Geneva, 21/1/2015
Sugar 2015

Results from the PAMELA space experiment

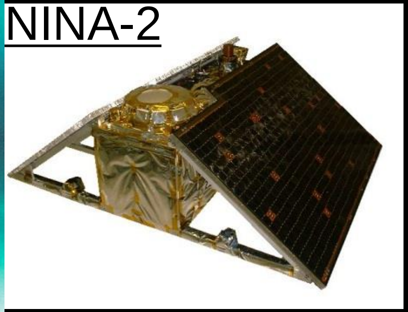
M. Casolino
INFN & University of Rome Tor Vergata
RIKEN

Past, present and future experiments

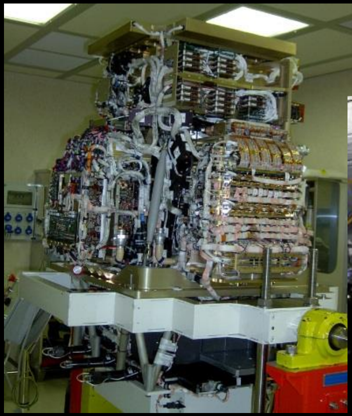
MASS-89, 91, TS-93, CAPRICE 94-97-98

NINA-1

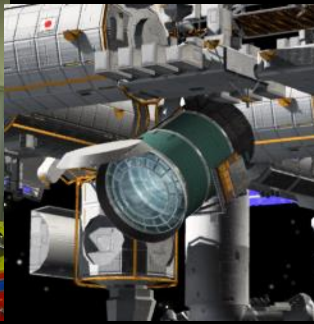
NINA-2



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

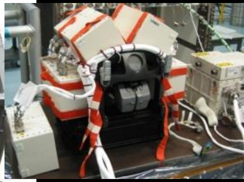
SILEYE-1 SILEYE-2 SILEYE-3 ALTEA

SILEYE-

SILEYE-2

SILEYE-3/ ALTEINO:

LAZIO-SIRAD



SILEYE-4/ALTEA

Pamela Collaboration

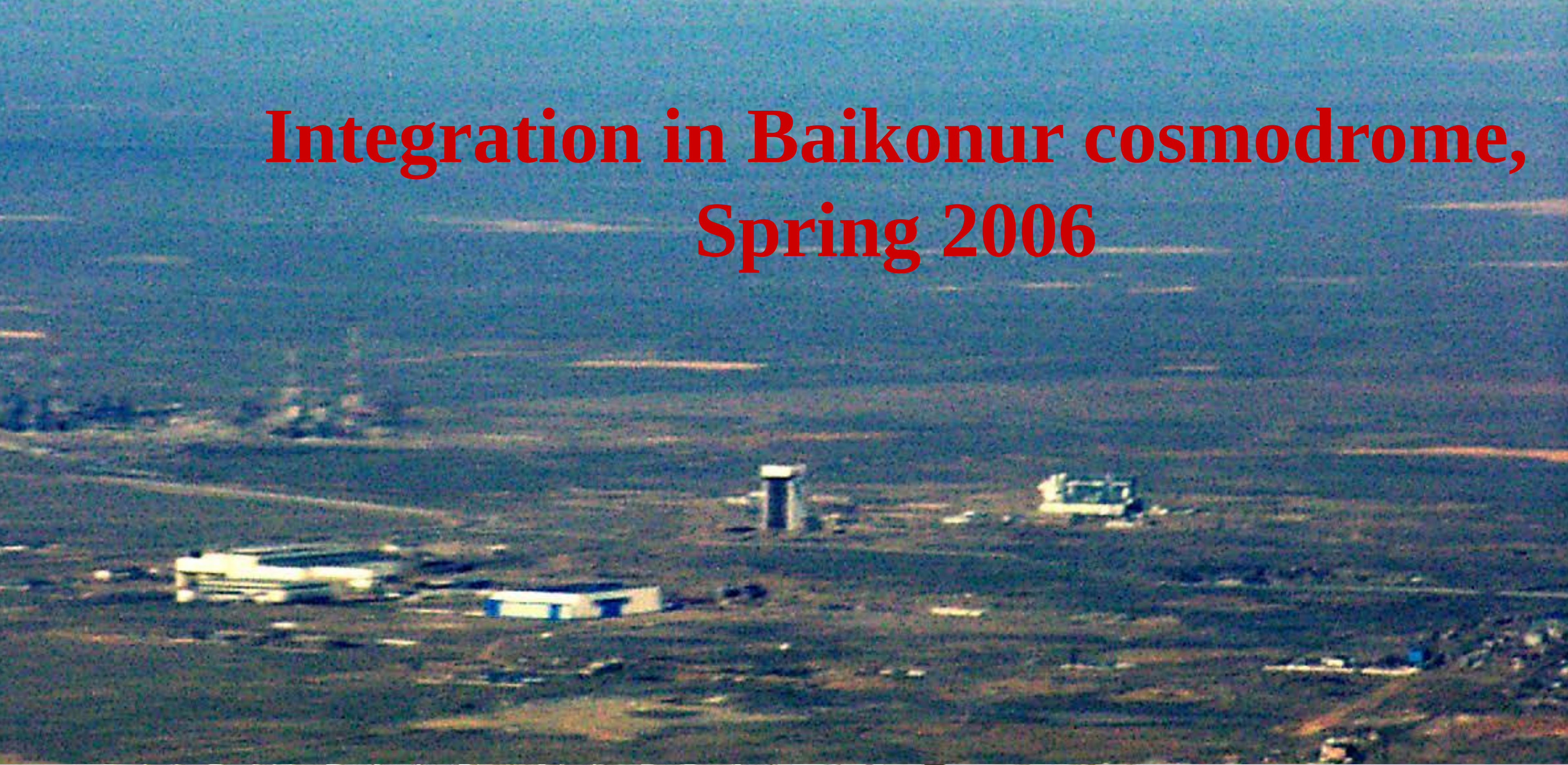
Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

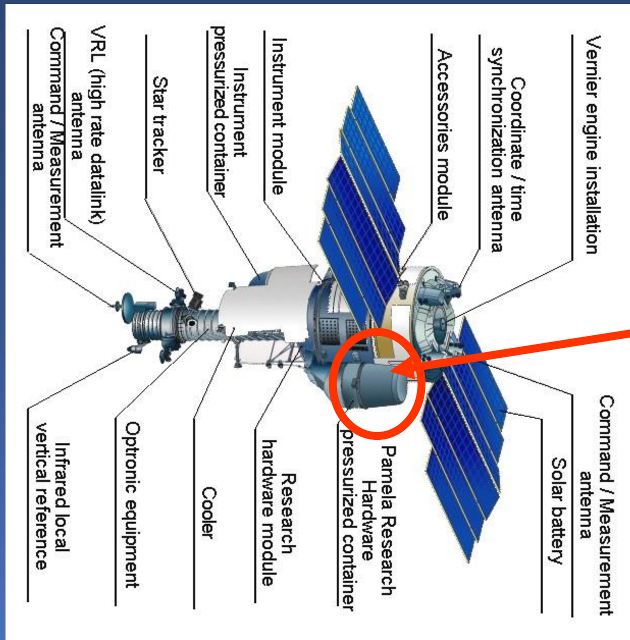
Russia: Moscow, St. Petersburg

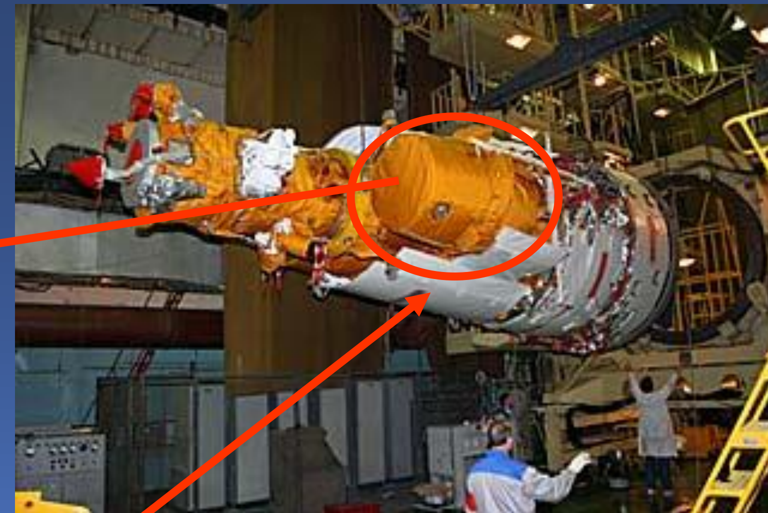
Germany: Siegen

Sweden: KTH, Stockholm

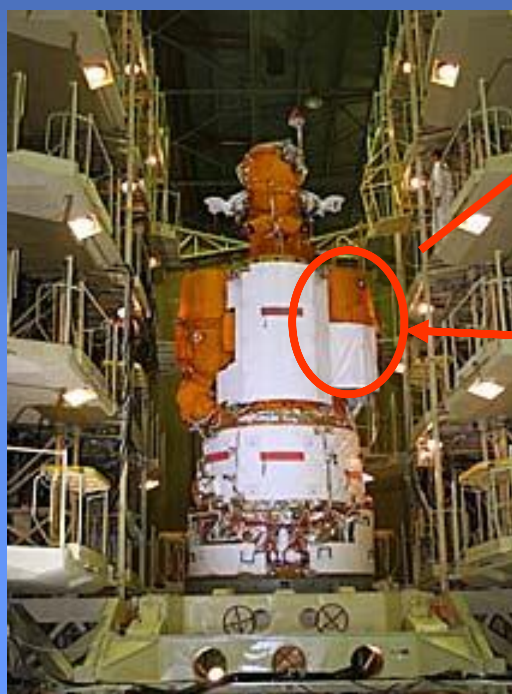
Integration in Baikonur cosmodrome, Spring 2006



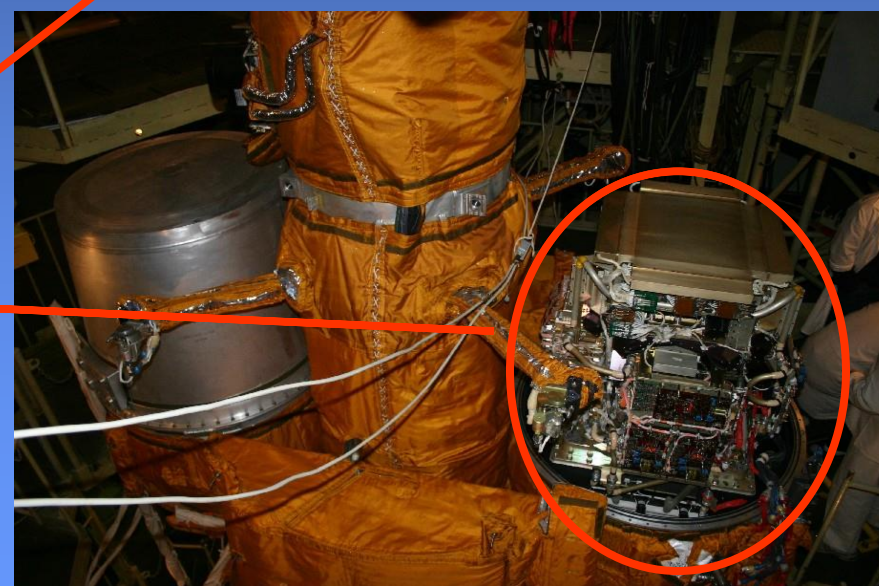




Coupling to Soyuz



Resurs DK integrated

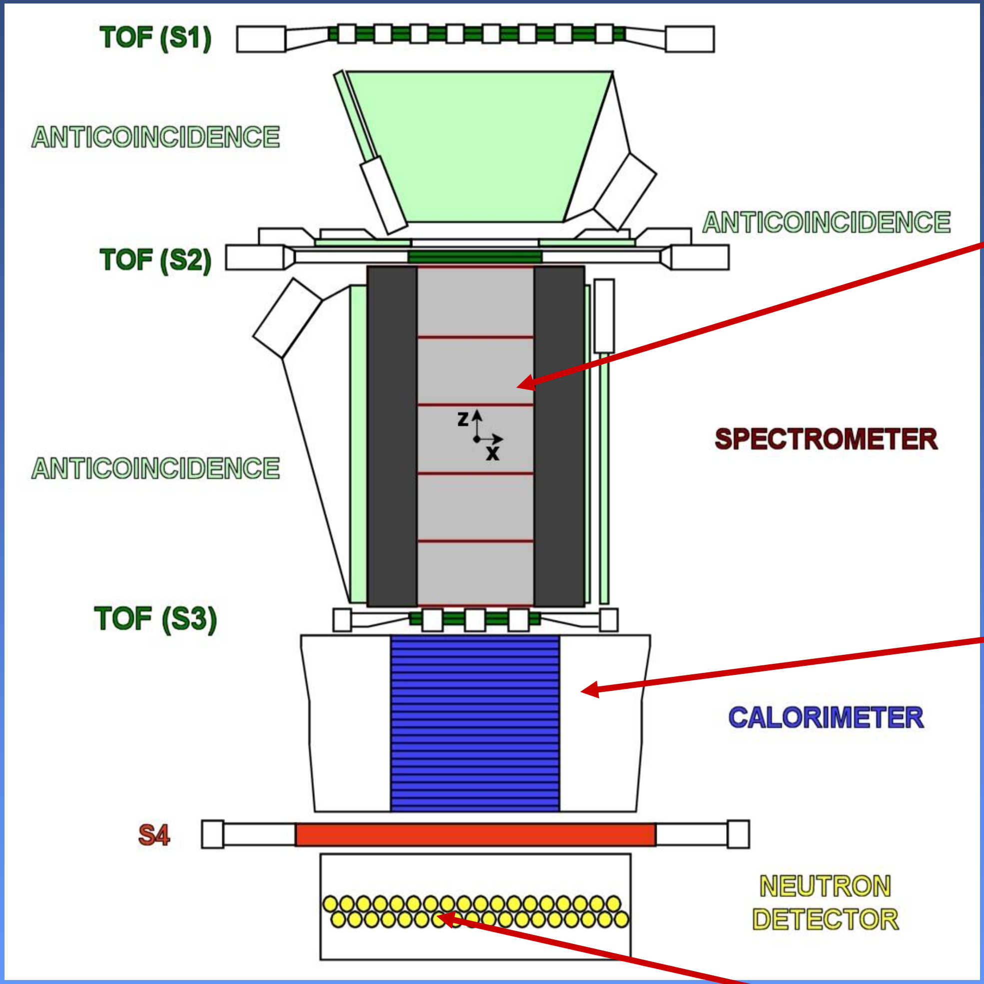


Pamela during integration in Baikonur


Gagarinsky Start, 14/6/2006

Launch on June 15th 2006 Soyuz-U rocket

The 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

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

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

Pamela Instrument

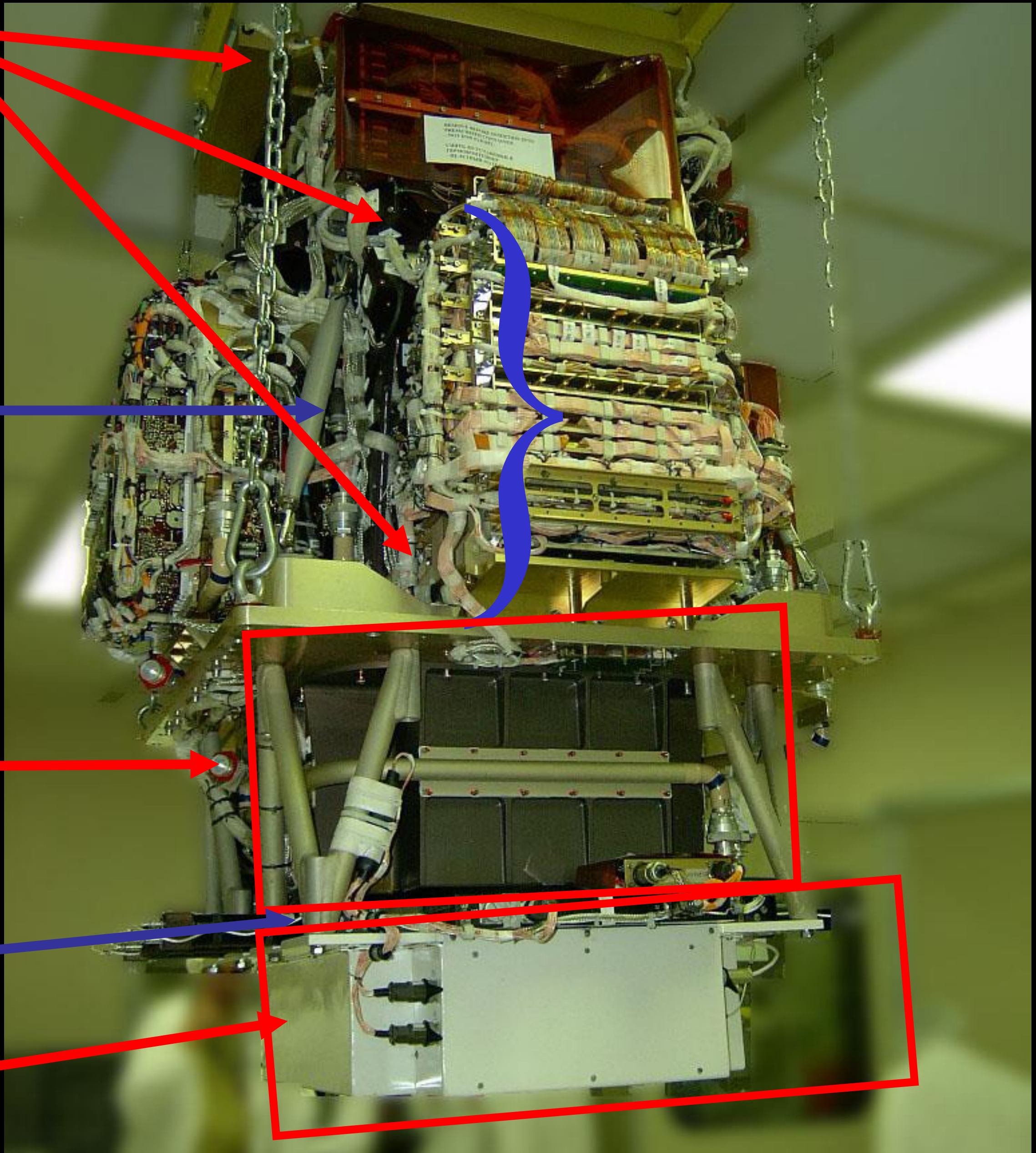
Time of Flight
(three scintillators, 6 planes, 48 phototubes)

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

Silicon Tungsten Tracking Calorimeter
(44 planes of 96 strip)

