PAMELA mission: heralding a new era in cosmic ray physics

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On behalf of the PAMELA collaboration

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Summary

- Introduction.

  PAMELA apparatus and satellite mission.

- Selected results from measurements with PAMELA.

  (1) Primary cosmic-ray particles: H, He

  (2) CR antiparticles: e^+ , antiproton

  (3) CR light nuclei and isotopes: B/C, $^2H/^1H$

  [(4) Solar modulation of cosmic rays]

  [(5) Solar energetic particles (SEP)]

  [(6) Cosmic rays in the Earth magnetosphere]

PAMELA apparatus and satellite mission

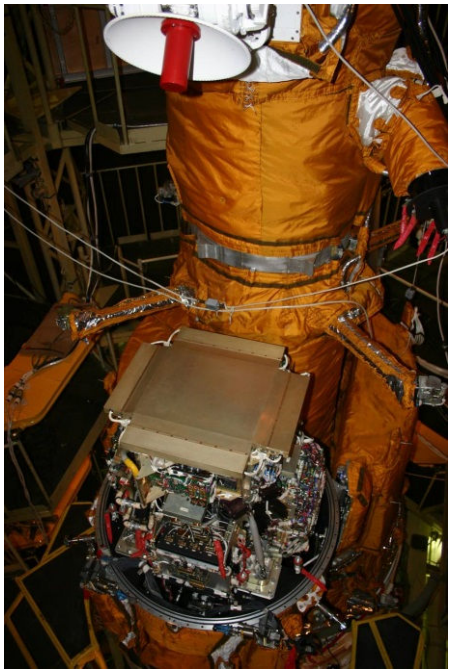
- High-precision cosmic-rays detectors.
  - **Sensitive to both particles and antiparticles (charge sign) and light nuclei.**
  - **Kinetic energy range depending on species:**
    e.g. for p, e^- it goes (roughly) from ~ 50 MeV to ~ 1 TeV.

- Satellite mission.
  - **Absence of atmospheric overburden.**
  - **More than 7 years continuous data taking.**

The PAMELA collaboration

Italy

Bari, Florence, Naples, Rome, Trieste, Frascati



Russia

Moscow,
St. Petersburg

Germany

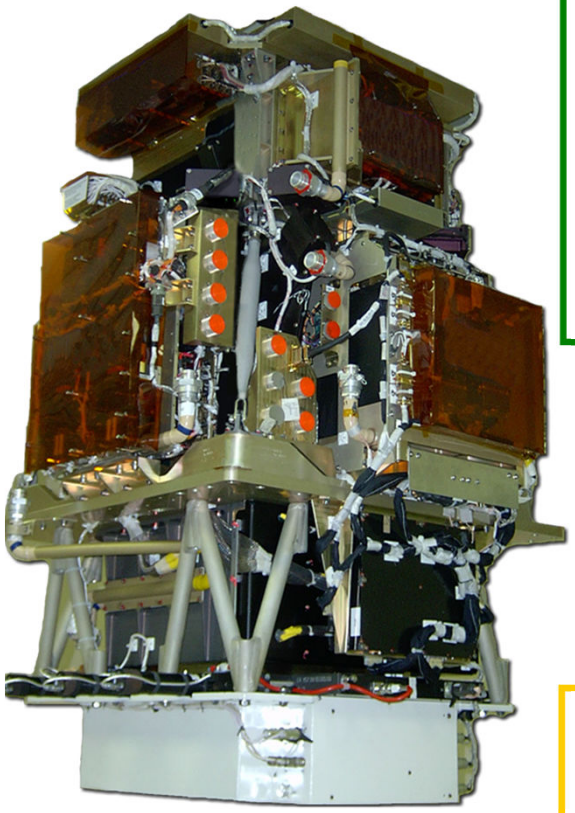
Siegen

Sweden

Stockholm

PAMELA detectors

Main requirements: high-sensitivity antiparticle identification; accurate momentum measurement.



GF: 21.6 cm² sr

Mass: 470 kg

Size: 130 · 70 · 70 cm³

Power budget: 360 W

Time-Of-Flight

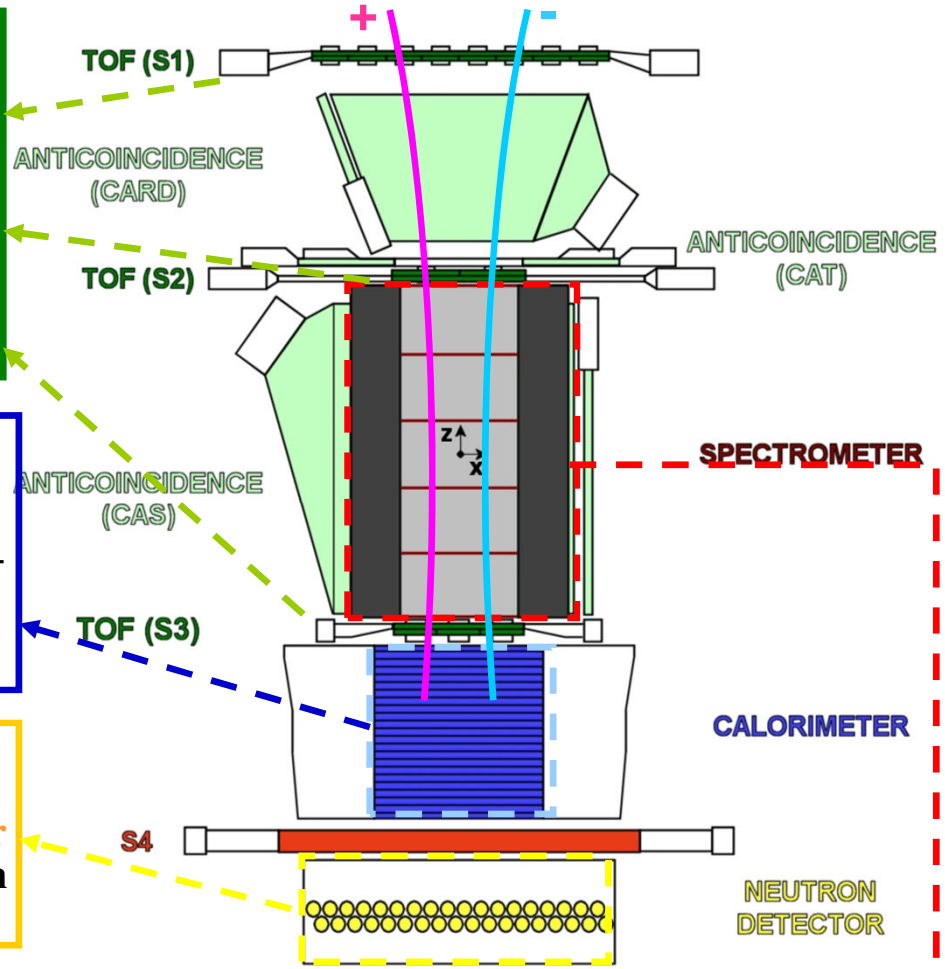
Plastic scintillators + PMT
- **Trigger - Albedo rejection**
- **Mass identification up to E ~ 1 GeV**
- **Charge identification |Z| from dE/dL**

Electromagnetic calorimeter

W/Si sampling (16.3 X_0, 0.6 λ_I)
- **Discrimination e^+ / p, anti-p / e^- (shower topology)**
- **Direct E measurement for e^-/e^+**

Neutron detector

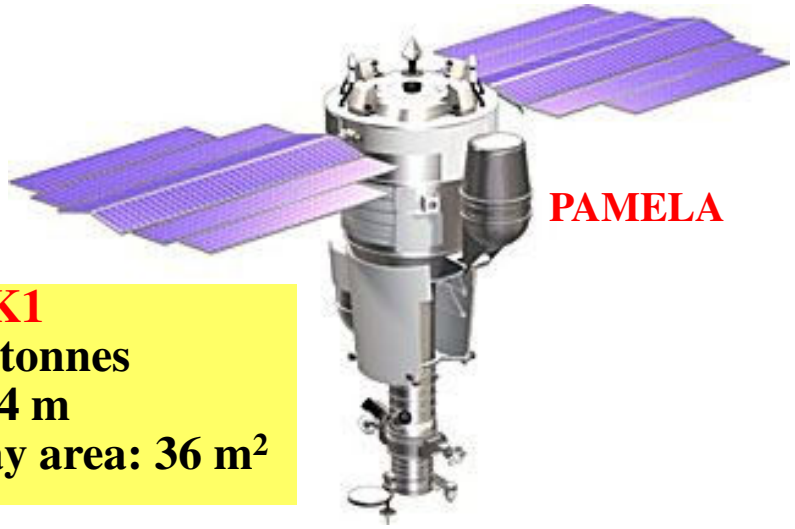
^{3}He tubes + polyethyl. moderator
- **High-energy e/h discrimination**



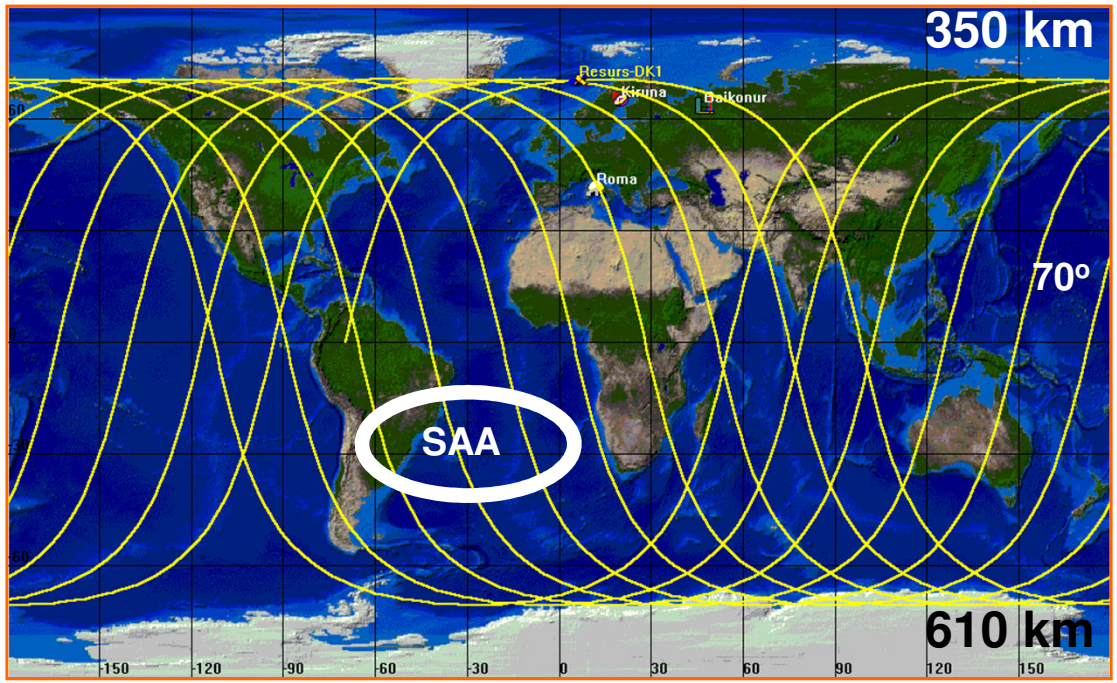
Spectrometer

microstrip silicon tracking system + permanent magnet
- **Magnetic rigidity R = Pc/|Z|e**
- **Charge sign**
- **Charge value |Z| from dE/dL**

