The PAMELA mission: results after ten years in space

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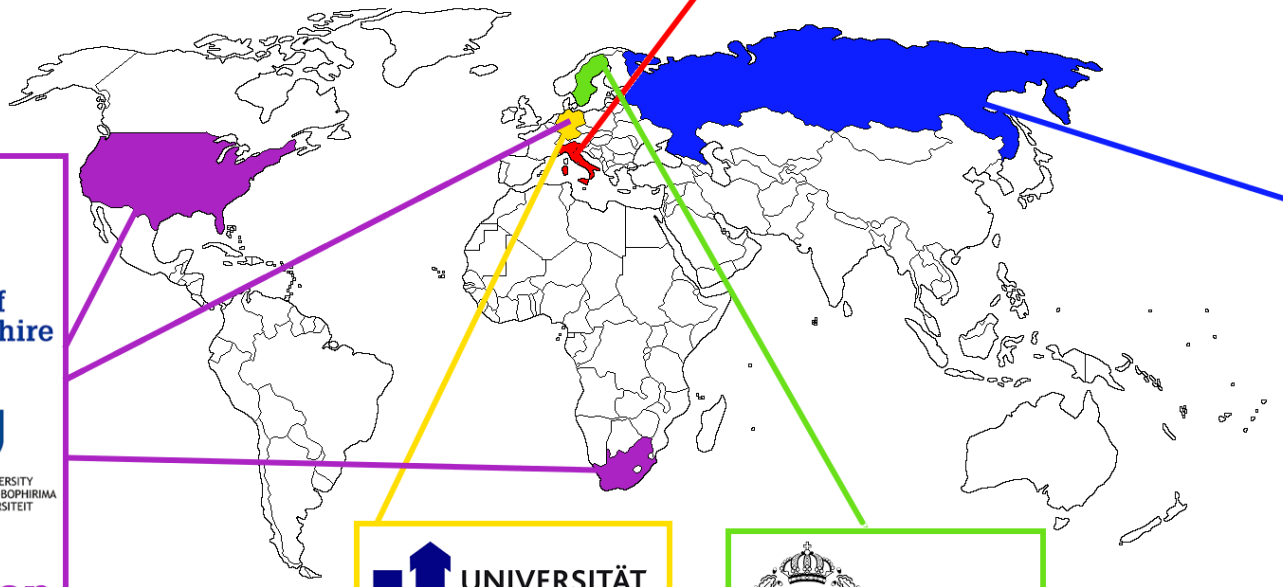
7th Roma International Conference on AstroParticle Physics

PAMELA Collaboration

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



External collaboration

Germany

Sweden

Moscow

St. Petersburg

PAMELA Mission

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Launch in June 15th of 2006
(Soyuz vector on board the
Resurs-DK1 russian satellite

- Quasi-polar and elliptical orbit
- Inclination ~70°
- Altitude 300 – 600
- After 2010 → circular orbit (stable @ ~500 km)

PAMELA Instrument

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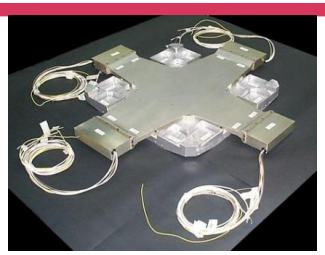
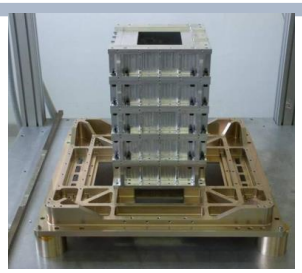
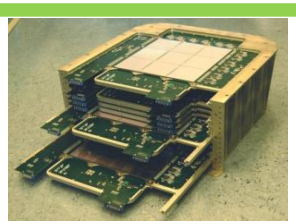
Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.



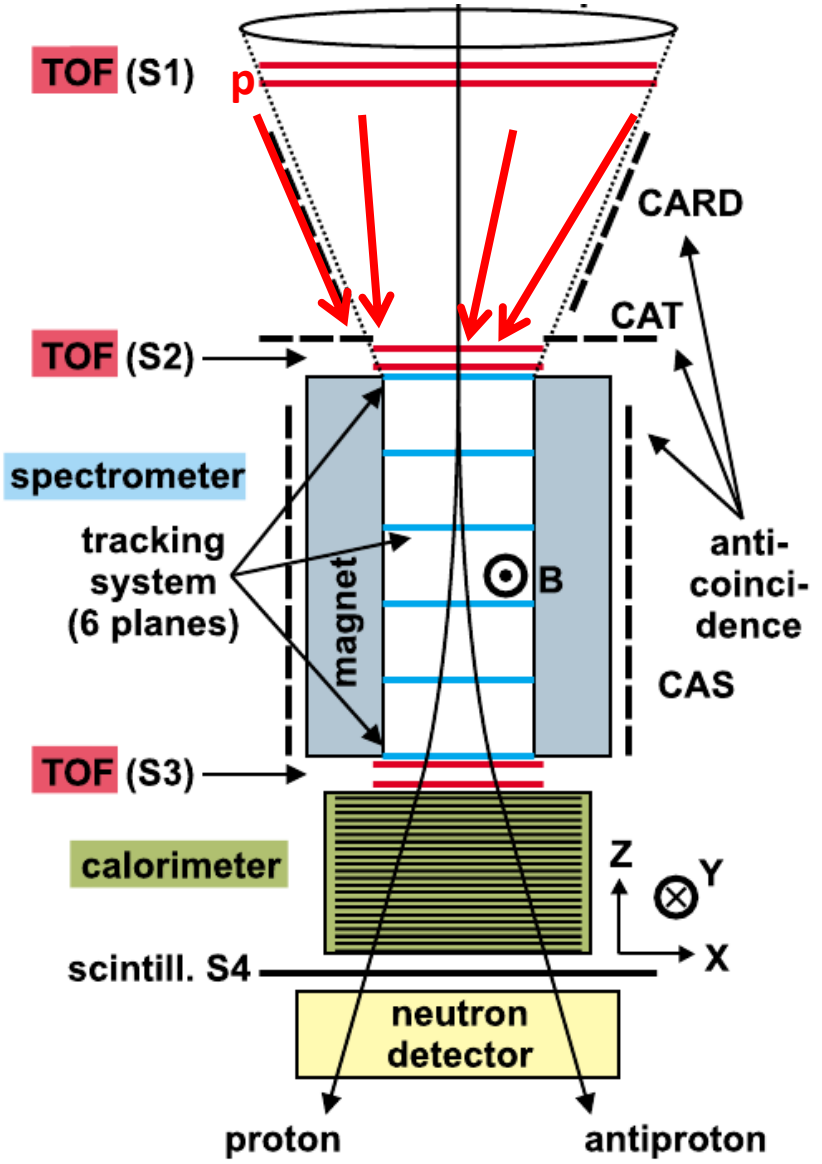
Spectrometer
microstrip silicon tracking system
- *Magnetic rigidity → R = pc/Ze*
– *Charge sign*
– *Charge value from dE/dx*
+ permanent magnet



