A decade of Cosmic Rays Investigation with the PAMELA Experiment

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Cosmic Ray International Seminar (CRIS) 2018

18-22 June 2018 - *Portopalo di Capo Passero (SR) - Italy*

PAMELA Collaboration

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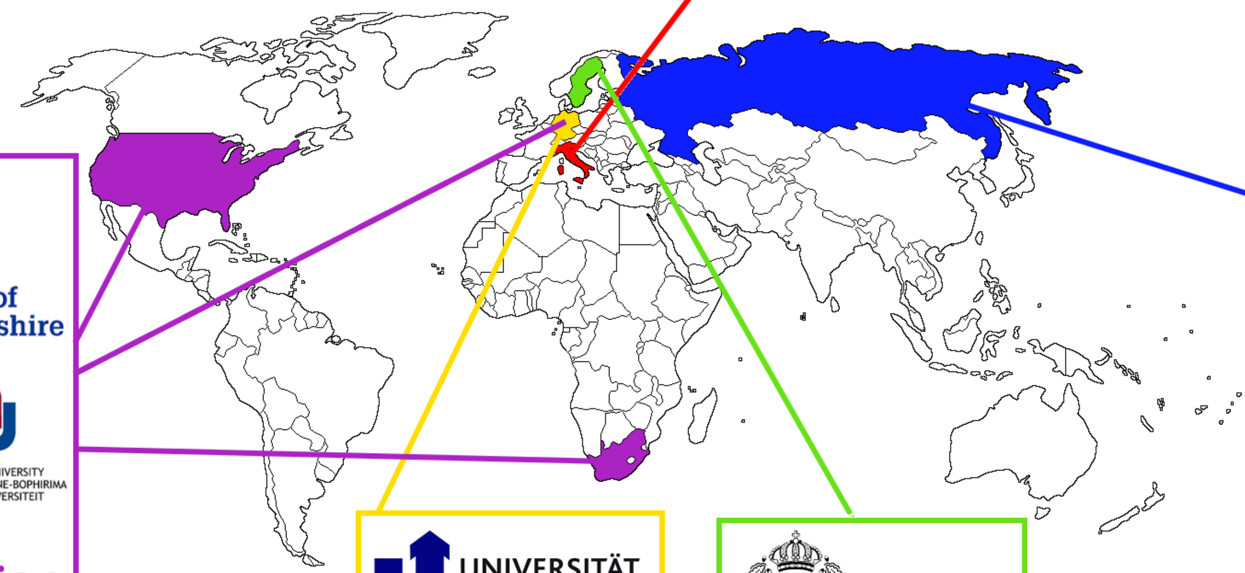
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Università di Roma Tor Vergata

Consiglio Nazionale delle Ricerche

Naples Bari Florence Frascati Rome Trieste CNR, Florence



NM STATE UNIVERSITY

NASA Goddard Space Flight Center

University of New Hampshire

CAU Christian-Albrechts-Universität zu Kiel

NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT

External collaboration

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Germany

VETENSKAP OCH KONST

KUNGL TEKNISKA HÖGSKOLAN

Sweden

Ioffe Physical Technical Institute

Физический институт имени П.Н.Лебедева ФИАН

МИФИ

Moscow

St. Petersburg

Yaroslavl State University

PAMELA orbit

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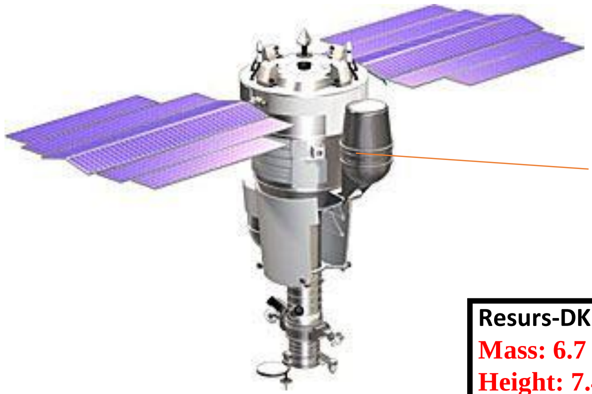
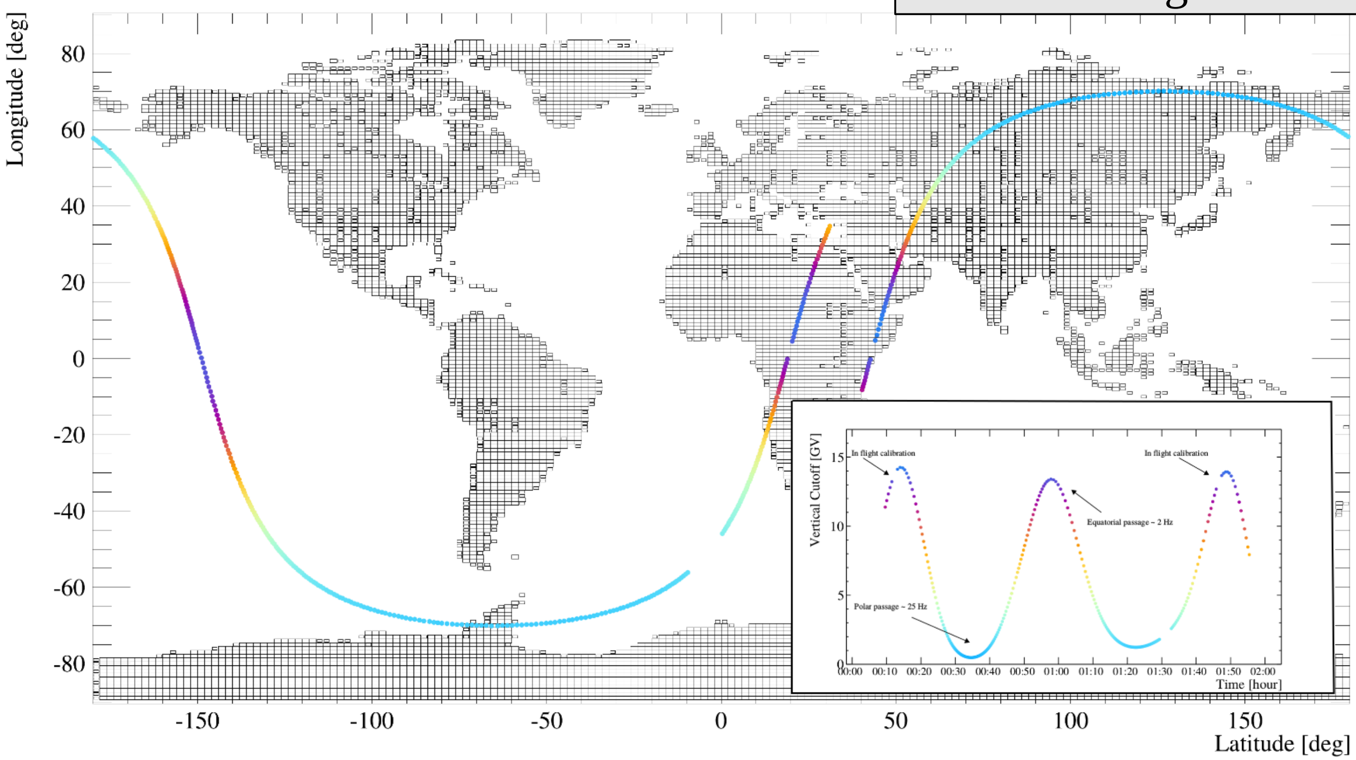


Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

- ✓ Quasi polar and elliptical orbit
- ✓ Inclination ~ 70°
- ✓ Altitude ~ 300 - 600 km
- ✓ From 2010 circular orbit
- ✓ data-taking 2006-2016



PAMELA instrument

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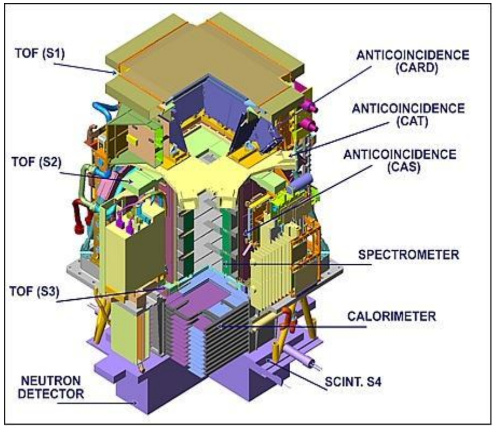
GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W



Time-Of-Flight

plastic scint.+ PMT:

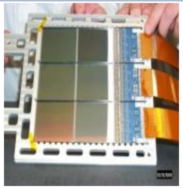
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Spectrometer

microstrip Si track sys

- *Rigidity → R = pc/Ze*
- *Charge sign*
- *Charge value from dE/dx*

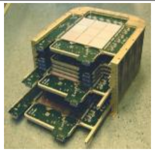
\+ permanent magnet

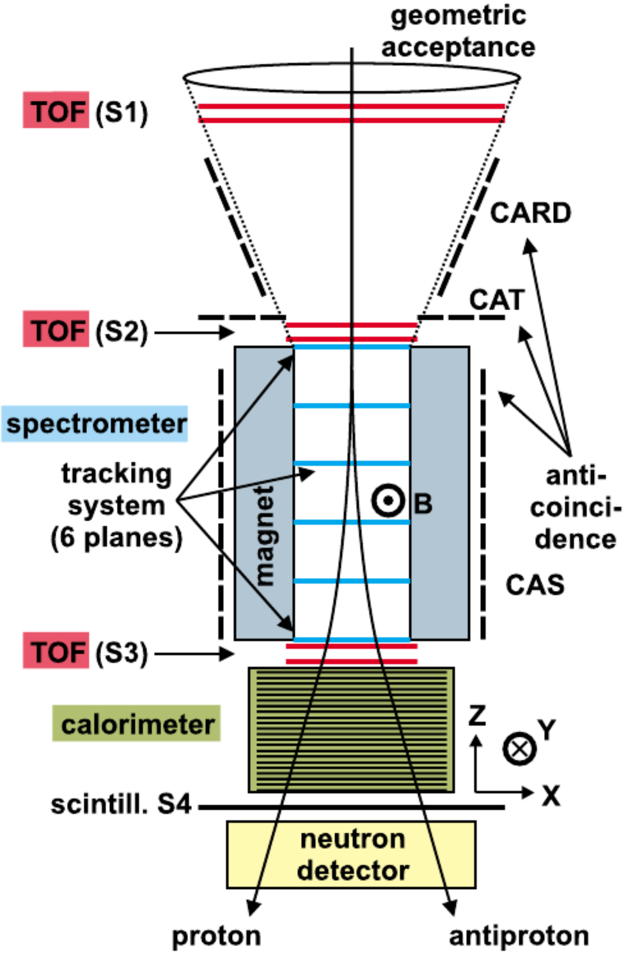


Electromag .calorimeter

W/Si samp (16.3 X_0, 0.6 λ_I)

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





Neutron detector

³He tubes + PMT:

- High-energy e/h discrimination

PAMELA positron fraction

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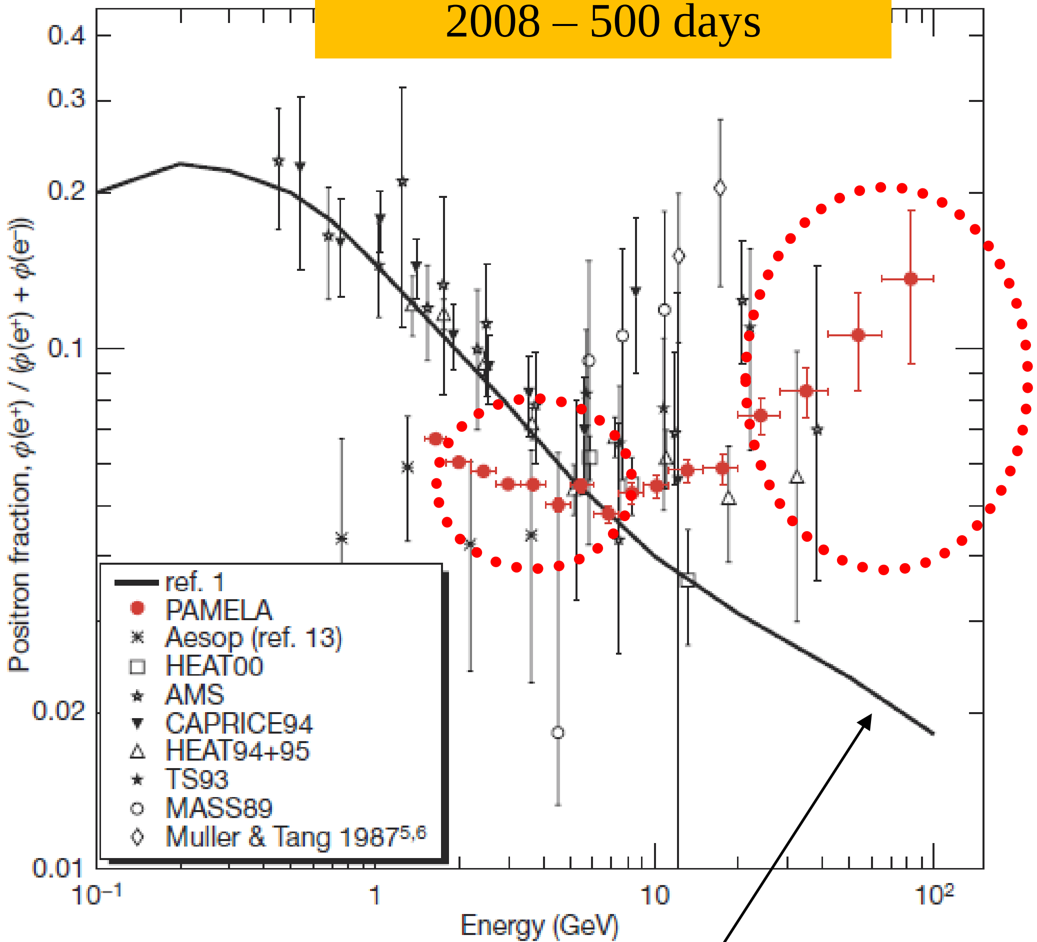
June 2006 – Februaary 2008 – 500 days



