The PAMELA Experiment: A decade of Cosmic Rays Investigation

Riccardo Munini

INFN Trieste

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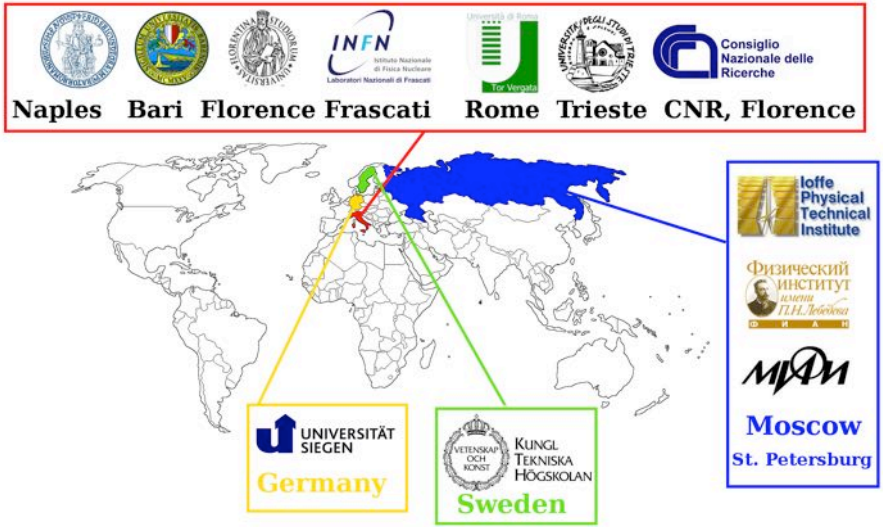
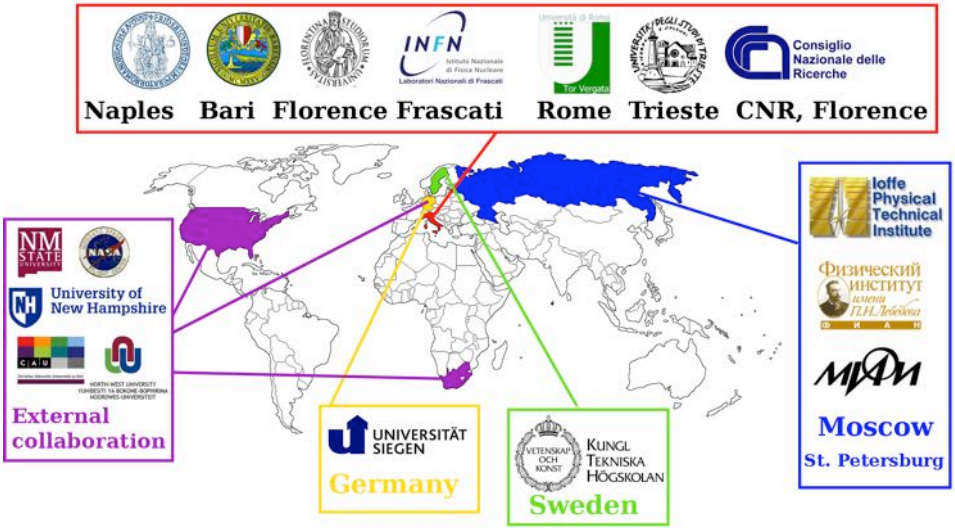
PAMELA COLLABORATION

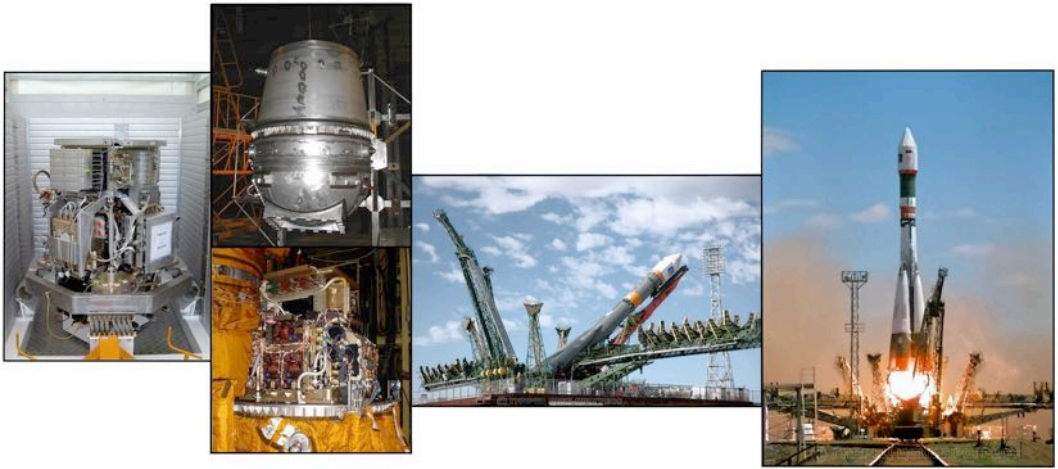


PAMELA collaboration and external collaboration



10 years of PAMELA

Launched on 15th June 2006. Recently celebrate 10 years in flight!



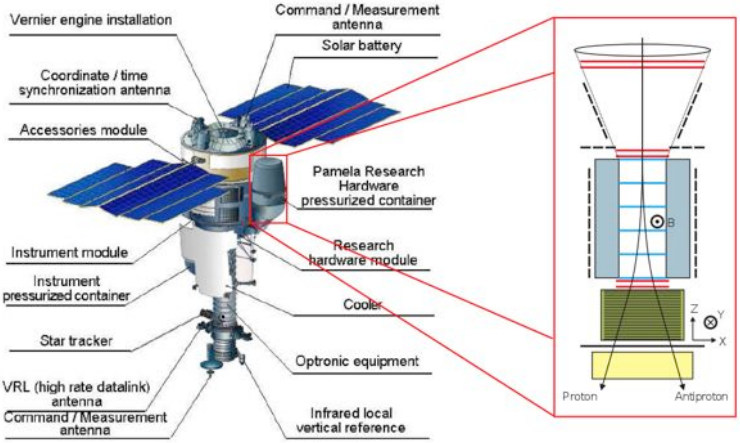
The PAMELA instrument

PAMELA

- Resurs DK1 satellite, high quality camera;
- Quasi-polar elliptical orbit 70 degree inclination 350/610 km.
- Circular from 2010 at 600 km.

Main goals

- Direct detection of CRs in space;
- Precise measurement of (anti)particles;
- **Solar modulation, solar physics.**



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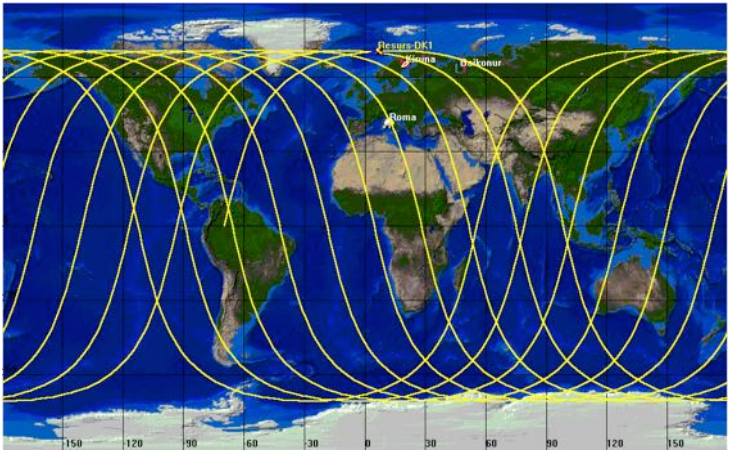