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+

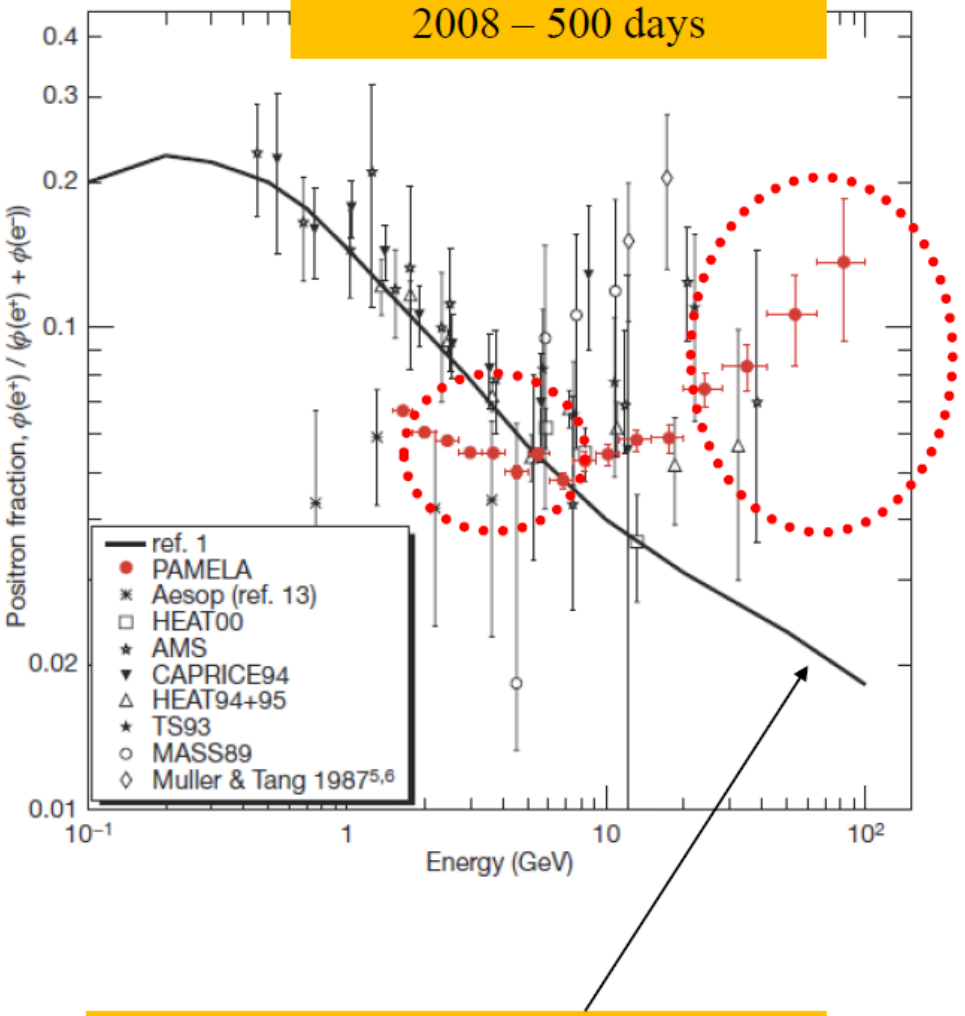


Neutron detector
3He tubes + PMT:
- High-energy e/h discrimination

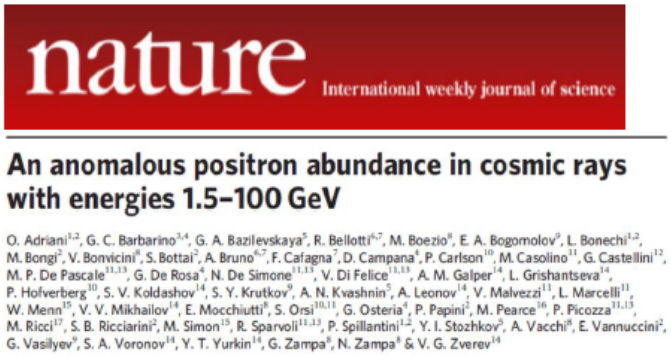


The positron fraction result

June 2006 – Februaary
2008 – 500 days



Secondary production: Moskalenko & Strong 98



nature International weekly journal of science

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

> 2400 citations

- High energy: first clear evidence of increasing positron fraction above 10 GeV with respect to pure secondary production;
- Low energy: charge-dependent solar modulation

The antiproton/proton ratio and flux

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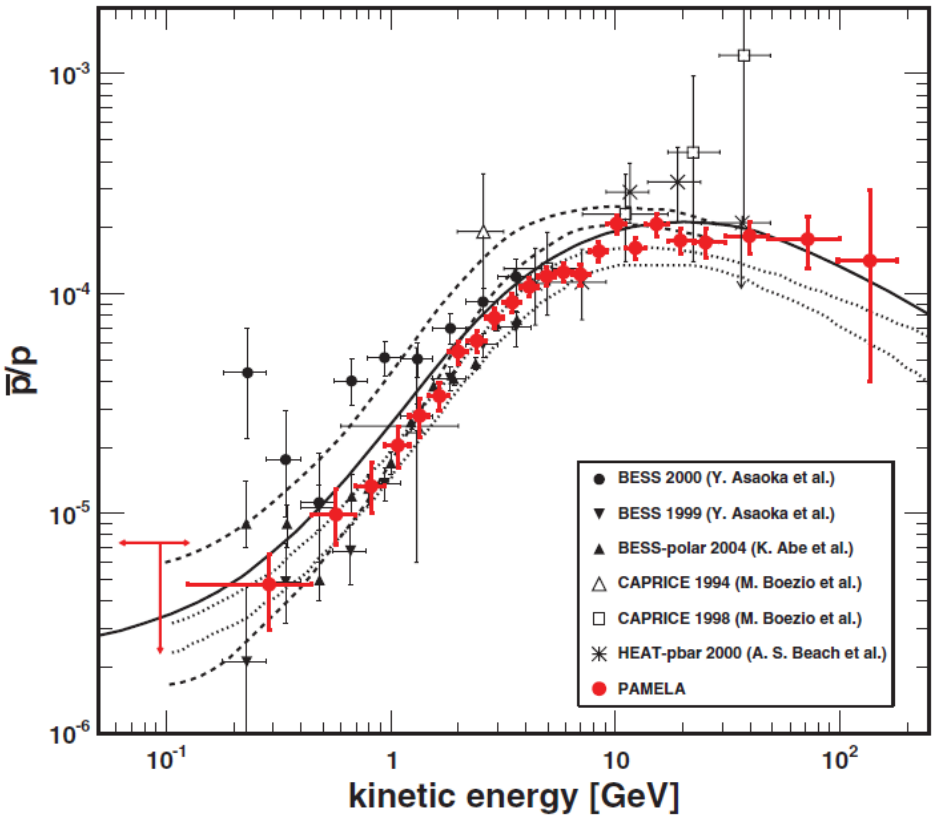
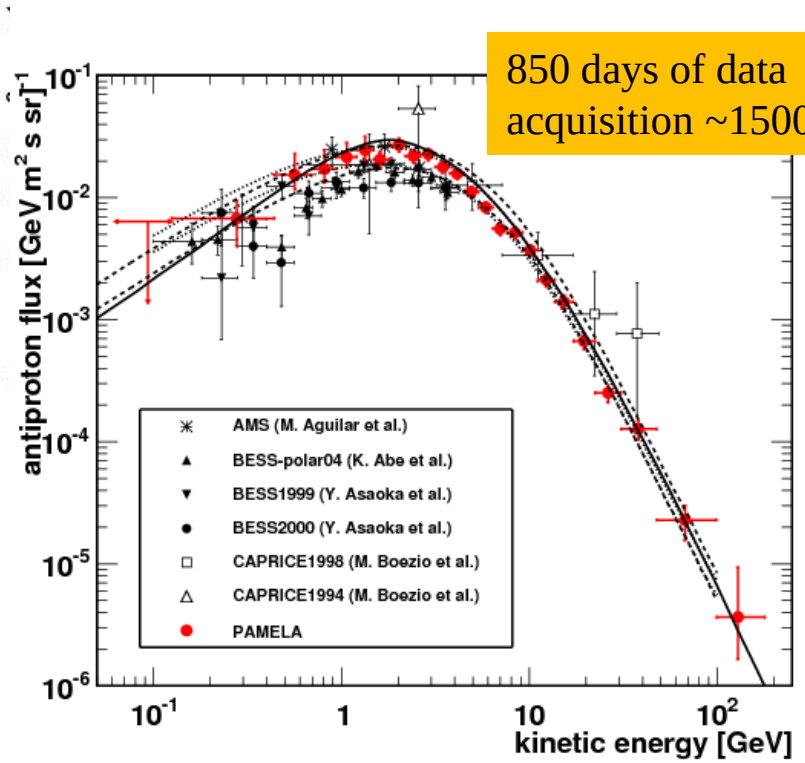
Adriani, O et al., 105, 121101 (2010)

