Results from the PAMELA Space Experiment

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On behalf of the PAMELA collaboration

VULCANO Workshop 2014
Frontier Objects in Astrophysics and Particle Physics

18th - 24th, May 2014
Vulcano Island, Sicily, Italy

Presentation outline

- Introduction
- PAMELA apparatus
- The travel of a cosmic ray: from source to Earth
- Summary

PAMELA

PAMELA Collaboration

Italy

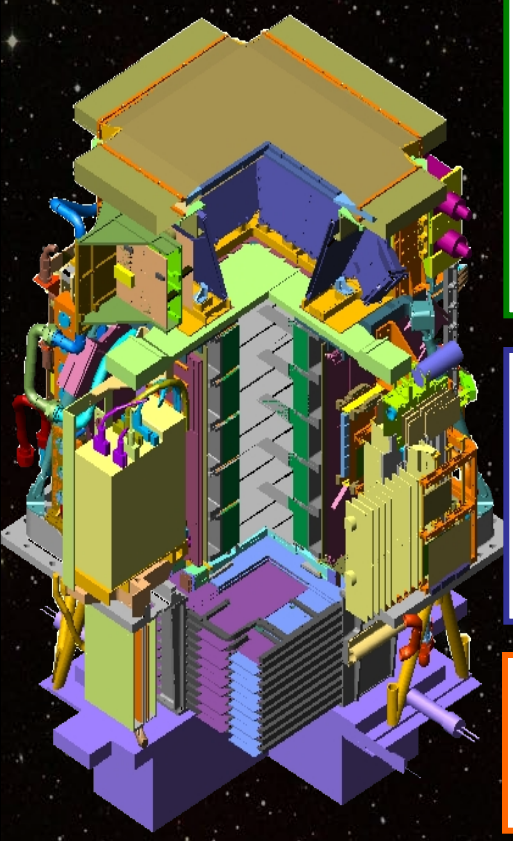
Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Germany: Siegen

Sweden: KTH, Stockholm

Russia: Moscow / St. Petersburg

The PAMELA apparatus

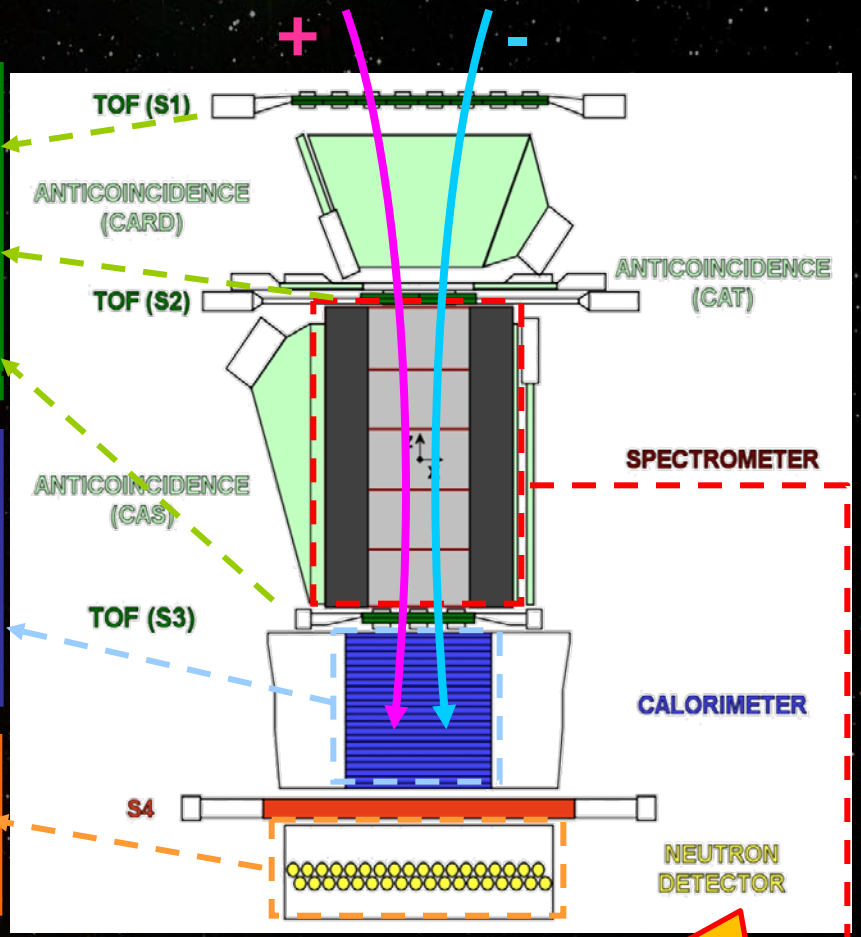


GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, **0.6 λ_I**)
- Discrimination e^+ / p, p-bar / e^- (shower topology)
- Direct E measurement for e^-

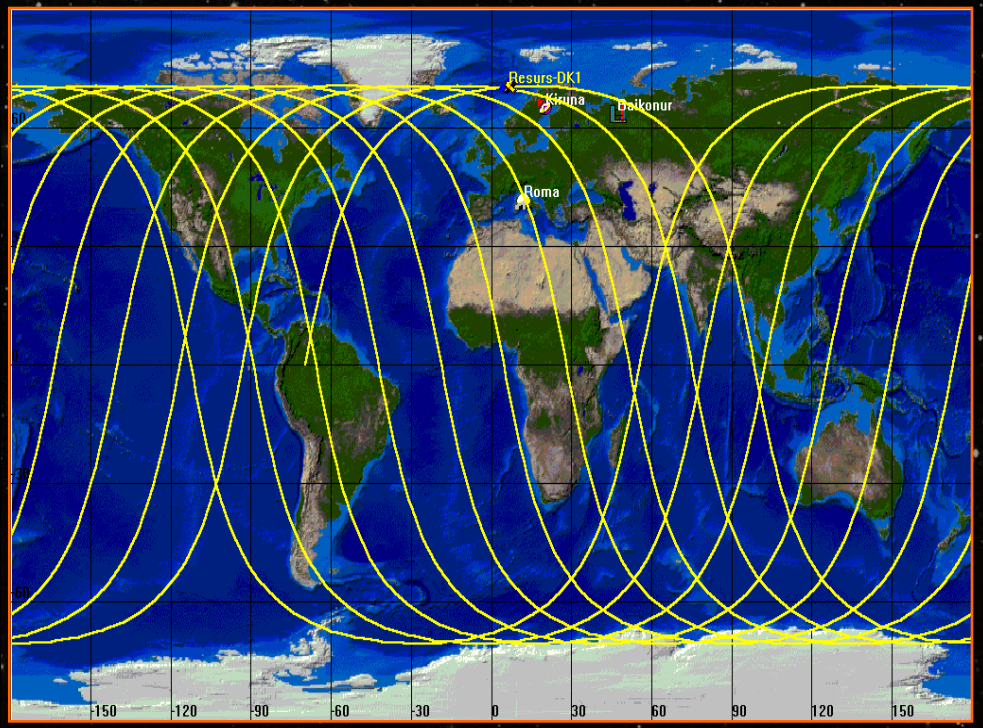
Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination

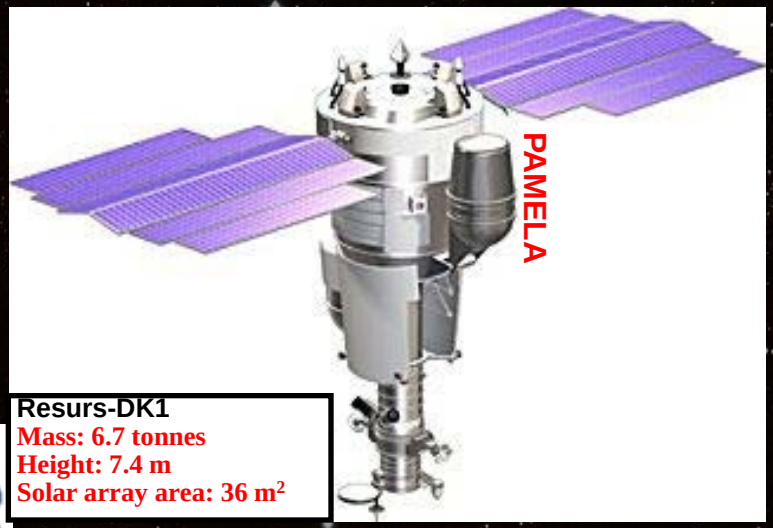


Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- Magnetic rigidity → R = pc/Ze
- Charge sign
- Charge value from dE/dx

today:
2900 days
~8 years!

Resurs-DK1 satellite and orbit



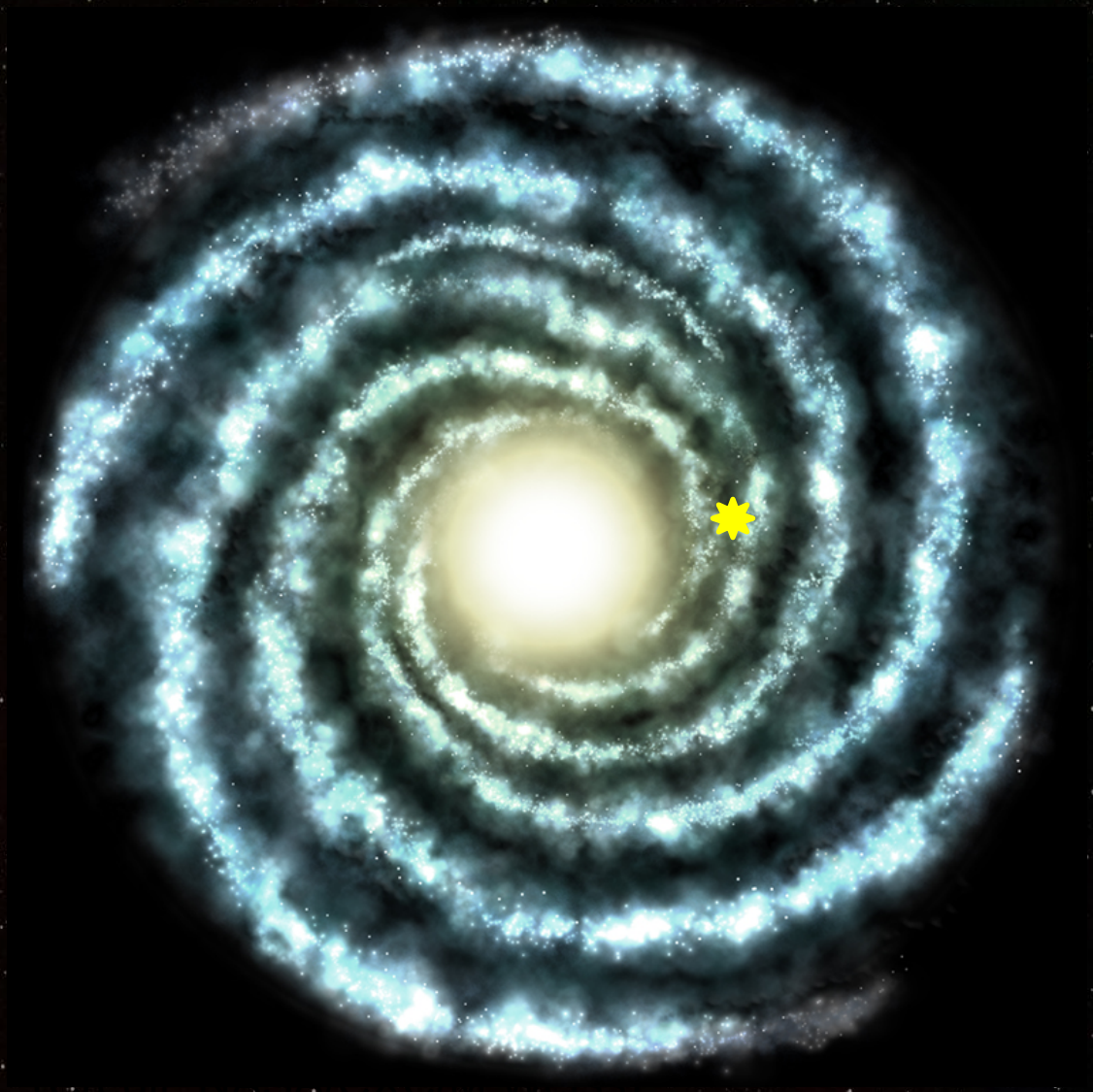


Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

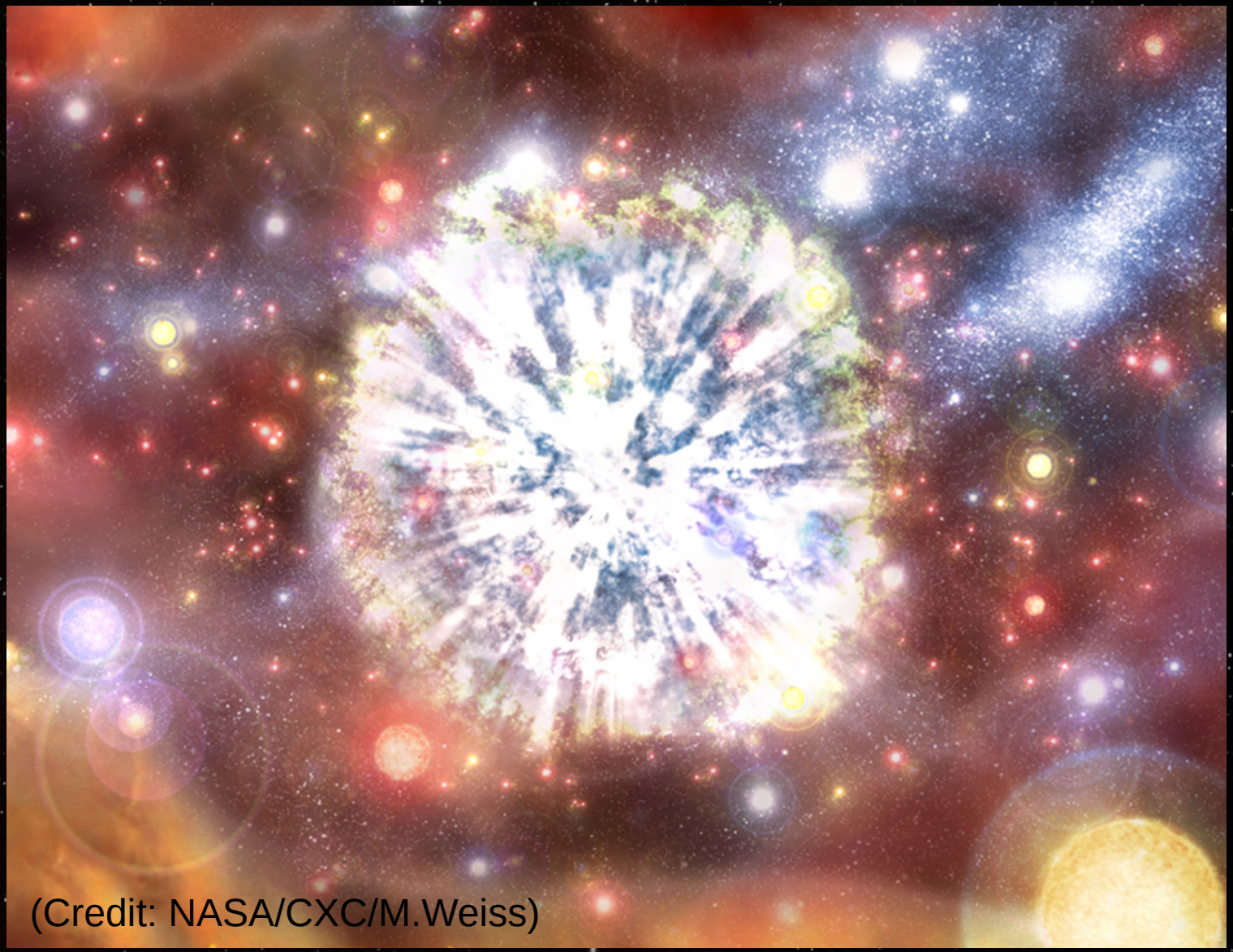
- **Resurs-DK1 satellite: multi-spectral imaging of Earth's surface**
- **PAMELA mounted inside a pressurized container**
- **Launch 15/06/2006 - lifetime >3 years (assisted), extended till end of satellite operations**
- **Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day**
- **Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km) – from 2010 circular orbit (70.0°, 600 km)**
- **Traverses the South Atlantic Anomaly**
- **Crosses the outer (electron) Van Allen belt at south pole**

Primary Cosmic Rays

Primary Cosmic Rays

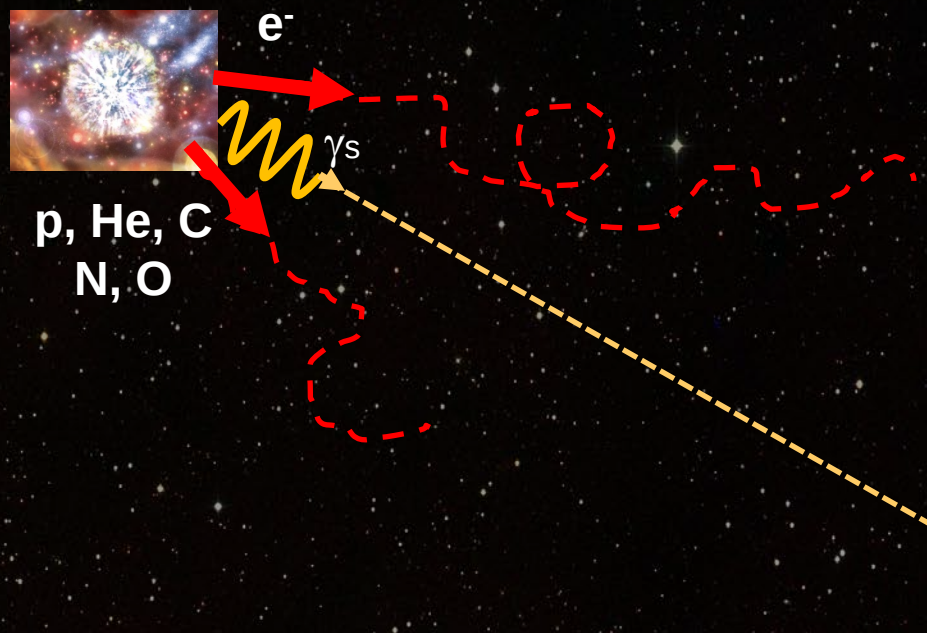


Primary Cosmic Rays



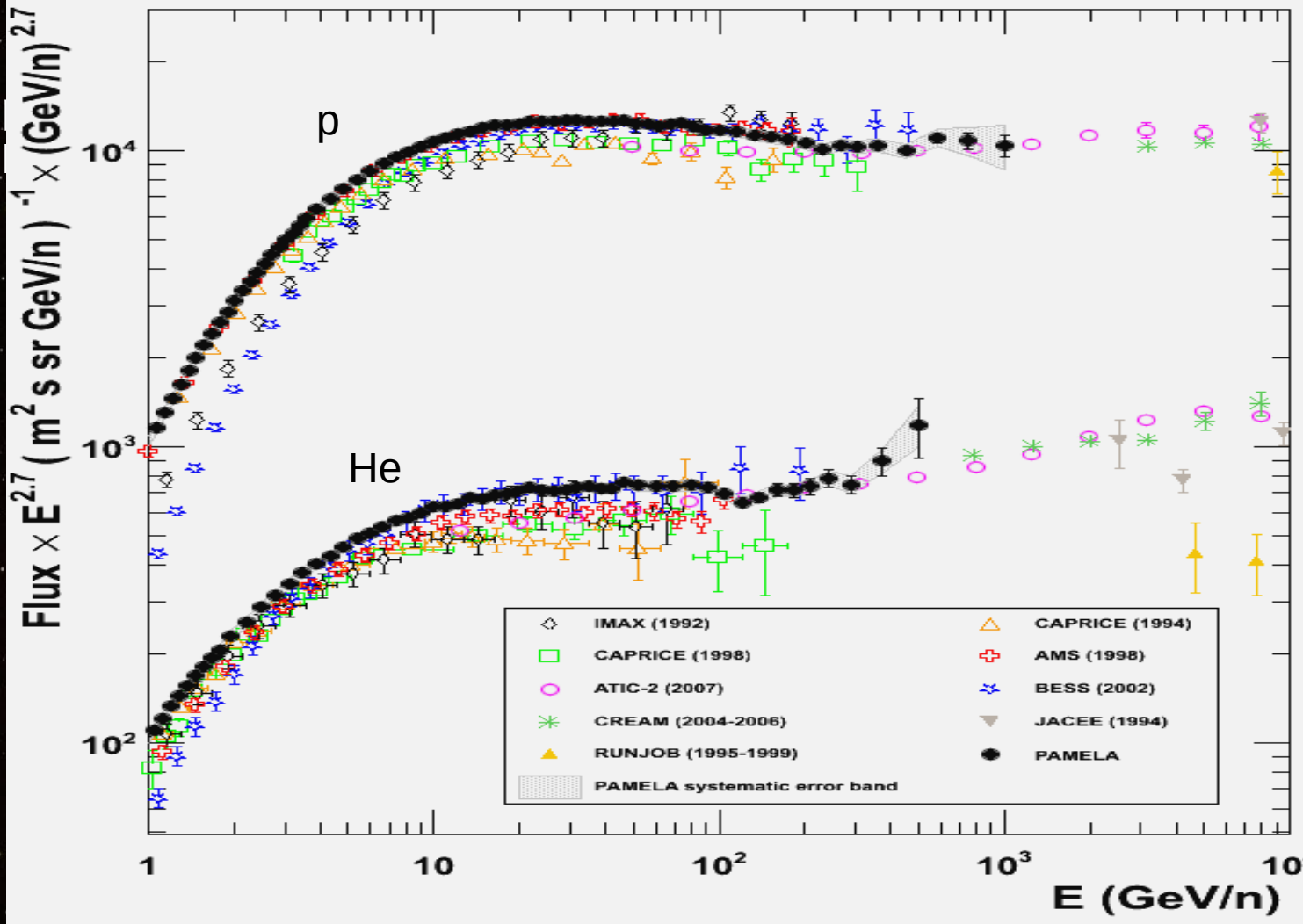
(Credit: NASA/CXC/M.Weiss)

