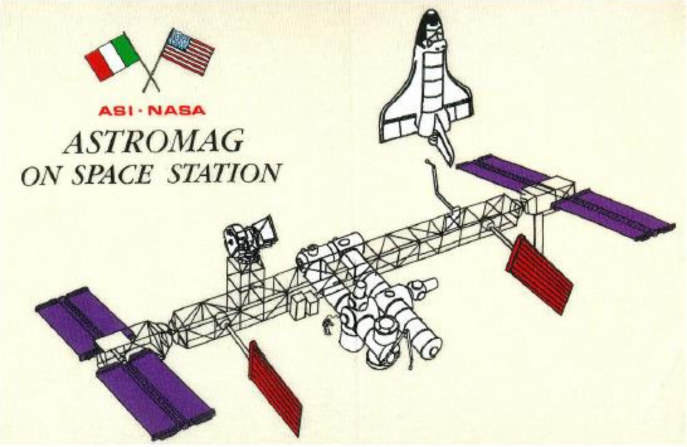
# Risultati scientifici dell'esperimento Wizard/PAMELA

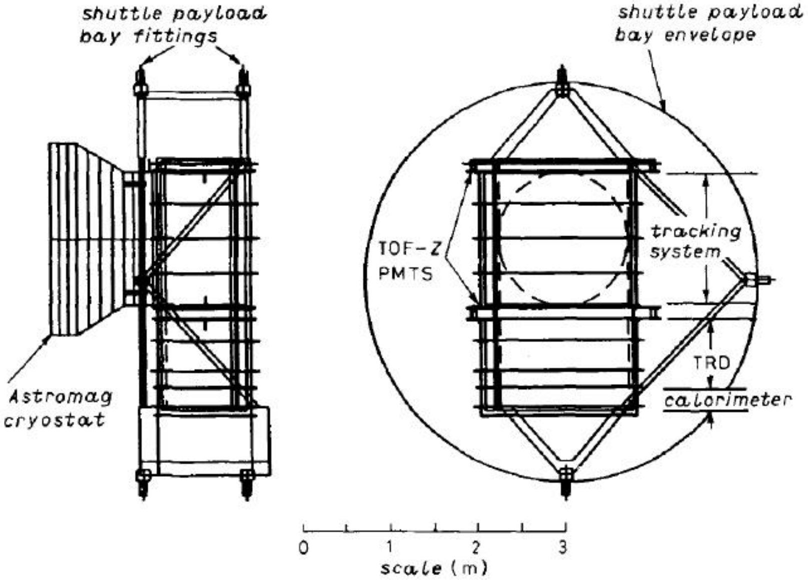
Vannuccini Elena

# Astromag/WiZard





- Extensive R&D in the '80s aiming to optimize **superconducting magnet facility** to be flown as a U.S.-Italy project on Space Station Freedom in the late '90s
  - **WiZard** experiment dedicated to search for primoridial antimatter

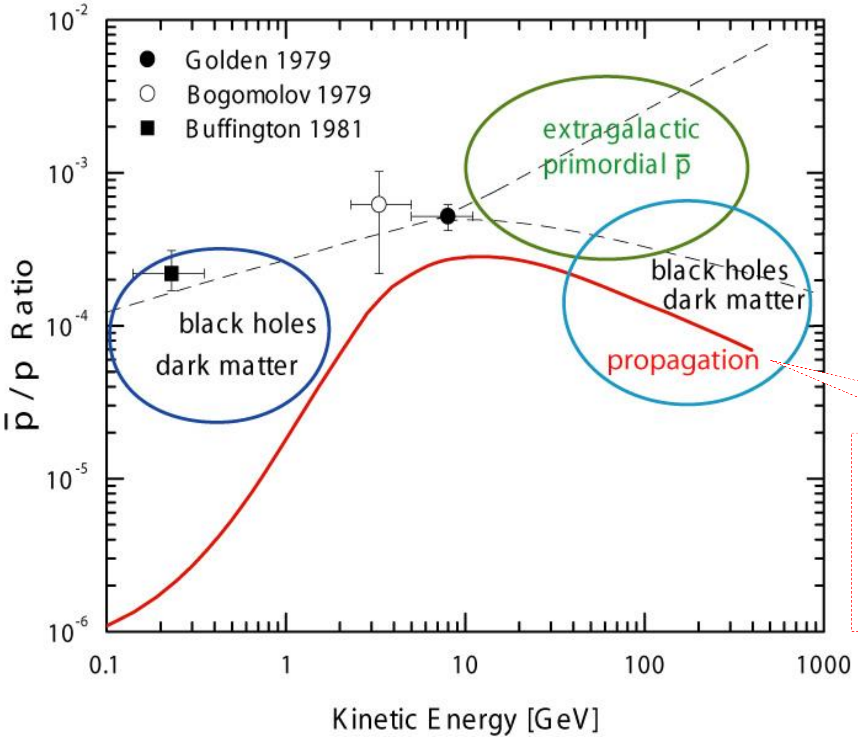



Golden et al N.Cim. 105 (1990) 191

Project canceled!

# Antimatter in CRs

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

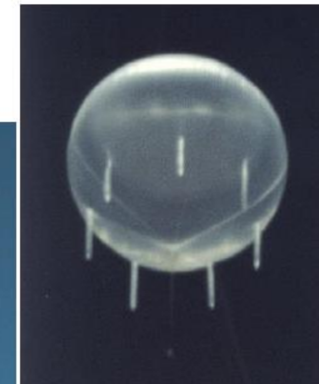


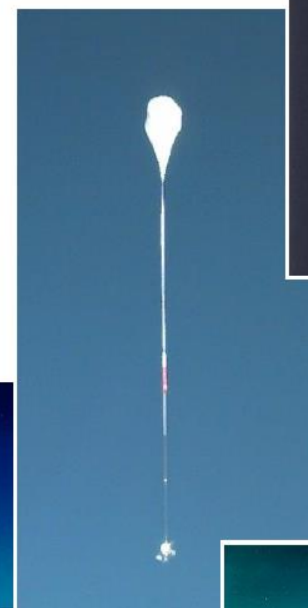

Background:
CR interaction with ISM
CR + ISM → p-bar + …

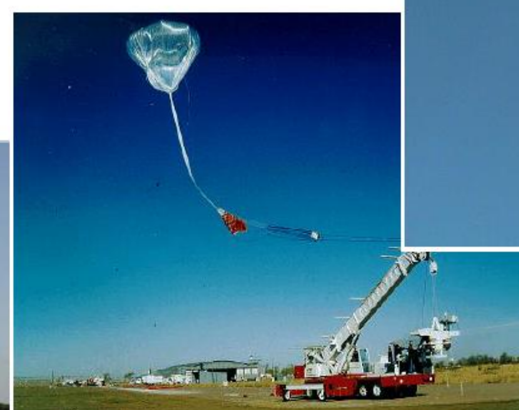
# CR-antimatter measurements in the ‘90s

- Extensive campaign of **daily balloon flights** operated by several groups
  - Wizard (MASS, TS, CAPRICE)
  - BESS
  - Others (HEAT, IMAX…)

- Main instrument characteristics
  - Superconducting magnets ($\sim 1T$ field)
  - MWPC & drift chamber tracking systems ( $O(100\mu m)$ resolution )
  - MDR $\sim 100 \div 300\ GV$



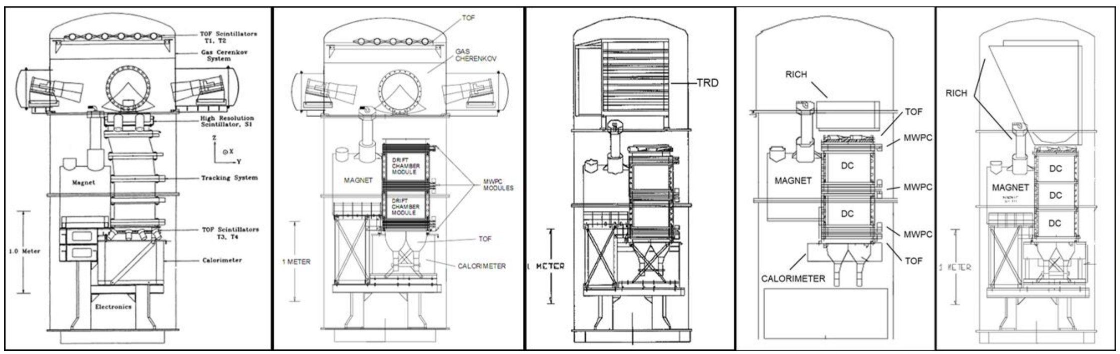


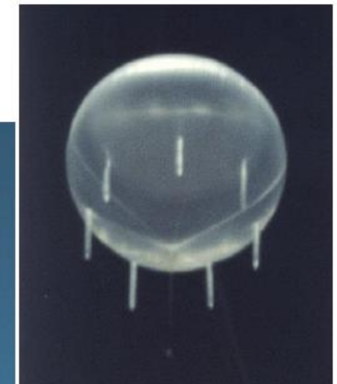


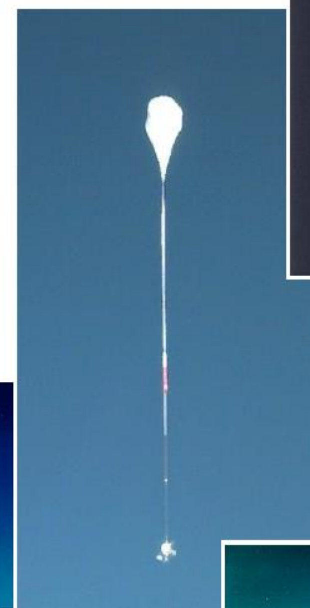
# CR-antimatter measurements in the '90s

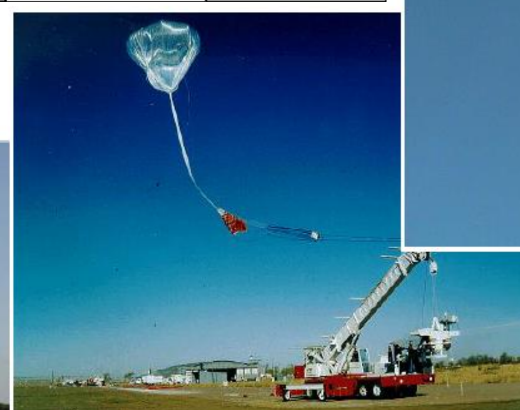
- Extensive campaign of **daily balloon flights** operated by several groups
  - Wizard (MASS, TS, CAPRICE)

MASS98 MASS91 TS93 CAPRICE94 CAPRICE98



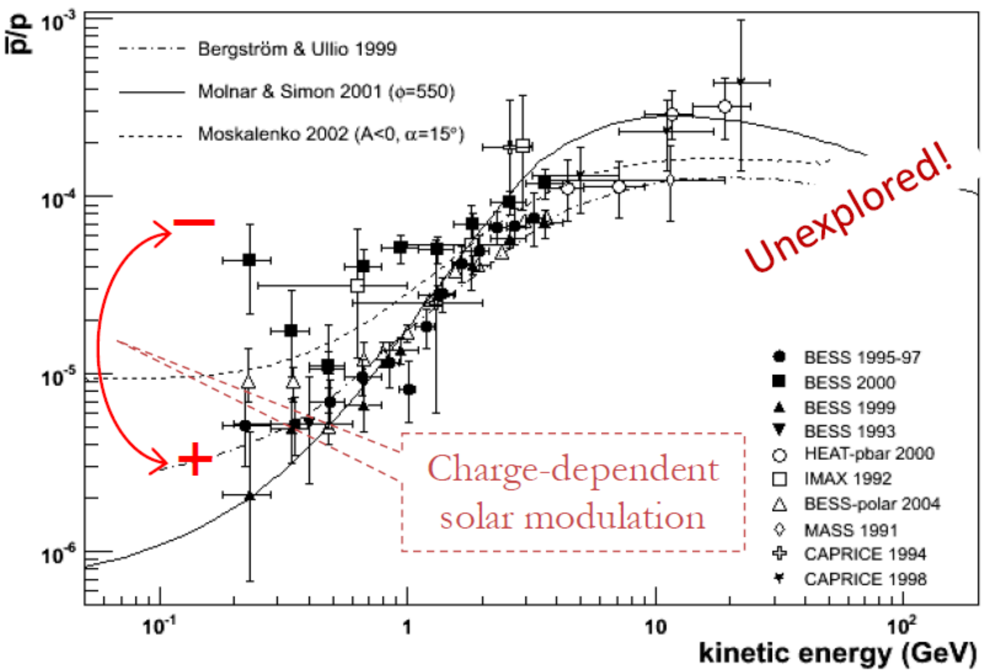





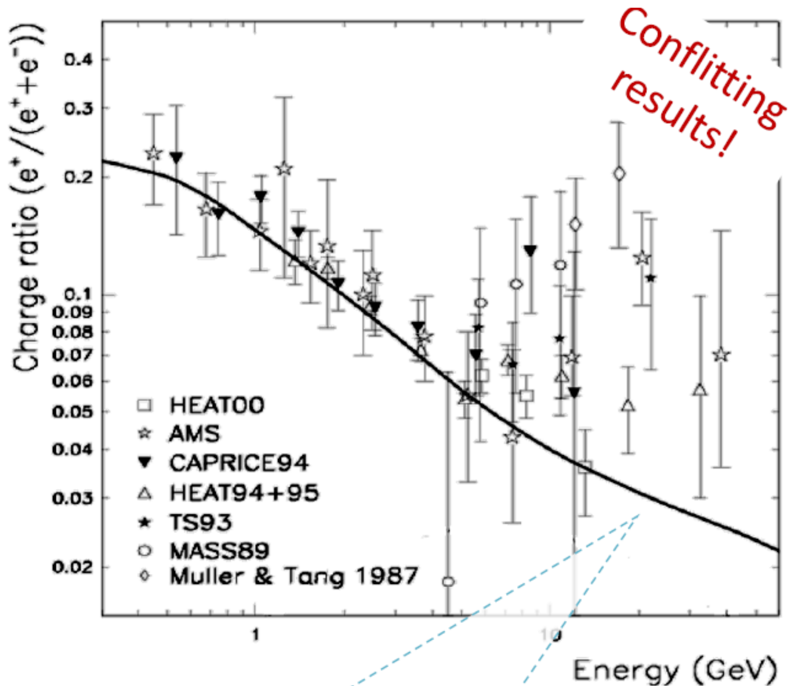


# Status at the beginning of 2000s

### ANTIPROTONS




### POSITRONS




$\mathrm{GCR} + \mathrm{ISM} \rightarrow \pi^{\pm} + x \rightarrow \mu^{\pm} + x \rightarrow e^{\pm} + x$

$\mathrm{GCR} + \mathrm{ISM} \rightarrow \pi^{0} + x \rightarrow \gamma\gamma \rightarrow e^{\pm}$

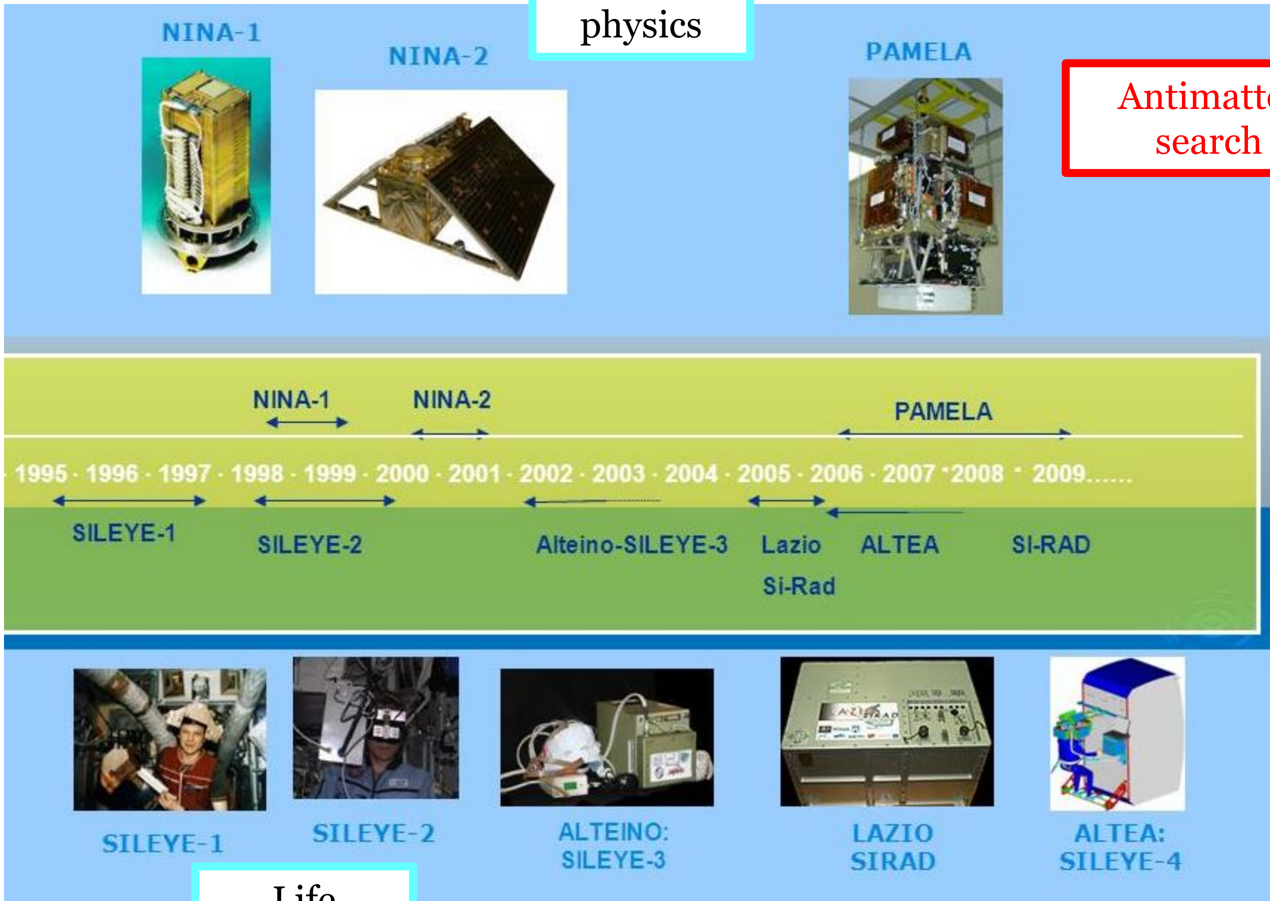
Two directions for the future:

- High-statistics measurement of $\bar{p}$ @low energy→ BESS-Polar
- $\bar{p}$ and $e^+$ measurement @ high energy → PAMELA & AMS02

# The Russian-Italian Mission

Solar physics

Antimatter search



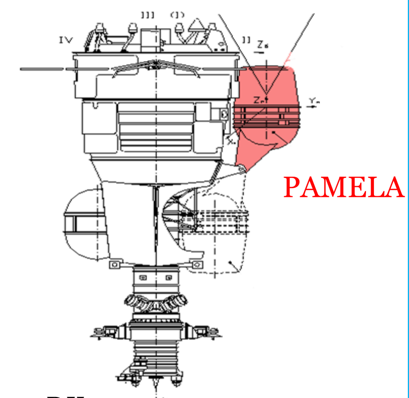

Life science

**PAMELA timeline**

**1998→** MoU between INFN and Russian Space Agency

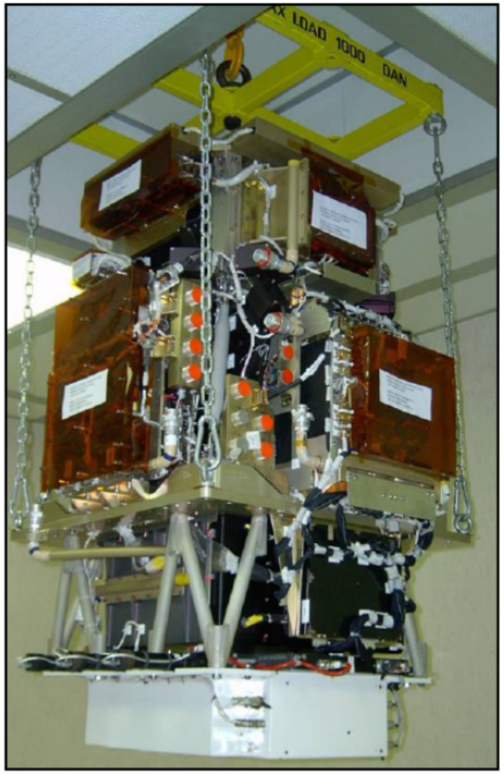
**2006→** June 15, Launch!

**2016 →** January, downlink operation were terminated




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

# The PAMELA apparatus

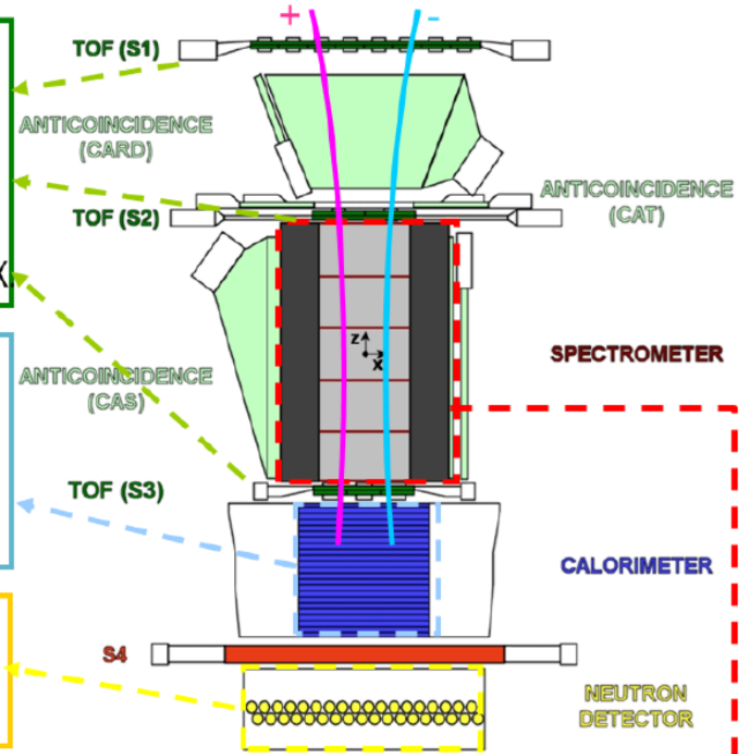


**GF**: 21.5 $cm^2$ sr
Mass: 470 kg
Size: 130x70x70 $cm^3$
Power Budget: 360W

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

<u>Electromagnetic calorimeter</u>
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / $e^-$ (shower topology)
- Direct E measurement for $e^-$

<u>Neutron detector</u>
plastic scintillators + PMT:
- High-energy e/h discrimination



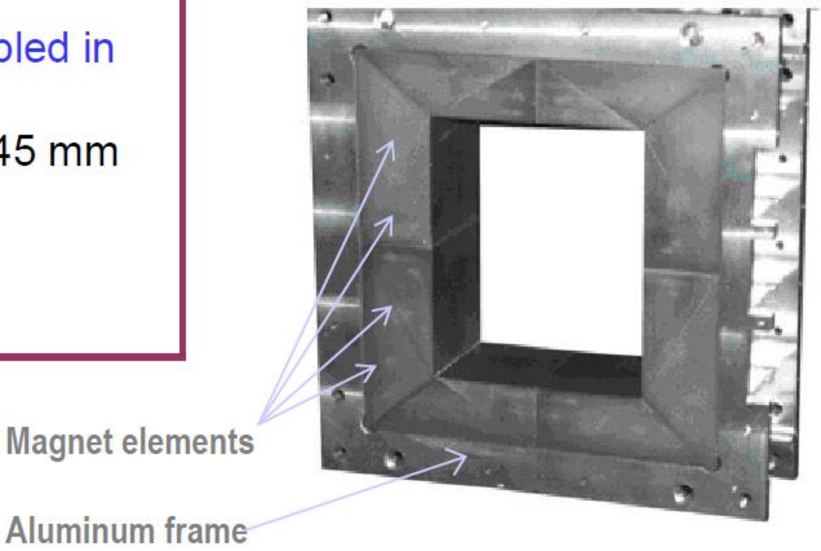

<u>Spectrometer</u>
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

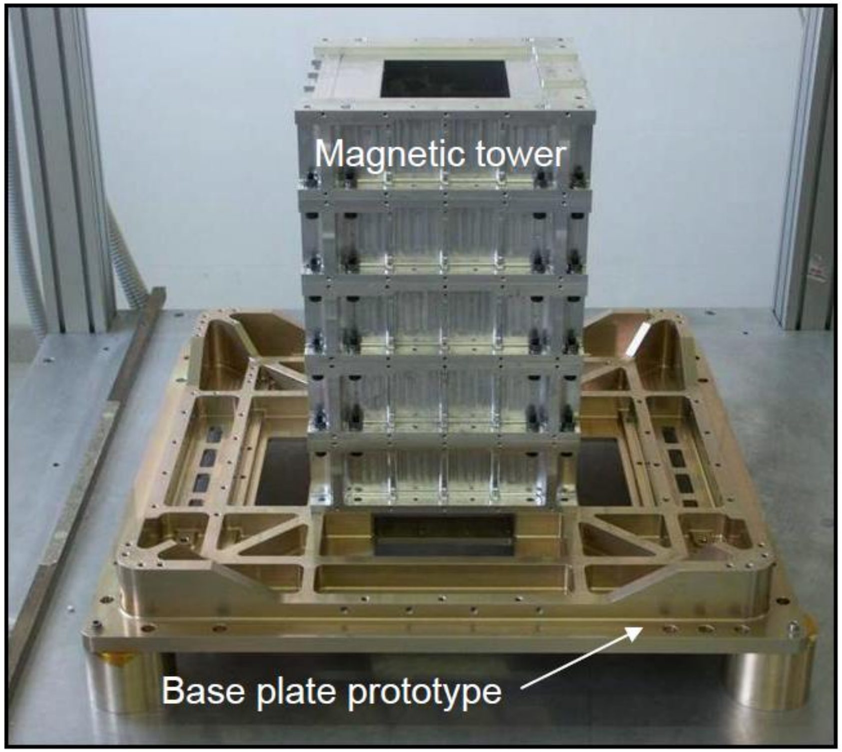
MDR ~1TV

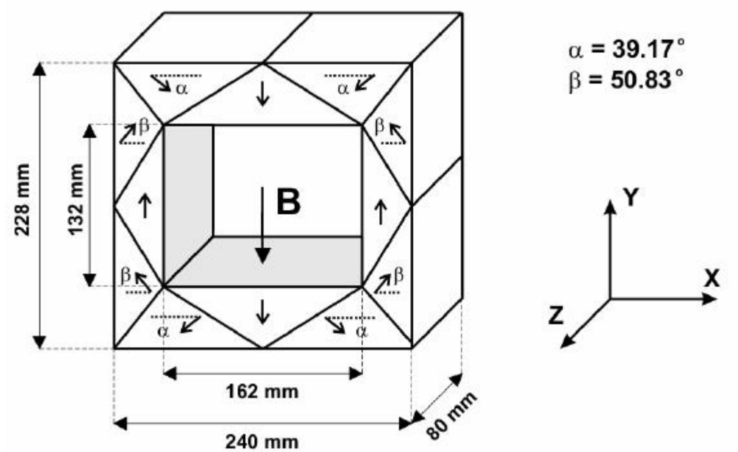
# The magnet

- 5 magnetic modules
- Permanent magnet (Nd-Fe-B alloy) assembled in an aluminum mechanics
- Magnetic cavity sizes (132 x 162) $mm^2$ x 445 mm
- *Geometric Factor*: **20.5 $cm^2$sr**
- Black IR absorbing painting
- Magnetic shields

Magnetic module

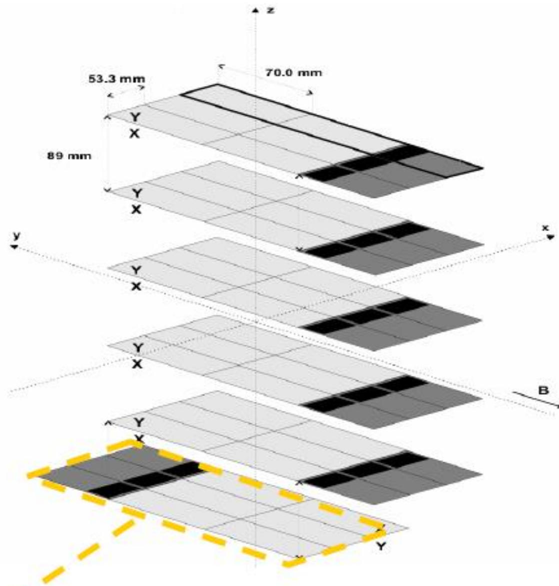



- **0.48 T** @ center
- Average field along the axis: **0.43 T**

# The tracking system

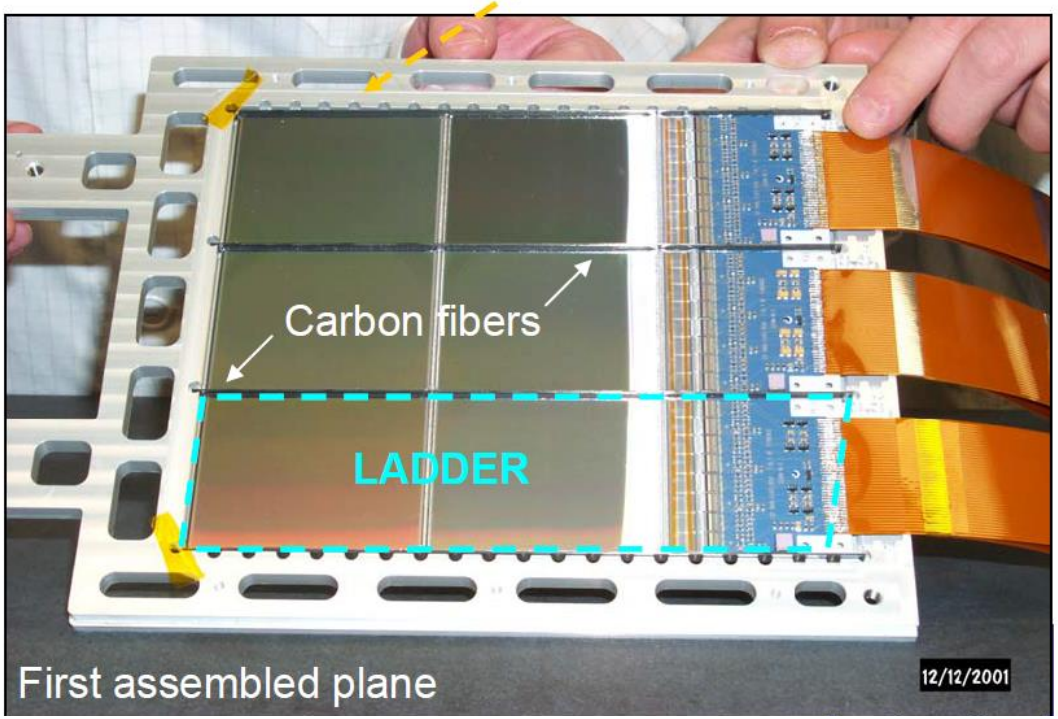



6 detector planes, each composed by 3 ladders

Mechanical assembly

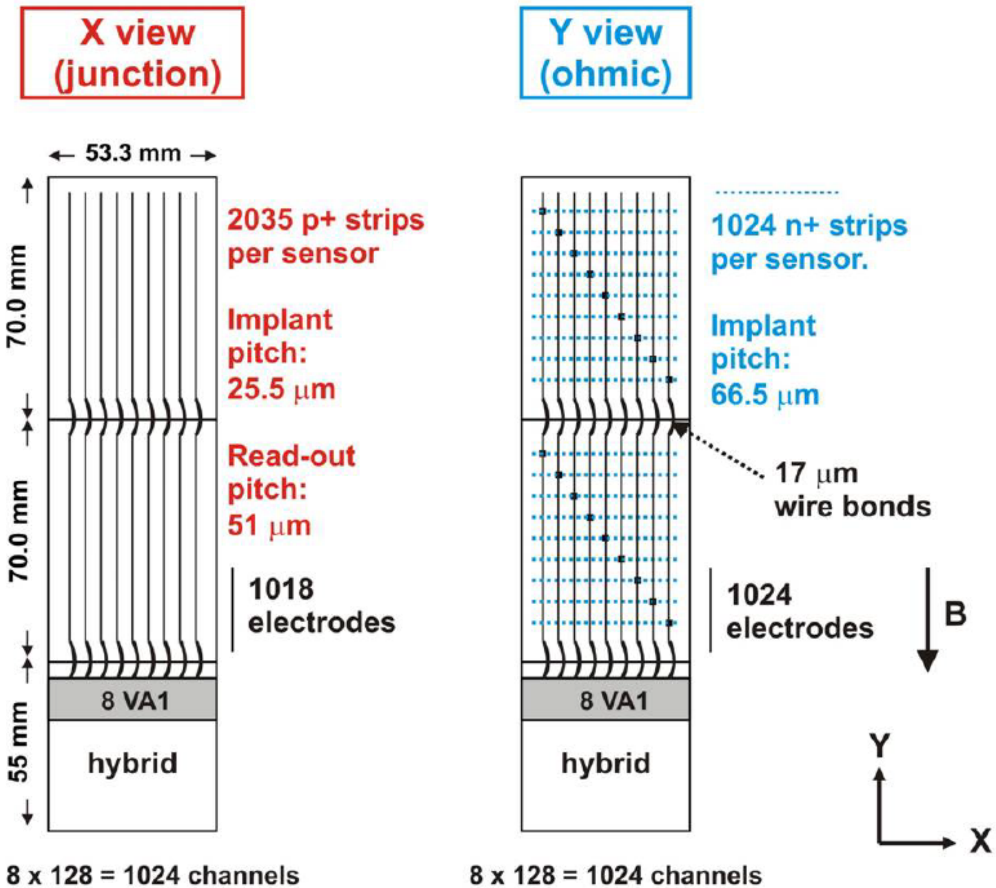
- aluminum frames
- carbon fibers stiffeners glued laterally to the ladders
- no material above/below the plane
  - 1 plane = **0.3% $X_0$** → reduced multiple scattering
- elastic + rigid gluing

