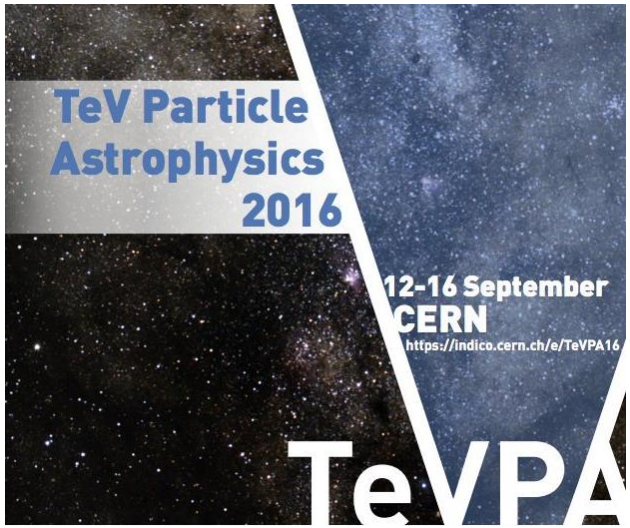
# New results from PAMELA after 10 years in orbit




**Matteo Martucci**

*INFN, Laboratori Nazionali di Frascati & University of Rome "Tor Vergata"*

*Matteo.martucci@roma2.infn.it*

# PAMELA COLLABORATION

**Italy**

Bari Florence Frascati Naples Rome Trieste

**USA**

New Mexico

New Hampshire

**Russia**

Moscow
St. Petersburg

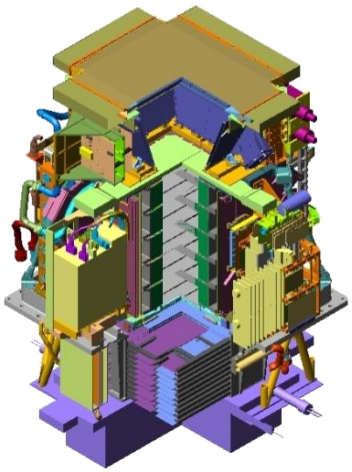
**Germany**

Siegen

**Sweden**

KTH, Stockholm

# PAMELA INSTRUMENT

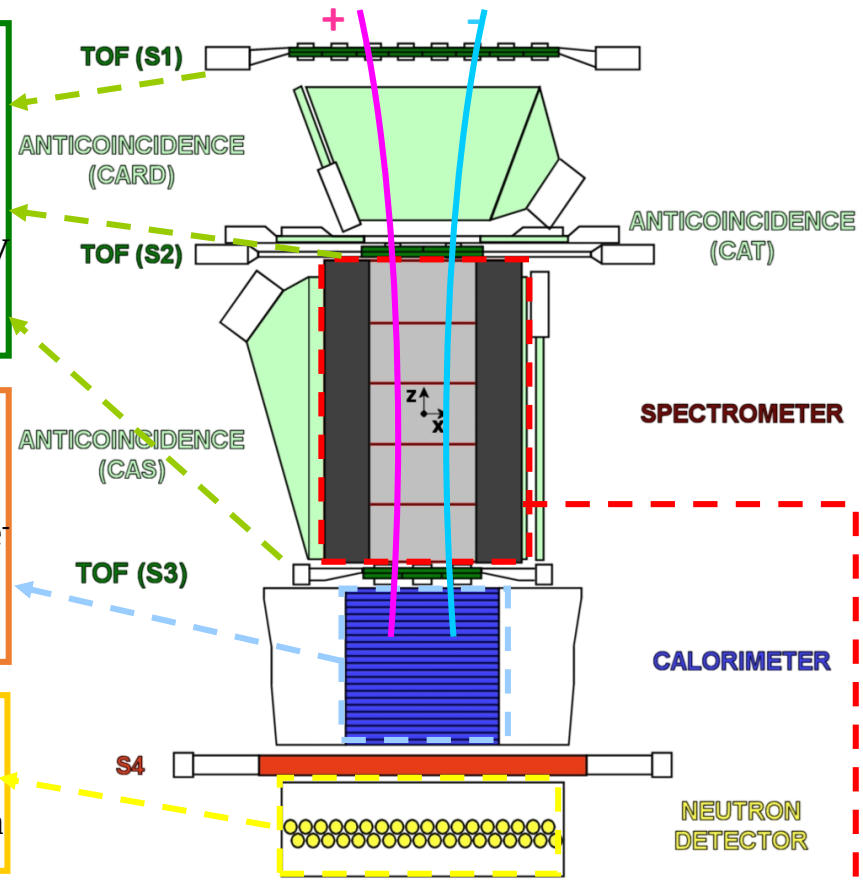


GF: 21.5 $cm^2$ sr
Mass: 470 kg
Size: 130x70x70 $cm^3$
Power Budget: 360W

**Time-Of-Flight**
plastic scintillators + PMT
- Trigger
- Albedo rejection
- Mass identification up to 1 GeV
- Z identification from *dE/dx*

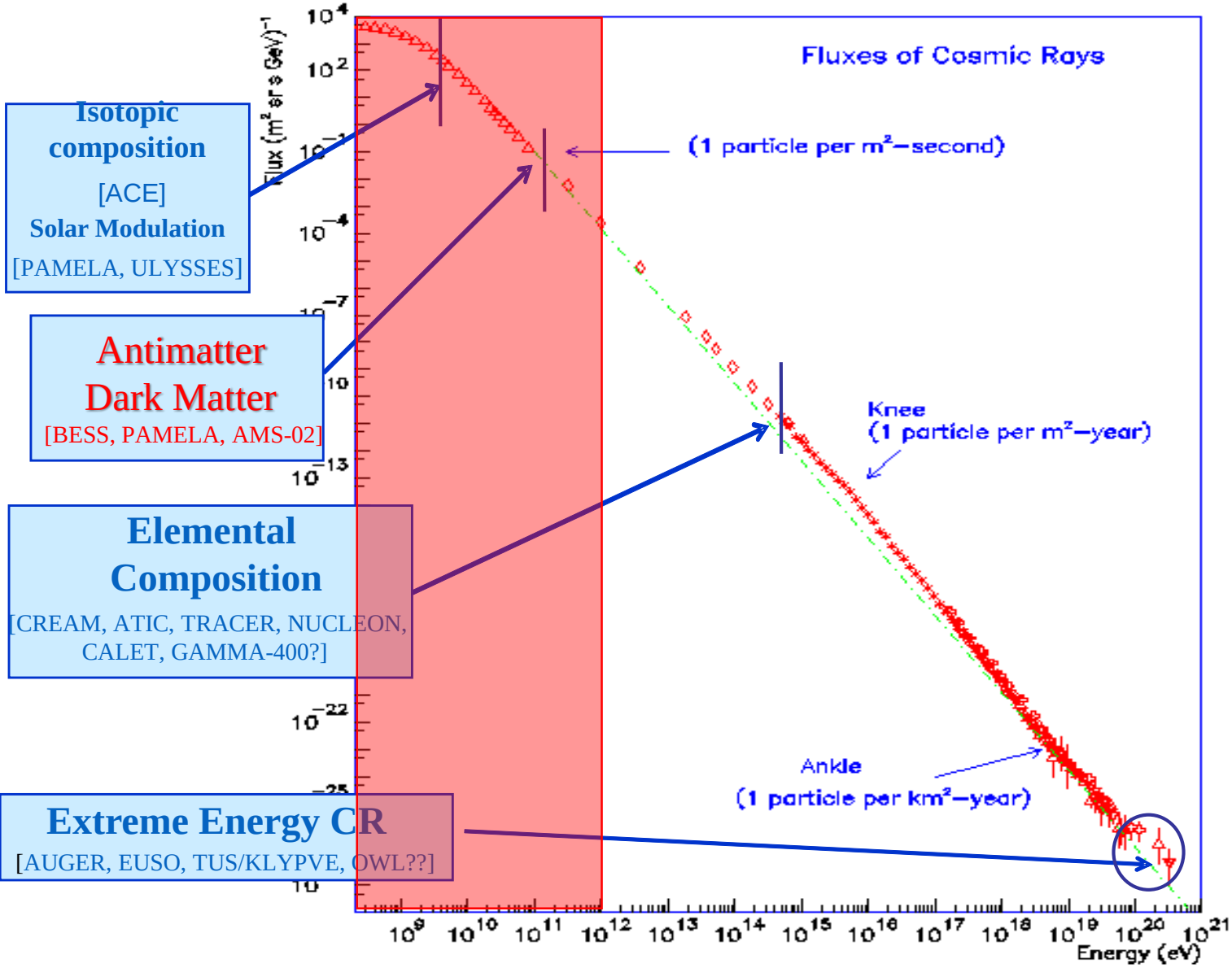
**Electromagnetic calorimeter**
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination $e^+$ / p, anti-p / $e^-$
- Direct E measurement for $e^-$

**Neutron detector**
plastic scintillators + PMT
- High-energy e/h discrimination

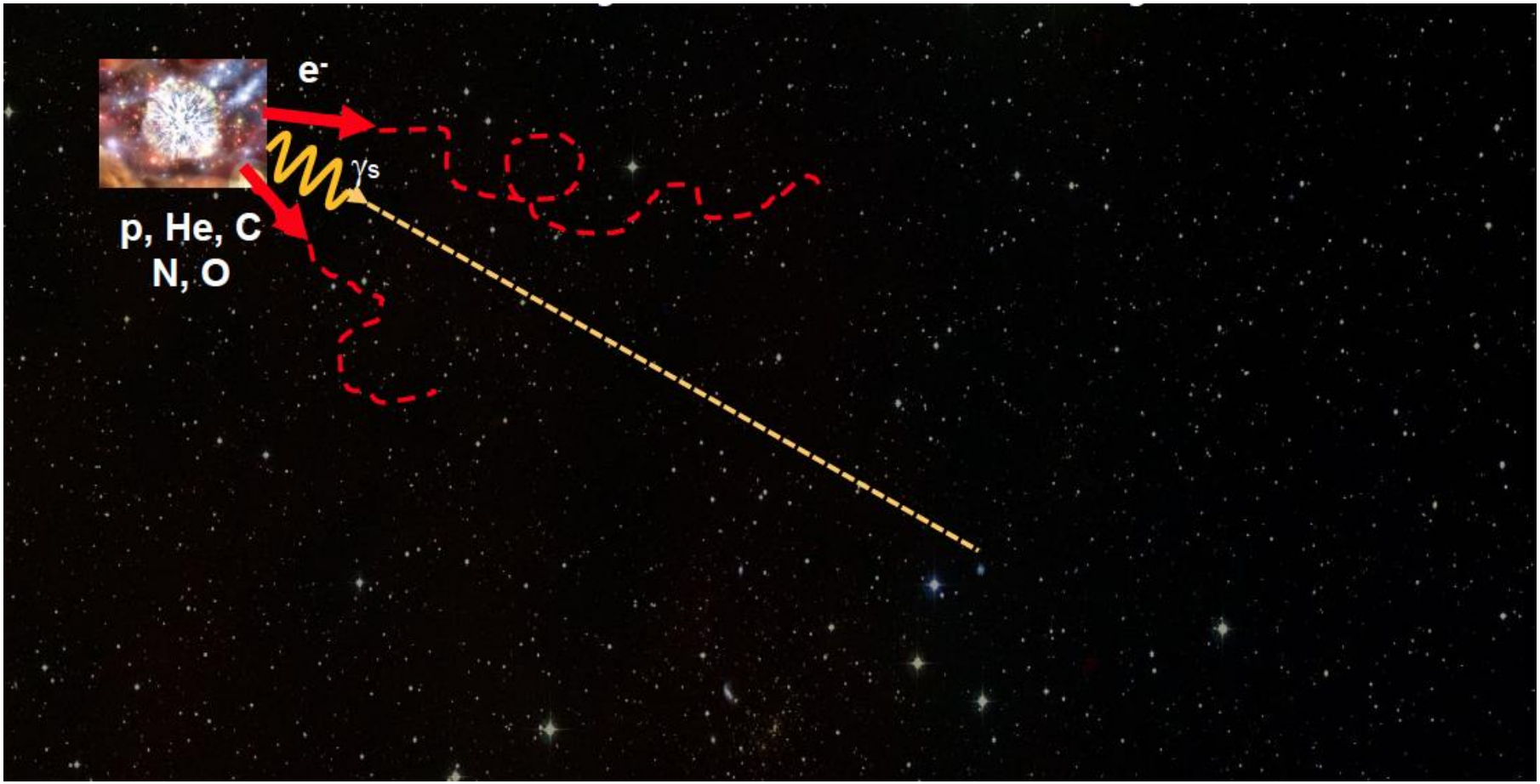



**Spectrometer**
microstrip silicon tracking system + permanent magnet
- Magnetic rigidity → R = pc/Ze
- Z sign
- Z value from *dE/dx*

