutti [h], A. Monaco [f,g], N. Mori [a,b], R. Munini [h,j,k,o], N. Nikonov [i,l,n], G. Osteria [d], P. Papini [b], M. Pearce [j,k], P. Picozza [l,n,*], C. Pizzolotto [h,s,t], M. Ricci [q], S.B. Ricciarini [b,m], L. Rossetto [j,k], R. Sarkar [h], M. Simon [r], R. Sparvoli [l,n], P. Spillantini [a,b], Y.I. Stozhkov [e], A. Vacchi [h], E. Vannuccini [b], G.I. Vasilyev [i], S.A. Voronov [p], J. Wu [j,k,u], Y.T. Yurkin [p], G. Zampa [h], N. Zampa [h], V.G. Zverev [p]

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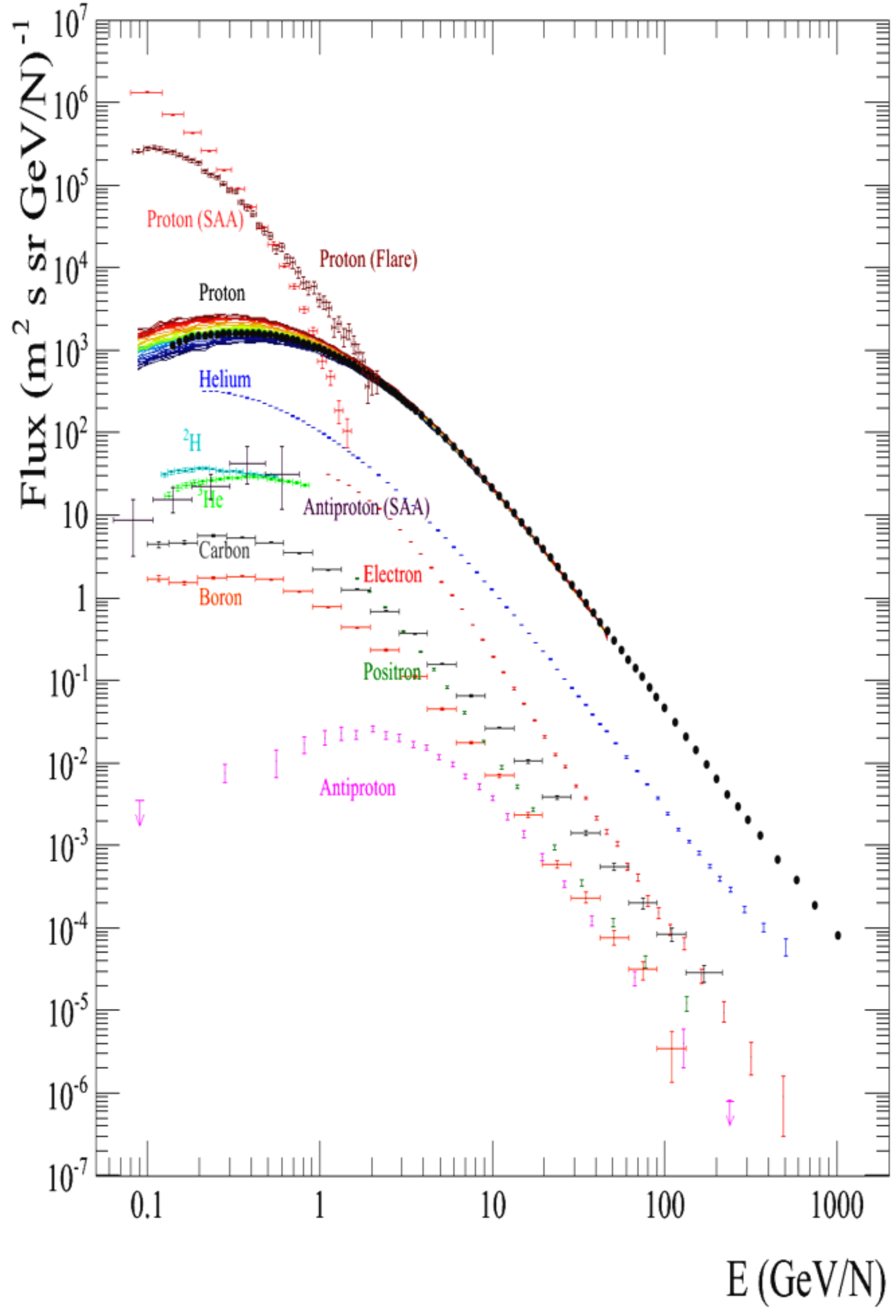
[t] Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati, Italy
[u] School of Mathematics and Physics, China University of Geosciences, CN-430074 Wuhan, China



Summary and conclusions (1)

PAMELA has been in orbit and studying cosmic rays for almost 9 years. Its operation time will continue until end 2015, possibly until end of current solar cycle.

- **Antiproton energy spectrum and ratio** → Measured up to ~300 GeV. No compelling deviations from secondary production expectations.
- **High energy positron fraction (>10 GeV)** → Measured up to ~300 GeV. Increases significantly (and unexpectedly!) with energy. → **Primary source?**
- **Positron flux** -> **Consistent with a new primary source**.
- **Anisotropy studies**: no evidence of anisotropy.
- **AntiHe/He ratio**: broader energy range ever achieved.

Summary and conclusions (2)

- **H and He absolute fluxes →** Measured up to ~1.2 TV. **Complex spectral structures observed (spectral hardening at ~200 GV)**.
- **H and He isotope ratio** -> **Different slope between the two species**.
- **Electron (e^-) absolute flux →**Measured up to ~600 GeV. Possible deviations from standard scenario, not inconsistent with an additional electron component.
- **B/C ratio and absolute fluxes** up to 100 GeV/n.
- **Solar physics**: measurement of modulated fluxes and solar-flare particle spectra.
- **Physics of the magnetosphere**: first measurement of trapped antiproton flux and detailed measurement of trapped proton flux.

Other studies and forthcoming results: ***Primary and secondary-nuclei abundance (up to Oxygen), Solar modulation (long-term flux variation and charge-dependent effects), Solar events: several new events under study.***

Thanks!