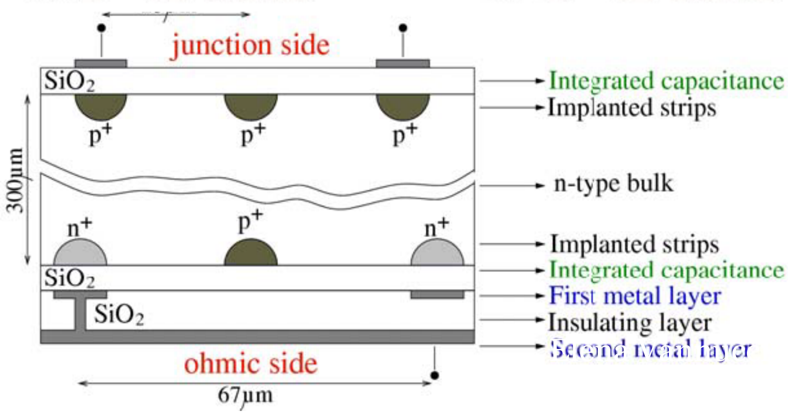

Test of plane lodging inside the magnet




First assembled plane

# Silicon detector ladders




- 2 microstrip silicon sensors
- 1 "hybrid" with front-end electronics

Silicon sensors (Hamamatsu):

- **300 µm, double sided - x & y view**
- **AC coupled** (no external chips)
- **double metal** (no kapton fanout)
- 1024 read-out channels per view
  - strip/electrode coupling ~ 20 pF/cm;
  - channel capacitance to ground:
    - junction: < 10 pF
    - ohmic: < 20 pF

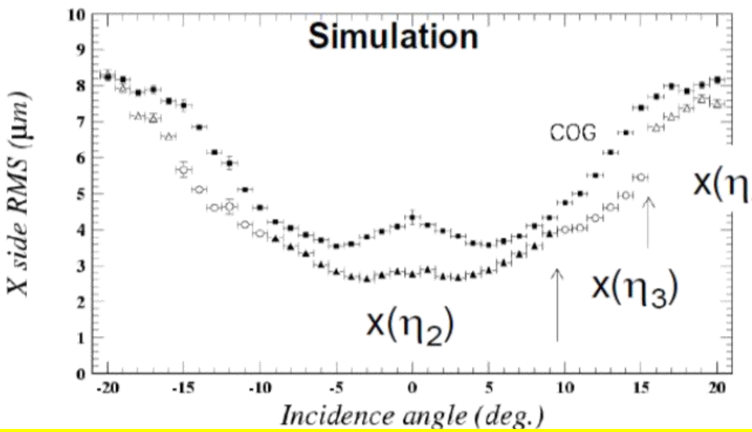
Bias:

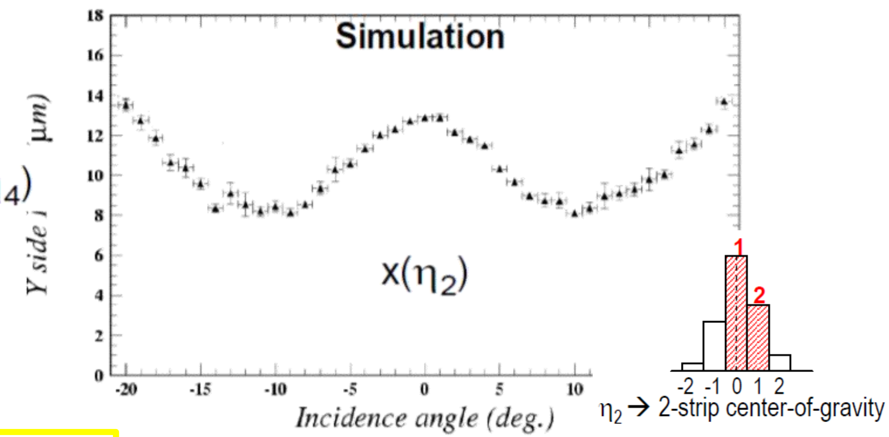
- VY -VX = + 80 V fed through guard ring surrounding the strips
- Bias resistor:
  - junction: punch-through, > 50 MΩ;
  - ohmic: polysilicon, > 10 MΩ.
- Leakage current < 1 µA/sensor.

# Spatial resolution

## Sensor instrinsic resolution

Spatial resolution studied by means of beam-test of silicon detectors and simulation



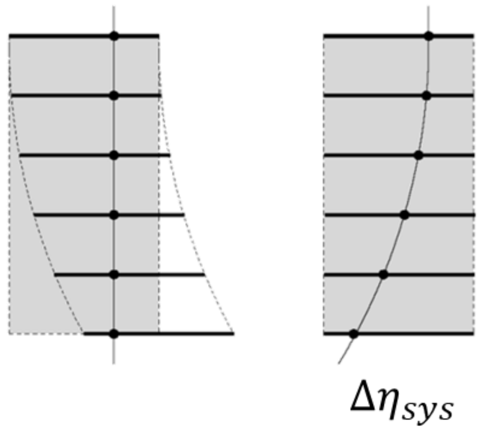

- junction side (X): 3 $\mu$m @0°, < 4 $\mu$m up to 10° (→ determines momentum resolution)
- ohmic side (Y): 8÷13 $\mu$m
- Position finding algorithm accounts for non-linear charge collection, asymmetric signal distribution, discretization effects → Landi NIMA 554 (2005)

## Sensor alignment

Track-based alignment: minimization of spatial residuals as a function of the roto-traslational parameters of each sensor

- Proton beam (@CERN-SPS 2003) and atmospheric muons (cross-check) → **~100±1 $\mu$m**
- In-flight corrections with protons → **~10 $\mu$m**

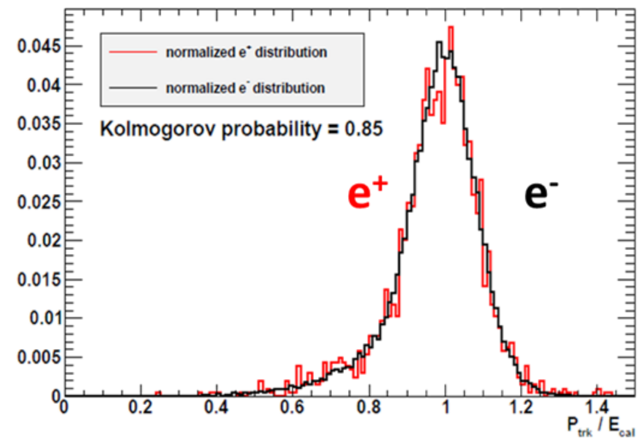
# Spectrometer systematics



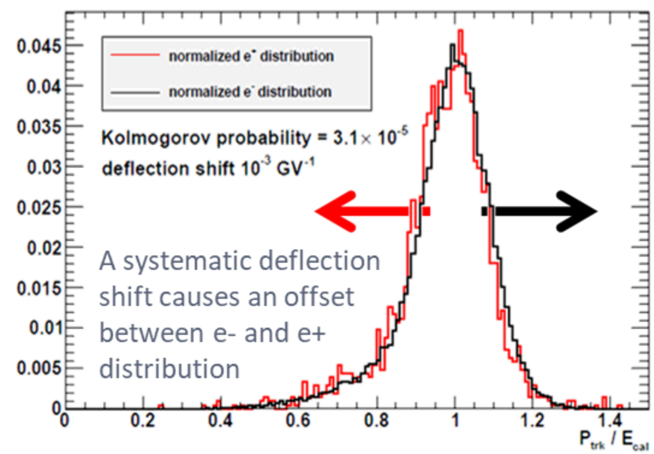

- Due to possible residual distortion of the tracking system
- Evaluated from electron/positron data by comparing the spectrometer momentum with the calorimeter energy
- Upper limit set by positron statistics:

$$\boldsymbol{\Delta\eta_{sys} \sim 10^{-4} GV^{-1}}$$

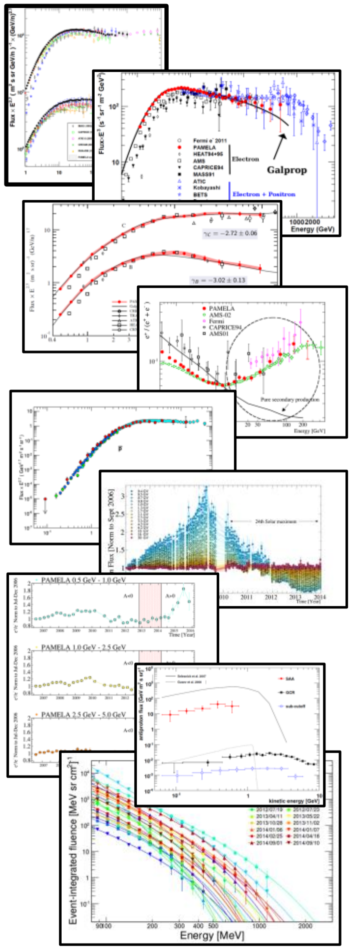
(MDR$_{max}$~1200 GV)




$$\frac{P_{trk}}{E_{cal}} \xrightarrow{sys} \frac{1}{E_{cal}(1+\varepsilon_{sys})\cdot|\eta_{trk}+\Delta\eta_{sys}|}$$



# Ten years of PAMELA data



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


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## Ten years of PAMELA in space


Authors: *PAMELA Collaboration - O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, C. De Santis, V. Di Felice, A. M. Galper, A. V. Karelin, S. V. Koldashov, S. Koldobskiy, S. Y. Krutkov, A. N. Kvashnin, A. Leonov, V. Malakhov, L. Marcelli, M. Martucci, A. G. Mayorov, W. Menn, M. Mergè, V. V. Mikhailov, E. Mocchiutti, A. Monaco, R. Munini, N. Mori, G. Osteria, B. Panico, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. Simon, R. Sparvoli, P. Spillantini, Y. I. Stozhkov, A. Vacchi, E. Vannuccini, G. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa*



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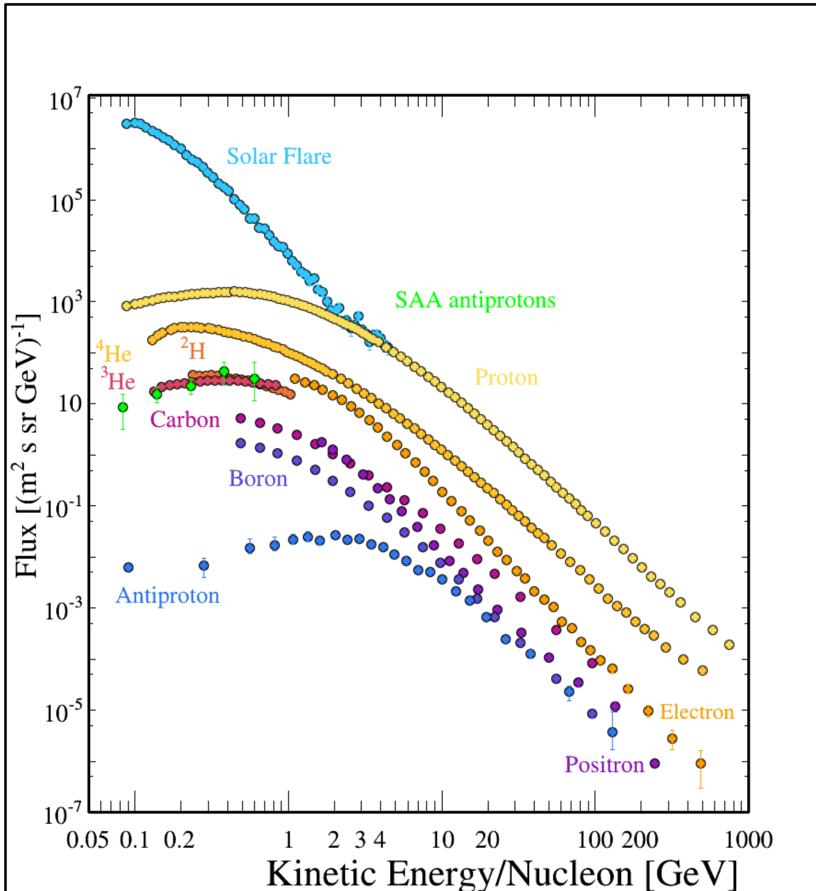
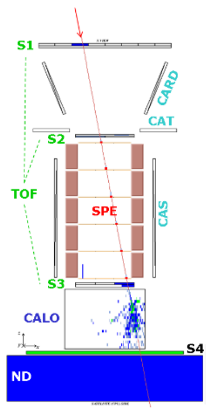
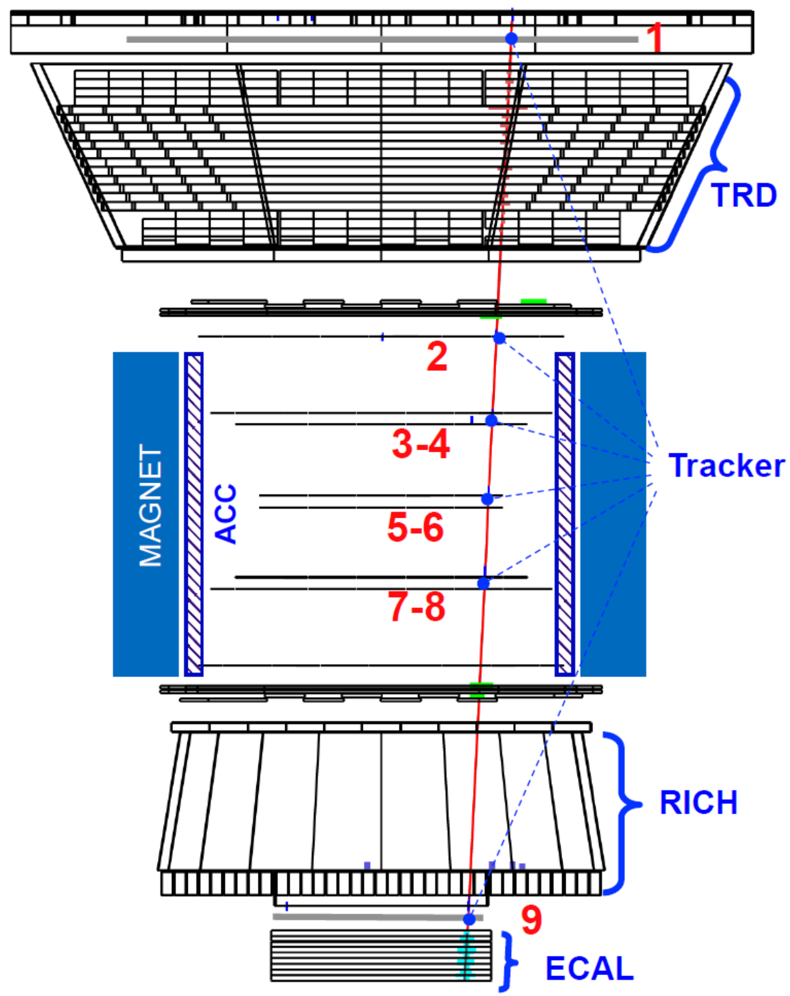


# PAMELA & AMS-02

2006-2016
GF 21.5 cm²sr
MDR ~1.2 TV



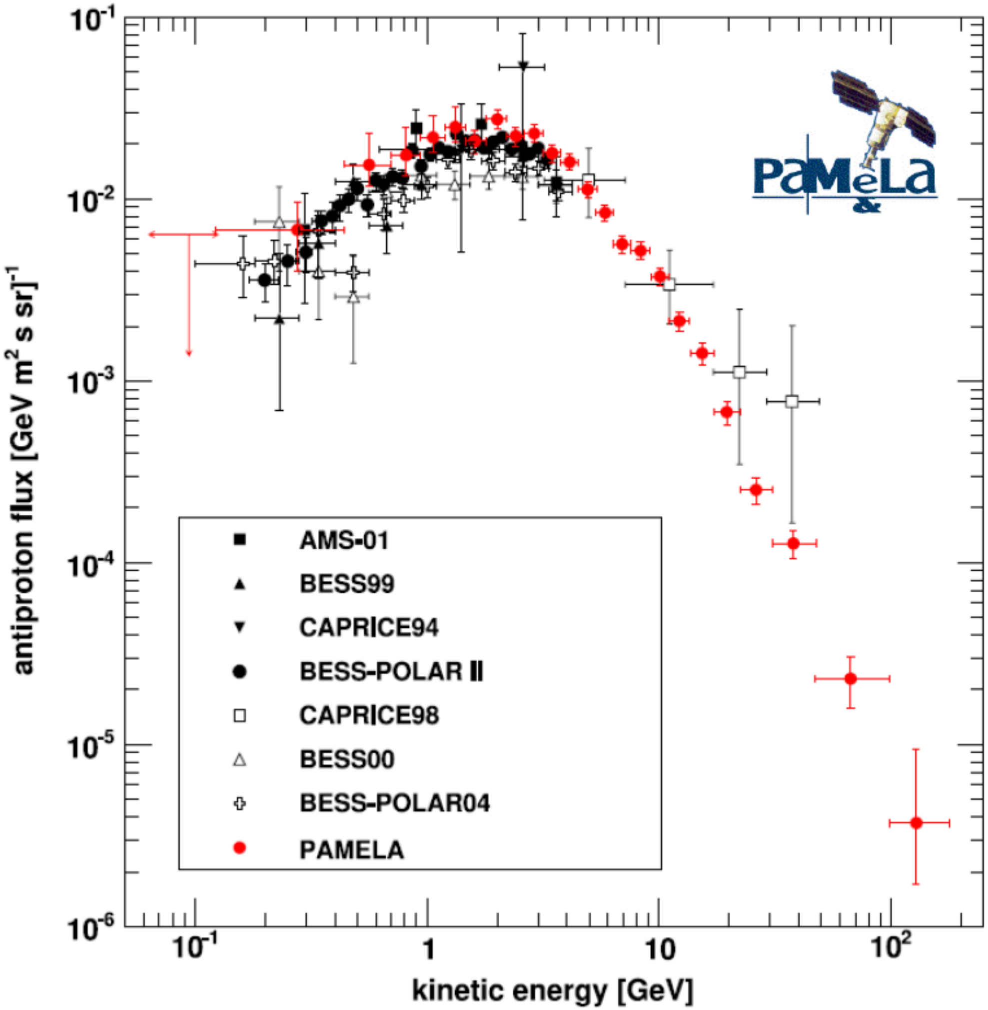




2011
GF 0.5 m²sr
MDR ~ 2 TV

# Antiparticles &co.

- Antiproton abundance
- Positron & electron abundance, upper limity on anysotropy
- Upper limits on Anti-Helium and SQM

# Antiprotons

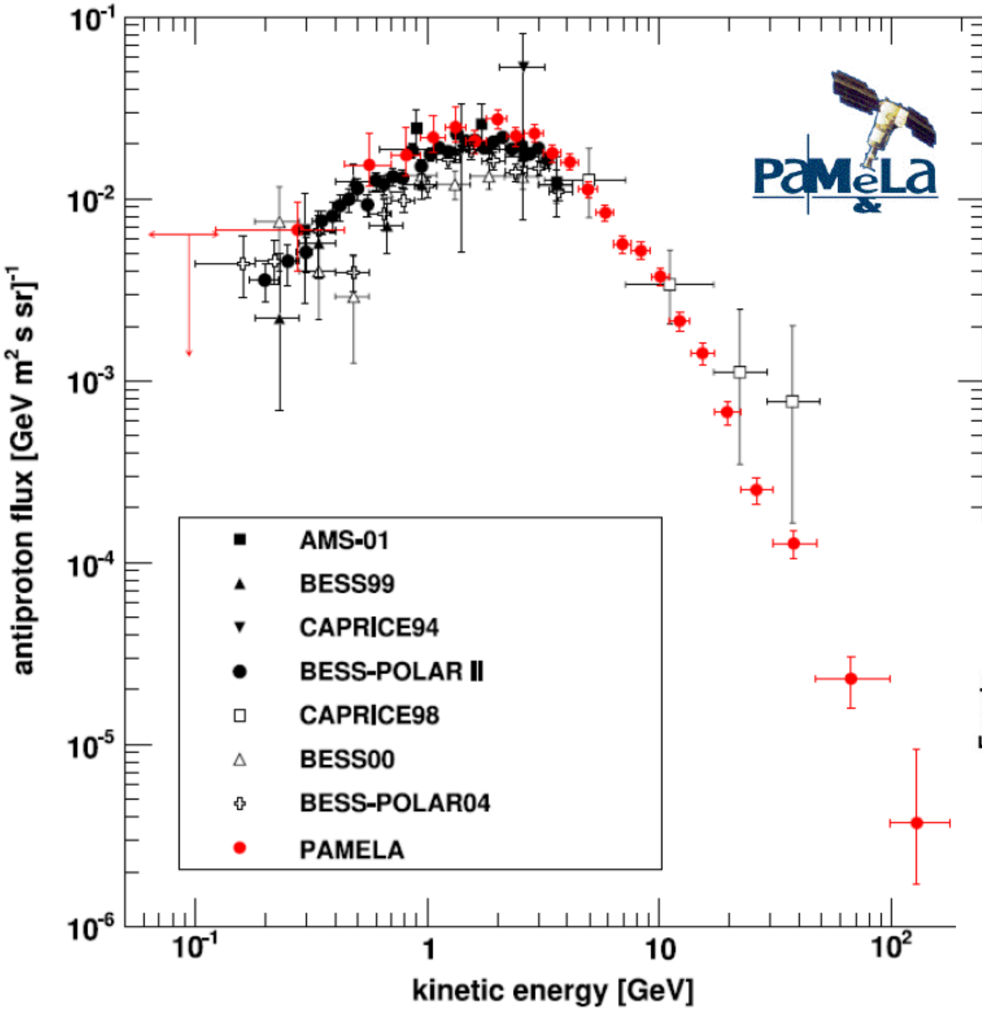



Adriani et al. - PRL 102 (2009) 051101
Adriani et al. - PRL 105 (2010) 121101
Adriani et al. - PR 544 (2014) 323

First measurement extending up to 200 GV

Larget energy range covered up to then

# Antiprotons

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First measurement extending up to 200 GV

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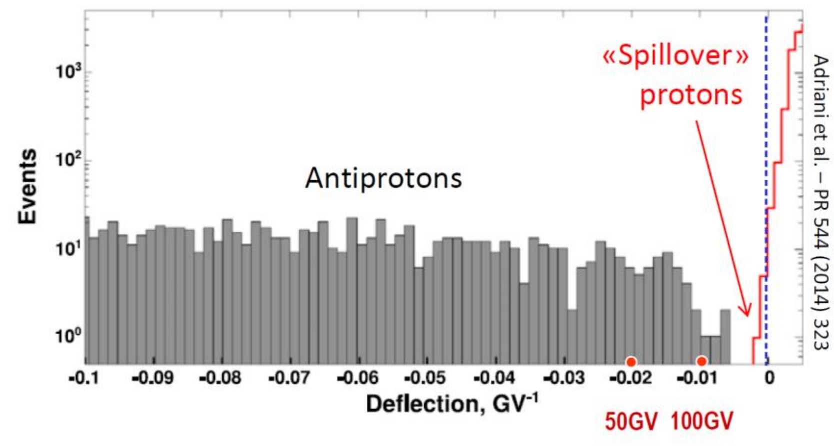
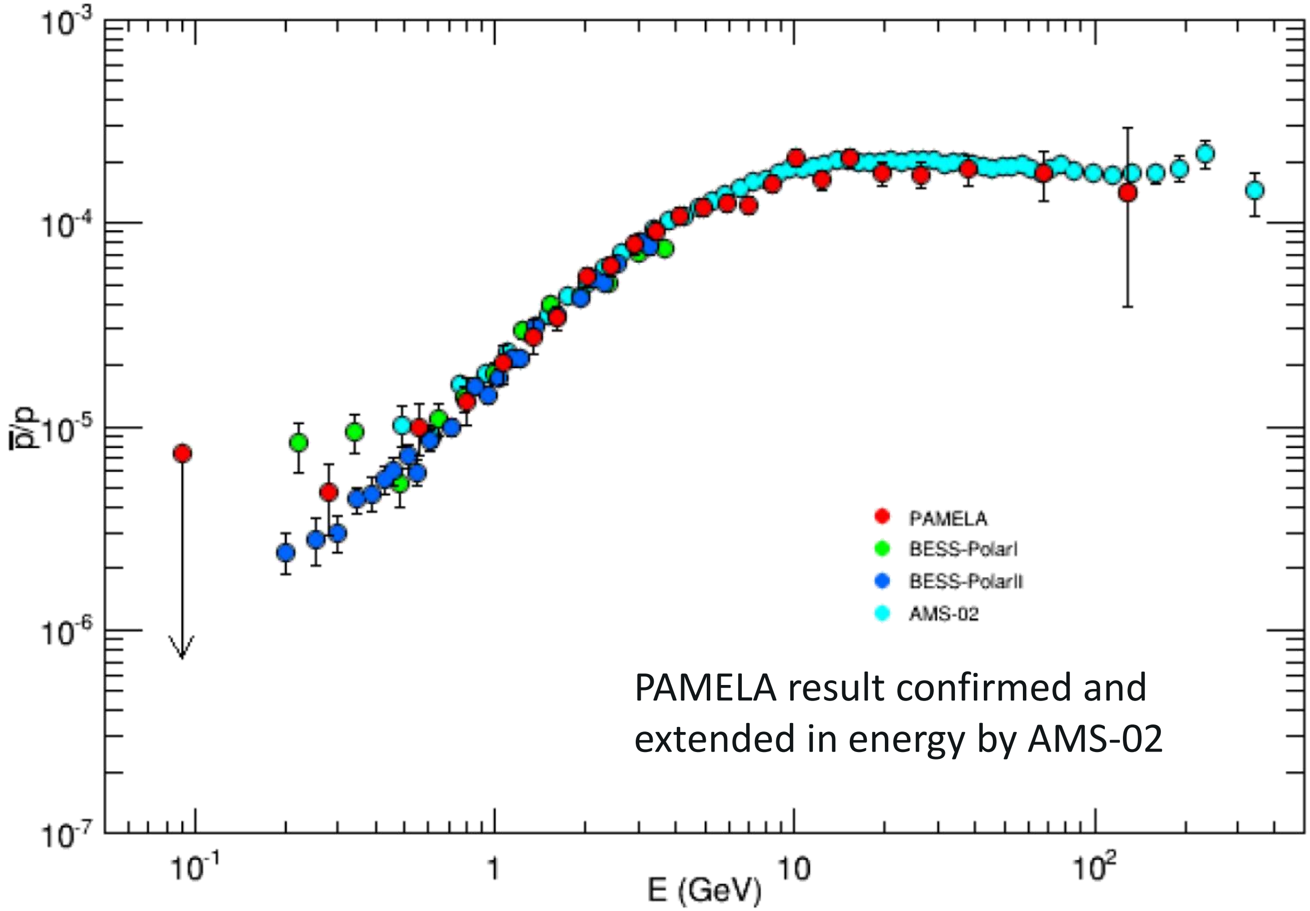


