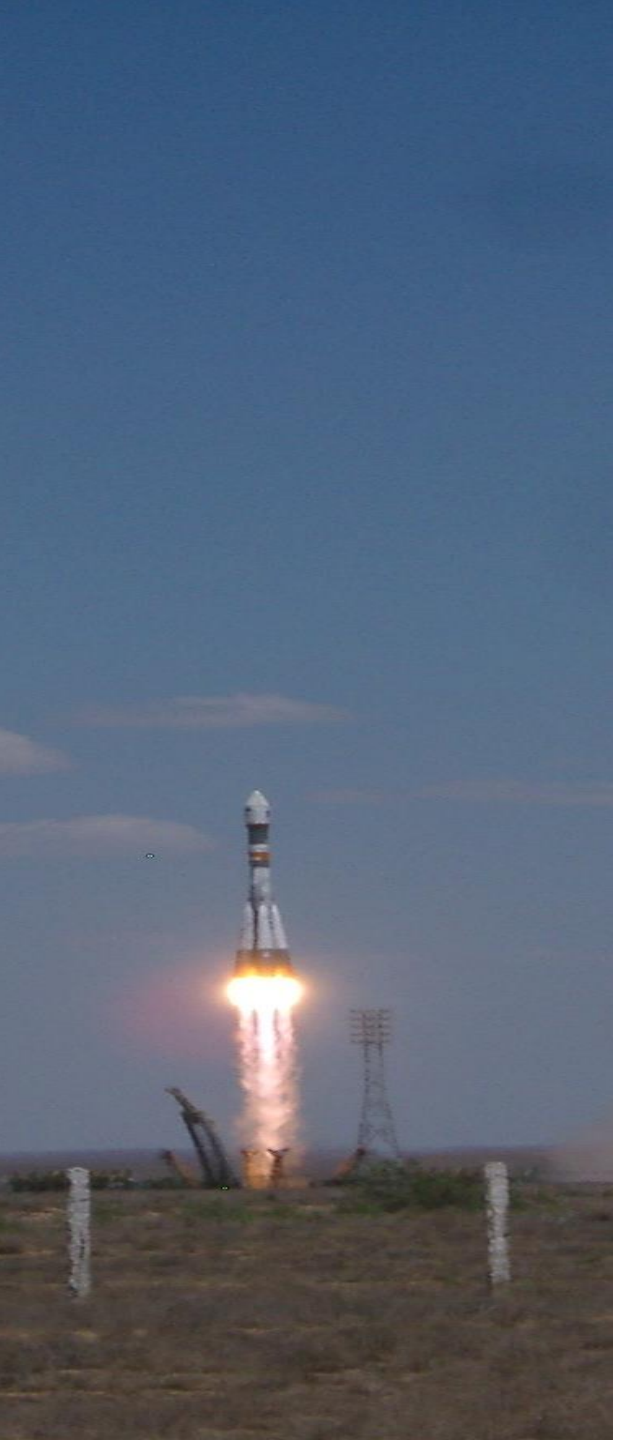


The PAMELA experiment: Seven Years of Cosmic Rays Investigation

Mirko Boezio

INFN Trieste, Italy

On behalf of the PAMELA collaboration

TeVPA 2013, Irvine

August 26th 2013

PAMELA Collaboration

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

Russia:

Moscow
St. Petersburg

Germany: Universität Gesamthochschule Siegen

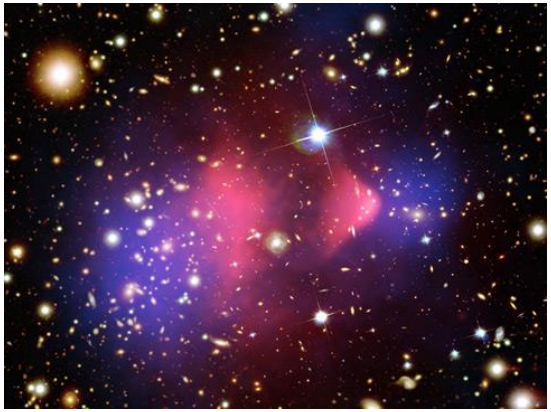
Siegen

Sweden: Kungl Tekniska Hogskolan

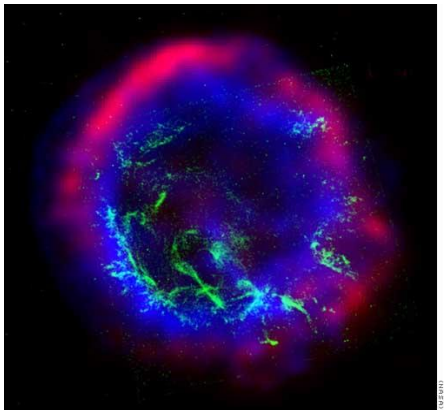
KTH, Stockholm

Scientific goals

- **Search for dark matter annihilation**

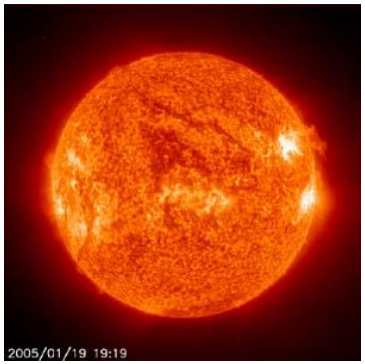


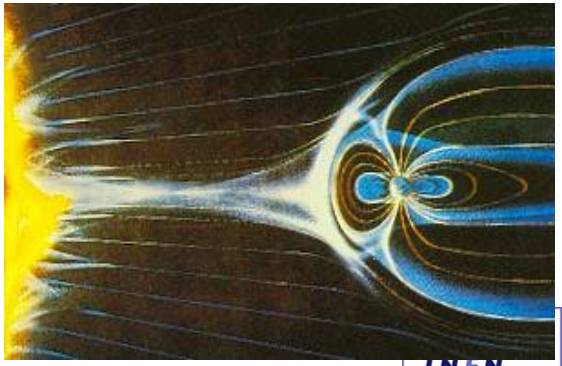
- **Search for antihelium (primordial antimatter)**
- **Search for new Matter in the Universe (Strangelets?)**



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

- **Study solar physics and solar modulation**
- **Study terrestrial magnetosphere**

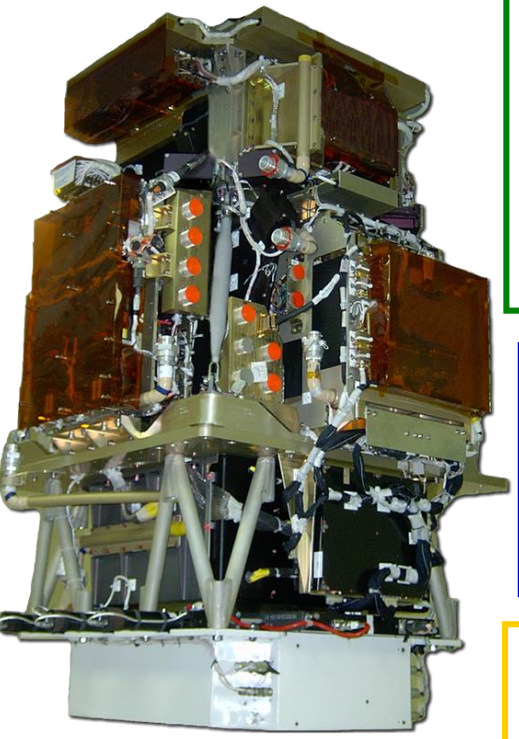




PAMELA apparatus

PAMELA detectors

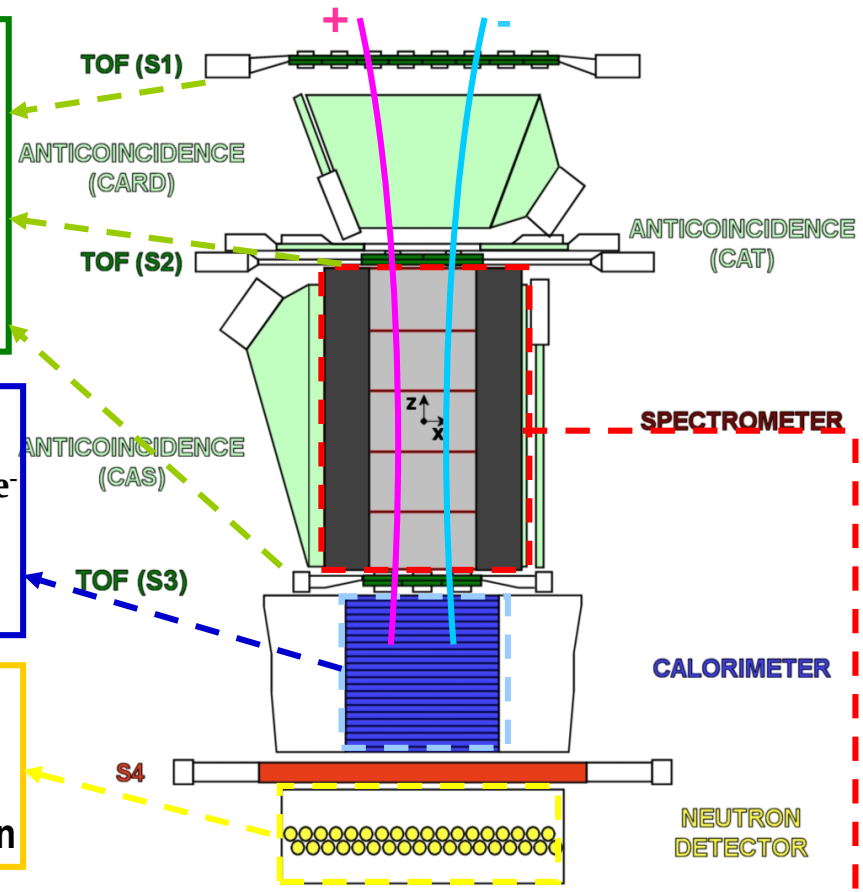
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



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

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^-

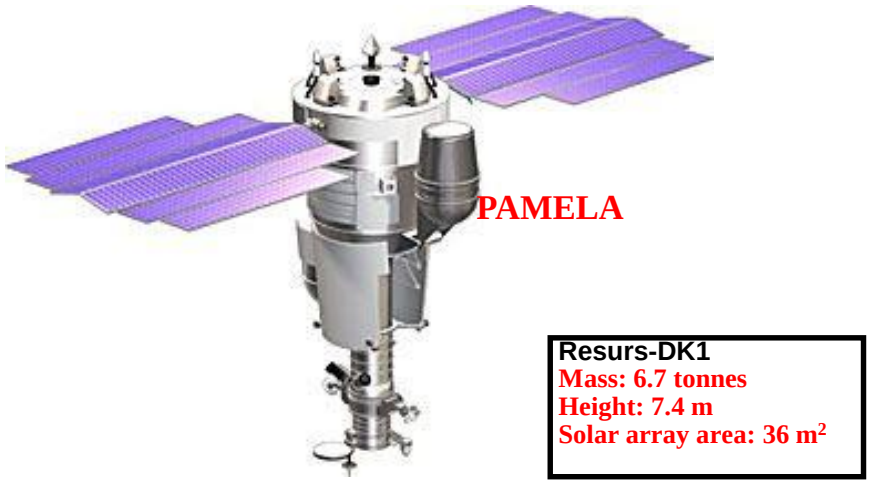
Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination

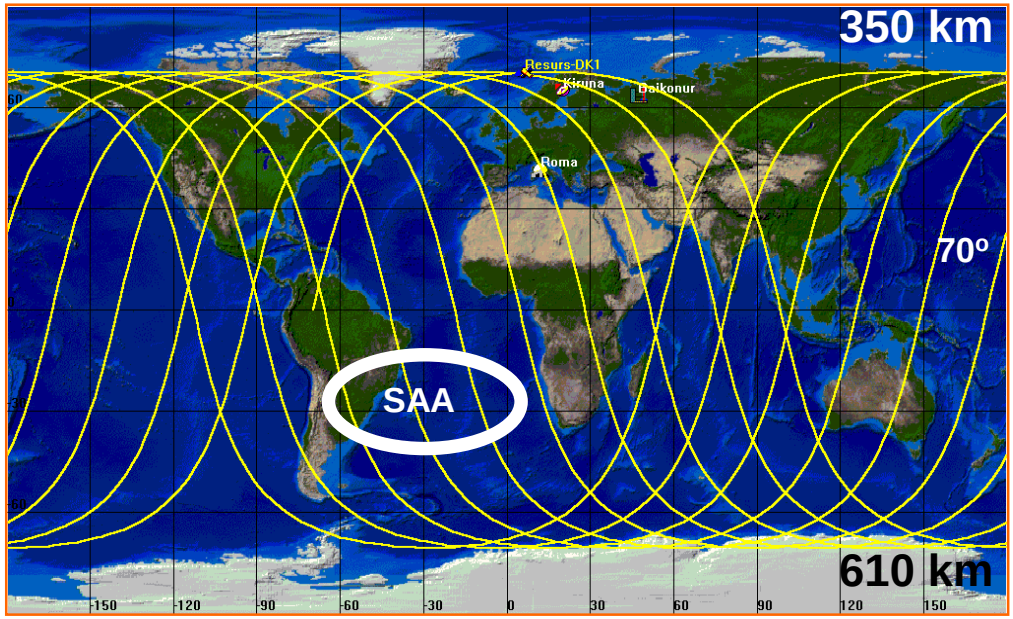


GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

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

Resurs-DK1 satellite + orbit





~90 mins

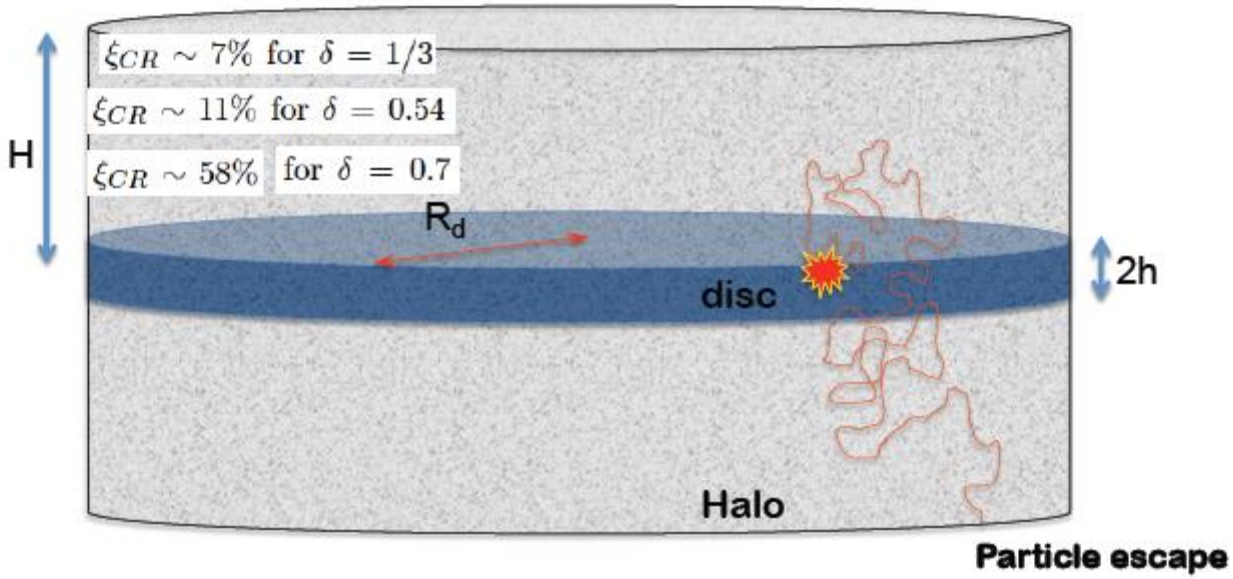
- Resurs-DK1: multi-spectral imaging of earth's surface
- PAMELA mounted inside a pressurized container
- Lifetime >3 years (assisted, first time February 2009), extended till end of satellite operations
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day
- Quasi-polar 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

Cosmic Ray Spectra

Cosmic-Ray Acceleration and Propagation in the Galaxy

Mirko Boezio, TeVPA2013, Irvine, 2013/08/26

Pillars of the SNR paradigm

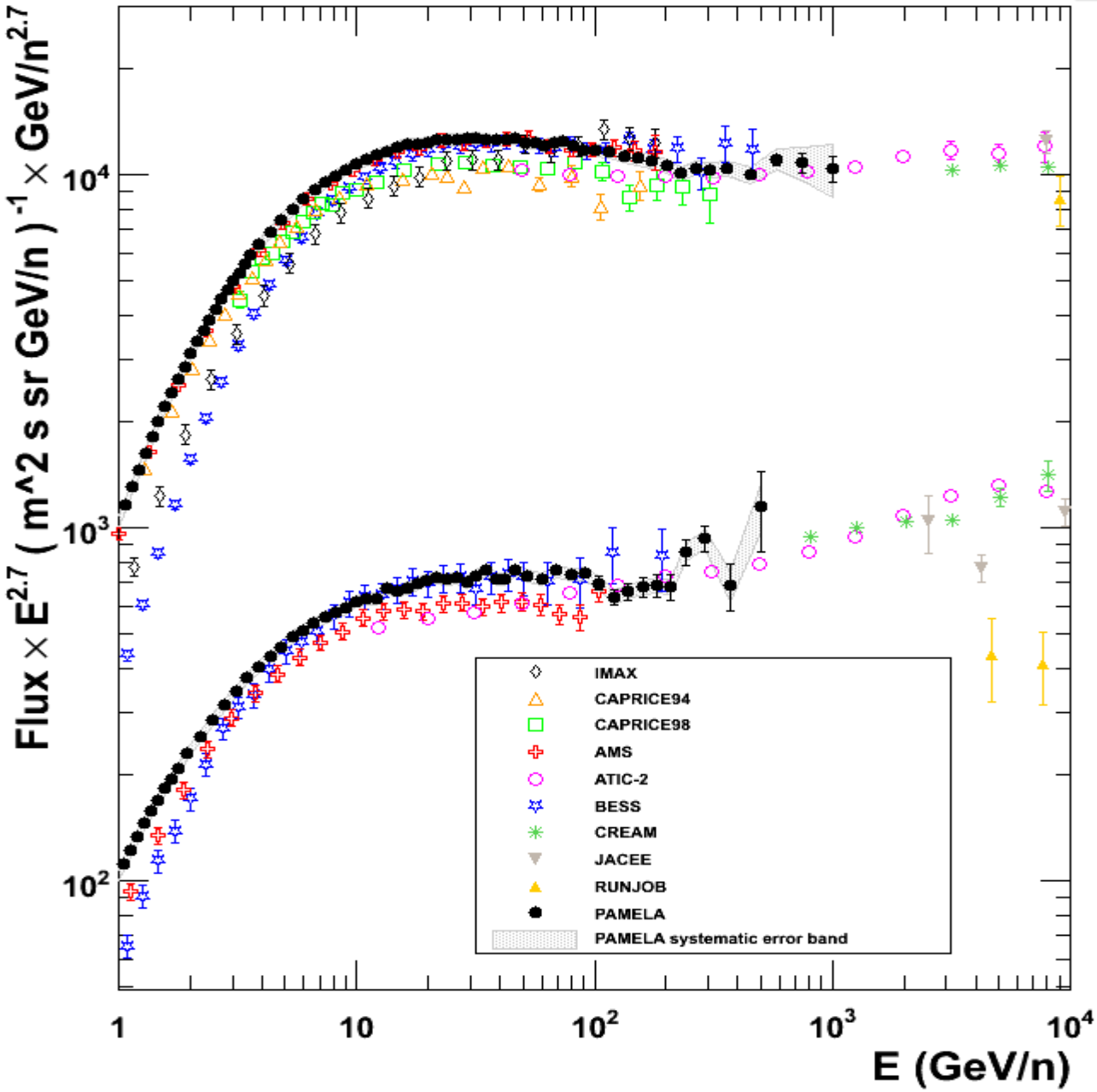


CRs IN SNR → DIFFUSIVE SHOCK ACCELERATION, $Q(E) \sim E^{-\gamma}$

PROPAGATION OF CRs IN THE GALAXY with $D(E) \sim E^{\delta}$ → $n(E) \sim E^{-\gamma-\delta}$

