26/10/2015

Precision research of cosmic rays from space with PAMELA detector: Results and perspectives

M. Casolino

INFN & University of Rome Tor Vergata

RIKEN

Pamela Collaboration

Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Russia: Moscow, St. Petersburg

Germany: Siegen

Sweden: KTH, Stockholm

Gagarinsky Start, 14/6/2006

Launch on June 15th 2006 Soyuz-U rocket

70 degrees polar orbit
350*600km i,
now 600km

Pamela Instrument

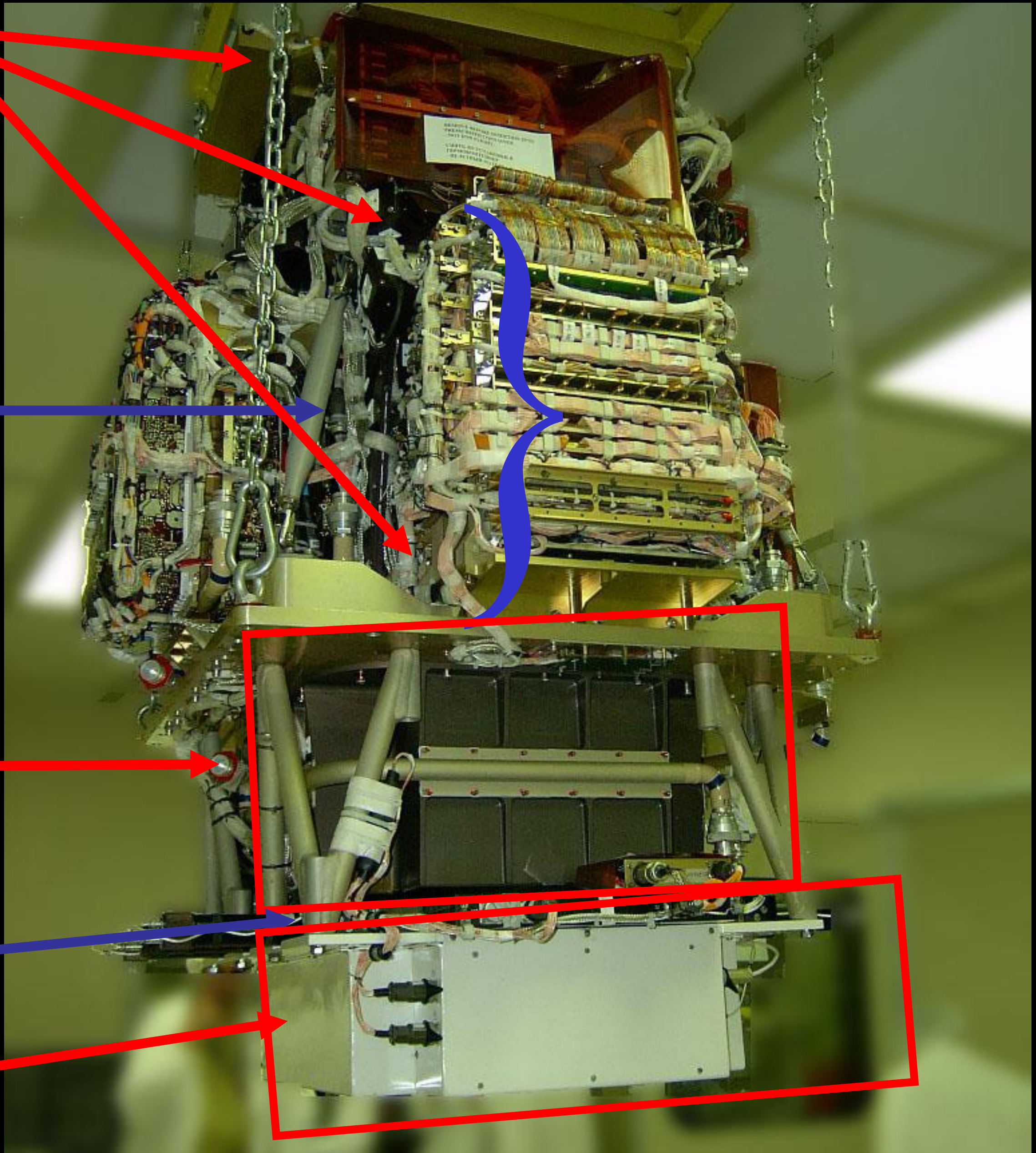
Time
of Flight
(three scintillators,
6 planes, 48 phototubes)

Magnetic (0.46T)
Spectrometer
Microstrip
detector
(6 double sided
microstrip planes)

Silicon
Tungsten
Tracking
Calorimeter
(44 planes of 96 strip)

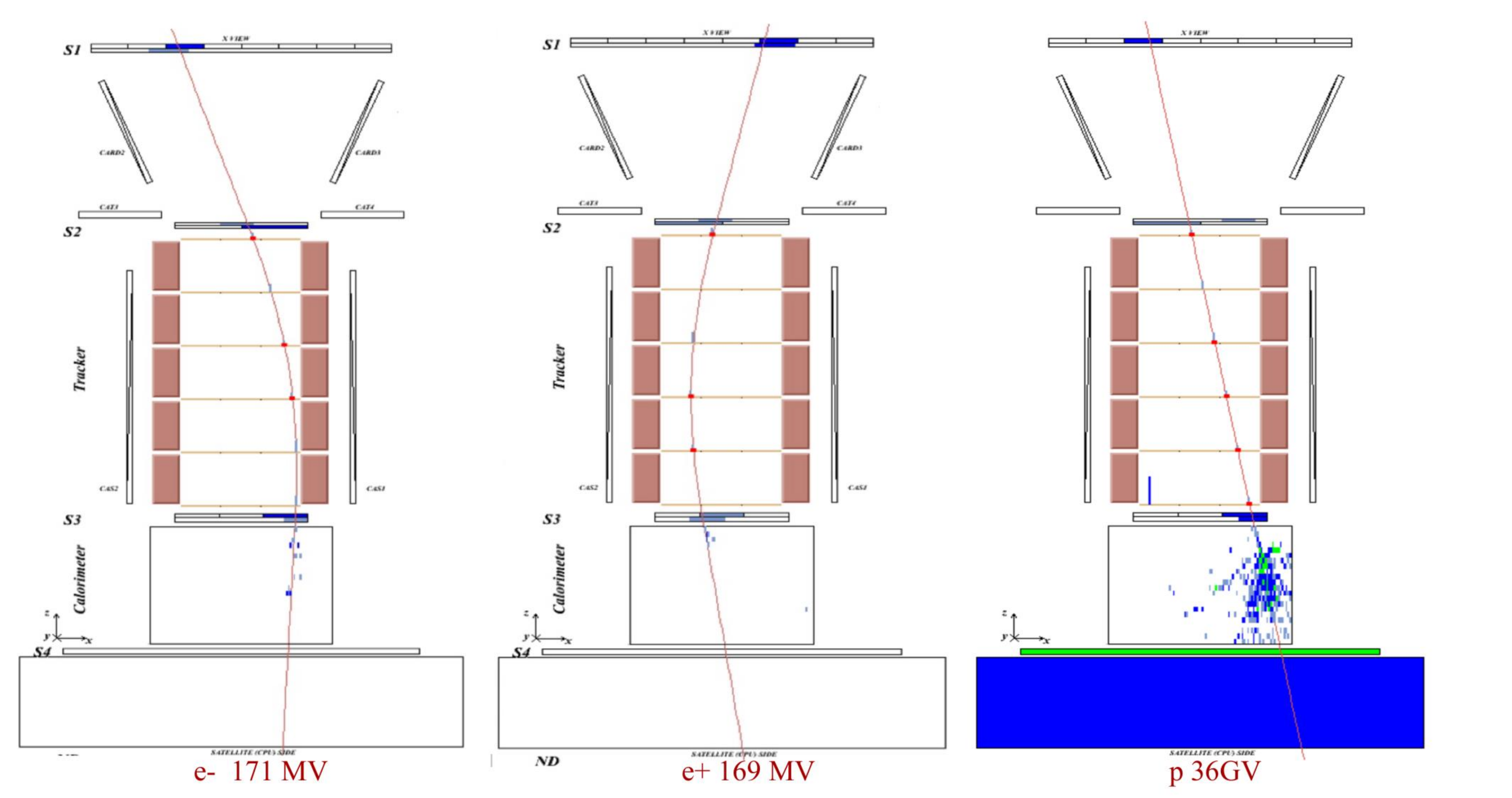
Shower
Catcher
Scintillator

Neutron
Detector



Principle of detection

Electrons Positrons Protons

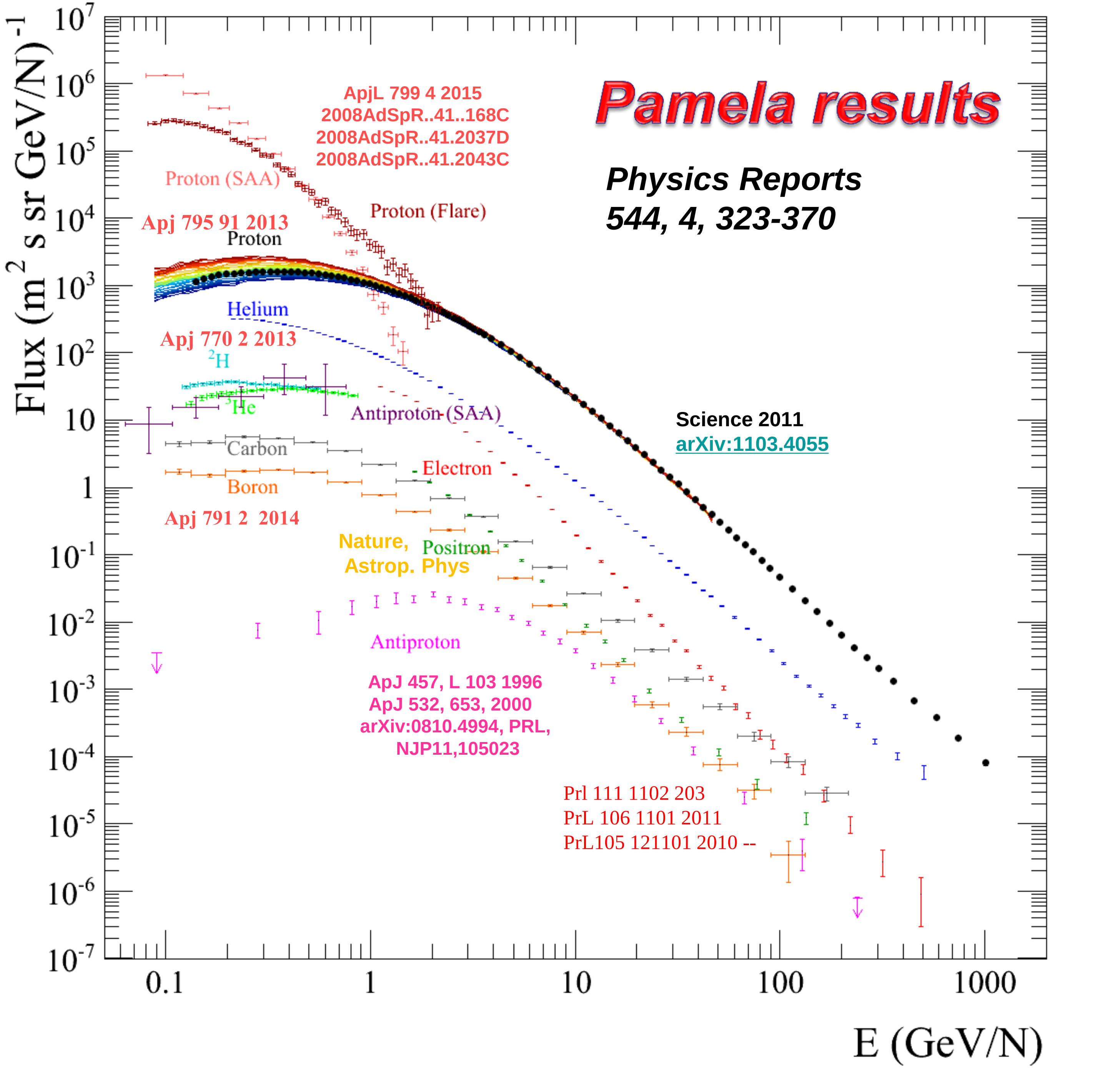


High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere

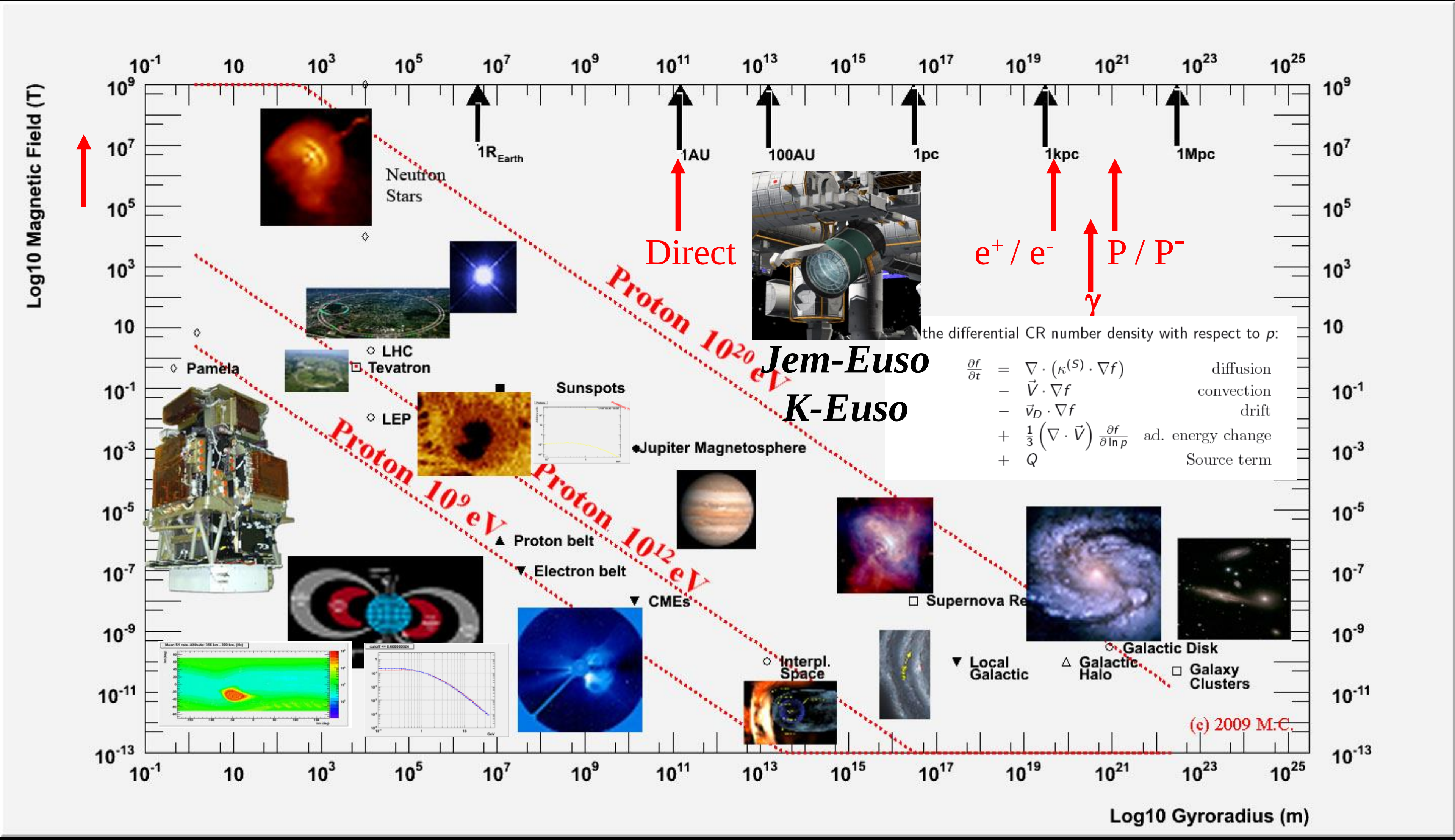
On several different scales

→ Modeling

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



Pamela Physics objectives in the Hillas Plot



Cosmological scale,
(beyond Cosmic Microwave Background)

Matter / Antimatter Asymmetry in the Universe

Sakharov conditions

1) Direct violation of baryonic number
particle "X" decays breaking baryon symmetry

2) CP violation
to avoid specular antiparticle decay

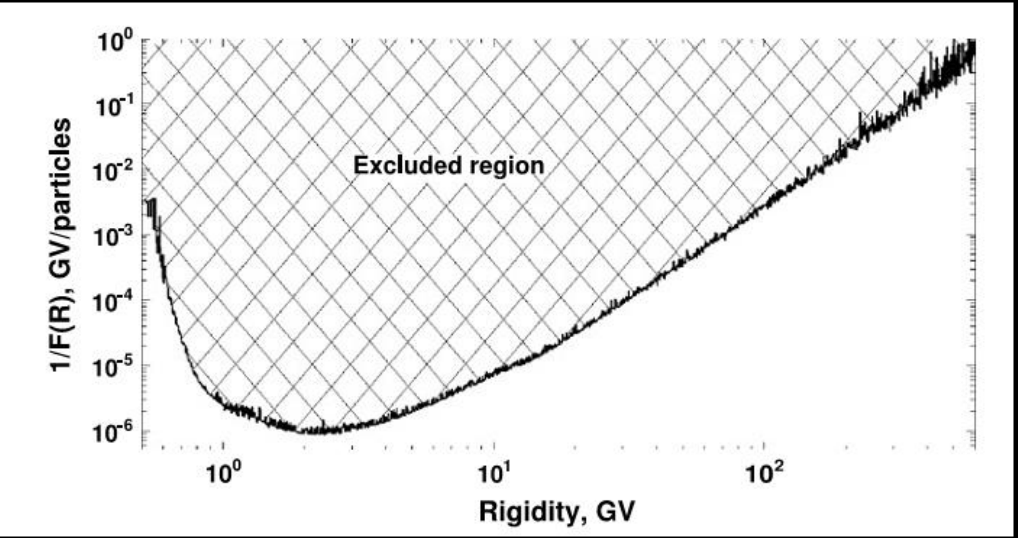
3) Non thermal equilibrium at a given time
To avoid baryon compensation through inverse processes

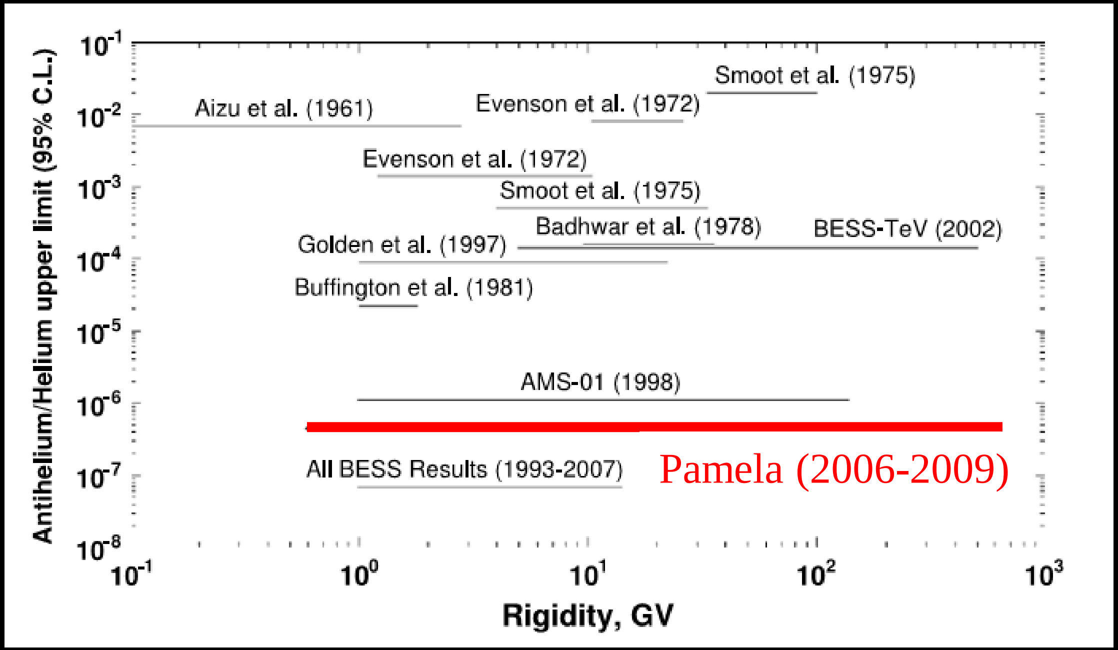
Sakharov, A.D. 1967, J. of Exper. and Theo. Phys. Letters, 5, 24-28,
"Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe"

Search for antinuclei

Antihelium also from primordial nucleosyinthesis

Antinuclei only from antistars

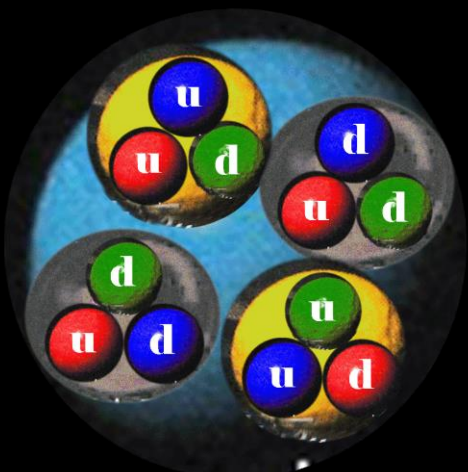




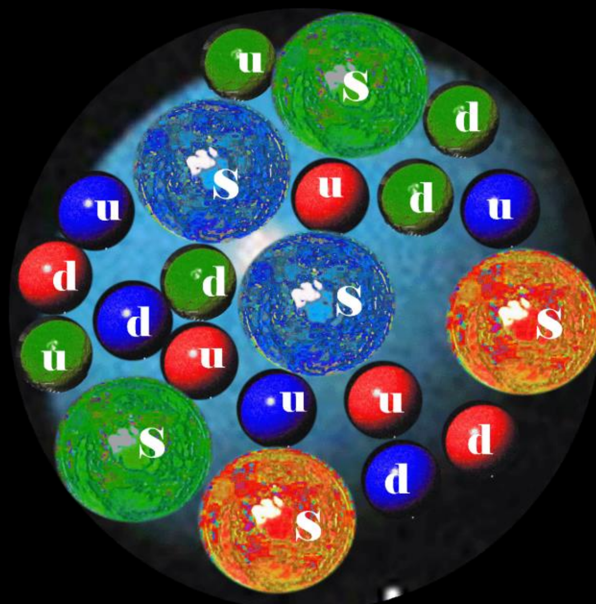
Search for exotic matter: Strangelets

(Lumps of Strange Quark Matter)

Roughly equal numbers of u,d,s quarks in a single ‘bag’ of cold hadronic matter.



