The Lesson of PAMELA

Piergiorgio Picozza

INFN and University of Rome Tor Vergata

RICAP 2018

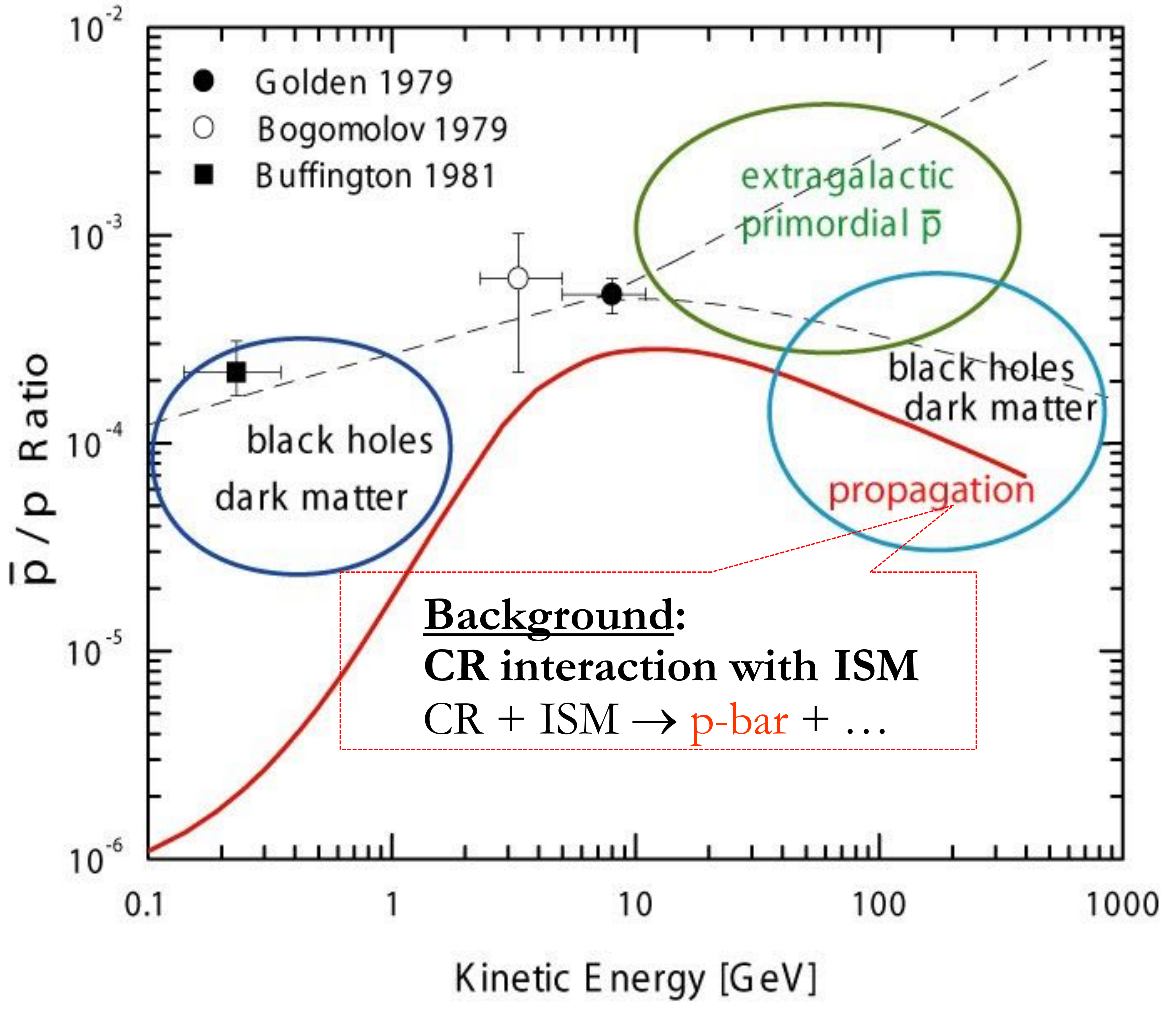
Rome, September 5-7, 2018

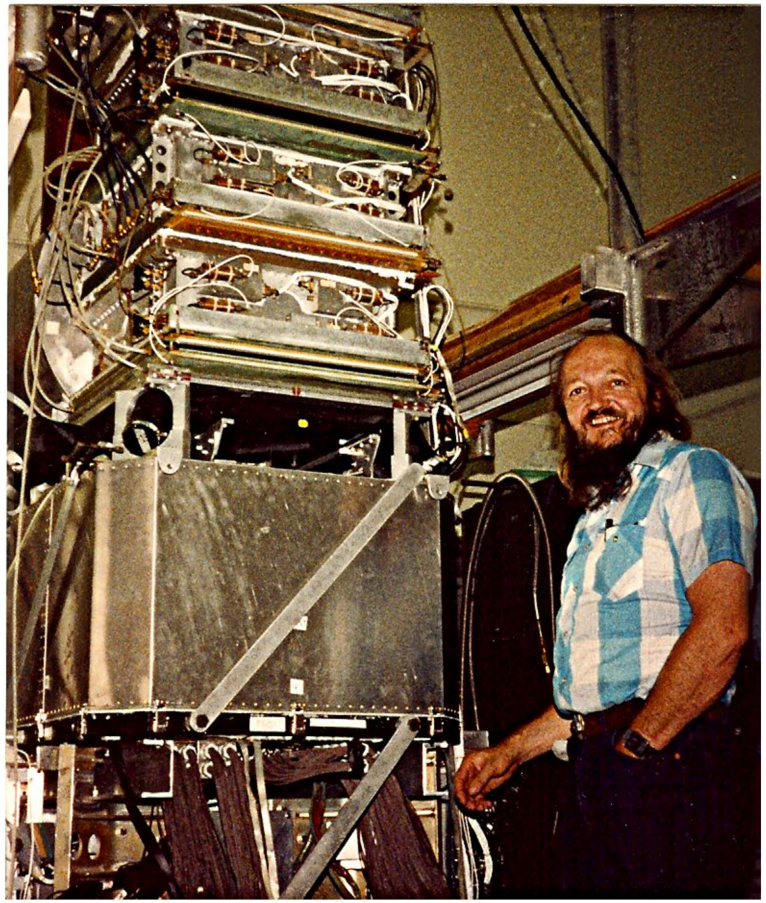
PAMELA

History and Results

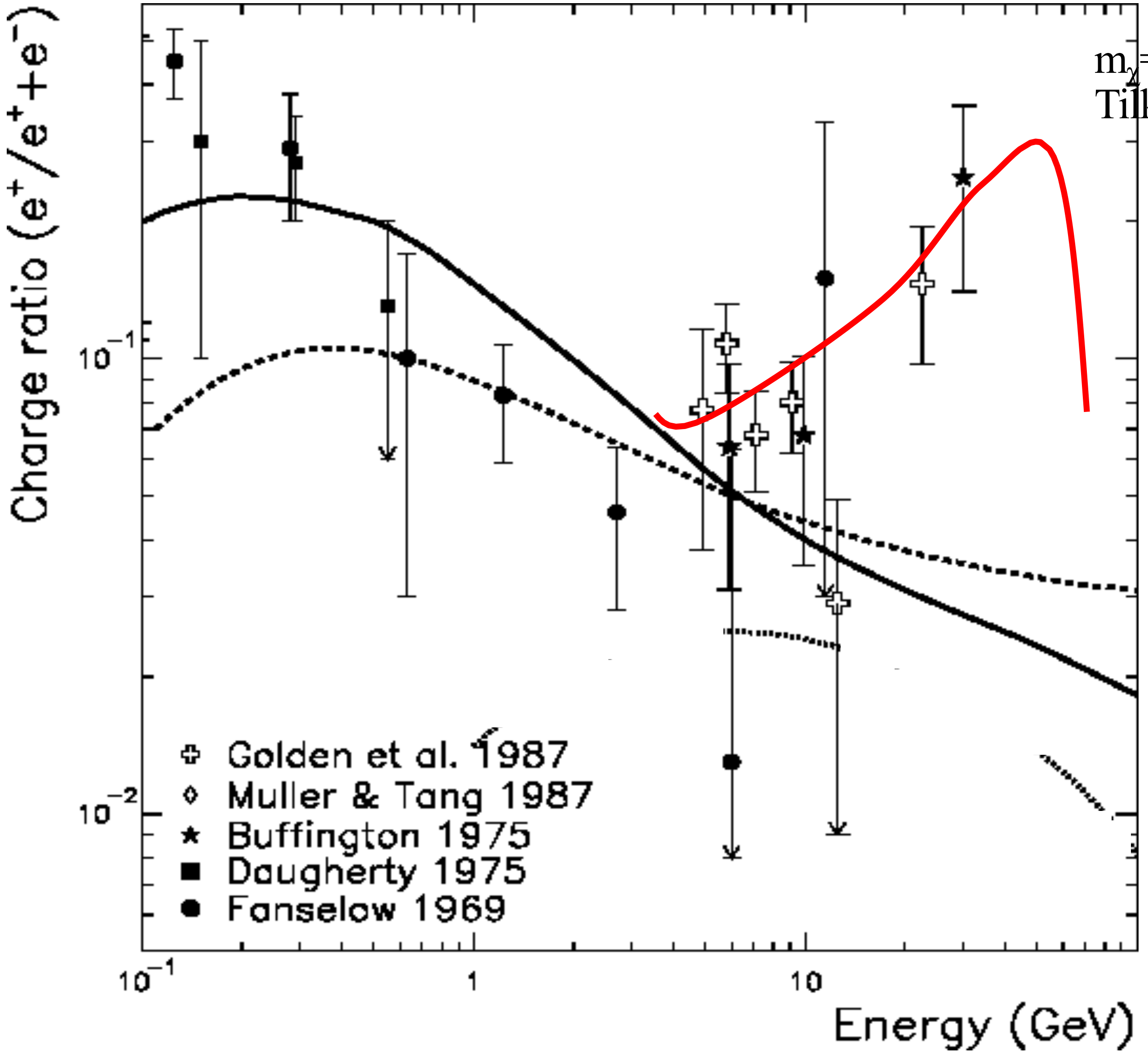
The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations

The Beginning





Balloon data : Positron fraction before 1990



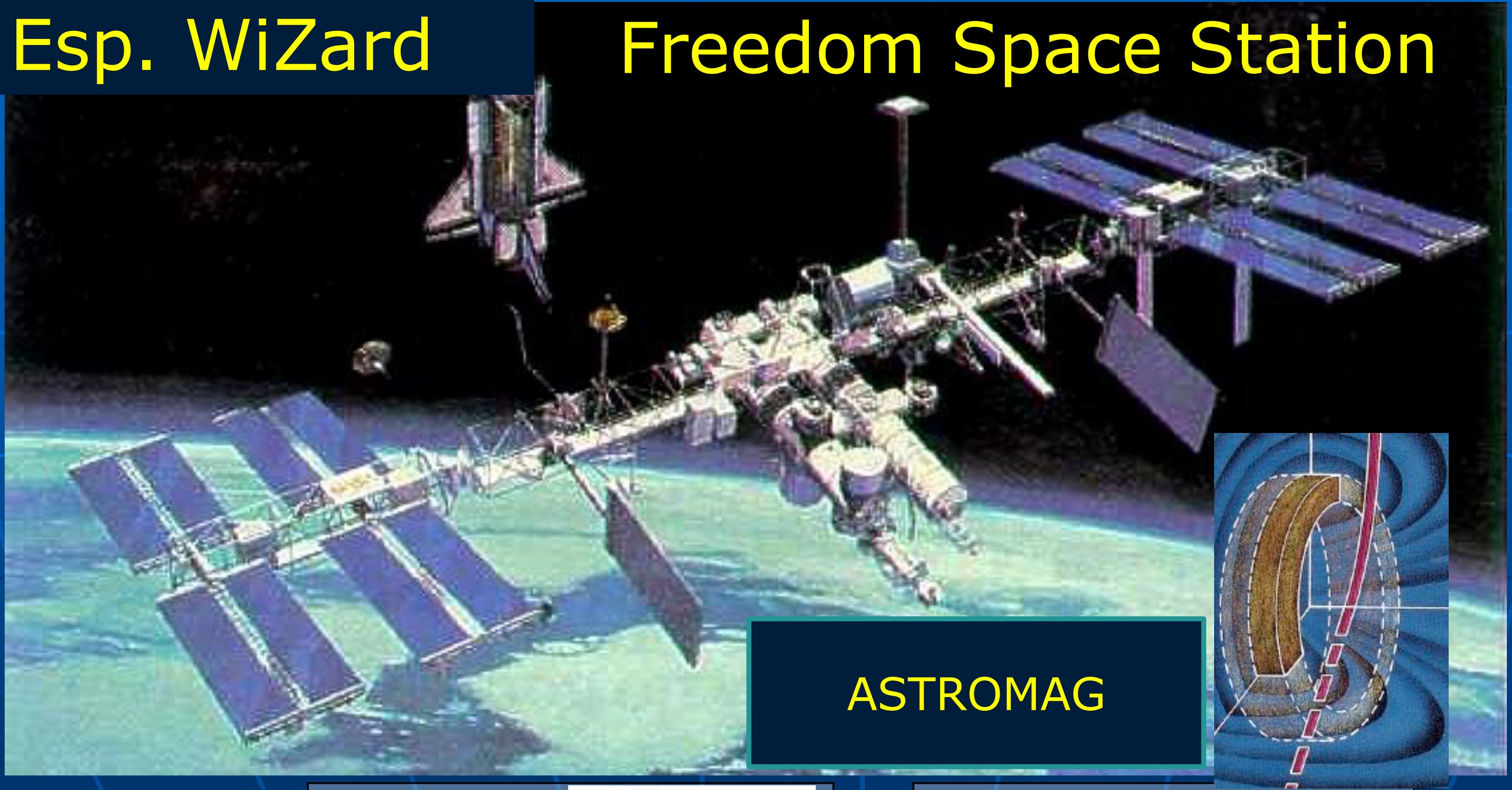
m_χ=20GeV
Tilka 89

Towards PAMELA

INFN Istituto Nazionale di Fisica Nucleare

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

Esp. WiZard



Germany: Universität Gesamthochschule Siegen

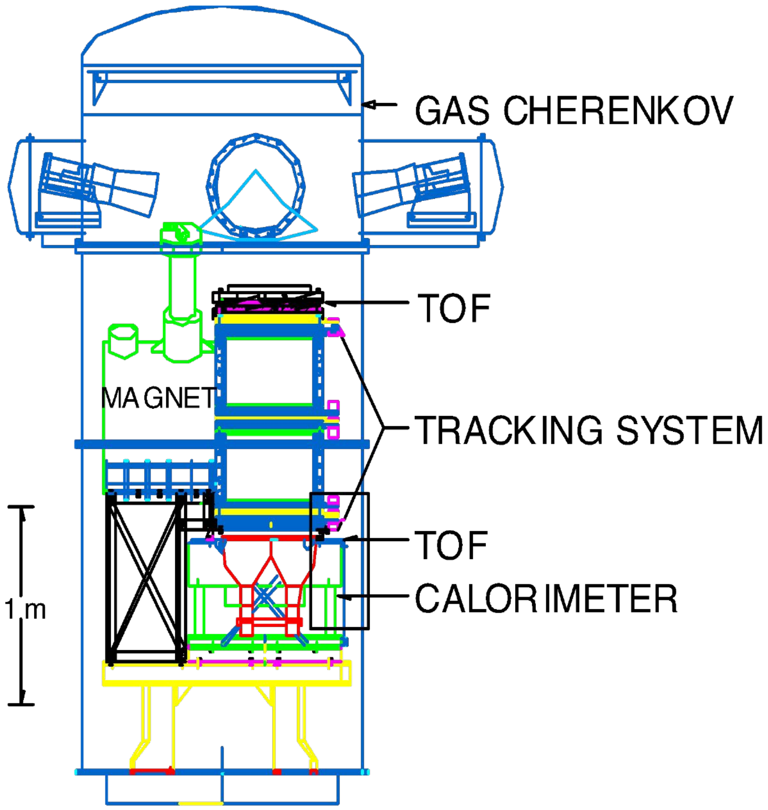
Siegen

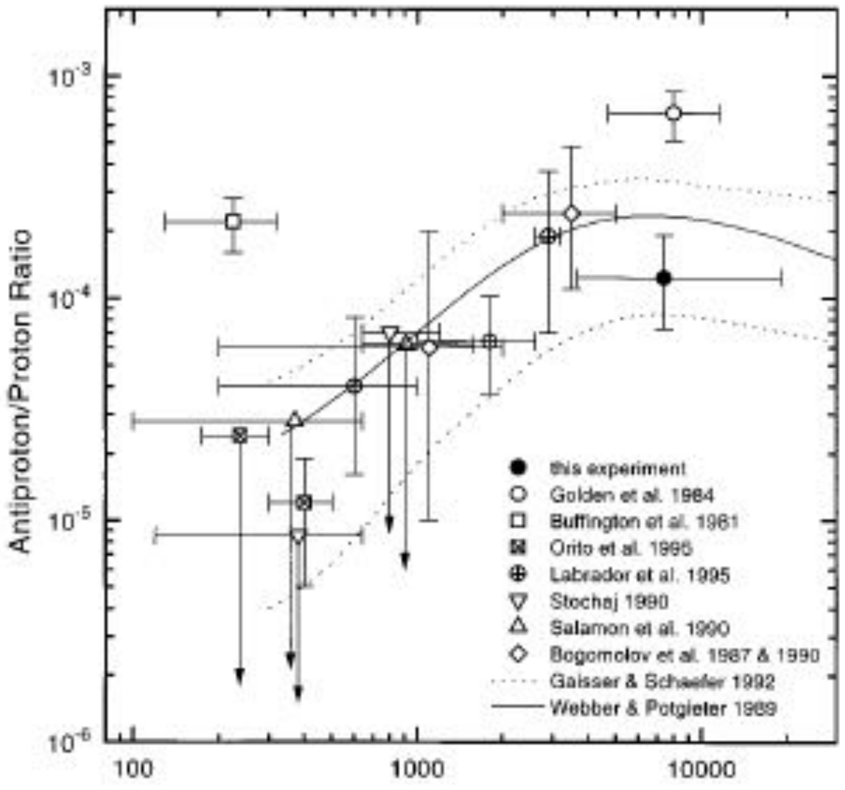
Sweden: Kungl Tekniska Högskolan

KTH, Stockholm

MASS 2 - 1991

Matter Antimatter Space Spectrometer





RIM Program

May 1993

INFN Istituto Nazionale di Fisica Nucleare

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

SILEYE-1
1995

SILEYE-2
1998

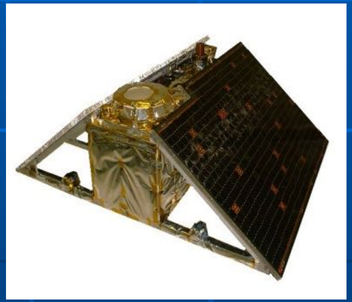
SILEYE-3
2002

Russia:

Ioffe Physico-Technical Institute

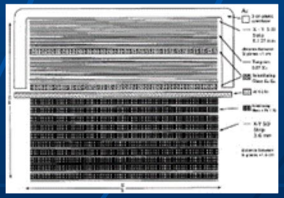
Moscow
St. Petersburg

NINA 1
1998



NINA 2
2000

PAMELA
2006

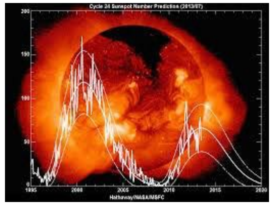


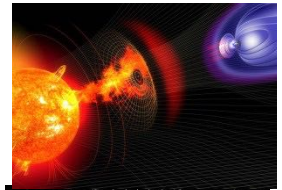
GILDA

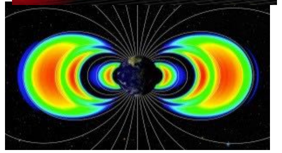
Germany: Universität Gesamthochschule Siegen
Siegen

