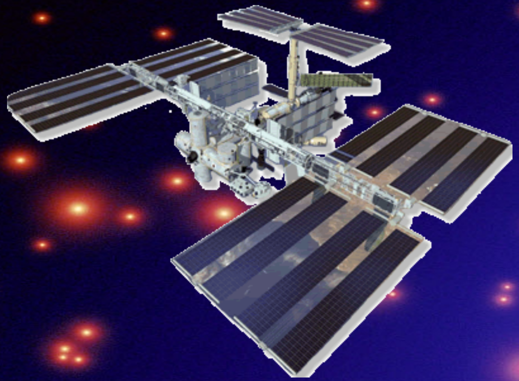
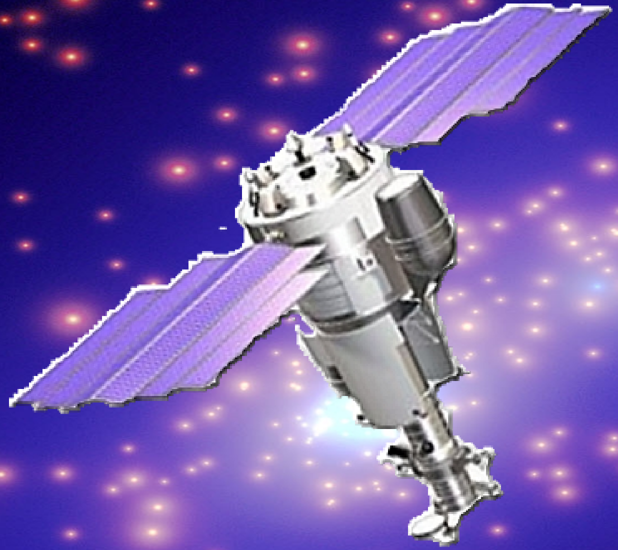
Exploring Cosmic Rays
with Balloon and Space Experiments





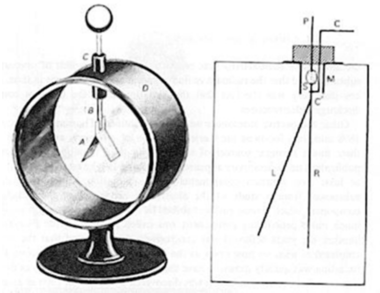
Piergiorgio Picozza
INFN and University of Rome Tor Vergata

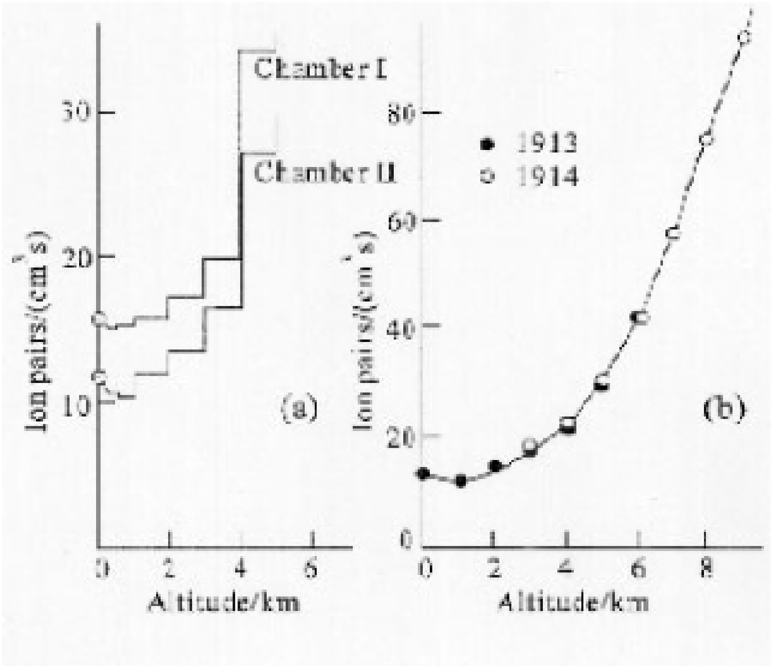
At the Edge of Discovery

September 2-9, 2015

The Discovery of Cosmic Rays

- Victor Hess ascended to 5000 m in a balloon in 1912
- Noticed that his electroscope discharged more rapidly as altitude increased
- Not expected as background radiation was thought to be terrestrial
- NPP 1936 (with Carl 'e+' Anderson)





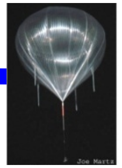
Mark Pearce [pearce@particle.kth.se]

Primary cosmic ray

~500 km

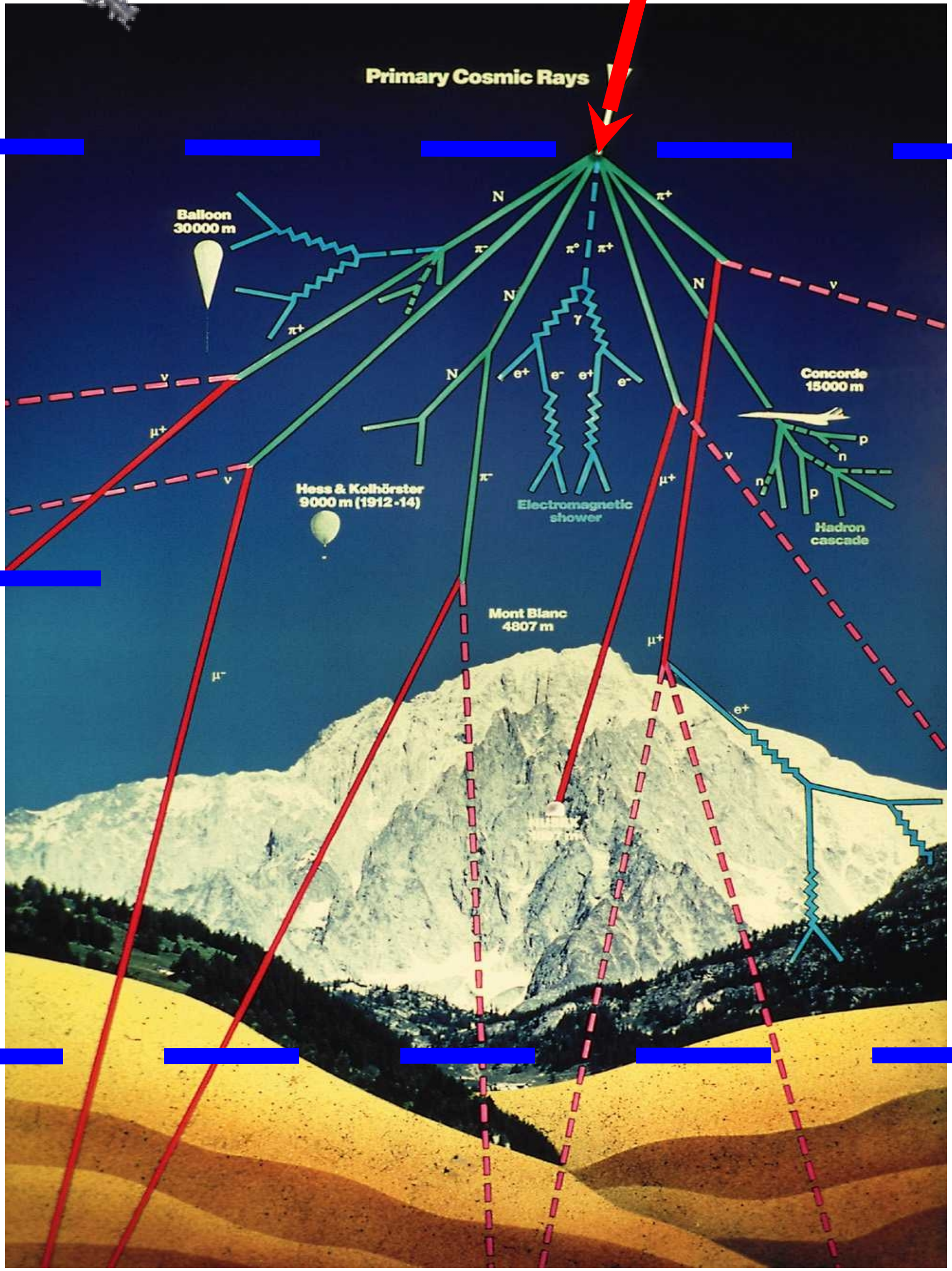
Smaller detectors but long duration.
PAMELA!

Top of atmosphere



~40 km

Large detectors but short duration. Atmospheric overburden ~5 g/cm^2.
Almost all data on cosmic antiparticles from here.

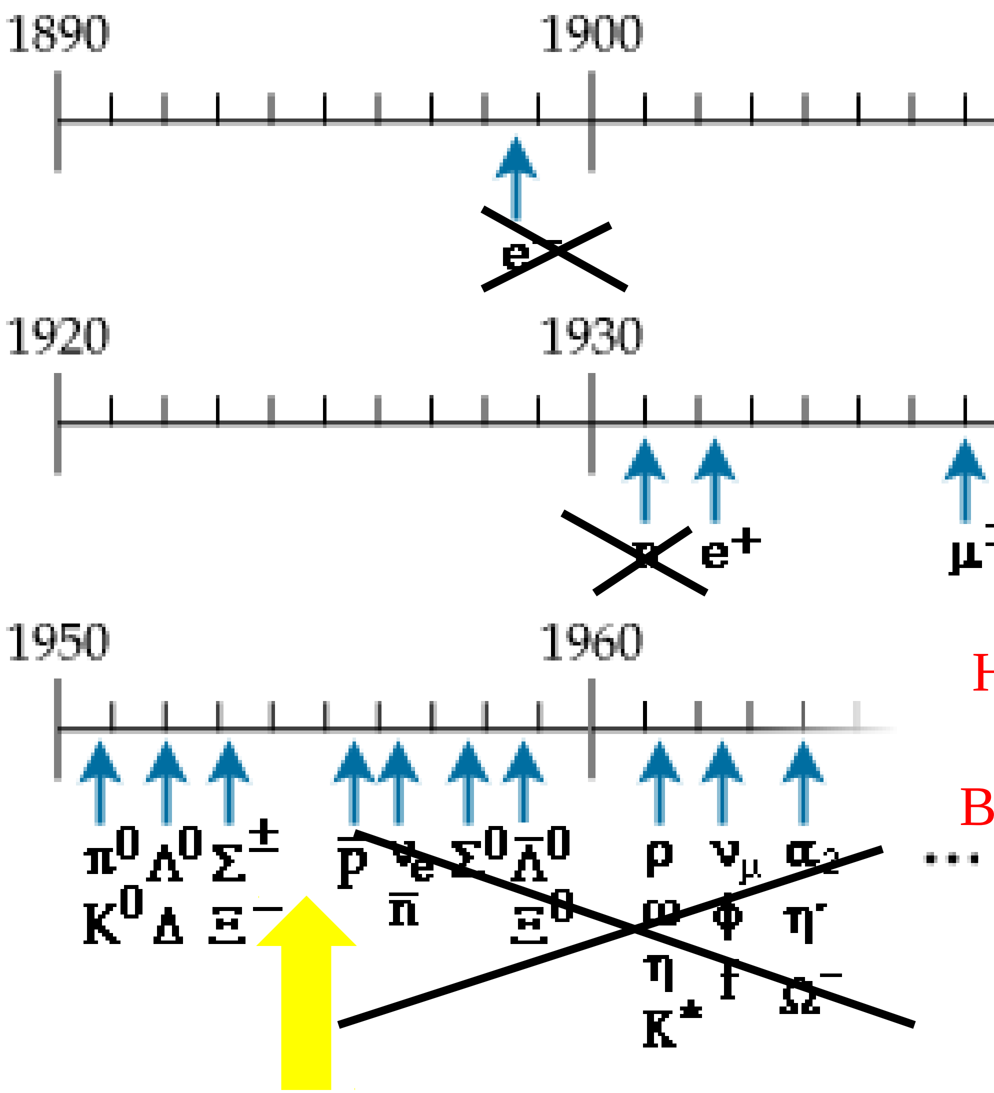


~5 km

Ground

0 m

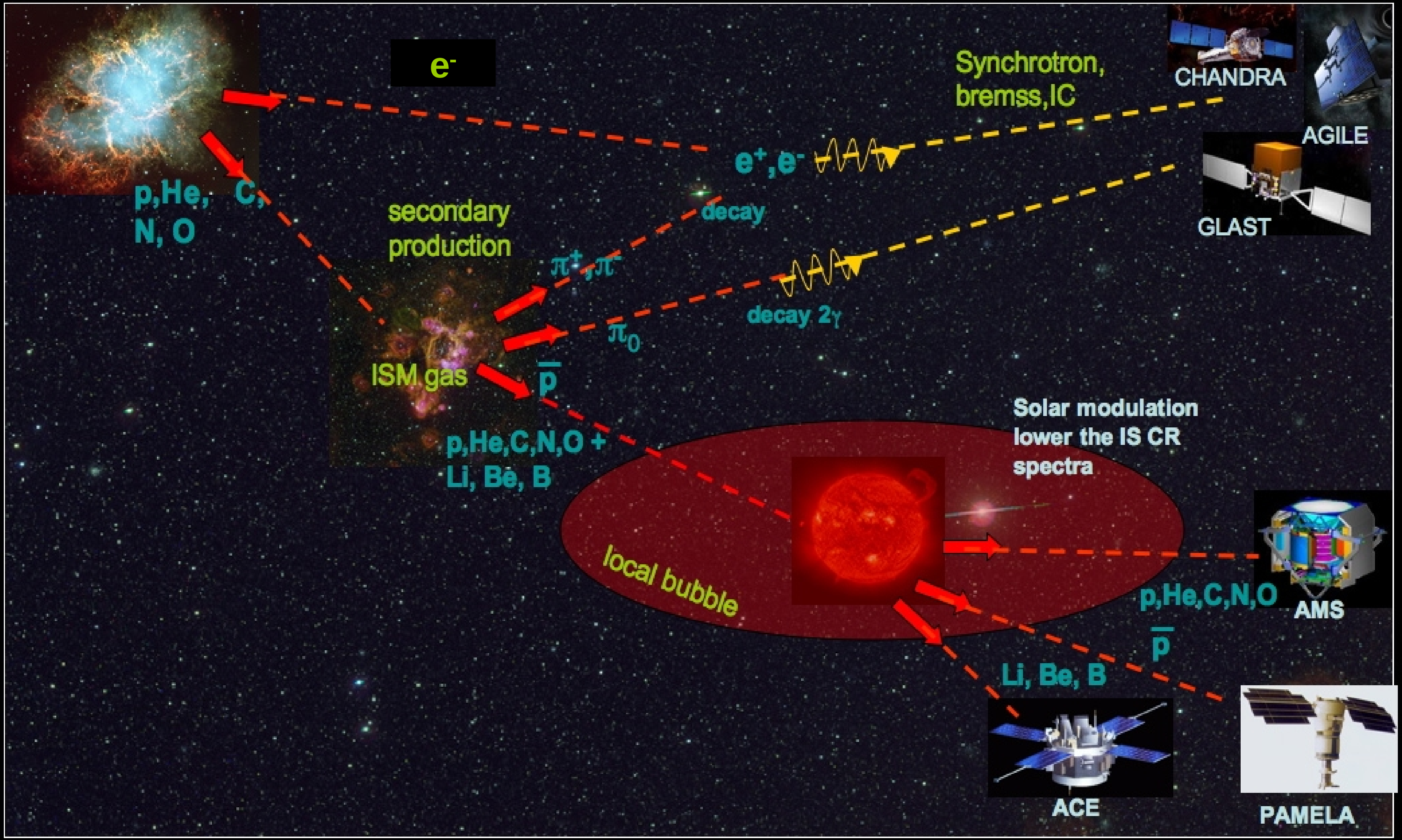
PARTICLE PHYSICS BIRTH WAS DUE TO COSMIC RAYS

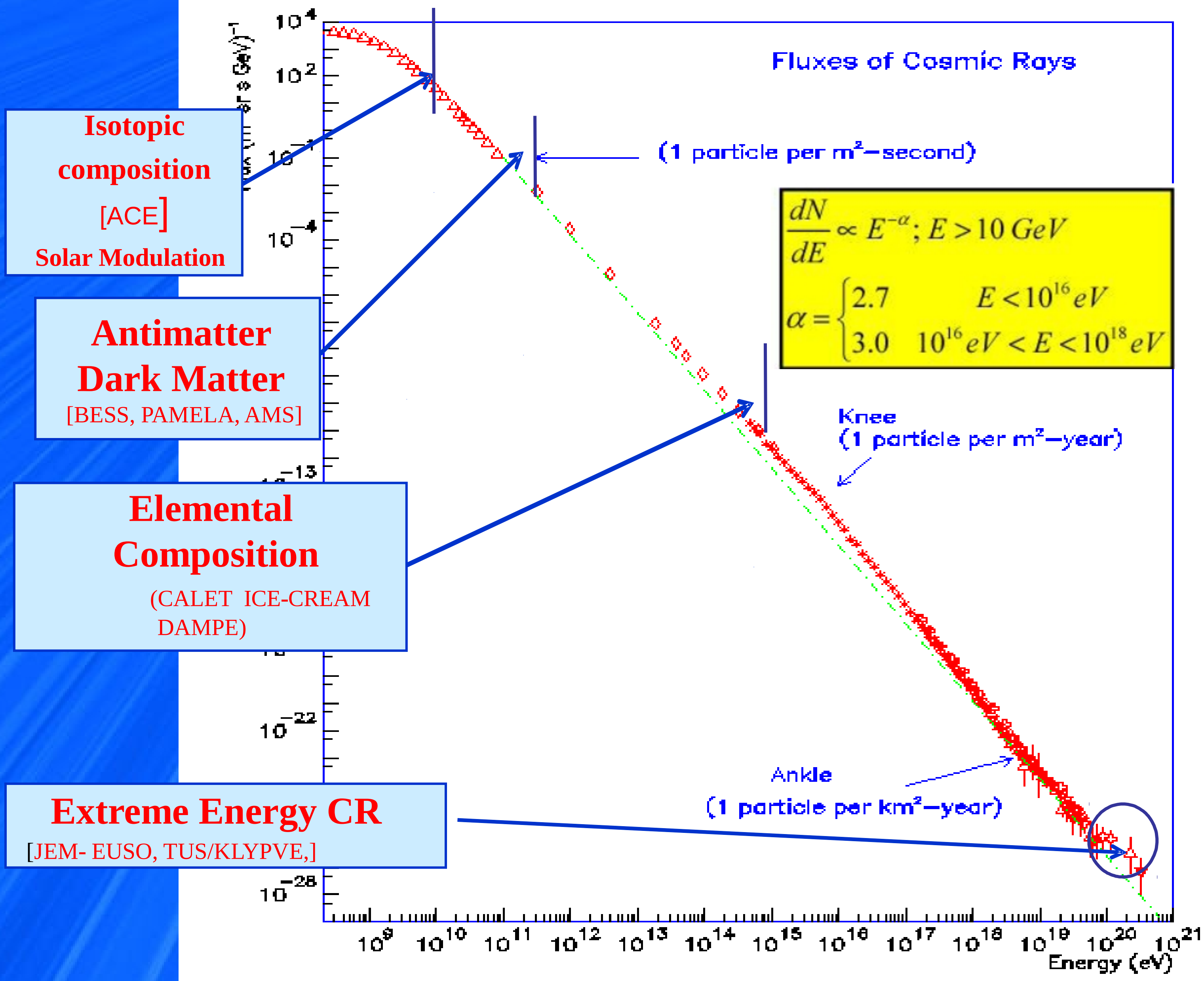


Hesse, Wulf, Wilson, Anderson,
Bothe, Kohlorster, Millikan,
Blackett, Skobeltsyn, Rochester,
Butler, Rossi, Pancini ,
Conversi, Powell, Occhialini
……

Advent of accelerators

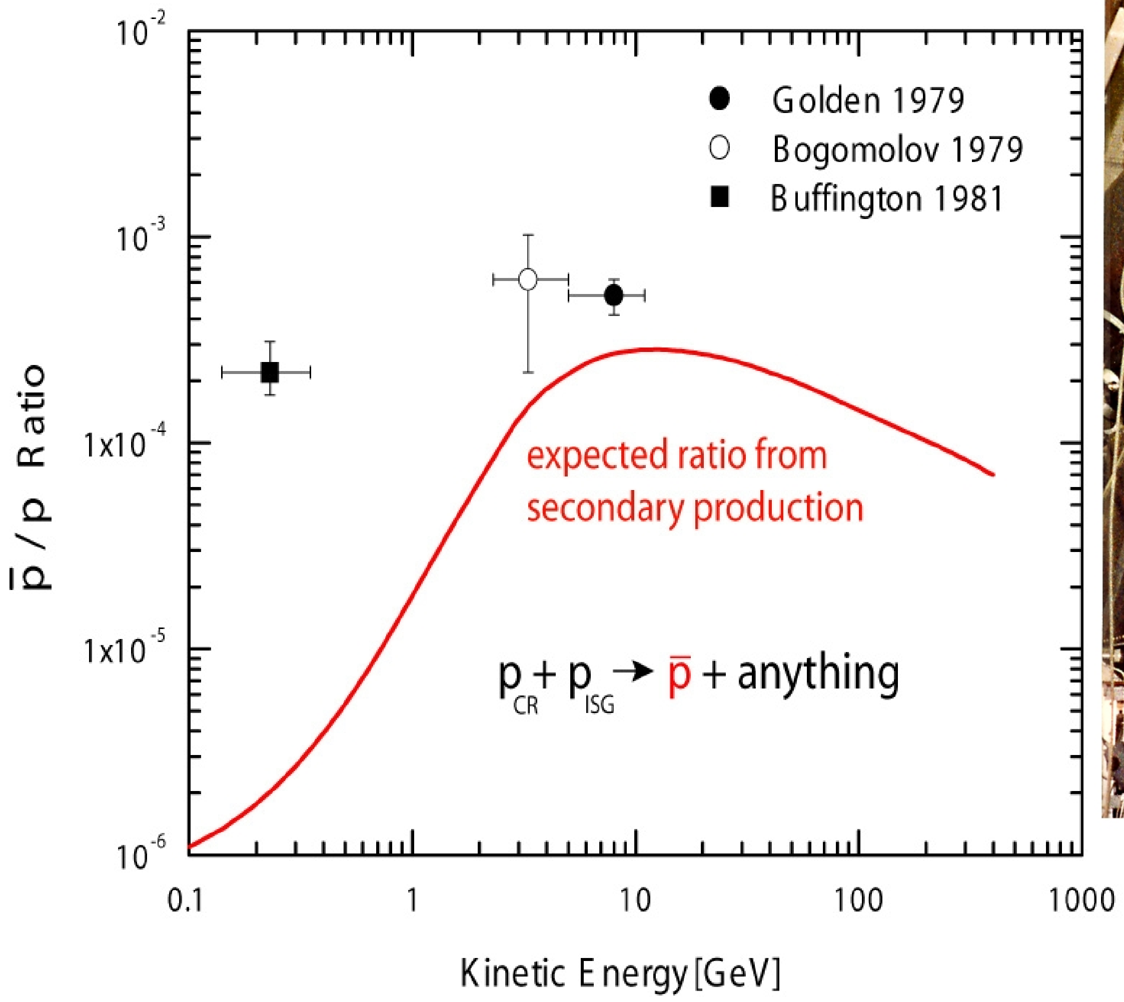
COSMIC RAYS PRODUCTION MECHANISMS

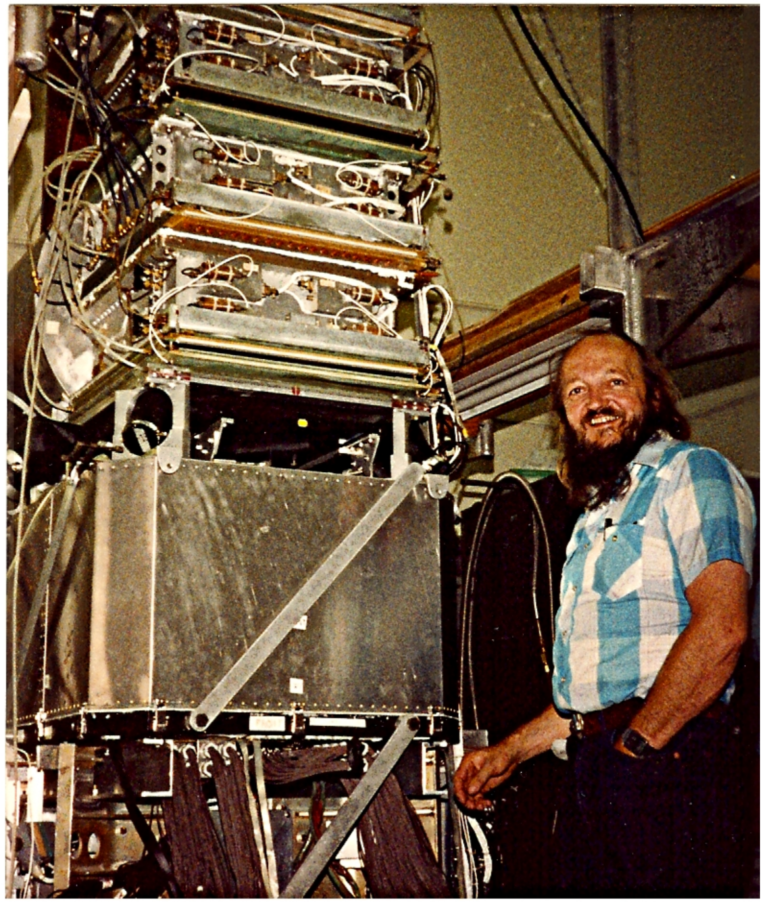




Fluxes of Cosmic Rays
(1 particle per m²–second)
$\frac{dN}{dE} \propto E^{-\alpha}; E > 10\,GeV$
$\alpha = \begin{cases} 2.7 & E < 10^{16} eV \\ 3.0 & 10^{16} eV < E < 10^{18} eV \end{cases}$
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Energy (eV)
Isotopic composition
[ACE]
Solar Modulation
Antimatter
Dark Matter
[BESS, PAMELA, AMS]
Elemental Composition
(CALET ICE-CREAM DAMPE)
Extreme Energy CR
[JEM- EUSO, TUS/KLYPVE,]

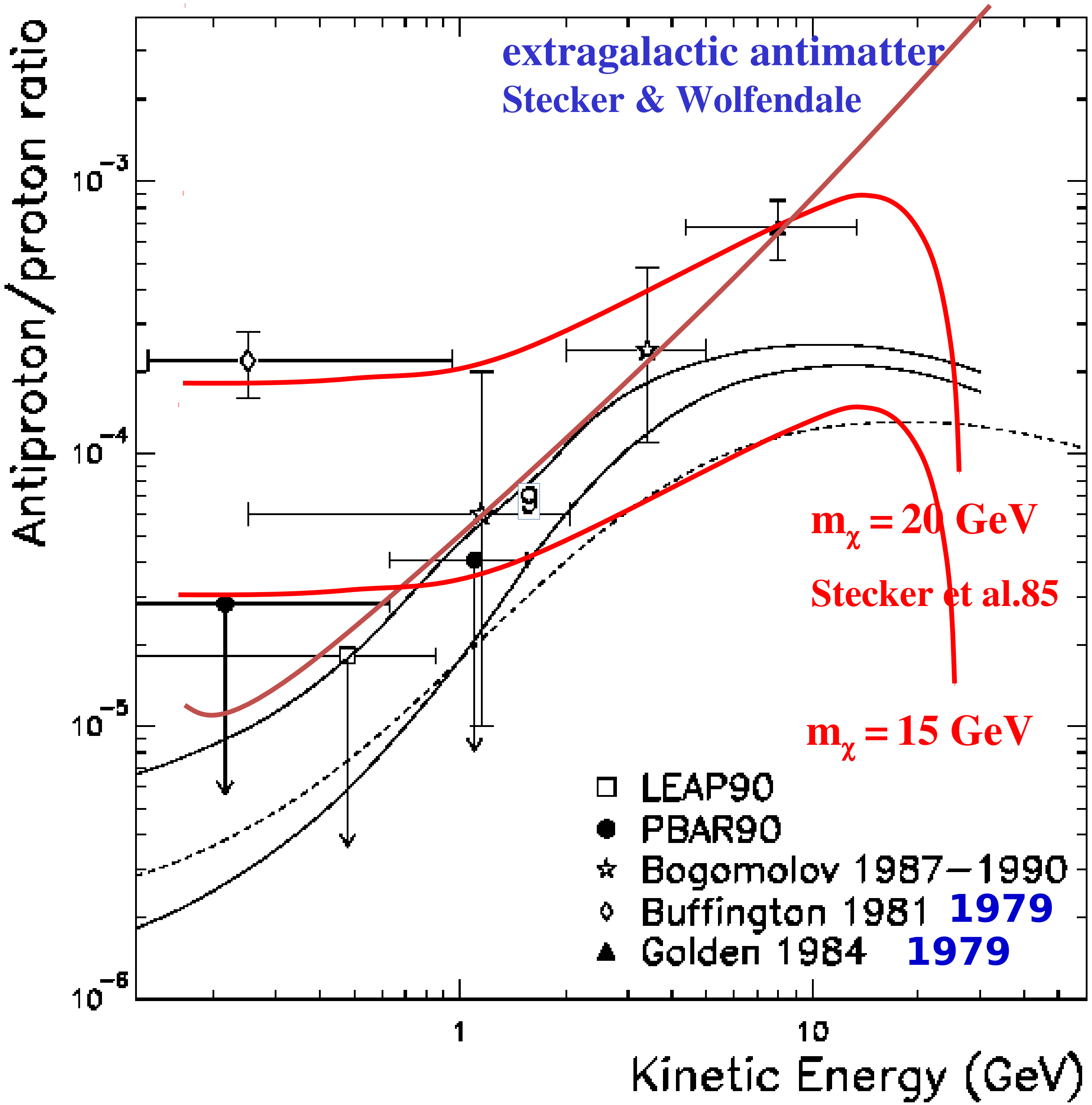
The first historical measurements on galactic antiprotons





