The PAMELA Experiment: More Than Six Years of Cosmic Rays Investigation.

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

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

INFN Istituto Nazionale di Fisica Nucleare

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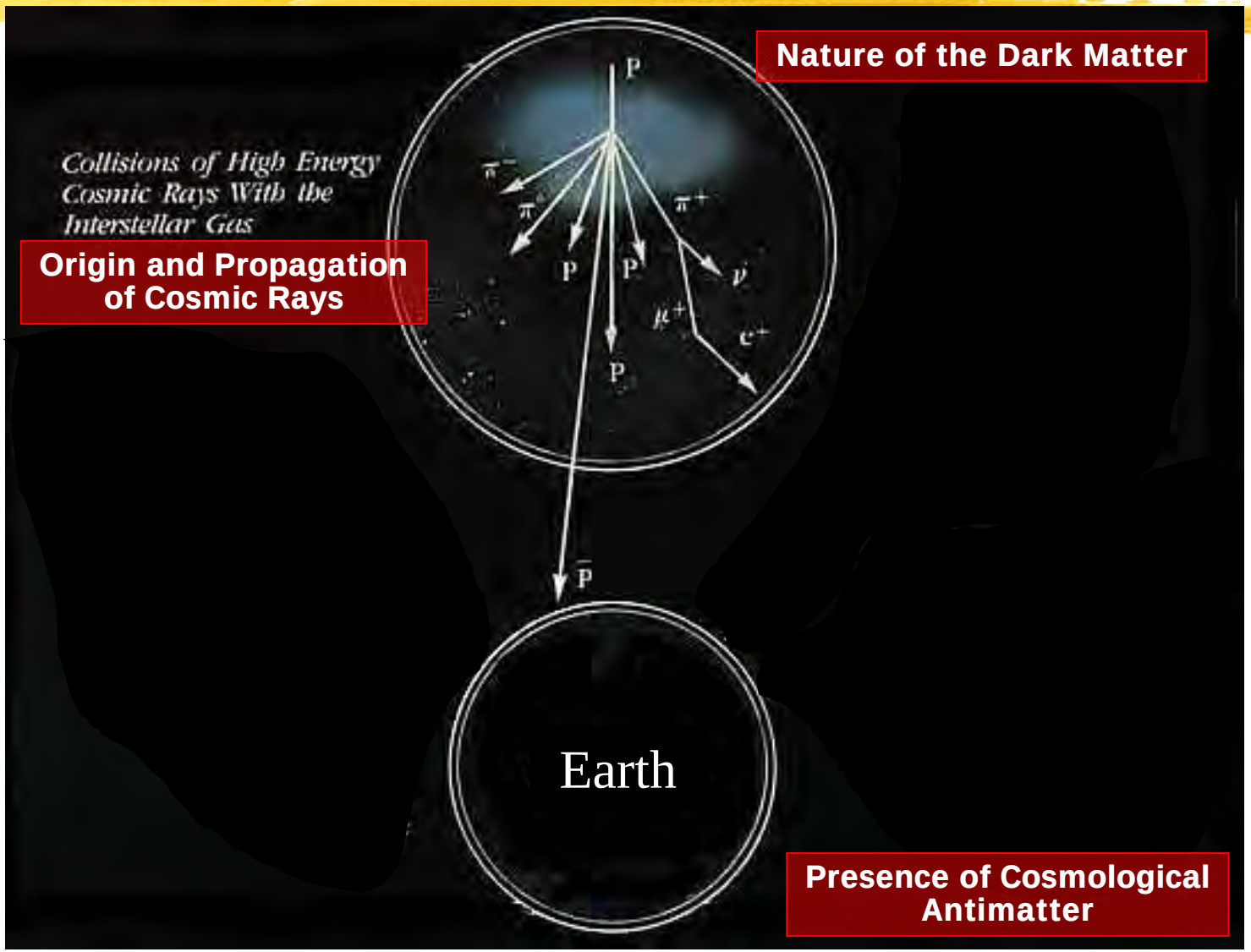
Why Anti(particle)matter matters?



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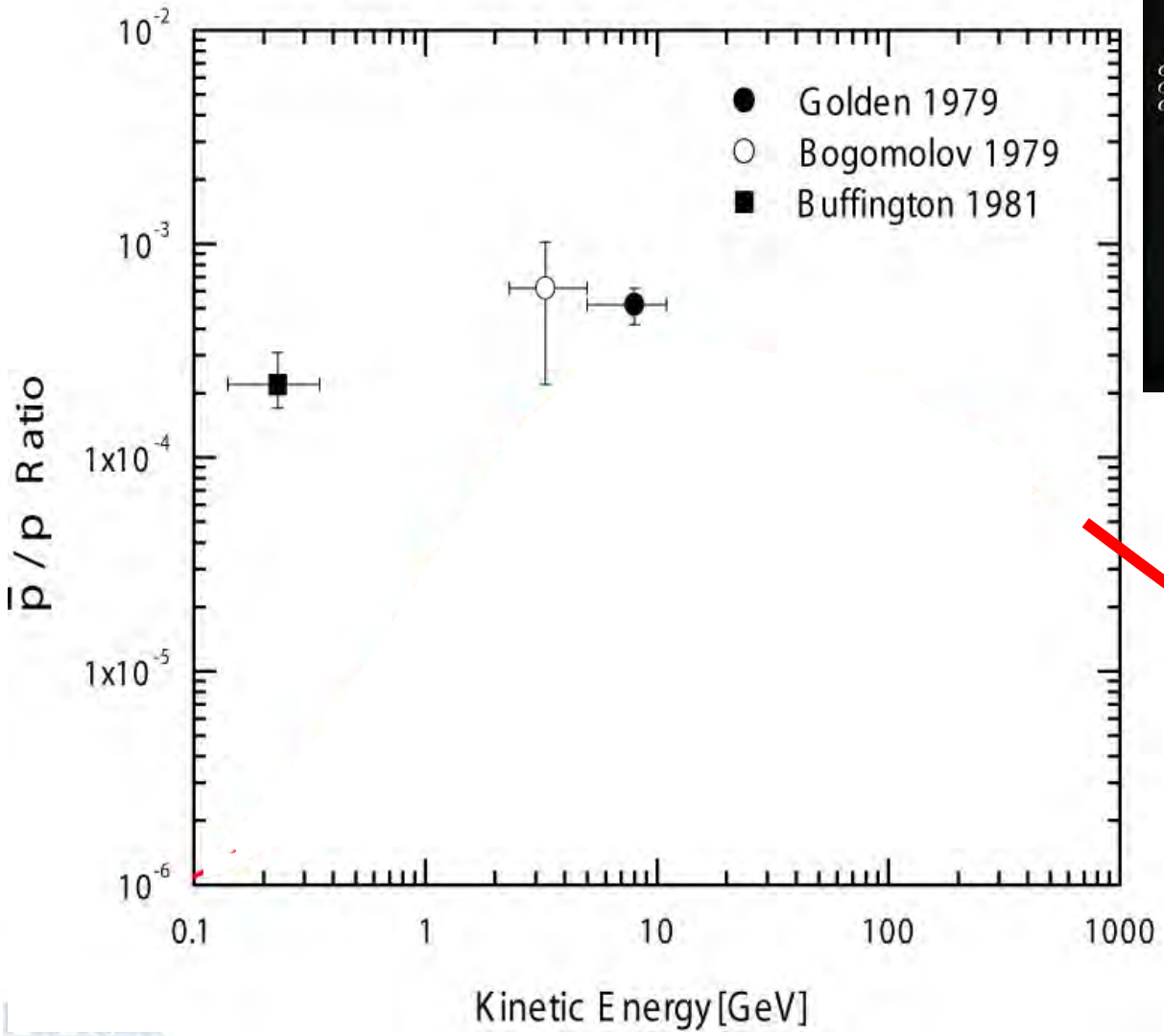

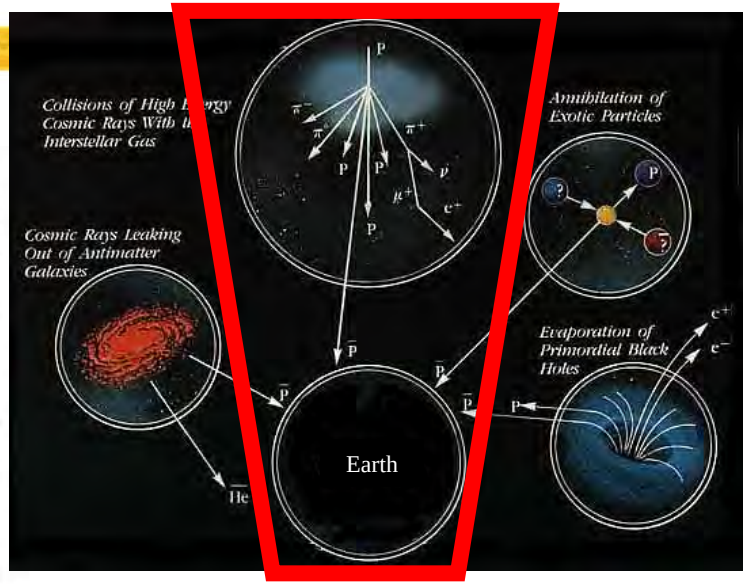

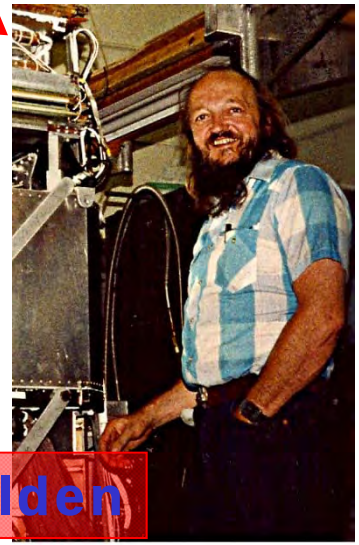

R.L. Golden

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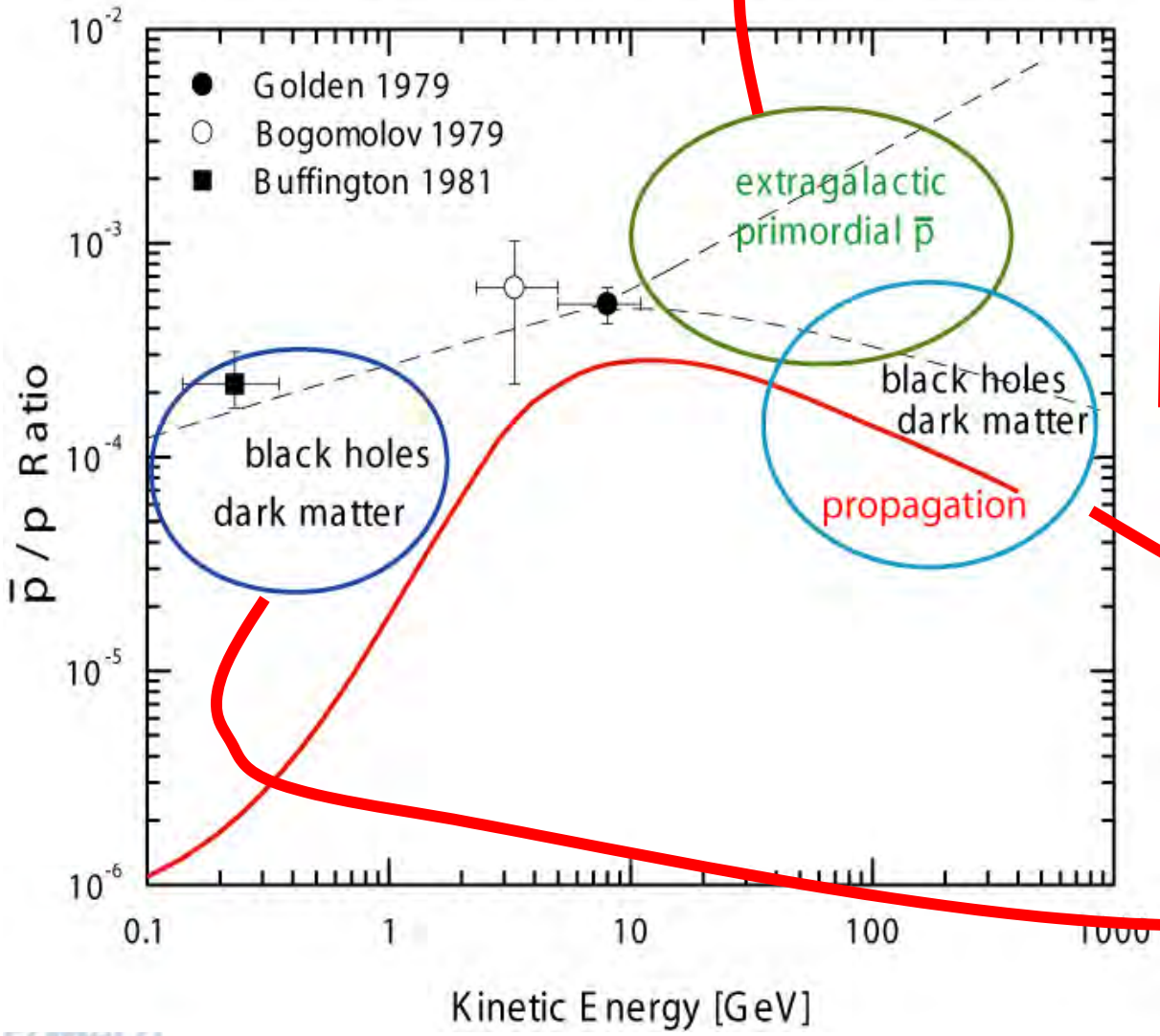

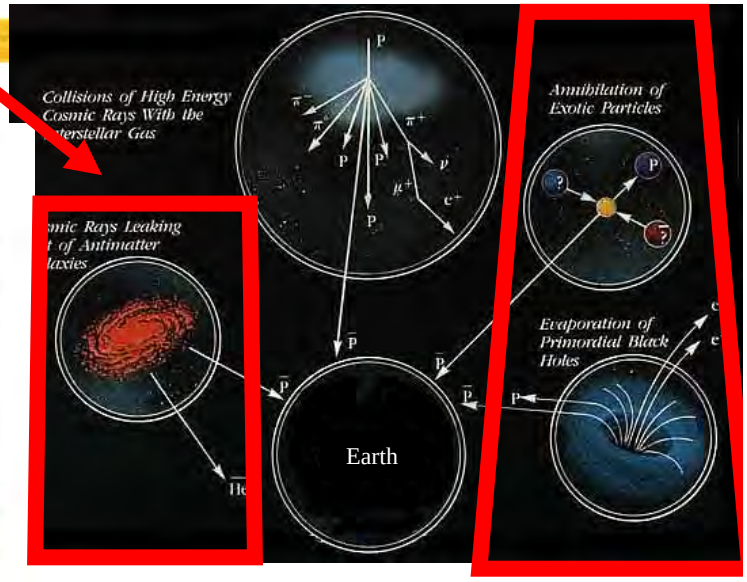

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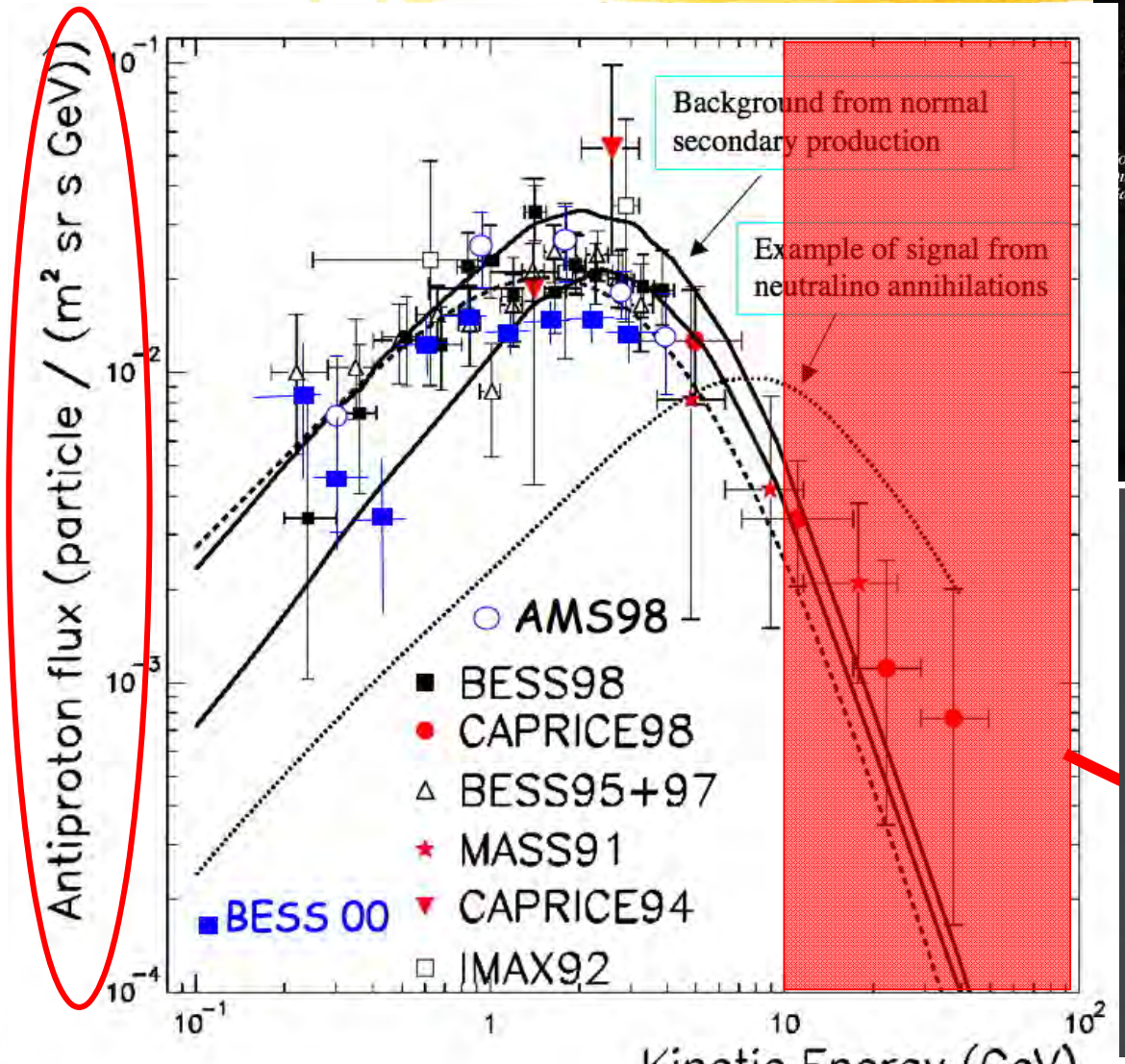

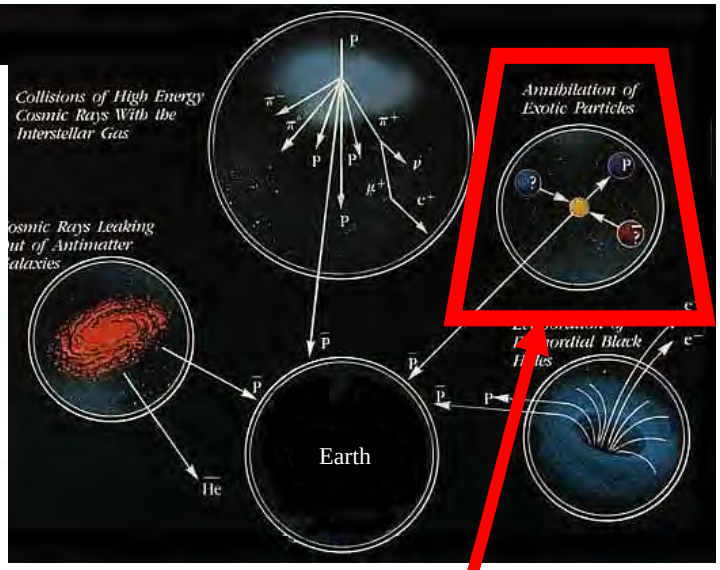

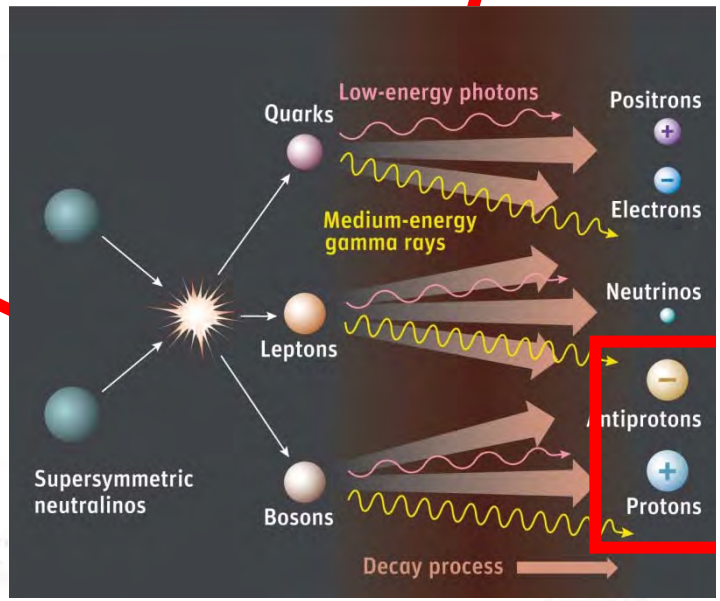

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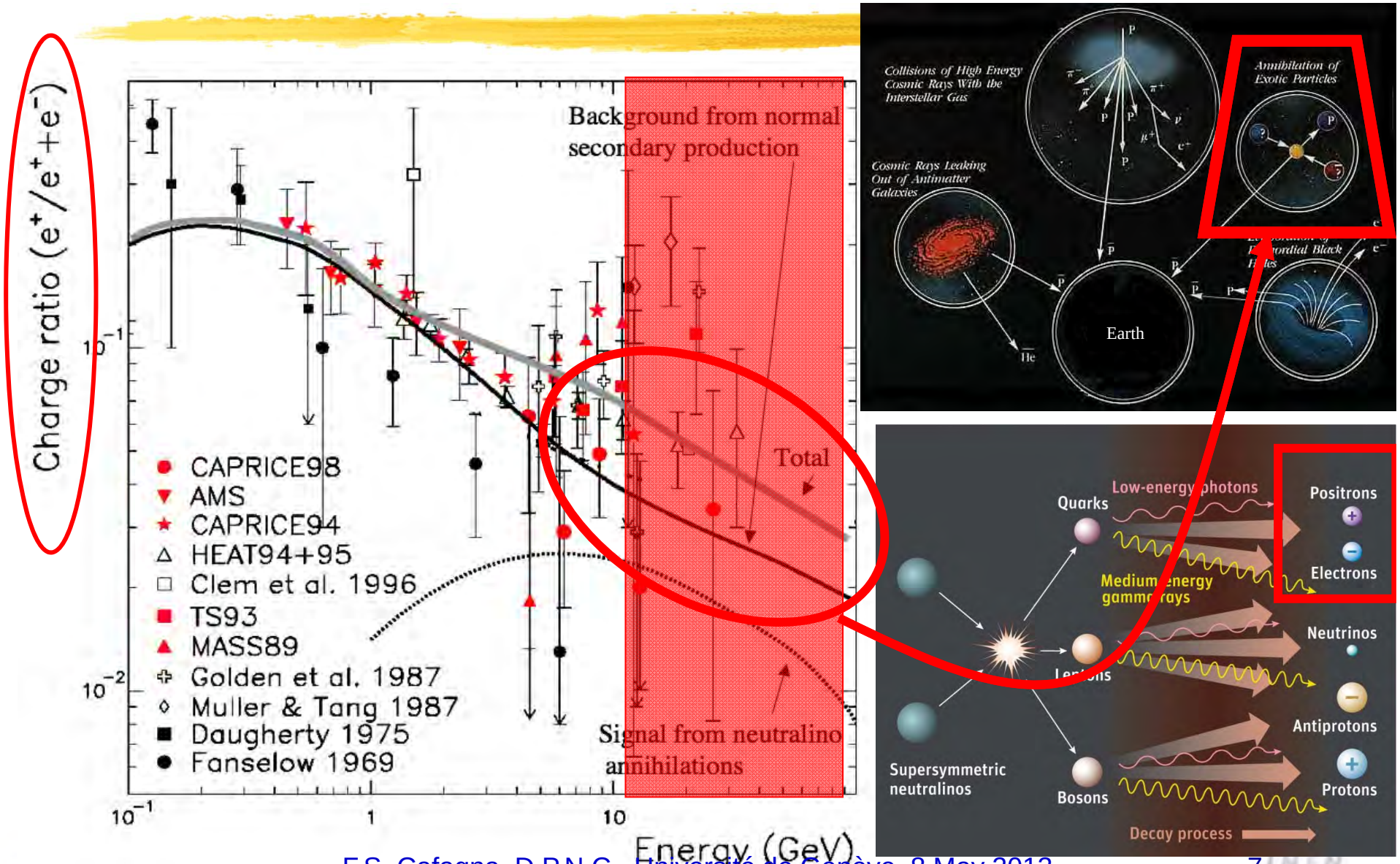

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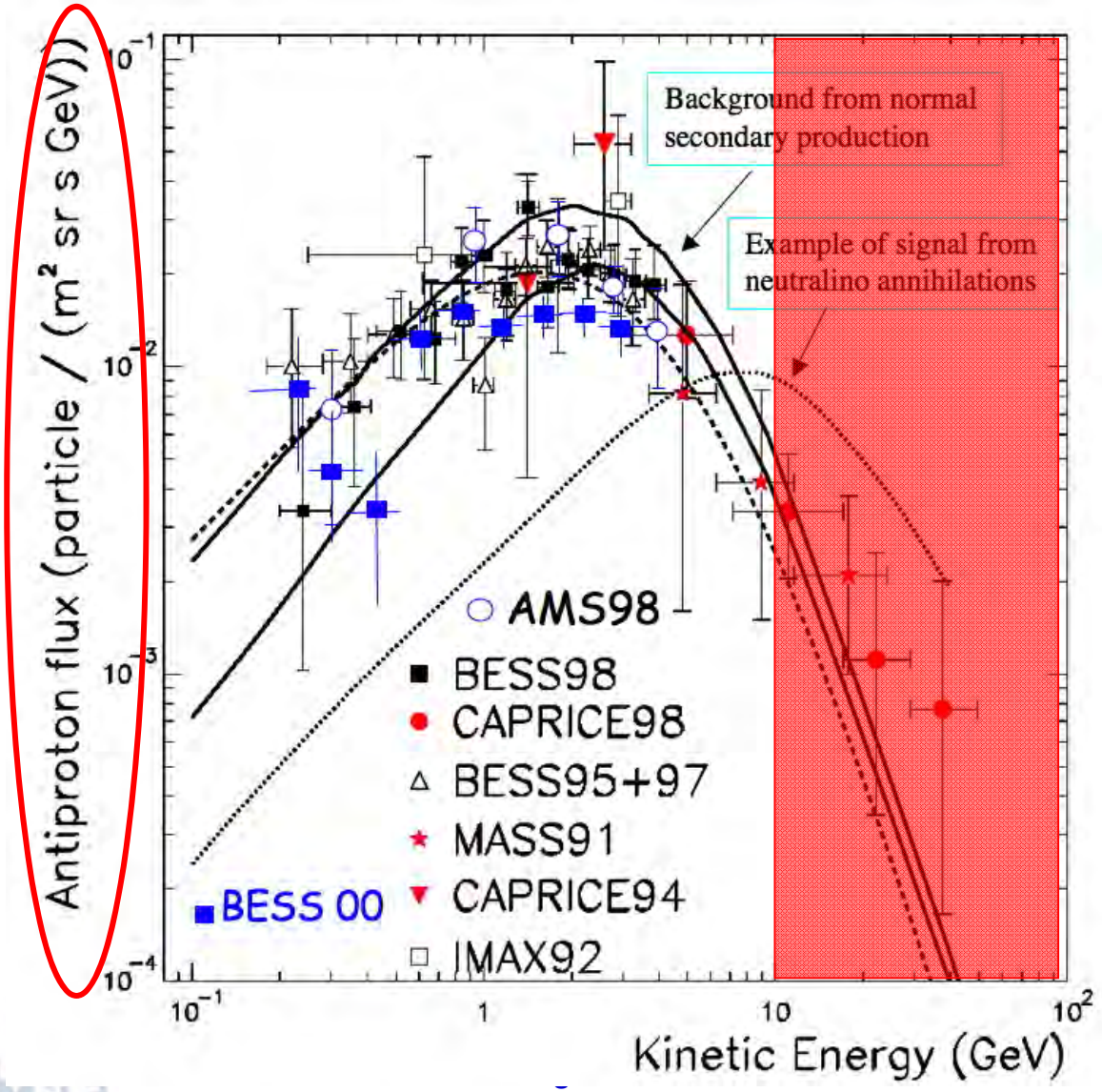

- Detecting antimatter in the cosmic rays, at «high» (>10GeV) energies not only helps you modelling propagation or in the indirect dark matter search but also ...
- Helps in having a better control of your detectors studying systematics that could be charge dependent (we need to measure absolute fluxes ...).

