JPS ・高知, 22/9/2010

宇宙線

宇宙学会シンポジュウム

Cosmic Ray Observations with the Pamela Space Experiment

M. Casolino

RIKEN INFN Univ. Rome Tor Vergata

on behalf of the PAMELA collaboration

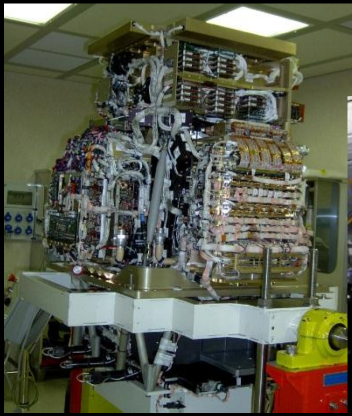
Past, present and future experiments

MASS-89, 91, TS-93, CAPRICE 94-97-98

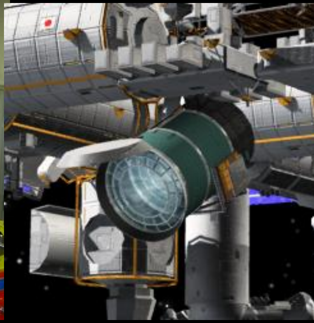
NINA-1

NINA-2

PAMELA



JEM-EUSO



89 M 91 TS 93 C 94 C 97 C 98

PAMELA

89 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2006 ...

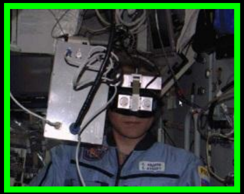
NINA-1 NINA-2

LAZIO-SIRAD

SILEYE-1 SILEYE-2 SILEYE-3

ALTEA

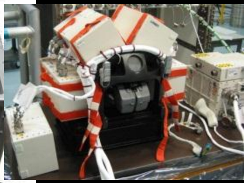
SILEYE-



SILEYE-2

SILEYE-3/ ALTEINO:

LAZIO-SIRAD



SILEYE-4/ALTEA

LBL-30773
ASTROMAG-034

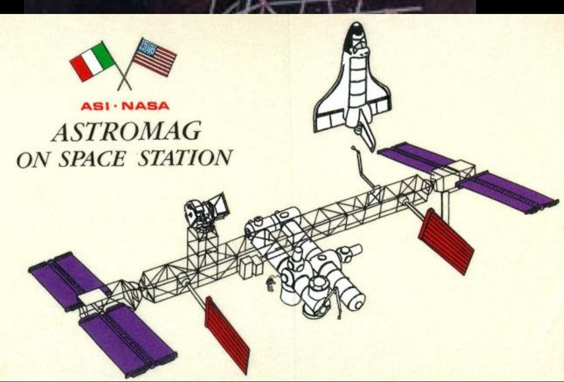
THE ASTROMAG SUPERCONDUCTING MAGNET FACILITY CONFIGURED FOR A FREE FLYING SATELLITE

M. A. Green and G. F. Smoot

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

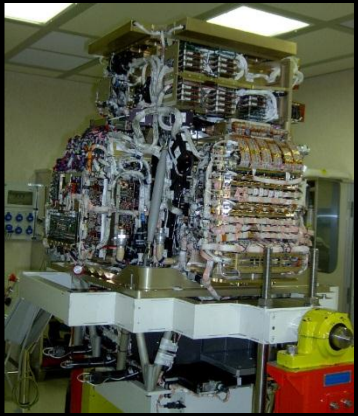
June 1991

1991 Space Cryogenics Workshop
June 18-20, 1991
NASA Lewis Space Flight Center
Cleveland, Ohio



MASS-89, 91, TS-93, CAPRICE 94-97-98

PAMELA



PAMELA Collaboration

Italy:

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

Russia:

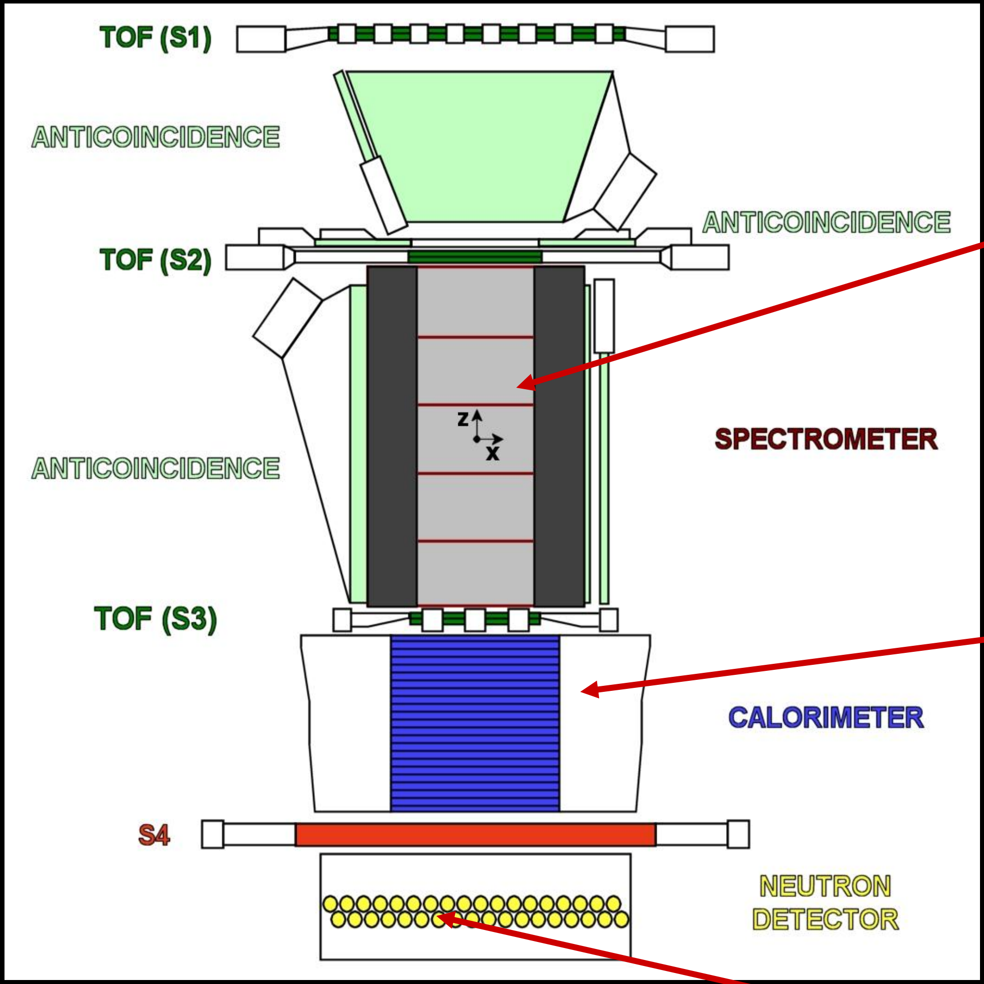
Ioffe Physico-Technical Institute

Moscow
St. Petersburg

Germany: Universität Gesamthochschule Siegen
Siegen

Sweden: Kungl Tekniska Högskolan
KTH, Stockholm

The PAMELA apparatus



Spatial Resolution
- ≅ 2.8 μm bending view
- ≅ 13.1 μm non-bending view

MDR from test beam data ≅ 1 TV

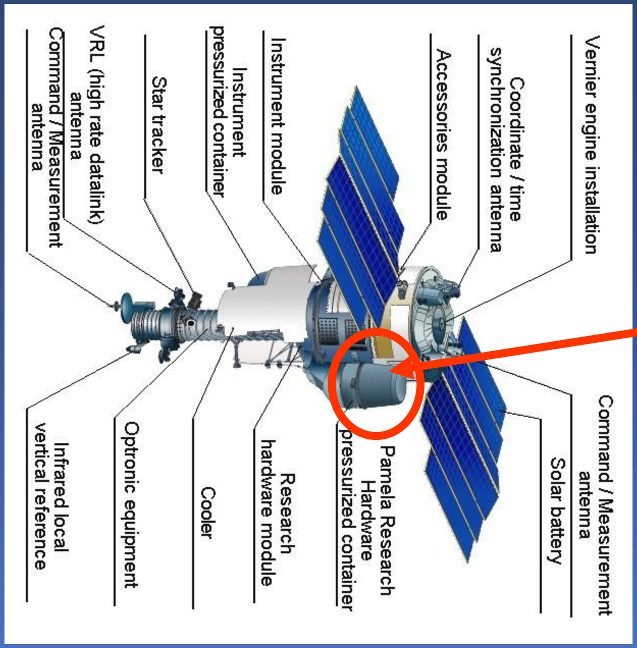
Calorimeter Performances:
- $\bar{p}/e^+$ selection eff. ~ 90%
- p rejection factor ~ 10^5
- e^- rejection factor > 10^4

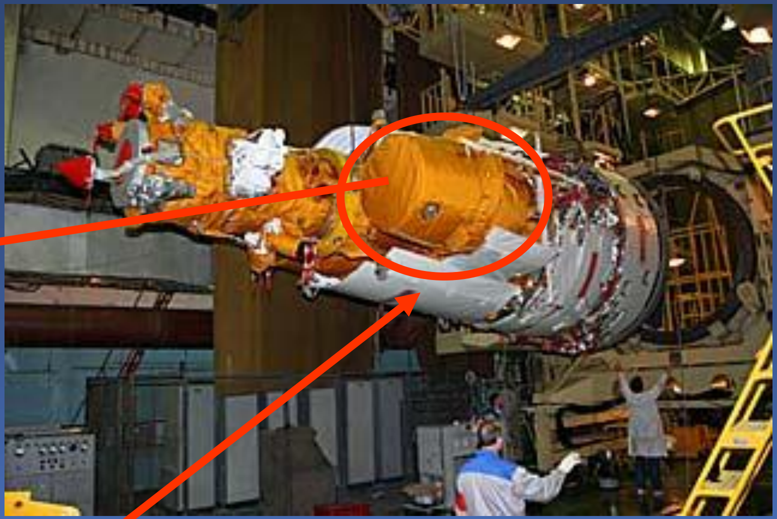
GF ~20.5 cm^{2}sr
Mass: 470 kg
Size: 120x40x45 cm^3
Power Budget: 360 W

ND p/e separation capabilities >10 above 10 GeV/c, increasing with energy

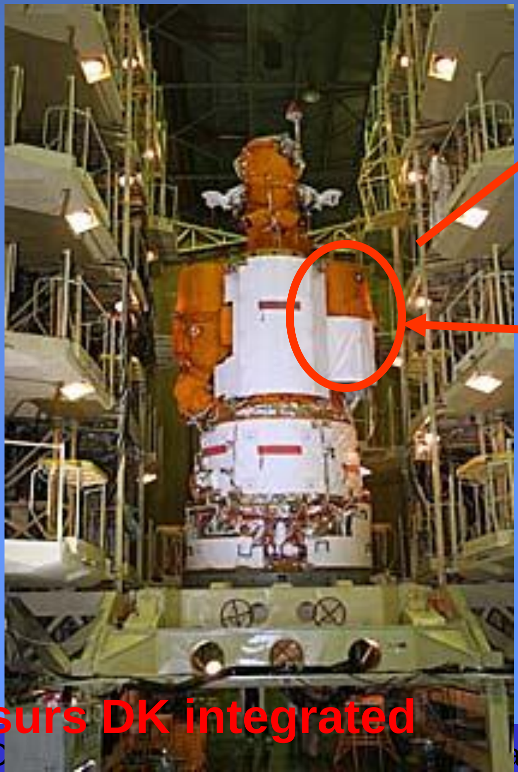
Integration in Baikonur cosmodrome,
Spring 2006

Gagarinsky Start, 14/6/2006

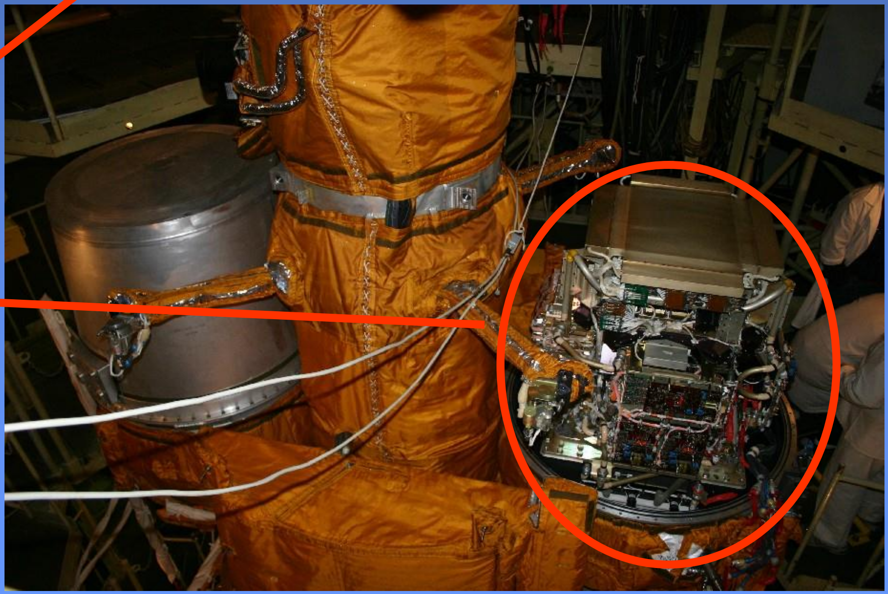




Coupling to Soyuz



Resurs DK integrated

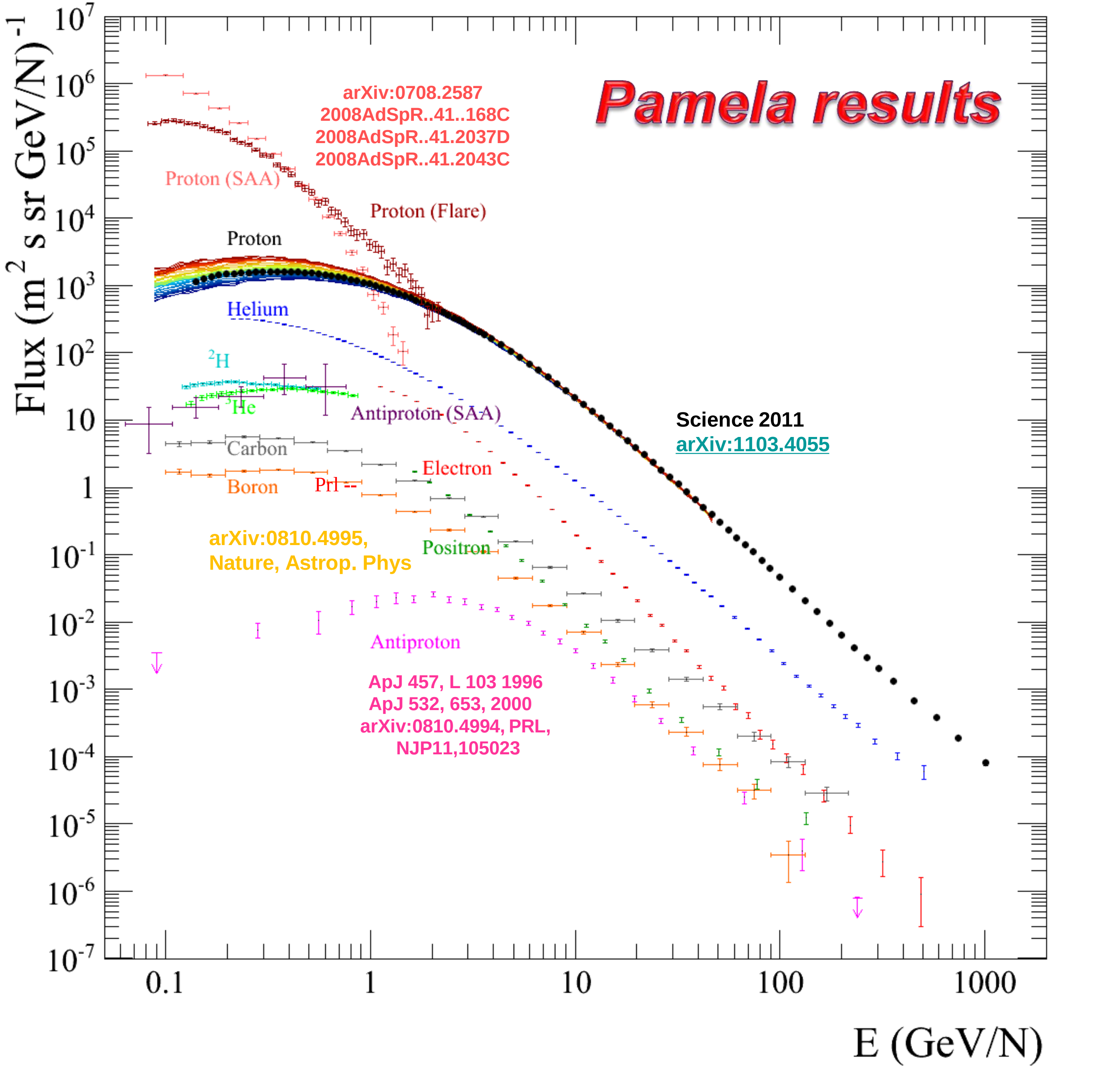


Pamela during integration in Baikonur


Launch on June 15th 2006 Soyuz-U rocket
70 degrees polar orbit
350*600km inclination,
now 600km
Low cutoff

Concentrate on measurements

For interpretation(s) see later talks

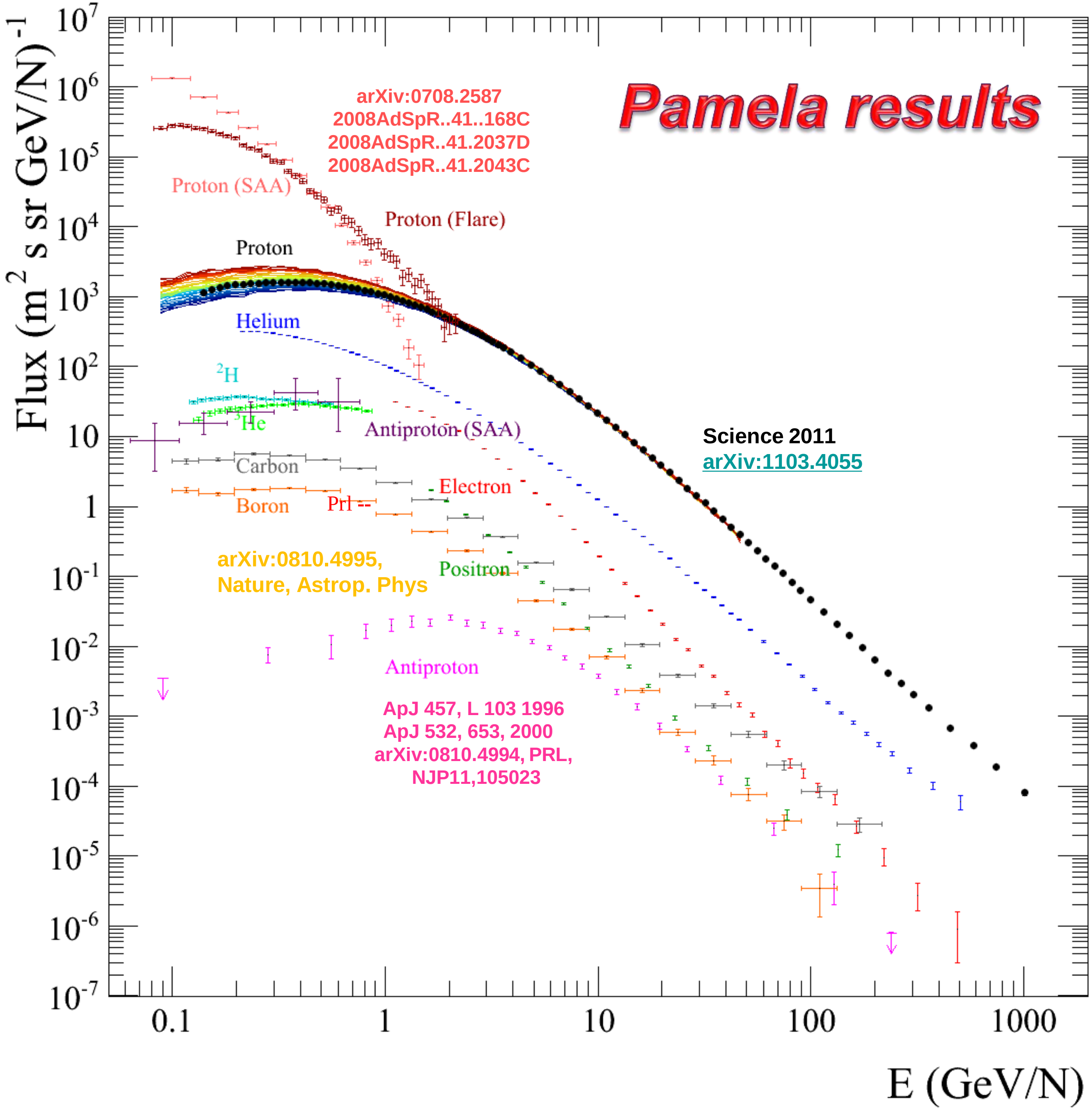


High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere

On several different scales

→ Modeling

→ Dose and risk estimation for astronauts on ISS and Moon/Mars



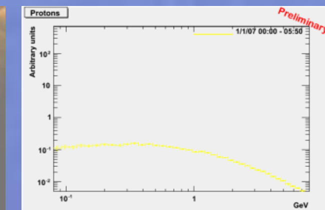
PAMELA, a Space observatory at 1AU

High Inclination Orbit 70.0°

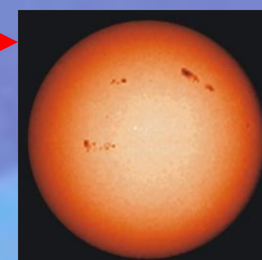
Gradients in the heliosphere

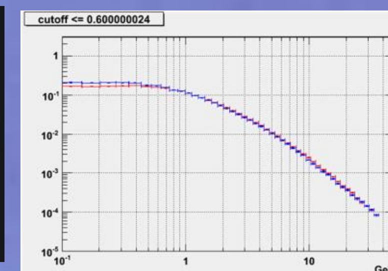
Galactic cosmic ray
Matter / Antimatter
/ Dark Matter

Solar Energetic particles : Low Cut

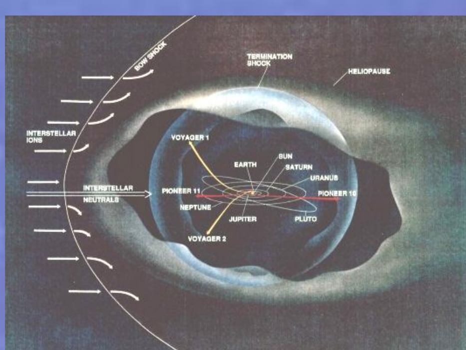


Solar Modulation

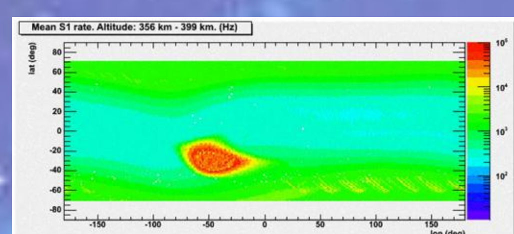




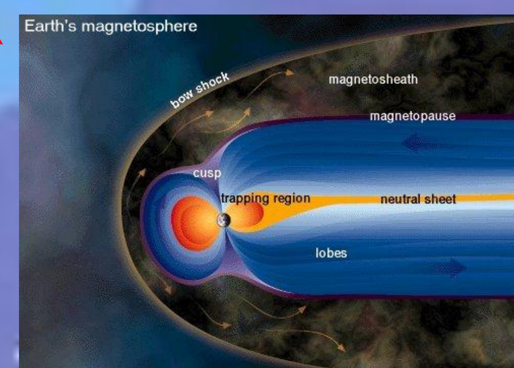
Interplanetary Physics,
Solar Wind Termination Shock



SAA, Albedo,
secondary particle



Magnetospheric physics



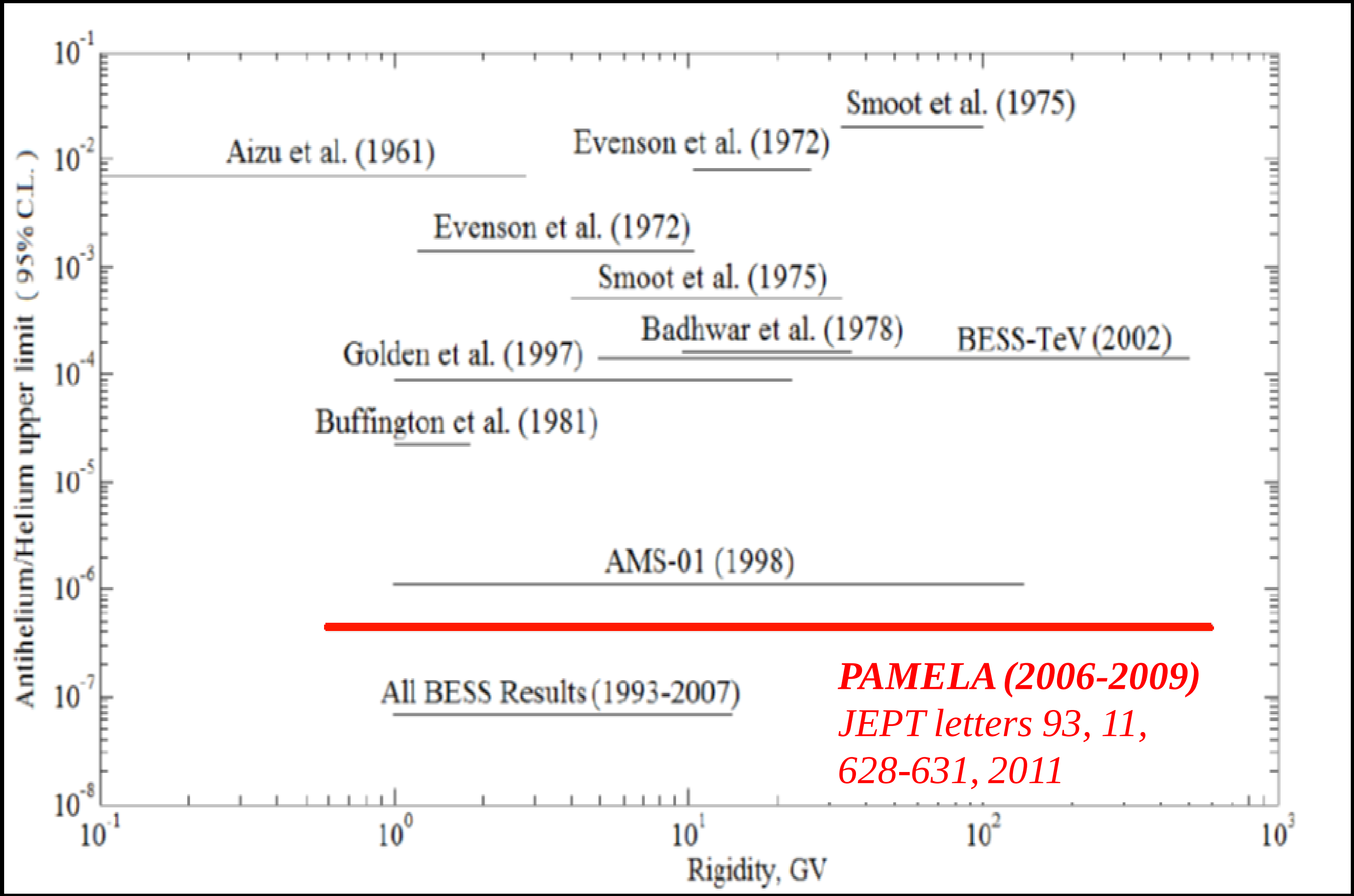
Search for antinuclei
cosmological matter-antimatter asymmetry