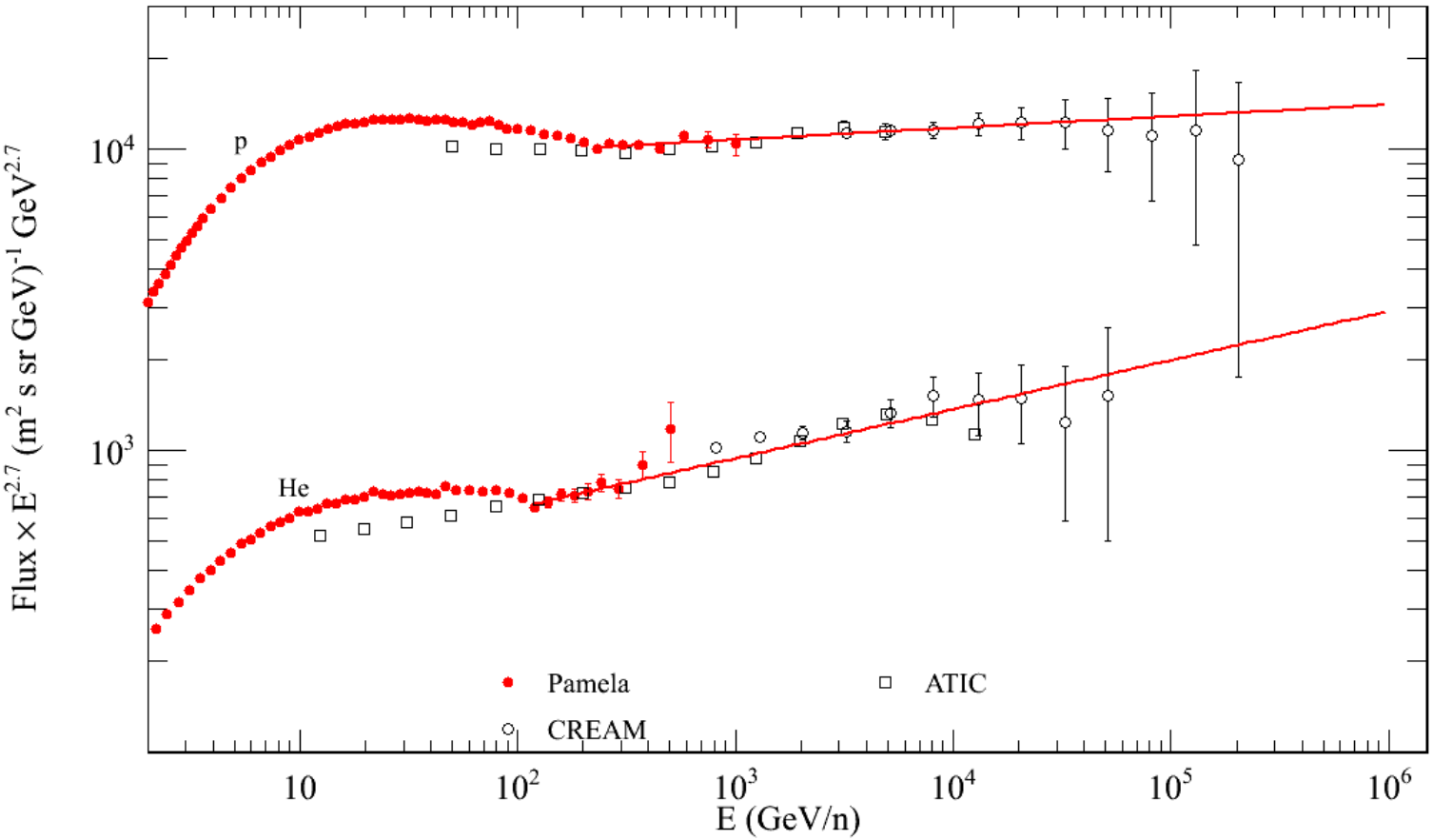
P. Blasi, TeVPA 2011, Stockholm 2011

Proton and Helium Nuclei Spectra



O. Adriani et al., Science 332 (2011) 69

Proton and Helium Nuclei Spectra



H & He absolute fluxes @ high energy

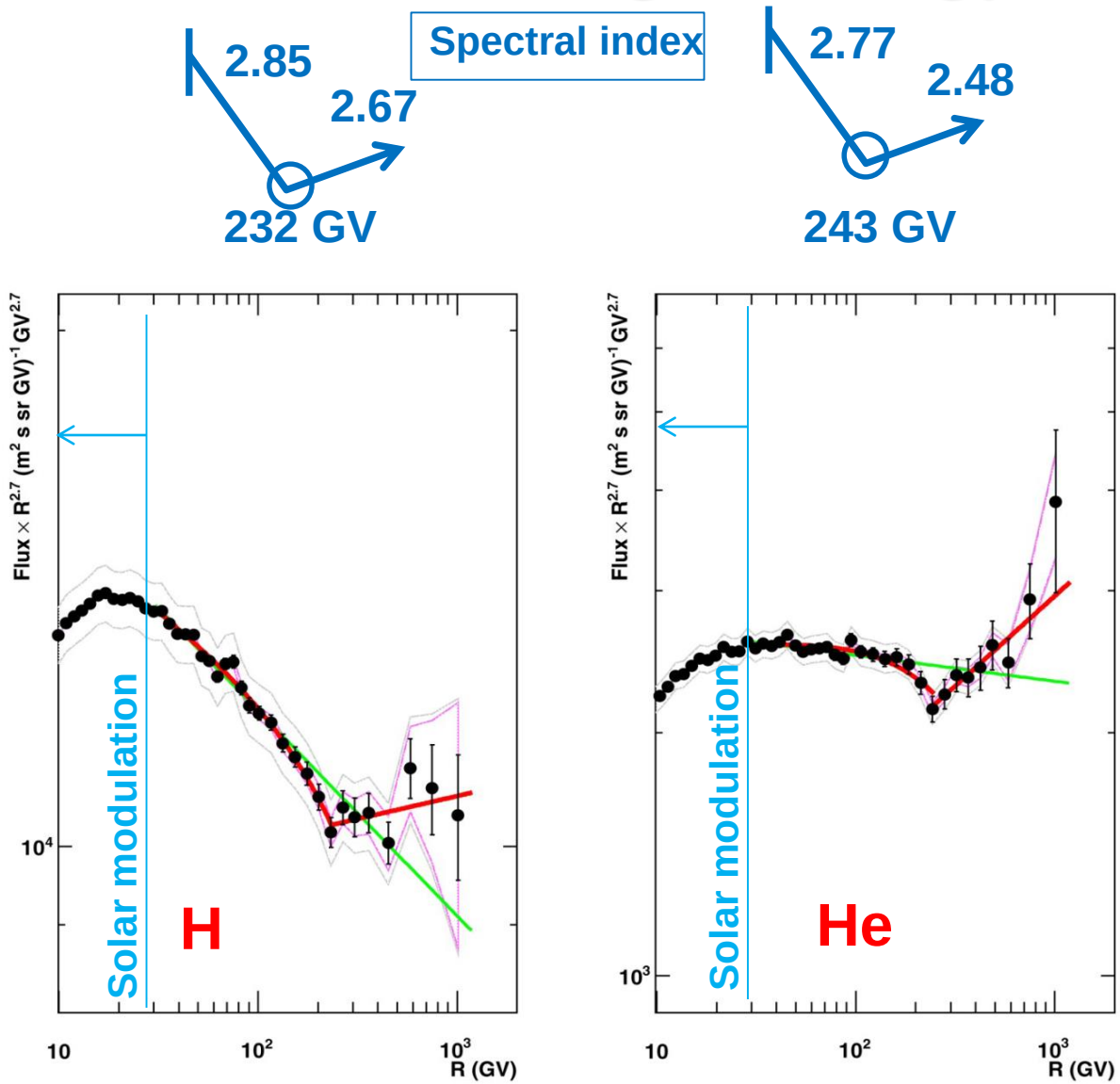
Deviations from single power law (SPL):

- 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

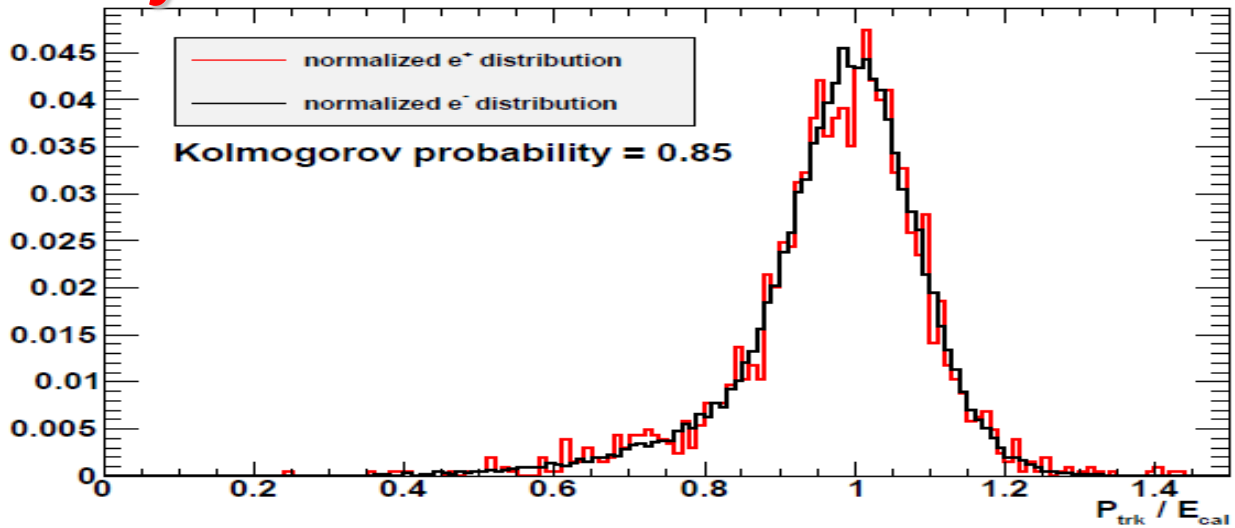


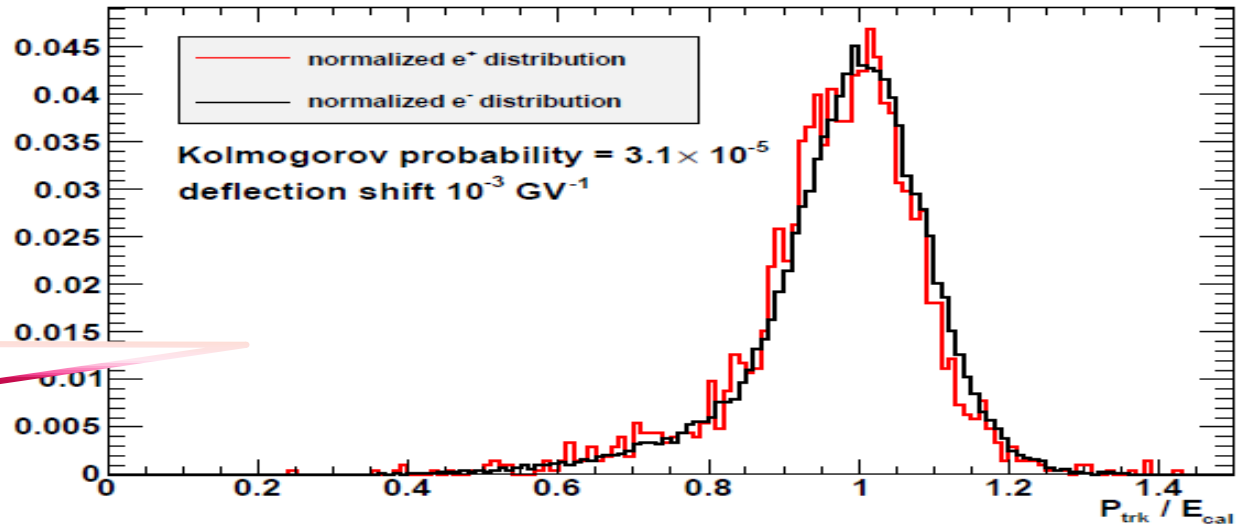
Spectrometer Systematic Uncertainties

With real data:

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

- **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:

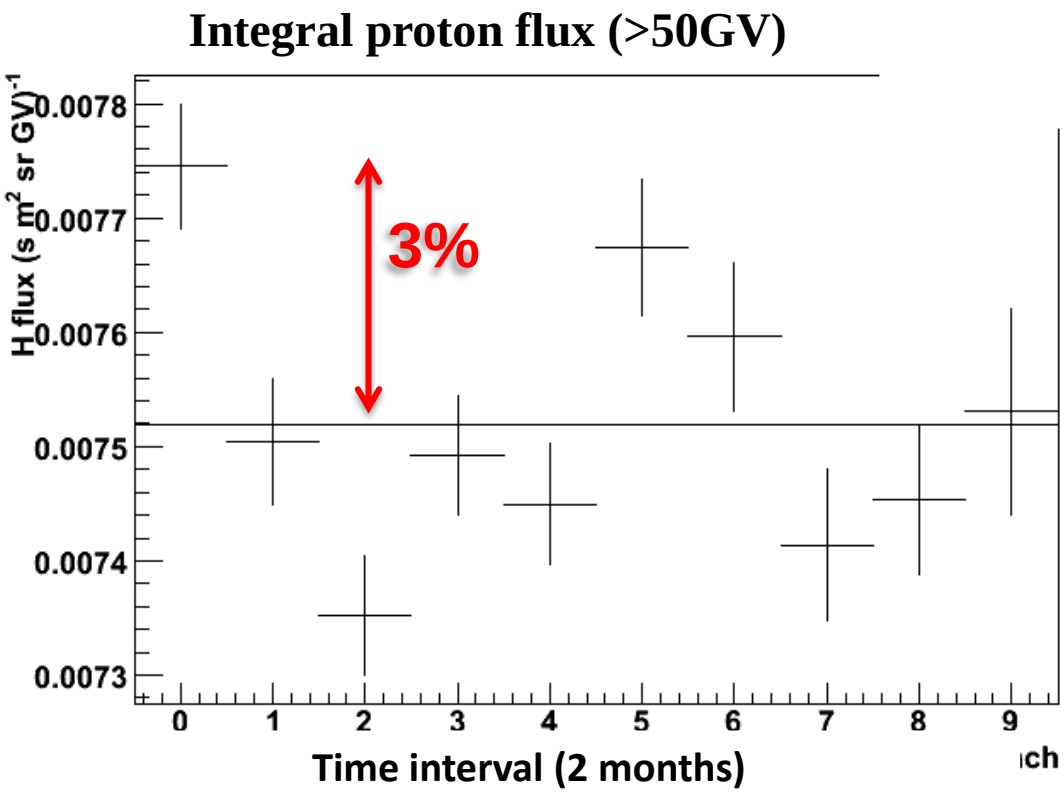
- **$\Delta\eta_{sys} \sim 1 \cdot 10^{-4}\ GV^{-1}$**

Check of systematics

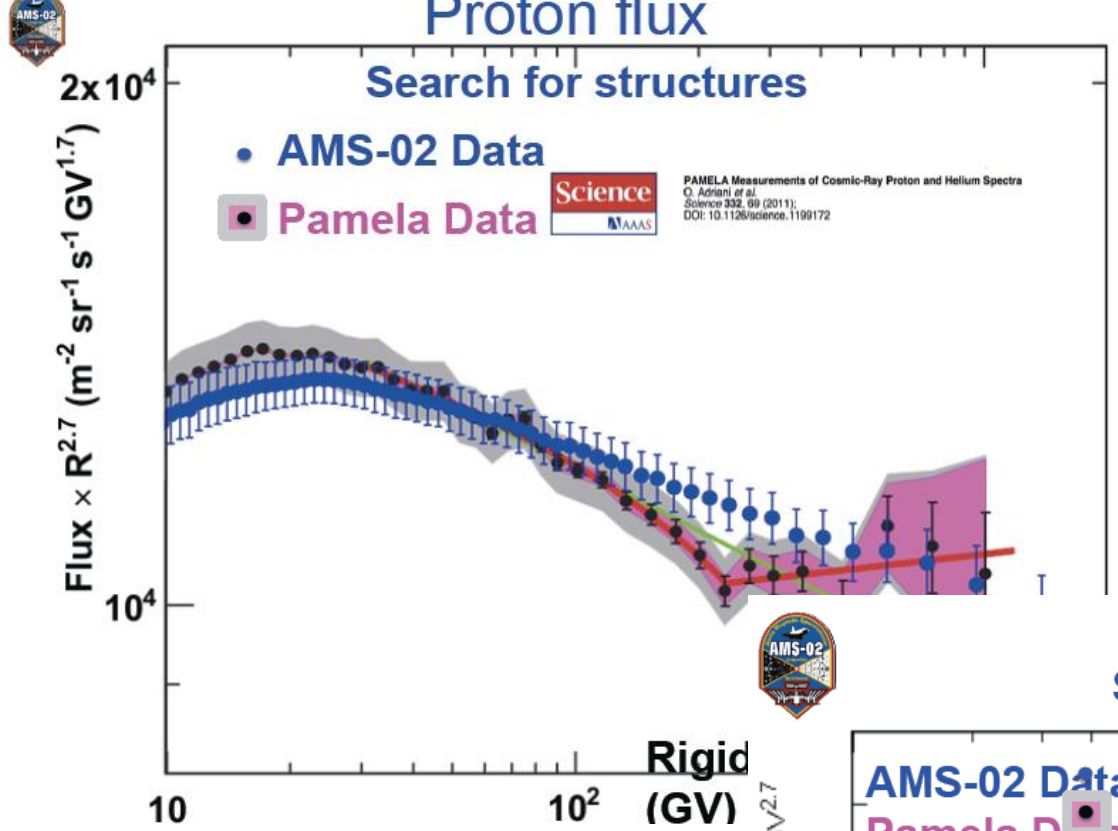
Fluxes evaluated by varying the selection conditions:

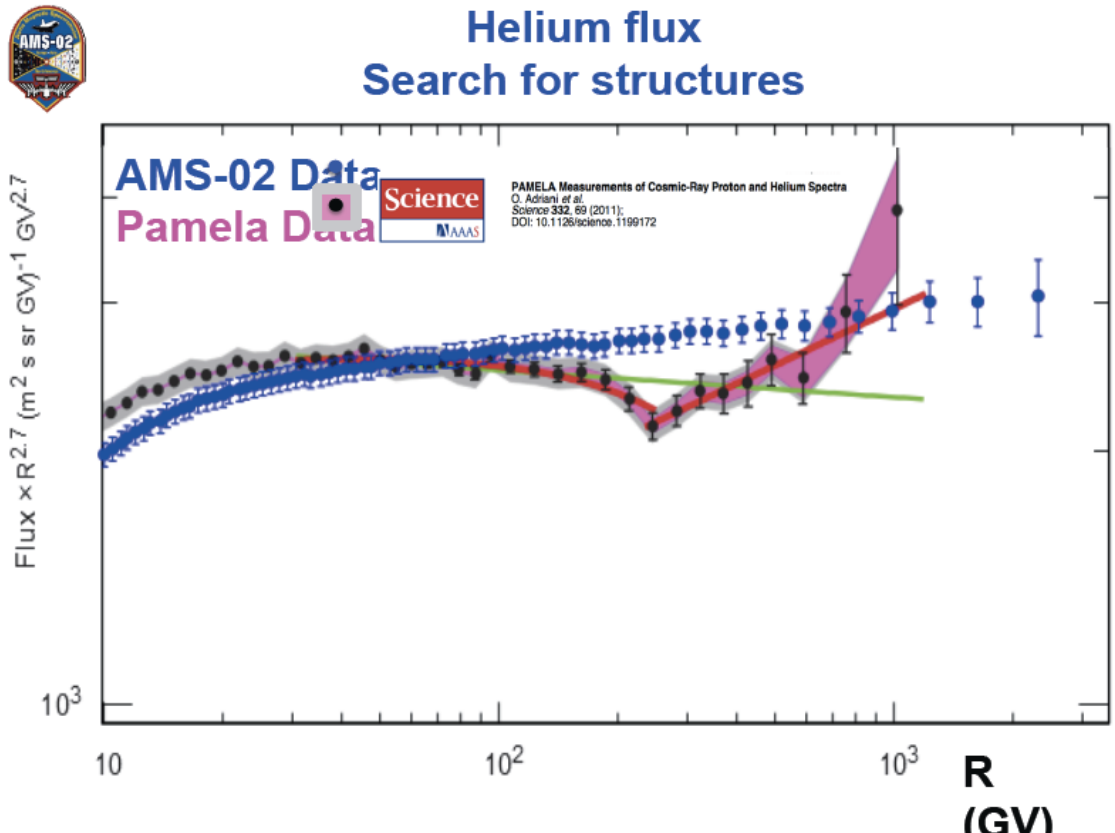
- Flux vs time
- Flux vs polar/equatorial
- Flux vs reduced acceptance
- Flux vs different tracking conditions (⇒ different response matrix)

…



PAMELA & AMS


Proton flux
Search for structures
AMS-02 Data
Pamela Data
Science
AAAS
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
Flux × R^2.7 (m^-2 sr^-1 s^-1 GV^1.7)
2x10^4
10^4
10
10^2
Rigid
(GV)


Helium flux
Search for structures
AMS-02 Data
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PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
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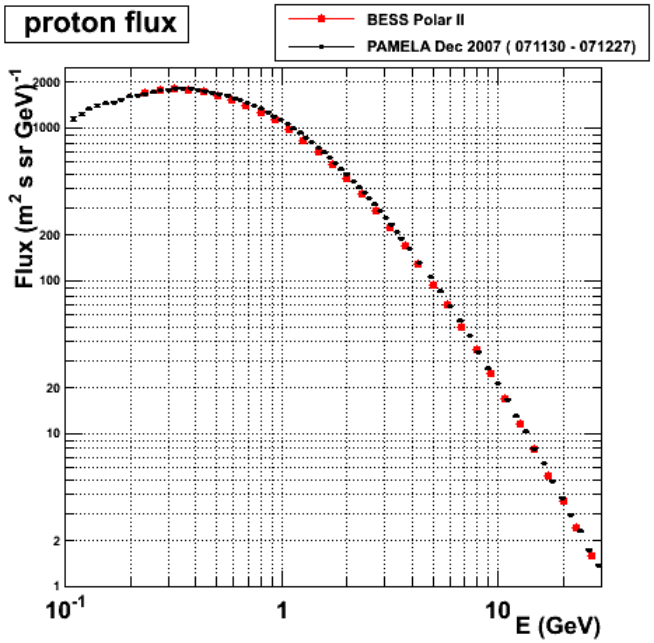
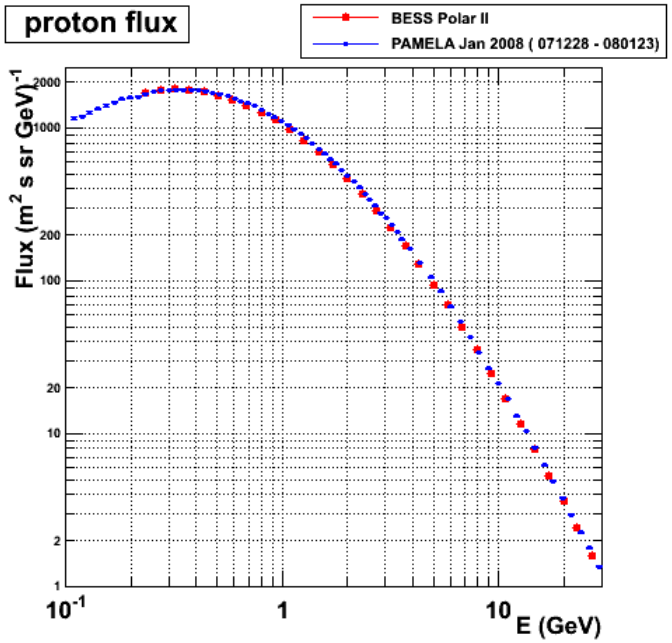
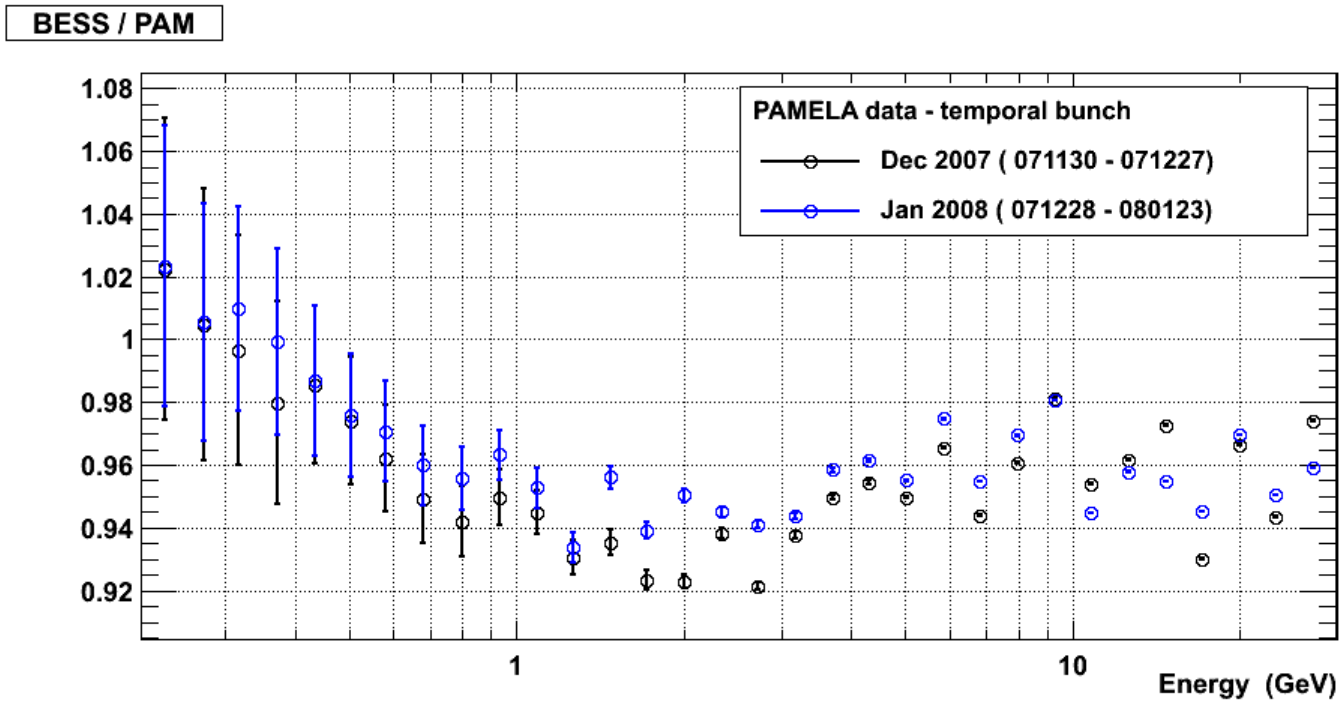
Flux × R^2.7 (m^2 s sr GV)^-1 GV^2.7
10^3
10
10^2
10^3
R
(GV)







PAMELA & BESS-PolarII proton spectrum

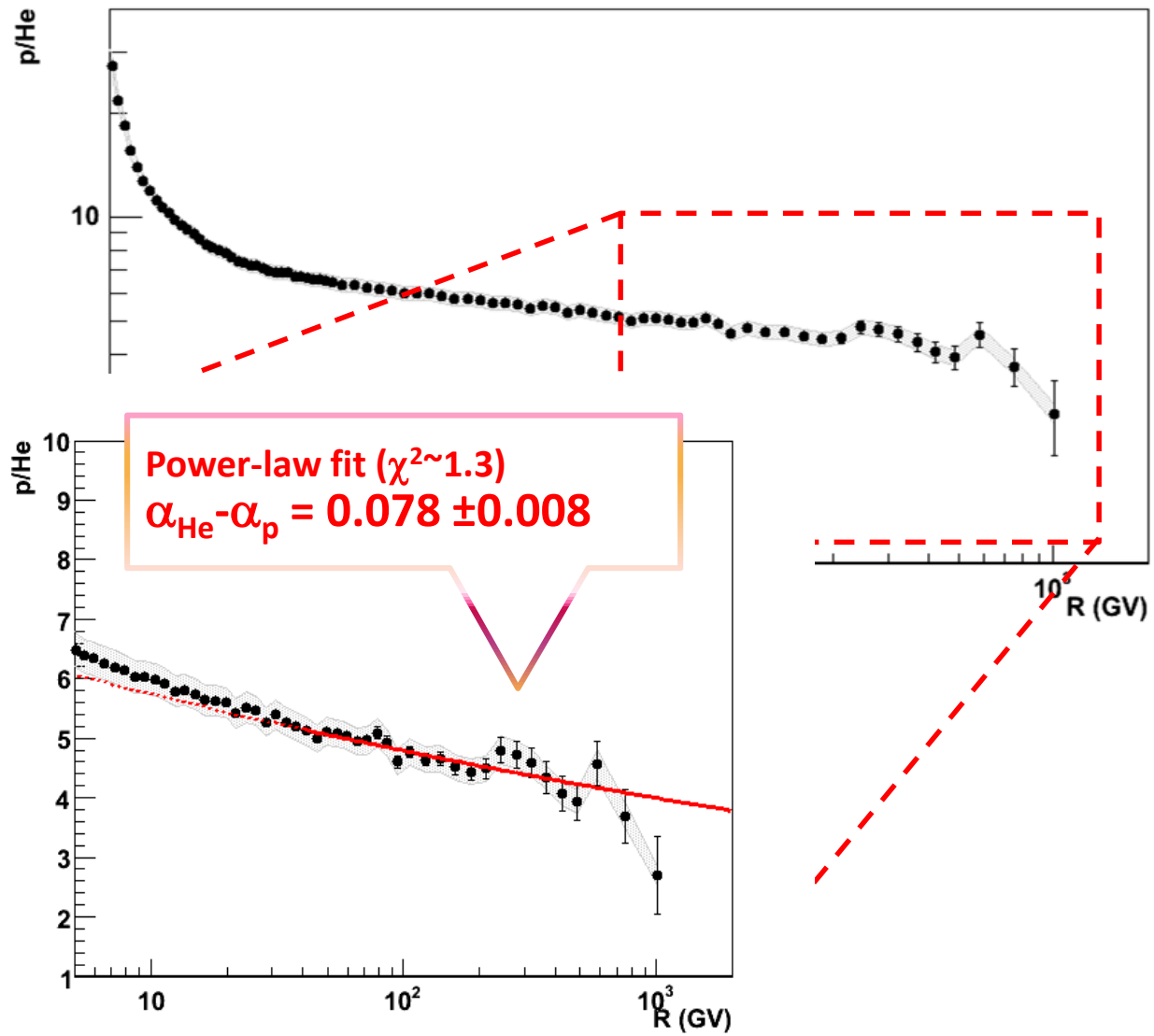
H/He ratio vs R

Instrumental p.o.v.

- Systematic uncertainties partly cancel out

Theoretical p.o.v.

- Solar modulation negligible → information about IS spectra down to GV region
- Propagation effects small above ~100GV → information about source spectra



H/He ratio vs R

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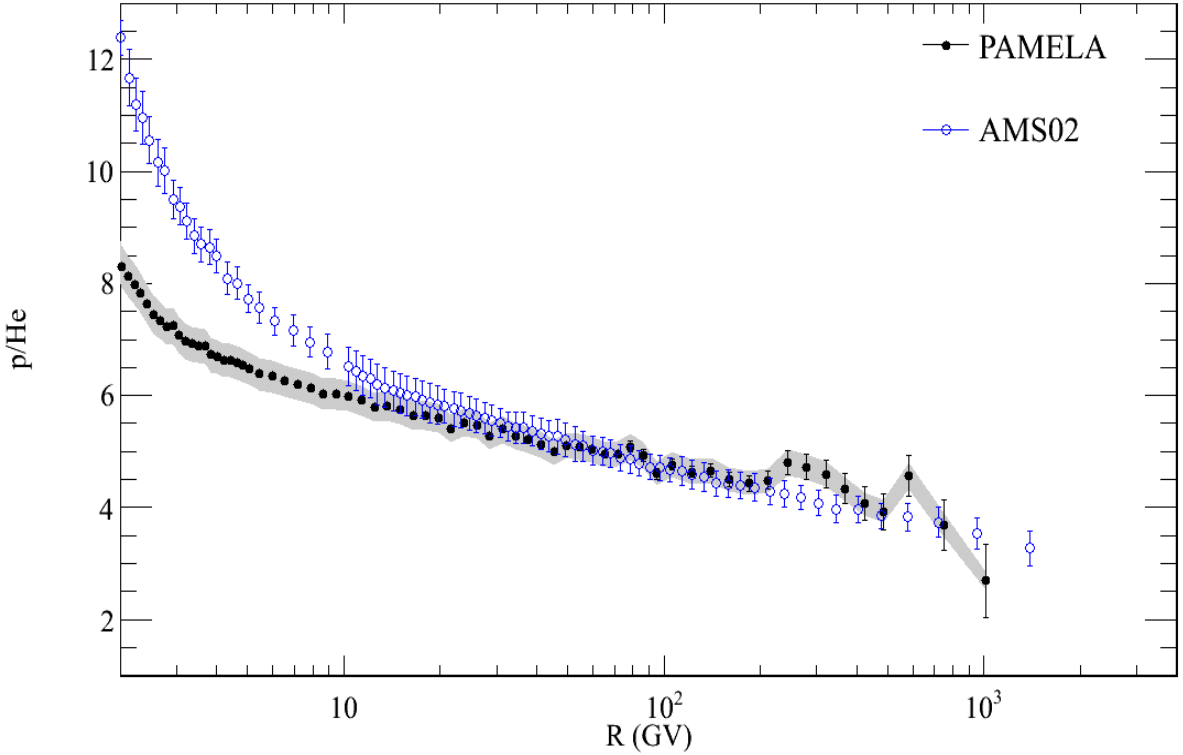
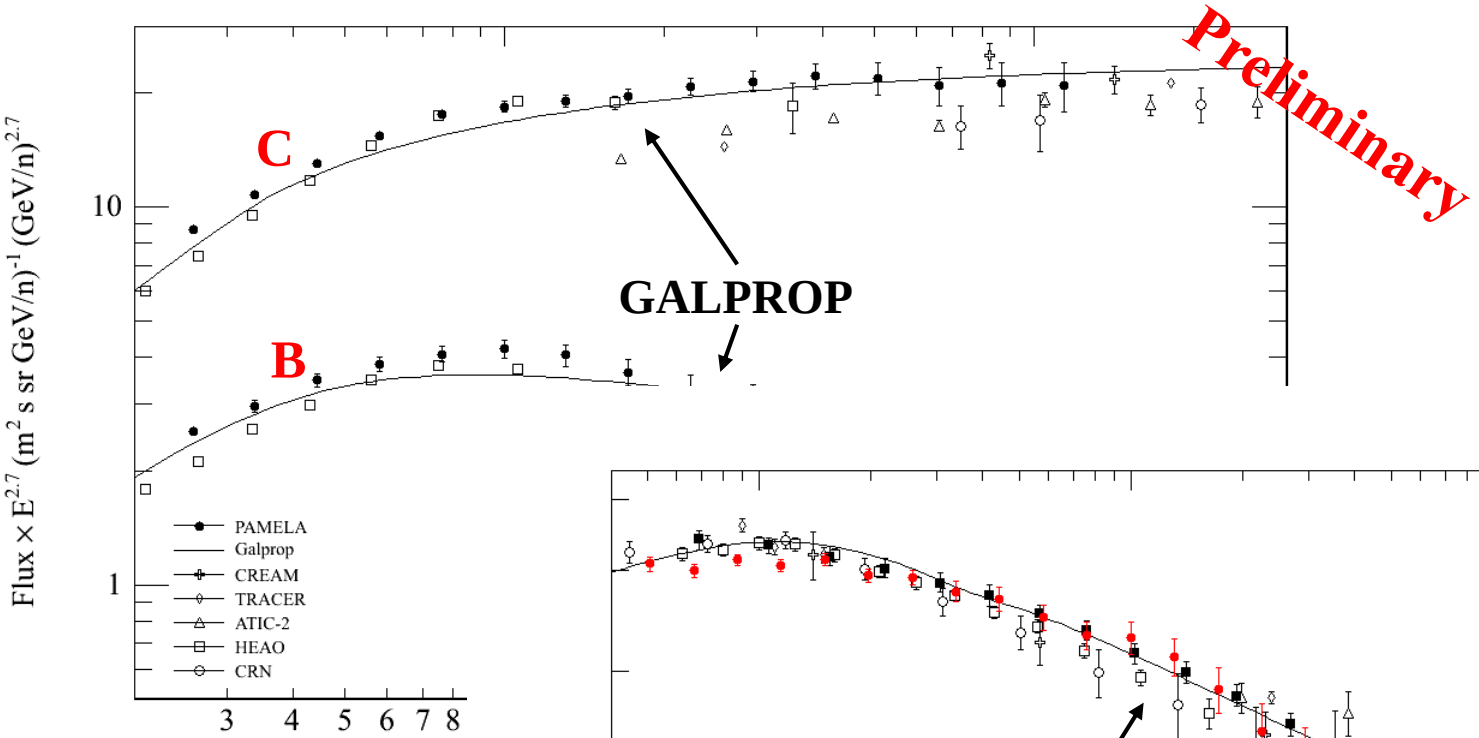