Primary Cosmic Rays

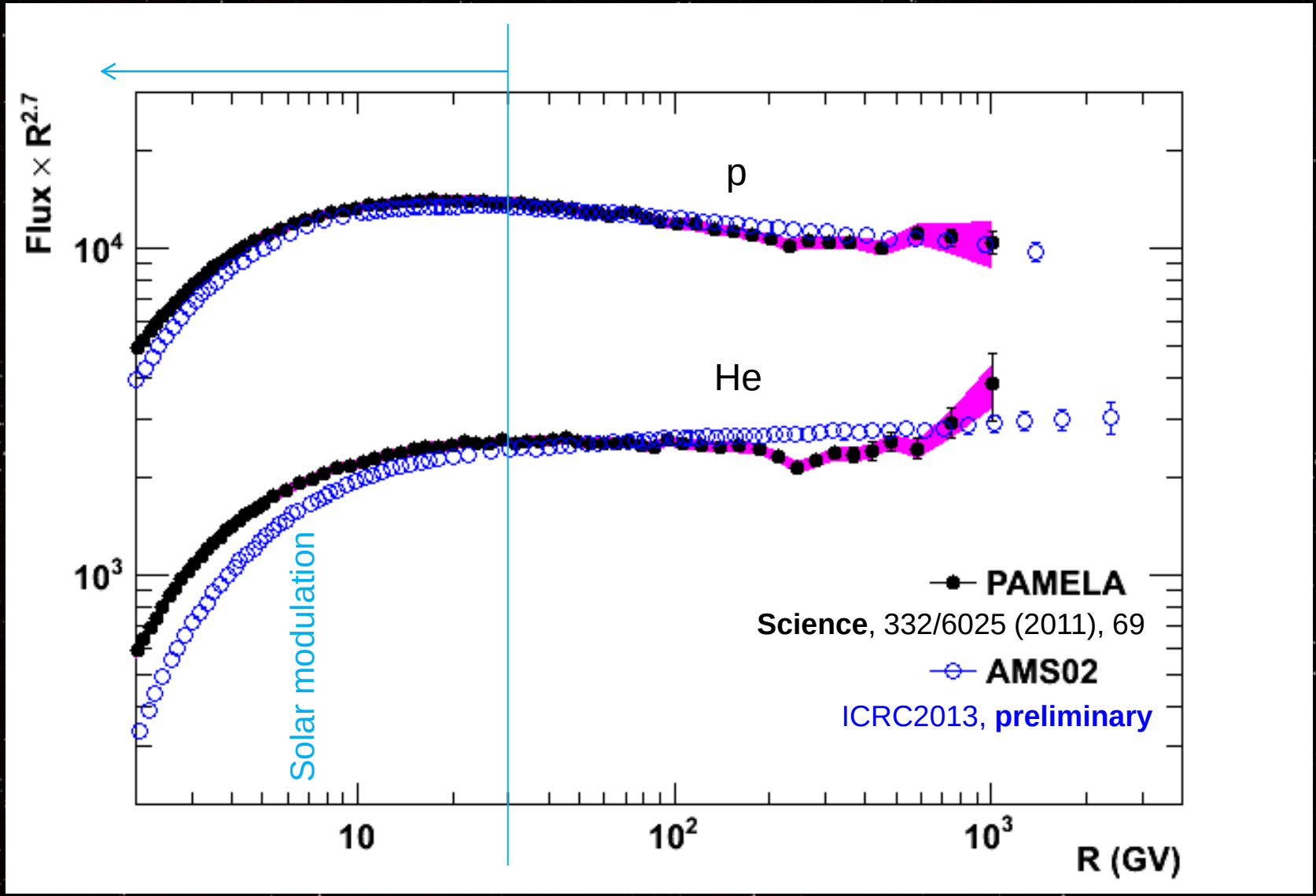


Proton and Helium Nuclei Spectra

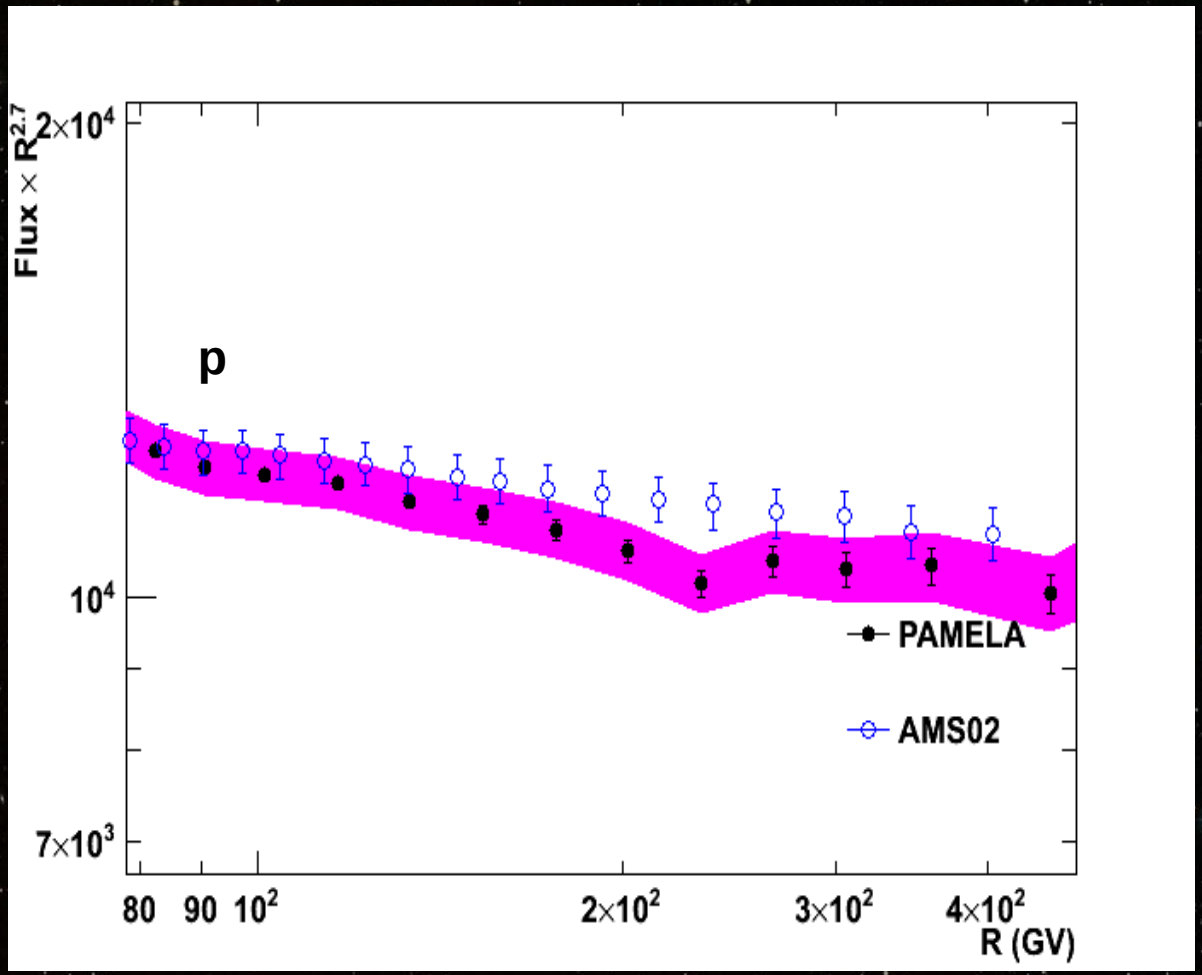
O. Adriani et al., Science, vol. 332 no. 6025 (2011), arXiv: 1103.4055



Comparison with AMS: not (too) bad!



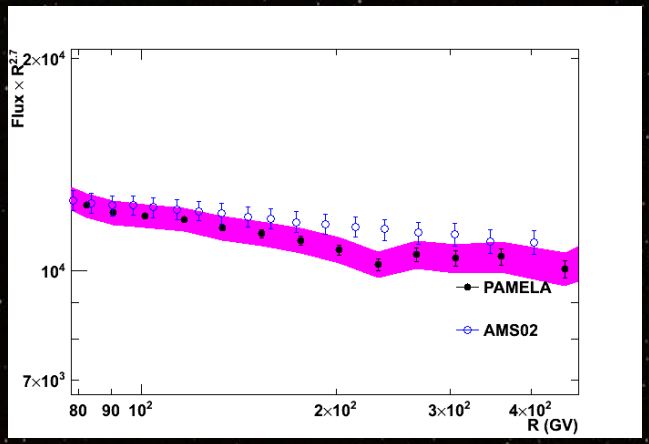
Great, but…



Wide energy range!
Huge statistics!
Fine binning!
Systematics at % level!

Systematic uncertainties are too big!
systematics >> statistical uncertainties

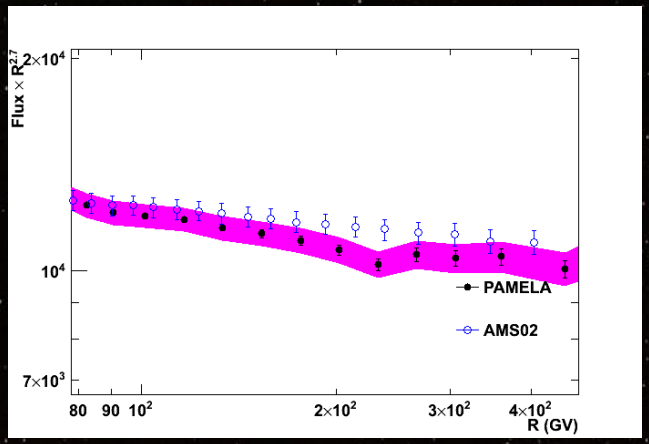
Systematic uncertainties ***estimation***

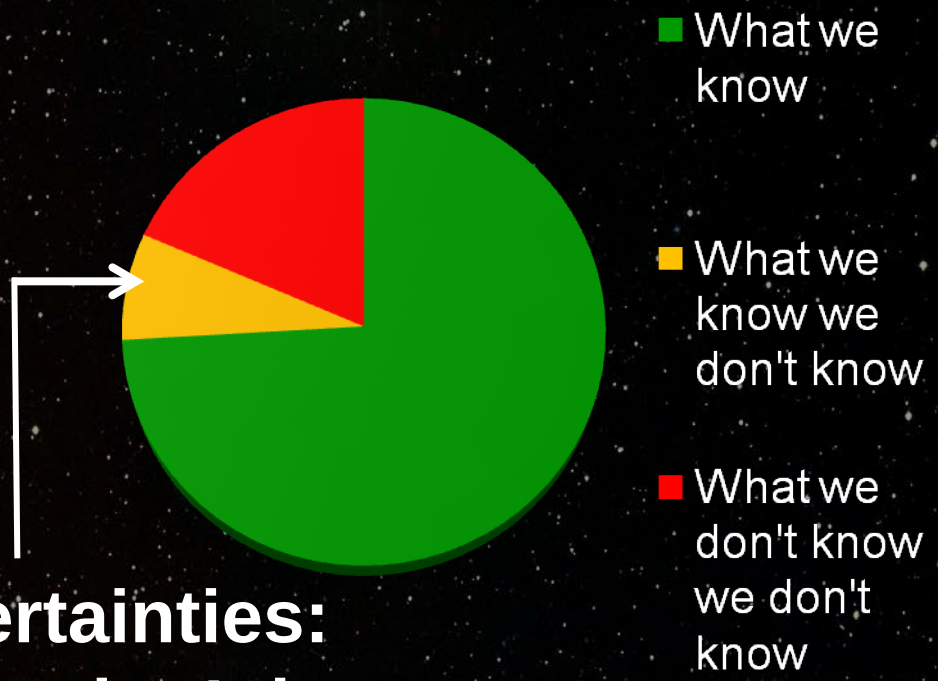


Systematic uncertainties:
represent the level of knowledge of our detector

Systematics are NOT measured but ESTIMATED!!

Systematic uncertainties ***estimation***





Systematic uncertainties: what we know we don't know about the detector

Systematics are NOT measured but ESTIMATED!!

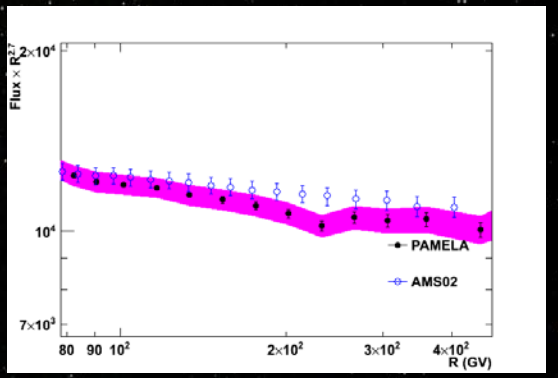
Systematics: many sources, different effects

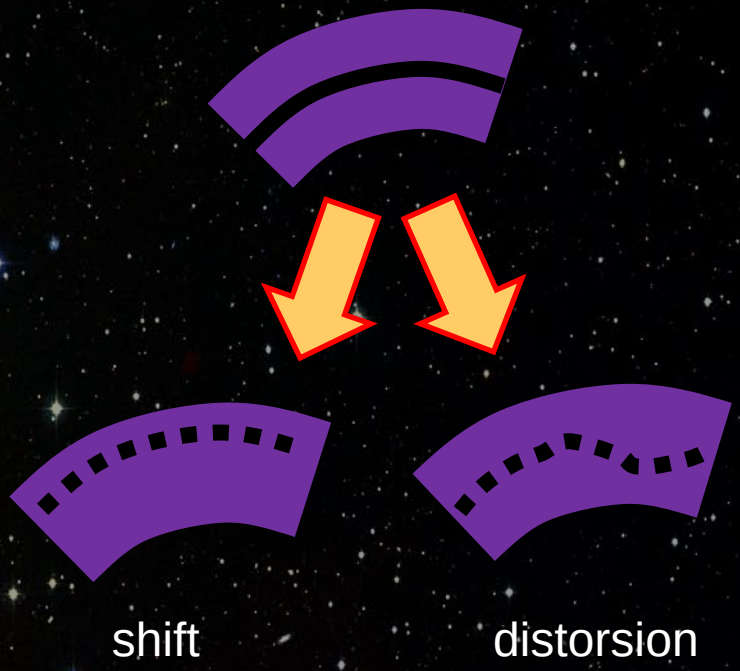
Sources of systematic uncertainties:

- **Under- or over-estimation of efficiencies:**
  - **Flight data measurements:**
    - **energy/acceptance/time dependencies;**
    - **selections cuts correlations;**
    - **samples contamination;**
  - **Simulation measurements:**
    inadequacies of the model involved (physics; modeling of the detector).