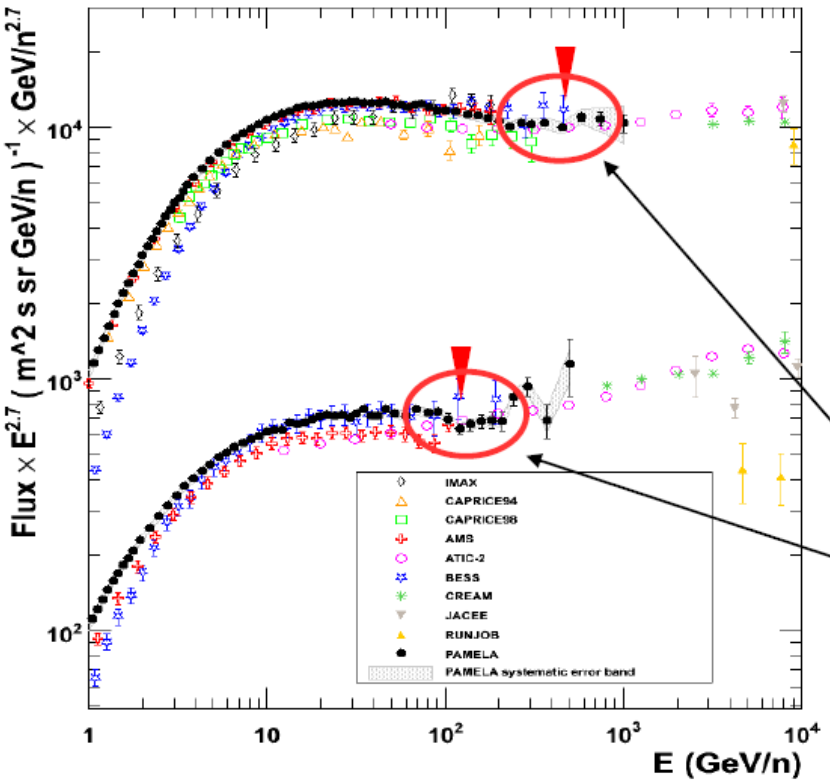




850 days of data acquisition ~1500 $\bar{p}$

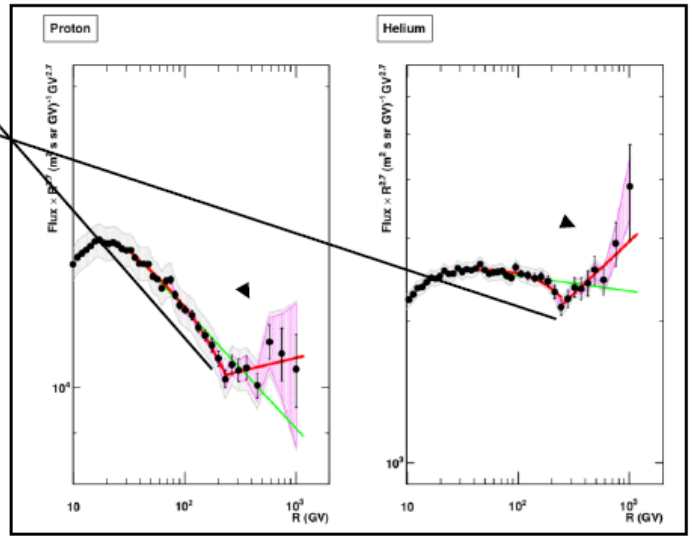
Consistent with secondary production models

The proton and Helium result



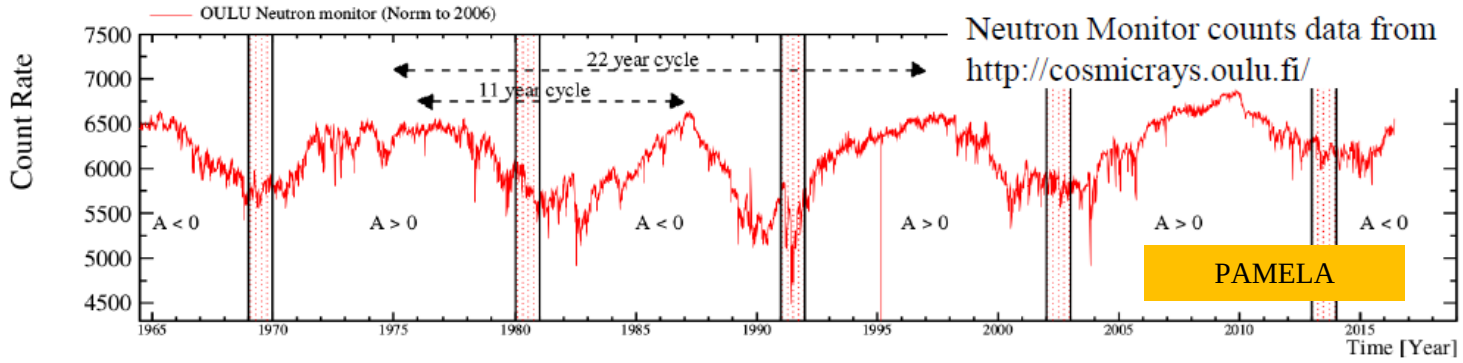
- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta\gamma \sim 0.2 \div 0.3$ SPL is rejected at 98% CL