Z=2 A=4 (He)
Z/A=0.5



Z=2 A=7
Z/A=0.286

u,d,s quark matter might be stable

Not limited in A

A=100, 1000….

Z is almost zero due to cancellation of quark charge

Could account for a (small) part of DM

Also candidate of UHECR

Strangelet upper limit

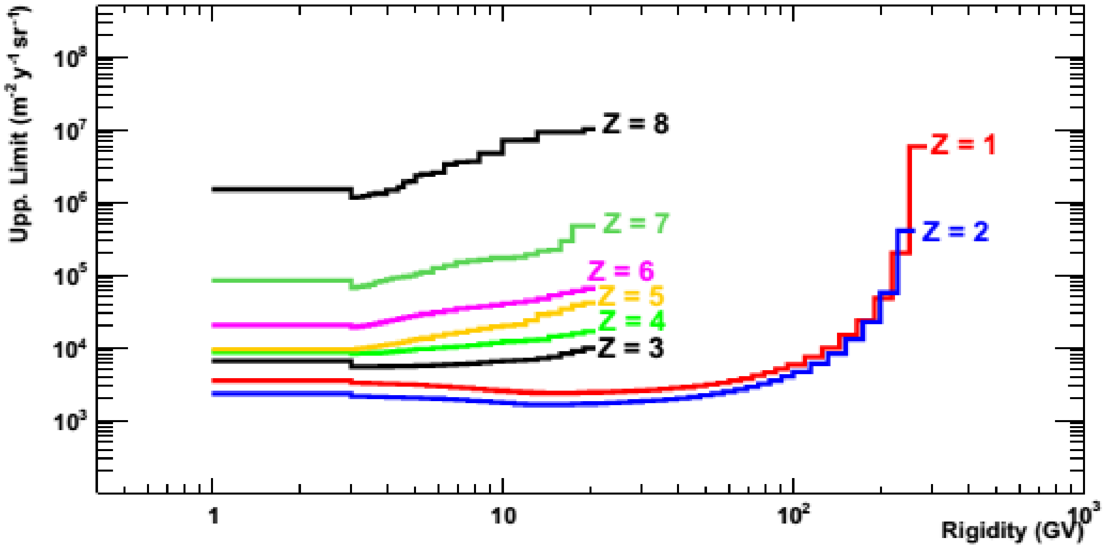
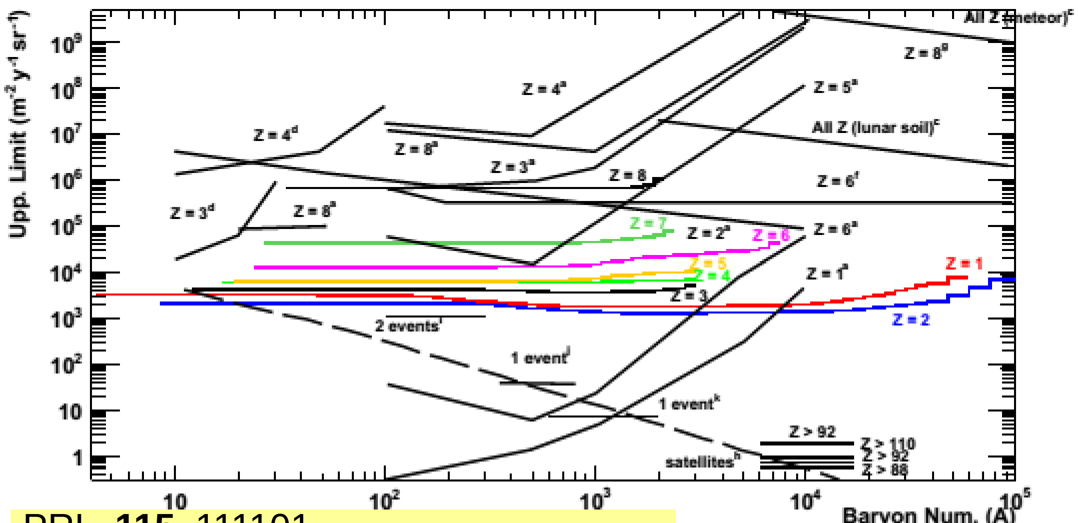


FIG. 4. Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to Z=8.



PRL **115**, 111101 –

predicted:

Phys. Rev. D **71**, 014026 (2005)

relic searches:

a) Phys. Rev. D **41**, 2074 (1990)
b) PRL **92**, 022501 (2004)
d) PRL **43**, 429 (1979)
e) Phys. Rev. D **30**, 1986 (1984)
f) Nuclear Phys. B **206**, 333 (1982)

heavy ion bombarding experiments:

c) PRL **81**, 2416 (1998)

g) satellite-based searches:

ARIEL-6 APJ **314**, 739 (1987)
HEAO-3 APJ **346**, 997 (1989)
Skylab APJ **220**, 719 (1978)
TREK Nature **396**, 50 (1998)

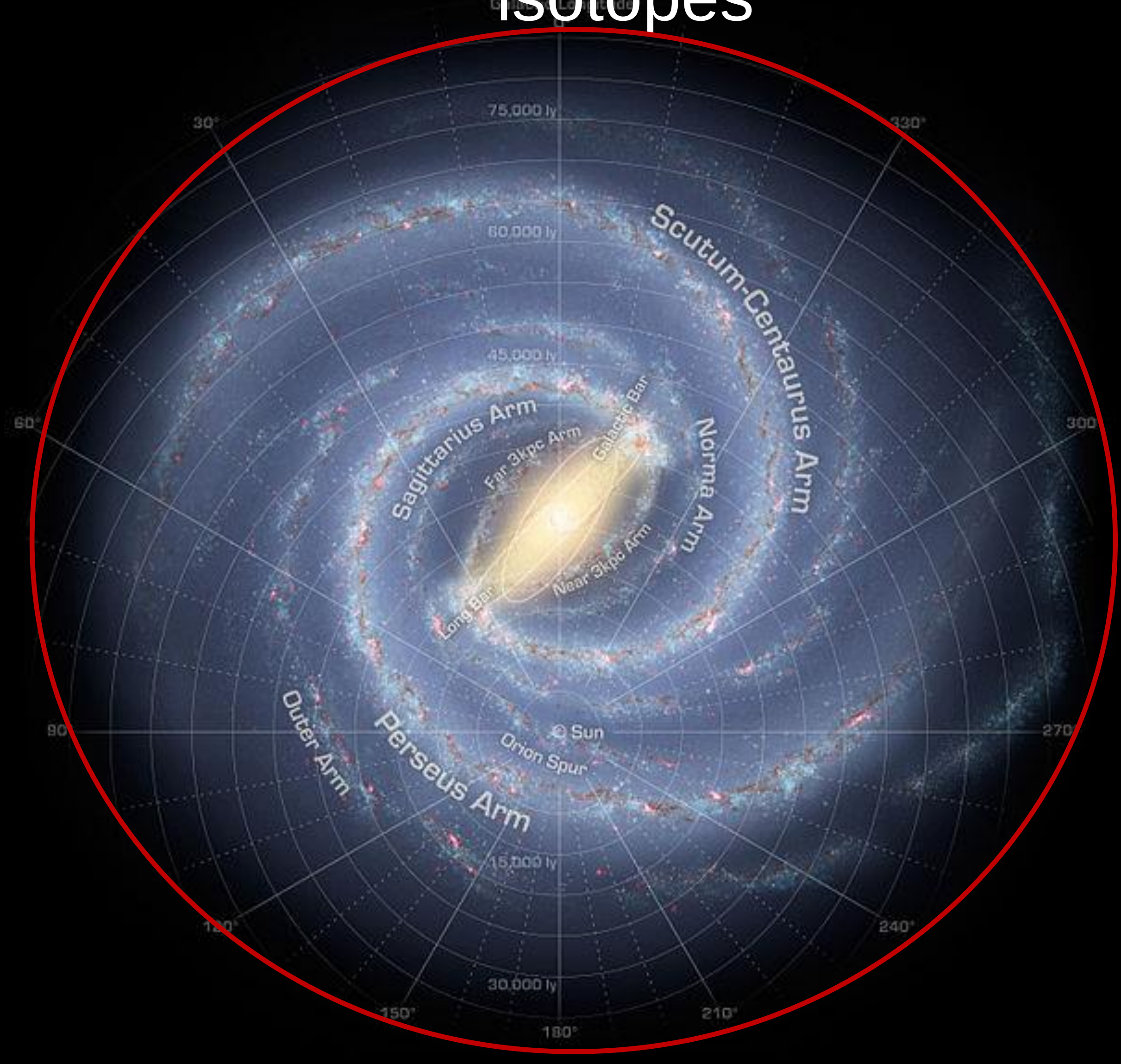
PAMELA, Z=1

PAMELA, Z=2

Strangelet-like events detected by:

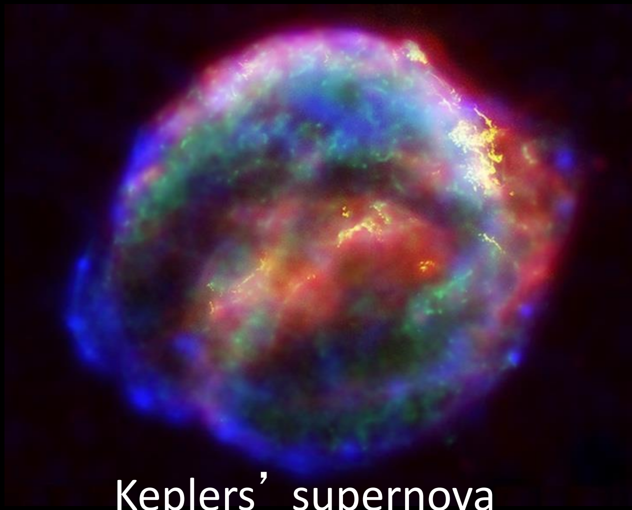
i) HECRO-81 PRL **65**, 2094 (1990)
j) ET Nuovo Cimento A Serie **106**, 843 (1993)
k) Phys. Rev. D **18**, 1382 (1978)

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

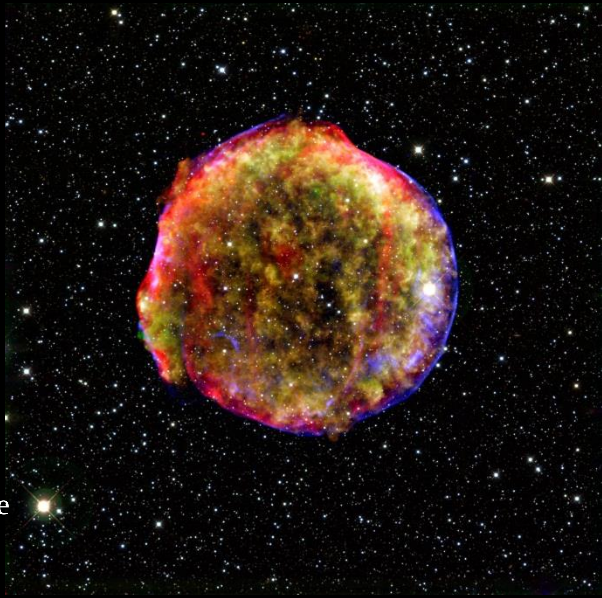


Cosmic rays are accelerated in Supernova explosions (probably)

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



Keplers' supernova

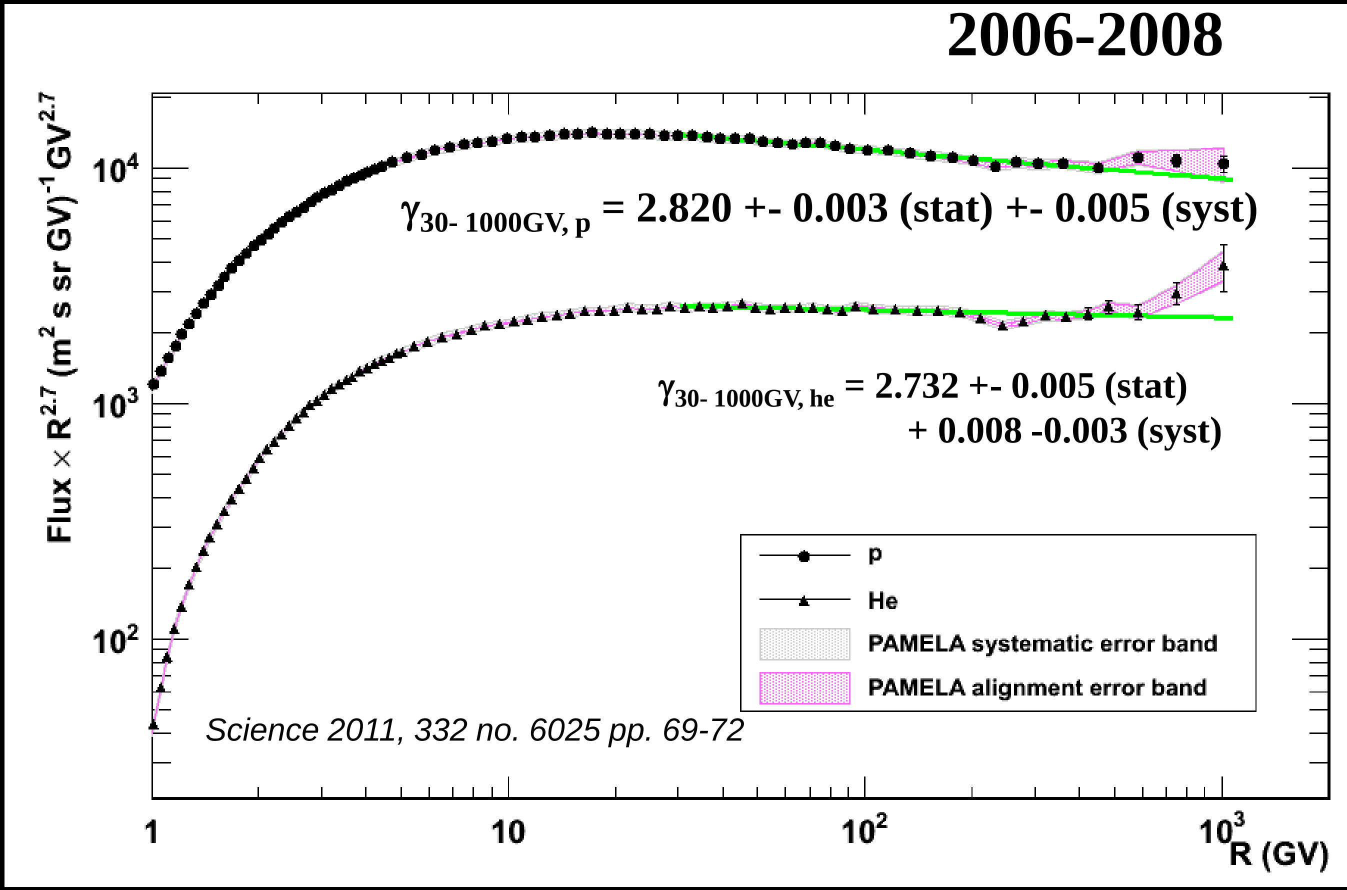


Tycho's supernova

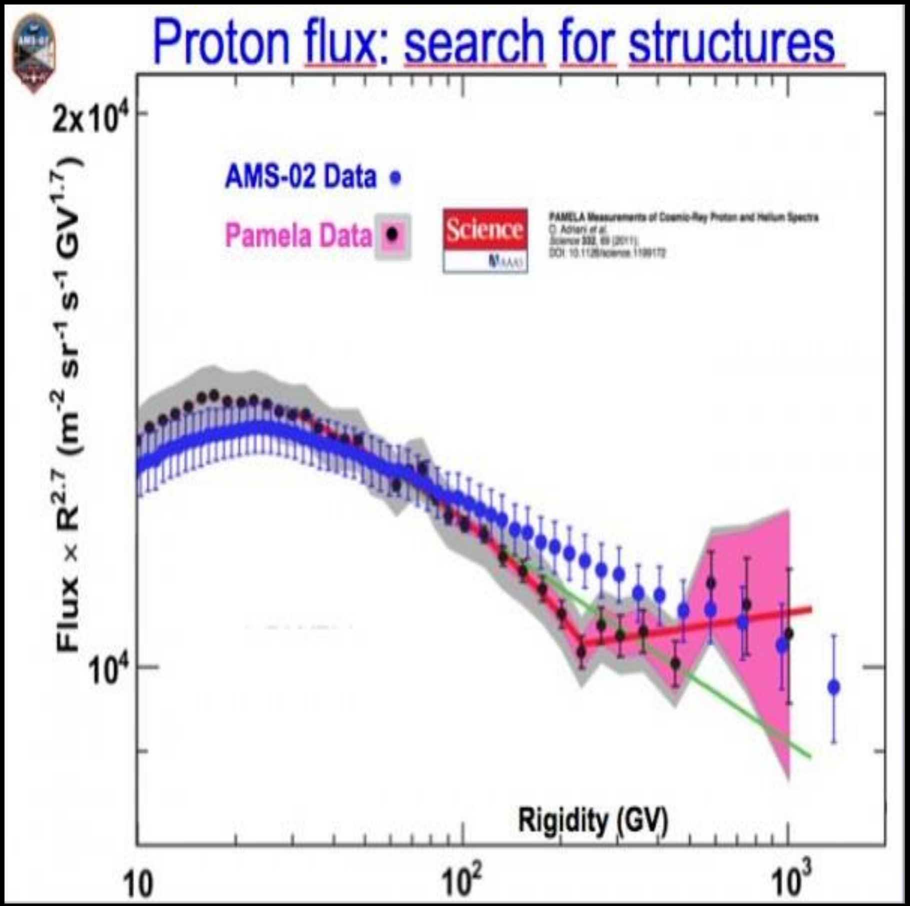
- HESS TeV emision from SNR RX J1713.7-3946 → hadronic inter. Of cr. E>10^14eV *F. Aharonian, et al., Astron. Astrophys. 464, 235 (2007).*
- X-ray measurements of the same SNR → evidence that protons and nuclei can be accelerated E>10^15 eV in young SNR *Uchiyama, et al., Nature 449, 576 (2007).*
- AGILE: 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*

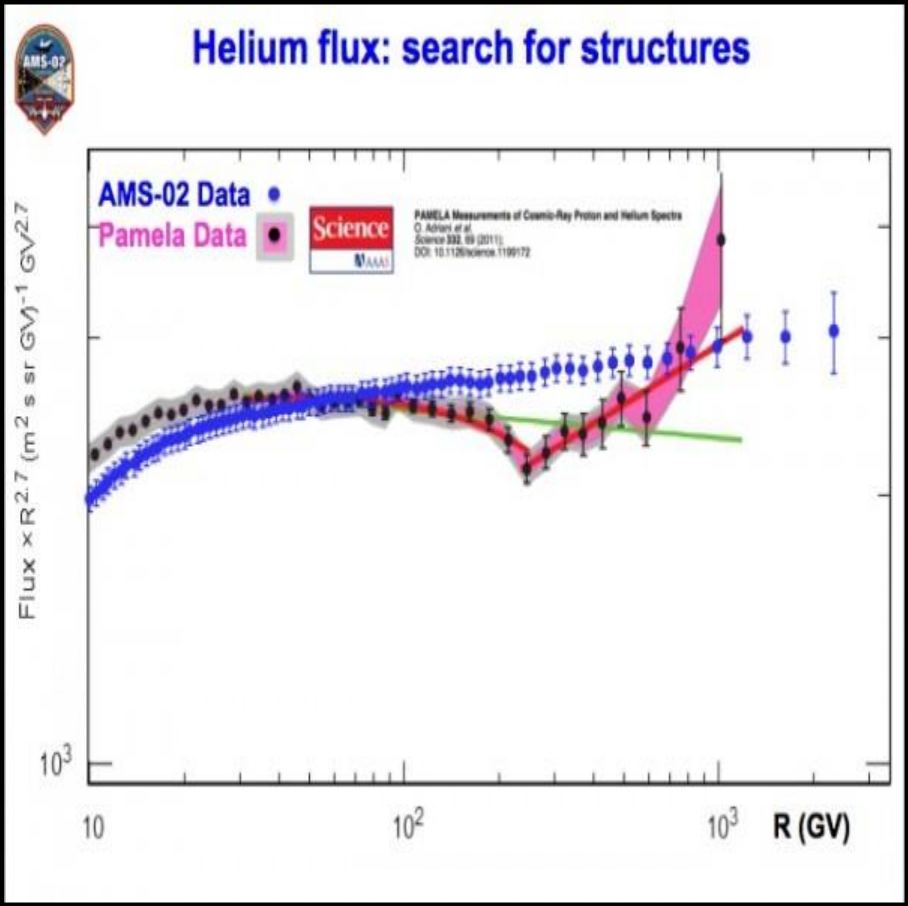
Pamela galactic proton and He

- 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.