Secondary production: Moskalenko & Strong 98

nature International weekly journal of science

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

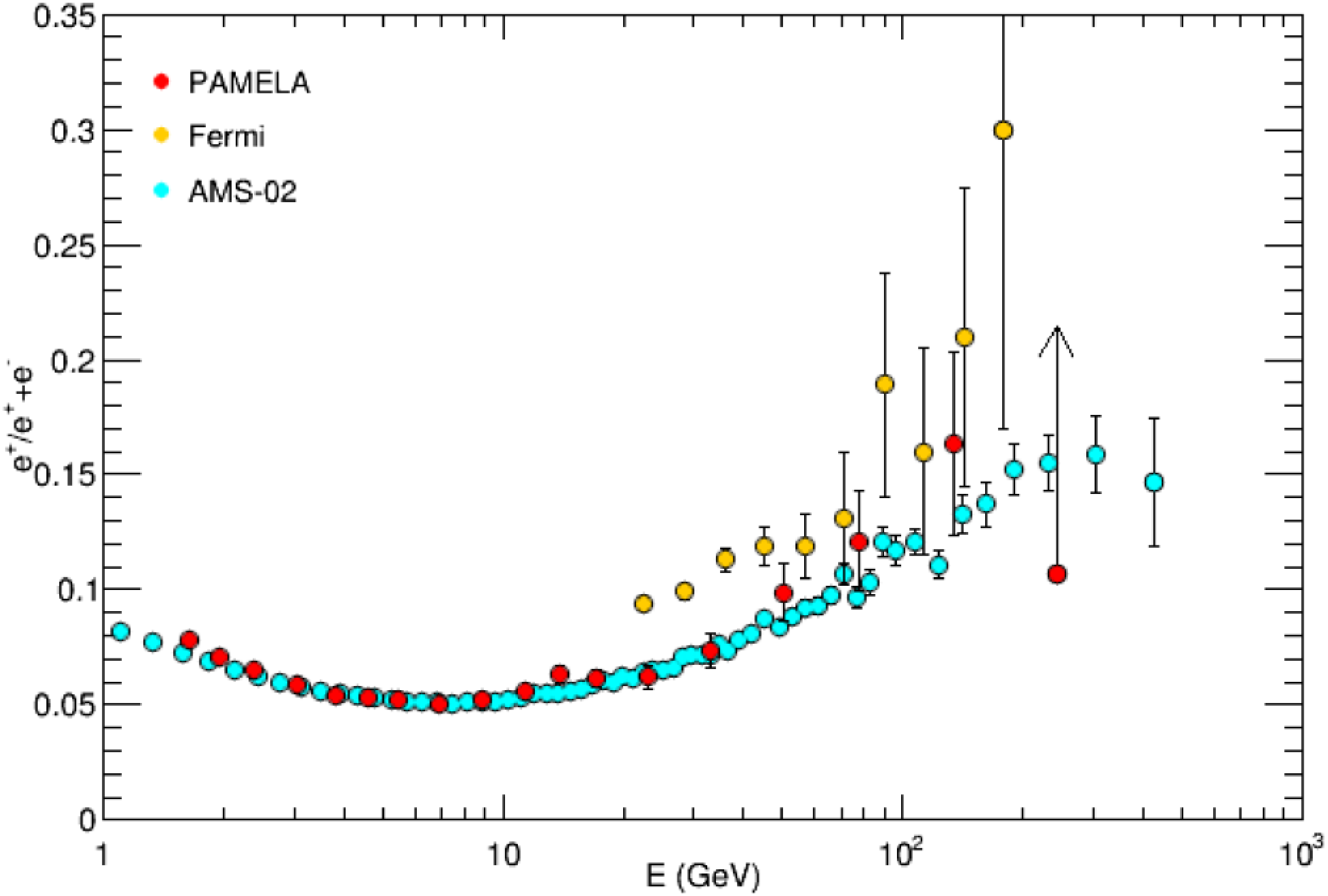
O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De 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]

>1350 cit

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

PAMELA positron fraction

Good agreement with AMS02!



PAMELA positrons

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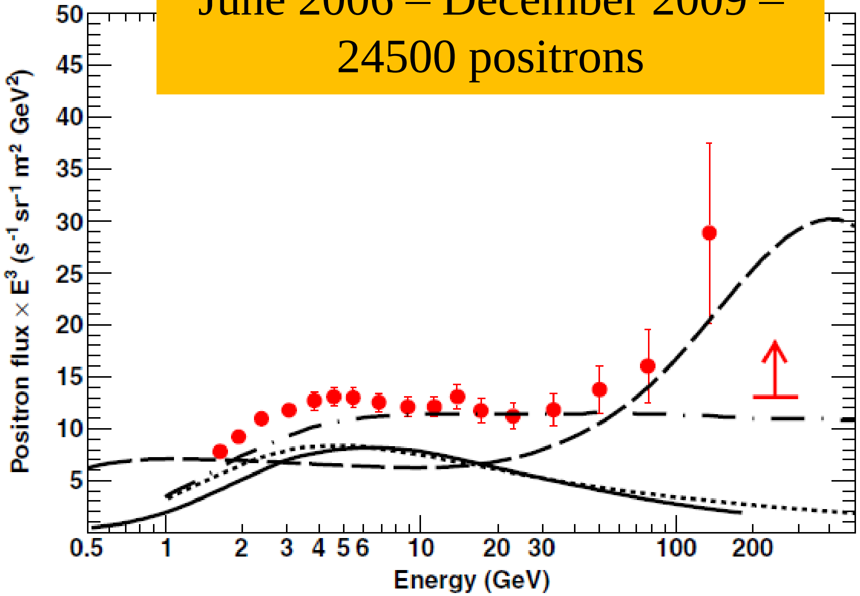
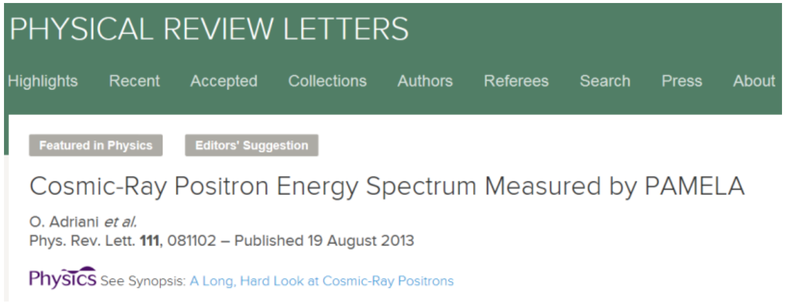
June 2006 – December 2009 – 24500 positrons

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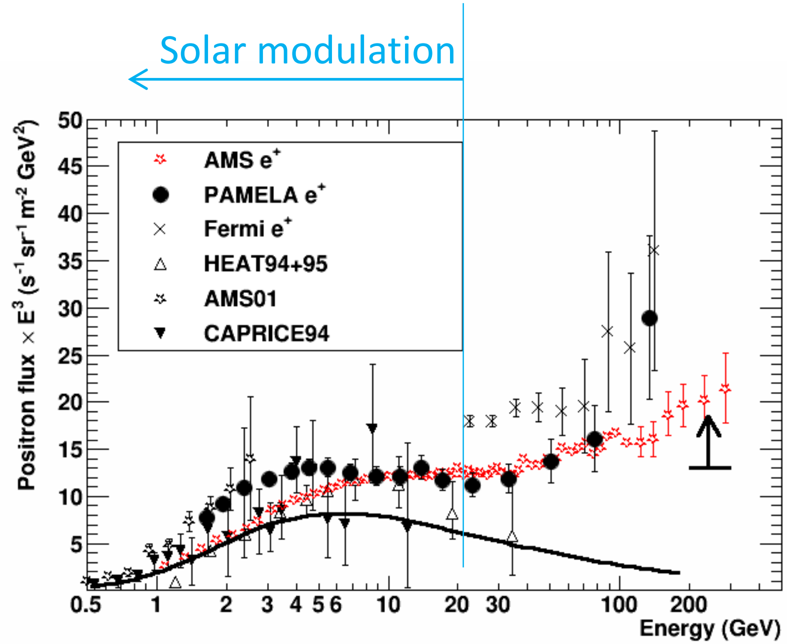
Cosmic-Ray Positron Energy Spectrum Measured by PAMELA

O. Adriani *et al.*
Phys. Rev. Lett. **111**, 081102 – Published 19 August 2013

Physics See Synopsis: A Long, Hard Look at Cosmic-Ray Positrons



Results confirmed by AMS02!

PAMELA antiprotons

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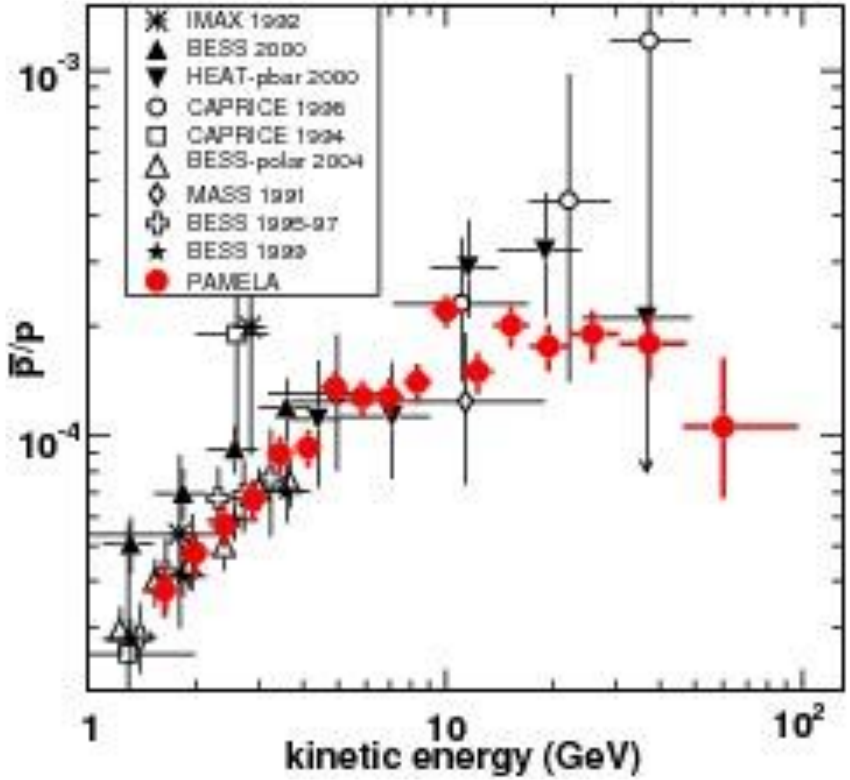
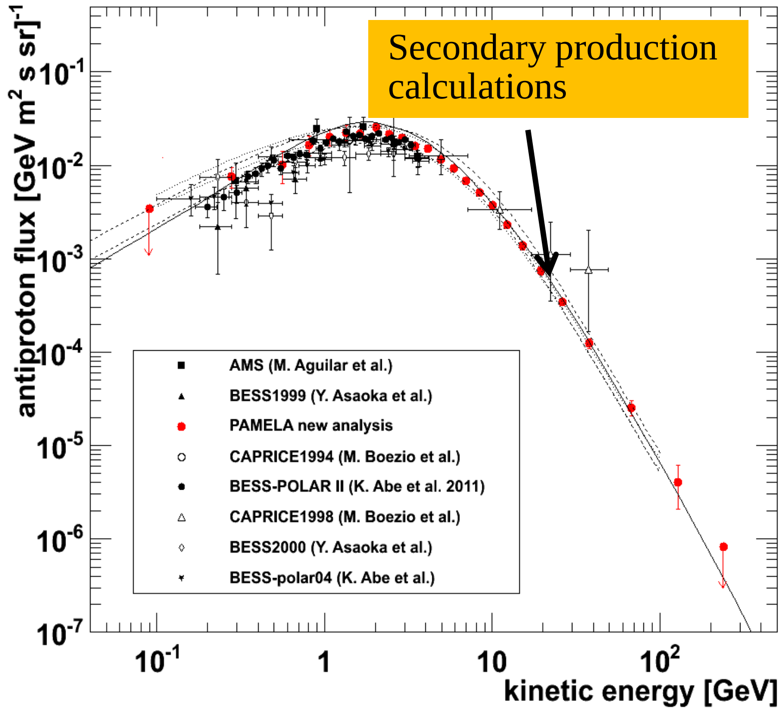
Adriani, O et al., PRL 102, 051101 (2009)