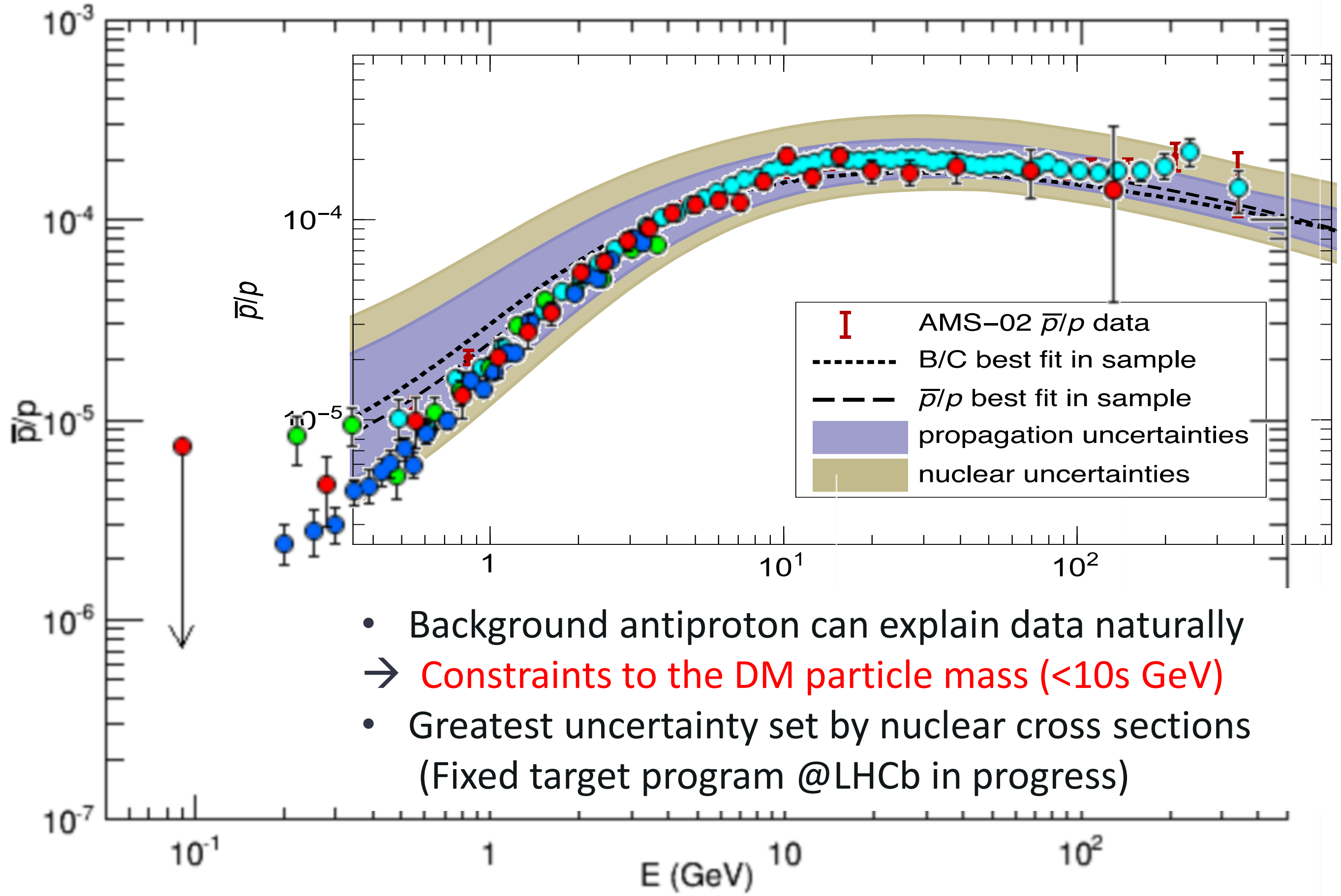

Selected particles with h-like pattern in the calorimeter

# Antiprotons




Adriani et al., Riv. N.Cim., 10, 473-522, 2017

# Antiprotons




Kappl, Reinert, Winkler JCAP 2015

Adriani et al., Riv. N.Cim., 10, 473-522, 2017

- Background antiproton can explain data naturally

→ Constraints to the DM particle mass (<10s GeV)

- Greatest uncertainty set by nuclear cross sections (Fixed target program @LHCb in progress)

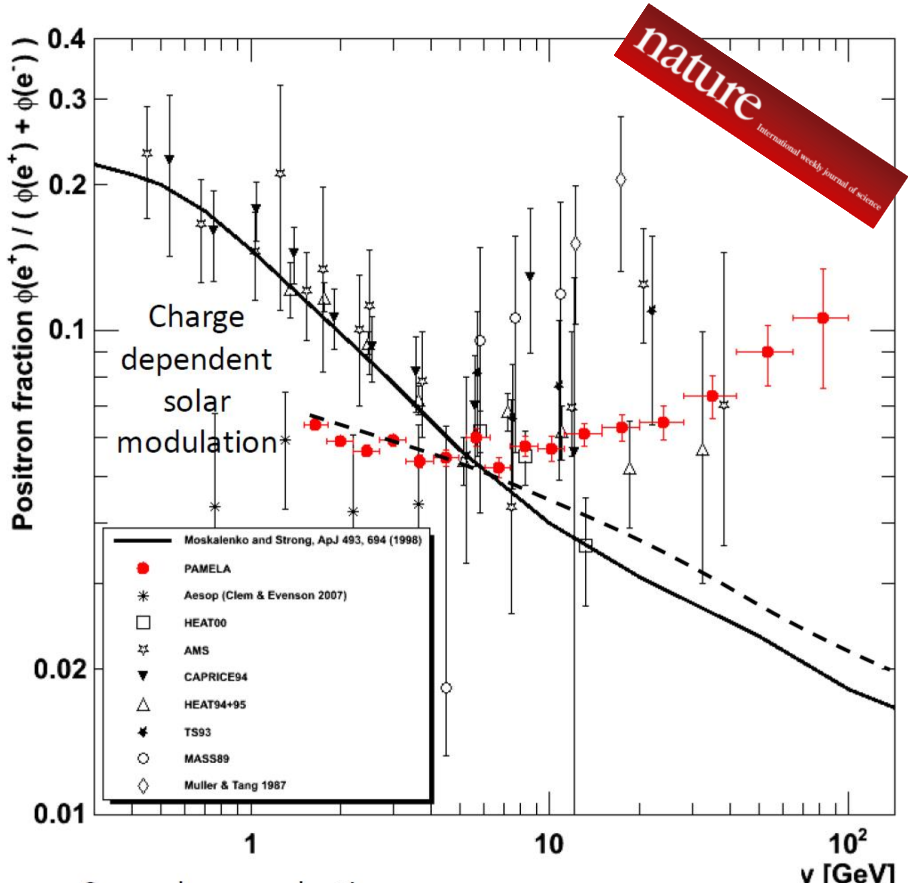
# The positron excess

@high energy:

- First measurement extending up to 200 GV
- Clear evidence of increasing positron fraction above 10 GeV with respect to pure secondary production

@low-energy

- Deviation from previous measurements → charge-dependent solar modulation



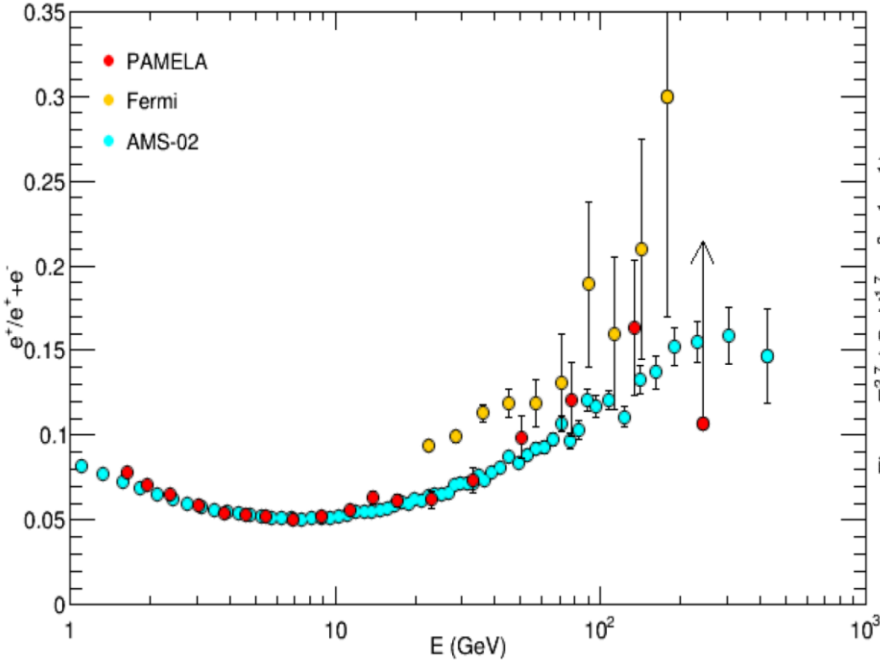

Secondary production:

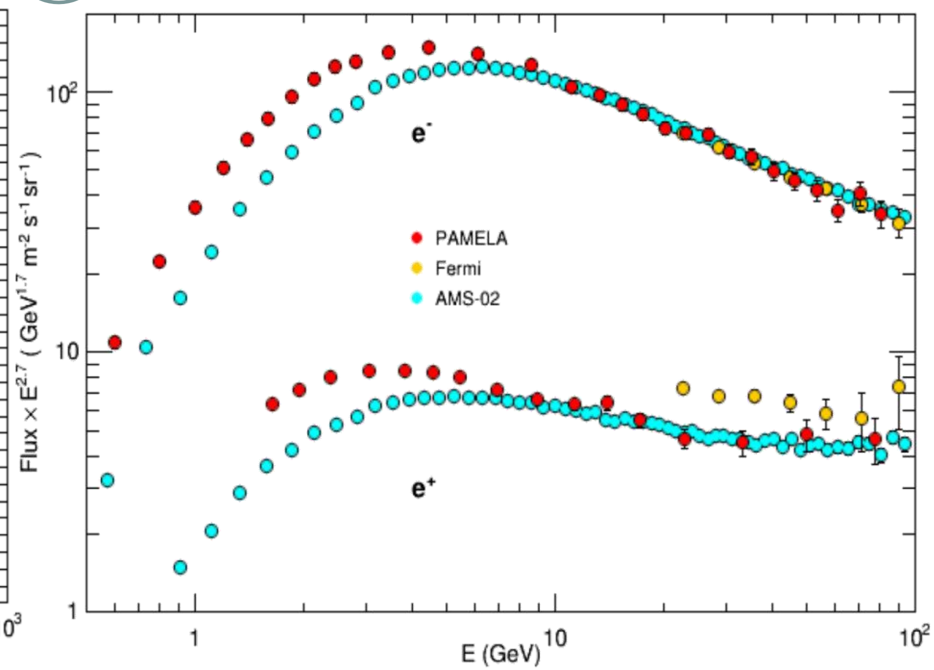
------ Moskalenko & Strong 1998 (GALPROP code)

- - - - Delahaye et al. 2010

Adriani et al, Nature 458 (2009) 607;
Adriani et al. Astropart. Phys. 34 (2010) 1

# CR leptons

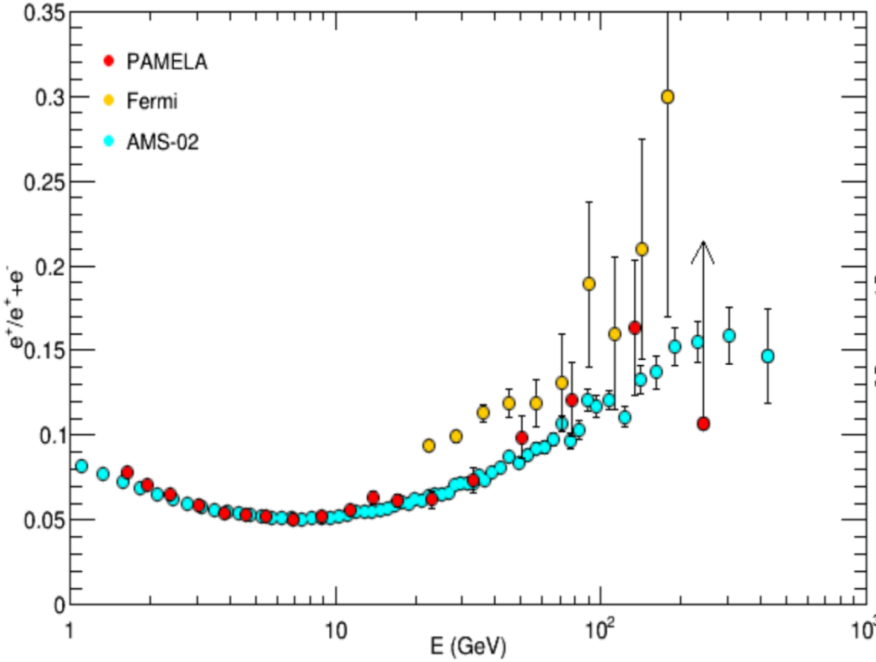


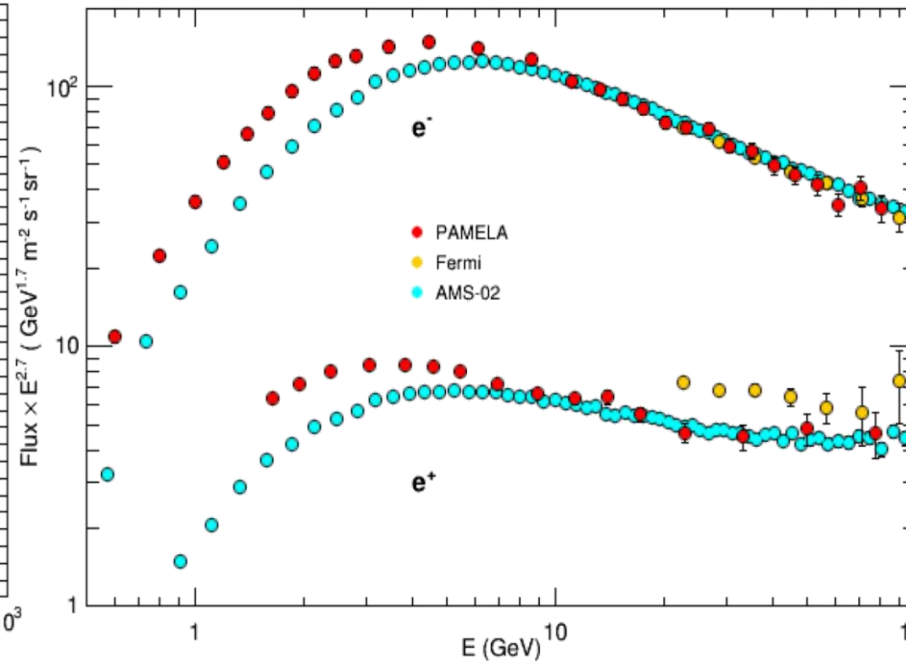




Adriani et al., Riv. N.Cim., 10, 473-522, 2017

PAMELA result confirmed by AMS-02 and extended in energy.
(Indication for a decreasing trend above 300 GV…)

# CR leptons




Adriani et al., Riv. N.Cim., 10, 473-522, 2017

Measurement of individual spectra confirms the presence of an additional positron component

Possible interpretations:

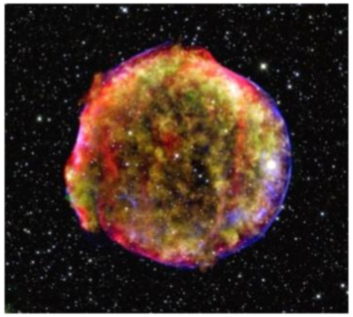
**Dark matter** → lepton vs hadron yield must be consistent with $\bar{p}$ observations

**Astrophysical processes** → known processes (eg. pulsars, dense SNR) , but large uncertainties on environmental parameters

**Propagation** → diffusion coefficient with weird energy dependency or other subtleties, disfavored

# The nuclear component of GCRs

- H&He primary nuclei
- Secondary nuclei from GCR interactions with the ISM:
  - B-to-C abundance
  - H and He isotopes
  - Li, Be, B isotopes

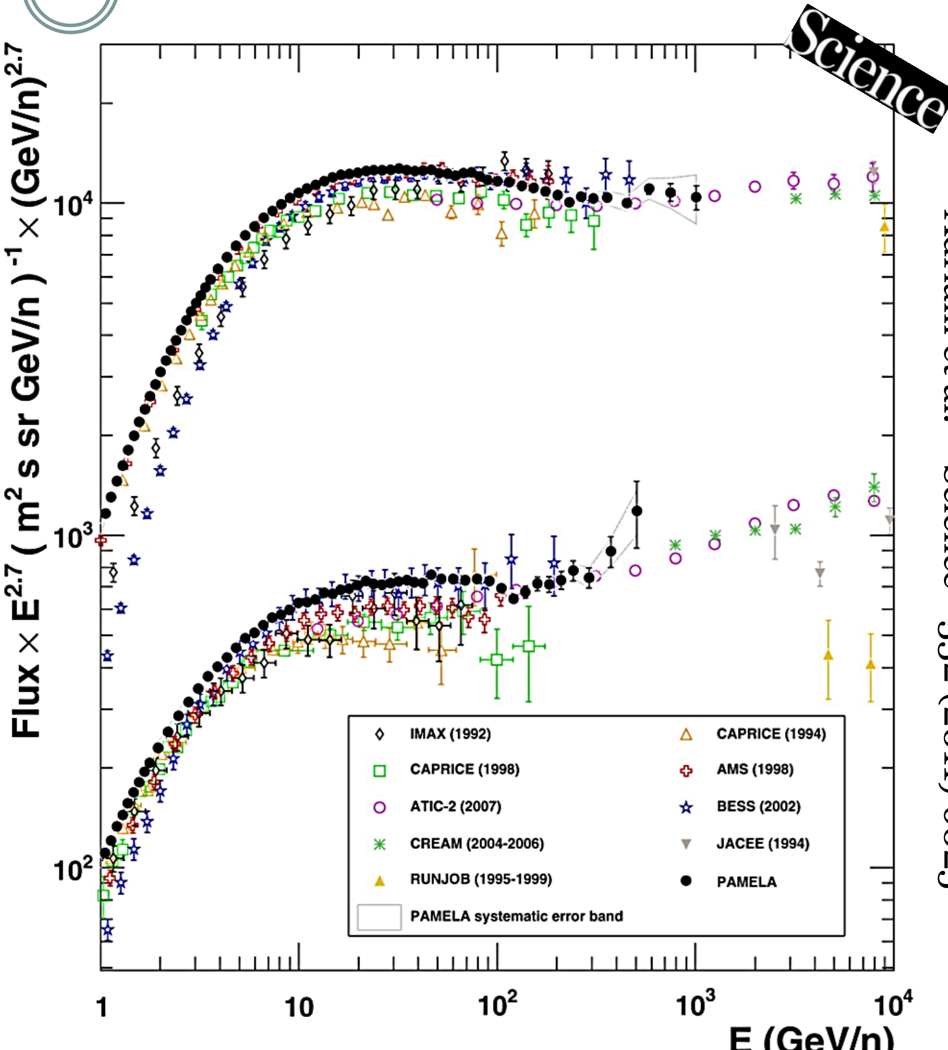


# H&He absolute fluxes

First high-statistics and high-precision measurement over three decades in energy

@ Low energy → minimum solar activity ($\phi$ = 450÷550 GV)

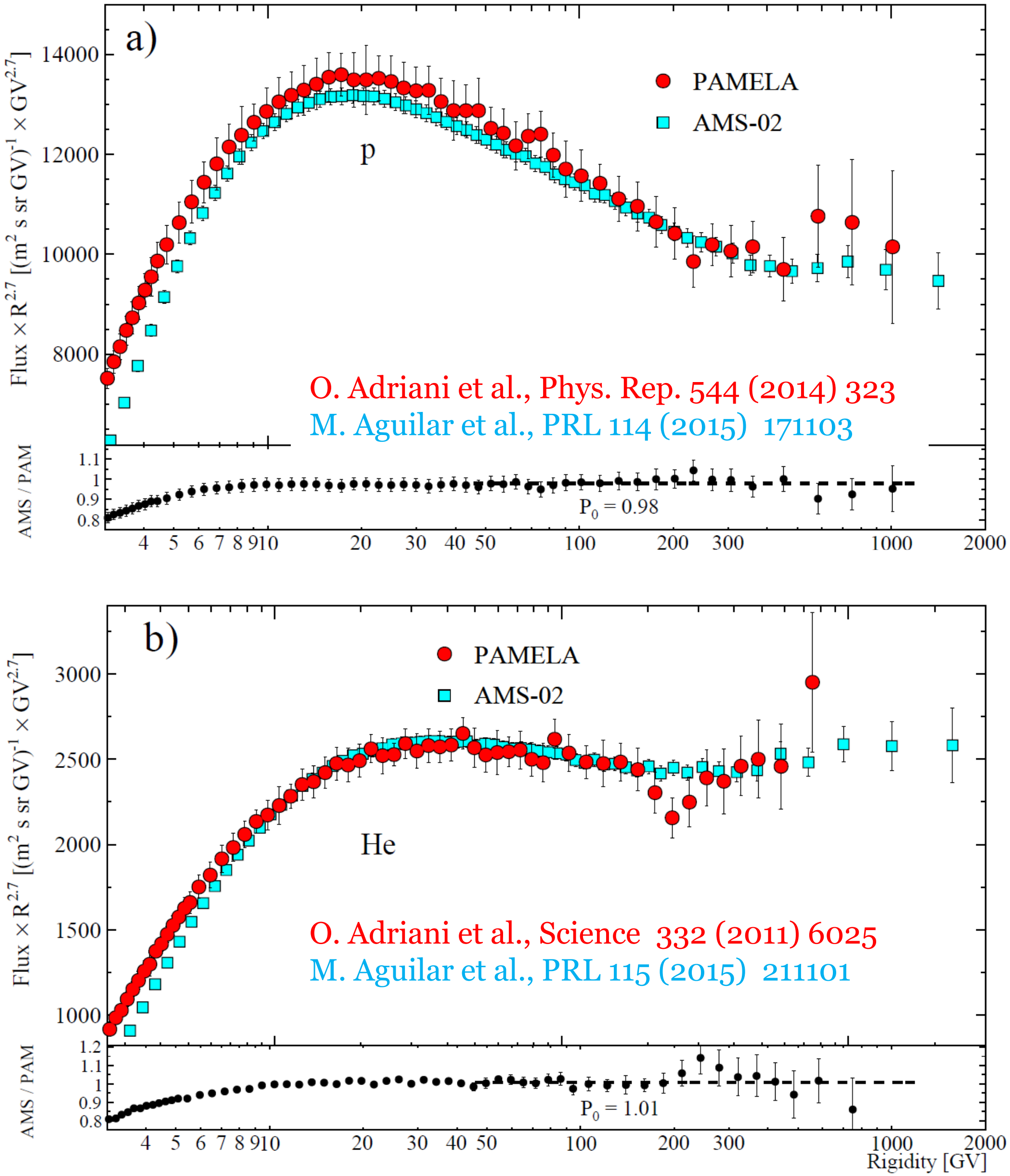
@ High-energy → Significant hardening above 230 GV for both H and He.



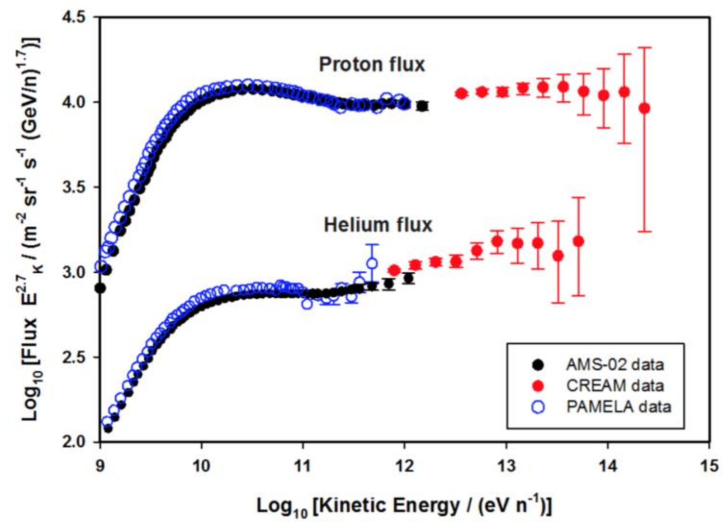

Adriani et al. - Science - 332 (2011) 6025

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

# H & He

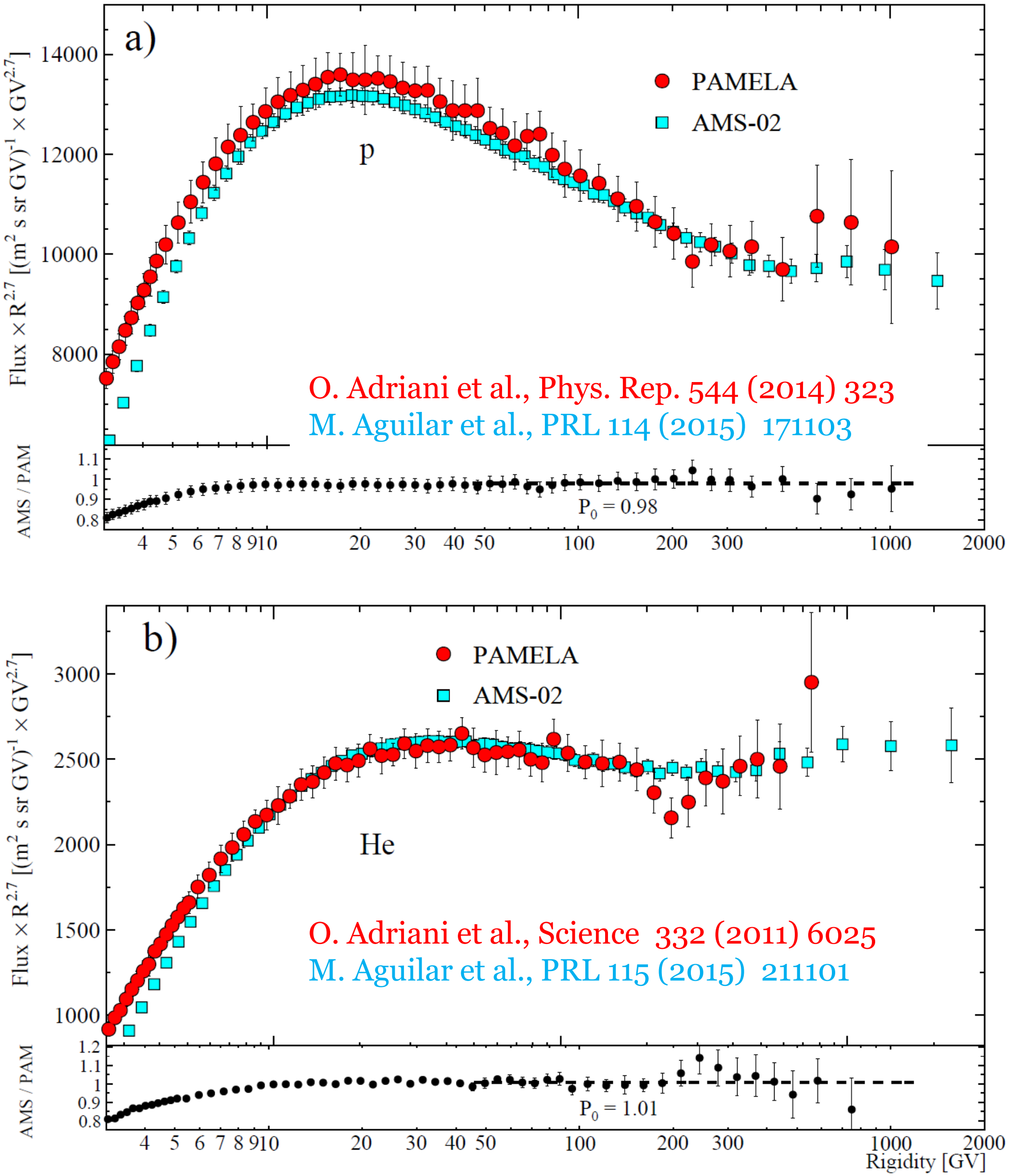



- Excellent agreement between PAMELA and AMS-02 results, within 2%
- Significant hardening above 230 GV for both H and He.
- Consistent with high-energy calorimetric measurements



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

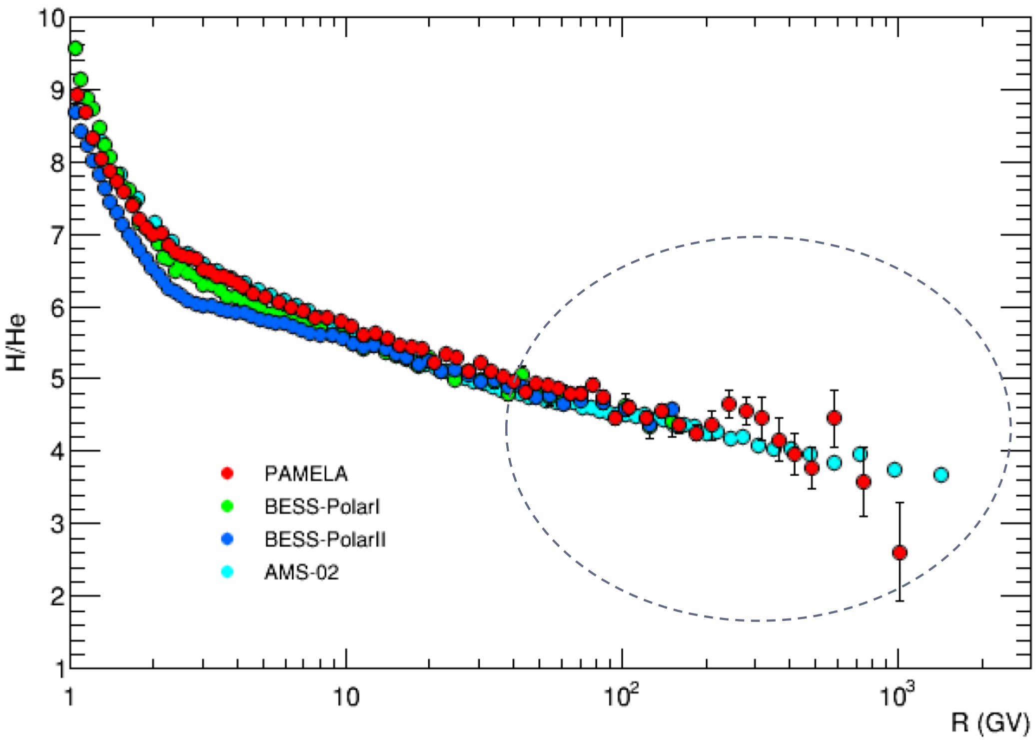
# H & He




- Excellent agreement between PAMELA and AMS-02 results, within 2%
- Significant hardening above 230 GV for both H and He.
- Consistent with high-energy calorimetric measurements

Possible interpretations:
- Source effect (multi-population, spectral features at injection)
- Propagation effect