Robert L. Golden

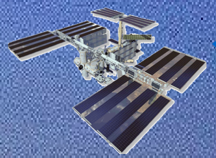
Antiproton/proton ratio before 1990



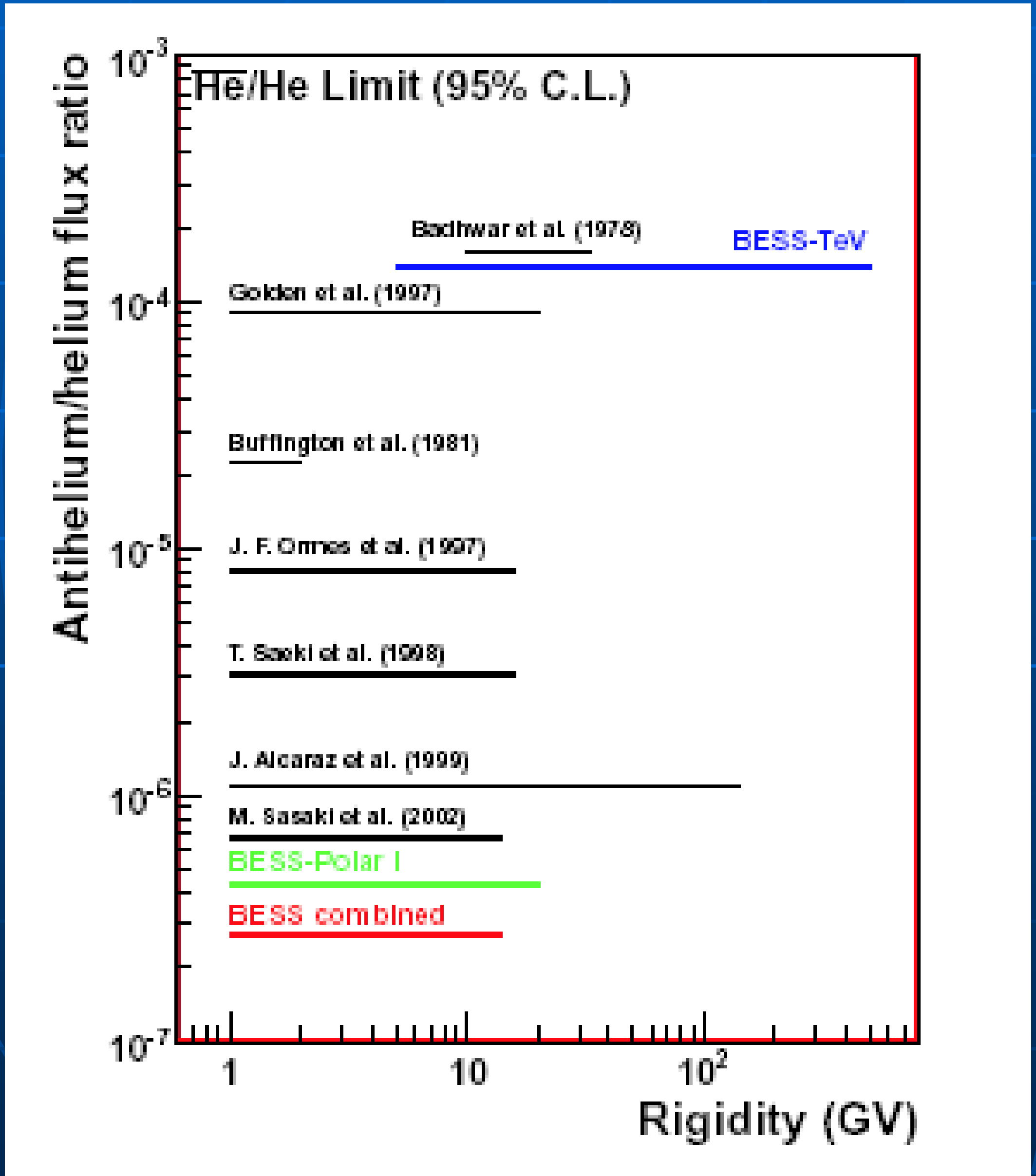
Antimatter Search

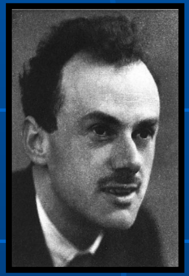
Wizard Collaboration

- ✓ MASS – 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)
- ✓ BESS (93, 95, 97, 98, 2000)
- ✓ BESS Polar I (2004)
- ✓ Heat (94, 95, 2000)
- ✓ IMAX (96)
- ✓ AMS-01 (1998)



Antimatter

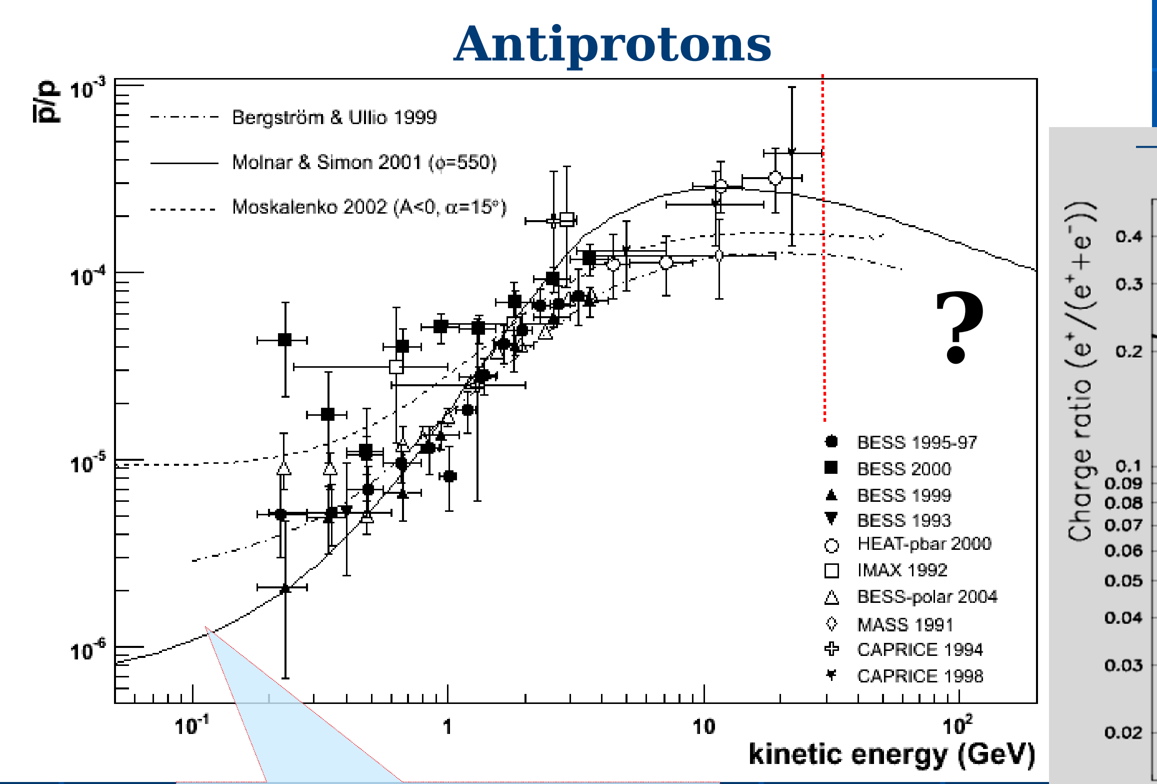


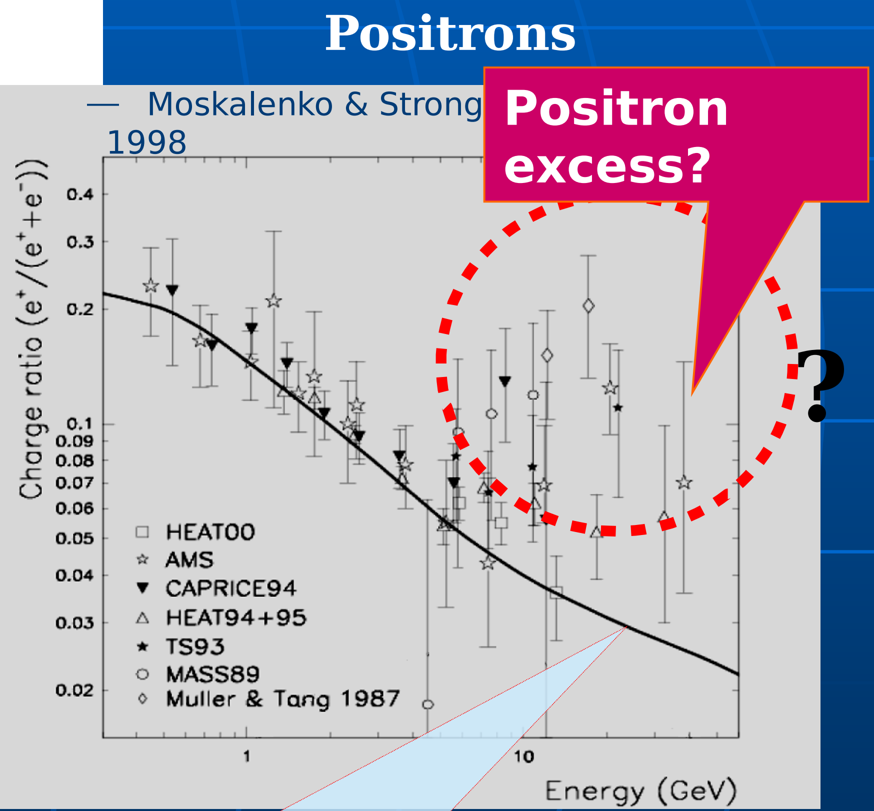


"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

P. Dirac, Nobel lecture (1933)

Cosmic Ray Antimatter





CR + ISM → **p-bar** + …

kinematic threshold: $pp \rightarrow \bar{p}ppp$ the reaction

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **$e^{\pm}$** + x

CR ISM → π^0 + x → $\gamma\gamma$ → **$e^{\pm}$**

Satellite Missions and LDF

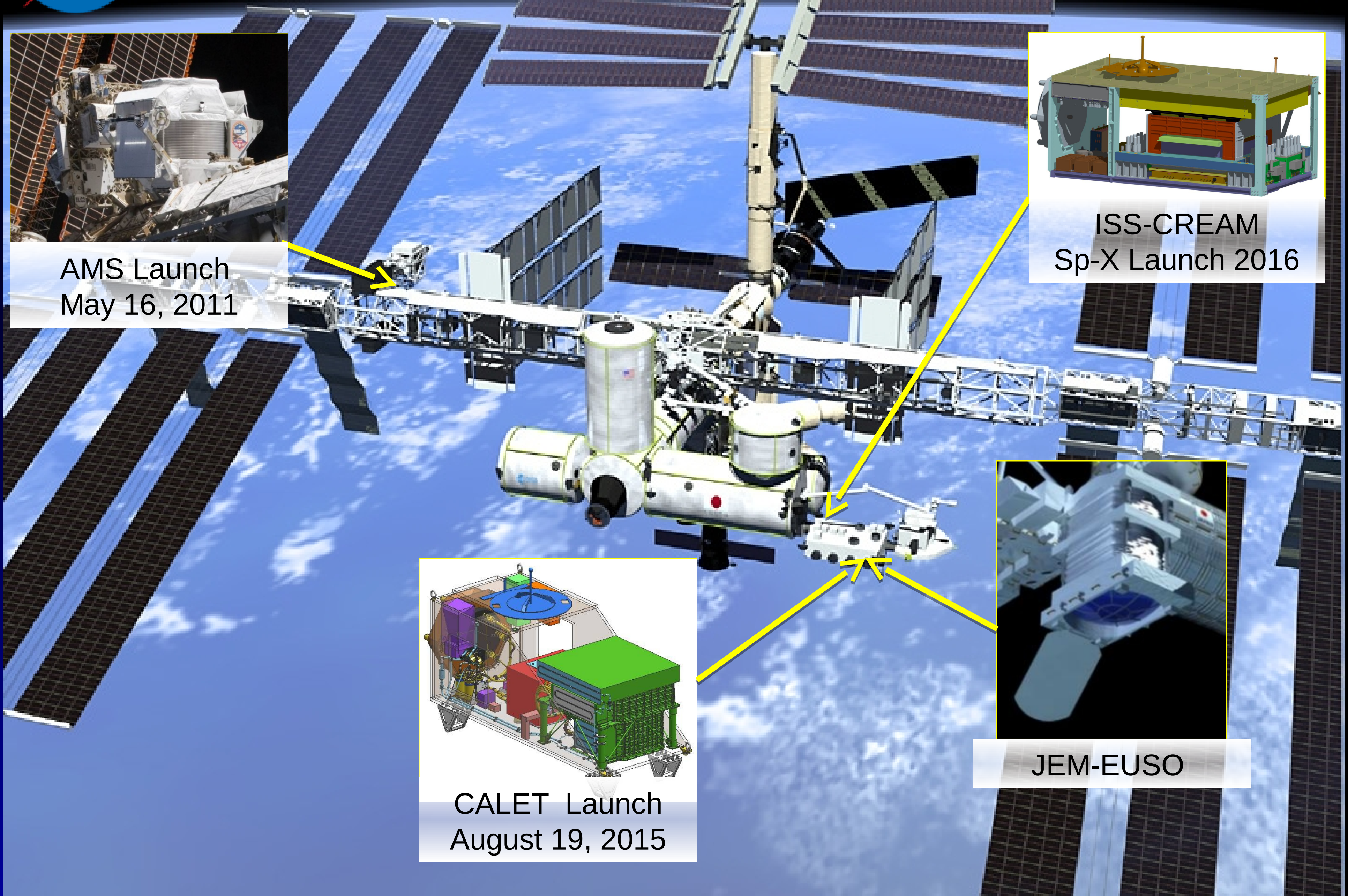
PAMELA
15-06-2006

BESS
Polar II 23-12-2007

Fermi/GLAST
11-6-2008

DAMPE end 2015

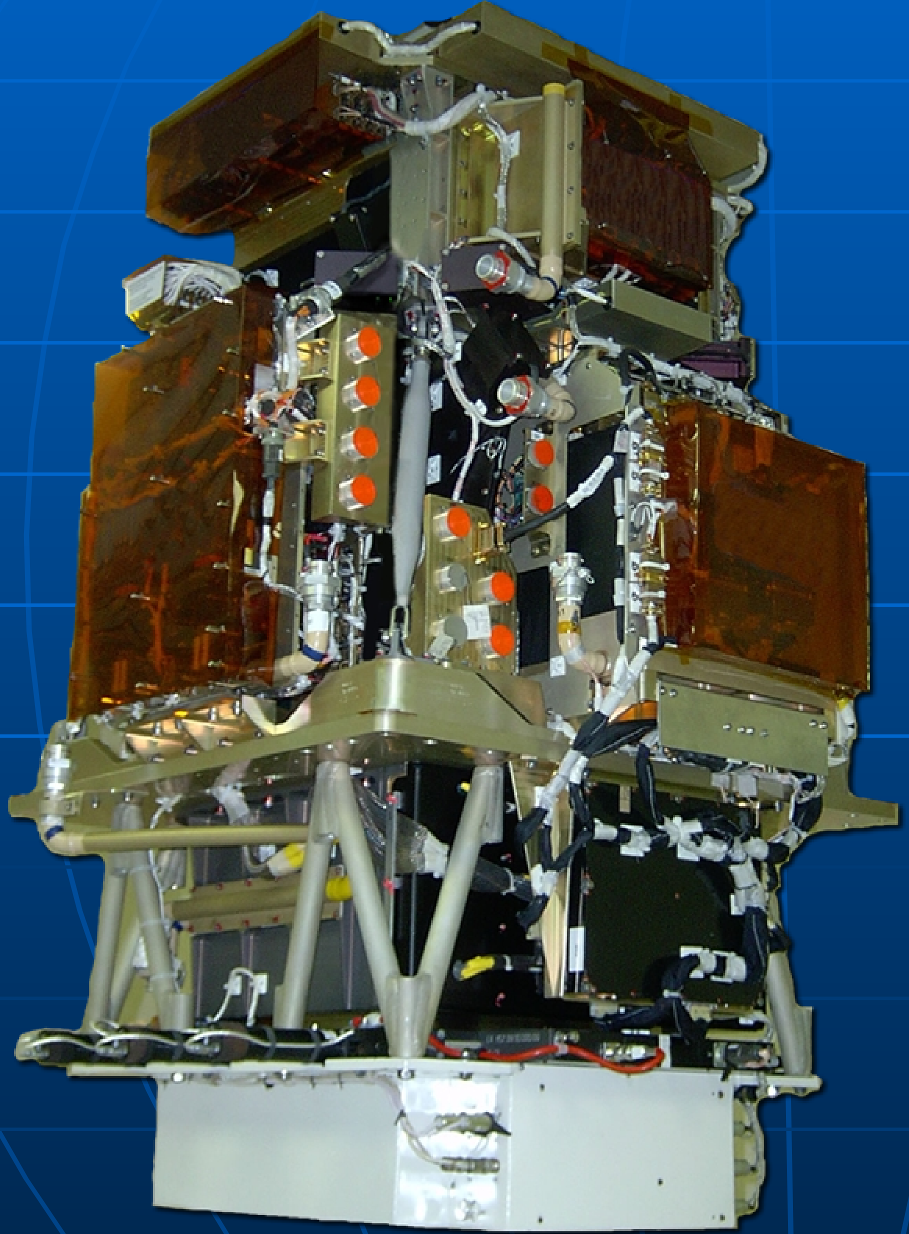
“Cosmic Ray Observatory on the ISS”



PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Instrument



GF ~21.5 $cm^2 sr$

Mass: 470 kg

Size: 130x70x70 cm^3

PAMELA Collaboration

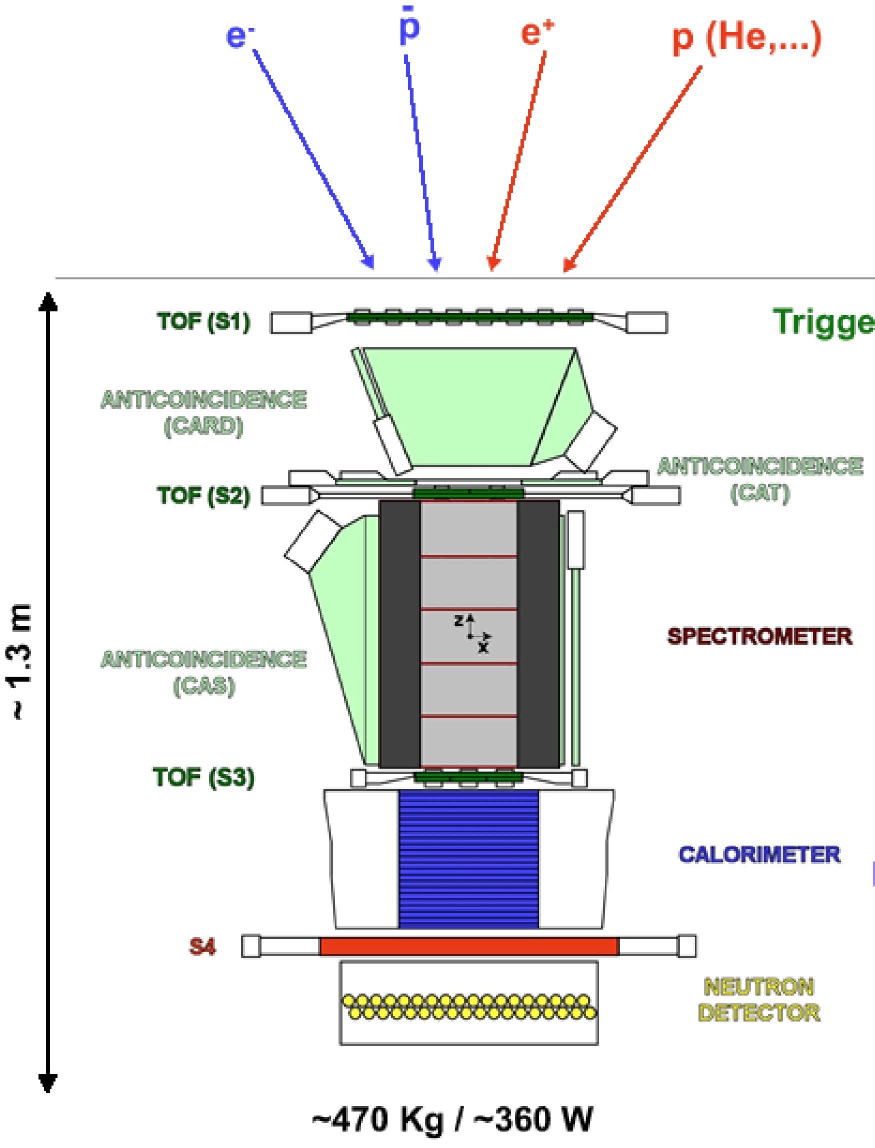
Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Russia: Moscow, St. Petersburg

Germany: Siegen

Sweden: KTH, Stockholm

PAMELA Instrument



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR

MDR 1.2 TeV

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

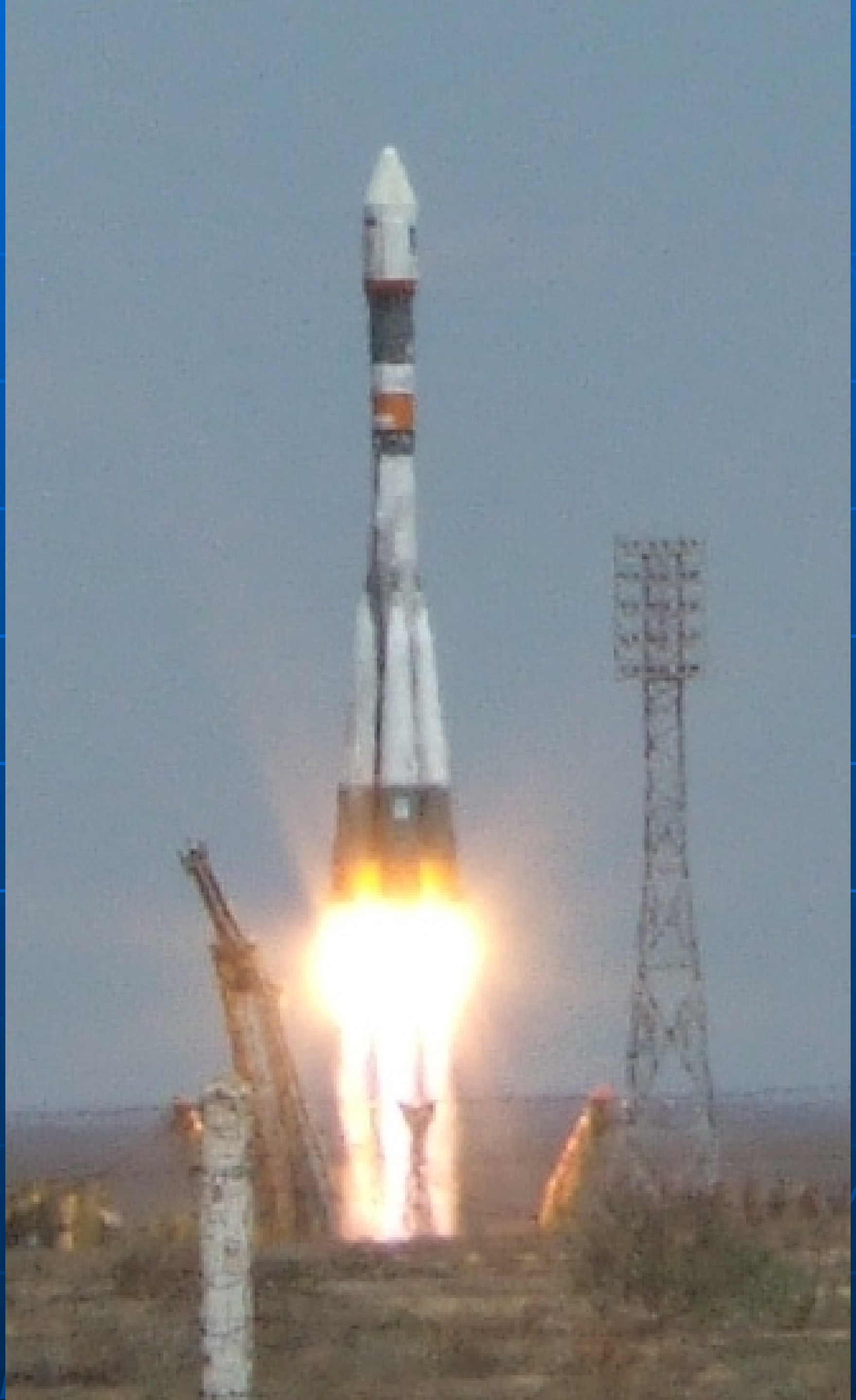
PAMELA

Launch 15/06/06

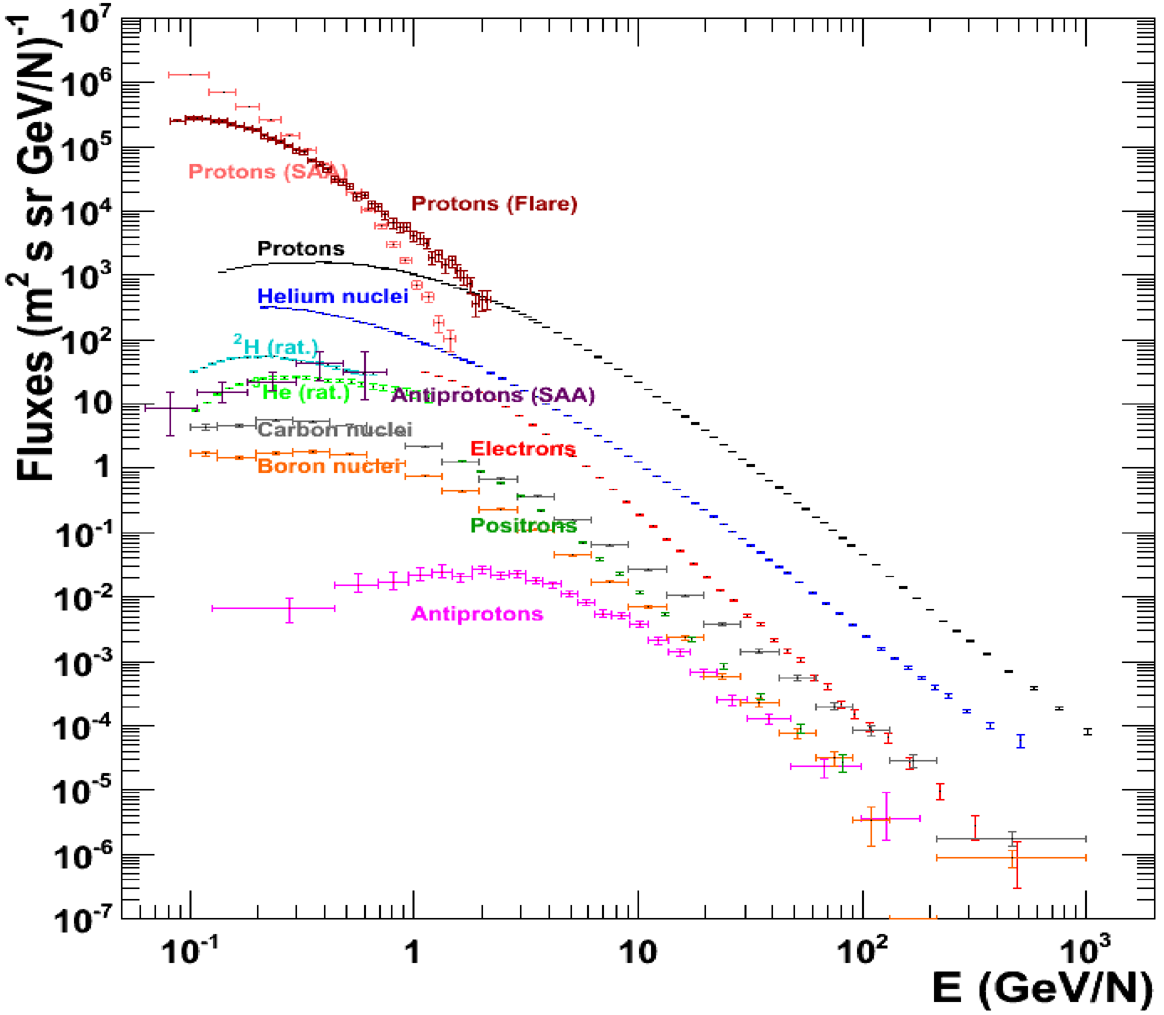
Bajkonour Launch site

Low-earth elliptical orbit
350 – 610 km
Quasi-polar (70^o inclination)

