# Results from the PAMELA Experiment after nine years of cosmic ray investigation

**F.S. Cafagna, INFN (Italian Institute for Nuclear Physics) Bari Unit**

**On behalf of the PAMELA Collaboration**

**CRIS 2015**

**Cosmic Ray International Seminar 2015**

PaMeLa a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

INFN Istituto Nazionale di Fisica Nucleare

# PAMELA Collaboration

Italy

INFN

Bari | Florence | Frascati | Naples | Rome | Trieste | CNR, Florence

Germany: Siegen

Sweden: KTH, Stockholm

Russia: Moscow / St. Petersburg

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Tor Vergata

IFAC

**Payload for Antimatter & Matter Exploration and Light nuclei Astrophysics**

Germany: Universität Gesamthochschule Siegen

Siegen

Sweden: Kungl Tekniska Högskolan

KTH, Stockholm

Russia: Физический Институт

Ioffe Physico-Technical Institute

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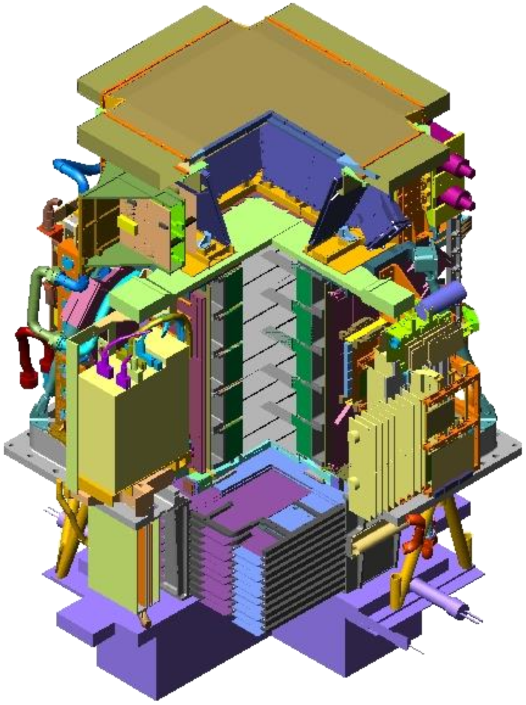
# PAMELA detectors



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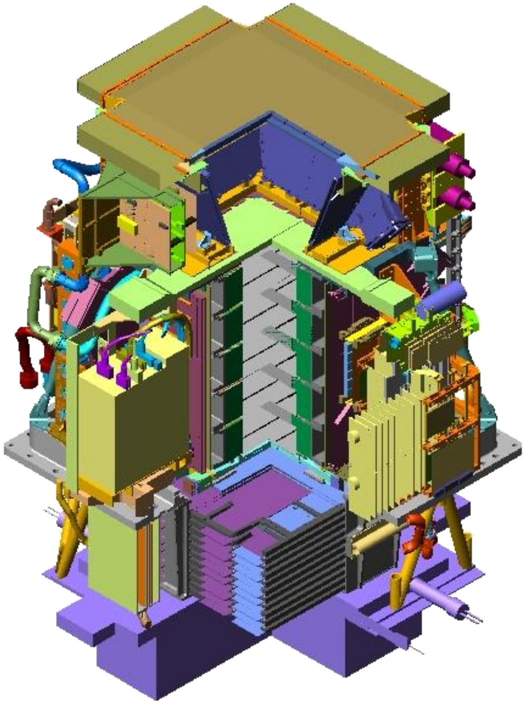

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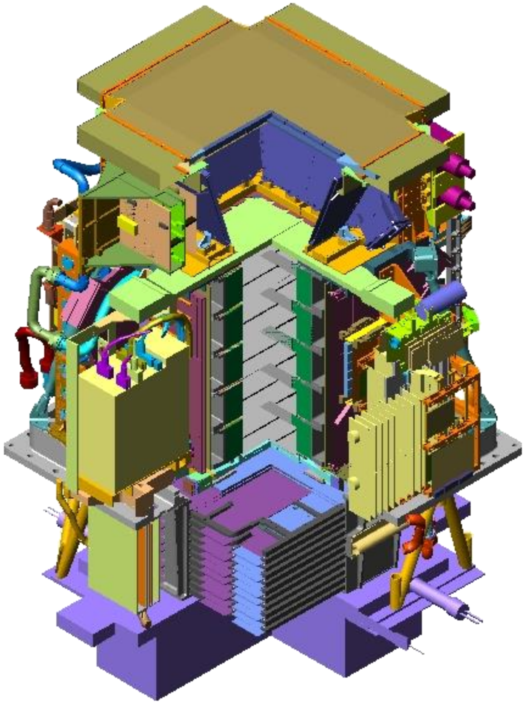
| **GF:** | **21.5 cm$^2$ sr** |
| **Mass:** | **470 kg** |
| **Size:** | **130x70x70 cm$^3$** |
| **Power Budget:** | **360W** |

# PAMELA detectors

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



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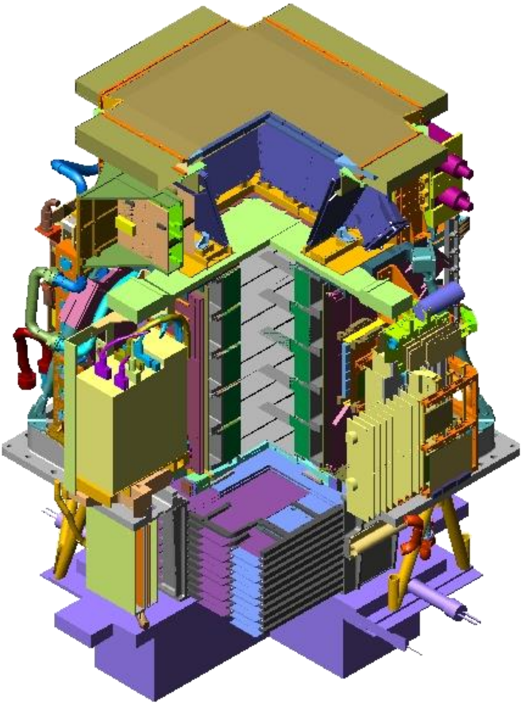

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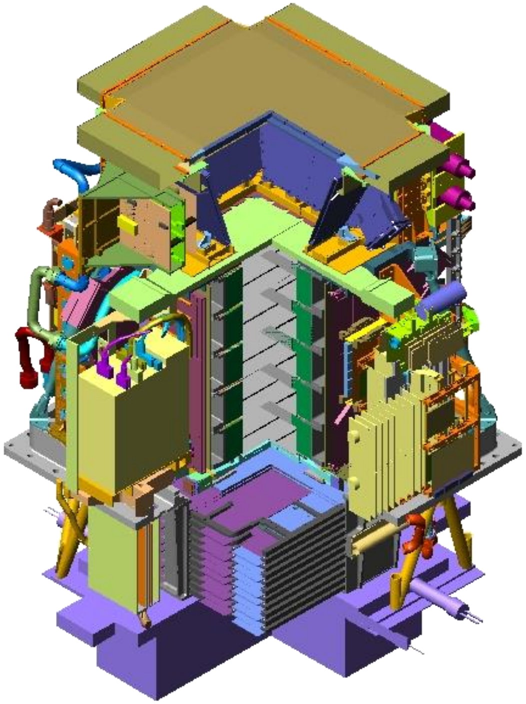

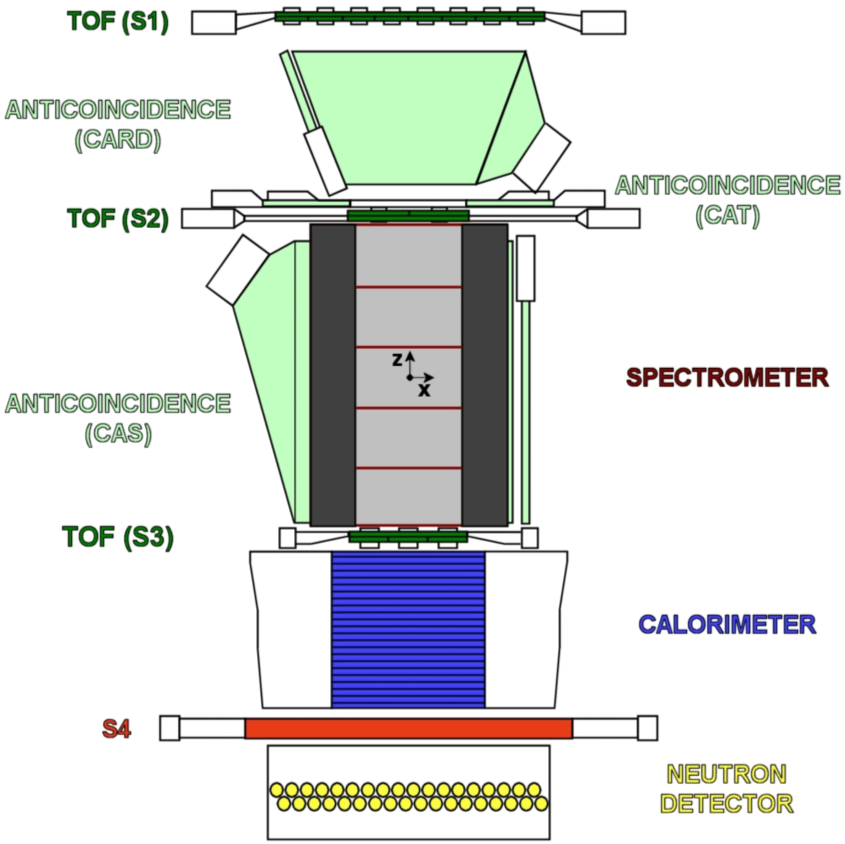


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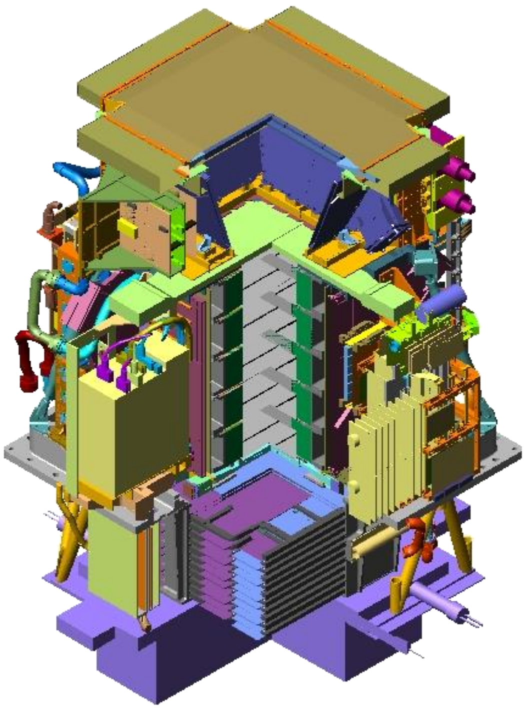

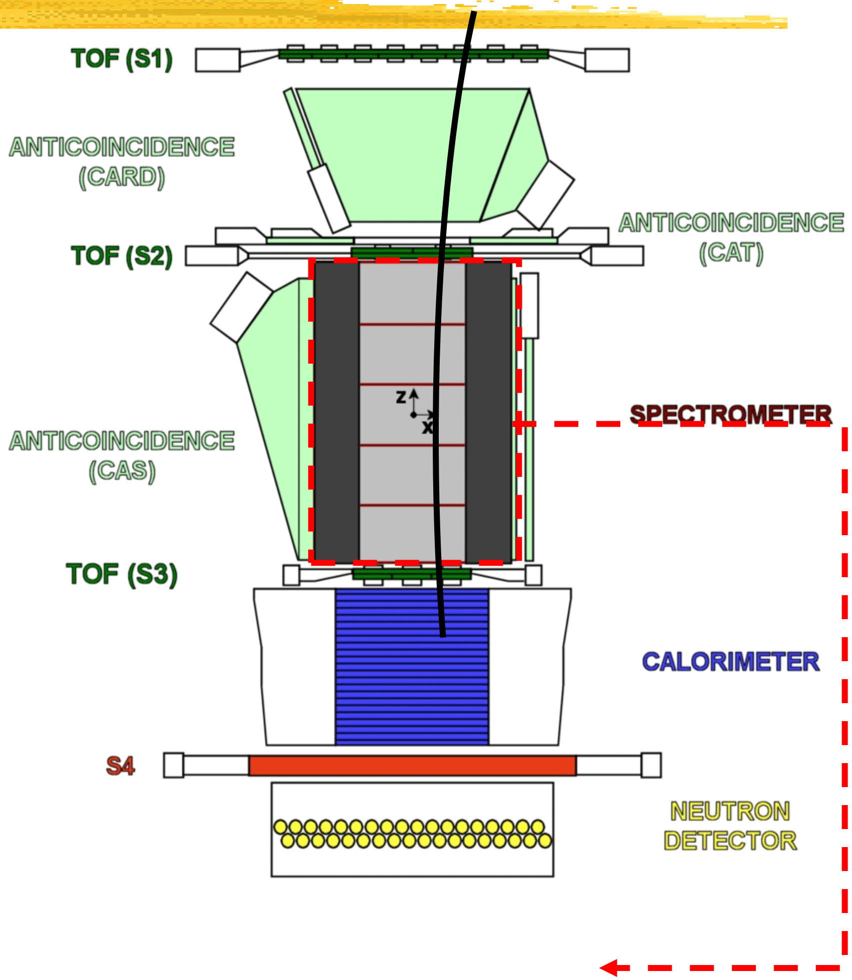


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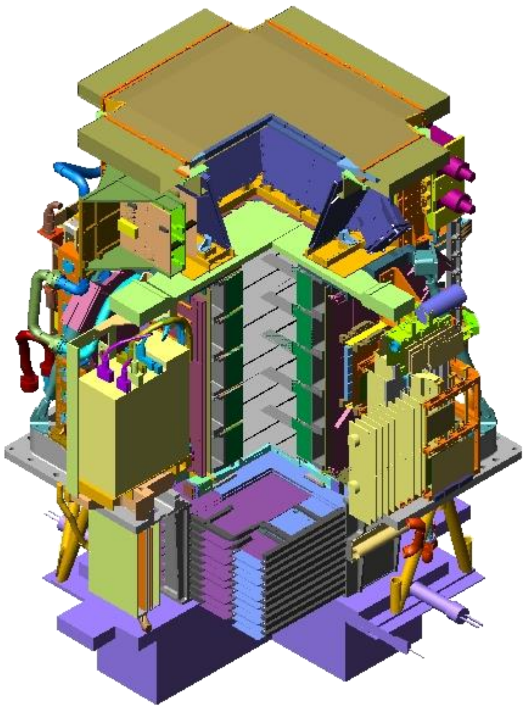

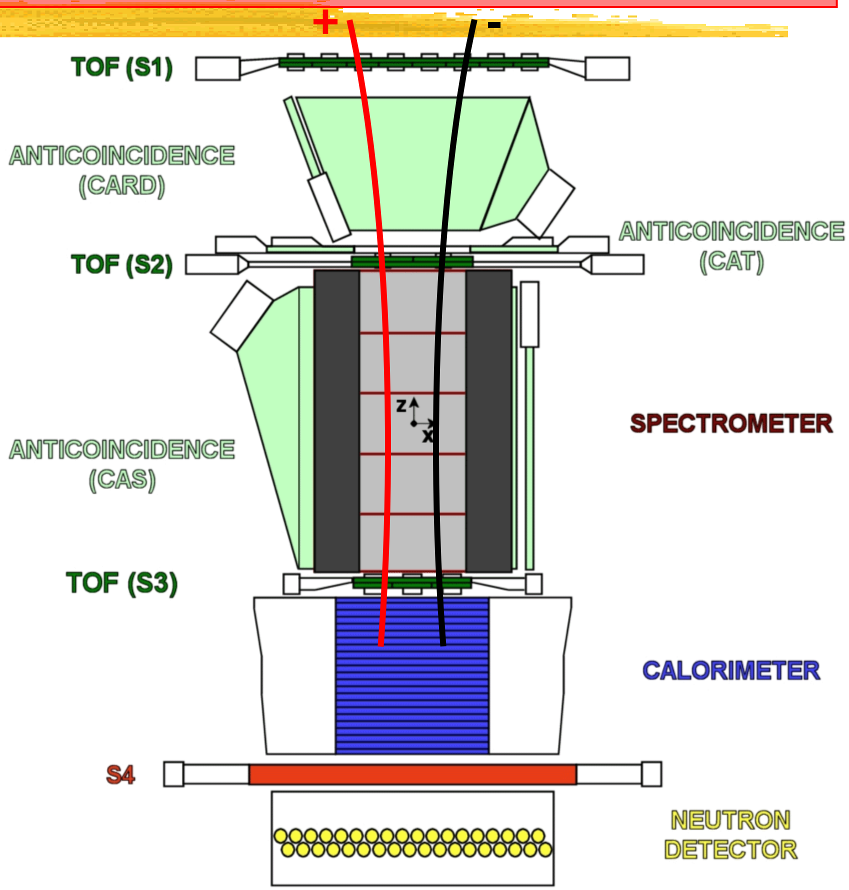


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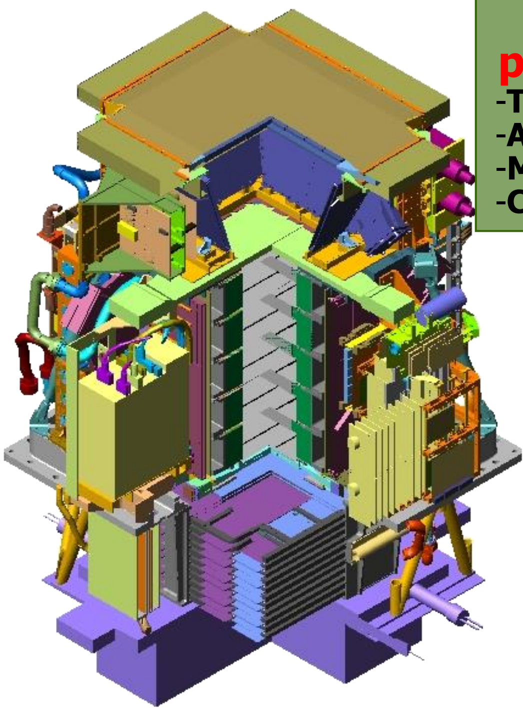
**Spectrometer microstrip silicon tracking system+permanent magnet**

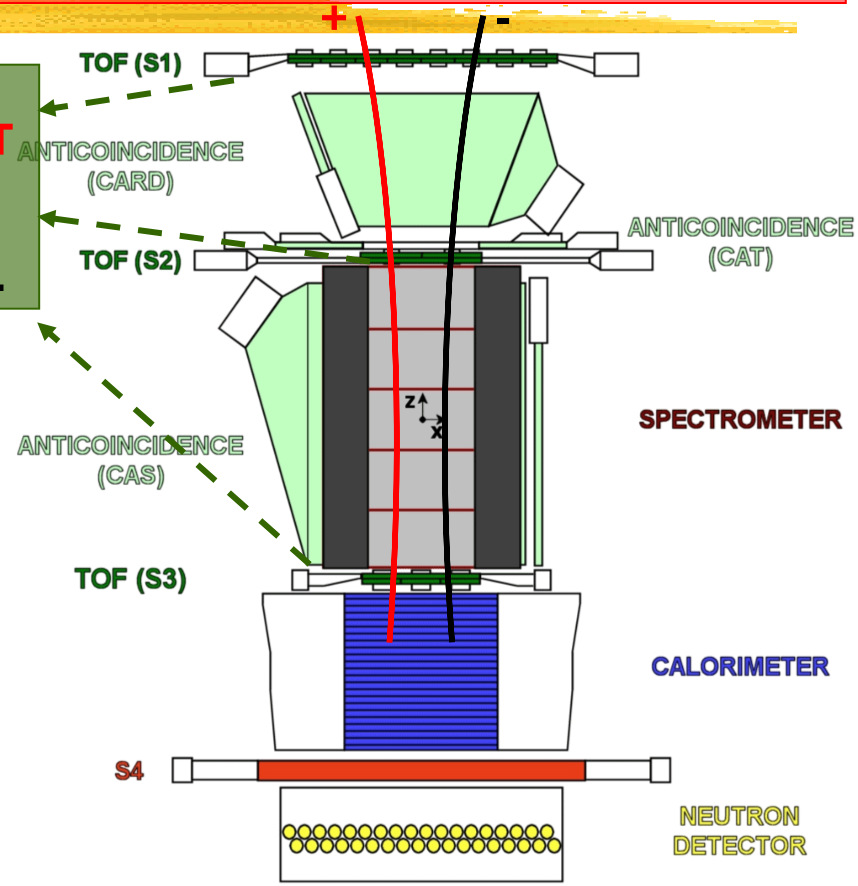
- **Magnetic rigidity (R = pc/Ze)**
- **Charge sign**
- **Charge value from dE/dx**

# 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.**



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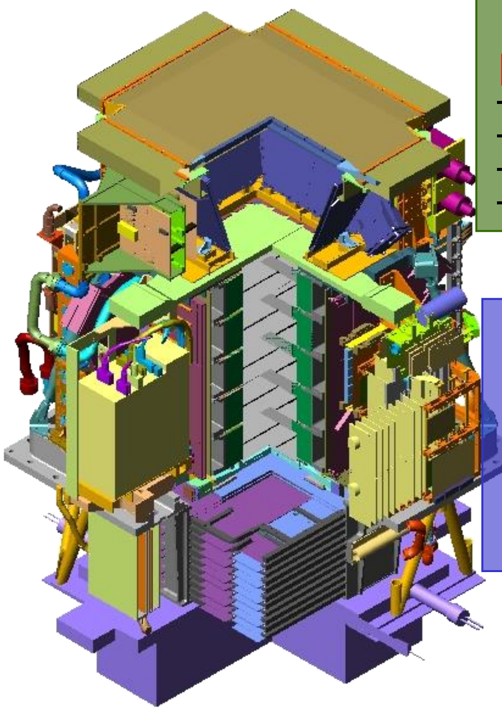

**Time-Of-Flight plastic scintillators + PMT**
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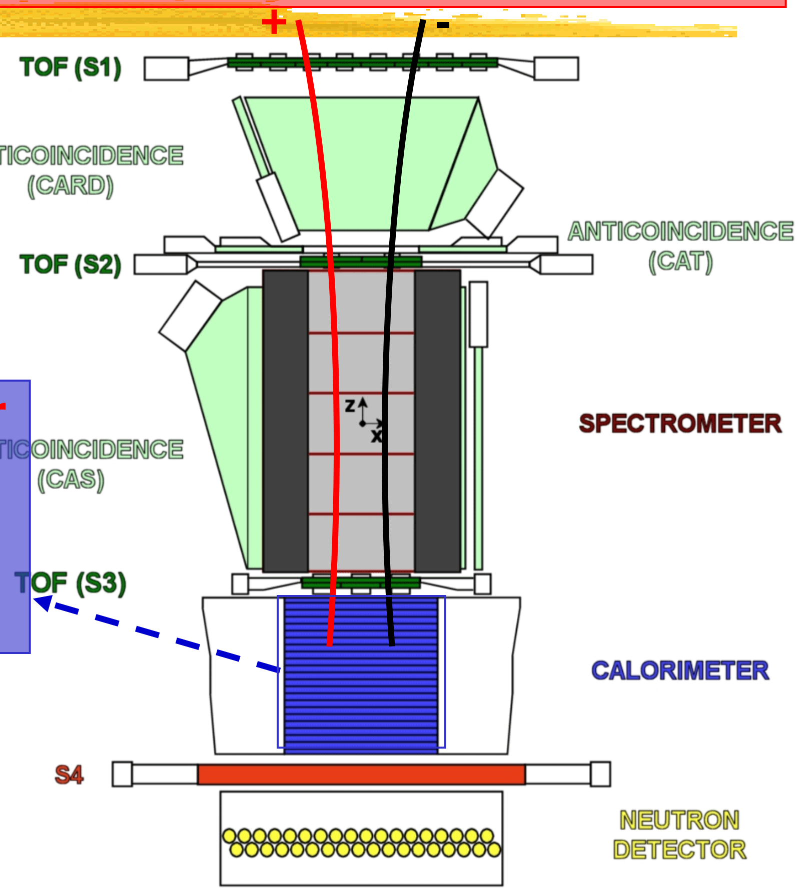
- Discrimination $e^+$/ p, pbar/$e^-$ (shower topology)
- Direct E measurement for $e^-$

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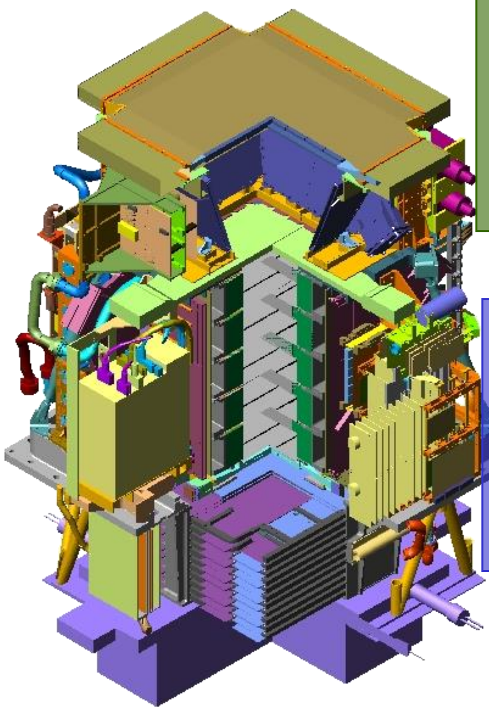

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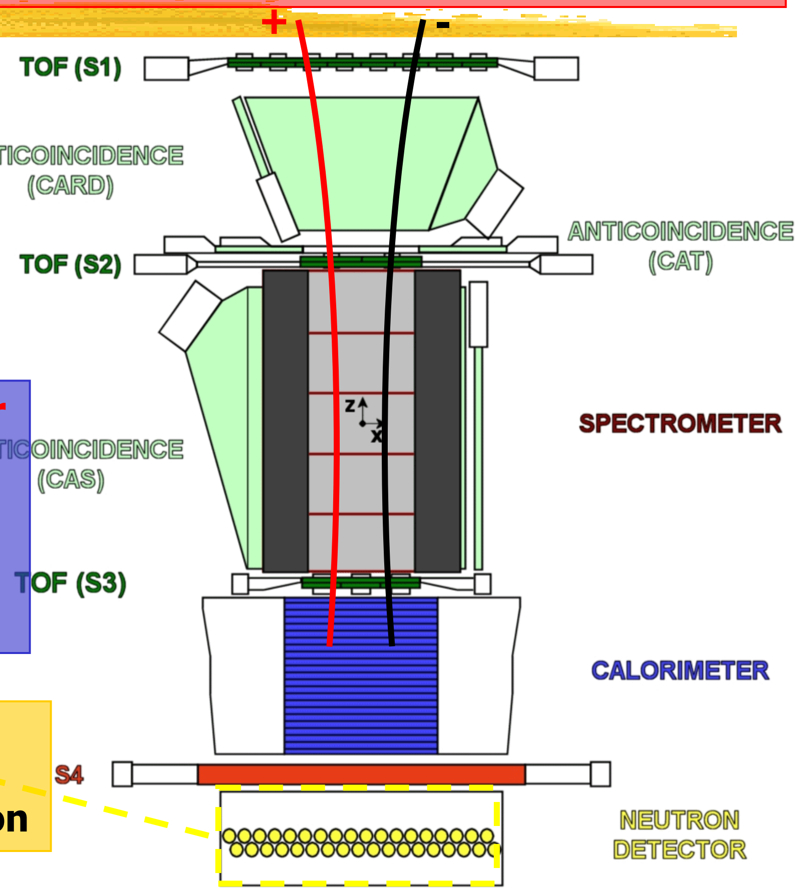
**Neutron detector & Shower-tail catcher (S4):**
- -High-energy e/h discrimination

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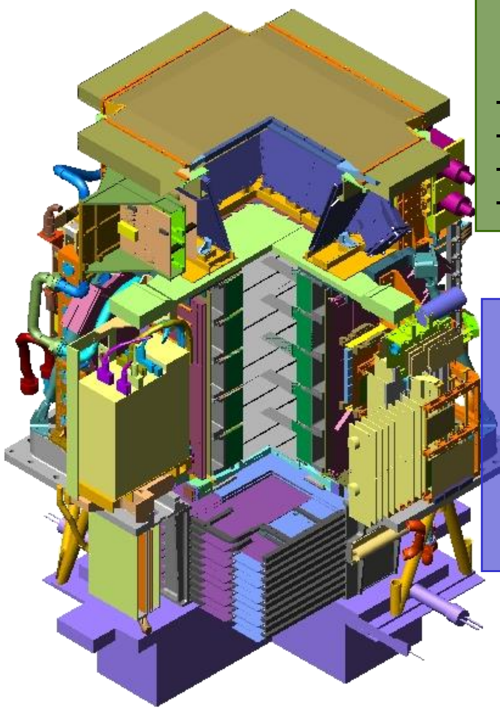

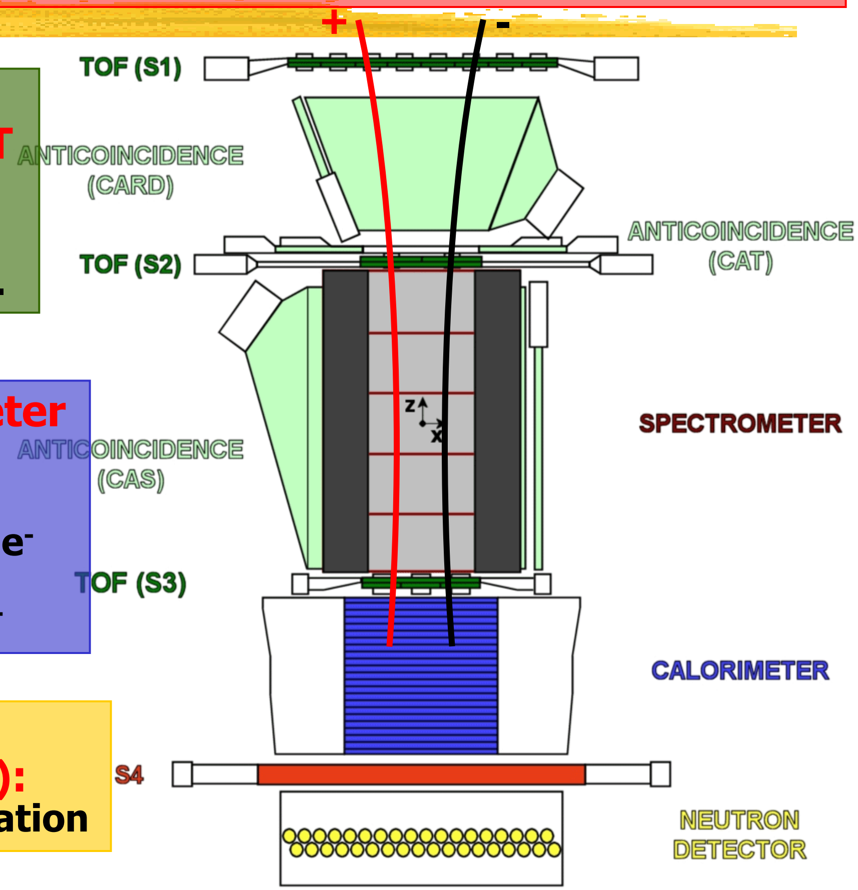


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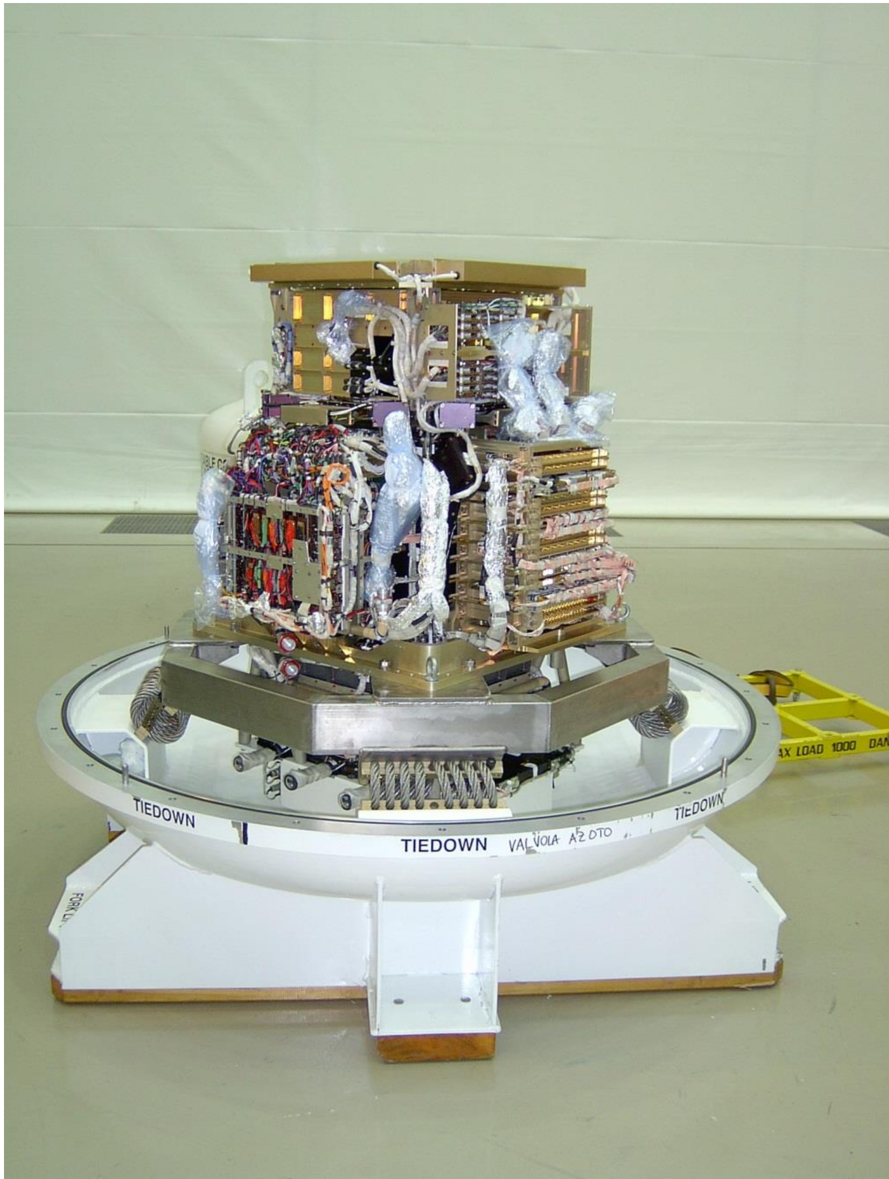
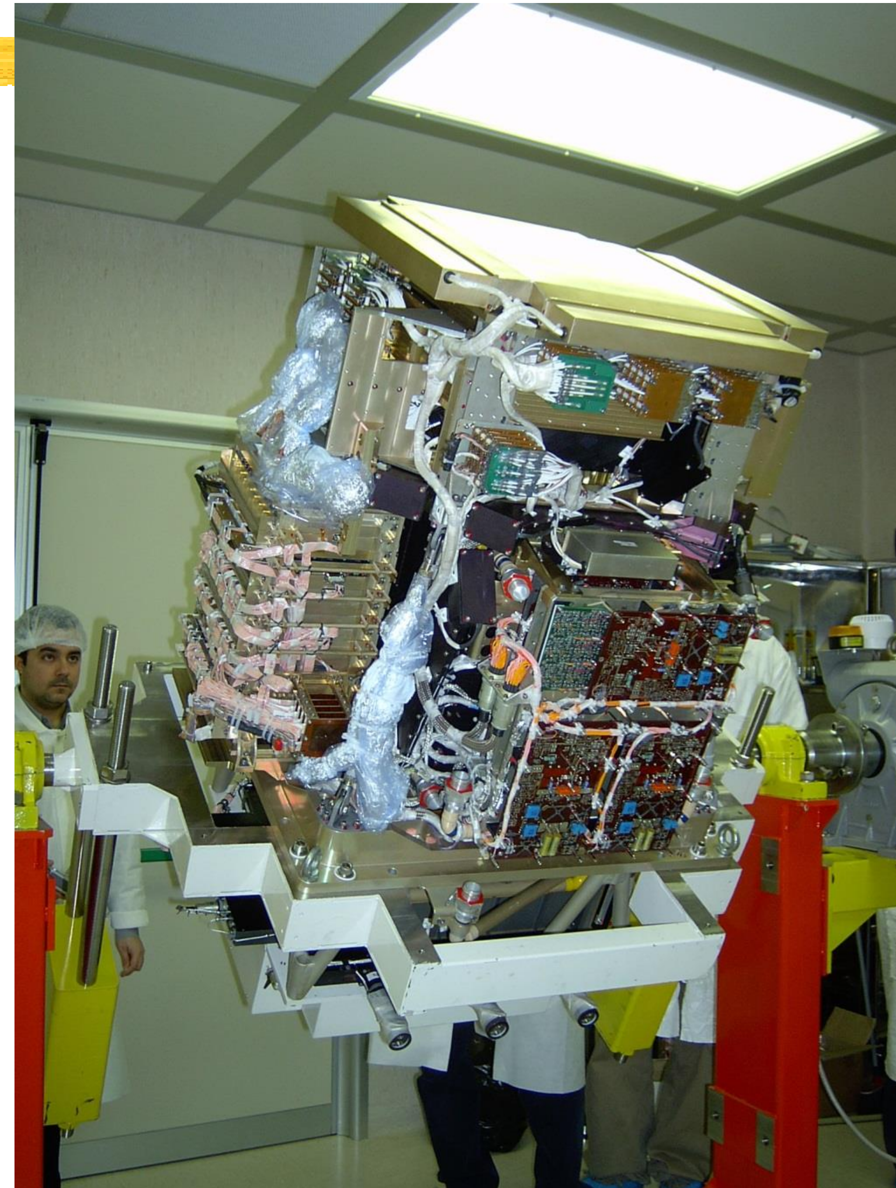
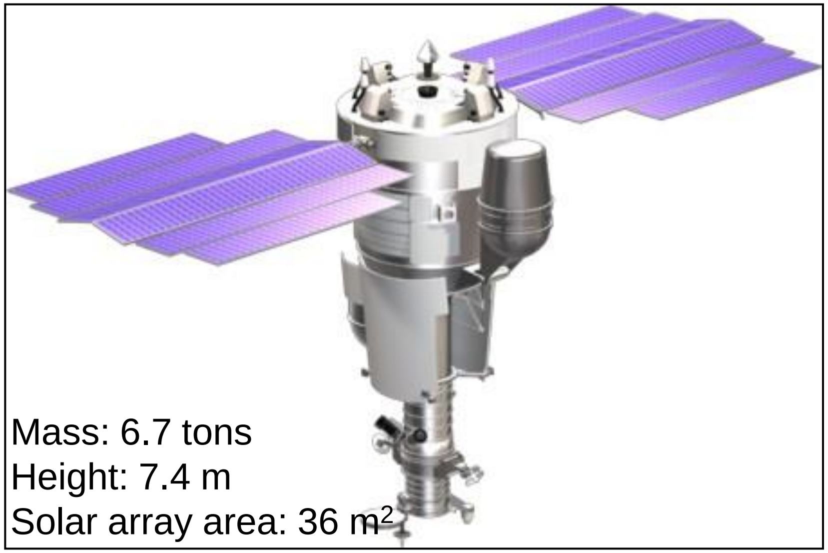
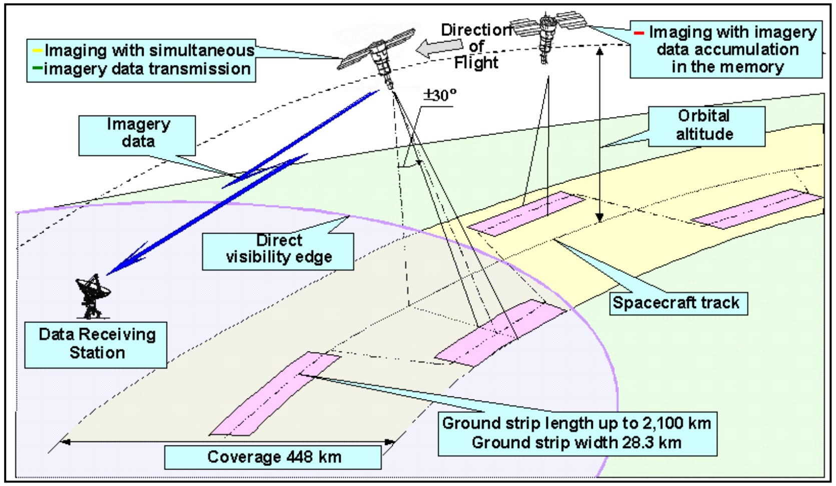


# The Resurs DK-1 spacecraft



Mass: 6.7 tons
Height: 7.4 m
Solar array area: 36 $m^2$



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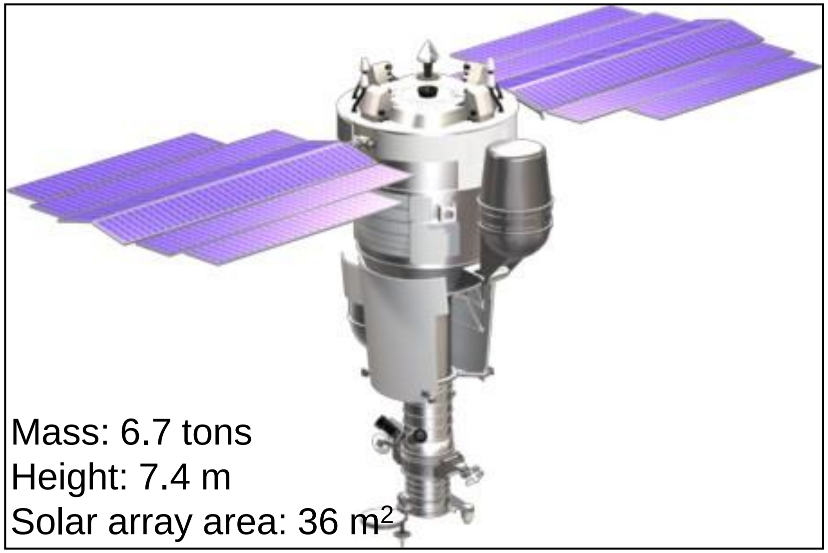


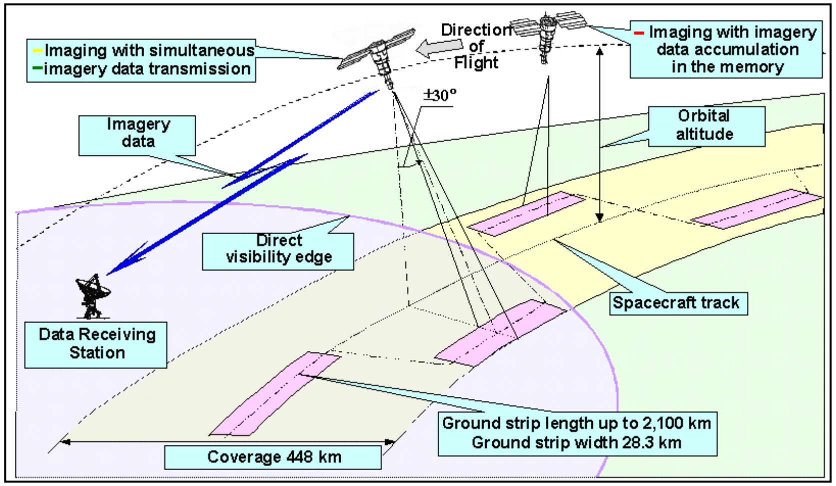


- Multi-spectral remote sensing of earth's surface
  → near-real-time high-quality images

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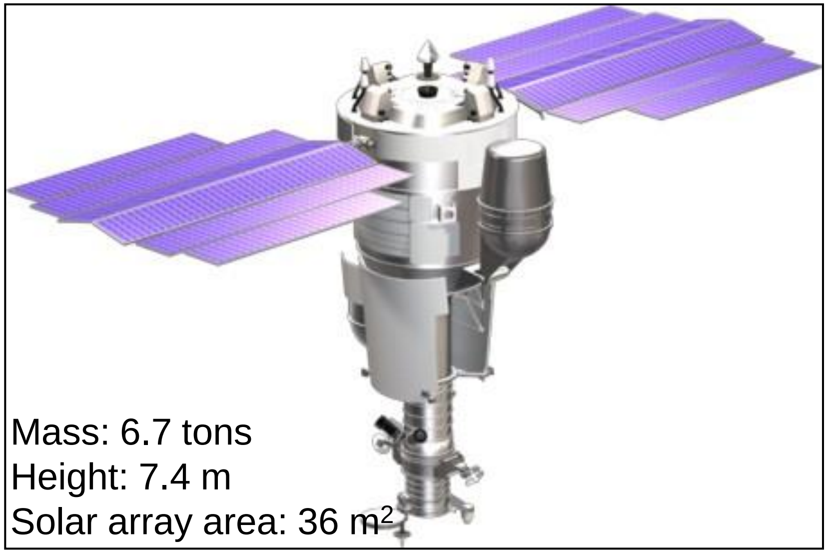


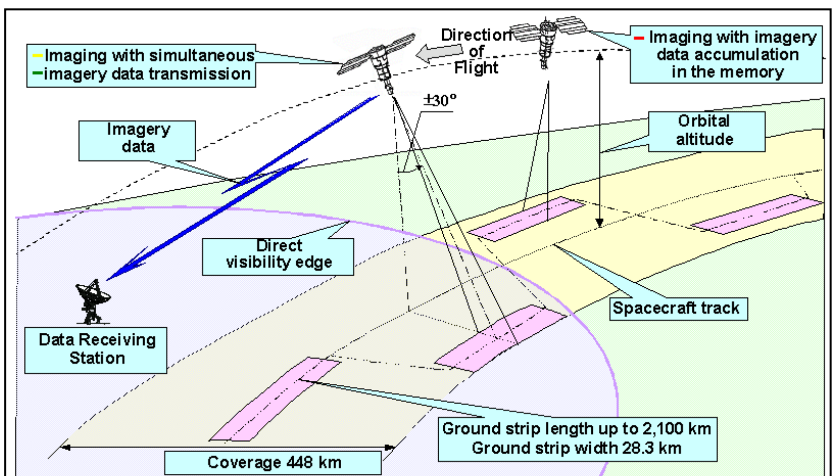


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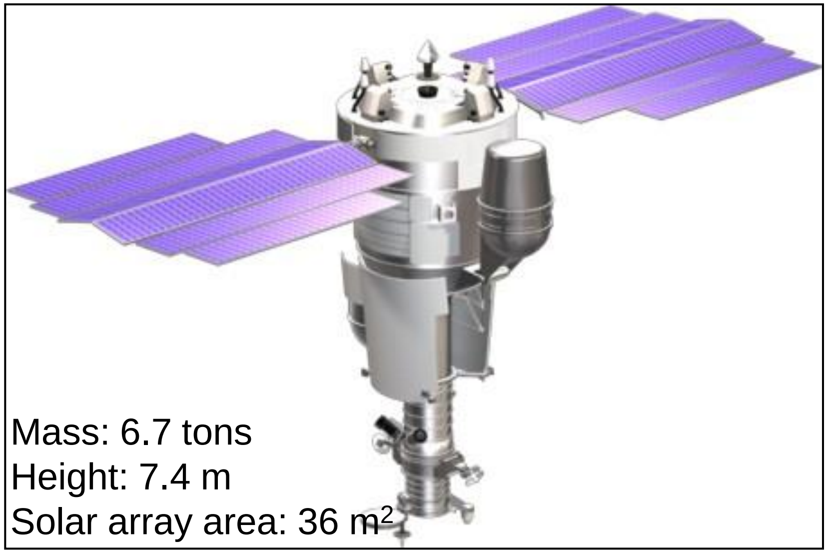