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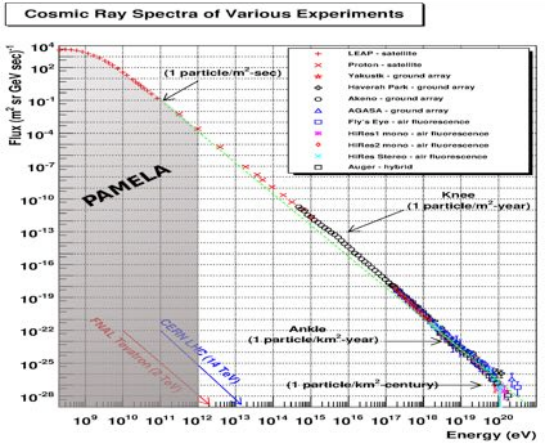

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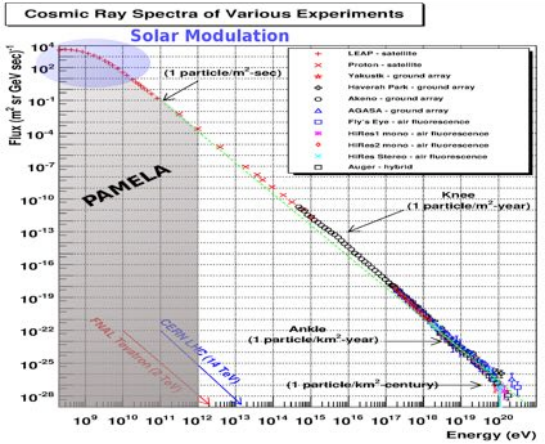

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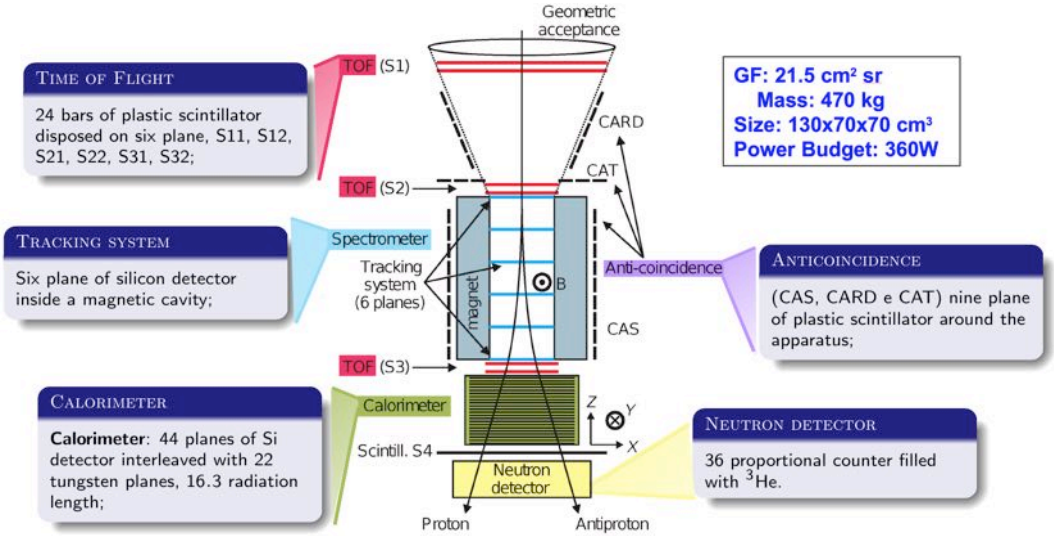


Time of Flight

24 bars of plastic scintillator disposed on six plane, S11, S12, S21, S22, S31, S32;

Tracking system

Six plane of silicon detector inside a magnetic cavity;

Calorimeter

Calorimeter: 44 planes of Si detector interleaved with 22 tungsten planes, 16.3 radiation length;

Anticoincidence

(CAS, CARD e CAT) nine plane of plastic scintillator around the apparatus;

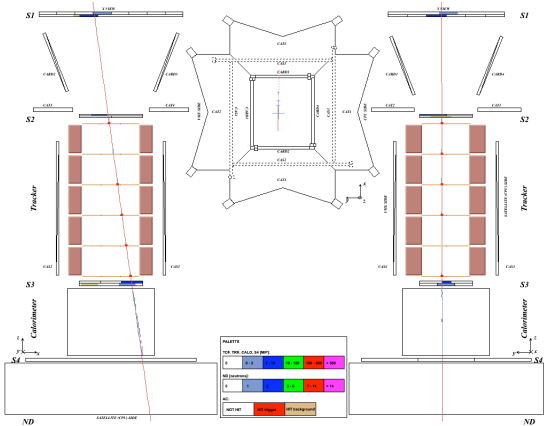
Neutron detector

36 proportional counter filled with ^{3}He.

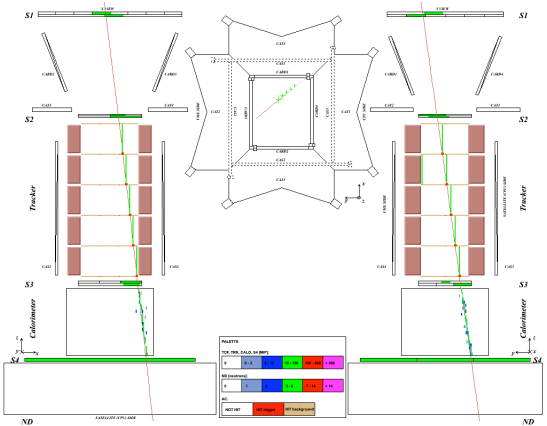
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Detection Principle