Also in Operation at an altitude of 560 km

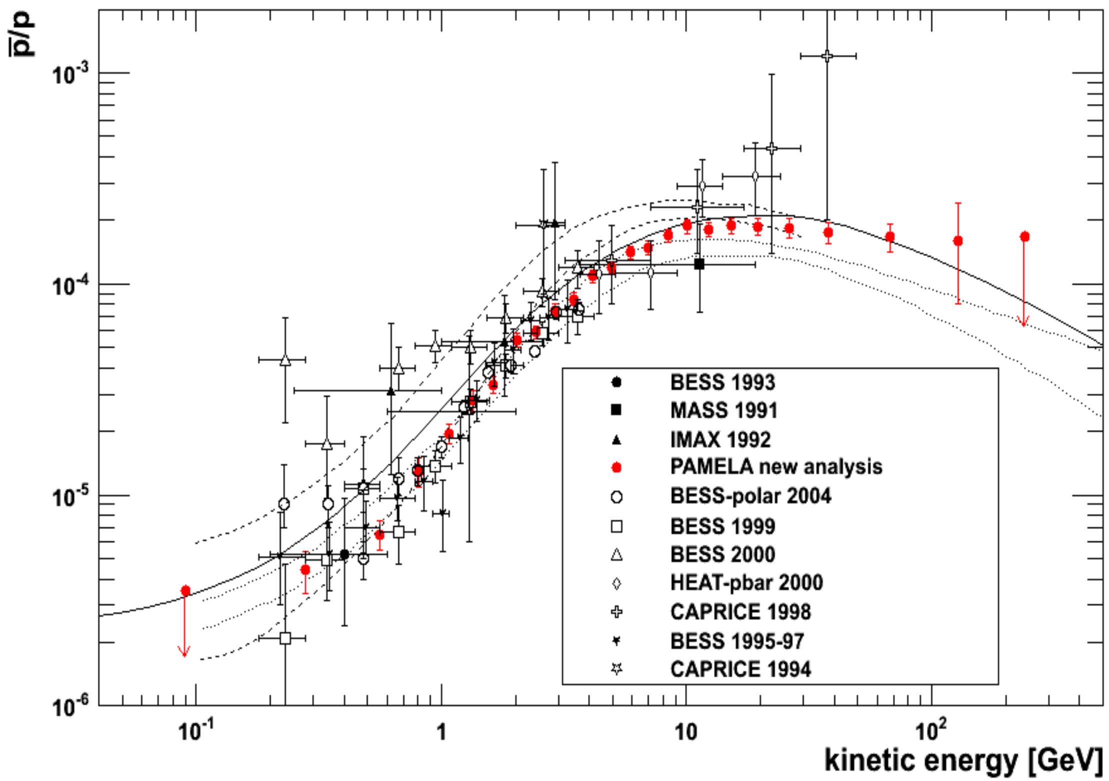


Summary of PAMELA results

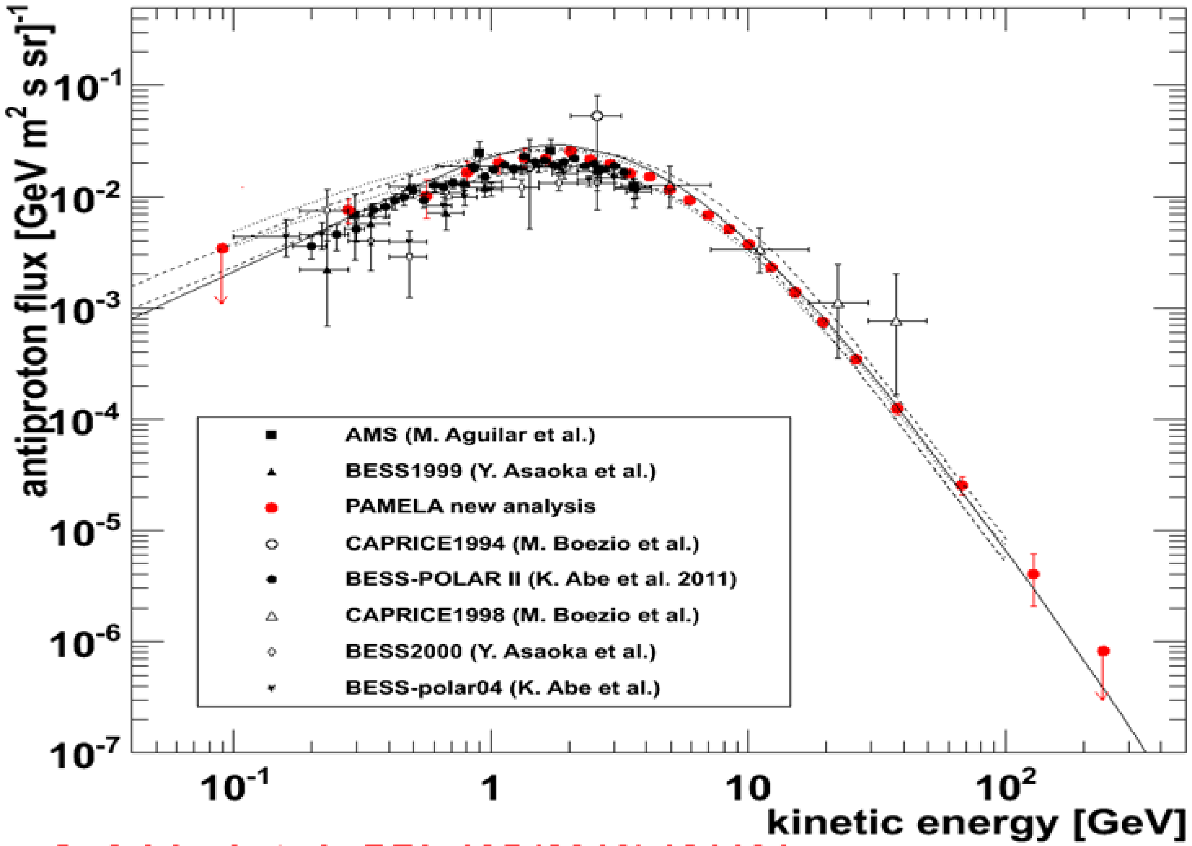


All data in Physics Reports 544/4 (2014), 323

PAMELA Antiprotons



O. Adriani et al.,
PRL 102 (2009) 051101
PRL 105 (2010) 121101

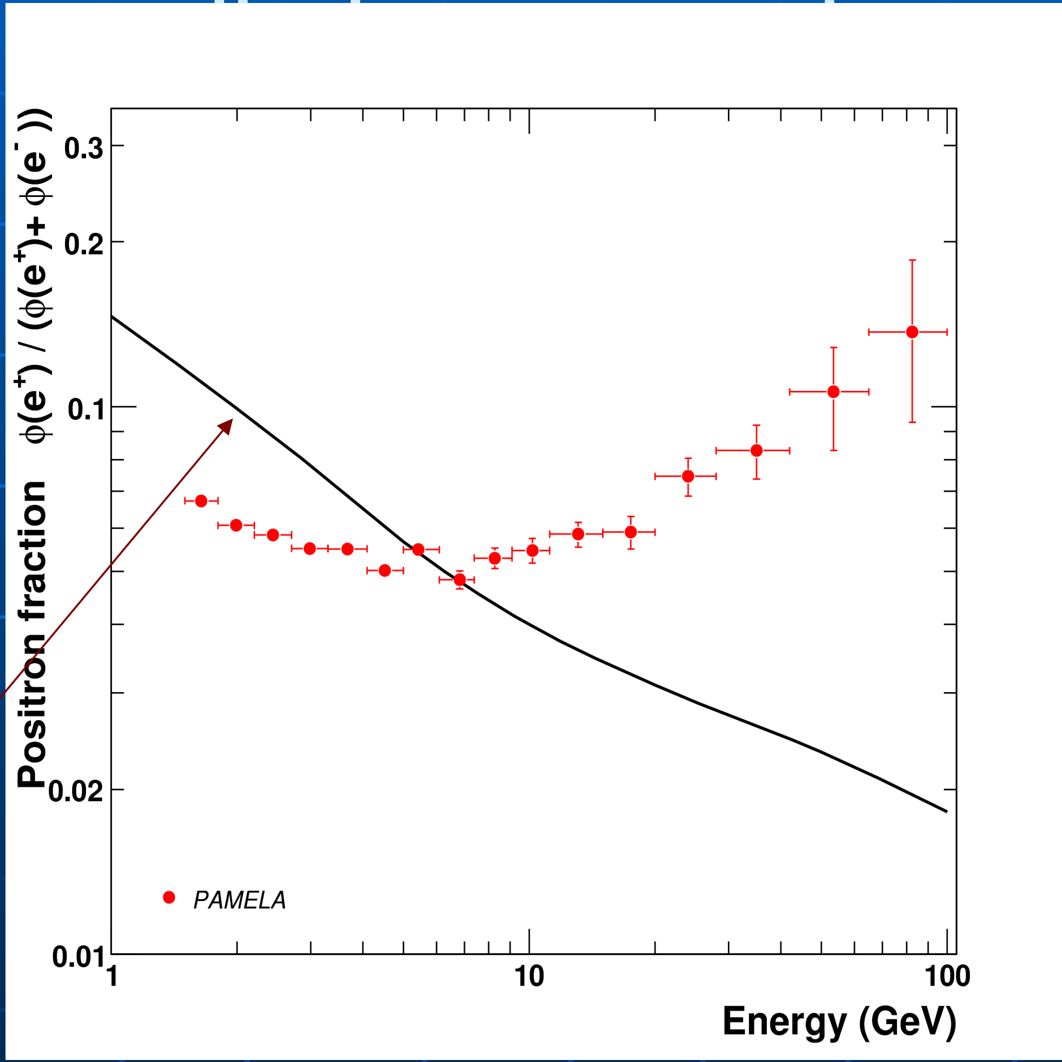


O. Adriani et al., PRL 105 (2010) 121101
O. Adriani et al.,Phys. Rep. (2014)

PAMELA Positron

Nature 458, 697, 2009

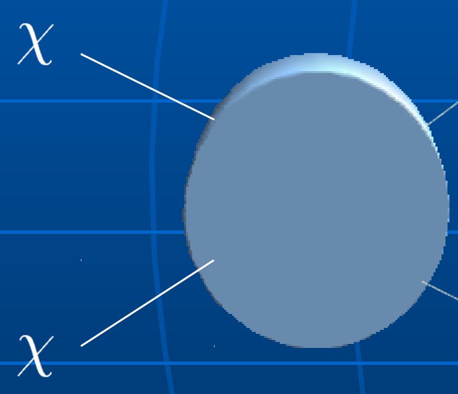
$$R(E) = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$



<u>**Secondary production**</u>
Moskalenko & Strong 98

DM annihilations

DM particles are stable. They can annihilate in pairs.



$W^-, Z^0, b, \tau^-, t, h^0, \ldots$ ⇒ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D}, \ldots$

$W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots$ ⇒ $e^\pm, \overset{(-)}{p}, \overset{(-)}{D}, \ldots$

Primary annihilation channels

Decay

Final states

flux $\propto n^2 \, \sigma_{\rm annihilation}$

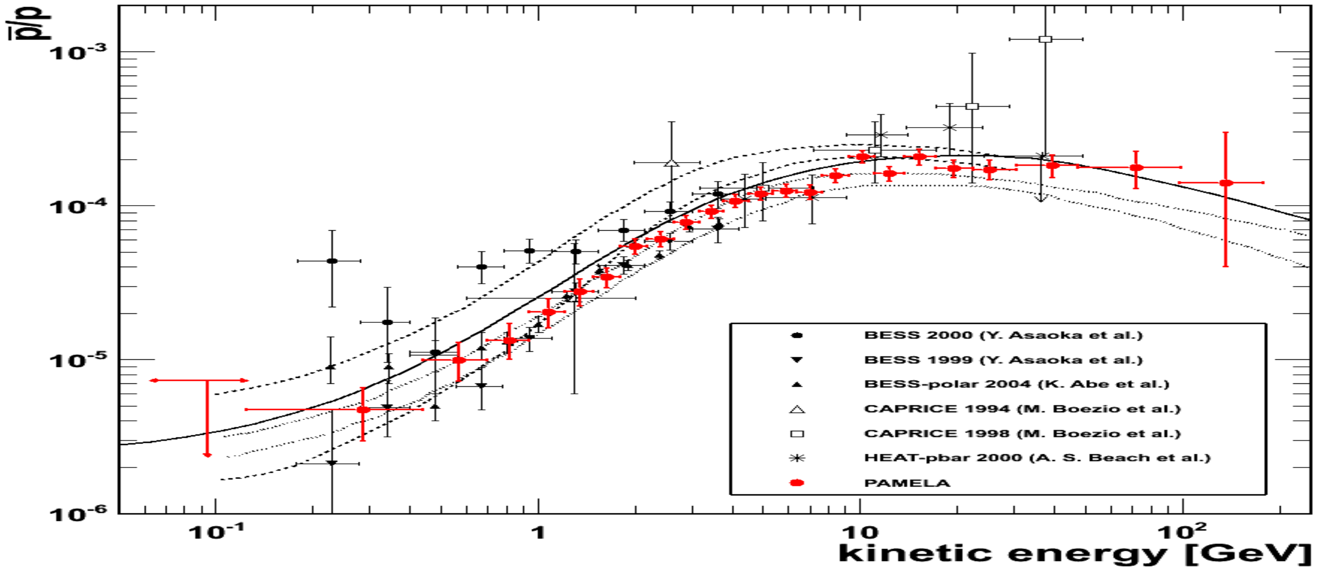
astro& cosmo — particle

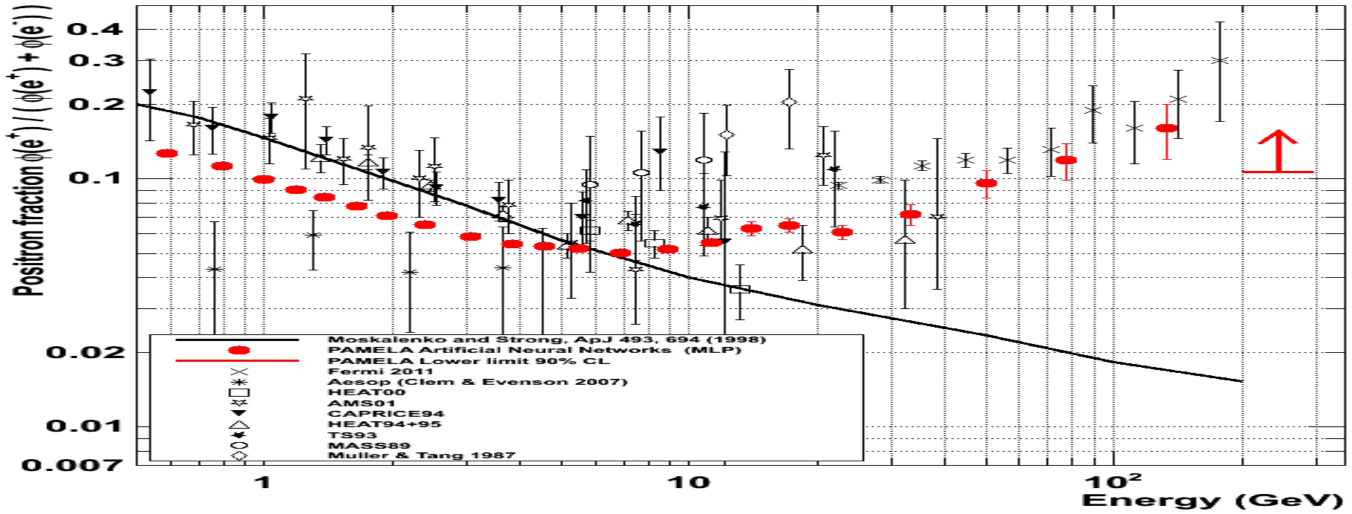
reference cross section:

$\sigma = 3 \cdot 10^{-26} \, {\rm cm}^3/{\rm sec}$

$\sigma_a = \langle \sigma v \rangle$

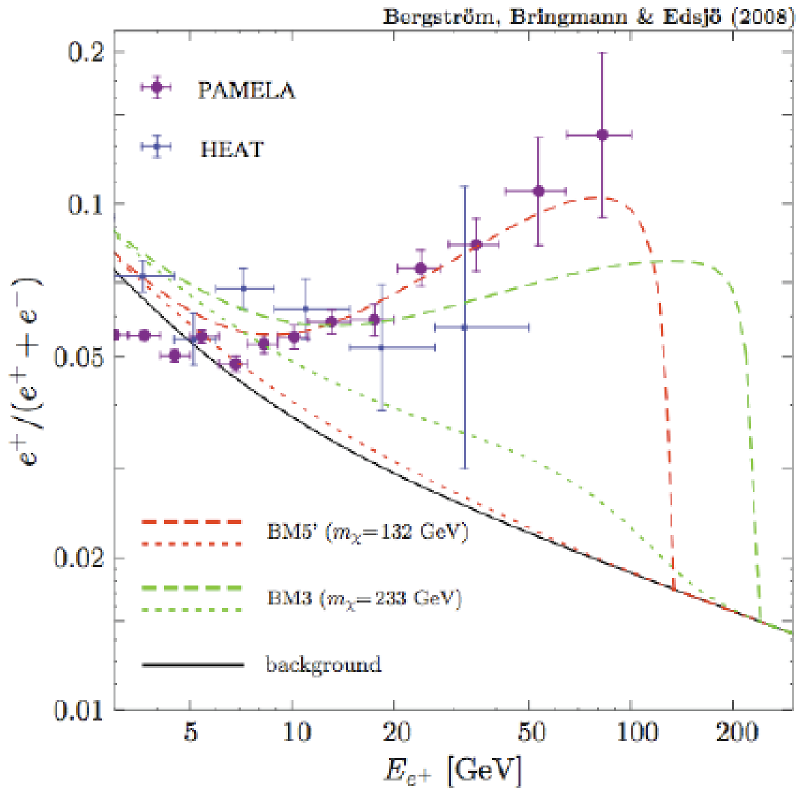
A Challenging Puzzle for Dark Matter Interpretation





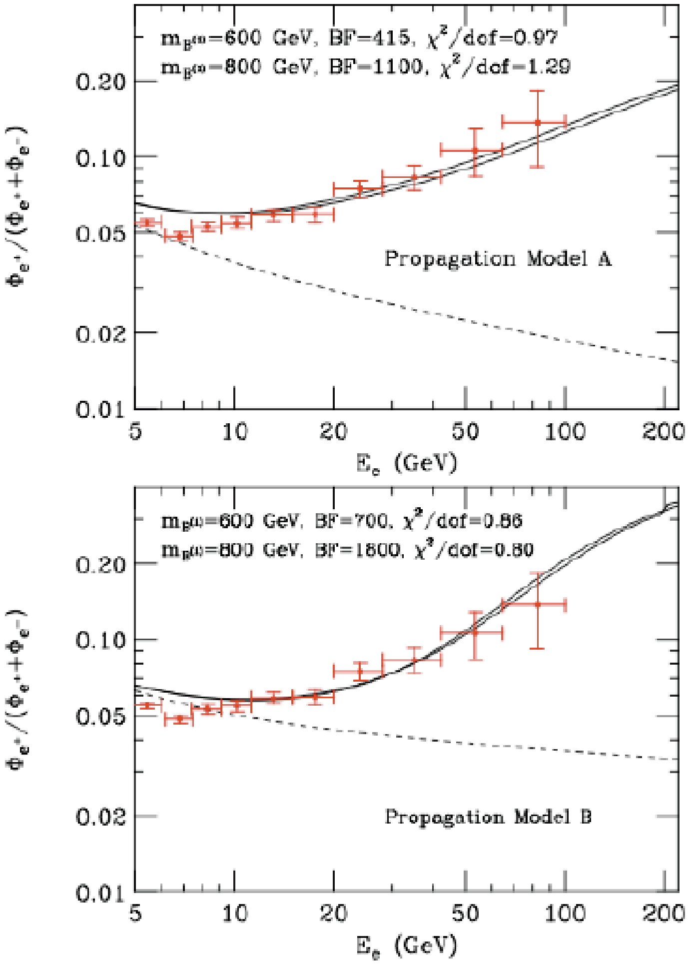
Example: Dark Matter

Phys.Rev.D8:103520,2008



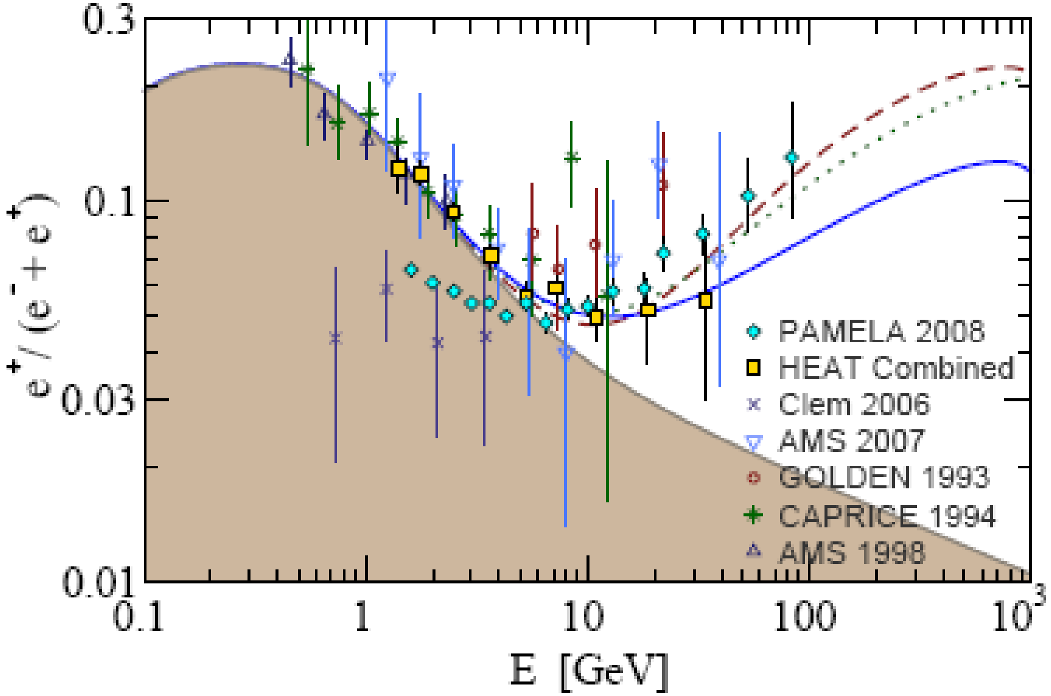
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Phys.Rev.D79:103529,2009

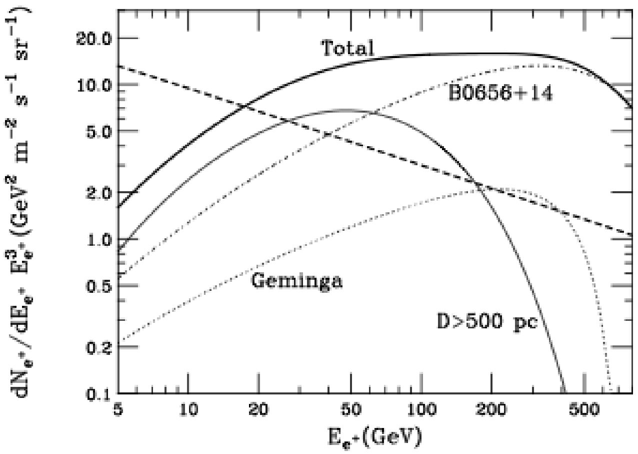


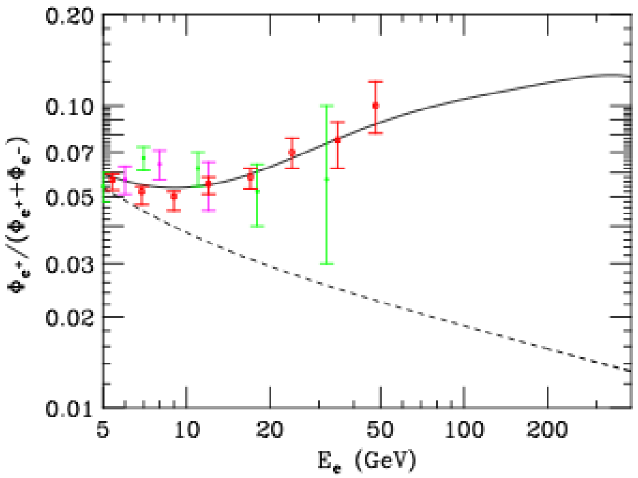
Kaluza-Klein dark matter

Example: pulsars



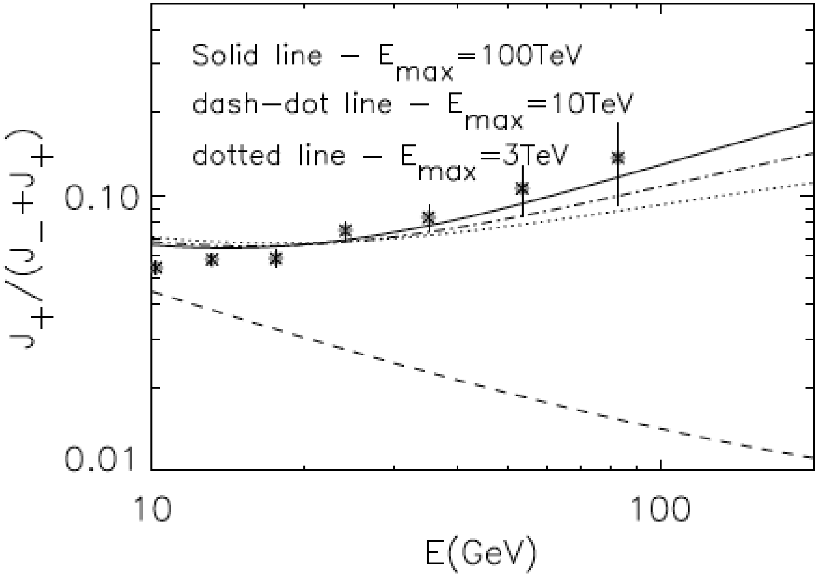
H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar





