Direct measurements of cosmic rays in space

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Primary and secondary CR's

Astroparticle physics in space is performed by the detection and analysis of the properties of **Cosmic Rays**.

The **primary Cosmic Rays** reach the top of the atmosphere, without interacion.

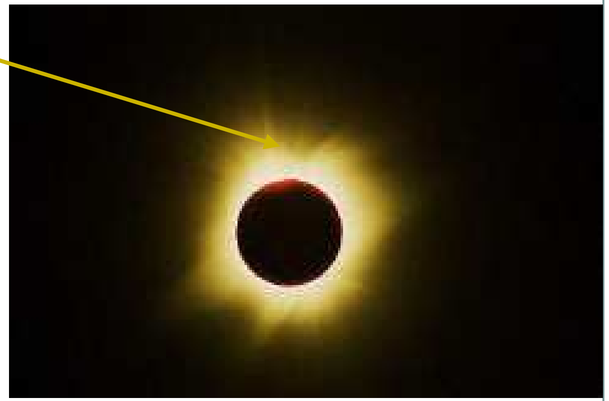
- The atmosphere acts as a *convertor:* the interaction of the CR's with the nuclei in atmosphere produces showers of secondary particles (**secondary Cosmic Rays**).

- The primary radiation can be studied **directly** only above the terrestrial atmosphere.

- The primary cosmic radiation is affected by the effect of the Solar System magnetic fields: the **Earth's magnetic field** and the **Solar magnetic field**.

The influence of the Sun

The photosphere, visible surface of the Sun, has a temperature of T=6000 ºK, but the overlying corona has a T exceeding 10^6 ºK.

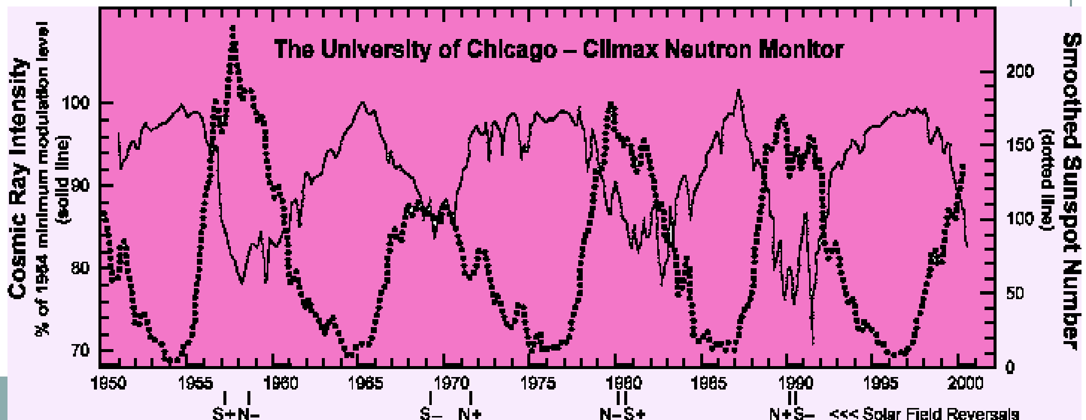


At these temperatures, part of the ionized gas of the solar ambient has speed enough to escape the solar gravitational attraction.

→ **Solar Wind**

Antimodulation of CR:

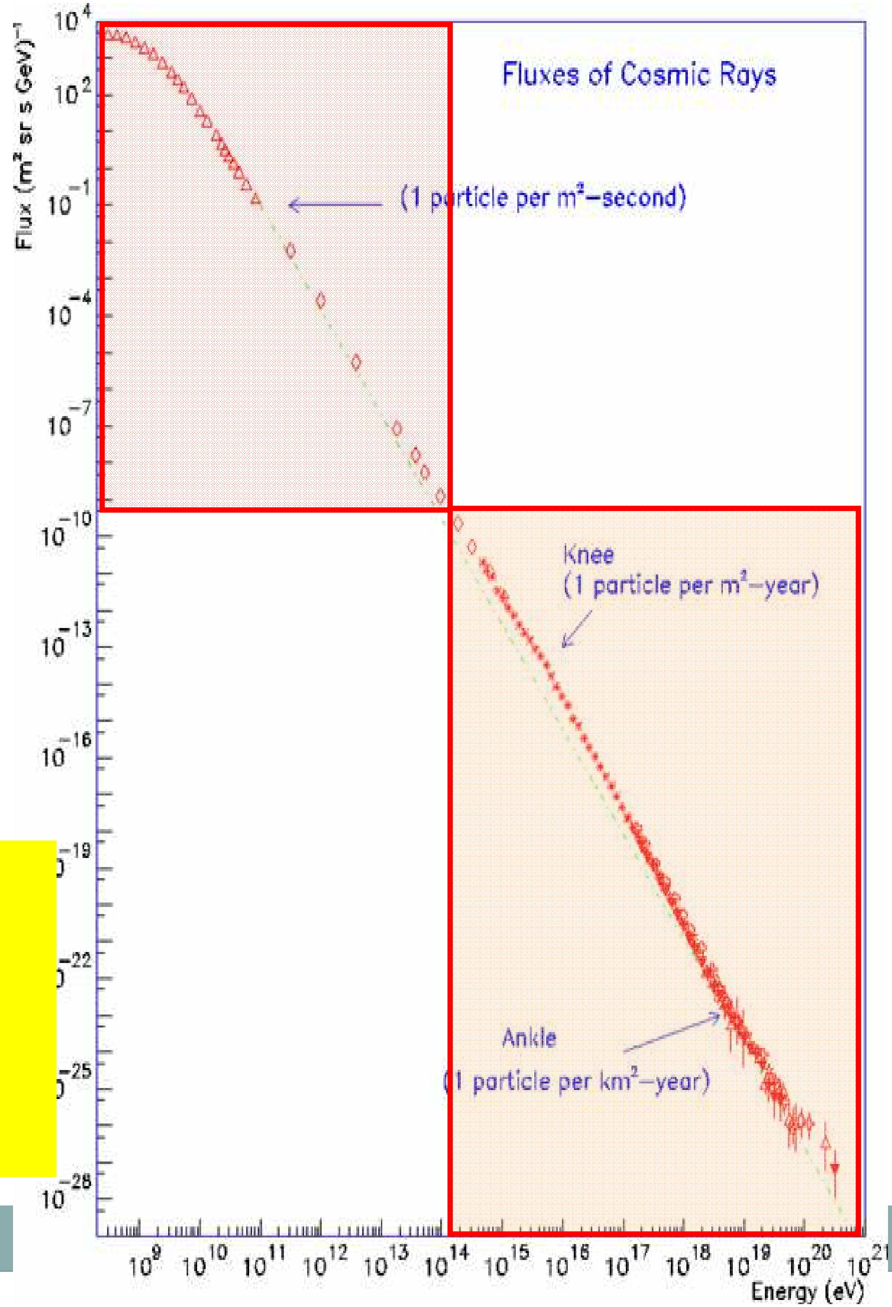
neutron monitors at ground found an anti-correlation between the particle fluxes and the sunspot number (solar activity cycling every 11 years).



How to measure cosmic rays

- Directly, E<10^{14} eV
  - High Z particles
  - Antiparticles
  - Light Nuclei and isotopes
  - Composition below the knee
- Indirectly, E>10^{14} eV
  - Composition at the knee
  - UHECR

  (Chiavassa's talk tomorrow)



Fundamental questions remain unanswered!

- **What is the origin of this extra solar system matter?**
  - Do GCR come from a single class of source?
  - Can individual sources be detected?
  - What does the GCR composition tell us about the nucleosynthetic history of this matter?
- **How does this matter get accelerated to such high energies?**
  - Are there different astrophysical sites associated with different energy regimes?
- **Are there signatures of any exotic physics?**
  - Are there anti-matter regions in the universe?
  - Can we detect 'effects' associated with "Dark Matter"?

P. BLASI will say something about that soon…

Main physics research lines

-- **The High Energy Frontier** (Sources, Acceleration)

-- **The Composition Frontier** (source material, dust/gas, nucleosynthesis, selection effects)

-- **The Anti-matter Frontier** (dark matter limits, anti-matter limits, non-SNR contributions, nearby sources)

According to the physics line, different platforms and detections techniques have been adopted.

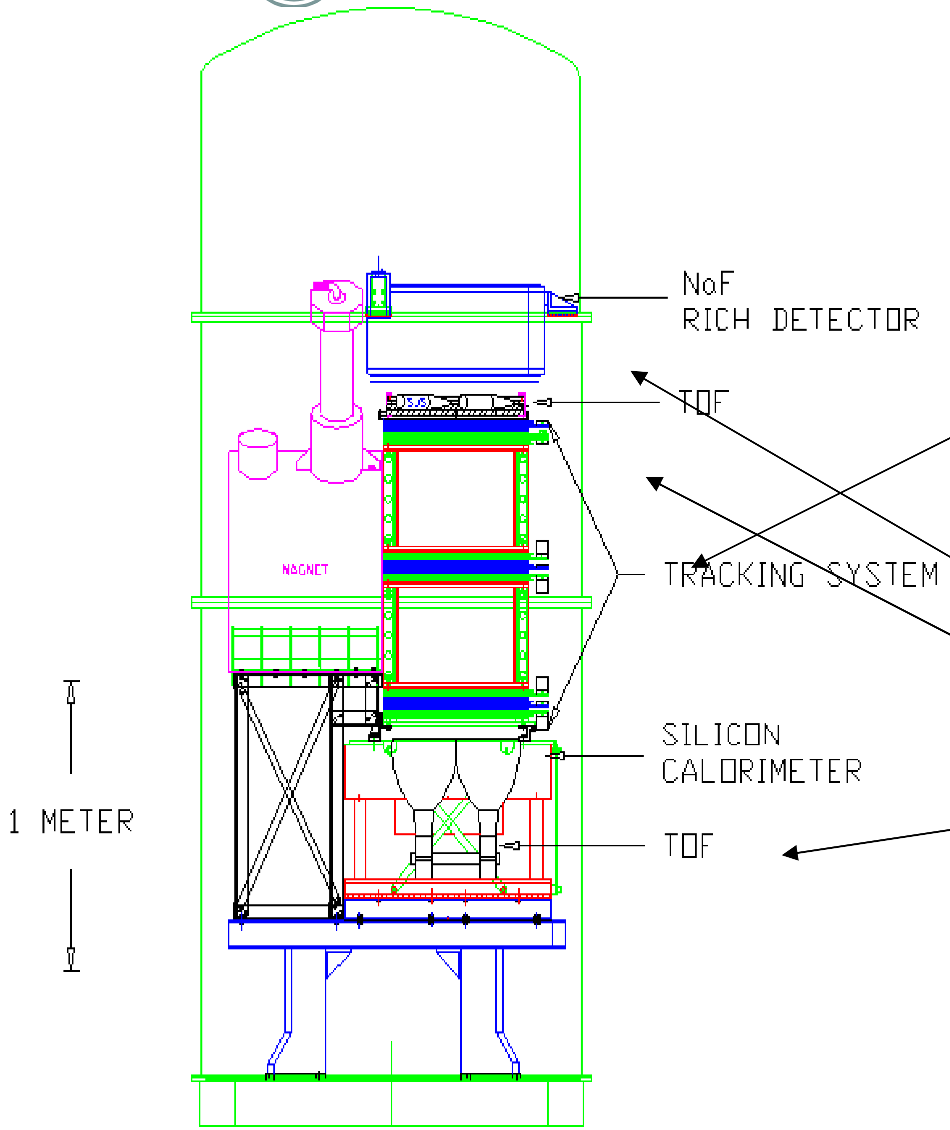
Stratospheric balloons

The antimatter balloon flights: overview

Aim of the activity is the detection of antimatter and dark matter signals in CR nei RC (antiprotons, positrons, antinuclei) for energies from hundreds of MeV to about 30 GeV, and measurements of primary CR from hundreds of MeV to about 300 GeV.

6 flights from the WIZARD collaboration: **MASS89, MASS91, TRAMP-SI, CAPRICE 94, 97, 08**. The flights started from New Mexico or Canada, with different geomagnetic cut-offs to optimize the investigation of different energy regions. The flights lasted about 20 hours.

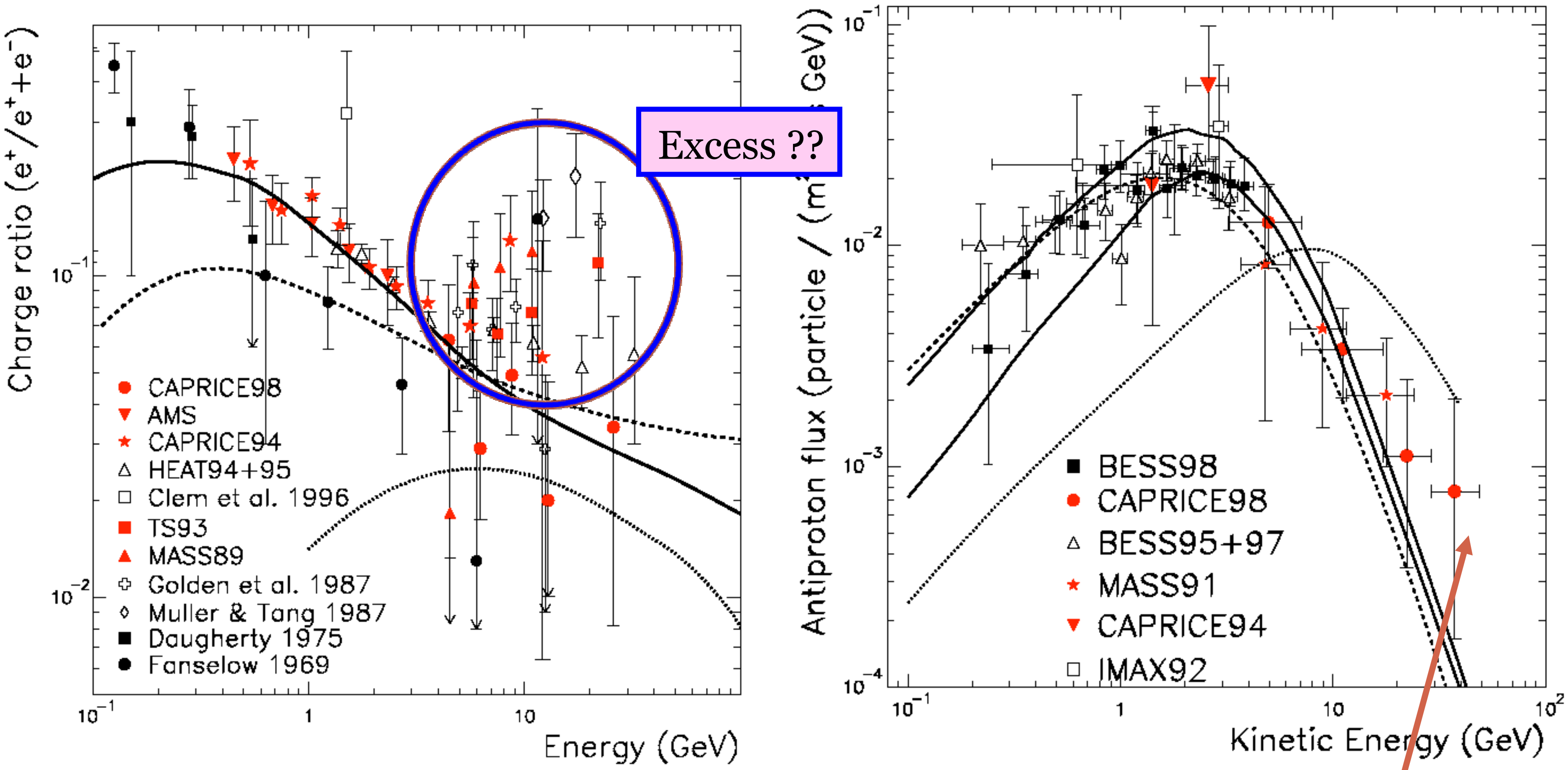
4 flights from the HEAT collaboration: 2 **HEAT-e+**, in 1994 and 1995, and 2 **HEAT-pbar** flights, in 2000 and 2002



- Charge sign and momentum determination;
- Beta selection
- Z selection
- hadron – electron discrimination

CAPRICE-94

Results from MASS/TrampSI/CAPRICE/HEAT: Positrons & antiprotons



Highest energetic points available from balloons

The BESS program

- The BESS program had **11 successful flight campaigns since 1993 up to 2008.**
- Aim of the program is **to search for antimatter (antip, antiD) and to provide high precision p, He, μ spectra**.

- A modification of the BESS instrument, **BESS-Polar**, is similar in design to previous BESS instruments, but is completely new with an ultra-thin magnet and configured to minimize the amount of material in the cosmic ray beam, so as to allow the lowest energy measurements of antiprotons.

- BESS-Polar has the largest geometry factor of any balloon-borne magnet spectrometer currently flying (0.3 m^2-sr).

BESS Collaboration

High Energy Accelerator Research Organization(KEK)

National Aeronautical and Space Administration Goddard Space Flight Center

The University of Tokyo

BESS Collaboration

University of Maryland

Kobe University

University of Denver (Since June 2005)

Institute of Space and Astronautical Science/JAXA

BESS Detector

Rigidity measurement

SC Solenoid (L=1m, B=1T)

- Min. material (4.7g/cm²)
  - Uniform field
  - Large acceptance

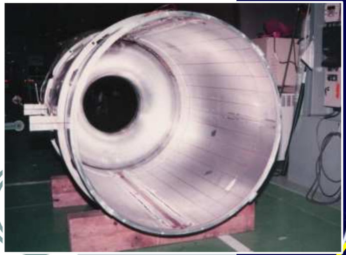
Central tracker

- Drift chambers (Jet/IDC)
  - δ ~200 **μm**

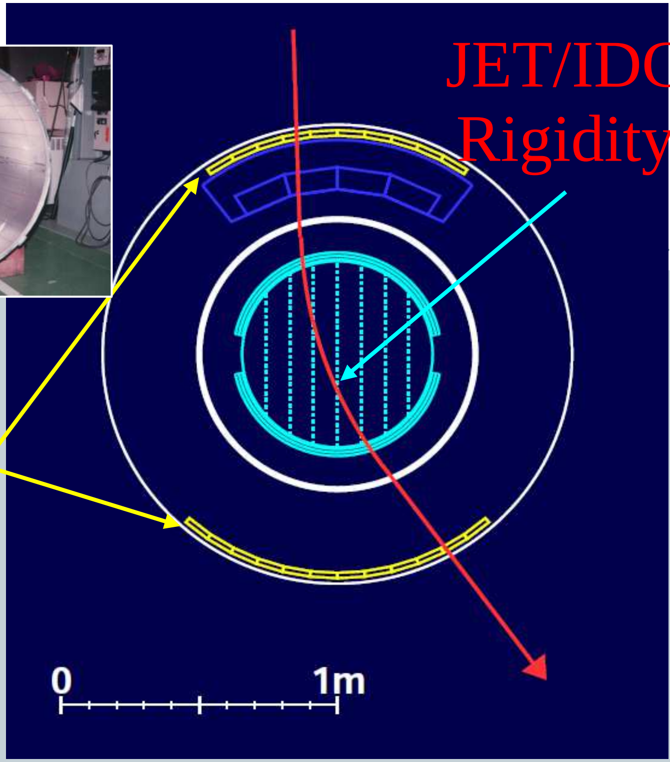
***Z, m* measurement**

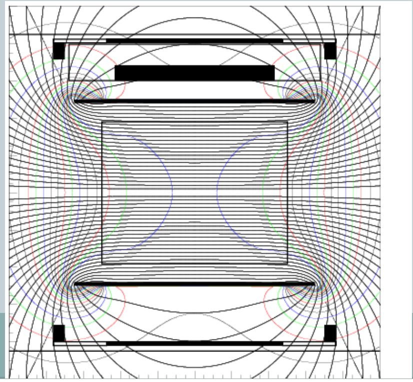
***R*,β --> $m = ZeR\sqrt{1/\beta^2-1}$**