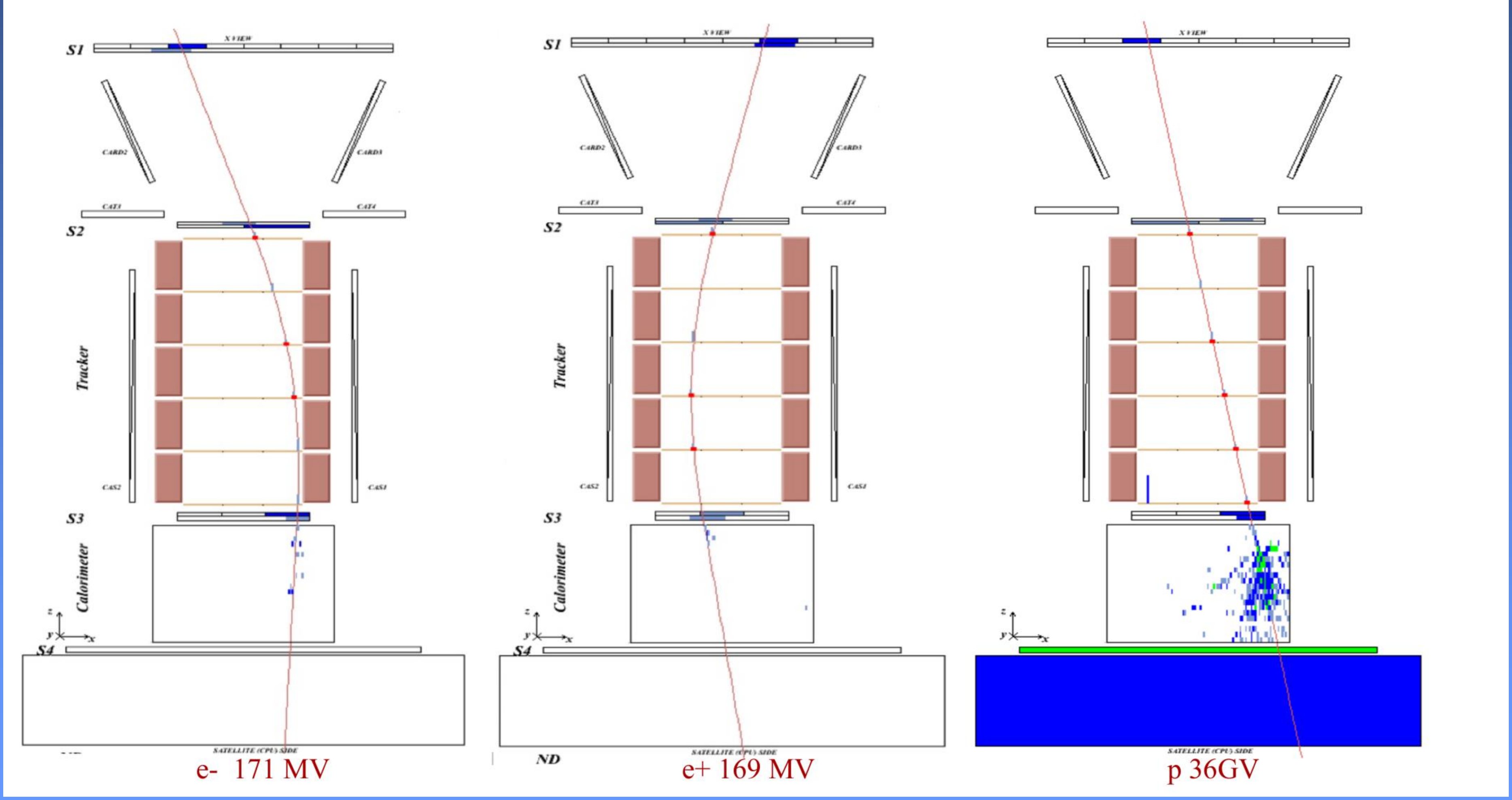
Shower Catcher Scintillator

Neutron Detector

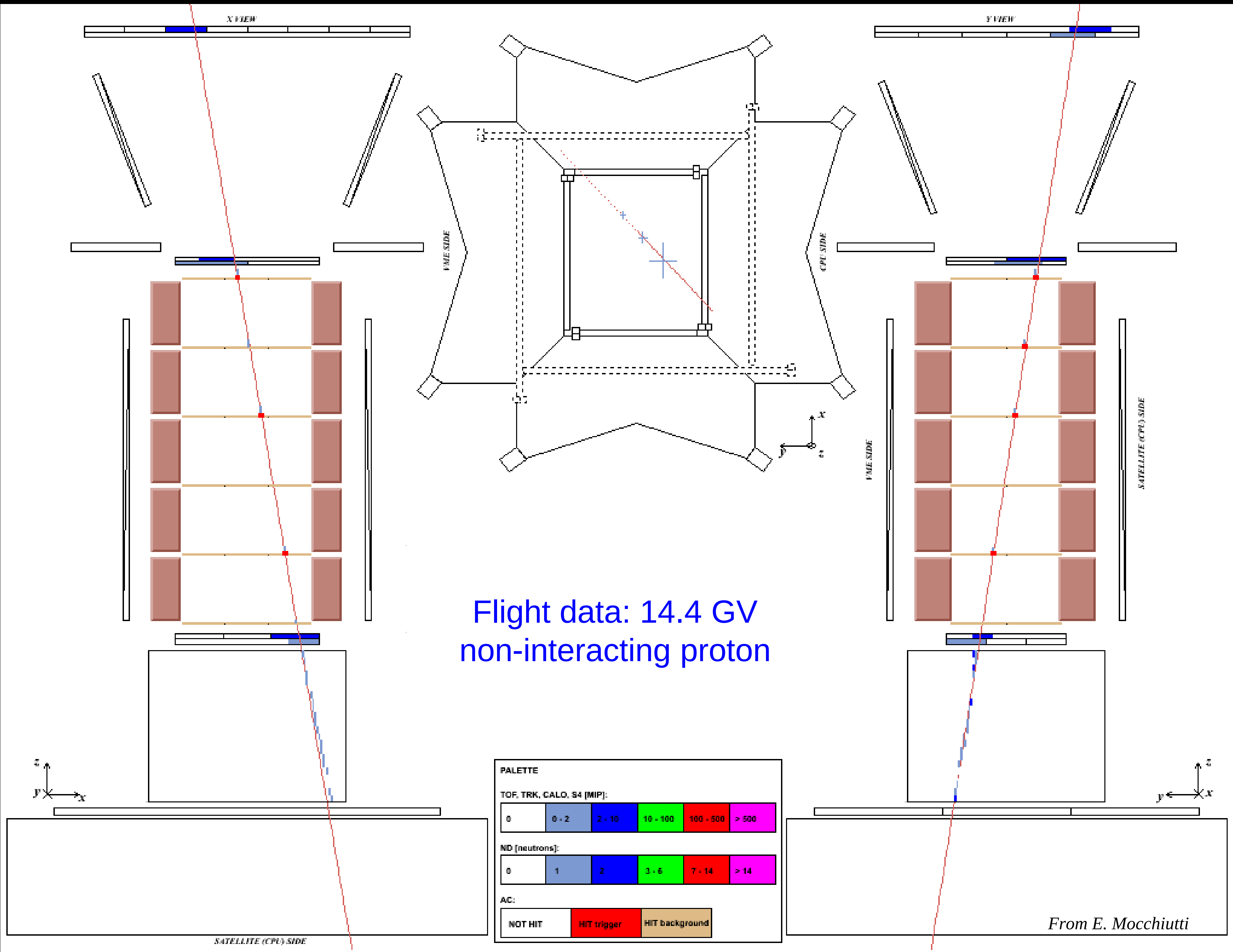


Principle of detection

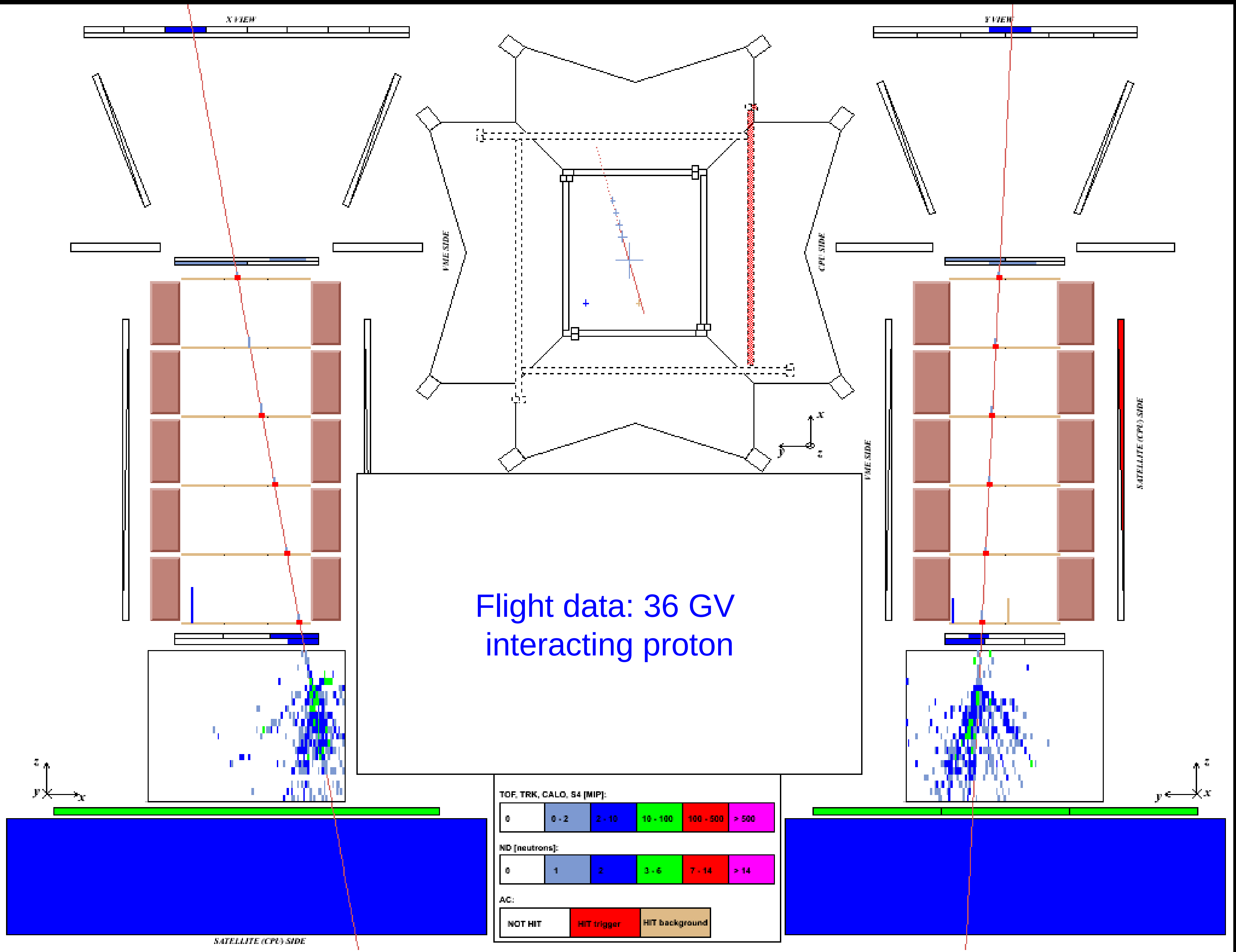
Electrons | Positrons | Protons

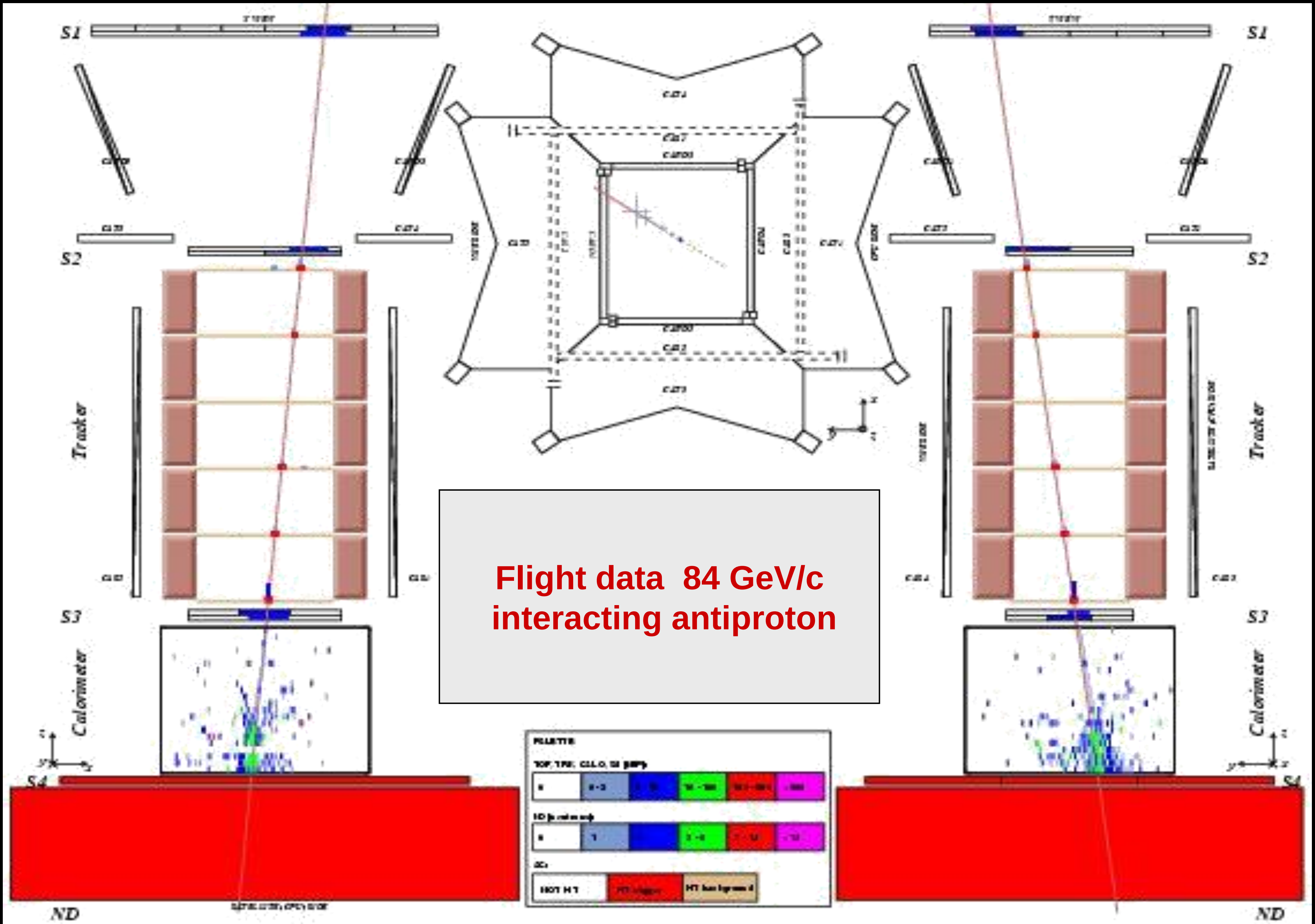


Flight data: 14.4 GV non-interacting proton

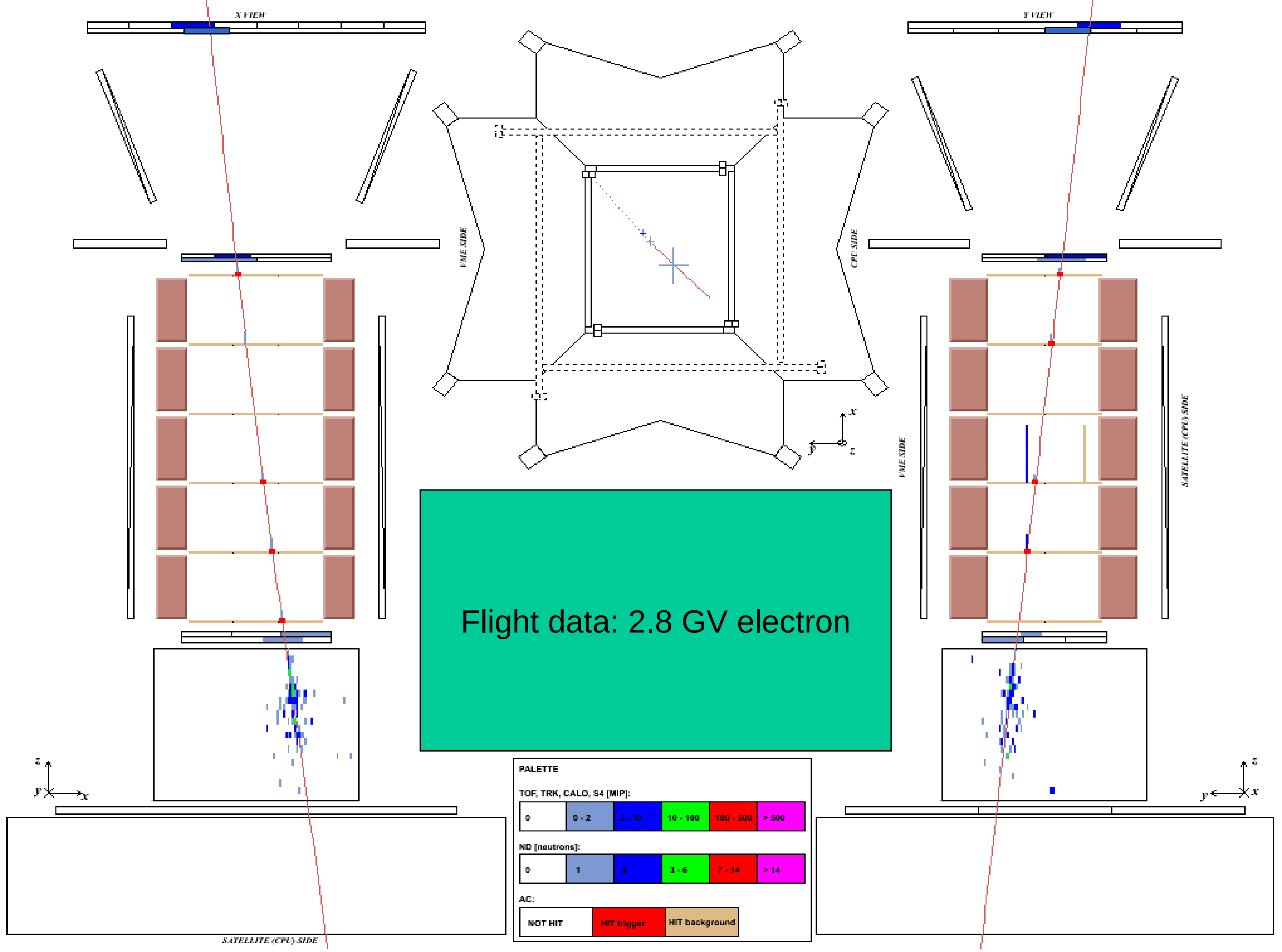


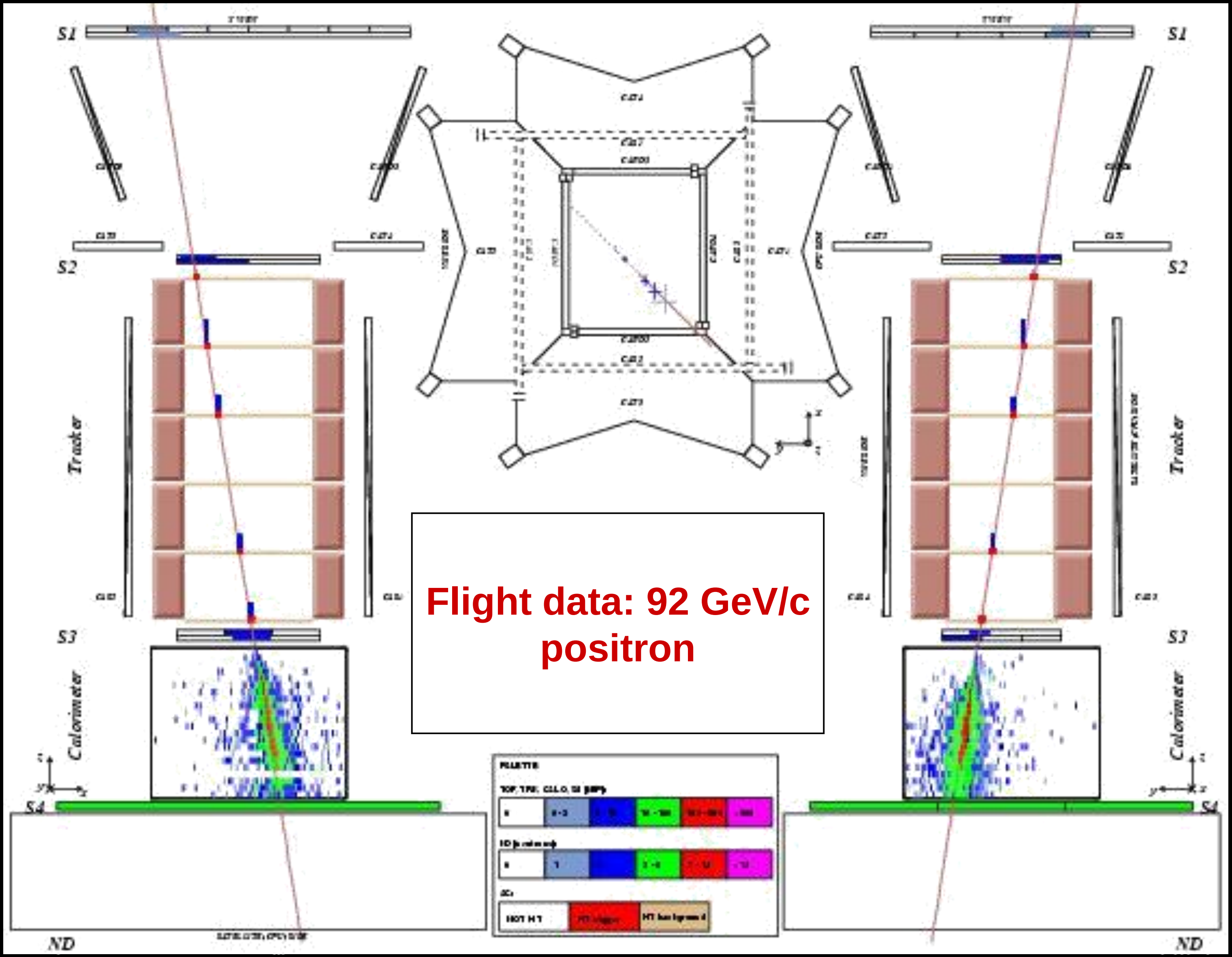
From E. Mocchiutti


Flight data: 36 GV
interacting proton
X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



Flight data 84 GeV/c interacting antiproton


X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
Flight data: 2.8 GV electron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



Flight data: 92 GeV/c positron

Particle identification

Selection criteria

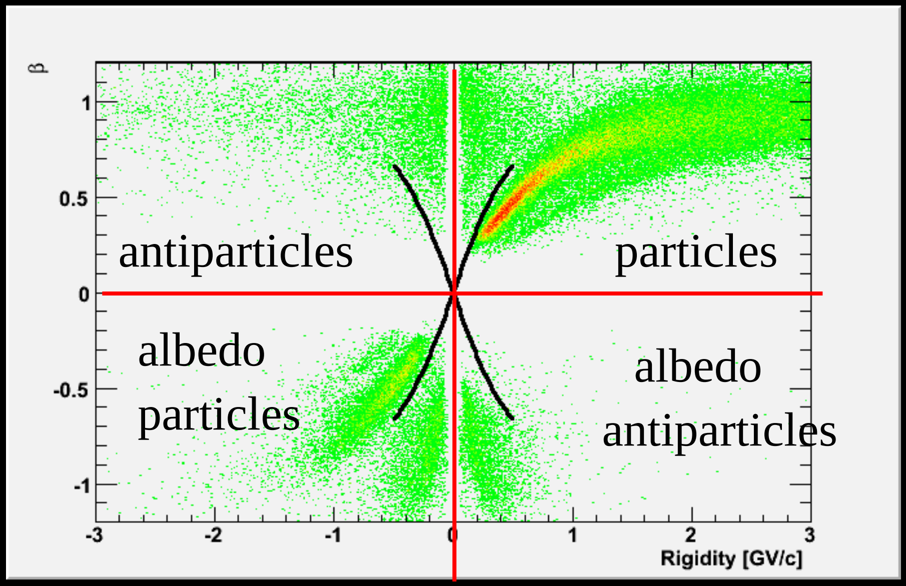
Fitted, single track
High lever arm, Nx
Rigidity R>0
Beta>.2
No anticoincidence

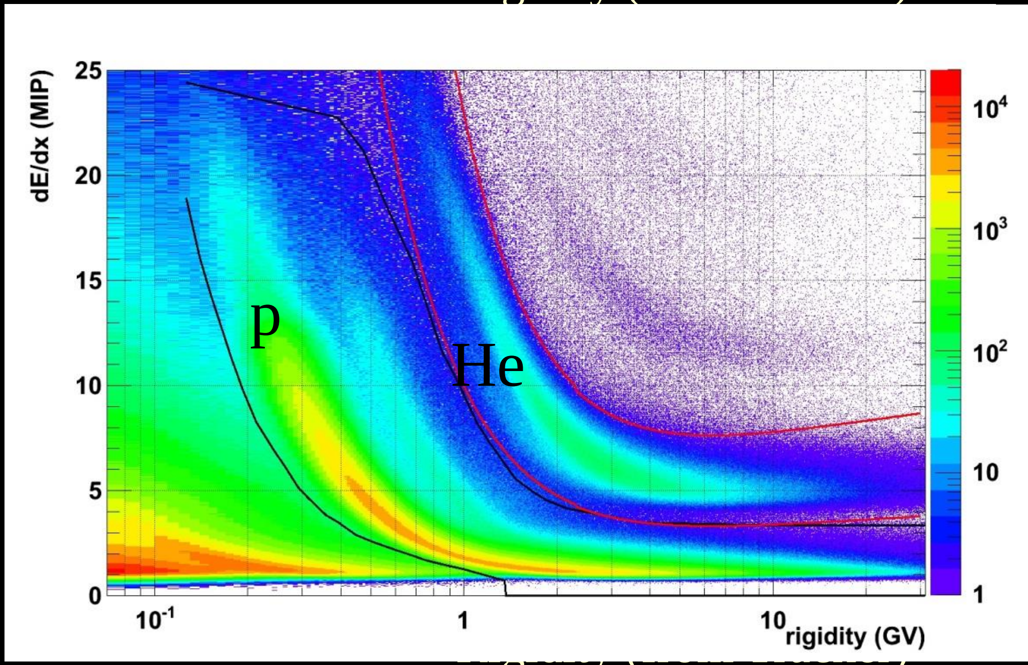
- **Montecarlo efficency for cuts**
- **Trigger efficiency**
- **Tracking efficiency**
- **Multiple Scattering**

Correction for energy loss in Jet

- **Back scattering…**
- **Systematics**

about 1-2% uncertainty on abs flux.



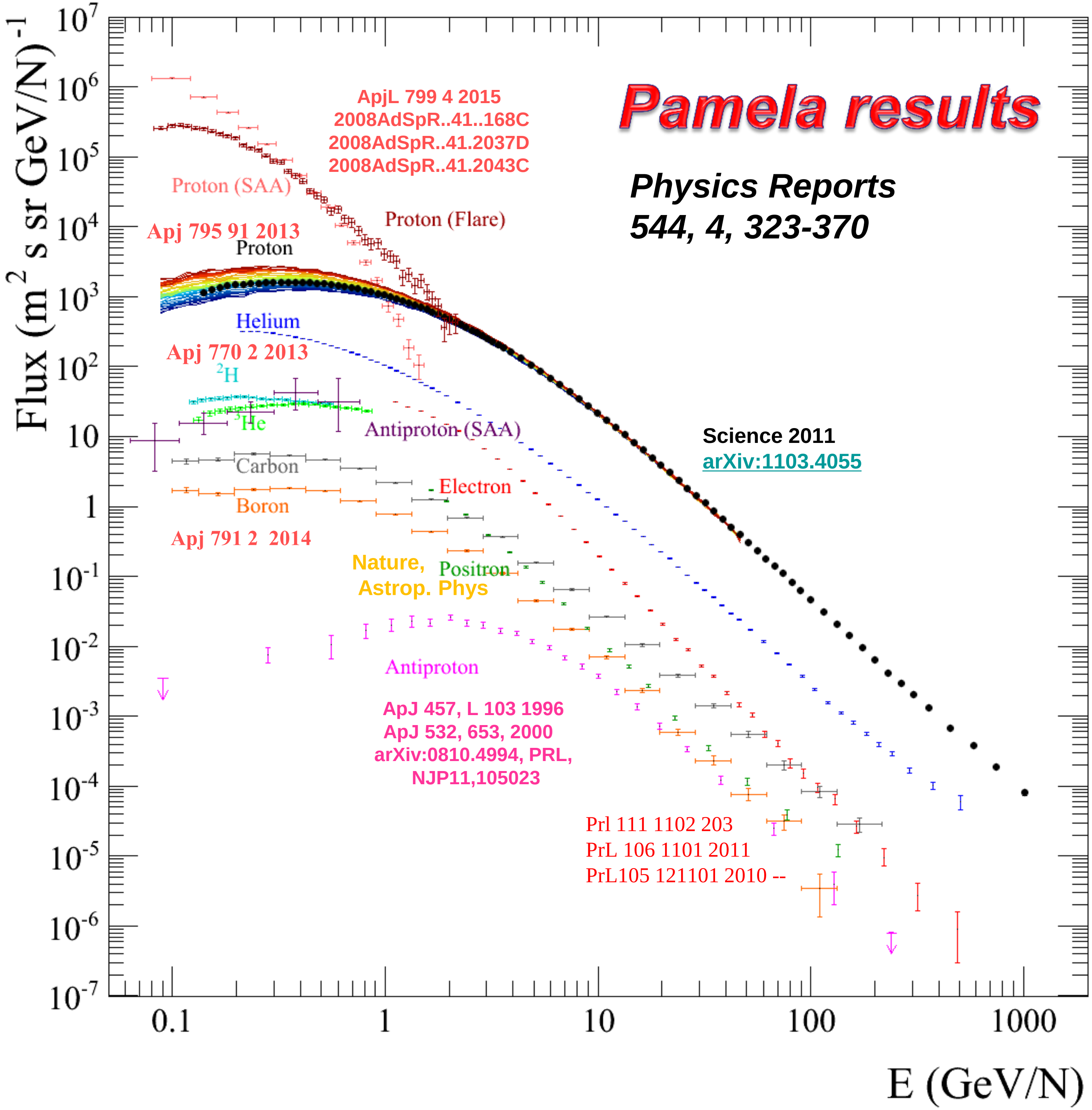


High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere

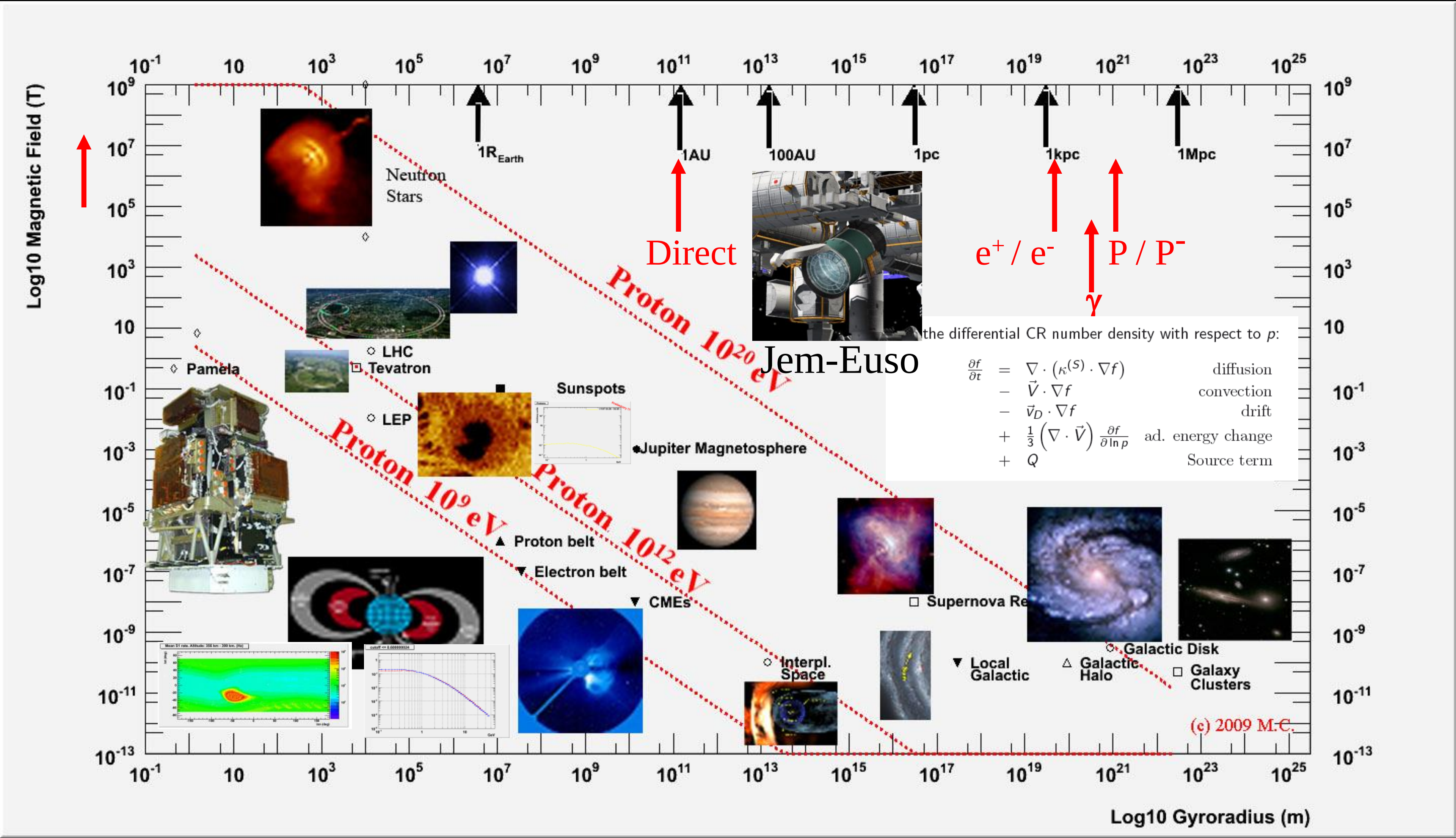
On several different scales

→ 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”

Matter – Antimatter domain separation?

- Antihelium and antinuclei search

- γ-ray ≈ 0.1 GeV from annihilation in Antihelium search boundary regions

- ***Current limit: separation above cluster of galaxy (≥ 10 Mpc)***

Steigman, G. 1976, Ann. Rev. Astron. Astrophys. 14, 339,
"Observational tests of antimatter cosmologies"

M33

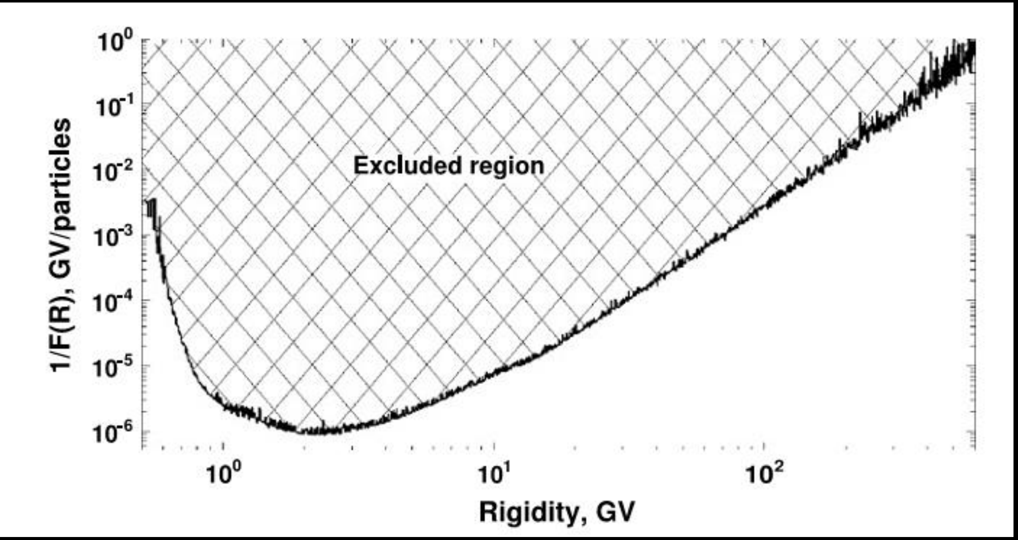
- Observable?
- Magnetic fields ?
- Survival probability?

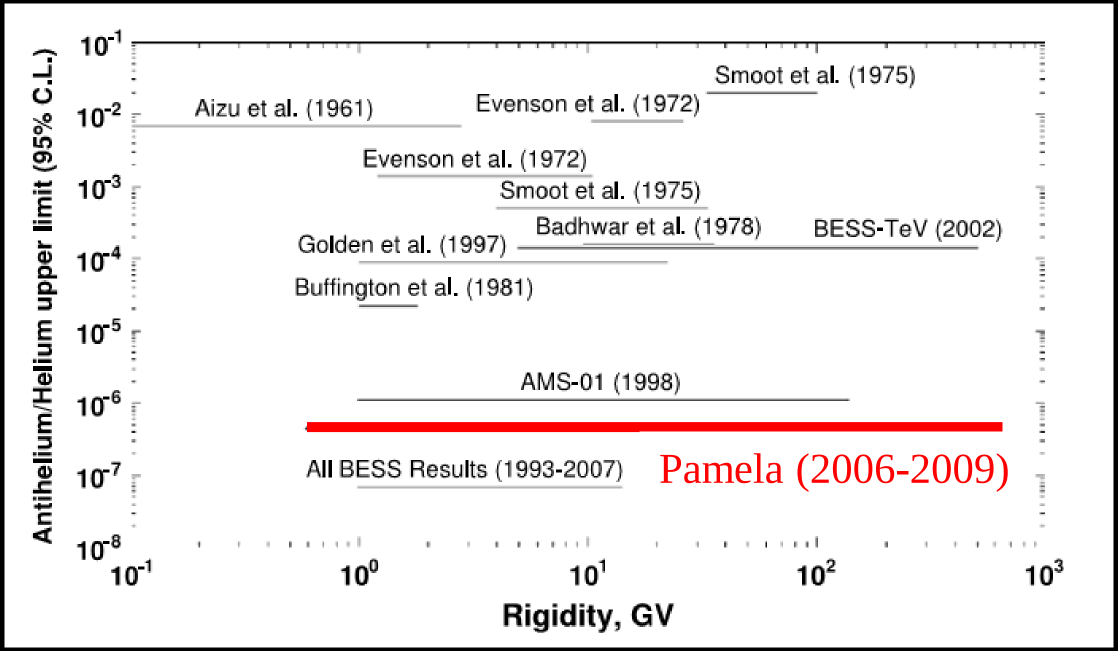
Ahlen, S.P. et al. 1982, ApJ, 260, 20,
"Can we detect antimatter from other galaxies?"

Search for antinuclei

Antihelium also from primordial nucleosyinthesis

Antinuclei only from antistars

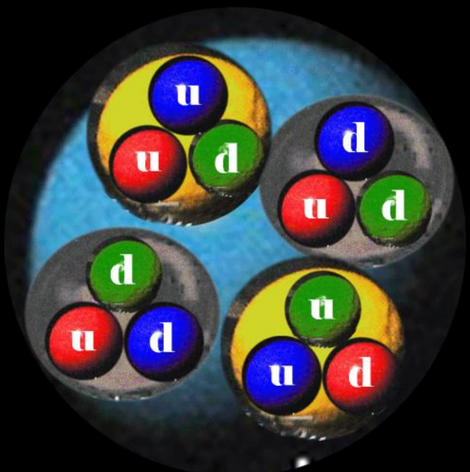




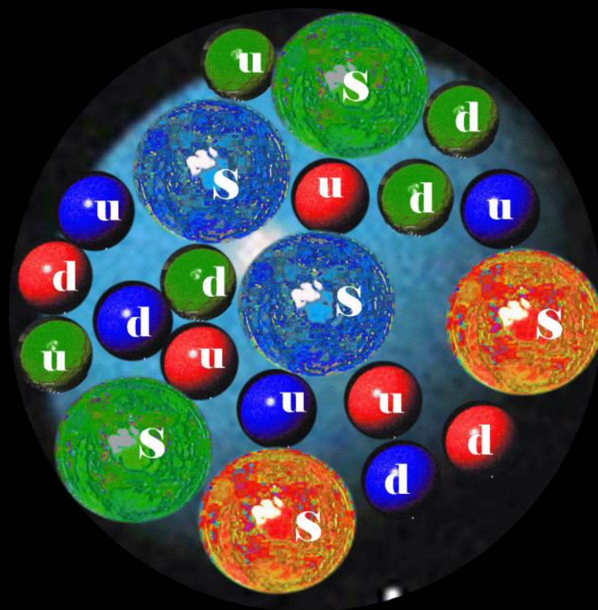
Search for exotic matter: Strangelets

(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

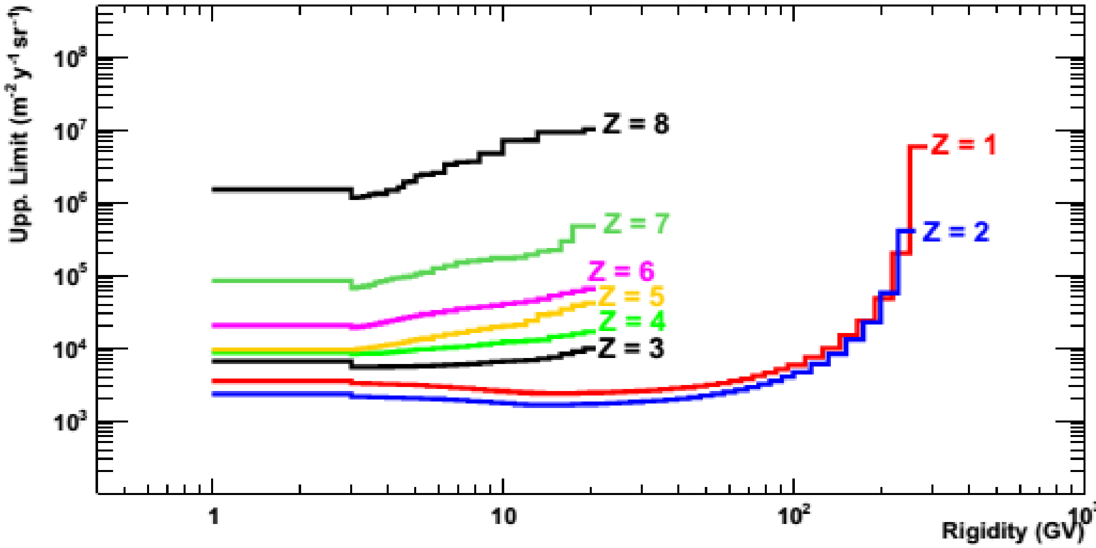
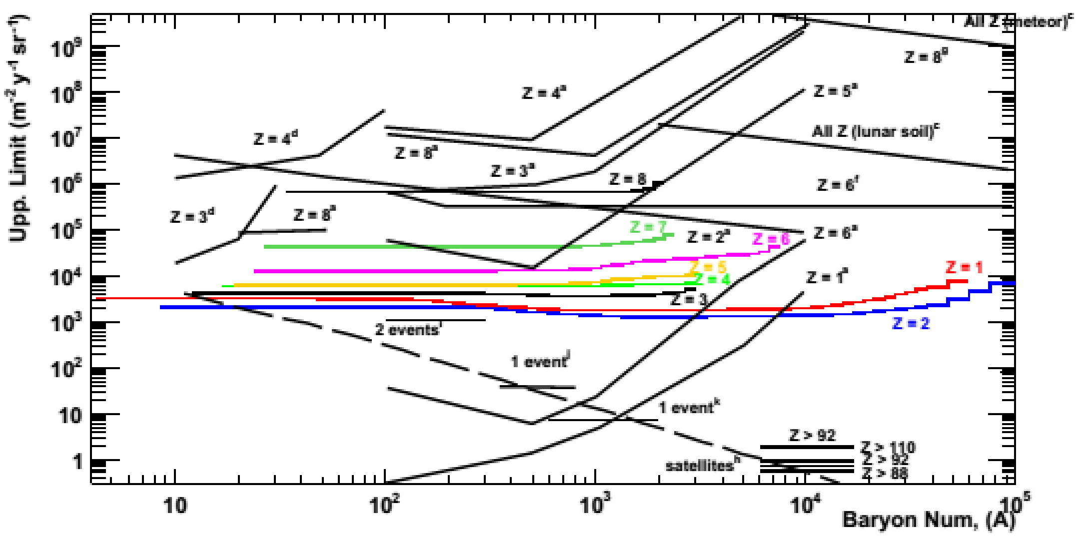


FIG. 4. Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to Z=8.