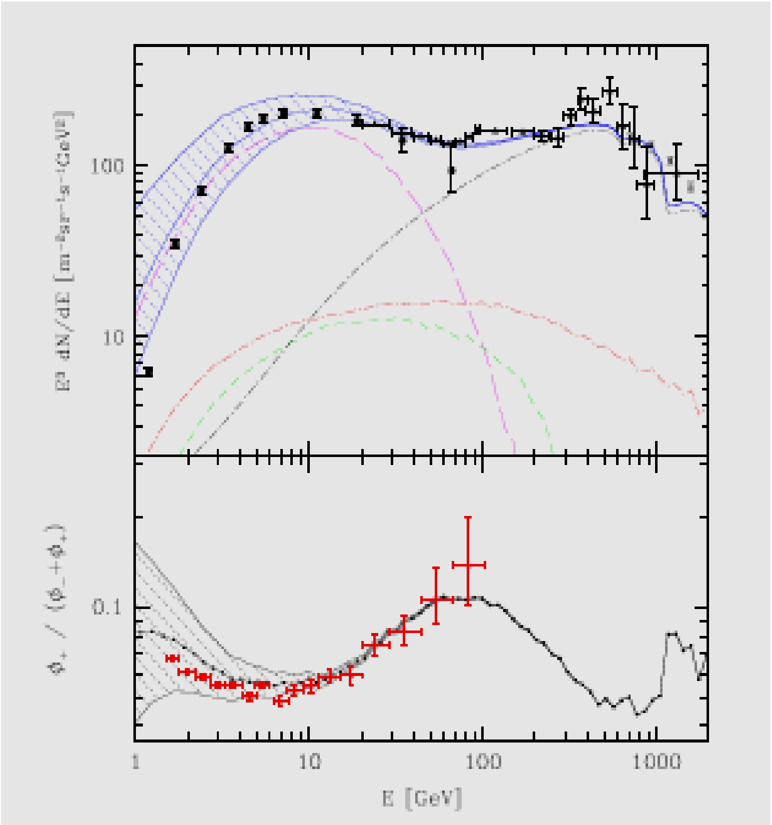
Hooper, Blasi, and Serpico
arXiv:0810.1527

A Challenging Puzzle for CR Physics



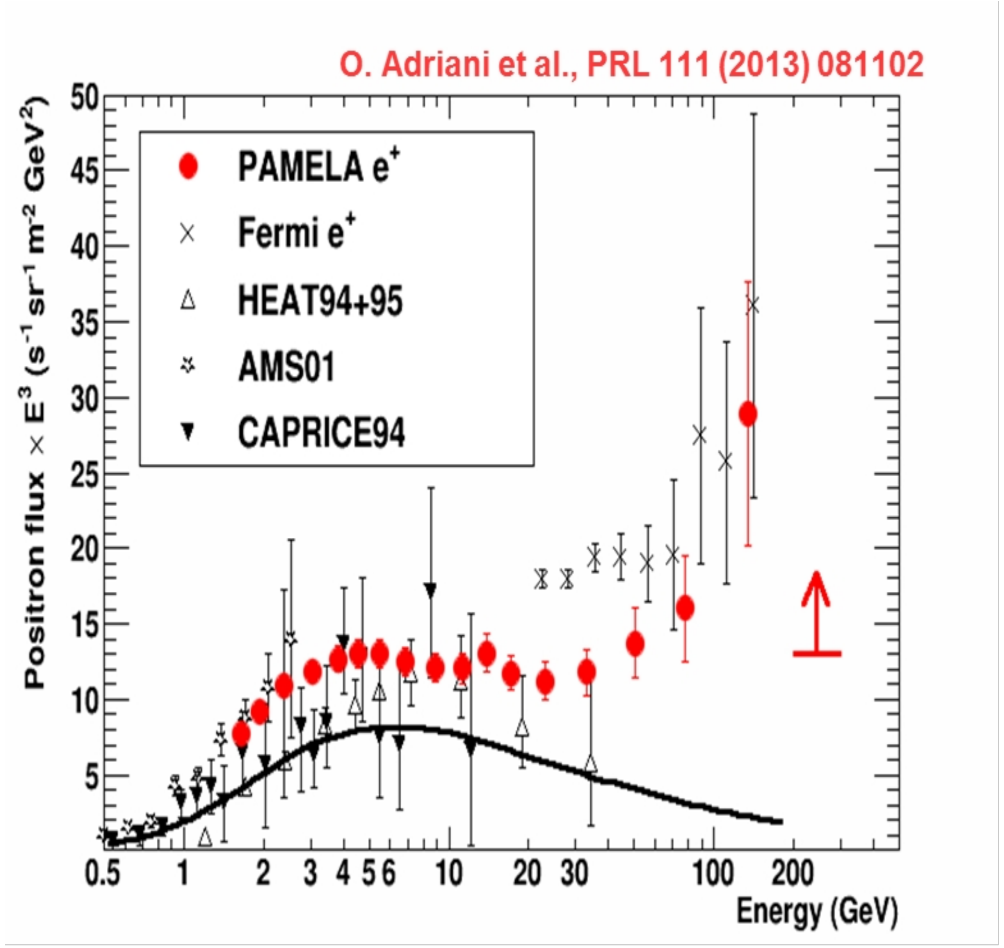
P.Blasi, PRL 103 (2009) 051104; 4
Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.
S: Sarkar Phys.Rev.Lett.103:081104,2009 arXiv:1108.1753. Nearby sources
But also other secondaries are produced: significant increase expected in the p/p and B/C ratios.

Y. Fujita Phys.Rev.D80:063003,2009

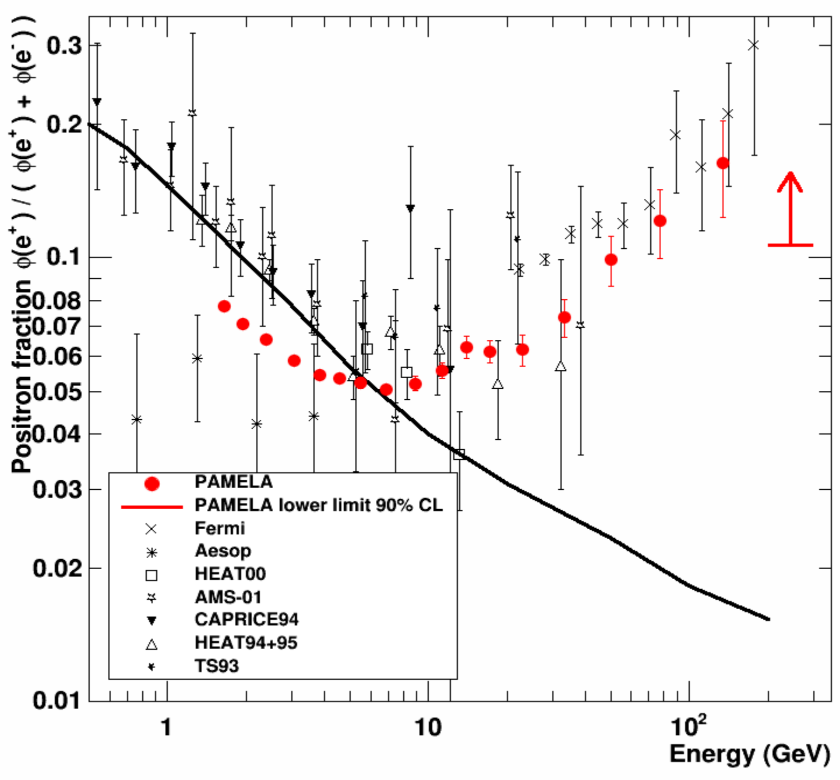


N.J. Shaviv et al., PRL 103 (2009) 111302;

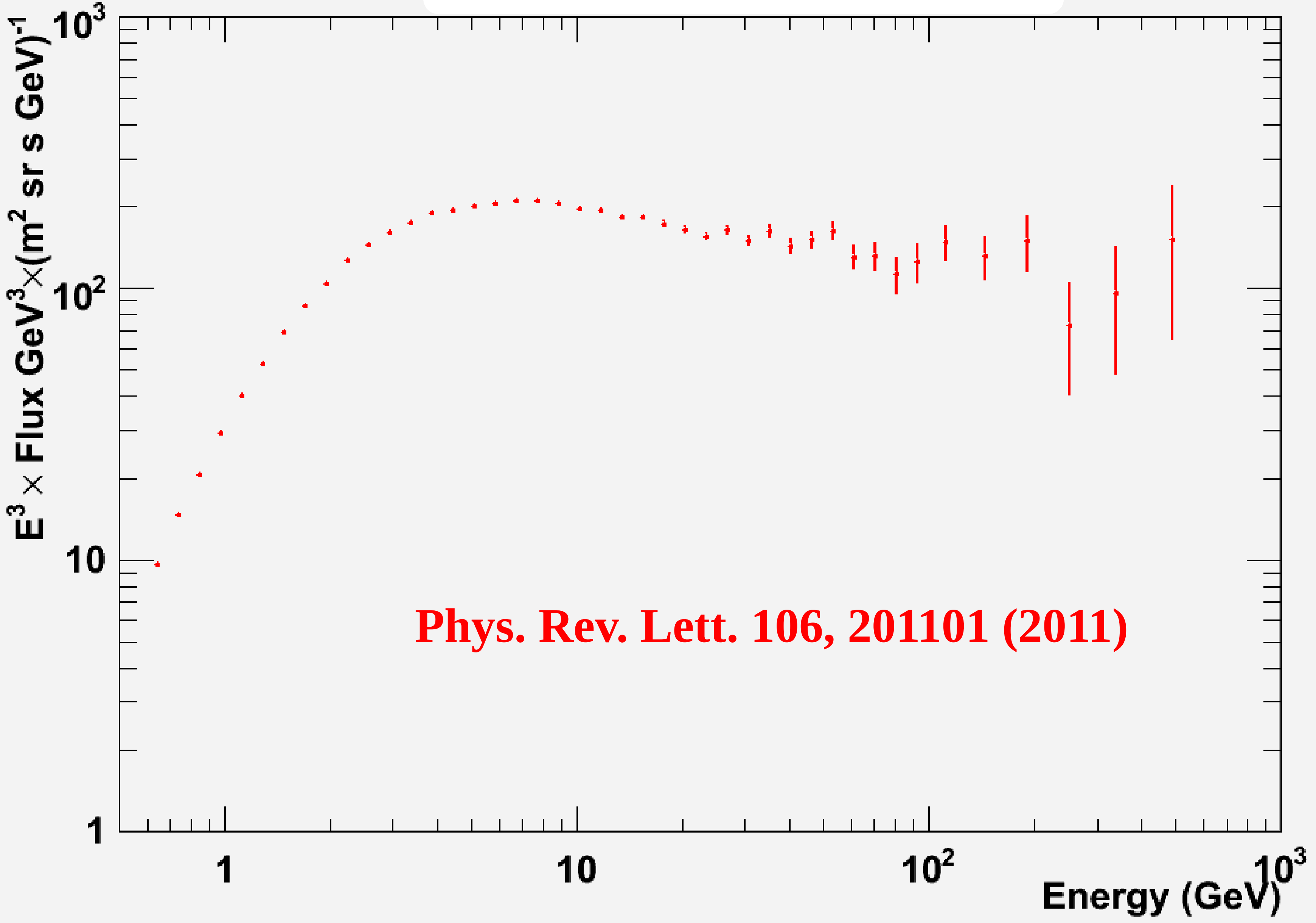
Positrons



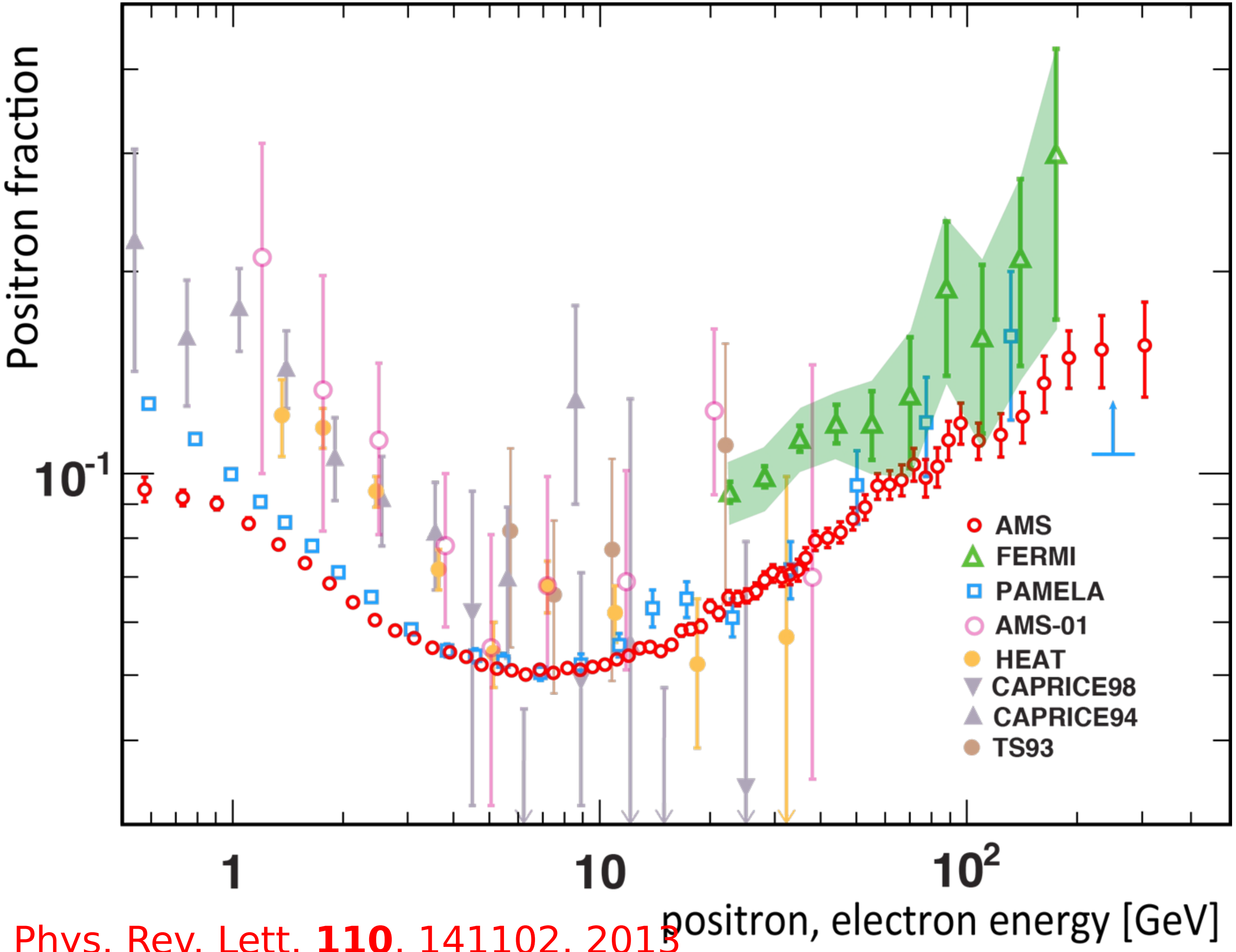
O. Adriani et al.,
Nature 458 (2009) 607;
Astropart. Phys. 34 (2010) 1;
PRL 111 (2013) 081102



PAMELA Electron flux

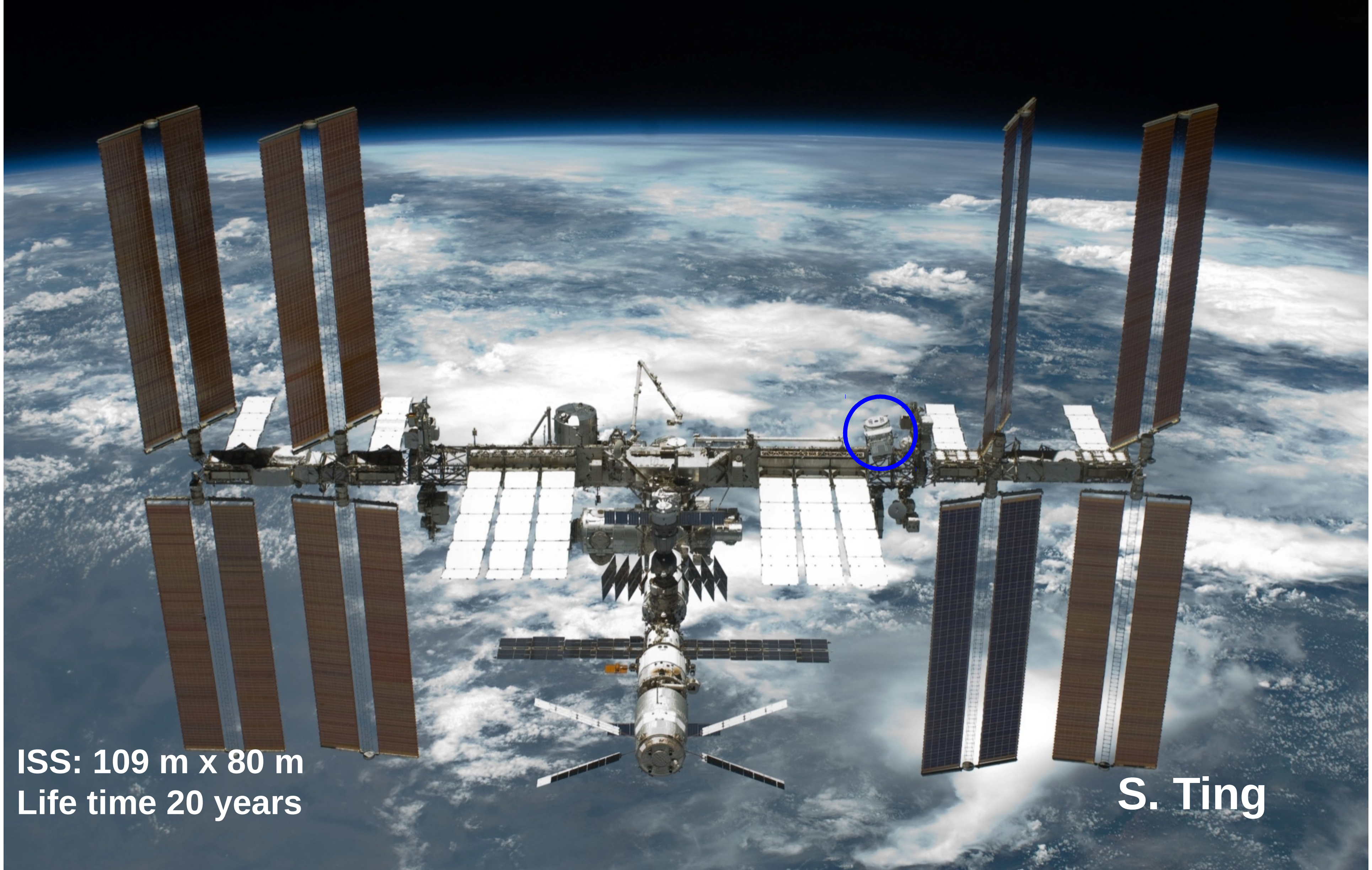


Four Years Later: AMS-02



Phys. Rev. Lett. **110**, 141102, 2013

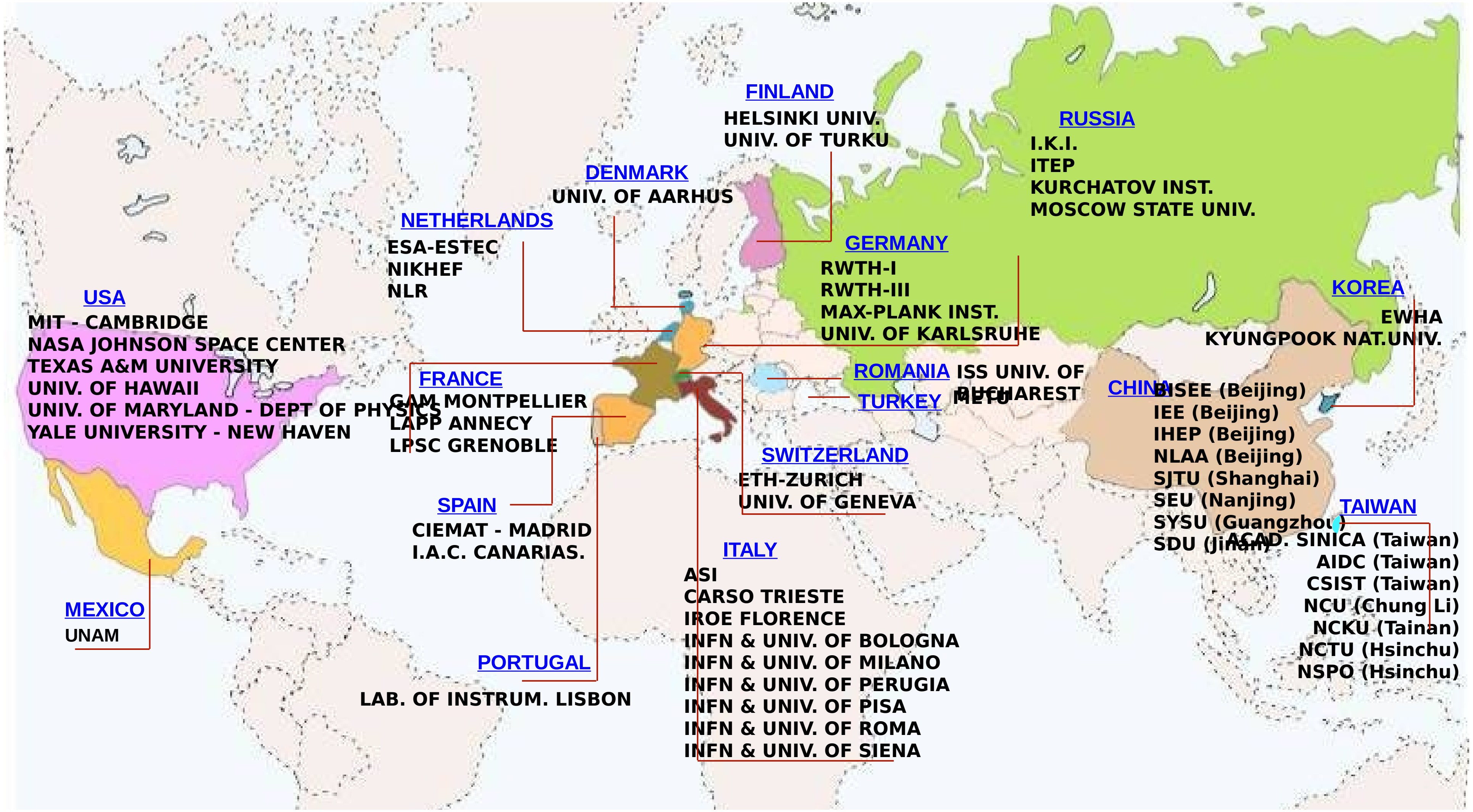
The Alpha Magnetic Spectrometer (AMS) Experiment *on the International Space Station.*



ISS: 109 m x 80 m
Life time 20 years

S. Ting

AMS: U.S. DOE sponsored international collaboration



Strong support from

NASA (D. Goldin, C. Bolden, L. Garver, G. Abbey, W. Gerstenmaier, M. Sistilli, T. Martin, K. Bollweg, …)

and DOE (J. Siegrist, M. Salamon, D.Kovar, S. Gonzalez, R. Staffin, J. O'Fallon, …)

A TeV Range Large Aperture Magnetic Spectrometer

300,000 electronic channels
650 computers

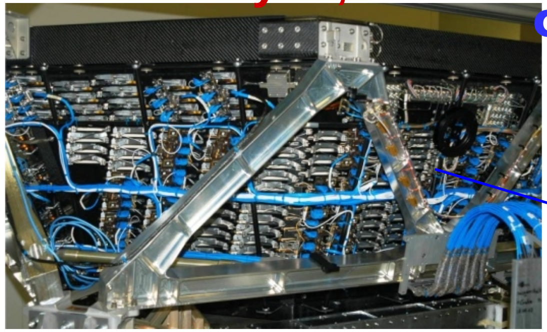
2 billion$

5m x 4m x 3m
7.5 tons

AMS: A TeV precision, multipurpose spectrometer

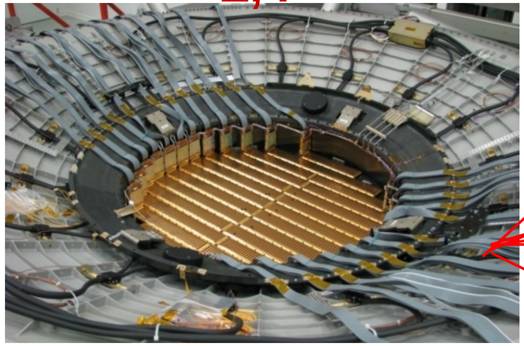
Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

