Dark matter searches by charged cosmic rays detection in space

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SIGNALS from RELIC WIMPs

For a review, see i.e. Bergstrom hep-ph/0002126

Direct searches: **elastic scattering of a WIMP off detector nuclei**
Measure of the recoil energy

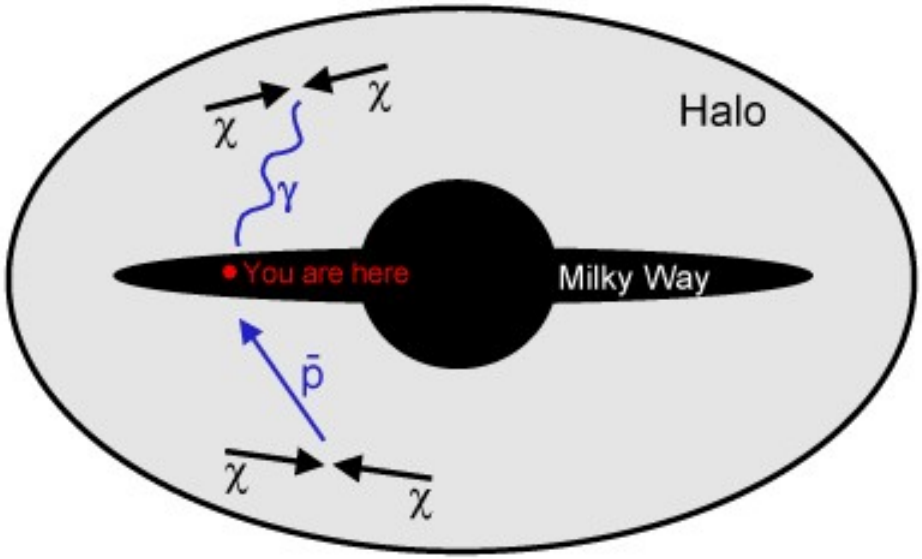
Indirect detection: in cosmic radiation

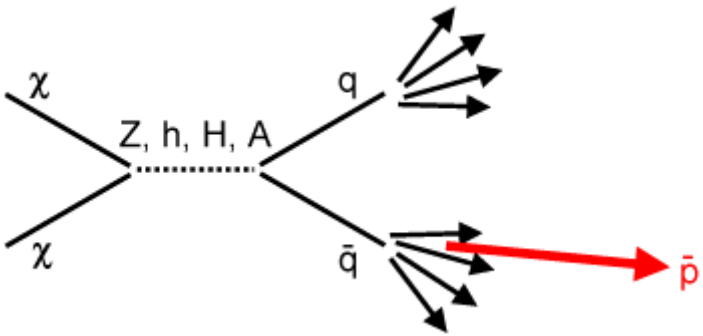
- **signals due to annihilation of accumulated $\chi\chi$ in the centre of celestial bodies (Earth and Sun)**
  $\rightarrow$ **neutrino flux**

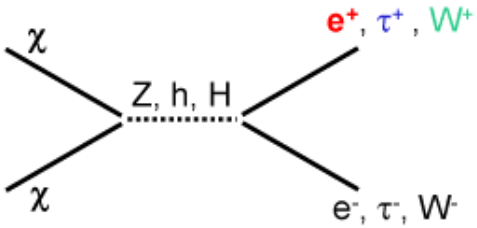
- **signals due to $\chi\chi$ annihilation in the galactic halo**
  $\rightarrow$ **neutrinos**
  $\rightarrow$ **gamma-rays**
  $\rightarrow$ **antiprotons, positrons, antideuterons**

ν and γ keep directionality
can be detected only if emitted from high χ density regions
Charged particles diffuse in the galactic halo
antimatter searched as rare components in cosmic rays (CRs)

Neutralino annihilation







$$\chi + \bar{\chi} \rightarrow X + \gamma$$ (GLAST)

$$+ \nu$$ (AMANDA / IceCube)

$$+ \bar{p}$$

$$+ e^{+}$$

$$+ \bar{D}$$

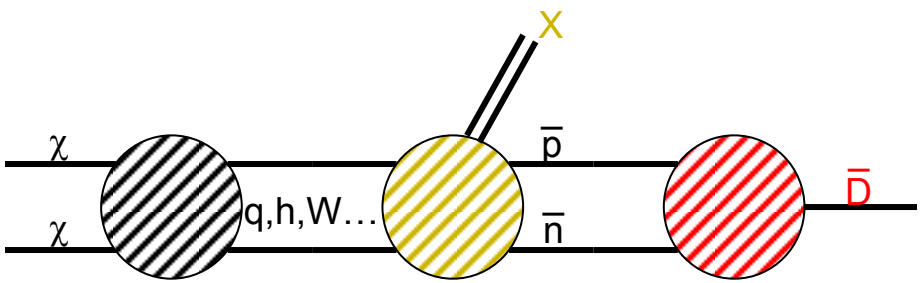
PAMELA (and Bess, HEAT, AMS etc.)

The presence of neutralino annihilation will <u>destort the positron, antiproton and gamma energy spectrum</u> from purely secondary production

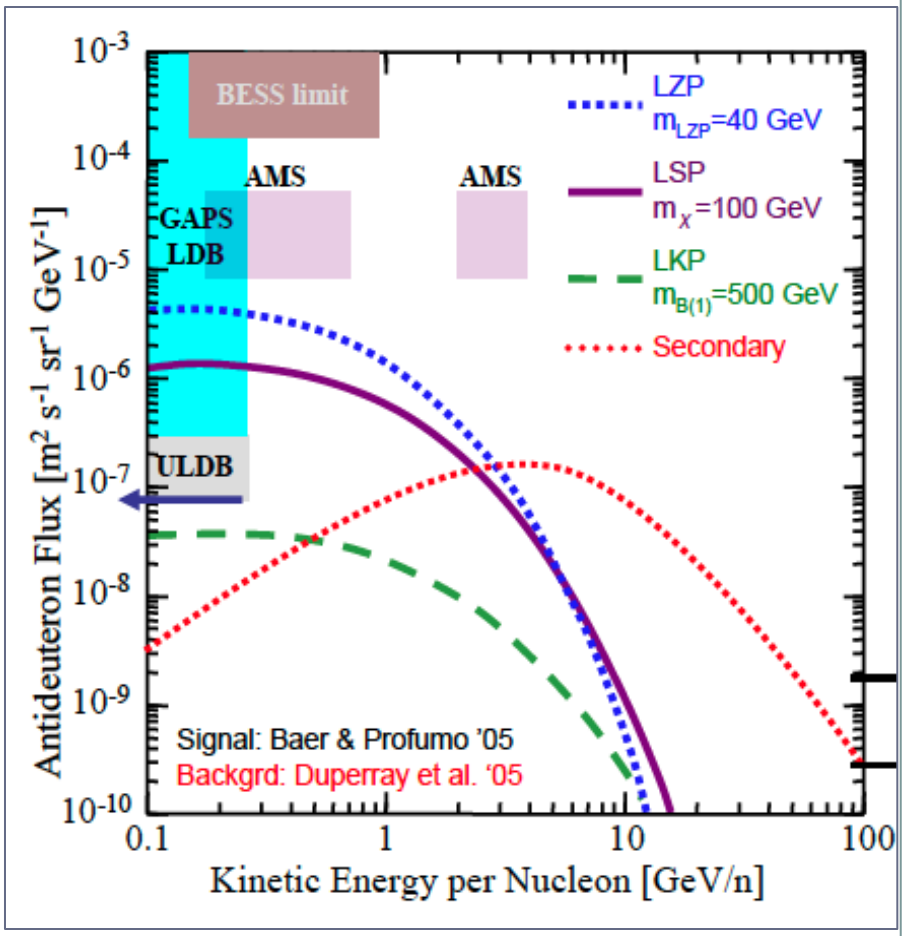
Antideuterons

- Pair annihilating WIMPS produce:

γ, ν, e^+… $\bar{p}$…



Dark Matter Model | Hadronization Monte Carlo | Coalescence Model



F. Donato *et al.* Antideuterons as a signature of supersymmetric dark matter. *Phys. Rev D*, 62(4):043003

Cosmic antideuterons represent a near "smoking gun" signature of dark matter

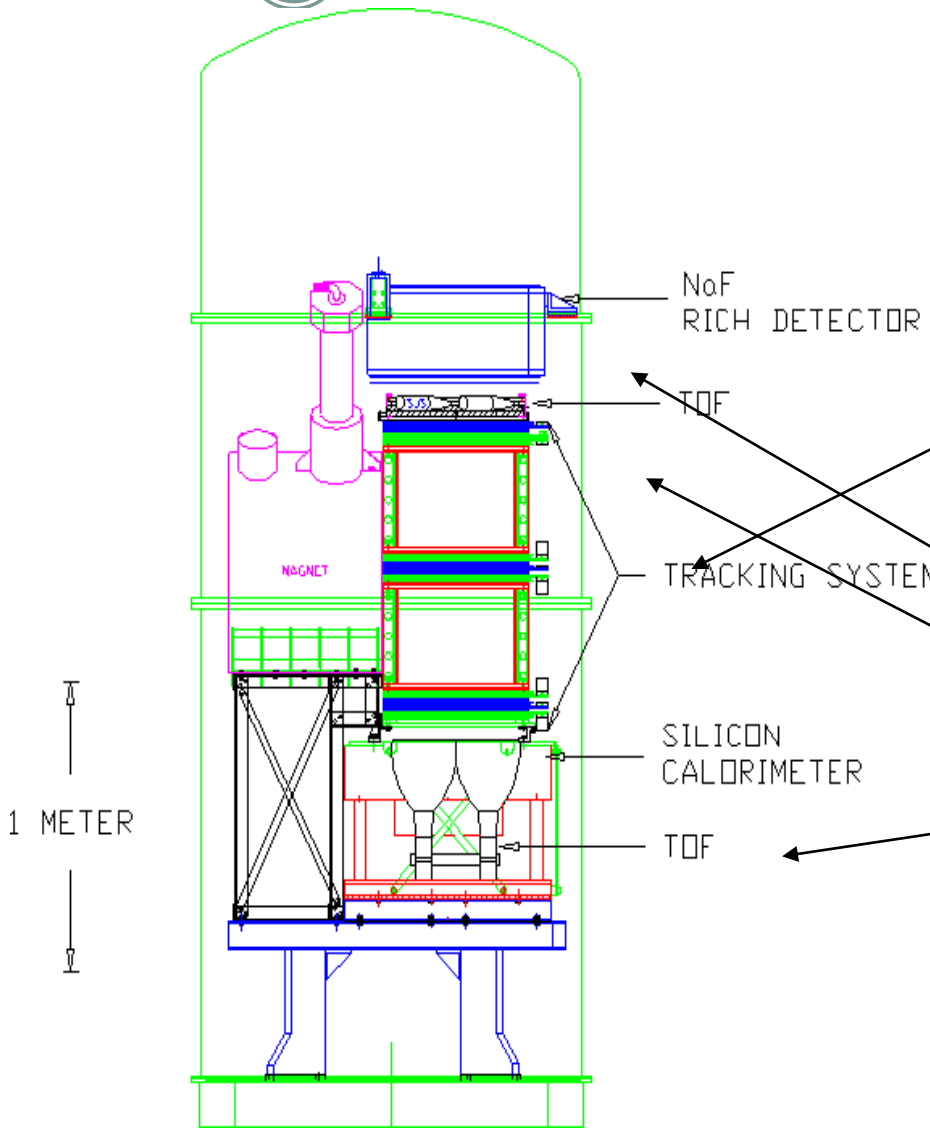
Stratospheric balloons

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.

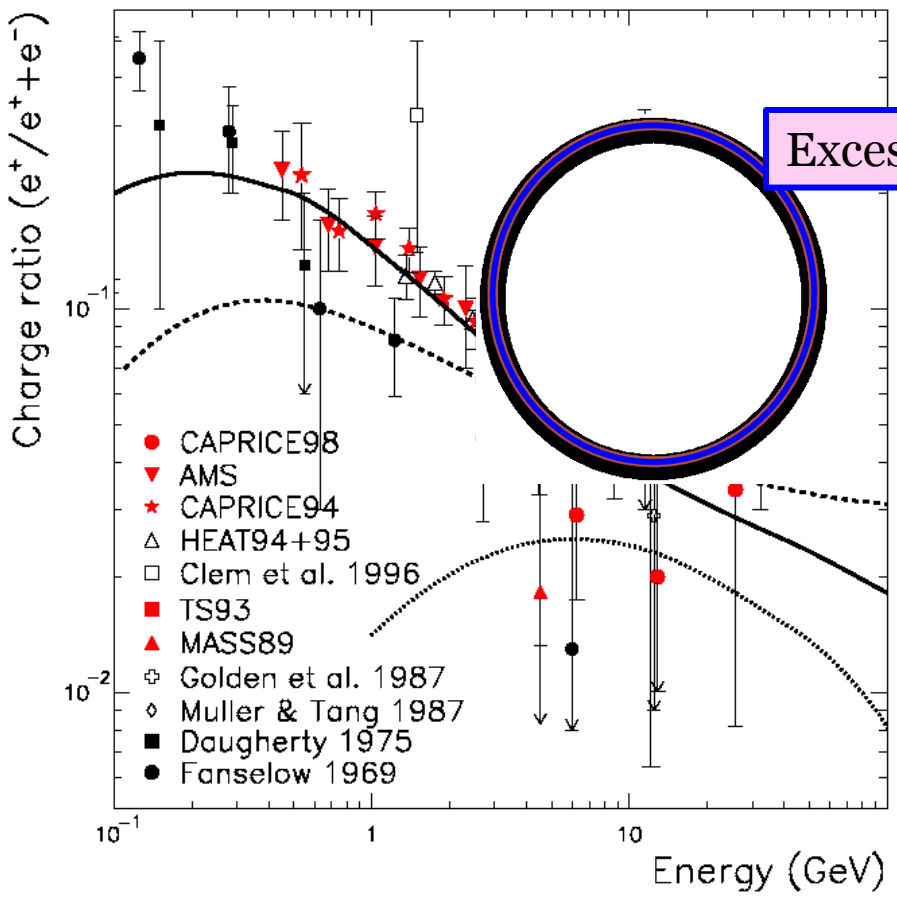
4 flights from the HEAT collaboration: 2 **HEAT-e+**, in 1994 and 1995, and 2 **HEAT-pbar** flights, in 2000 and 2002



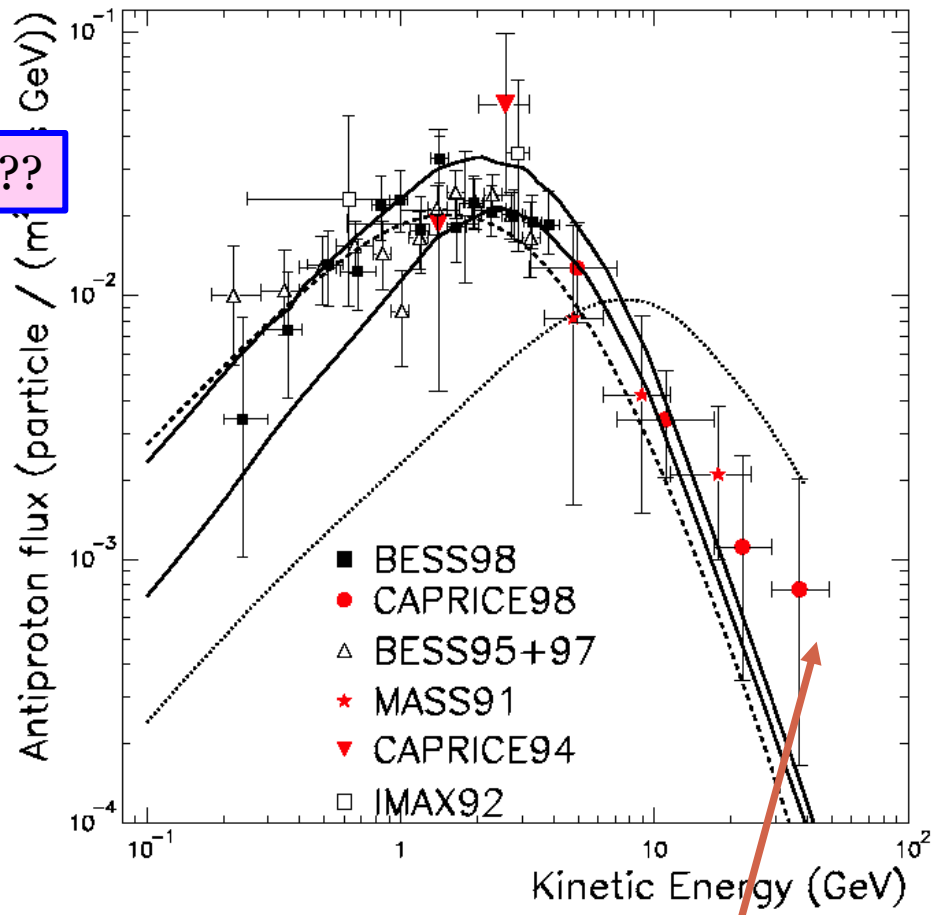
- Charge sign and momentum determination;
- Beta selection
- Z selection
- hadron – electron discrimination