Sweden: Kungl Tekniska Högskolan
KTH, Stockholm

The Observatory PAMELA

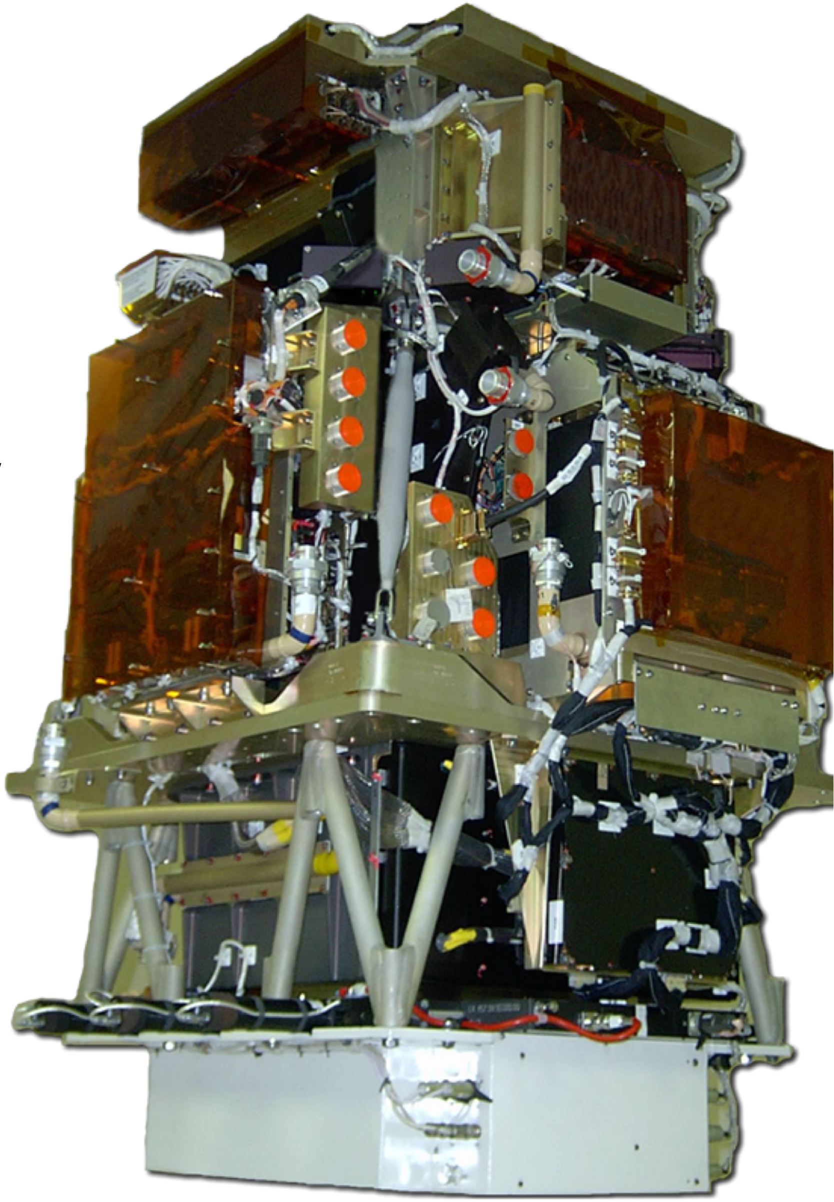






Precise measurements of protons, electrons, their antiparticles and light nuclei in the cosmic radiation

- Search for Dark Matter indirect signatures
- Search for antihelium (primordial antimatter) and new form of matter in the Universe (Strangelets?)
- Investigation of the cosmic-ray origin and propagation mechanisms in the Galaxy, the heliosphere and the terrestrial magnetosphere
- Detailed measurement of the high energy particle populations (galactic, solar, geomagnetically trapped and albedo) in the near-Earth radiation environment



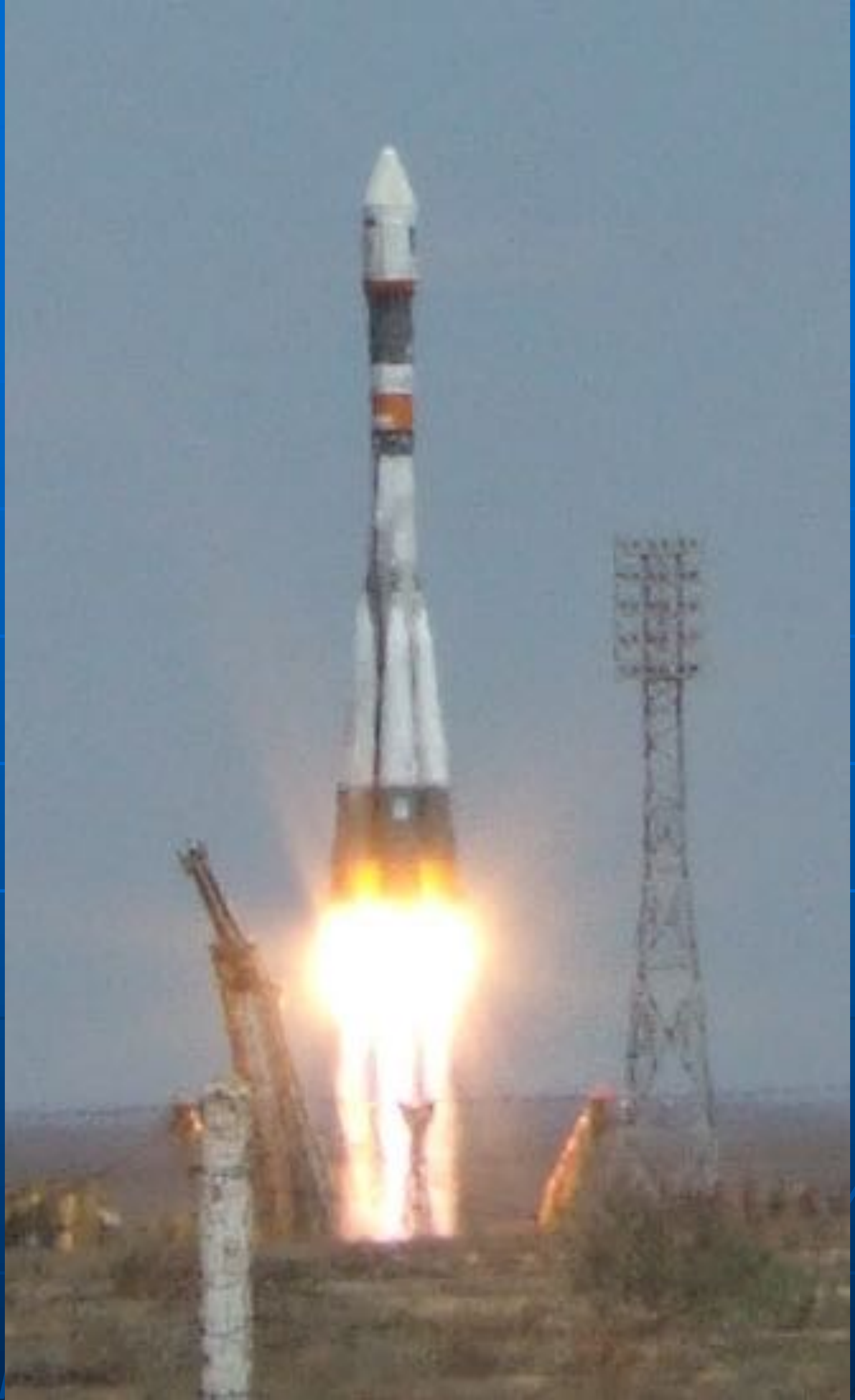
PAMELA History

- December 1998: MoU INFN and Russian Space Agency
- March 2001: Satellite Russian Decision Operative
- April 2005: Flight Model Delivery
- June 15th, 2006: Flight
- Ten Years of Data Taking

•PAMELA

Launch
15/06/06

Low-earth elliptical orbit
350 – 610 km
Quasi-polar (70^{o} inclination)
SAA crossed



Nature

June 16, 2006

Home > News

NEWS

Published online: 16 June 2006; | doi:10.1038/news060612-15

PAMELA, or virtue rewarded (from Samuel Richardson novel, 1740)

After a decade's work, physicists are flying an antimatter observatory.

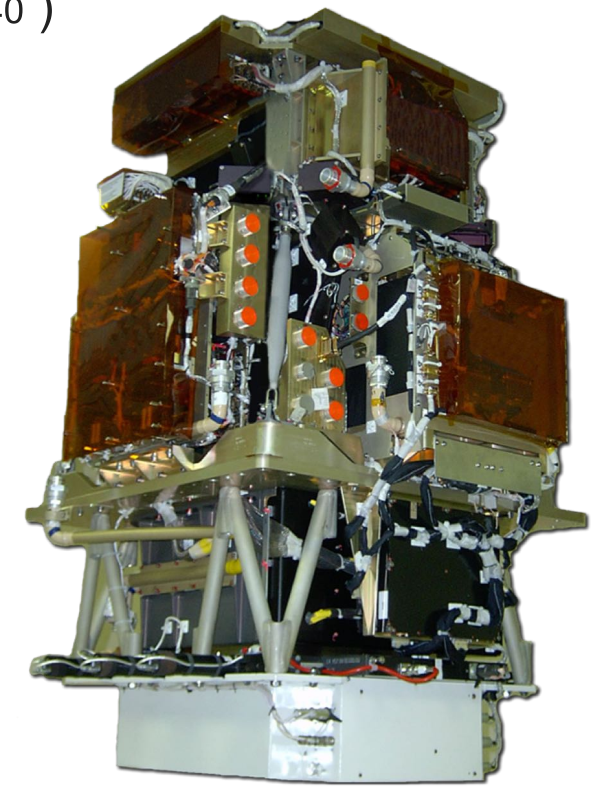
Mark Peplow

The first satellite built to detect antimatter in space launched safely yesterday, boosting the chances of identifying the mysterious 'dark matter' that makes up more than 80% of the stuff in the Universe.

The PAMELA satellite: click here to see detailed diagram.

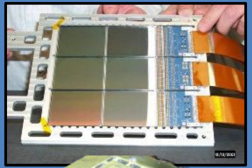
The PAMELA probe (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) took off from the Baikonur Cosmodrome in Kazakhstan on 15 June, carrying instruments that will catch antiprotons and positrons, the mirror particles of protons and electrons.

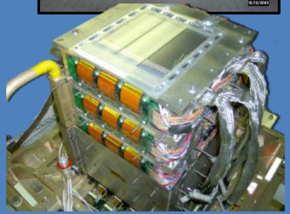
High-energy particles from elsewhere

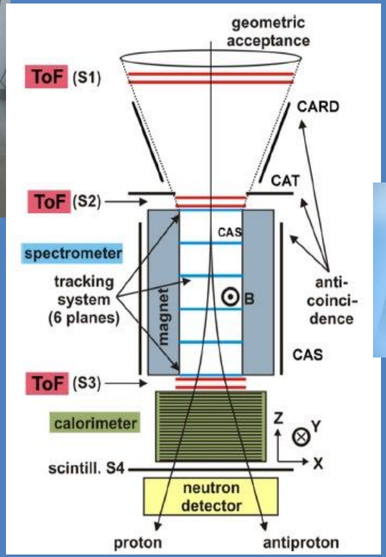


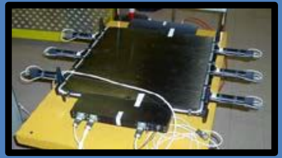
PAMELA Instrument

INFN Bari Florence Frascati Naples Rome Trieste CNR, Florence









Russia:

Ioffe Physico-Technical Institute

Moscow
St. Petersburg

Germany: Universität Gesamthochschule Siegen
Siegen

Sweden: Kungl Tekniska Högskolan
KTH, Stockholm

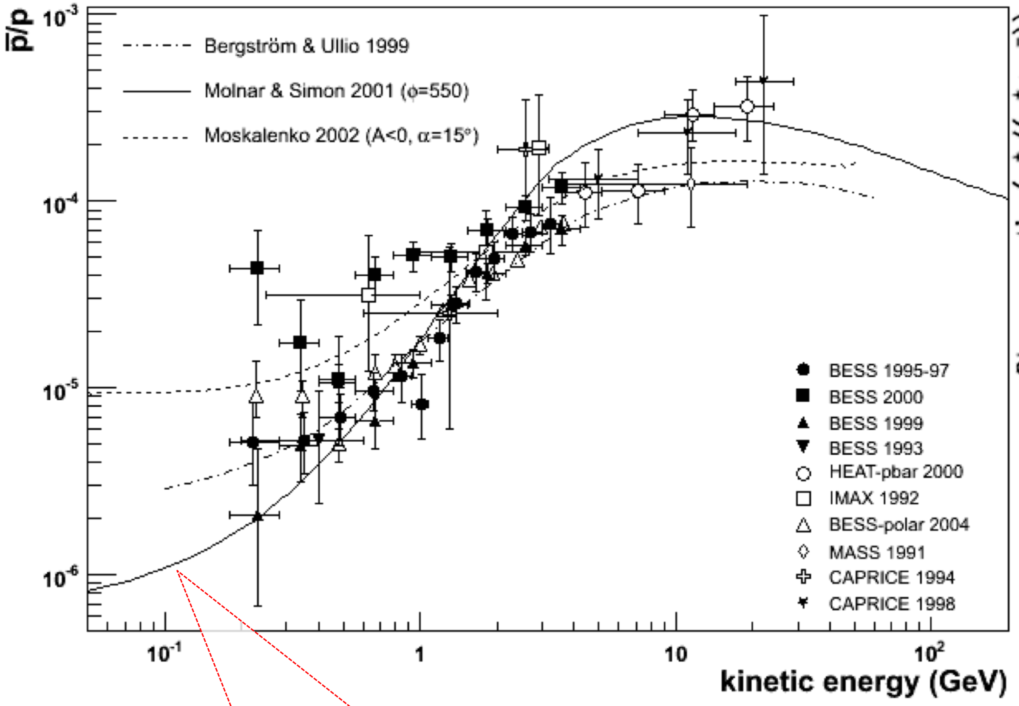
agenzia spaziale italiana

РОСКОСМОС

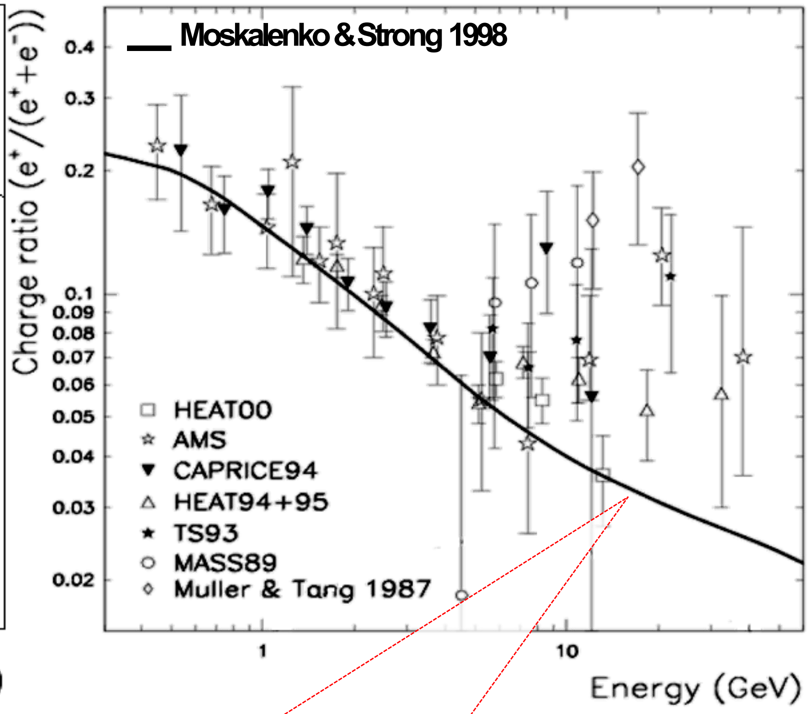
CR Antimatter

Status at the time of PAMELA launch

Antiprotons



Positrons

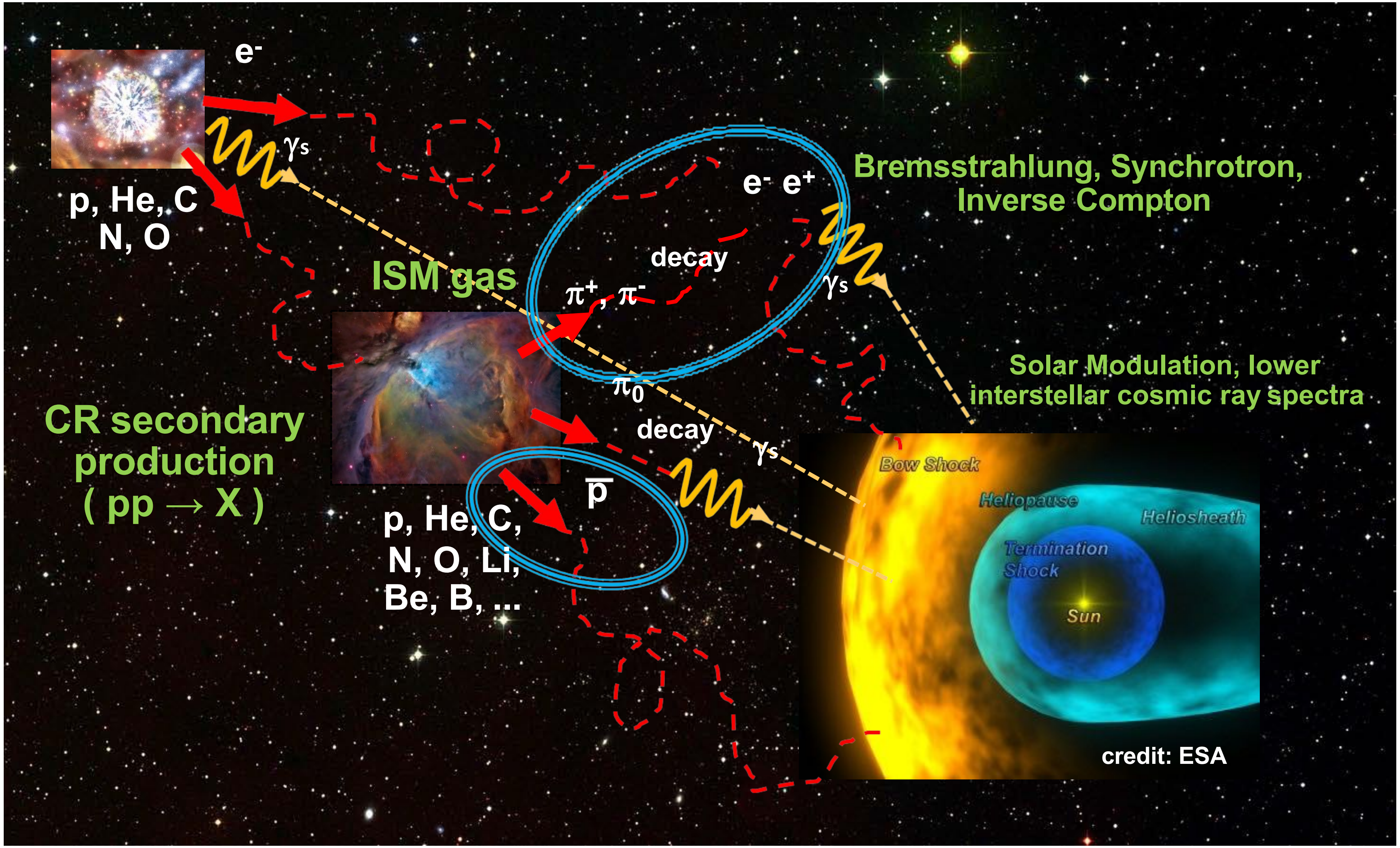


CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

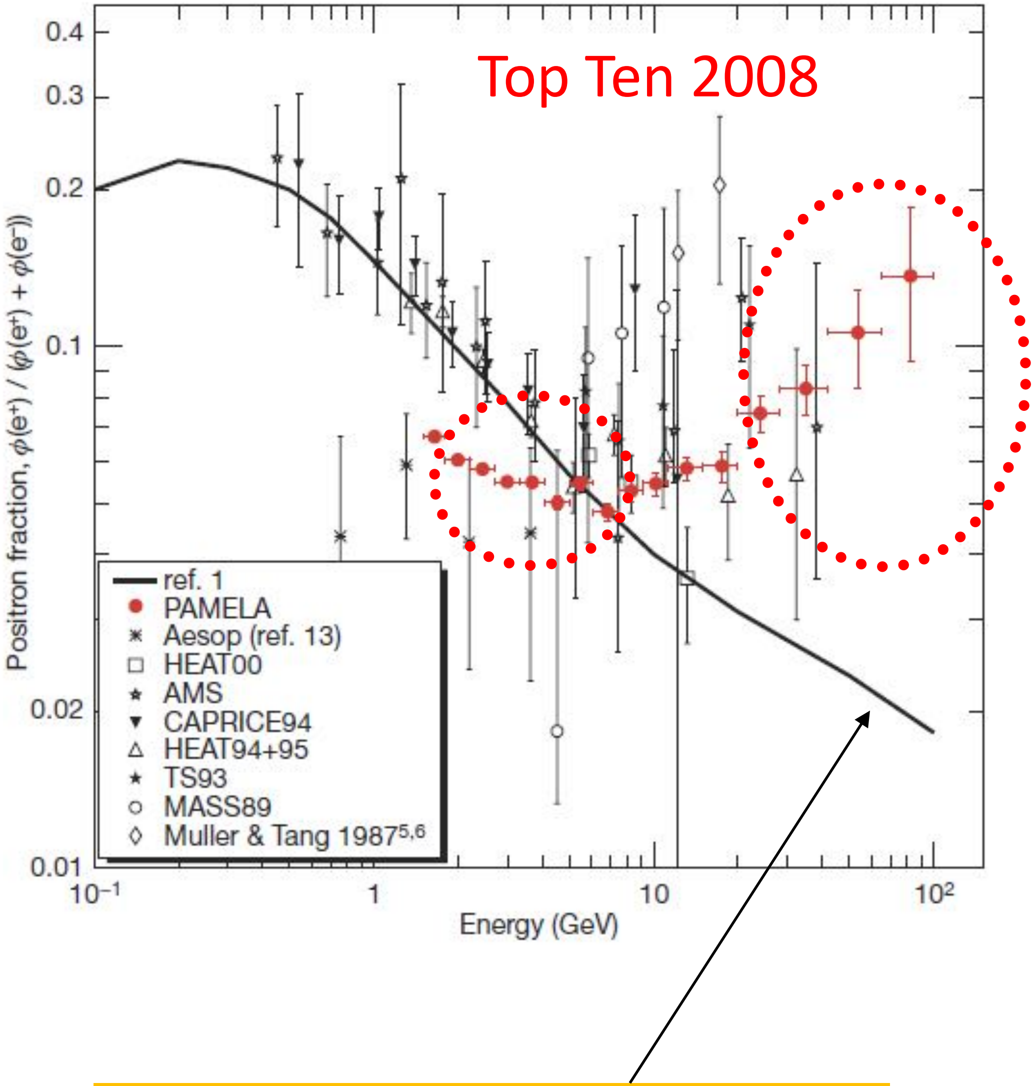
$pp \rightarrow \bar{p}ppp$

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x
CR + ISM → π^0 + x → $\gamma\gamma$ → **$e^{\pm}$**

Cosmic Rays and Antiparticles



PAMELA Positron Fraction



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]

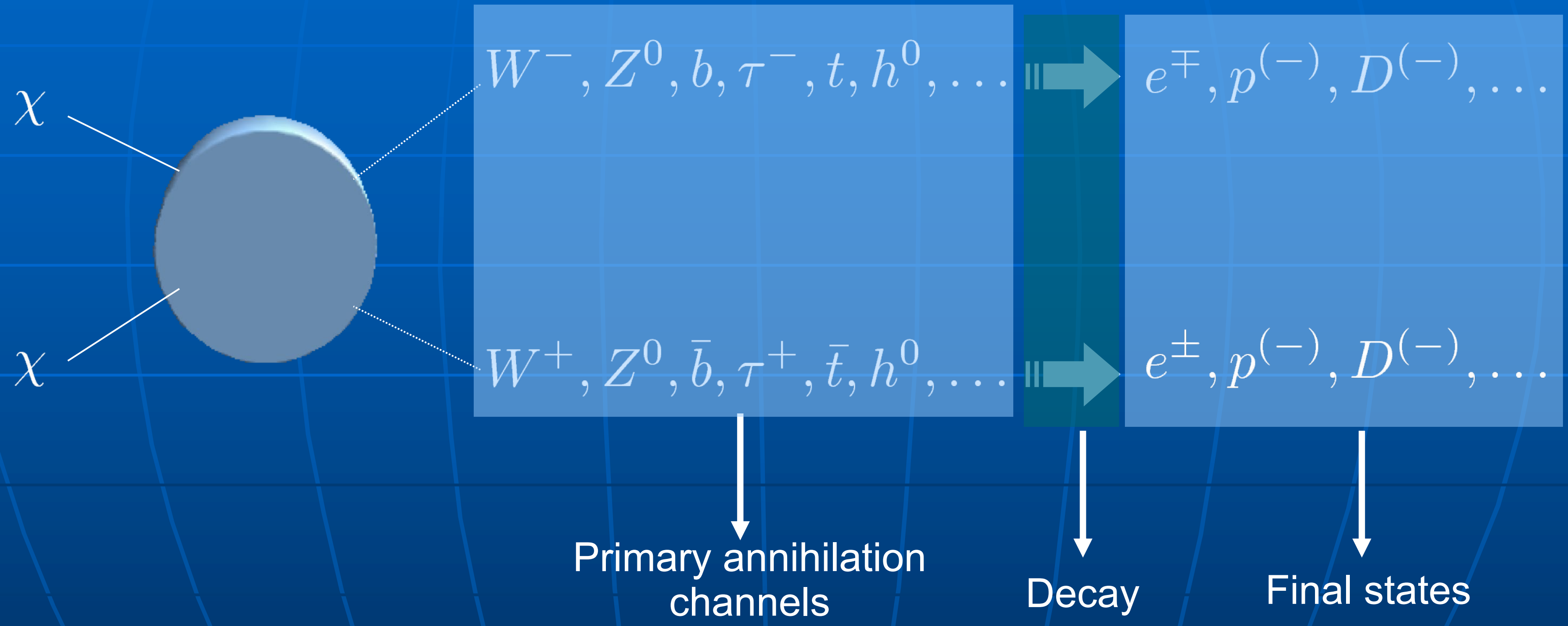
April 2nd, 2009

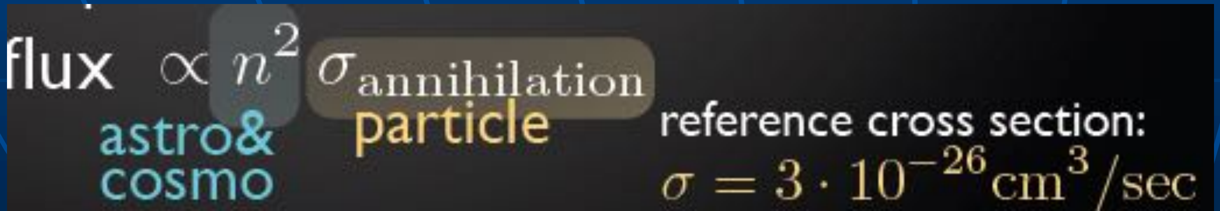
Citations: >1340

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

DM annihilations

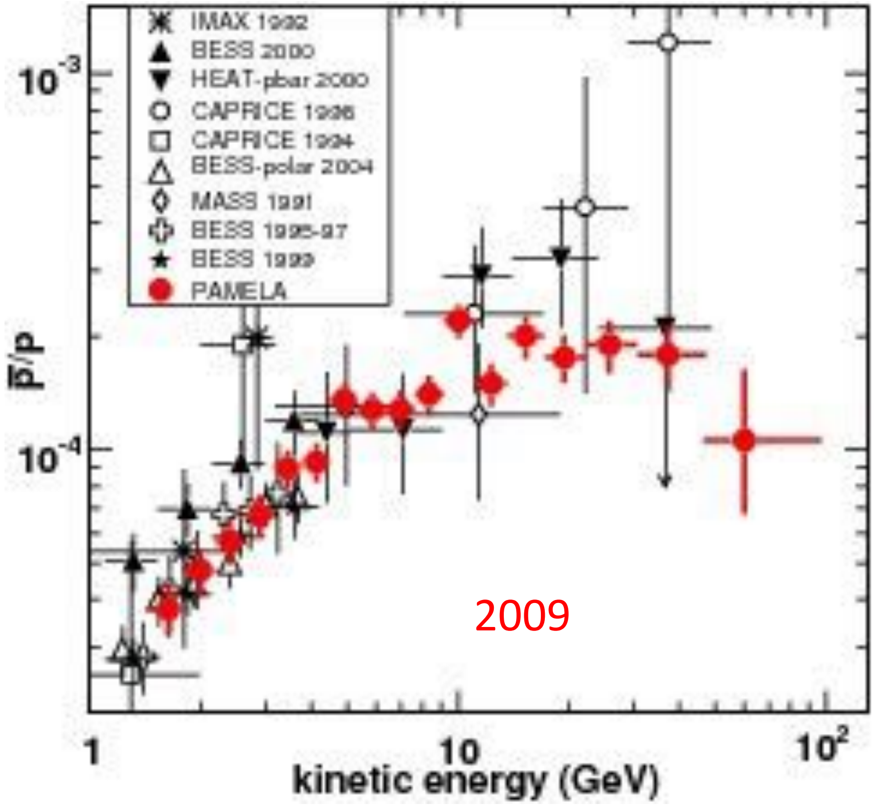
DM particles are stable. They can annihilate in pairs.





$\sigma_a = \langle \sigma v \rangle$

PAMELA Results: Antiprotons



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Featured in Physics Editors' Suggestion

New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation

O. Adriani *et al.* (PAMELA Collaboration)
Phys. Rev. Lett. **102**, 051101 – Published 2 February 2009

Physics See Viewpoint: Debating the source of a rare particle

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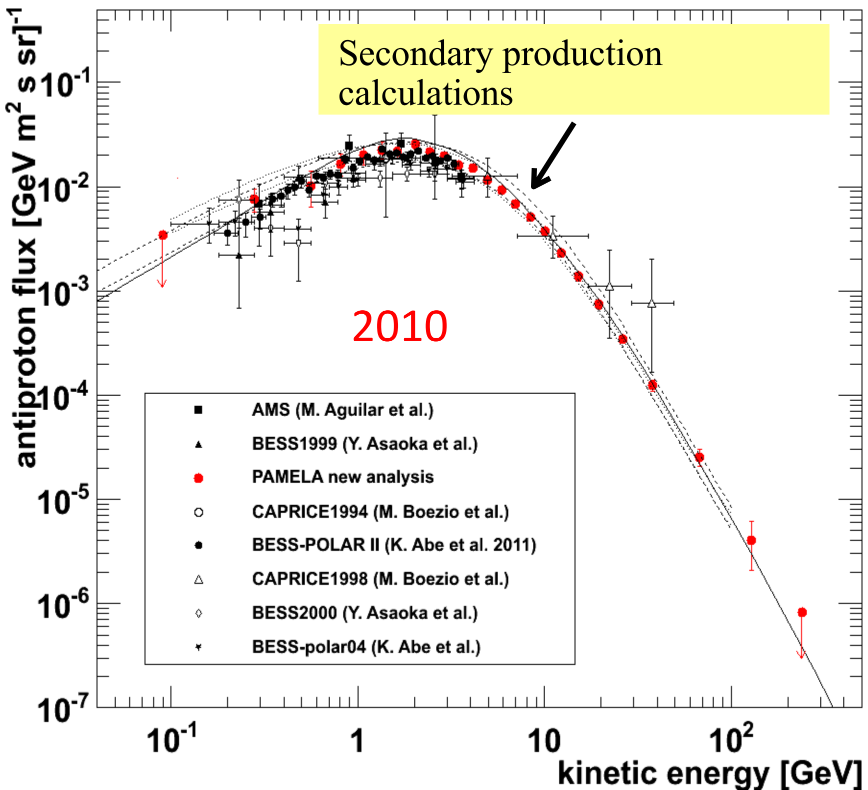
PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy

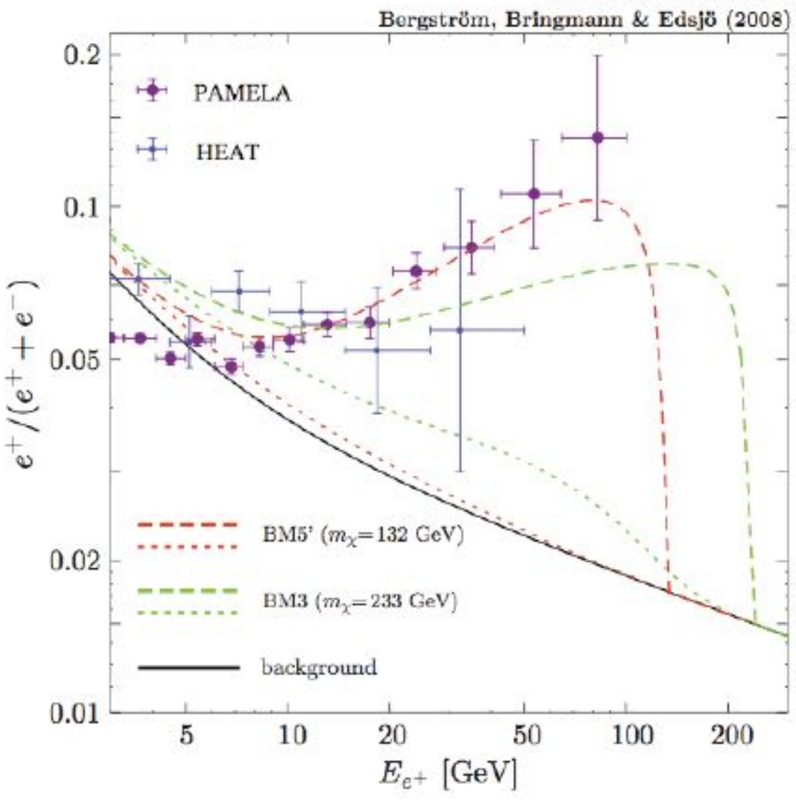
O. Adriani *et al.*
Phys. Rev. Lett. **105**, 121101 – Published 13 September 2010

Physics See Synopsis: Uncertain sources



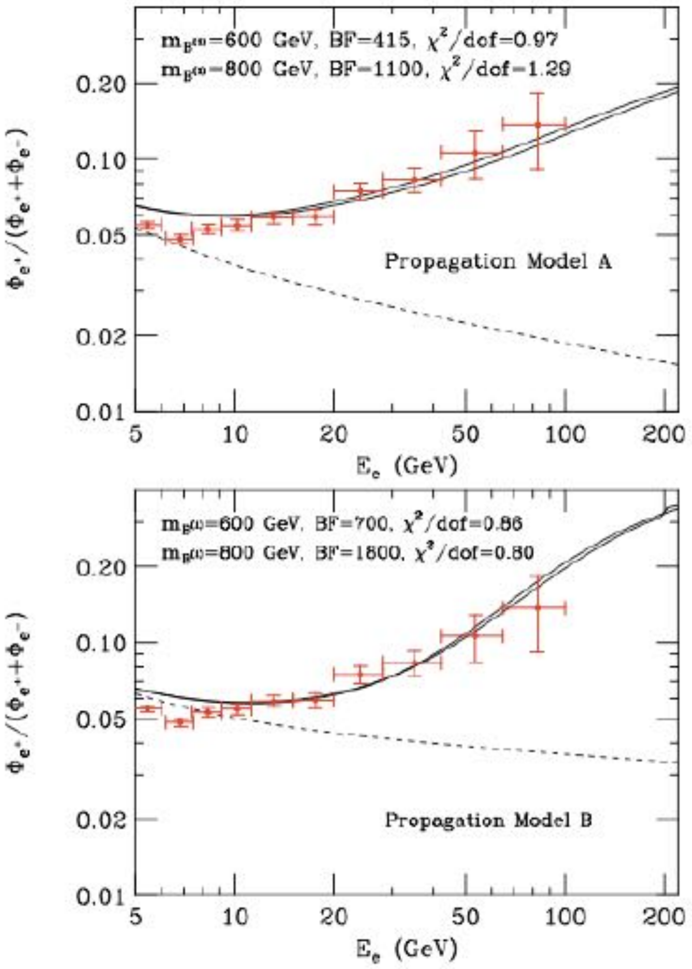
Example: Dark Matter

arXiv:0808.3725

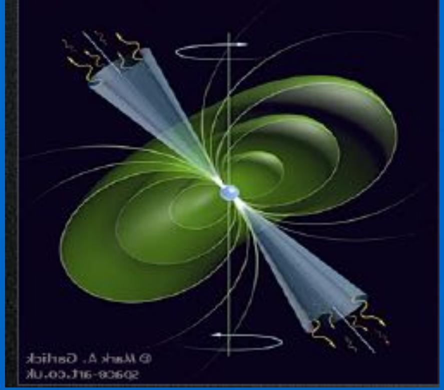


Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek
arXiv:0902.0593v1



Kaluza-Klein dark matter



Astrophysical Explanation
Pulsars

S. Profumo Astro-ph 0812-4457

- Mechanism: the spinning $\vec{B}$ of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

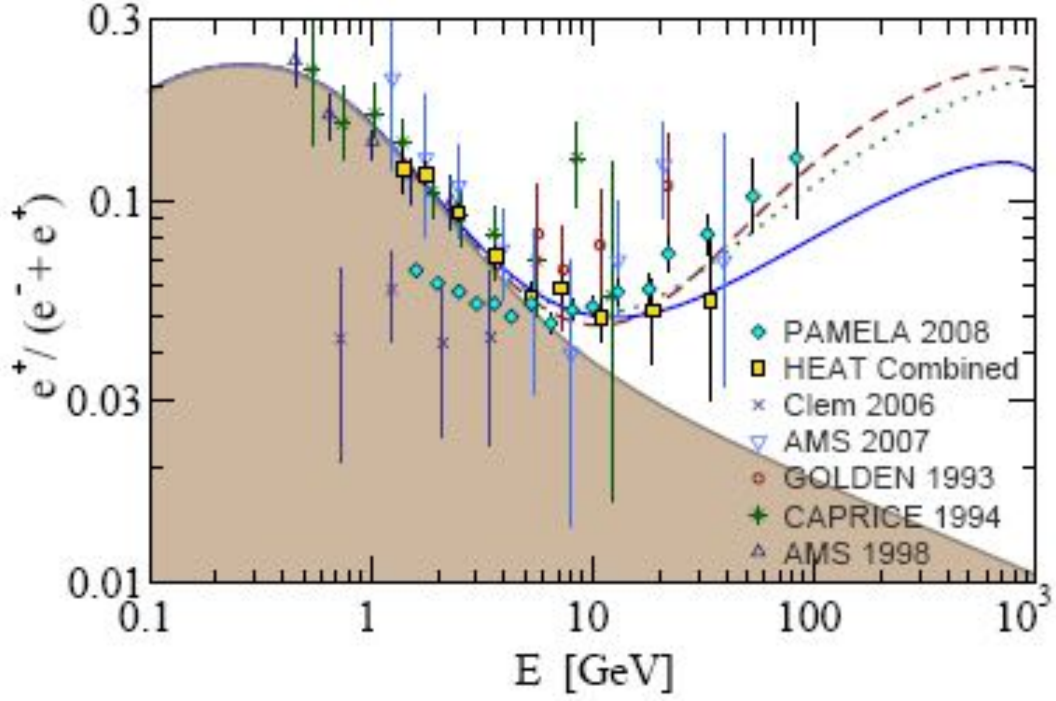
$$E_{tot} \simeq 10^{46}\,\mathrm{erg}$$

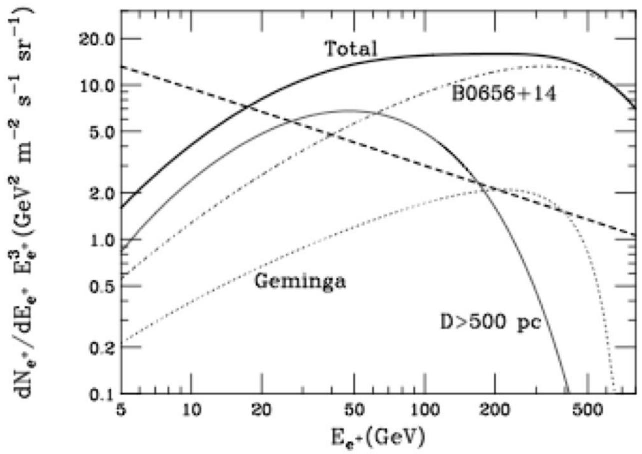
- Young ($T \sim 10^5$ years) and nearby (< 1kpc)
- If not: too much diffusion, low energy, too low flux.