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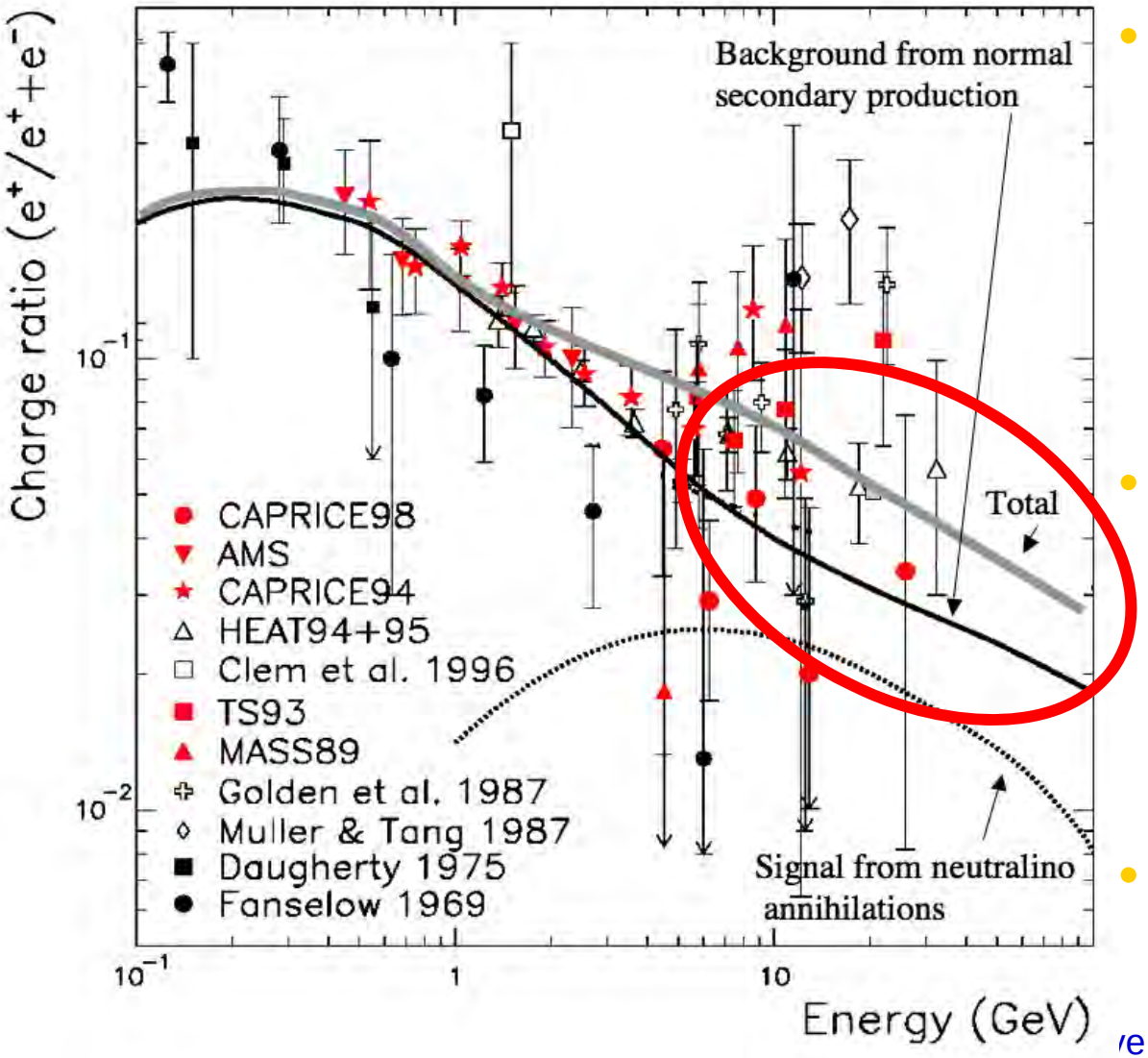

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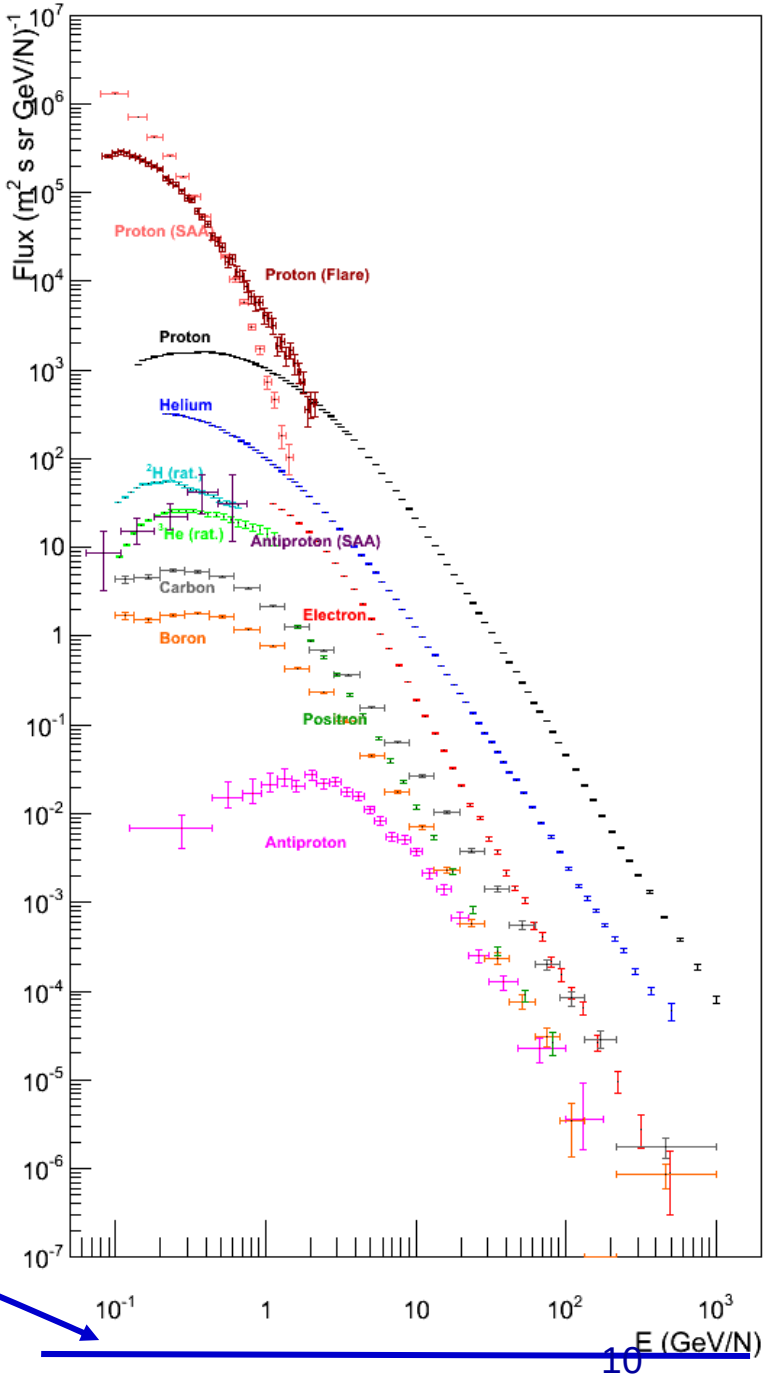
- Helps in having a better control of your detectors studying systematics that could be charge dependent (we need to measure absolute fluxes ...).
- e^+ & e^- in PAMELA are also used for that.

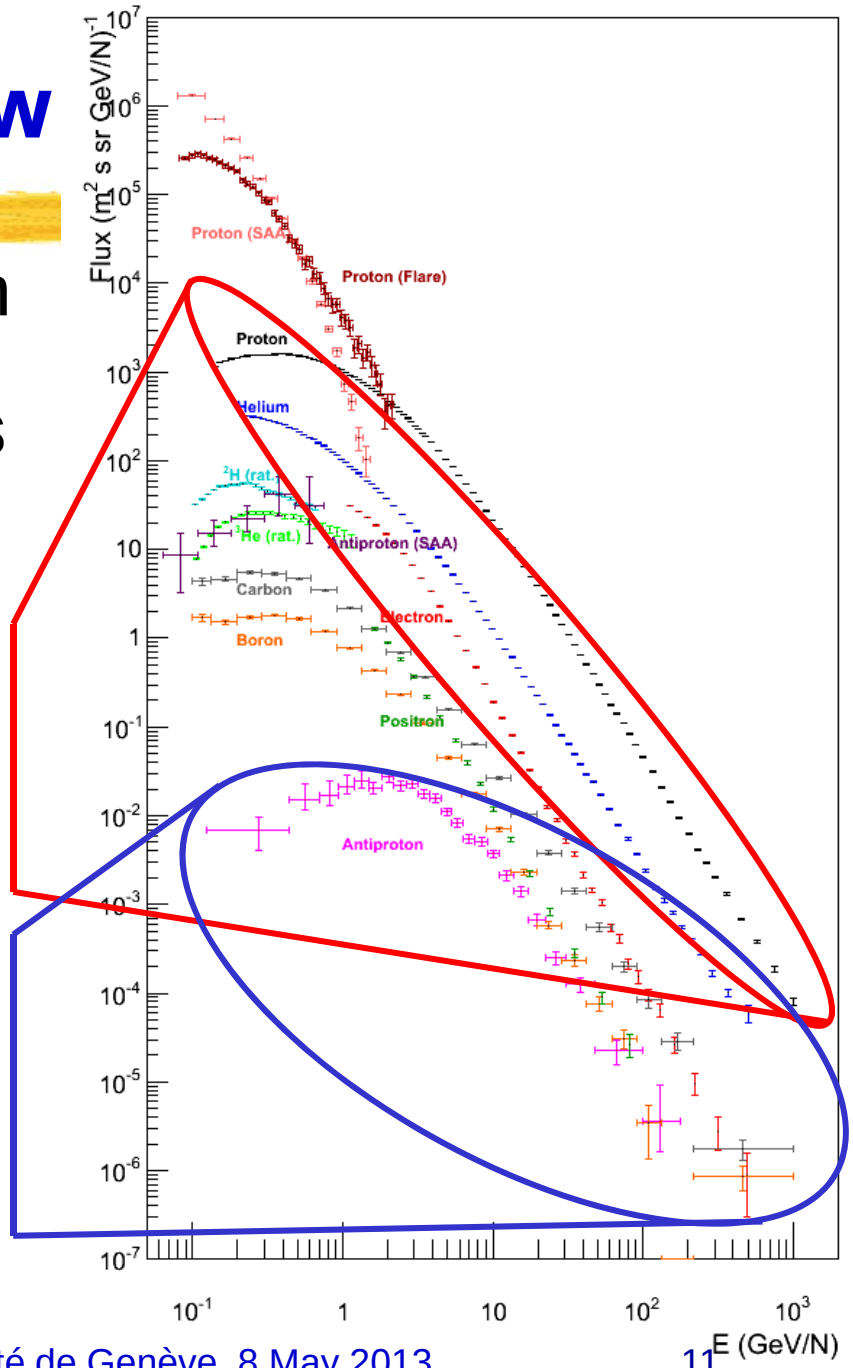
The PAMELA C.R. view

- Large flux range, from 10^{-7} to 10^{7} $(m^2\ s\ sr\ GeV)^{-1}$
- "Large" energy range, from .5 to 1000 TeV.
- Several measurements with the same detector.



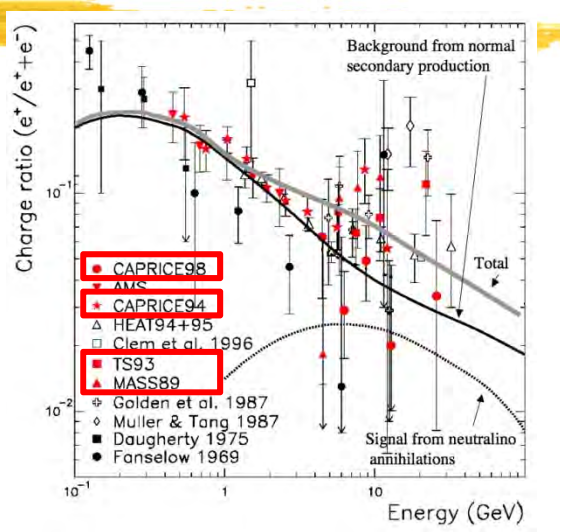
The PAMELA C.R. view

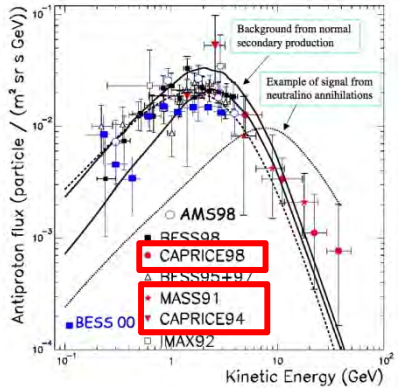
- Measurement of spectra from different particle families requires different approaches in systematics treatment and evaluation.
- Small features in spectra of high statistic particles fluxes, like H, He and e^-, can be hint of new astrophysical effects.
- As well as distortions in the spectra of the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

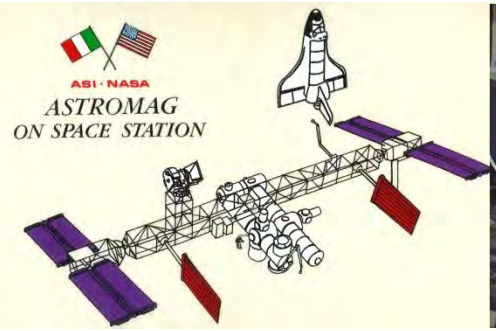


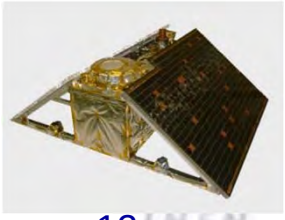
PAMELA Heritage: WiZard activities

- Balloon-borne experiments to measure antimatter: **MASS-89,91 TS-93 CAPRICE-94,97,98**
- **Astromag/WiZard** project (PAMELA precursor) on board of the Space Station Freedom, was canceled.
- Space experiments to study low energy nuclei and space radiation environment: **NINA-1,2 SILEYE-1,2,3 ALTEA.**









PAMELA Collaboration

Italy

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

Payload for Antimatter & Matter Exploration and Light nuclei Astrophysics

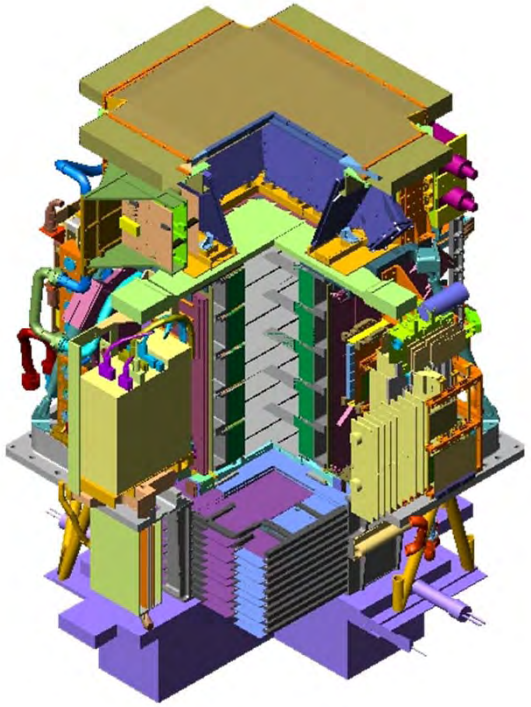
Germany: Siegen

Sweden: KTH, Stockholm

Russia: Moscow / St. Petersburg

PAMELA detectors

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



GF:	**21.5 cm² sr**
Mass:	**470 kg**
Size:	**130x70x70 cm³**
Power Budget:	**360W**

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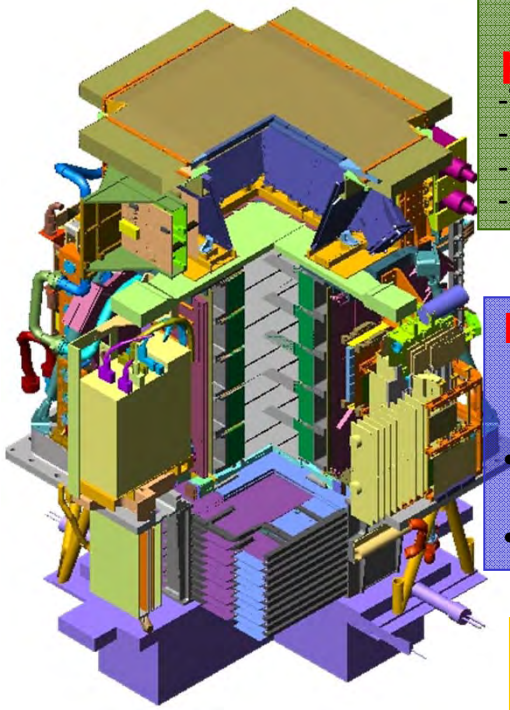

Time-Of-Flight
plastic scintillators + PMT
- -Trigger;
- -Albedo rejection;
- -Mass identification up to 1 GeV;
- -Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling
(16.3 X_0, 0.6λ_I)
- •Discrimination e^+/ p, pbar/e^- (shower topology)
- •Direct E measurement for e^-

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

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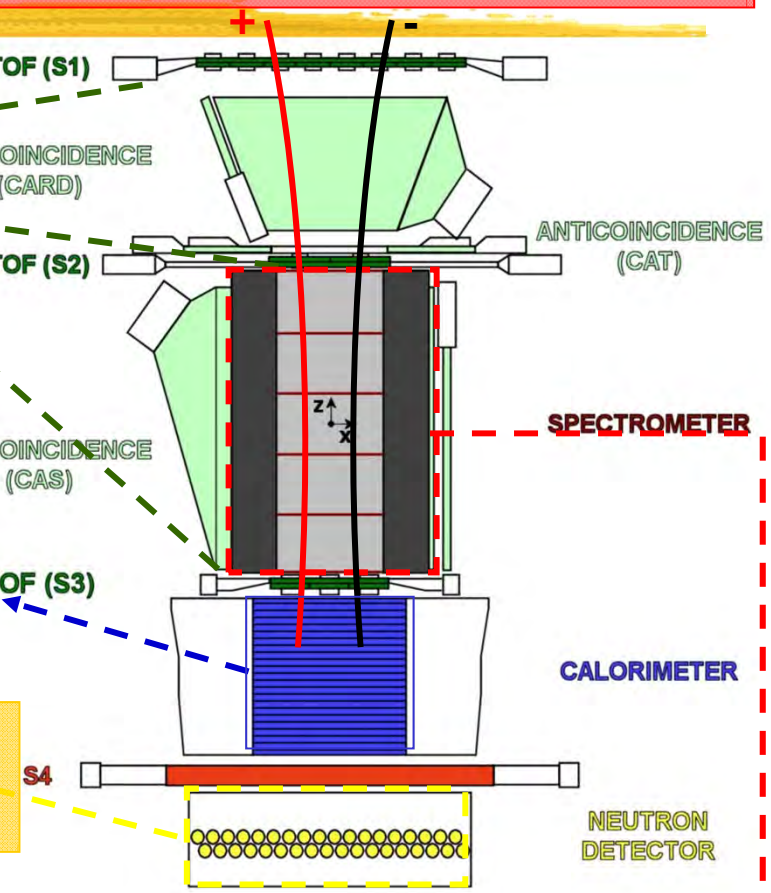


Spectrometer microstrip silicon tracking system + permanent magnet

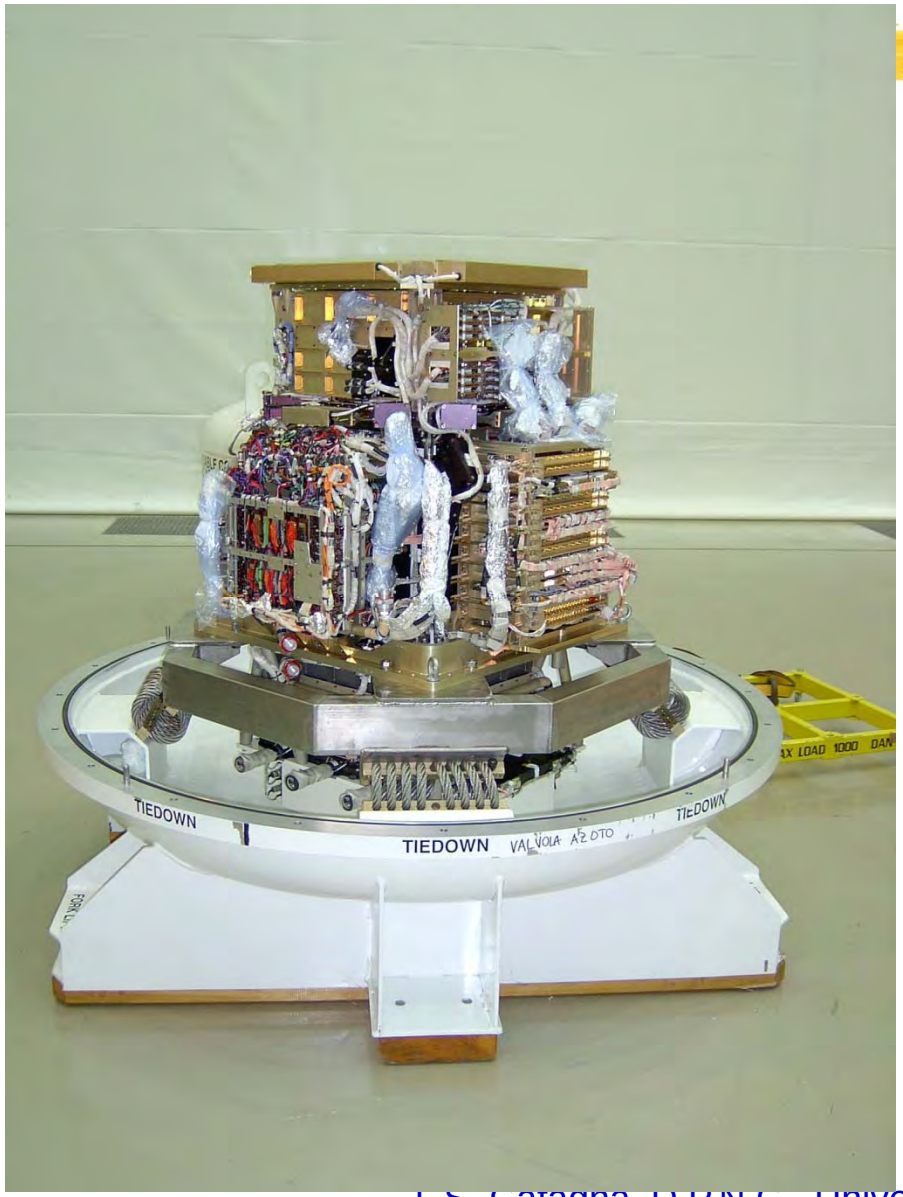
- •Magnetic rigidity (R = pc/Ze)
- •Charge sign
- •Charge value from dE/dx

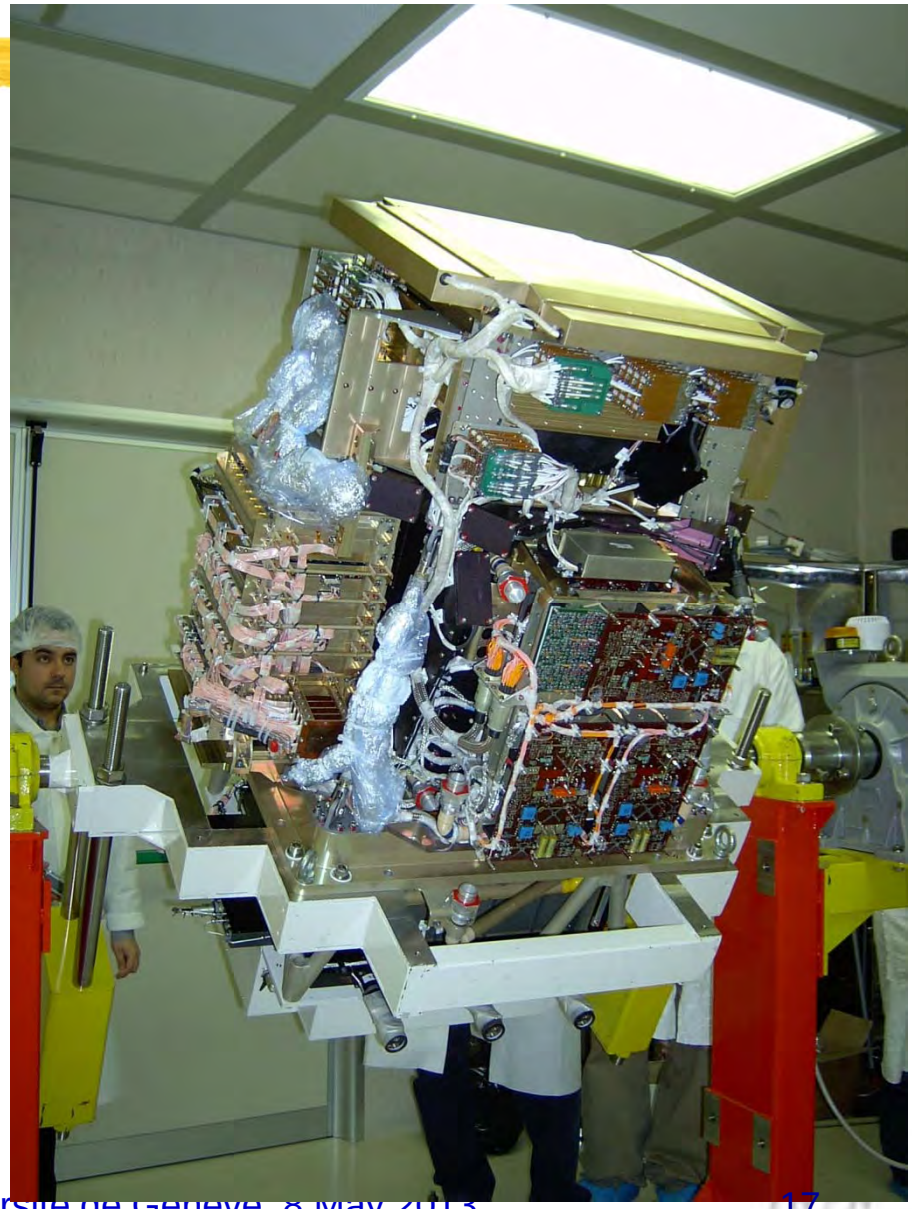
Design Performance

• Antiprotons	80 MeV - 150 GeV
• Positrons	50 MeV – 270 GeV
• Electrons	up to 400 GeV
• Protons	up to 700 GeV
• Electrons+positrons	up to 2 TeV (calorimeter alone)
• Light Nuclei (He/Be/C)	up to 200 GeV/n
• AntiNuclei search	sensitivity of 3×10^{-8} in $\overline{\text{He}}$/He