CAPRICE-94

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

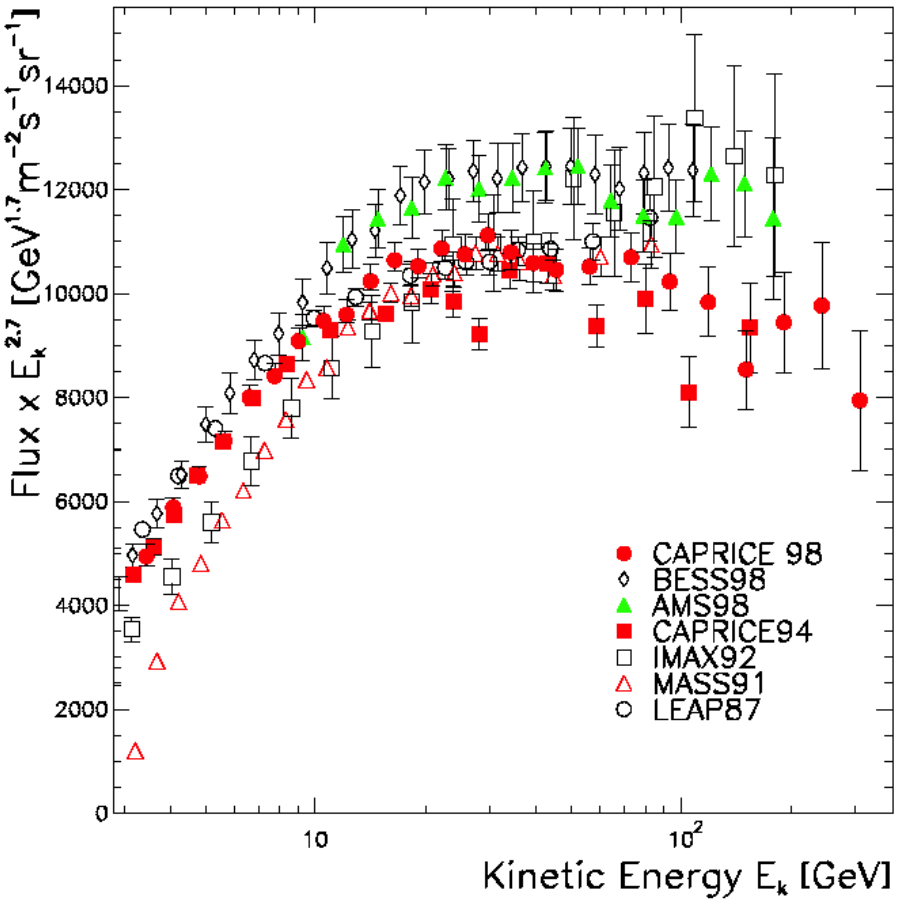


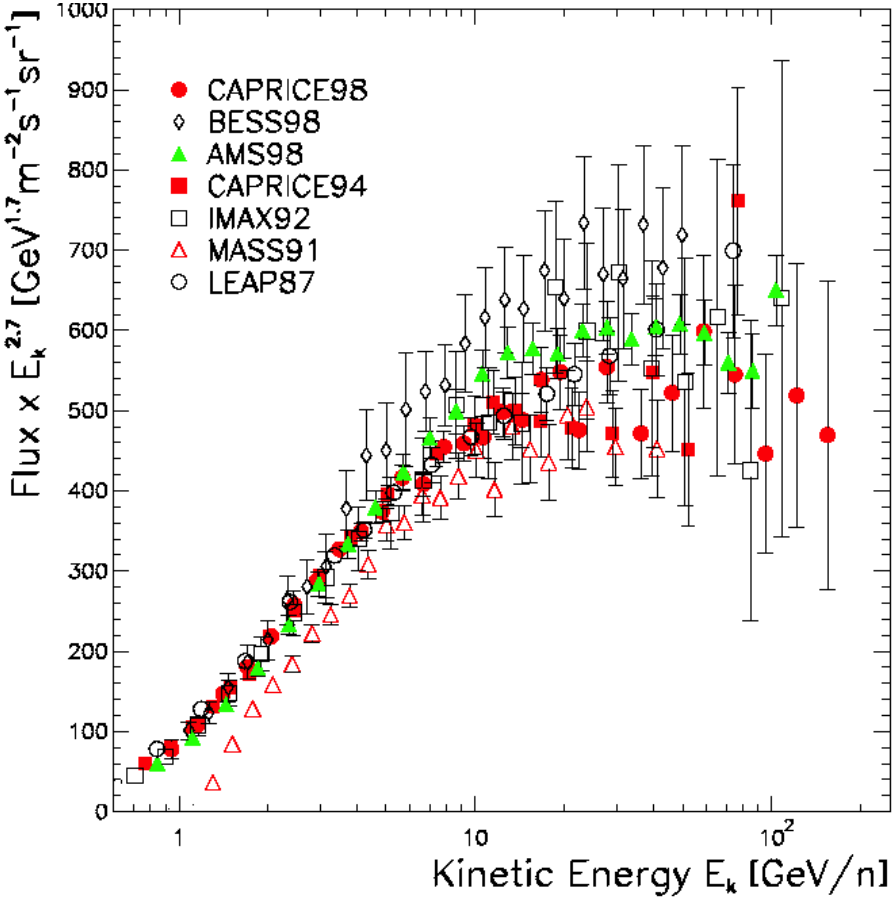
Excess ??



Highest energetic points available from balloons

Protons and heliums





The BESS program

- The BESS program had **11 successful flight campaigns since 1993 up to 2008.**

- 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).

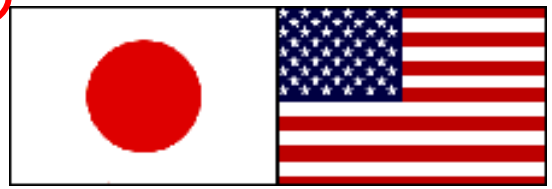
BESS Collaboration

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

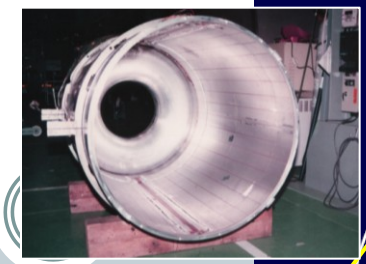
Central tracker

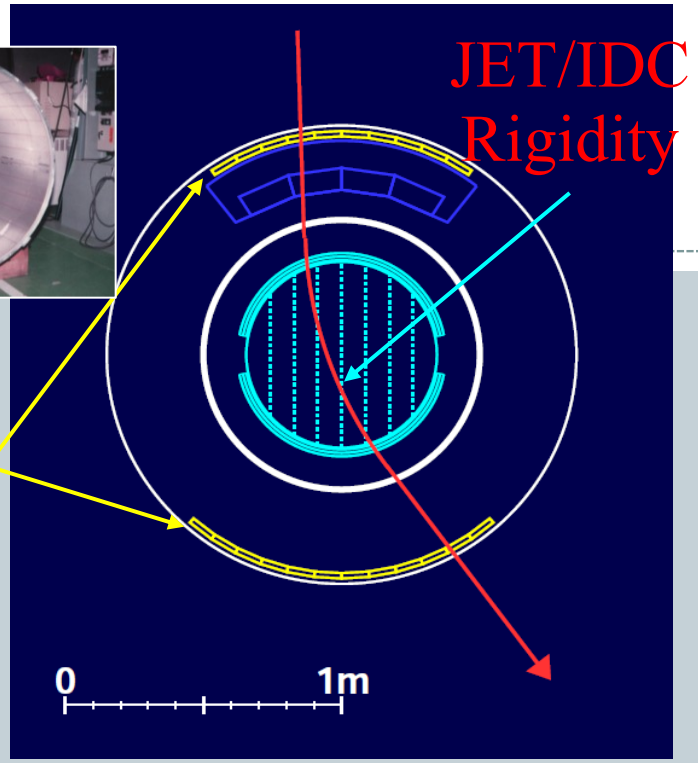
- Drift chambers (Jet/IDC)
  - δ ~200 μm