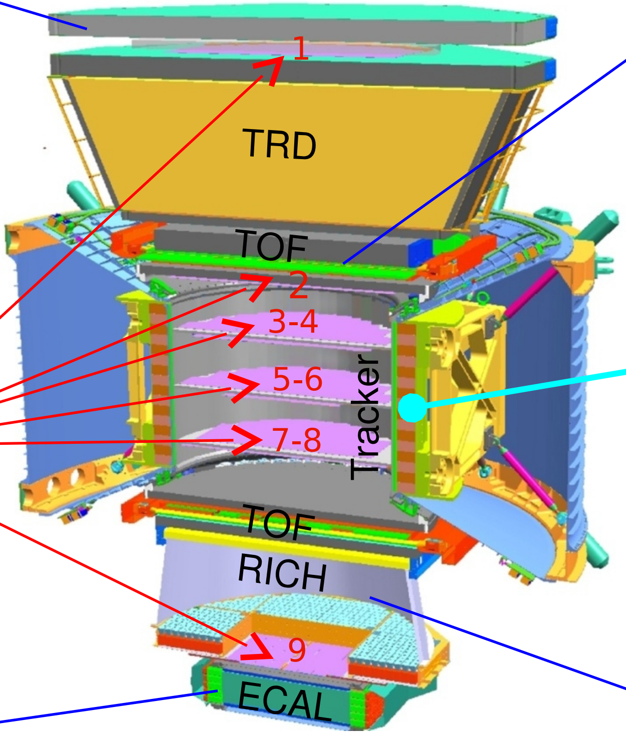
TRD
Identify e^+, e^-



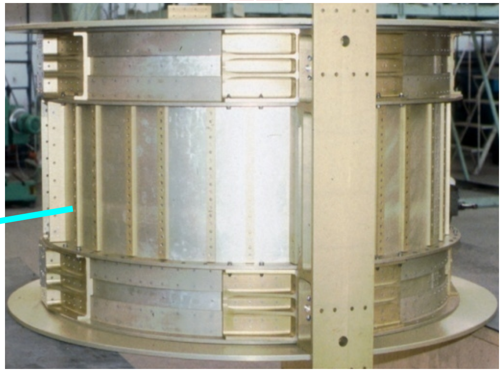
TOF
Z, E

Silicon Tracker
Z, P

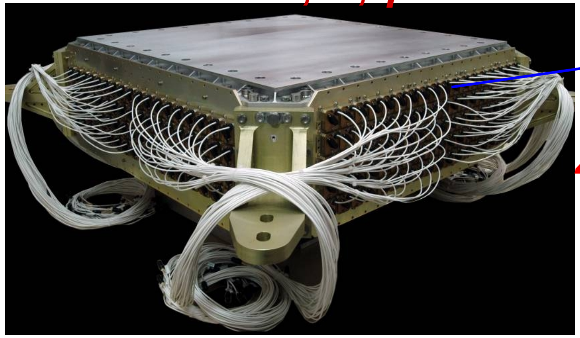




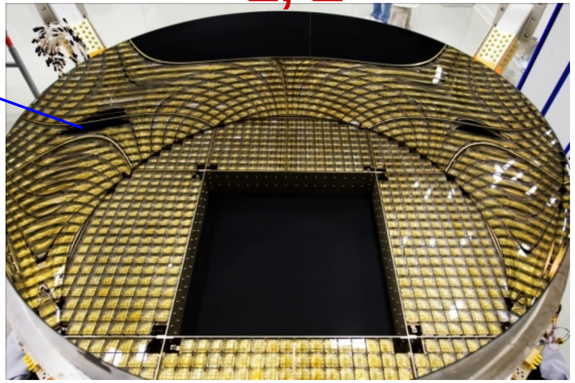
Magnet
±Z



ECAL
E of e^+, e^-, γ

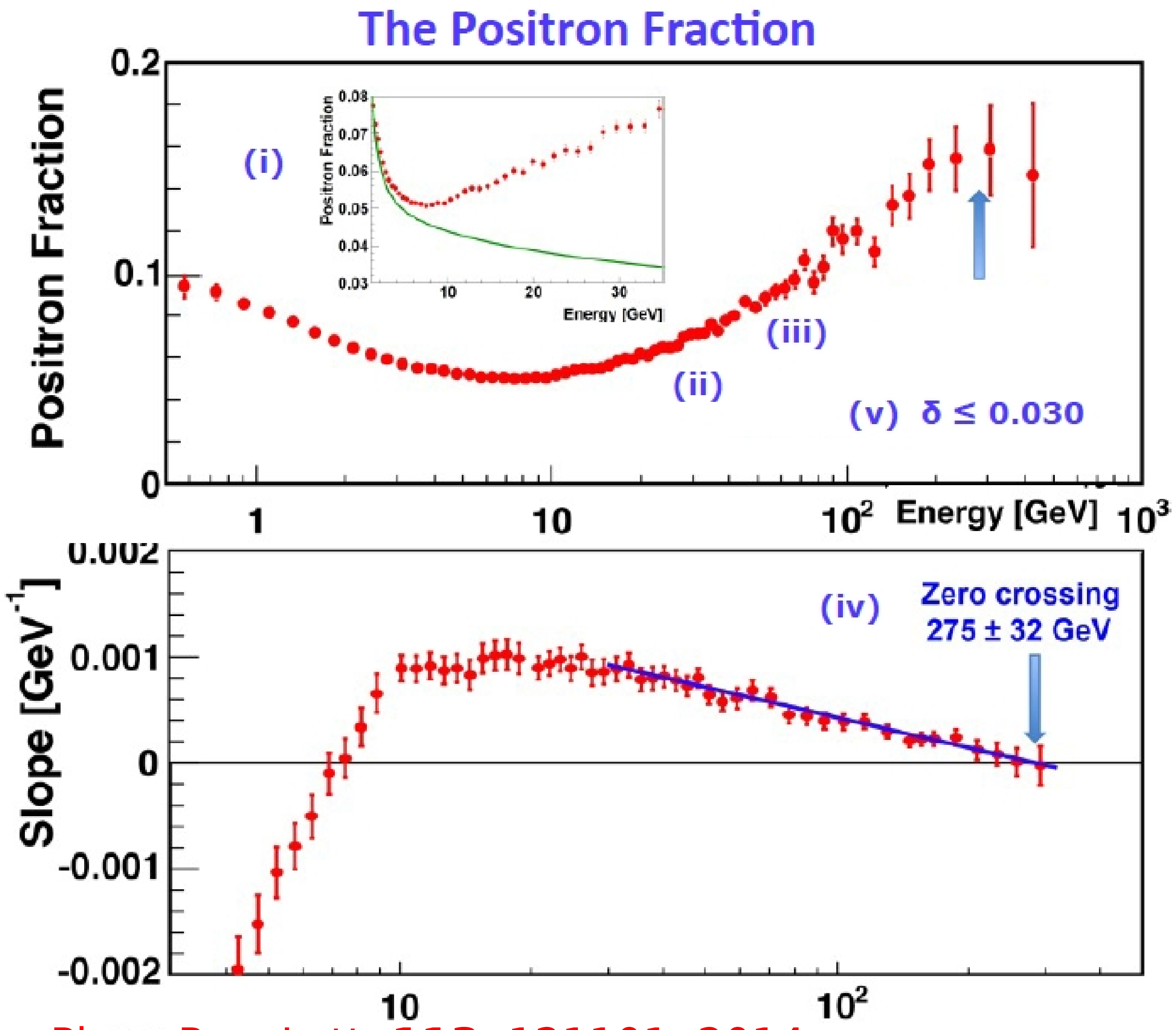


RICH
Z, E



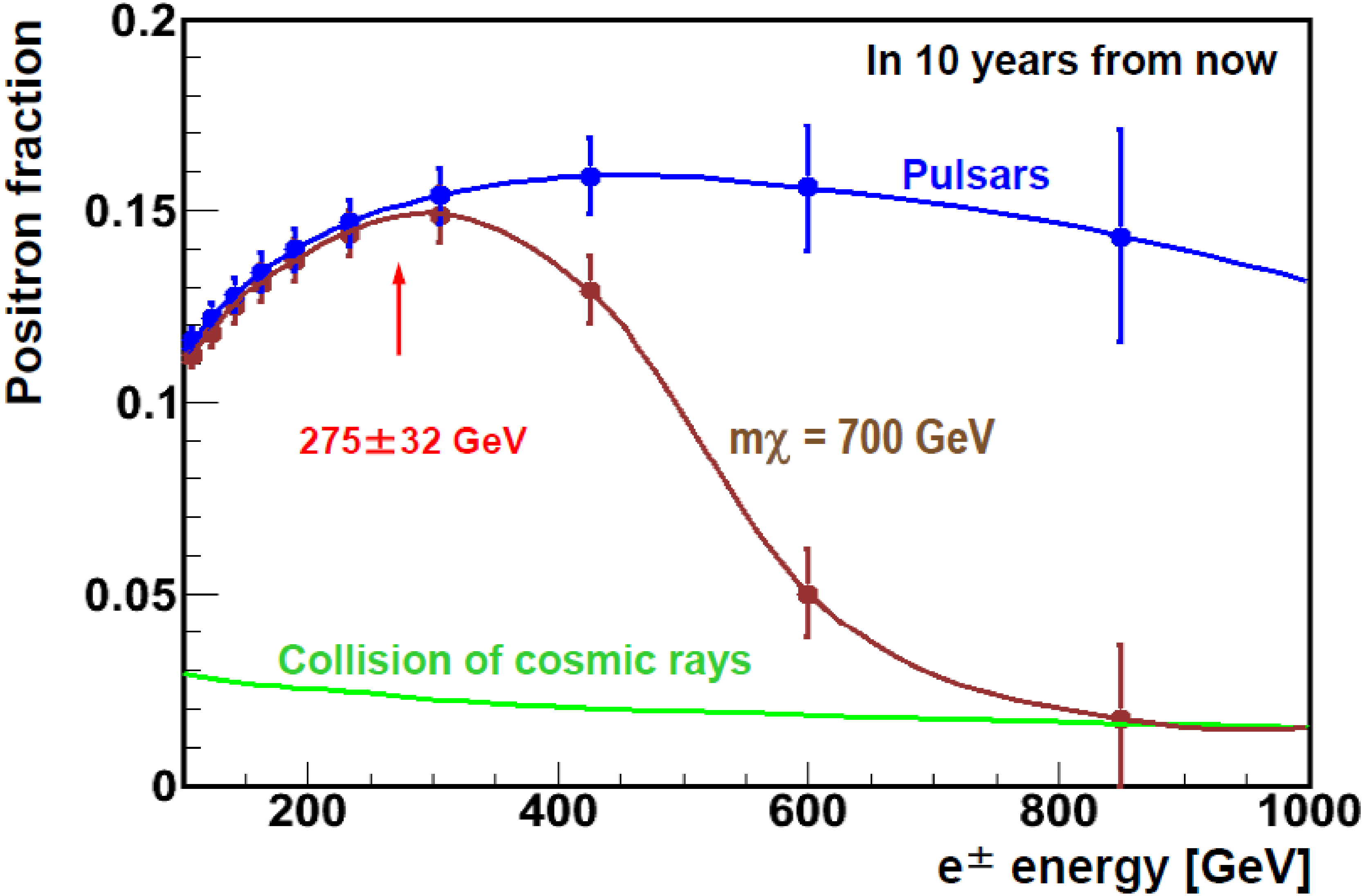
Z, P *are measured independently by the Tracker, RICH, TOF and ECAL*

AMS-02

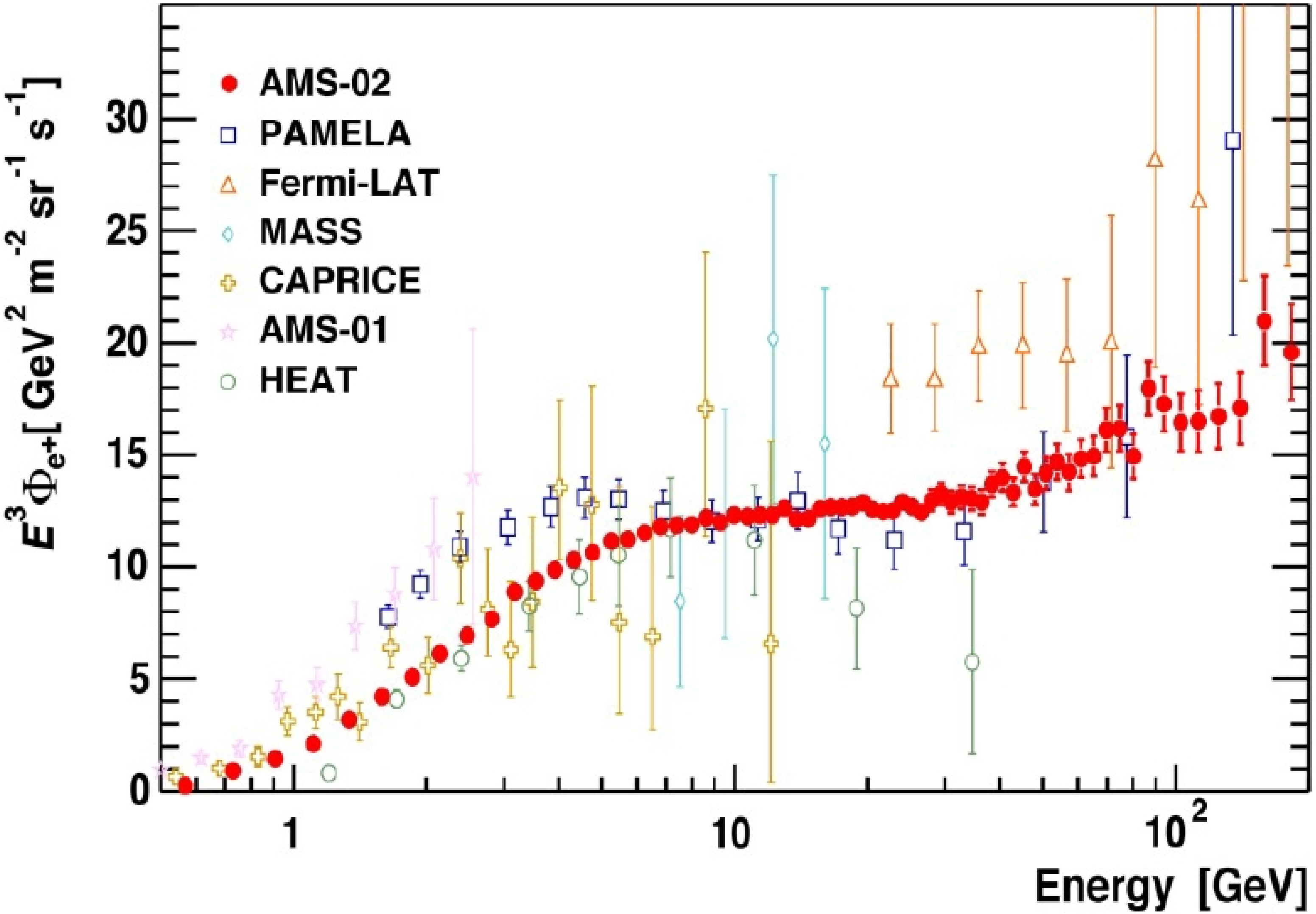


Phys. Rev. Lett. **113**, 121101, 2014

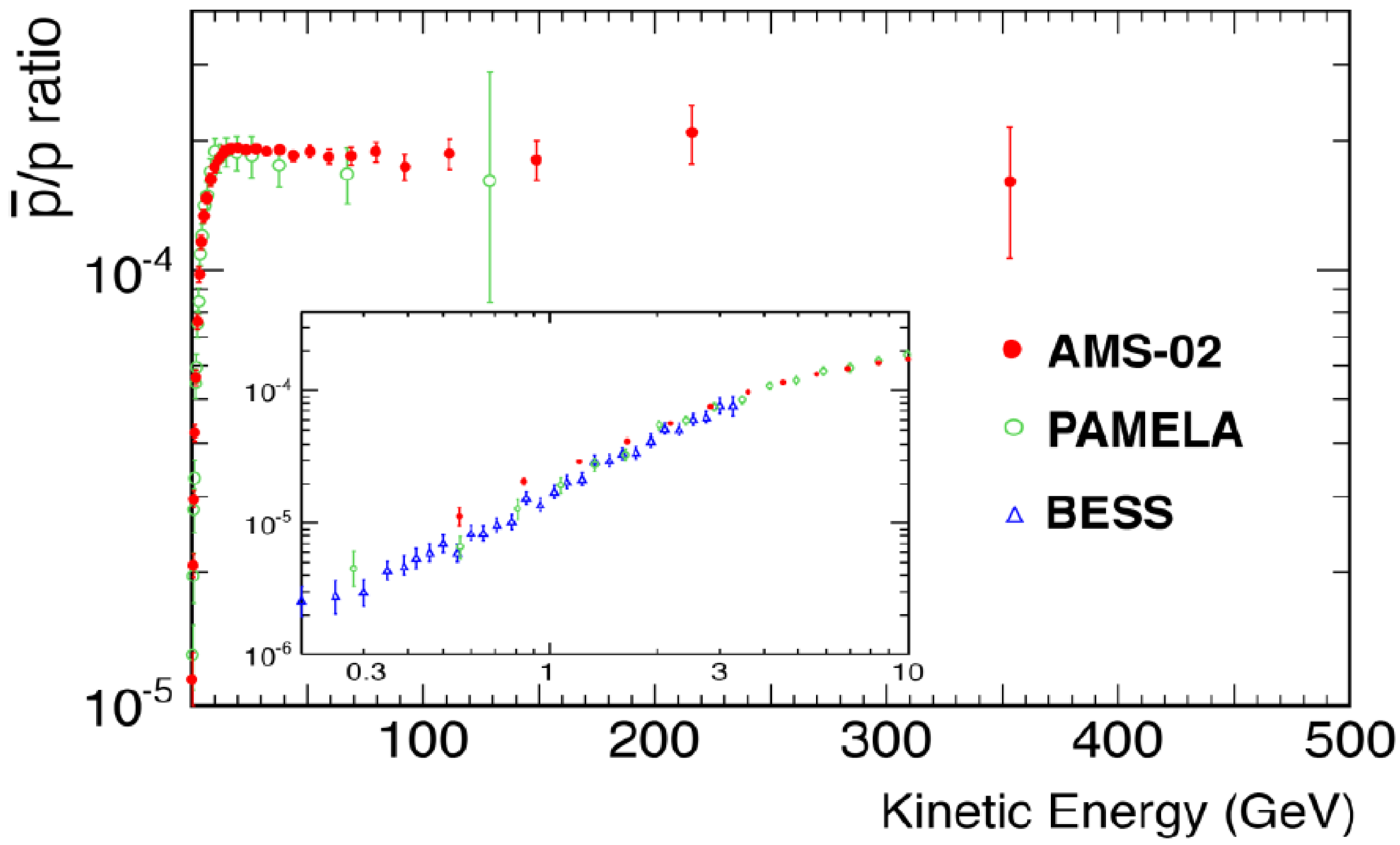
The expected rate at which it falls beyond the turning point.



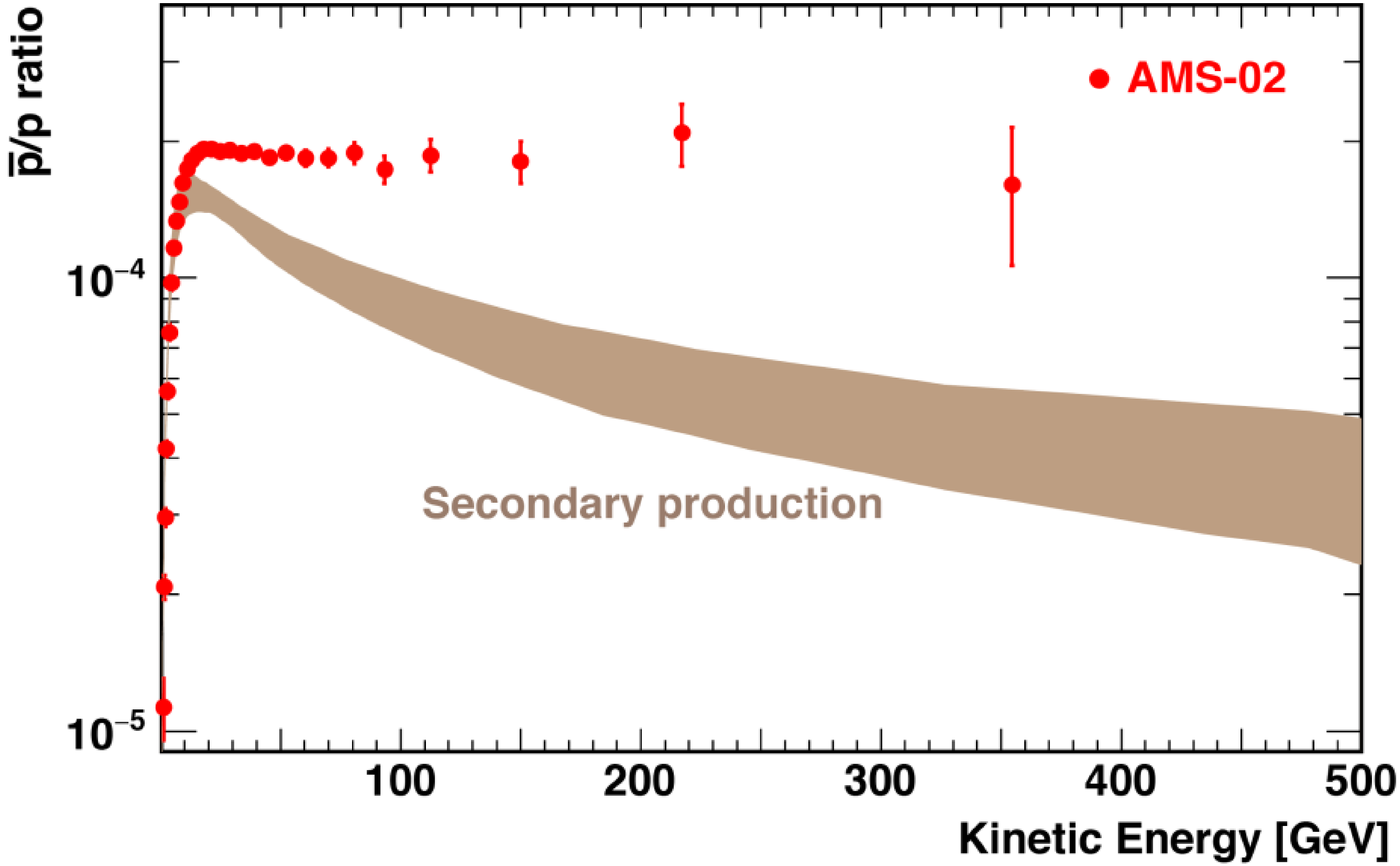
Positron Flux



AMS $\bar{p}/p$ results



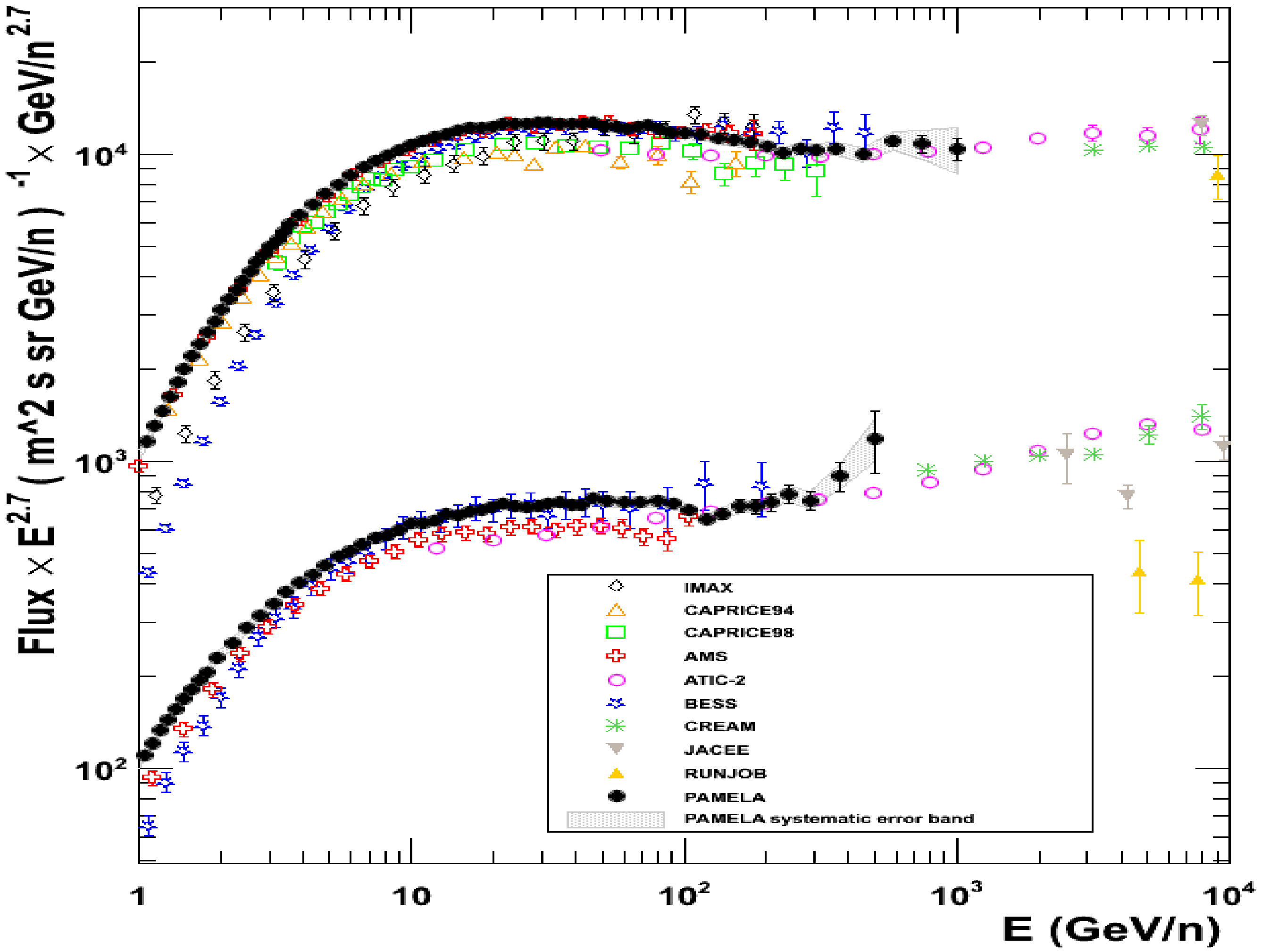
Antiproton to proton fraction



Absolute fluxes of primary GCRs

Protons, helium nuclei, light nuclei, electrons

Proton and Helium fluxes

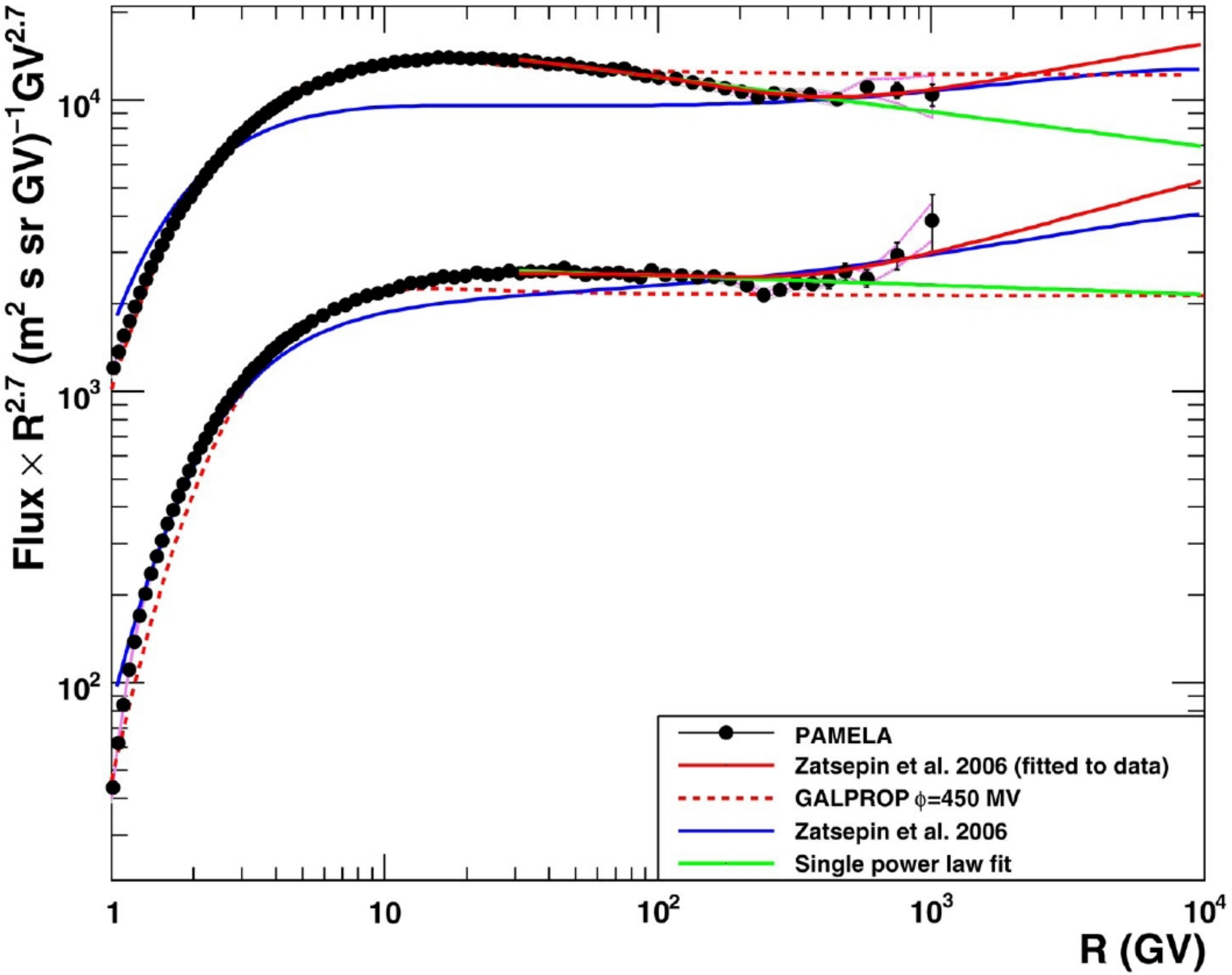


p

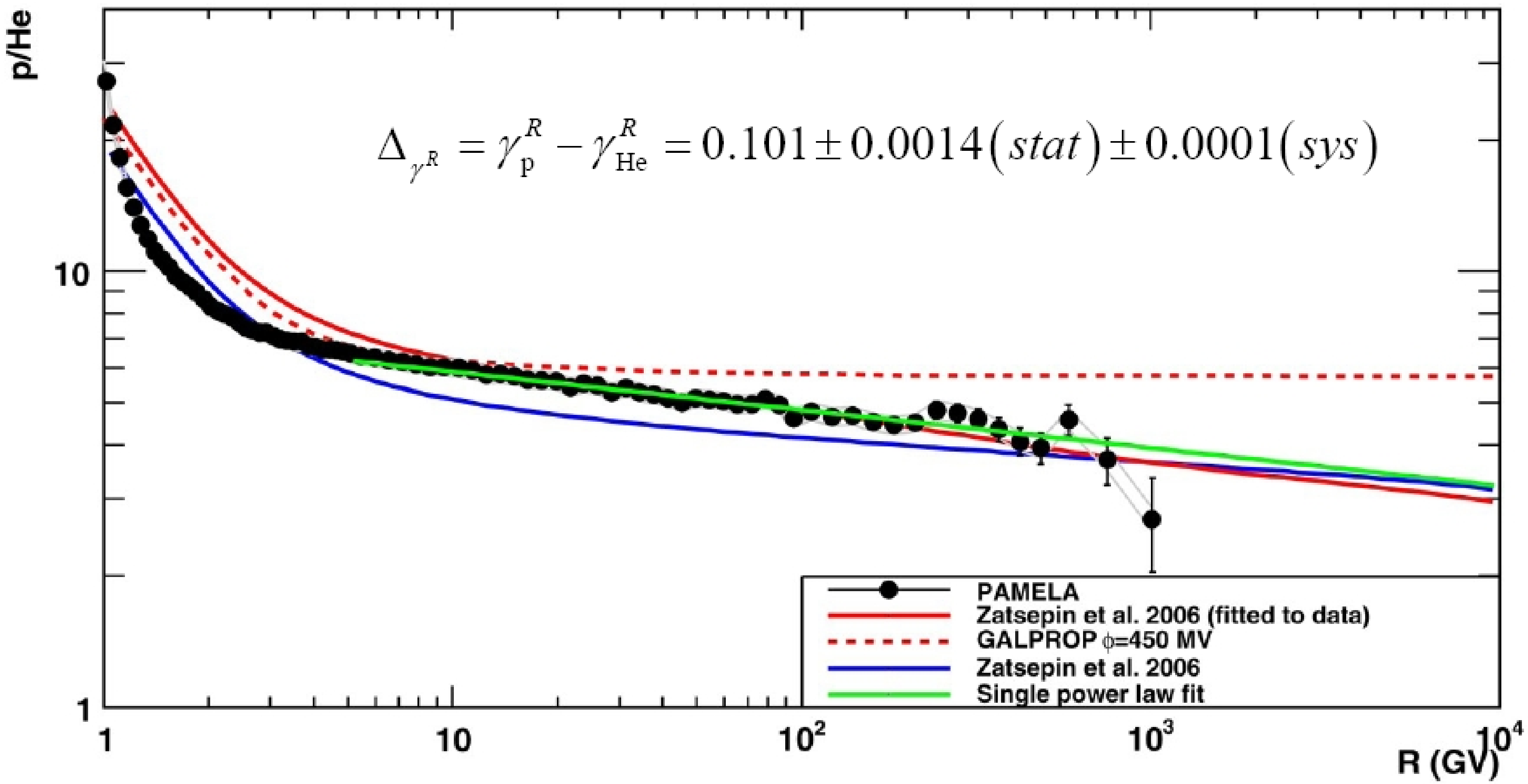
He

PAMELA Science 332,69 (2011)