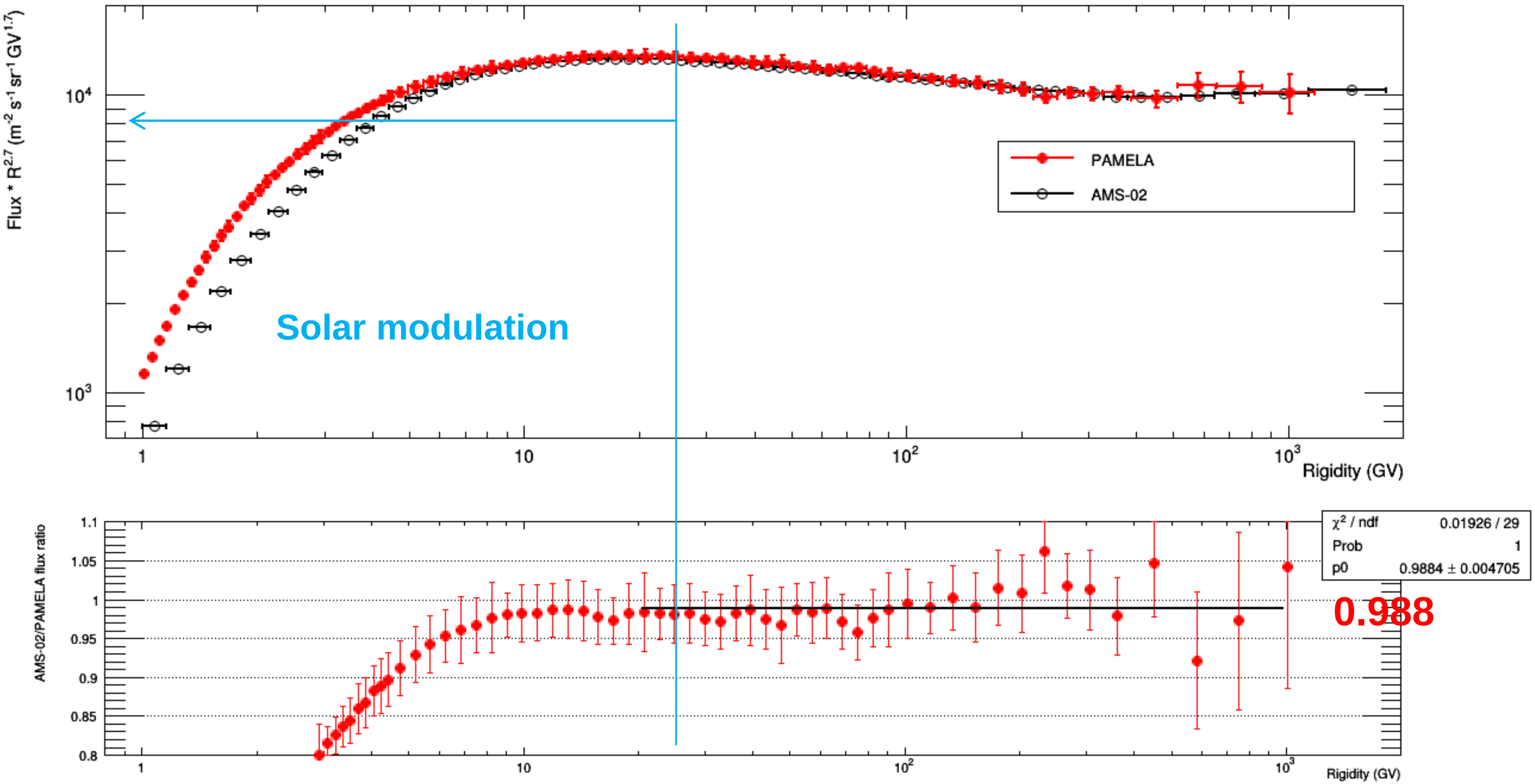


AMS-02 @ ICRC 2013
the importance of systematics



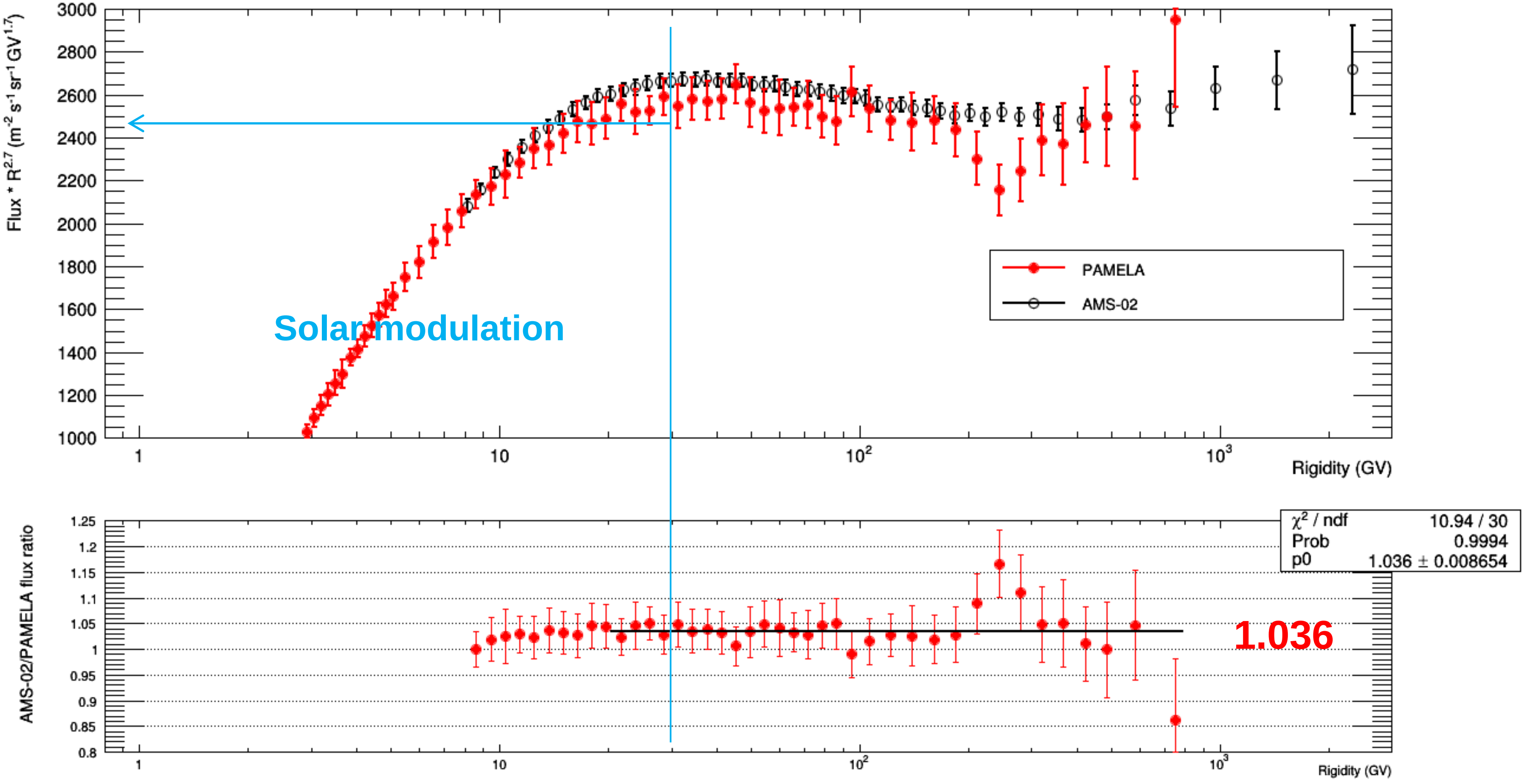


Global picture: PAMELA vs AMS-02 proton spectrum



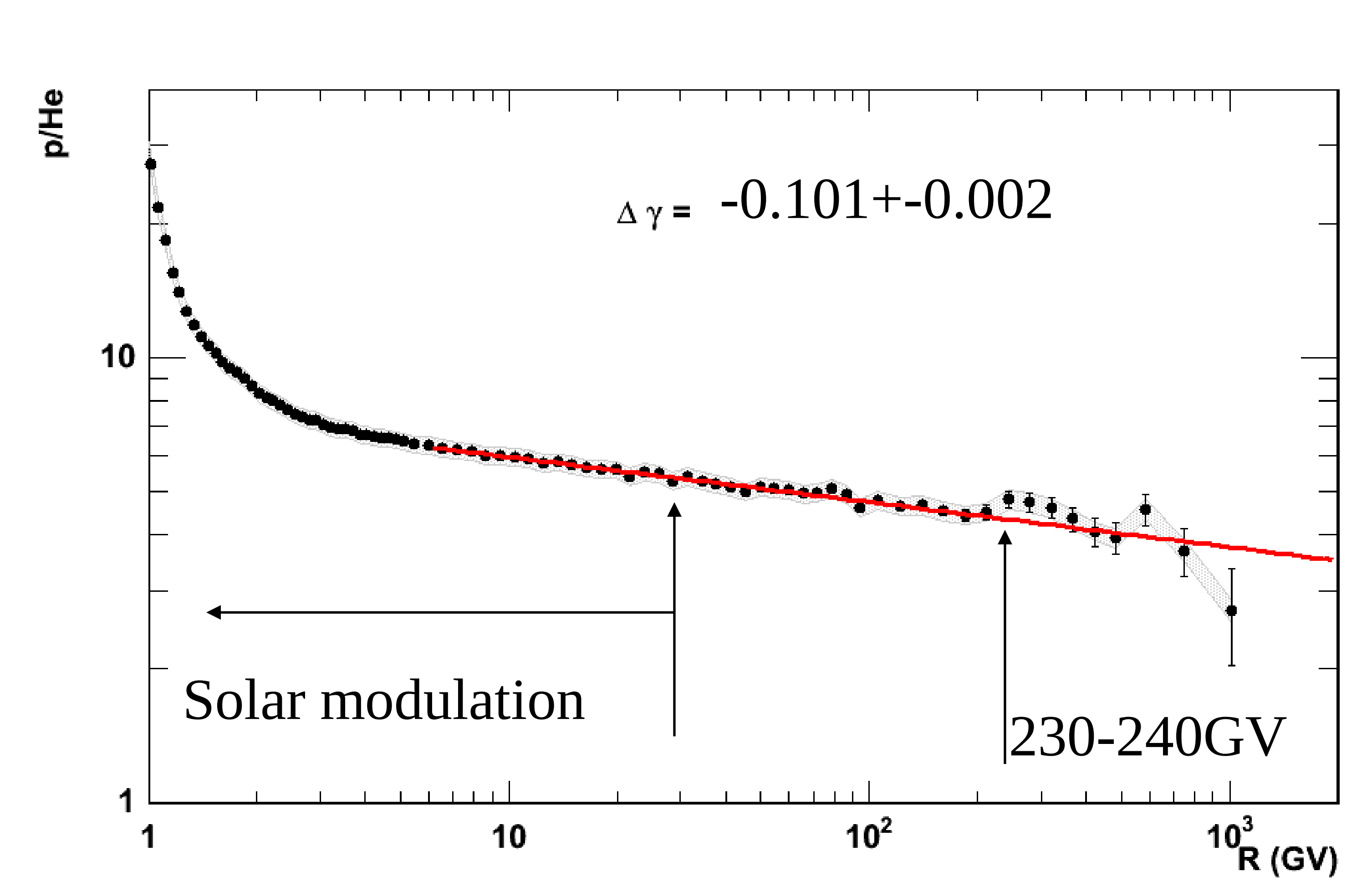
O. Adriani et al, Phys. Rep. (2014)

Global picture: PAMELA vs AMS-02 helium nuclei spectrum



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



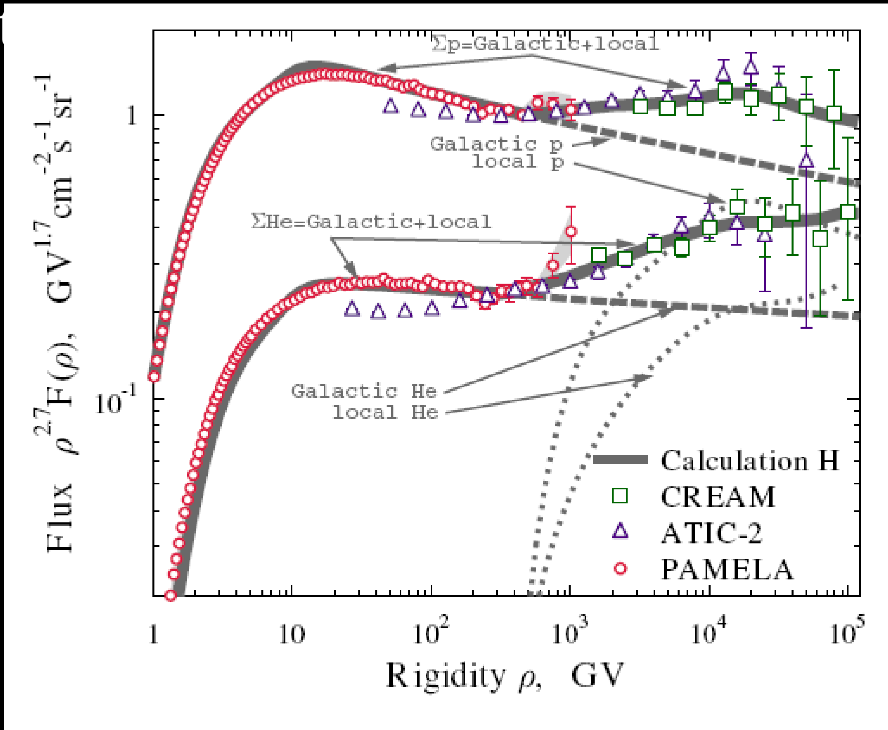
Conclusion from Proton and Helium

- Proton and Helium undergo different processes even in GeV-TeV scale
- Change in spectral index around 230-240GV

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*
- *Various models, Moskalenko 1108.1023*



B/C ratio

Propagation in the Galaxy

ApJ 791 2 2014

- B/C ratio

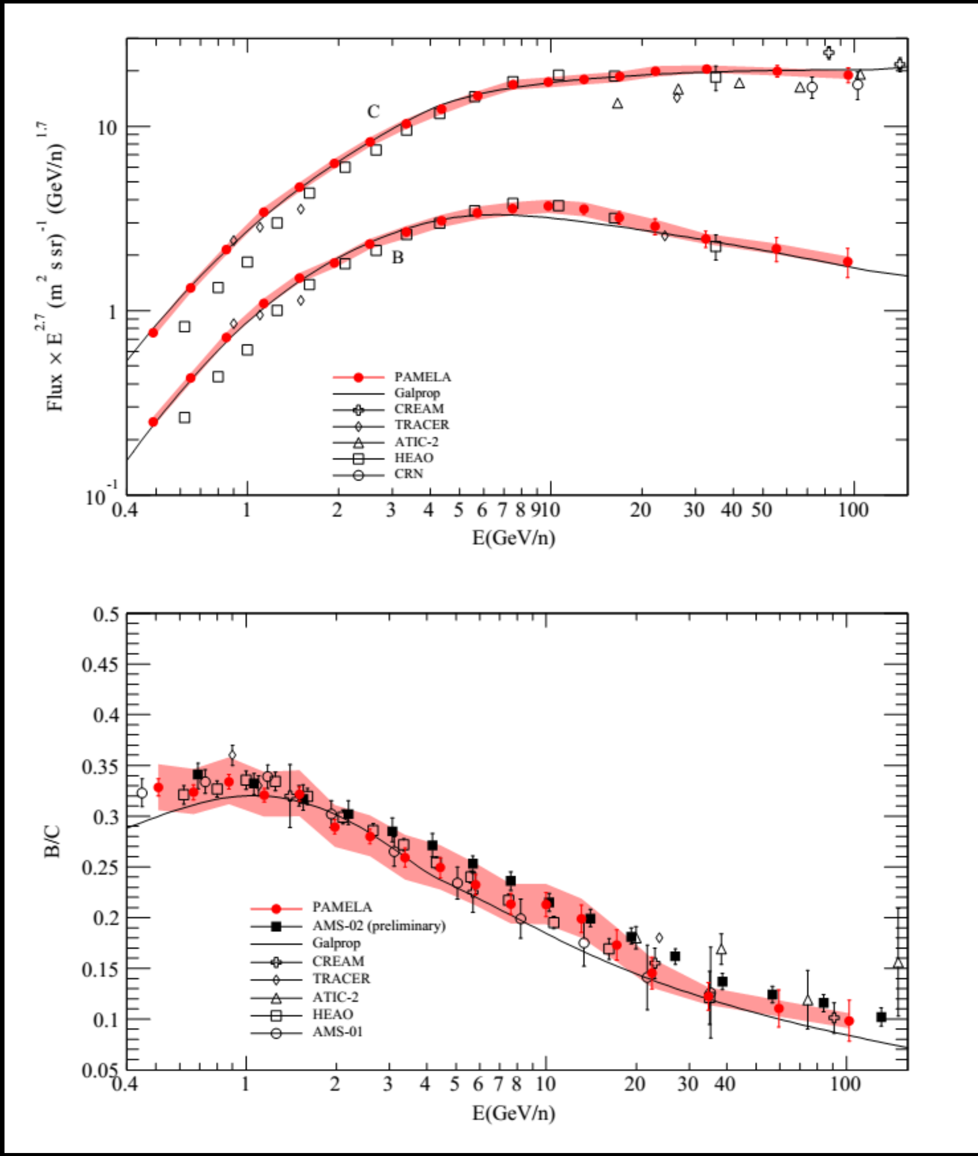
Secondary/primay

CNO+ISM → B

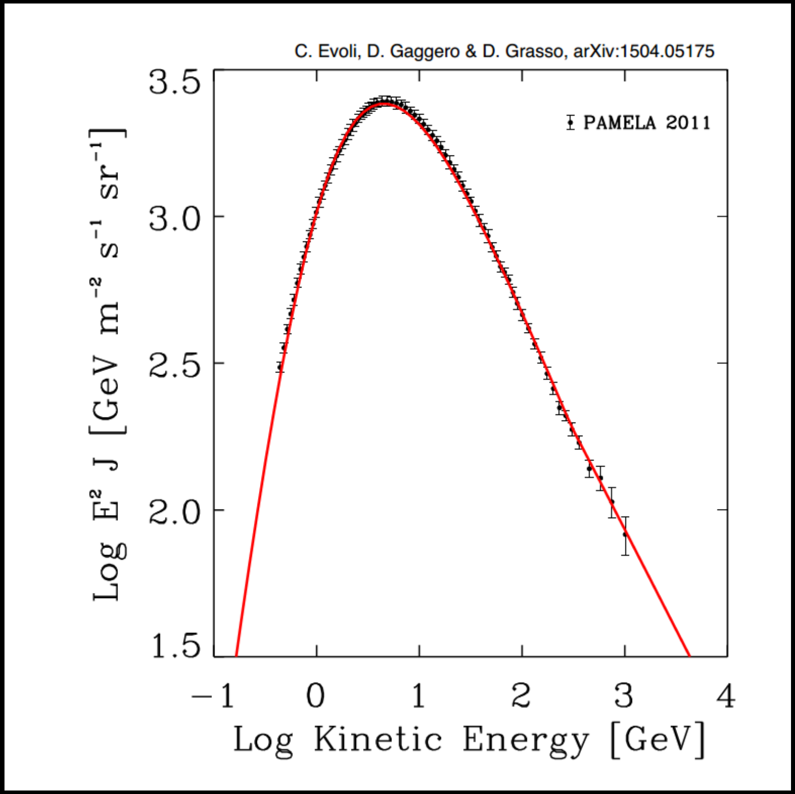
$$N_B / N_C \propto \lambda_{esc} \cdot \sigma_{CNO \to B}$$