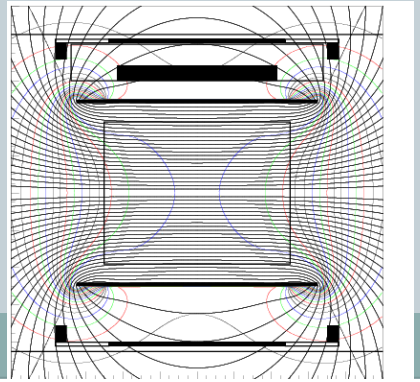
Z, m measurement

R,β --> $m = Ze\sqrt{R\ 1/\beta^2-1}$

dE/dx --> *Z*

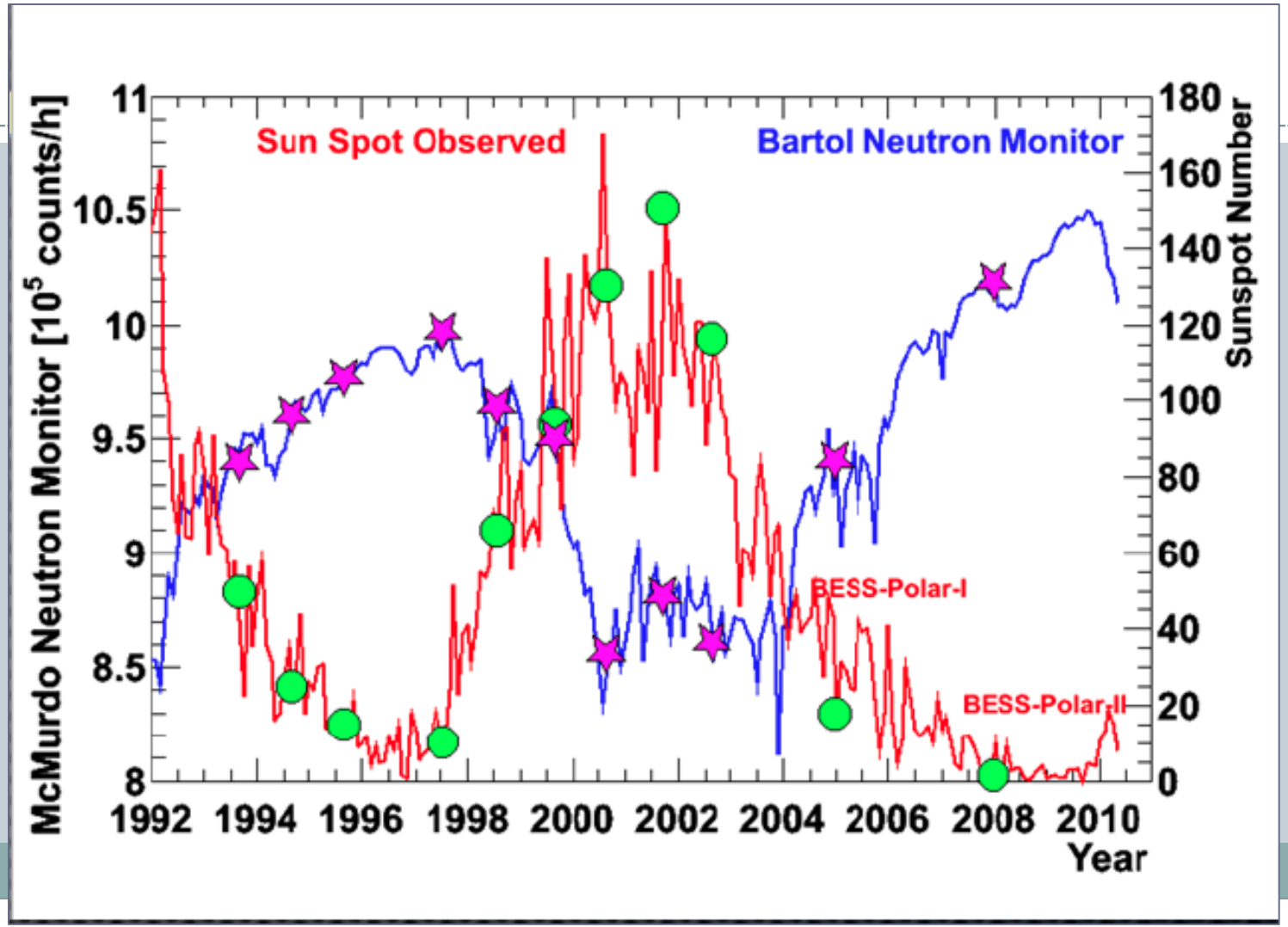




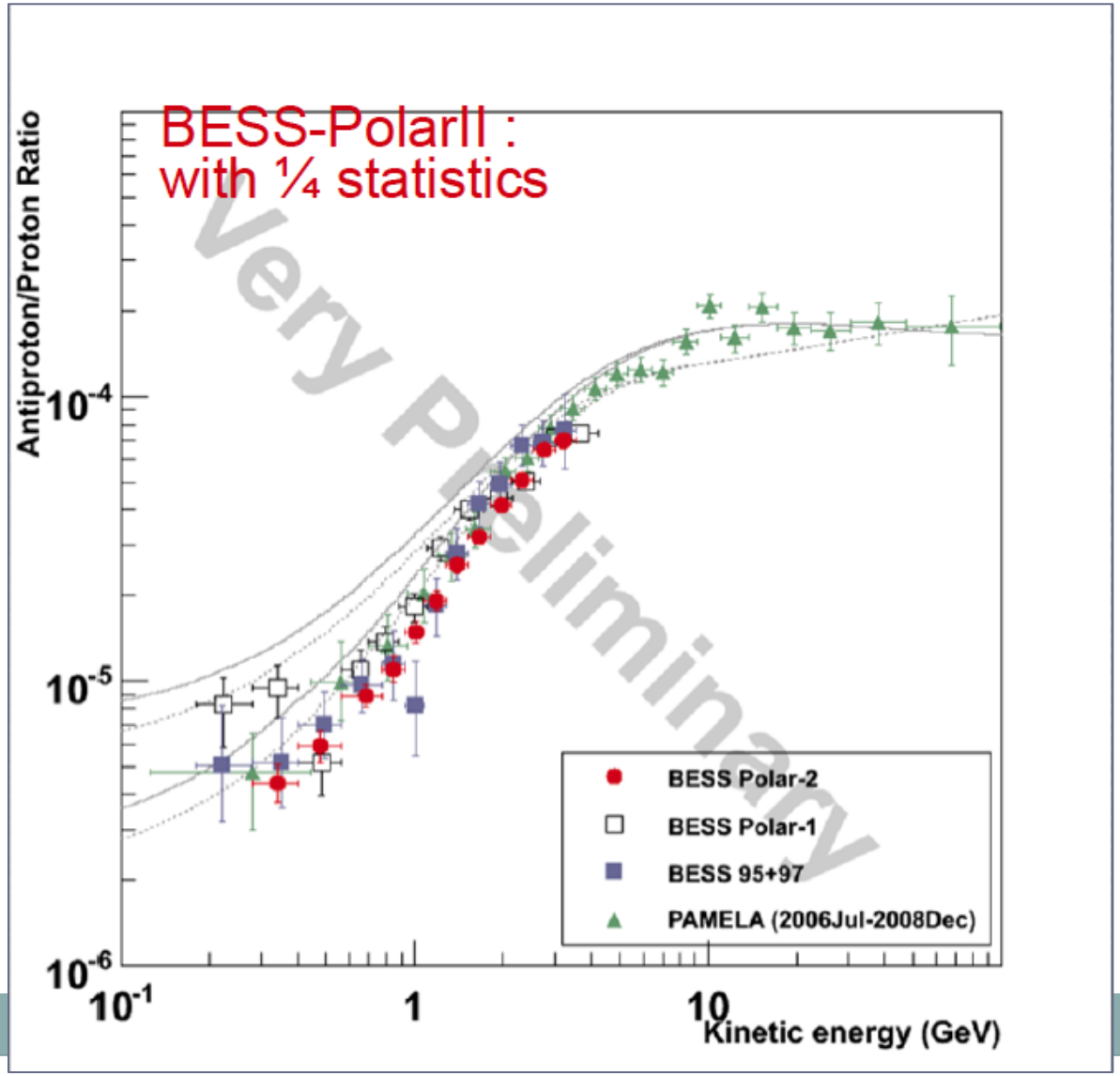


BESS-Polar I and II

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

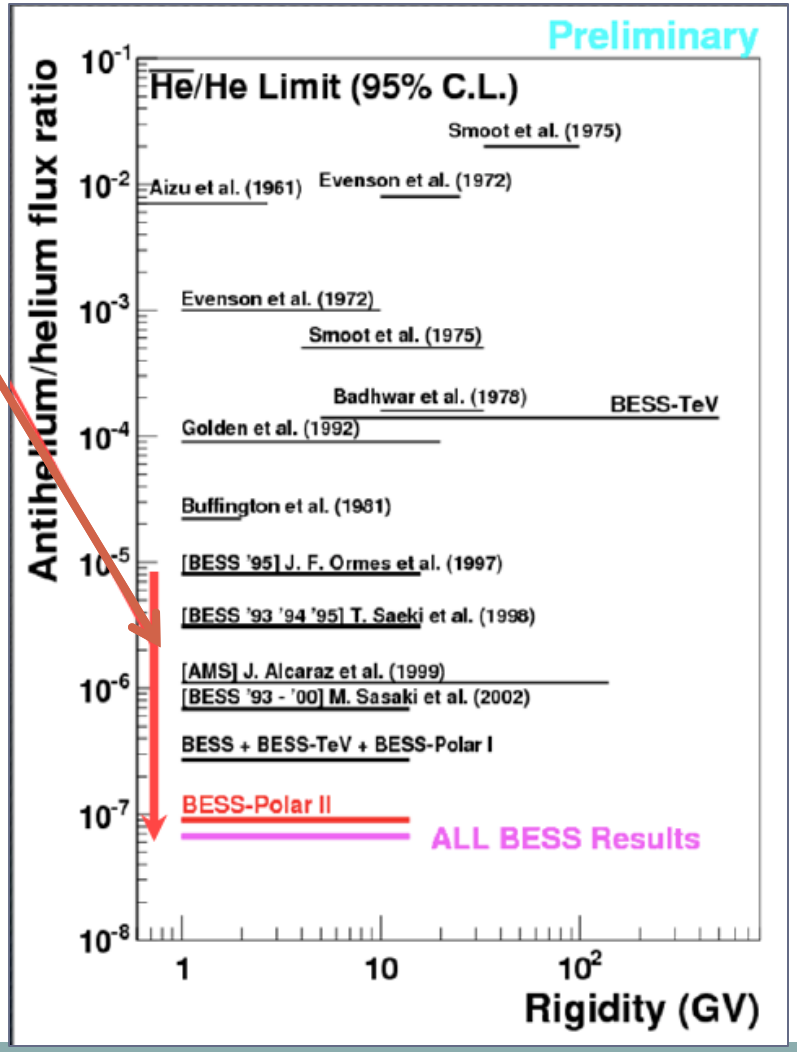


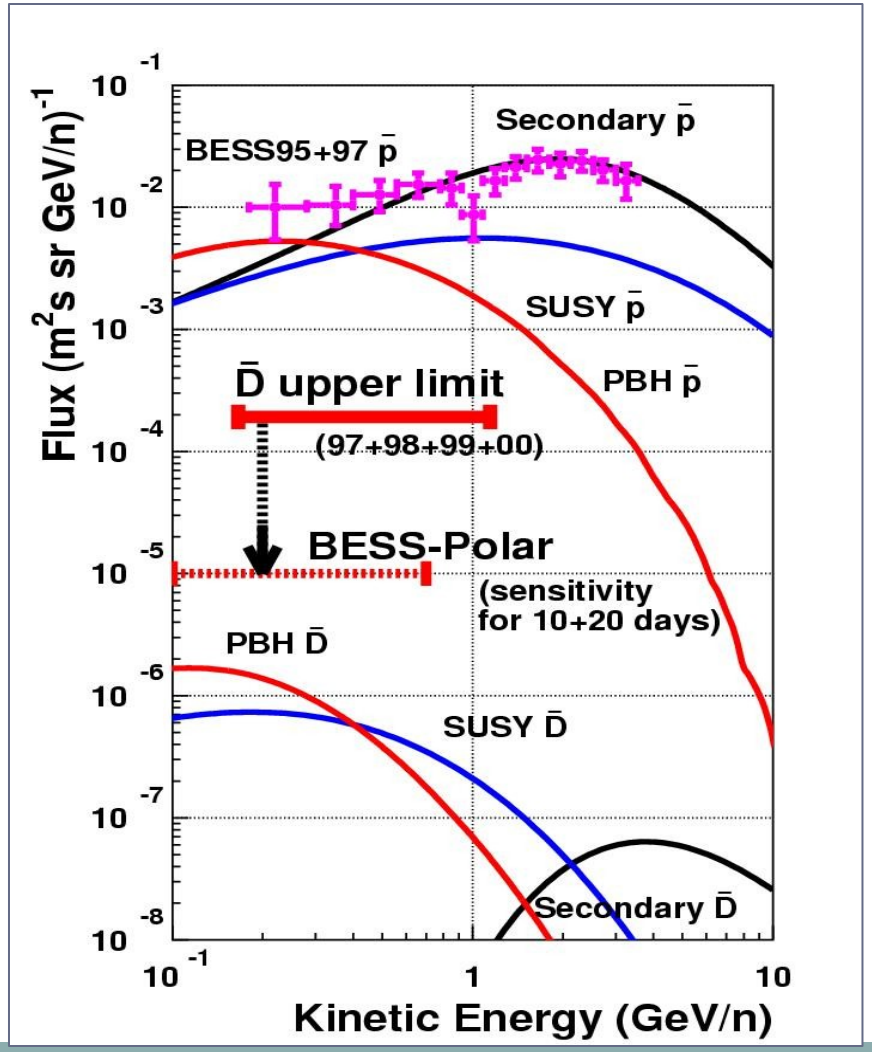
Results: antiproton/proton ratio



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.