Antihelium also from primordial nucleosyinthesis

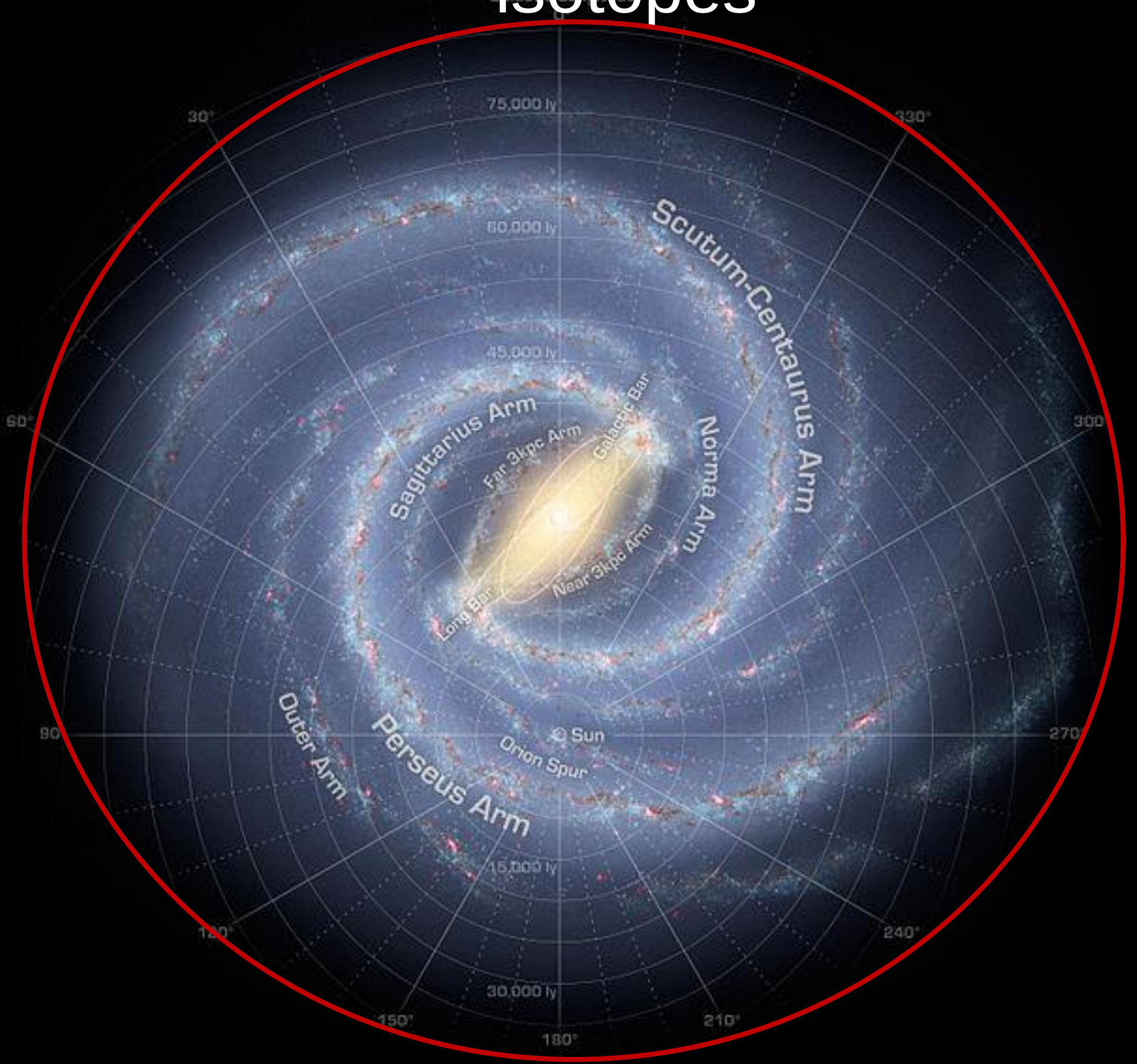
Antinuclei only from antistars

Also strange quark matter

→ AMS02

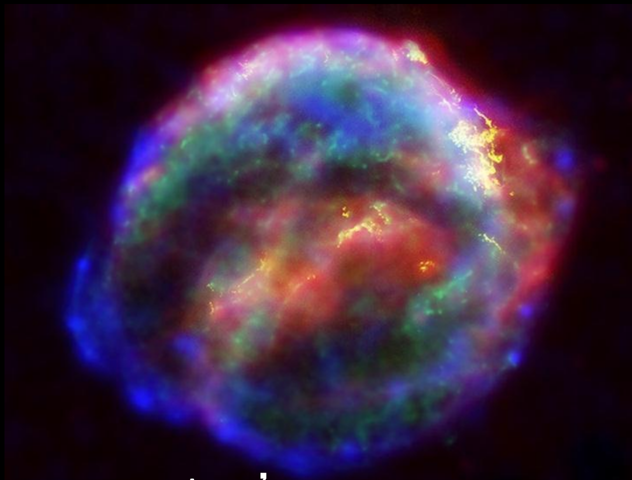


Cosmic rays on Galactic scale: Nuclei, protons, antiprotons, isotopes

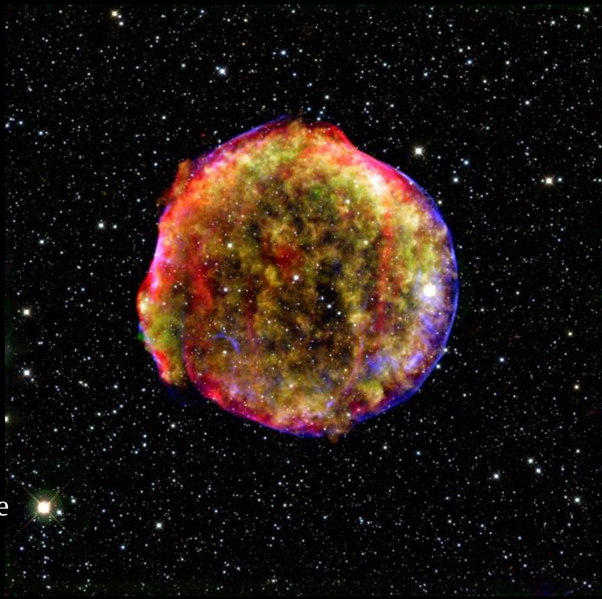


Cosmic rays are accelerated in Supernova explosions (probably)

- Meet energy criteria
- First order Fermi shock acceleration produces power law spectrum
- Observed in gamma by Agile and Fermi
- *Blasi, ICRC1291*



Keplers’ supernova



Tycho’s supernova

- HESS TeV emision from SNR RX J1713.7-3946 → hadronic inter. Of cr. E>10^14eV *F. Aharonian, et al., Astron. Astrophys. 464, 235 (2007)*.
- X-ray measurements of the same SNR → evidence that protons and nuclei can be accelerated E>10^15 eV in young SNR *Uchiyama, et al., Nature 449, 576 (2007)*.
- AGILE: diffuse gamma-ray (100 MeV – 1 GeV) SNR IC 443 outer shock → hadronic acceleration *M. Tavani, et al., ApJL 710, L151 (2010)*.
- Fermi: Shell of SNR W44 have → decay of pi0 produced in the interaction of hadrons accelerated in the shock region with the interstellar medium *A. Abdo, et al., Science 327, 1103 (2010)*.
- Starburst galaxies (SG), where the SN rate in the galactic center is much higher than in our own, the density of cosmic rays in TeV gamma-rays (H.E.S.S infers cosmic rays density in SG NGC 253 three orders of magnitude higher than in our galaxy *F. Acero, et al., Science 326, 1080 (2009)*.
- VERITAS: SG M82 cosmic rays density is reported to be 500 times higher than in the Milky Way *VERITAS Collaboration, et al., Nature 462, 770 (2009*

B/C ratio

Propagation in Galaxy

- B/C ratio

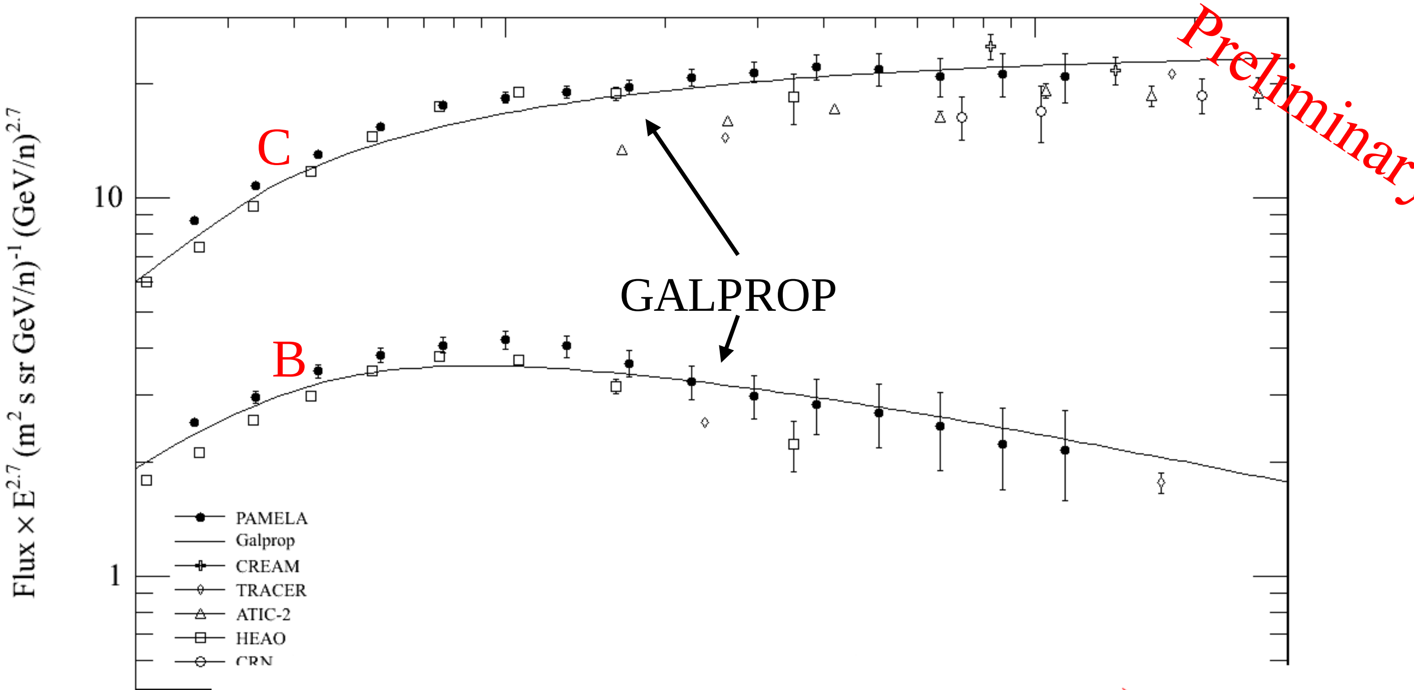
Secondary/primay

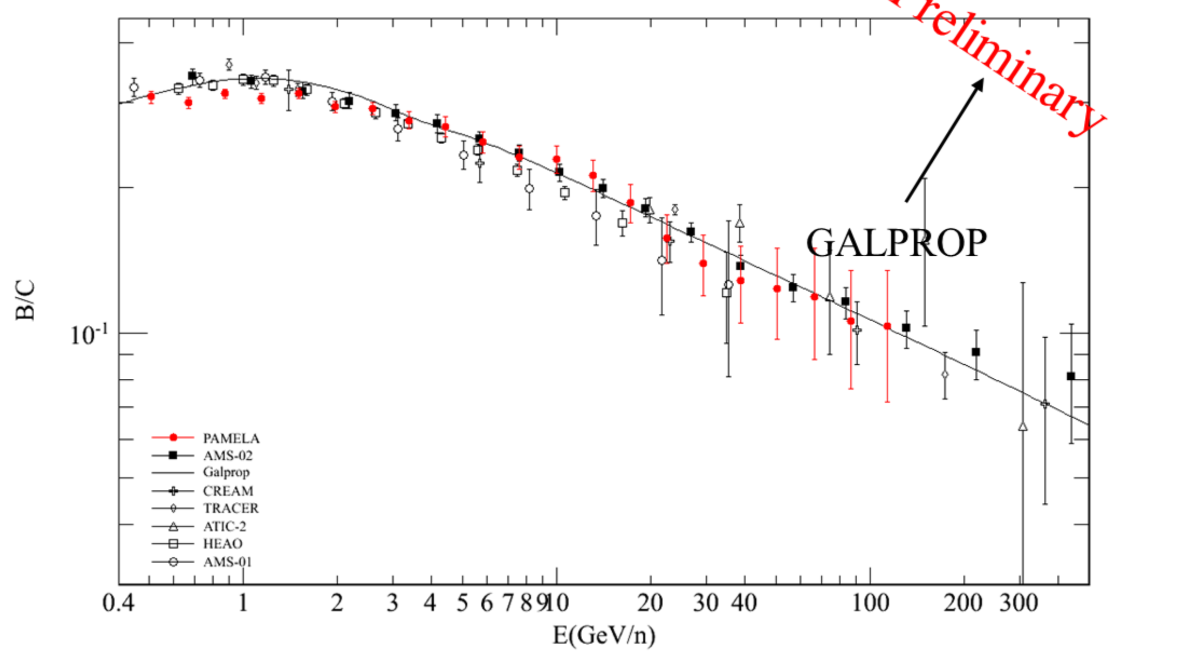
CNO+ISM → B

→ Propagation in the Galaxy

Time of permanence of cr

$$N_B / N_C \propto \lambda_{esc} \cdot \sigma_{CNO \to B}$$



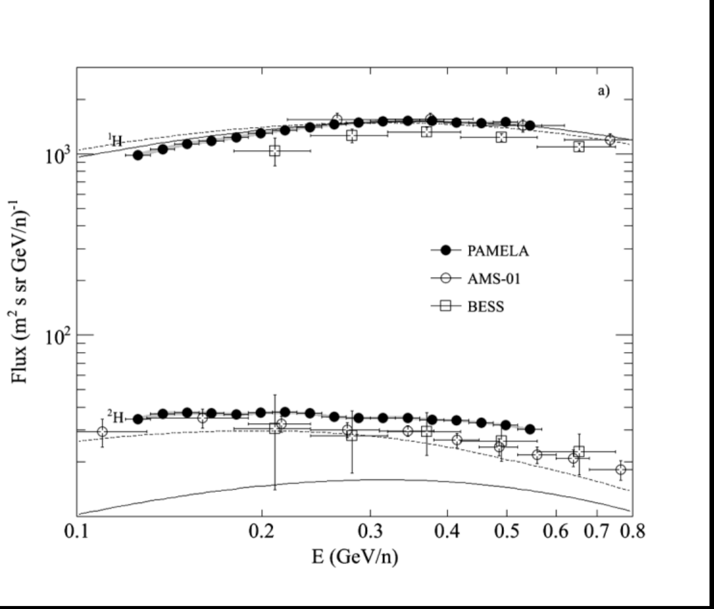


H isotopes

Propagation in the Galaxy

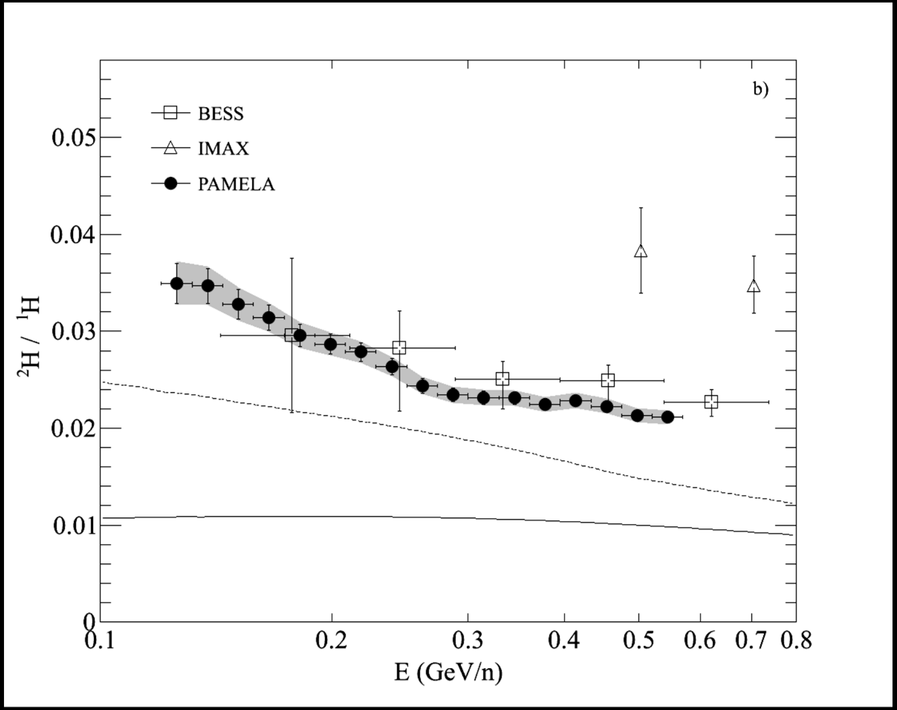
- Flux depends on solar modulation
- Ratio is less dependent
- Strong tool for evaluating secondary particle production in the galaxy
- Complementary to B/C

^{1}H and ^{2}H fluxes



O. Adriani et al., ApJ 770, (2013) 2

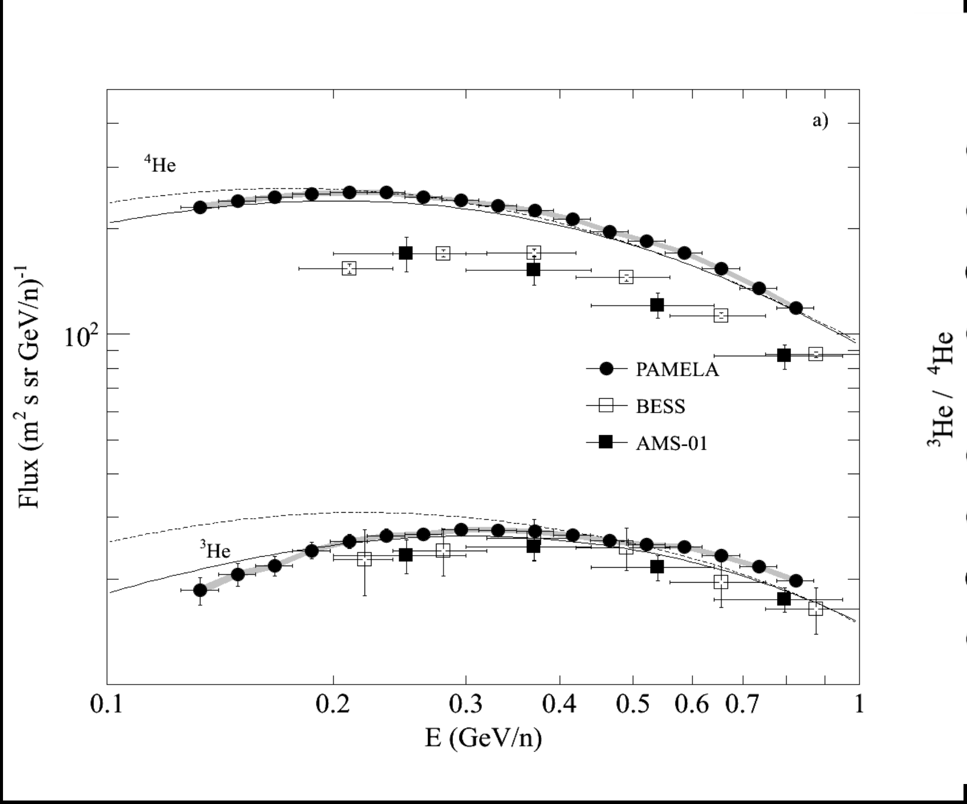
$^{2}H/^{1}H$



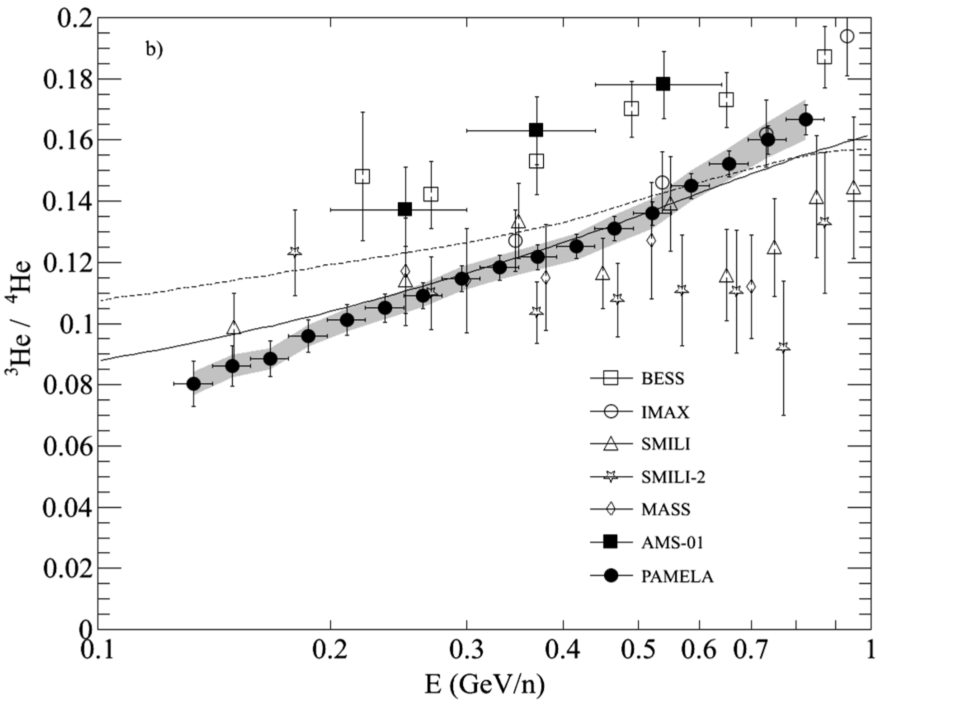
Moskalenko 2003
Tomassetti 2012
Coste et al 2012
Moskalenko ICRC832

Helium Isotopes

^4He and ^3He fluxes



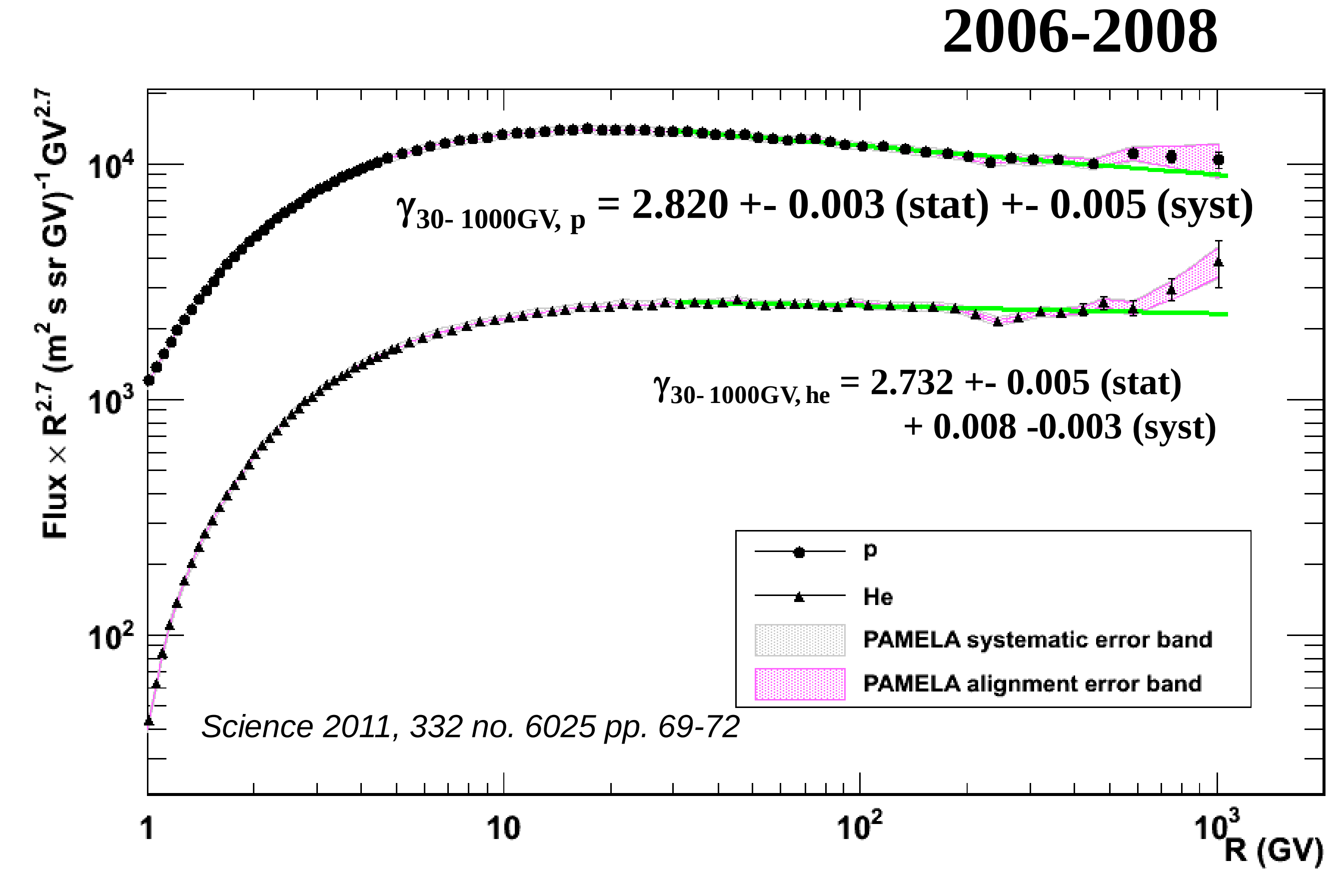
$^3He/^4He$



O. Adriani et al., ApJ 770, (2013) 2

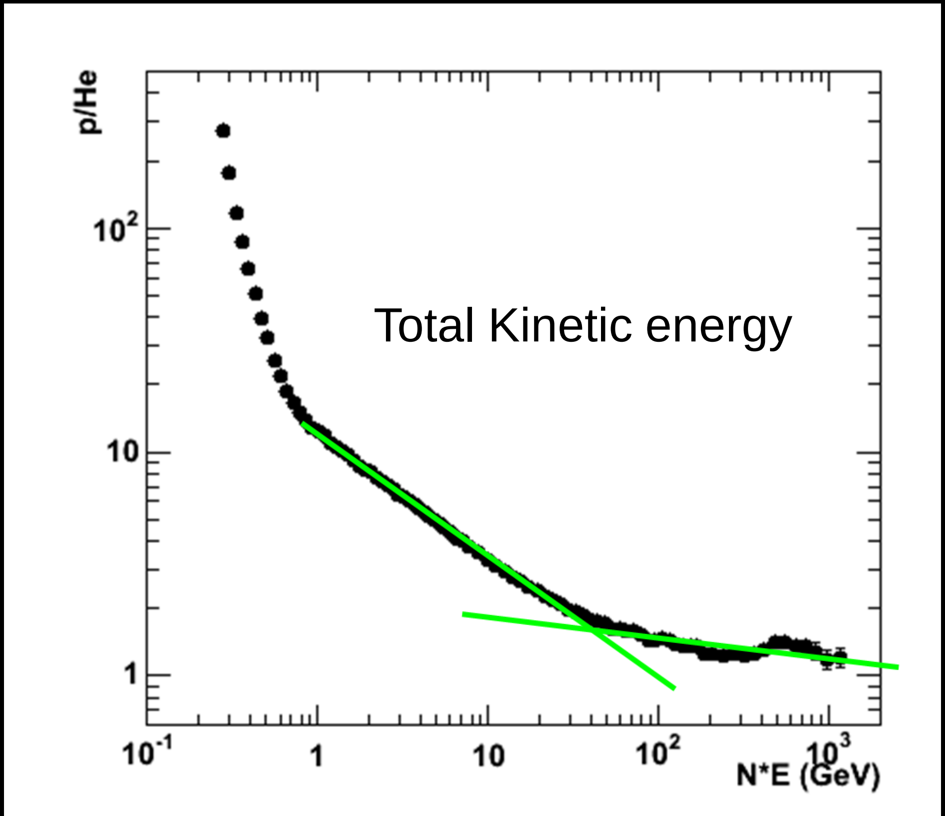
Pamela galactic proton and He

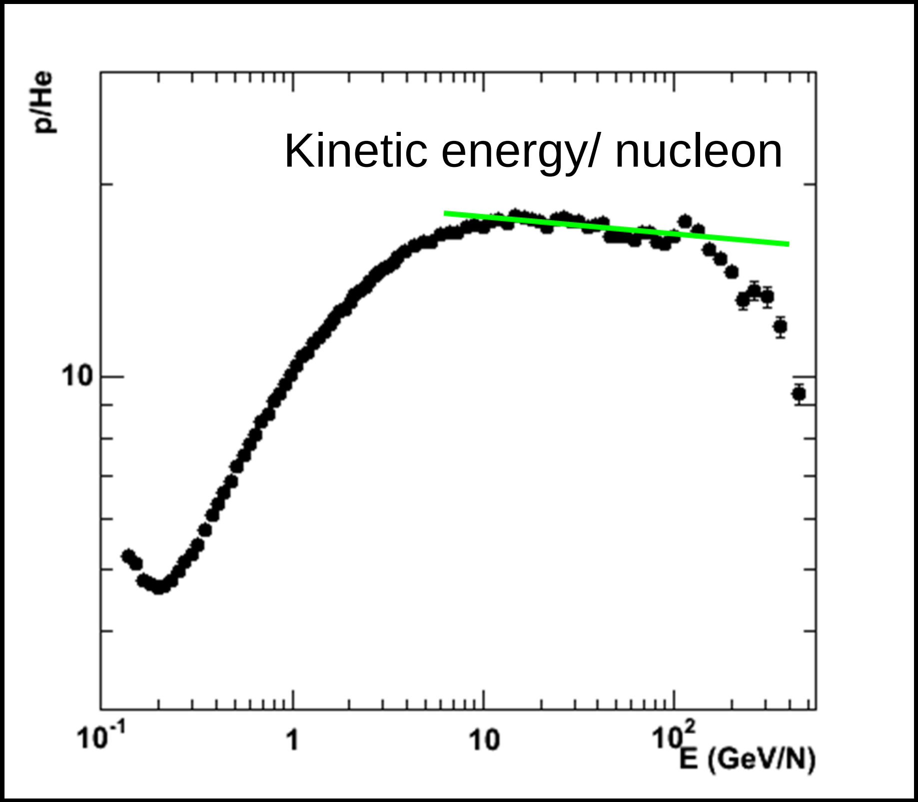
- Different spectral index for proton and helium.
- Helium percentage is growing with rigidity
- Challenges Supernova only origin of cosmic ray and/or acceleration/propagation models.