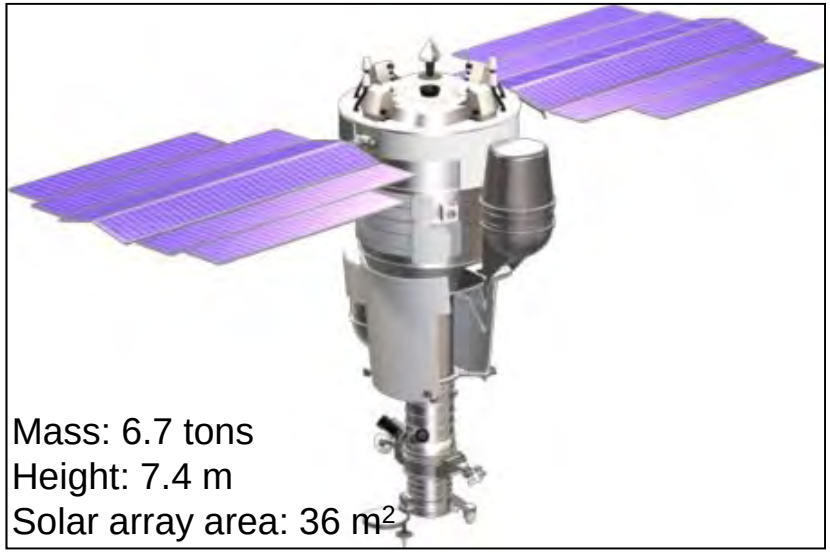
→ Simultaneous measurement of many cosmic-ray species
→ New energy range
→ Unprecedented statistics

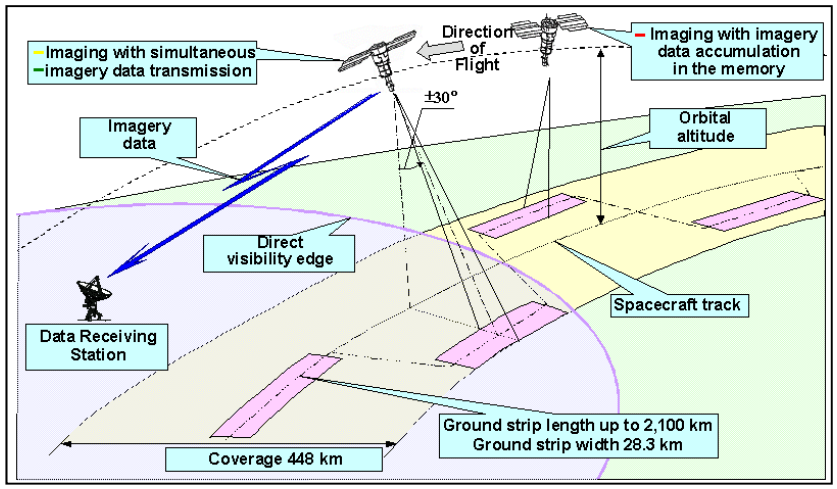
PAMELA: the integration





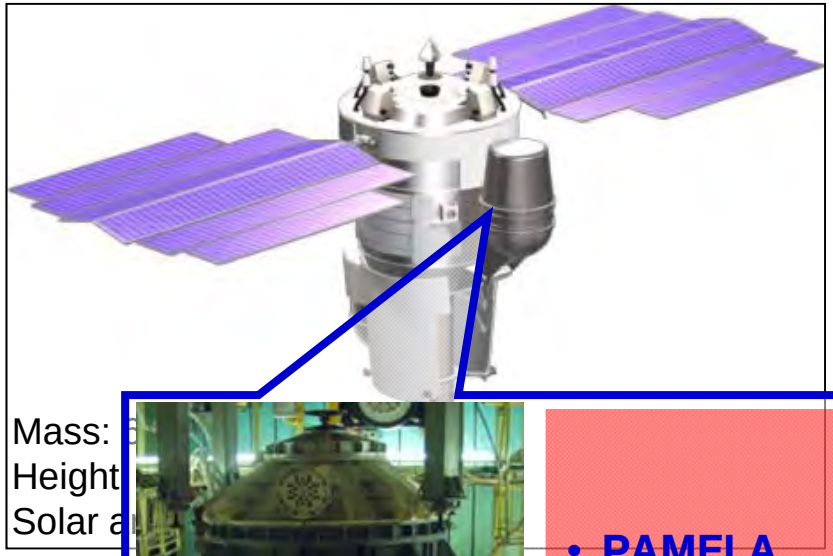
The Resurs DK-1 spacecraft



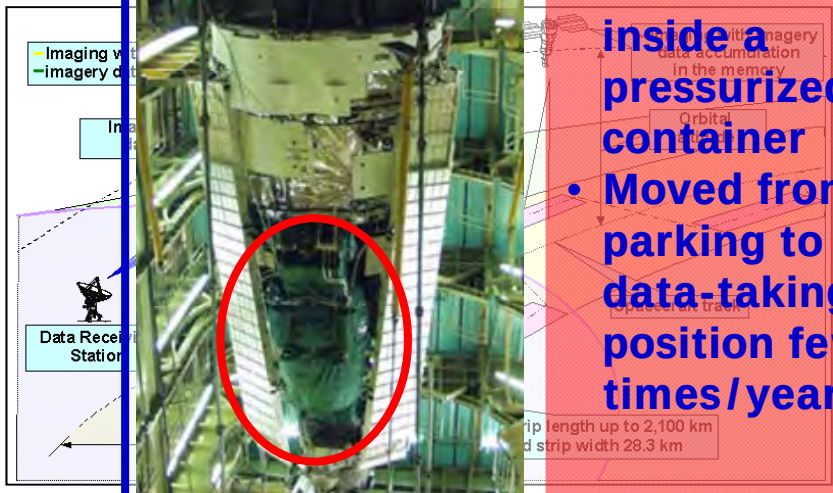


- Multi-spectral remote sensing of earth's surface
  - → near-real-time high-quality images
- Built by the Space factory TsSKB Progress in Samara (Russia)
- Operational orbit parameters:
  - inclination ~70°
  - altitude ~ 350-600 km (elliptical)
- Active life >3 years

The Resurs DK-1 spacecraft



Mass: 6
Height
Solar a



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

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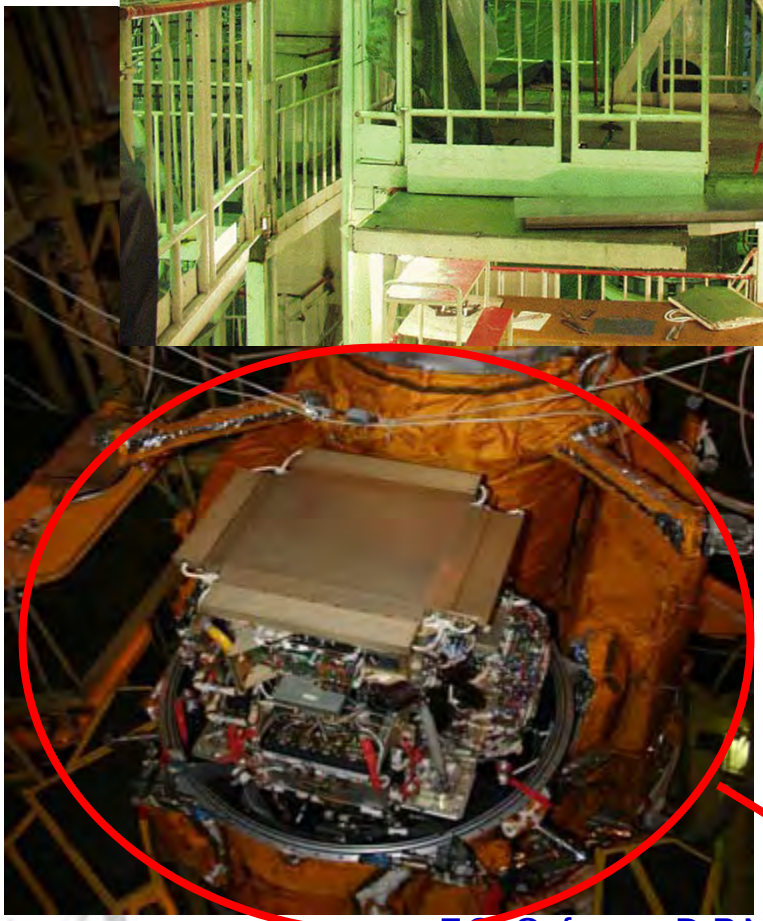
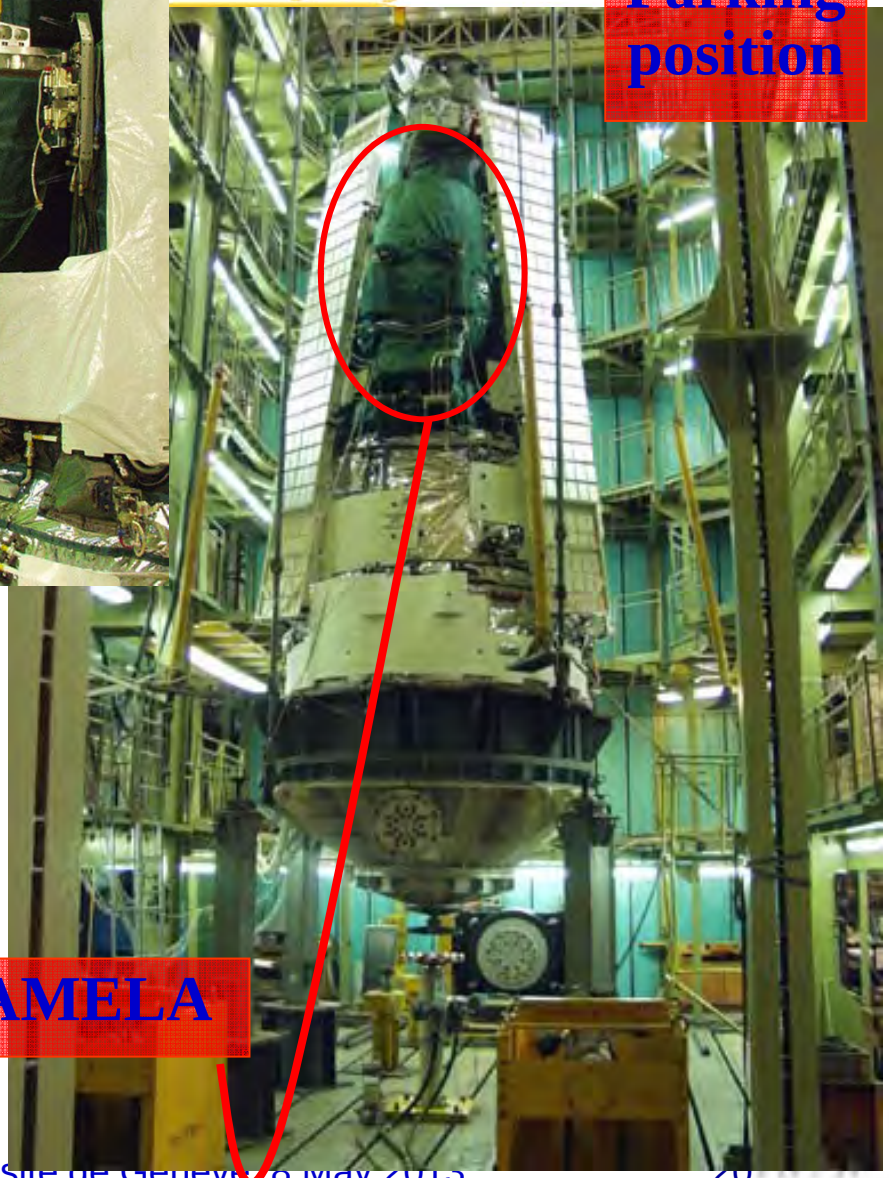
atellite

From flight to parking position

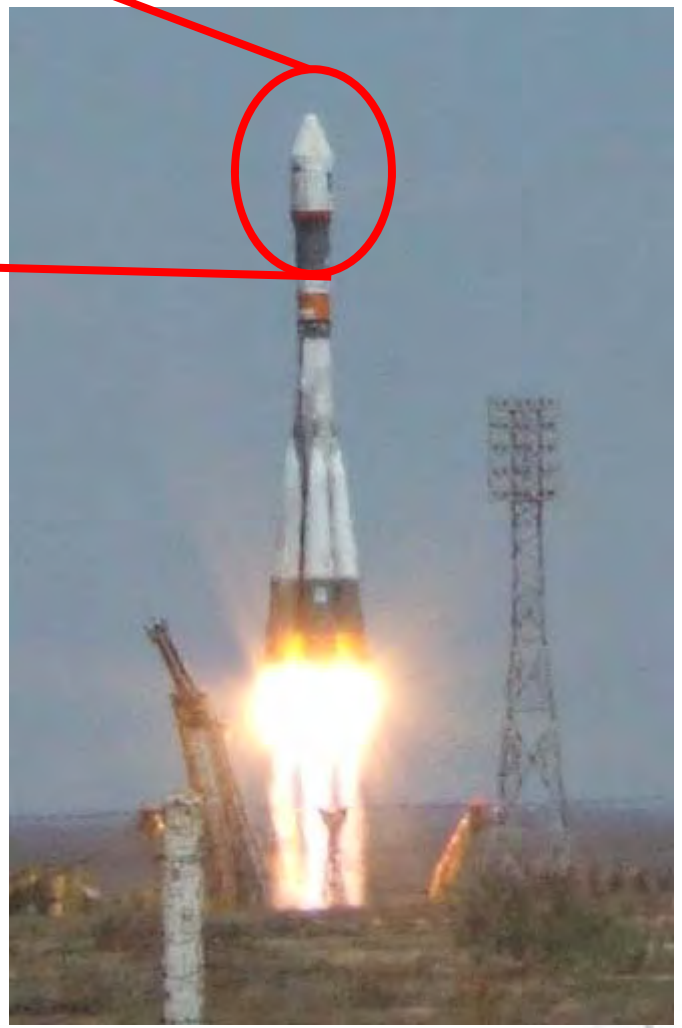
Parking position

PAMELA

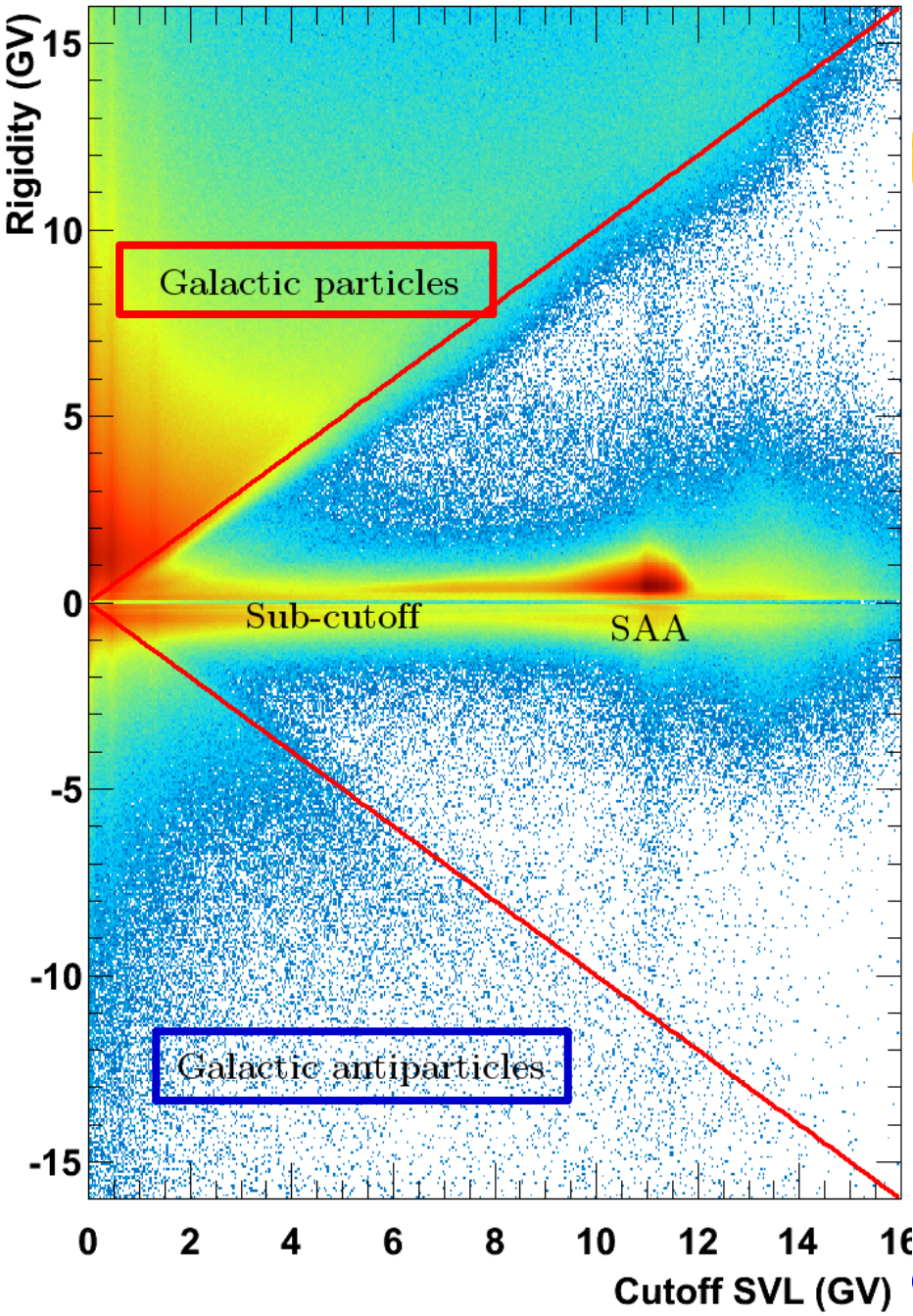


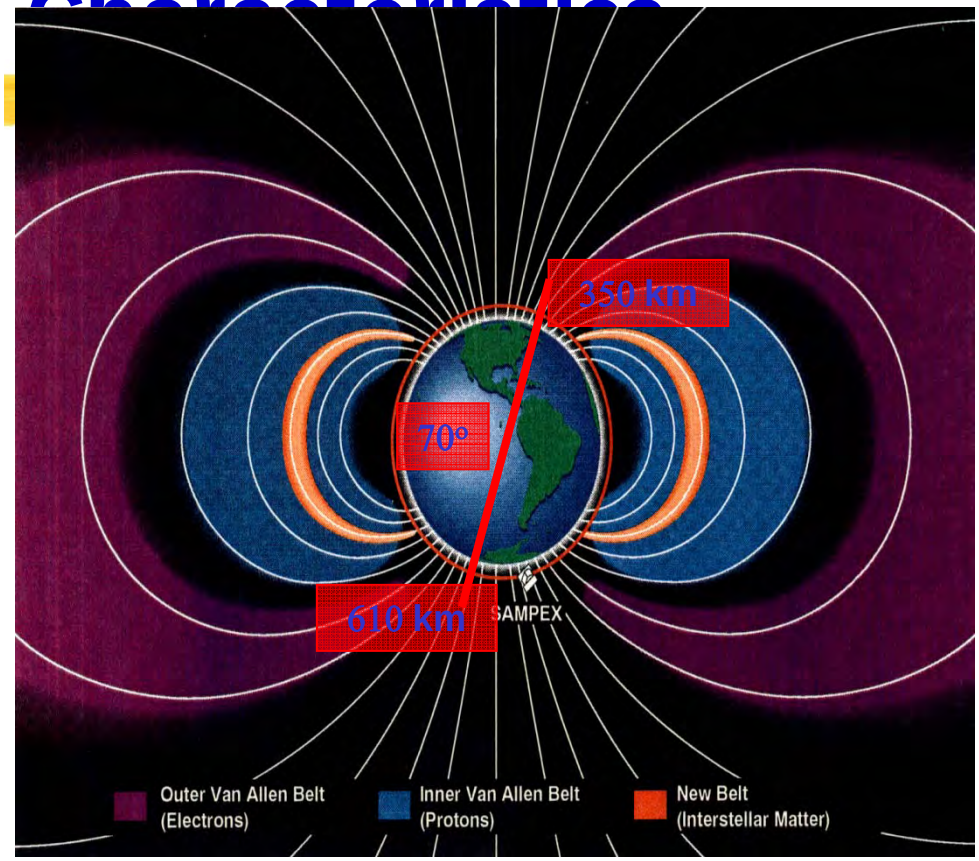


the satellite & launch



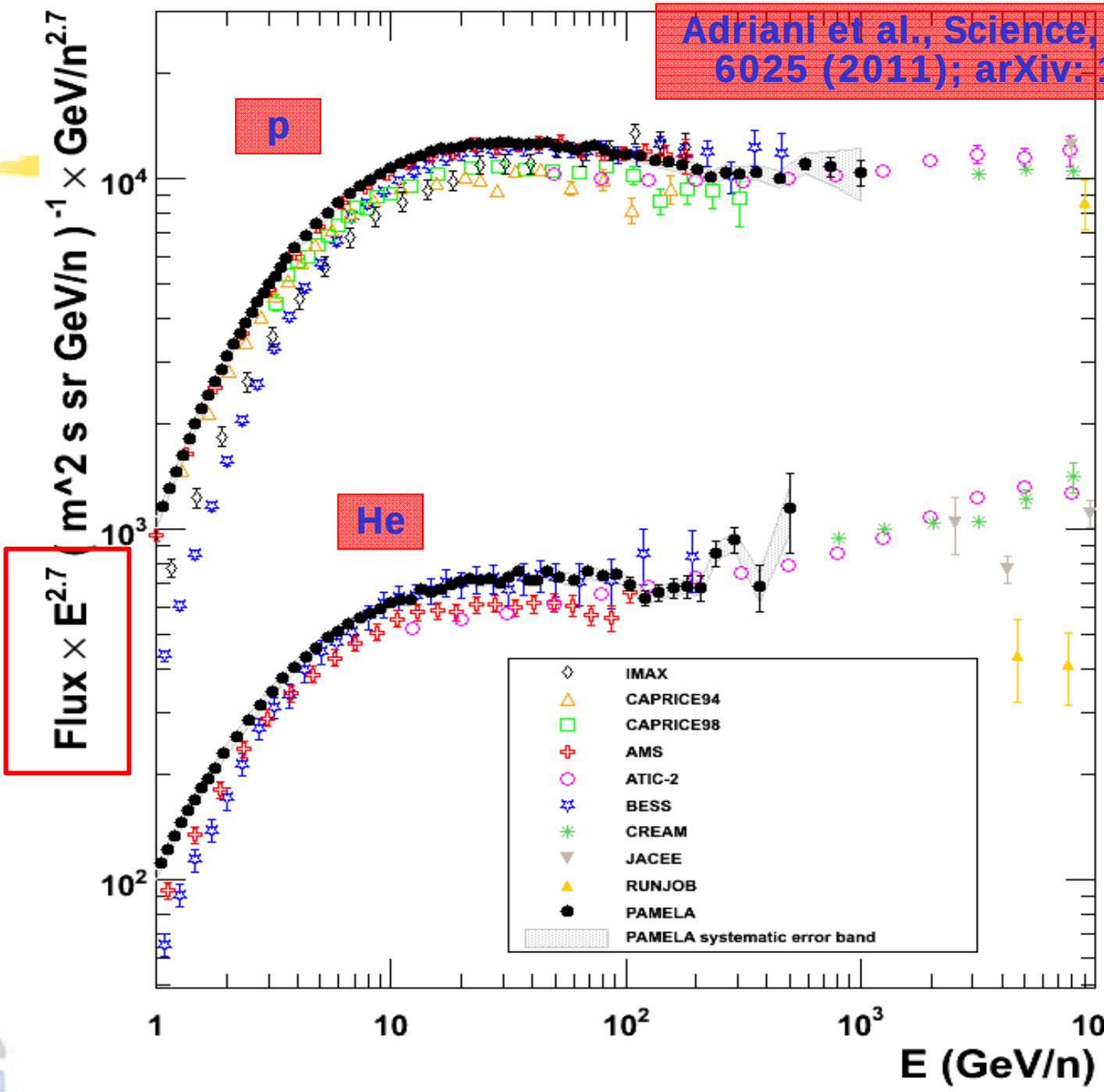
- Launch from Baikonur:
  June 15th 2006, 0800 UTC.
  Power On: June 21st 2006, 0300 UTC.
  Detectors operated as expected after launch
- PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006
  - >6 year of data taking (~75% live-time)
  - >30 TByte of raw data downlinked
  - >2×10^9 triggers recorded and under analysis





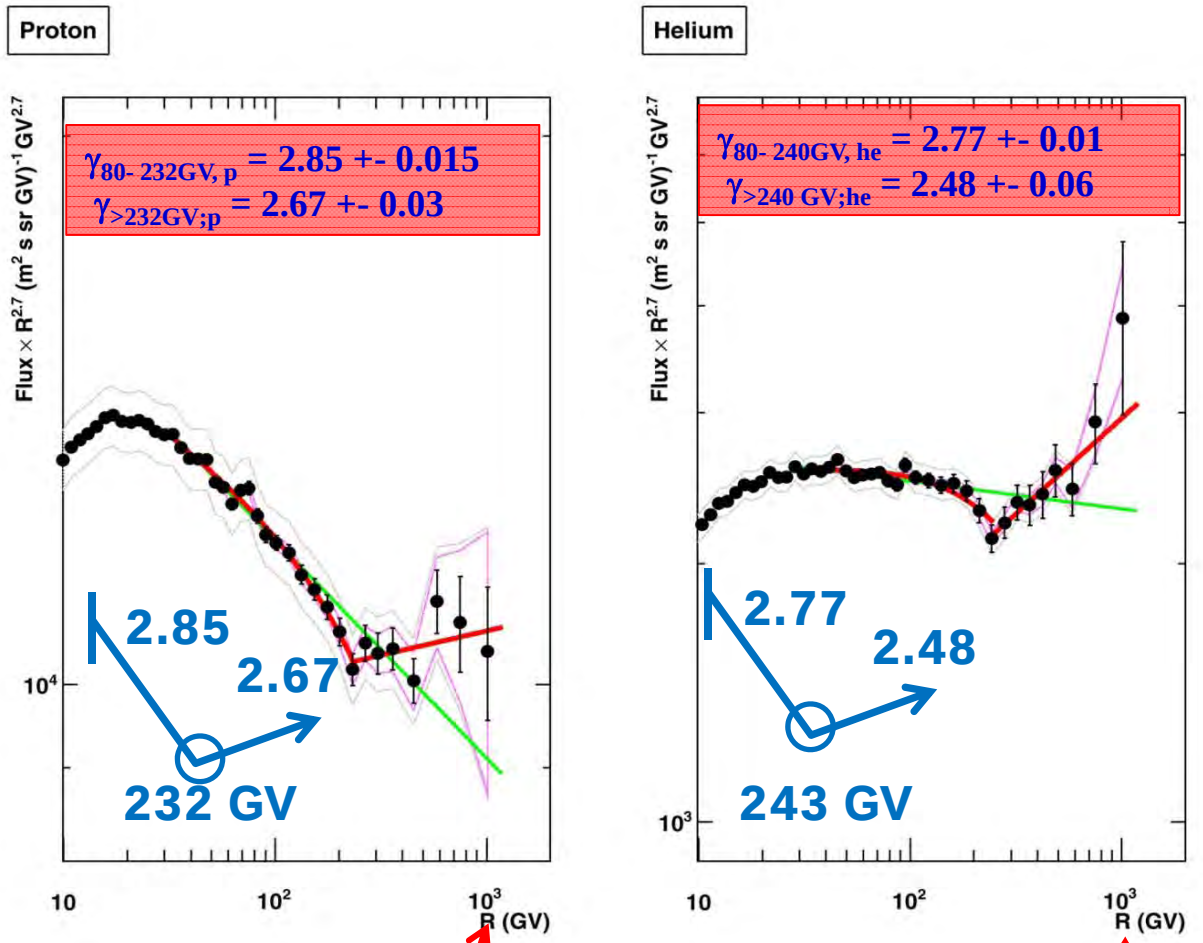
- Thanks to the PAMELA orbit we are able to measure different particle and antiparticle families.