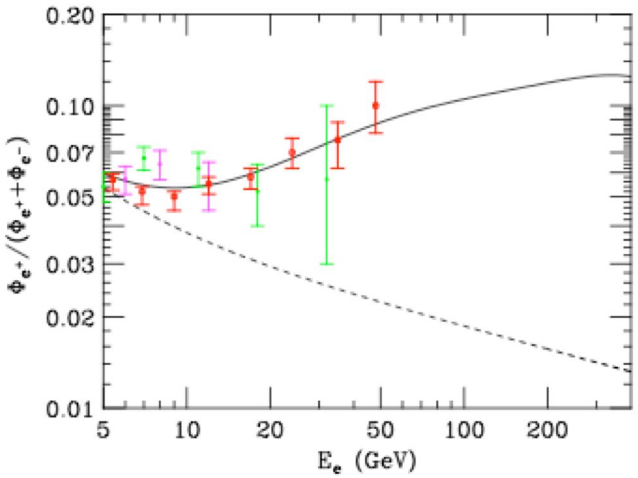
- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old
- Many others after Fermi/GLAST

- Diffuse mature pulsars

Example: pulsars







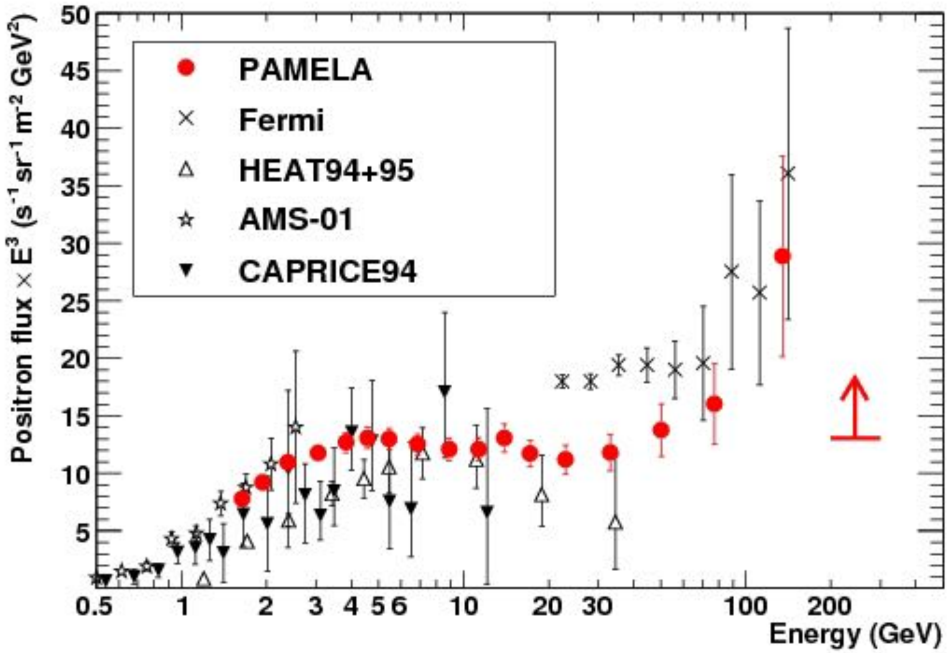
H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar

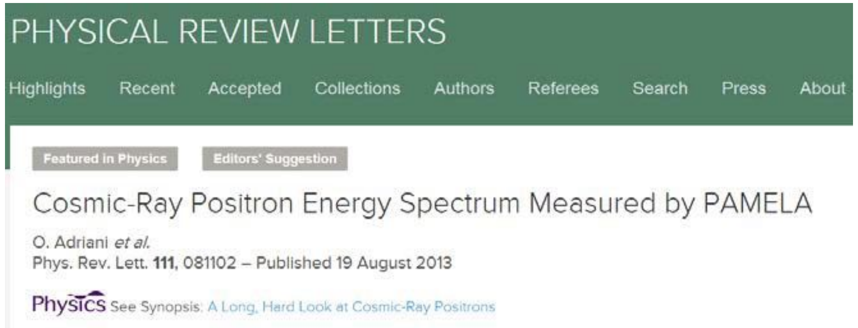
Hooper, Blasi, and Serpico arXiv:0810.1527

Only secondaries?
P. Serpico hep-ph 0810.4846

- Anomalous primary electron source spectrum
- Spectral feature in the proton flux responsible for secondaries
- Role of Helium nuclei in secondary production
- Difference between local and ISM spectrum of protons
- Anomalous energy-dependent behaviour of the diffusion coefficient
- Rising cross section at high energies
- High energy beaviour of the e^+/e^-

PAMELA Results: Positrons

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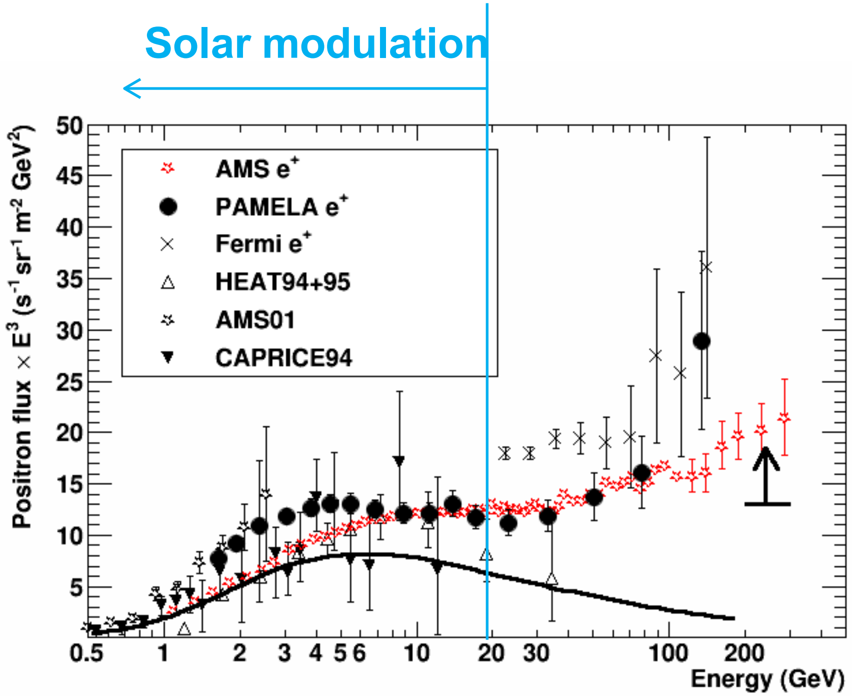
Cosmic-Ray Positron Energy Spectrum Measured by PAMELA

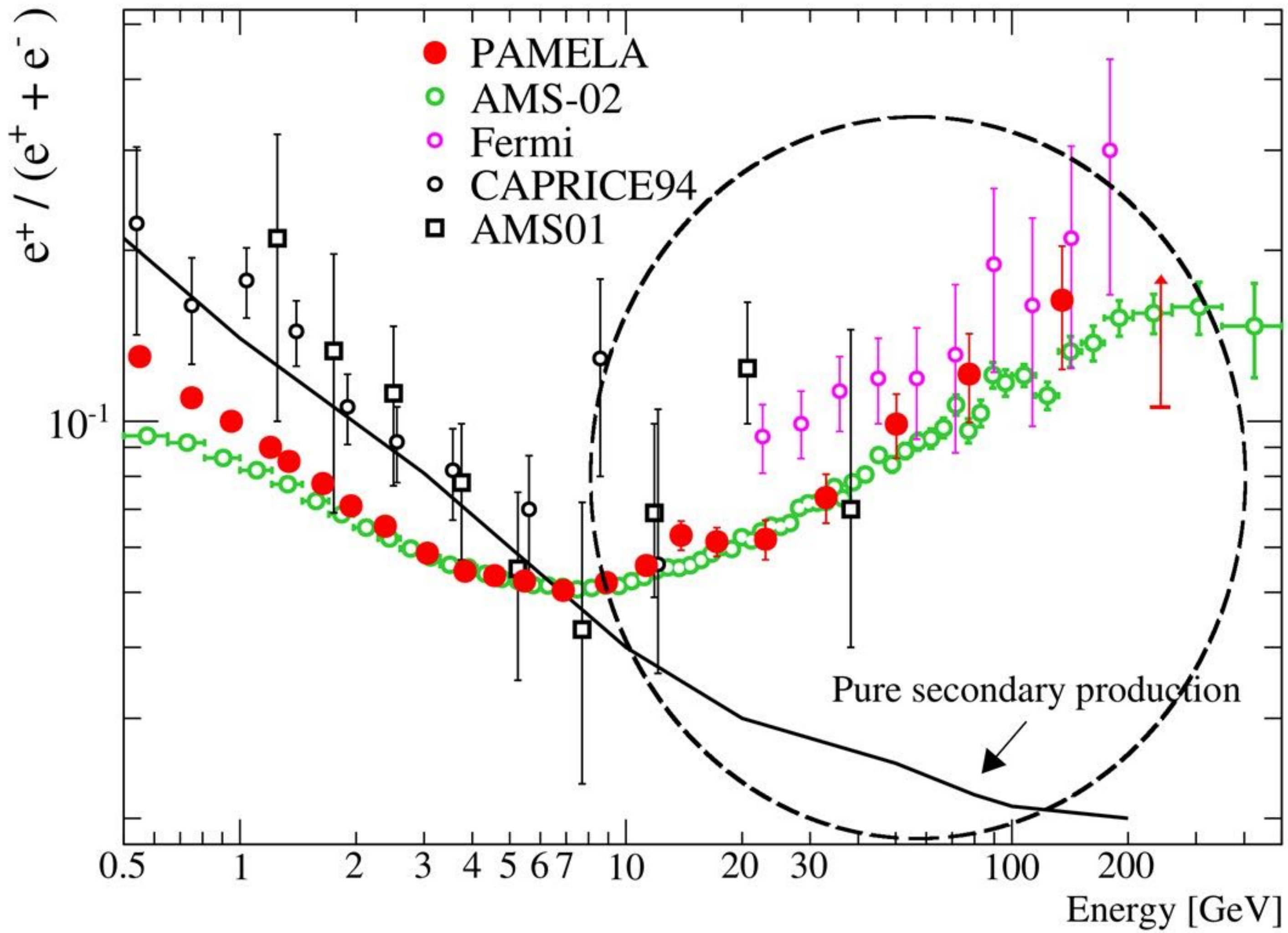
O. Adriani *et al.*

Phys. Rev. Lett. **111**, 081102 – Published 19 August 2013

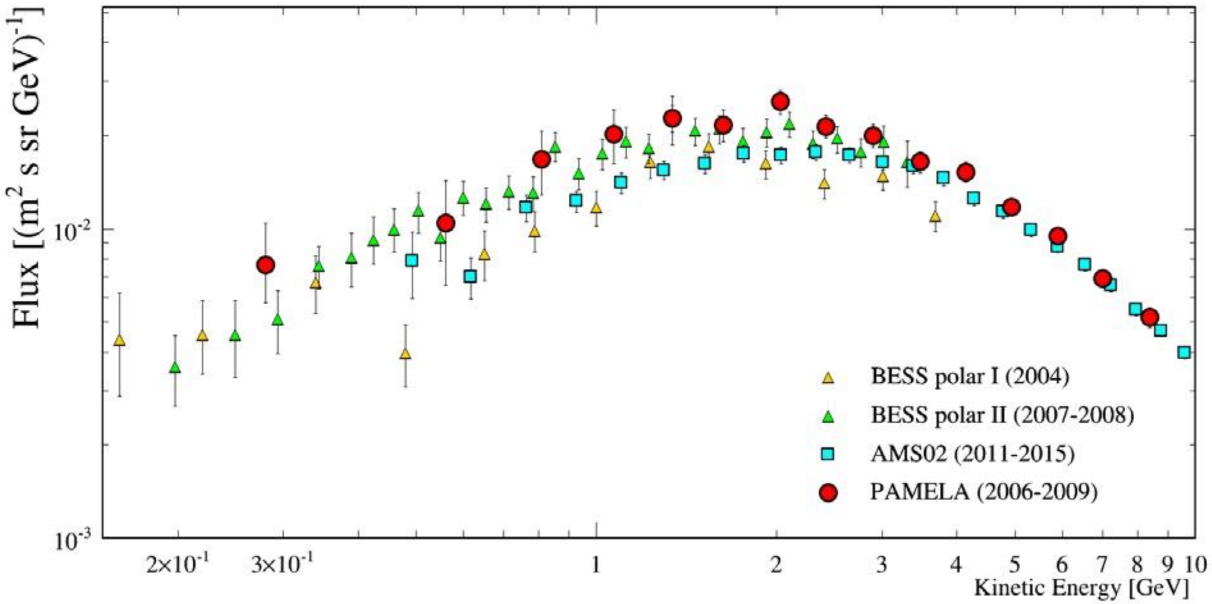
Physics See Synopsis: A Long, Hard Look at Cosmic-Ray Positrons