P/He Ratio

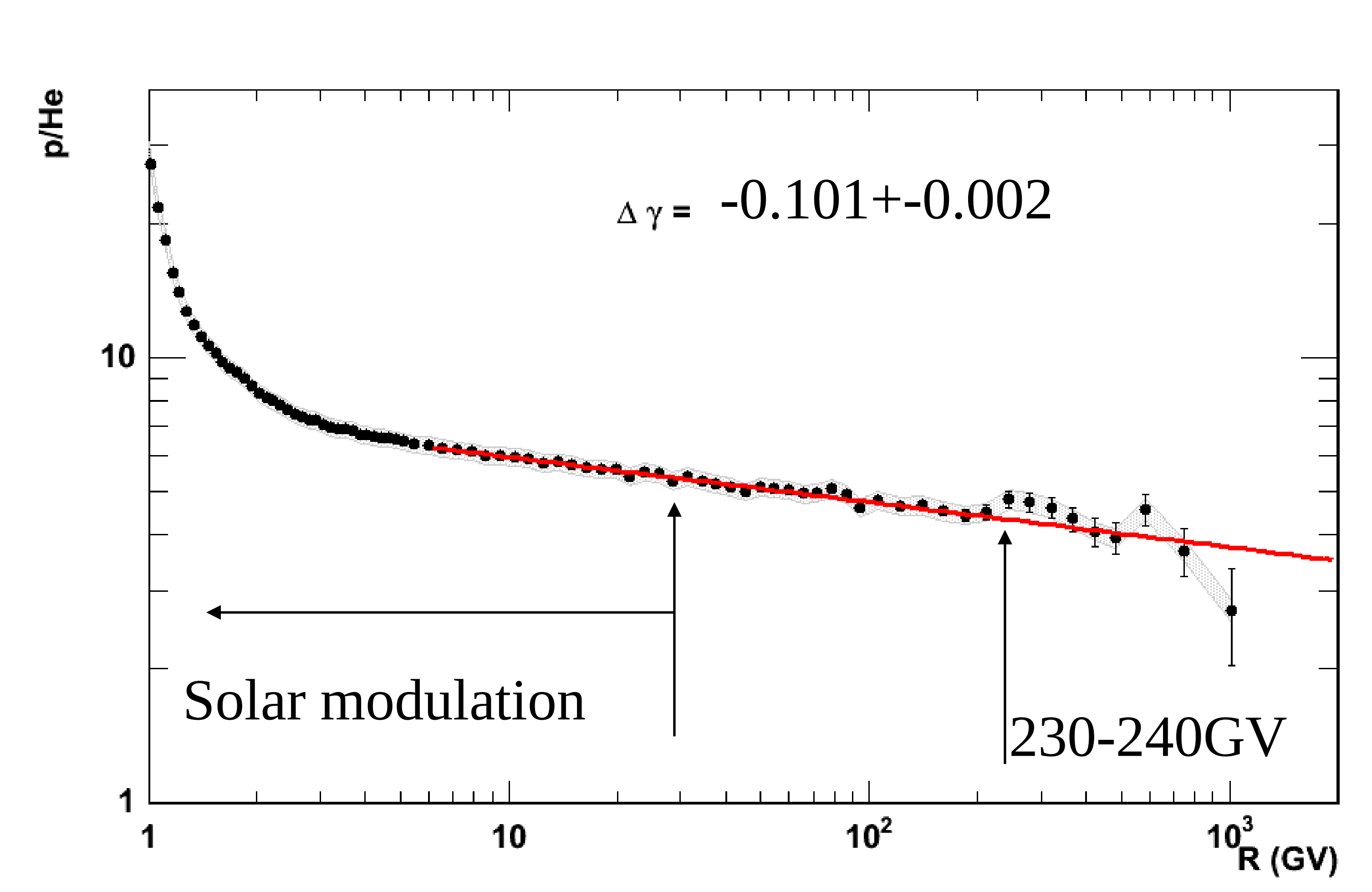
Clean ratio only in Rigidity



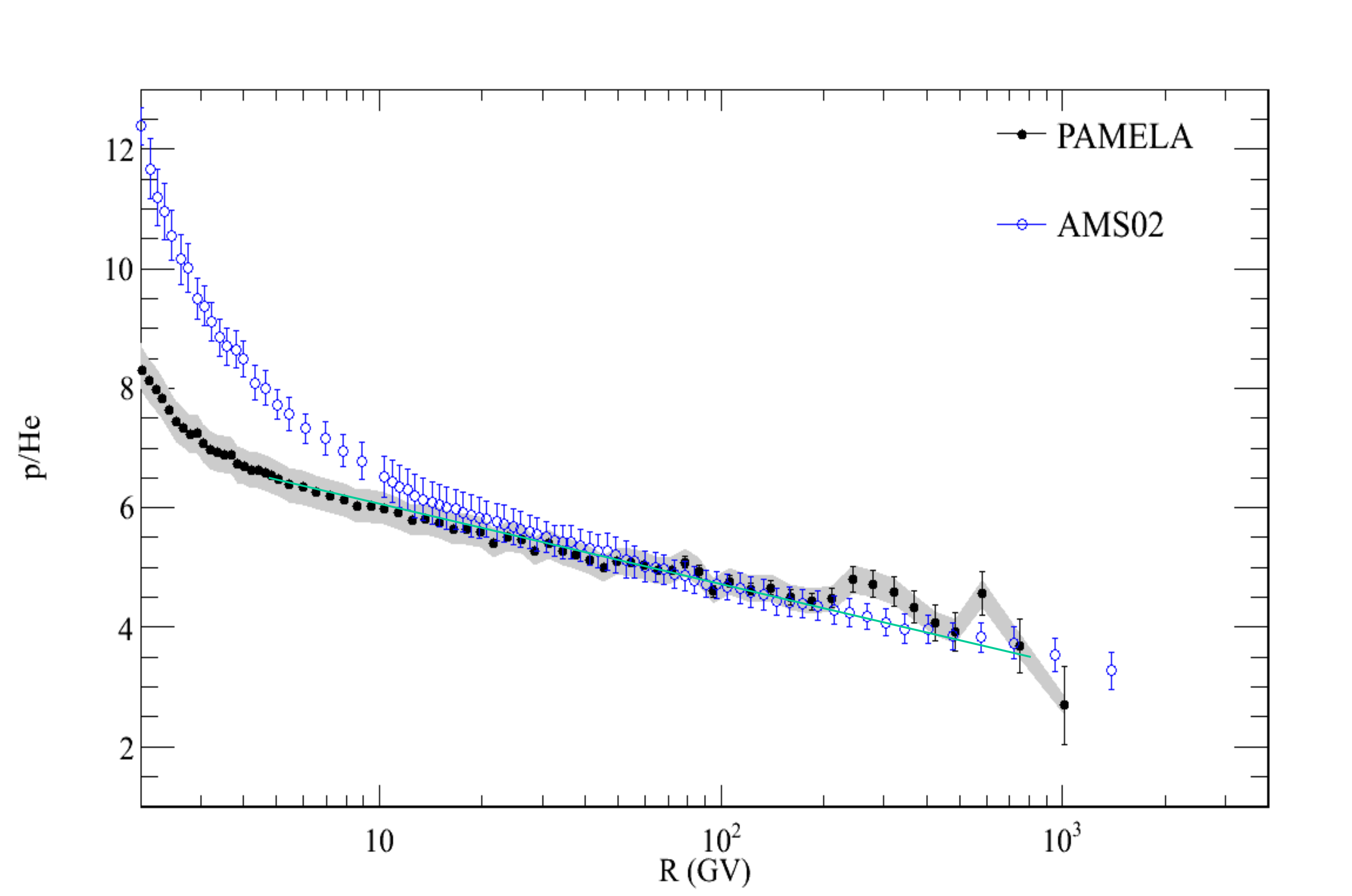


Ratio P/He: Rigidity

1. Acceleration is a rigidity dependent effect
2. The ratio decreases→ More He at high energies → Acceleration mechanisms or sources are different?
3. Measurement valid also below the (low) solar modulation



- Comparison Pamela - AMS (ICRC2013) data



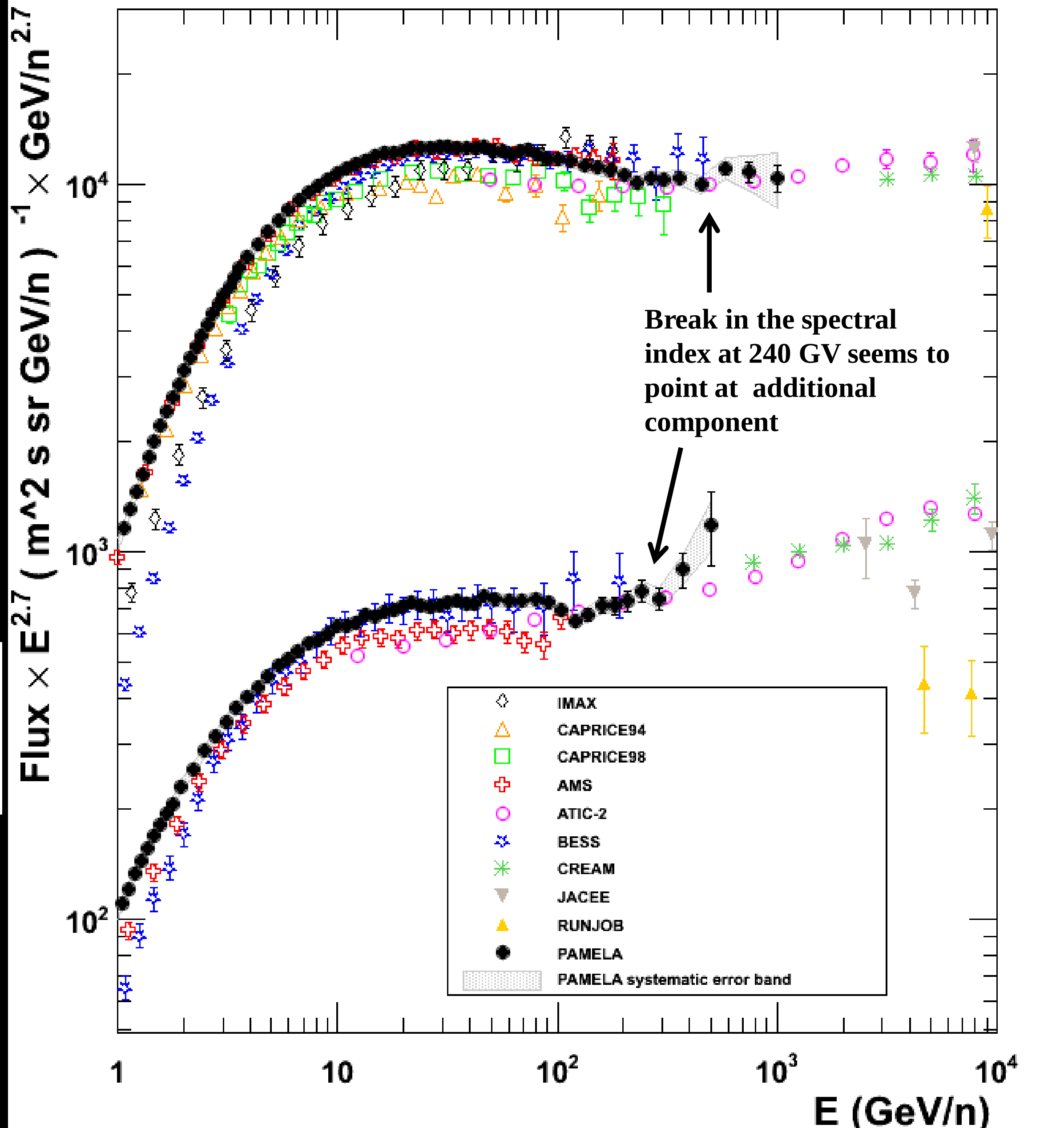
Excellent overlap with high energy experiments

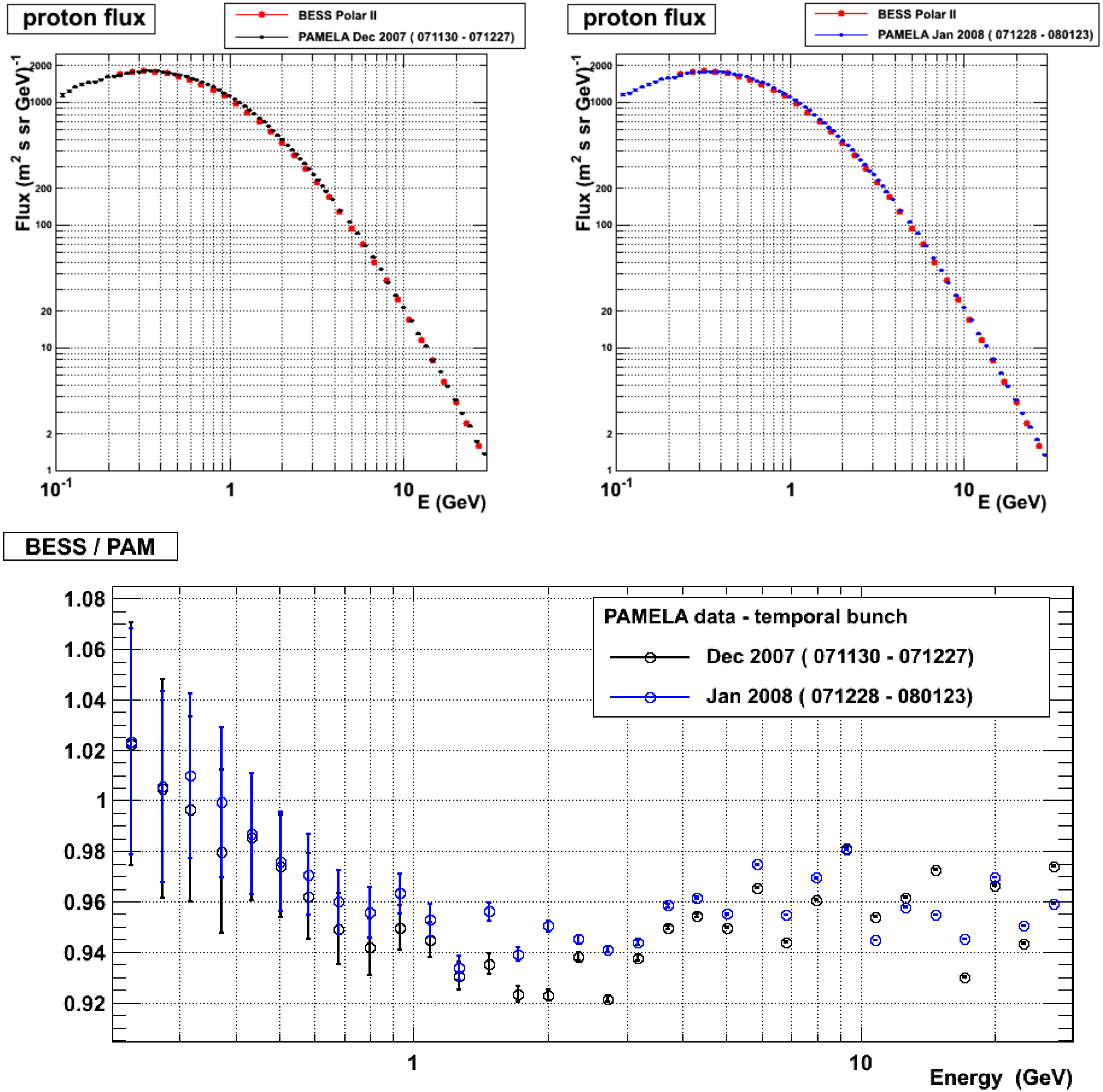
BESS
Brige with ATIC & CREAM toward high energy

$\gamma_{30\text{-}1000\text{GeV, p}}$ = 2.782 +- 0.003 (stat) +- 0.004 (syst)

$\gamma_{15\text{-}600\text{GeV/n, he}}$ = 2.71 +- 0.01 (stat) +- 0.007 (syst)

$$\gamma_T = \frac{dlog(\phi_T)}{logT} = (\gamma_R - 1)\frac{T^2 + Tmc^2}{T^2 + 2Tmc^2} + \frac{T}{T + mc^2}$$

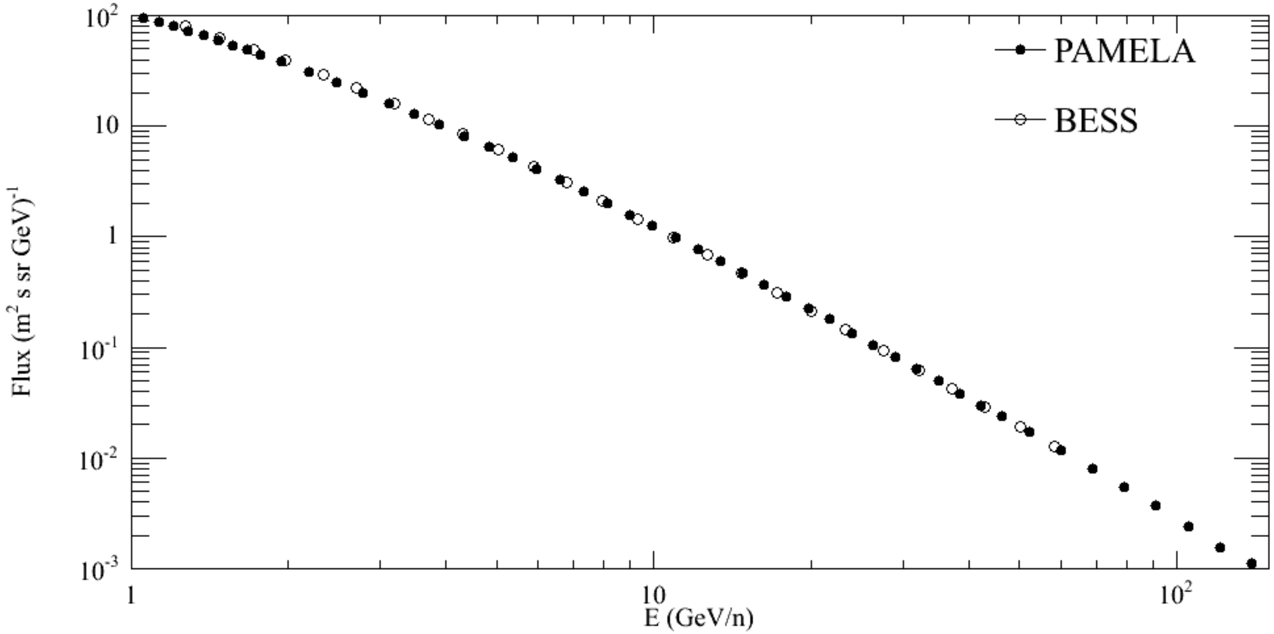


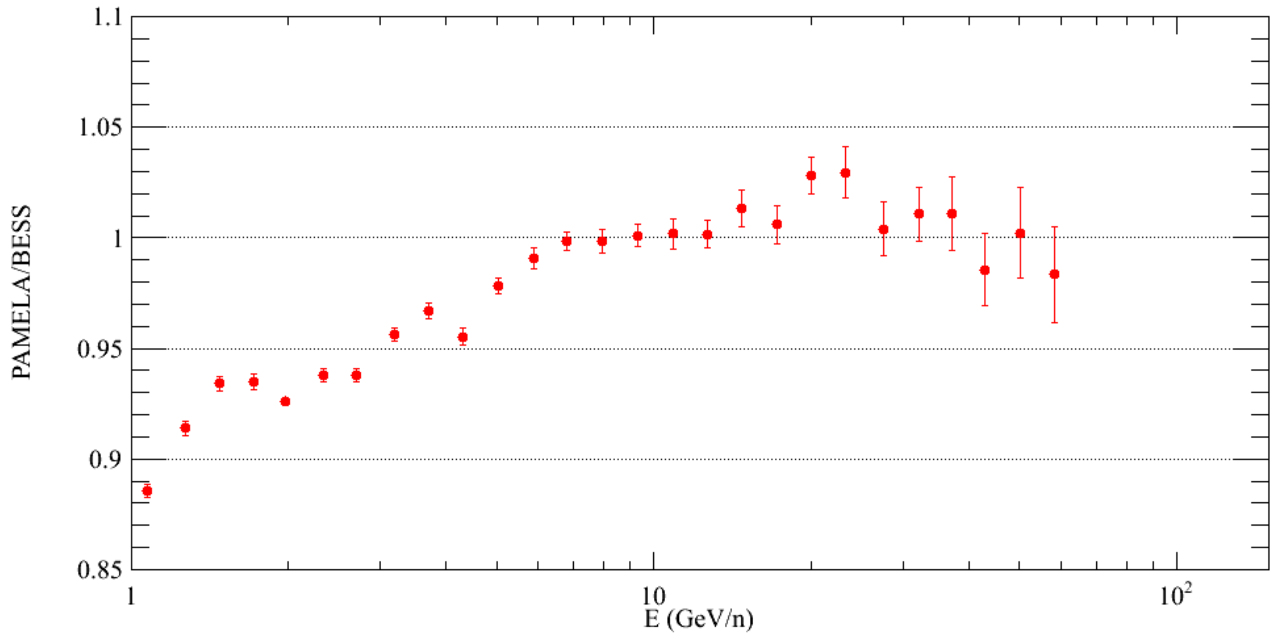


PAMELA & BESS-PolarII proton spectrum in same temporal frame

Agrement within 4%

Constant with years

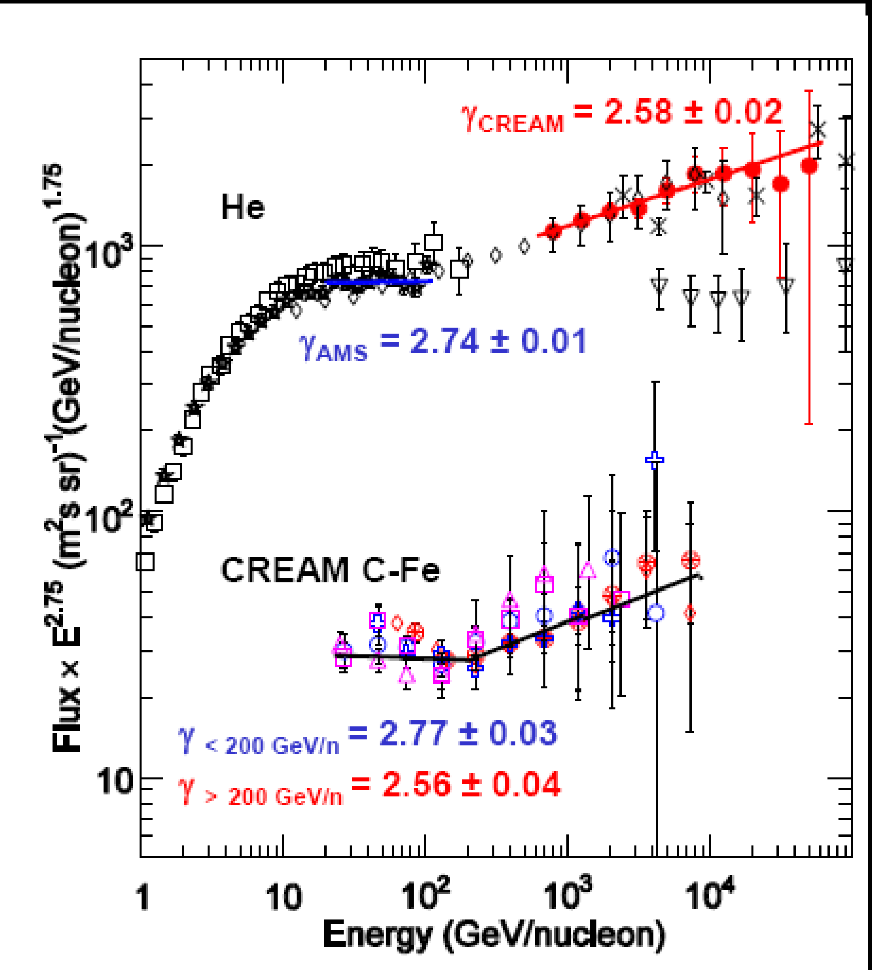


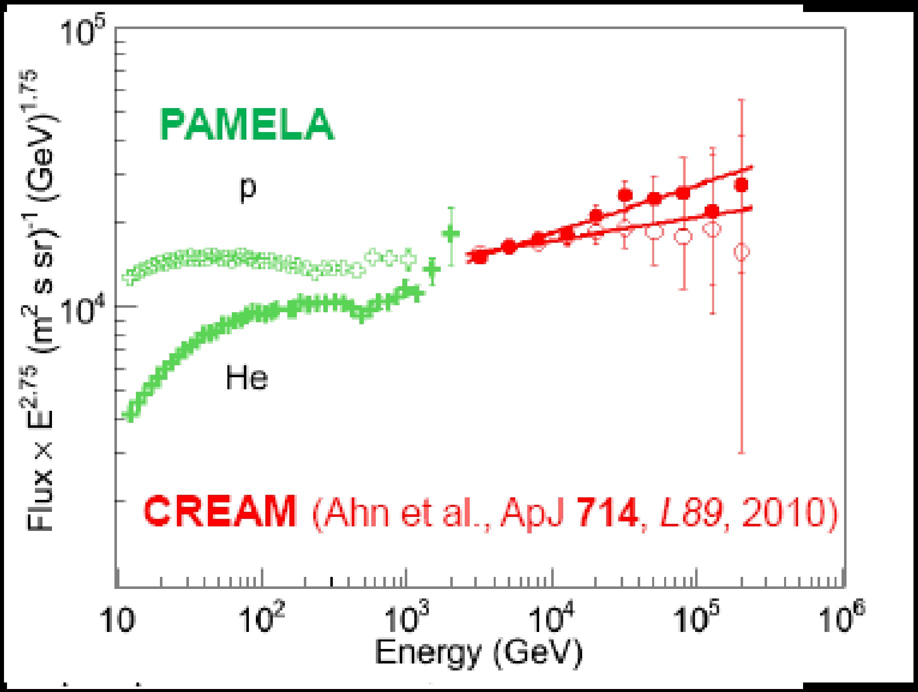


PAMELA & BESS-PolarII helium spectrum

Agreement within stat errors at high energy

At higher energies: Cream data



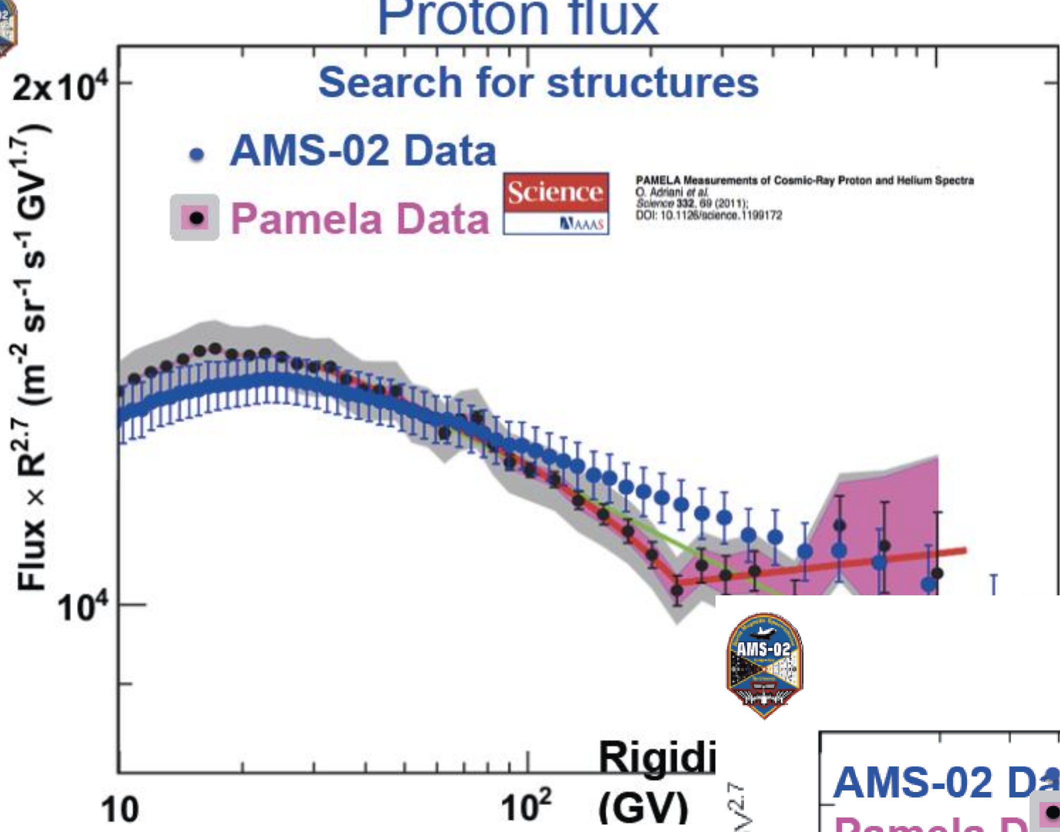


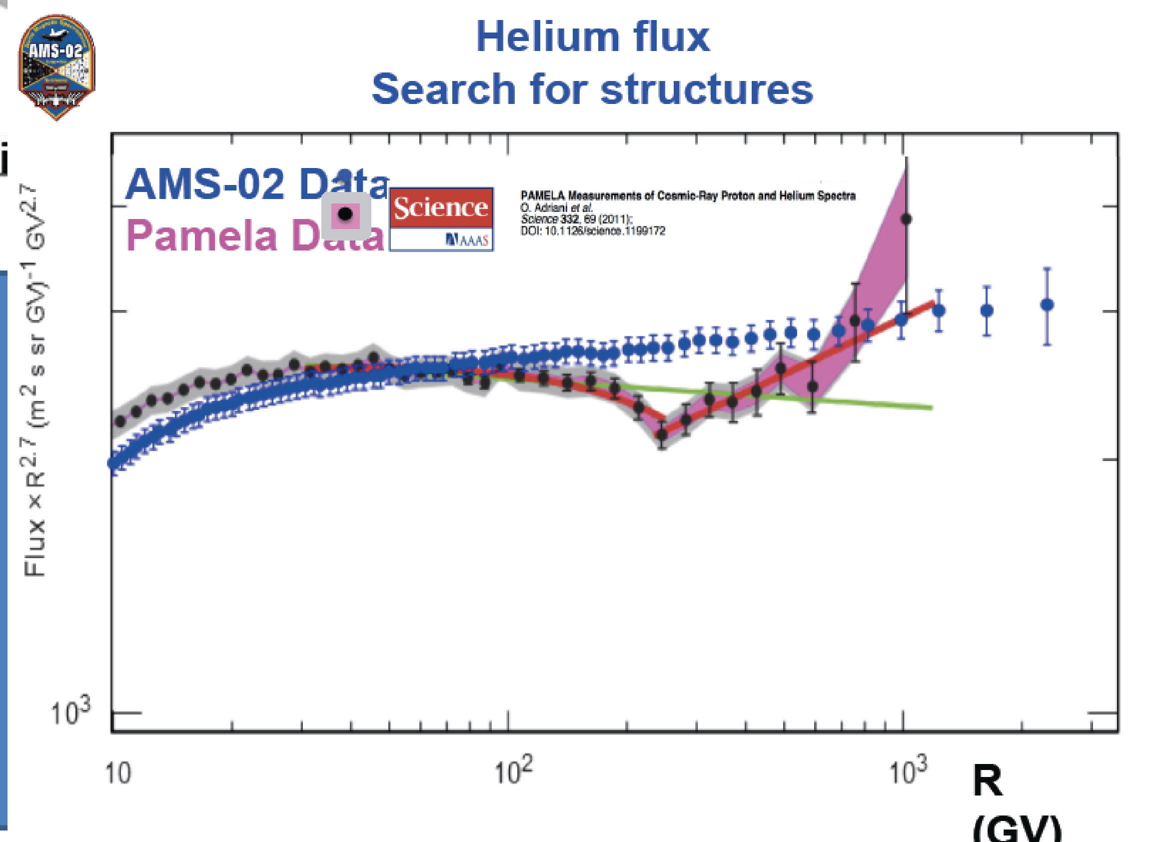
Ahn et al, ApJL 2010

200 GeV/n (PAMELA at 120 GeV/n)

Indirect p, He Direct C-Fe

PAMELA & AMS ICRC 2013 talk





We now understand
the systematic errors to ~1%.