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)

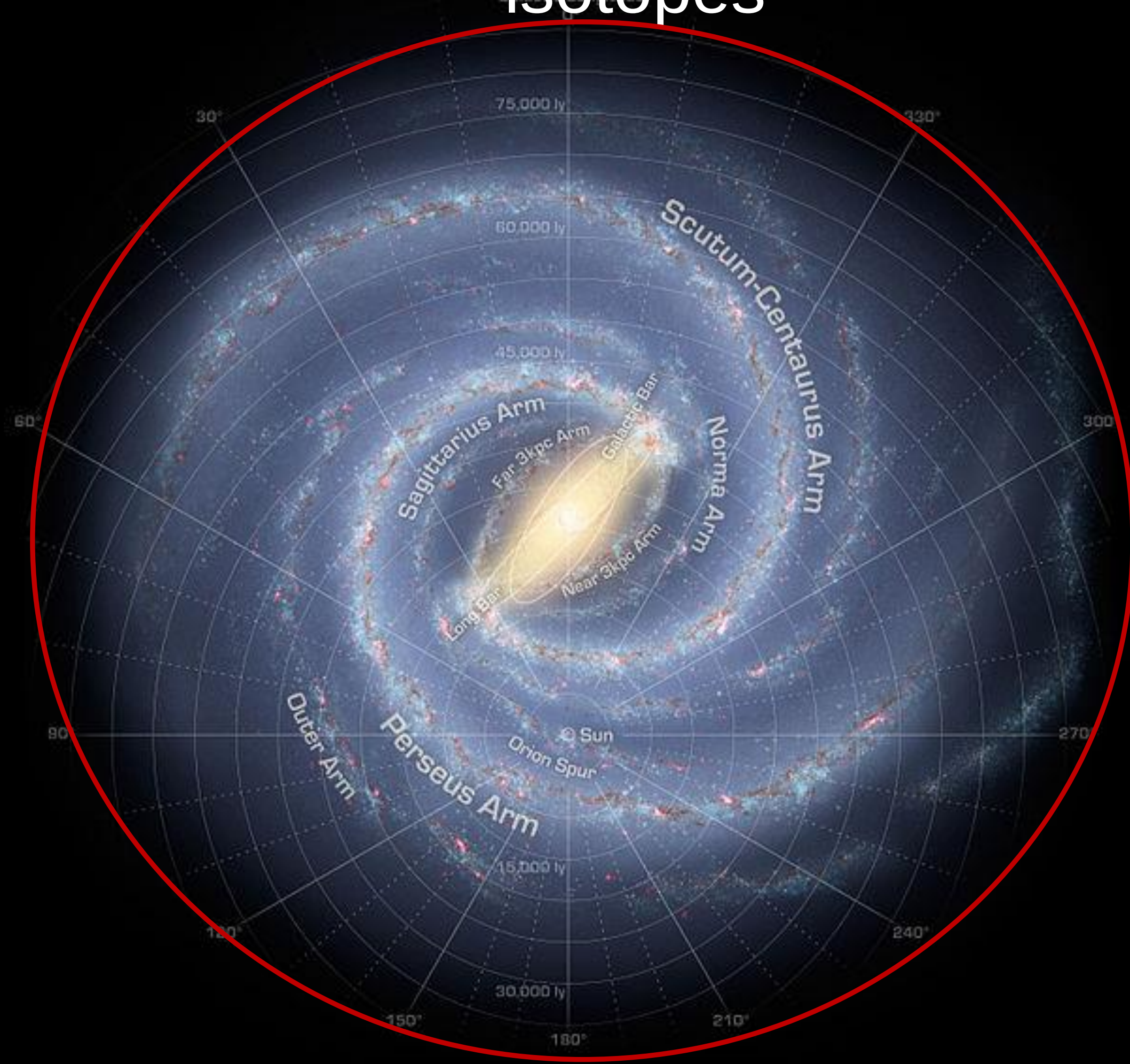
PAMELA, Z=1

PAMELA, Z=2

Strangelet-like events detected by:

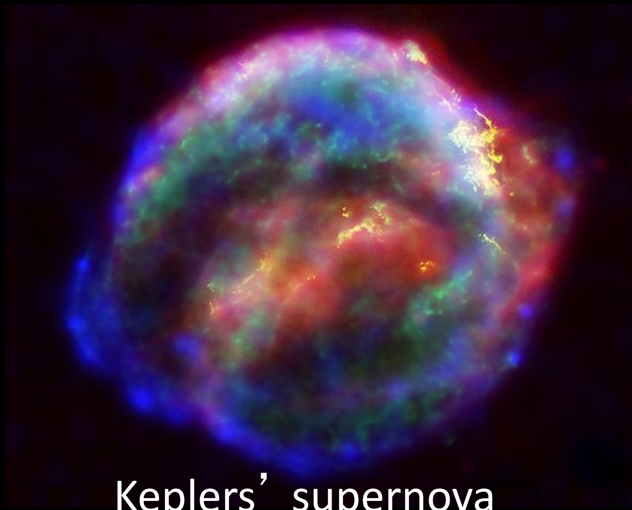
i) HECRO-81 PRL **65**, 2094 (1990)
j) ET Nuovo Cimento A Serie **106**, 843 (1993)
k) Phys. Rev. D **18**, 1382 (1978)

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

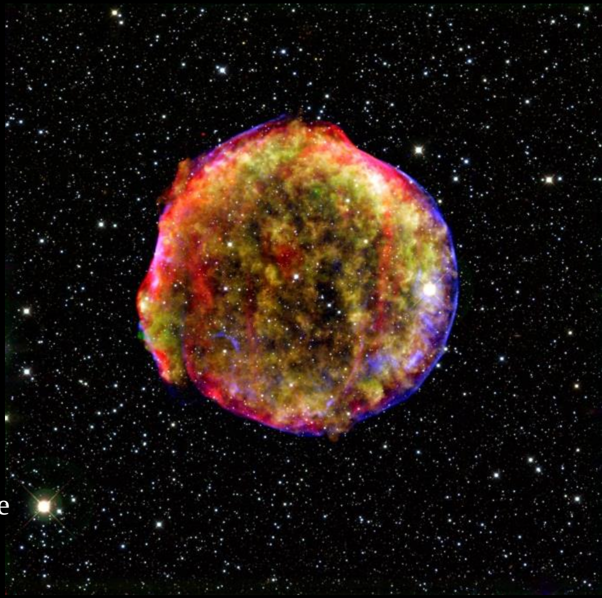


Cosmic rays are accelerated in Supernova explosions (probably)

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



Keplers' supernova

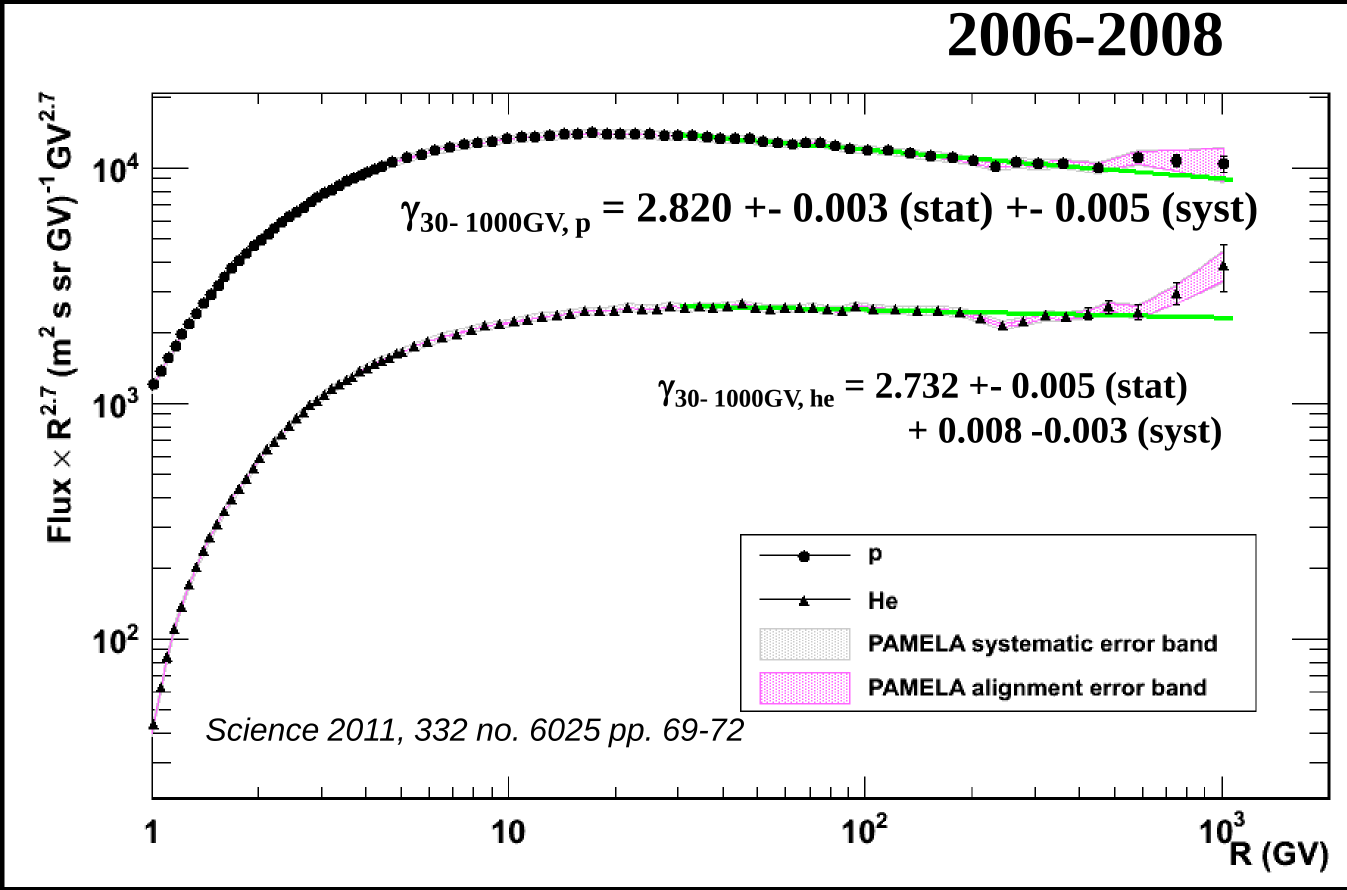


Tycho's supernova

– 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*

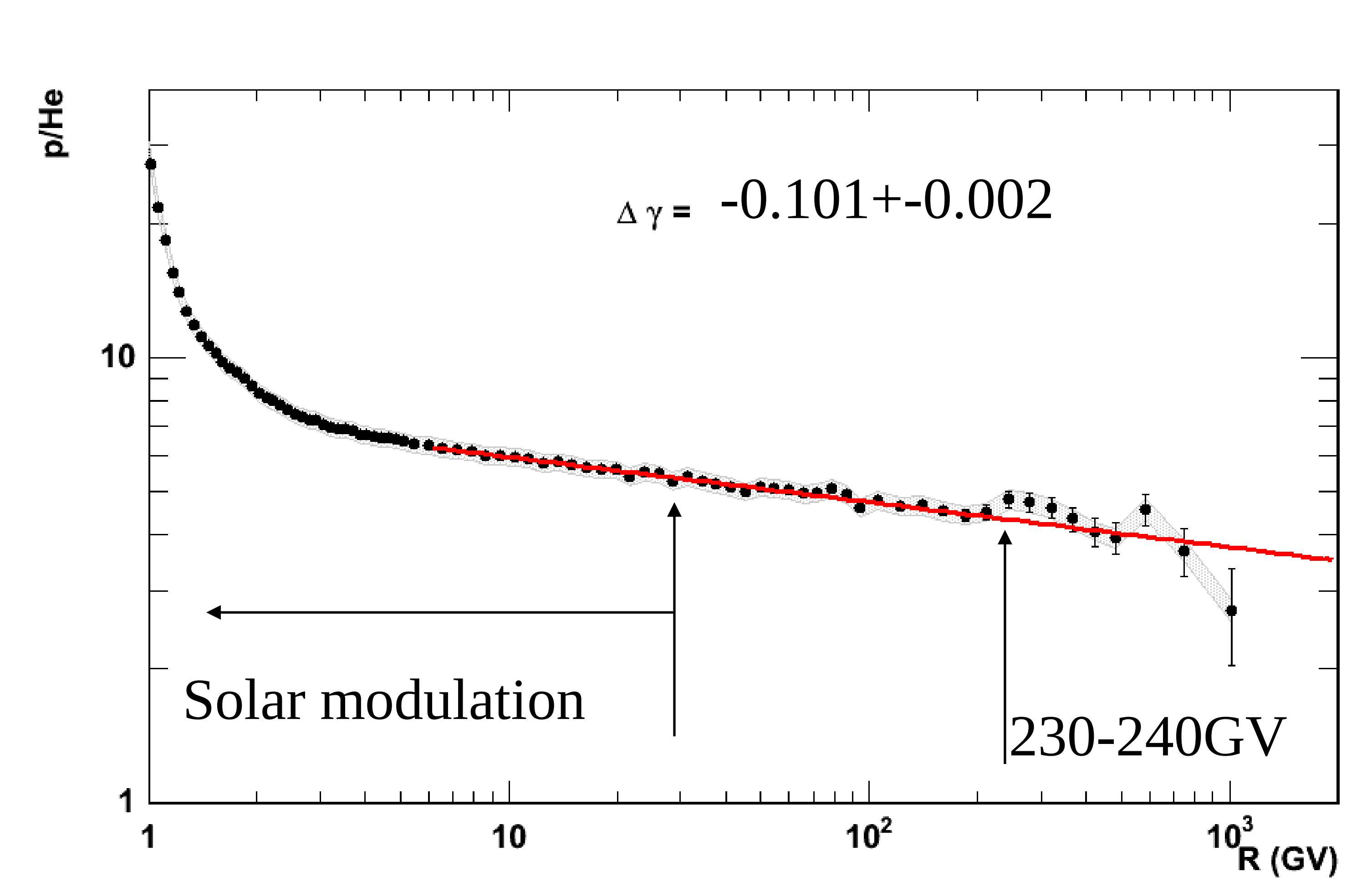
Pamela galactic proton and He

- 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.

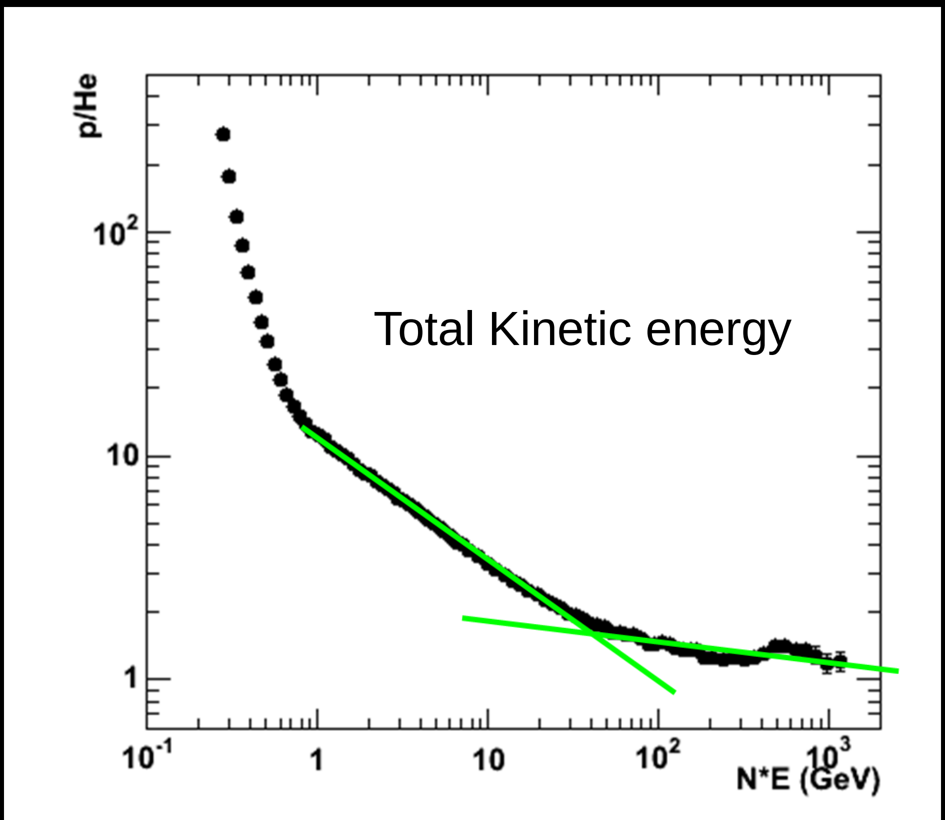


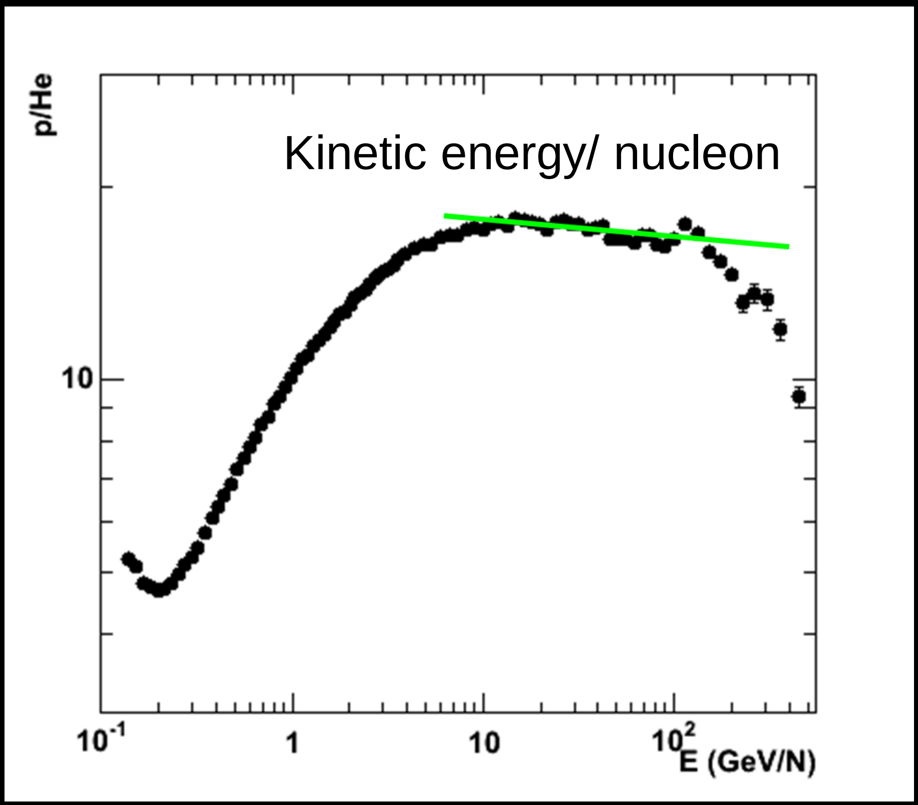
Ratio P/He: Rigidity

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





Excellent overlap with previous experiments

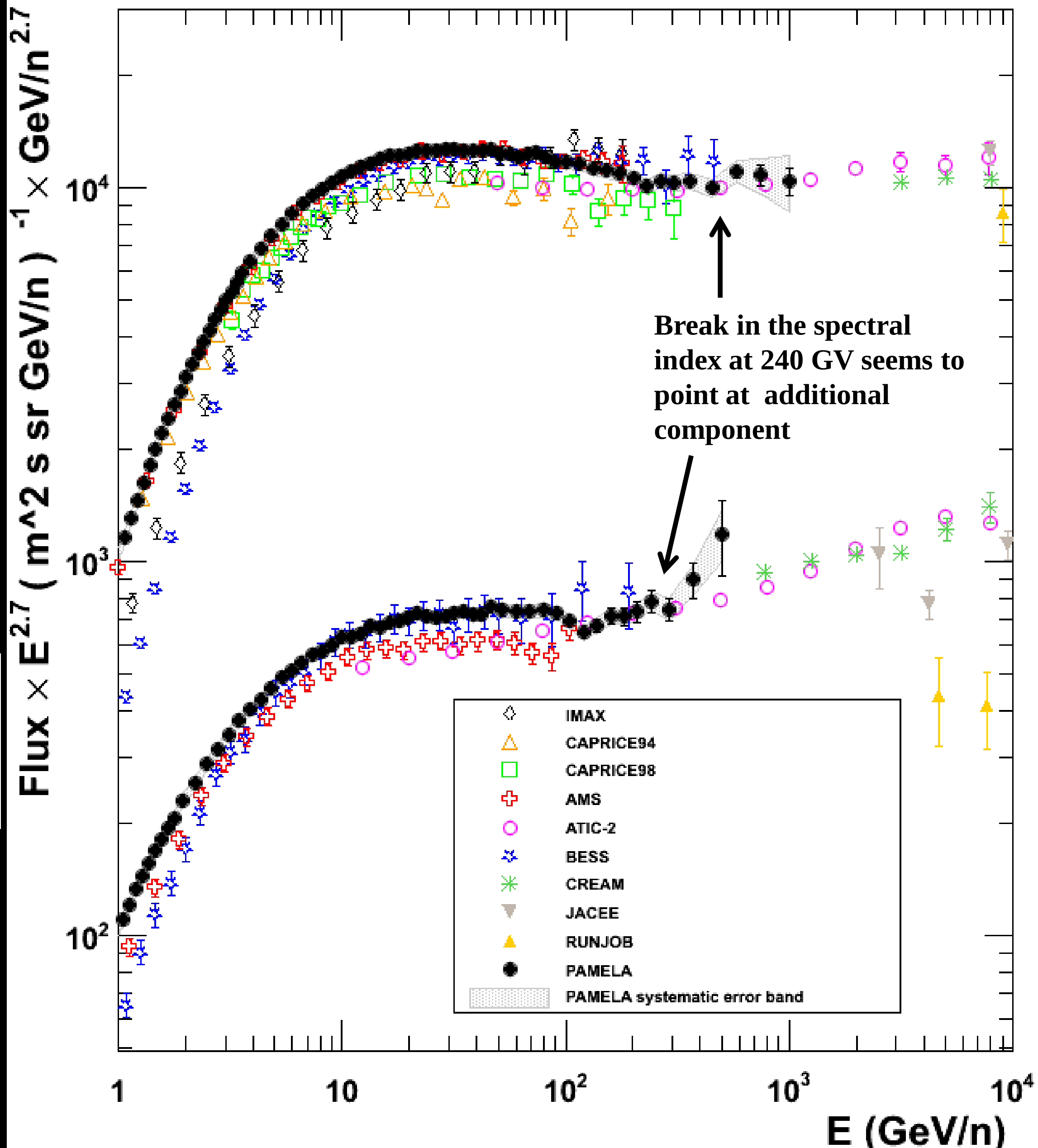
BESS

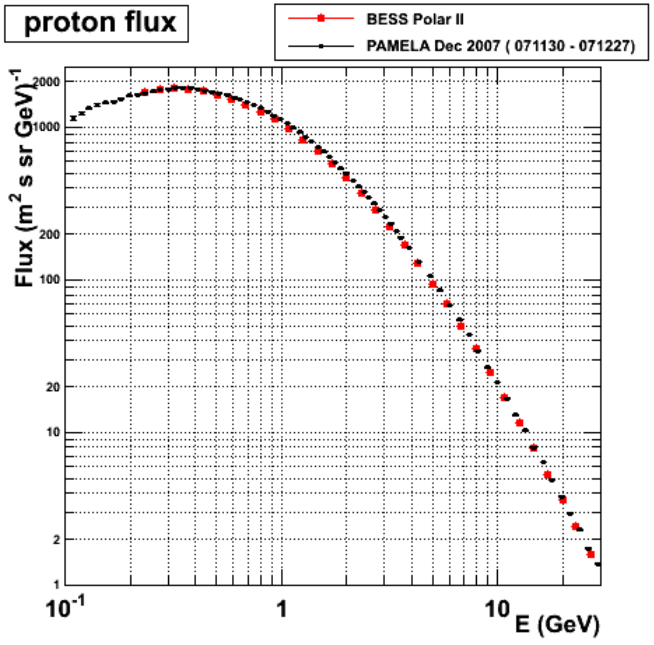
Brige with ATIC & CREAM toward high energy

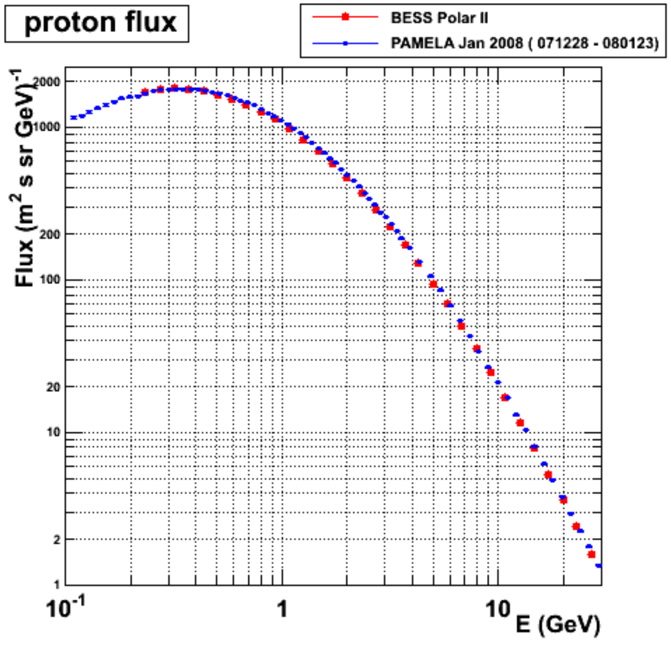
$\gamma_{30\text{-}1000\,\mathrm{GeV,\,p}} = 2.782 \pm 0.003\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst})$

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

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



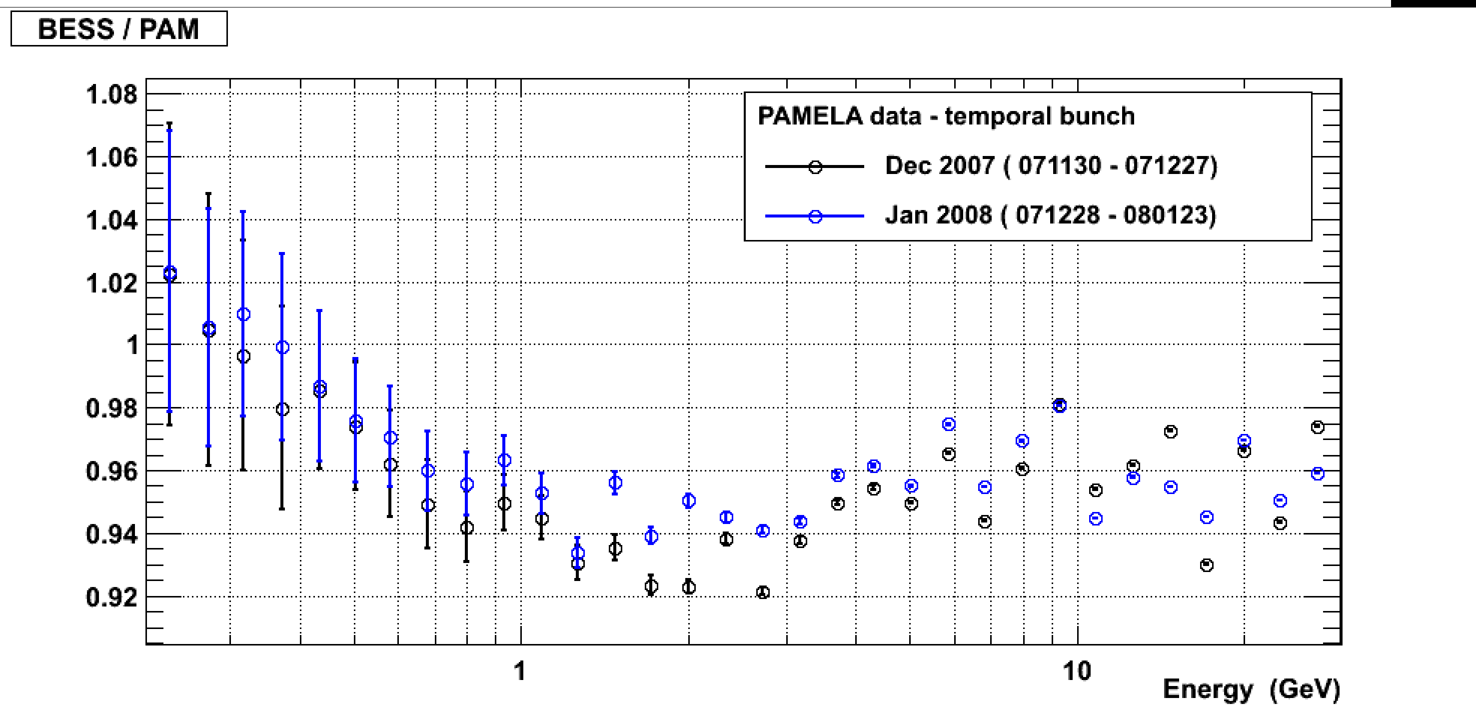




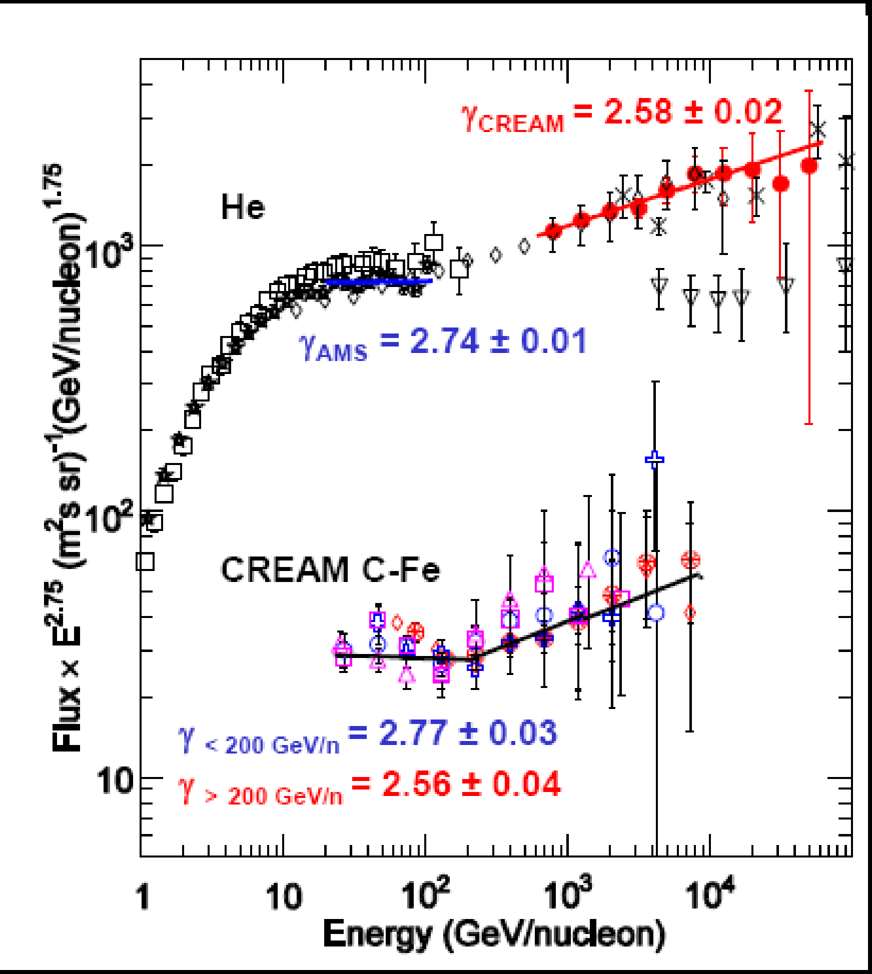
PAMELA & BESS-PolarII proton spectrum in same temporal frame