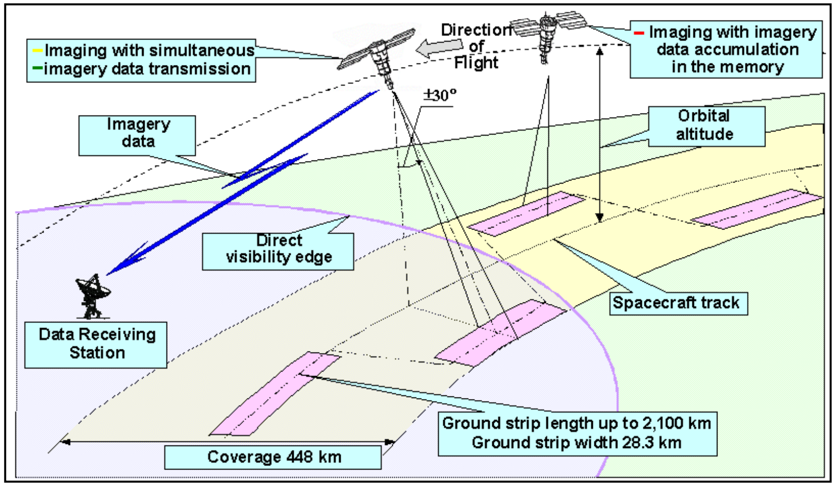


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- Built by the Space factory TsSKB Progress in Samara (Russia)
- Operational orbit parameters:
  - inclination ~70°
  - altitude ~ 350-600 km (elliptical)

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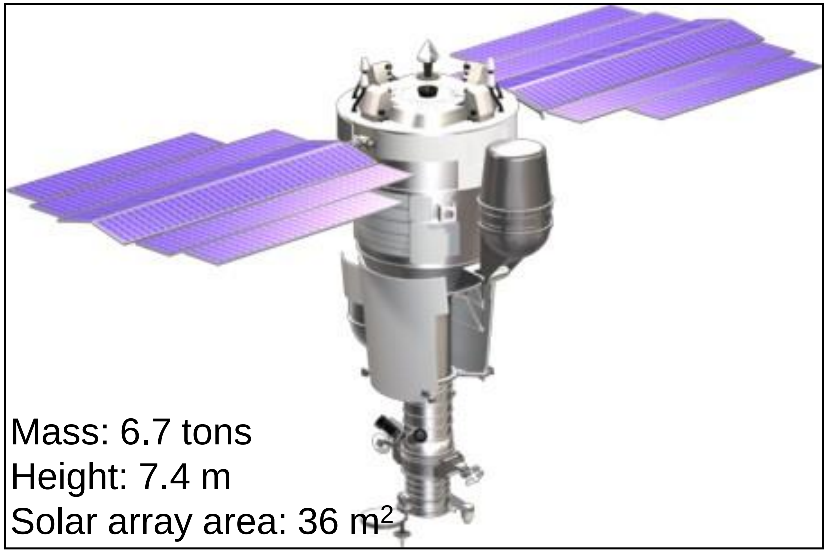


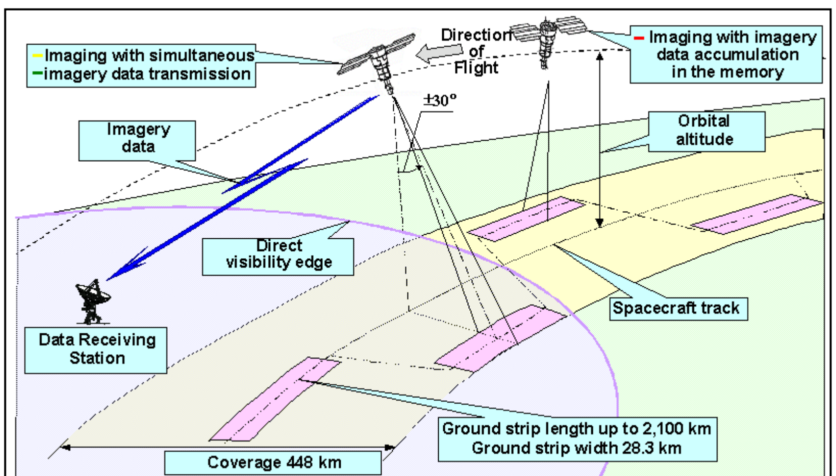


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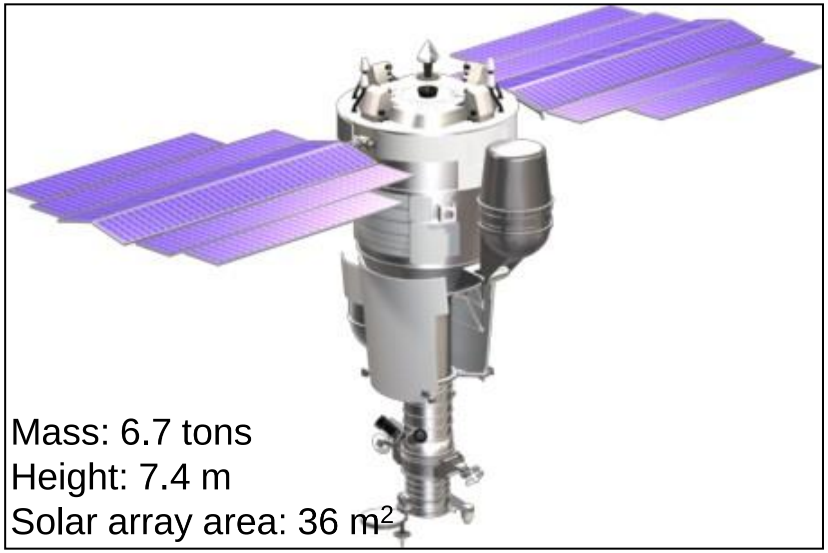


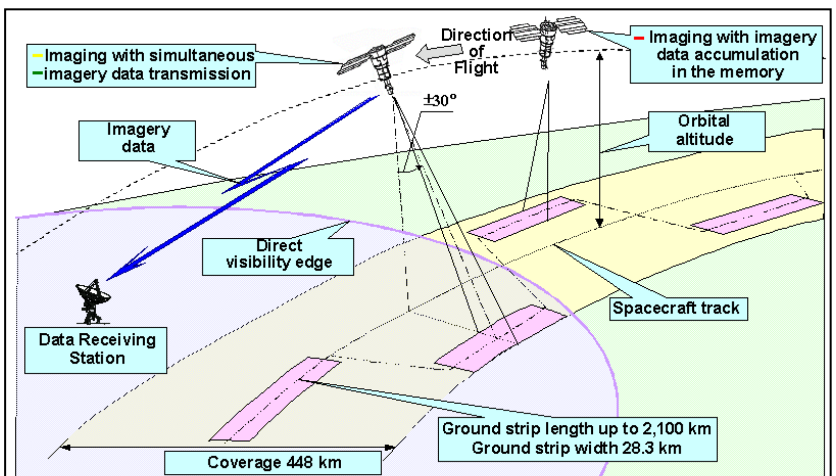


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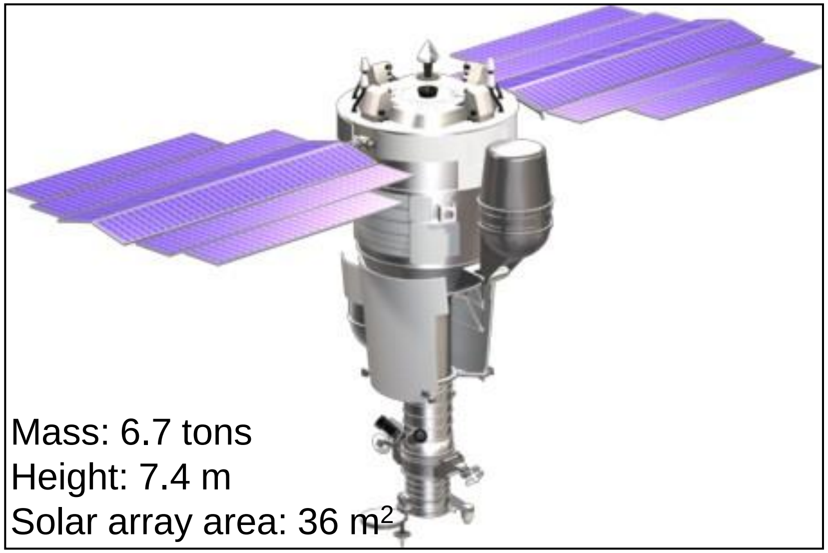


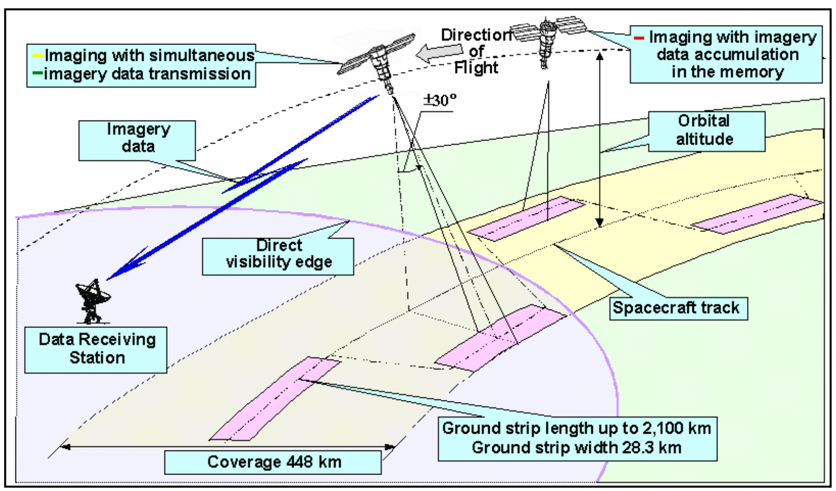


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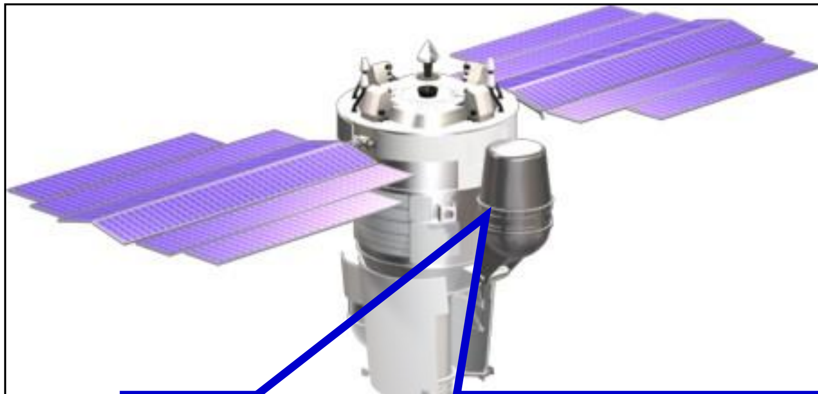

- **PAMELA inside a pressurized container**
- **Moved from parking to data-taking position few times/year**

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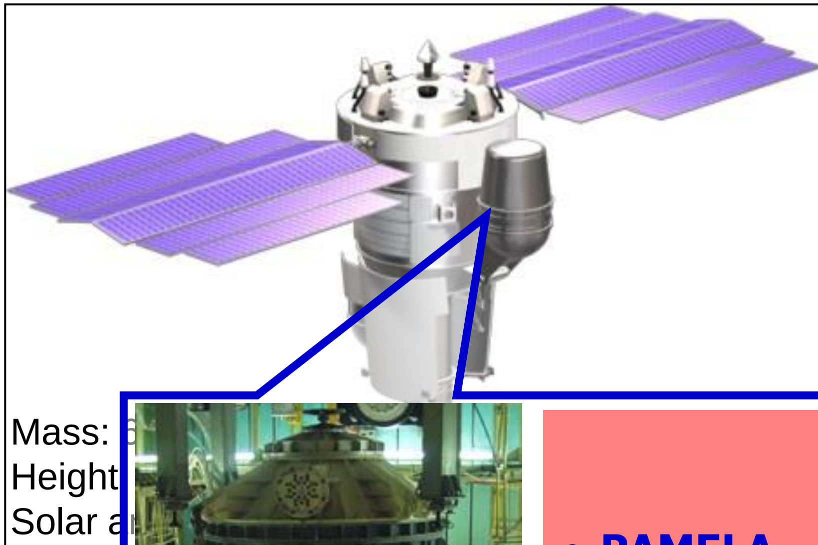


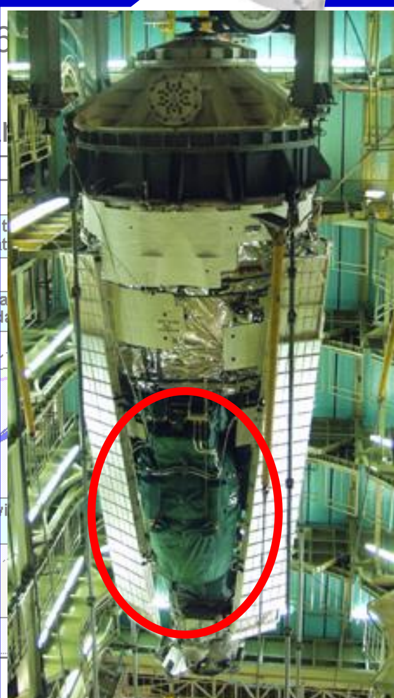

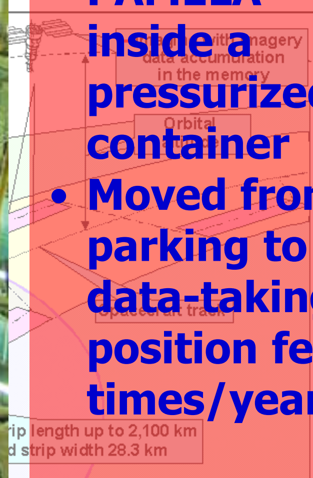


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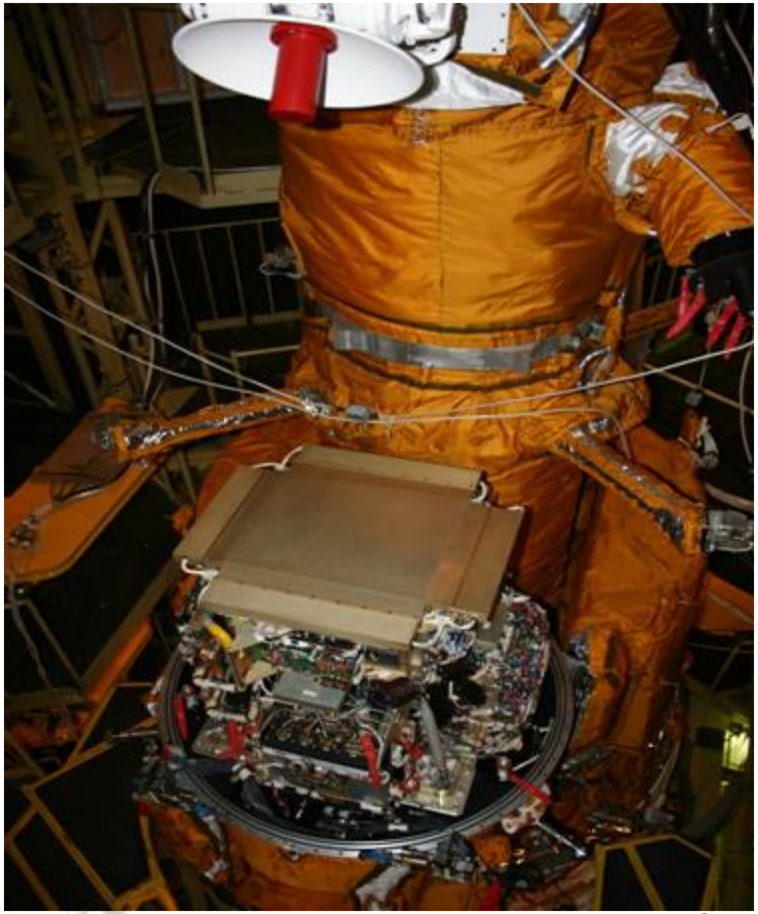

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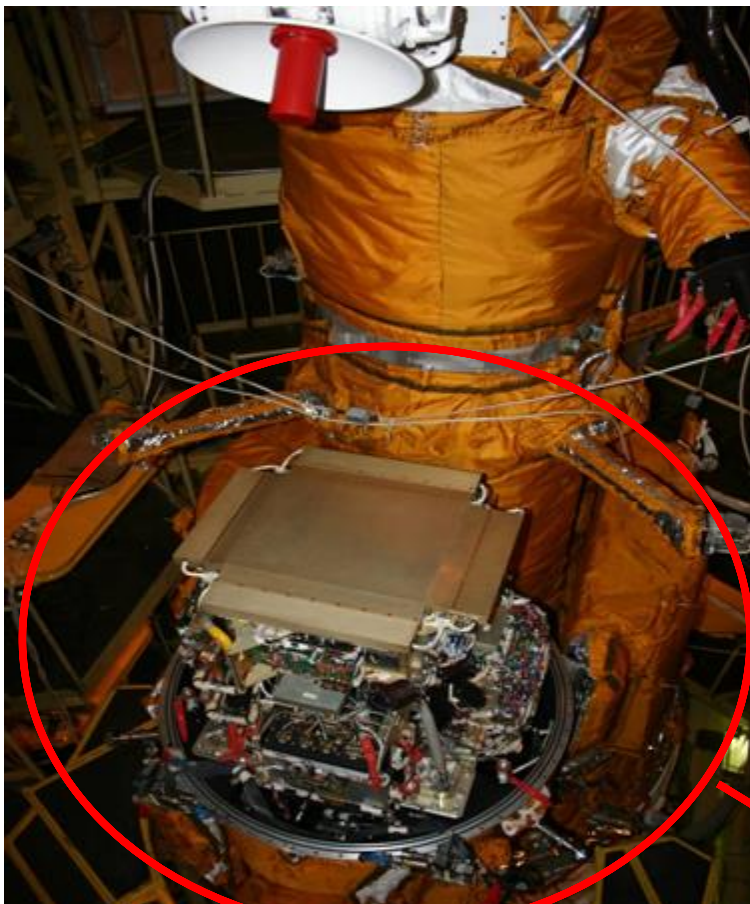
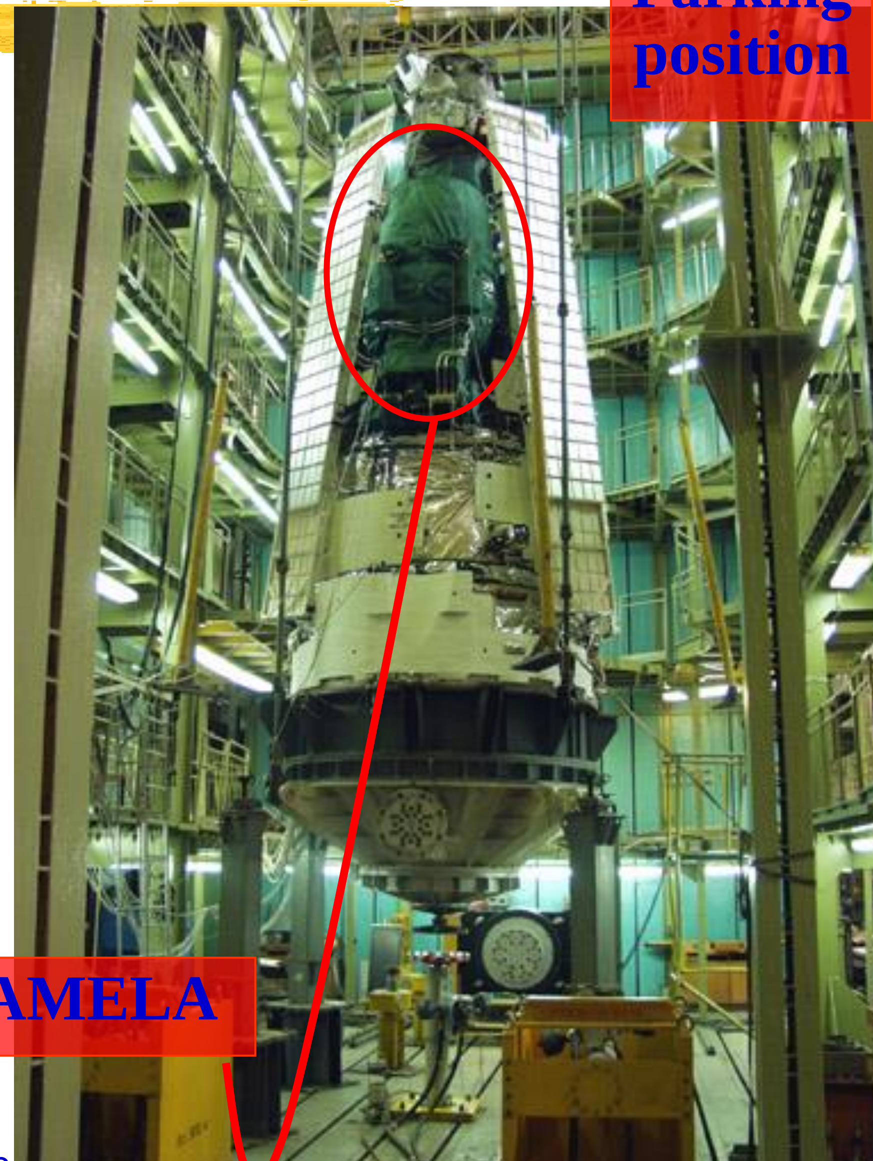


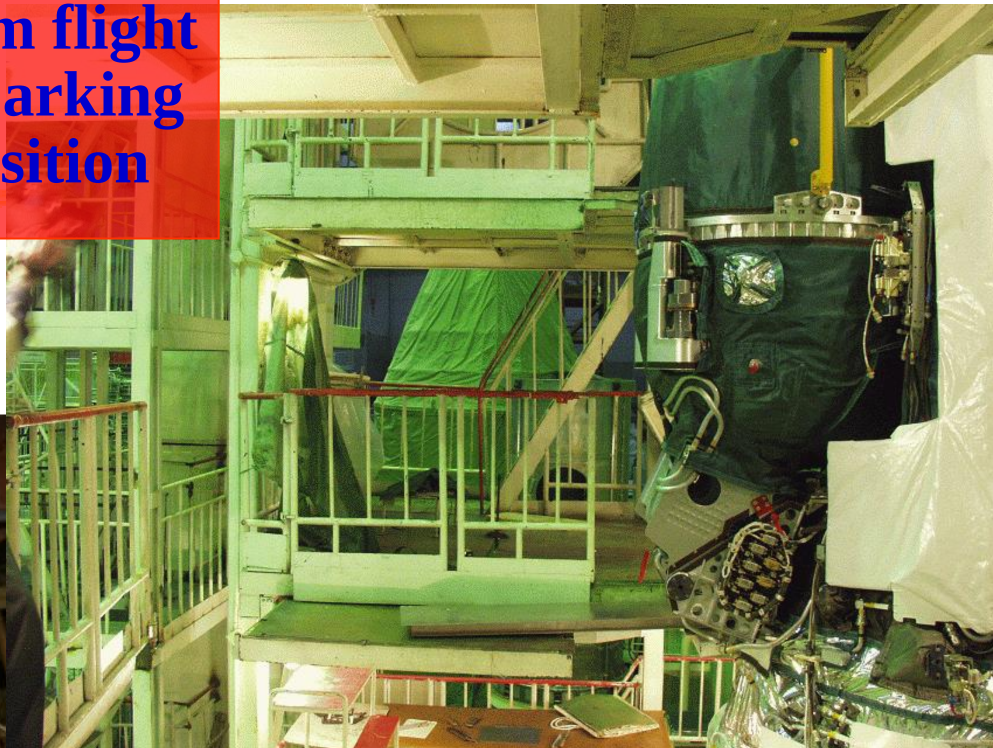


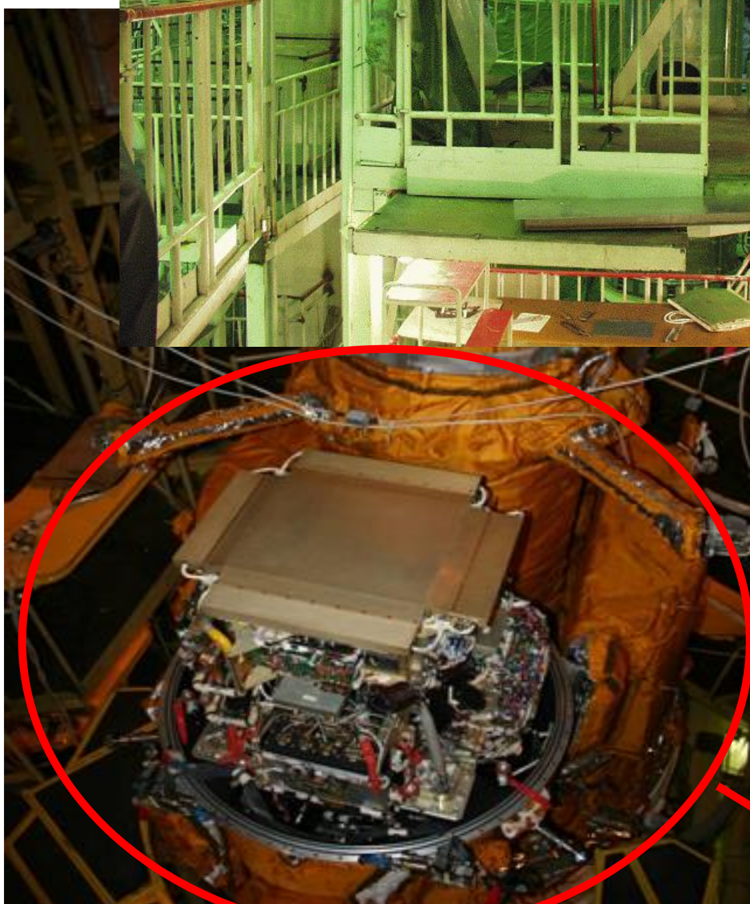
Parking position

PAMELA

**atellite**

**From flight to parking position**





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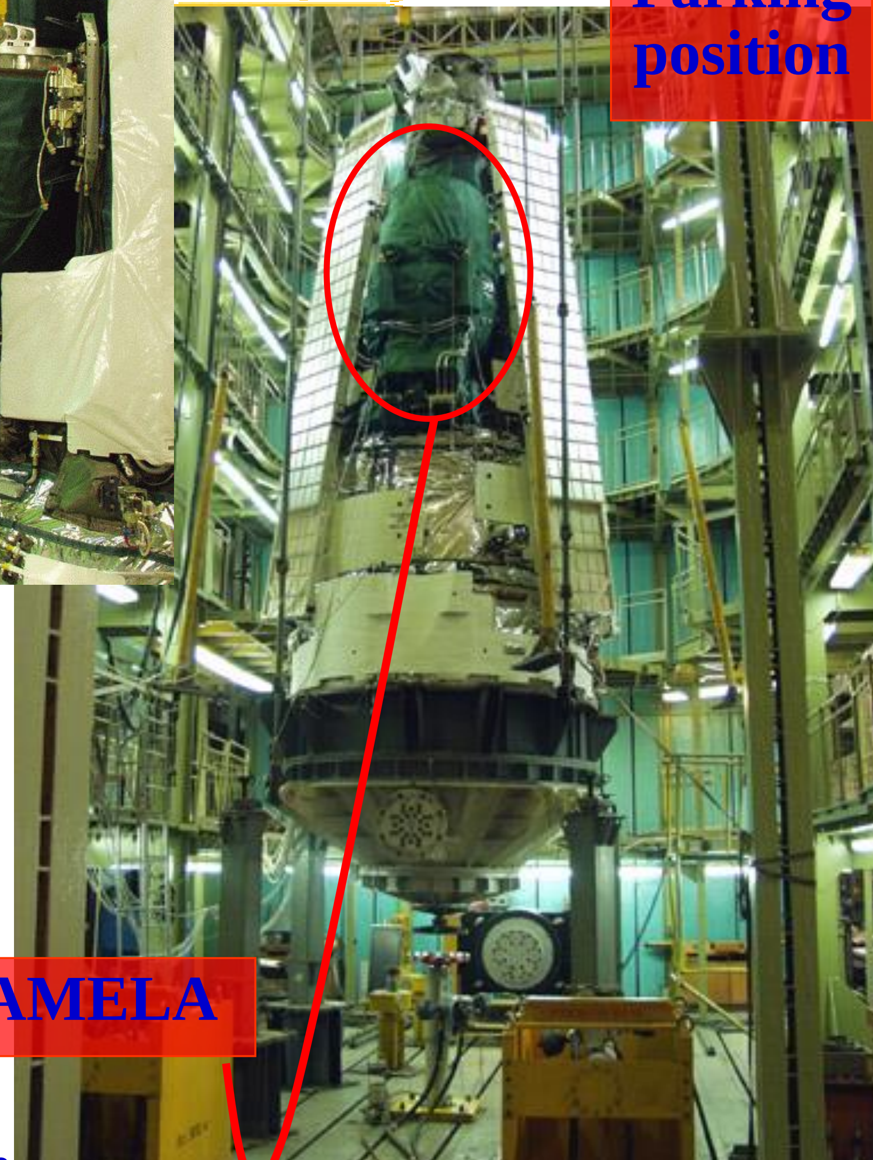

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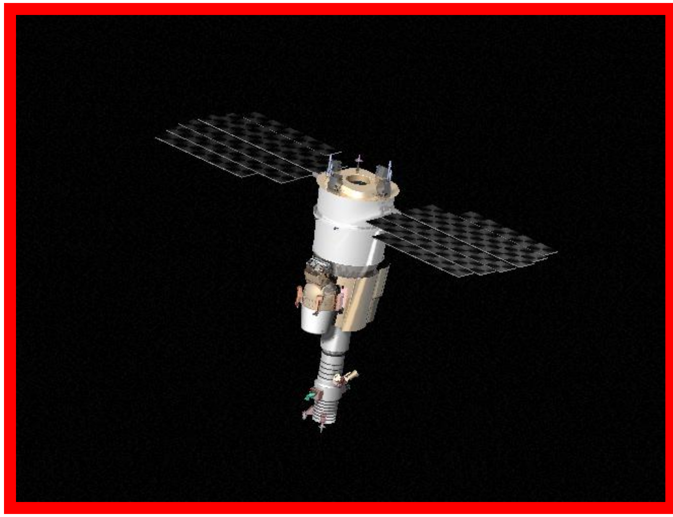
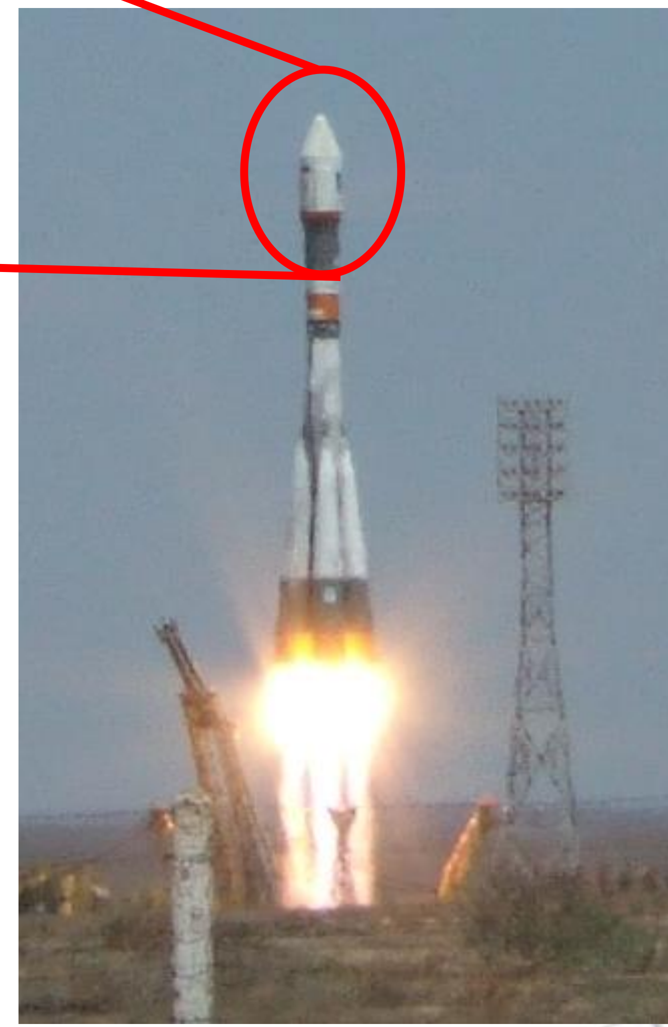


# the satellite & launch



- Launch from Baikonur:
  June 15th 2006, 0800 UTC.
  Power On: June 21st 2006, 0300 UTC.
  Detectors operated as expected after launch

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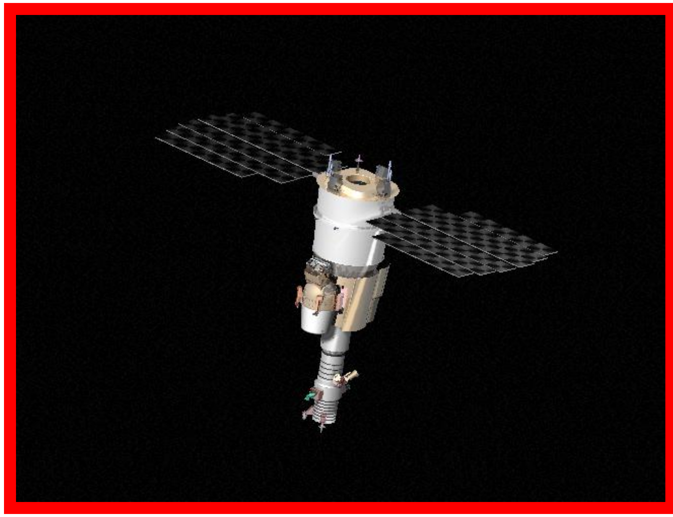

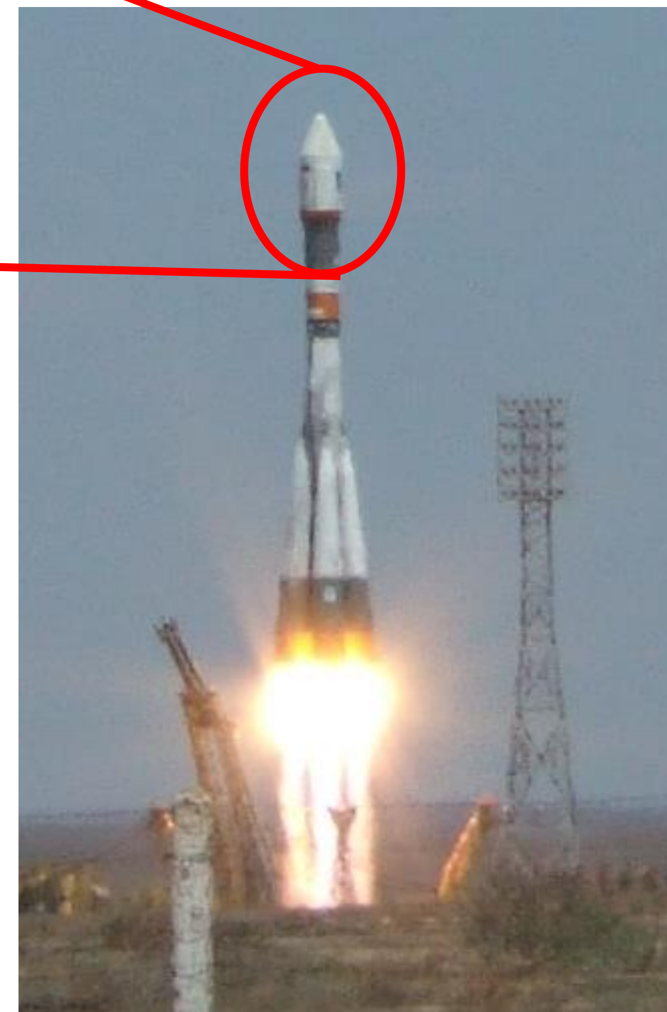

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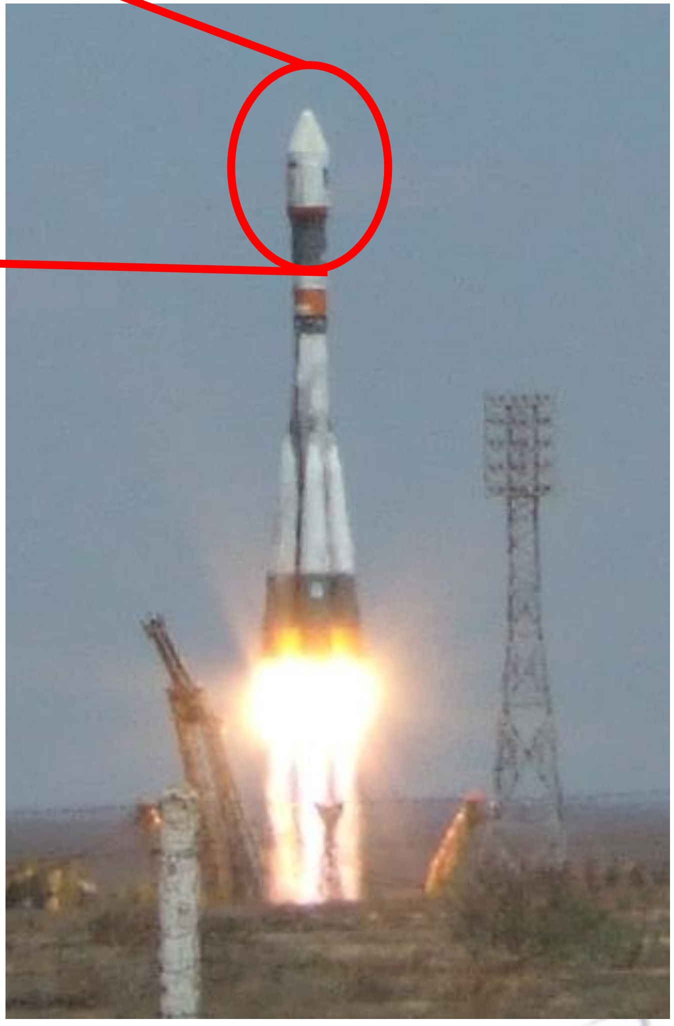

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  Detectors operated as expected after launch
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  - >9 year of data taking (~75% live-time)

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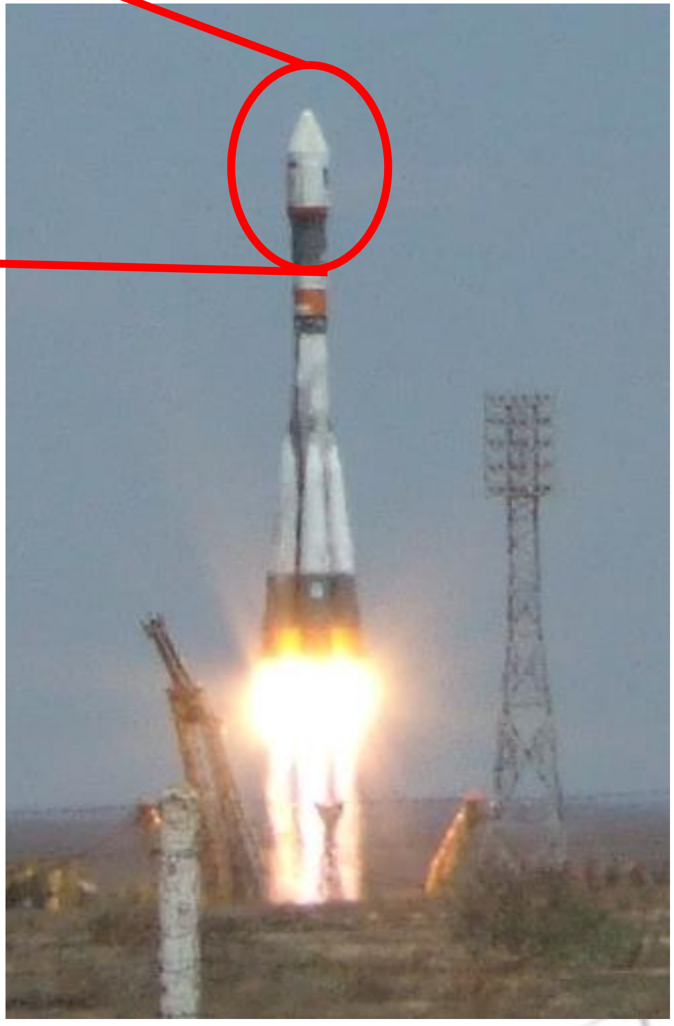

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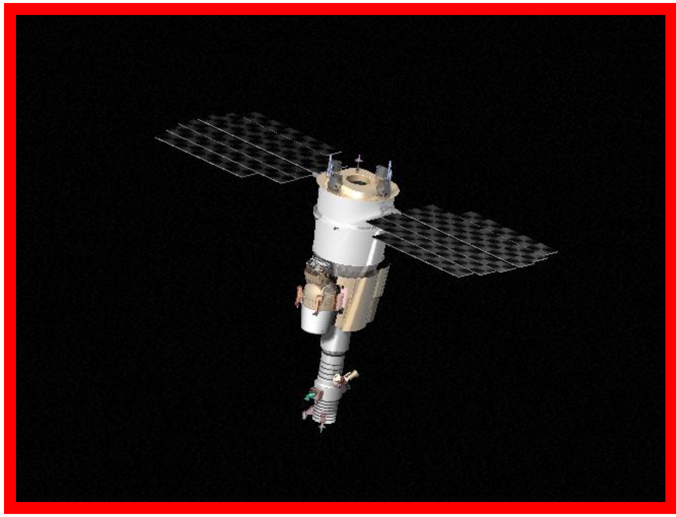