Studies with 1% statistical error
will take time to collect the data.

Slide from R. Battiston talk 18-9-2013
Frascati, Rome

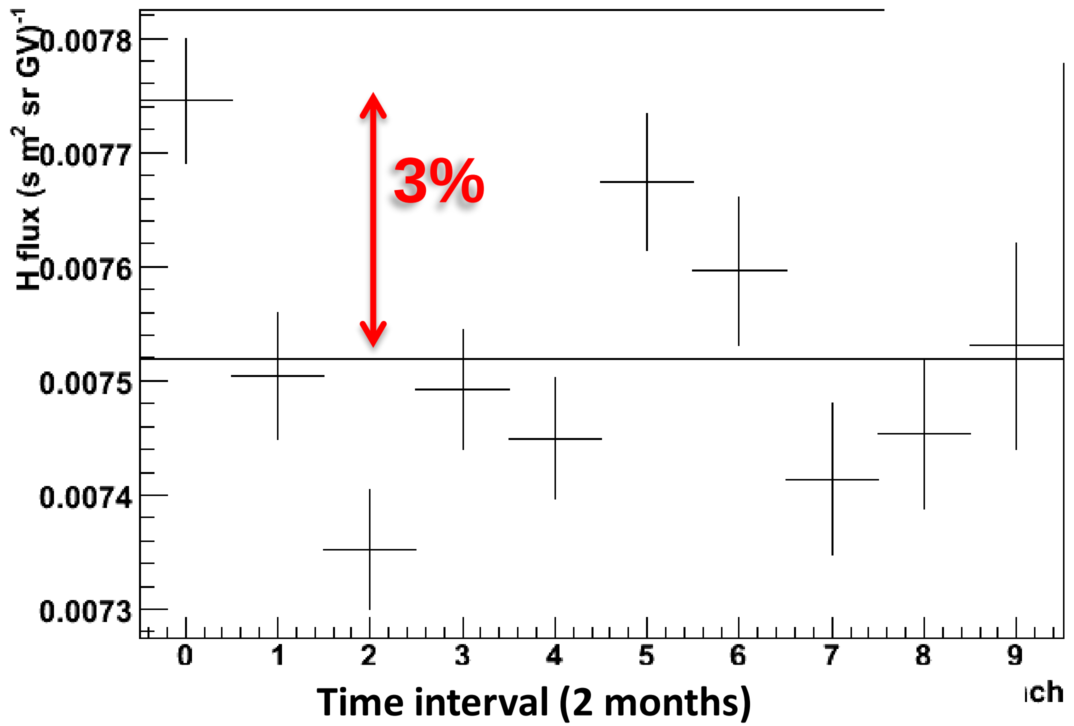
Check of systematics

Fluxes evaluated by varying the selection conditions:

- Flux vs time
- Flux vs polar/equatorial
- Flux vs reduced acceptance
- Flux vs different tracking conditions (⇒ different response matrix)

…

Integral proton flux (>50GV)



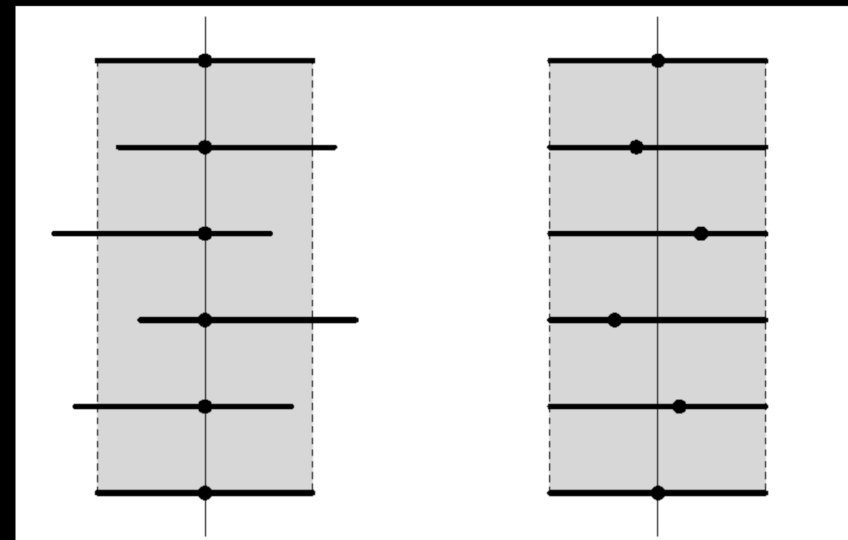
Alignment

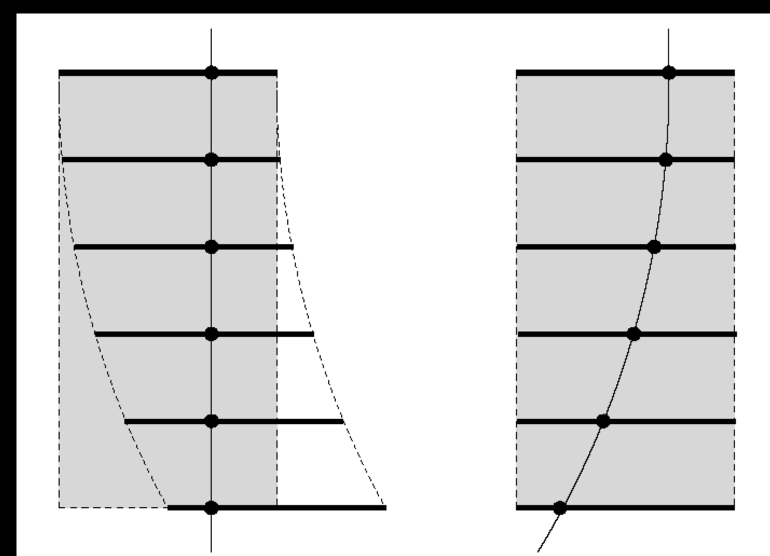
Critical Issue especially for protons and helium

Flux large → Small GF OK
Only tracker .

Performed *only once* after launch
No changes detected in 7 years

Coherent misalignment
Correction with electrons (or electrons + positrons) and comparison with simulation

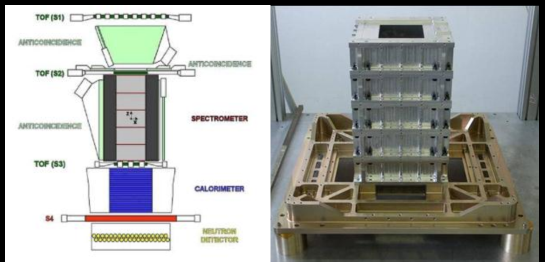


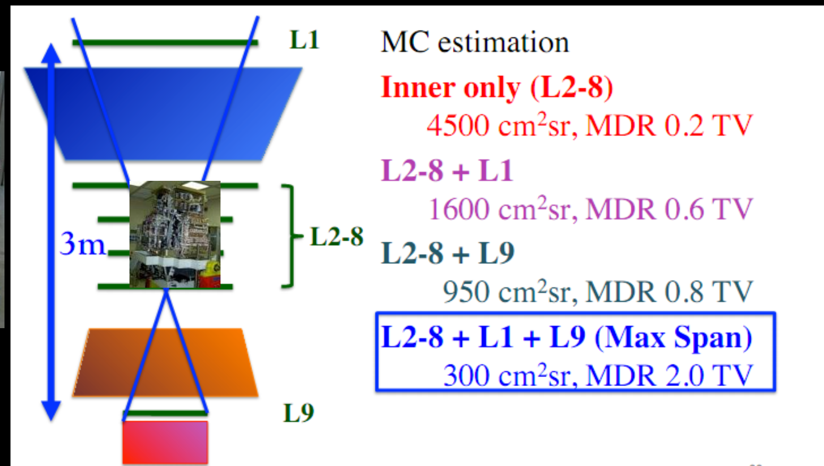


Instrument comparison

AMS

PAMELA





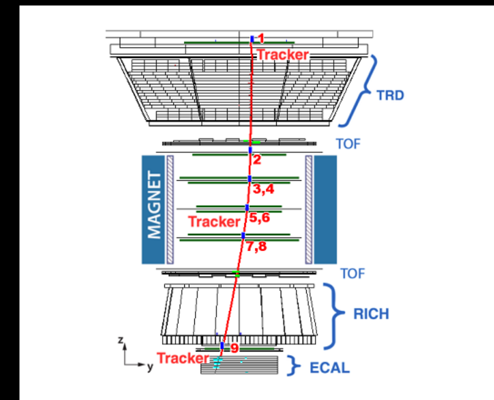


Fig. 1: Schematic view of AMS-02 detector in the bending (y–z plane) with a cosmic-ray proton track in space. Tracker layers (1–9) are also shown.

- Magnetic cavity sizes (132 x 162) mm^2 x 445 mm
- Field inside the cavity 0.48 T at the center
- Only silicon
- Average field along the central axis of the magnetic cavity : **0.43 T**

<u>Geometric Factor</u>: **20.5 cm^{2}sr**

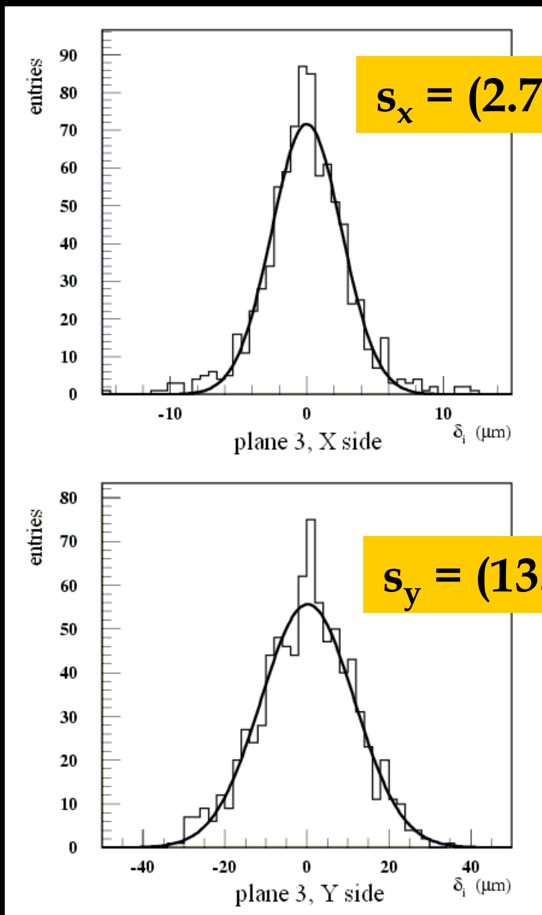
MDR 1.2 TV

- ***Aligned** once in seven years. Stable.*

Large Magnetic Cavity
Permanent magnet replaced
Superconducting
MDR 0.2 TV
TRD RICH between first and last planes
Need to move one silicon plane on top and bottom
To increase lever arm → 2TV
Not mechanically stable → Thermal movements
Require align every 20 minutes
Average on different orbit

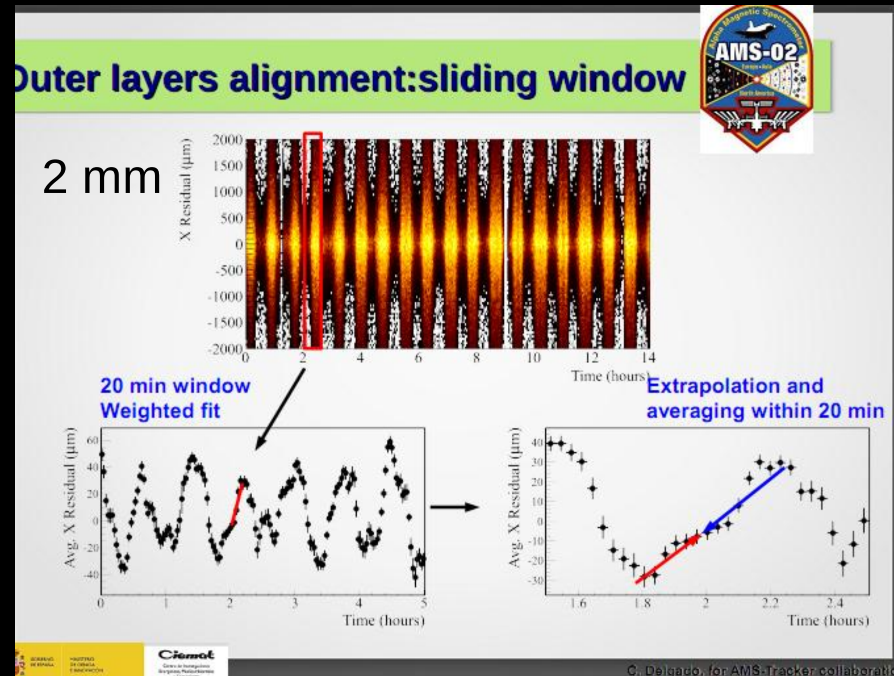
PAMELA

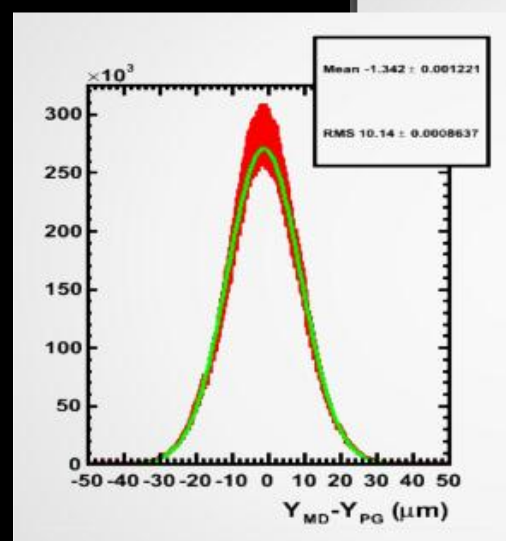
AMS

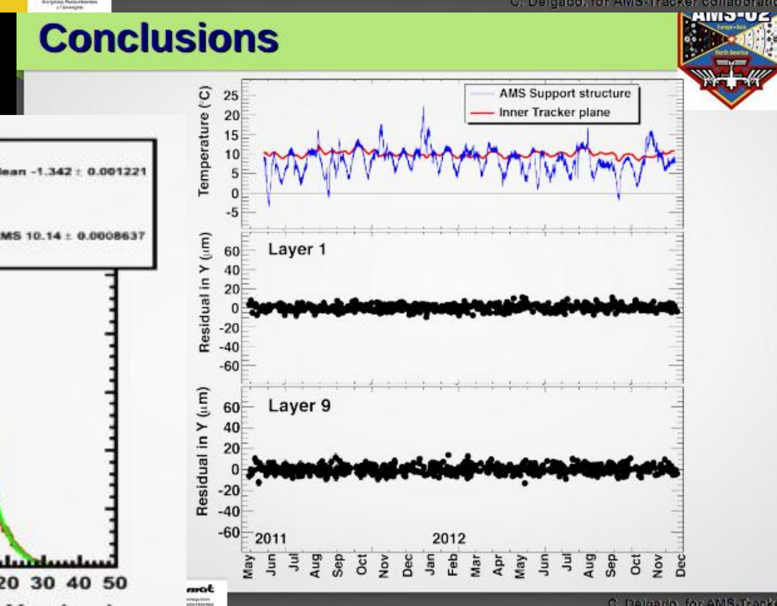


$s_x = (2.77 \pm 0.04)$ μm

$s_y = (13.1 \pm 0.2)$ μm







Conclusion from Proton and Helium

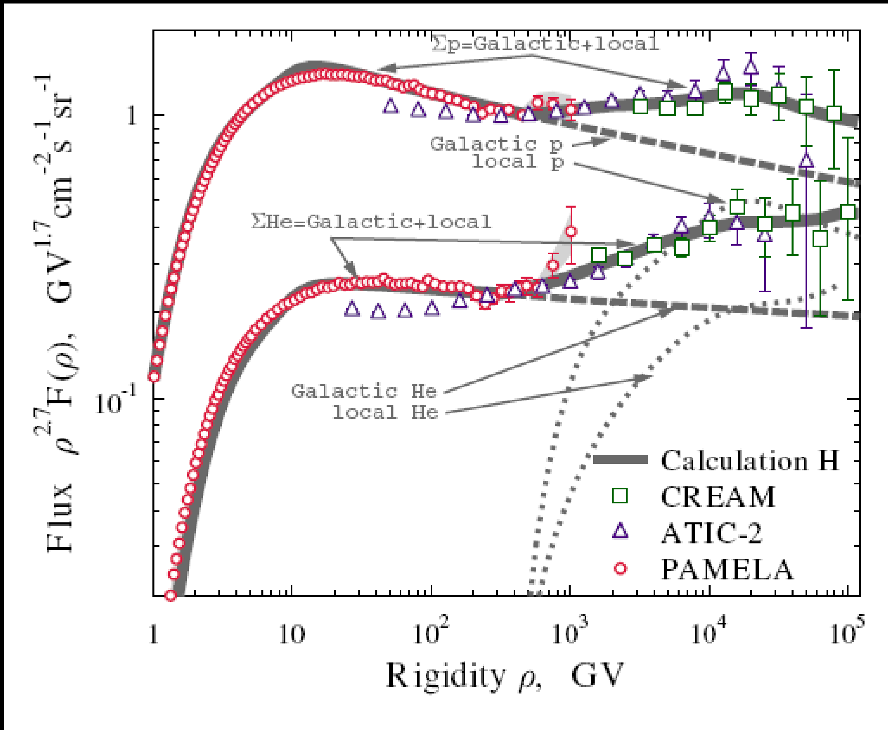
- Proton and Helium undergo different processes even in GeV-TeV scale
- Change in spectral index around 230-240GV
- Check discrepancy with AMS
- Change present in all analysis

Needed to bridge to high energy

Various hypotesis to explain Pamela data

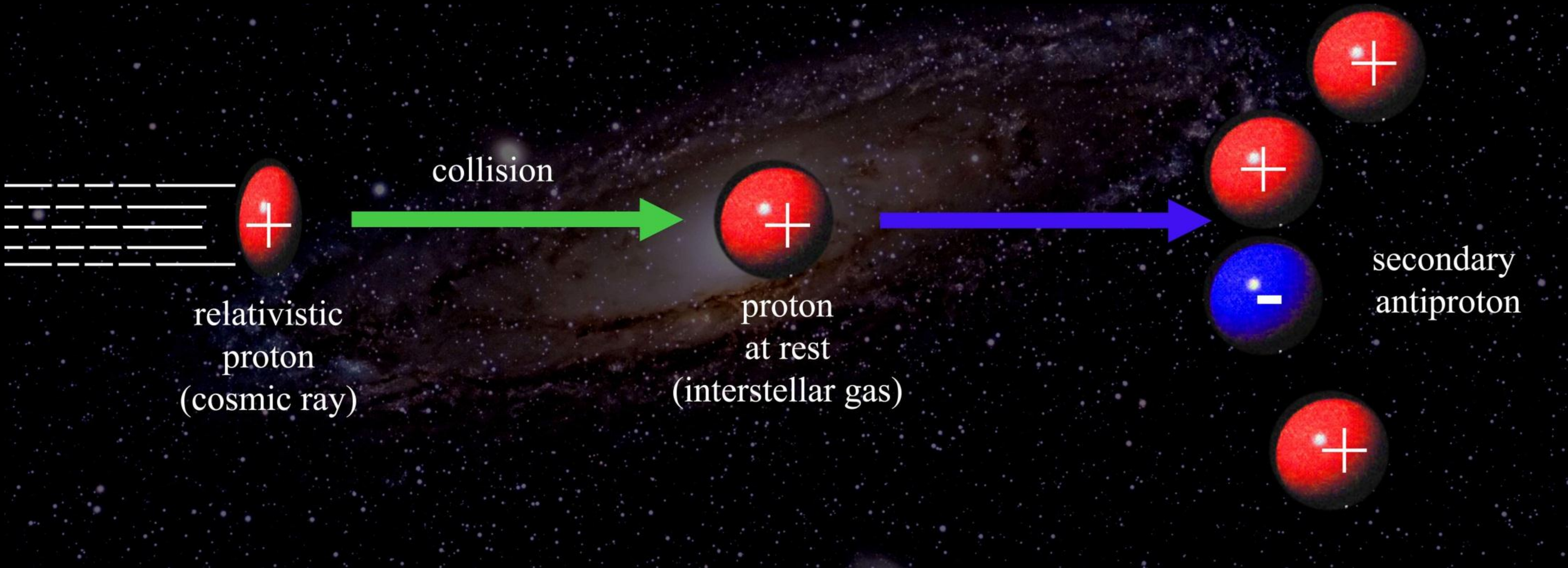
- Additional Sources *Wolfendale 2011, 2012*
- Spallation, Propagation *Blasi & Amato 2011, 2013*
- Weak local component (+ others) *Vladimirov, Johanesson, Moskalenko 2011*
- Reacceleration

Thoudam & Horandel, 2013

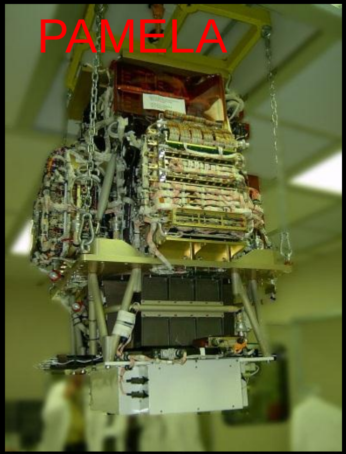


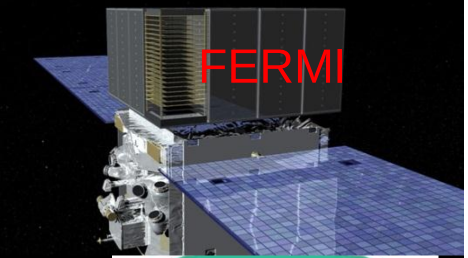
Antiprotons

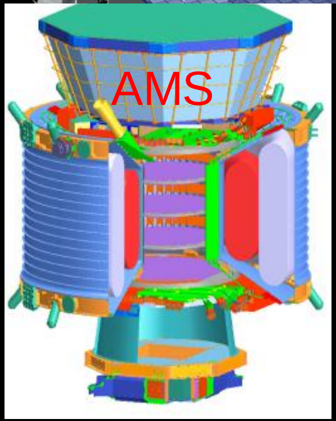
- Secondary production, kinematics well understood
- Probe for extra sources
- Galactic scale

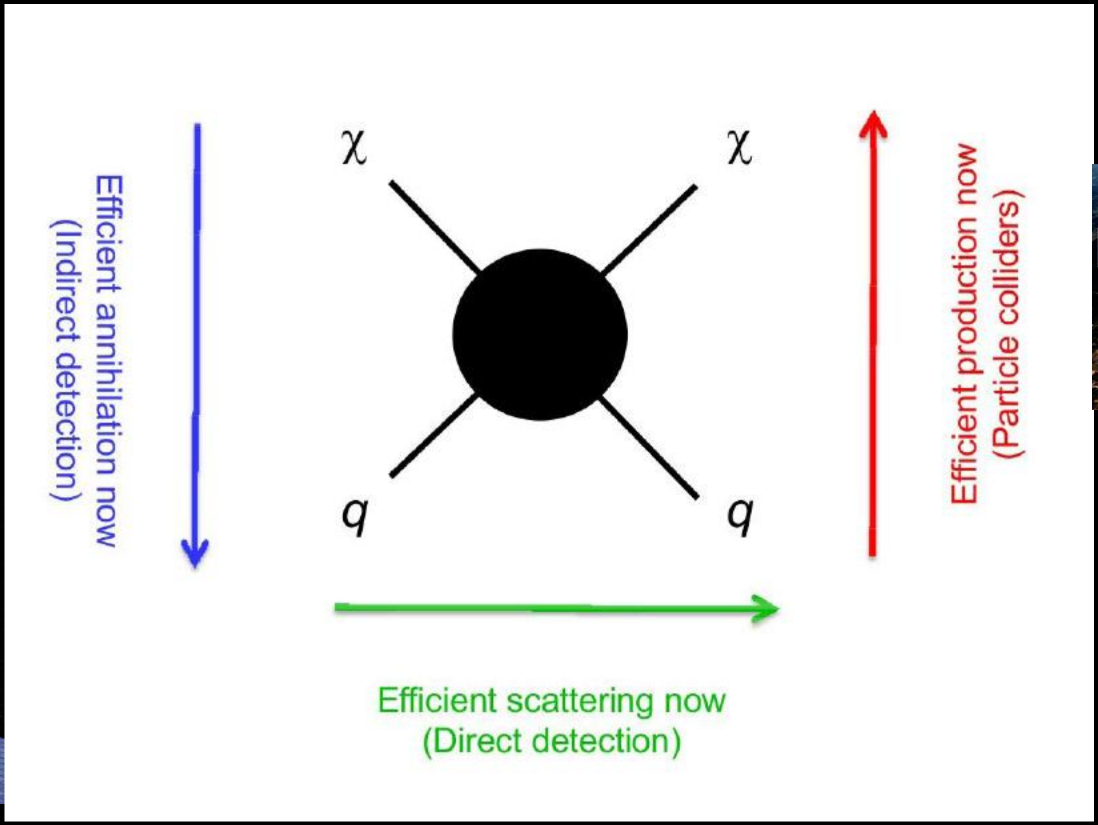


Search (and constrain) Dark Matter







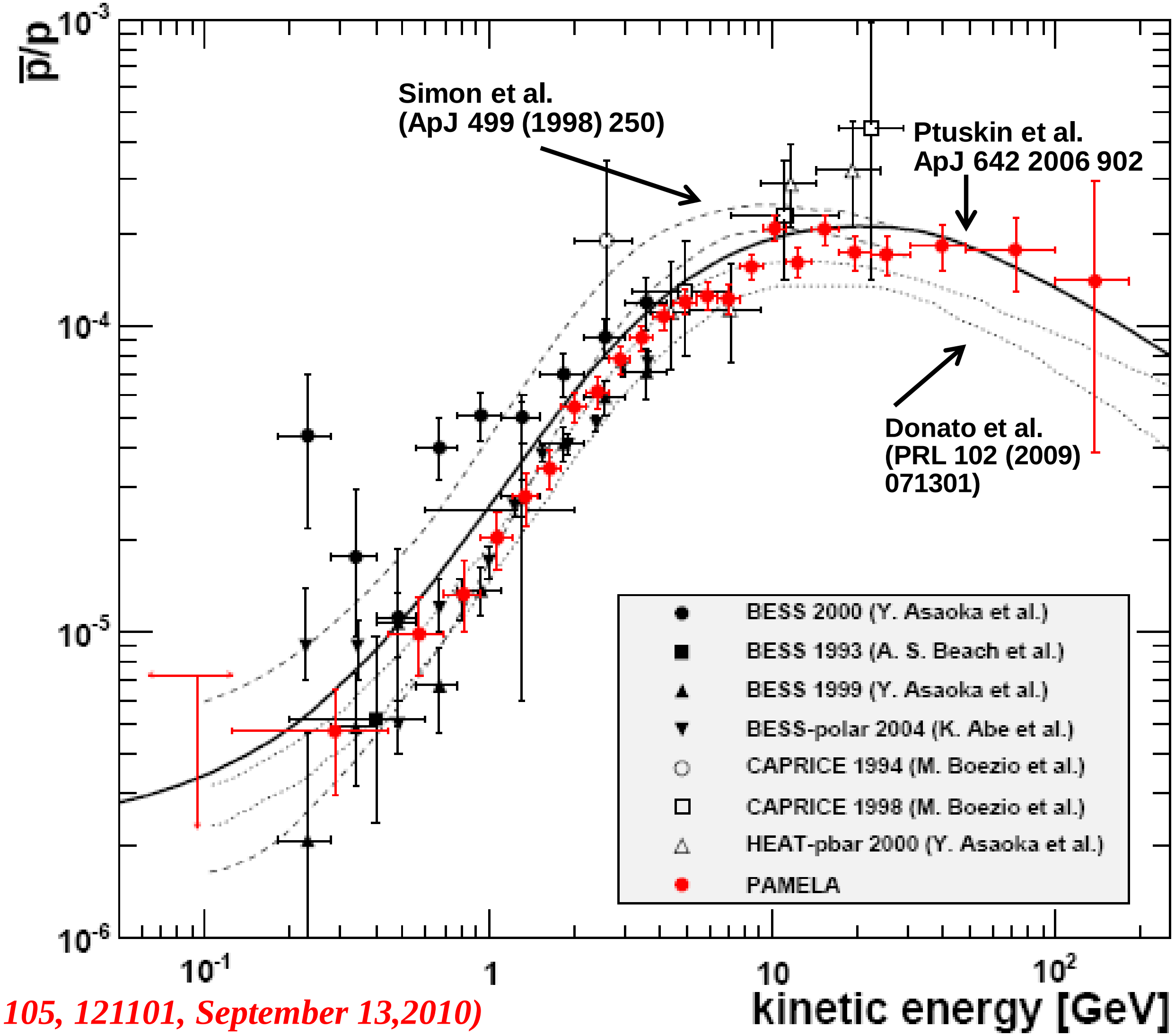


→ Pinfold ICRC1280
→ Weiner ICRC1303
→ Smith ICRC1290

Antiproton/proton ratio

Low Energy →
Confirms charge dependent solar modulation

High Energy →
Consistent with models (Galprop, Donato…)