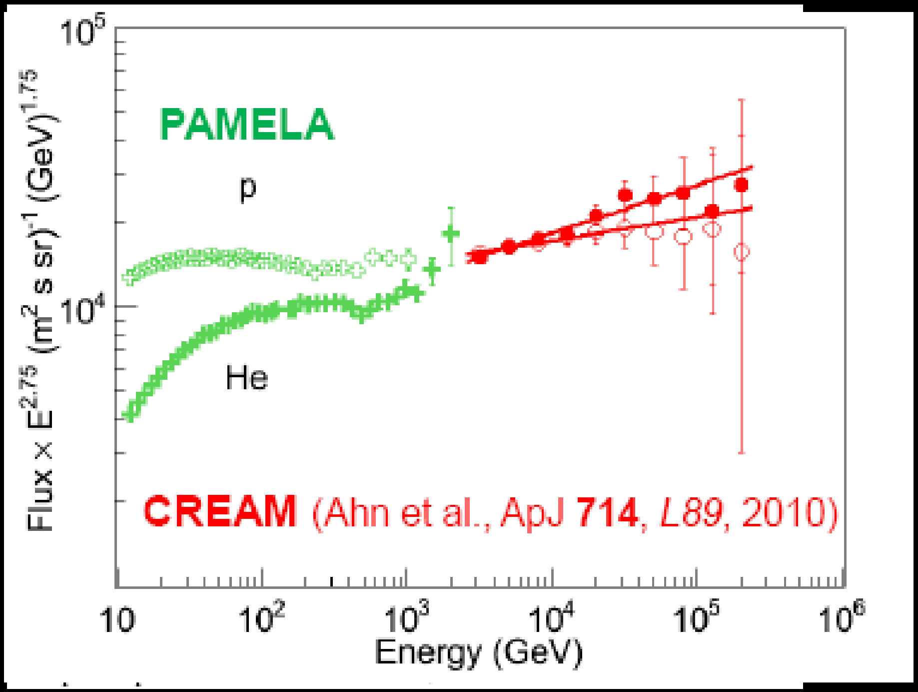
Agrement within 4%

Constant with years



At higher energies: Cream data



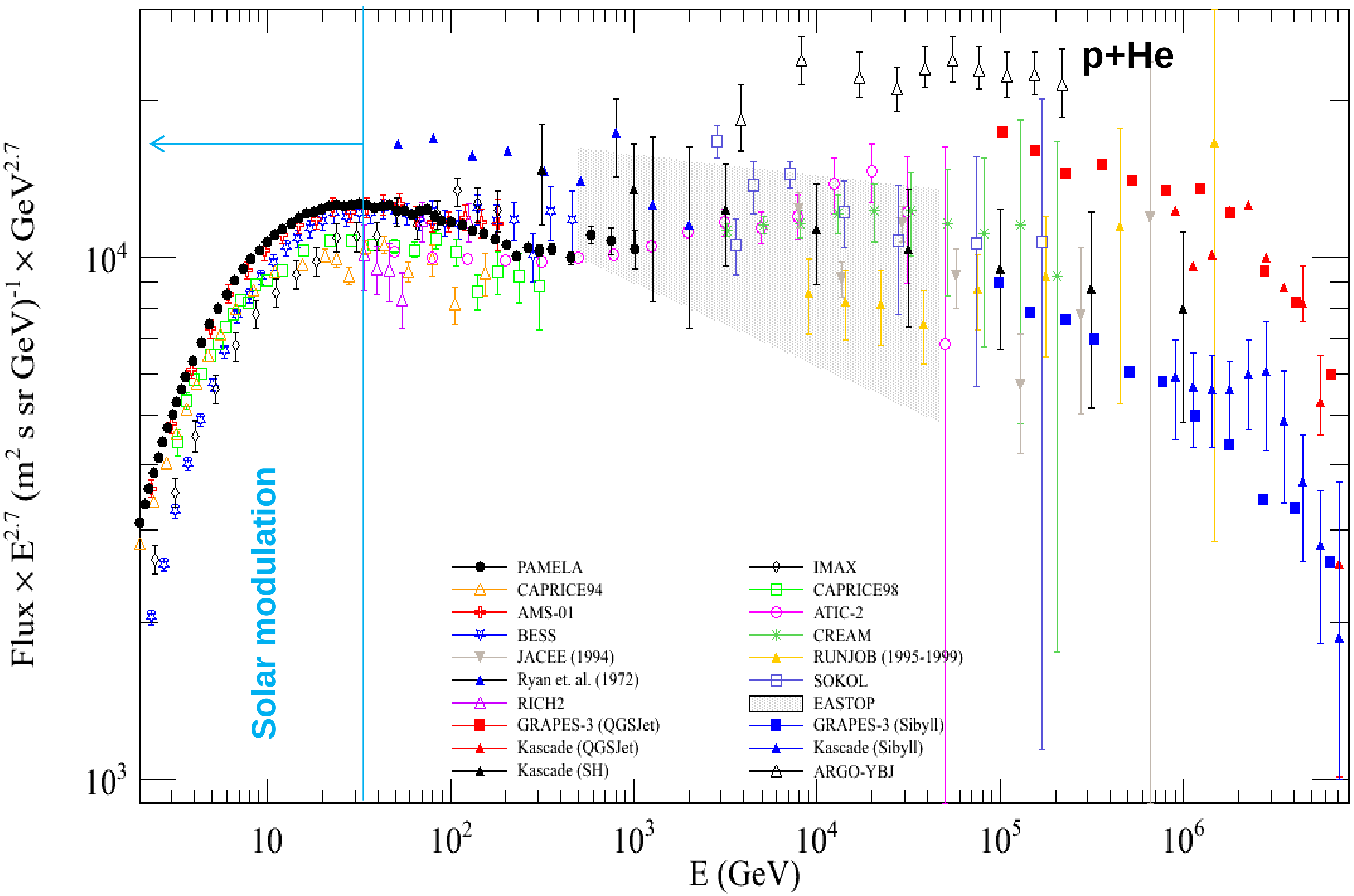


Ahn et al, ApJL 2010

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

Indirect p, He Direct C-Fe

…at yet higher energies



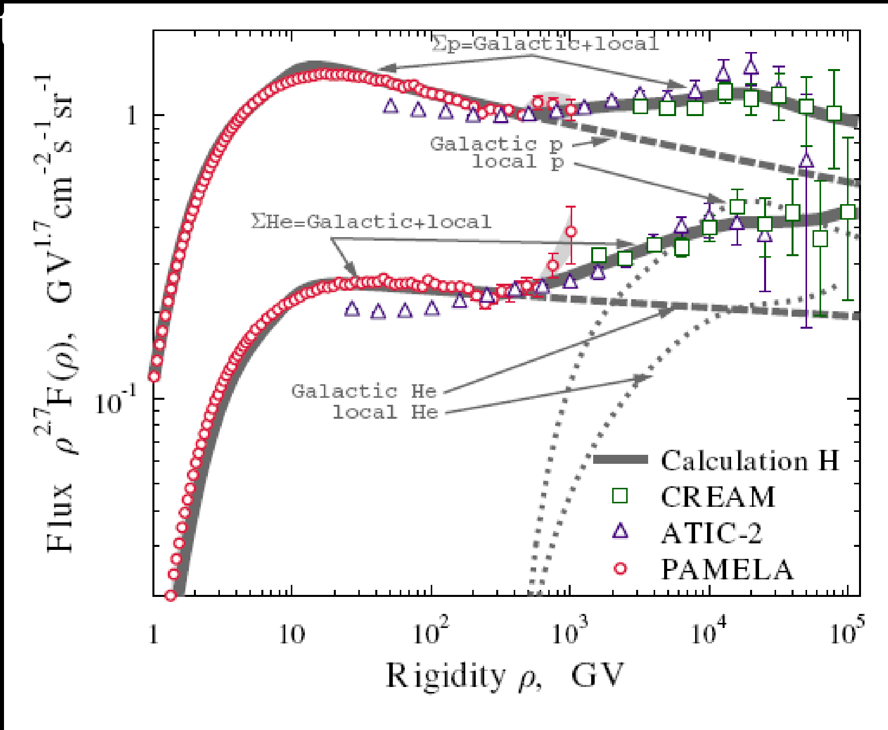
Conclusion from Proton and Helium

- 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

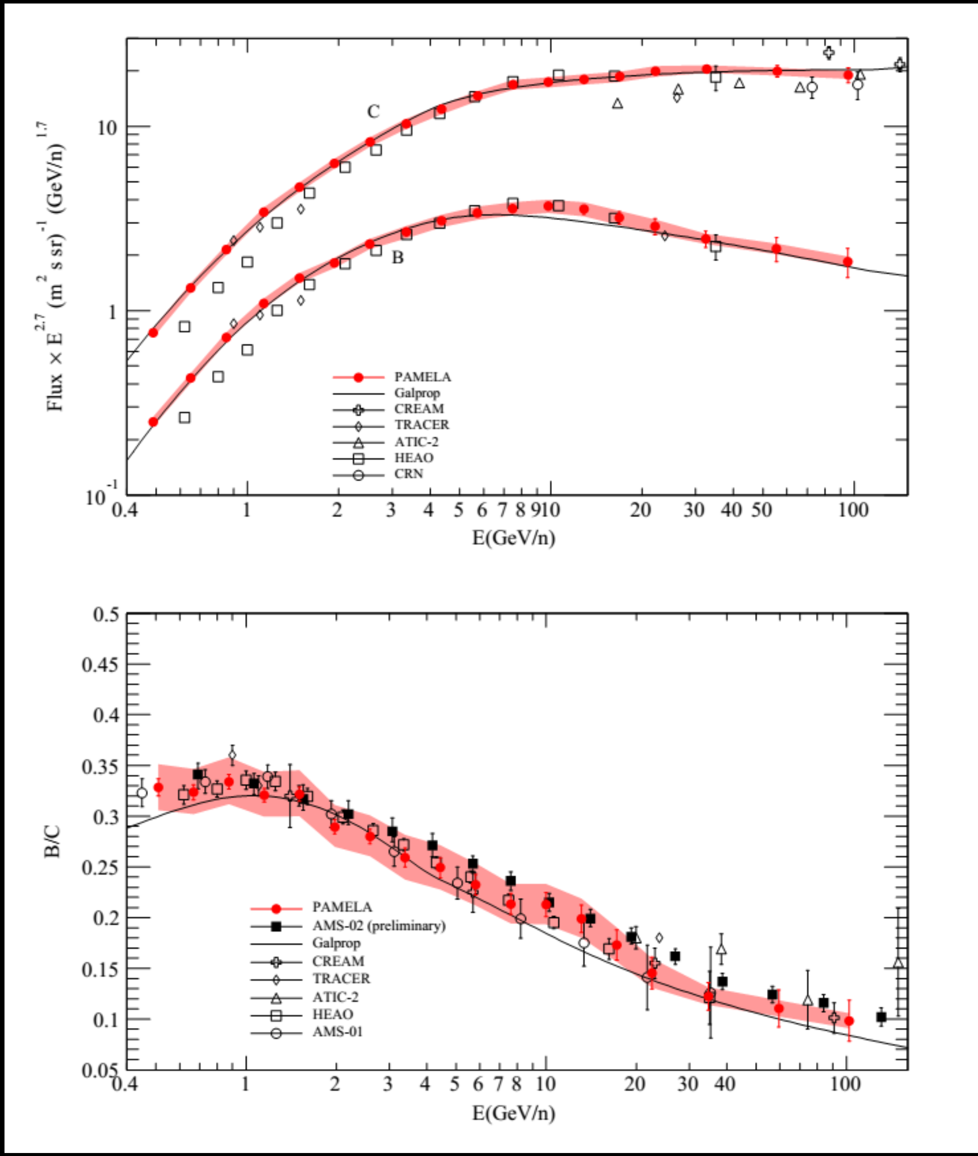
Secondary/primay

CNO+ISM → B

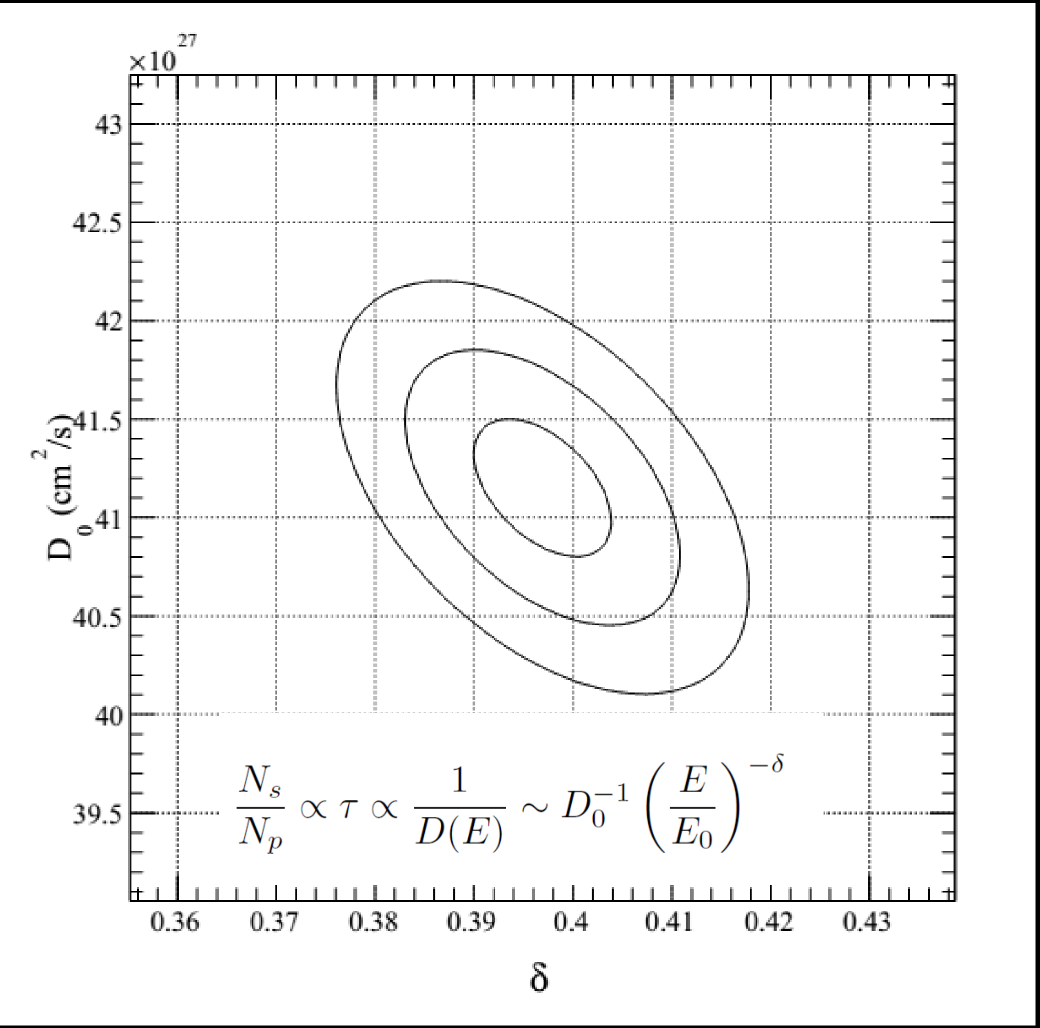
$$N_B / N_C \propto \lambda_{esc} \cdot \sigma_{CNO \to B}$$

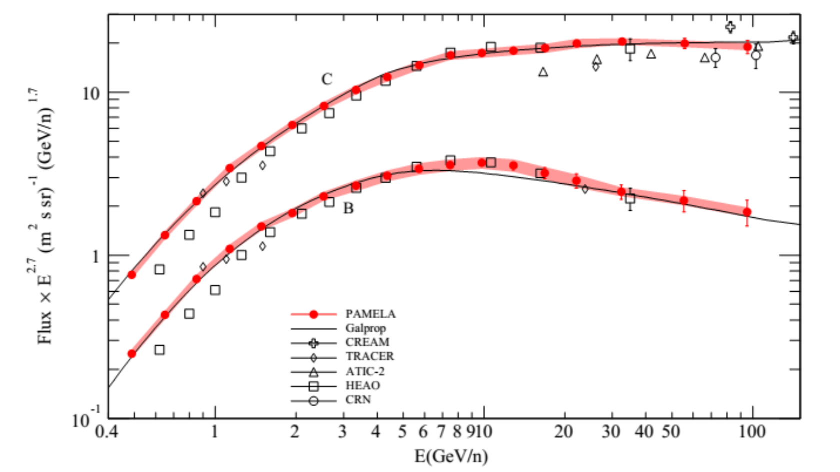
→ Propagation in the Galaxy

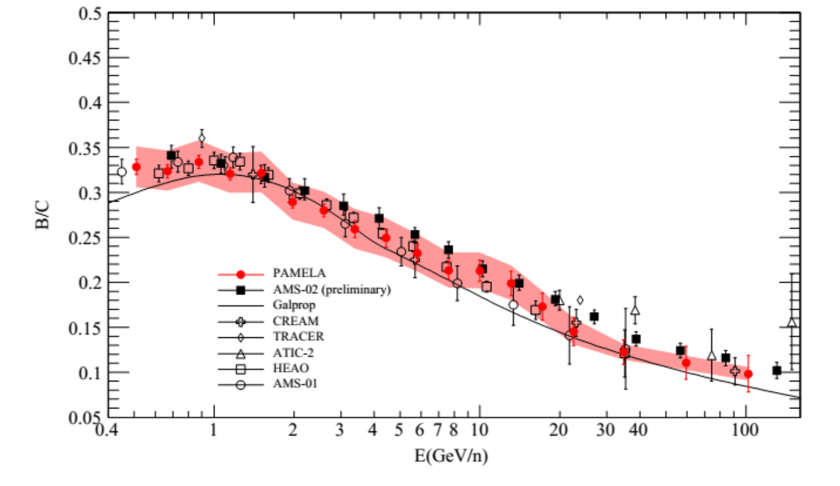
Time of permanence of cr



Propagation in the galaxy





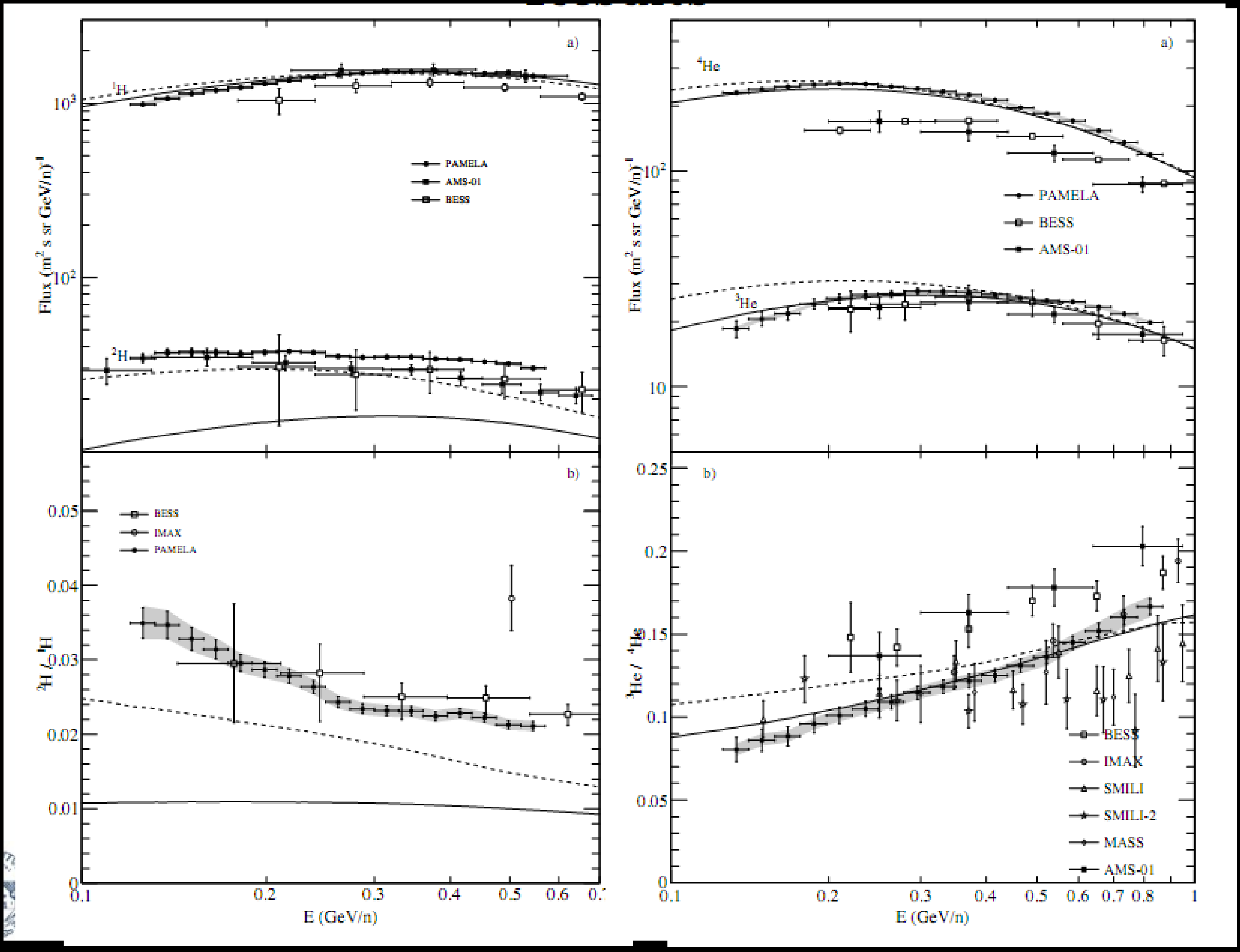


H and He Isotopes

Propagation in the Galaxy

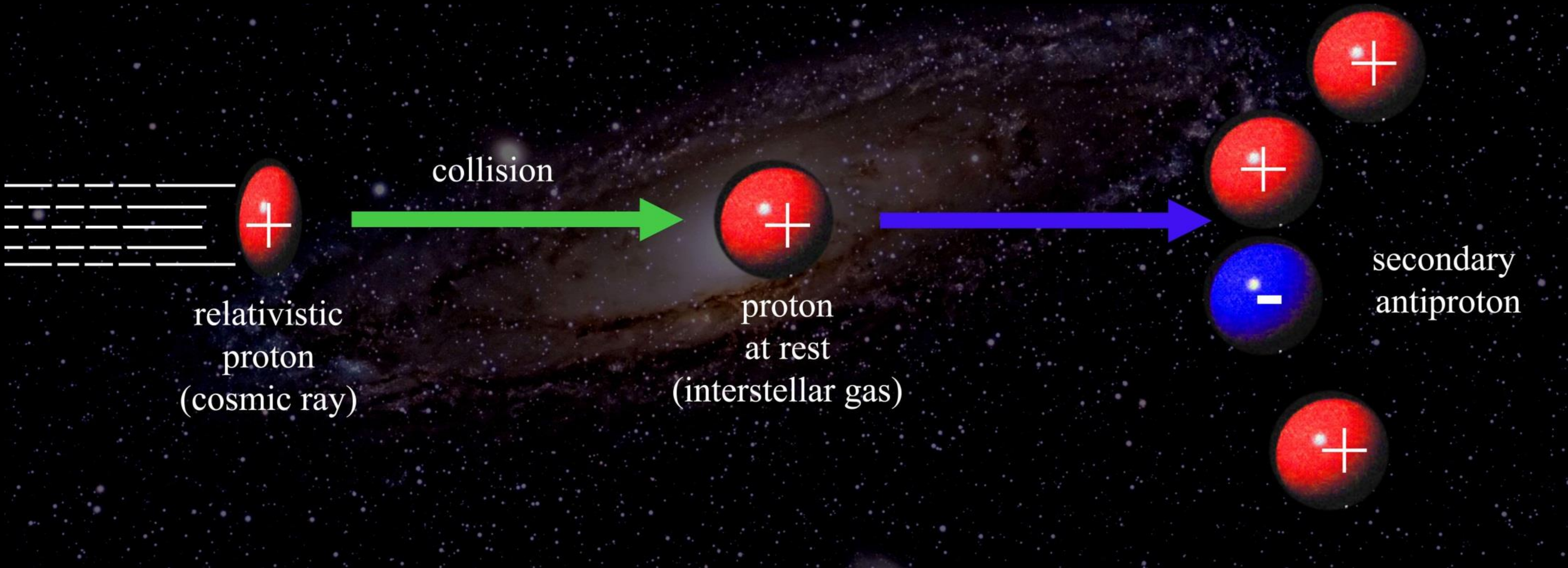
- Flux depends on solar modulation
- Ratio is less dependent
- Strong tool for evaluating secondary particle production in the galaxy
- Complementary to B/C

ApJ 770:2, 2013

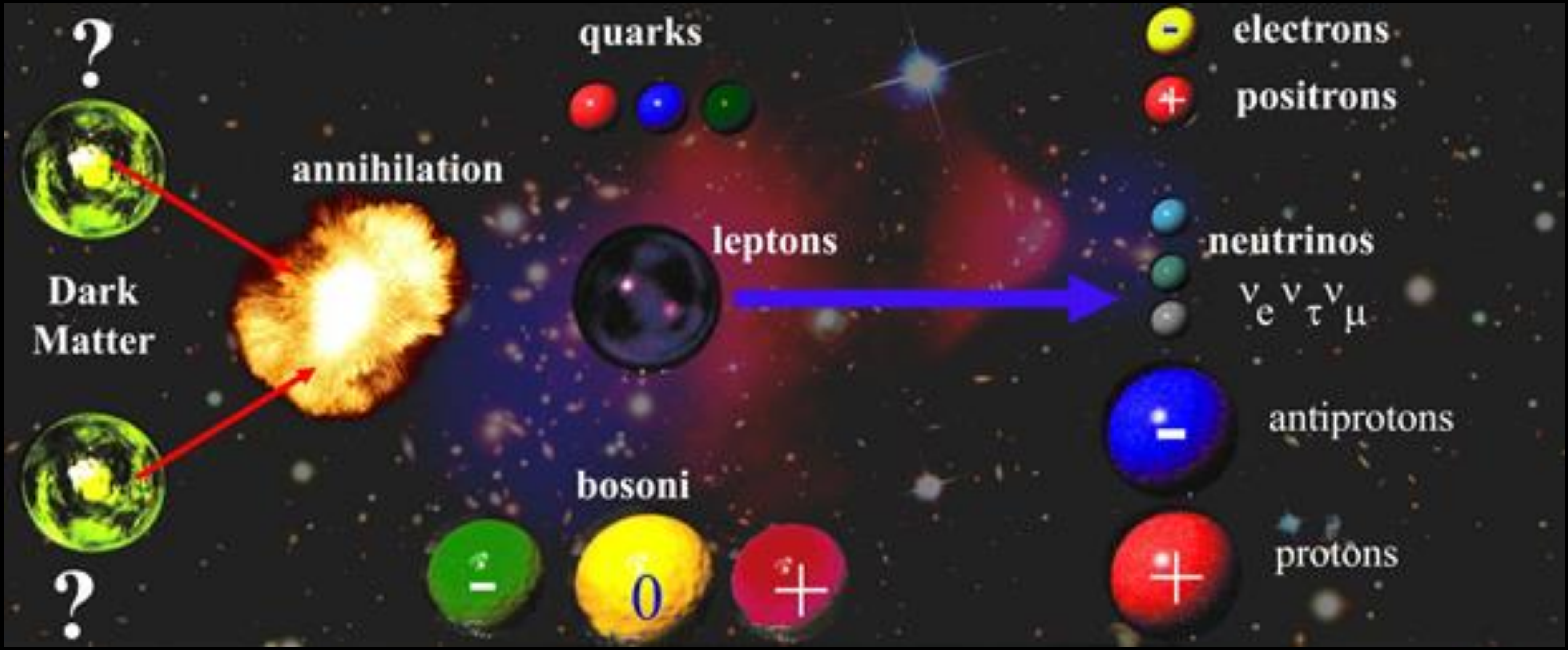


Antiprotons

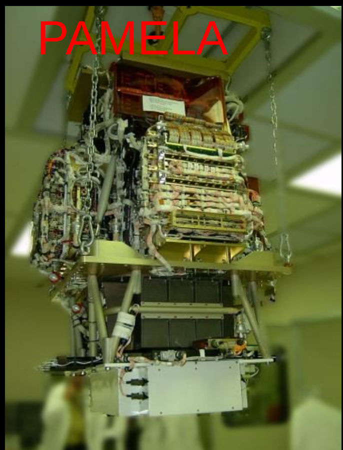
- Secondary production, kinematics well understood
- Probe for extra sources
- Galactic scale

