19/03/2017

Precision research of cosmic rays from space after 10 years of PAMELA observations

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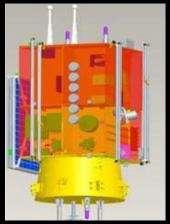
Past, present and future experiments



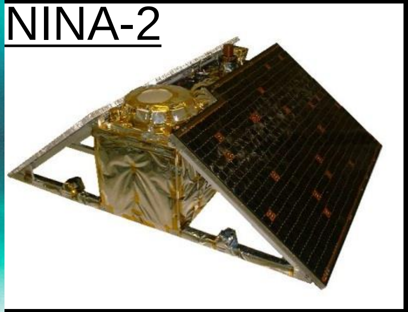
CSES

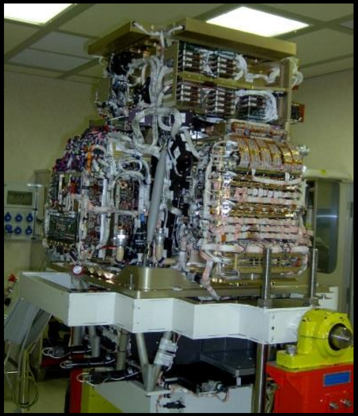
PAMELA

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

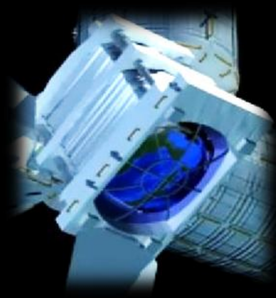
NINA-1

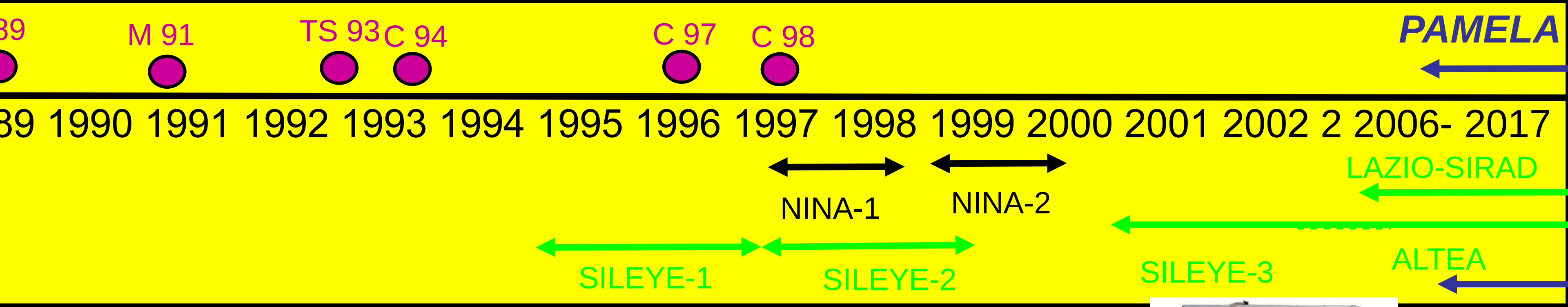
NINA-2



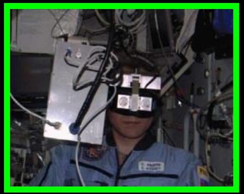


JEM-EUSO





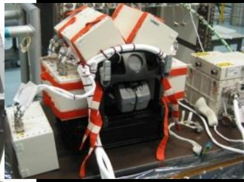
SILEYE-



SILEYE-2

SILEYE-3/ ALTEINO:

LAZIO-SIRAD



SILEYE-4/ALTEA

Pamela Collaboration

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

Russia: Moscow, St. Petersburg

Ioffe Physico-Technical Institute

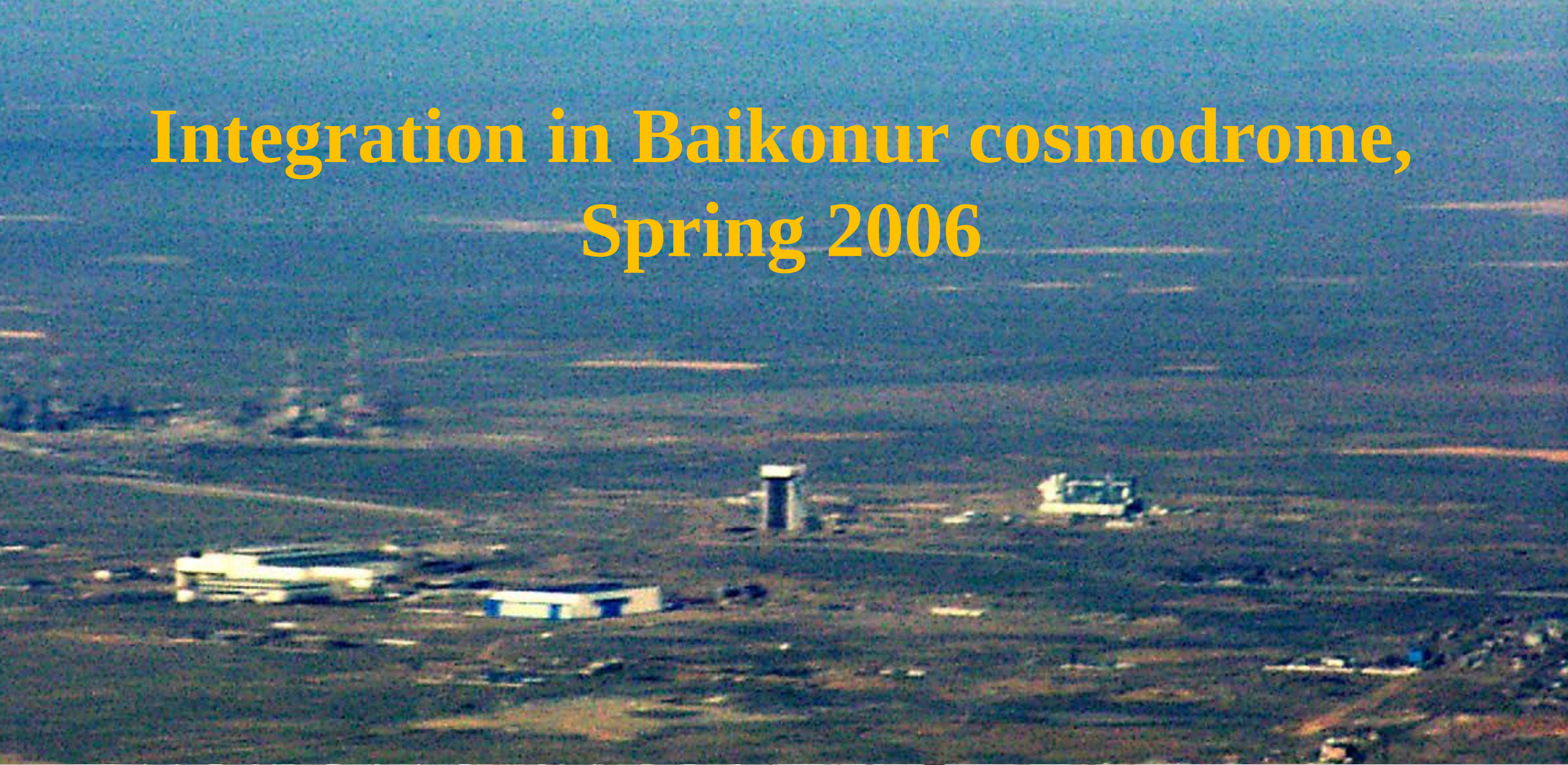
Germany: Siegen

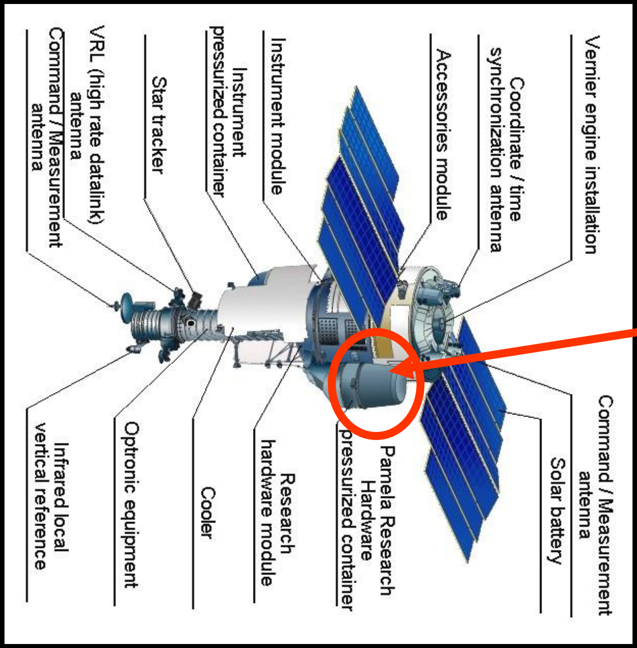
Universität Gesamthochschule Siegen

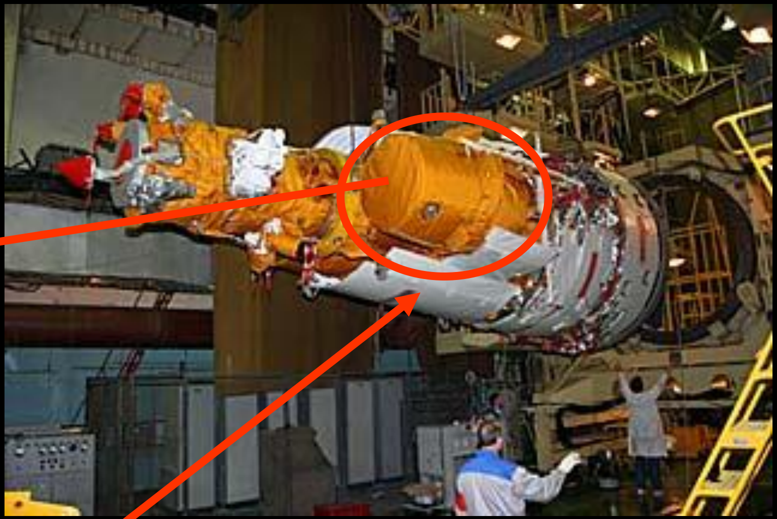
Sweden: KTH, Stockholm

Kungl Tekniska Högskolan

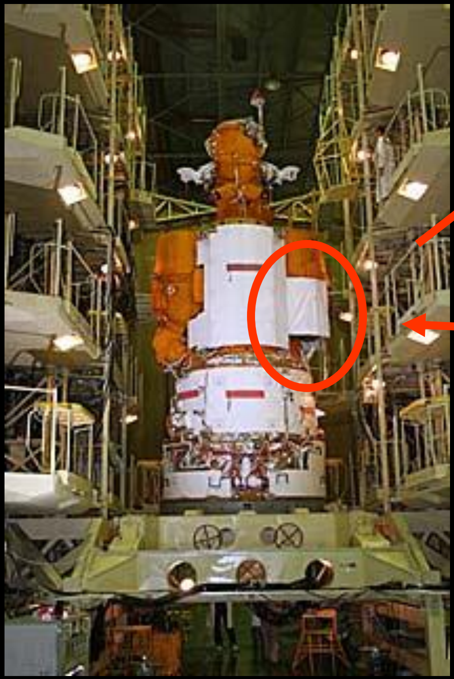
Integration in Baikonur cosmodrome, Spring 2006



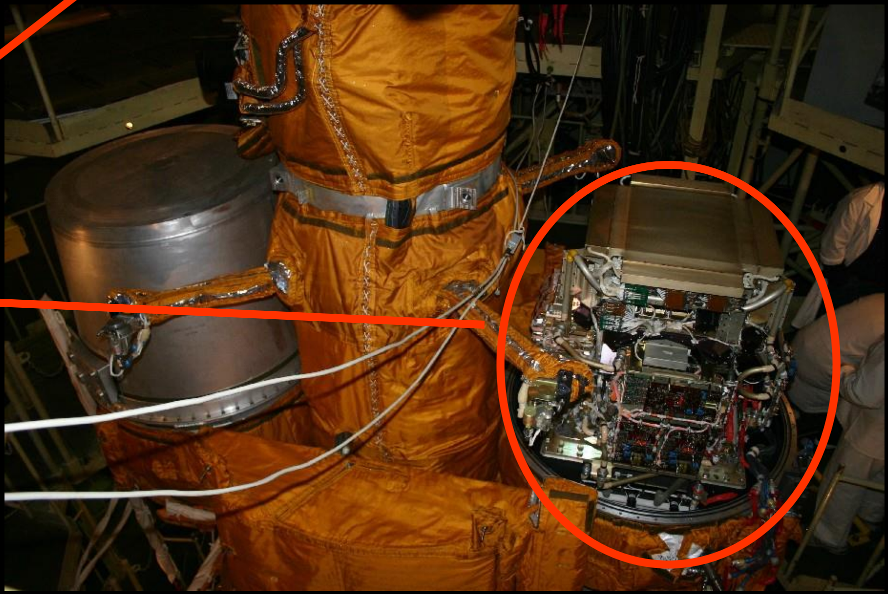




Coupling to Soyuz



Resurs DK integrated

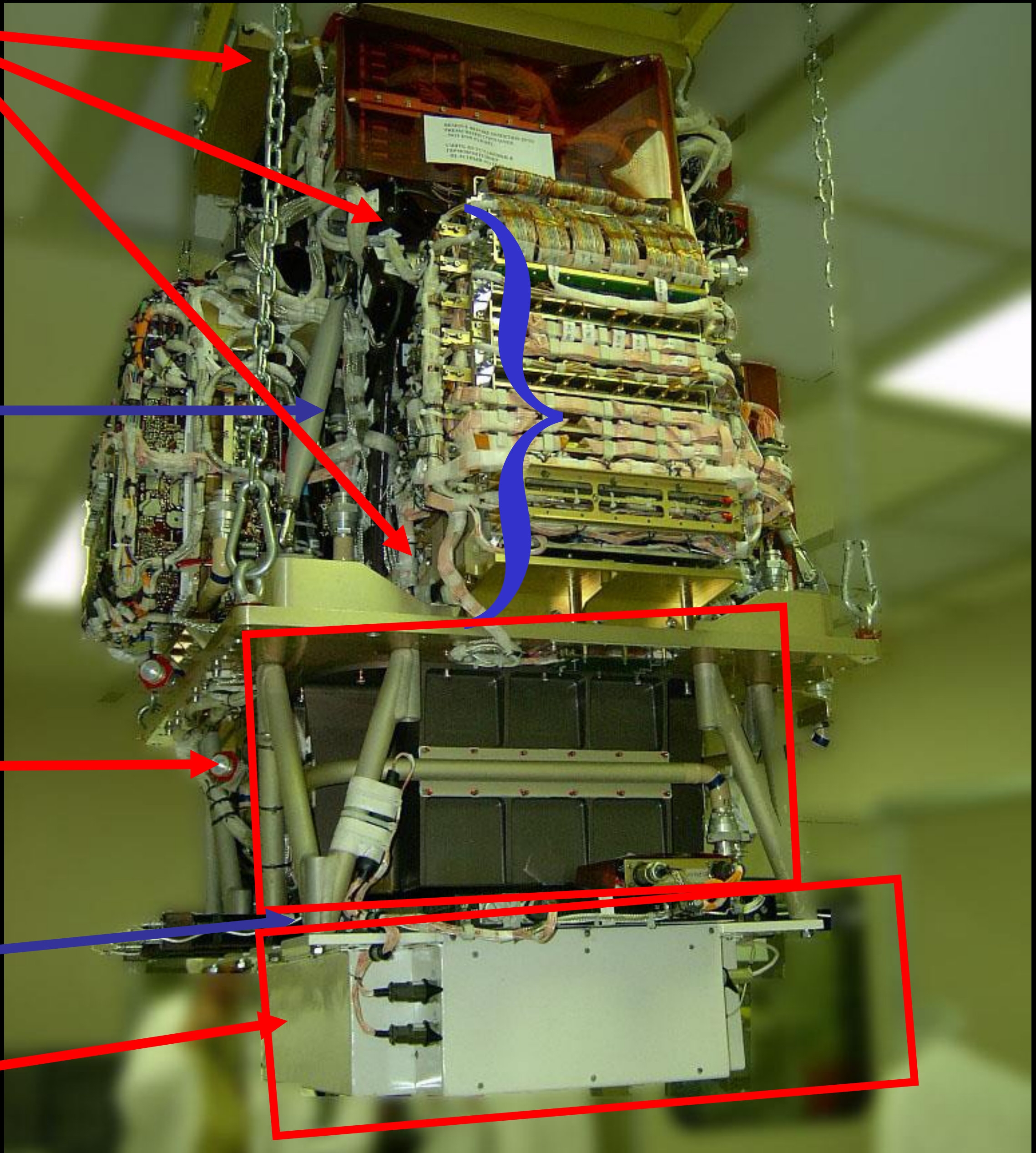


Pamela during integration in Baikonur

Gagarinsky Start, 14/6/2006

Launch on June 15th 2006 Soyuz-U rocket

The detector



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

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

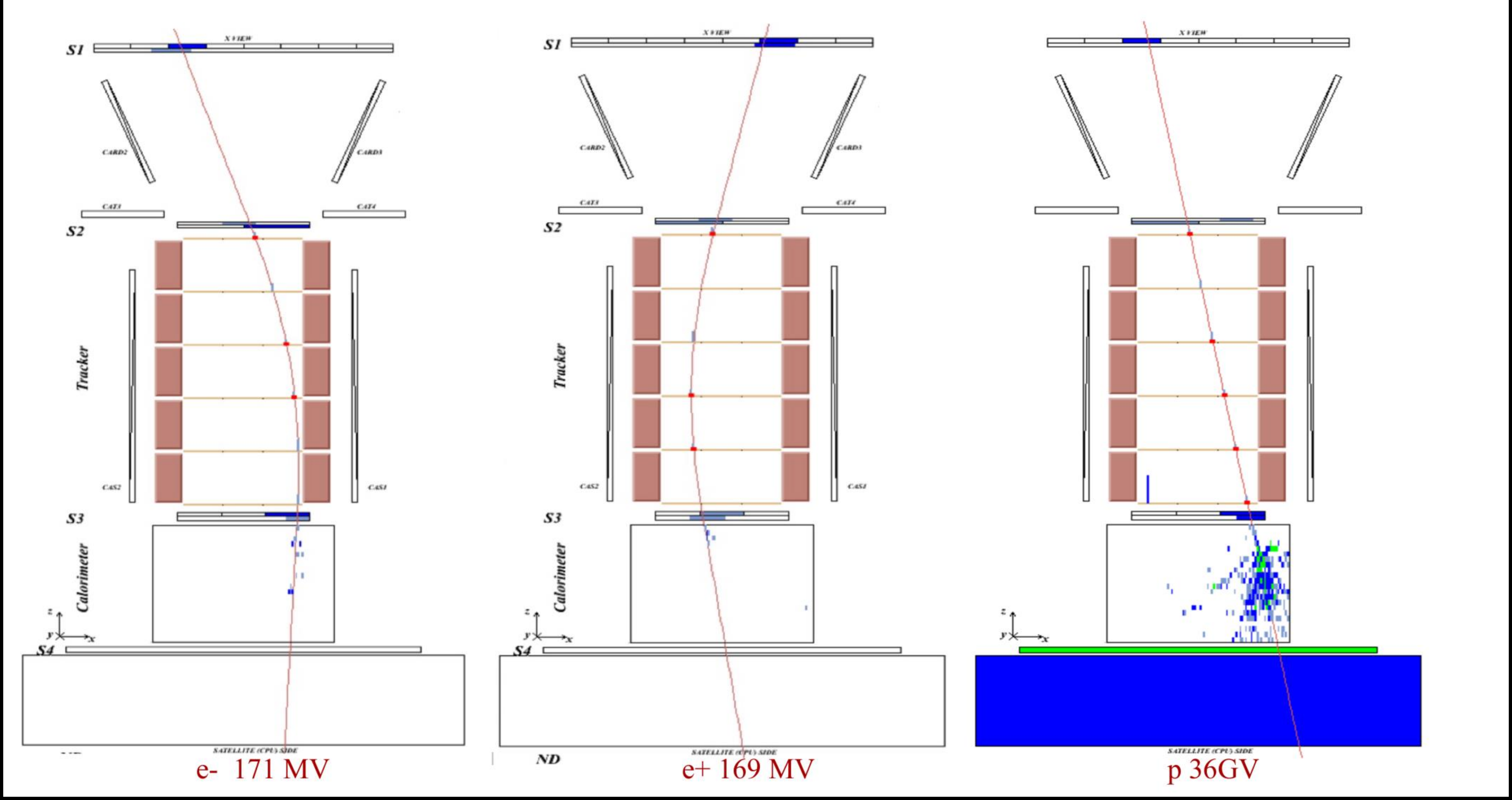
Silicon
Tungsten
Tracking
Calorimeter
(44 planes of 96 strip)

Shower
Catcher
Scintillator

Neutron
Detector

Principle of detection

Electrons Positrons Protons

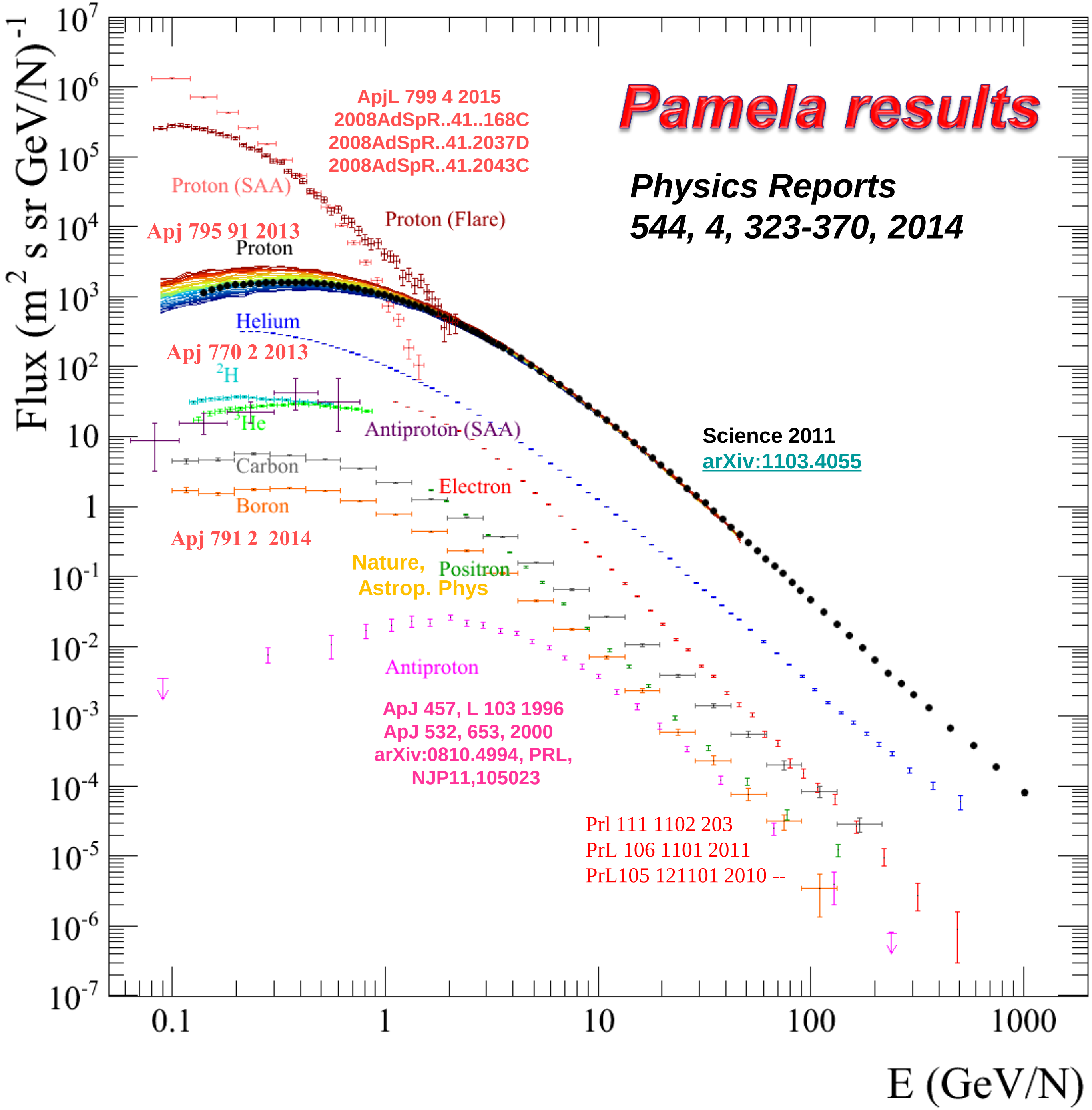


High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere

On several different scales

→ Modeling

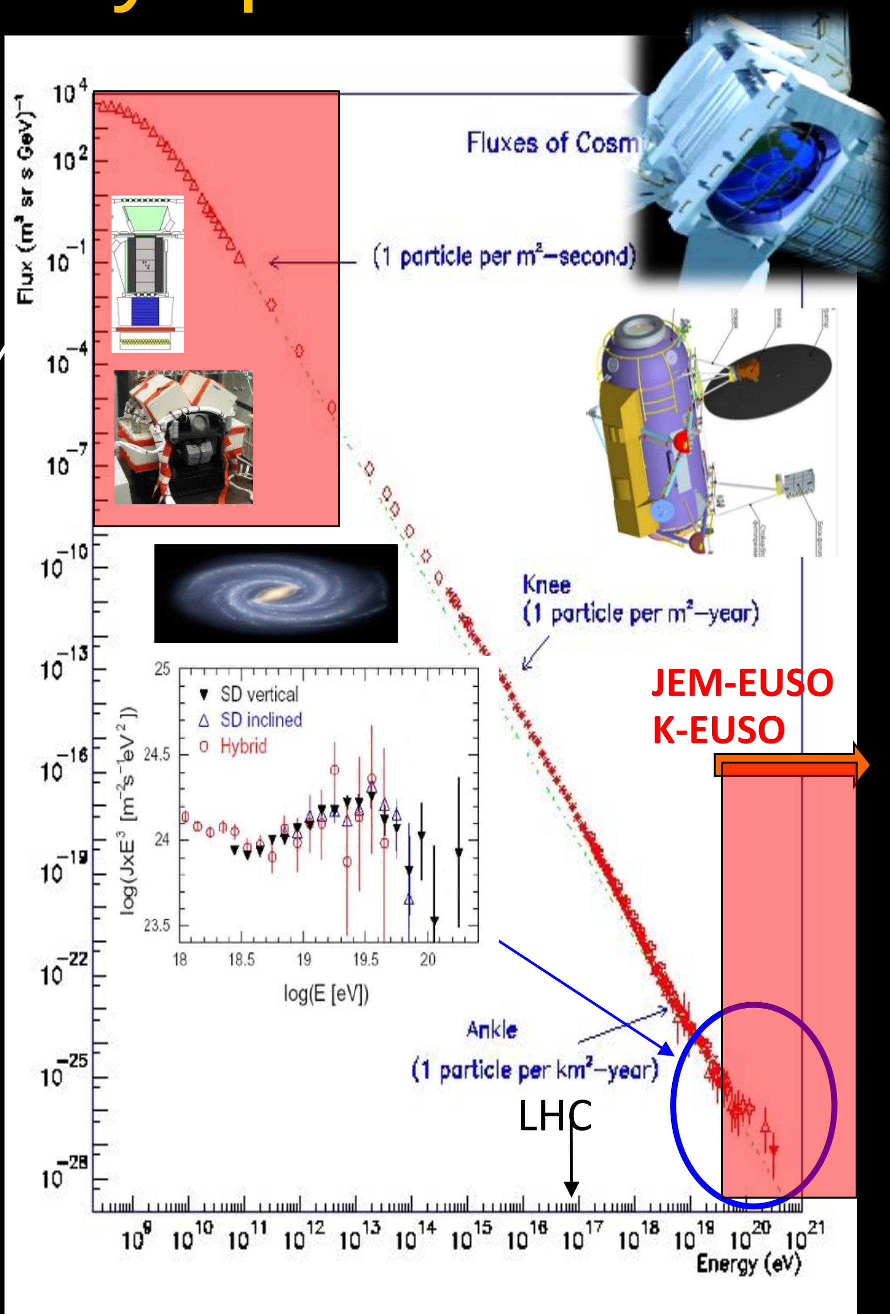
→ Dose and risk estimation for astronauts on ISS and Moon/Mars



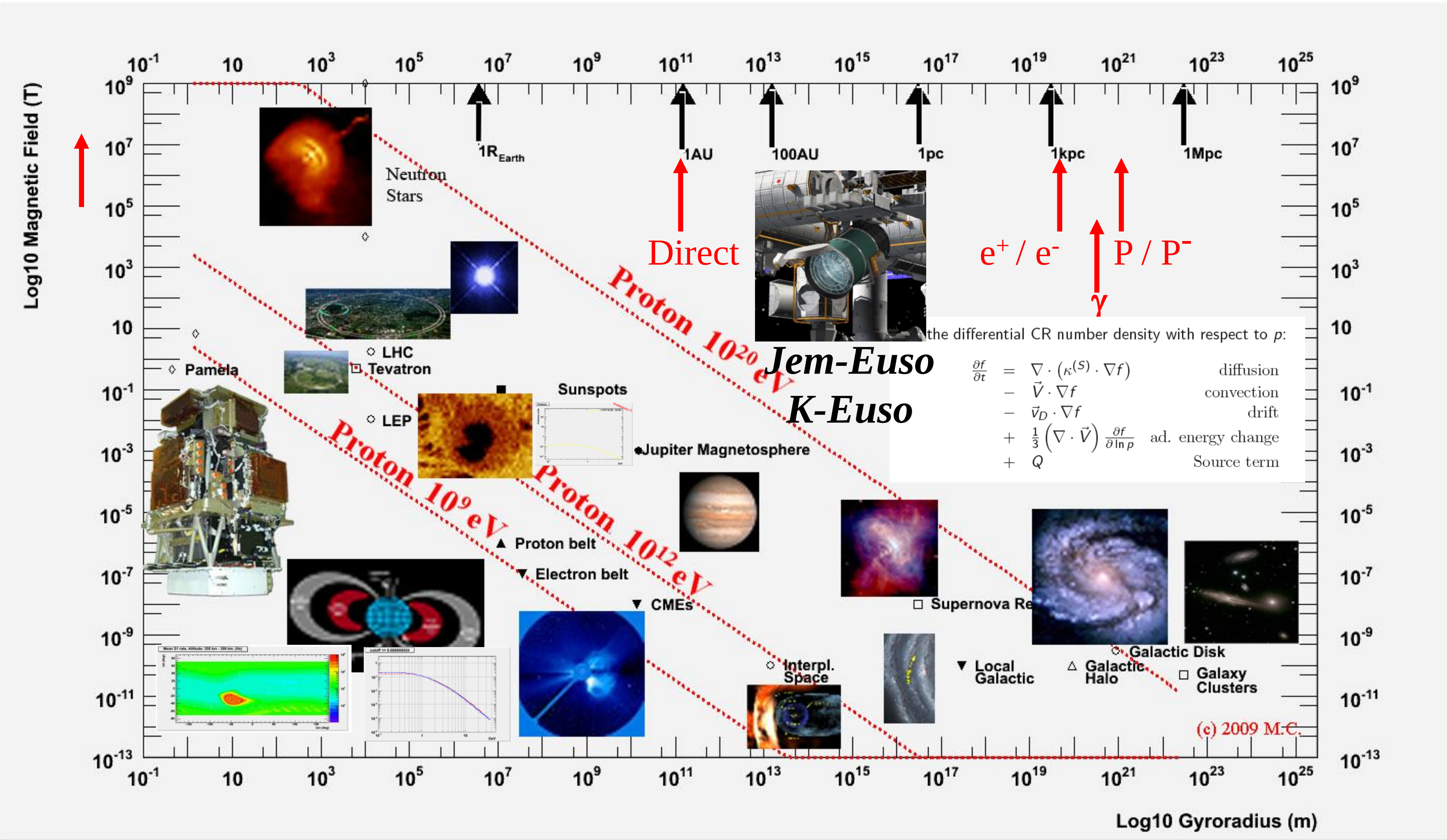
Charged cosmic ray spectrum

- •Power law spectrum
- •Solar Modulation
- •Galactic Cosmic Rays
- •Extragalactic Cosmic Rays