dE/dx* --> *Z



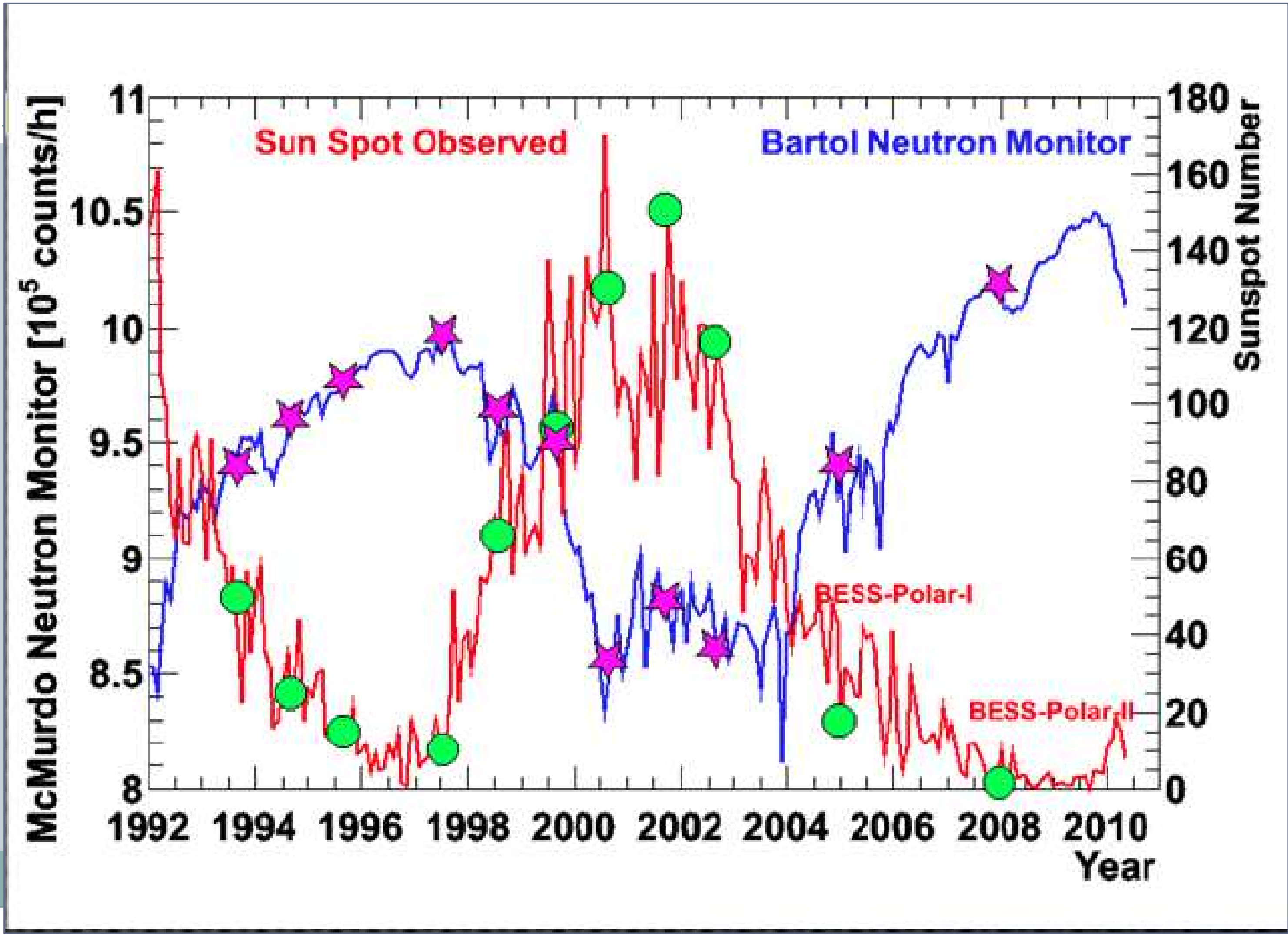
TOF
β, d*E*/d*x*



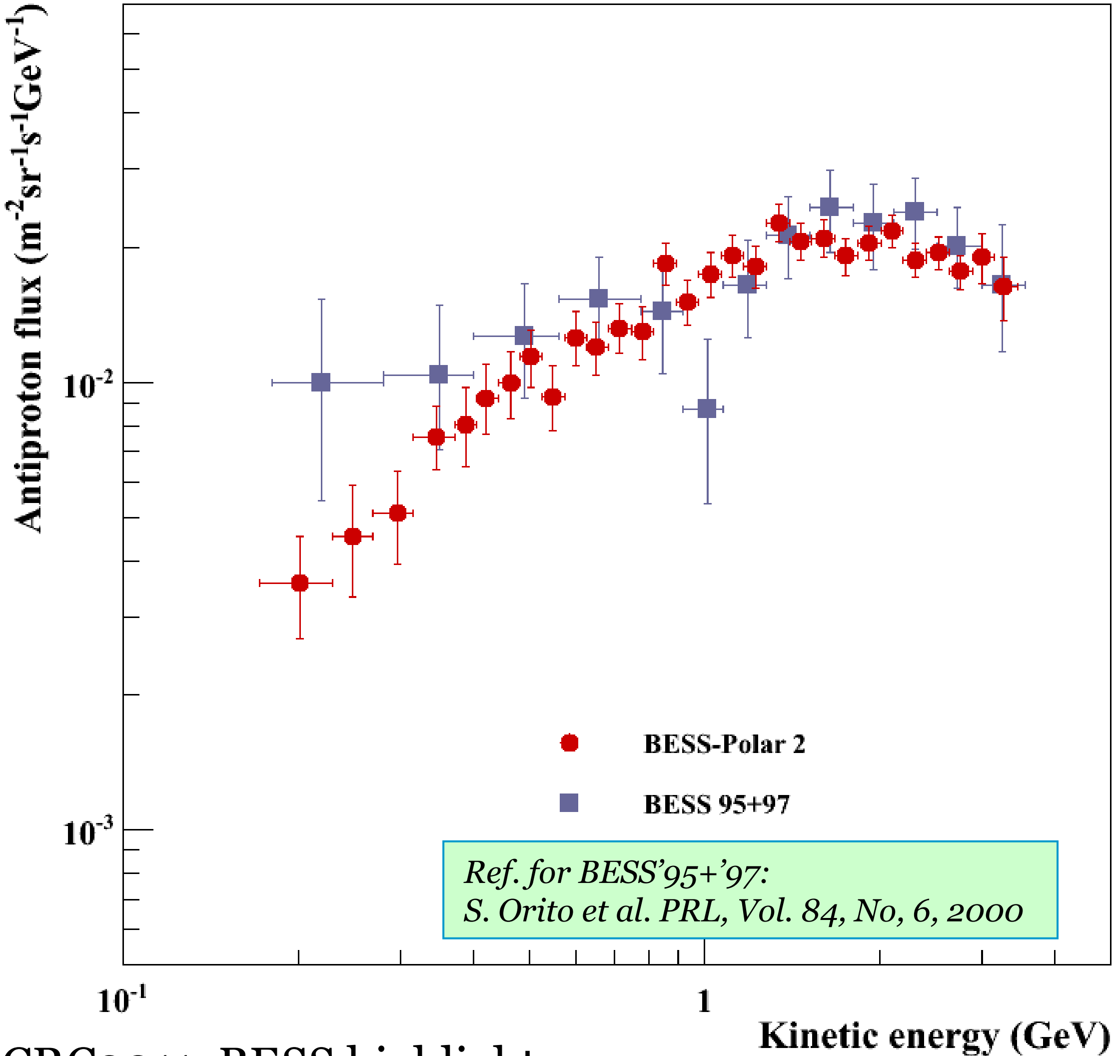


BESS-Polar I and II

Long duration flights of total **38 days** with two circles around the Pole



BESS-Polar II Antiproton Spectrum



Compared with BESS'95+'97:

- x 14 statistics at < 1 GeV
- Flux peak consistent at 2 GeV
- Spectral shape different at low energies.

BESS-Polar II results

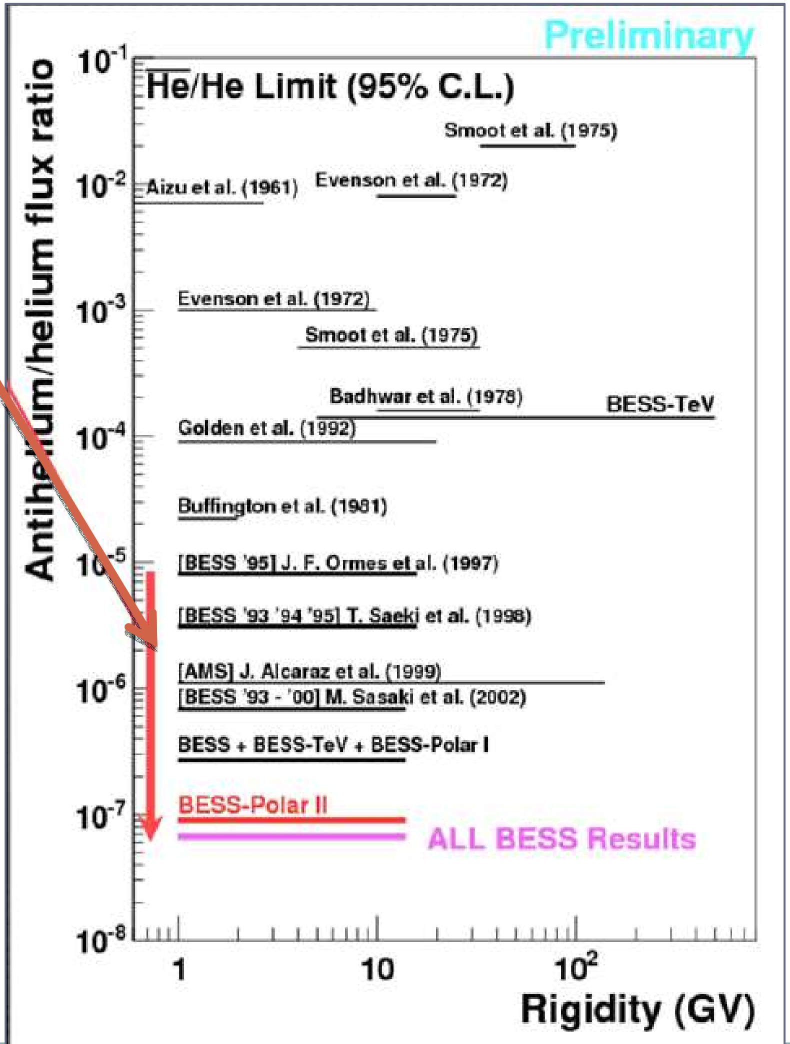
-generally consistent with secondary p-bar

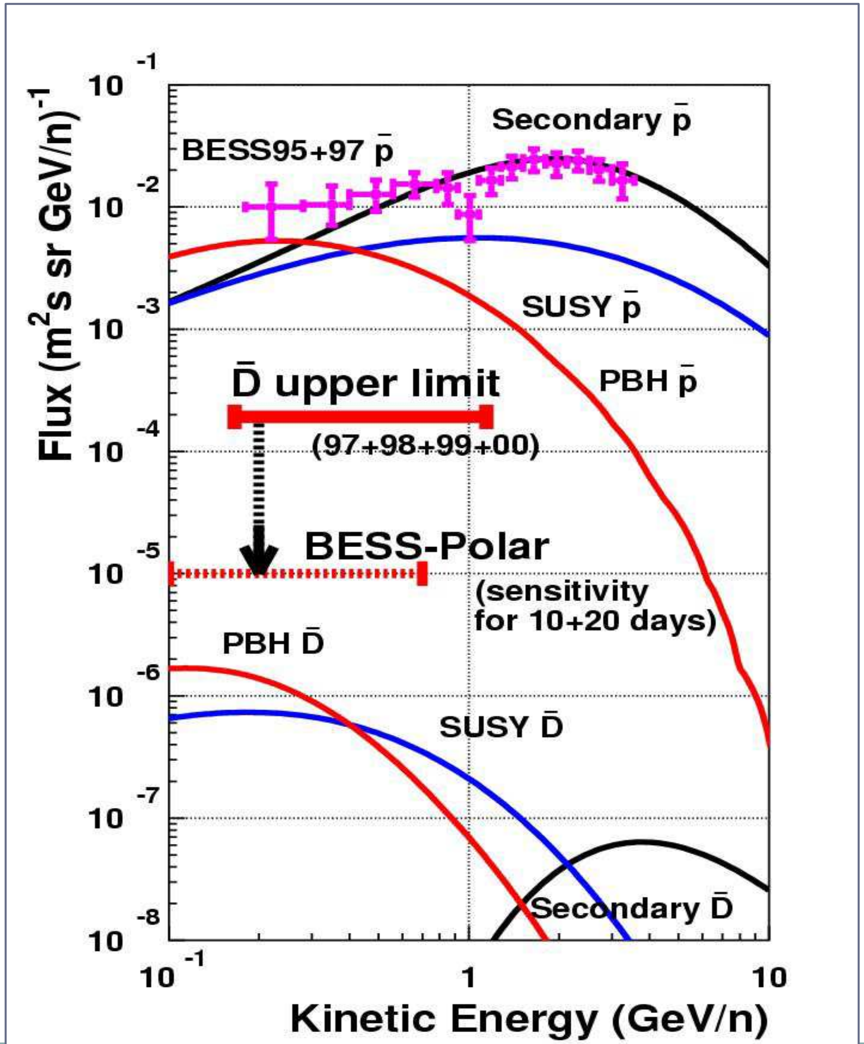
-calculations under solar minimum conditions.

-NO low energy enhnacement due to PBH

Limits on antimatter (antiHe and antiD)

100 times improvement





CREAM – Overview

- Aim is the study of CR from 10^{12} to $5x10^{14}$ eV, from proton to Iron, by means of a series of Ultra Long Duration Balloon (ULDB) flights from Antarctica.

- 6 flights up to now: 2004, 2005, 2007, 2008, 2009, 2010.

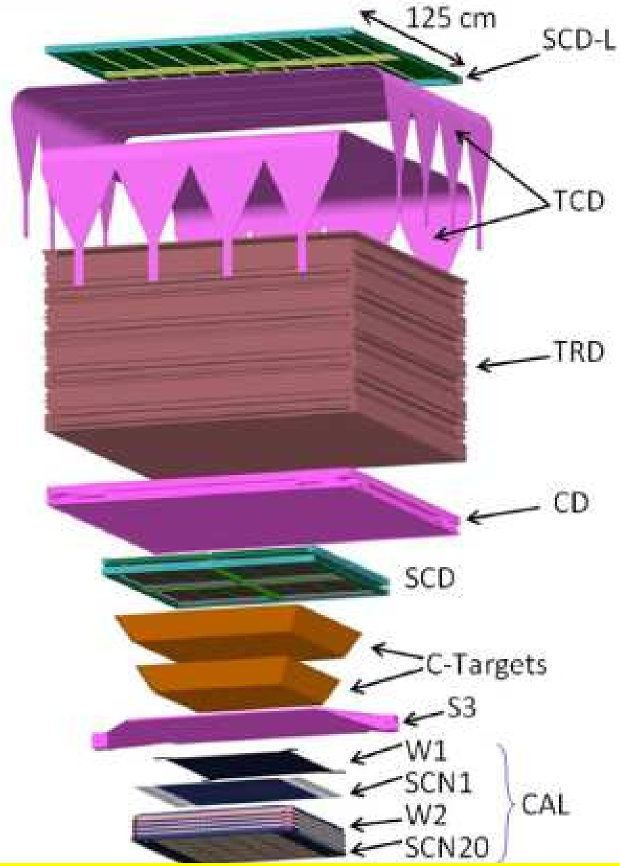
The instrument is composed by a sampling tungsten/scintillating fibers calorimeter (20 r.l.), preceded by a graphite target with layers of scintillating fibers for trigger and track reconstruction, a TRD for heavy nuclei, and a timing-based segmented charge device.

A fundamental aspect of the instrument is the capability to obtain simultaneous measurements of energy and charge for a sub-sample of nuclei by calorimeter and TRD, thus allowing an inter-calibration in flight of the energy.

The CREAM instrument

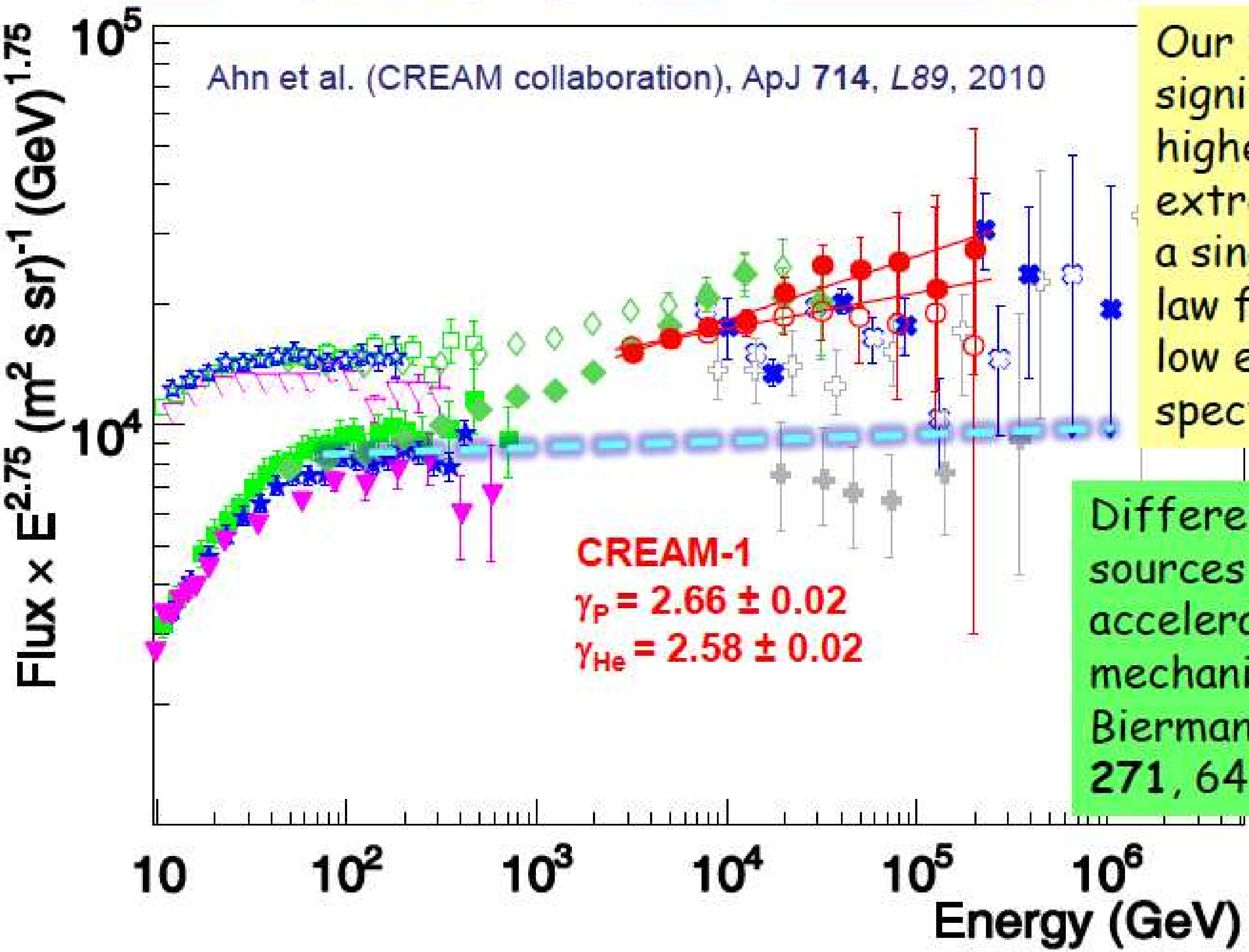
- Transition Radiation Detector (TRD) and Tungsten Scintillating Fiber Calorimeter
  - In-flight cross-calibration of energy scales for Z > He
- Complementary Charge Measurements
  - Timing-Based Charge Detector
  - Cherenkov Counter
  - Pixelated Silicon Charge Detector

- **CREAM uses two designs**
  - With and without the TRD
- This exploded view shows the “With TRD” design
- The “Without TRD” design uses Cherenkov Camera



Collecting power: 300 m2-sr-day for proton and helium, 600 m2-sr-day nuclei

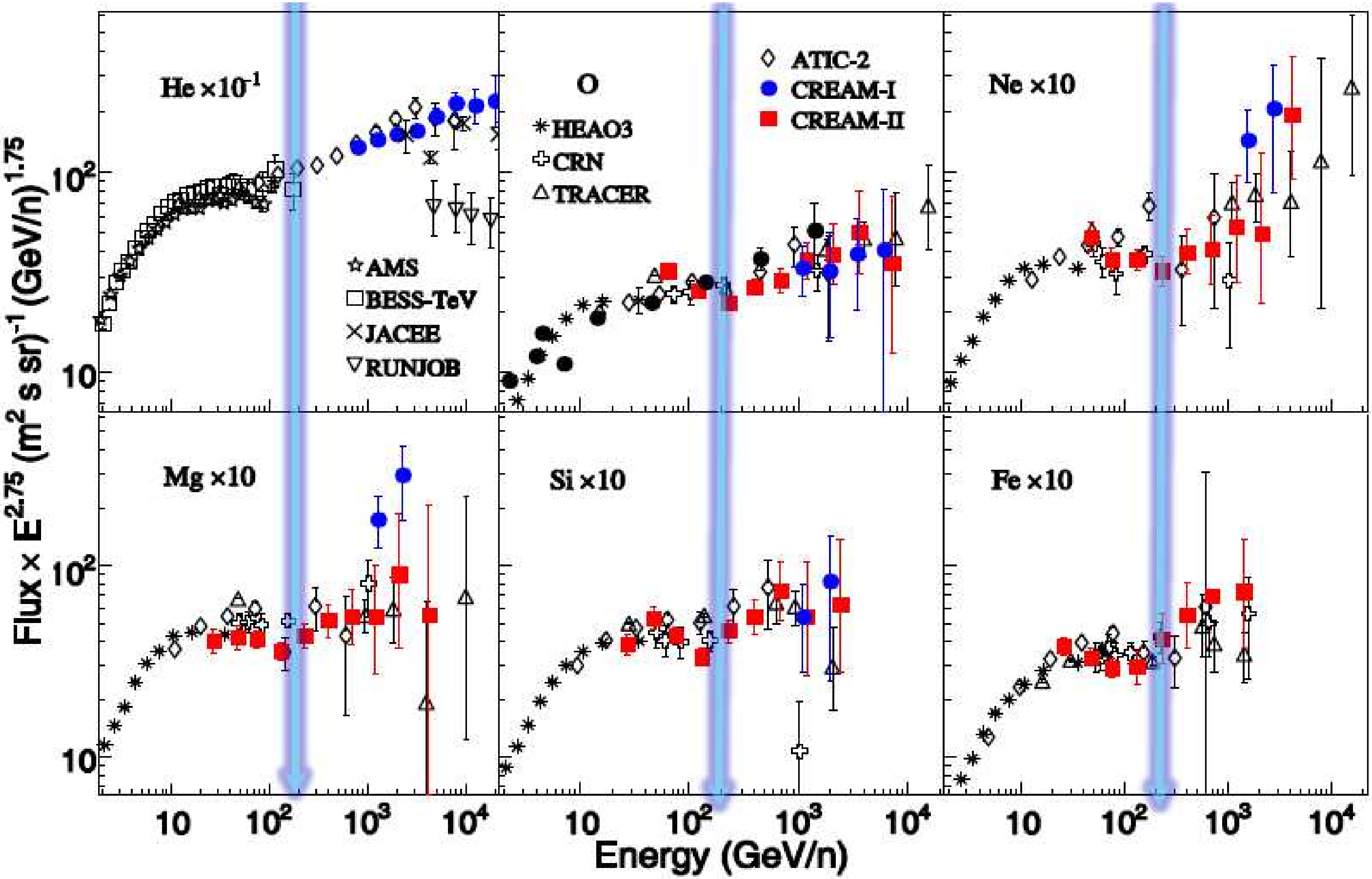
Protons and heliums



Our fluxes are significantly higher than the extrapolation of a single-power law fit to the low energy spectra

Different types of sources or acceleration mechanisms? (e.g., Biermann, P. L. *A&A* **271**, 649,1993)

Heavier elements: hardening



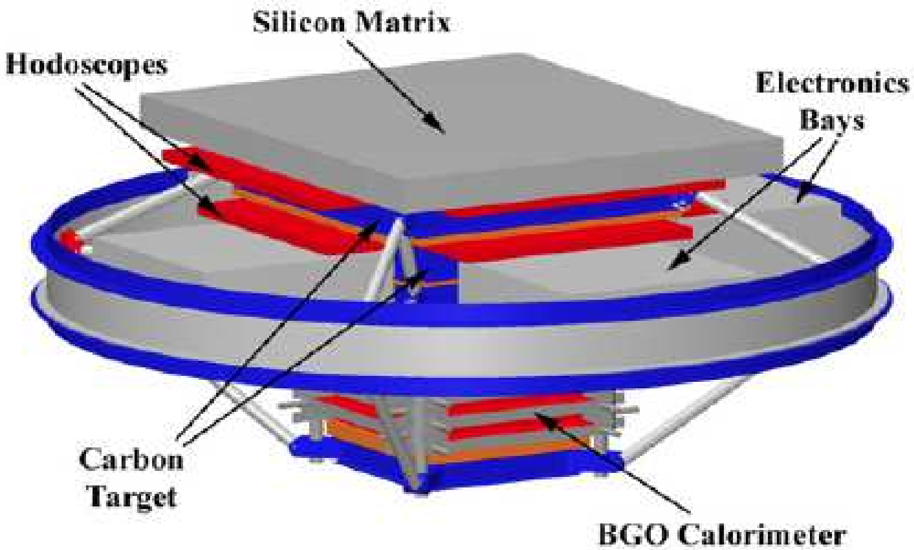
Advanced Thin Ionization Calorimeter (ATIC)

ATIC COLLABORATION:
Institute for Physical Science and Technology, University of Maryland, College Park, MD, USA
Marshall Space Flight Center, Huntsville, AL, USA
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
Purple Mountain Observatory, Chinese Academy of Sciences, China
Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany
Department of Physics, Southern University, Baton Rouge, LA, USA
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA, USA
Department of Physics, University of Maryland, College Park, MD, USA

The ATIC balloon flight program measures the cosmic ray spectra of nuclei:
$1 < Z < 26$
between 10^{11} eV and 10^{14} eV.

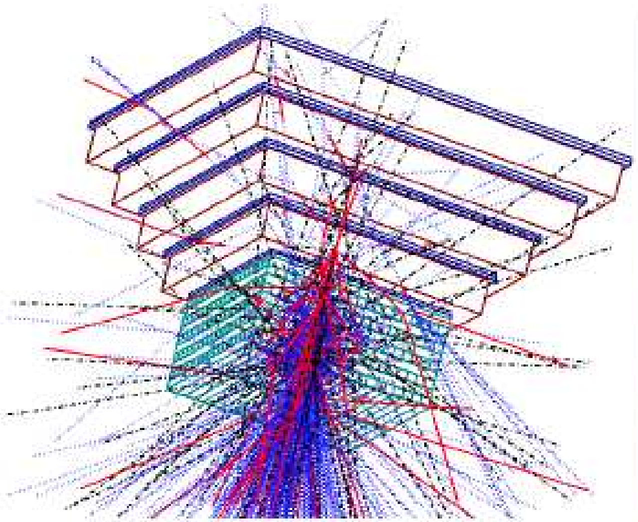
ATIC has had three successful long-duration balloon (LDB) flights launched from McMurdo Station, Antarctica in 2000, 2002 and 2007.

