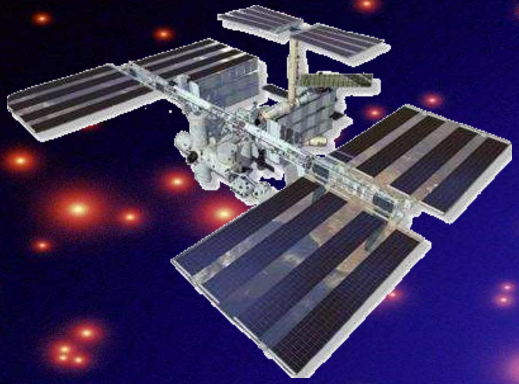
Cosmic Ray Direct Detection



Piergiorgio Picozza

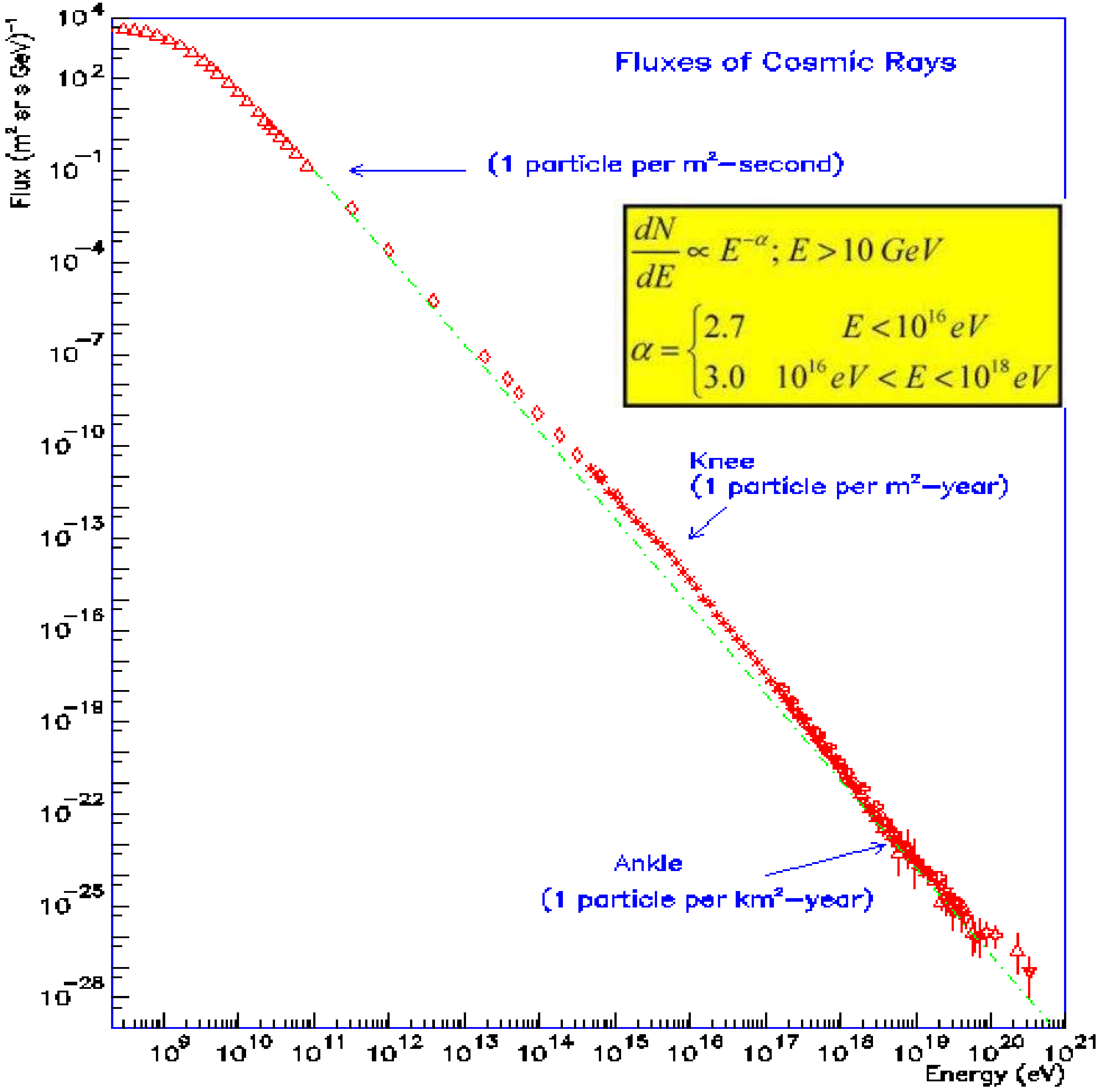
INFN and University of Rome Tor Vergata

VULCANO Workshop 2016

Frontier Objects in Astrophysics and Particle Physics

Vulcano Island

May, 22-28, 2016



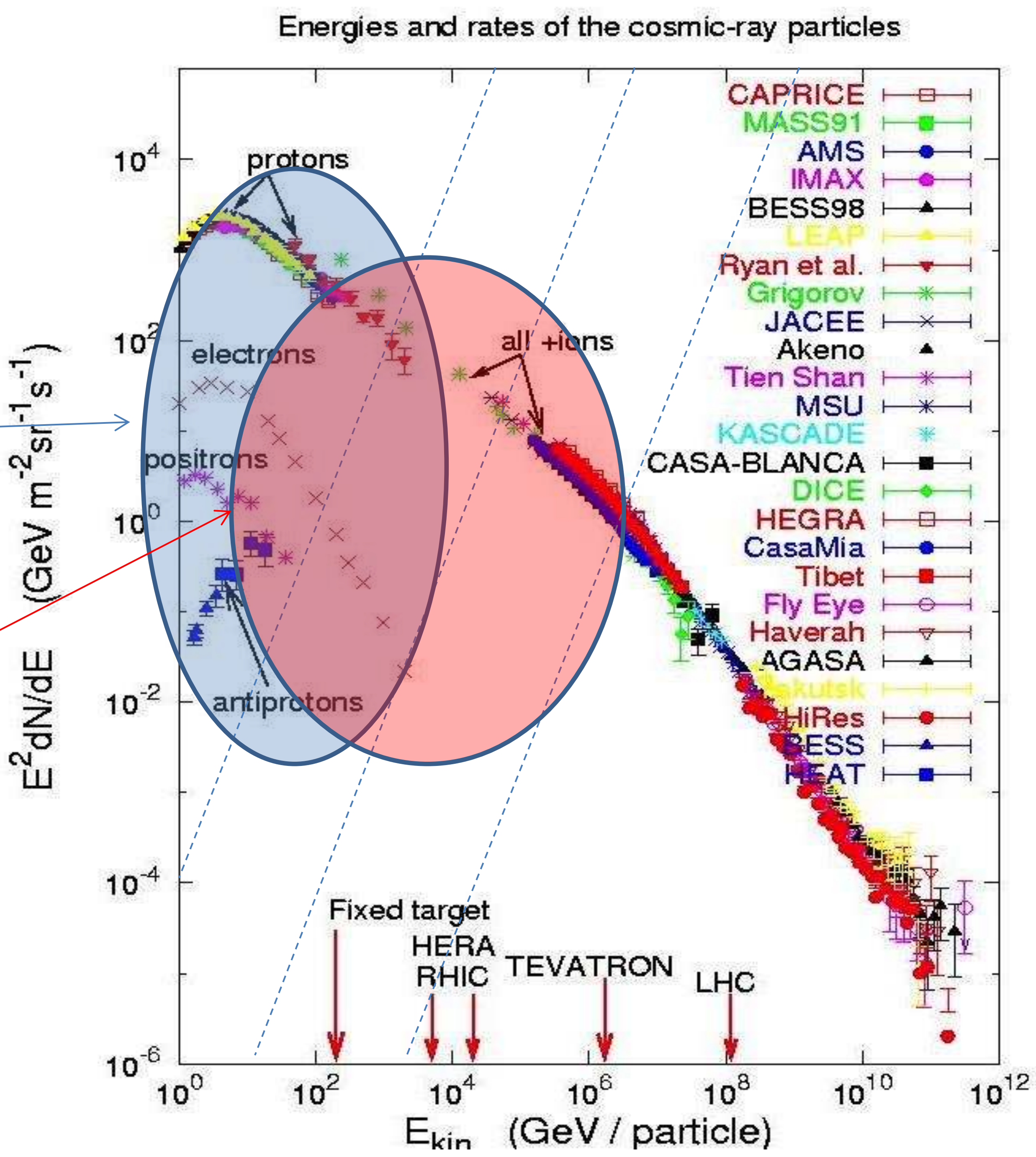
Fluxes of Cosmic Rays
(1 particle per m²–second)
$\frac{dN}{dE} \propto E^{-\alpha}; E > 10\,GeV$
$\alpha = \begin{cases} 2.7 & E < 10^{16} eV \\ 3.0 & 10^{16} eV < E < 10^{18} eV \end{cases}$
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

The beam !

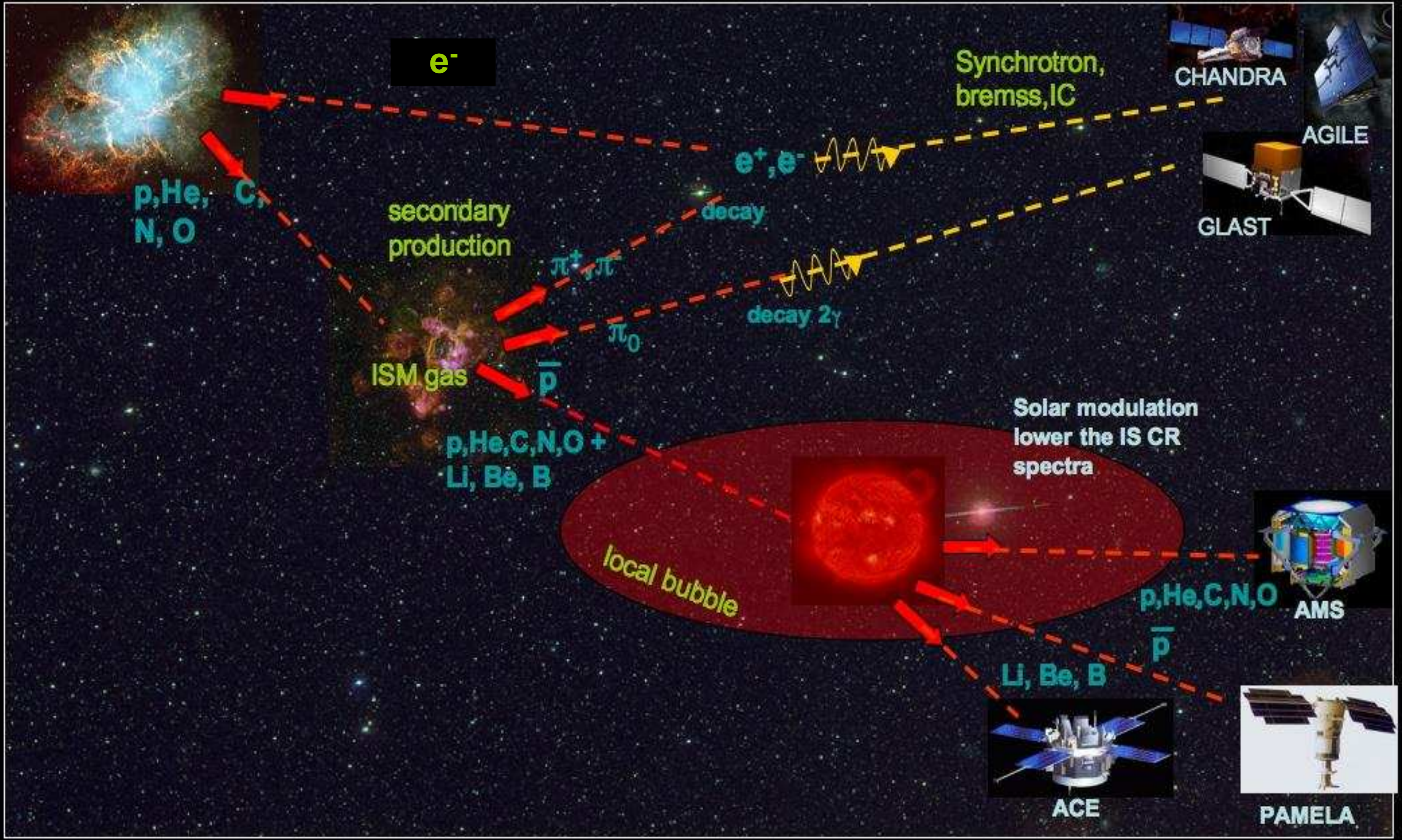
(charged particles)

PAMELA
CREAM
ATIC
FERMI
AMS-02

CALET
DAMPE
ISS-CREAM
GAMMA-400
HERD



COSMIC RAYS PRODUCTION MECHANISMS

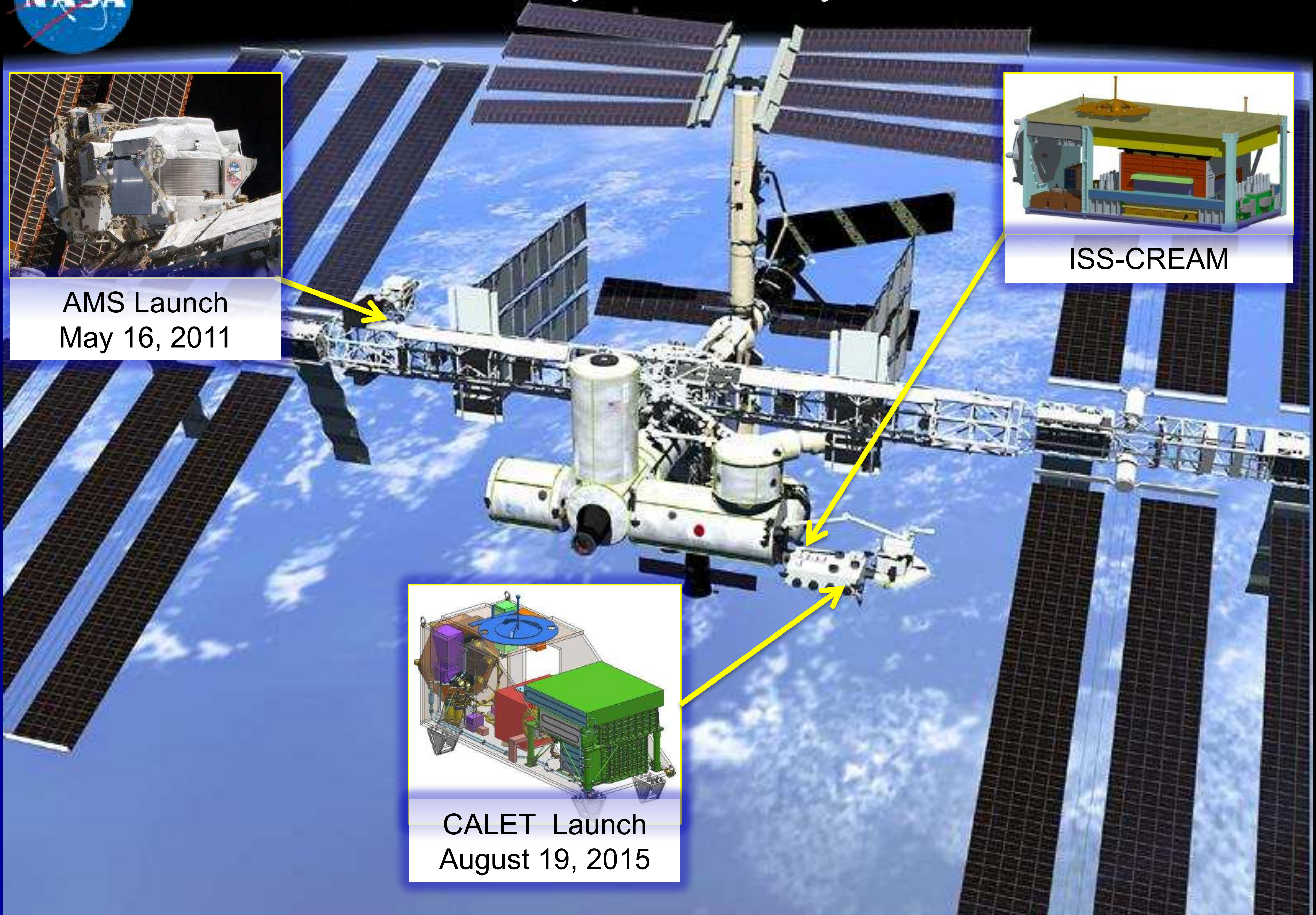


Satellite Missions

PAMELA
15-06-2006

DAMPE
17/12/2015

"Cosmic Ray Observatory on the ISS"



PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

GF ~21.5 $cm^2 sr$

Mass: 470 kg

Size: 130x70x70 cm^3

Launch 15/06/06
elliptical orbit 350 – 610 km
70^o inclination
Now in operation at 560 km

PAMELA Collaboration

Italy:

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

Russia:

Ioffe Physico-Technical Institute

Moscow
St. Petersburg

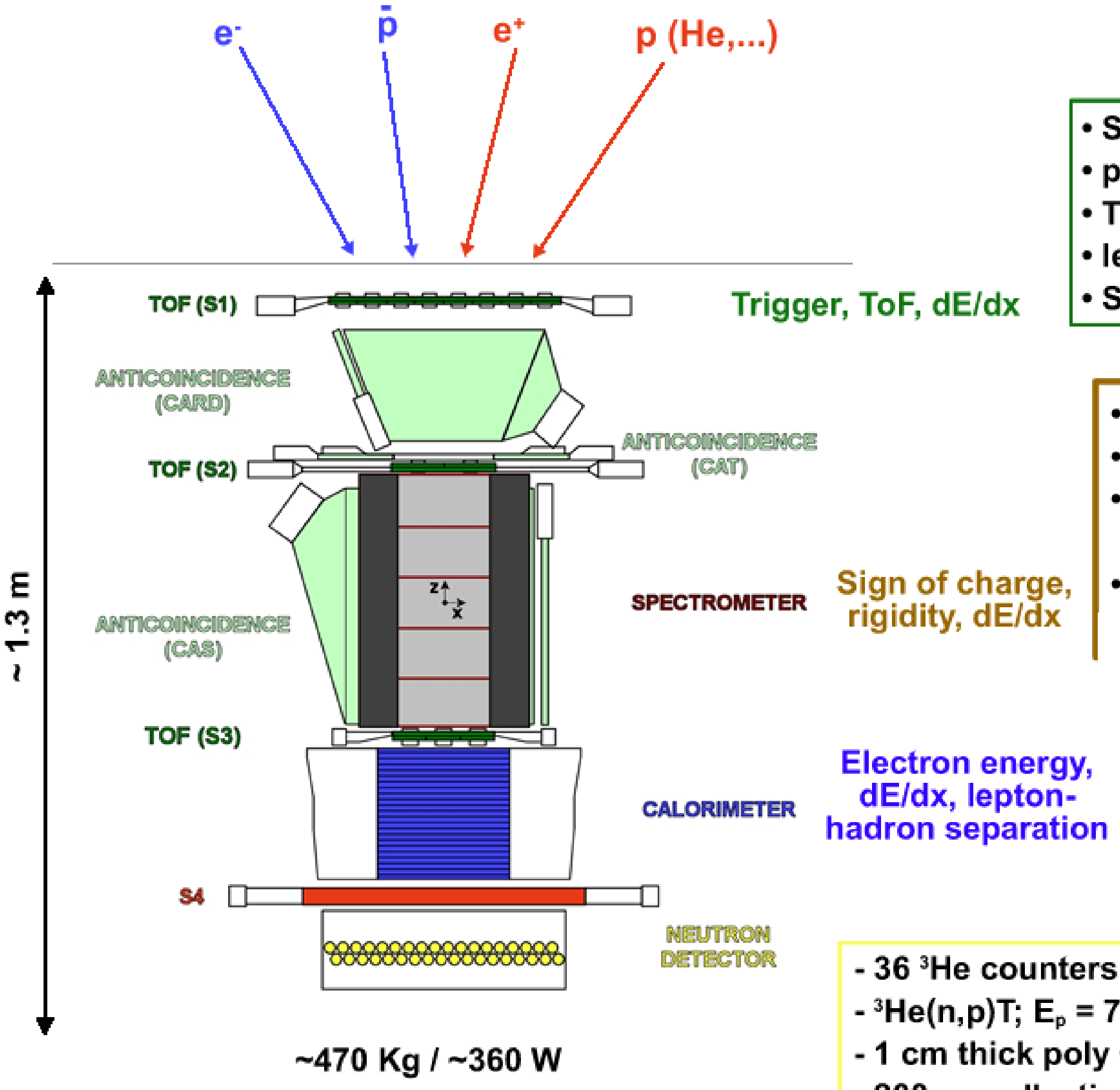
Germany: Universität Gesamthochschule Siegen

Siegen

Sweden: Kungl Tekniska Högskolan

KTH, Stockholm

PAMELA Instrument



- 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)

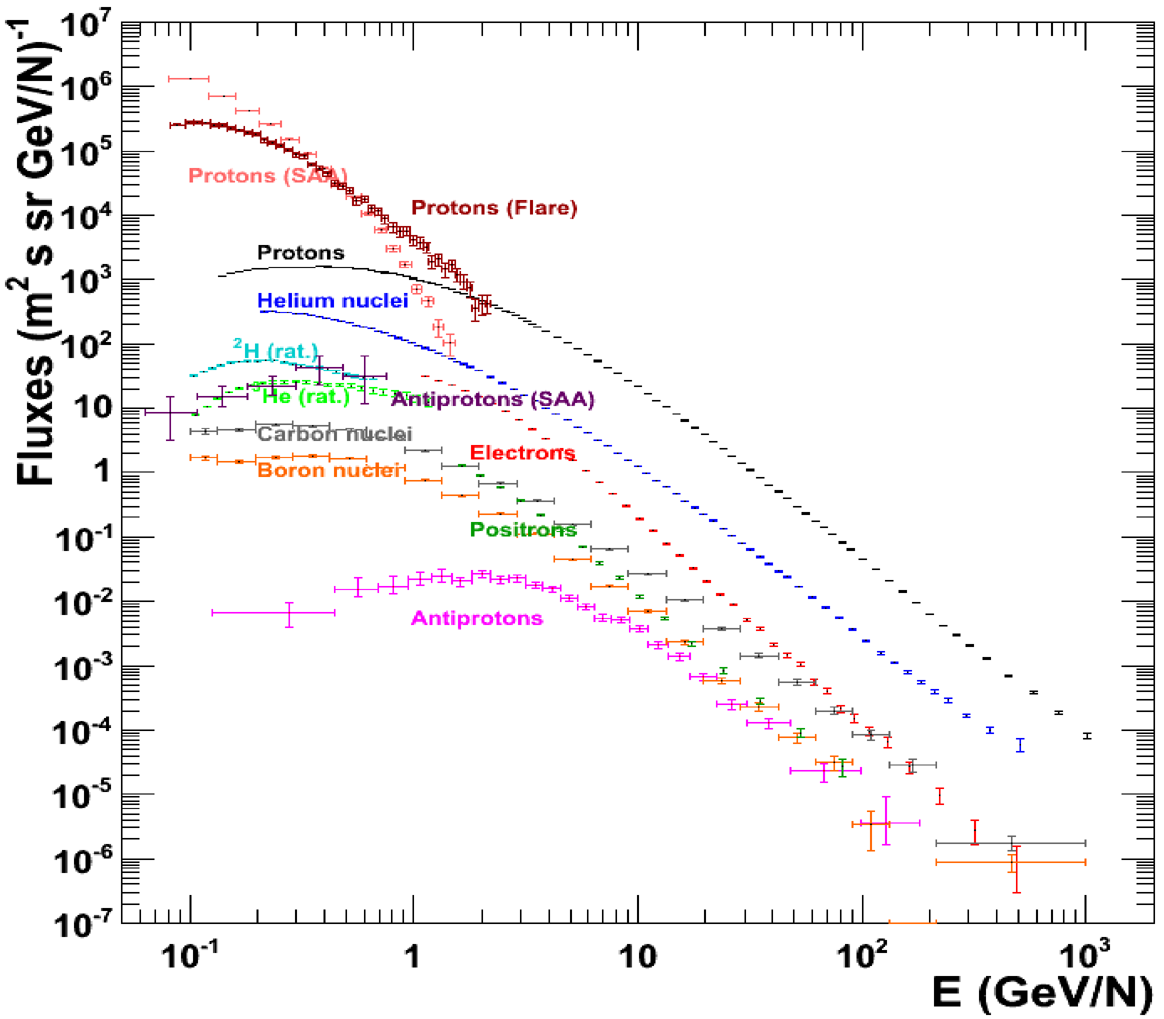
- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR

MDR 1.2 TeV

- 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

Summary of PAMELA results

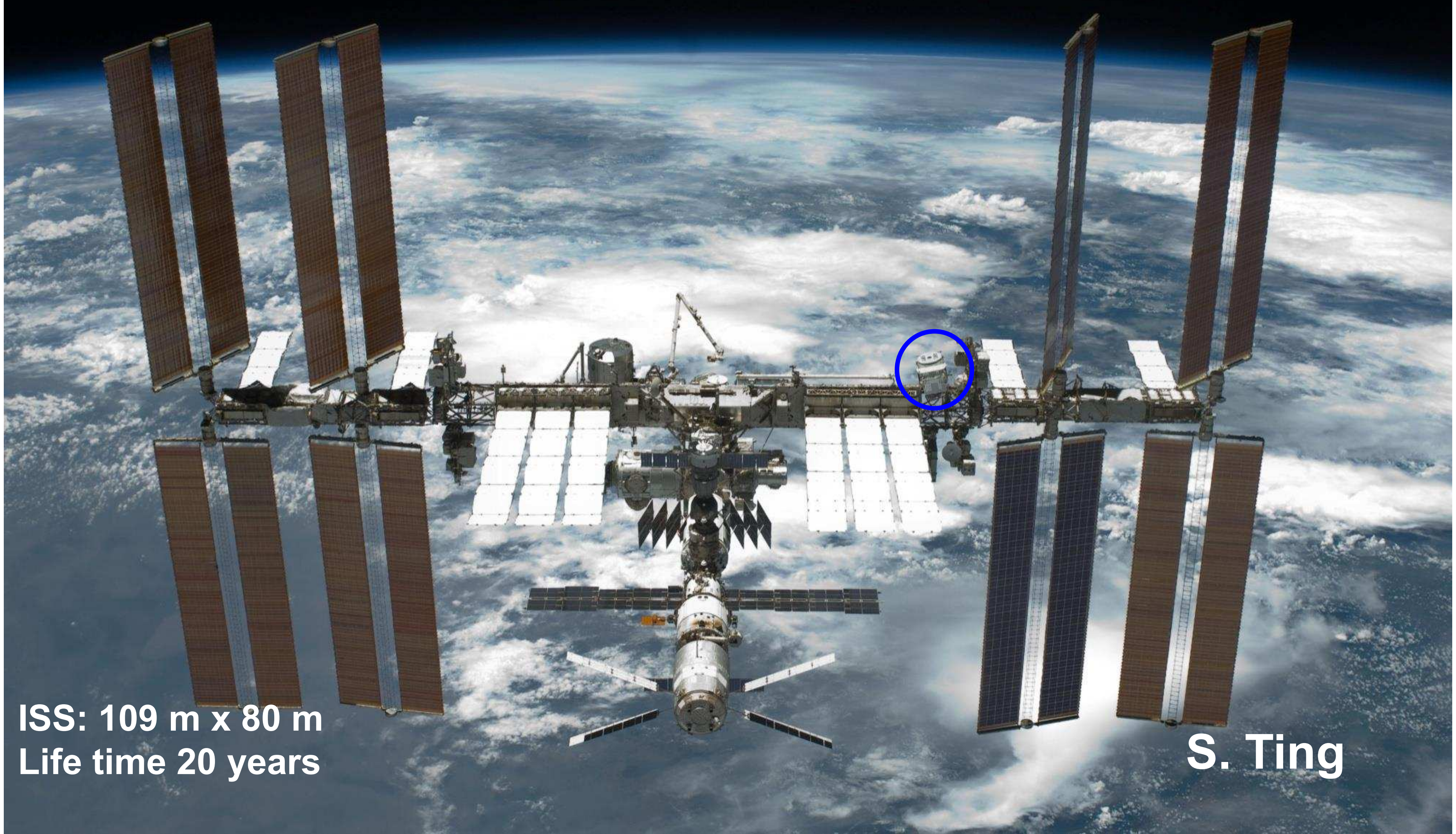


Physics Reports 544/4 (2014), 323

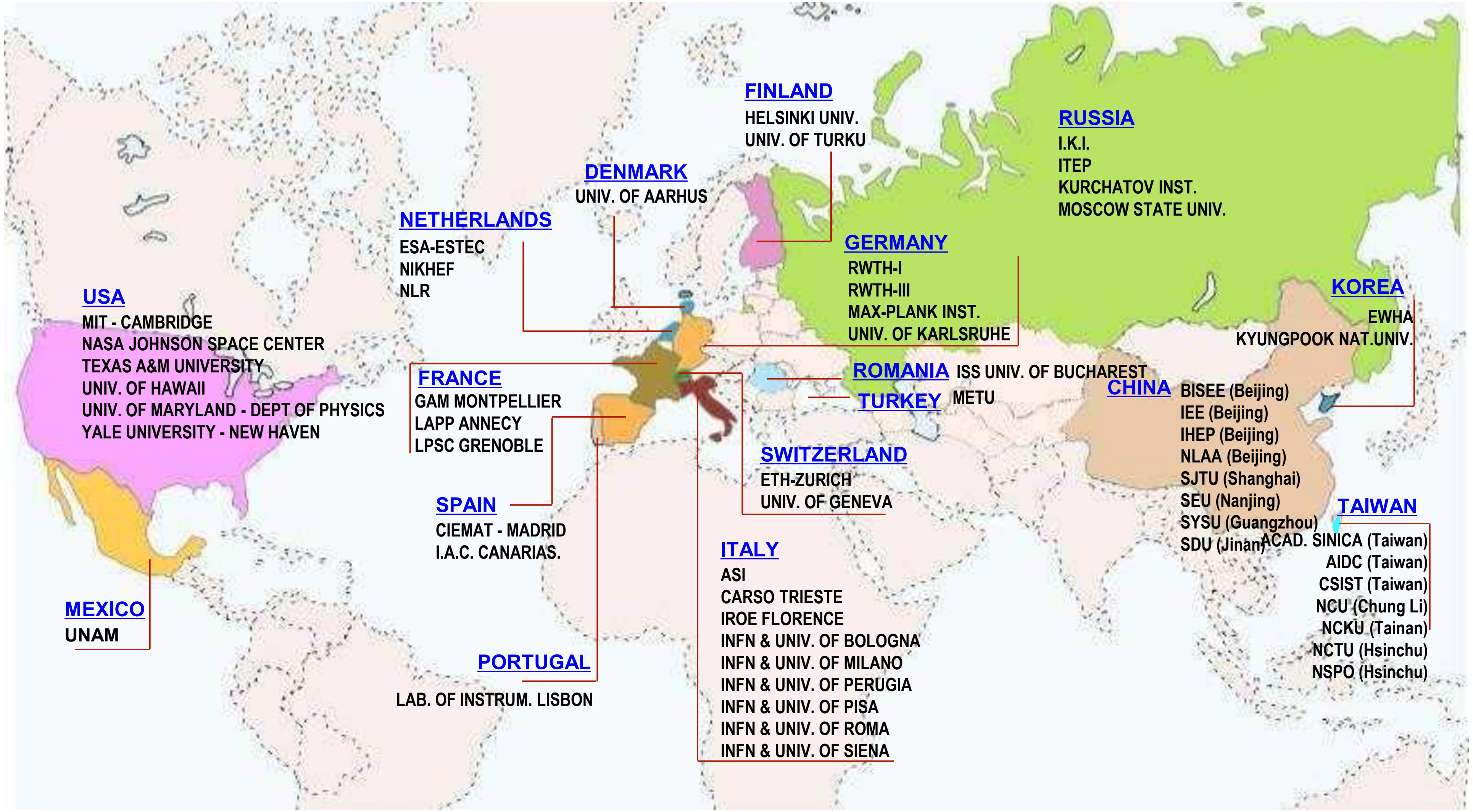
The Alpha Magnetic Spectrometer (AMS) Experiment
on the International Space Station.