PAMELA
Altea
Alteino



Pamela Physics objectives and 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

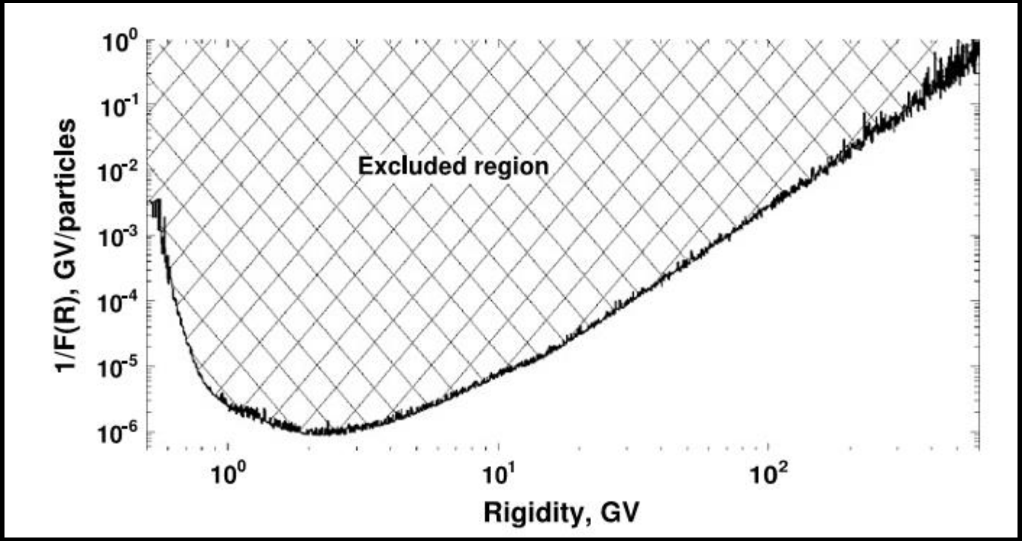
To avoid baryon compensation through inverse processes

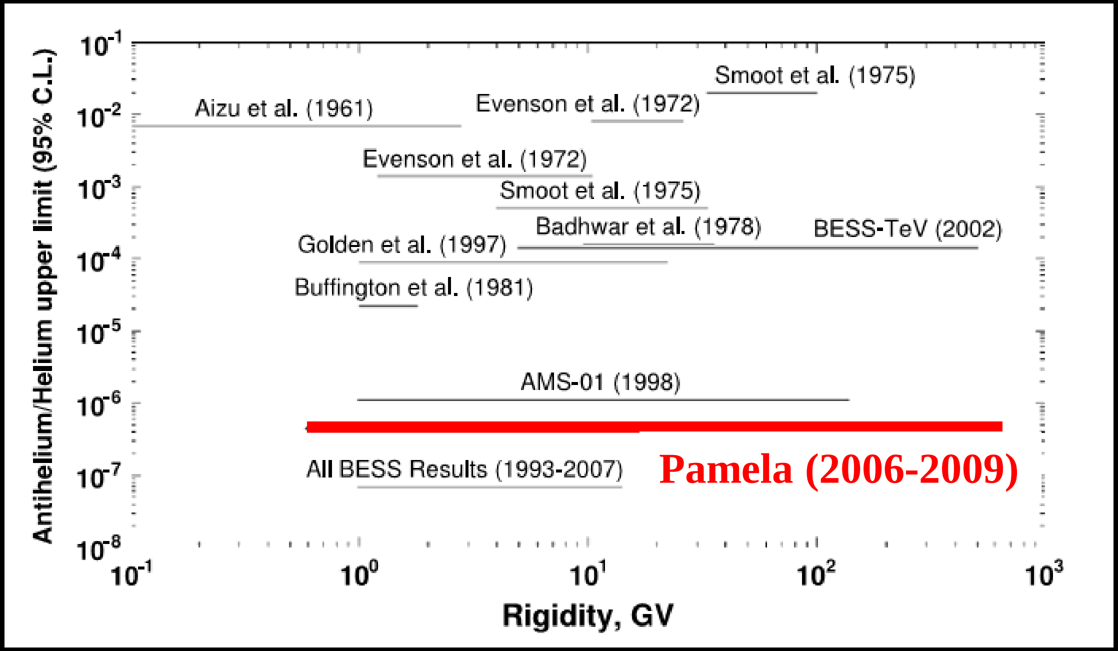
Sakharov, A.D. 1967, J. of Exper. and Theo. Phys. Letters, 5, 24-28,
“Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe”

Search for antinuclei

Antihelium also from primordial nucleosyinthesis

Antinuclei only from antistars

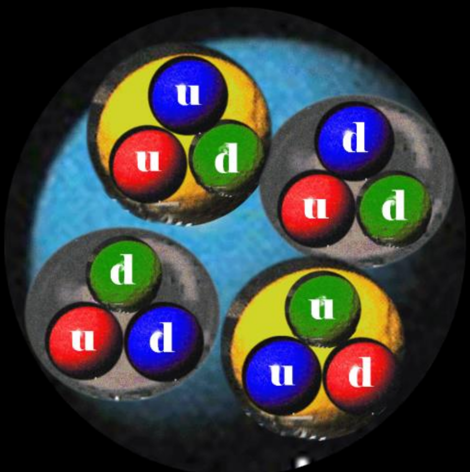




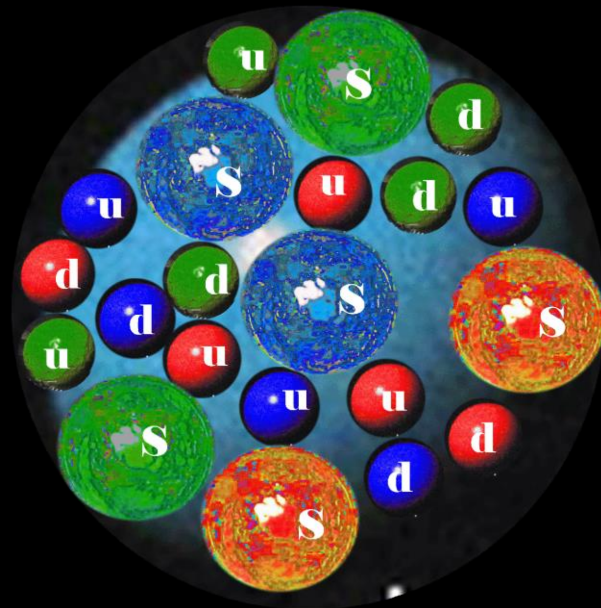
Search for exotic matter: Strangelets

(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

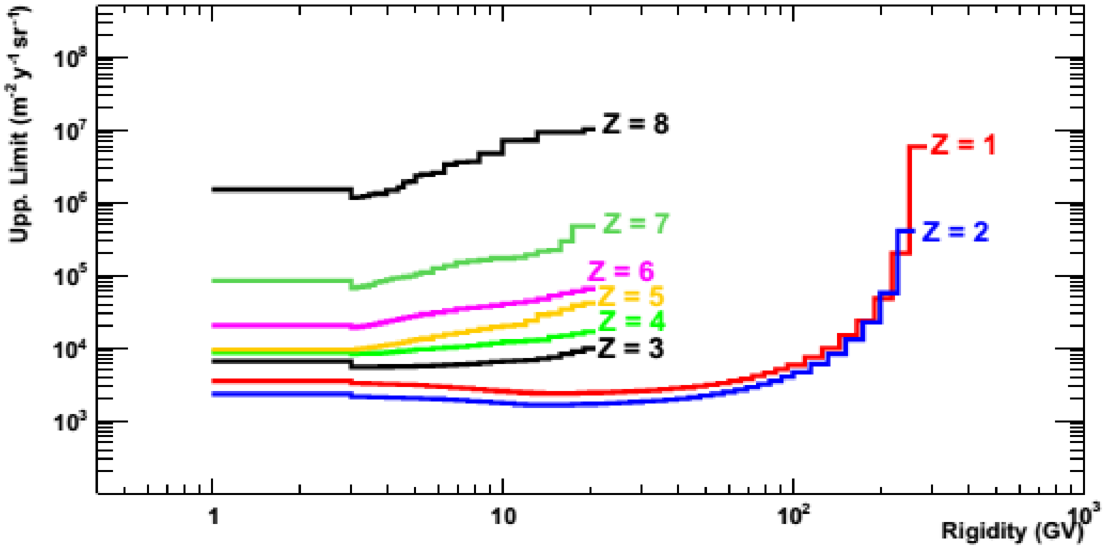
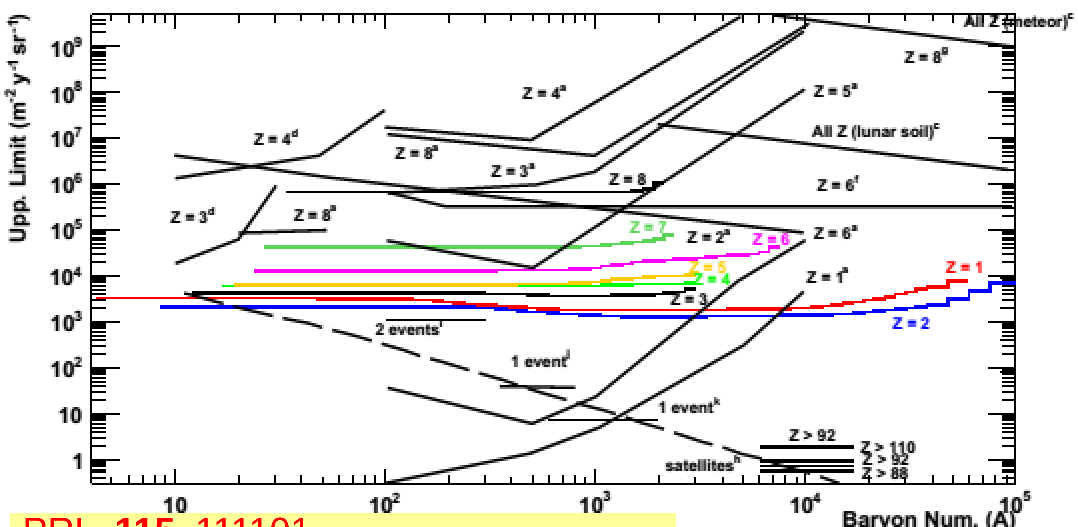


FIG. 4. Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to Z=8.



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

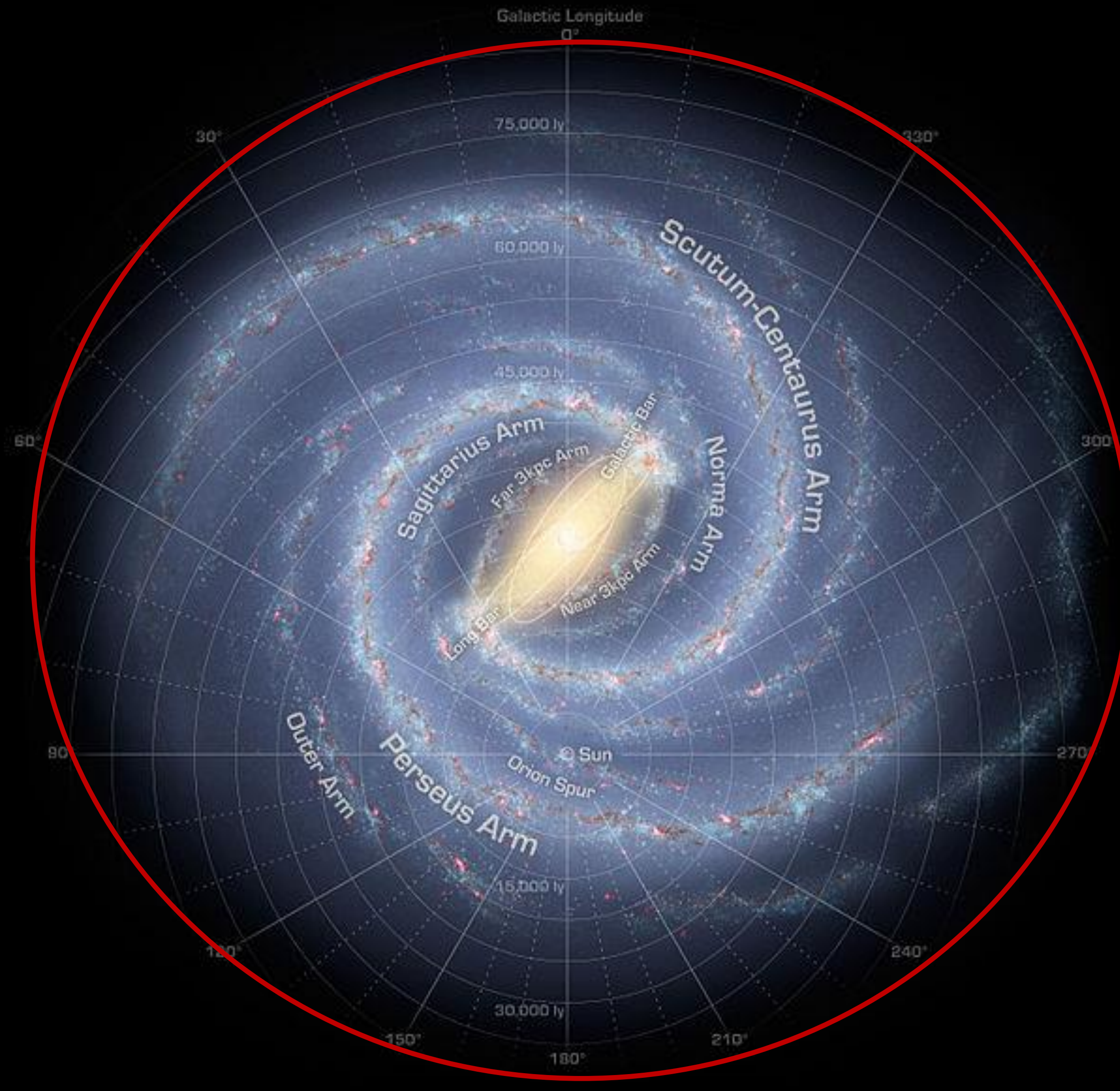
PAMELA, Z=2

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)

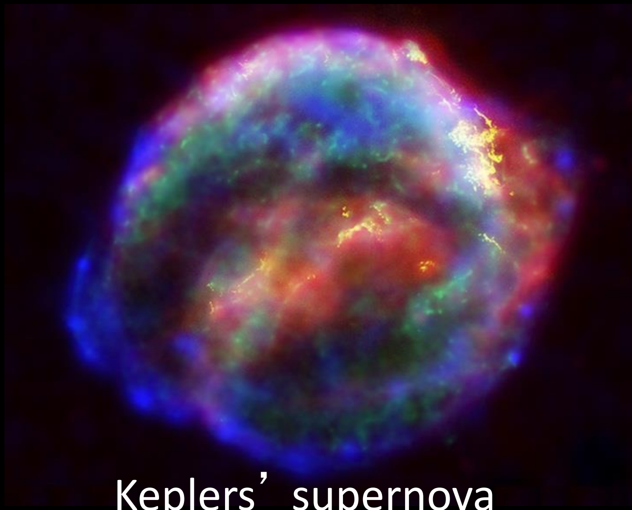
PRL **115**, 111101 –

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



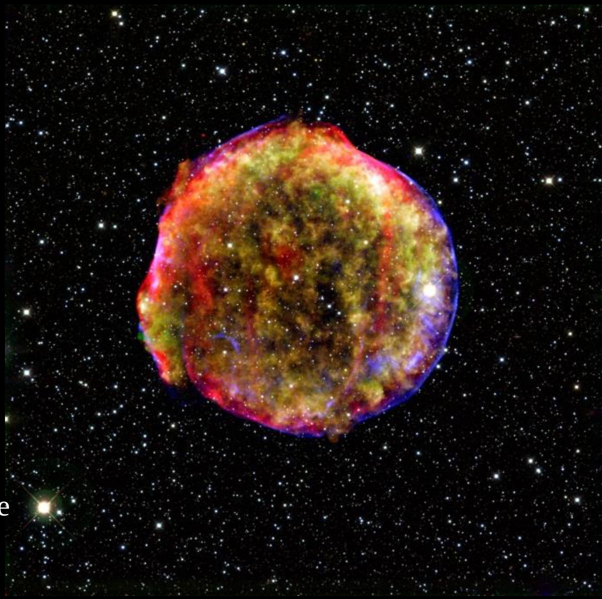
Cosmic rays are accelerated in Supernova explosions (probably)

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



Keplers' supernova

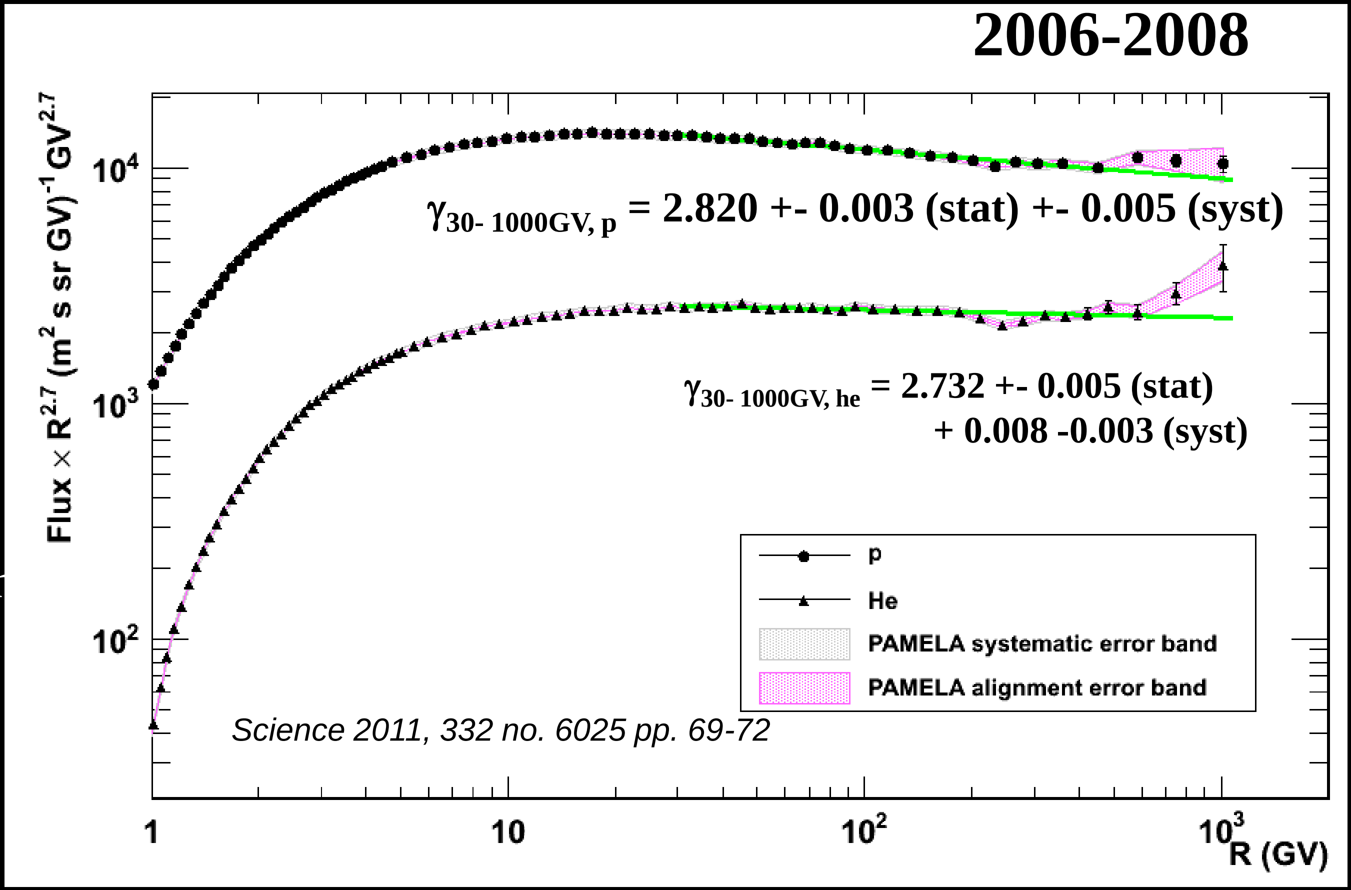
- HESS TeV emision from SNR RX J1713.7-3946 → hadronic inter. Of cr. E>10^14eV *F. Aharonian, et al., Astron. Astrophys. 464, 235 (2007).*
- X-ray measurements of the same SNR → evidence that protons and nuclei can be accelerated E>10^15 eV in young SNR *Uchiyama, et al., Nature 449, 576 (2007).*
- AGILE: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



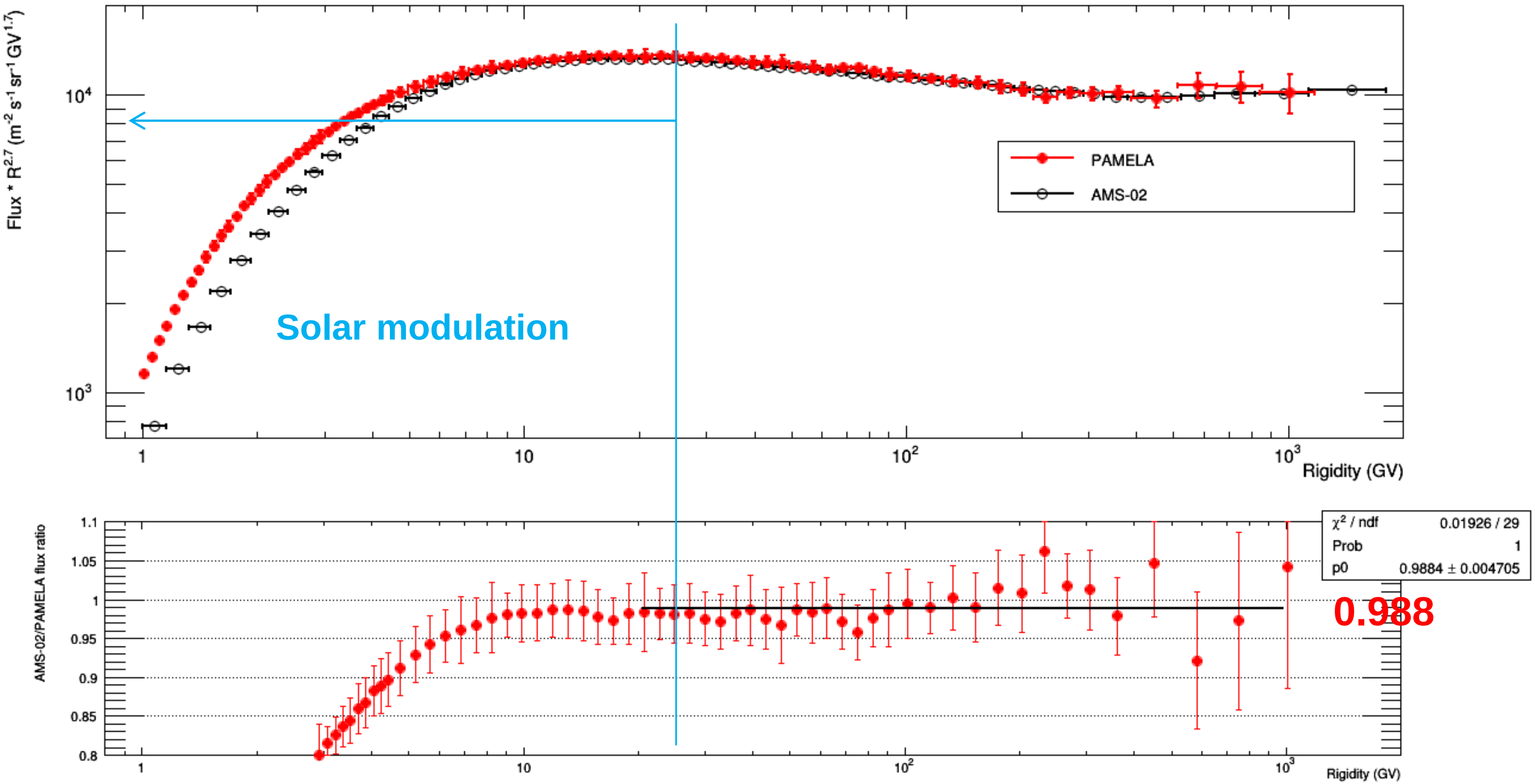
Tycho's supernova

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.

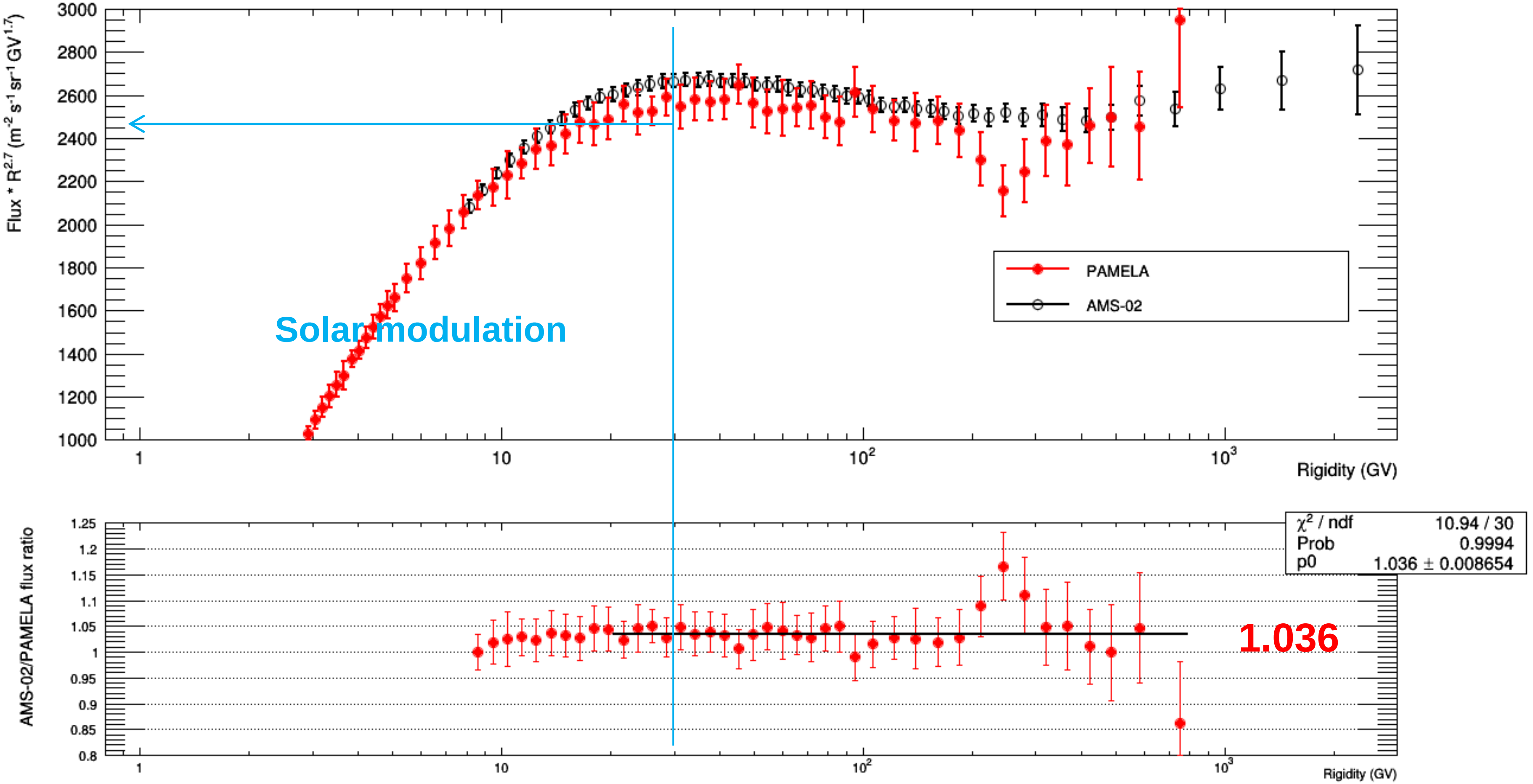


Global picture: PAMELA & AMS-02 proton spectrum



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

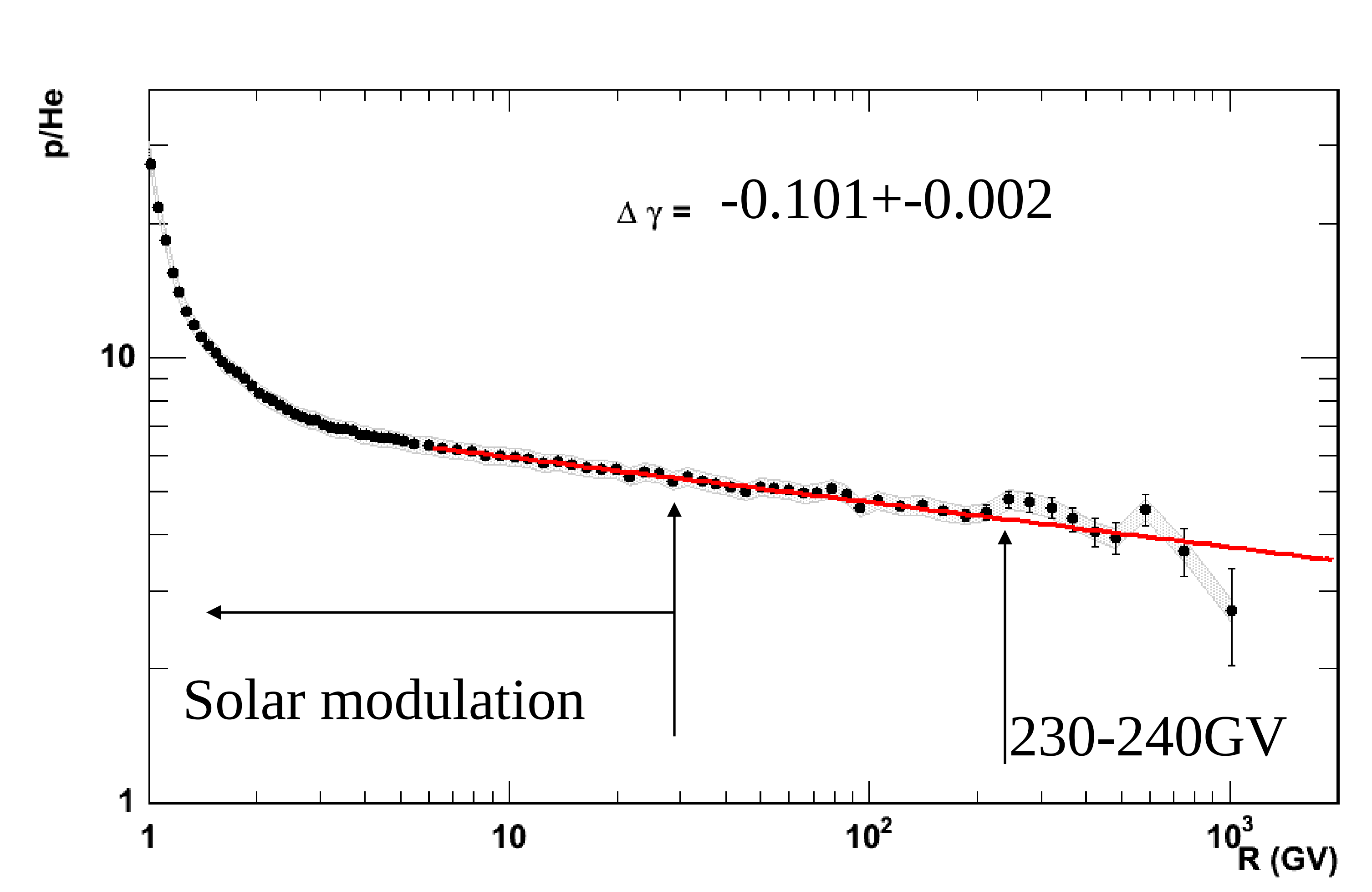
Global picture: PAMELA & AMS-02 helium nuclei spectrum