Non interacting antiproton 18 GV

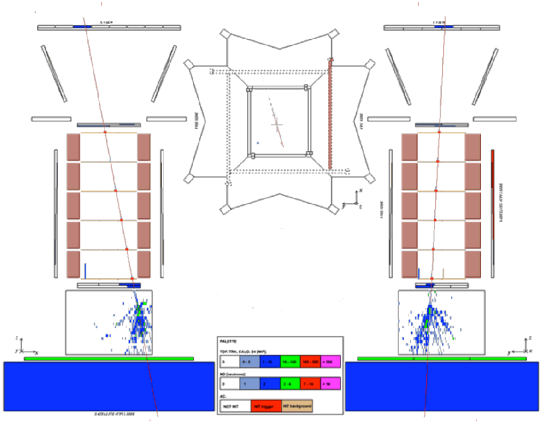


Non interacting carbon nucleus 5.7 GV

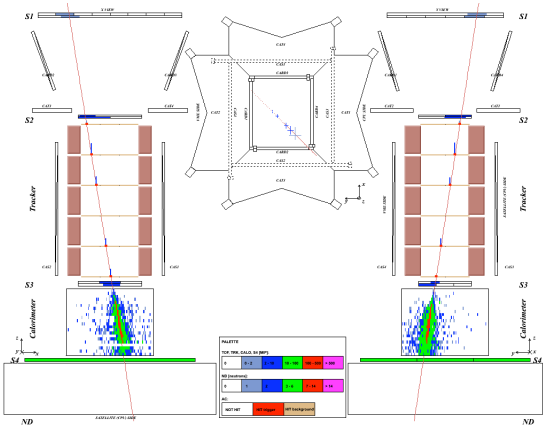


Detection Principle

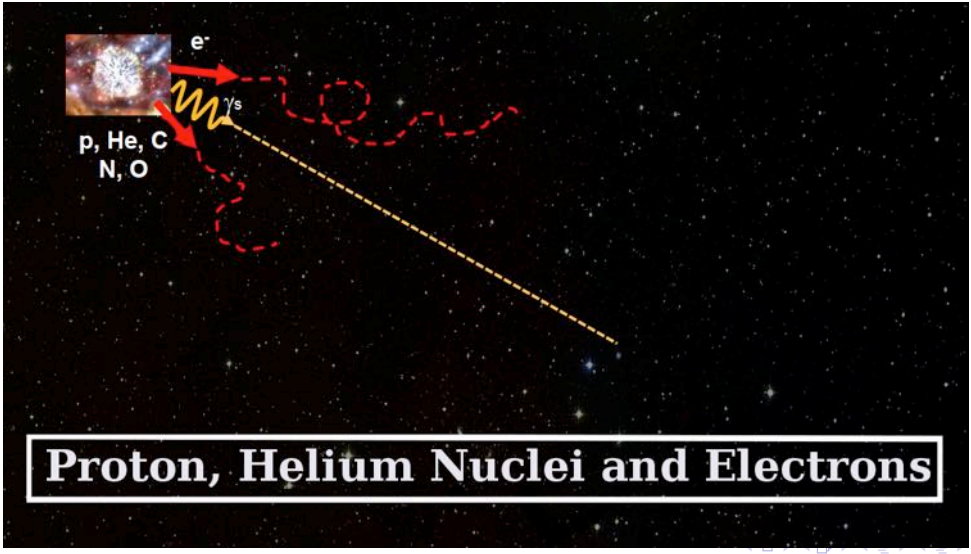
Interacting proton 16 GV



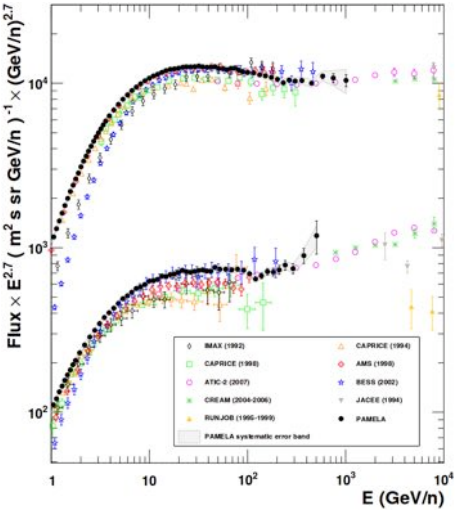
Positron 92 GV



Primary Cosmic Rays

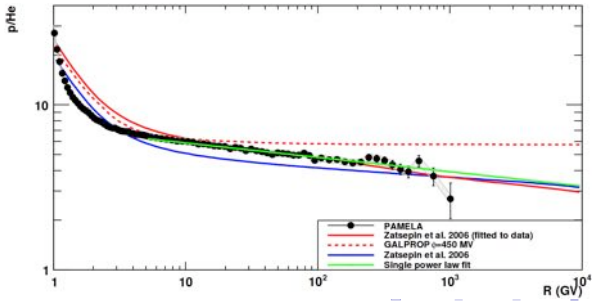


Proton and Helium



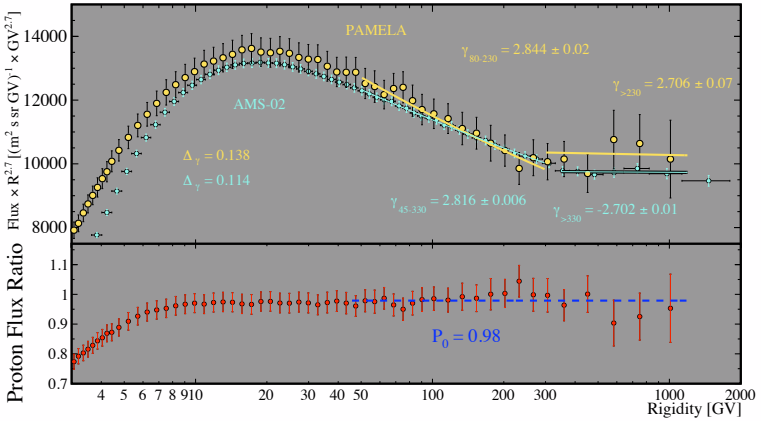
Adriani et al., Science 332 (2011) 6025

- **First high-statistics measurement** over 3 decades in energy
- Spectra **softening** up to $230 - 250$ GV, **hardening** above;
- Single power law rejected at 99.7%, $\Delta\gamma \sim 0.1 - 0.2$;
- $\gamma_H \neq \gamma_{He}$ but **featureless** ratio $\rightarrow$ same acceleration;
- Acceleration in He enriched environment? injection (Larmor radius)?
- **Spectral break**: propagation? different sources (novae, SN)?



Proton: PAMELA and AMS02

Result confirmed by AMS-02!



O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103

Helium: PAMELA and AMS02

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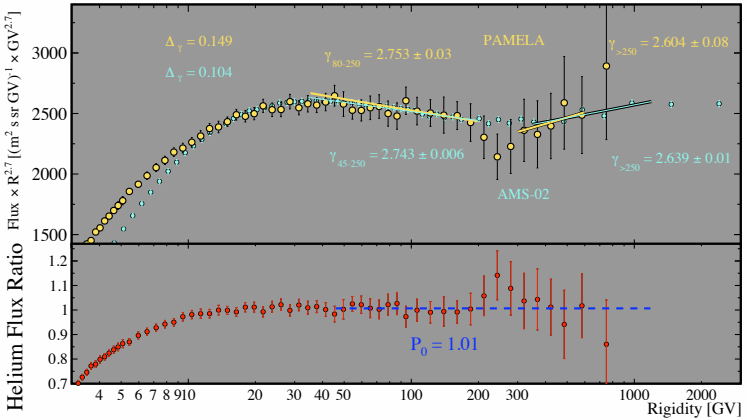
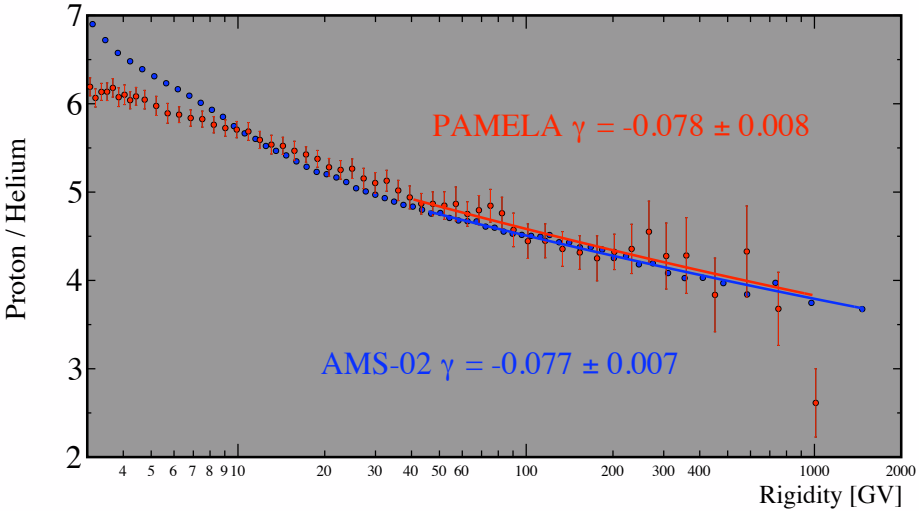