May 16, 2011

May 16, 2011



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

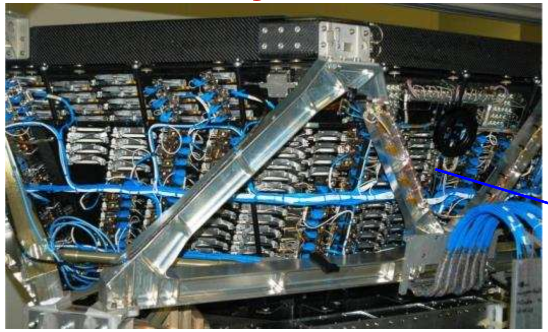
2 billion$

5m x 4m x 3m
7.5 tons

AMS: A TeV precision, multipurpose spectrometer

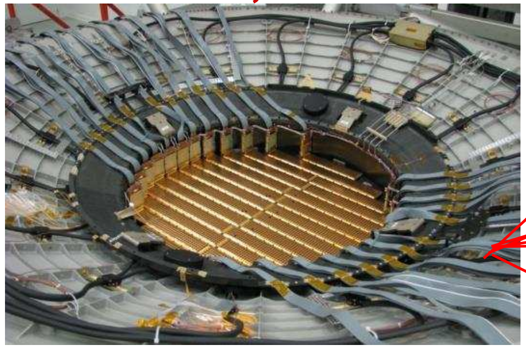
Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

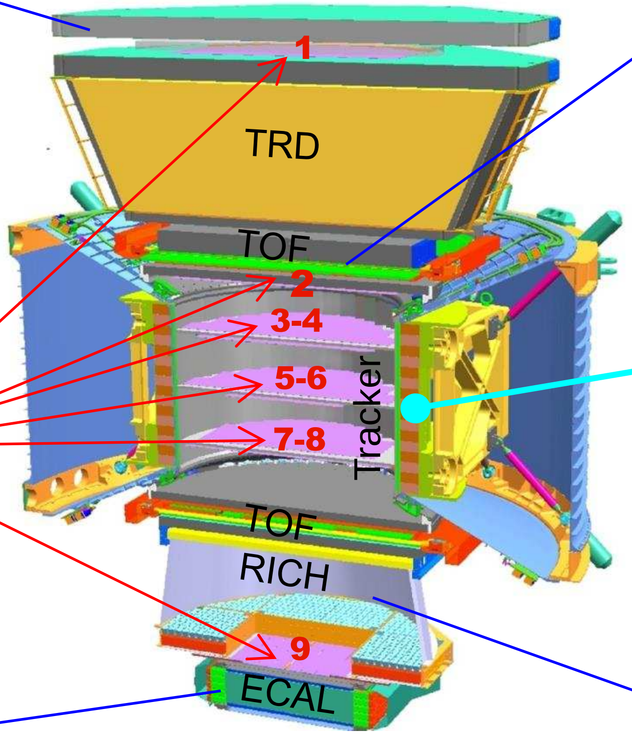
TRD
Identify e^+, e^-



TOF
Z, E

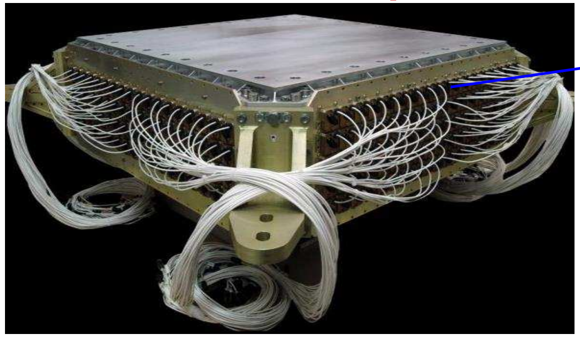
Silicon Tracker
Z, P



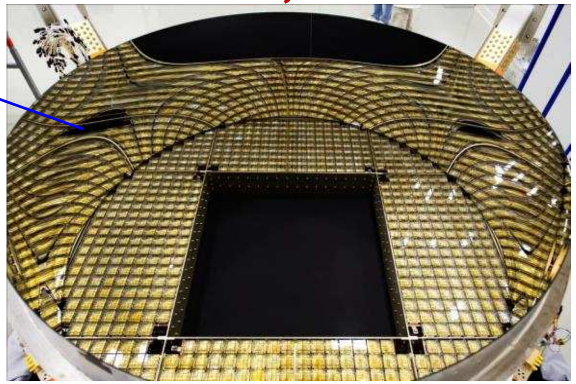


Magnet
±Z

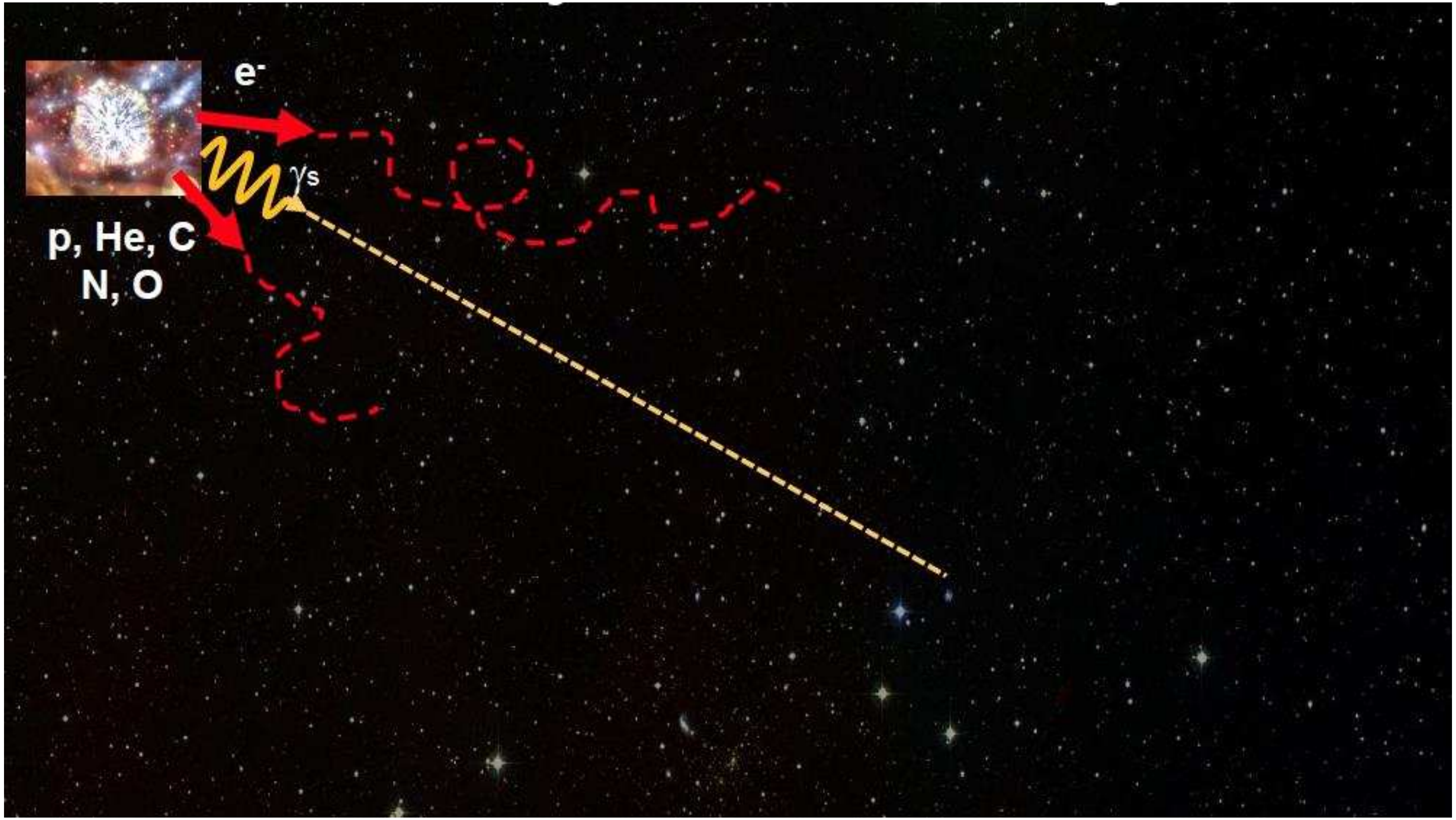
ECAL
E of e^+, e^-, γ



RICH
Z, E



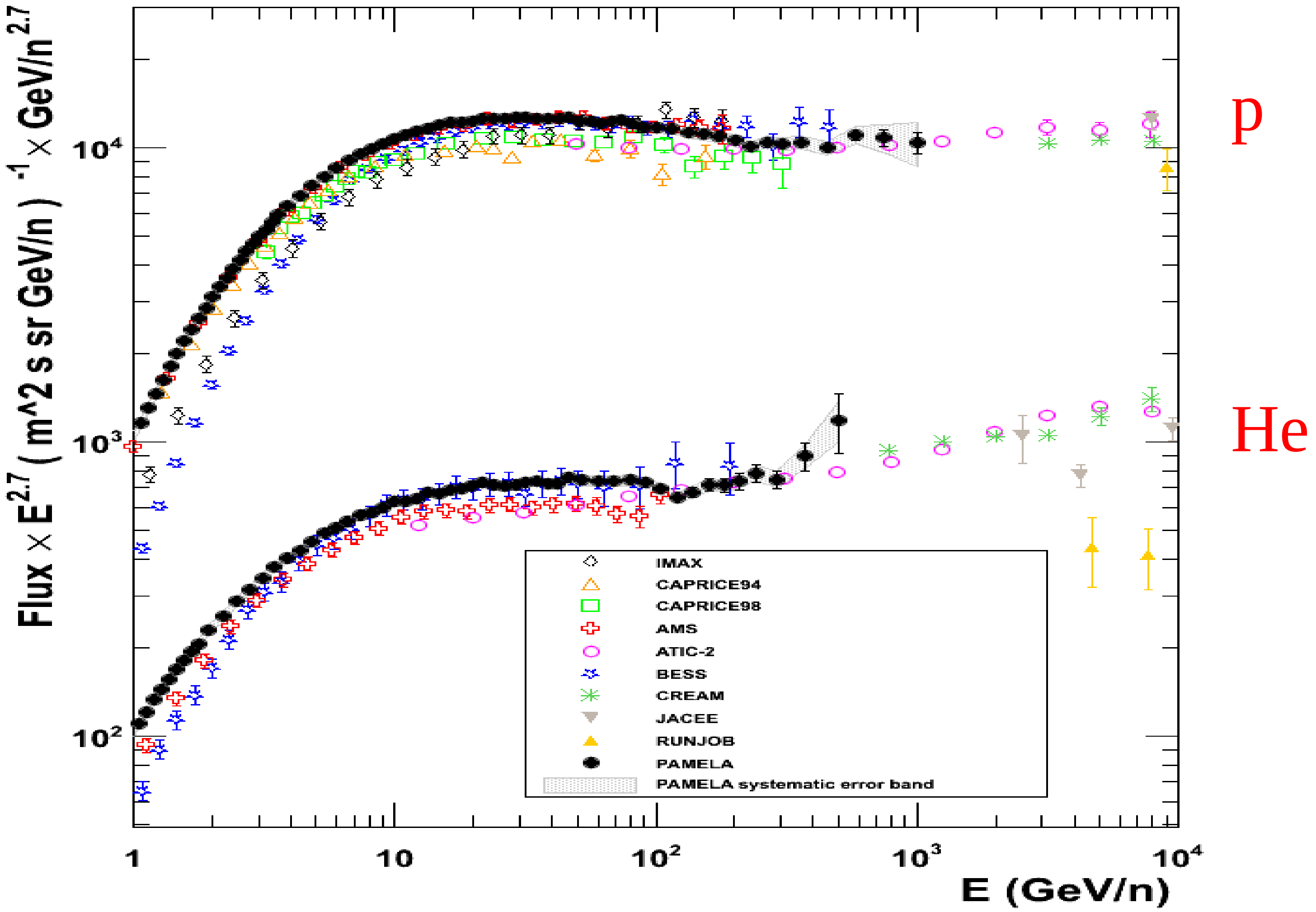
Z, P are measured independently by the Tracker, RICH, TOF and ECAL



Absolute fluxes of primary GCRs

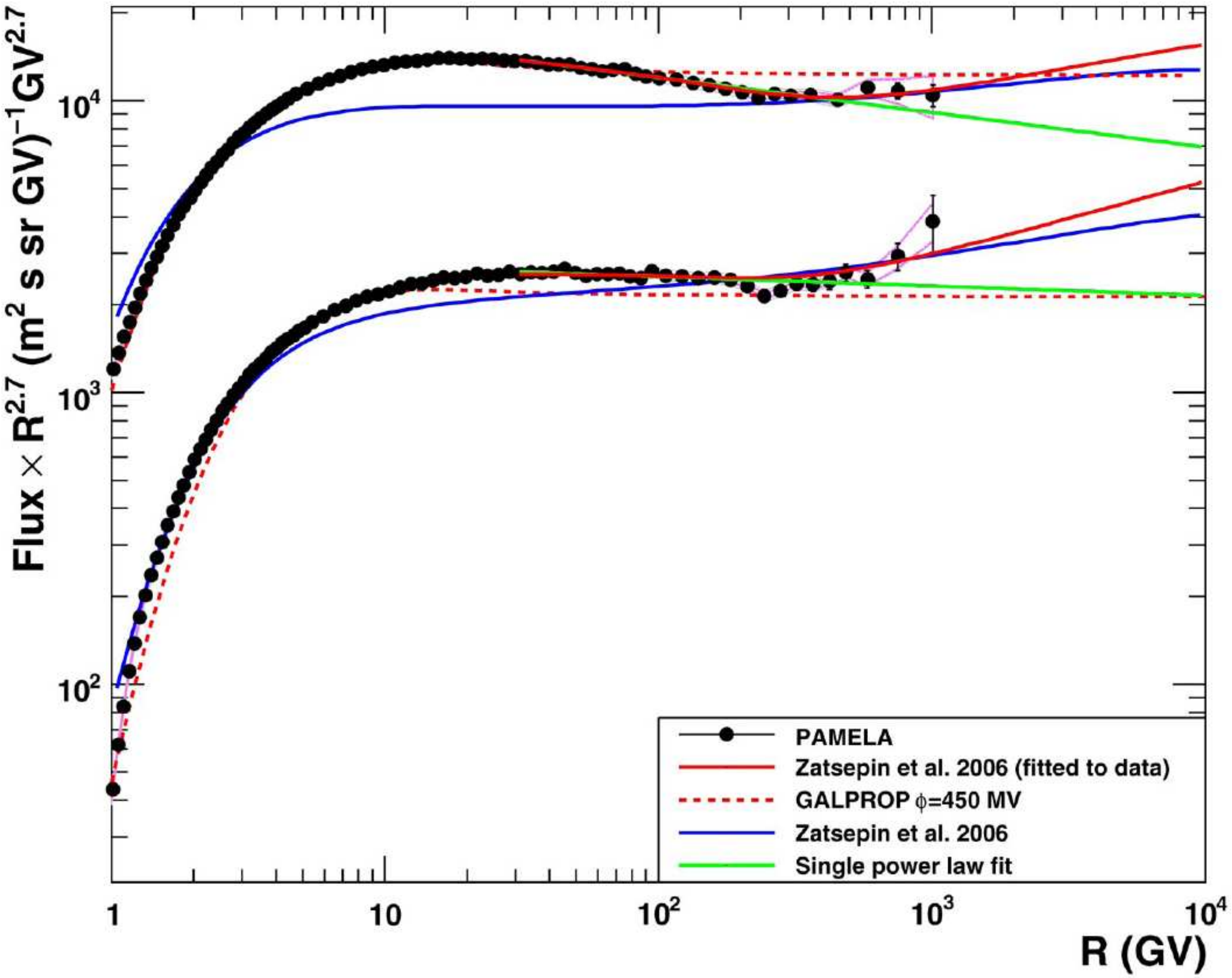
Protons, helium nuclei, light nuclei, electrons

Proton and Helium fluxes

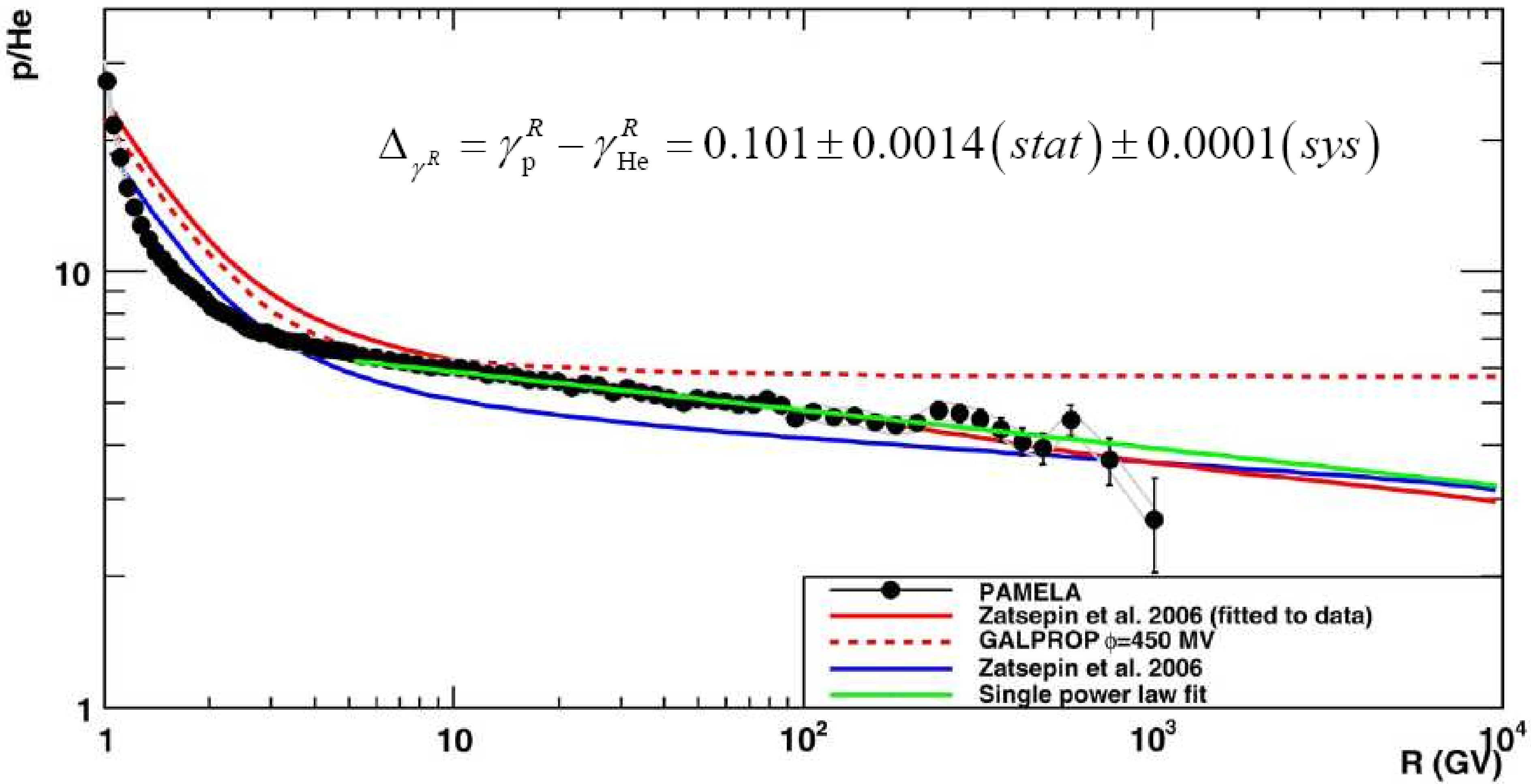


PAMELA Science 332,69 (2011)