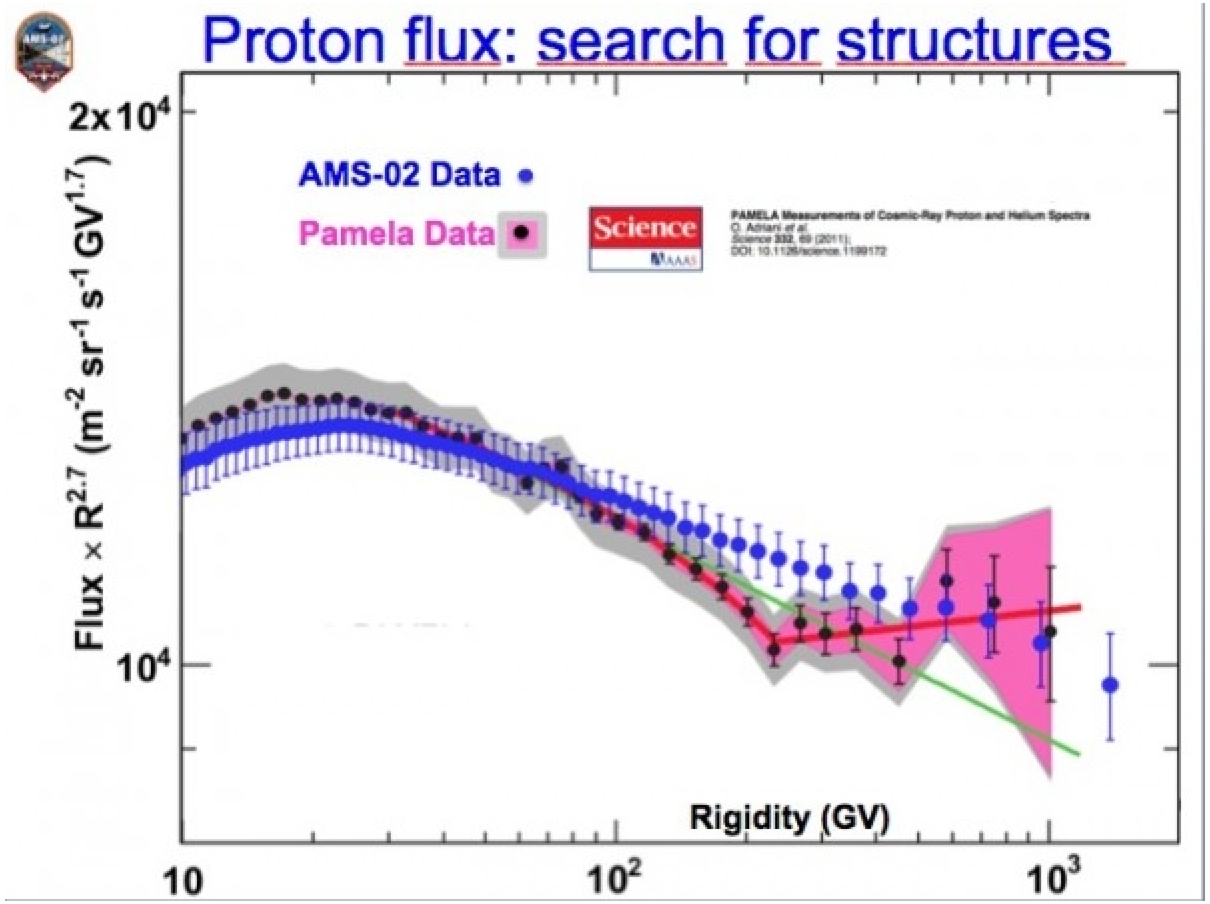
Proton and Helium fluxes



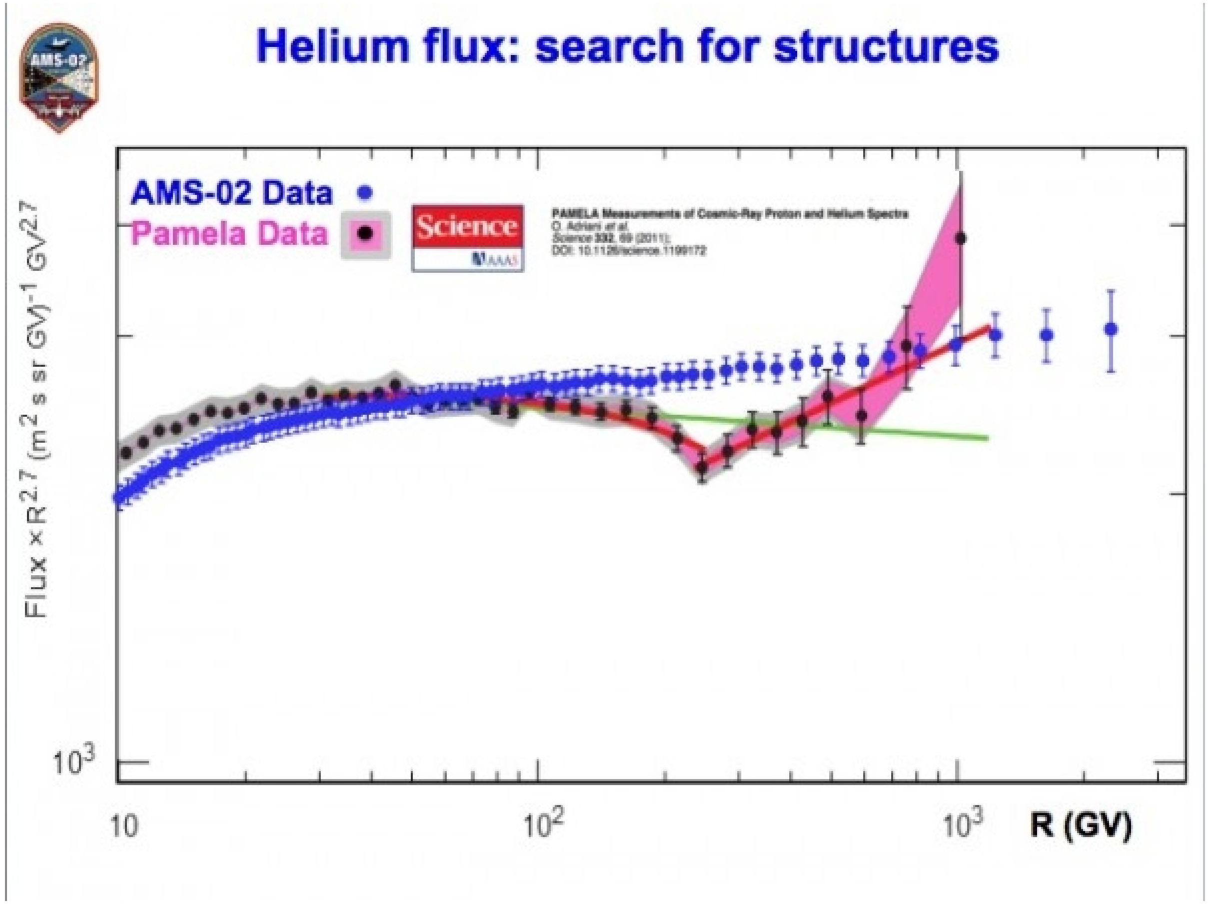
Proton to Helium ratio



ICRC 2013

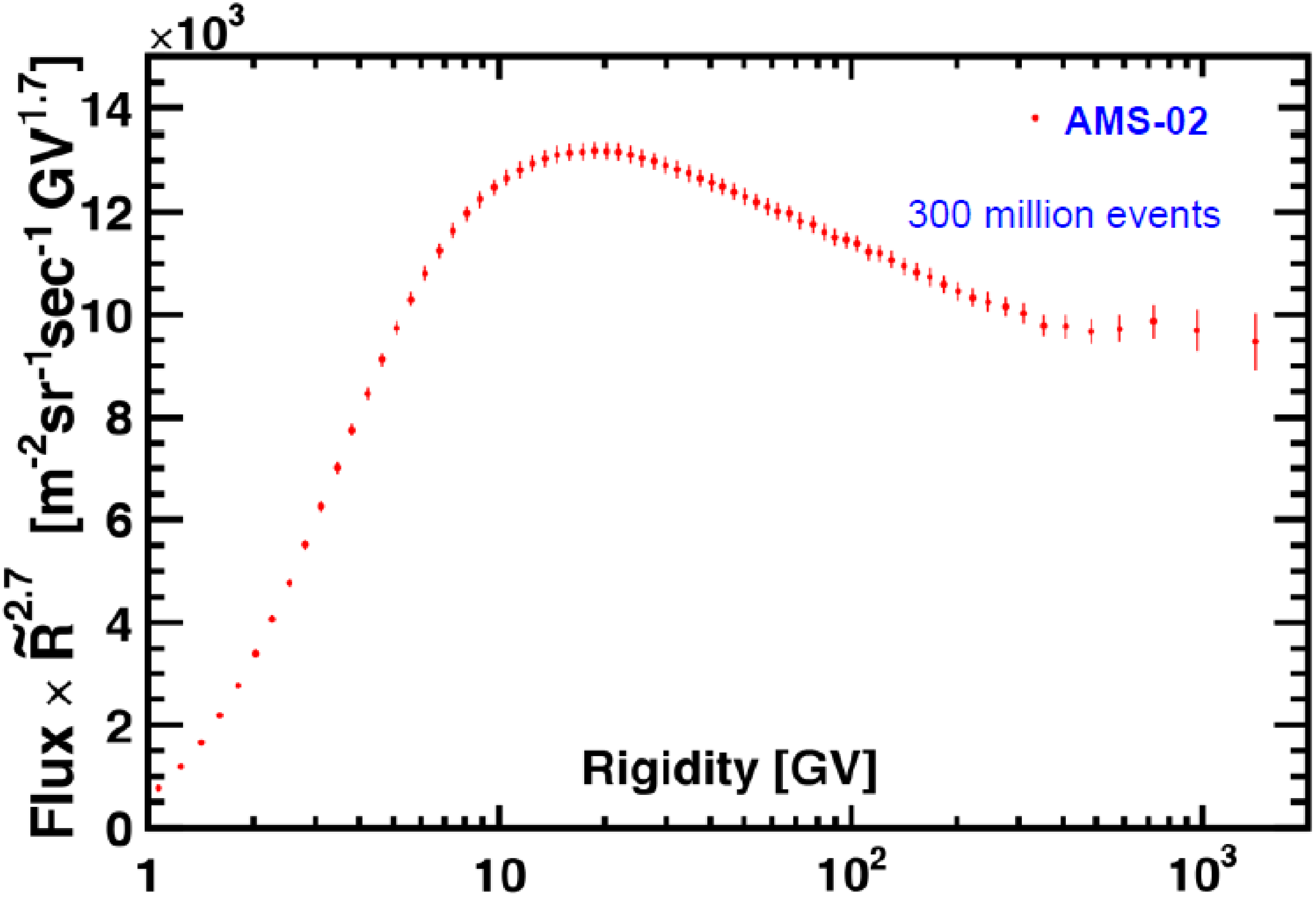


Proton flux: search for structures
AMS-02 Data
Pamela Data
Science
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
Flux × R^2.7 (m^-2 sr^-1 s^-1 GV^1.7)
2x10^4
10^4
Rigidity (GV)
10
10^2
10^3



Helium flux: search for structures
AMS-02 Data
Pamela Data
Science
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
Flux × R^2.7 (m^2 s sr GV)^-1 GV^2.7
10^3
10
10^2
10^3
R (GV)

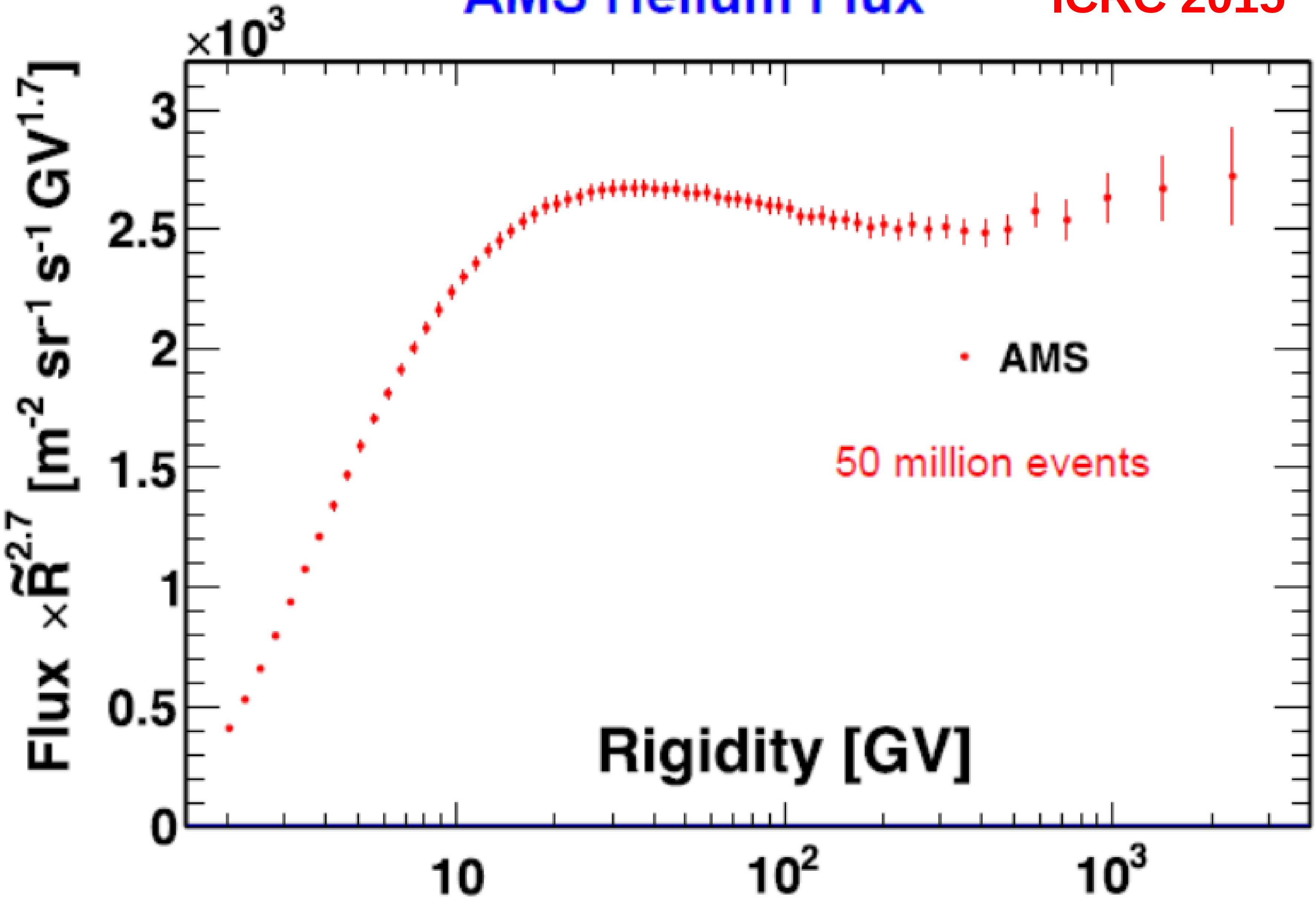
AMS proton flux



Phys. Rev. Lett. **114**, 171103, 2015

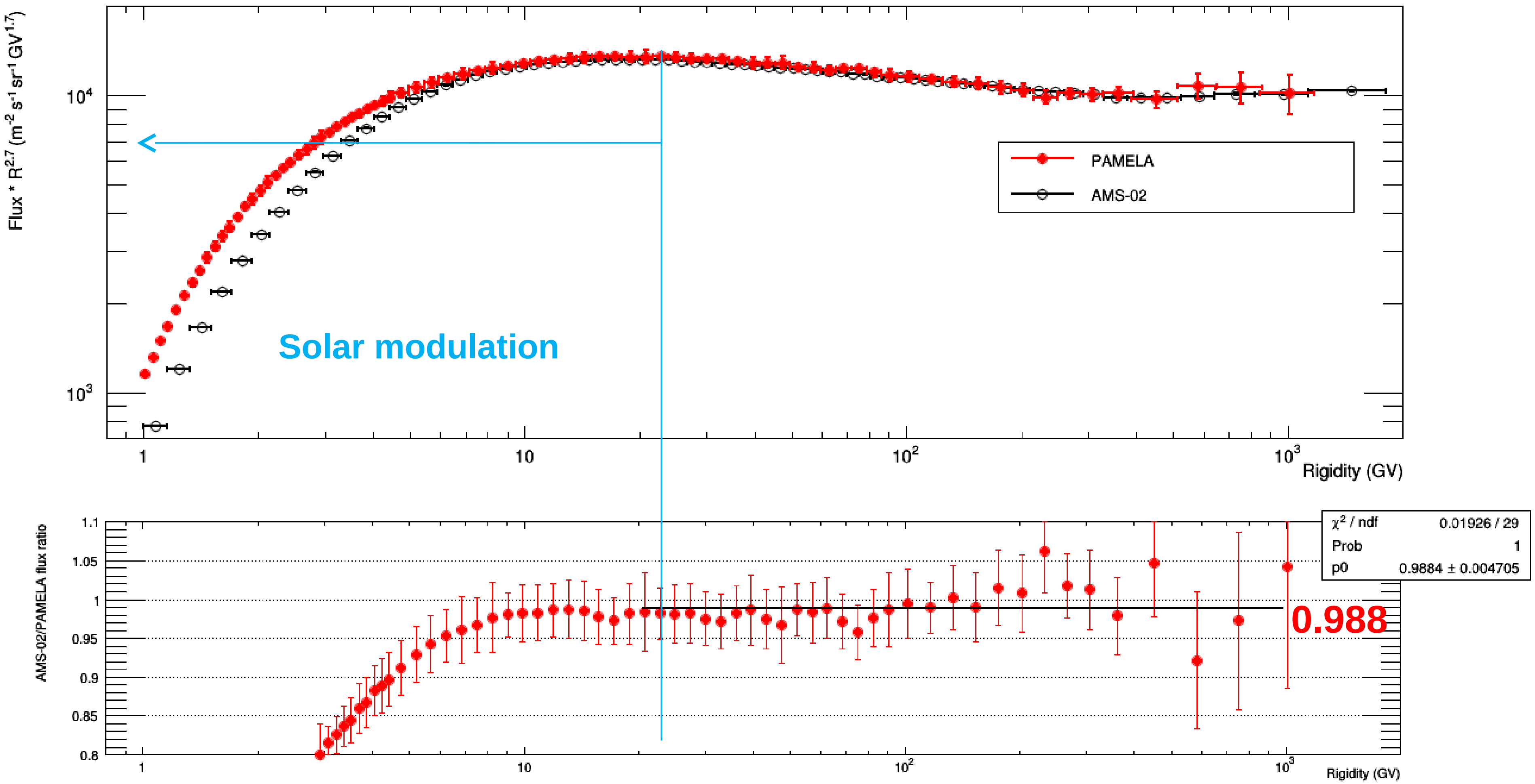
AMS Helium Flux

ICRC 2015



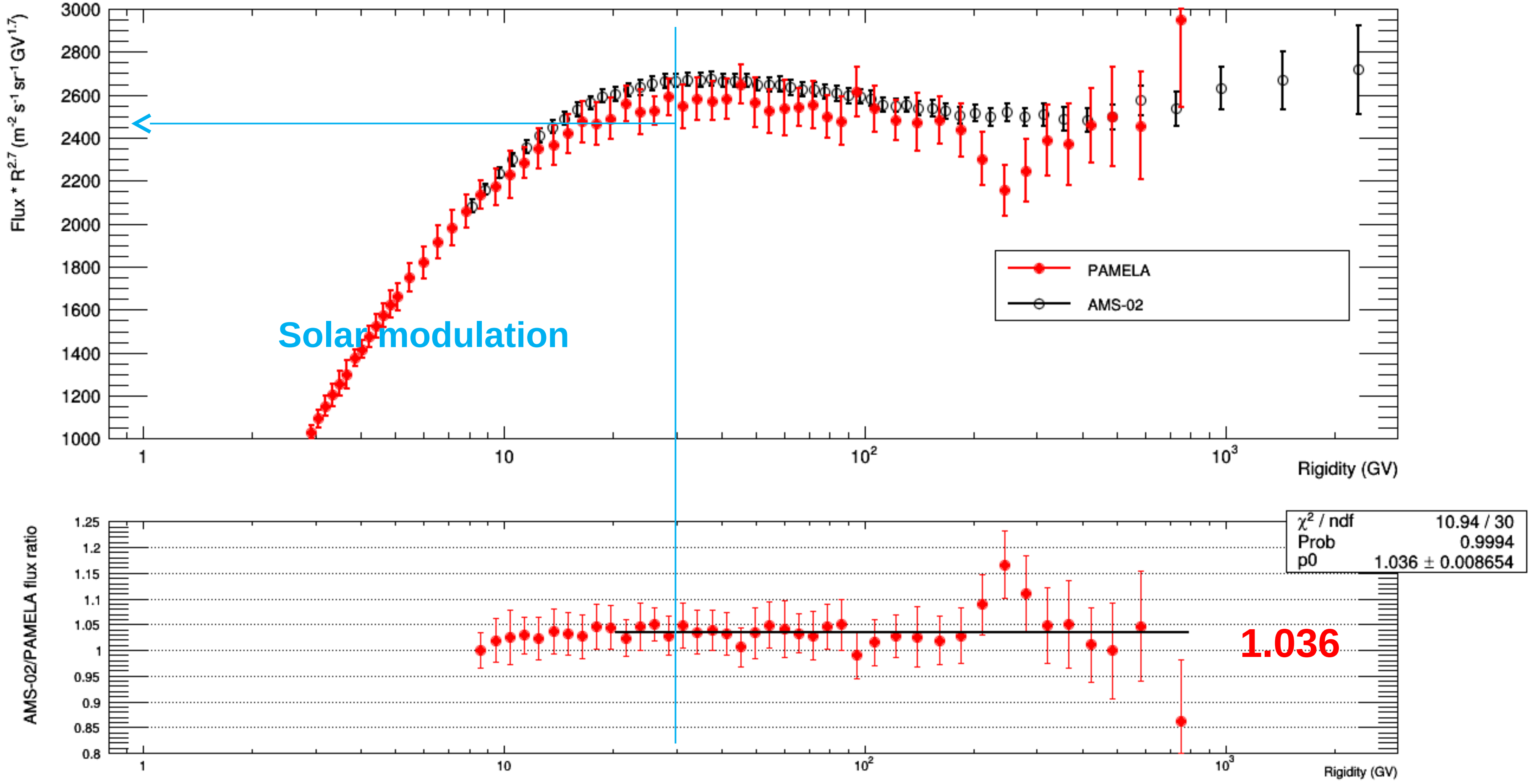
To be presented by S. Haino (Academia Sinica, Taiwan)