# THE COSMIC RAY SPECTRUM



# PAMELA STUDIES: PRIMARY COMPONENT

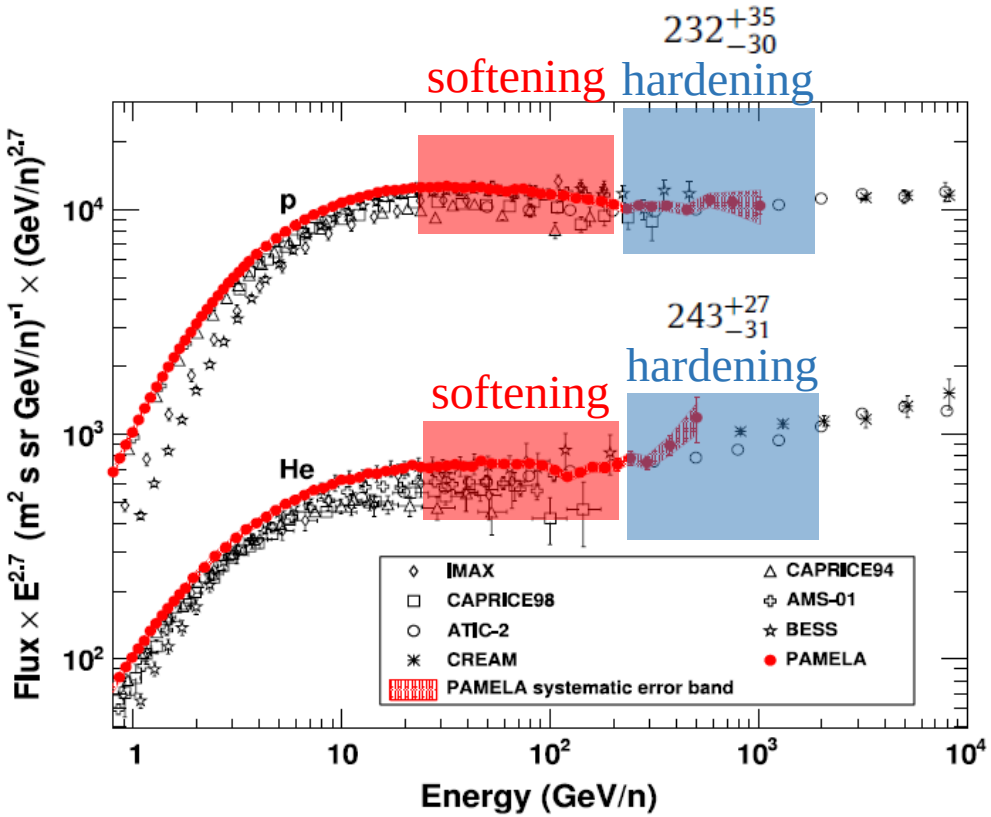



**Absolute fluxes of primary GCRs**

Protons, Helium nuclei, electrons etc

# p, He SPECTRA & H/He RATIO

**July 2006 – March 2008**

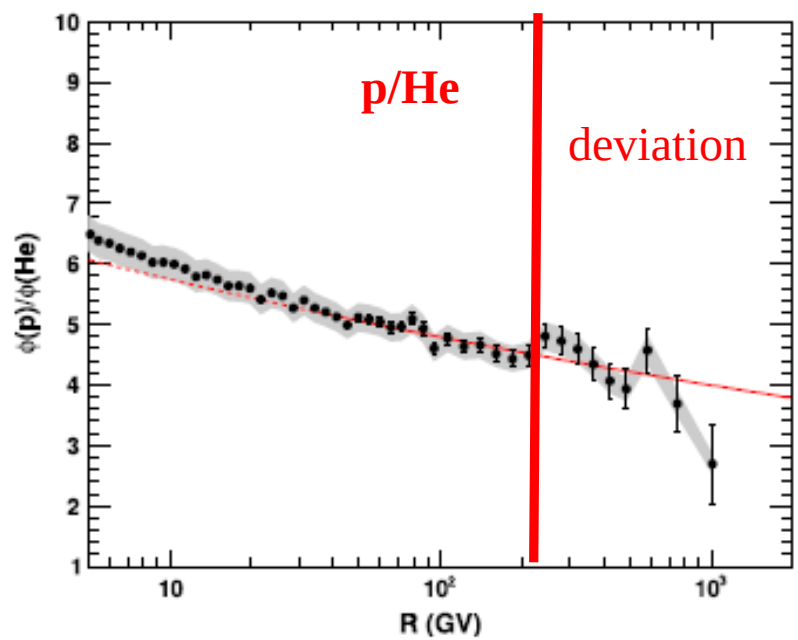



Adriani, O et al., Science 332 (2011) 6025

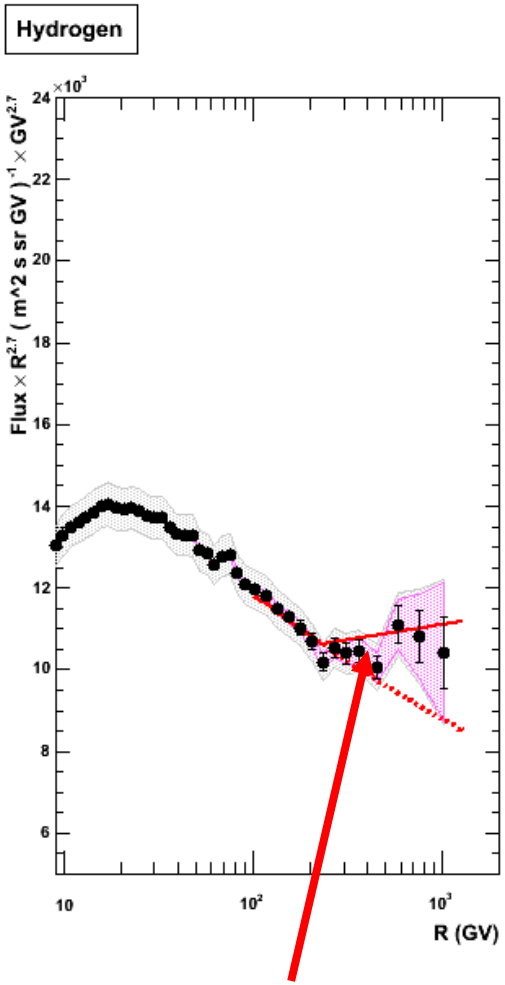
Adriani, O et al, Phys. Rep. (2014)

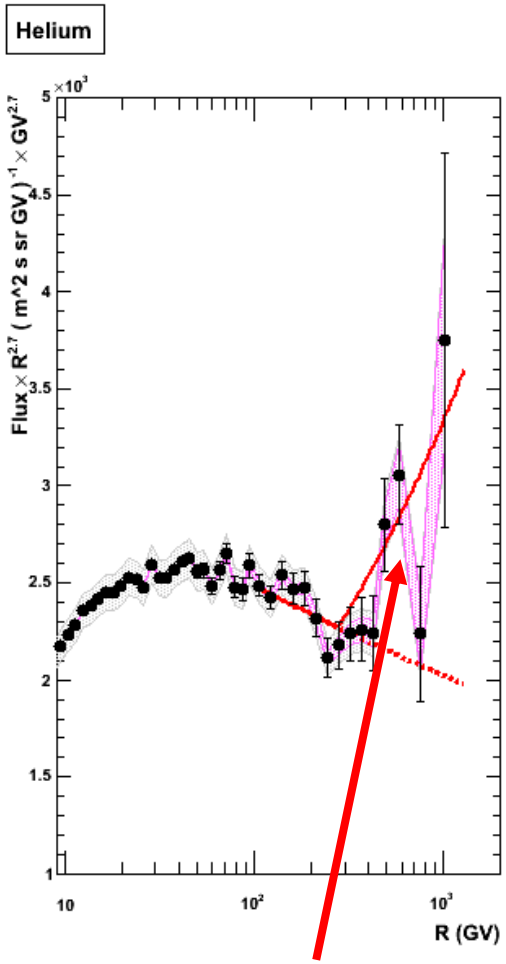
- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (99.7 %):
  - Spectra gradually **soften** in the range 30÷230 GV
  - Spectral **hardening** @ R~235 GV $\Delta\gamma$~0.2÷0.3

Origin of the hardening?
(e.g. *see P. Blasi, arXiv:1312.1590*)
- At the sources: multi-populations, etc.?
- Propagation effects?



# P, He SPECTRA & H/He RATIO




$$\gamma^{R}_{>232\mathrm{GV,p}} = 2.67 \pm 0.03 \pm 0.05$$

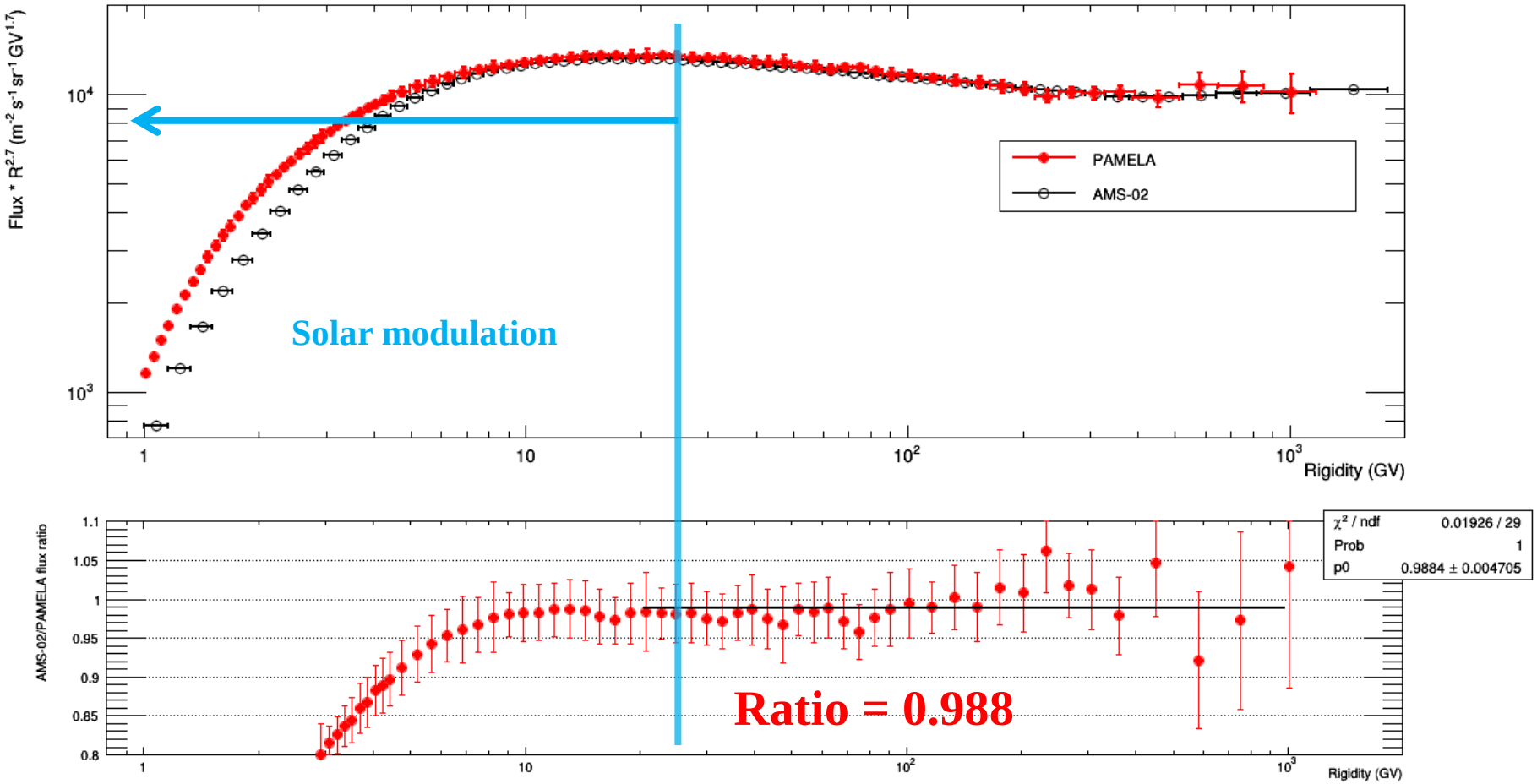
$$\gamma^{R}_{>243\mathrm{GV,He}} = 2.477 \pm 0.06 \pm 0.03 .$$

**Clear evidence of different H and He slopes**

## INTERPRETATIONS

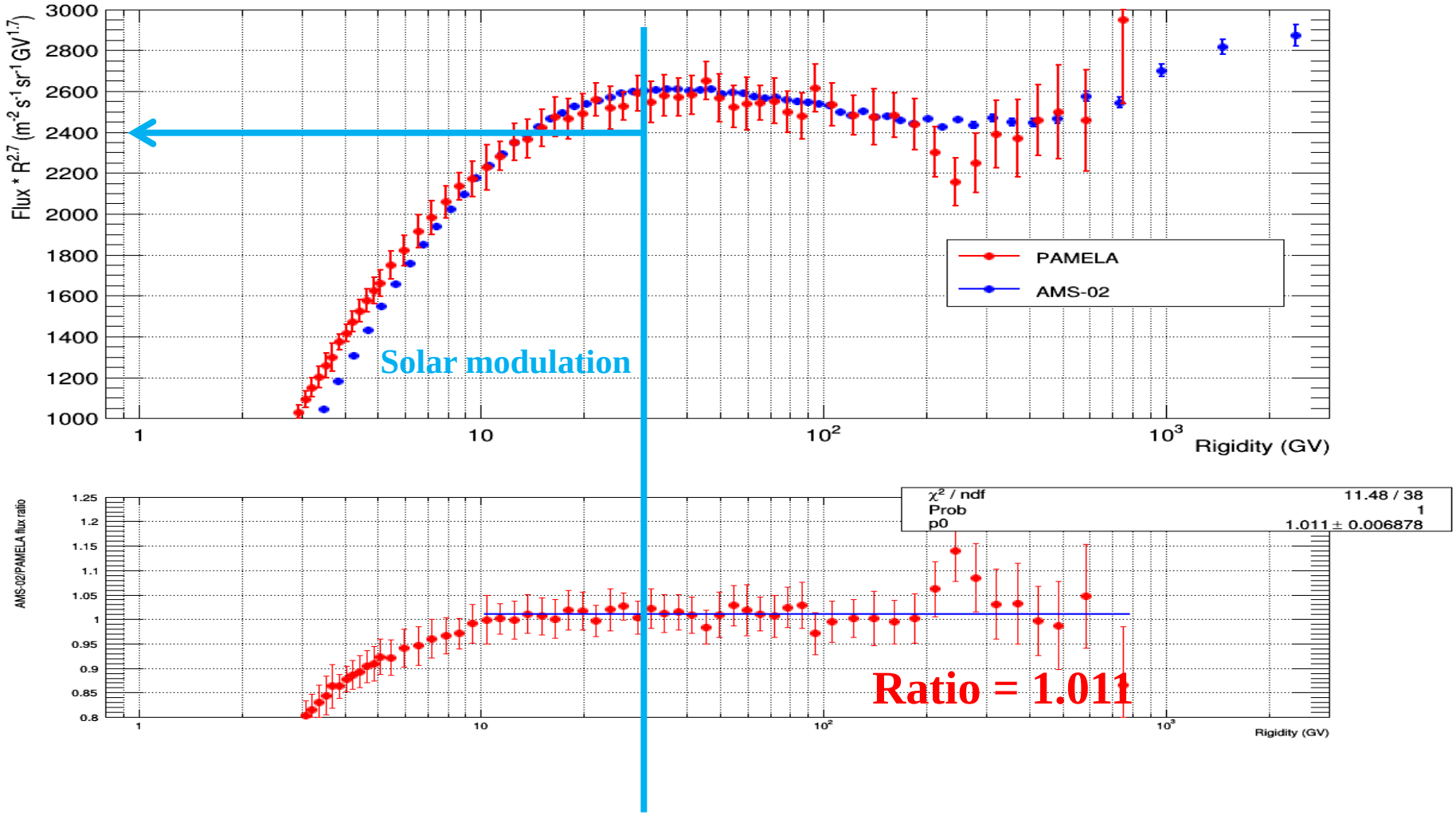
- Local source of hadrons at high energies?
- Multi-source distributed across the Galaxy
- Single source with spectral breaks?
- Different tipe of acceleration / propagation mechanisms?