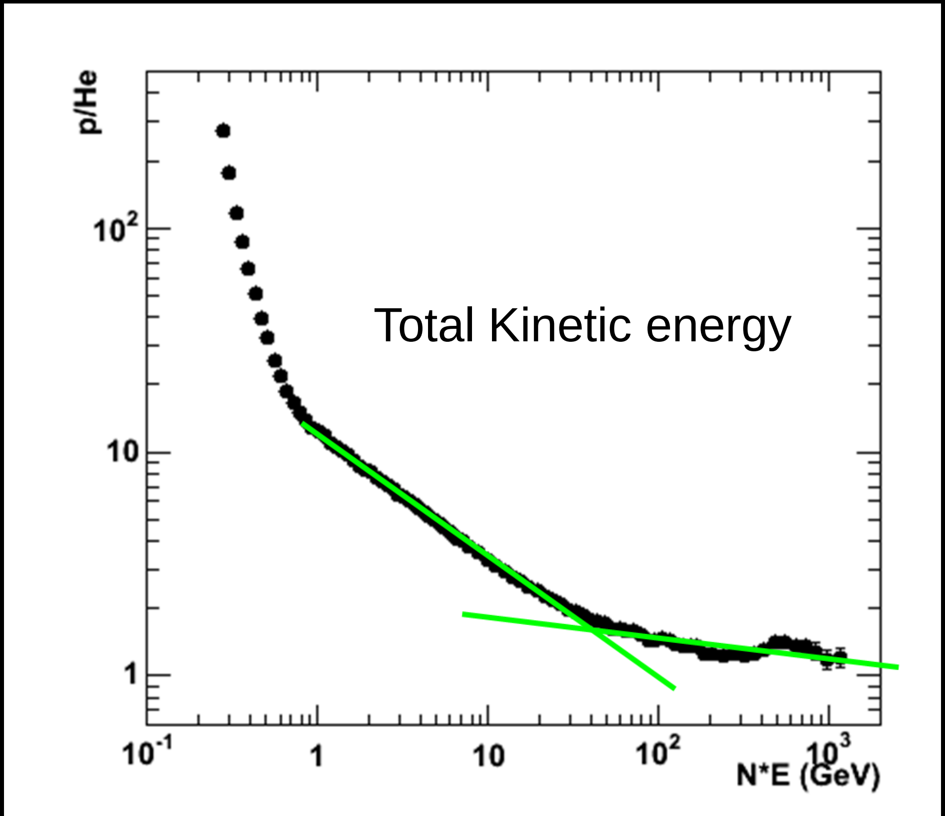
O. Adriani et al, Phys. Rep. (2014)

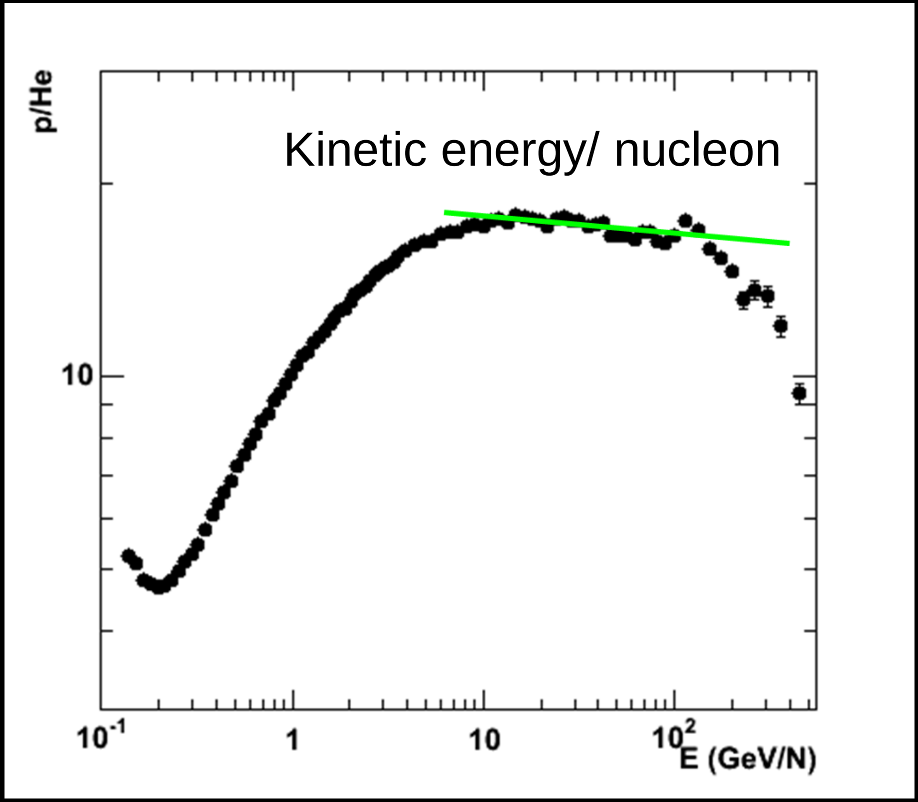
Ratio P/He: Rigidity

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

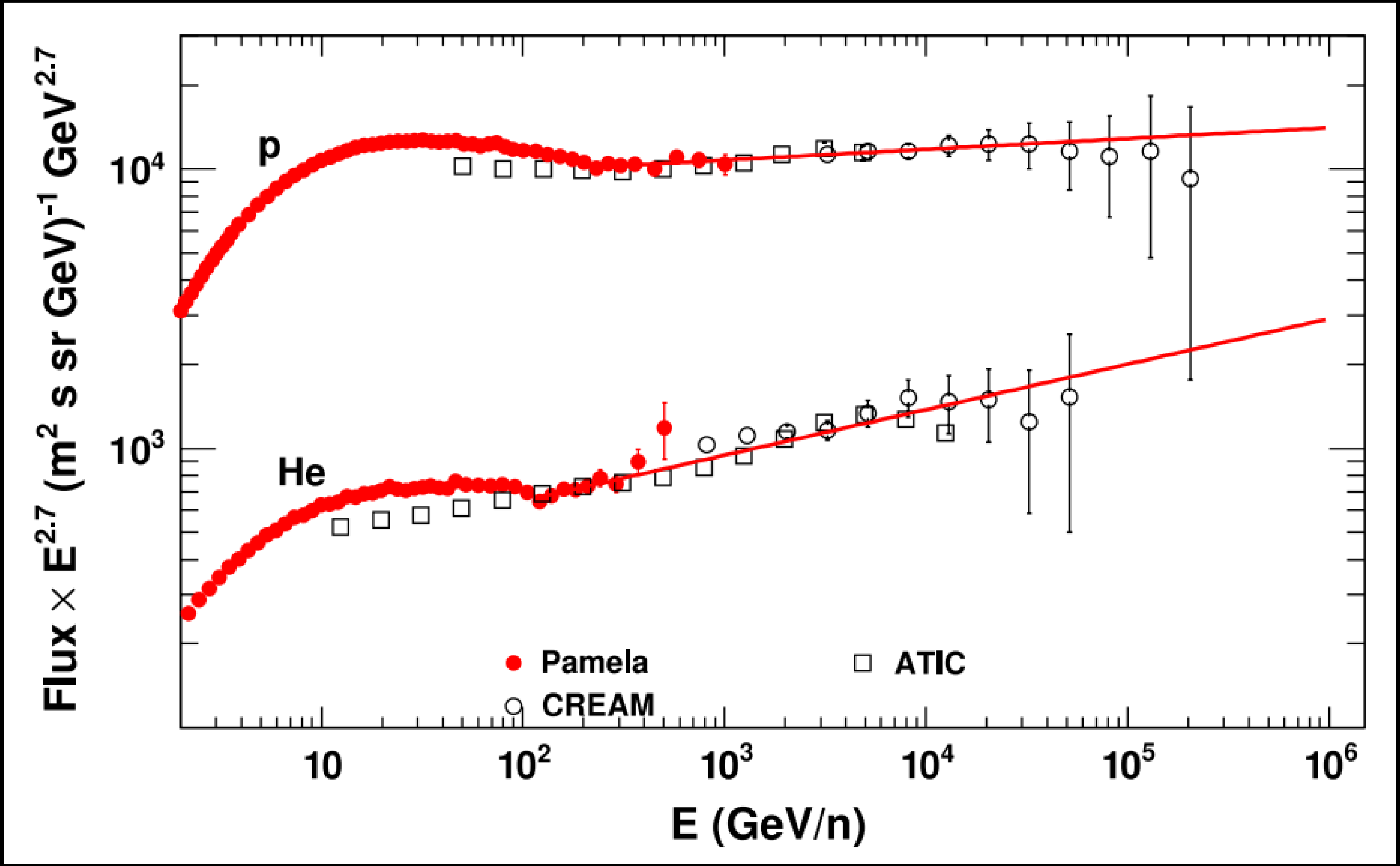


Acceleration / Propagation is a rigidity phenomenon





At higher energies: Cream and ATIC data



Ahn et al, ApJL 2010

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

Indirect p, He Direct C-Fe

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

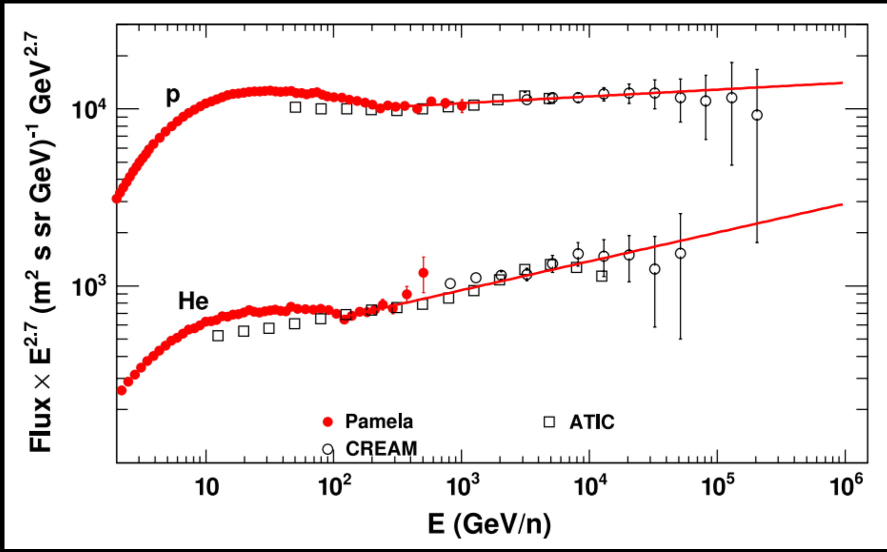
Additional Sources *Wolfendale 2011, 2012*

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

- B/C ratio

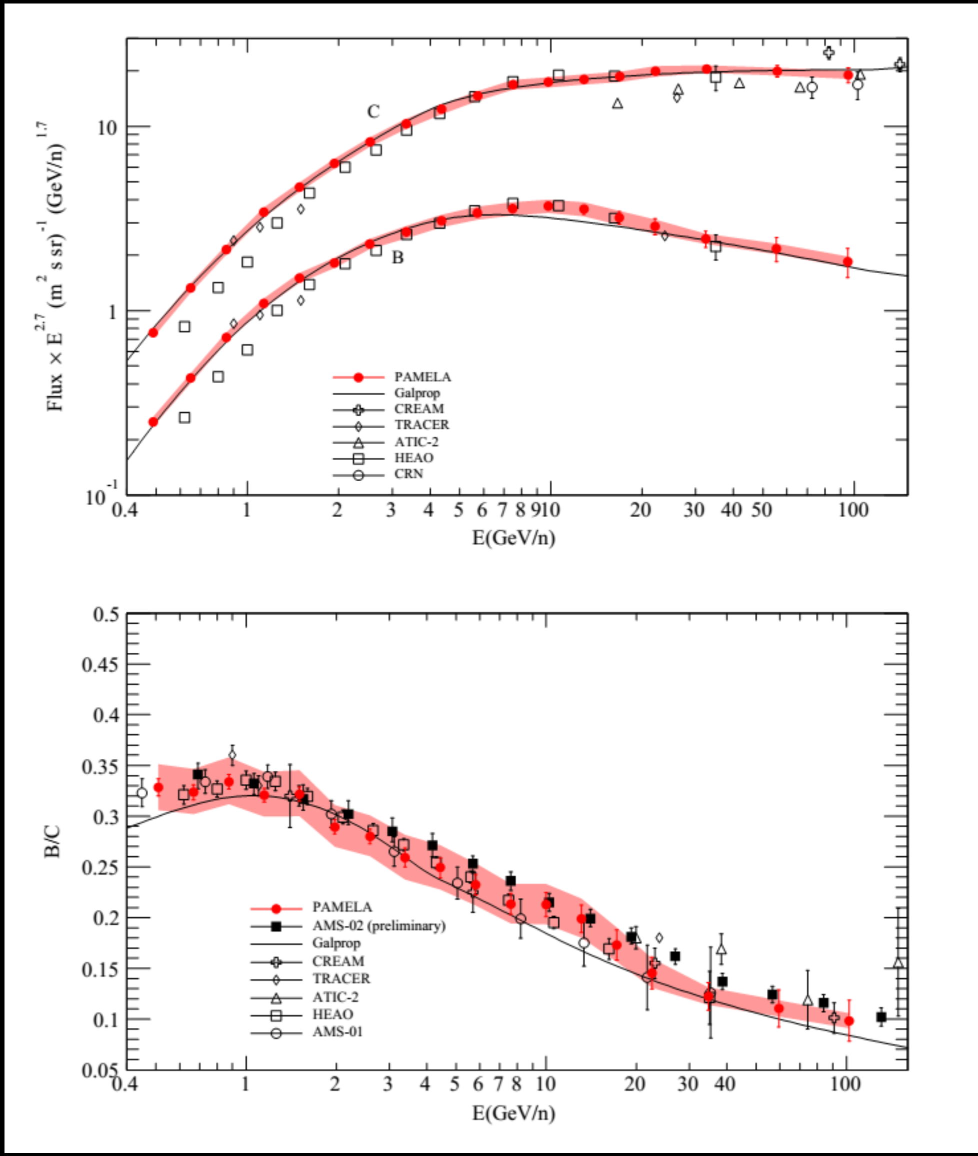
Secondary/primay

CNO+ISM → B

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

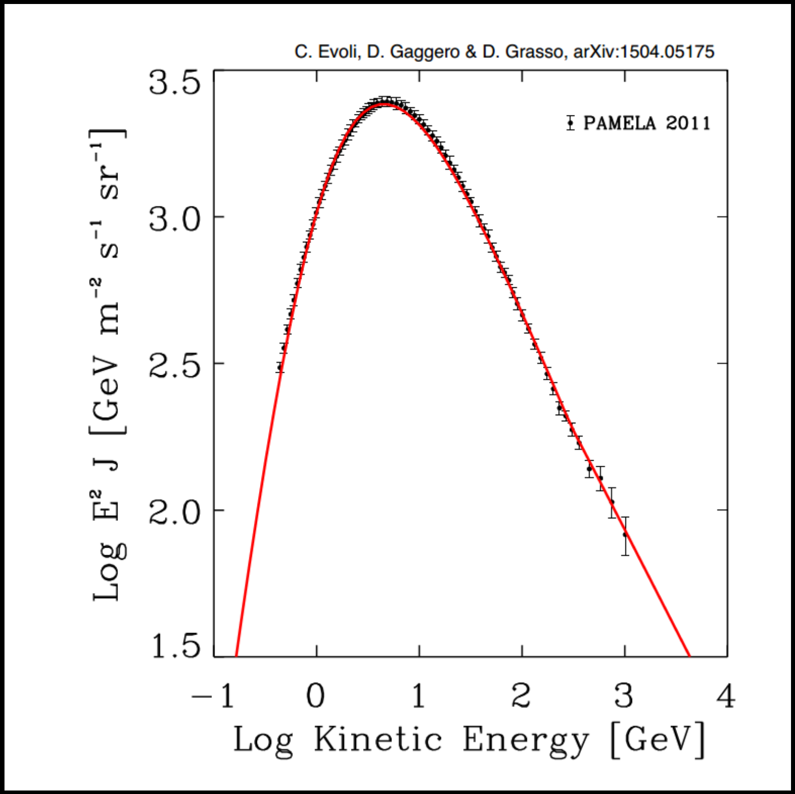
→ Propagation in the Galaxy

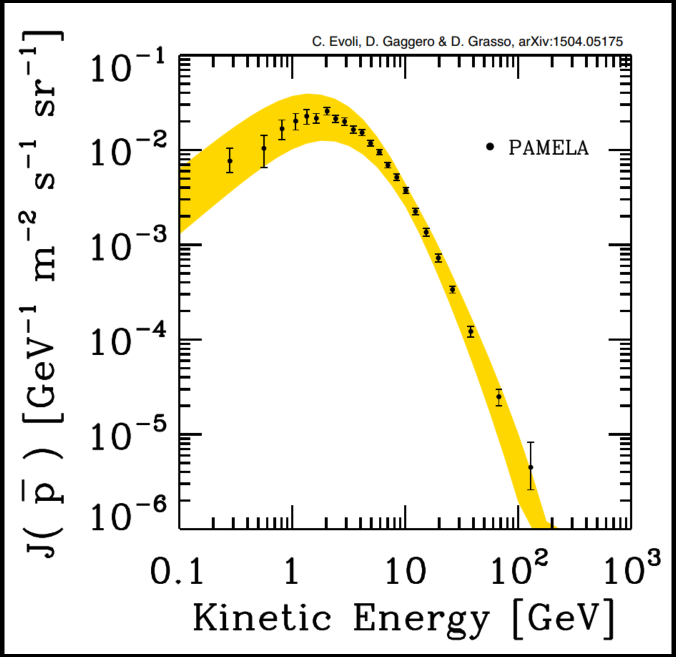
Time of permanence of cr

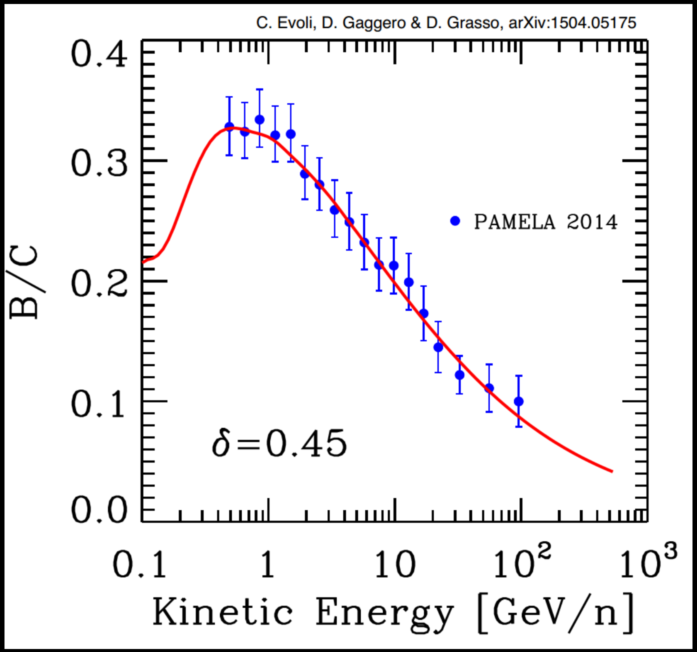


ApJ 791 2 2014

Puzzle of production and propagation in the galaxy





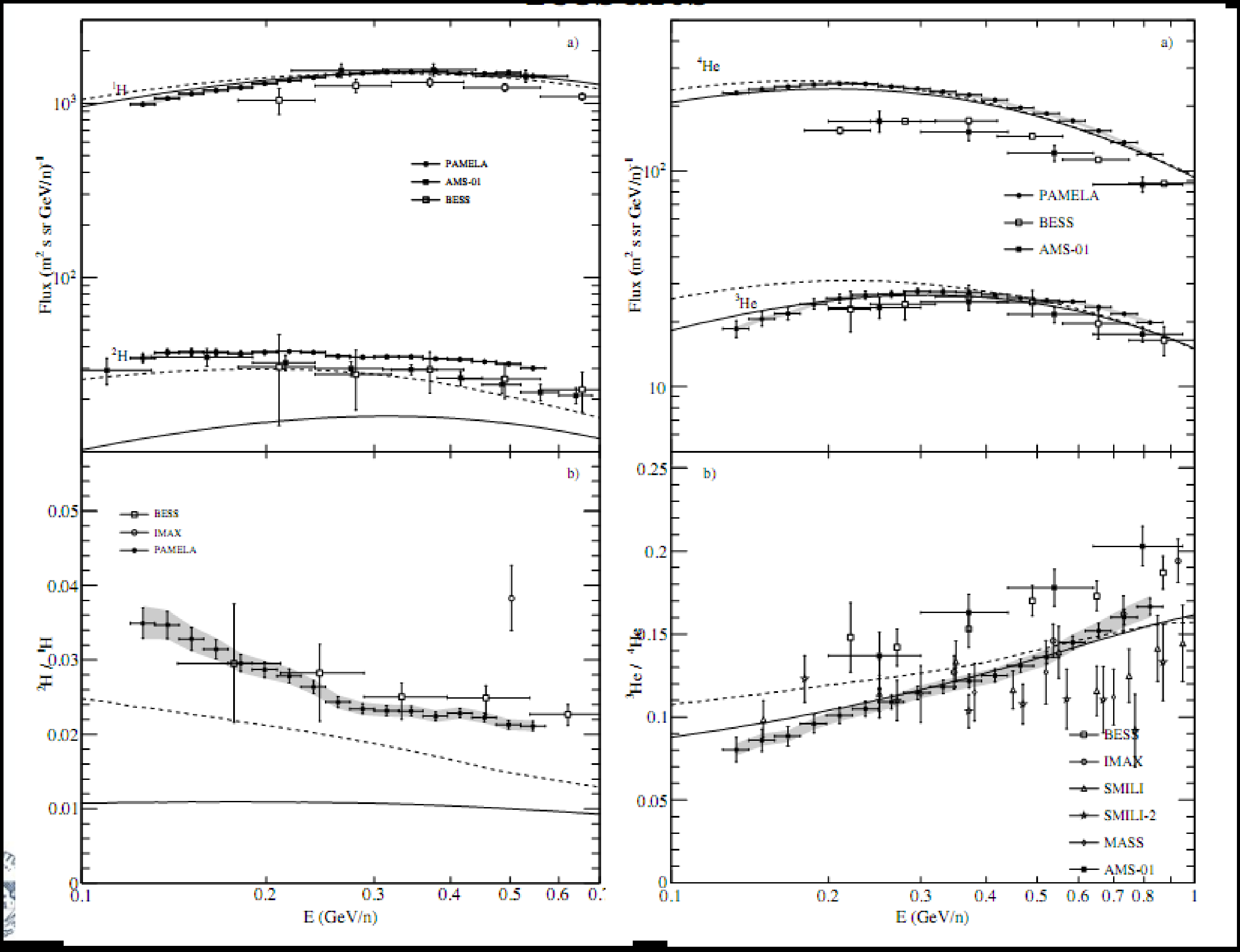


H and He Isotopes

Propagation in the Galaxy

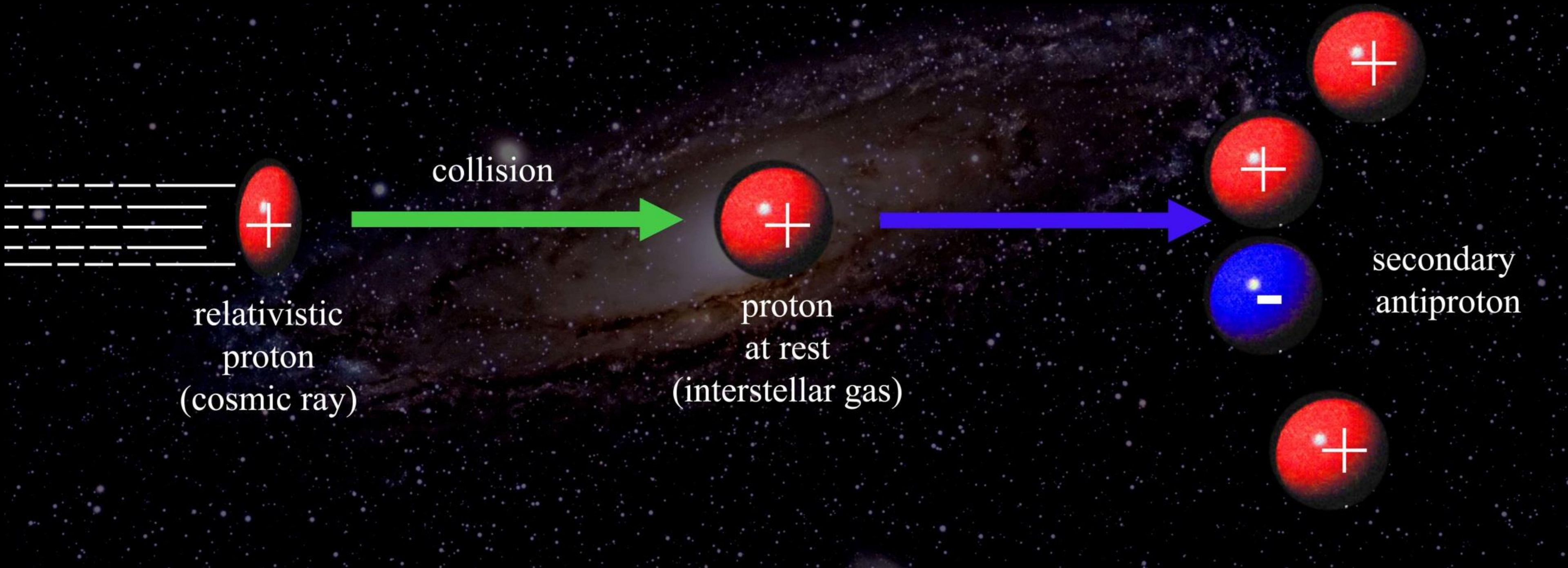
- Flux depends on solar modulation
- Ratio is less dependent
- Strong tool for evaluating secondary particle production in the galaxy
- Complementary to B/C