O. Adriani et al., Science 332 (2011) 6025 ; M. Aguilar et al., PRL 115, (2015) 211101

Proton Helium Ratio: PAMELA and AMS02

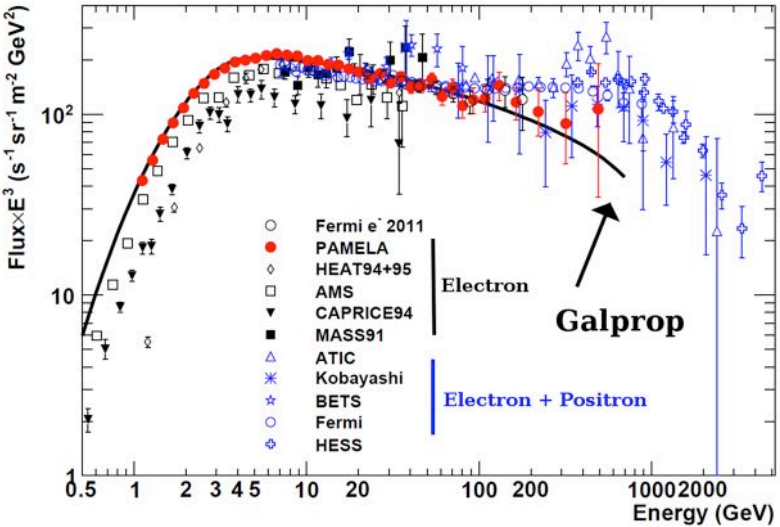


Electron Flux

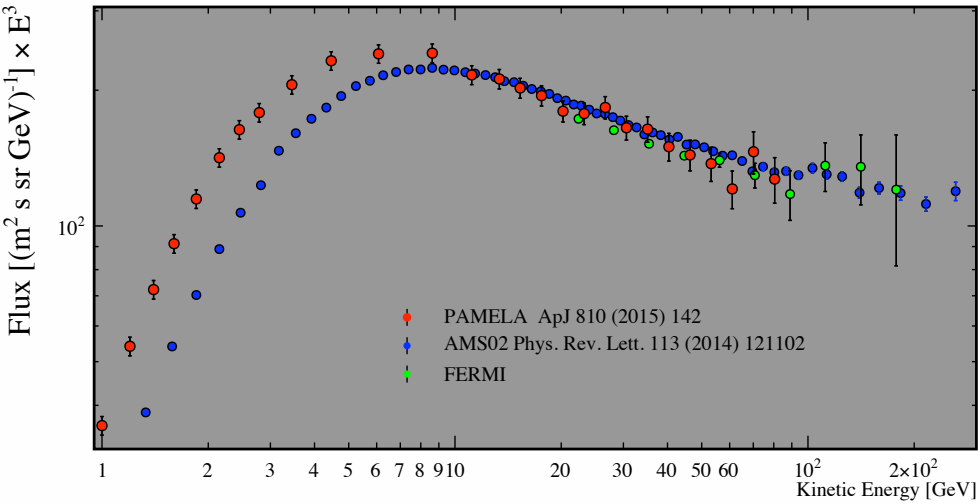
Electron Flux

- First electron measurement above 50 GeV;
- Consistent with standard model of CR acceleration and propagation (GALPROP) at low energies;
- Hardening above several tens of GeV;
- No exclusion of additional secondary or primary component at high energies.

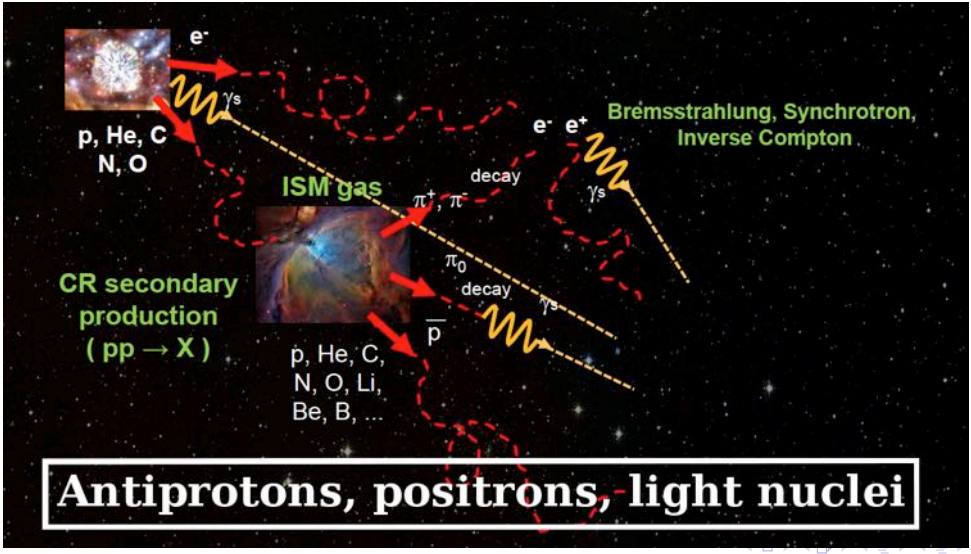
O. Adriani et al., PRL 106, (2011) 201101



Electron Flux



Secondary Cosmic Rays



Helium and Hydrogen isotopes

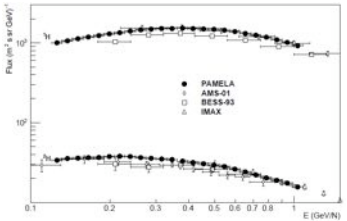
Production

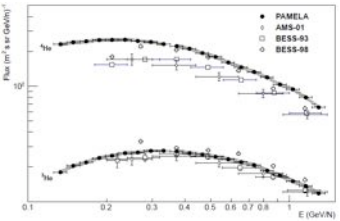
- p p $\rightarrow$ ^{2}H π^+;
- ^{4}He p $\rightarrow$ ^{3}He p n;
- ^{4}He p $\rightarrow$ ^{3}H p p $\rightarrow$ ^{3}He p p e$^-$.

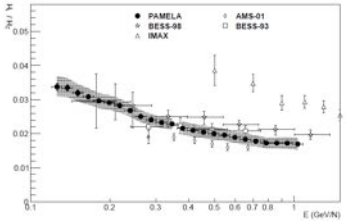
Information

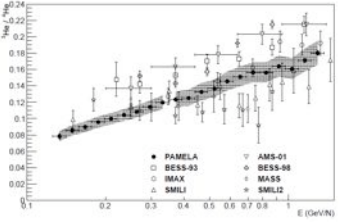
- ^{2}H/^{1}H and ^{3}He/^{4}He complimentary to B/C measurements in constraining propagation models (*Coste et al., A&A 539 (2012) A88*);
- Agreement with BESS results for ^{2}H, IMAX ones for ^{3}He;

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









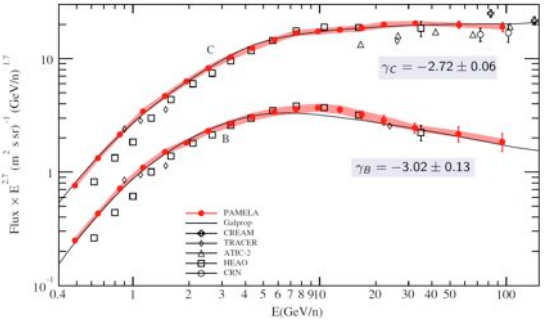
Boron and Carbon

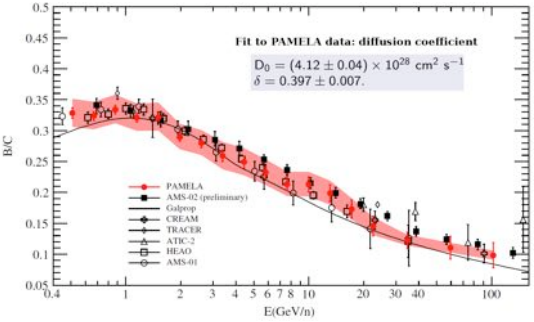
Boron and Carbon

- Flux measure from 2 to 260 GV;
- Different spectral shape;

B/C ratio

- Standard tool for studying propagation models;
- B/C $\propto$ diffusion coefficient, $K = D_0\, E^{-\delta}$;



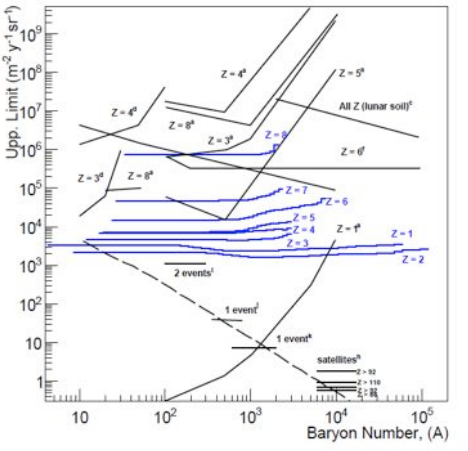


O. Adriani et al., ApJ 791 (2014), 93

What can antimatter in CRs tell us?