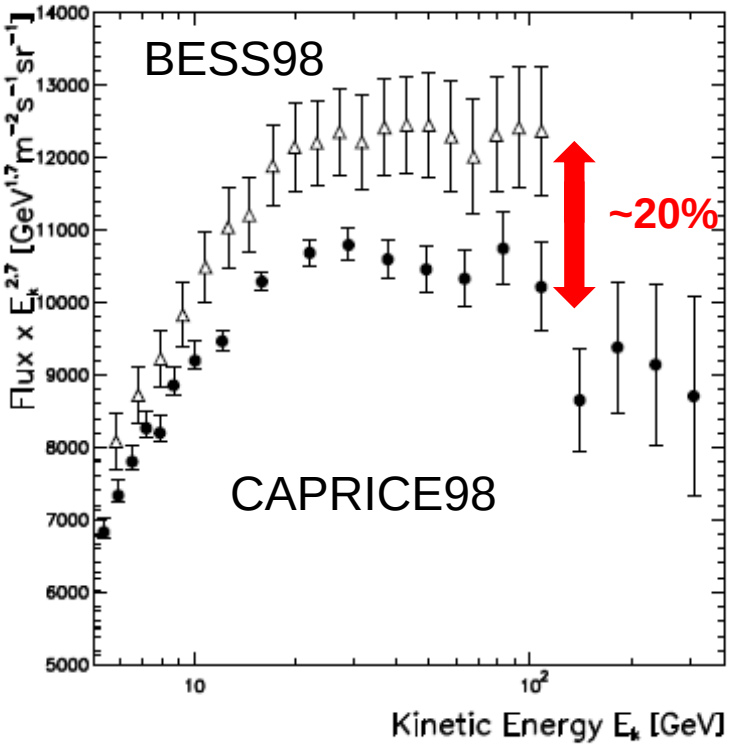
- **Residual contamination(s);**

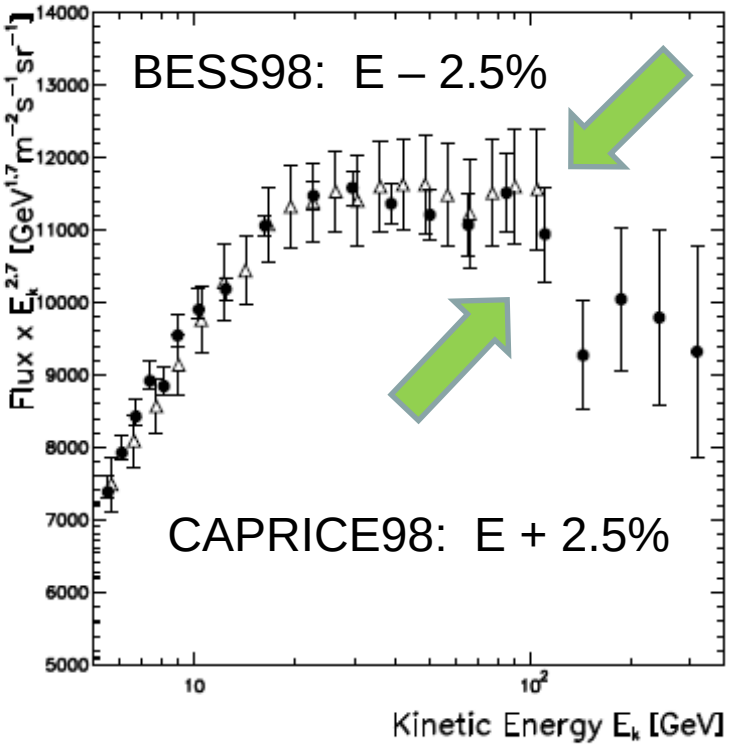
- **Energy measurement.**





Systematic estimation: energy

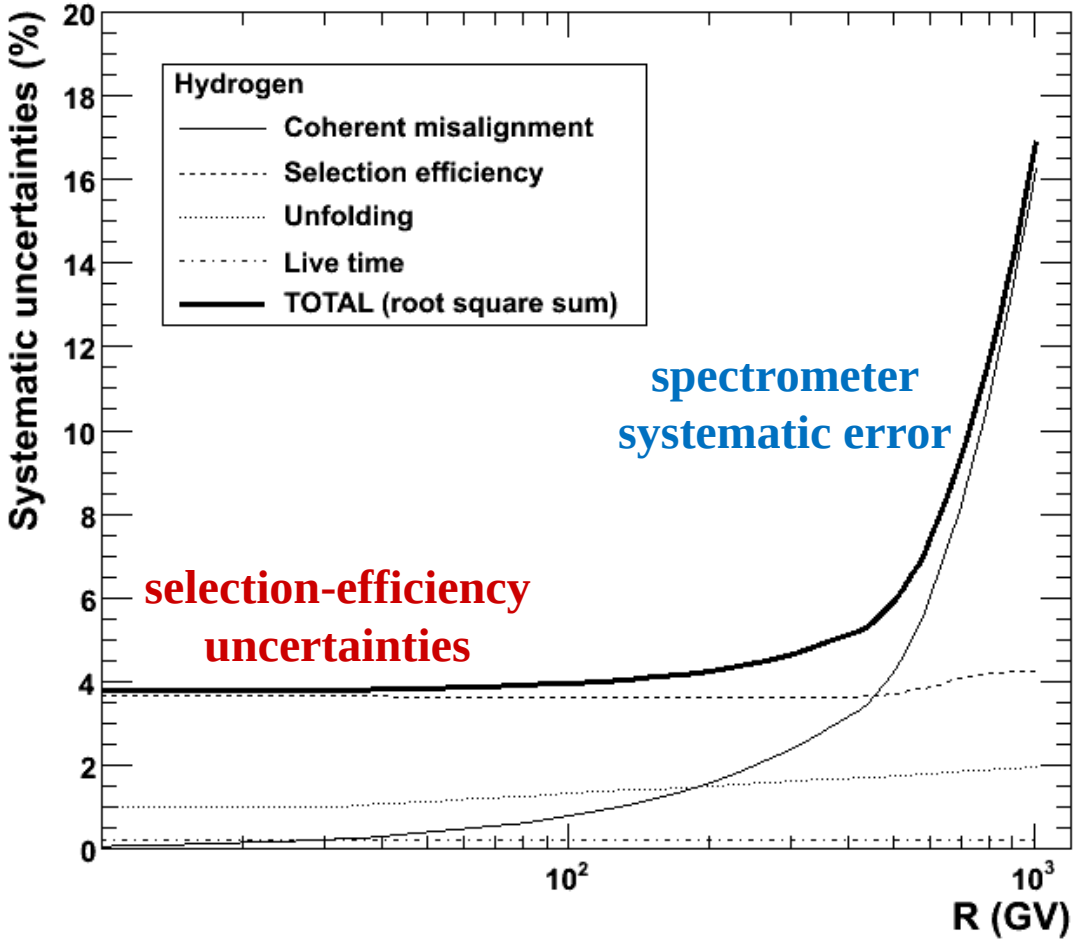




E. Mocchiutti (2003): http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-3643

Overall systematic uncertainties

Science paper, online supplementary material



Overall systematic uncertainties

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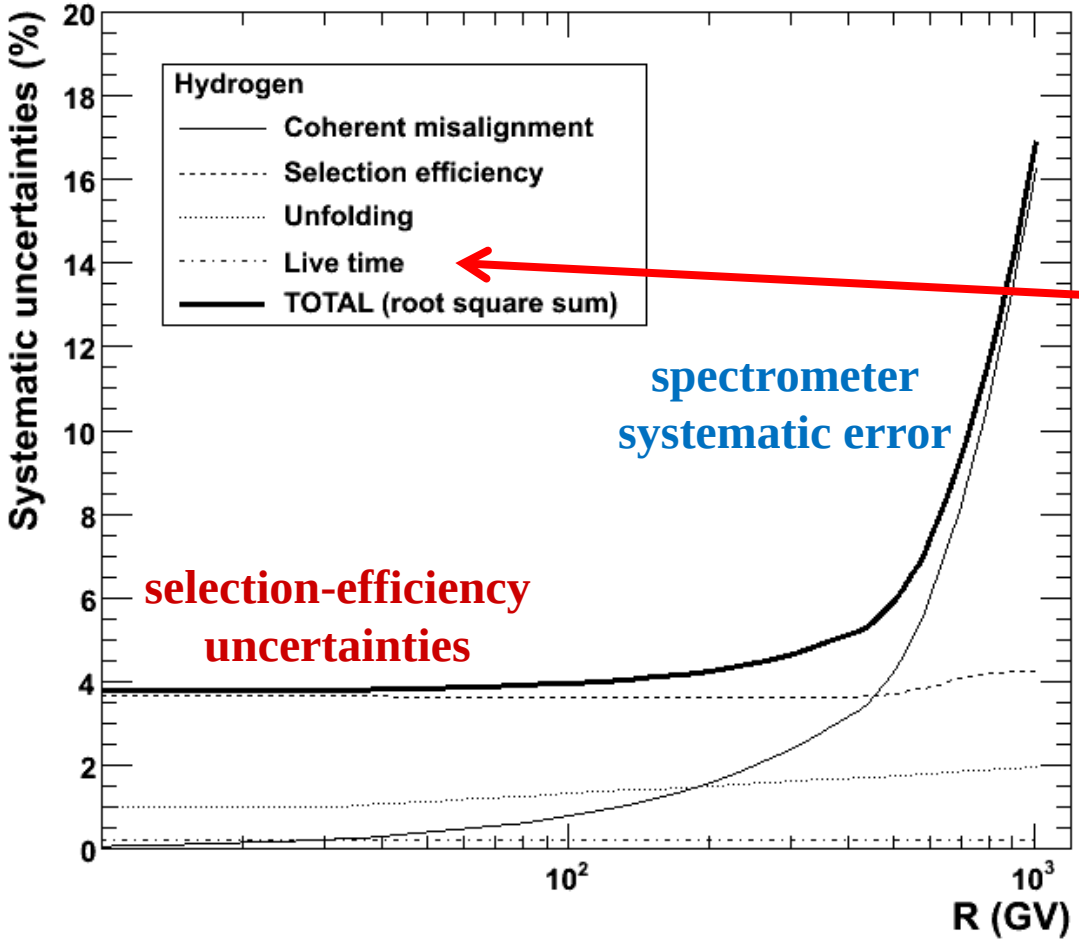
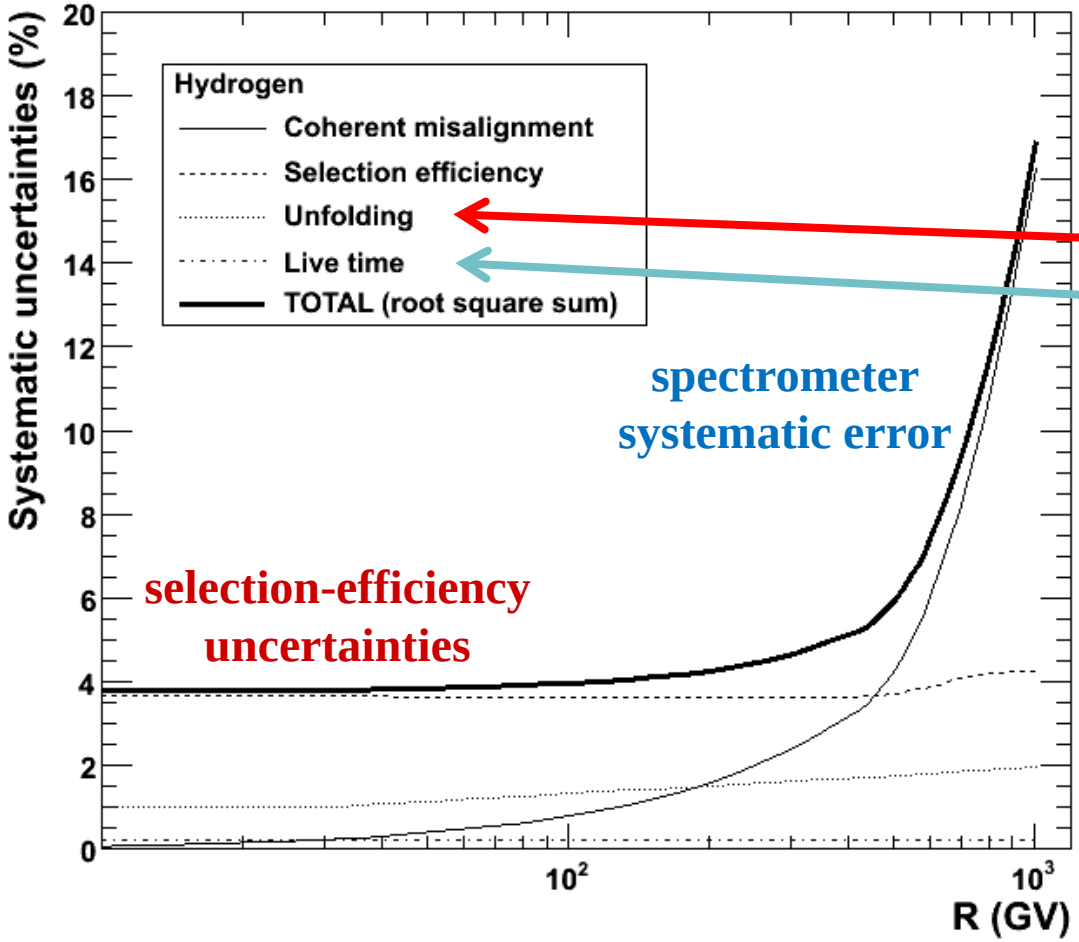


Solid shift

Overall systematic uncertainties

Science paper, online supplementary material

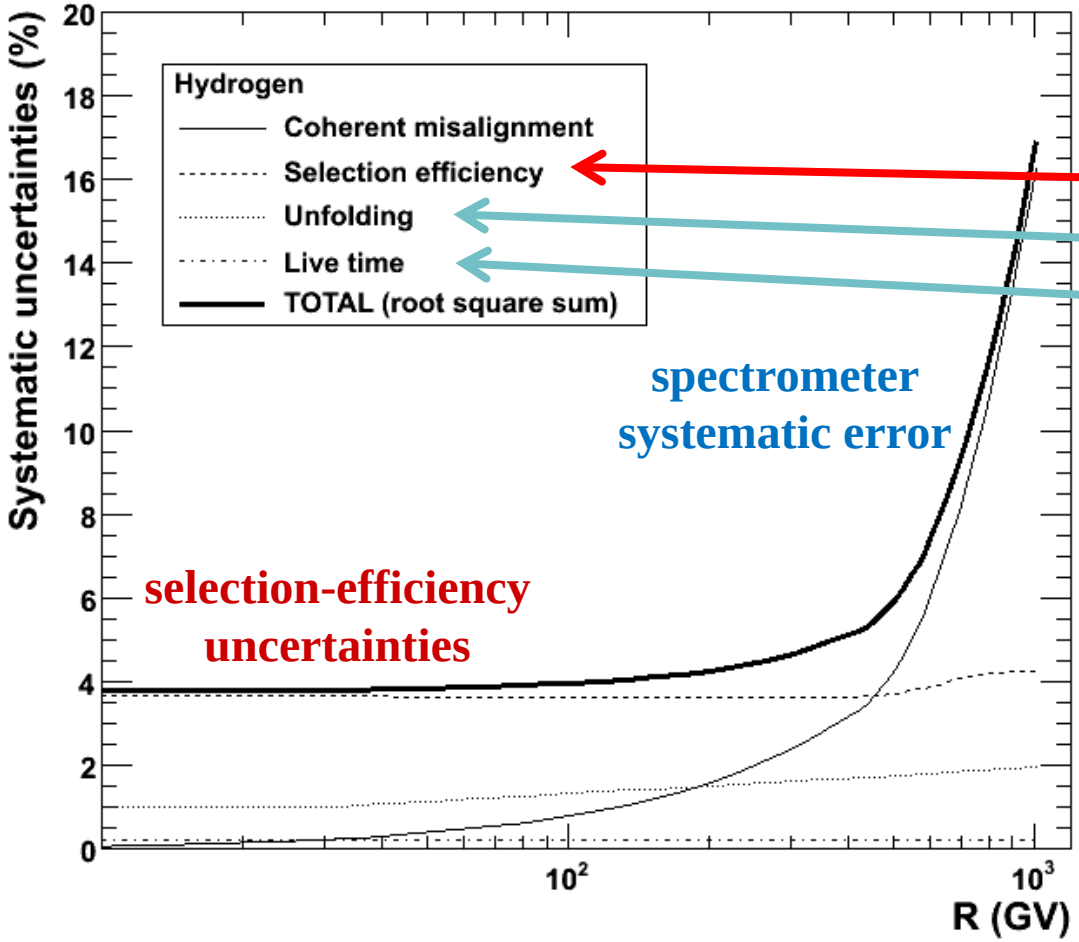


Distorsion

Solid shift

Overall systematic uncertainties

Science paper, online supplementary material



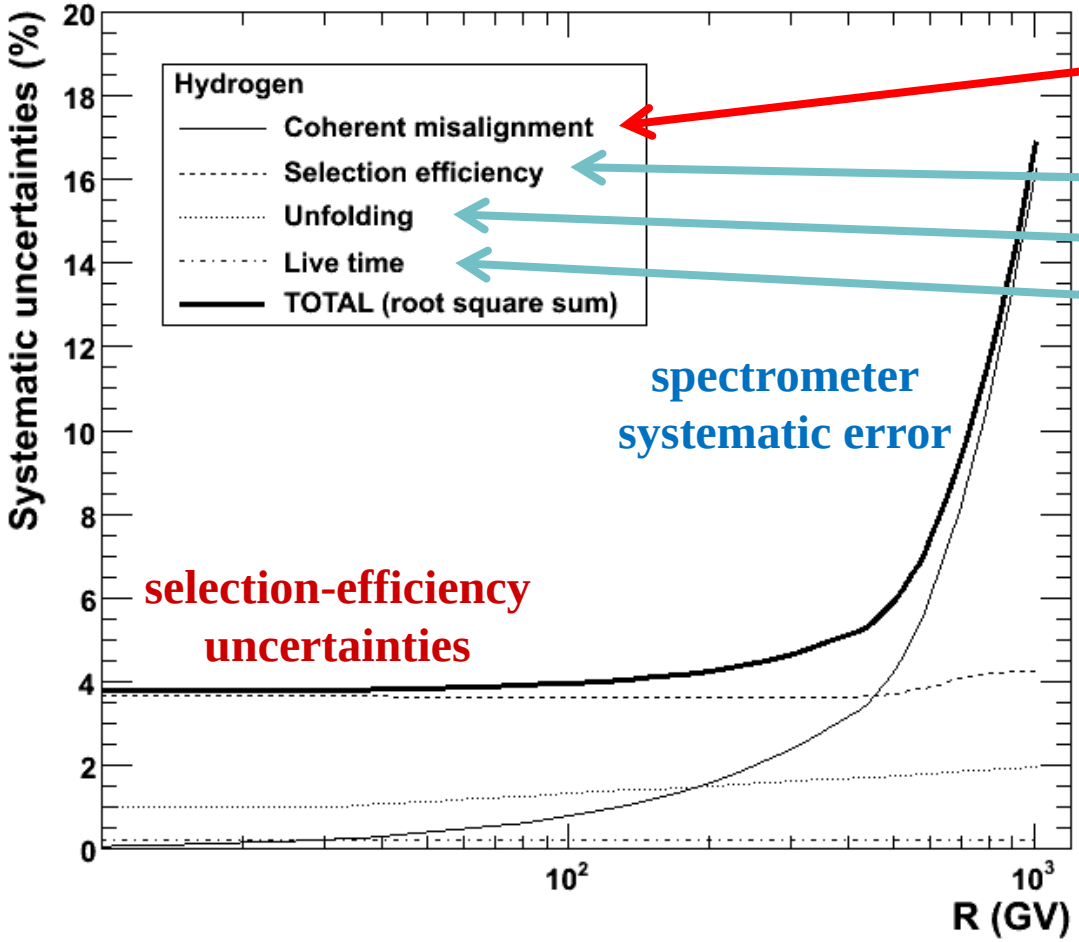
Shift & distorsion

Distorsion

Solid shift

Overall systematic uncertainties

Science paper, online supplementary material



Shift in energy
(distorsion in $E^{2.7}$ plots)

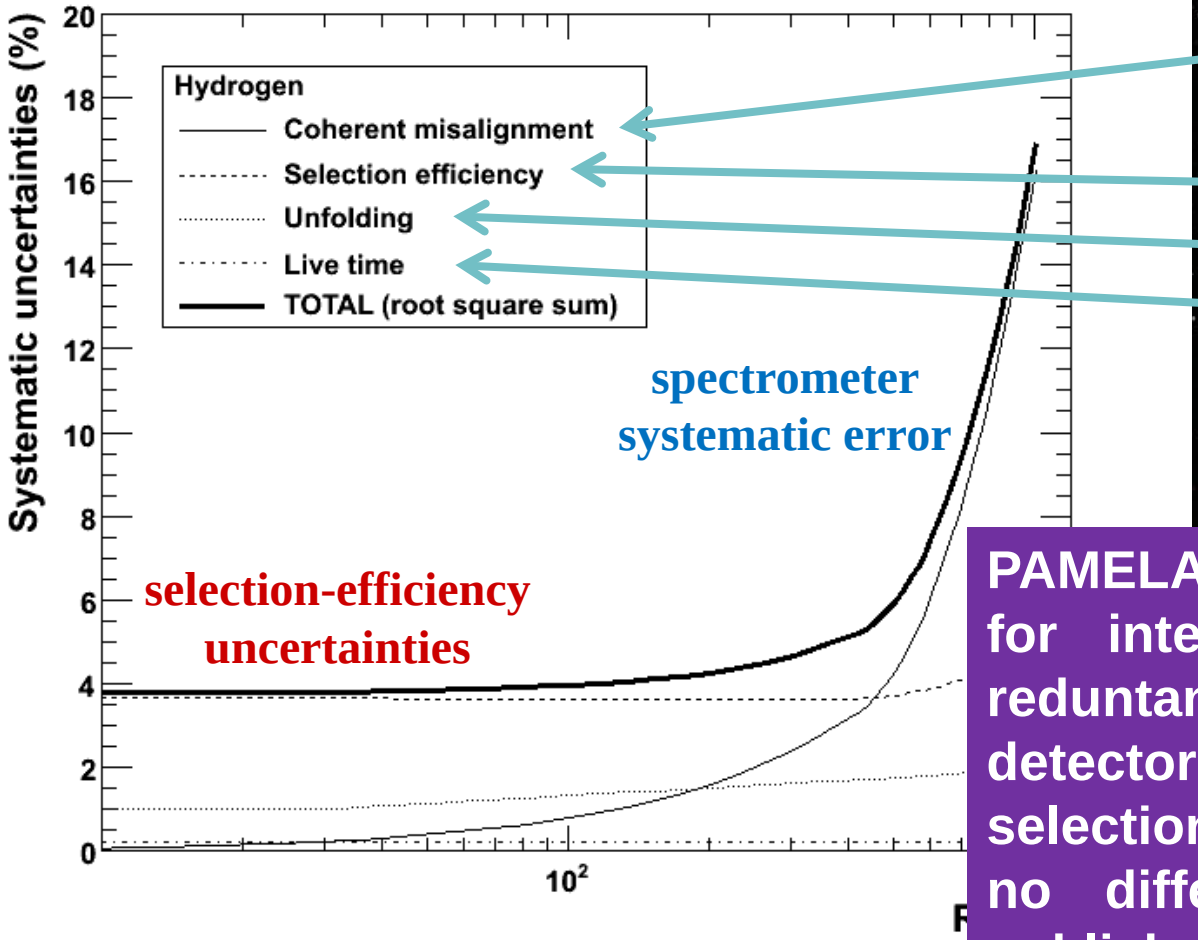
Shift & distorsion

Distorsion

Solid shift

Overall systematic uncertainties

Science paper, online supplementary material



Shift in energy (distorsion in $E^{2.7}$ plots)