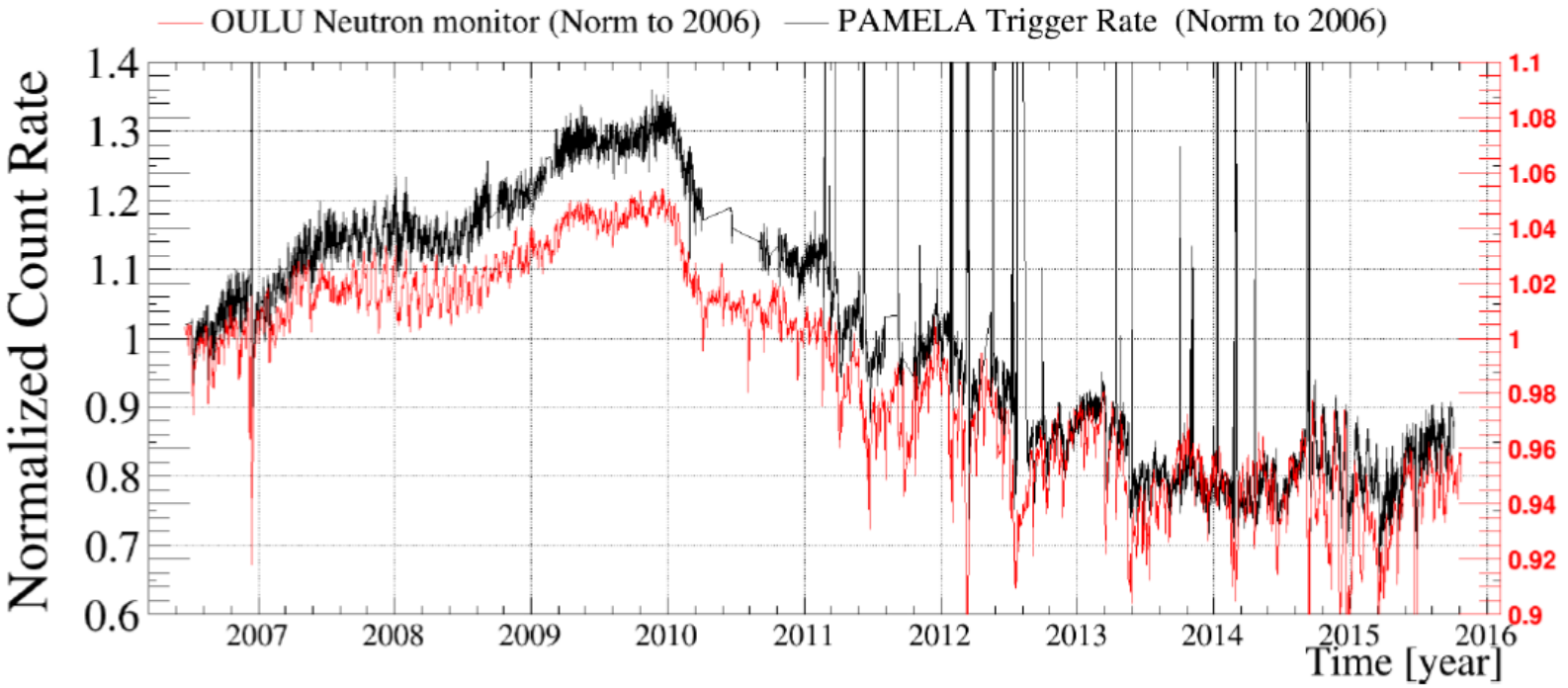
- Origin of the hardening?
- (e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)
- - At the sources: multi-populations, etc.?
- - Propagation effects?



O. Adriani et al., Science 332 (2011) 6025

PAMELA observation (2006-2016)

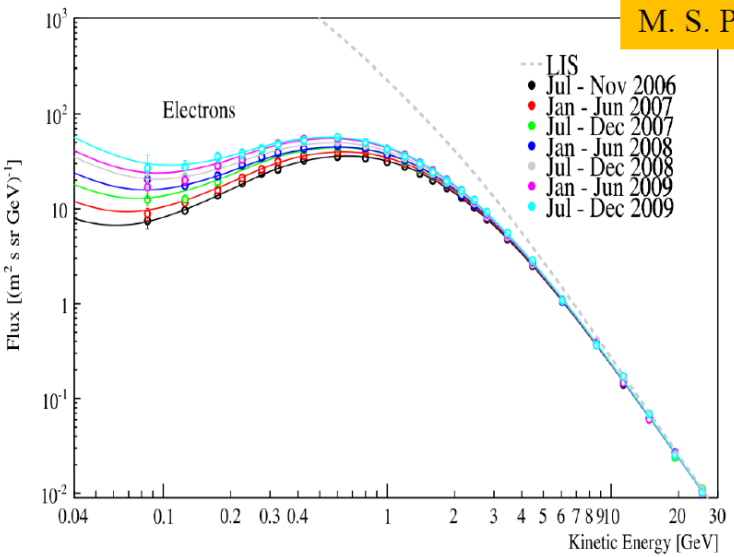




PAMELA observations covers about one solar cycle

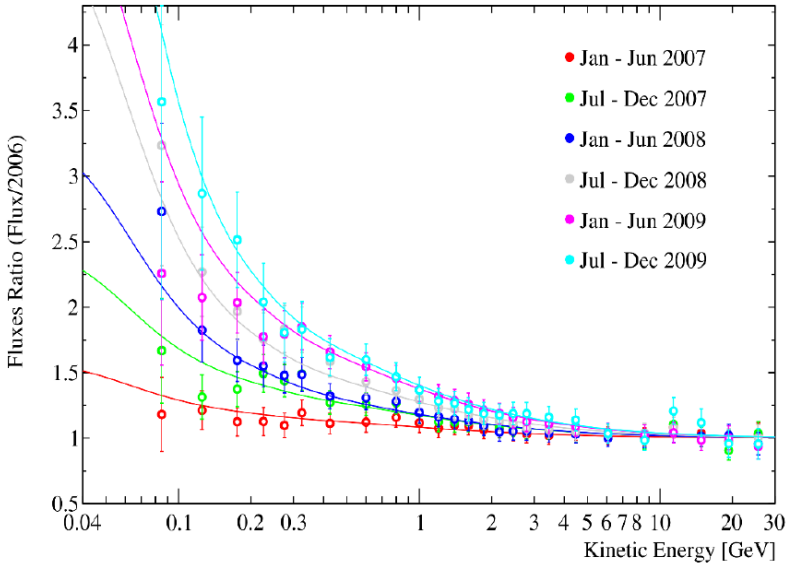
Time dependence of the electron flux

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



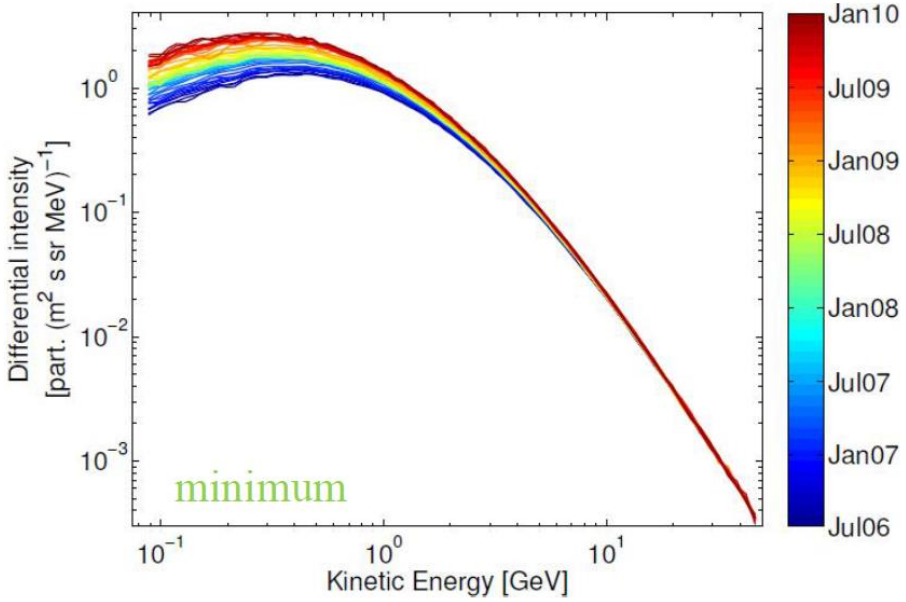
Evolution of the electron (e^-) energy spectrum from July 2006 to December 2009

The ratios between the measured e^- fluxes from January 2007 till December 2009 and the measured fluxes for the period July-November 2006 with the corresponding computed spectra.