Adriani et al., Science, vol. 332 no. 6025 (2011); arXiv: 1103.4055

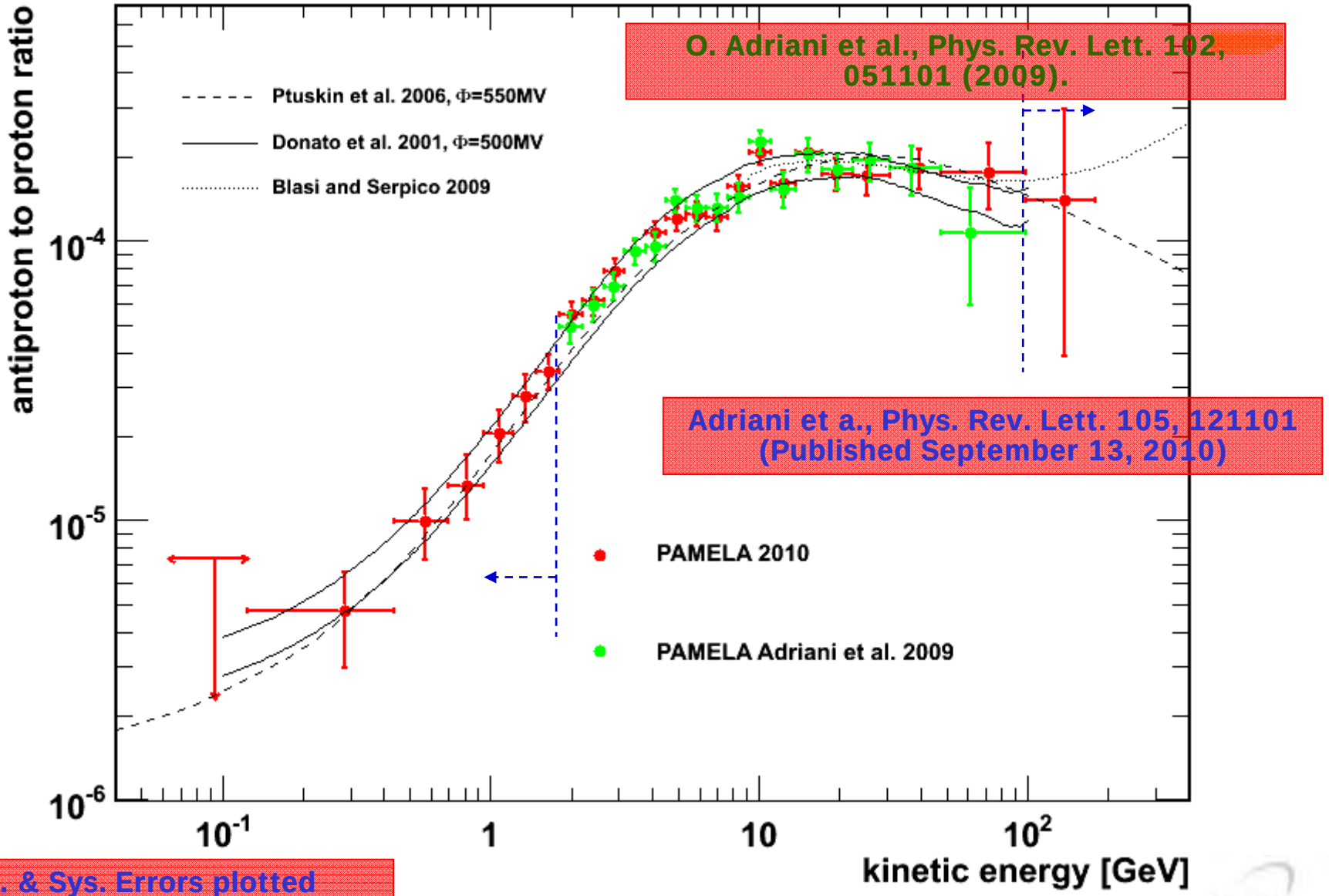


PAMELA Galactic H & He

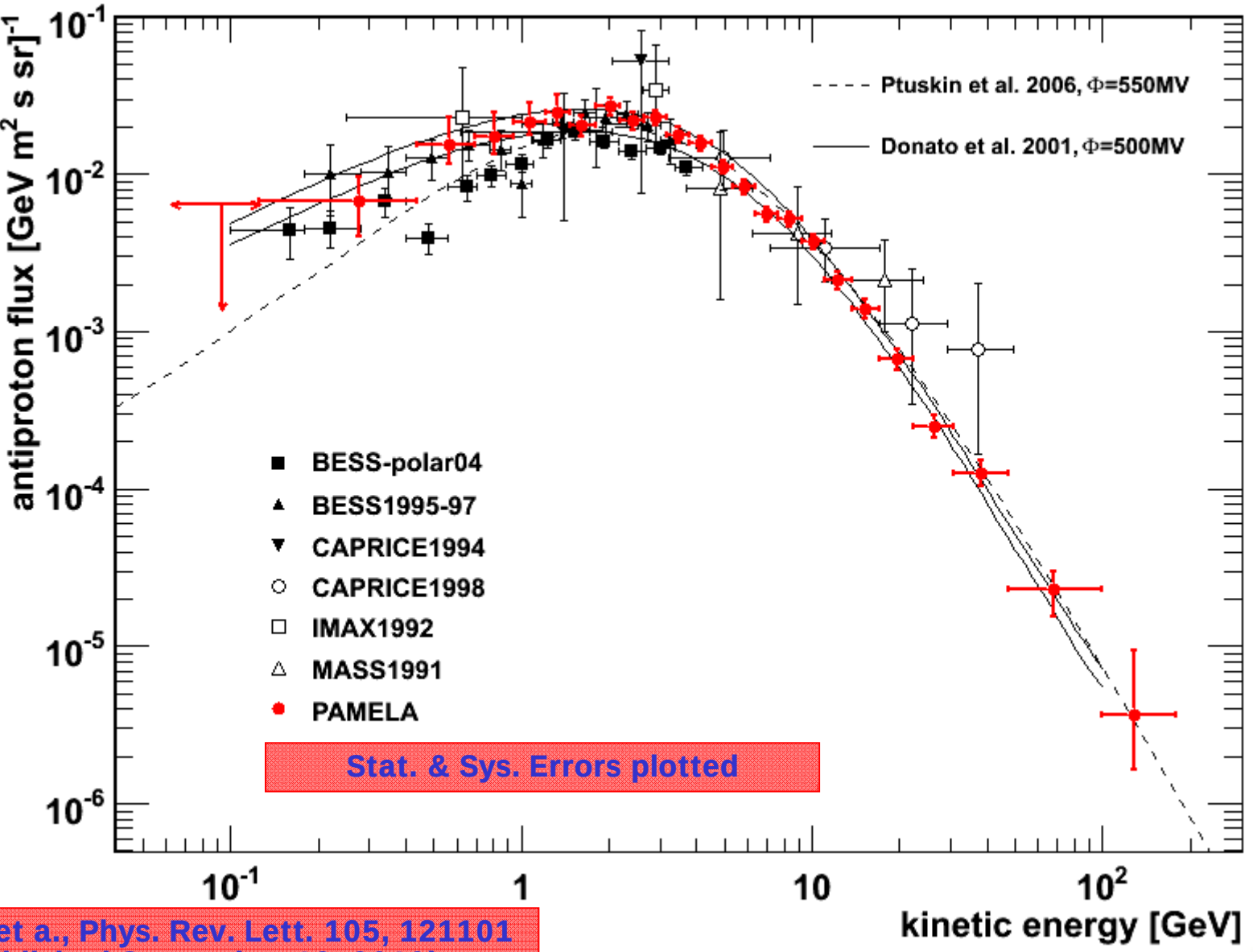
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta\gamma$~0.2÷0.3
- SPL is rejected at 98% CL
- Origin of the structures?
  - At the sources: multi-populations, non-linear DSA.
  - Propagation effects.



Antiproton to Proton Ratio



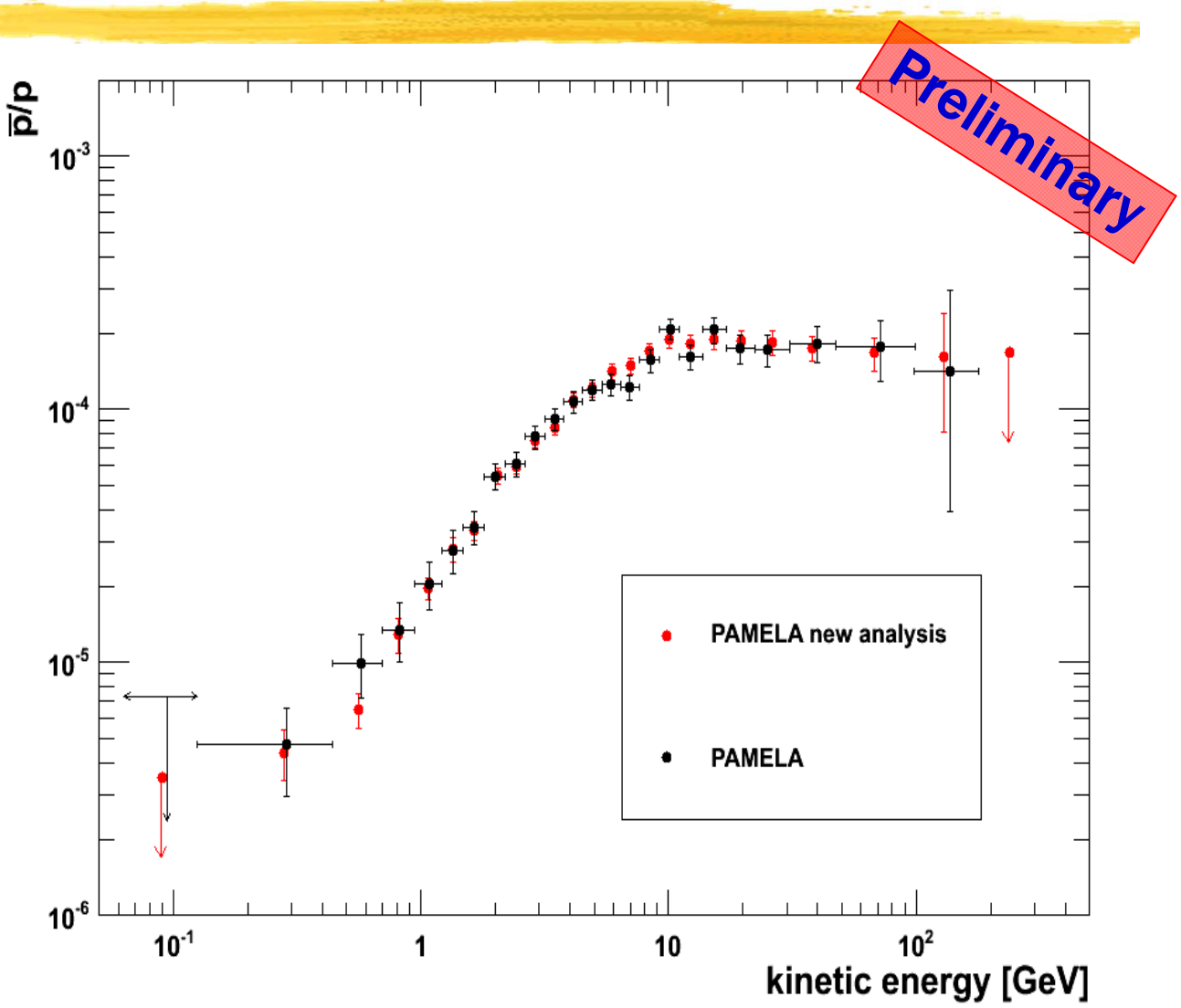
Antiproton Flux



Adriani et a., Phys. Rev. Lett. 105, 121101 (Published September 13, 2010)

Antiproton to proton flux ratio

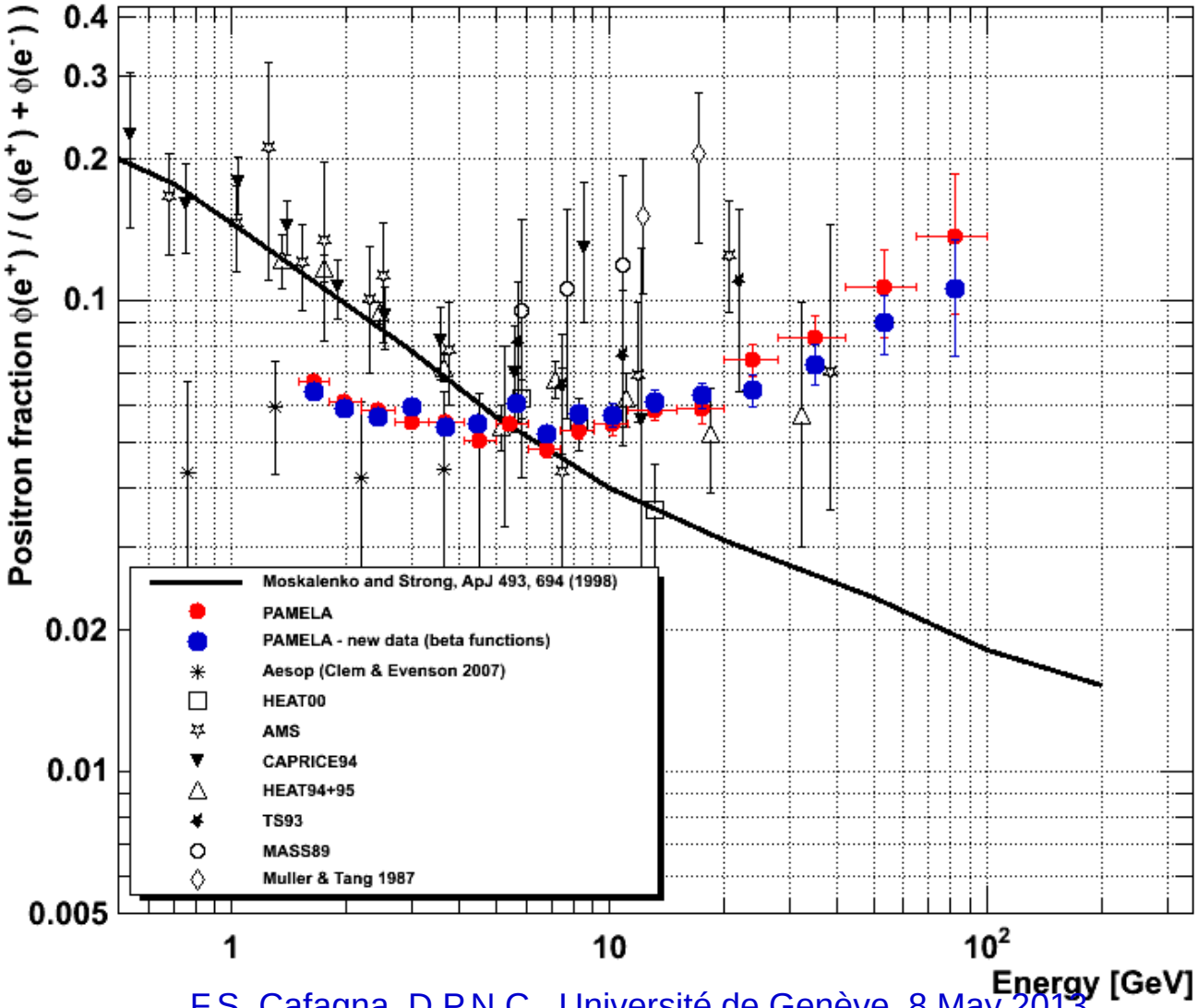
- Using all data till 2010 and multivariate classification algorithms about a **20÷50%** of statistical increase in respect to published analysis



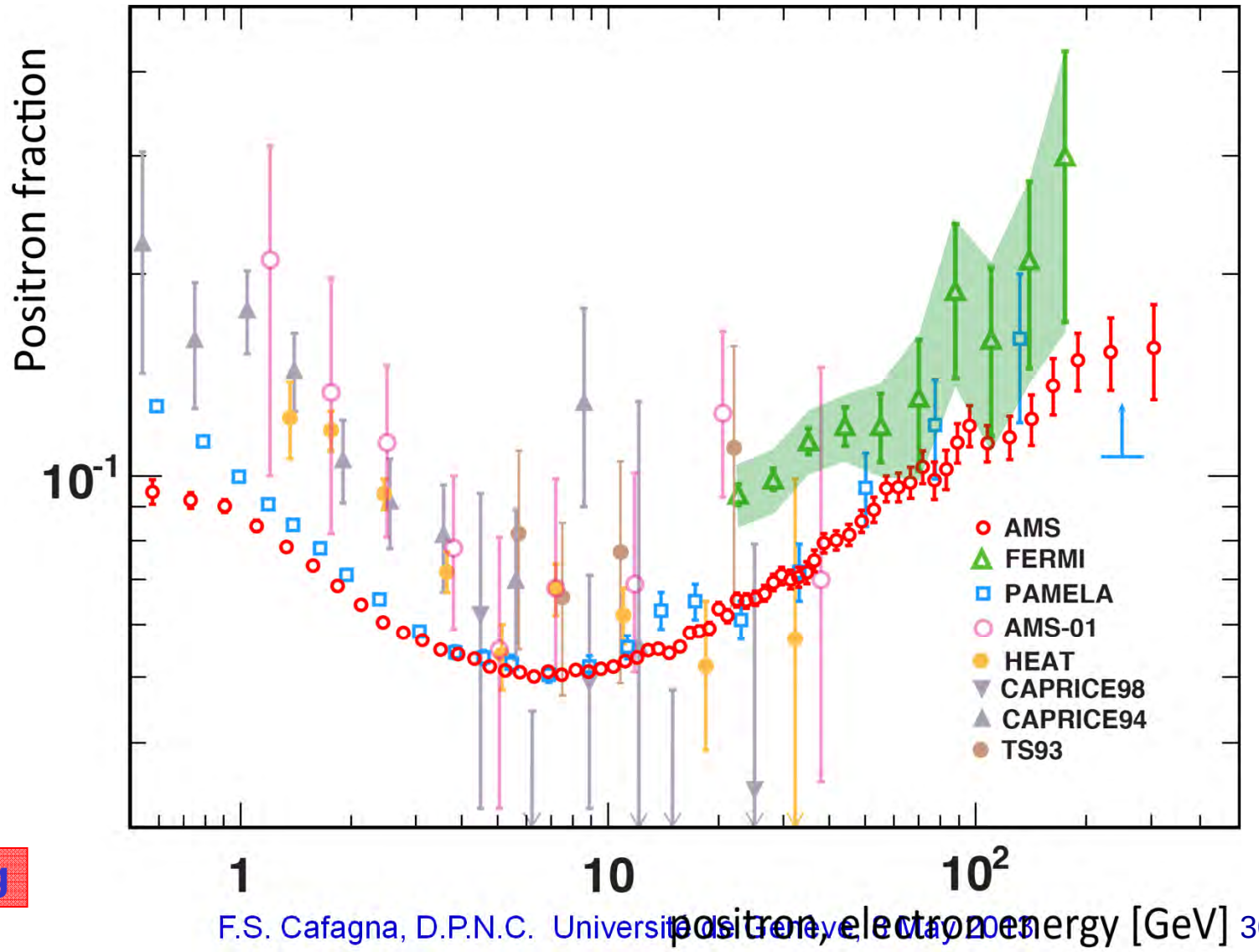
New results

Positron to All Electron Fraction

Adriani et al., Astropart. Phys. 34 (2010) 1 - arXiv:1001.3522

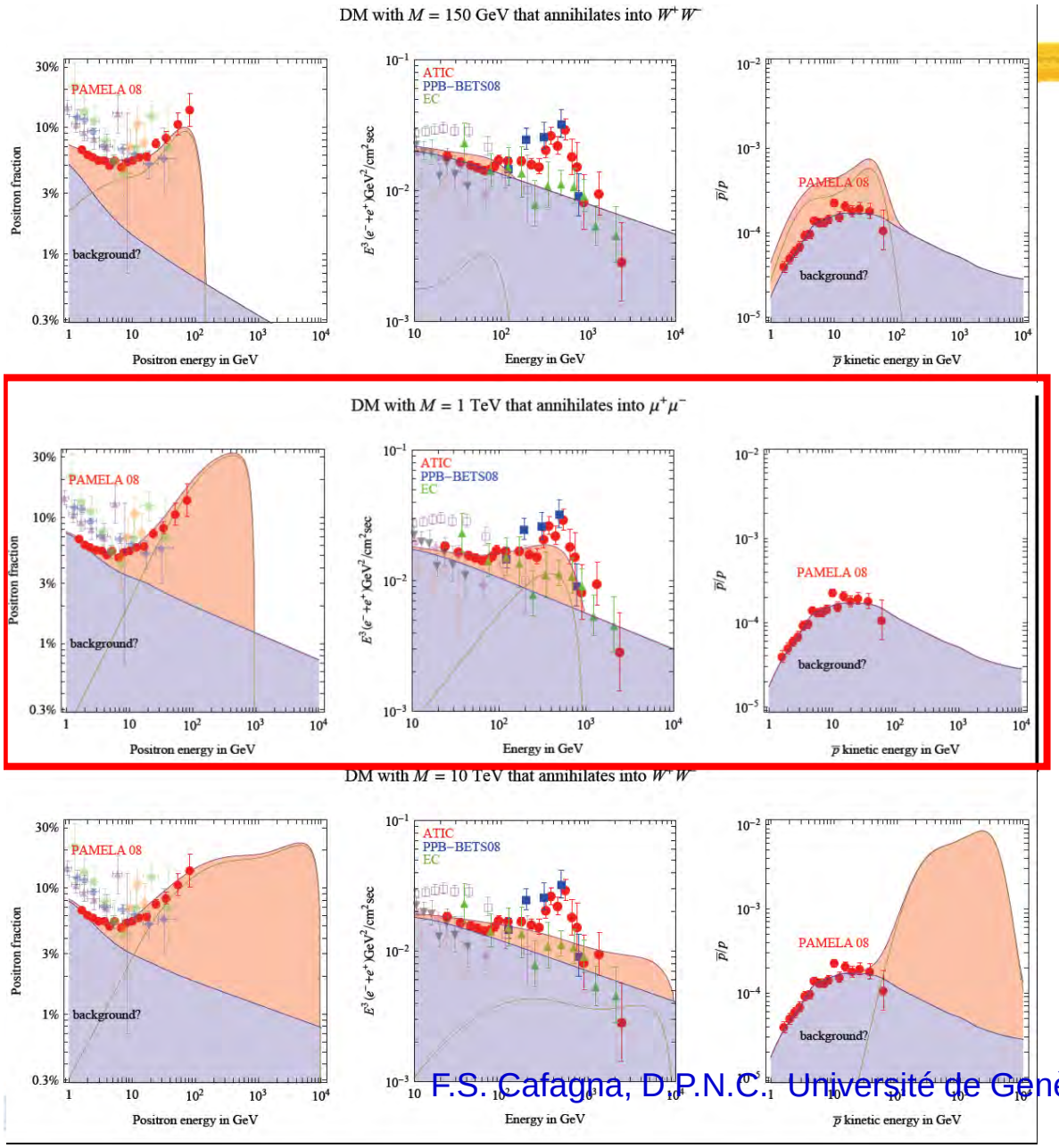


Positron to all electron fraction



S. Ting

DM ?



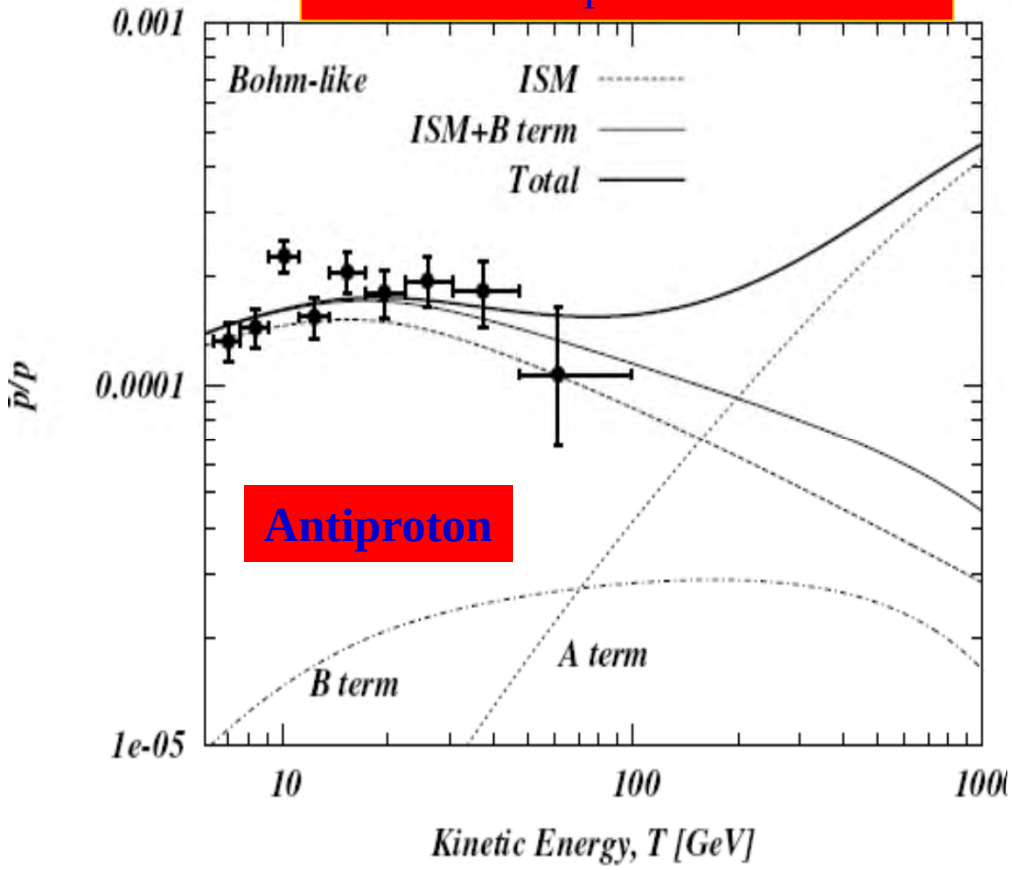
- PAMELA ability of measuring both proton and electron charge ration, make it possible to put several constrains to the models
- But you have the puzzling feature of having excess only in the positron sector, not in the antiproton one.