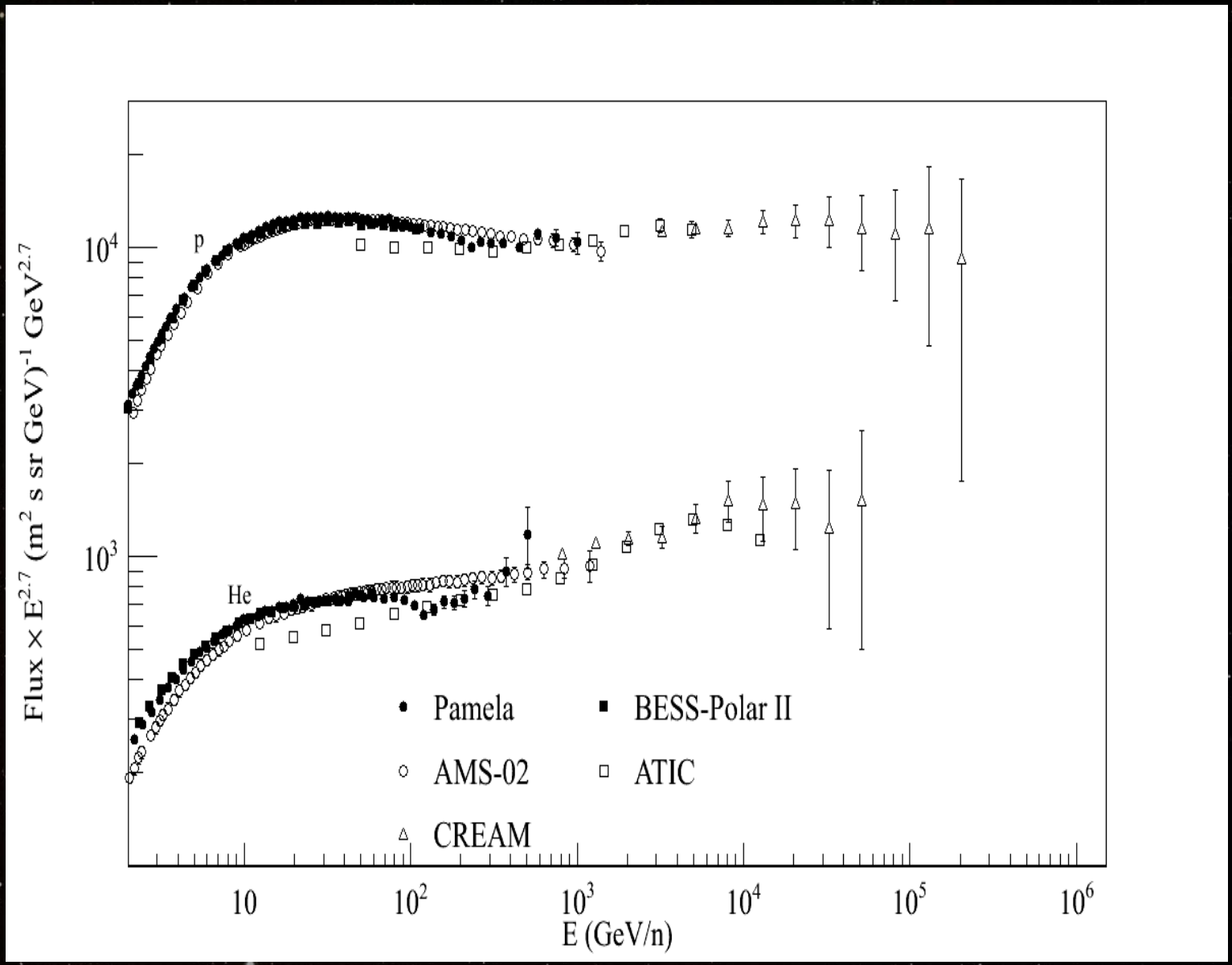
Shift & distorsion

Distorsion

Solid shift

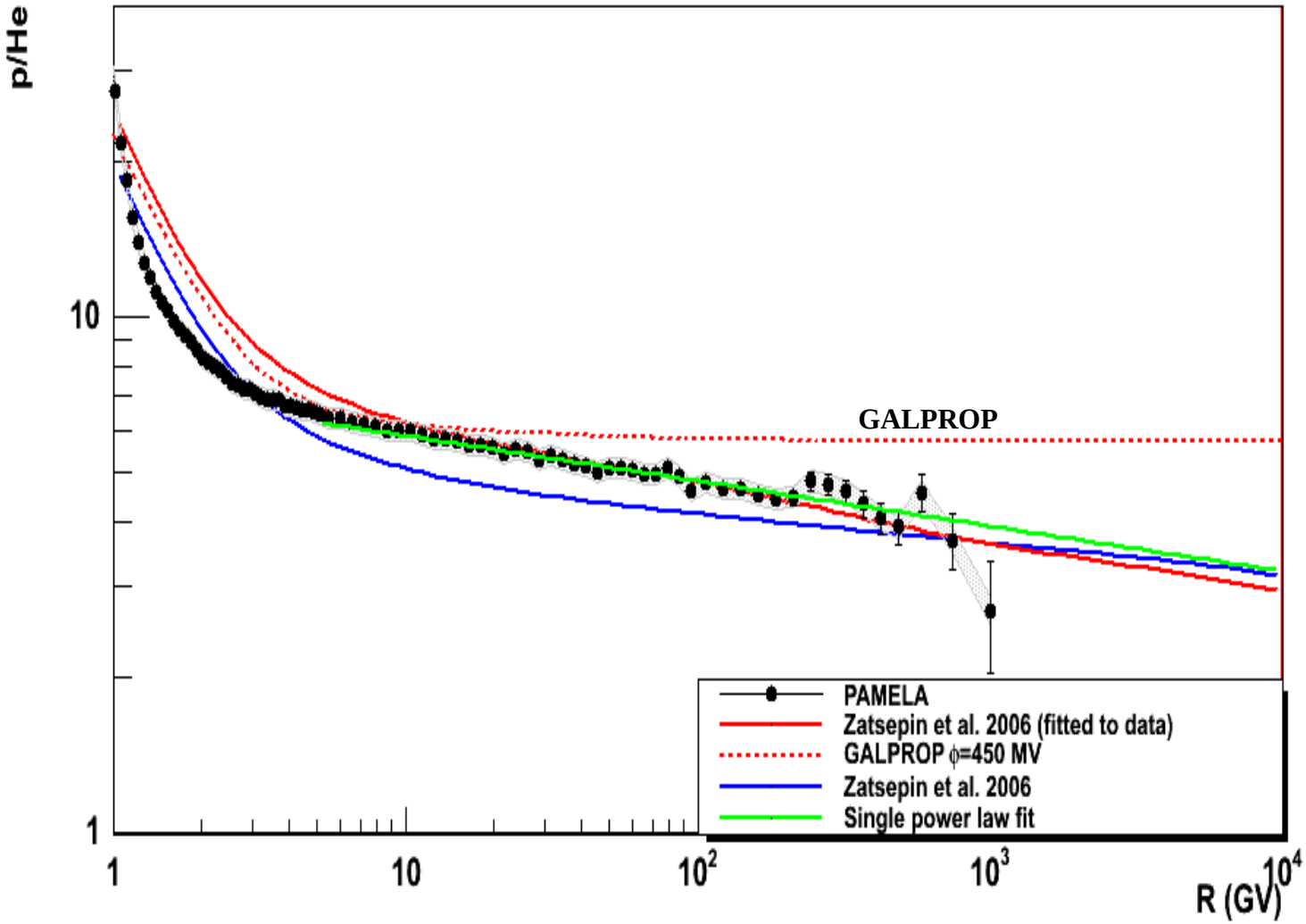
PAMELA p and He results tested for internal consistency: many reduntant tests on different detector configurations, data selections, efficiency estimation… no difference with respect to published data!

The big picture: good agreement with some “tension”

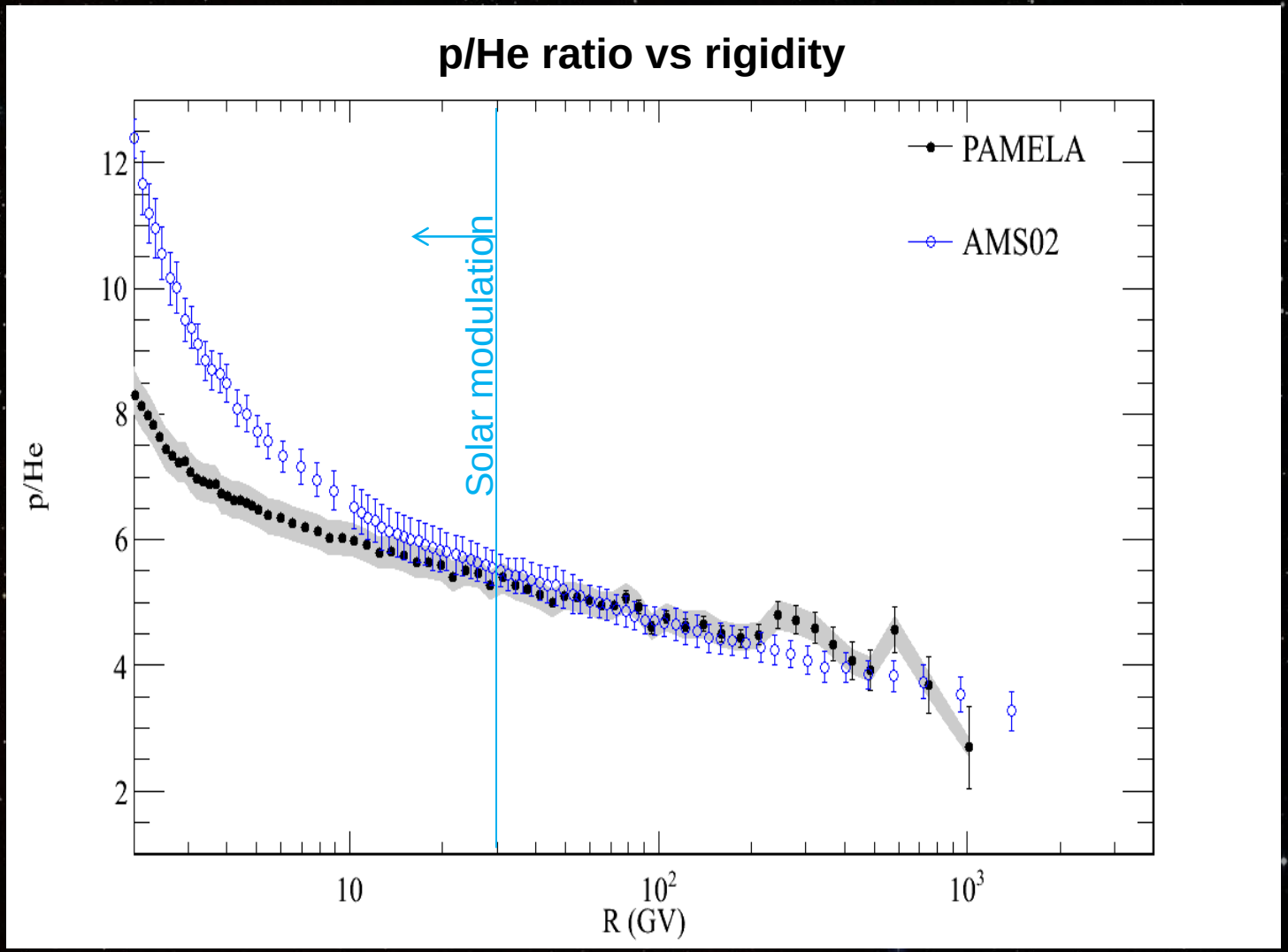


p/He: a solid measurement

O. Adriani et al., Science, vol. 332 no. 6025 (2011), arXiv: 1103.4055

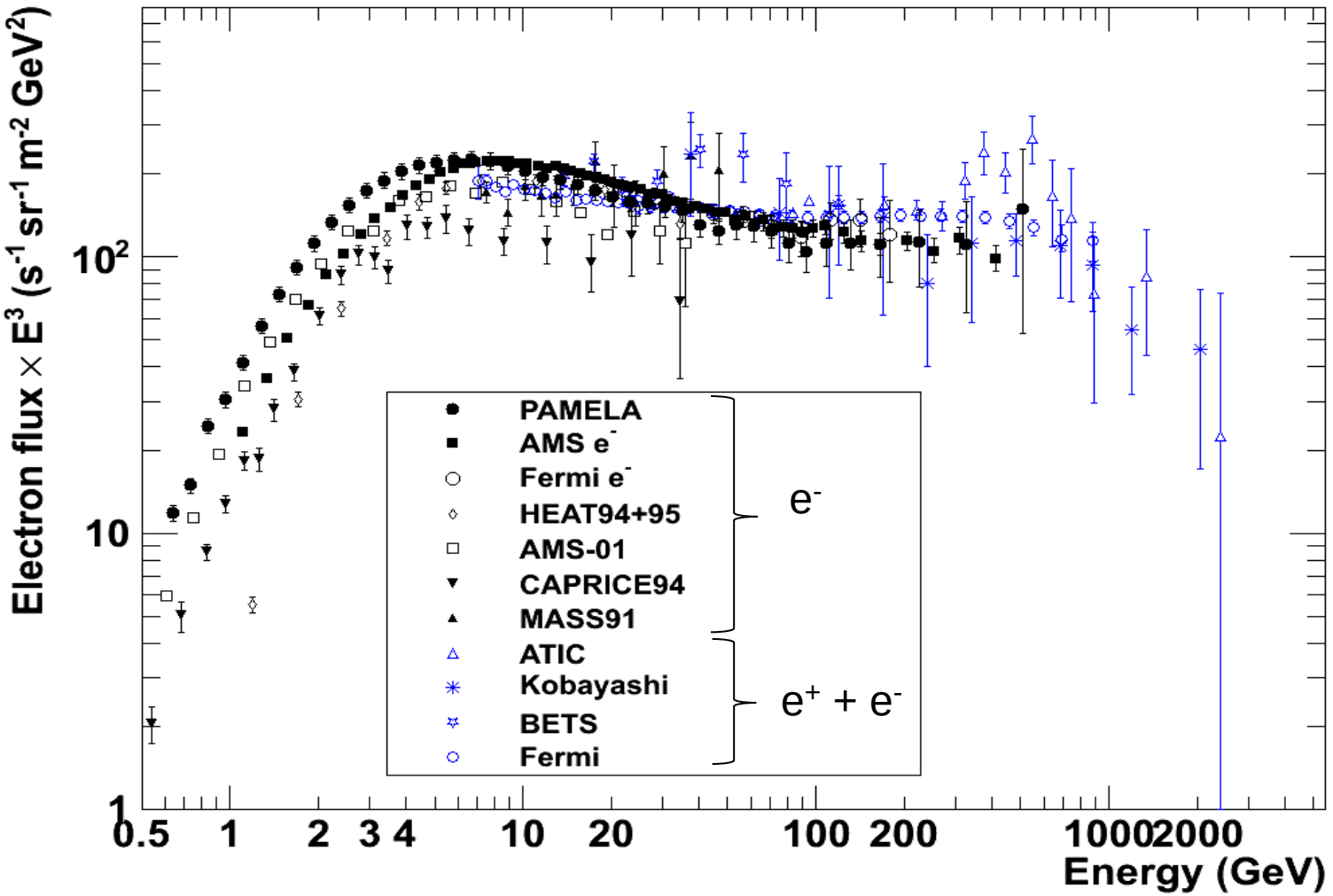


p/He: most systematics cancel out



Electron (e^-) spectrum

O. Adriani et al., Phys. Rev. Lett. 106, 201101 (2011)



Electron (e^-) spectrum

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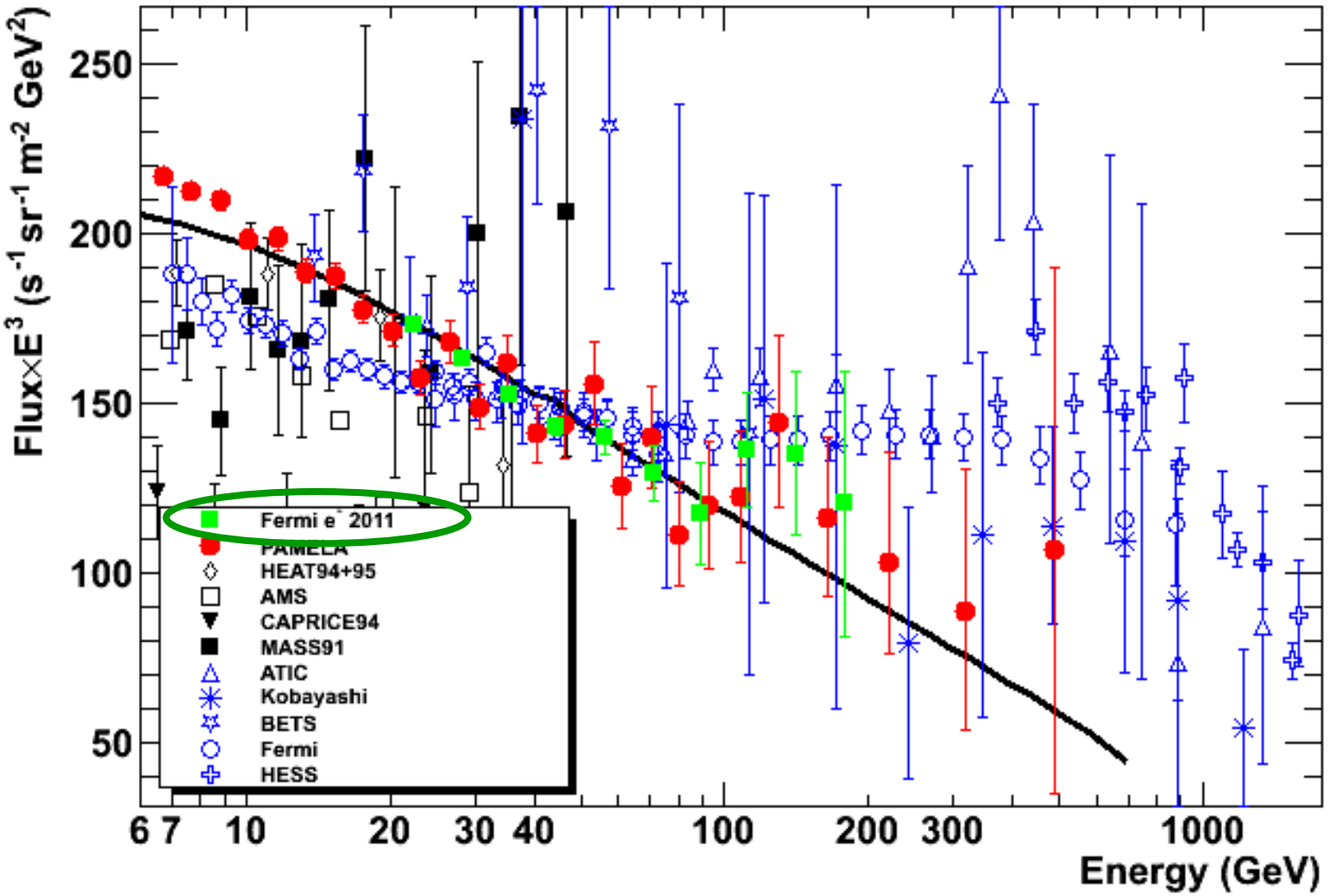


Primary Cosmic Rays

Standard paradigm:

sources of cosmic rays: homogeneously distributed SNR via II order Fermi acceleration

PAMELA results:

protons, Helium nuclei, light nuclei, electrons spectra

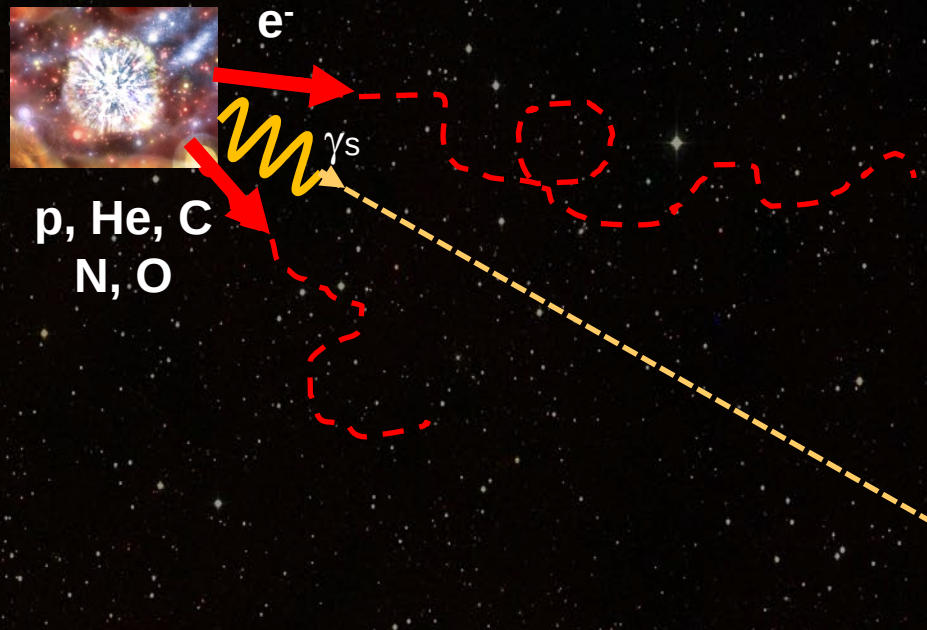
structures + p/He not constant!