- **Origin** and **propagation** of the cosmic radiation;
- Nature of **Dark Matter**?
- Absence of **cosmological antimatter**?

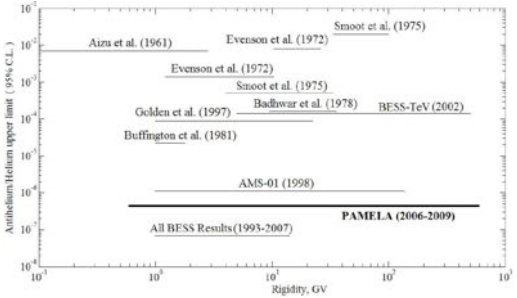
AntiHelium and Strange Matter



O. Adriani et al., AP 34 (2010) 1

No anomalous A/Z particle for $Z < 8$ between $1 < R < 1.0 \times 10^3$ GV and mass $4 < A < 1.2 \times 10^5$

No antiHe detected in a sample of 6×10^6 events with $|Z| \geqslant 2$,from 0.6 to 600 GV.

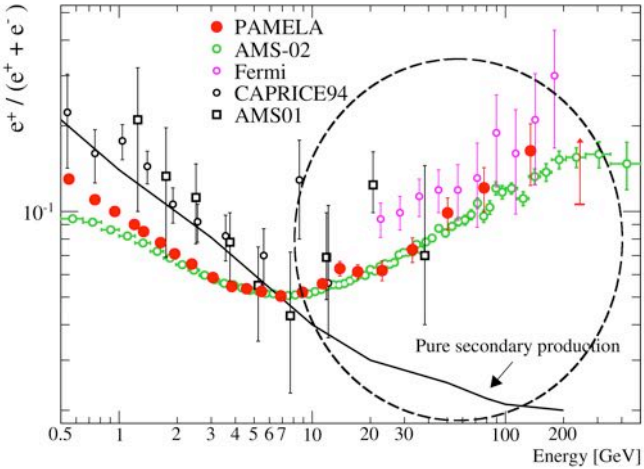


Positron Fraction

- **High energy**: (quite robust) evidence of positron excess above 10 GeV with respect to pure secondary production;
- **Low energy**: charge-dependent solar modulation (see later)

O. Adriani et al. , Nature 458 (2009) 607

O. Adriani et al., AP 34 (2010) 1



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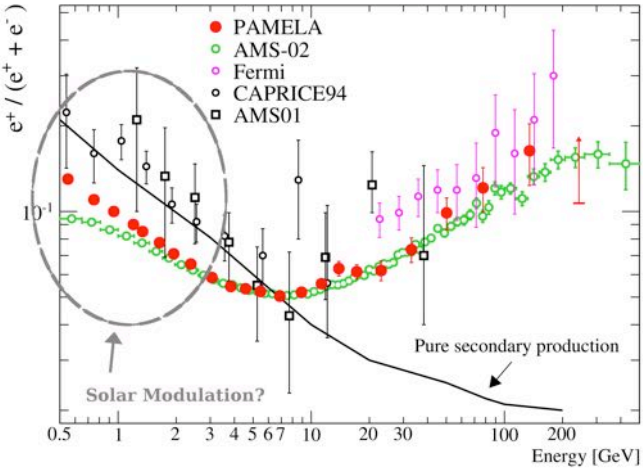
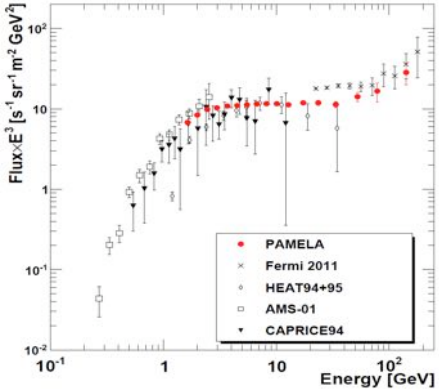
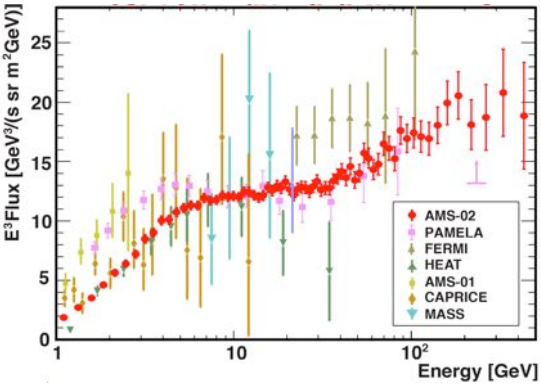


Positron Fluxes

Positron fraction increase → harder positron spectrum, not to a softer electron one!



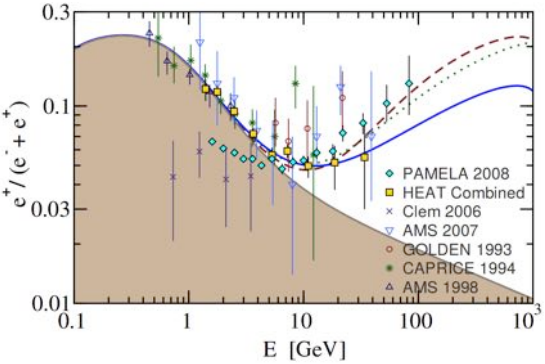
O. Adriani et al. , PRL 111 (2013) 081102



M. Aguilar, Phys.Rev.Lett. 113 (2014) 121102

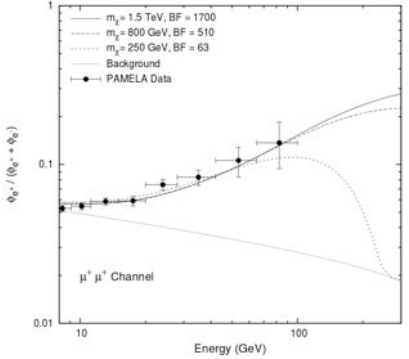
Contribution from Pulsars and Dark Matter

Electrons and positrons from Geminga assuming different distance, age and energetic of the pulsar.



H. Yuksel et al., PRL 103 (2009) 051101; arXiv:0810.2784v2

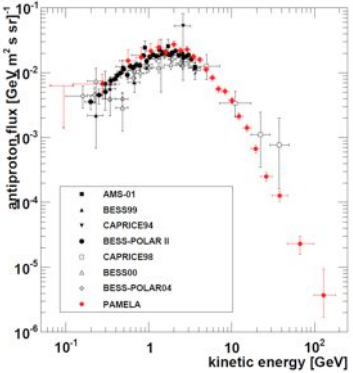
Possible contribution from dark matter annihilation in the galaxy.



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

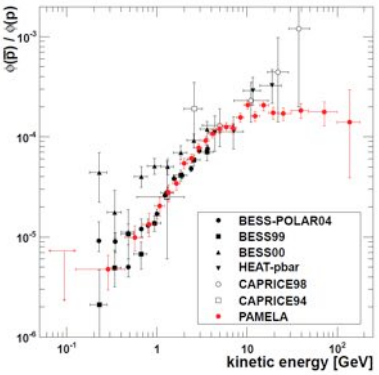
Antiproton Fluxes

Contrarily to the leptonic case, there is no unambiguous excess in antiproton data...
..however, a flat $p/\bar{p}$ is somewhat difficult to obtain in current astrophysical models.