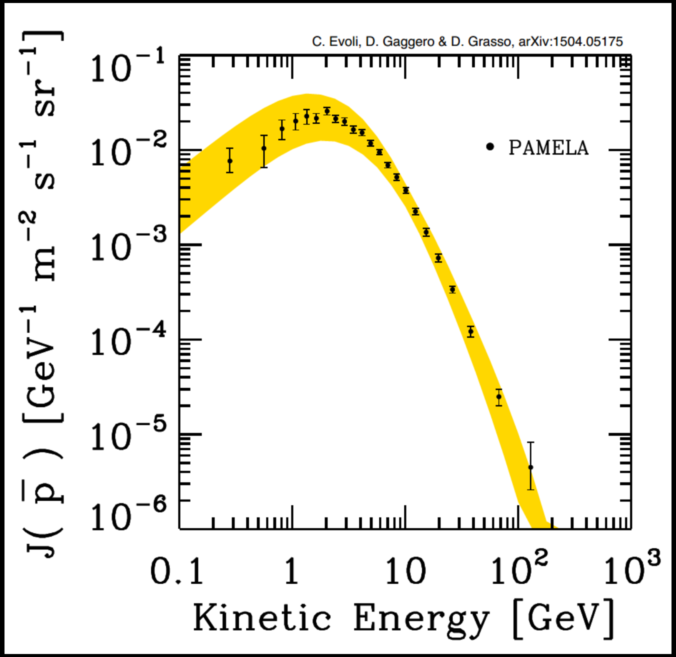
→ Propagation in the Galaxy

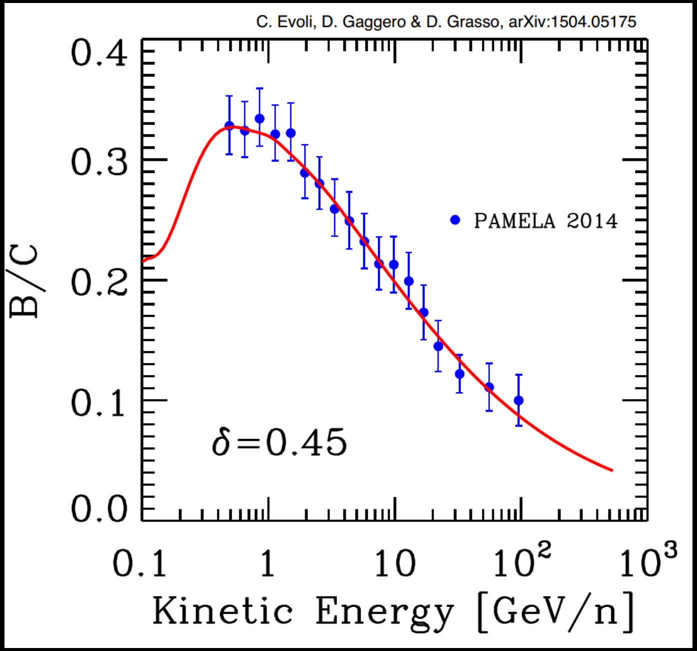
Time of permanence of cr



Puzzle of production and propagation in the galaxy





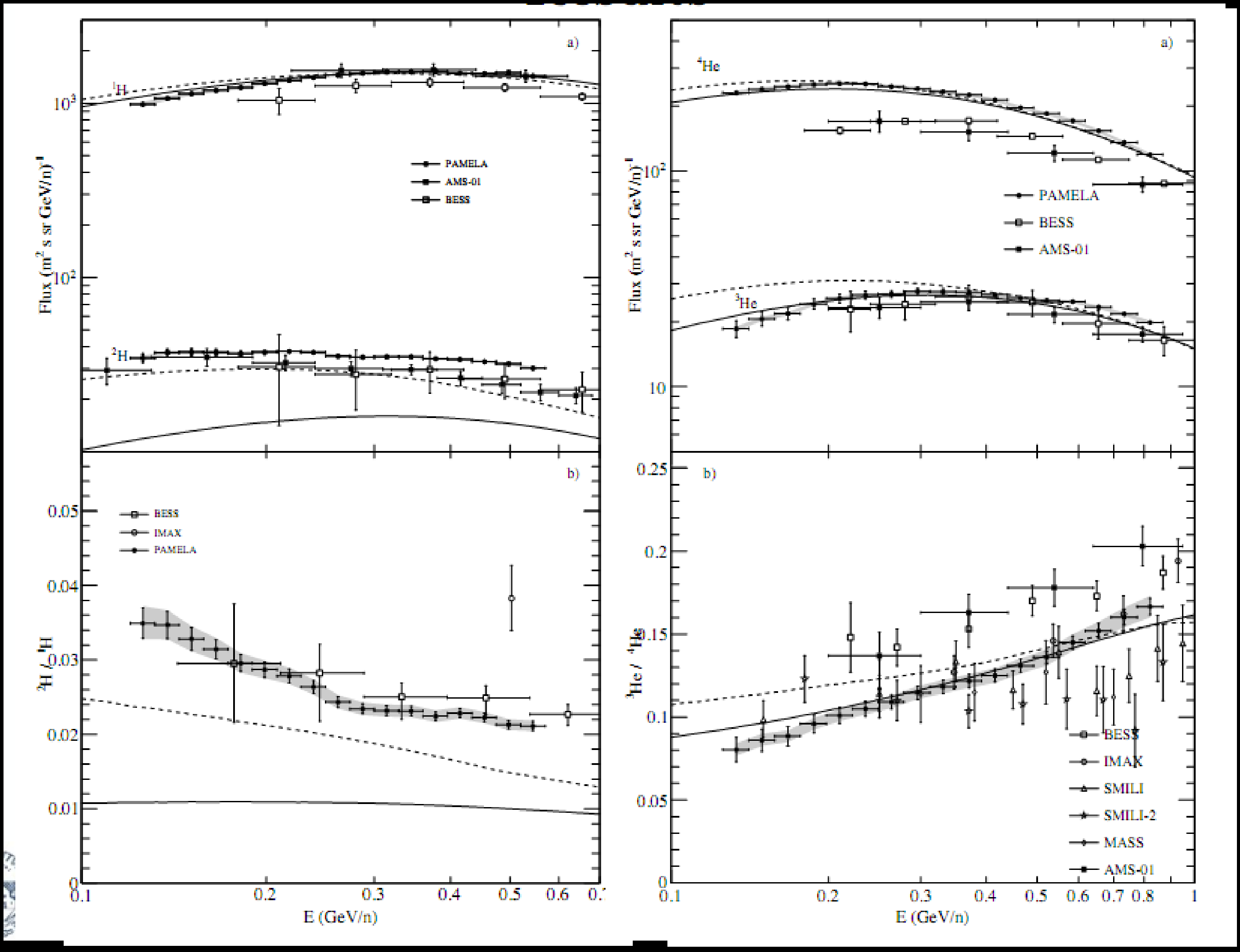


H and He Isotopes

Propagation in the Galaxy

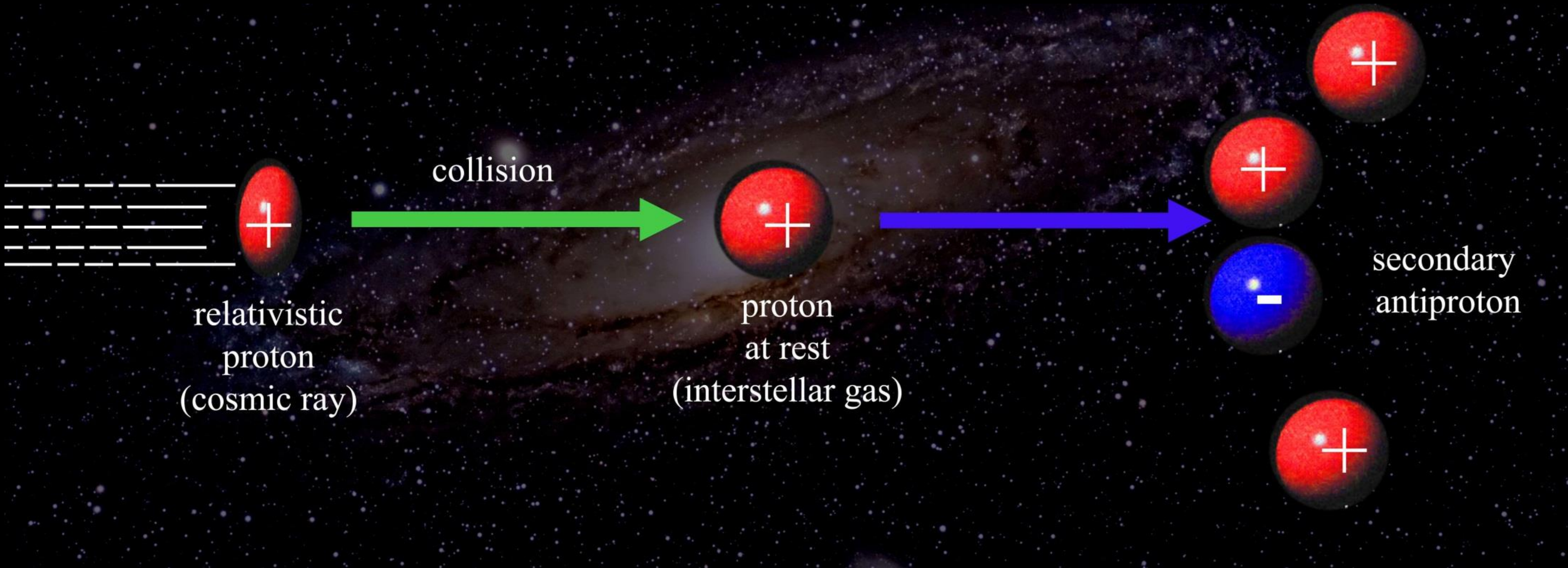
- Flux depends on solar modulation
- Ratio is less dependent
- Strong tool for evaluating secondary particle production in the galaxy
- Complementary to B/C