ATIC Instrument Details

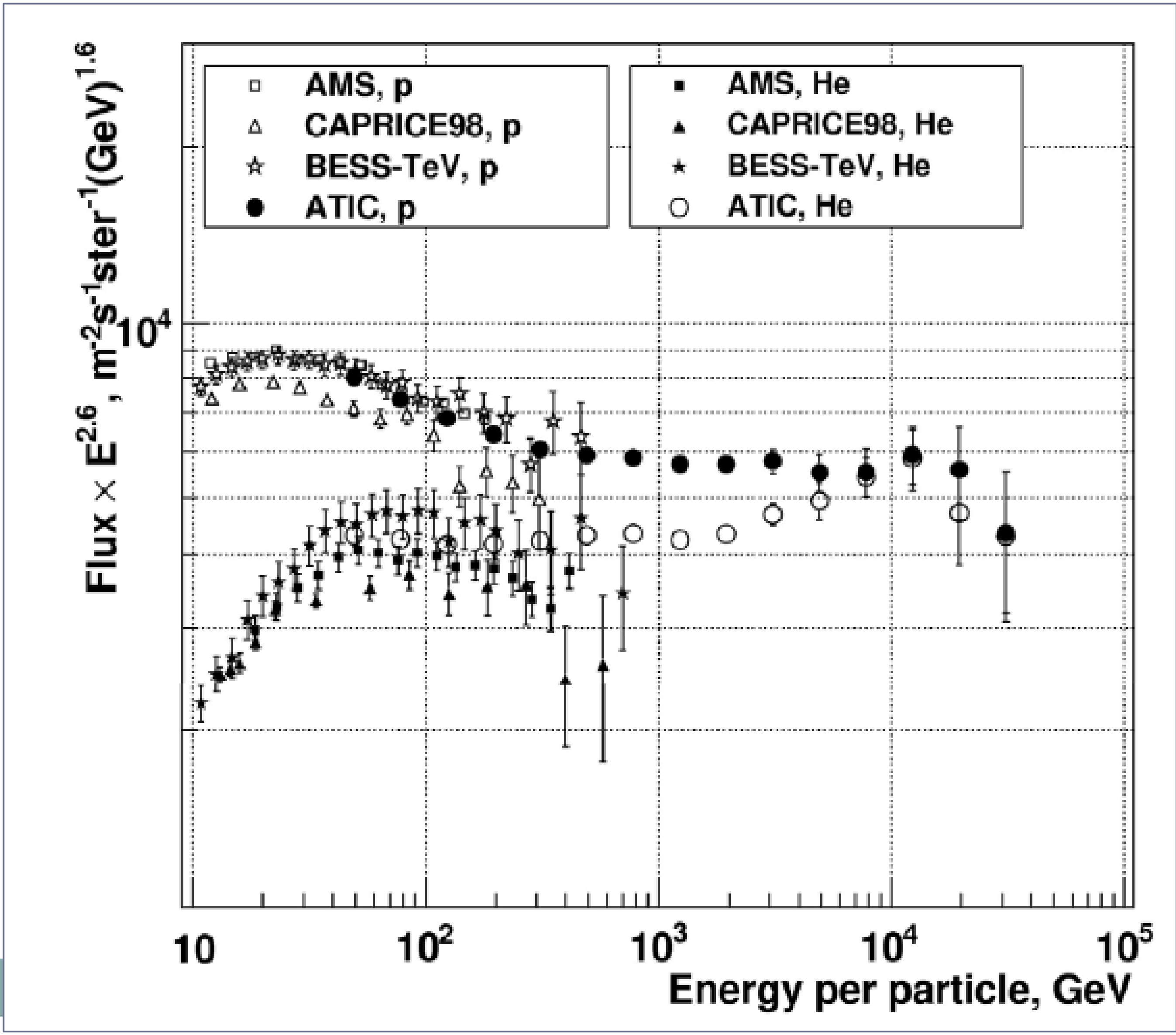


Antarctic Flights:

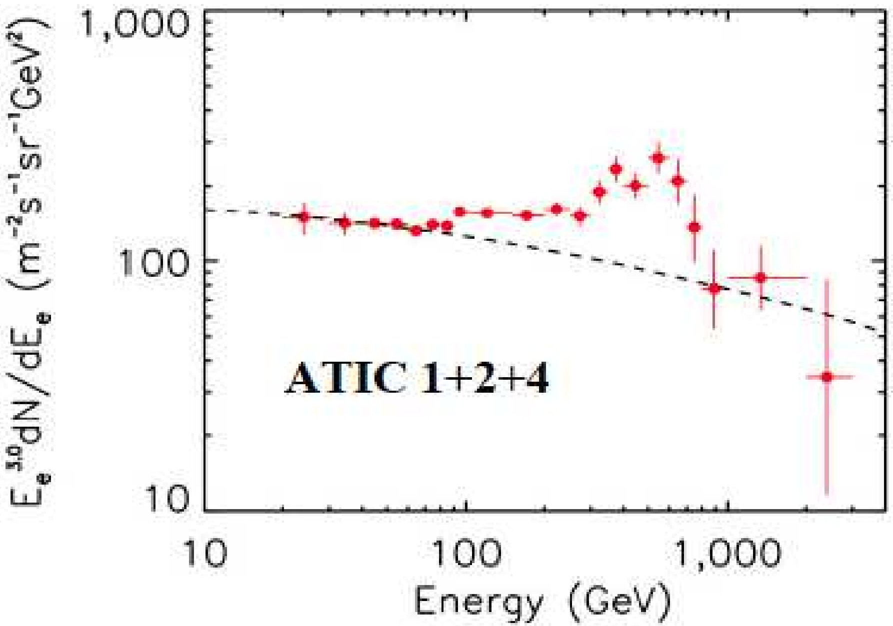
- 12/28/00 - 1/13/01
- 12/29/02 – 1/18-03
- 12/27/07 – 1/15/08

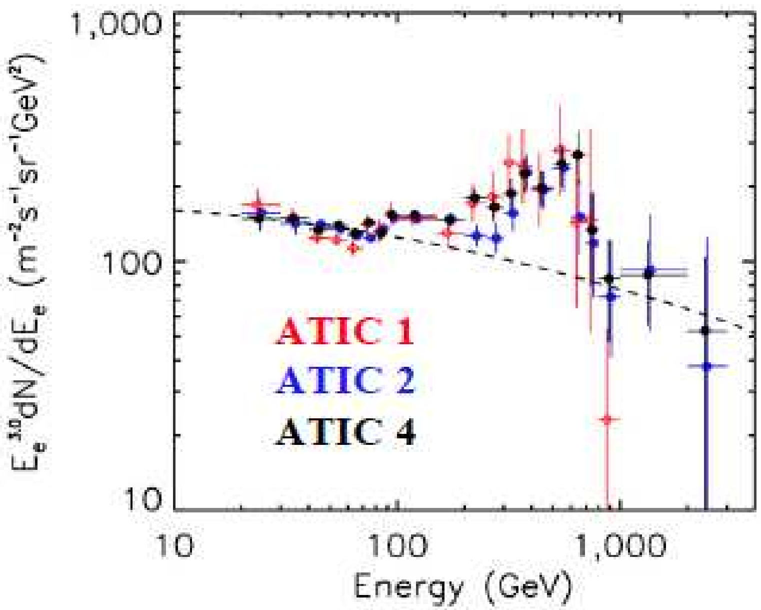


Protons and heliums



The ATIC “bump” in the all-electron spectrum



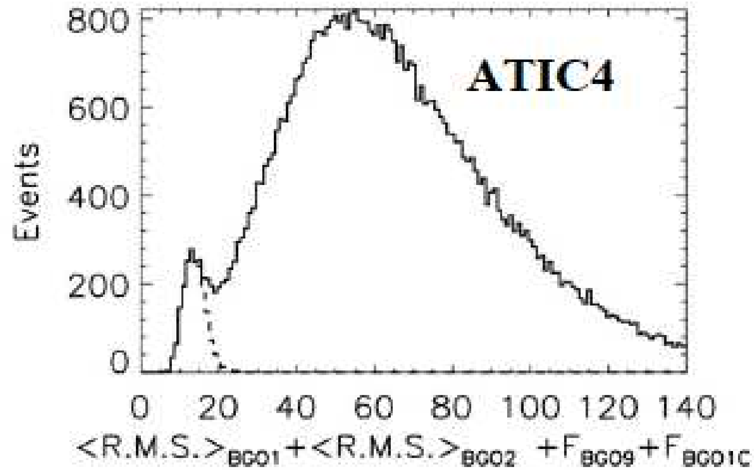


“Source on/source off” significance of bump for ATIC1+2 is about 3.8 sigma

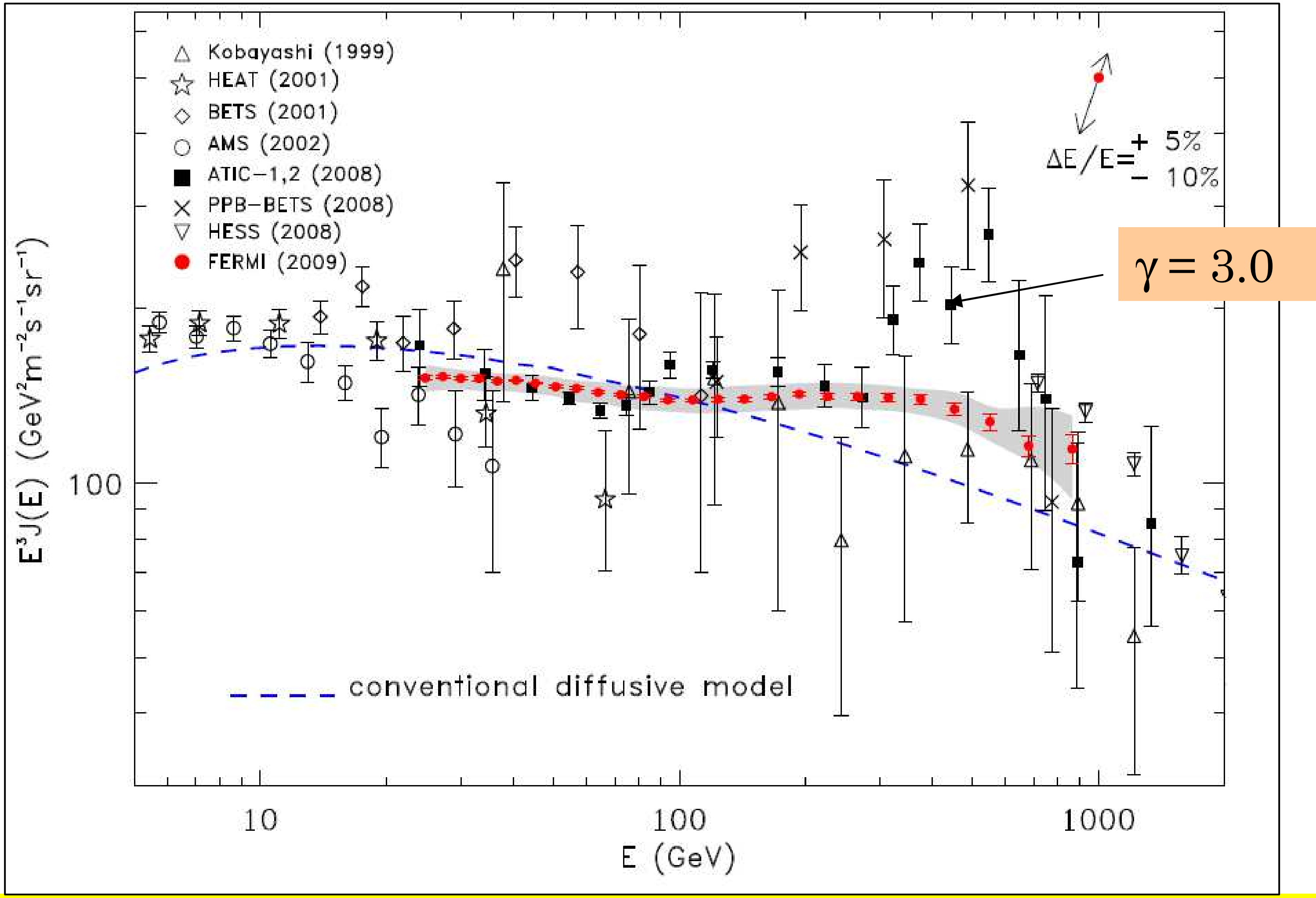
ATIC-4 with 10 BGO layers has improved e , p separation.

“Bump” is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma



Reply from FERMI



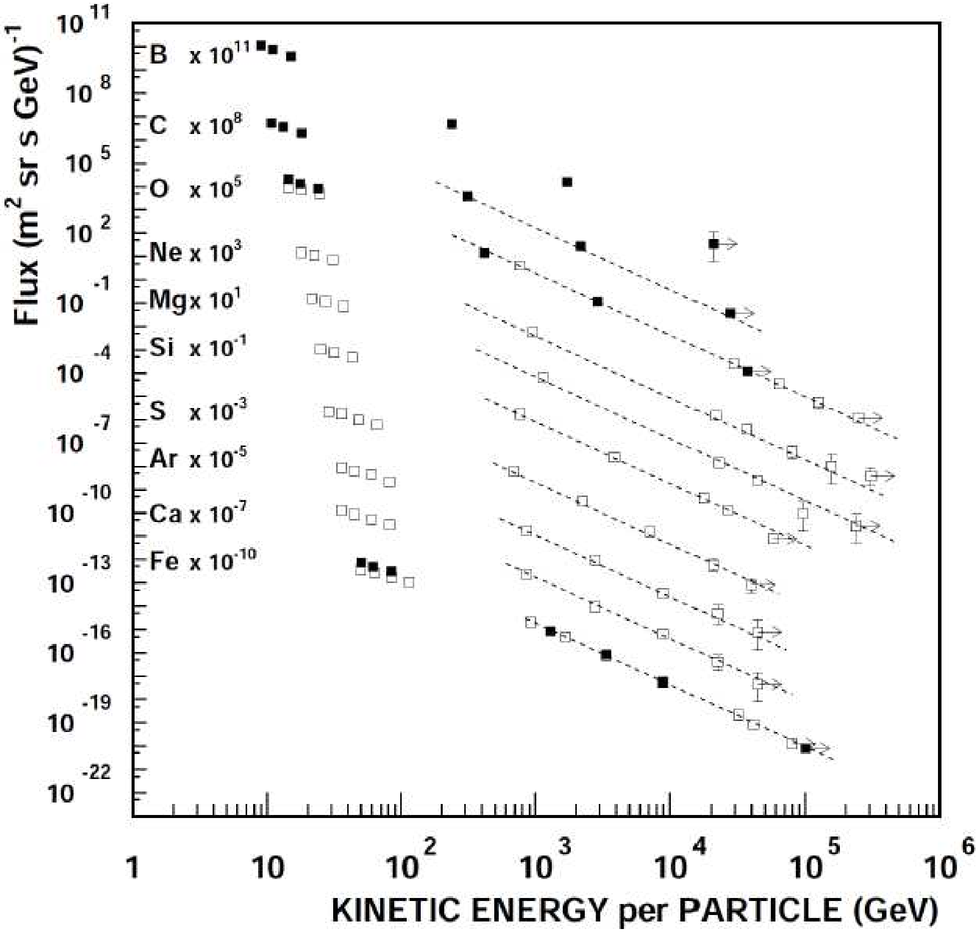
FERMI does not confirm the ATIC bump but finds an excess wrt conventional diffusive models (SEE TALK BY SGRO' soon)

TRACER balloon flights

Transition Radiation Array for Cosmic Energetic Radiation (TRACER)

-Direct measurements of O to Fe from ~50 GeV to several 100 TeV;
- 5 m2 sr
- 1614 kg (3550 lbs)
- Flights in 2003 (Antarctica) and 2006 (Sweden)

CR energy spectra



TRACER 2 flights data:
POWER_LAW fit above 20 GeV/n:

$$\text{index } 2.65 \pm 0.05$$

Comparison between experimental results

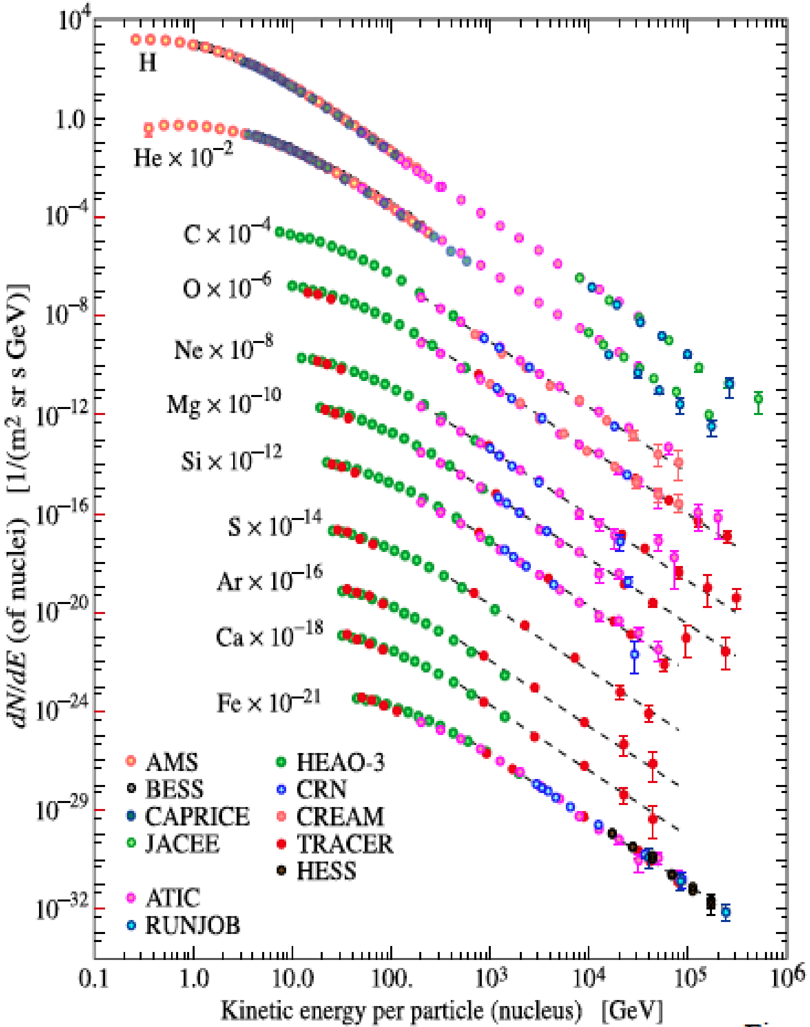


Figure courtesy of P.J. Boyle and D. Mueller

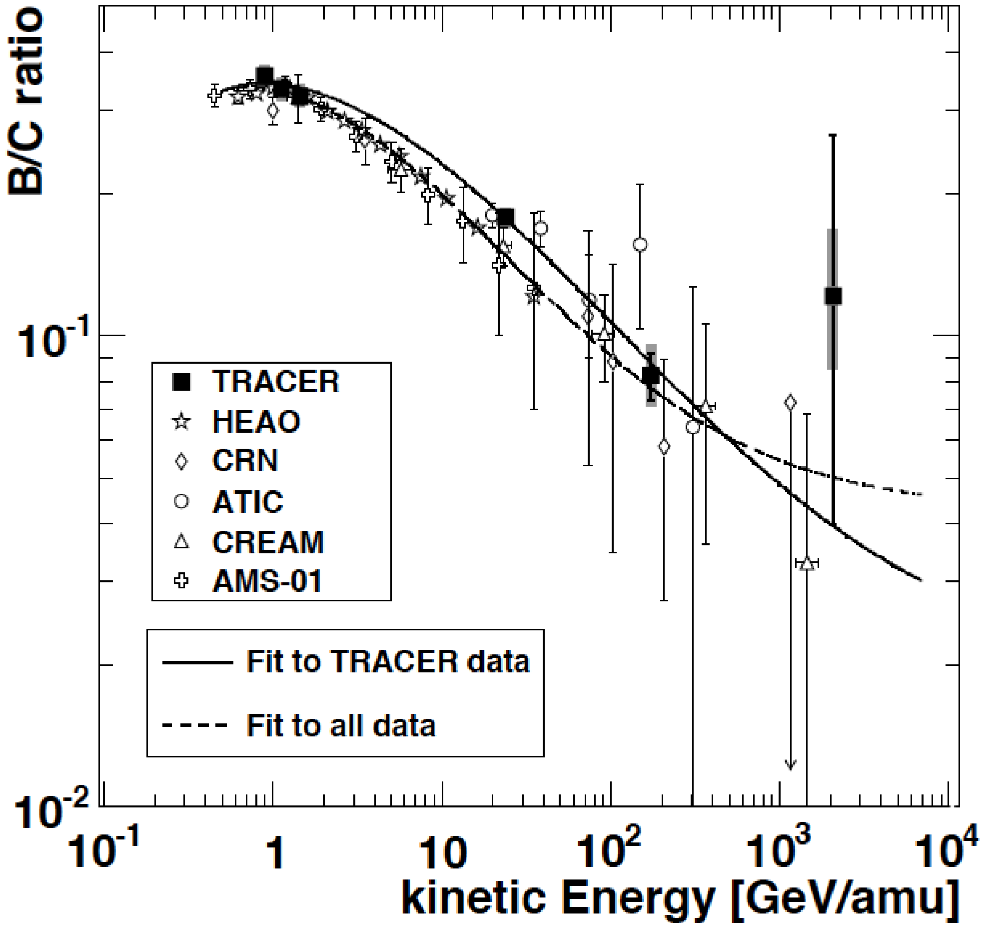
QUESTION:

Are all the hi-Z spectra simple power laws or is there beginning to be evidence for evolution (hardening), as now seems to be the case for H and He?

ANSWER:

You be the judge!