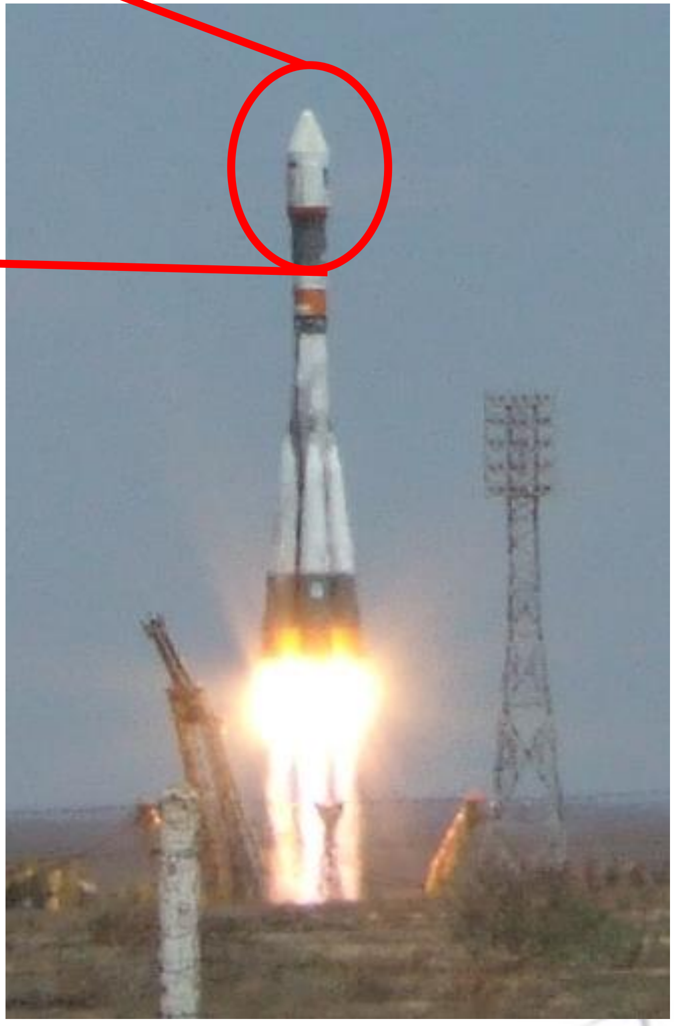

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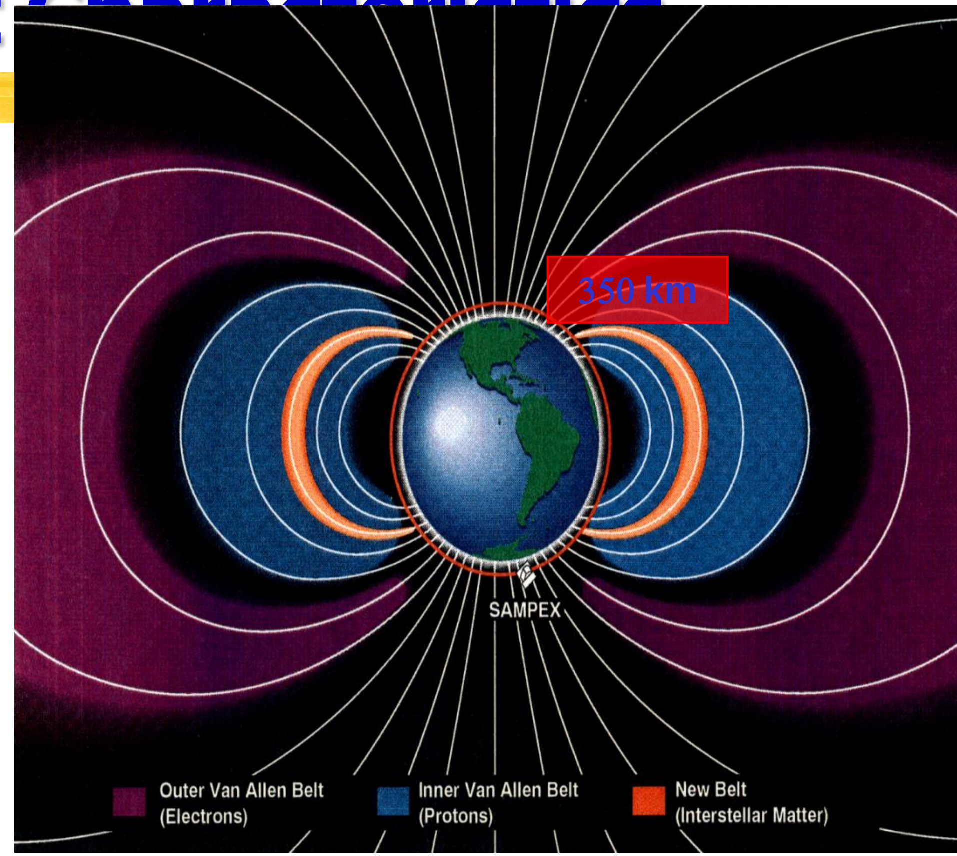
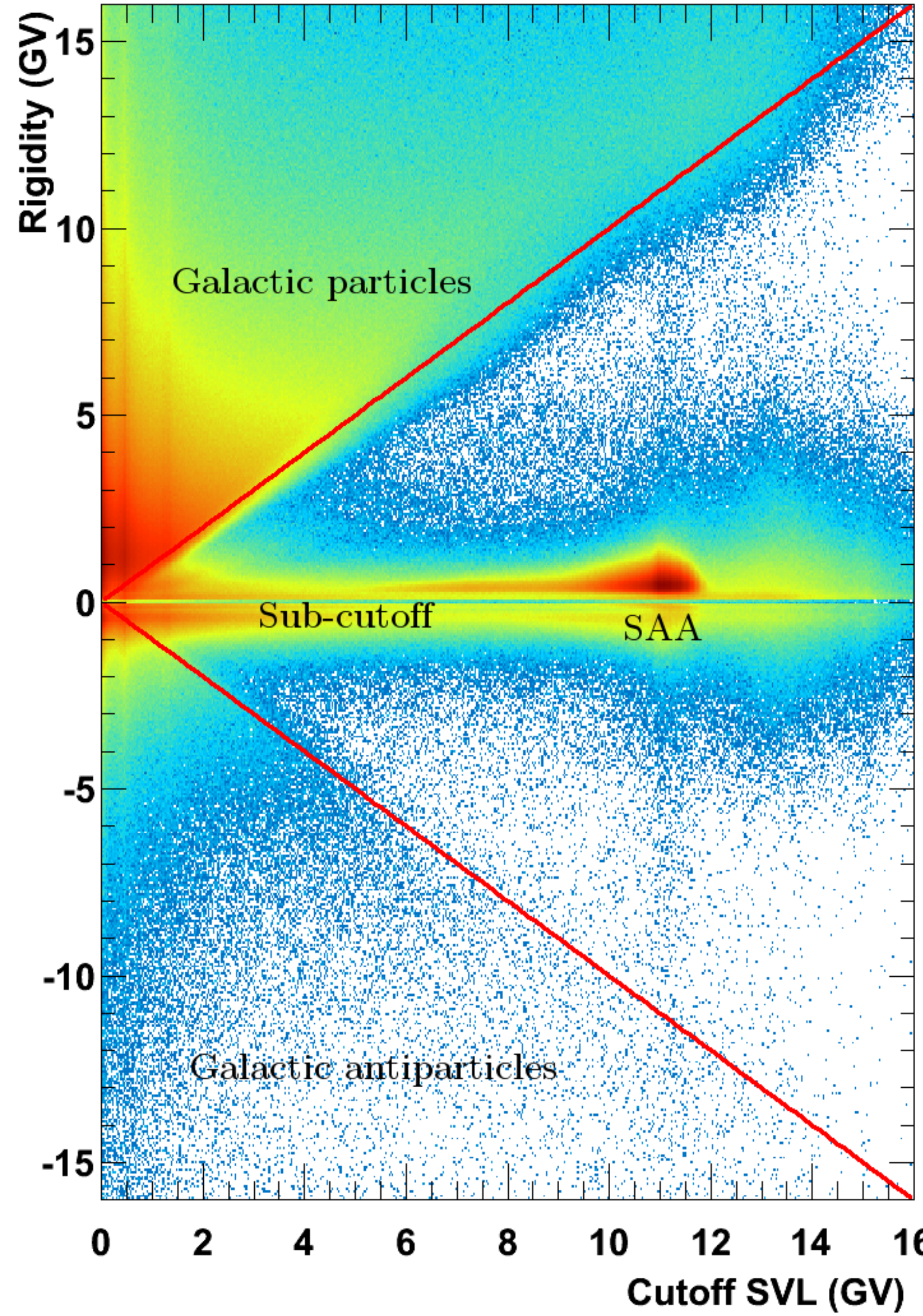
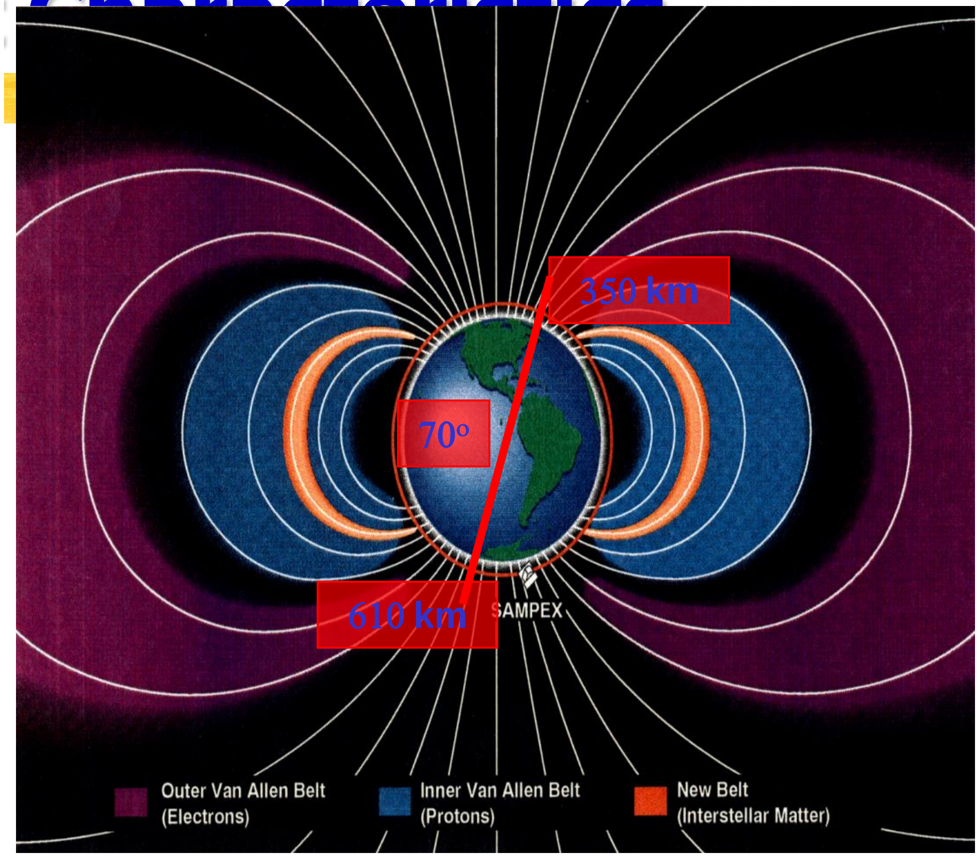
  - >7x10$^9$ triggers recorded and under analysis

# PAMELA: Orbit Characteristics




- Thanks to the PAMELA orbit we are able to measure different particle and antiparticle families.

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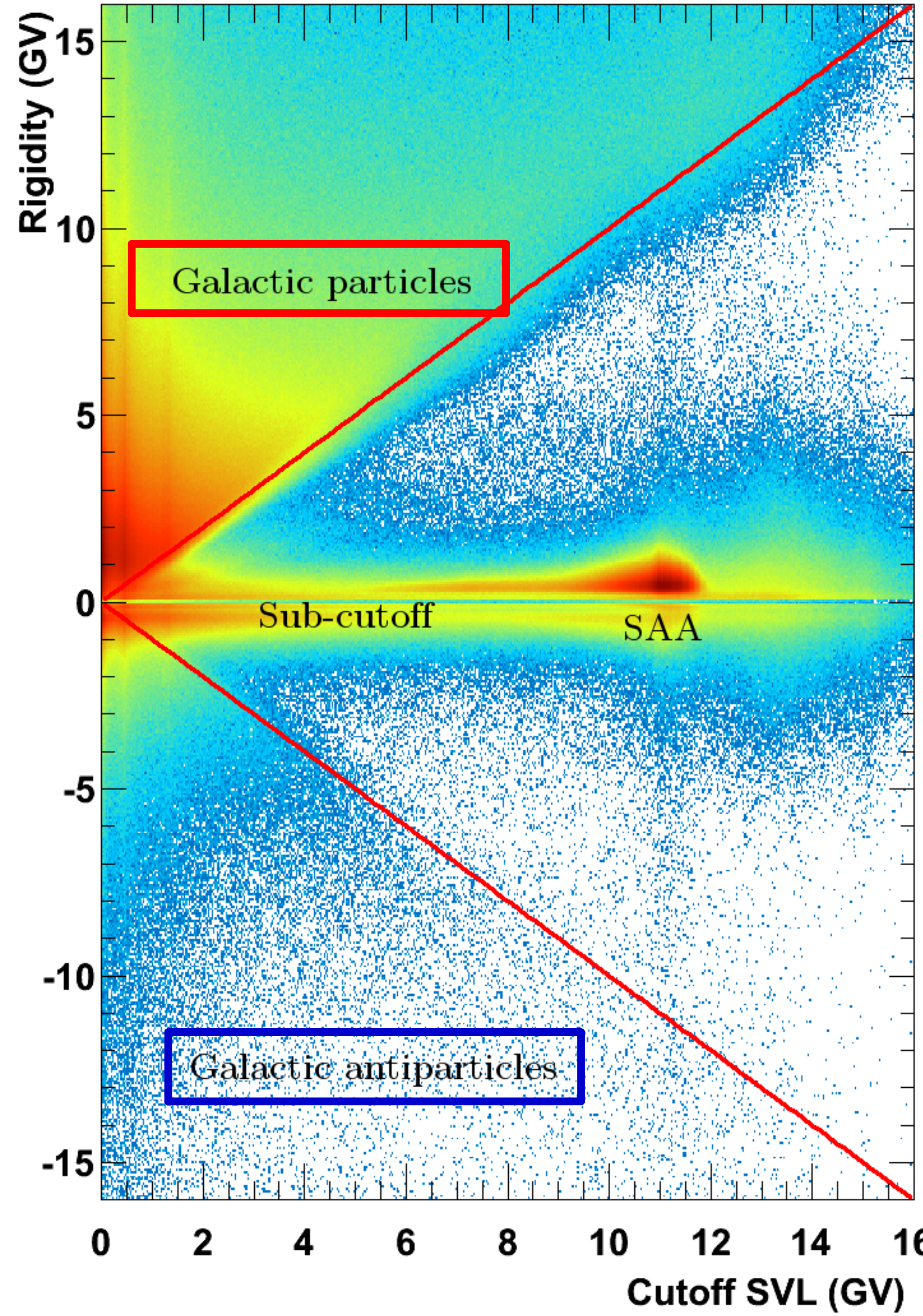


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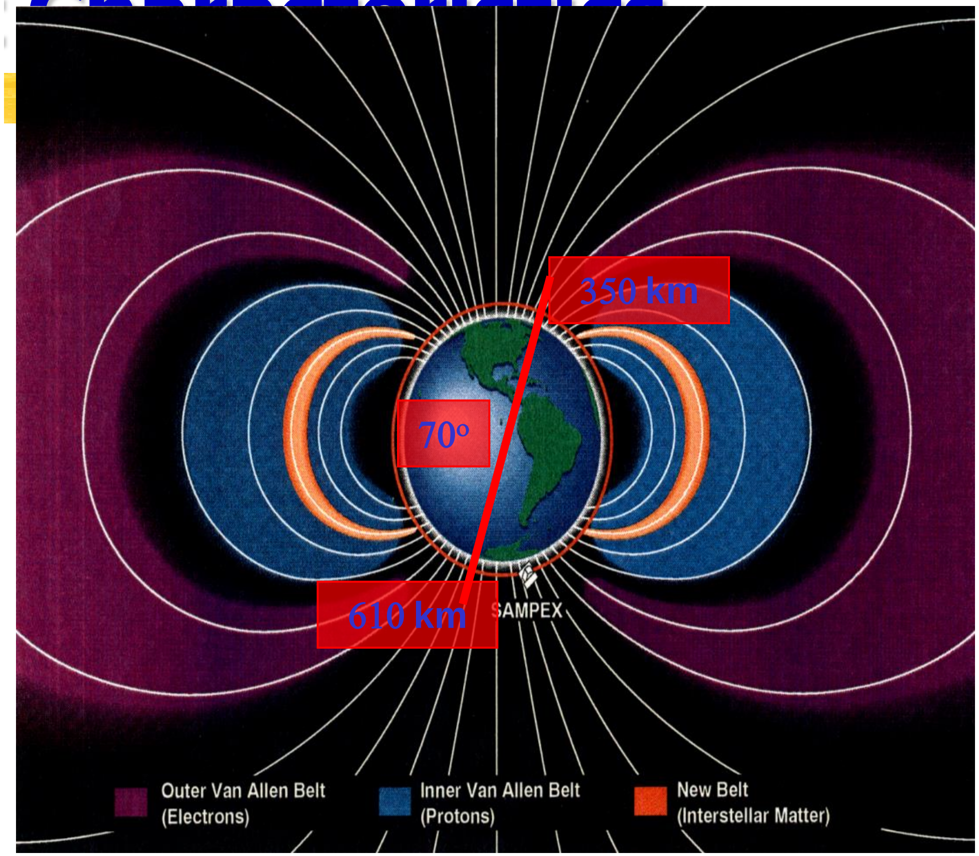


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- Investigating the heliosphere and Earth magnetosphere.

# The PAMELA C.R. view

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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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[q] INFN, Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[r] Universität Siegen, Department of Physics, D-57068 Siegen, Germany
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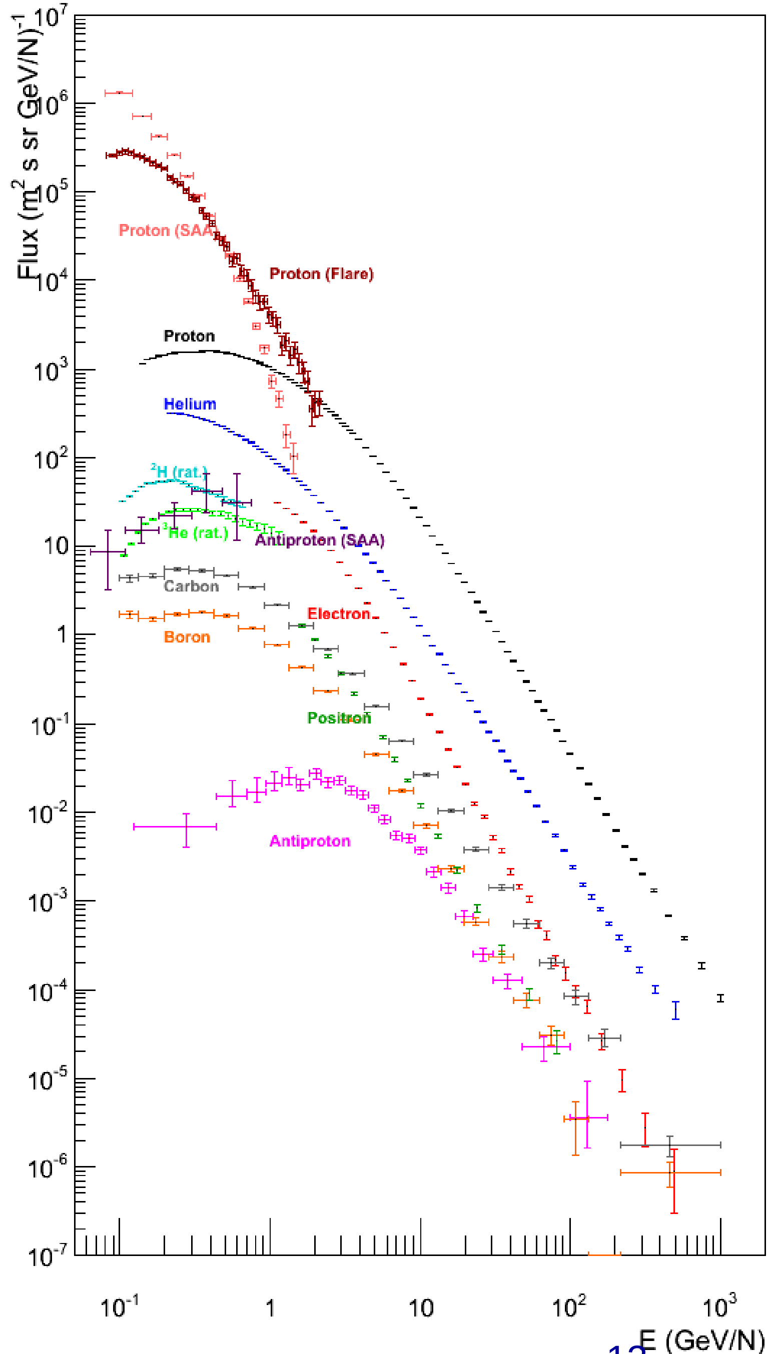
[t] Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati, Italy
[u] School of Mathematics and Physics, China University of Geosciences, CN-430074 Wuhan, China

**O. Adriani et al., Phys. Rep., 544, 4, 323-370 (2014)**



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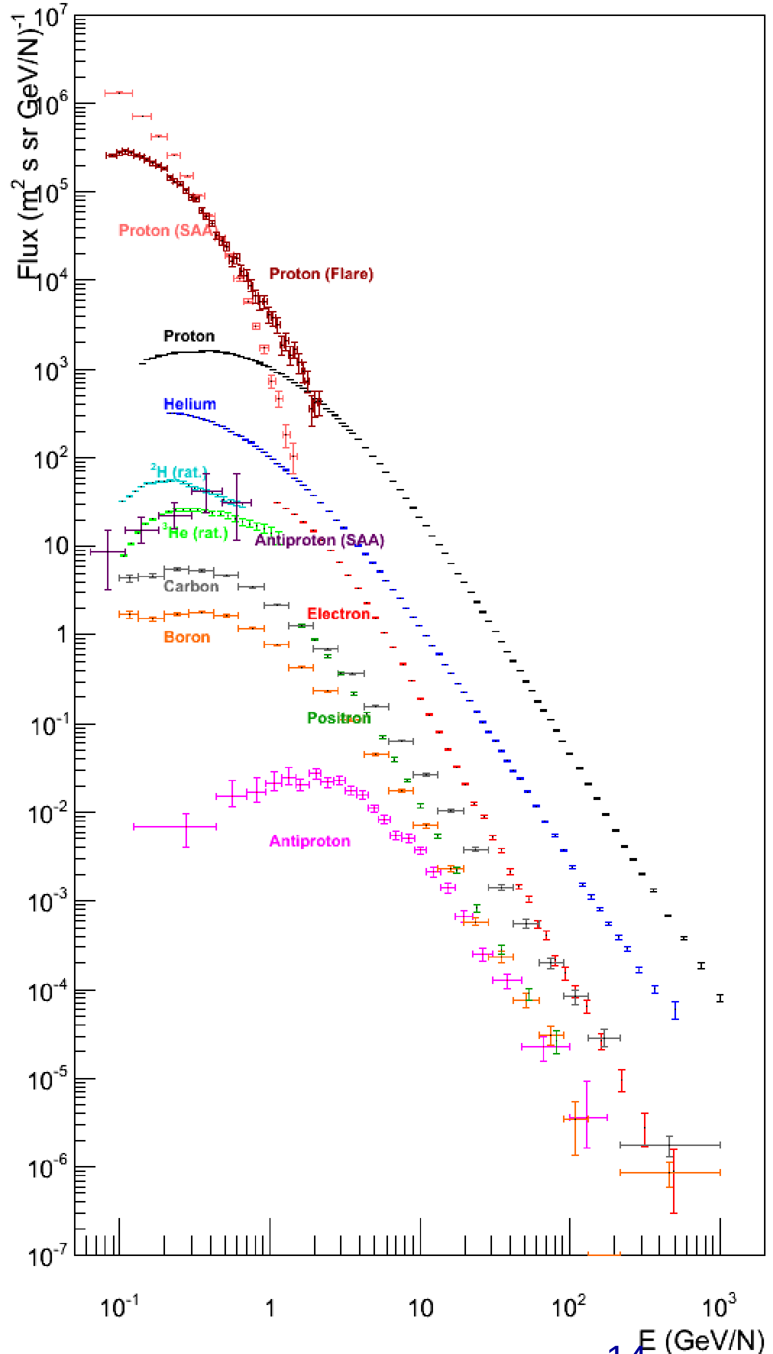
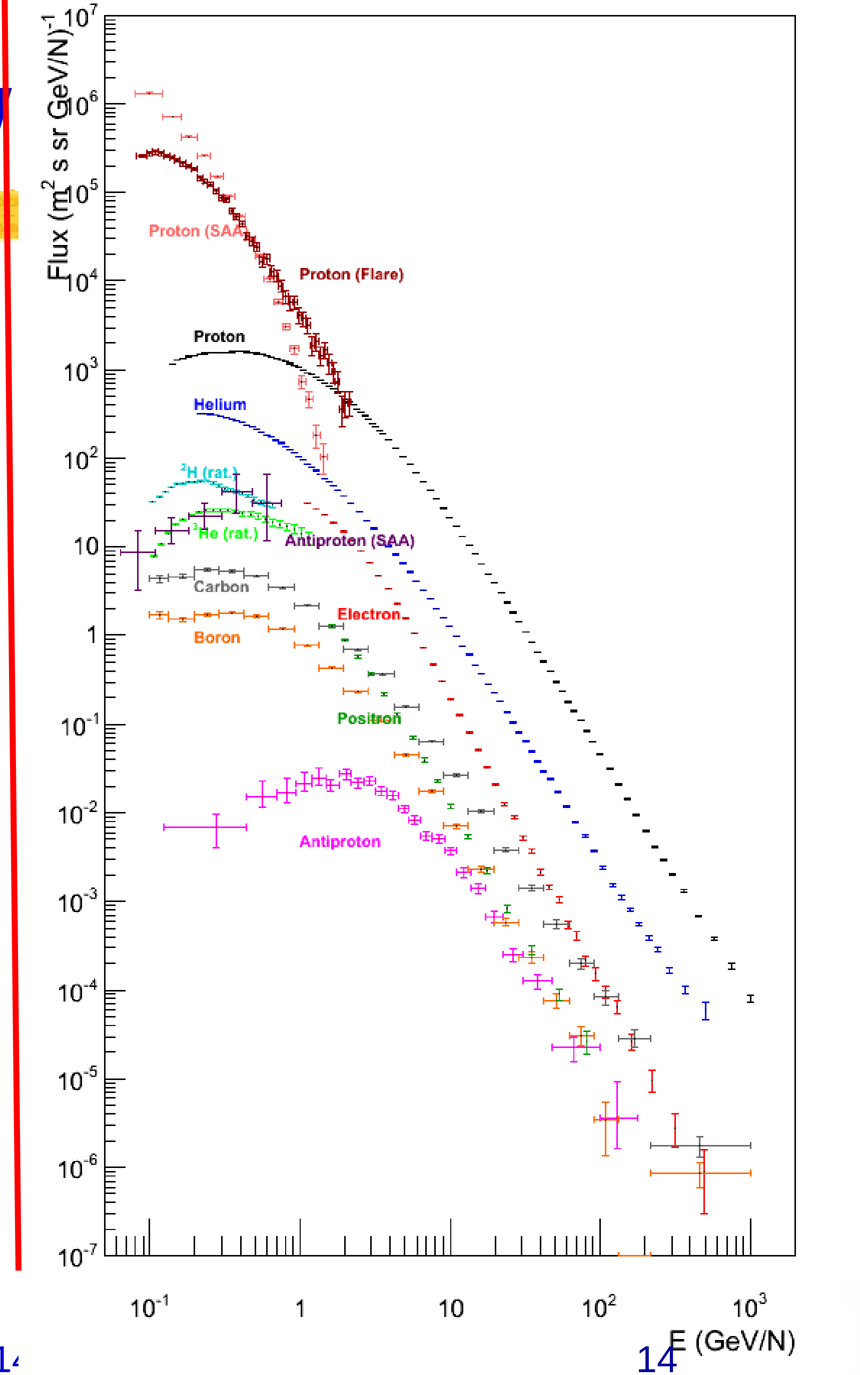


# The PAMELA C.R. view

- Large flux range, from $10^{-7}$ to $10^{7}$ $(m^2\ s\ sr\ GeV)^{-1}$



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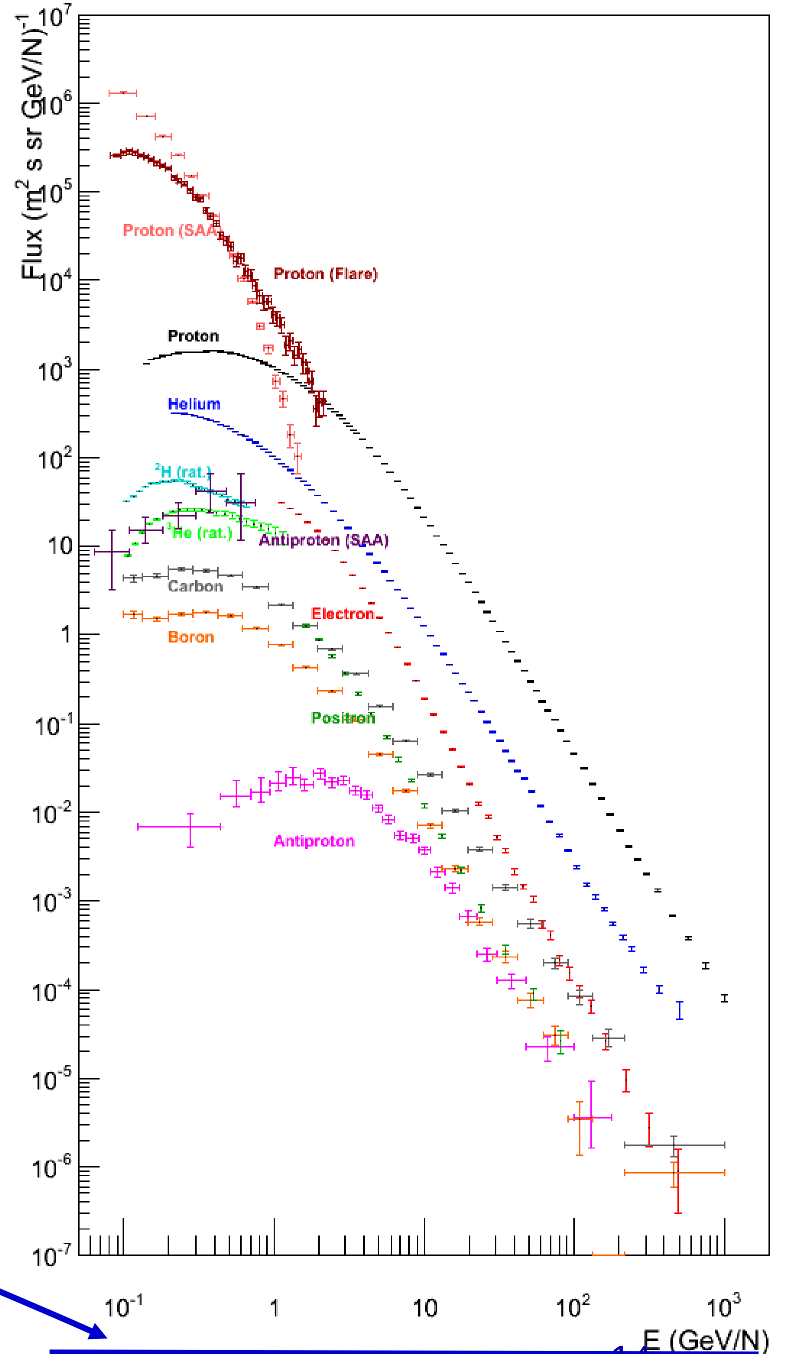

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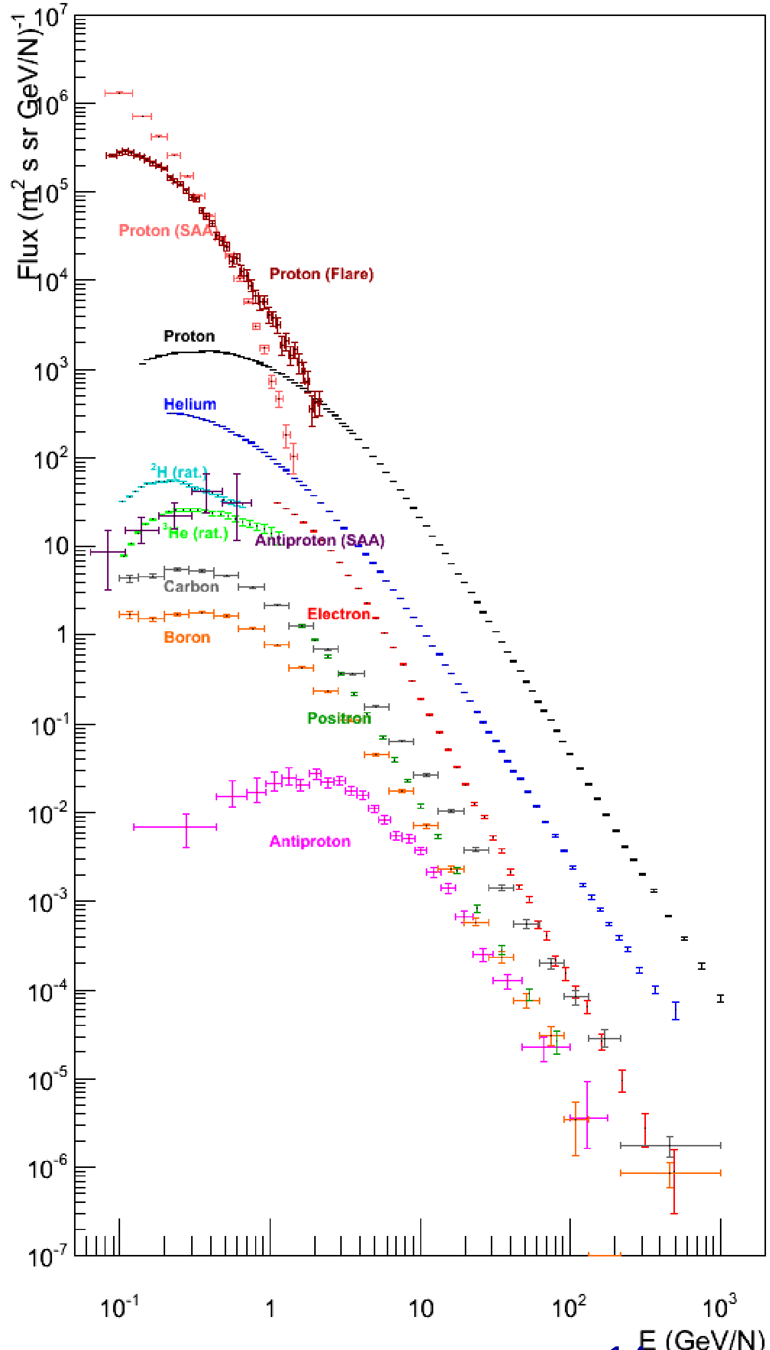
- Several measurements with the same detector.



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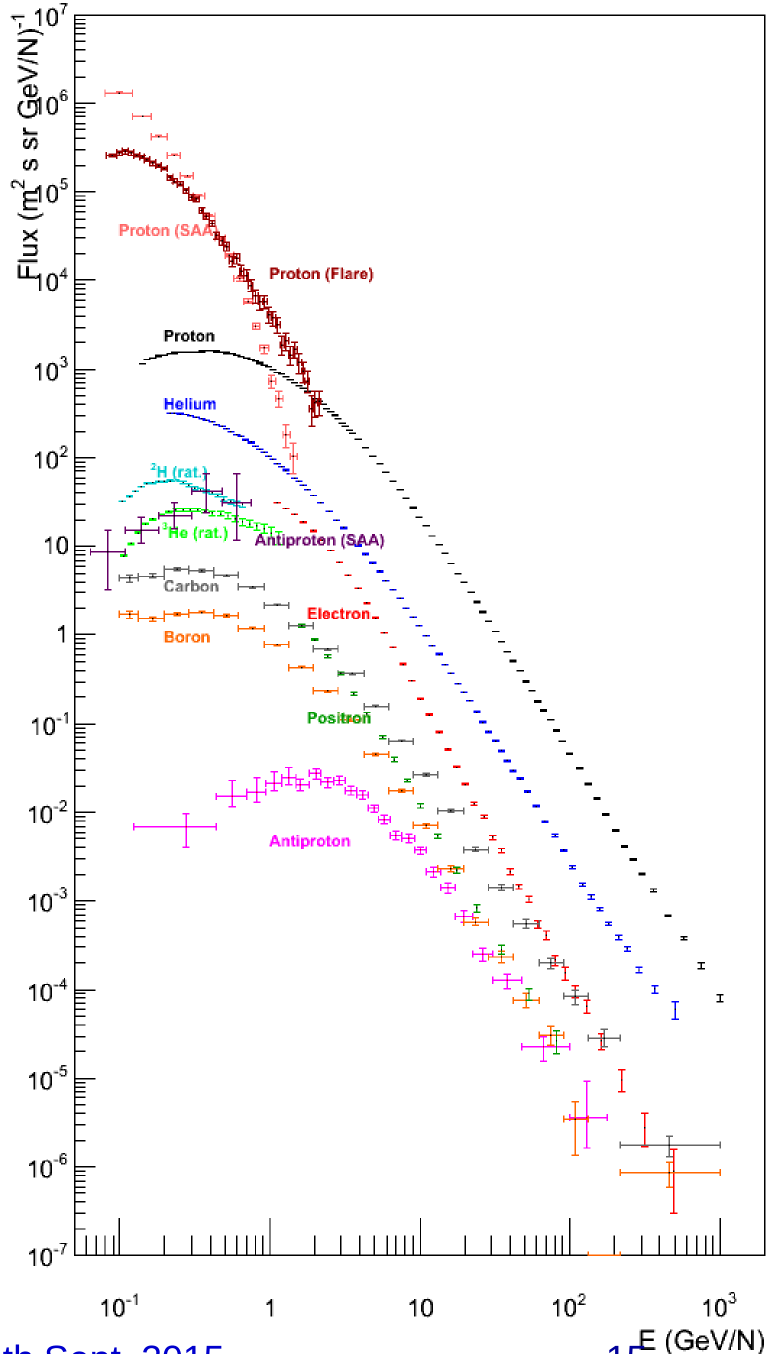

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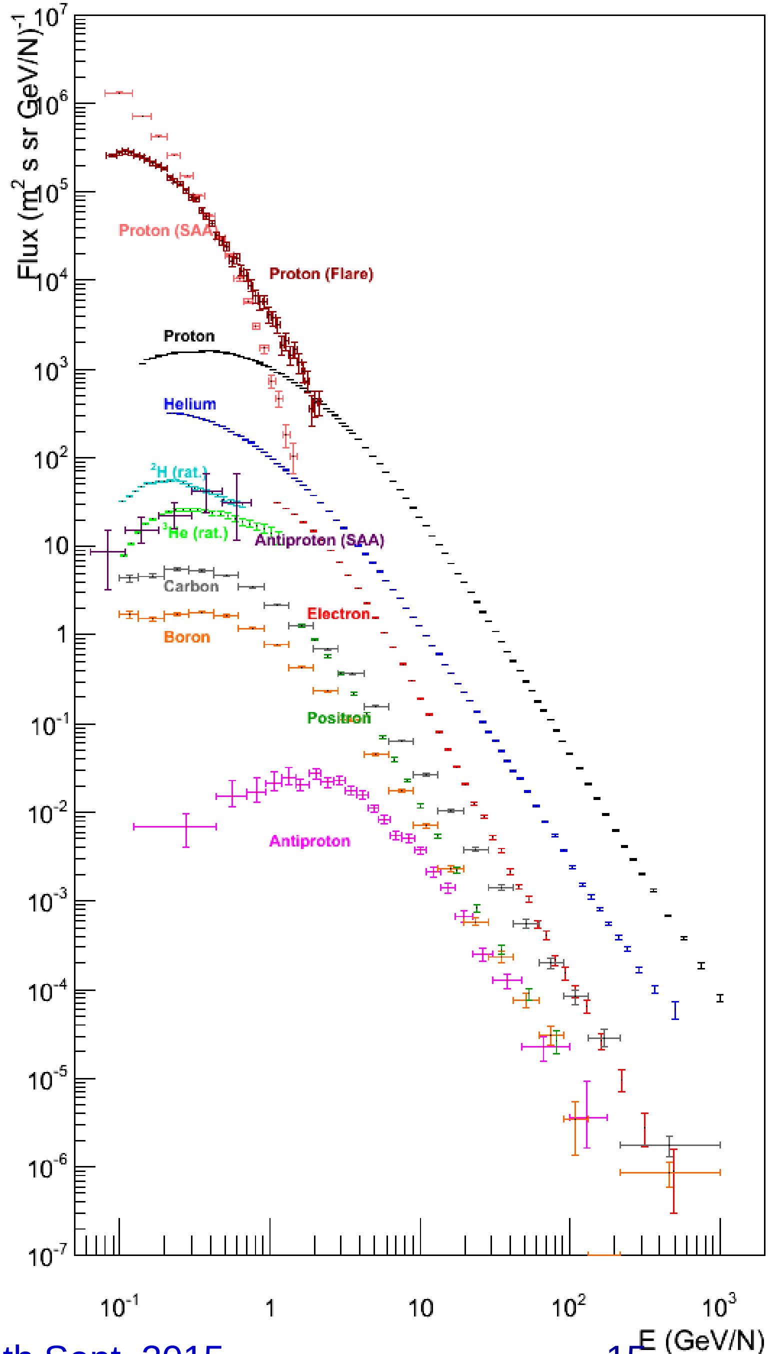

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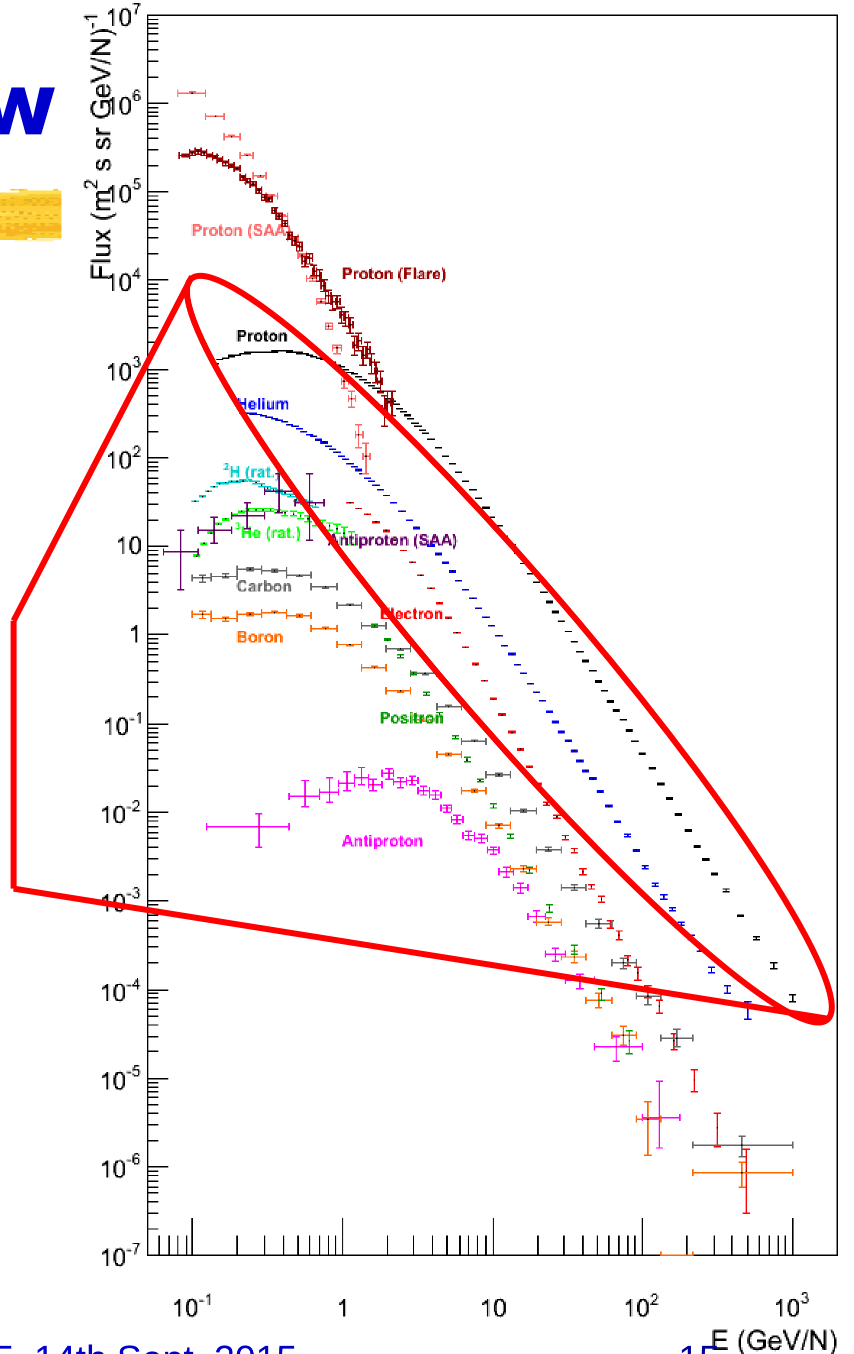

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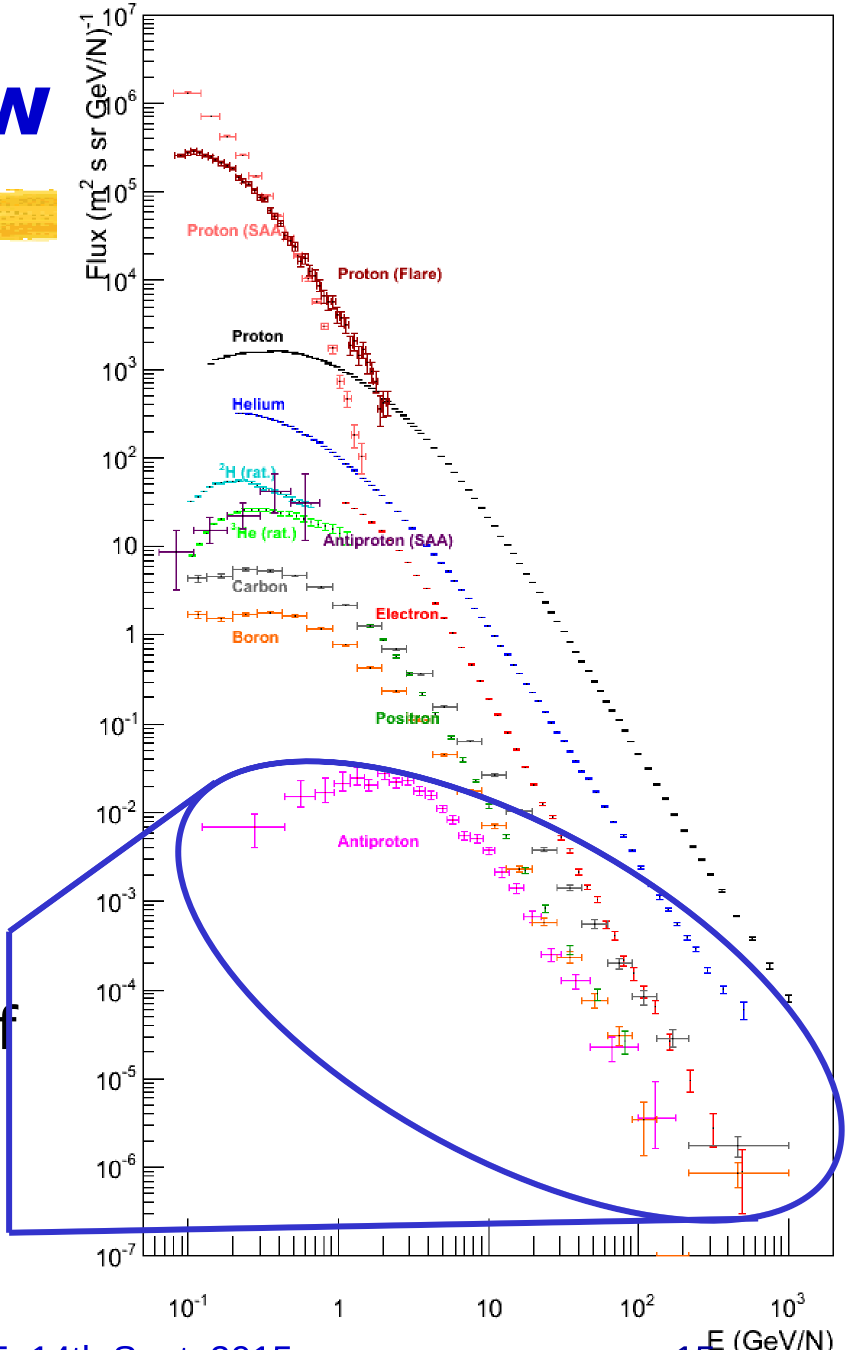
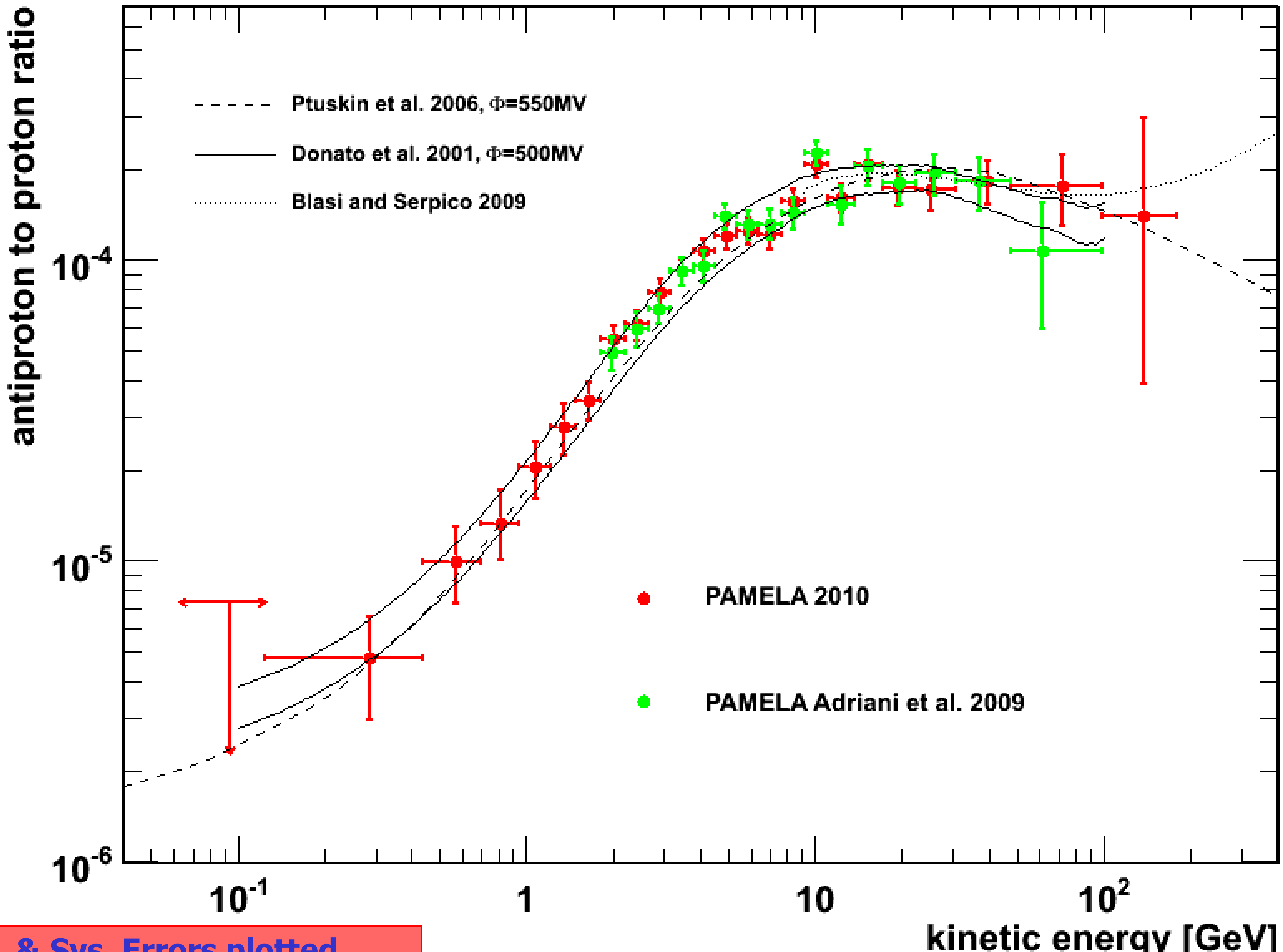
- Measurement of spectra from different particle families requires different approaches in systematics treatment and evaluation.
- Small features in spectra of high statistic particles fluxes, like H, He and $e^-$, can be hint of new astrophysical effects.
- As well as distortions in the spectra of the more rare antiparticle can be indicators of not standard sources of antimatter.