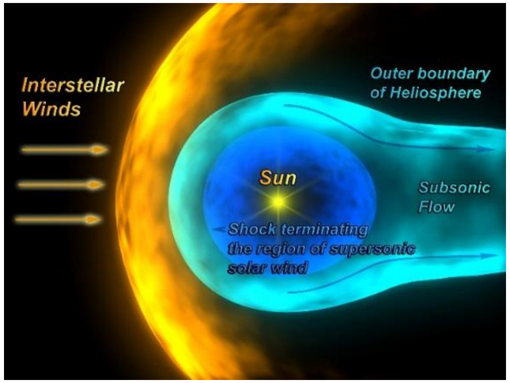
# H-to-He ratio

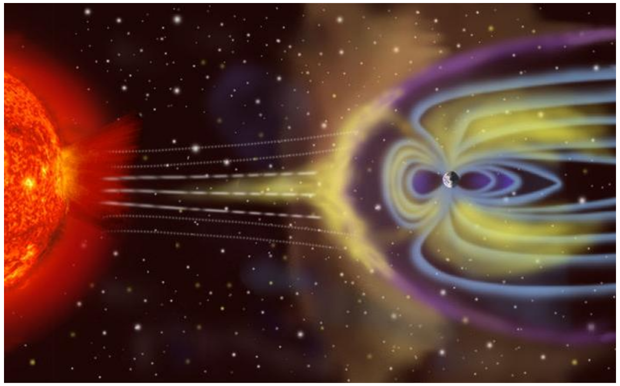


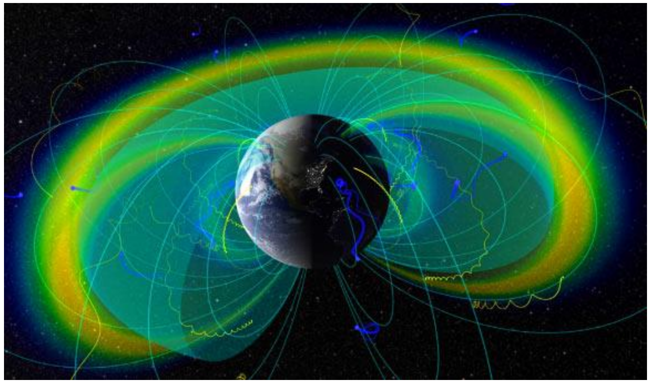

Systematic uncertainties partly cancel out at high energy

- Propagation effects small above ~100GV
  → information about source spectra
- Different slope for H and He
- No indication of spectral features above 10 GV

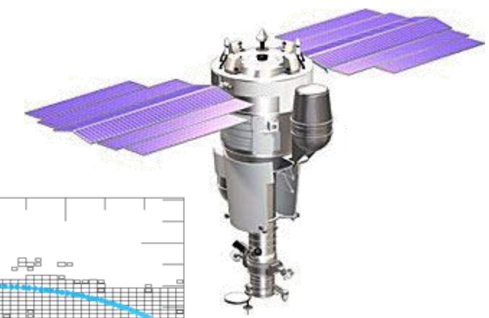
# Heliosphere end Magnetosphere



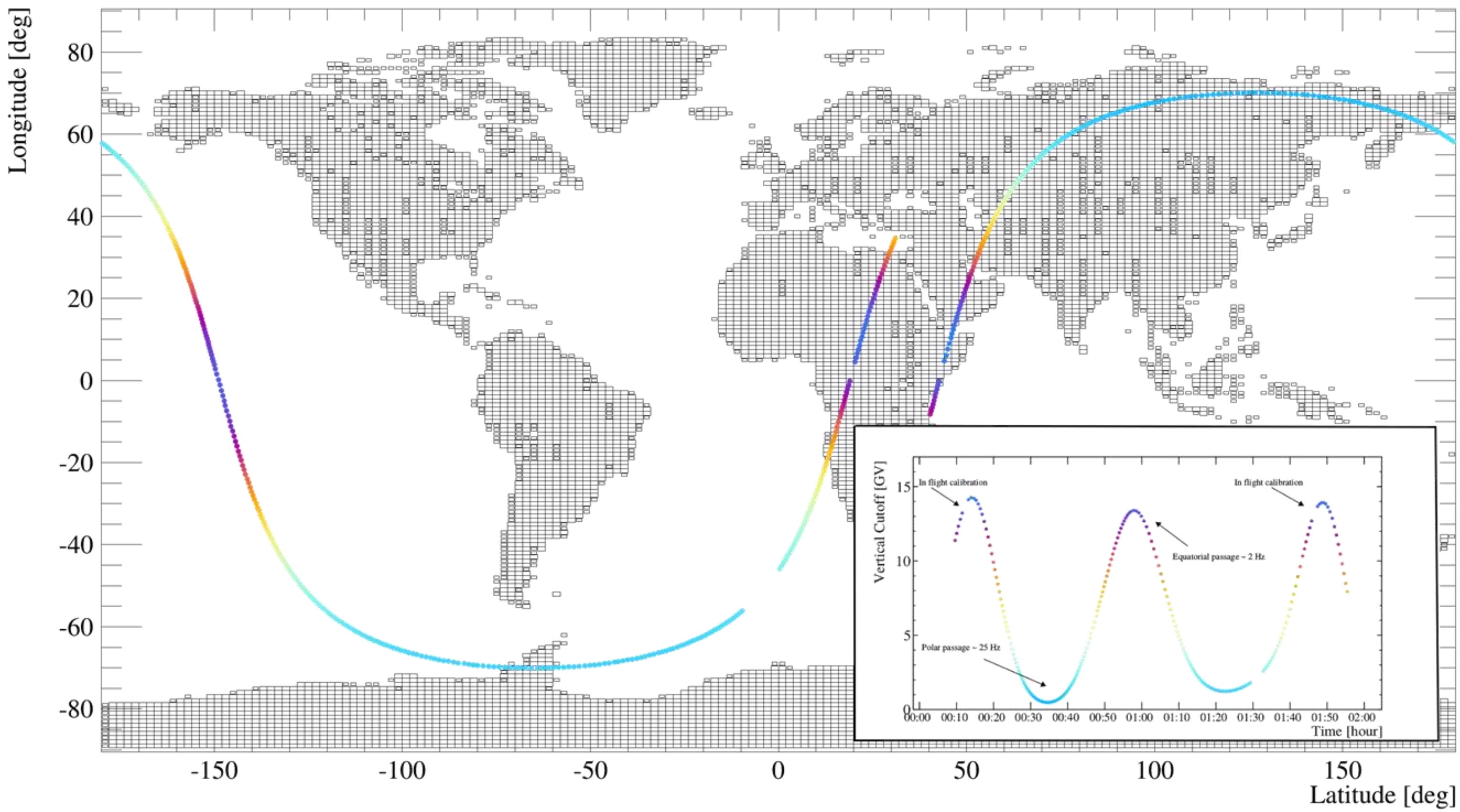





# Resurs-DK1 orbit

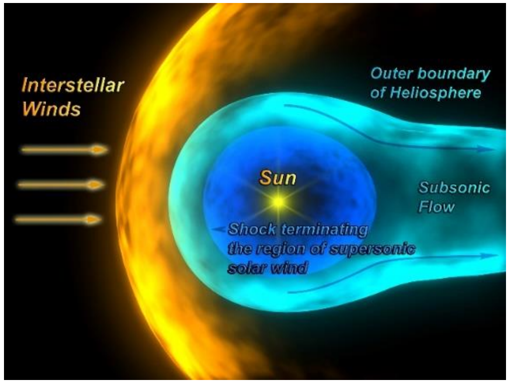


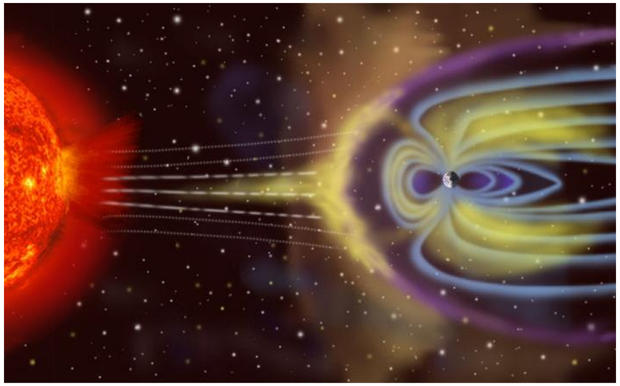
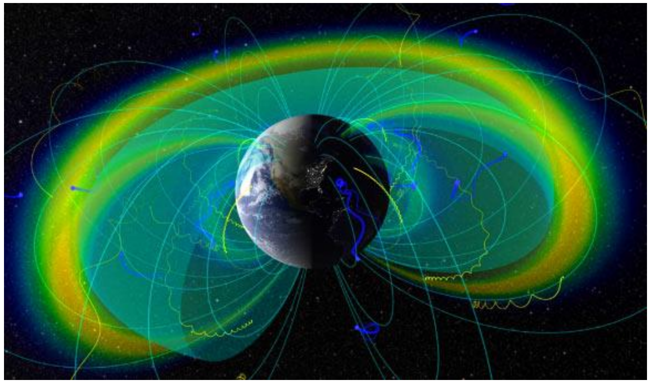
Quasi-polar elliptical orbit ( circular from 2010)
Inclination ~ 70°
Altitude ~ 300÷600km



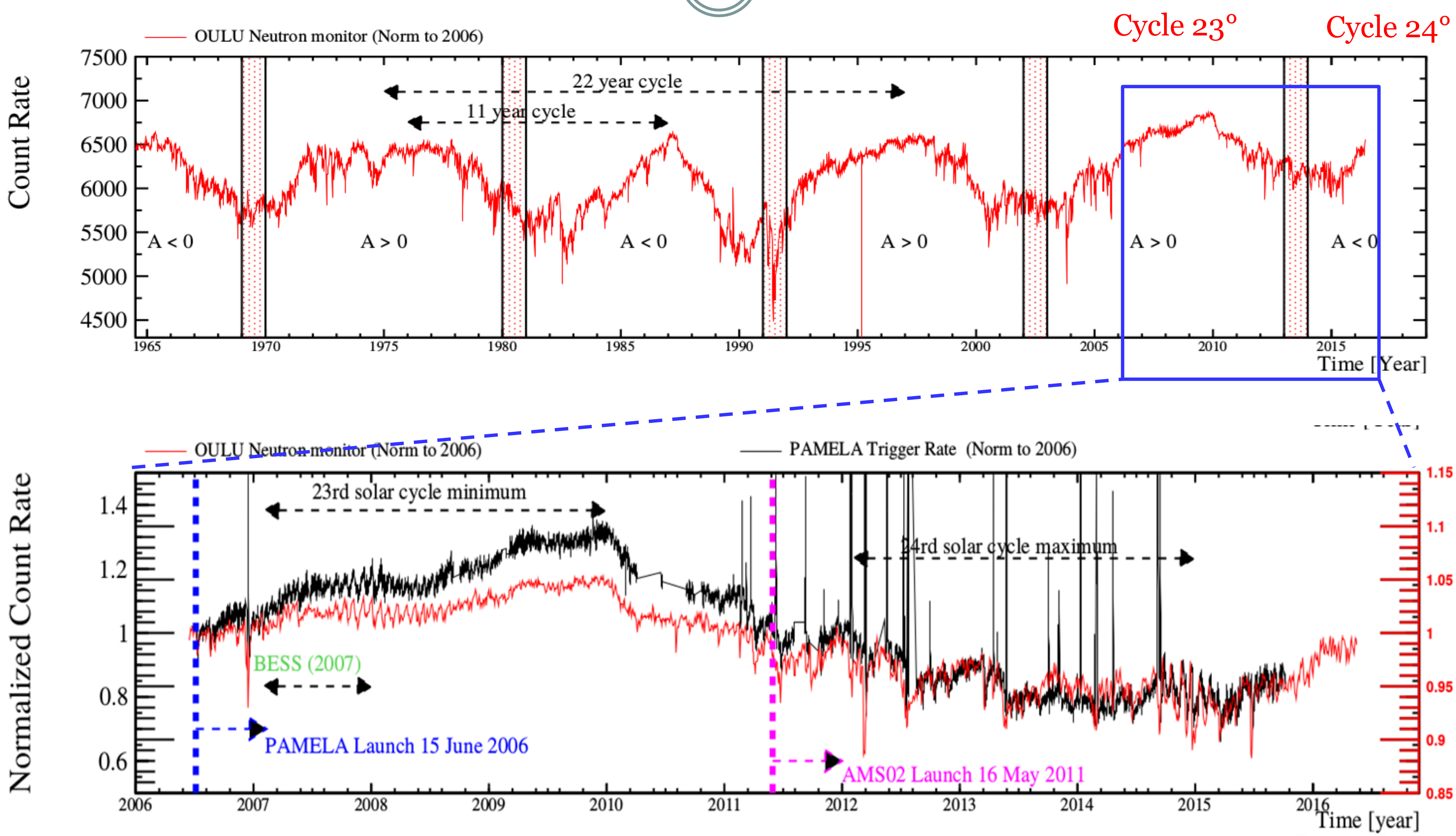
# Heliosphere end Magnetosphere

- Long-term CR-flux variations → solar modulation of various CR components
- Solar-particle events (SEPs)
- Short- and mid-term CR-flux variations (semi-periodic & transient phenomena)
- Geomagnetically trapped and re-entrant albedo particles

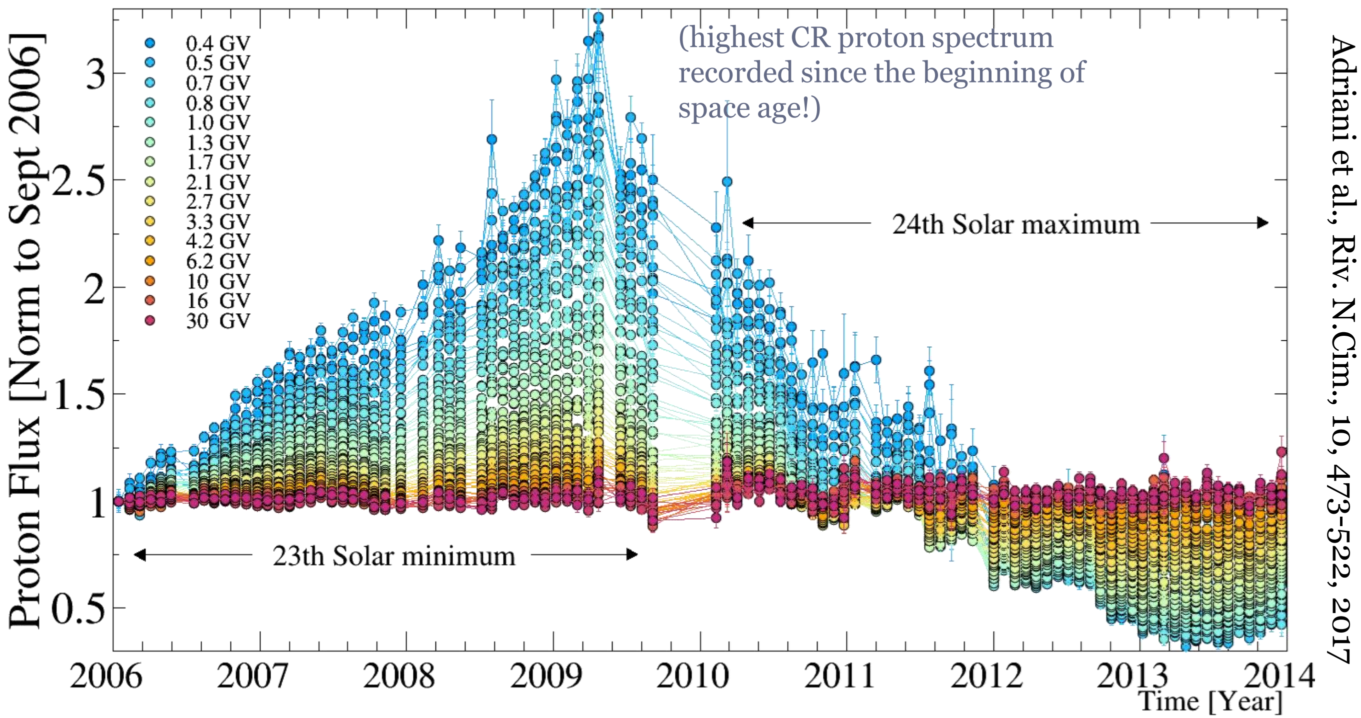


# PAMELA observations during 23° and 24° solar cycles



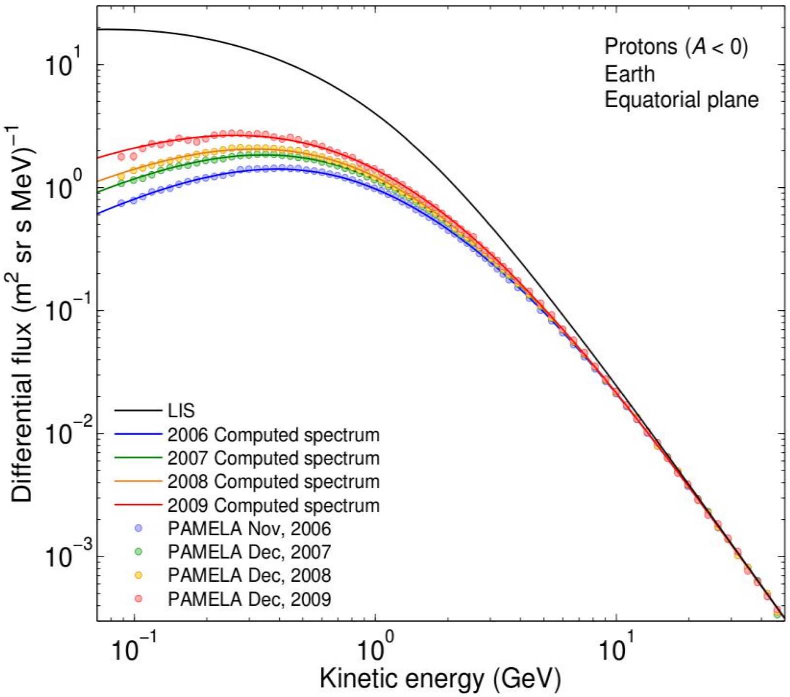
# Solar modulation



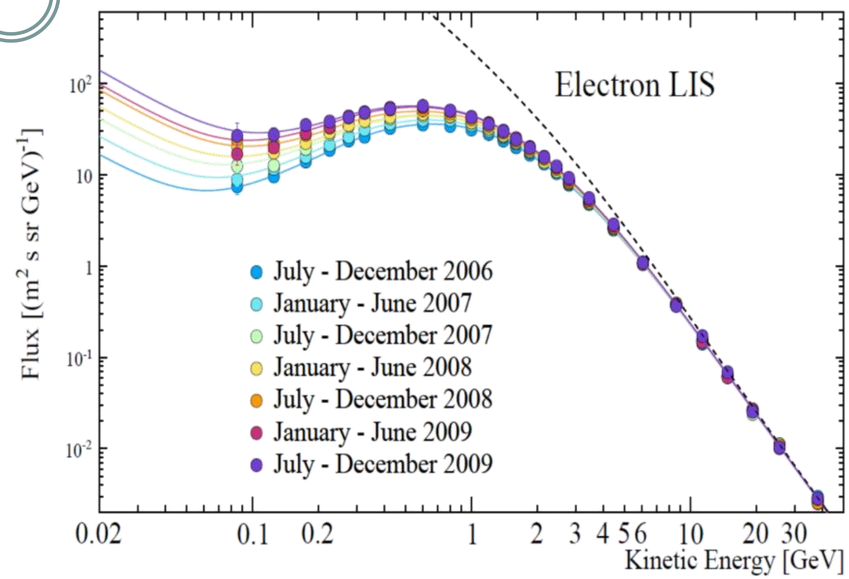

- CRs at Earth strongly affected by Heliosphere below ~30 GV

- Heliosphere → Ideal environment to test theory for propagation of charged particles under conditions which well approximate cosmic conditions

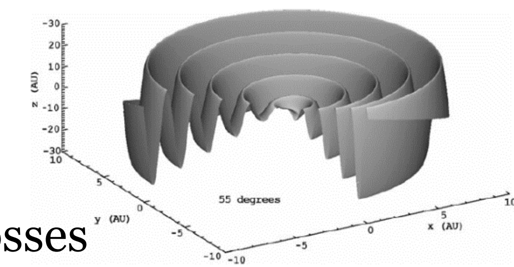
# Heliospheric propagation modeling




Potgieter et al. Solar Phys. 289 (2014) 391
Adriani et al. ApJ 765 (2013) 91



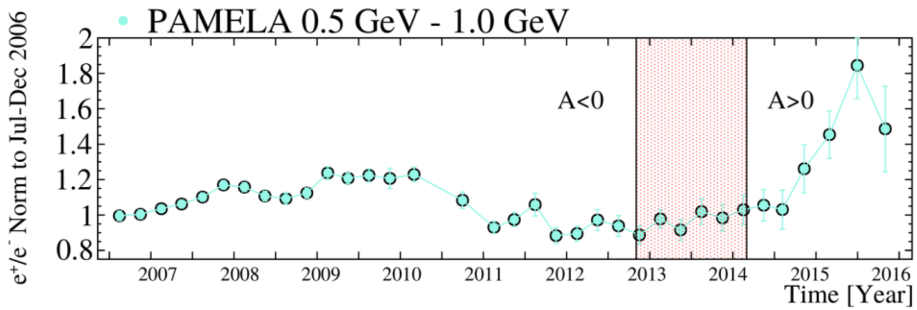

Adriani et al. ApJ 810(2015) 142
Potgieter et al. ApJ 810 (2015) 141

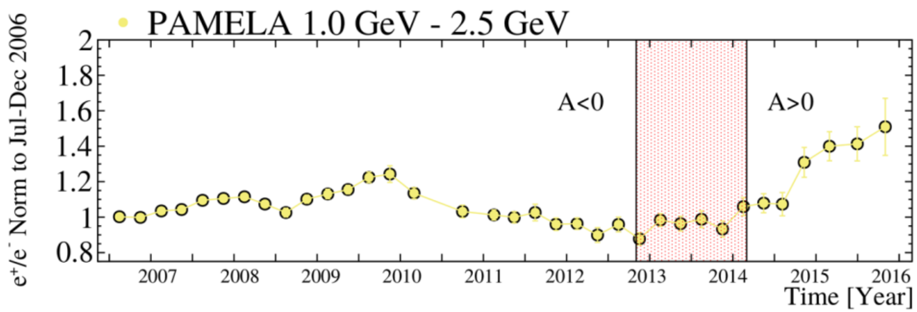


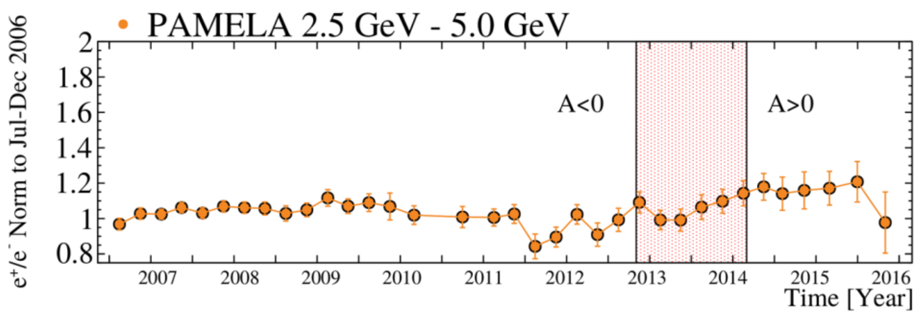

- 3D heliopheric model
- Transport processes: convection, diffusion, drift, adiabatic losses
- Stationary approximation during minimum solar activity

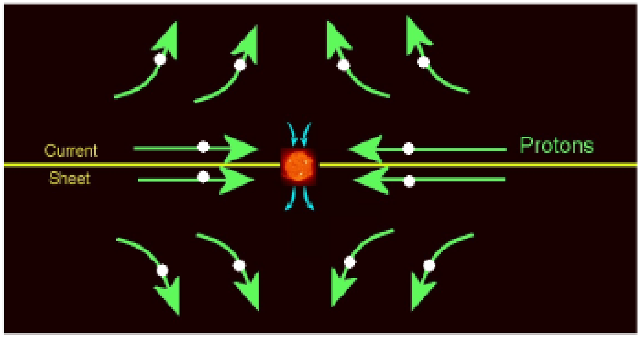
PAMELA multi-species low-energy time-dependent spectra used to constrain model parameters

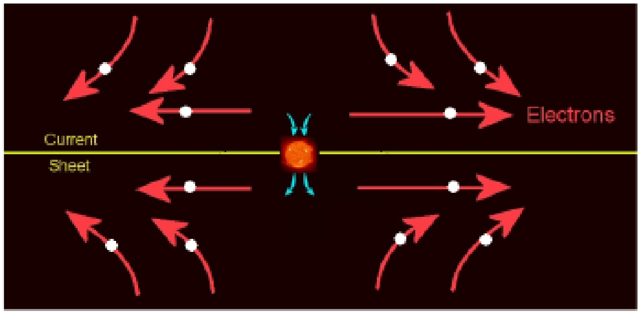
# Charge-dependent solar modulation



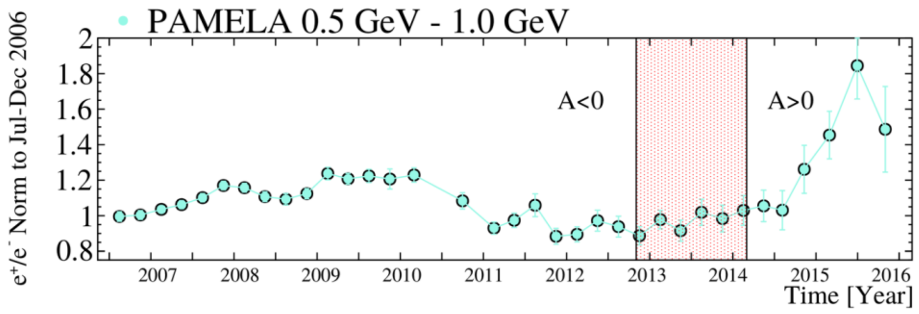



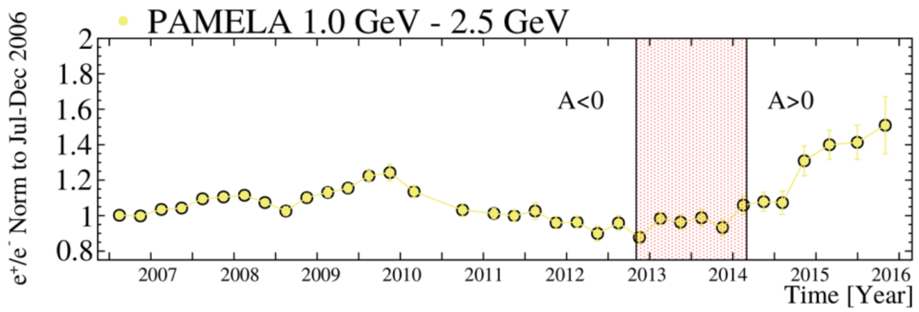



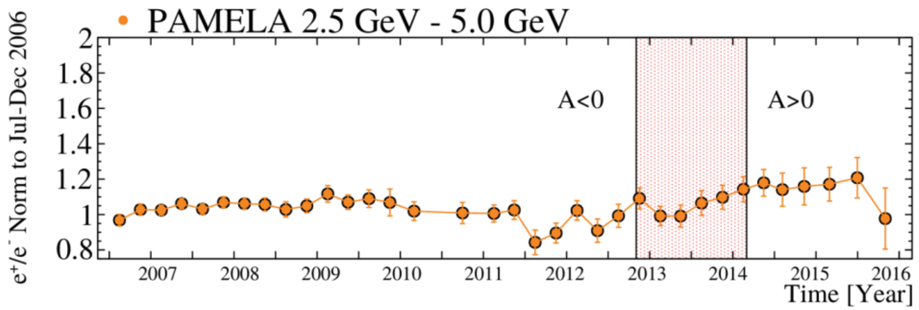



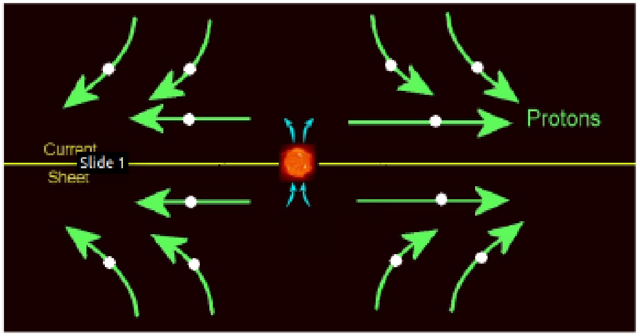

charge sign dependence introduced by drift motions experienced by the GCRs during their propagation through the heliosphere

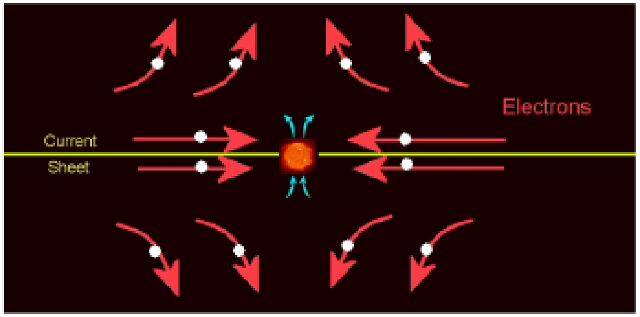
# Charge-dependent solar modulation



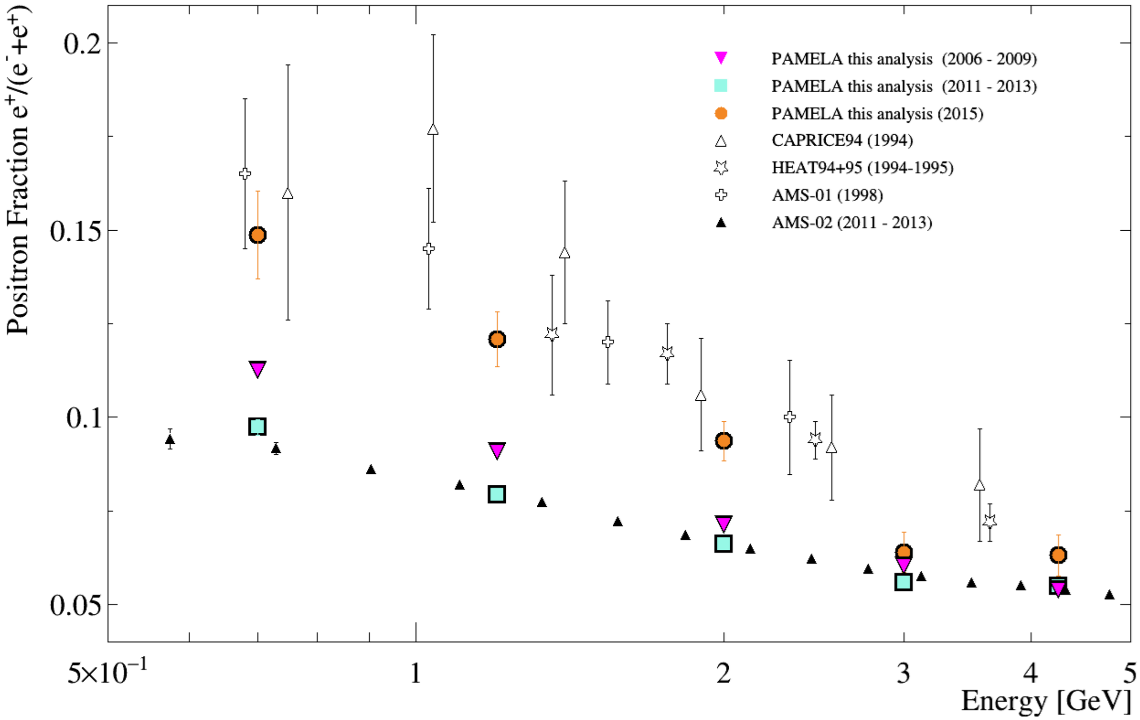



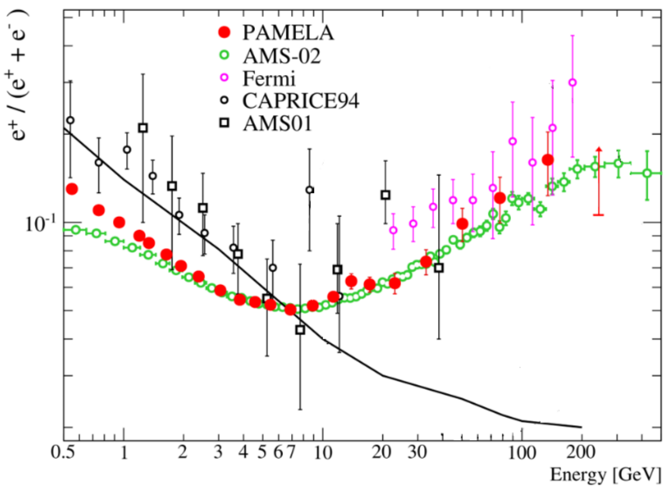




charge sign dependence introduced by drift motions experienced by the GCRs during their propagation through the heliosphere