B/C ratio



GALPROP fit with reacceleration:

$$\alpha = 2.34$$
$$\delta \approx 0.34$$

GALPROP fit without reacceleration:

$$\alpha \approx 2.15$$
$$\delta \approx 0.6$$

Leaky Box:

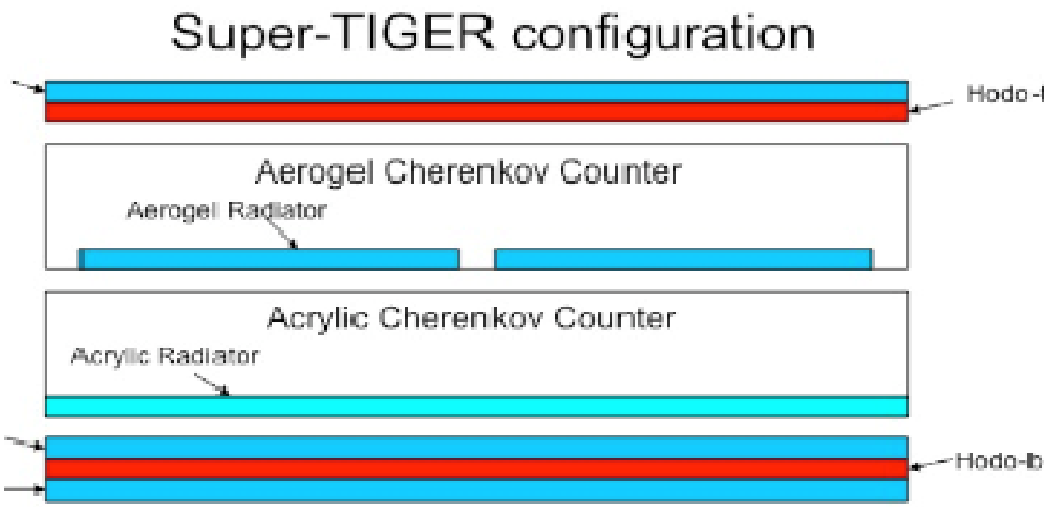
$$\alpha = 2.37 \pm 0.12$$
$$\delta = 0.53 \pm 0.06$$

TIGER and SuperTIGER balloon flights

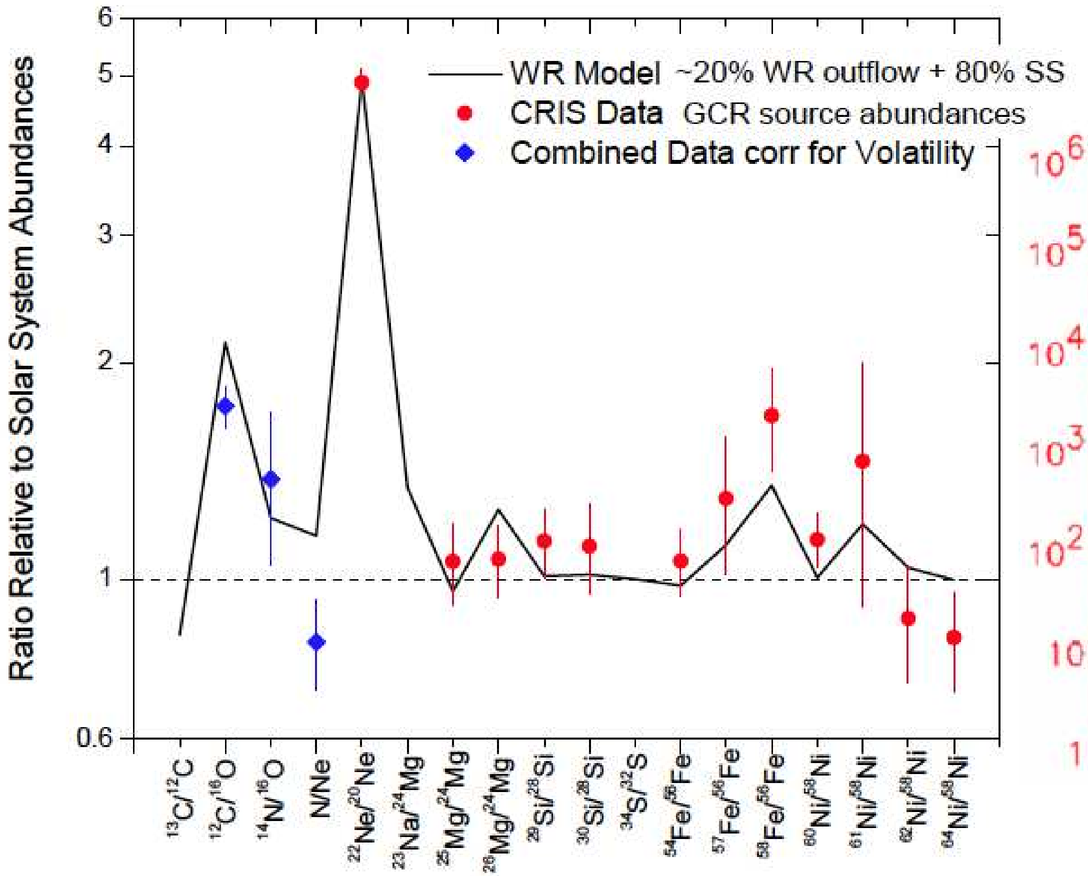
Super-TIGER builds on the smaller Trans-Iron Galactic Element Recorder (TIGER), flown twice on balloons in Antarctica in Dec. 2001 and 2003.
TIGER yielded a total of 50 days of data and producing measurements of elemental abundances of the elements $_{31}$Ga, $_{32}$Ge, and $_{34}$Se, and an upper-limit on the abundance of $_{33}$As.

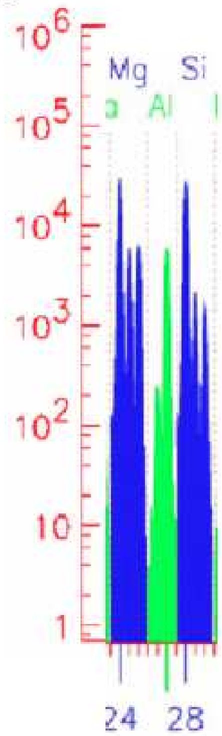
Excellent charge resolution in the $10 \leq Z \leq 38$ charge range.

SUPERTIGER:
$30 \leq Z \leq 42$

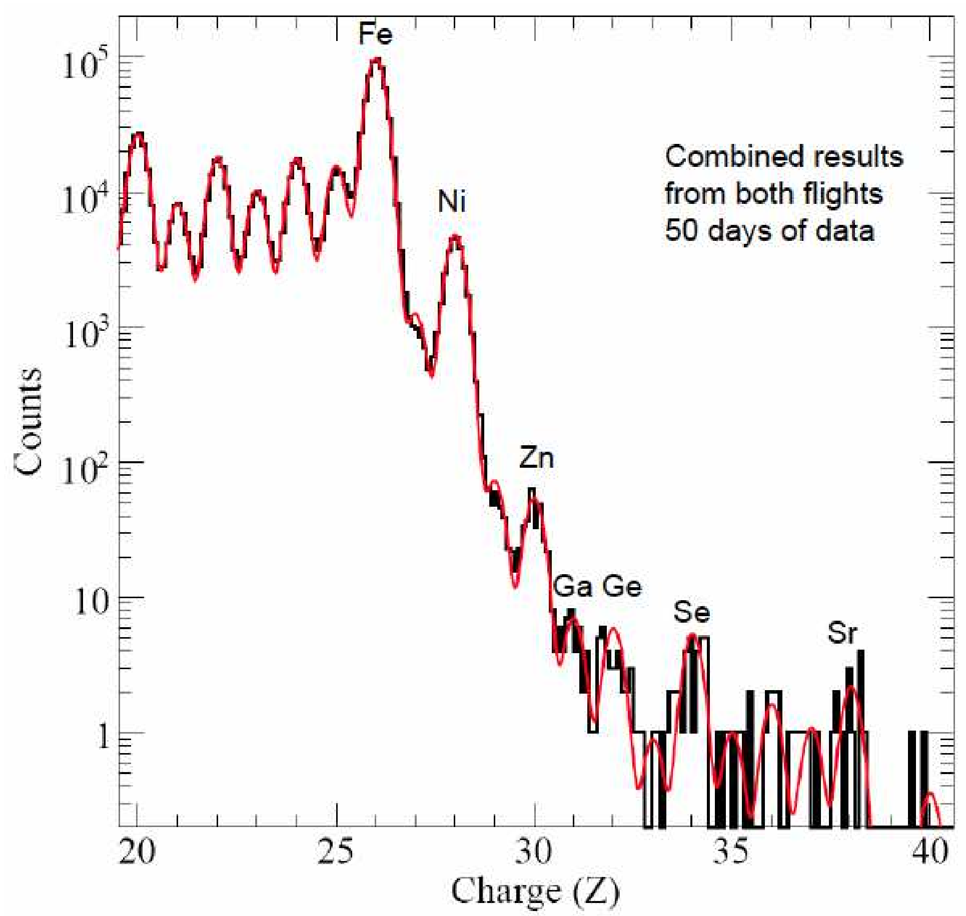


It is known by ACE_CRIS data that the abundance of 22Ne points towards a contribution from outflow of massive starts (Wolf-Rayet stars).
TIGER and SuperTIGER search for the enrichments of hevy elements expected from nucleosynthesis in massive stars.

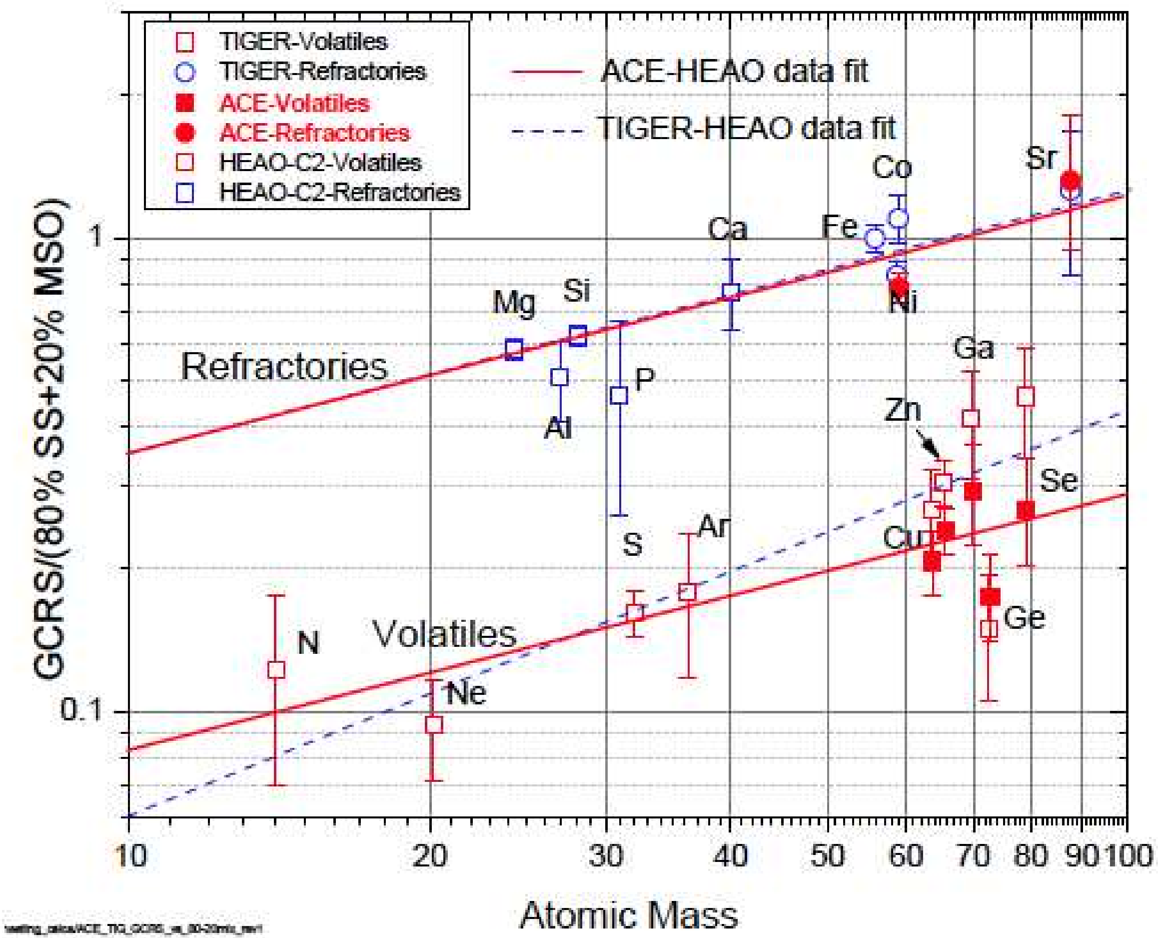




TIGER 1 and 2 combined results



CRIS-UH results (prelim.) superimposed on TIGER data



A reasonably consistent picture emerges with the following features:

Cosmic-ray source mix of ~80% Solar System plus ~20% ejecta from massive stars.

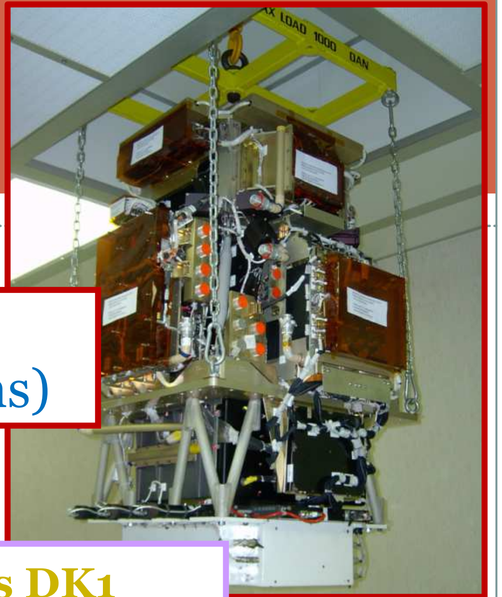
Refractory elements are accelerated more efficiently than volatile elements.

Both refractory and volatile elements have a mass-dependent acceleration efficiency,

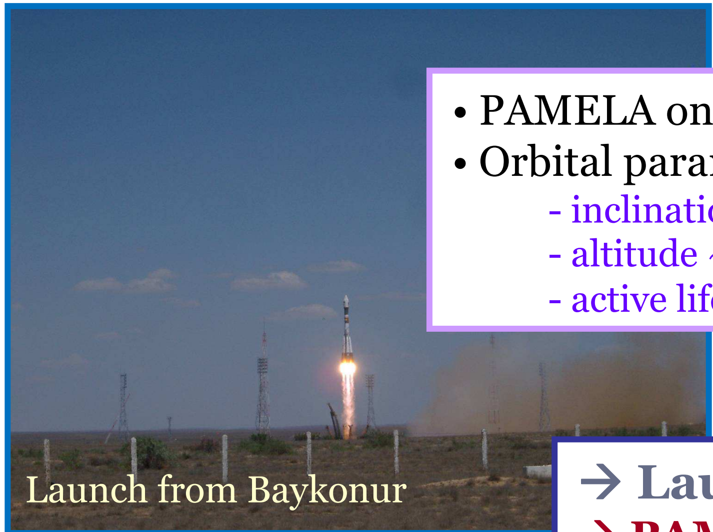

Satellite flights

PAMELA

Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics

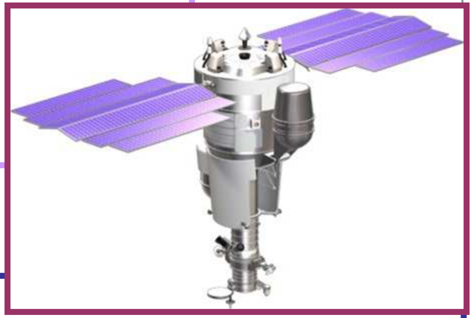


- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)



Launch from Baykonur

- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70° (⇒ low energy)
  - altitude ~ 360-600 km (elliptical)
  - active life >3 years (⇒ high statistics)



→ **Launched on 15th June 2006**

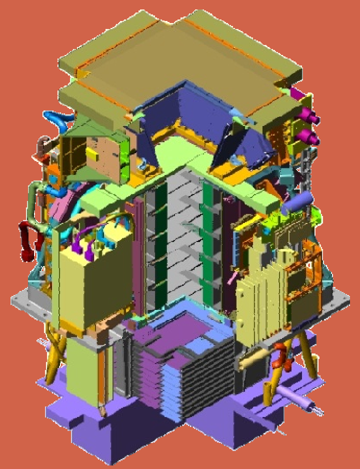
→ **PAMELA in continuous data-taking mode since then!**

PAMELA detectors

Main requirements:

- high-sensitivity antiparticle identification

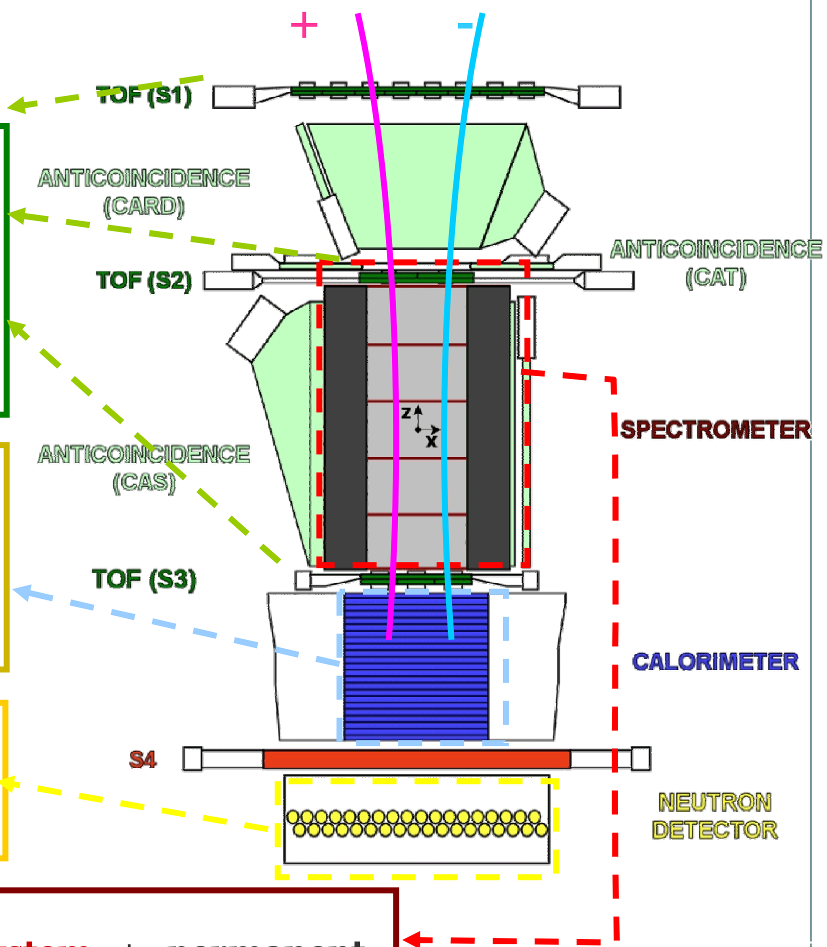
- precise momentum measurement



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, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
36 He^3 counters :
- High-energy e/h discrimination



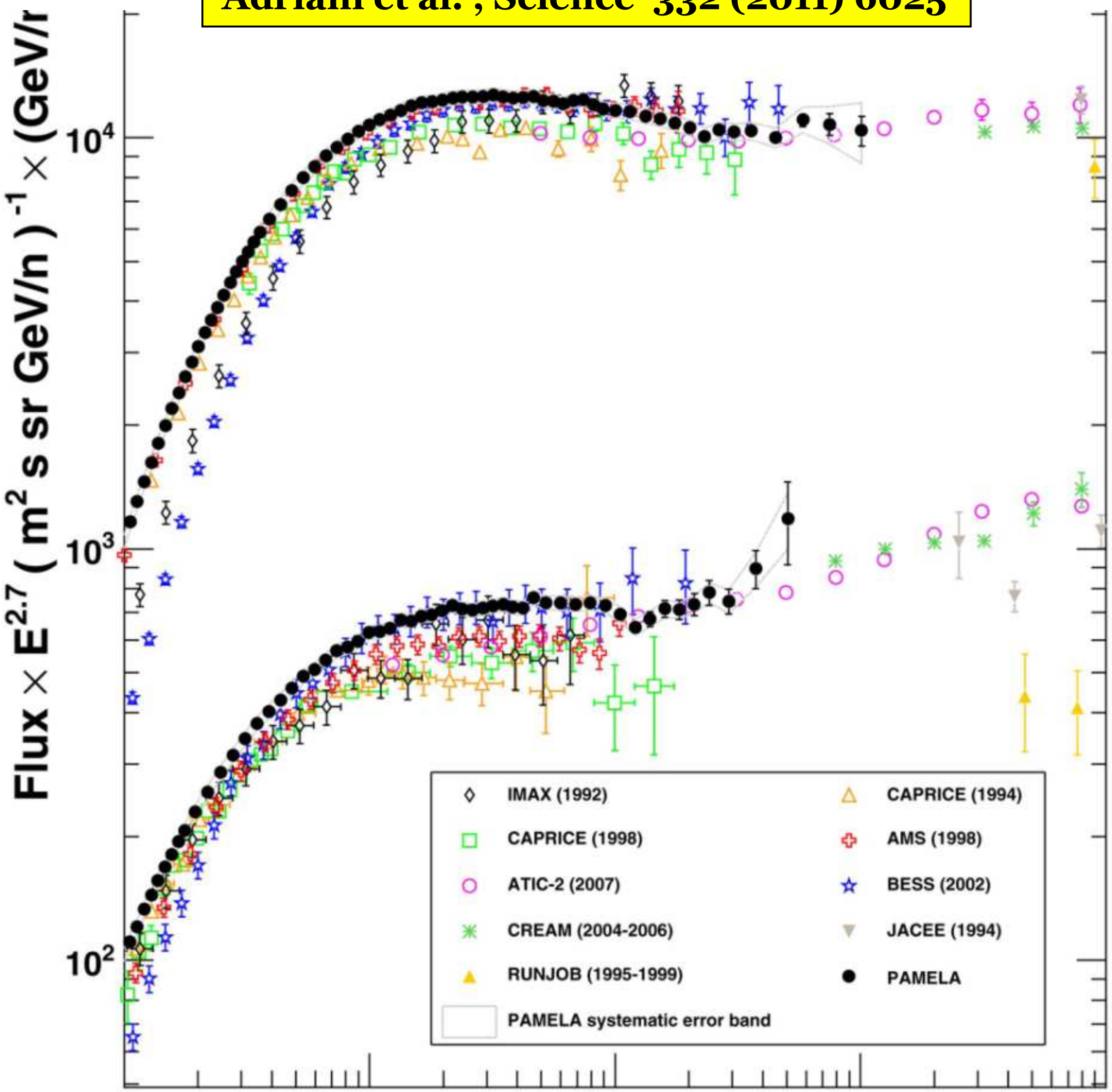
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

H & He absolute fluxes

- First high-statistics and high-precision measurement over three decades in energy
- Dominated by systematics (~4% below 300 GV)
- **Low energy** → minimum solar activity ($\phi = 450 \div 550$ GV)
- **High-energy** → a complex structure of the spectra emerges…

Adriani et al. , Science 332 (2011) 6025



P & He absolute fluxes @ high energy

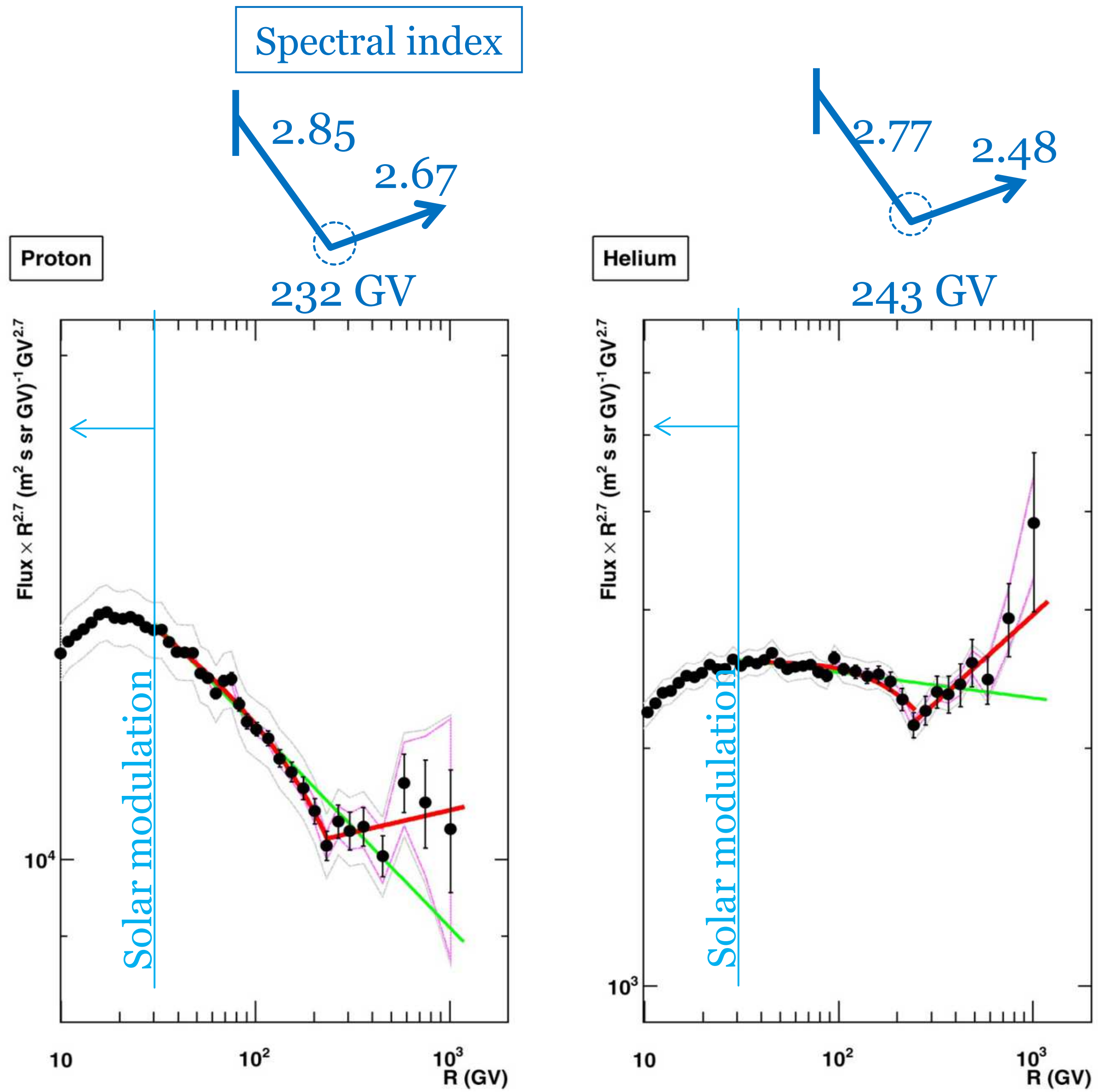
Deviations from single power law (SPL):

▪Spectra gradually soften in the range 30÷230GV

▪Abrupt spectral hardening @ ~235GV

Eg: statistical analysis for protons

- SPL hp in the range 30÷230 GV rejected @ >95% CL
- SPL hp above 80 GV rejected @ >95% CL



H/He ratio vs R

Instrumental p.o.v.