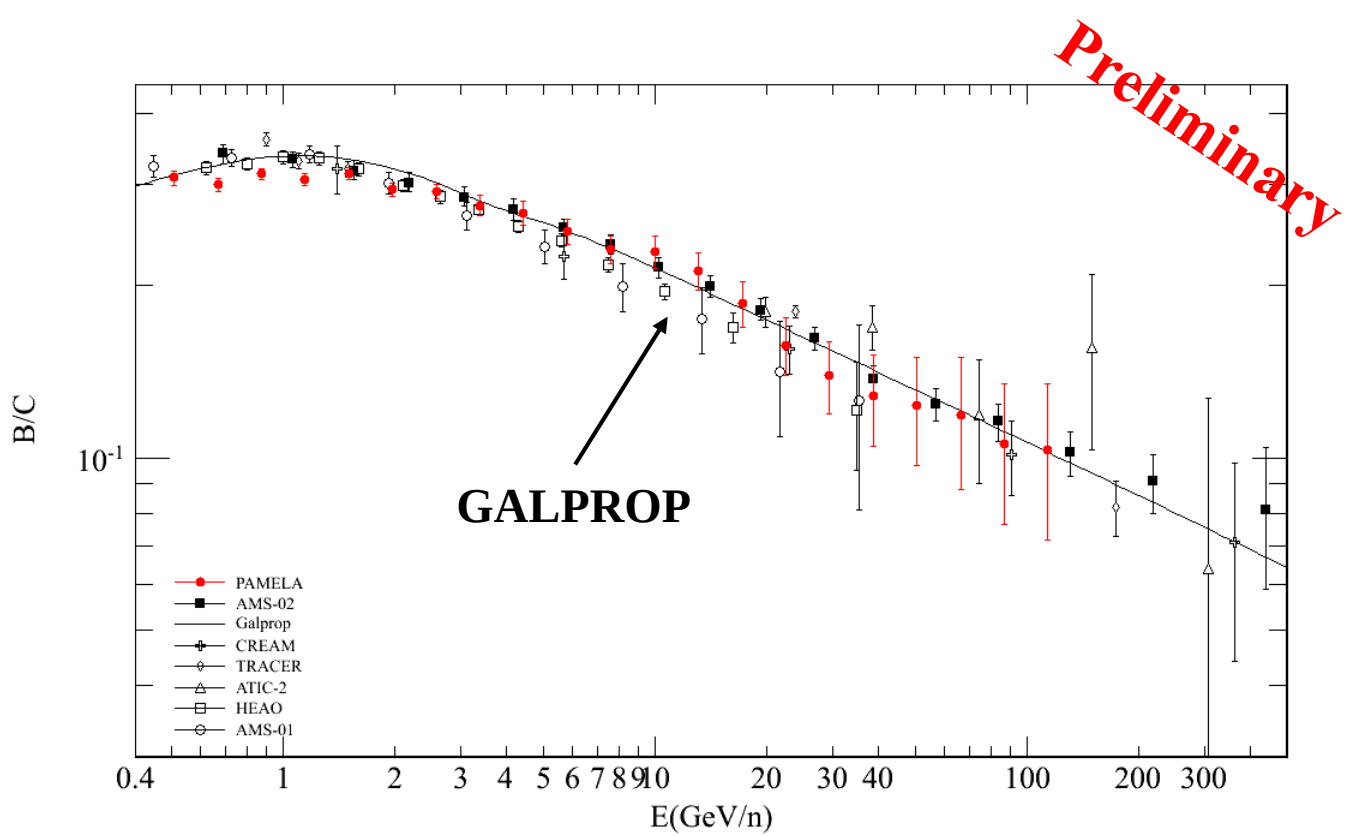
Light Nuclei and Isotopes

- **Tuning of cosmic-ray propagation models with measurements of secondary/primary flux ratio**

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

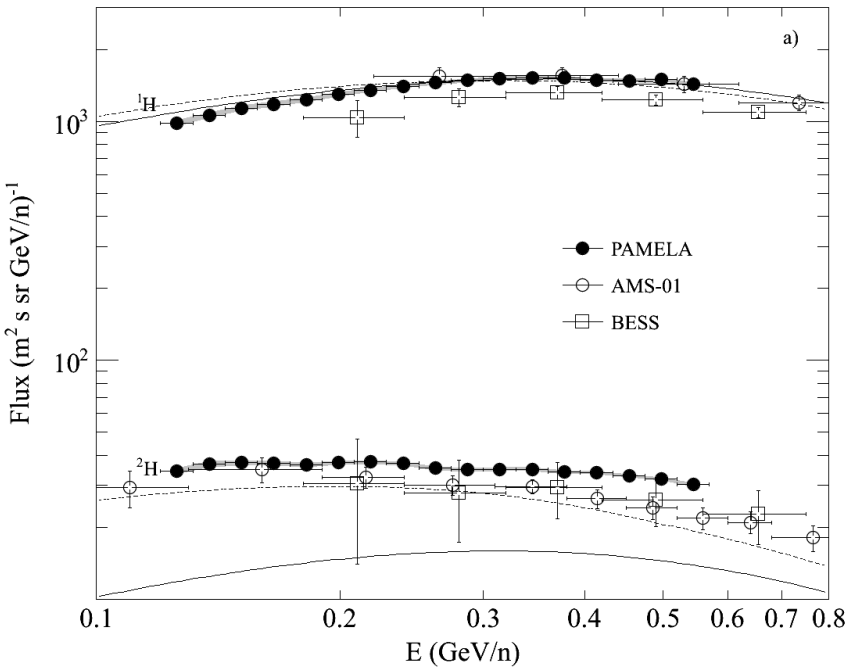
Boron and Carbon



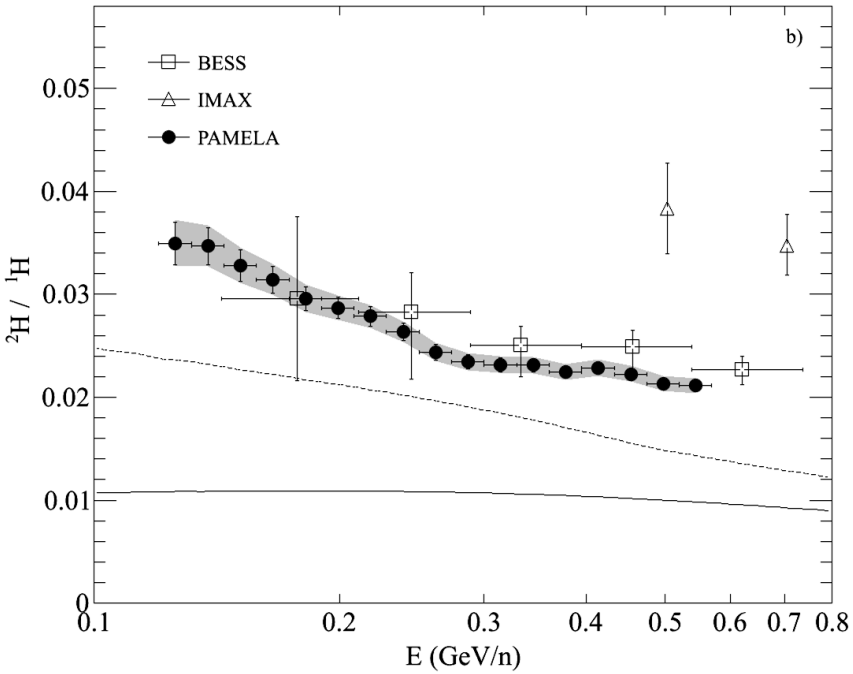


Hydrogen Isotopes

^{1}H and ^{2}H fluxes



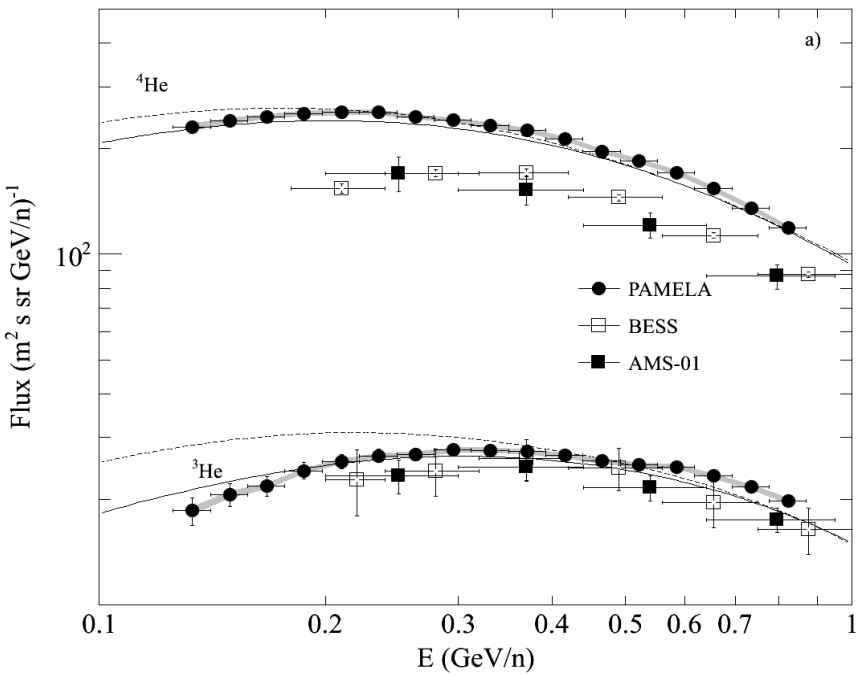
^{2}H/^{1}H



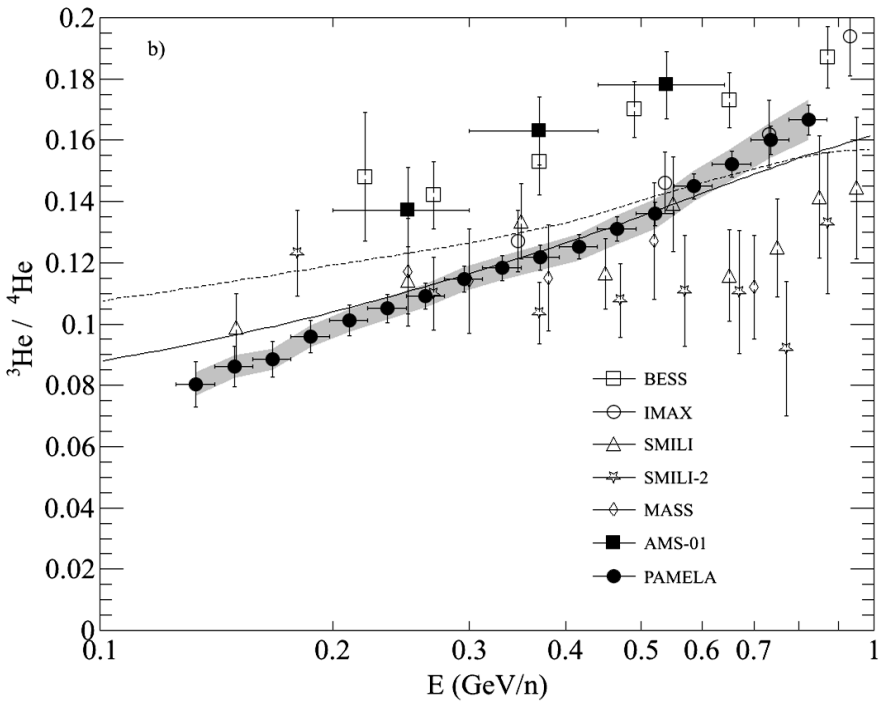
O. Adriani et al., ApJ 770, (2013) 2

Helium Isotopes

^{4}He and ^{3}He fluxes



^{3}He/^{4}He



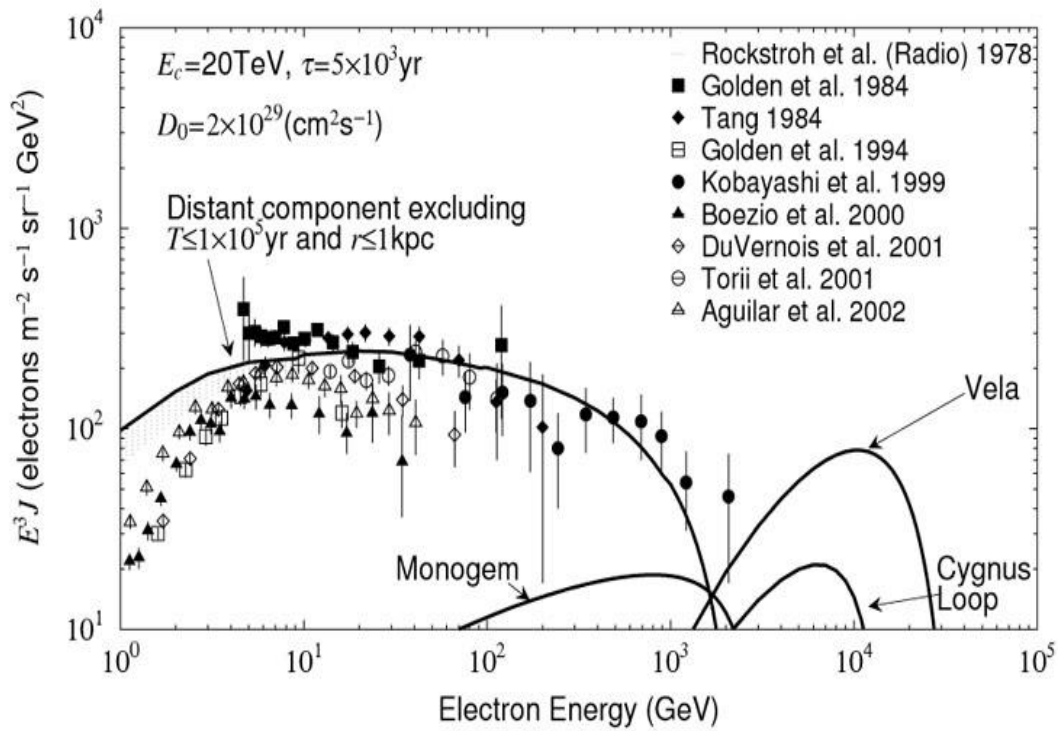
O. Adriani et al., ApJ 770, (2013) 2

Electrons

Electrons can tell us about local GCR sources

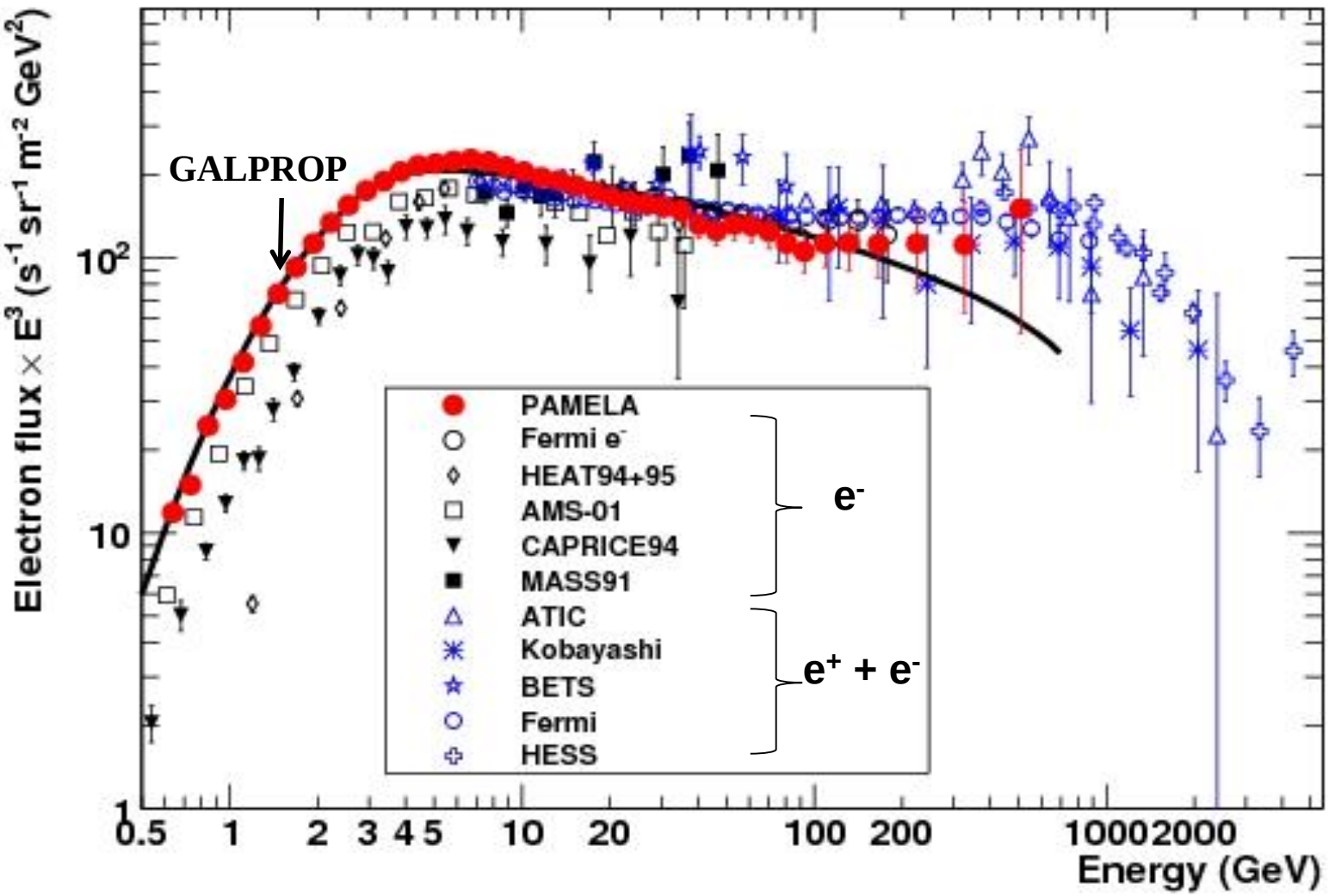
- **High energy electrons have a high energy loss rate ∝ E^2**
  - **Lifetime of ~10^5 years for >1 TeV electrons**
- **Transport of GCR through interstellar space is a diffusive process**
  - **Implies that source of high energy electrons are < 1 kpc away**