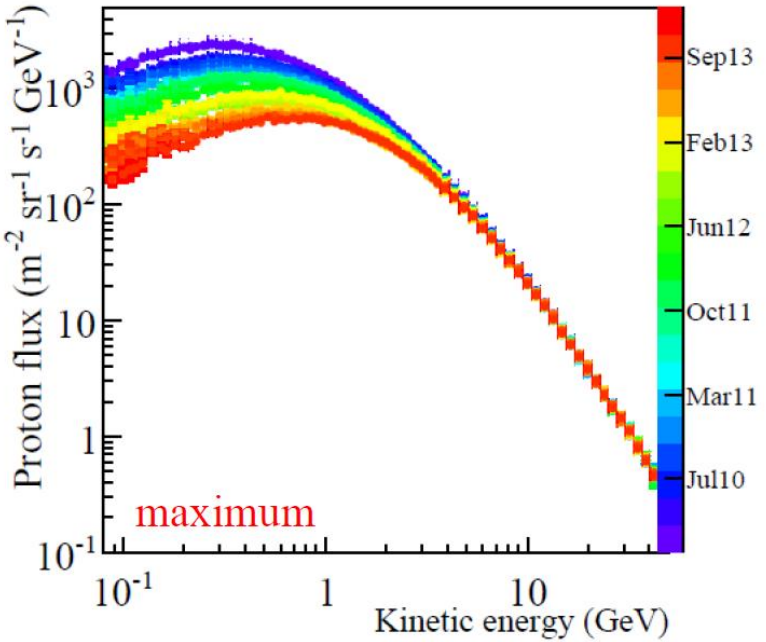


Time dependence of the proton flux

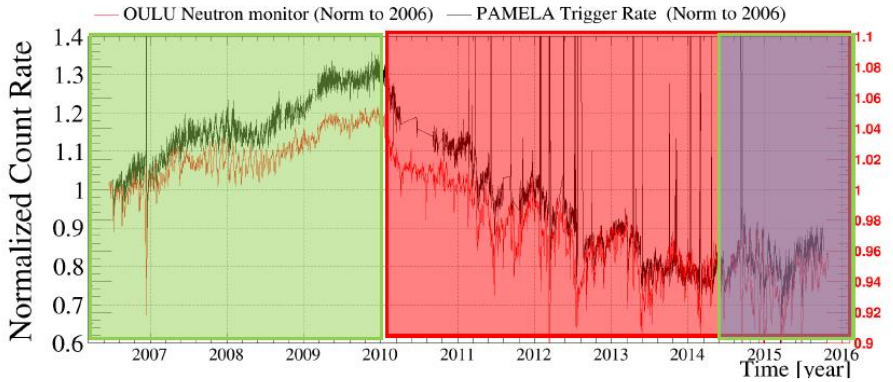
O. Adriani *et al.*, ApJ 765, 91 (2013)



Martucci, M. *et al.*, ApJL 854 L1 (2018)

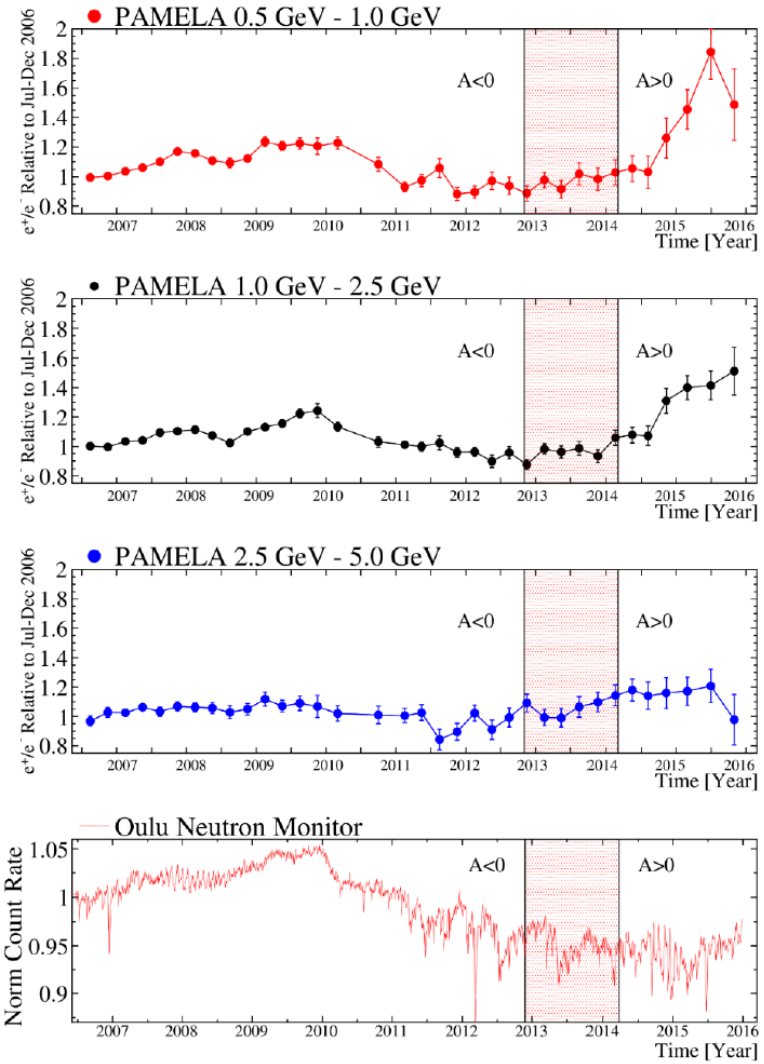


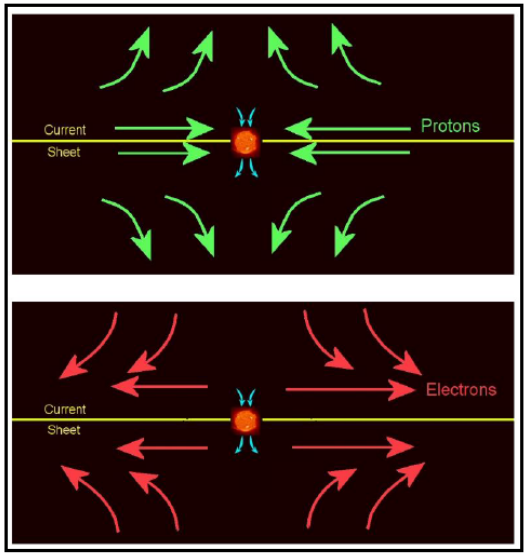
minimum maximum



Time dependence of the e^+/e^- ratio

polarity reversal of the HMF





The positron to electron ratio measured in this time period clearly shows a sign-charge dependence of the solar modulation introduced by particle drifts