# Antiproton to Proton Ratio




Stat. & Sys. Errors plotted

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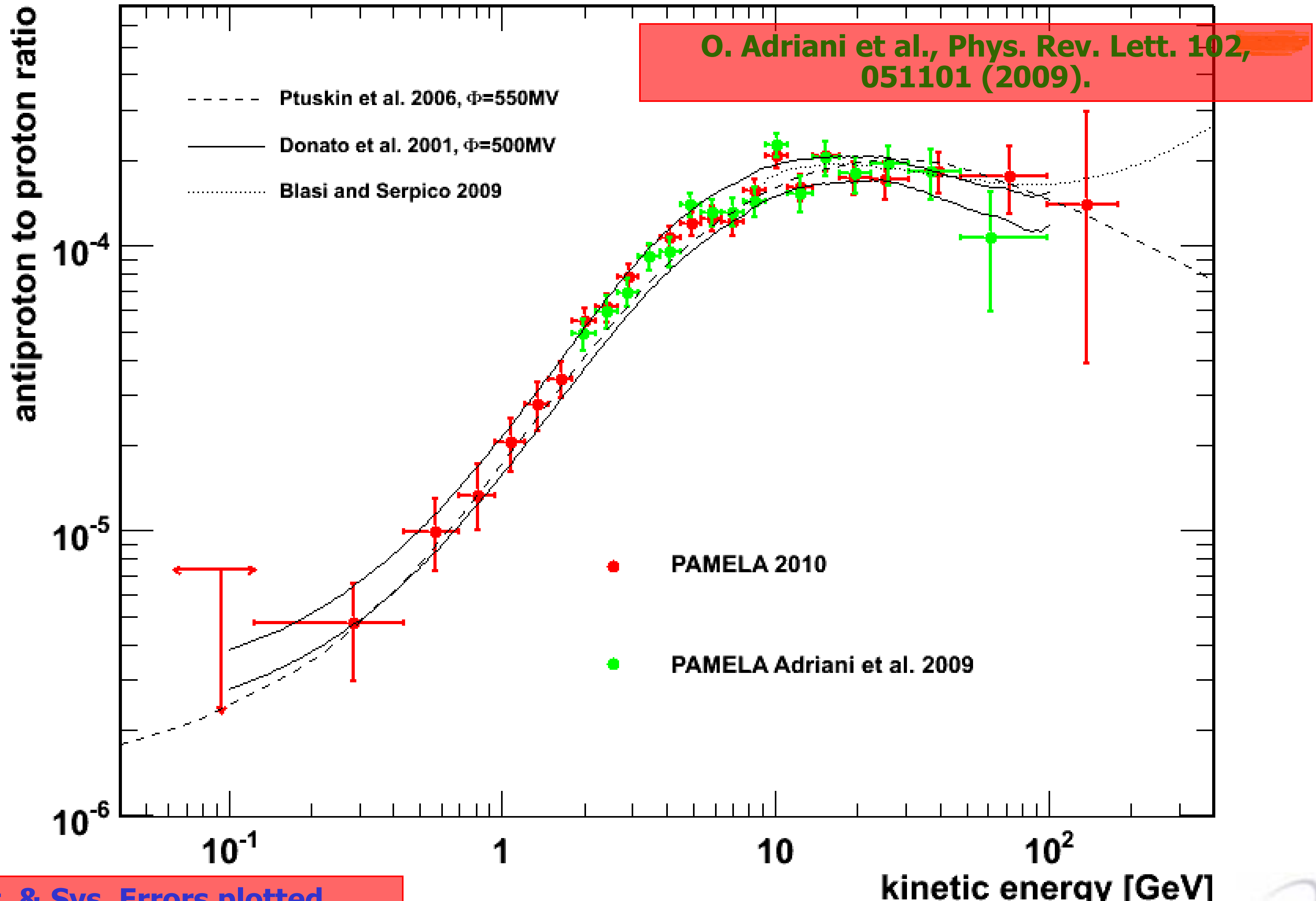


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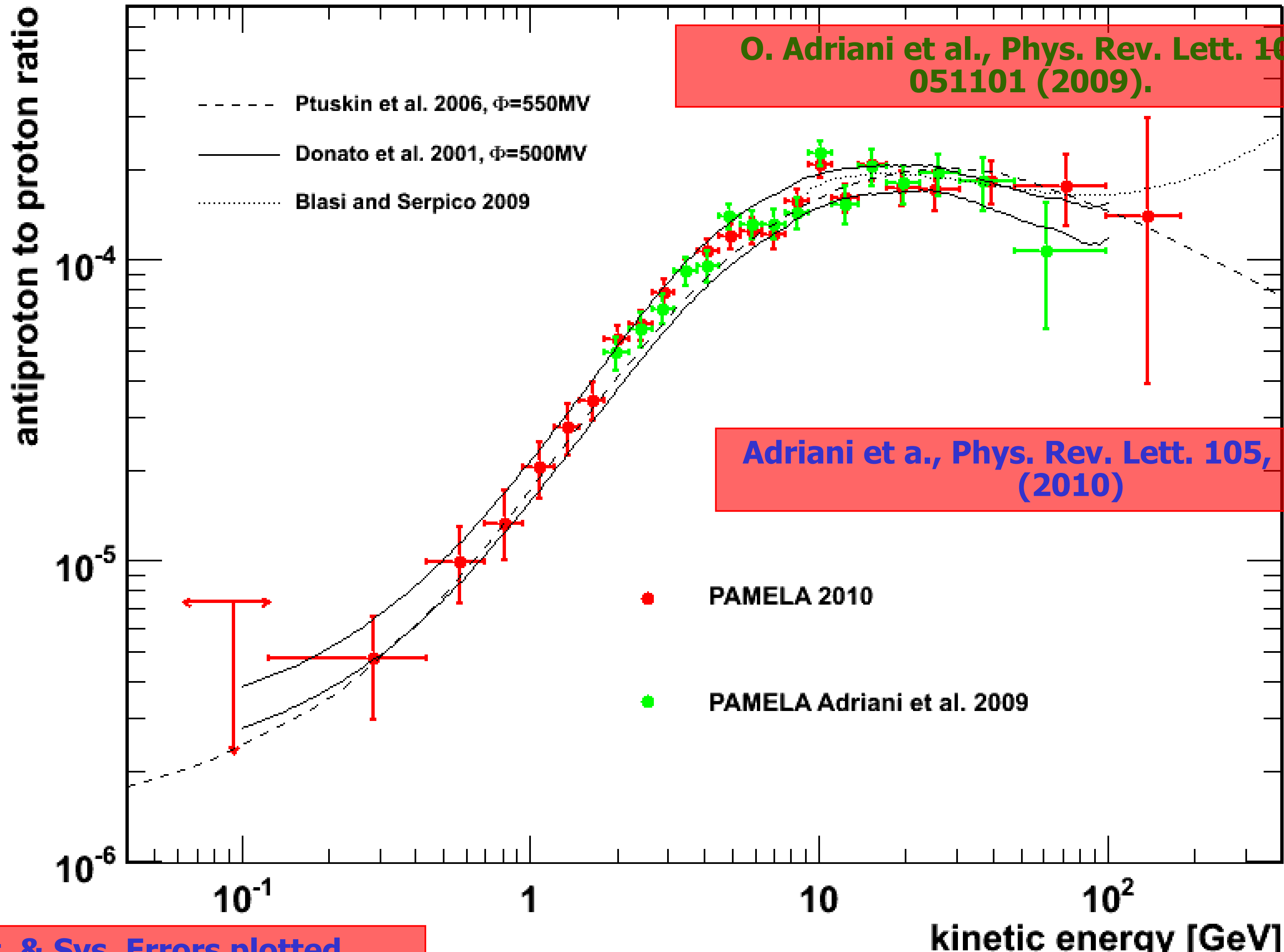


O. Adriani et al., Phys. Rev. Lett. 102, 051101 (2009).

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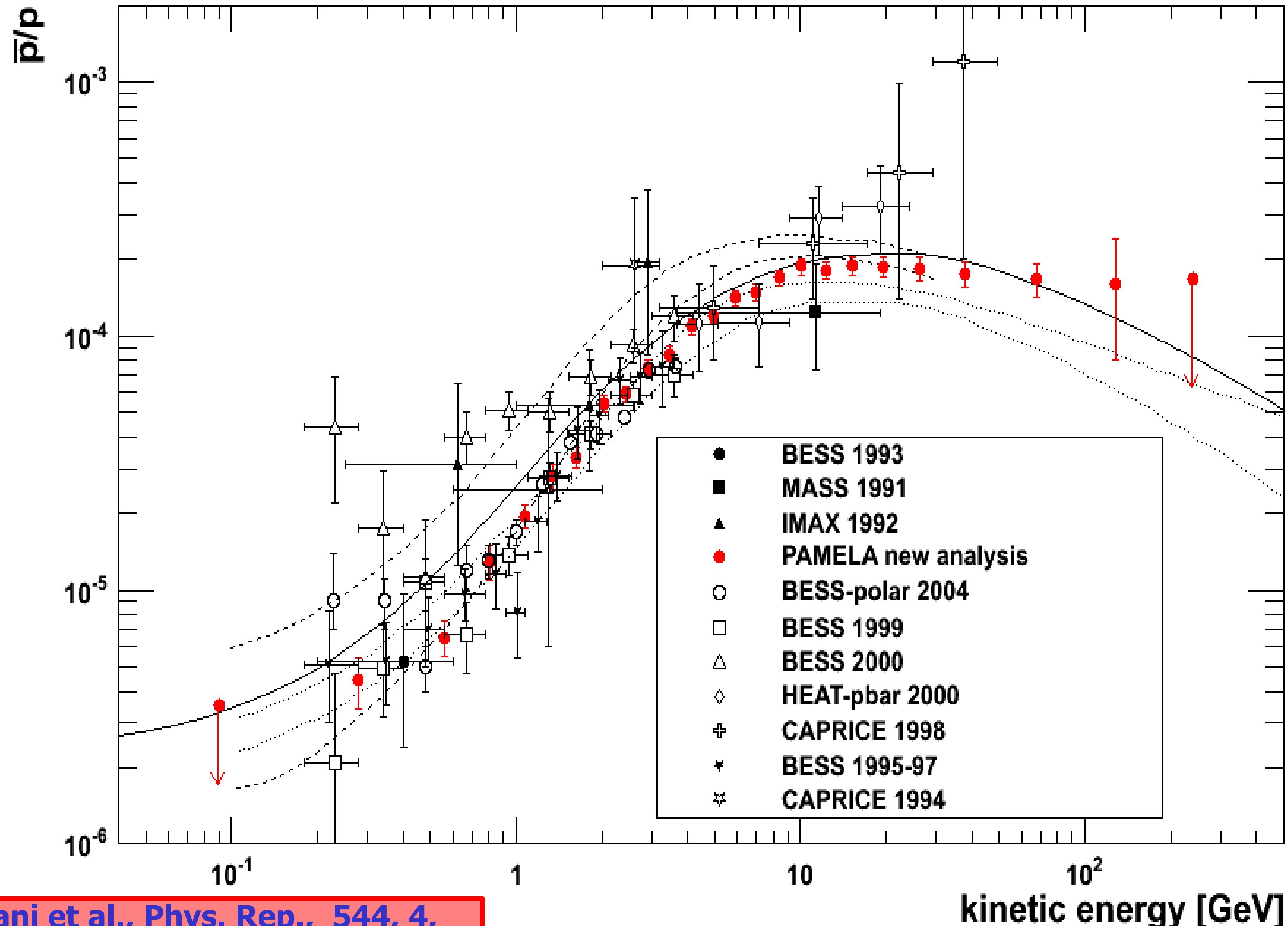


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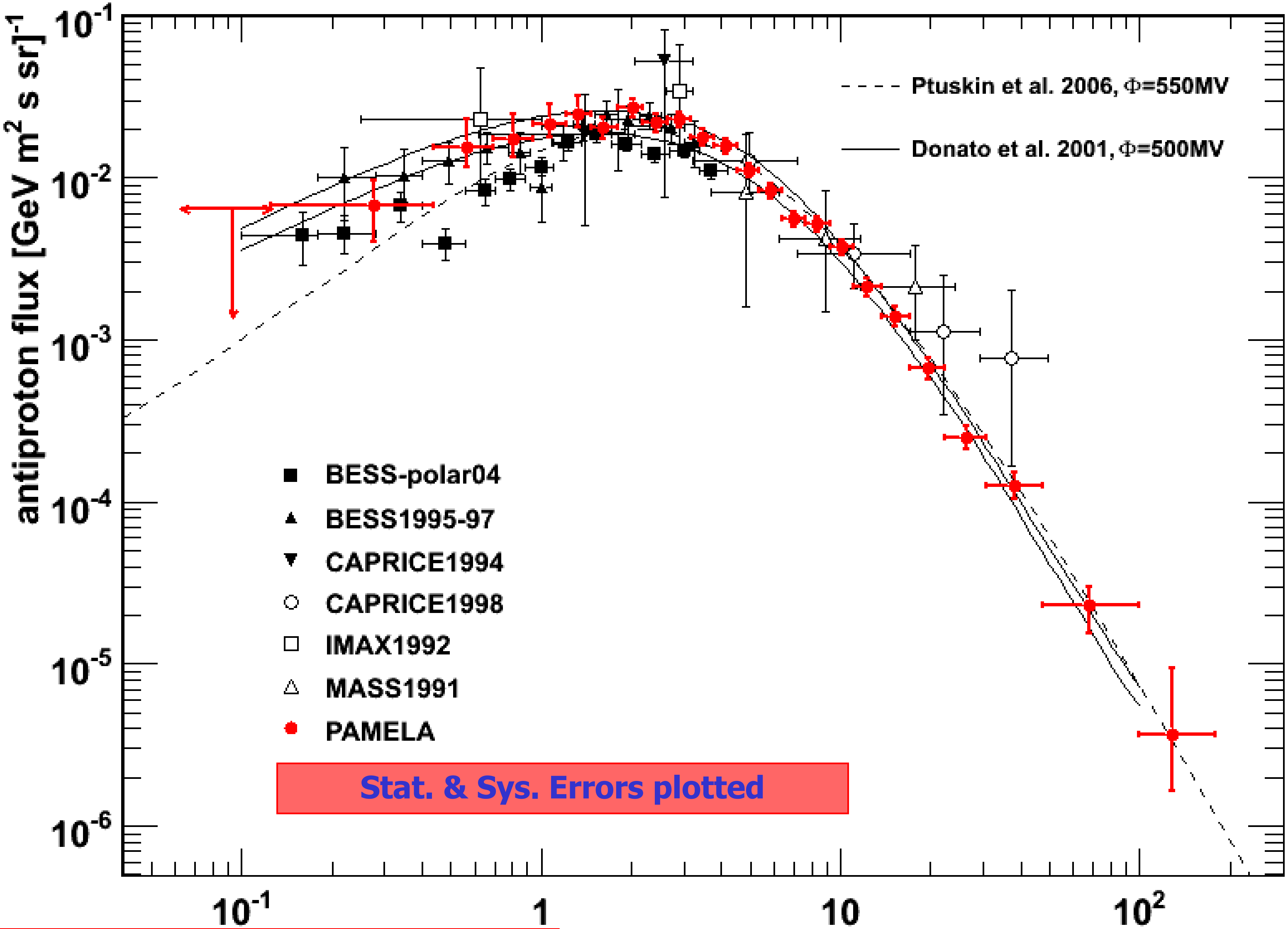


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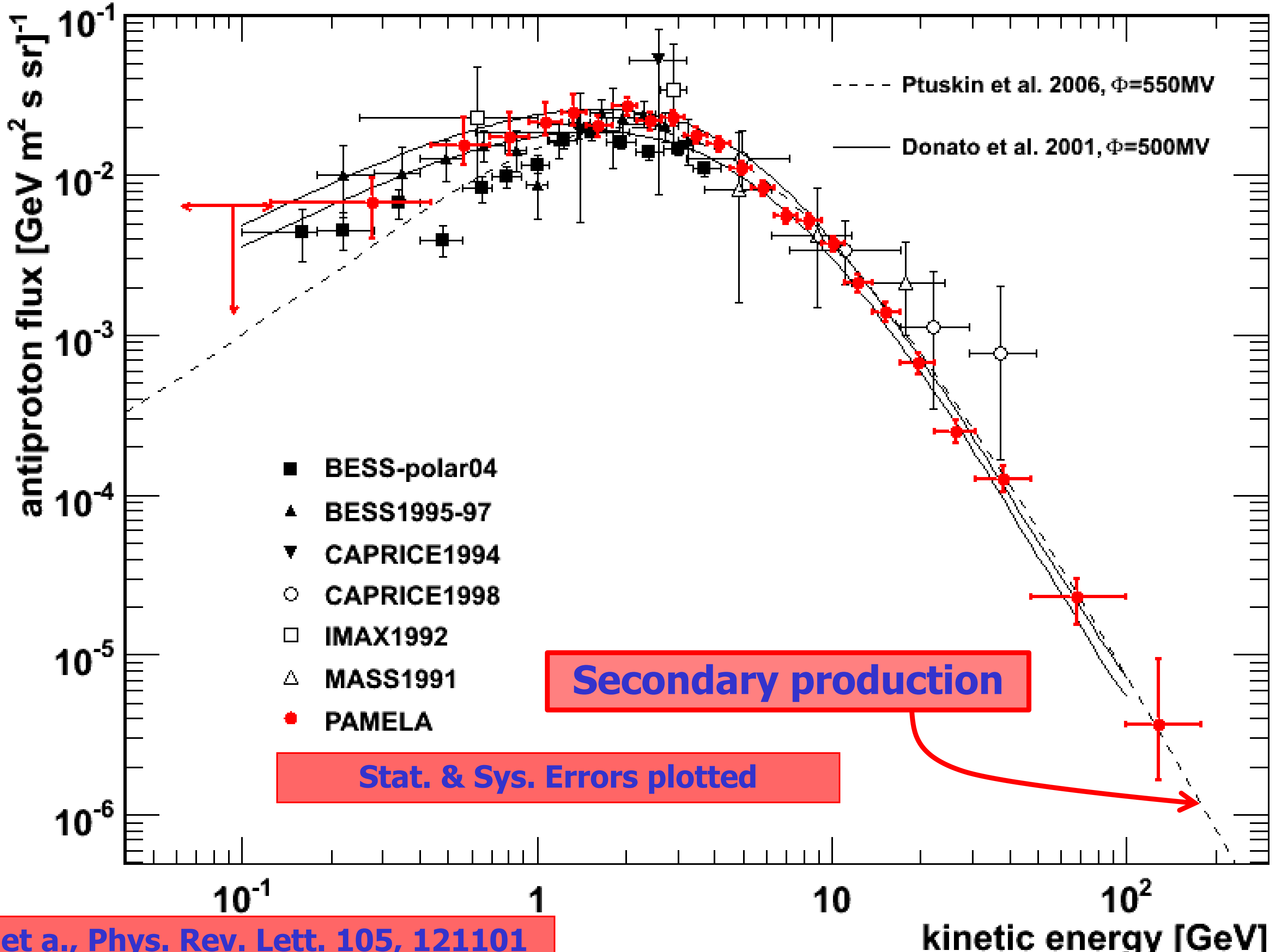


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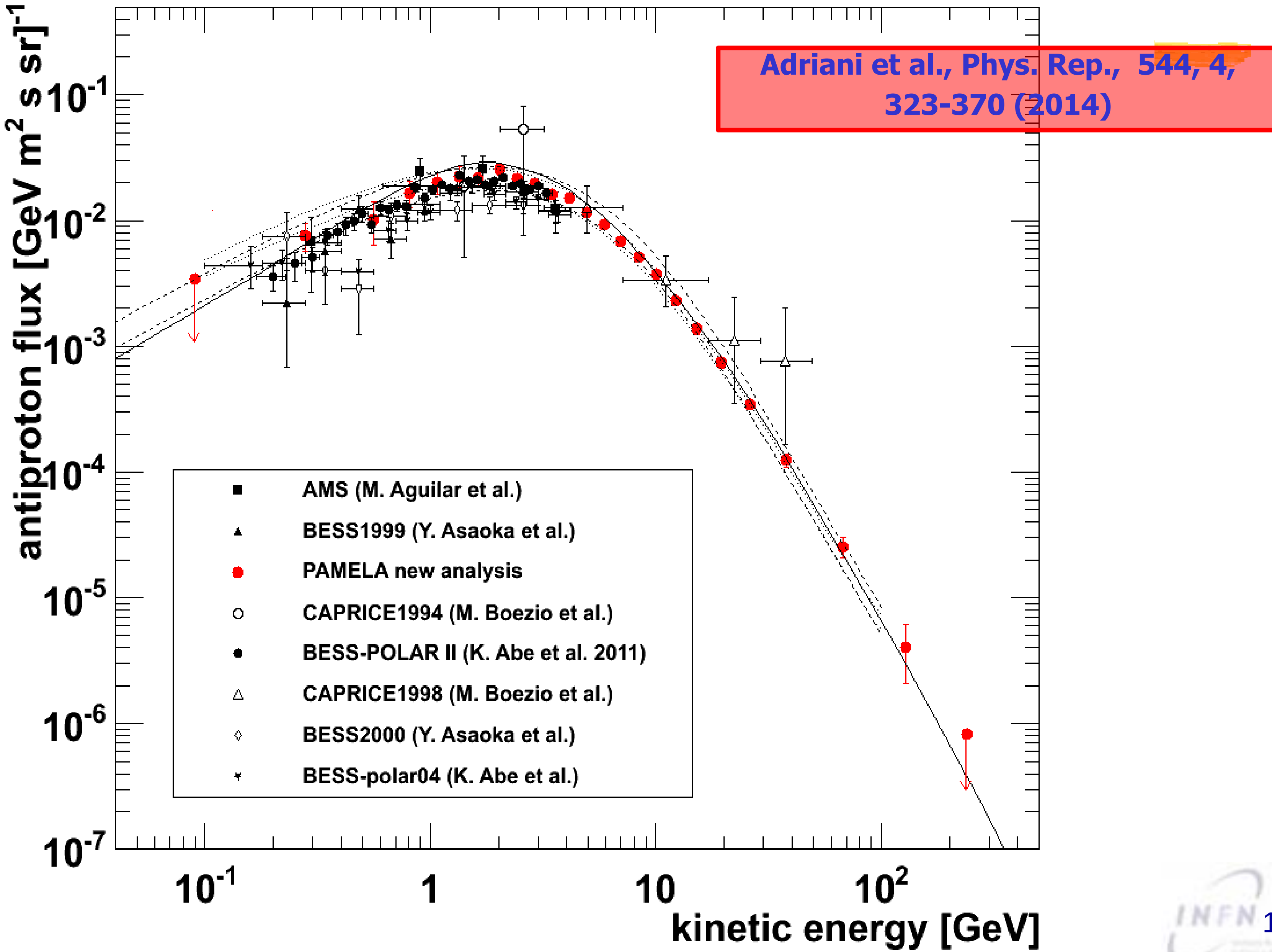

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Adriani et al. , Nature 458 (2009) 607
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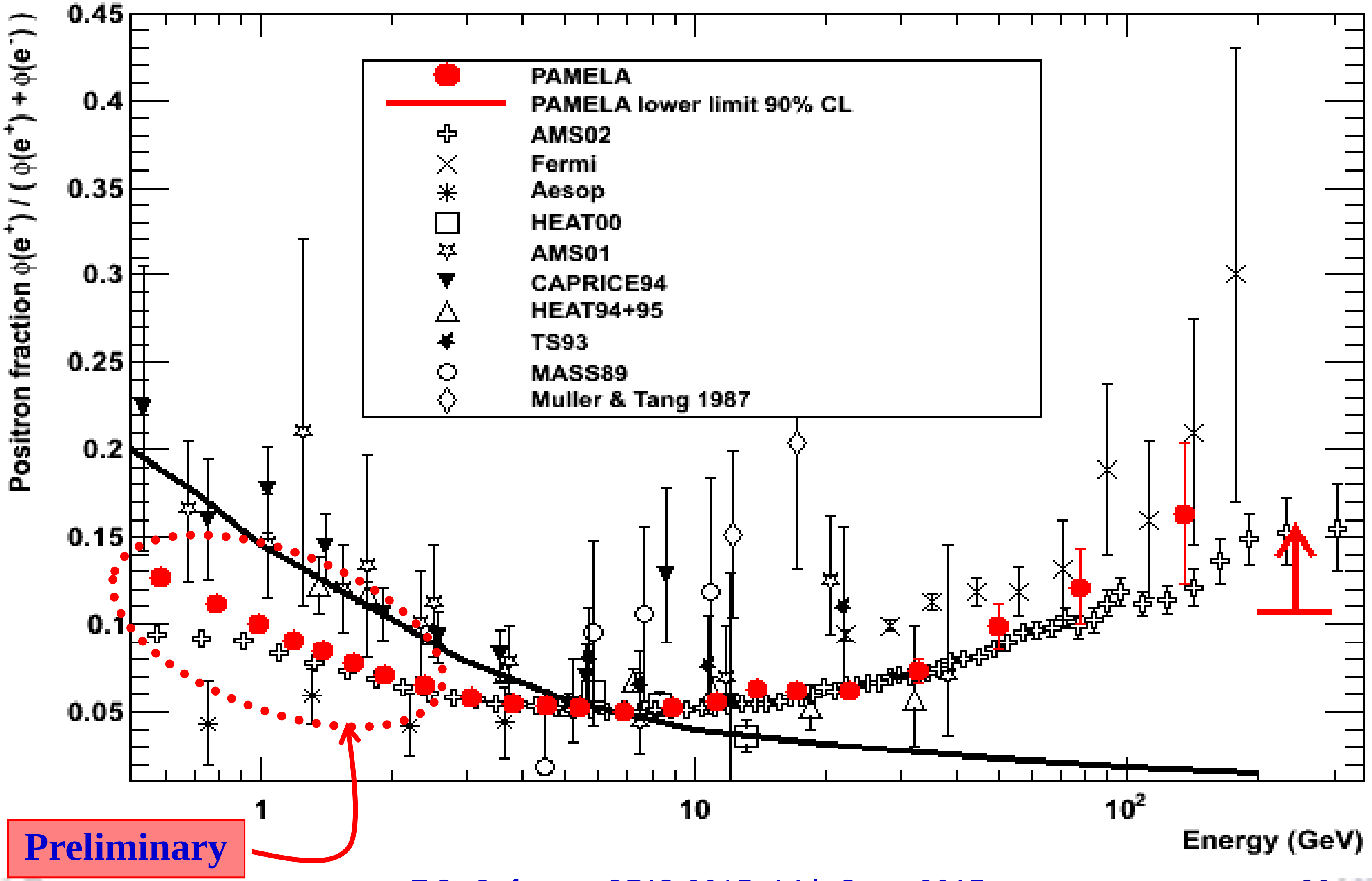

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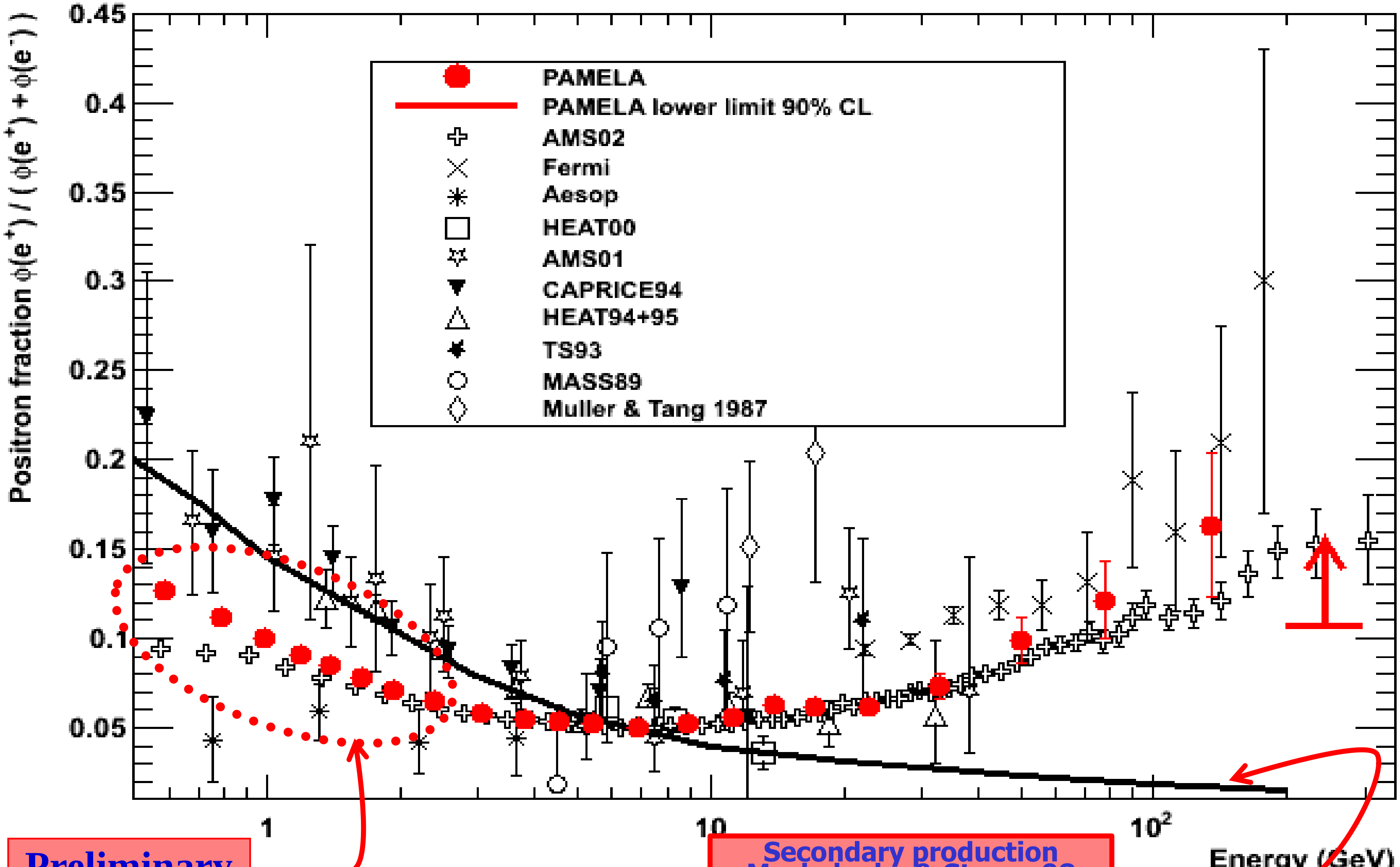


Preliminary

Secondary production
Moskalenko & Strong 98

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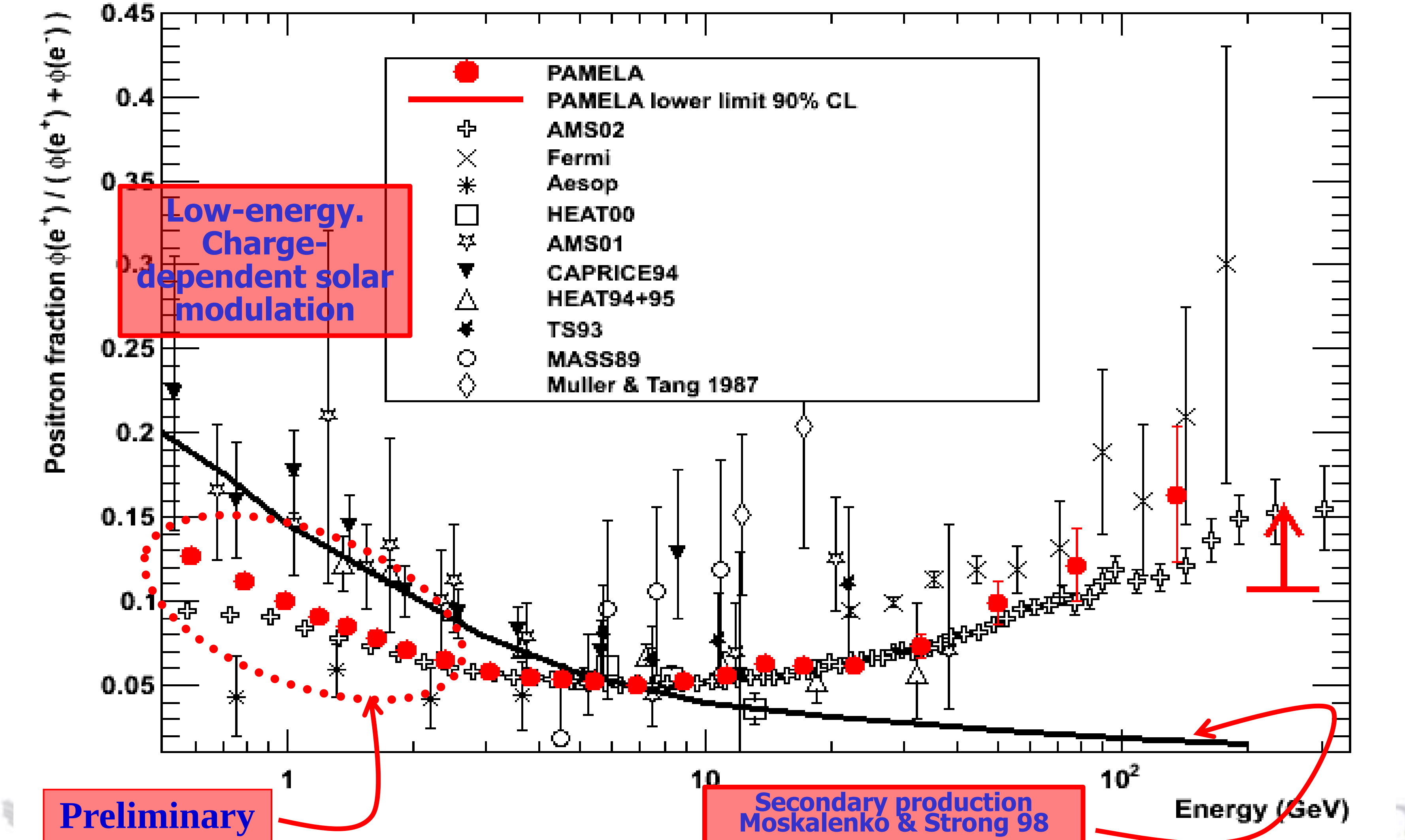

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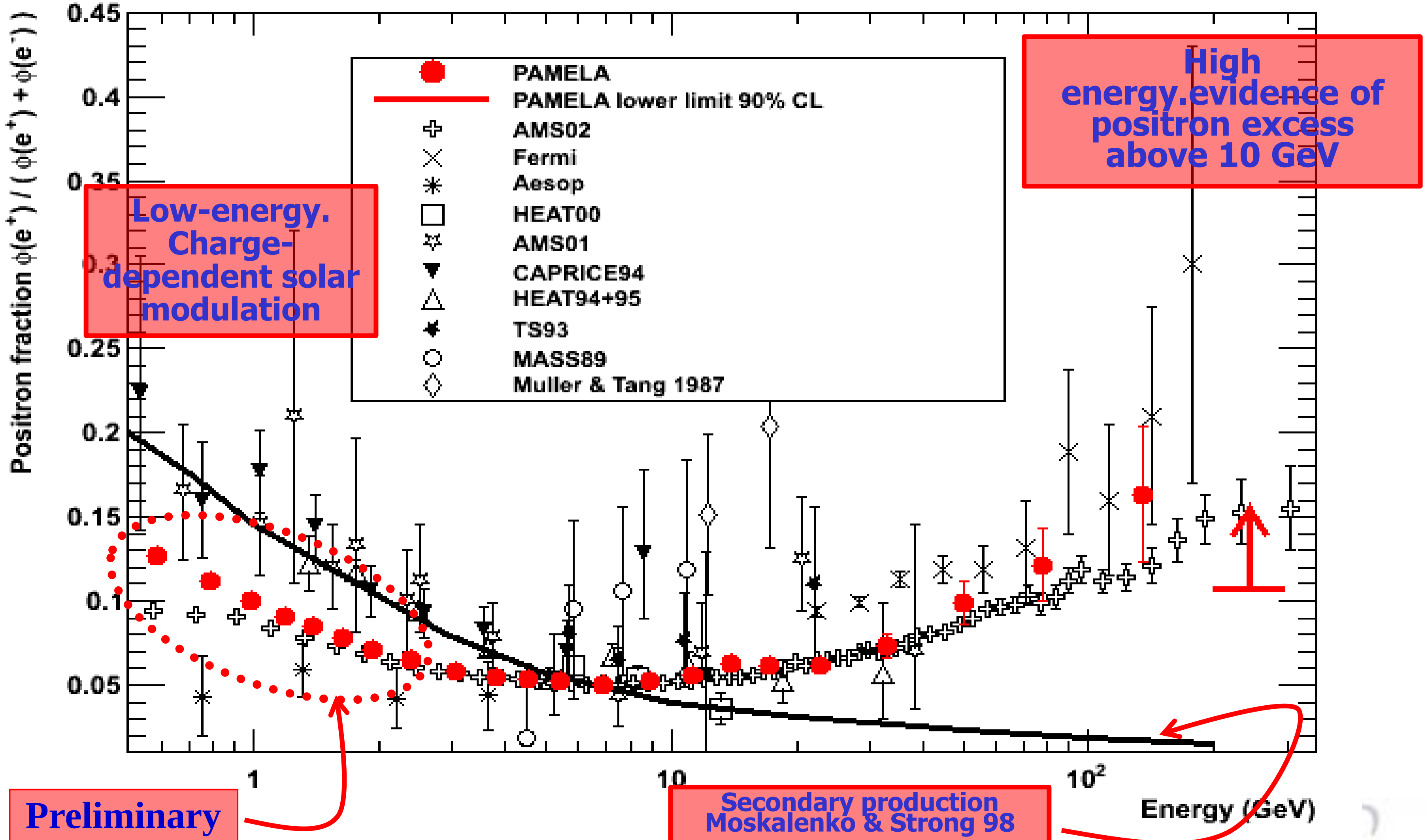
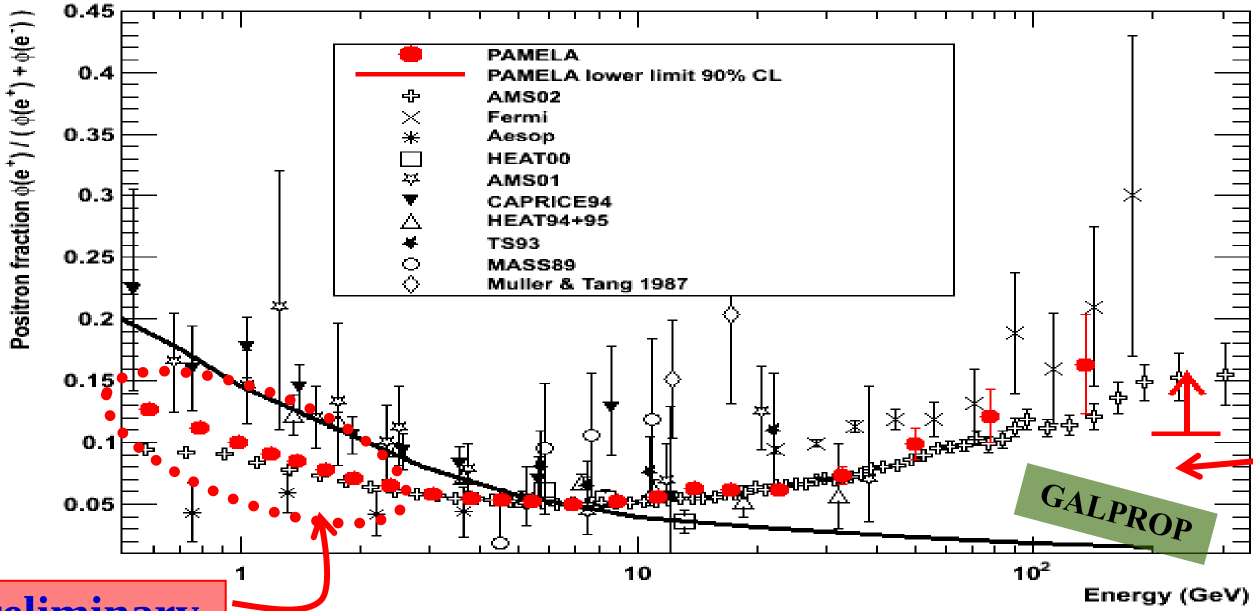
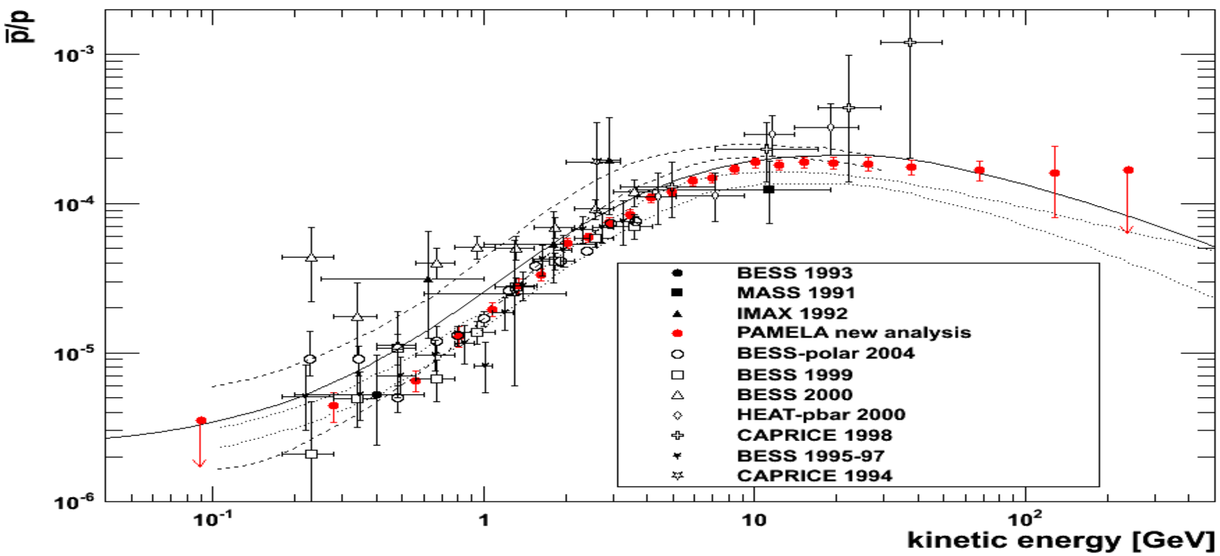


# The latest (still) puzzling picture




Positron spectrum significantly harder than expectations from secondary production

Preliminary




INFN

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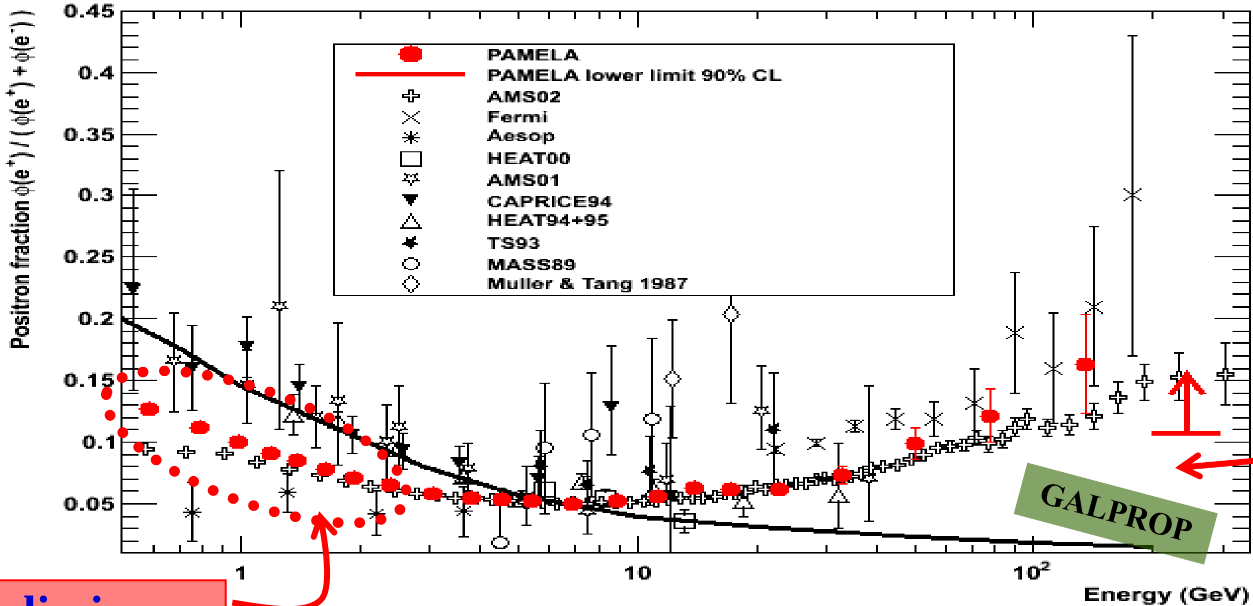