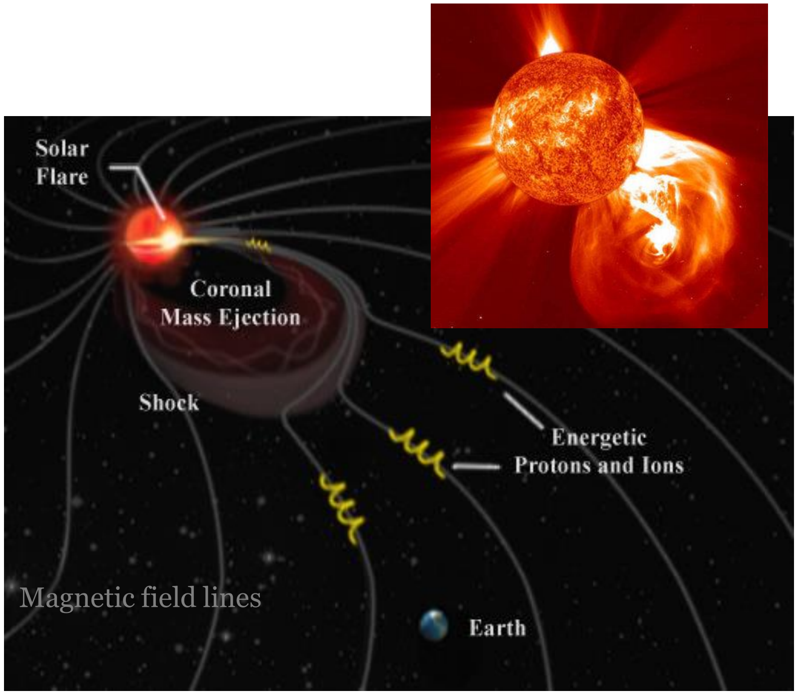
# Positron fraction




Charge-dependent solar-modulation effect accounts for discrepancies among PAMELA, AMS-02 and data collected during previous solar cycle

# Solar energetic particles (SEPs)



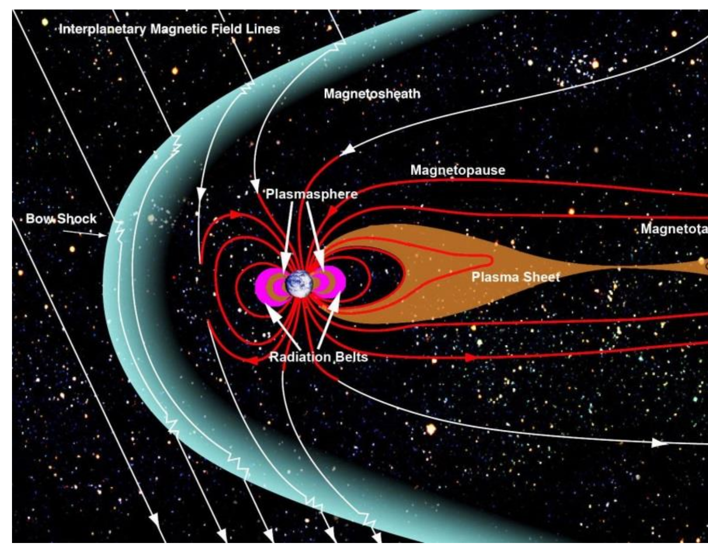

Sun can accelerate particles up to relativistic energies

- 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)
- …



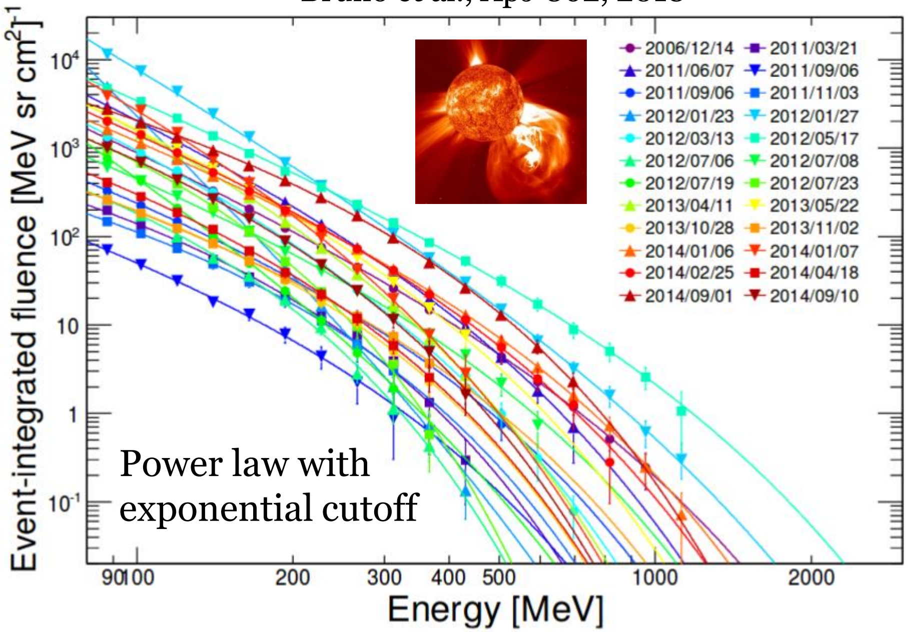

SEP observation on Earth:

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

# SEPs detected by PAMELA

| | 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 |

Bruno et al., ApJ 862, 2018



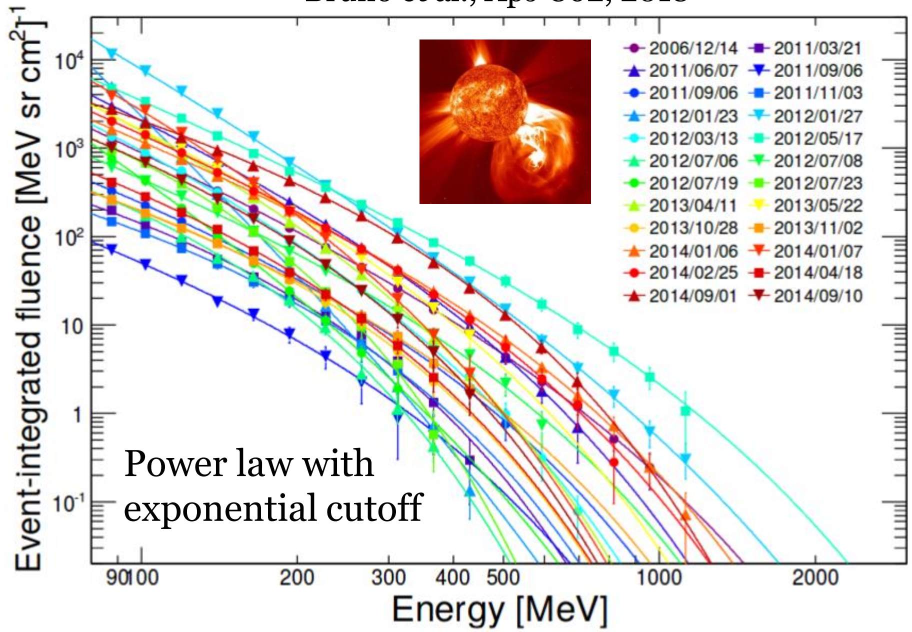

- PAMELA bridges the gap between low-energy in-situ spacecrafts and ground-based NM network observations (GLEs)
- 26 SEPs observed within 2006-2014

# SEPs detected by PAMELA

| | 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 0 | | | | | | | | | 06, 22:30 |
| 7 | 2011 1 | | | | | | | | | - - |
| 8 | 2012 0 | | | | | | | | | 23, 04:00 |
| 9 | 2012 0 | | | | | | | | | 27, 18:30 |
| 10 | 2012 0 | | | | | | | | | 07, 01:00 |
| 11 | 2012 0 | | | | | | | | | 13, 17:35 |
| 12 | 2012 0 | | | | | | | | | 17, 01:40 |
| 13 | 2012 0 | | | | | | | | | 06, 23:10 |
| 14 | 2012 0 | | | | | | | | | 08, 16:35 |
| 15 | 2012 0 | | | | | | | | | 19, 05:30 |
| 16 | 2012 0 | | | | | | | | | 23, 02:30 |
| 17 | 2013 0 | | | | | | | | | 11, 07:10 |
| 18 | 2013 0 | | | | | | | | | 22, 13:10 |
| 19 | 2013 1 | | | | | | | | | 28, 15:24 |
| 20 | 2013 1 | | | | | | | | | - - |
| 21 | 2014 0 | | | | | | | | | 06, 07:58 |
| 22 | 2014 0 | | | | | | | | | 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 |

SEP-analysis issues:
- Source identification & classification
  - Association to flares, CMEs…
- GLEs
  - different class of events?
- Spectra evolution
  - Intensity, time profile , spectral signatures…
- Composition
  - p/He, ³He content…
- Magnetospheric effects

Bruno et al., ApJ 862, 2018




- PAMELA bridges the gap between low-energy in-situ spacecrafts and ground-based NM network observations (GLEs)
- 26 SEPs observed within 2006-2014

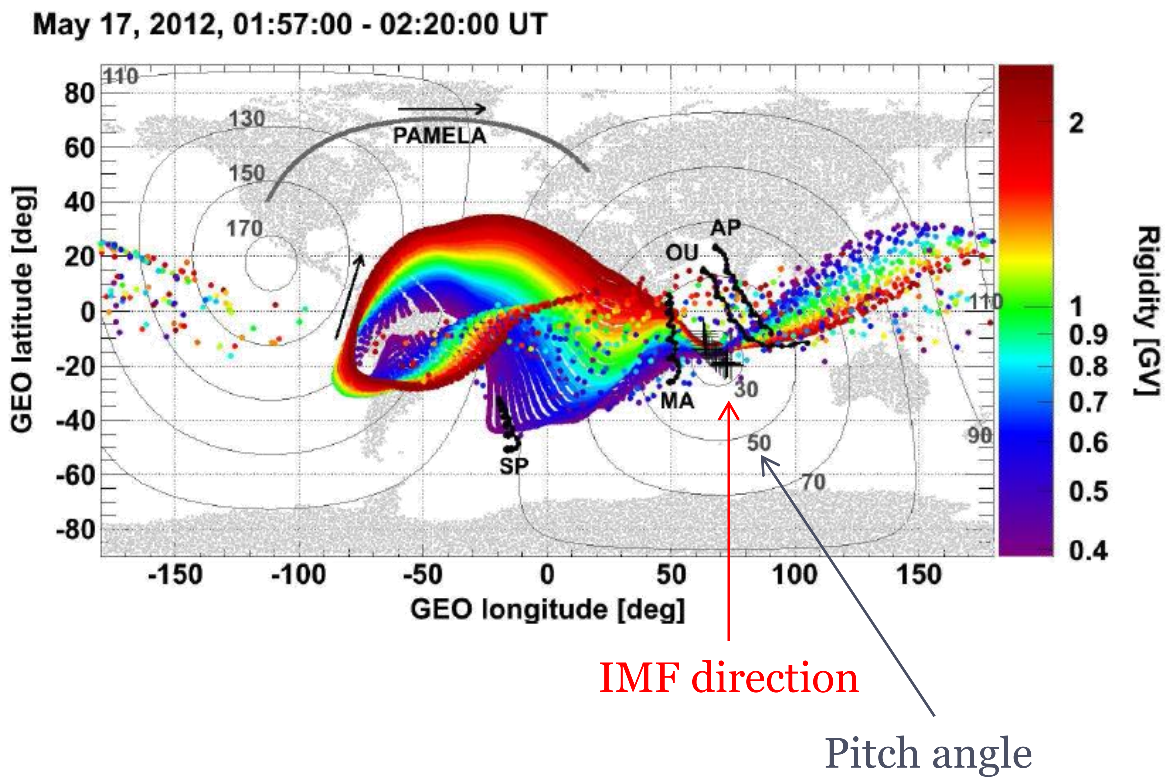
- Spectra consistent with CME-driven shock acceleration (finite escape time)
- No qualitative distinction between SEPs observed as GLEs and those that are not

# May 17°, 2012 SEP event

- First observed GLE of 24° solar cycle
- Earth magnetically connected to the Sun
- Associated to M1.5-class X-ray flare
- Extended emission (>100MeV) seen by Fermi-LAT

Unique possibility to measure pitch angle distribution over broad energy range, to disentangle interplanetary **transport** process

Asymptotic direction during first polar pass after the event onset



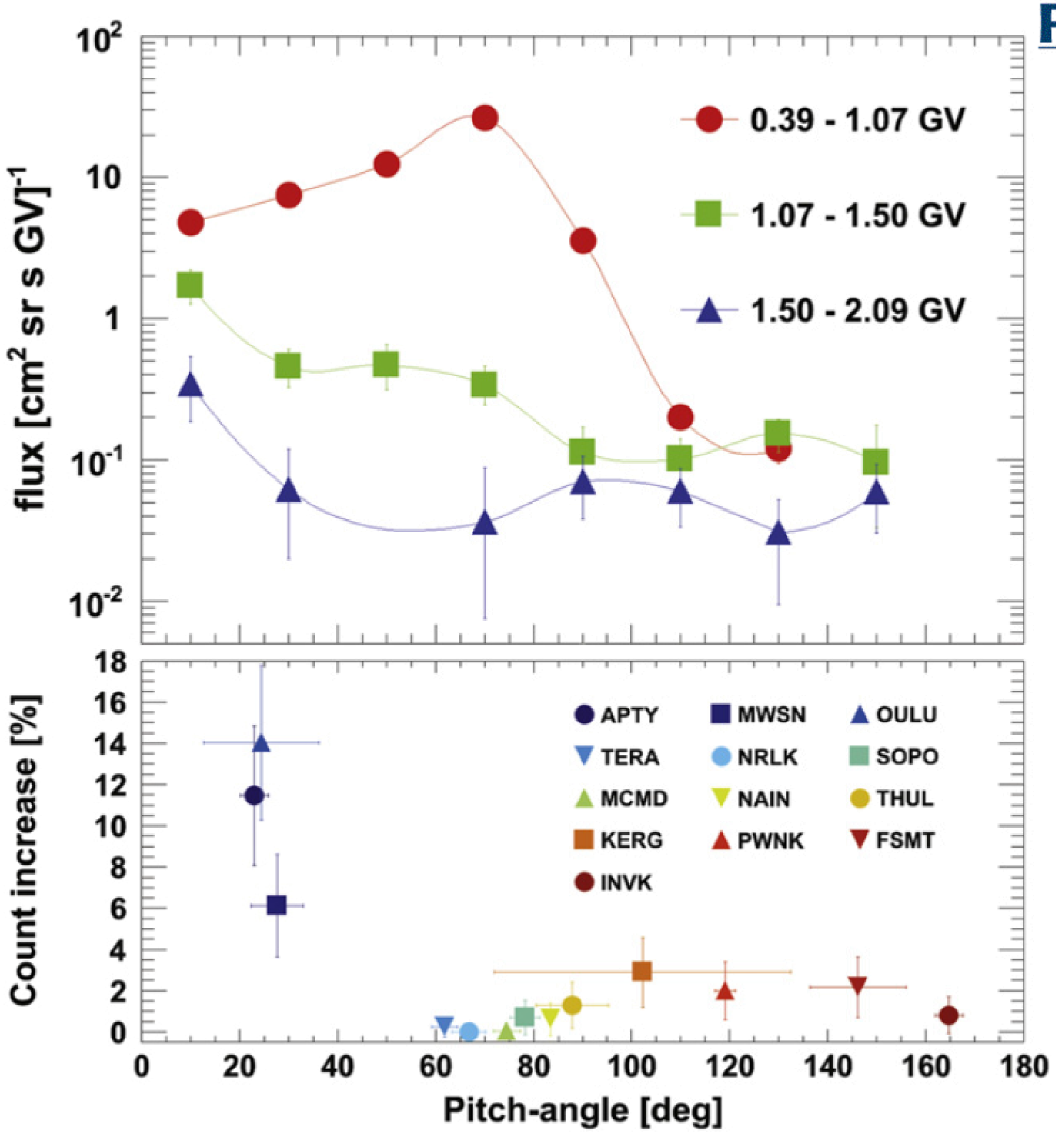

Adriani et al. - ApJL - 801 (2015) L3

# May 17°, 2012 SEP event

First evidence of two simultaneous particle populations:

- High rigidity component consistent with NM where particles are field aligned → Beam width ~40-60° (not scattered)
- Low rigidity component shows significant scattering for pitch angles ~90°

Adriani et al. - ApJL - 801 (2015) L3

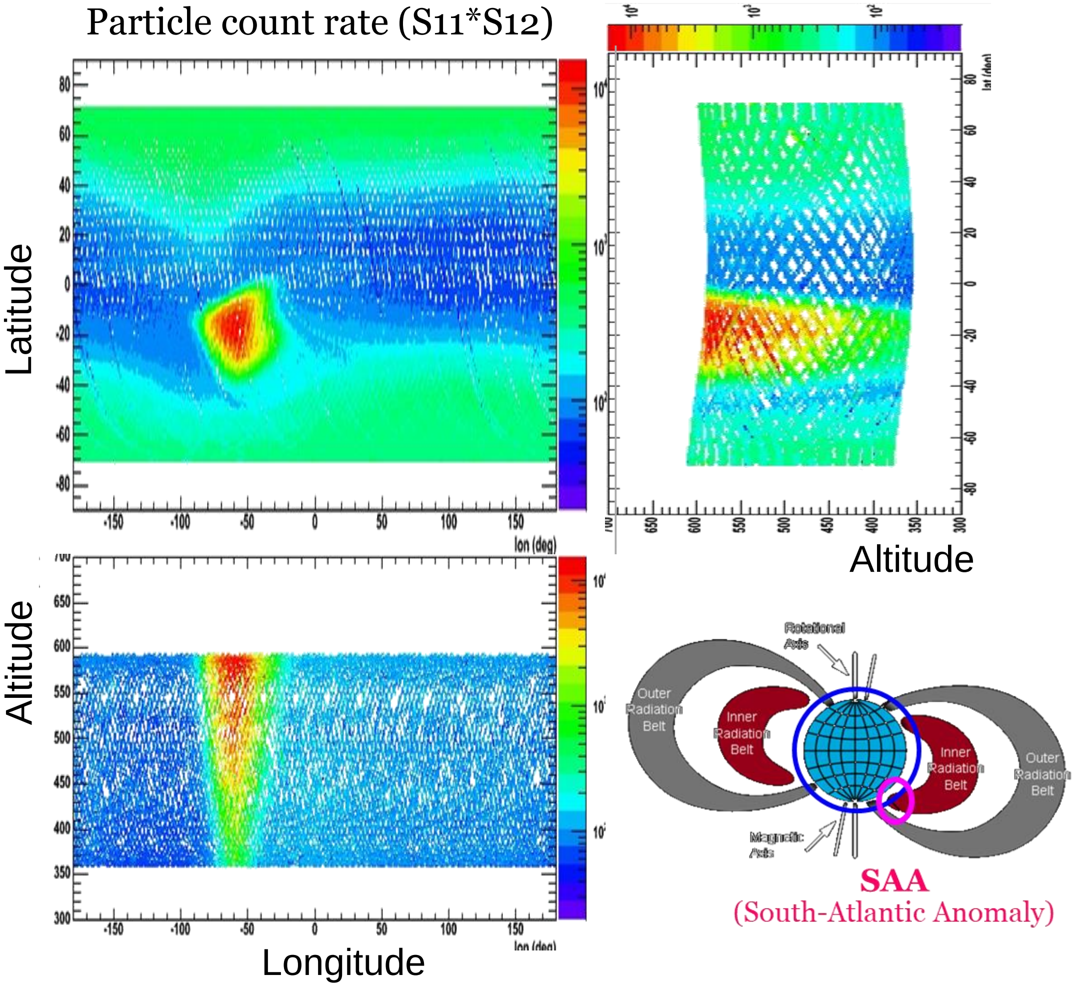


# The PAMELA obital environment

PAMELA sweep through the magnetosphere along a near-Earth semipolar orbit

- Observation of trapped radiation
- Characterization of high-energy albedo population

→ Improvement in low-altitude radiation-environment description

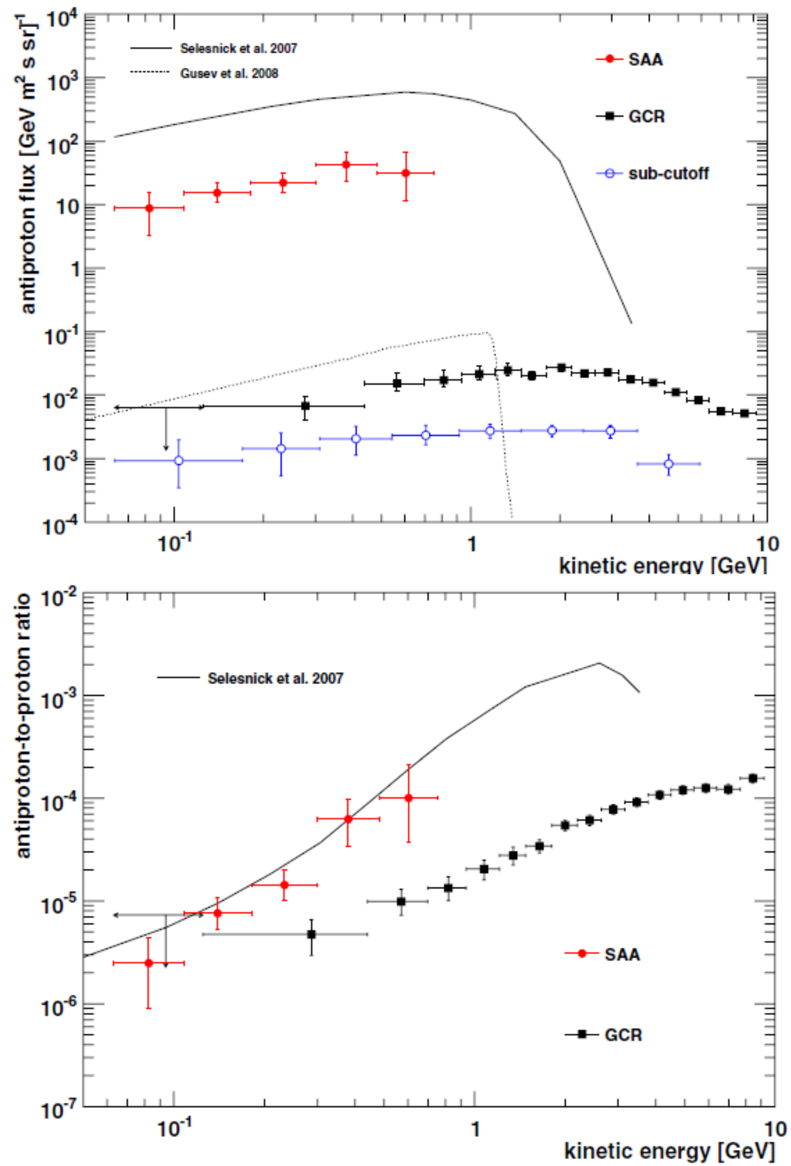


# Trapped antiprotons

First observation of geomagnetically trapped p-bar

Produced by CR interaction with atmosfere and trapped by the magnetosphere

Most abundant p-bar source near the Earth!




Adriani et al. - ApJ Lett. - 737 (2011) L29

# Conclusions

Before PAMELA

- Standard paradigm
  - GCRs originates from uniformly distributed SNRs via shock-driven 2°-order Fermi acceleration (**single power-law spectra**)
  - **Antiparticles** are produced by nuclear interactions with uniformly distributed matter within the Galaxy
  - Absolute fluxes of GCRs altered while penetrating the heliosphere, modulation described by **spherical potential**

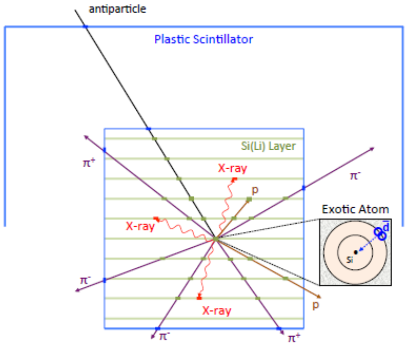
# Conclusions

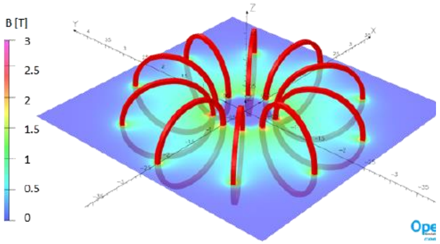
After PAMELA

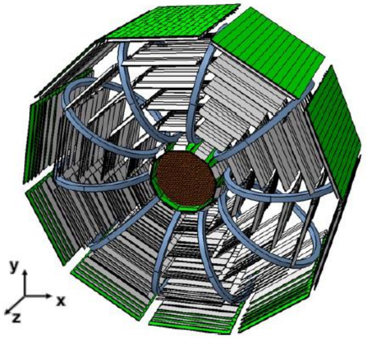
- Measurement of GCR particles and antiparticles over a wide energy range:
  - Spectral hardening of H and He at about 200GV and different slope for H and He indicate a more complex scenario of nuclear GCR origin and/or propagation
  - Evidence of a positron excess above 10GeV indicates new phenomena (dark matter? astrophysical e+- sources?)
  - p-bar consistent with secondary production hypothesis up to 200 GeV puts further constraints to possible sources
  - Precise measurements of light particle spectra provides improvement to propagation models
- Measurement of long- and short- time variation of low-energy particles:
  - Tuning of fluid-dynamic model of heliosphere
  - Study of solar phenomena, bridging the information provided by low-energy in-situ observations and high-energy surface observations
- Measurement of trapped and quasi-trapped particles:
  - Significant improvement in magnetosphere modeling (radiation-environment)

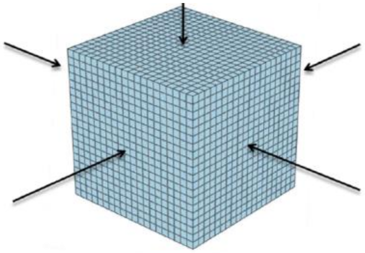
# Continuita` con l'attivita` Wizard

- Cosmic-antimatter search
  - Independent approach to anti-nuclei search
    - GAPS experiment
  - Next generation spectrometers → must relay on superconducting magnets
    - LAPUTA r&d, ALADINO proposal
- High-energy CRs
  - Calorimetric measurements
    - CALET experiment
    - CaloCube r&d
    - HERD experiment

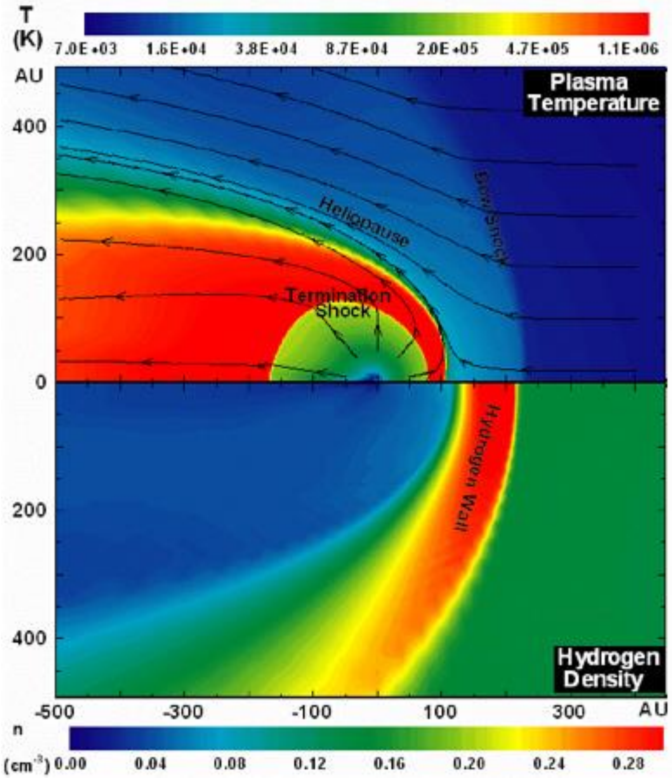



# Spares

# Heliospheric transport equation

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




( Parker 1965 )

a: $f(\mathbf{x}, p, t)$, omnidirectional function distribution of CRs;

b: convection with solar wind $\mathbf{V}$;

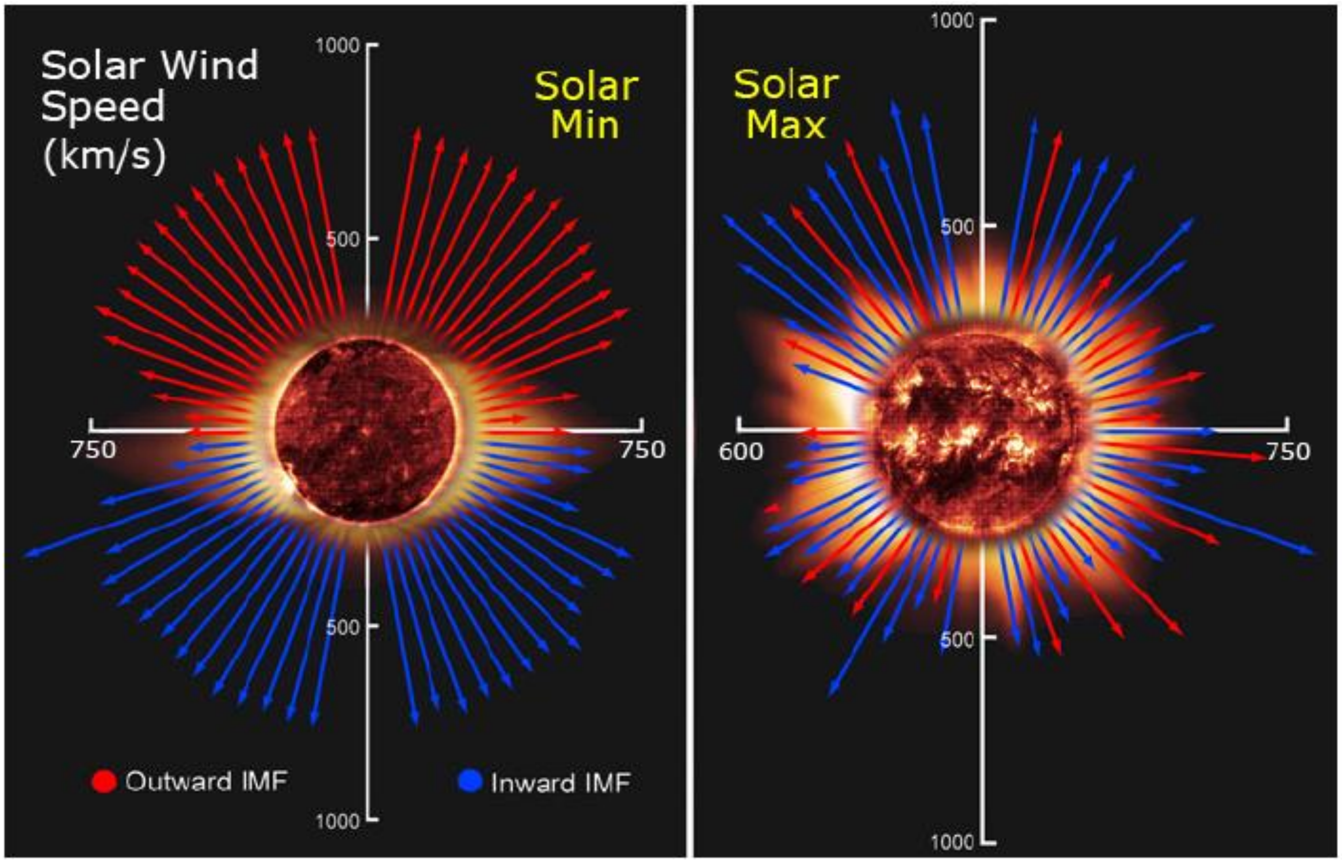
c: diffusion by magnetic field irregualrities;

d: drift, curvature and gradient in magnetic field;

e: adiabatic energy losses;