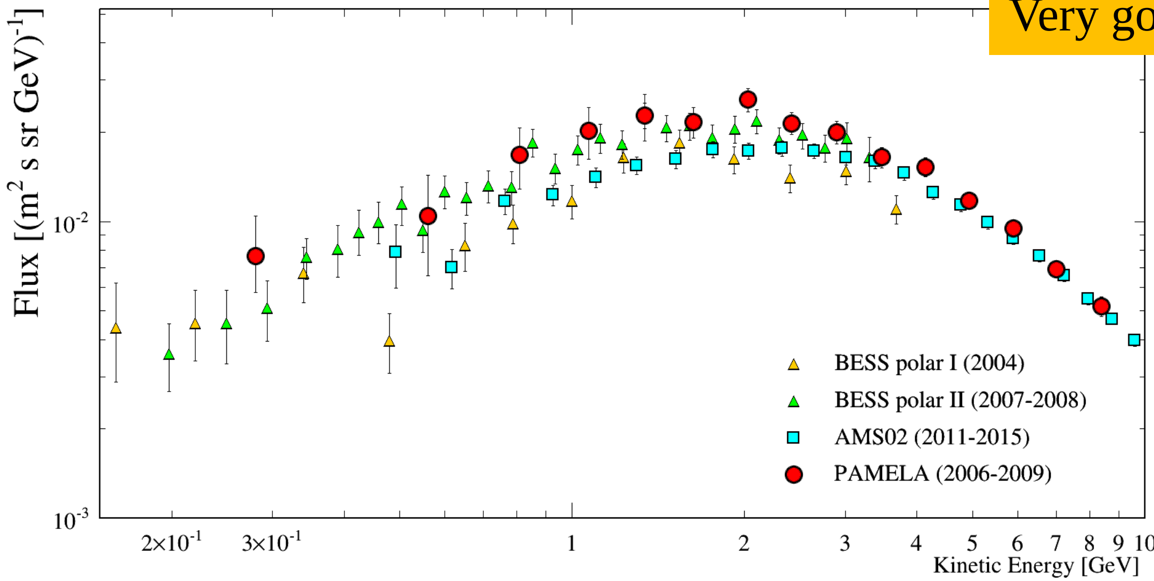
Adriani, O et al., 105, 121101 (2010)



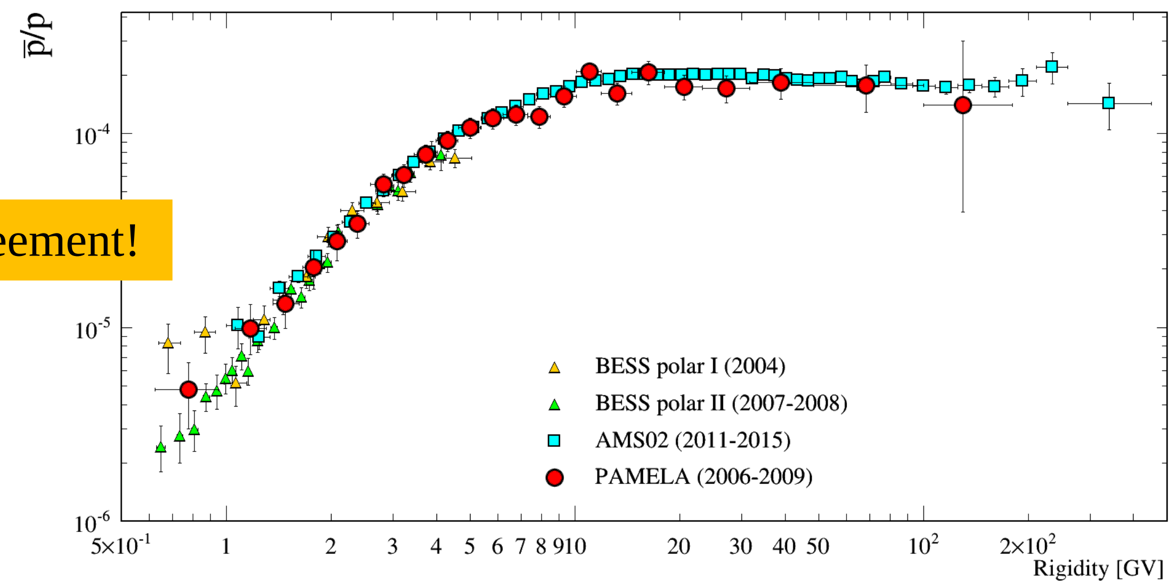
Consistent with secondary production models

Comparison with AMS02/BESS

Very good agreement!



O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10



Very good agreement!

PAMELA H, He and H/He spectra

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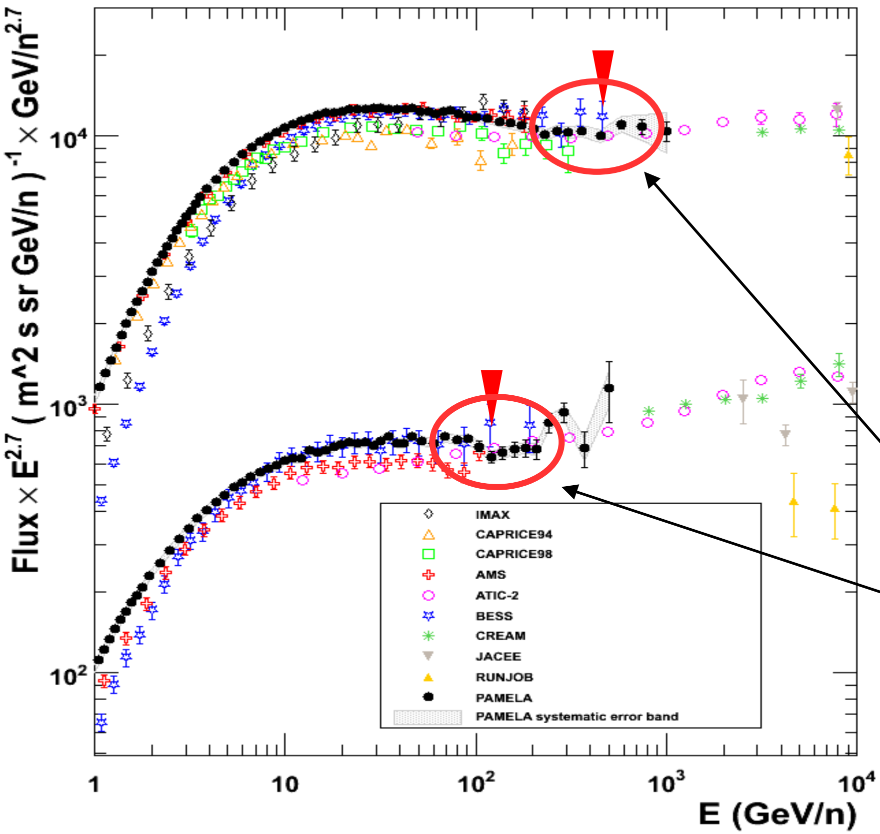
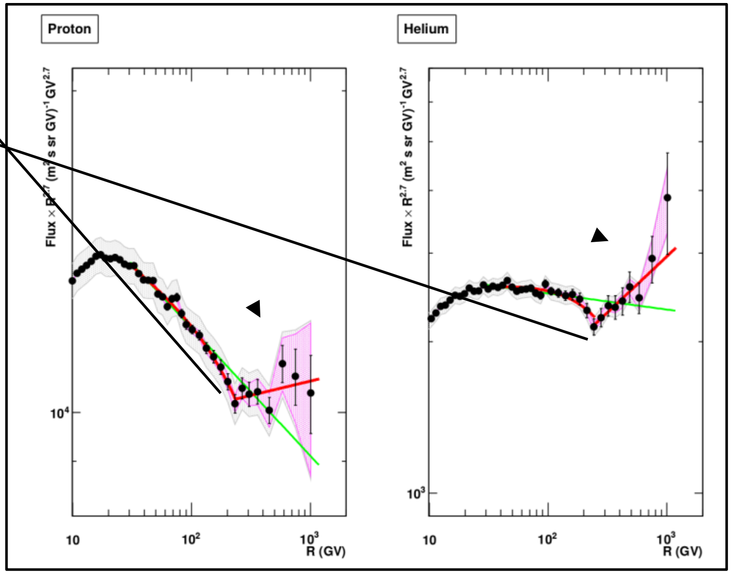
- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV Δγ~0.2÷0.3 SPL is rejected at 98% CL

- 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

Results confirmed by AMS02: protons

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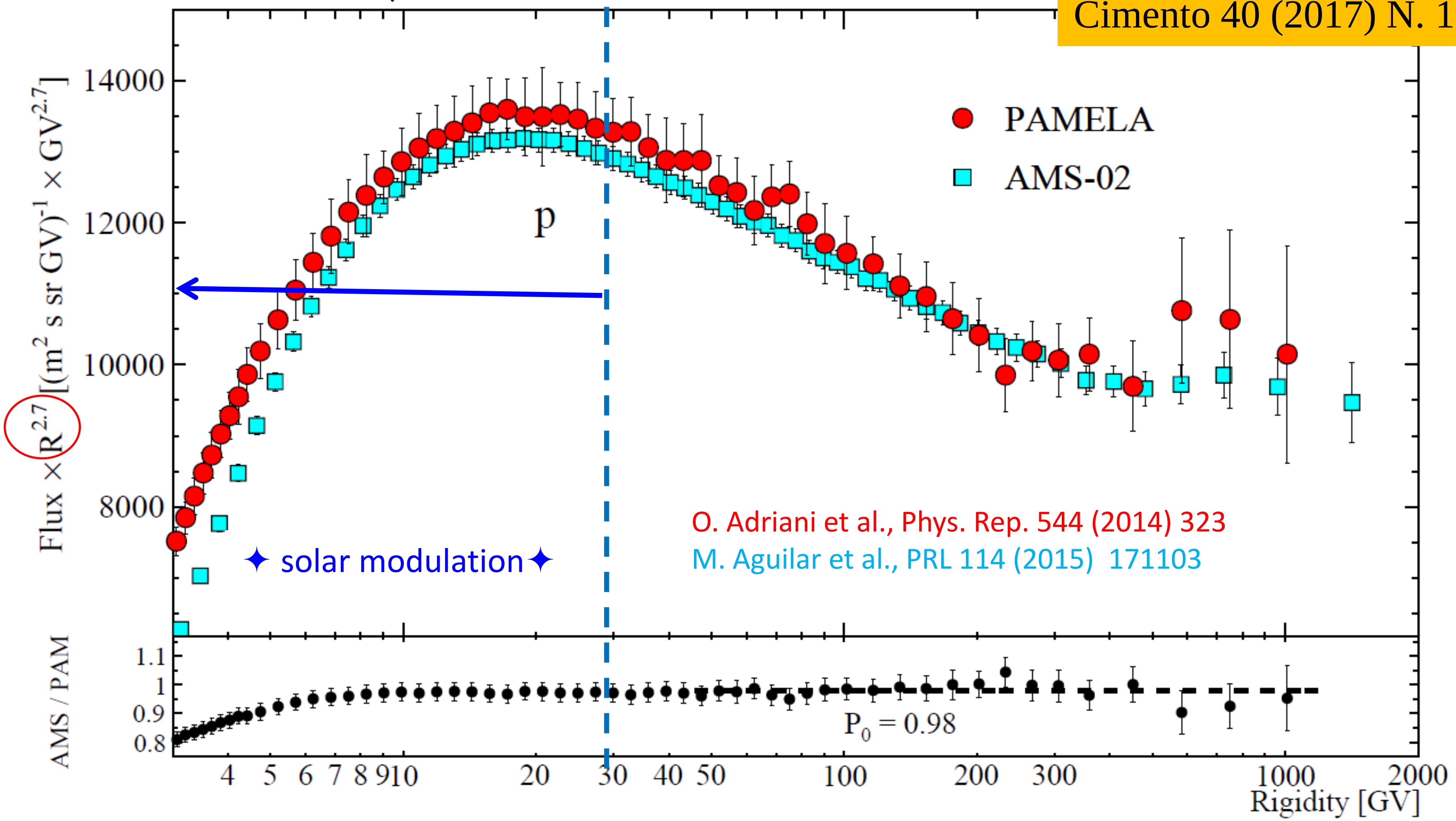
PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10