PAMELA vs AMS-02 proton spectrum

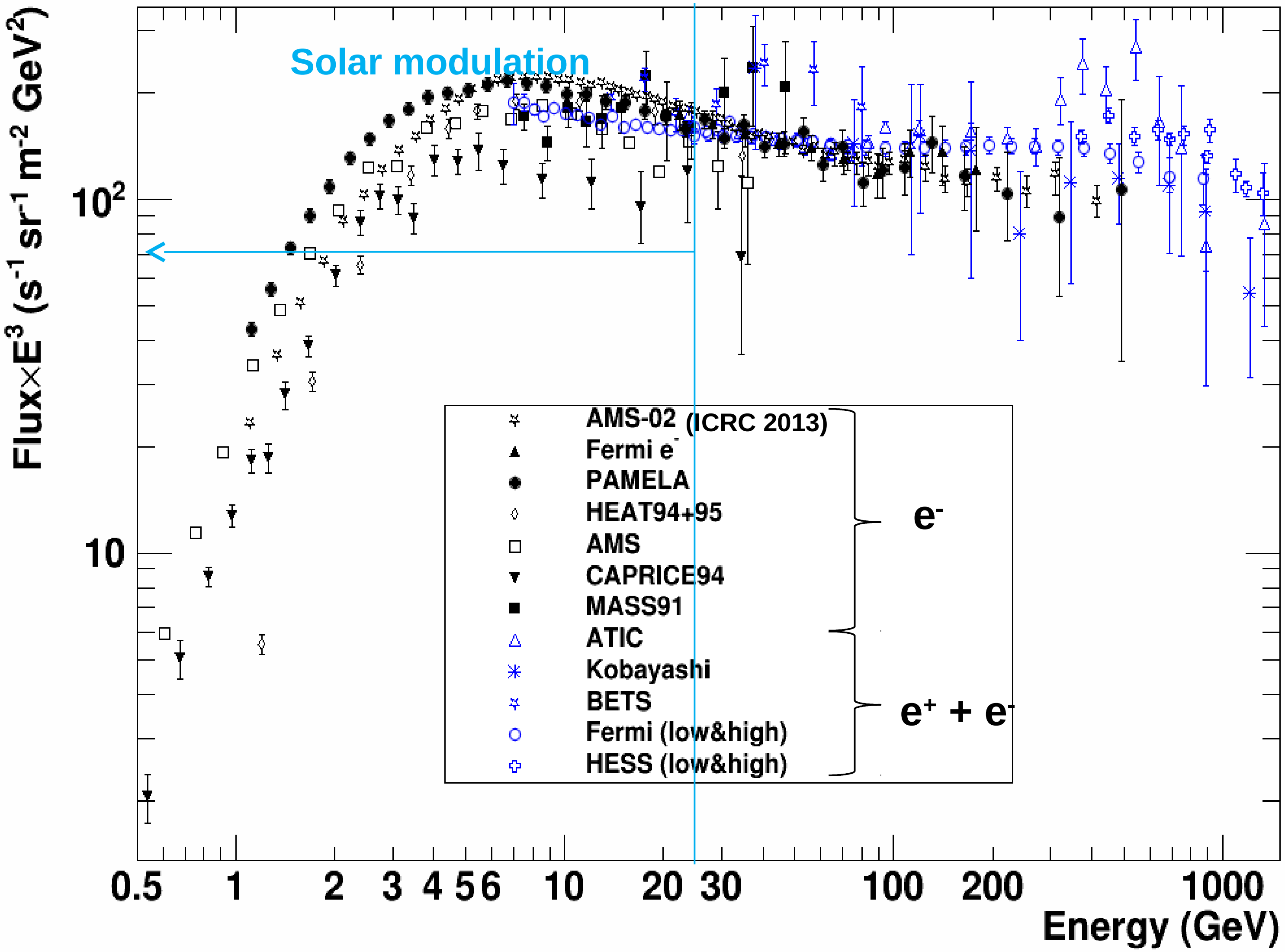


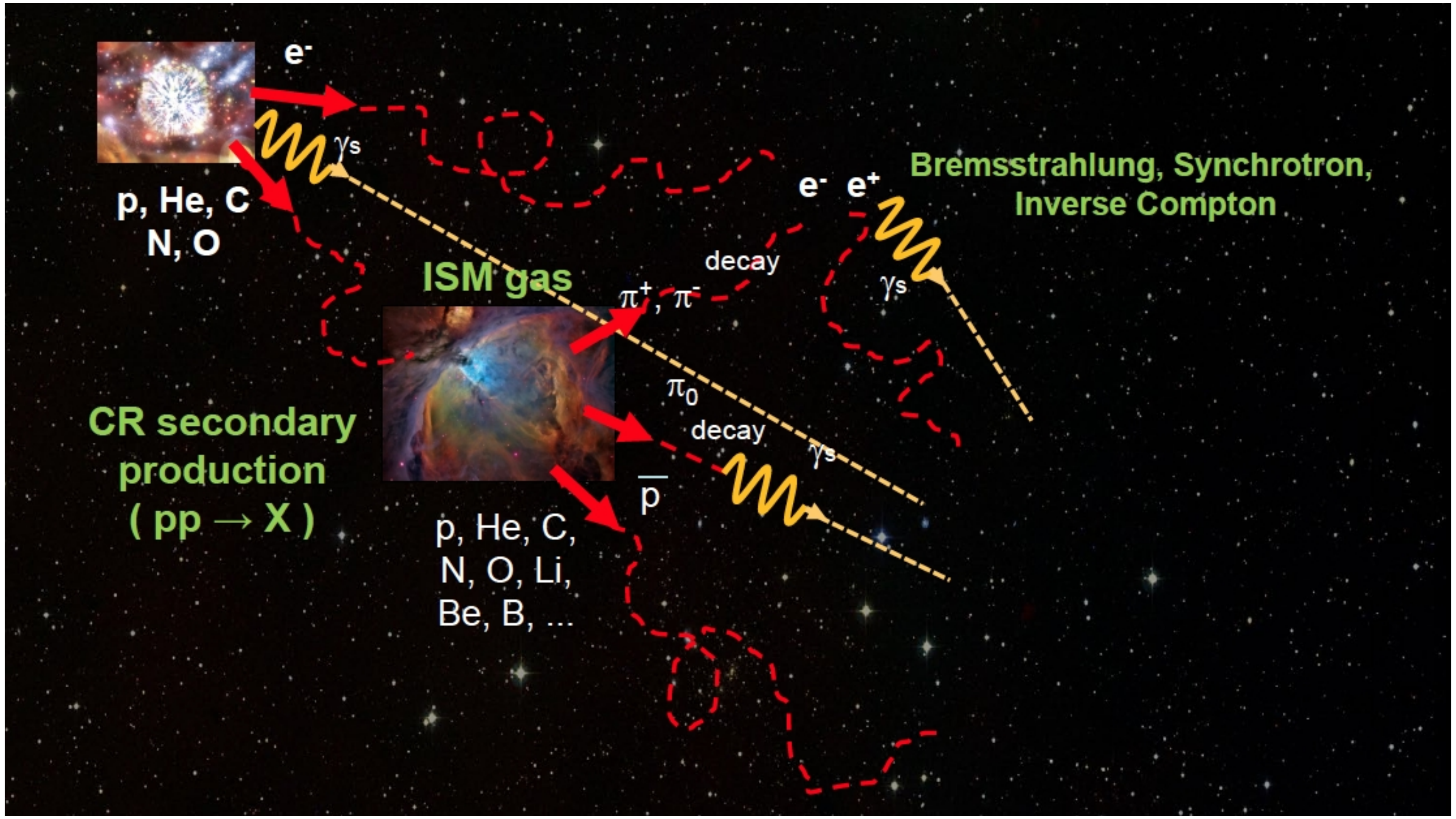
O. Adriani et al, Phys. Rep. (2014)

PAMELA vs AMS-02 helium spectrum



Electron Spectrum

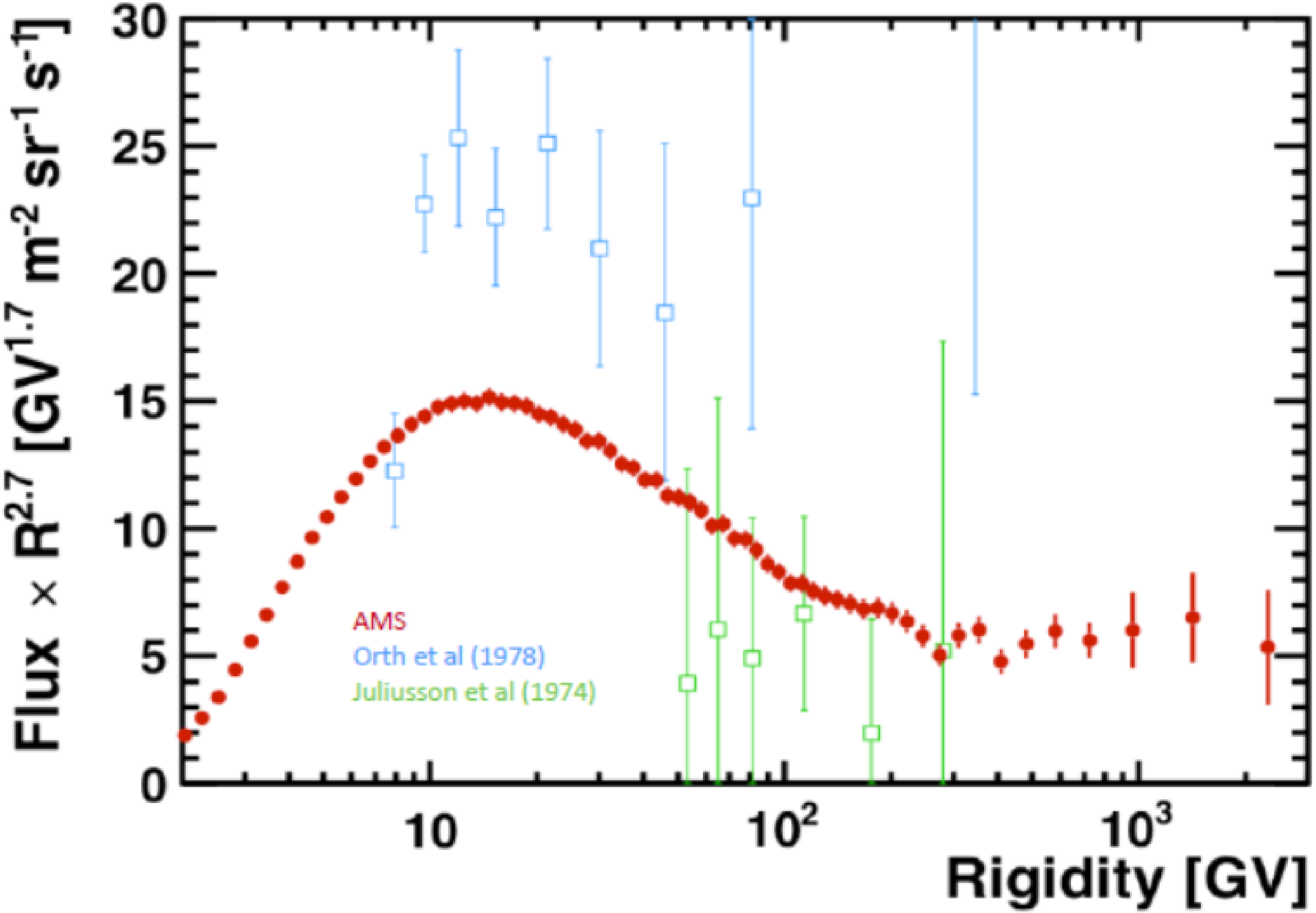




Secondary cosmic rays

Secondaries from homogeneously distributed interstellar matter (light nuclei)

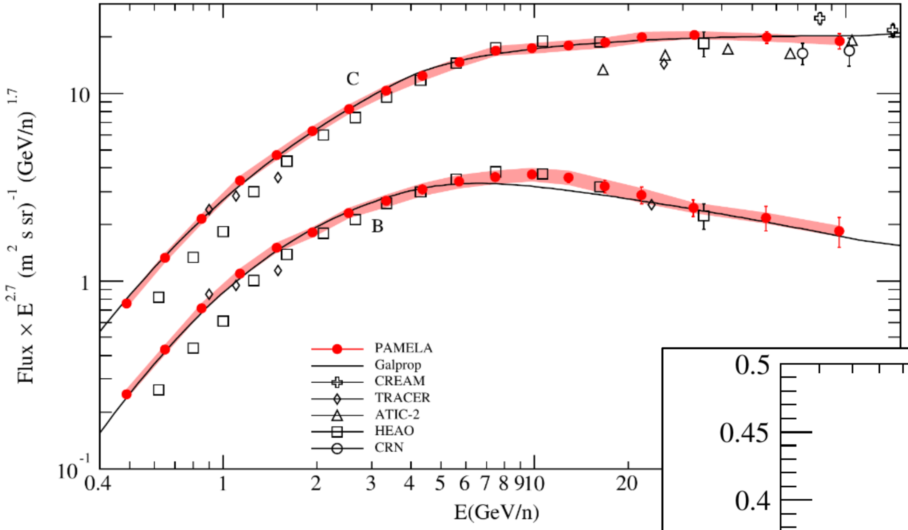
AMS Lithium flux – current status



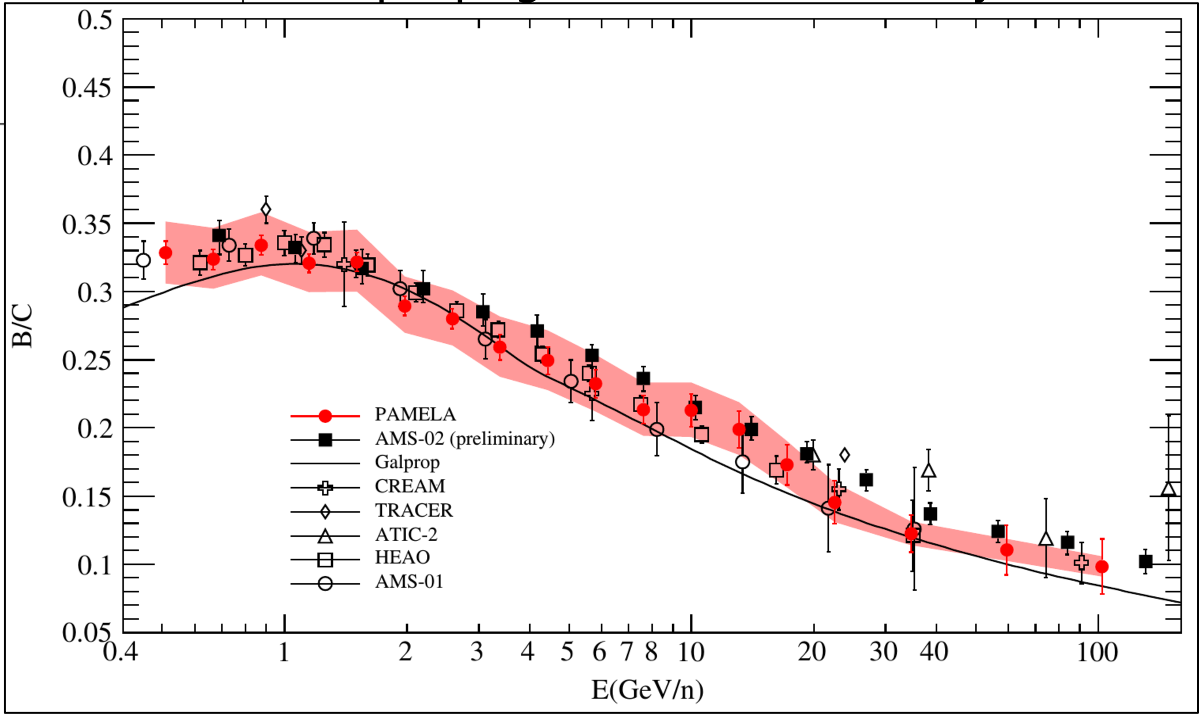
To be presented by L. Derome (LPSC, Grenoble)

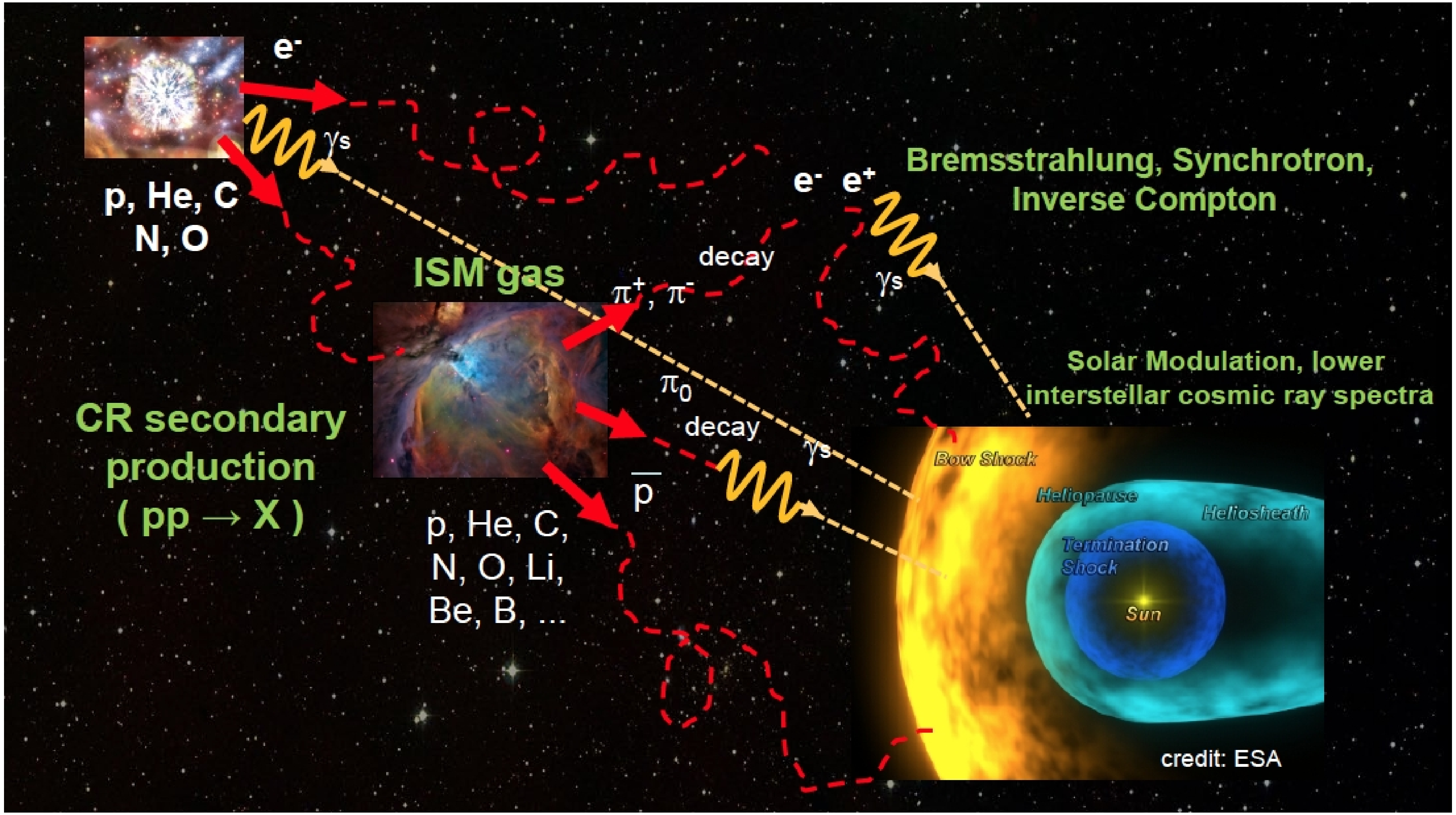
PAMELA Boron and carbon fluxes and B/C

- Tracking performance:
  - σ_x = 14 μm, σ_y = 19 μm
  - MDR = 250 GV
- Modelization of cosmic-ray propagation in the Galaxy