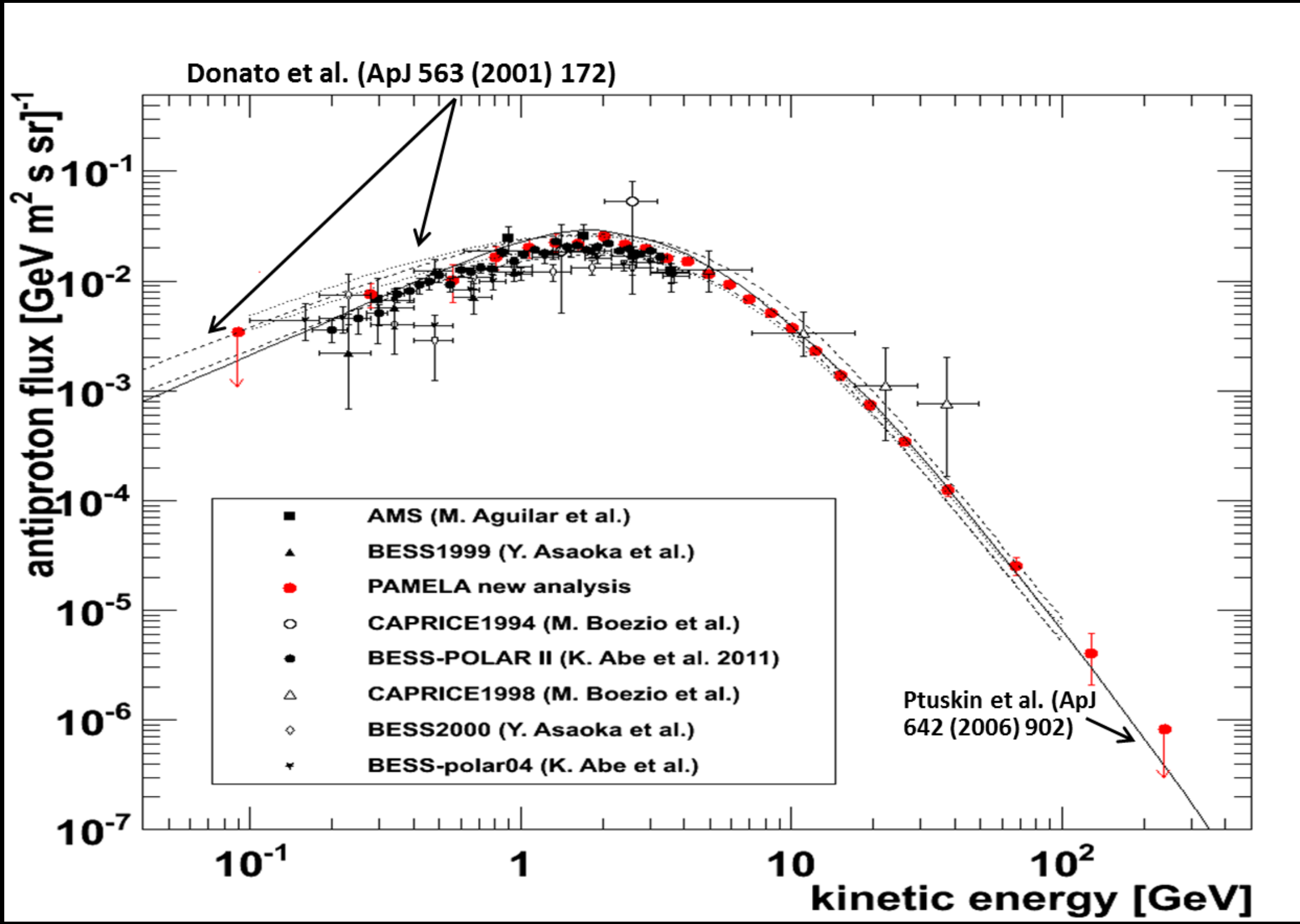
PRL. 105, 121101, September 13,2010)

PRL 102:051101,2009

Antiproton absolute flux

Apparently no extra sources

Rule out and strongly constrain many models of DM

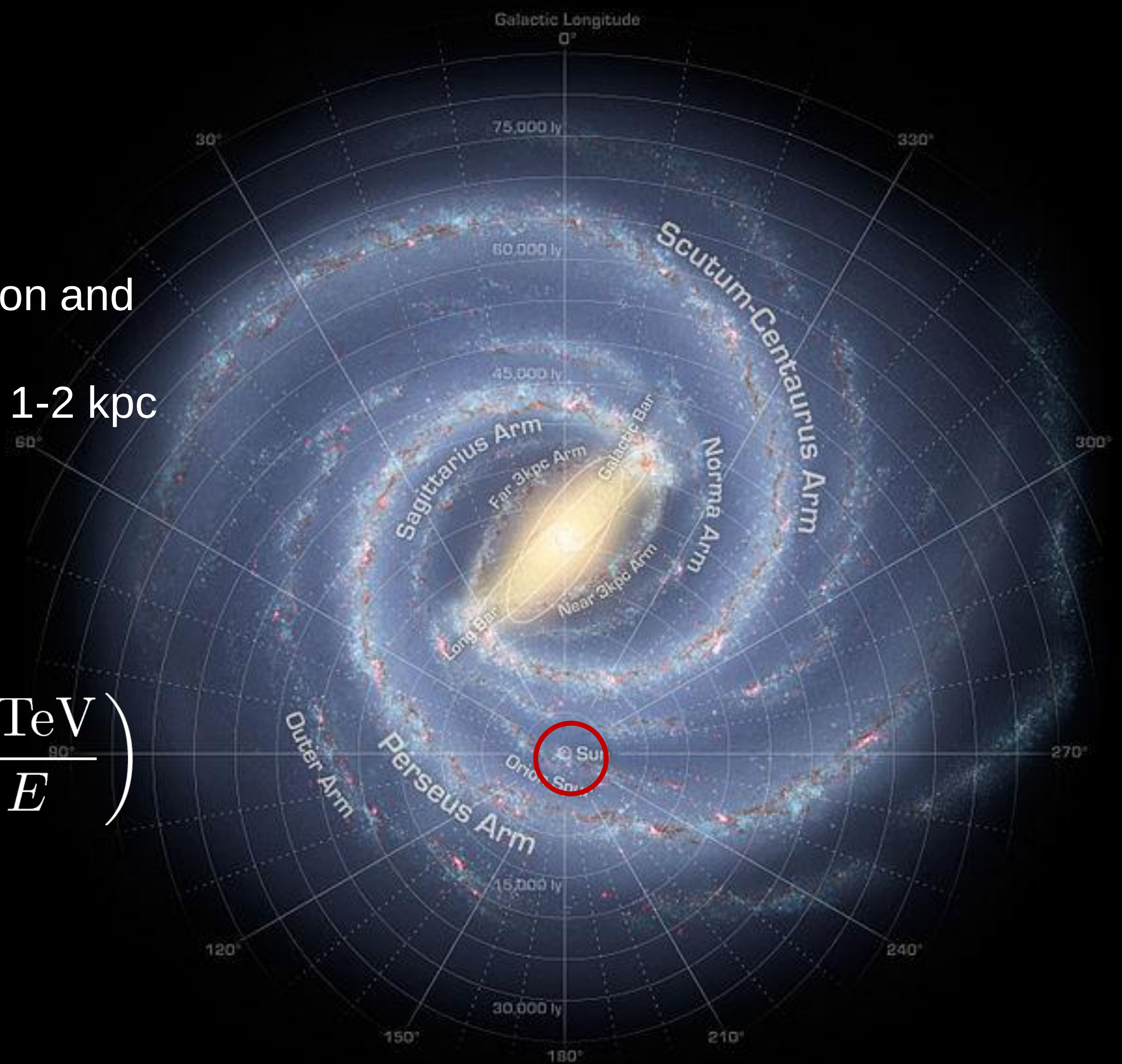


S M. Asano, et al, Phys. Lett. B 709 (2012) 128.
R. Kappl et al , PRD 85 (2012) 123522
M. Garnyet al, JCAP 1204 (2012) 033
D. G. Cerdeno, et al, Nucl. Phys. B 854

Galactic neighborhood:
e+, e- (1-2 kpc)

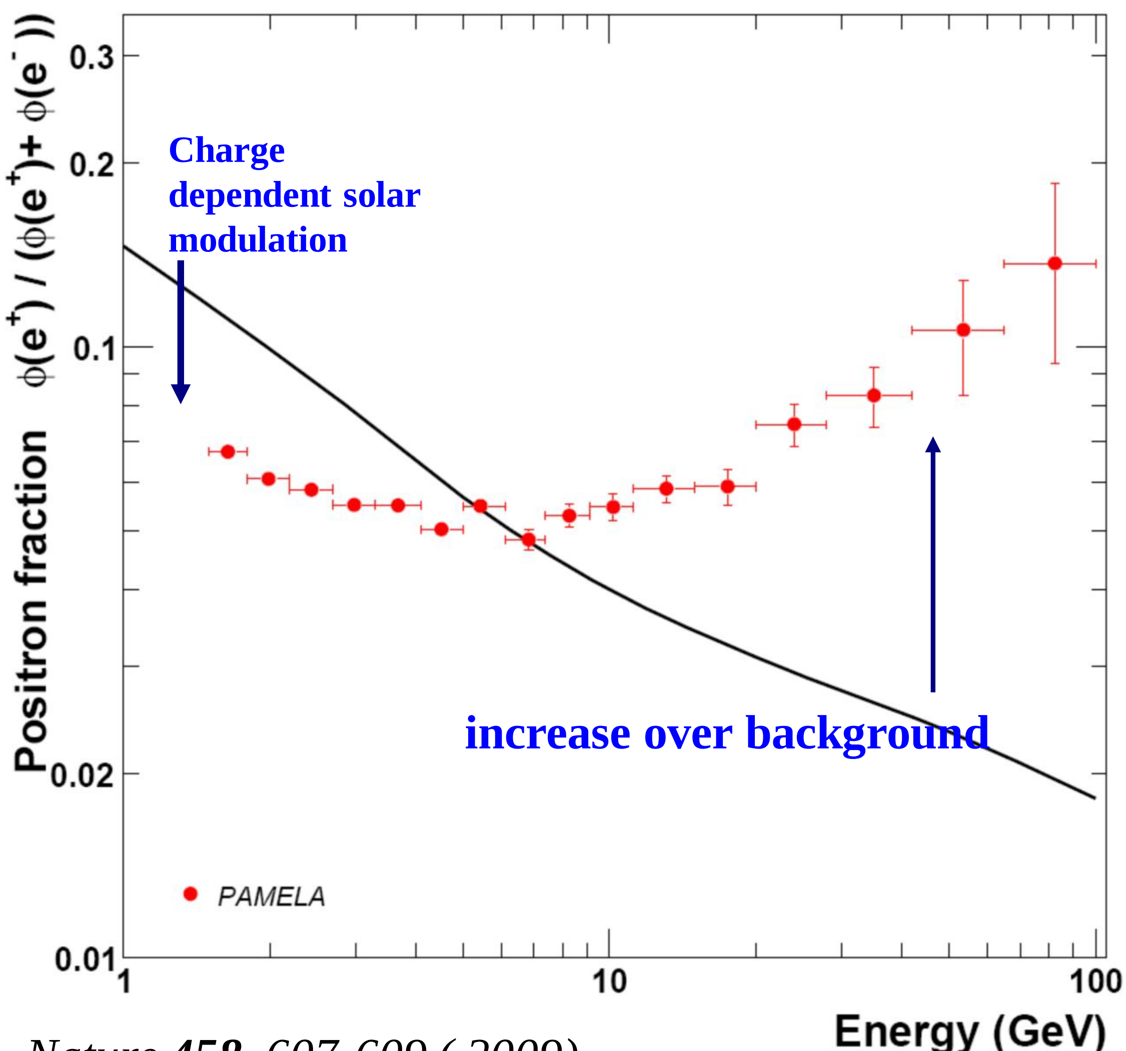
Synchrotron Radiation and
Inverse Compton
Limit propagation to 1-2 kpc

$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$



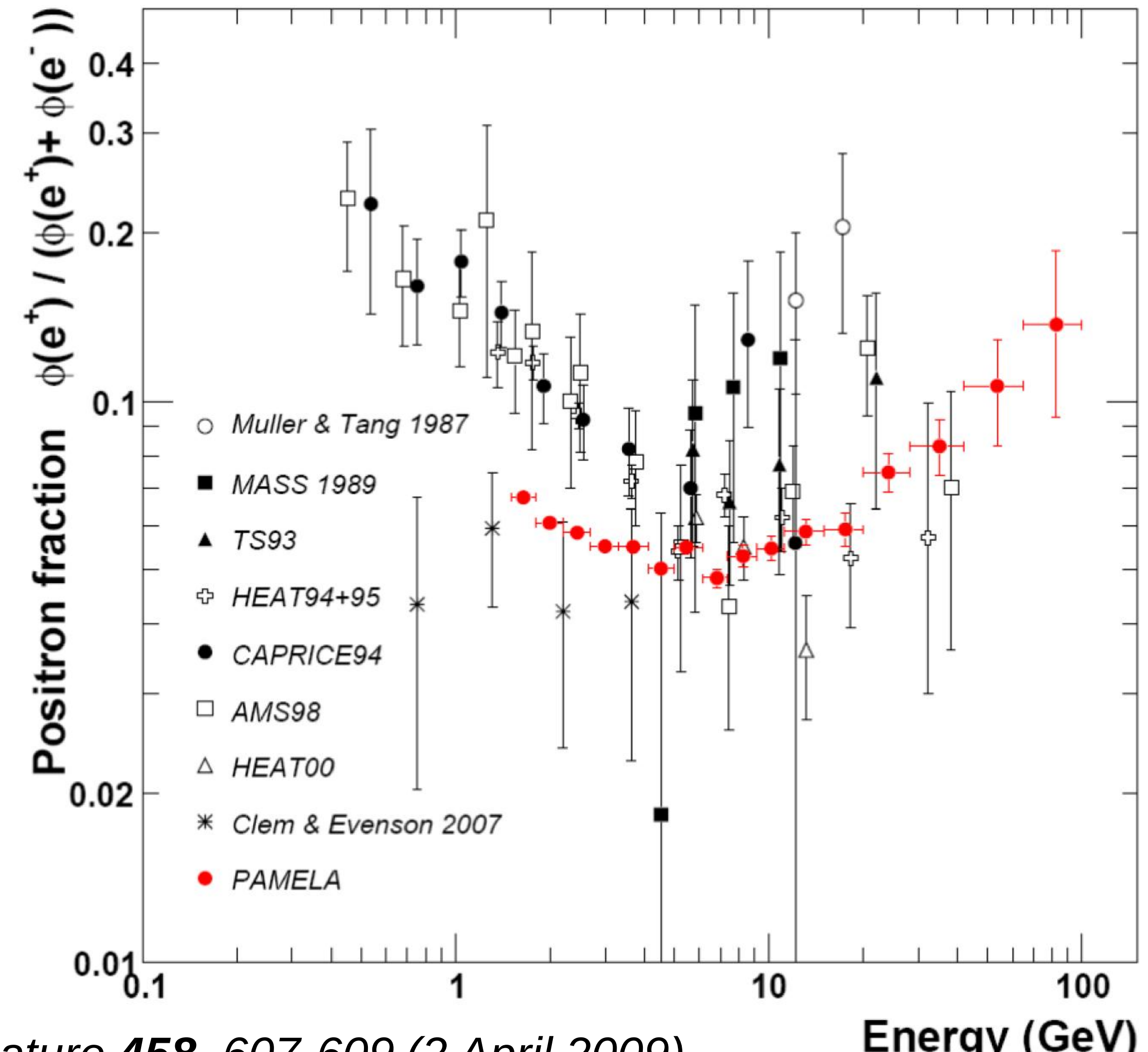
Pamela positron fraction

Also
Mikhailov ICRC520,
ICRC516



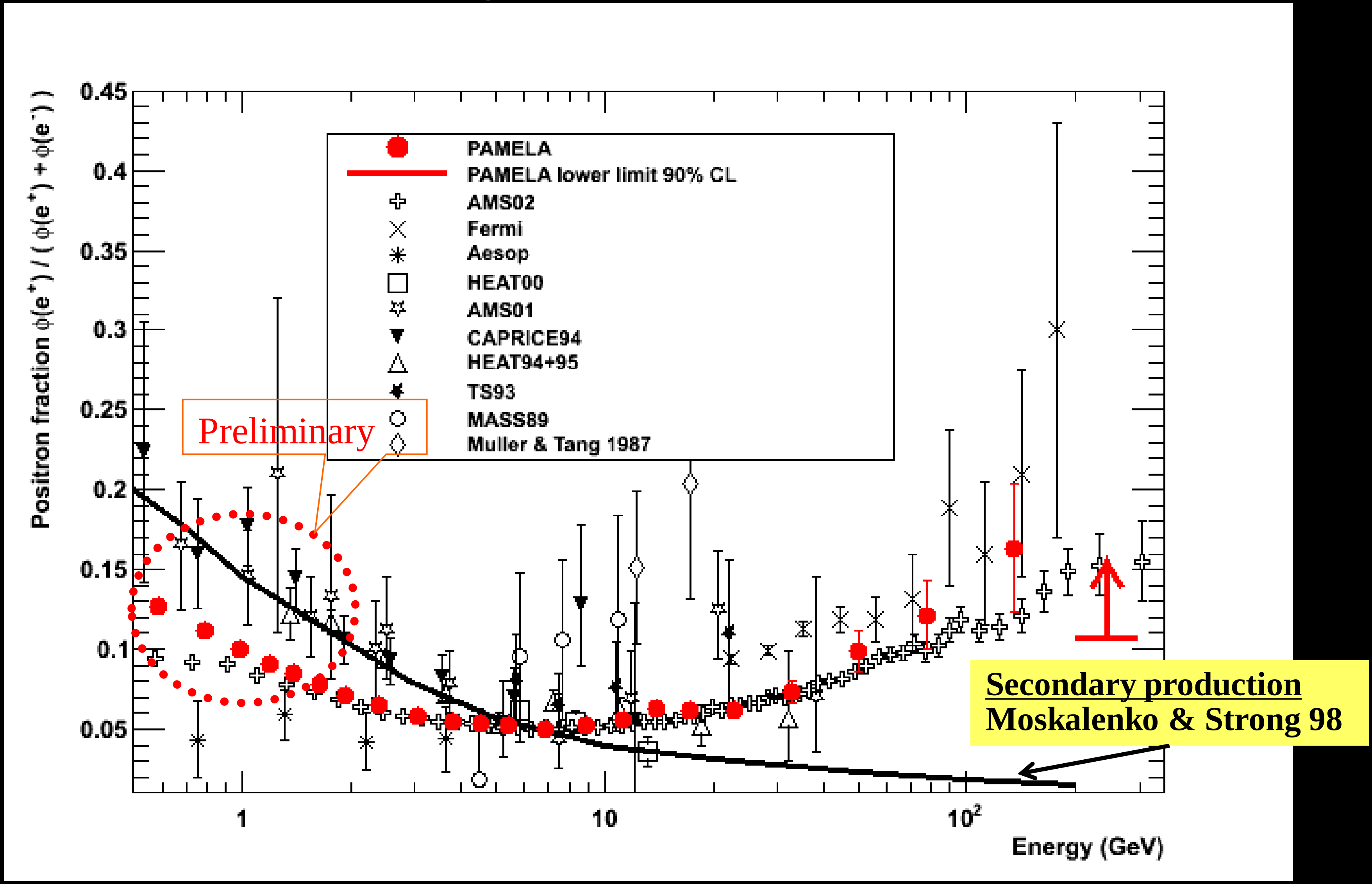
Nature ***458****, 607-609 (2009)*

Pamela positron fraction: comparison with other data



Nature ***458****, 607-609 (2 April 2009)*

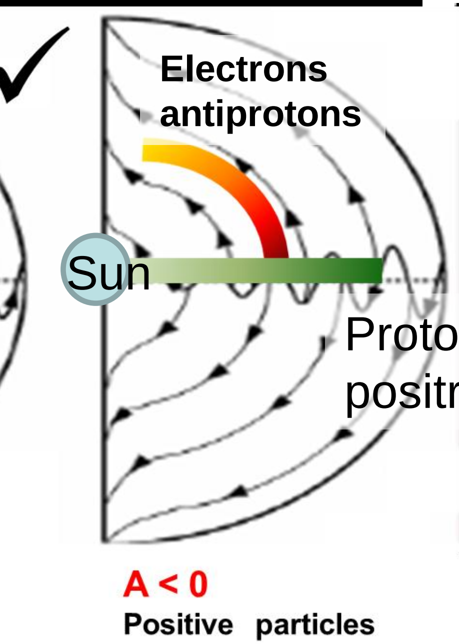
Pamela positron fraction:
Extension at low energy
comparison with current data

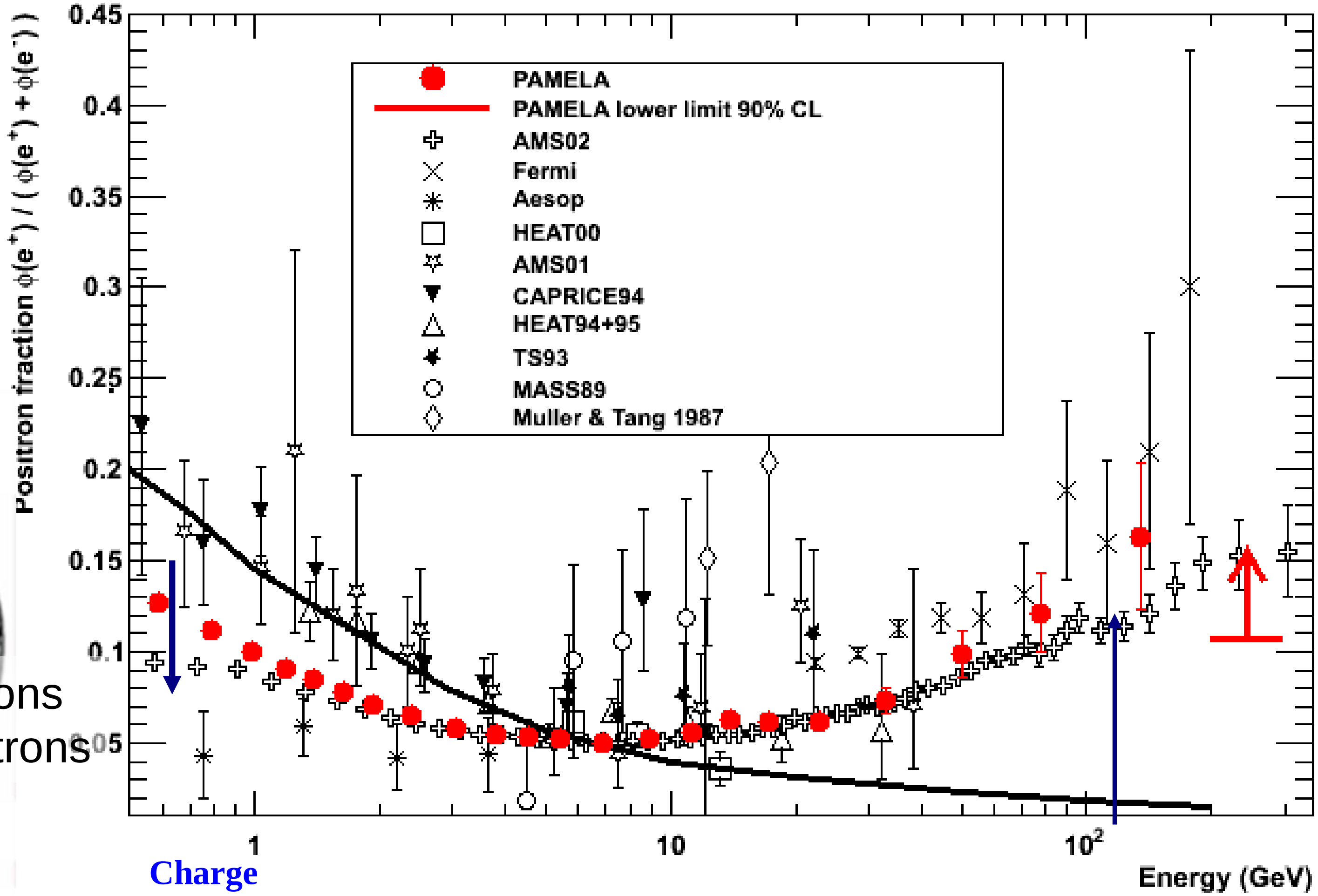


AMS & FERMI confirm PAMELA data

Anomalous source at high energy

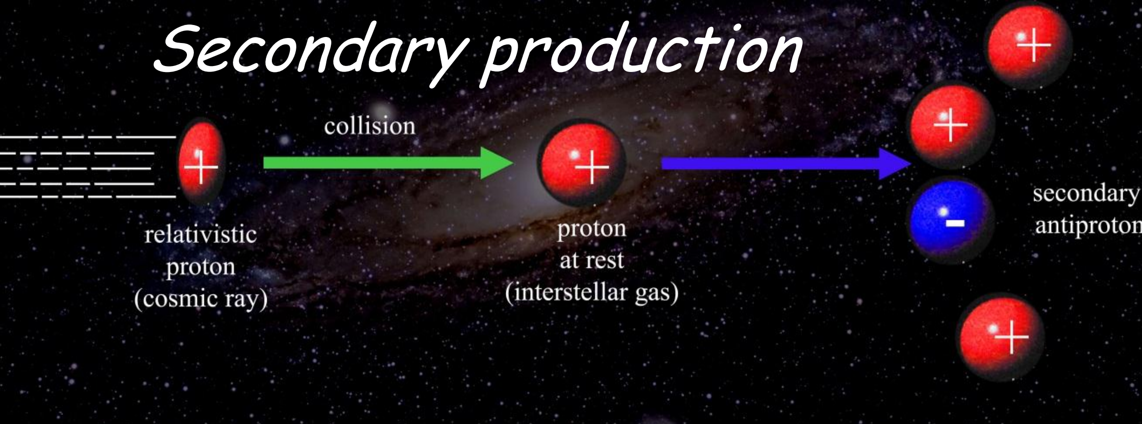
Charge dependet Solar modulation at low energy → Need 3D model of heliosphere

