Cosmic Rays from PAMELA

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INFN Bari, Italy

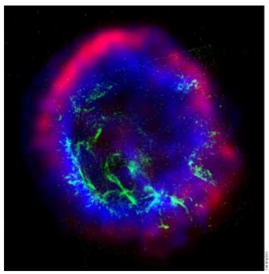
On behalf of the PAMELA collaboration

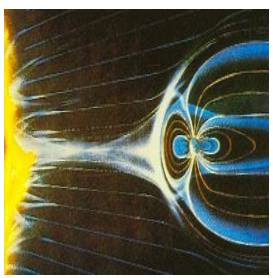
Vulcano Workshop 2012

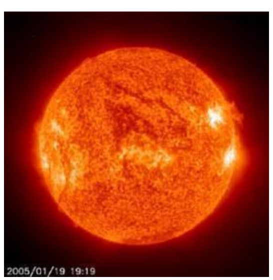
Frontier Objects in Astrophysics and Particle Physics

28 May - 2 June, Vulcano, Italy

The PAMELA experiment

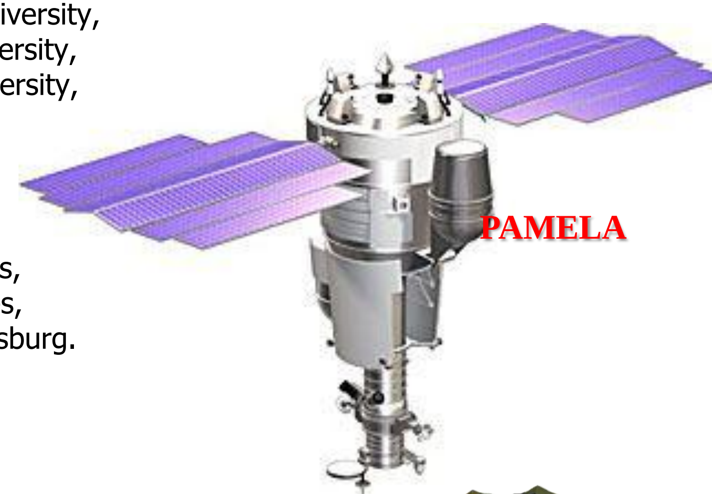






The PAMELA collaboration:

- **ITALY**: Sezione INFN and Physics Department of Roma Tor Vergata University,
  Sezione INFN and Physics Department of Bari University,
  Sezione INFN and Physics Department of Florence University,
  Sezione INFN and Physics Department of Naples University,
  Sezione INFN and Physics Department of Trieste University,
  INFN National Laboratories of Frascati,
  IFAC - CNR Florence.
- **RUSSIA**: Cosmic Rays Laboratory,
  Moscow Engineering and Physics Institute,
  Moscow Laboratory of Solar and Cosmic Ray Physics,
  P.N. Lebedev Physical Institute Academy of Sciences,
  Moscow Ioffe Physical Technical Institute, St. Petersburg.
- **GERMANY**: Physics Department of Siegen University.
- **SWEDEN**: Royal Institute of Technology, Stockholm.

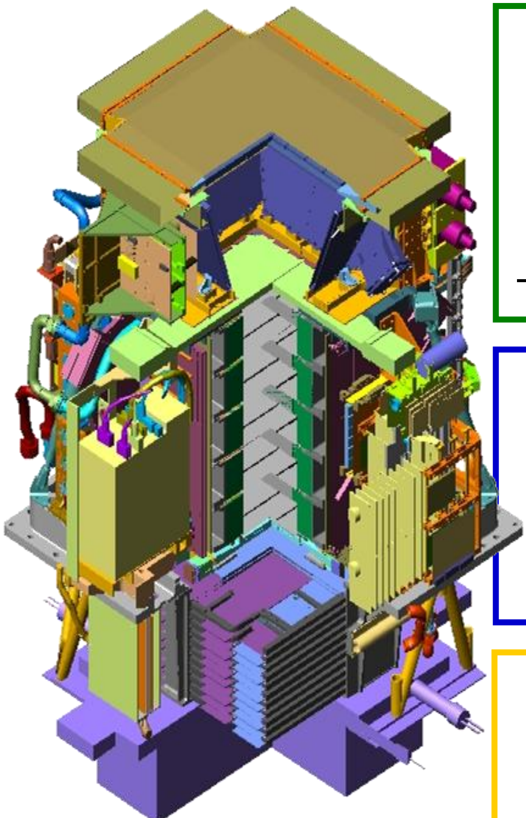


Scientific goals

- Search for dark matter annihilation
- Search for anti-Helium (primordial antimatter)
- Search for new matter in the Universe (Strangelets?)
- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere

The PAMELA apparatus

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



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;
- Charge identification from dE/dX.

Electromagnetic calorimeter

W/Si sampling (16.3 X_0, 0.6 λI)

- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

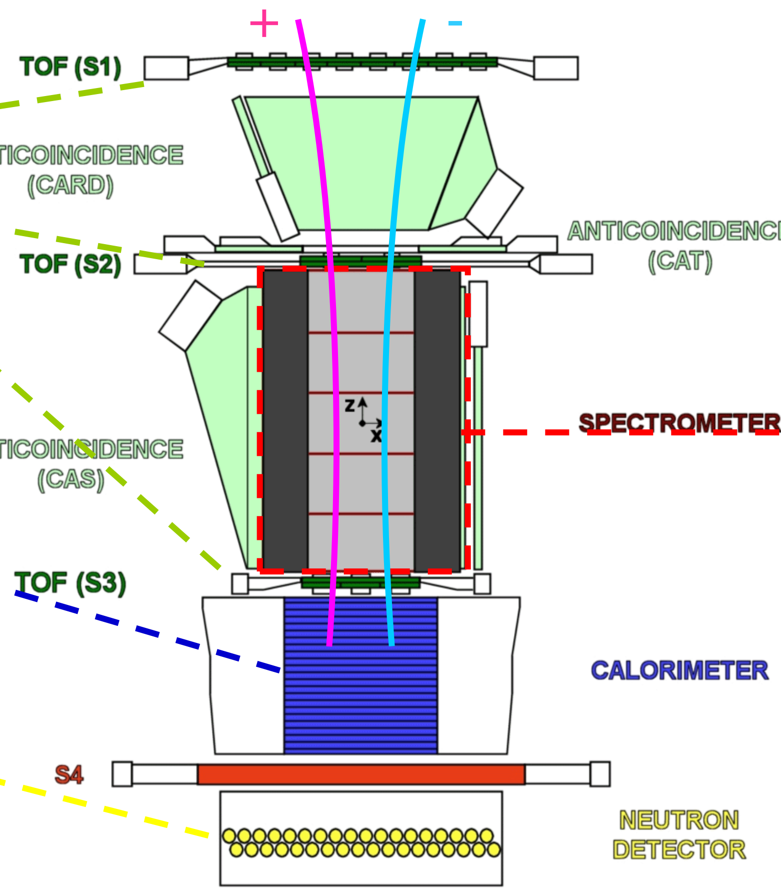
Neutron detector

^{3}He counters

- High-energy e/h discrimination

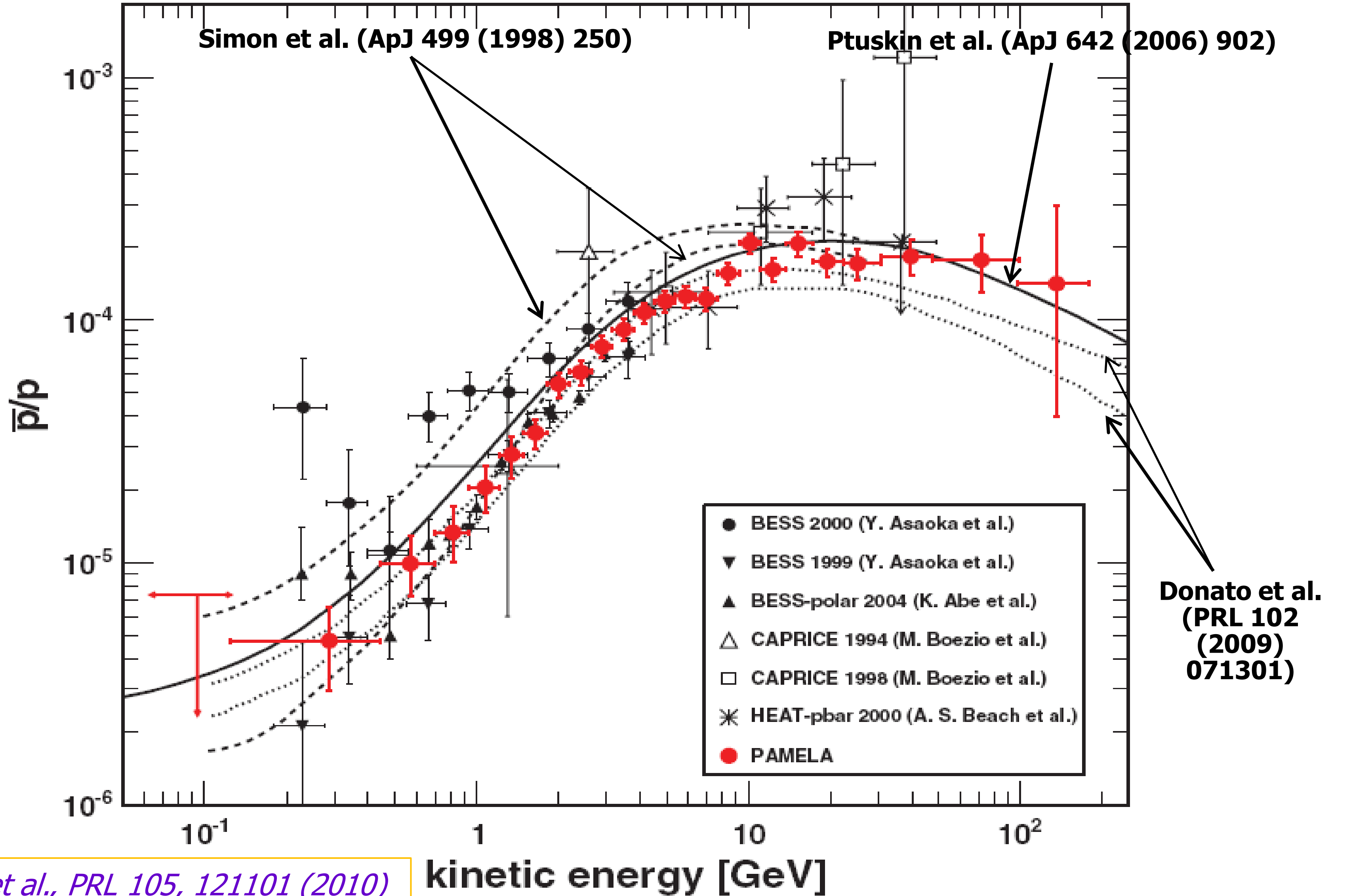
Spectrometer

microstrip silicon tracking system + permanent magnet



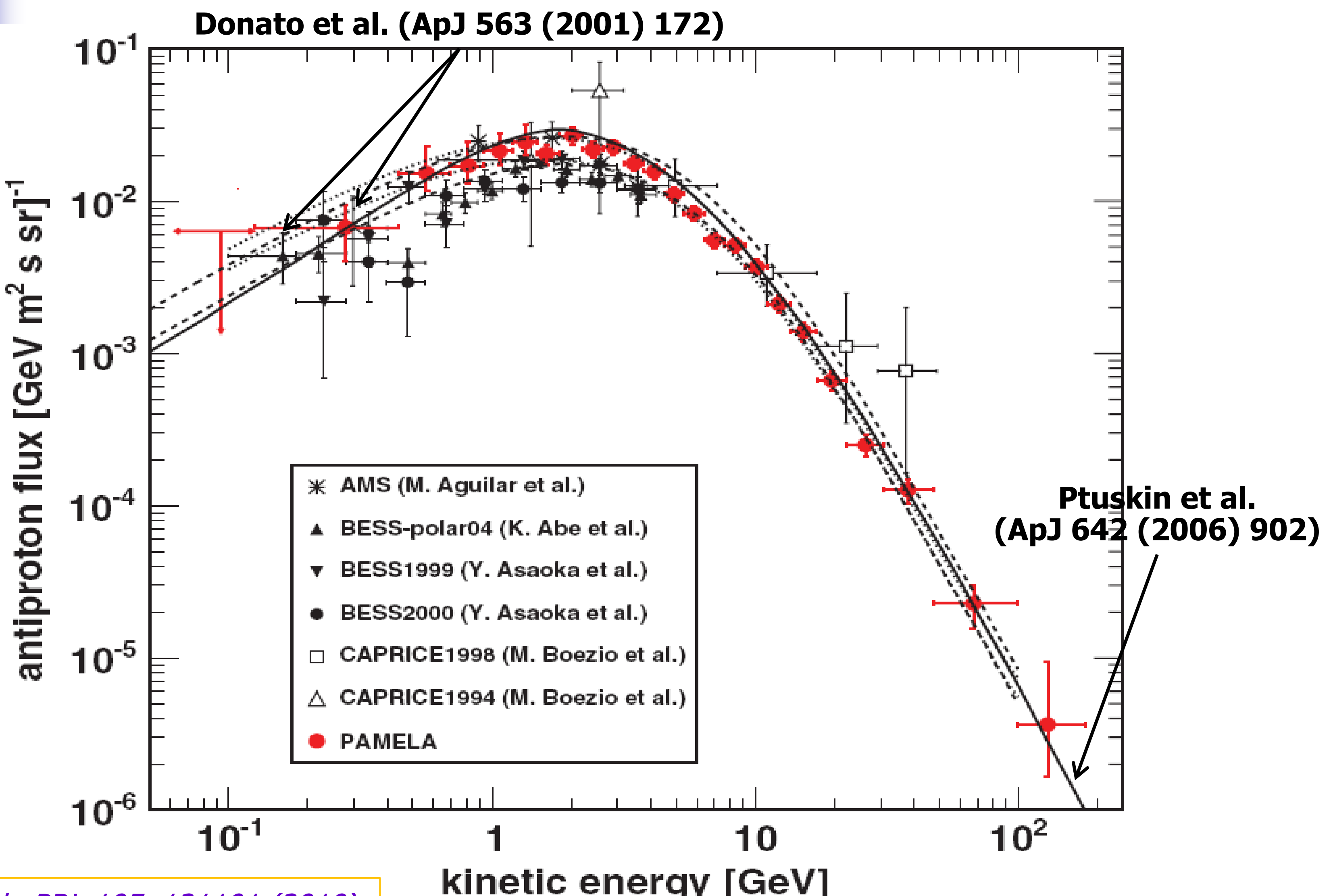
PAMELA antiparticle results

Antiprotons/protons ratio



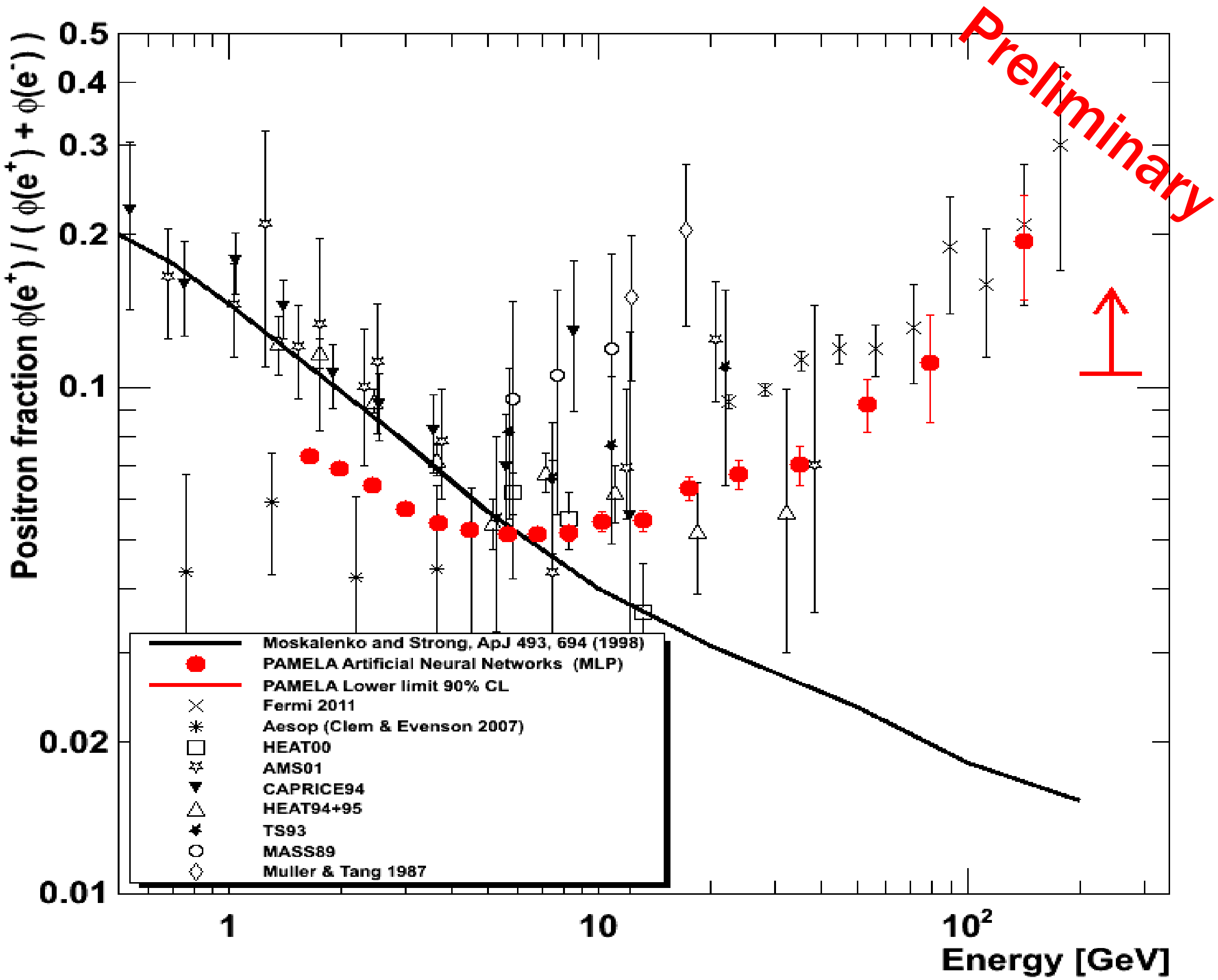
Adriani et al., PRL 105, 121101 (2010)

Antiproton spectrum



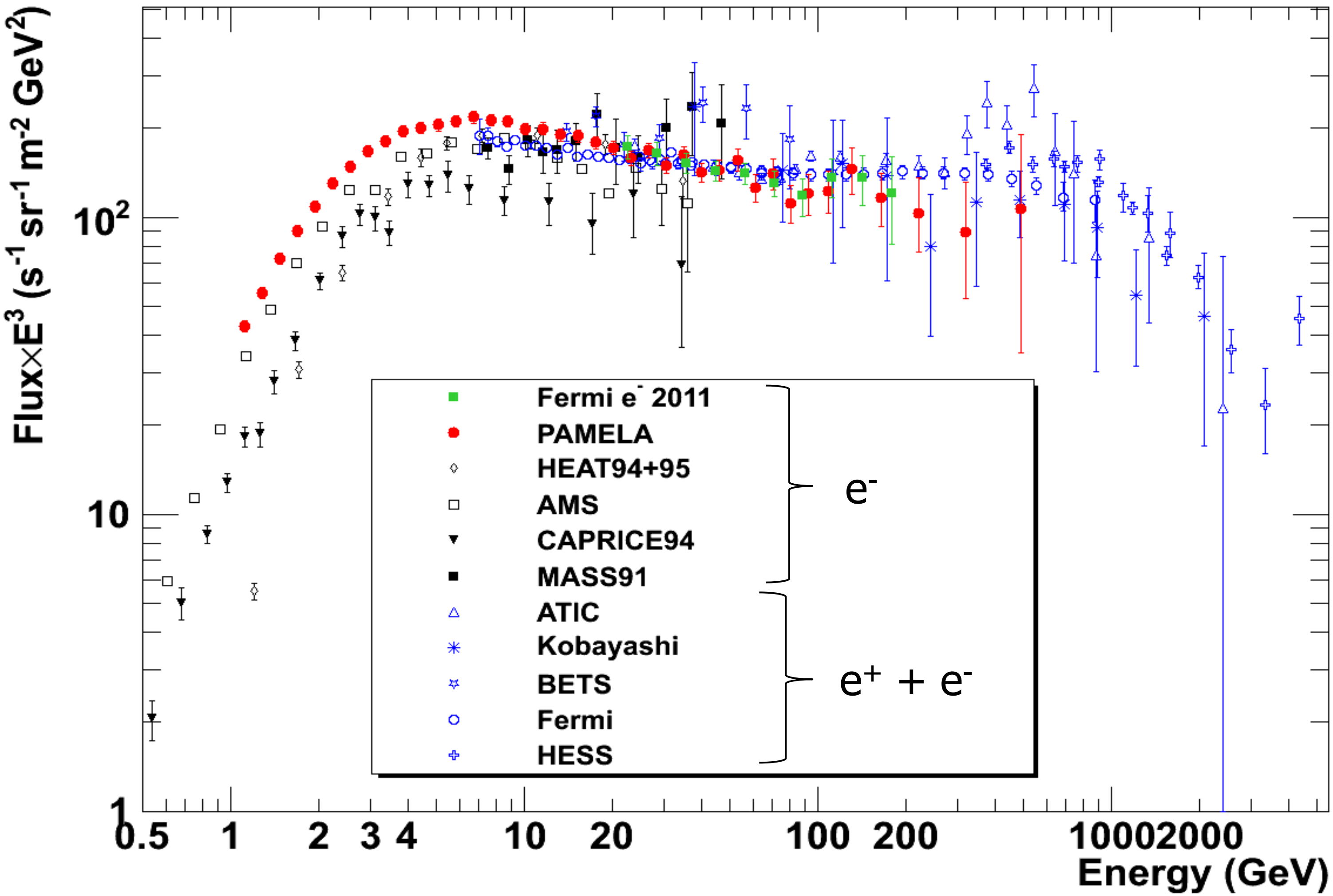
Adriani et al., PRL 105, 121101 (2010)