# GLOBAL PICTURE: PROTON SPECTRUM (PAMELA & AMS-02)

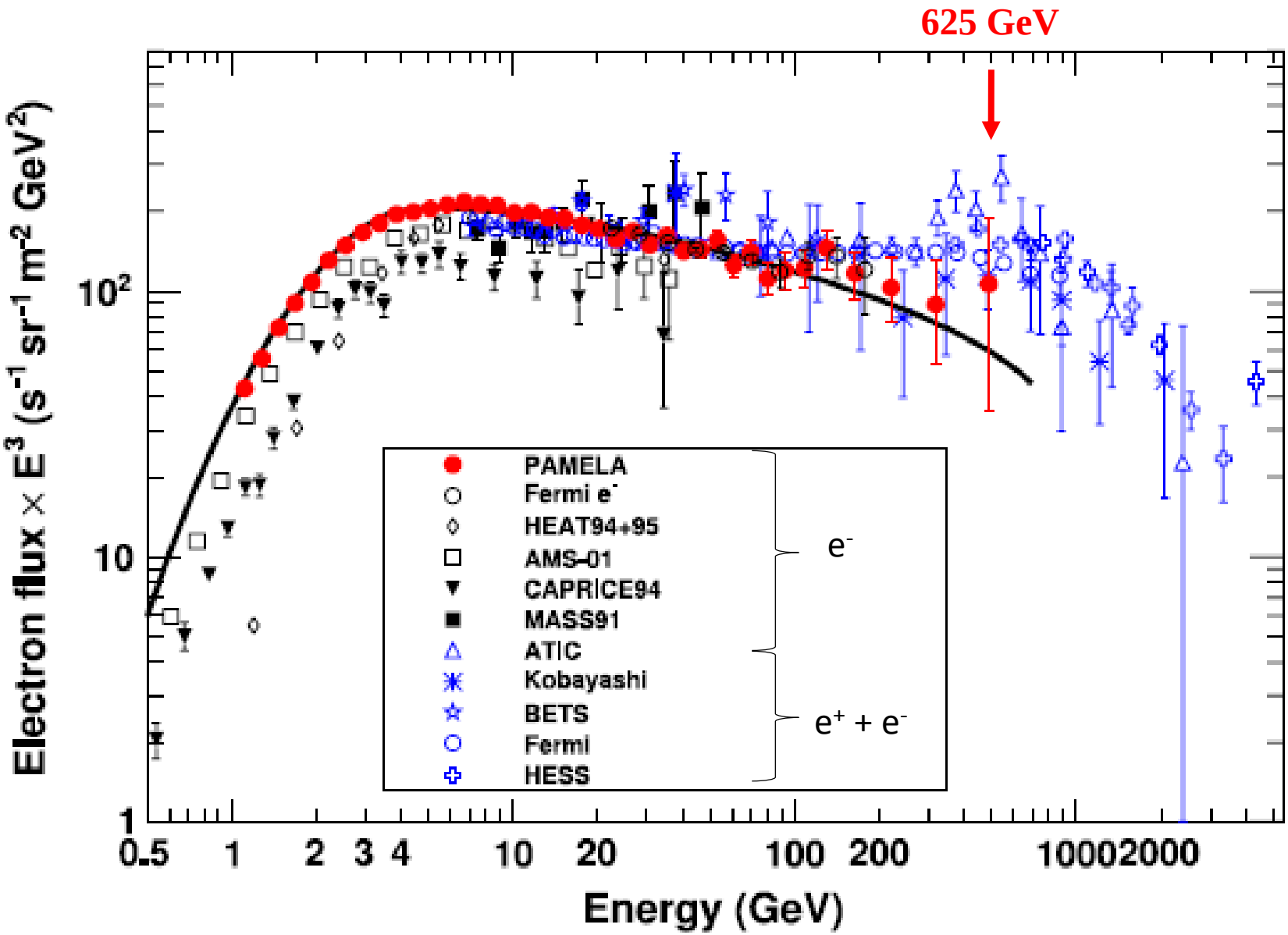



Adriani, O et al, Phys. Rep. (2014)

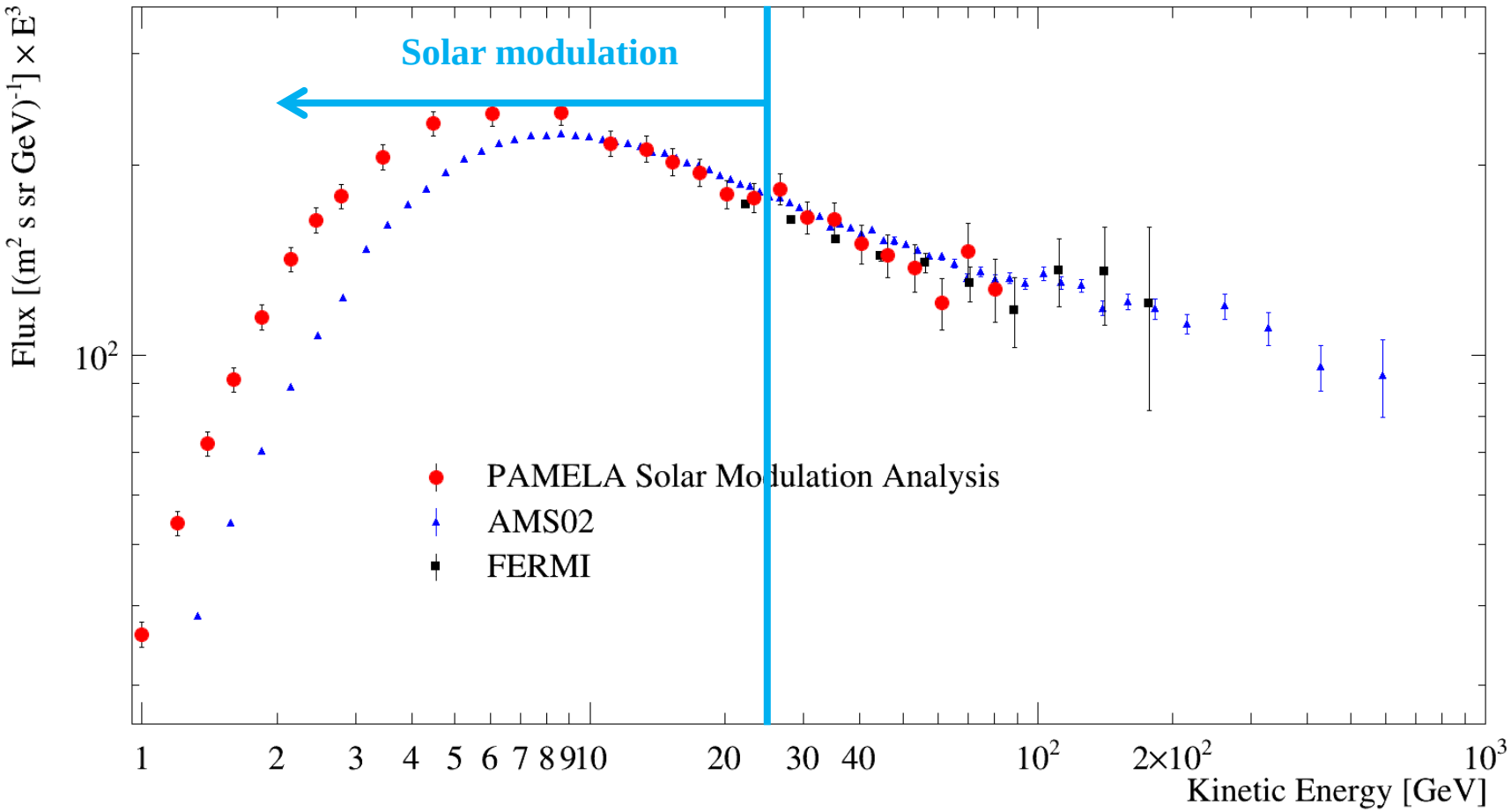
# GLOBAL PICTURE: HELIUM NUCLEI SPECTRUM (PAMELA & AMS-02)



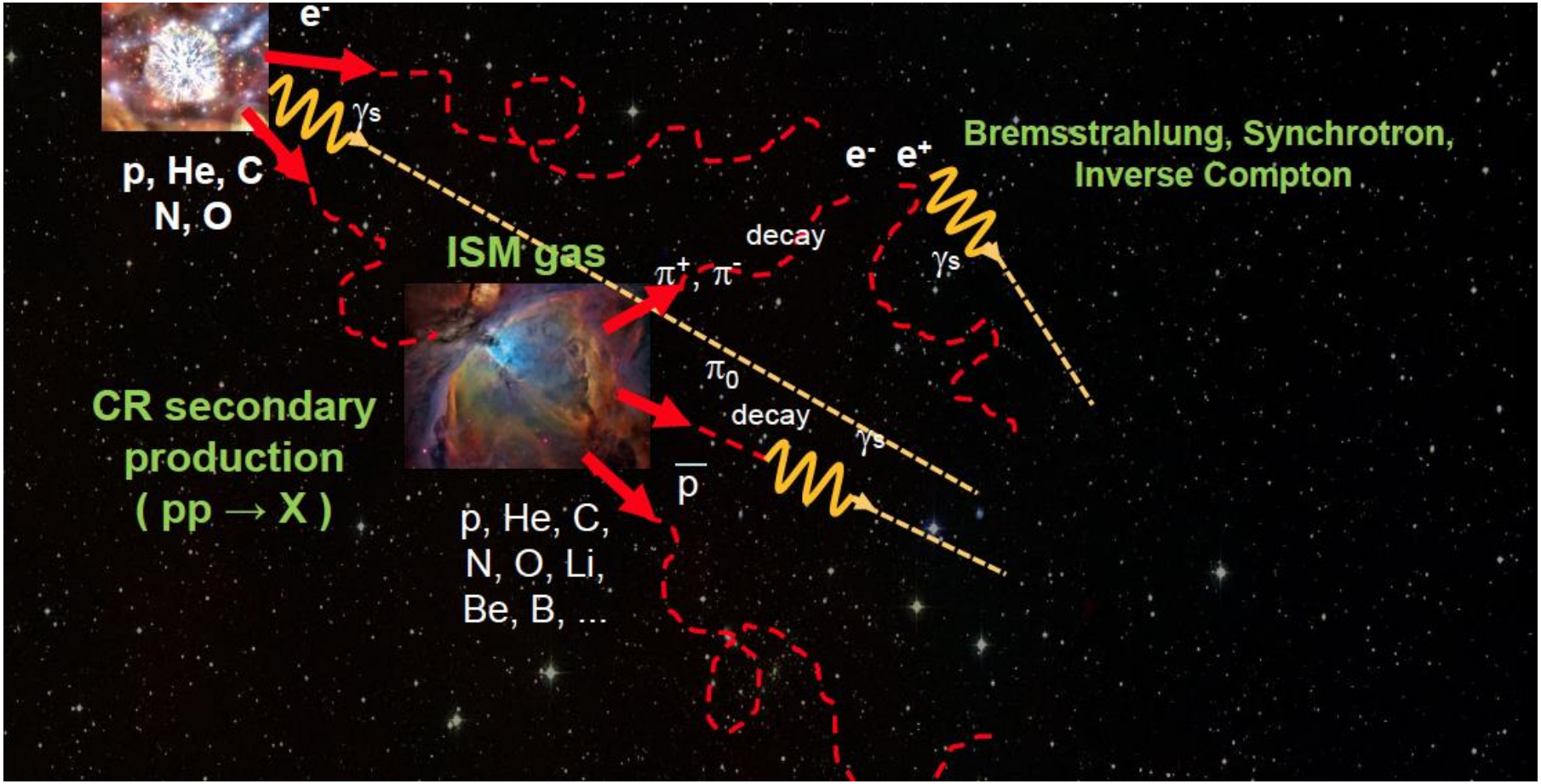
# GLOBAL PICTURE:ELECTRON SPECTRUM



# GLOBAL PICTURE: ELECTRON SPECTRUM (PAMELA & AMS-02)



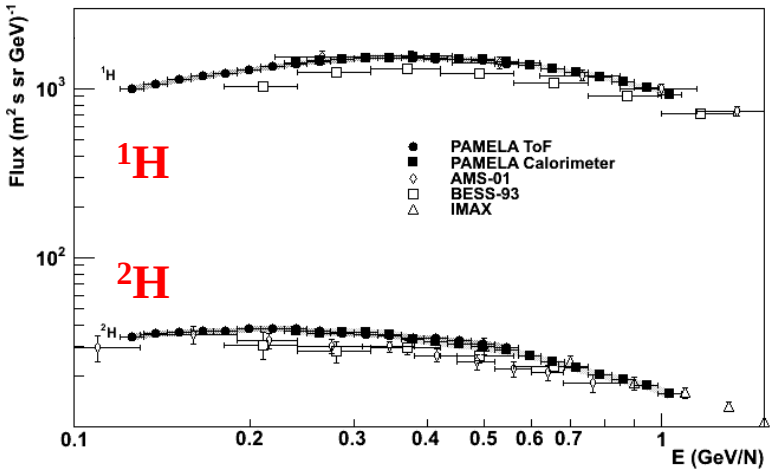
# PAMELA STUDIES: SECONDARY COMPONENT

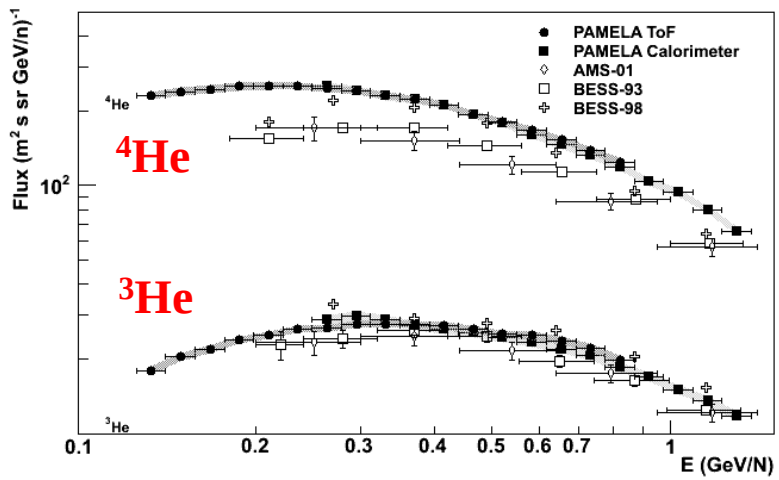


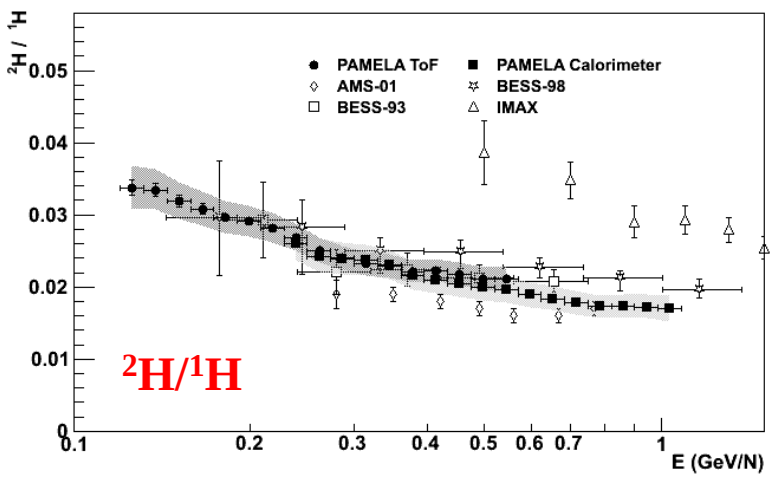

## Secondary cosmic rays

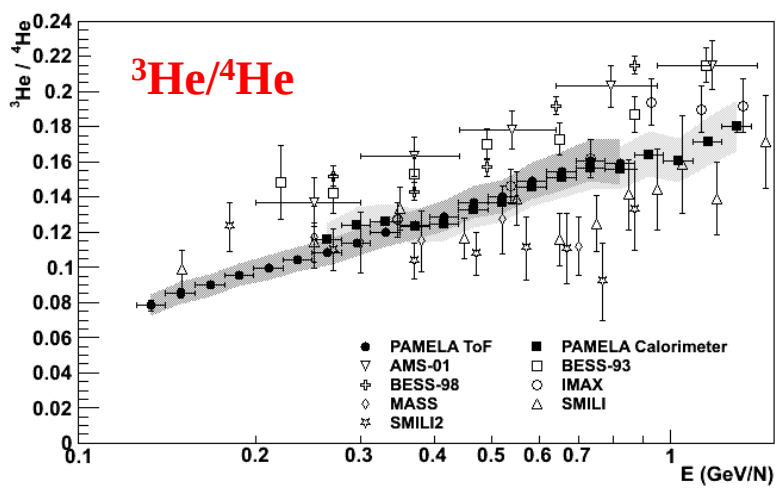
Antiparticles (antiprotons, positrons), secondaries from homogeneously distributed interstellar matter (light nuclei)