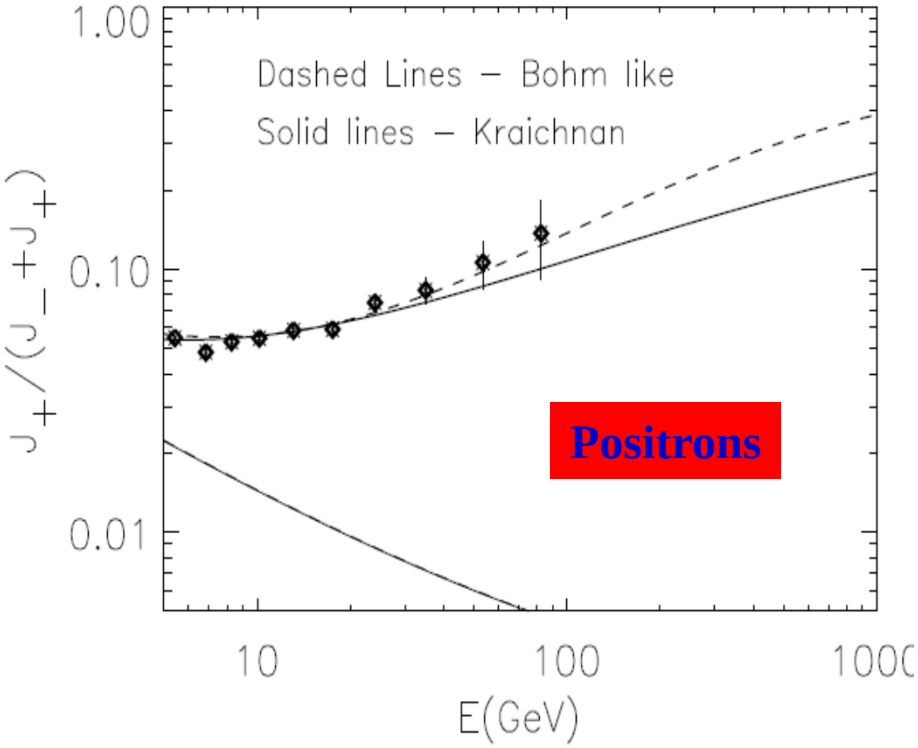
M. Cirelli, M. Kadastik, M. Raidal, A. Strumia arXiv:0809.2409v3

Antiprotons & positrons from old SNR's

P.Blasi Astro-ph.HE 0904.0871

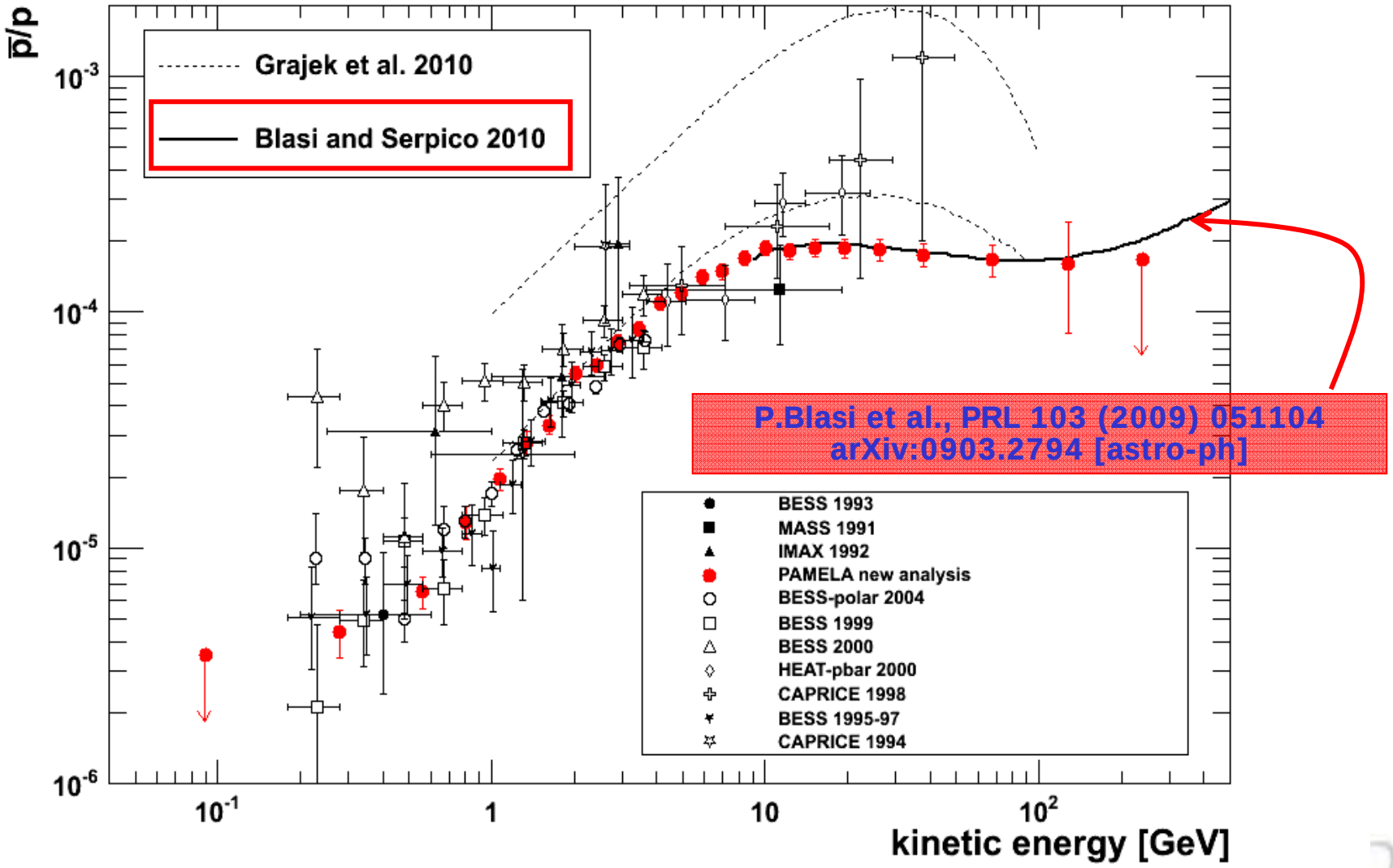
P. Blasi 0903.2794



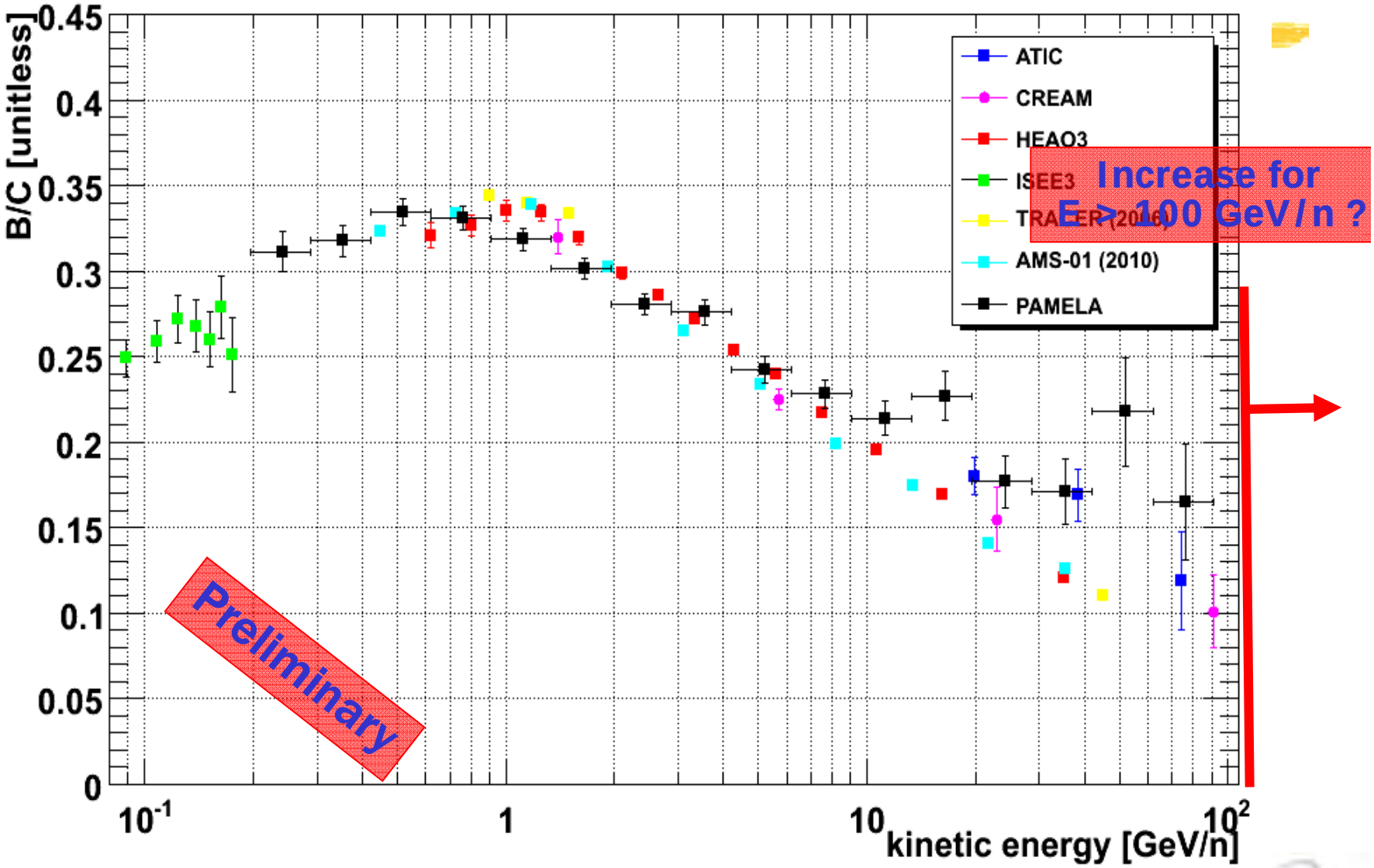


- Positrons created as secondary products of hadronic interactions inside the sources
- Secondary production takes place in the same region where cosmic rays are being accelerated.
- Antiproton/proton and B/C increase for E> 100GeV