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

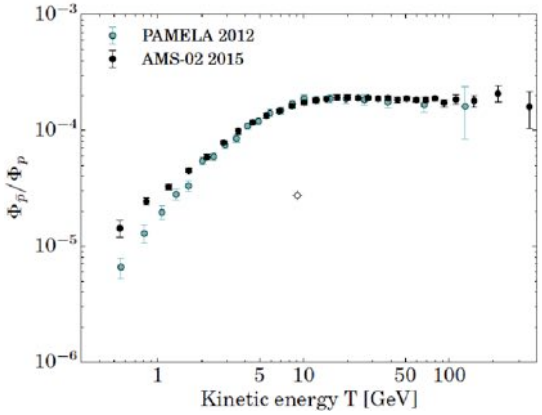
O. Adriani et al, Phys. Rep. 544 (2014) 323



O. Adriani et al, PRL 102 (2009) 051101

Confirmation of Antiproton results

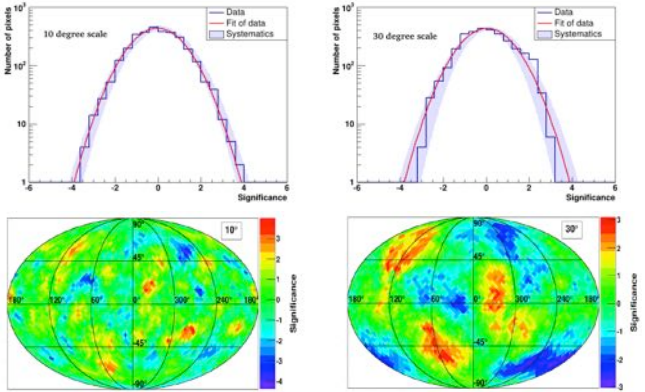
Good agreement with preliminary AMS-02 results.



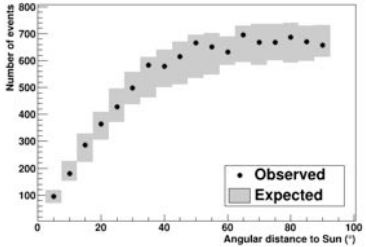
M. Circelli, Rapporteur talk ICRC 2015

Anisotropy studied

Existence of a single point source (pulsar)? Extended isotropy source (DM)?



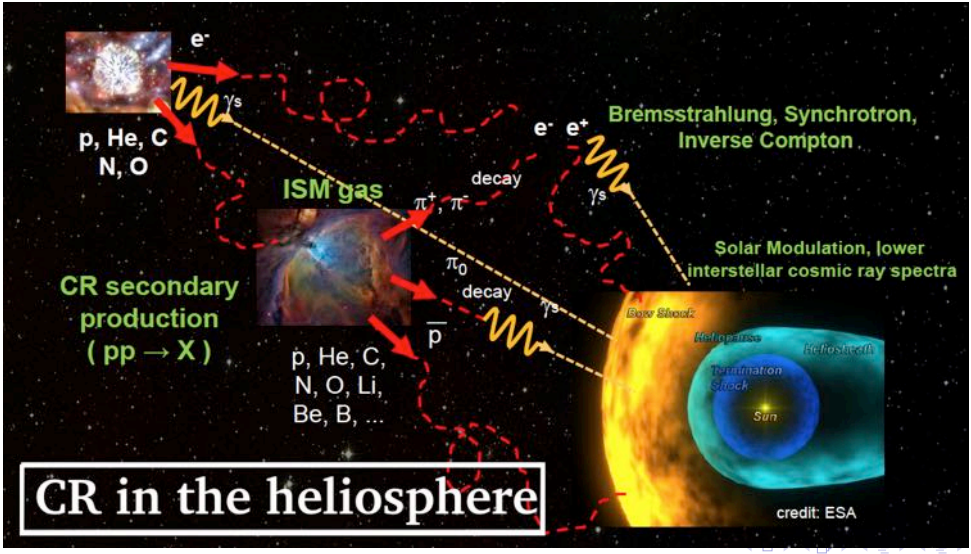
From the Sun



O. Adriani et al., ApJ 811 (2015) 21

Isotropic distributions of arrival directions are found.

Cosmic Rays in the heliosphere



CRs and the heliosphere

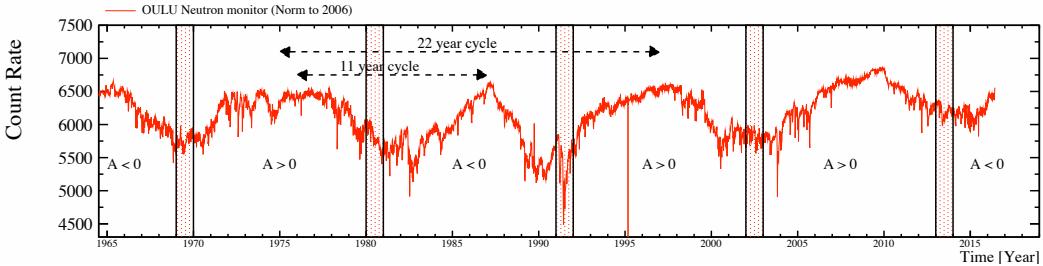
Below $\sim$ 30 GV heliosphere strongly affects CRs at Earth

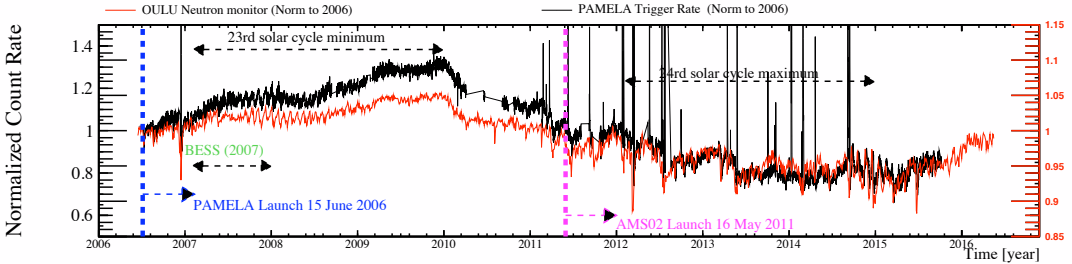
$$\underbrace{\frac{\partial f}{\partial t}}_{a} = \underbrace{-\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K_s}\cdot\nabla f)}_{c} \underbrace{-\langle\mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

(a) $f(\mathbf{x}, p, t)$, omnidirectional function distribution of CRs; **(b)** convection with solar wind $\mathbf{V}$; **(c)** diffusion by magnetic field irregularities; **(d)** drift, curvature and gradient in magnetic field; **(e)** adiabatic energy losses; **(f)** local sources (Jovian electrons);

Heliosphere: ideal environment to test the theory for propagation of charged particles under conditions which well approximate cosmic condition.

Solar Activity and Cosmic Rays





Time Dependent Proton Fluxes

O. Adriani et al., ApJ 765 (2013) 91

Time Dependent Proton Fluxes

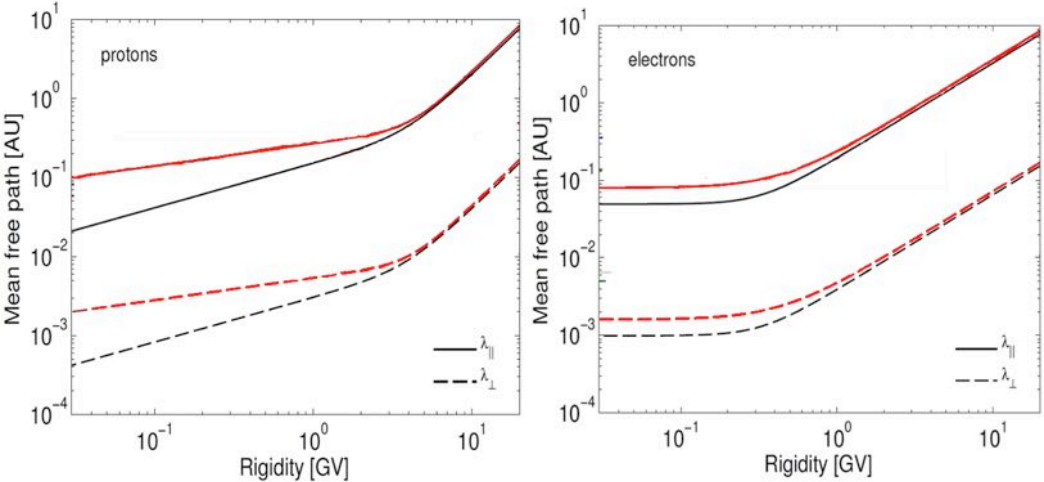
M. S. Potgieter et al., Solar Phys. 289 (2014) 391