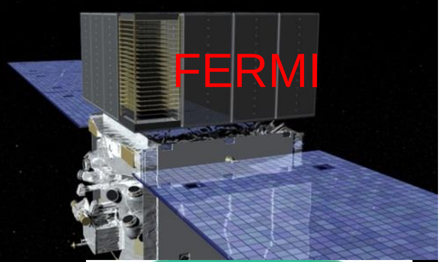


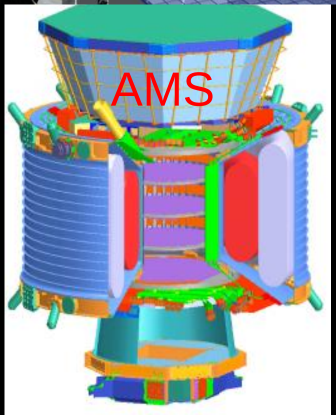
Indirect Dark matter search in space

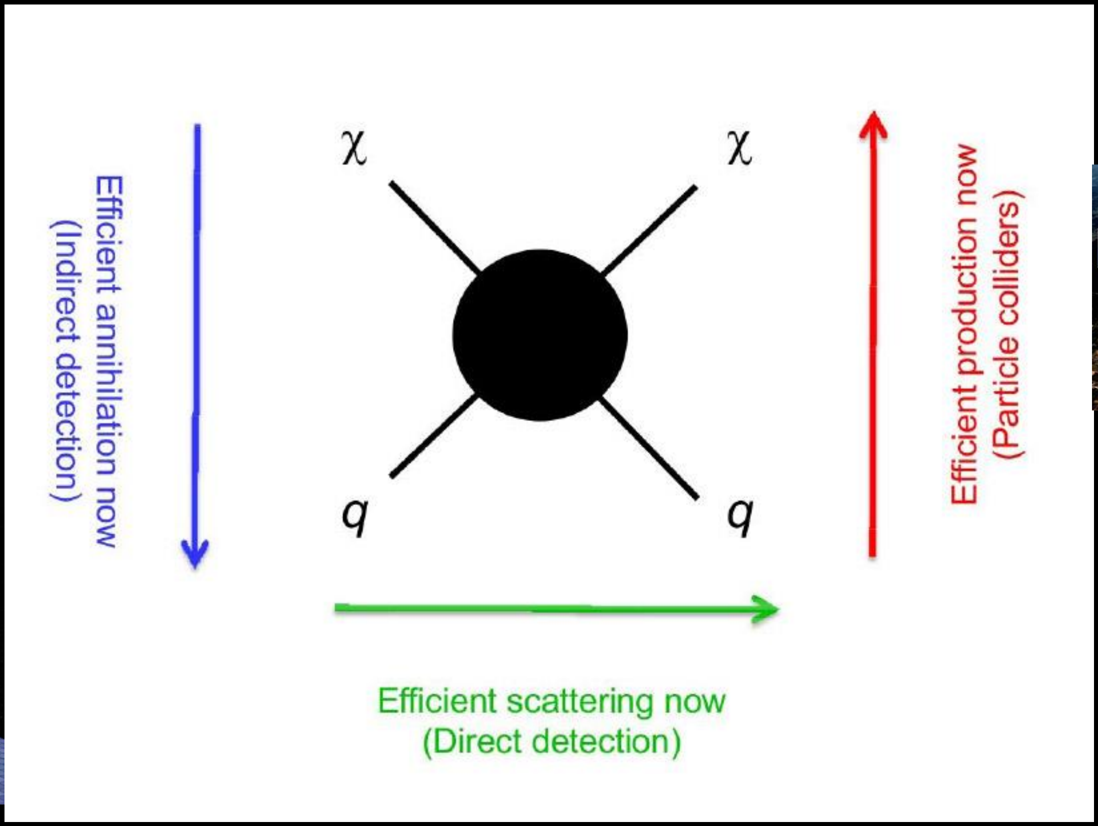


Search (and constrain) Dark Matter





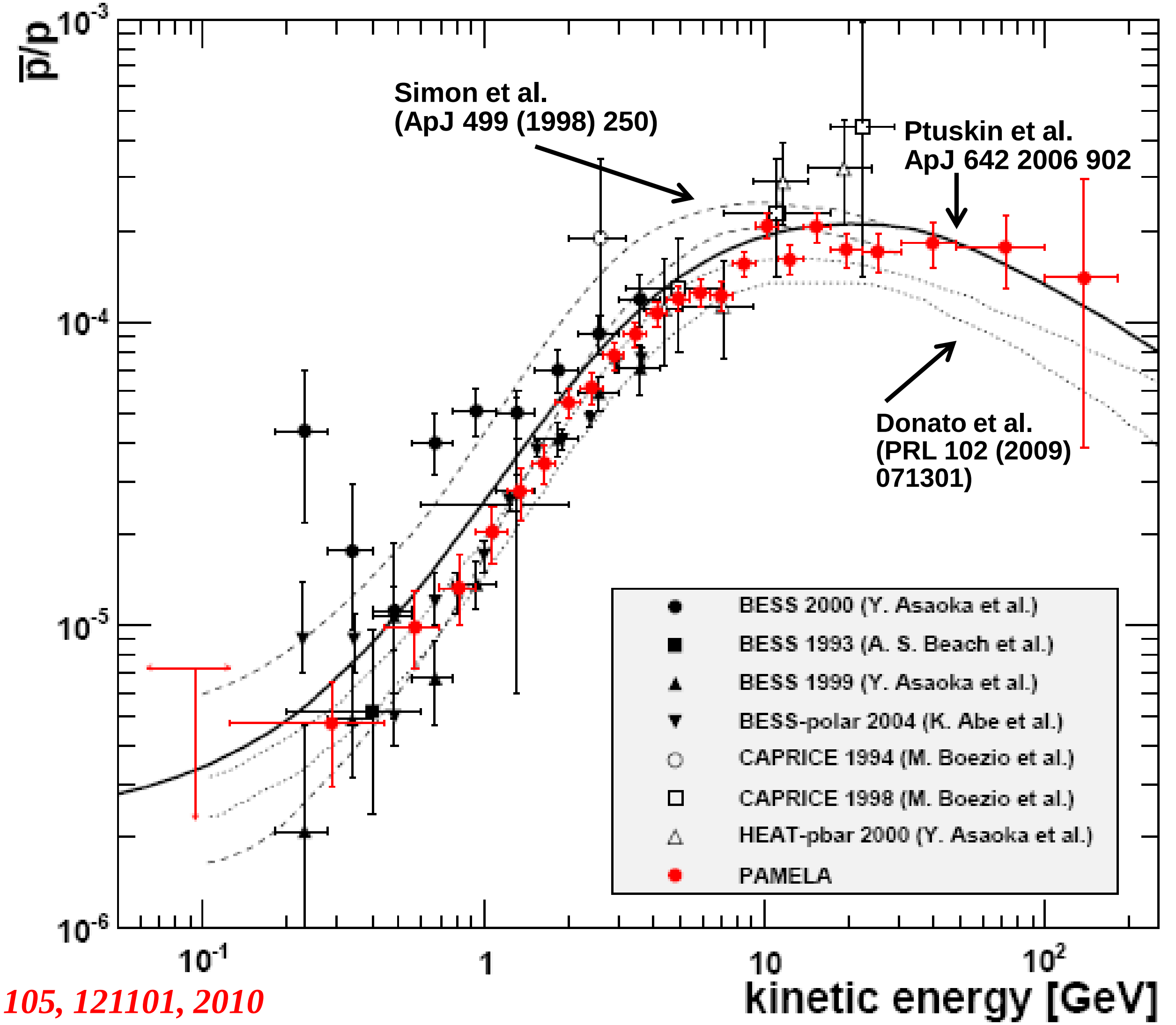




Antiproton/proton ratio

Low Energy →
Confirms charge dependent solar modulation

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



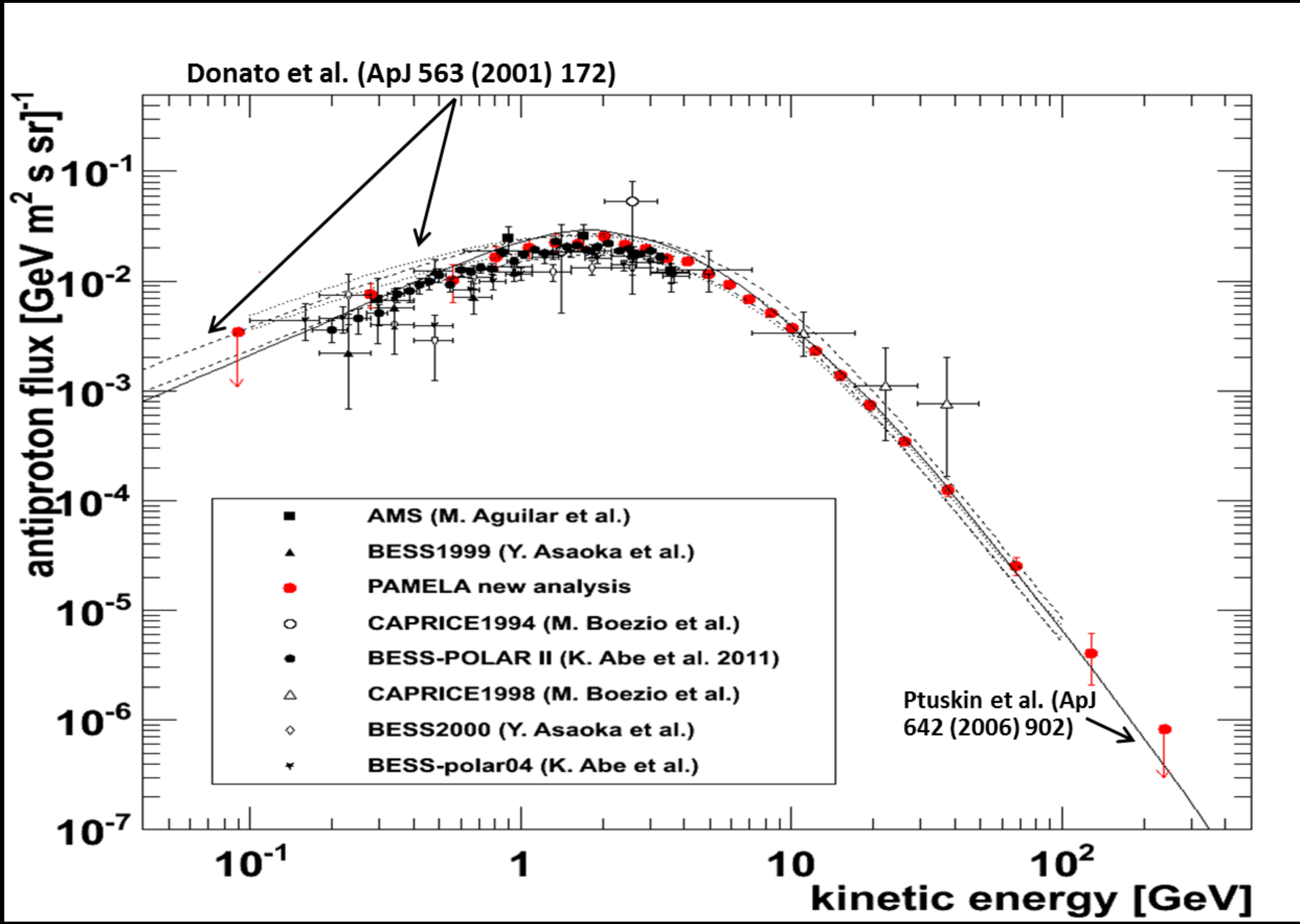
PRL. 105, 121101, 2010

PRL 102:051101,2009

Antiproton absolute flux

Apparently no extra sources

Rule out and strongly constrain many models of DM

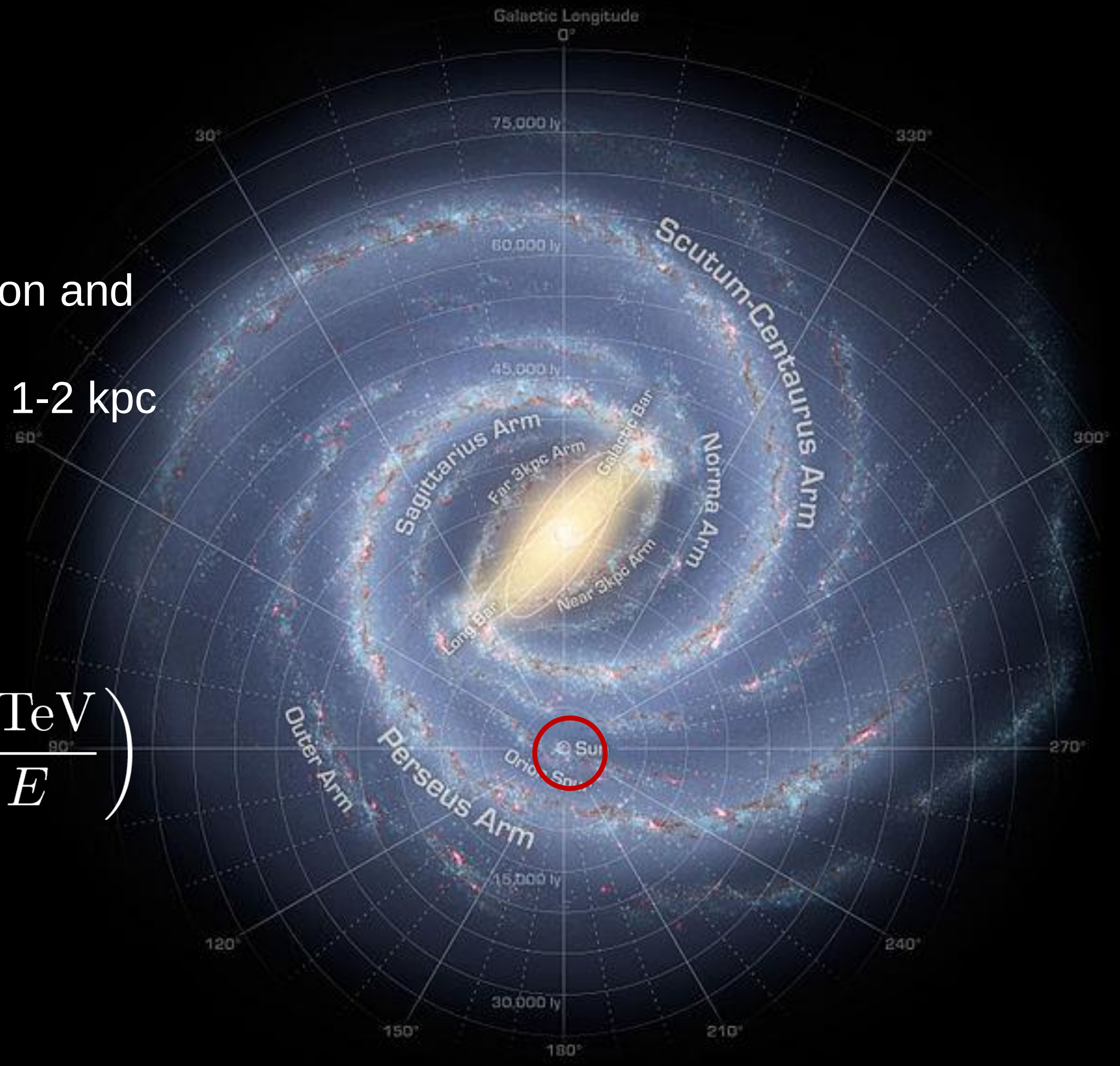


S M. Asano, et al, Phys. Lett. B 709 (2012) 128.
R. Kappl et al , PRD 85 (2012) 123522
M. Garnyet al, JCAP 1204 (2012) 033
D. G. Cerdeno, et al, Nucl. Phys. B 854

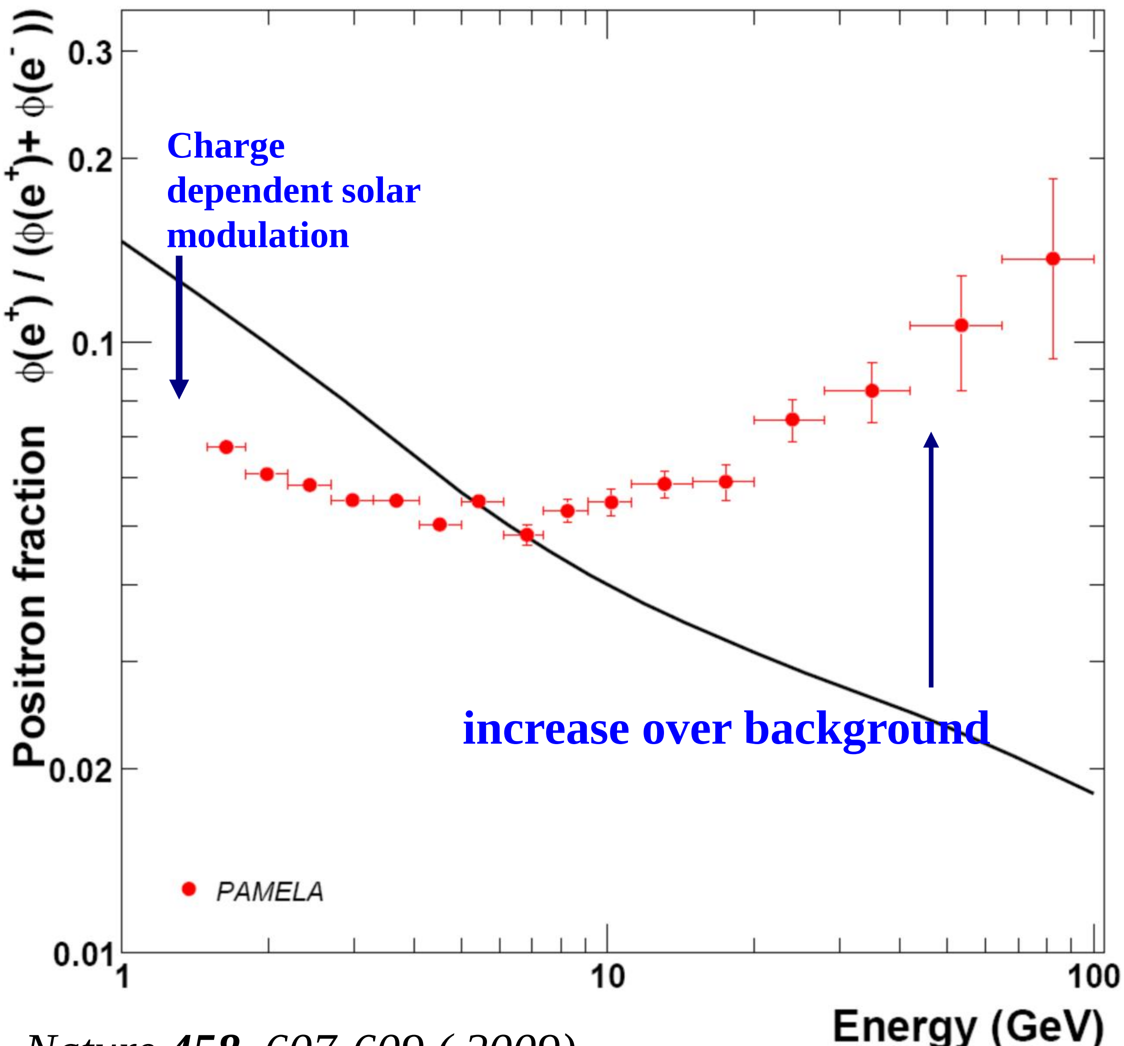
Galactic neighborhood:
e+, e- (1-2 kpc)

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

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

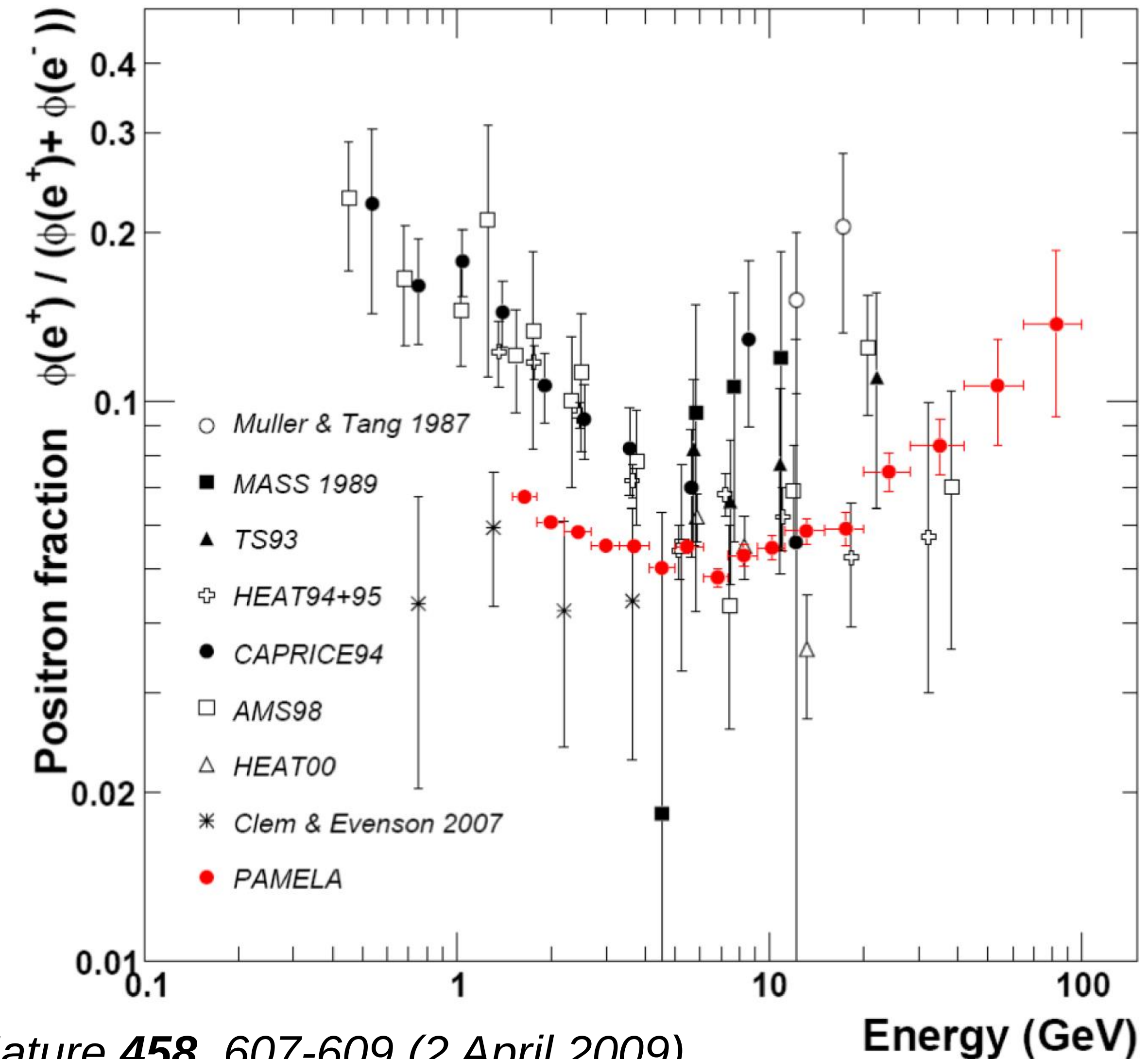


Pamela positron fraction

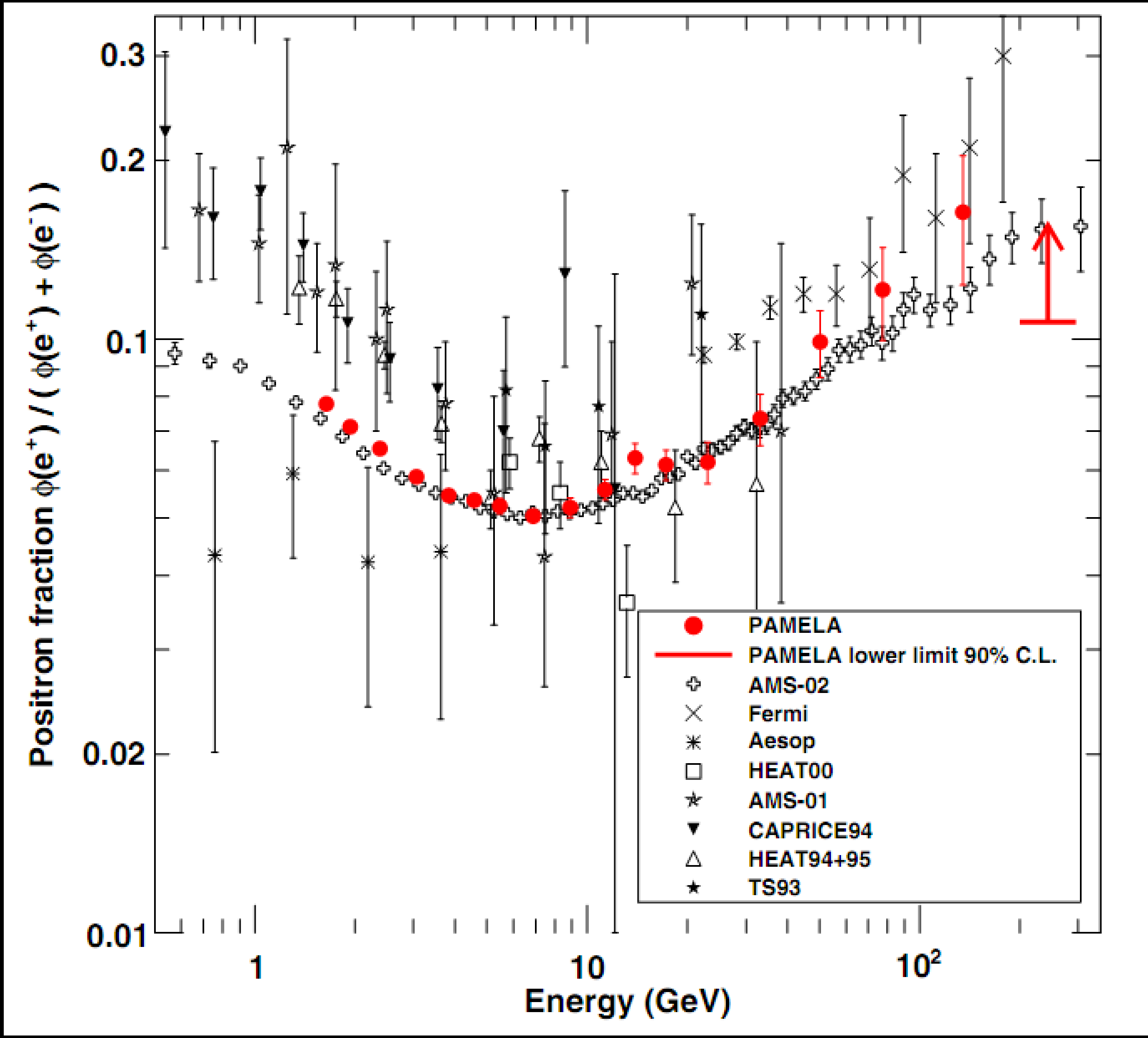


Nature ***458****, 607-609 (2009)*

Pamela positron fraction: comparison with other data



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

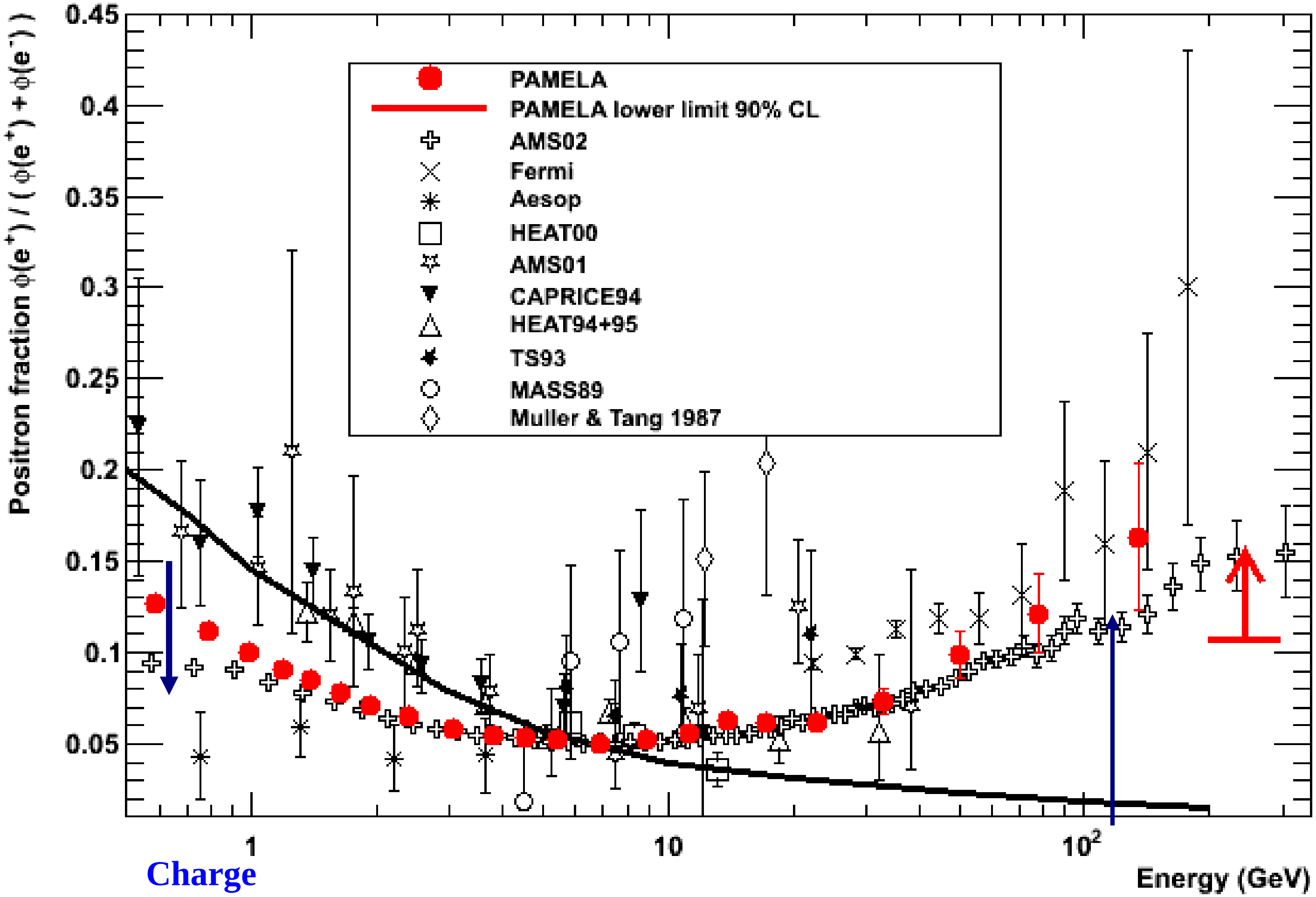


Positron fraction φ(e⁺) / (φ(e⁺) + φ(e⁻))
0.3
0.2
0.1
0.02
0.01
1
10
10²
Energy (GeV)
PAMELA
PAMELA lower limit 90% C.L.
AMS-02
Fermi
Aesop
HEAT00
AMS-01
CAPRICE94
HEAT94+95
TS93

AMS & FERMI confirm PAMELA data

Anomalous source at high energy

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

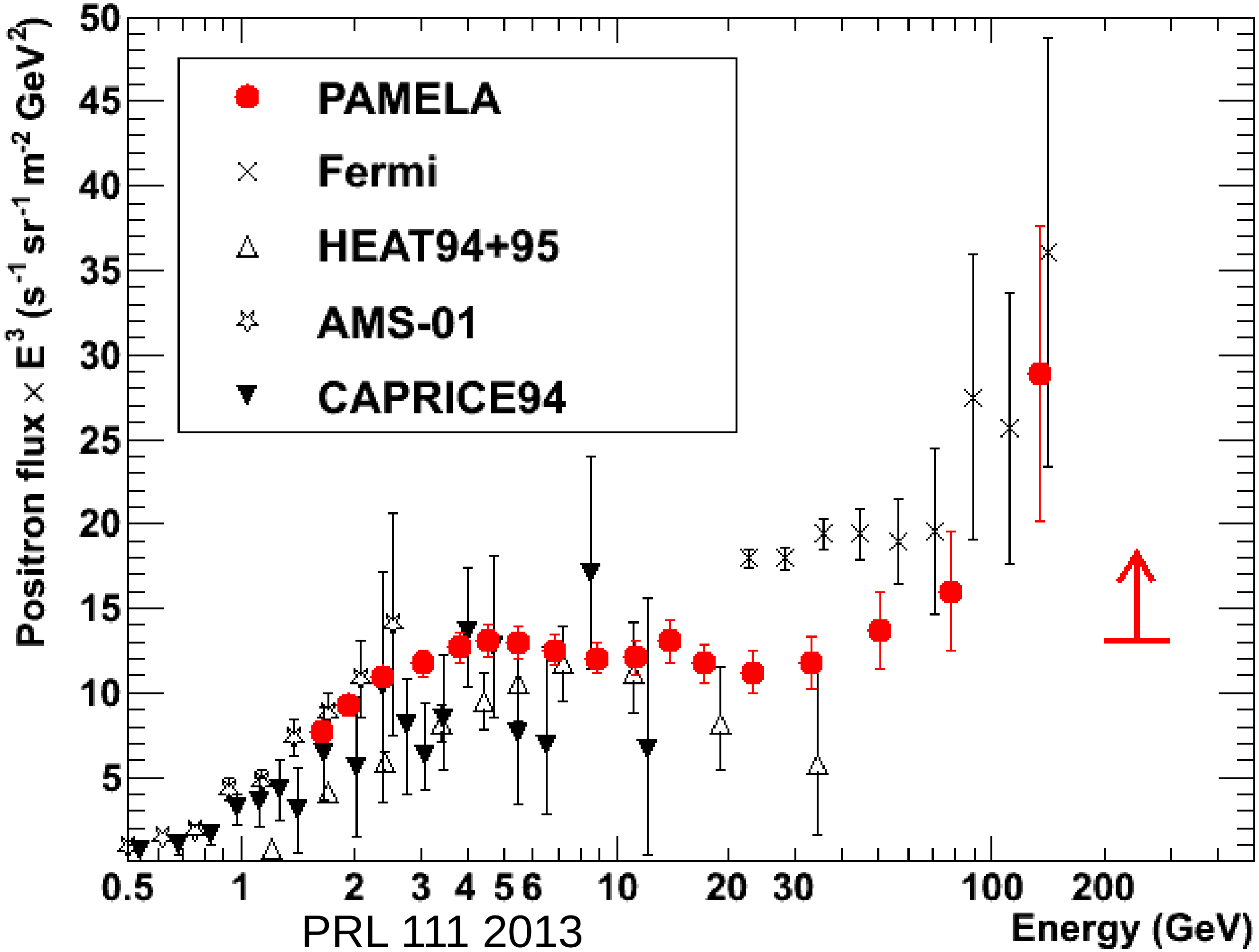


Charge dependent solar modulation

L. Maccione, PRL 110 (2013) 081101

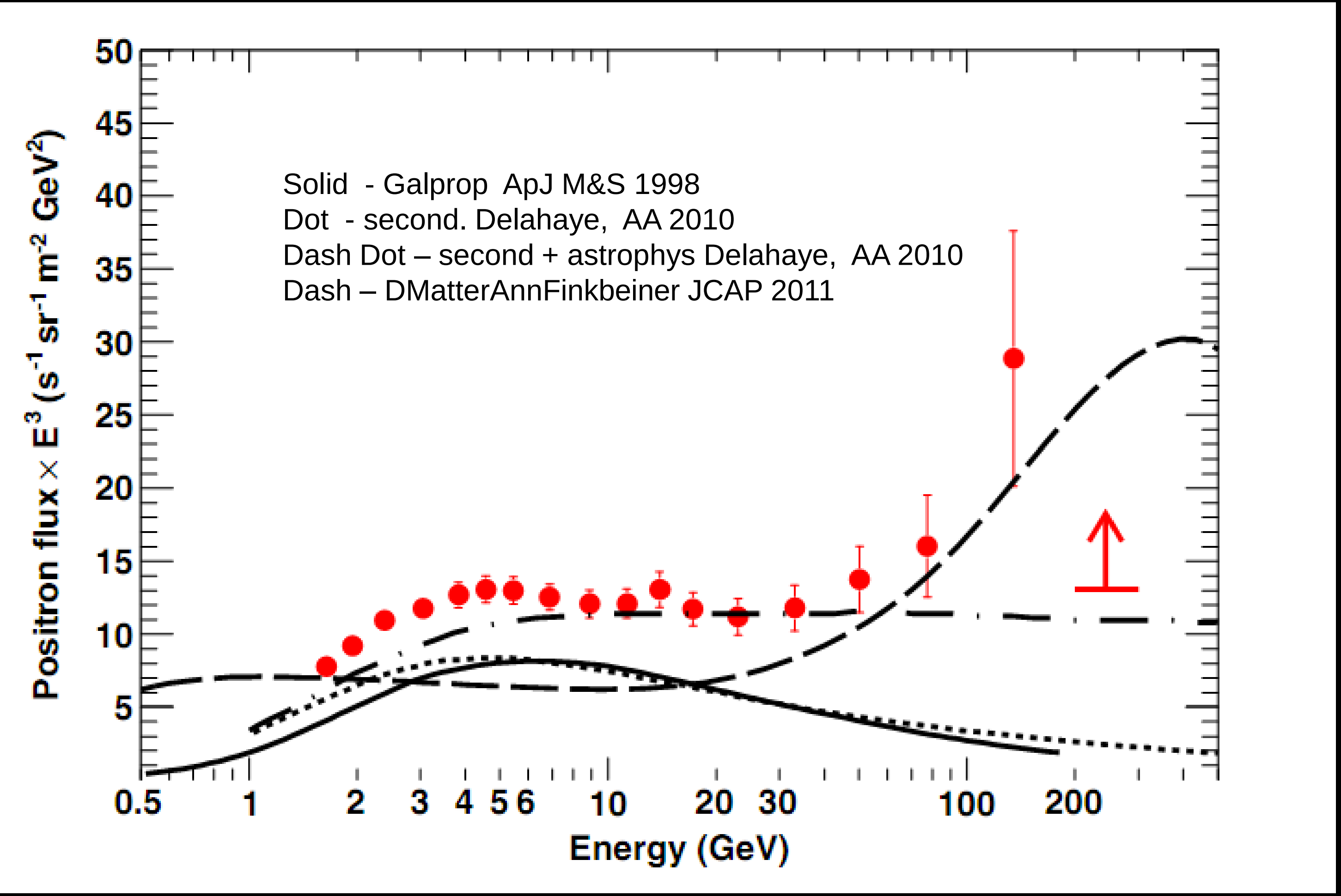
Absolute positron spectrum

Propagation
Charge
dependent solar
modulation

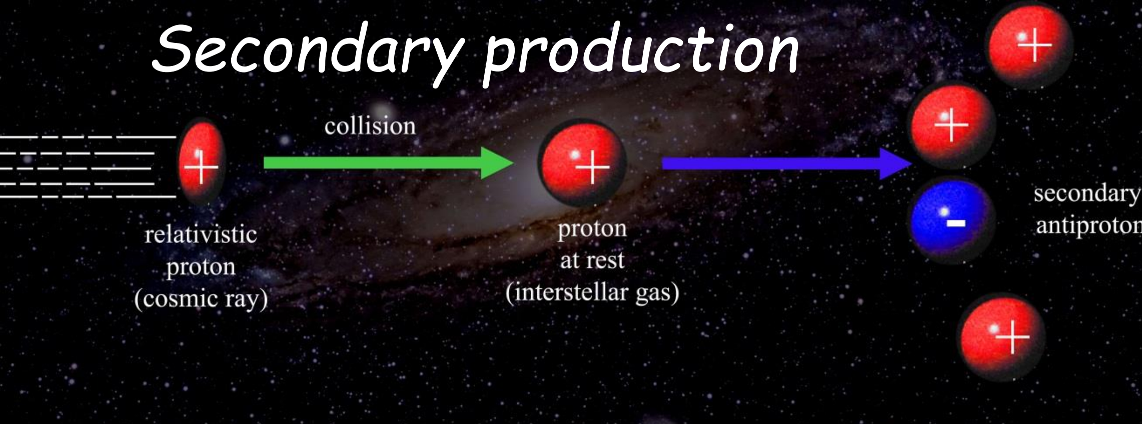


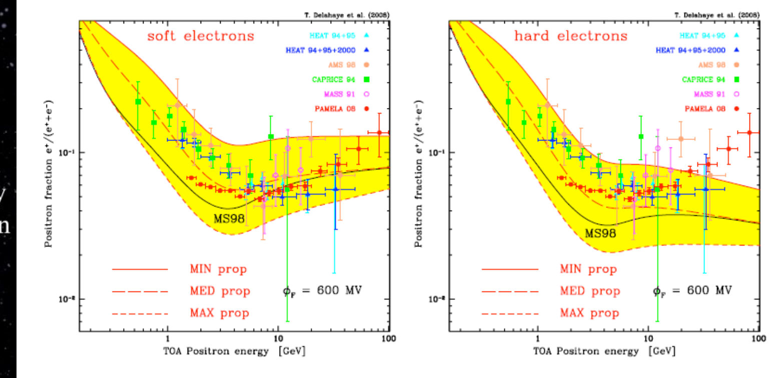
PRL 111 2013

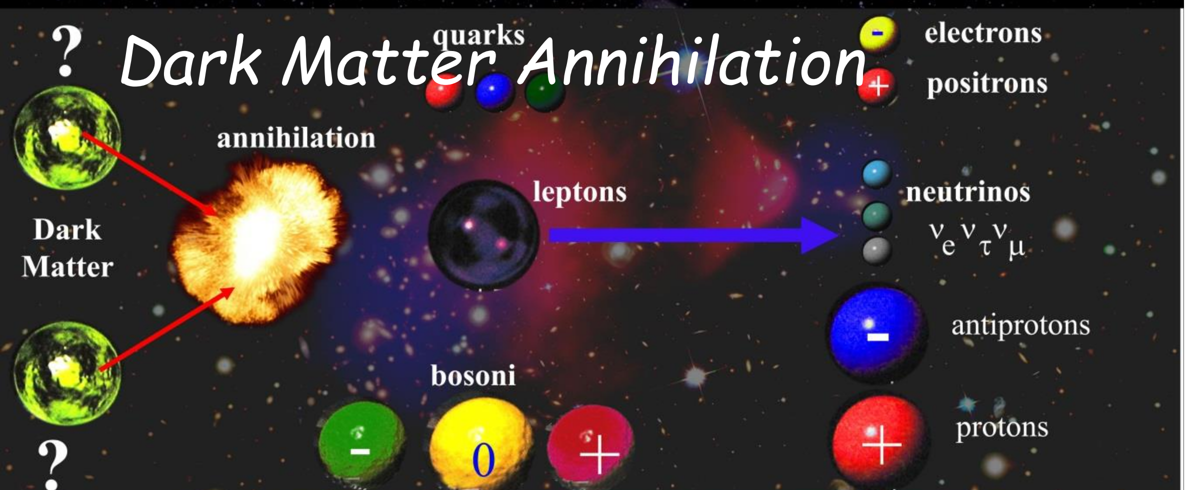
PRL111, 081102 (2013)