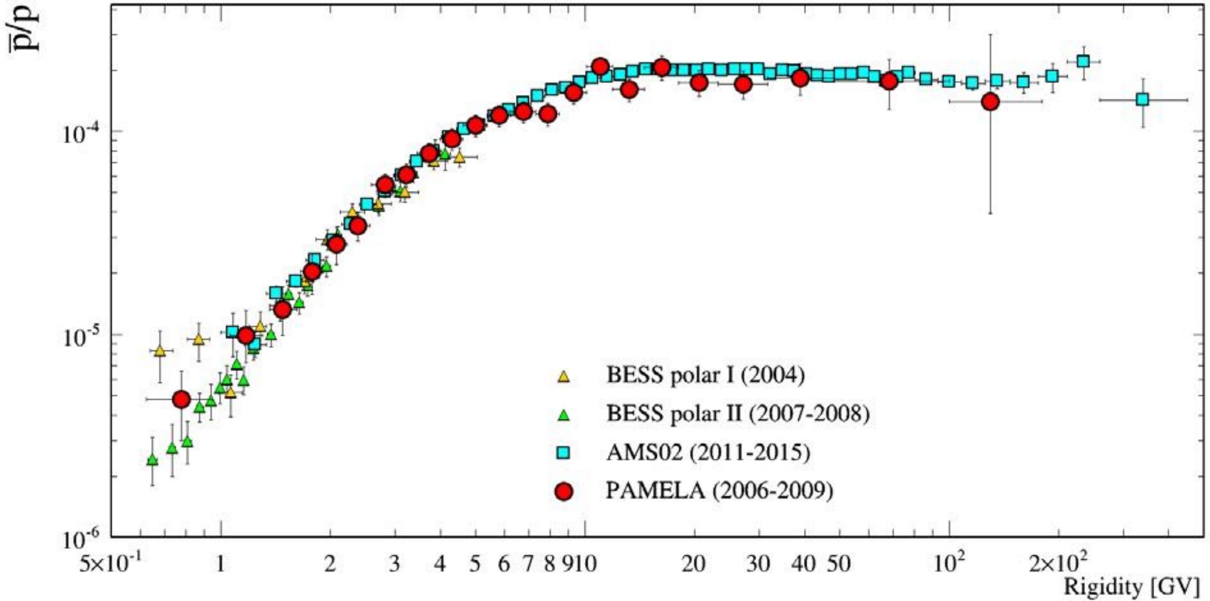


The positron Anomaly

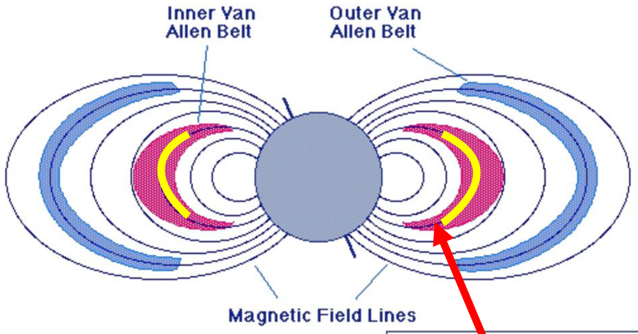


PAMELA & BESS Polar & AMS-02

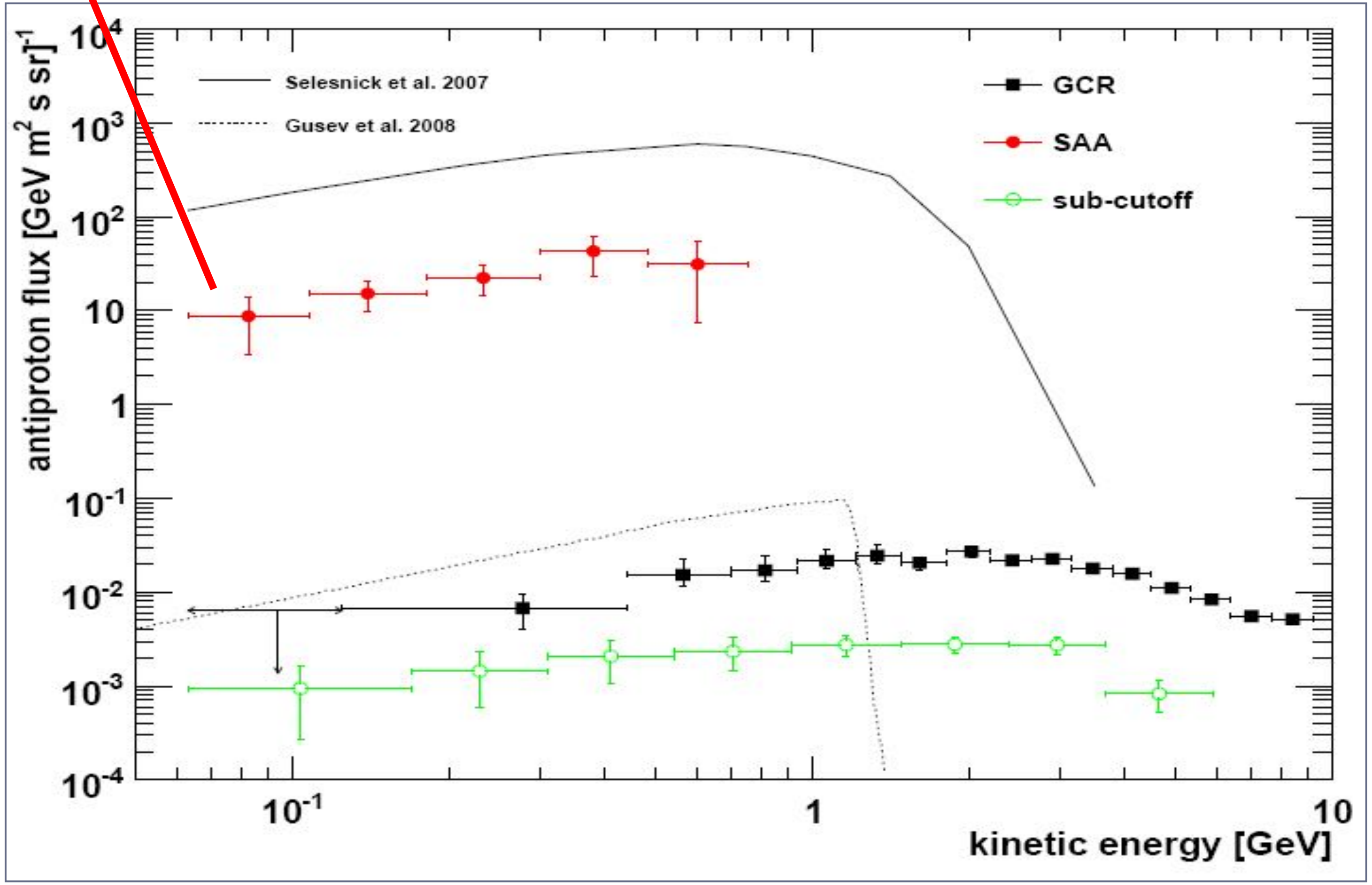




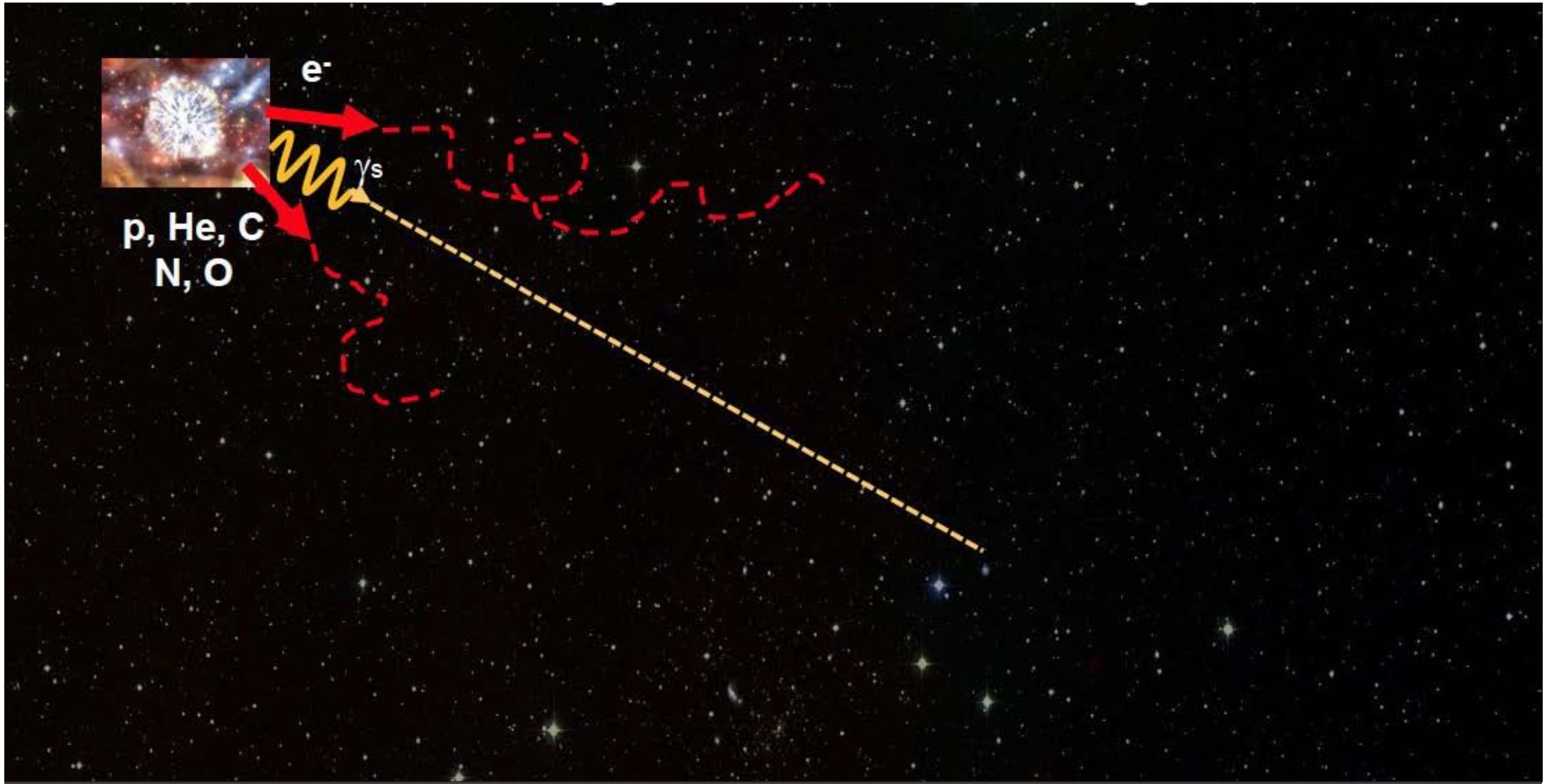
Anti-proton radiation belt



PAMELA



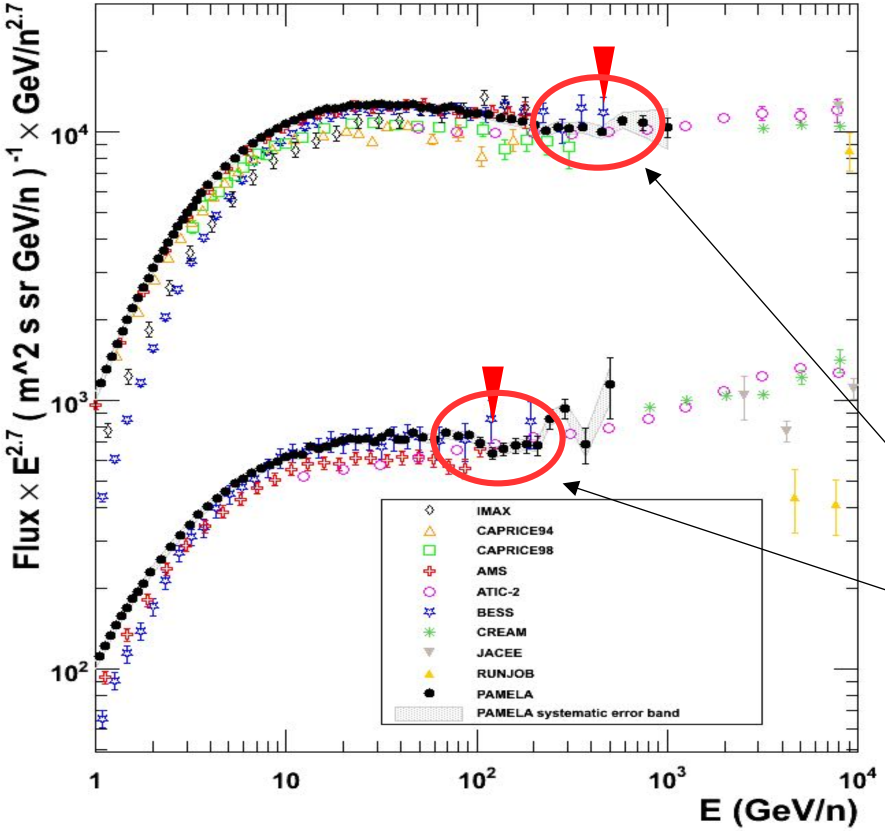
O. Adriani et al., ApJL 737 (2011), L29

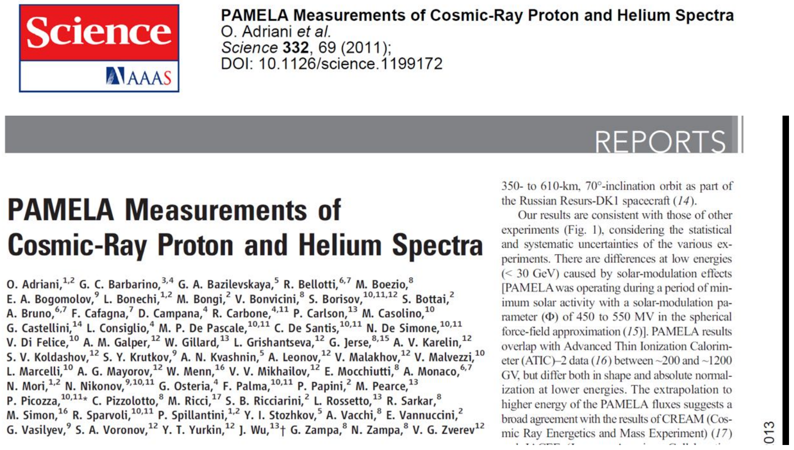


Absolute fluxes of primary GCRs

Protons, helium nuclei, light nuclei, electrons

PAMELA H, He spectra





PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani *et al.*
Science **332**, 69 (2011);
DOI: 10.1126/science.1199172

REPORTS

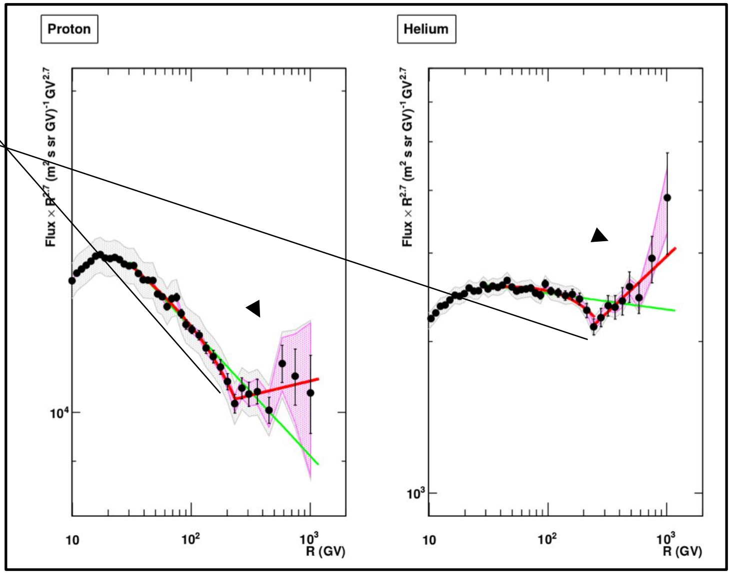
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra

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. Borisov,[10,11,12] S. Bottai,[2] A. Bruno,[6,7] F. Cafagna,[7] D. Campana,[4] R. Carbone,[4,11] P. Carlson,[13] M. Casolino,[10] G. Castellini,[14] L. Consiglio,[4] M. P. De Pascale,[10,11] C. De Santis,[10,11] N. De Simone,[10,11] V. Di Felice,[10] A. M. Galper,[12] W. Gillard,[13] L. Grishantseva,[12] G. Jerse,[8,15] A. V. Karelin,[12] S. V. Koldashov,[12] S. Y. Krutkov,[9] A. N. Kvashnin,[5] A. Leonov,[12] V. Malakhov,[12] V. Malvezzi,[10] L. Marcelli,[10] A. G. Mayorov,[12] W. Menn,[16] V. V. Mikhailov,[12] E. Mocchiutti,[8] A. Monaco,[6,7] N. Mori,[1,2] N. Nikonov,[9,10,11] G. Osteria,[4] F. Palma,[10,11] P. Papini,[2] M. Pearce,[13] P. Picozza,[10,11*] C. Pizzolotto,[8] M. Ricci,[17] S. B. Ricciarini,[2] L. Rossetto,[13] R. Sarkar,[8] M. Simon,[16] R. Sparvoli,[10,11] P. Spillantini,[1,2] Y. I. Stozhkov,[5] A. Vacchi,[8] E. Vannuccini,[2] G. Vasilyev,[9] S. A. Voronov,[12] Y. T. Yurkin,[12] J. Wu,[13†] G. Zampa,[8] N. Zampa,[8] V. G. Zverev[12]

350- to 610-km, 70°-inclination orbit as part of the Russian Resurs-DK1 spacecraft (*14*).

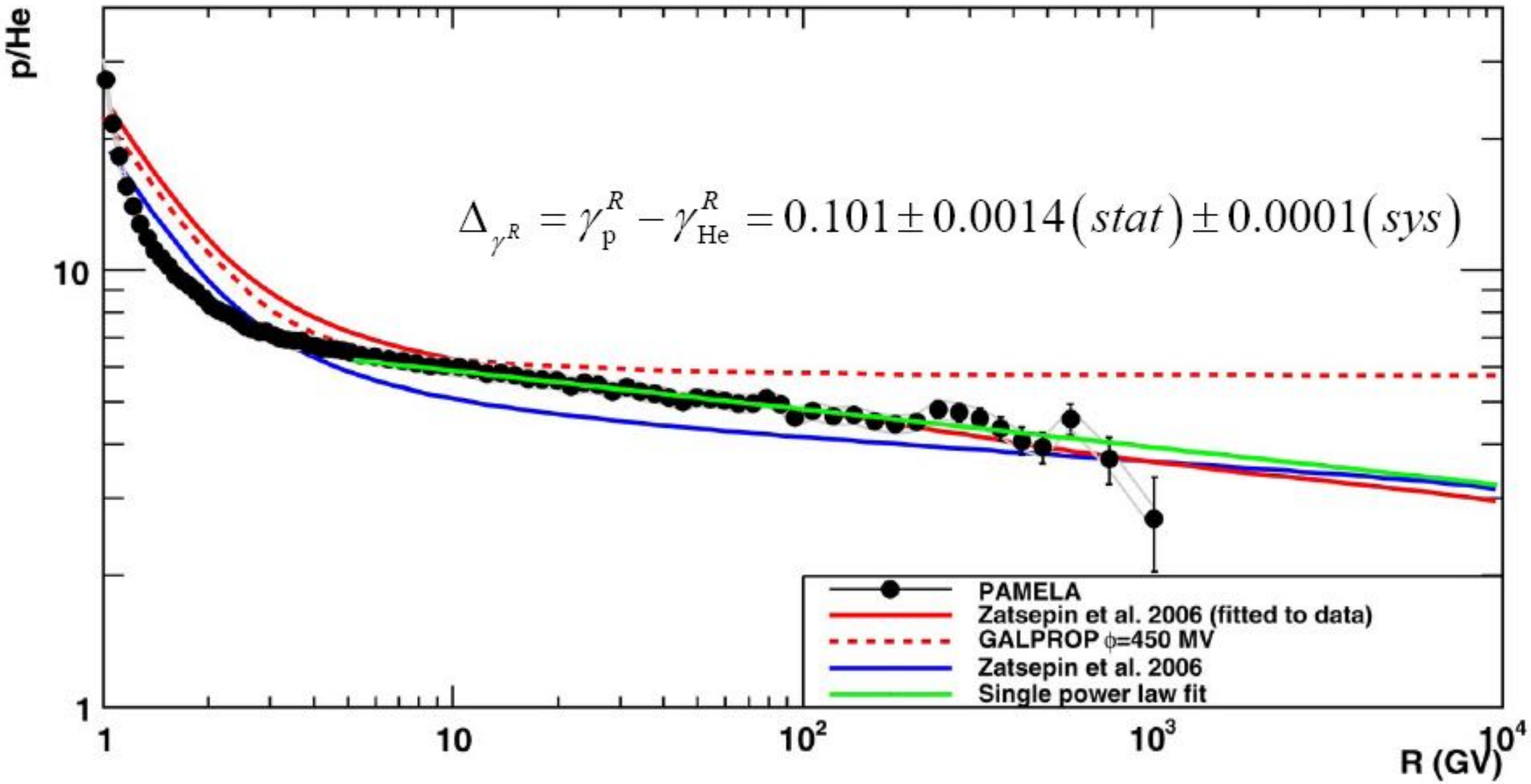
Our results are consistent with those of other experiments (Fig. 1), considering the statistical and systematic uncertainties of the various experiments. There are differences at low energies (< 30 GeV) caused by solar-modulation effects [PAMELA was operating during a period of minimum solar activity with a solar-modulation parameter (Φ) of 450 to 550 MV in the spherical force-field approximation (*15*)]. PAMELA results overlap with Advanced Thin Ionization Calorimeter (ATIC)–2 data (*16*) between ~200 and ~1200 GV, but differ both in shape and absolute normalization at lower energies. The extrapolation to higher energy of the PAMELA fluxes suggests a broad agreement with the results of CREAM (Cosmic Ray Energetics and Mass Experiment) (*17*)

> 450 citations



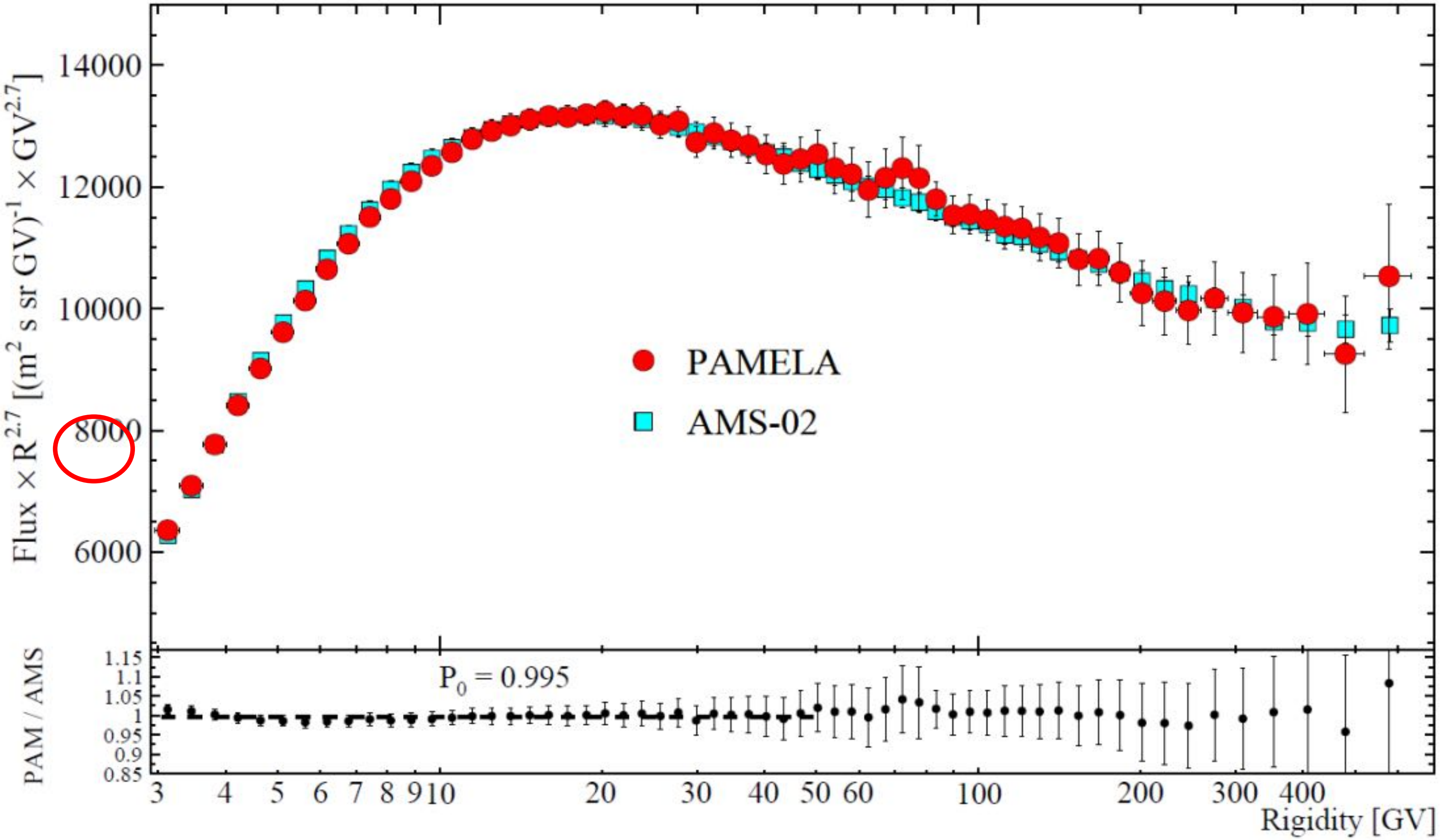
O. Adriani et al. , Science 332 (2011) 6025