Results confirmed by AMS02: helium

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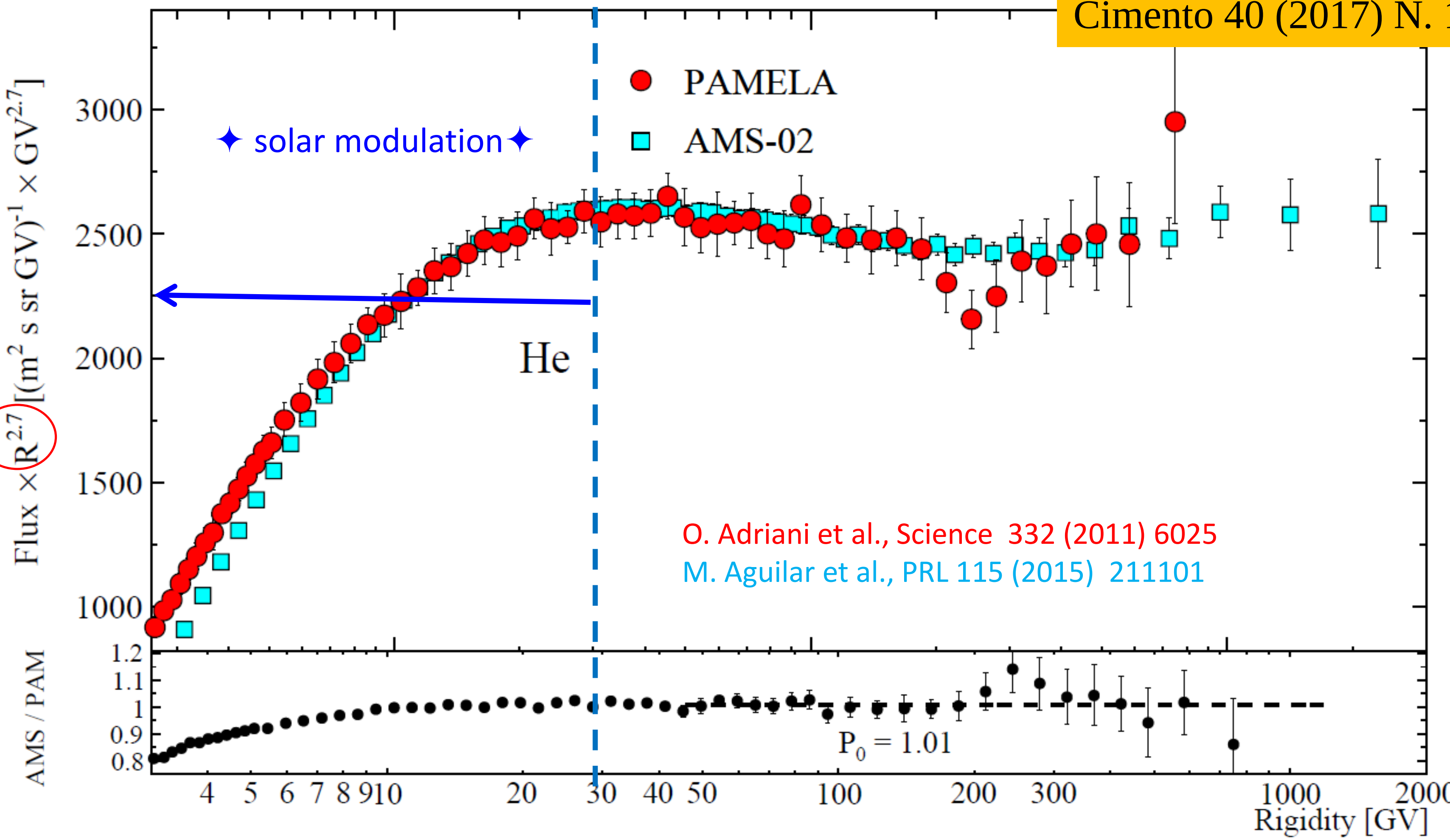
PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

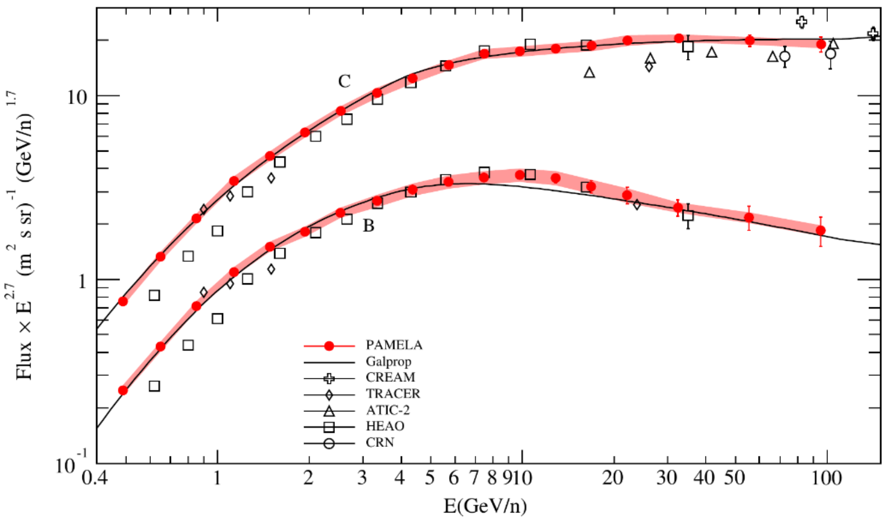
O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10



PAMELA boron/carbon

Li, Be, B are produced by fragmentation of heavier nuclei, mostly C, N, O, on H and He

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



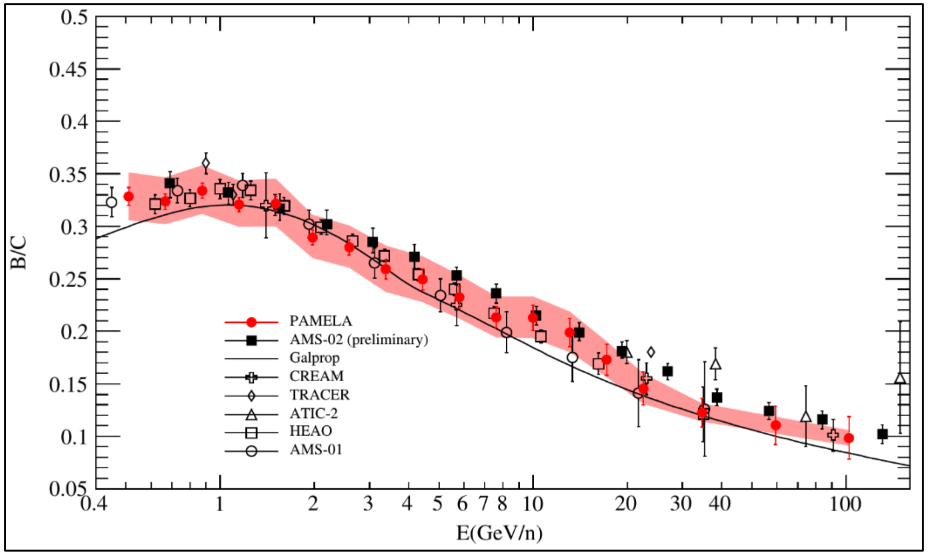
B/C = Sec/Prim

$\sim Q_{sec}(E)/Q_{prim}(E)$

$\sim Q_{prim}(E)/D(E) \;/\; Q_{prim}(E)$

$\sim 1/D(E)$

Diffusion coefficient: $D(R)=D_0\beta R^{\delta}$



PAMELA e$^-$ and e$^+$

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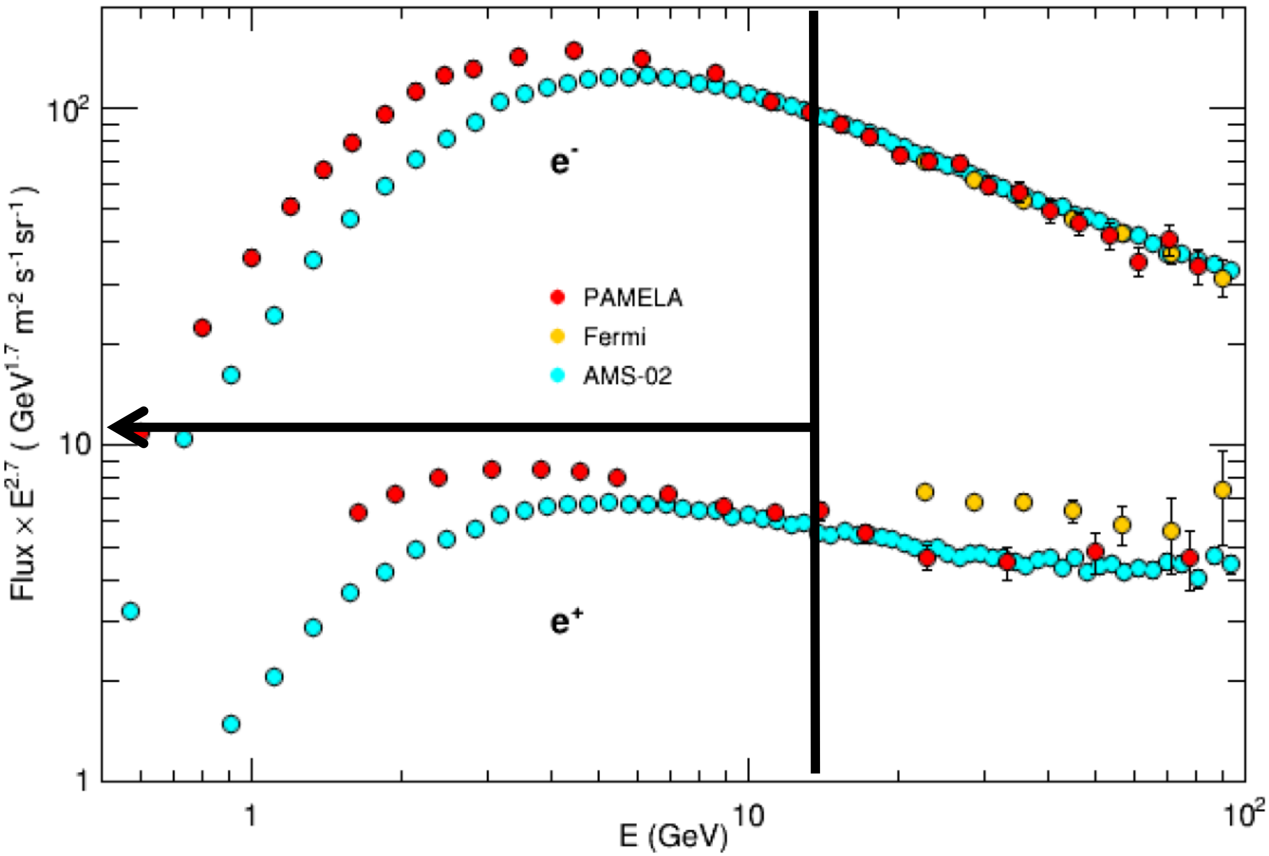
O. Adriani *et al.*, ApJ 810 (2015) 142
O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10

O. Adriani *et al.*, PRL 111, 081102 (2013)
O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10

Solar modulation



PAMELA observations (2006-2016)