ApJ 770:2, 2013

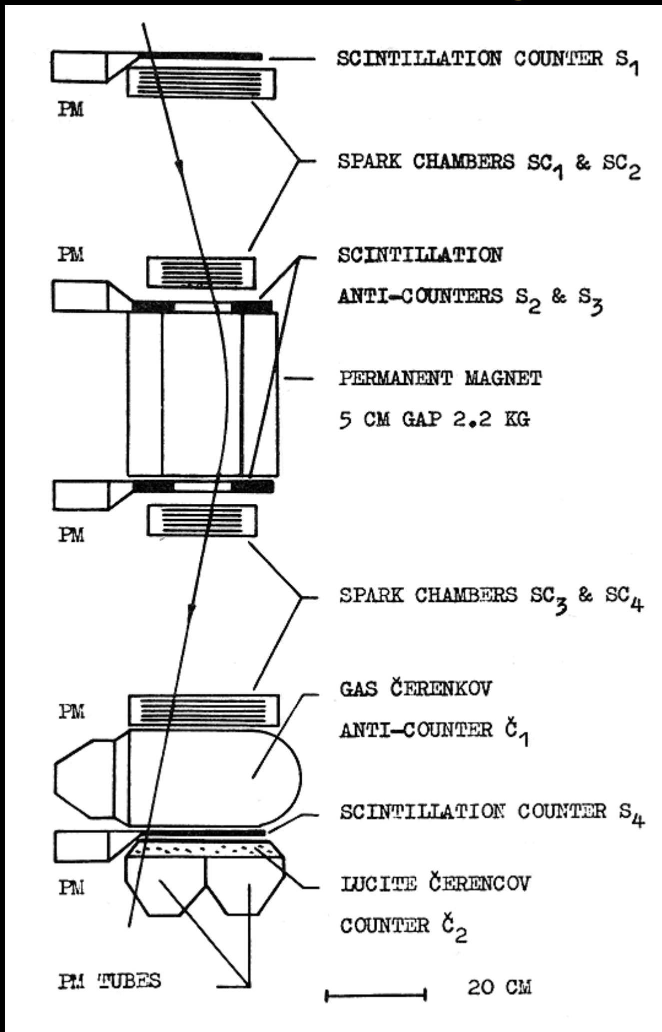


Antiprotons

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



Discovery of antiprotons in cr, 1979

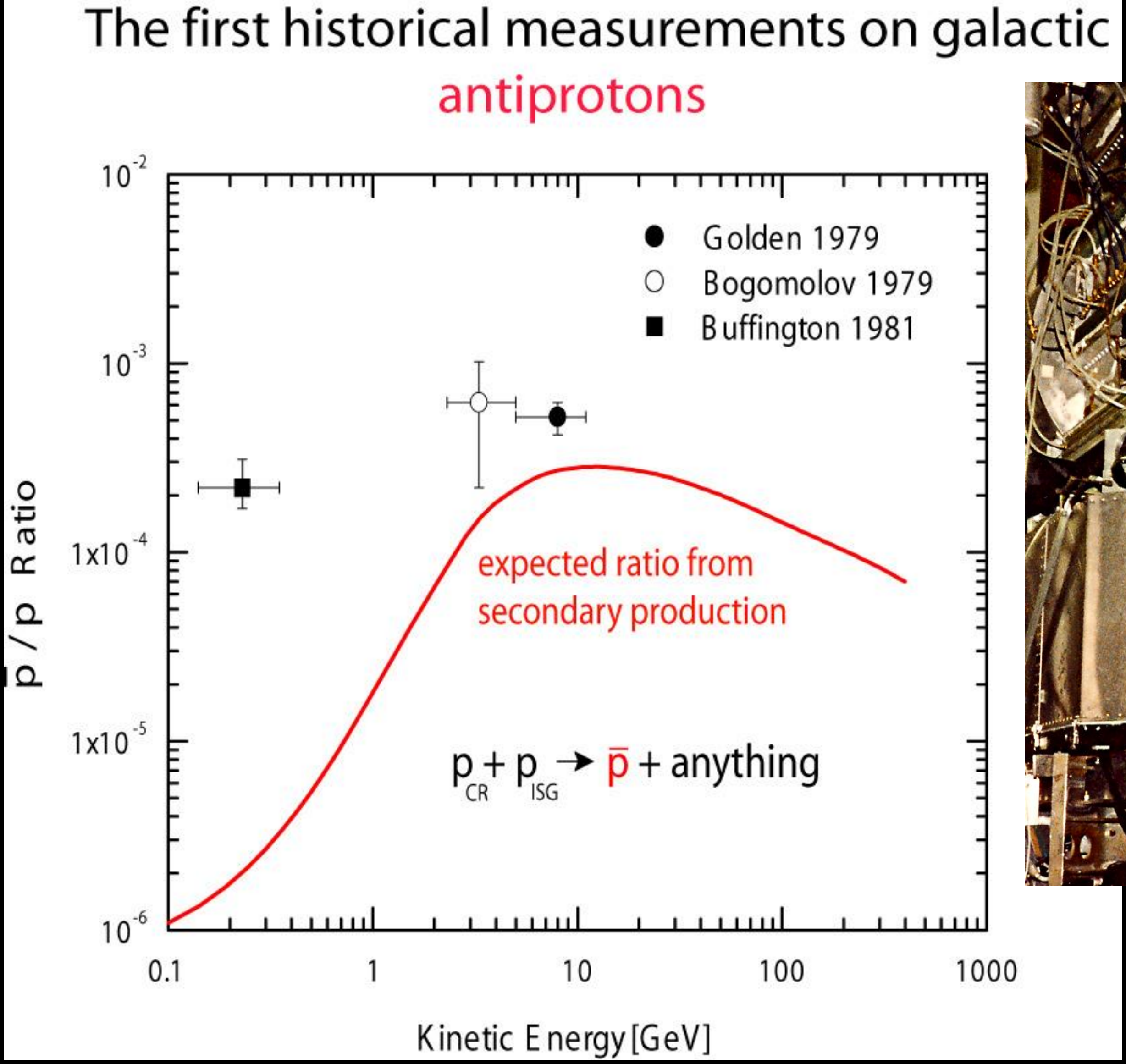


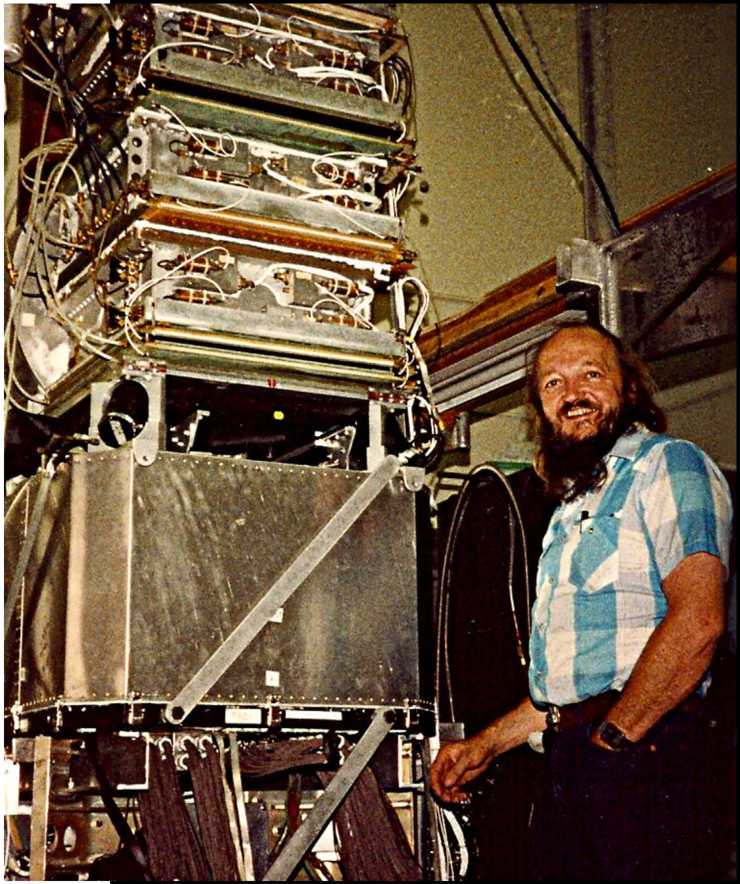
p/p ratio
6×10^{-4}
2-5 GeV

From
Robert E. Streitmatter

Bogomolov, E.A. et al. 1979, Proc. 16th ICRC, Kyoto, 1, 330,
"A Stratospheric Magnetic Spectrometer Investigation of the Singly Charged Component Spectra and Composition of the Primary and Secondary Cosmic Radiation"

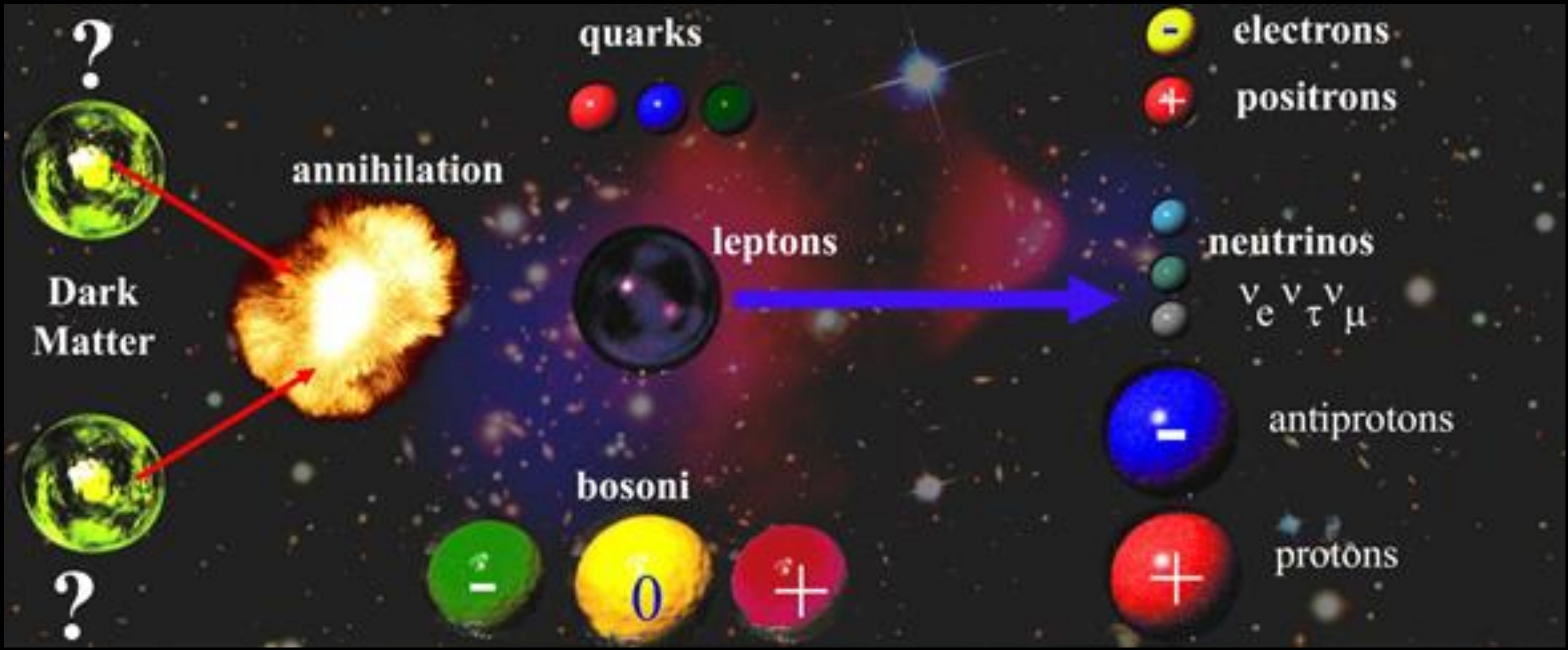
Also Golden, 1979





Robert L. Golden

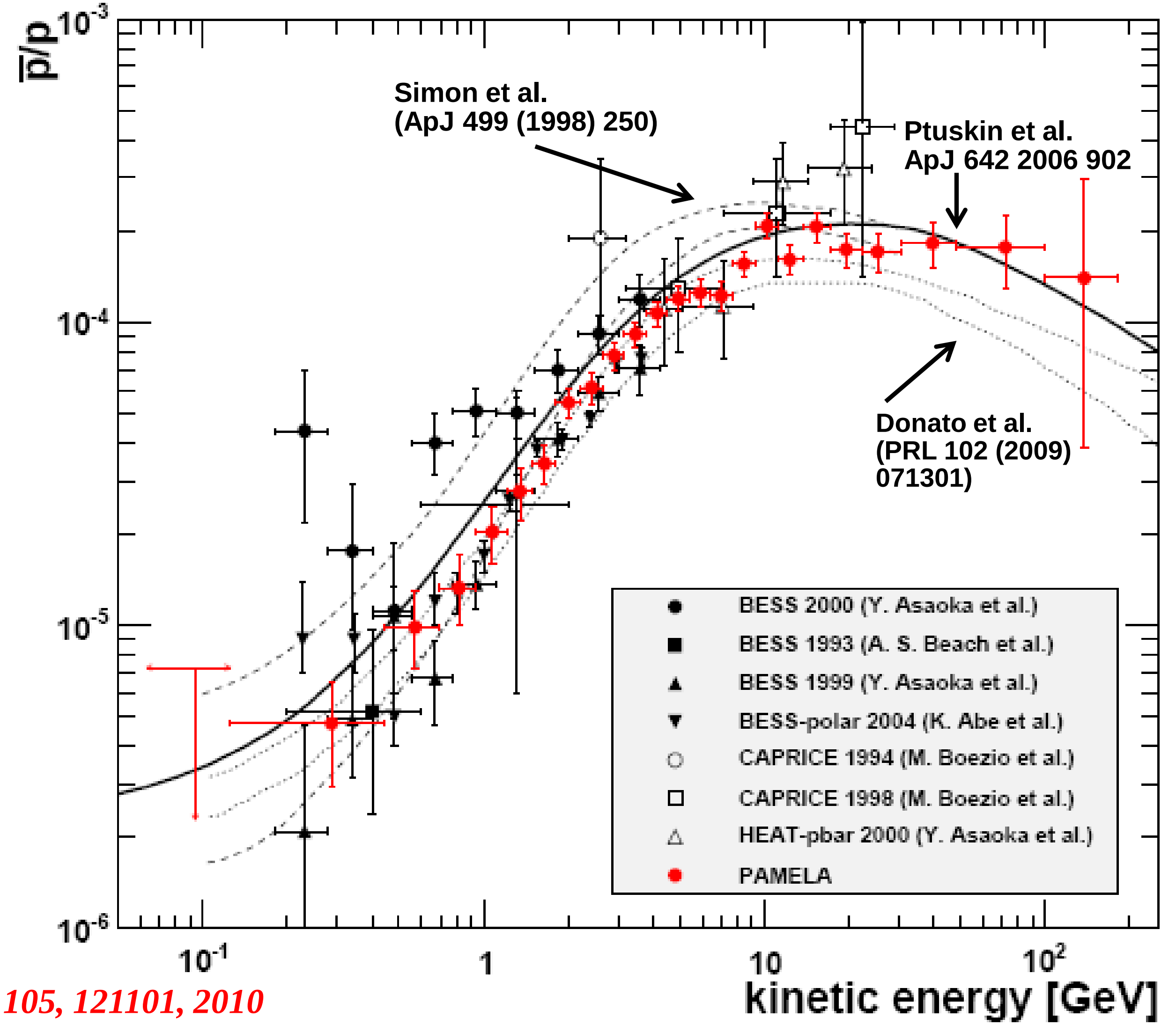
Indirect Dark matter search in space



Antiproton/proton ratio

Low Energy →
Confirms charge dependent solar modulation

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



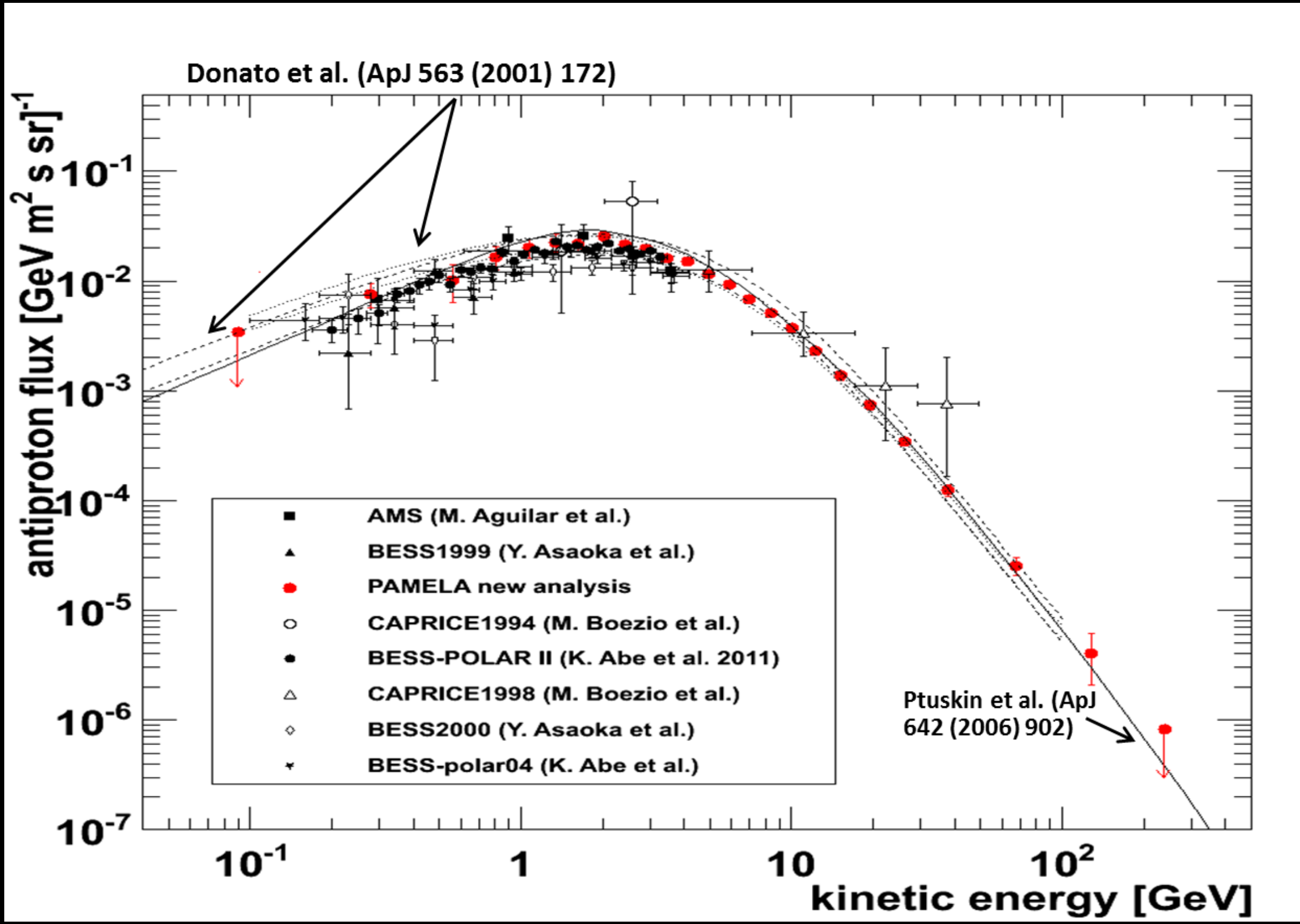
PRL. 105, 121101, 2010

PRL 102:051101,2009

Antiproton absolute flux

Apparently no extra sources

Rule out and strongly constrain many models of DM

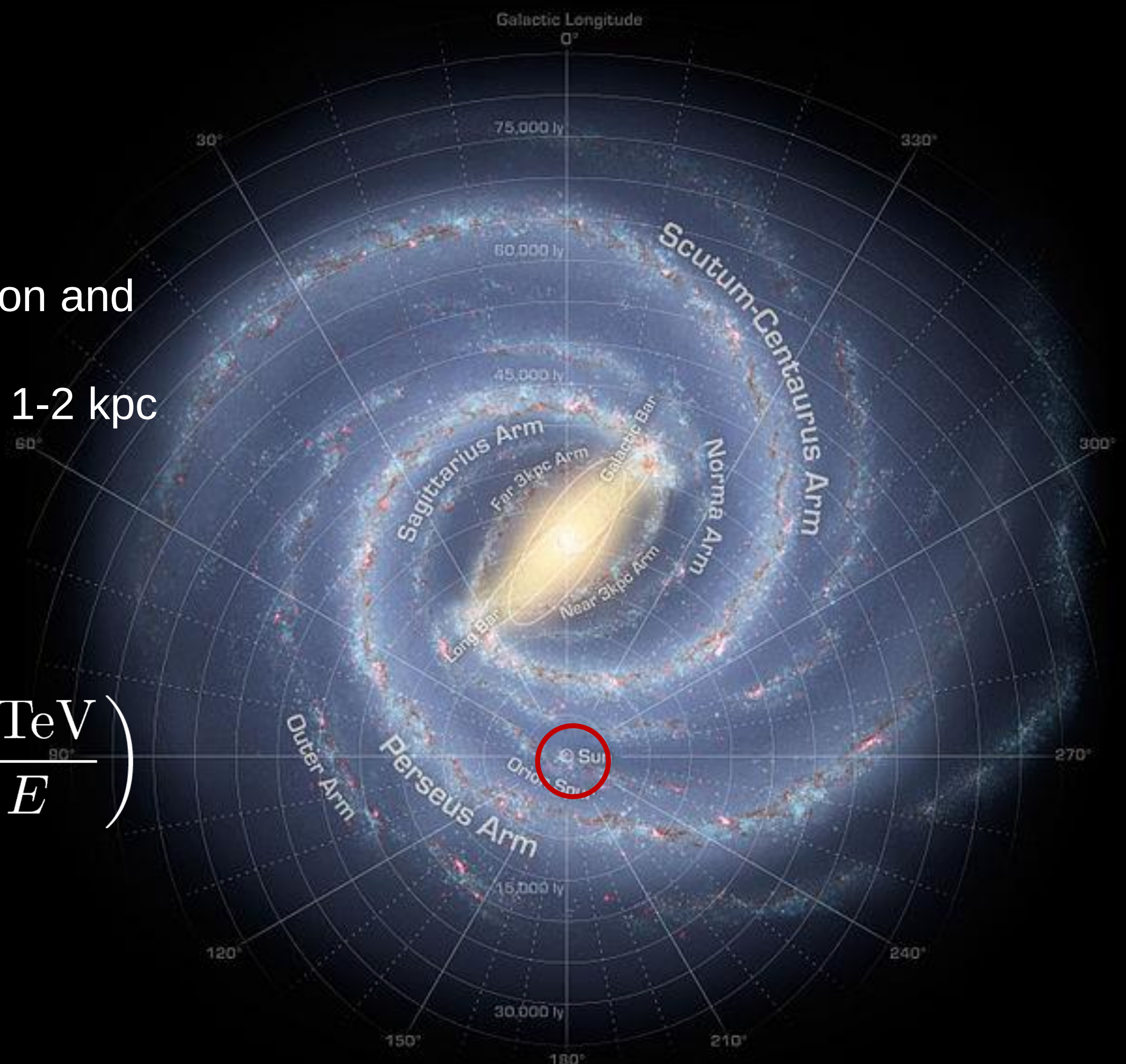


S M. Asano, et al, Phys. Lett. B 709 (2012) 128.
R. Kappl et al , PRD 85 (2012) 123522
M. Garnyet al, JCAP 1204 (2012) 033
D. G. Cerdeno, et al, Nucl. Phys. B 854

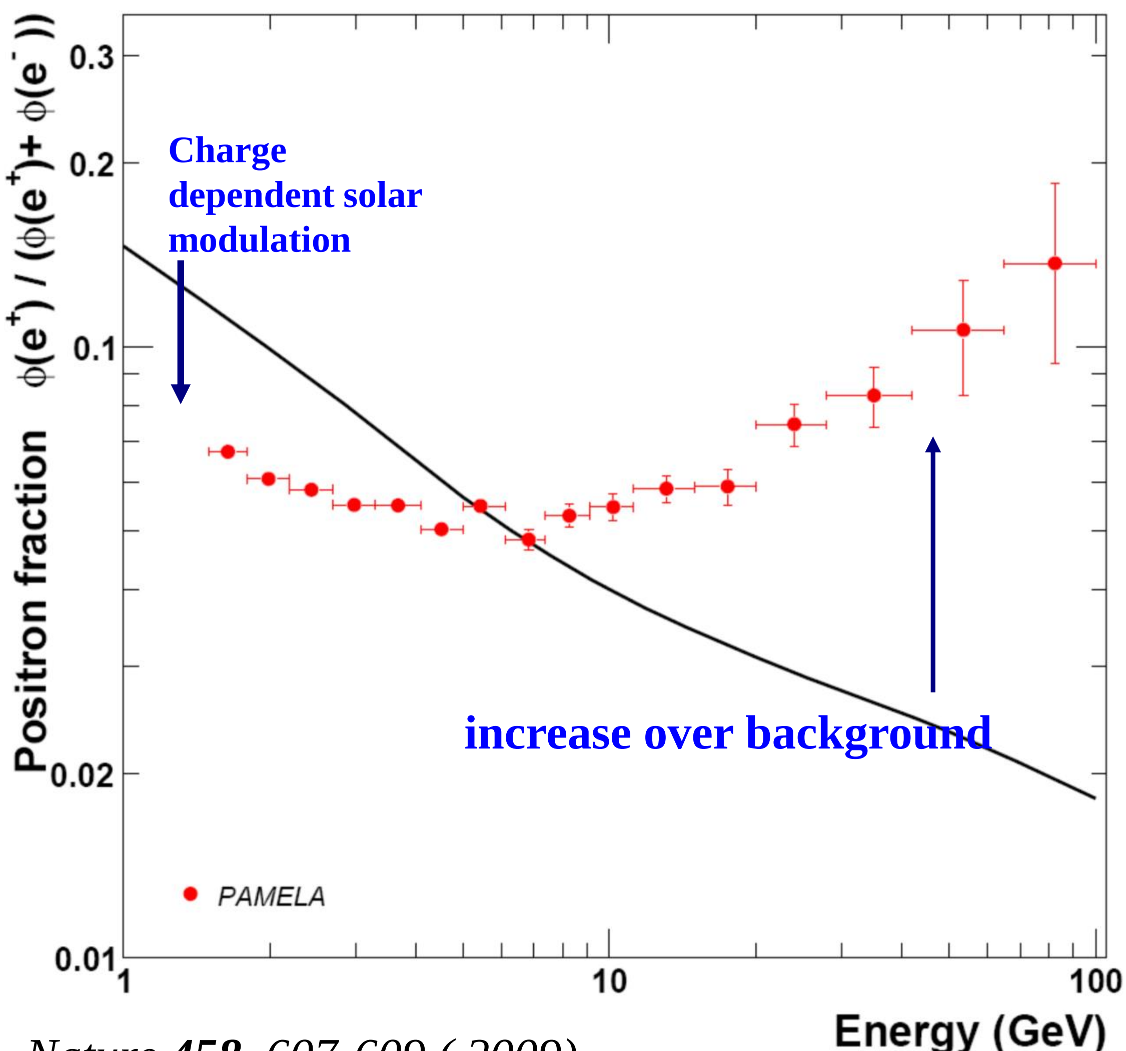
Galactic neighborhood: e+, e- (1-2 kpc)