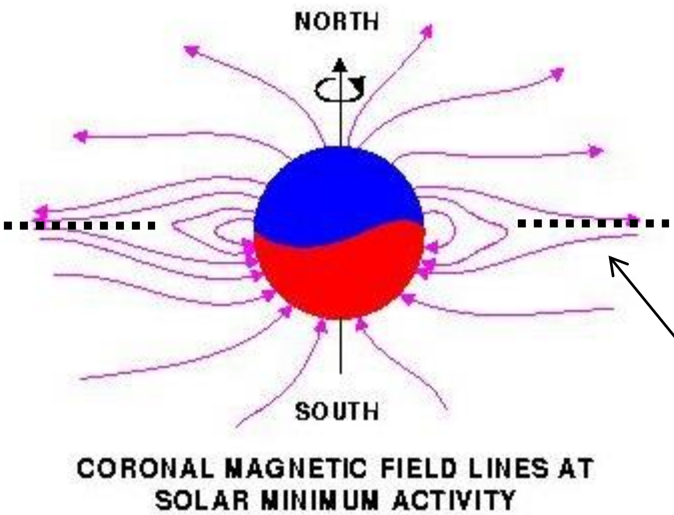
Stationary approximation during minimum solar activity

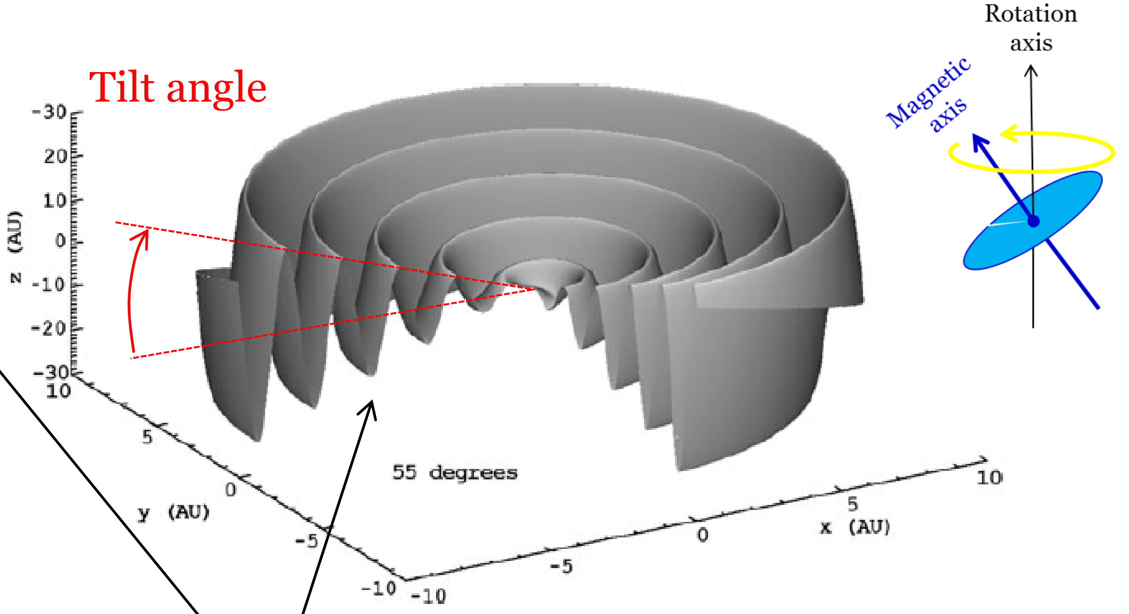
# The solar wind




- **Convection** with solar-wind velocity $\boldsymbol{V}$
- Adiabatic energy changes ($\propto \nabla \cdot \boldsymbol{V}$ )

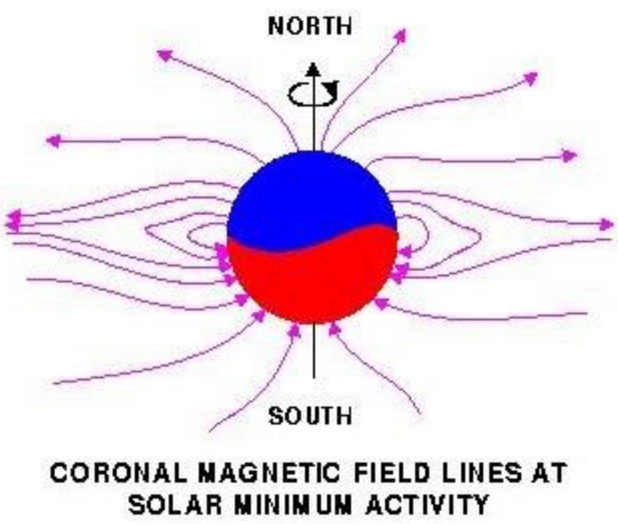
# Heliospheric magnetic field (HMF)




Heliospheric Current Sheet (HCS)

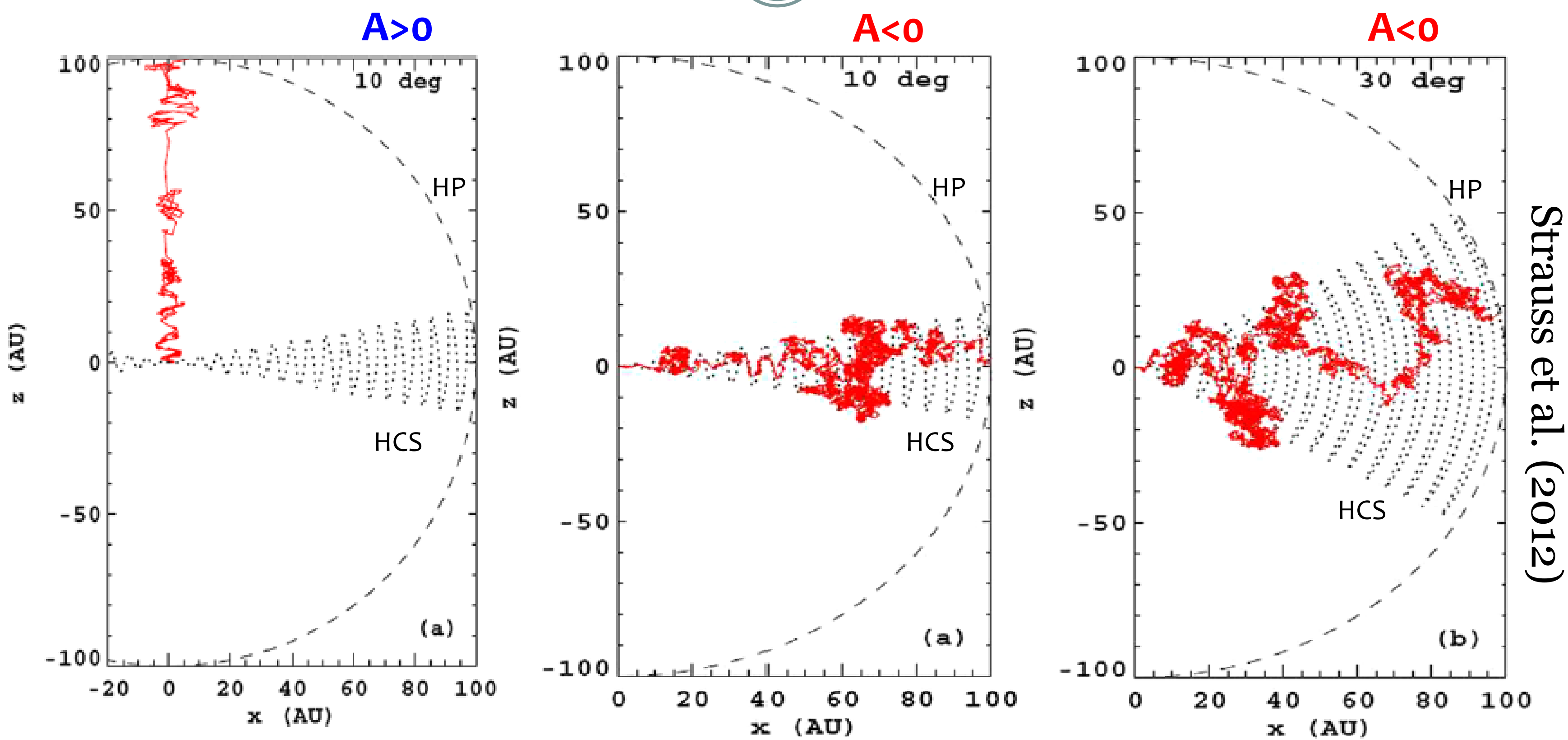
# Heliospheric magnetic field (HMF)




A>0 ⟶ magnetic-field reversal ⟶ A<0

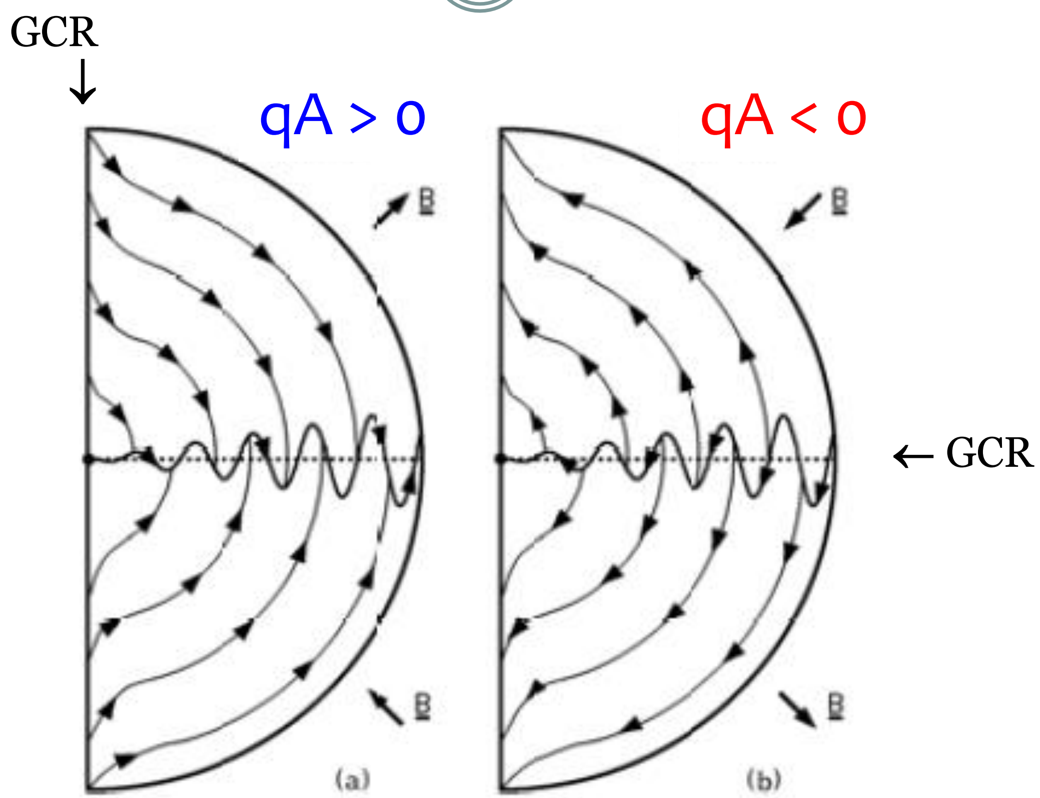
⟷ ~22-year cycle

# Drift & diffusion




- **Diffusion**, driven by small-scale HMF irregularities
- **Drift** caused by gradients and curvature in the global HMF

# Drift path



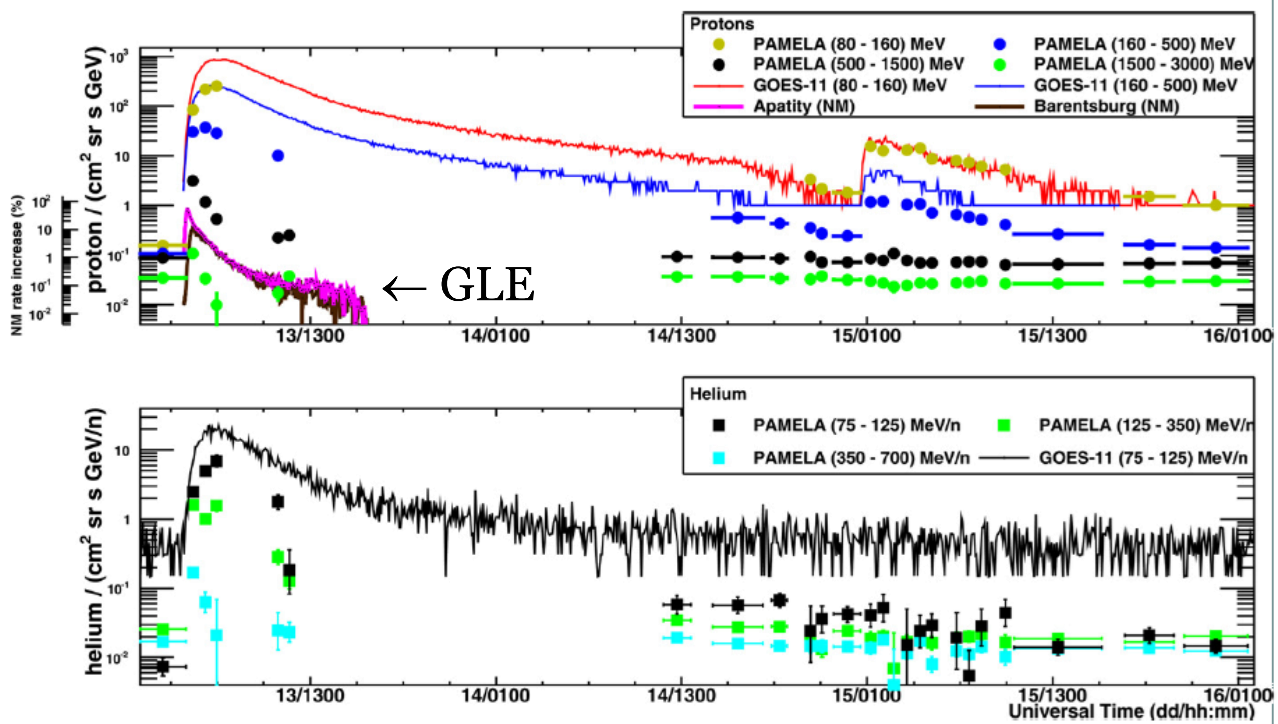

- Drift path changes at each field reversal → ~22-year cycle
- Asimmetry between particle of opposite charge →charge dependent solar modulation

# Dec 13°-14° 2006 SEP event

First instrument to directly measure relativistic SEPs in near-Earth space.

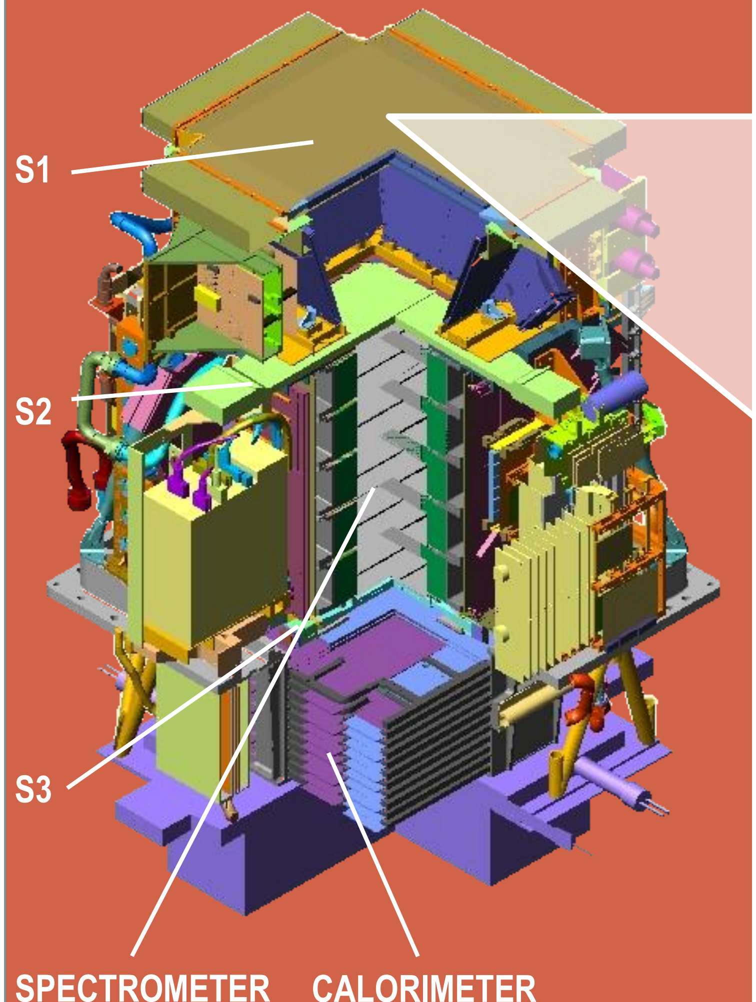
It bridges the gap between low-energy direct space-based observations (GOES) with high-energy indirect gound-based measurements (NM GLEs)

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



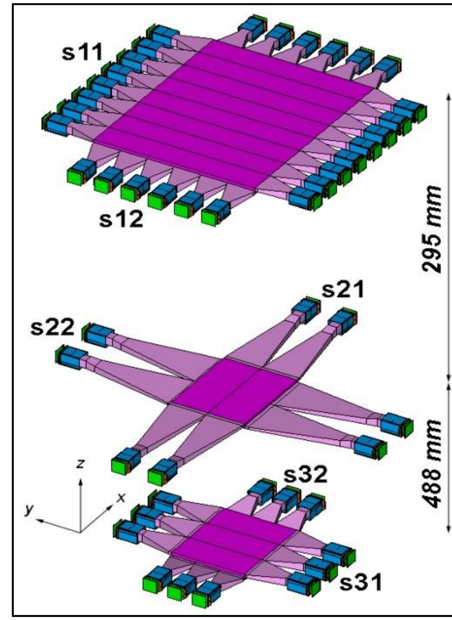

PAMELA observation done during passages over high-latitude regions

## The apparatus



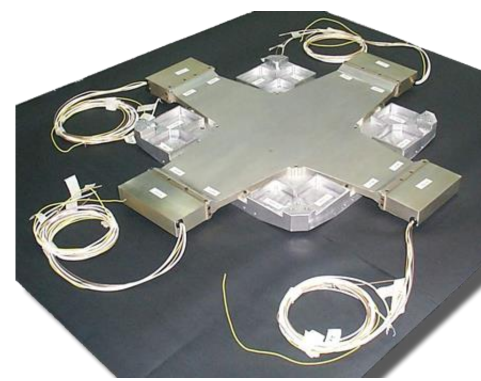

# The Time-of-Flight system

- 3 double-layer scintillator paddles
- X/Y segmentation
- Total: 48 Channels




### Main tasks:

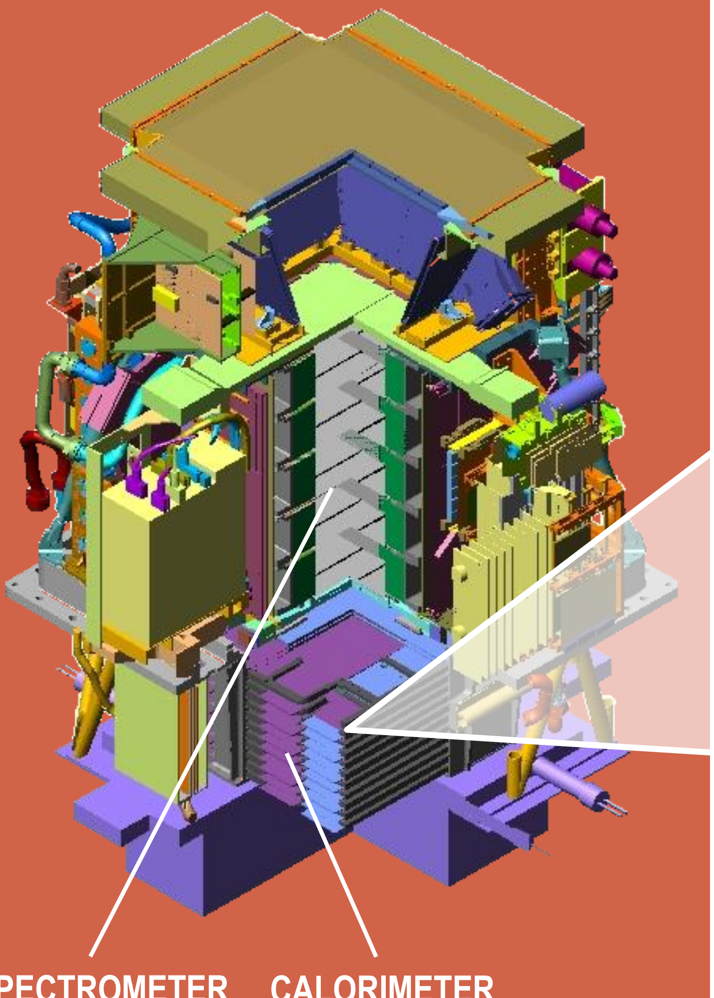
- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification (<1GeV/c)



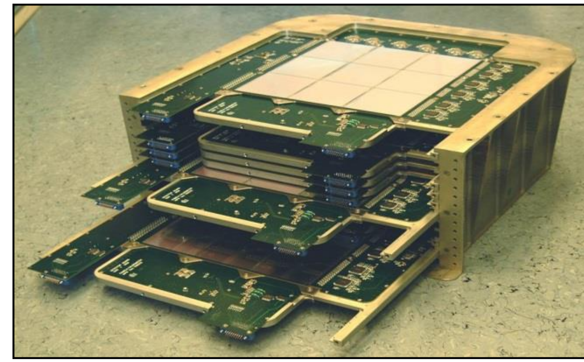
### Performances:

- $\sigma_{paddle}$ ~ 110ps
- $\sigma_{TOF}$ ~ 330ps (for MIPs)

# The apparatus




# The em calorimeter



- **44 Si layers (X/Y) +22 W planes**
- **$16.3\ X_o$ / $0.6\ l_0$**
- 4224 channels
- Dynamic range 1400 mip
- Self-trigger mode (> 300 GeV GF~600 $cm^2$ sr)

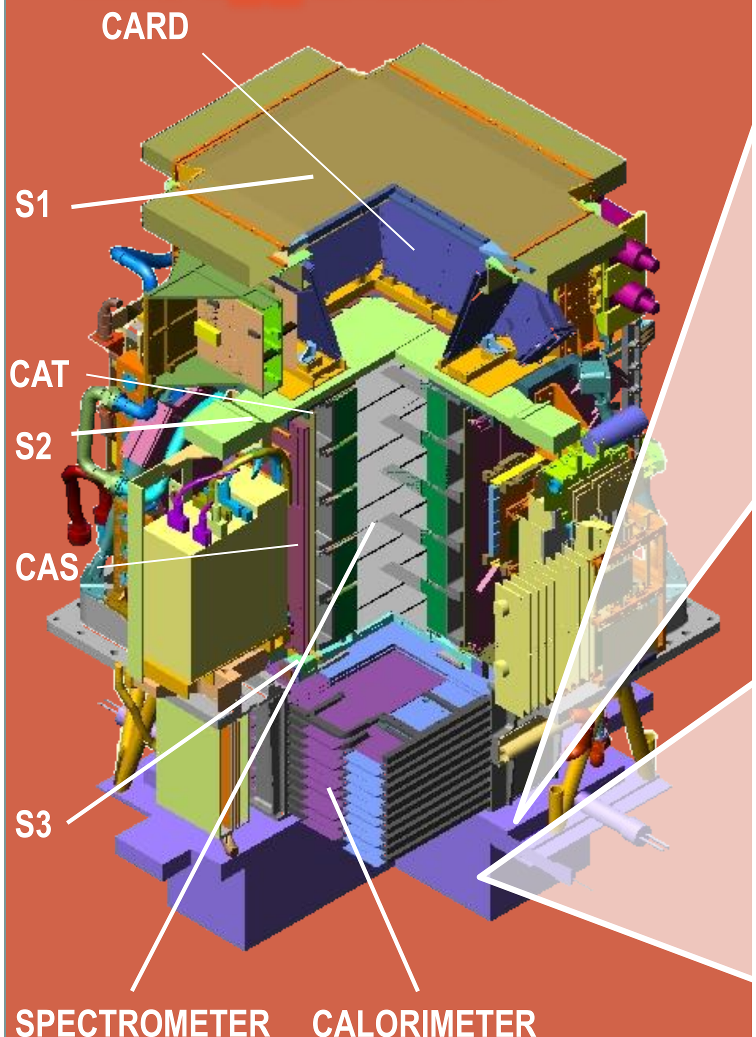
## Main tasks:

- e/h discrimination
- $e^{+/-}$ energy measurement

## Performances:

- $p/e^+$ selection efficinecy ~ 90%
- p rejection factor **$10^6$**
- e rejection factor **$>10^4$**
- Energy resolution **~5%** @200GeV

# The apparatus

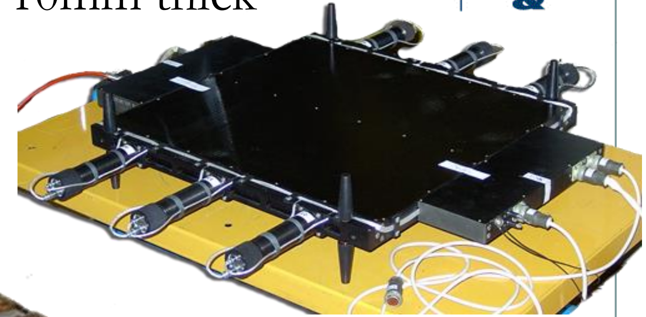


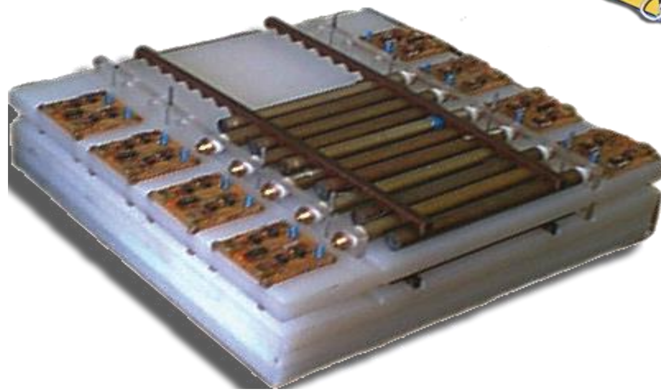

## Shower-tail catcher (S4)

- 1 scintillator paddle 10mm thick

Main tasks:

- ND trigger





## Neutron detector

- **36 $^3$He counters**: $^3$He(n,p)T → Ep=780 keV
- 1cm thick polyetilene moderators
- n collected within 200 μs time-window

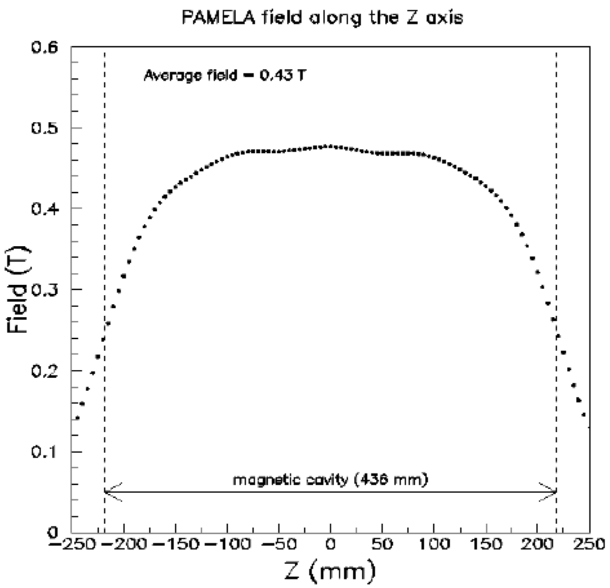
### Main tasks:

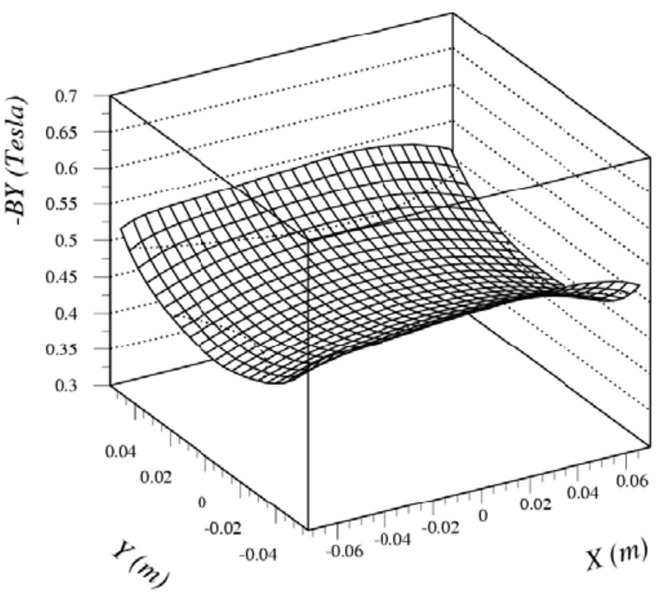
- e/h discrimination @high-energy

# The magnetic field

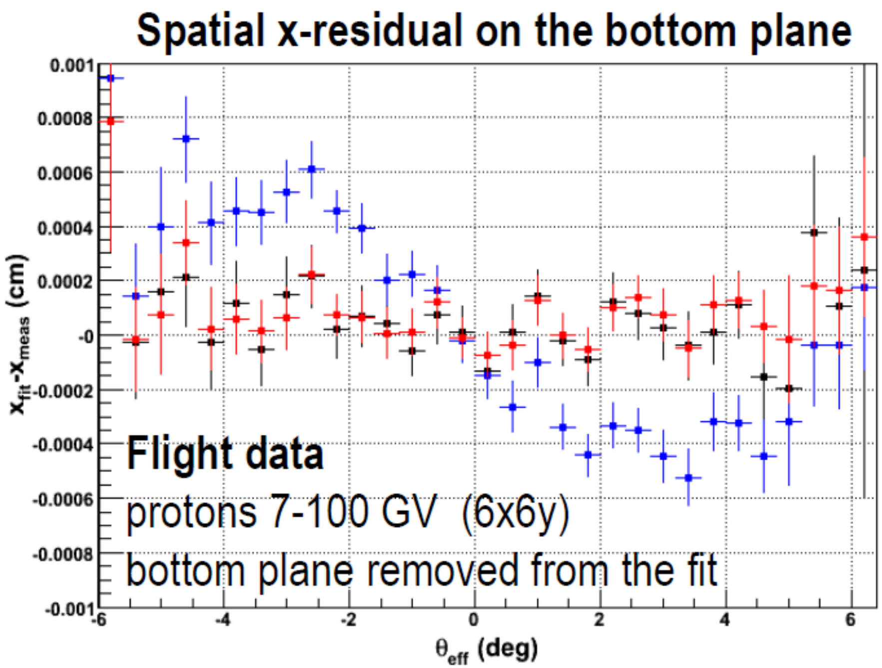
MAGNETIC FIELD MEASUREMENTS

- Gaussmeter (F.W. Bell) equipped with 3-axis probe mounted on a motorized positioning device (0.1mm precision)
- Measurement of the three components in 67367 points 5mm apart from each other
- Field inside the cavity:
    - **0.48 T** @ center
    - Average field along the axis: **0.43 T**
- **Good uniformity**
- External magnetic field: magnetic momentum < 90 $Am^2$

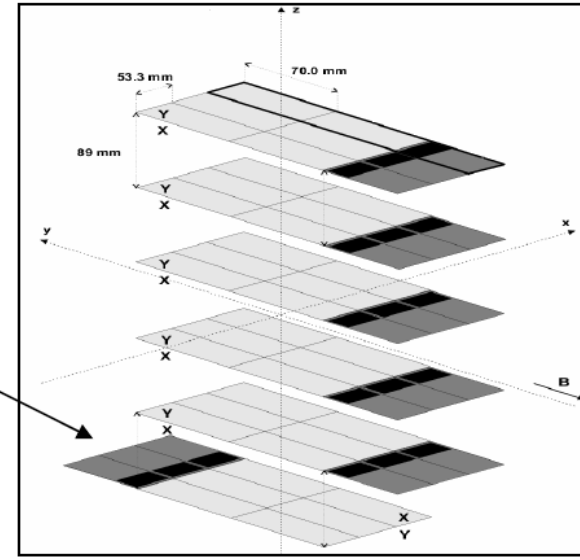


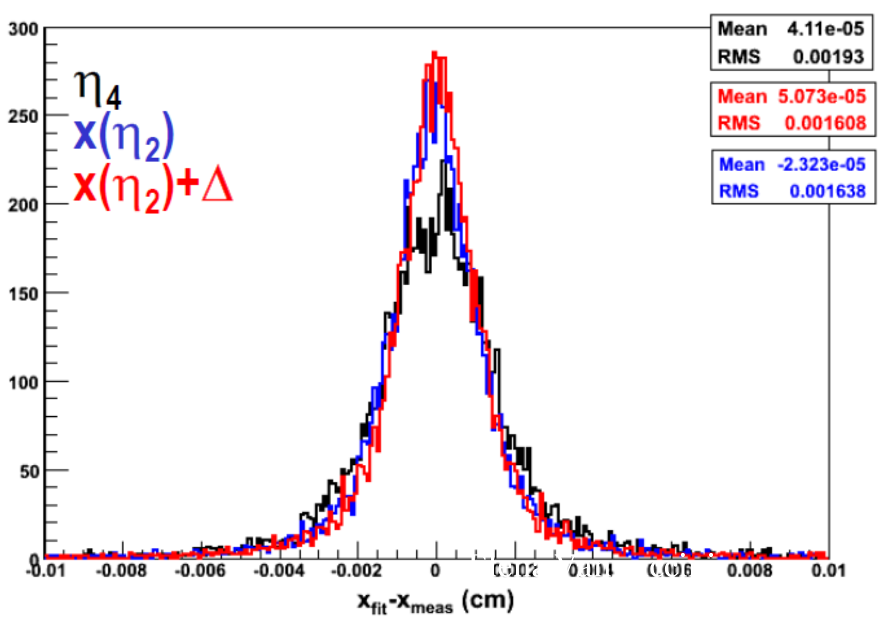



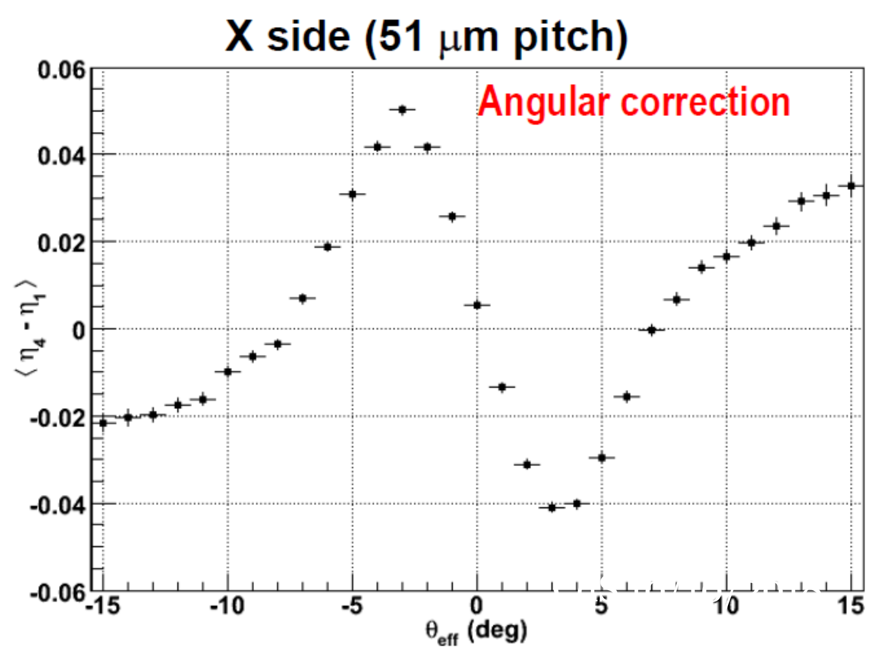
# Angular systematic (flight data)



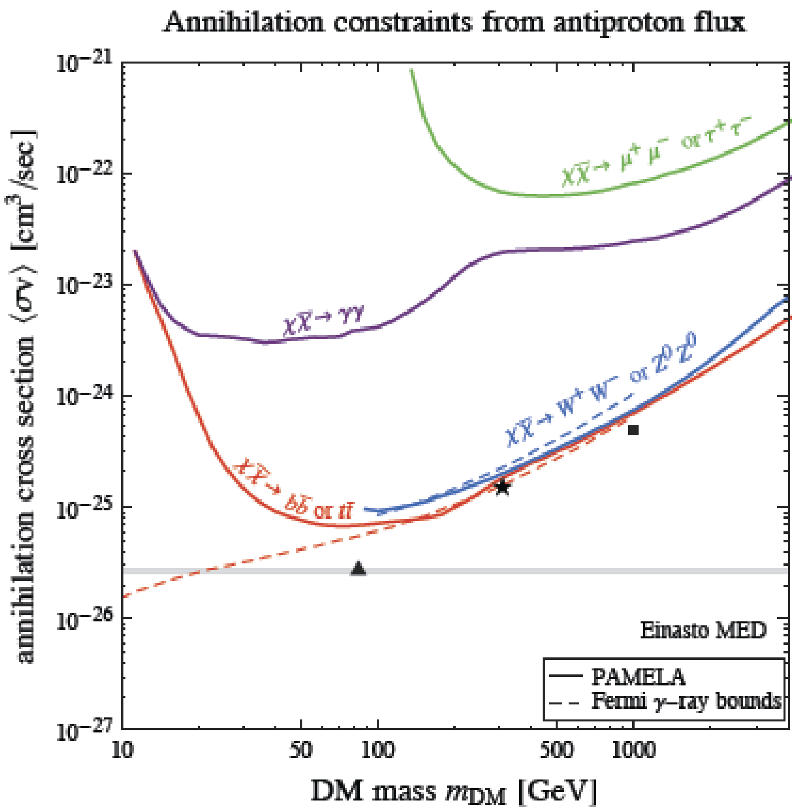

Angular systematic has opposite sign on the x view of the last plane



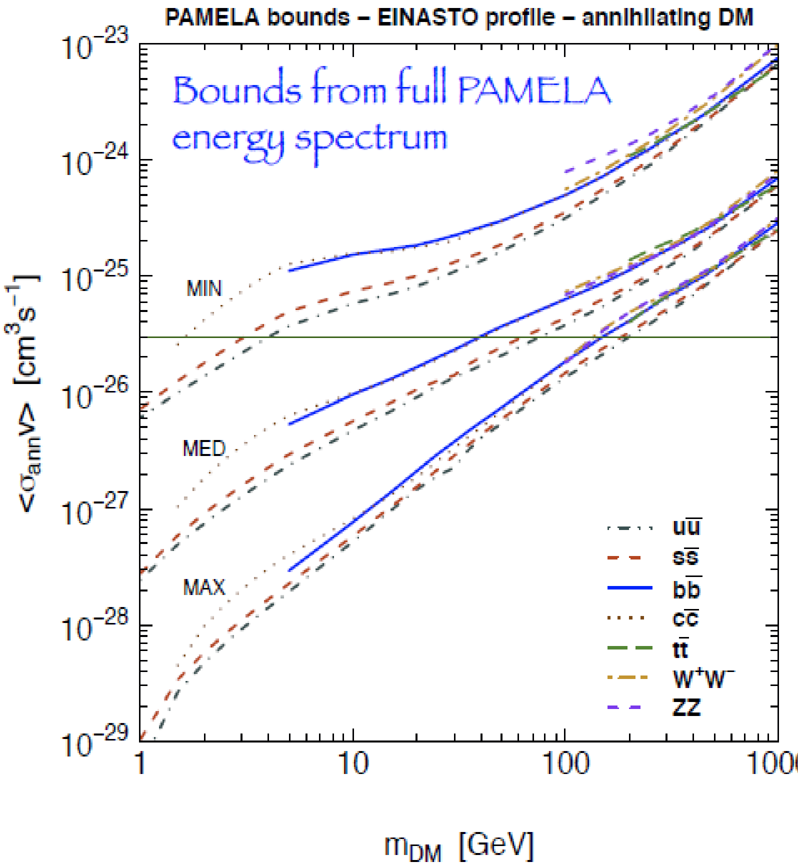



# PAMELA antiproton DM limits




M. Cirelli & G. Giesen, JCAP 1304 (2013) 015




Fornengo, Maccione, Vittino, JCAP 1404 (2014) 04, 003

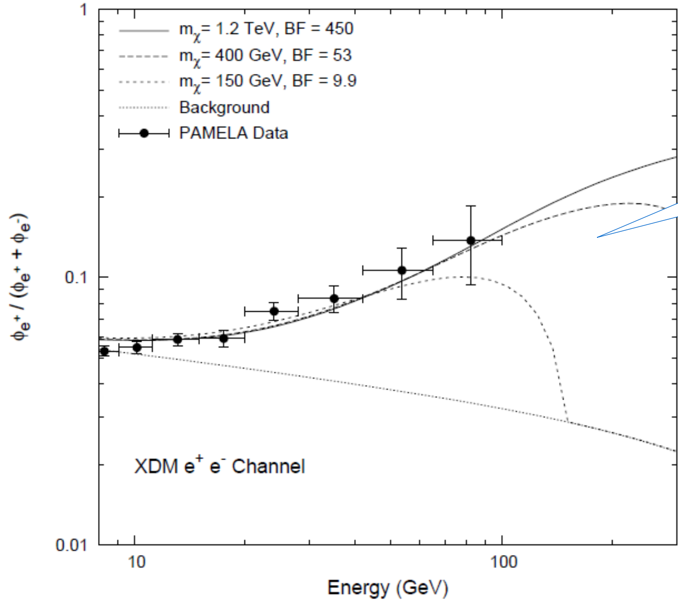
# Positron-excess interpretations

## Dark matter

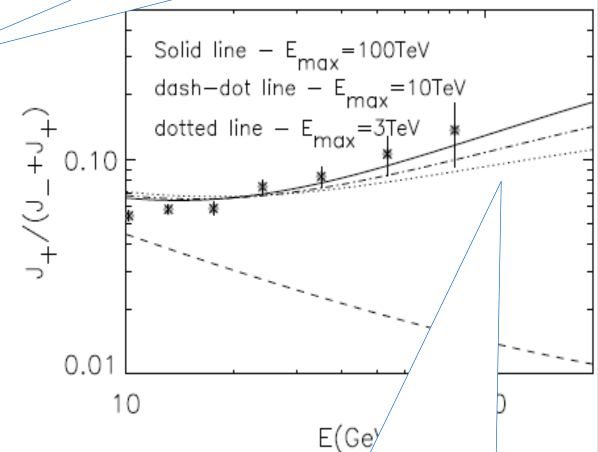
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

## Astrophysical processes

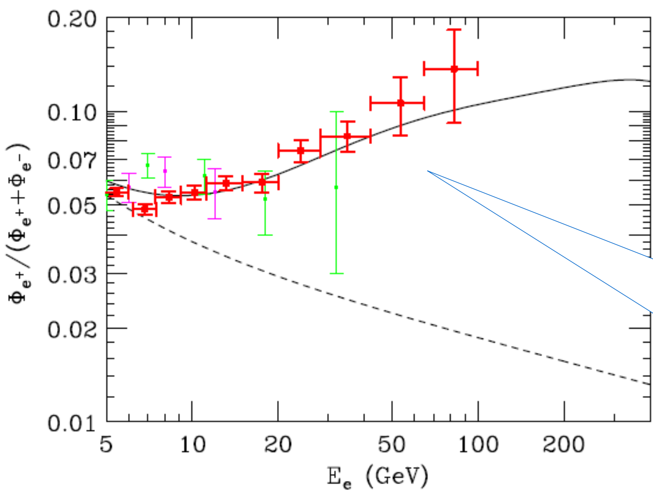
- known processes
- large uncertainties on environmental parameters




(Cholis et al. 2009)
Contribution from **DM annihilation**.



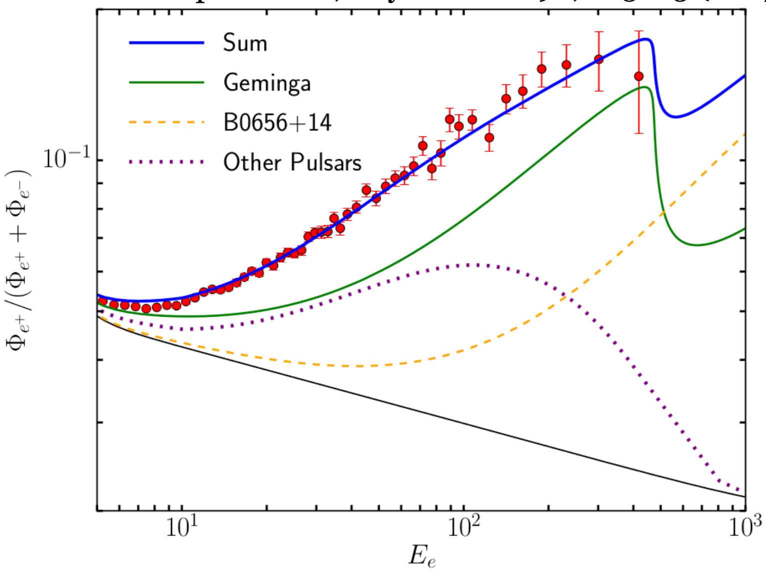

(Blasi 2009)
e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)




(Hooper, Blasi and Serpico, 2009)
contribution from diffuse mature & nearby young **pulsars**.

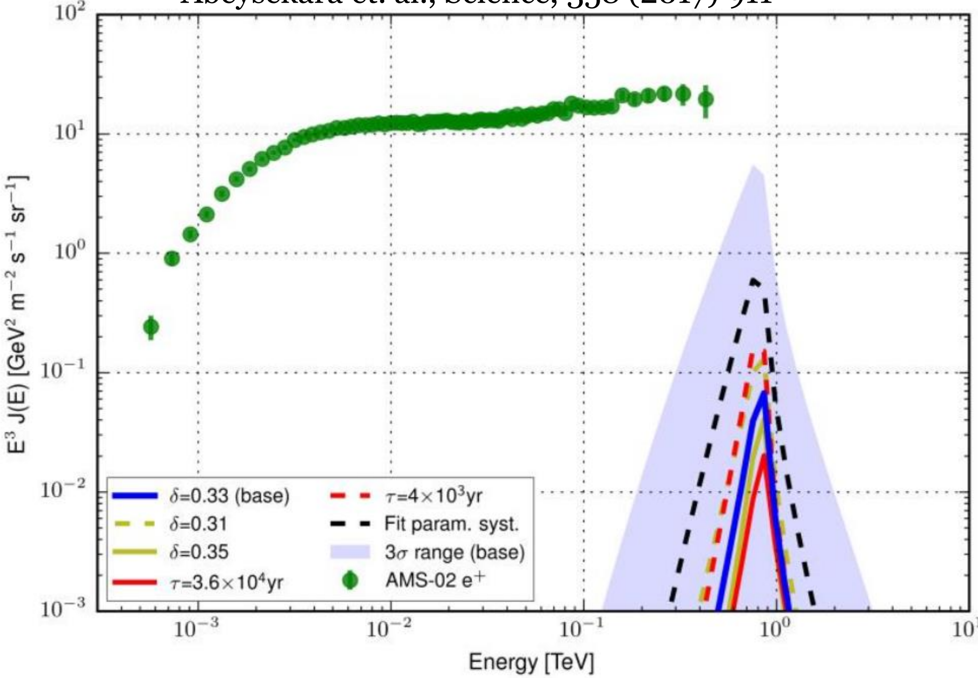
# Positrons from Geminga and PSR B0656+14

Dan Hooper et. al. , Phys. Rev. D 96, 103013 (2017)




"HAWC observations strongly favor pulsar interpretations of the cosmic-ray positron excess"

Abeysekara et. al., Science, 358 (2017) 911




"...leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin"

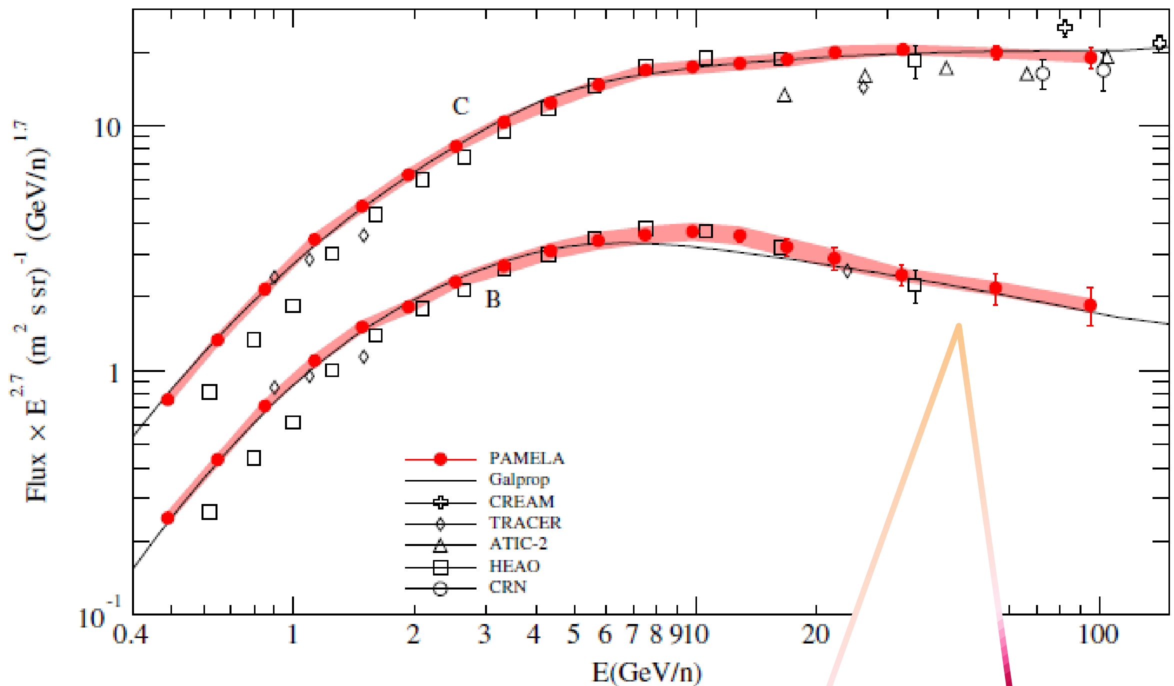
# B and C absolute fluxes

Widest energy range covered so far

Reduced tracking performance, due to detector saturation:

- $\sigma_x$ = 14 μm, $\sigma_y$ = 19 μm
- MDR = 250 GV

Adriani et al. - ApJ- 791 (2014) 93




GALPROP code tuned to PAMELA B&C data
- **Plain diffusion model** (Vladimirov et al. 2012)
- Solar modulation: spherical model ( ϕ=400MV )

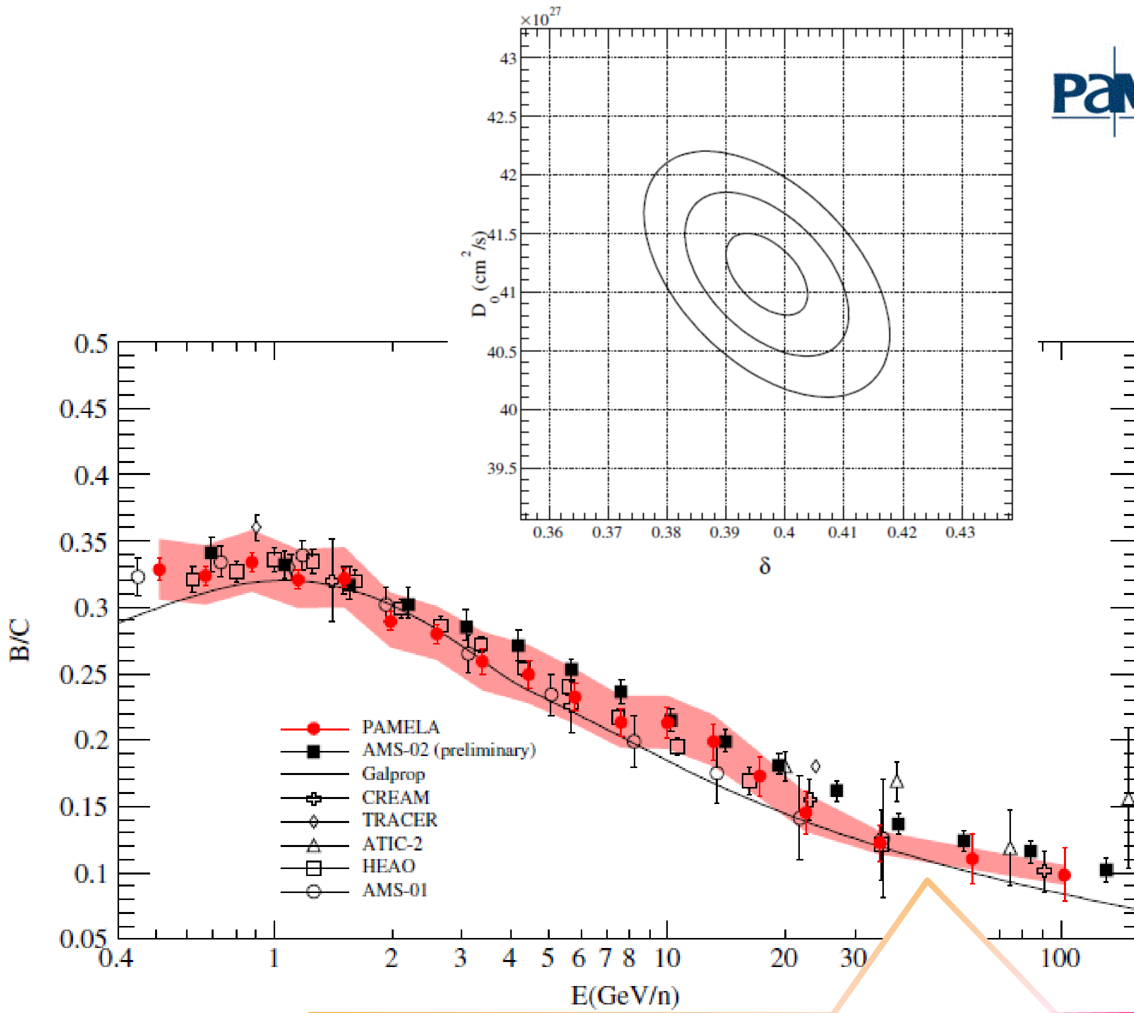
# B/C ratio

B nuclei are of ~pure **secondary** origin

C,N,O + ISM → B + ...

→ B/C provides the strongest constraint to propagation parameters so far

PAMELA data consistent with previous measurements and with a standard scenario

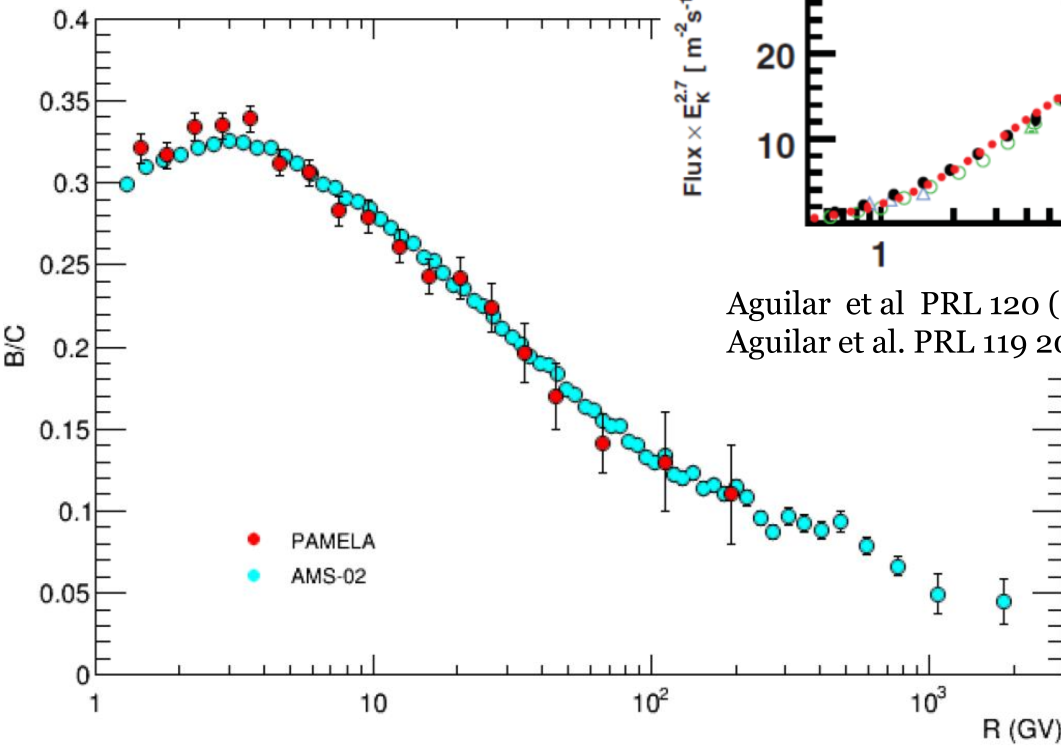


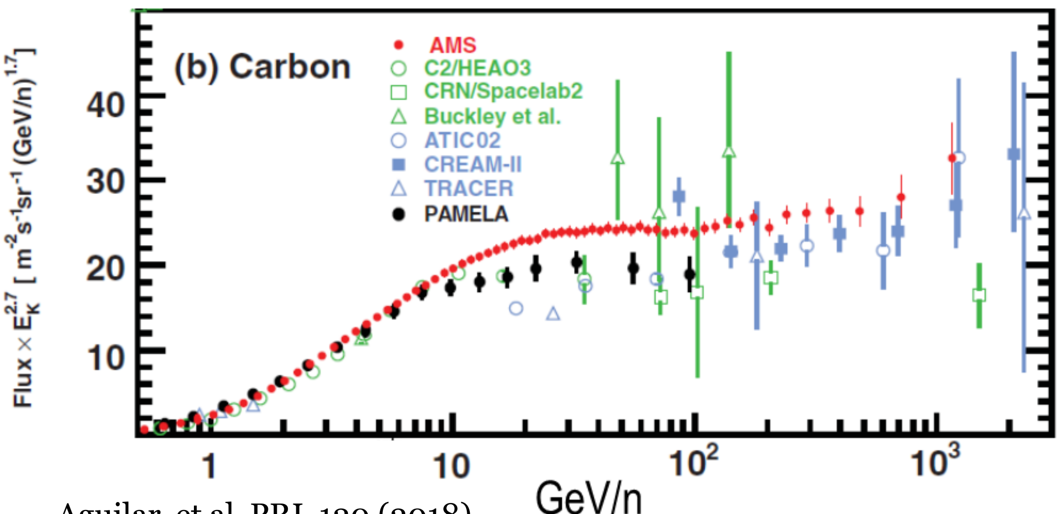

Adriani et al. - ApJ- 791 (2014) 93

GALPROP code tuned to PAMELA B&C data

- **Plain diffusion model** (Vladimirov et al. 2012)
- Solar modulation: spherical model ( $\phi$=400MV )

# B and C abundances




Aguilar et al PRL 120 (2018)
Aguilar et al. PRL 119 2017

20% discrepancy in C absolute flux between AMS-02 and PAMELA…

# H isotopes

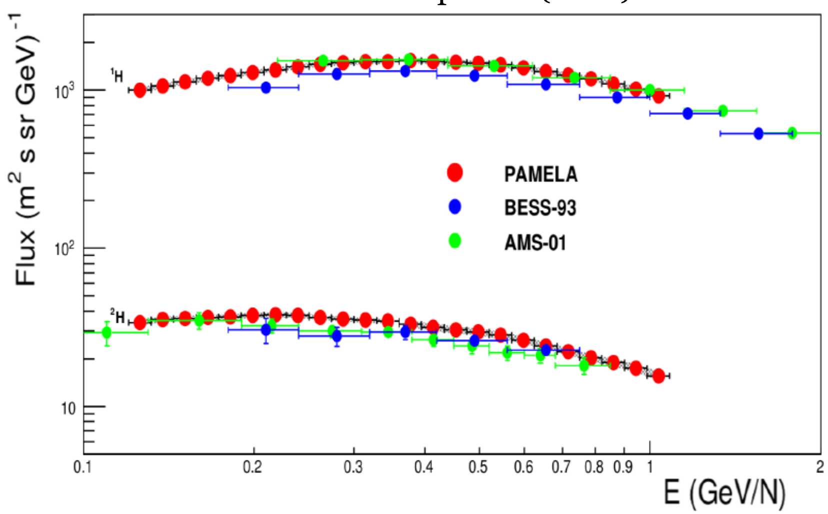
Parameter constraint competitve/complementary to B/C measurement with current instrument precision