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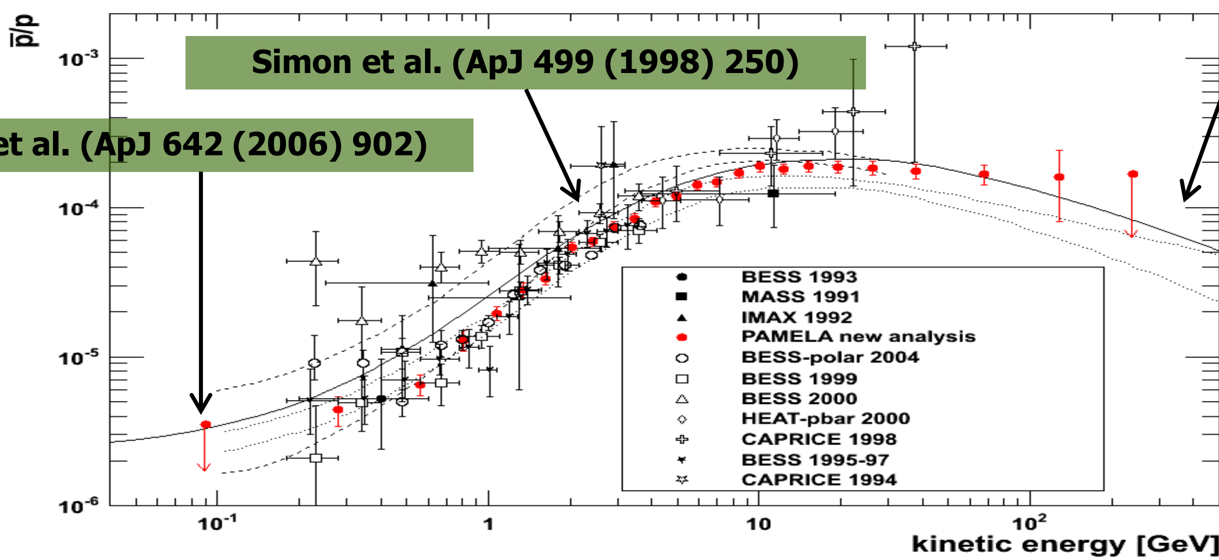


Simon et al. (ApJ 499 (1998) 250)

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

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

But antiprotons in CRs are in agreement with secondary production

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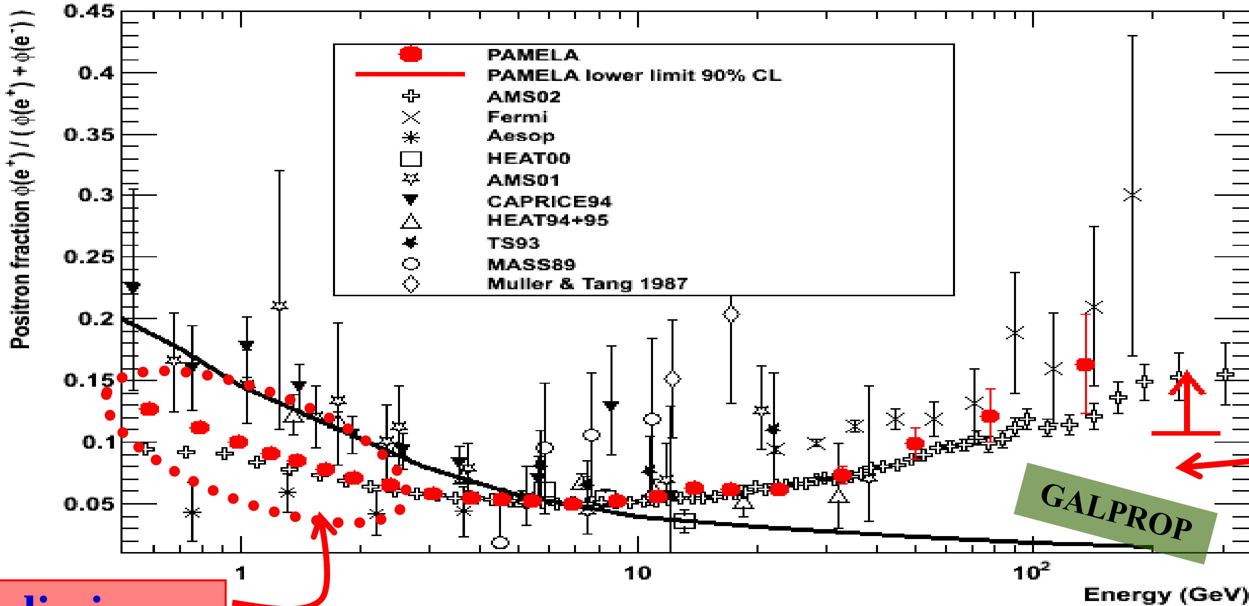


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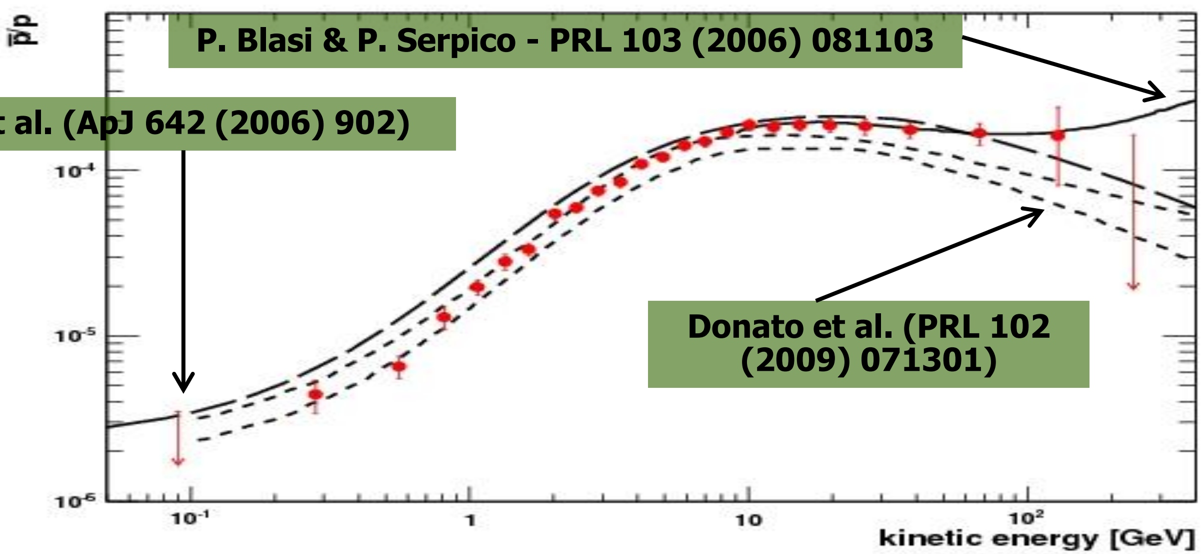
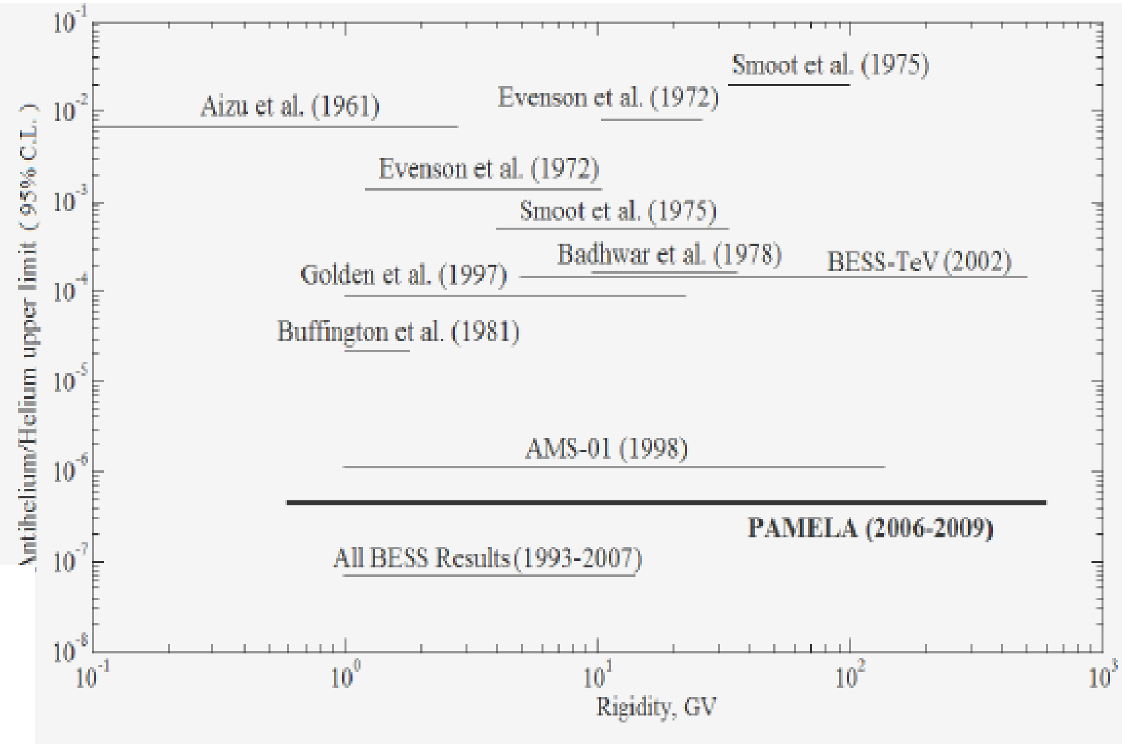


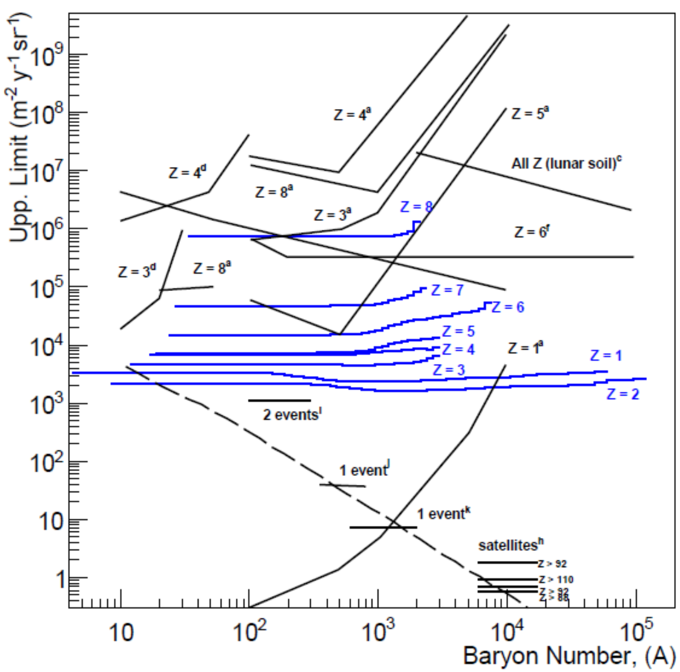

$e^+$ (and $e^-$) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

But also other secondaries are produced: significant increase expected in the p/p and B/C ratios.

# Antinuclei & 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

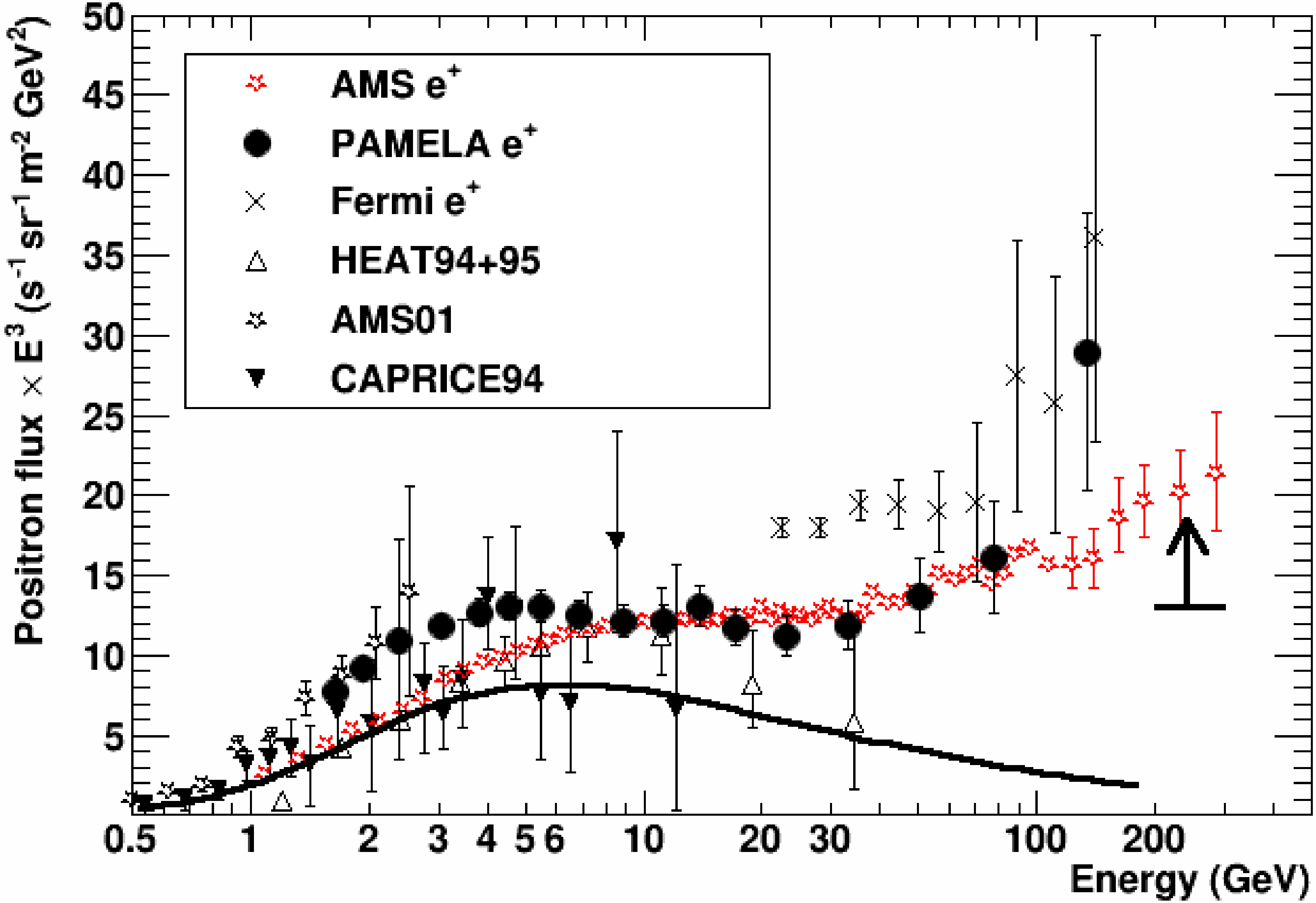



- **No anomalous A/Z particle** has been found (for Z <8 ) in the rigidity range: 1 < R < 1.0 x 103 GV, and mass range 4 < A < 1.2 x 105

# PAMELA $e^+$ spectra

Adriani et al. , PRL 111 (2013) 081102



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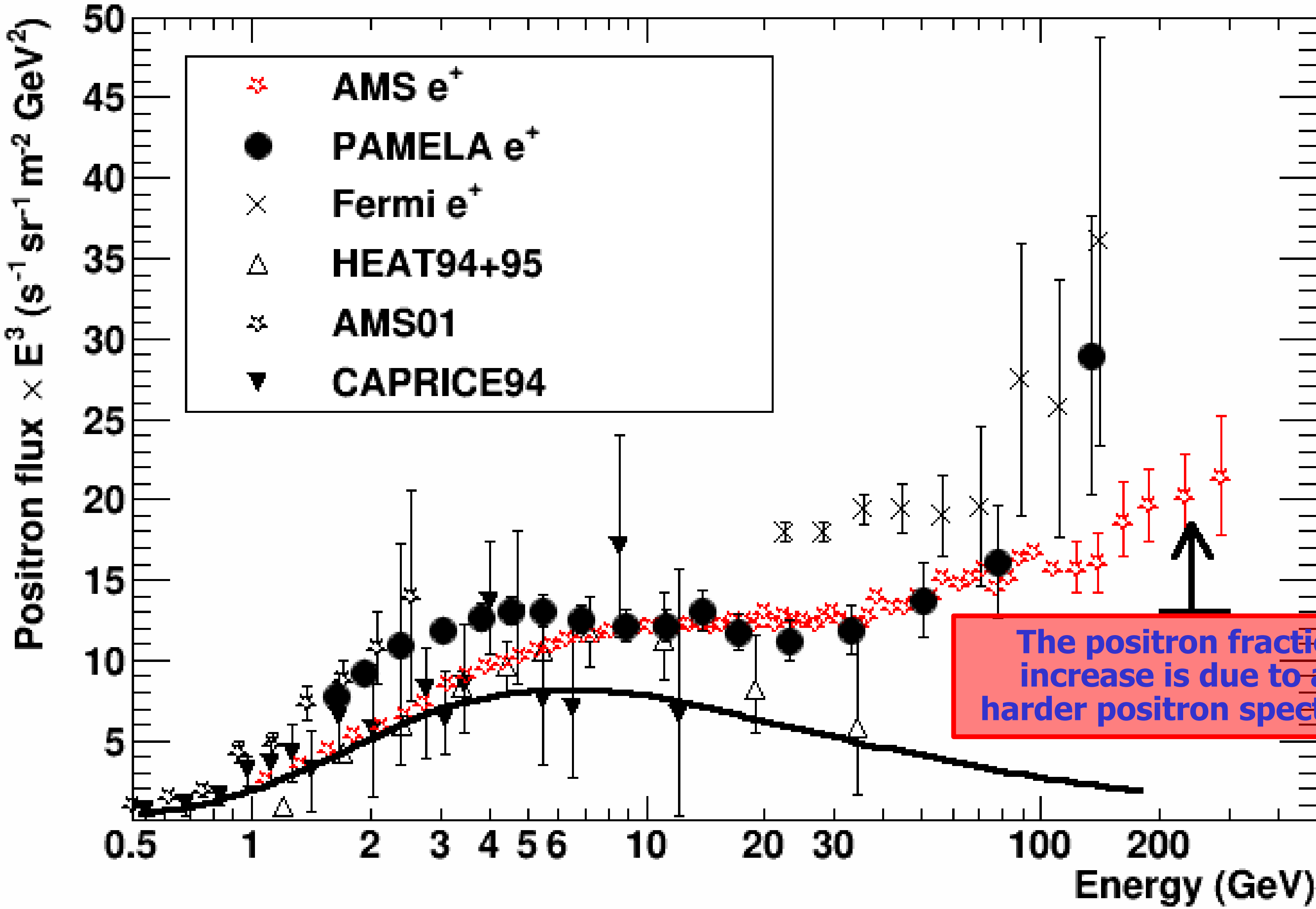
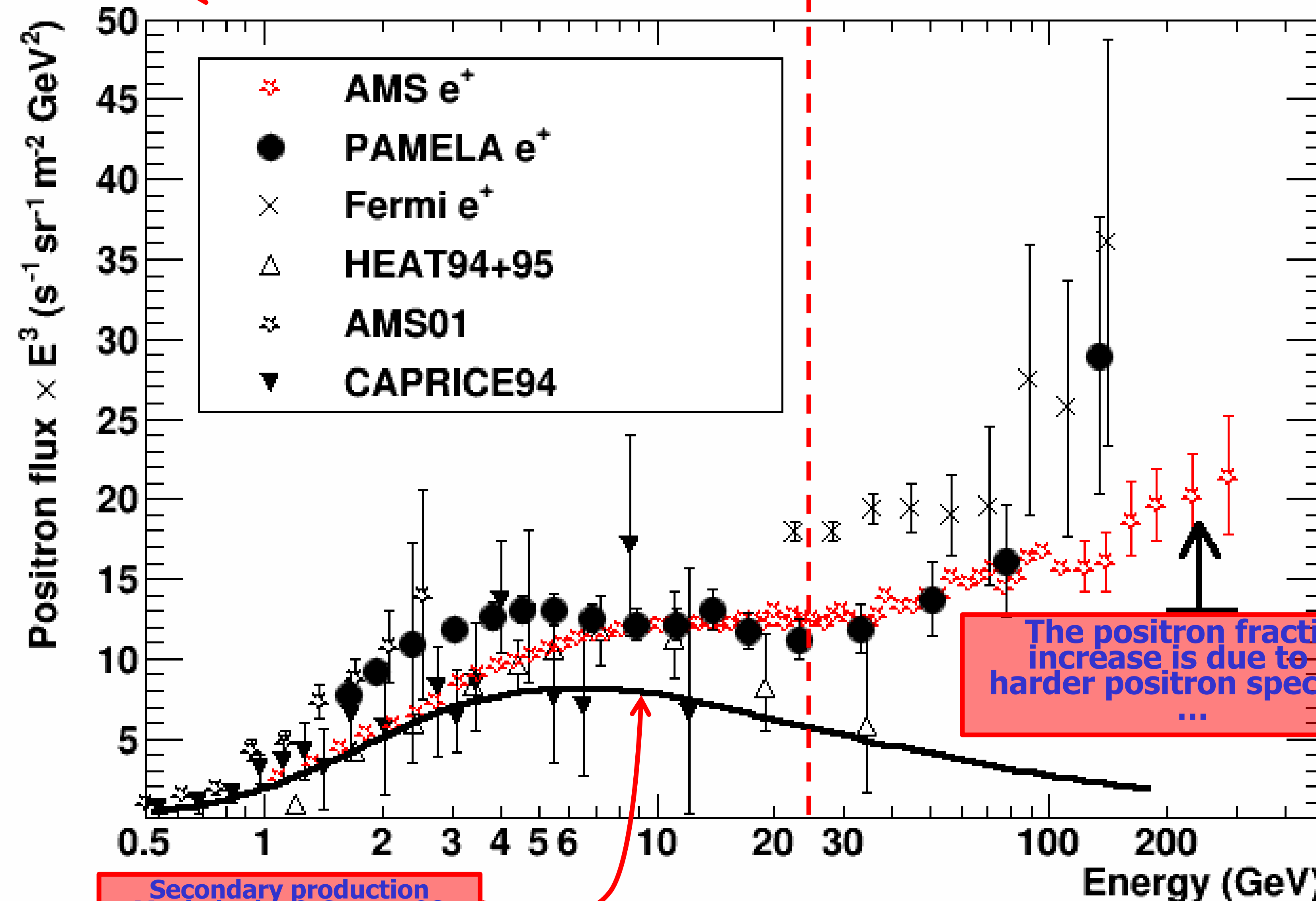



The positron fraction increase is due to an harder positron spectrum

# PAMELA $e^+$ spectra

Solar modulation

Adriani et al. , PRL 111 (2013) 081102

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Secondary production Moskalenko & Strong 98

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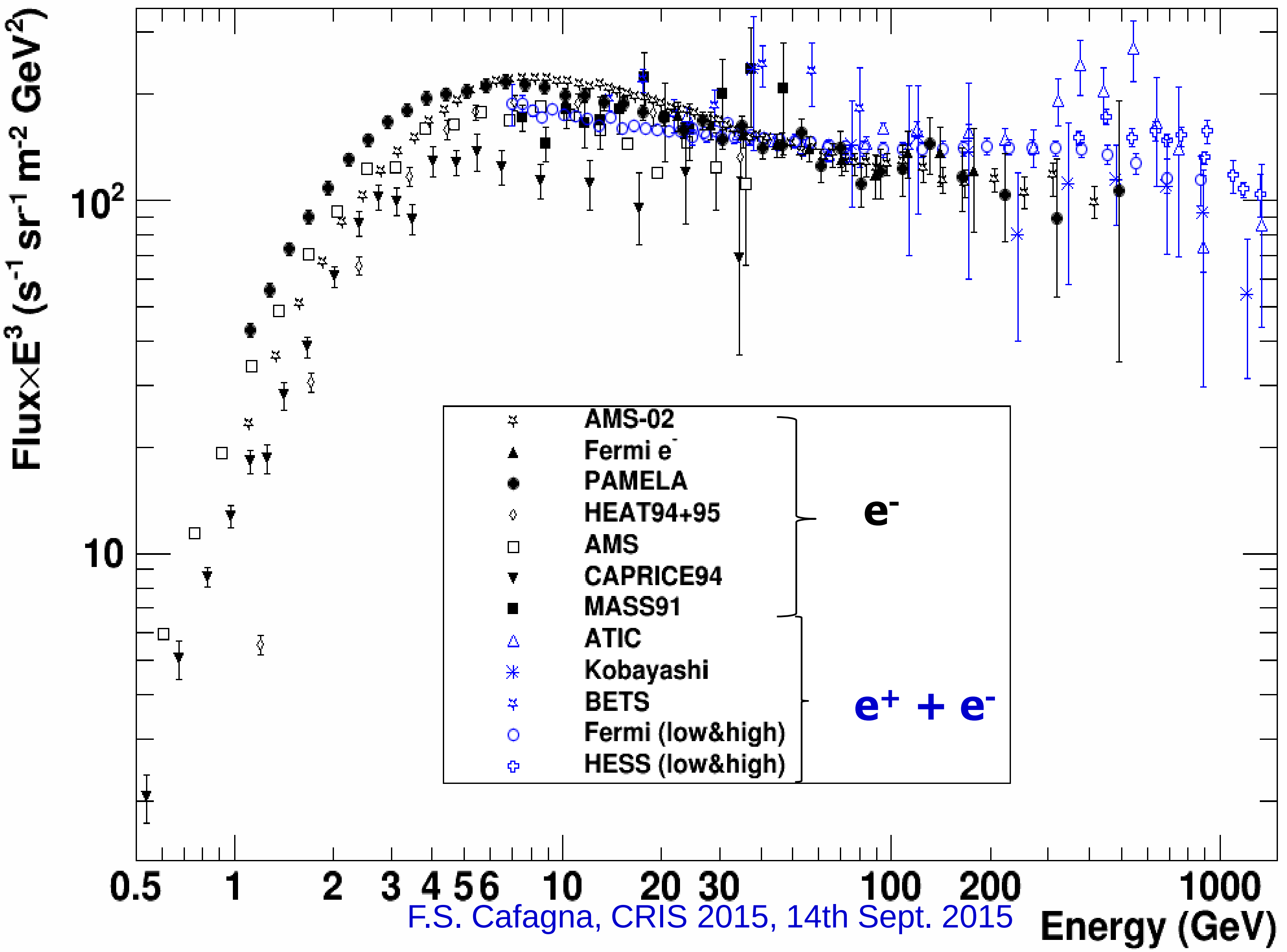
Adriani et al., Phys. Rev. Lett. 106, 201101 (2011)



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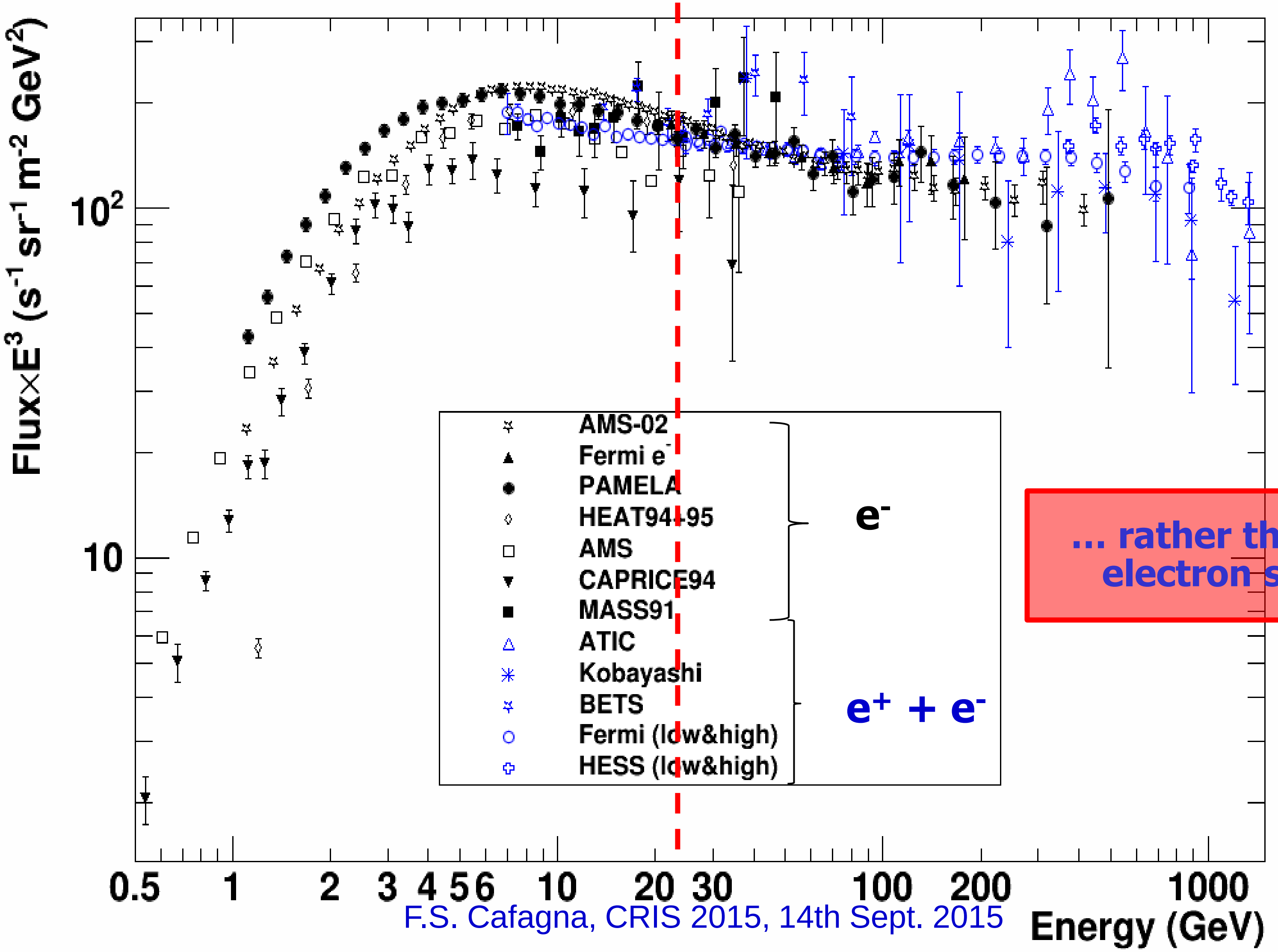


... rather than a softer electron spectrum.

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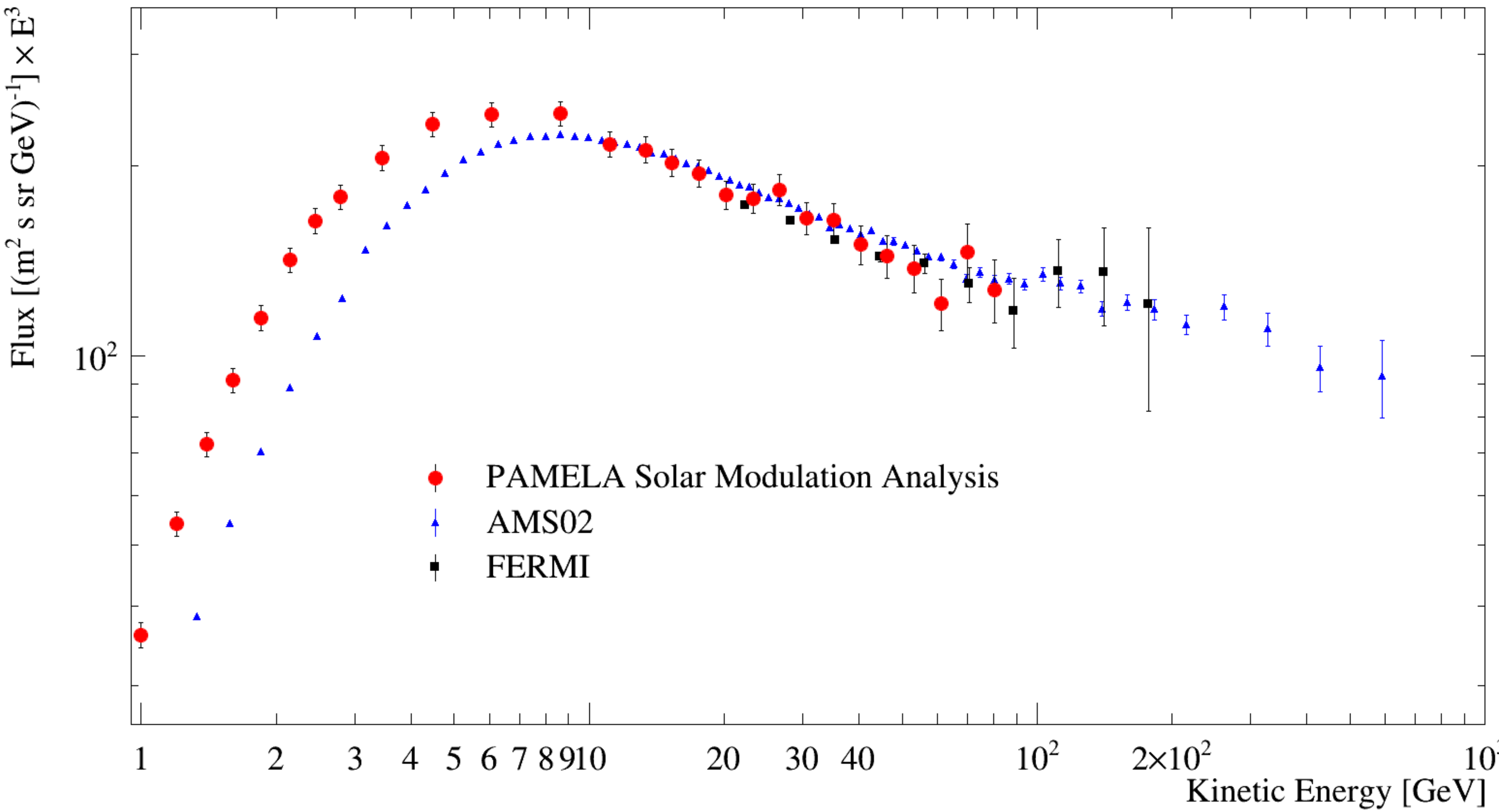

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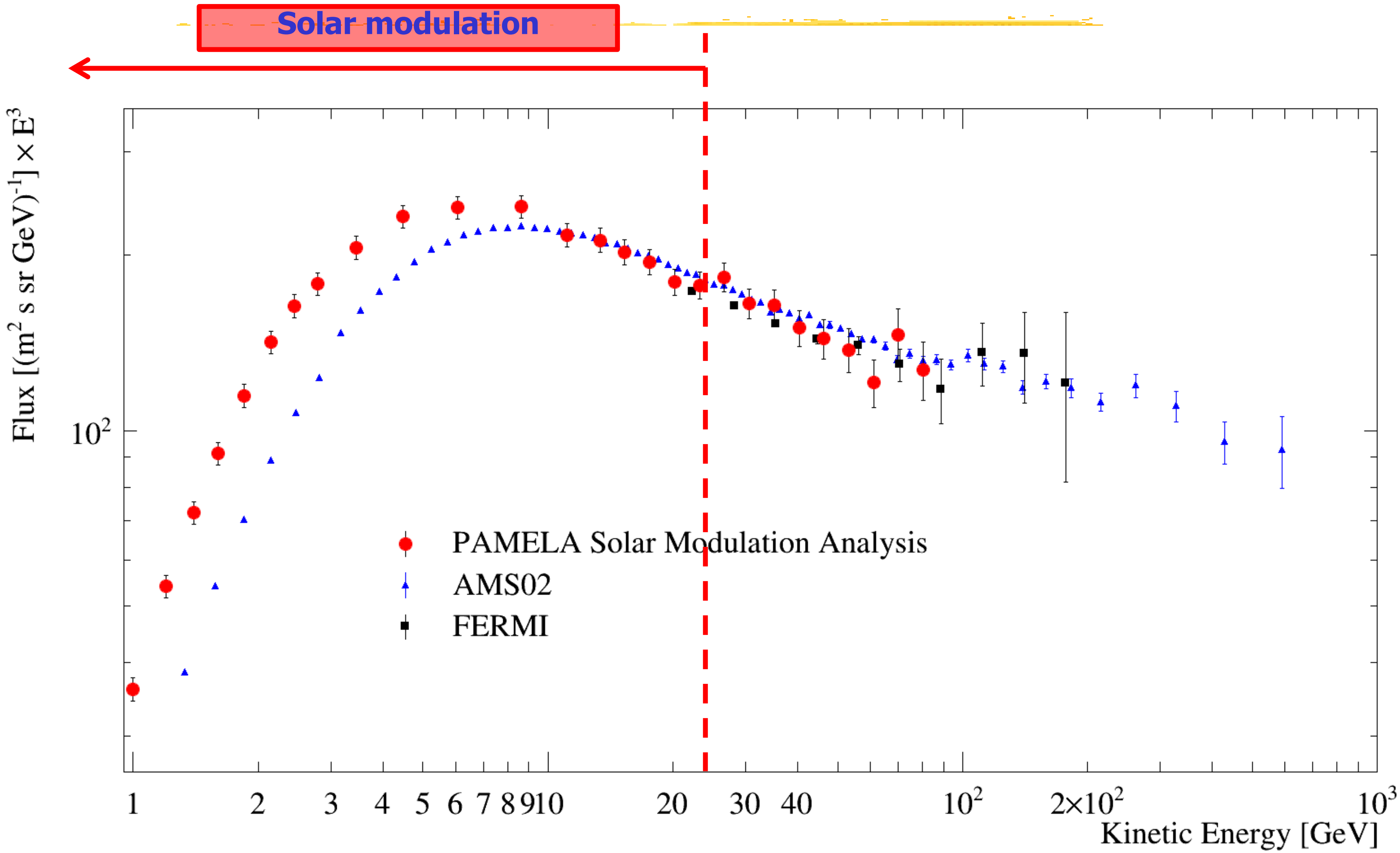


# e⁺ & e⁻ anisotropy

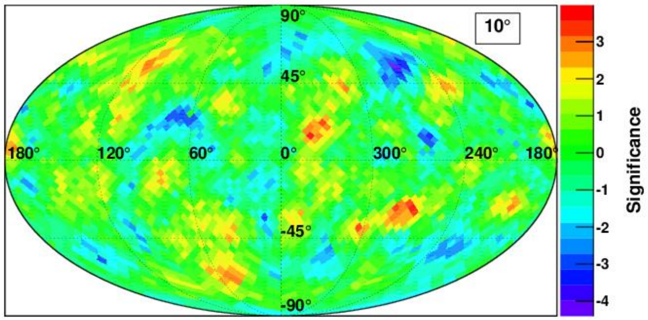
Electrons R > 10 GV

Significance map for

*backtraced* positrons

Background: Protons

Angular scale 10°




Significance map for

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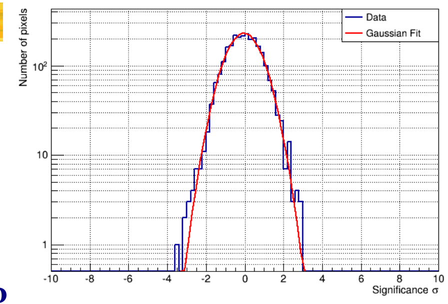
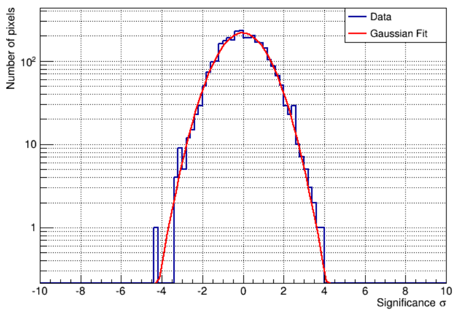
Background: Monte Carlo simulations



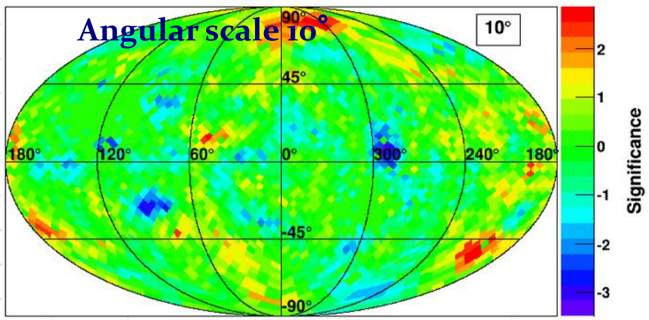

Histogram of calculated significance




Histogram of calculated significance

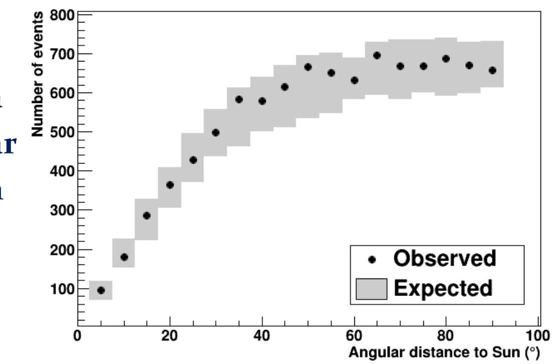
Positrons - R > 10 GV

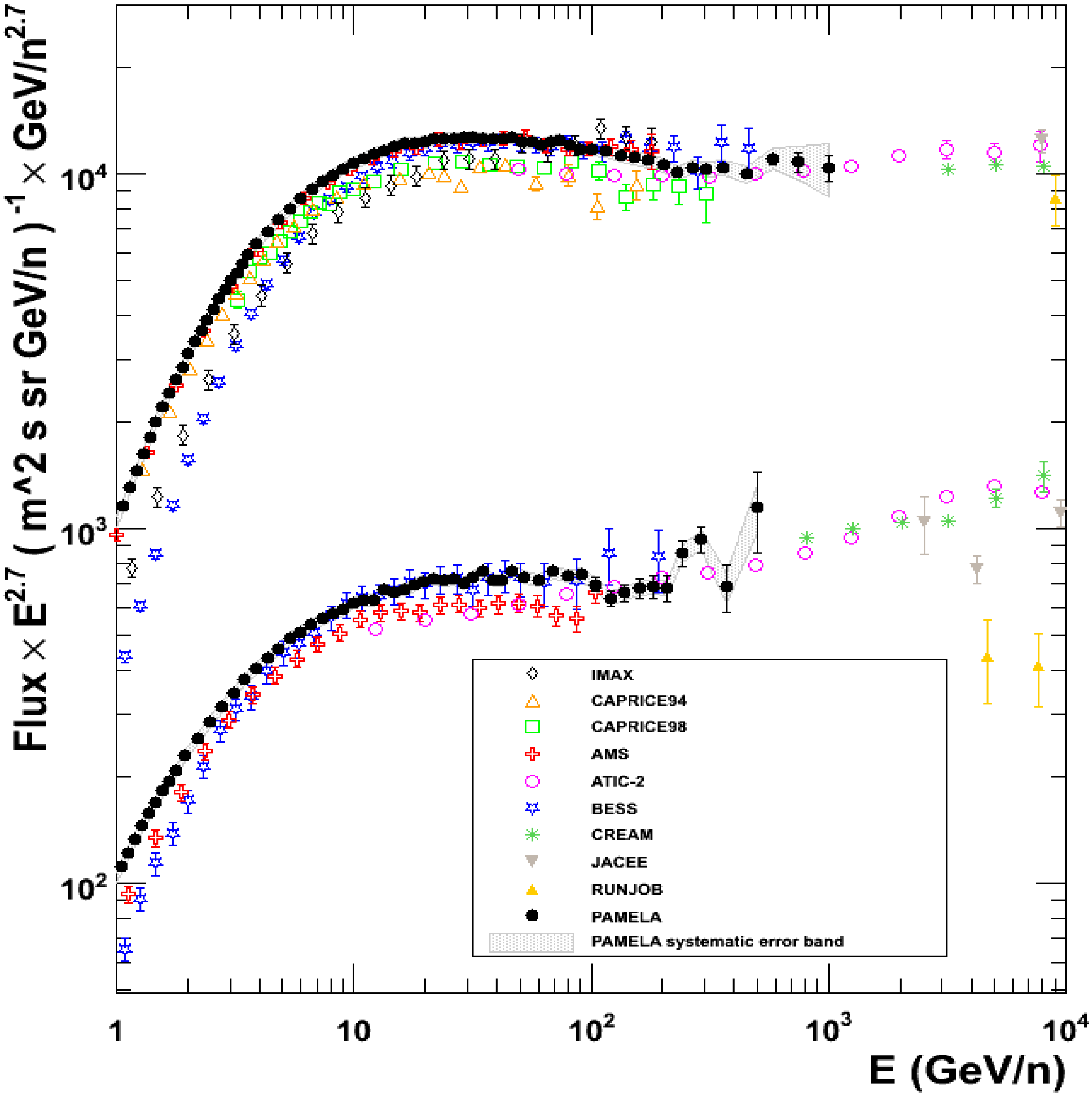
Angular scale 10°



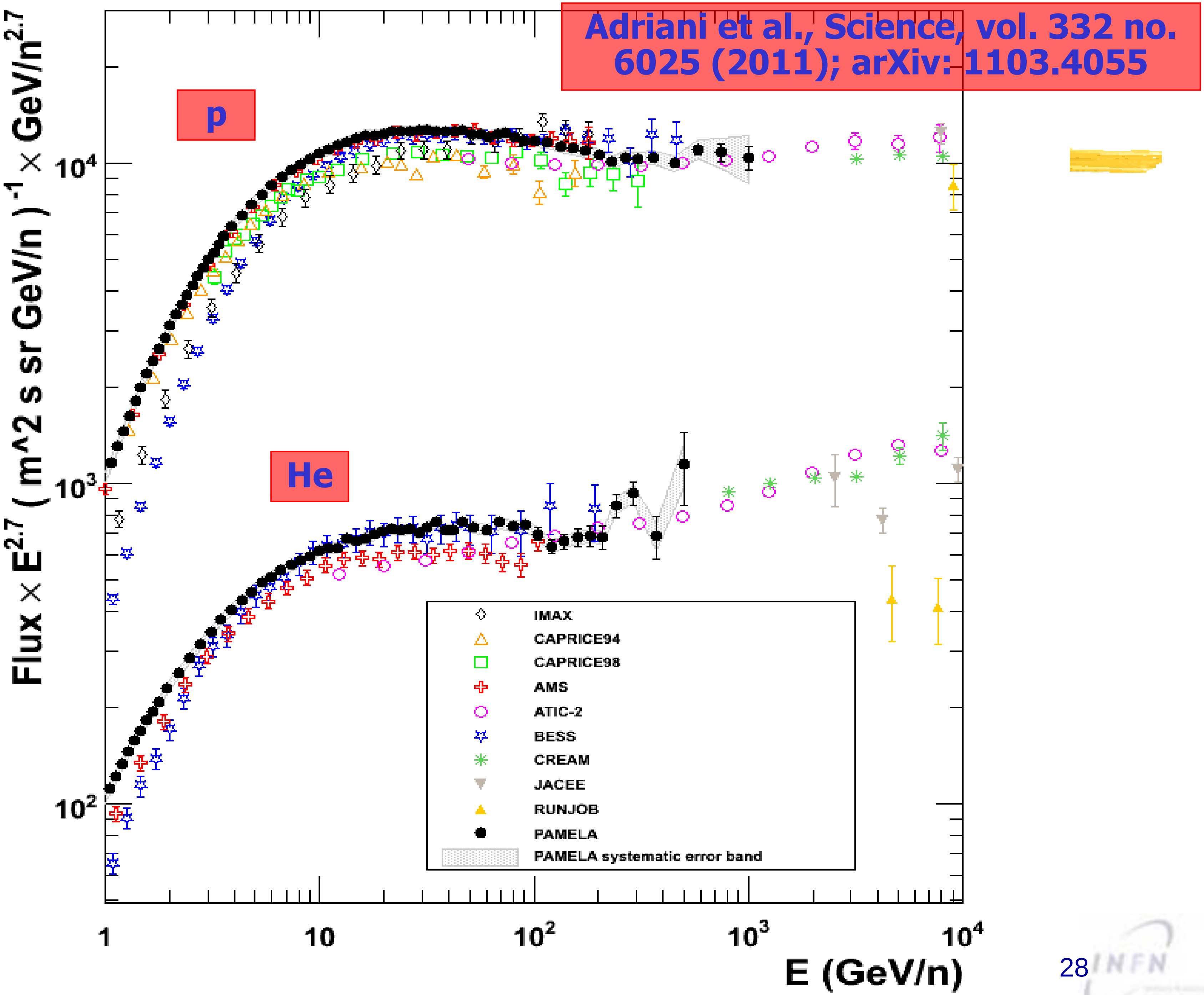

Preliminary

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



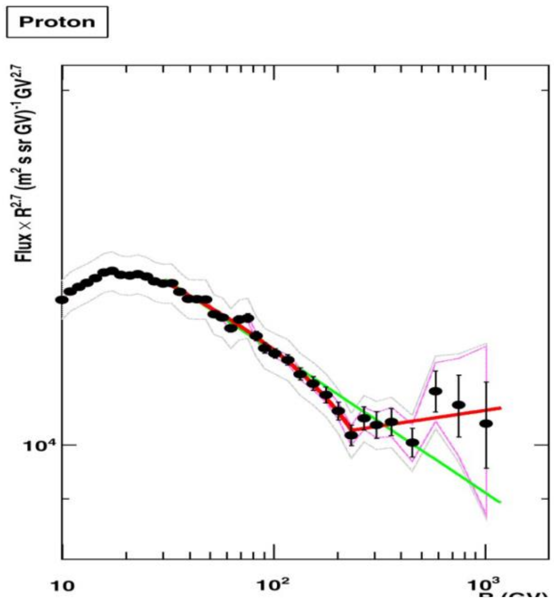


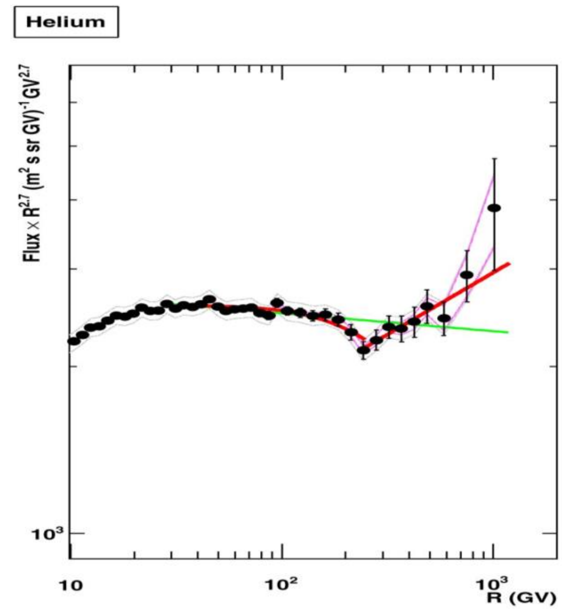
Flux × E^2.7 ( m^2 s sr GeV/n )^-1 × GeV/n^2.7
10^4
10^3
10^2
1
10
10^2
10^3
10^4
E (GeV/n)
IMAX
CAPRICE94
CAPRICE98
AMS
ATIC-2
BESS
CREAM
JACEE
RUNJOB
PAMELA
PAMELA systematic error band