Only a handful of SNR meet the lifetime & distance criteria
Kobayashi et al., ApJ 601 (2004) 340 calculations show structure in electron spectrum at high energy

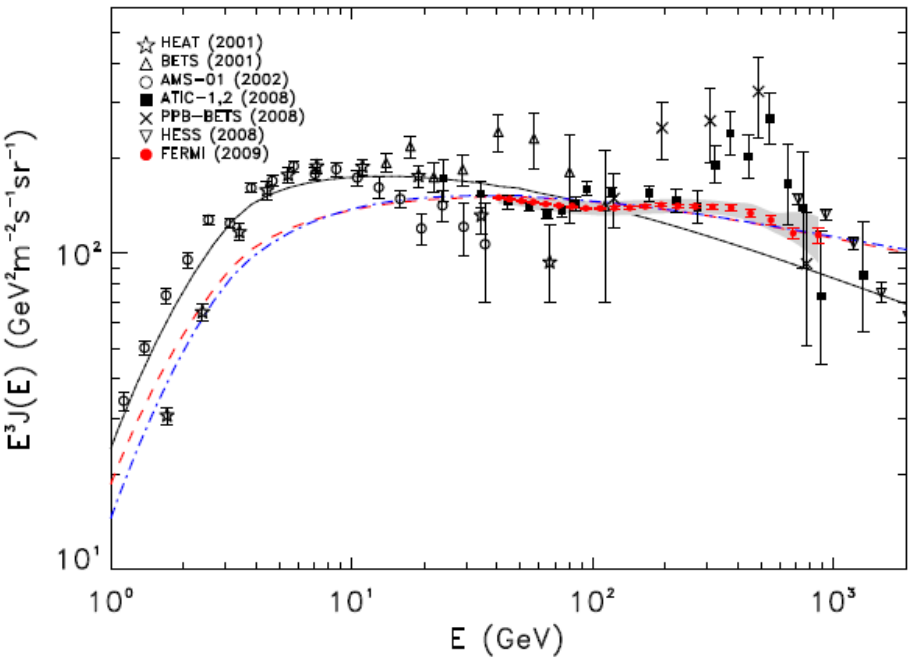


J. P. Wefel, TevPA 2011, Stockholm (2011)

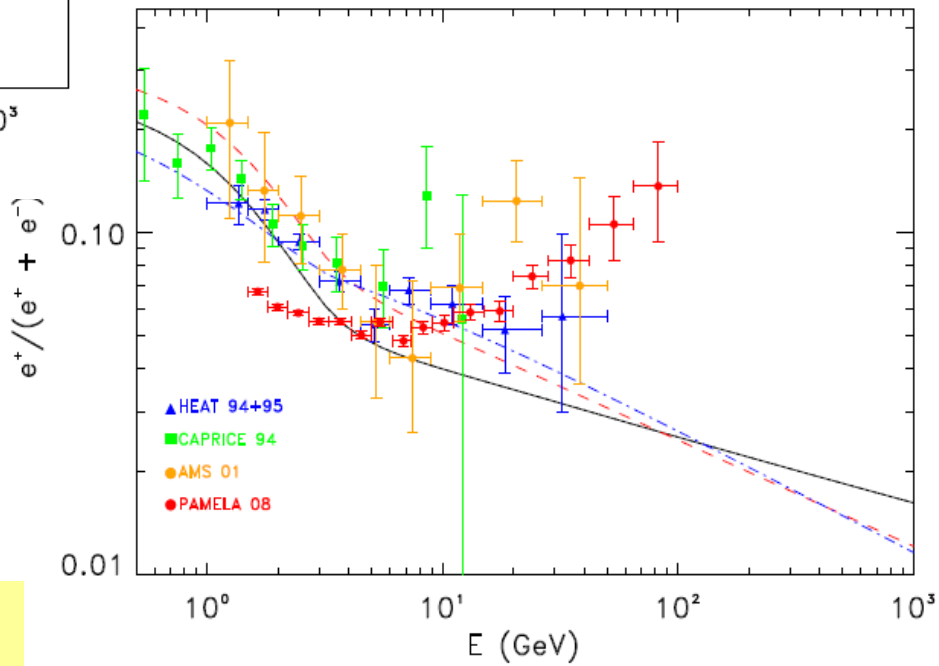
PAMELA Electron (e^-) Spectrum



Electron Spectrum and Positron Fraction

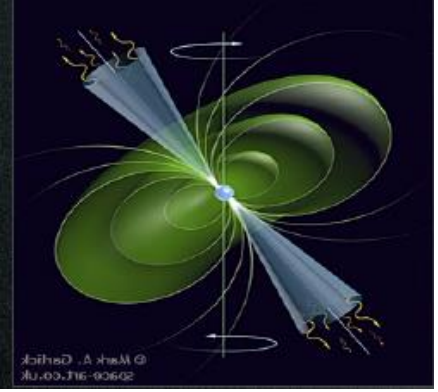


Modify the injection indices of GALPROP?

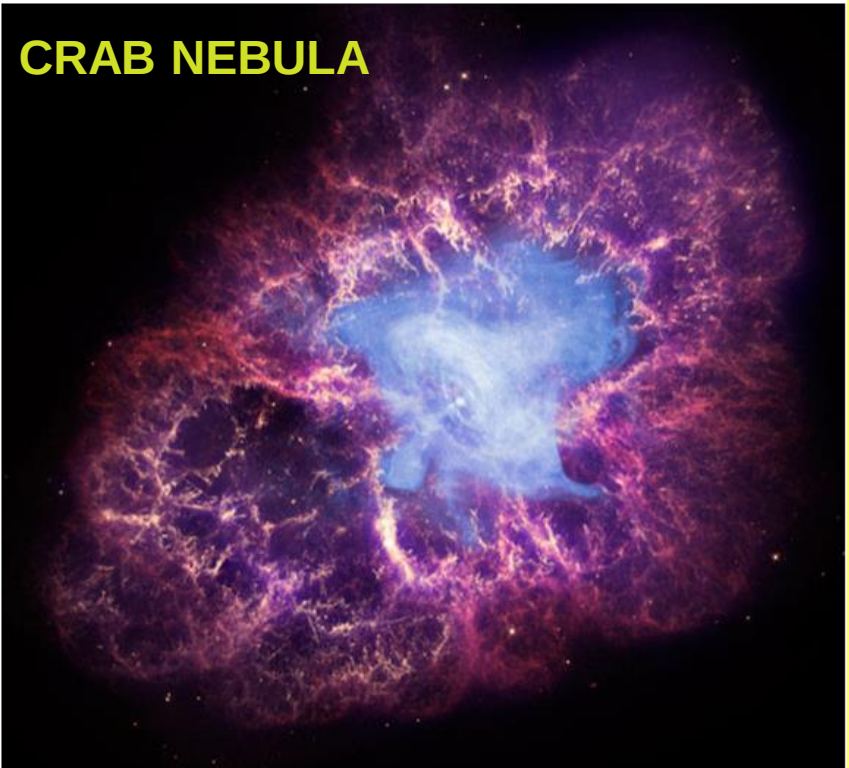


Does not fit at all the positron fraction:

D. Grasso et al., Astropart.Phys. 32 (2009) 140; arXiv:0905.0636

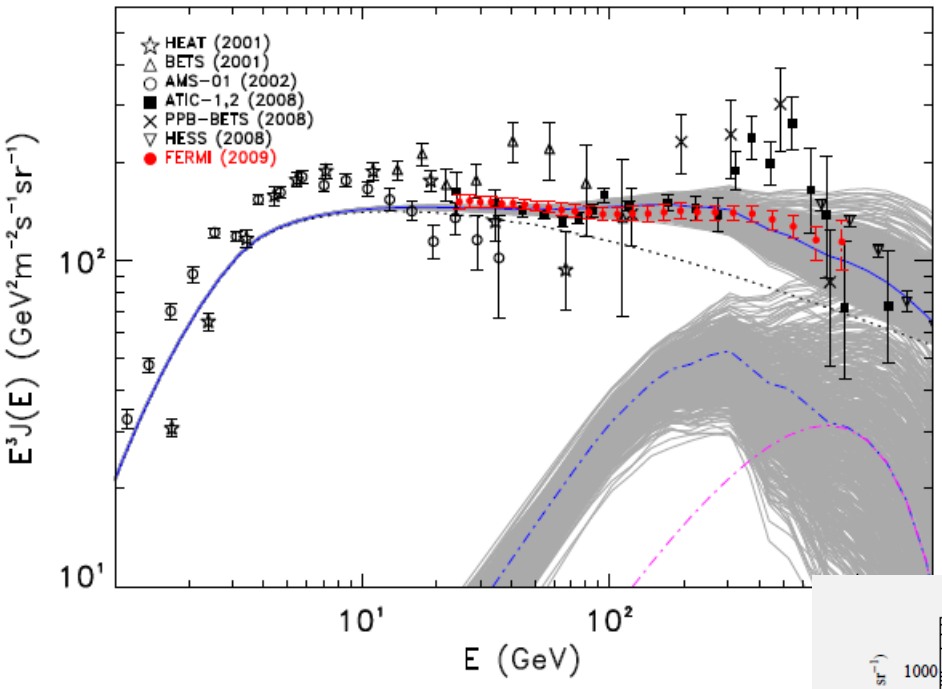


Astrophysical Explanation: Pulsars



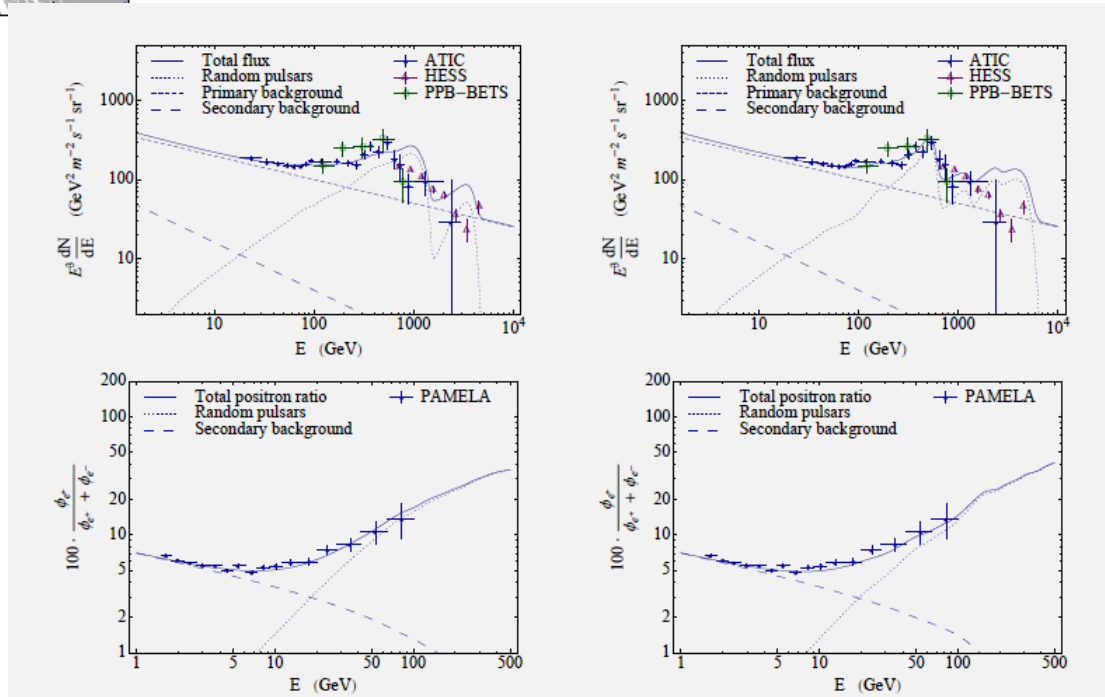
- **Mechanism: the spinning B of the pulsar strips e^- that accelerated in the outer magnetosphere emit γ that produce $e^\pm$. But pairs are trapped in the cloud. After (4-5)x10^4 years pulsars leave remanent and pairs are liberated (e.g. P. Blasi & E. Amato, arXiv:1007.4745).**
- **Young (T < 10^5 years) and nearby (< 1kpc)**
- **If not: too much diffusion, low energy, too low flux.**
- **Not a new idea, e.g.: Harding & Ramaty, ICRC 2 (1987), Boulares, ApJ 342 (1989), Atoyan et al. PRD 52 (1995)**

Pulsar Explanation



Some structure in the curve should eventually be seen for pulsars? (D. Grasso et al., Astropart. Phys. 32, 140, 2009).

D. Malyshev, I. Cholis and J. Gelfand, PRD 80 (2009) 063005



Antiparticles with PAMELA

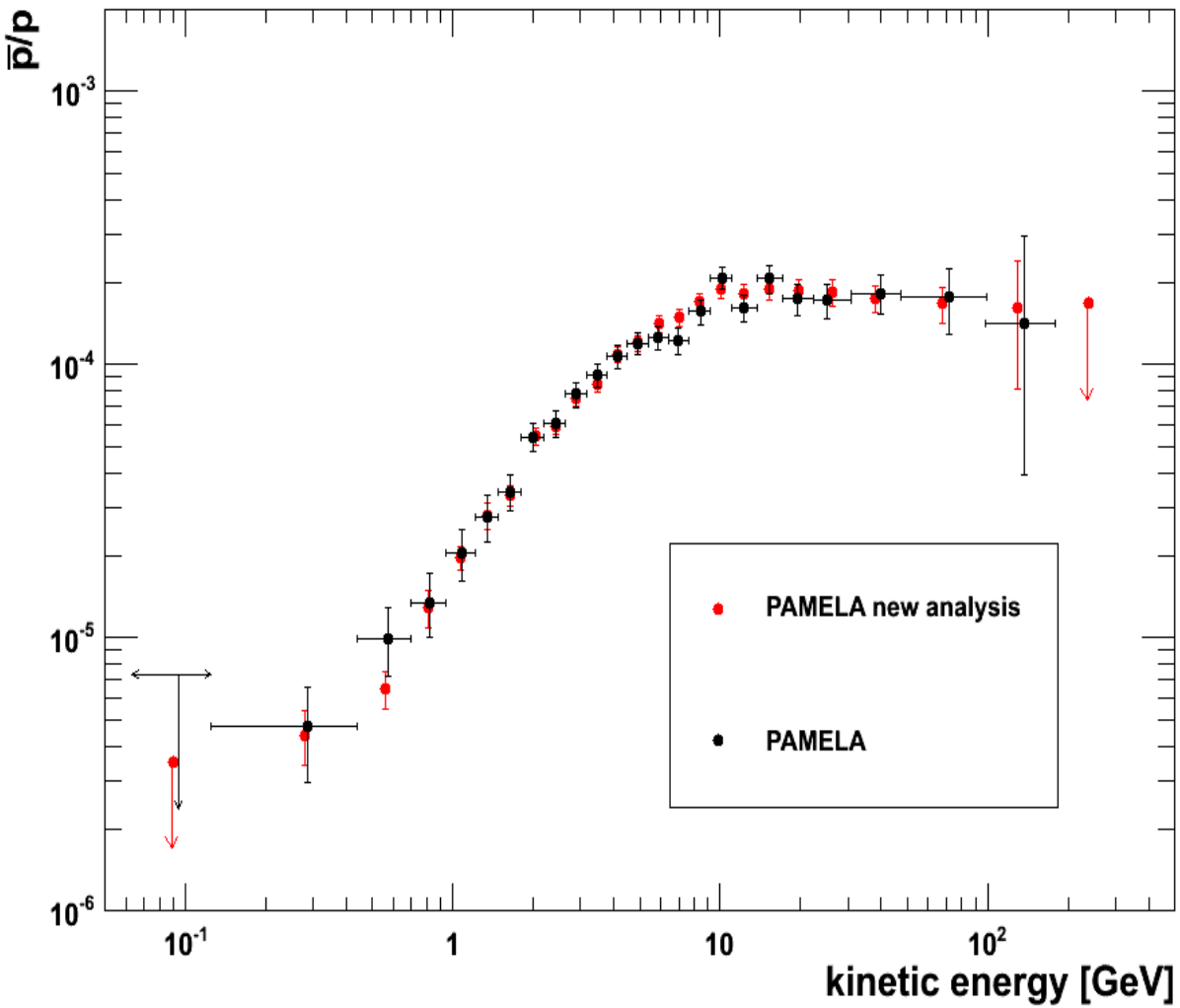
Mirko Boezio, TeVPA2013, Irvine, 2013/08/26