Resurs-DK1 satellite and orbit



Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m²



~90 min orbit duration

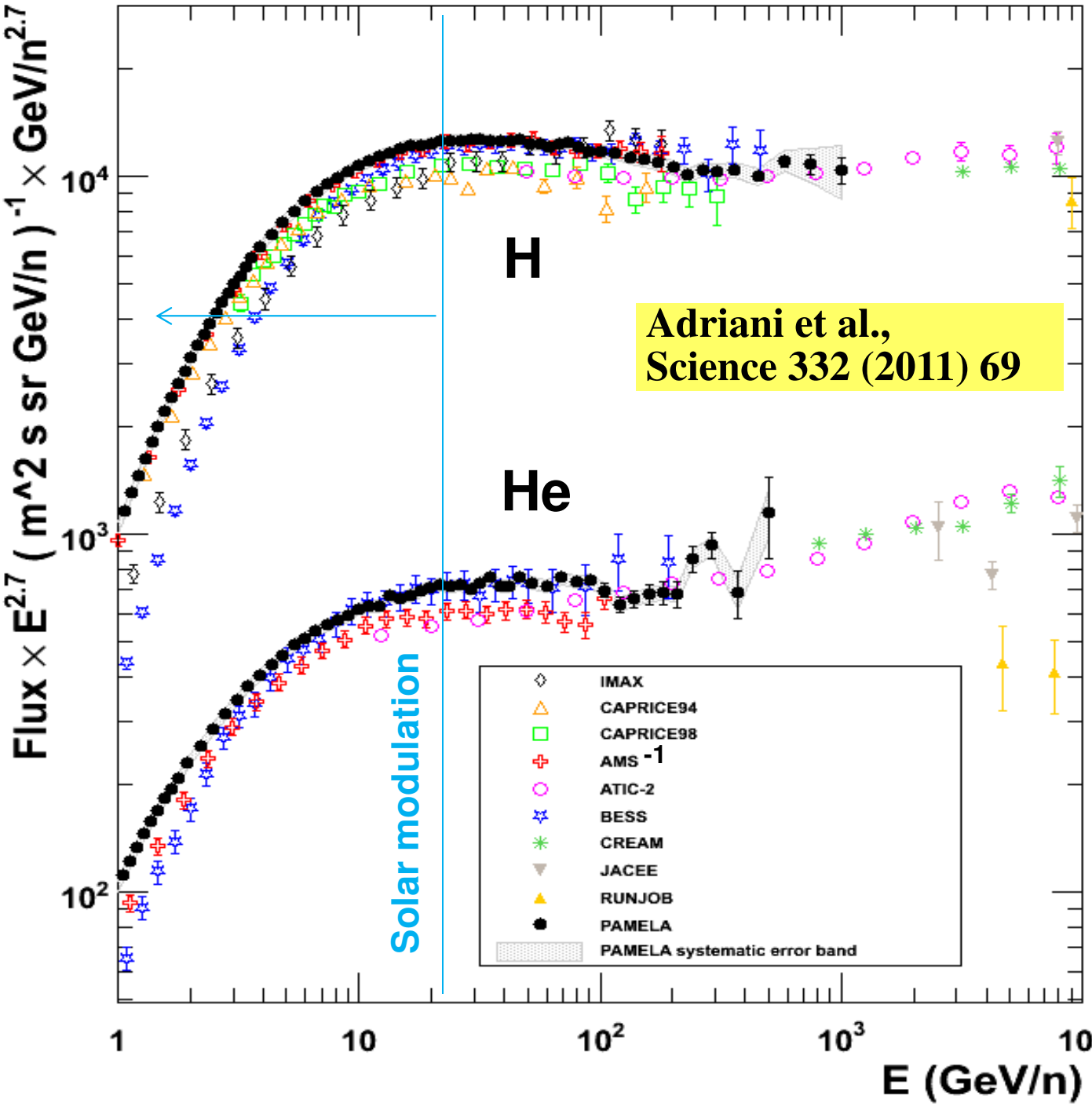
- Resurs-DK1: multi-spectral imaging of earth's surface.
- PAMELA mounted inside pressurized container.
- **Launched: June 2006.**
- **Lifetime > 3 years (assisted, first time February 2009); extended till end of satellite operations (currently 2014).**

- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km). From 2010: circular orbit (70.0°, 600 km).
- Traverses the South Atlantic Anomaly (SAA).
- Crosses the outer (electron) Van Allen belt in southern polar regions.
- **Data transmitted to NTsOMZ (Moscow) via high-speed radio downlink, ~16 GB per day.**

(1) Primary cosmic-ray particles: H, He

- PAMELA high-precision measurements of galactic H and He fluxes challenge standard model of cosmic-ray acceleration and propagation.
  - **Propagation effects, previously not taken into account?**
  - **Acceleration effects?**
  - **Effect of discrete space/time distribution of SNR? Nearby SNRs?**
  - **Different types of sources and acceleration mechanisms?**

PAMELA H and He absolute fluxes



Adriani et al., Science 332 (2011) 69

Historically the first high-precision measurement (at level of few %).

Found several fine deviations from standard description (simple power-law spectra with spectral index α ~ -2.7).

Note: AMS-2 recently reported measurements done with comparable precision, showing disagreements of several %, which have now become very important for theoretical models.

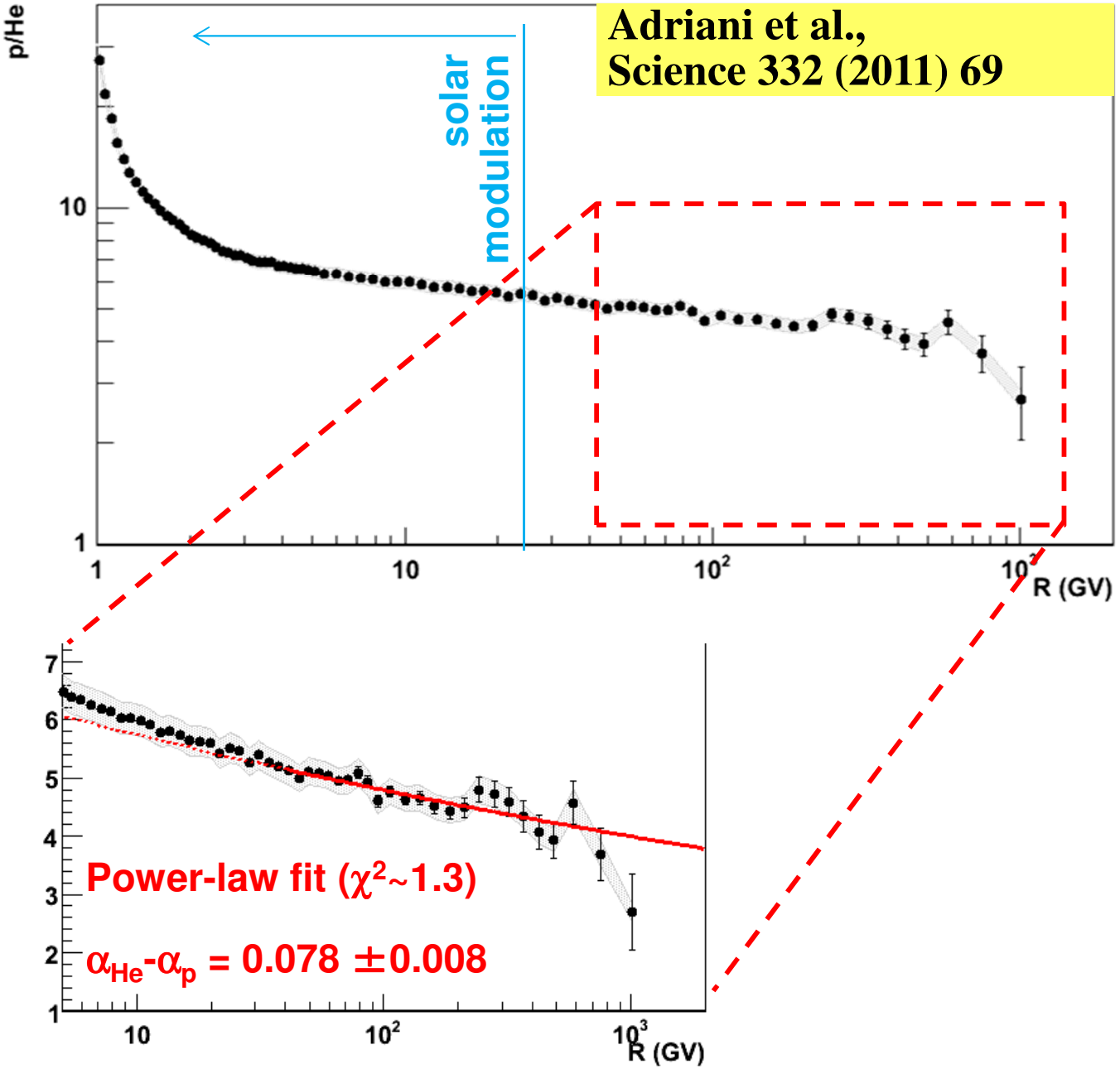
PAMELA H/He ratio vs rigidity

(1) Found different spectral index for H and He.

Very accurate measurement: systematic uncertainties partially cancel out in the ratio of fluxes.

Theoretical explanations.

- Spallation effects (from higher-Z nuclei) during propagation: Blasi & Amato, JCAP 1 (2012) 10.
- Acceleration effects (difference in the injection phase of the diffusive shock acceleration): Malkov et al., PRL 108 (2012) 081104.



H, He absolute fluxes at high energy

(2) Found deviations from single power law (SPL).

- Spectra gradually soften in the range 30 ÷ 230 GV.
- Spectral hardening: at rigidity R ~ 235 GV, $\Delta\alpha \sim 0.2 \div 0.3$.