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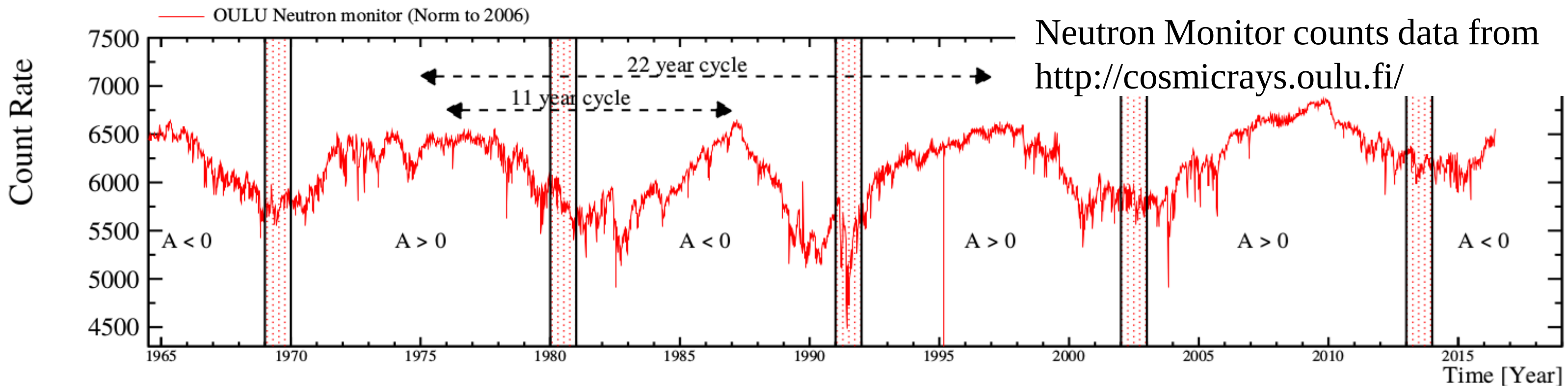
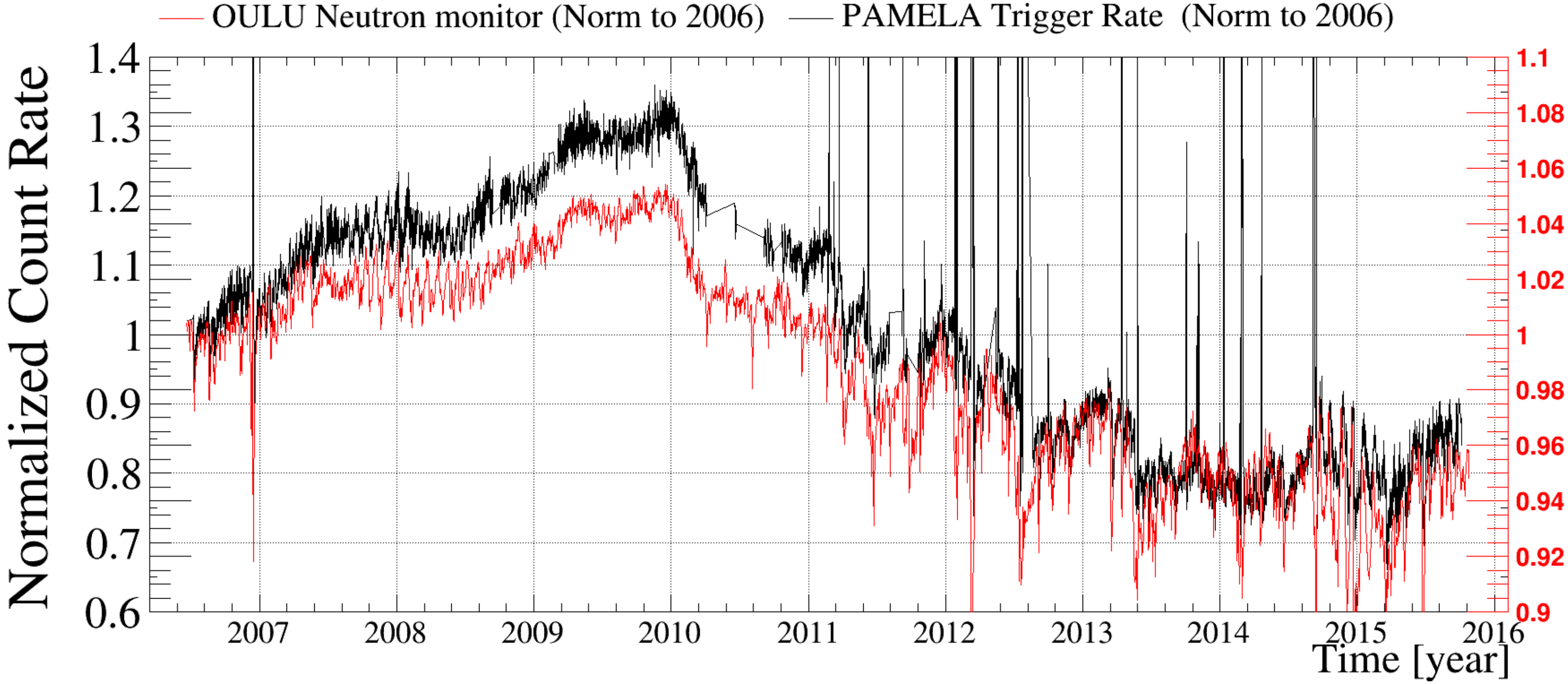
Neutron Monitor counts data from http://cosmicrays.oulu.fi/





PAMELA observations covers about one solar cycle

Time Dependance of the e^- flux

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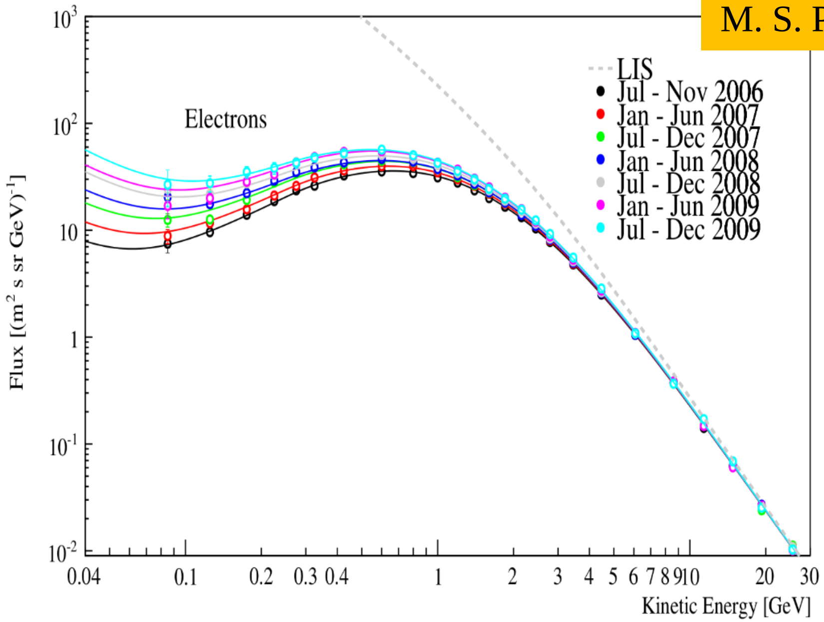
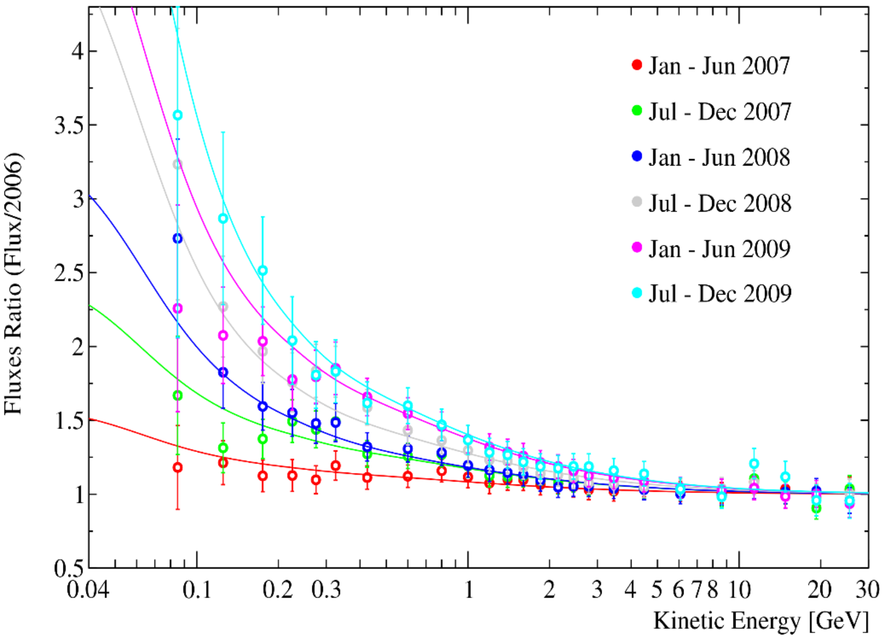
O. Adriani *et al.*, ApJ 810 (2015) 2, 142;
M. S. Potgieter *et al.*, ApJ 810 (2015) 2, 141



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

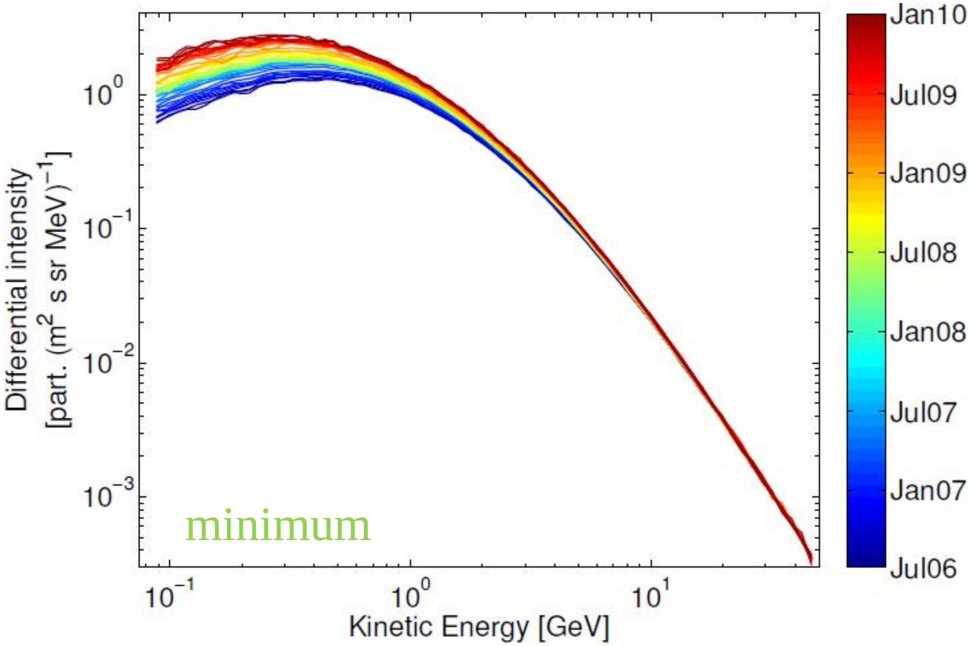
The ratios between the measured e^- fluxes from January 2007 till December 2009 and the measured fluxes for the period July-November 2006 with the corresponding computed spectra.



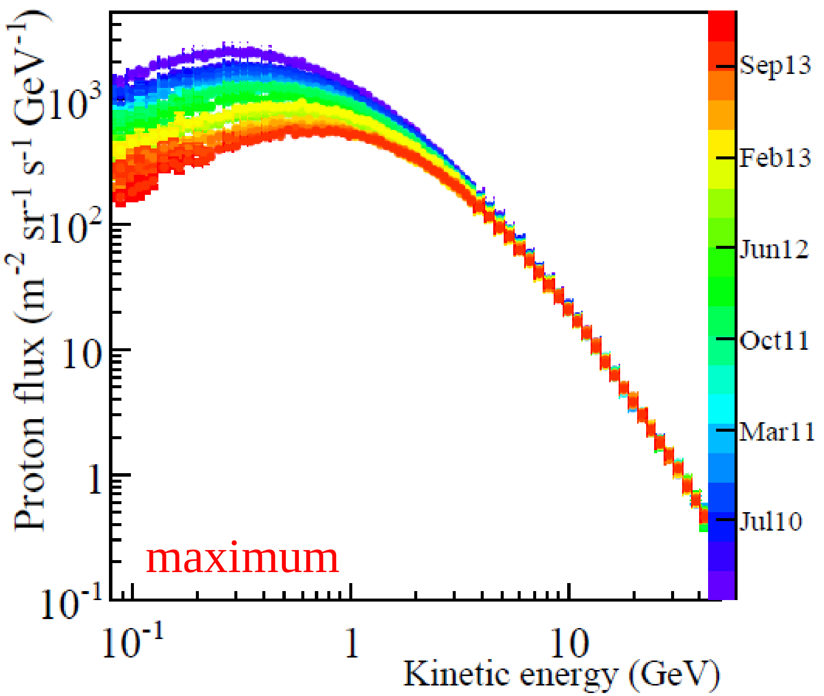
Time Dependance of the *p* flux

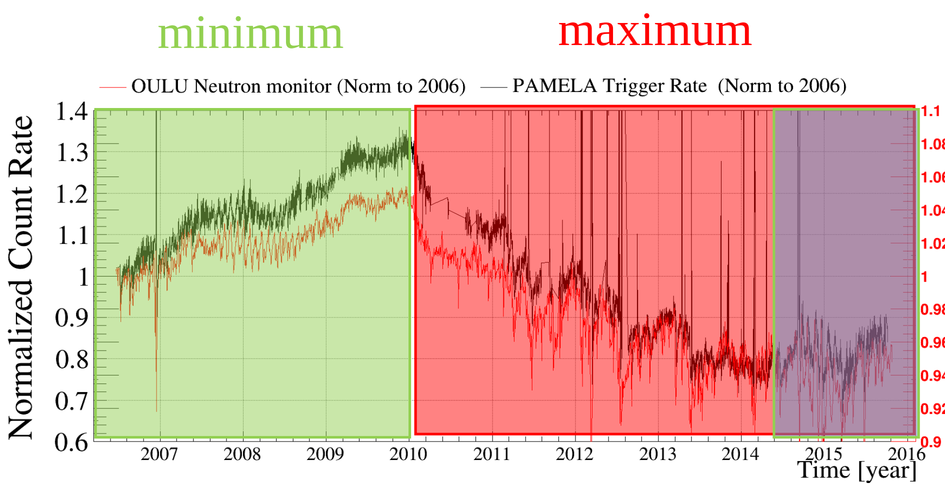
UNIVERSITA' degli STUDI di ROMA TOR VERGATA