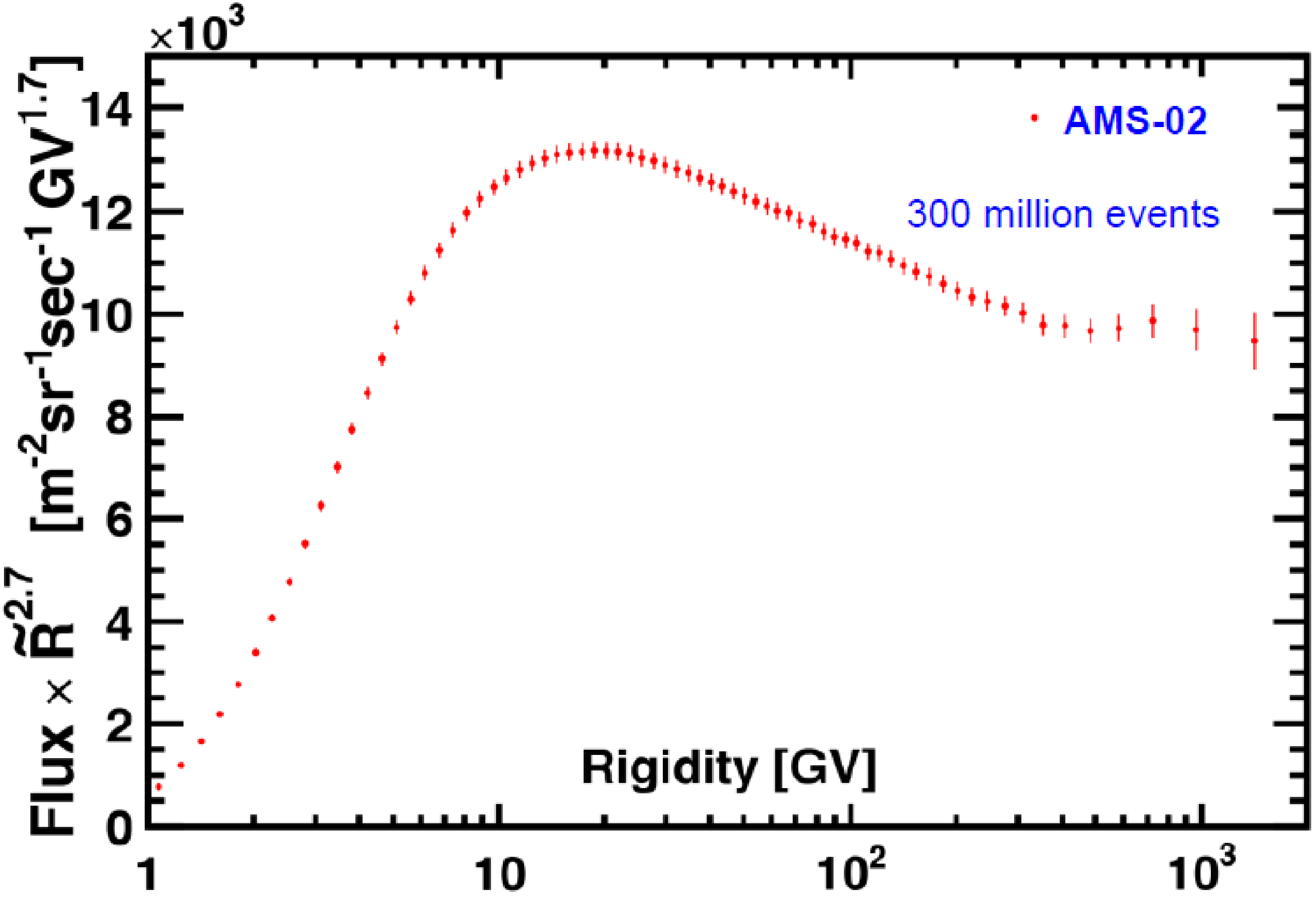
Proton and Helium fluxes



Proton to Helium ratio

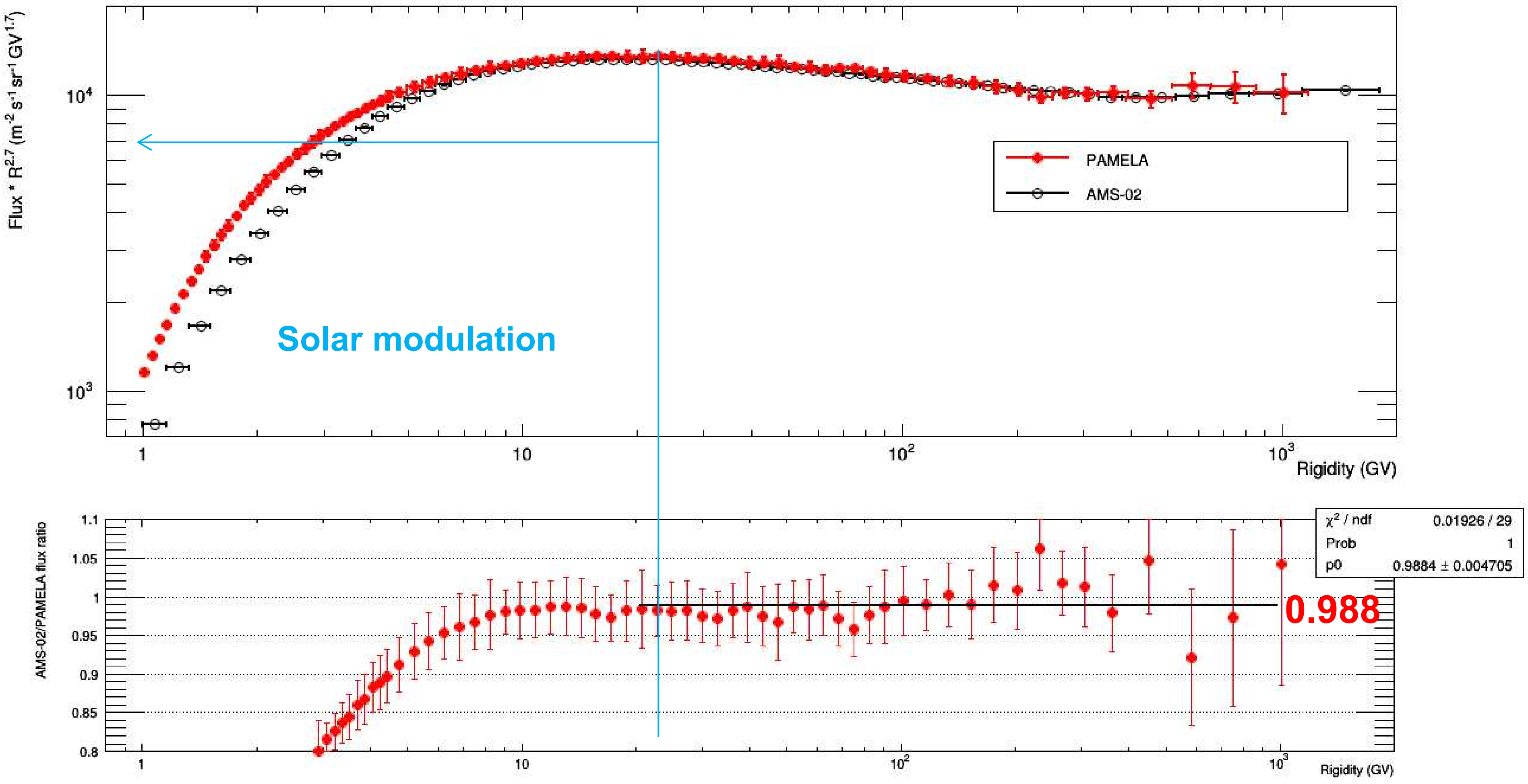


AMS proton flux

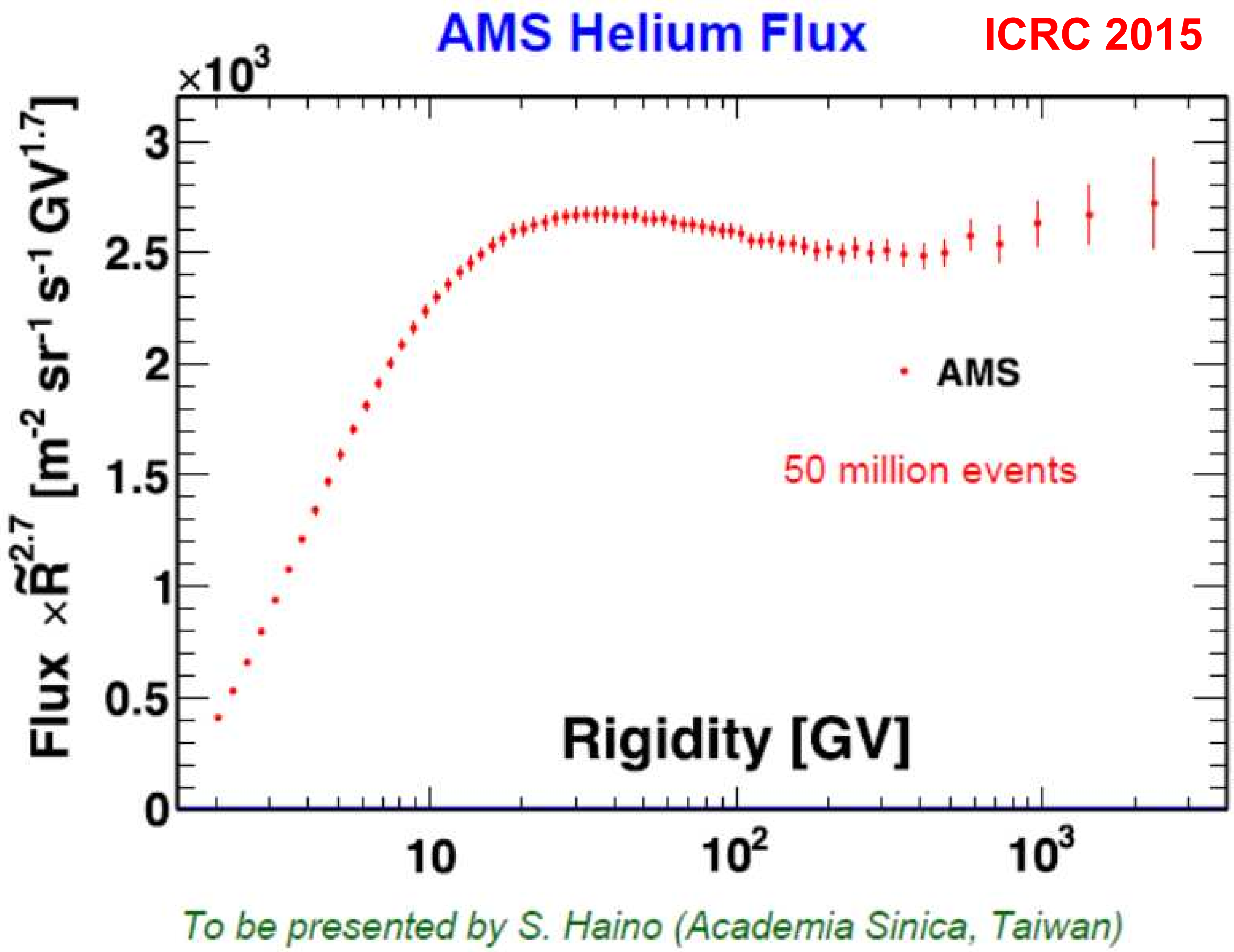


Phys. Rev. Lett. **114**, 171103, 2015

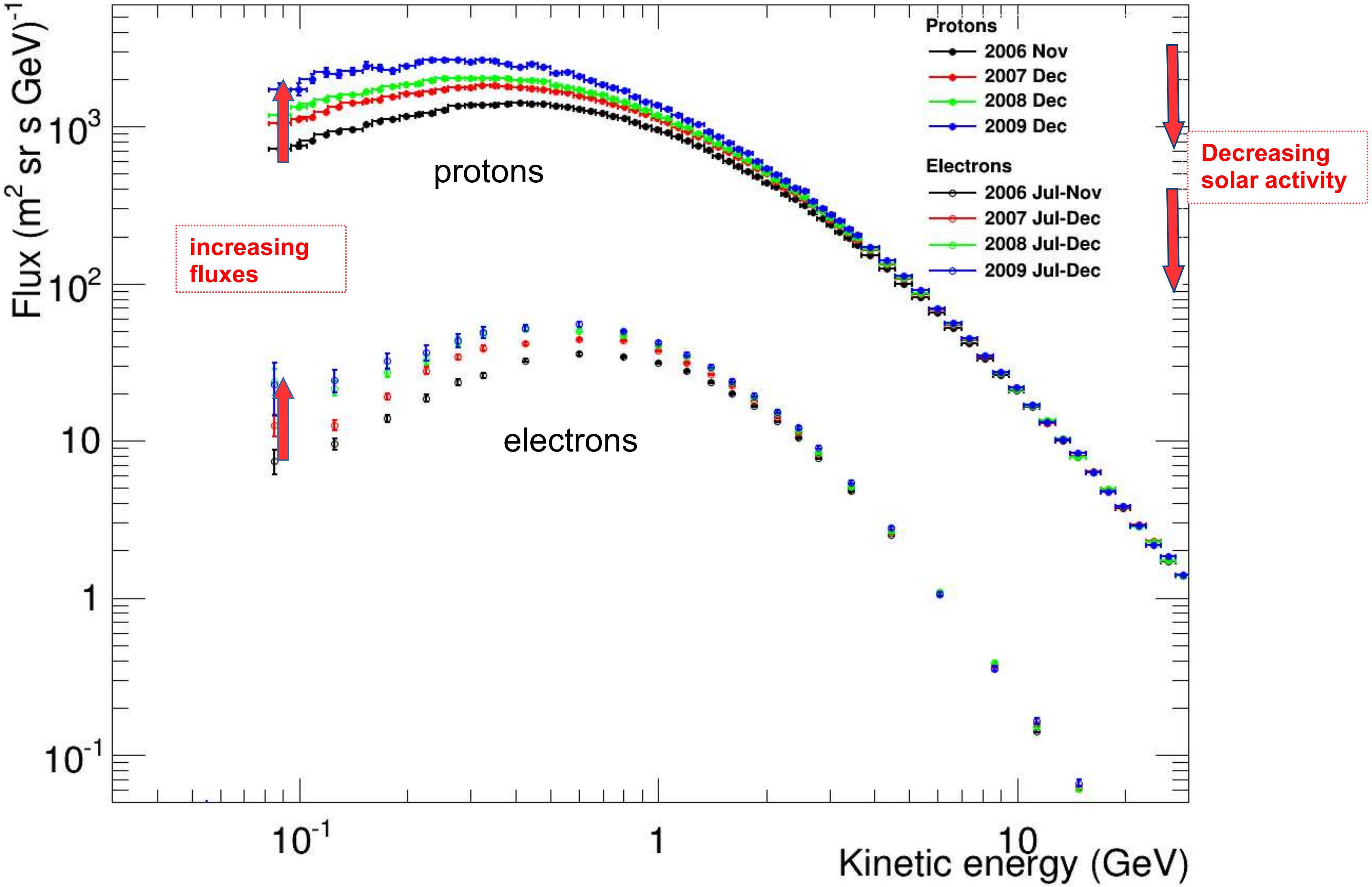
PAMELA vs AMS-02 proton spectrum



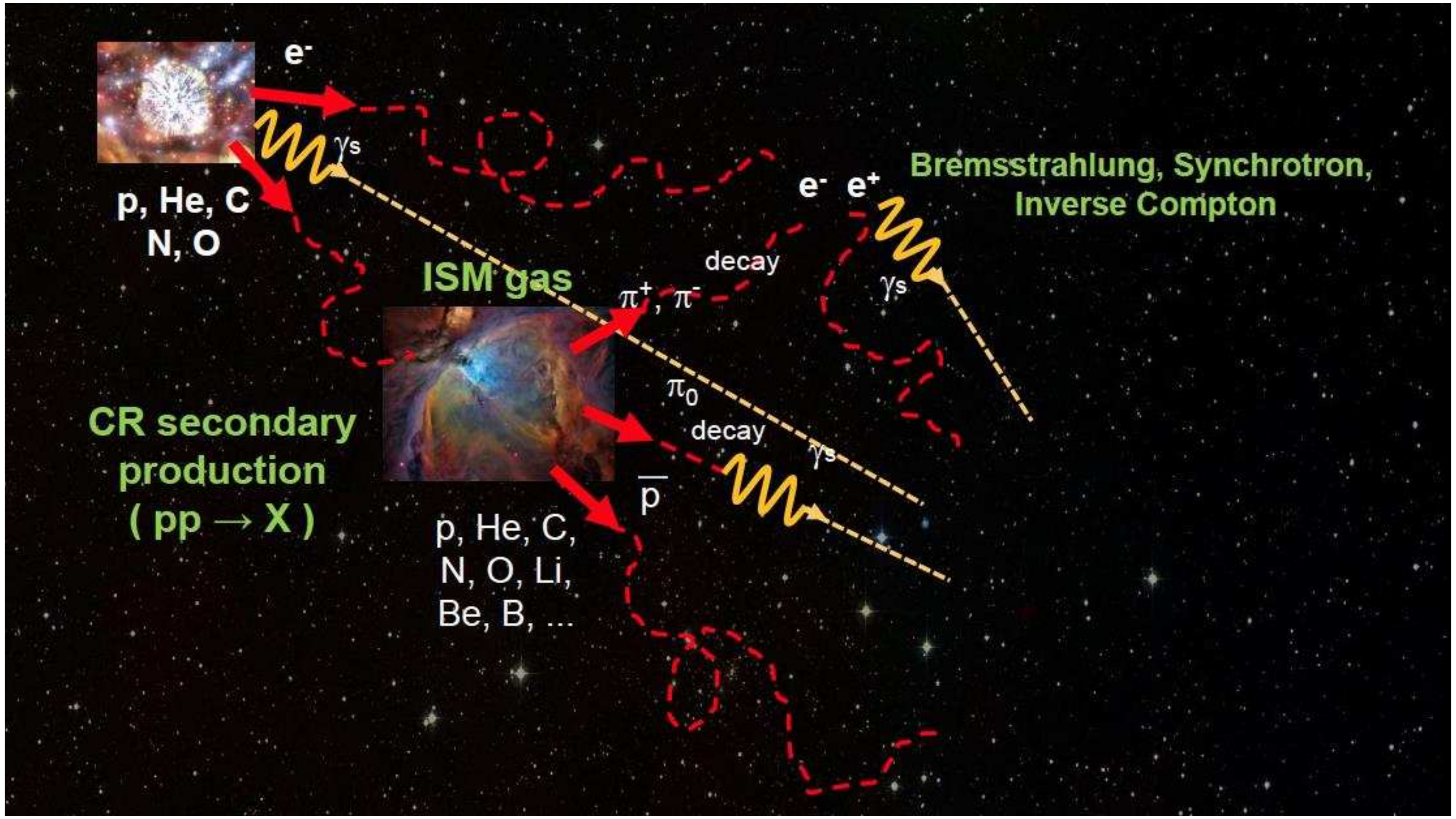
O. Adriani et al, Phys. Rep. (2014)


AMS Helium Flux
ICRC 2015
×10^3
Flux ×R̃^2.7 [m^-2 sr^-1 s^-1 GV^1.7]
3
2.5
2
1.5
1
0.5
0
AMS
50 million events
Rigidity [GV]
10
10^2
10^3
To be presented by S. Haino (Academia Sinica, Taiwan)

Solar modulation in the heliosphere



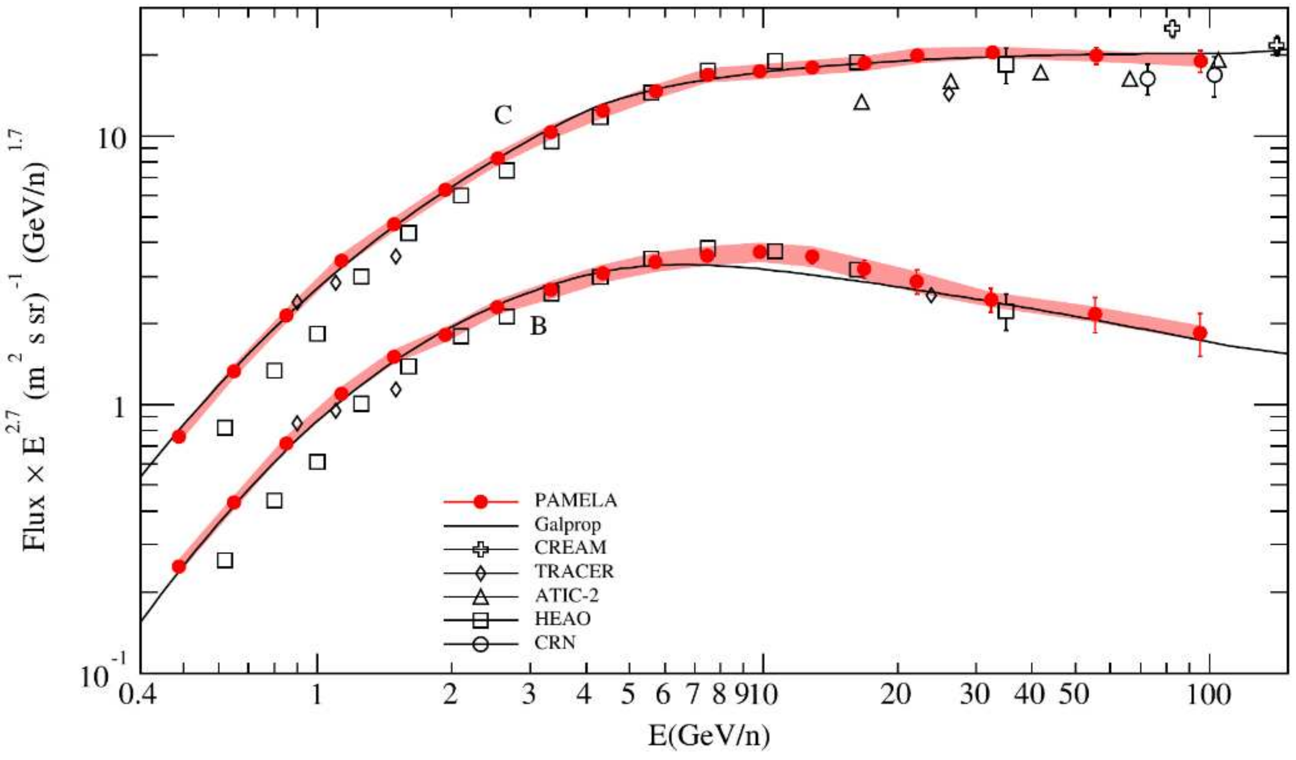
PAMELA coll., ApJ 765 (2013), 91;



Secondary cosmic rays

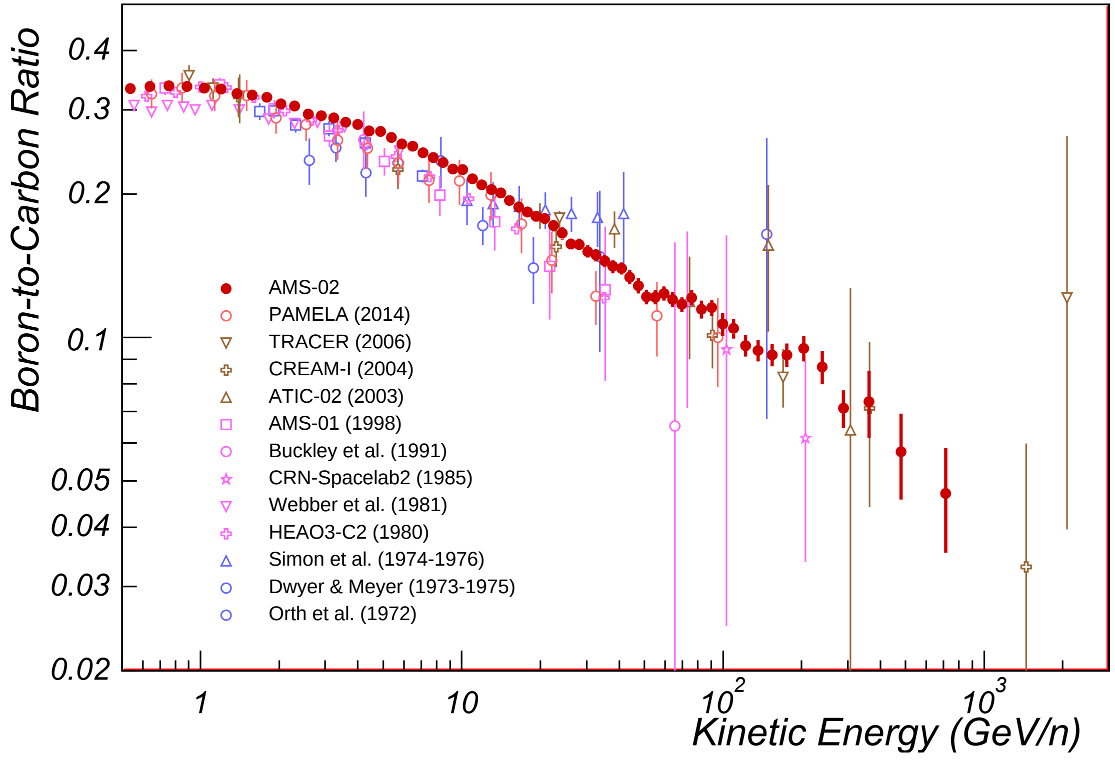
Secondaries from homogeneously distributed interstellar matter (light nuclei)

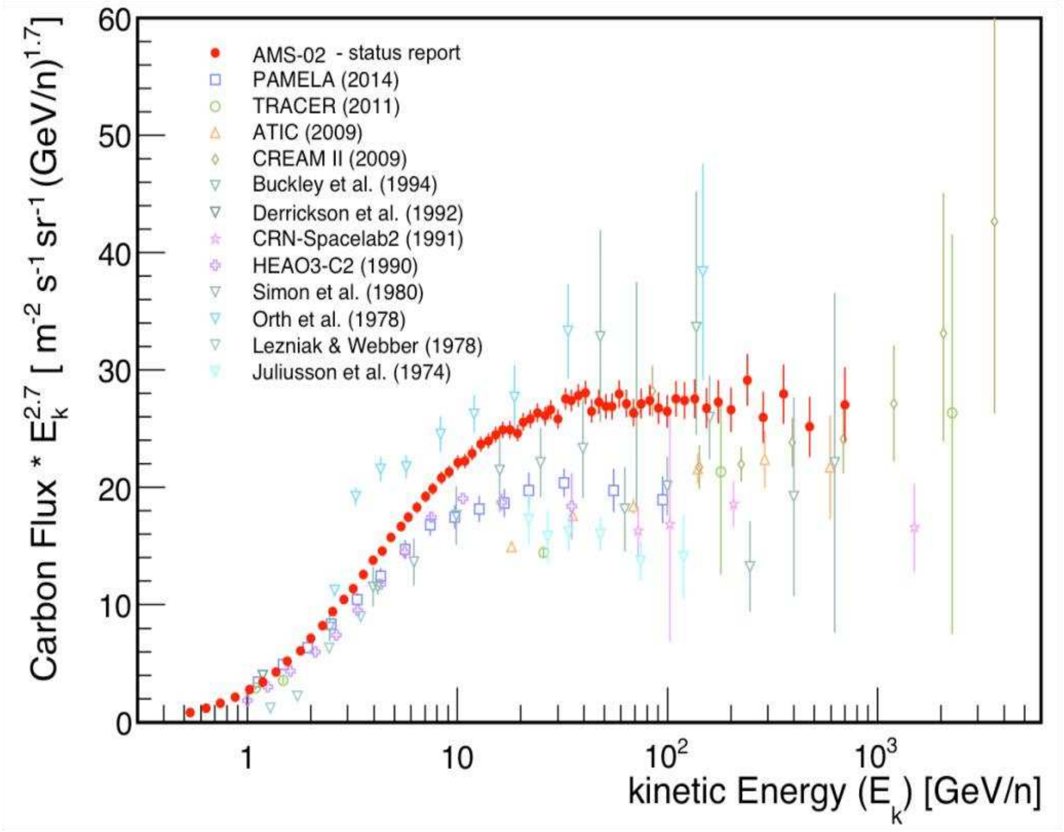
Boron and Carbon fluxes



PAMELA Coll., ApJ 791 (2014), 93

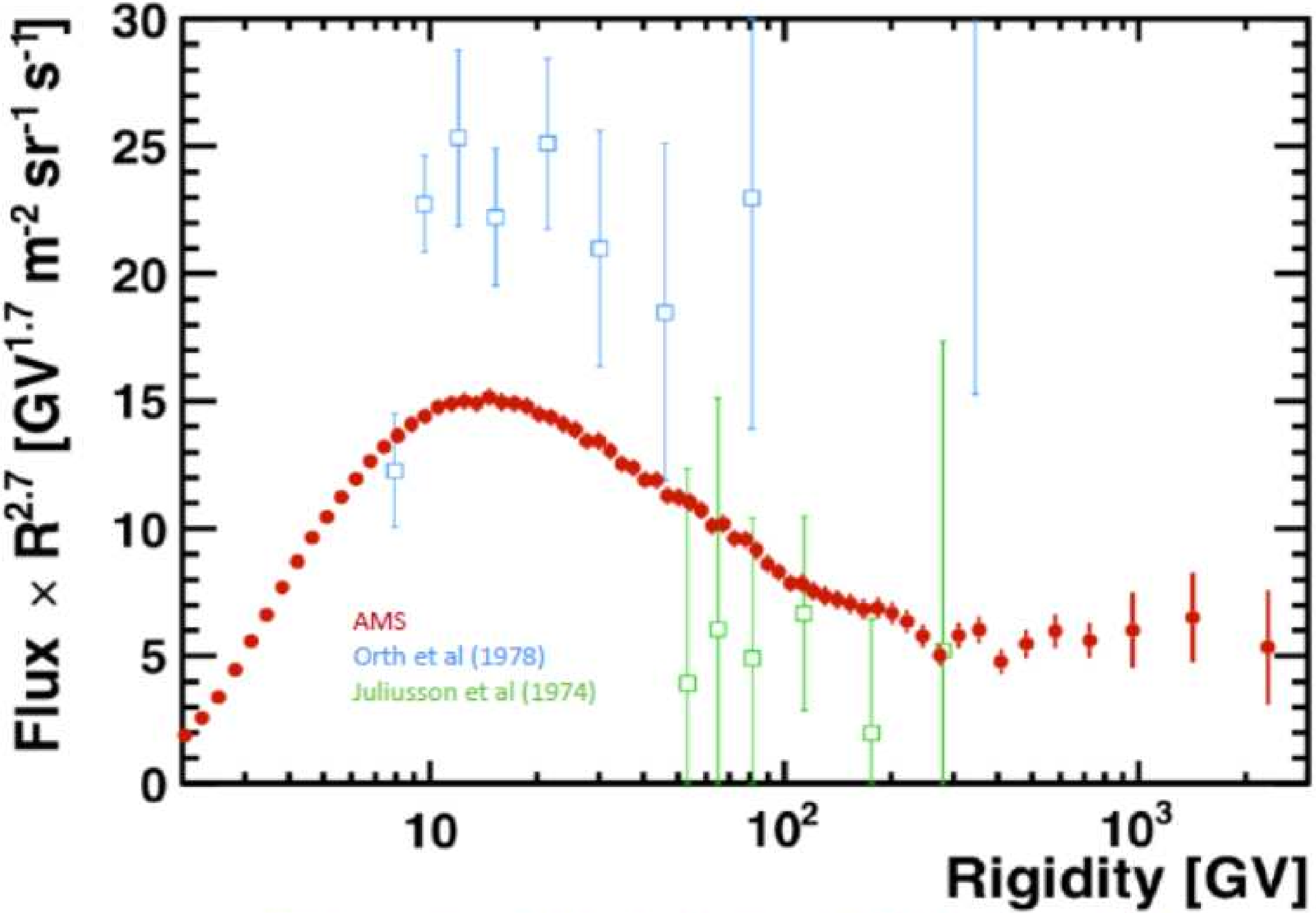
B/C and Carbon flux





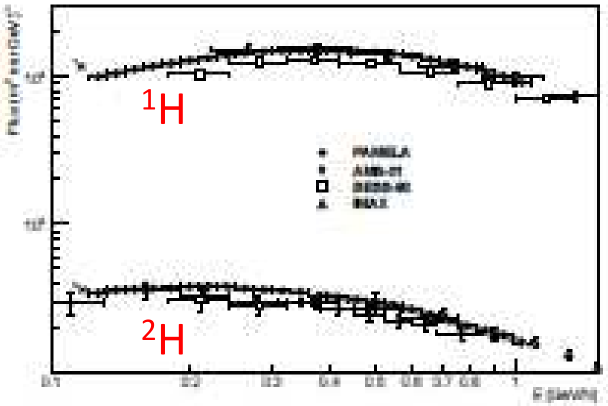
B. Bertucci, CRIS 2015, Gallipoli, Italy

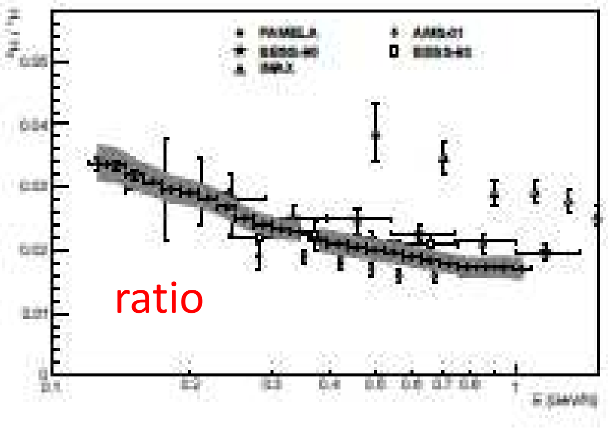
AMS Lithium flux – current status

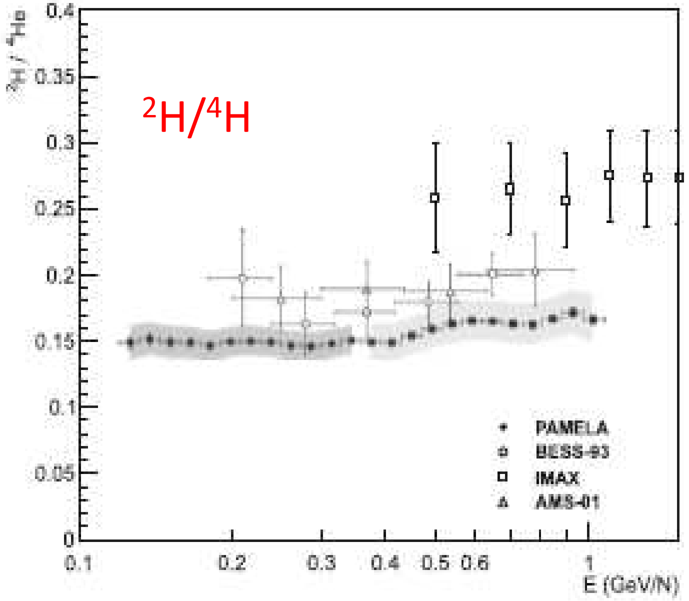


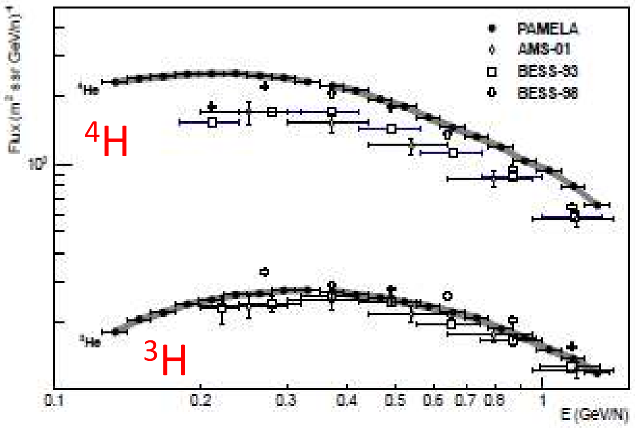
To be presented by L. Derome (LPSC, Grenoble)