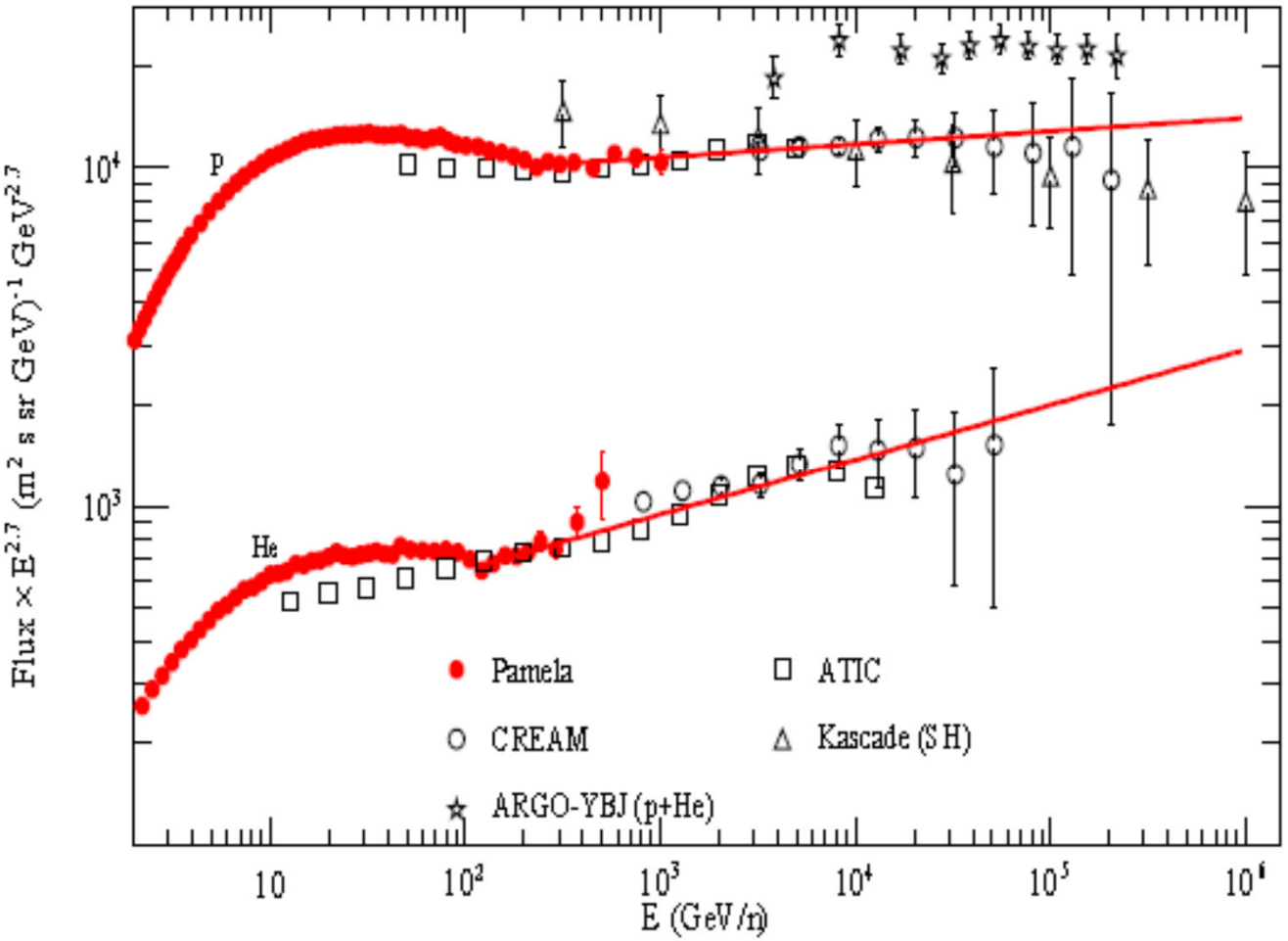
SPL rejected at 98% CL.

Agreement with higher energy measurements.

Origin of the structures?

- At the sources: multi-populations, etc.?
- Propagation effects?

Comprehensive study:
Vladimirov et al., APJ 752 (2012) 68.



(2) Cosmic-ray antiparticles: e^+ and antiproton

- Standard model:

  cosmic-ray antiparticles originated from secondary processes (nuclear interactions of CR with interstellar gas).

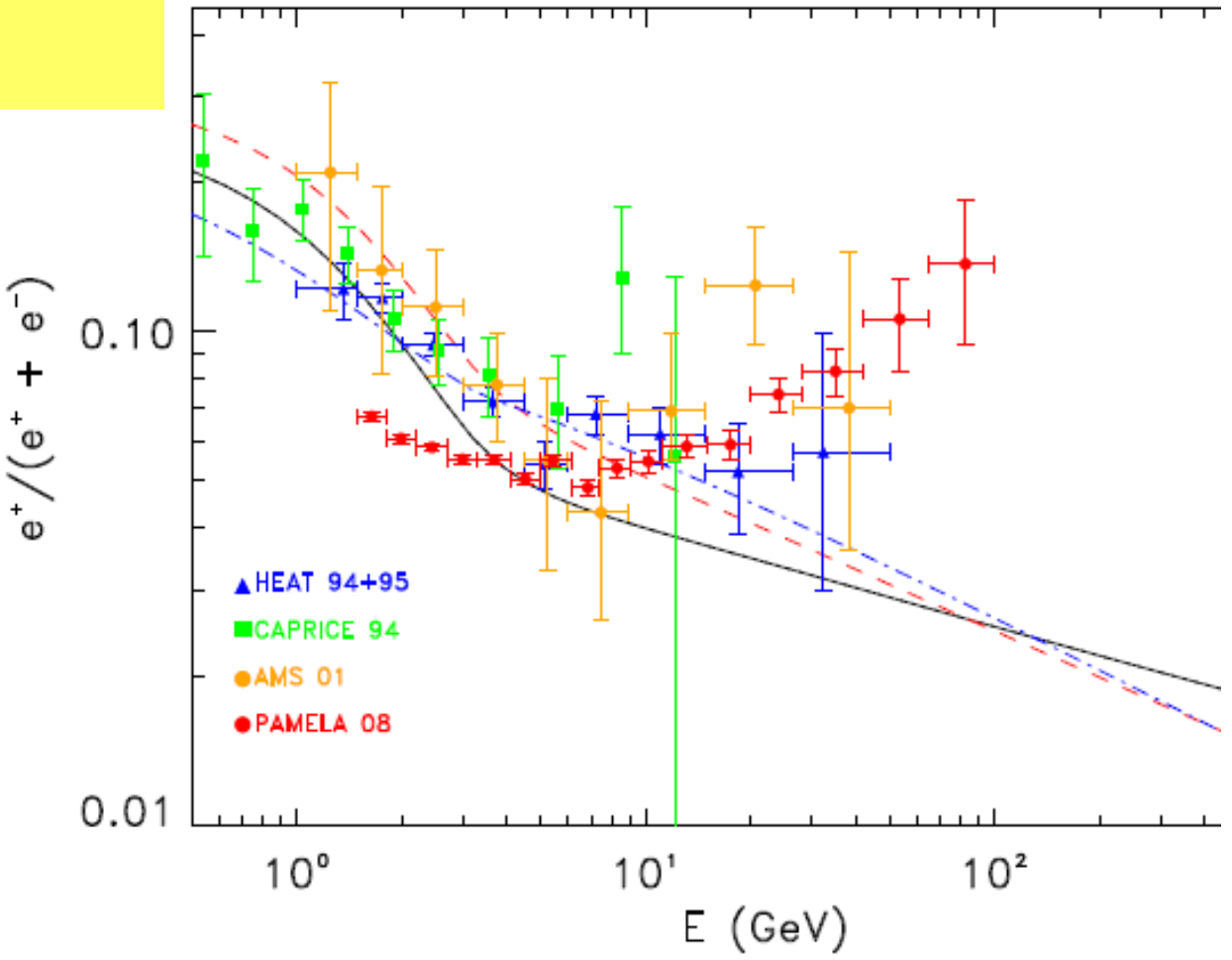
- **PAMELA e^+ measurements challenge standard model.**
  - Nearby astrophysical primary source?
    Pair production in pulsar magnetosphere?
    Secondary production and re-acceleration in SNR?
  - Exotic primary source? DM decay/annihilation in the galactic halo?

- **PAMELA antiproton measurements put very strict contraints on non-standard models, especially DM ones.**

PAMELA positron fraction

Historically the first clear evidence of a high-energy excess.
Nature 458, 607 (April 2009).

Needed additional primary source of e^+ with harder spectrum than e^-.
Several mechanisms proposed (DM, pulsar, SNR…) in ~10^3 papers. See e.g.:
<u>DM:</u>
Bergstrom et al., Phys. Rev. D 78 (2008) 103520;
Cholis et al., Phys. Rev. D 80 (2009) 123518.
<u>Pulsar:</u>
Yuksel et al., PRL 103 (2009) 051101;
Blasi & Amato, arXiv:1007.4745.
<u>Both:</u>
Hooper & Xue, PRL 110 (2013) 041302.