Positron fraction

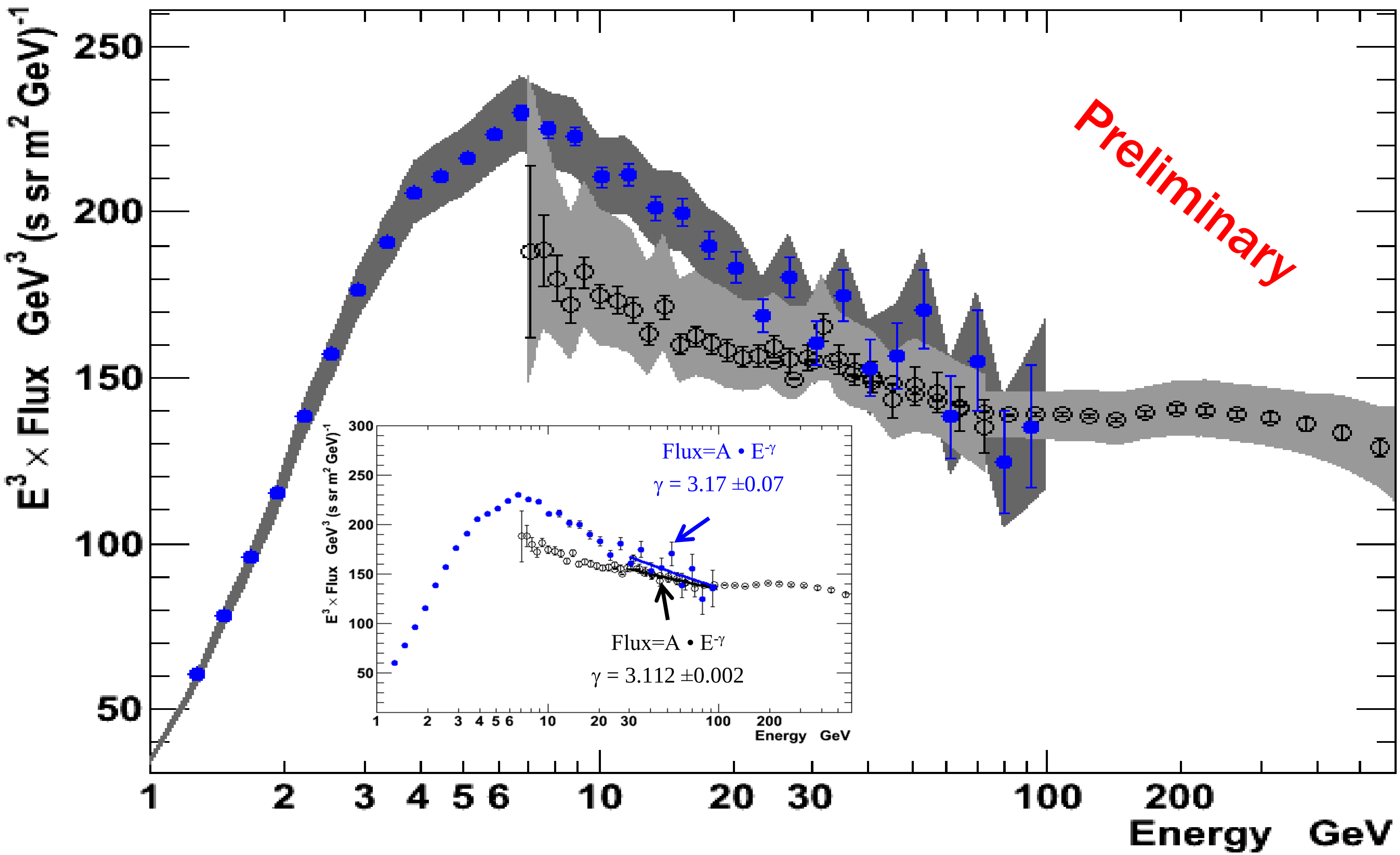


Using all data till 2010 and multivariate classification algorithms about factor 2-3 increase in respect to published analysis

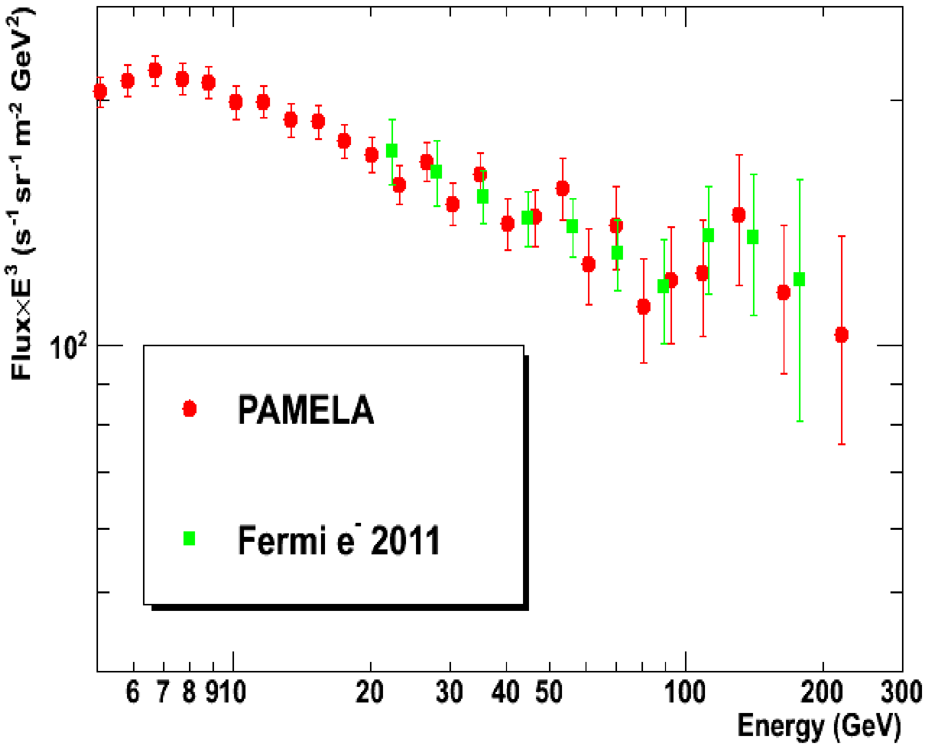
Electron spectrum

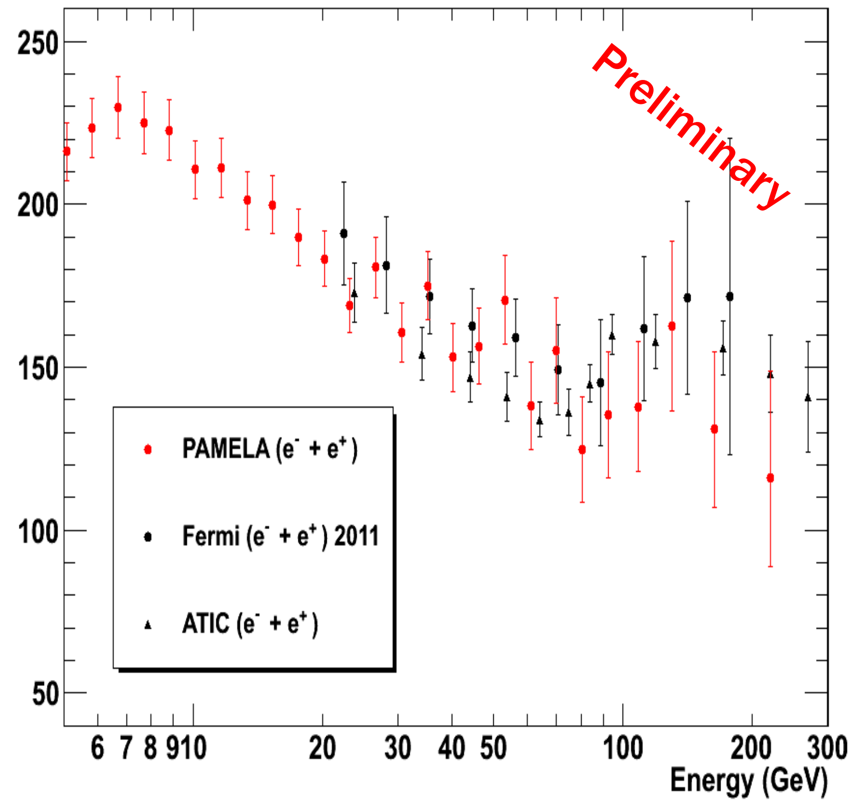


Electron spectra

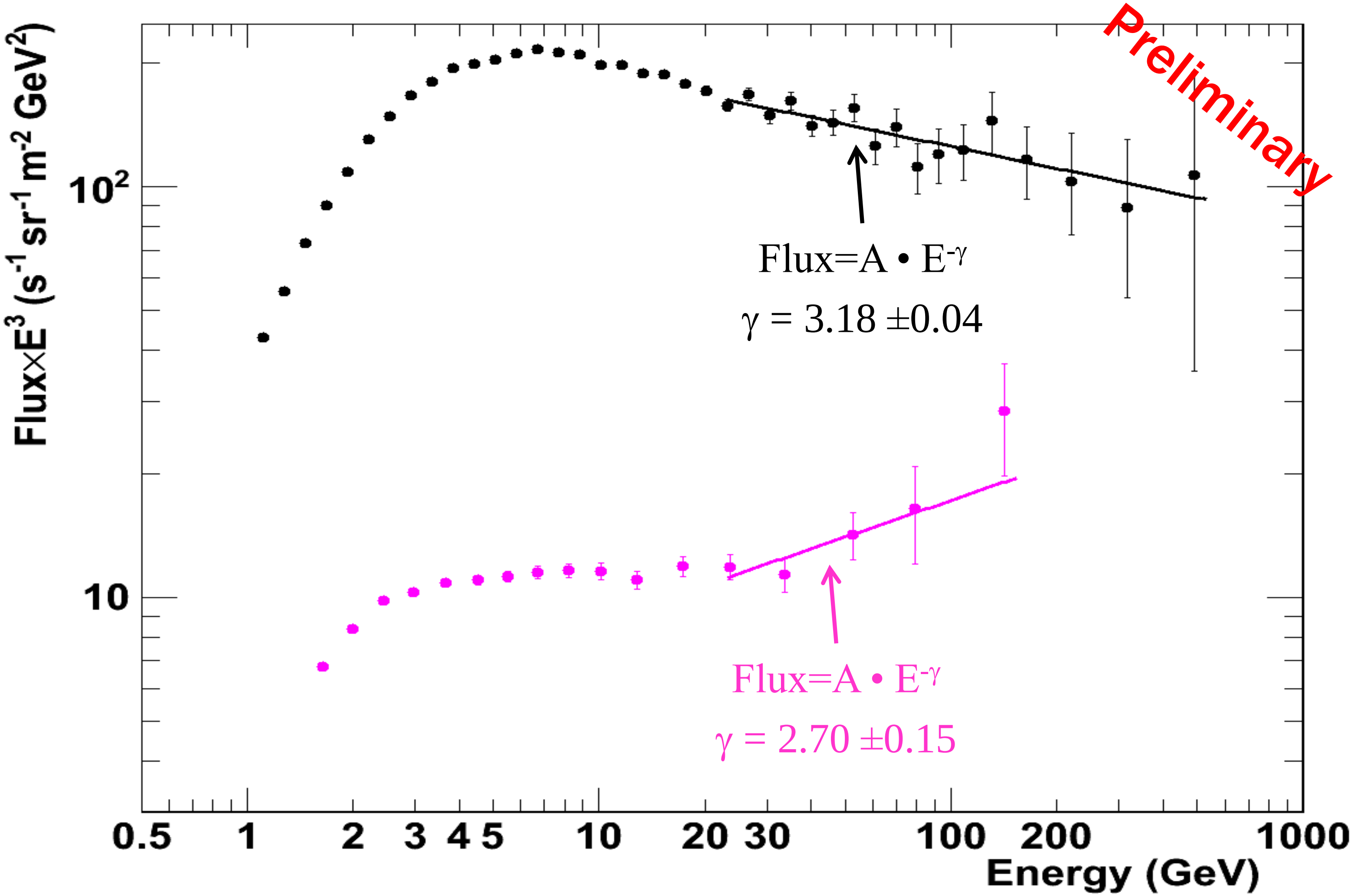


Electron spectra

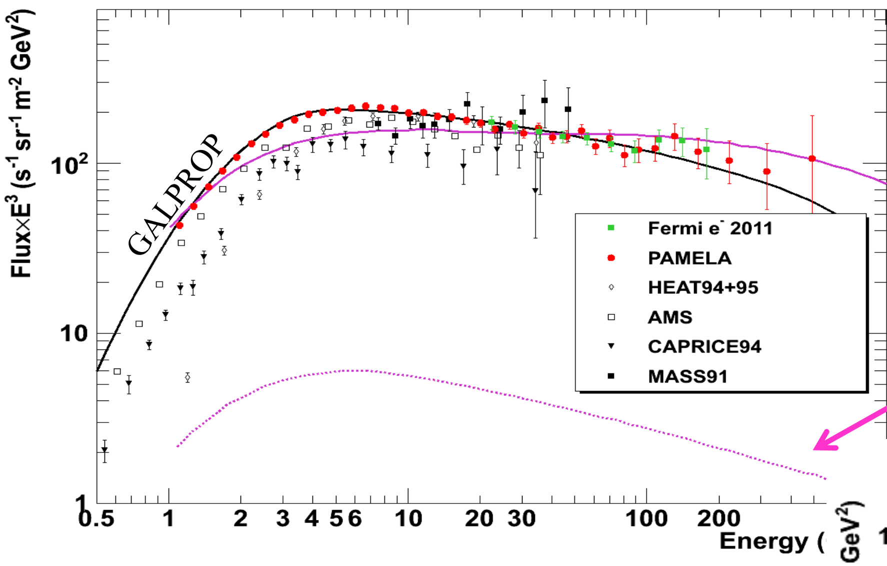




Electron and Positron spectra



Electron and Positron spectra

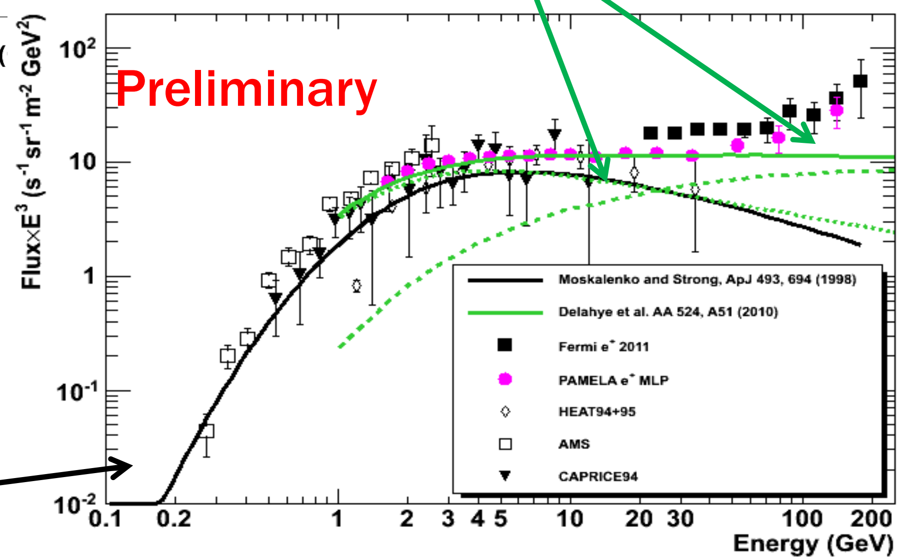


T. Delahaye et al., A&A 524 (2010) A51

Secondary & Primary productions

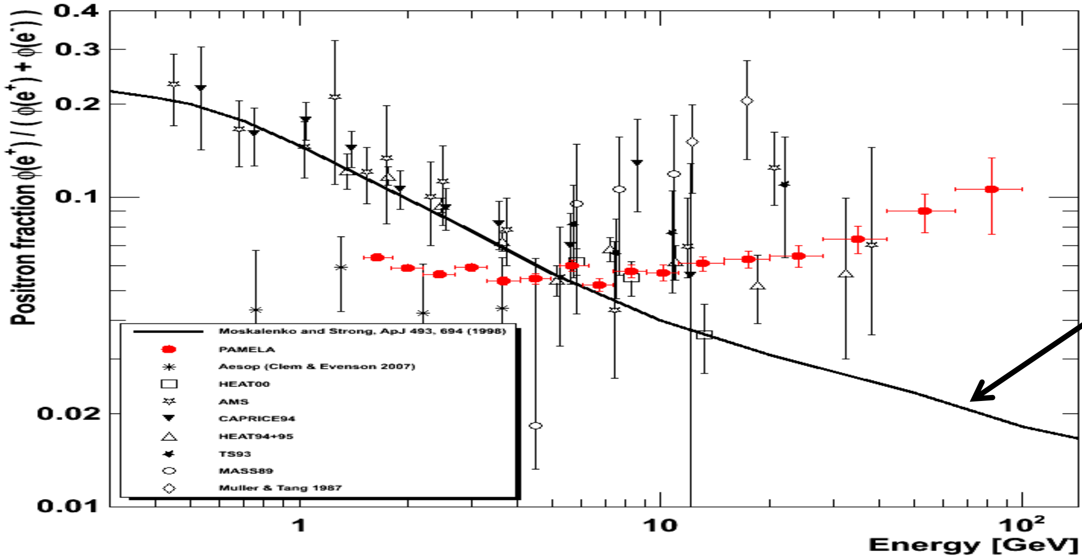
(from Astrophysical Sources)

spectral features at high energies that may point to additional components



Secondary production
Moskalenko & Strong 98

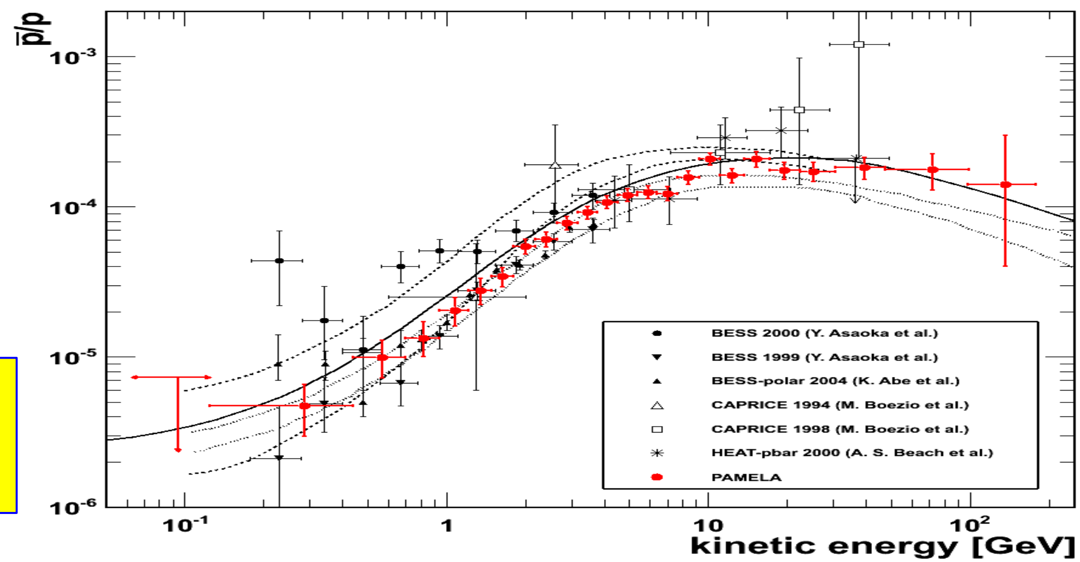
A challenging puzzle for CR physics



NB! Uncertainties on:

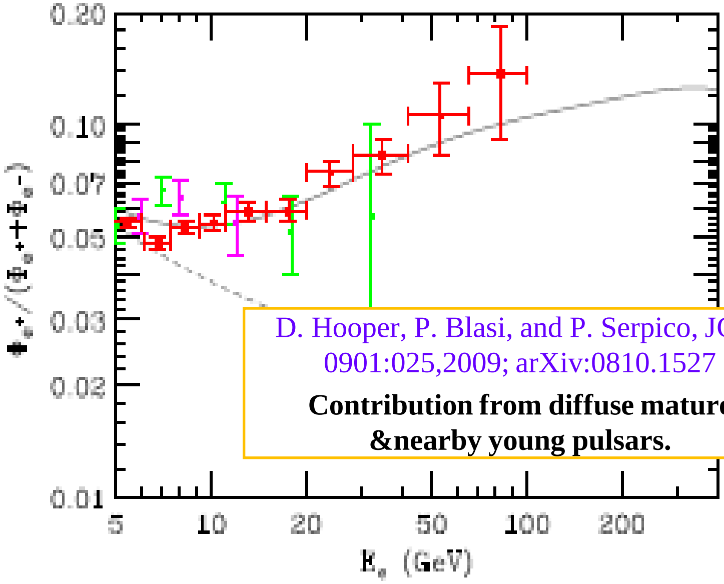
- Secondary production (primary fluxes, cross section)
- Propagation models
- Electron spectrum