ApJ 770:2, 2013

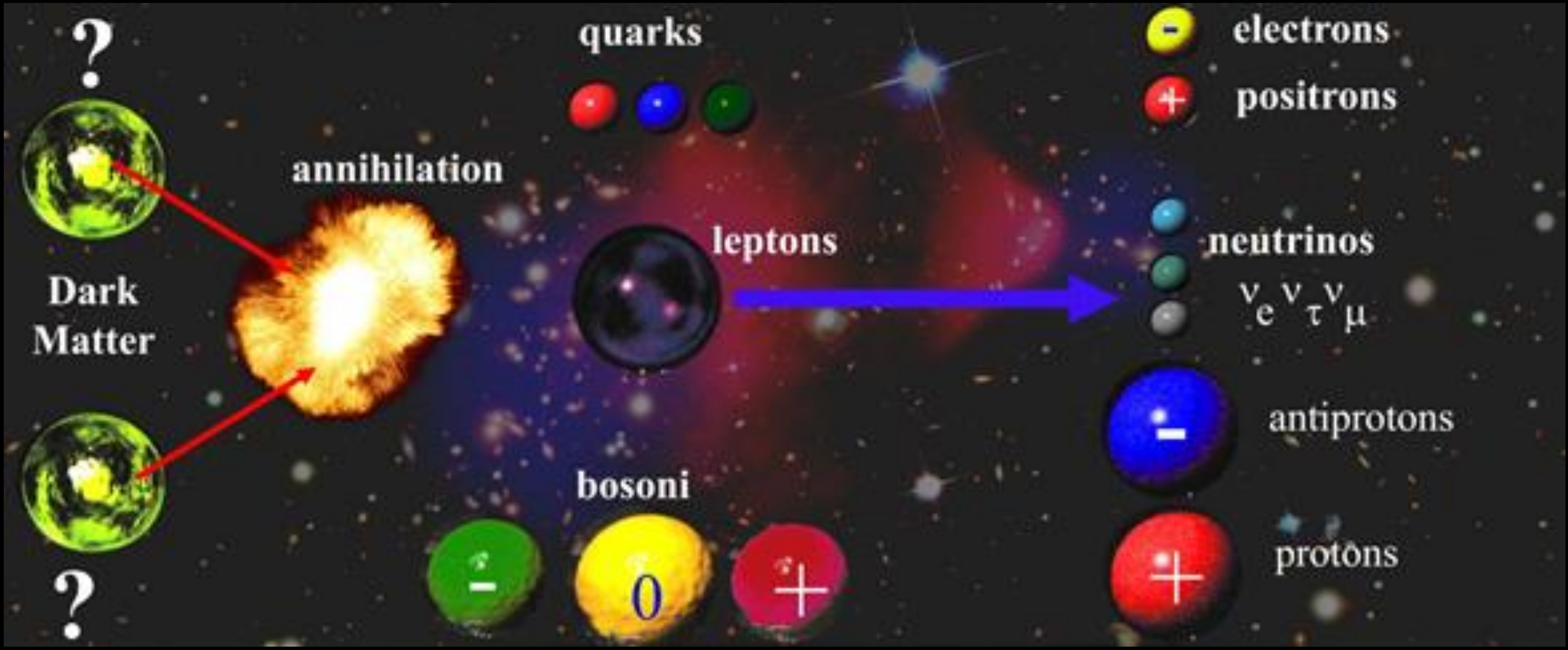


Antiprotons

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



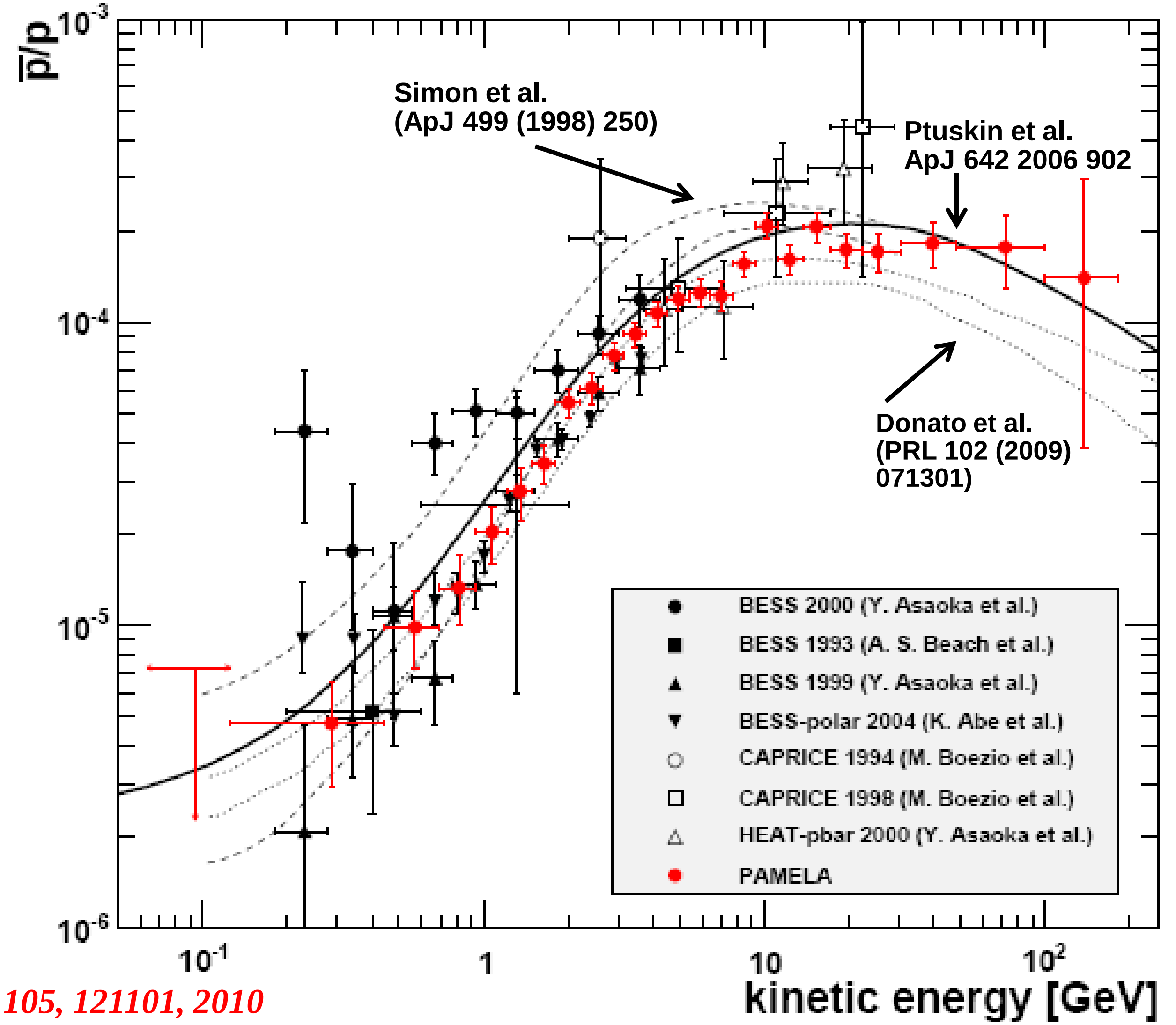
Indirect Dark matter search in space



Antiproton/proton ratio

Low Energy → *Confirms charge dependent solar modulation*

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



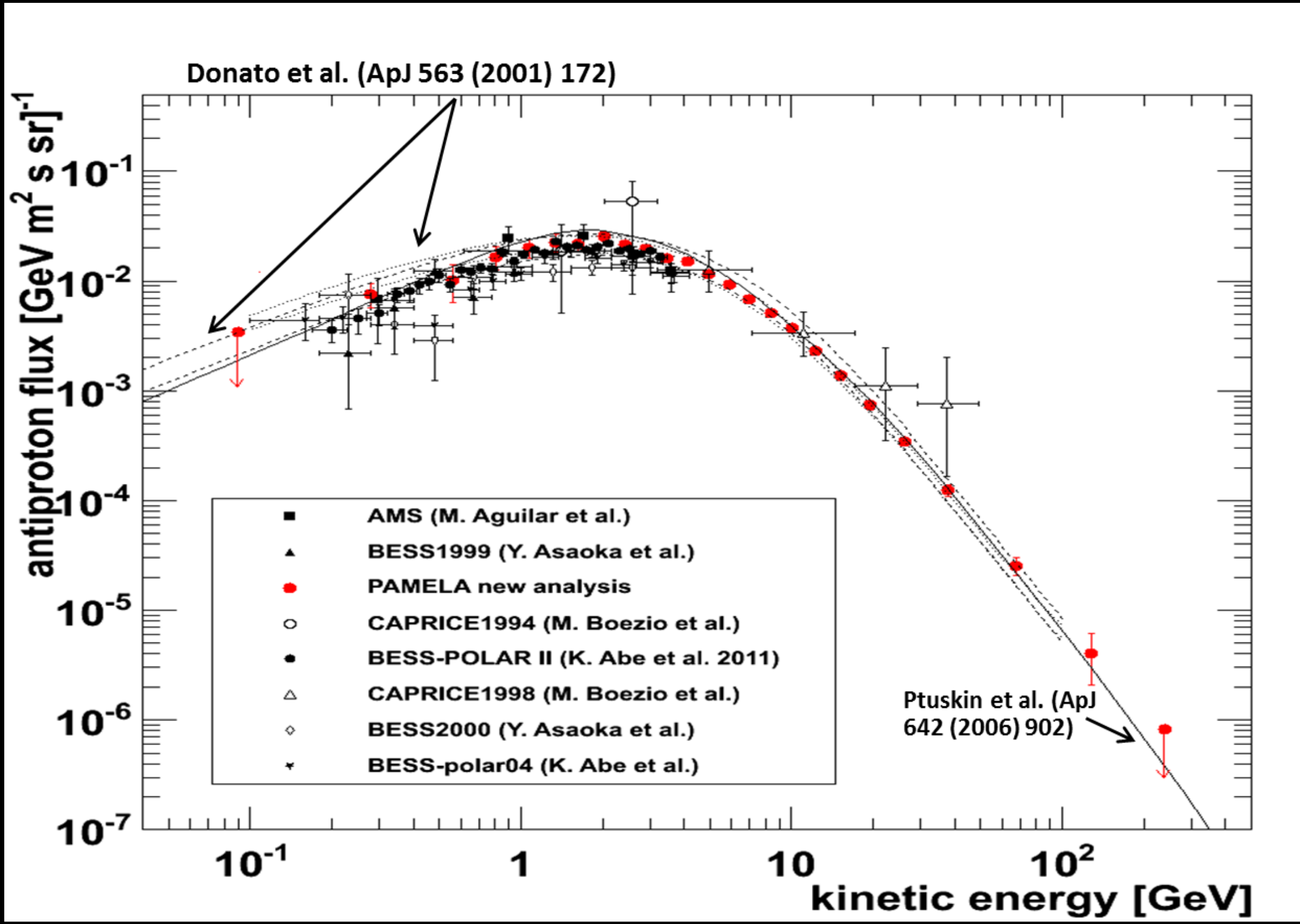
PRL. 105, 121101, 2010

PRL 102:051101,2009

Antiproton absolute flux

Apparently no extra sources

Rule out and strongly constrain many models of DM

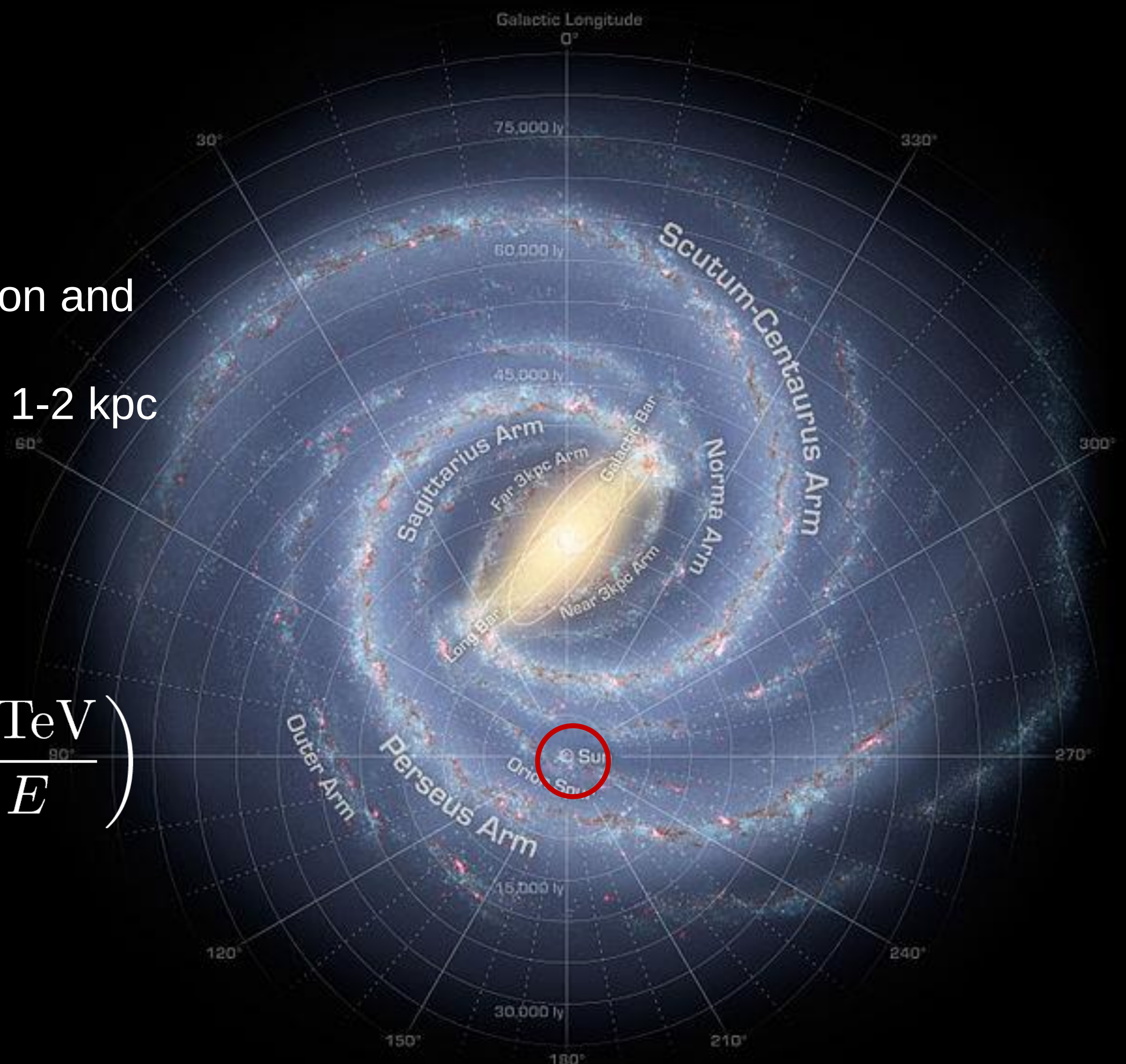


S M. Asano, et al, Phys. Lett. B 709 (2012) 128.
R. Kappl et al , PRD 85 (2012) 123522
M. Garnyet al, JCAP 1204 (2012) 033
D. G. Cerdeno, et al, Nucl. Phys. B 854

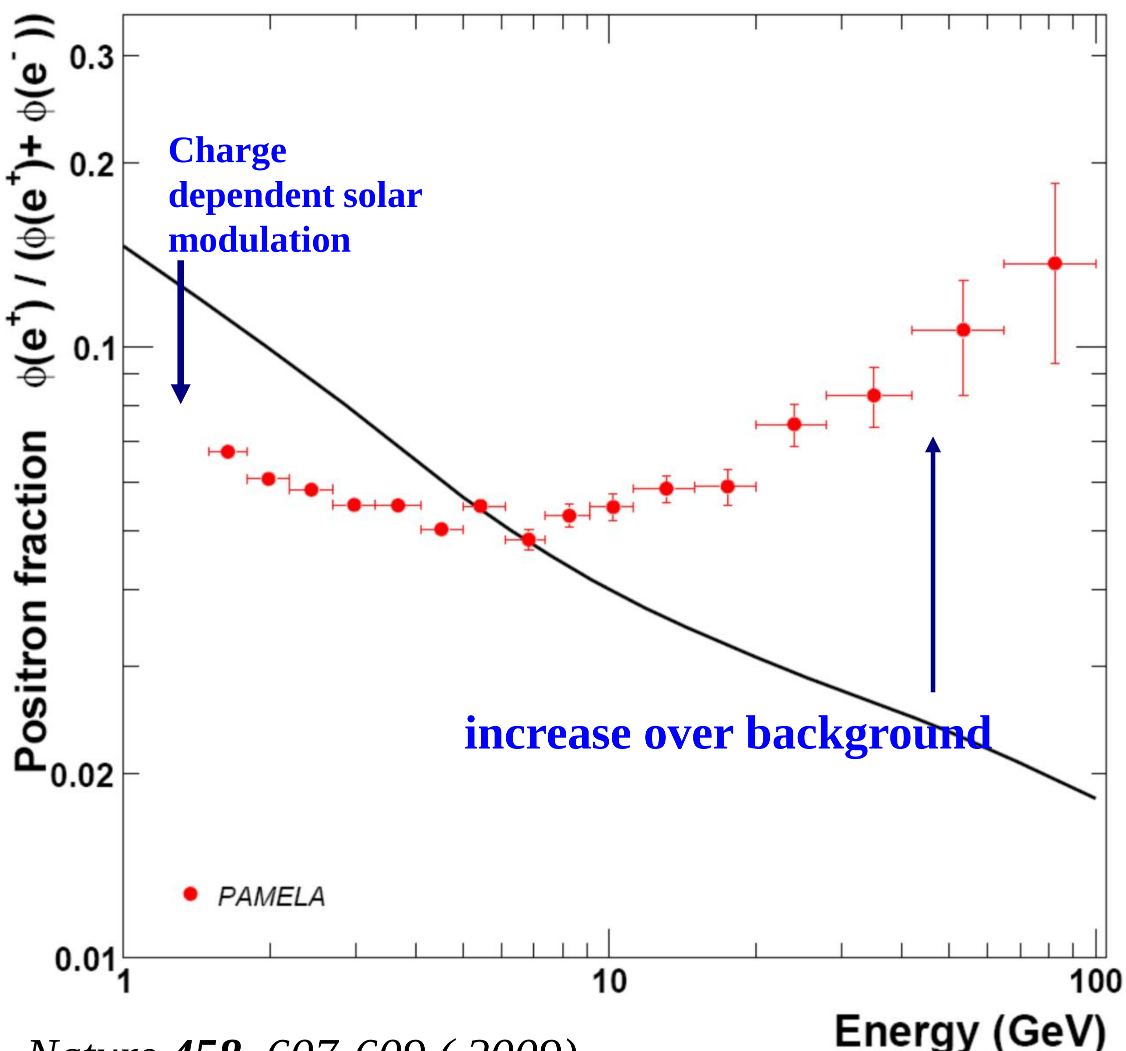
Galactic neighborhood:
e+, e- (1-2 kpc)

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

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

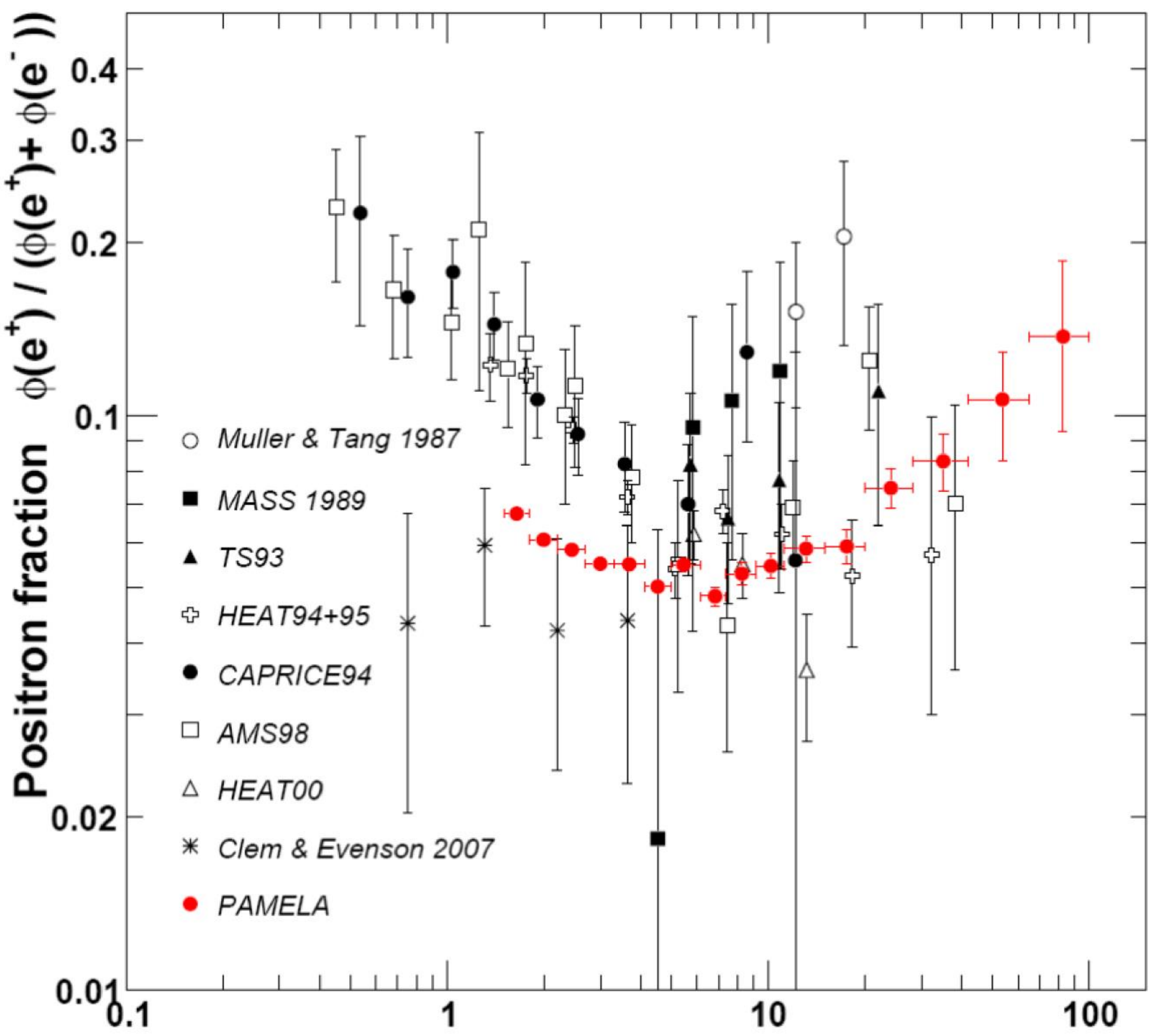


Pamela positron fraction

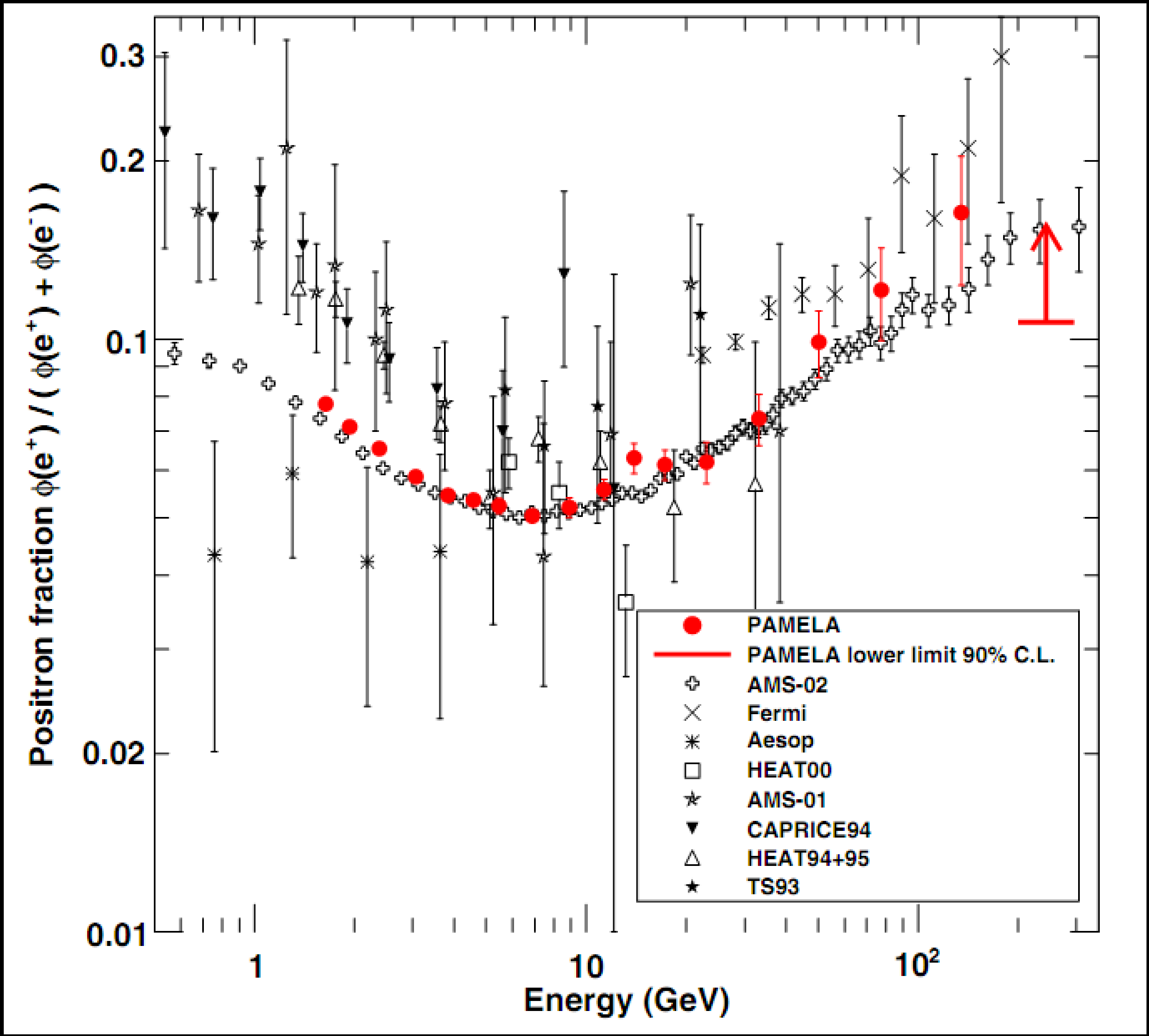


Nature ***458***, *607-609 (2009)*

Pamela positron fraction: comparison with other data



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

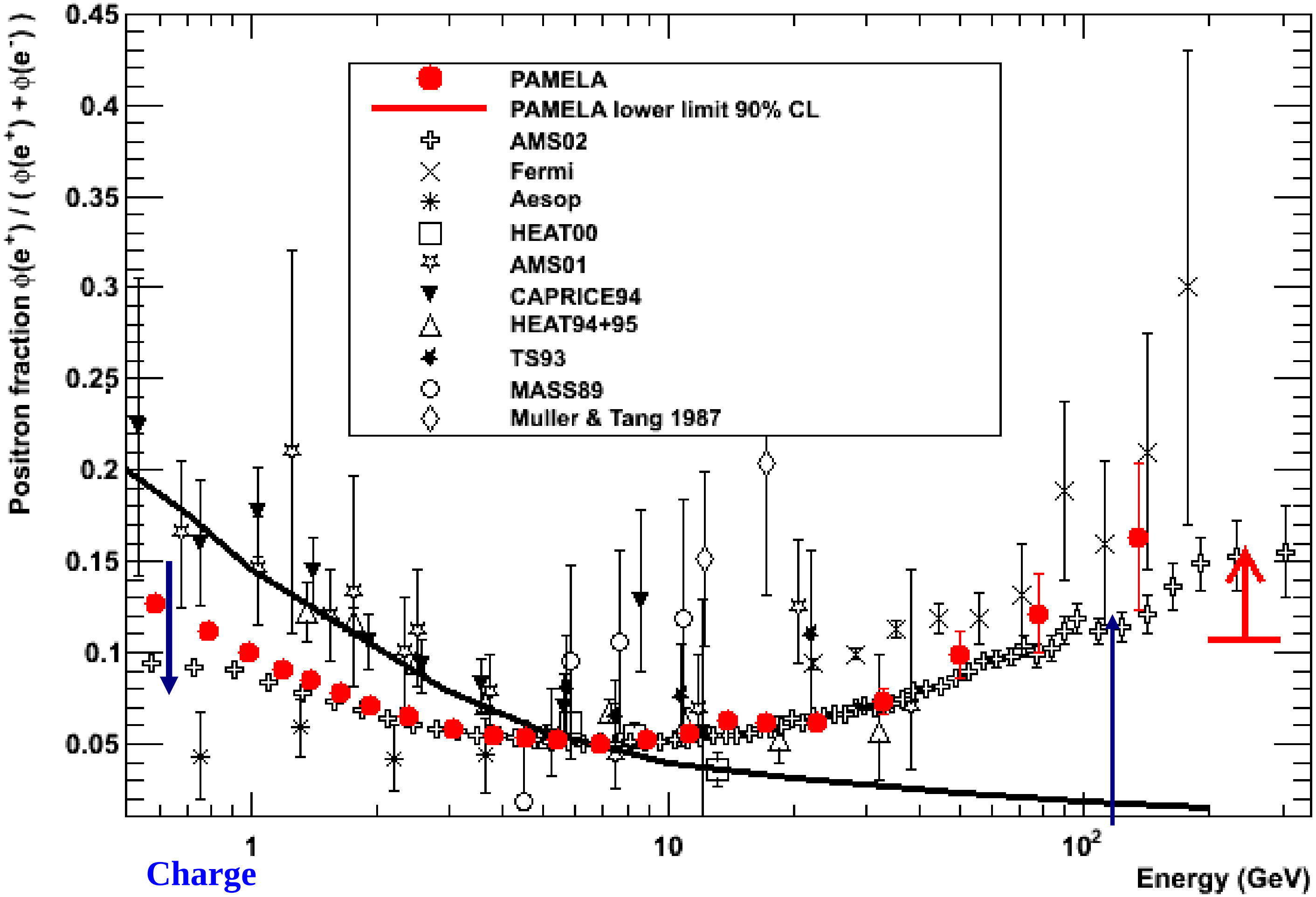


Positron fraction $\phi(e^+) / (\phi(e^+) + \phi(e^-))$
0.3
0.2
0.1
0.02
0.01
1
10
10^2
Energy (GeV)
PAMELA
PAMELA lower limit 90% C.L.
AMS-02
Fermi
Aesop
HEAT00
AMS-01
CAPRICE94
HEAT94+95
TS93