Proton to Helium ratio



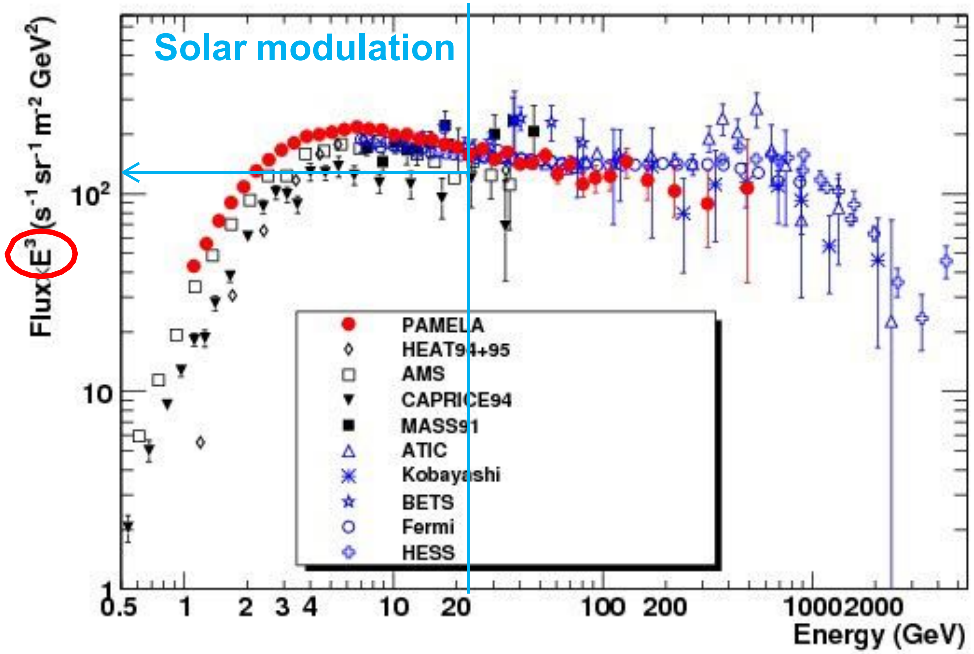
O. Adriani et al. , Science 332 (2011) 6025

Protons: PAMELA and AMS-02 same period 2011-2013



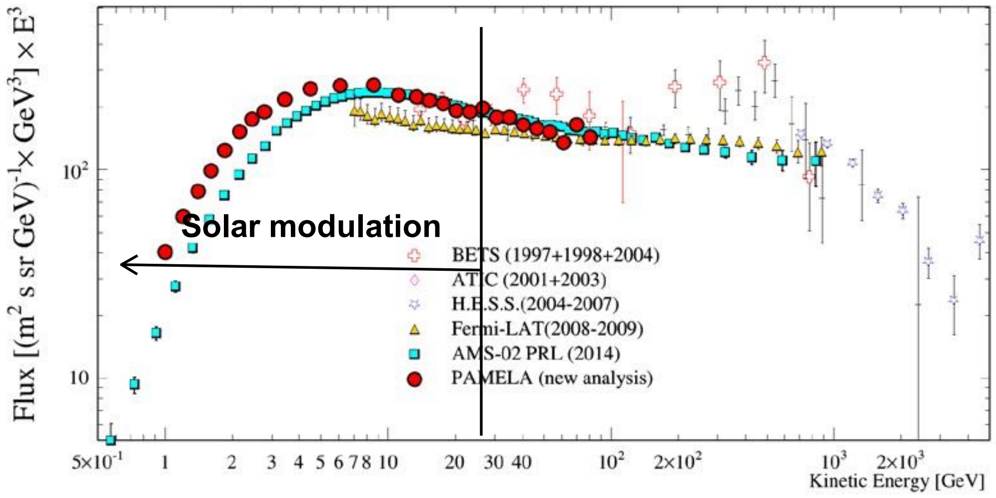
O. Adriani et al., ***Rivista del Nuovo Cimento, vol. 40, Issue 10 (2017)***

PAMELA Results: Electrons

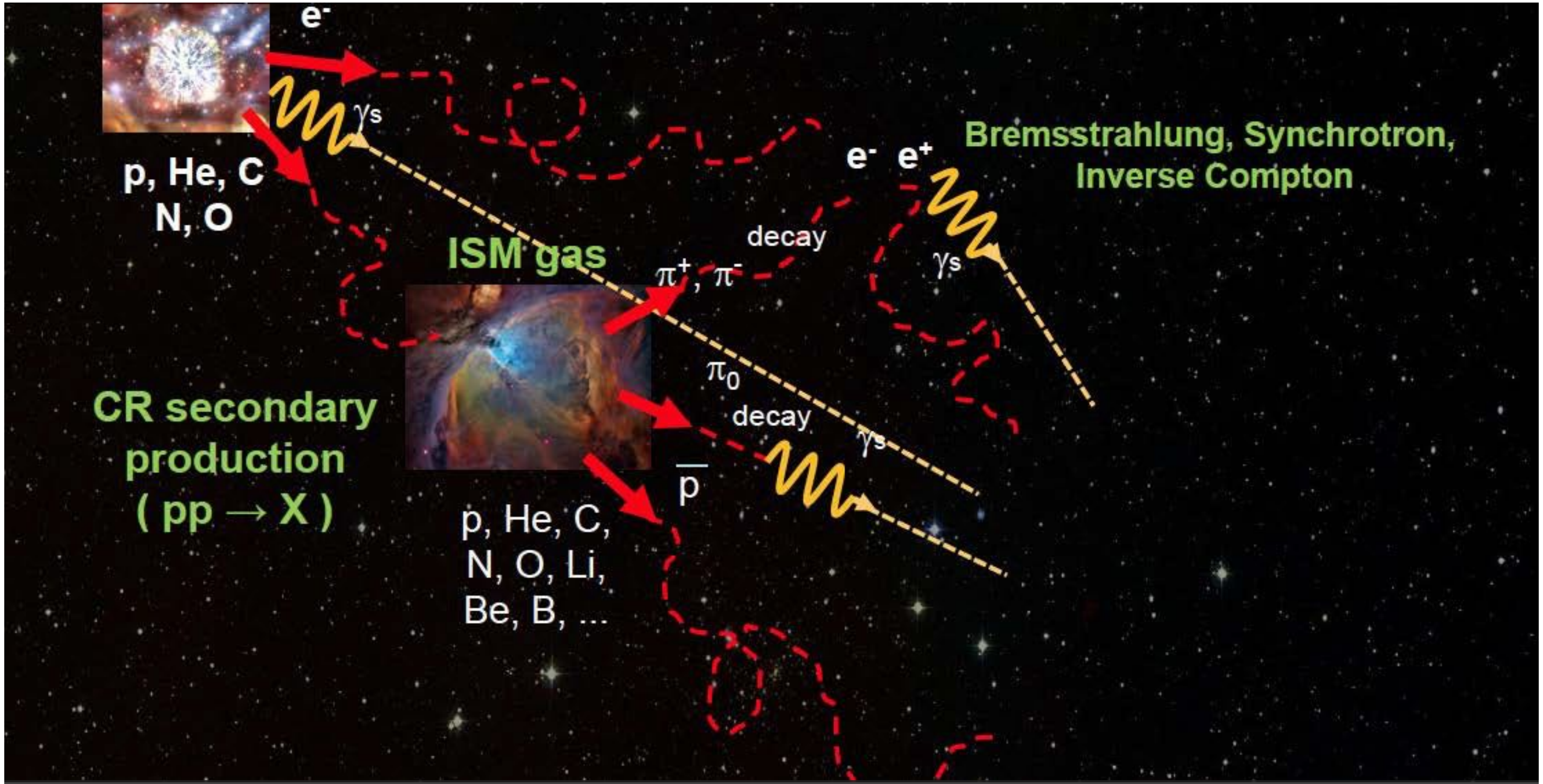


Citations: ~200

$e^- + e^+$



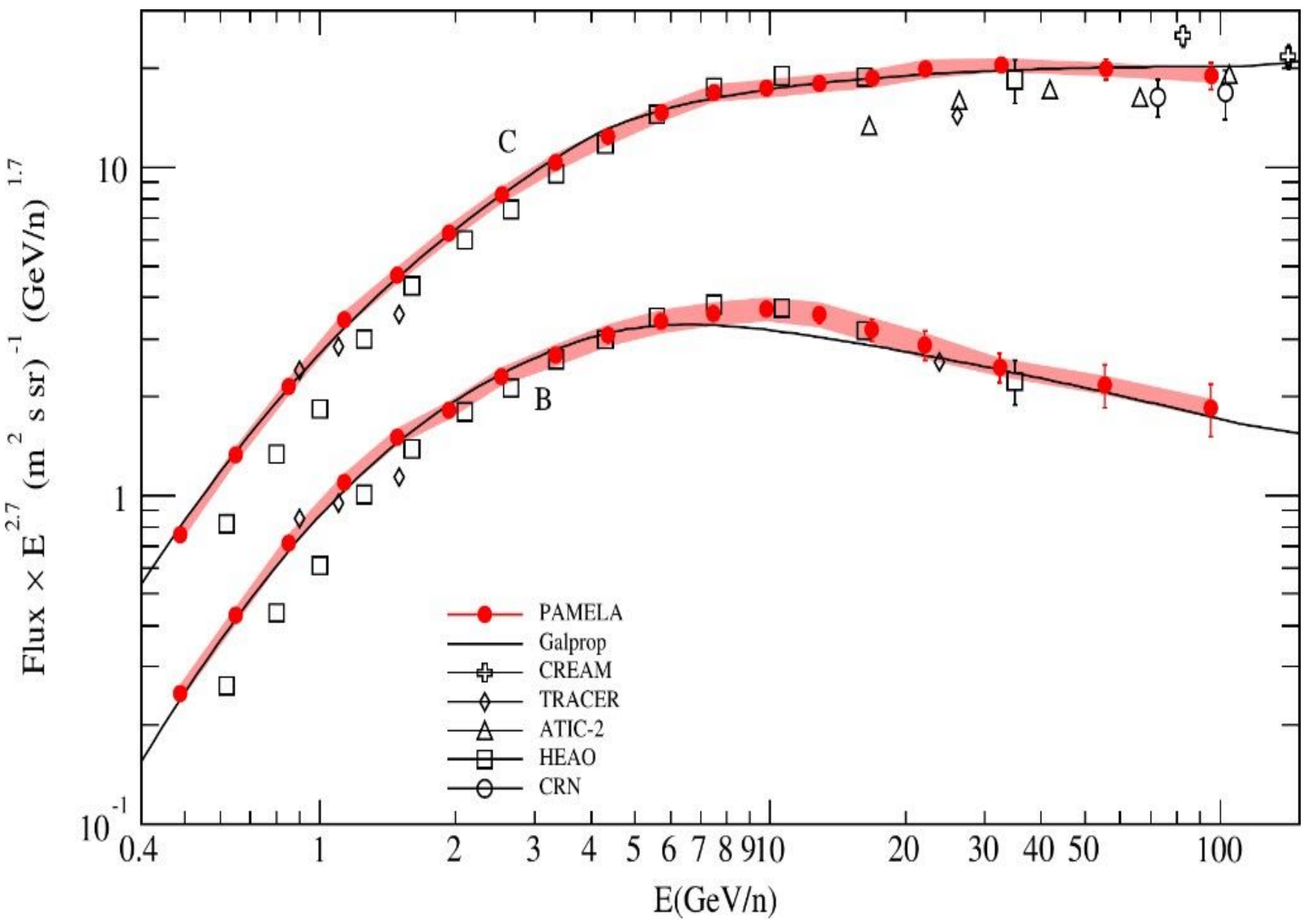
O. Adriani et al., ApJ 810 (2015) 142
O. Adriani et al., Rivista Nuovo Cimento 40 (2017) N. 10



Secondary cosmic rays

Secondaries from homogeneously distributed interstellar matter (light nuclei)

Boron and carbon fluxes



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

Boron-to-Carbon ratio

B/C is very sensitive to propagation effects

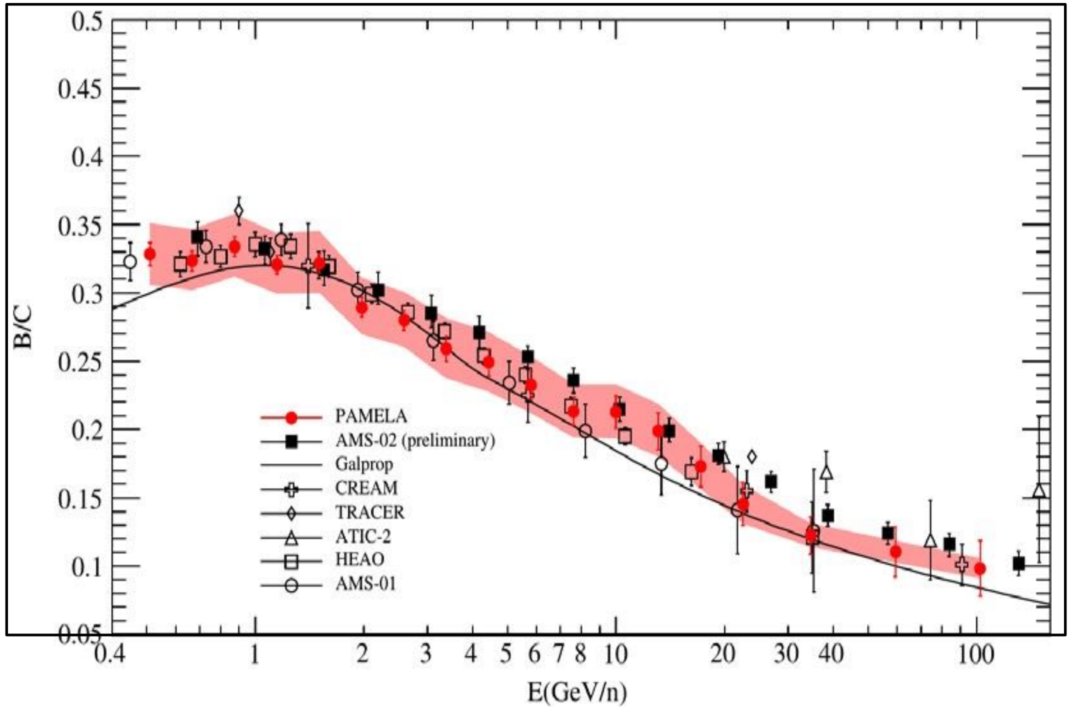
B/C = Sec/Prim

~ $Q_{sec}(E)/Q_{prim}(E)$

~ $Q_{prim}(E)/D(E)$ / $Q_{prim}(E)$

~ $1/D(E)$

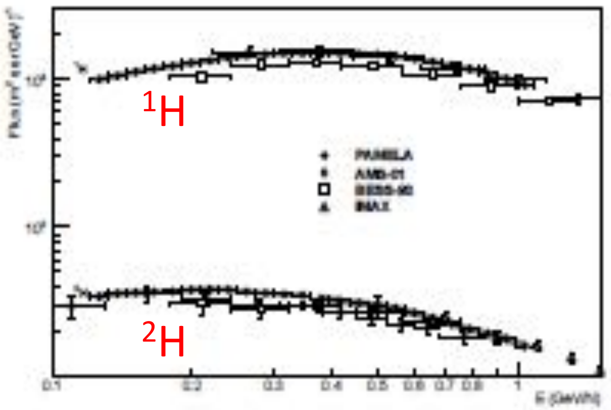
Diffusion coefficient: $D(R)=D_0\beta R^{\delta}$