Rising positron fraction



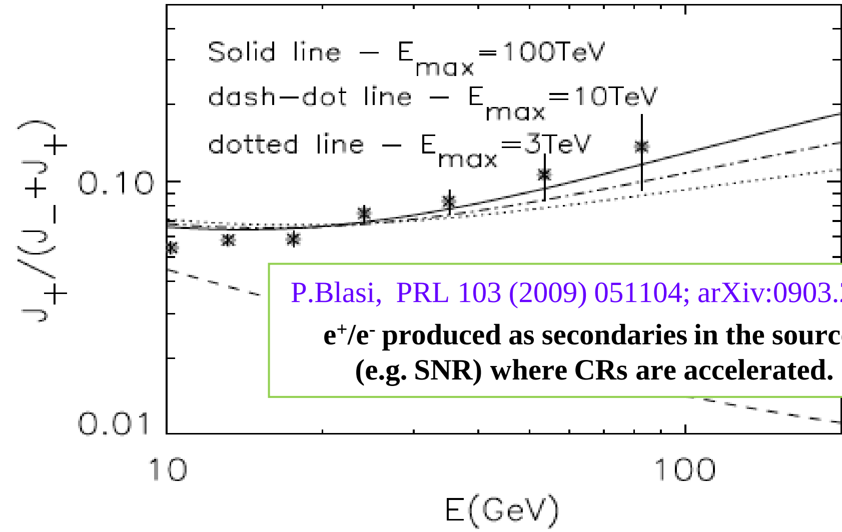
But antiprotons in CRs are in agreement with secondary production

Astrophysical and DM scenarios



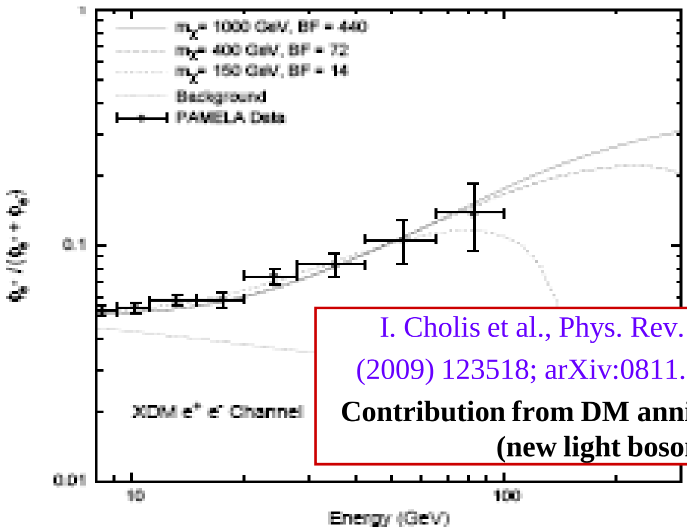
D. Hooper, P. Blasi, and P. Serpico, JCAP 0901:025,2009; arXiv:0810.1527

Contribution from diffuse mature &nearby young pulsars.



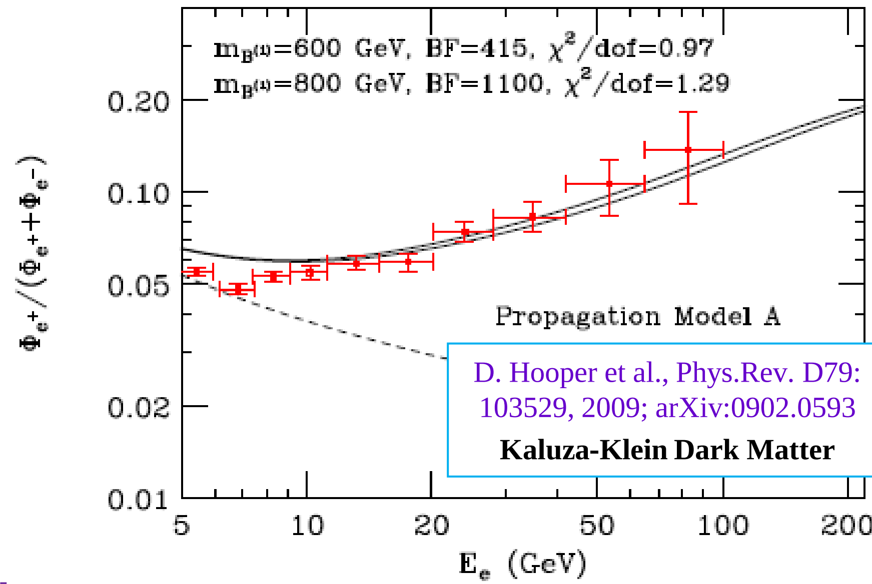
P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794

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



I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1

Contribution from DM annihilation (new light boson).



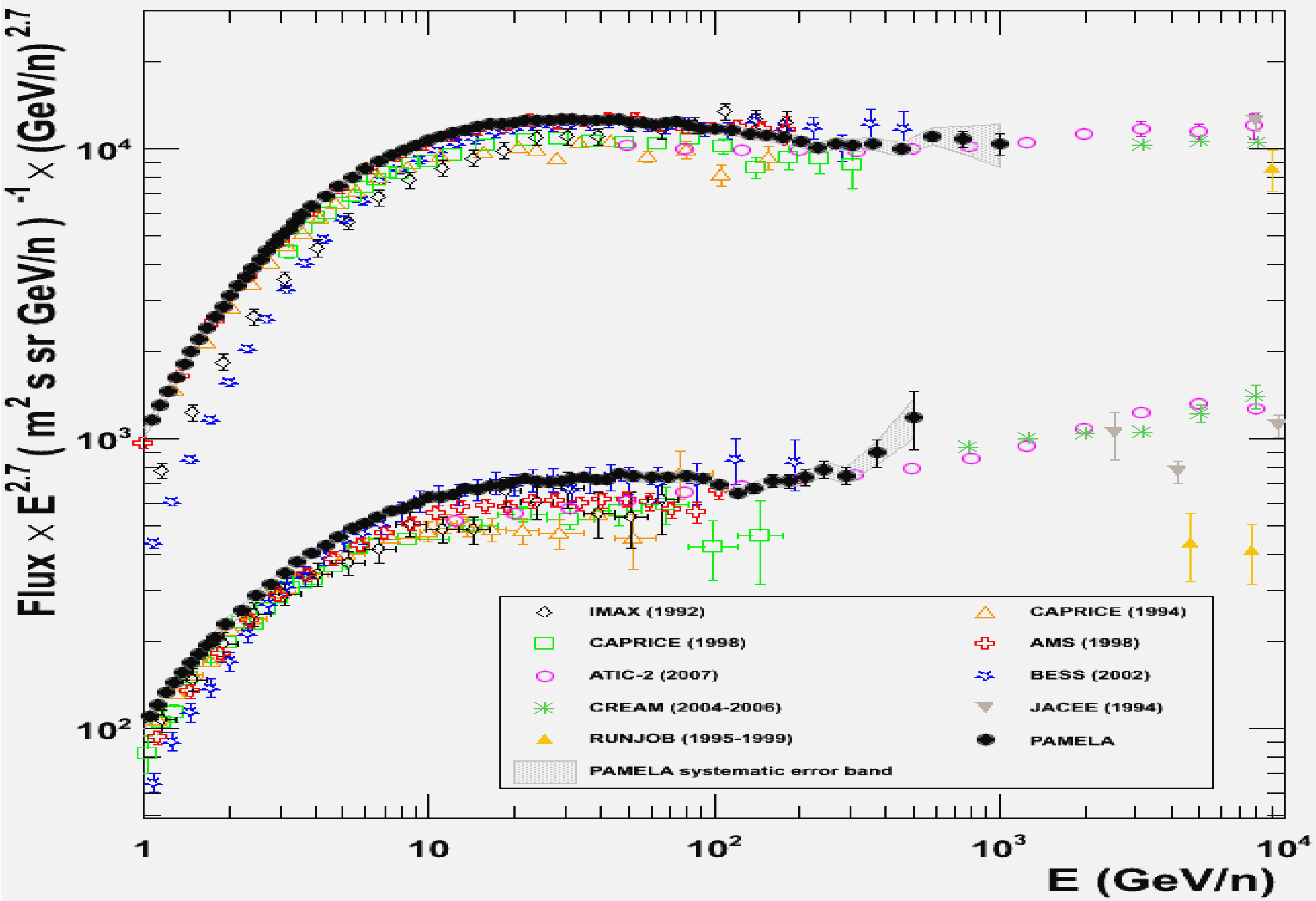
D. Hooper et al., Phys.Rev. D79: 103529, 2009; arXiv:0902.0593

Kaluza-Klein Dark Matter

PAMELA proton and He results

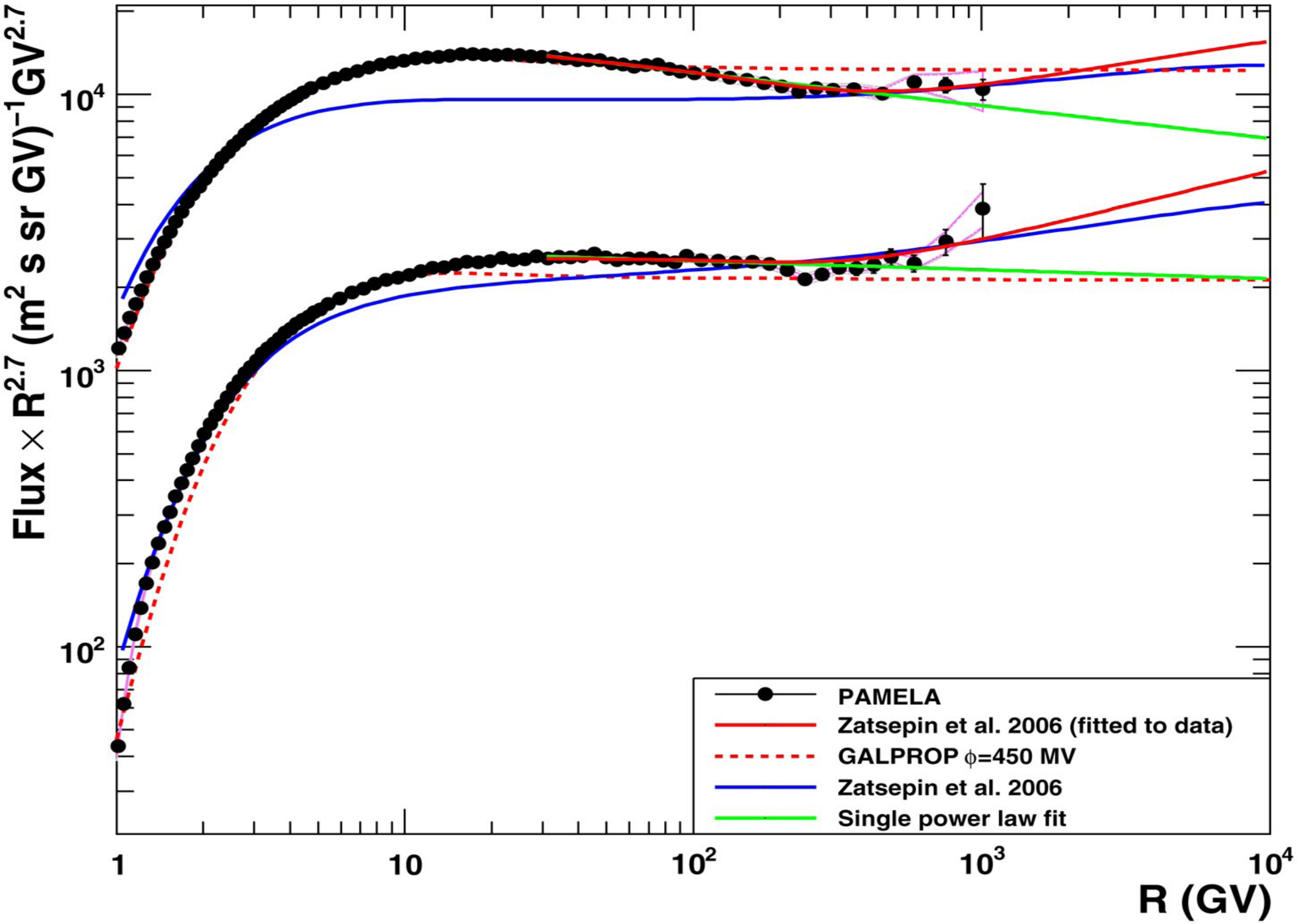
Proton and He spectra

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



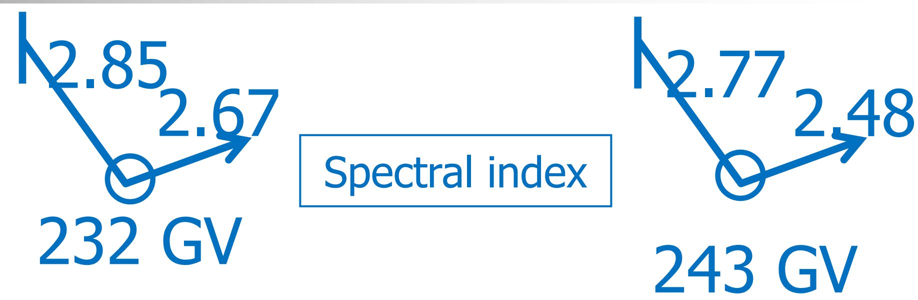
Proton and He spectra

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



Proton and He spectra

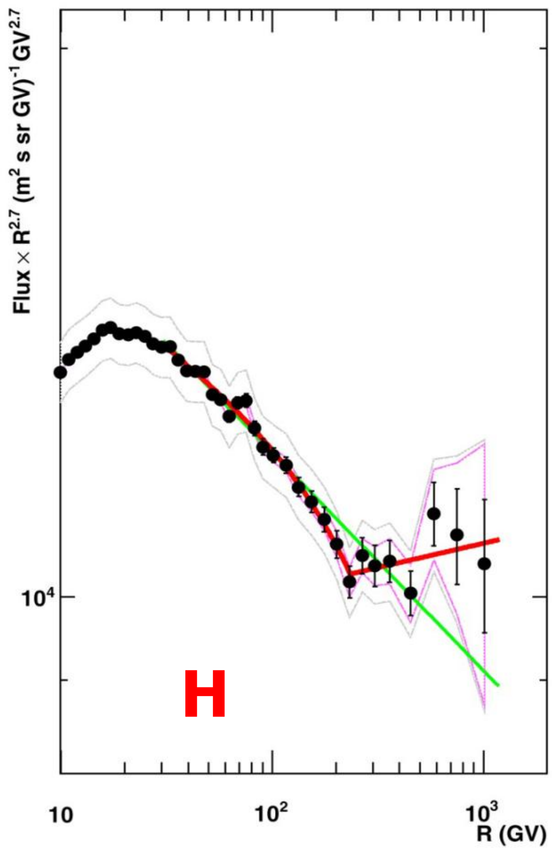
Proton and He spectra have different spectral shapes

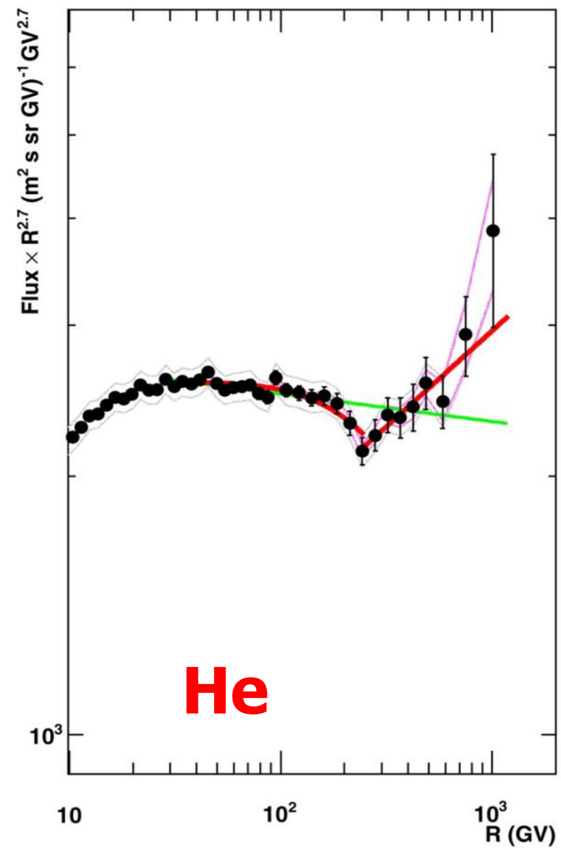


Deviations from single power law (SPL):

- ➢ Spectra gradually soften in the range 30÷230GV
- ➢ Spectral hardening @R~235GV, $\Delta\gamma$~0.2÷0.3

SPL is rejected at 98%CL



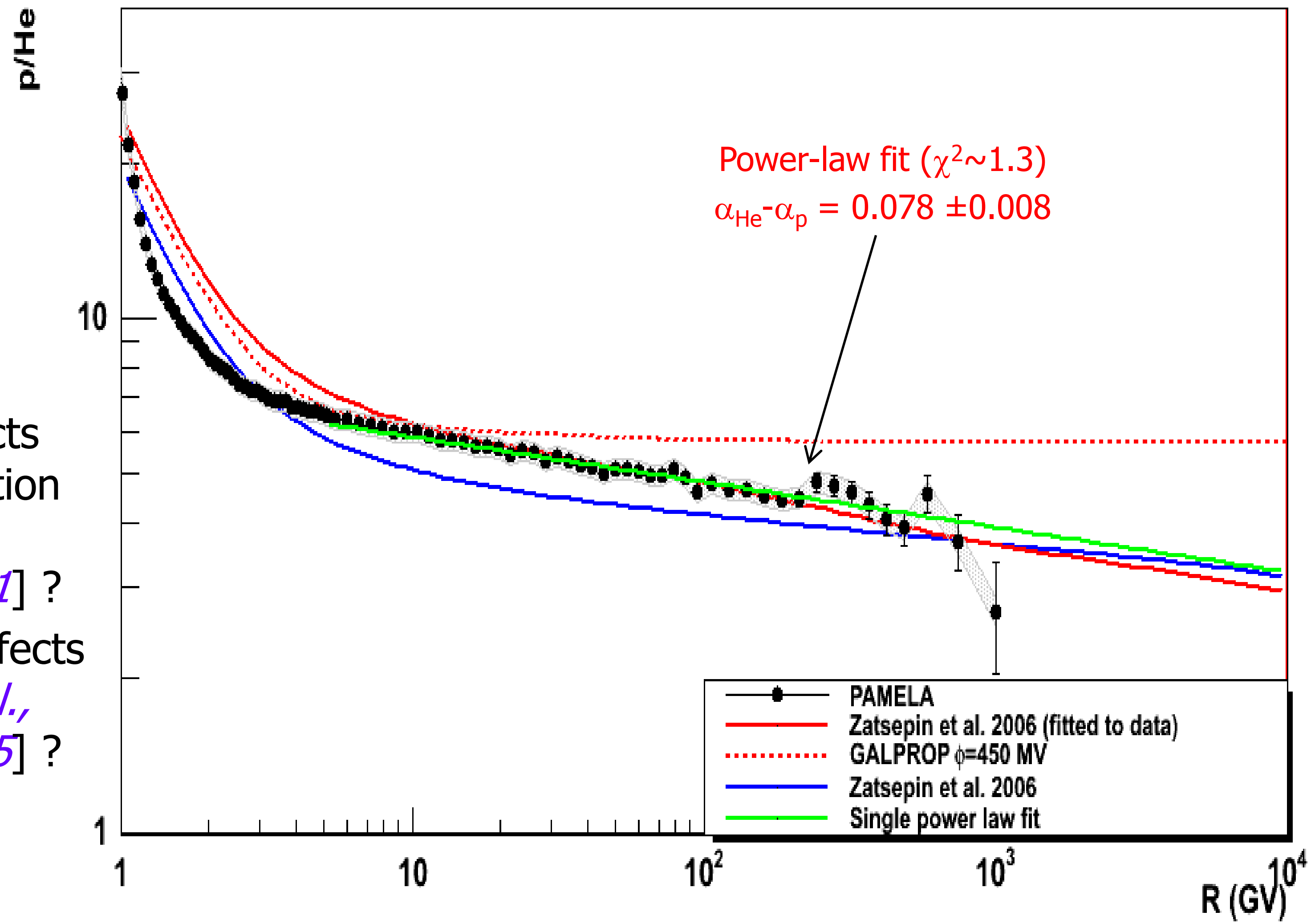


Origin of the structures?

- ❖ At the sources: multi-populations (novae stars SN explosions in superbubbles, etc.)?
- ❖ Propagation effects?
- ❖ Or?