Implications:

challenging standard paradigm: non uniform distribution of sources? local source? different type of sources or acceleration mechanisms? acceleration process? propagation effect?

Secondary Cosmic Rays

Secondary Cosmic Rays



Secondary Cosmic Rays

p, He, C
N, O

e^-

γ_s

ISM gas

p, He, C,
N, O, Li,
Be, B, ...

π^+, π^-

decay

π_0

decay

γ_s

$\overline{p}$

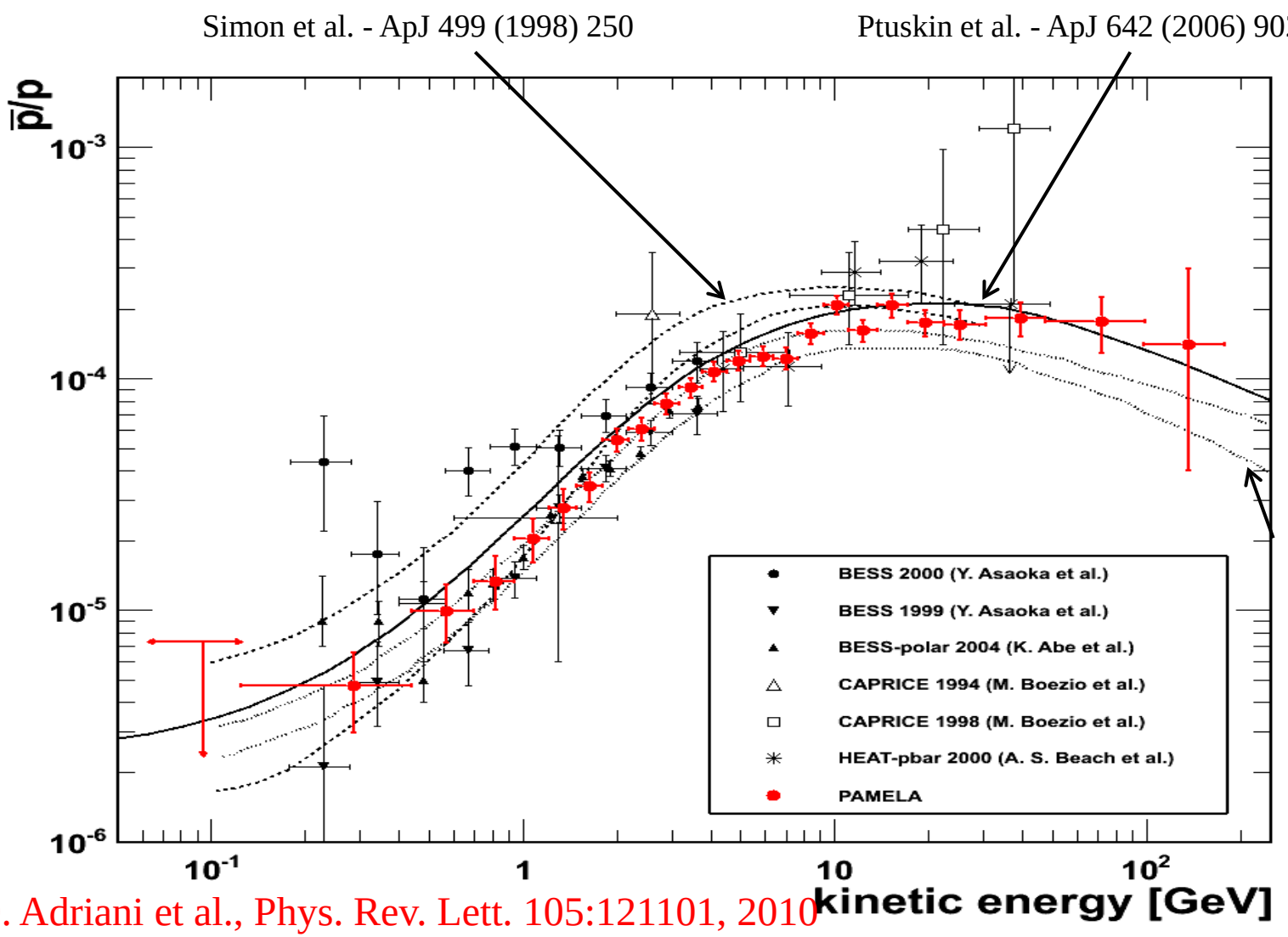
e^- e^+

γ_s

Bremsstrahlung, Synchrotron, Inverse Compton

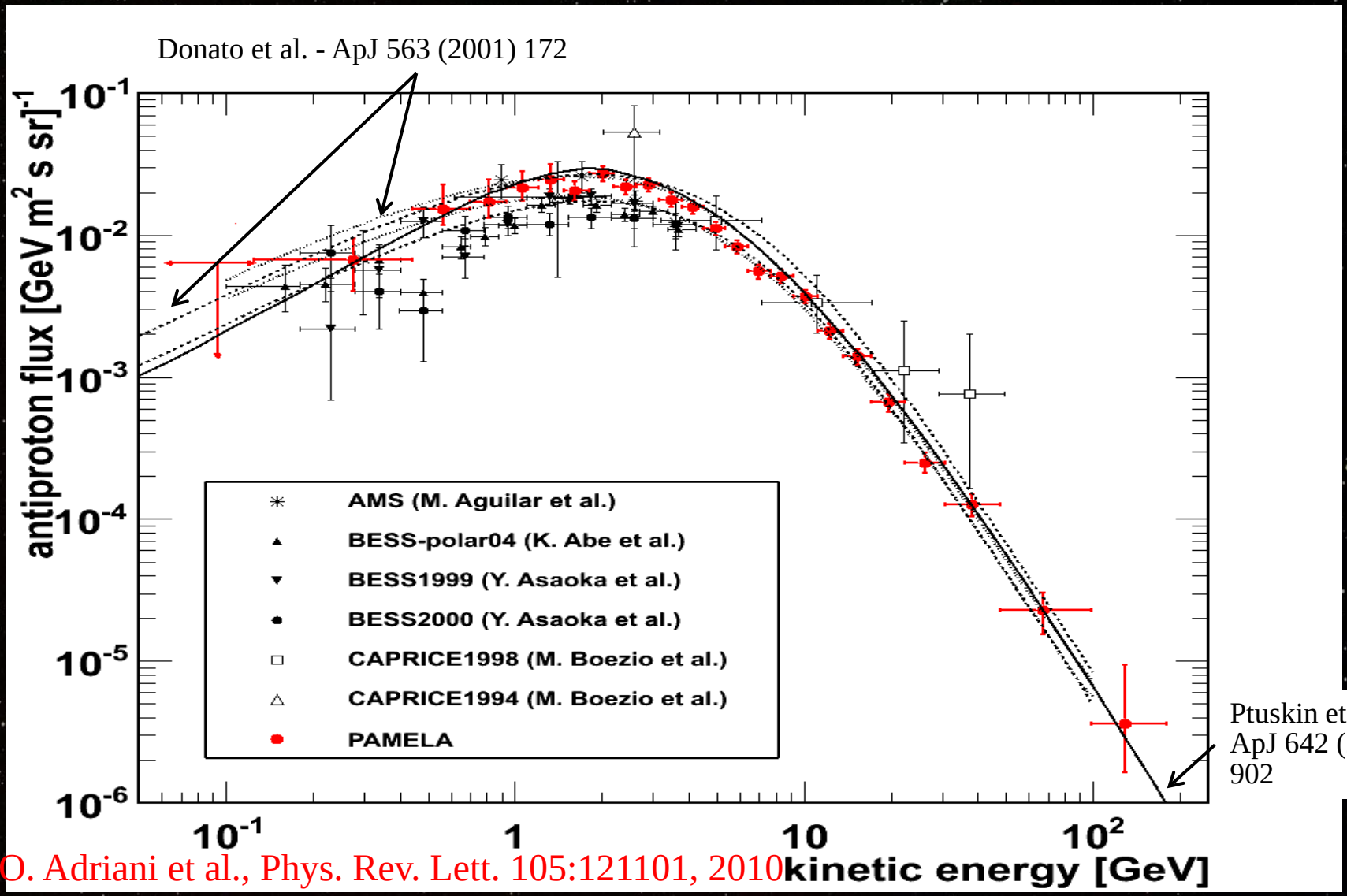
CR secondary production (pp → X)

Antiproton to proton ratio



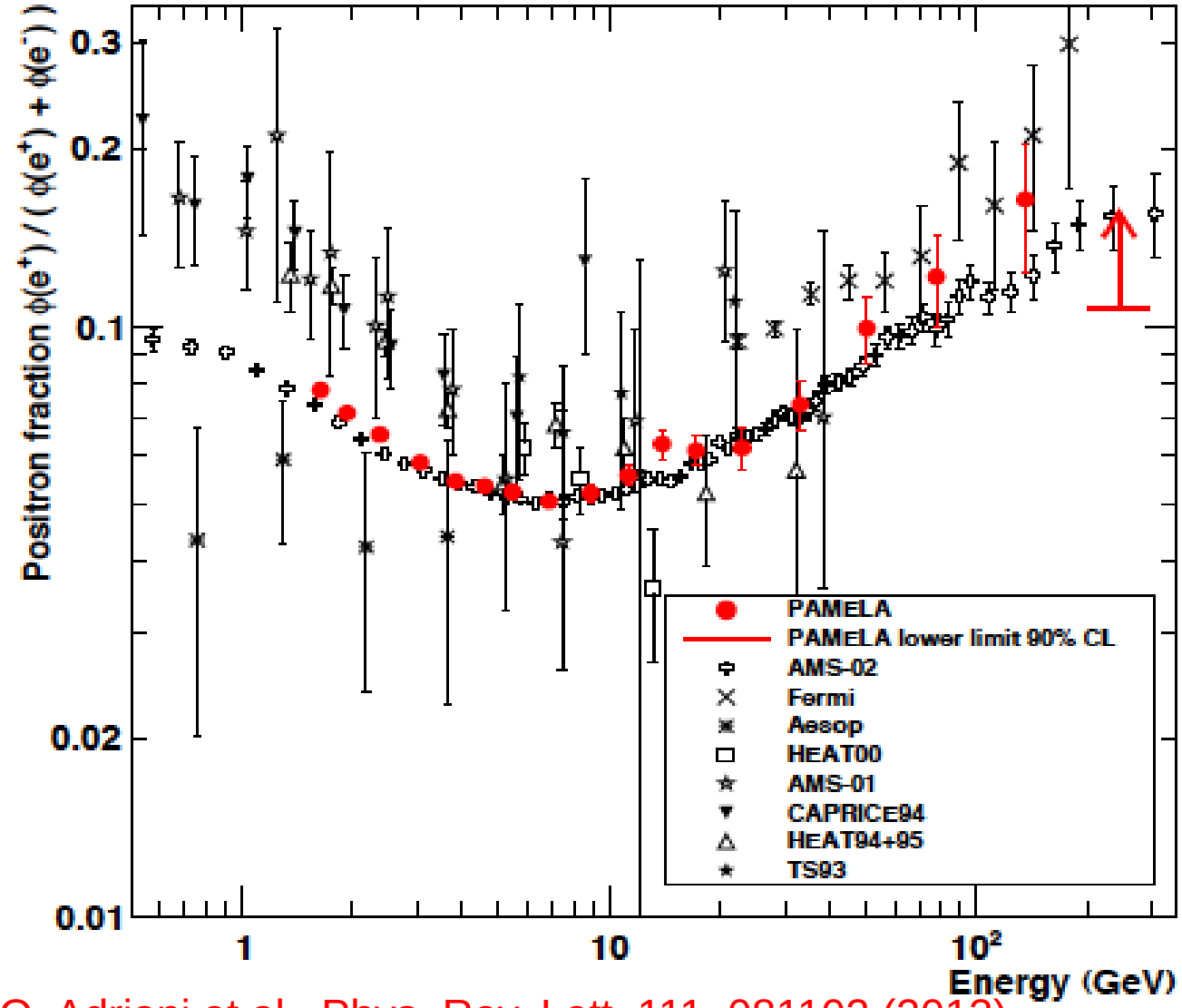
O. Adriani et al., Phys. Rev. Lett. 105:121101, 2010