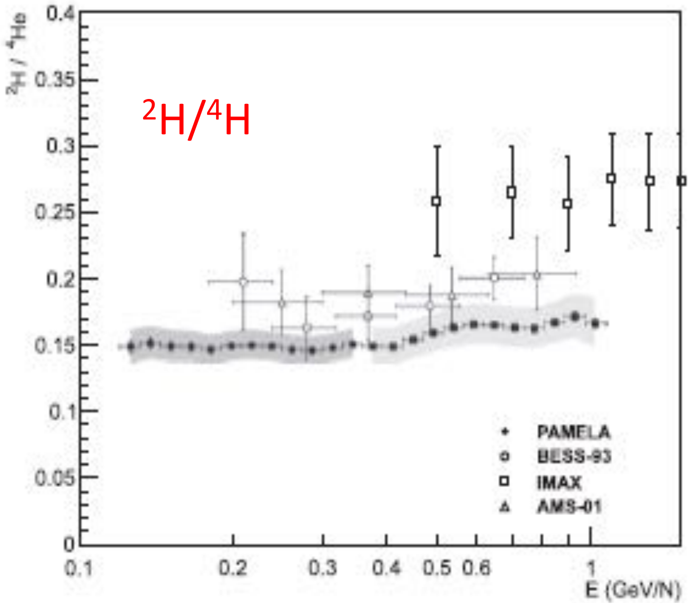


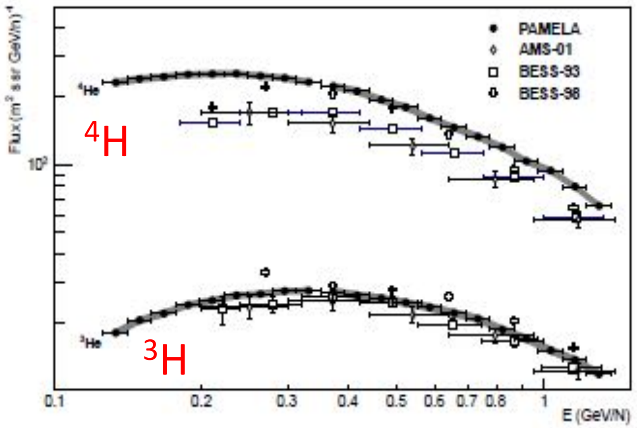
O. Adriani et al., ApJ 791 (2014), 93

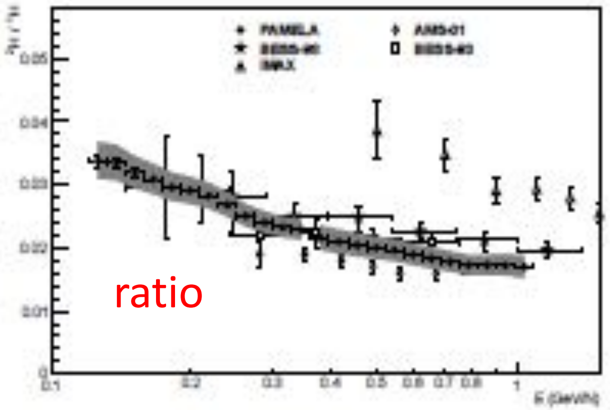
Courtesy by F.Donato

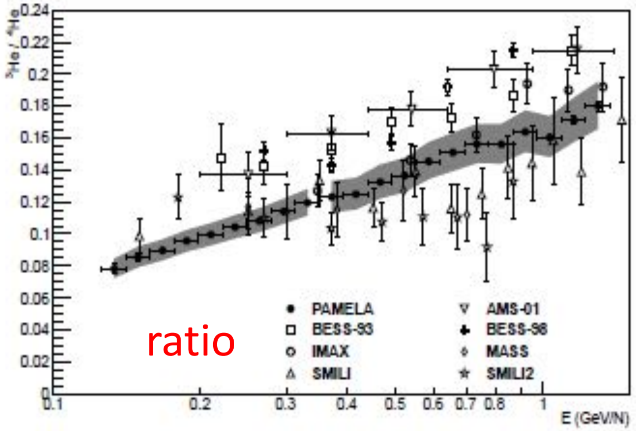
Hydrogen and Helium Isotopes





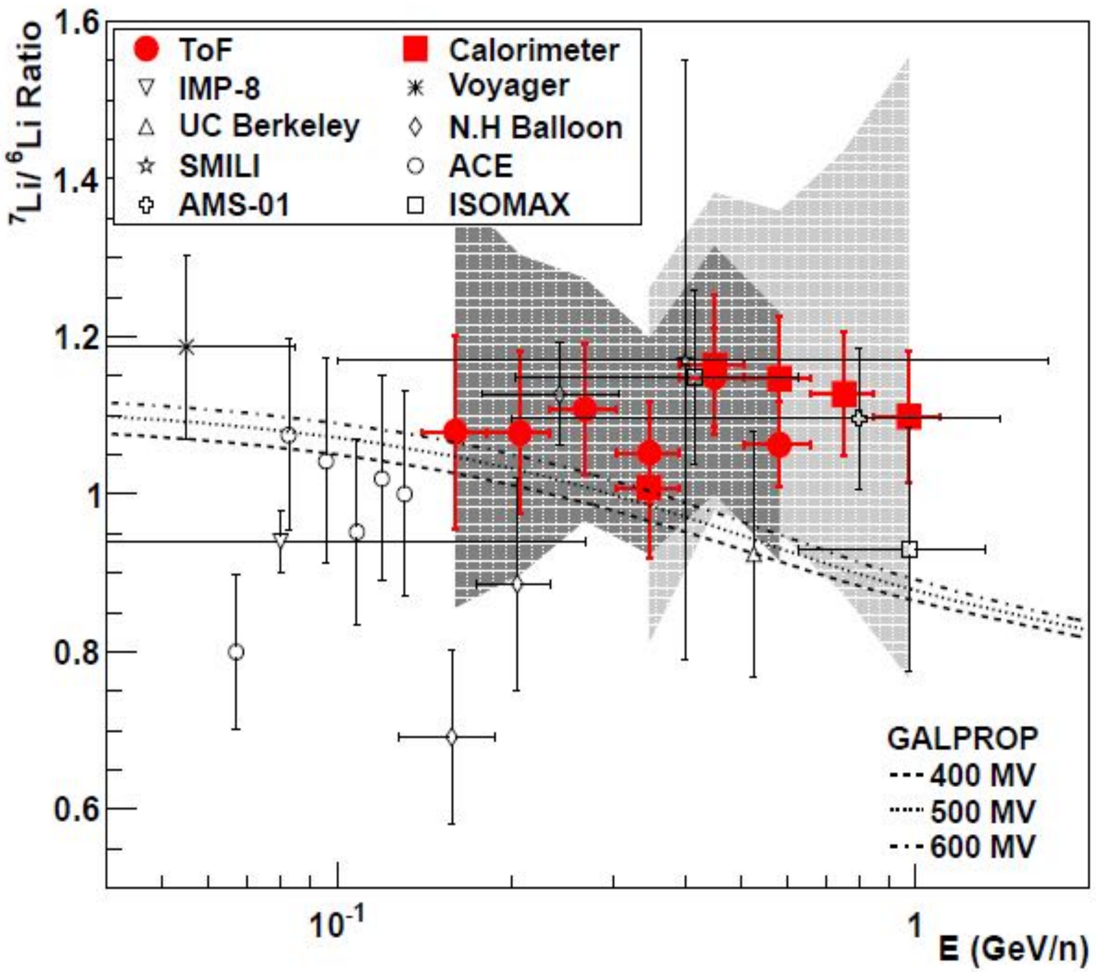


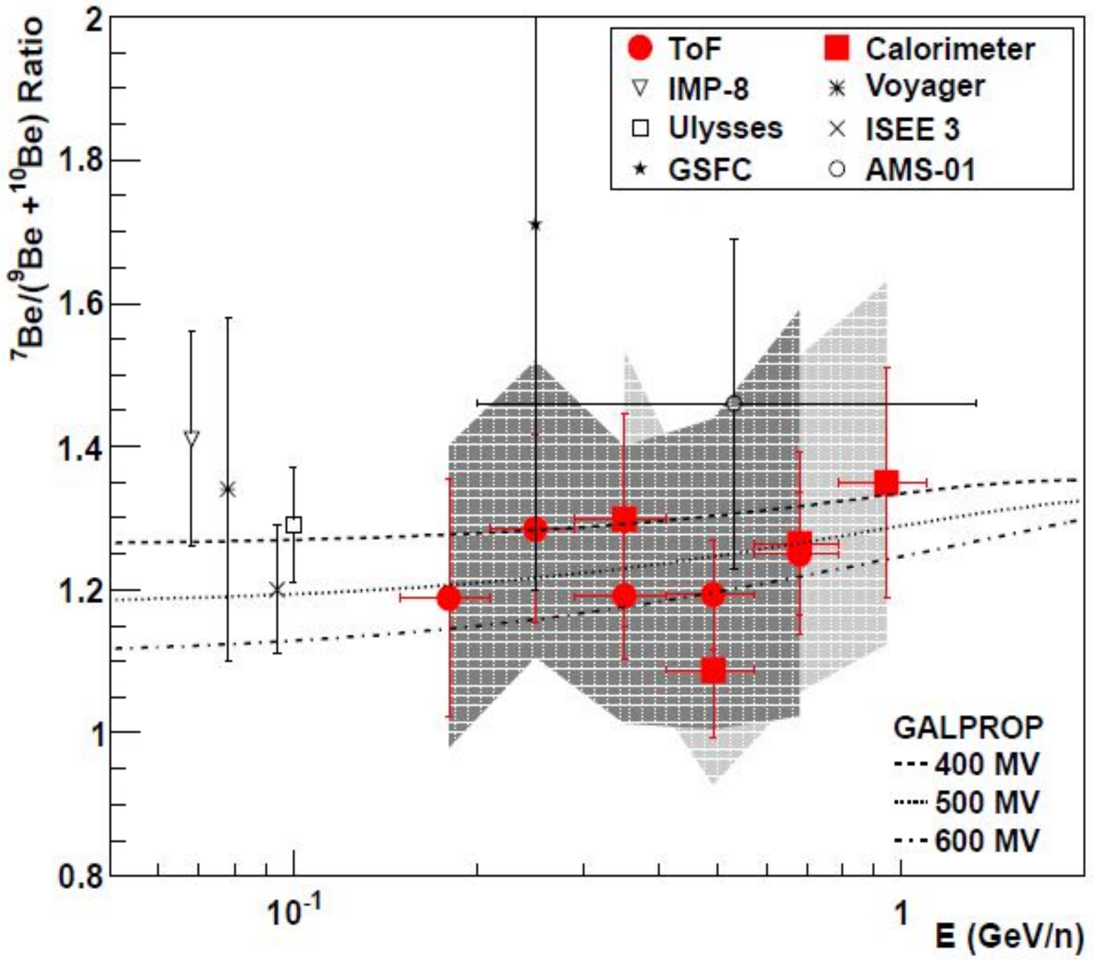




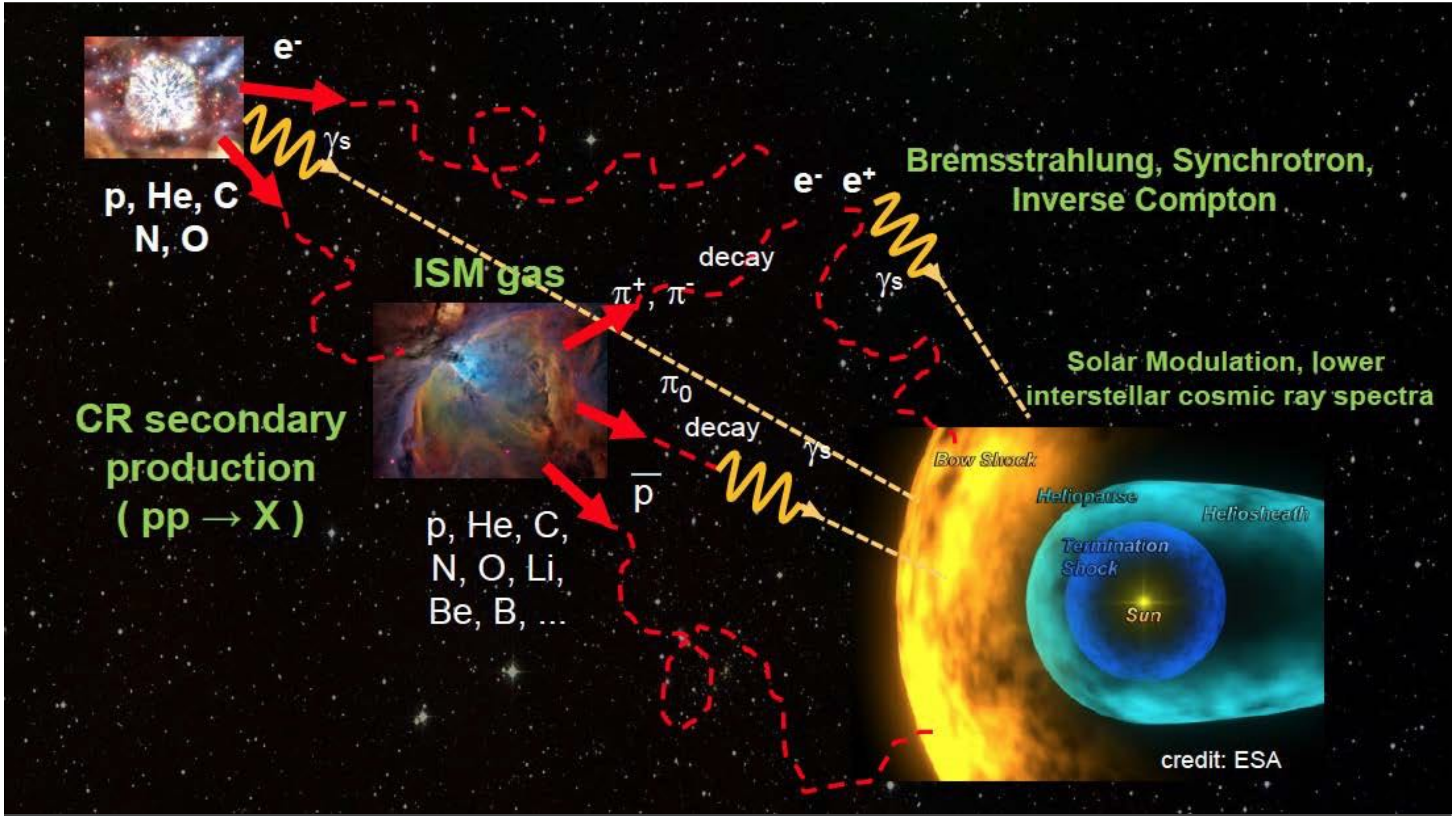
Adriani et al. APJ 818,1,68 (2016)

Lithium and Beryllium Isotopes



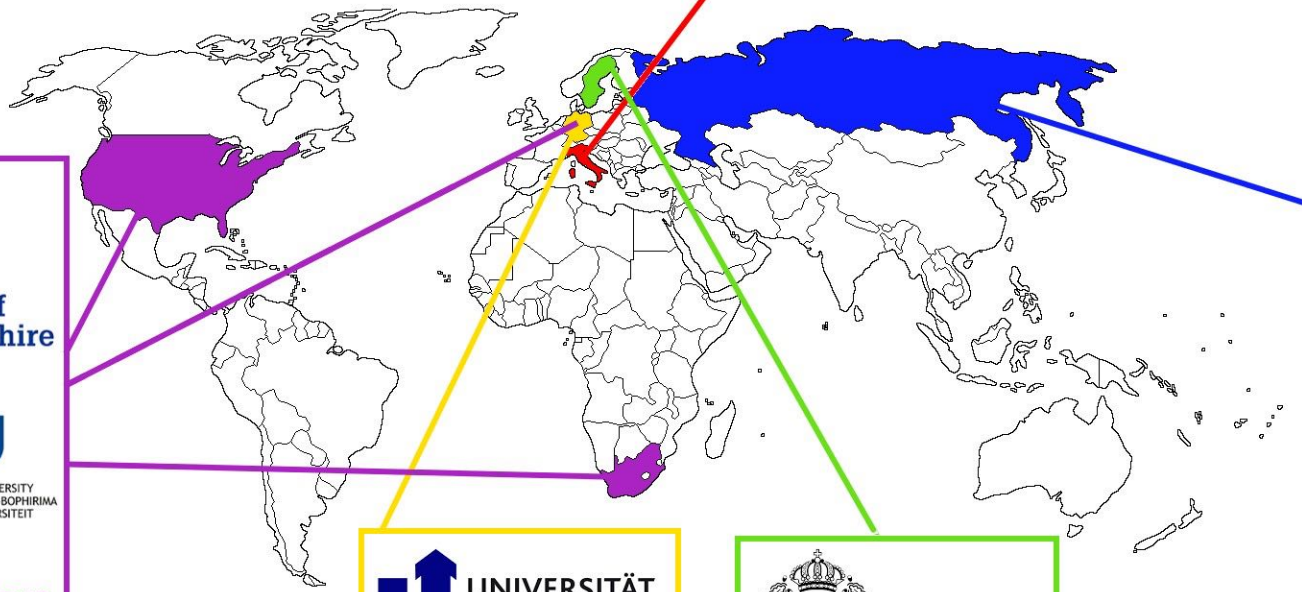


W. Menn et al. *APJ 862, 141 (2018)*



Cosmic rays in the heliosphere

Naples Bari Florence Frascati Rome Trieste CNR, Florence



University of New Hampshire

External collaboration

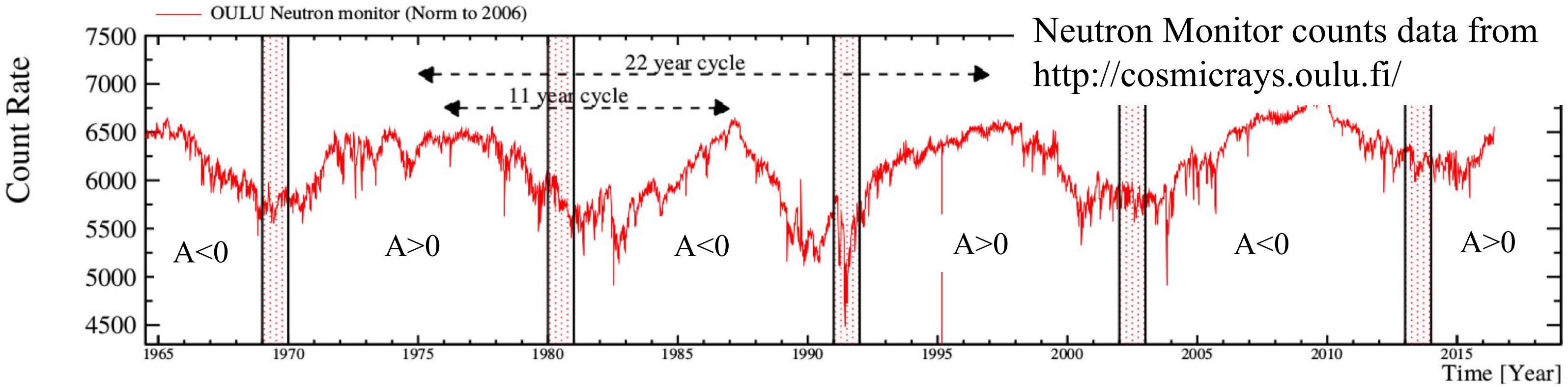
Germany

Sweden

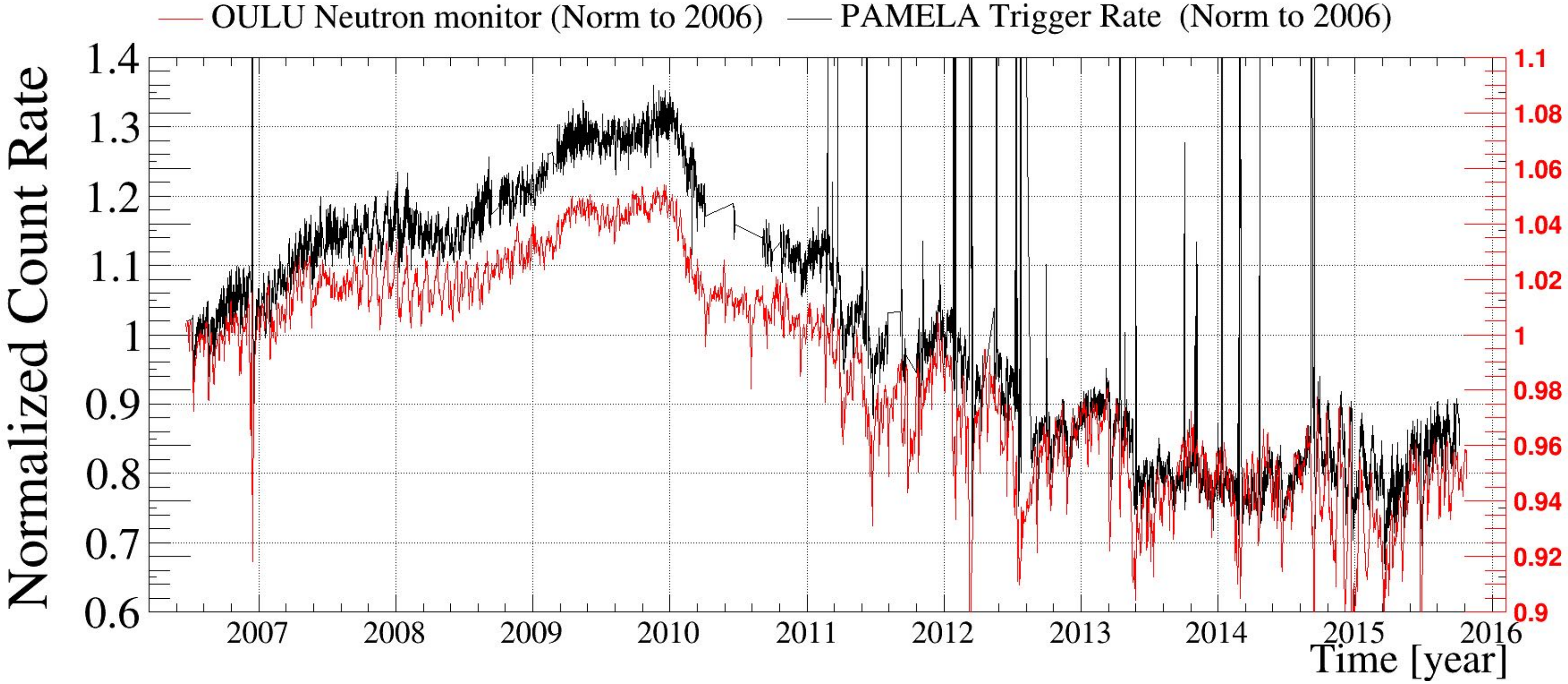
Moscow

St. Petersburg

PAMELA observations (2006-2016)