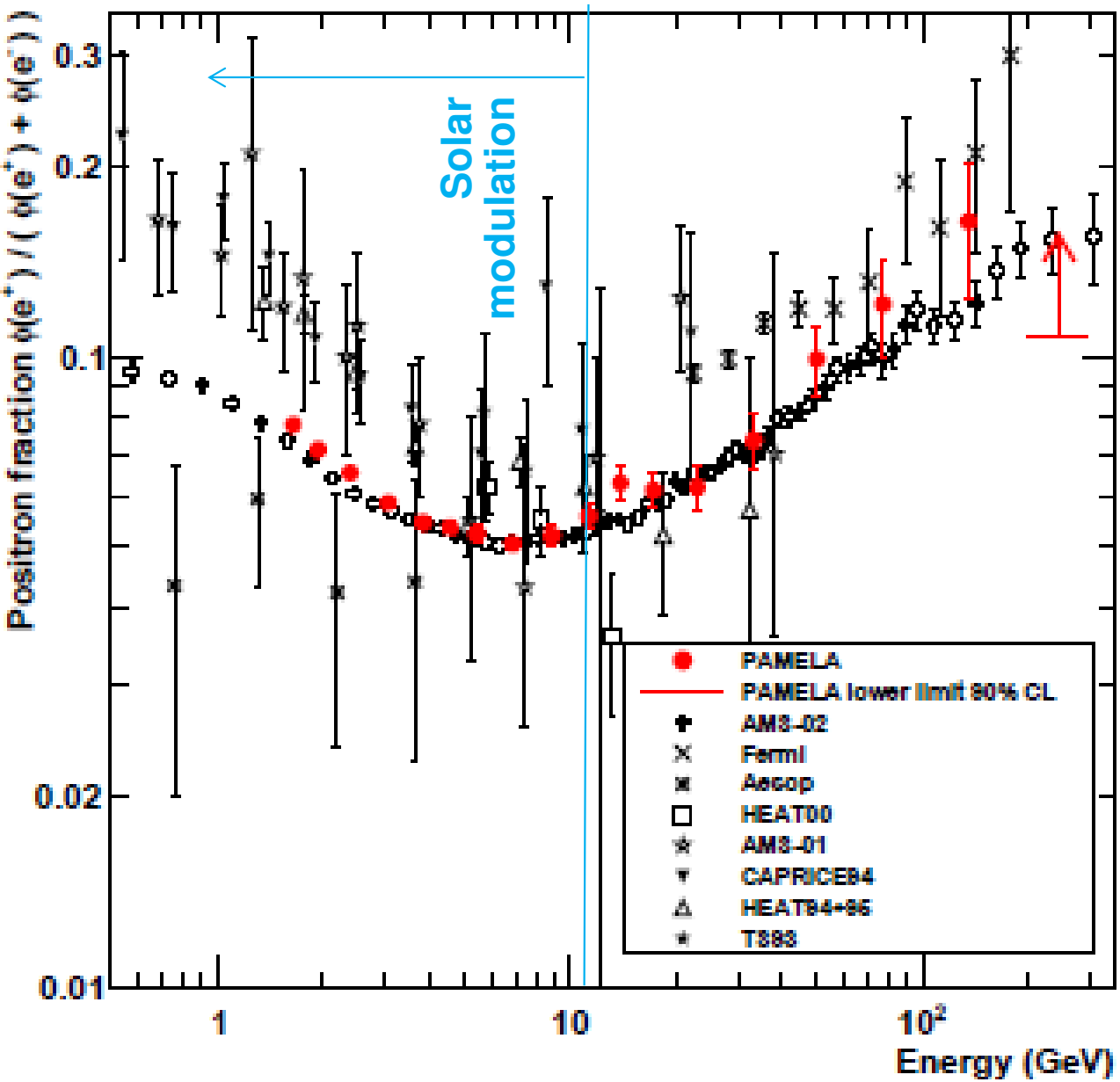


Grasso et al., Astropart. Phys. 32 (2009) 140

Positron fraction: new PAMELA data

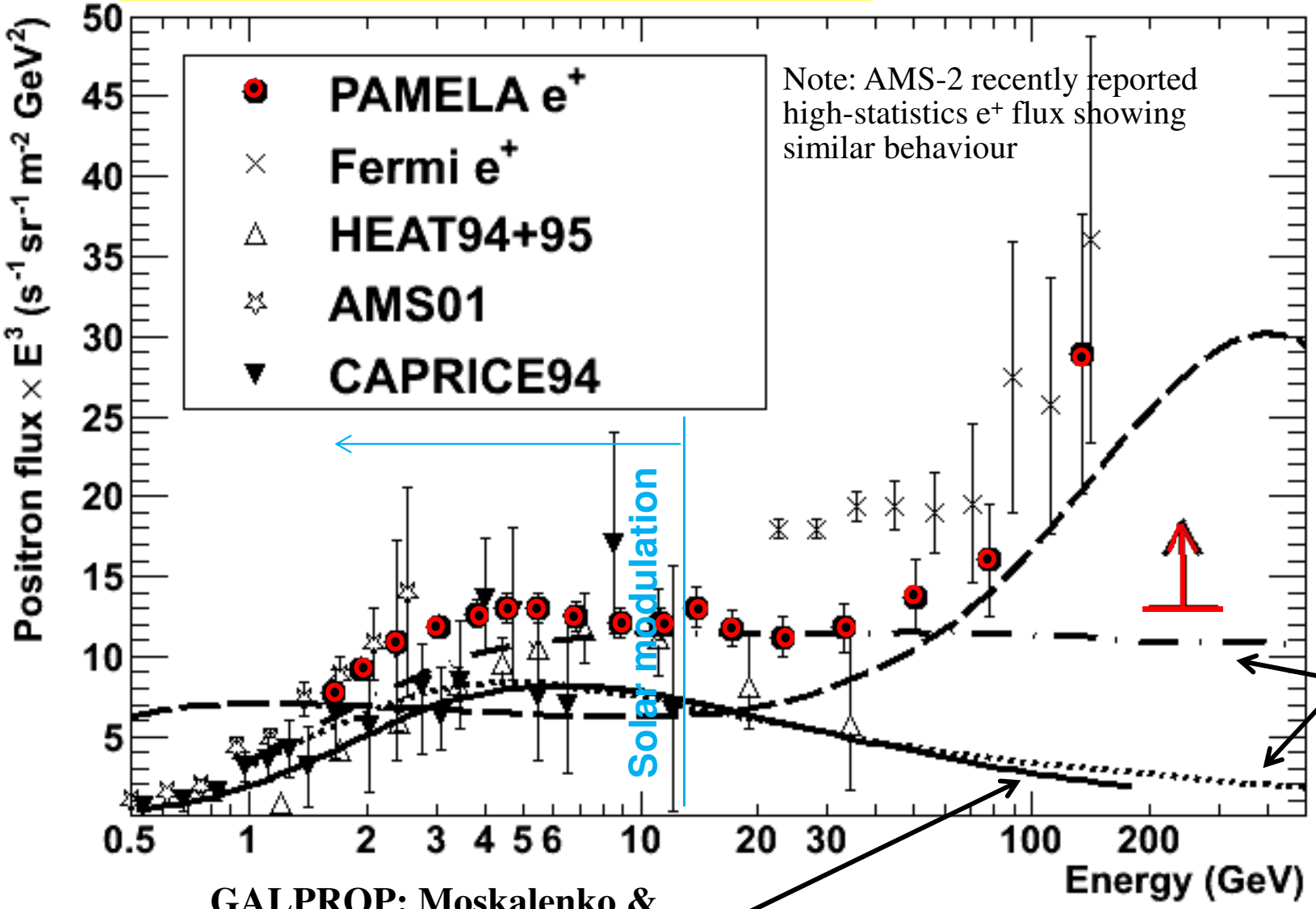
PAMELA measurement of excess subsequently confirmed by Fermi and, with more statistics, by AMS-02.

Here shown new PAMELA analysis using all data till 2010 and multivariate classification algorithms (with ~250% increase in statistics).
Adriani et. al, PRL 111 (2013) 081102.



PAMELA positron flux

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



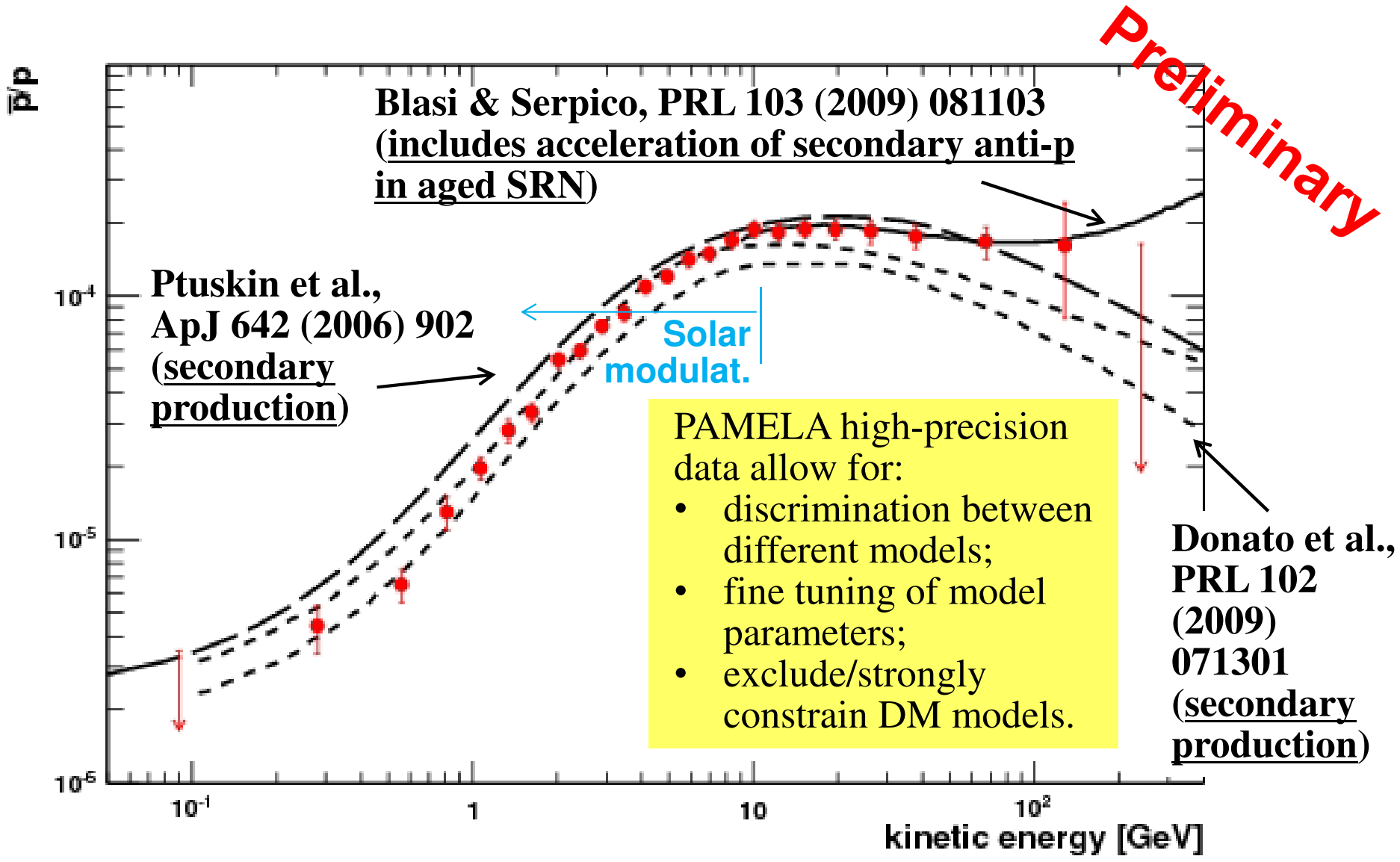
Note: AMS-2 recently reported high-statistics e^+ flux showing similar behaviour

Finkbeiner et al., JCAP 1105, 002 (2011). Secondary + primary production (from dark matter annihilation)

Delahaye et al., A&A 524 (2010) A51 Secondary & Secondary + Primary productions (from astrophysical sources)