Antiproton spectrum



O. Adriani et al., Phys. Rev. Lett. 105:121101, 2010

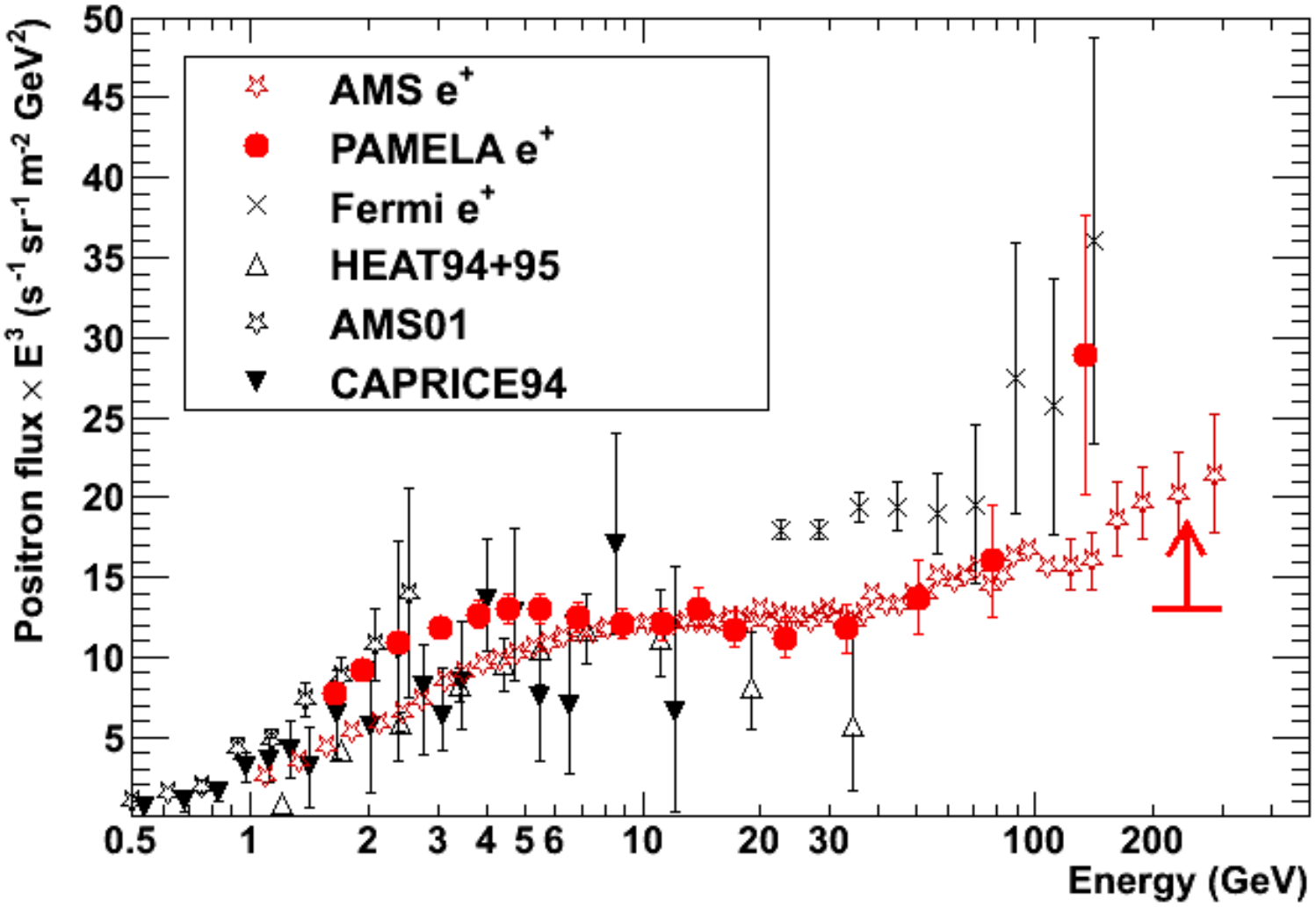
Positron fraction



O. Adriani et al., Phys. Rev. Lett. 111, 081102 (2013)

Positron flux

O. Adriani et al., Phys. Rev. Lett. 111, 081102 (2013)

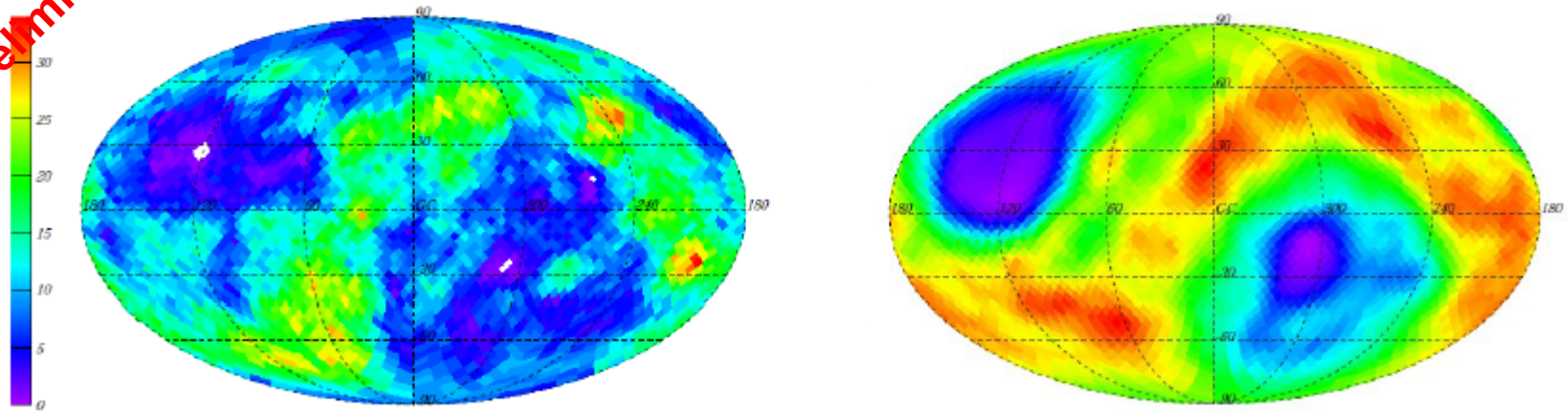


Positron: isotropic distribution

Preliminary

Event map | **Background map**

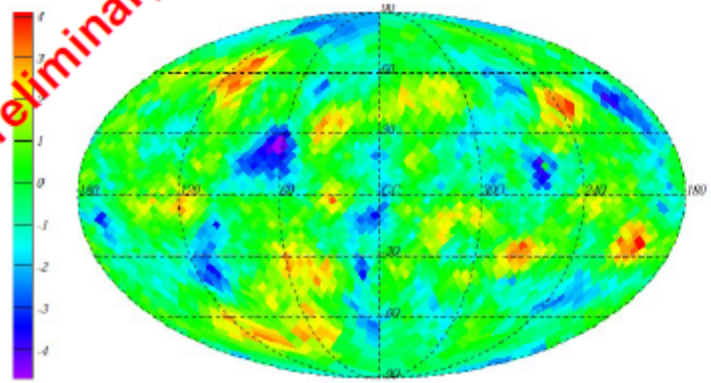
Angular scale 10°

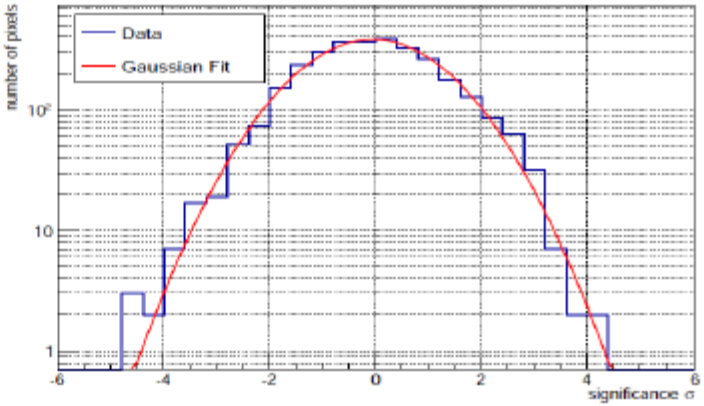


Significance sky map as a function of the integration radius

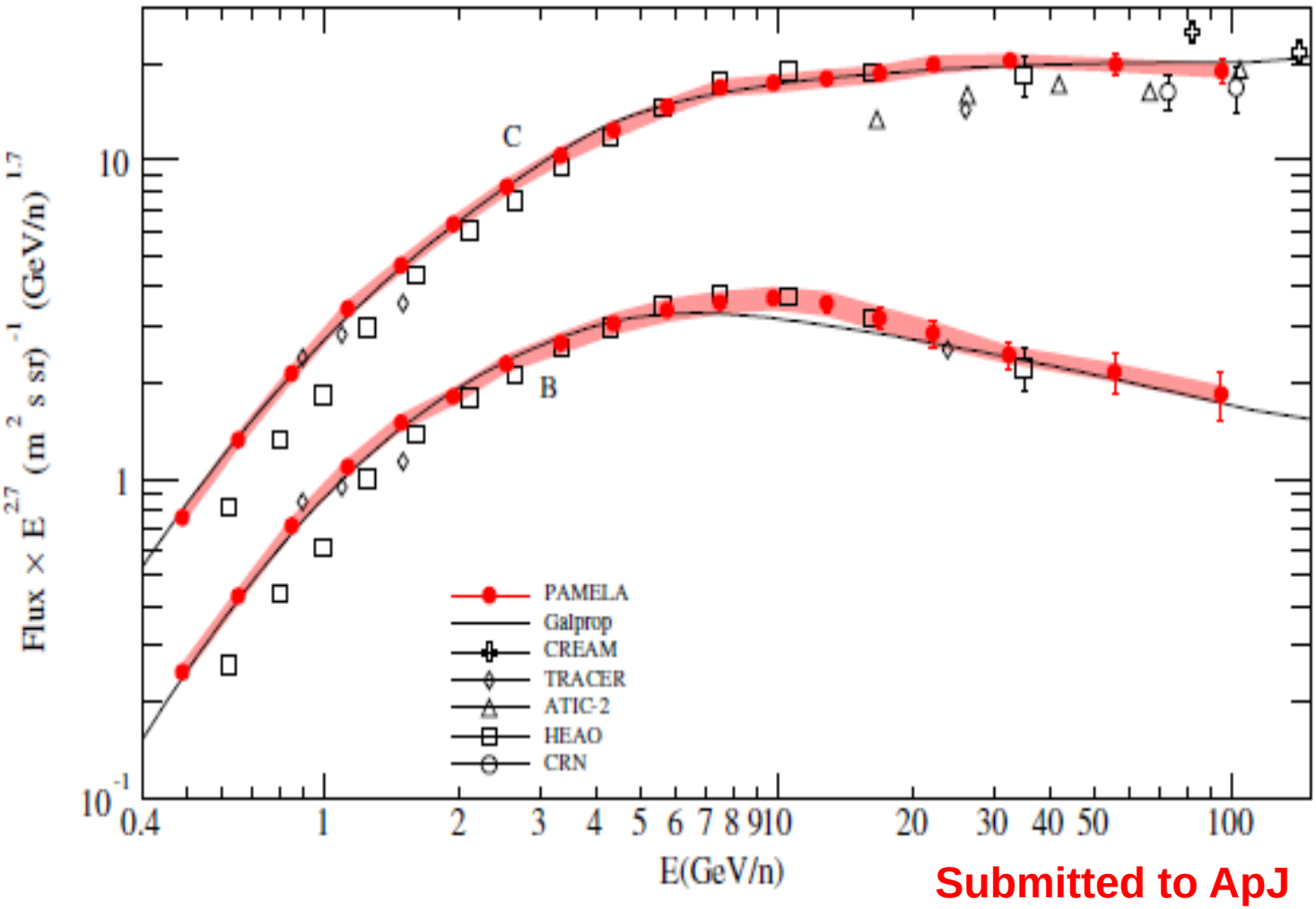
Preliminary

Angular scale 10°

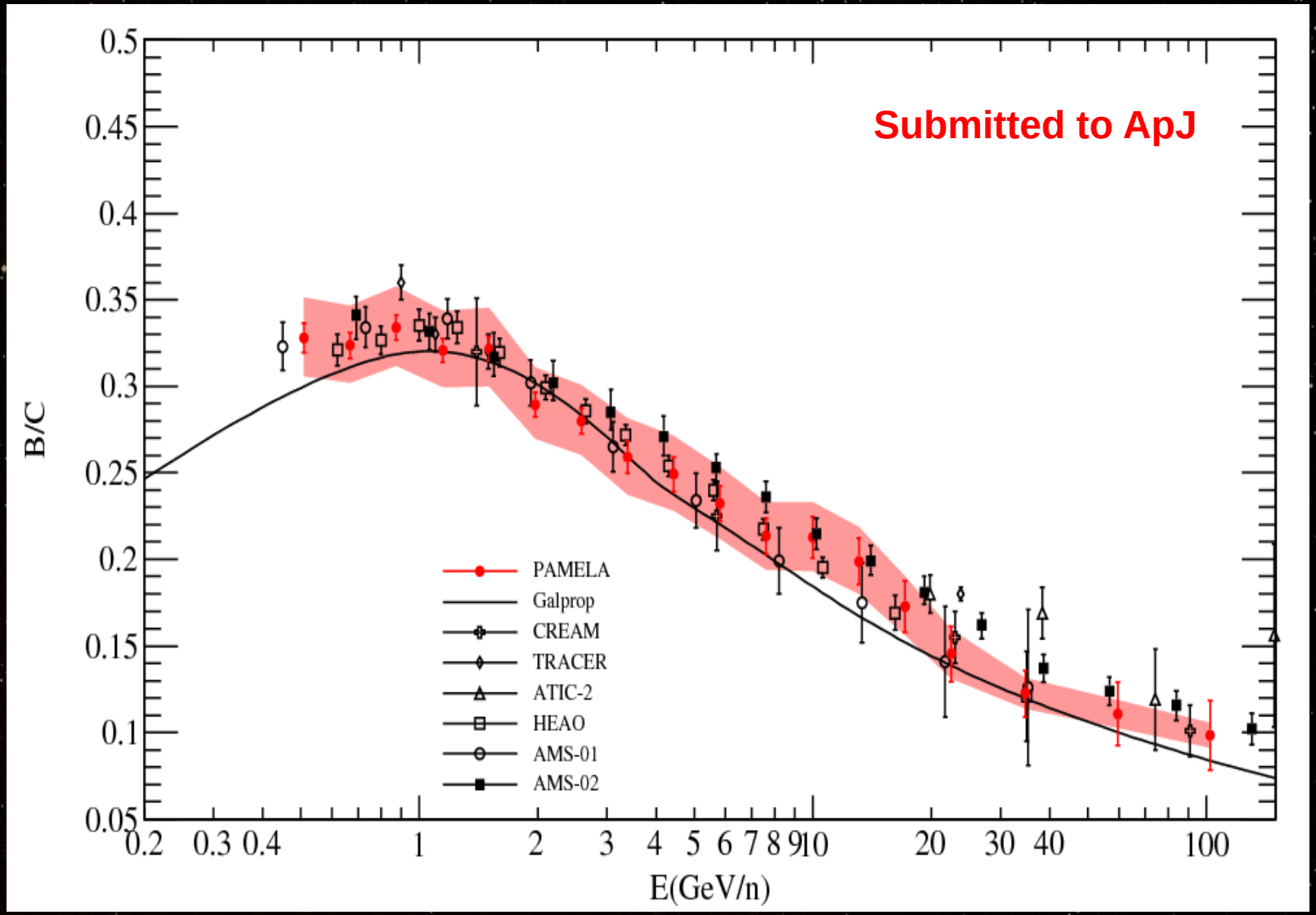




Boron and Carbon nuclei Spectrum



PAMELA B/C


Submitted to ApJ
B/C
E(GeV/n)
PAMELA
Galprop
CREAM
TRACER
ATIC-2
HEAO
AMS-01
AMS-02

Secondary Cosmic Rays

Standard paradigm:

antiparticles: secondaries from homogeneously distributed interstellar matter

PAMELA measurements:
anti-protons, positrons, light nuclei spectra
anti-protons as expected, positrons source?

Implications:
challenging standard paradigm: close local source of electrons and positrons? electrons and positrons astrophysical sources (PWN, mini black-holes,...)? dark matter decay/annihilation?

Cosmic Rays in the Heliosphere

Cosmic rays in the Heliosphere

e^-

γ_s

p, He, C
N, O

e^- e^+

Bremsstrahlung, Synchrotron,
Inverse Compton

decay

ISM gas

π^+, π^-

γ_s

π_0
decay

γ_s

CR secondary
production
(pp → X)

$\overline{p}$

p, He, C,
N, O, Li,
Be, B, ...

Cosmic rays in the Heliosphere

e^-

γ_s

p, He, C
N, O

ISM gas

p, He, C,
N, O, Li,
Be, B, ...

CR secondary production (pp → X)

π^+, π^- decay

π_0 decay

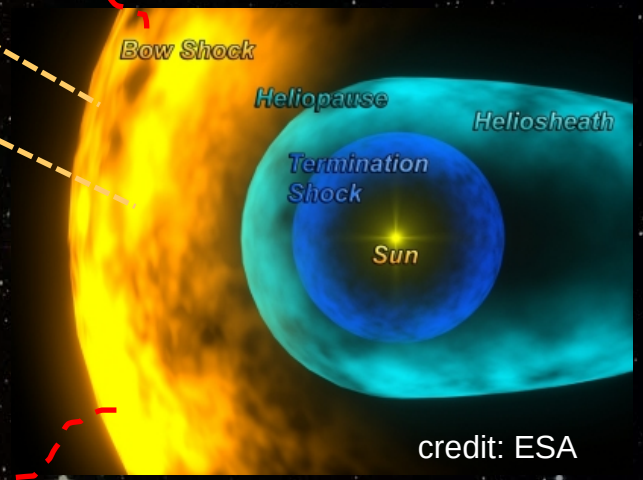
$\overline{p}$

e^- e^+

γ_s

Bremsstrahlung, Synchrotron, Inverse Compton

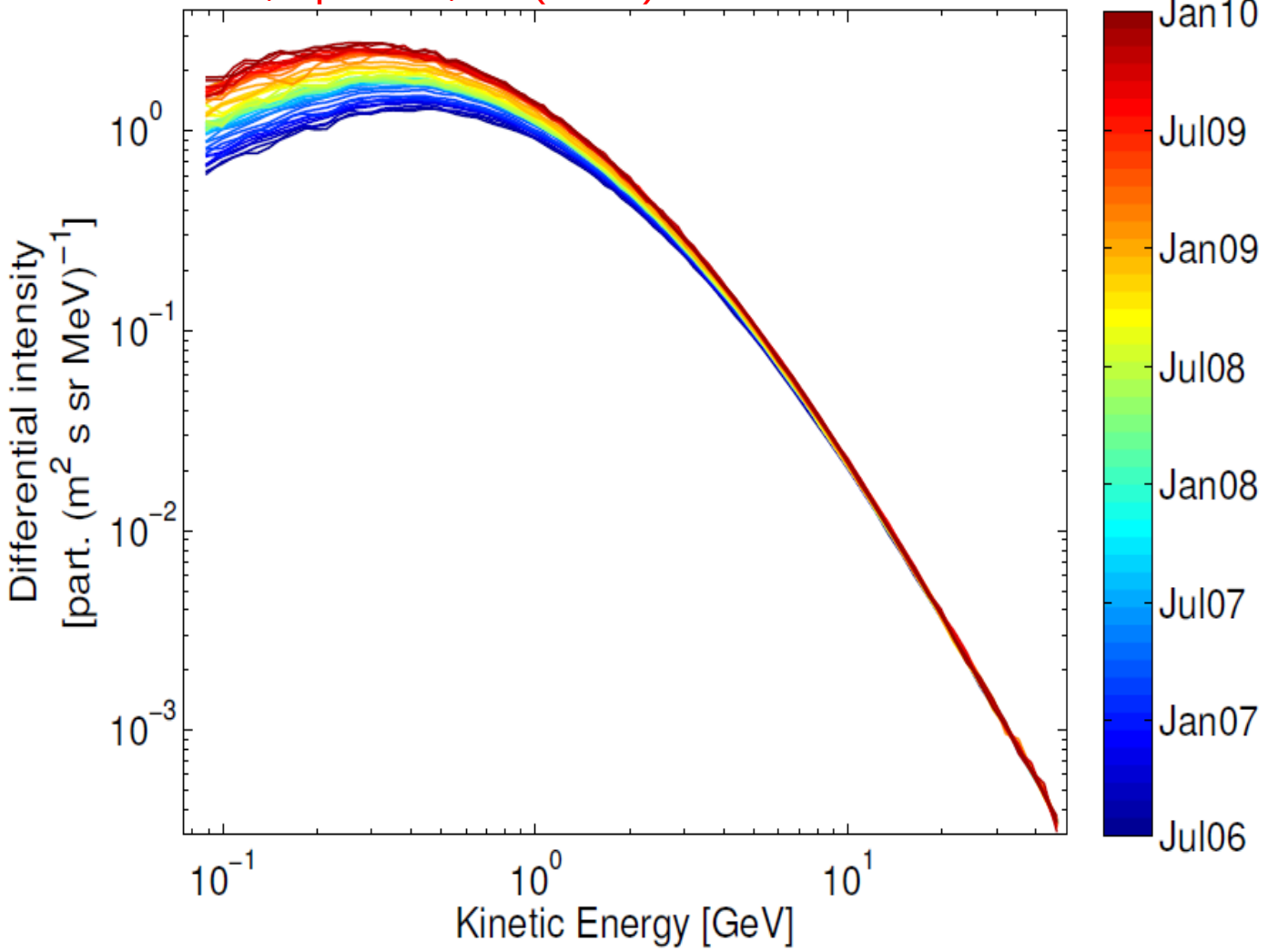
Solar Modulation, lower interstellar cosmic ray spectra



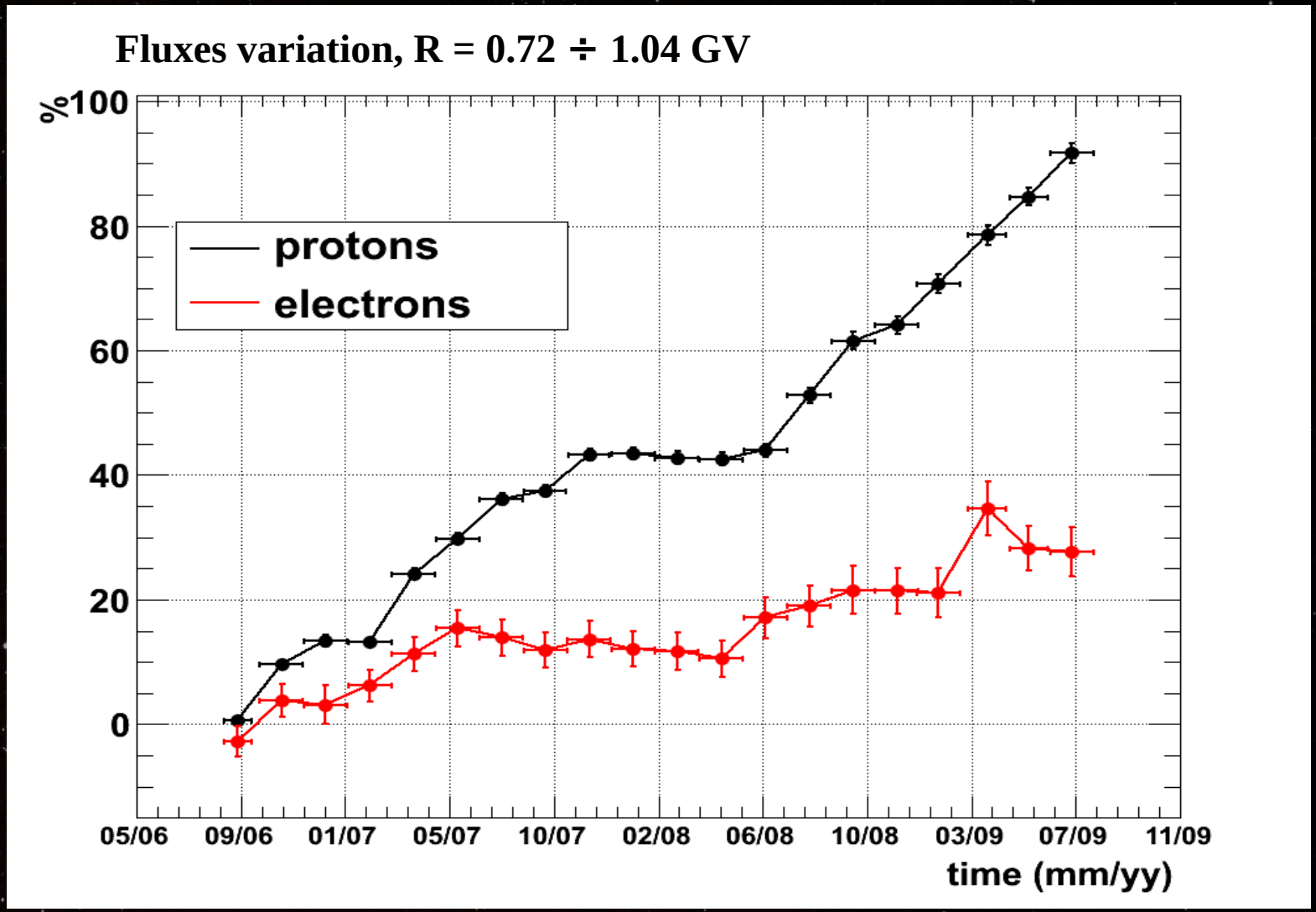
credit: ESA

Time Dependence of Proton Flux

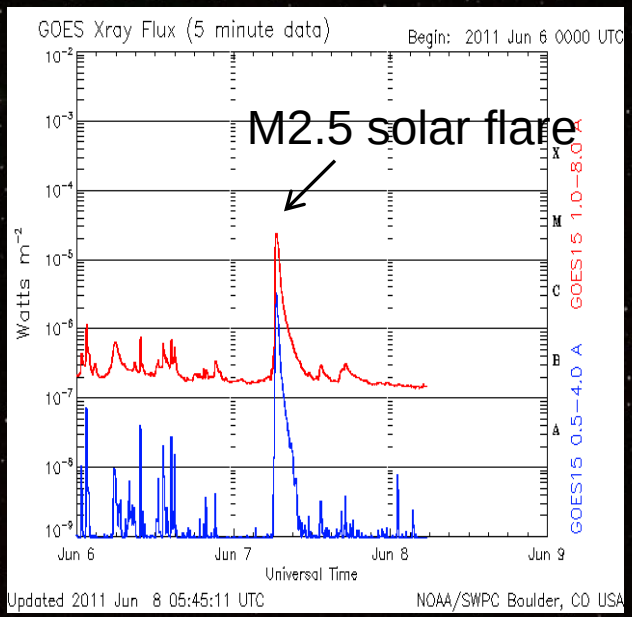
O. Adriani et al., ApJ 765, 91 (2013)