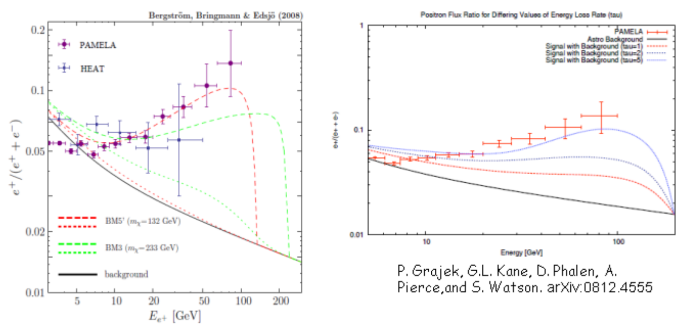
PRL111, 081102 (2013)





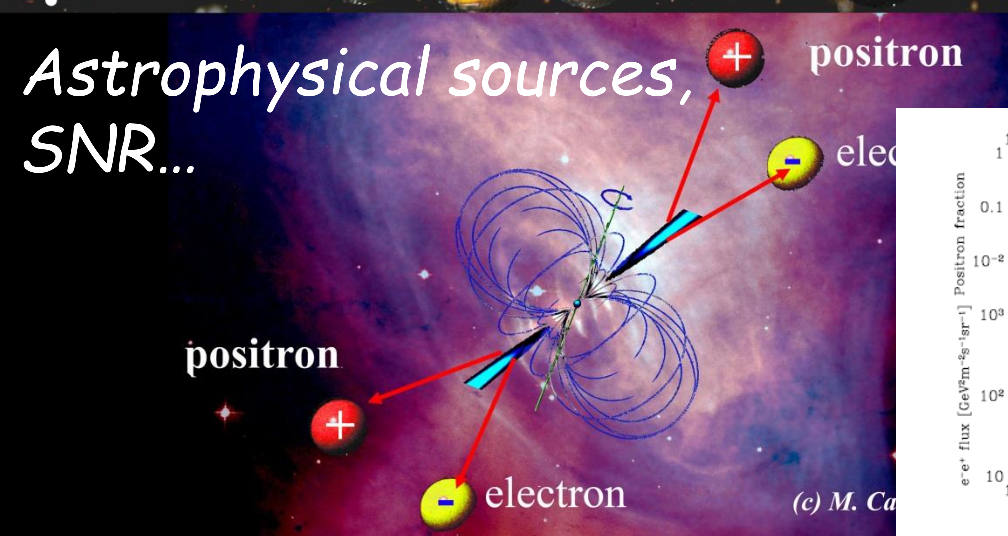


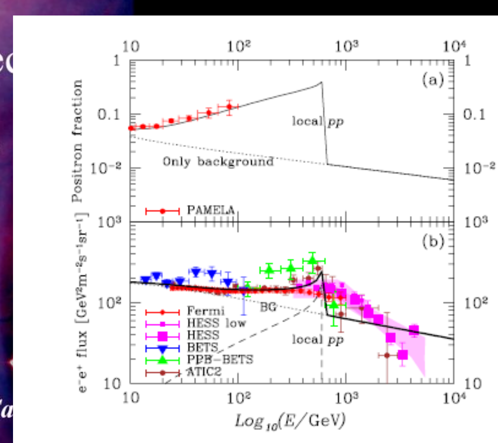
2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum:

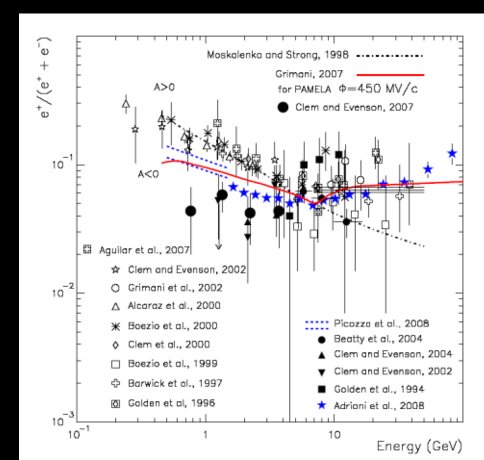


P. Grajek, G.L. Kane, D. Phalen, A. Pierce, and S. Watson. arXiv:0812.4555

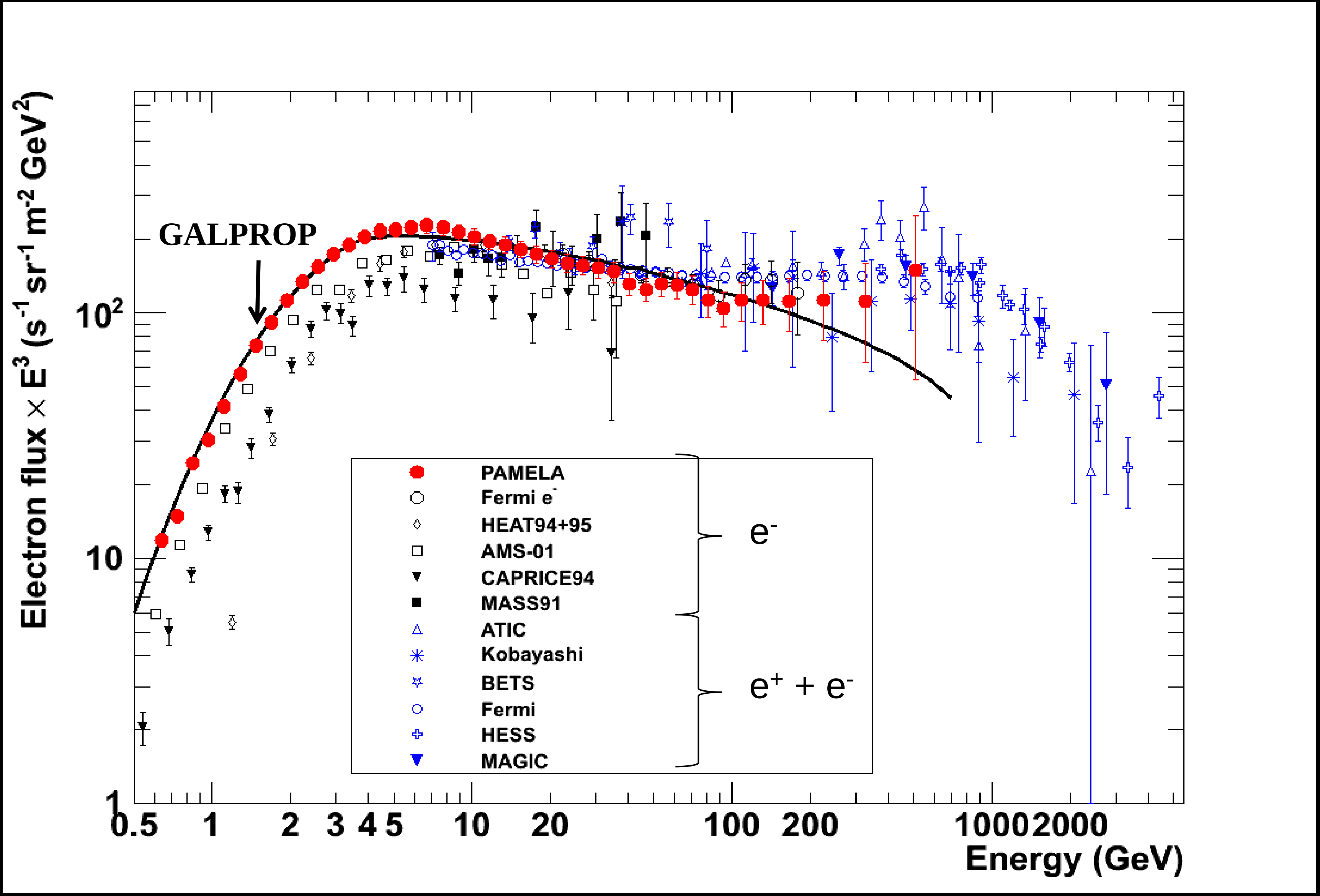
However, does not explain new electron plus positron data (see later)



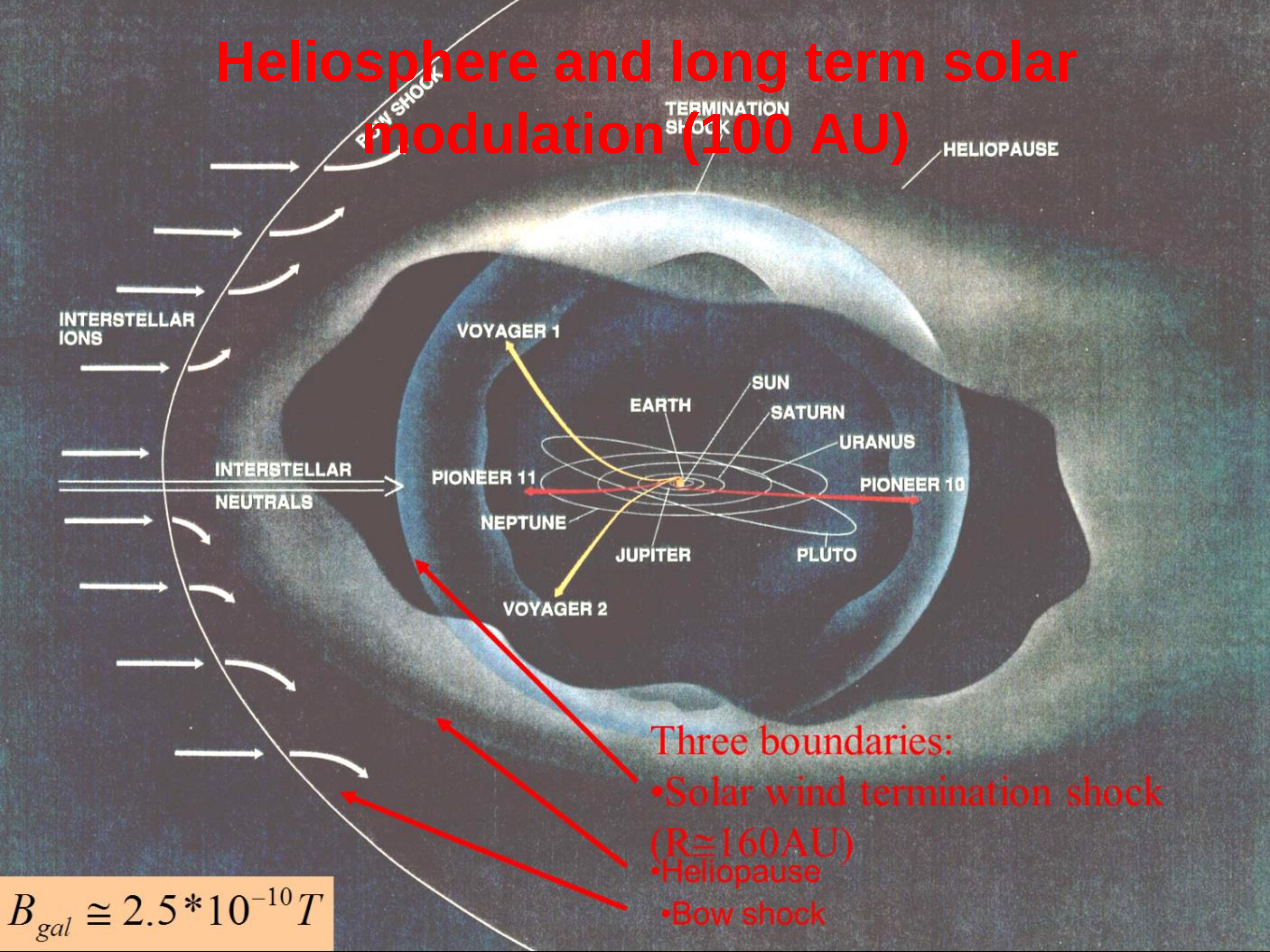




Electron spectrum



Heliosphere and long term solar modulation (100 AU)

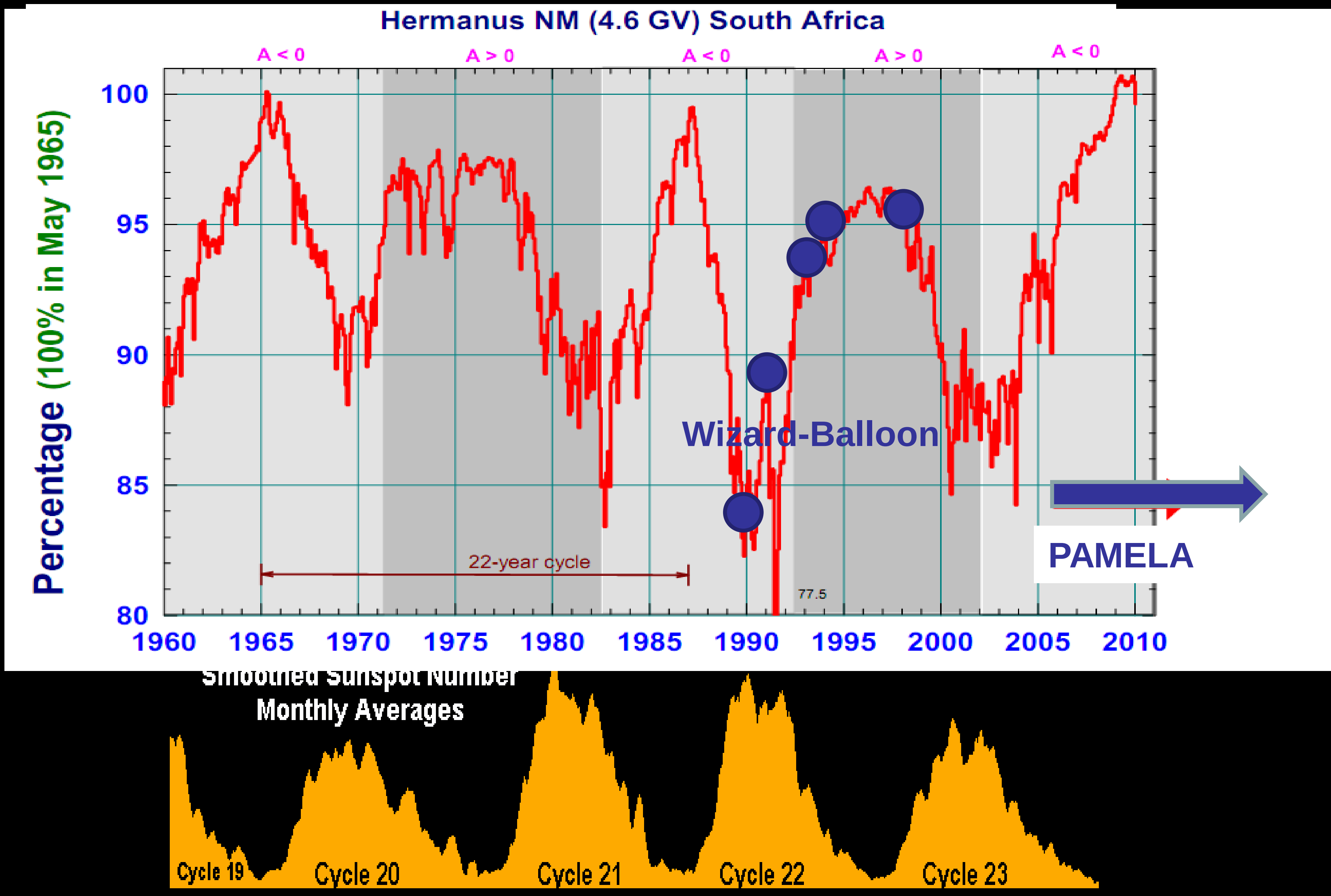


Three boundaries:

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

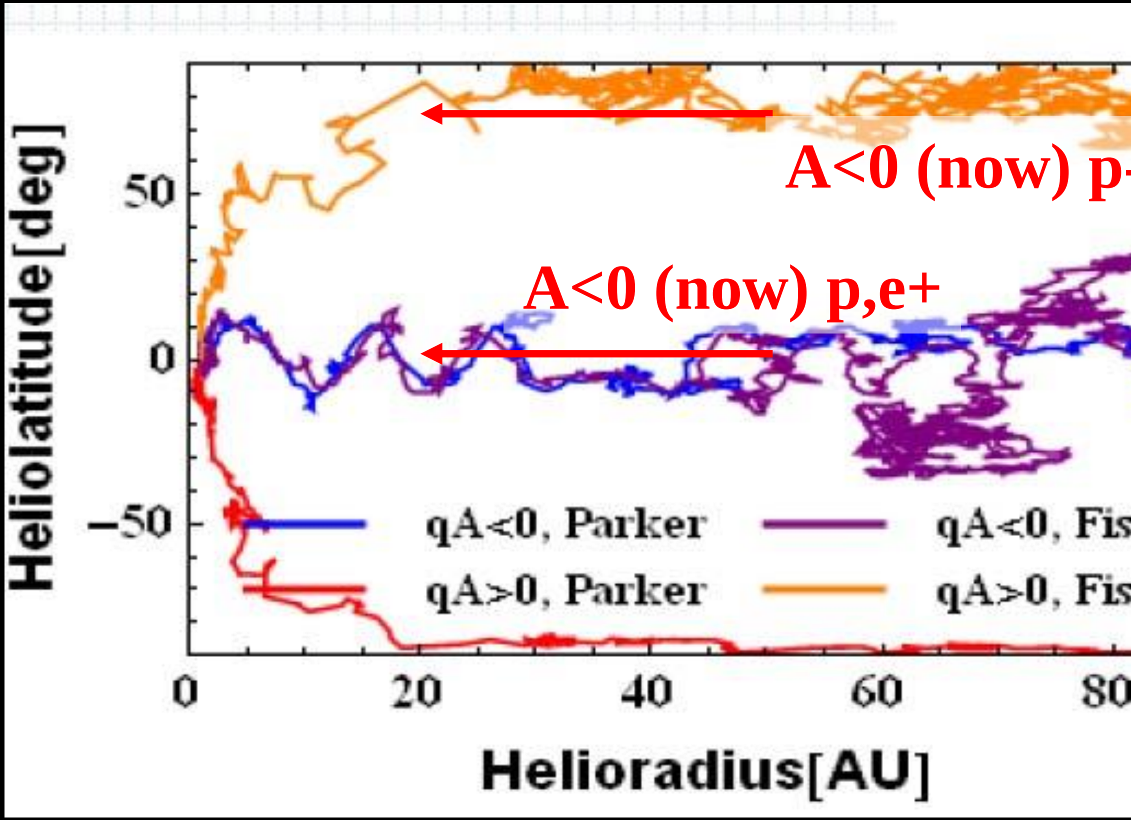
$$B_{gal} \cong 2.5 * 10^{-10} T$$

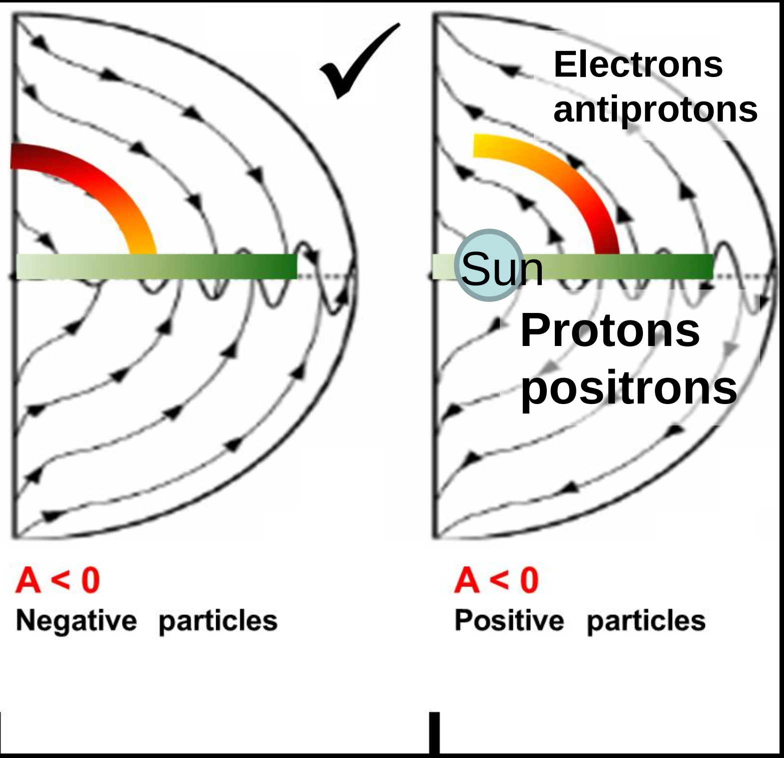
Solar modulation at minimum of solar cycle 23-24: 2006-2013



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



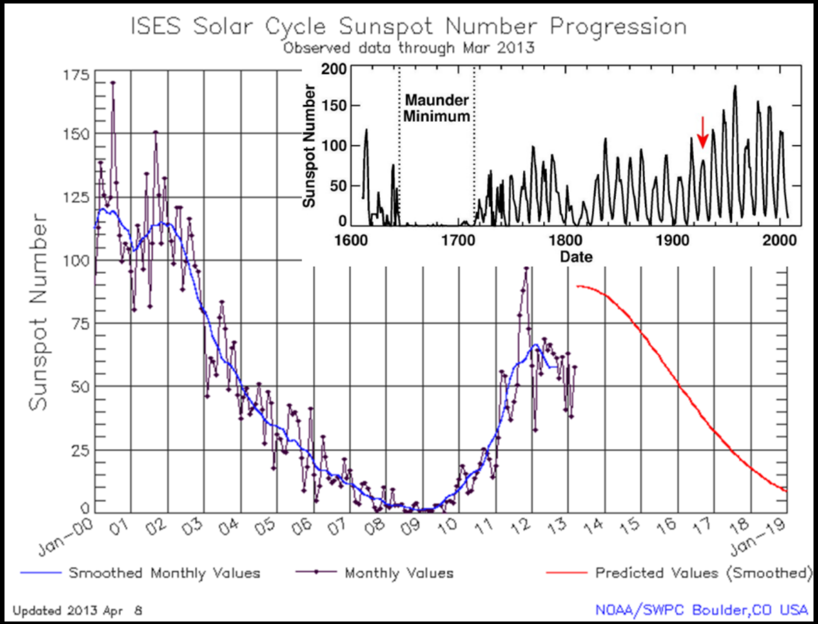


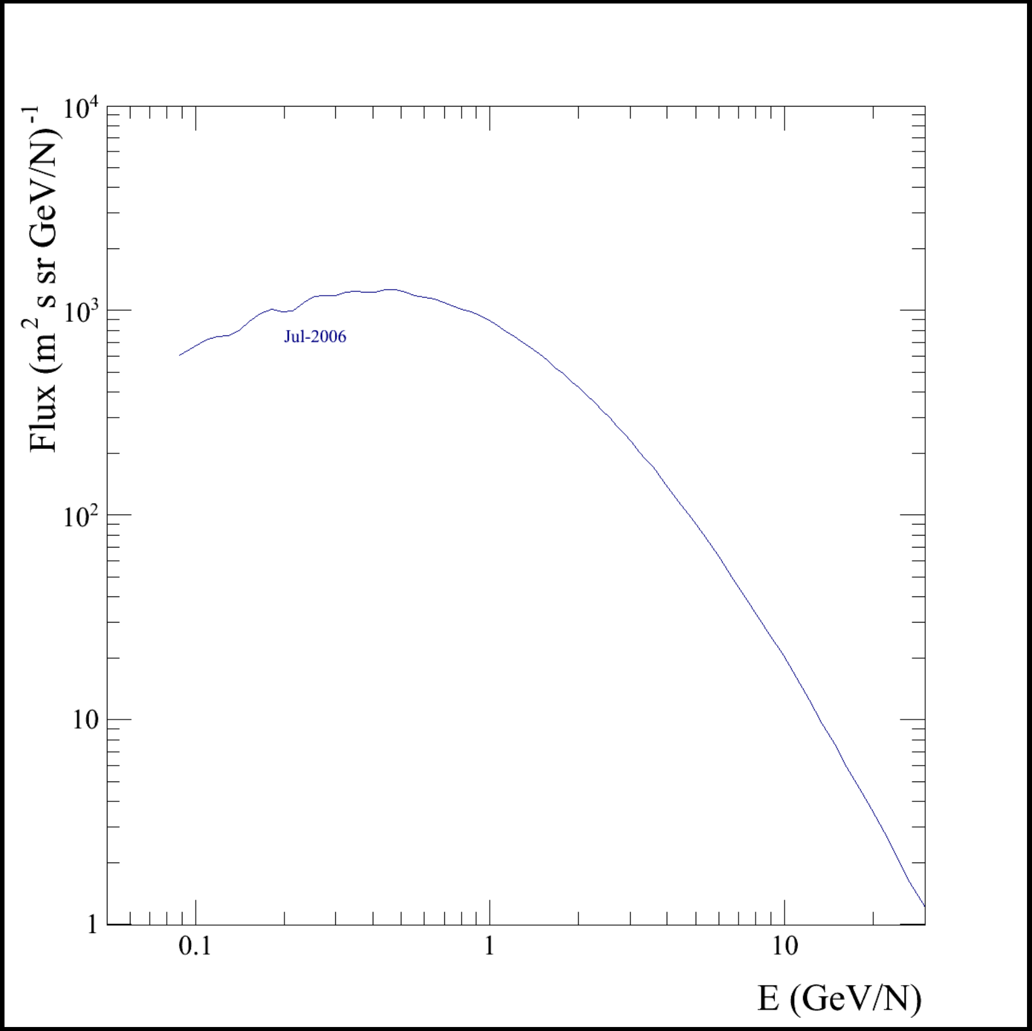
Solar modulation of galactic protons and nuclei

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)

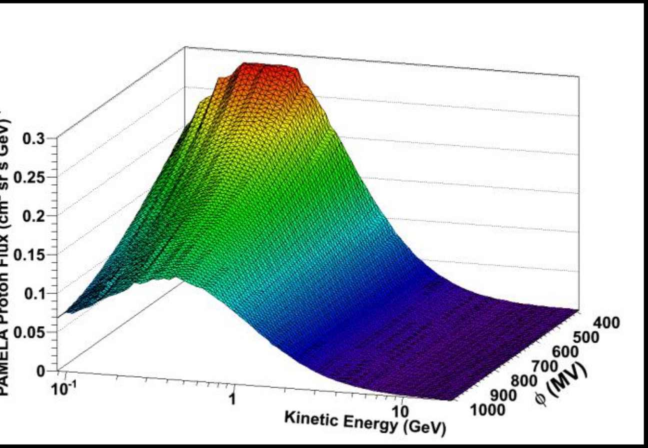
Spectral index

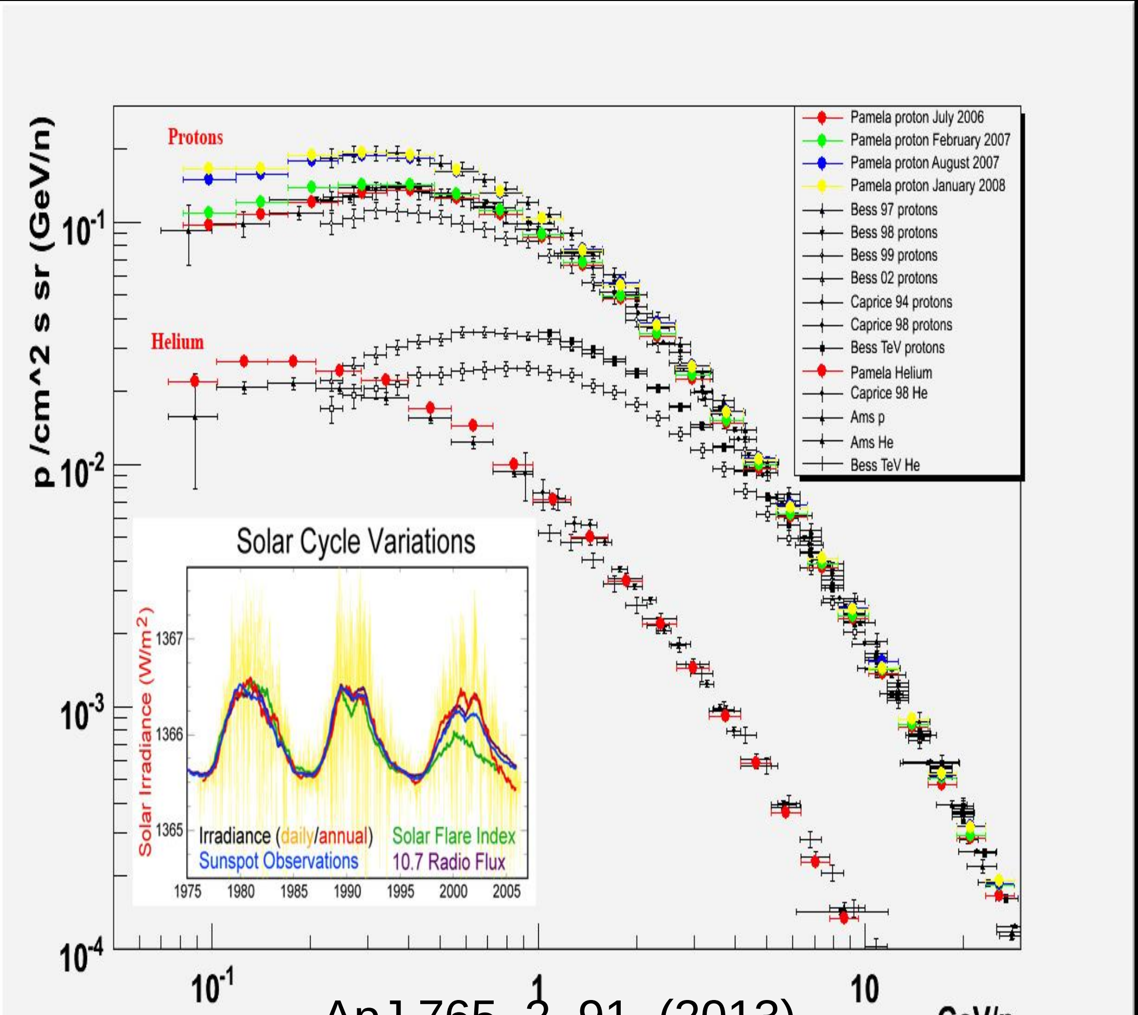
2.76 ±0.01

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

Solar modulation parameter

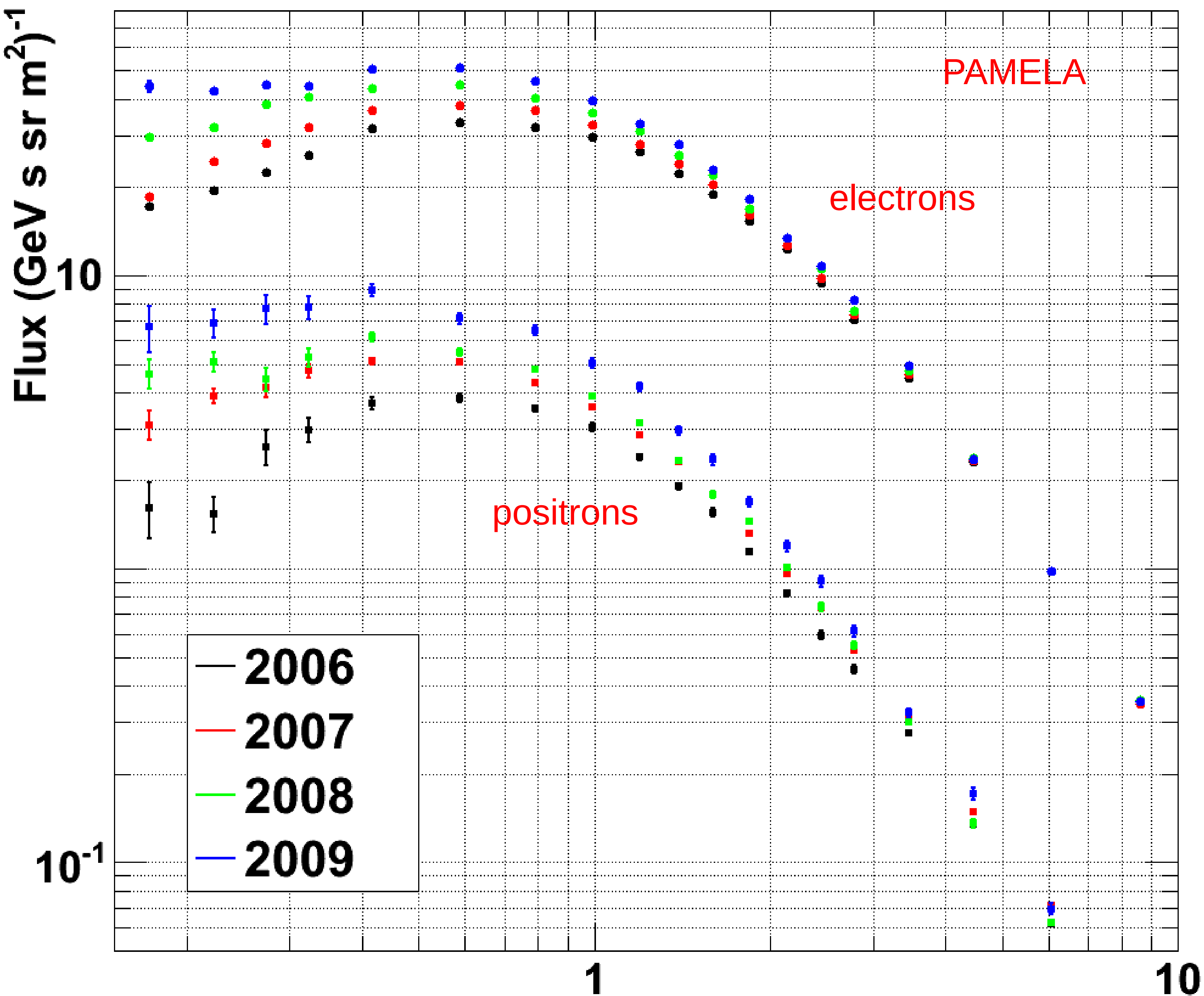
ϕ(GV)