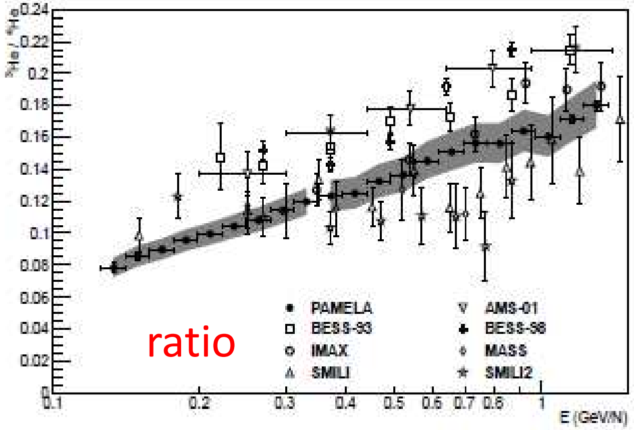
Hydrogen and Helium Isotopes





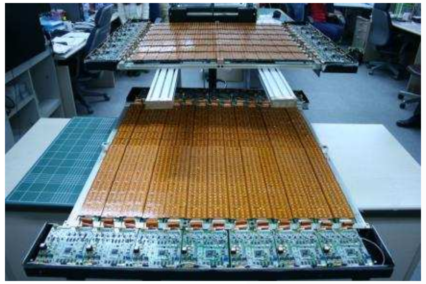




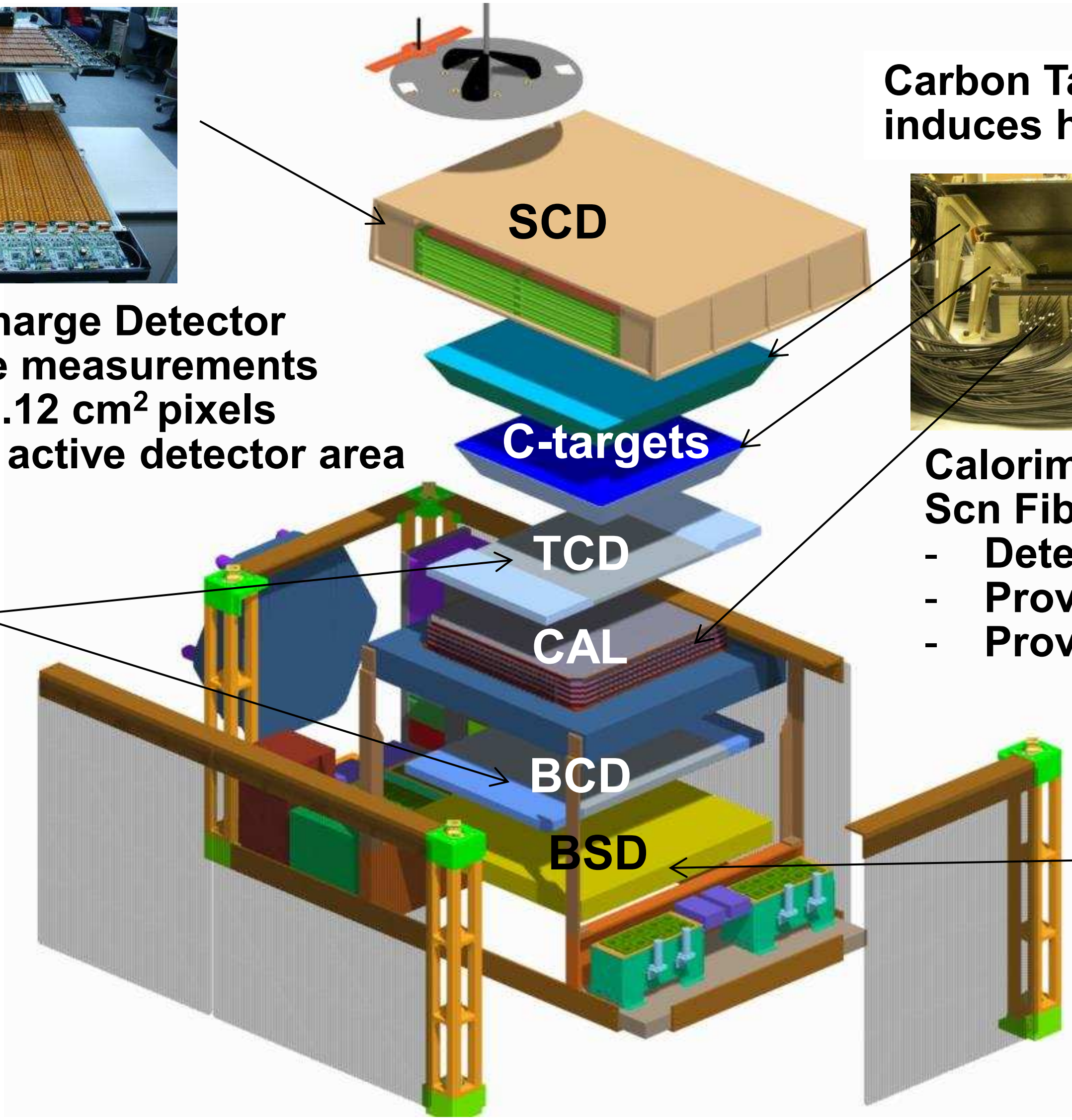


Pamela coll. APJ 818,1,68 (2016)

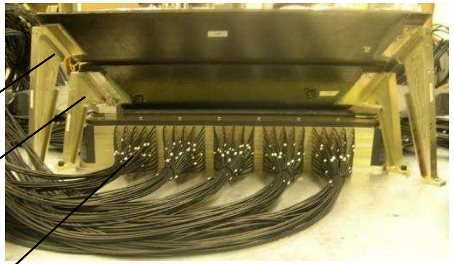
ISS-CREAM Instrument



4 layer Silicon Charge Detector
- Precise charge measurements
- 380-μm thick 2.12 cm^2 pixels
- 79 cm x 79 cm active detector area



Carbon Targets (0.5 λ_{int}) induces hadronic interactions



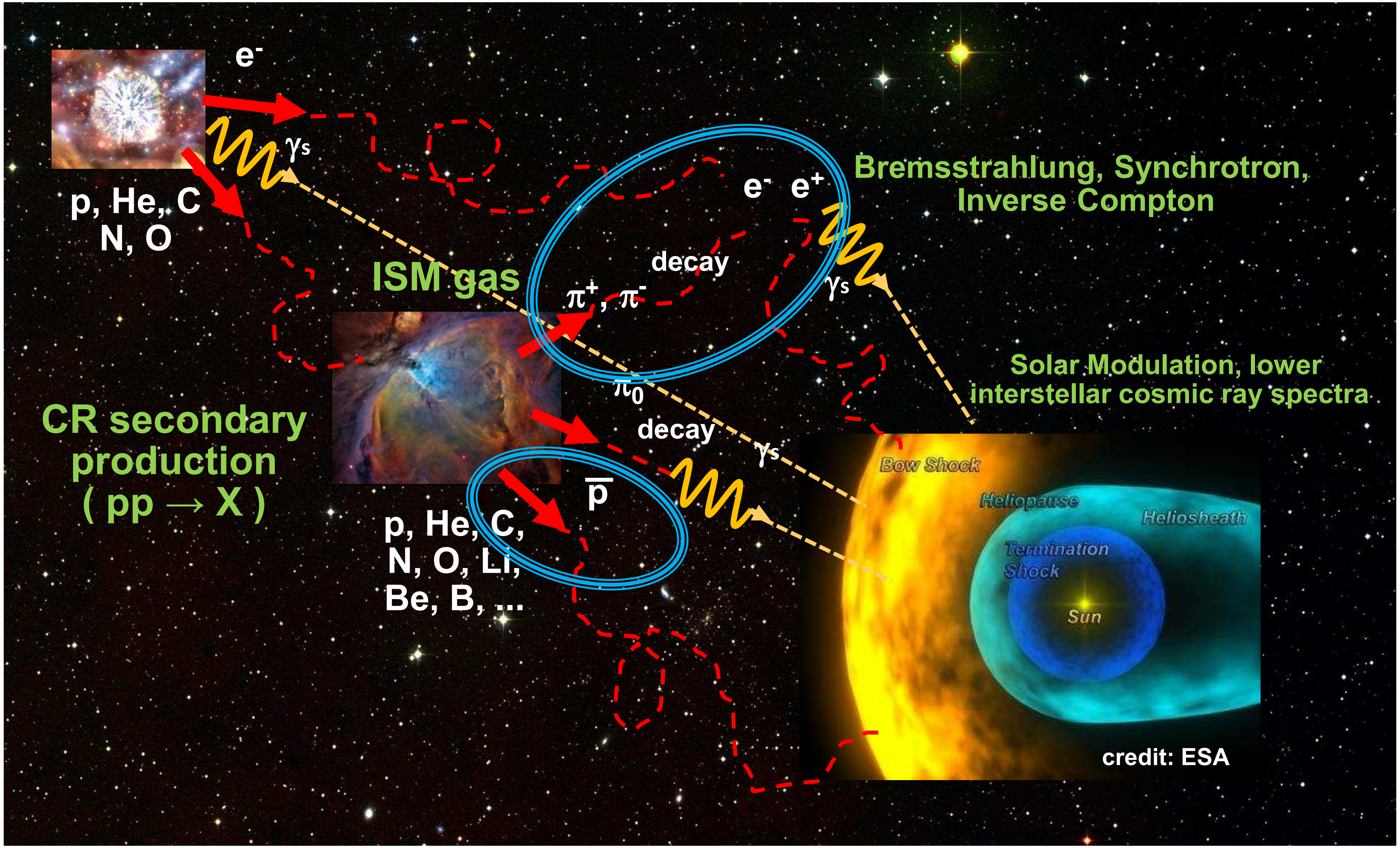
Calorimeter (20 layers W + Scn Fibers)
- Determine Energy
- Provide tracking
- Provide Trigger

Top & Bottom Counting Detectors
- Each with 20 x 20 photodiodes and a plastic scitillator for e/p separation
- Independent Trigger

Boronated Scintillator Detector
- Additional e/p separation
- Neutron signals

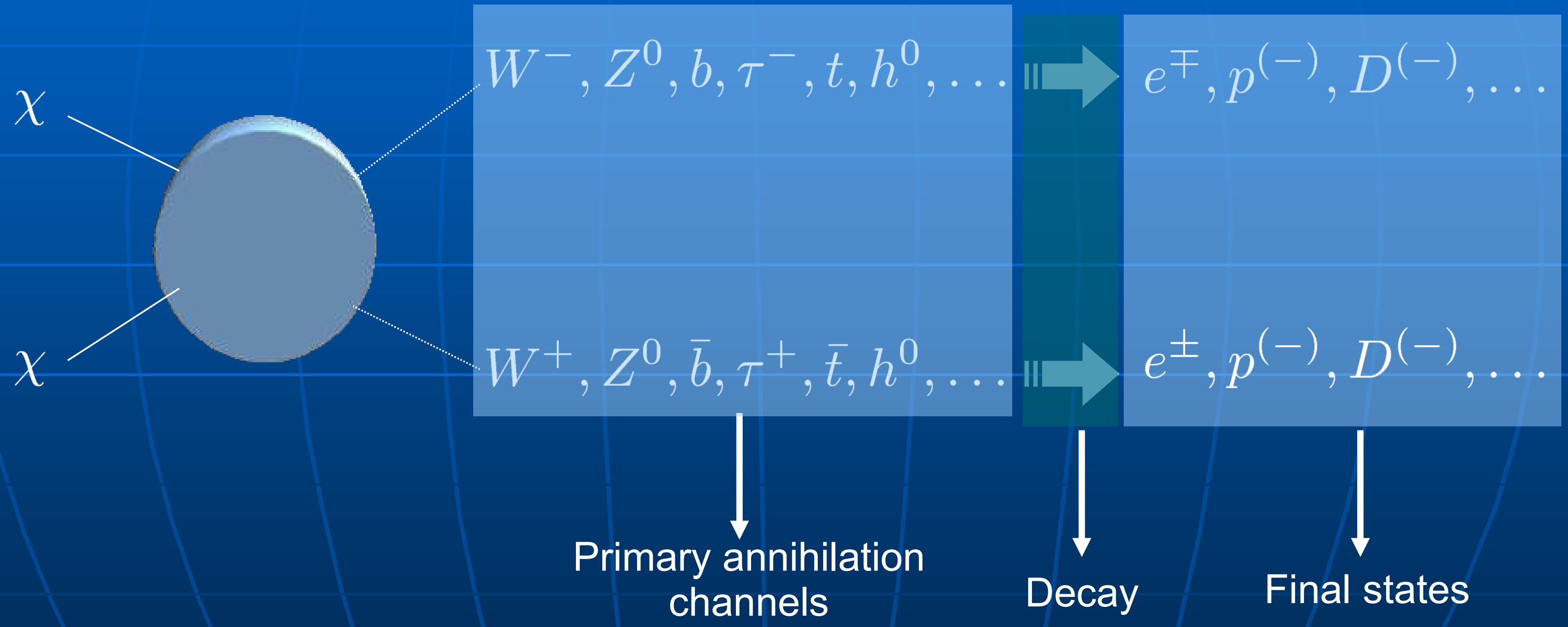
Launch 2017

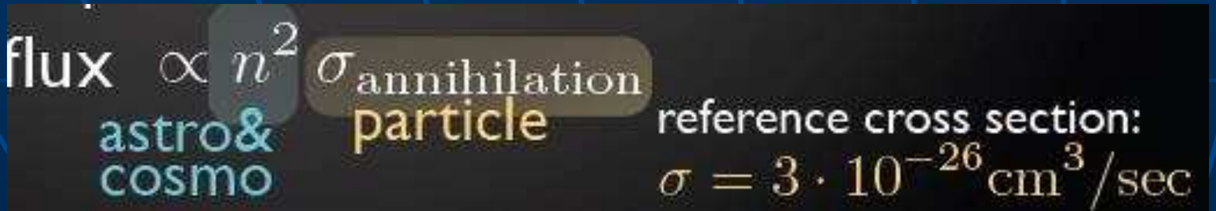
Cosmic Rays and Anti-Particles



DM annihilations

DM particles are stable. They can annihilate in pairs.



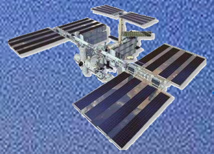


$\sigma_a = \langle \sigma v \rangle$

Antimatter Search

Wizard Collaboration

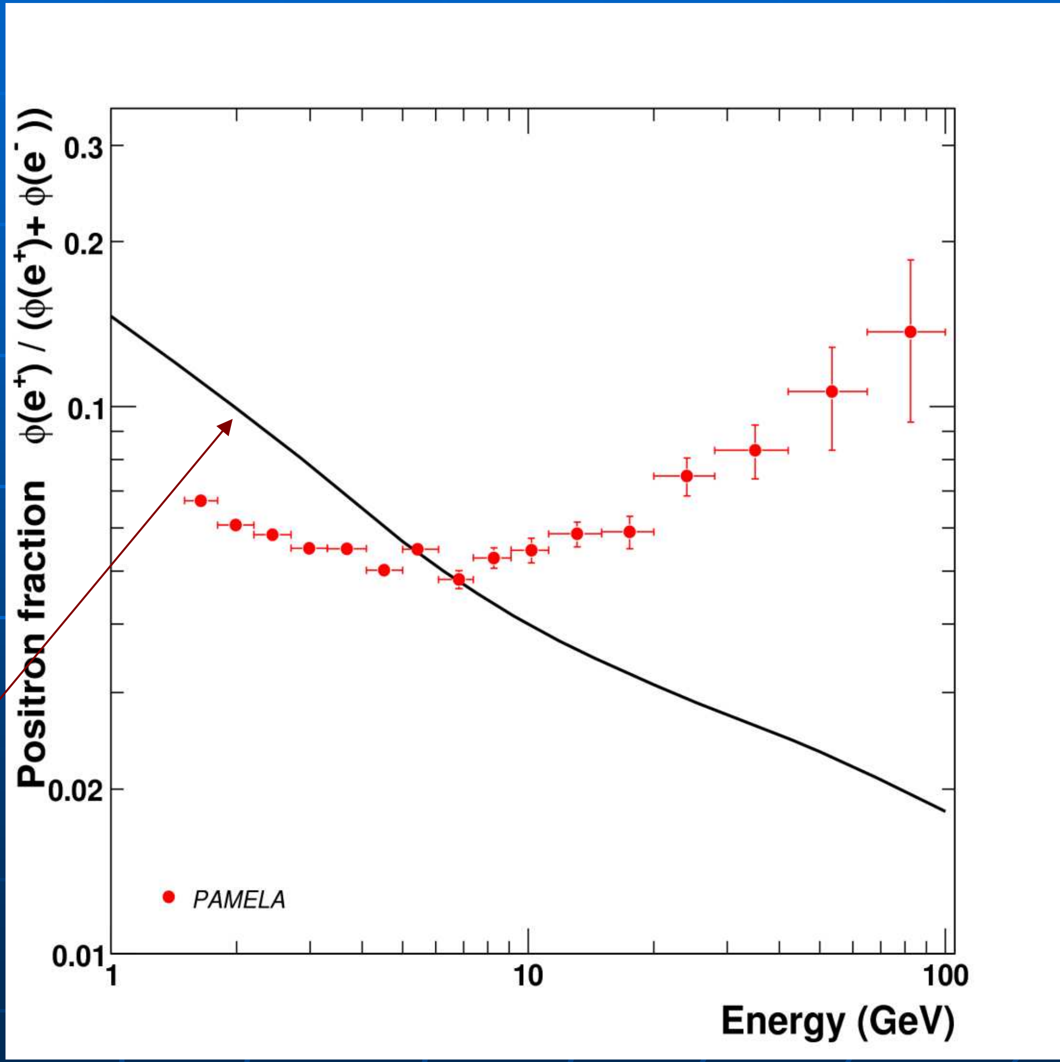
- ✓ MASS - 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)
- ✓ BESS (93, 95, 97, 98, 2000)
- ✓ BESS Polar I (2004)
- ✓ Heat (94, 95, 2000)
- ✓ IMAX (96)
- ✓ AMS-01 (1998)



PAMELA Positron to all electron ratio

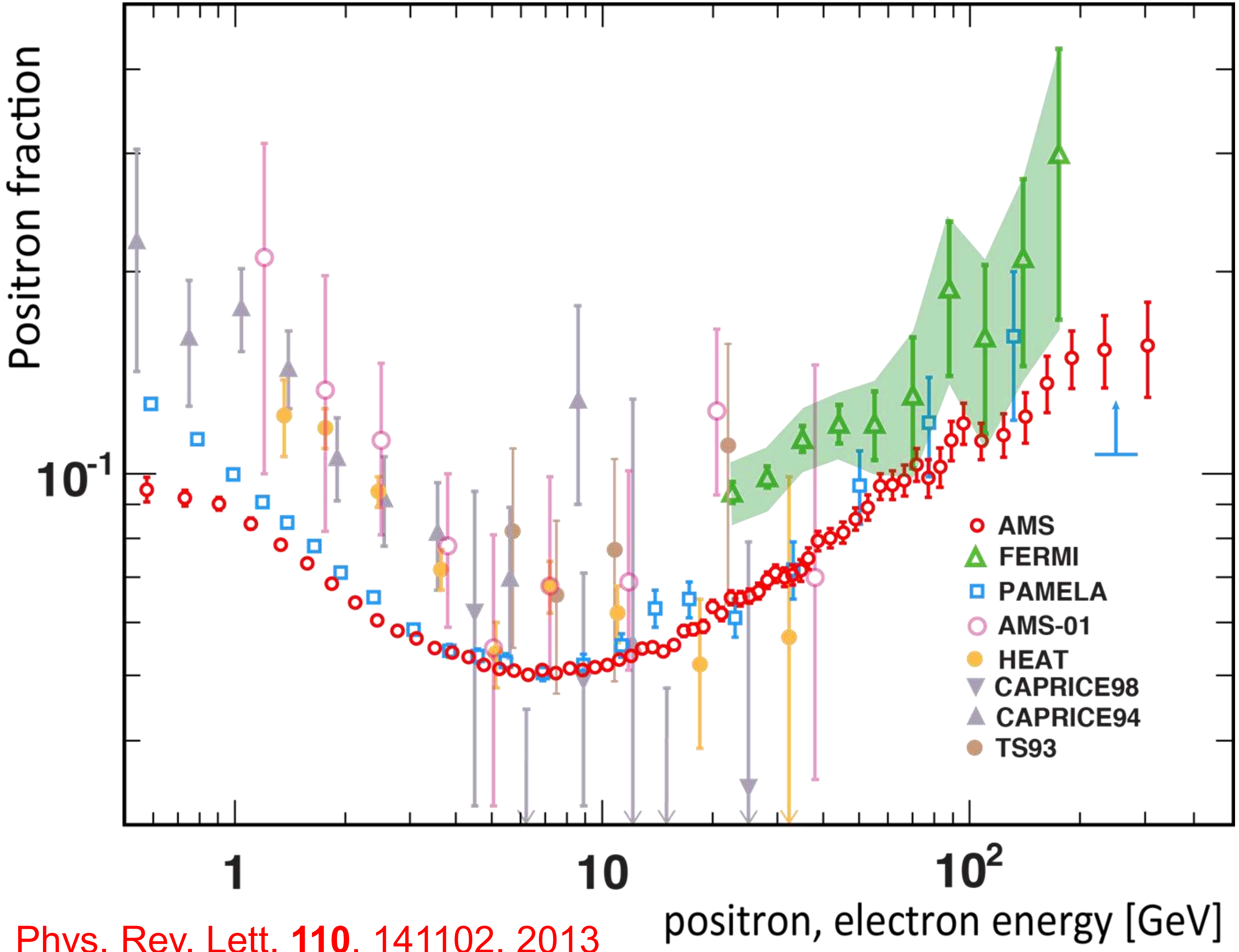
Nature 458, 697, 2009

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



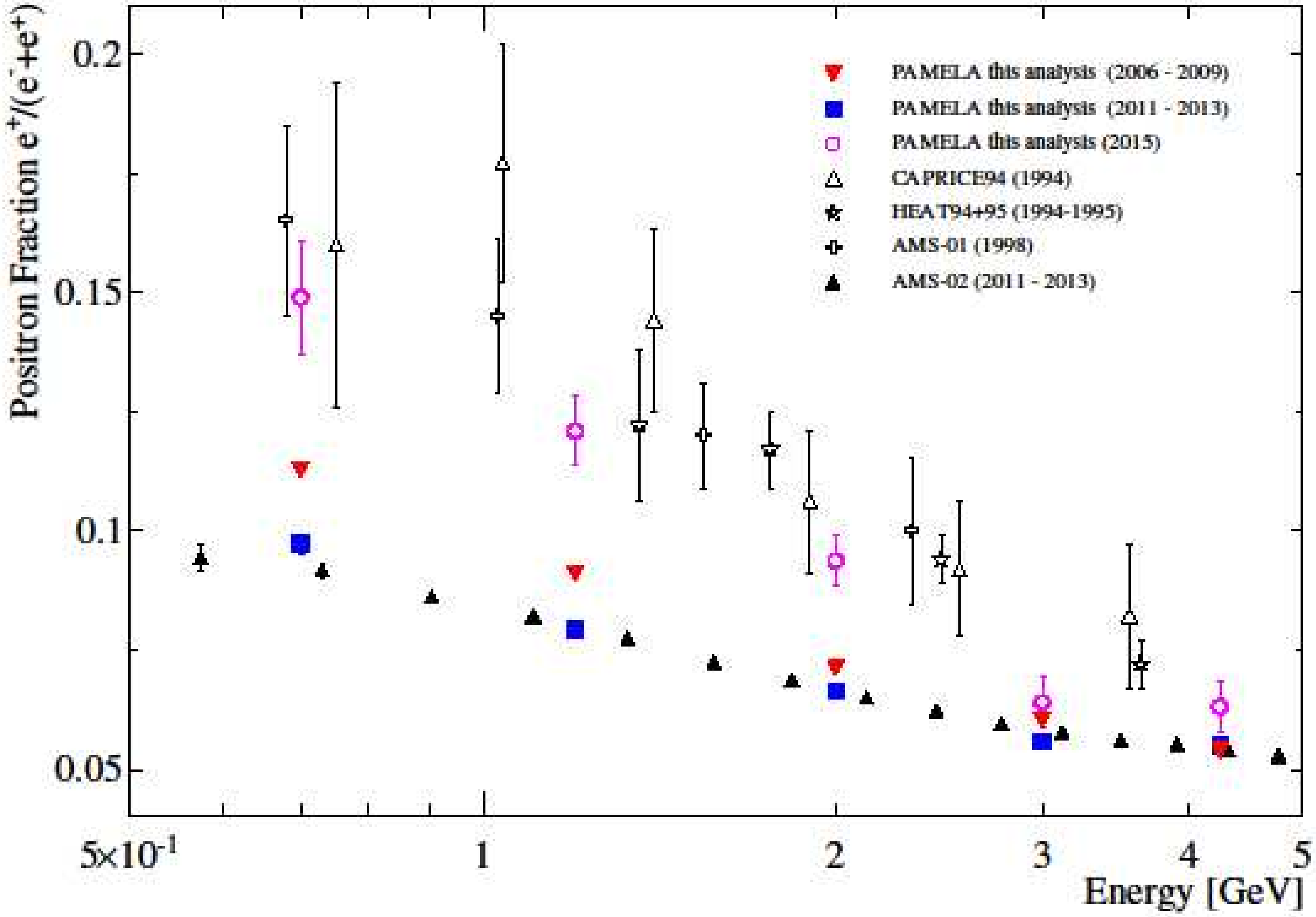
Secondary production
Moskalenko & Strong 98