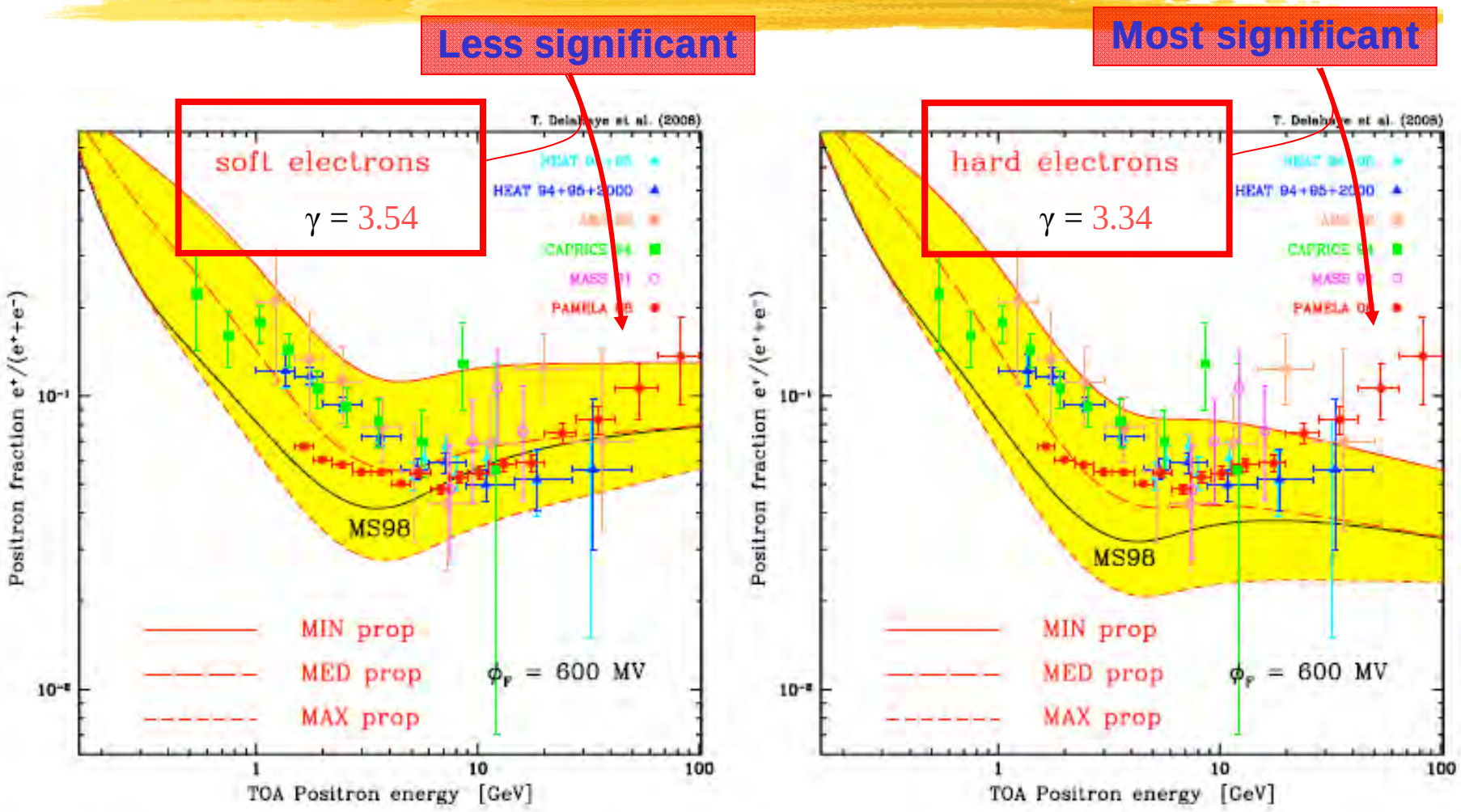
Antiprotons & positrons from old SNR's



Antiprotons & positrons from old SNR's



Positron Fraction Theoretical Uncertainties

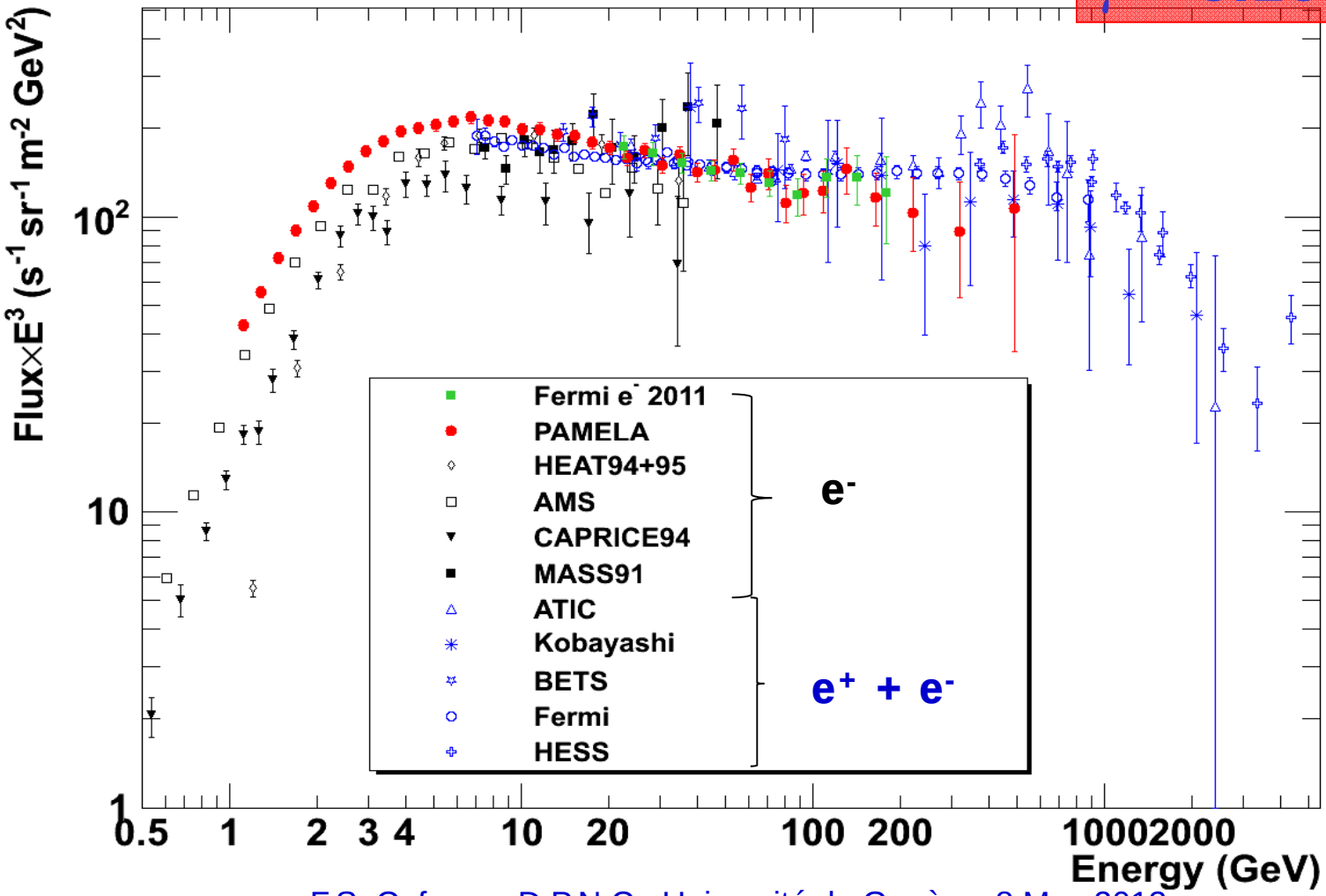


T. Delahaye et al., arXiv: 0809.5268v3

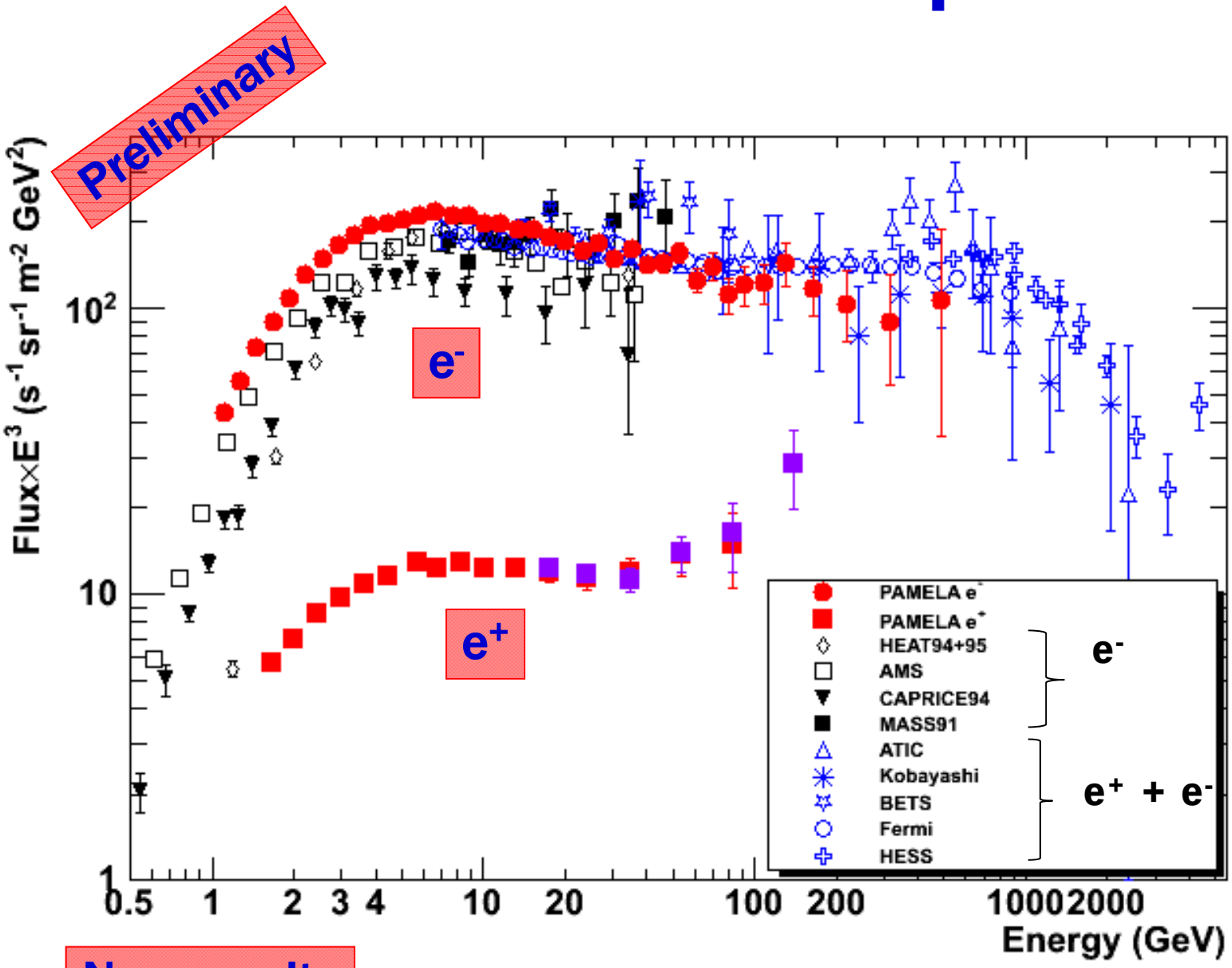
PAMELA Electron (e^-) flux

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

$\gamma = 3.18 \pm 0.05$

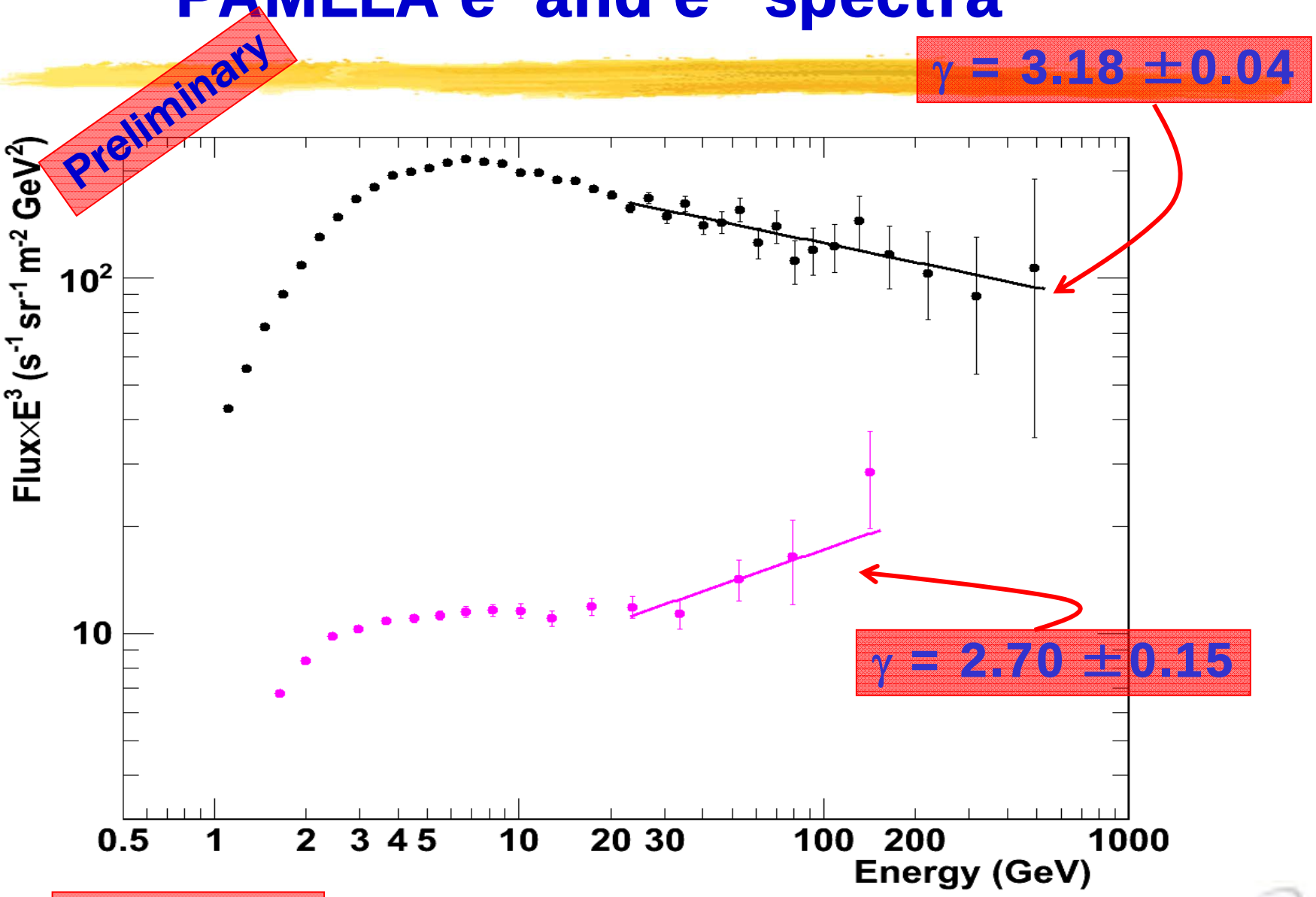


PAMELA e^- and e^+ spectra



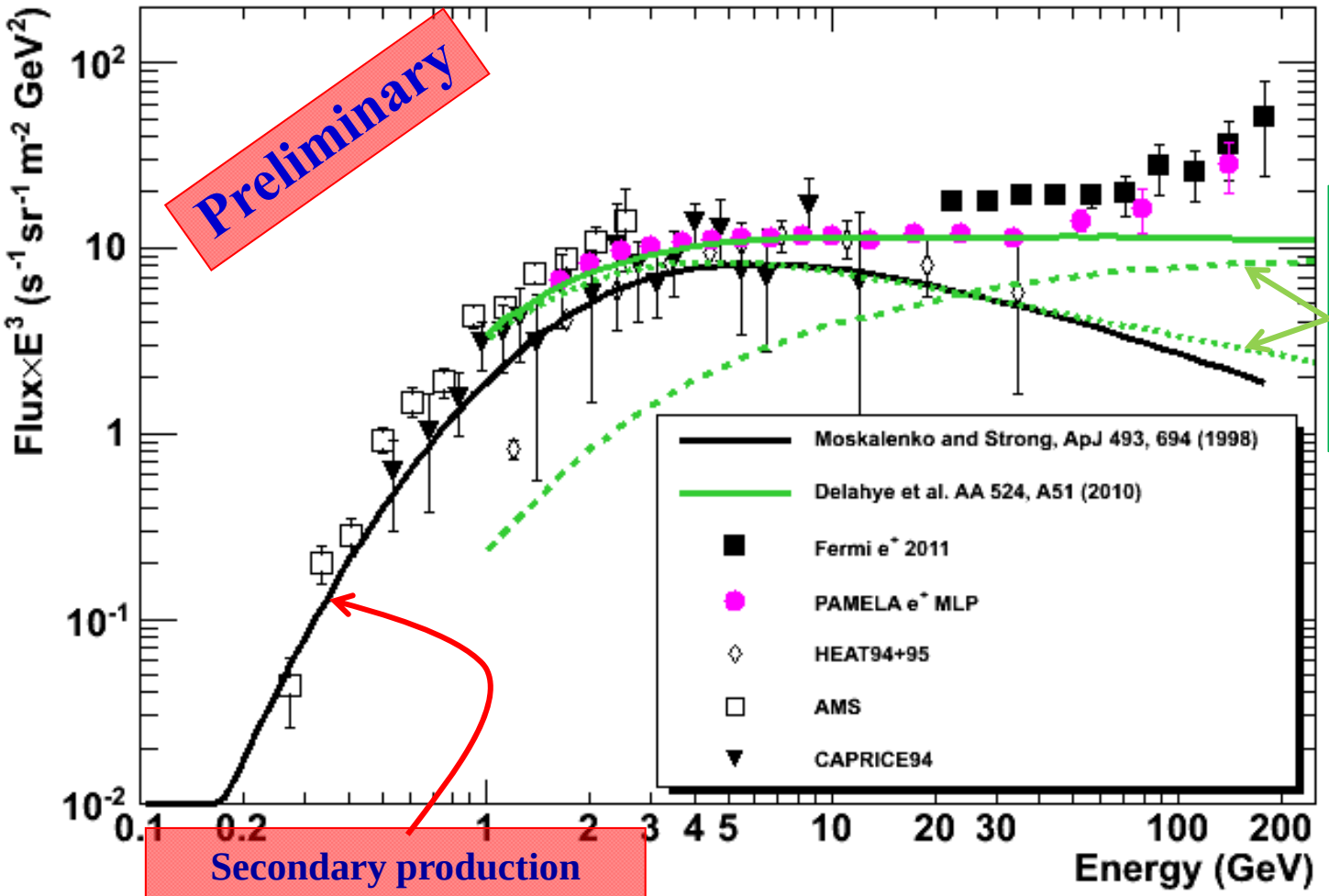
New results

PAMELA e^- and e^+ spectra



New results

PAMELA e^+ spectra



T. Delahaye et al., A&A 524 (2010) A51. Secondary & Primary productions (from Astrophysical Sources)

New results

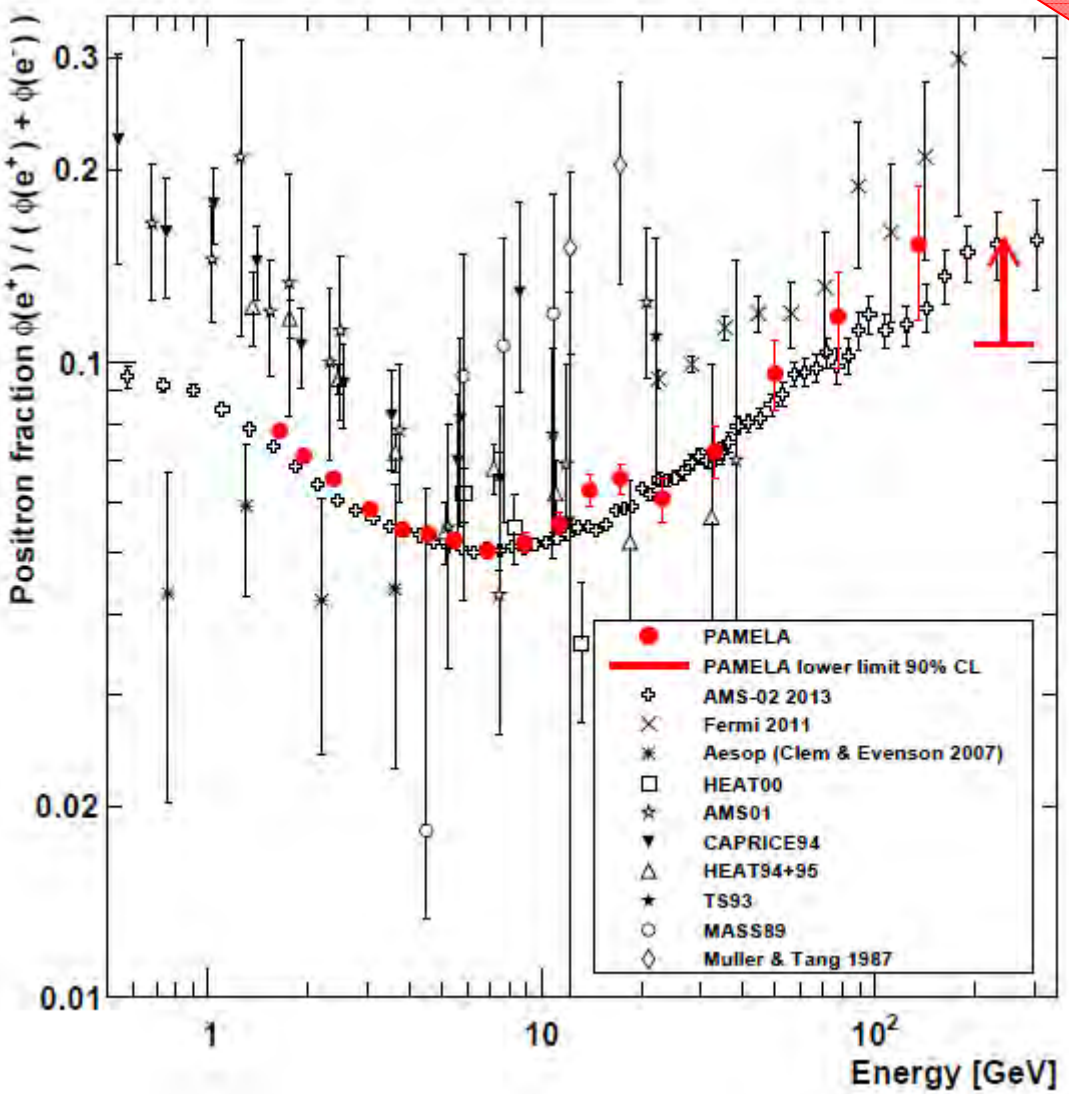
Secondary production

Moskalenko & Strong 98

PAMELA positron fraction

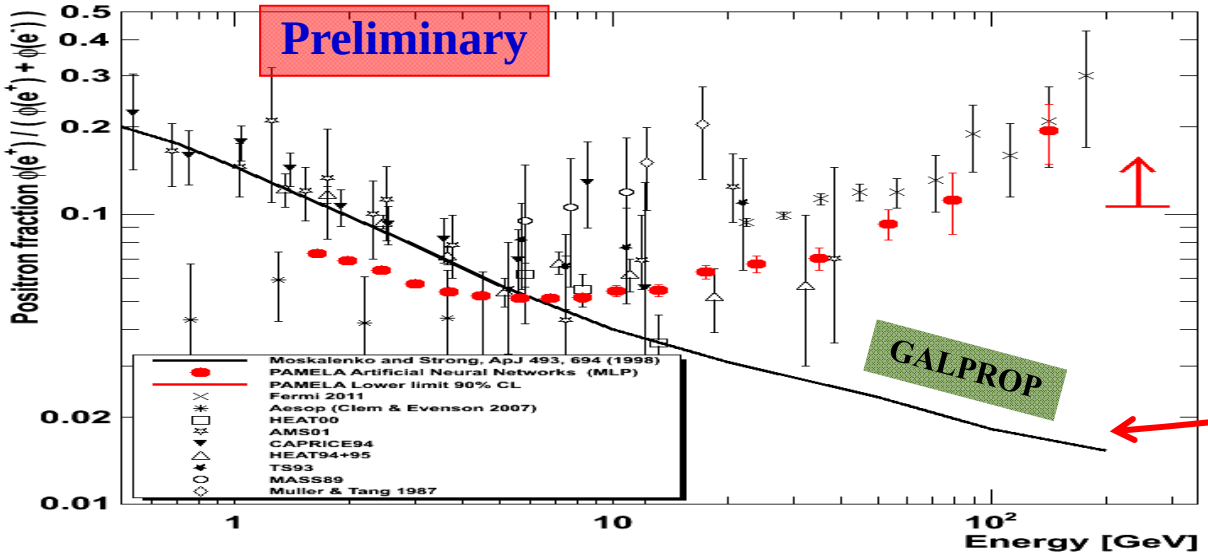
Preliminary

- Using all data till 2010 and multivariate classification algorithms about a **factor 2÷3** of statistical increase in respect to published analysis

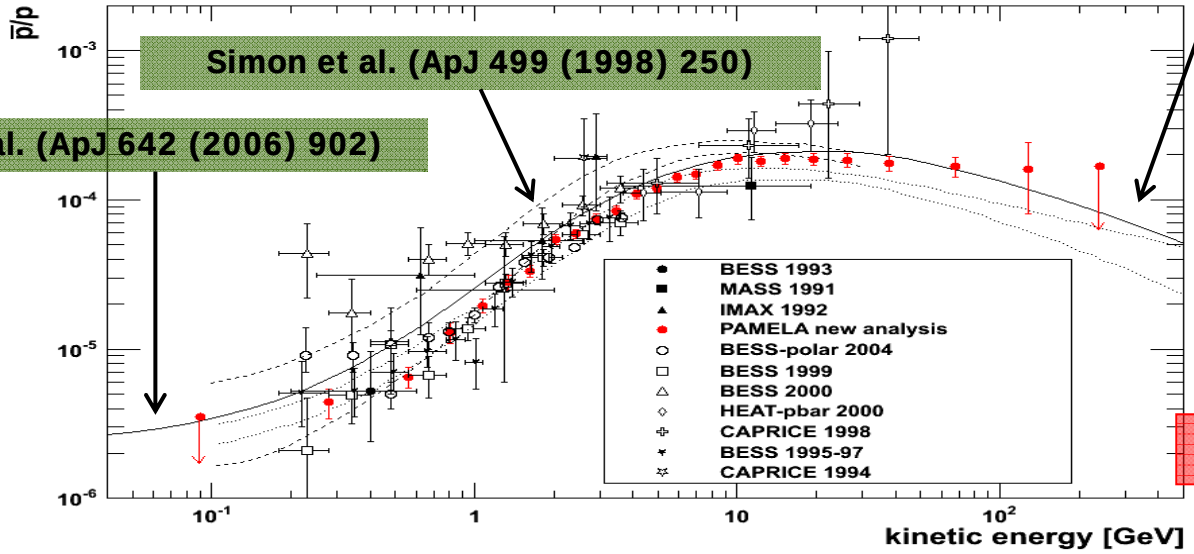


New results

The latest (still) puzzling picture



Positron spectrum significantly harder than expectations from secondary production



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

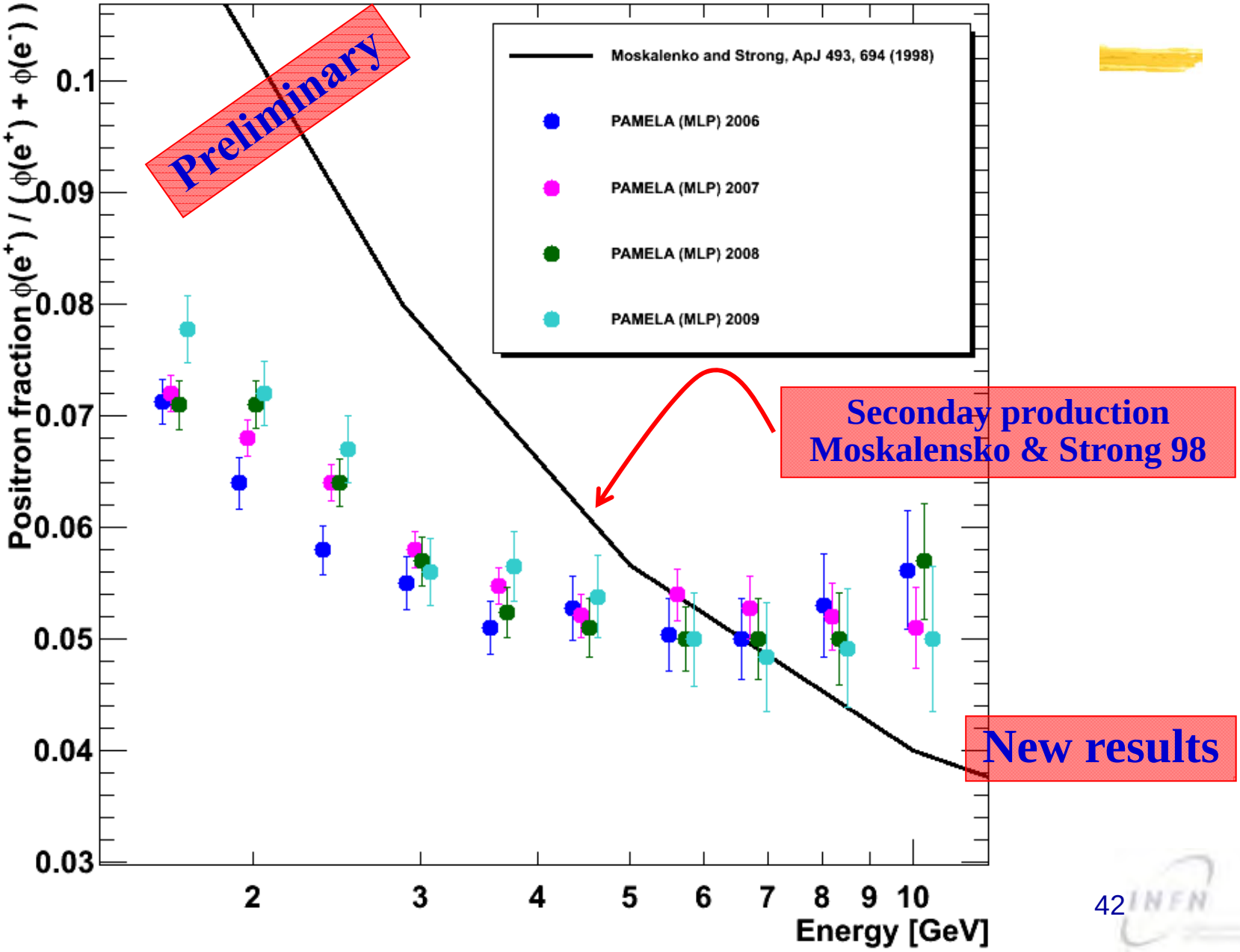
Ptuskin et al. (ApJ 642 (2006) 902)

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

But antiprotons in CRs are in agreement with secondary production

Preliminary

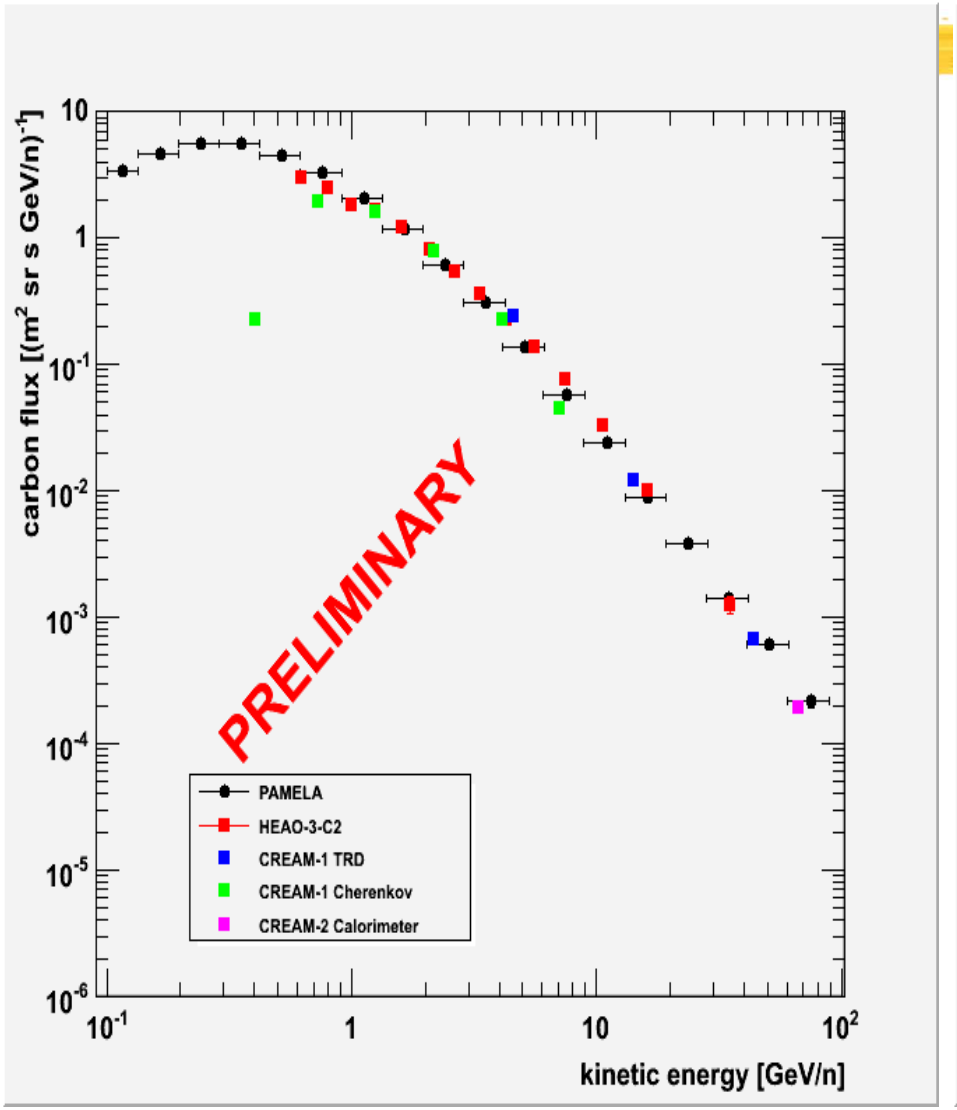
PAMELA e^+ fraction vs time

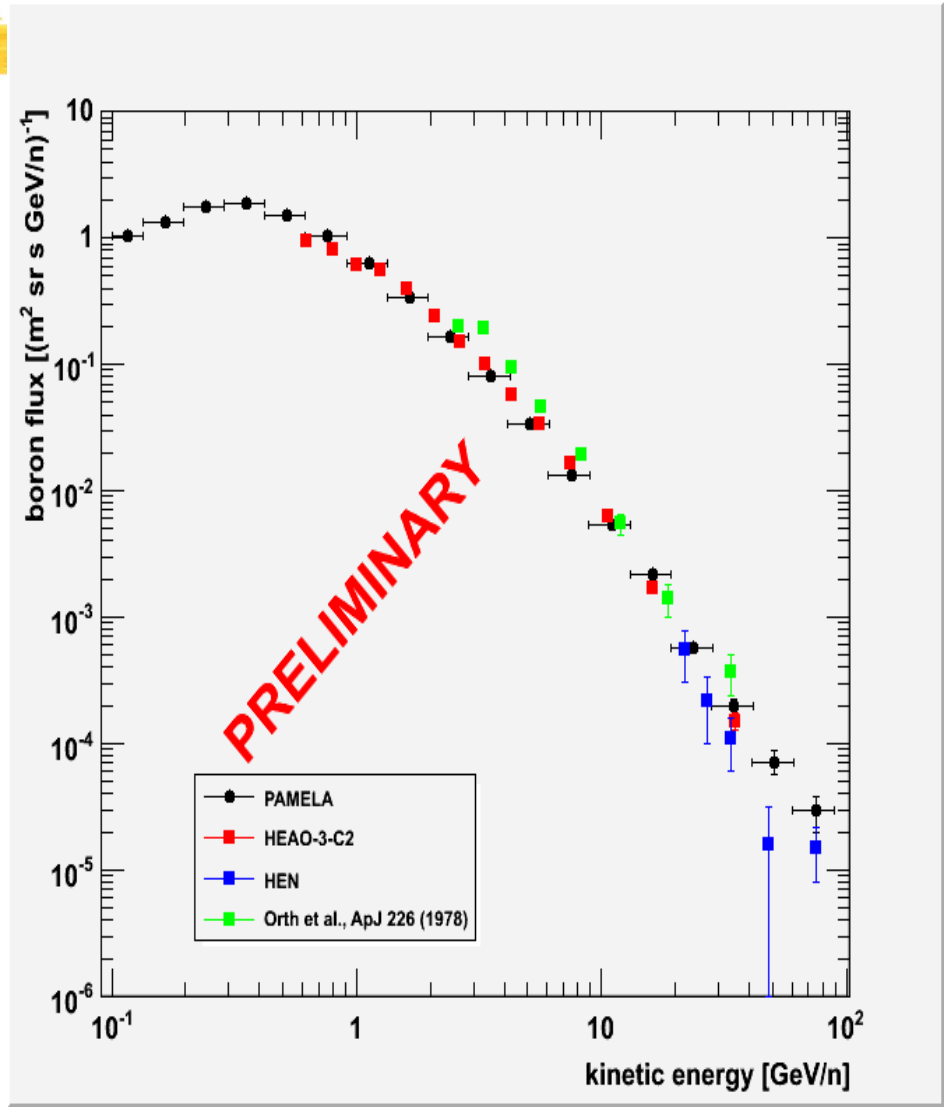


Seconday production
Moskalensko & Strong 98

New results

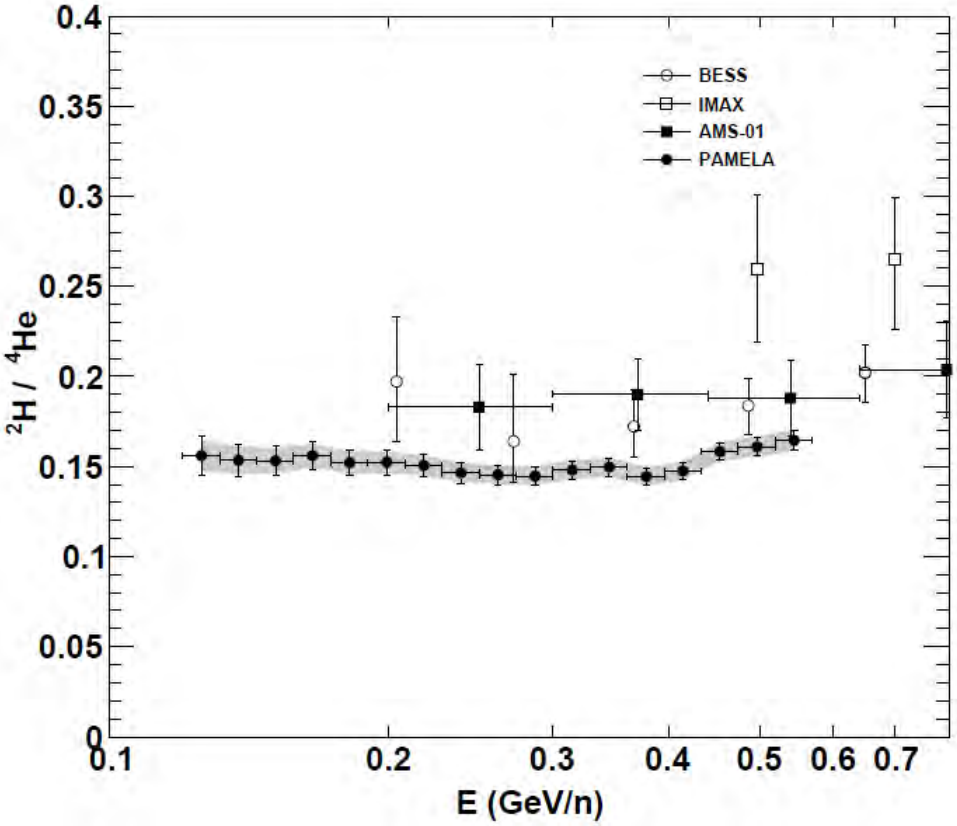
Boron and Carbon nuclei spectra



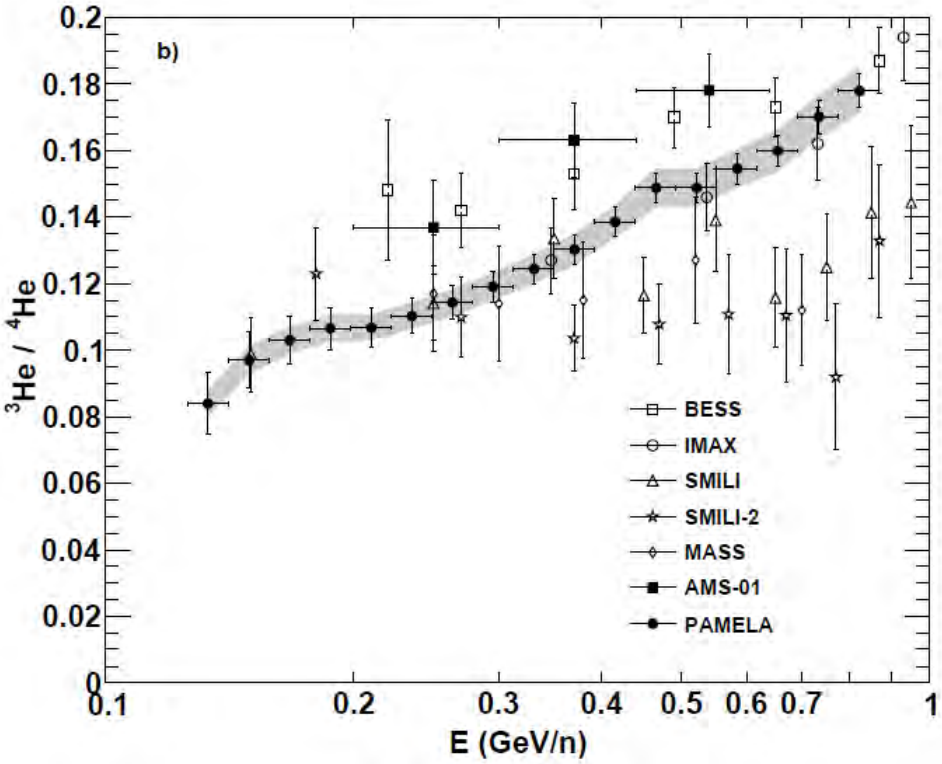


Isotopes

$^2H/^4He$ ratio



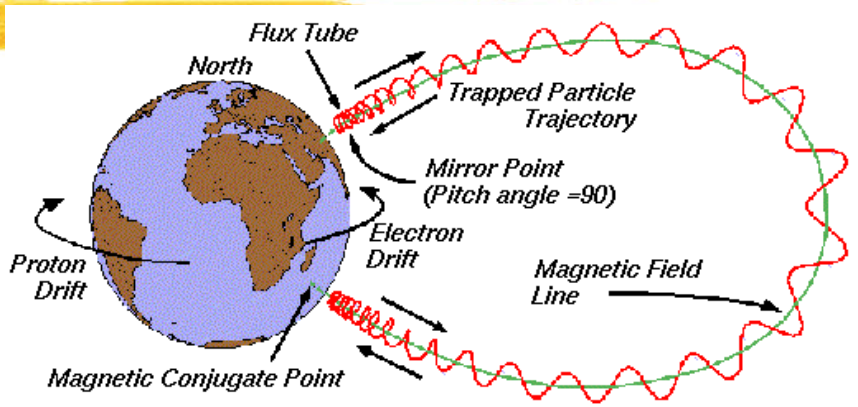
$^3H/^4He$ ratio



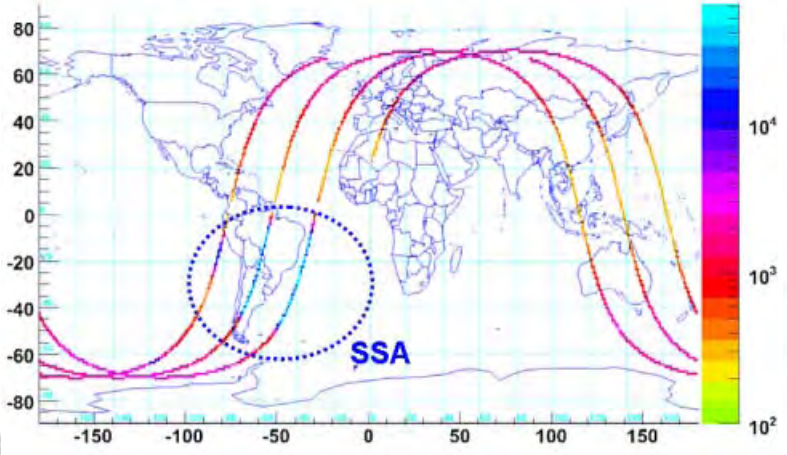
O. Adriani et al., arXiv:1304.5420, accepted for pubblication on ApJ

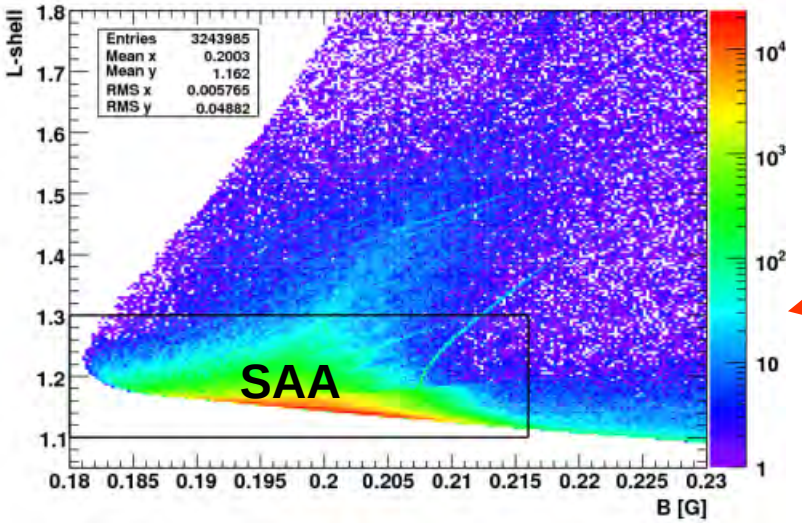
Under cut-off (anti)particles

- 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.