AMS & FERMI confirm PAMELA data

Anomalous source at high energy

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

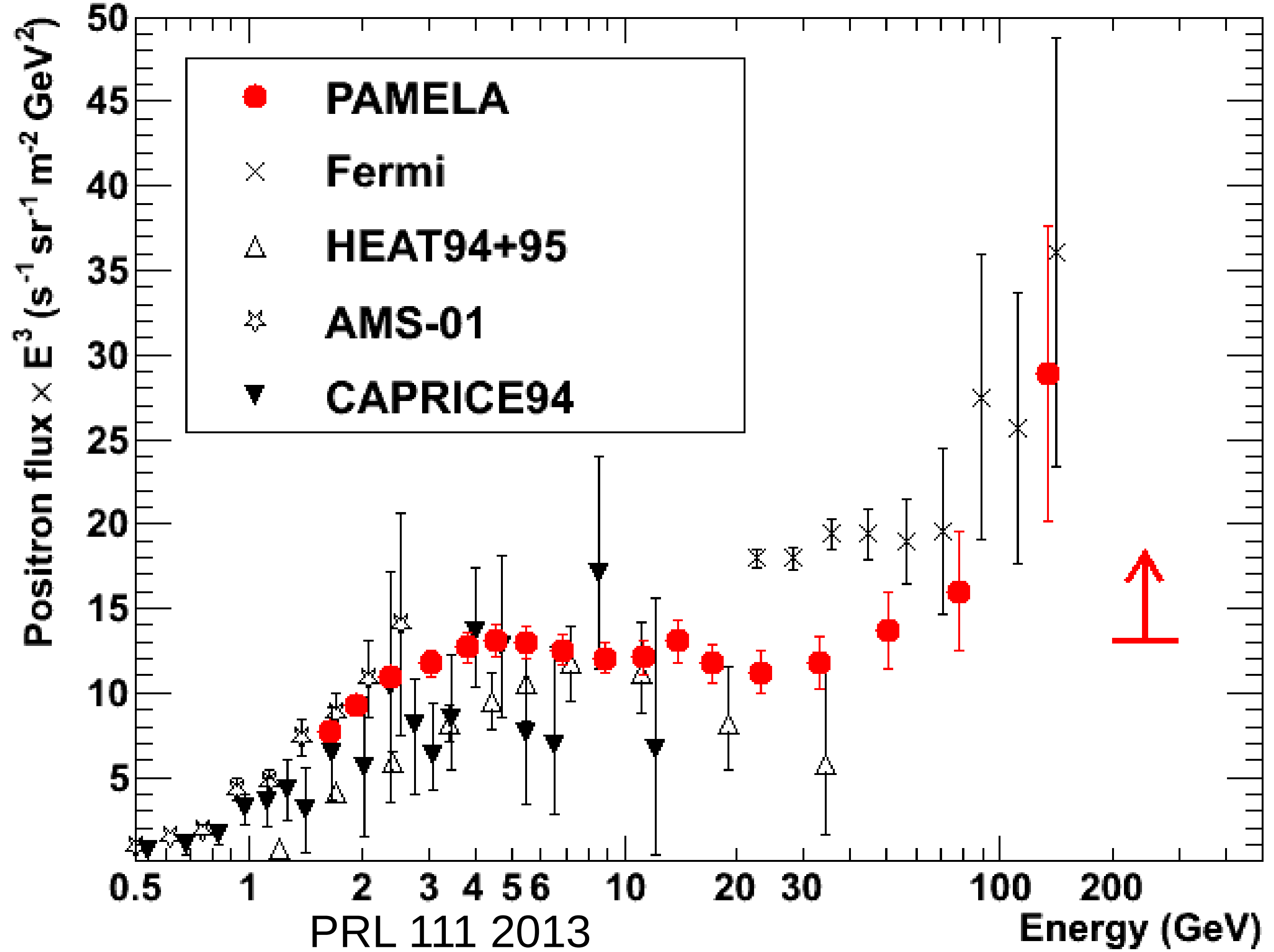


Charge dependent solar modulation

L. Maccione, PRL 110 (2013) 081101

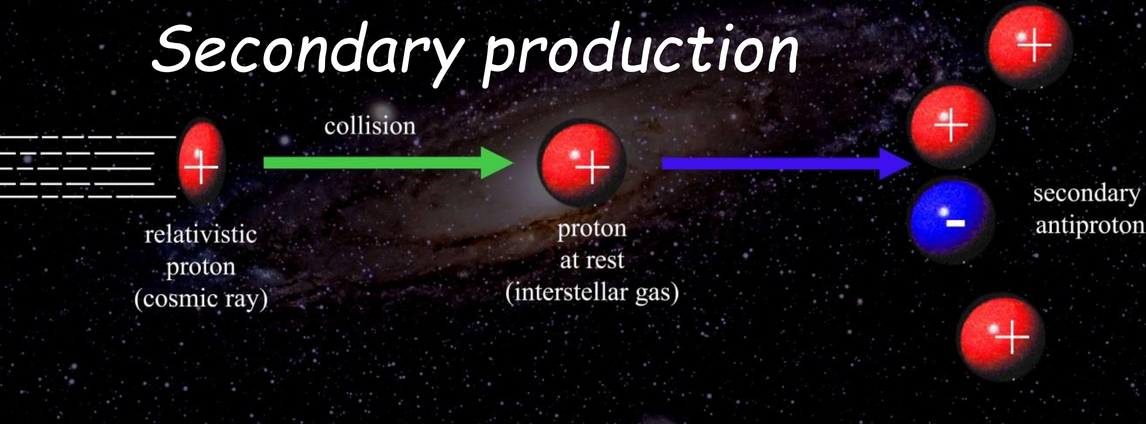
Absolute positron spectrum

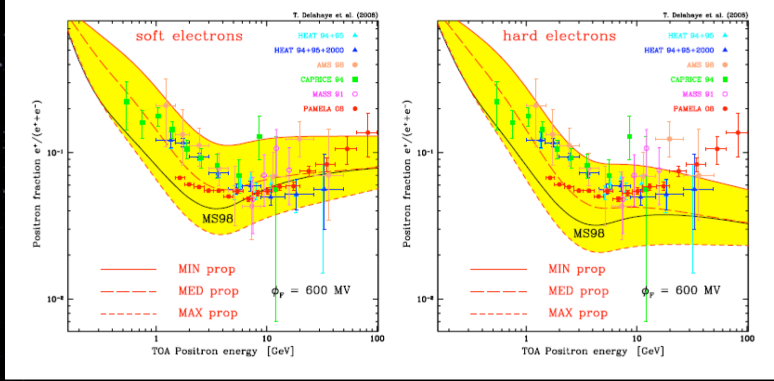
Propagation
Charge dependent solar modulation

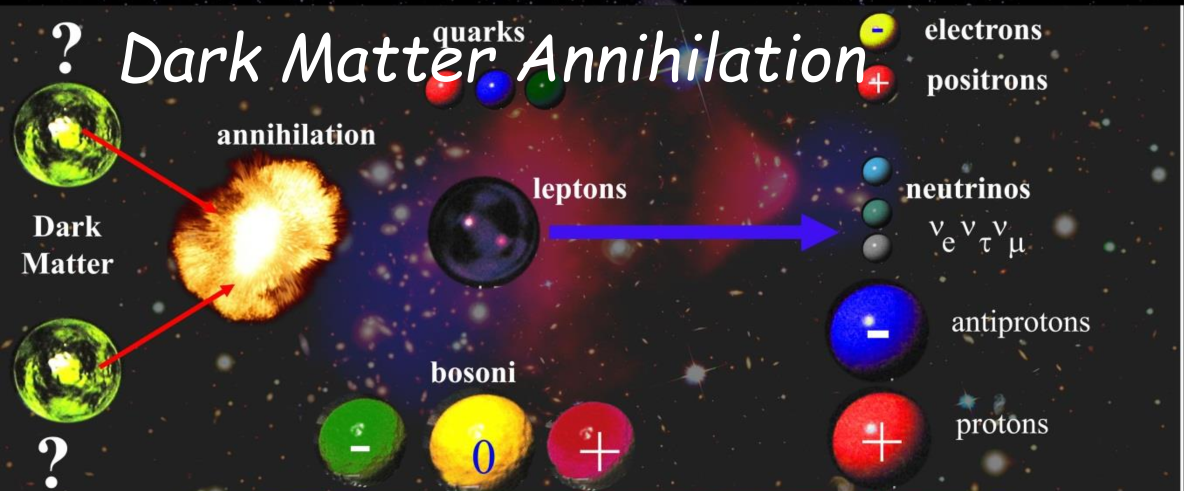


PRL 111 2013

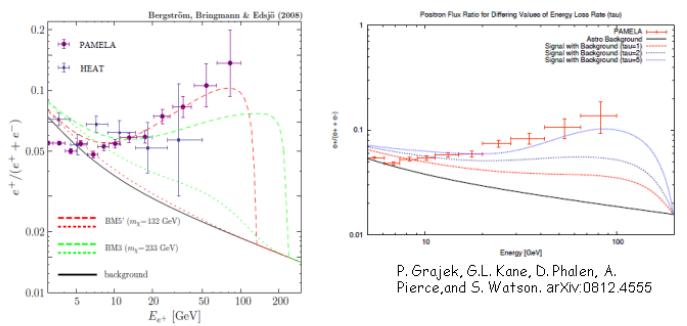
PRL111, 081102 (2013)





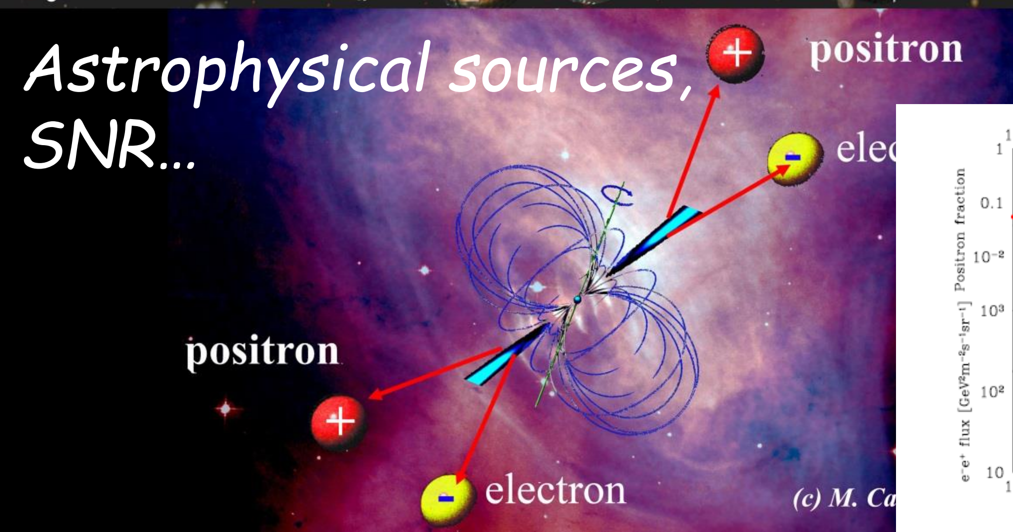


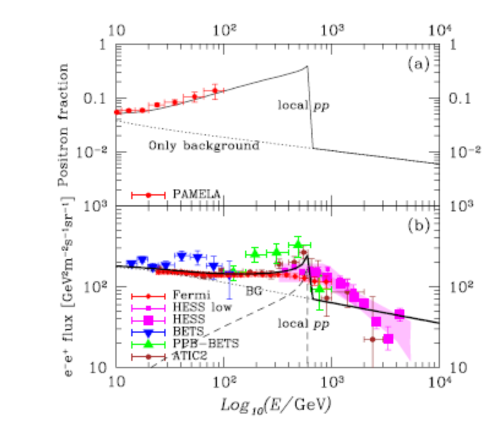
2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:

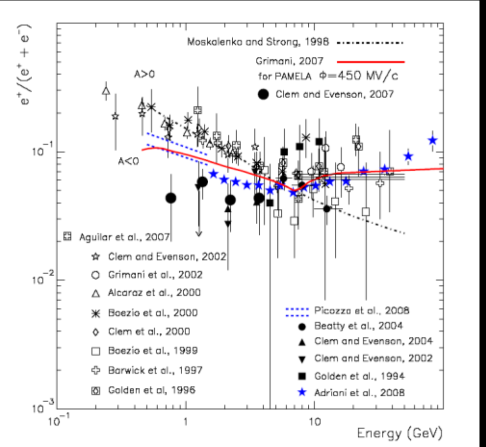


P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555

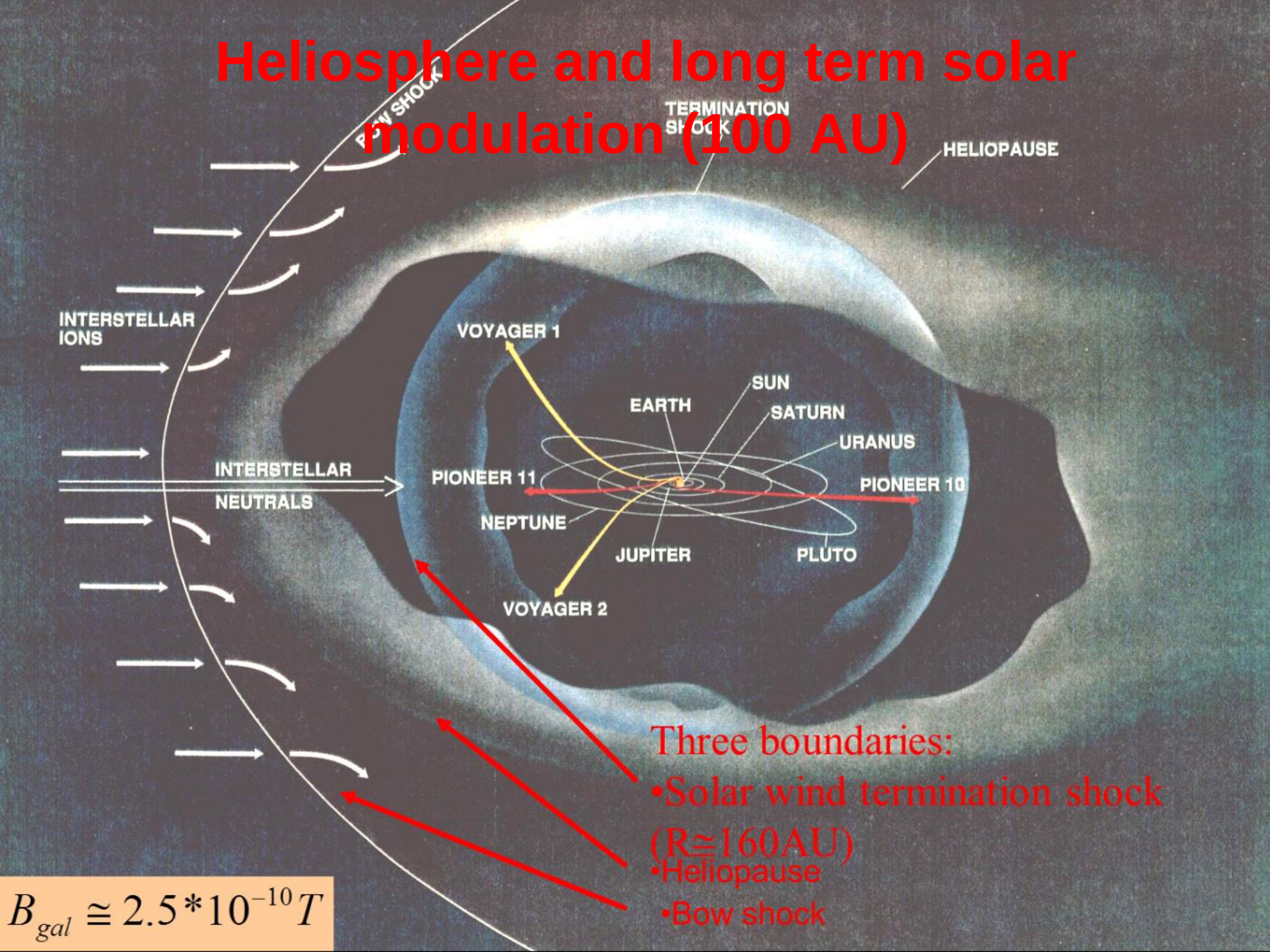
However, does not explain new electron plus positron data (see later)







Heliosphere and long term solar modulation (100 AU)

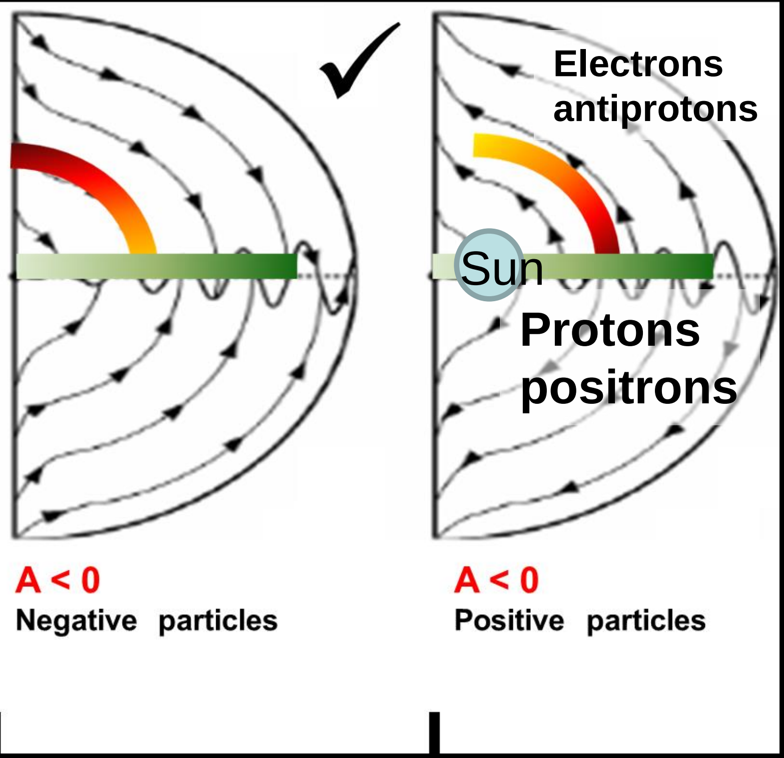


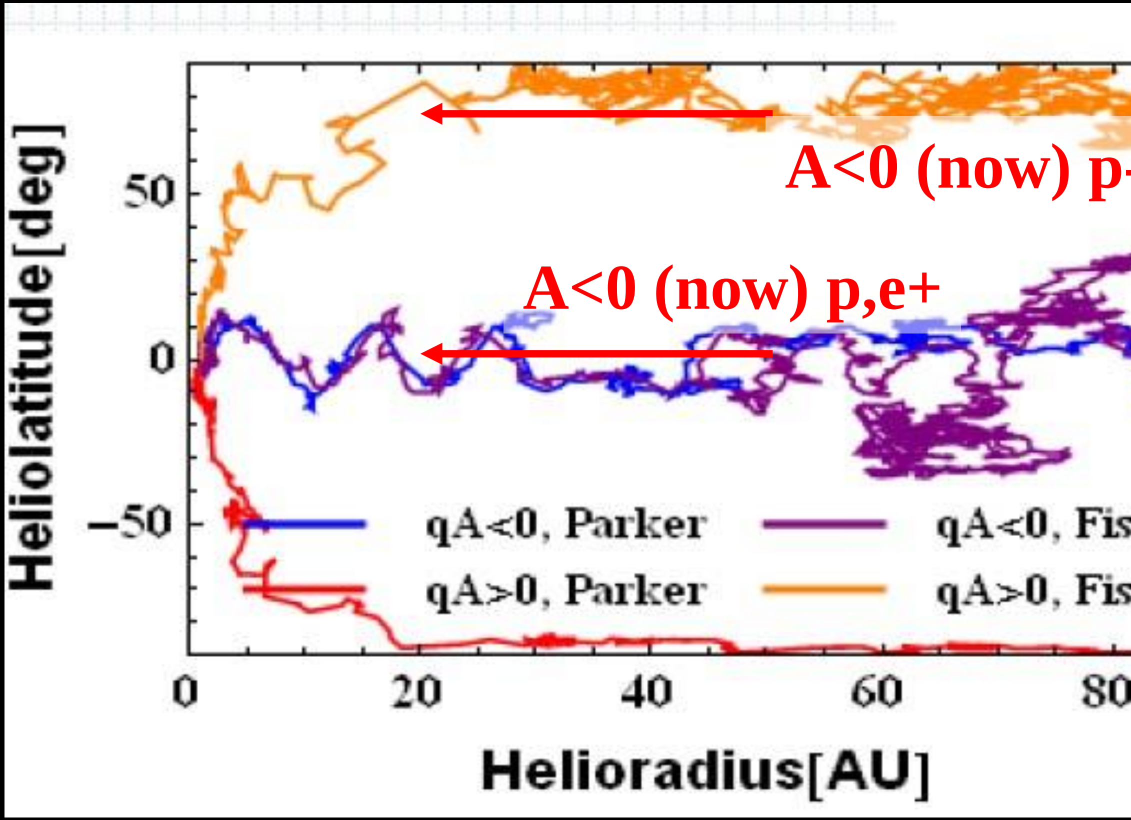
Three boundaries:
- Solar wind termination shock ($R \simeq 160AU$)
- Heliopause
- Bow shock

$$B_{gal} \cong 2.5 * 10^{-10} T$$

Charge dependent solar modulation of low energy positrons

- Charge dependent solar modulation
- Separate qA>0 with qA<0 solar cycles
- Evident in the proton flux
- Observed in the antiproton channel by BESS
- Full 3D solution of the Parker equation – drift term depends on sign of the charge