Astrophysics and Cosmology compelling Issues

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

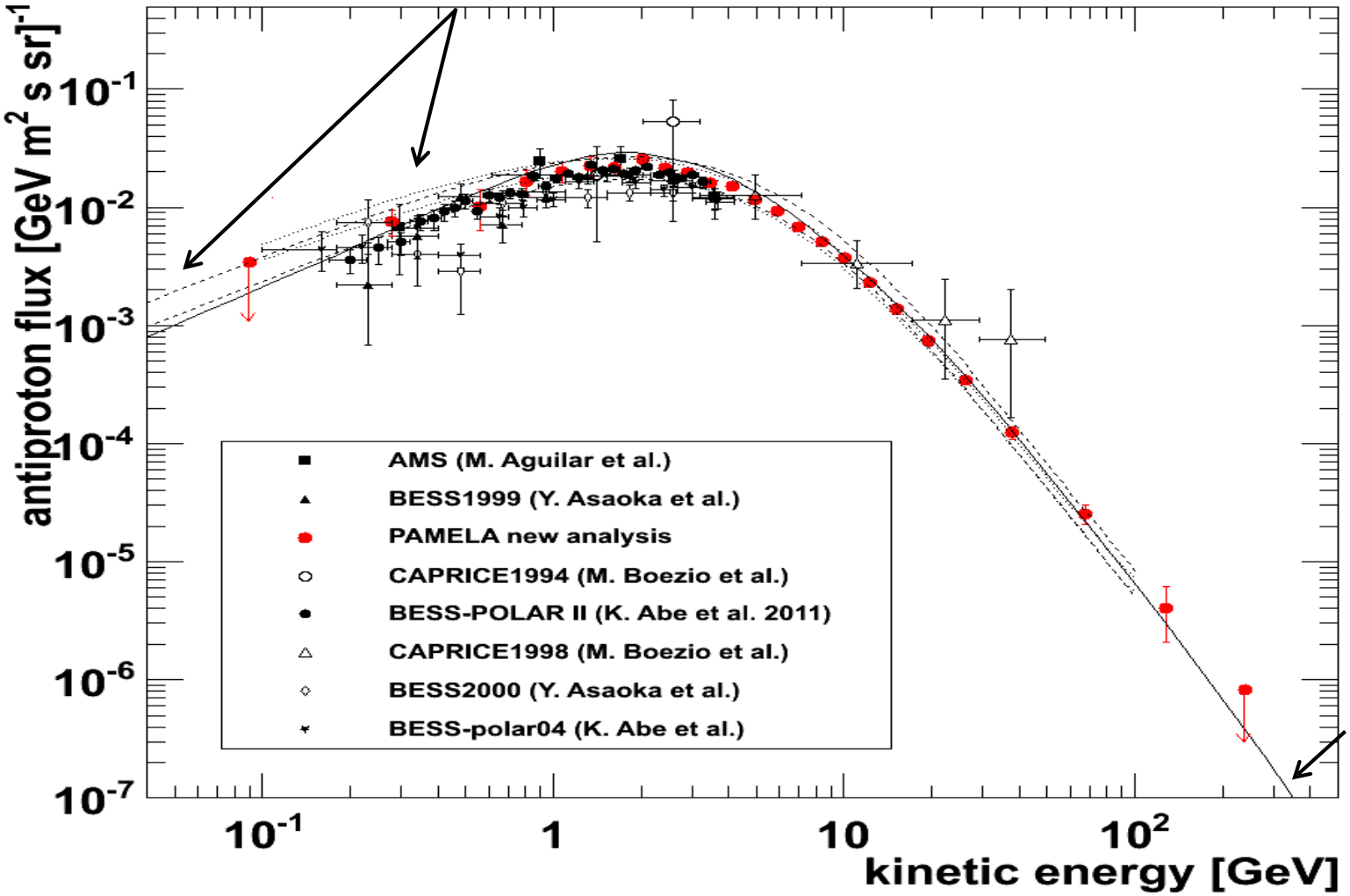
Antiproton to proton flux ratio

Using all data till 2010 and multivariate classification algorithms 20-50% increase in respect to published analysis



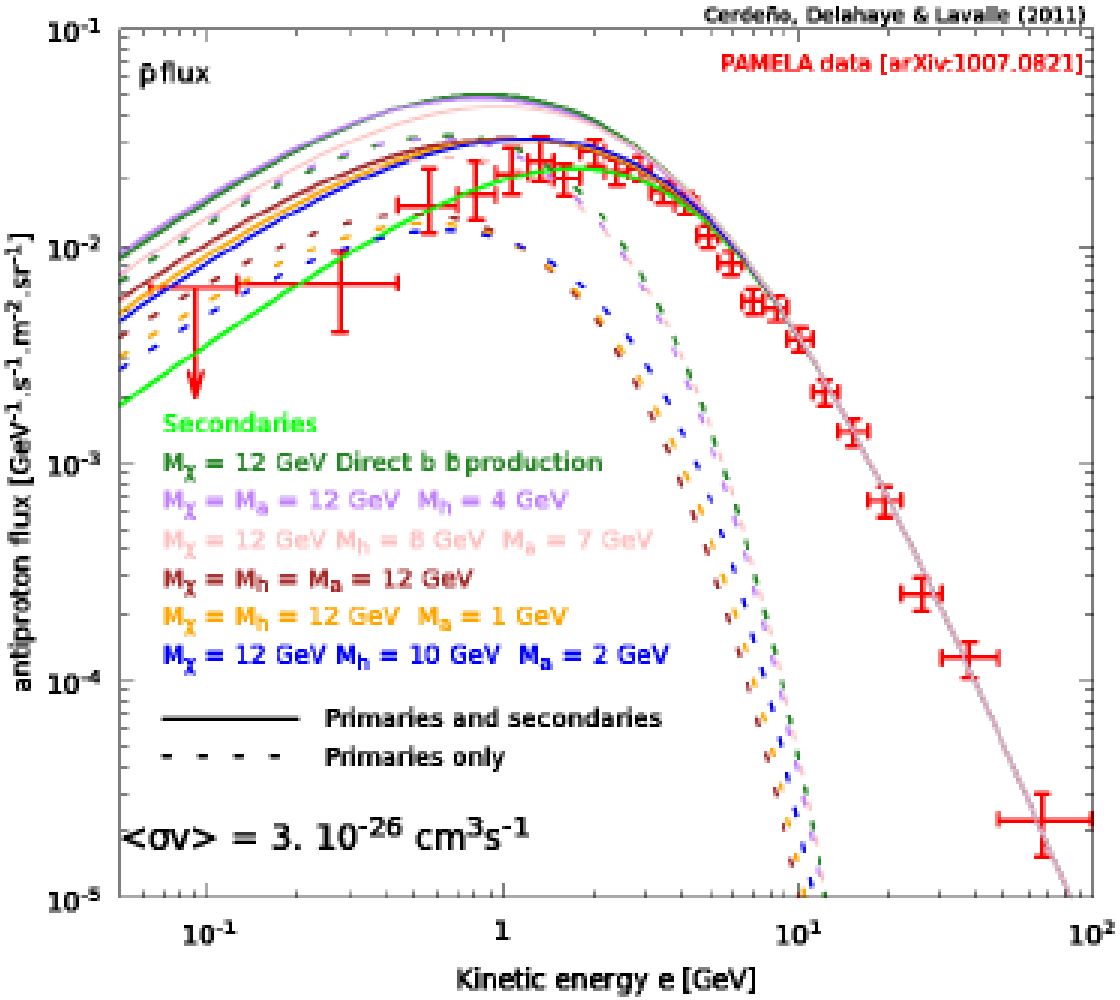
Antiproton energy spectrum

Donato et al., ApJ 563 (2001) 172



Ptuskin et al. ApJ 642 (2006) 902

Cosmic-Ray Antiprotons and DM limits



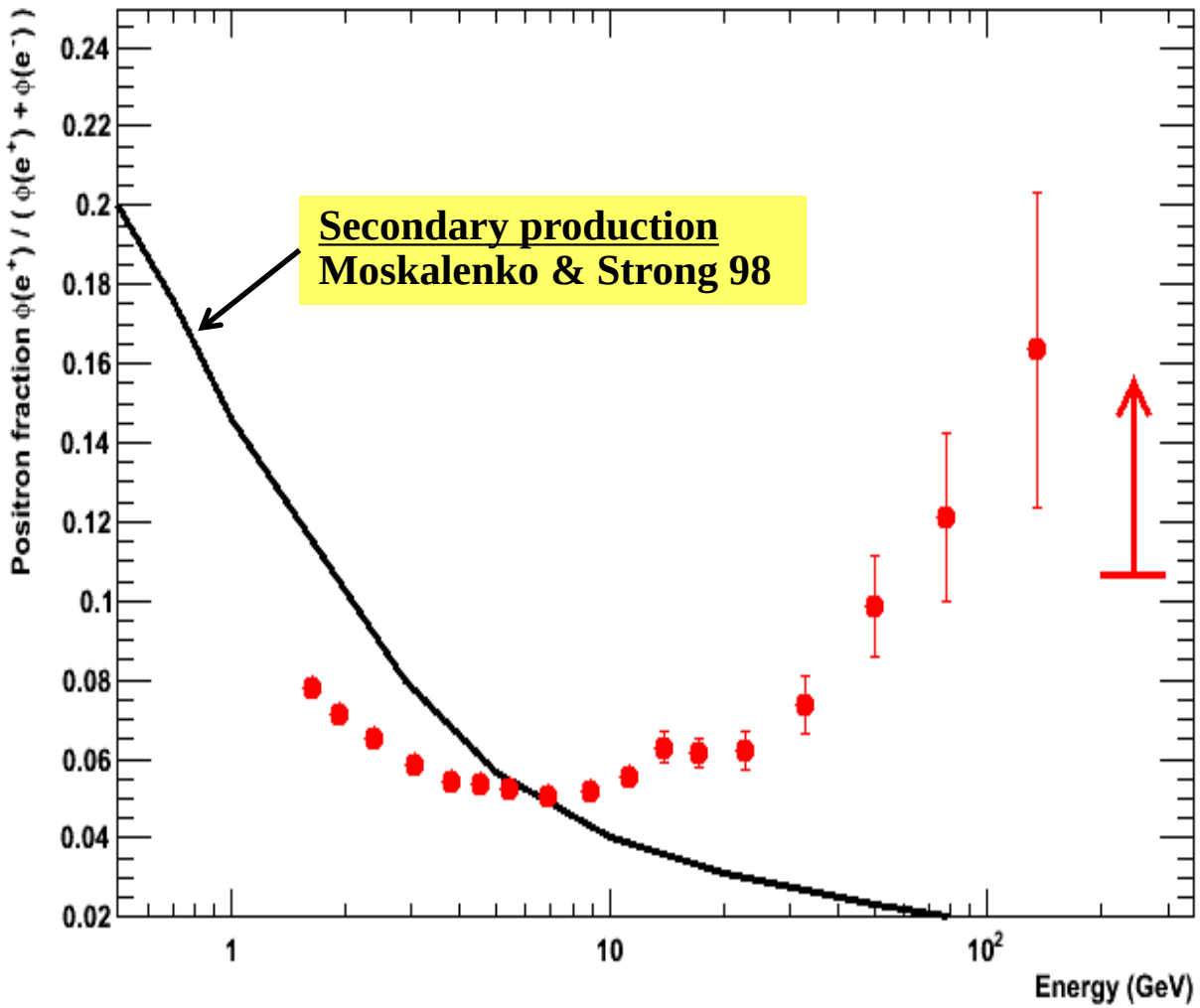
D. G. Cerdeno, T. Delahaye & J. Lavalle, Nucl. Phys. B 854 (2012) 738 Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