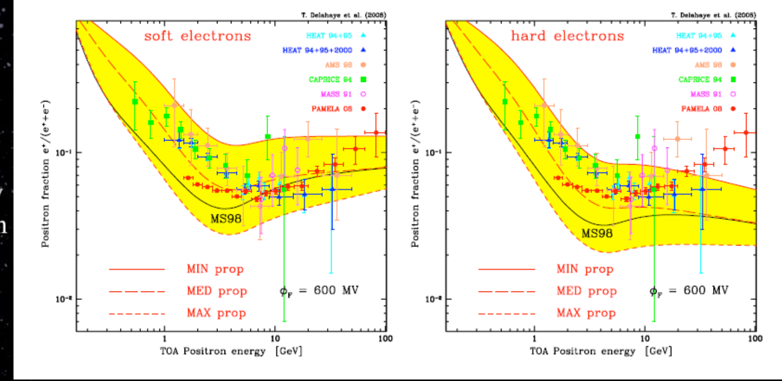


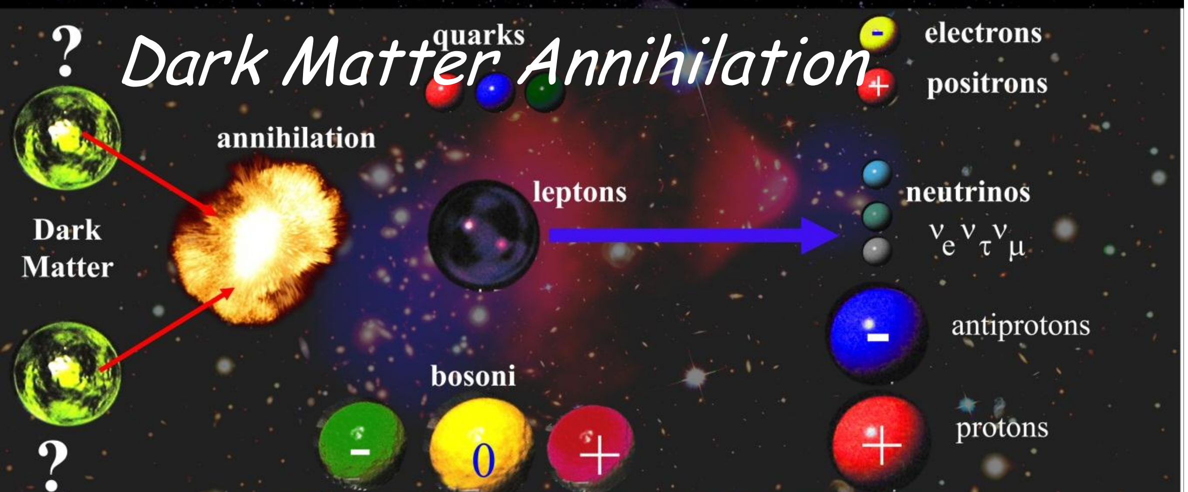


Charge dependent solar modulation

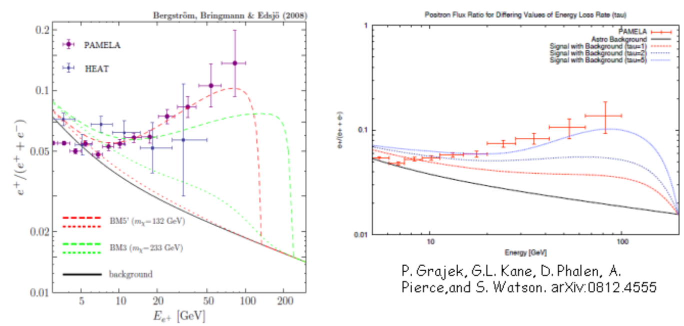
L. Maccione, PRL 110 (2013) 081101





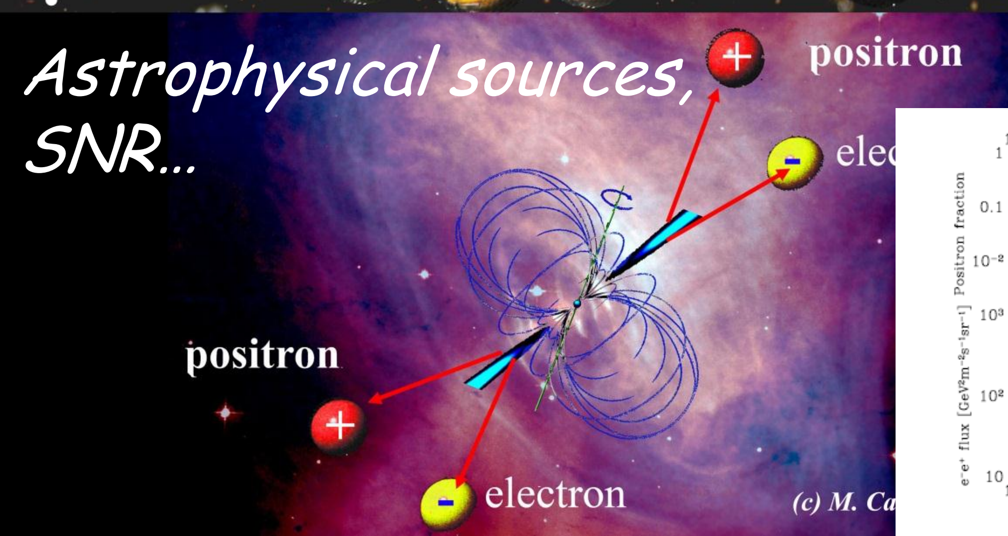


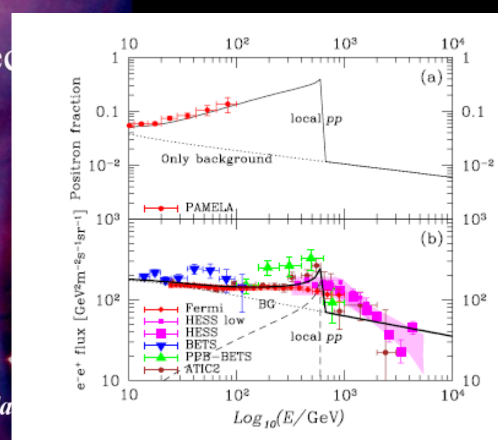
2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:

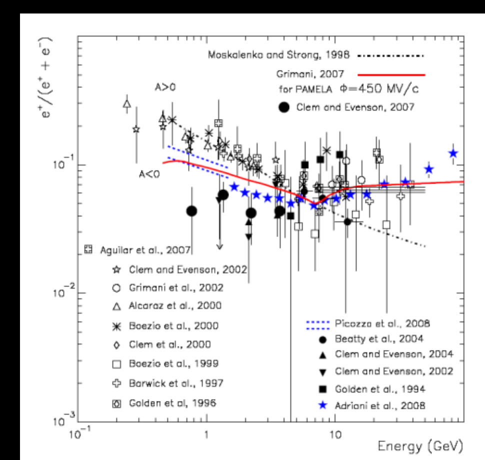


P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555

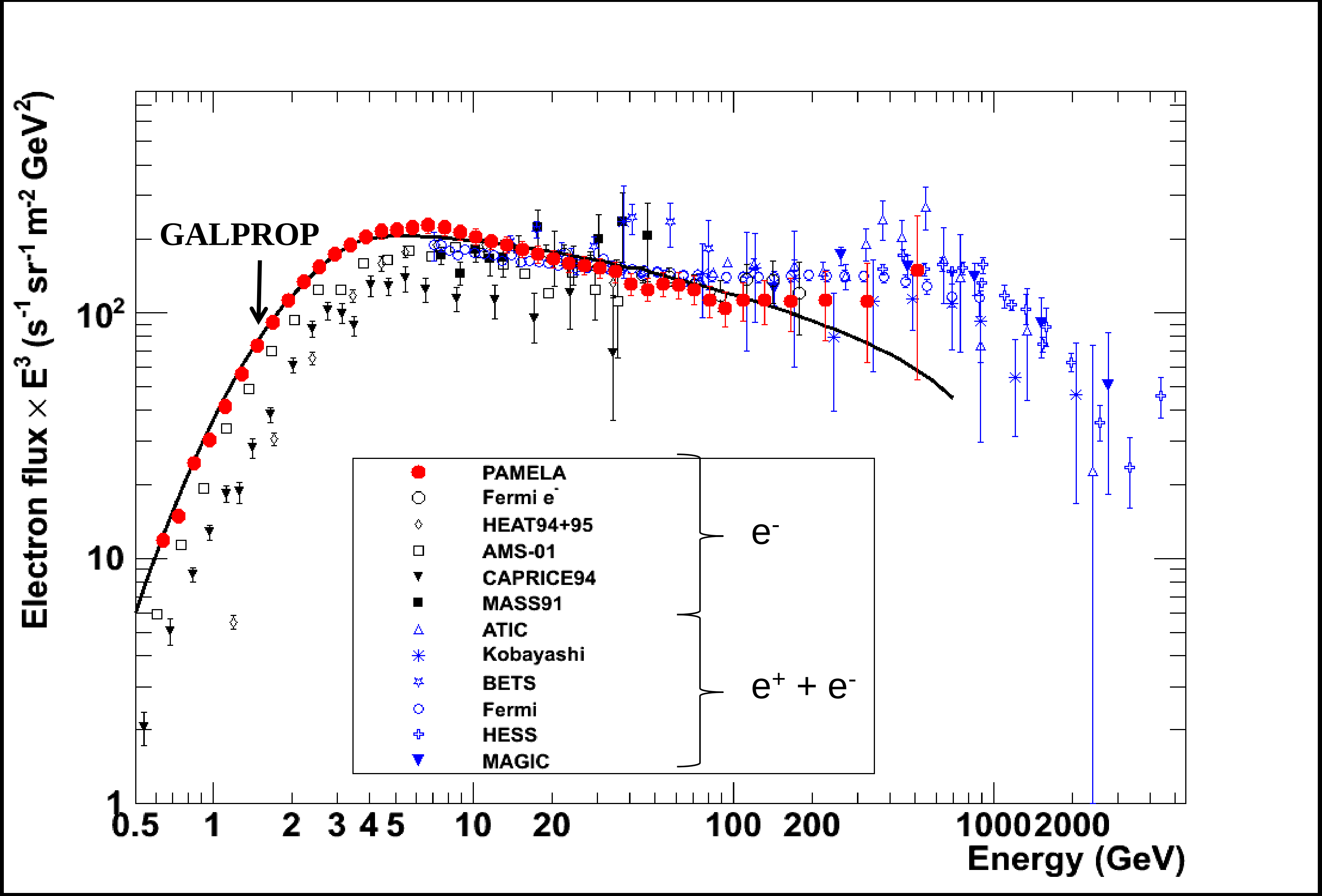
However, does not explain new electron plus positron data (see later)







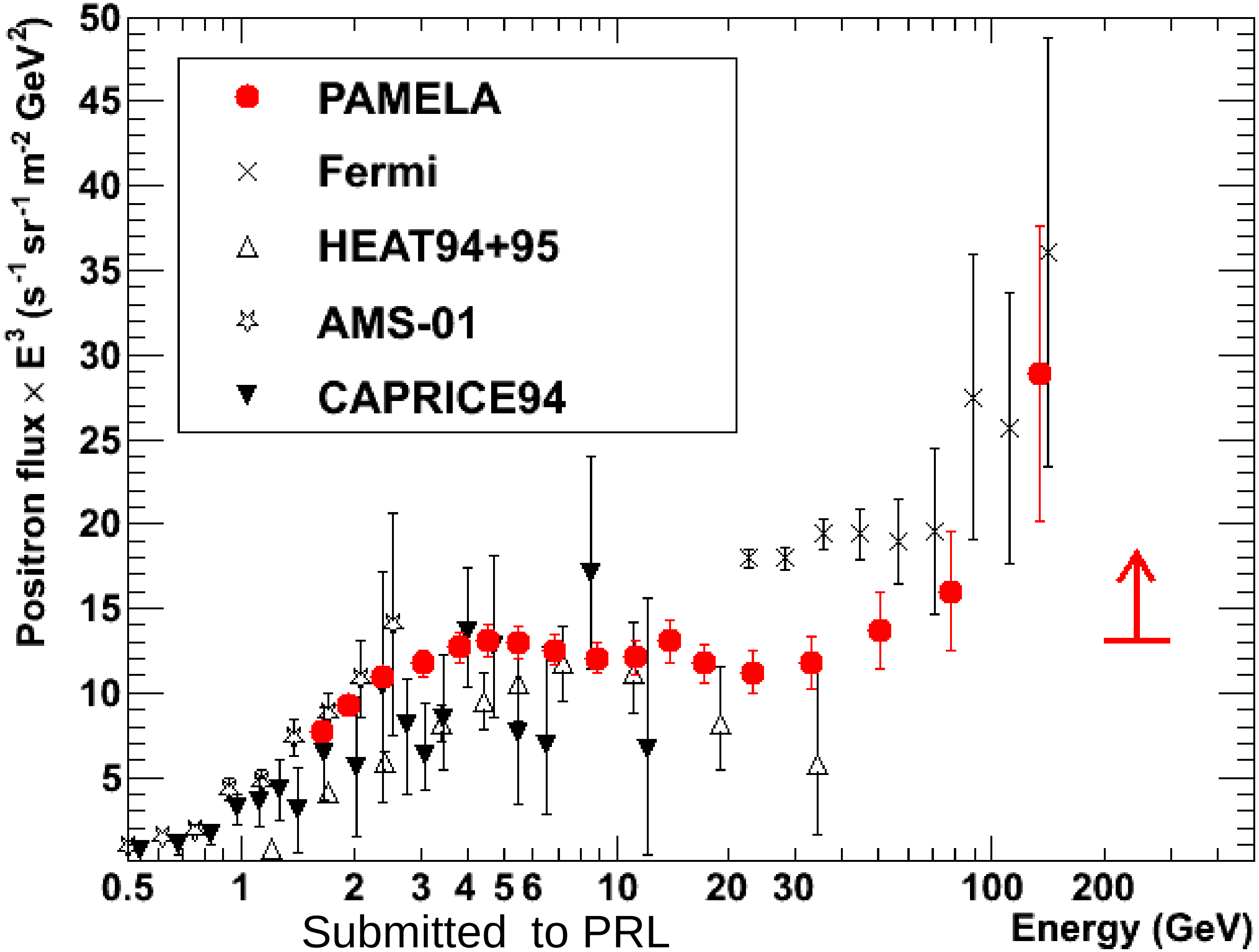
Electron spectrum



Absolute positron spectrum

Positron fraction: disagreement with pure secondary production model

Propagation
Charge dependent solar modulation

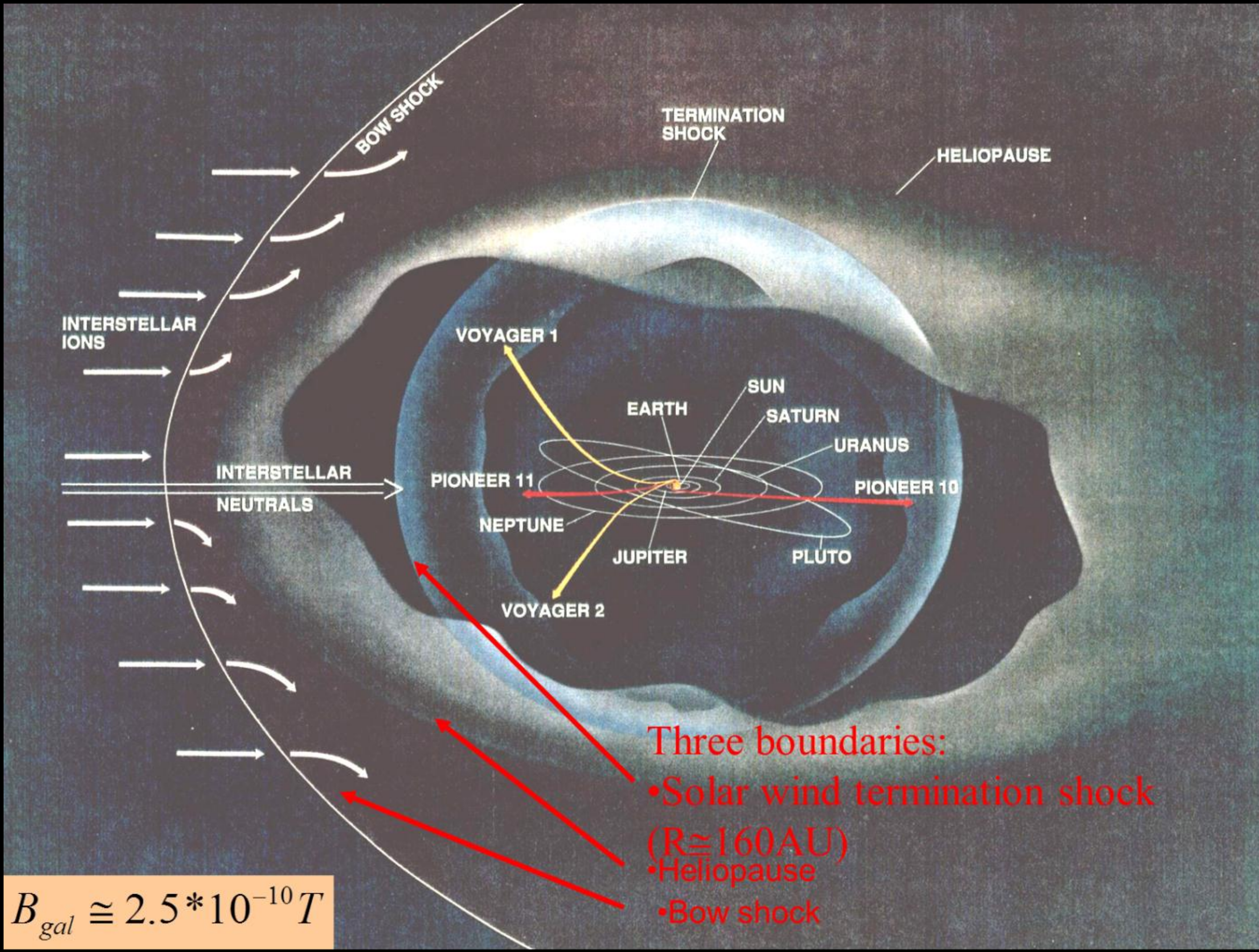


Submitted to PRL

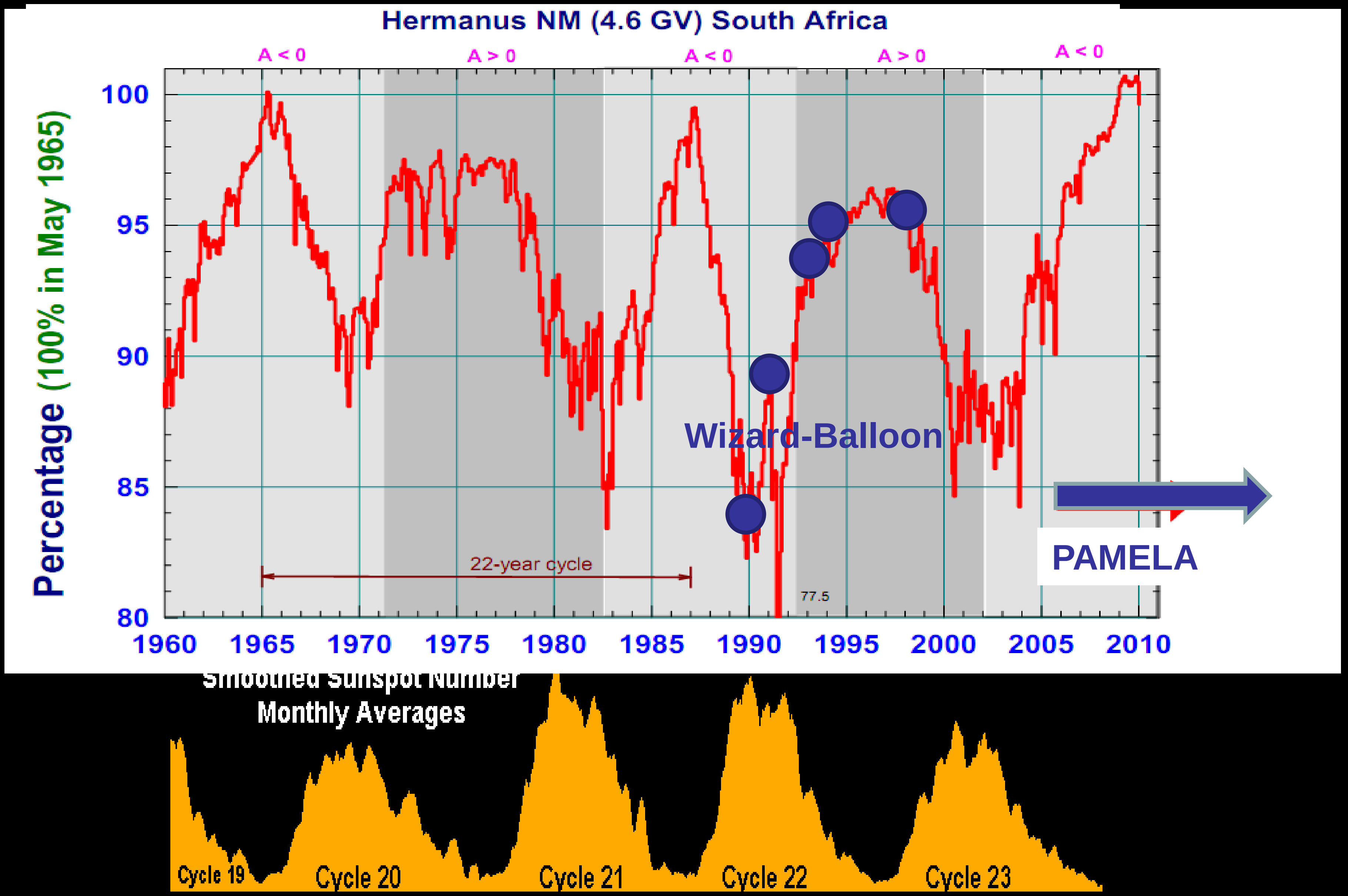
O. Adriani et al., PRL 111 (2013) 081102; arXiv:1308.0133

Heliosphere and long term solar modulation (100 AU)

- Next talk by Potgieter
- Nndanganeni ICRC33
- Potgieter ICRC70
- Vos ICRC273



Solar modulation at minimum of solar cycle 23-24: 2006-2013

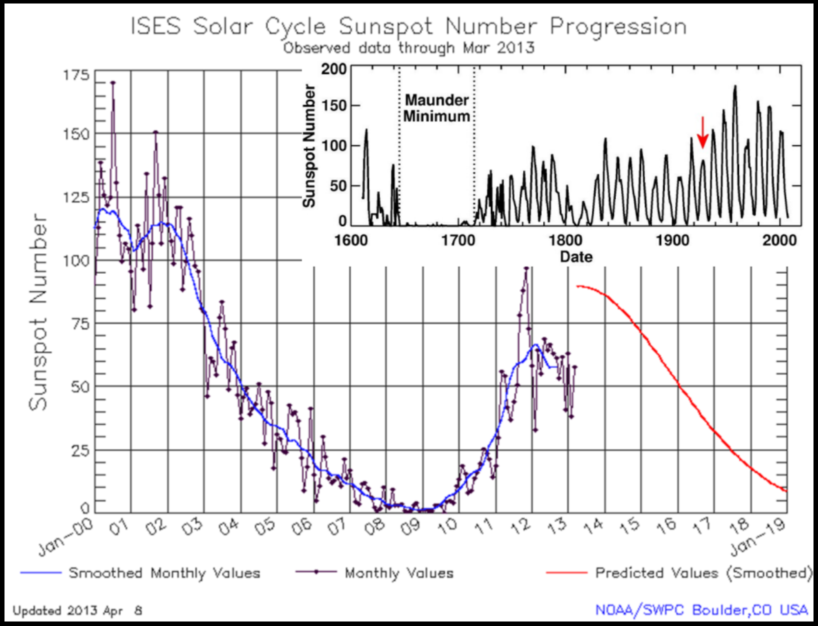


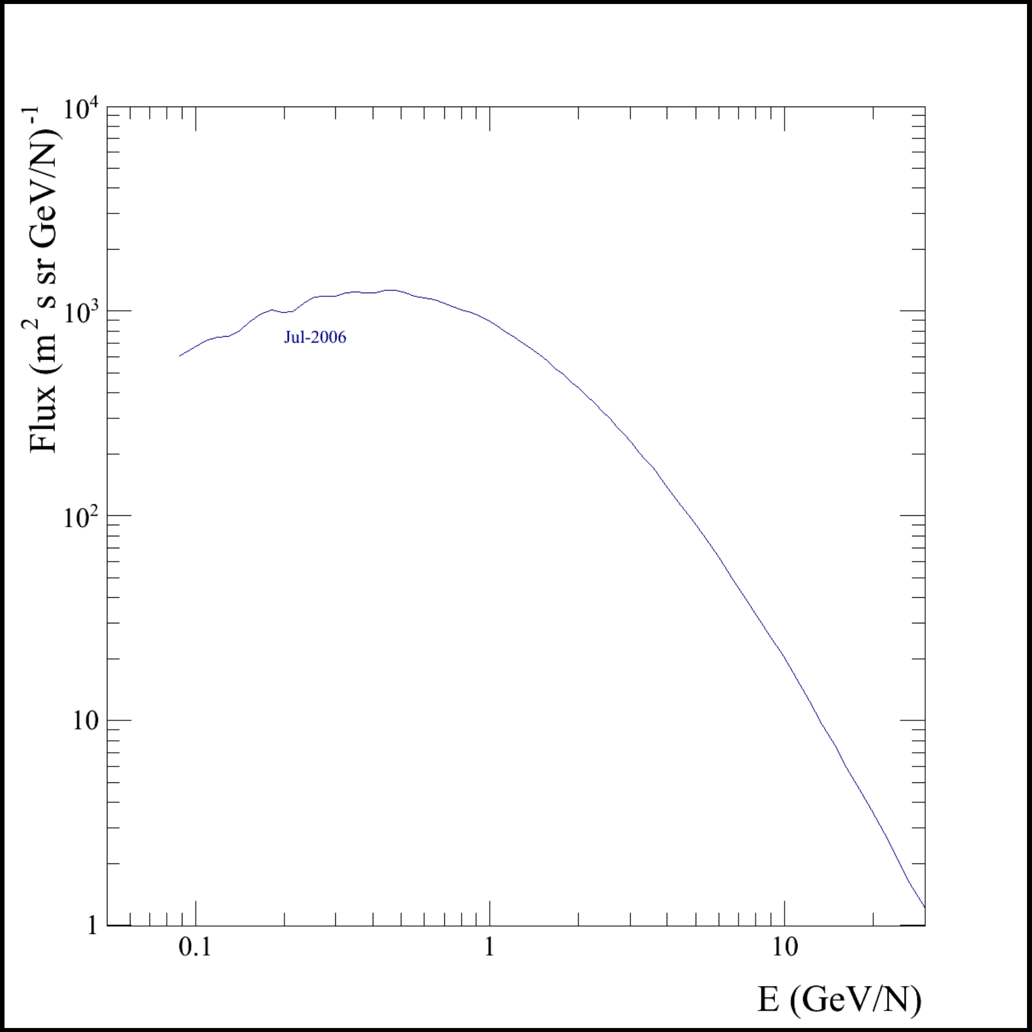
Solar modulation of galactic protons and nuclei

Very long and peculiar solar minimum.

Current solar cycle (24) late and weak.