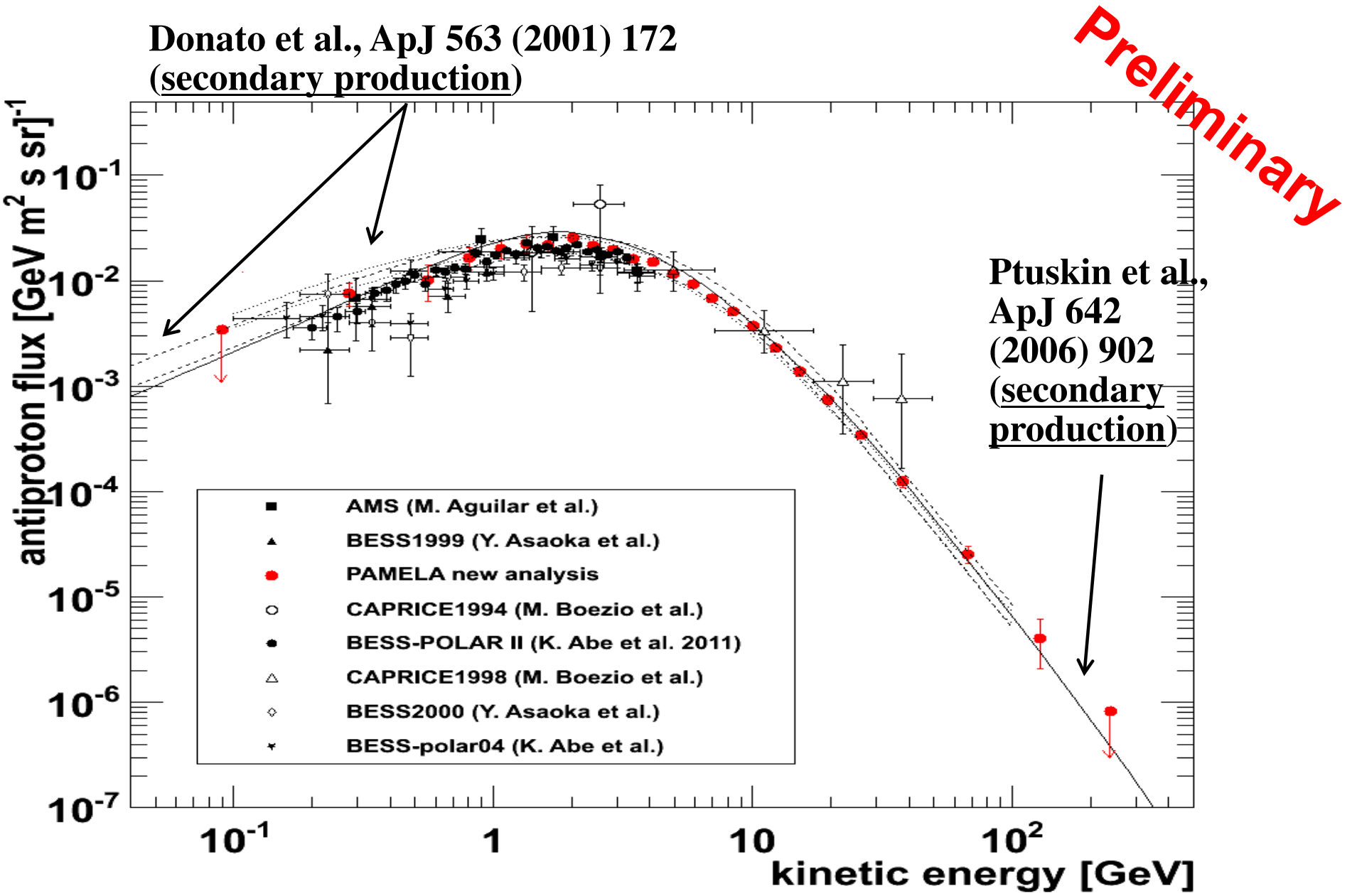
GALPROP: Moskalenko & Strong ApJ 493, 694 (1998) Secondary production

Antiproton/proton ratio: new data

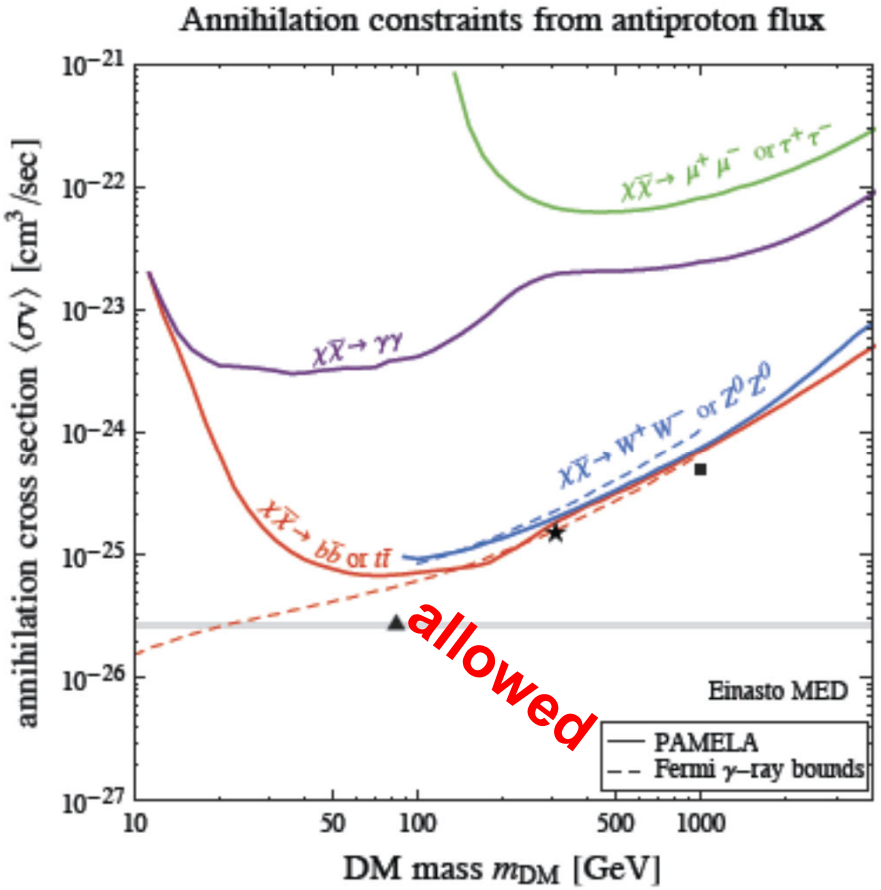


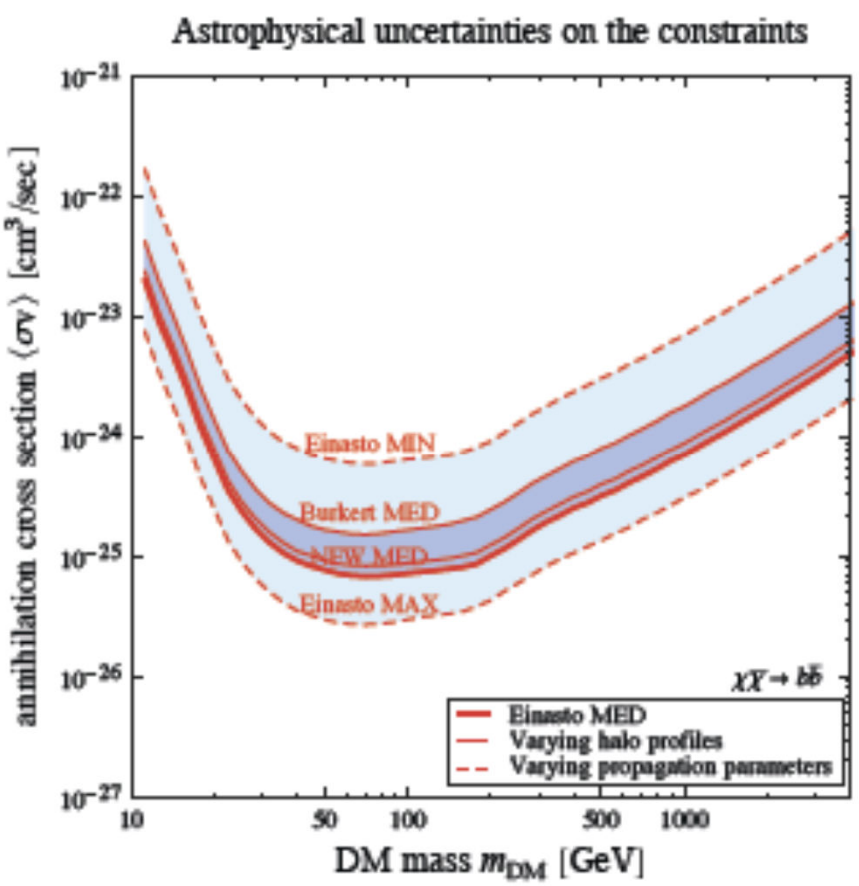
Here presented results with new analysis method (multivariate classification algorithms), allowing for significant increase in statistics. See also previously published results: Adriani et al., PRL 102, 051101 (2009); PRL 105, 121101 (2010).

Antiproton flux: new data



DM limits from cosmic-ray antiprotons





Cirelli & Giesen, arXiv: 1301:7079

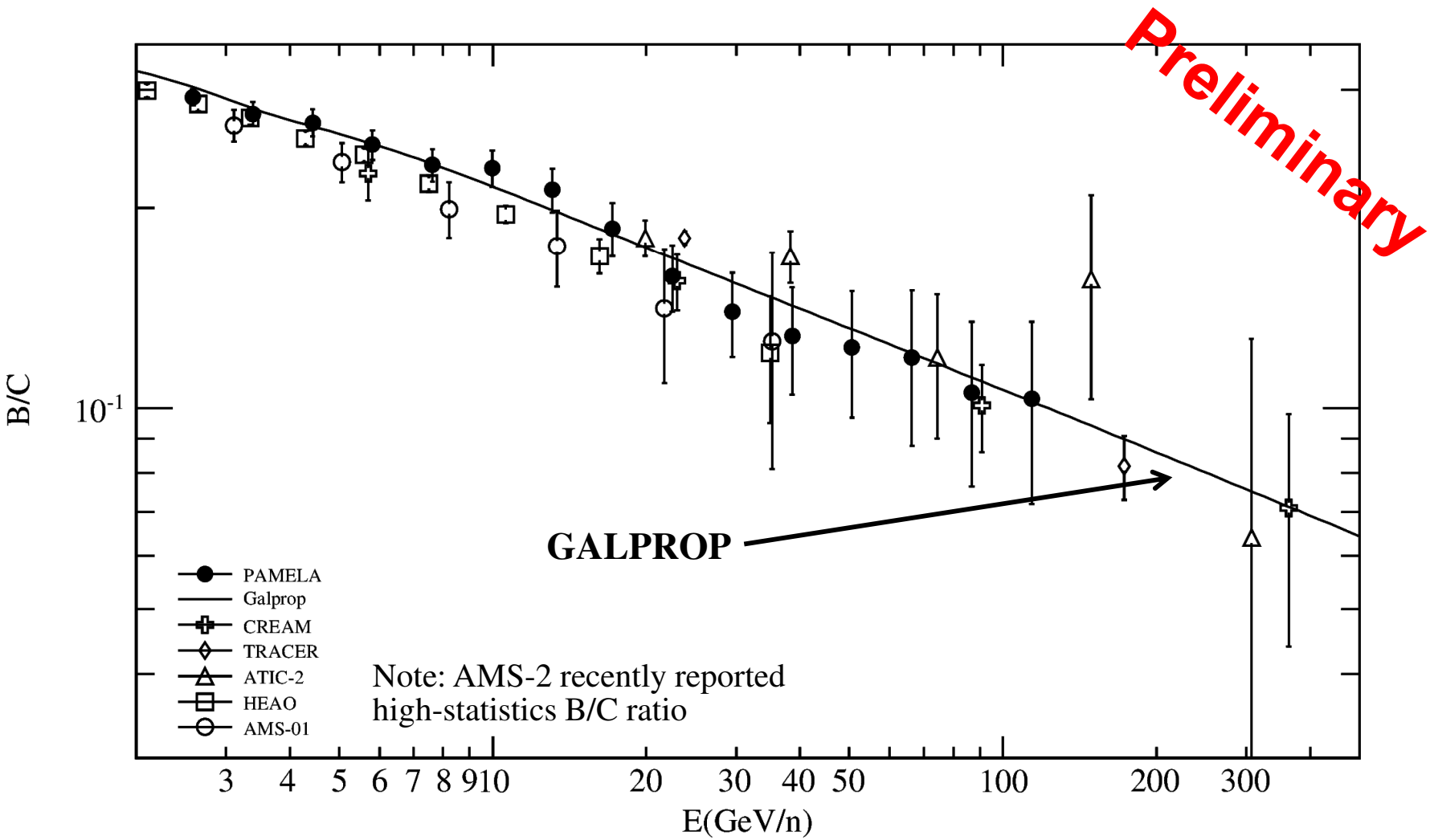
Antiprotons are a very relevant tool to constrain Dark Matter annihilation and decay models.
Current PAMELA data and upcoming AMS-2 data allow probing large regions of the parameter space.