O. Adriani *et al.*, PRL 116, 241105 (2016)

Mid-term variations studies

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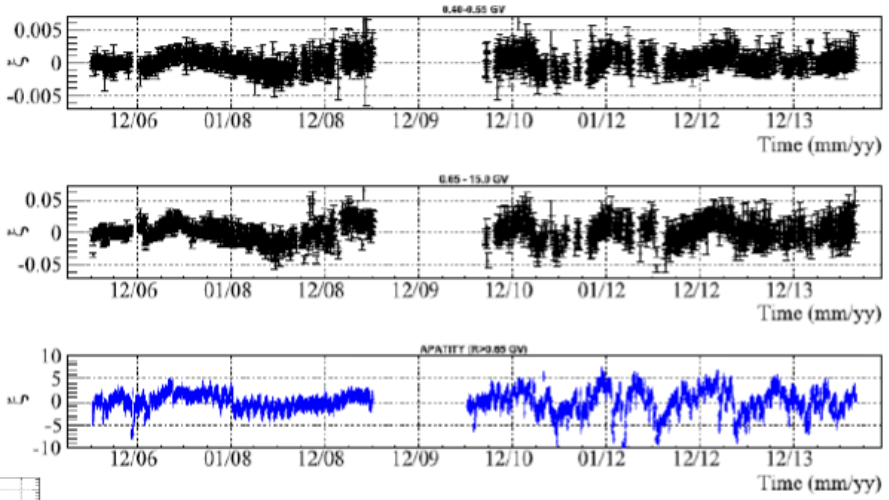
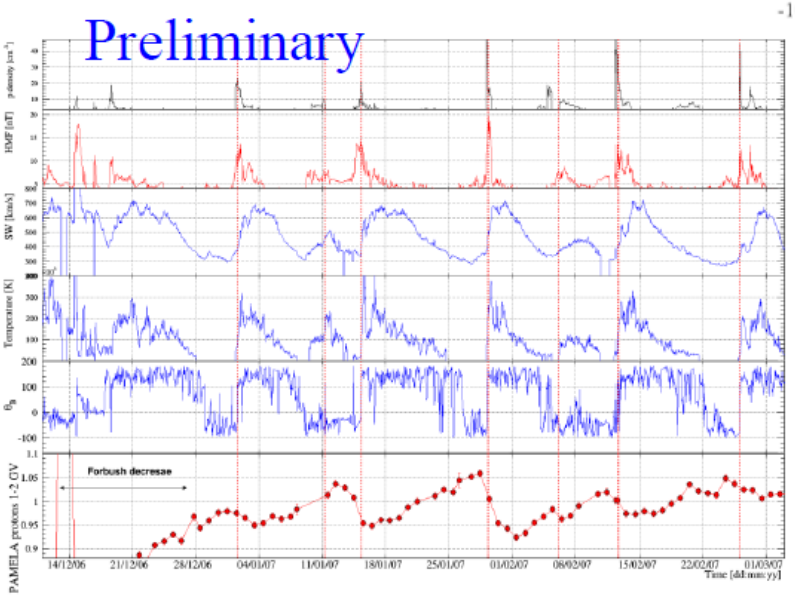
O. Adriani *et al.*, ApJL 852, L28 (2018) ;

A periodicity of about 450 days is observed in the proton flux which could be due to known variation in solar activity, called Quasi-Biennial Oscillations, but is also consistent with Jupiter periodicity.





2006 December – 2007 January

A 13:5 days periodicity is found in the proton flux between December 2006 and March 2007.
This phenomenon could be interpreted as an effect of prominent structures of compressed plasma in the solar wind (CIRs) or to the latitudinal gradient due to the crossing of the HCS.

Multi-particle observation of Forbush decrease

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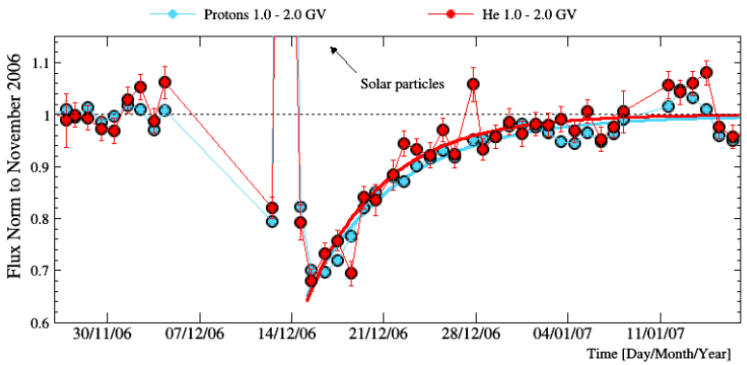
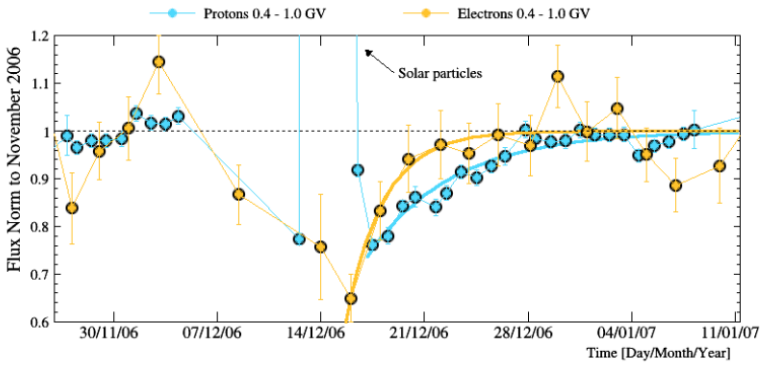
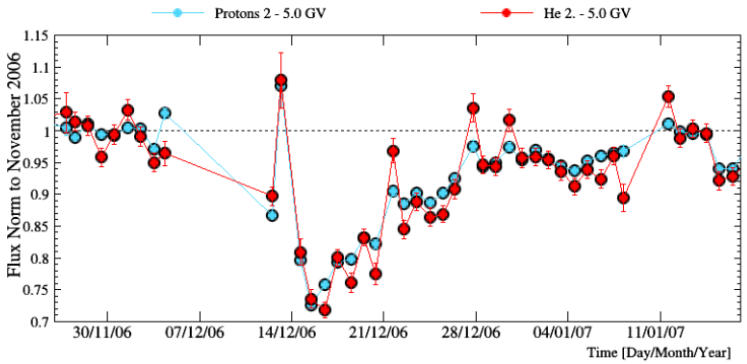
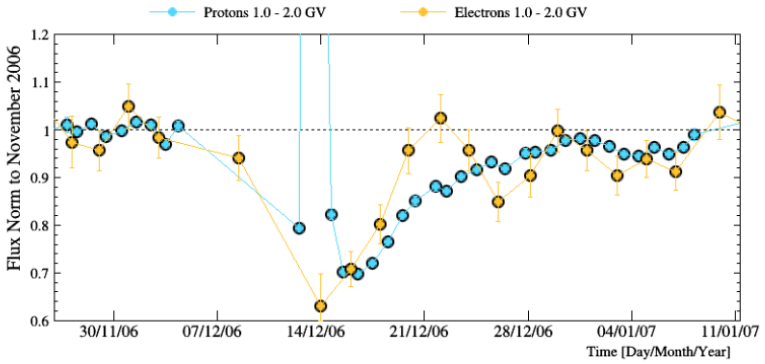








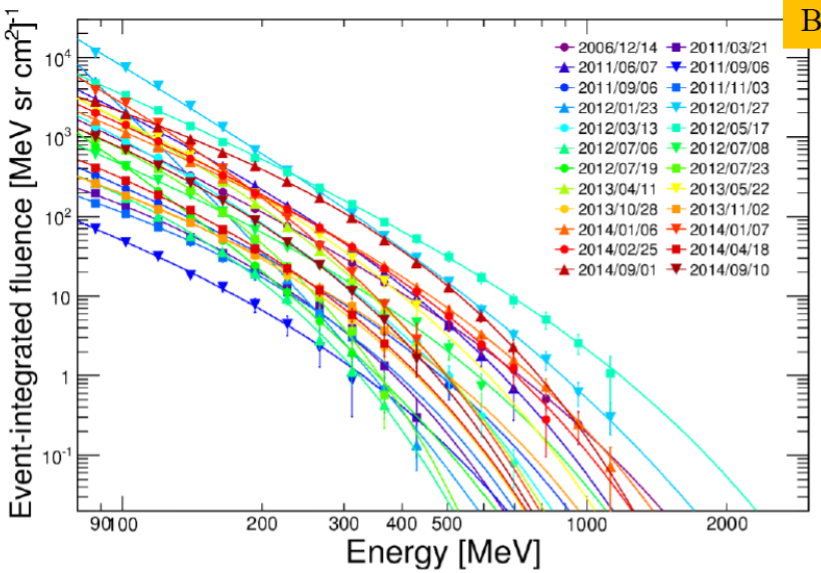
R. Munini *et al.*, ApJ 853, 1 (2018)