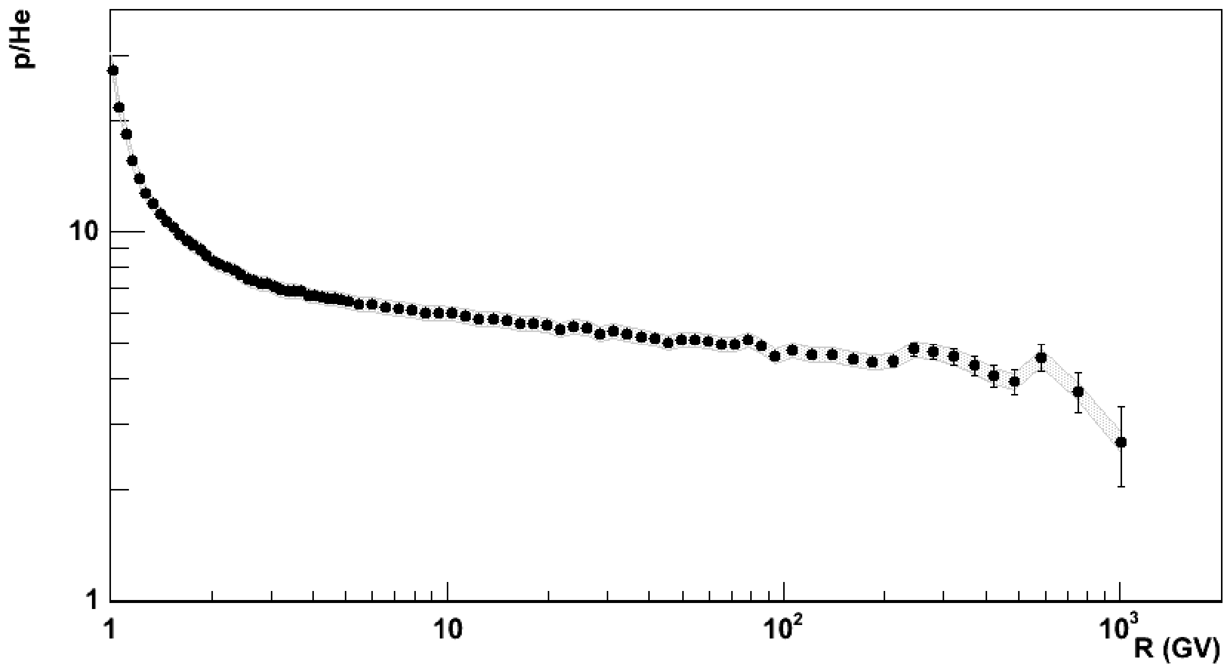
▪Systematic uncertainties **partly cancel out** (livetime, spectrometer reconstruction, …)

Theoretical p.o.v.

▪Solar modulation negligible
→ information about IS spectra down to GV region

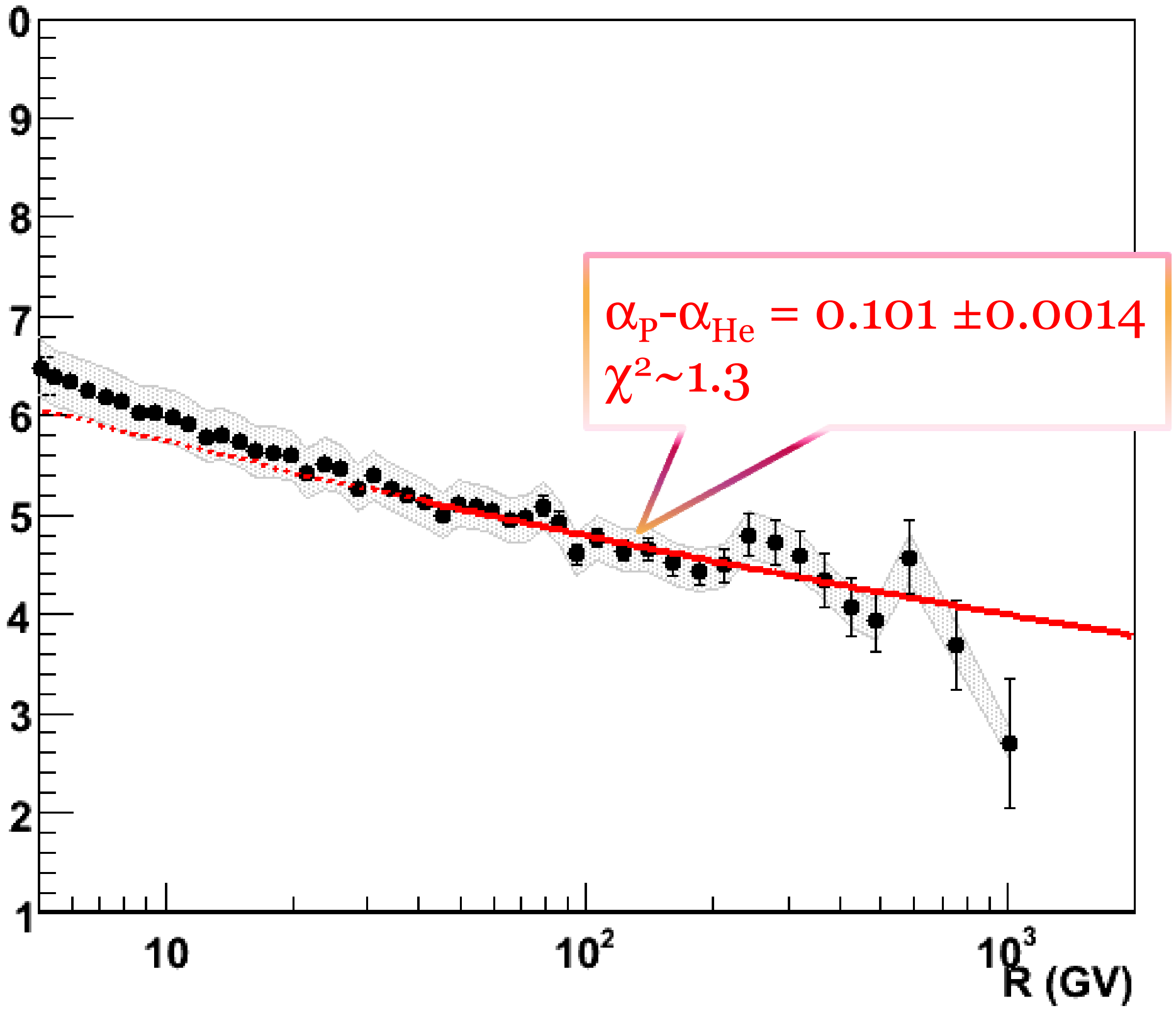
▪Propagation effects (diffusion and fragmentation) negligible above ~100GV
→ information about source spectra

(Putze et al. 2010)



P/He ratio vs R

- First clear evidence of **different H and He slopes above ~10GV**
- Ratio described by a **single power law** (in spite of the evident structures in the individual spectra)

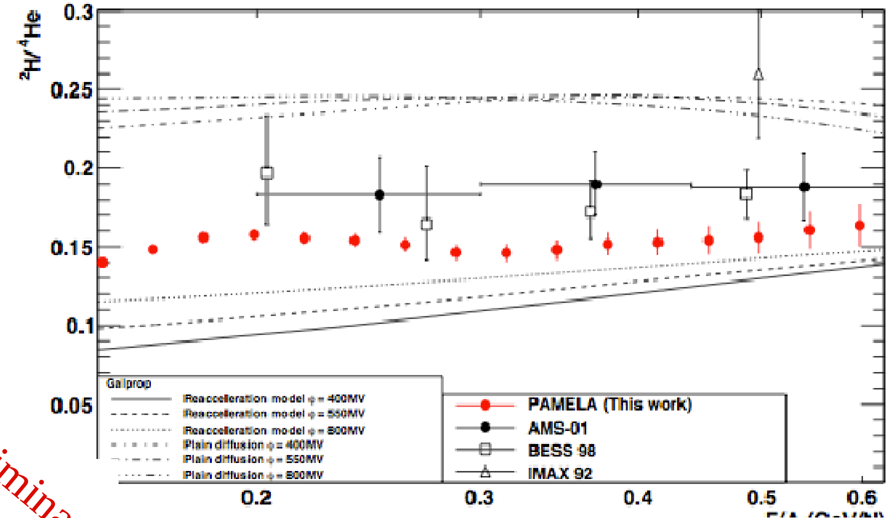


Light nuclei isotopes

Fluxes of deuterium and 3He are ready for publication.

3He/4He, 2H/1H, 2H/4He ratios ready

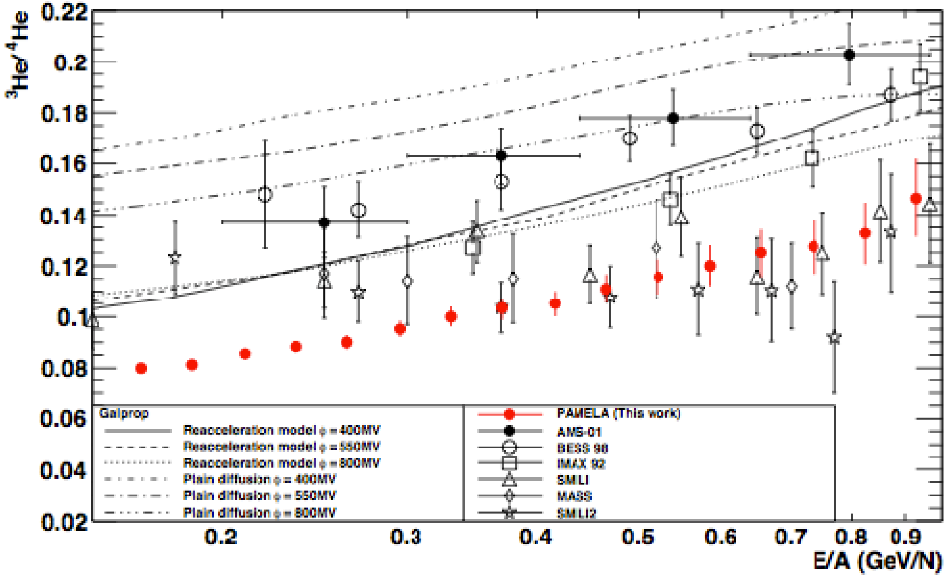
Preliminary



$^2H/^4He$

$^3He/^4He$

Preliminary



Electron energy measurements

Two independent ways to determine electron energy:

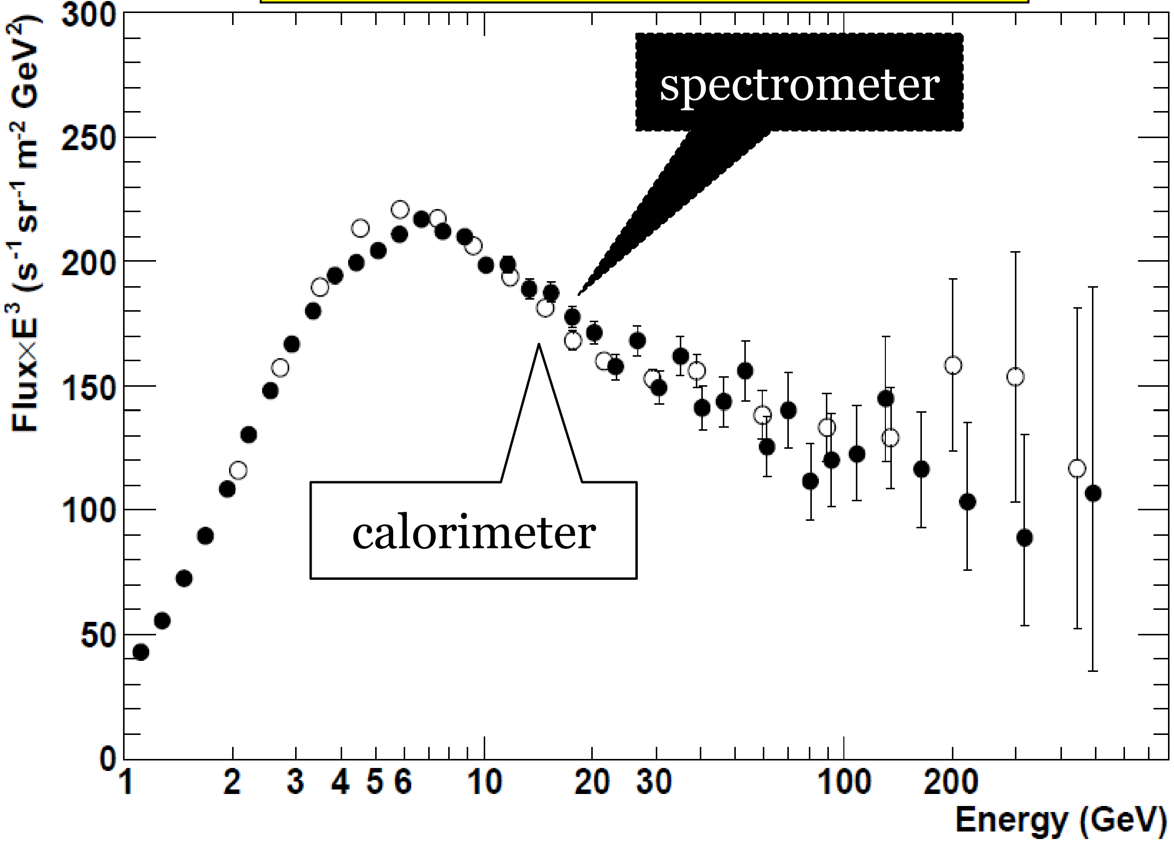
1.Spectrometer

- Most precise
- Non-negligible energy losses (bremsstrahlung) above the spectrometer → unfolding

2.Calorimeter

- Gaussian resolution
- No energy-loss correction required
- Strong containment requirements → smaller statistical sample

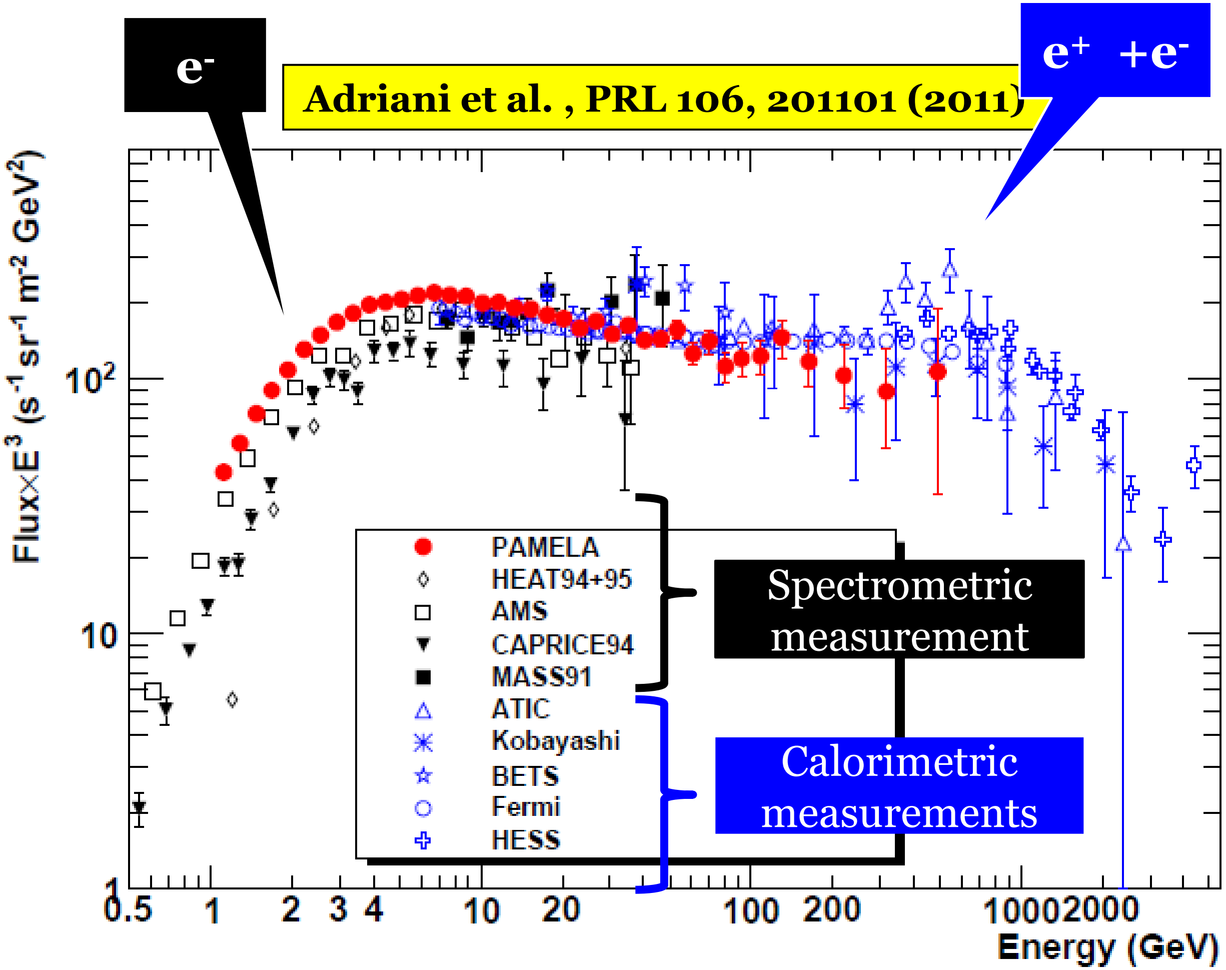
Adriani et al. , PRL 106, 201101 (2011)



Electron identification:
•Negative curvature in the spectrometer
•EM-like interaction pattern in the calorimeter

Electron absolute flux

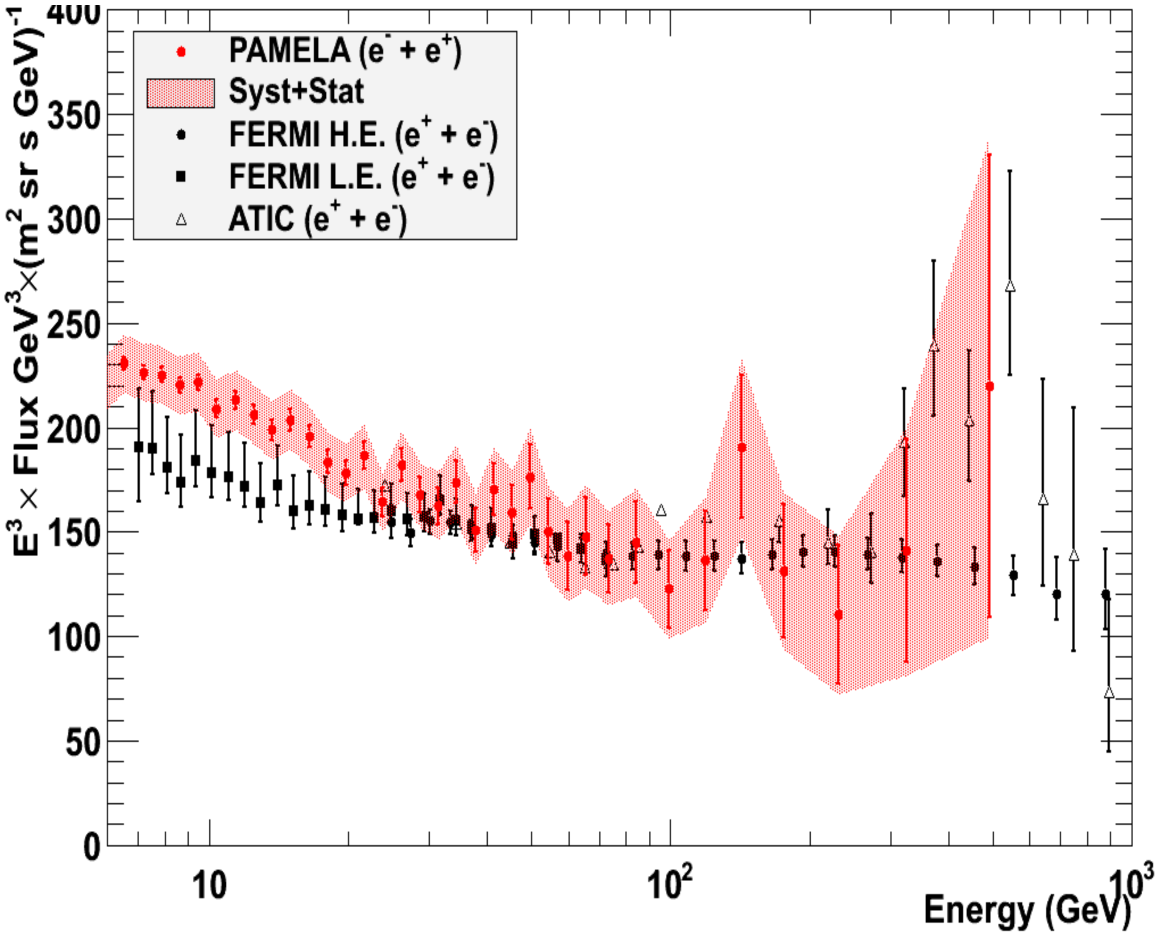
- Largest energy range covered in any experiment hitherto with no atmospheric overburden
- **Low energy**
  - minimum solar activity ($\phi = 450 \div 550$ GV)
- **High energy**
  - No significant disagreement with recent ATIC and Fermi data
  - Softer spectrum consistent with both systematics and growing positron component



$(e^+ + e^-)$ absolute flux

- Compatibility with FERMI (and ATIC) data
- Beware: positron flux not measured but **extrapolated** from PAMELA positron flux!
- Low energy discrepancies due to solar modulation

ONLY AN EXERCISE ....