(3) Light nuclei and isotopes in cosmic rays: B/C, $^{2}H/^{1}H$

- Tuning of galactic cosmic-ray propagation models with measurement of secondary/primary flux ratio.
  - Local (solar system) secondary/primary ratio is sensitive to average amount of traversed matter from the source (SNR).

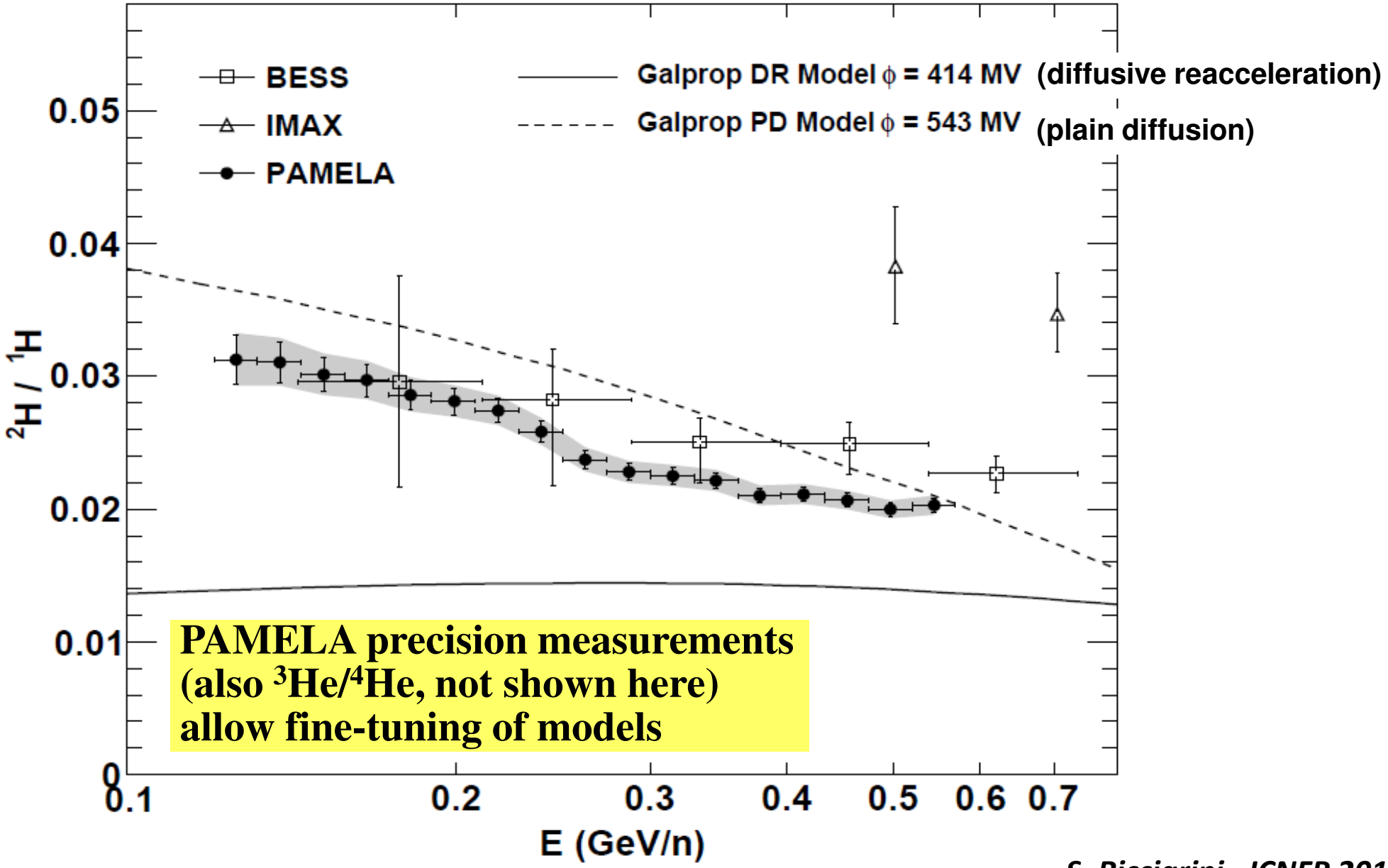
- **$^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complimentary to B/C measurement** in constraining propagation models (Coste et al., A&A 539 (2012) A88).

PAMELA Boron/Carbon flux ratio



PAMELA $^2H/^1H$ flux ratio

Adriani et al., ApJ 770 (2013) 2



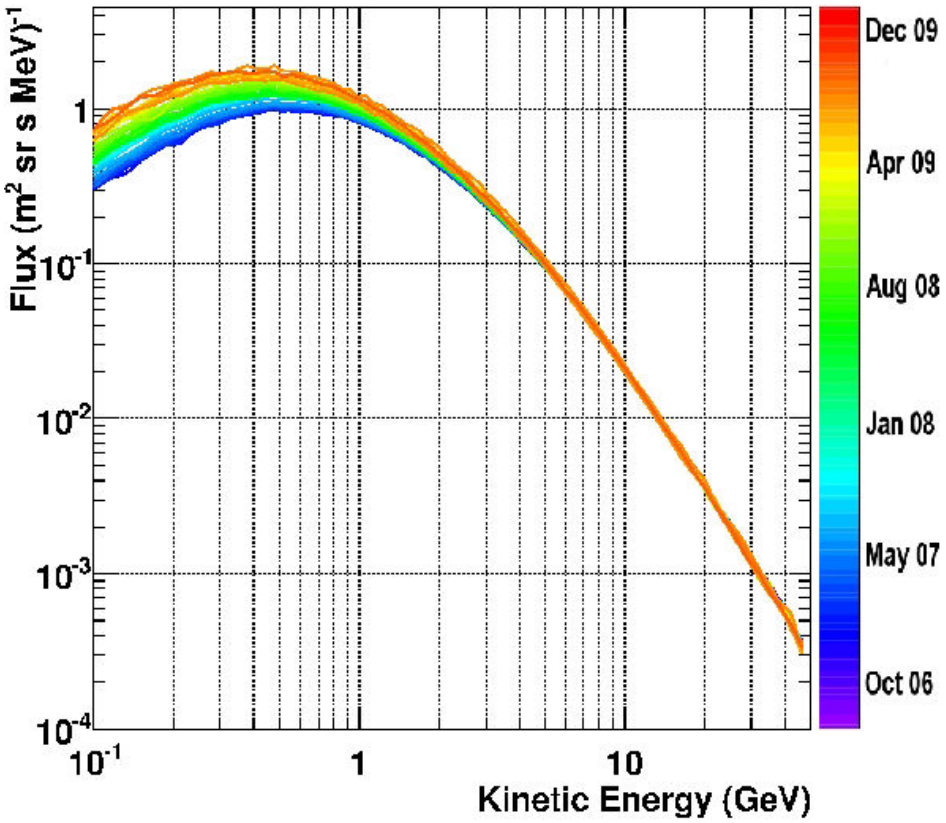
PAMELA precision measurements (also $^3He/^4He$, not shown here) allow fine-tuning of models

(4) Solar modulation of cosmic rays

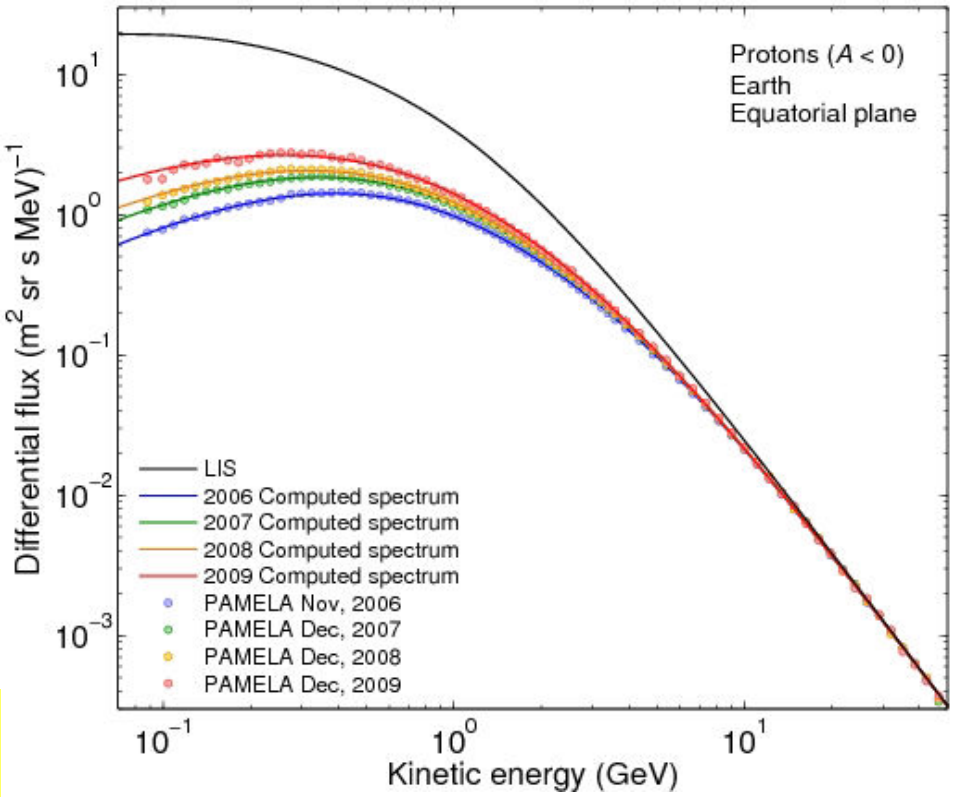
- PAMELA performed unique continuous multi-particle observations over several years (2006-2009) of solar minimum activity.
  - **Allow fine tuning of 3D fluido-dynamic models of heliosphere (convection / drift / diffusion / adiabatic change).**