# HYDROGEN & HELIUM ISOTOPES



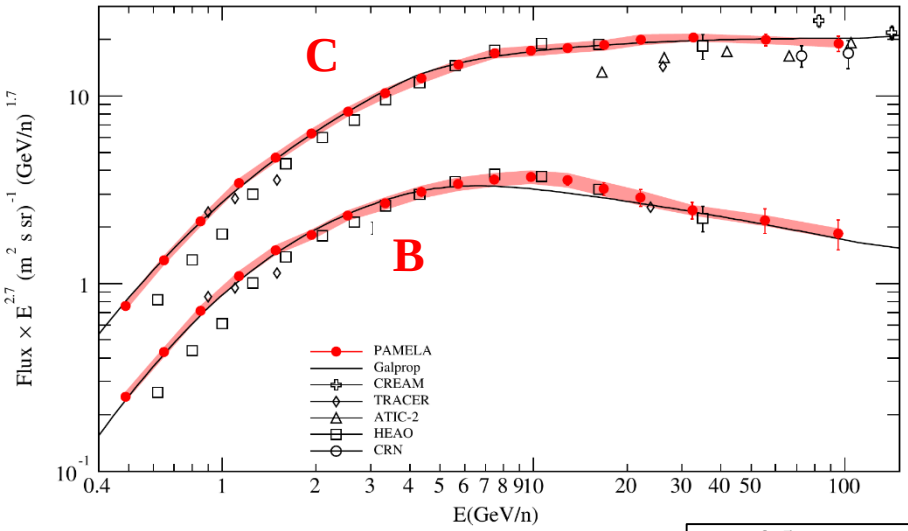




Adriani, O et al. ApJ 818:68 (14pp), 2016

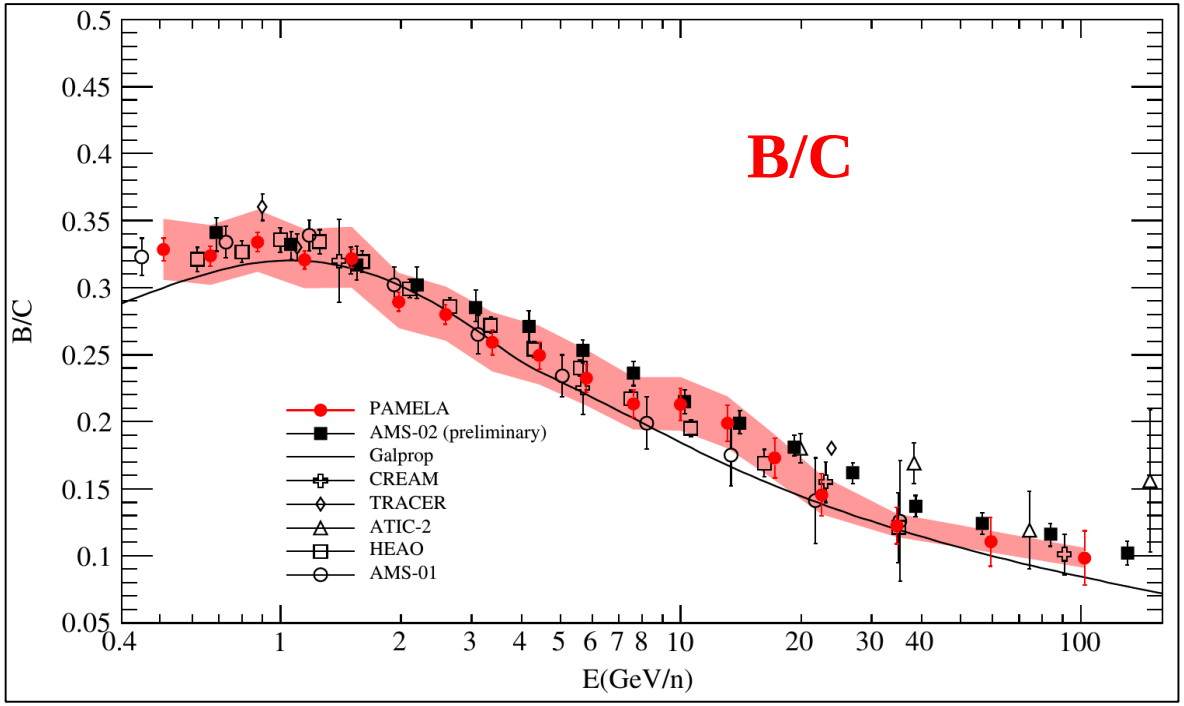
# BORON & CARBON SPECTRA & B/C RATIO




- Boron & Carbon are important proxies for transport
  - **B** is pure secondary
  - C is its parent nucleus (primary)
- B/C linkrd to the diffusion coefficient *D(E)* → <u>*modelisation*</u>

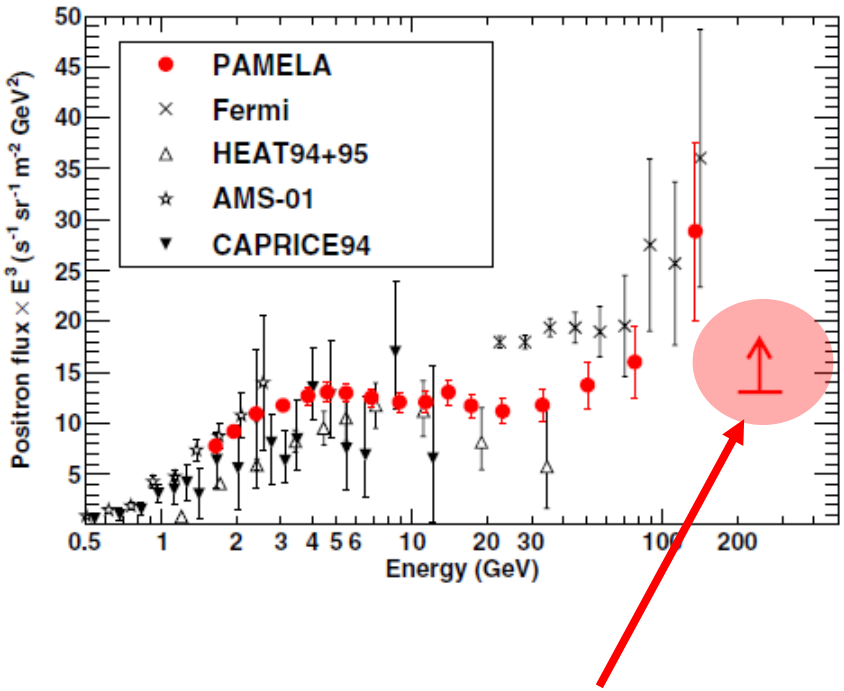
July 2006 – December 2009
(0.44–129 GeV/n)

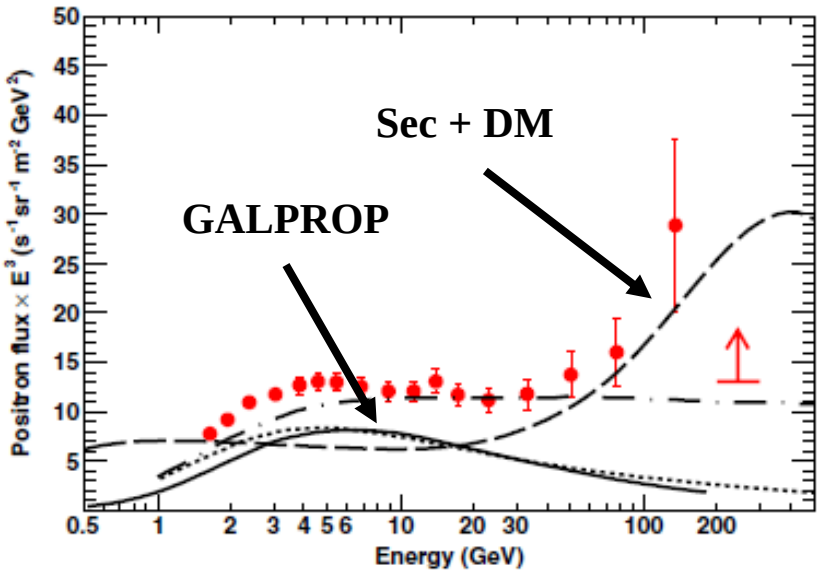
Adriani et al., ApJ 791 (2014), 93



# POSITRON FRACTION & POSITRON FLUX

July 2006 – December 2009




- In 200 -300 GeV region only a lower limit @90% C.L. is presented because of a possible overestimation of the proton contamination

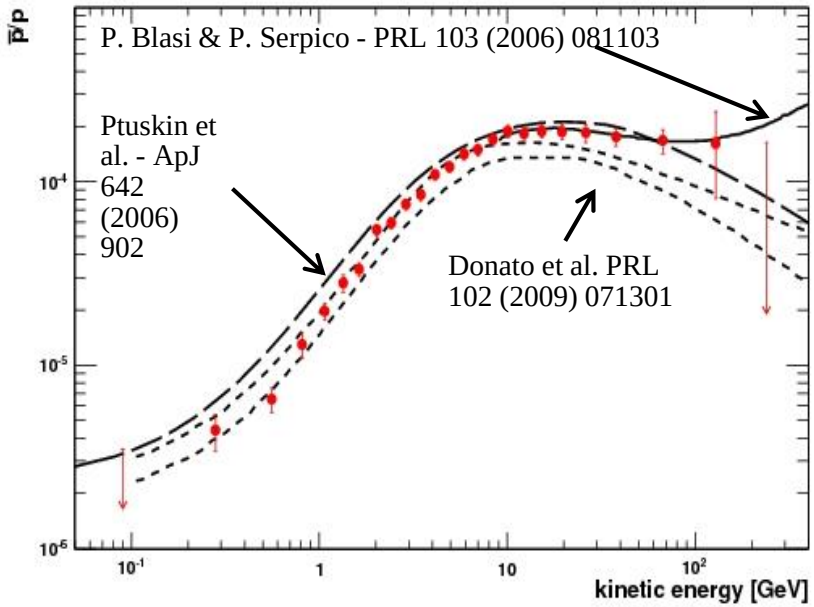
- PAMELA data along + theoretical predictions(GALPROP & DM model)

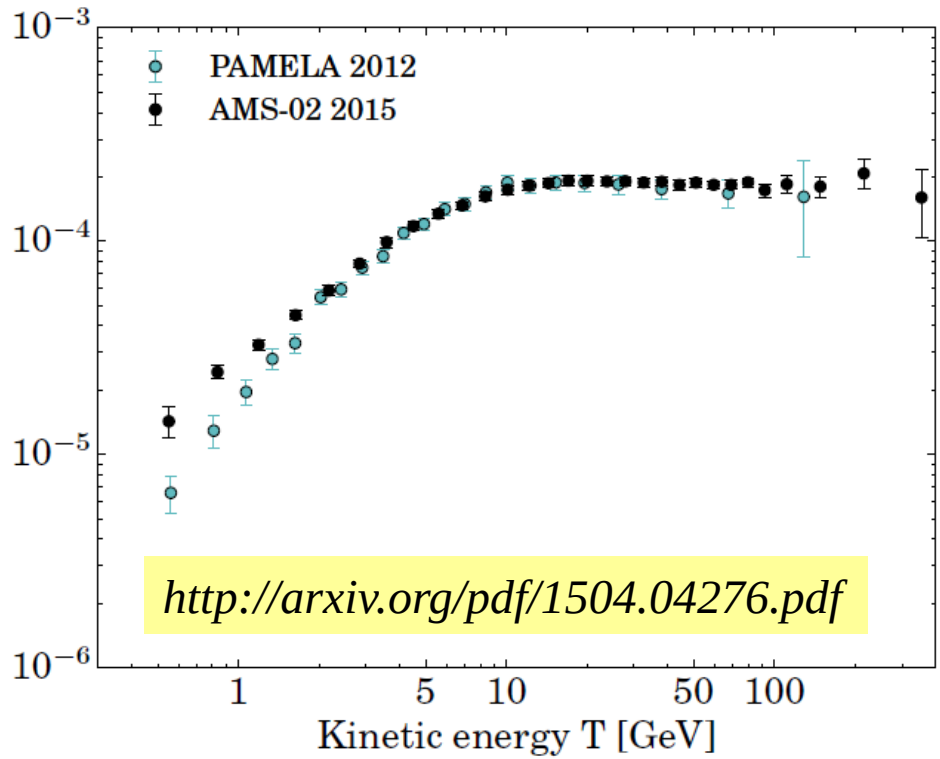
- DM annihilation of particles (mass 1.2 TeV) via a boson (580 MeV mass) to charged lepton pairs
- Pulsars?

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

# PAMELA ANTIPROTON SPECTRA

July 2006 – December 2009



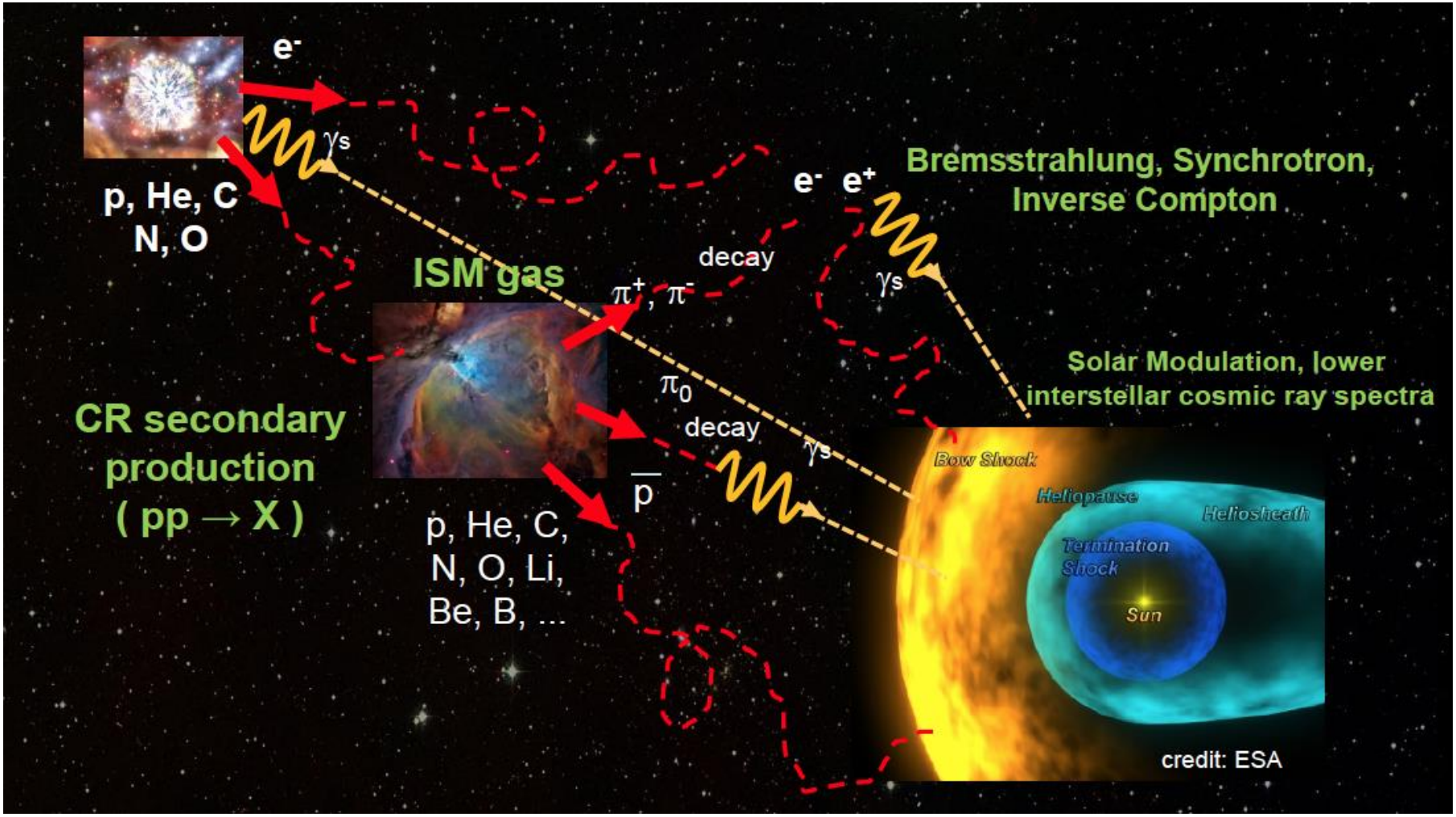

*http://arxiv.org/pdf/1504.04276.pdf*

- The good agreement between the experimental data and the calculations of secondary production can constrain models of galactic DM i.e. predicting heavy WIMP candidates)