AMS-02



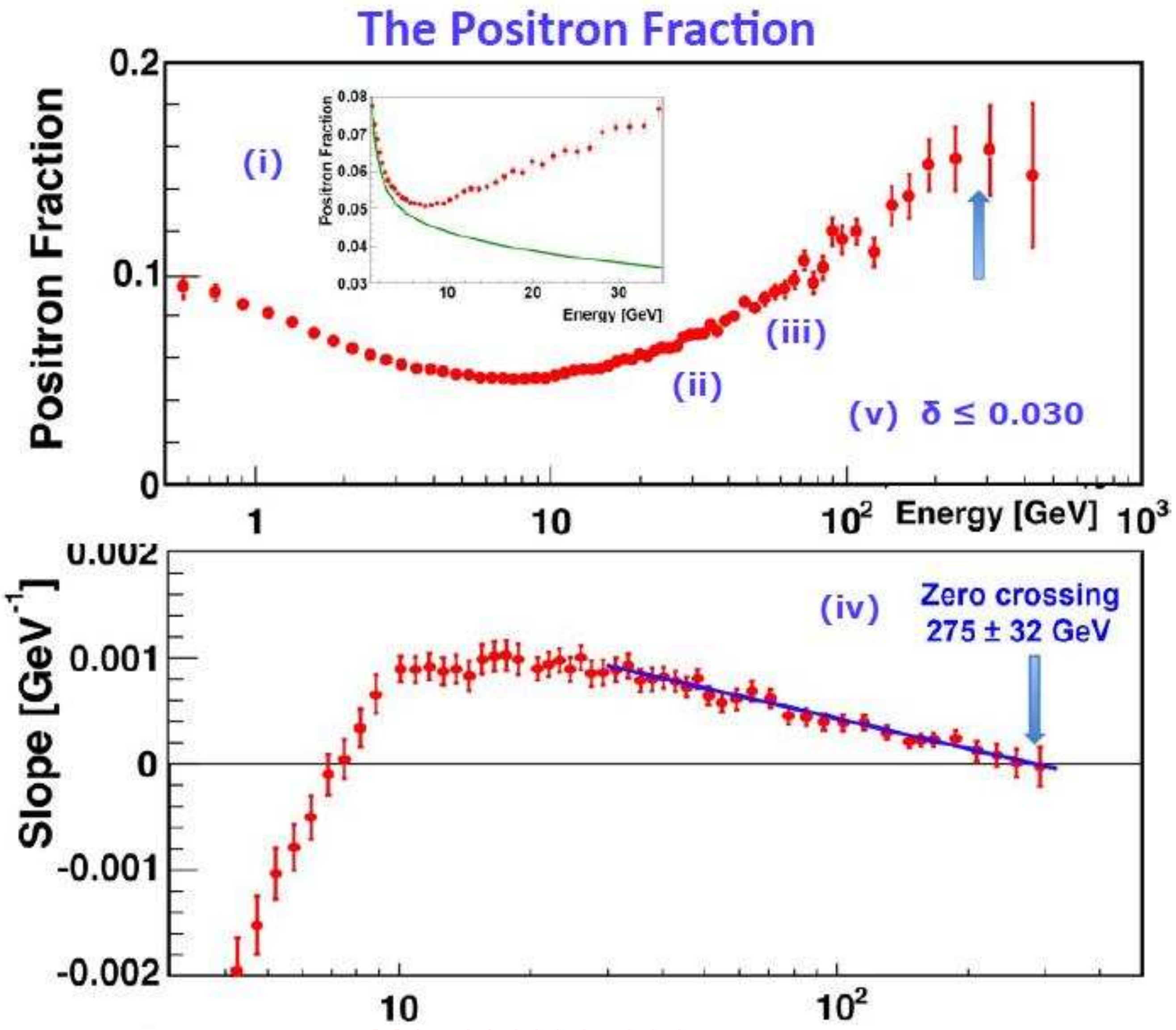
Phys. Rev. Lett. **110**, 141102, 2013

Positron Fraction Solar Modulation



PAMELA coll. PRL in press

AMS-02



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

Implications

A rising positron fraction requires:

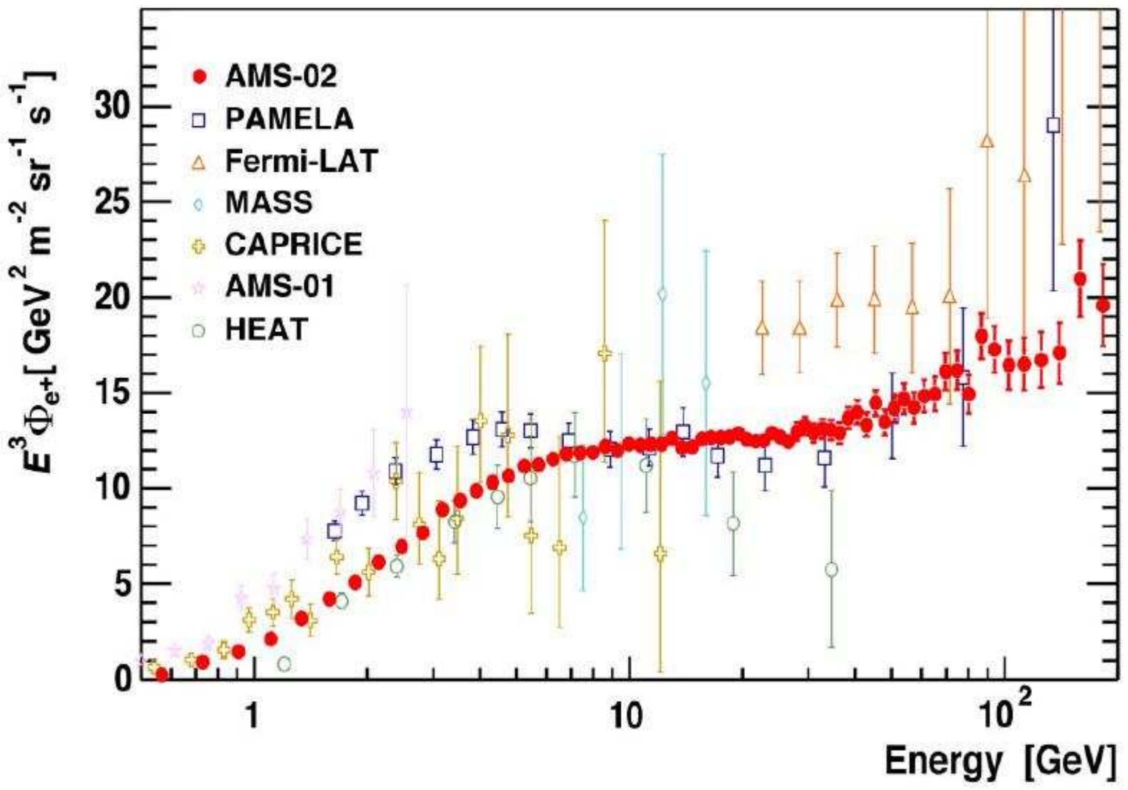
1. **An additional component of positrons with spectrum flatter than CR primary electrons**

2. **A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)**

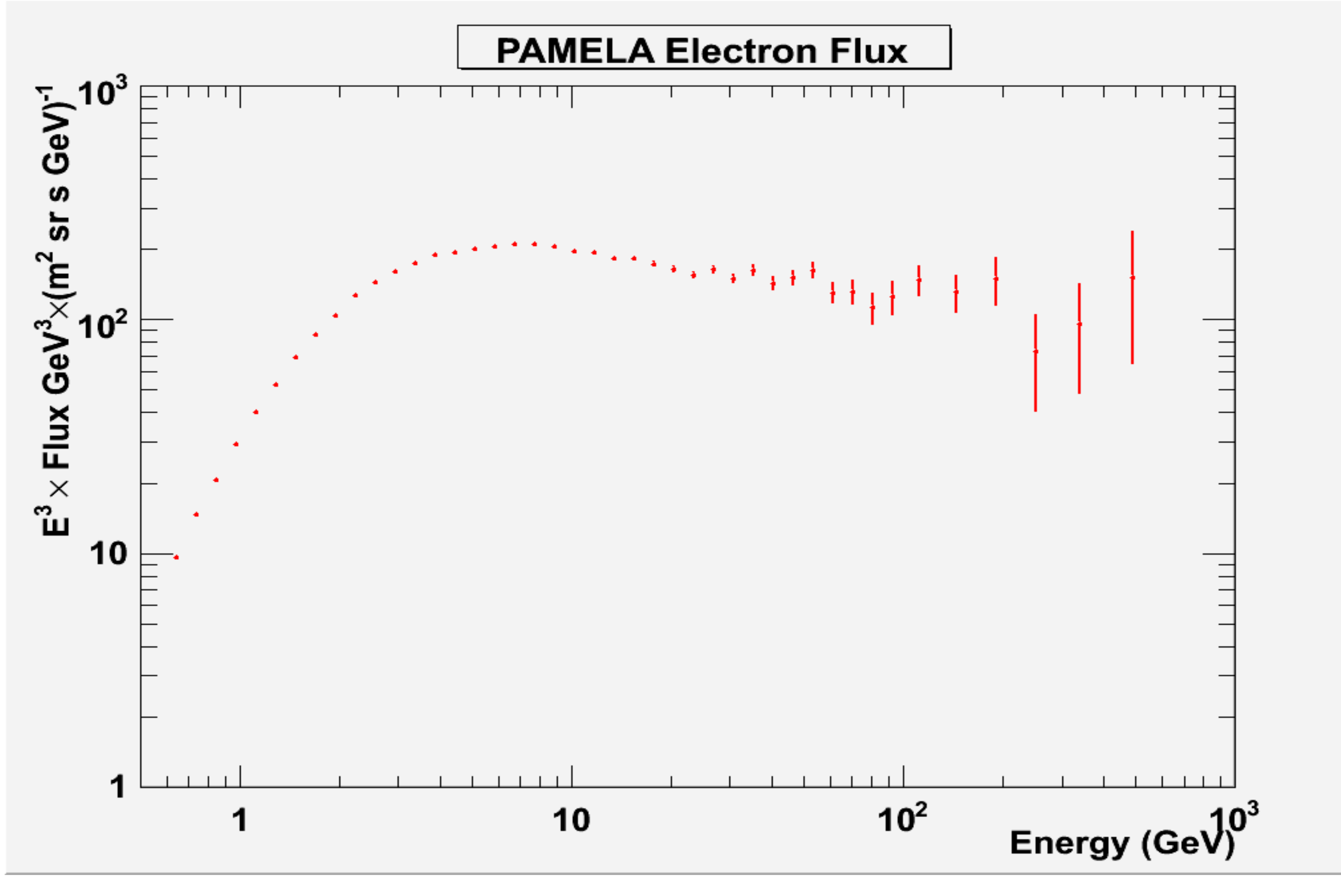
3. **Subtleties of Propagation**

Courtesy by P. Blasi

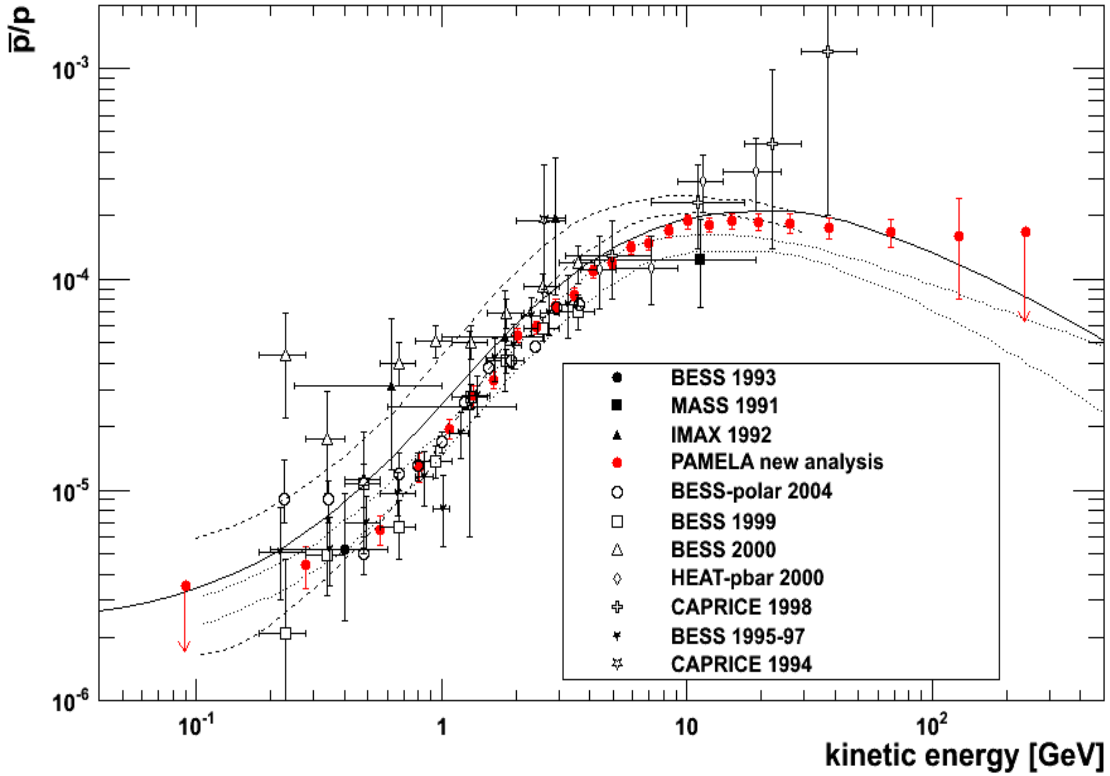
Positron Flux



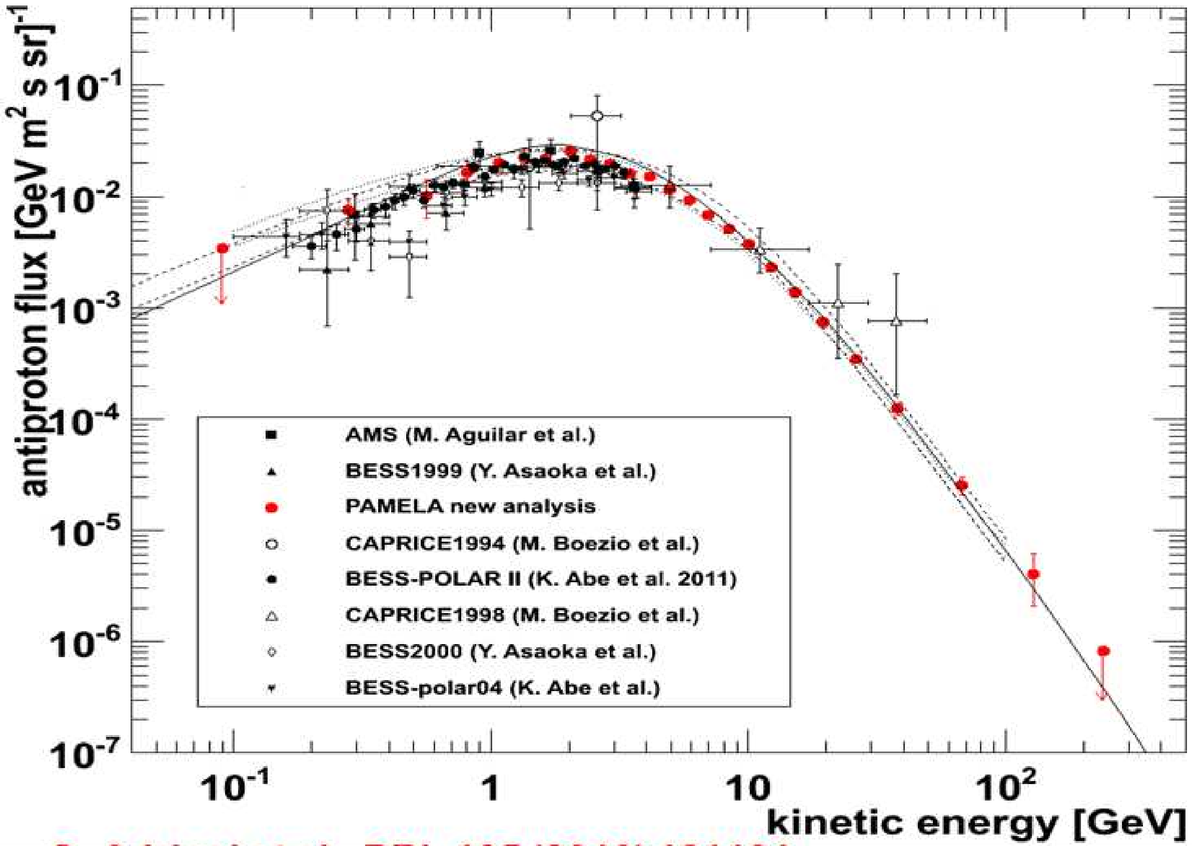
27



PAMELA Antiprotons

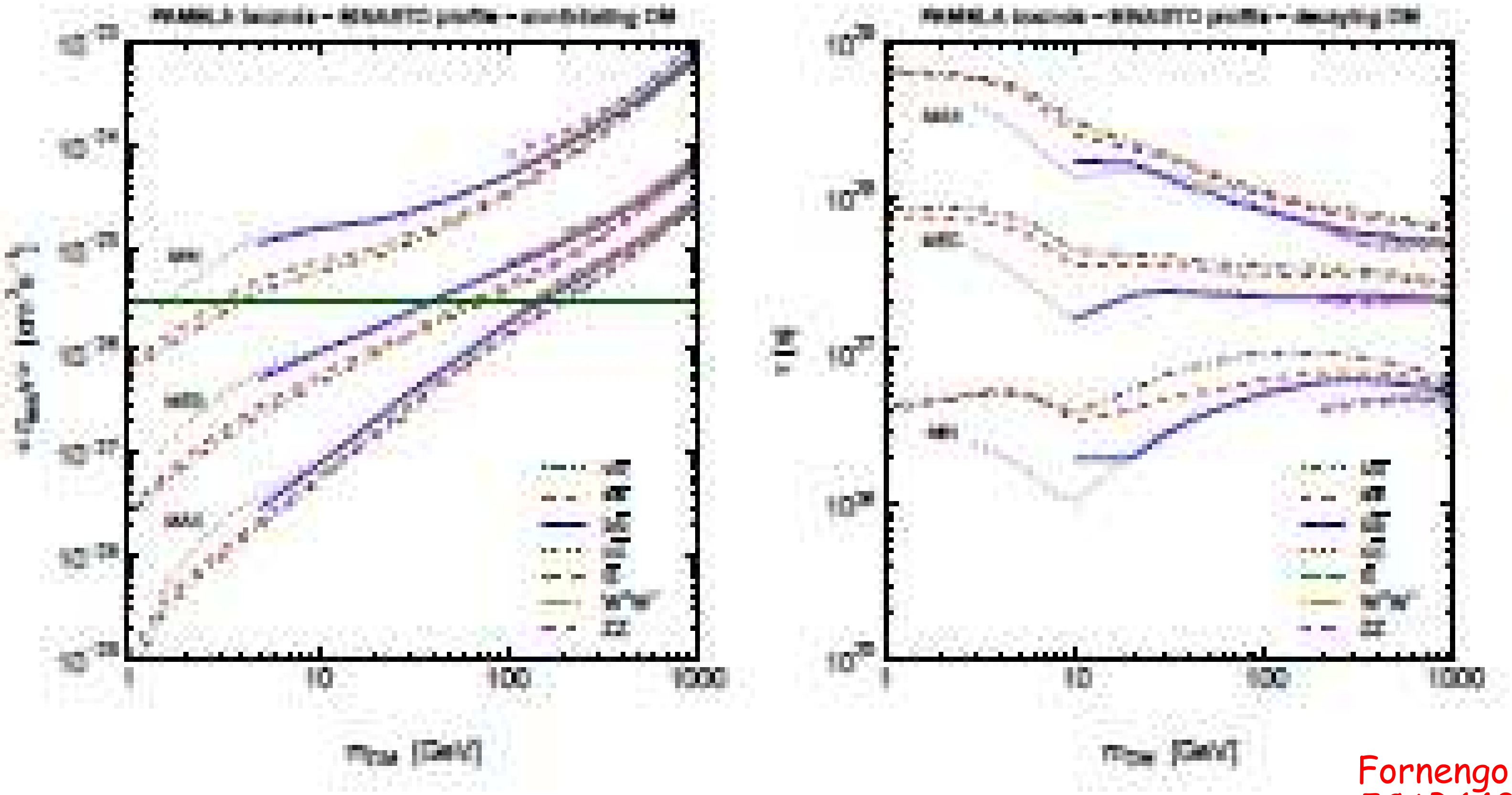


O. Adriani et al.,
PRL 102 (2009) 051101
PRL 105 (2010) 121101



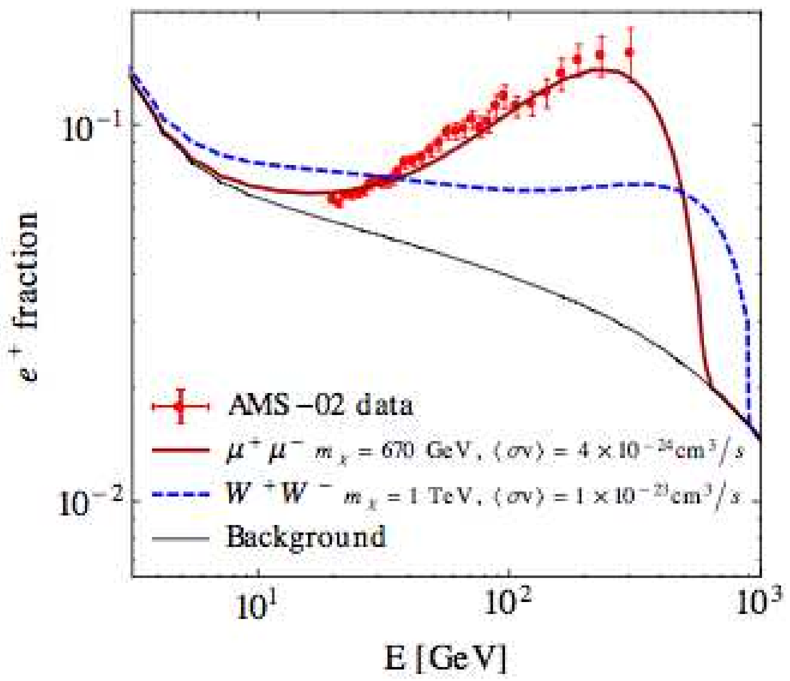
O. Adriani et al., PRL 105 (2010) 121101
O. Adriani et al.,Phys. Rep. (2014)

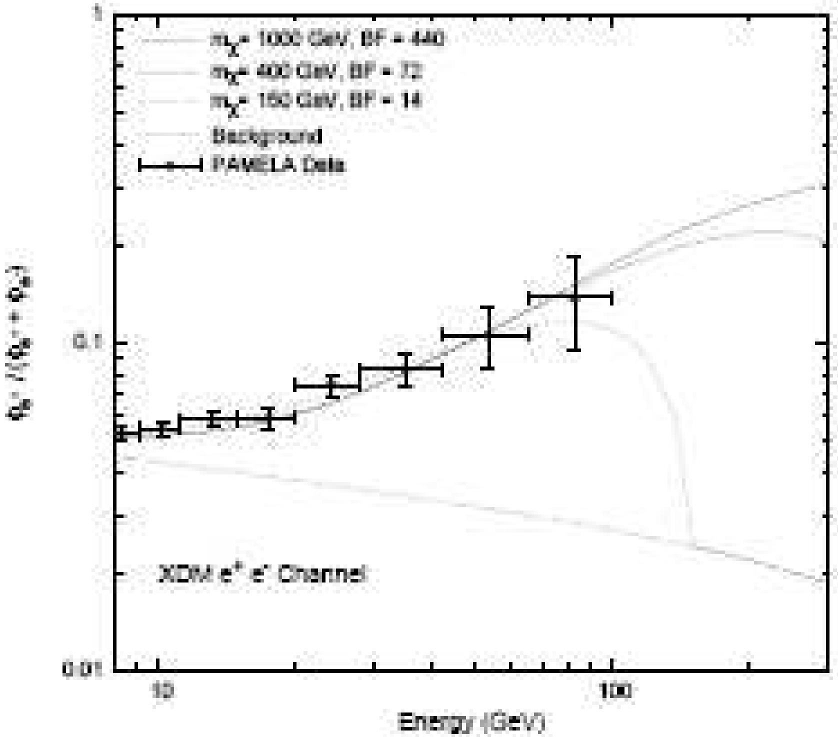
Bounds from PAMELA Antiproton Spectrum



Fornengo, Maccione, Vittino,
JCAP 1404 (2014) 04, 003

Dark Matter Explanation

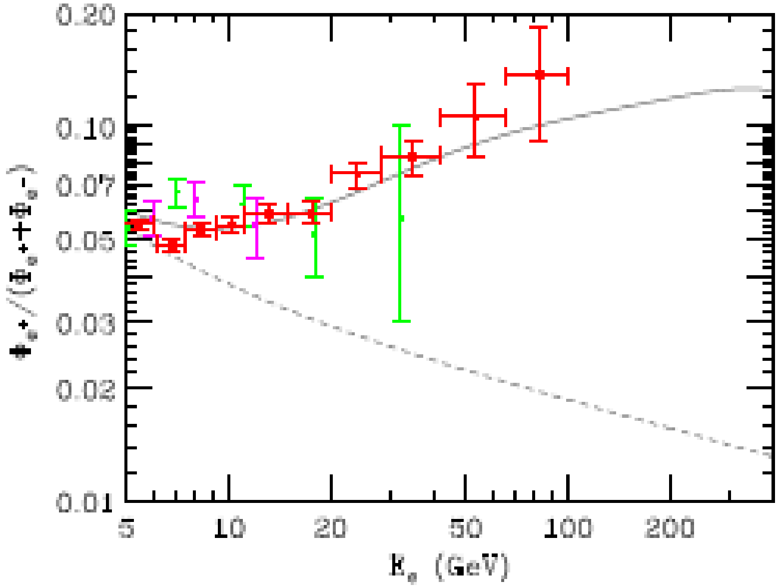




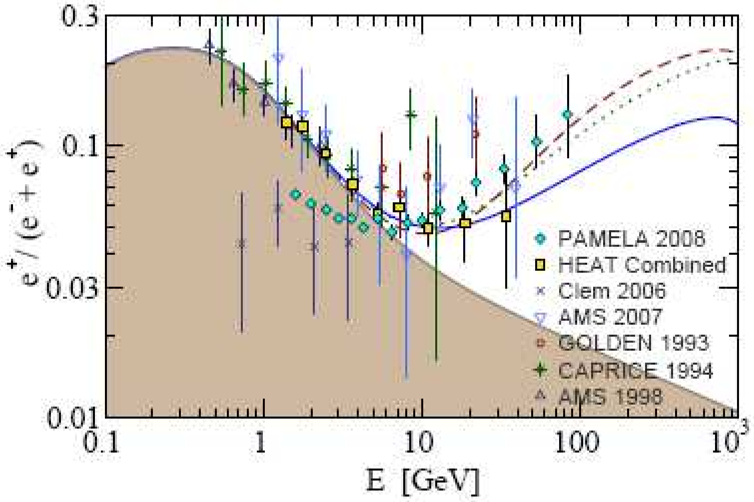
J. Kopp, Phys. Rev. D 88 (2013) 076013; arXiv:1304.1184

I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1

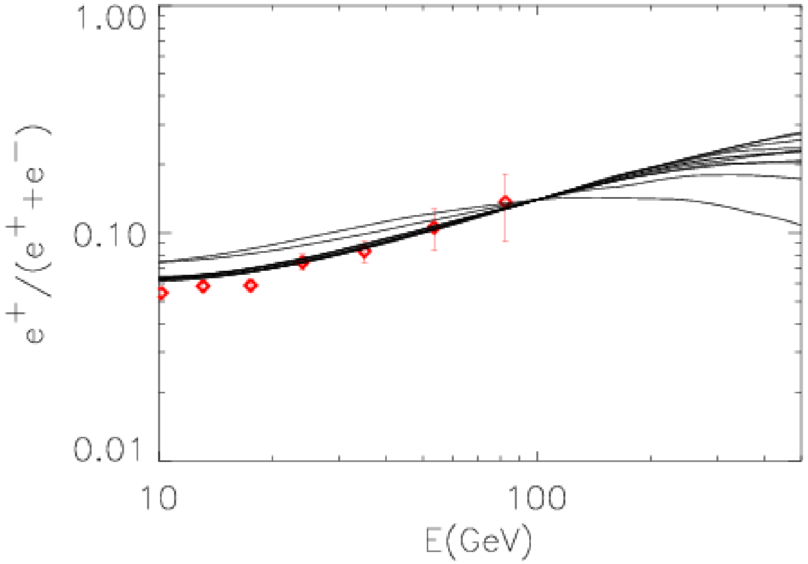
Pulsar Explanation



D. Hooper, P. Blasi, and P. Serpico, JCAP 0901:025,2009; arXiv:0810.1527
Contribution from diffuse mature &nearby young pulsars.