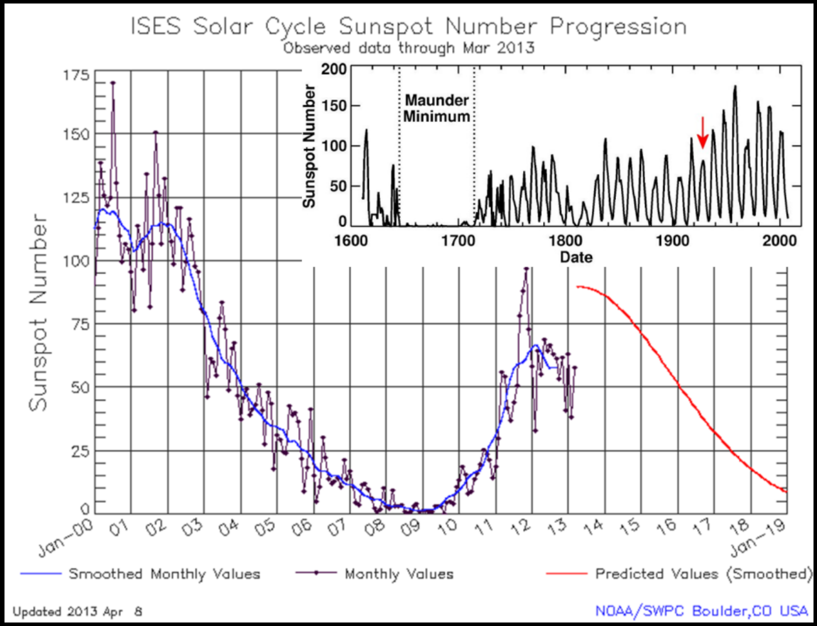


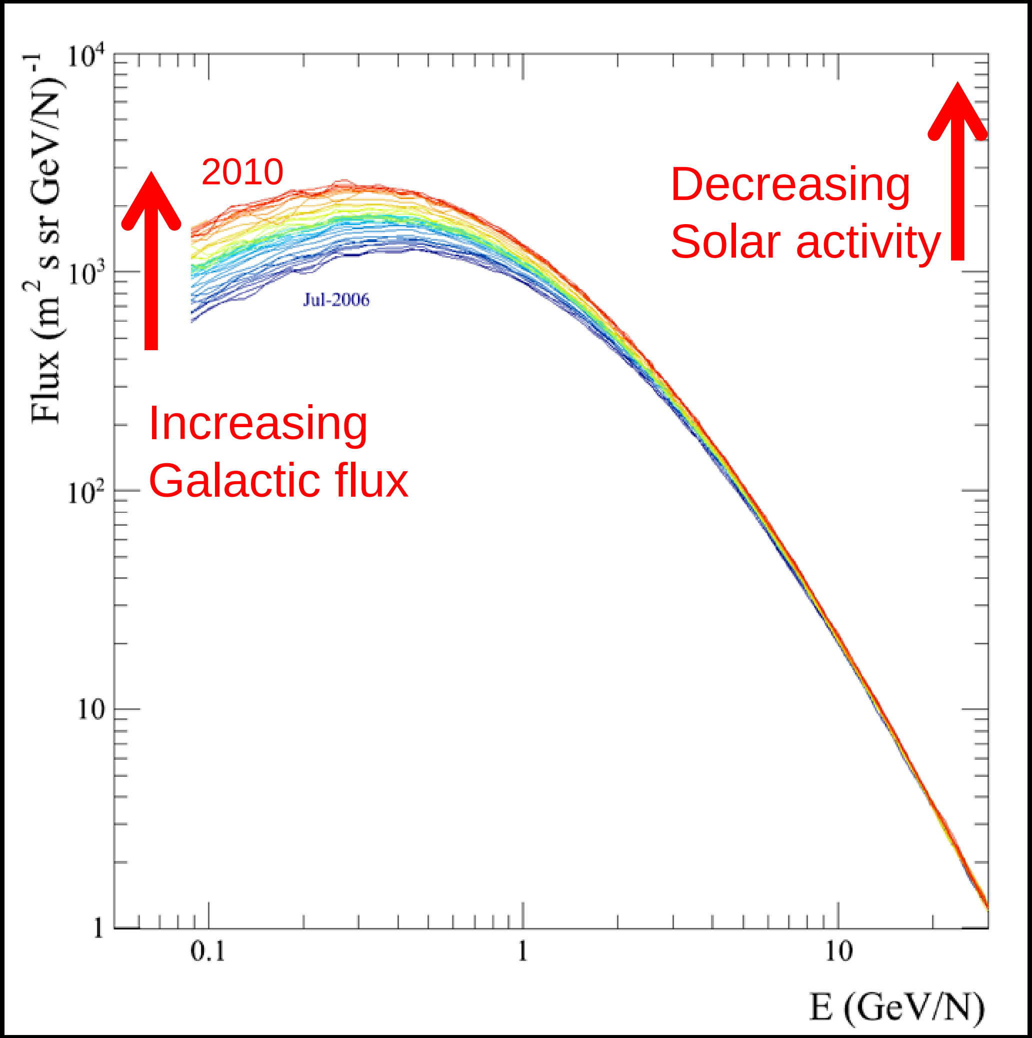
Solar modulation of protons and nuclei: monthly

Very long and peculiar solar minimum.

Current solar cycle (24) late and weak.

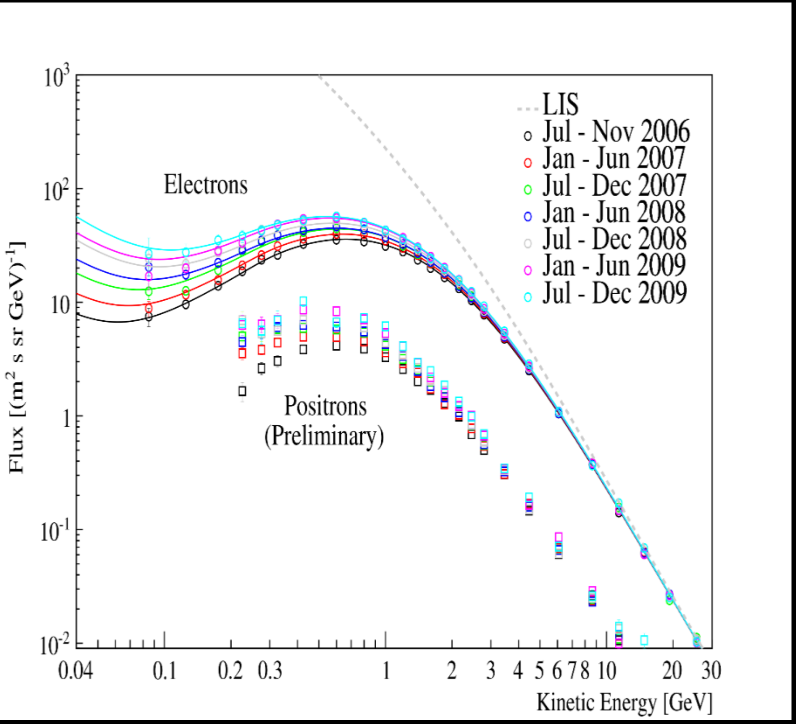
Closer to interstellar medium.
Good reference field for dosimetry



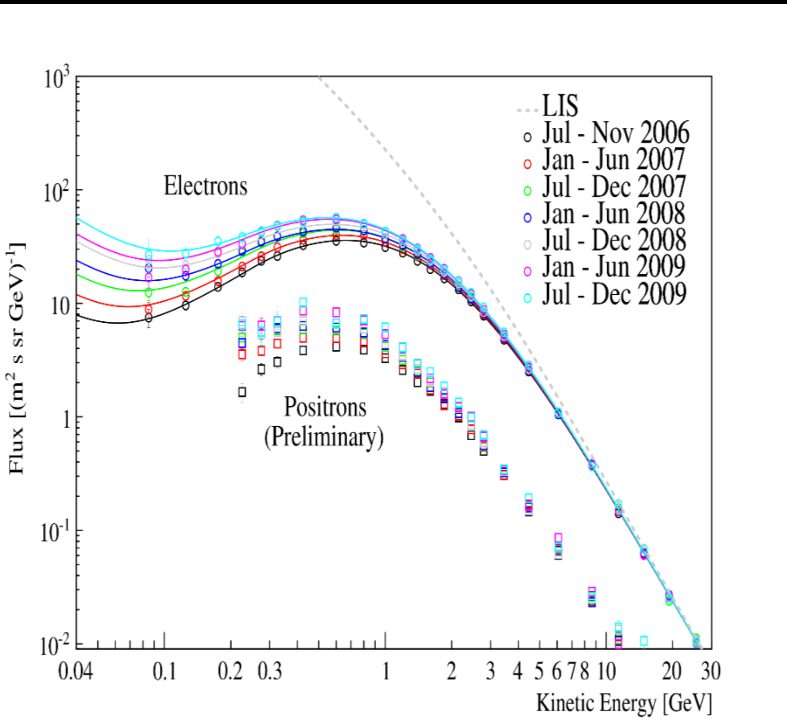


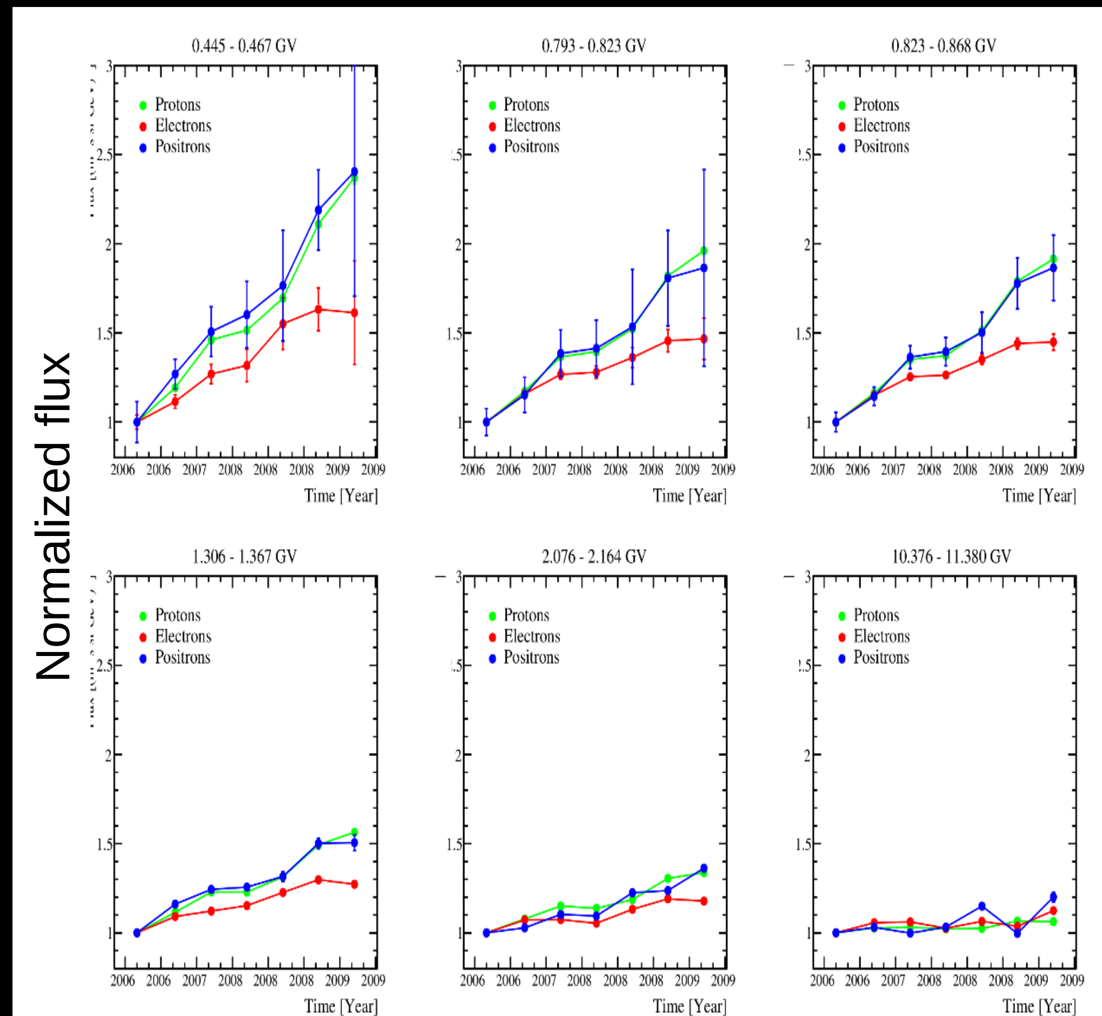
ApJ 765, 2, 91, (2013)

Charge dependent solar modulation: PAMELA electron and positron spectra over the last solar minimum



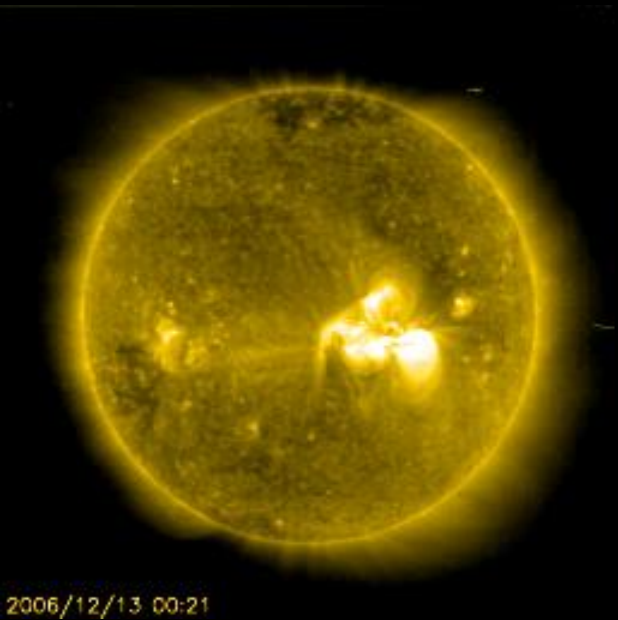
Charge dependent solar modulation: PAMELA electron and positron spectra over the last solar minimum

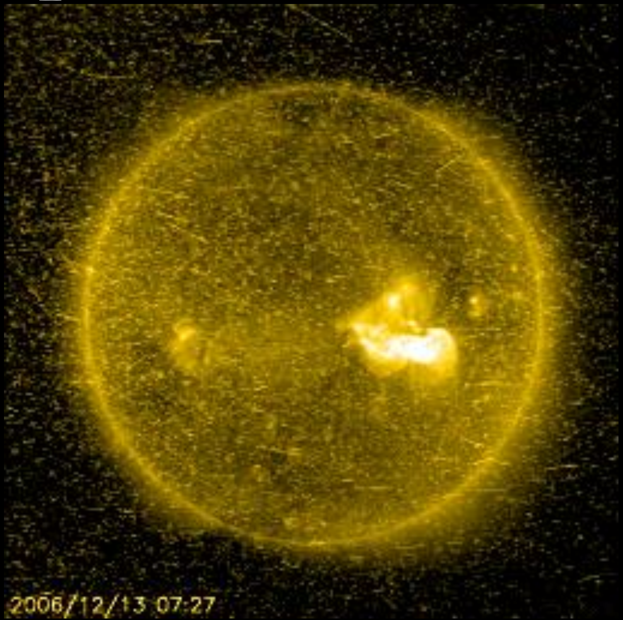


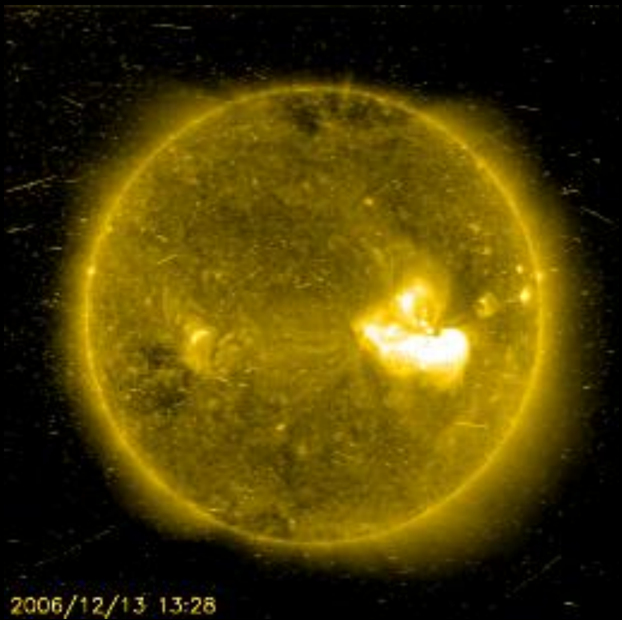


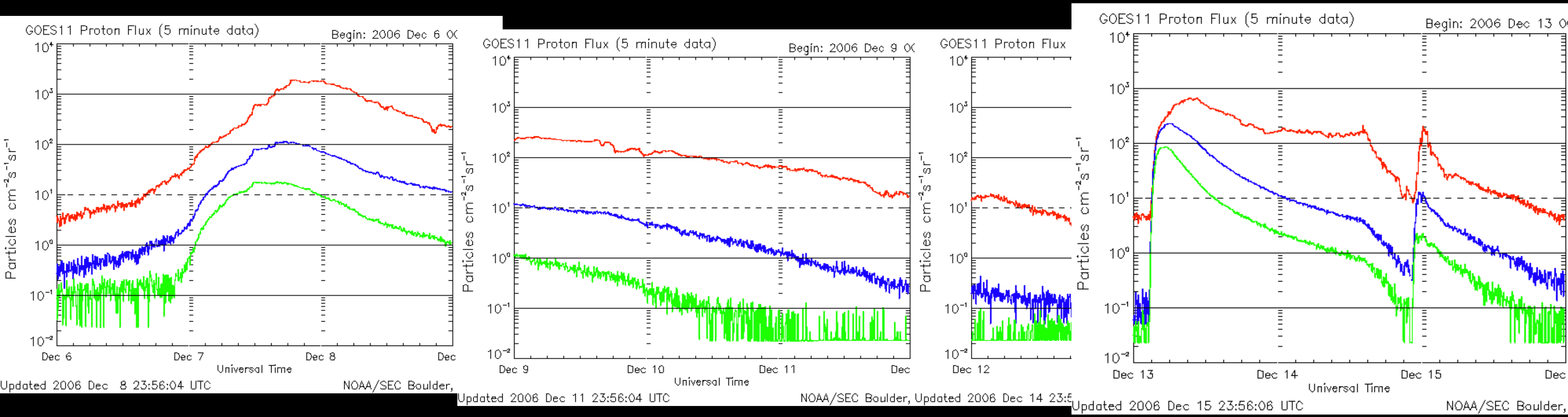
Variation of the e^-, e^+ and p flux between Jul 2006 and December 2009

Solar particle events (1 AU)