Time Dependent Electron Fluxes

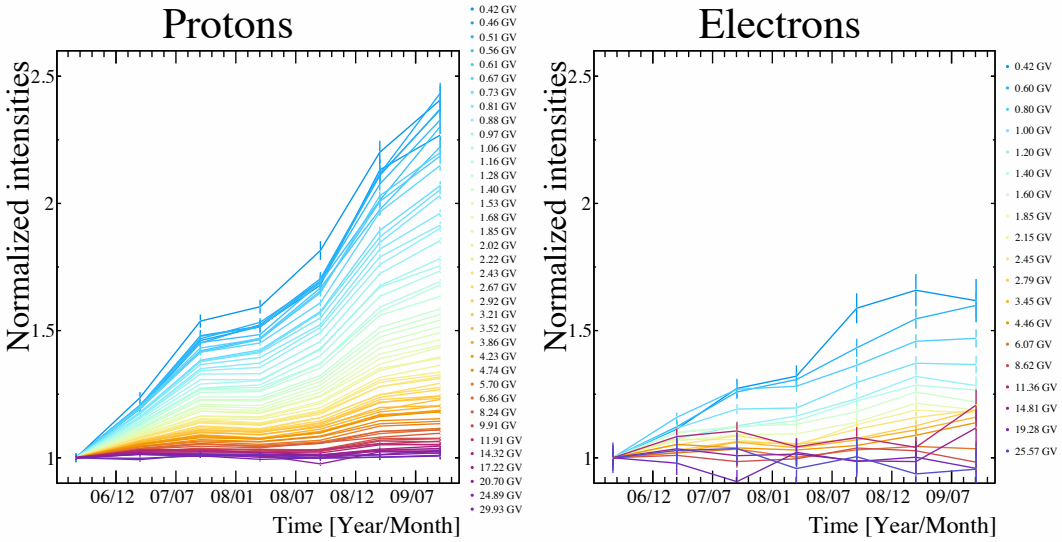
O. Adriani et al., ApJ 810 (2015) 142 *M. S. Potgieter et al., ApJ 810 (2015) 2, 141*

Time Dependent Positron Fluxes

Modelling and Interpretation



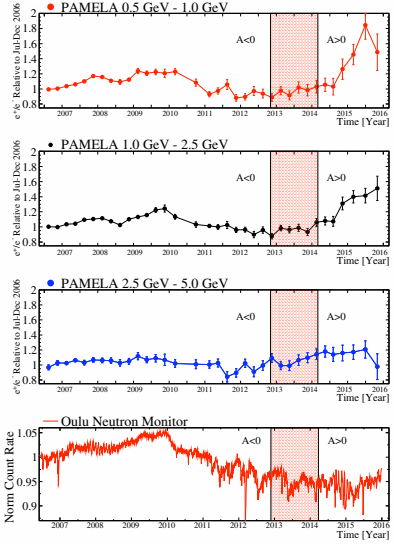
Charge-sign modulation



Reversal of the Sun magnetic field polarity

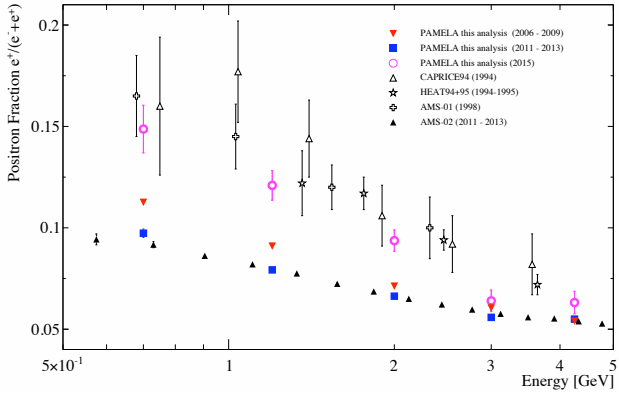
- Polarity reversal change global drift pattern for positive and negative particles;
- During the 24th solar cycle this took place between November 2012 and March 2014 (16 months apart);
- After few months the new condition "propagate" through the heliosphere and positron starts to increase abruptly.

O. Adriani et al., Phys. Rev. Lett. 116, (2016), 241105

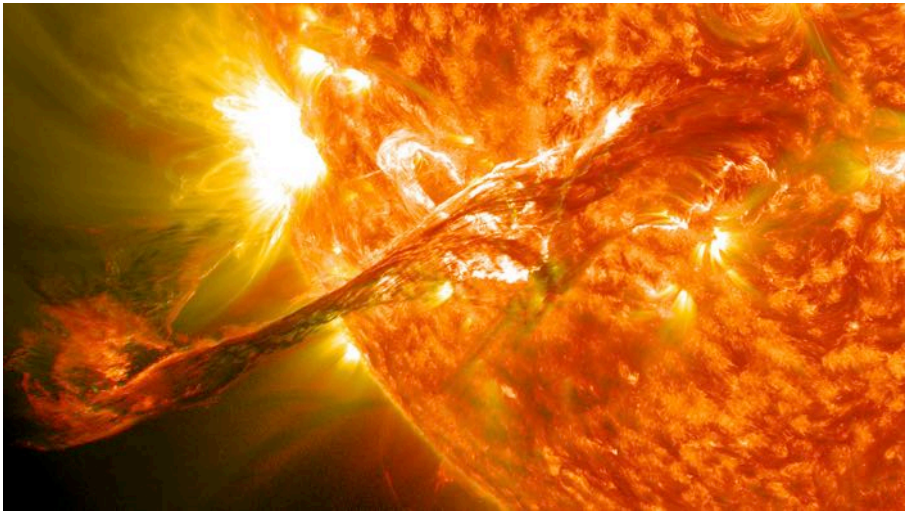


Time dependence of the positron fraction

- Low energy "tension" between experiment explain with charge-sign dependence;
- Positron fraction in 2015 approach previous measure obtained in A > 0 epochs.



Solar Energetic Particle

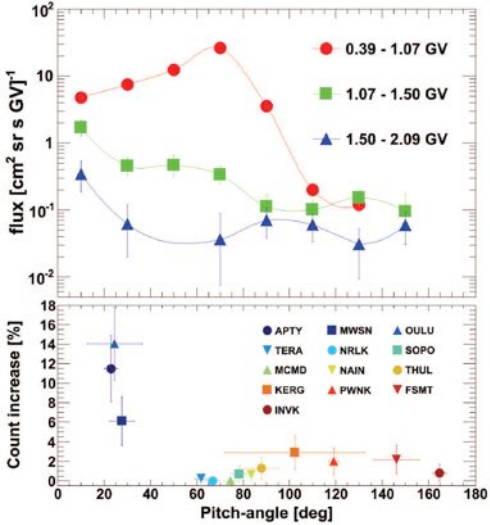


SEP 2006 December 13th

PAMELA bridge a critical energy gap between space-based measurements and ground-based.