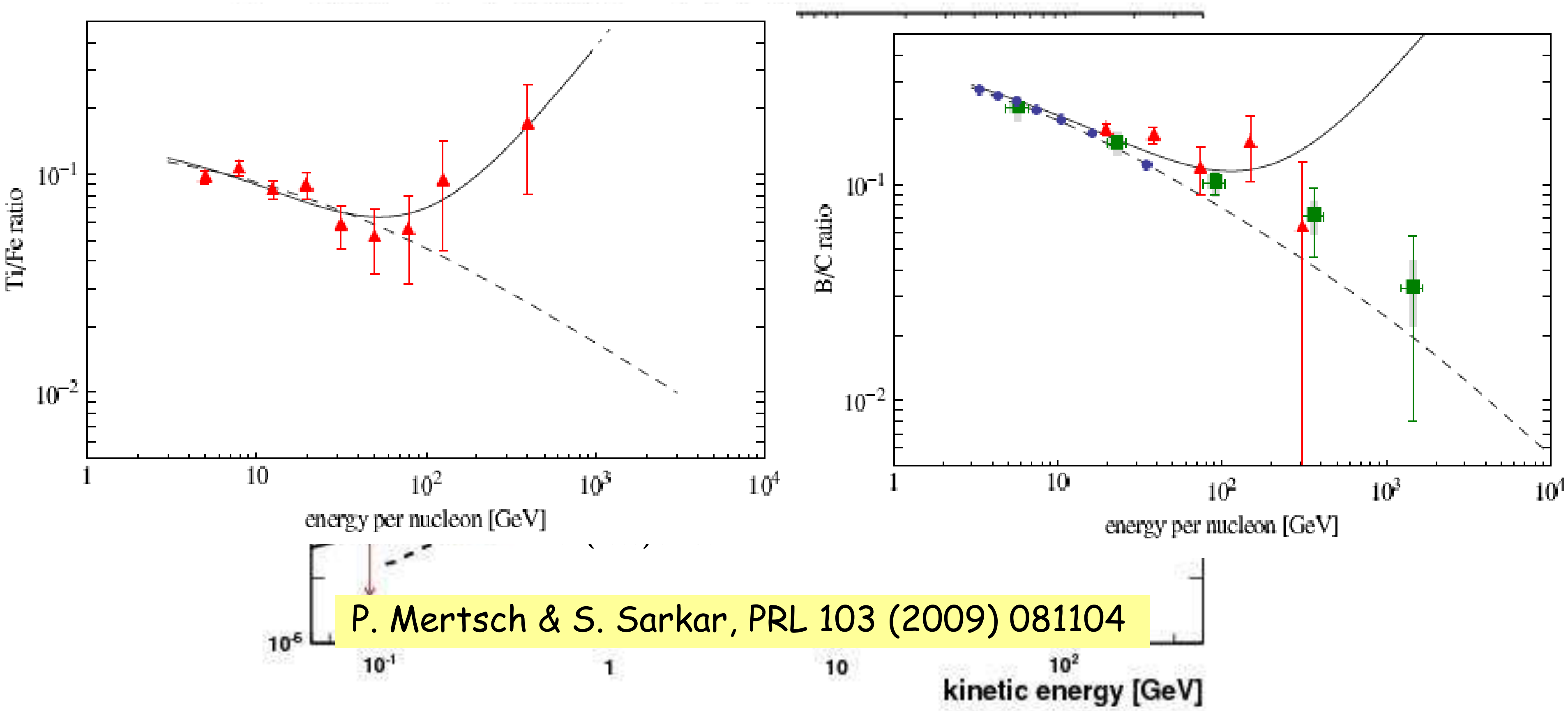


H. Yuksel et al., PRL 103 (2009) 051101; arXiv:0810.2784v2
Contributions of e^- & e^+ from Geminga assuming different distance, age and energetic of the pulsar



P. Blasi & E. Amato, arXiv:1007.4745
Contribution from pulsars varying the injection index and location of the sources.

SNR Explanation

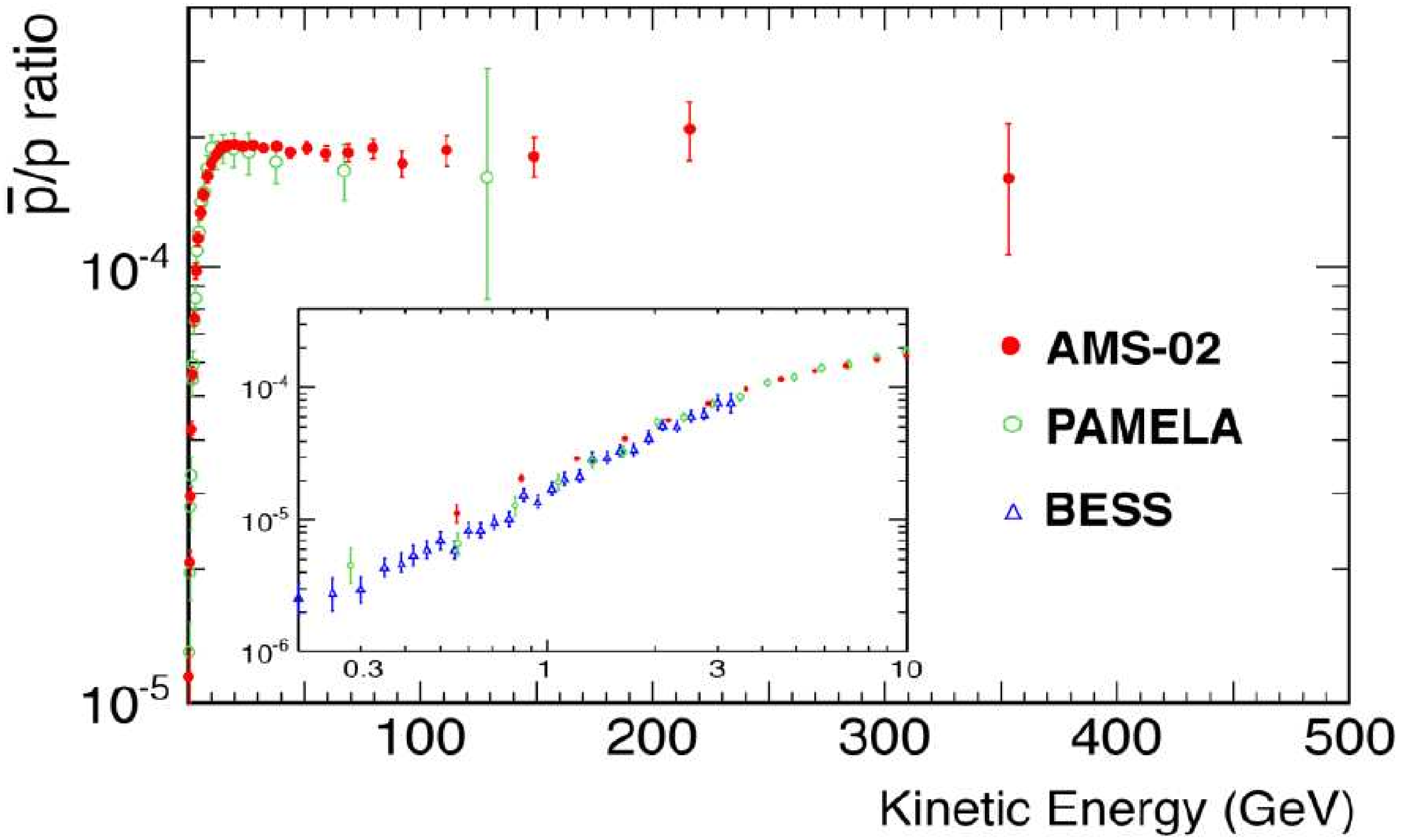


P. Mertsch & S. Sarkar, PRL 103 (2009) 081104

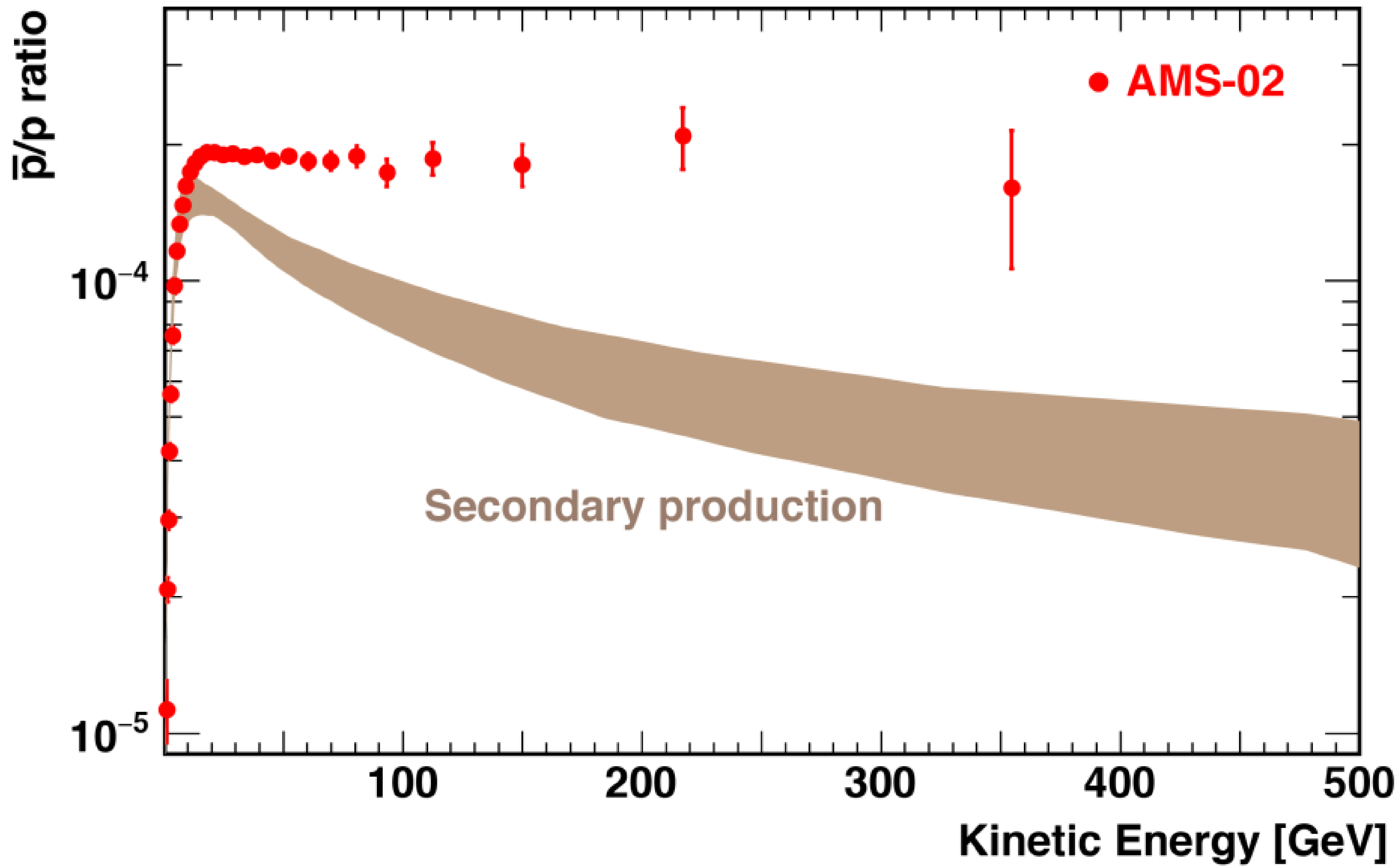
P.Blasi, PRL 103 (2009) 051104 (see also Y. Fujita et al., PRD 80 (2009) 063003, M. Ahlers et al. PRD 80 (2009) 123017) Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

But also other secondaries are produced: significant increase expected in the p/p and secondary nuclei ratios.

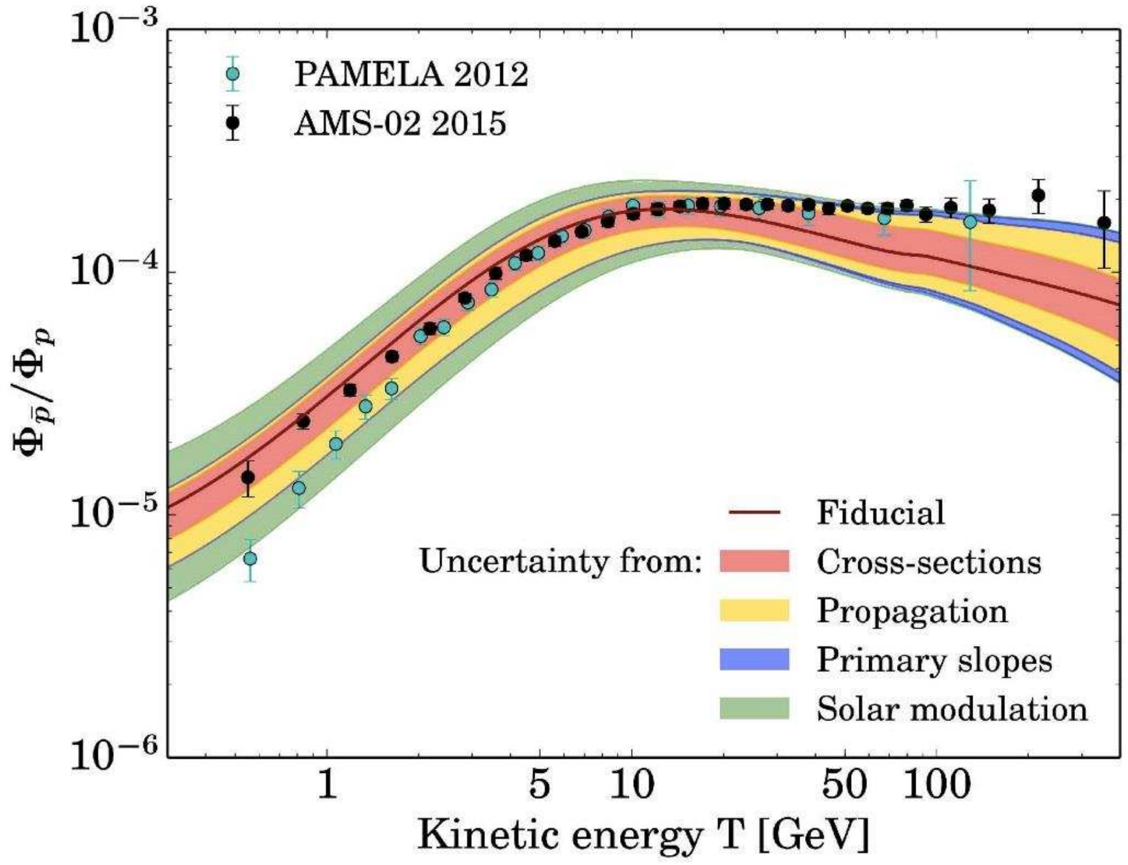
AMS $\bar{p}/p$ results



Antiproton to proton fraction

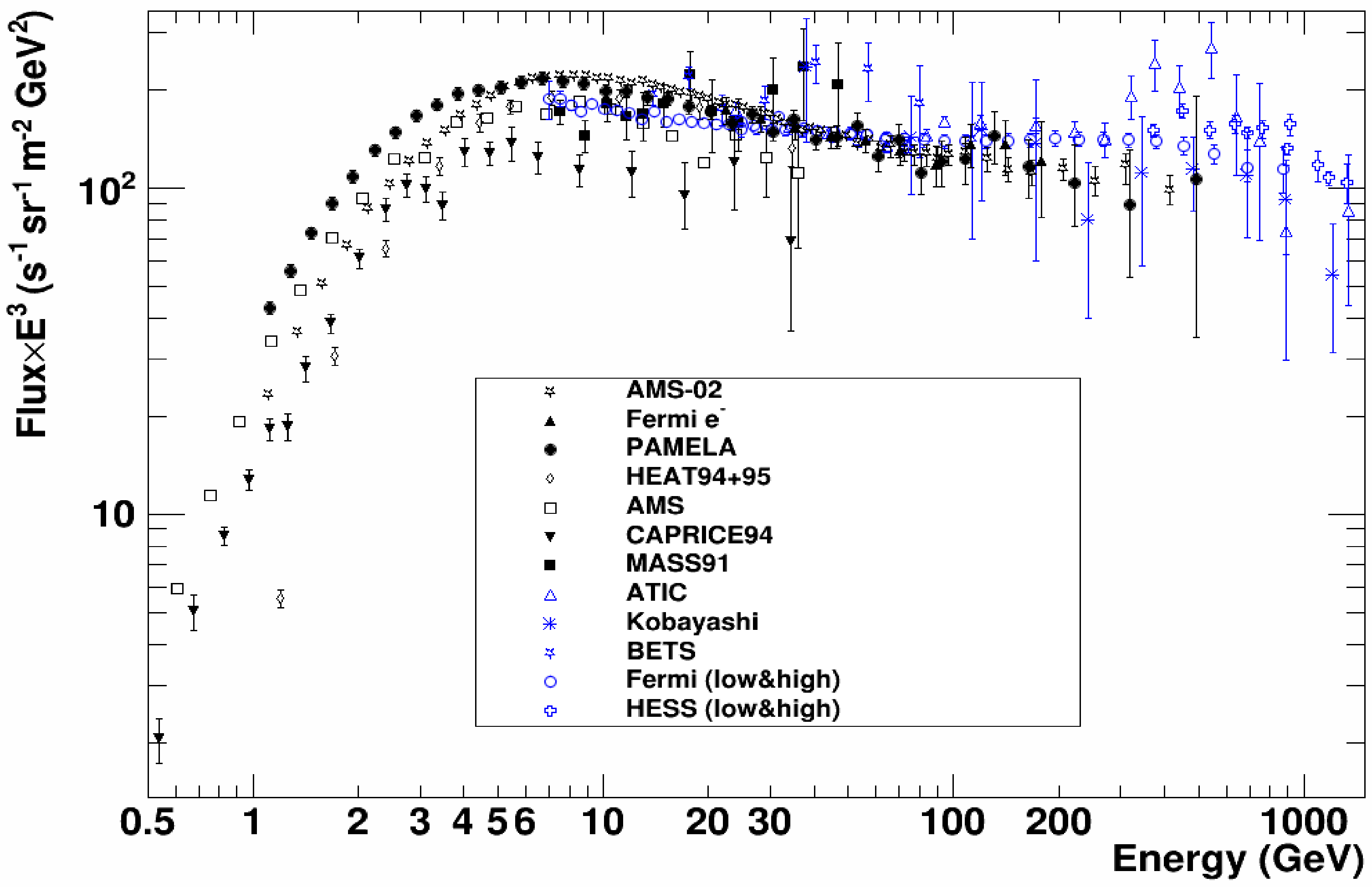


Cosmic-Ray Antiprotons and DM limits

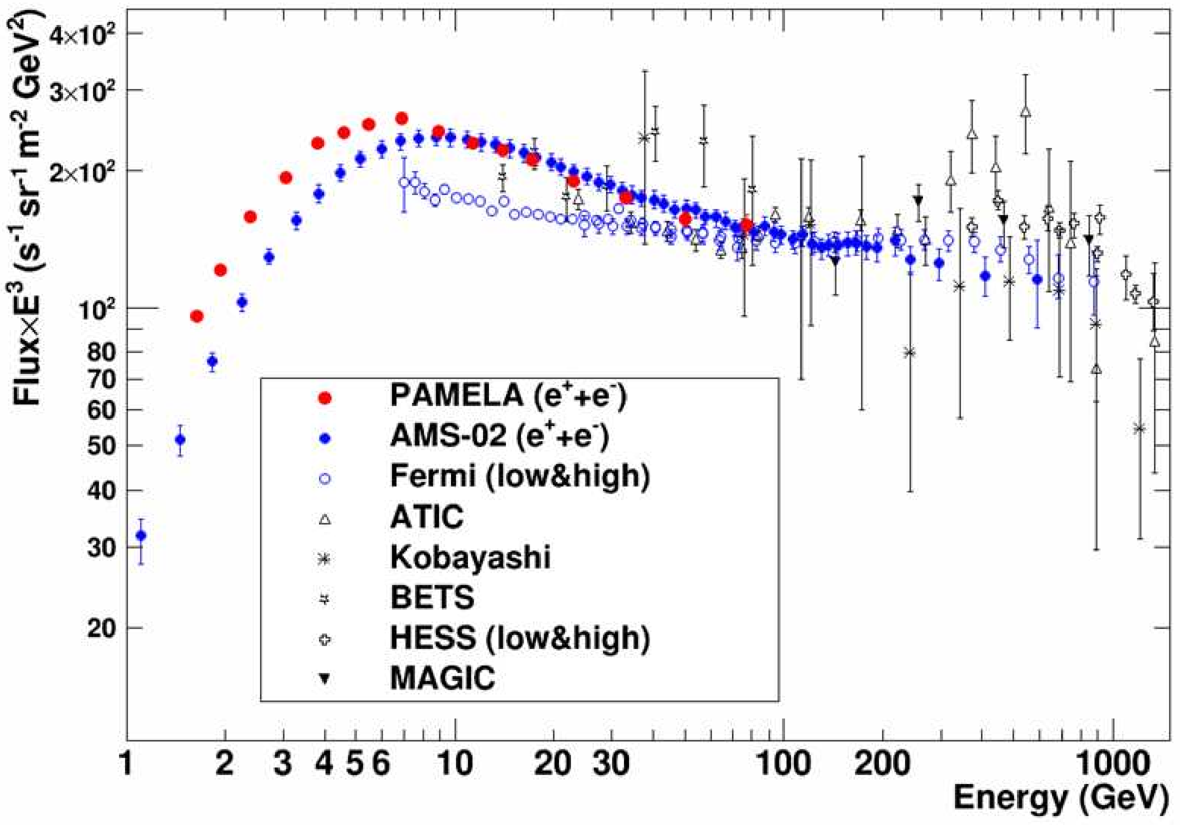


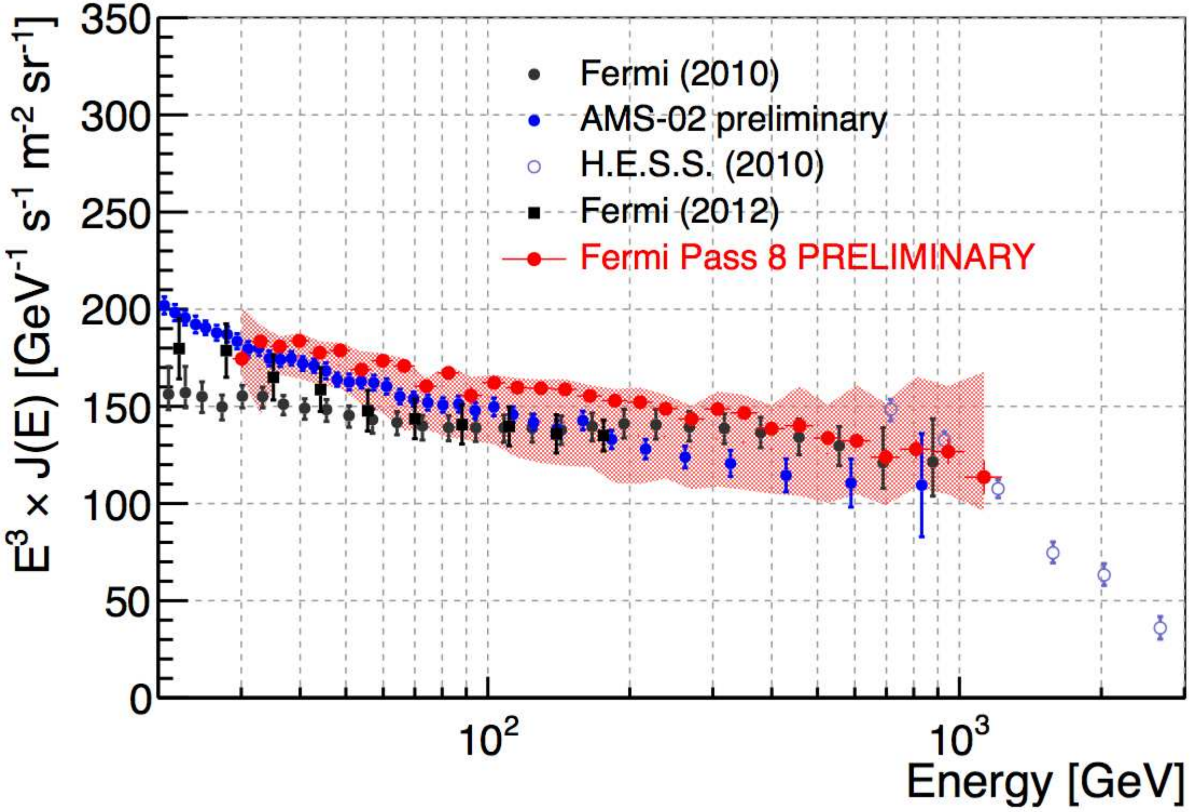
G. Giesen et al., JCAP 1509 (2015) 023,
arXiv: 1504:04276

Electron Spectrum



Electron (e^-+e^+) Spectrum



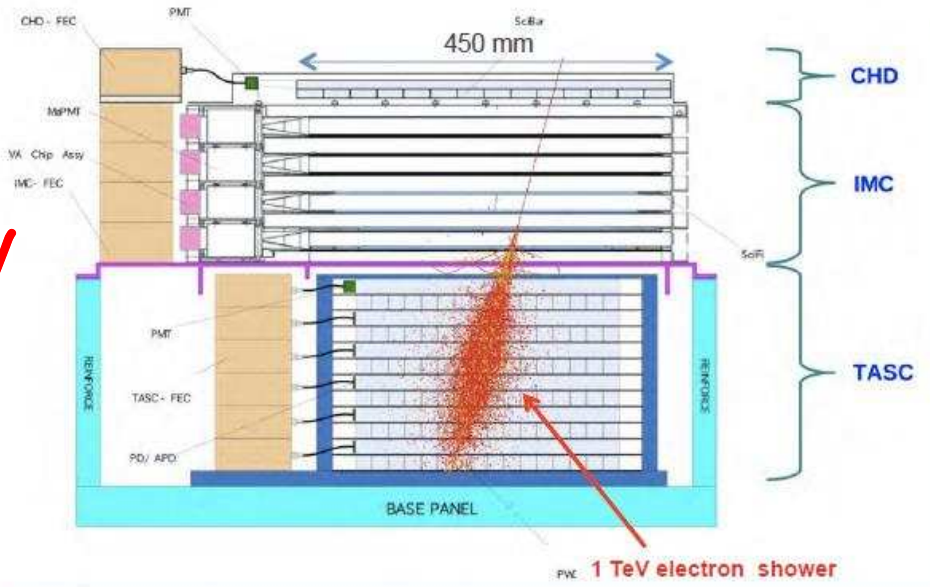


CALET

CALorimetric Electron Telescope

Main Telescope: CAL (Calorimeter)

1GeV – 10TeV

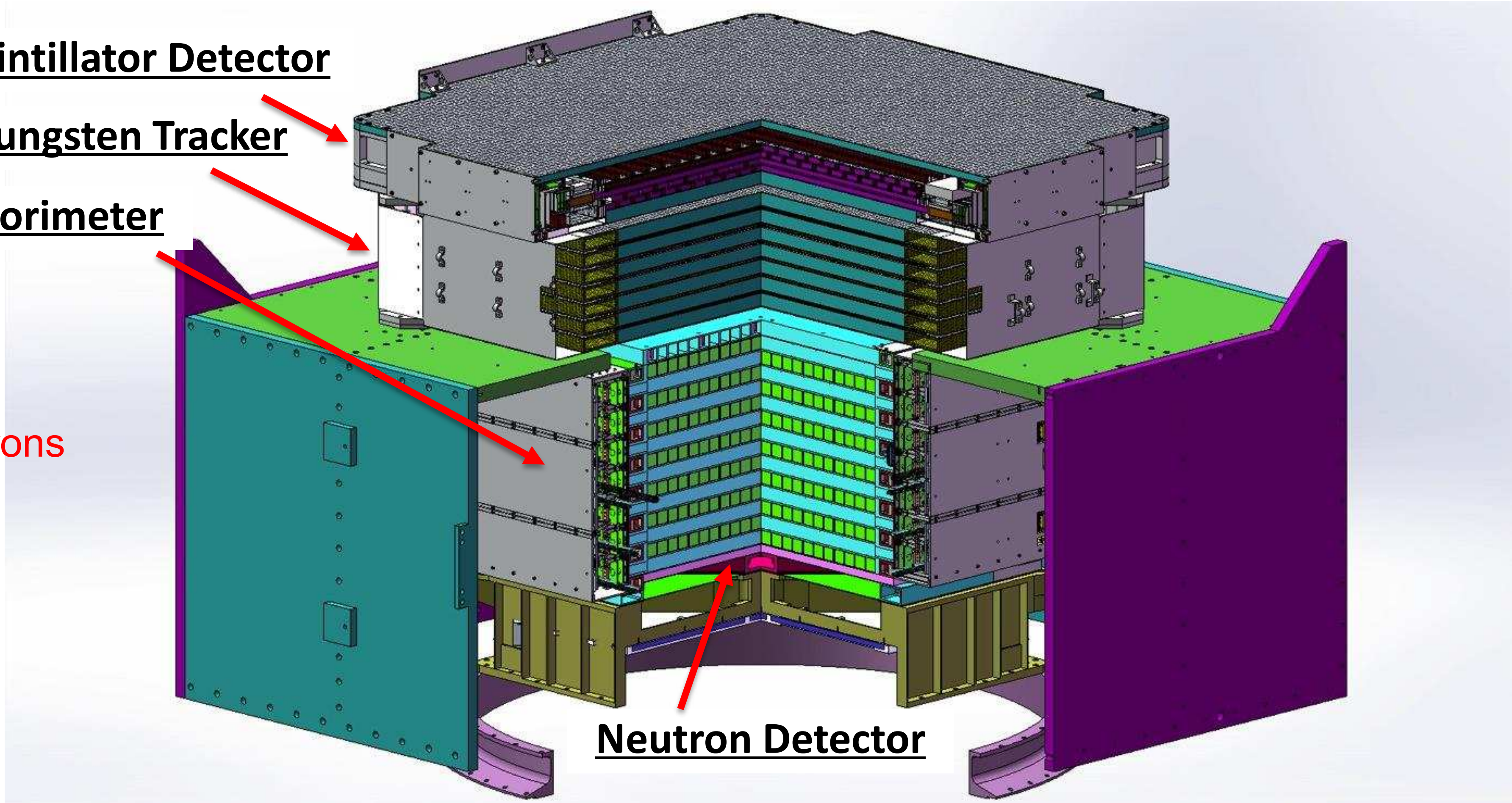


Expected Performance
(from Simulations and/or Beam Tests)