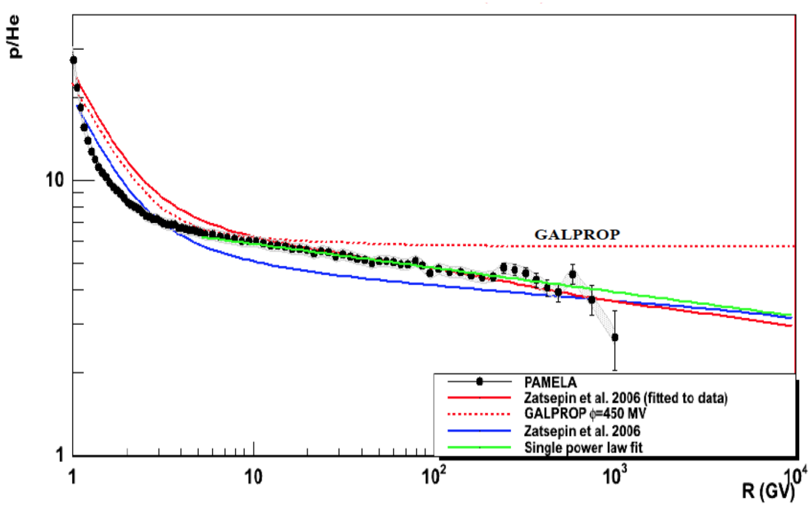


Adriani et al., Science, vol. 332 no. 6025 (2011); arXiv: 1103.4055
p
He
Flux × E^2.7 ( m^2 s sr GeV/n )^-1 × GeV/n^2.7
E (GeV/n)
IMAX
CAPRICE94
CAPRICE98
AMS
ATIC-2
BESS
CREAM
JACEE
RUNJOB
PAMELA
PAMELA systematic error band

# PAMELA Galactic H & He

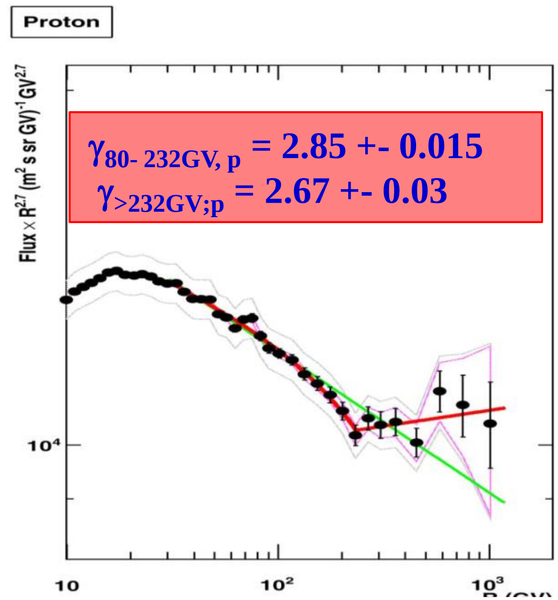


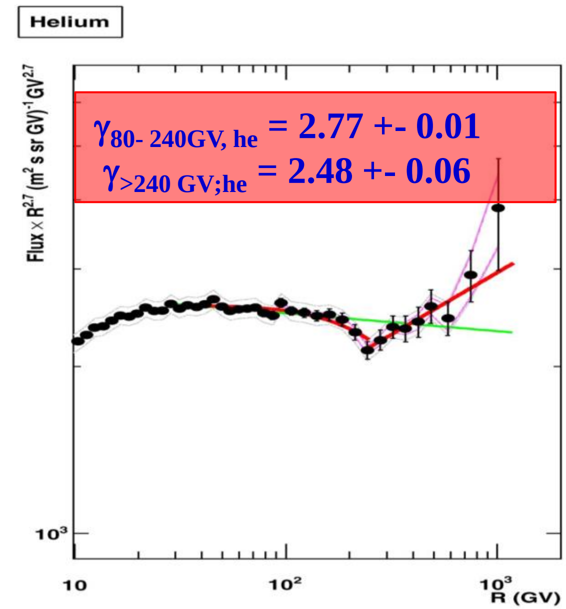



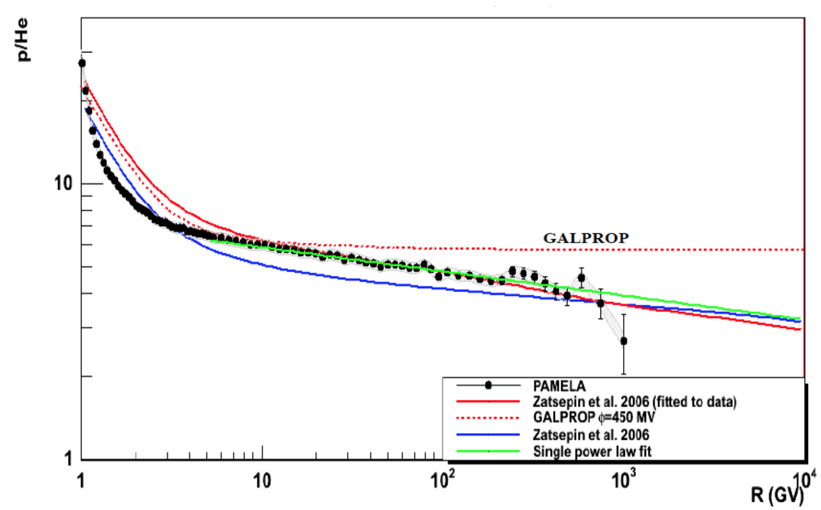



# PAMELA Galactic H & He

- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta\gamma$~0.2÷0.3

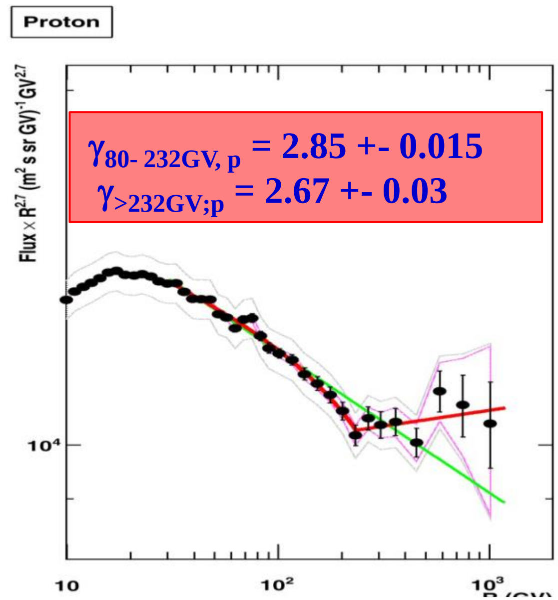


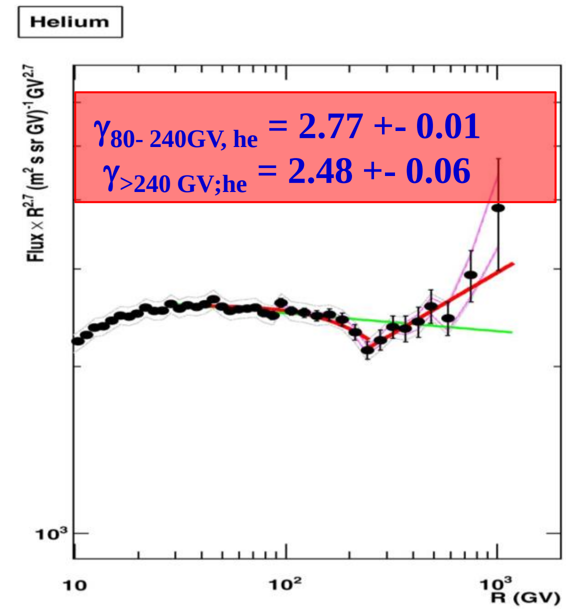



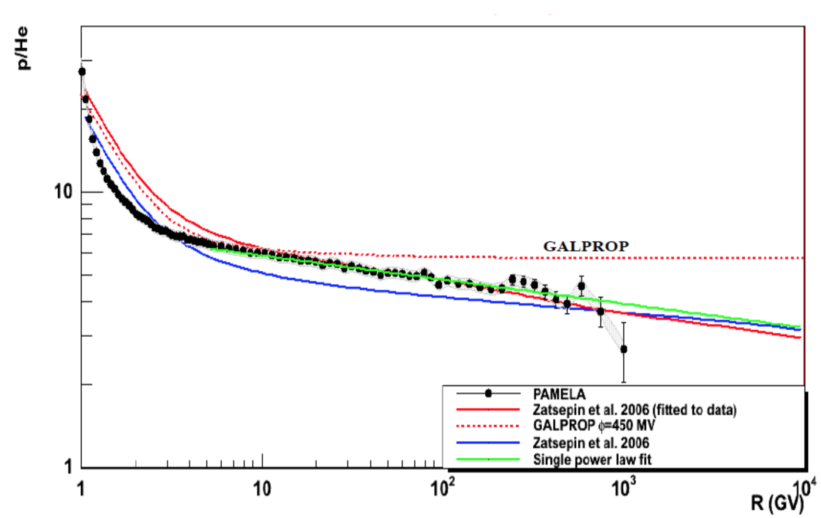



# PAMELA Galactic H & He

- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta\gamma$~0.2÷0.3
- SPL is rejected at 98% CL

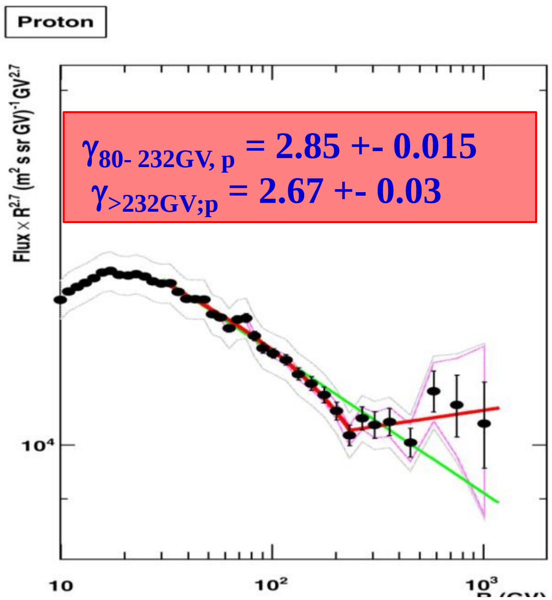


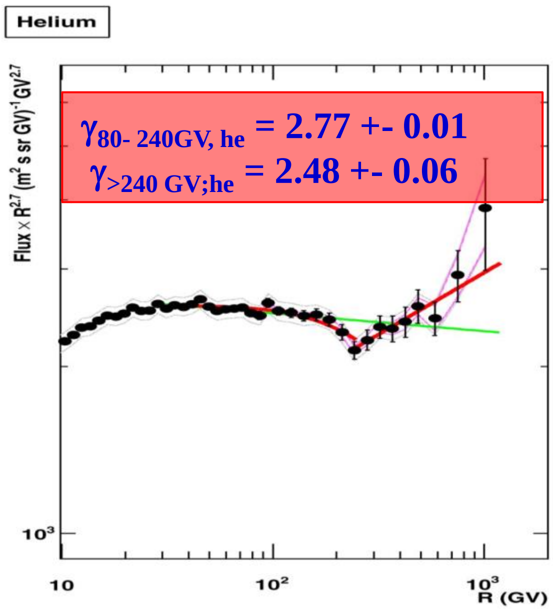



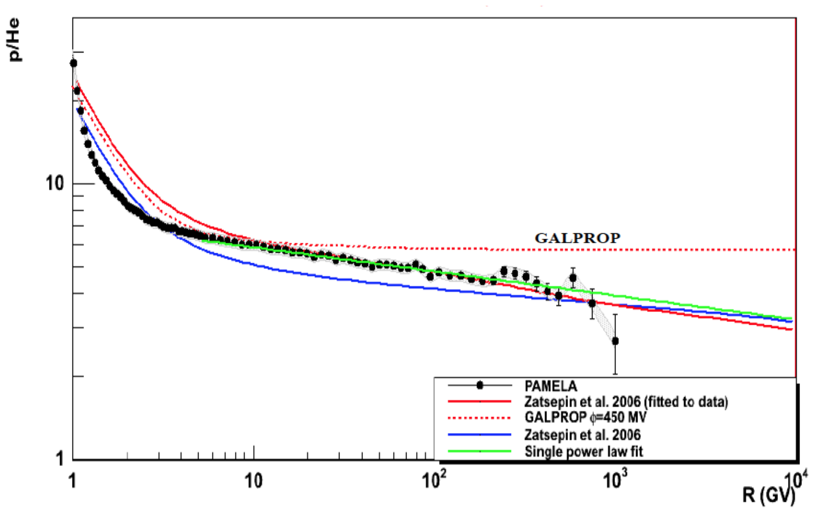



# PAMELA Galactic H & He

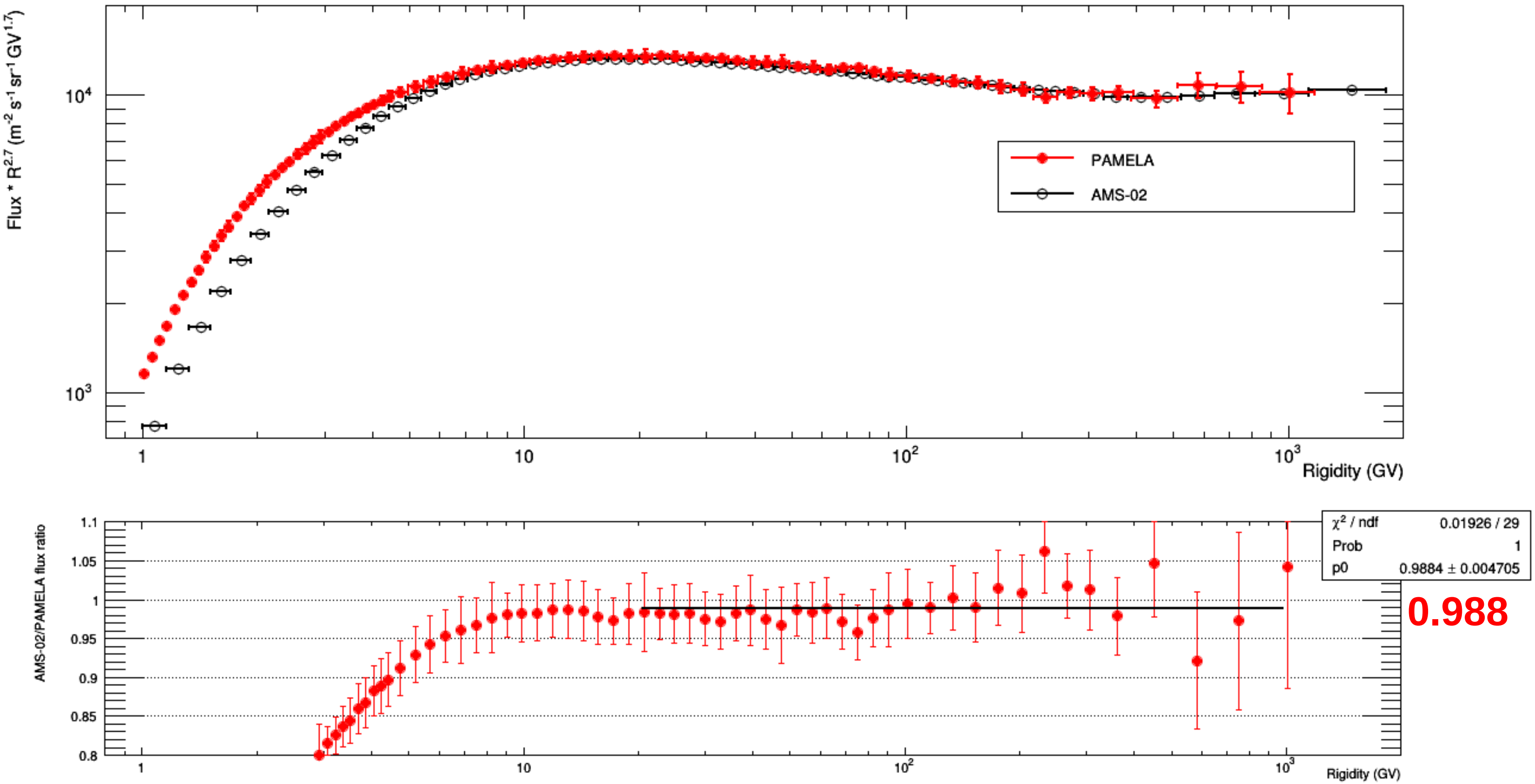
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV Δγ~0.2÷0.3
- SPL is rejected at 98% CL
- Origin of the structures?
  - At the sources: multi-populations, non-linear DSA.
  - Propagation effects.



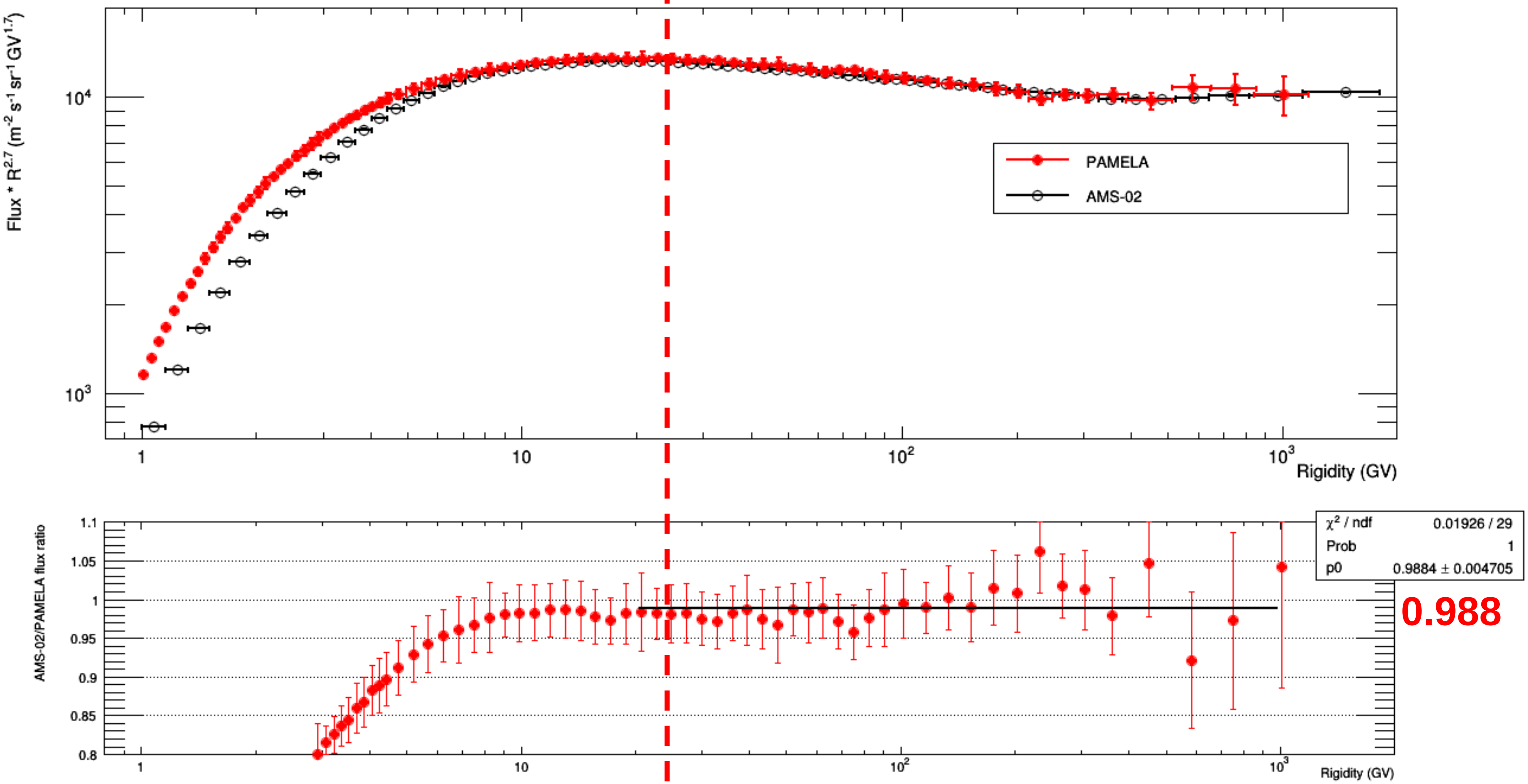
# PAMELA Galactic H




**Adriani et al., Phys. Rep., 544, 4, 323-370 (2014)**

# PAMELA Galactic H

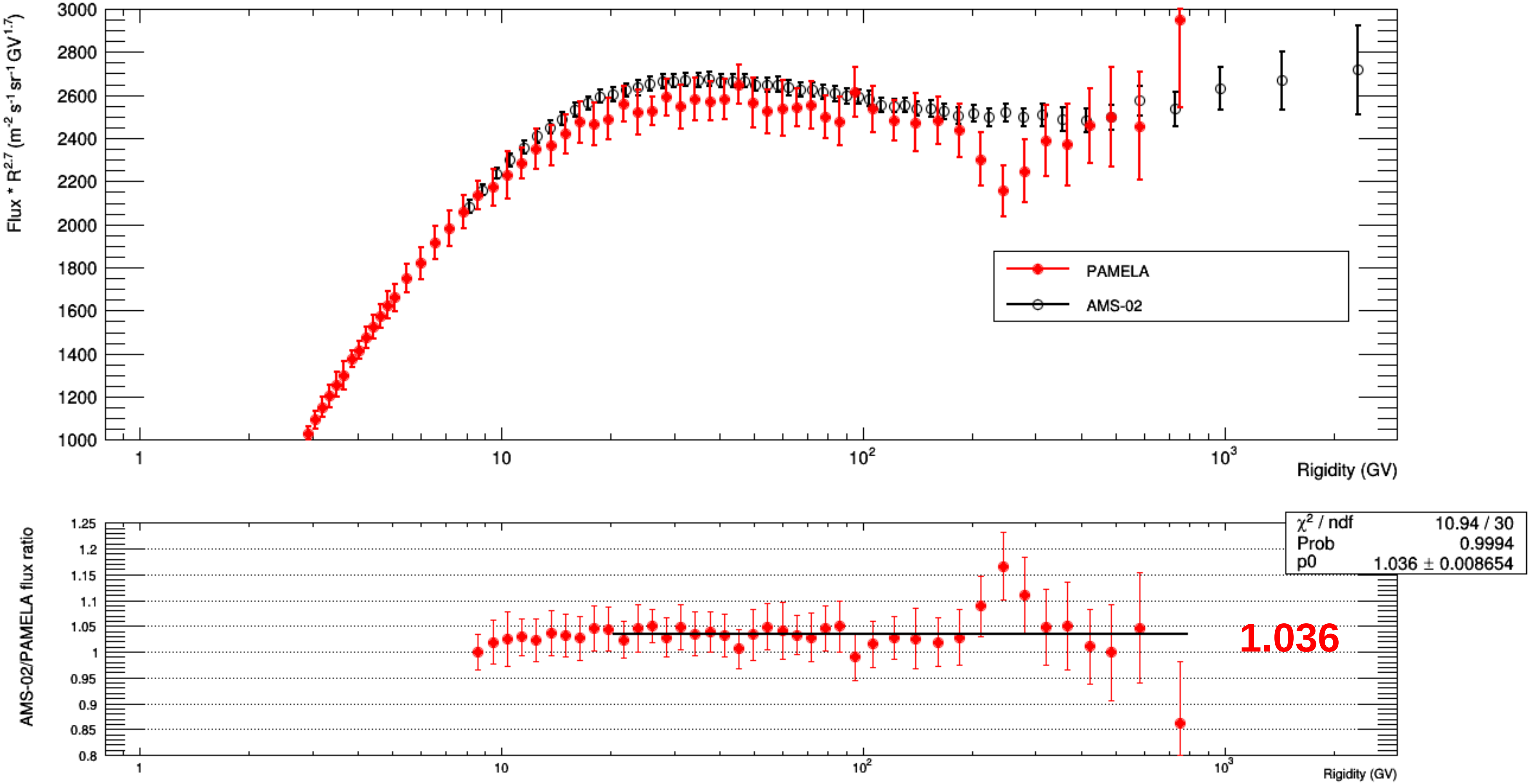
Solar modulation



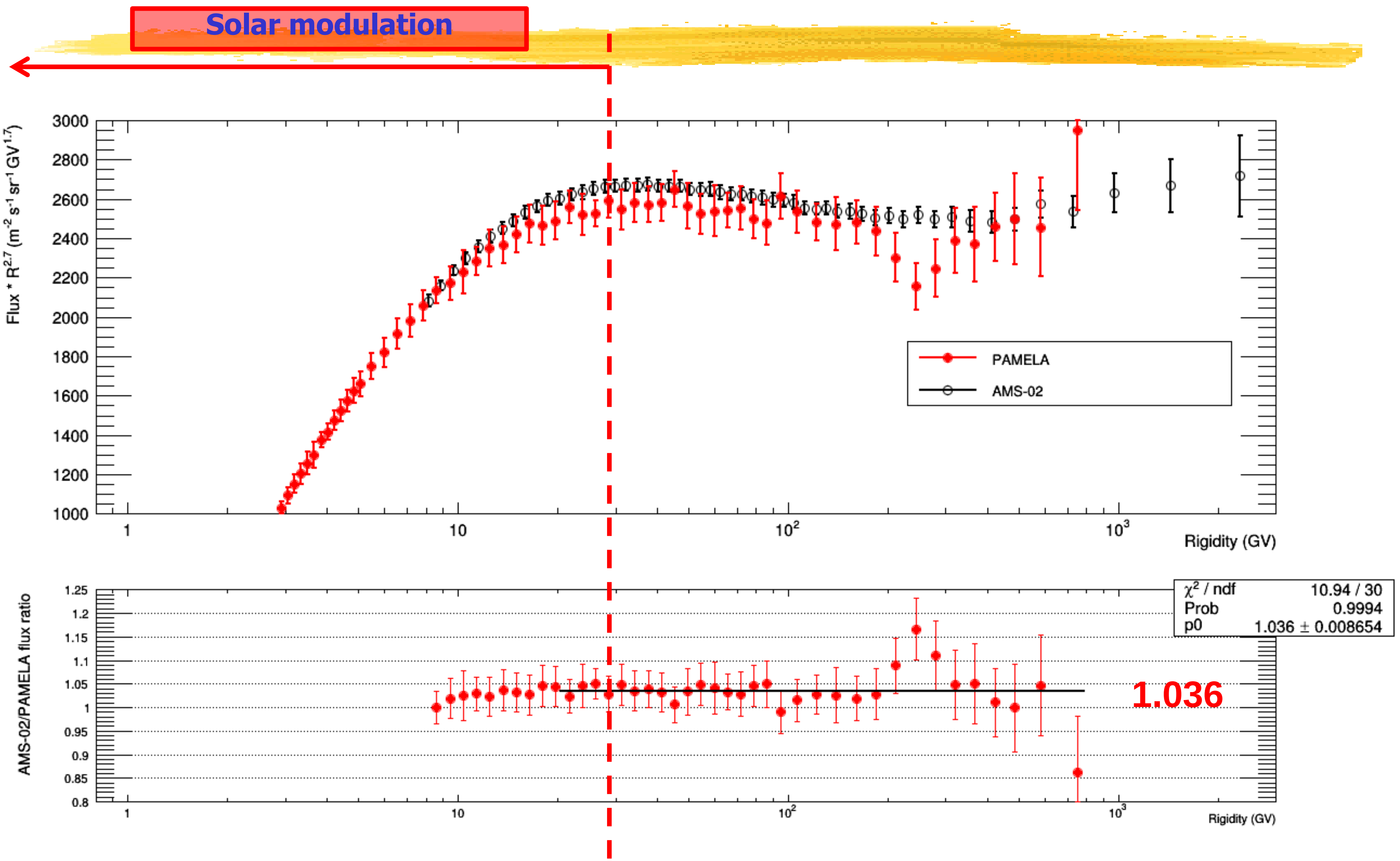

0.988

Adriani et al., Phys. Rep., 544, 4, 323-370 (2014)

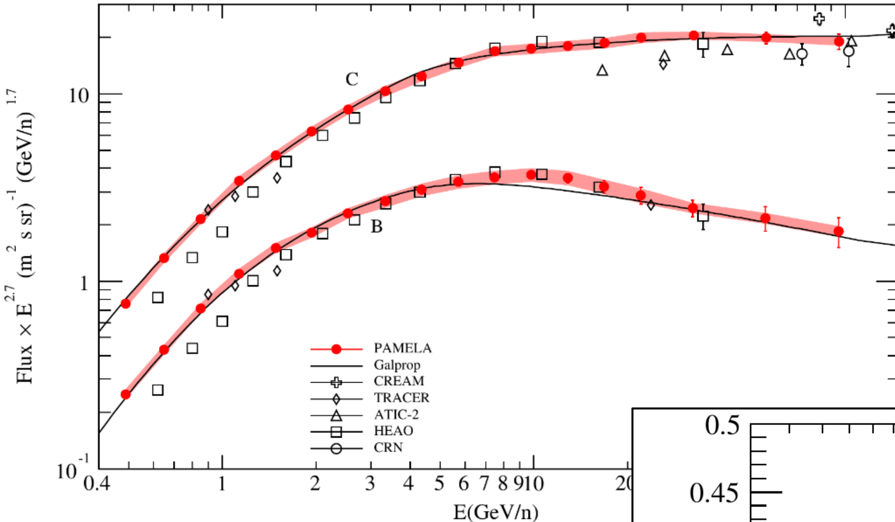
# PAMELA Galactic He



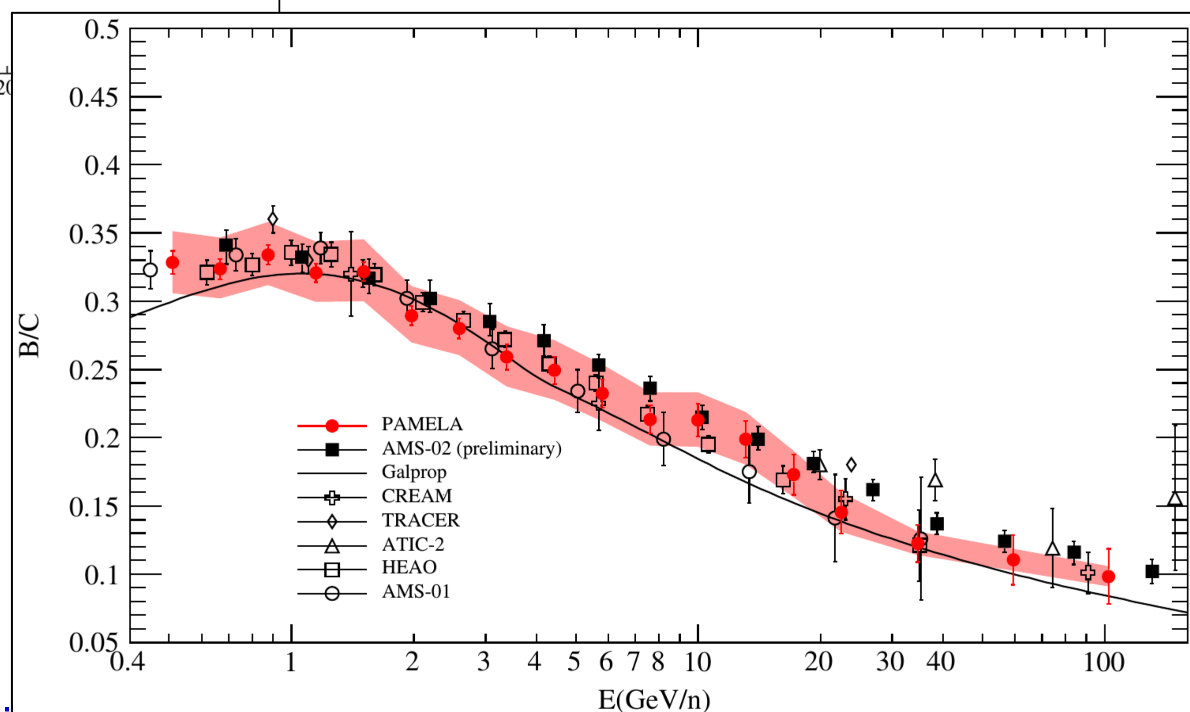
# PAMELA Galactic He



# PAMELA B & C fluxes and ratio



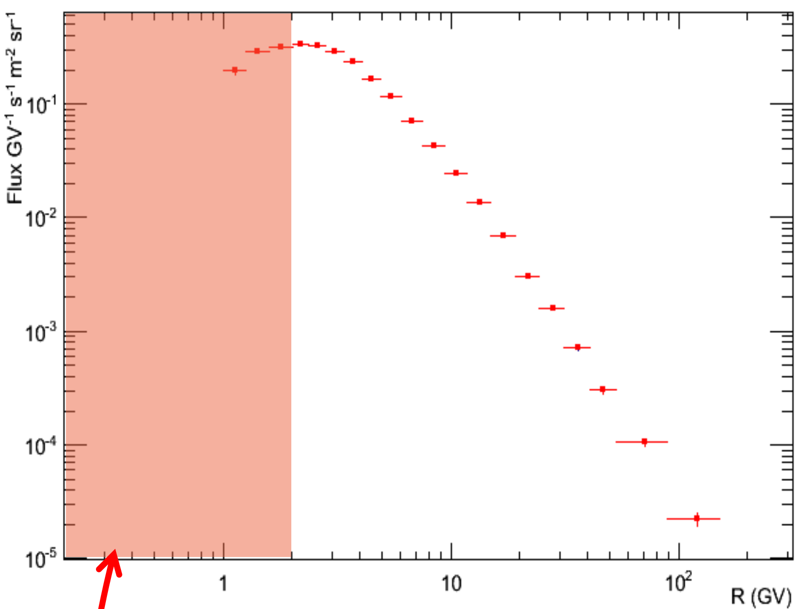

- Modelization of cosmic-ray propagation in the Galaxy
- Tracking performance:
  - $\sigma_x$ = 14μm, $\sigma_y$ = 19μm
  - MDR = 250 GV

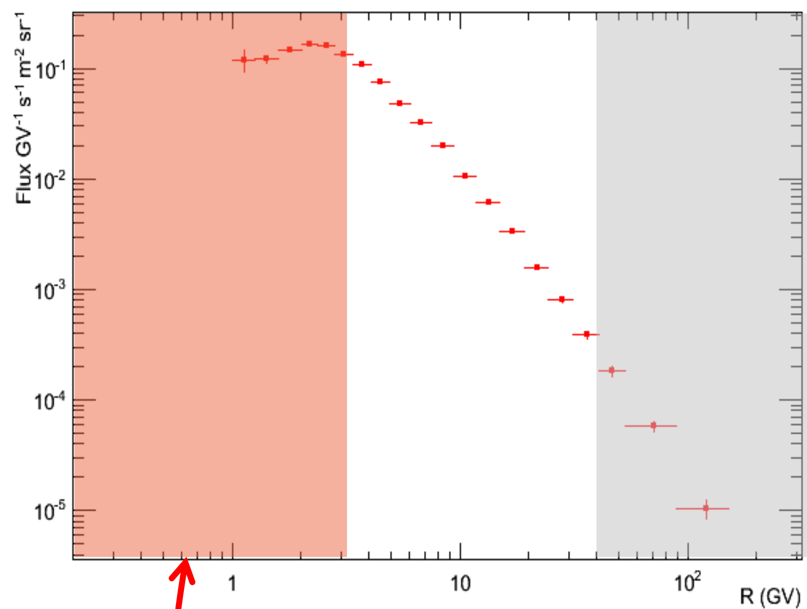



F.S.