ApJ 765, 2, 91, (2013)

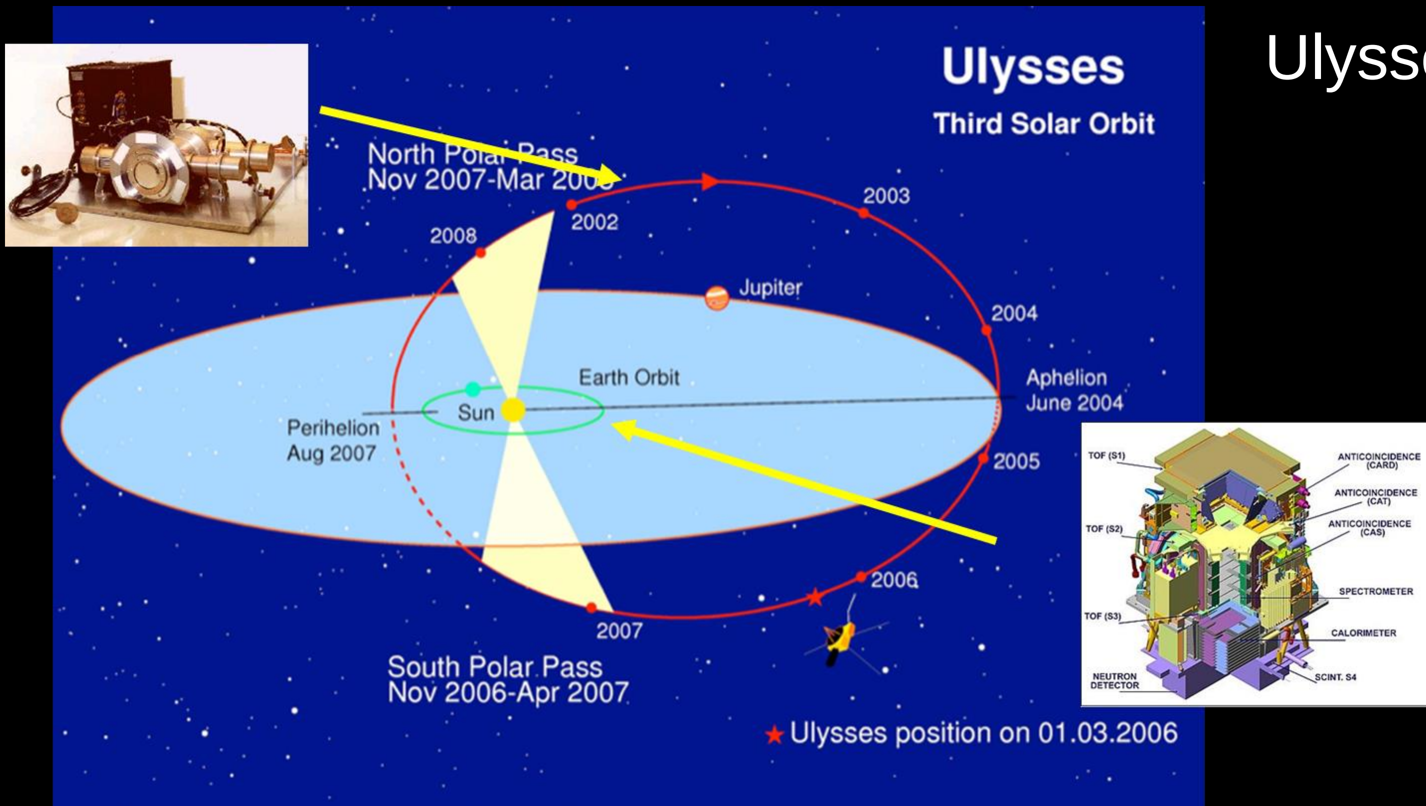
However spherical approximation is not sufficient. E.g. charge dependent solar modulation



Flux (GeV s sr m^2)$^{-1}$
10
10^{-1}
1
10
PAMELA
electrons
positrons
2006
2007
2008
2009

GRADIENTS IN THE HELIOSPHERE L=5AU

Ulysses – Pamela



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

Gradients in the heliosphere

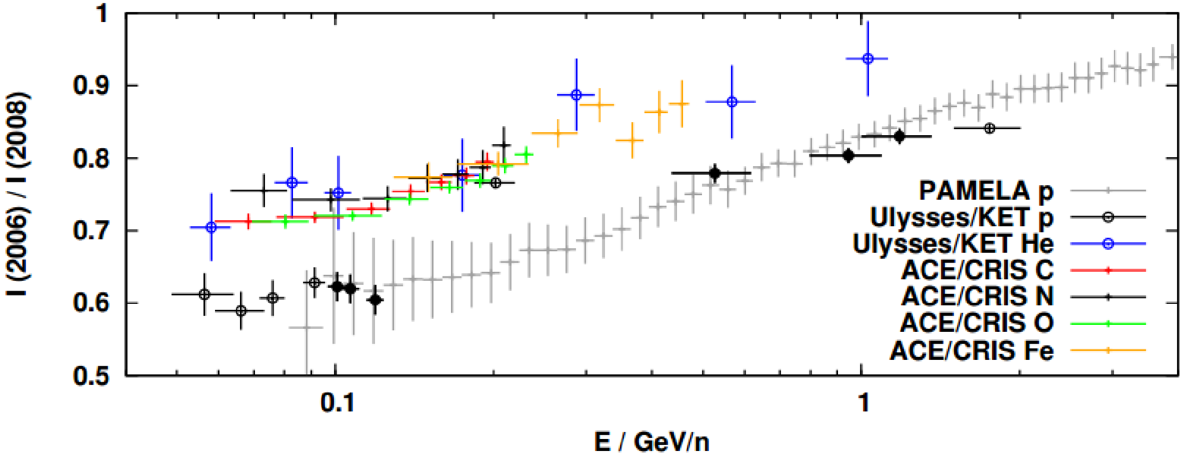


Figure 2: Time variations from 2006 to 2008 of different particle intensity measurements with respect to energy. Marked by full circles are the Ulysses/KET proton channels used here for gradient calculations.

1-5 AU

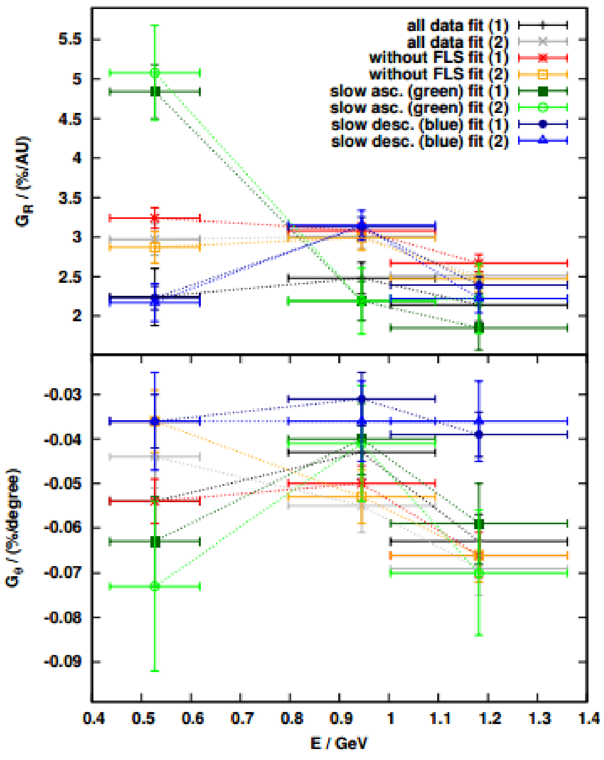
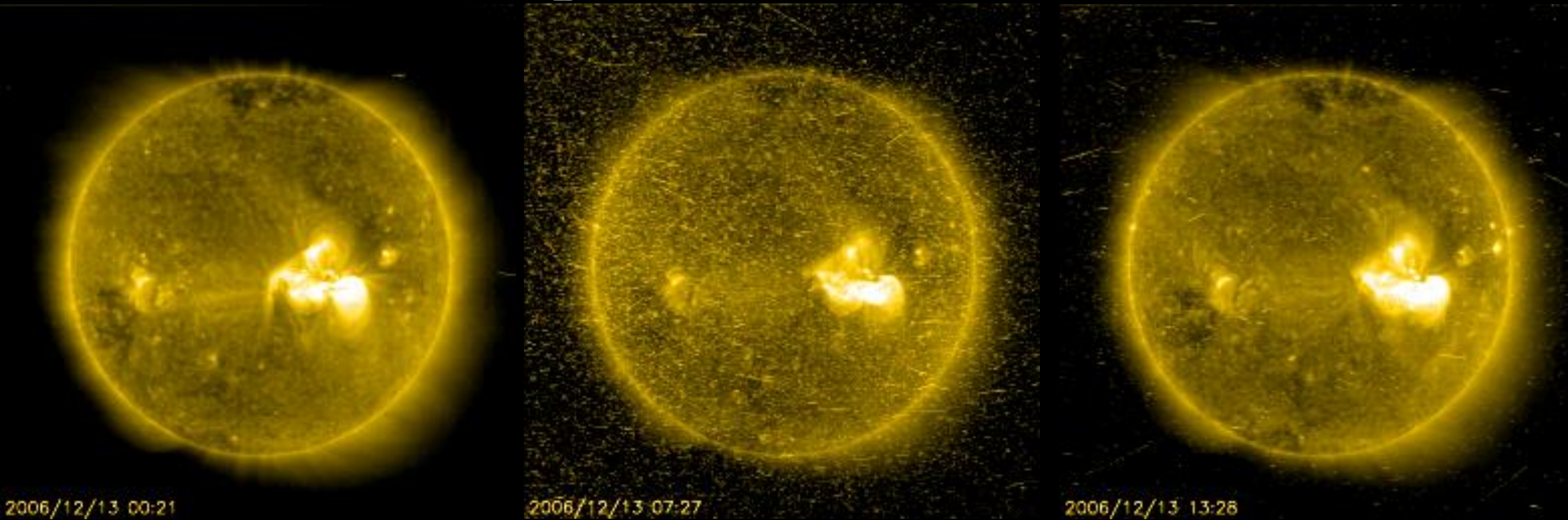
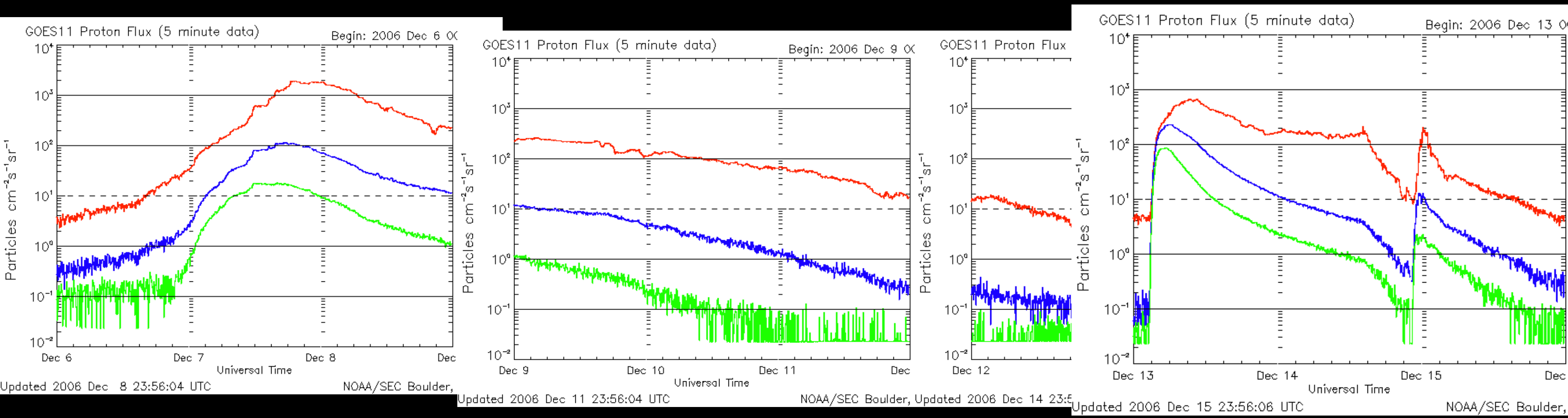


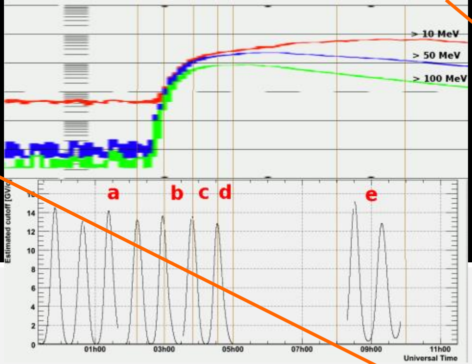
Figure 6: Radial and latitudinal gradients for differen
selection criteria and fit methods, as in Tab. 2.

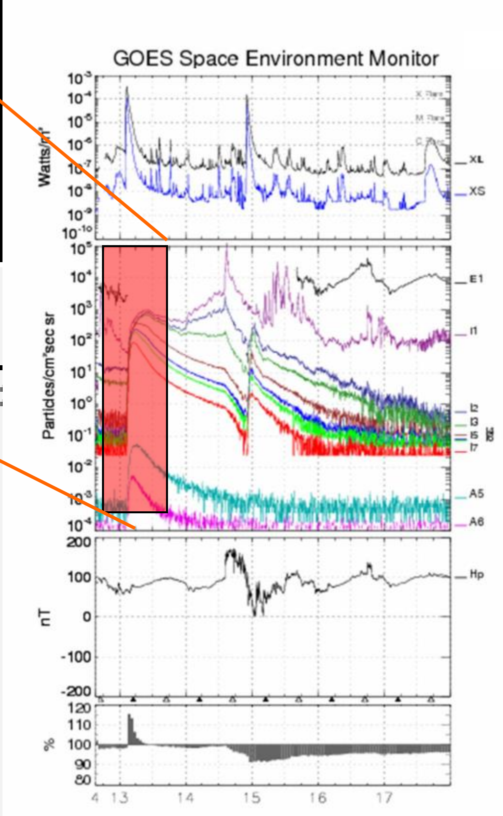
Solar particle events (1 AU)

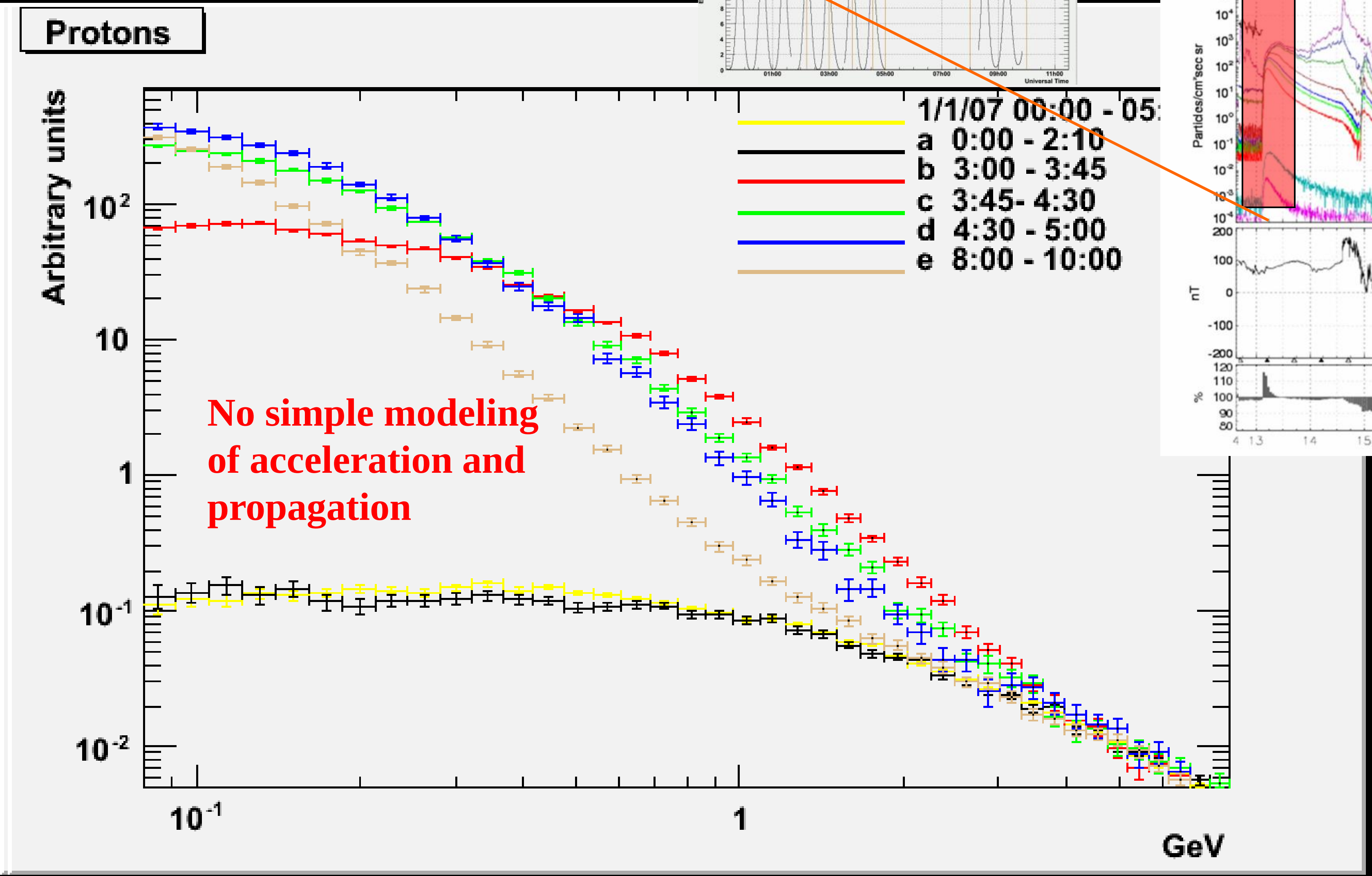




December 13th 2006 event



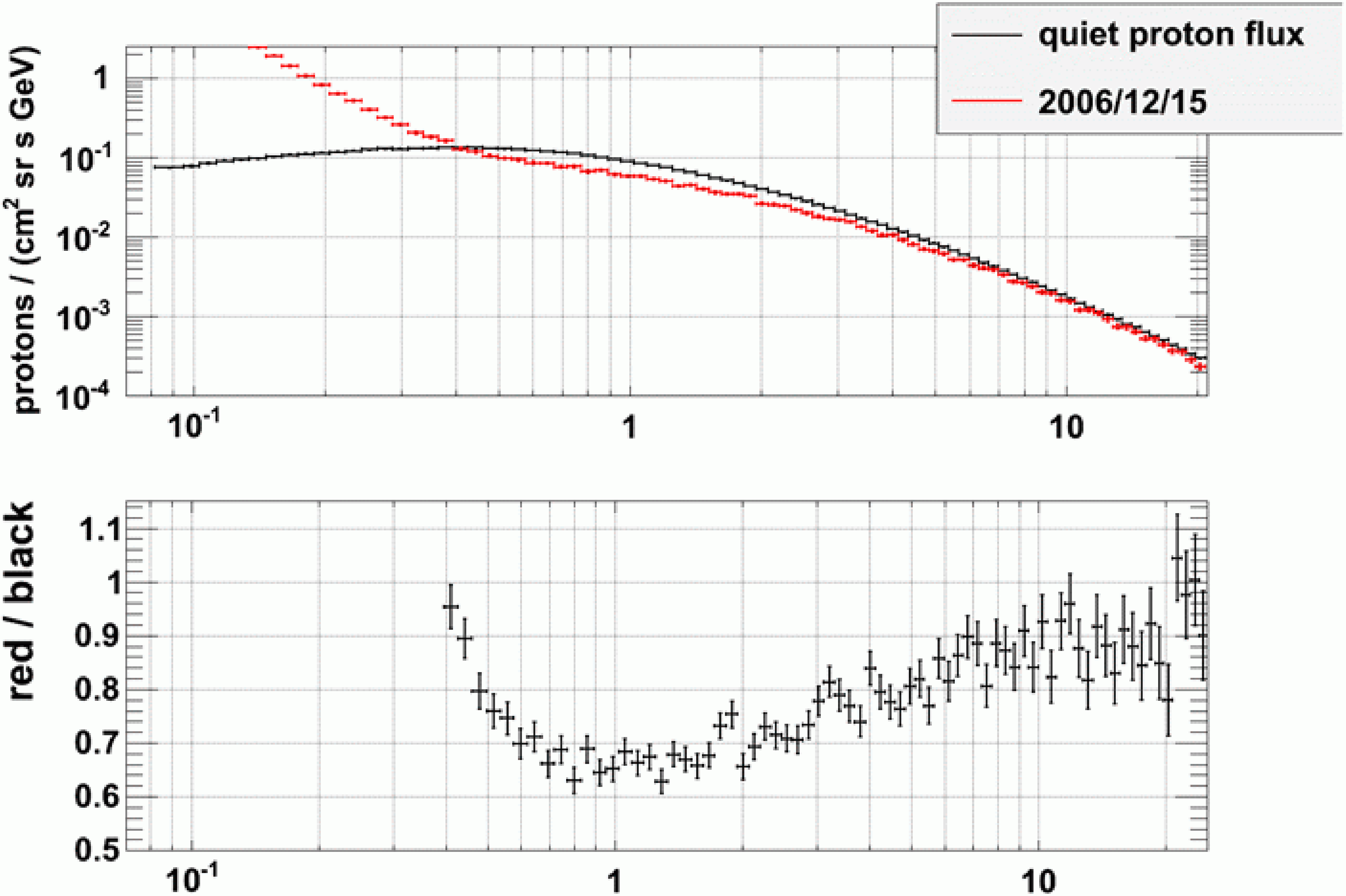




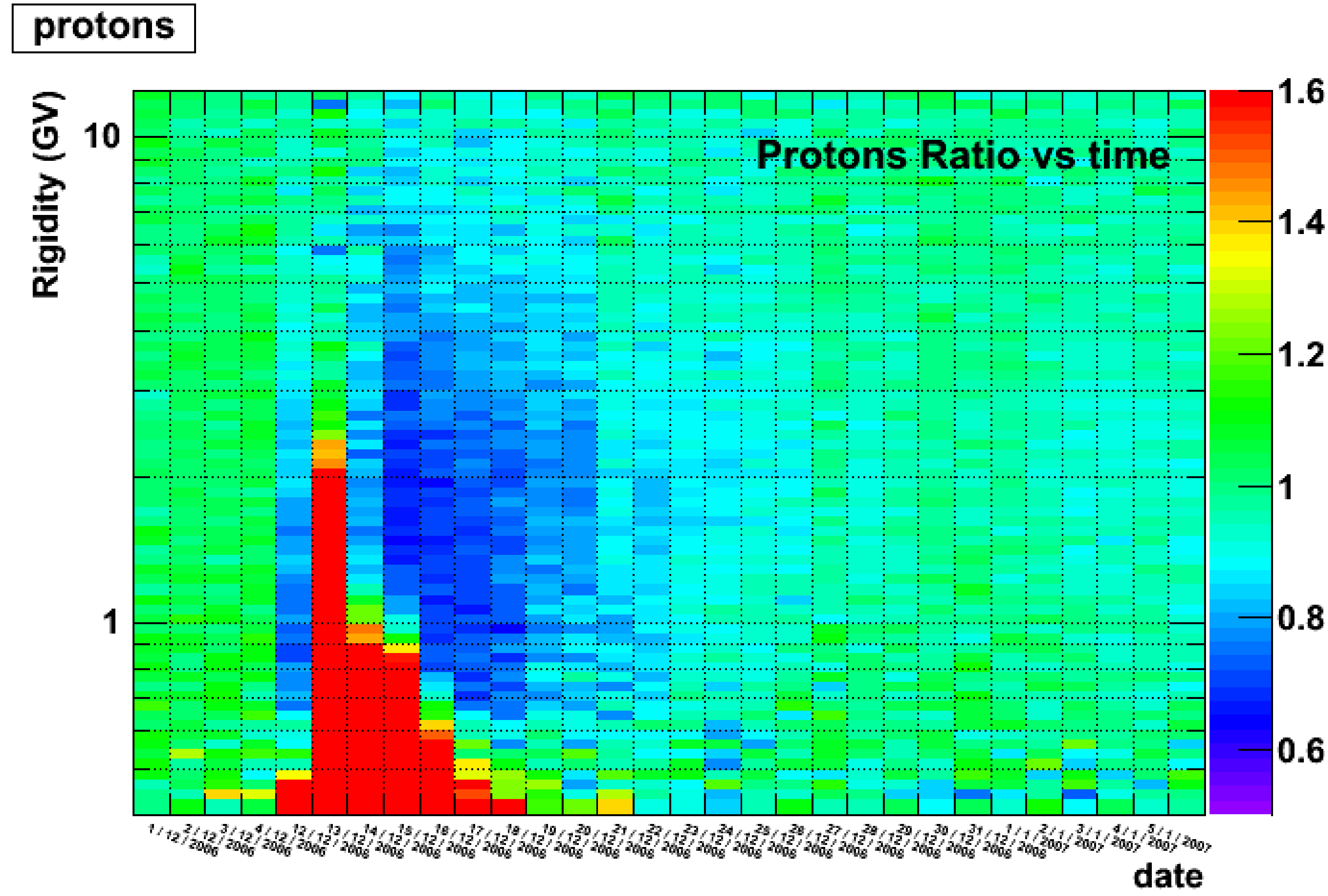
No simple modeling of acceleration and propagation

ApJ 742, 2, 102, 11, 2011.