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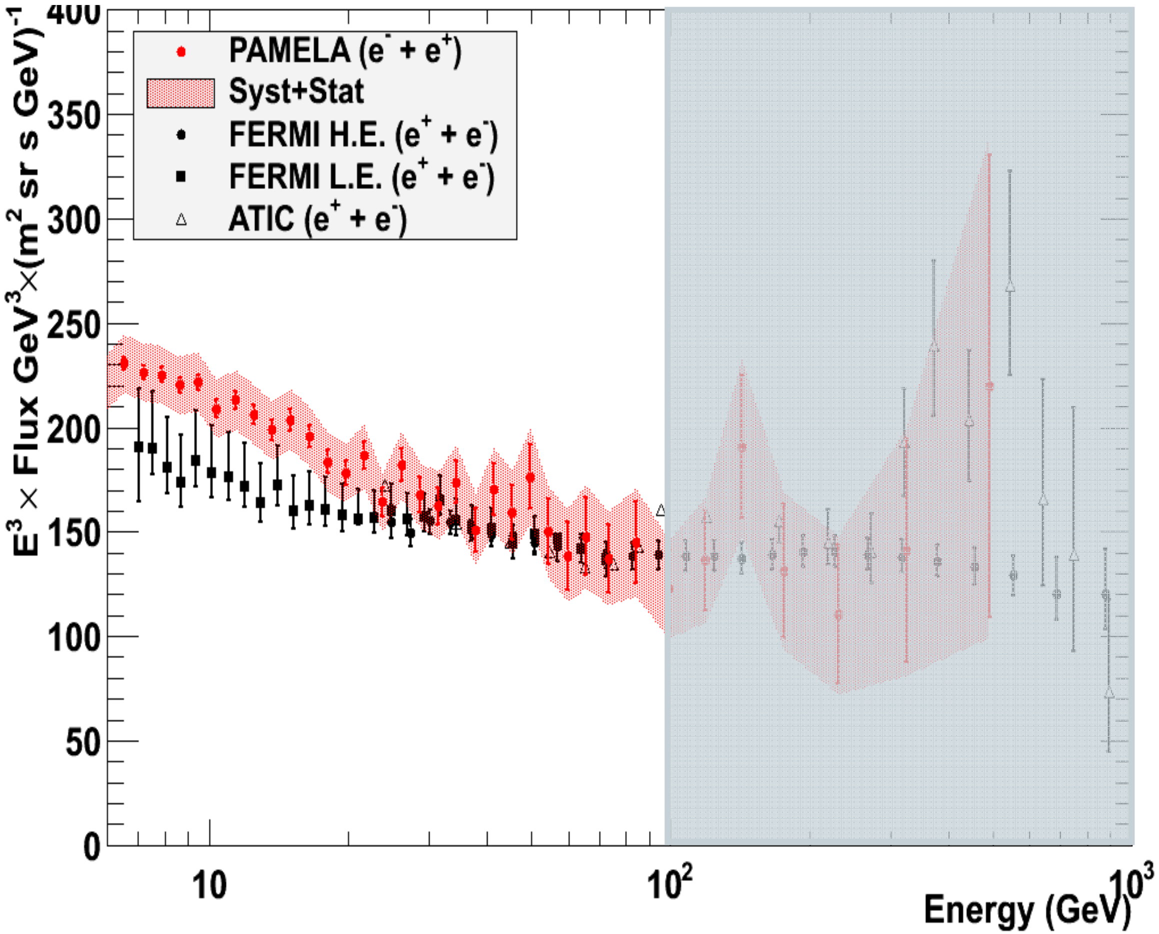
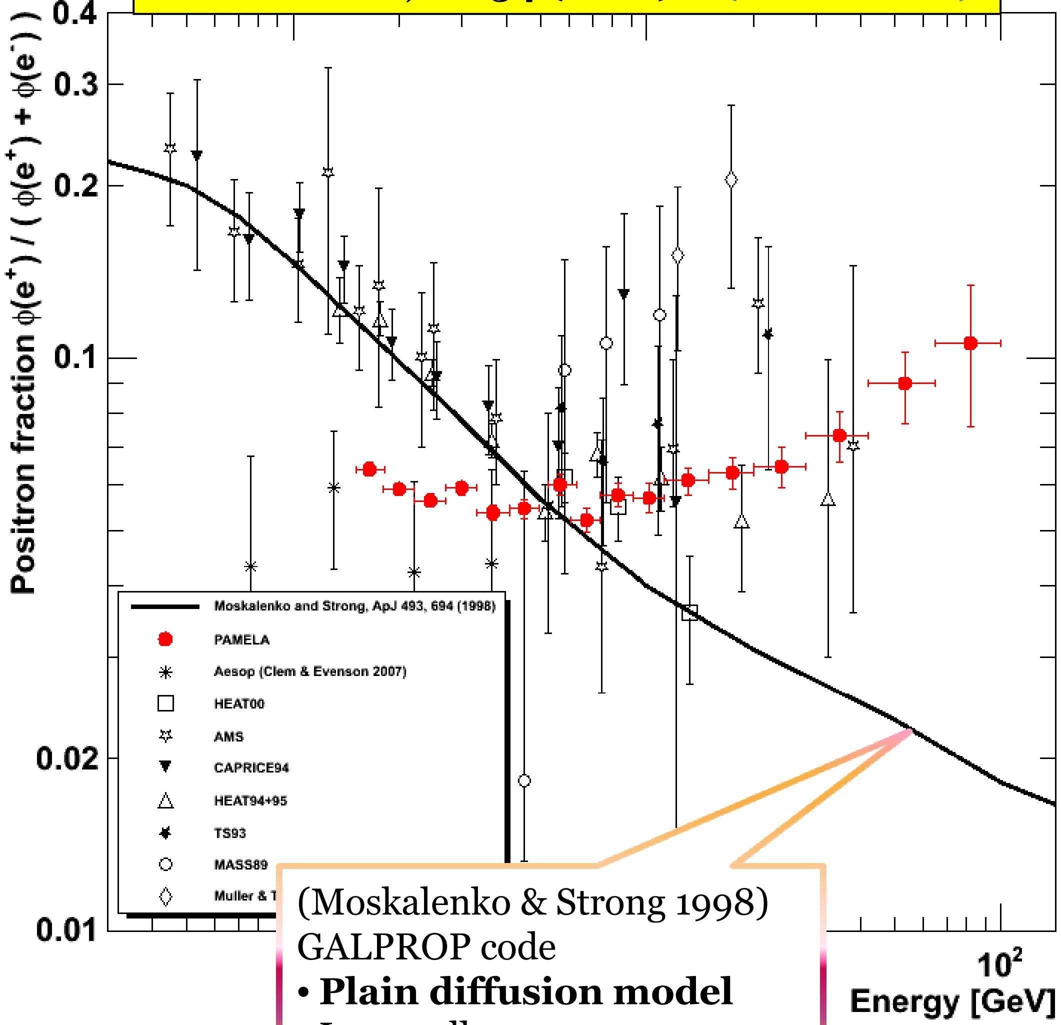


Positron fraction

- **Low energy**
  → charge-dependent solar modulation (see later)
- **High energy**
  → (quite robust) evidence of positron excess above 10GeV

Adriani et al. , Nature 458 (2009) 607
Adriani et al., AP 34 (2010) 1 (new results)



(Moskalenko & Strong 1998)
GALPROP code
- **Plain diffusion model**
- Interstellar spectra

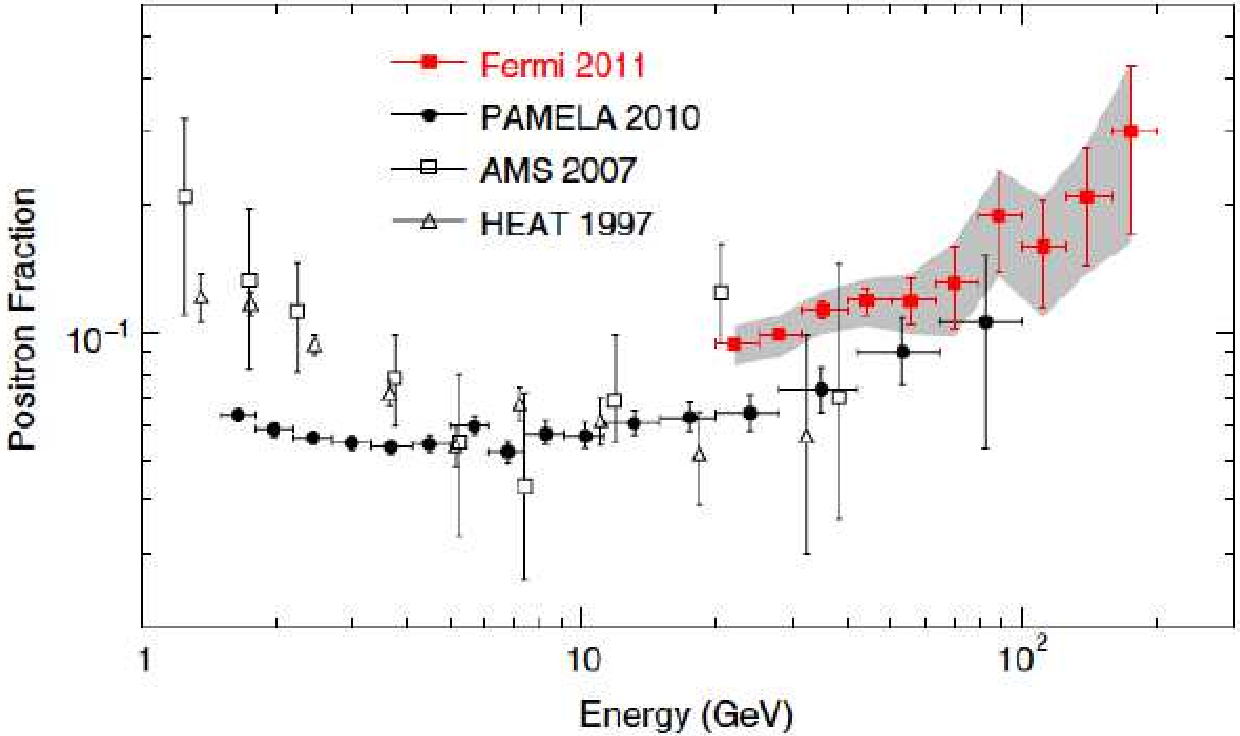
FERMI positron/electron ratio

The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth's magnetic field as a charge discriminator

The two independent methods of background subtraction, Fit-Based and MC-Based, produce consistent results

The observed positron fraction is consistent with the one measured by PAMELA

Warit Mitthumsiri et al. @ Positrons in Astrophysics (March 2012)

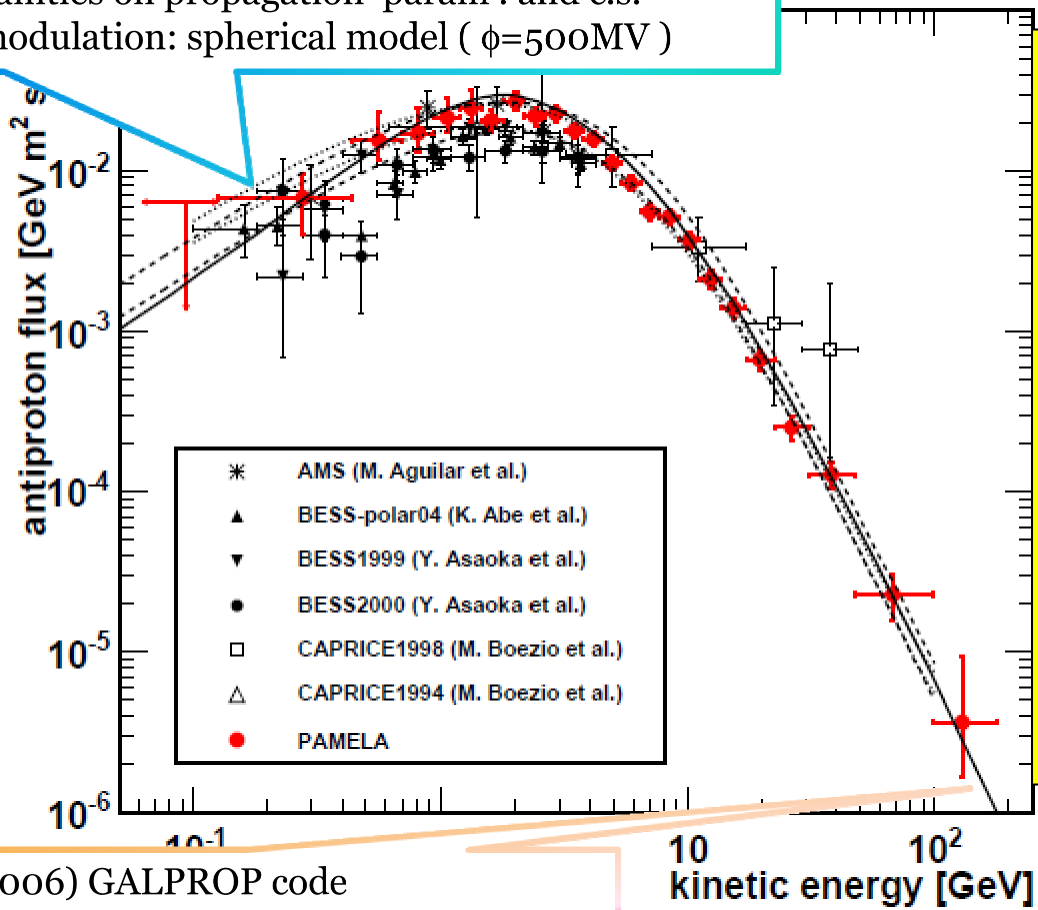


SEE TALK BY SGRO' soon

Antiproton flux

- Largest energy range covered hiterto
- Overall agreement with pure secondary calculation
- Experimental uncertainty (stat⊕sys) smaller than spread in theoretical curves
  → constraints on propagation parameters

(Donato et al. 2001)
•**Diffusion model with convection and reacceleration**
•Uncertainties on propagation param . and c.s.
•Solar modulation: spherical model (ϕ=500MV)



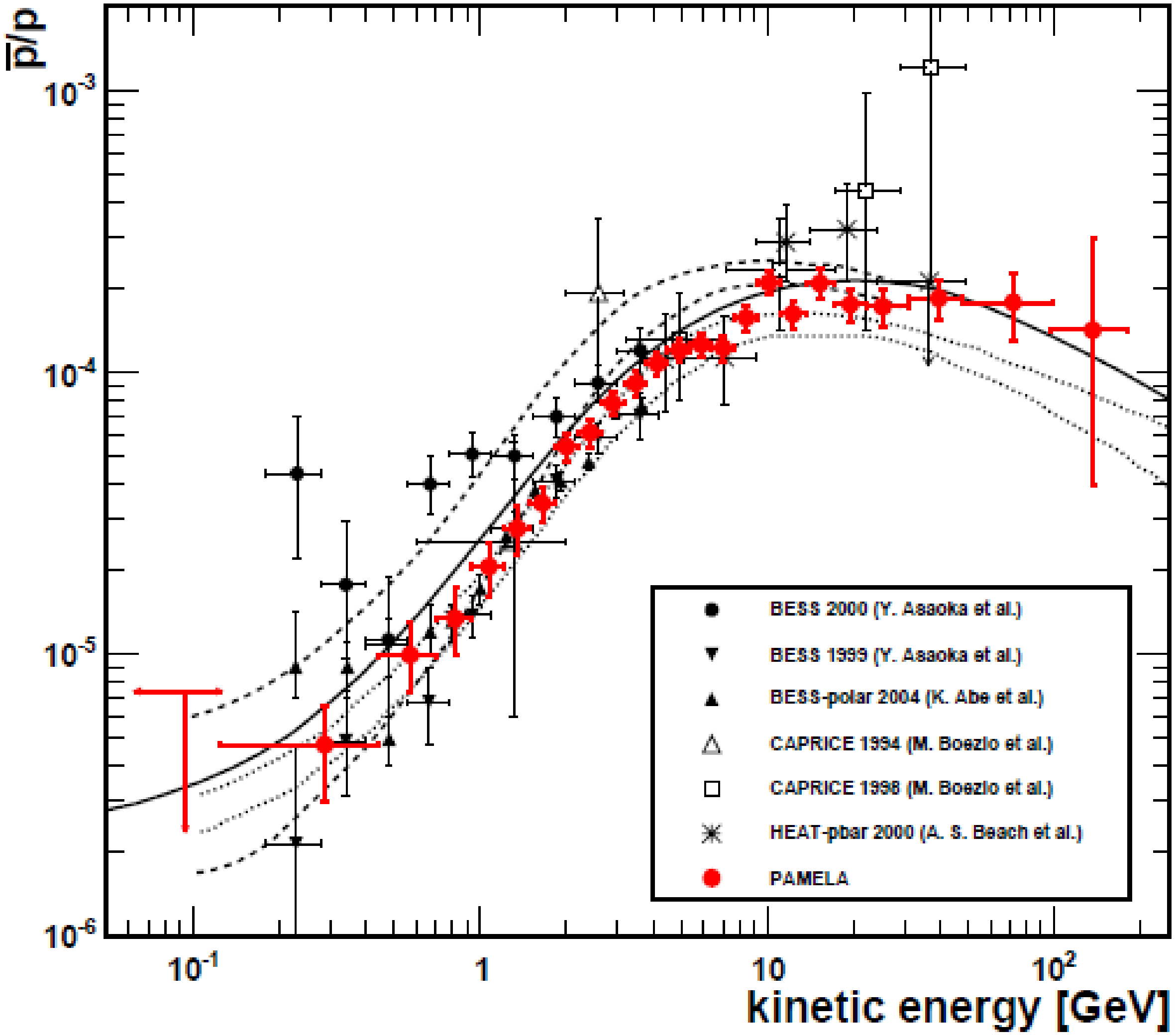
Adriani et al. - PRL 105 (2010) 121101

(Ptuskin et al. 2006) GALPROP code
• **Plain diffusion model**
• Solar modulation: spherical model (ϕ=550MV)

Antiproton-to-proton ratio

- Overall agreement with pure secondary calculation

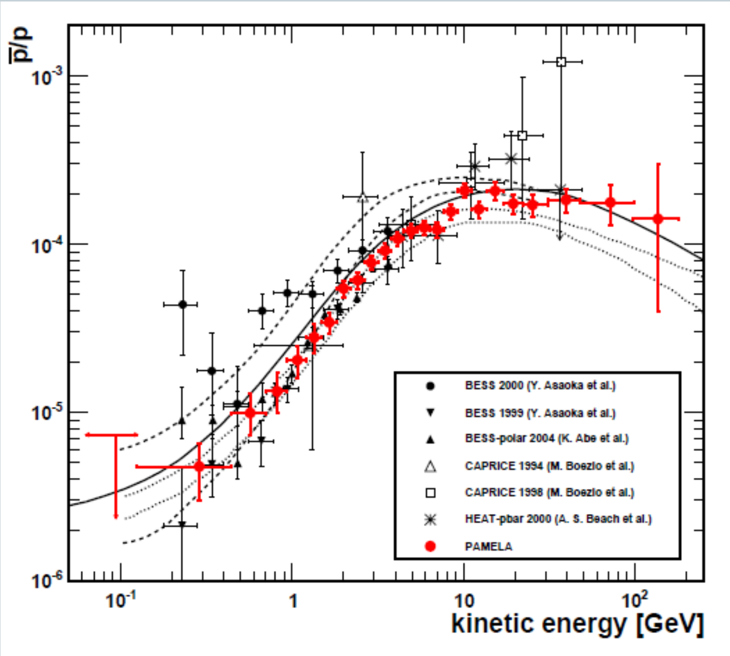
Adriani et al. - PRL 105 (2010) 121101



A challenging puzzle for CR physicists

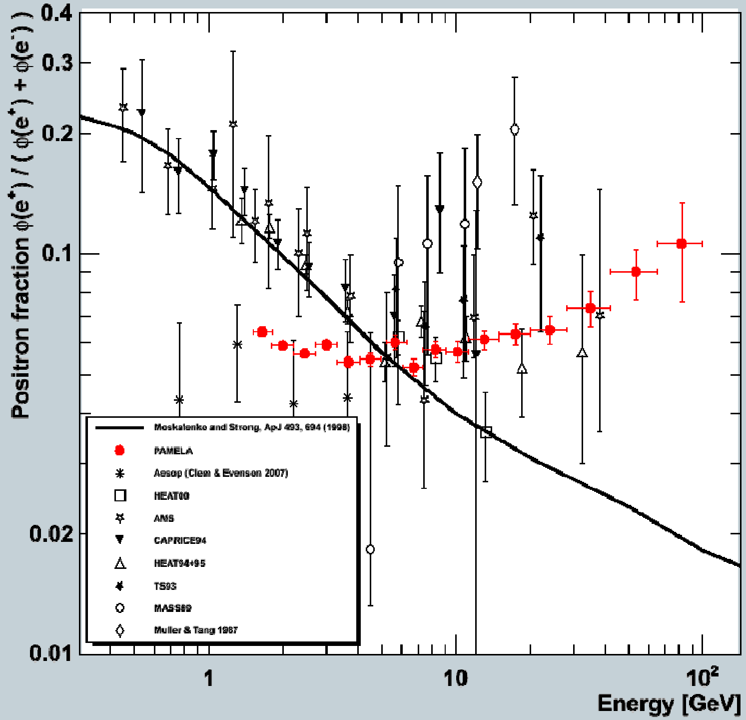
Antiprotons

→ Consistent with pure secondary production



Positrons

→ Evidence for an excess



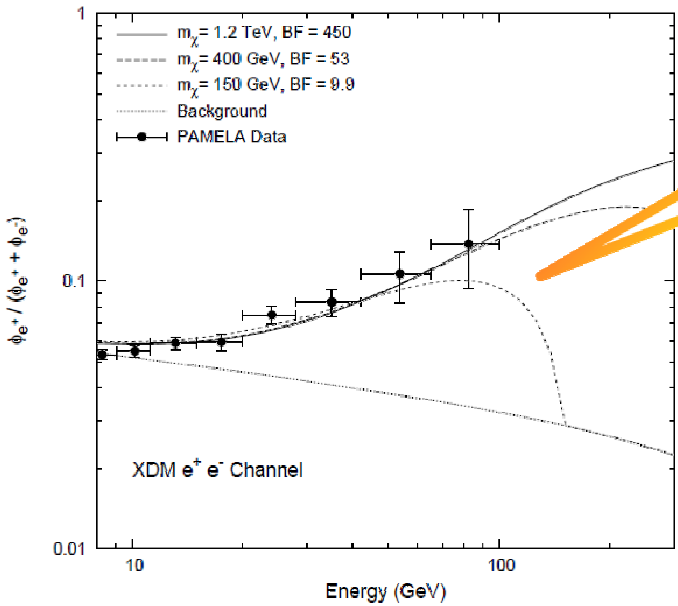
Positron-excess interpretations

Dark matter

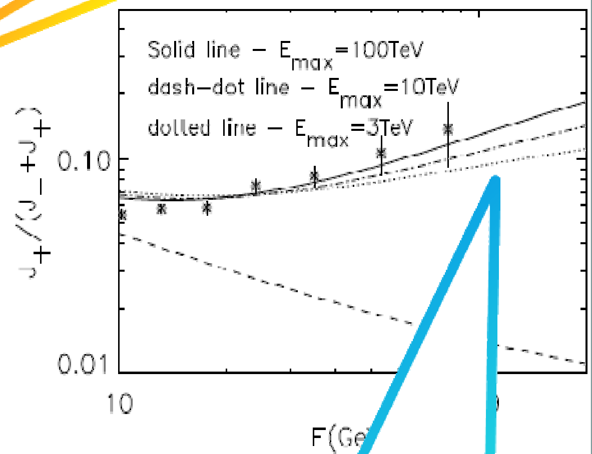
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

Astrophysical processes

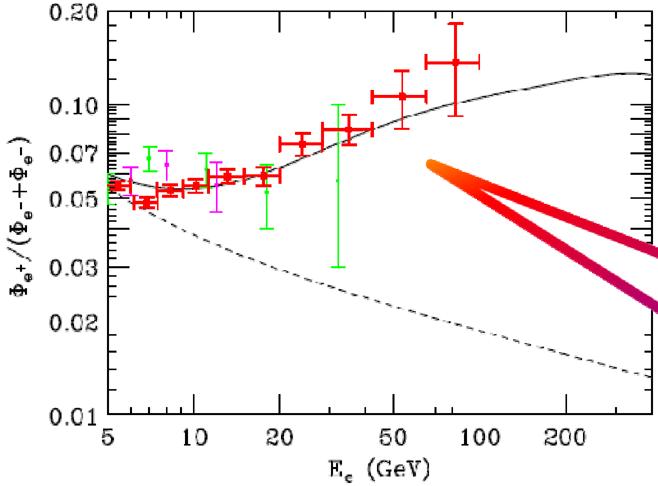
- known processes
- large uncertainties on environmental parameters



(Cholis et al. 2009)
Contribution from **DM annihilation**.