- Low-energy data can constrain models with light (~10 GeV) candidates

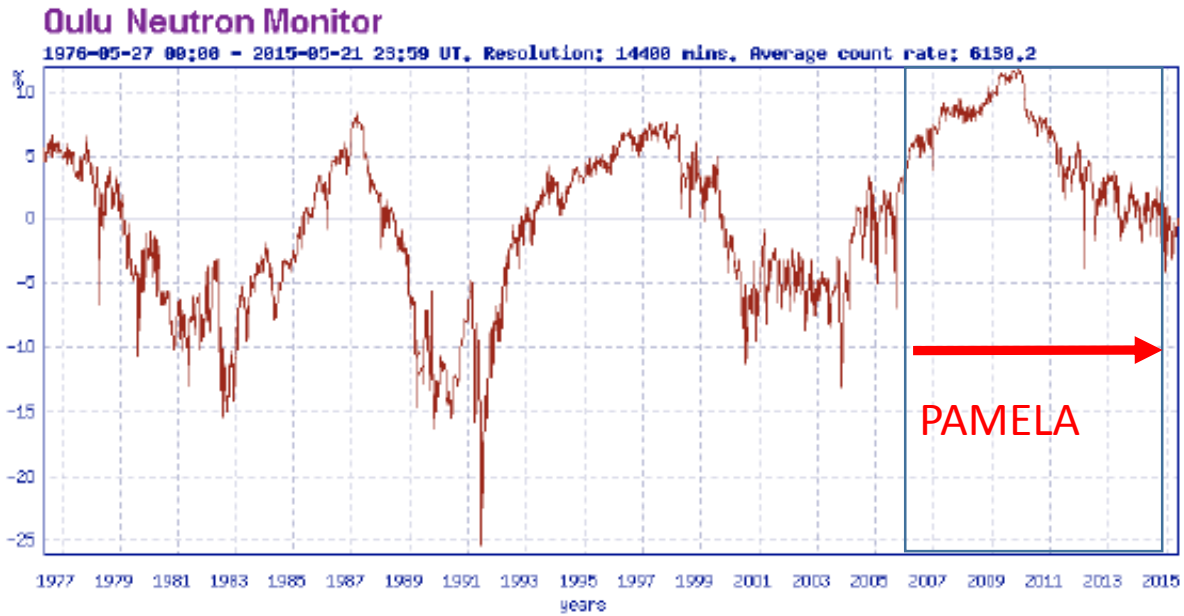
Adriani, O et al, PRL 102 (2009) 051101; PRL 105 (2010) 121101; Phys. Rep. (2014).

# PAMELA STUDIES: HELIOSPHERE




# Cosmic Rays in the Heliosphere

# PAMELA OBSERVATIONS IN THE HELIOSPHERE



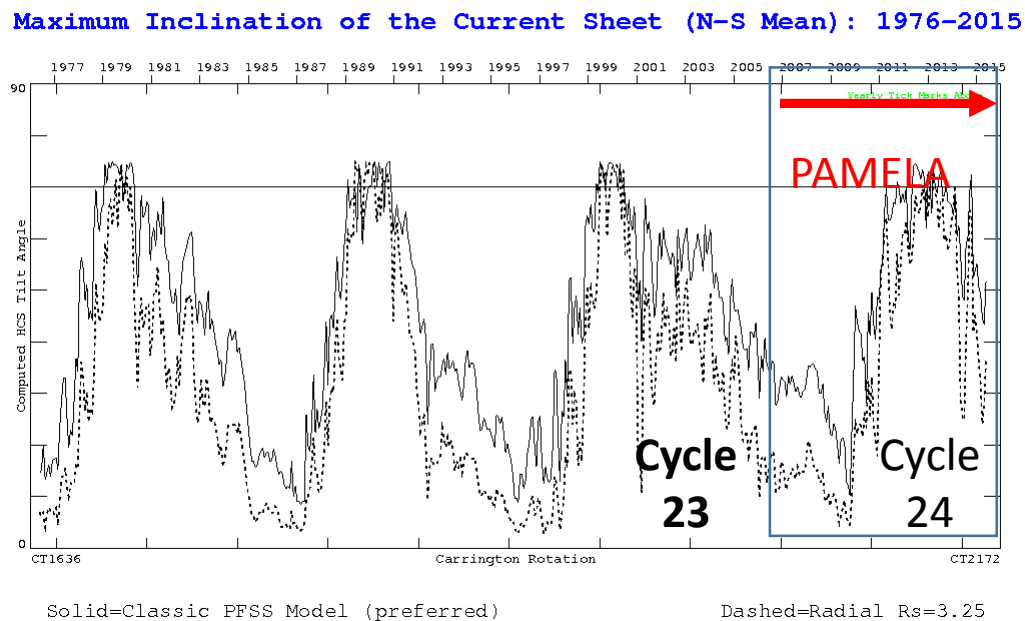

Neutron Monitor counts

http://cosmicrays.oulu.fi/

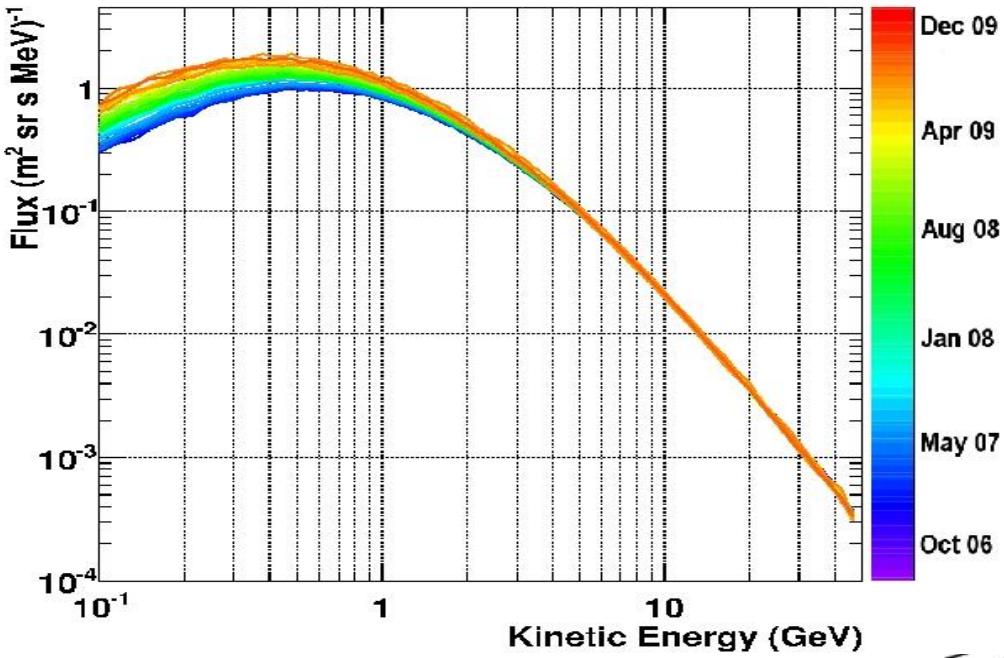
Computed HCS tilt angle

http://wso.stanford.edu/

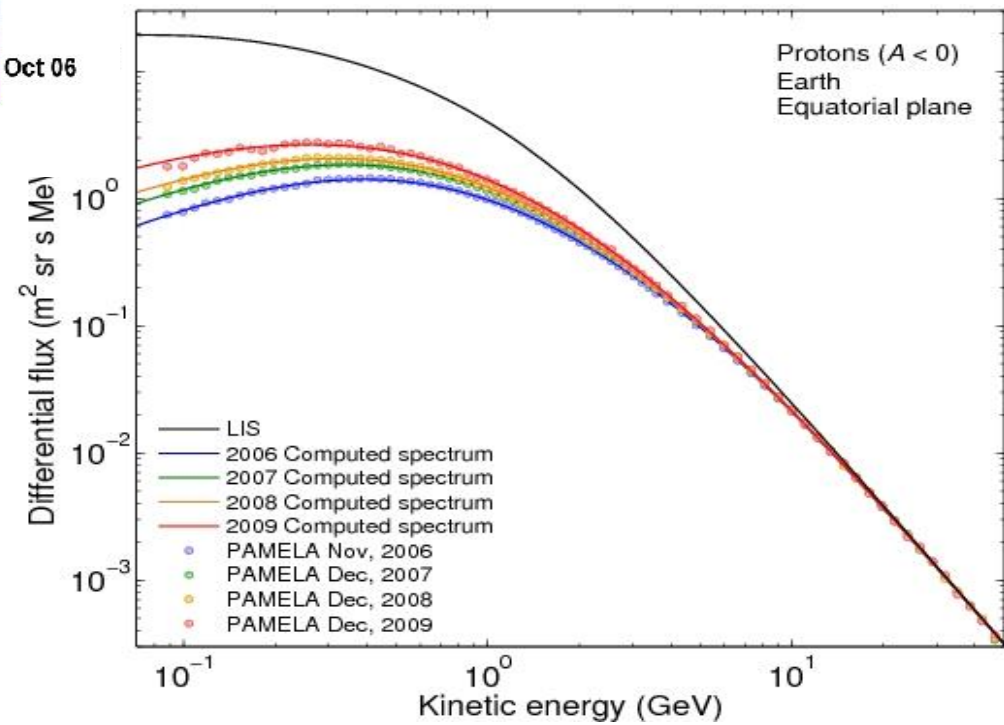
**PAMELA observations covers ~ one solar cycle**



# TIME DEPENDENCE OF THE P FLUX: 2006-2009



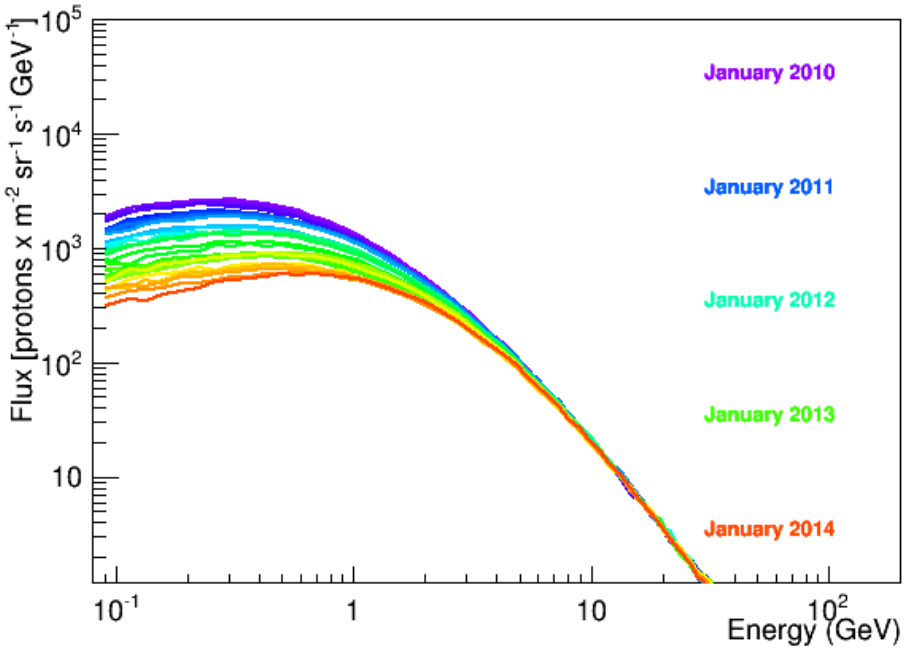

Evolution of the proton energy spectrum from July 2006 to December 2009



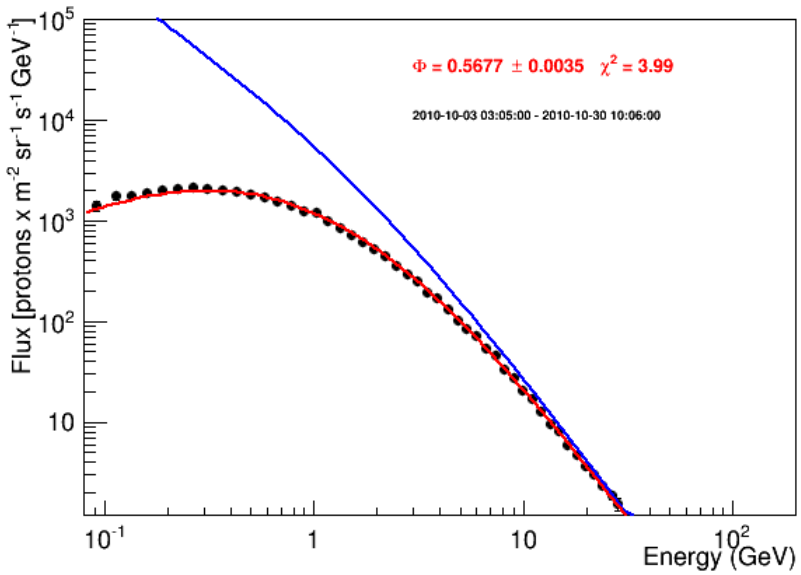

The PAMELA proton spectra over four months compared with the computed spectra

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

# TIME DEPENDENCE OF THE P FLUX: 2010-2014

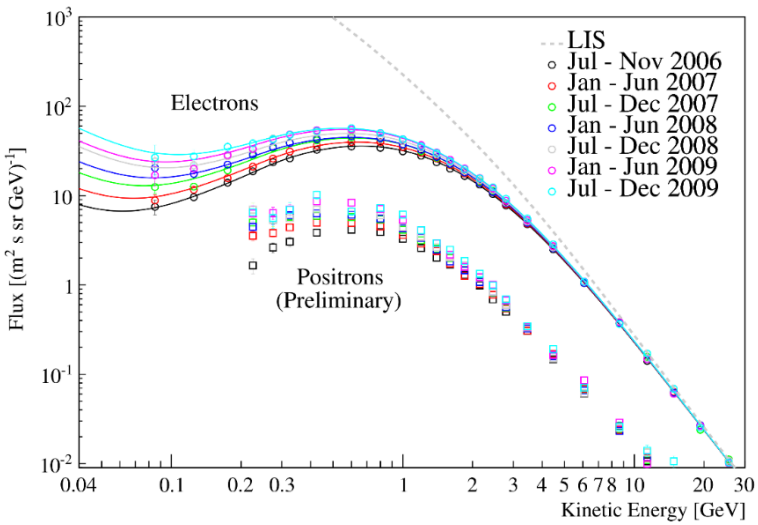



- 2010 – 2014 period
- The overall flux decreases from the maximum
- Solar particles subtracted from calculation