Closer to interstellar medium.
Good reference field for dosimetry





From V. Formato

Solar modulation at minimum of solar cycle XXIII-XXIV

$F_{is} = 1.54\ \beta_{is}^{0.7}\ R_{is}^{-2.76}$

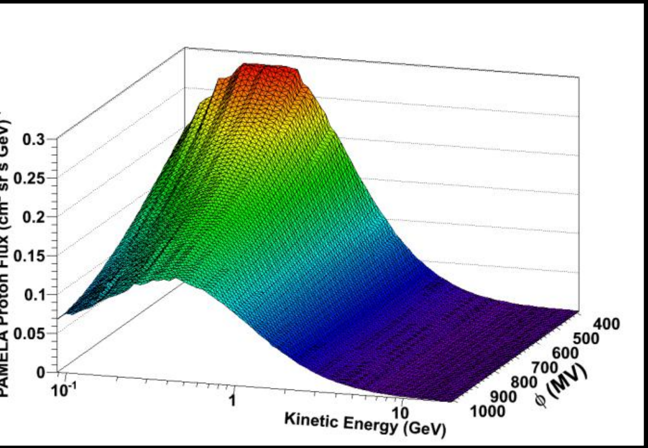
p/(cm² s sr GV)

Spectral index

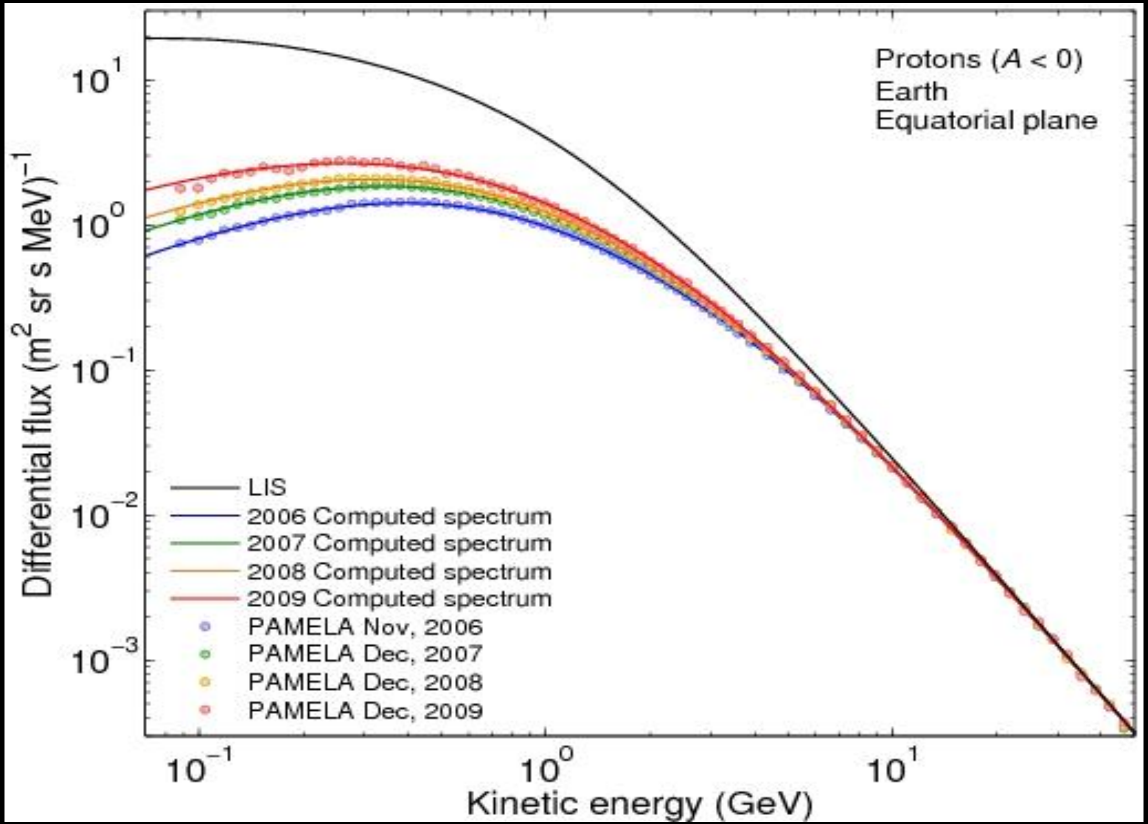
2.76 ±0.01

$$J(r,E,t) = \frac{E^2 - E_0^2}{(E^2+\Phi(t))^2 - E_0^2} J(\infty, E+\Phi(t))$$

Solar modulation parameter ϕ(GV)



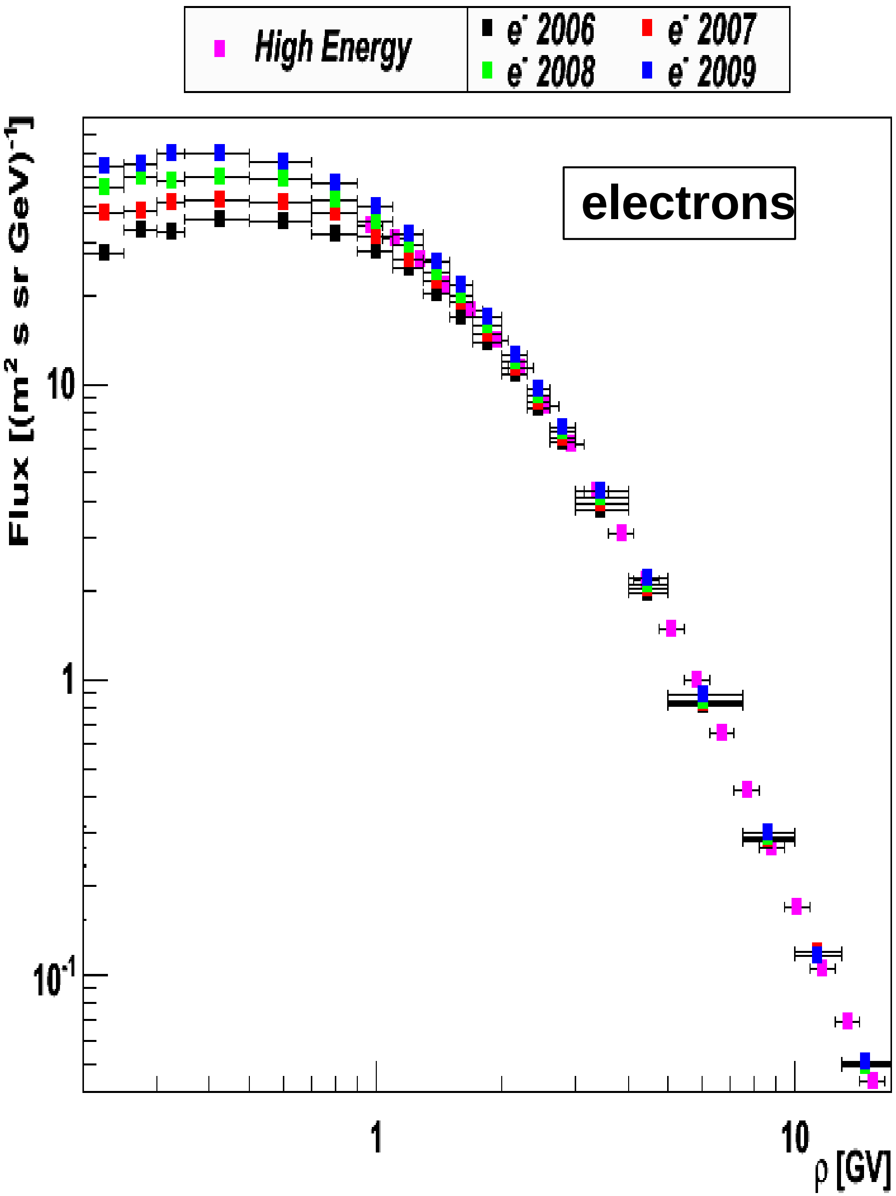
However spherical approximation is not sufficient. E.g. charge dependent solar modulation

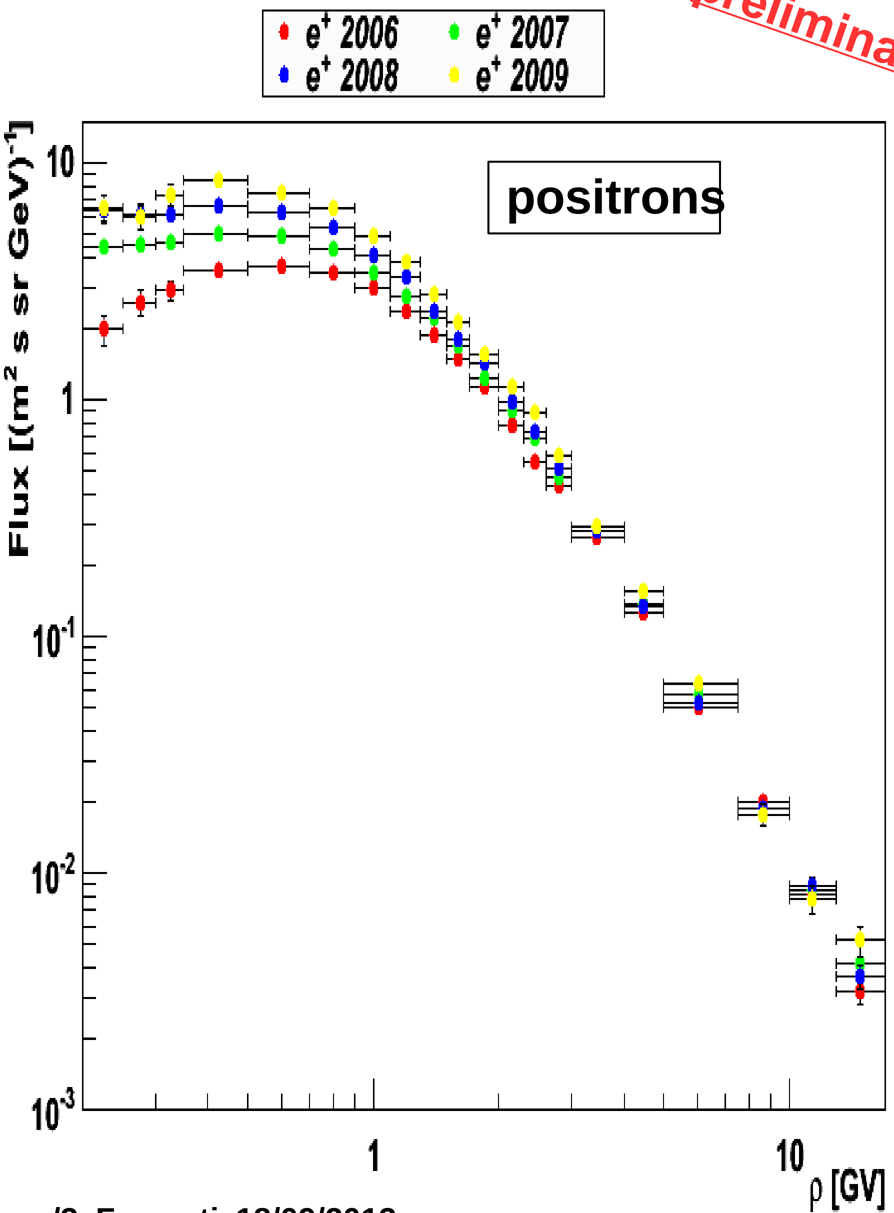


O. Adriani **et al.,** ApJ 765 (2013) 91;
M. S. Potgieter et al., arXiv:1302.1284

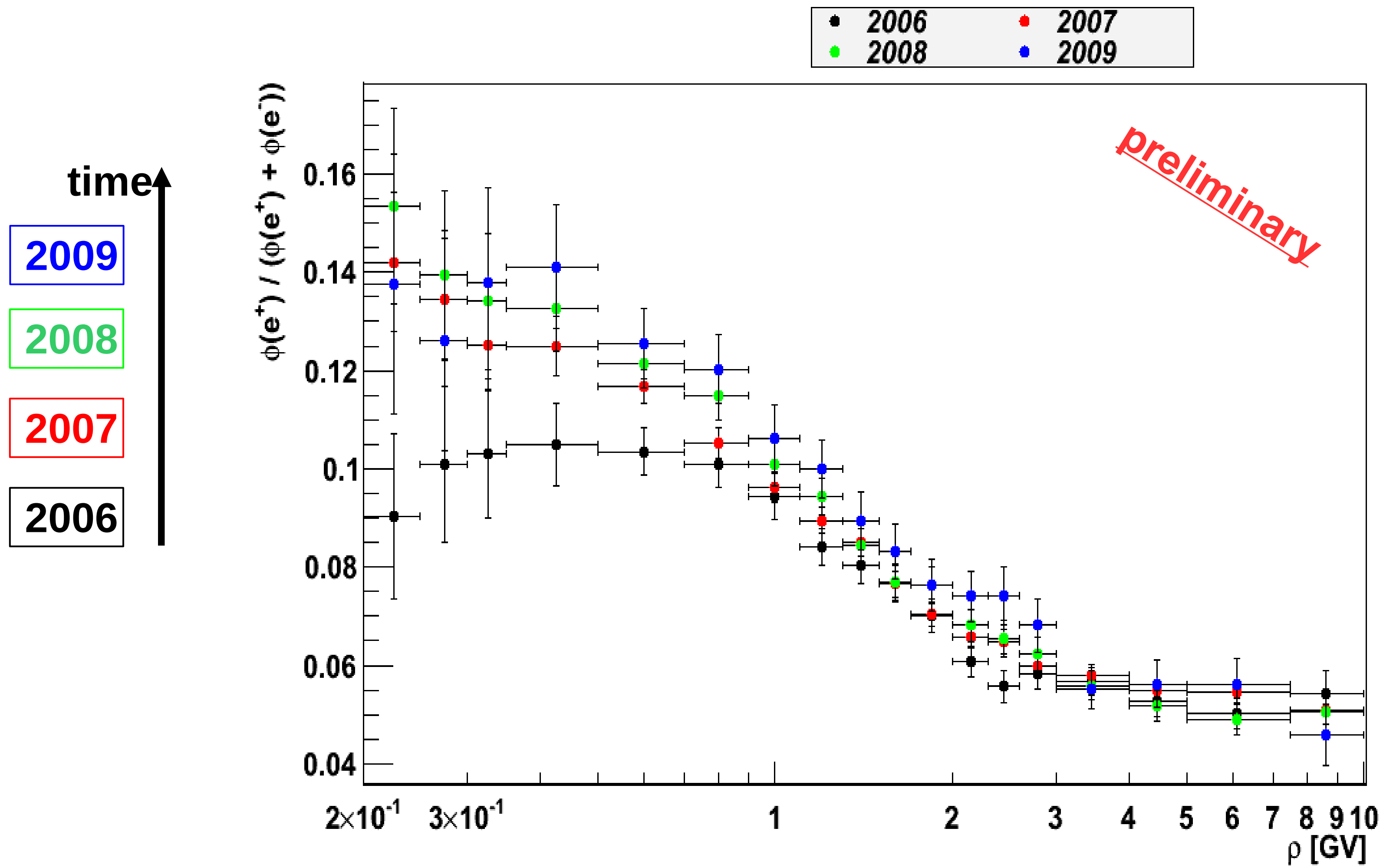
Galactic e- and e+ modulation

preliminary



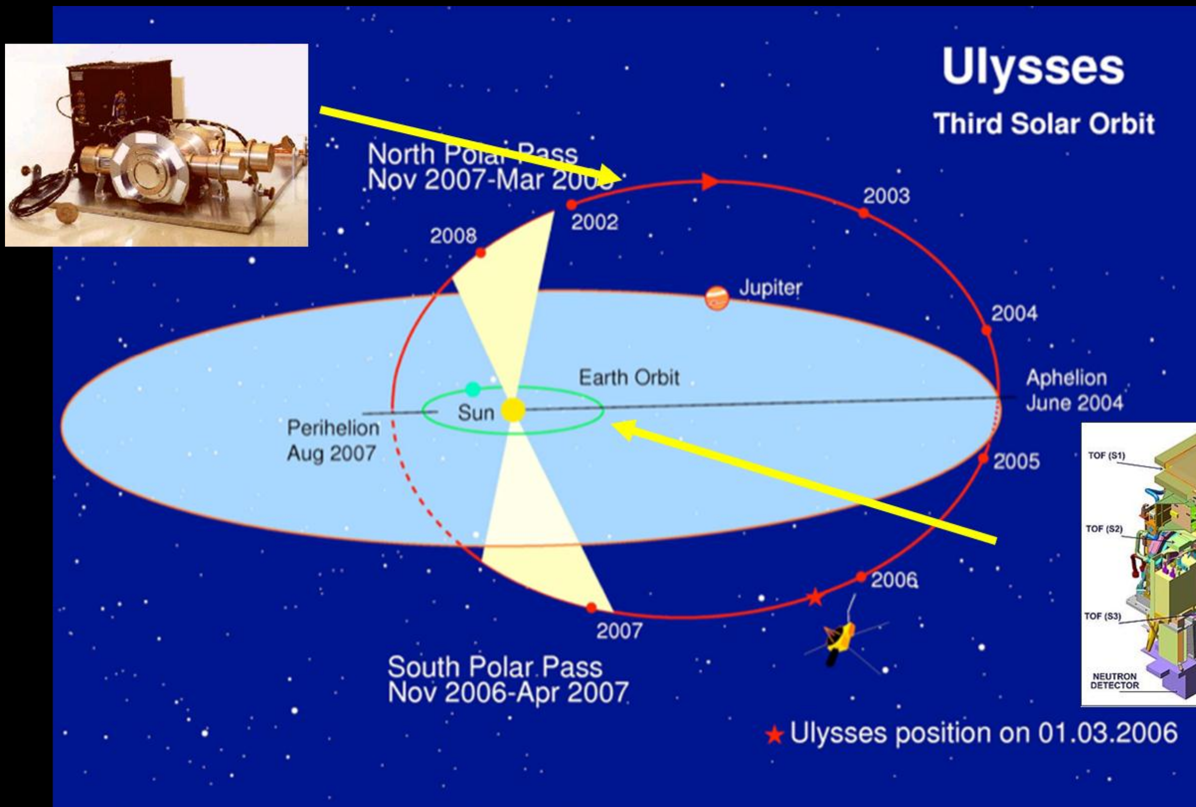


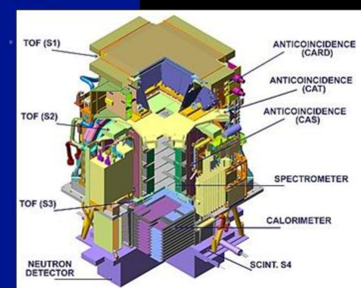
Positron fraction increases going towards solar minimum



Positron fraction increases from 2006 to 2009.

GRADIENTS IN THE HELIOSPHERE L=5AU





Ulysses – Pamela

Gieseler ICRC341

$$ln\Big(\frac{I(t,R,\theta)}{I_{PAMELA}(t)}\Big) = G_R R + G_\theta \theta$$

Gradients in the heliosphere

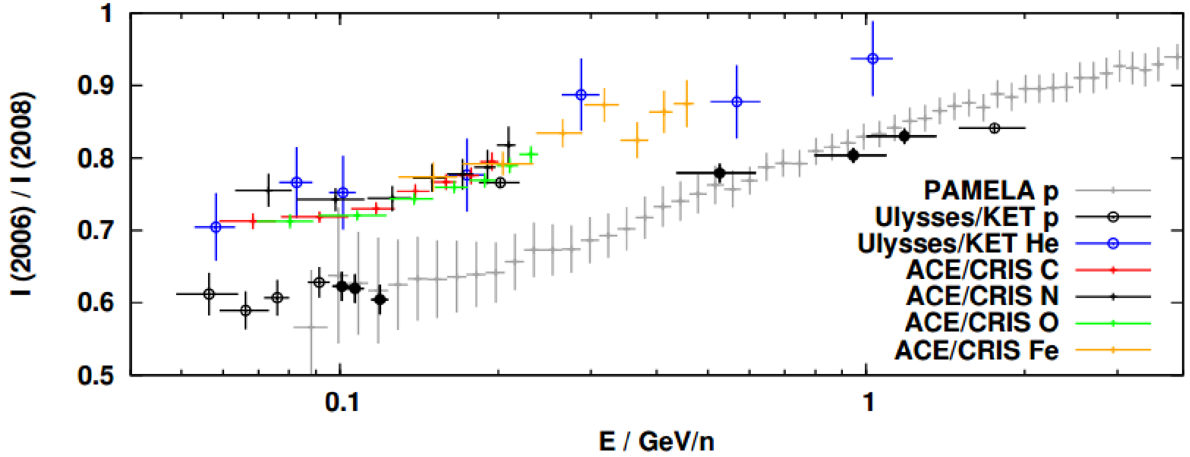


Figure 2: Time variations from 2006 to 2008 of different particle intensity measurements with respect to energy. Marked by full circles are the Ulysses/KET proton channels used here for gradient calculations.

1-5 AU

See Stone's talk ICRC349
for 120+ AU

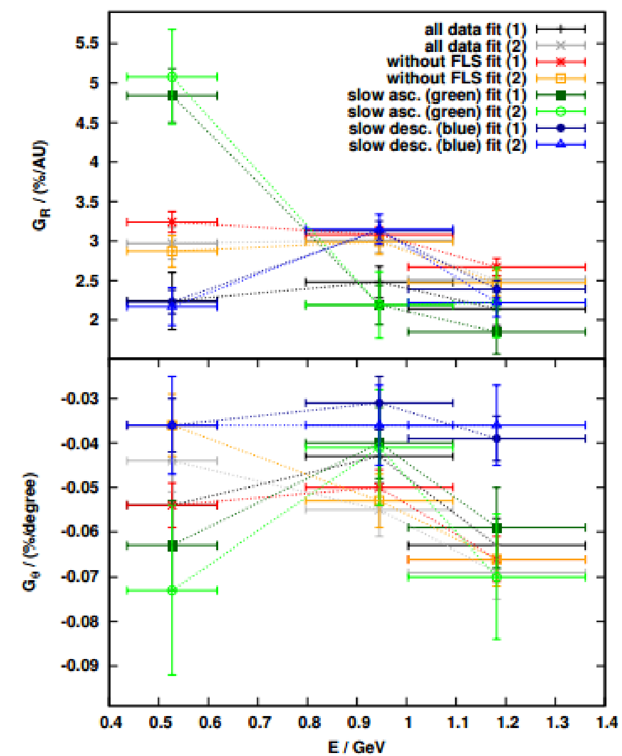
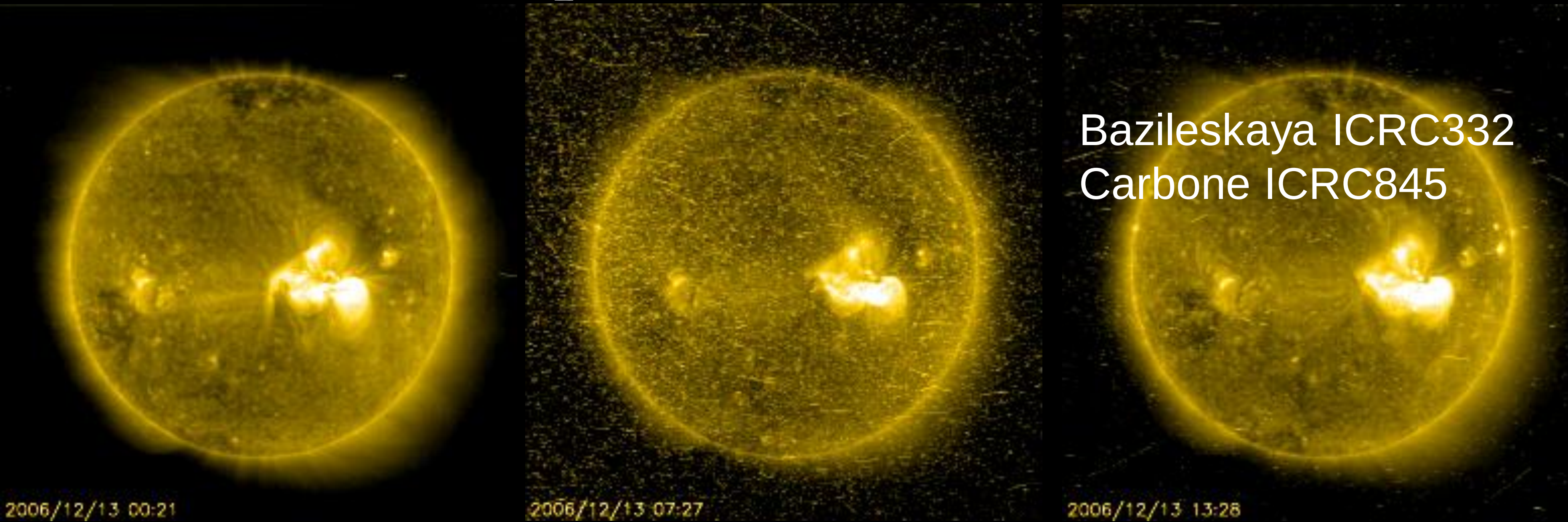
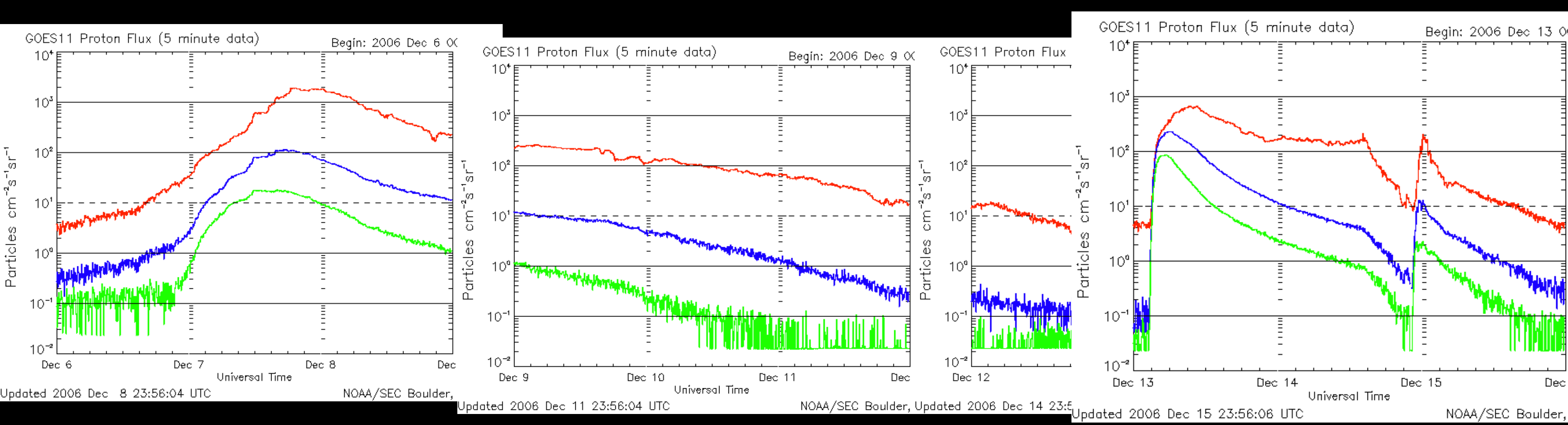


Figure 6: Radial and latitudinal gradients for differen
selection criteria and fit methods, as in Tab. 2.

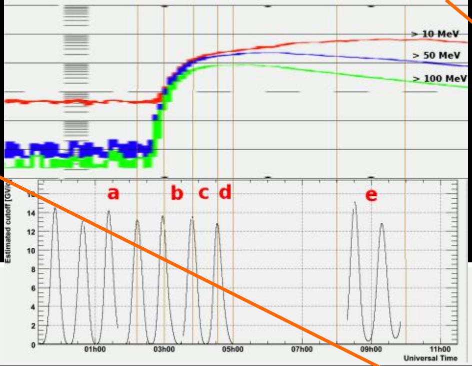
Solar particle events (1 AU)