Solar modulation of proton flux

Adriani et al., ApJ 765 (2013) 91



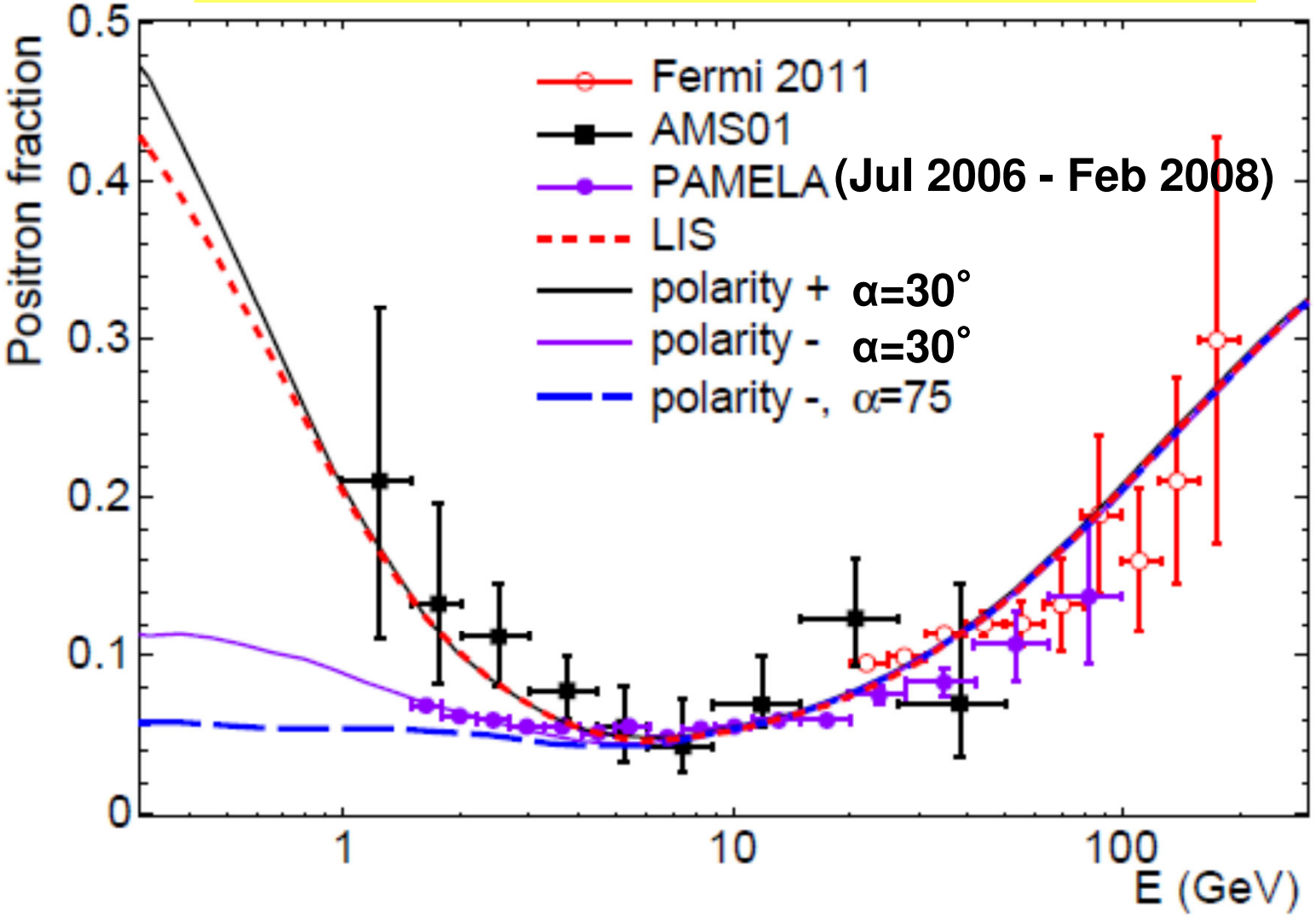
Evolution of the proton energy spectrum from July 2006 to December 2009 (unusually long solar activity minimum).



Precise PAMELA spectra allow fine tuning of 3D models of the heliosphere.
Here: **Potgieter et al. 2012, subm. to ApJ.**

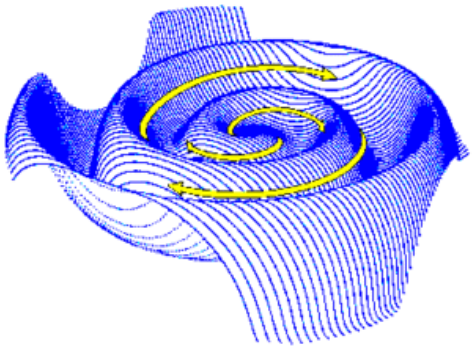
Charge-sign dependence of modulation

Flux ratio enhanced/suppressed depending on polarity (A) of solar magnetic field and amount of solar activity.



Maccione, PRL 110 (2013) 081101

α describes the angular extension of the **heliospheric current sheet** (increases with solar activity).



(5) Solar energetic particles (SEP)

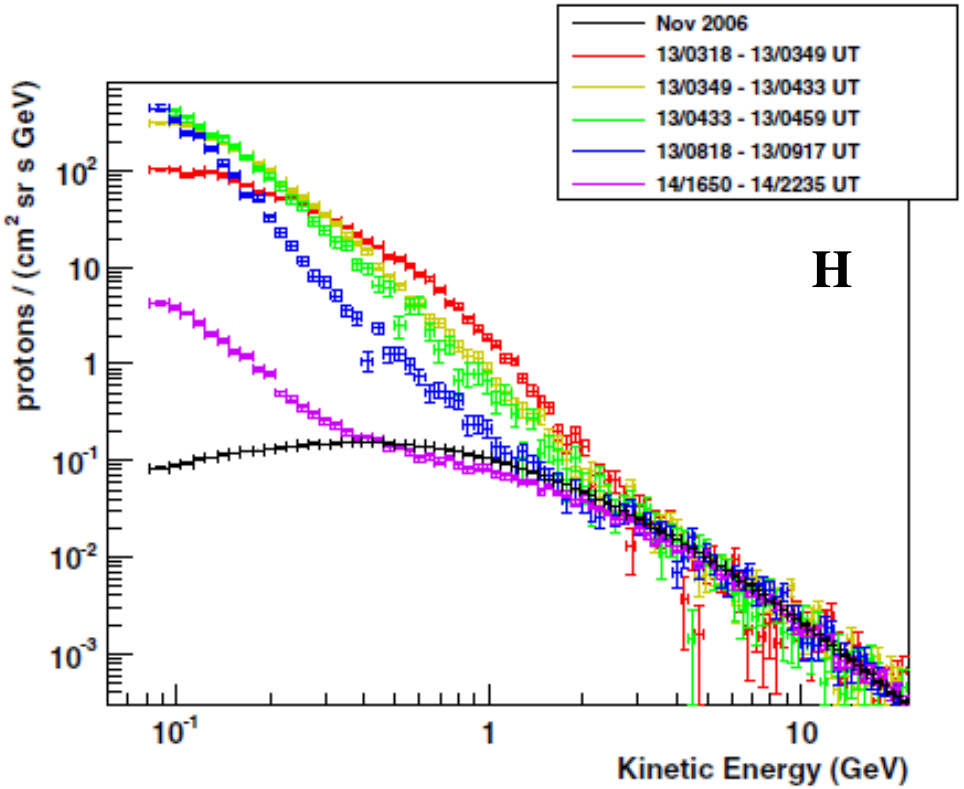
- PAMELA direct SEP measurements in high-energy range (from 80 MeV/n to relativistic energies) complement:
  - **low-energy direct measurements in space** (GOES, ACE satellites);
  - **high-energy indirect measurements on ground** (neutron monitors, atmospheric shower detectors), which are feasible only for induced Ground Level Events (GLE).

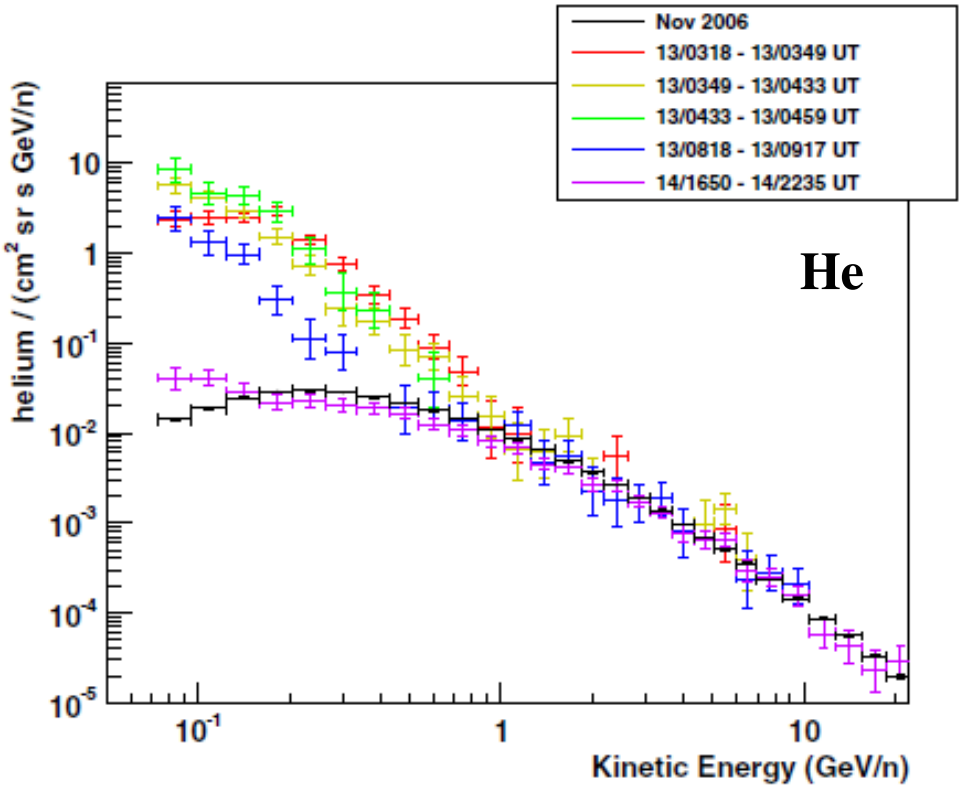
December 13th 2006 SEP event as seen by PAMELA

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

First ever direct measurement of relativistic SEP.