# PAMELA Li & Be fluxes

**Li** **Preliminary** **Be**



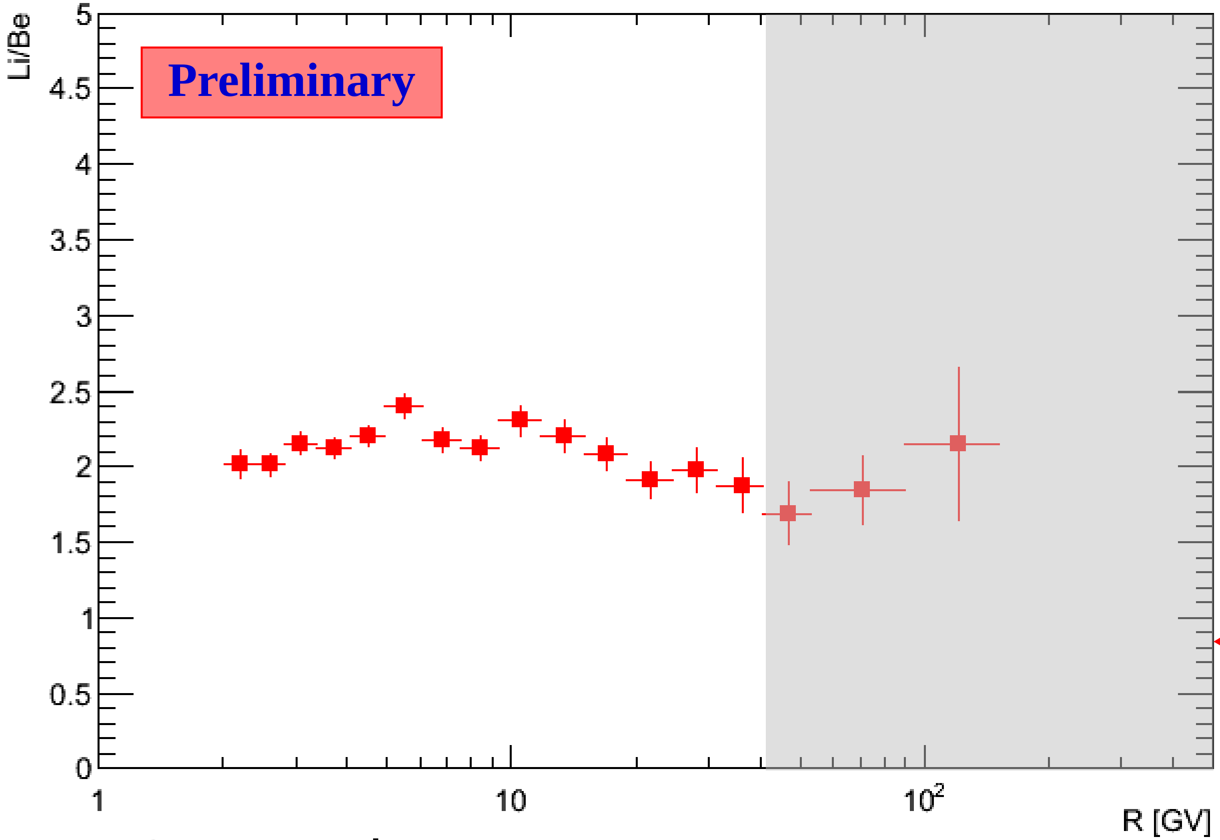




- No MC corrections
- Not unfolded
- Only statistical errors

**Slow down effect still to be corrected**

**MDR effects still to be corrected**

# PAMELA Li & Be ratio

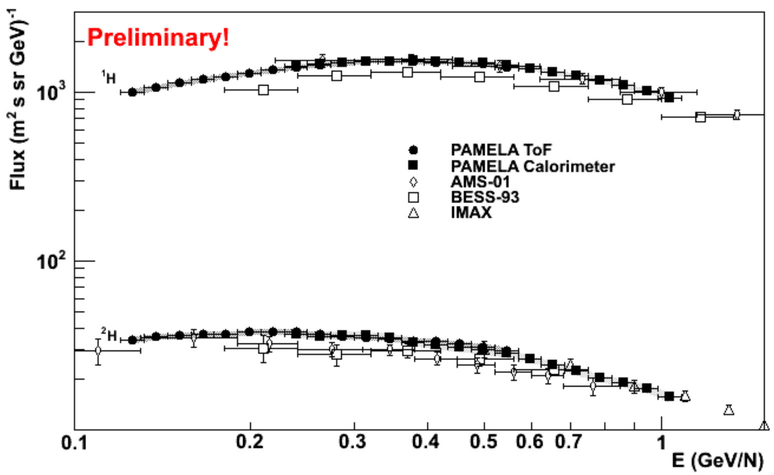


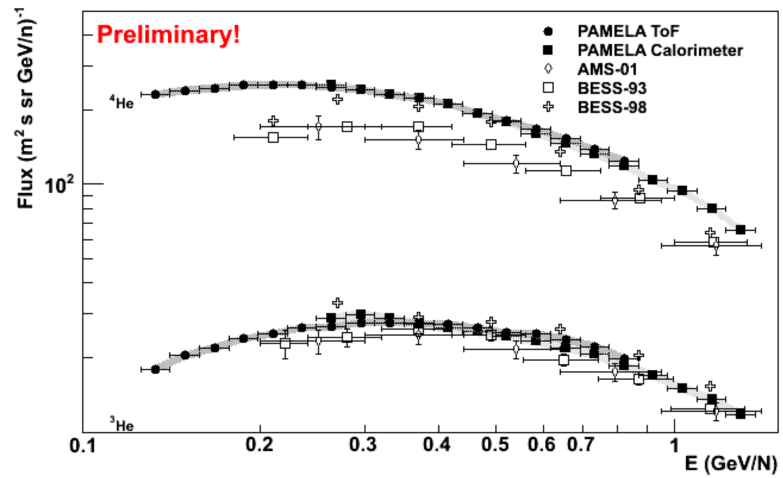

- No MC corrections
- Not unfolded
- Only statistical errors

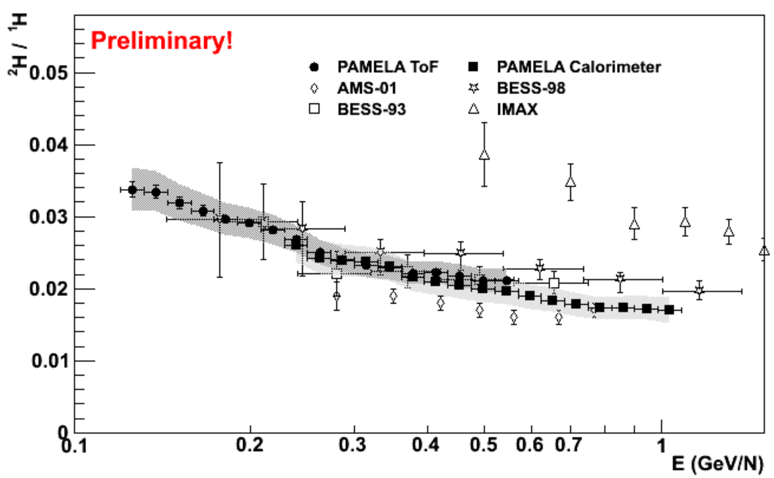
MDR effects still to be corrected

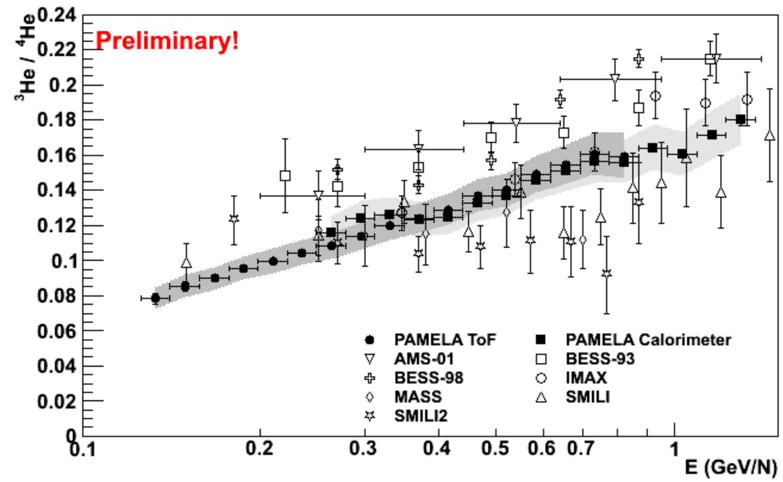
# PAMELA H & He Isotopes

**$^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complimentary to B/C measurements in constraining propagation models (Coste et al., A&A 539 (2012) A88)**



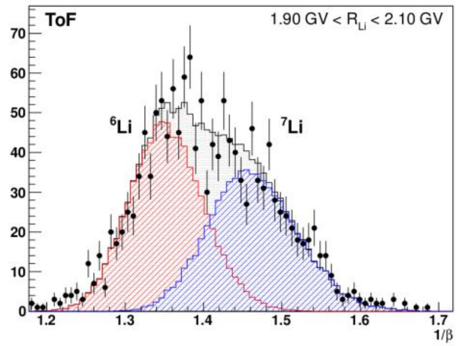



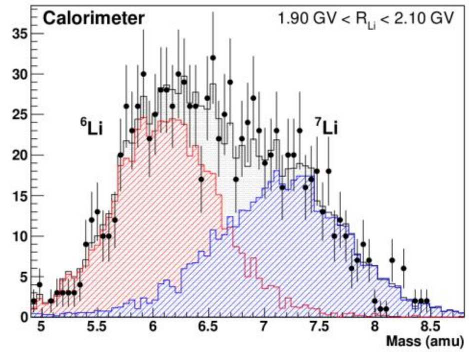



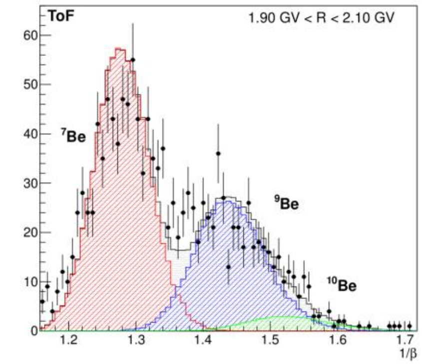
# PAMELA Li & Be Isotopes

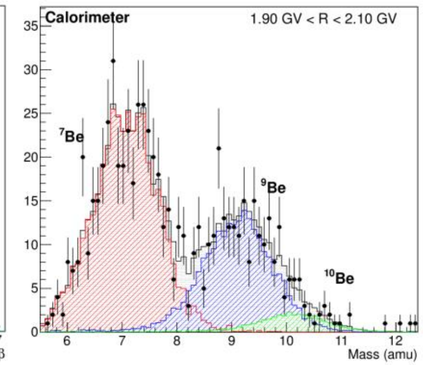
## Lithium



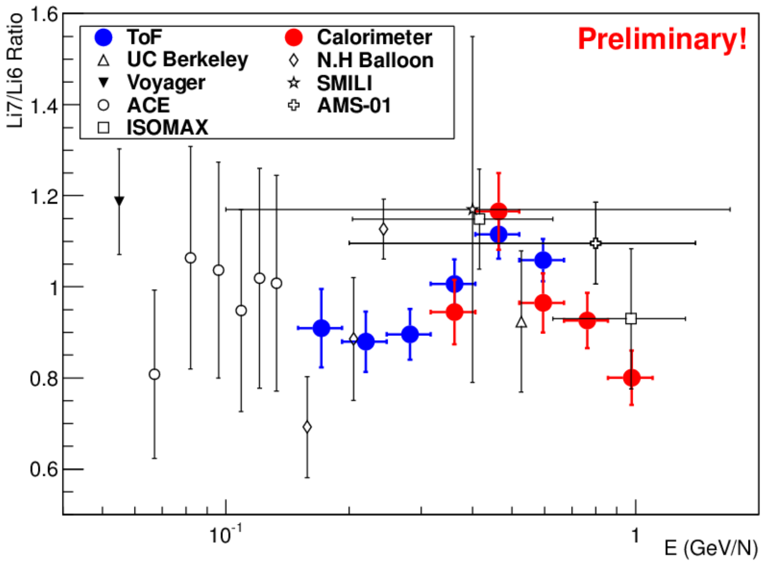




## Beryllium

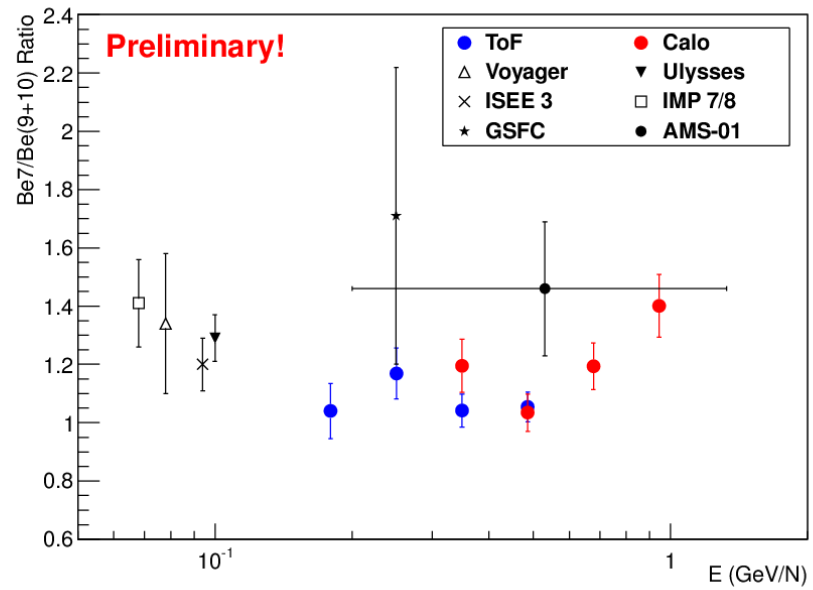


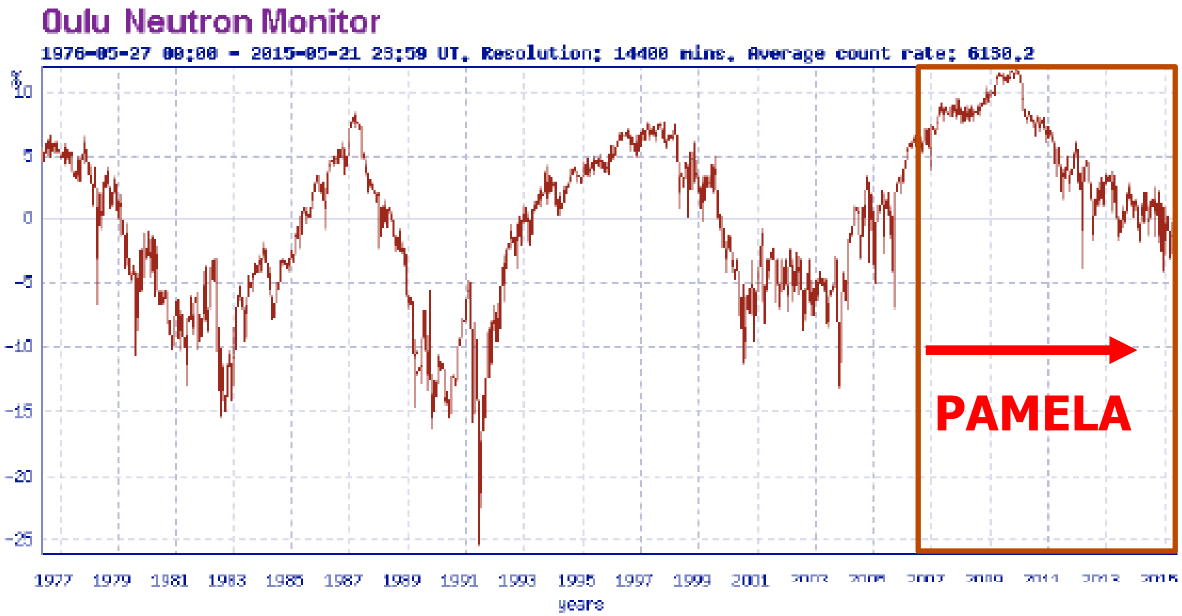

## Ratio $^7$Li / $^6$Li




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



# Heliospheric conditions during PAMELA observations

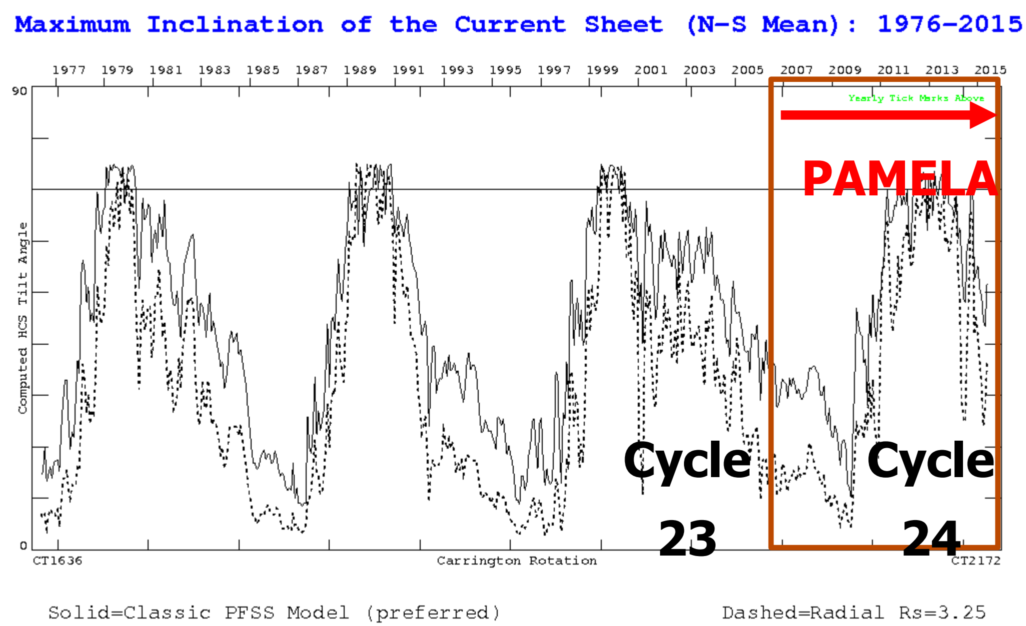



**Neutron Monitor Counts**

**From: http://**cosmicrays.oulu.fi

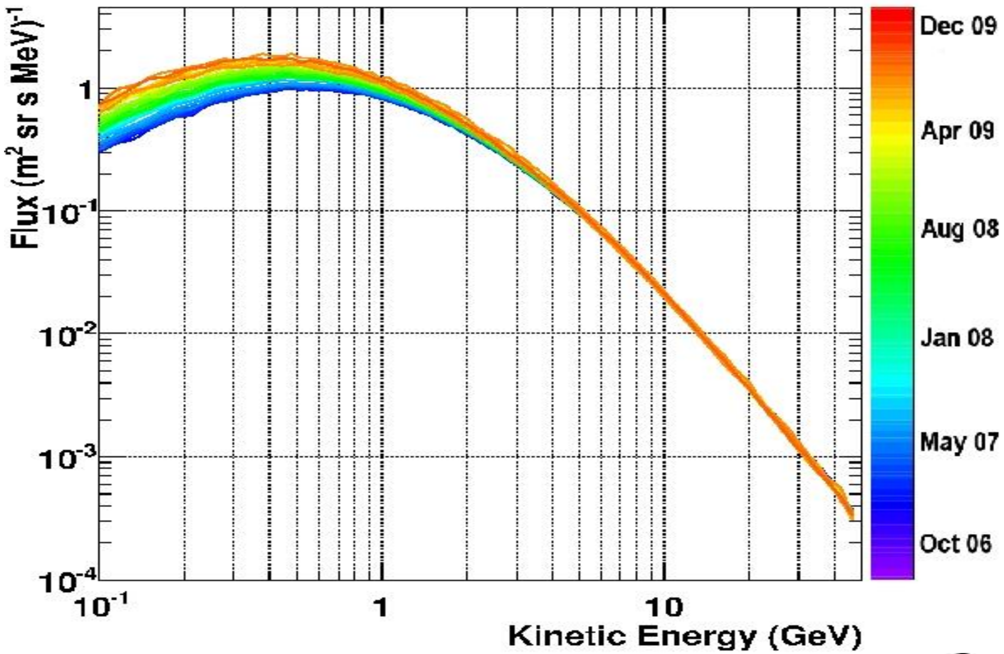
**Computed HCS tilt angle**

**From: http://**wso.stanford.edu

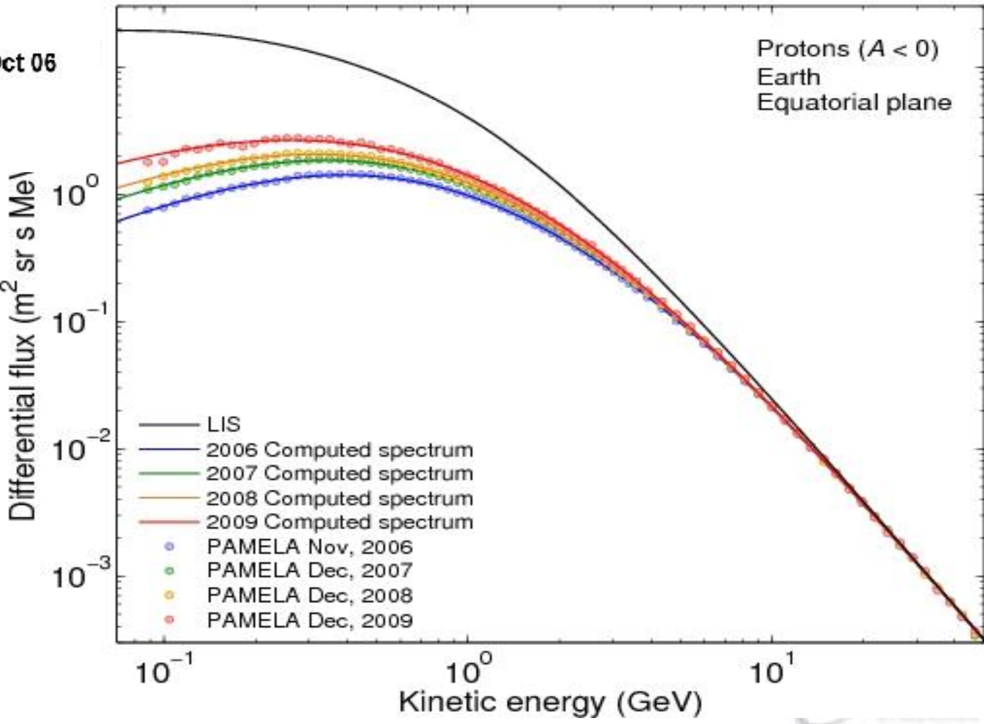



**PAMELA observations covers ~ one solar cycle**

# Time dependance of the proton flux




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

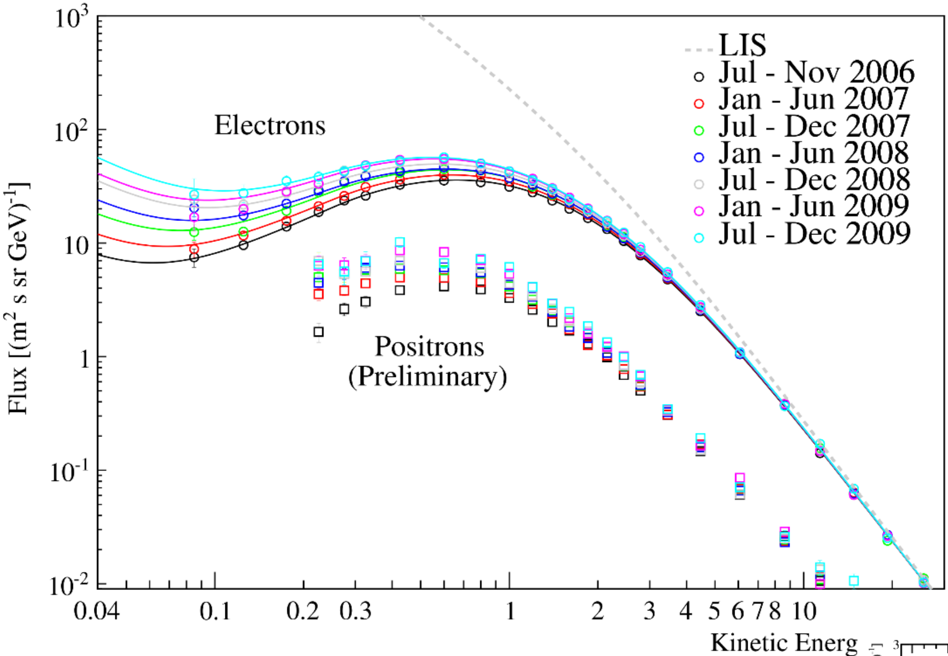



The PAMELA proton spectra over four months compared with the computed spectra

O. Adriani et al., ApJ 765 (2013) 91;

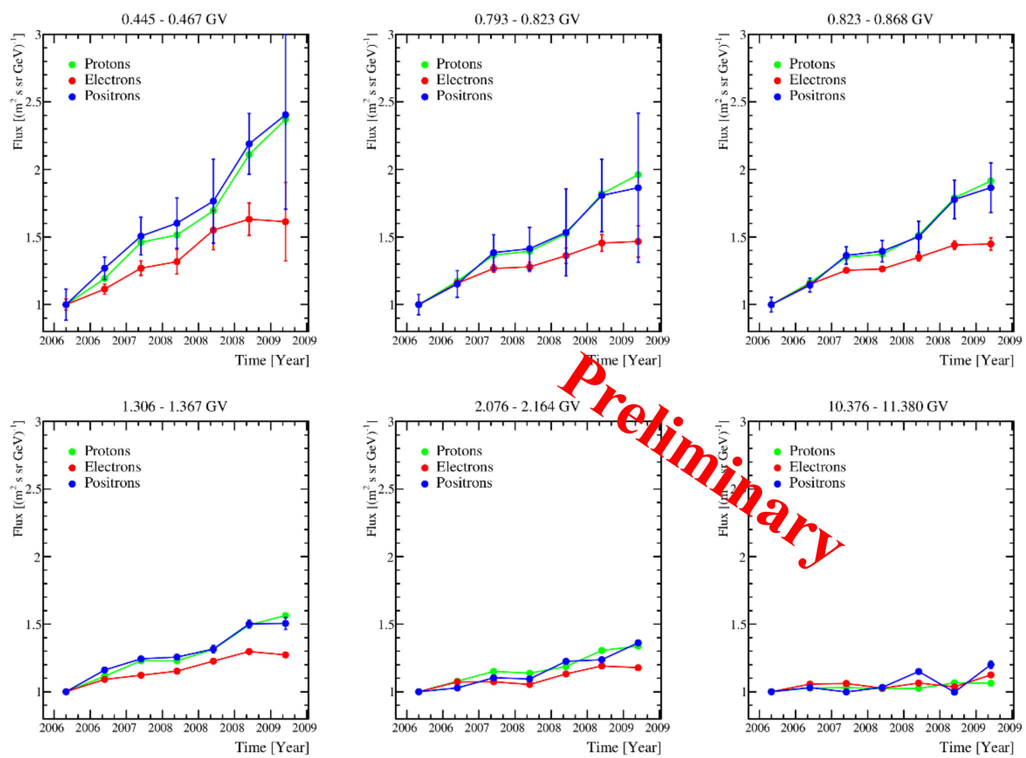
M. S. Potgieter et al., Solar Phys. 289 (2014) 391

# Time dependance of the $e^+$, $e^-$ and p fluxes over the last solar minimum

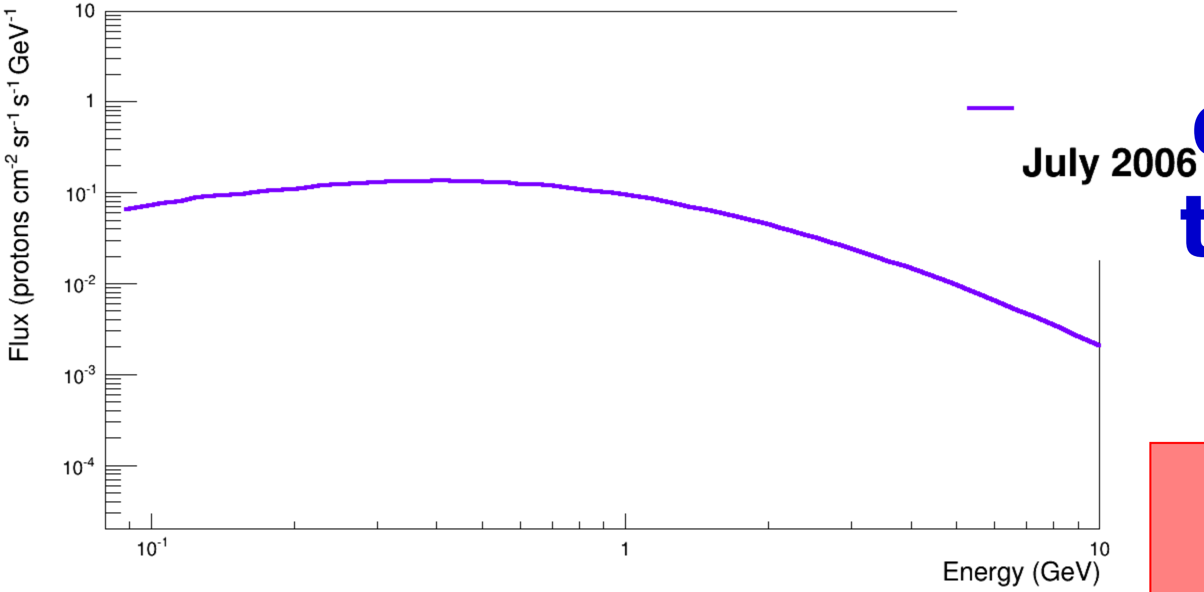



The PAMELA electron and positron spectra over the last solar minimum

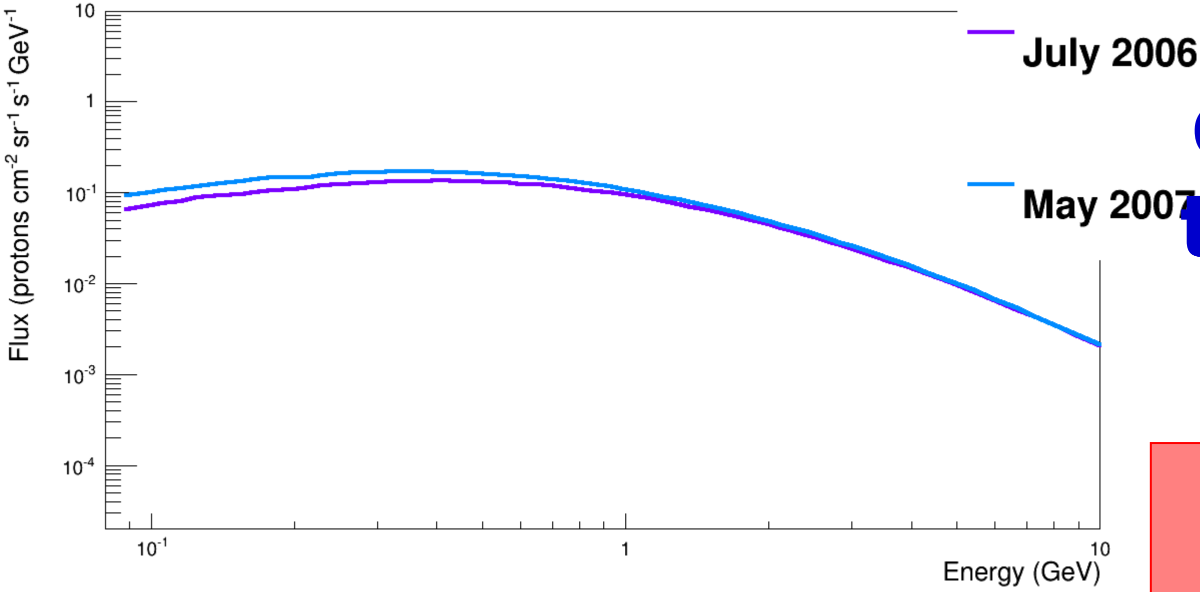
Variation of the $e^-$, $e^+$ and p flux between July 2006 and December 2009



# Time dependance of the $e^+$, $e^-$ and p fluxes



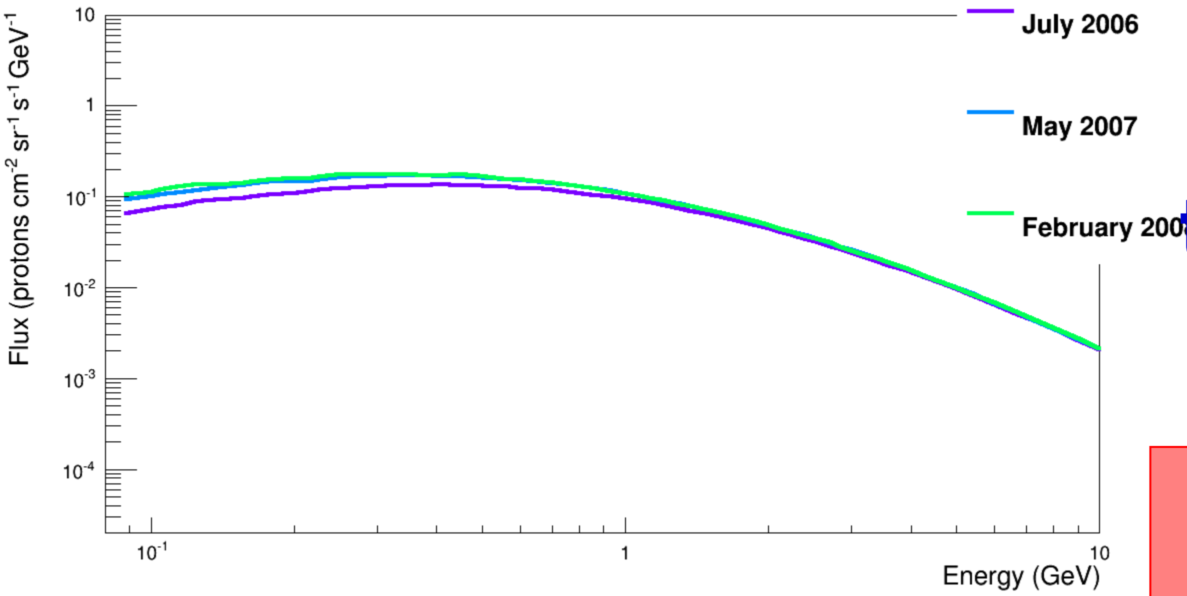

The proton spectrum from July 2006 to January 2014



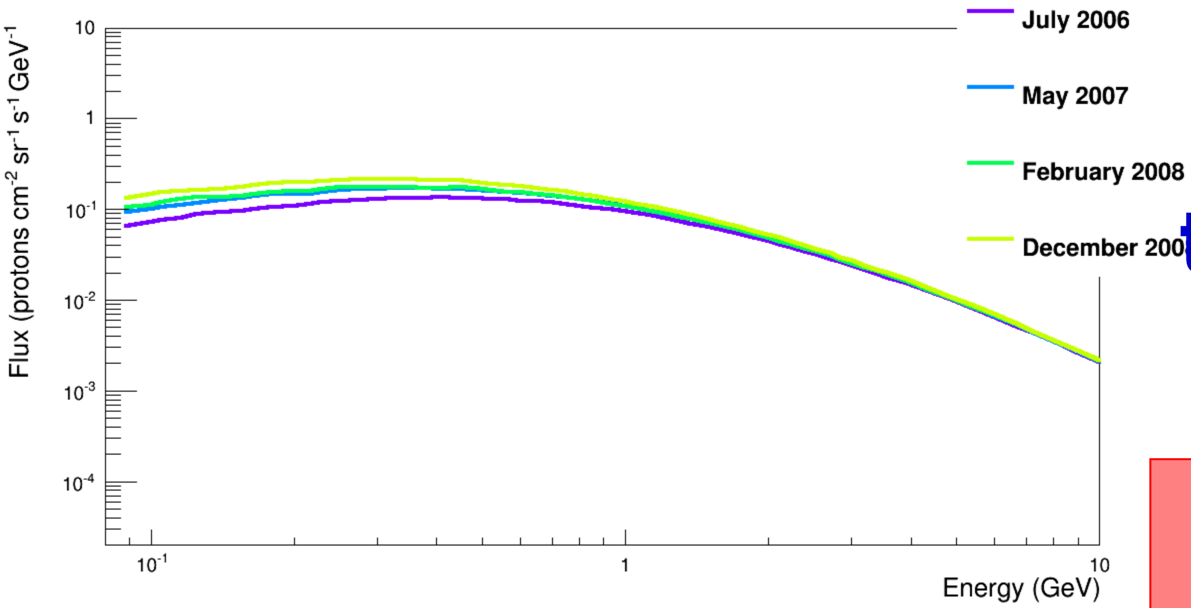

# Time dependance of the $e^+$, $e^-$ and p fluxes

The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes



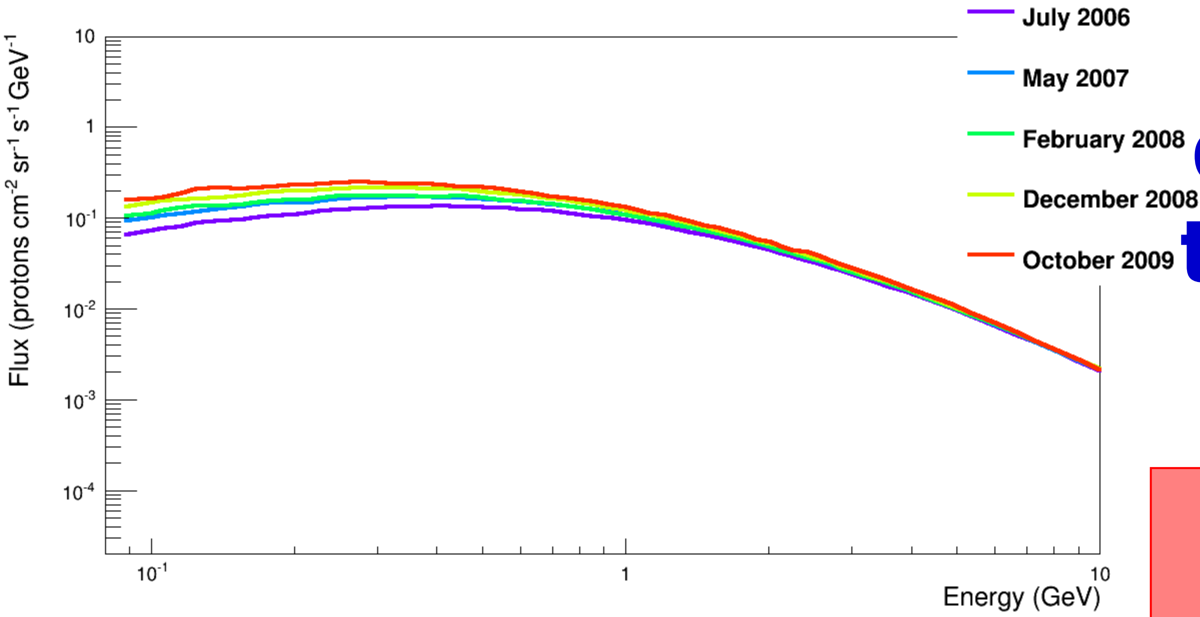

The proton spectrum from July 2006 to January 2014



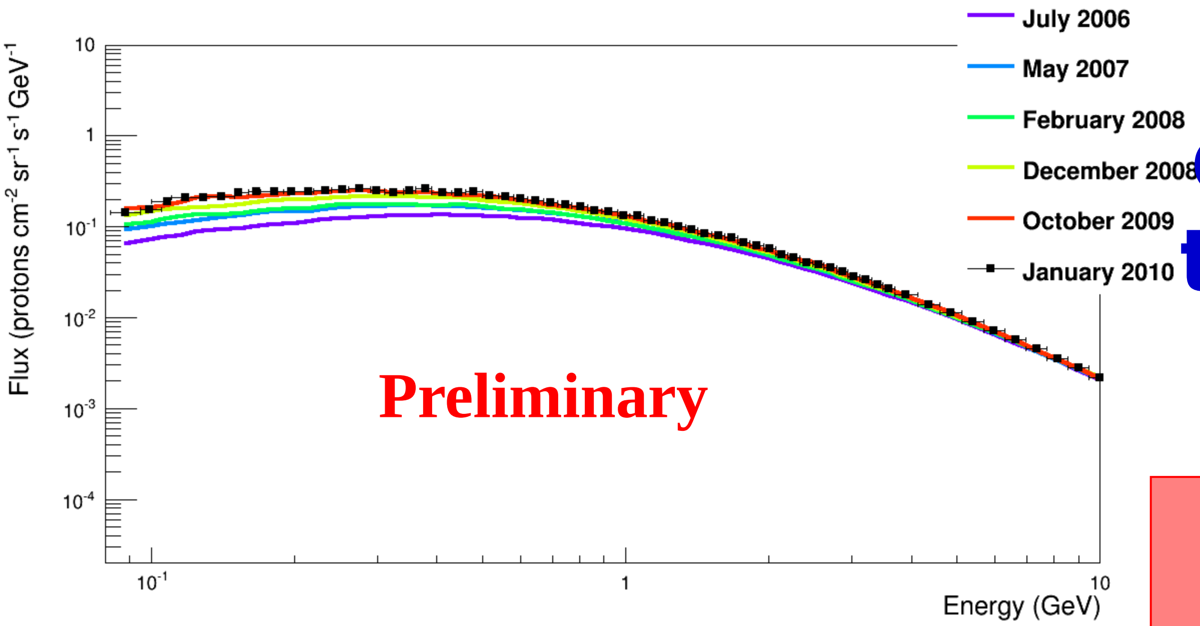

# Time dependance of the $e^+$, $e^-$ and p fluxes

The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes



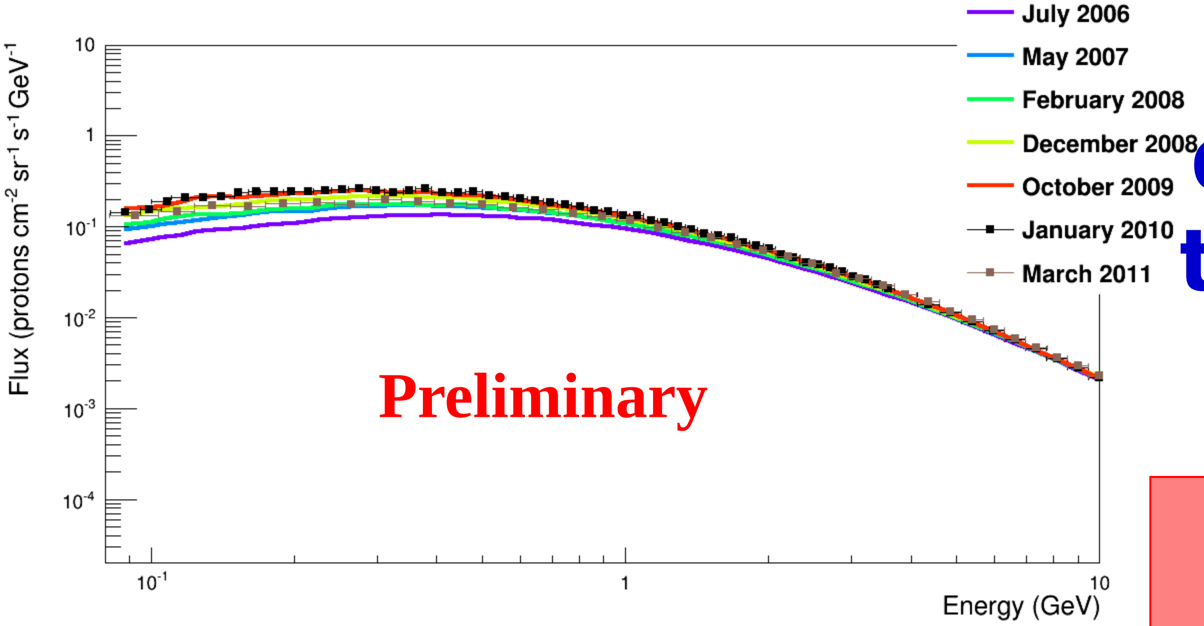

The proton spectrum from July 2006 to January 2014




# Time dependance of the $e^+$, $e^-$ and p fluxes

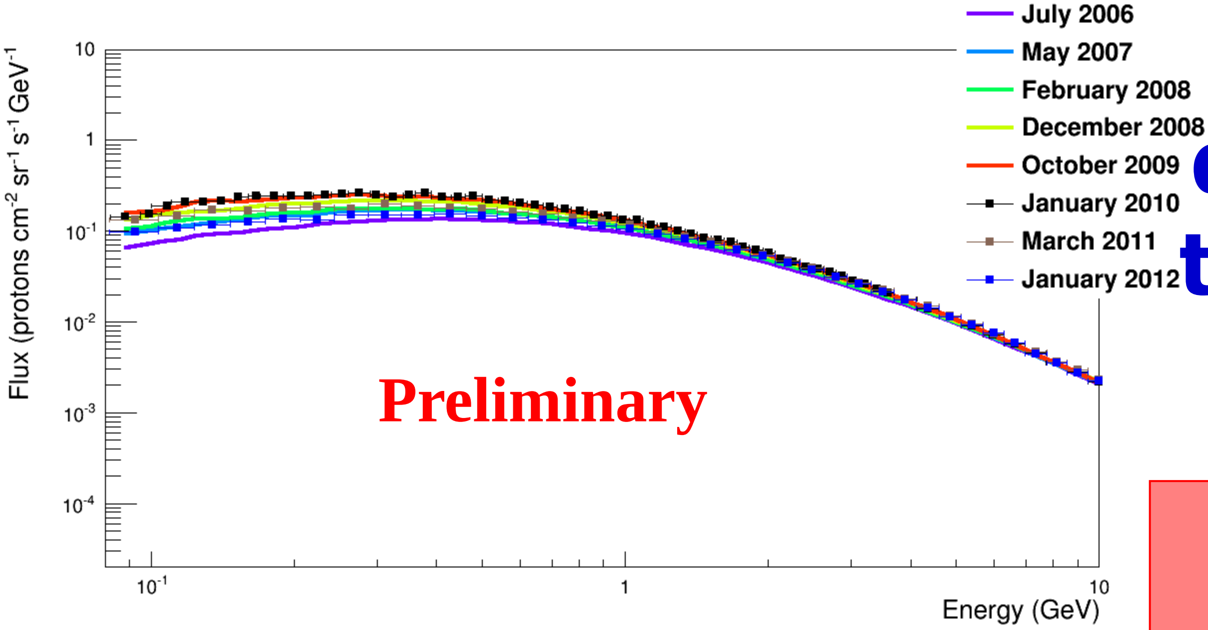
**The proton spectrum from July 2006 to January 2014**