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

Positrons with PAMELA

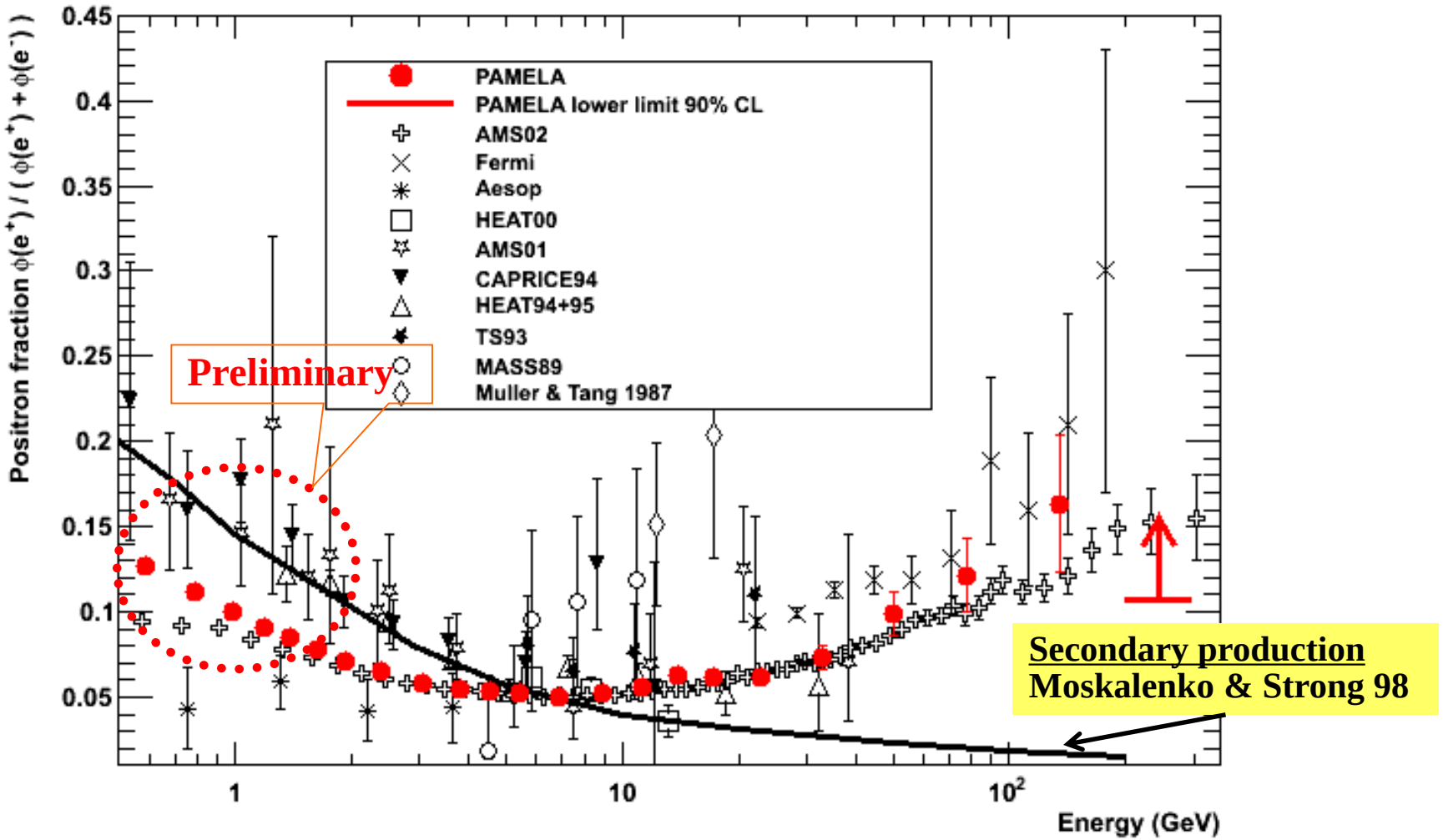
Positron to Electron Fraction

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

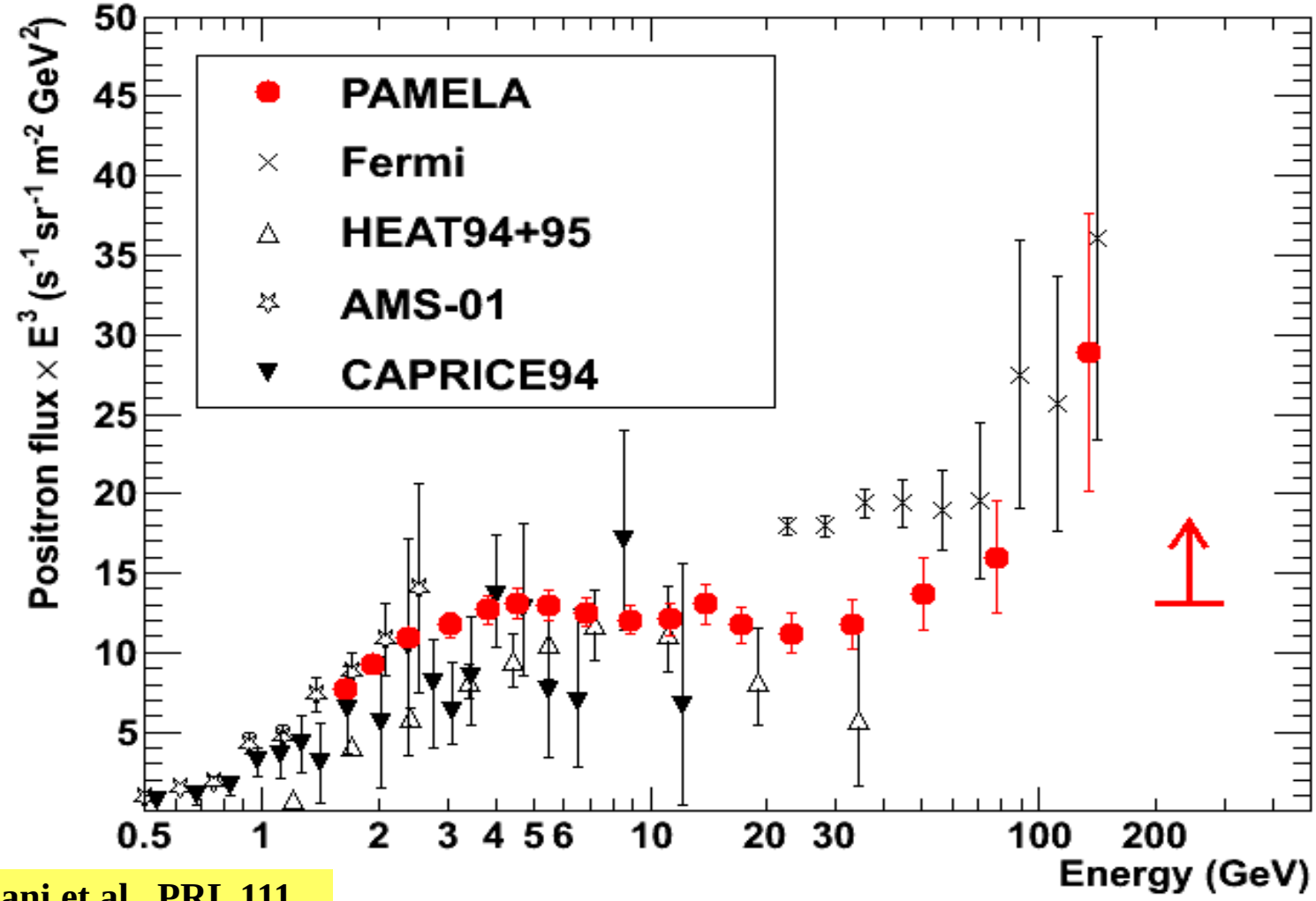


O. Adriani et al., PRL 111 (2013) 081102; arXiv:1308.0133

Positron to Electron Fraction

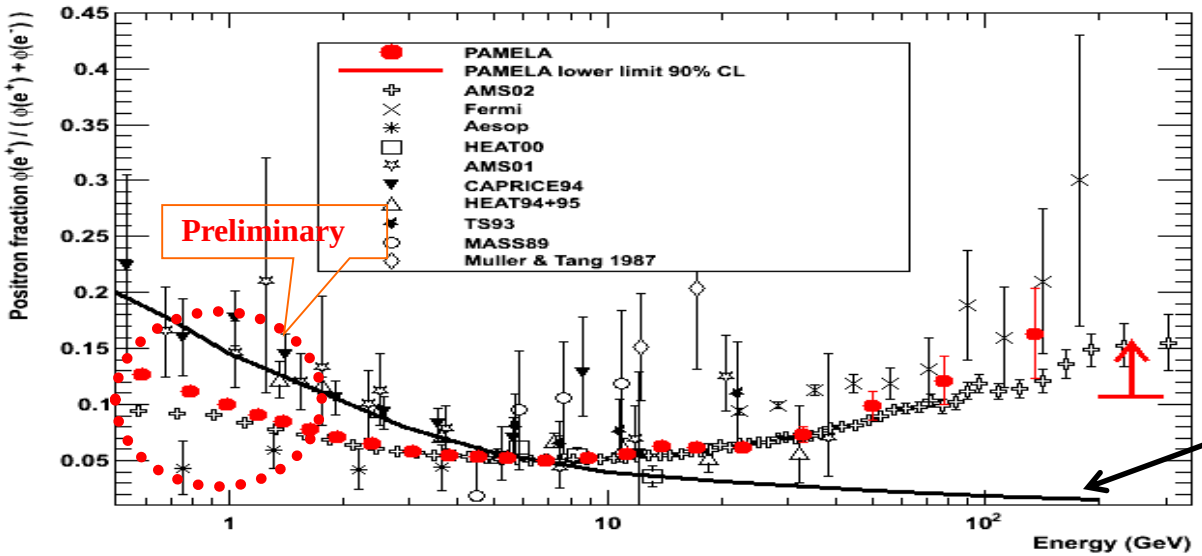


Positron Energy Spectrum

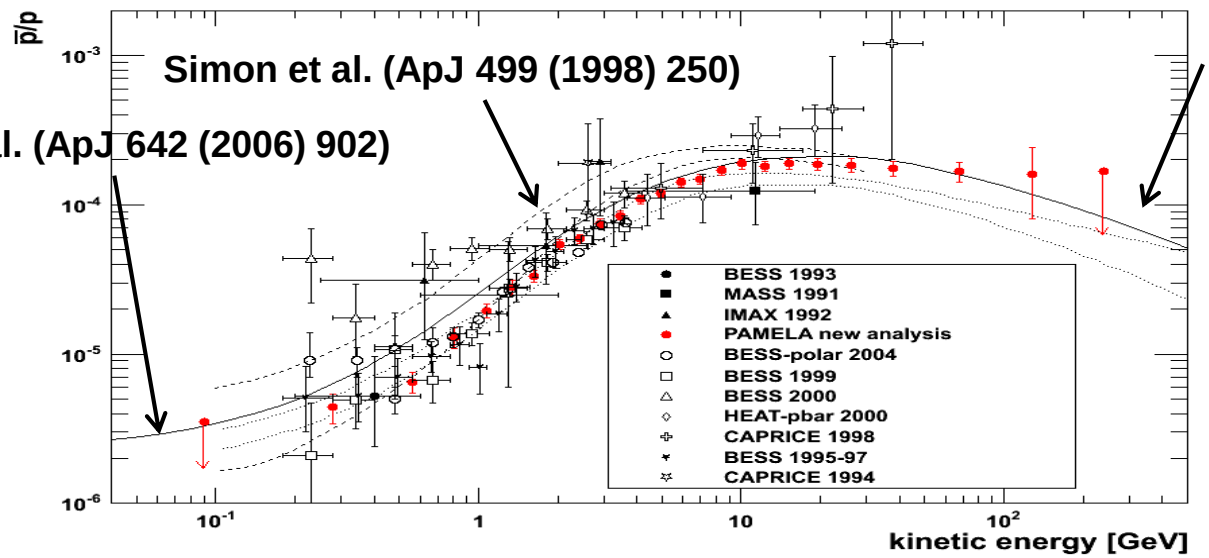


O. Adriani et al., PRL 111 (2013) 081102; arXiv:1308.0133

A Challenging Puzzle for CR Physics



CR Positron spectrum significantly harder than expectations from secondary production Moskalenko & Strong 98



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

Implications

A rising positron fraction requires:

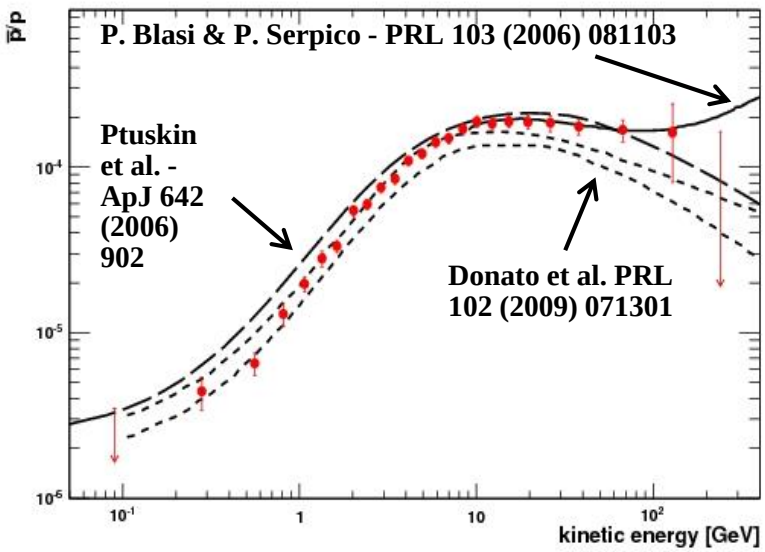
1. **An additional component of positrons with spectrum flatter than CR primary electrons**

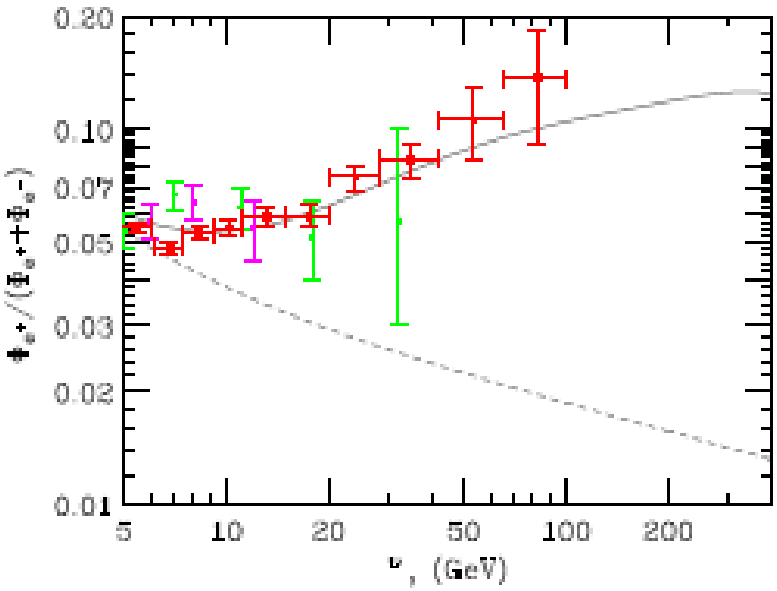
2. **A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)**

3. **Subtleties of Propagation**

Courtesy by P. Blasi

A Challenging Puzzle for CR Physics

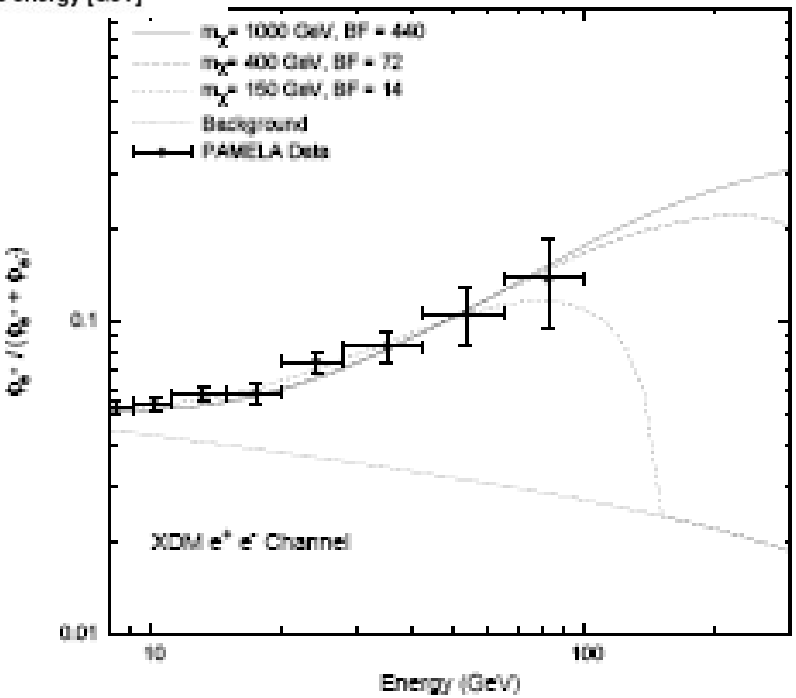




P.Blasi, PRL 103 (2009) 051104; arXiv:0903.2794
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

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

i, and P. Serpico, JCAP
Xiv:0810.1527
diffuse mature &nearby

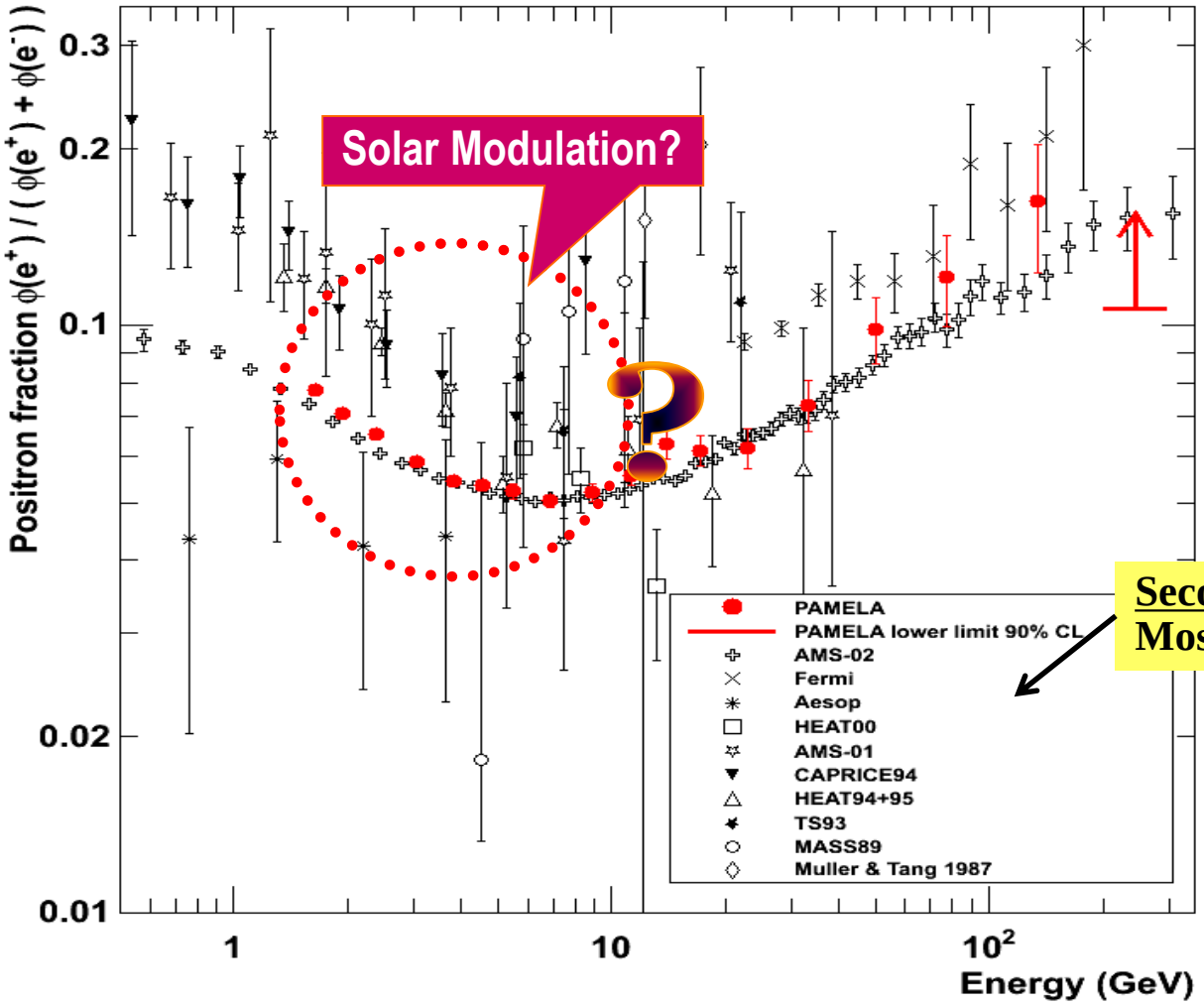


I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1
Contribution from DM annihilation.

Cosmic Rays in the Heliosphere

Mirko Boezio, TeVPA2013, Irvine, 2013/08/26

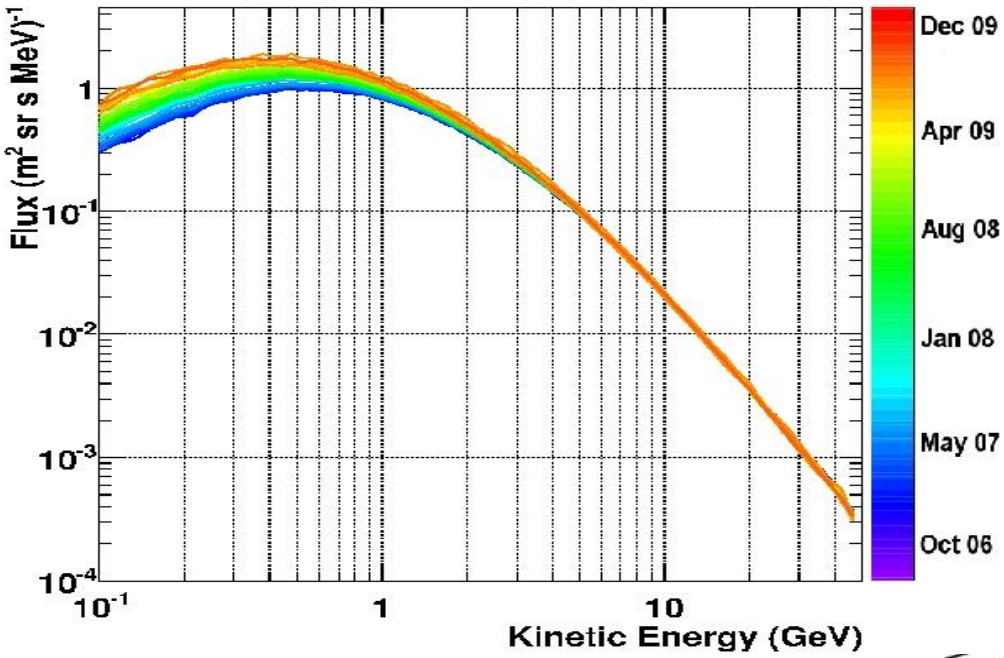
Positron to Electron Fraction



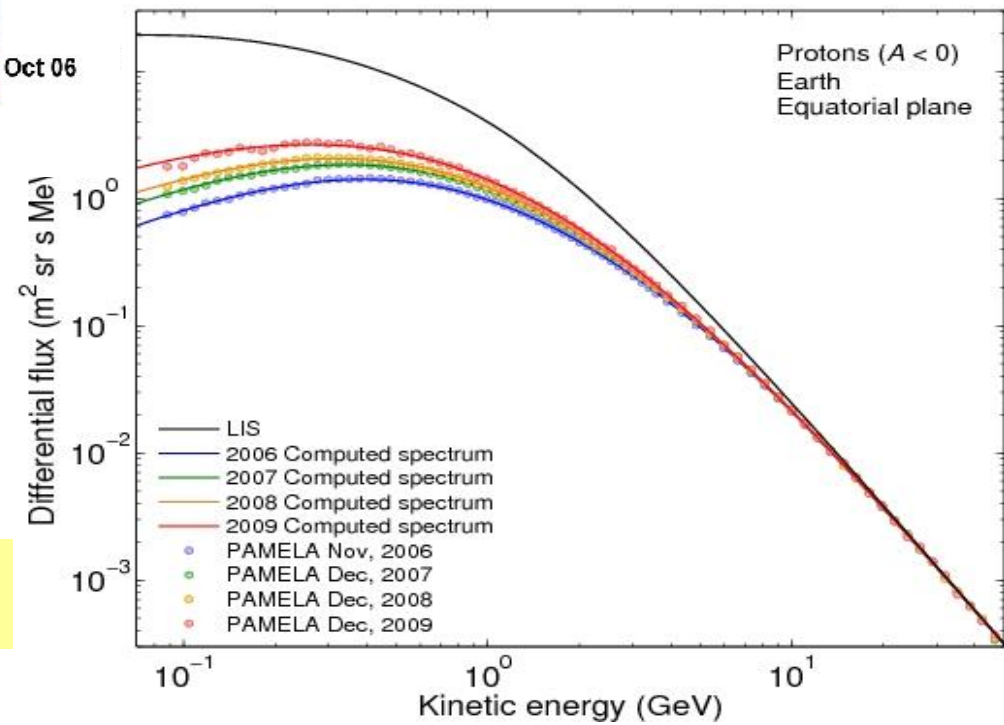
Secondary production
Moskalenko & Strong 98

Adriani et al, Astropart. Phys. 34 (2010) 1
arXiv:1001.3522 [astro-ph.HE]