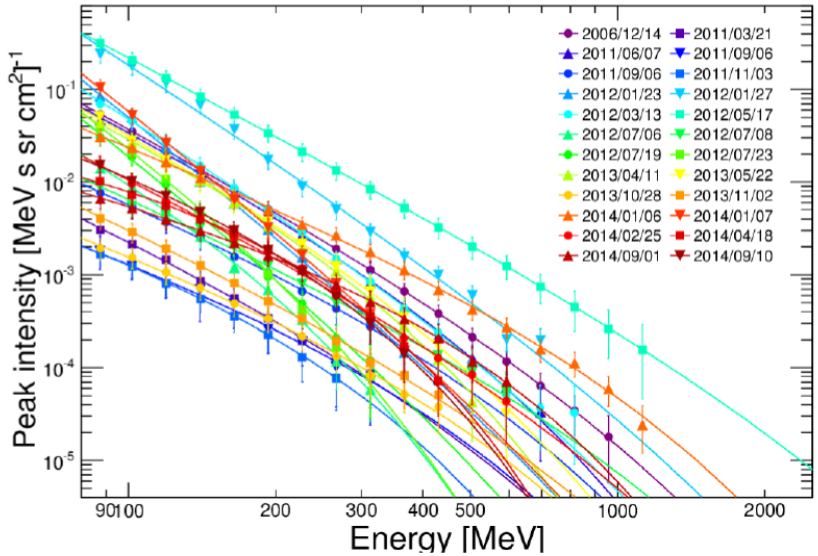
The proton and the helium amplitude and recovery time are in good agreement while electrons on average shows a faster recovery.
This could be interpreted as a charge-sign dependence due to the different global drift pattern between proton and electrons.

PAMELA SEP list

	SEP Event	Flare			CME				m-type II	DH-type II
#	Date	Onset time	Class	Location	1^{st}-app. time	V_{app}	V_{spa}	Width	Onset time	Onset time
1	2006 12/13, 02:55	12/13, 02:14	X3.4	S06W23	12/13, 02:54	1774	2184	H	12/13, 02:26	12/13, 02:45
2	2006 12/14, 22:55	12/14, 21:58	X1.5	S06W46	12/14, 22:30	1042	1139	H	12/14, 22:09	12/14, 22:30
3	2011 03/21, 04:10	03/21, 02:00	- -	N23W129	03/21, 02:24	1341	1430	H	- -	- -
4	2011 06/07, 07:20	06/07, 06:16	M2.5	S21W54	06/07, 06:49	1255	1321	H	06/07, 06:25	06/07, 06:45
5	2011 09/06, 02:20	09/06, 01:35	M5.3	N14W07	09/06, 02:24	782	1232	H	- -	09/06, 02:00
6	2011 09/06, 23:00	09/06, 22:12	X2.1	N14W18	09/06, 23:05	575	830	H	- -	09/06, 22:30
7	2011 11/03, 23:00	11/03, 22:00	- -	N09E154	11/03, 23:30	991	1188	H	- -	- -
8	2012 01/23, 04:45	01/23, 03:38	M8.7	N28W21	01/23, 04:00	2175	2511	H	- -	01/23, 04:00
9	2012 01/27, 18:55	01/27, 18:03	X1.7	N27W71	01/27, 18:27	2508	2541	H	01/27, 18:10	01/27, 18:30
10	2012 03/07, 02:50	03/07, 00:13	X5.4	N17E27	03/07, 00:24	2684	3146	H	03/07, 00:17	03/07, 01:00
11	2012 03/13, 18:05	03/13, 17:12	M7.9	N17W66	03/13, 17:36	1884	1931	H	03/13, 17:15	03/13, 17:35
12	2012 05/17, 01:55	05/17, 01:25	M5.1	N11W76	05/17, 01:48	1582	1596	H	05/17, 01:31	05/17, 01:40
13	2012 07/06, 23:30	07/06, 23:01	X1.1	S13W59	07/06, 23:24	1828	1907	H	07/06, 23:09	07/06, 23:10
14	2012 07/08, 18:10	07/08, 16:23	M6.9	S17W74	07/08, 16:54	1497	- -	157	07/08, 16:30	07/08, 16:35
15	2012 07/19, 06:40	07/19, 04:17	M7.7	S13W88	07/19, 05:24	1631	1631	H	07/19, 05:24	07/19, 05:30
16	2012 07/23, 08:00	07/23, 01:50	- -	S17W132	07/23, 02:36	2003	2156	H	- -	07/23, 02:30
17	2013 04/11, 08:25	04/11, 06:56	M6.5	N09E12	04/11, 07:24	861	1369	H	04/11, 07:02	04/11, 07:10
18	2013 05/22, 14:20	05/22, 13:08	M5.0	N15W70	05/22, 13:25	1466	1491	H	05/22, 12:59	05/22, 13:10
19	2013 10/28, 16:30	10/28, 04:32	M4.4	S06E28	10/28, 15:36	812	1098	H	- -	10/28, 15:24
20	2013 11/02, 07:00	11/02, 04:00	- -	N03W139	11/02, 04:48	828	998	H	- -	- -
21	2014 01/06, 08:15	01/06, 07:30	X3.5	S15W112	01/06, 08:00	1402	1431	H	01/06, 07:45	01/06, 07:58
22	2014 01/07, 19:55	01/07, 18:04	X1.2	S15W11	01/07, 18:24	1830	2246	H	01/07, 18:17	01/07, 18:27
23	2014 02/25, 03:50	02/25, 00:39	X4.9	S12E82	02/25, 01:25	2147	2153	H	02/25, 00:56	02/25, 00:56
24	2014 04/18, 13:40	04/18, 12:31	M7.3	S20W34	04/18, 13:25	1203	1359	H	04/18, 12:55	04/18, 13:06
25	2014 09/01, 17:20	09/01, 10:58	X2.4	N14E127	09/01, 11:12	1901	2017	H	- -	09/01, 11:12
26	2014 09/10, 21:35	09/10, 17:21	X1.6	N14E02	09/10, 18:00	1267	1652	H	- -	09/10, 17:45

Solar Particle Events studies





Bruno, A et al, accepted in ApJ!

Consistent with diffusive shock acceleration theories, the measured SEP spectra are well reproduced by a power-law modulated by an exponential cutoff attributed to particles escaping the CME-driven shock during acceleration

Cutoff energies fall above and below the GLE threshold (~1 GV). Three GLEs are among the group, but also some events falling above 1 GV that were not registered as GLEs, but might have.

From the spectrum perspective, we see *no qualitative distinction* between those events that are GLEs, those that could be, or those that are not.