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



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





Time Dependance of the *He* flux

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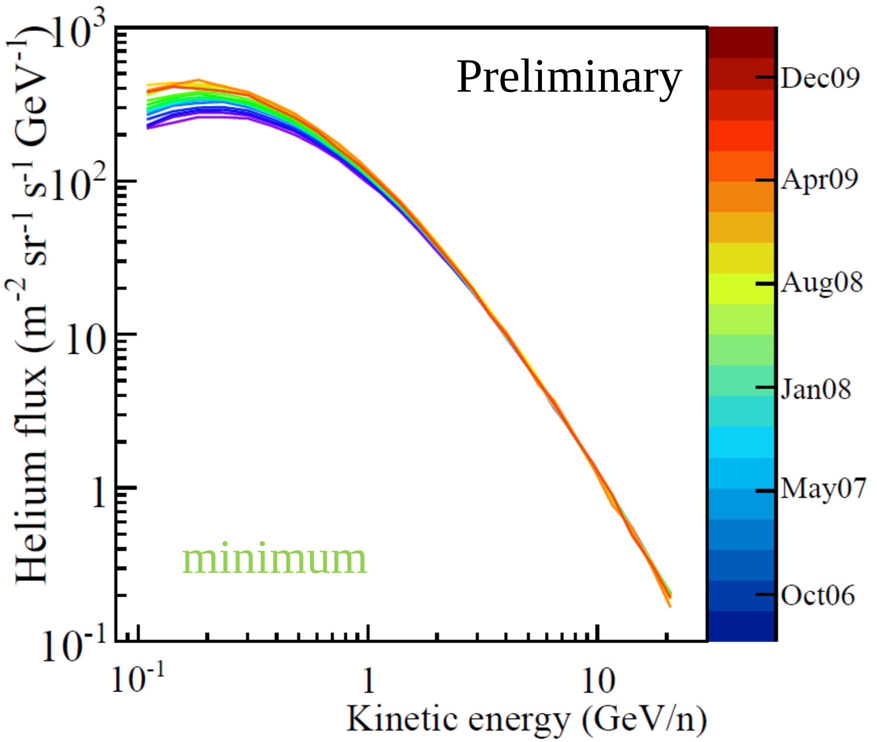
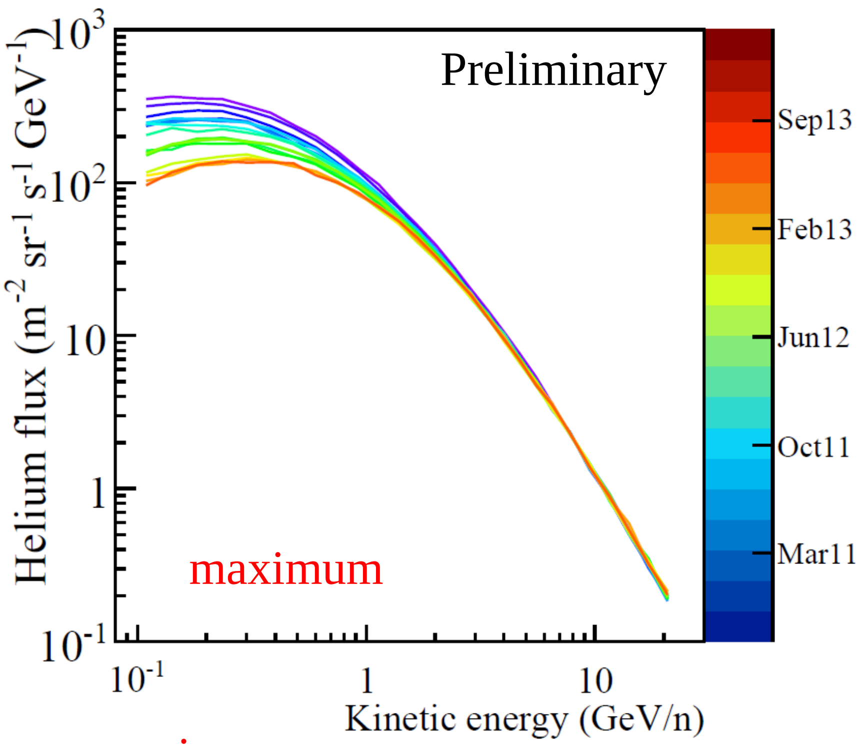
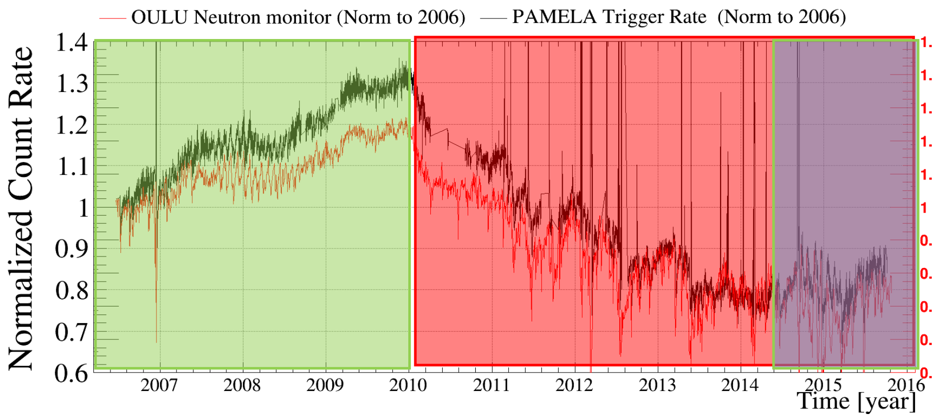


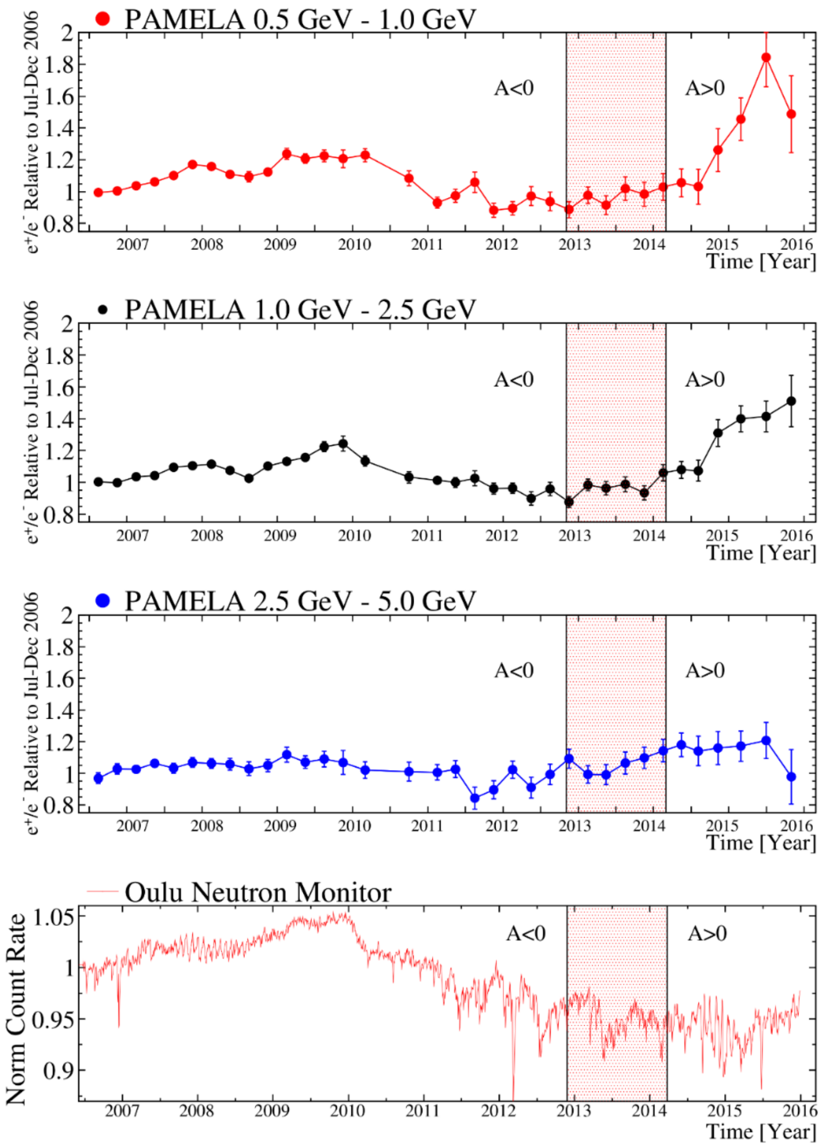


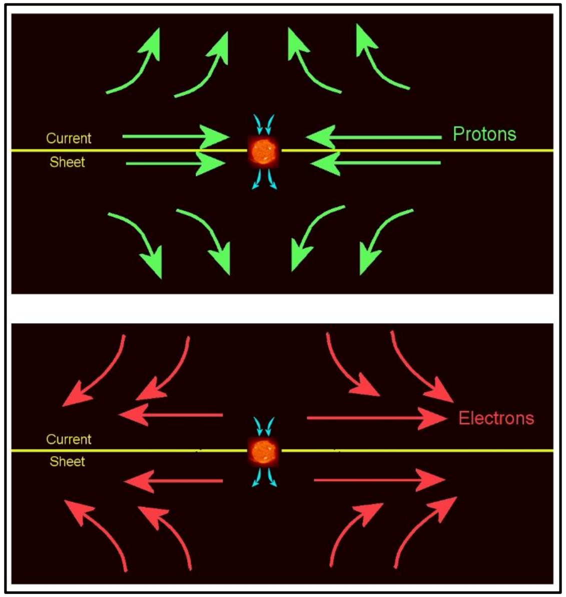
minimum maximum



Time Dependance of the e^-/e^+ flux

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)