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

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

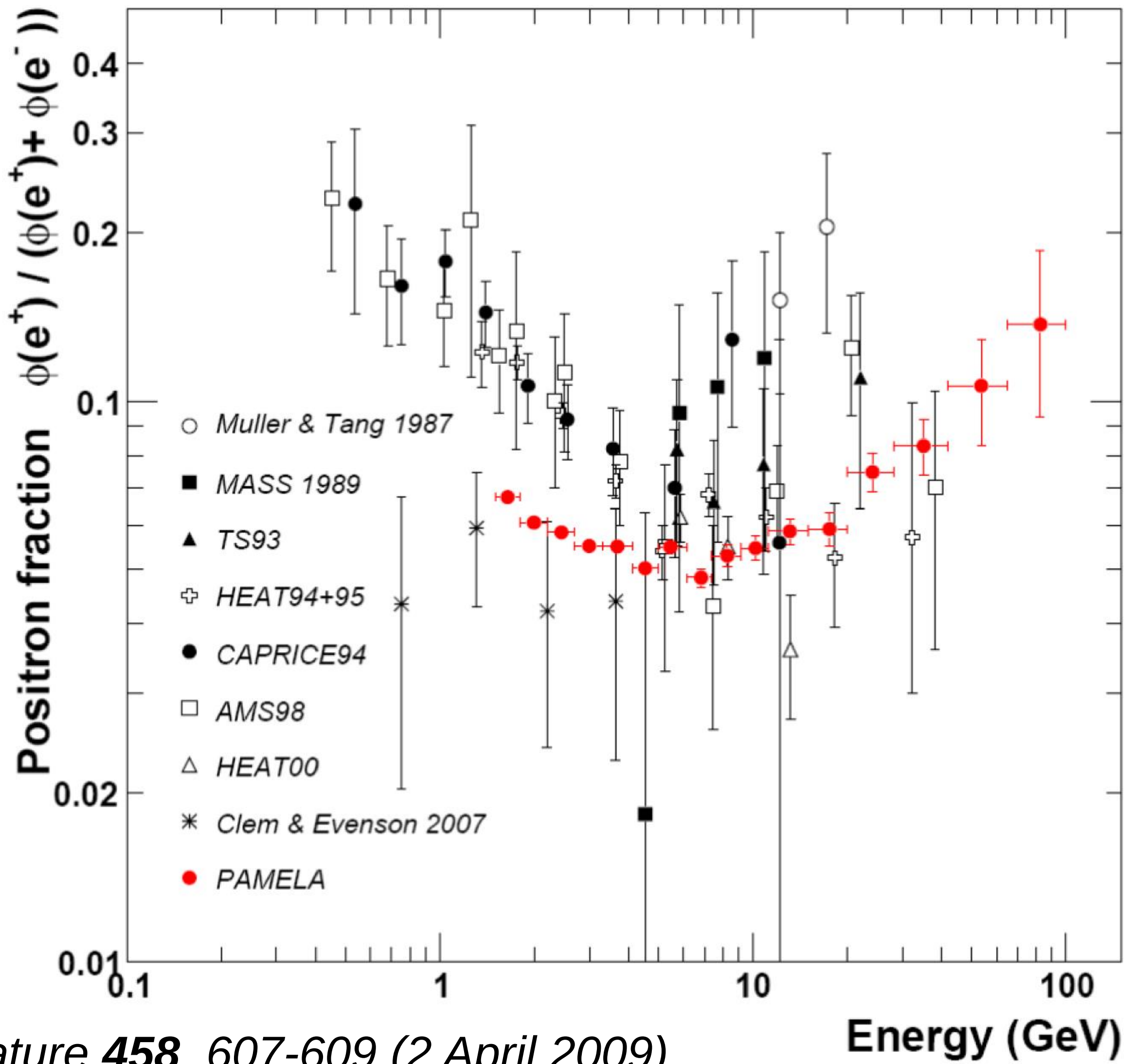


Pamela positron fraction



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

Pamela positron fraction: comparison with other data

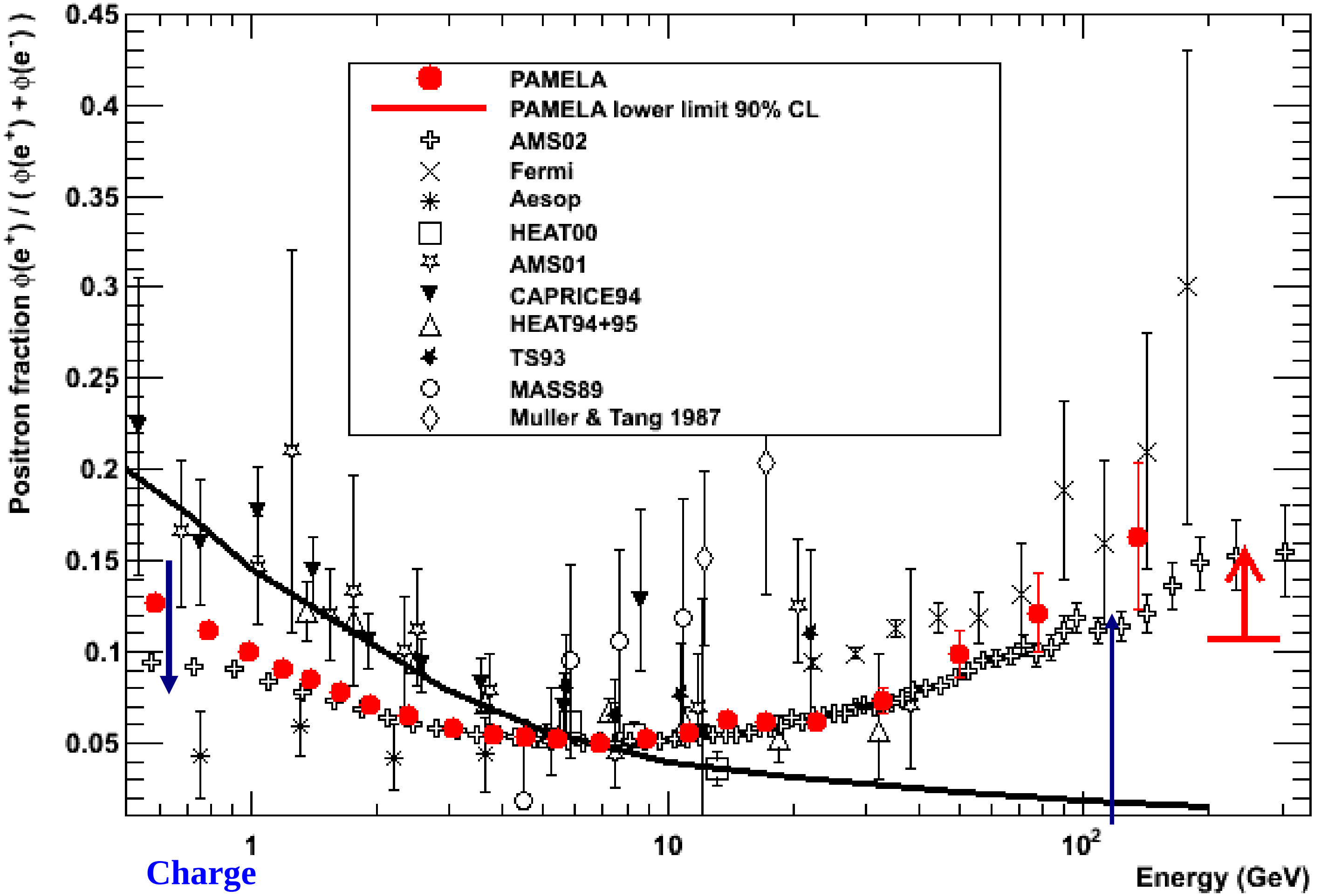


Nature ***458***, *607-609 (2 April 2009)*

AMS & FERMI have confirmed PAMELA data

Anomalous source at high energy

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

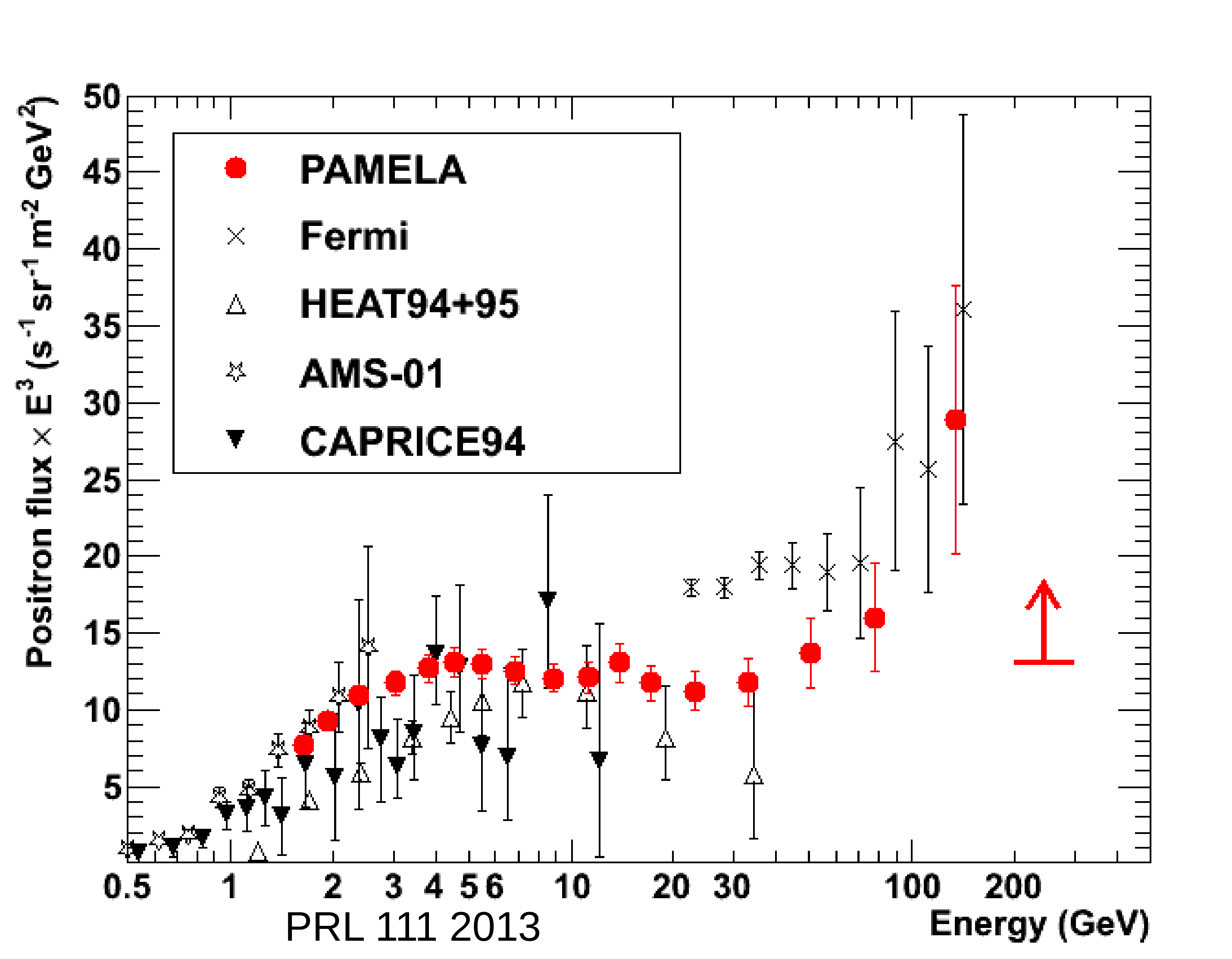


Charge dependent solar modulation

L. Maccione, PRL 110 (2013) 081101

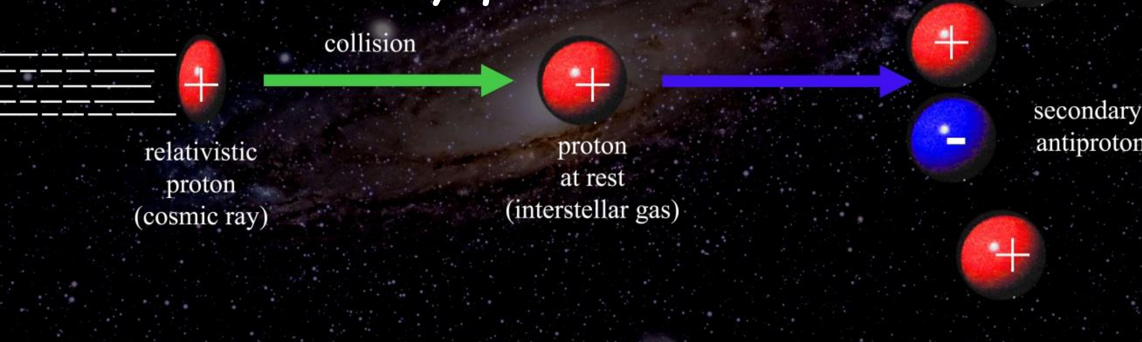
Absolute positron spectrum

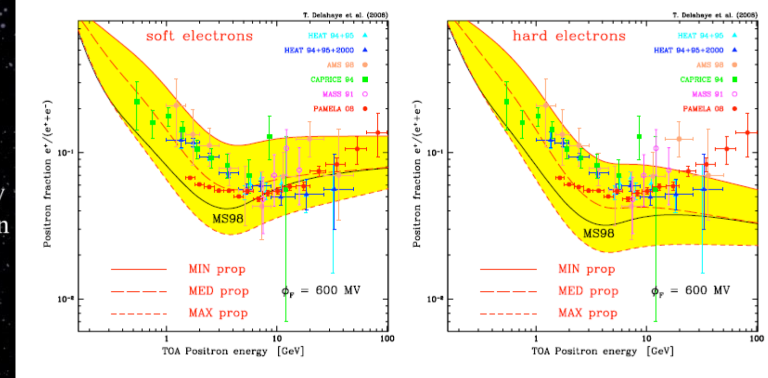
Propagation
Charge
dependent solar
modulation



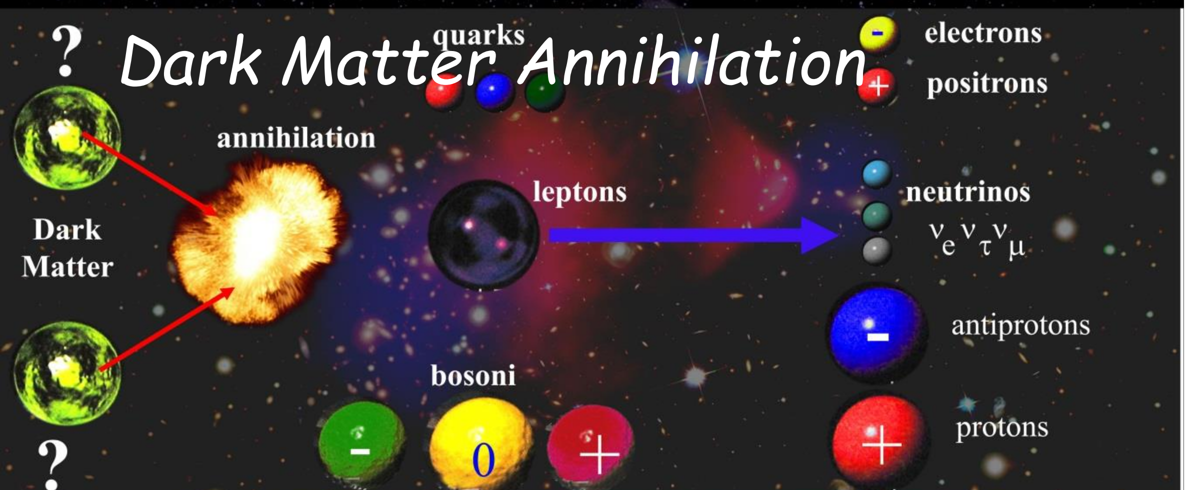
PRL111, 081102 (2013)

Secondary production

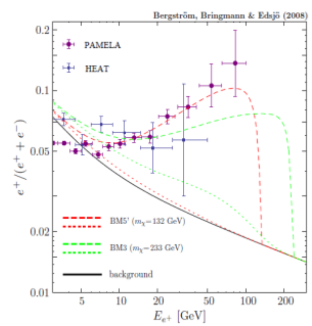


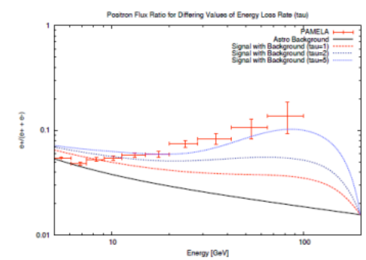


Dark Matter Annihilation



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

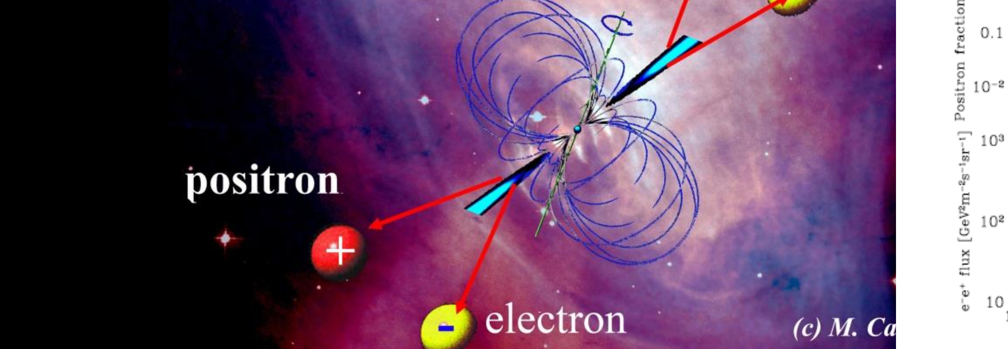


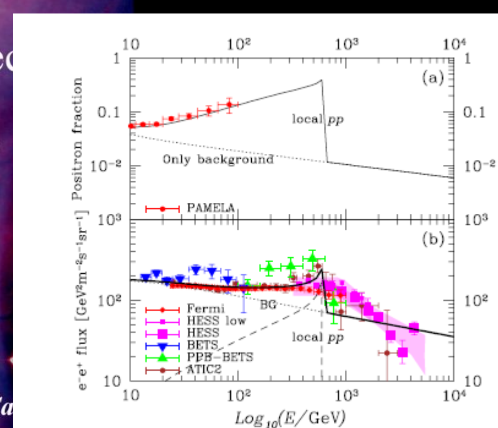


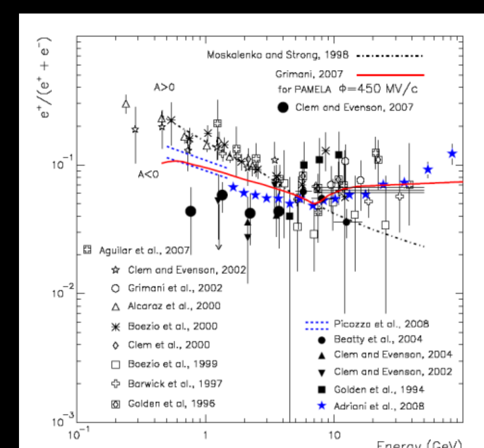
P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555

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

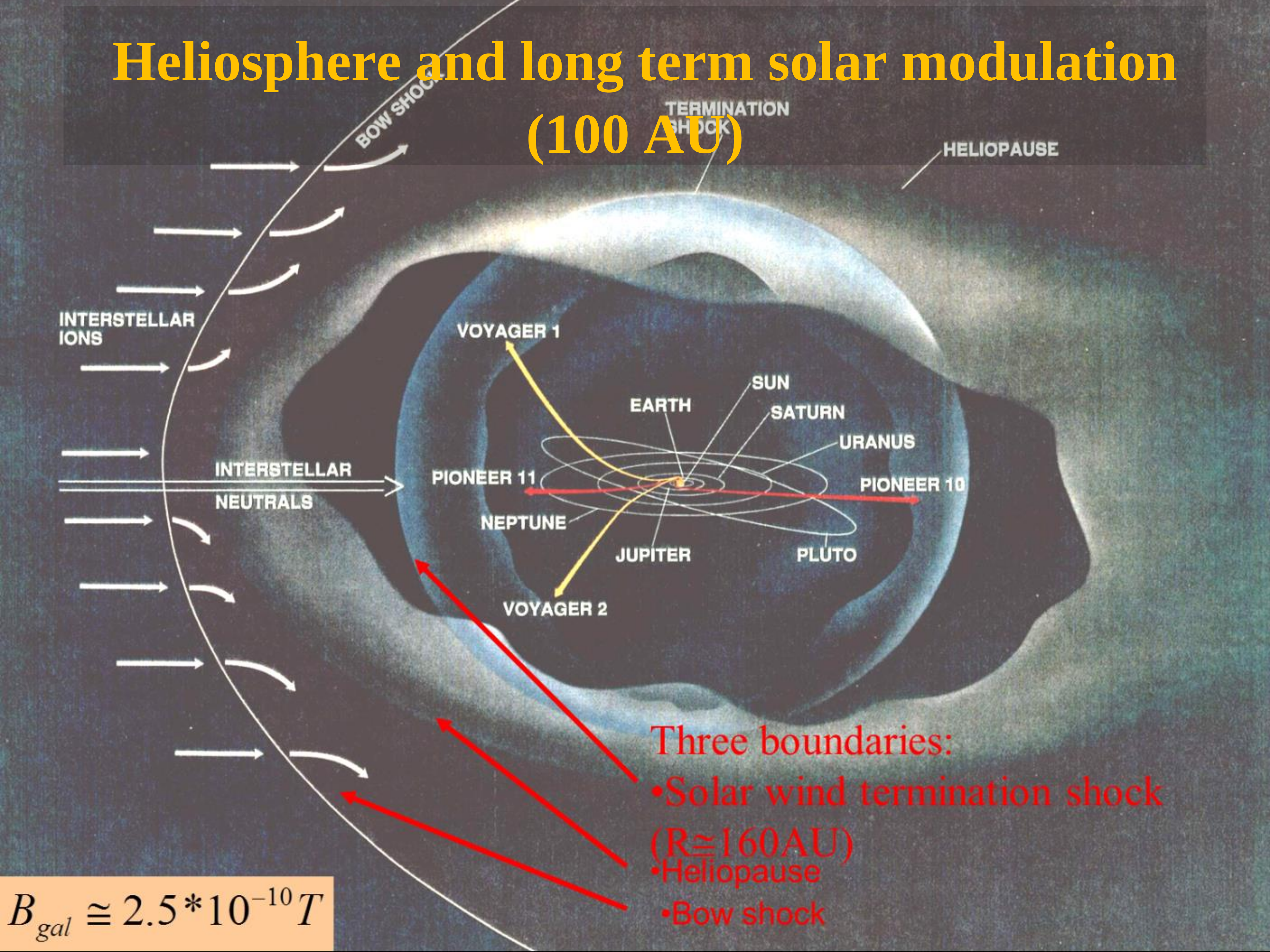
Astrophysical sources, SNR...







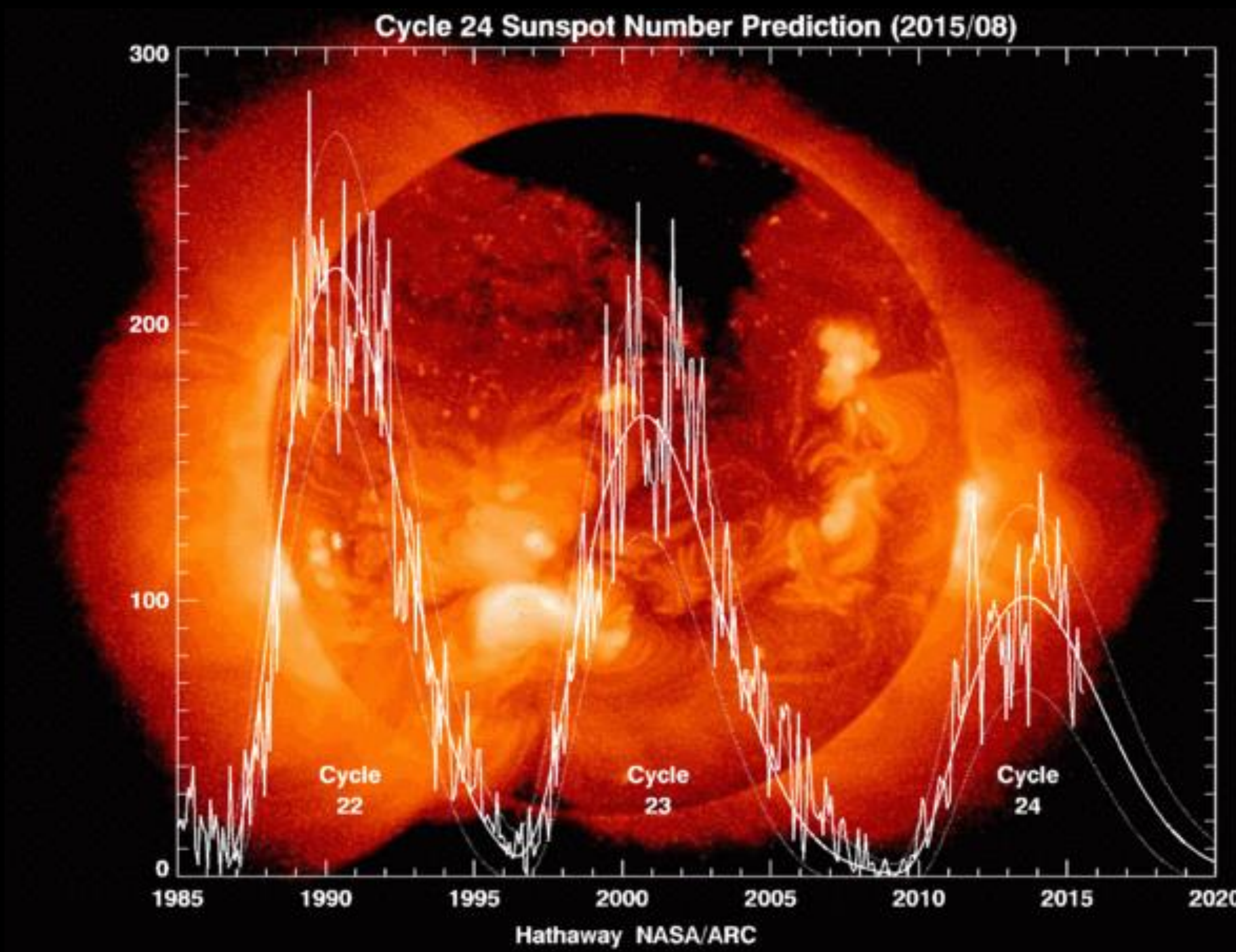
Heliosphere and long term solar modulation (100 AU)



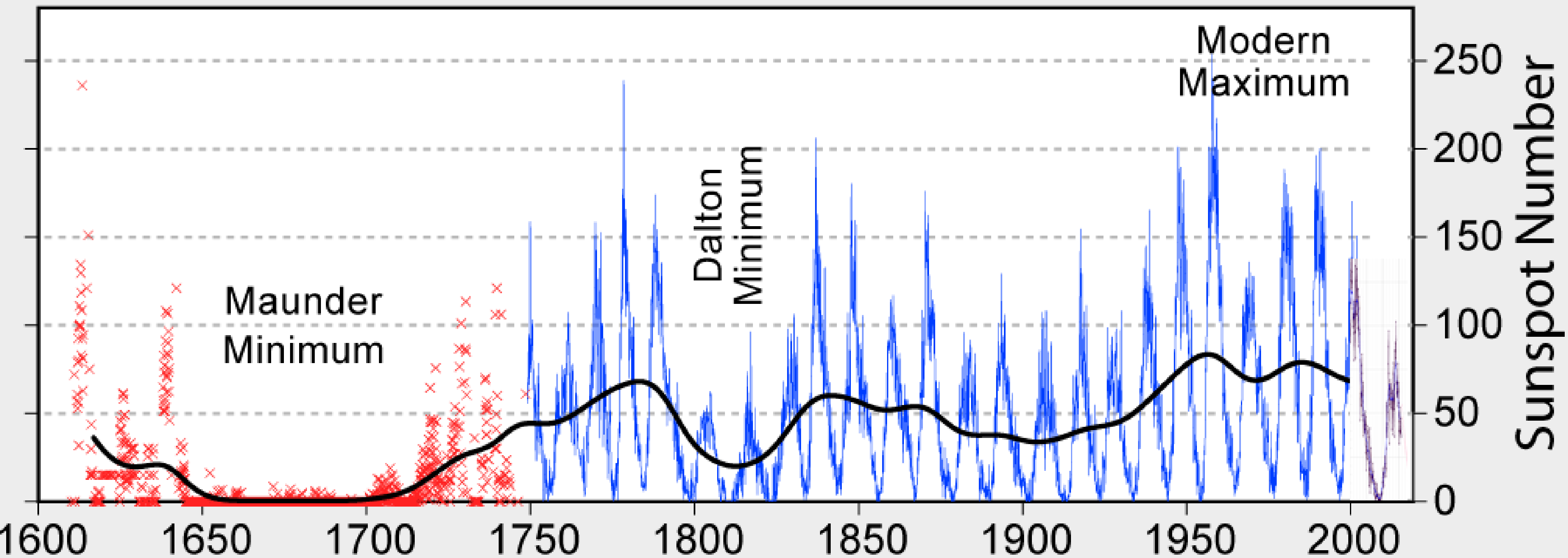
Three boundaries:

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

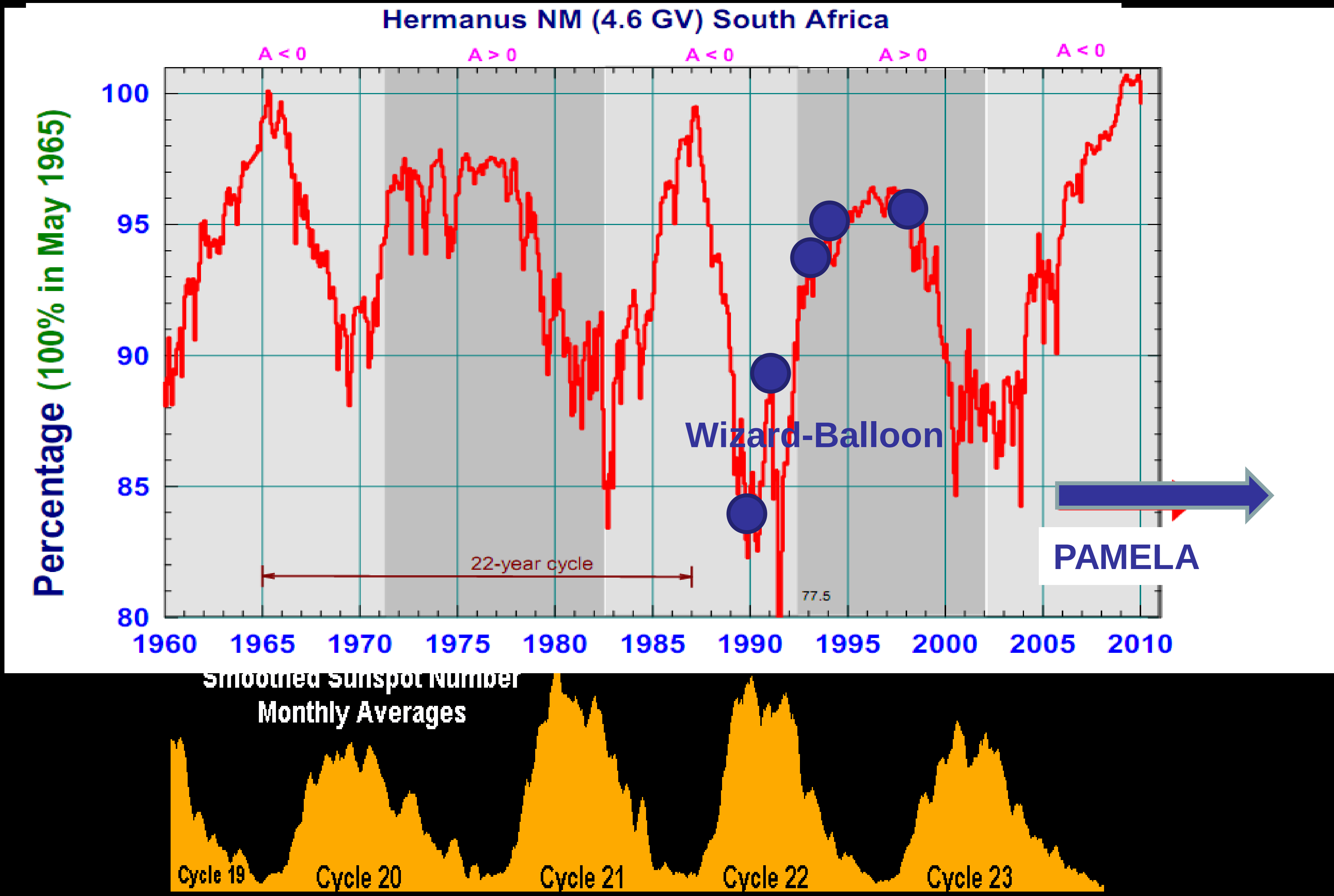
$$B_{gal} \cong 2.5*10^{-10} T$$


Cycle 24 Sunspot Number Prediction (2015/08)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway NASA/ARC

400 Years of Sunspot Observations



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

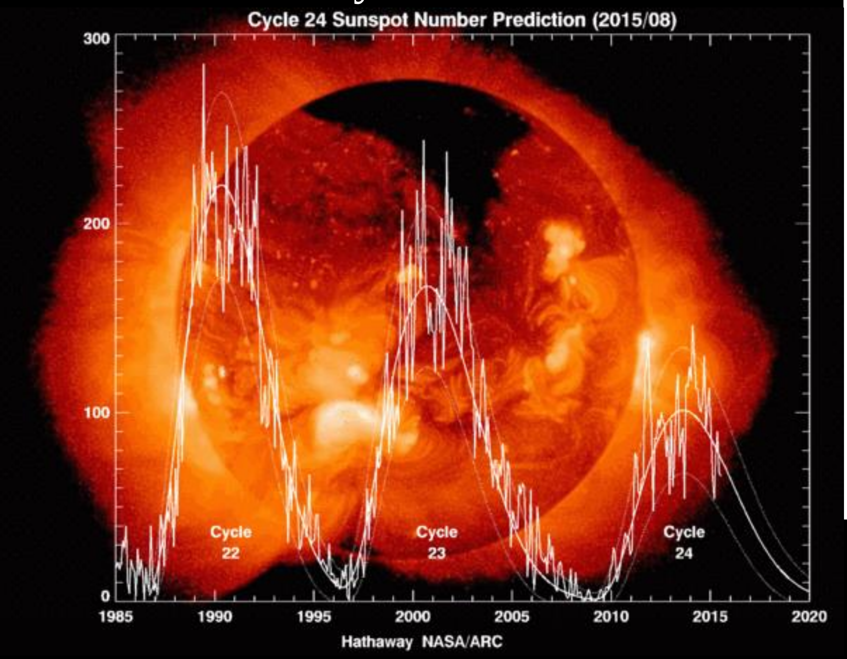


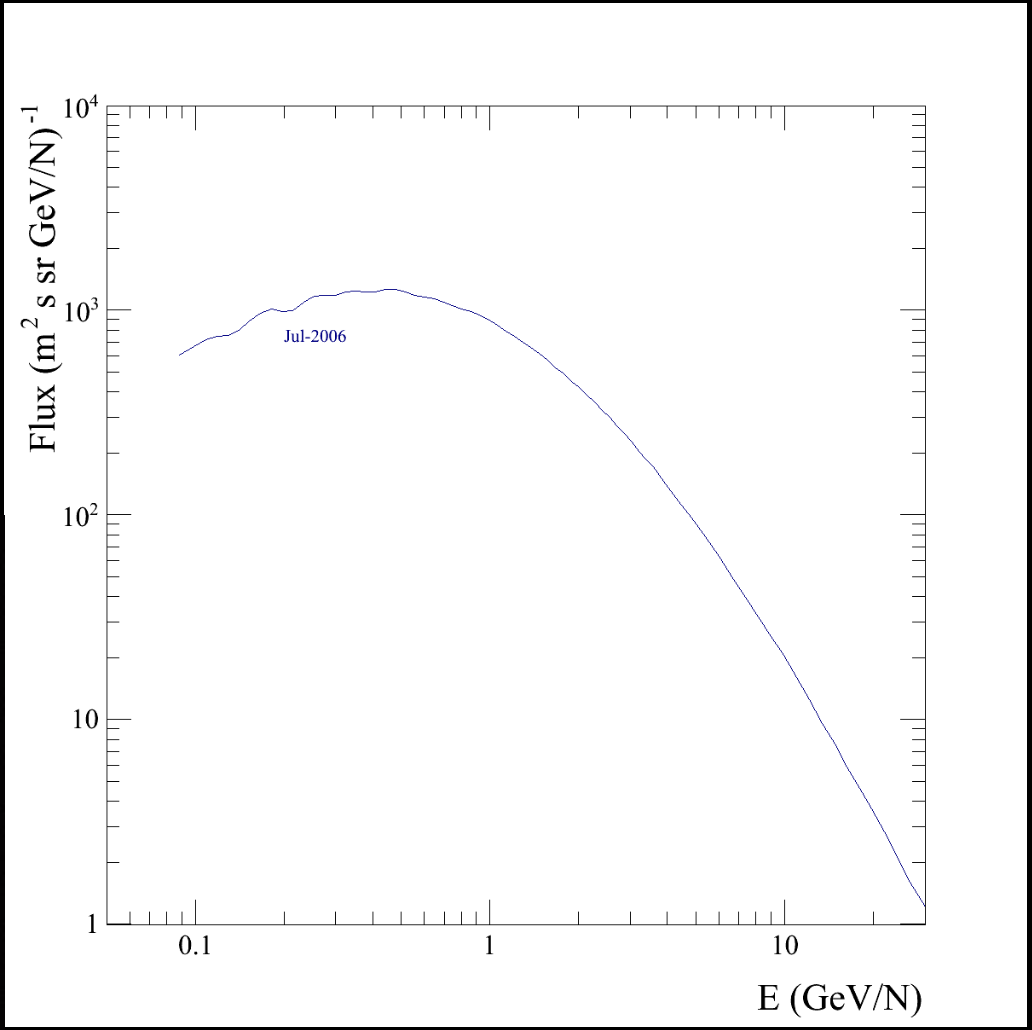
Solar modulation of protons and nuclei: monthly

Very long and peculiar solar minimum.