Time Dependance of the Proton Flux



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

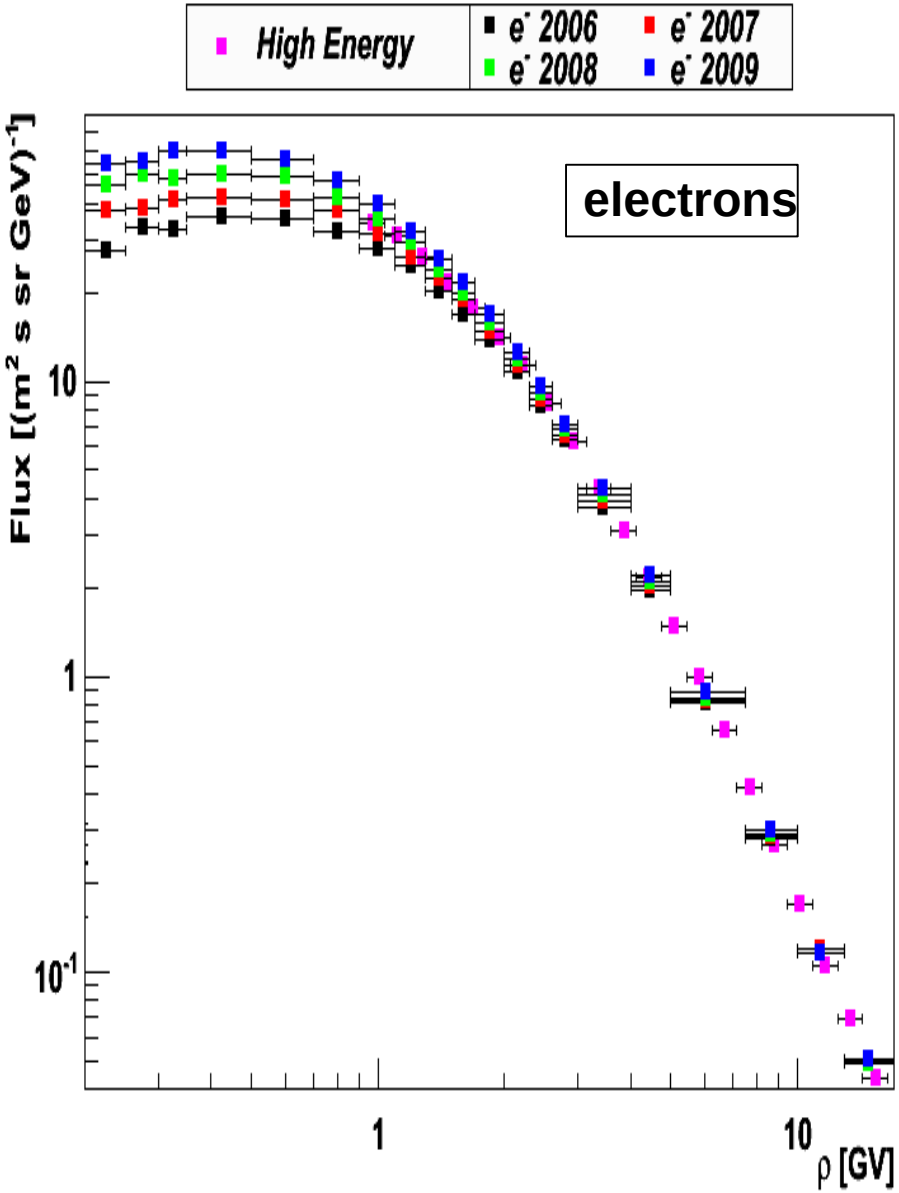


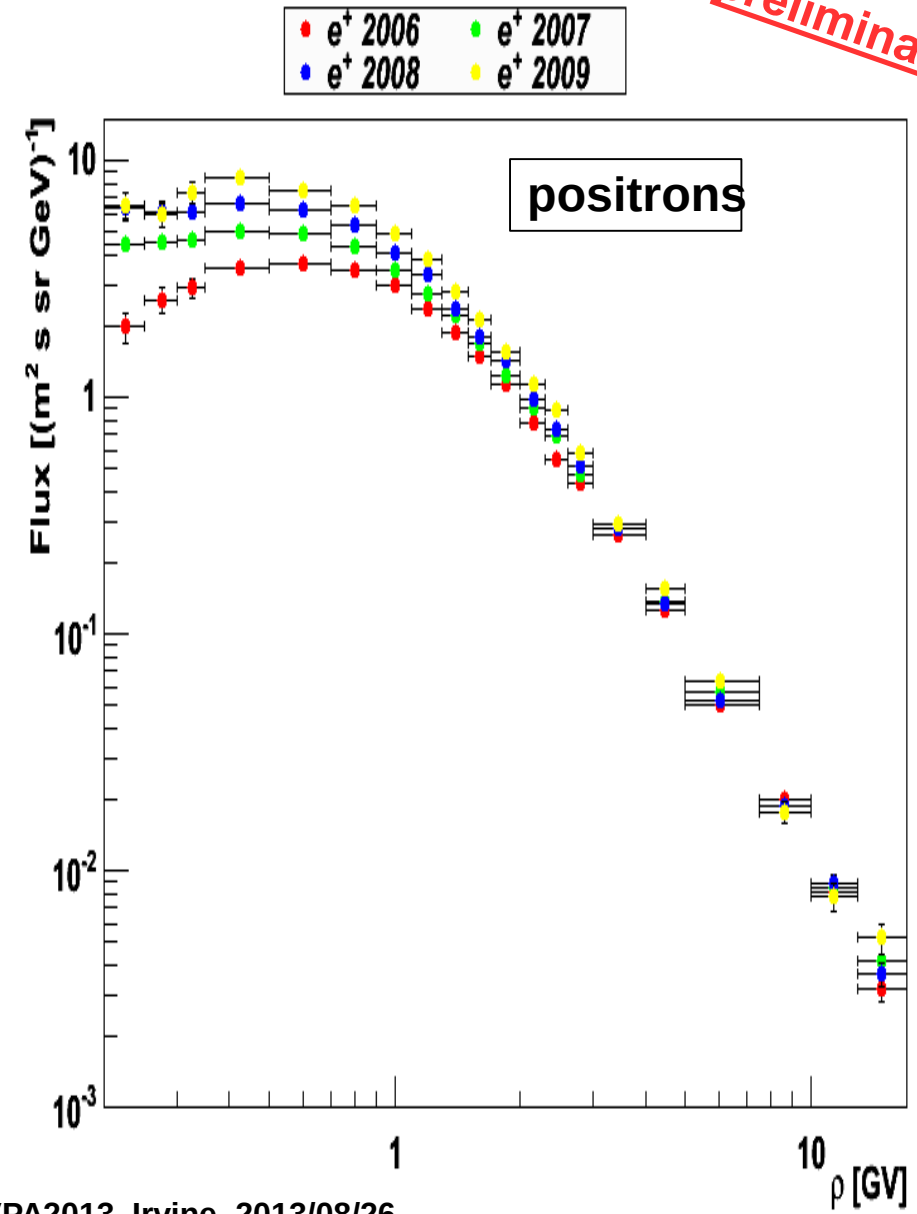
The PAMELA proton spectra over four months compared with the computed spectra

O. Adriani et al., ApJ 765 (2013) 91;
M. S. Potgieter et al., arXiv:1302.1284

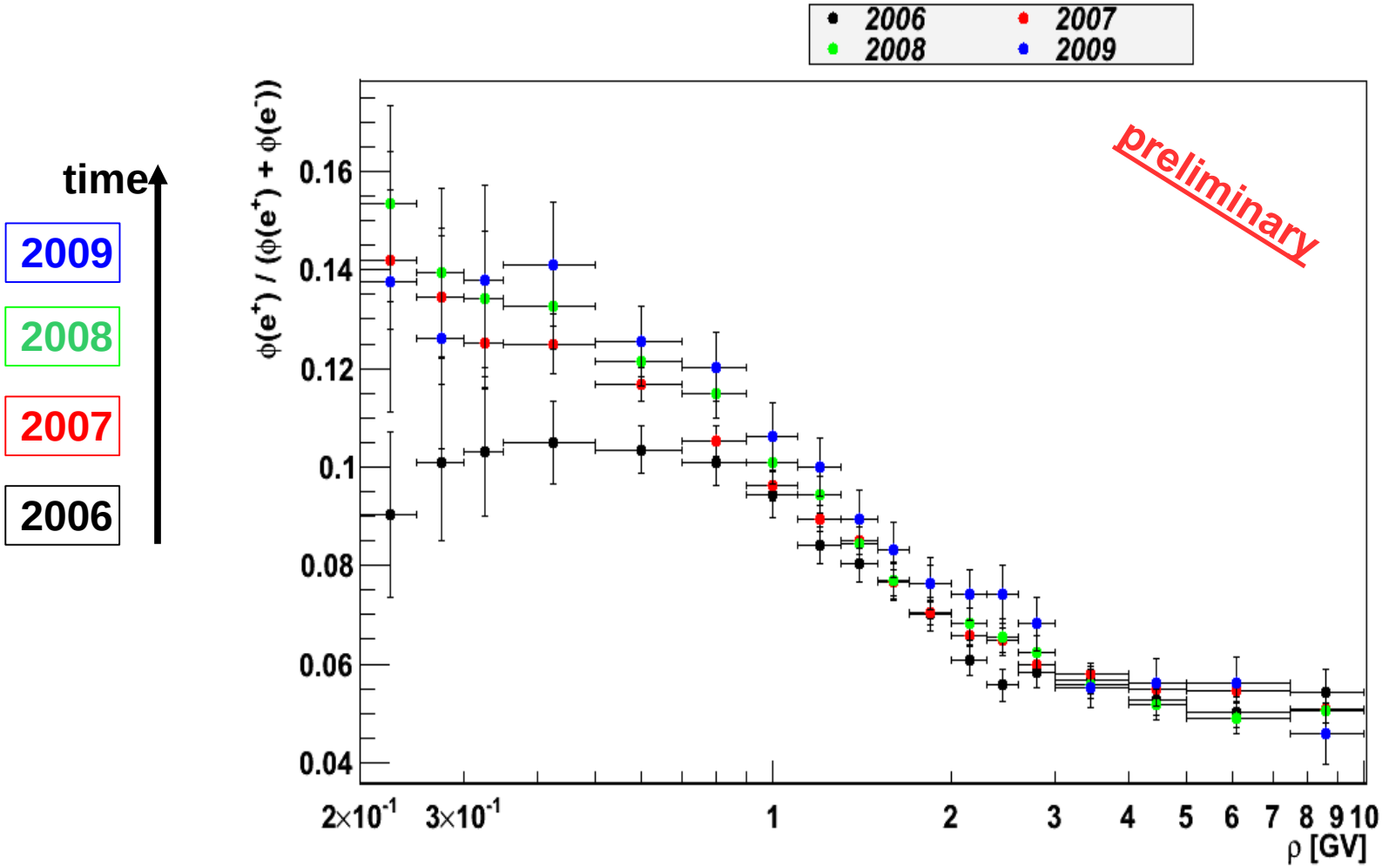
Galactic e⁻ and e⁺ modulation

preliminary



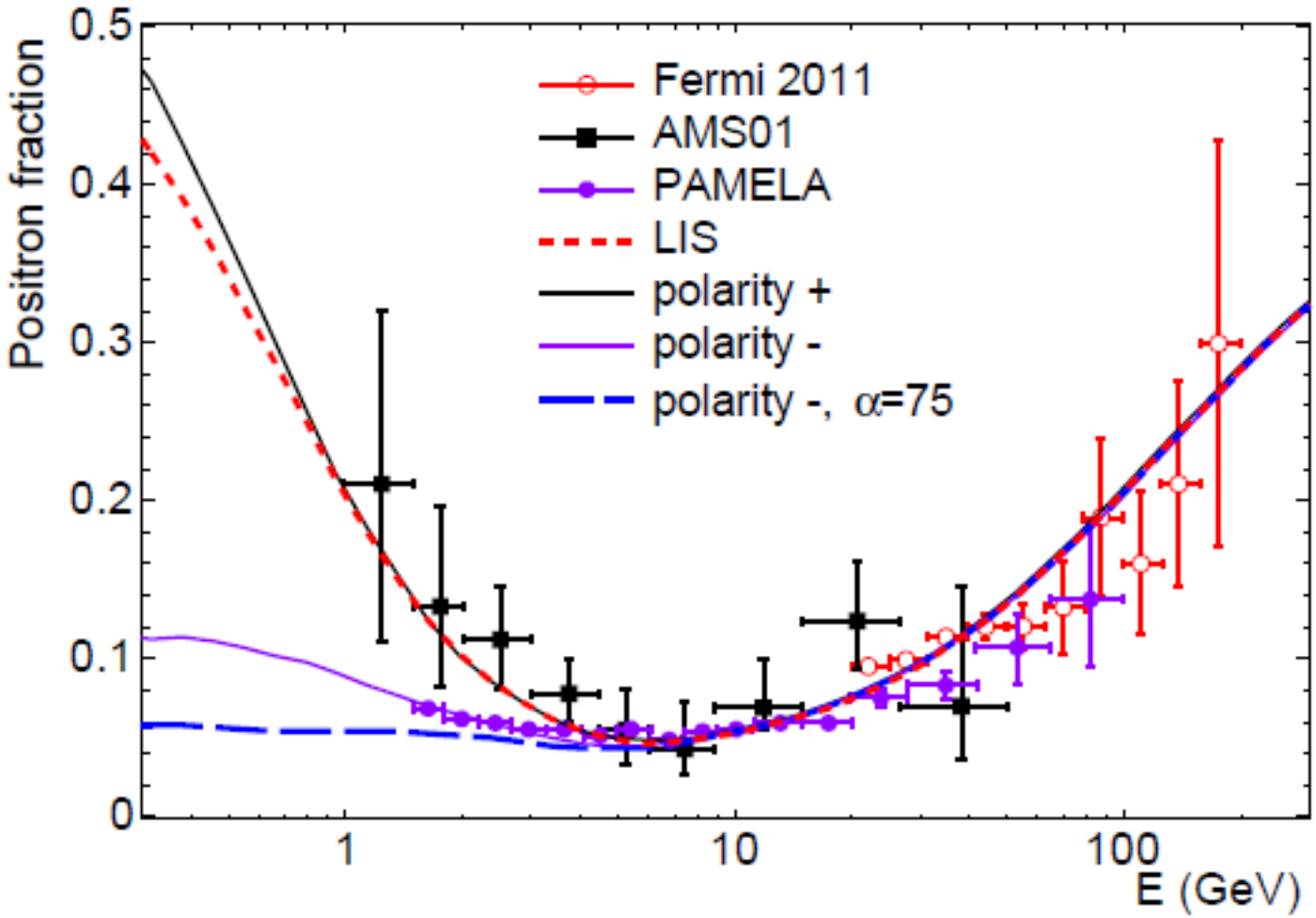


Positron fraction increases going towards solar minimum



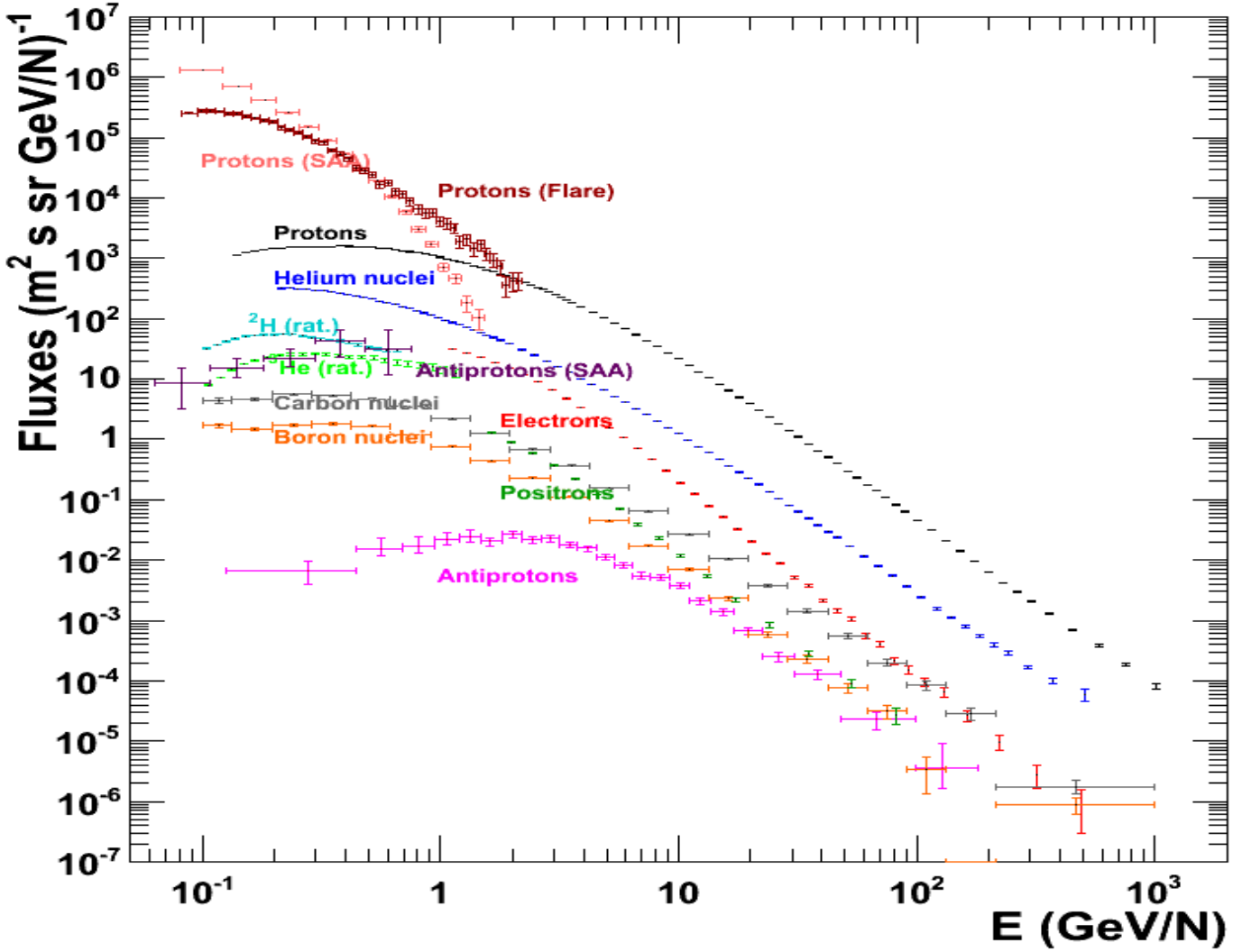
Positron fraction increases from 2006 to 2009.

Charge-Sign Dependent Solar Modulation



L. Maccione, PRL 110 (2013) 081101.

Summary of PAMELA results



Summary

- PAMELA has been in orbit and studying cosmic rays for ~7 years. >10^9 triggers registered and >30 TB of data down-linked.

- Hydrogen and helium nuclei spectra measured up to 1.2 TV. Theses observations challenge the current paradigm of cosmic ray acceleration and propagation

- Antiproton-to-proton flux ratio and antiproton energy spectrum (~100 MeV - ~200 GeV) show no <u>significant</u> deviations from secondary production expectations.
- High energy (>10 GeV) positron fraction and energy spectrum increases significantly (and unexpectedly!) with energy. Primary source?

- Continuous study of solar modulation effects.

Thanks!