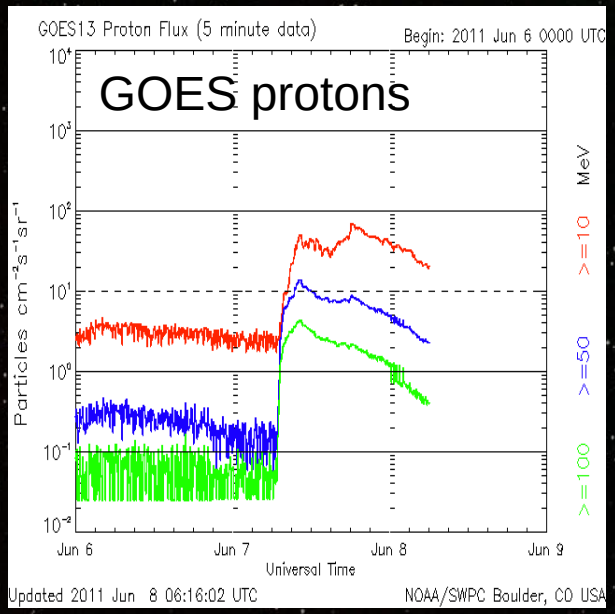


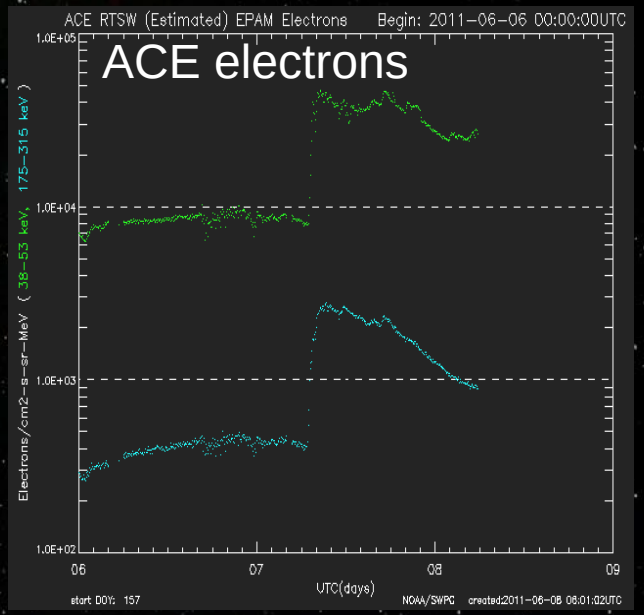
p and e^- : different behavior

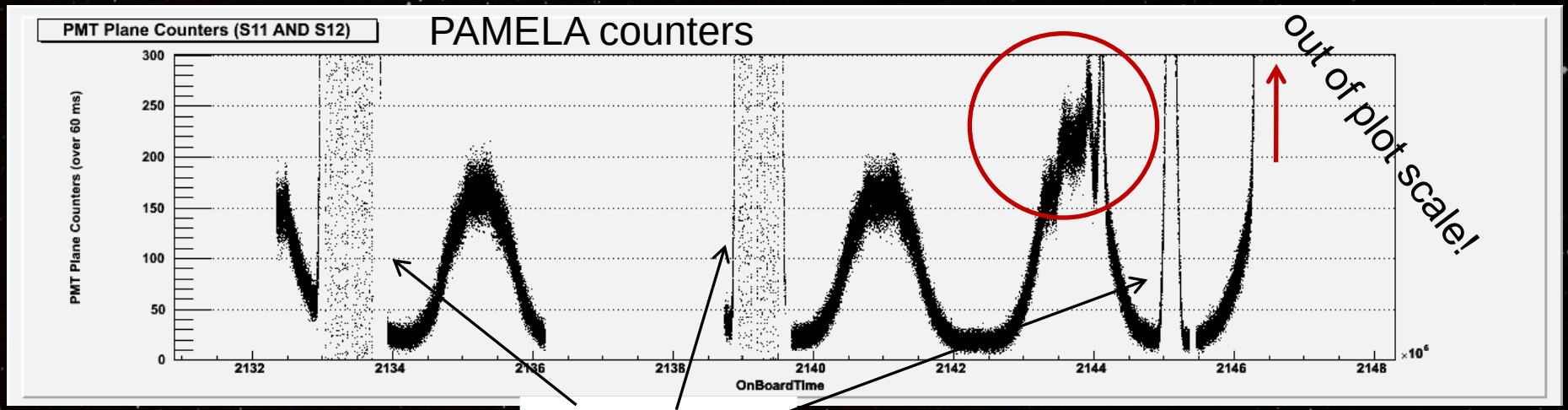


Solar Physics: 7th June 2011

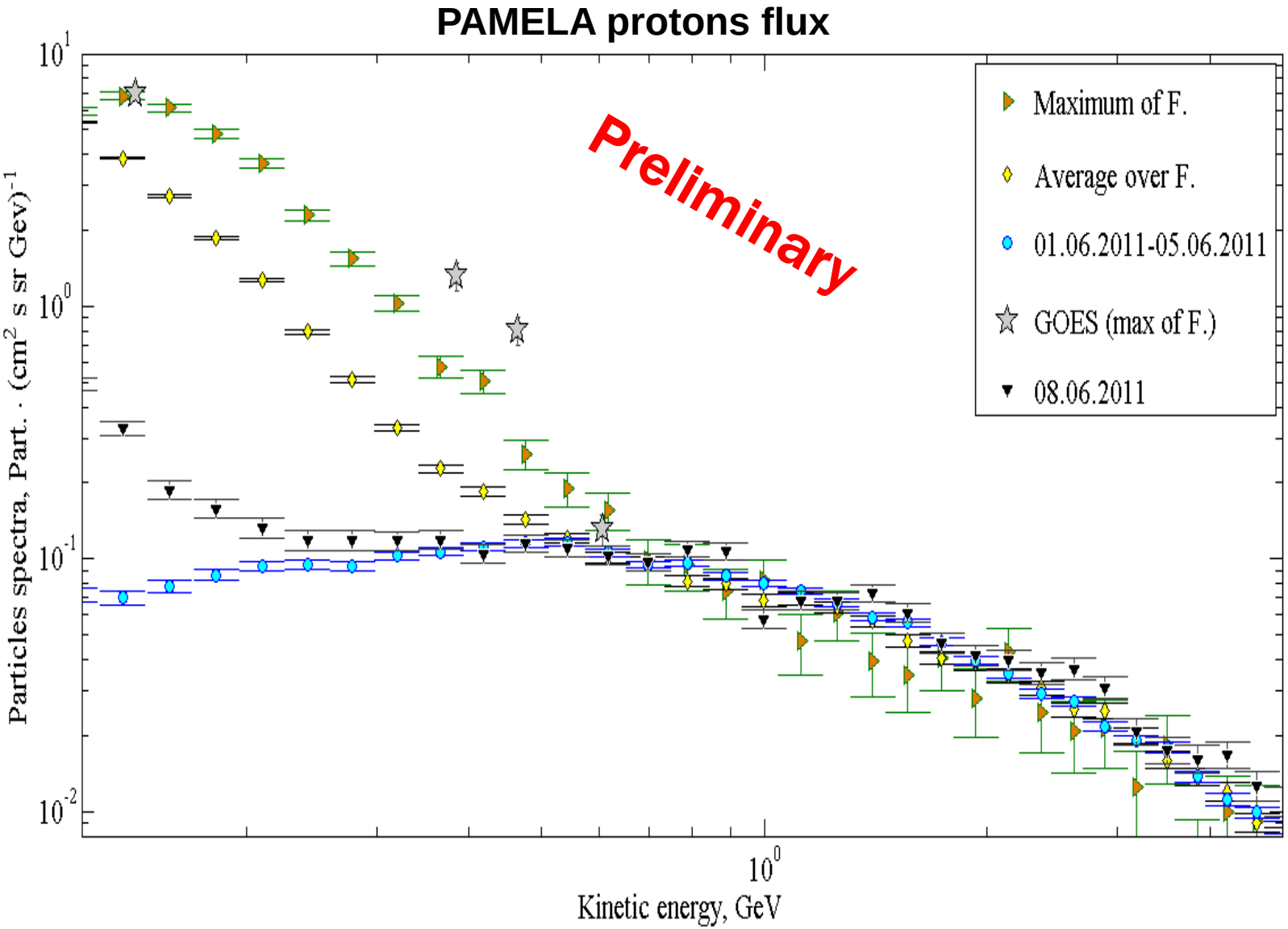








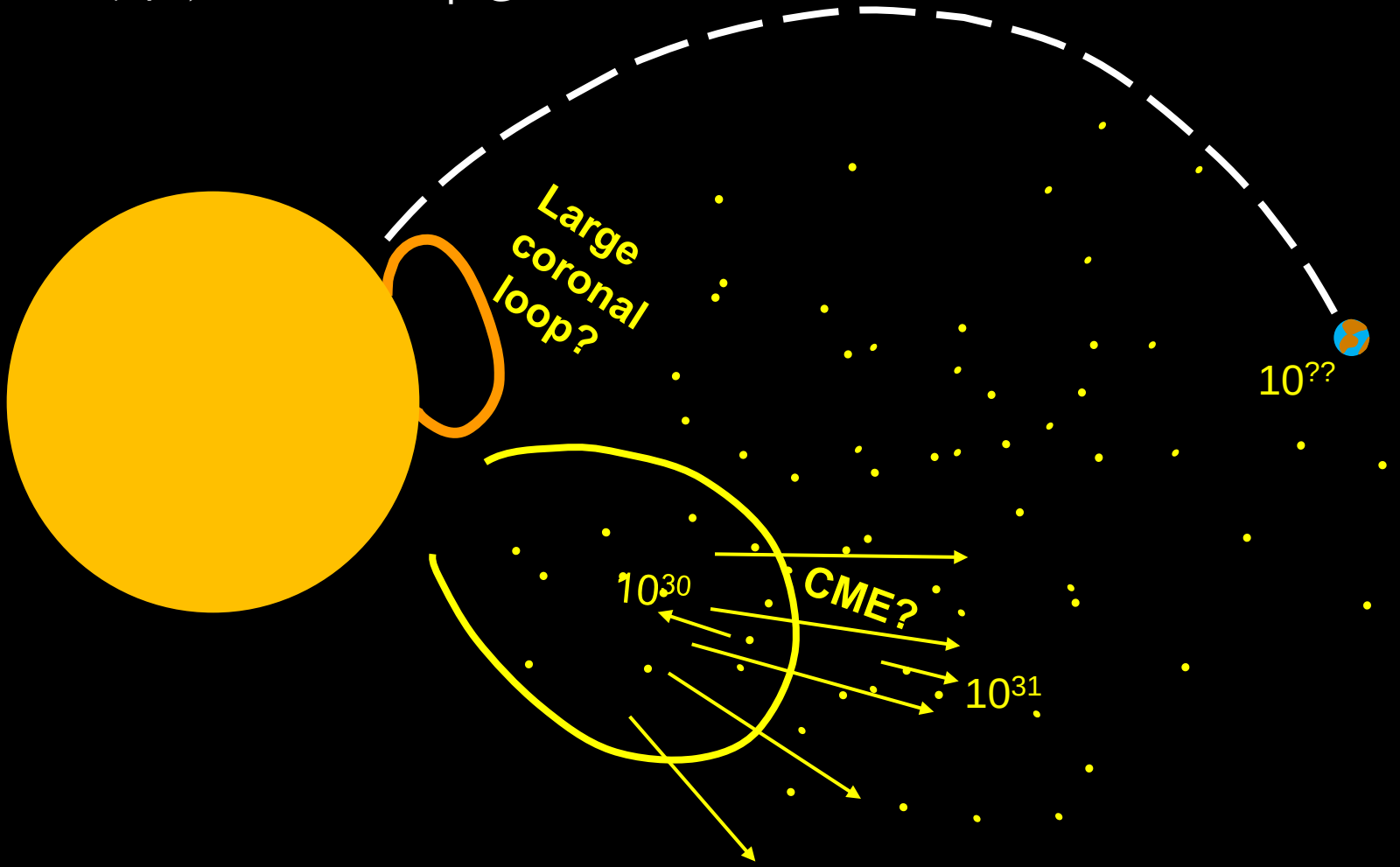
Solar Physics: 7th June 2011



PAMELA and Fermi: correlation between highest SEPs and flare extended emission

Fermi γ (π^0) $\overset{?}{\leftrightarrow}$ PAMELA p @ ~200 MeV

March 7th 2012



Cosmic Rays in the Heliosphere

Common simplified view:

solar effect interpreted using a spherical potential model

PAMELA measurements:

protons, electrons, positrons, light nuclei low energy spectra as function of time (years)

Implications:

Combined with measurements taken out of the ecliptic plane (Ulysses experiment) → determining parameters of a fluido-dynamic model of heliosphere, understanding SEP acceleration mechanism

Cosmic Rays in the Earth Magnetosphere

Cosmic rays in the Earth Magnetosphere

p, He, C
N, O

e^-

γs

Bremsstrahlung, Synchrotron, Inverse Compton

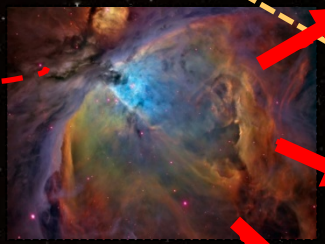
e^- e^+

decay

π^+, π^-

γs

ISM gas



π_0

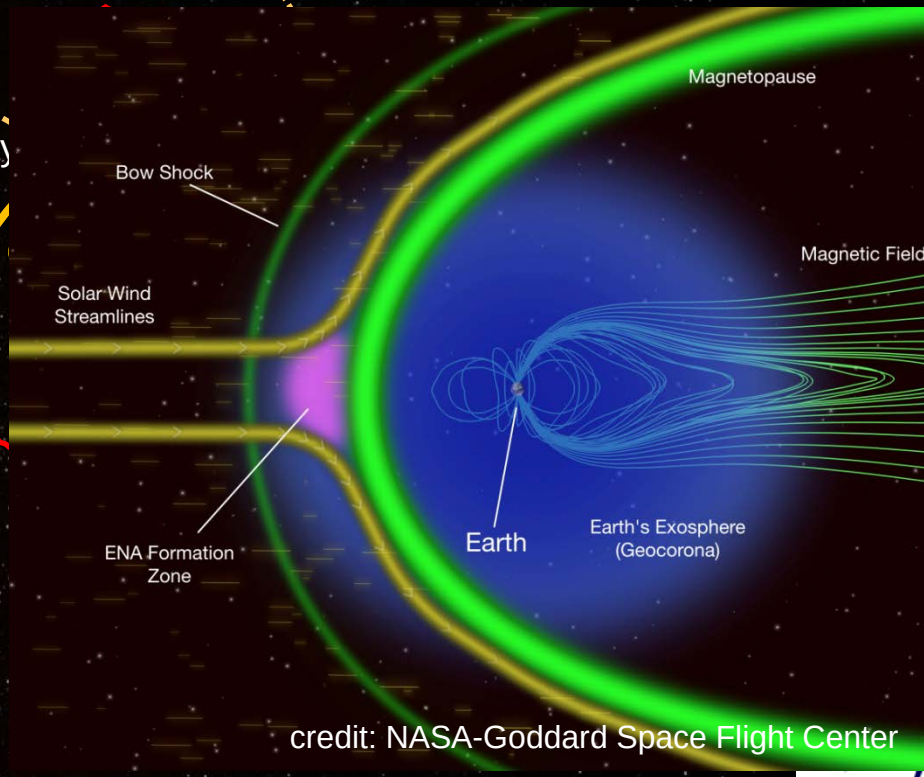
decay

γs

$\overline{p}$

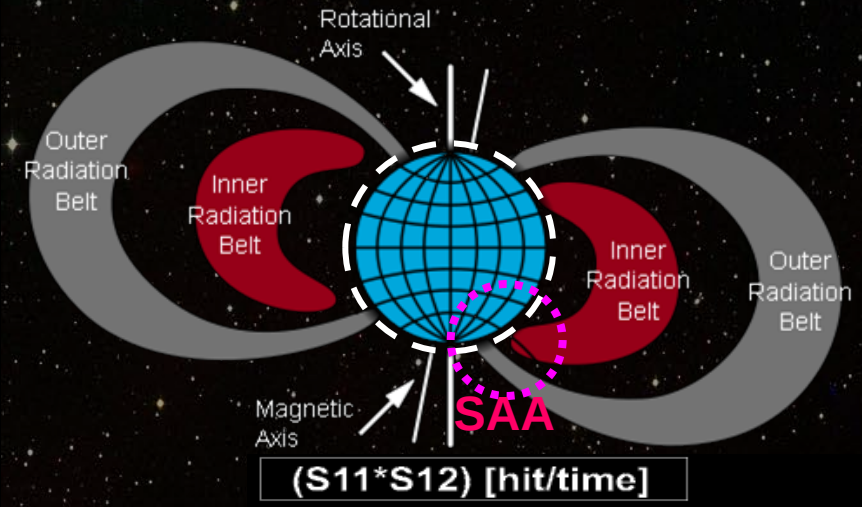
p, He, C,
N, O, Li,
Be, B, ...

CR secondary production (pp → X)

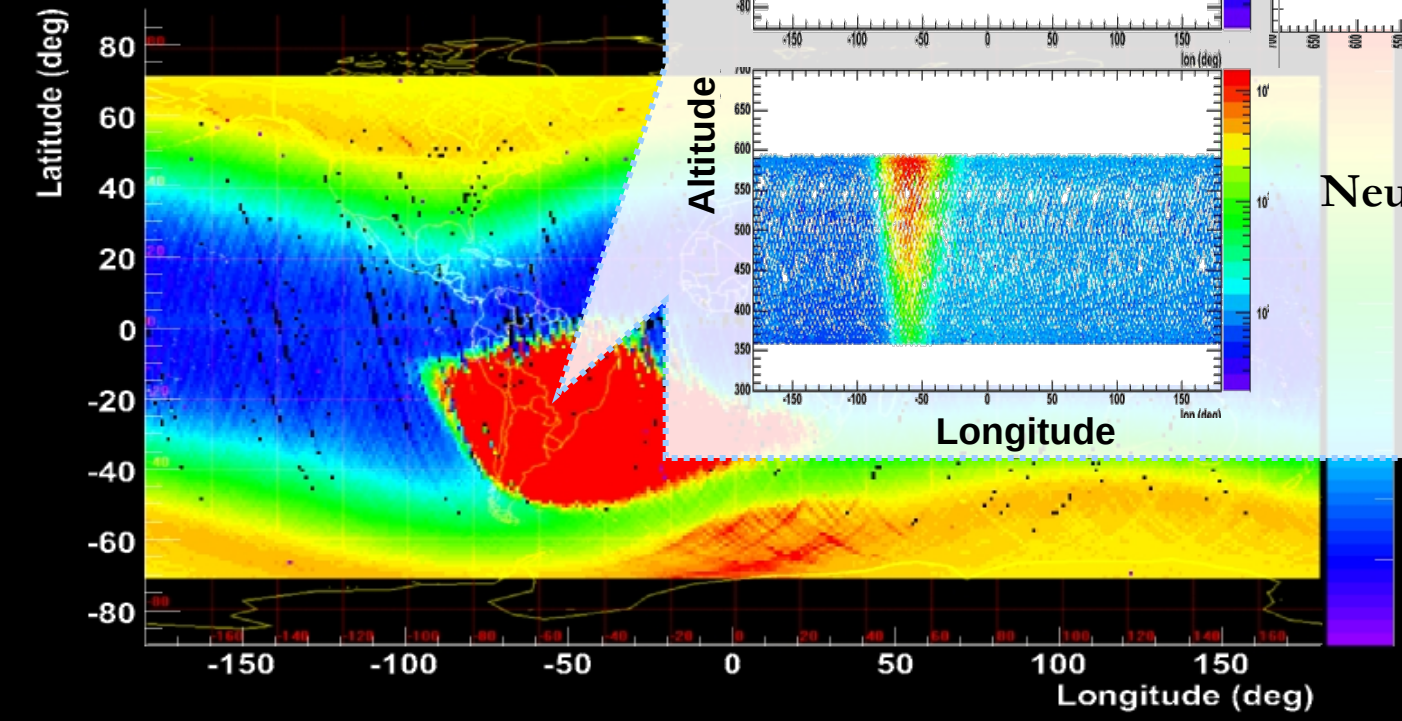


credit: NASA-Goddard Space Flight Center

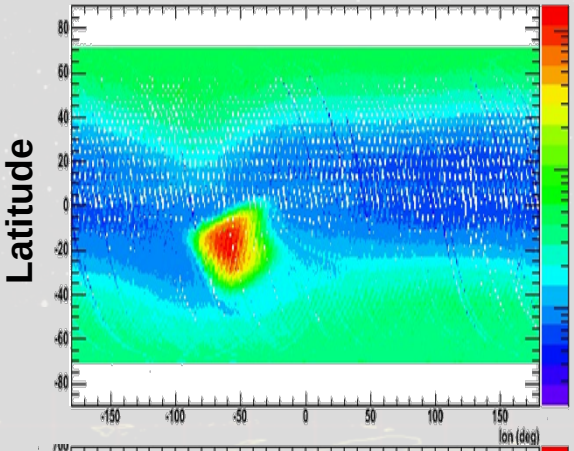
South-Atlantic Anomaly (SAA)