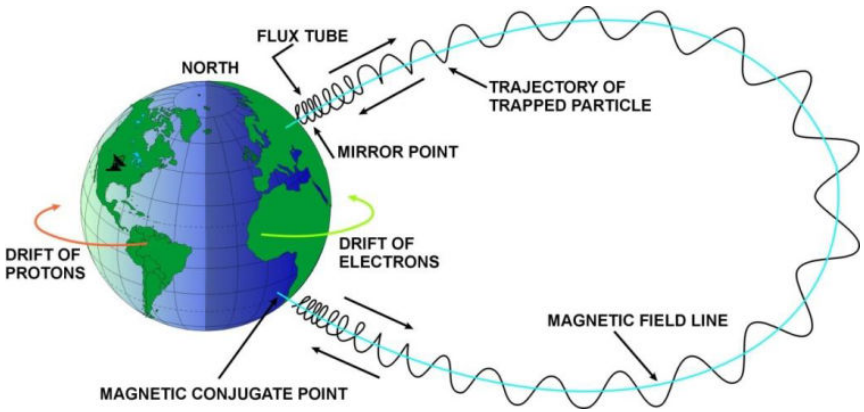
Measured also Forbush decrease of galactic particles after the arrival of the Coronal Mass Ejection (CME).





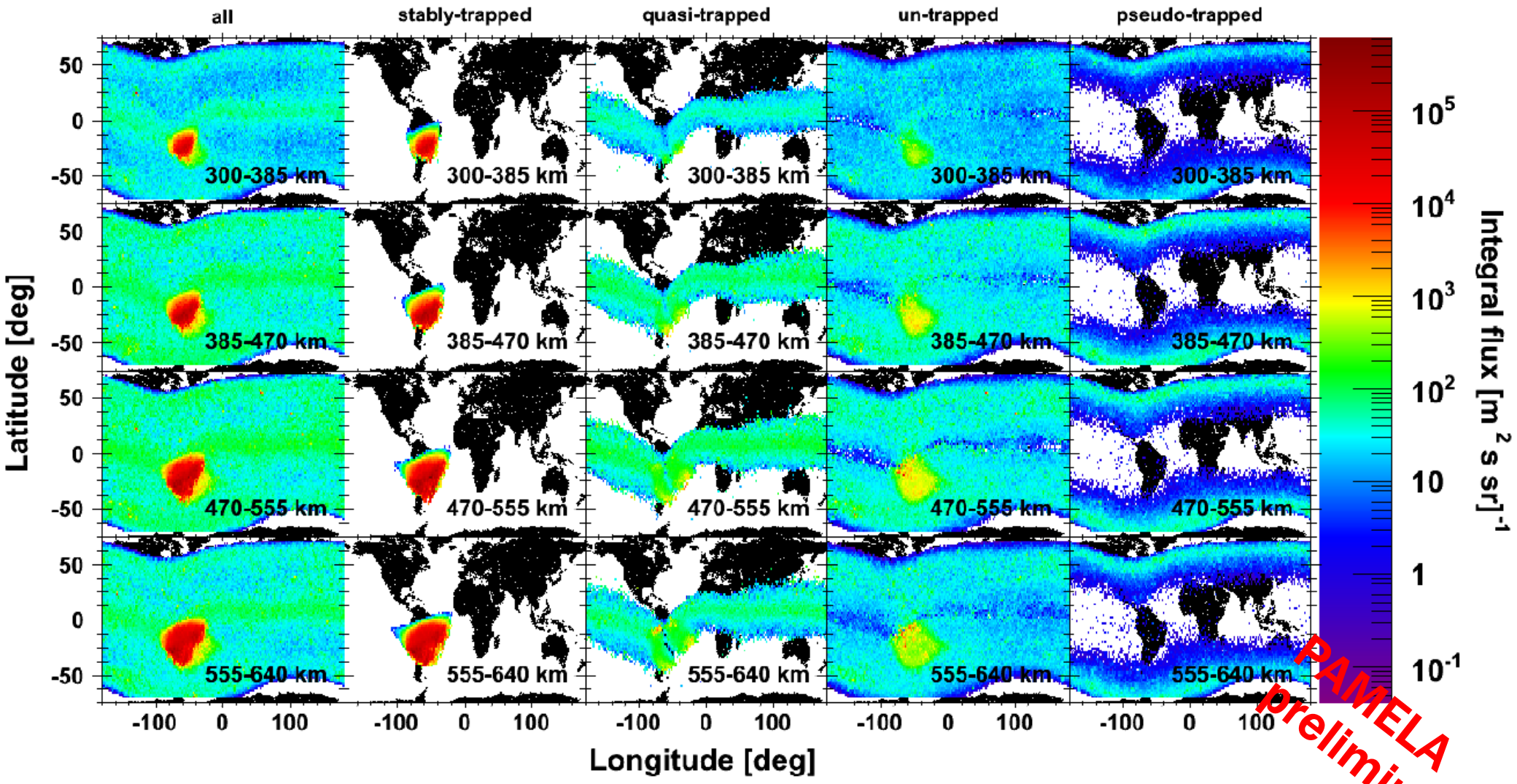
(6) Cosmic rays in the Earth magnetosphere

- Significant improvement in description of interaction processes of CR in geomagnetic field and atmosphere.
  - **Observational range of trapped protons extended to low altitudes (L-shell ~ 1.05) and to highest kinetic energies (~ 4 GeV).**



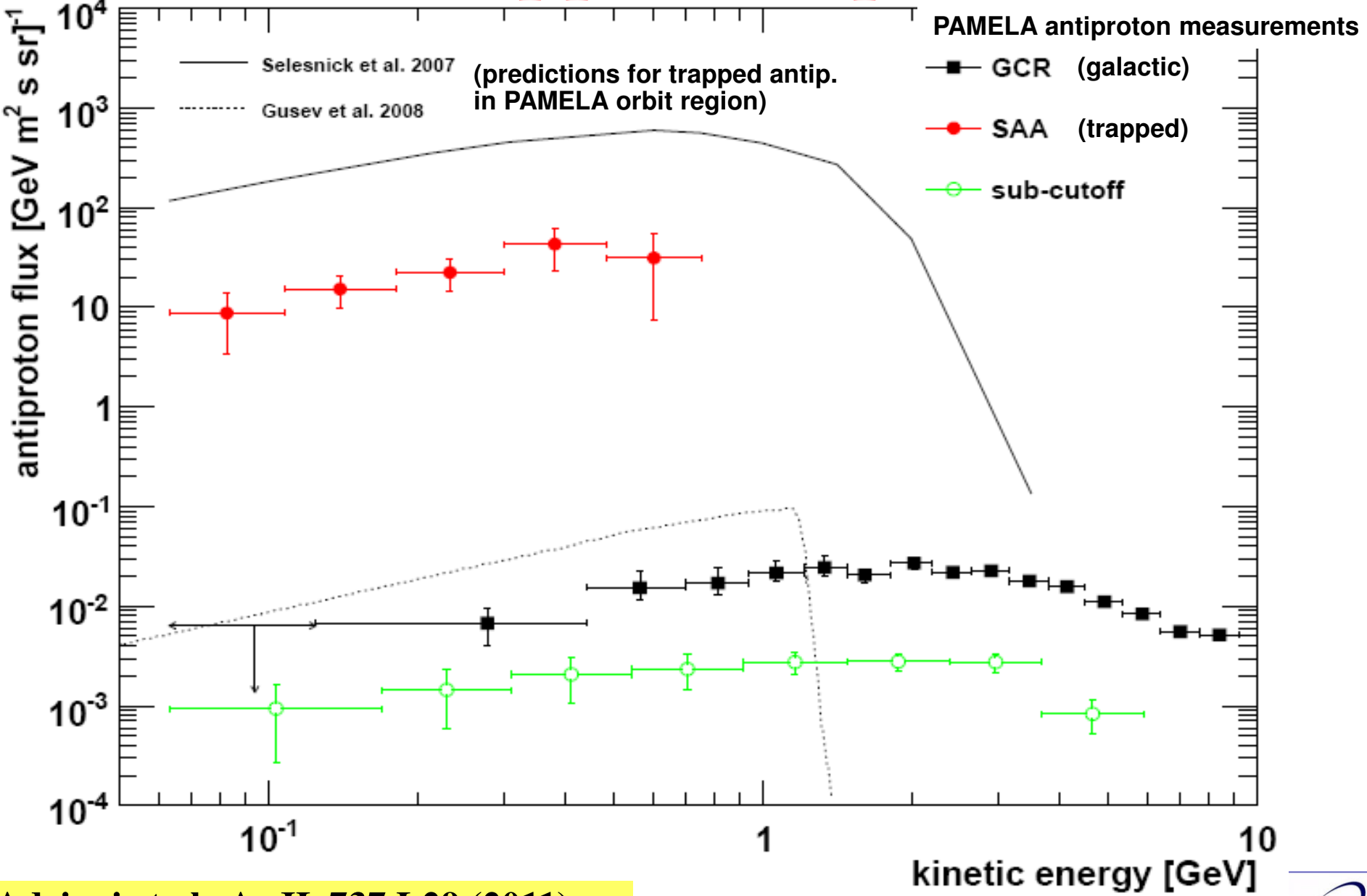
- Important for knowledge of:
  - **radiation dose and particle background on board of Low-Earth-Orbit (LEO) satellites.**
  - **particle cross sections in the atmosphere, contribution to muon and neutrino fluxes.**

Integral fluxes of "sub-cutoff" protons



For e^- and e^+ see Adriani et al., JGR, 114, A12 (2009).

PAMELA discovery of SAA trapped antiprotons



Adriani et al., ApJL 737 L29 (2011)

PAMELA highlights

- **PAMELA in orbit and studying cosmic rays since ~7 years:**
  $> 10^9$ triggers registered; ~ 30 TB data down-linked.

- **Measured high energy positron fraction (> 10 GeV) and positron absolute flux increase significantly (and unexpectedly!) with energy. Primary source?**

- **Precision measurements of antiproton/proton flux ratio and antiproton energy spectrum (~100 MeV to ~200 GeV) show no significant deviations from secondary production expectations.**

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

- **Unique continuous study of solar modulation effects at low energy.**

- **Study of trapped particles in the Earth magnetosphere, with the discovery of an antiproton radiation belt.**