Current solar cycle (24) late and weak.

Closer to interstellar medium.
Good reference field for dosimetry





From V. Formato

Solar modulation of protons and nuclei: monthly

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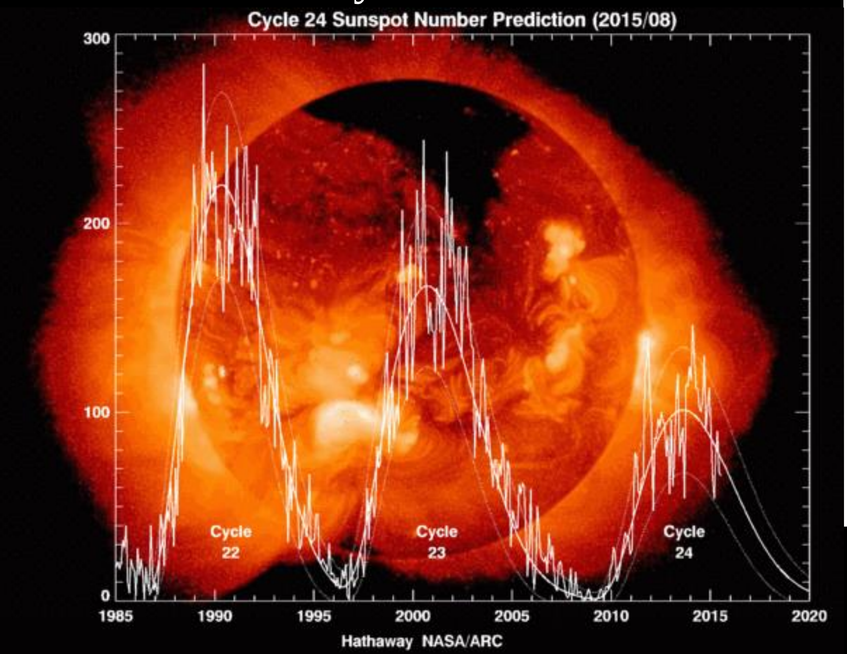
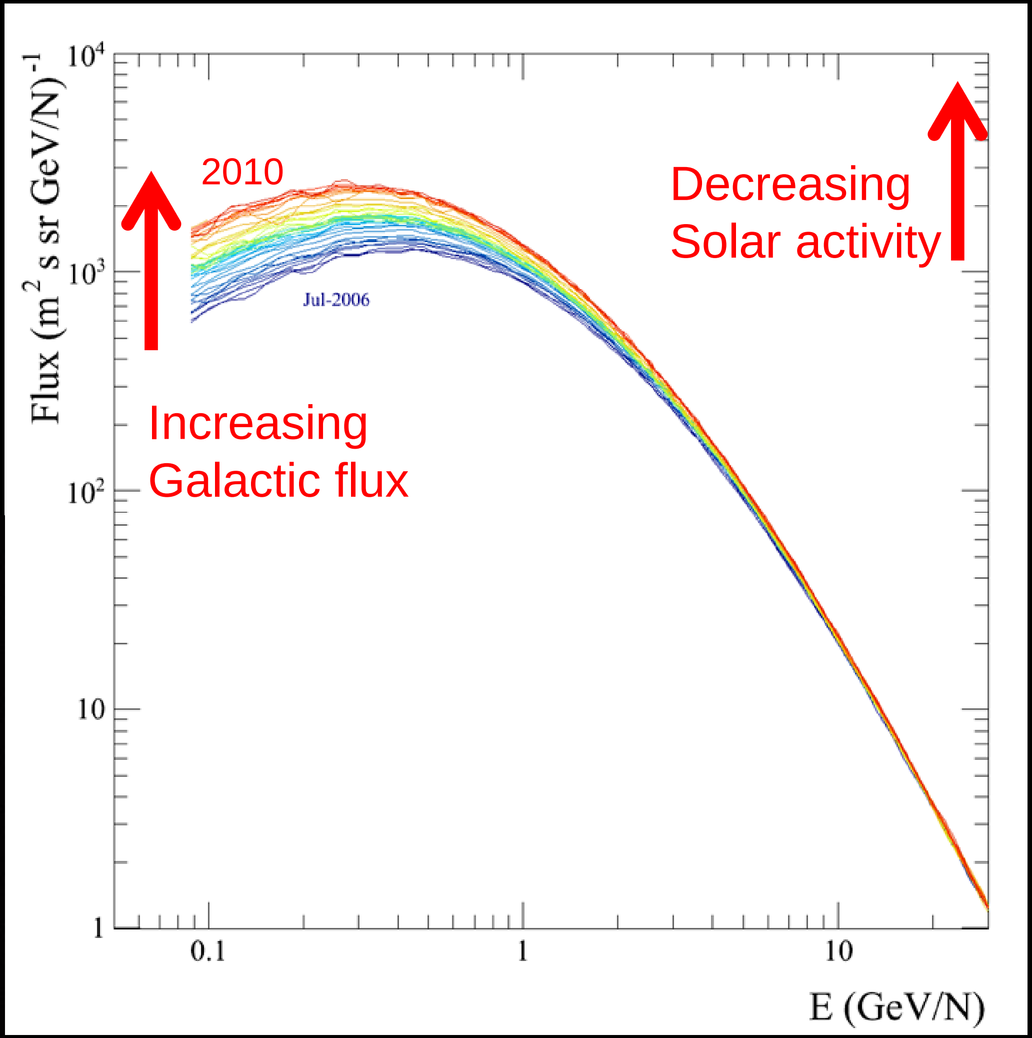
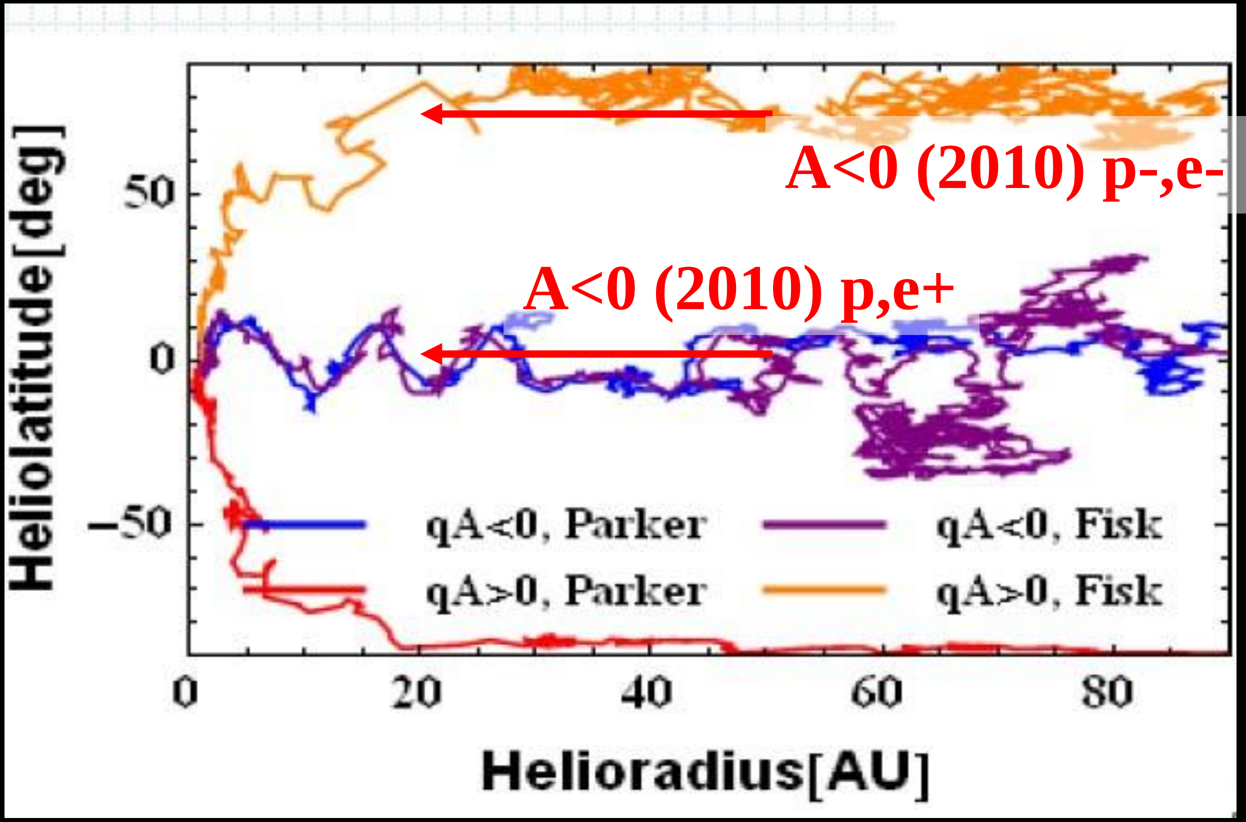


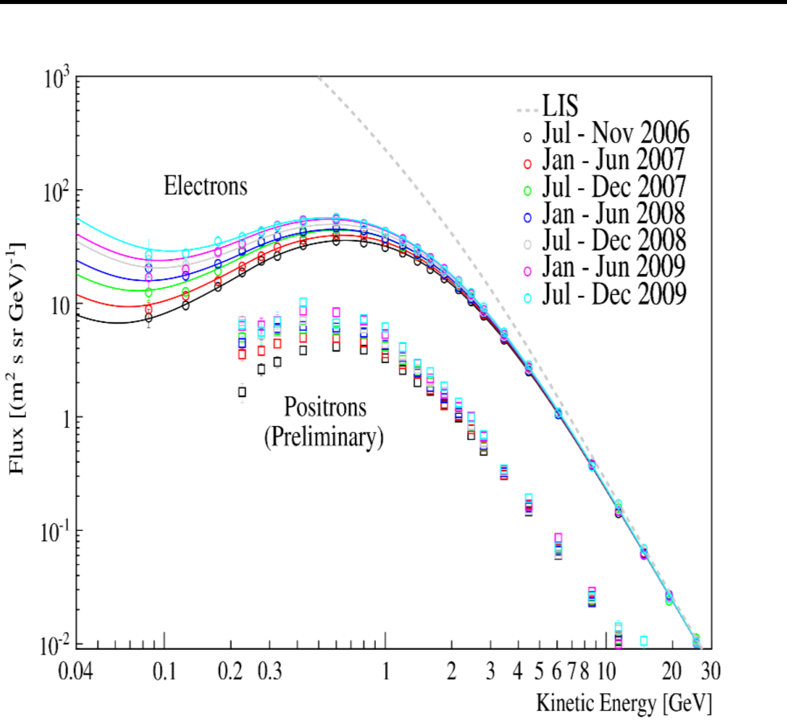


ApJ 765, 2, 91, (2013)

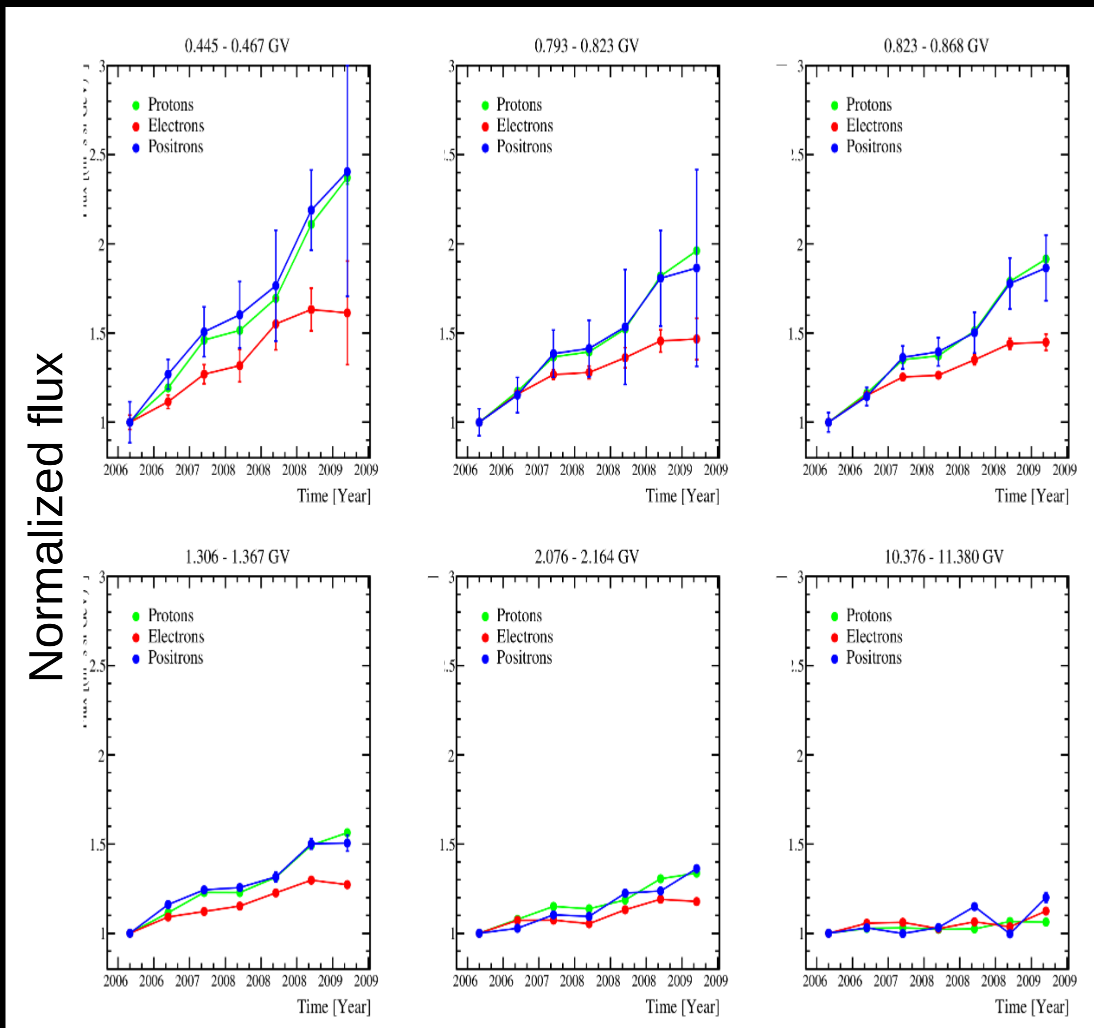
Charge dependent solar modulation of low energy positrons

- 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



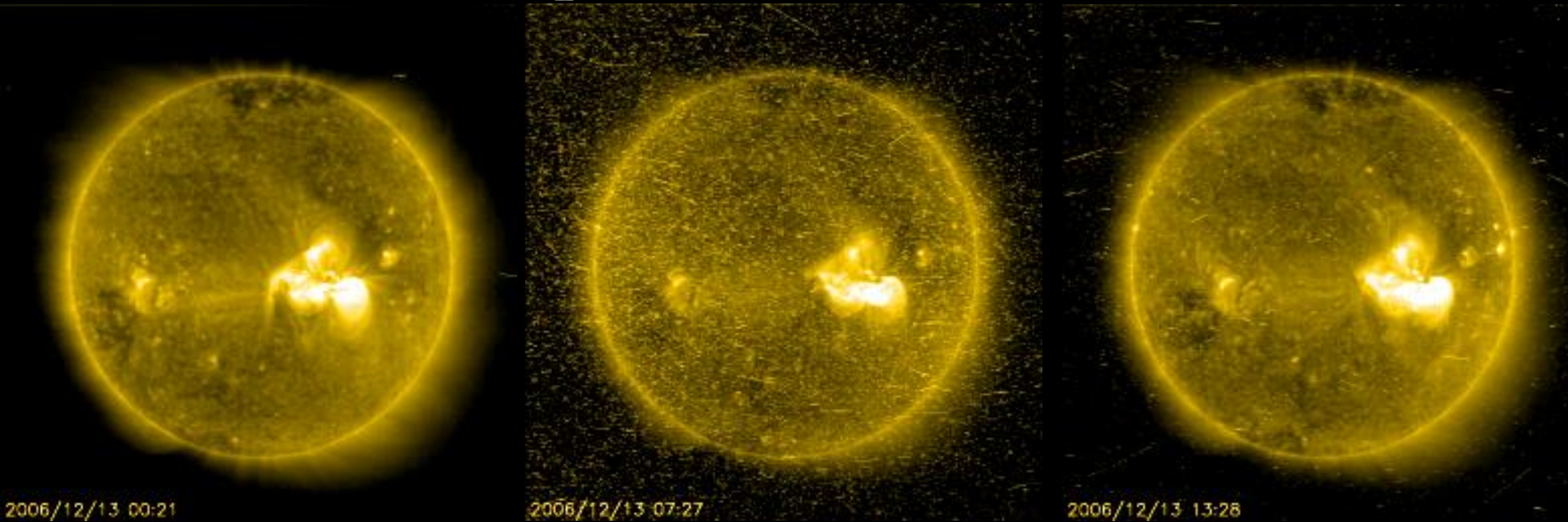


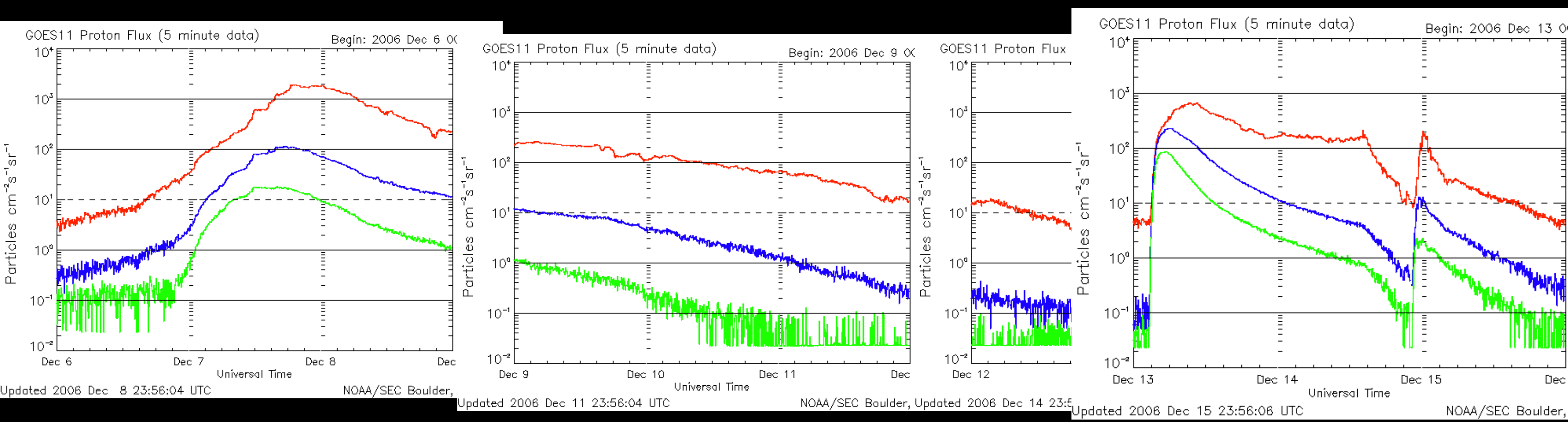
Charge dependent solar modulation: PAMELA electron and positron spectra over the last solar minimum



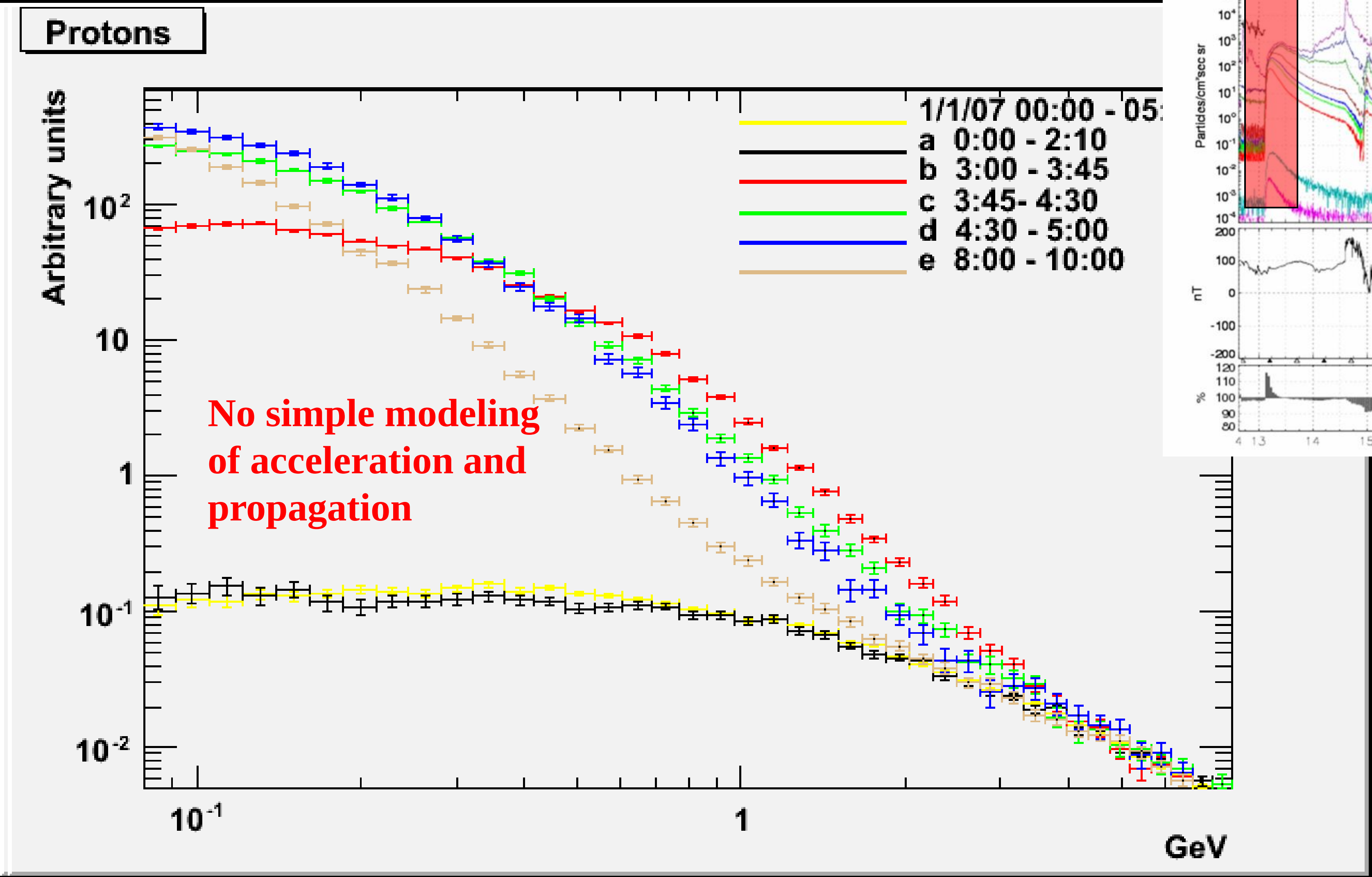
Variation of the e^-, e^+ and p flux
between Jul 2006 and December 2009

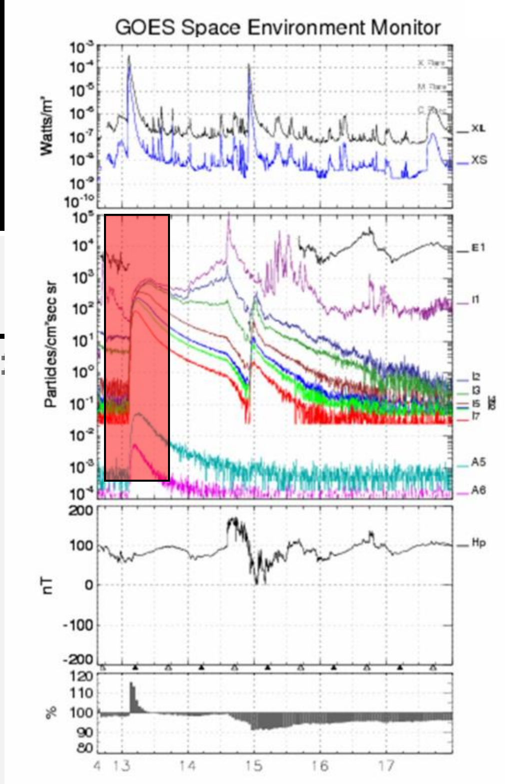
Solar particle events (1 AU)





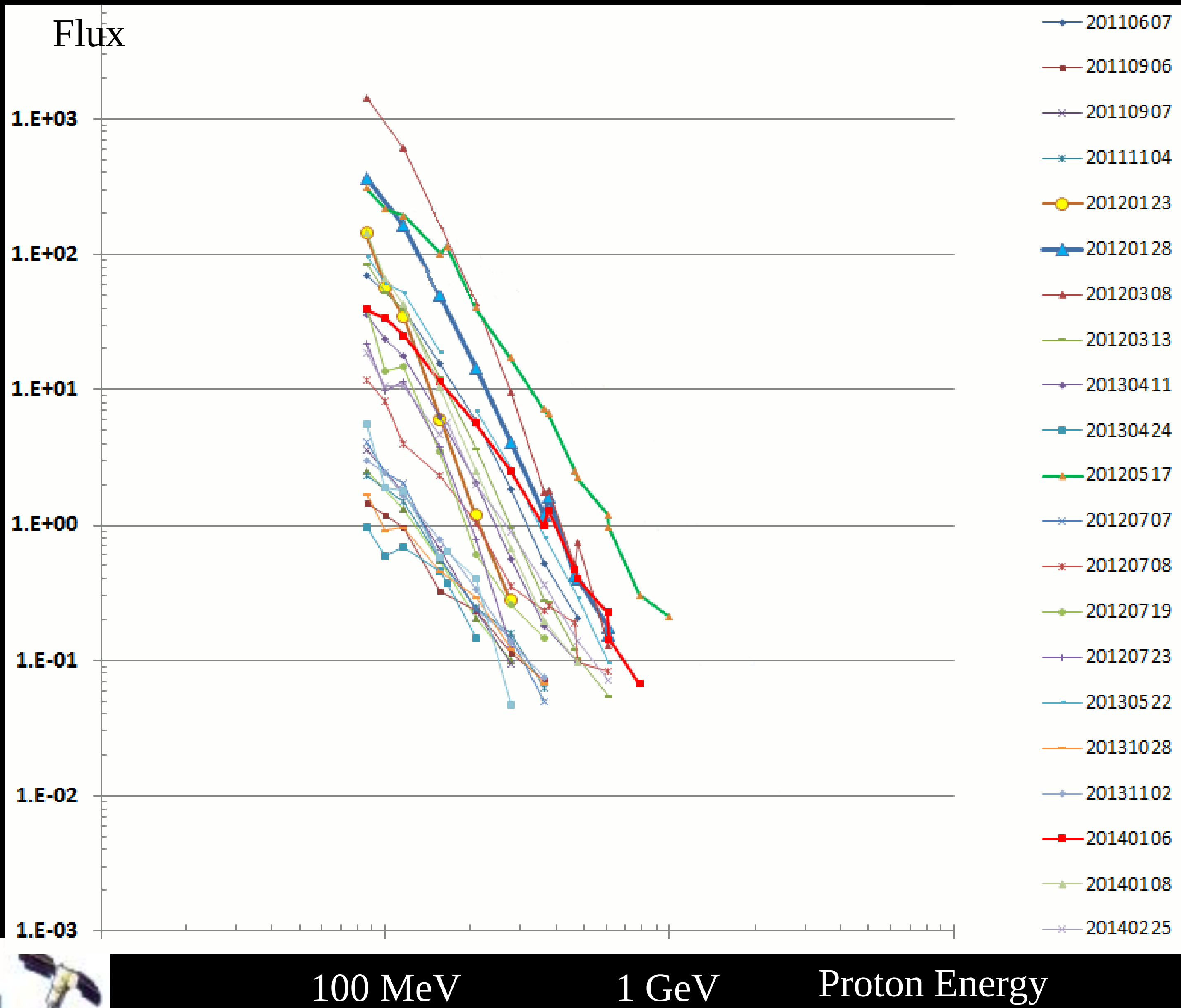
December 13th 2006 event





ApJ 742, 2, 102, 11, 2011.