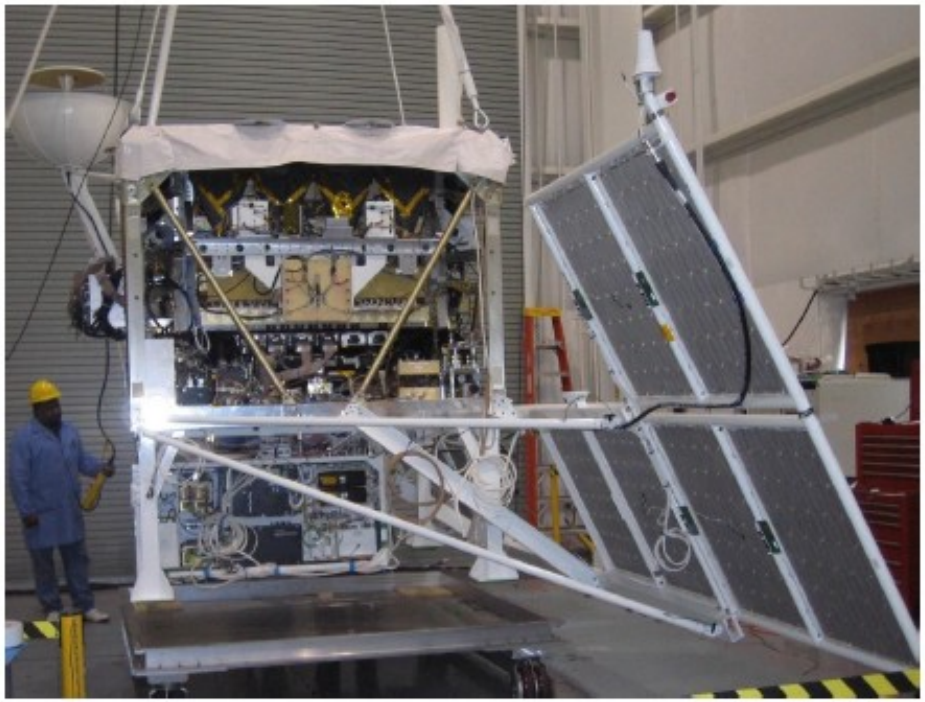
- 6 flights up to now: 2004, 2005, 2007, 2008, 2009, 2010.

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.

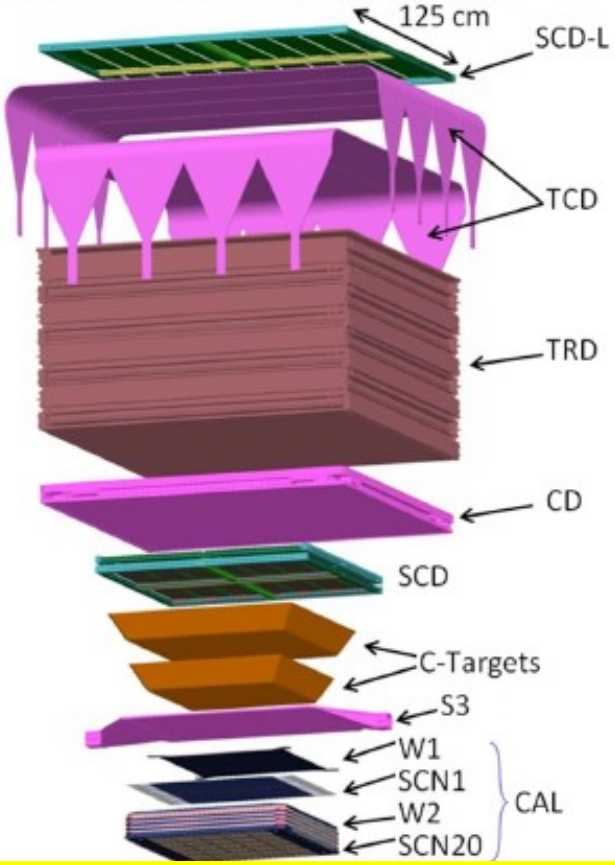
A fundamental aspect of the instrument is the capability to obtain simultaneous measurements of energy and charge for a sub-sample of nuclei by calorimeter and TRD, thus allowing an inter-calibration in flight of the energy.