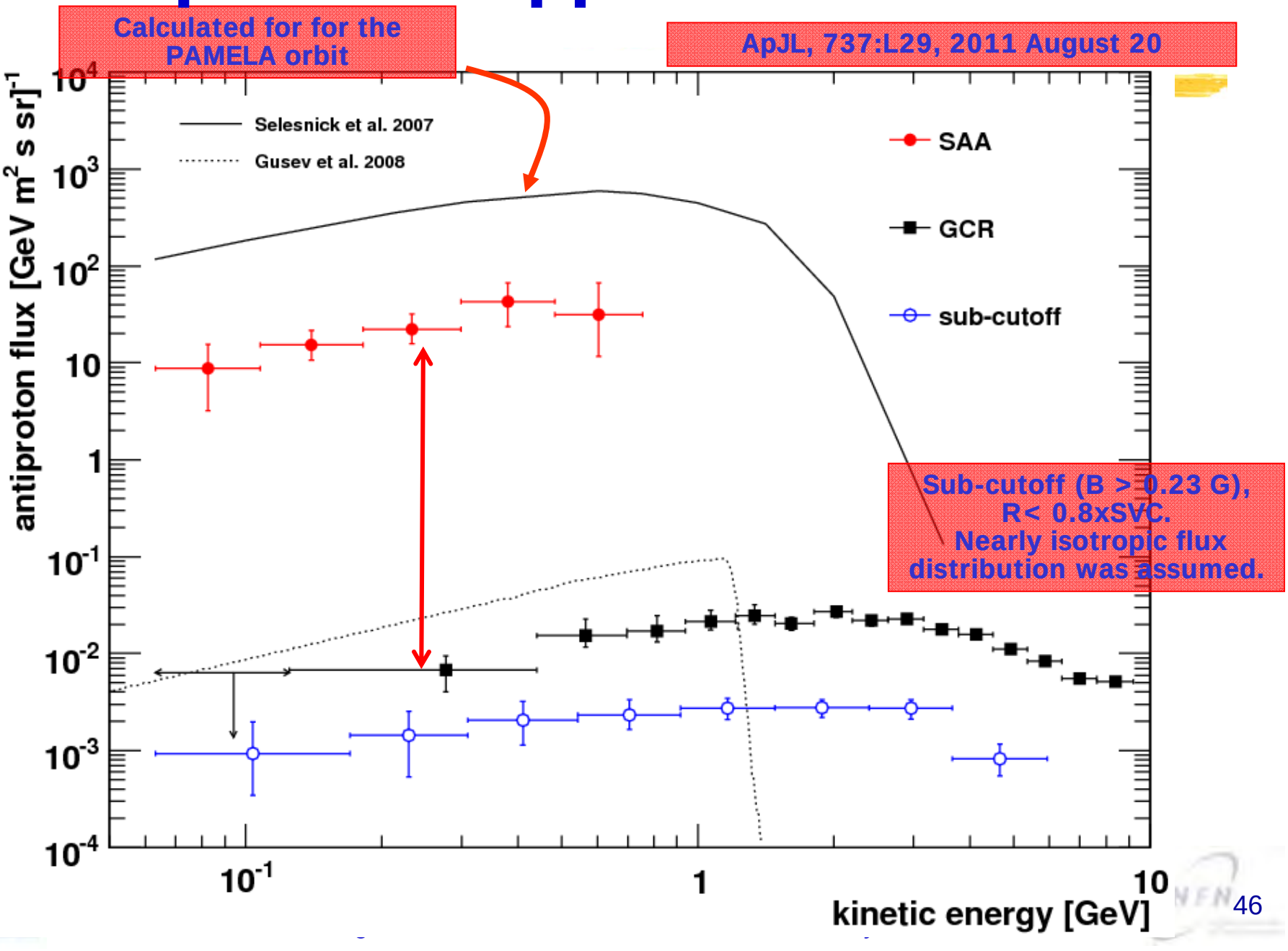


Under-cutoff proton candidates distribution as a function of L-shell and geomagnetic field intensity B [G].