Time Dependance of the e^-/e^+ flux

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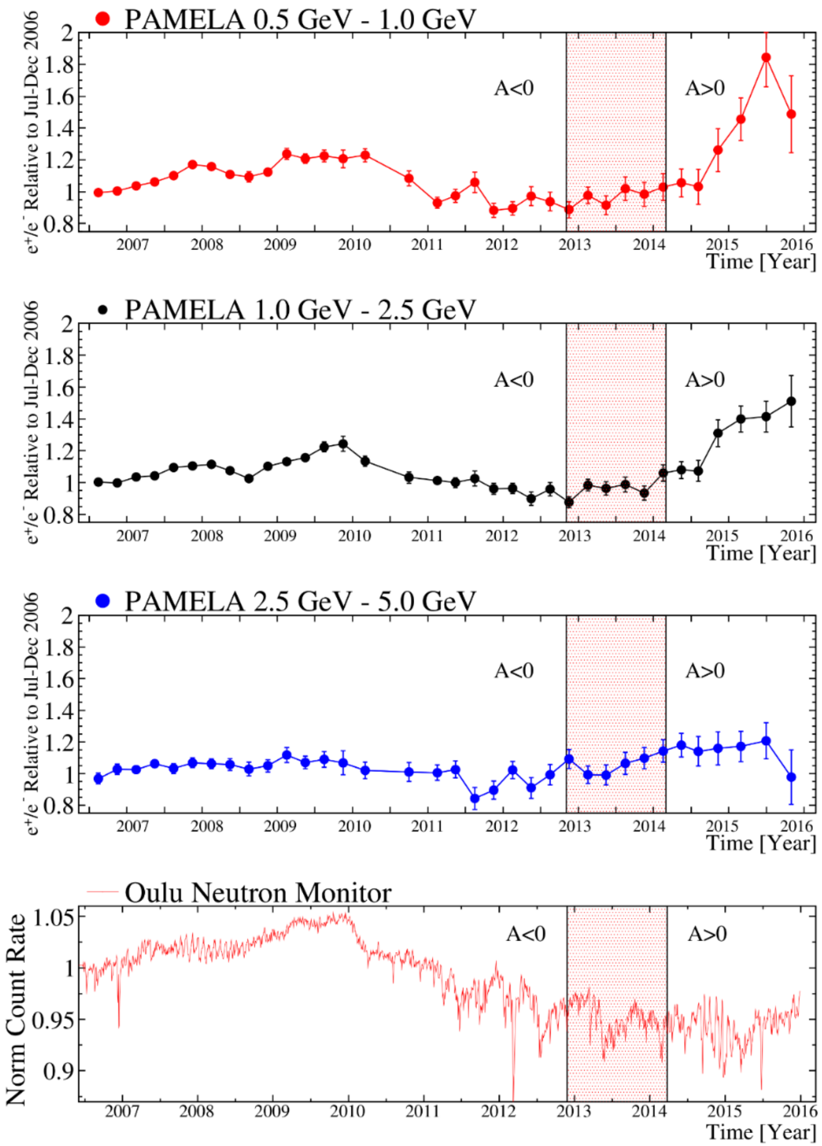
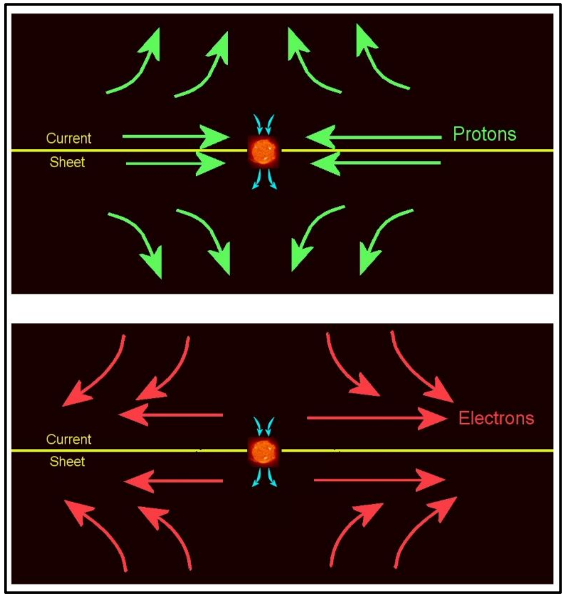
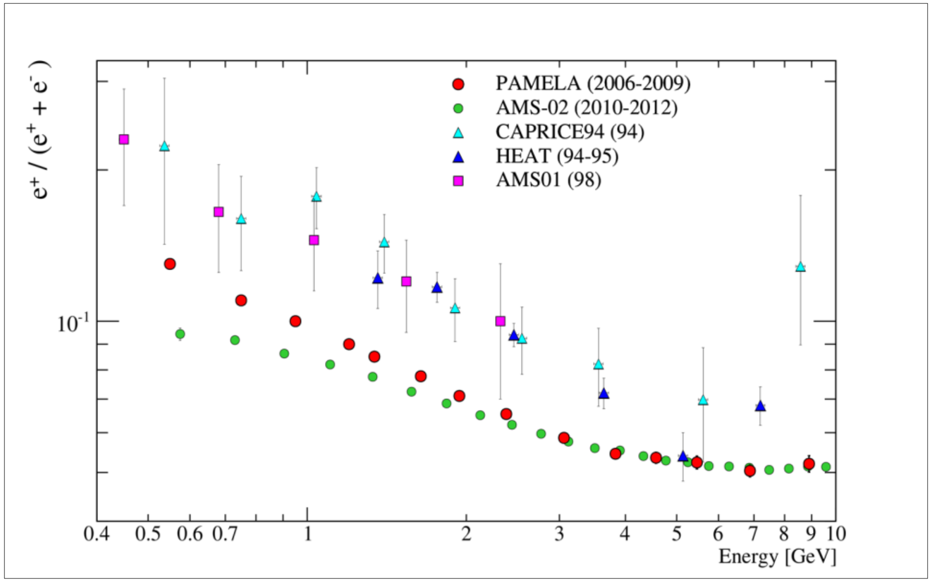
polarity reversal of the HMF







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

Time Dependance of the e^-/e^+ flux

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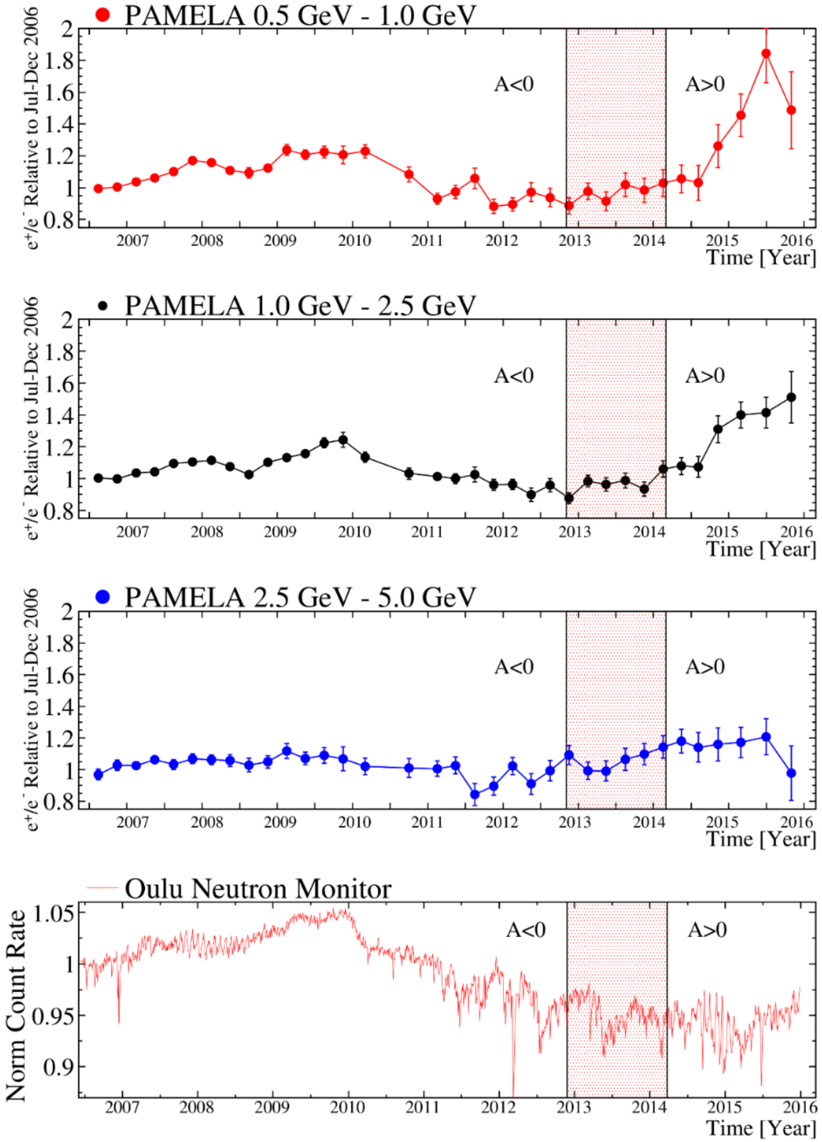
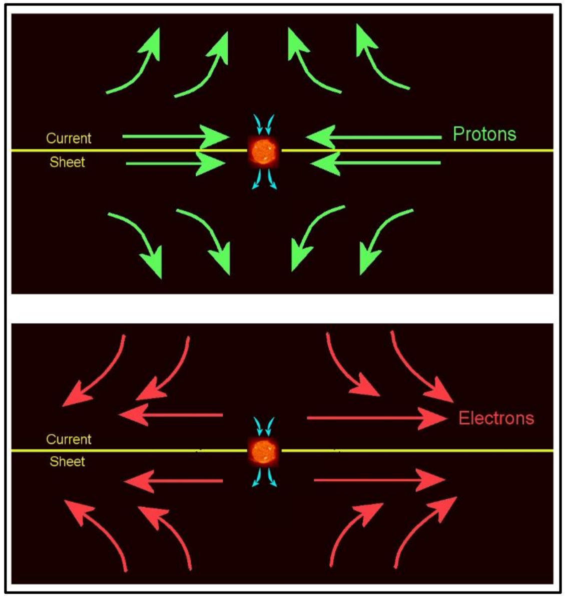
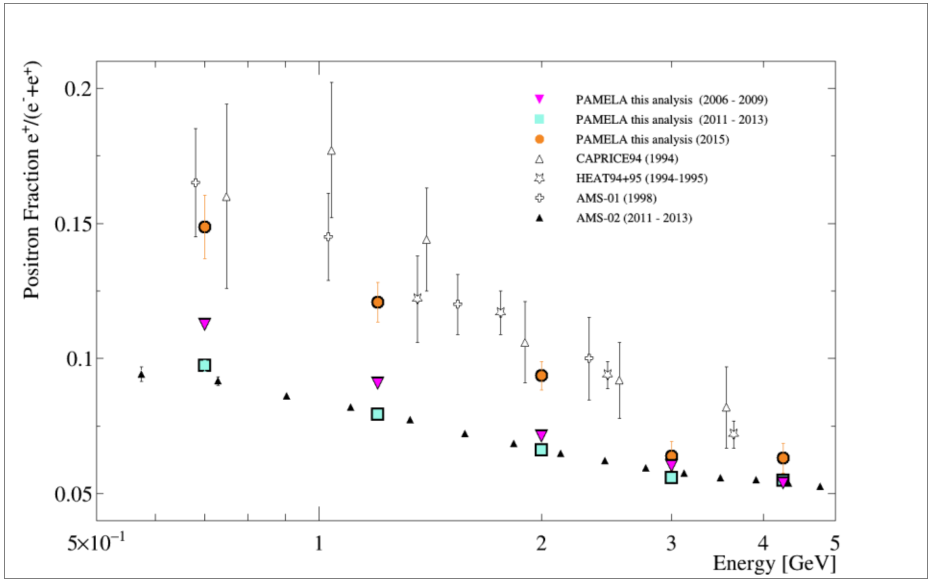
polarity reversal of the HMF







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

Solar Energetic Particles (SEP)

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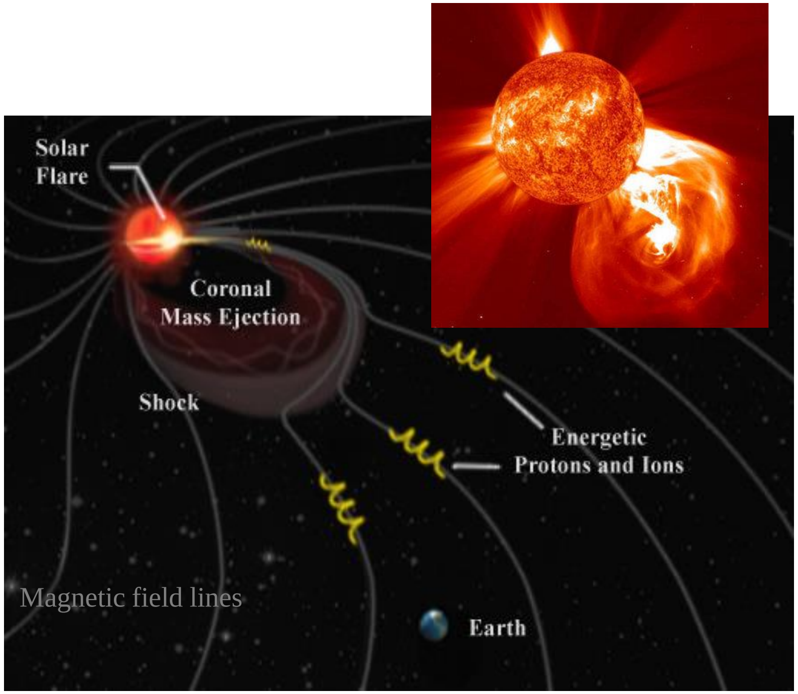
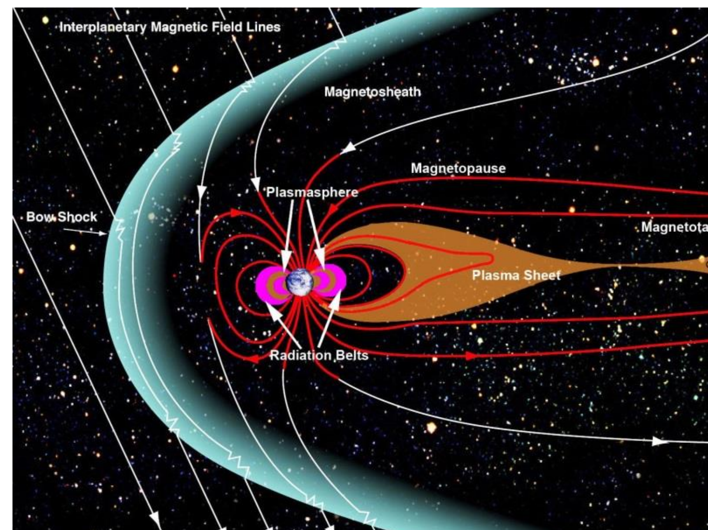


Sun can accelerate particles up to relativistic energies
- Magnetic reconnections
- CME-driven shock

SEPs can be observed in the interplanetary space

Often associated to other solar phenomena, eg:
- X and gamma-ray flares
- Coronal-mass ejections (CMEs)
- ...