# Time dependance of the $e^+$, $e^-$ and p fluxes



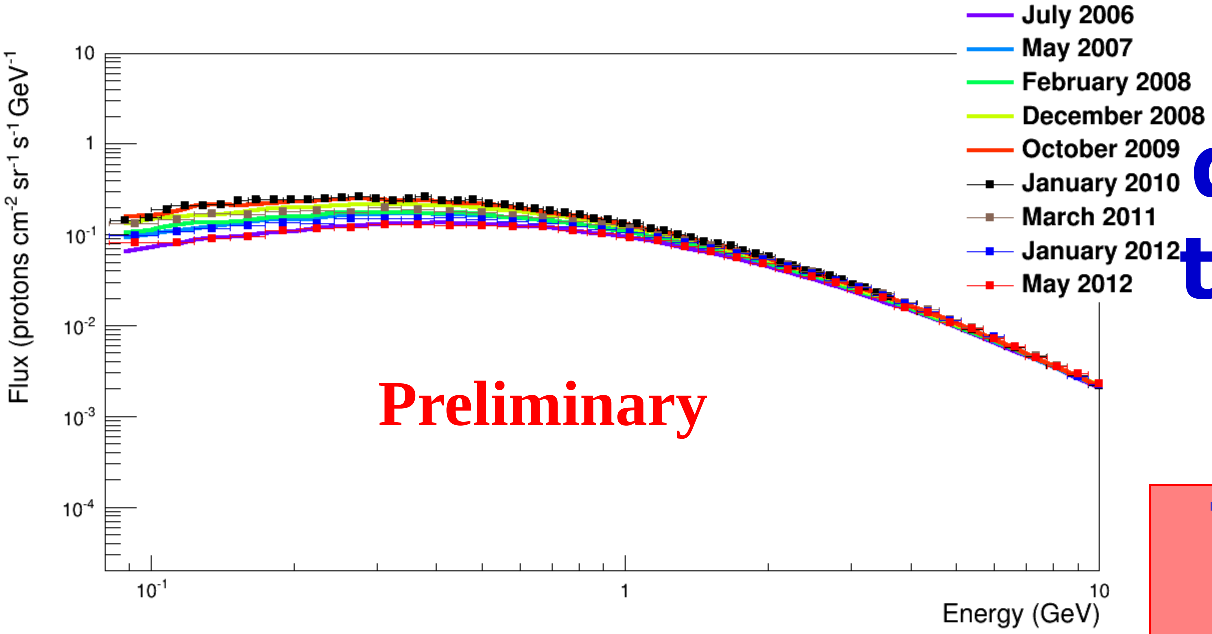

The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes



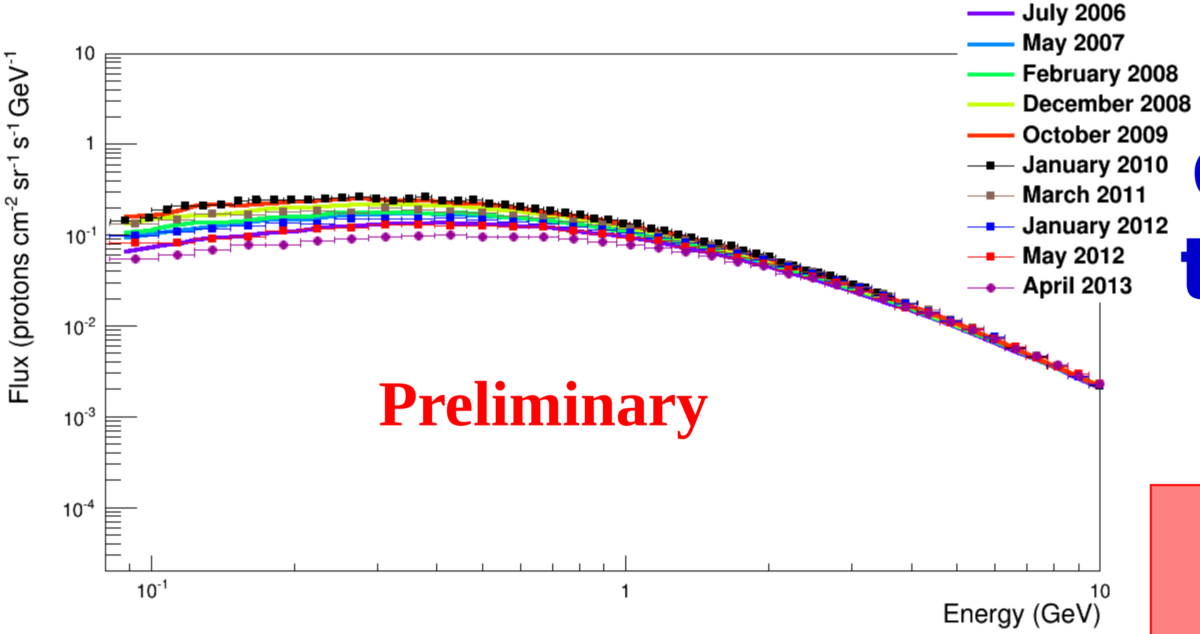

The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes

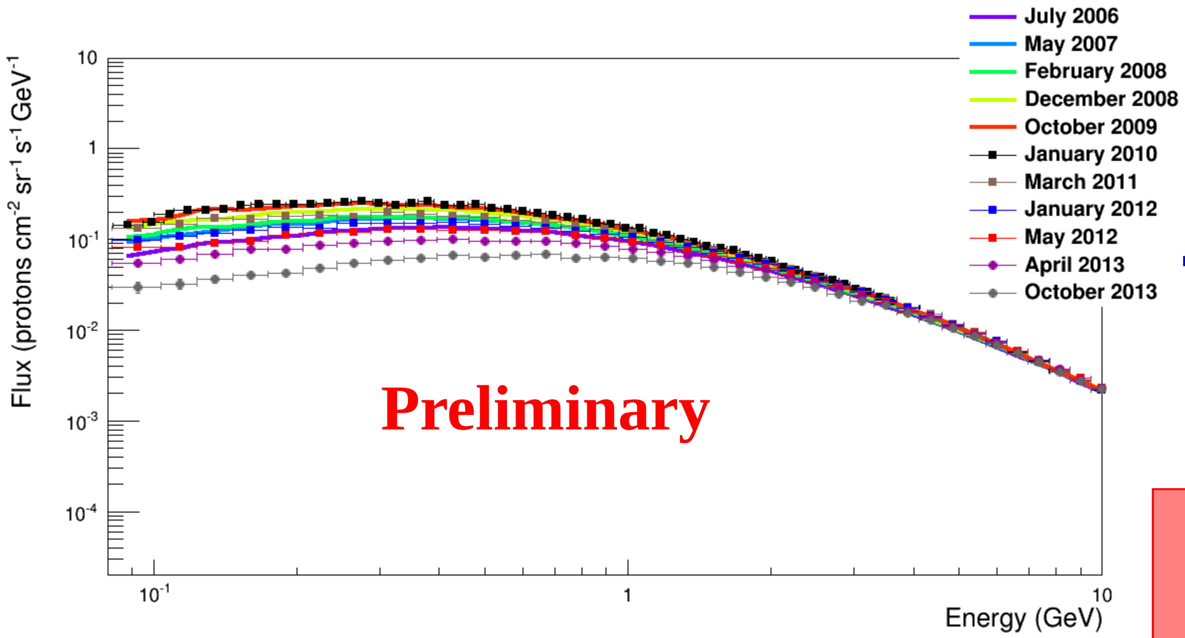



The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes



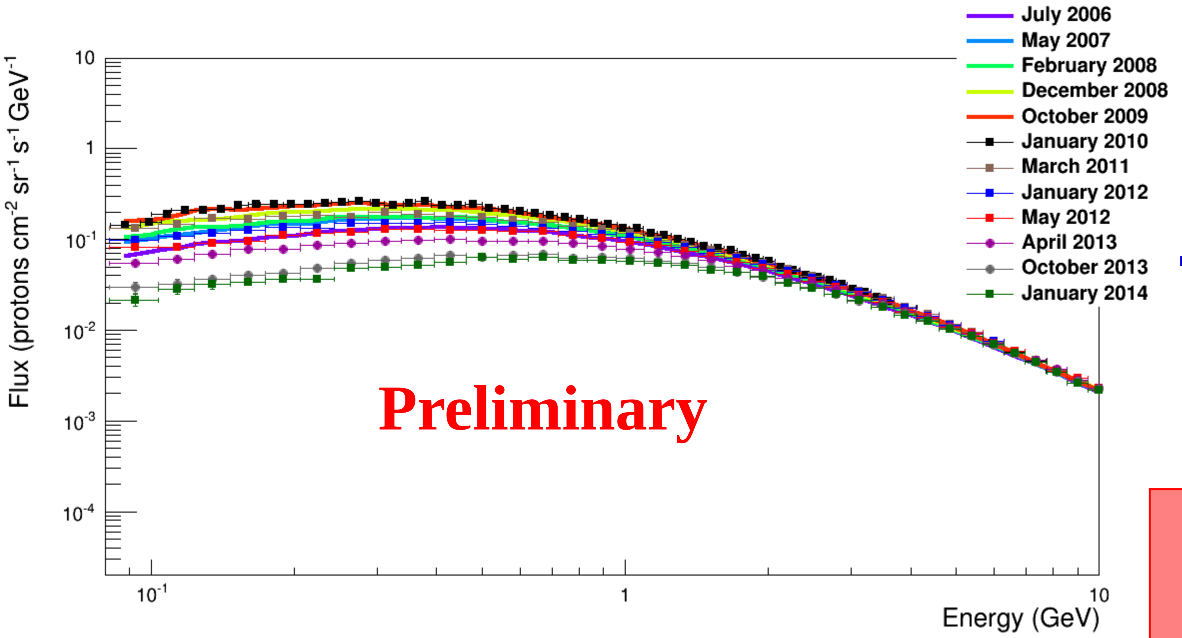

The proton spectrum from July 2006 to January 2014




# Time dependance of the $e^+$, $e^-$ and p fluxes

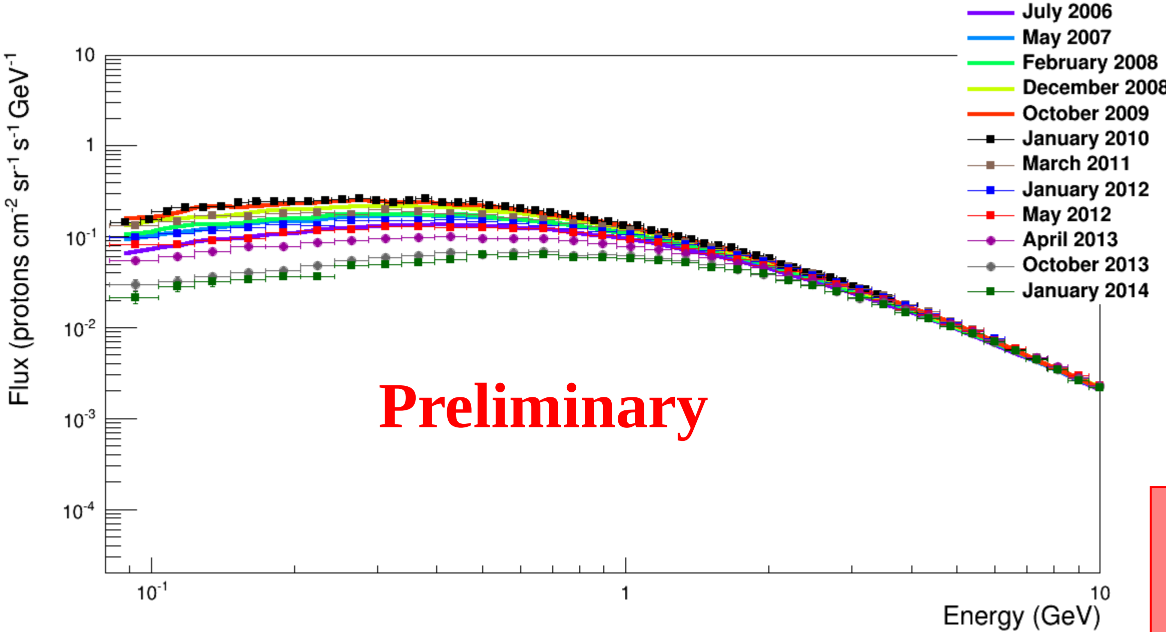
The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes



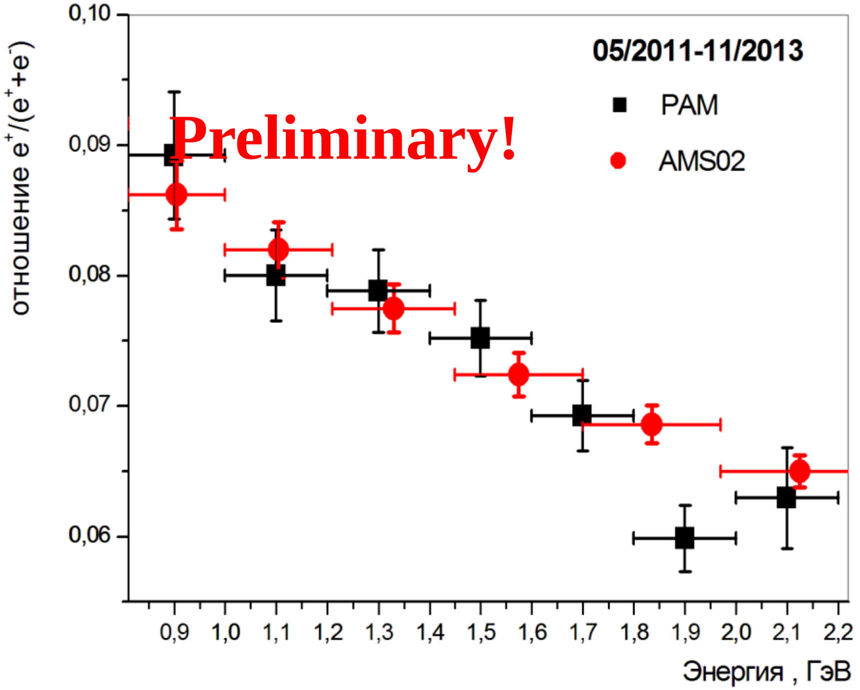

The proton spectrum from July 2006 to January 2014

# Time dependance of the $e^+$, $e^-$ and p fluxes

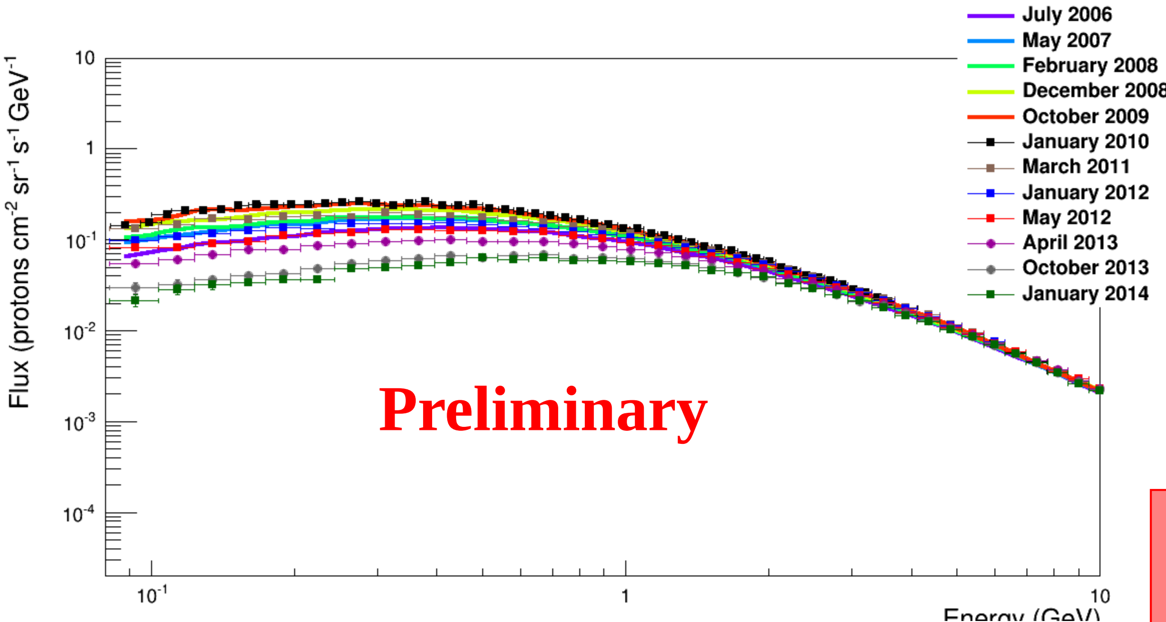



The proton spectrum from July 2006 to January 2014

Variation of the positron fraction from July 2006. Positron energy: 1.2 GeV

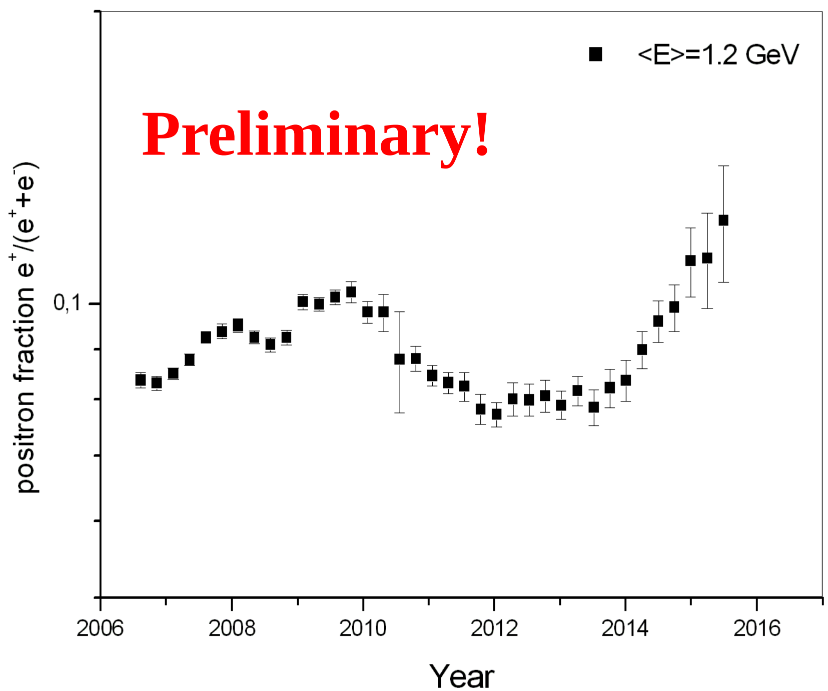


# Time dependance of the e+, e- and p fluxes

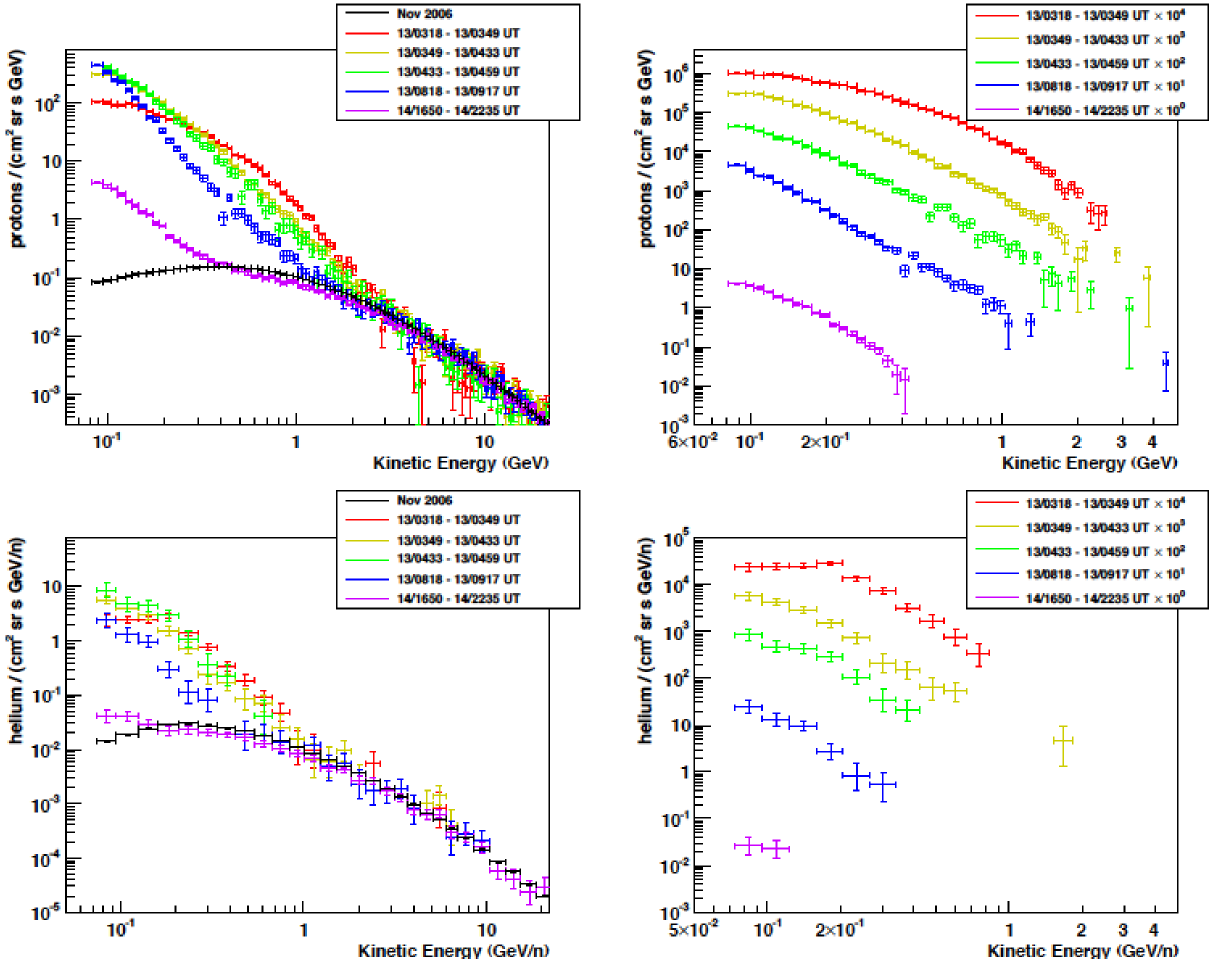



The proton spectrum from July 2006 to January 2014

Variation of the positron fraction from July 2006. Positron energy: 1.2 GeV

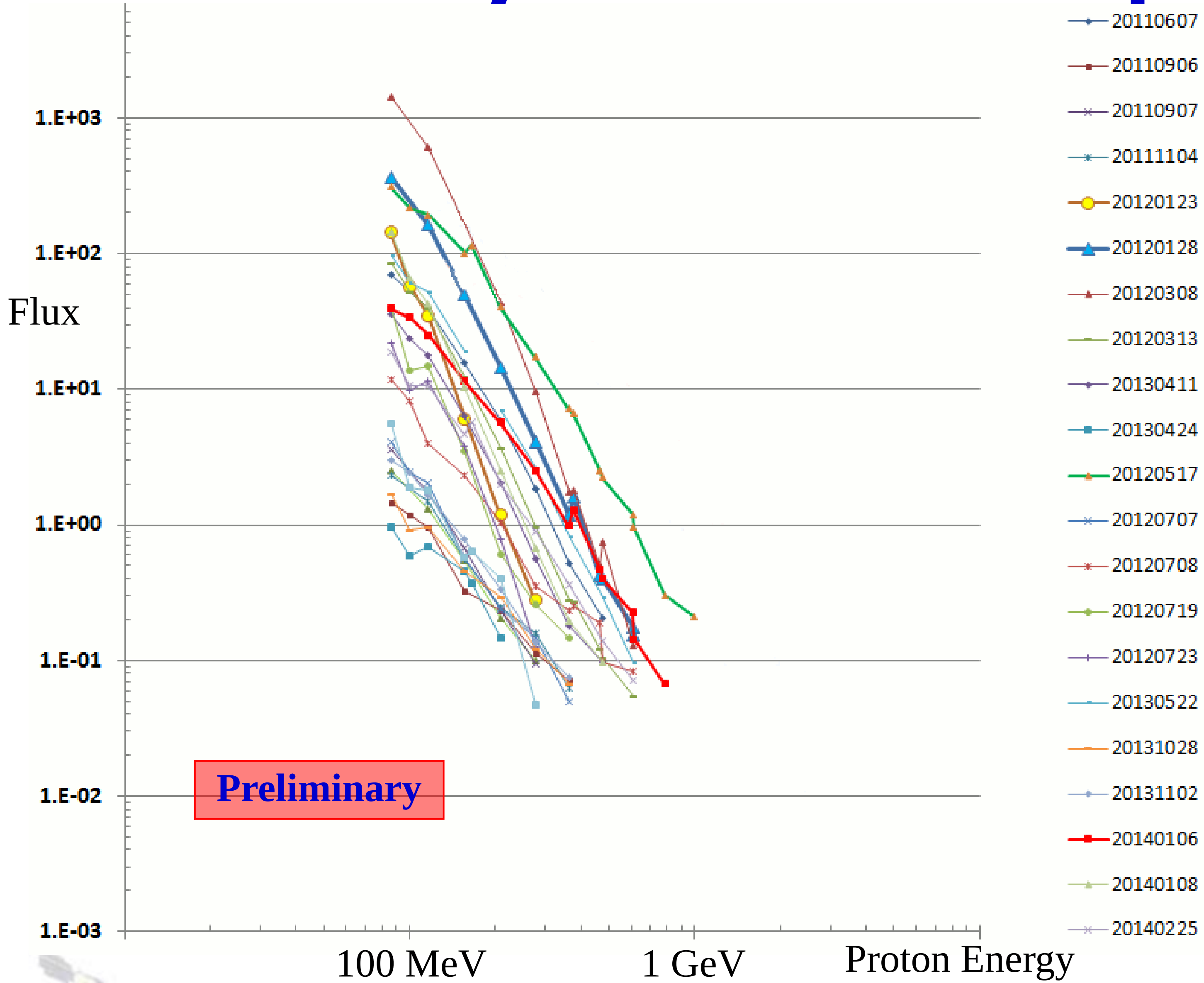


# SEP events (SEP from 2006 Dec. 13th)

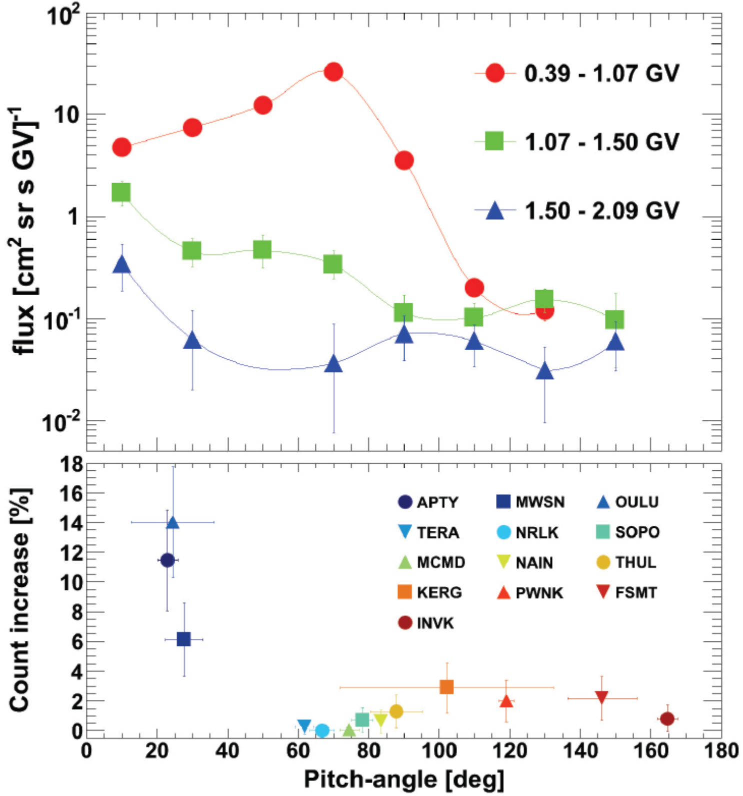


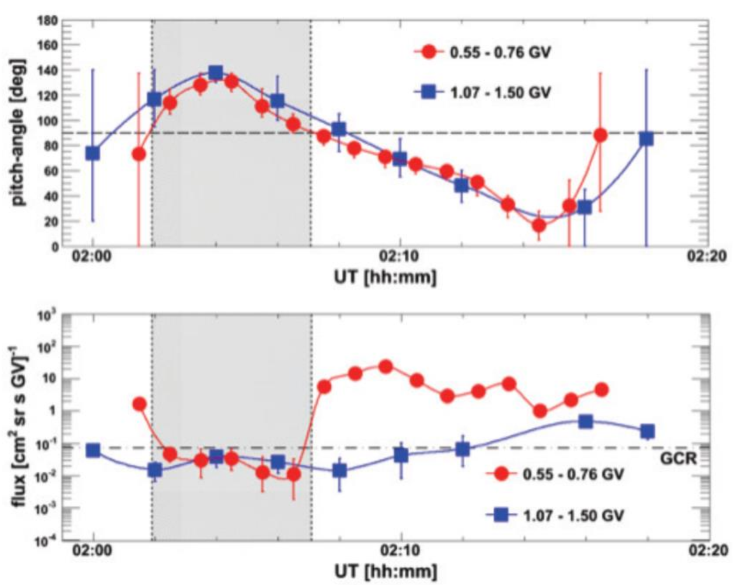

Adriani et al. - ApJ 742 102, 2011

# Preliminary PAMELA SEP Spectra




- PAMELA bridges the gap between low energy space-based and ground--based measurements to obtain a complete spectrum



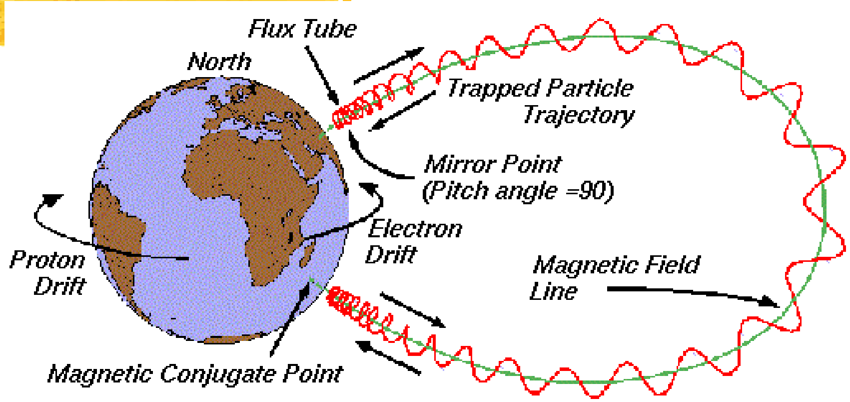

- During 2012 May 17th event PAMELA observed 2 energy components with different pitch angle distribution:
  - **High rigidity component** consistent with NM where particles are field aligned -> Beam width ~40-60° (not scattered)
  - **Low rigidity component** shows significant scattering for pitch angles ~90°

- For both populations to arrive at Earth simultaneously and soon after onset of the event (~ 8 minutes) the scattering must take place locally

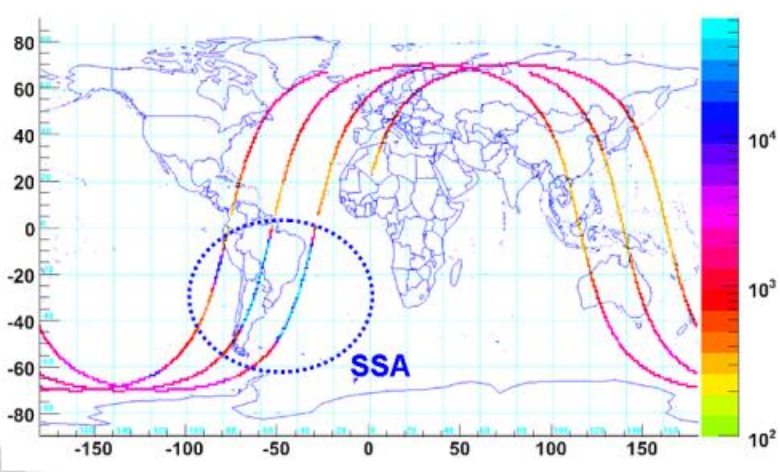
**Adriani et al., ApJL 801 (2015) L3**

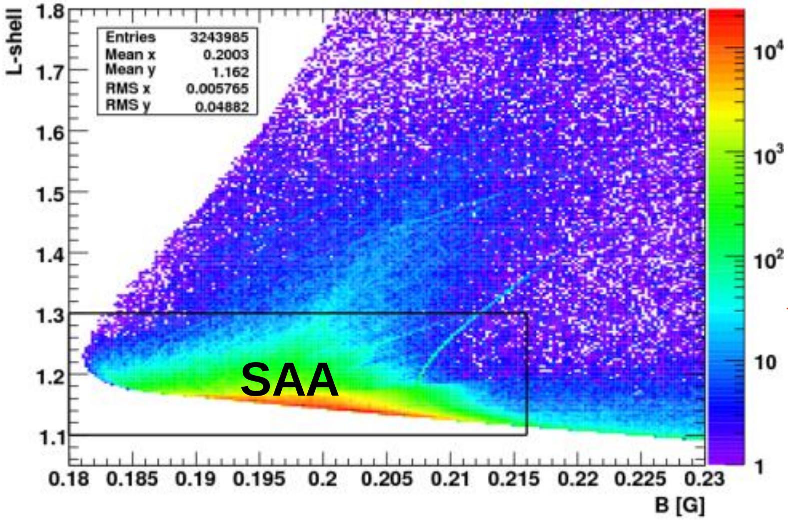
# Under cut-off (anti)particles

- Thanks to the semi-polar (70 deg inclination) and elliptical (350-610 km altitude) satellite orbit, PAMELA is able to perform energy spectra and particle composition measurements in different regions of the terrestrial magnetosphere.
- Clear separation of the trapped, untrapped and semi-trapped components in the lower magnetosphere and SAA.



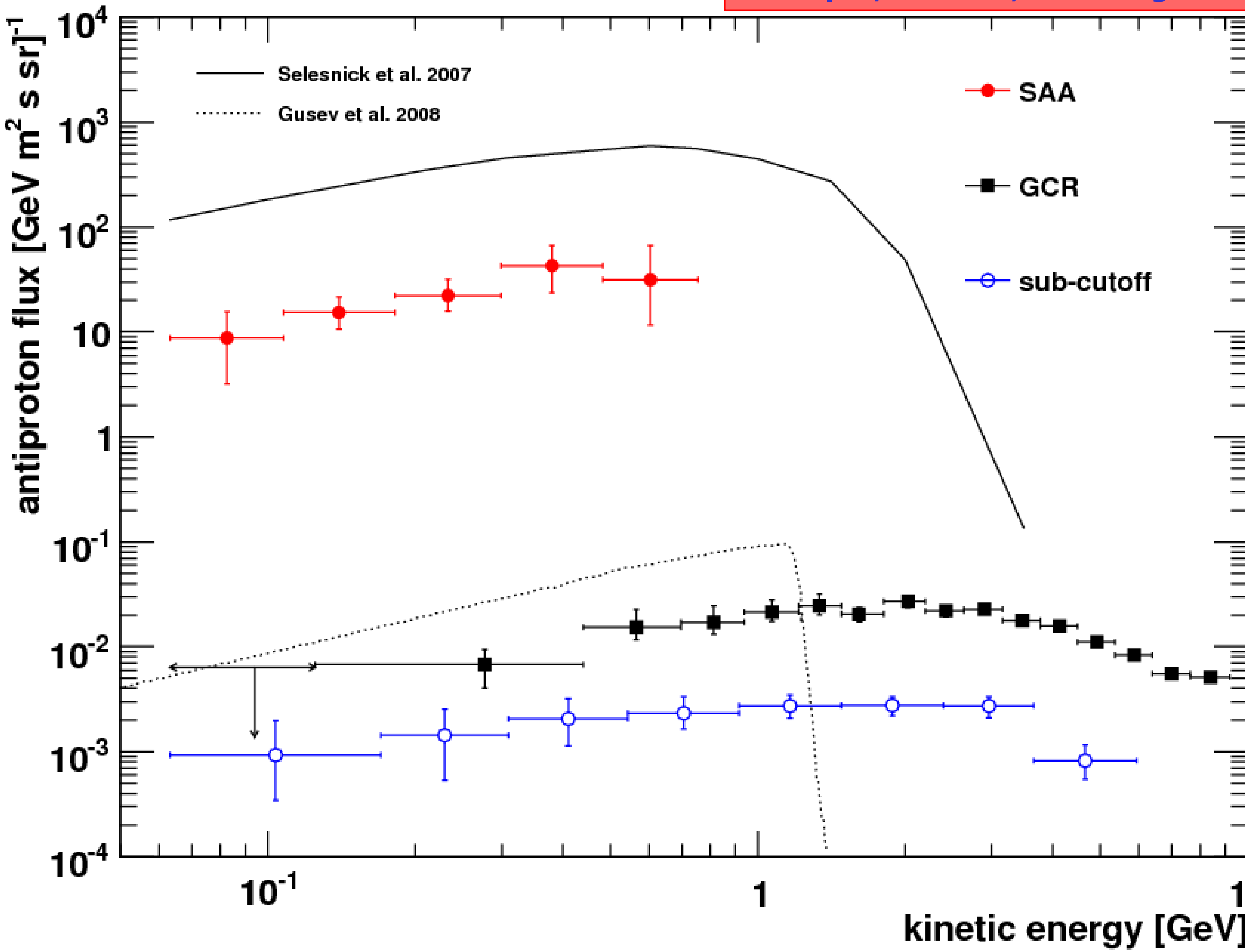

**Under-cutoff proton candidates distribution as a function of L-shell and geomagnetic field intensity B [G].**



# Antiproton trapped in the SAA

ApJL, 737:L29, 2011 August 20



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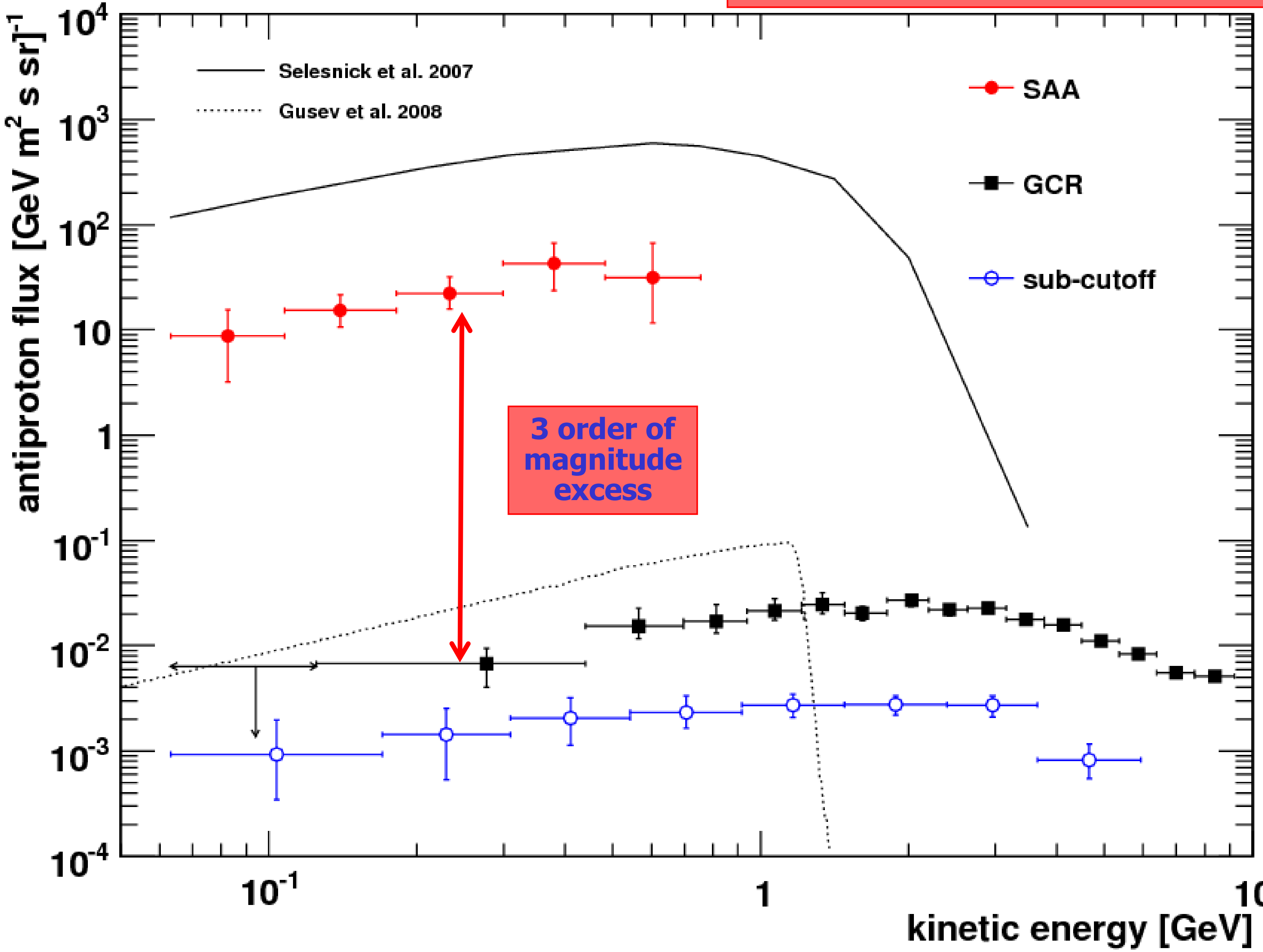
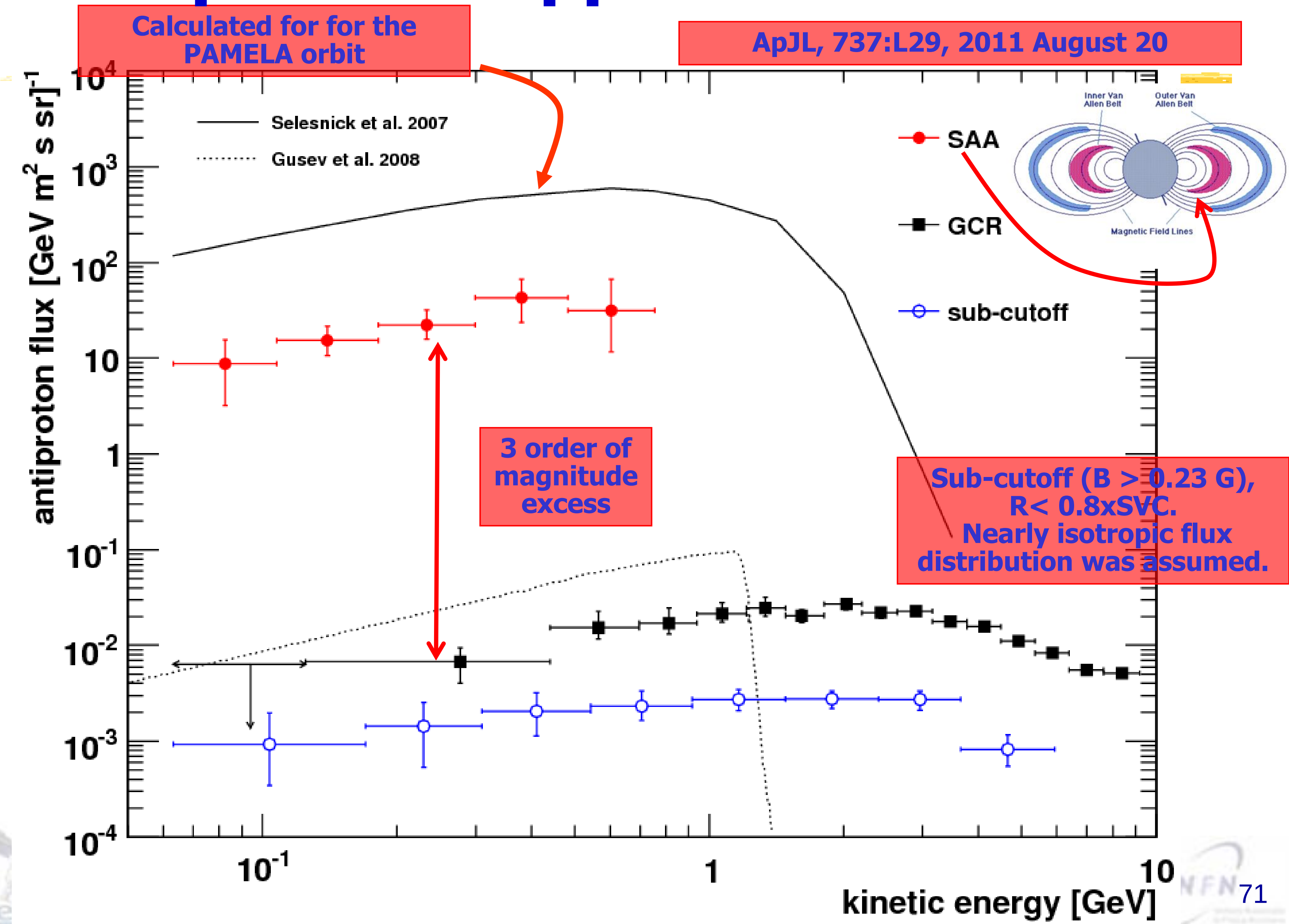
ApJL, 737:L29, 2011 August 20

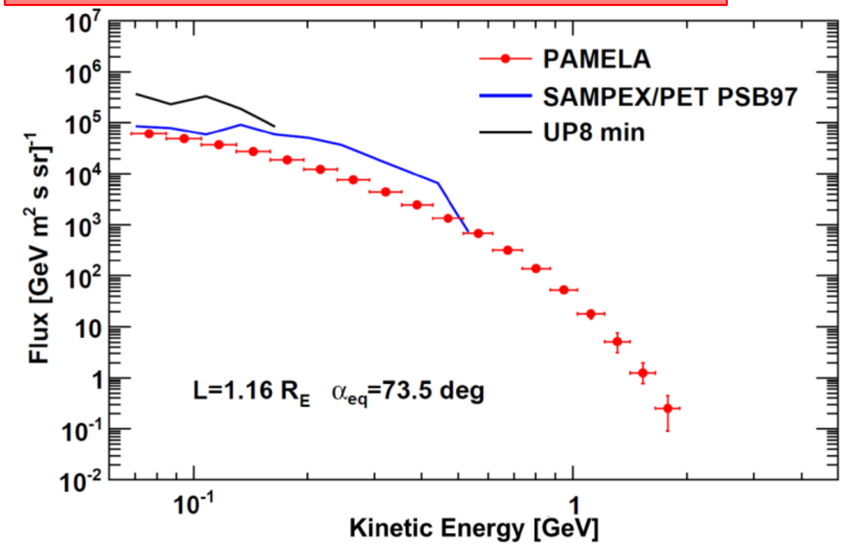


# Antiproton trapped in the SAA



# Geomagnetically trapped and albedo protons

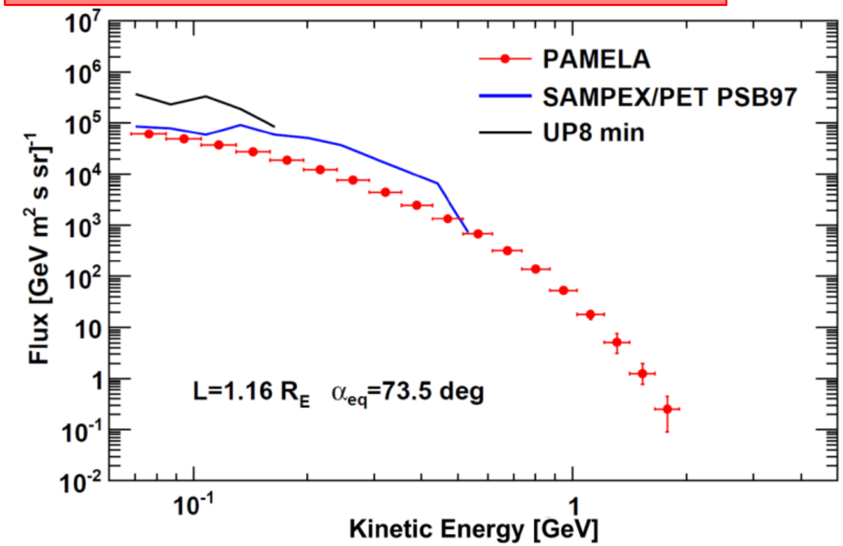
Trapped proton in the SAA, comparison with empirical models



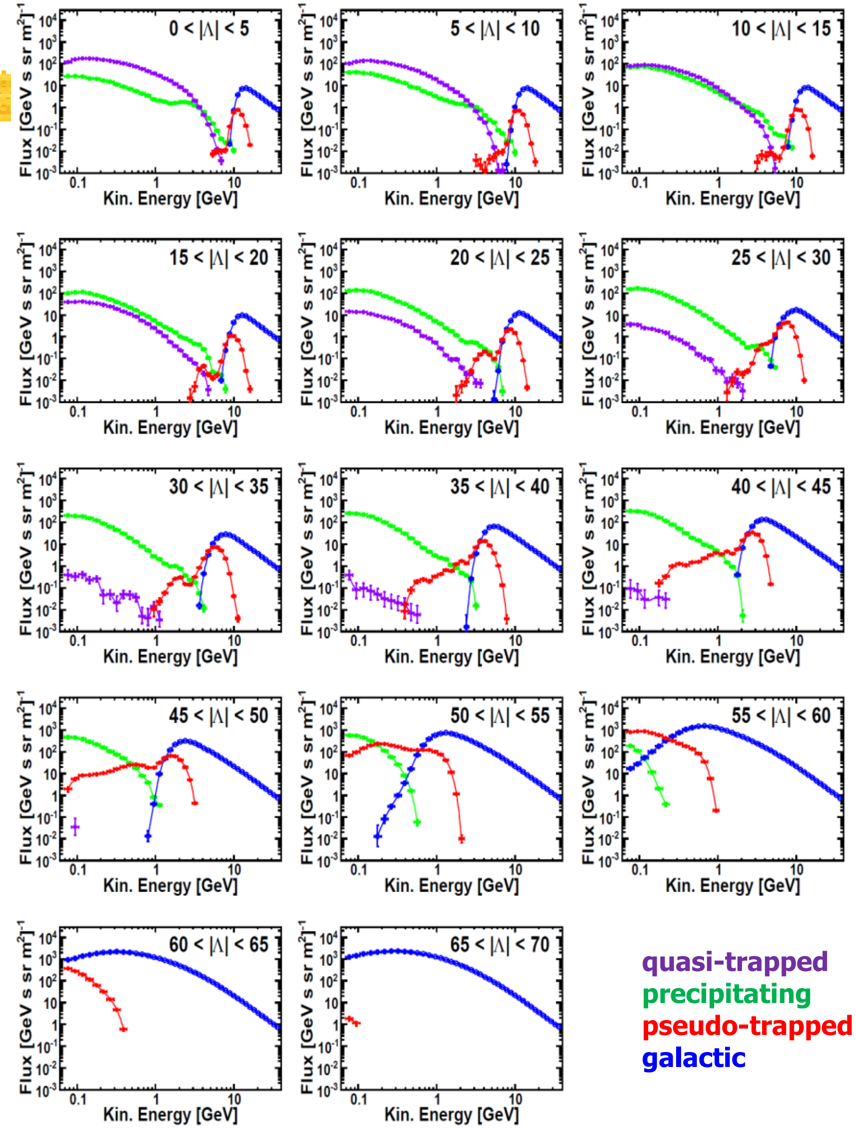

Adriani et al., ApJL 799 (2015) L4

# Geomagnetically trapped and albedo protons

**Trapped proton in the SAA, comparison with empirical models**




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




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

# Conclusions

- With PAMELA we are entered in the new era of precision measurements of (anti)particle fluxes in CR.
- 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.
- What has been done:
  - Antiproton energy spectrum and ratio ▪ Measured up to ~300 GeV. No significant 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.
  - H and He absolute fluxes ▪ Measured up to ~1.2 TV. Complex spectral structures observed (spectral hardening at ~200 GV).
  - H and He isotope fluxes and ratio -> most complete measurements so far.
  - 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 !!!!