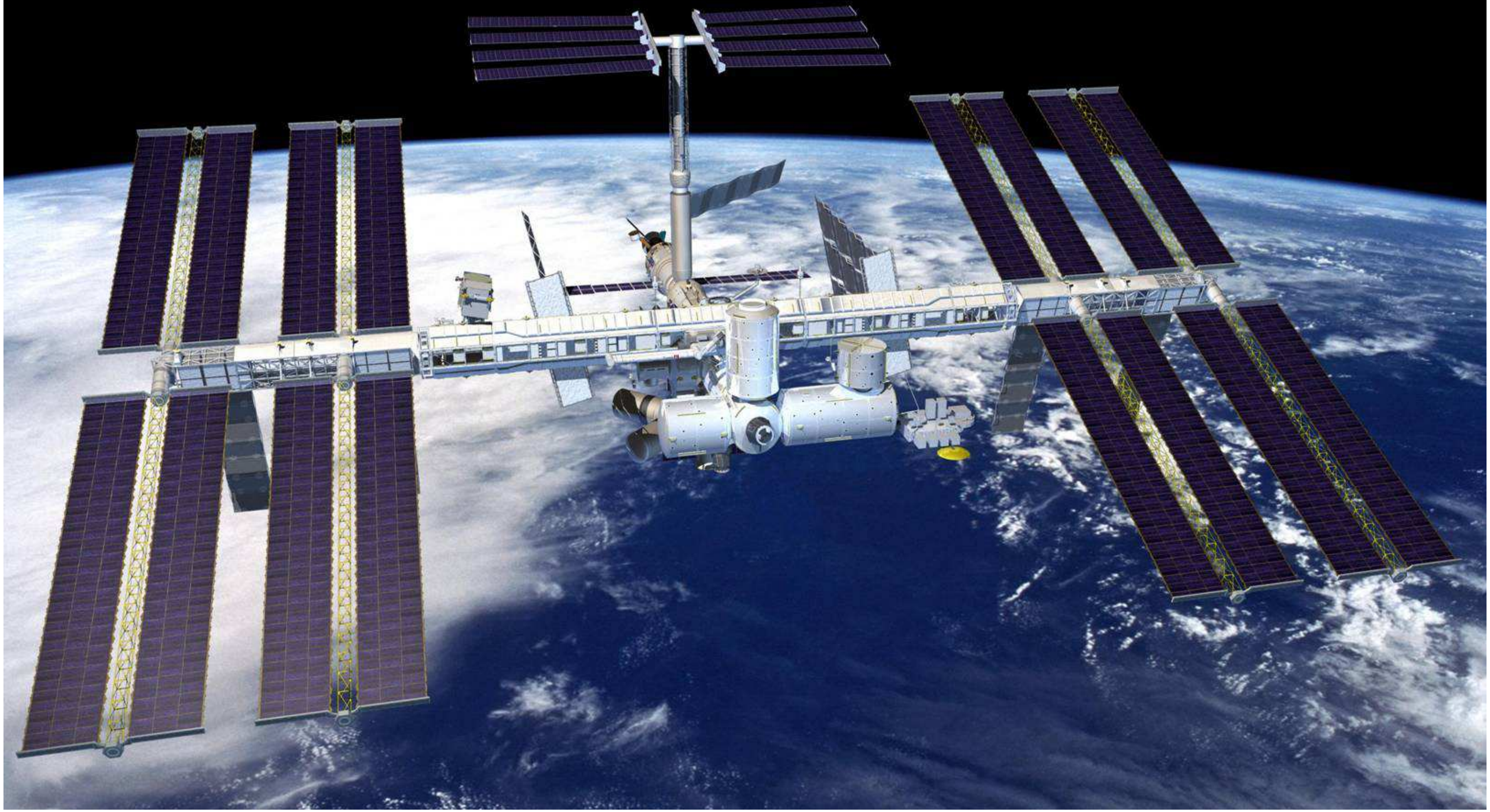


(Blasi 2009)
e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)



(Hooper, Blasi and Serpico, 2009)
contribution from diffuse mature & nearby young **pulsars**.

Orbiting Space Station



ALPHA MAGNETIC SPECTROMETER

→Search for primordial anti-matter

→Indirect search of dark matter

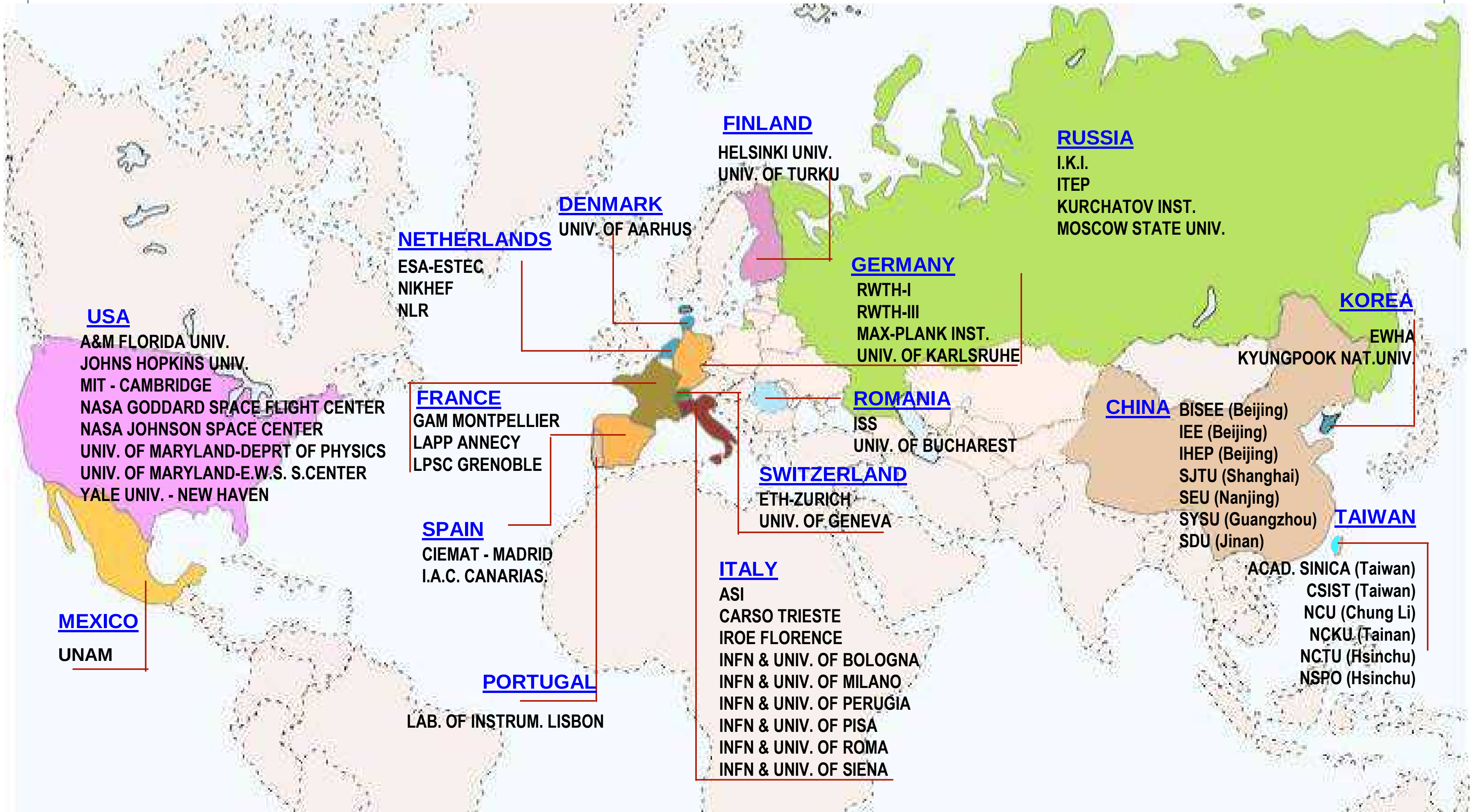
→High precision measurement of the energetic spectra and composition of CR from GeV to TeV

AMS-01: 1998 (10 days) - PRECURSOR FLIGHT ON THE SHUTTLE

AMS-02: **Since May 19th, 2011, safely on the ISS.** Four days after the Endeavour launch, that took place on Monday May 16th, the experiment has been installed on the ISS and then activated.

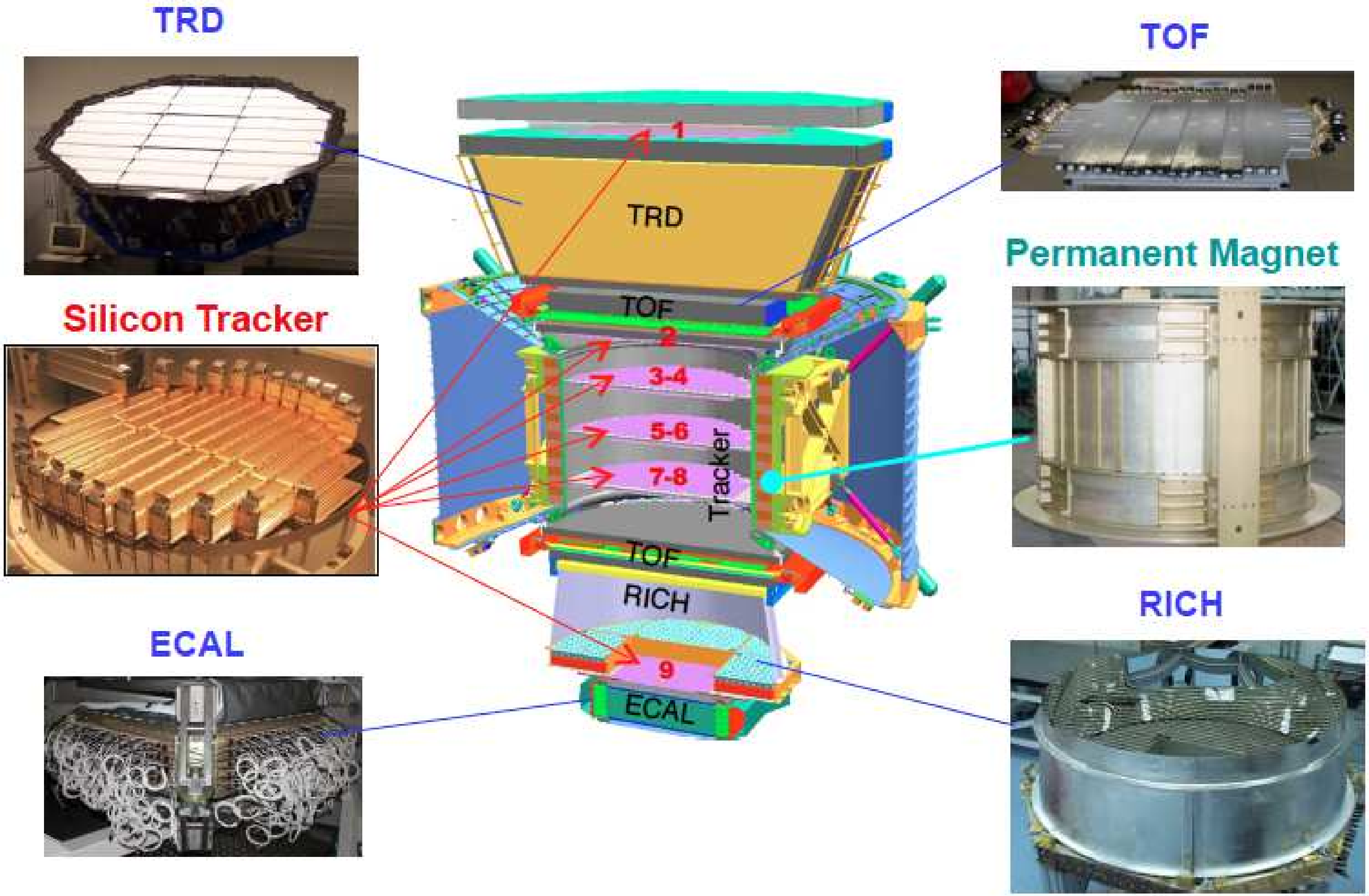
COMPLETE CONFIGURATION FOR >10 YEARS LIFETIME ON THE ISS

AMS-02 : the collaboration

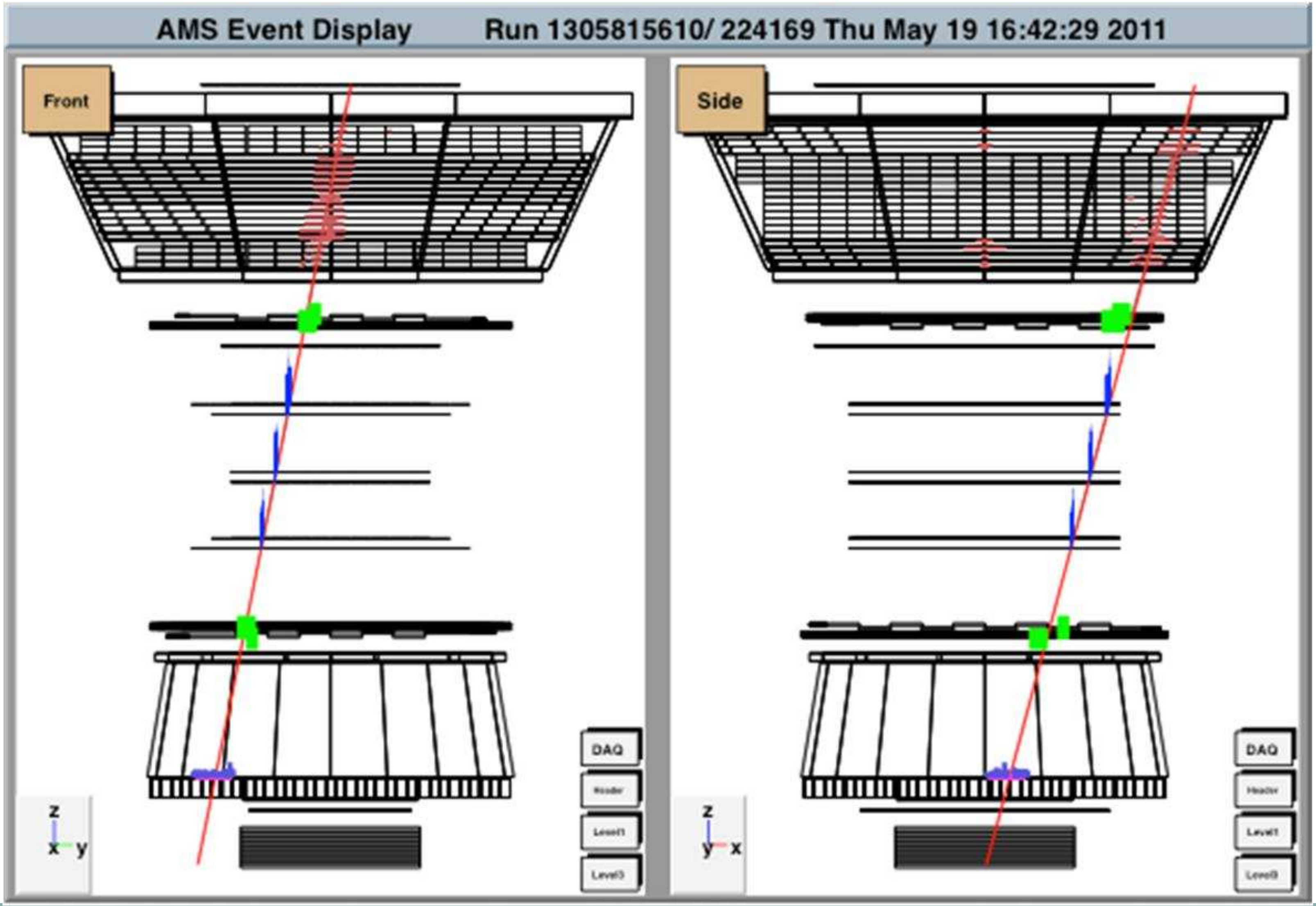


» 500 physicists, 16 countries, 56 Institutes

The AMS-02 detector

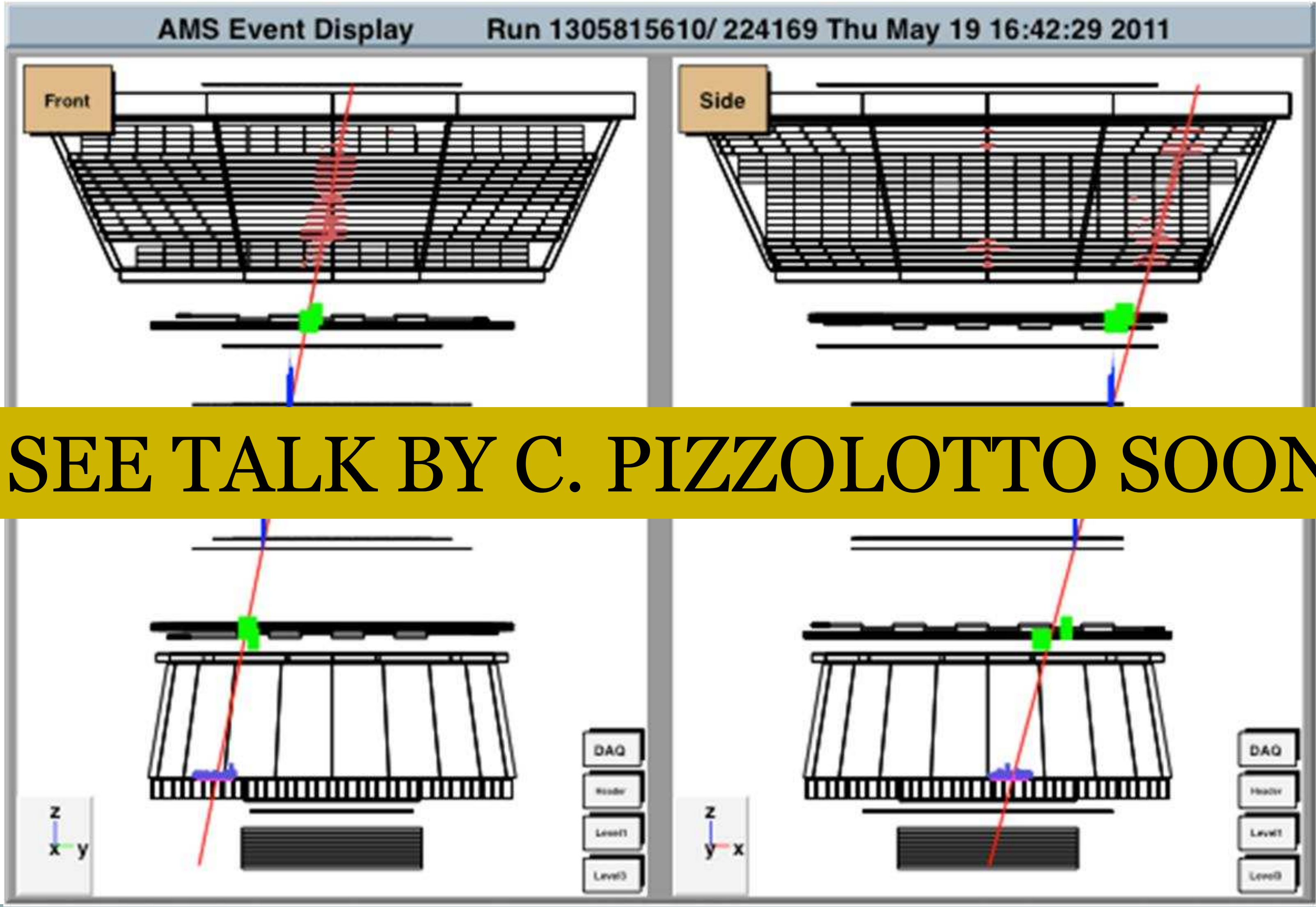


AMS first events



42 GeV Carbon nucleus

AMS first events



SEE TALK BY C. PIZZOLOTTO SOON

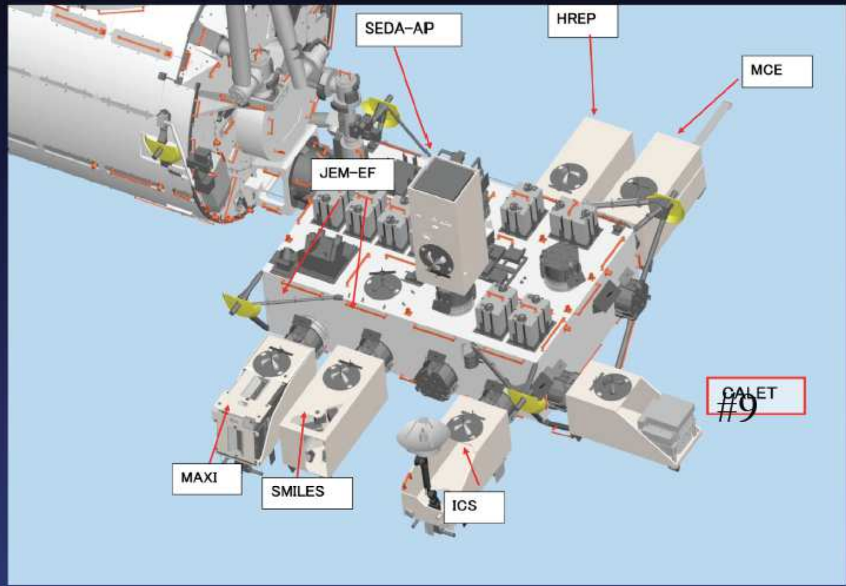
42 GeV Carbon nucleus


Future
experiments

CALorimetric Electron Telescope (CALET)

- **Instrument:**
  High Energy Electron and Gamma-Ray Telescope
- **Carrier:**
  HTV: H-IIA Transfer Vehicle
- **Attach Point on the JEM-EF: #9**
  for heavy (< 2000 kg) payloads
- **Nominal Orbit:**
  407 km, 51.6° inclination
- **Launch plan:**
  FY 2013
- **Life Time:**
  ≥ 5 years