- SΩ :
  1200 cm²sr for electrons, light nuclei
  1000 cm²sr for gamma-rays
  4000 cm²sr for ultra-heavy nuclei*
  * for E > 600 MeV/nucleon
- ΔE/E :
  ~2% (>10 GeV) for e's, γ's
  ~30 % for protons
- e/p separation: 10^{5}
- Charge resolution: 0.15-0.3 e
- Angular resolution: ~0.1° e's, γ's

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z=1-46)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	Plastic Scintillator : 14 × 1 layer (x,y) Unit Size: 32mm x 10mm x 450mm	SciFi : 448 x 8 layers (x,y) = 7168 Unit size: 1mm² x 448 mm Total thickness of Tungsten: 3 X_0	PWO log: 16 x 6 layers (x,y)= 192 Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 X_0
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

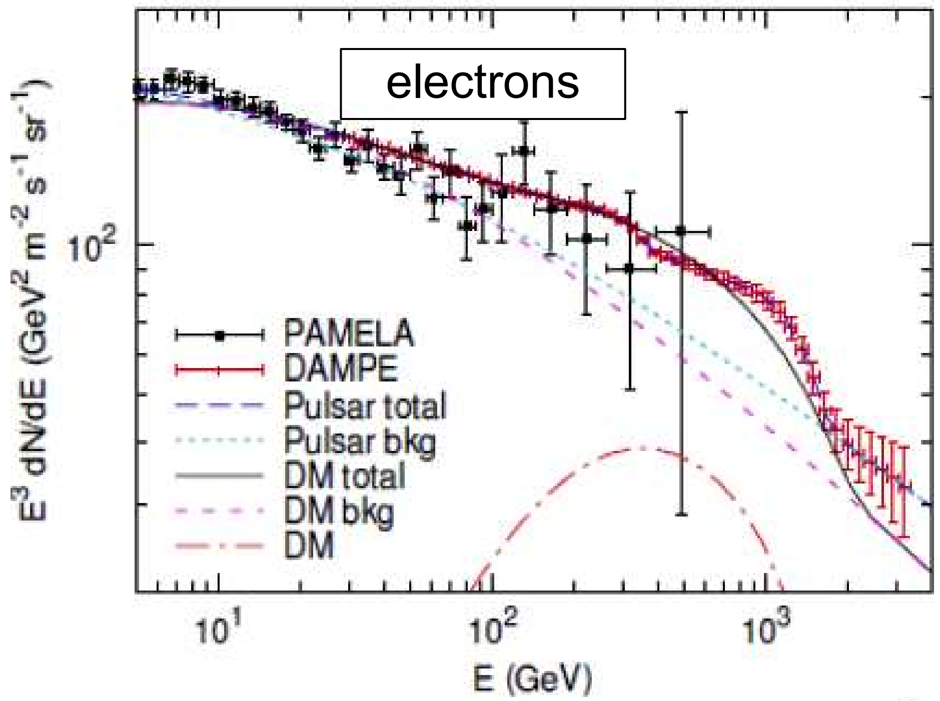
DAMPE -Dark Matter Particle Explorer

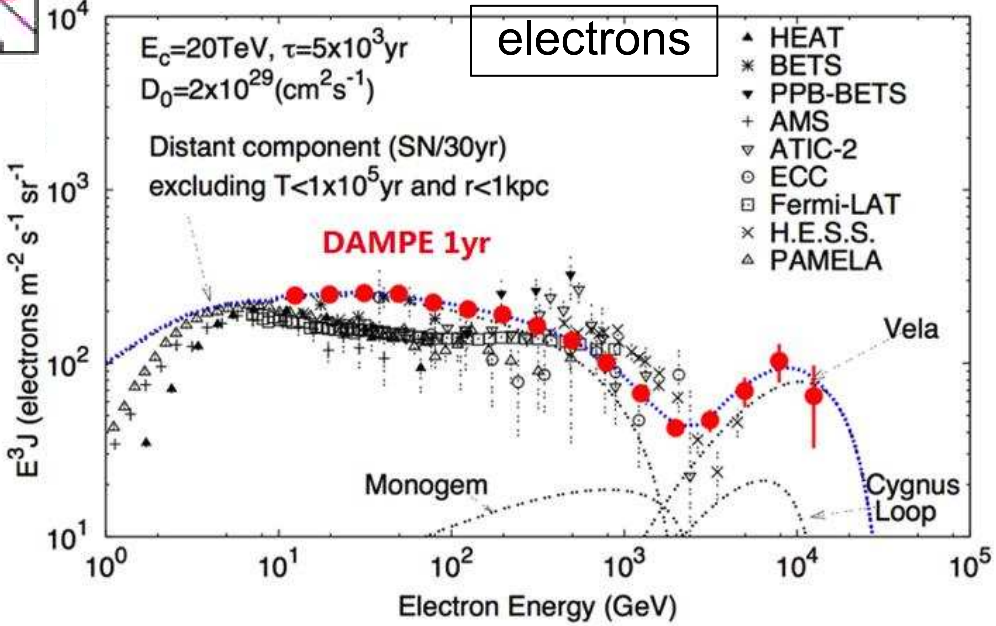


5 GeV – 10 TeV for electrons
100 Gev - !00TeV CR

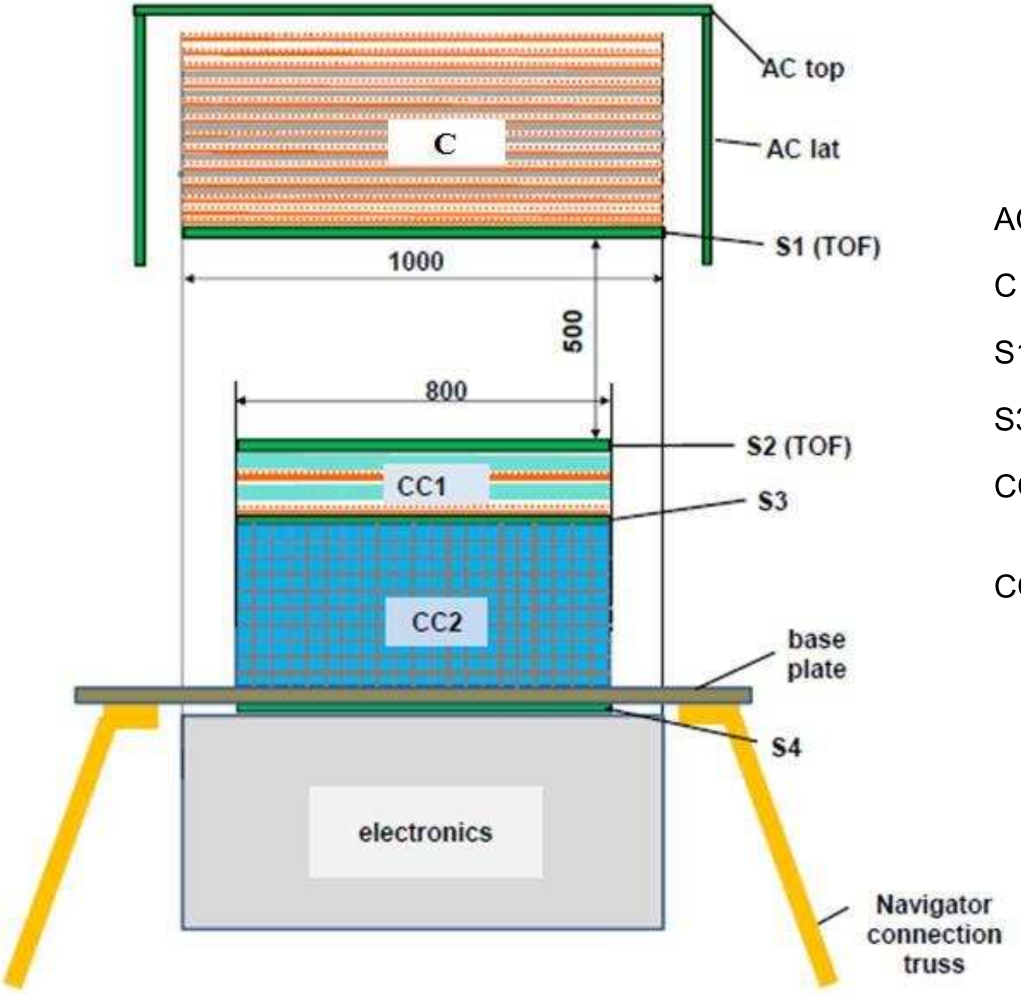
W converter + thick calorimeter (total 33 X_0)
+ precise tracking + charge measurement ➡
high energy γ-ray, electron and CR telescope

Electrons: Dark Matter vs Nearby Sources





GAMMA-400



AC – anticoincidence detectors

C – Conveter-Tracker

S1, S2 – ToF detectors

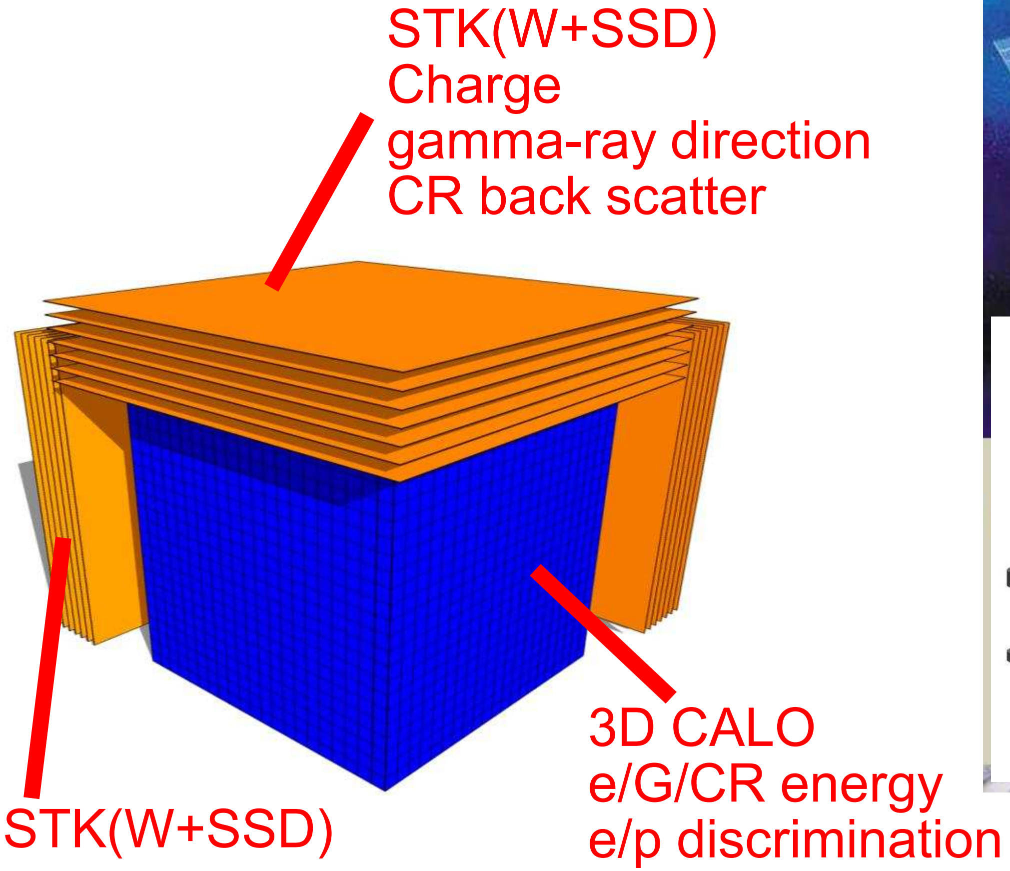
S3, S4 calorimeter scintillator detectors

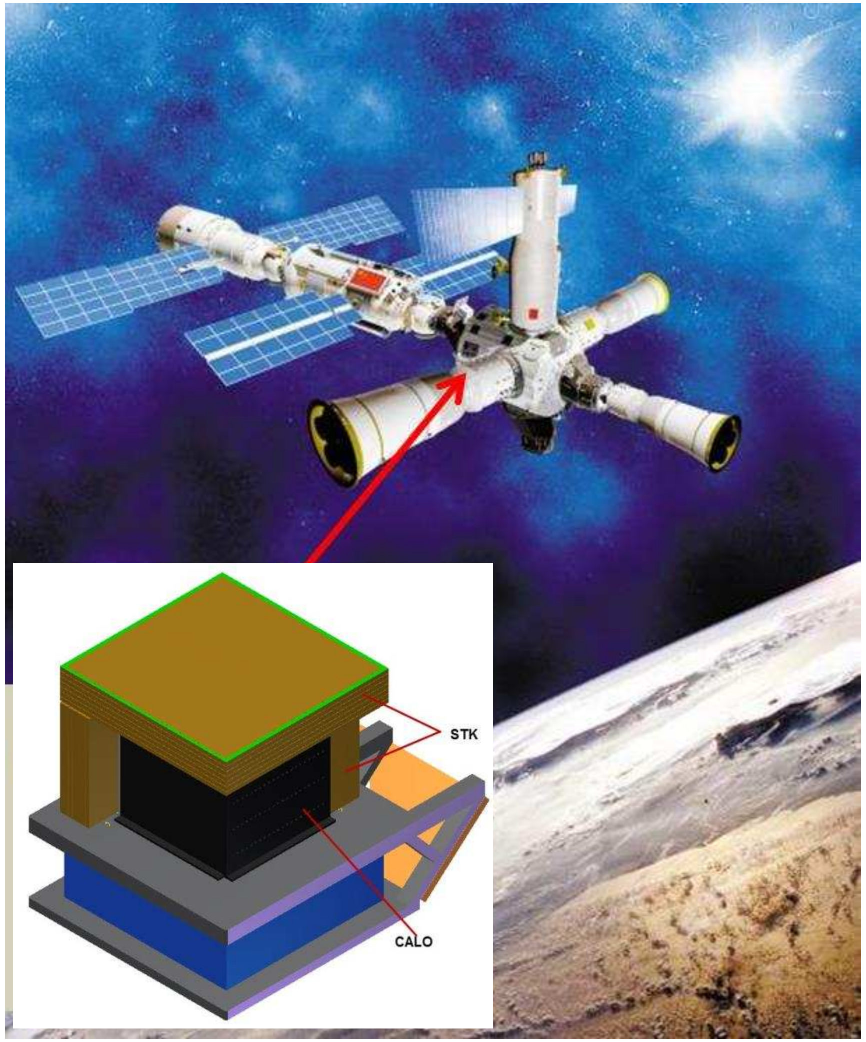
CC1 – imaging calorimeter (2 X_0)
2 layers: CsI(Ti) 1 X_0 + Si(x,y) (pitch 0.1 mm)

CC2 - electromagnetic calorimeter
CsI(TI) 20 X_0 3.6x3.6x3.6 cm^3 – 22x22x10 = 4840

HERD Design：3D Calo & 5-Side Sensitive

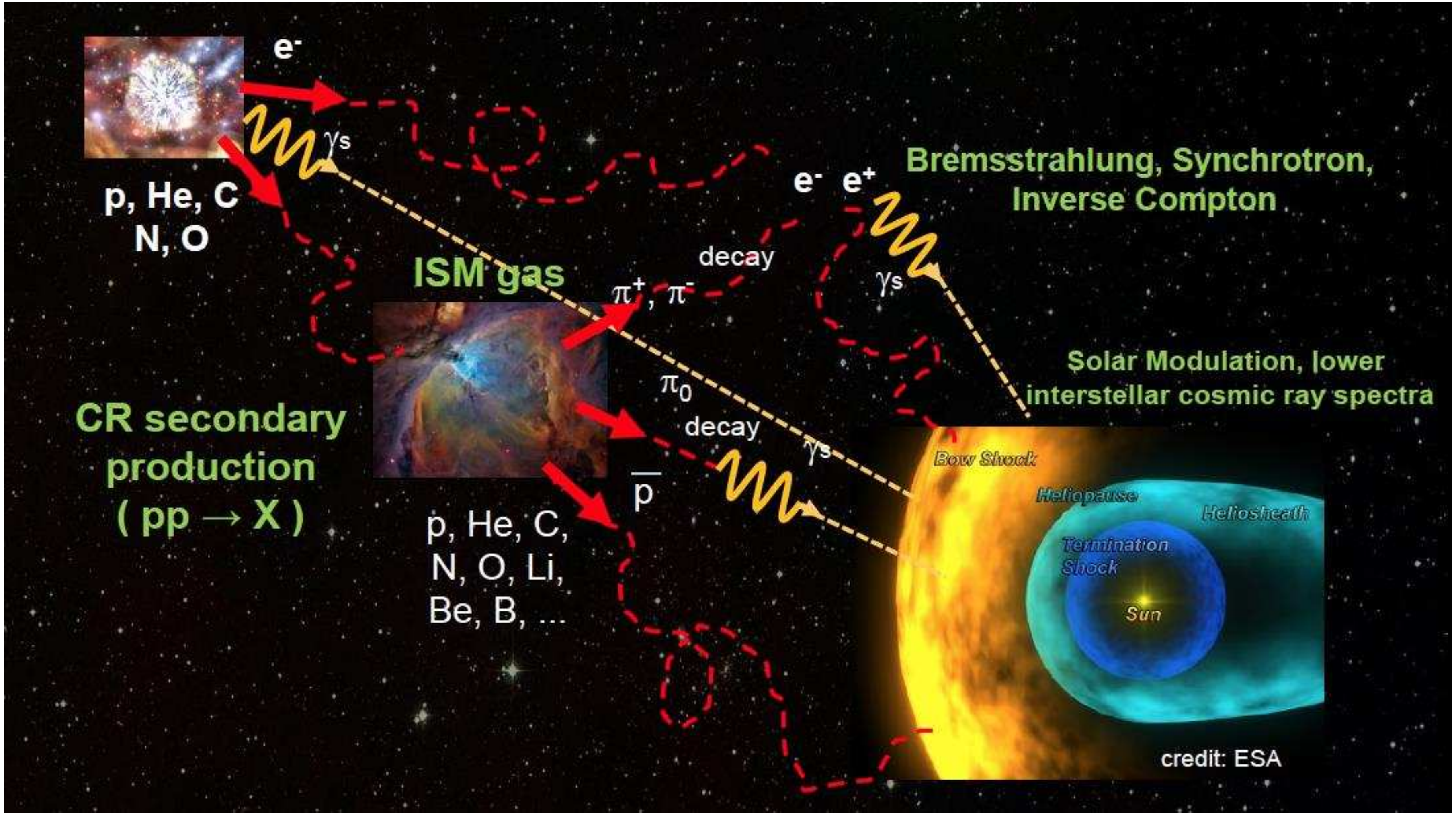
About a factor 10 increase in statistics respect to existing experiments with a weight 2.3 T ~1/3 AMS





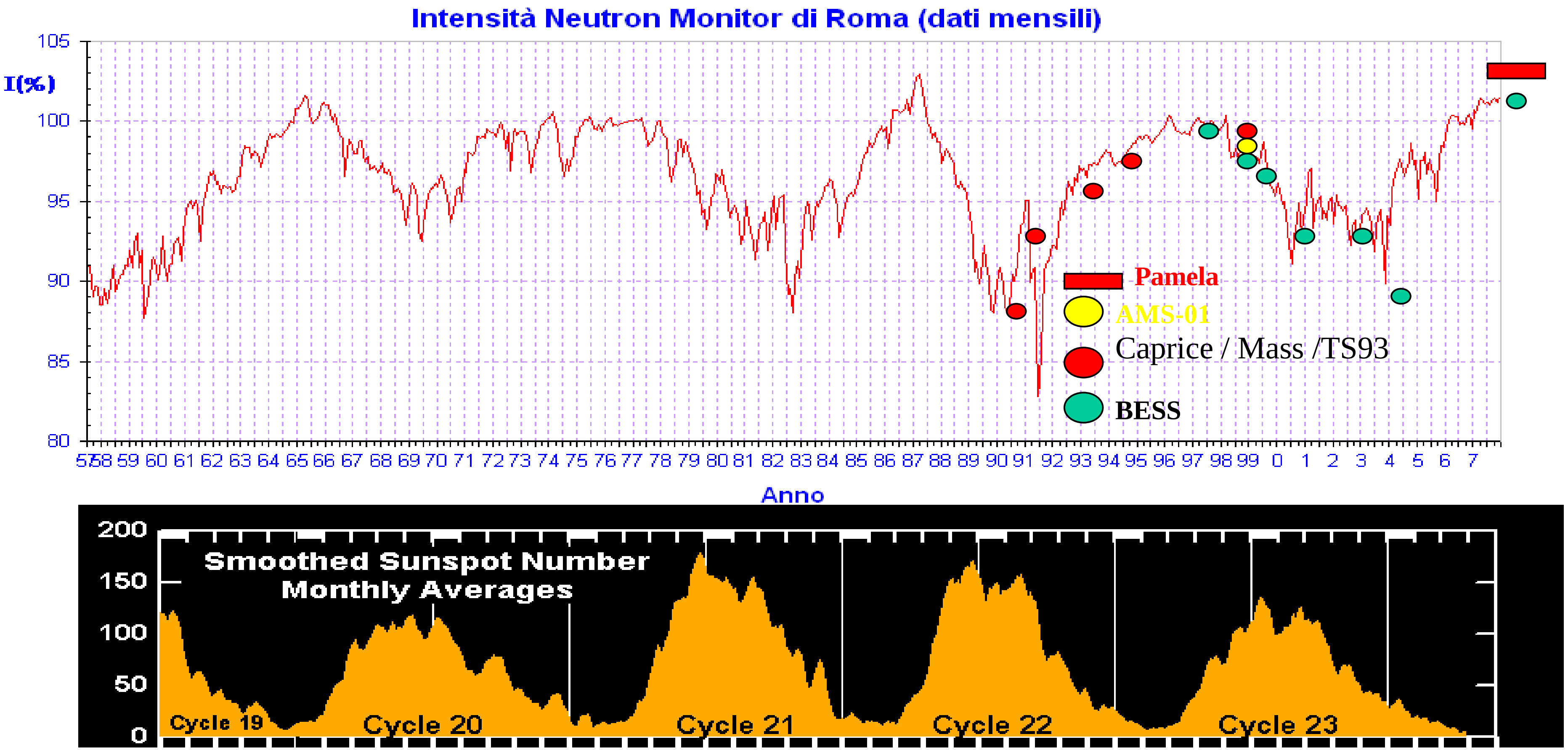
Thanks!