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

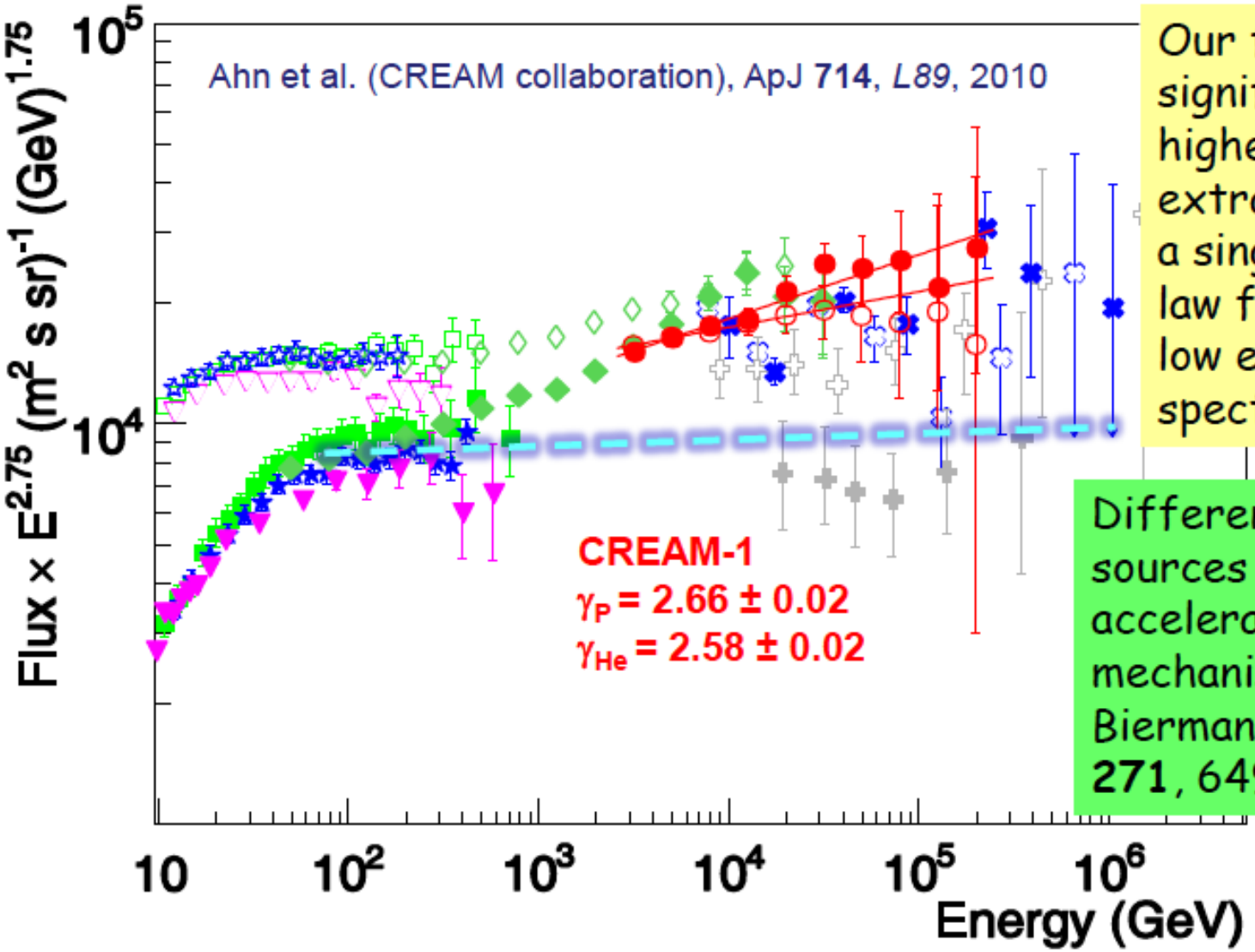


- **CREAM uses two designs**
  - With and without the TRD
- This exploded view shows the "With TRD" design
- The "Without TRD" design uses Cherenkov Camera



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

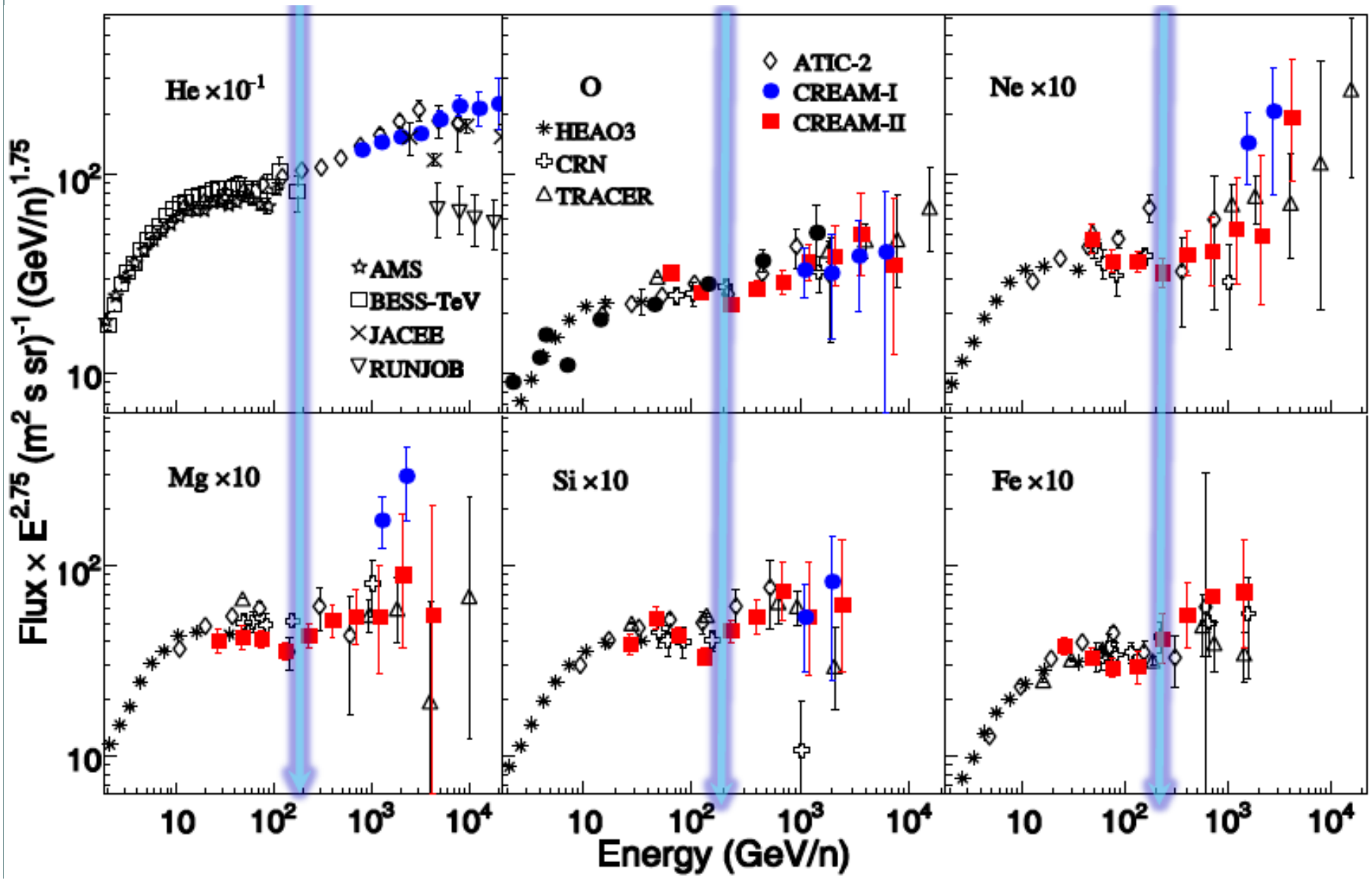
Protons and heliums



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



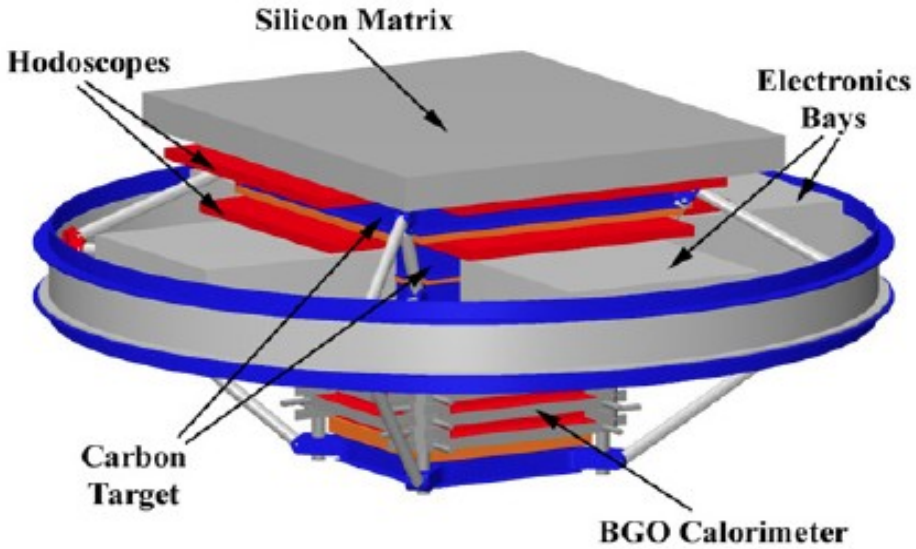
Advanced Thin Ionization Calorimeter (ATIC)

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.

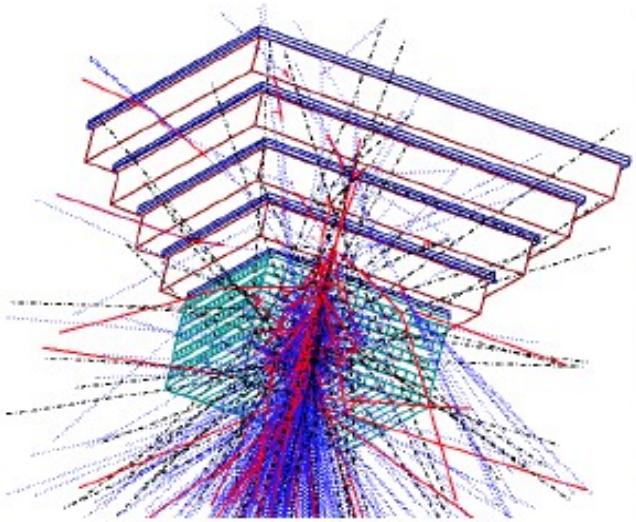
ATIC has had two successful long-duration balloon (LDB) flights launched from McMurdo Station, Antarctica in 2000 and 2002.