Forbush decrease

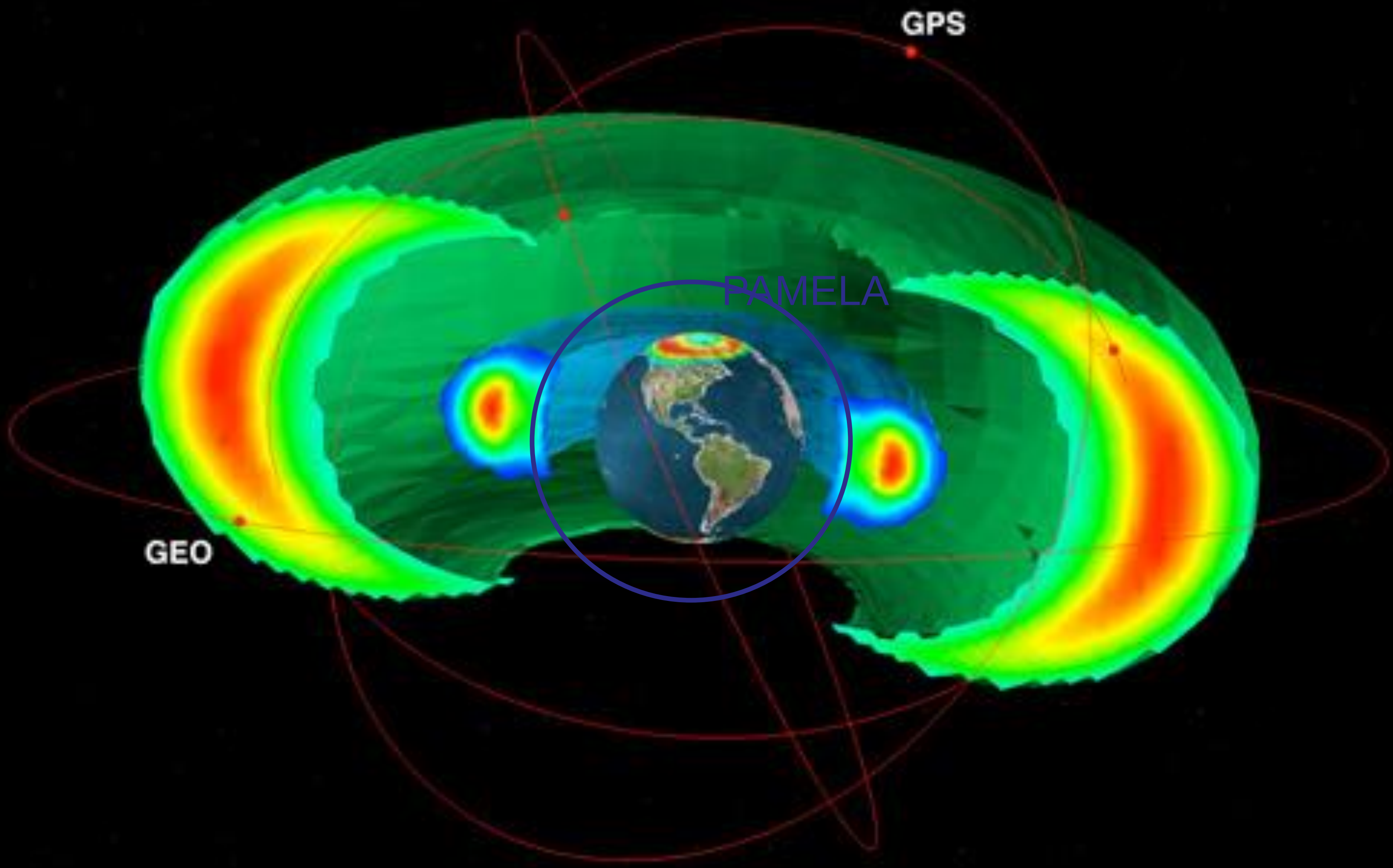


Time and rigidity dependence of Forbush decrease

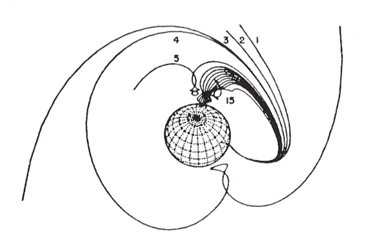


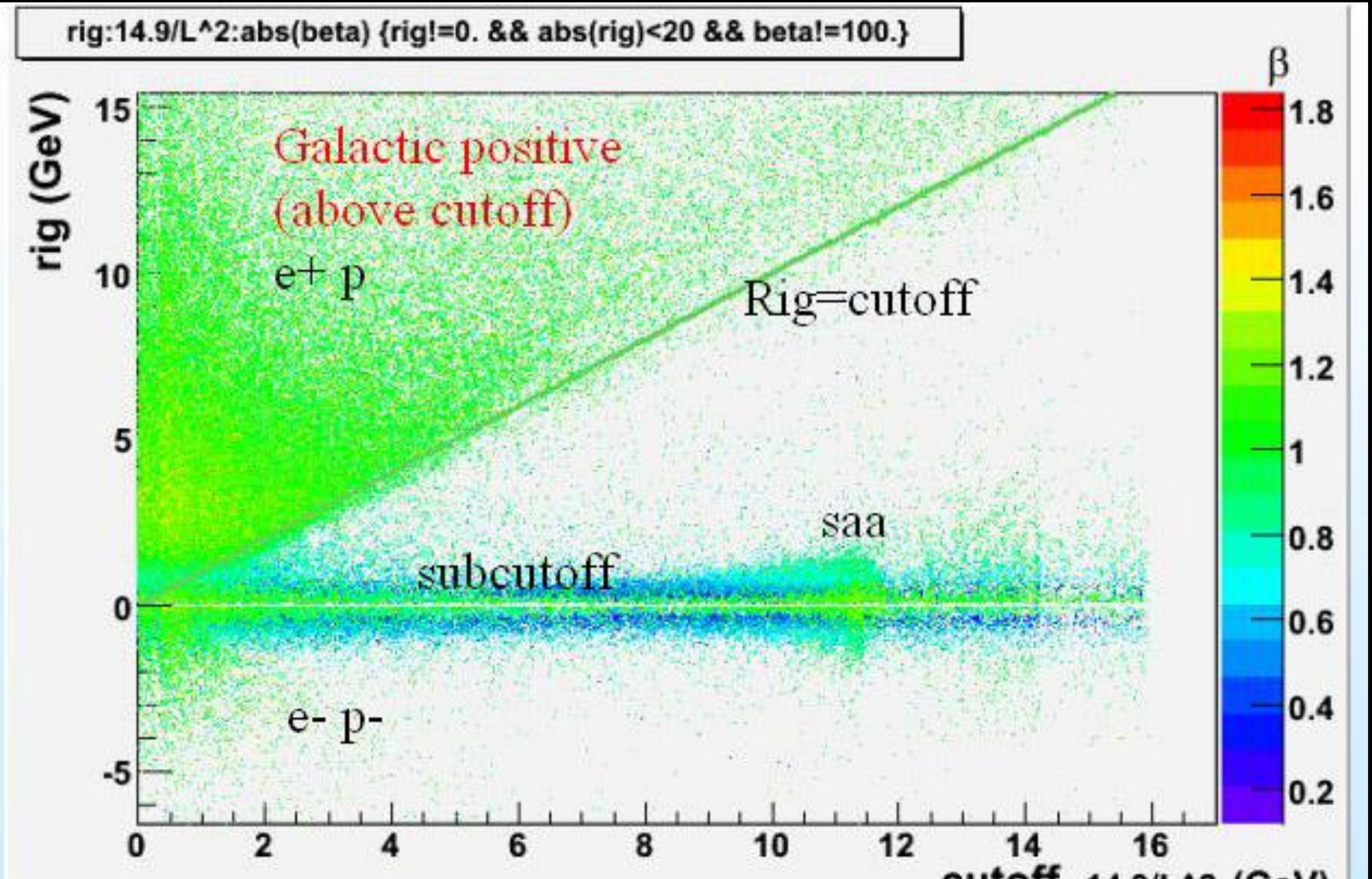
From Mergè Martucci Sotgiu

GEOMAGNETOSPHERE, VAN ALLEN BELTS



Selection of galactic component according to geomagnetic cutoff



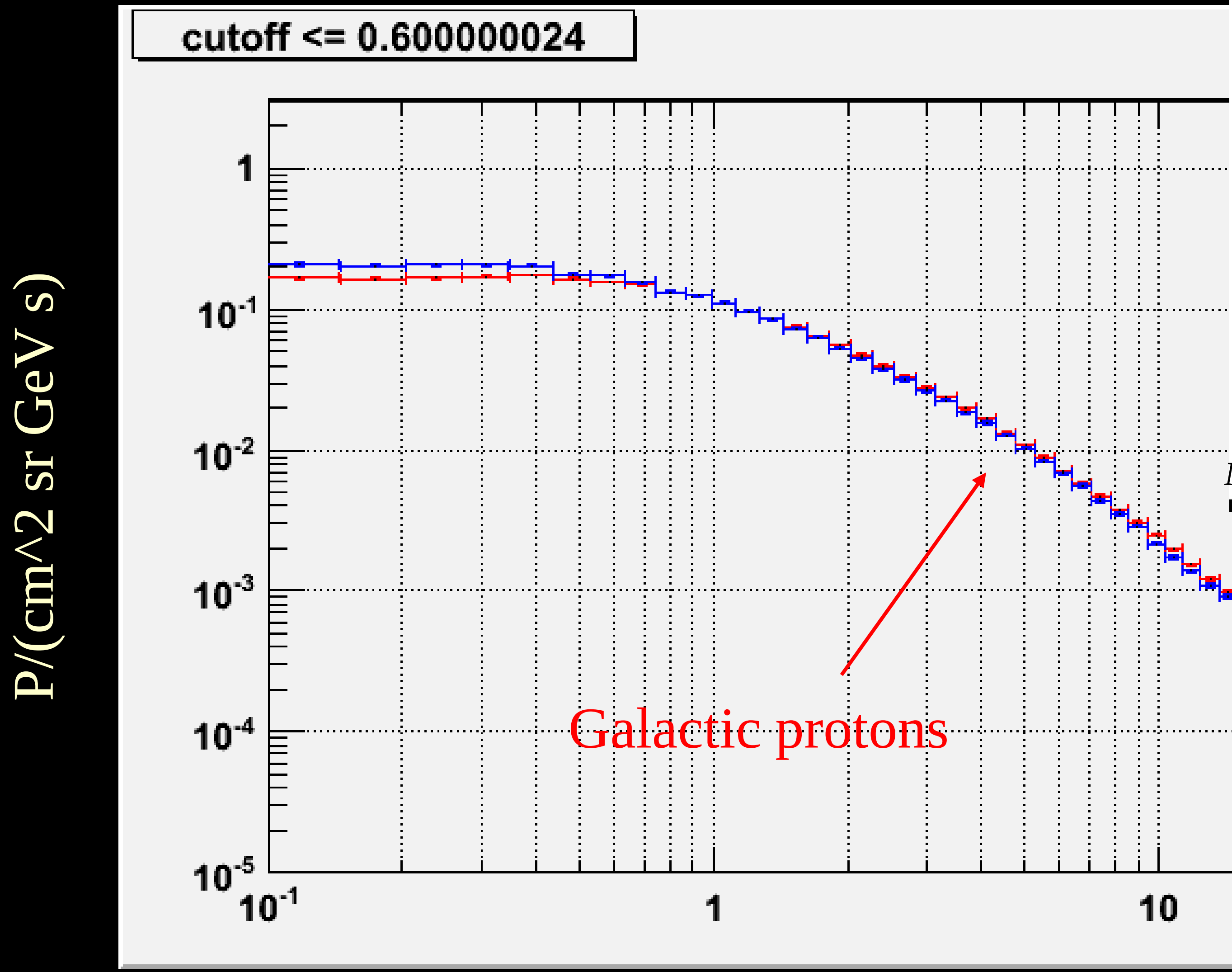


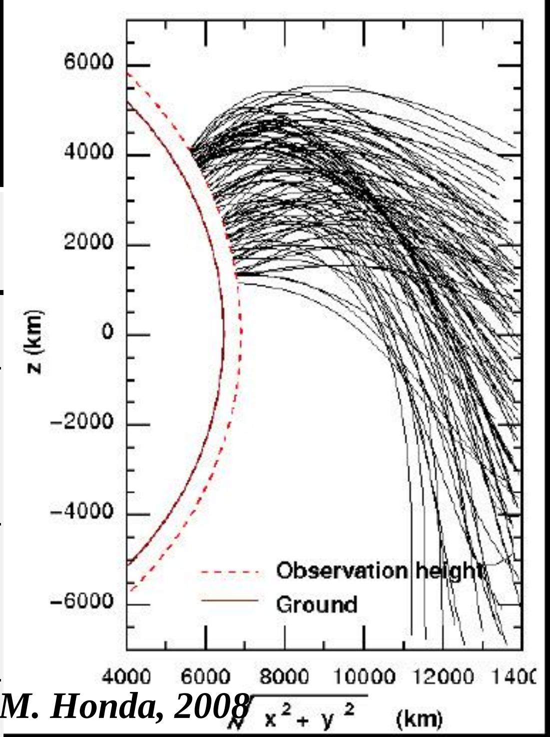
R_{cutoff}=14.9GV/L^2

Geomagnetosphere, Van Allen Belts (1000 km)

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

Primary (galactic) spectra: polar measurements



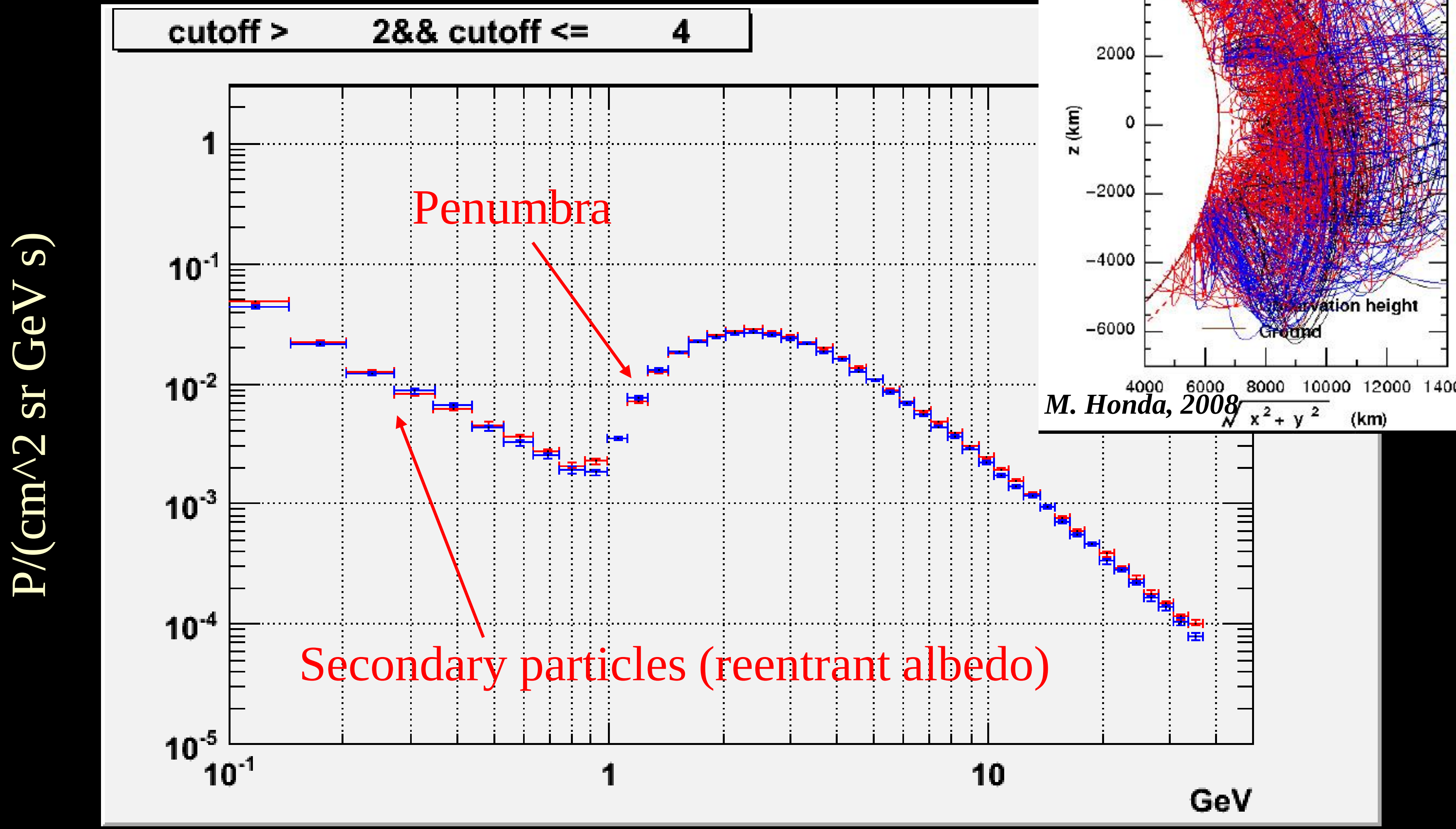


M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Intermediate latitudes

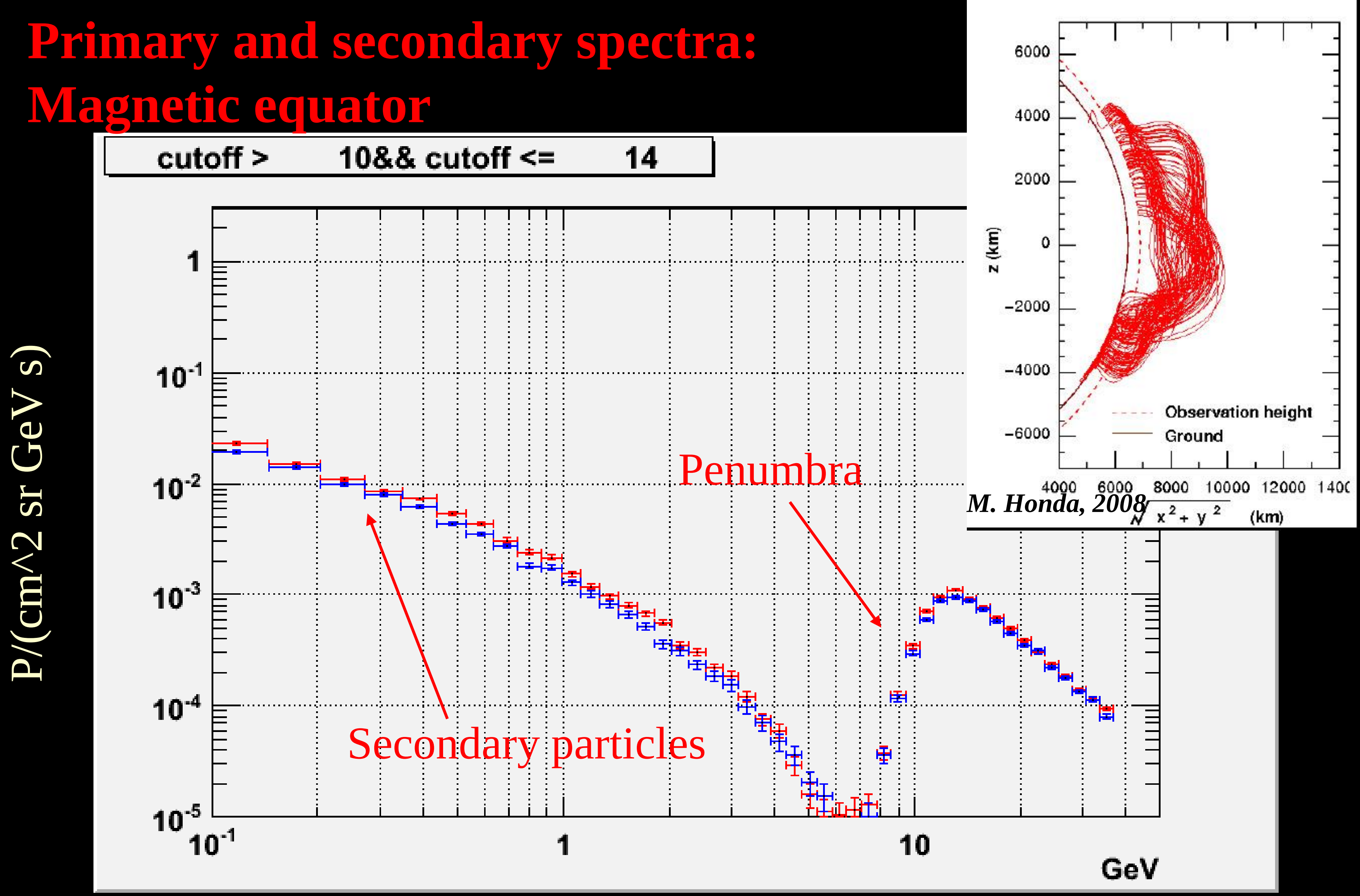


M. Honda, 2008

RED: JULY 2006

BLUE: AUGUST 2007

Primary and secondary spectra: Magnetic equator

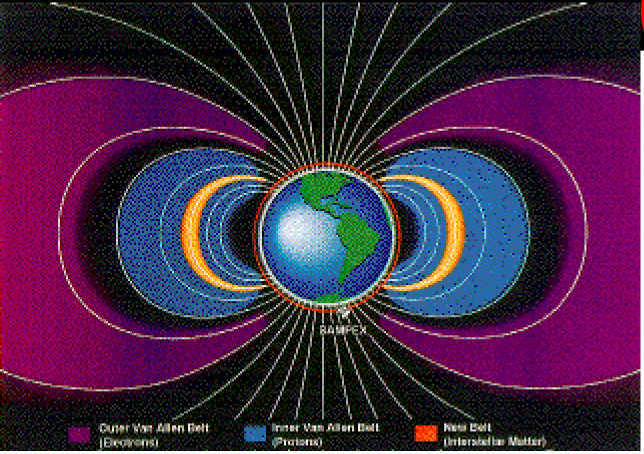


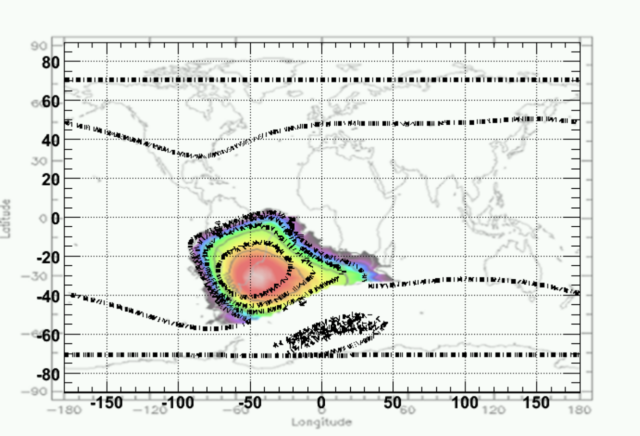
M. Honda, 2008

RED: JULY 2006

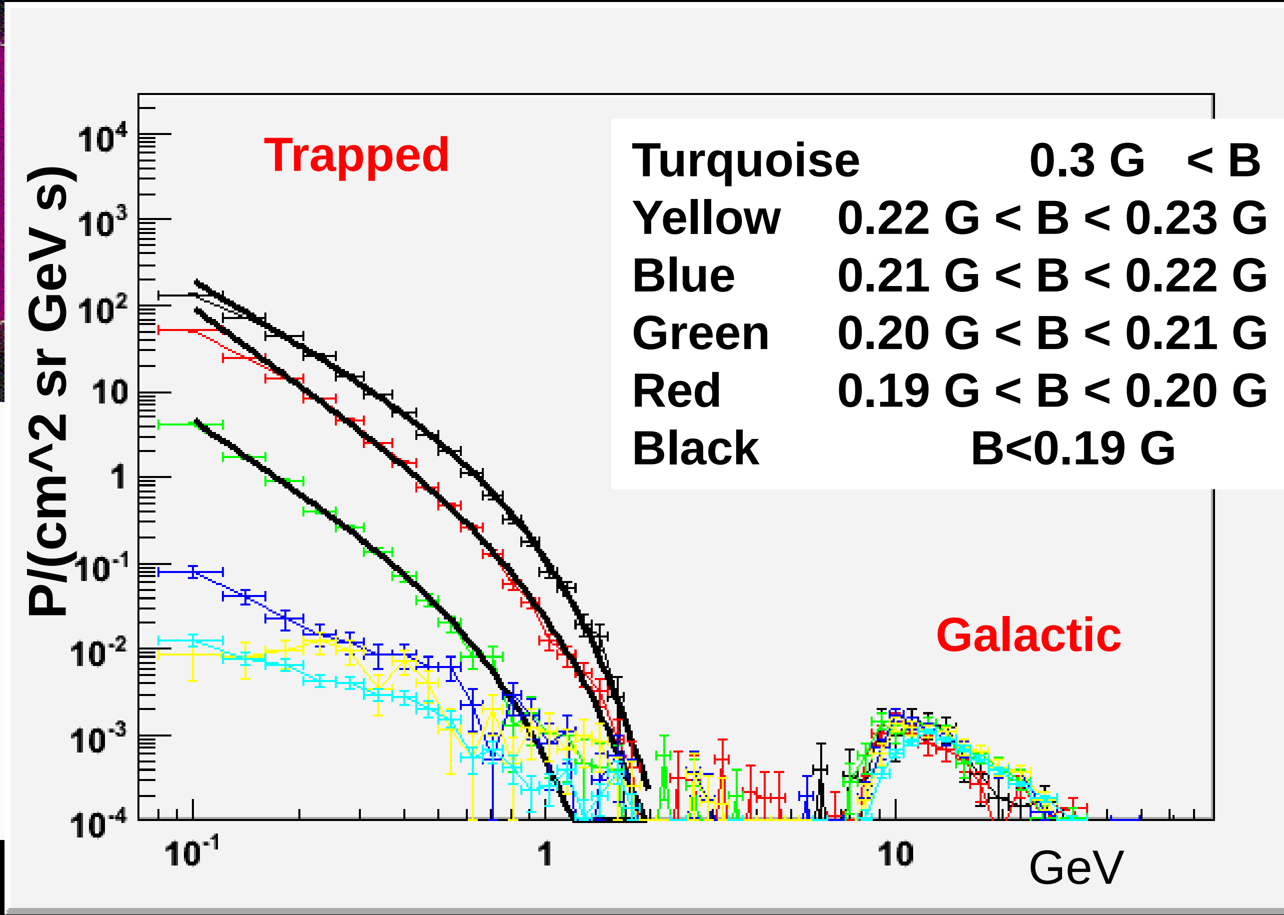
BLUE: AUGUST 2007

Trapped proton flux in the Van Allen belt (South Atlantic Anomaly) ApjL 799 4 2015



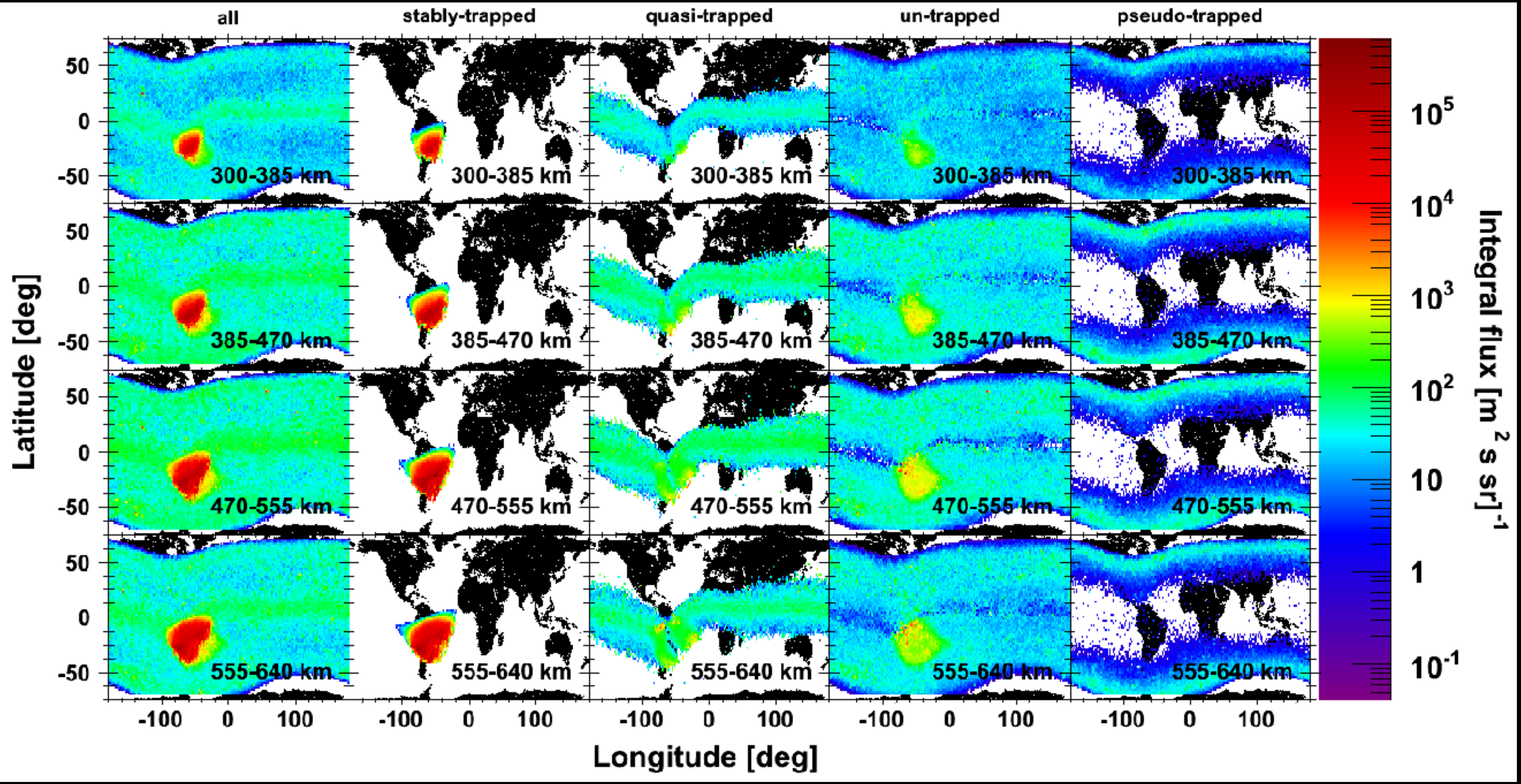


Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)



	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.

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

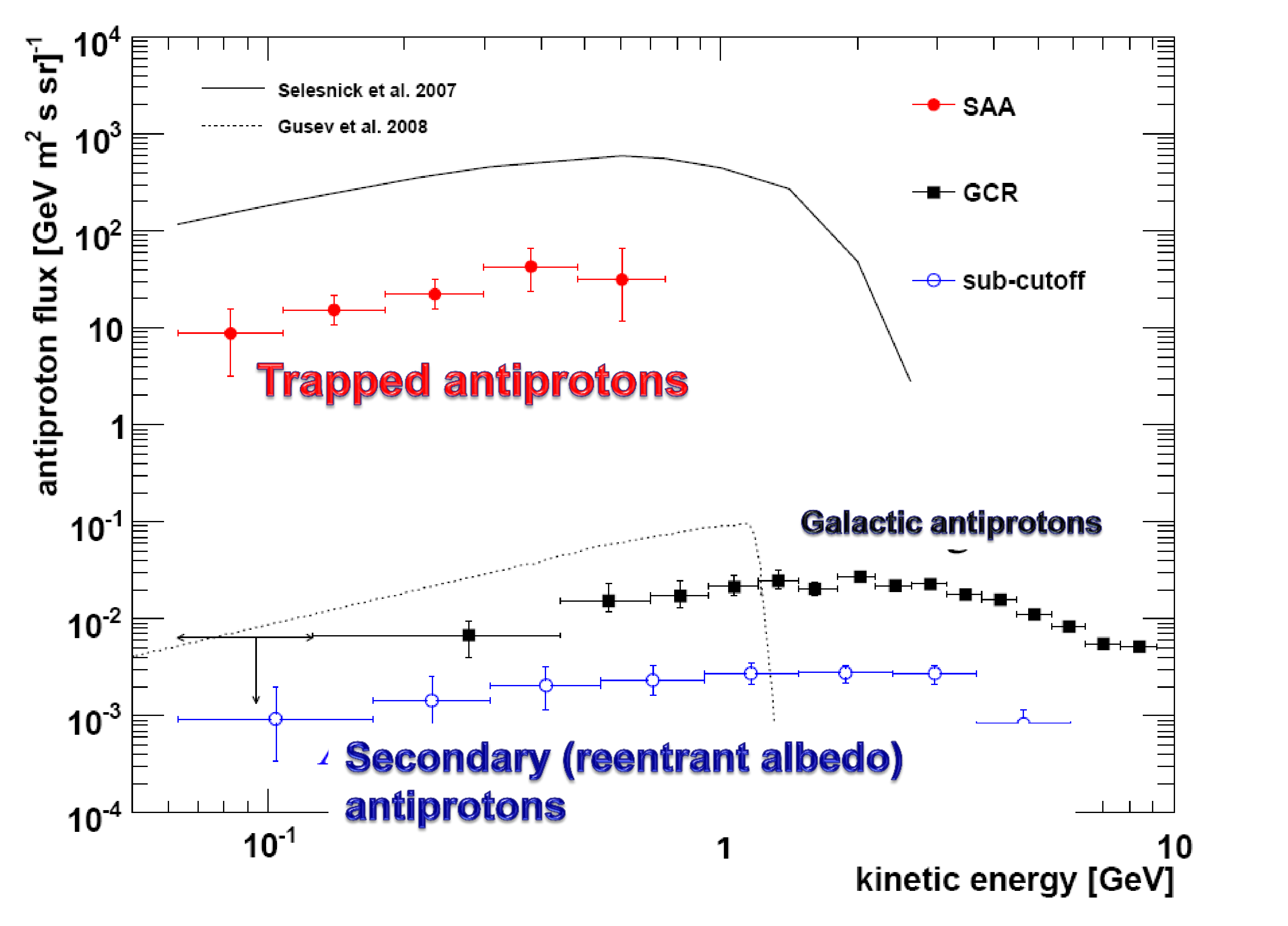


arXiv:1412.1765 Submitted to Apj

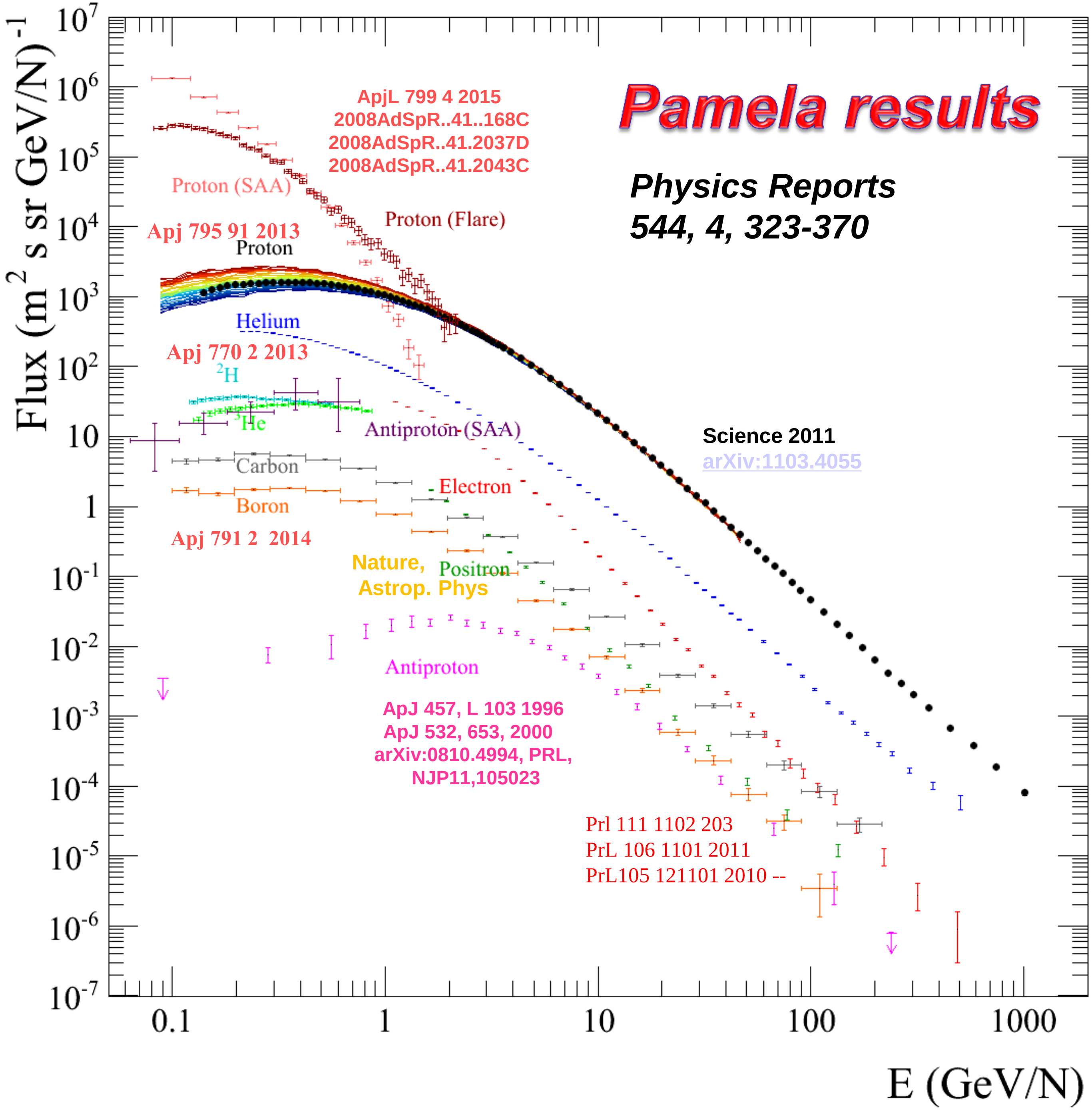
Discovery of stably trapped antiprotons in Earth's radiation belt

Total mass
Less than ng
Negligible but
replenishable

Saturn, Jupiter
mass μg



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



Pamela results
Physics Reports
544, 4, 323-370
ApjL 799 4 2015
2008AdSpR..41..168C
2008AdSpR..41.2037D
2008AdSpR..41.2043C
Proton (SAA)
Proton (Flare)
Apj 795 91 2013
Proton
Helium
Apj 770 2 2013
^{2}H
^{3}He
Antiproton (SAA)
Carbon
Electron
Boron
Apj 791 2 2014
Nature,
Astrop. Phys
Positron
Science 2011
arXiv:1103.4055
Antiproton
ApJ 457, L 103 1996
ApJ 532, 653, 2000
arXiv:0810.4994, PRL,
NJP11,105023
Prl 111 1102 203
PrL 106 1101 2011
PrL105 121101 2010 --
Flux (m^{2} s sr GeV/N)$^{-1}$
E (GeV/N)

- Pamela is operating successfully in space
- Expected three years of operations – survived 8.5!
- 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


7 YEARS of the PAMELA launch
15 June 2006-2013