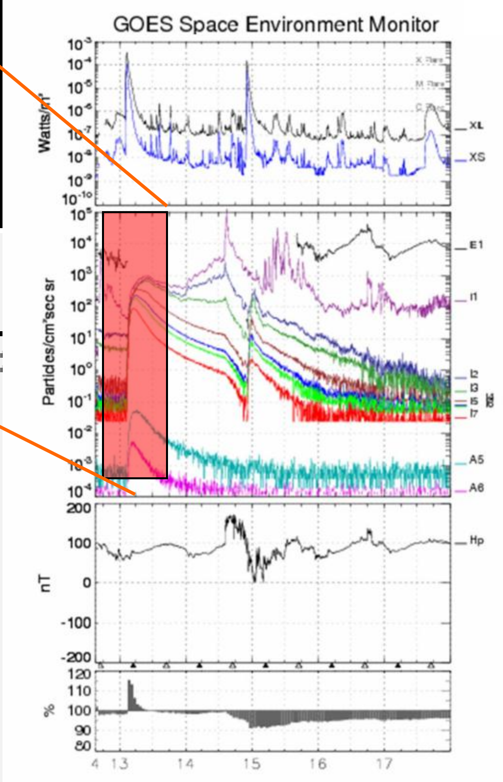


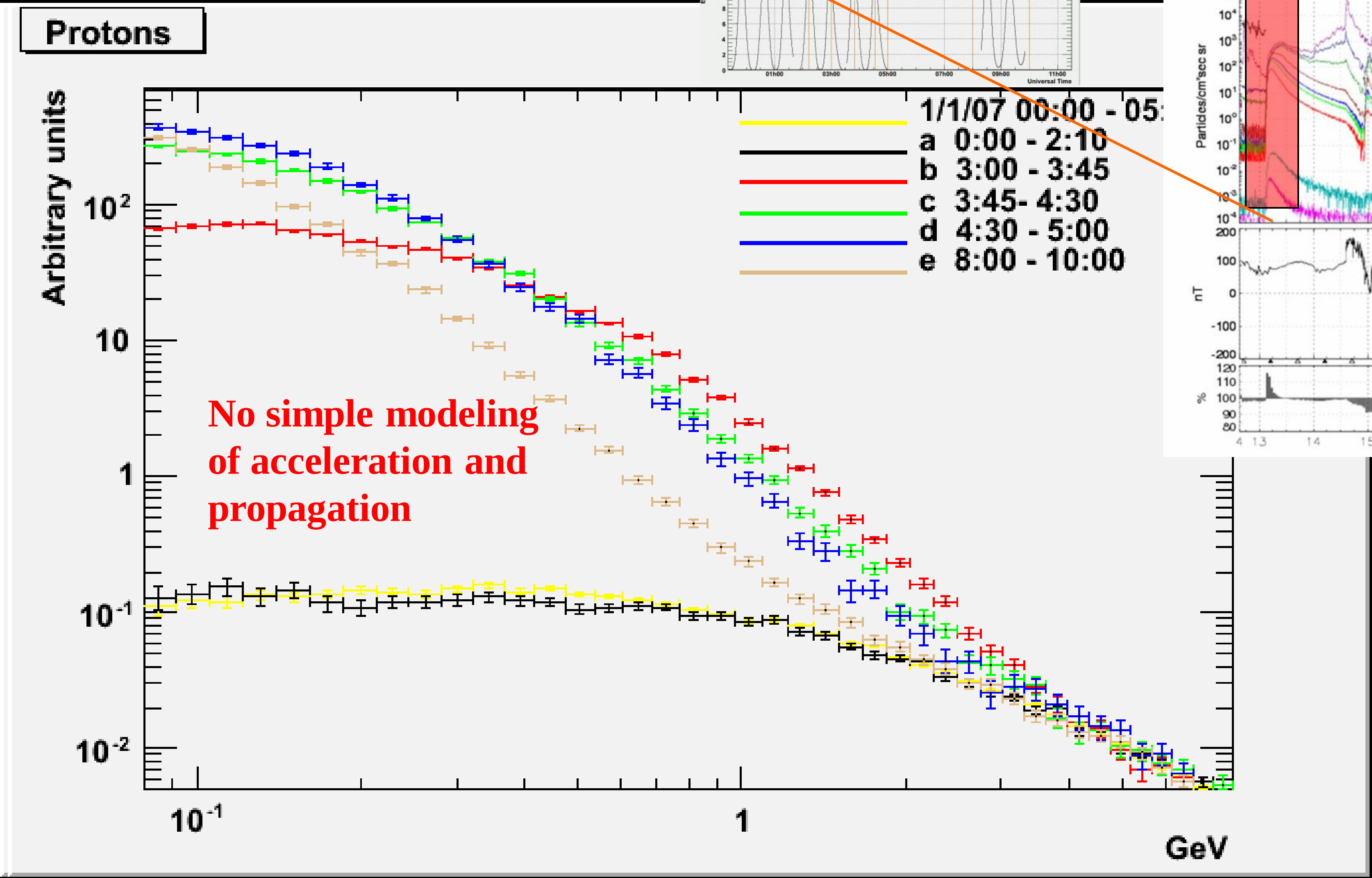
Bazileskaya ICRC332
Carbone ICRC845



December 13th 2006 event

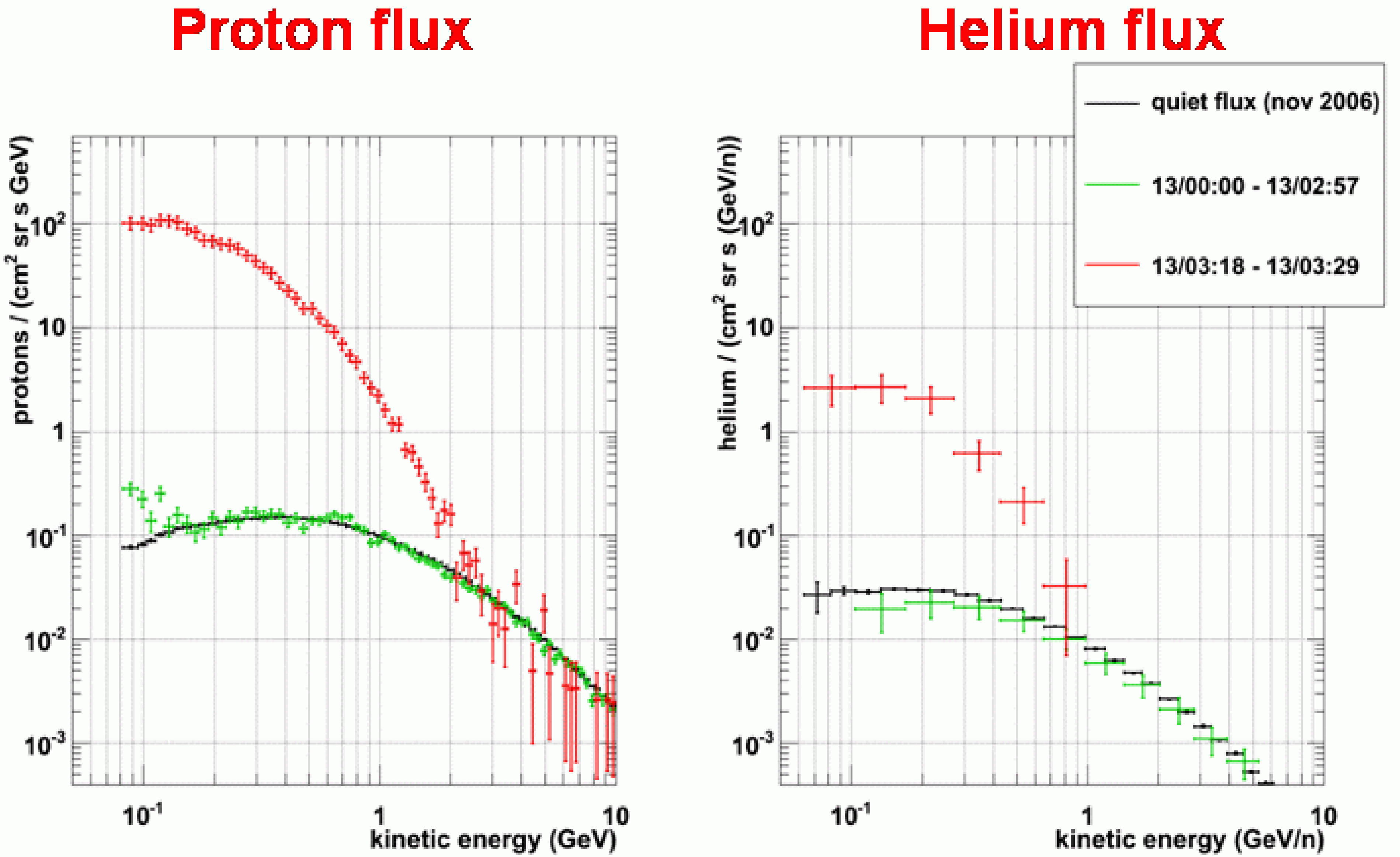






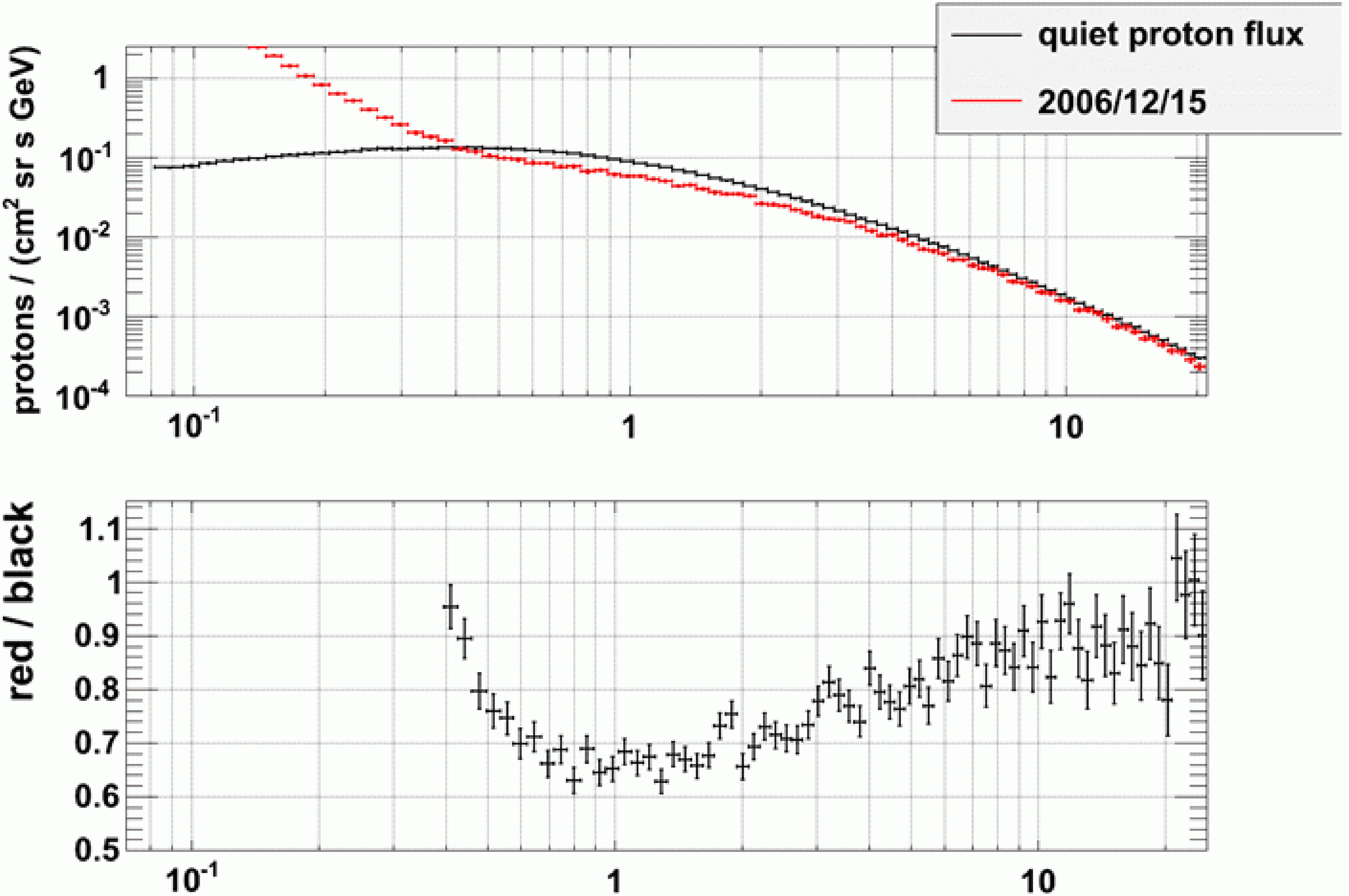
ApJ 742, 2, 102, 11, 2011.

December 13

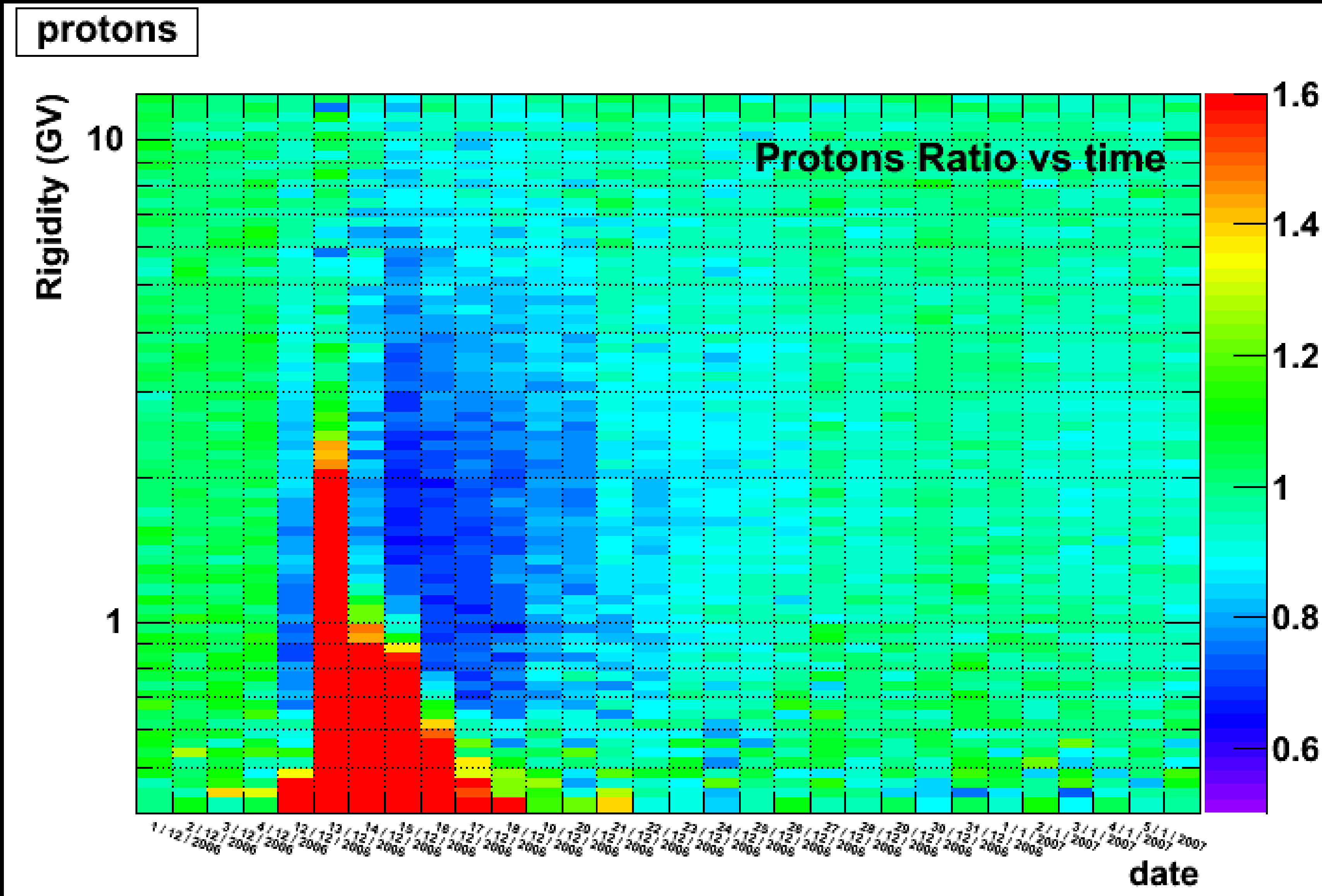


Proton flux
Helium flux
quiet flux (nov 2006)
13/00:00 - 13/02:57
13/03:18 - 13/03:29
protons / (cm² sr s GeV)
helium / (cm² sr s (GeV/n))
kinetic energy (GeV)
kinetic energy (GeV/n)

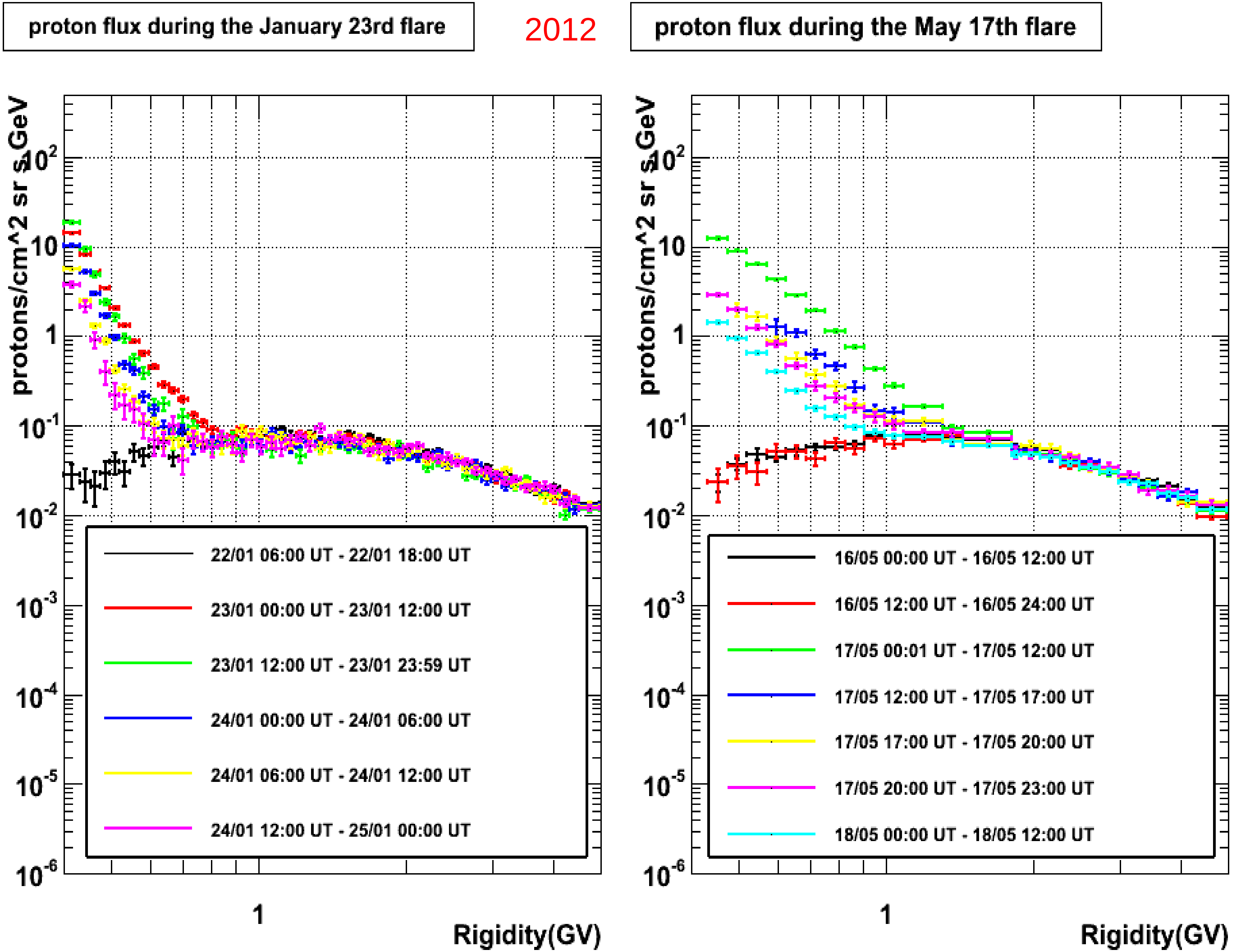
Forbush decrease



Time and rigidity dependence of Forbush decrease



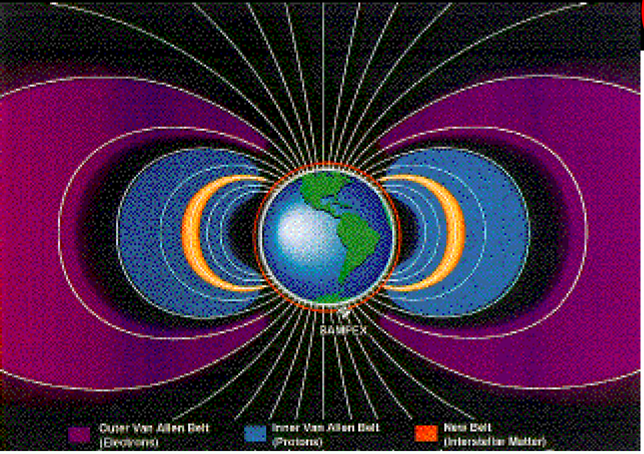
From Mergè Martucci Sotgiu

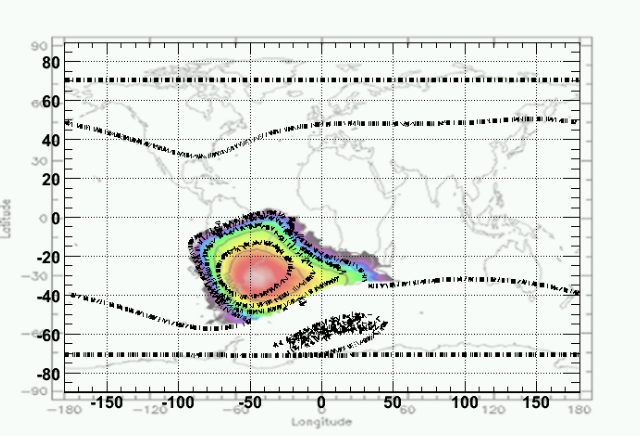


proton flux during the January 23rd flare
2012
proton flux during the May 17th flare
protons/cm^2 sr s GeV
Rigidity(GV)
22/01 06:00 UT - 22/01 18:00 UT
23/01 00:00 UT - 23/01 12:00 UT
23/01 12:00 UT - 23/01 23:59 UT
24/01 00:00 UT - 24/01 06:00 UT
24/01 06:00 UT - 24/01 12:00 UT
24/01 12:00 UT - 25/01 00:00 UT
16/05 00:00 UT - 16/05 12:00 UT
16/05 12:00 UT - 16/05 24:00 UT
17/05 00:01 UT - 17/05 12:00 UT
17/05 12:00 UT - 17/05 17:00 UT
17/05 17:00 UT - 17/05 20:00 UT
17/05 20:00 UT - 17/05 23:00 UT
18/05 00:00 UT - 18/05 12:00 UT

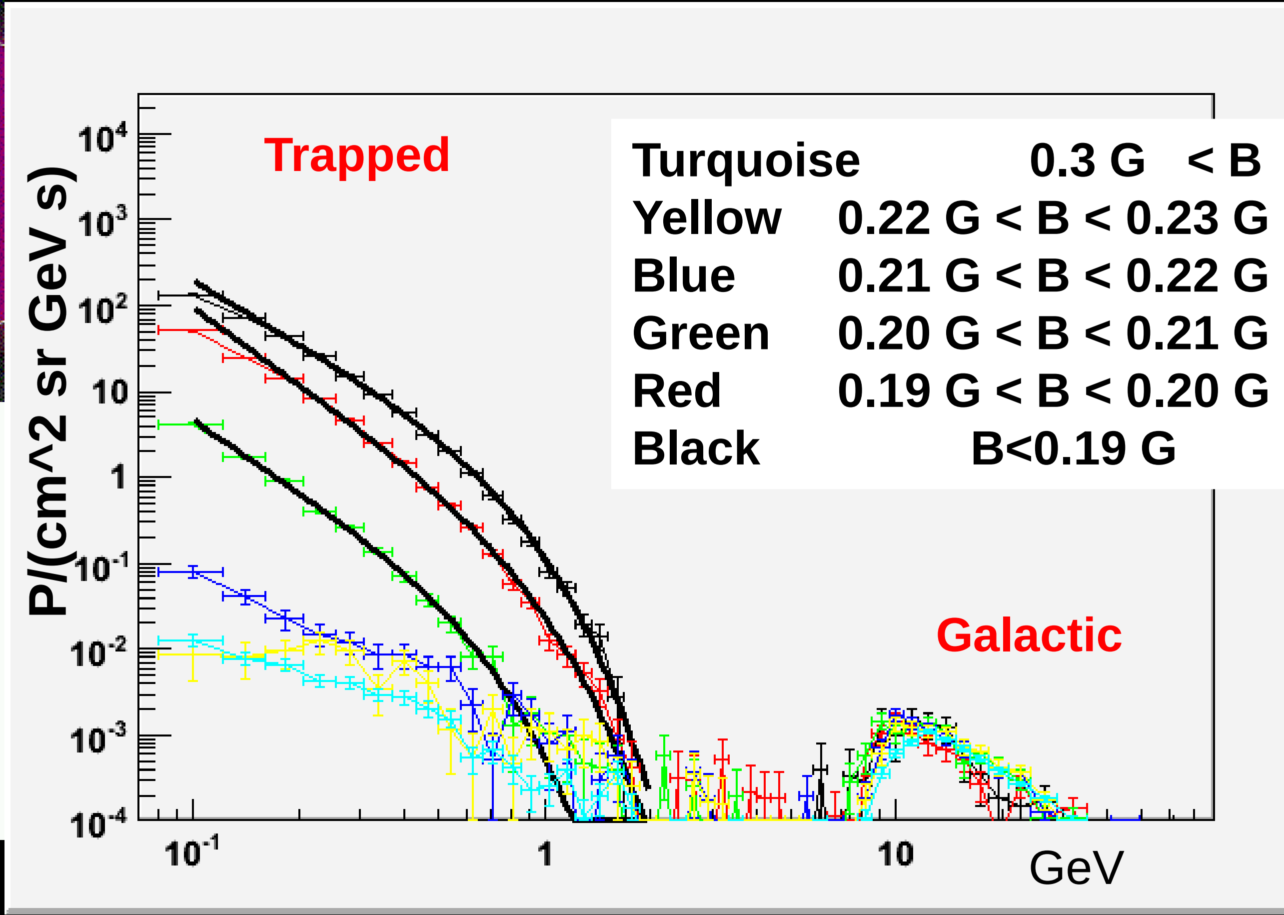
Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Arxiv 0810.4980v1



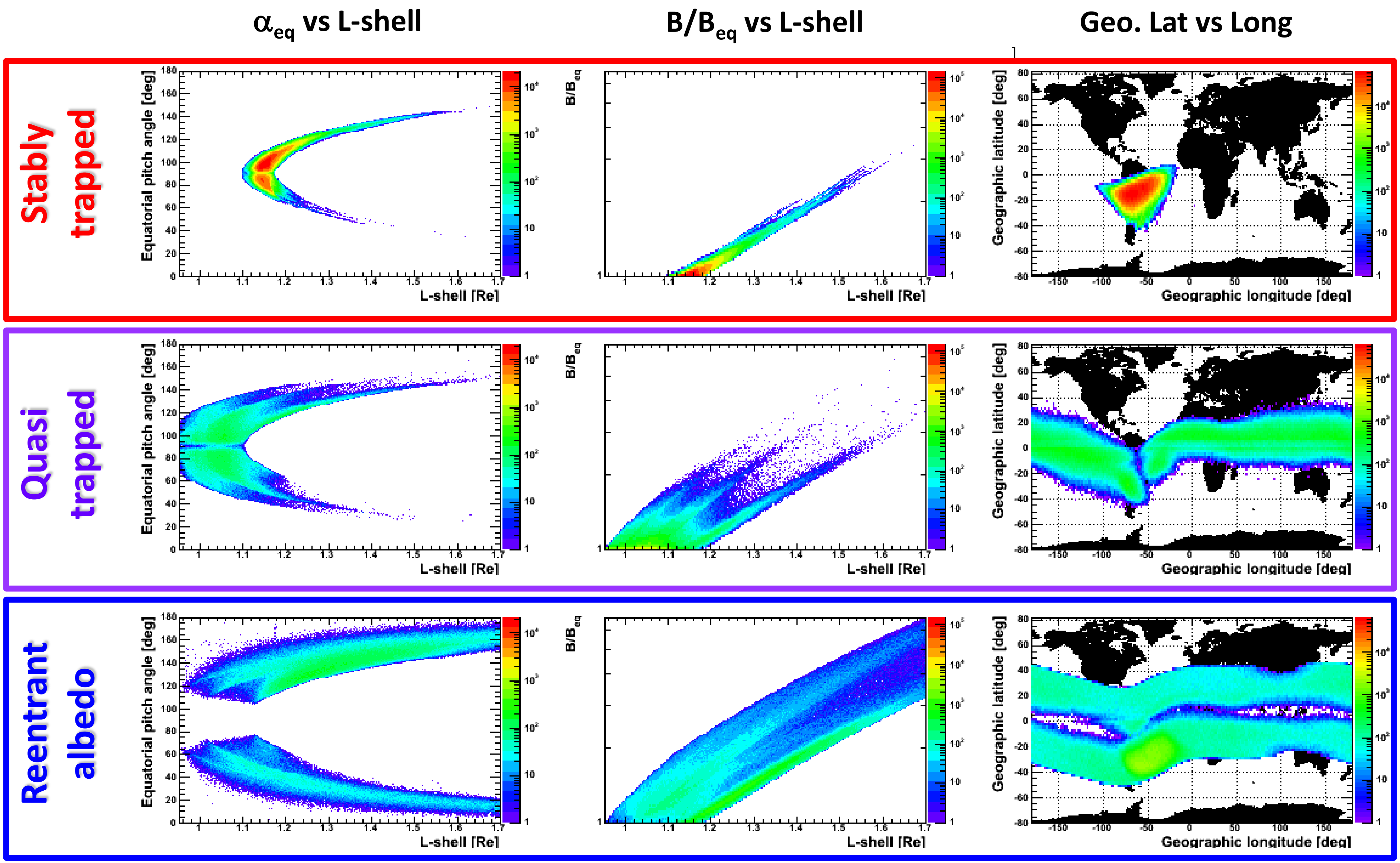


Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)



	A	γ_0	γ_1	χ^2/ndf
nero	0.11±0.01	6.0±0.4	3.1±0.5	7.1
rosso	(2.3±0.3) 10^{-2}	5.9±0.5	2.6±0.6	6.8
verde	(5±3) 10^{-4}	8.1±1.8	4.7±1.8	10.

Distributions of sub-cutoff proton counts

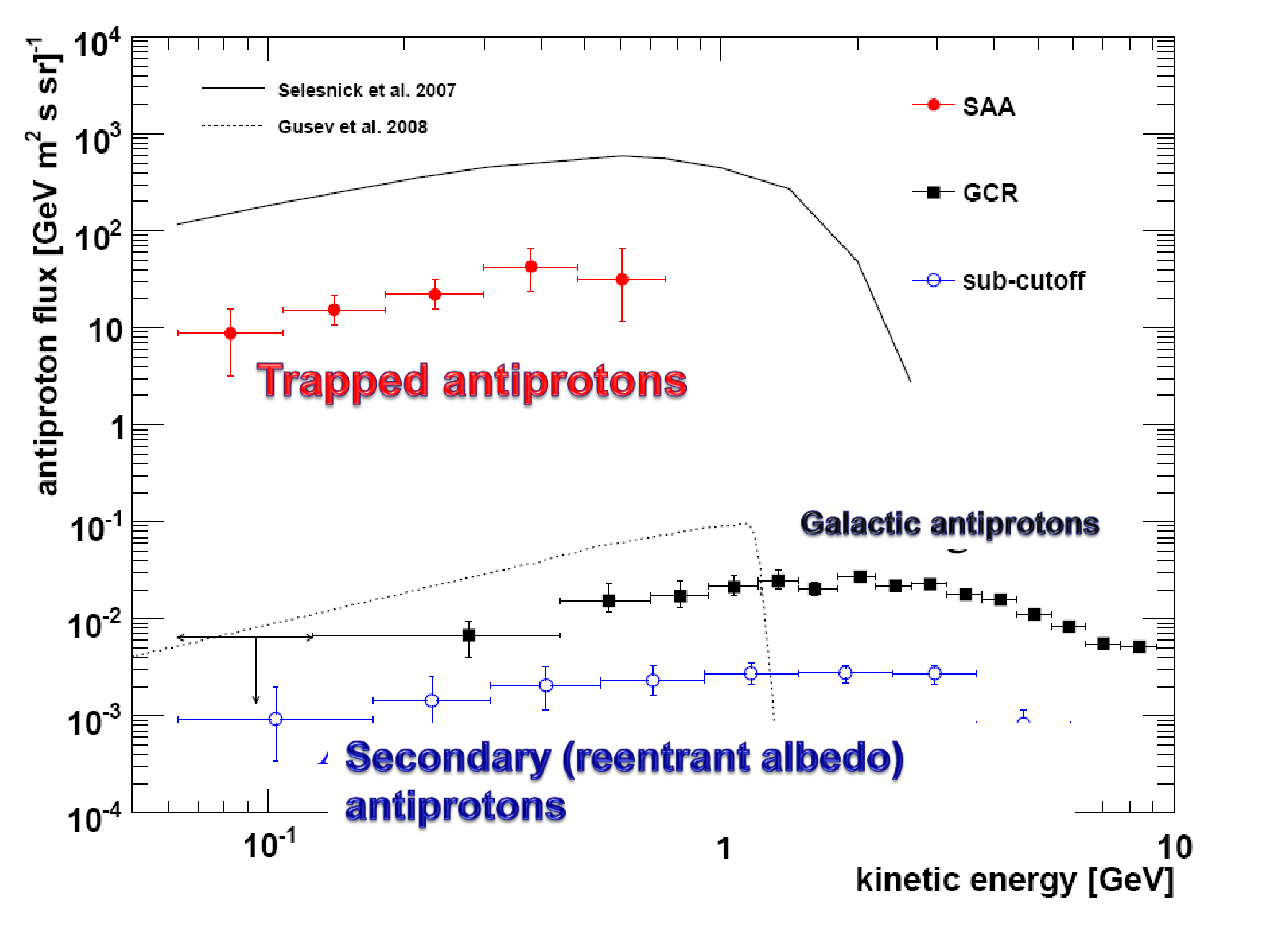


A. Bruno, F. Cafagna ICRC 292

Discovery of stably trapped antiprotons in Earth's radiation belt

Total mass
Less than ng
Negligible but
replenishable

Saturn, Jupiter
mass μg



O. Adriani *et al.* 2011 *ApJ* **737** L29

- Pamela is operating successfully in space
- Expected three years of operations – survived seven!
- Mission prolonged at least 1 more year
- Most critical results confirmed by FERMI and AMS
  → protons He
- Hope to continue measure deep in the 24th solar cycle

http://pamela.roma2.infn.it

http://www.casolino.it