http:// pamela.roma2.infn.it

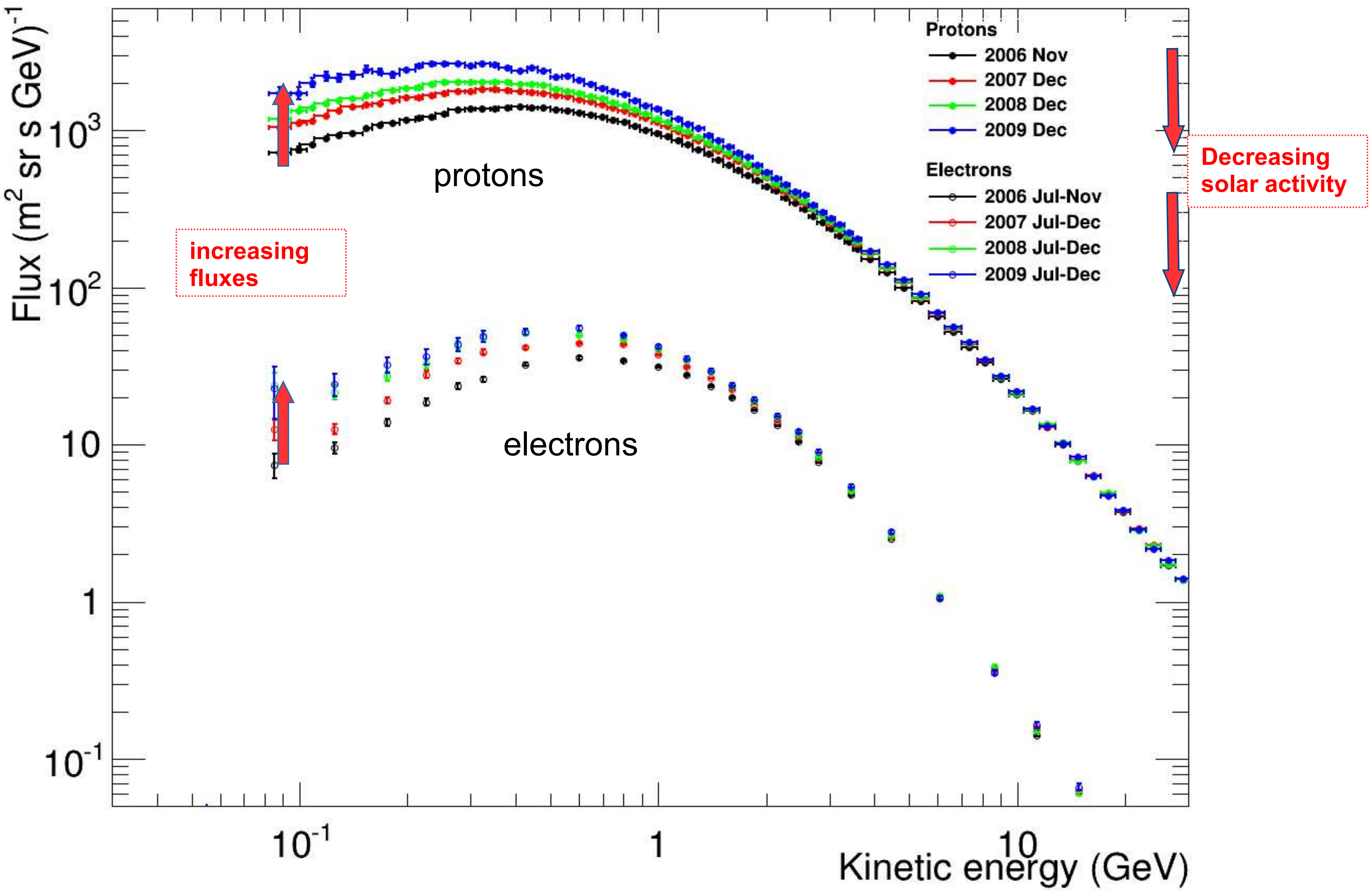


Cosmic rays in the heliosphere

Solar Modulation of Galactic Cosmic Rays

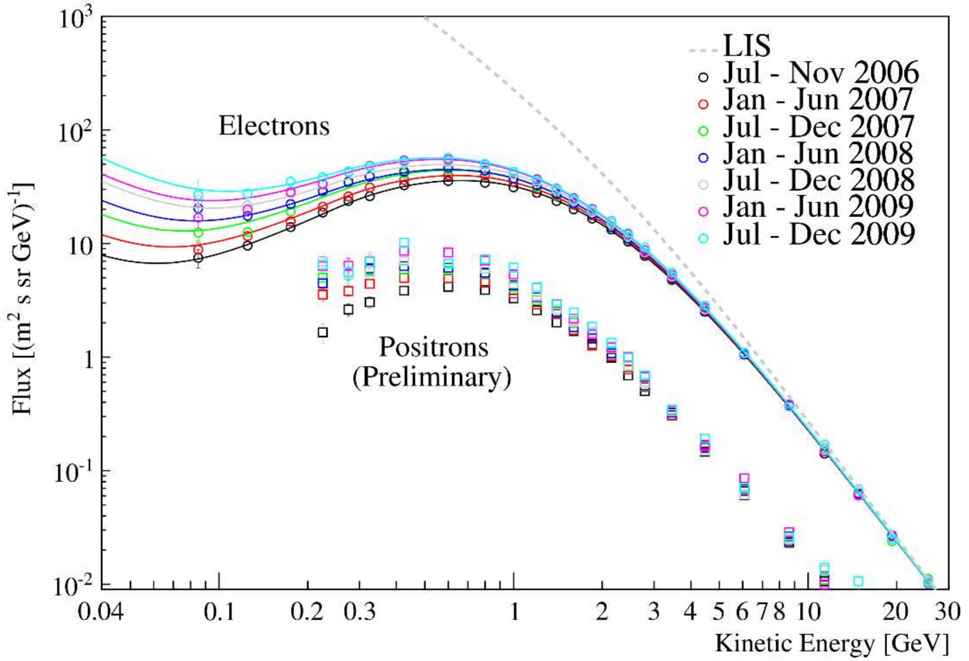


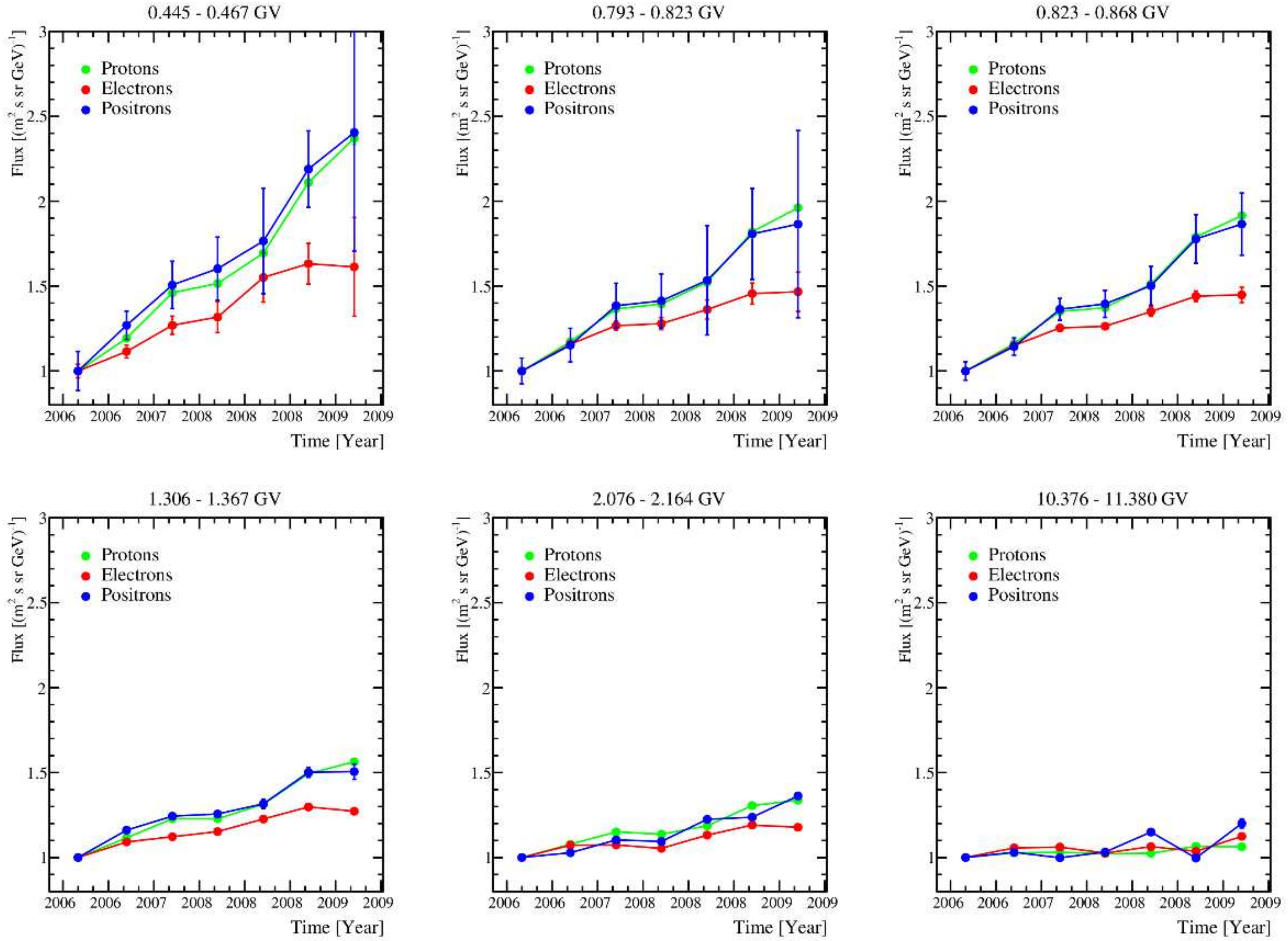
Solar modulation in the heliosphere



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

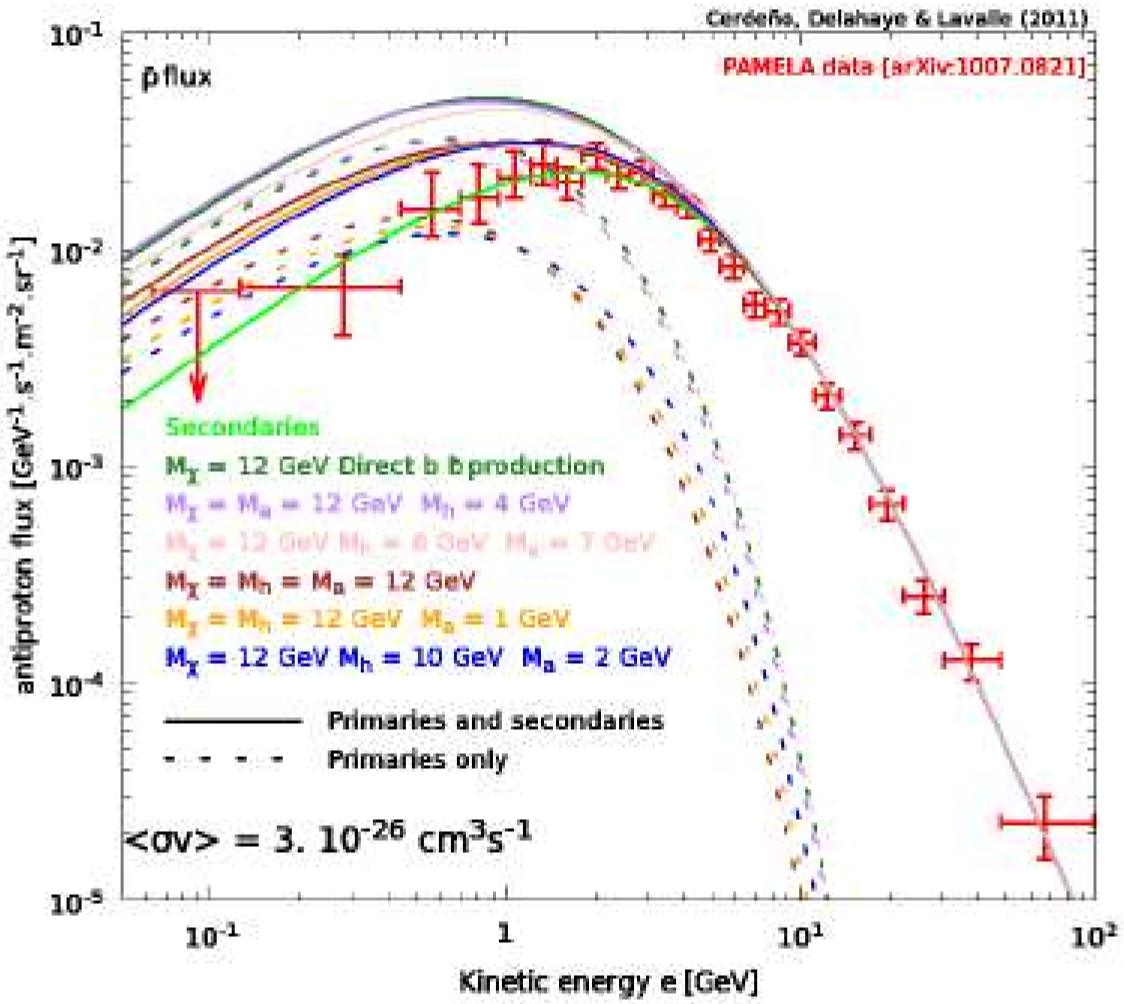
The PAMELA electron and positron spectra over the last solar minimum





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

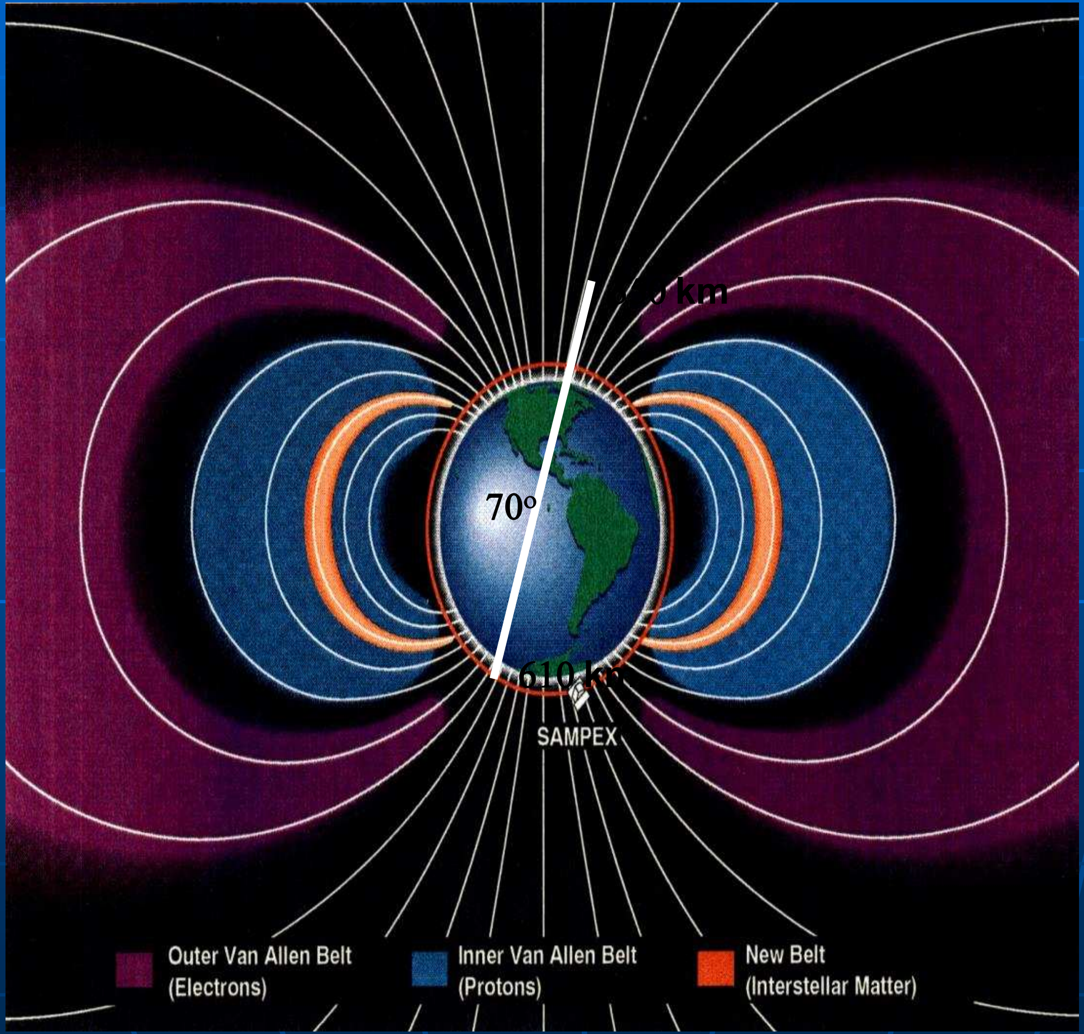
Cosmic-Ray Antiprotons and DM limits



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



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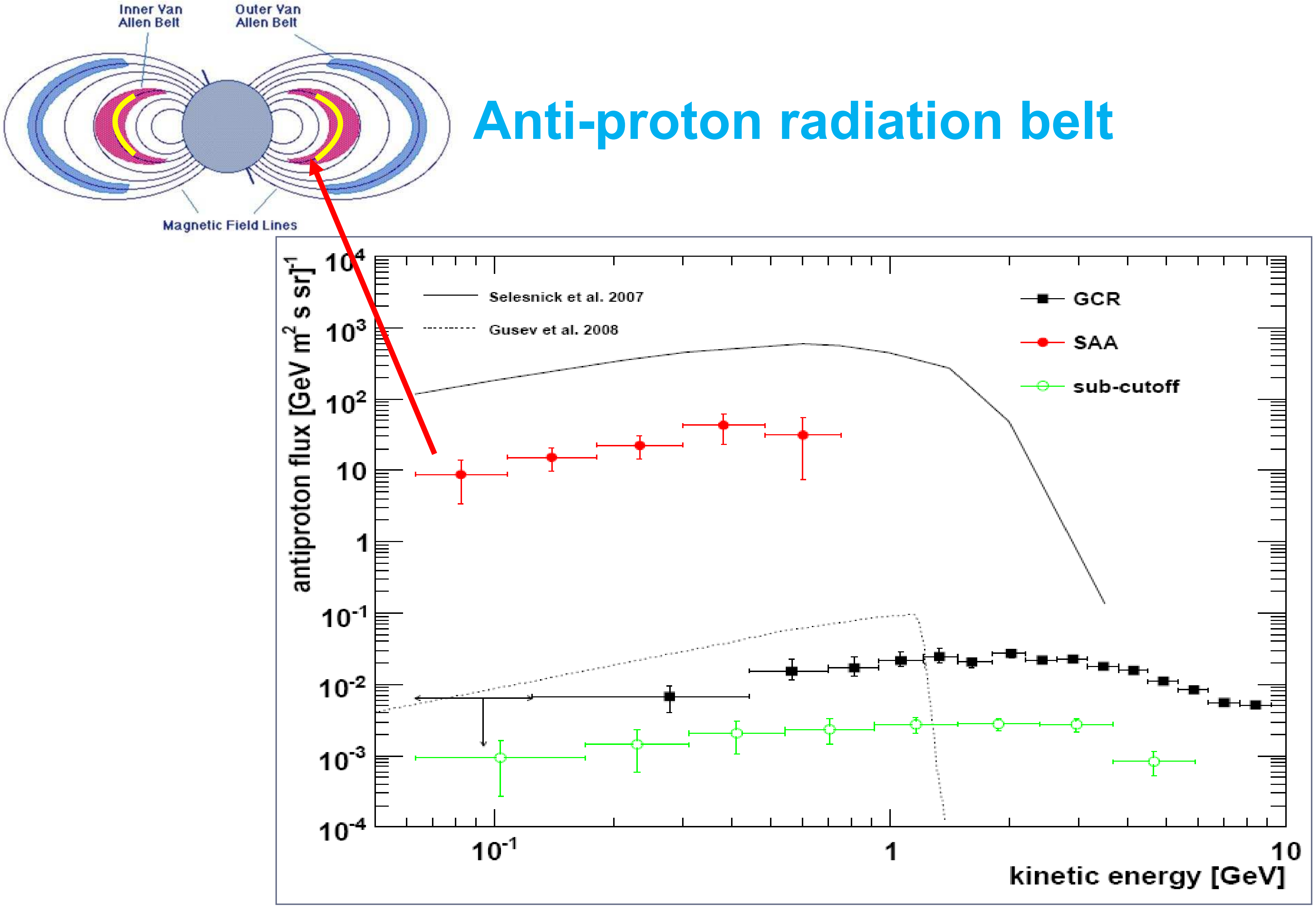
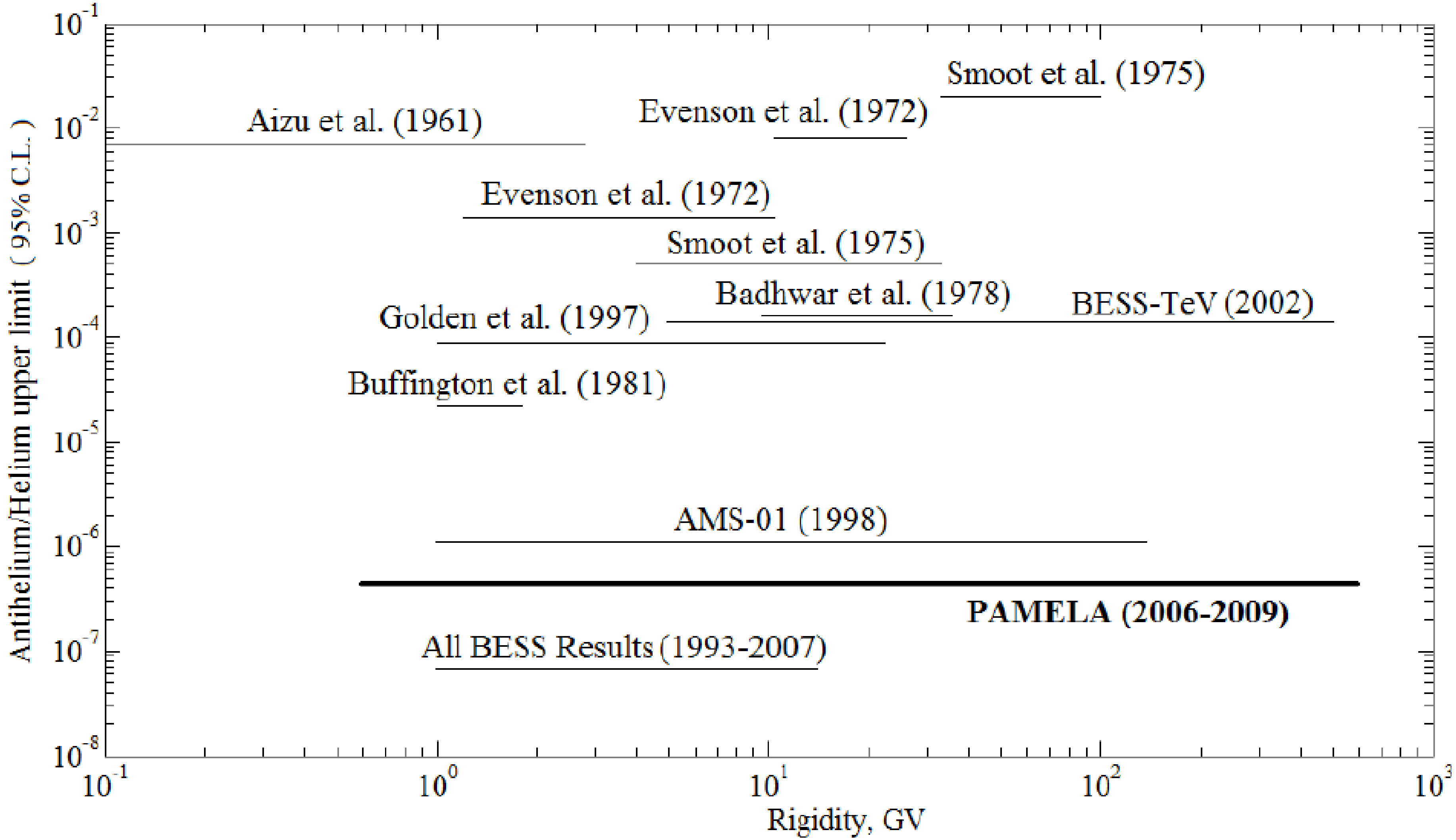
Anti-proton radiation belt



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

Antimatter limits

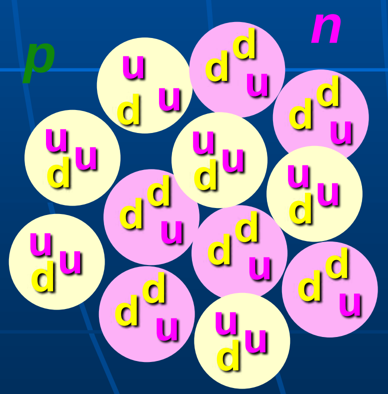


Search for New Matter in the Universe:

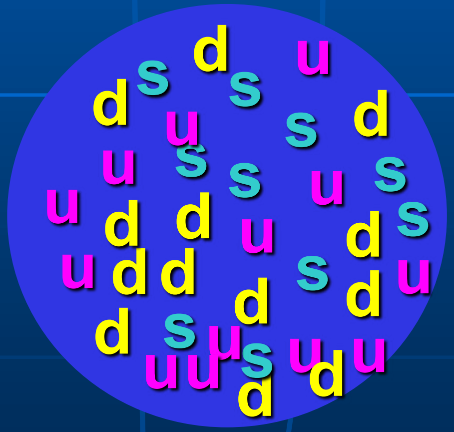
An example is the search for "strangelets".

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

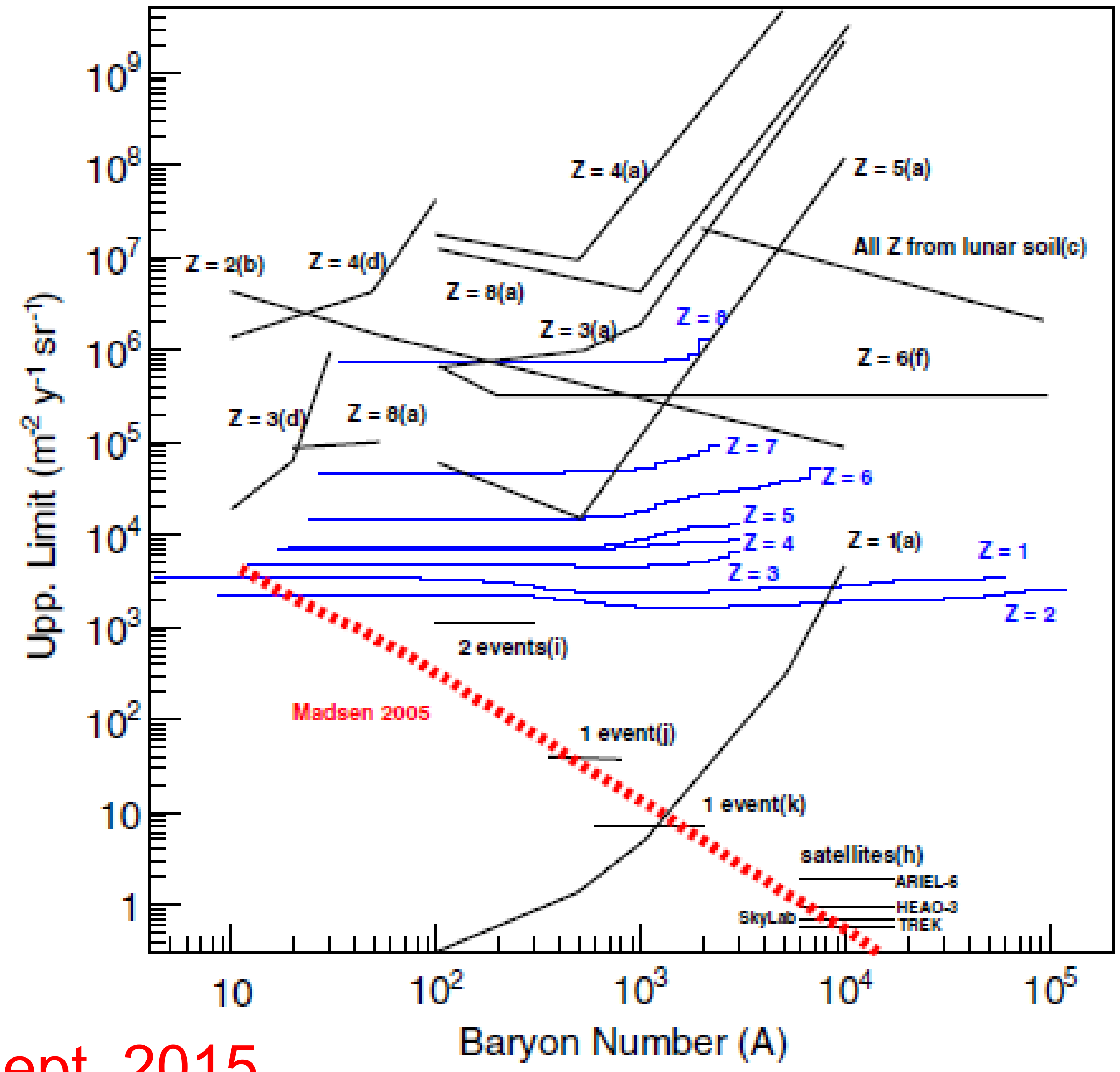


i. **A stable, single "super nucleon" with three types of quarks**

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

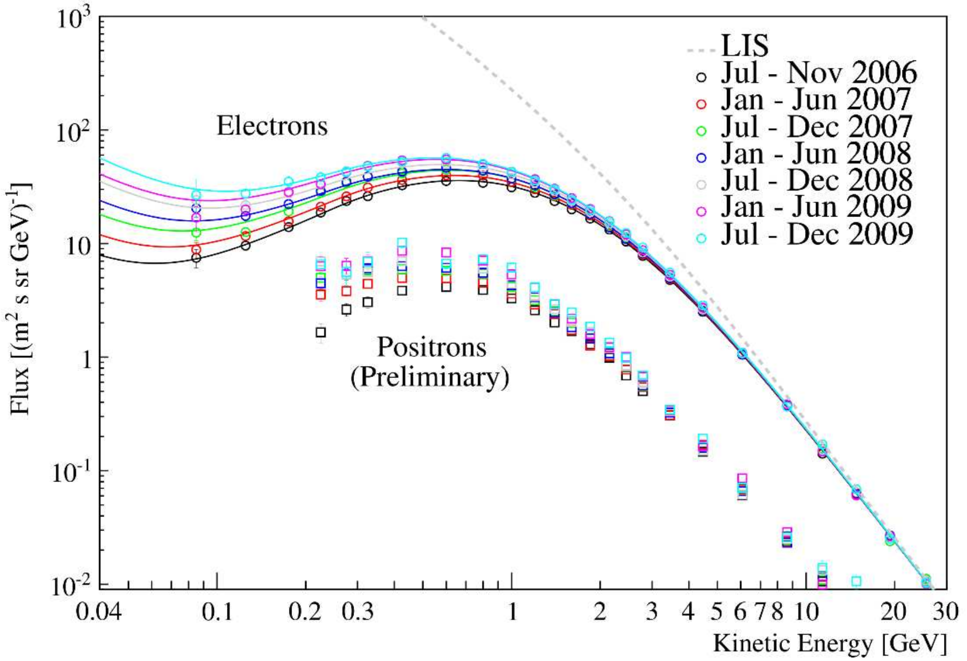
AMS courtesy

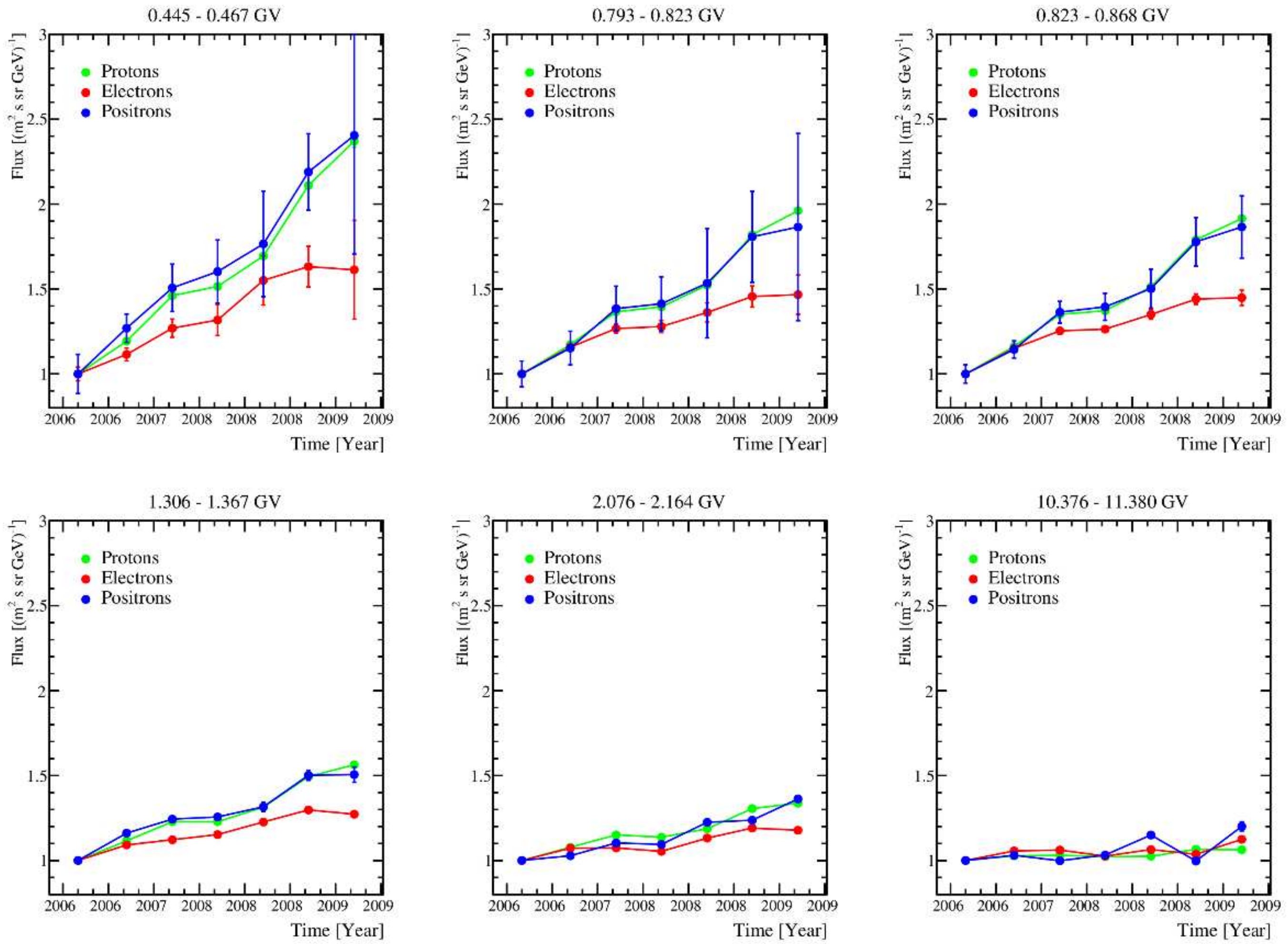
PAMELA limits for SQM



PRL sept. 2015

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