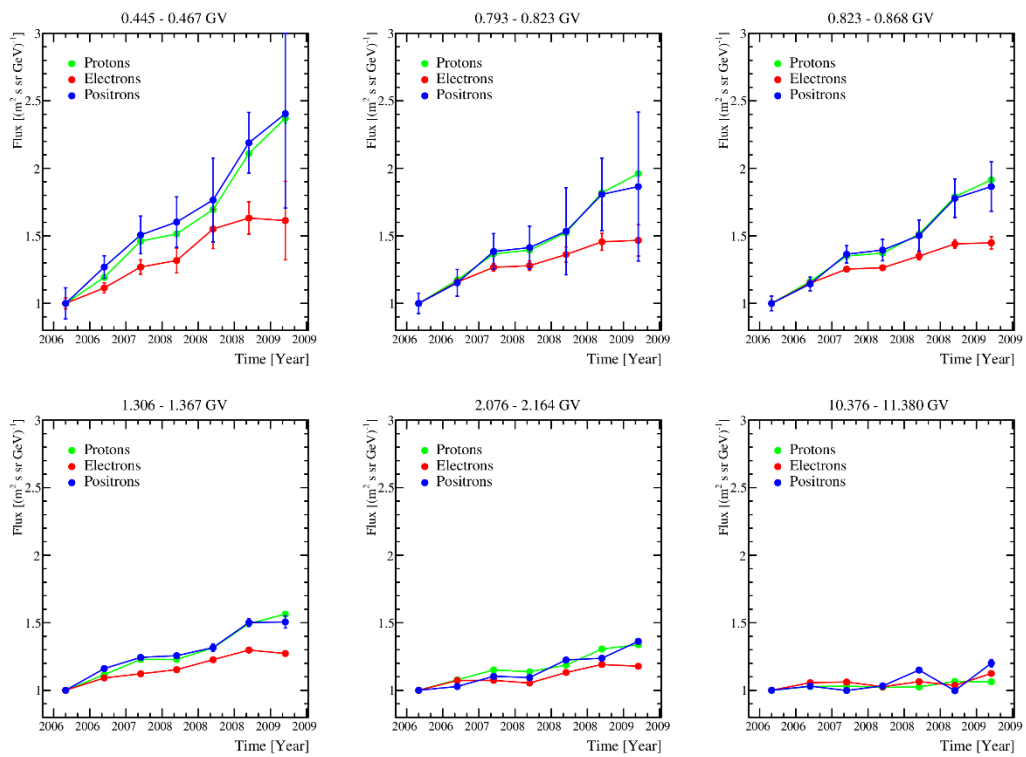

- Trying to medelize the galactic spectrum even in a condition of non-quiet environment

# TIME DEPENDENCE OF e⁻ , e+ and p



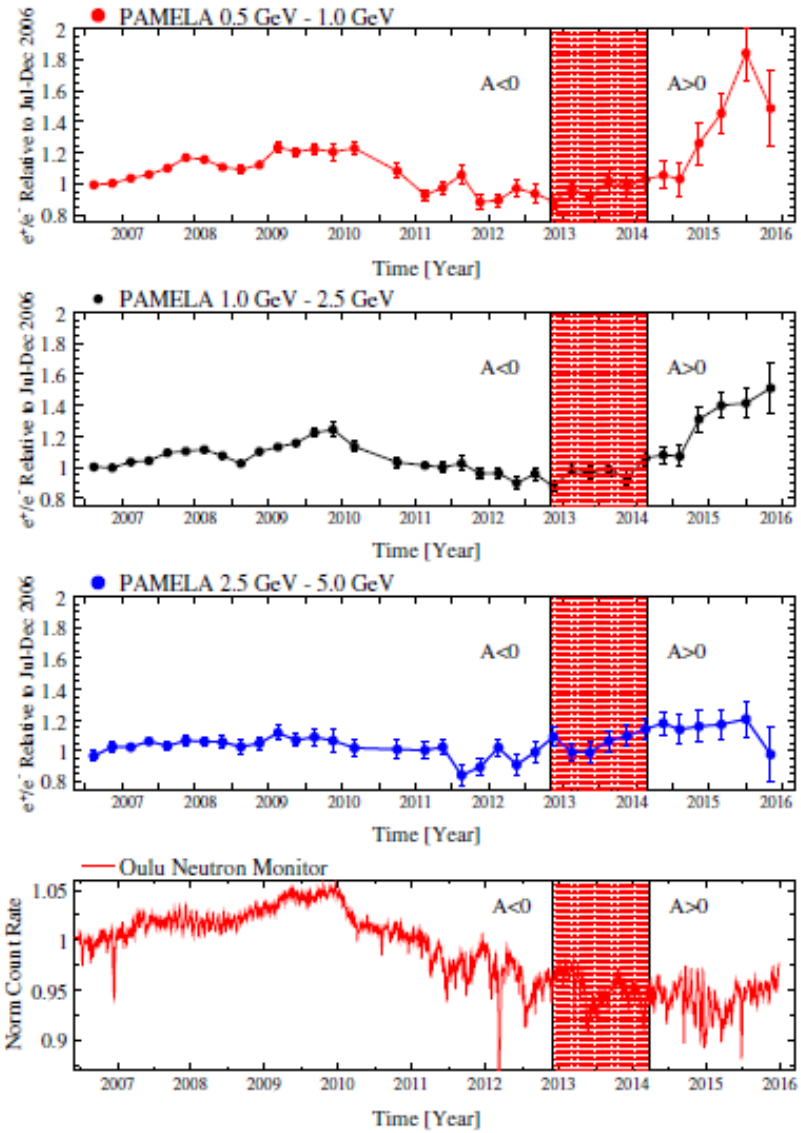

The PAMELA electron and positron spectra over the last solar minimum

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

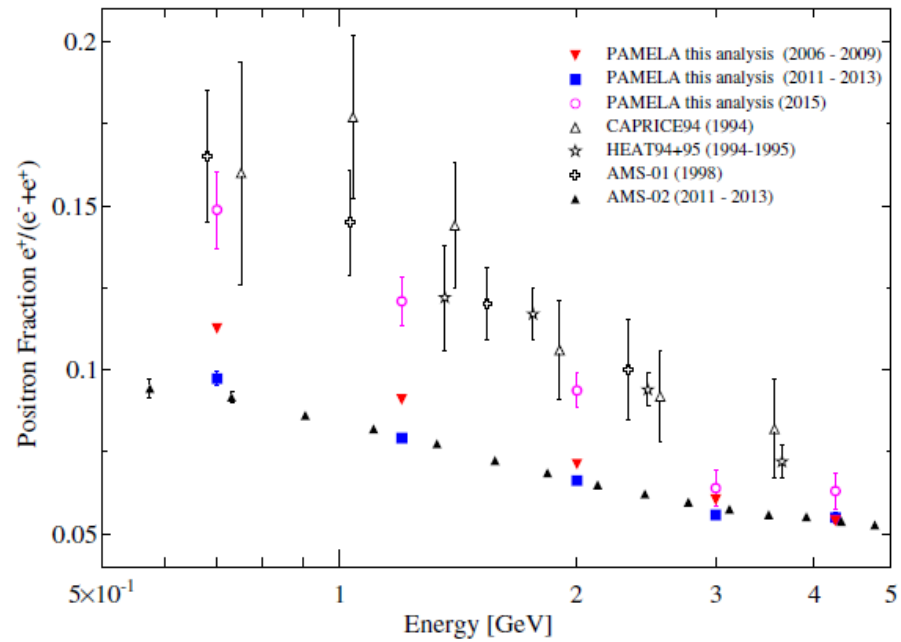



O. Adriani et al., ApJ 810 (2015) 142;
M. S. Potgieter et al., 810 (2015) 2, 141

# TIME DEPENDENCE OF THE $e^+ / e^-$ RATIO



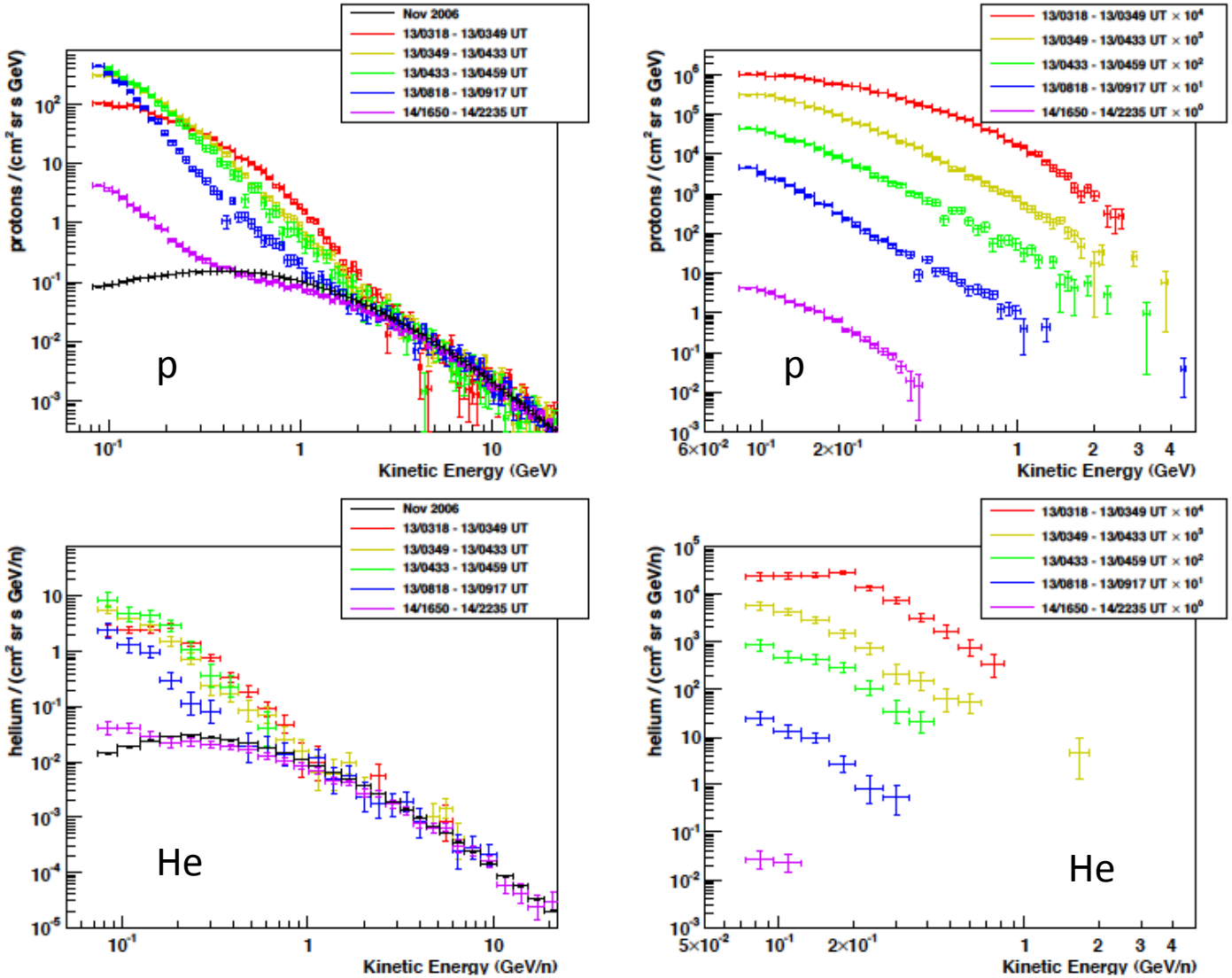

- The positron to electron ratios relative to July–December 2006 for three different energy intervals
- Shaded area = period with no well-defined HMF polarity
- The bottom panel: Oulu neutron monitor count rate




The positron fraction derived in for three time periods

Menn, W et al. Phys Rev Lett 116, 241105 (2016)

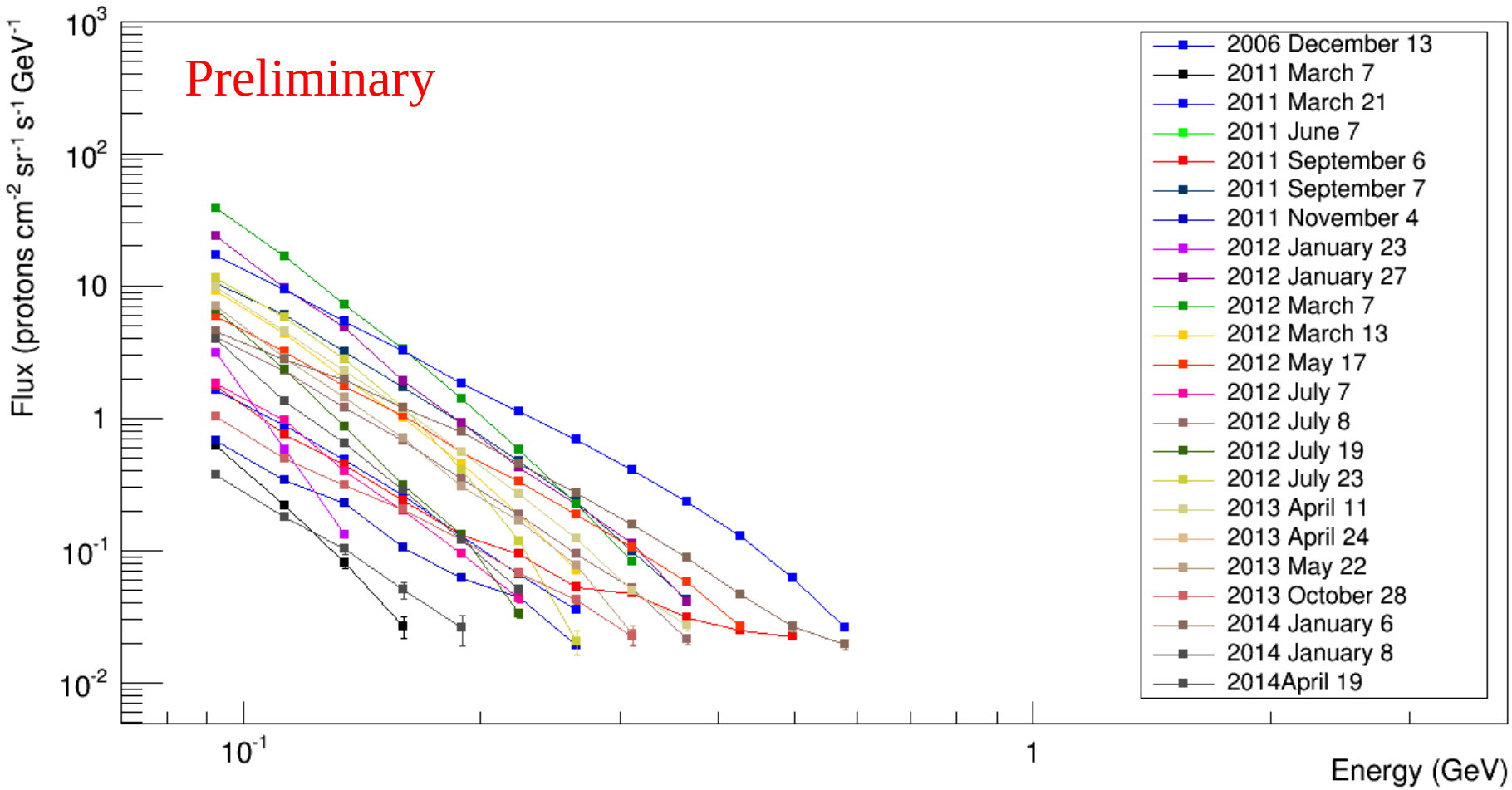
# THE 2006 DECEMBER 13th EVENT




- High performance even under high rate of particles
- Particle sensitivity to discriminate solar proton from solar helium (if present)
- Fluxes evaluated in narrow time intervals to study sudden variation of solar fluxes