H/He ratio

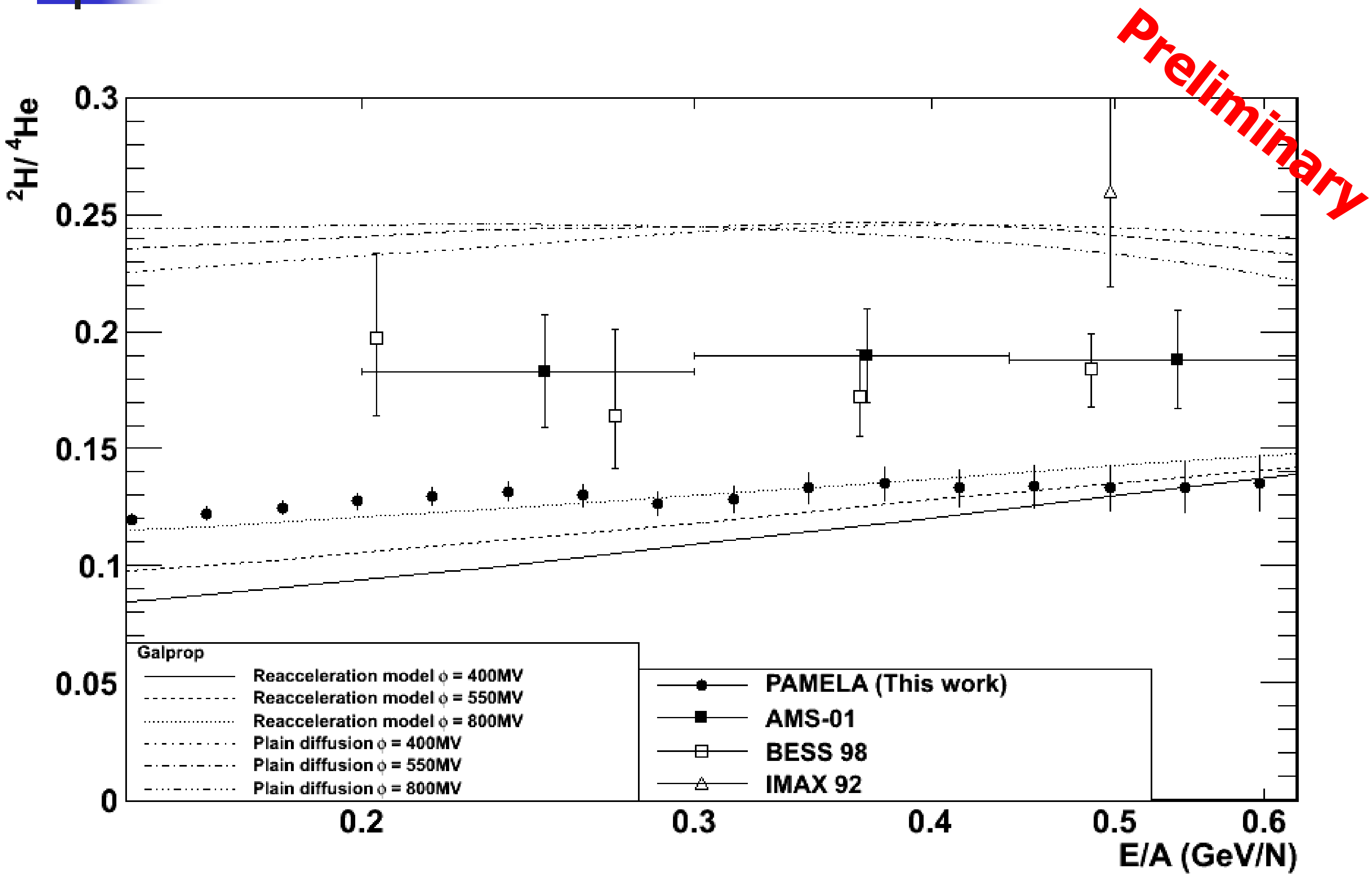
Adriani et al., Science, vol. 332 no. 6025 (2011), arXiv: 1103.4055



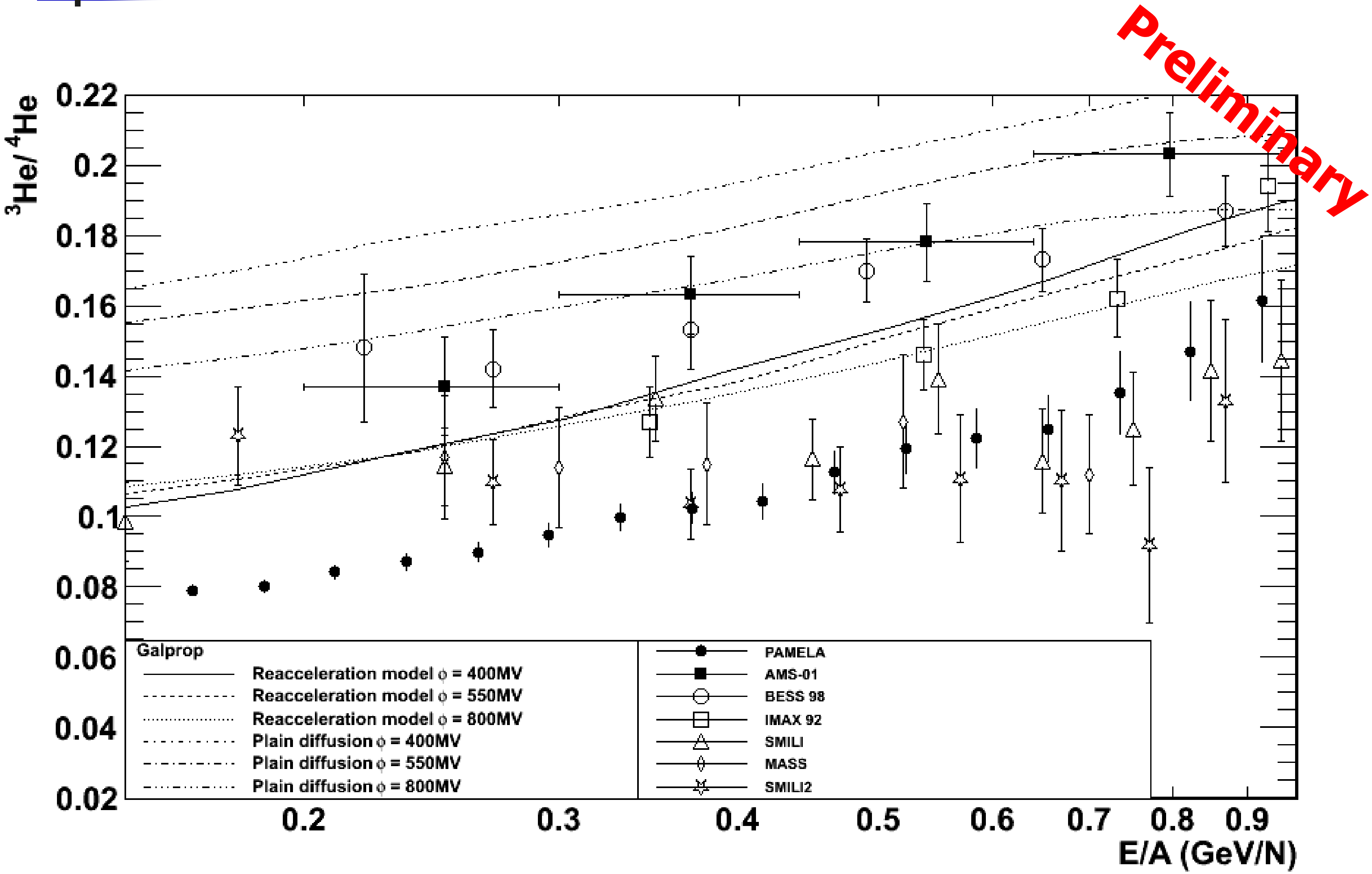
- Spallation effects during propagation [*Blasi & Amato: arXiv:1105.4521*] ?
- Acceleration effects [*M. Malkov et al., arXiv:1110.5335*] ?
- Or?

PAMELA light nuclei & isotopes results

He³/He⁴ ratio

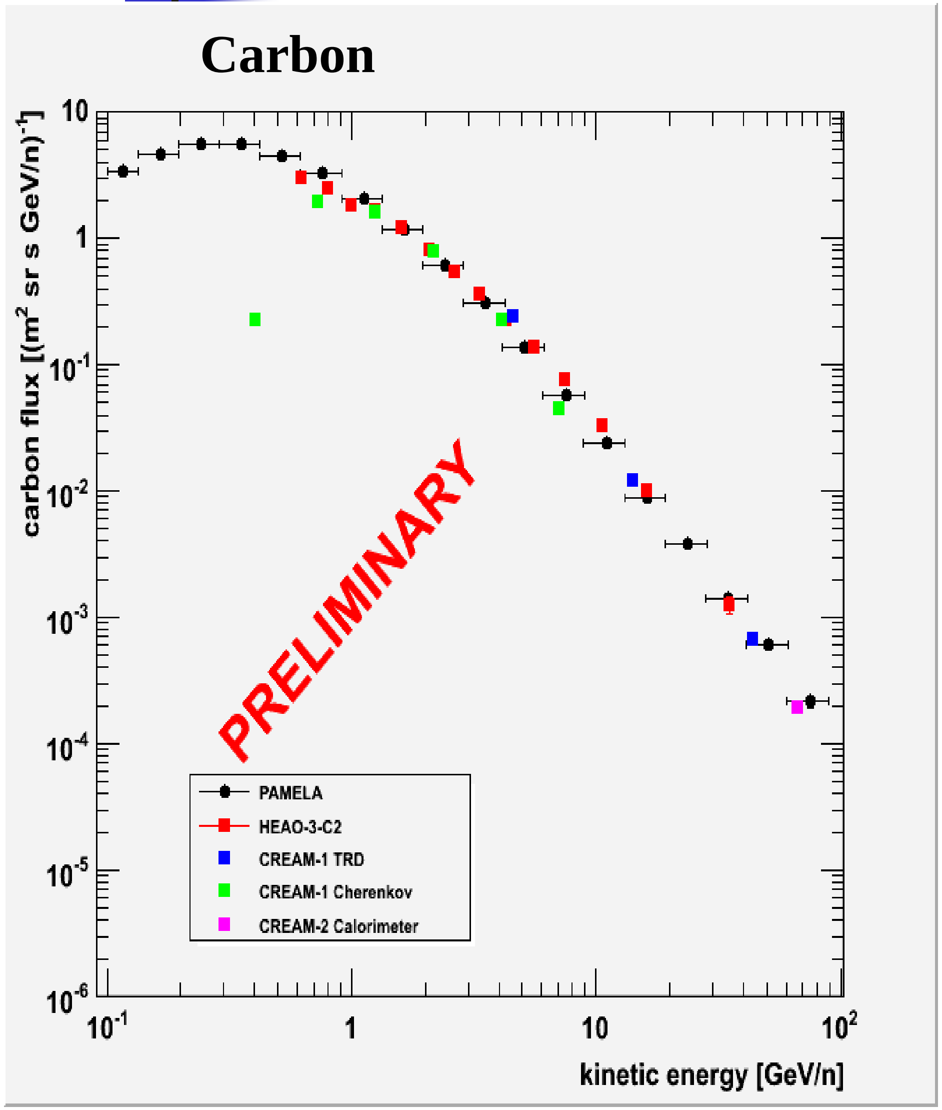


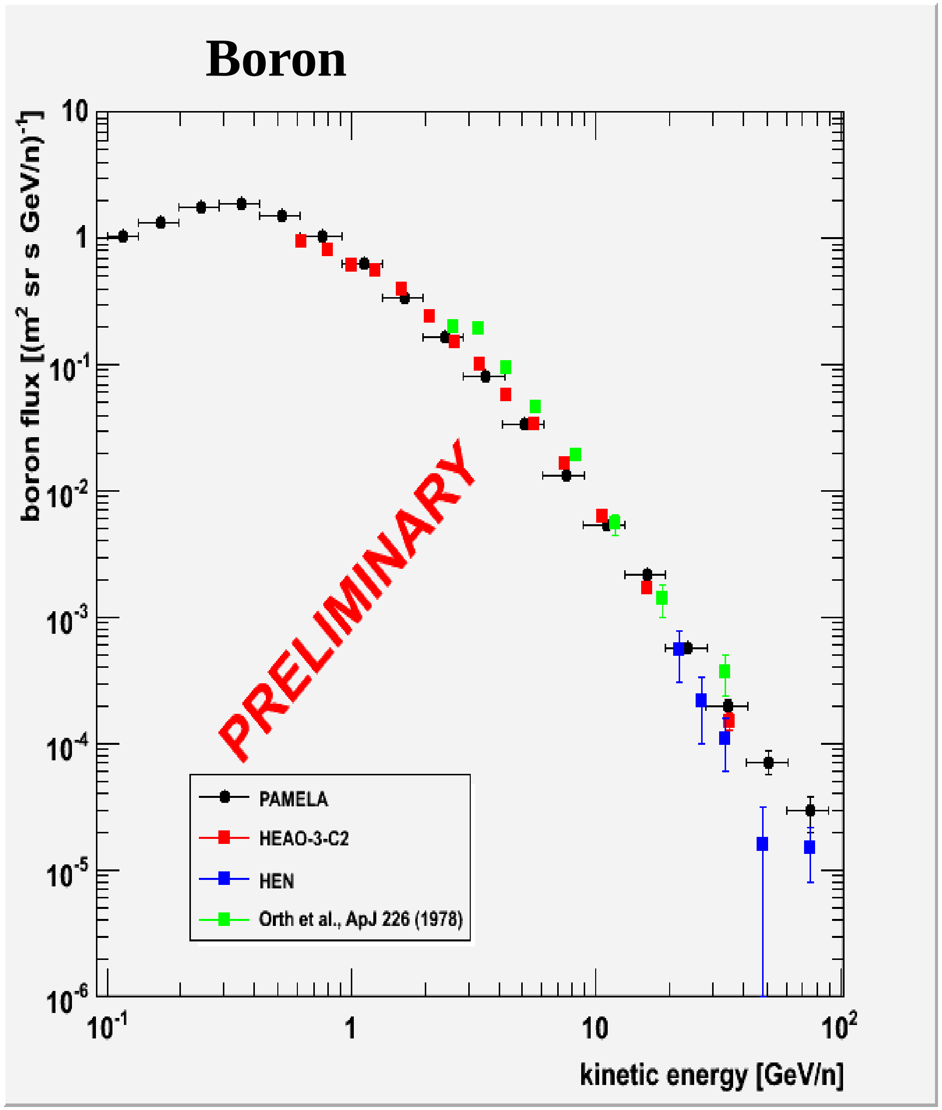
H^2/He^4 ratio



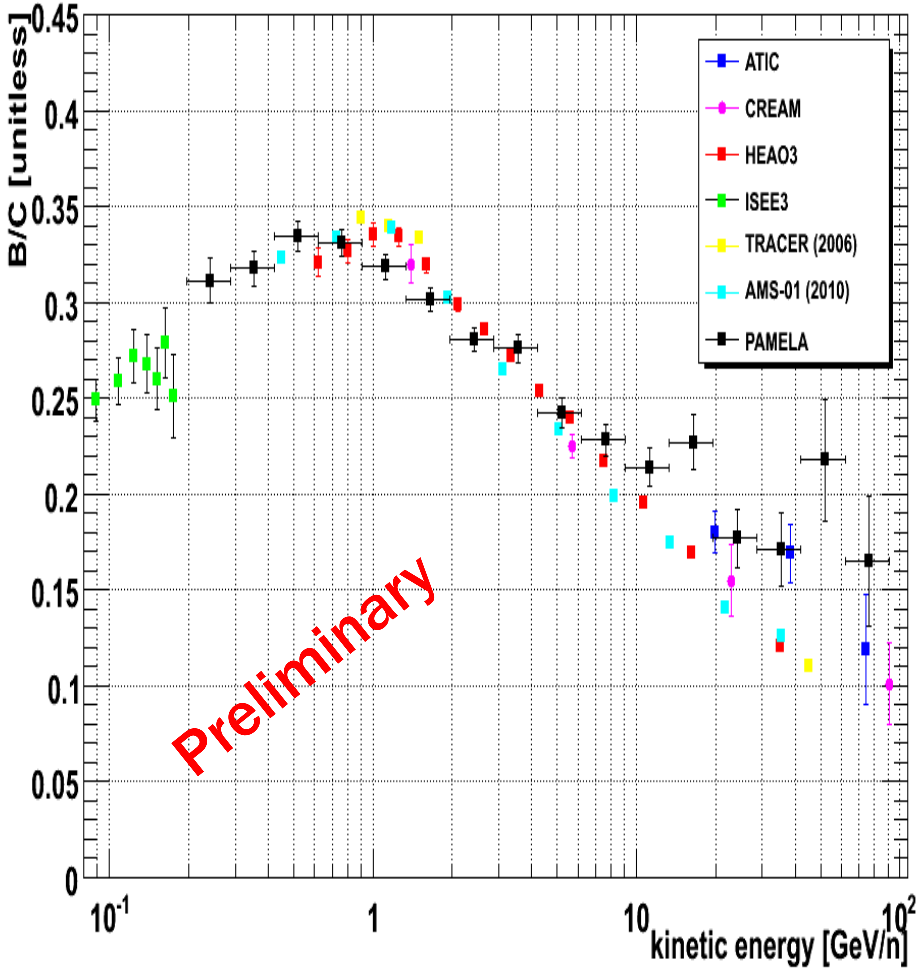
Preliminary
$^3He/^4He$
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
E/A (GeV/N)
Galprop
Reacceleration model ϕ = 400MV
Reacceleration model ϕ = 550MV
Reacceleration model ϕ = 800MV
Plain diffusion ϕ = 400MV
Plain diffusion ϕ = 550MV
Plain diffusion ϕ = 800MV
PAMELA
AMS-01
BESS 98
IMAX 92
SMILI
MASS
SMILI2