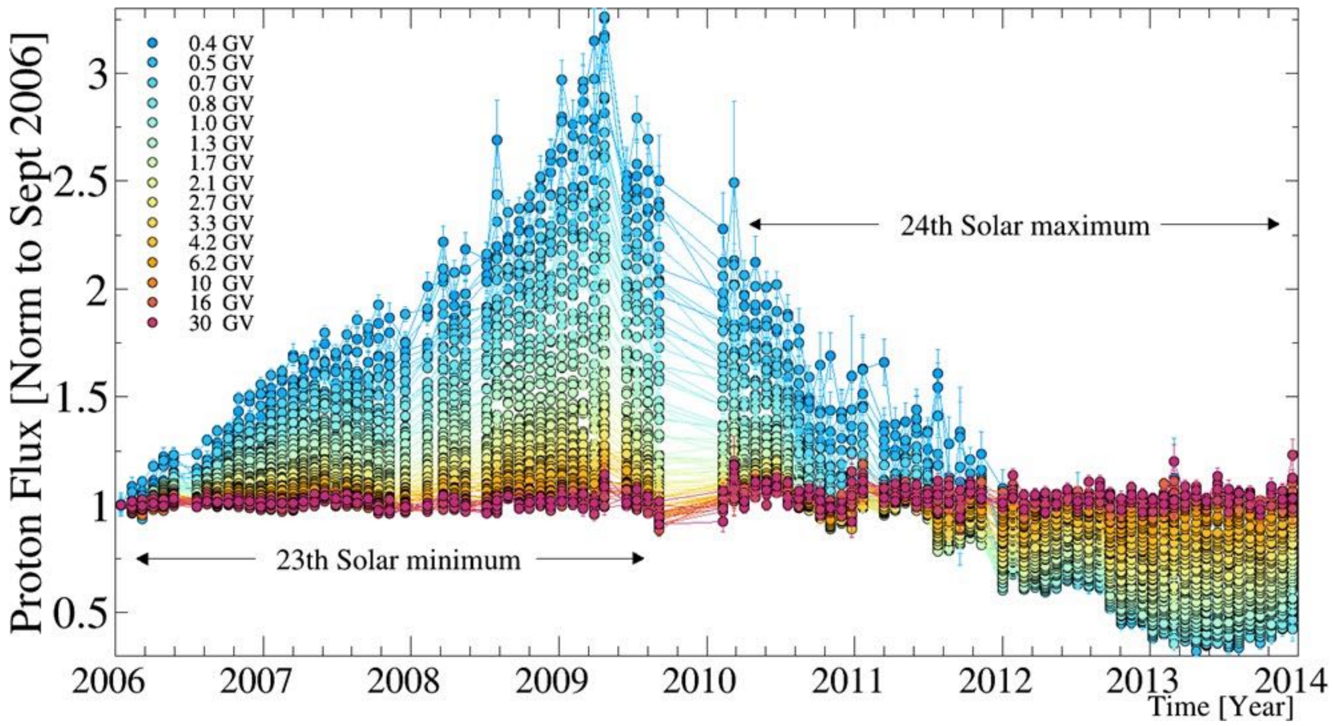


Neutron Monitor counts data from http://cosmicrays.oulu.fi/



PAMELA observations covers about one solar cycle

Propagation in the Heliosphere

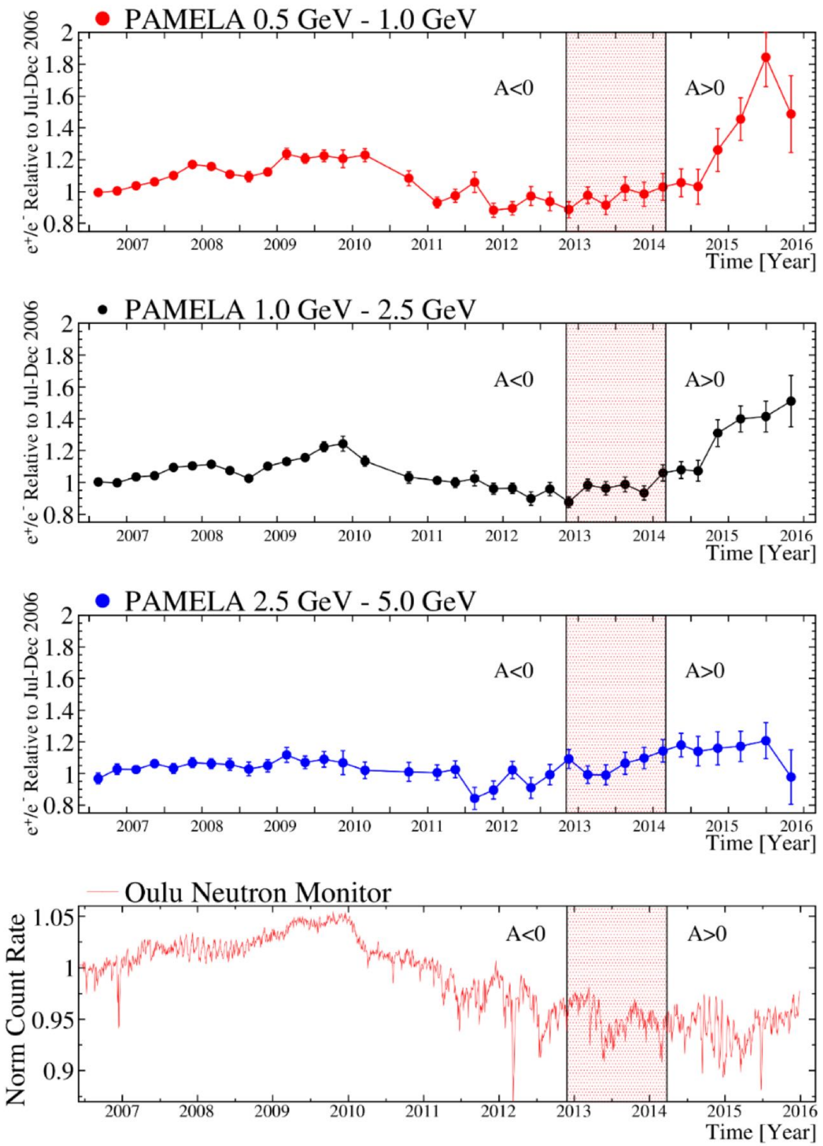


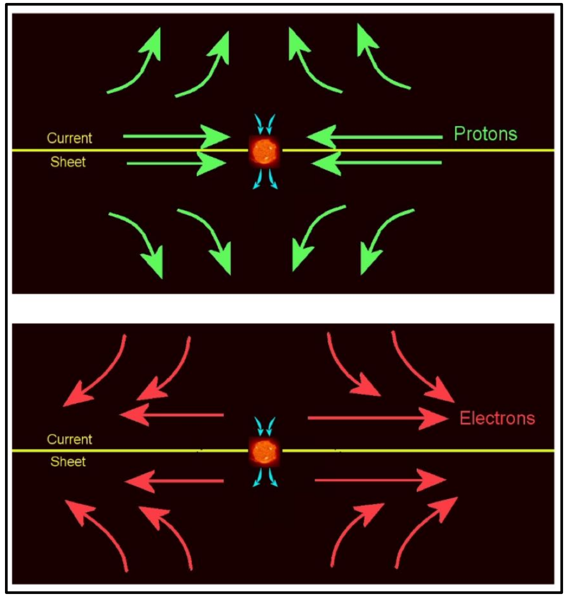
APJL, 854, 1, 2018

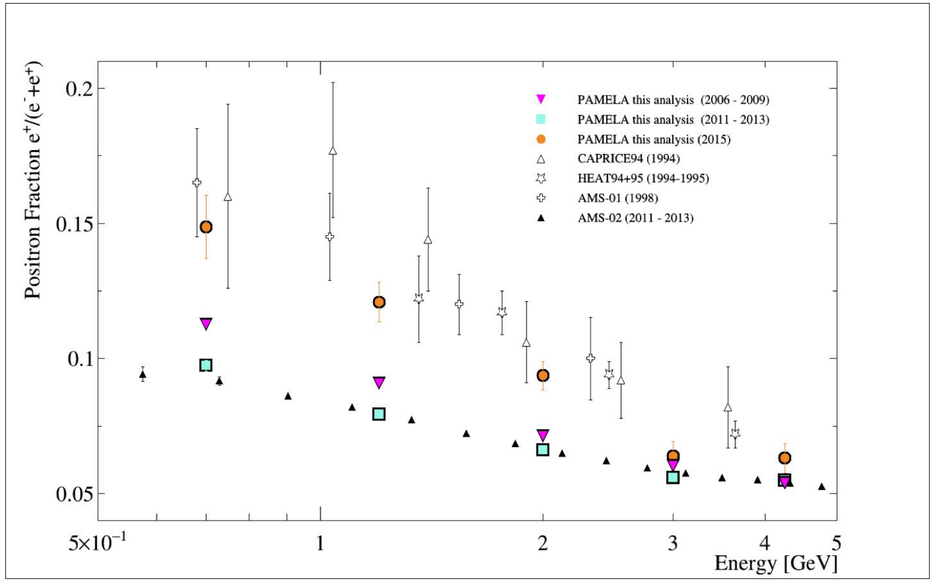
O. Adriani et al., Rivista Nuovo Cimento 40 (2017) N. 10

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

polarity reversal of the HMF

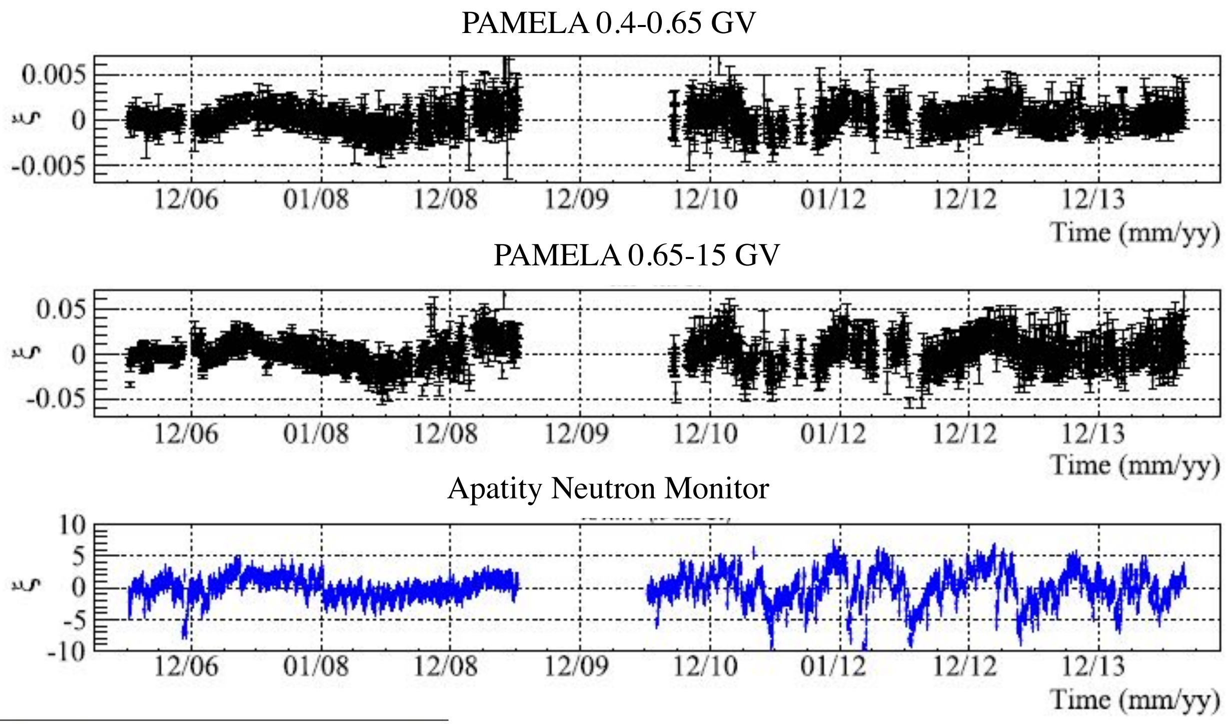






O. Adriani *et al*., PRL 116, 241105 (2016)

Mid-term variations in PAMELA data

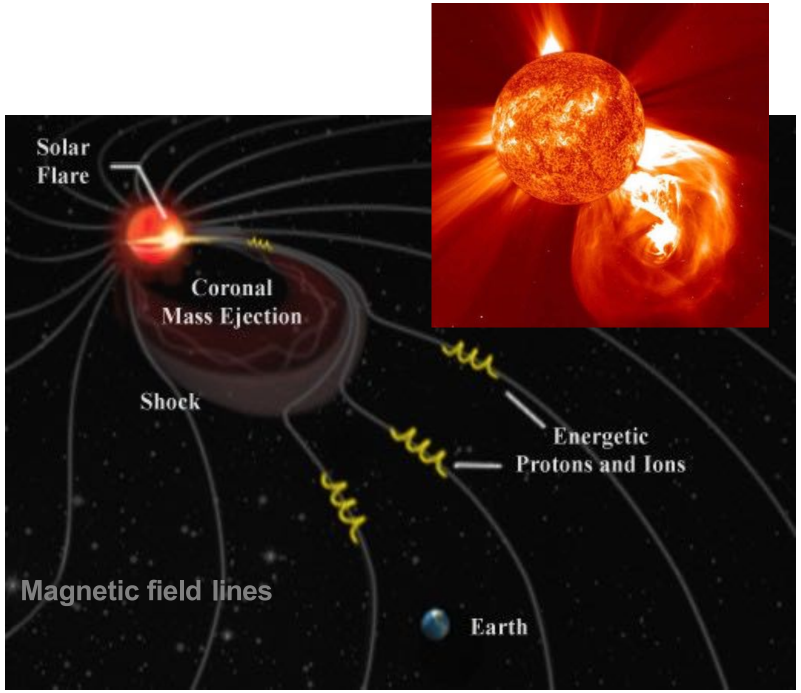


Rigidity (GV)	solar phase	excess(%)	SNR
0.4-0.65	total	4.3	11.7
0.4-0.65	ascending	2.6	6.9
0.4-0.65	descending	7.4	9.6
0.65-15	total	2.5	9.9
0.65-15	ascending	0.72	2.8
0.65-15	descendingm	4.8	10.2
15-50	total	0.96	4.2
15-50	ascending	0.74	3.3
15-50	descending	1.2	2.9

- A signal with periodicity of ~400 days is observed in the proton flux
- excess of ~4% in the 0.4-0.65 GV rigidity interval
  - known variation in solar activity (Quasi-Biennial Oscillations)
  - consistent with Jupiter periodicity (398 days)

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

Solar energetic particles (SEPs)



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

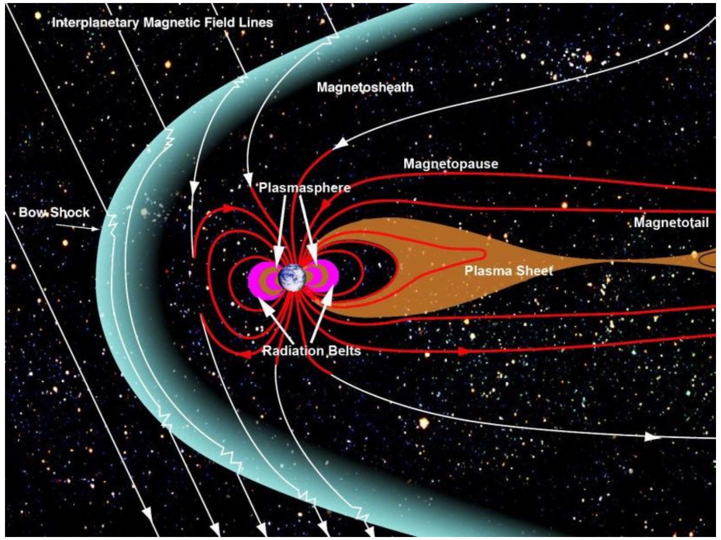
Sun can accelerate particles up to relativistic energies

- Magnetic reconnections
- CME-driven shock

SEPs can be observed in the interplanetary space

Often associated to other solar phenomena, eg:

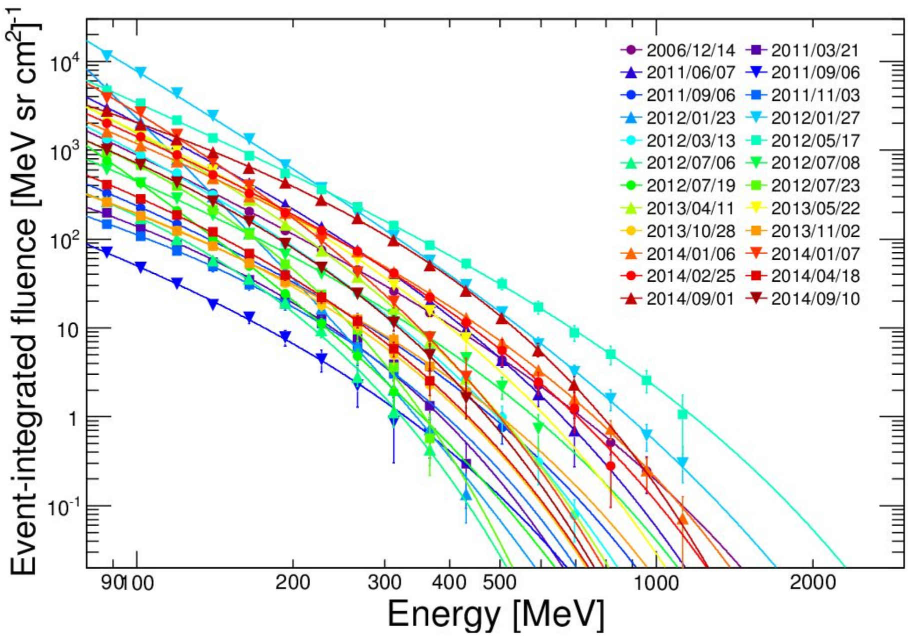
- X and gamma-ray flares
- Coronal-mass ejections (CMEs)
- ...

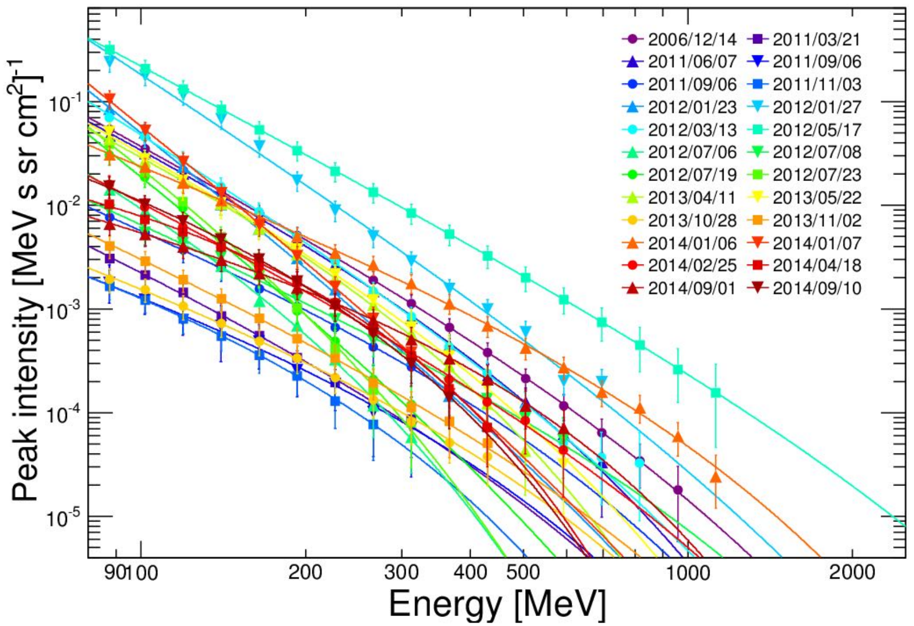


PAMELA SEP list

	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

PAMELA SEP spectra





Bruno, A et al, *APJ*, 862, 97 (2018)

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.

Physics Reports
Volume 544, Issue 4, 30 November 2014, Pages 323–370
The PAMELA Mission: Heralding a new era in precision cosmic ray physics

PAMELA Overall Results

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

- Results span 4 decades in energy and 13 in fluxes
- The PAMELA collaboration published more than 80 papers on international journals such as: Nature, Science, Physics Reports, Physical Review Letters, Astrophysical Journal, etc..

TEN YEARS OF COSMIC RAYS IN SPACE

A new issue of La Rivista del Nuovo Cimento on the role of a satellite-borne detector uncovering the mysteries of cosmic rays

La Rivista del Nuovo Cimento Vol. 40 N. 10: online in OPEN ACCESS for 30 days

Ten years of PAMELA in space

PAMELA Collaboration