SEP observation on Earth:

- Propagation of SEPs along IMF lines
  $\Rightarrow$ Earth must be magnetically connected
- Anisotropic emission
  $\Rightarrow$ flux observed on Earth depends on geomagnetic location

PAMELA SEP list

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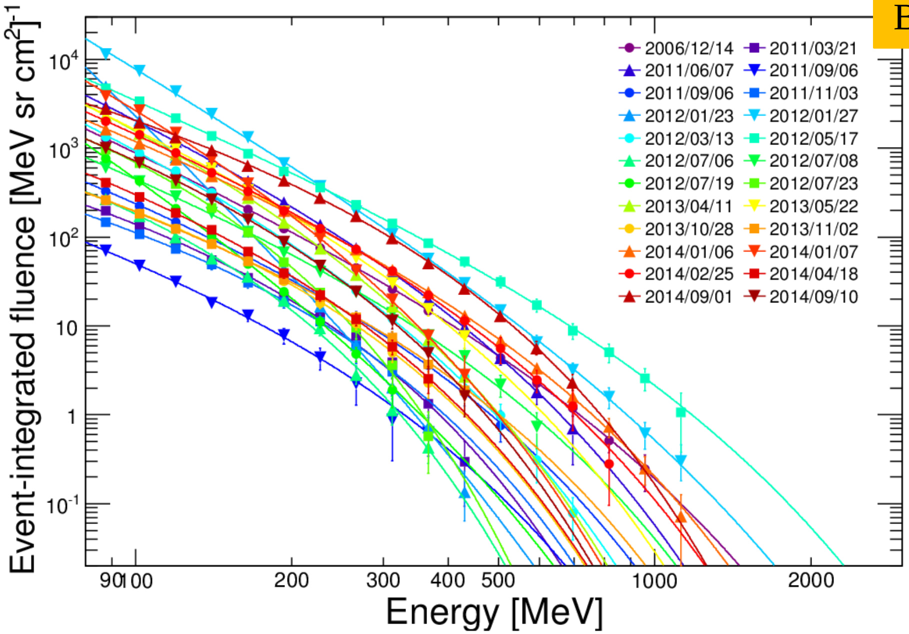
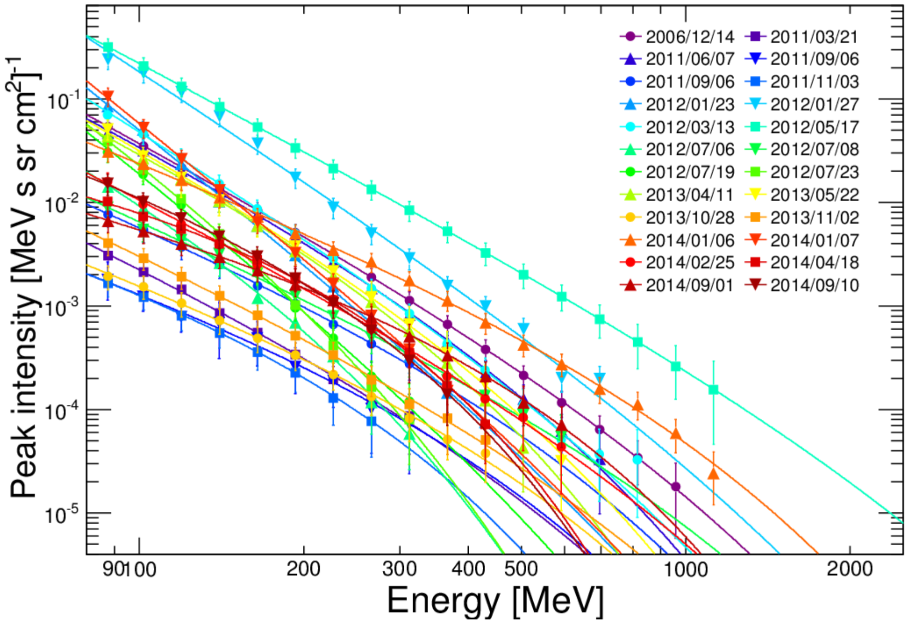
	SEP Event	Flare			CME				m-type II	DH-type II
#	Date	Onset time	Class	Location	1^{st}-app. time	V_{app}	V_{spa}	Width	Onset time	Onset time
1	2006 12/13, 02:55	12/13, 02:14	X3.4	S06W23	12/13, 02:54	1774	2184	H	12/13, 02:26	12/13, 02:45
2	2006 12/14, 22:55	12/14, 21:58	X1.5	S06W46	12/14, 22:30	1042	1139	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

PAMELA SEP spectra

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.

Multiparticle observation of Forbush decrease

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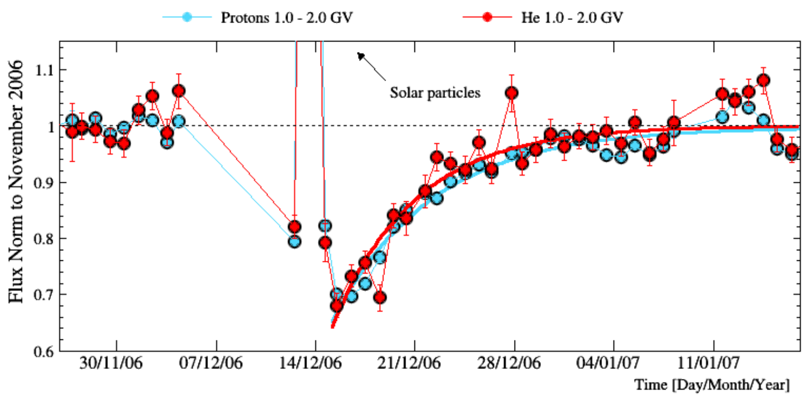

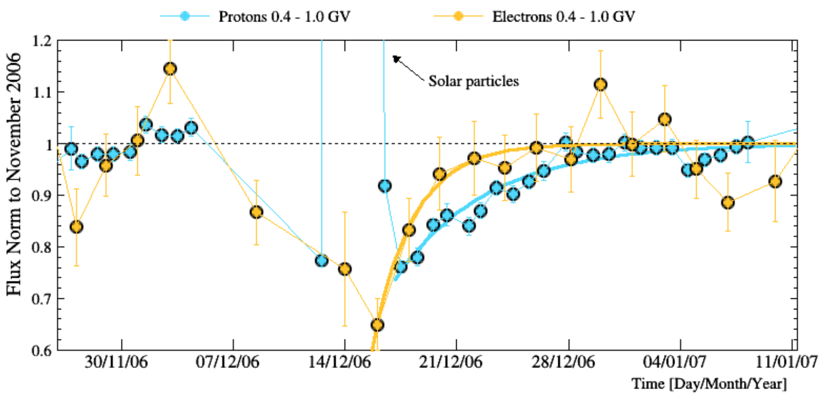

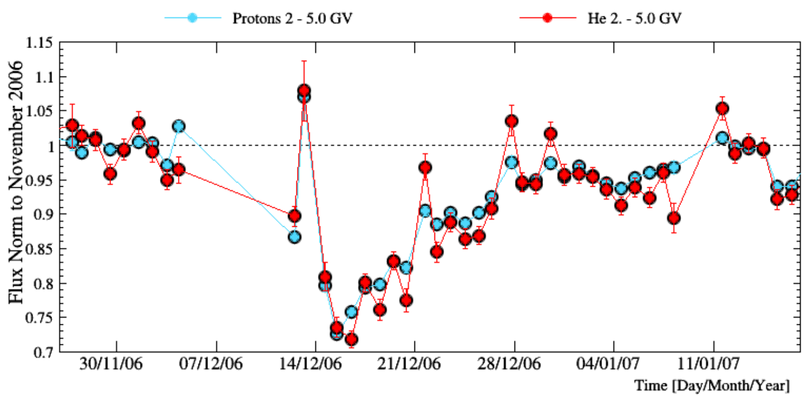

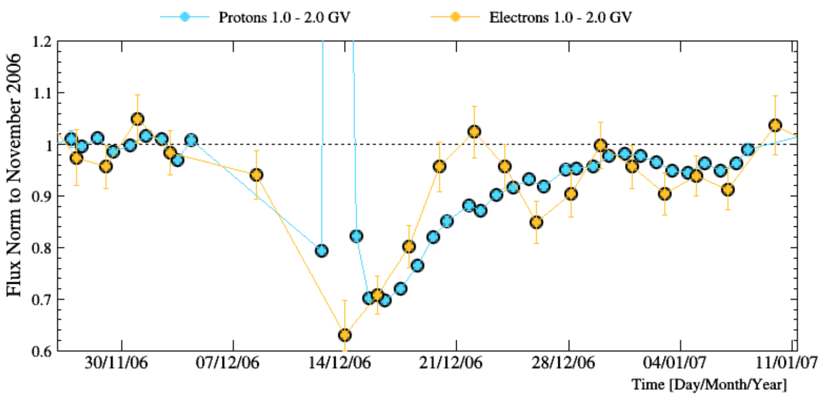

R. Munini *et al.*, ApJ 853, 1 (2018)

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.

Short/Mid-term variations in PAMELA data

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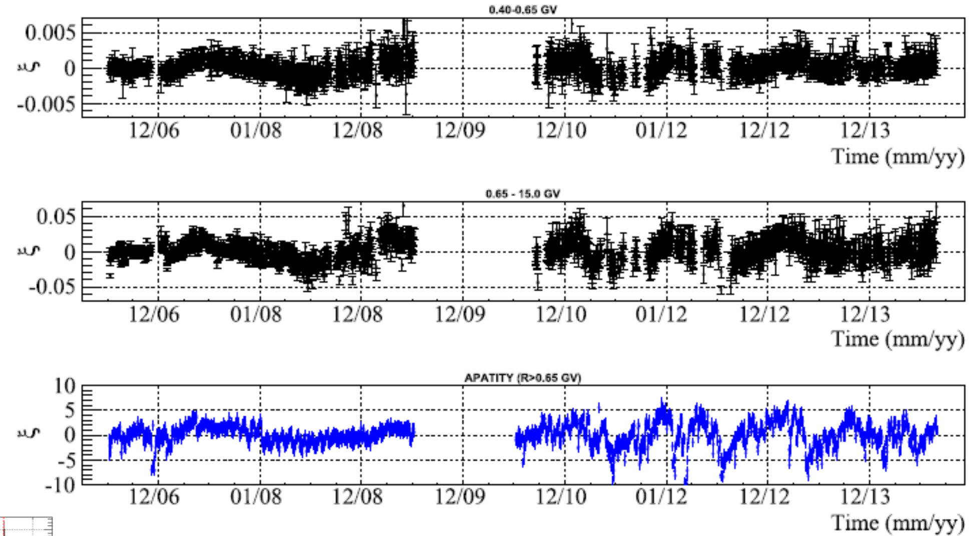
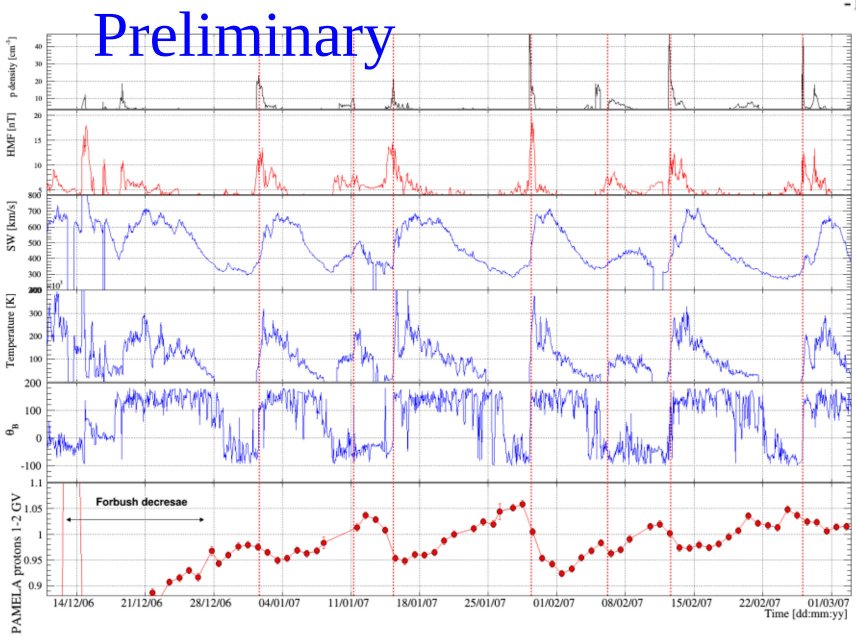
O. Adriani *et al.*, ApJL 852, L28 (2018) ;

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.



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.



2006 December – 2007 January

PAMELA overall results

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Review papers:

- O. Adriani *et al.*, Phys. Rept. 544 (2014) 323
- O. Adriani *et al.*, Nuovo Cimento 40 (2017) N. 10