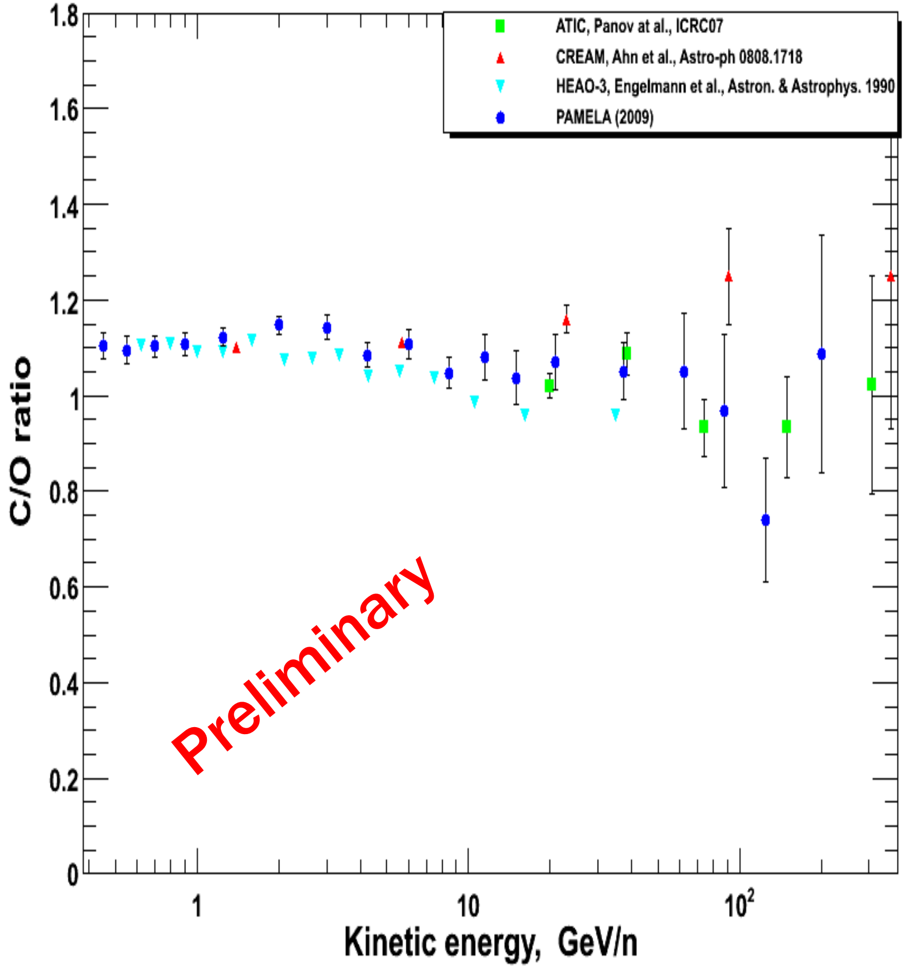
Light nuclei: Carbon & Boron





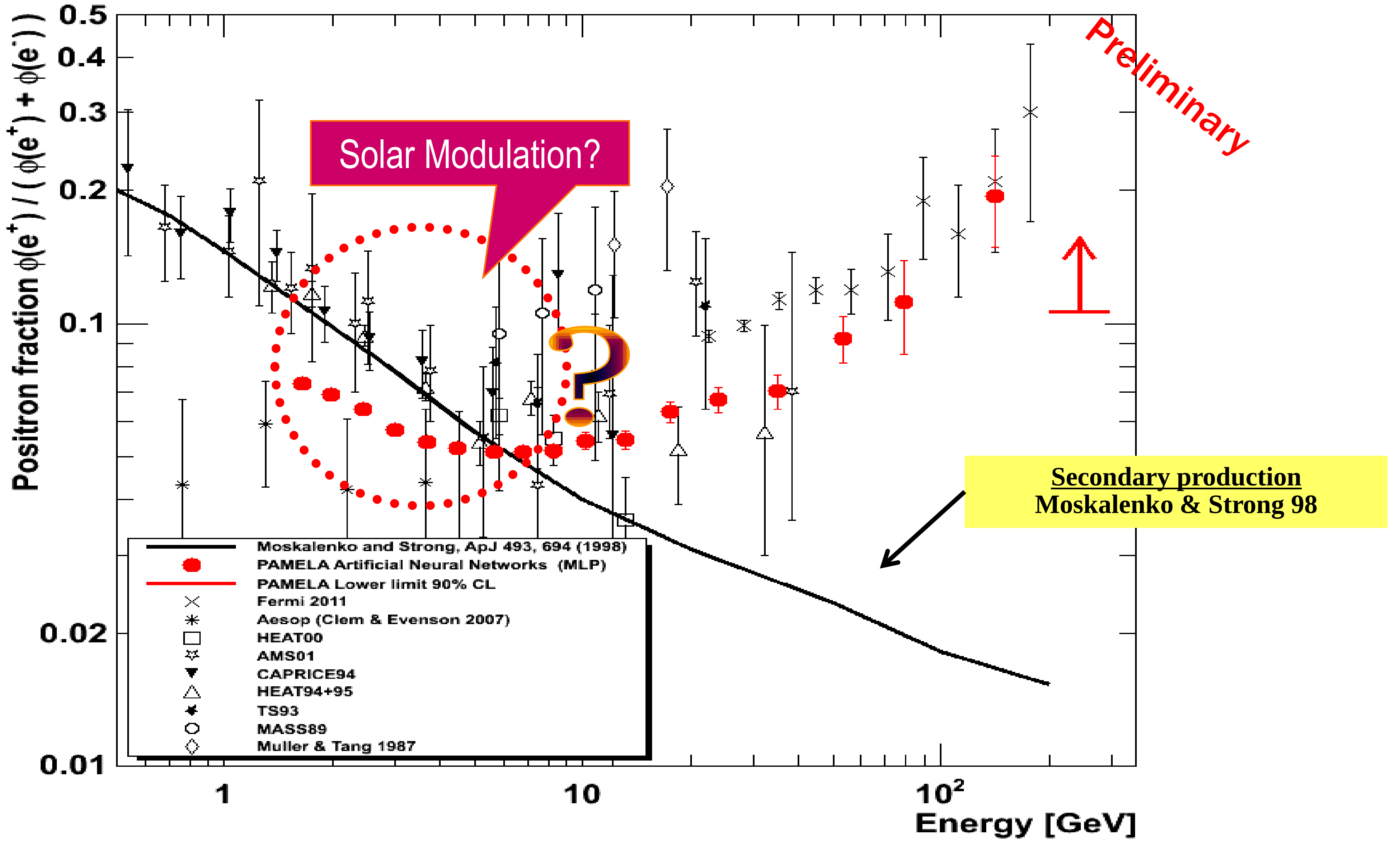
Light nuclei: B/C and C/O ratios



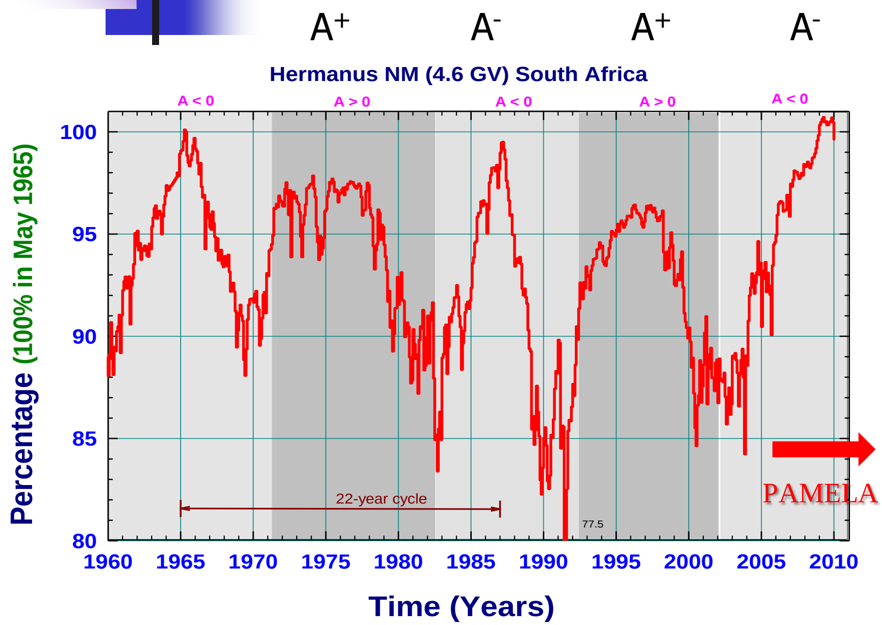


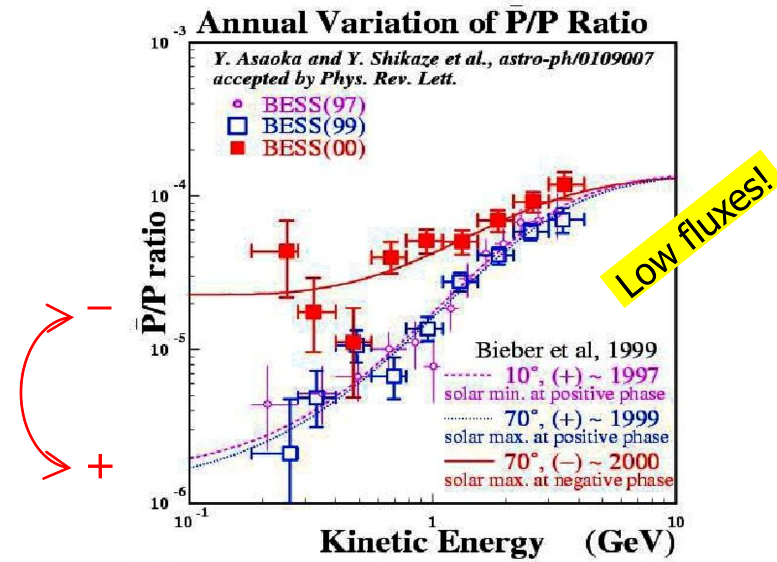
PAMELA solar physics results

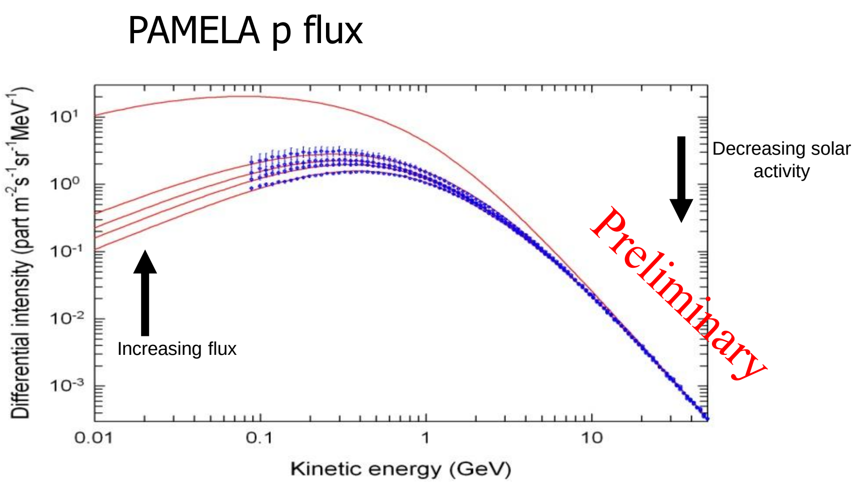
Solar modulation

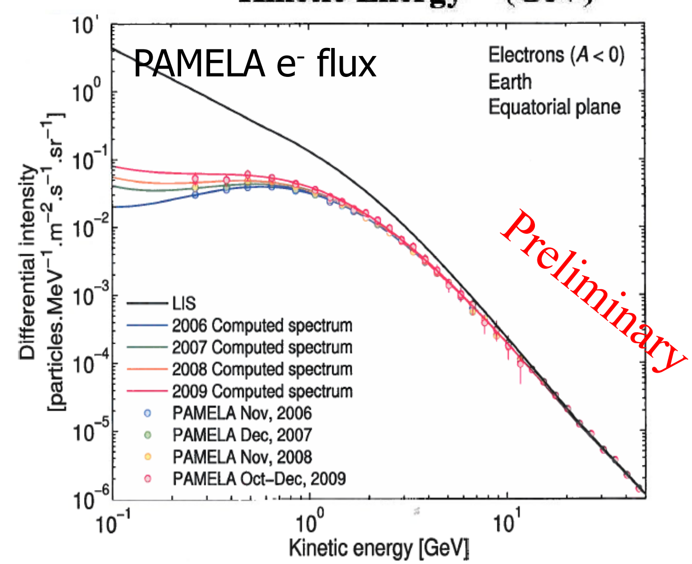


Solar modulation

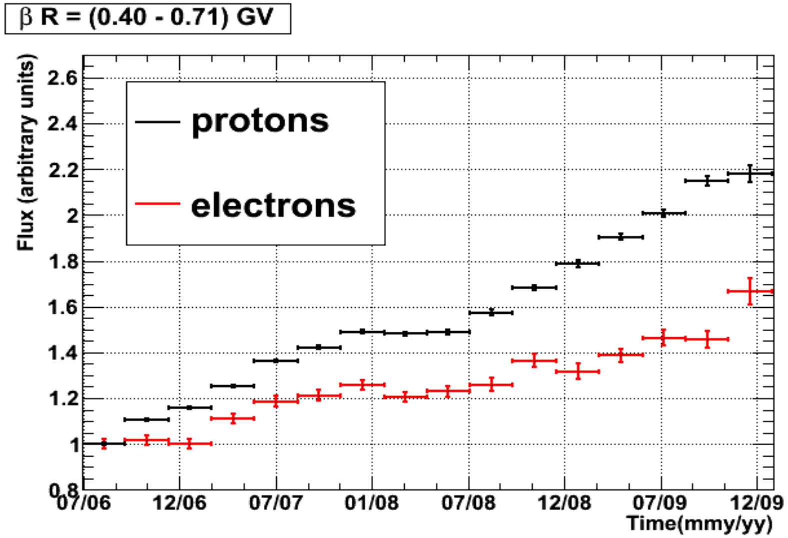


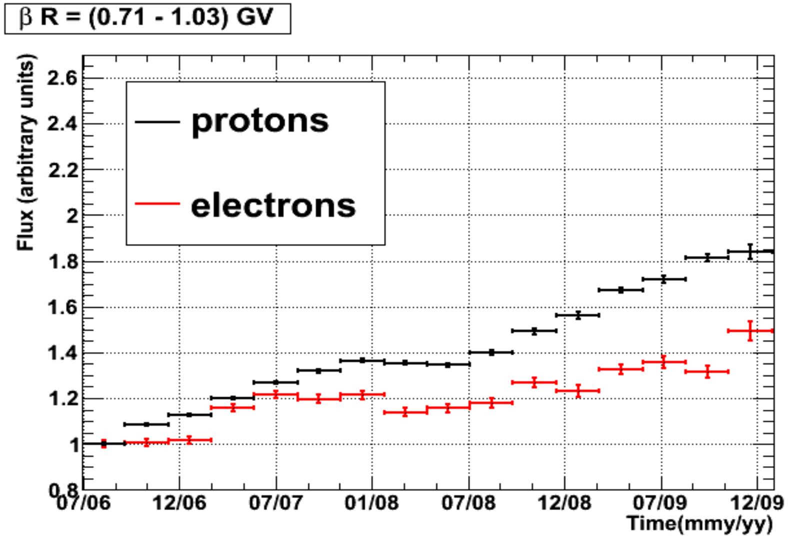


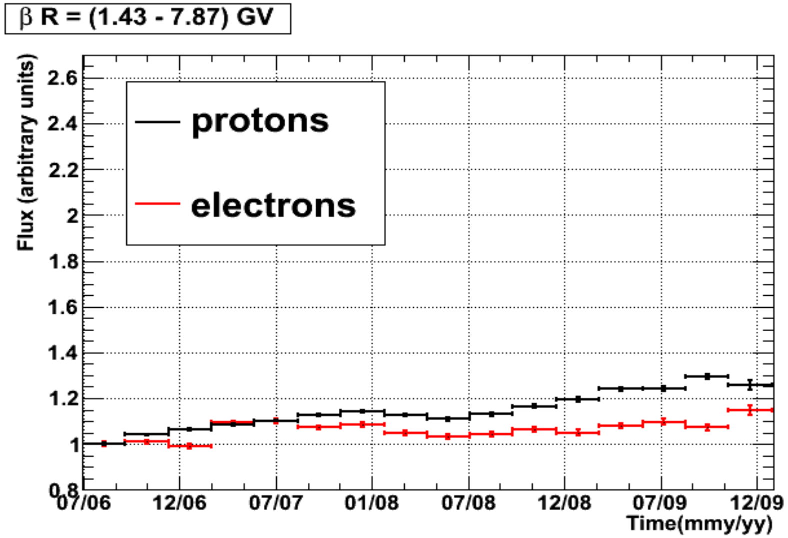


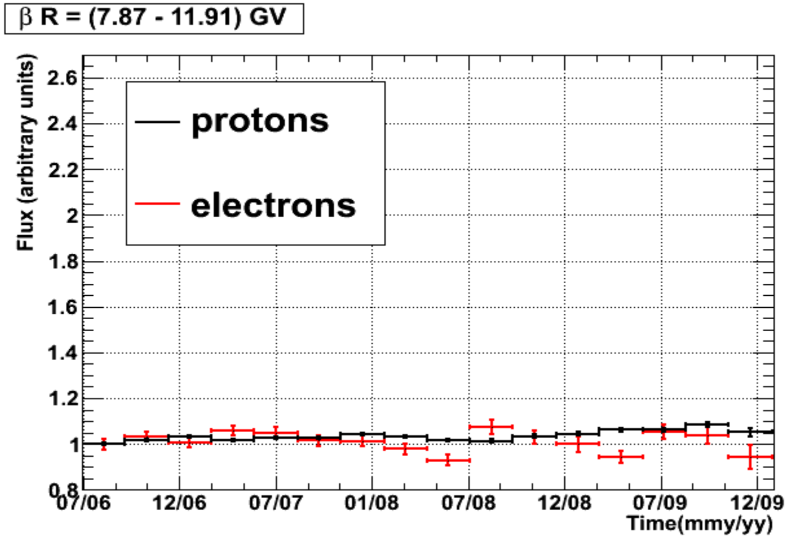


Solar modulation

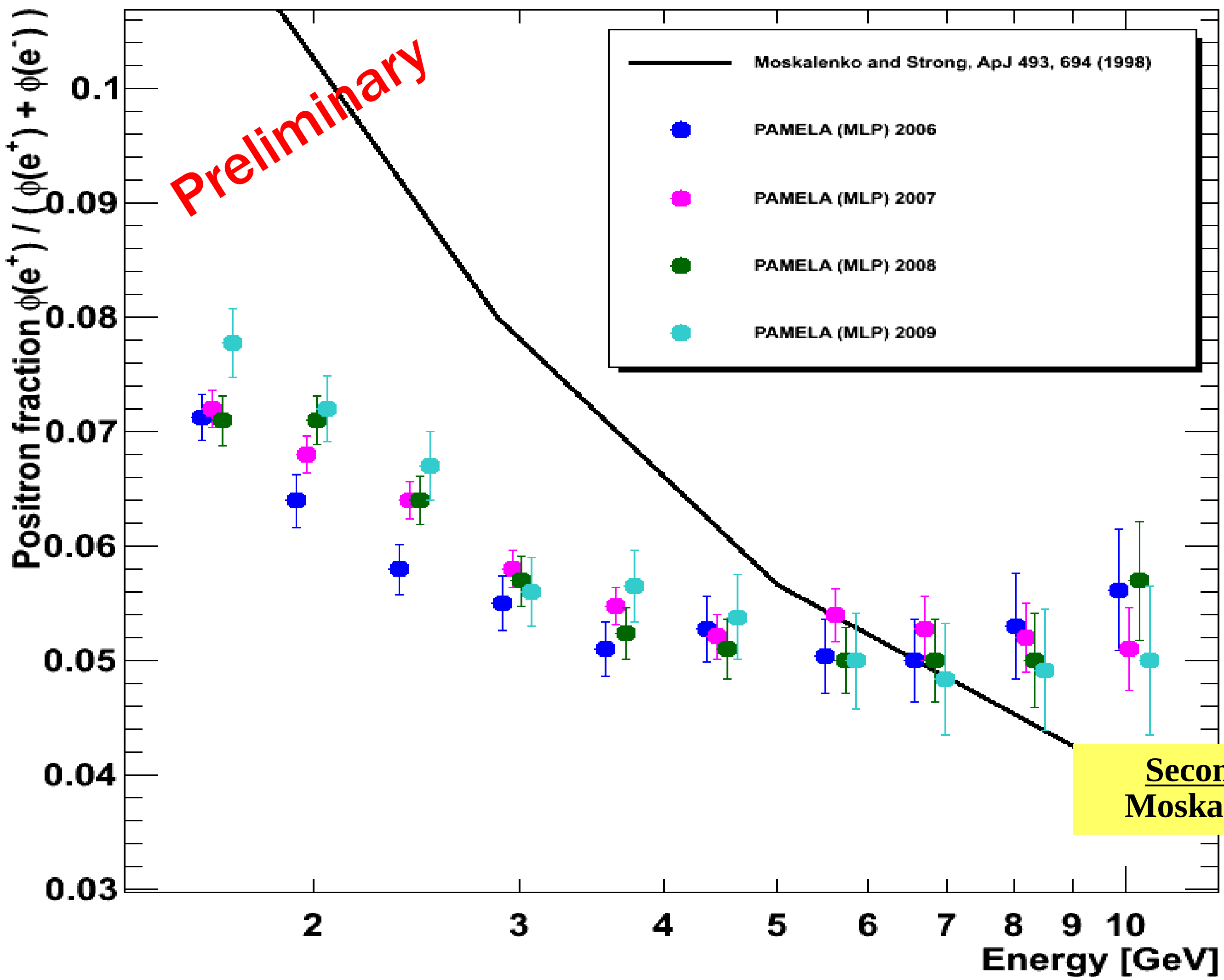








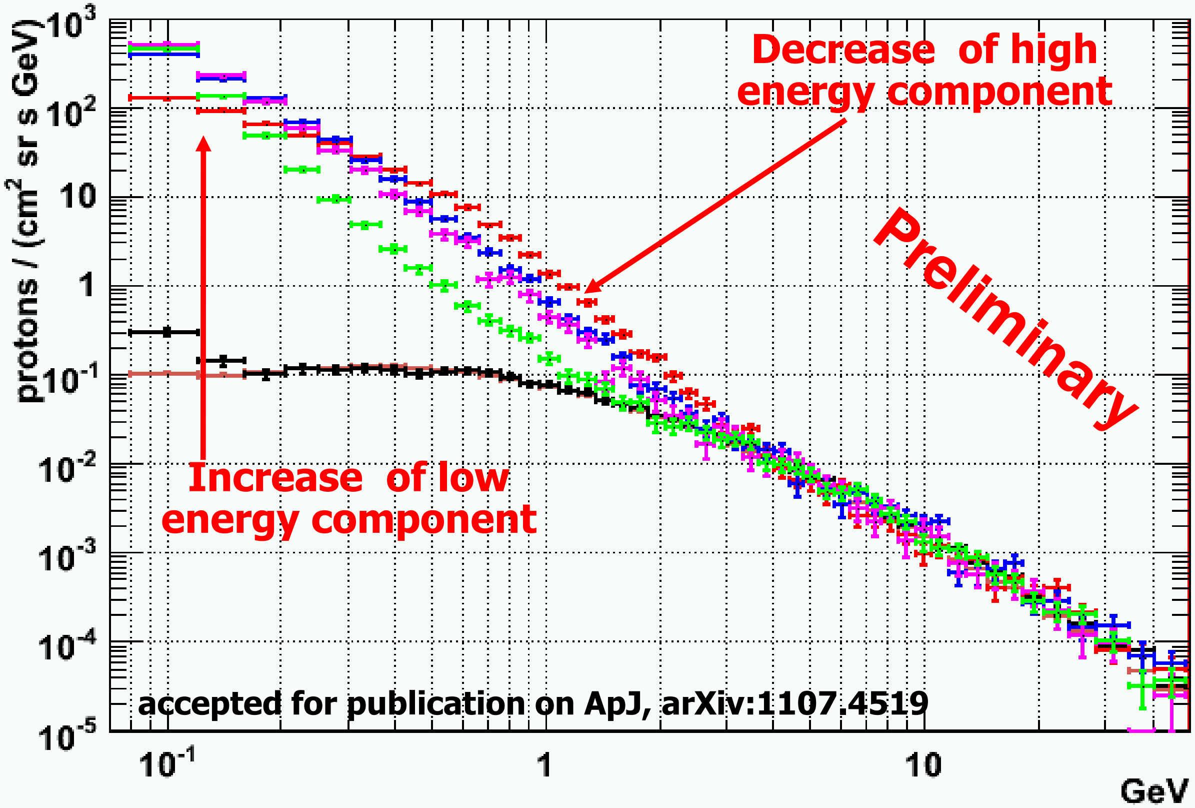
Solar modulation

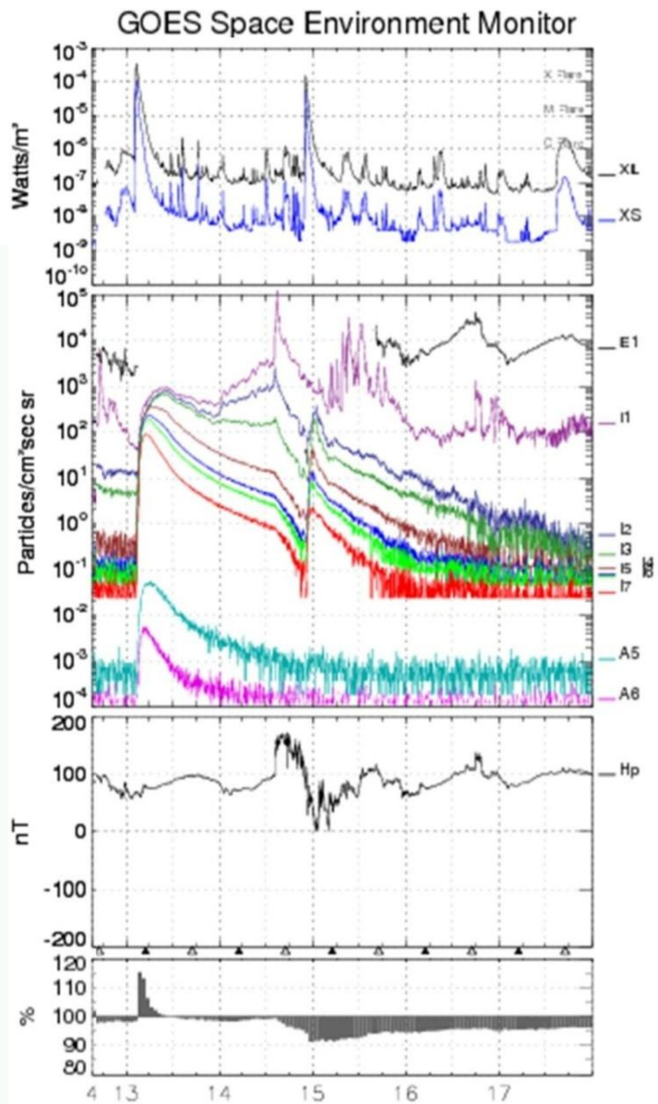


Secondary production
Moskalenko & Strong 98

Solar physics: December 13th 2006 event

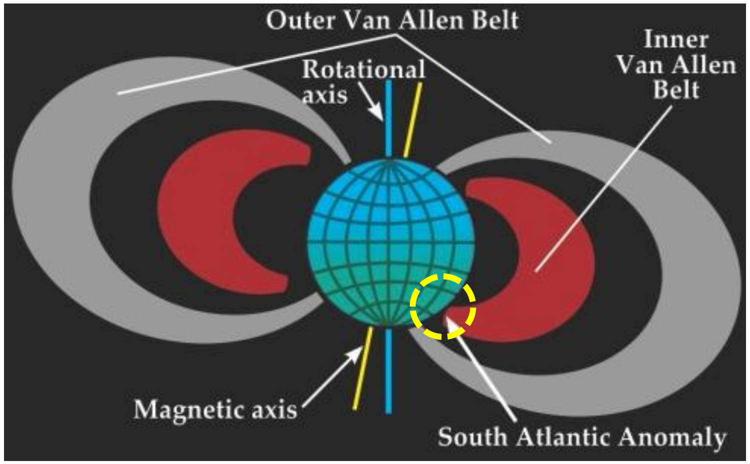
- from 2006-12-1 to 2006-12-4
- from 2006-12-13 00:23:02 to 2006-12-13 02:57:46
- from 2006-12-13 02:57:46 to 2006-12-13 03:49:09
- from 2006-12-13 03:49:09 to 2006-12-13 04:32:56
- from 2006-12-13 04:32:56 to 2006-12-13 04:59:16
- from 2006-12-13 08:17:54 to 2006-12-13 09:17:34

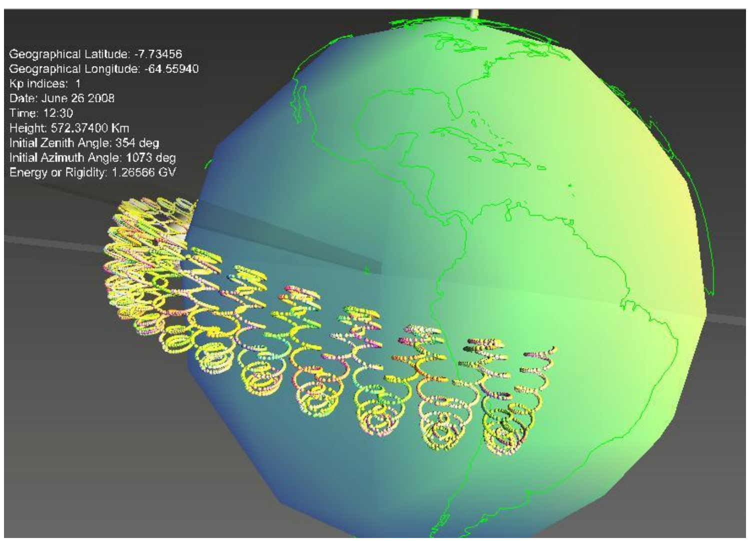


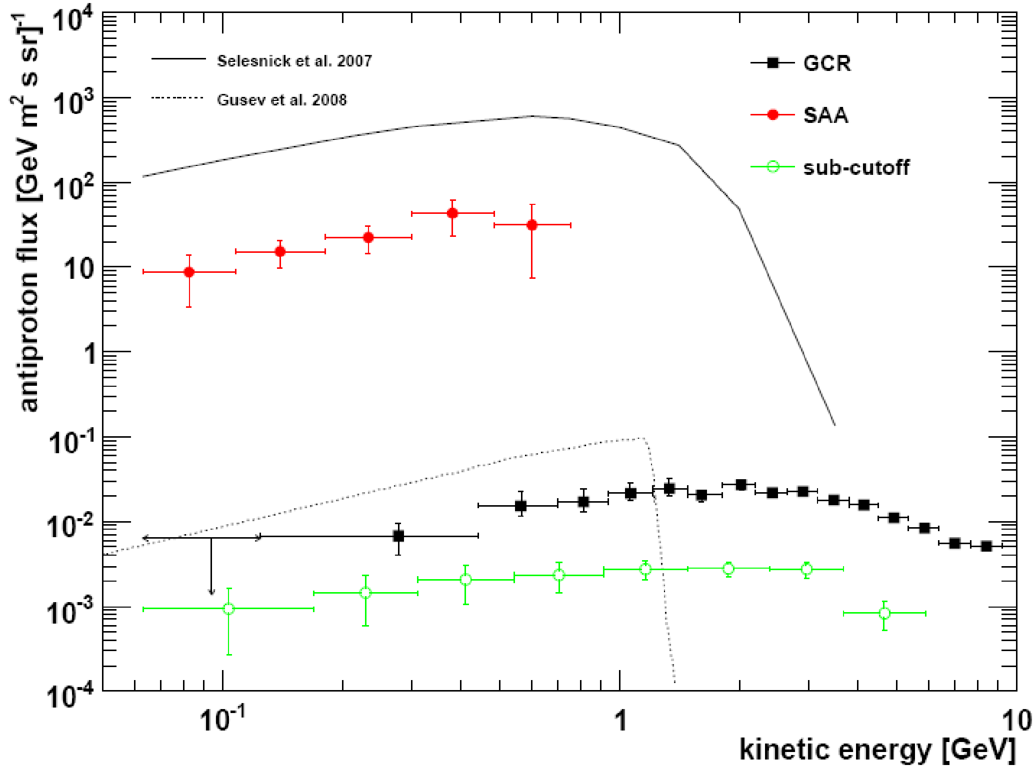