Adriani et al. - *ApJ 742 102, 2011*

# PAMELA SOLAR ENERGETIC PARTICLES SPECTRA



# 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,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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[f] University of Bari, Department of Physics, I-70126 Bari, Italy
[g] INFN, Sezione di Bari, I-70126 Bari, Italy
[h] INFN, Sezione di Trieste, I-34149 Trieste, Italy
[i] Ioffe Physical Technical Institute, RU-194021 St. Petersburg, Russia
[j] KTH Royal Institute of Technology, Department of Physics, AlbaNova University Centre, SE-10691 Stockholm, Sweden
[k] The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova University Centre, SE-10691 Stockholm, Sweden
[l] INFN, Sezione di Rome "Tor Vergata", I-00133 Rome, Italy
[m] IFAC, I-50019 Sesto Fiorentino, Florence, Italy
[n] University of Rome "Tor Vergata", Department of Physics, I-00133 Rome, Italy
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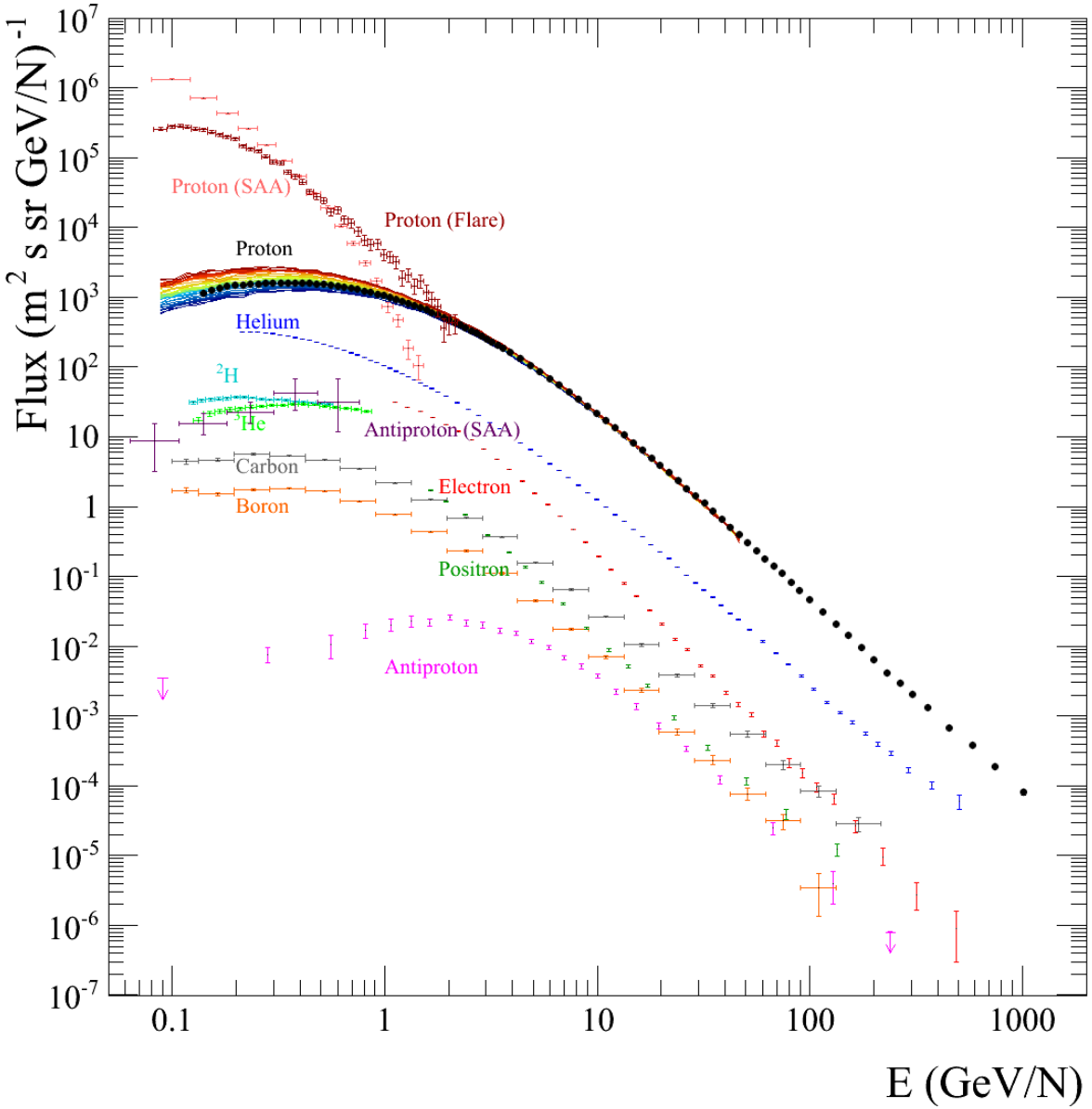
[q] INFN, Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[r] Universität Siegen, Department of Physics, D-57068 Siegen, Germany
[s] INFN, Sezione di Perugia, I-06123 Perugia, Italy
[t] Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati, Italy
[u] School of Mathematics and Physics, China University of Geosciences, CN-430074 Wuhan, China



# FURTHER ANALYSIS

- PAMELA has been in orbit studying cosmic rays for ~10 years → $>10^{10}$ triggers registered and > 38 TB of data has been down-linked

- Study on solar energetic particles emitted during solar events: information on acceleration mechanisms, transport processes and magnetospheric effects → 30 different events to study

- Solar Modulation:

1. Helium
2. positrons
3. light nuclei

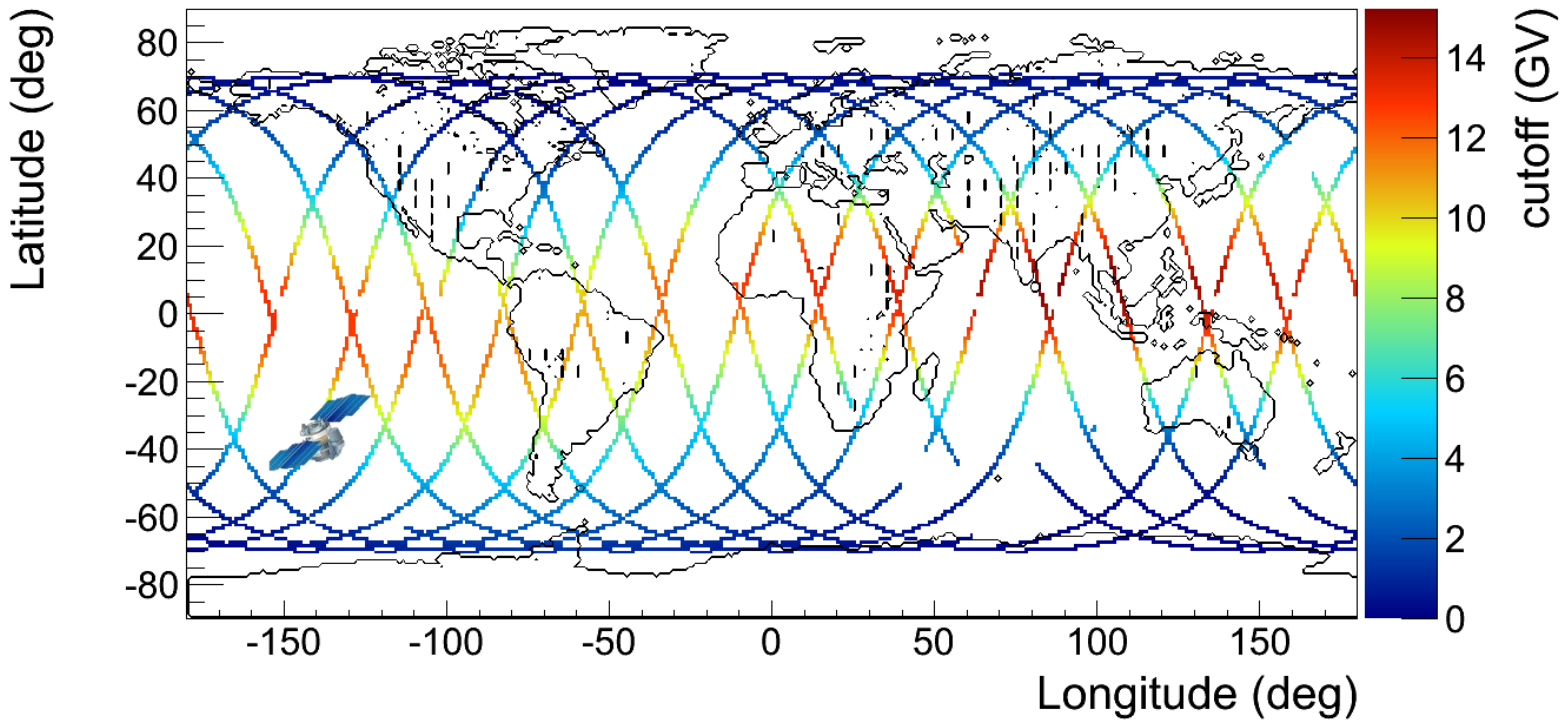
- Lithium & Beryllium absolute spectra

- Isotopic ratios

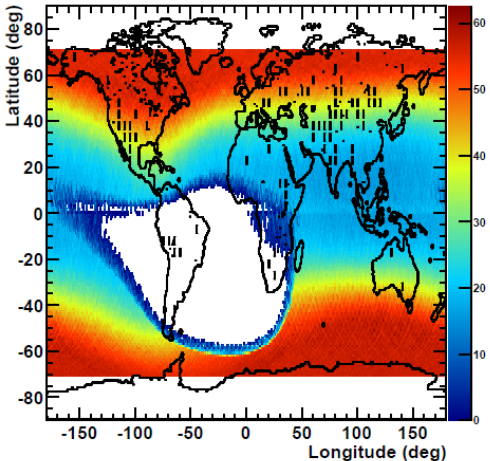
**MORE....**

# THANK YOU!

# PAMELA ORBIT

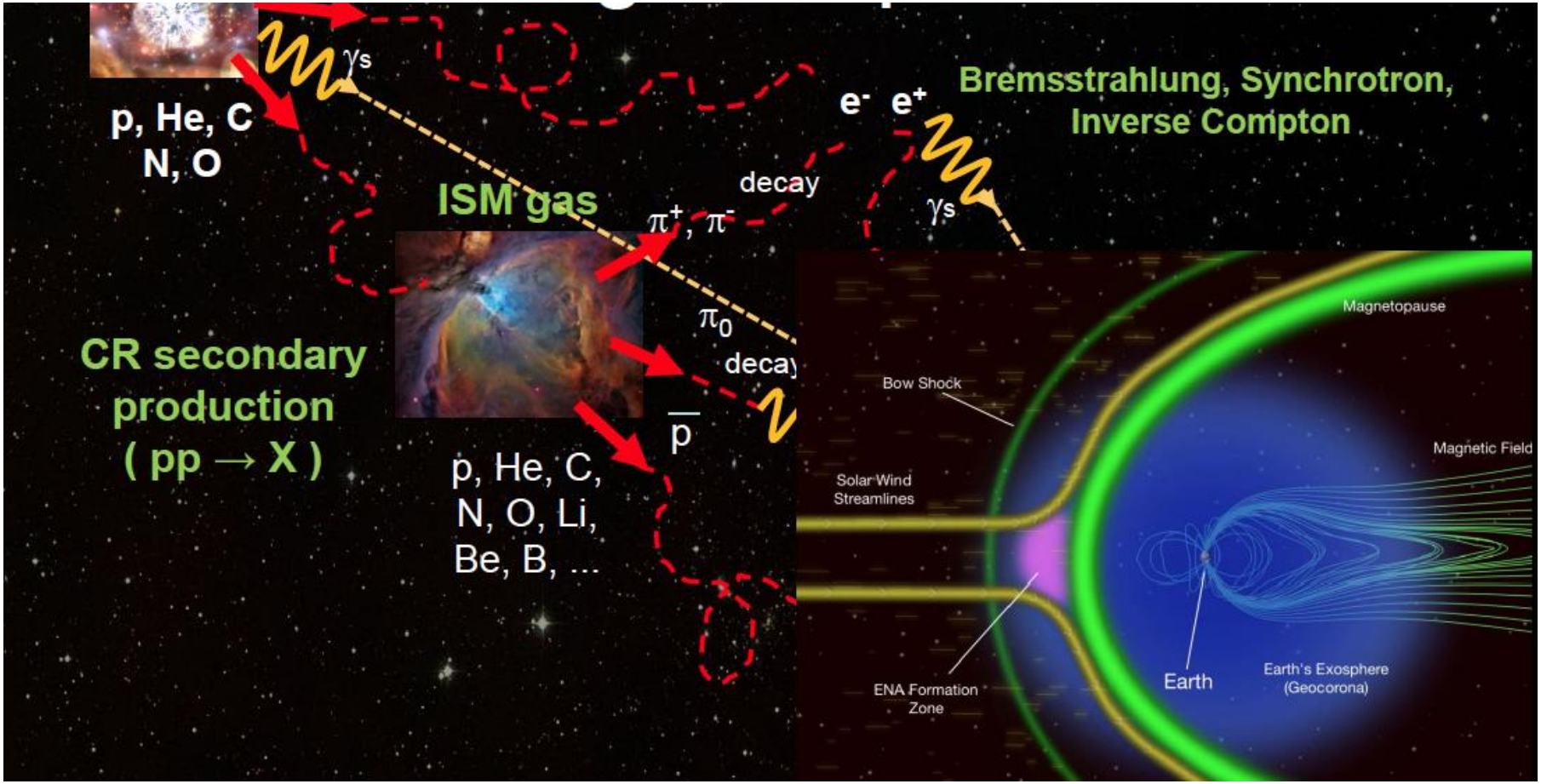



**Semi-polar orbit (70°) outside the atmosphere**



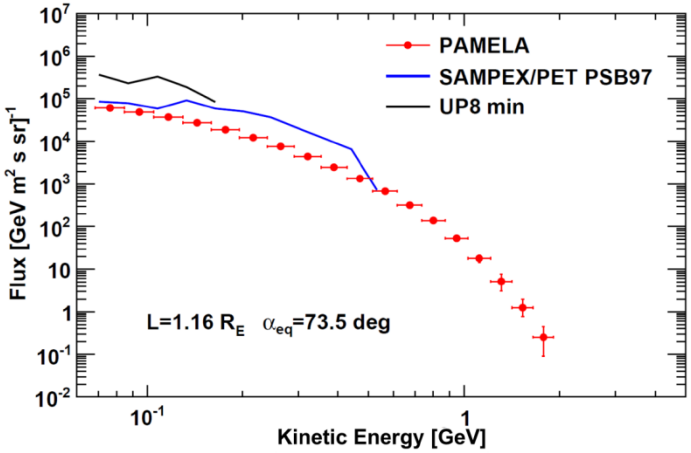

1) Different trigger configuration → optimal response to higher rates during SPE
2) Collecting solar particles down to 80 MeV and up to several GeVs (ideal for Ground Level Enhancement studies)
3) Over 30 polar passes every day → good capabilities in catching the onset of an event