ATIC Instrument Details

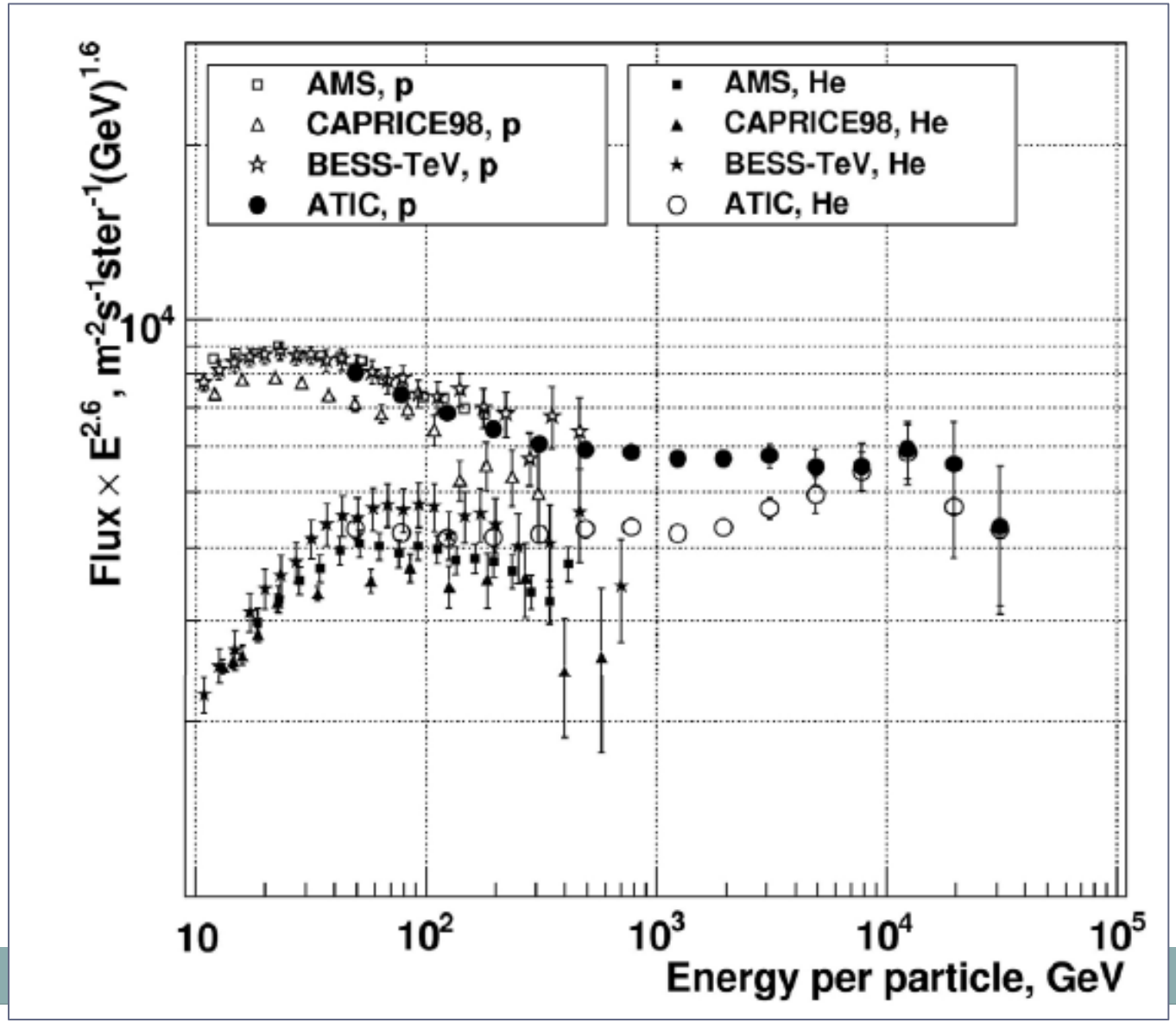


Antarctic Flights:

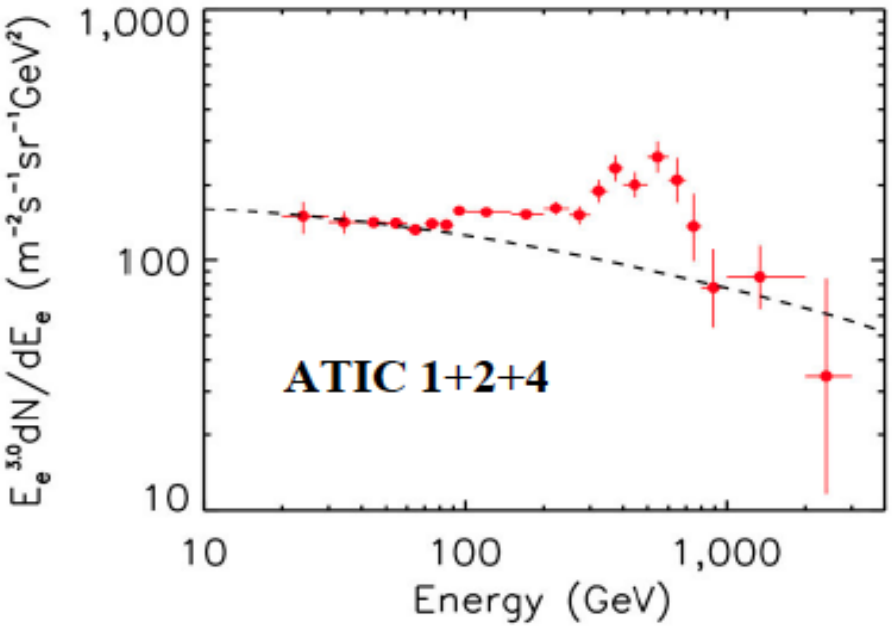
- 12/28/00 - 1/13/01
- 12/29/02 – 1/18-03
- 12/27/07 – 1/15/08