PAMELA magnetospheric physics results

The discovery of geomagnetically trapped antiprotons





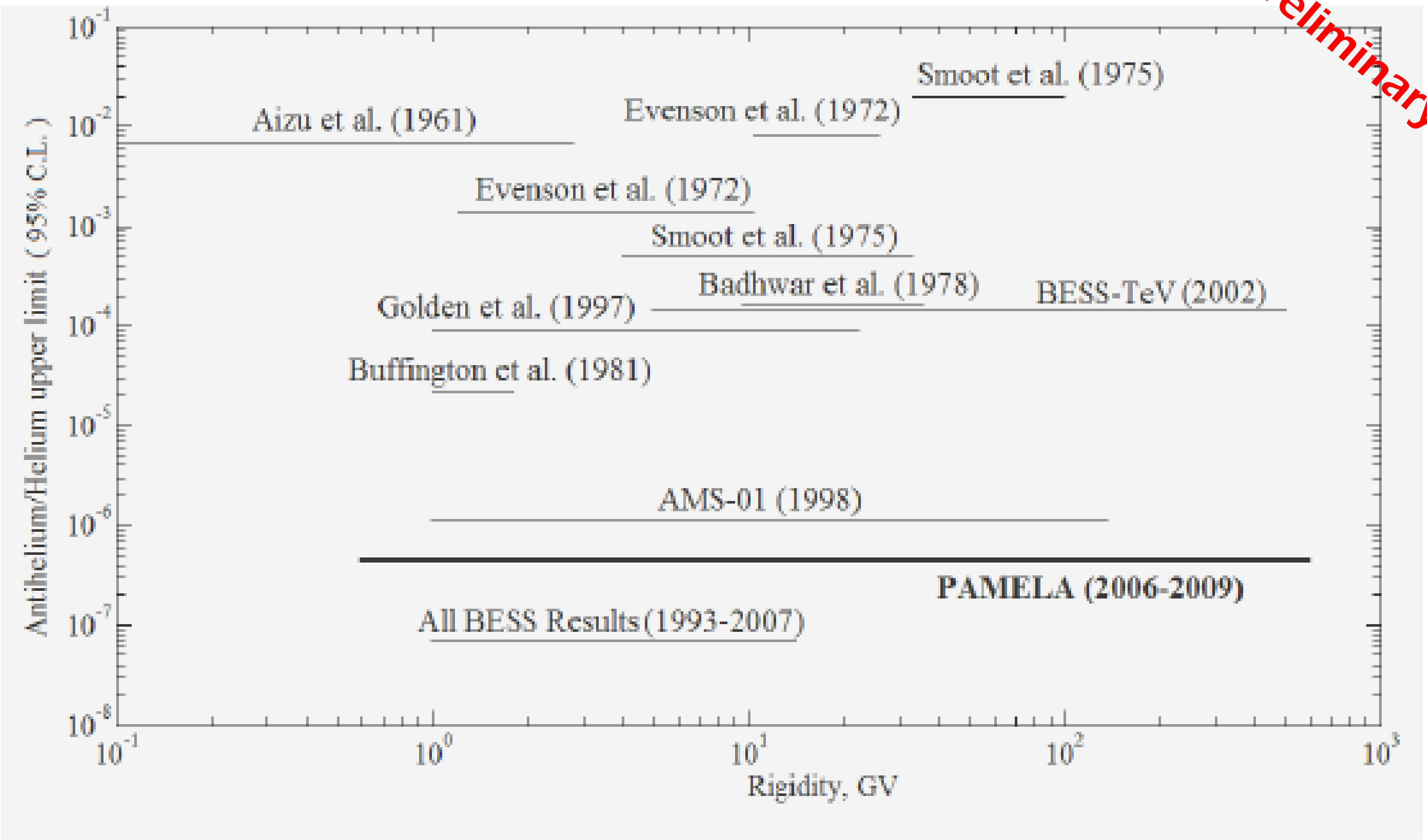


Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882

PAMELA anti-nuclei results

Anti-Helium

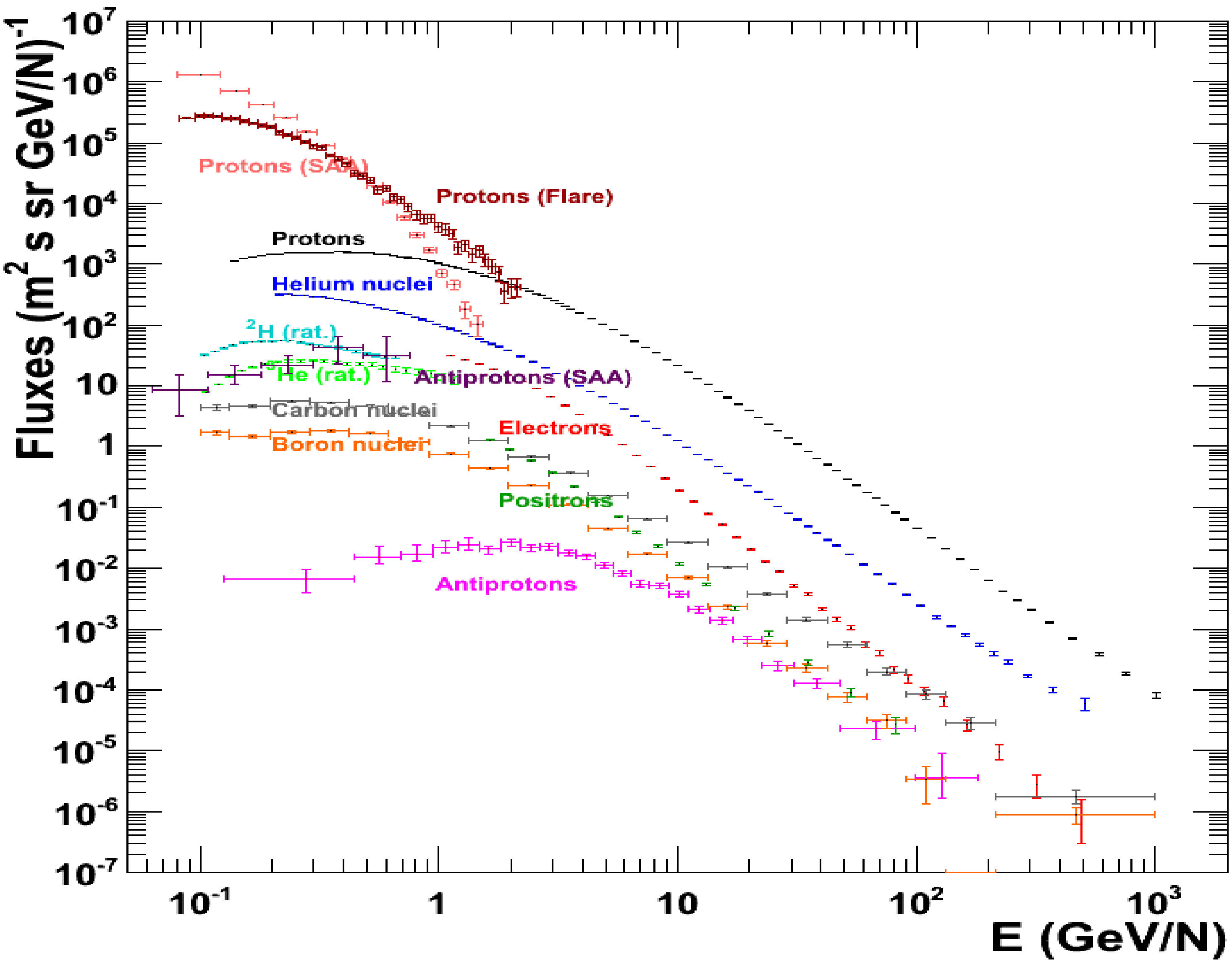
Preliminary



Conclusions

- PAMELA has been in orbit and studying cosmic rays for >2000 days. >10^9 triggers registered and >25 TB of data has been down-linked.
- Antiproton data show no significant deviations from secondary production expectations.
- High energy positron fraction (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?
- e^- and e^+ spectra show spectral features at high energies that may point to additional components.
- 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.
- Furthemore:
  - ✓ PAMELA is going to provide measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium;
  - ✓ PAMELA is able to measure the high energy tail of solar particles, and to measure magnetospheric CR populations;
  - ✓ PAMELA is going to set a new lower limit for finding Antihelium.

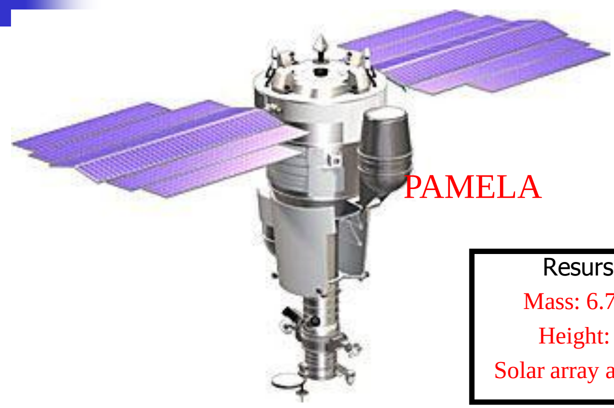
Summary: PAMELA results



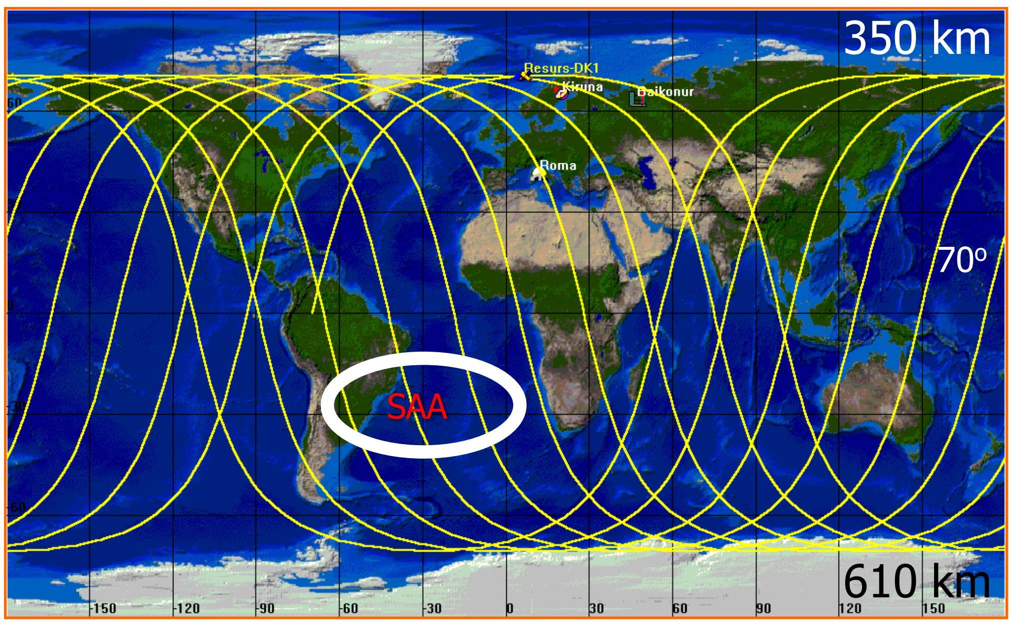
Thanks for your attention!