# PAMELA STUDIES: MAGNETOSPHERE



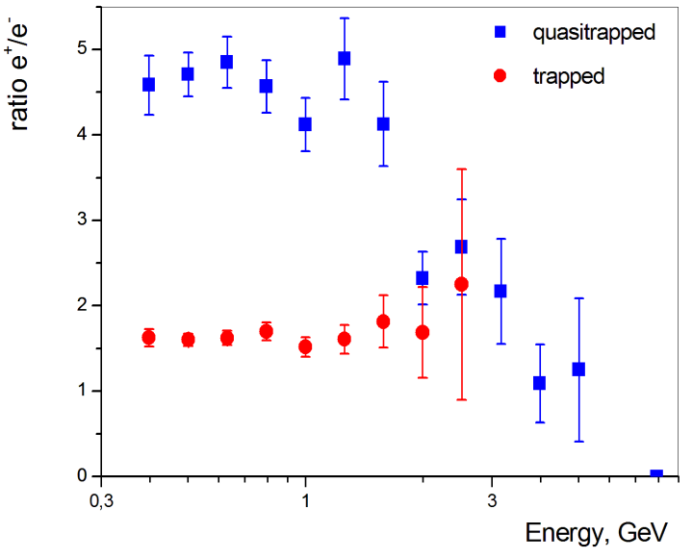

# Cosmic Rays in the Magnetosphere

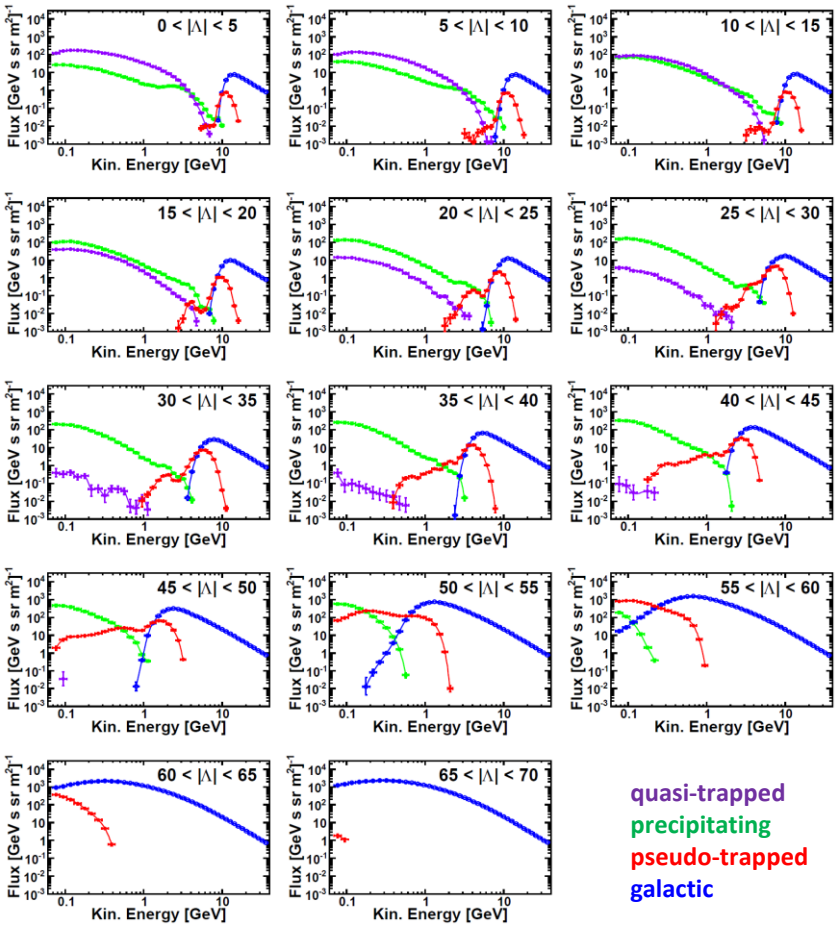
# TRAPPED AND ALBEDO PARTICLES




Comparison with trapped proton empirical models

Adriani et al., ApJL 799 (2015) L4



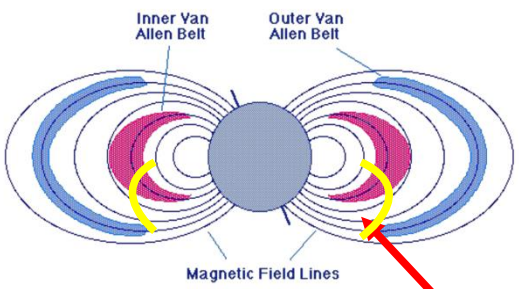



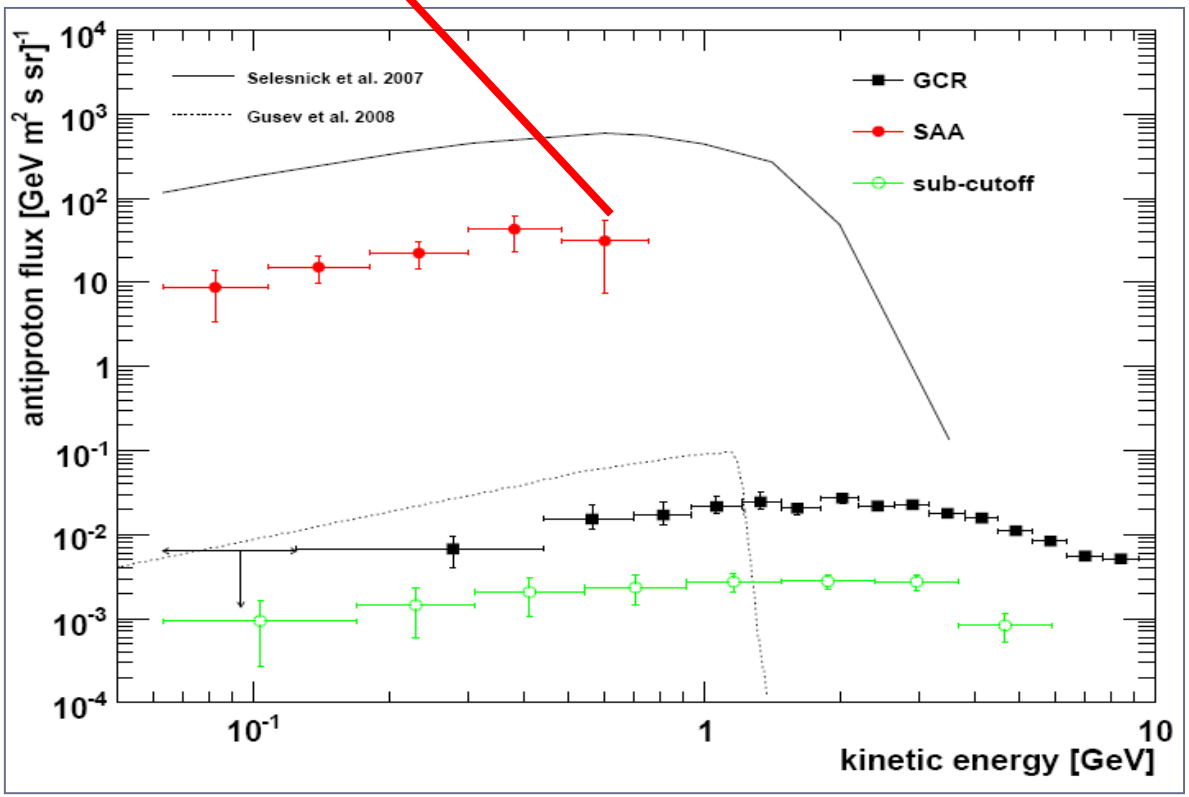

Re-entrant albedo proton spectra vs latitude |Λ|

Adriani et al., JGR A120 (2015) 3728

A. Bruno et al.: "PAMELA's measurement of geomagnetically trapped and albedo protons"- Poster 1 CR: 30/07/2015
V. Mikhailov et al.: "Secondary positrons and electrons observed by the PAMELA spectrometer" – CR04: 31/08/2015
S. Koldobskiy et al.: "Measurement of trapped and quasitrapped deuterons in PAMELA experiment" - CR06: 31/08/2015

# TRAPPED ANTIPROTON SPECTRUM




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

First measurement of p-bar trapped in the inner belt

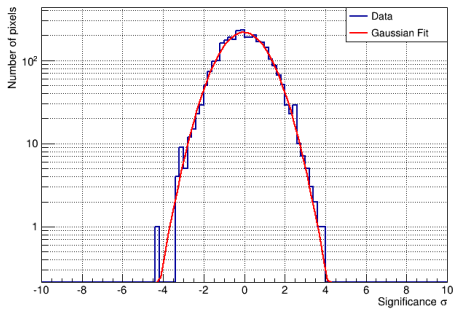
**29 p-bars** discovered in SAA and **traced back to mirror points**

p-bar flux exceeds GRC flux by **3 orders of magnitude,** as expected by models

# ANISOTROPIES IN THE $e^+$ DATA

## *Positrons - R > 10 GV*

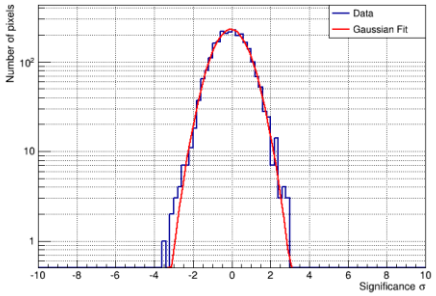
**Significance map for *backtraced* positrons**
**Background: Protons**
**Angular scale 10°**




**Histogram of calculated significance**

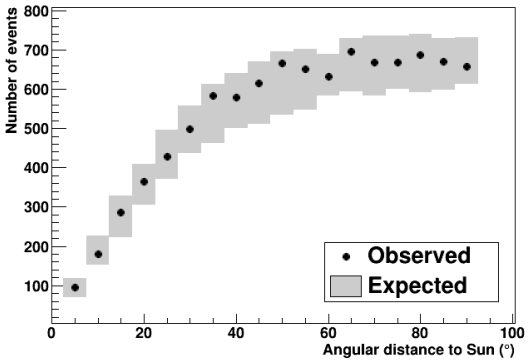
## *Electrons R > 10 GV*

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




**Histogram of calculated significance**

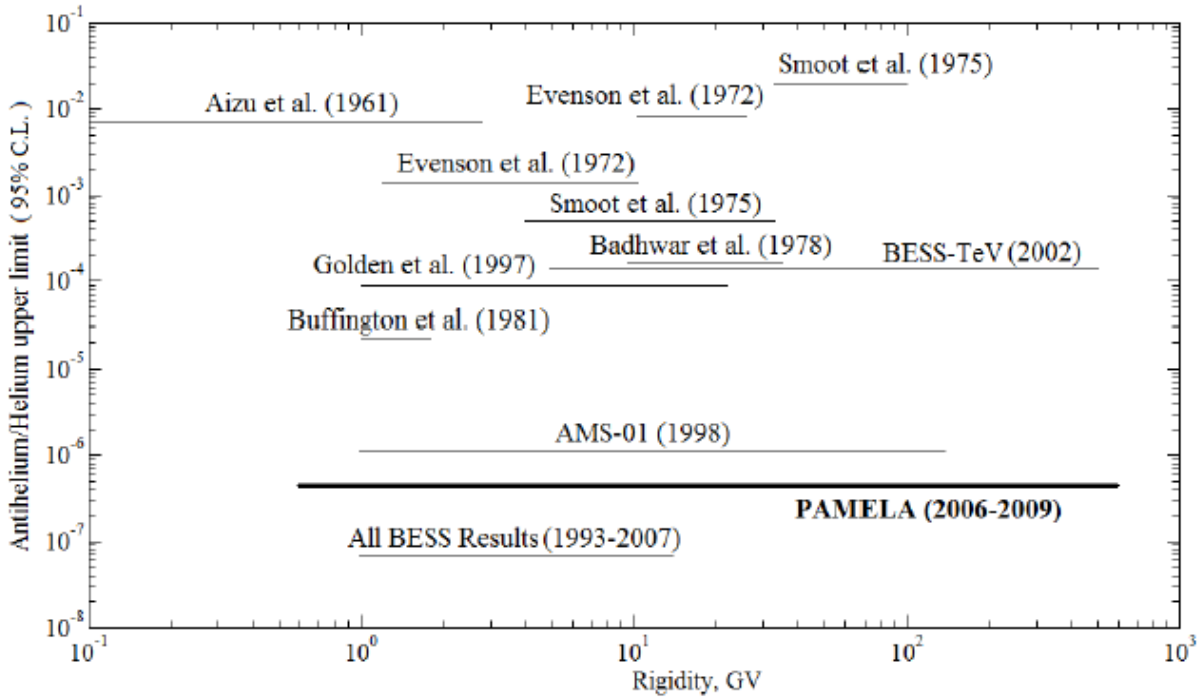
**Number of events as a function of the angular distance from the Sun direction**

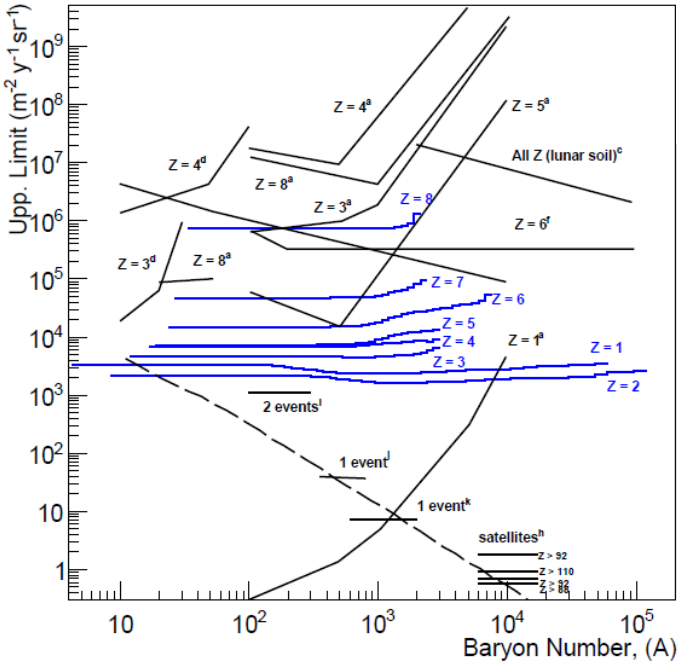


# ANTI-HE / HE AND STRANGE QUARK MATTER

**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

M. Ricci & M. Casolino, et al., "New upper limit on strange quark matter flux with the PAMELA space experiment" – Poster 1 CR: 30/07/2015