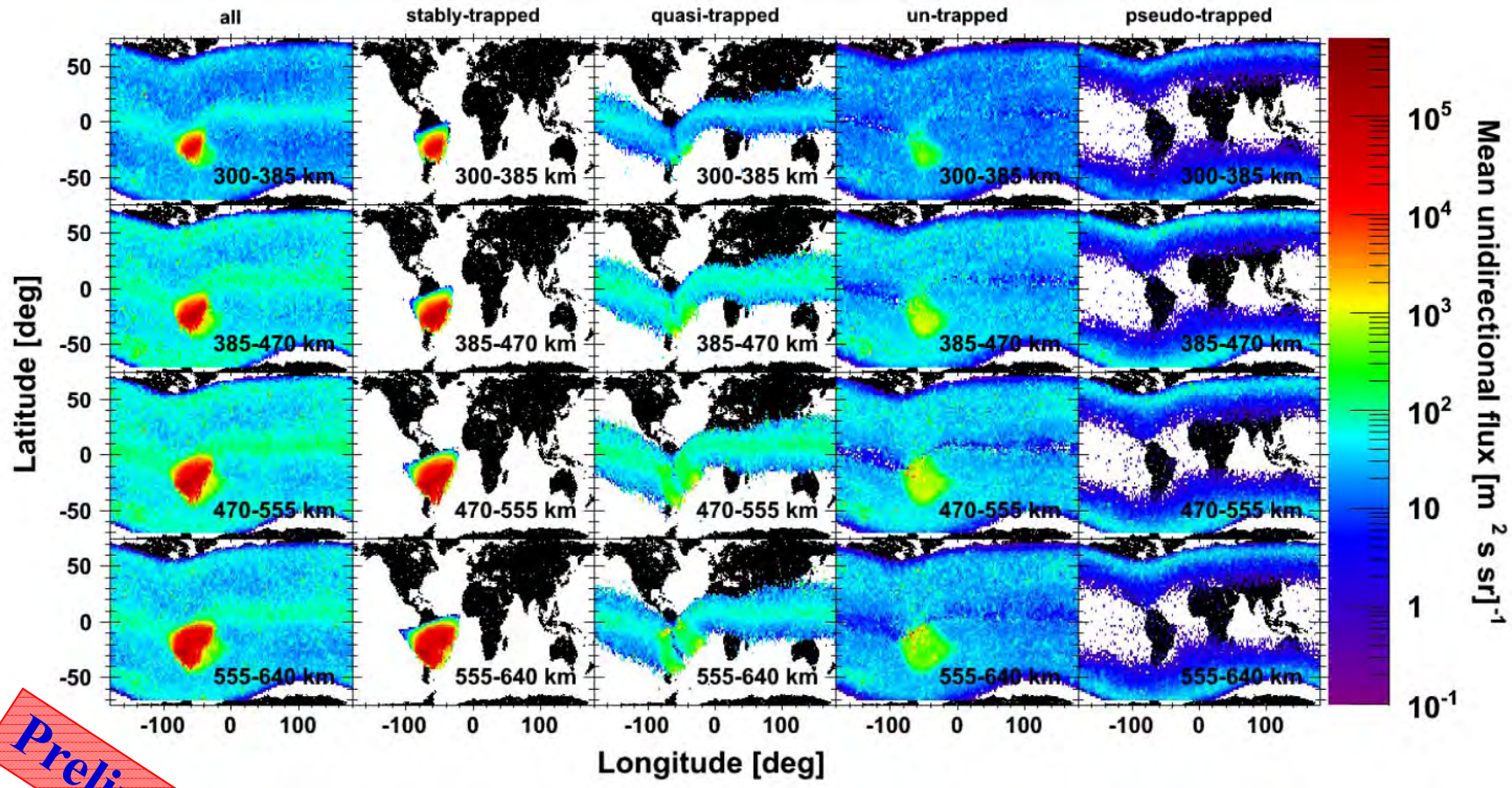




Antiproton trapped in the SAA



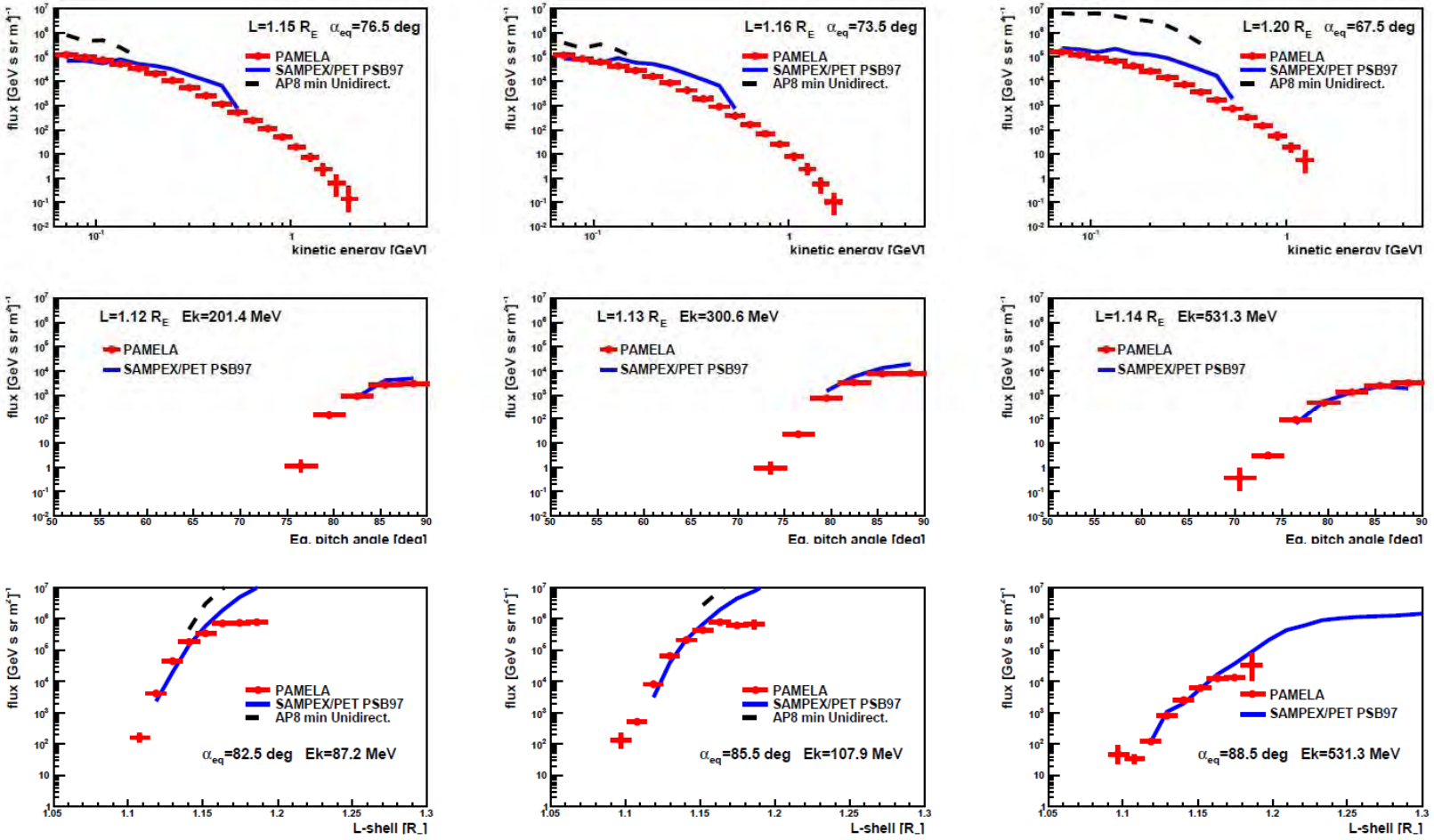
Under cut-off protons



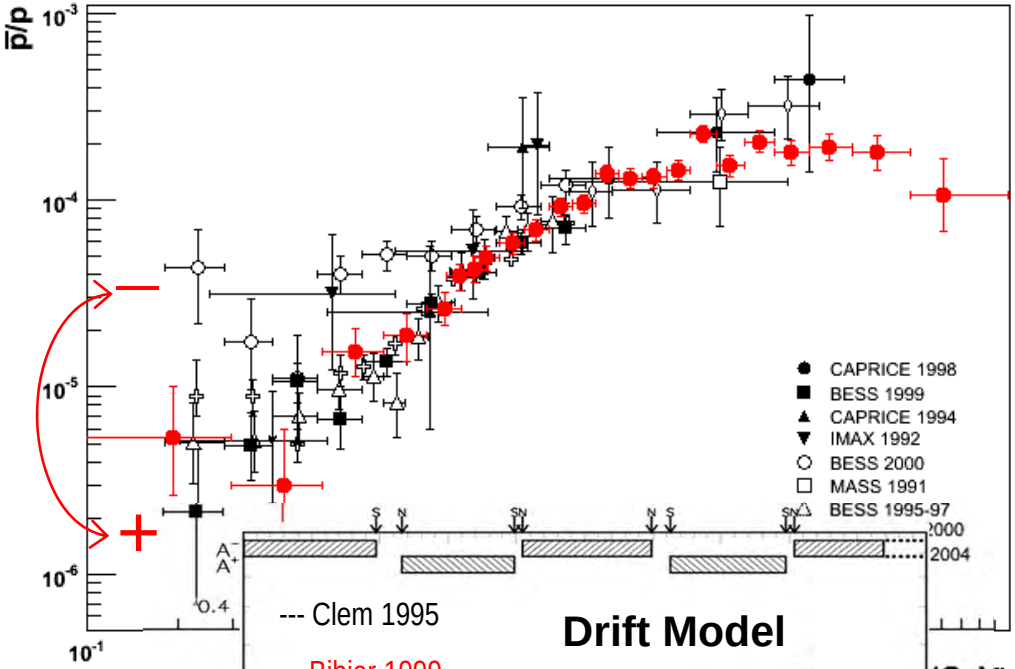
Preliminary

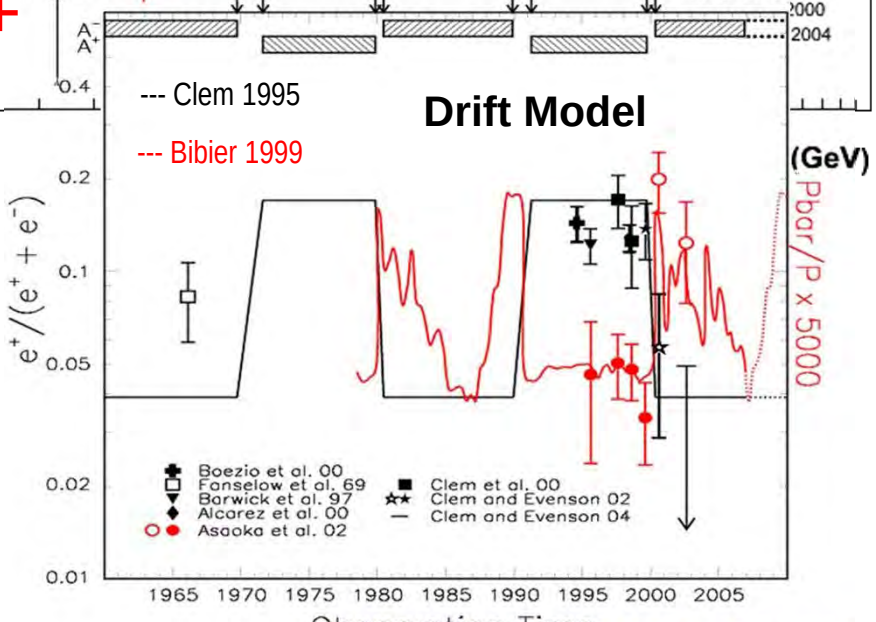
Under cut-off protons

Preliminary

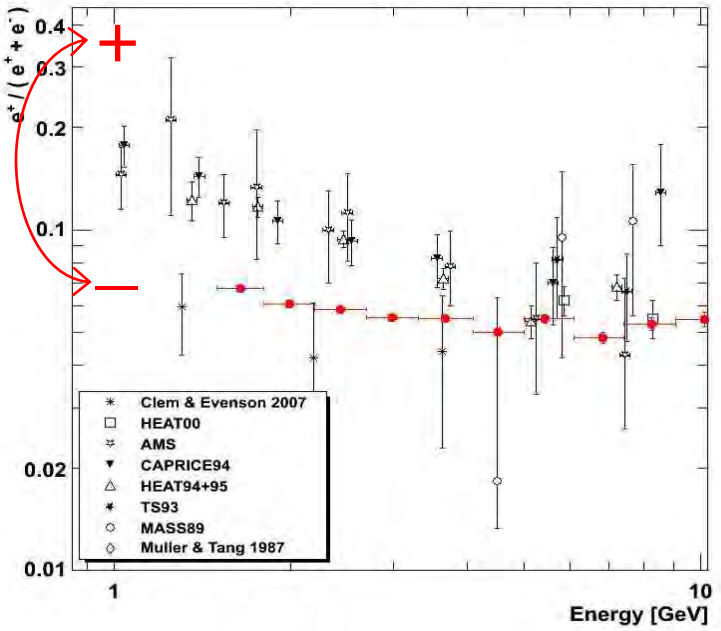


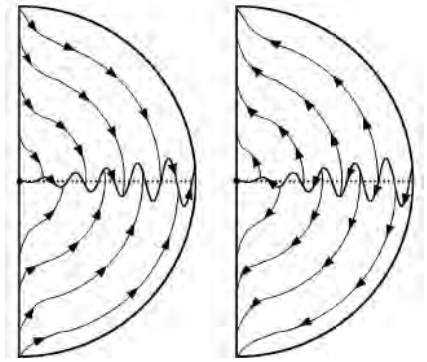
Solar modulation





Clem J. & Evenson 2007



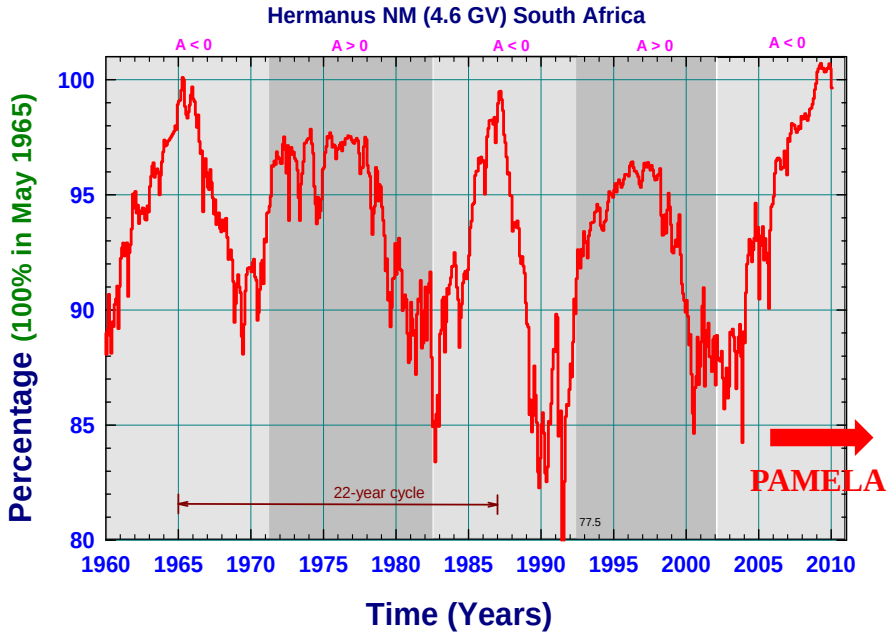


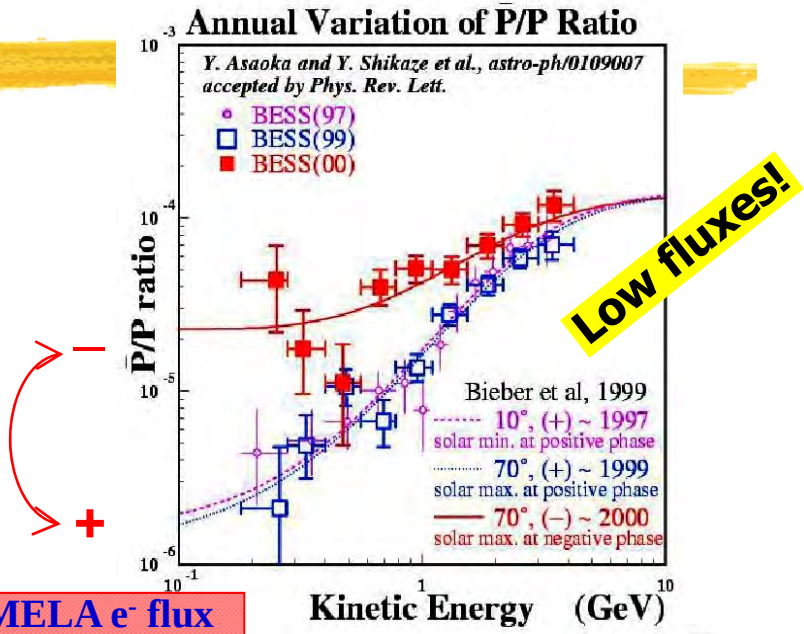
A > 0 **A < 0**

Positive particles

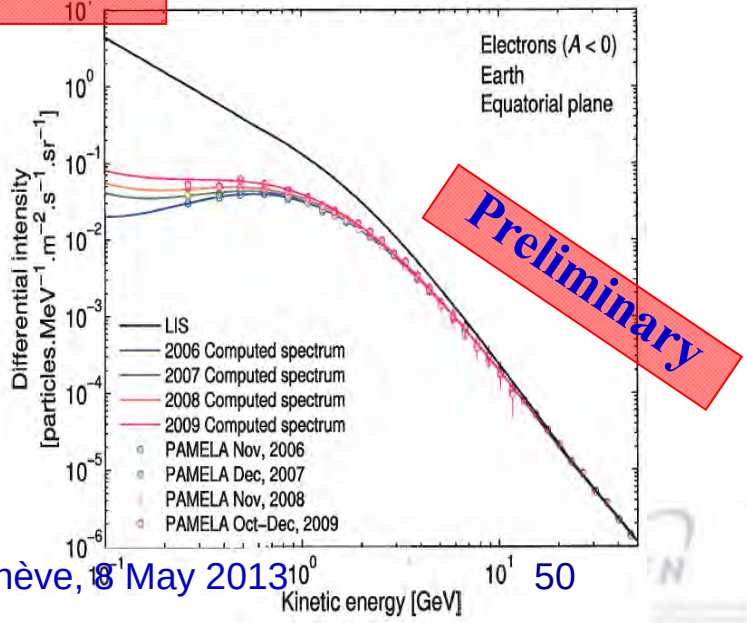
Solar modulation

A^+ A^- A^+ A^-

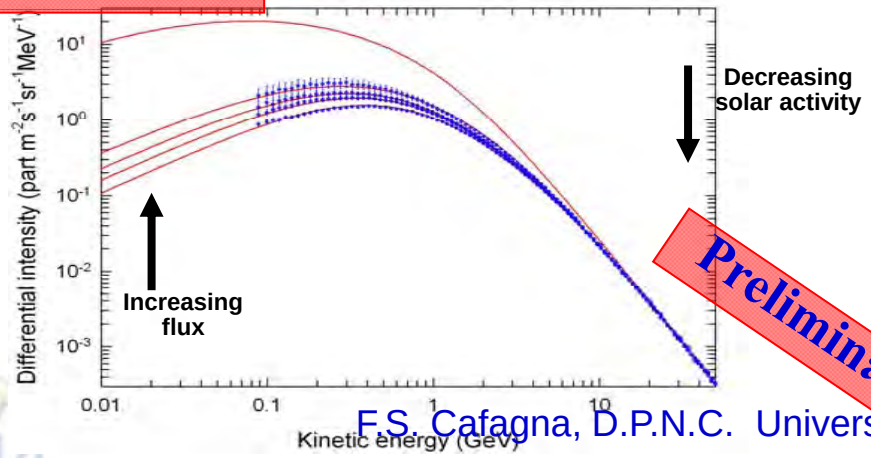




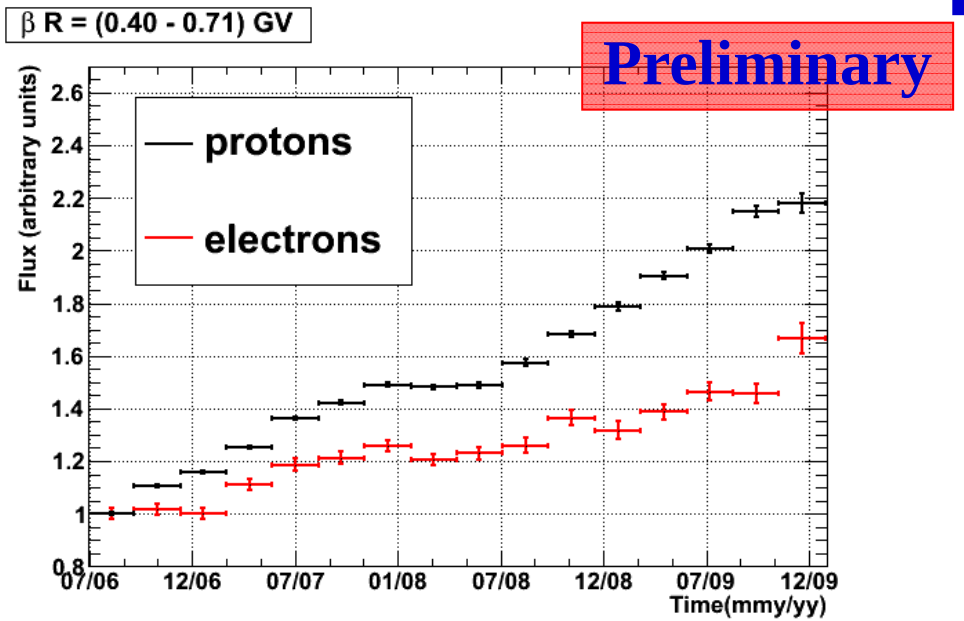
PAMELA e⁻ flux

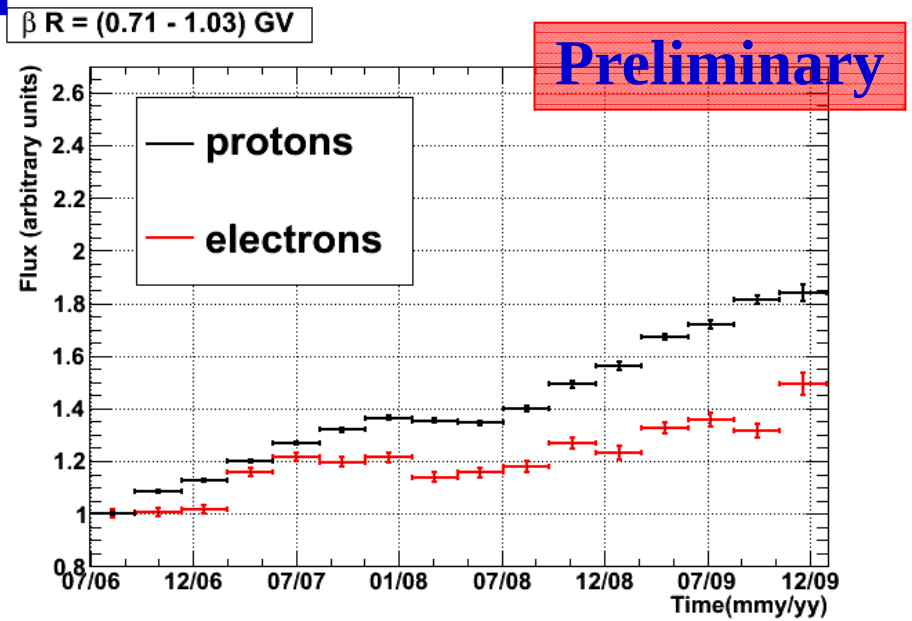


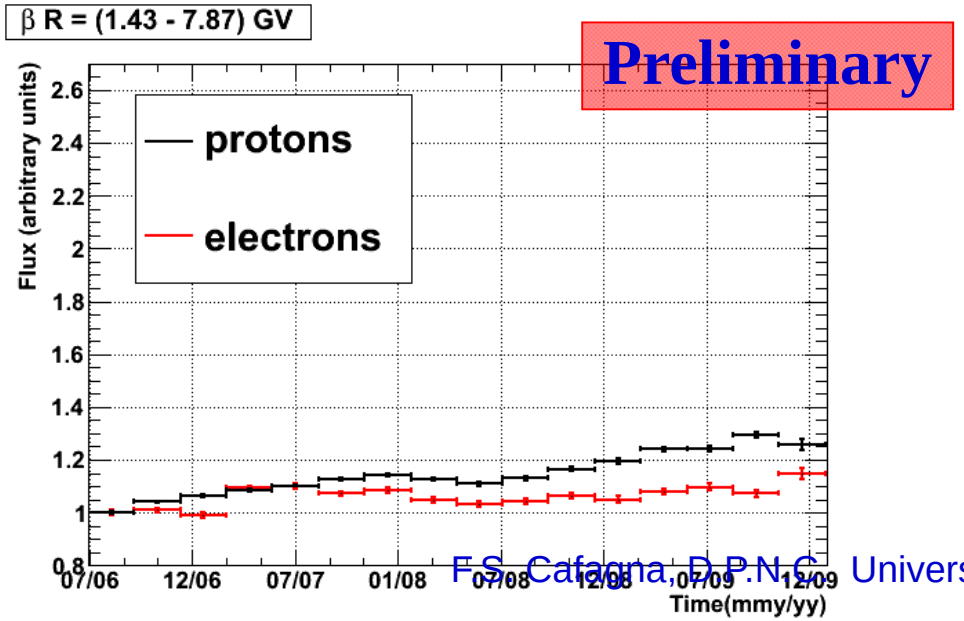
PAMELA p flux

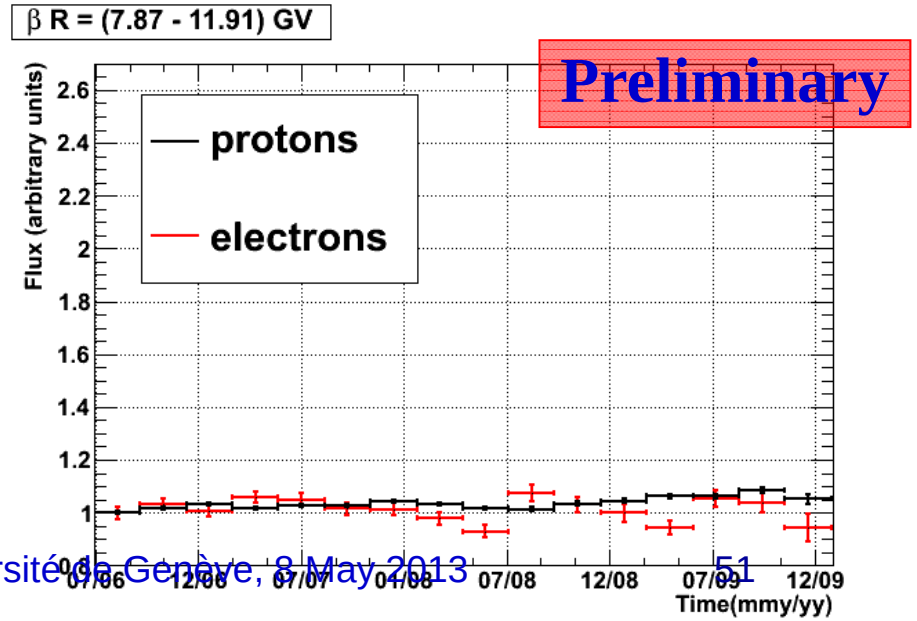


Flux time dependence

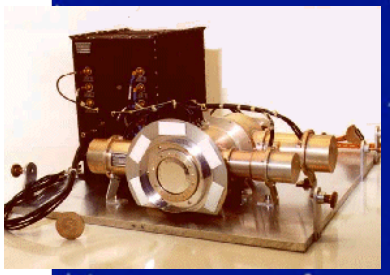


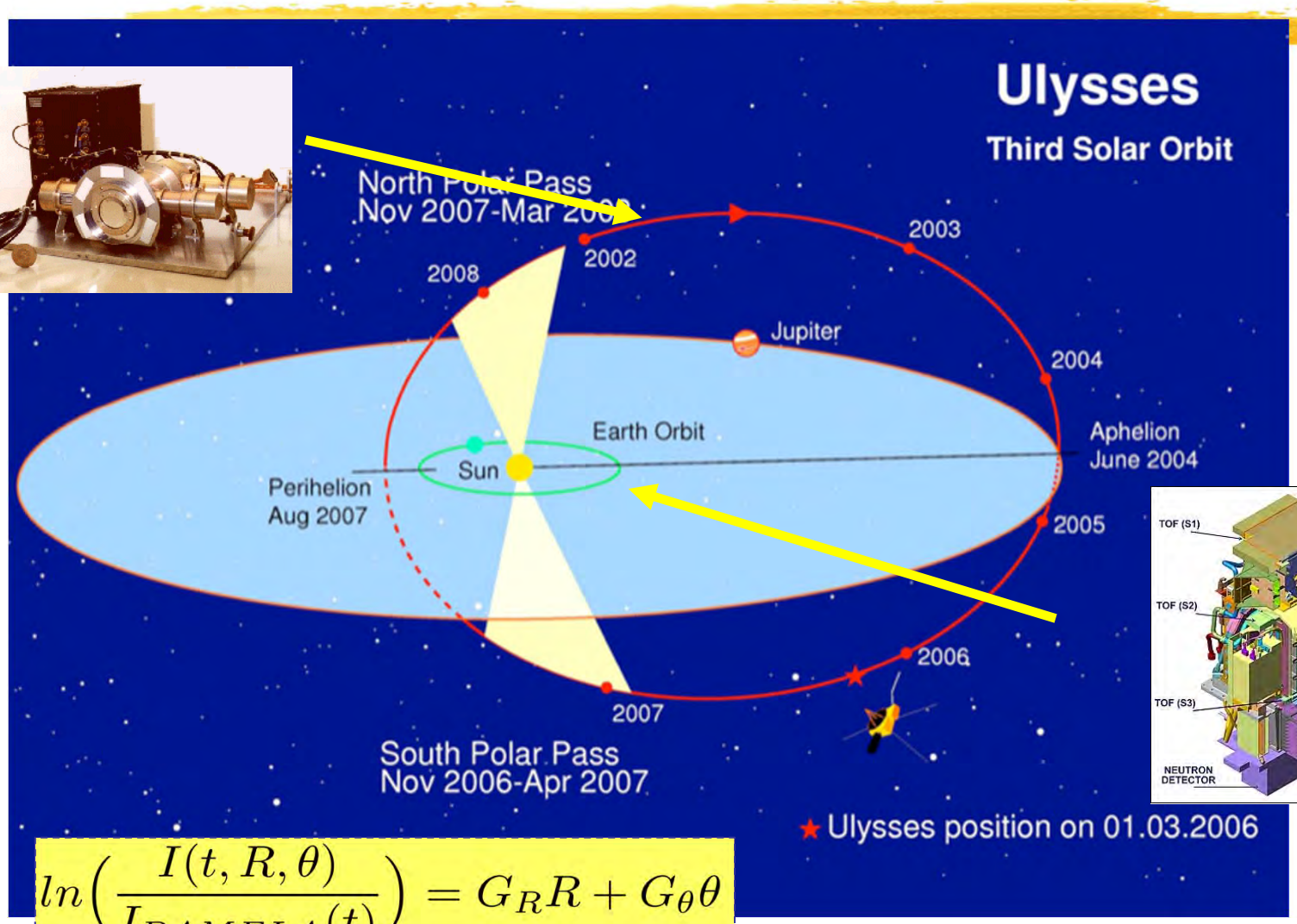


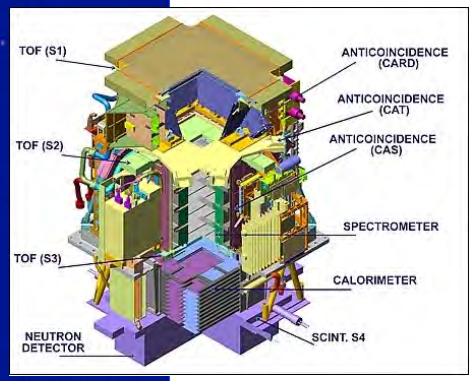




Gradients in the Heliosphere, PAMELA & ULYSSES

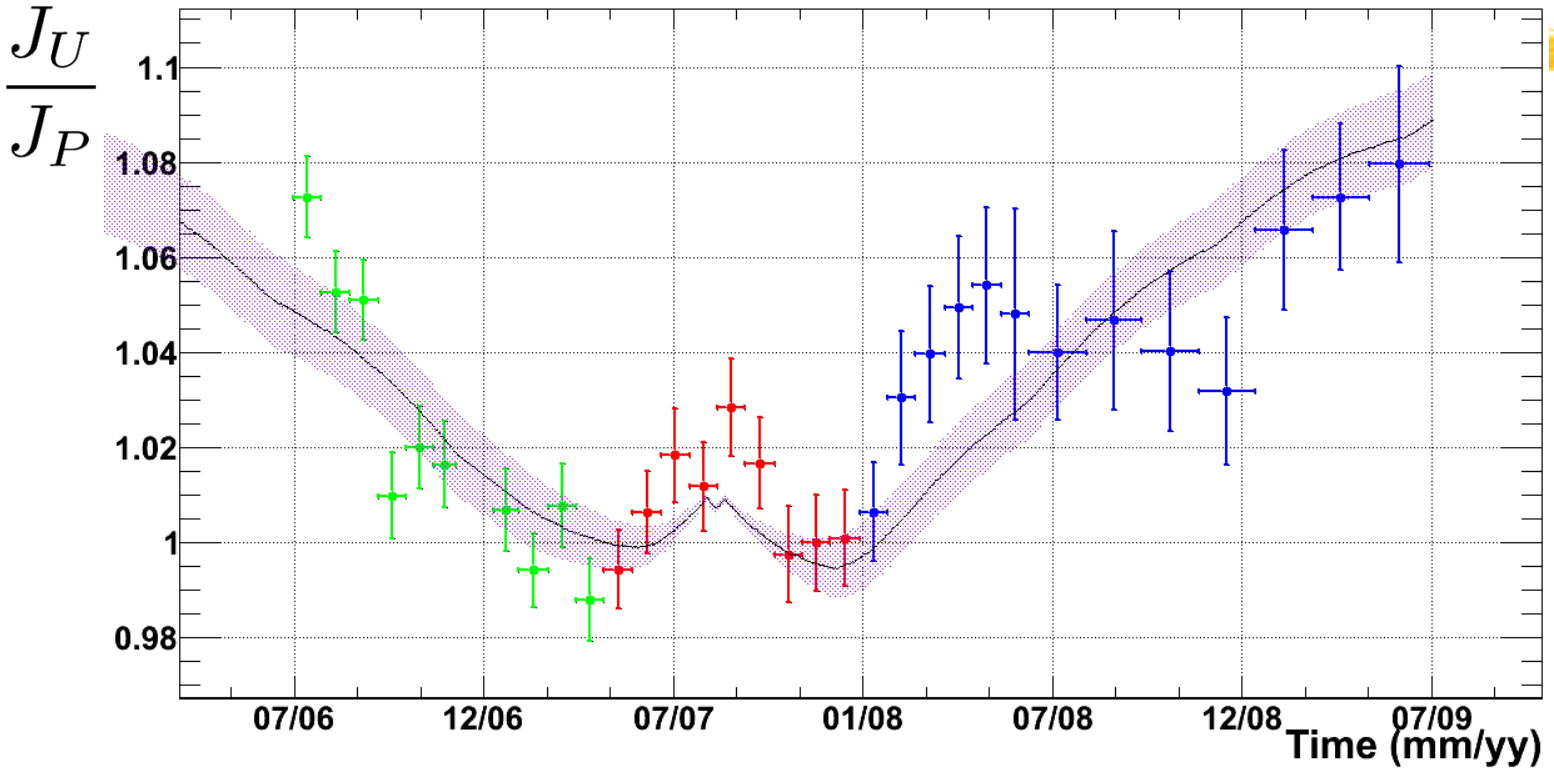






$$ln\left(\frac{I(t,R,\theta)}{I_{PAMELA}(t)}\right) = G_R R + G_\theta \theta$$

Spatial Gradients



1.97 GV

-

2.07 GV

Preliminary

$$\frac{J_U}{J_P} = exp(G_r \cdot \Delta r) \cdot exp(G_\theta \cdot \Delta\theta)$$

$$(2.51 \pm 0.1)\%/AU \qquad (-0.025 \pm 0.002)\%/deg$$

Comparison of the proton flux measured between 1.97 and 2.07 GV by PAMELA and ULYSSES as a function of time

Solar Physics

from 2006-12-1 to 2006-12-4

from 2006-12-13 00:23:02 to 2006-12-13 02:57:46

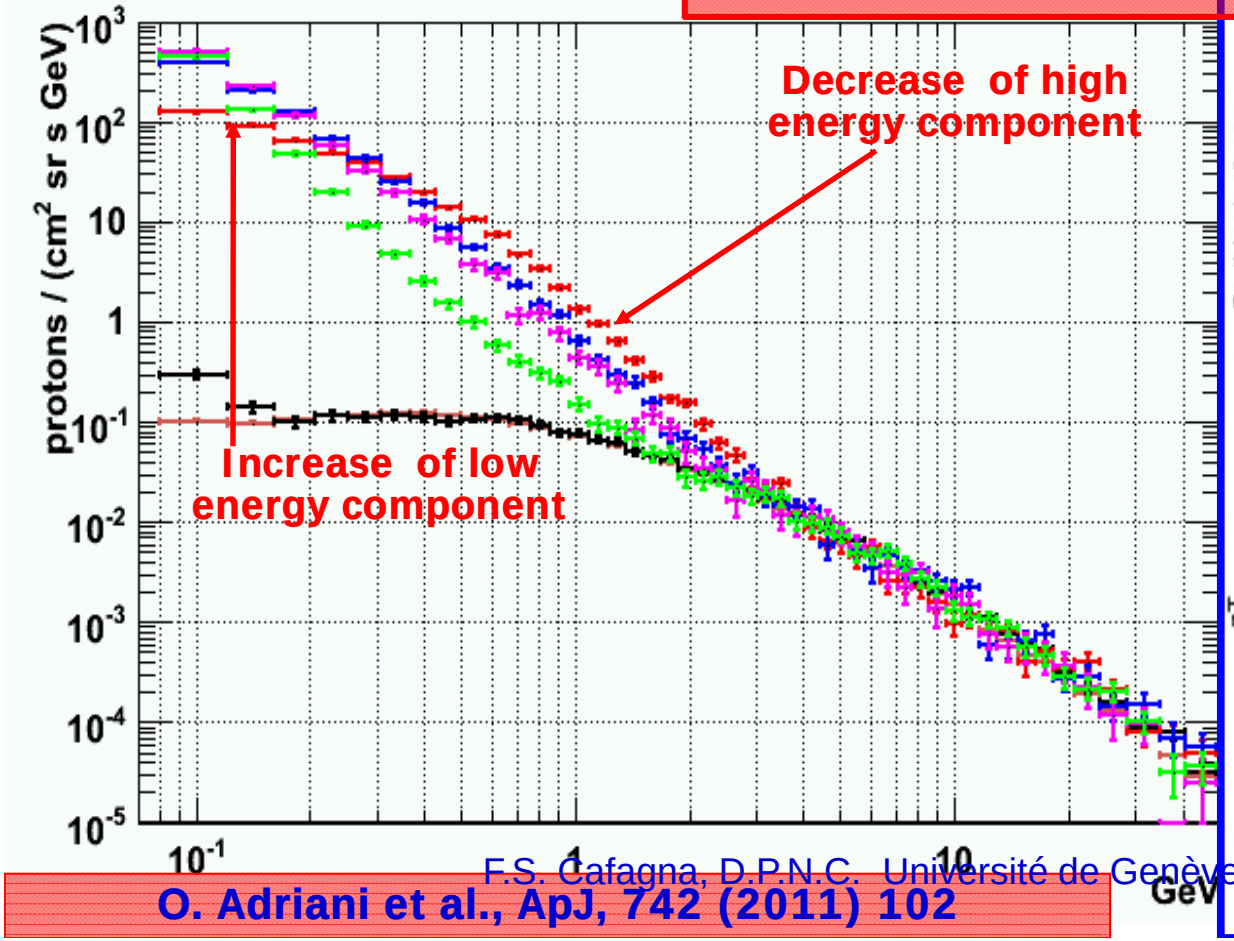
from 2006-12-13 02:57:46 to 2006-12-13 03:49:09

from 2006-12-13 03:49:09 to 2006-12-13 04:32:56

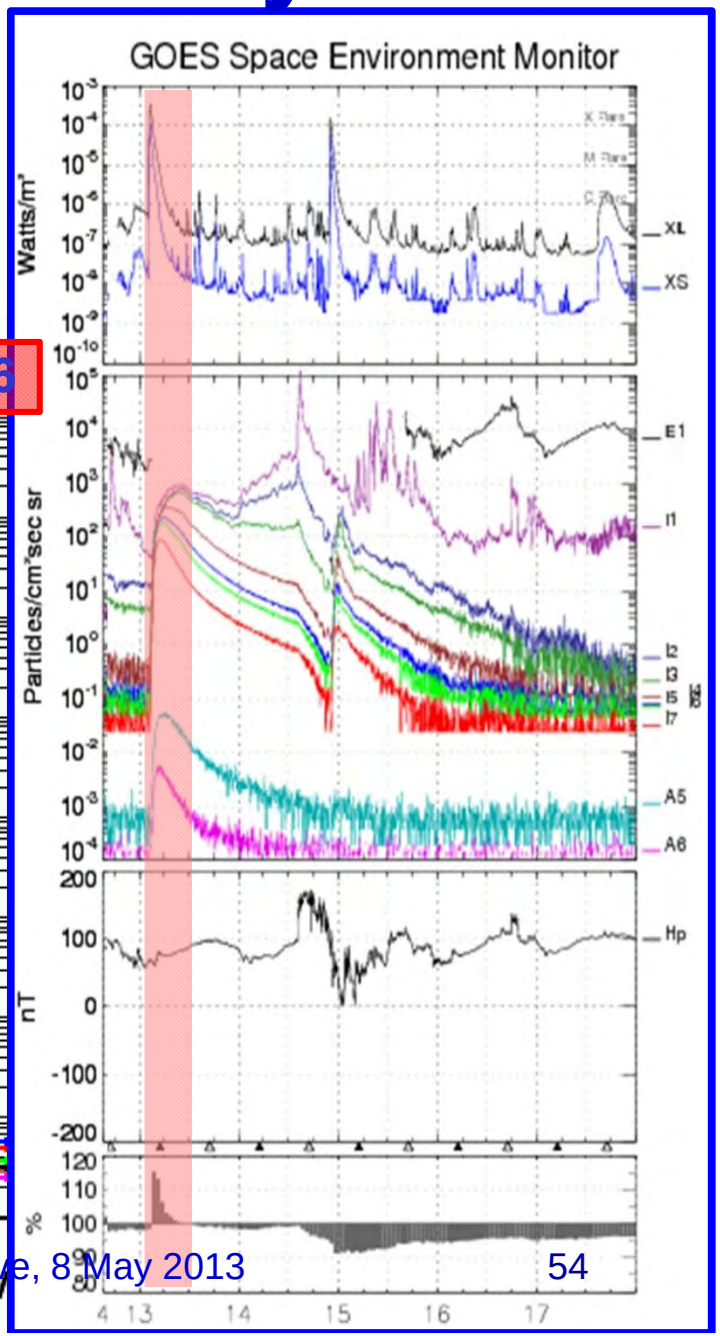
from 2006-12-13 04:32:56 to 2006-12-13 04:59:16

from 2006-12-13 08:17:54 to 2006-12-13 09:17:34

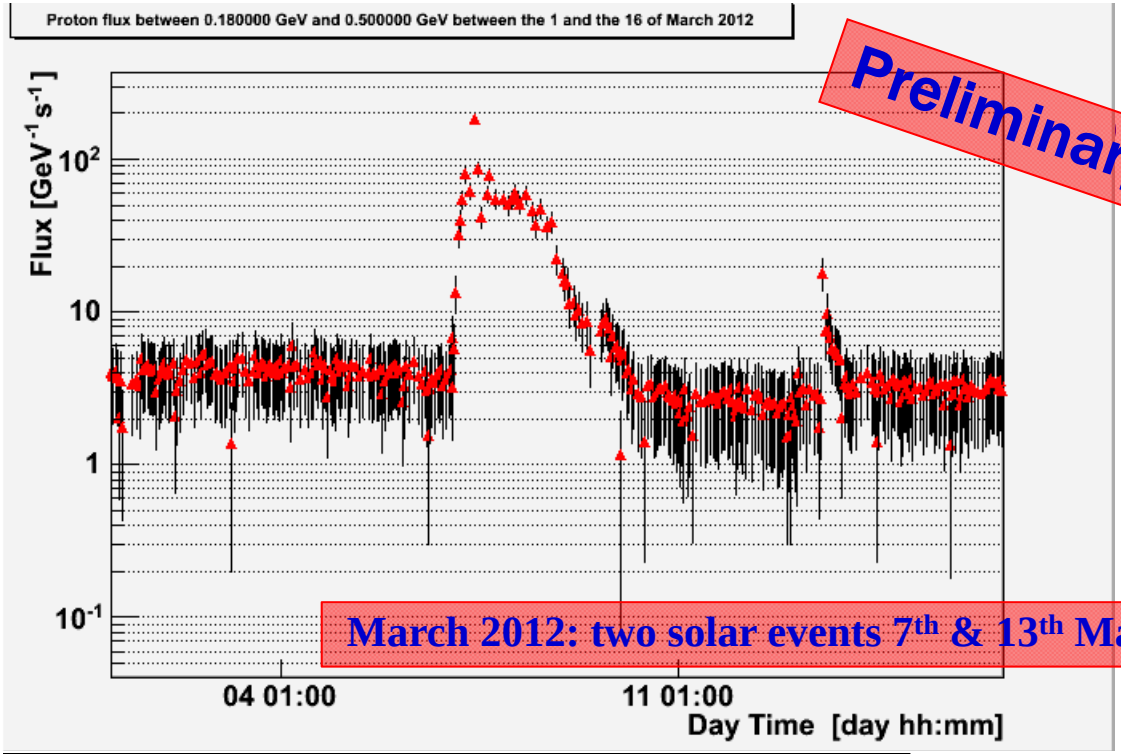
December 13th 2006

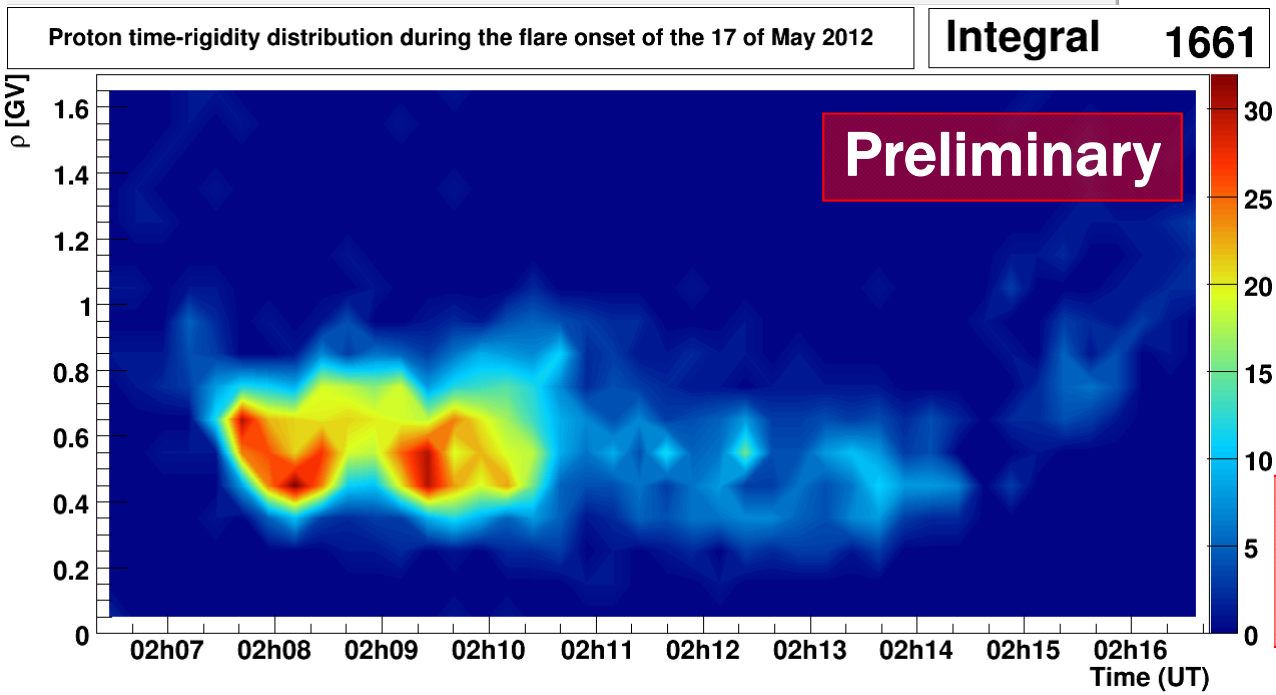


O. Adriani et al., ApJ, 742 (2011) 102



olar Physics





- 31st May NASA press release: "PAMELA recorded the incoming solar particles up in space, providing one of the first in-situ measurements of the stream of particles that initiated a GLE. Only the early data has been seen so far, but scientists have high hopes that as more observations are relayed down to Earth, they will be able to learn more about the May 17 onslaught of solar protons, and figure out why this event triggered a GLE (Ground Level Enhancement) when earlier bursts of solar protons in January and March, 2012 didn't."

17th May 2012: Solar event magnetically connected with Earth

Conclusions

- We are entered in the new era of precision measurements of (anti)particle fluxes in CR.
- PAMELA has been in orbit and studying particle and antiparticle in cosmic rays for more than **6 years**.($>10^9$ triggers registered and >25 TB of data has been down-linked).
- Antiproton-to-proton flux ratio and antiproton energy spectrum (~100 MeV - ~200 GeV) show no significant deviations from secondary production expectations.
- High energy positron fraction (>10 GeV) increases significantly with energy. It could be due to a primary source?
- The proton and helium nuclei spectra have been measured up to 1.2 TV. The observations challenge the current paradigm of cosmic ray acceleration and propagation.
- The e^- spectrum up to 600 GeV shows spectral features that may point to additional components.
- Stay tuned for next results on positron flux, solar and magnetospheric.
- Waiting for AMS to compare contemporary measurements!

THANKS !!!!