Spare slides

Resurs-DK1 satellite



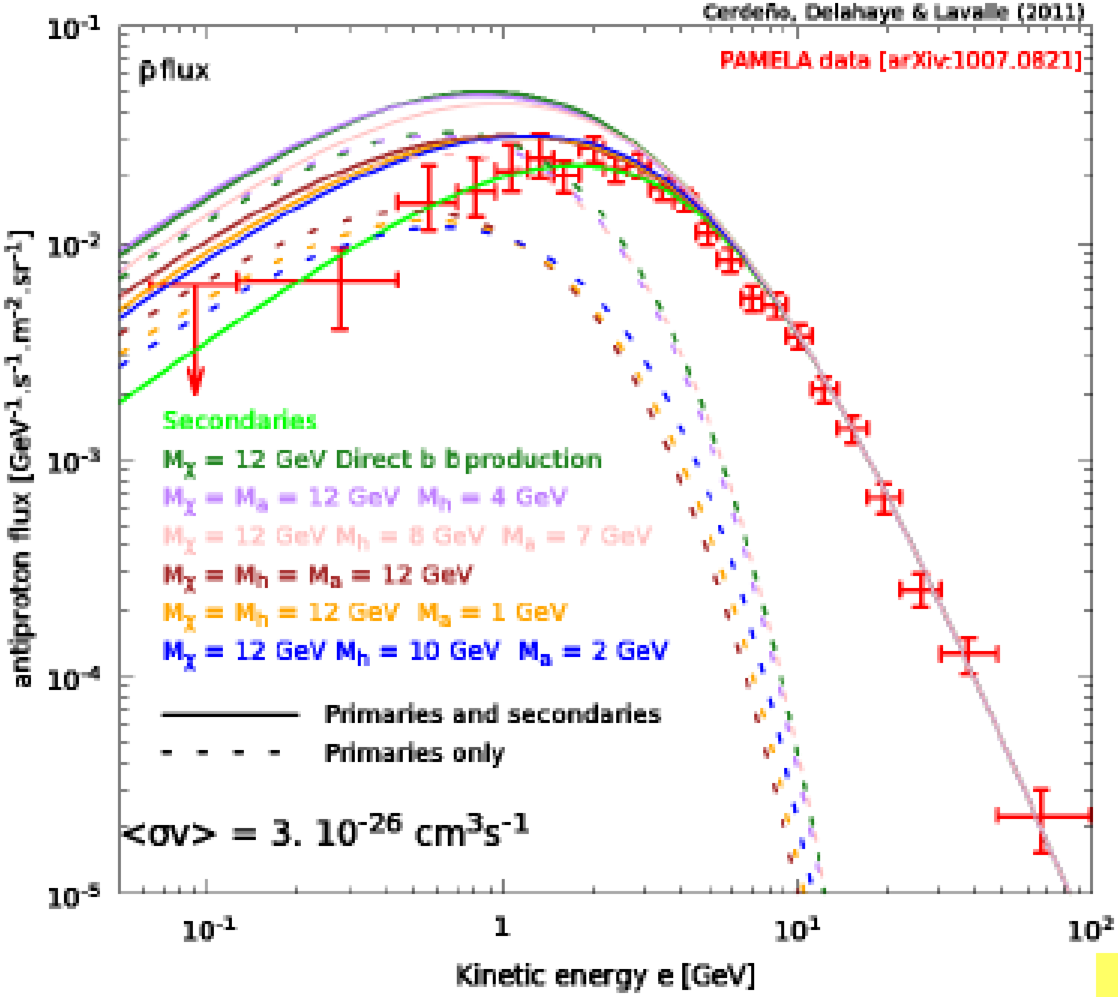
Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



~90 mins

- Resurs-DK1: multi-spectral imaging of Earth's surface
- PAMELA mounted inside a pressurized container
- Lifetime >3 years (assisted, first time February 2009), extended till end 2012
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day
- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km) – from 2010 circular orbit (70.0°, 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

Antiprotons & Dark Matter limits



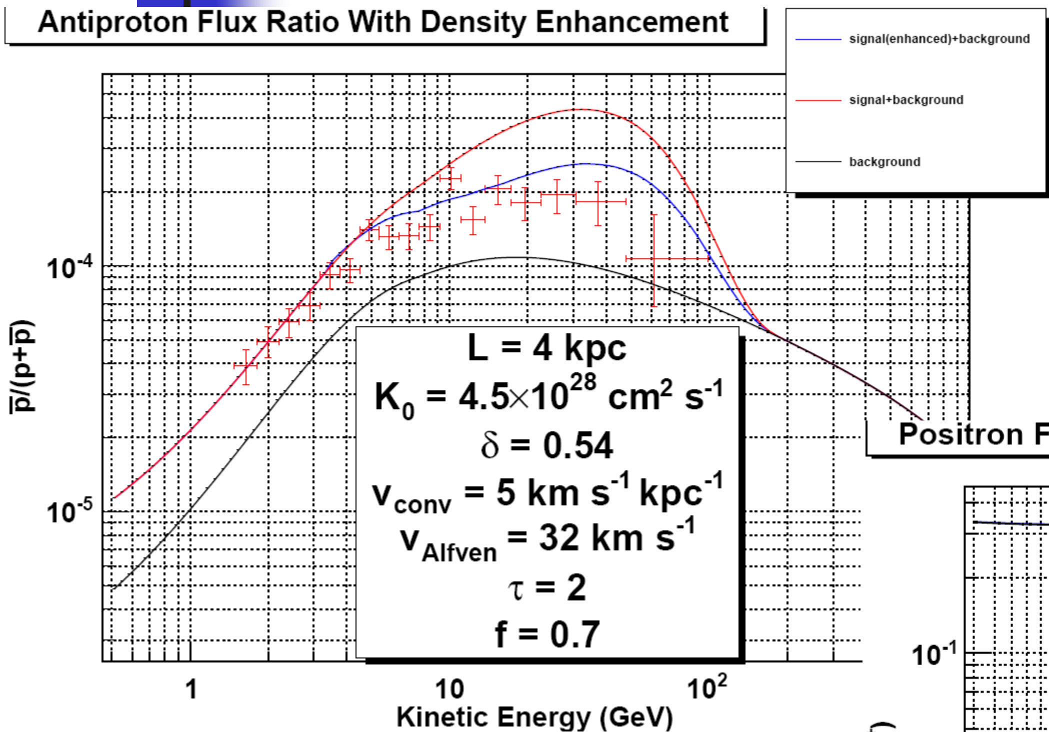
D. G. Cerdeno, T. Delahaye & J. Lavalle, arXiv: 1108:1128

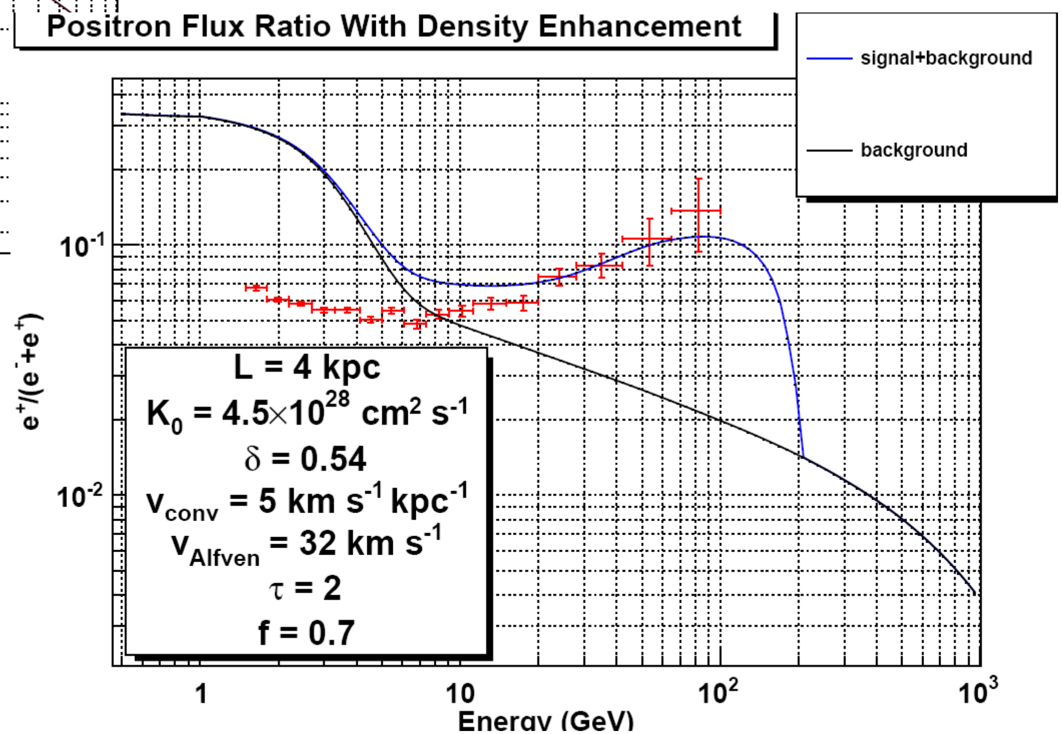
Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

See also:

- M. Asano, T. Bringmann & C. Weniger, arXiv:1112.5158.
- M. Garny, A. Ibarra & S. Vogl, arXiv:1112.5155
- R. Kappl & M. W. Winkler, arXiv:1140.4376

Interpretations: DM



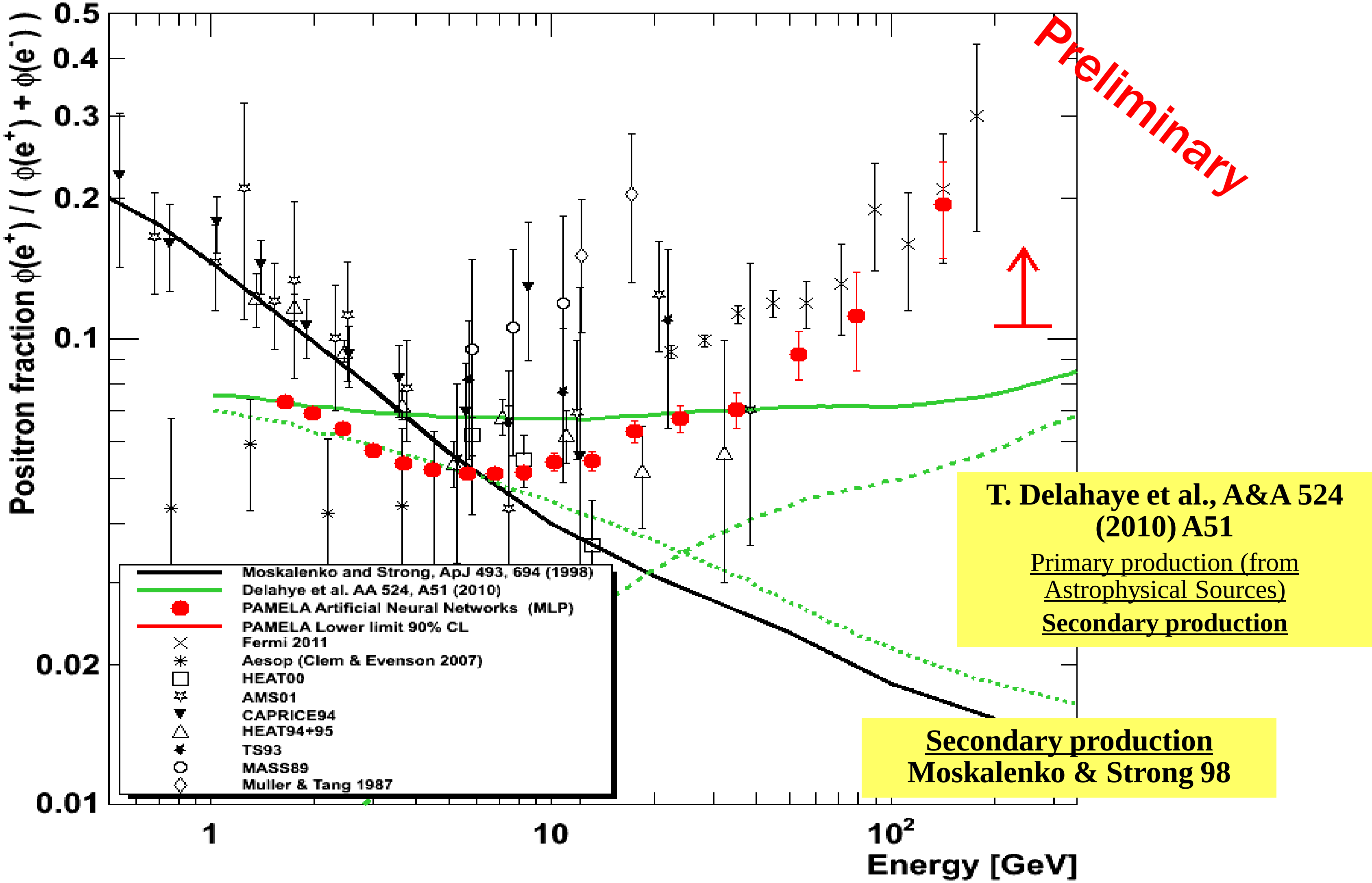


P. Grajek et al., Phys. Rev. D 79 (2009) 043506; arXiv: 0812.4555v1

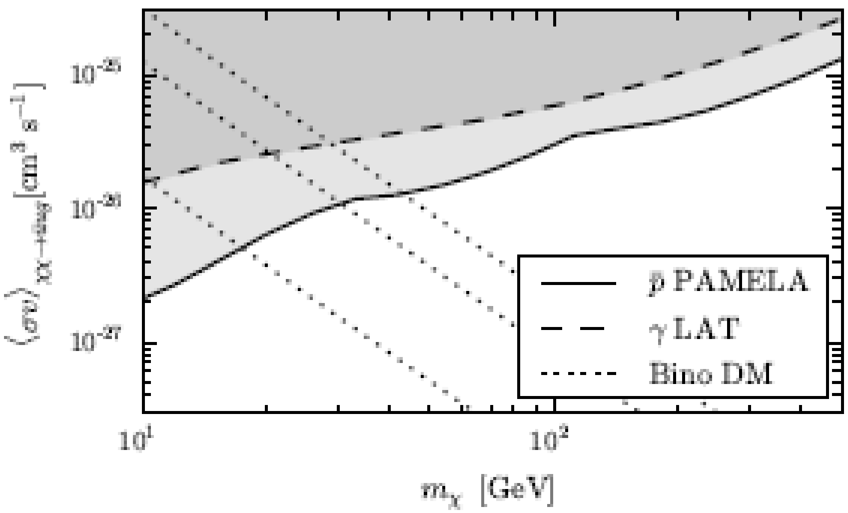
Non-thermal wino-like neutralino

Varying propagation model, no boost factor

Positron fraction

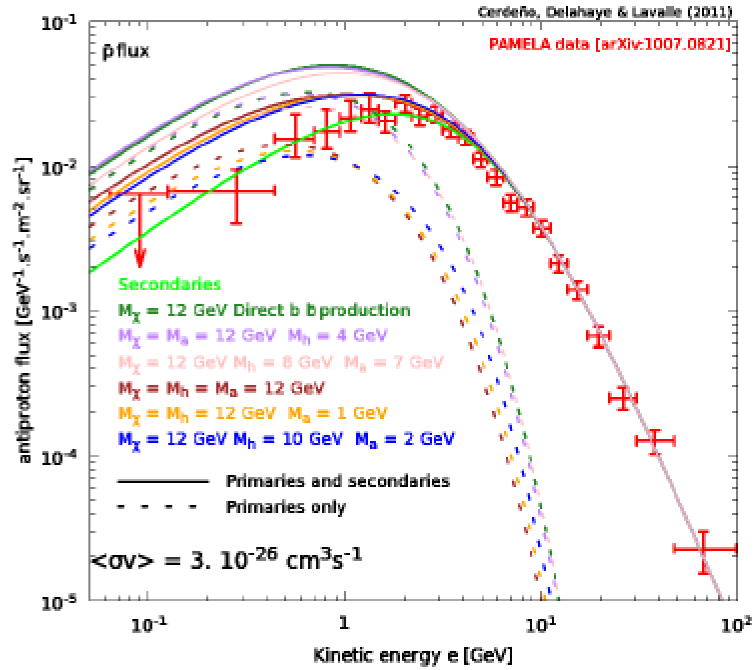


Antiprotons & Dark Matter limits



Limits on the DM annihilation cross-section assuming a 100% branching ratio into uug final states. Dotted lines show the theoretically expected values for Bino DM and mass splittings of $\mu \equiv m^2_{\mu}/m^2_{B}$=1.01; 1.2; 2.0 (from top to bottom).

[*M. Asano , T. Bringmann & C. Weniger, arXiv:1112.5158*]



Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

[*D. G. Cerdeno, T. Delahayea & J. Lavalle, arXiv: 1108:1128*]

See also:

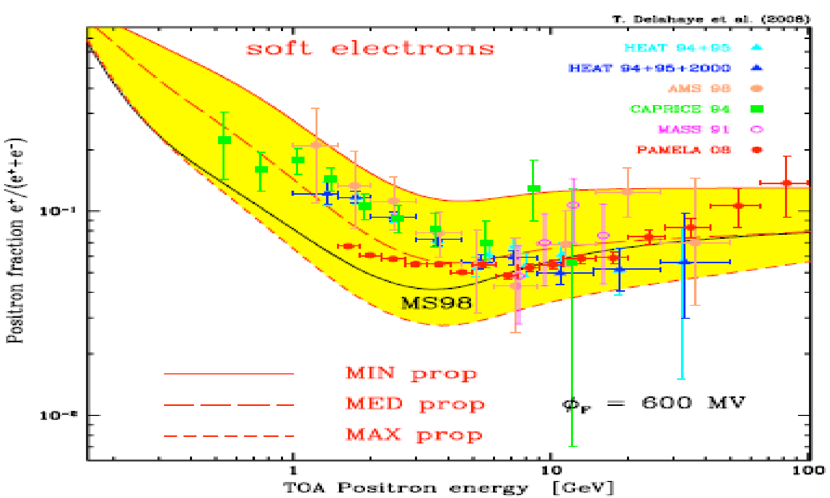
- *M. Garny, A. Ibarra & S. Vogl, arXiv:1112.5155*
- *R. Kappl & M. W. Winkler, arXiv:1140.4376*

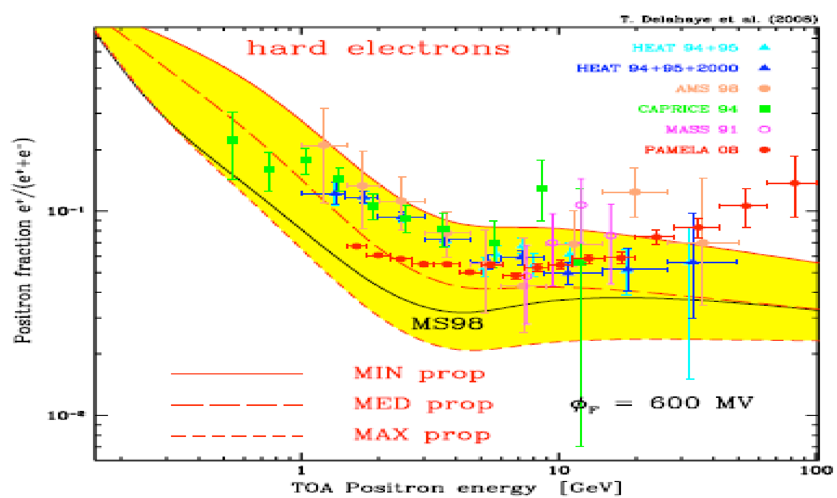
Theoretical interpretation of PAMELA antiparticle data

Theoretical uncertainties on standard positron fraction:

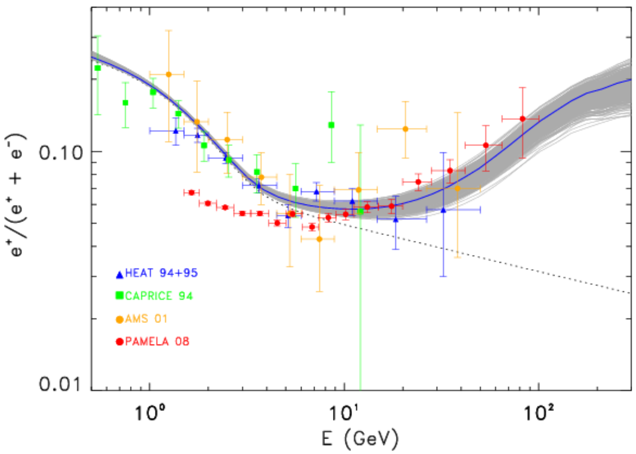
Secondary positrons are created by spallation reactions of CR nuclei on interstellar gas and propagate in a diffusive mode under the influence of the turbulent component of the galactic magnetic field.

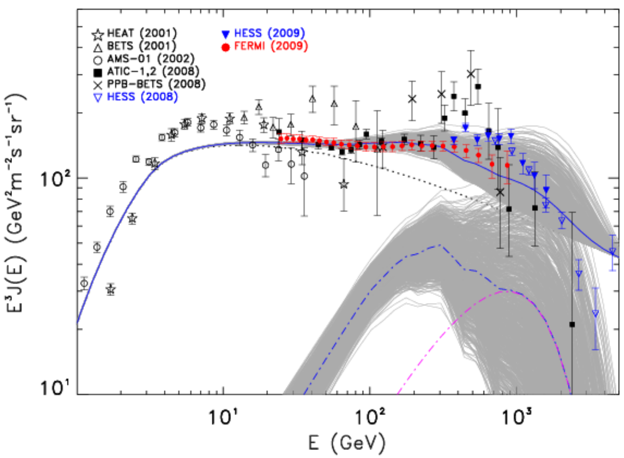
- Estimates of positron fraction suffer uncertainties about <u>cosmic nuclei spectra, nuclear cross sections</u> involved in the positron production mechanism and propagation parameters involved in the diffusion equation.
- Indeed, the secondary positron production depends on the <u>spatial distribution of CR nuclei and of the ISM</u>, and fluctuations of the local injection rate can influence some features in the measured spectrum.
- Moreover, a crucial ingredient for the calculation is given by the <u>electron flux</u> [*Delahaye et al. 2009*], with further complications arising from the lack of knowledge about different spectral contributions, including primary electrons from astrophysical sources, and about solar modulation effects.





Theoretical interpretation of PAMELA antiparticle data





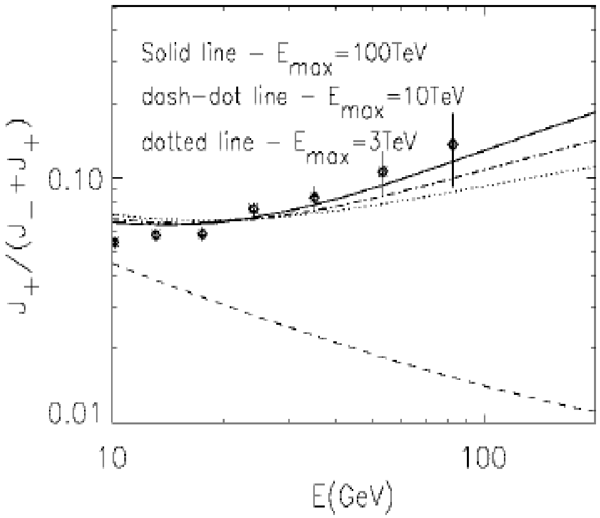
contribution of all nearby pulsars in the ATNF catalogue (~150 pulsars) with $d < 3$ kpc with age $5 \times 10^4 < T < 10^7$ yr

D. Grasso et al., Astrop. Phys. 32 (2009)

Astrophysical sources:

- As already proposed several years ago [*Boulares et al. 1989, Atoyan et al. 1995*], a possible enhancement of the $e^{\pm}$ flux could be explained by astrophysical sources like **nearby pulsars** [*Grasso et al. 2009, Blasi et al. 2009*].
- In this scenario, electrons are believed to be initially extracted from the surface of the star by the intense rotation induced electric fields and later to produce $e^{\pm}$ pairs via electromagnetic showers inside the magnetosphere;
- in addition, $e^{\pm}$ are possibly re-accelerated by the pulsar winds or in the supernova remnant shocks and released in the ISM [*Profumo 2008, Malyshev et al. 2009*]. Hence, no sizeable contribution from antiprotons is predicted, while counterparts in γ-rays are expected.
- In particular, magnetars are thought to generate a large amount of $e^{\pm}$ pairs, giving an important contribution despite their relatively low abundance [*Heyl et al. 2010*].
- Other possible sources are given by nearby γ-ray burst (GRB), GRB-like pulsars and microquasar [*Ioka 2010*].