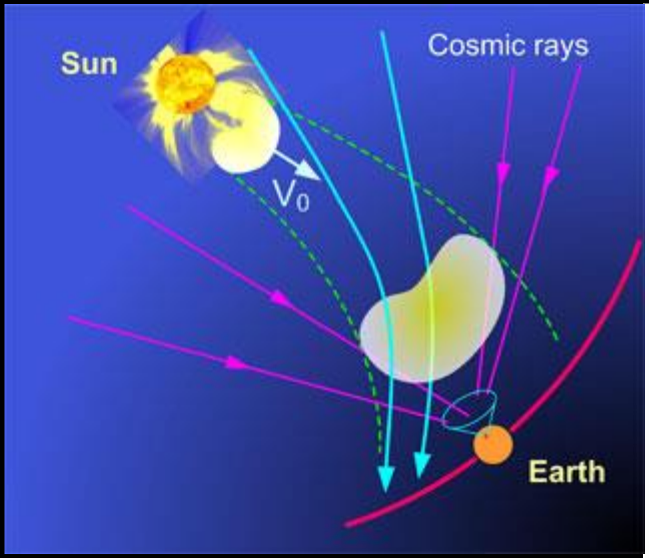
PAMELA SEP Spectra

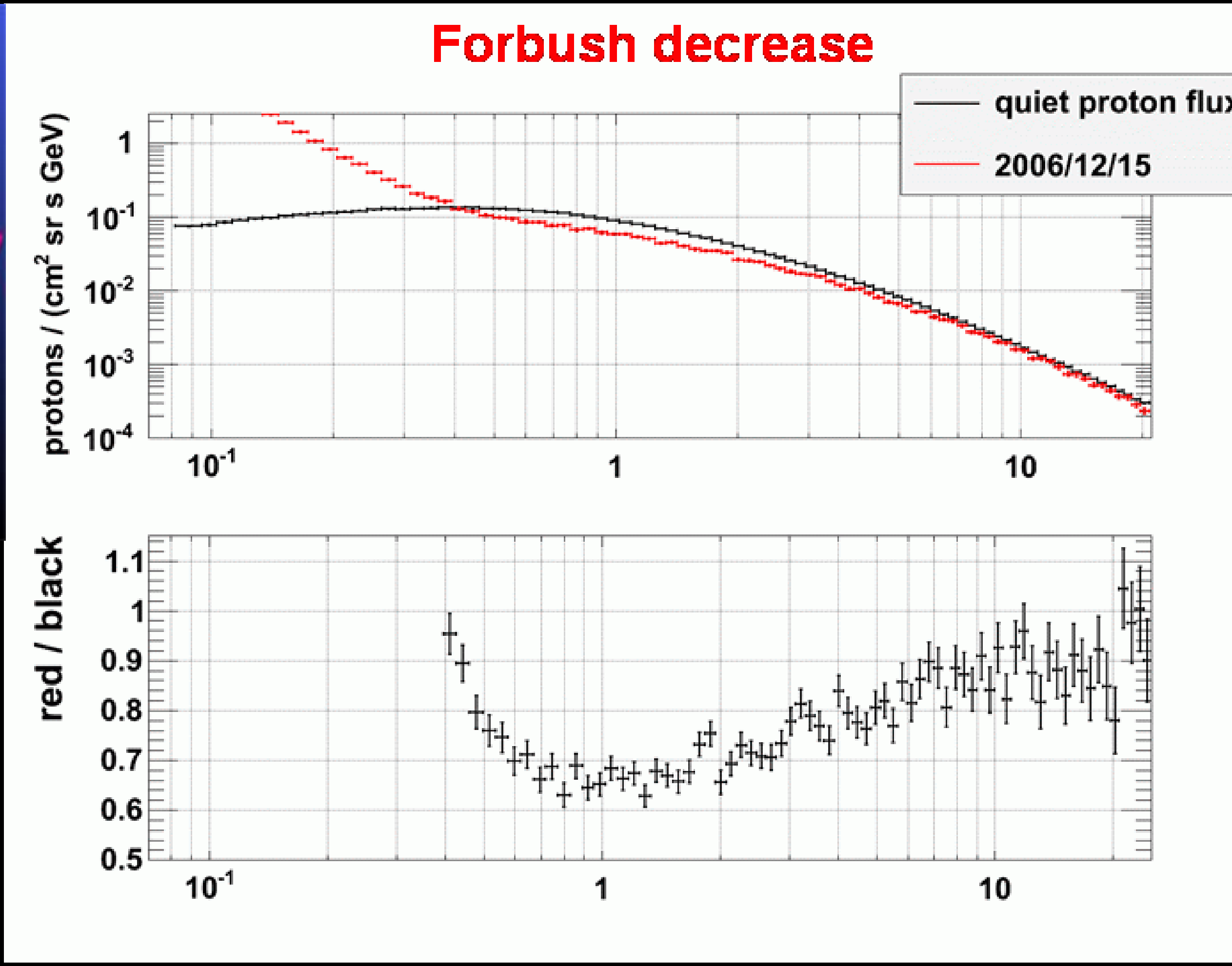


Completing the spectrum

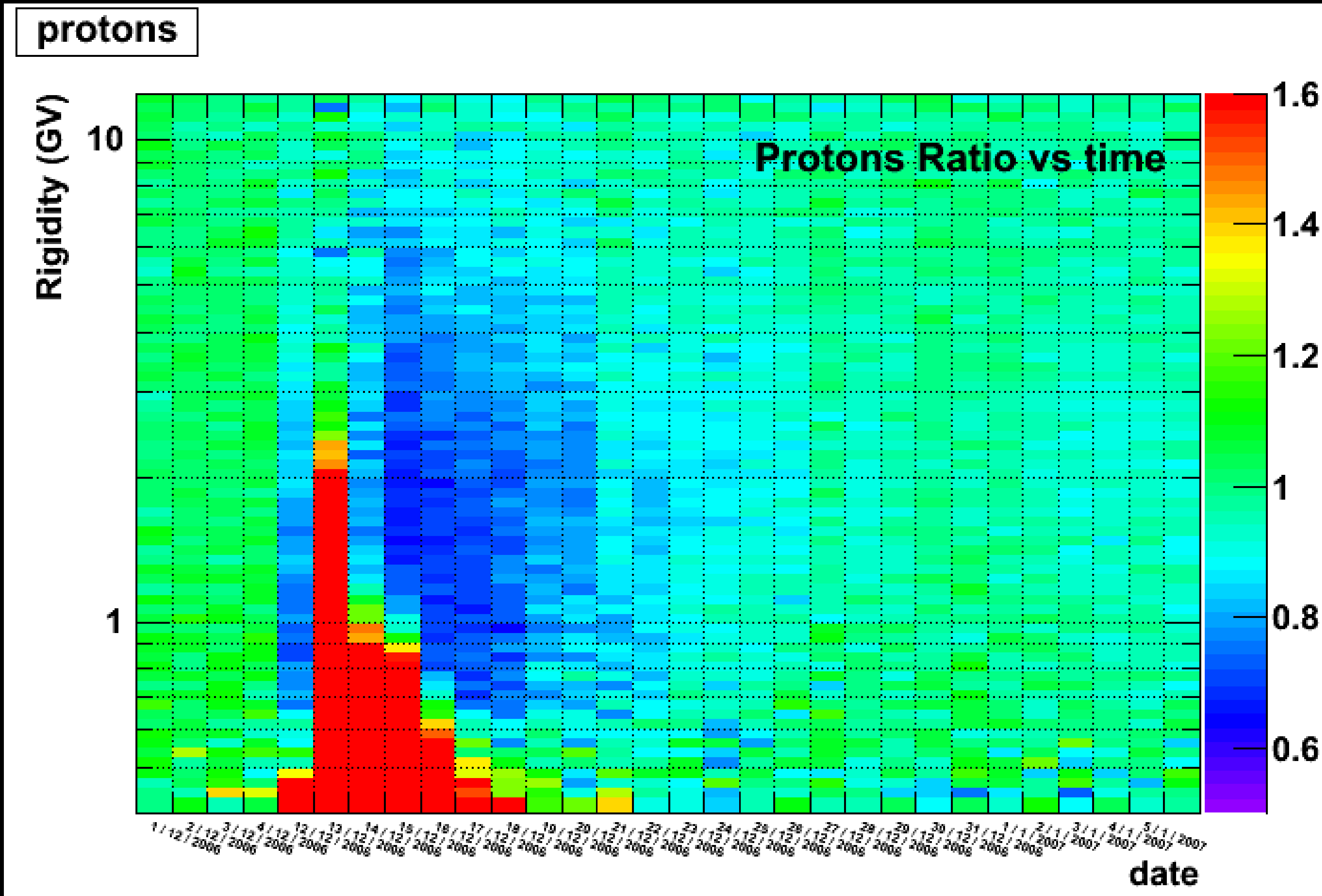
PAMELA bridges the gap between low energy space-based and ground--based measurements to obtain a complete spectrum

Forbush decrease



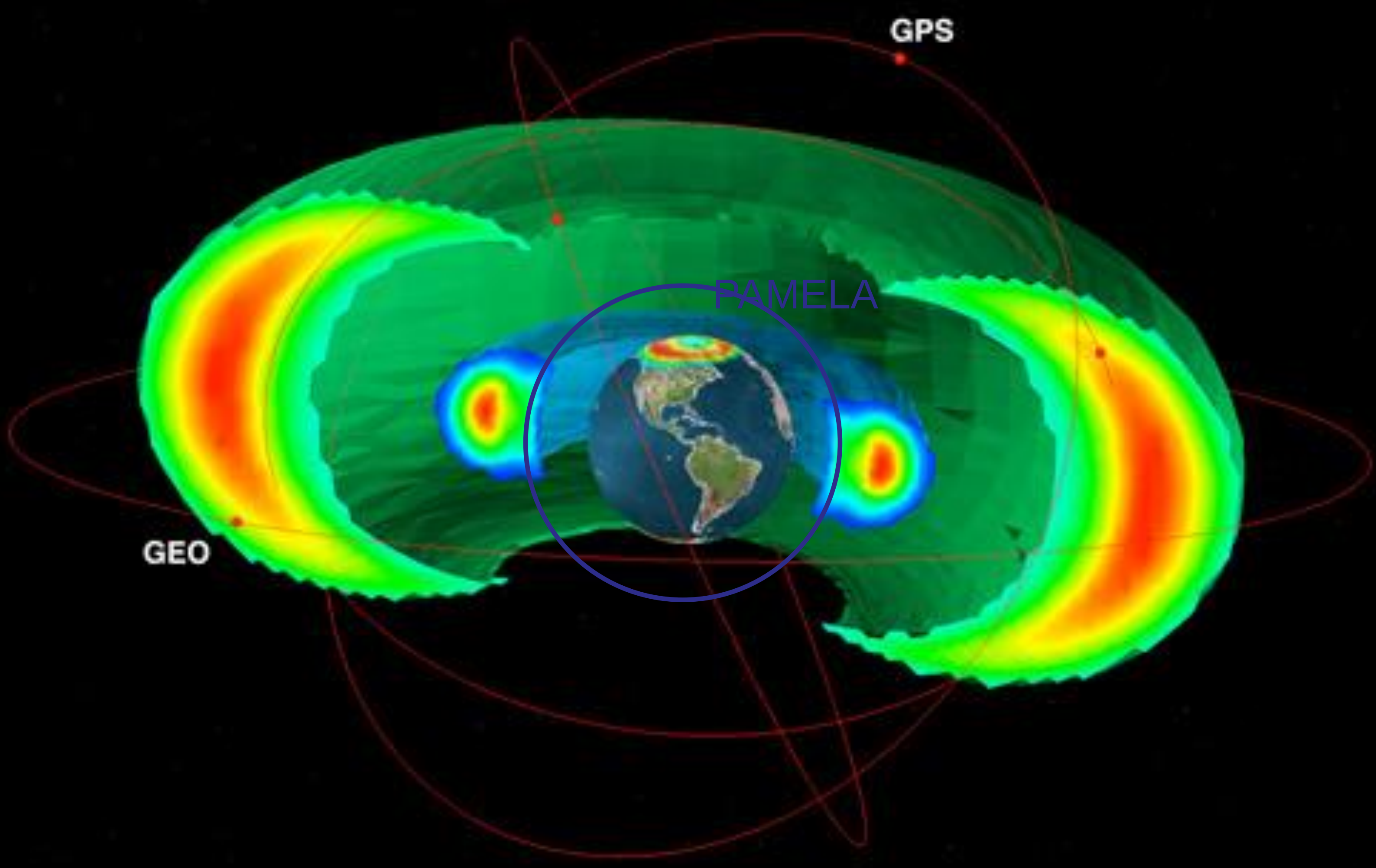


Time and rigidity dependence of Forbush decrease

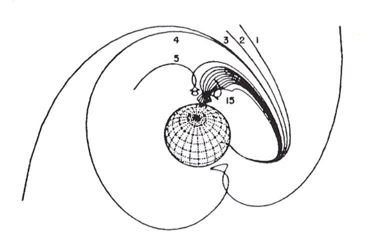


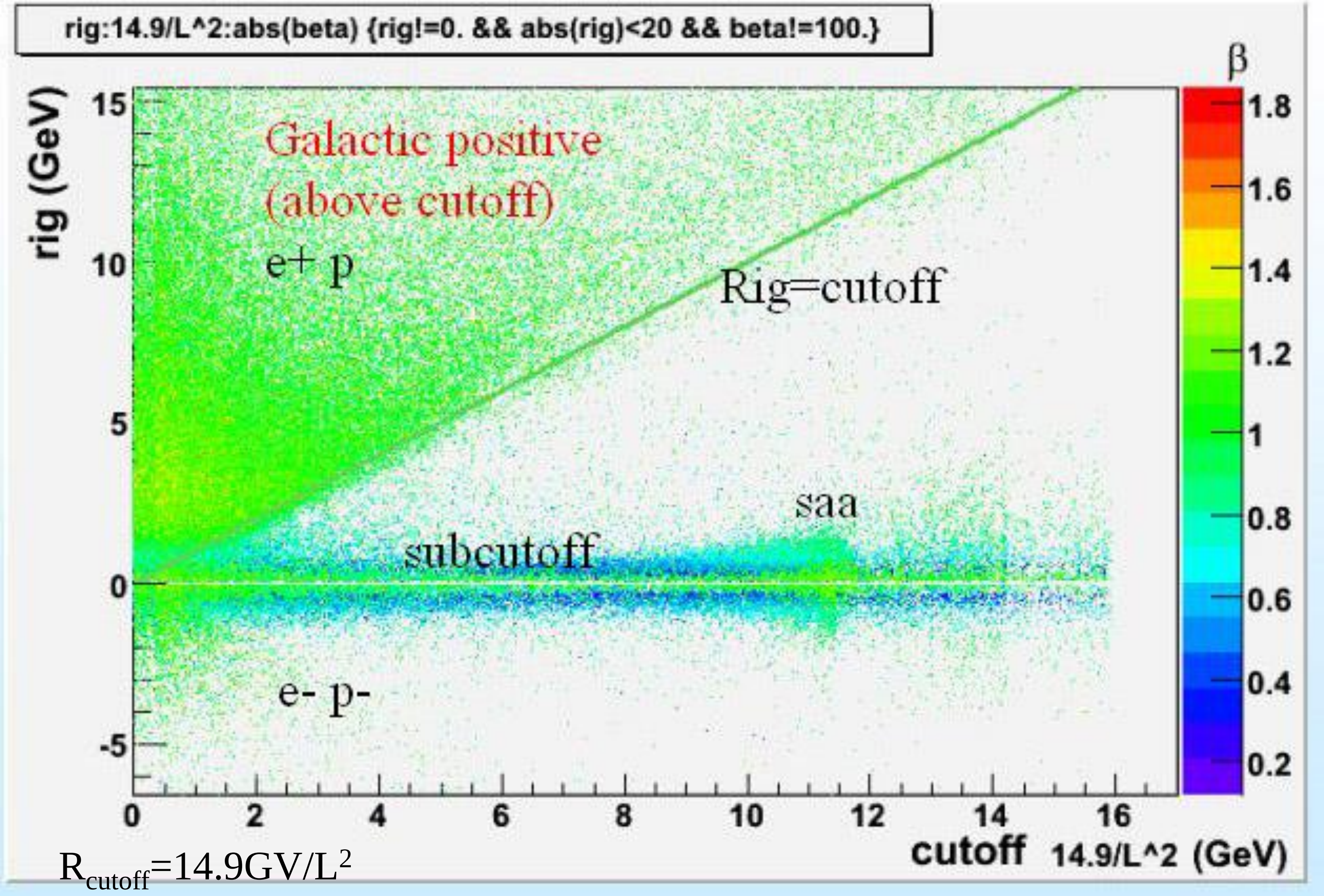
From Mergè Martucci Sotgiu

GEOMAGNETOSPHERE, VAN ALLEN BELTS



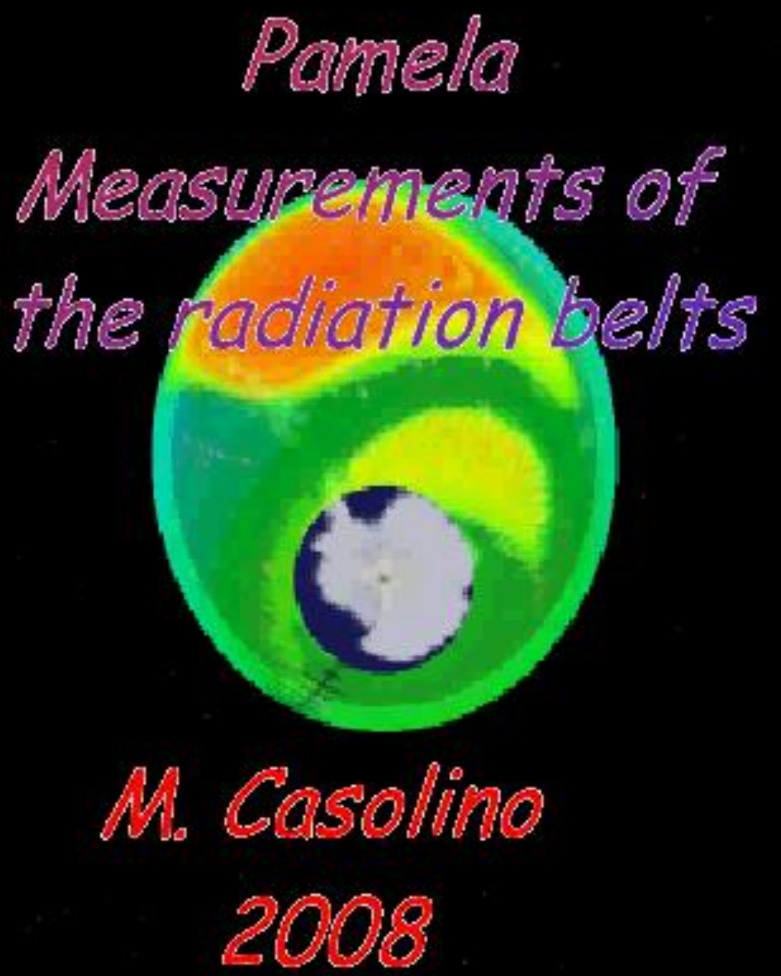
Selection of galactic component according to geomagnetic cutoff





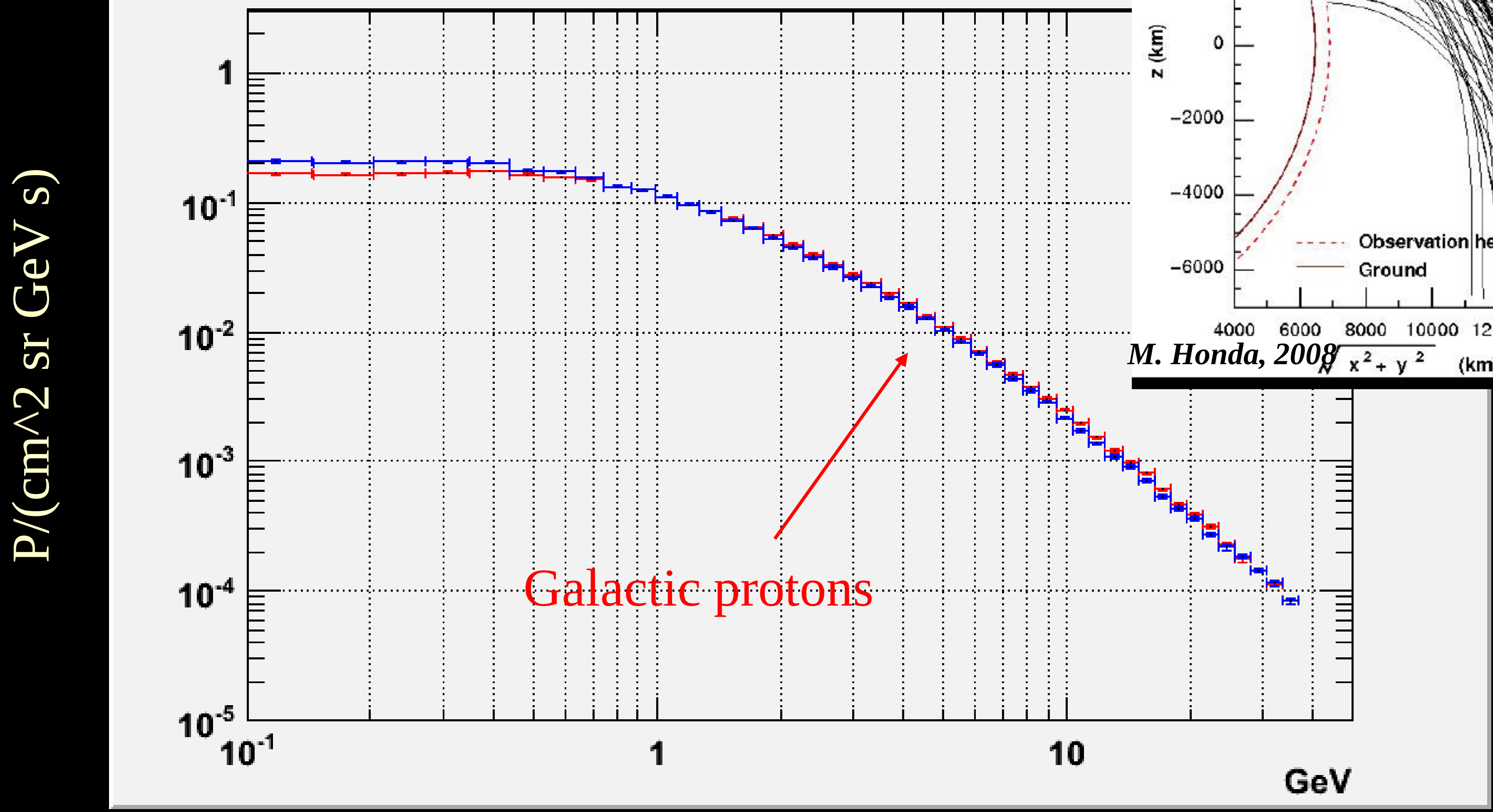
R_{cutoff}=14.9GV/L^2

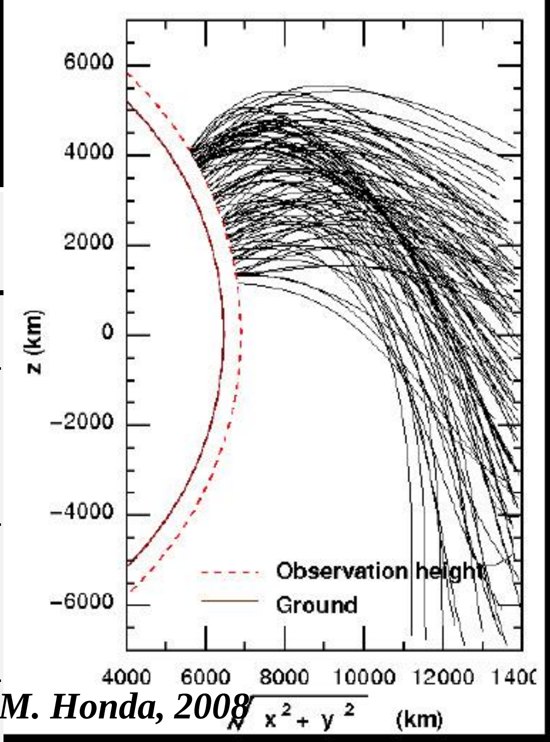
Geomagnetosphere, Van Allen Belts (1000 km)



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

Primary (galactic) spectra: polar measurements



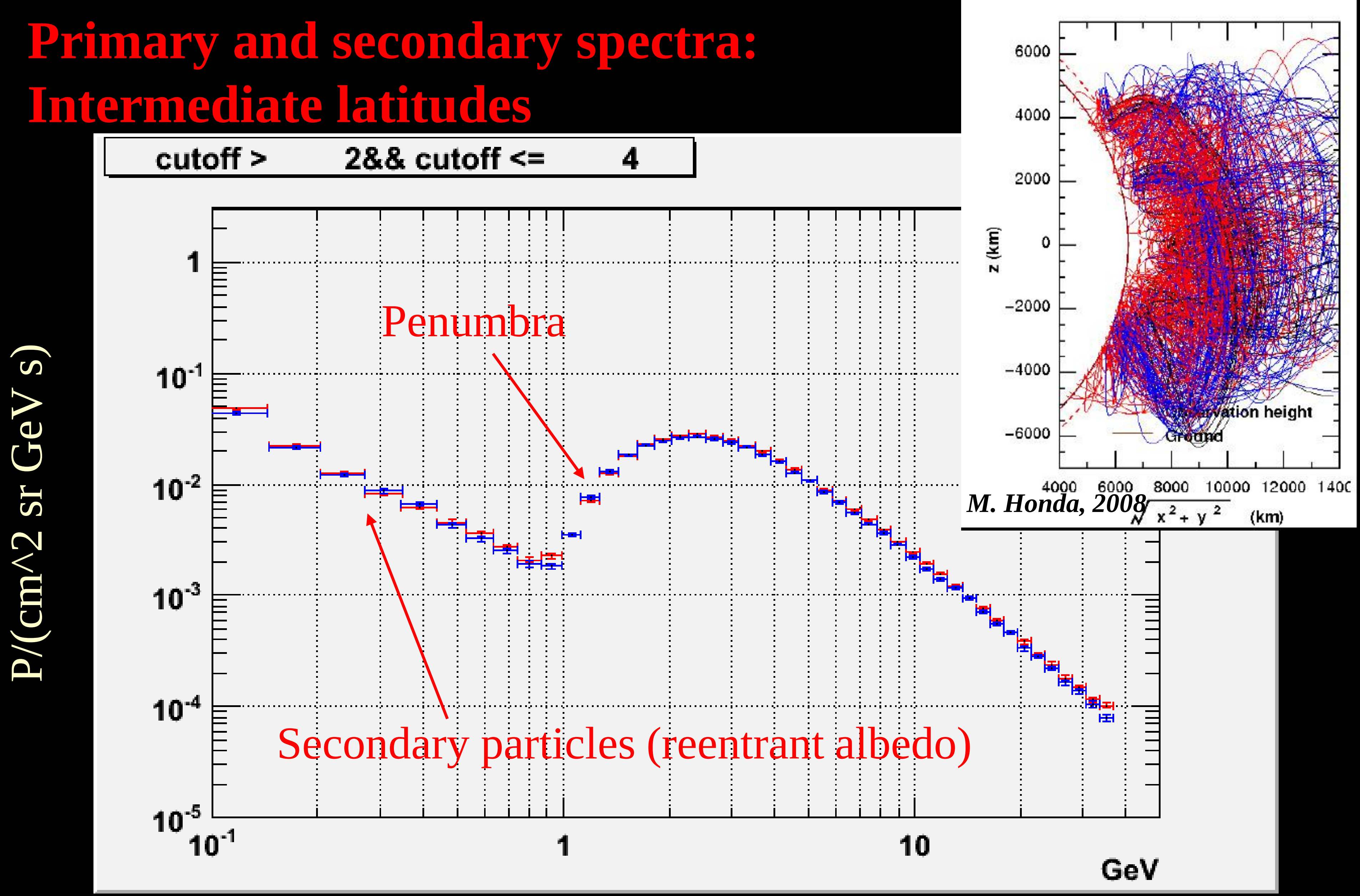


M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Intermediate latitudes



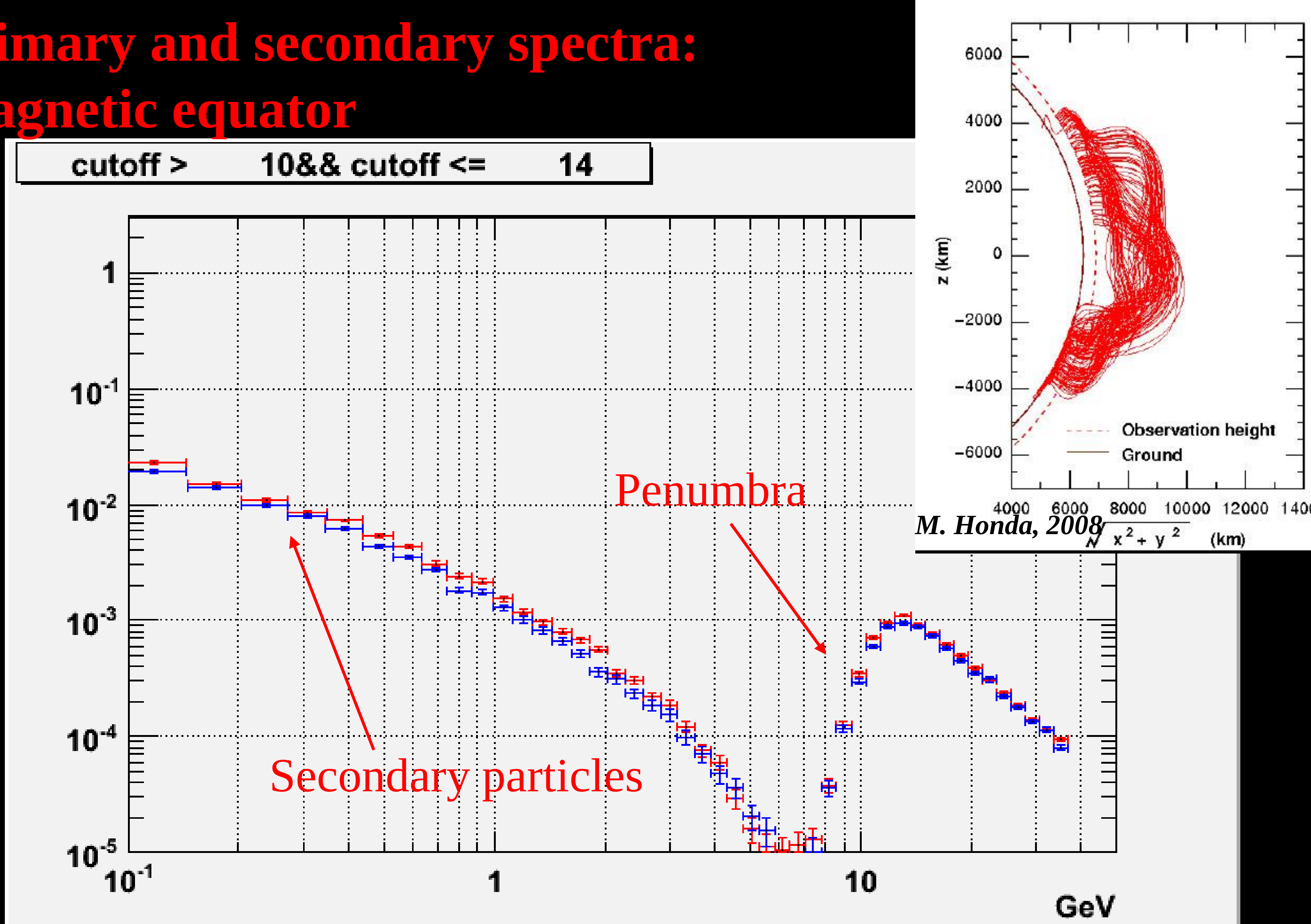
M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Magnetic equator

P/(cm^2 sr GeV s)



M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Proton Flux at various cutoff