Probe different Z/A regime

Test «universality» of propagation

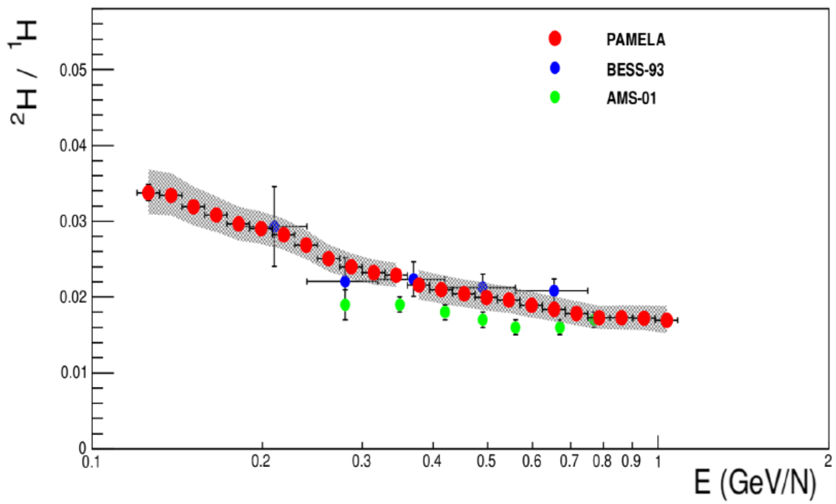
(Coste et al. 2012)

Adrianti et al ApJ 818 (2016)




1H → primary

2H → secondary
90% from 4He+1H
(40%@1GeV/n)



# He isotopes

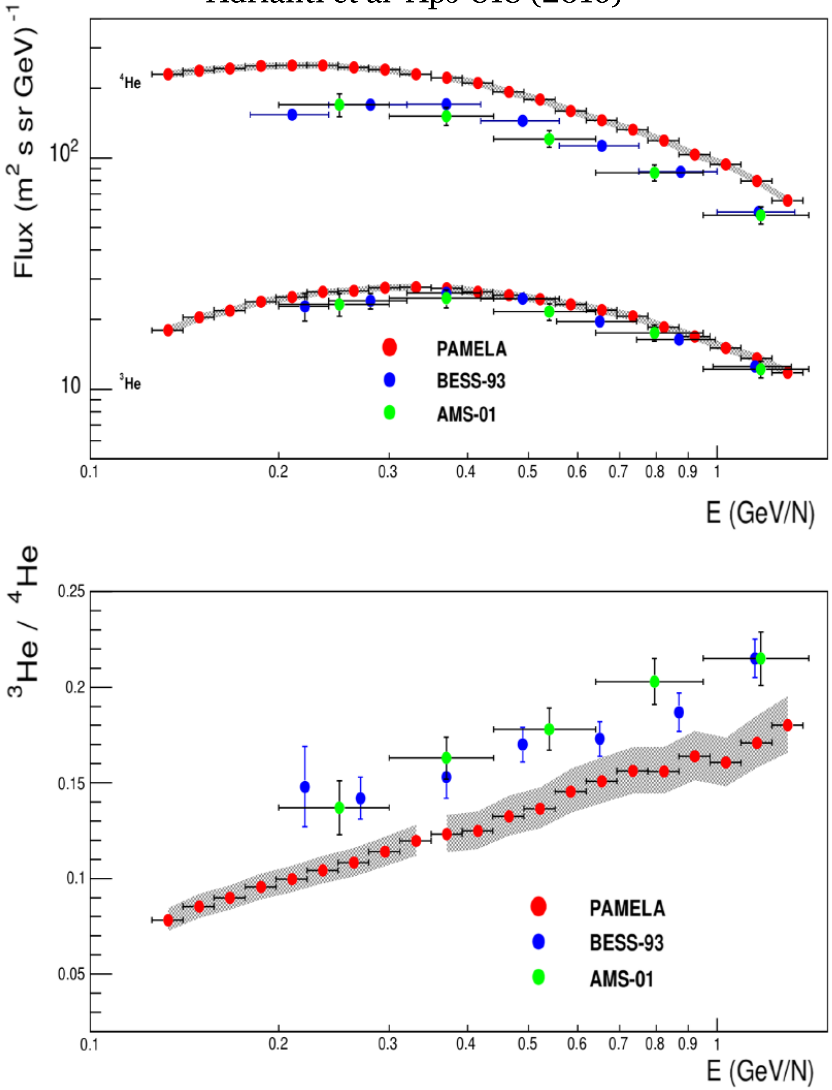
Parameter constraint competitve/complementary to B/C measurement with current instrument precision

Probe different Z/A regime

Test «universality» of propagation

(Coste et al. 2012)

Adrianti et al ApJ 818 (2016)

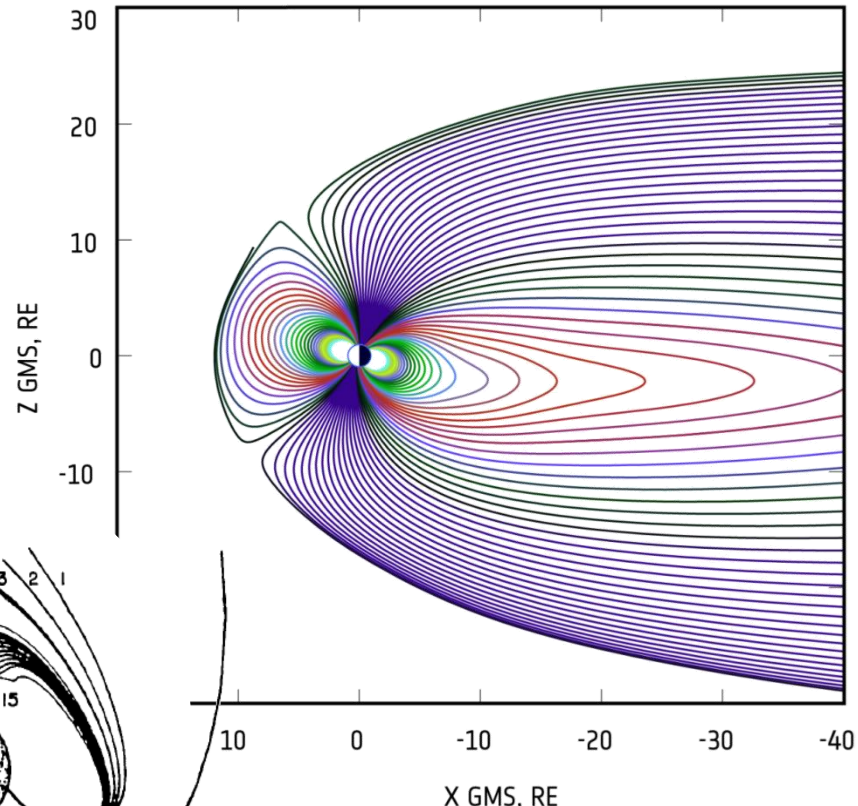


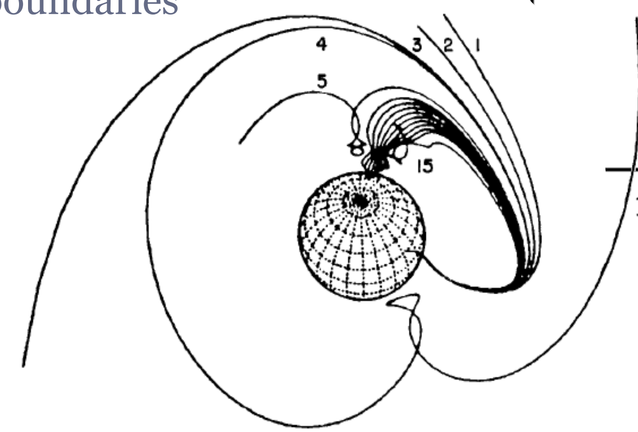

4He → primary + secondary ~10% @2GeV/n from CNO

3He → secondary 95% from 4He

# Trajectory analysis

- Trajectories propagated back and forth the measurement location
- Particles classified according to trajectory behaviour
  - Reach magnetosphere boundary
    - Interplanetary origin
  - Intersect atmosphere boundary
    - Albedo
  - Do not intersect the  boundaries
    - Stabily trapped



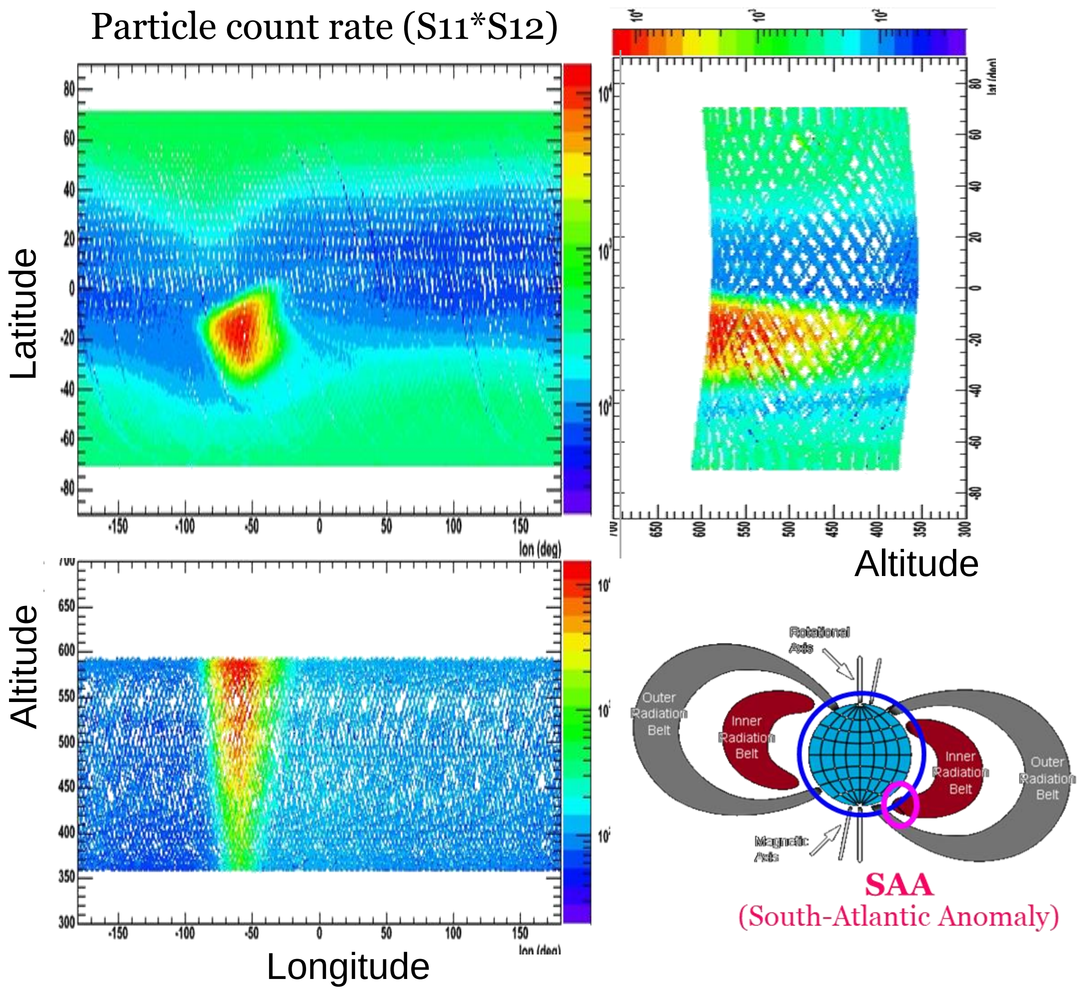
# The PAMELA obital environment

PAMELA sweep through the magnetosphere along a near-Earth semipolar orbit

- Observation of trapped radiation

- Characterization of high-energy albedo population

→ Improvement in low-altitude radiation-environment description

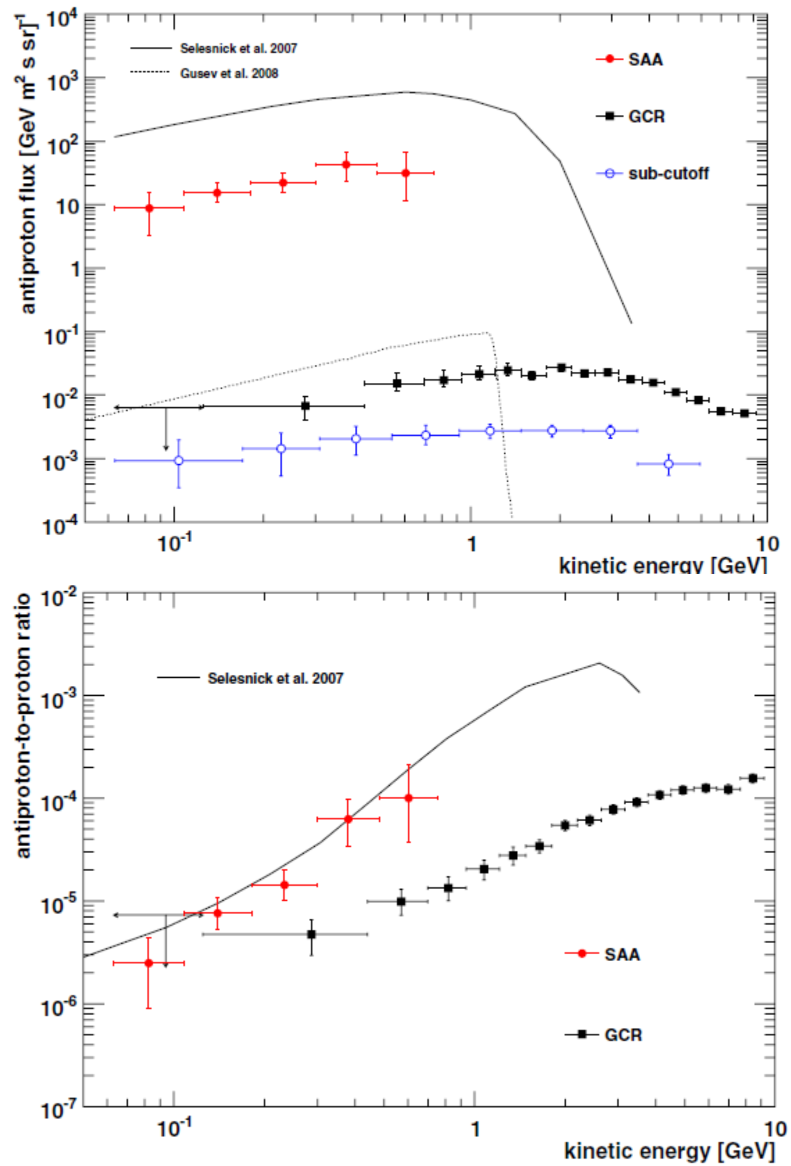


# Trapped antiprotons

First observation of geomagnetically trapped p-bar

Produced by CR interaction with atmosfere and trapped by the magnetosphere

Most abundant p-bar source near the Earth!



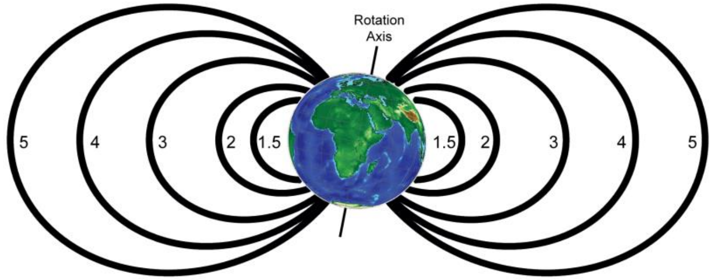

Adriani et al. - ApJ Lett. - 737 (2011) L29

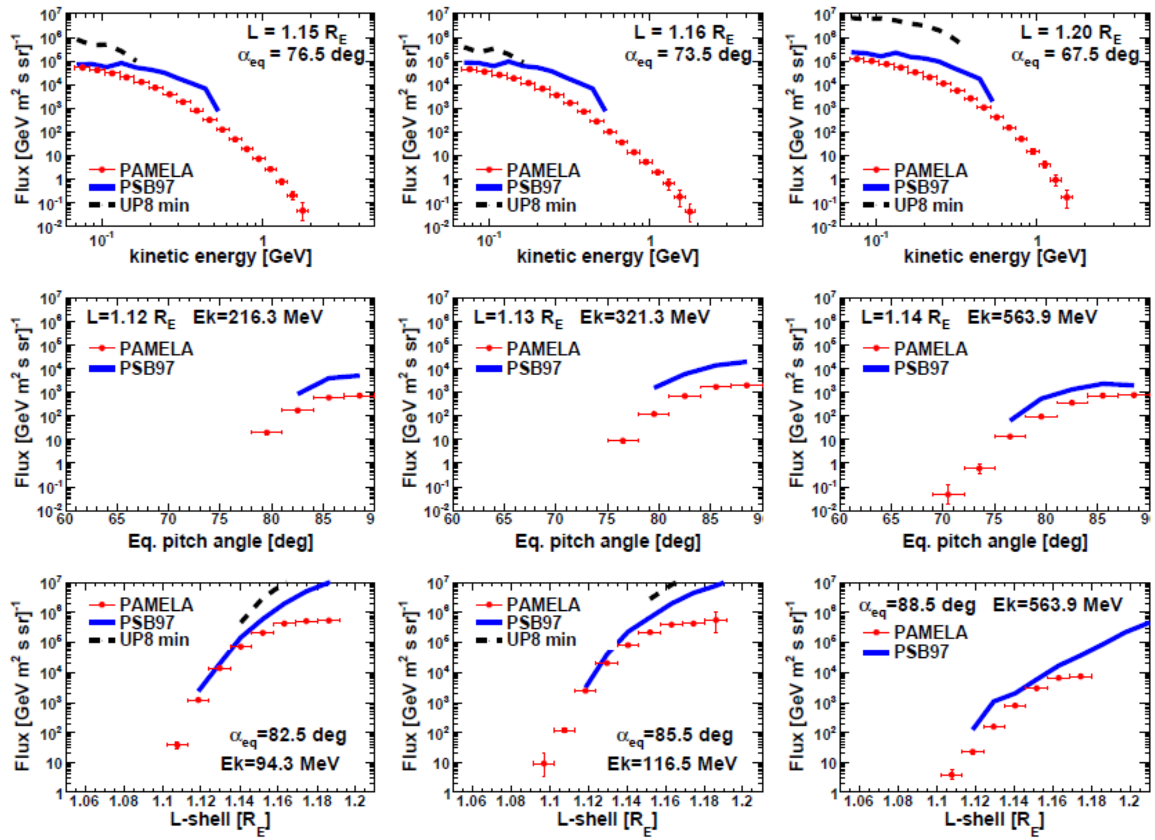
# Trapped protons

Observation of trapped radiation performed down to $L_{shell}$~$1.1R_E$ and up to 4 GeV

Comparison with empirical model

Improvement in low-altitude radiation-environment description

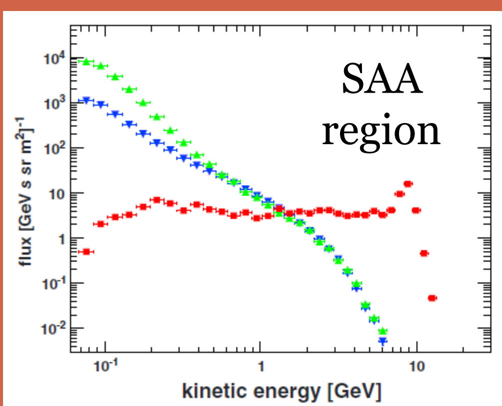


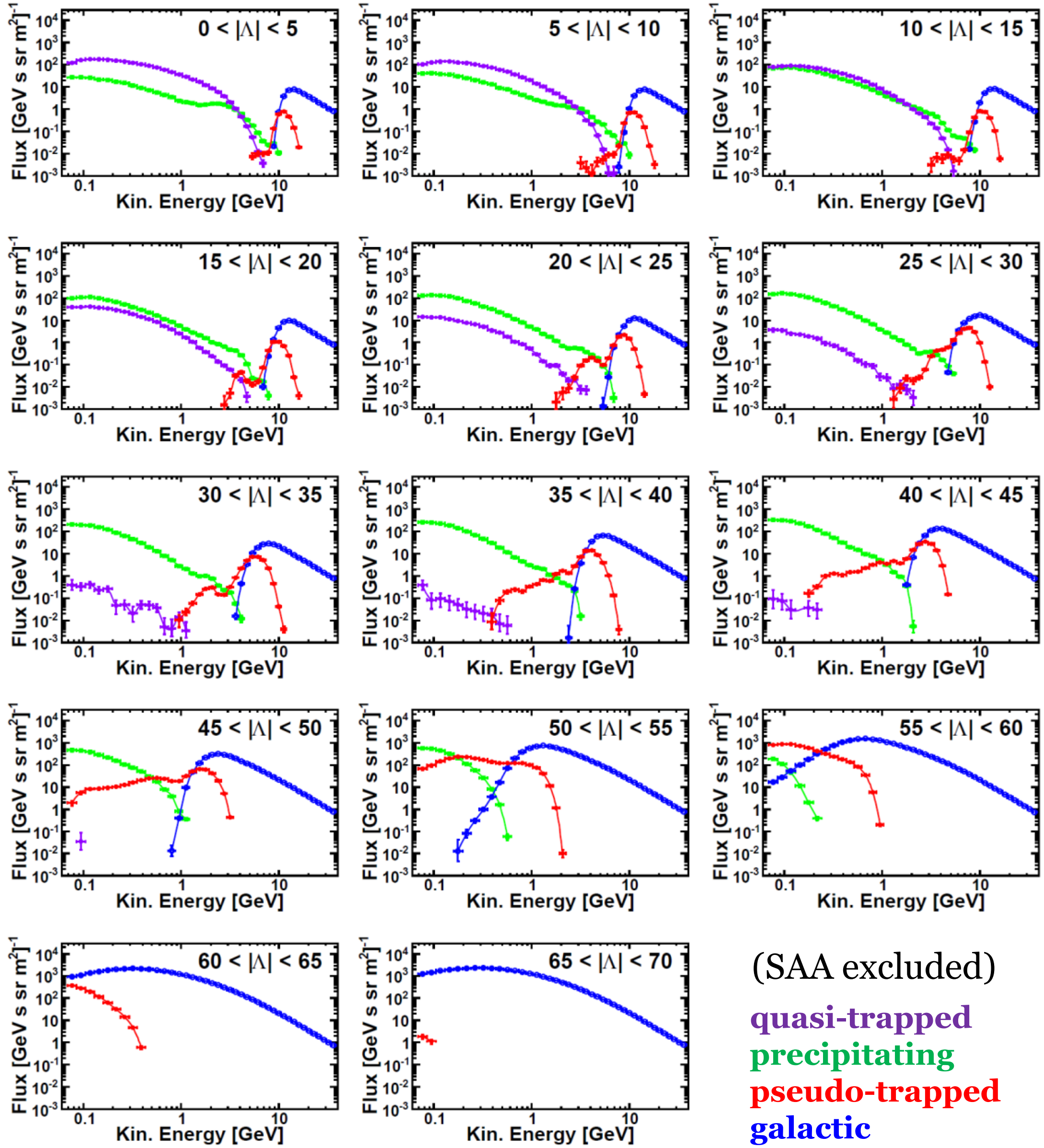




Adriani et al. - Apj Lett. – 799,(2015) L4

# Re-entrant albedo protons

Caracterization of high-energy albedo population



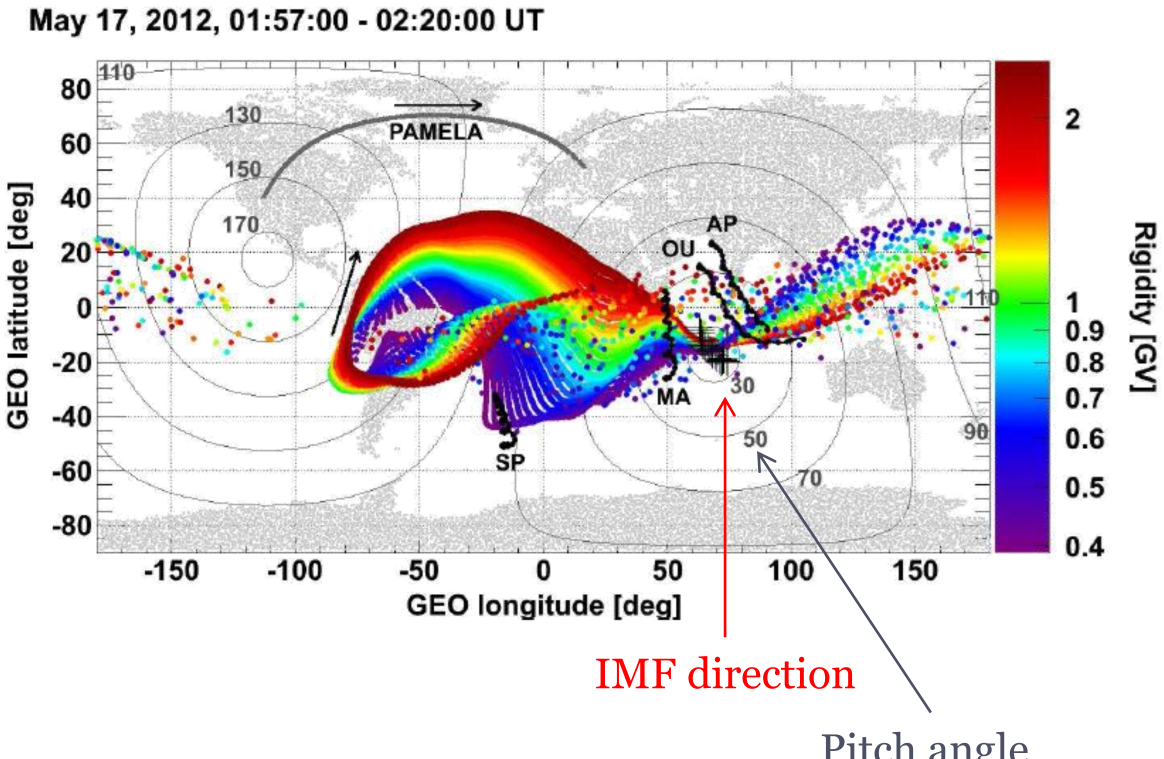



# May 17°, 2012 SEP event

- First observed GLE of 24° solar cycle
- Earth magnetically connected to the Sun
- Associated to M1.5-class X-ray flare
- Extended emission (>100MeV) seen by Fermi-LAT

Unique possibility to measure pitch angle distribution over broad energy range, to disentangle interplanetary **transport** process

Asymptotic direction during first polar pass after the event onset



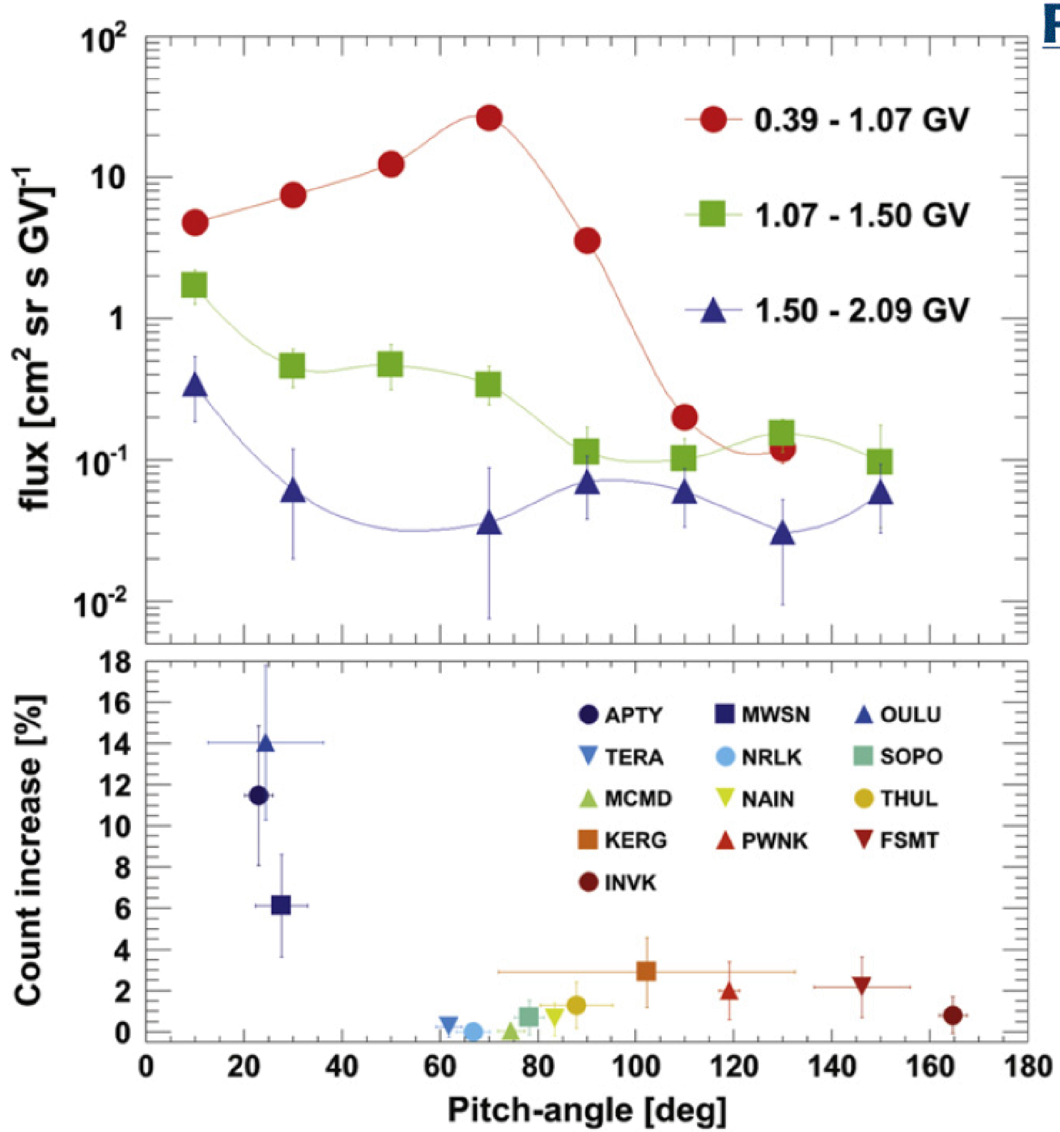

Adriani et al. - ApJL - 801 (2015) L3

# May 17°, 2012 SEP event

First evidence of two simultaneous particle populations:

- High rigidity component consistent with NM where particles are field aligned → Beam width ~40-60° (not scattered)
- Low rigidity component shows significant scattering for pitch angles ~90°

Adriani et al. - ApJL - 801 (2015) L3



# Electron inclusive spectrum