Firenze
Pisa
Siena
Roma Tor Vergata



1 GeV ~ 20 TeV for electrons

20 MeV ~ TeV for gamma-rays

Weight: 500 kg

GF (fiducial volume): ~ 0.12 m^2sr

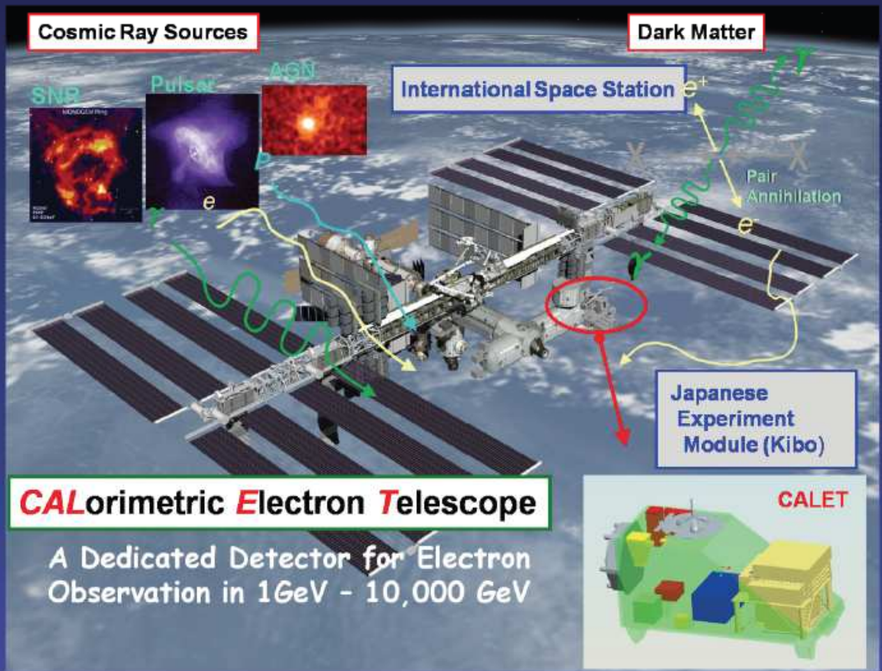
Power Consumption: 640 W

Data Rate: 300 kbps

CALET Overview

◻ Observation

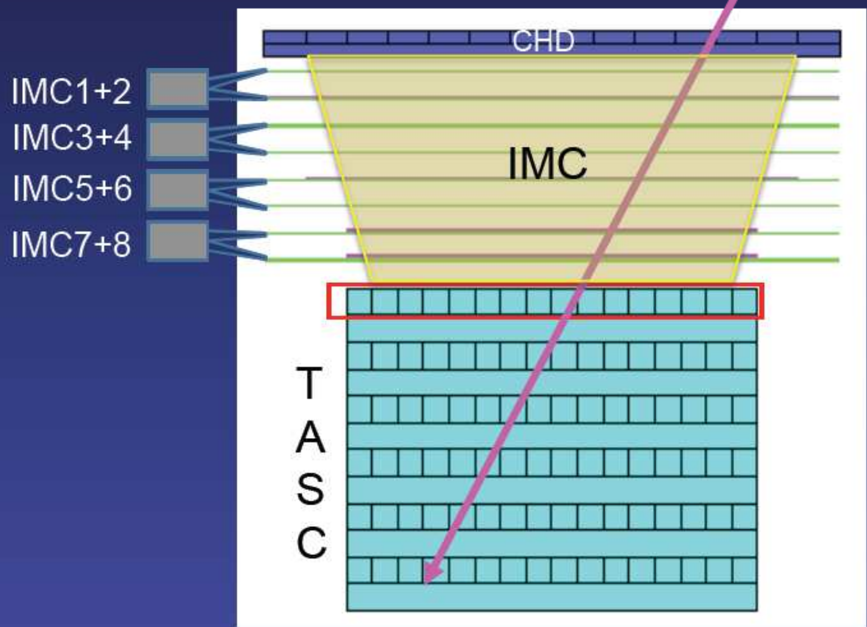
- **Electrons** : 1 GeV - 10 TeV
- ***Gamma-rays*** : 10 GeV-10 TeV (GRB > 1 GeV)
  + Gamma-ray Bursts : 7 keV-20 MeV
- **Protons, Heavy Nuclei**:
  several 10 GeV- 1000 TeV (per particle)
- ***Solar Particles and Modulated Particles in Solar System***: 1 GeV-10 GeV (Electrons)



Instrument

High Energy Electron and Gamma-Ray Telescope:

- CHarge Detector (CHD)
  (Charge Measurement in Z=1-40)
- Imaging Calorimeter (IMC)
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): 3 X_0 0.11 λ_I
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- Total Absorption Calorimeter (TASC)
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: 27 X_0 (24cm) , 1.35 λ_I



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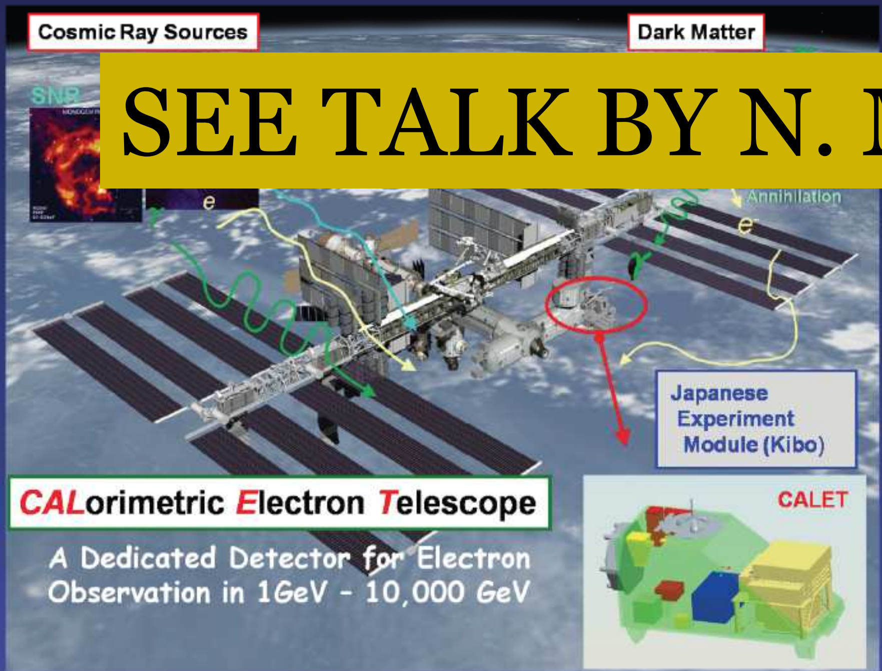
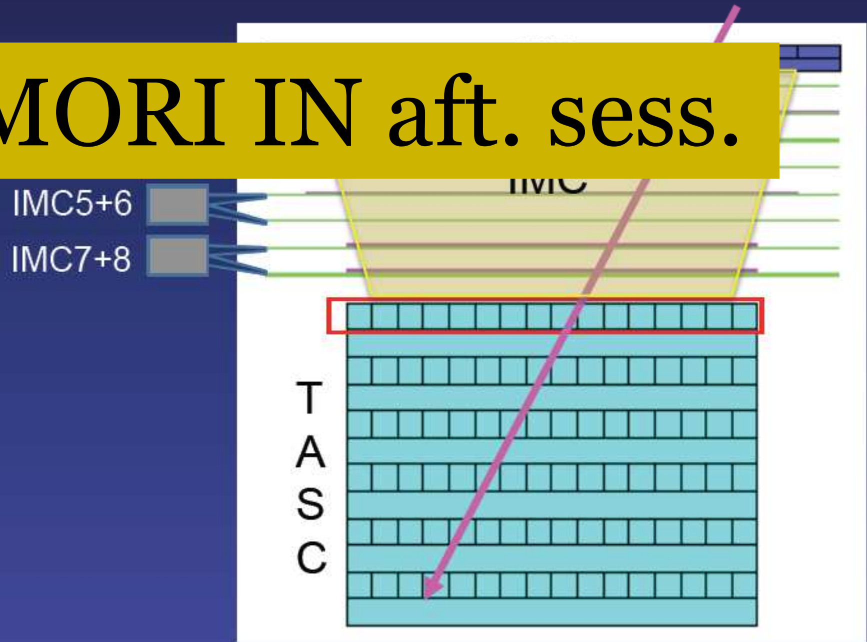


SEE TALK BY N. MORI IN aft. sess.



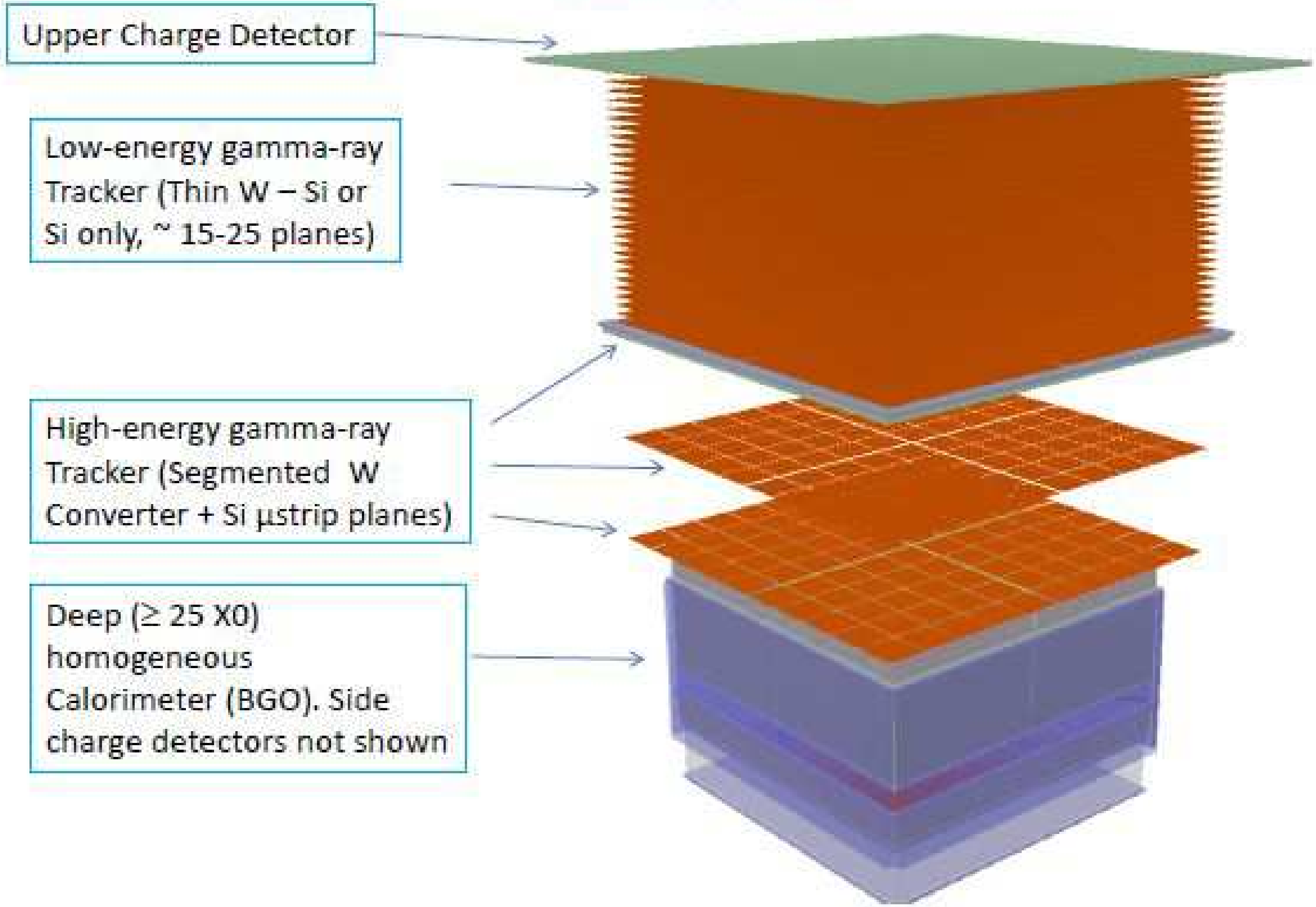
Gamma-400 on Russian satellite

It will combine for the first time photon and particle (electrons and nuclei) detection in a unique way

- **Excellent Silicon Tracker (30 MeV – 300 GeV),**
  - **breakthrough angular resolution 4-5 times better than Fermi-LAT at 1 GeV**
  - **improved sensitivity compared with Fermi-LAT by a factor of 5-10 in the energy range 30 MeV – 10 GeV**

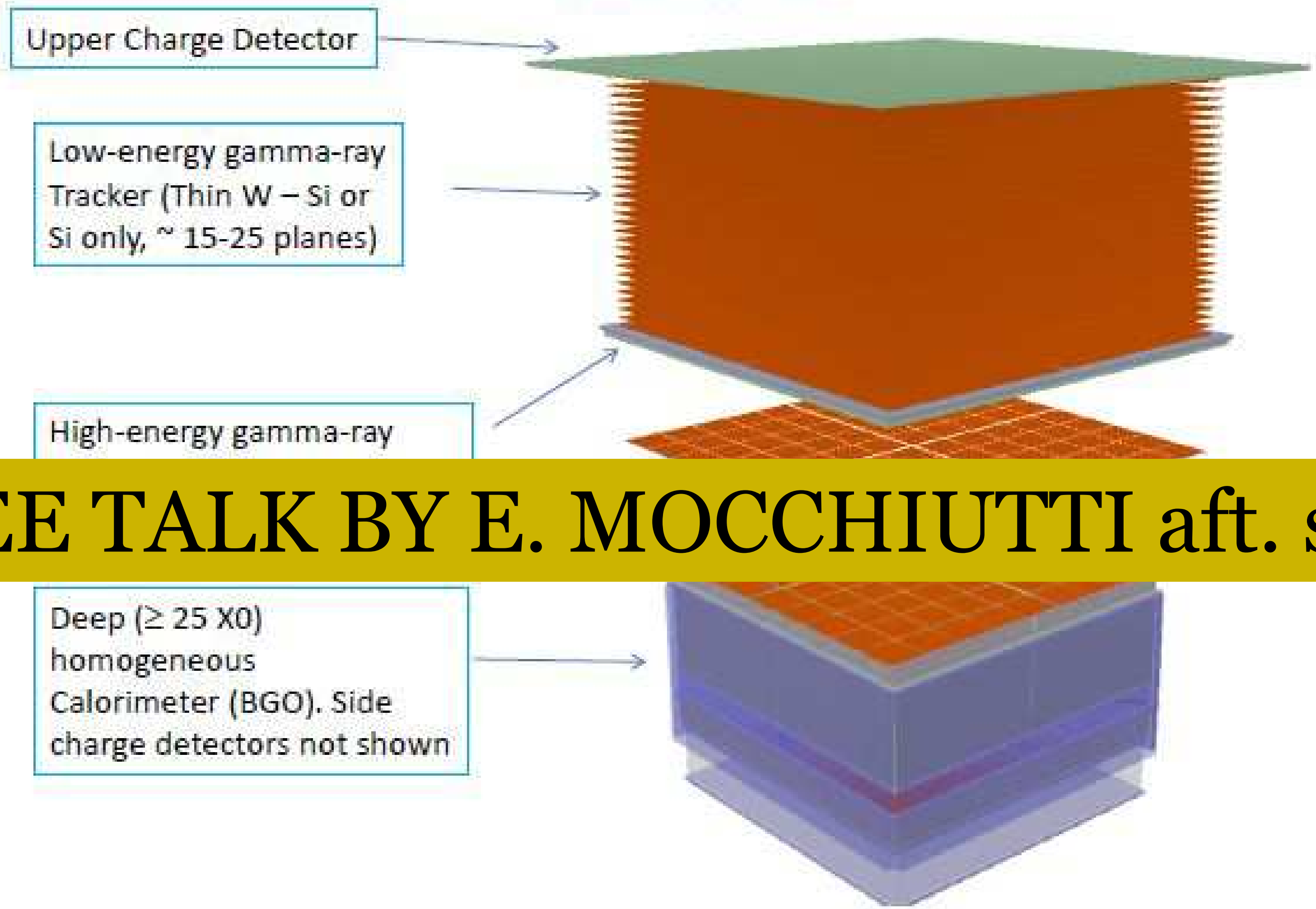
- **Heavy Calorimeter (25 X_0) with optimal energy resolution and particle discrimination**
  - **Electron/positron detection up to TeV energies**
  - **Nuclei detection up to 10^{15} eV energies**

Gamma-400



apparatus versions used in one of the preliminary simulations.

Gamma-400

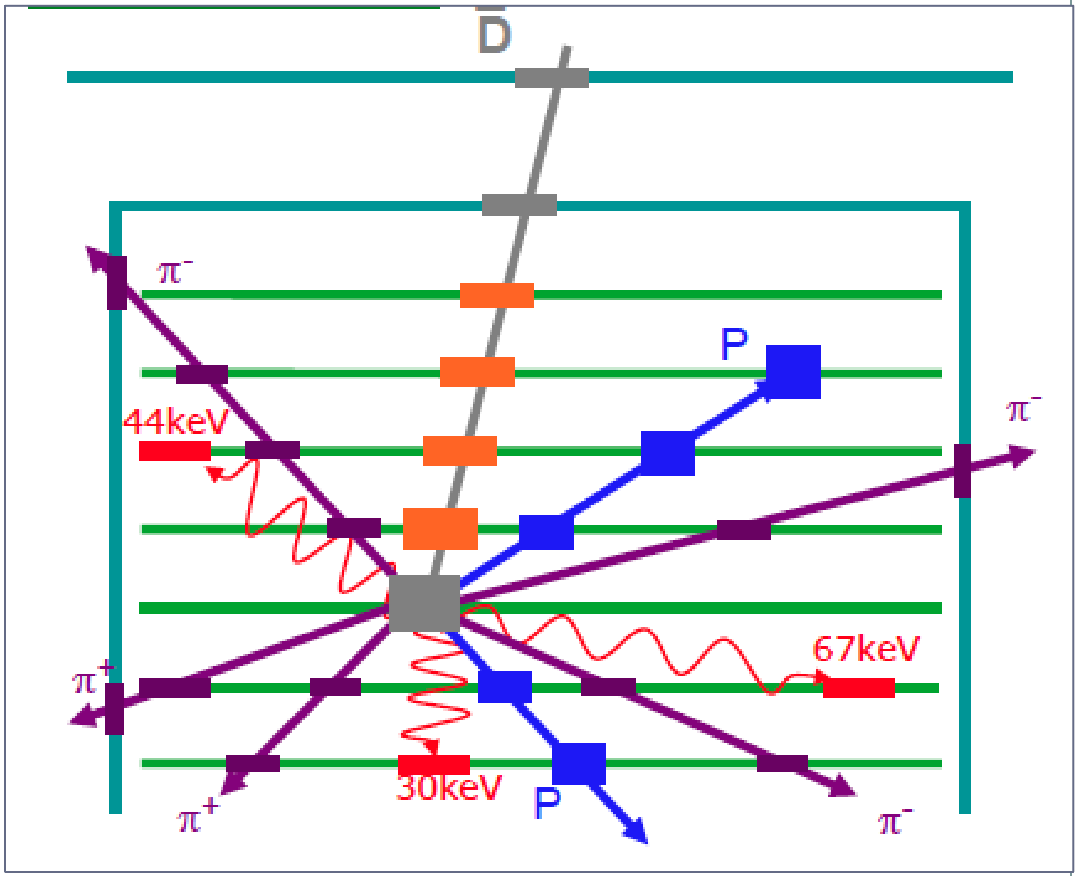


SEE TALK BY E. MOCCHIUTTI aft. sess.

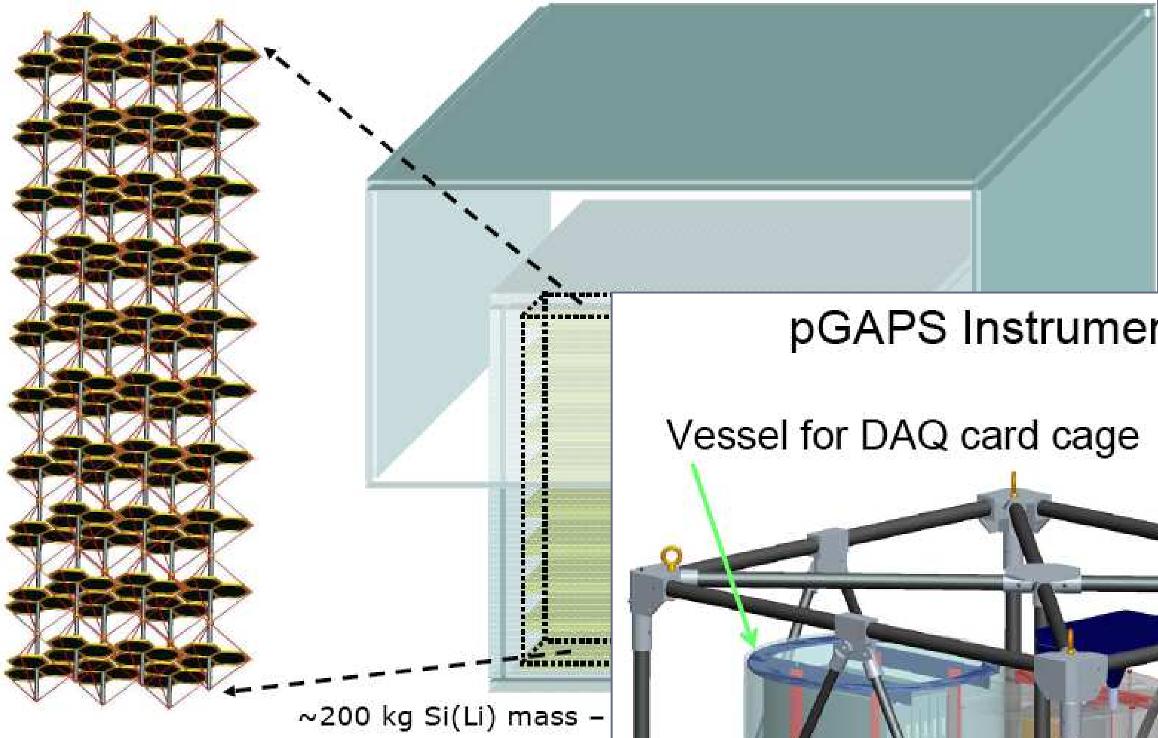
apparatus versions used in one of the preliminary simulations.

The GAPS experiment

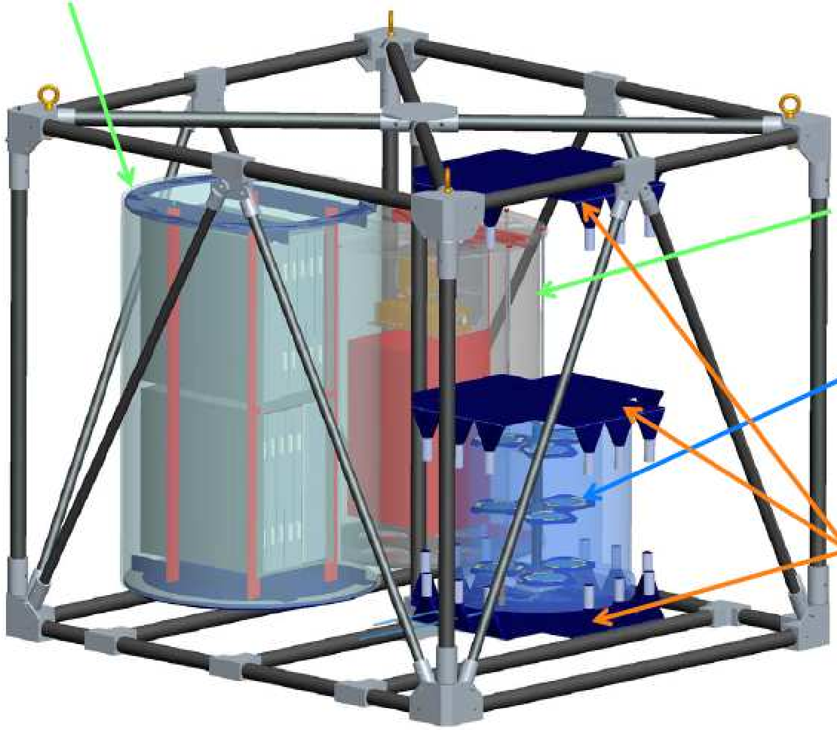
- A time of flight (TOF) system tags candidate events and records velocity
- The antiparticle slows down & stops in a target material, forming an excited exotic atom with near unity probability
- Deexcitation X-rays provide signature
- Pions and protons from annihilation provide added background suppression



Si(Li) Wafers will be hexagonally packed into detector planes & surrounded by segmented Plastic TOF



pGAPS Instrument for Taiki Launch 2011



- GAPS will provide 2-3 orders of magnitude improvement on the antideuteron limit obtained with BESS-polar
- Payload design and hardware fabrication is underway for a prototype (pGAPS) experiment from Taiki, Japan in 2011
- GAPS Development Plan Culminates in a Long-Duration Balloon (LDB) Experiment from Antarctica with the bGAPS science experiment in late 2014-2015

Conclusions

High energy line

- H and He spectra **are** different
- H and He spectra **harden with energy** (230 GV)
- Hi-Z spectra **might** show similar hardening
- Energy dependance of propagation **still undecided**

Composition line

- Source matter **must be** a composition of old ISM with newly sinthetized matherial, in percentage 80%-20% (sites of acceleration rich in massive stars?)

Conclusions

Antimatter line

- All electron spectrum **shows enhancement** at high energy (hundreds GeV). Nearby source?
- Positrons **show enhancement** in the E>10 GeV region (new e+ e- source. Correlated to previous?)
- **No antiproton excess** observed both at low and high energy (several DM models and exotics ruled out)
- **No heavier anti-nucleus** observed (very stringent limits)

New fresh data from AMS-02 could improve the understanding of some of the still open issues in the direct measurements sector

THANK YOU!