Astrophysical sources:



Blasi, P., Phys. Rev. Lett. 103 (2009) 051104 [arXiv:0903.2794].

- Alternatively, positrons can be created as **secondary products of hadronic interactions inside supernova remnants** (SNRs). The secondary production takes place in the same region where CR are being accelerated: secondary $e^{\pm}$ participate in the acceleration process and result in a very flat spectrum at high energy, thus providing a natural explanation for the observed positron excess, after propagation in the Galaxy has been taken into account. In particular, old SNRs appear the best candidates [*Blasi 2009*].
- On the other hand, counterparts in γ-rays and possibly in the antiproton channel as well are expected [*Blasi et al. 2009*]. The predicted antiproton flux, compatible with present data, should result in a harder component emerging at high energies (>100 GeV). Moreover, according to this scenario, an increase with energy of the Boron/Carbon ratio is also expected [*Mertsch et al. 2009*].

Theoretical interpretation of PAMELA antiparticle data

Dark matter annihilation or decay:

- The DM possibility, with annihilations in the halo of the Milky Way providing the anomalous antiparticle flux, is of great interest from the particle physics viewpoint. Minimal DM models can give a reasonably good fit to the PAMELA positron data, while antiprotons data put strong constraints on DM annihilations, disfavoring channels with gauge bosons, Higgs bosons or quarks.
- Nevertheless, the required hard spectrum would result by combining a very high DM particle mass (~ 10 TeV) and a very efficient enhancement mechanism for the annihilation into charged gauge bosons [*Cirelli et al. 2008, 2009*].
- In particular, annihilating DM particles with ~1 TeV mass or heavier have been proposed in order to accommodate the observations of Fermi and provide the PAMELA positron excess. Super-heavy DM candidates would also result in correct thermal relic abundance [*Profumo 2005*].

Theoretical interpretation of PAMELA antiparticle data

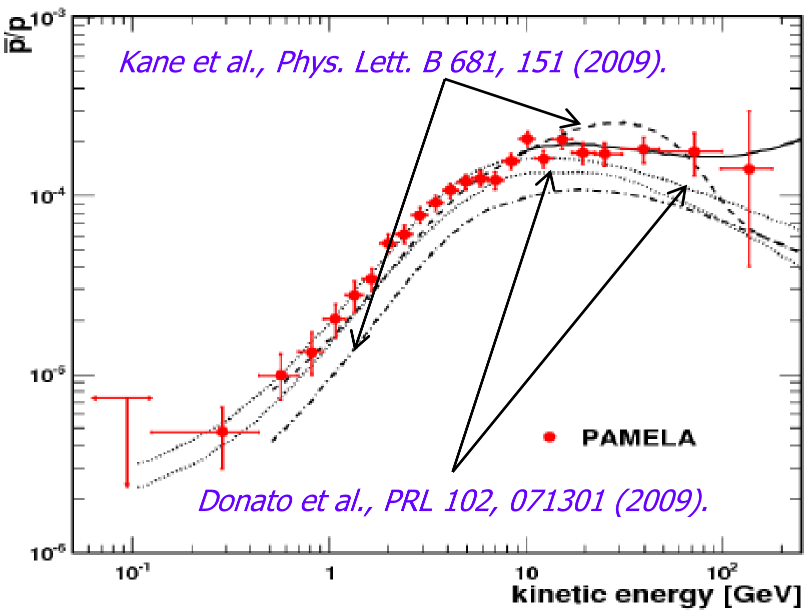
Dark matter annihilation or decay:

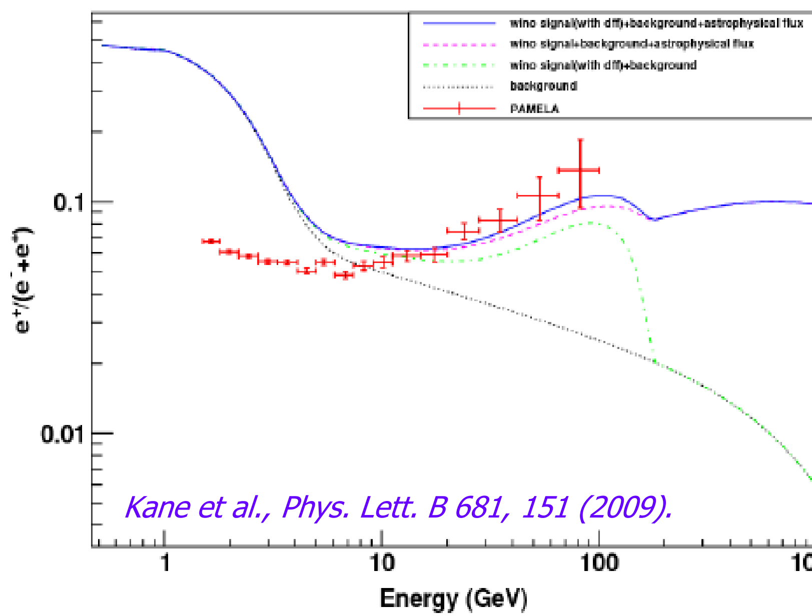
- Alternatively, DM models assuming a **dominant leptonic channel** can fit PAMELA positron and antiproton measurements as well [*Cirelli et al. 2008, 2009, Grasso et al. 2009*].
    - In pure $e^{\pm}$ models the DM annihilation yields a pair of monochromatic $e^{\pm}$, with injection energies equal to the mass of the annihilating DM particle. ``Lepto-philic'' models assume an equal pair-annihilation branching ratio into each charged lepton species.
- Indeed, **multistate DM models** with small mass splittings and couplings to light hidden sector bosons have been proposed as an explanation for the high energy lepton excesses [*Cholis et al. 2009, Cirelli et al. 2010*].

Theoretical interpretation of PAMELA antiparticle data

Dark matter annihilation or decay:

- Provided some modifications concerning underlying distribution of the DM or the propagation of its annihilation products, and given the inherent astrophysical uncertainties, a **wino-like neutralino** of mass about 200 GeV, non-thermally produced, normalized to the local relic density, and annihilating mainly into W-bosons, appears to be a plausible candidate [*Kane et al. 2009*], consistent with existing positron, antiproton and γ-ray data. Neutralinos with much larger mass do not fit to the PAMELA results unless very large astrophysical boost factors are employed [*Hooper et al. 2008*].





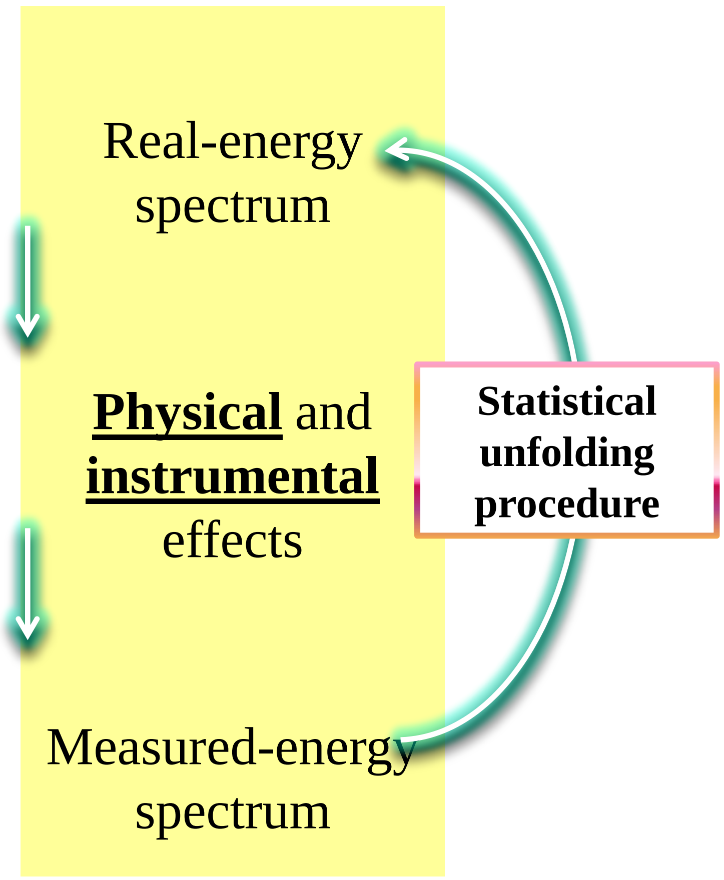
Theoretical interpretation of PAMELA antiparticle data

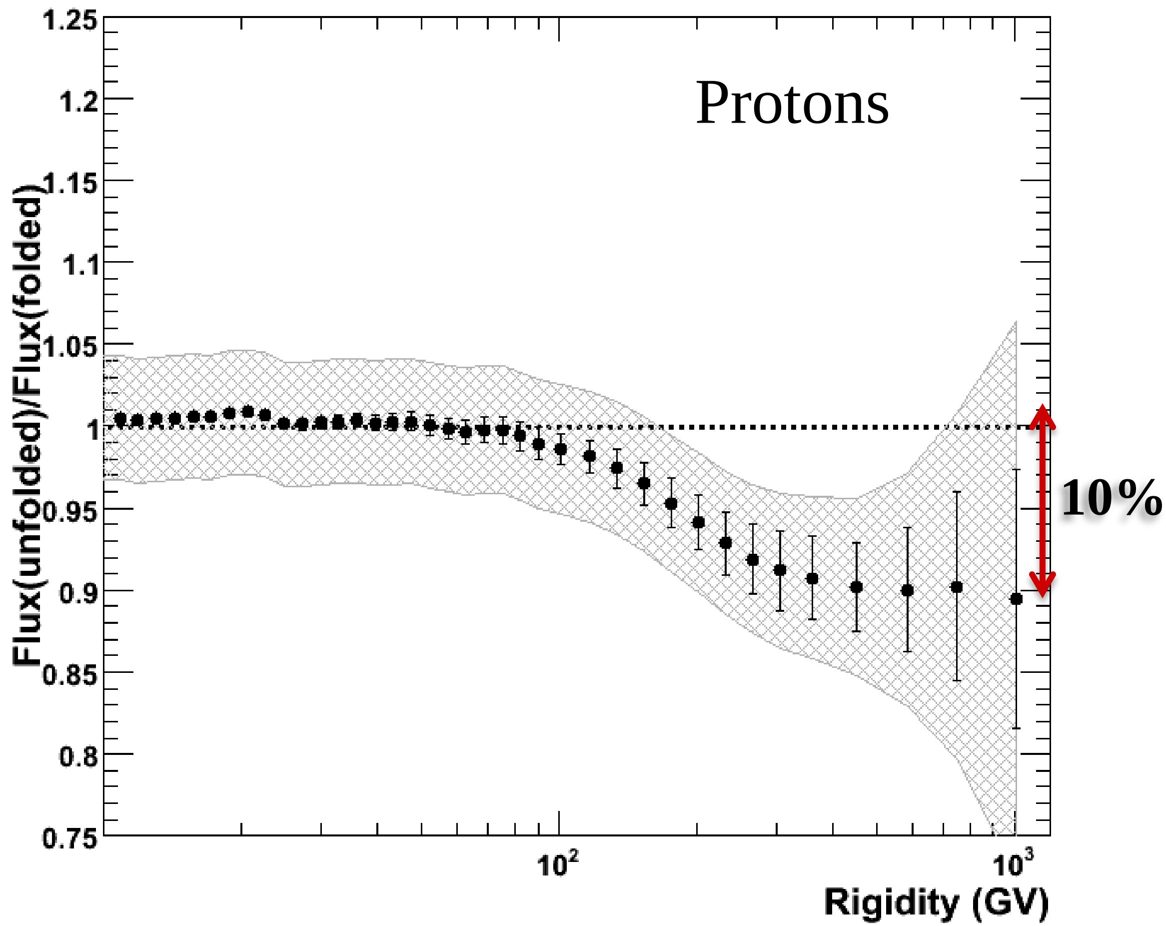
Dark matter annihilation or decay:

- Another possibility is offered by **Kaluza-Klein models** with one universal extra dimension [*Hooper et al. 2009*]. The DM particles annihilate largely to charged leptons, which enables them to produce a spectrum of CR electrons and positrons consistent with the PAMELA and ATIC [*Chang et al. 2008*] measurements, regardless of large boost factors and significant annihilation to hadronic modes. Corresponding masses are limited to approximately 600-900 GeV by relic abundance arguments.

- **Radiative corrections** may considerably enhance the DM induced positron yield and result in a pronounced spectral signature, a rising positron to electron ratio and a sharp cutoff in the positron spectrum at the neutralino mass. Again, very large boost factors have to be invoked to obtain such a spectral feature [*Bergstrom et al. 2008*].

Spectrum unfolding





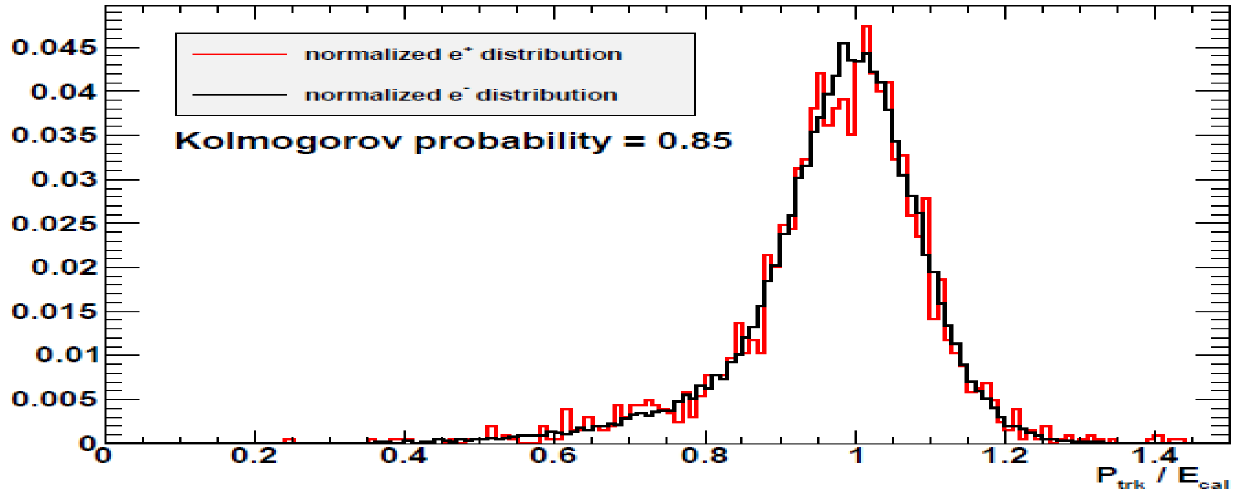
- Bayesian unfolding
- Spectrometer response matrix from MC

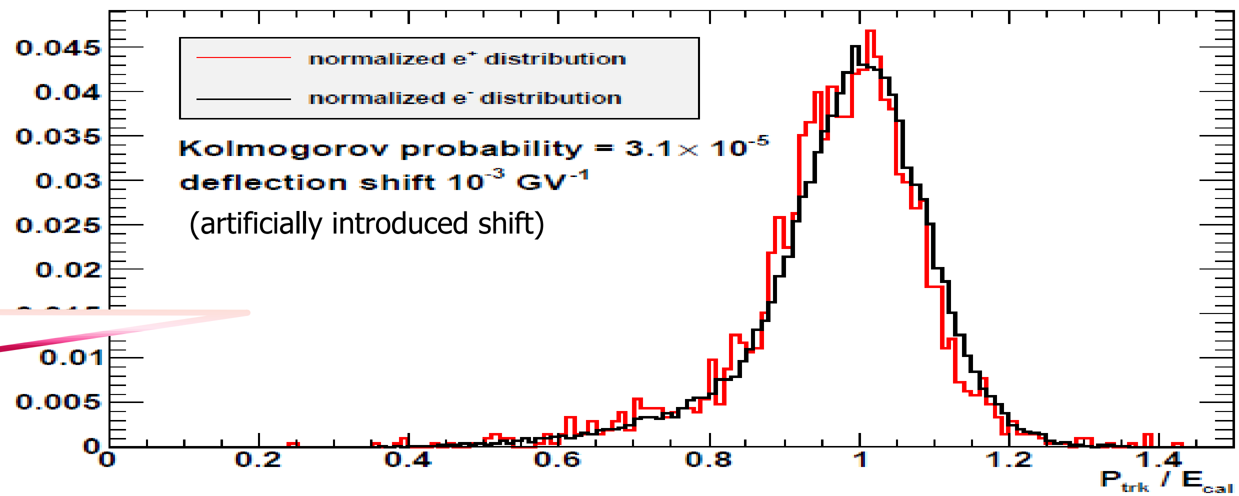
Spectrometer Systematic Uncertainties

With real data:

$$z = \frac{1}{E_C |\eta_S|} \longrightarrow \frac{1}{E_C(1+\varepsilon)\left(|\eta_S| \pm \Delta\eta\right)}$$

- The spectrometer may have a <u>charge-sign</u> dependent systematic
- A calorimeter systematic has <u>no such dependence</u>





A systematic deflection shift causes an offset between e^- and e^+ distribution

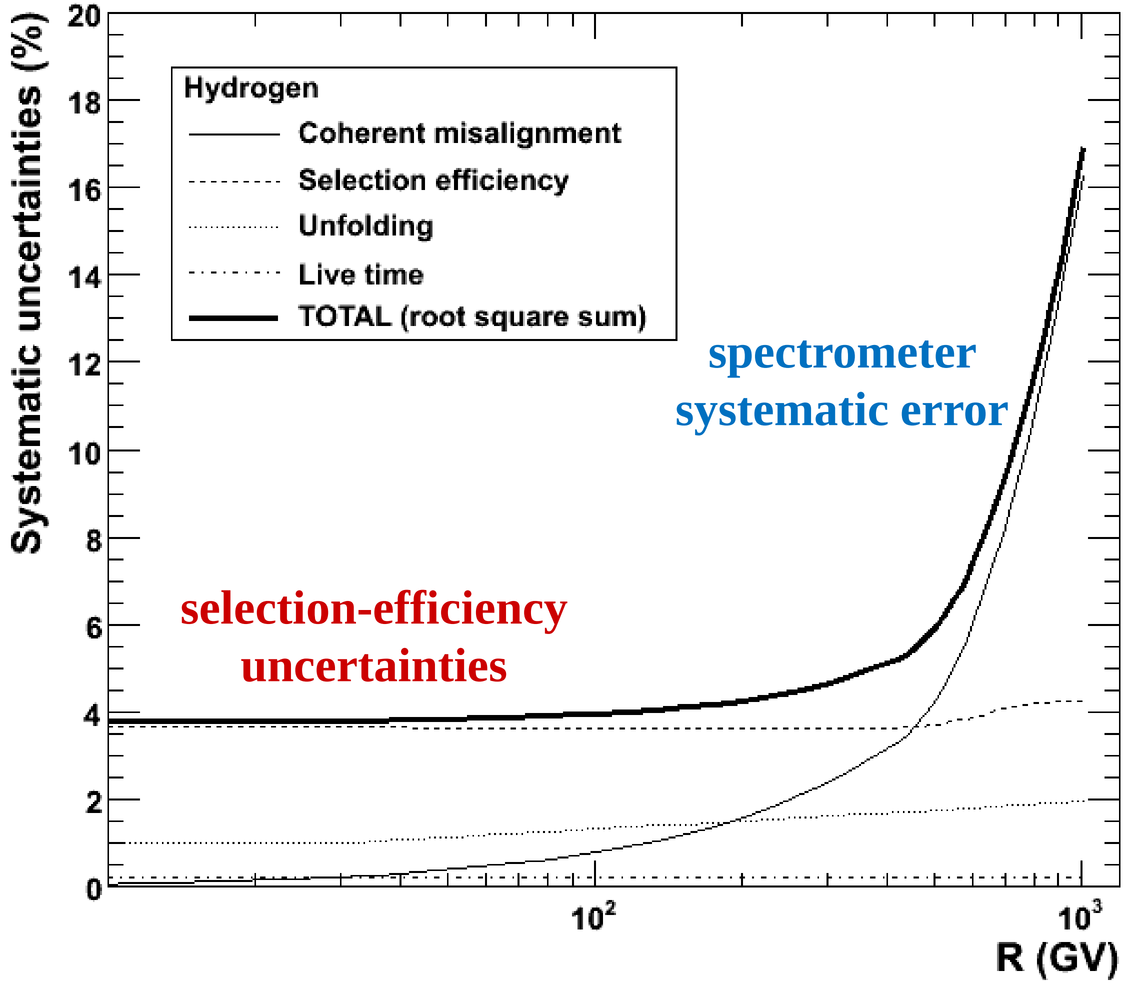
Upper limit set by positron statistics:

<u>**$\Delta\eta_{sys}$ ~$1 \cdot 10^{-4}$ GV^{-1}**</u>

Overall systematic uncertainties

- At low R selection-efficiency uncertainties dominate

- Above 500GV tracking-system (coherent) misalignment dominates



Check of systematics

Fluxes evaluated by varying the selection conditions:

- Flux vs time
- Flux vs polar/equatorial
- Flux vs reduced acceptance
- Flux vs different tracking conditions (⇒ different response matrix)

…