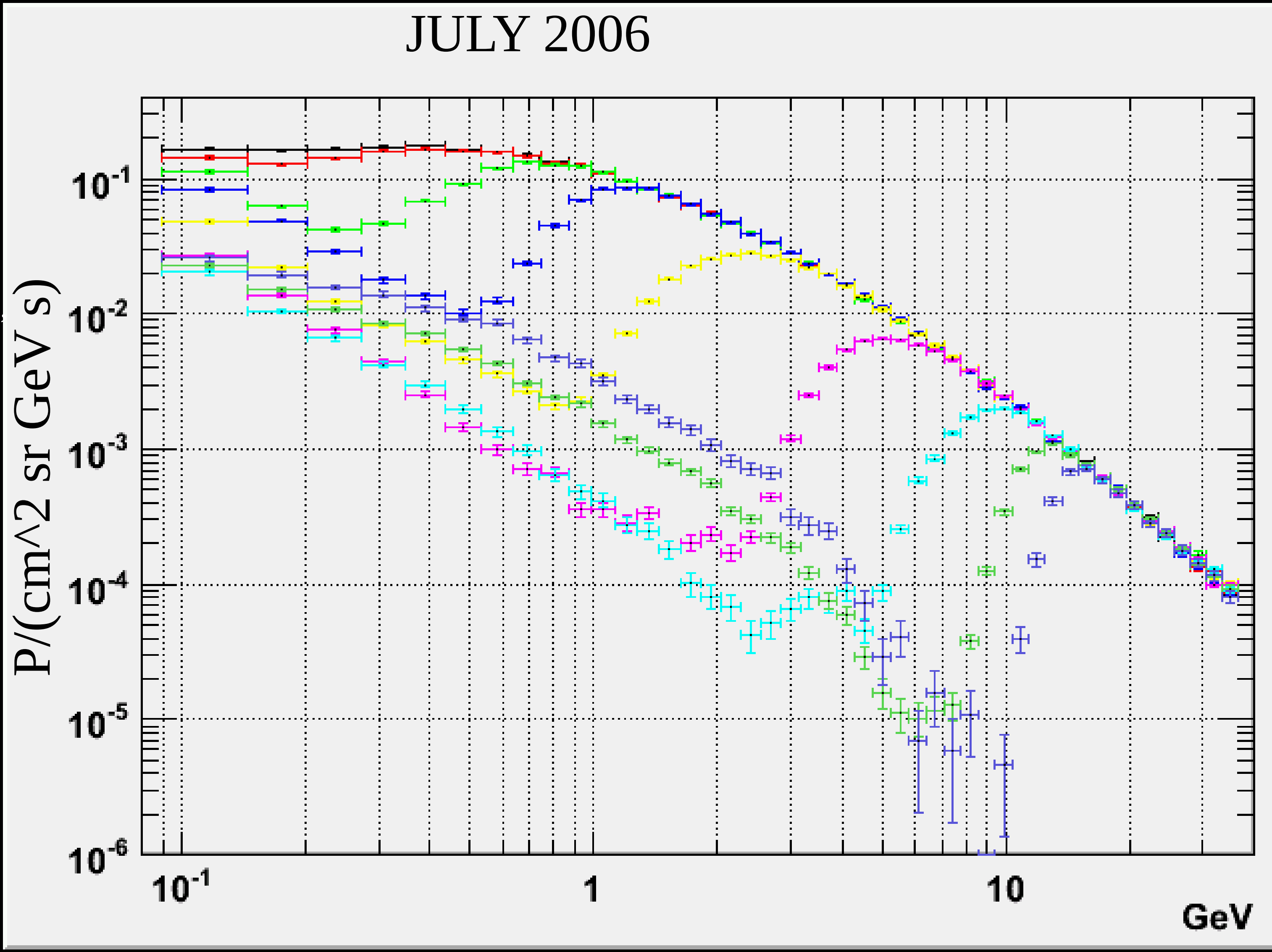
Subcutoff
(secondary albedo)
Particles

•P, e-,e+, P-

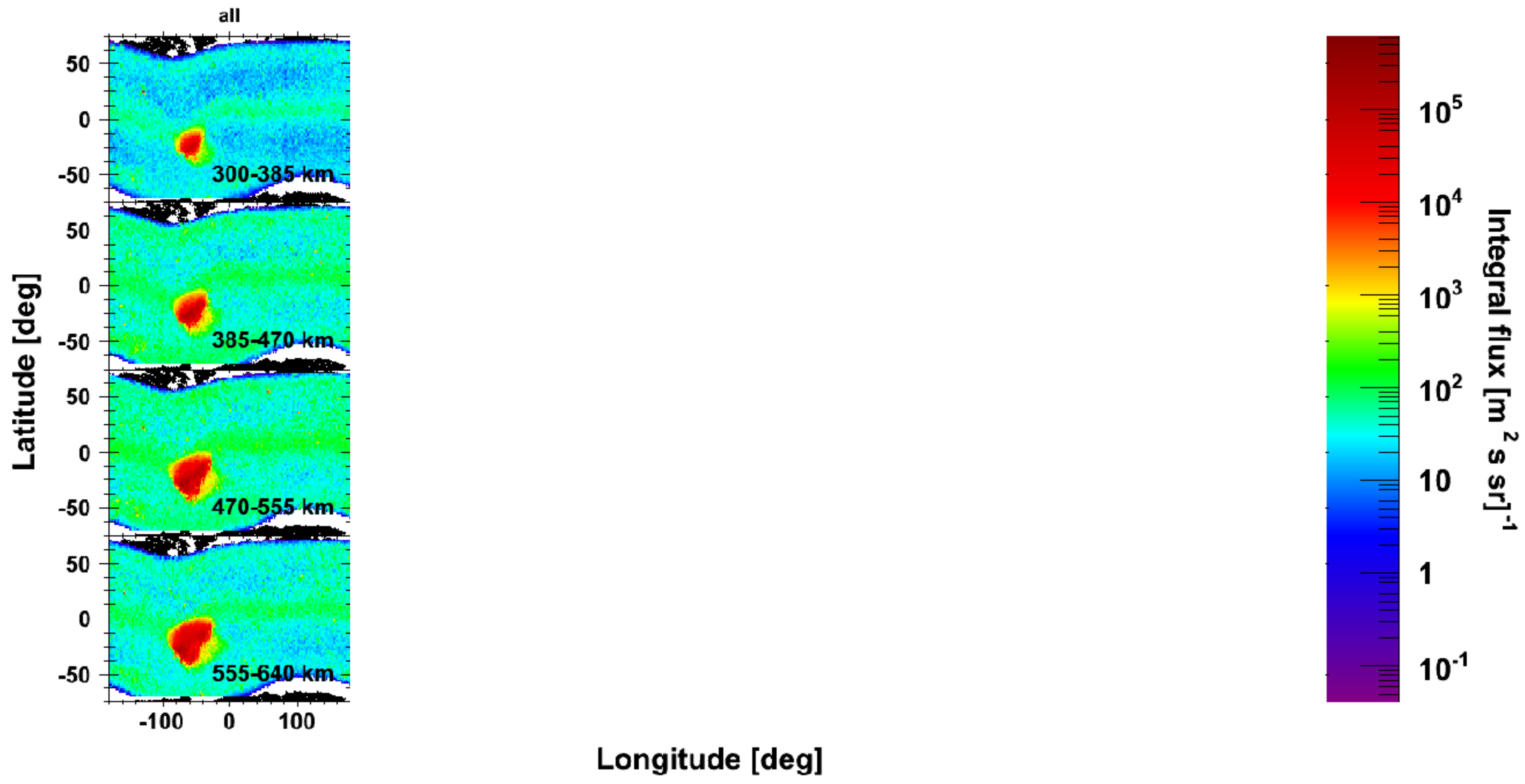
•Grigorov, Sov. Phys. Dokl. **22**, 305 1977
•NINA results:
  •ApJ Supp.132 365, 2001
•AMS results:
  Phys. Lett. B 472 2000.215,
  Phys. Lett. B 484 2000.10–22
•G. Esposito PhD

•+calculations

•Lipari, Astrop. Ph. 14, 171, 2000
•Huang et al, Pys Rev. D **68**, 053008 2003
•Sanuki et al, Phys Rev D75 043005 2007
•Honda et al, Phys Rev D75 043006 2007

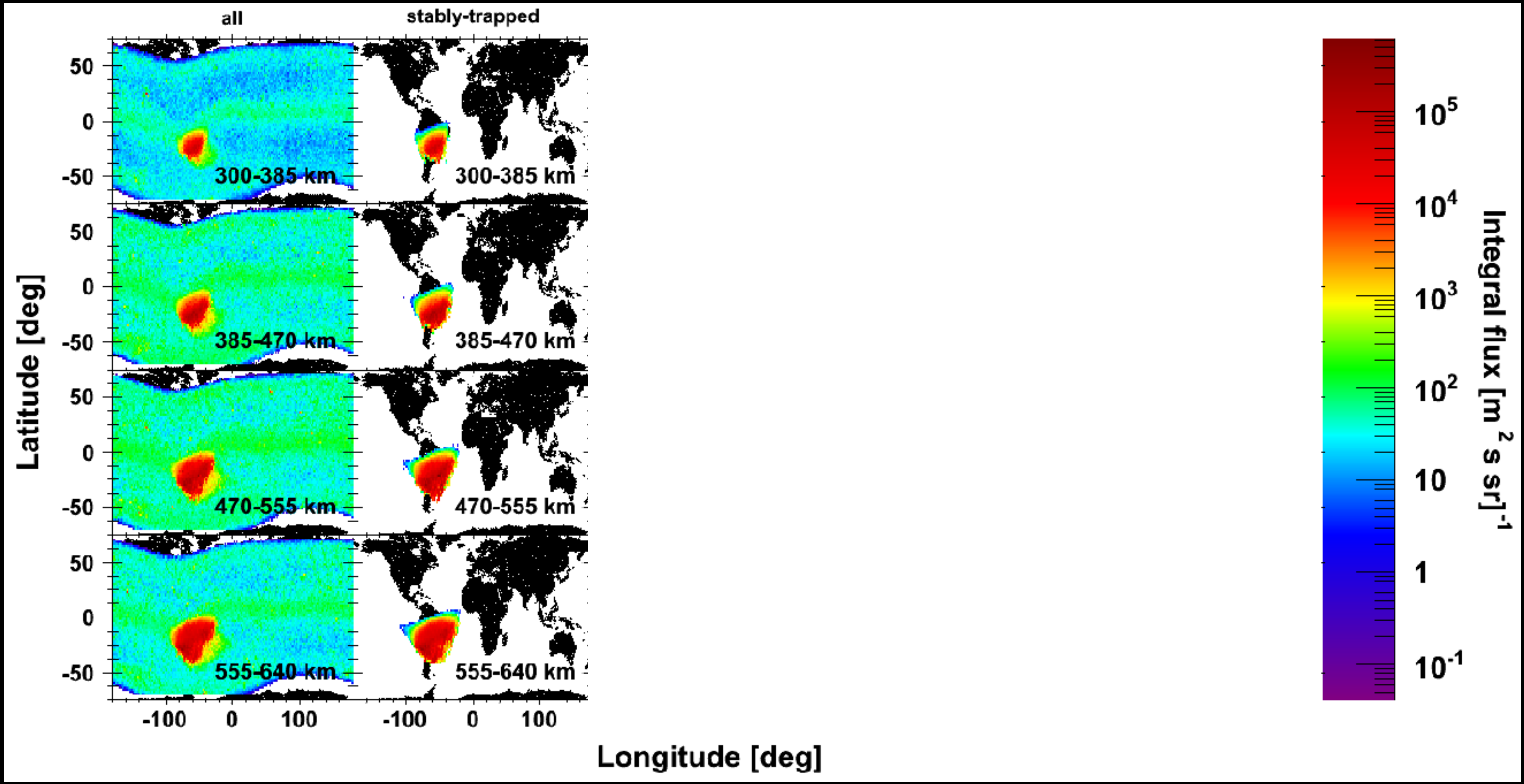


Integral fluxes at different GC altitudes, averaged over the explored pitch angle range



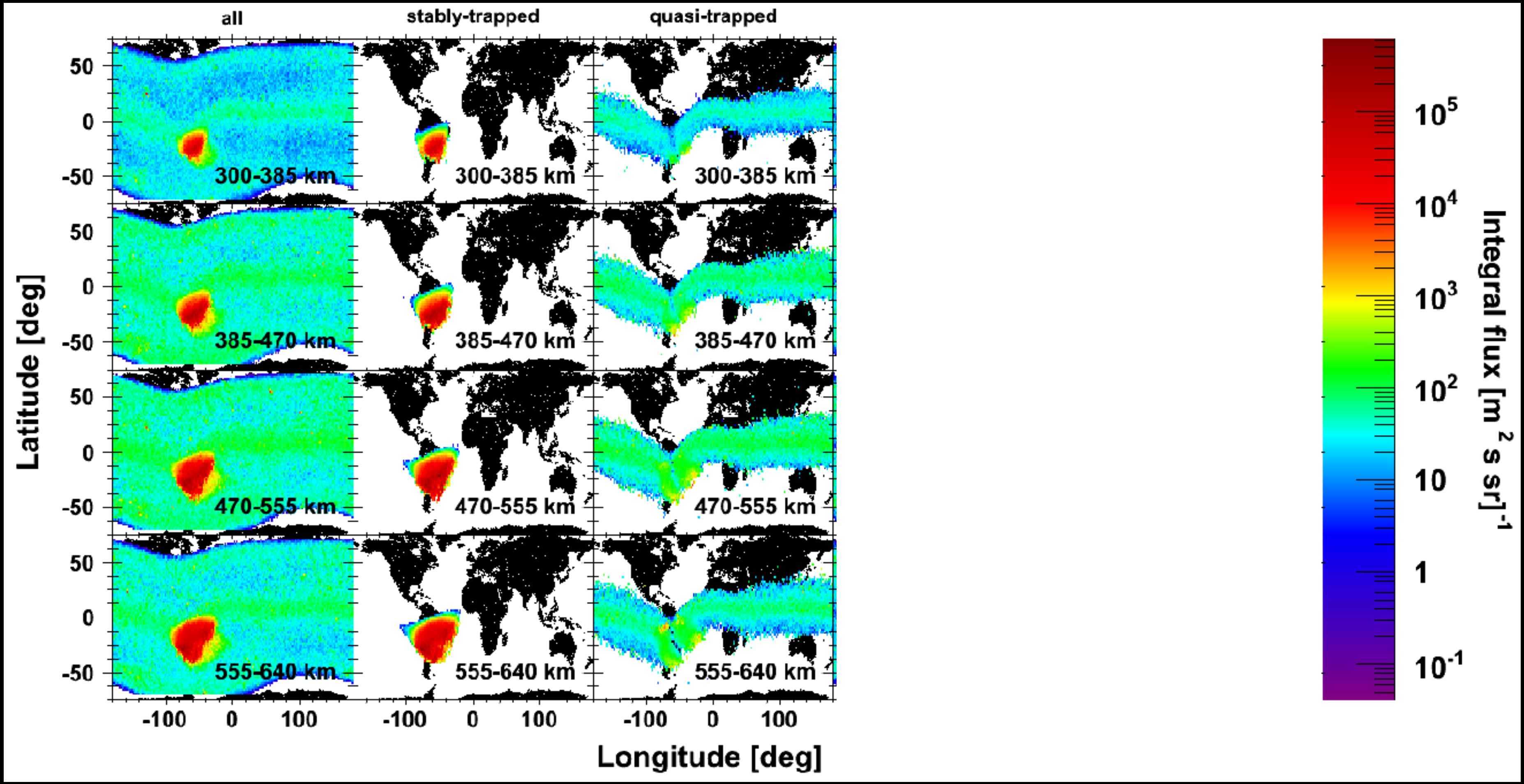
arXiv:1412.1765 , ASR 2016

Integral fluxes at different GC altitudes, averaged over the explored pitch angle range



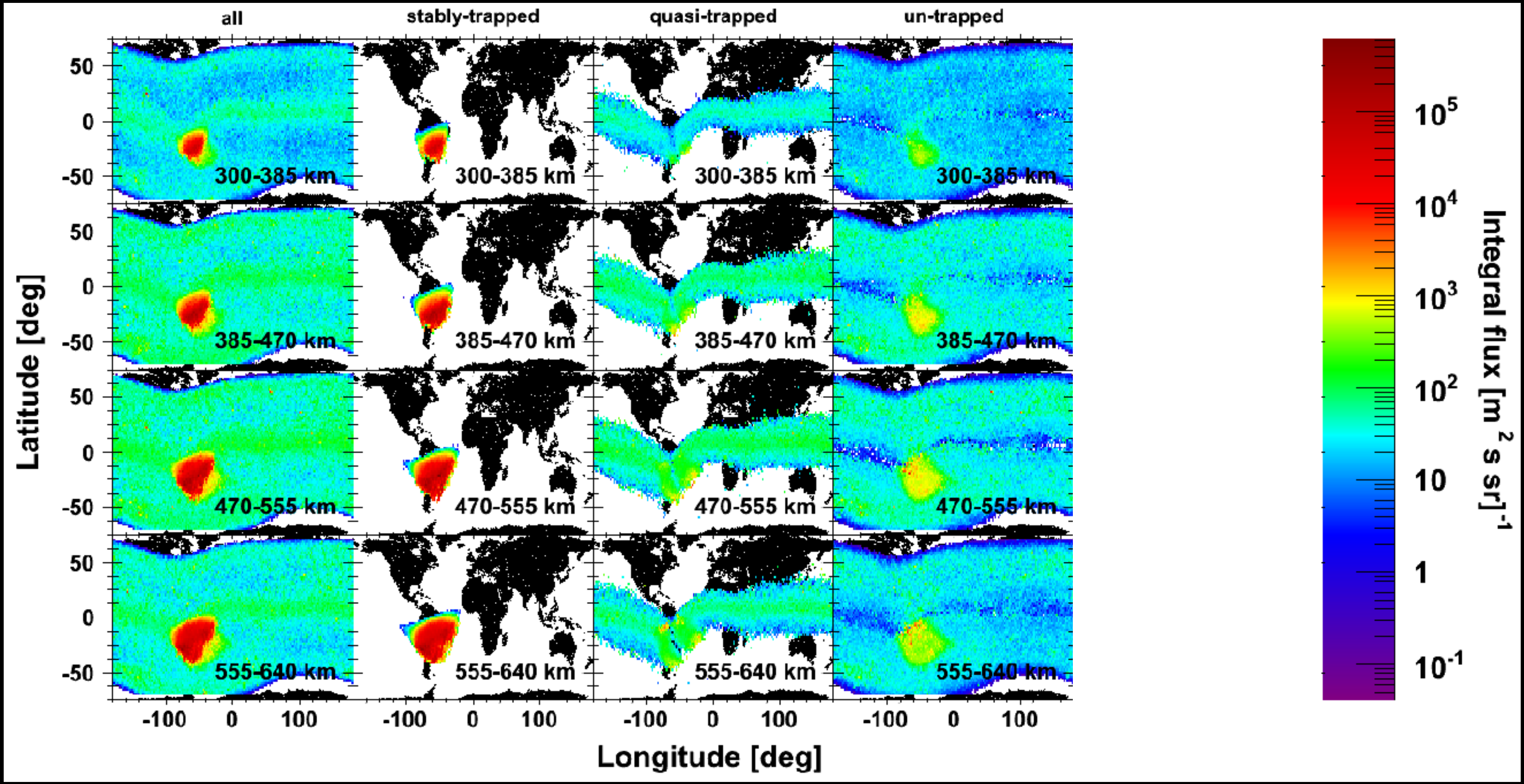
arXiv:1412.1765 , ASR 2016

Integral fluxes at different GC altitudes, averaged over the explored pitch angle range



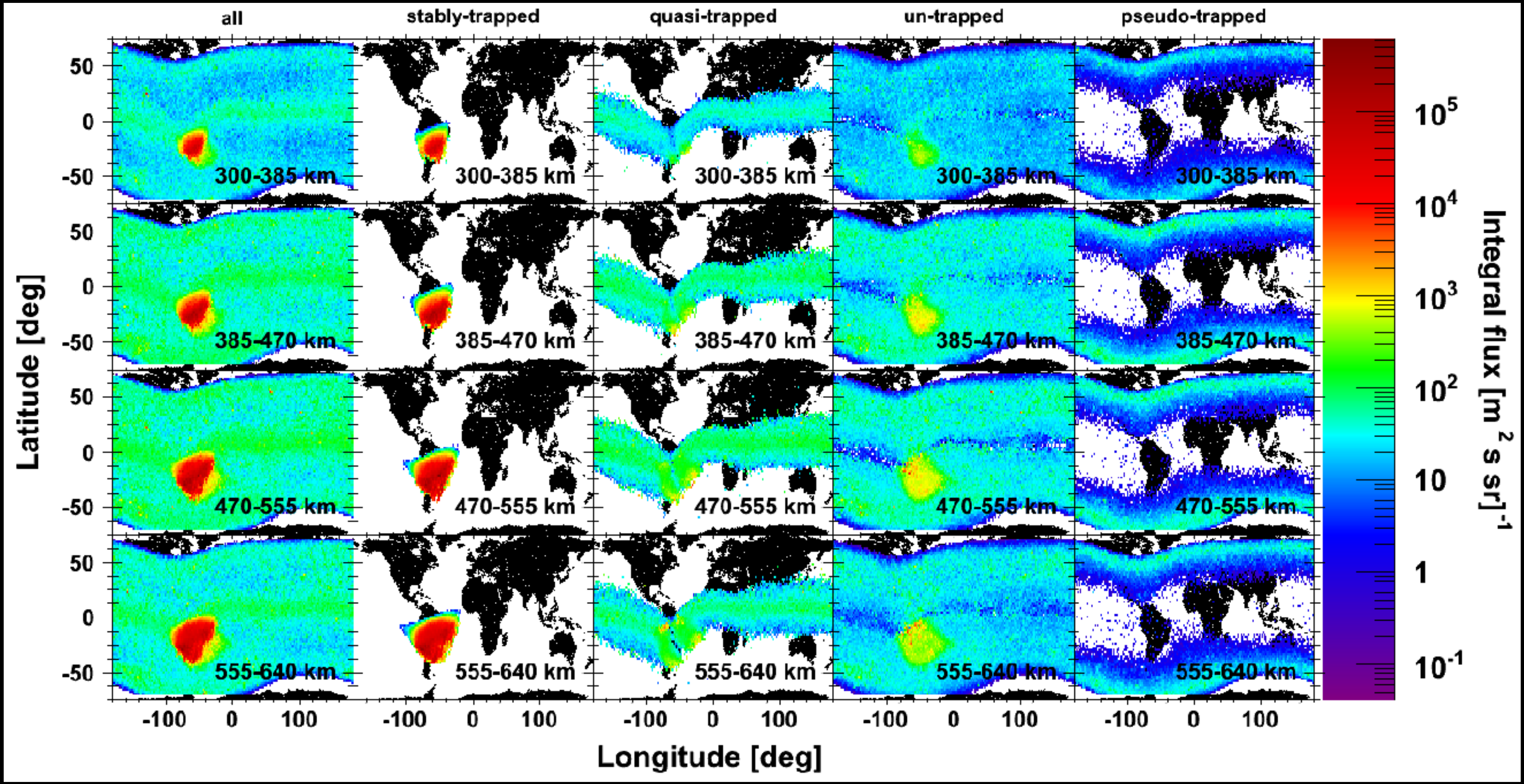
arXiv:1412.1765 , ASR 2016

Integral fluxes at different GC altitudes, averaged over the explored pitch angle range



arXiv:1412.1765 , ASR 2016

Integral fluxes at different GC altitudes, averaged over the explored pitch angle range

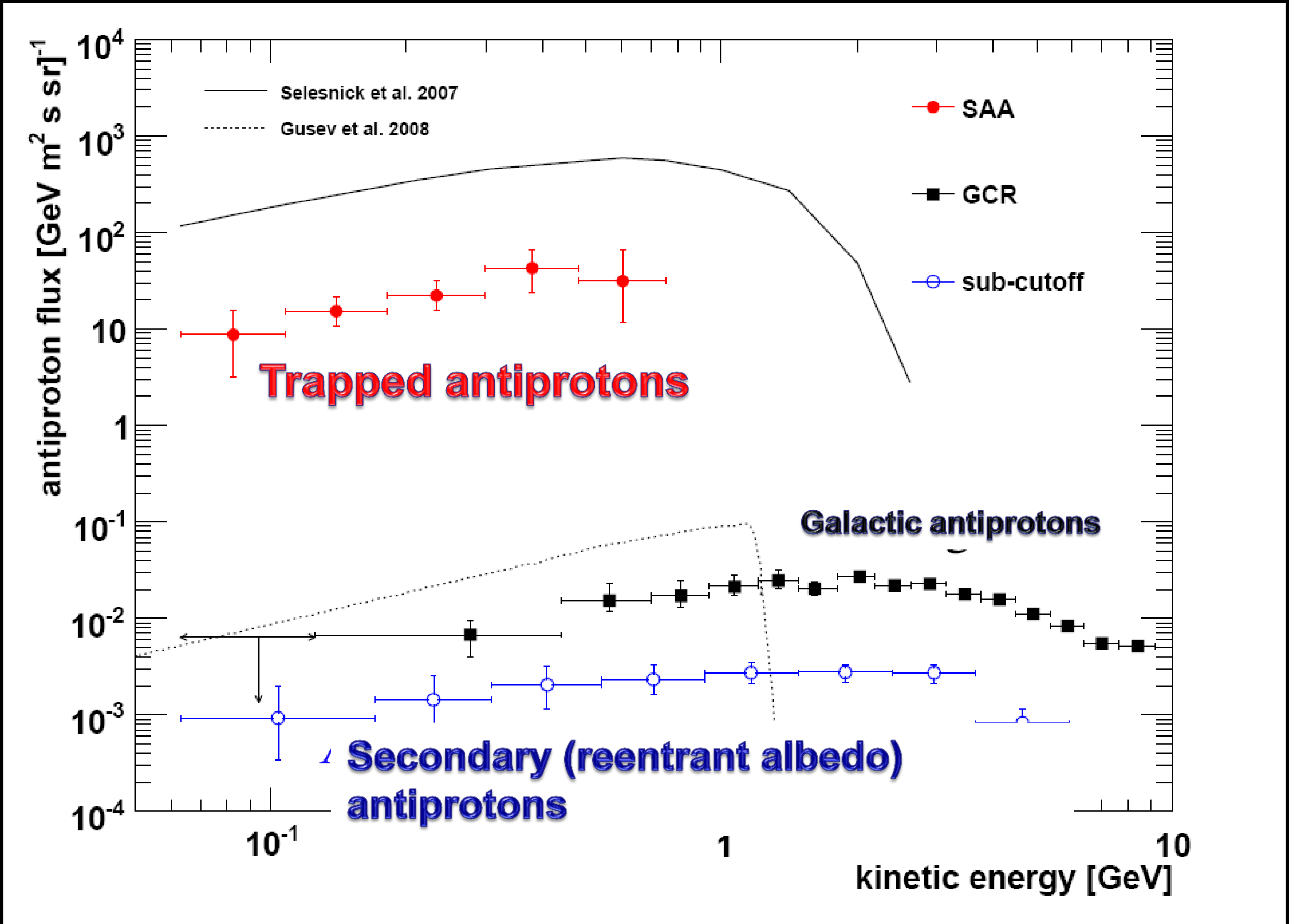


arXiv:1412.1765 , ASR 2016

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

•Expected three years of operations – survived 10!

•Data analysis is in progress

•Data available on ASI science data center (ASDC)

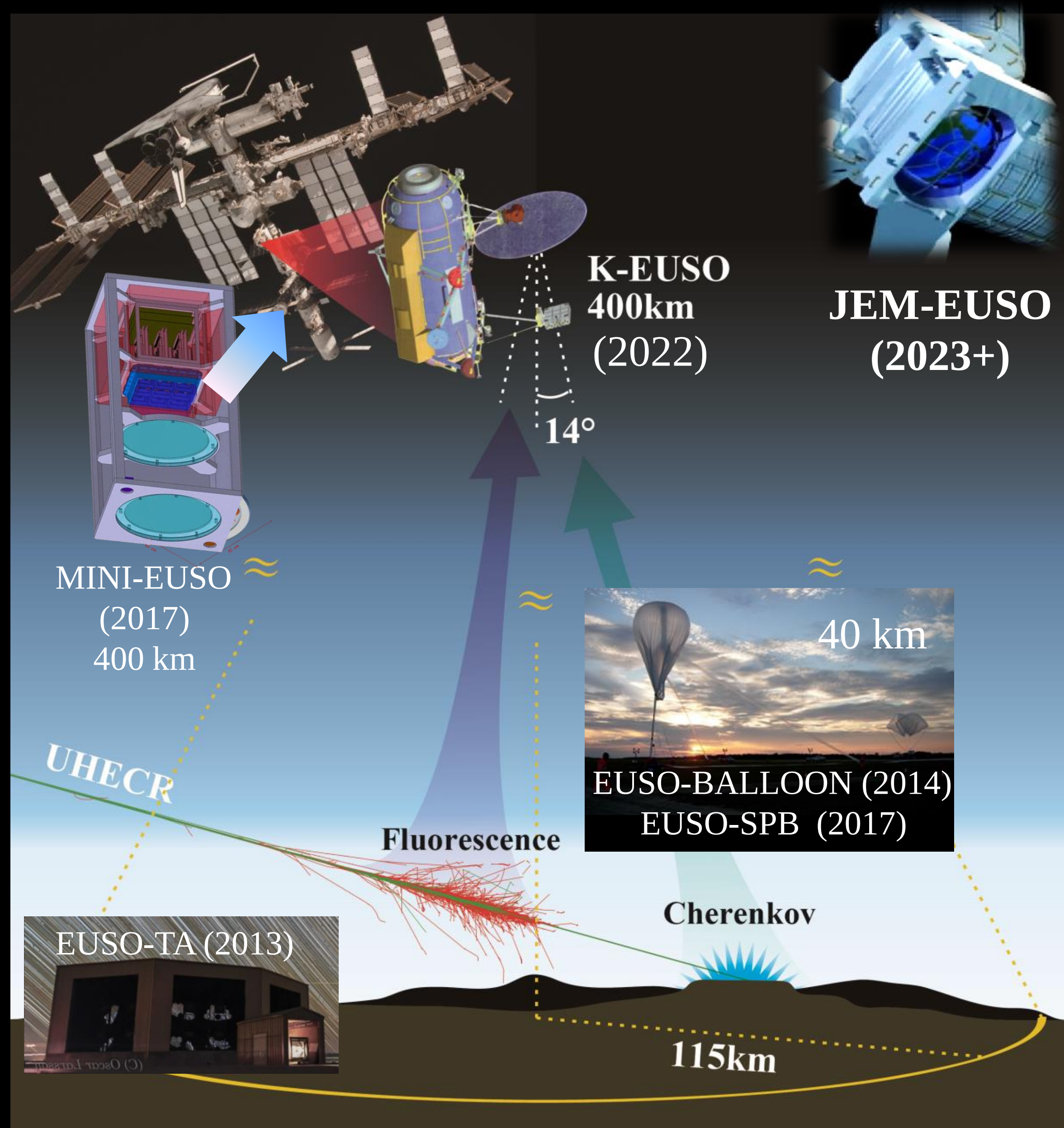
http://pamela.roma2.infn.it

http://www.casolino.it

The EUSO program

Ultra-High Energy cosmic rays from space

1. **EUSO-TA:** ***Ground detector installed in 2013 at Telescope Array site: currently operational***
2. **EUSO-BALLOON**: ***1st balloon flight from Timmins, CA (French Space Agency) Aug 2014; NASA Ultra long duration flight: 2017***
3. **MINI-EUSO (2017):** ***Precursor from International Space Station (ISS: 30kg 2017). Approved by Italian and Russian Space agencies***
4. **K-EUSO (2022):** ***ISS Approved by Russian Space Agency***



JEM-EUSO collaboration

16 Countries, 93 Institutes, 351 people