Adriani et al. - ApJ 742 102, 2011

2012 May 17th event as observed by PAMELA



Two protons components: different pitch angle distributions;

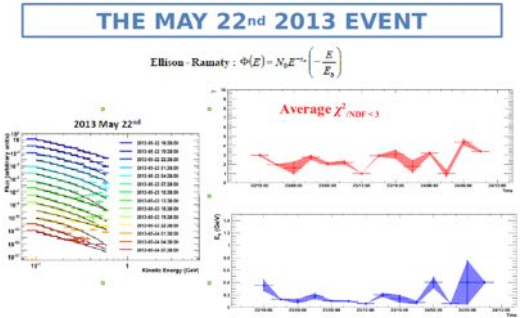
High rigidity: consistent with NM, anisotropic flux very beamed along the interplanenary magnetic field, beam width $\sim 40 - 60$ (not scattered);

Low rigidity: significant scattering for pitch angle ~ 90

Adriani et al., ApJL 801 (2015) L3

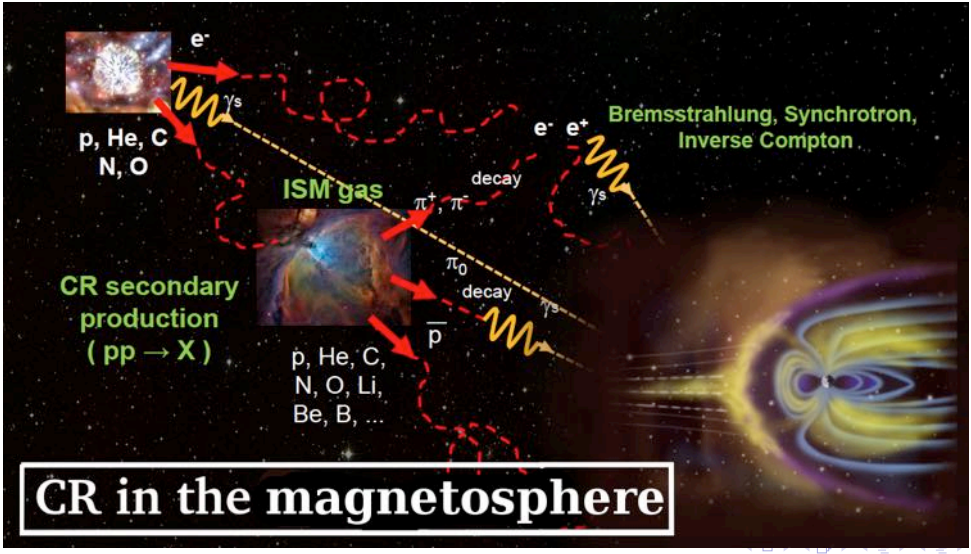
Future solar events analysis

PAMELA observed many solar events. The analysis is ongoing.



See Matteo Martucci presentation (Thursday 23 June 2016) **The Solar Event of May 22 of 2013: observations by the PAMELA experiment**

Cosmic Rays in the heliosphere

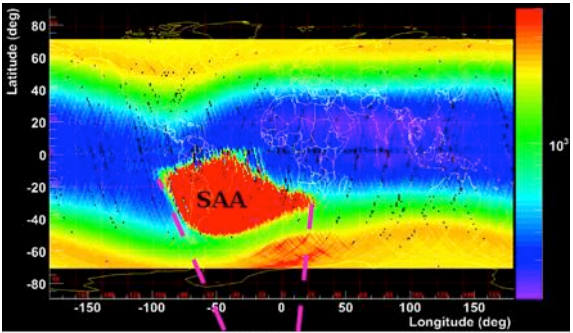


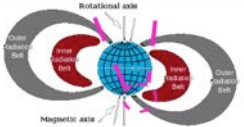
PAMELA WORLD MAP

Earth magnetic field strongly affects the propagation of CRs below $\sim 20 GV$.

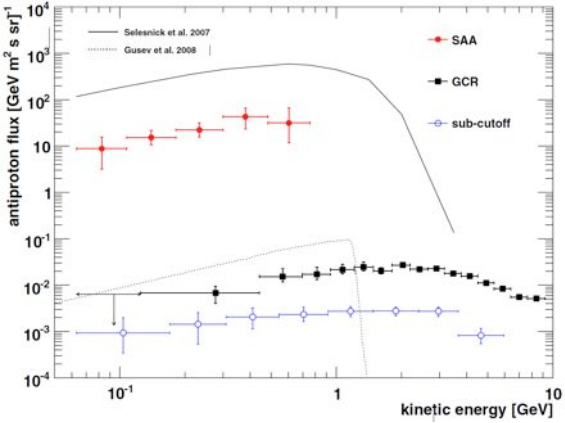
PAMELA counting rate over all altitude (350-610 km)

- **Inner Van Allen belt**: energetic proton (up to few GV)
- **Outer bell**: mostly electrons (hundreds of KeV or MeV)





Geomagnetic trapped particles (South Atlantic Anomaly)



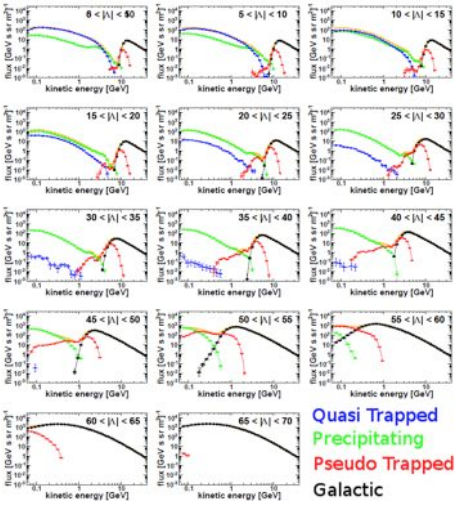
O. Adriani et al., ApJL 737 (2011), L29

Discovery of **geomagnetic trapped antiproton**, flux exceeds by 3 order of magnitude the galactic component!

Quasi-trapped particles

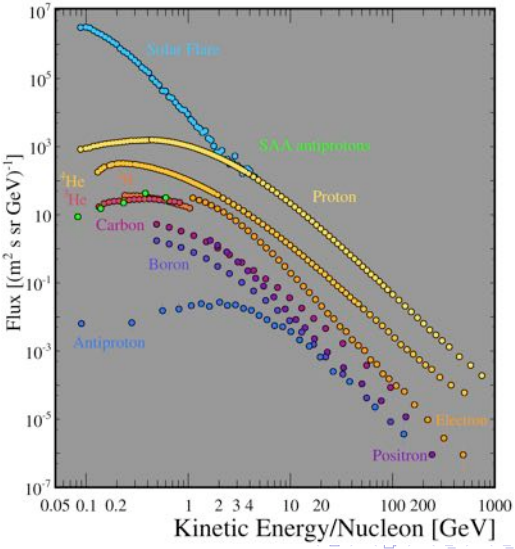
Re-entrant albedo proton spectra vs latitude $|\Lambda|$.

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



PAMELA overall results

PAMELA achieved precise results spanning more than 10 order of magnitude in flux and three order of magnitude in energy!



Conclusions and perspective

- **PAMELA has been in orbit and studying cosmic rays since 10 years.**
- PAMELA obtain a **huge amount of results measuring CR spectra with unprecedented precision** and opening the way of **high precision CR physics**.

- Many **unexpected results** open to the theoretical field new interpretation and speculation **beyond standard paradigm** of acceleration, propagation, production... of CRs.
- The PAMELA collaboration **published more than 80 papers** on international scientific magazine.

- **Other studies and forthcoming results**: Primary and secondary-nuclei abundance (up to Oxygen), Solar modulation (long-term flux variation and charge-dependent effects), Solar events: several new events under study.

Conclusions and perspective

1. **Antiproton**: spectrum and ratio up to 300 GeV. No significant deviations from secondary production expectations.
2. **Positron fraction**: measured up to 300 GeV. Increases significantly (and unexpectedly) with energy. Primary source?
3. **Positron flux**: consistent with a new primary source.
4. **Anisotropy studies**: no evidence of anisotropy.
5. $\bar{He}/He$ **ratio**: broader energy range ever achieved.
6. **H and He absolute fluxes**: up to 1.2 TV. Complex spectral structures observed (hardening at 200 GV).
7. **H and He isotope fluxes**: and ratio $\rightarrow$ most complete measurements so far.
8. **Electron (e^-) absolute flux**: up to 600 GeV. Not inconsistent with an additional electron component.
9. **B/C ratio and absolute fluxes**: up to 100 GeV/n.
10. **Solar physics**: measurement of modulated fluxes and solar-flare particle spectra
11. **Physics of the magnetosphere**: first measurement of trapped antiproton flux and detailed measurement of trapped proton flux.