PAMELA overall results

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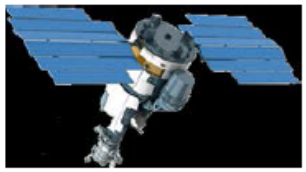

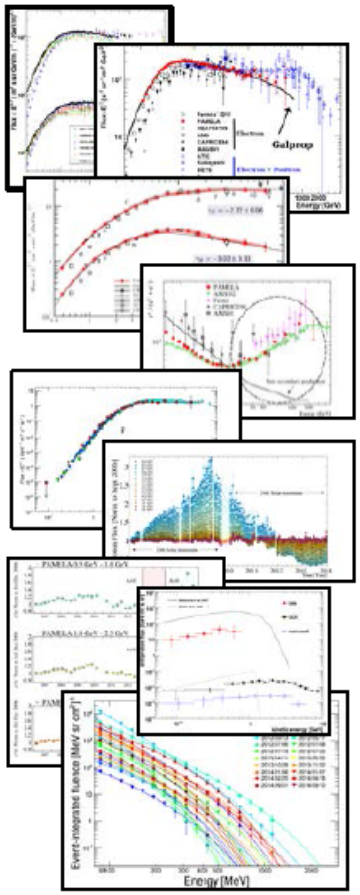

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The PAMELA Mission: Heralding a new era in precision cosmic ray physics

O. Adriani [a,b], G.C. Barbarino [c,d], G.A. Bazilevskaya [e], R. Bellotti [f,g], M. Boezio [h], E.A. Bogomolov [i], M. Bongi [a,b], V. Bonvicini [h], S. Borisov [j,b], A. Bruno [f,g], F. Cafagna [g], D. Campana [d], R. Carbone [d,b], P. Carlson [j,k], M. Casolino [l], G. Castellini [m], M.P. De Pascale [l,n,1], C. De Santis [l,n], N. De Simone [l], V. Di Felice [l], V. Formato [b,n], A.M. Galper [o], U. Giaccari [d], A.V. Karelin [o], M.D. Kheymits [o], S.V. Koldashov [o], S. Koldobskiy [o], S.Yu. Krutkov [i], A.N. Kvashnin [e], A. Leonov [o], V. Malakhov [o], L. Marcelli [n], M. Martucci [n,q], A.G. Mayorov [o], W. Menn [r], V.V. Mikhailov [o], E. Mocchiutti [h], A. Monaco [f,g], N. Mori [a,b], R. Munini [h,j,k,s], N. Nikonov [t,u], G. Osteria [s], P. Papini [c], M. Pearce [j,k], P. Picozza [l,n,*], C. Pizzolotto [f,g,s], M. Ricci [q], S.B. Ricciarini [b,m], L. Rossetto [j,k], R. Sarkar [n], M. Simon [r], R. Sparvoli [l,n], P. Spillantini [a,b], Y.I. Stozhkov [e], A. Vacchi [h], E. Vannuccini [b], G.I. Vasilyev [i], S.A. Voronov [o], J. Wu [j,k,u], Y.T. Yurkin [o], G. Zampa [h], N. Zampa [h], V.G. Zverev [o]

LA RIVISTA DEL NUOVO CIMENTO

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Ten years of PAMELA in space

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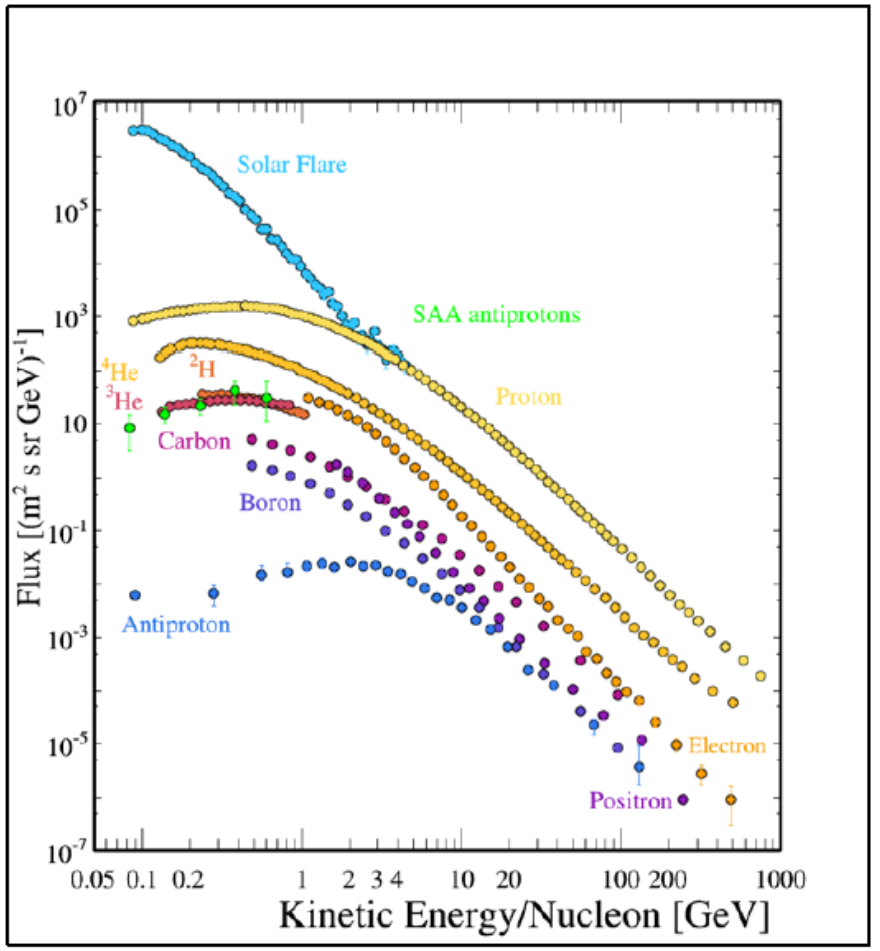
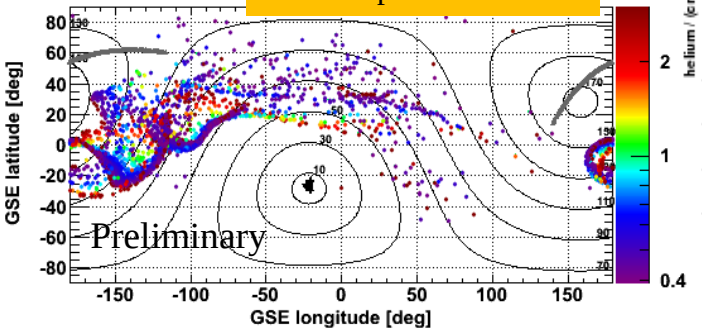
- Adriani, O *et al.* Nuovo Cimento
- Adriani,O *et al* Phys Rep.



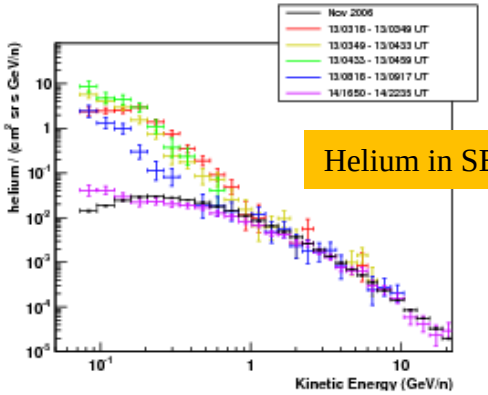
Conclusions

- Still room for new analysis i.e. Helium nuclei, positrons and deuterium time evolution from 2006 to 2016
- More work on solar events i.e. Anisotropies, Helium enhancement ...
- others

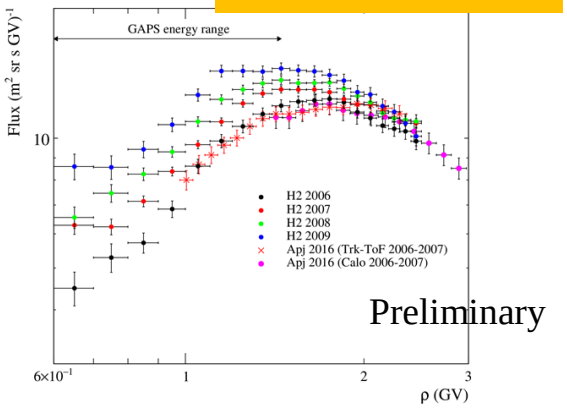
Anisotropies in SEPs



Helium in SEPs



Deuterium modulation



He flux time evolution