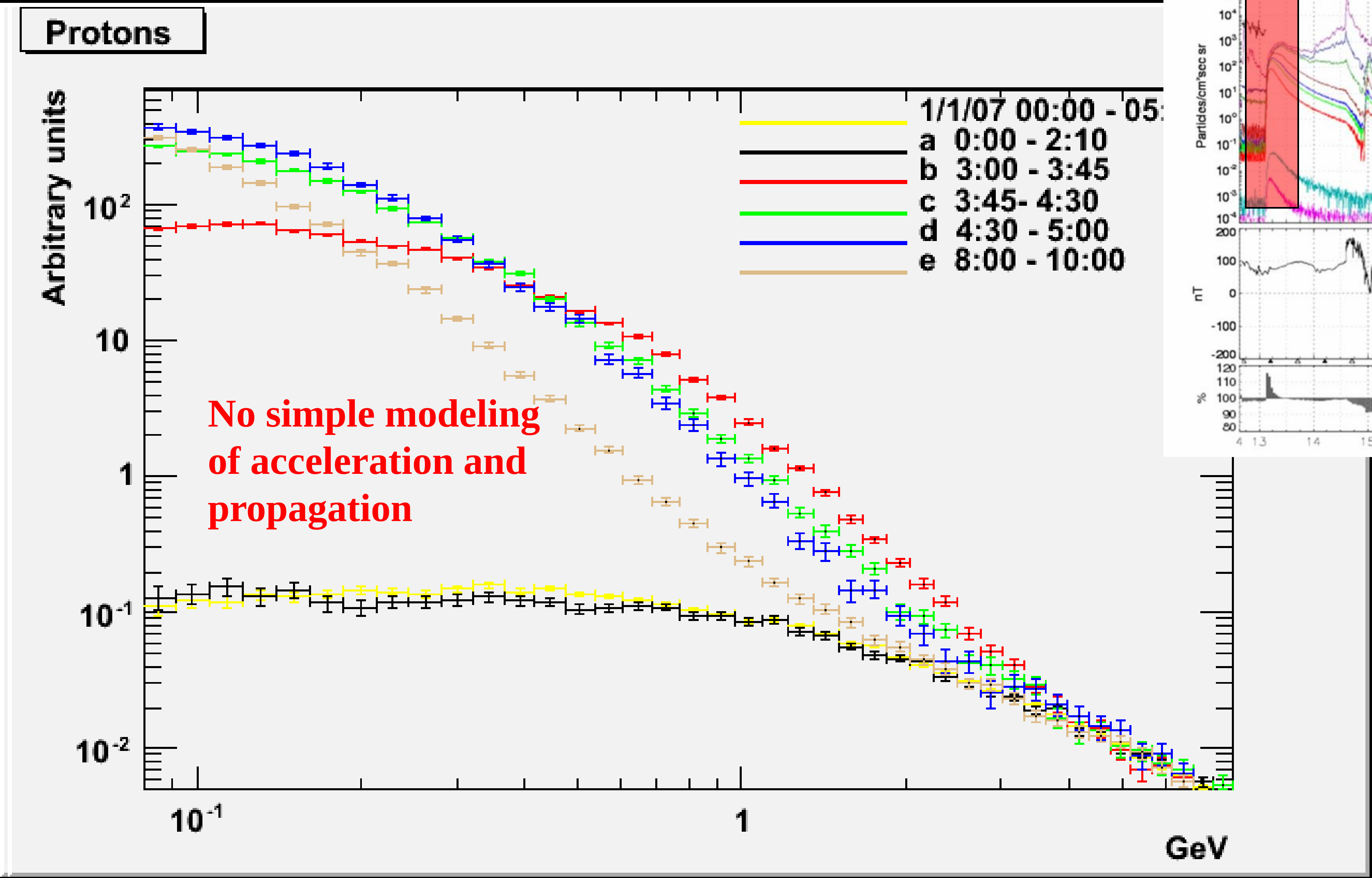


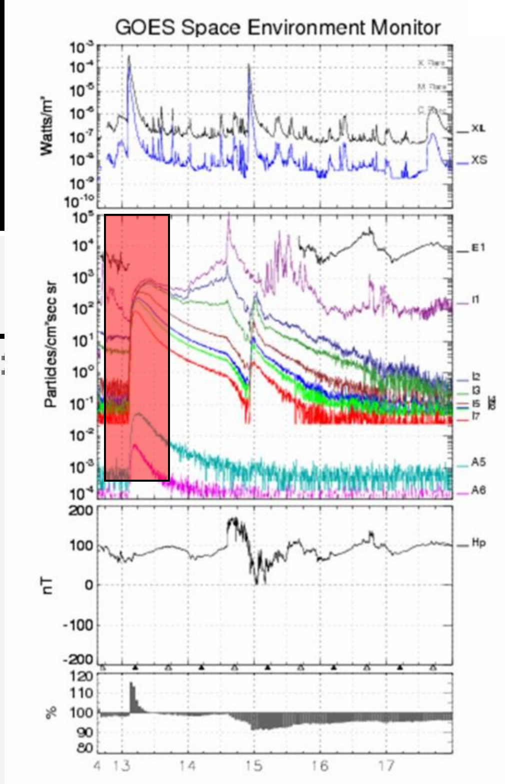






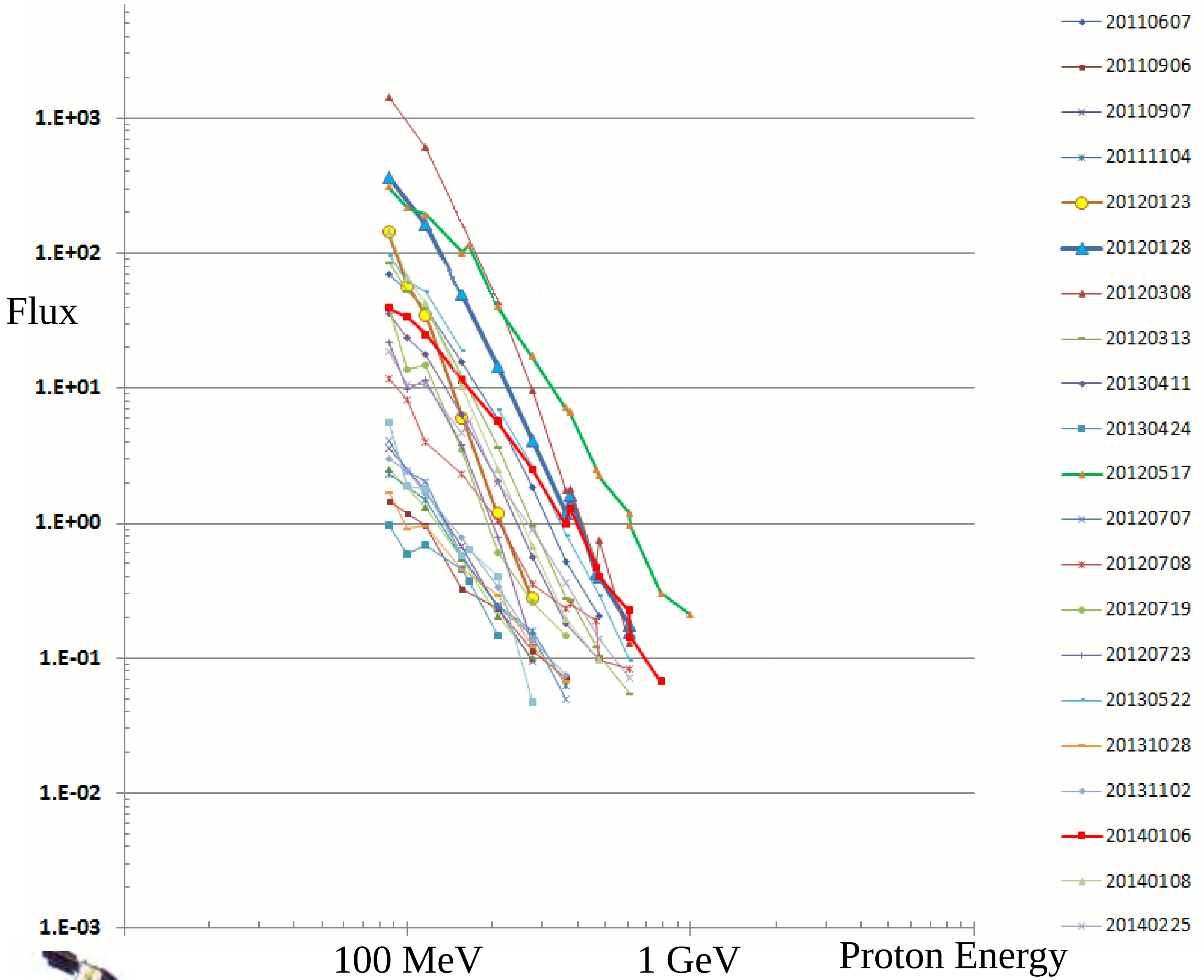
December 13th 2006 event





ApJ 742, 2, 102, 11, 2011.

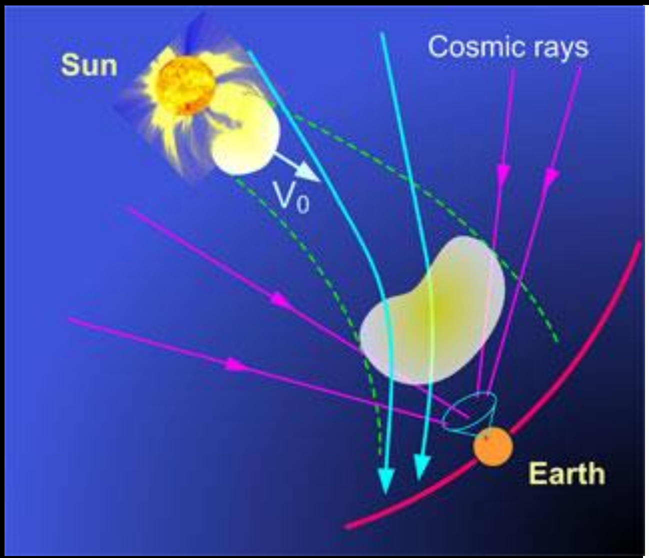
Preliminary PAMELA SEP Spectra

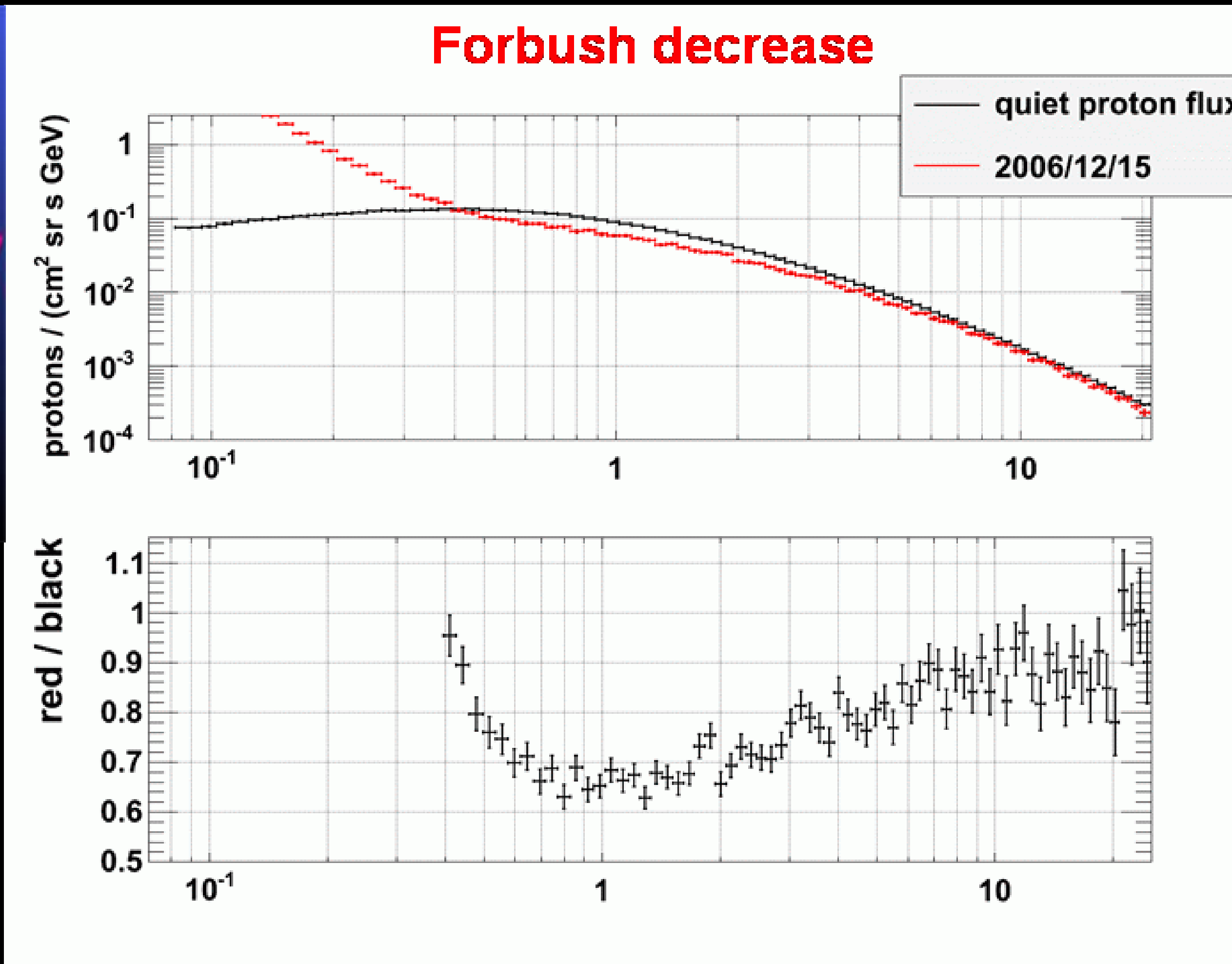


Completing the spectrum

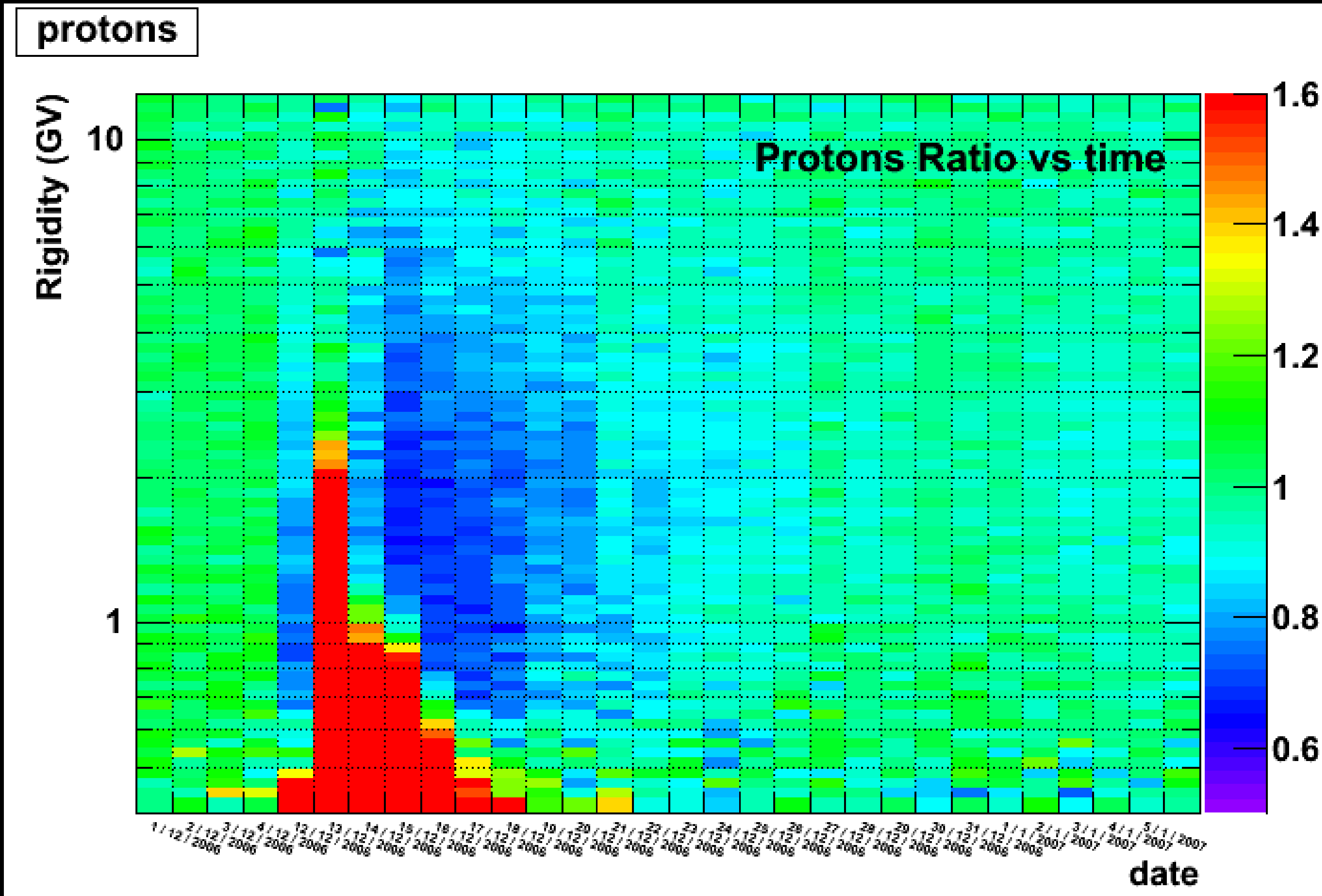
PAMELA bridges the gap between low energy space-based and ground--based measurements to obtain a complete spectrum

Forbush decrease



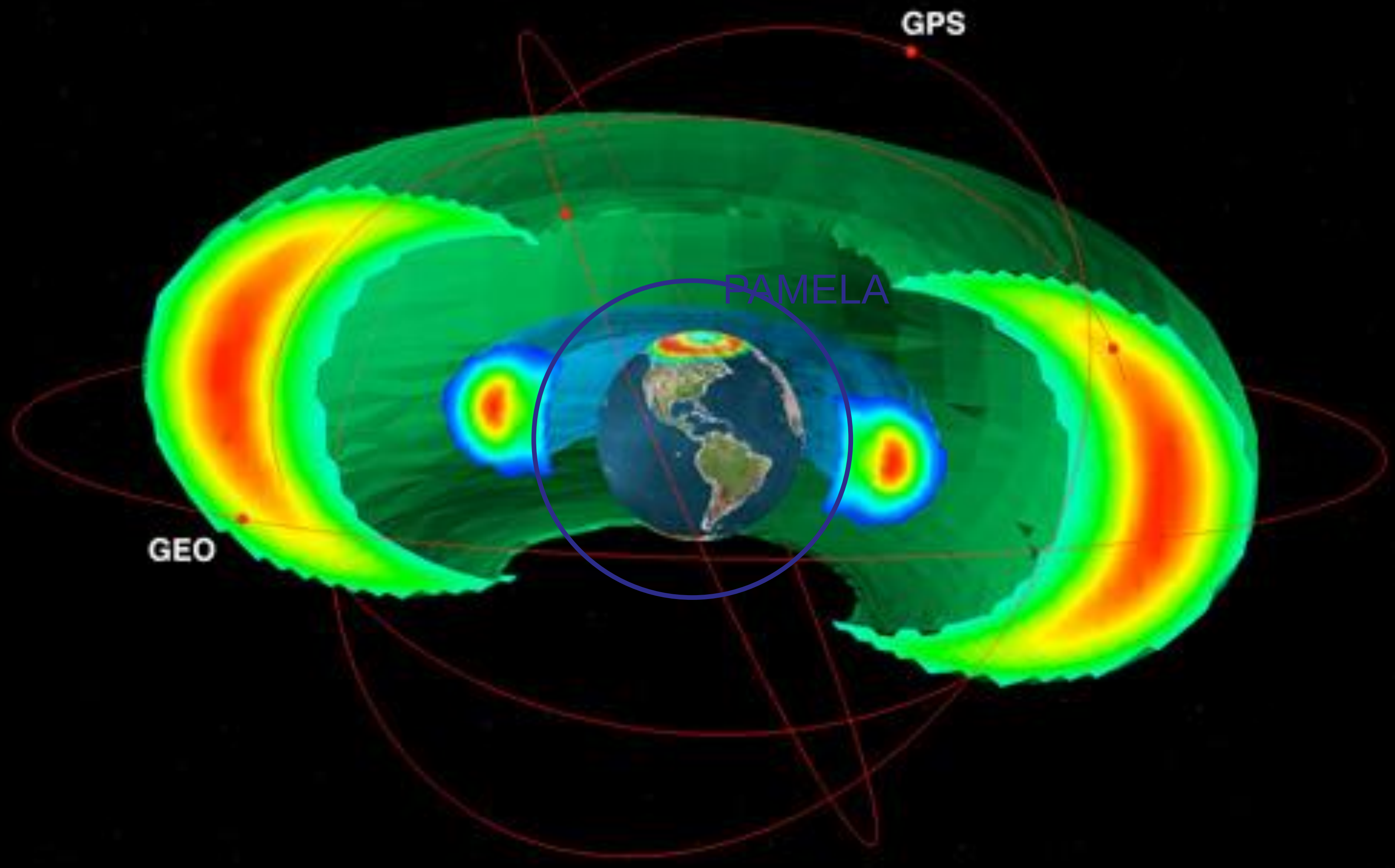


Time and rigidity dependence of Forbush decrease



From Mergè Martucci Sotgiu

GEOMAGNETOSPHERE, VAN ALLEN BELTS



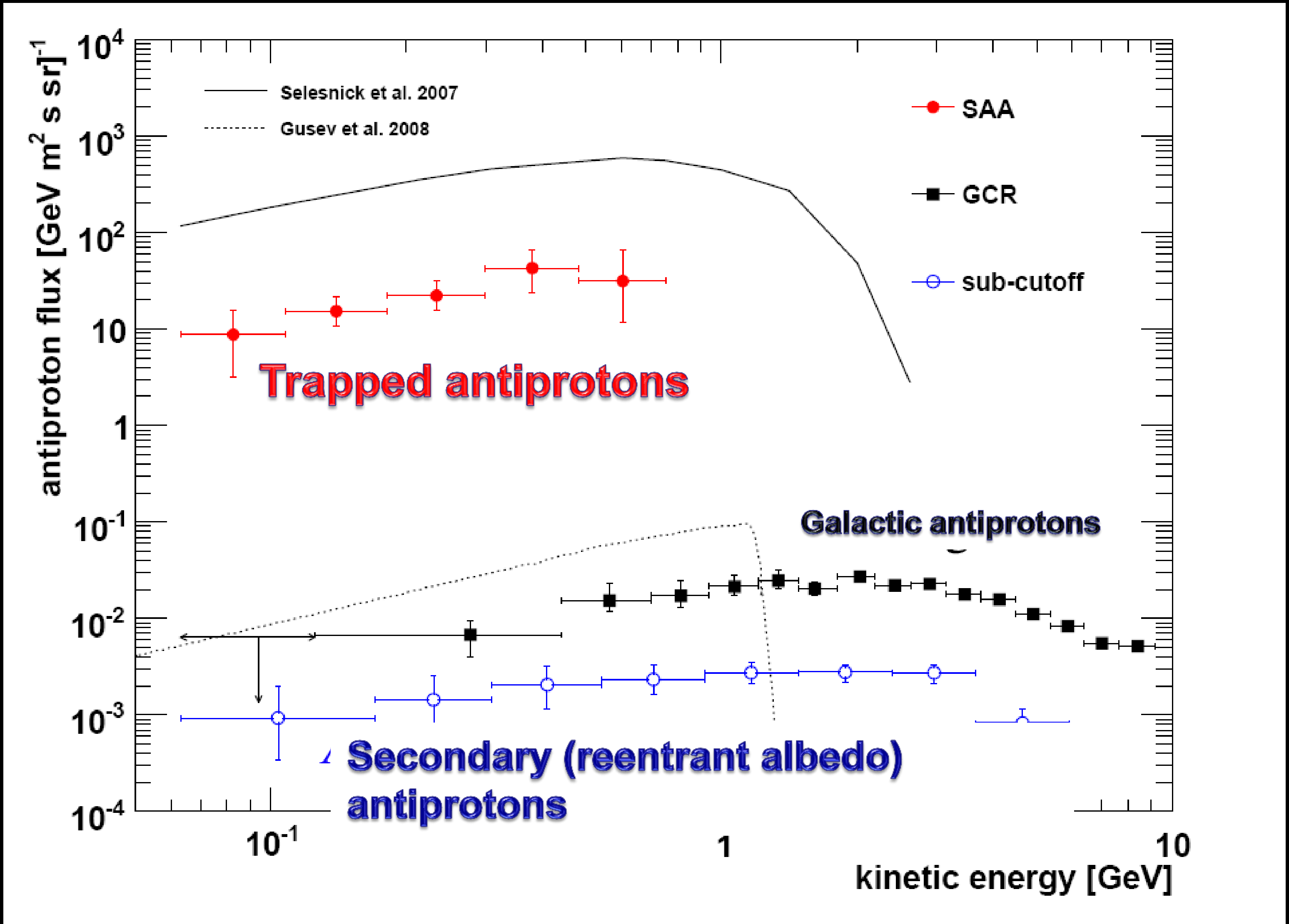
Geomagnetosphere, Van Allen Belts (1000 km)

http://www.youtube.com/watch?v=OaoiPw5Pqbg

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 >9!
- Mission prolonged at least 1 more year
- Hope to continue measure deep in the 24th solar cycle

http://pamela.roma2.infn.it

http://www.casolino.it