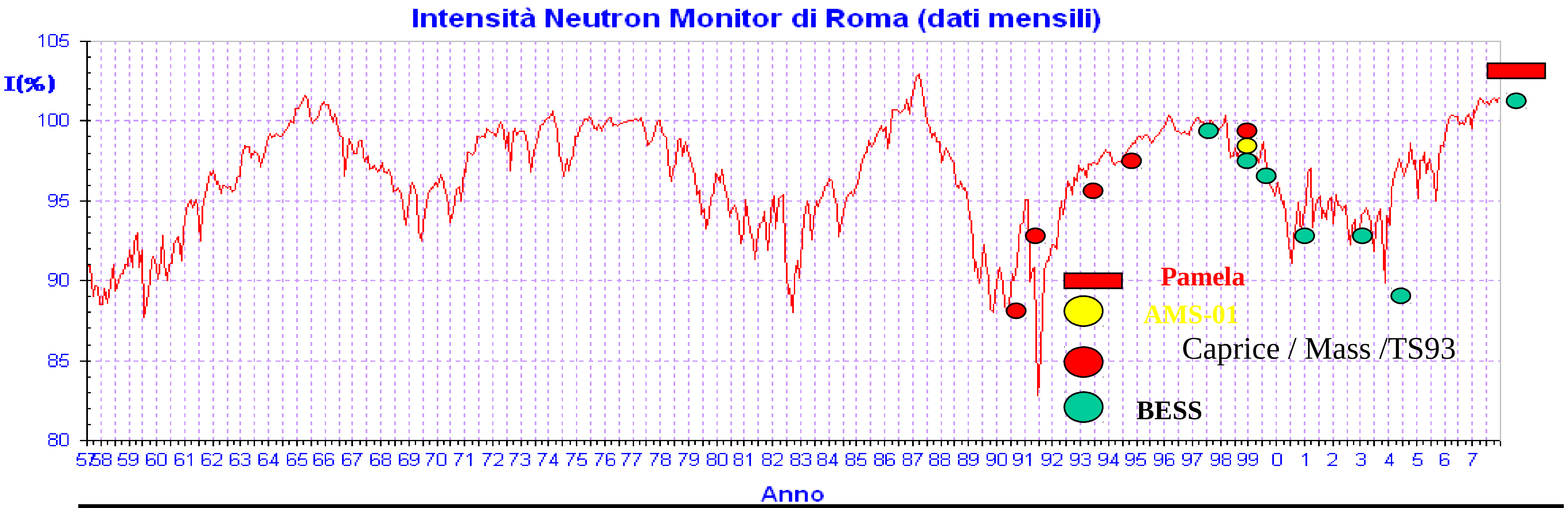
Adriani et al., ApJ 791 (2014), 93

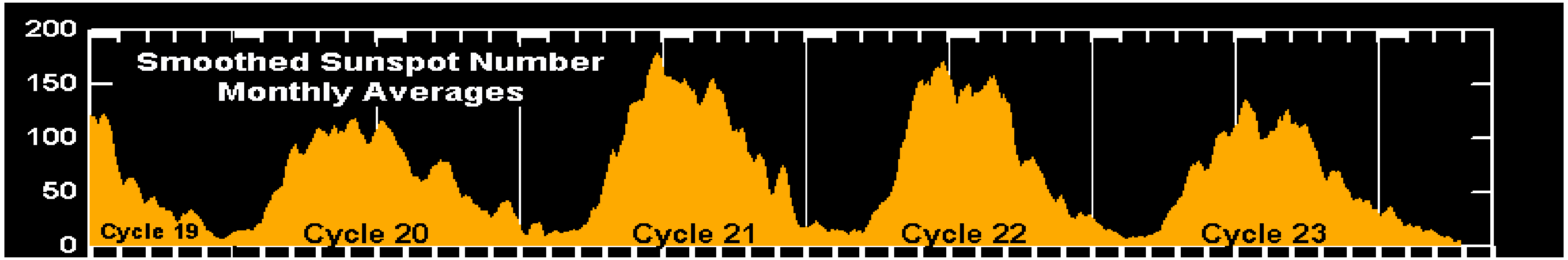




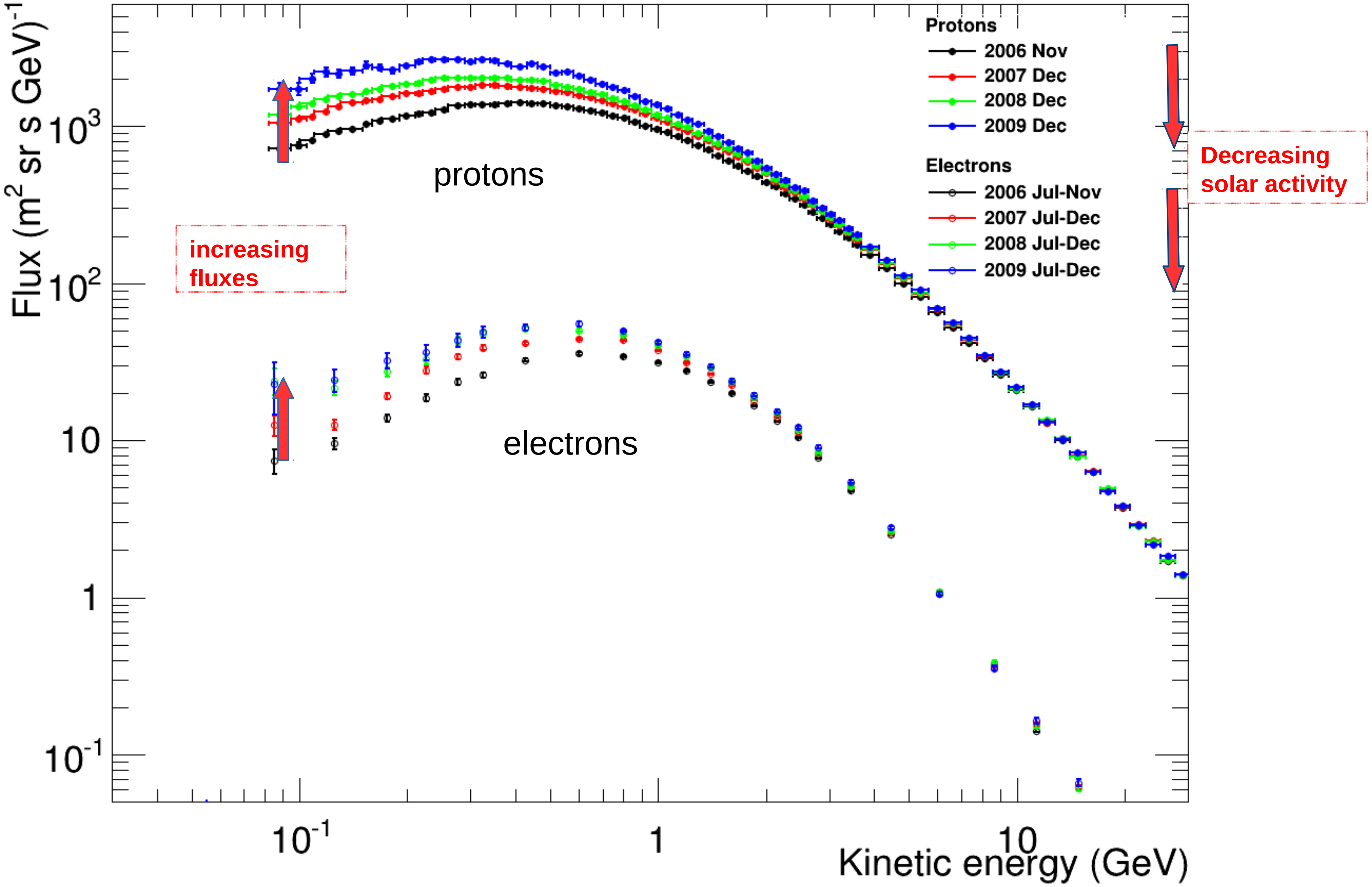
Cosmic rays in the heliosphere

Solar Modulation of Galactic Cosmic Rays

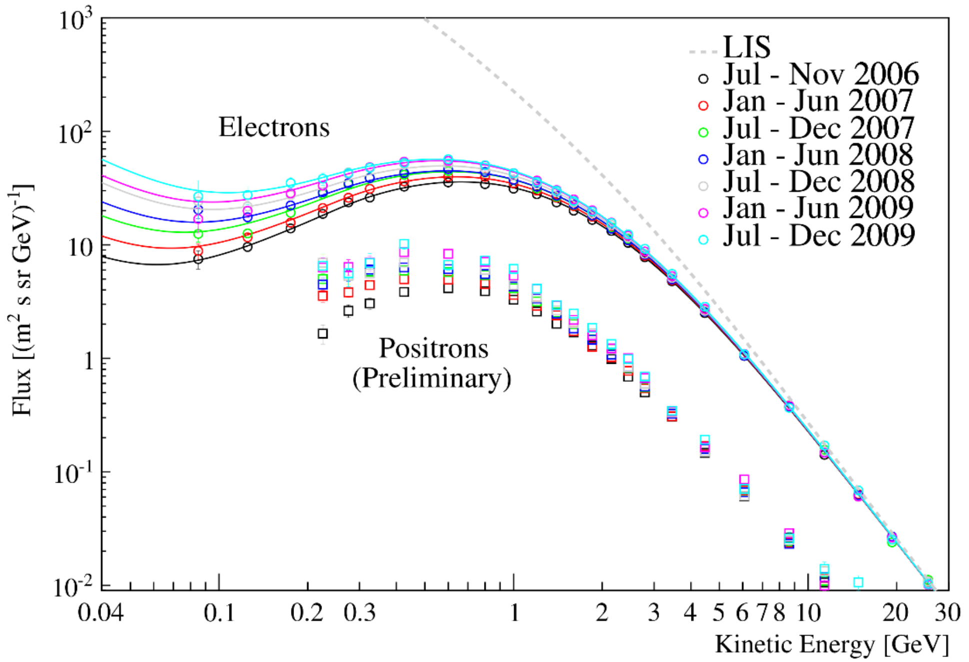




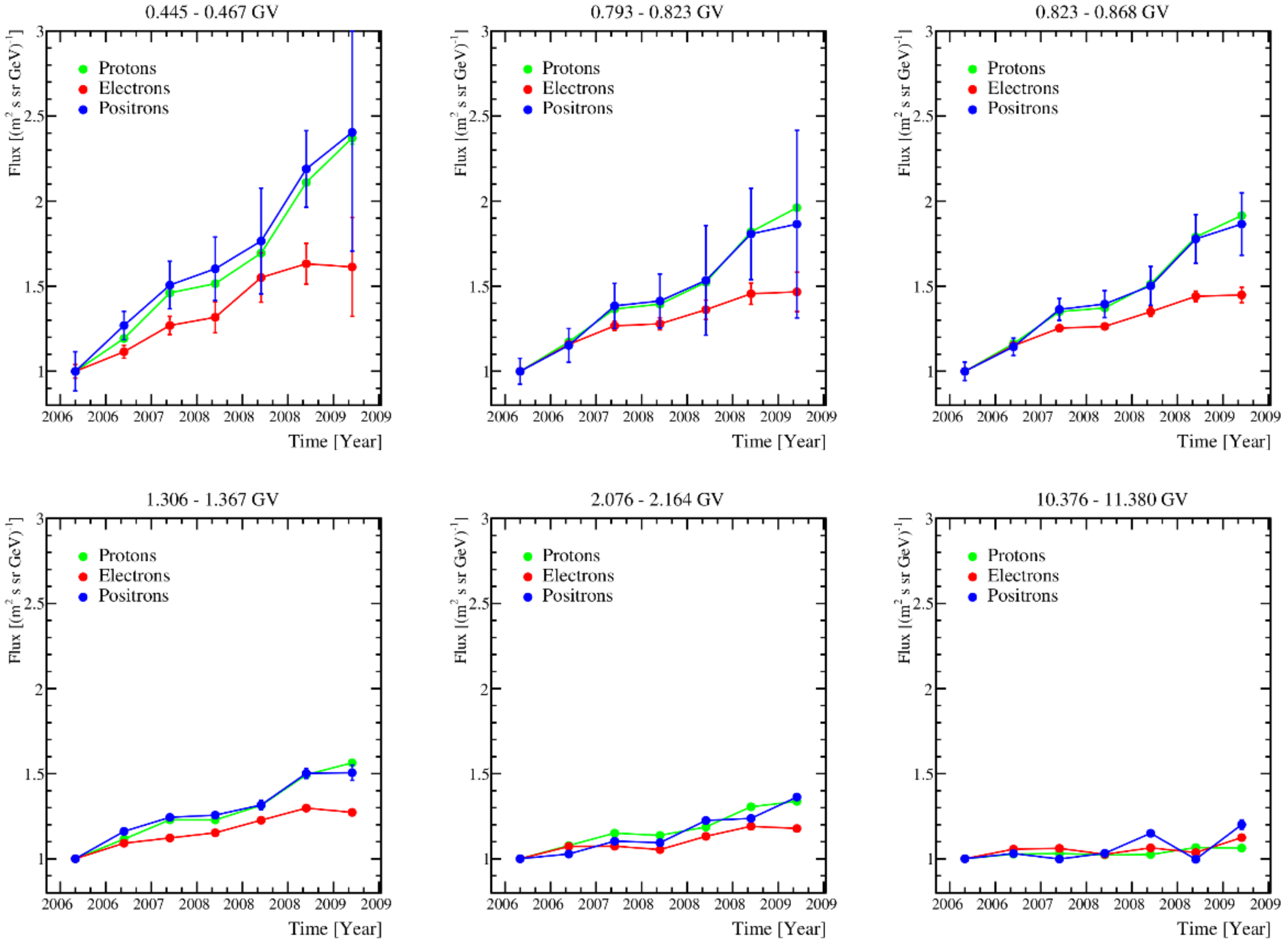
Solar modulation in the heliosphere



O. Adriani et al., ApJ 765 (2013), 91;
M. S. Potgieter et al., Sol. Phys. (2014), 289

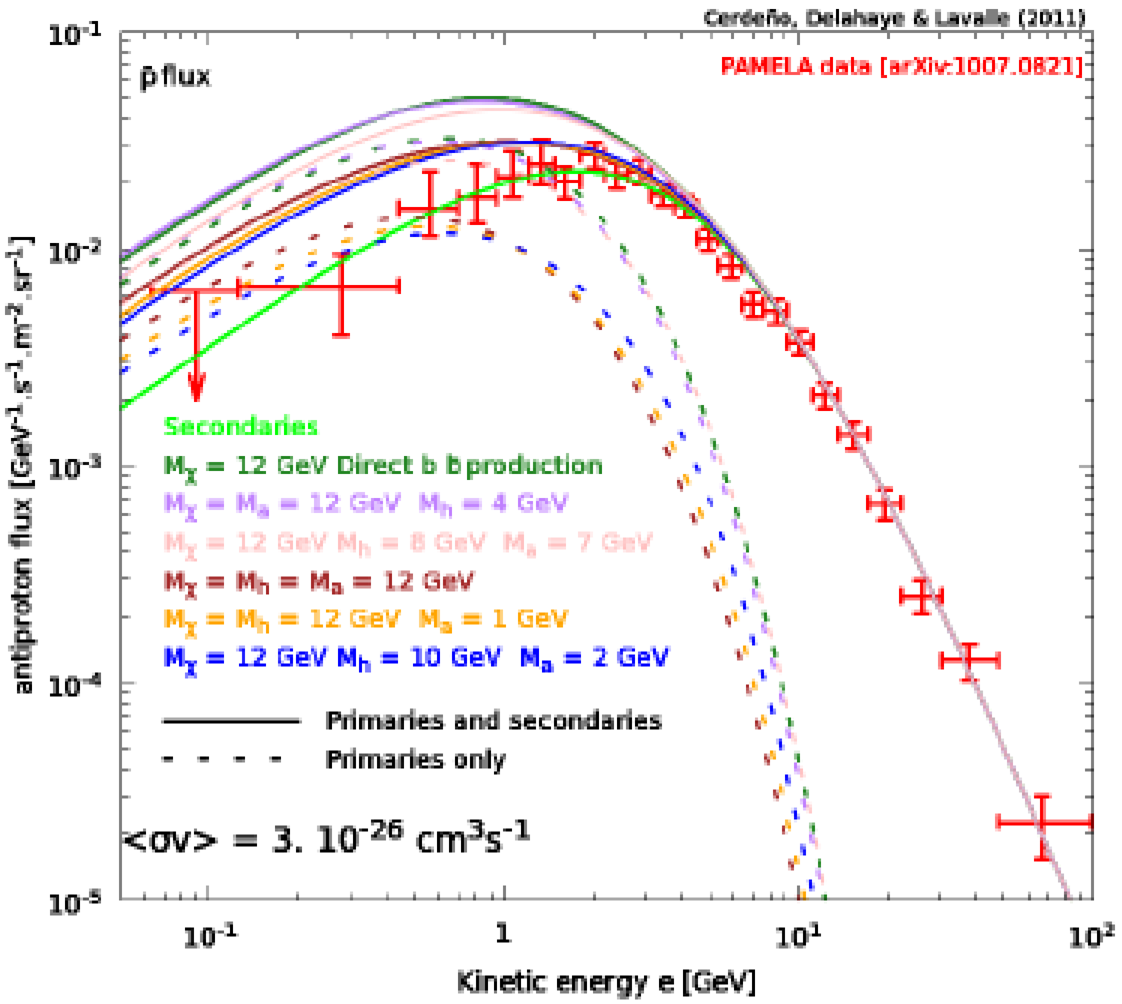


The PAMELA electron and positron spectra over the last solar minimum



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

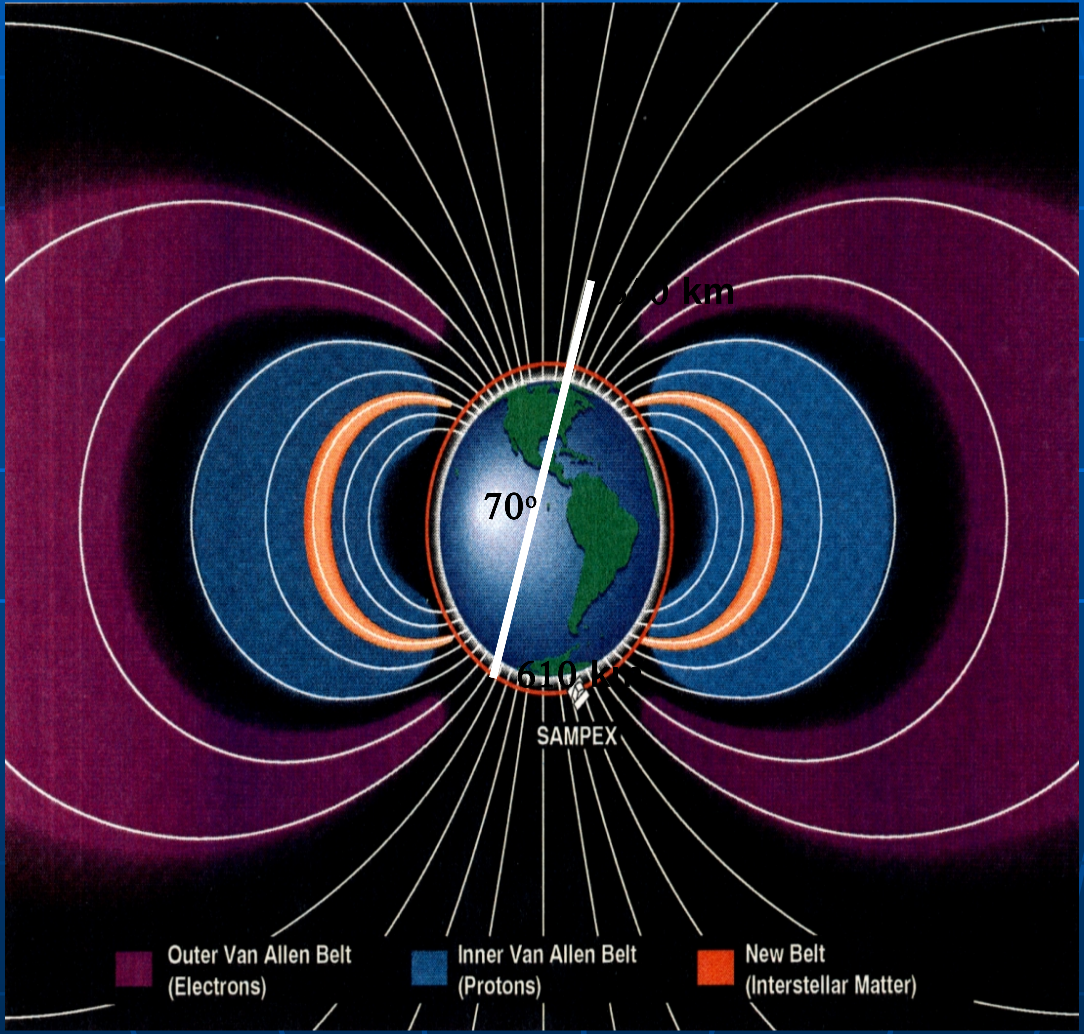
Cosmic-Ray Antiprotons and DM limits



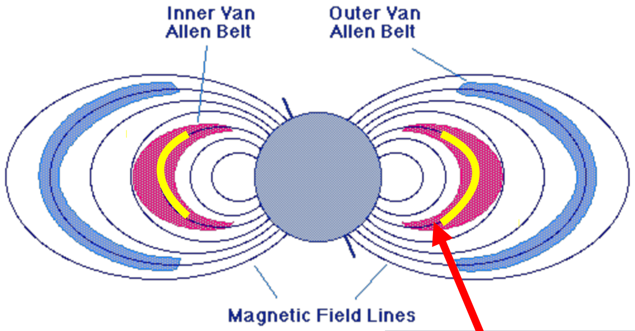
D. G. Cerdeno, T. Delahaye & J. Lavalle, arXiv: 1108:1128
Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

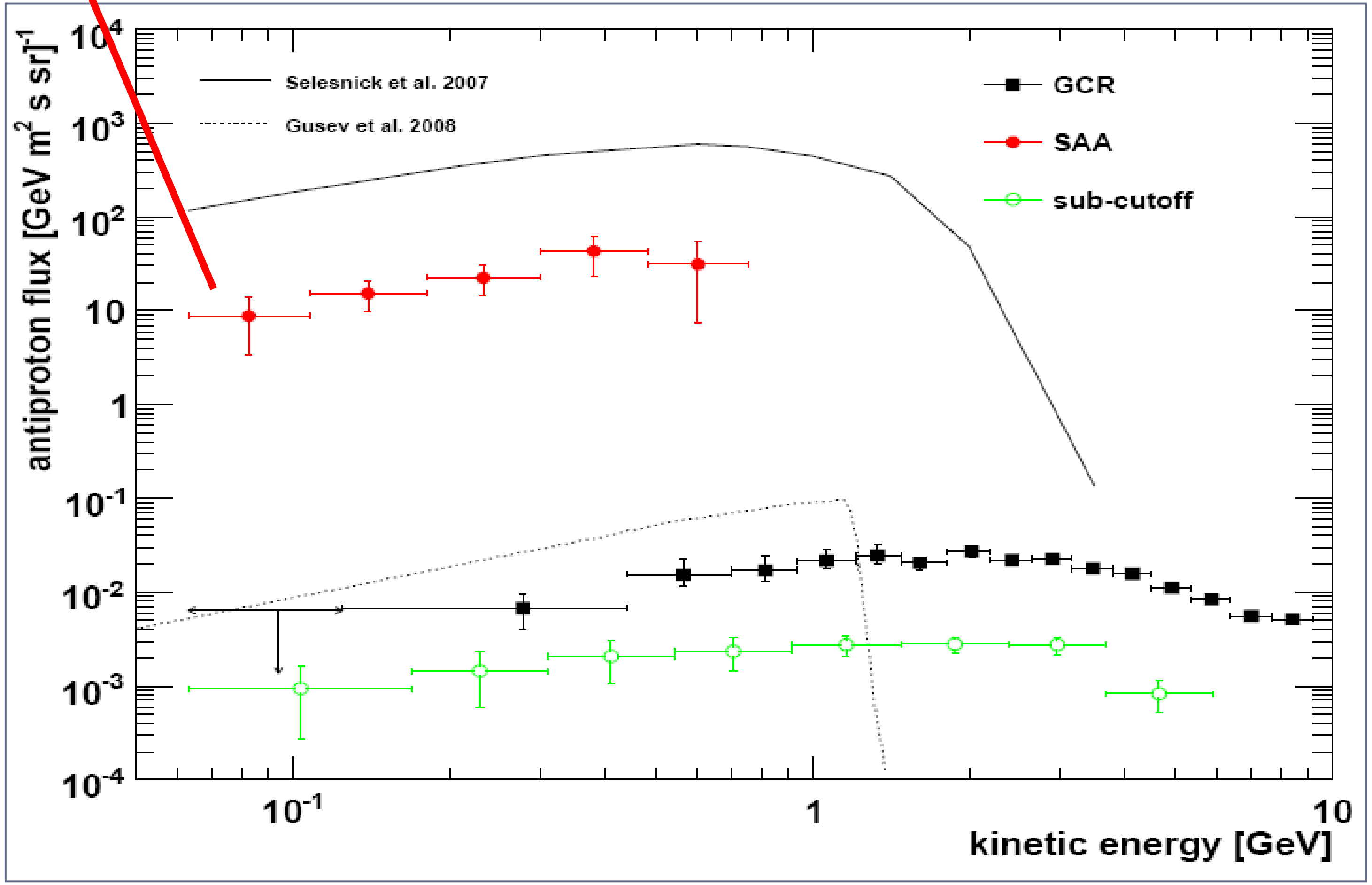
See also:
- M. Asano, T. Bringmann & C. Weniger, arXiv:1112.5158.
- M. Garny, A. Ibarra & S. Vogl, arXiv:1112.5155
- R. Kappl & M. W. Winkler, arXiv:1140.4376

Radiation Belts



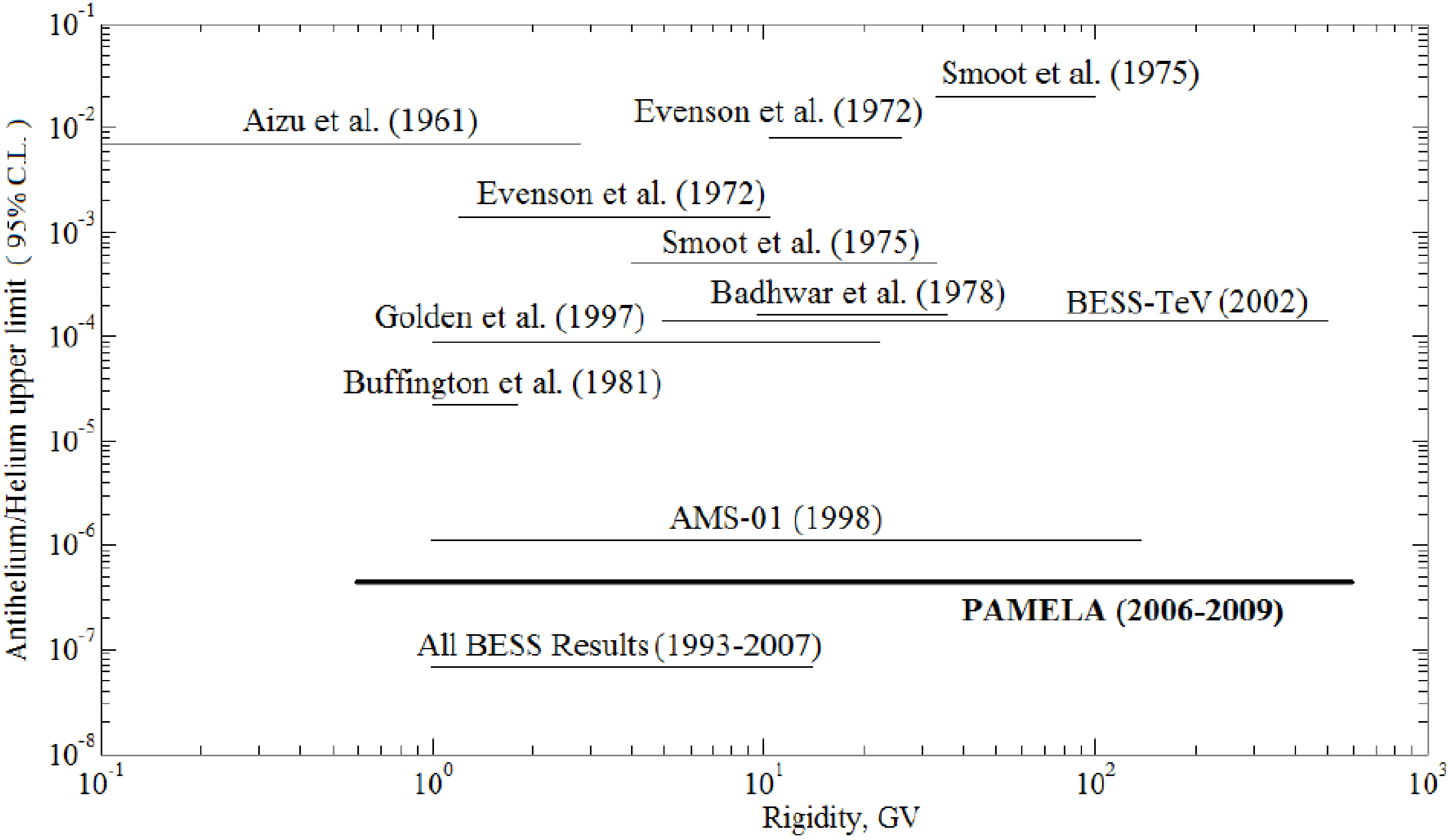
Anti-proton radiation belt





O. Adriani et al., ApJL 737 (2011), L29

Antimatter limits

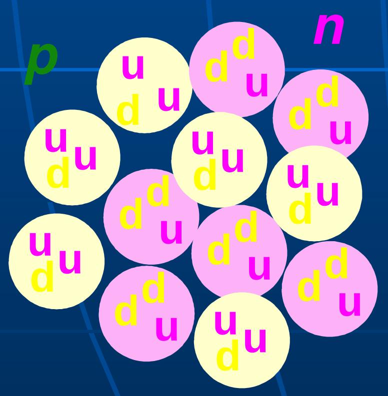


Search for New Matter in the Universe:

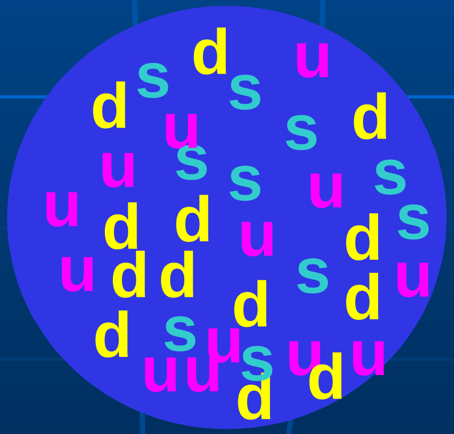
An example is the search for "strangelets".

There are six types of Quarks found in accelerators.
All matter on Earth is made out of only two types of quarks.
"Strangelets" are new types of matter composed of three types of quarks which should exist in the cosmos.

Carbon Nucleus



Strangelet

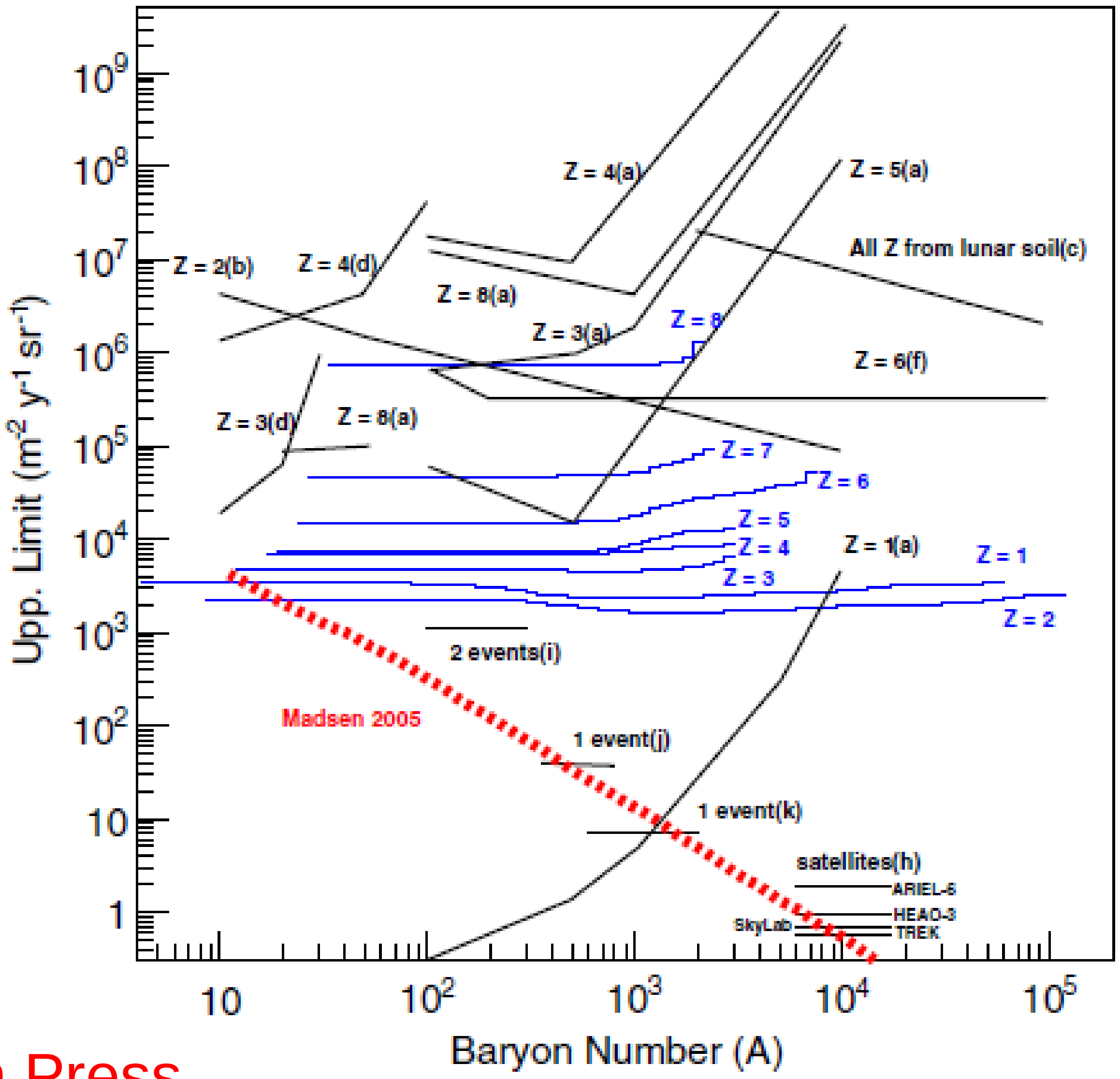


i. **A stable, single "super nucleon" with three types of quarks**

ii. **"Neutron" stars may be one big strangelet**

AMS courtesy

PAMELA limits for SQM

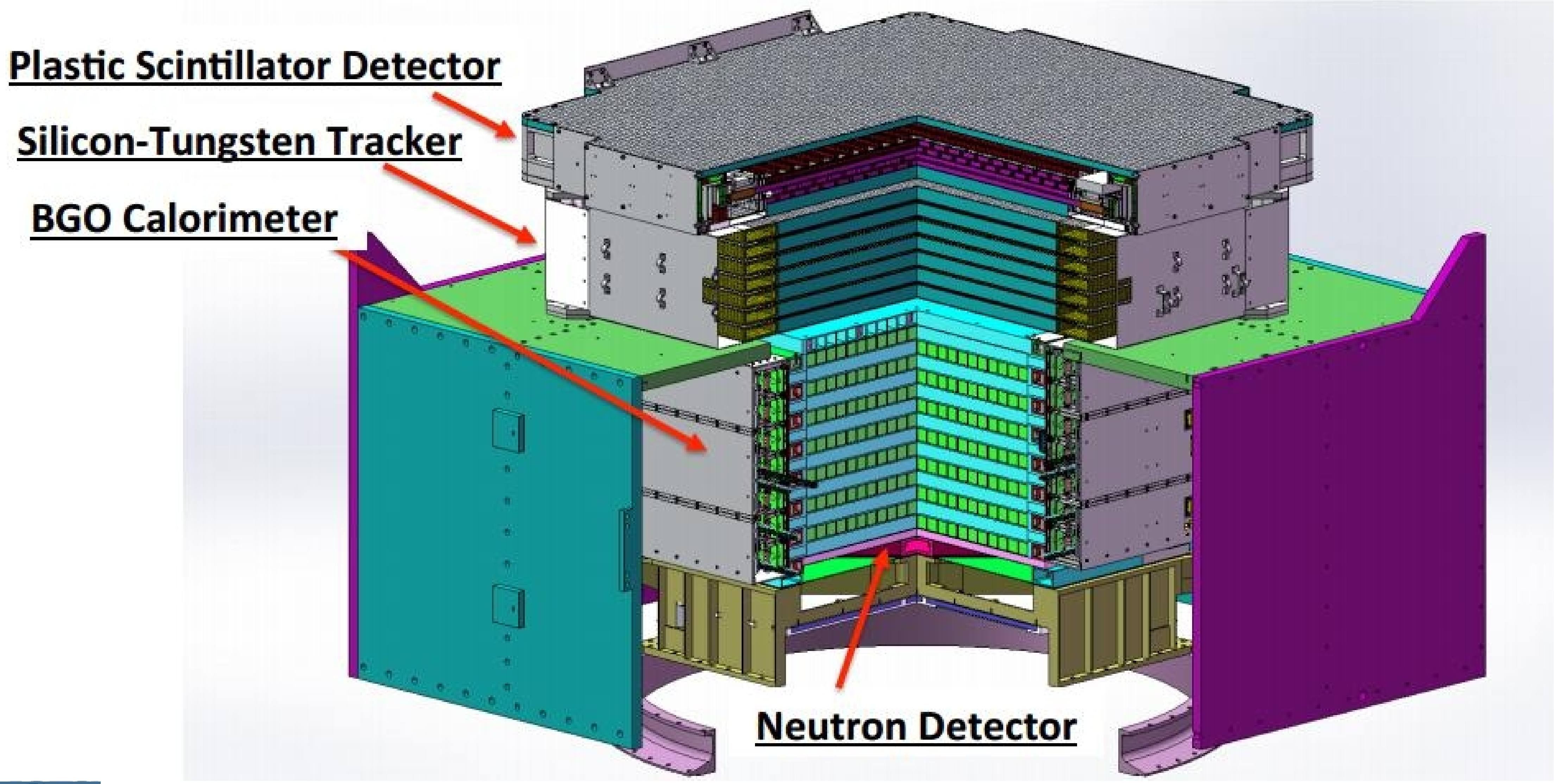


PRL in Press

CALET

<CALET Gamma-ray Burst Monitor (CGBM)>
Soft Gamma-ray Monitor (SGM)
Hard X-ray Monitor (HXM)
Advance Star Camera(ASC)
GPS Reciever (GPSR)
<Calorimeter (CAL)>
Charge Detector (CHD)
Imaging Calorimeter (IMC)
Total Absorption Calorimeter(TASC)
Mission Data Controller(MDC)
High-Voltage Power Supply Box(HV-BOX)
※Provided by ASI

DAMPE Detector Layout



Thanks!

http:// pamela.roma2.infn.it