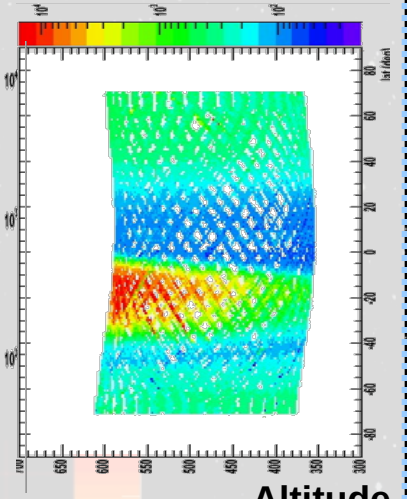


(S11*S12) [hit/time]



SAA morphology

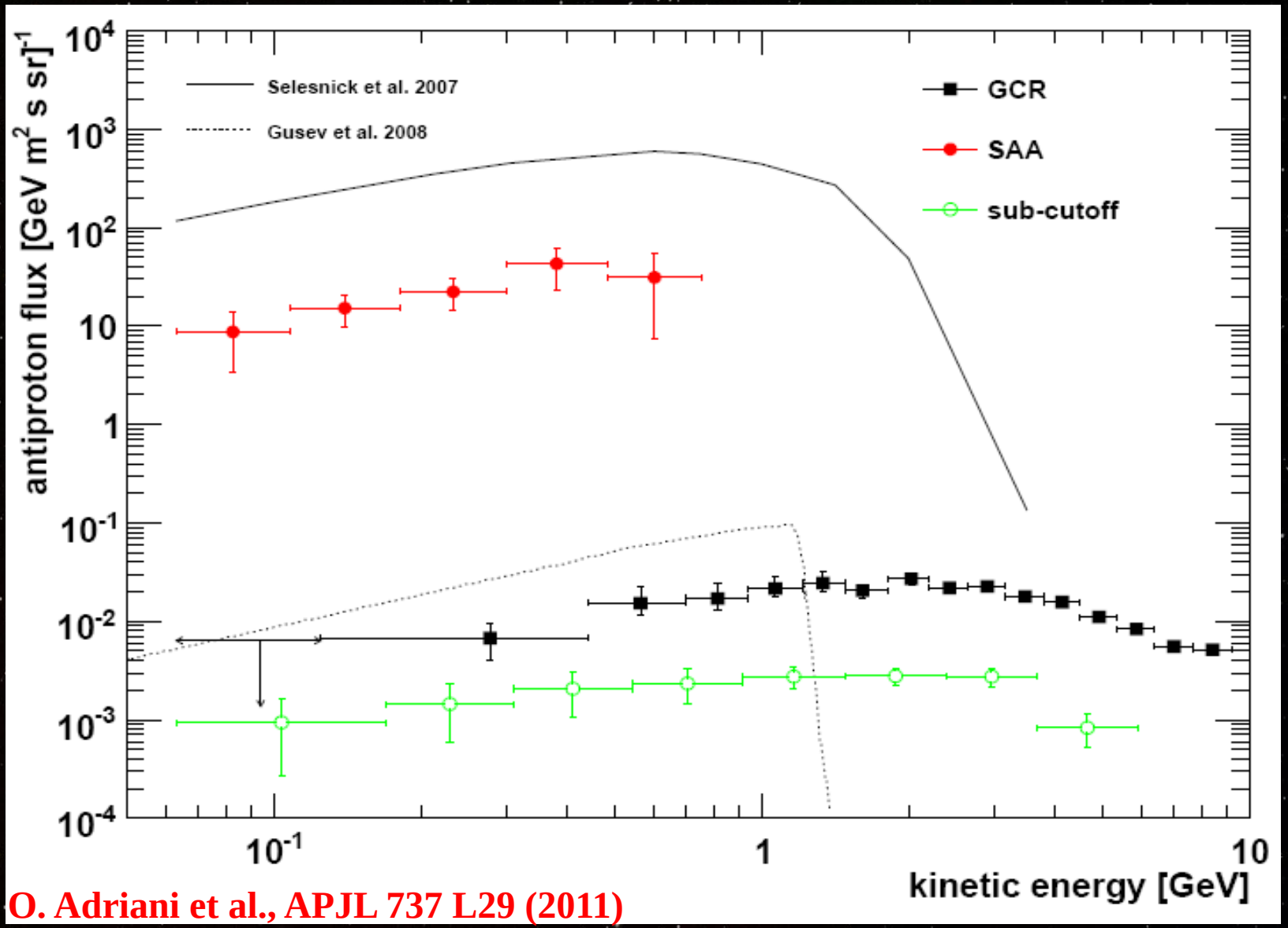




Neutron rate

10^3

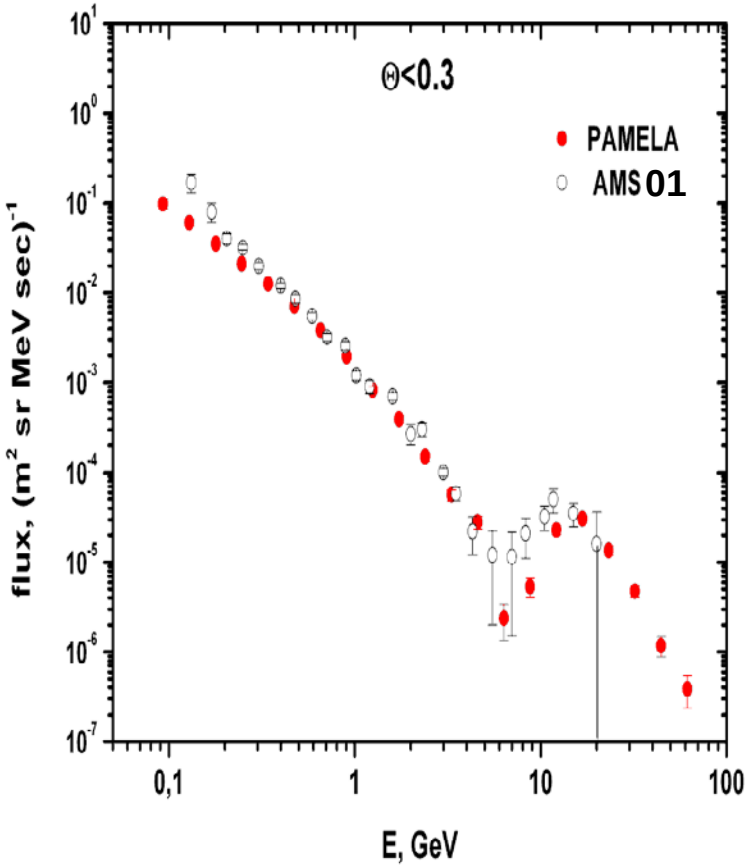
PAMELA trapped antiprotons



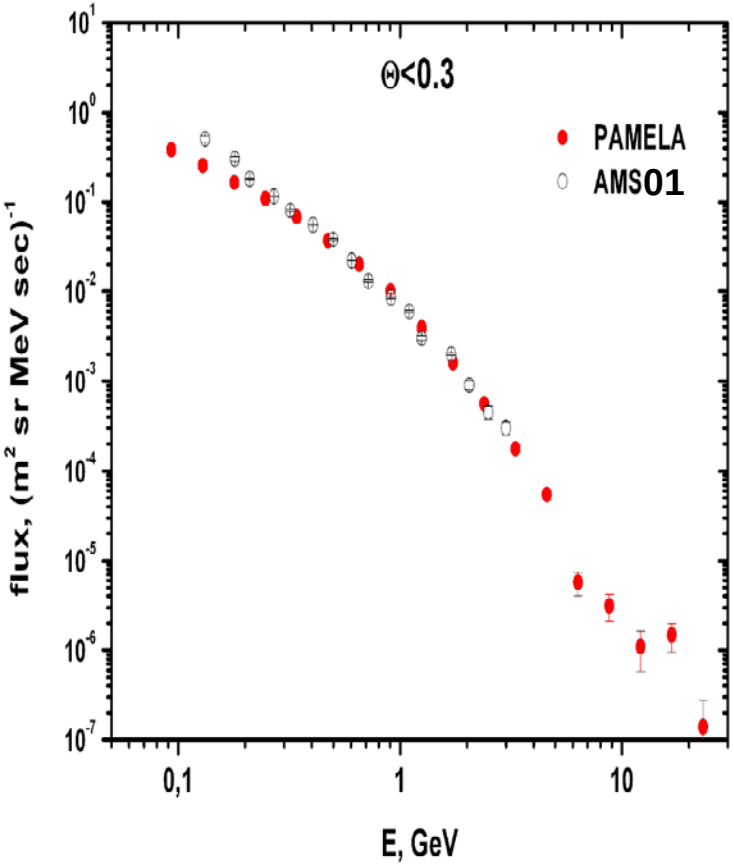
O. Adriani et al., APJL 737 L29 (2011)

Subcutoff particles spectra

e^-

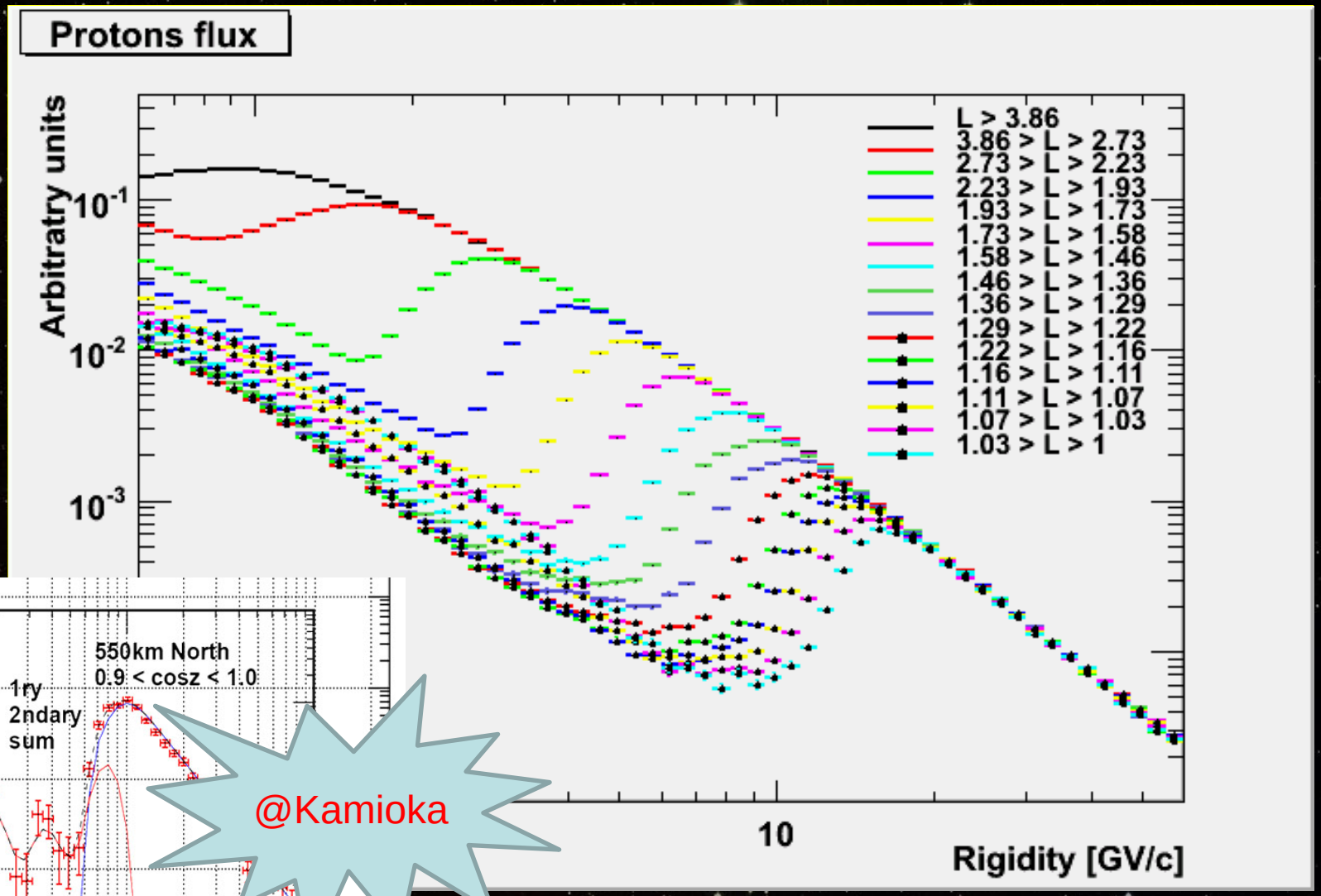


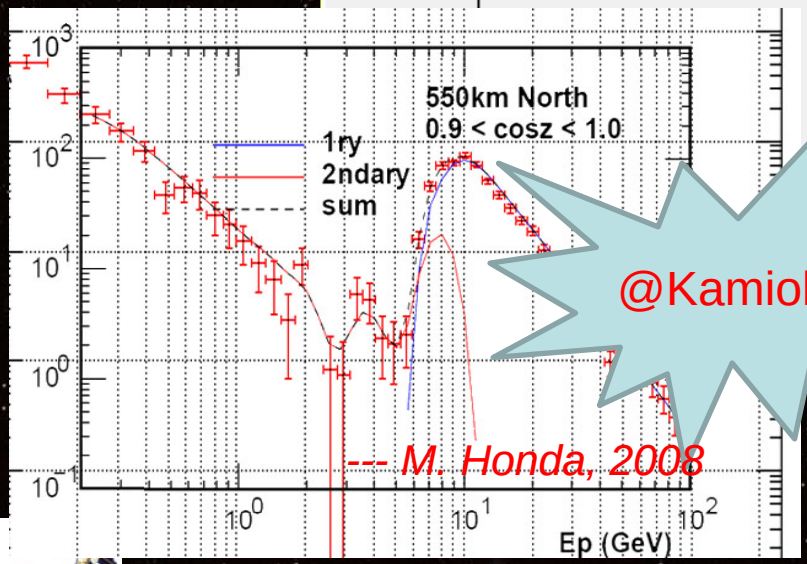
e^+



O. Adriani et al., Journal Geophysical Research, 114, No. A12, 2009

Subcutoff particles spectra





@Kamioka

--- M. Honda, 2008

Cosmic Rays in the Earth Magnetosphere

PAMELA measurements:
protons, antiprotons, electrons, positrons, light nuclei

Useful to:
study atmospheric neutrino contribution, measure astronaut dose on board ISS, indirectly measure cross section in the atmosphere, estimate background of different type of particles for LEO satellites

PAMELA in the dawn of AMS era

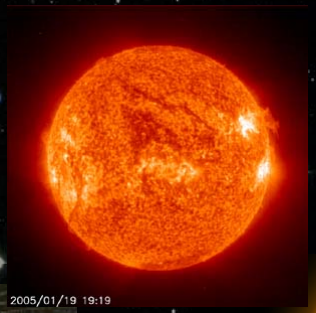
PAMELA is working and acquiring data continuously

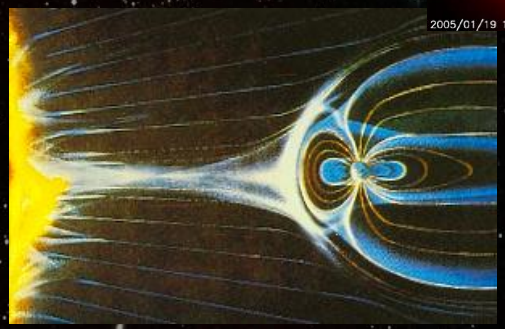
- Most of the detectors are working nominally with small or no effects on physics observables
- Time dependent calibrations and off-line corrections compensate for aging effects on detectors and electronics
- Reduced tracking efficiency makes low intensity fluxes more difficult to be detected

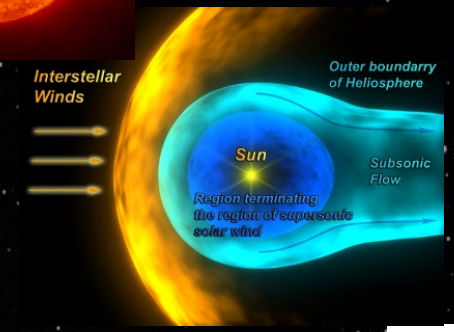
High intensity, low energy fluxes for:

- **studying solar physics**
- **studying solar modulation and heliosphere**
- **studying terrestrial magnetosphere**

over a long time window.







Astroparticle physics below 1 GeV with re-processed PAMELA data

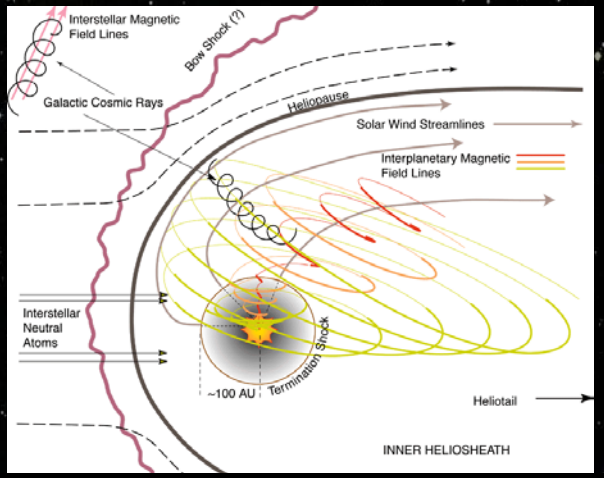
European Commission - Research - Participants
Proposal Submission Forms
European Research Council Executive Agency

(Astro-PAM)

Proposal ID **647303** *Acronym* **Astro-PAM**

1 - General information

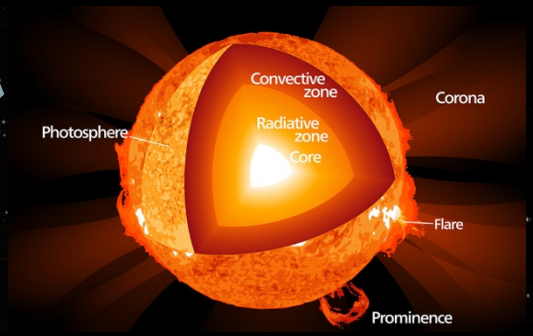
Topic	ERC-CoG-2014	Type of action	ERC-COG
Call identifier	ERC-2014-CoG	Acronym*	Astro-PAM
Proposal title*	Astroparticle physics below 1 GeV with re-processed PAMELA data		



Data analysis down to **MeV region**:

- **new trigger** configuration
- **new** data analysis **software** (low energies!)
- same experiment, full **new data set**
- **GPU cloud** processing

set the basis for a better modelling of the heliosphere

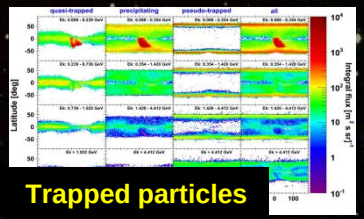


unlock new type of studies on solar events

Space travels Mars

Life in space

New space experiments

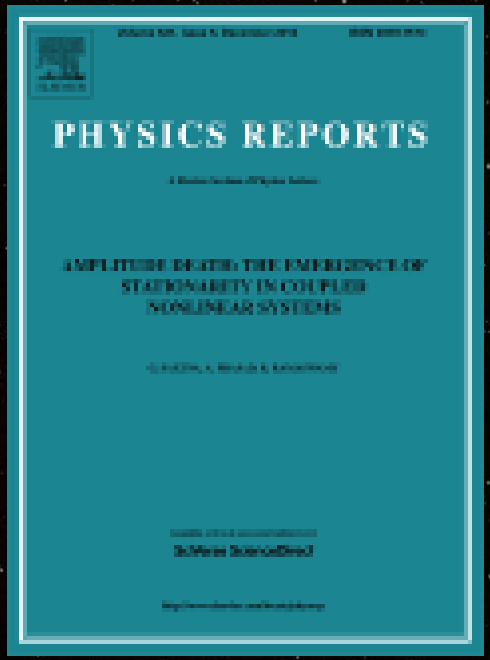


Trapped particles

Summary

- PAMELA has been in orbit and studying cosmic rays for 2900 days (almost 8 years!); $>10^9$ triggers registered and >45 TB of data have been down-linked.
- PAMELA lifetime extended, unlimited and depending on satellite operations.
- Many very interesting measurements from PAMELA, which are challenging astroparticle physics standard model.
- Analysis ongoing to finalize the antiparticle measurements (positron anisotropy), continuous study of solar modulation, solar flares and magnetosphere at low energy.
- Good agreement between PAMELA and AMS results.

Summary of PAMELA results



"The PAMELA Space Mission: Heralding a New Era in Precision Cosmic Ray Physics"

To appear on Physics Reports

(78 pages)

Summarizes published and unpublished (but final) PAMELA results.