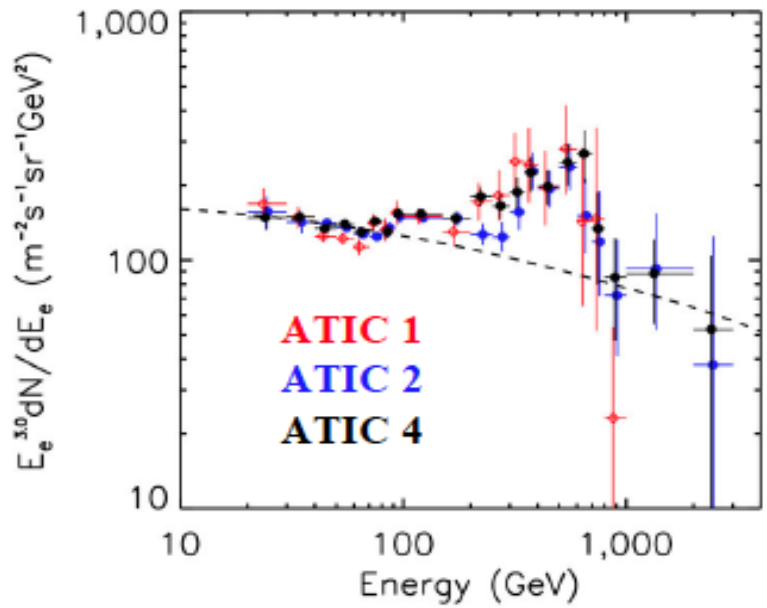


Protons and heliums



The ATIC "bump" in the all-electron spectrum



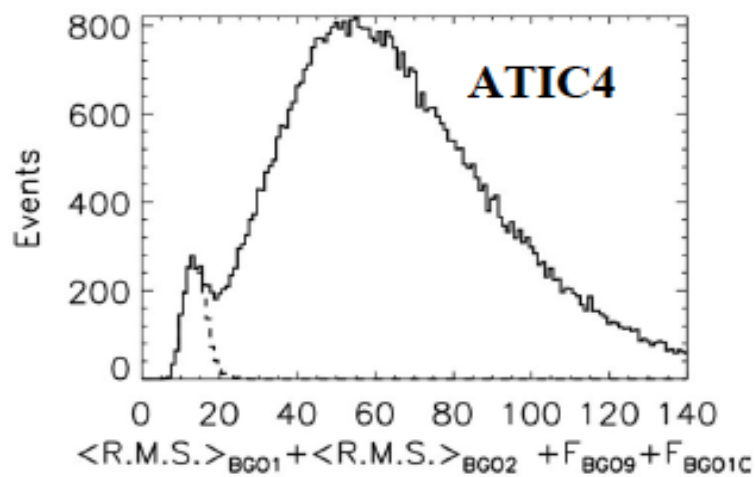


"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

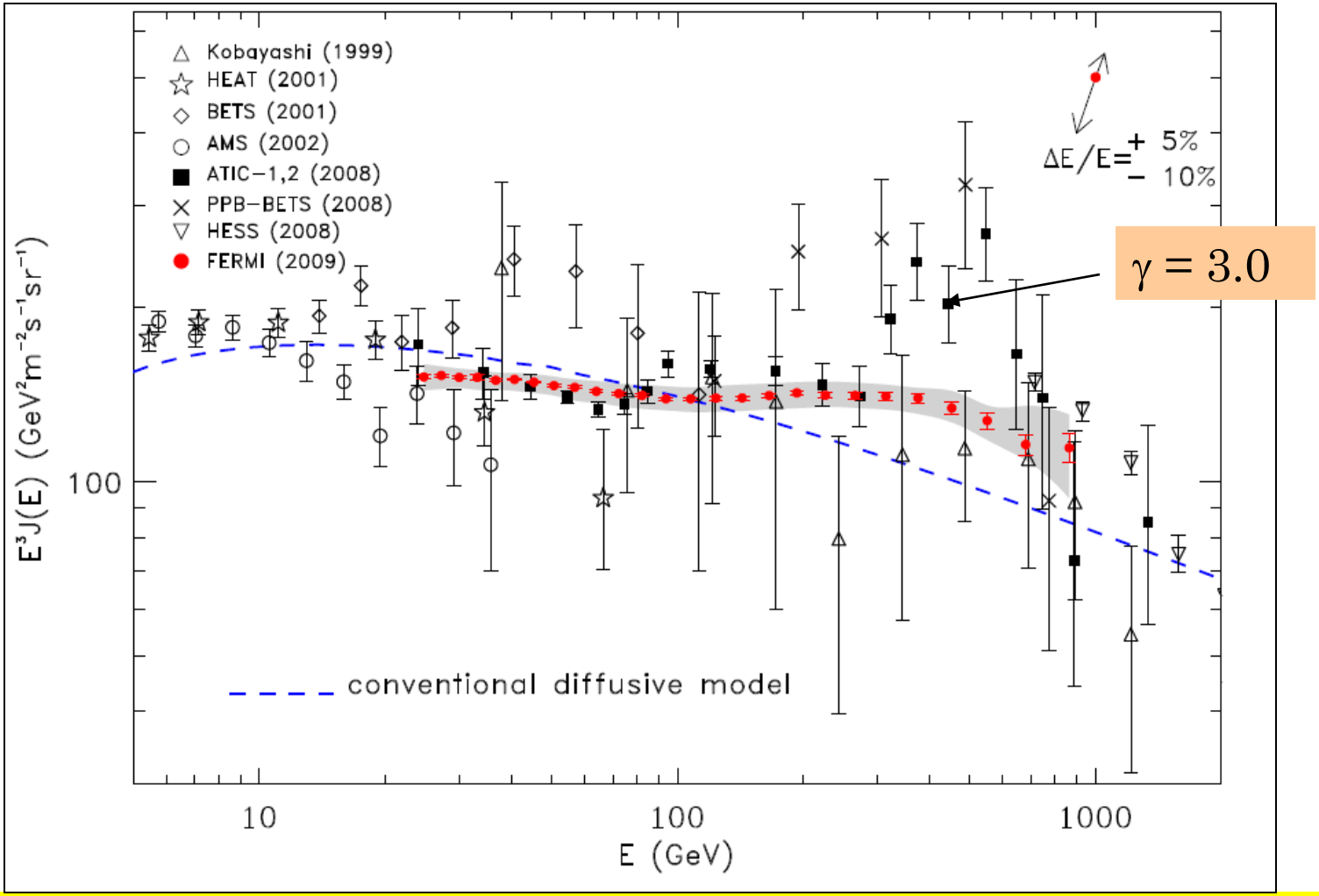
ATIC-4 with 10 BGO layers has improved e , p separation.

"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma



Reply from FERMI

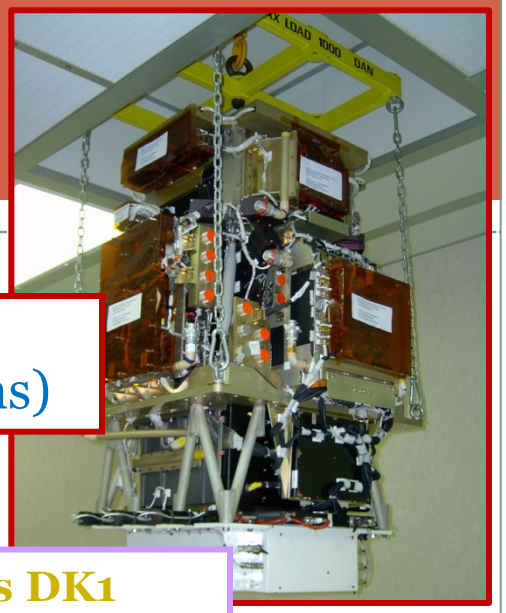


FERMI does not confirm the ATIC bump but finds an excess wrt conventional diffusive models

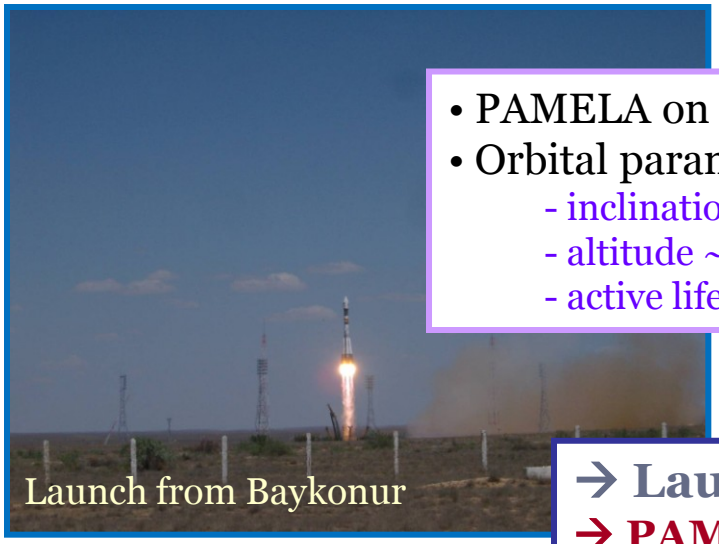
Satellite flights

PAMELA

Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics

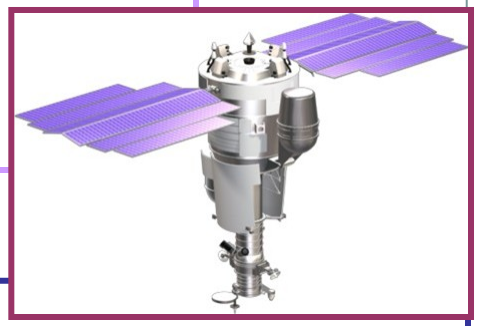


- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)



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**

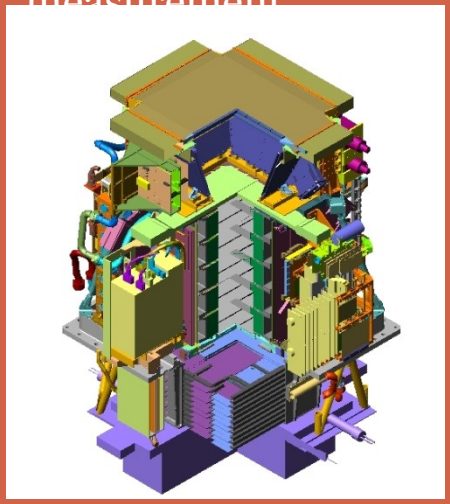
→ **PAMELA in continuous data-taking mode since then!**

PAMELA detectors

Main requirements:

- high-sensitivity antiparticle identification

- precise momentum measurement

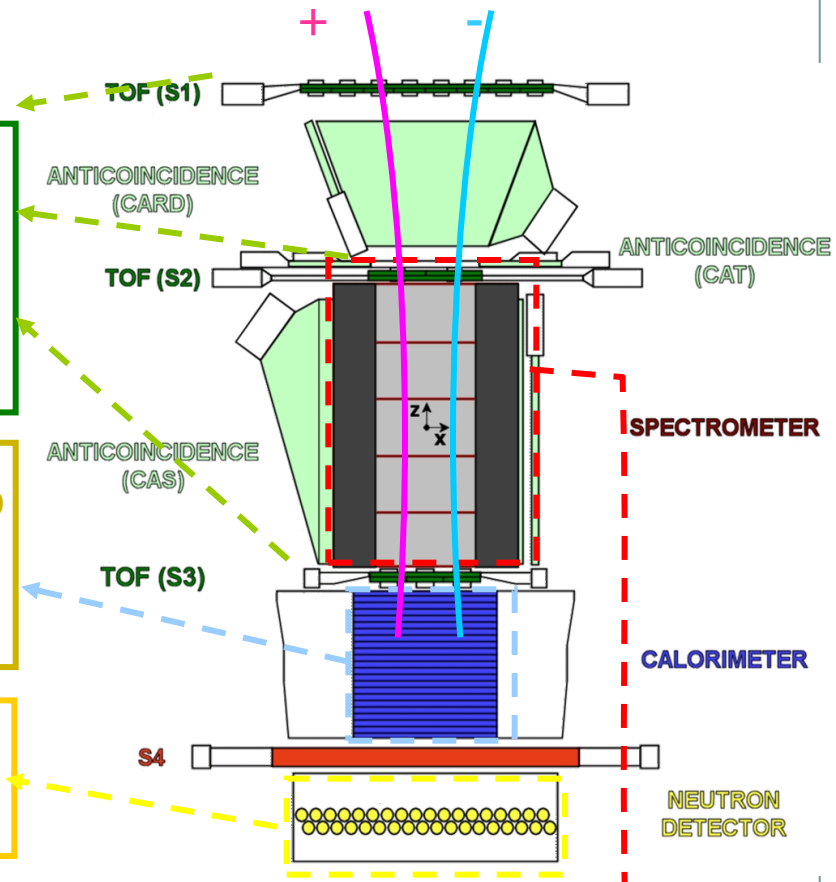


Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- 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*

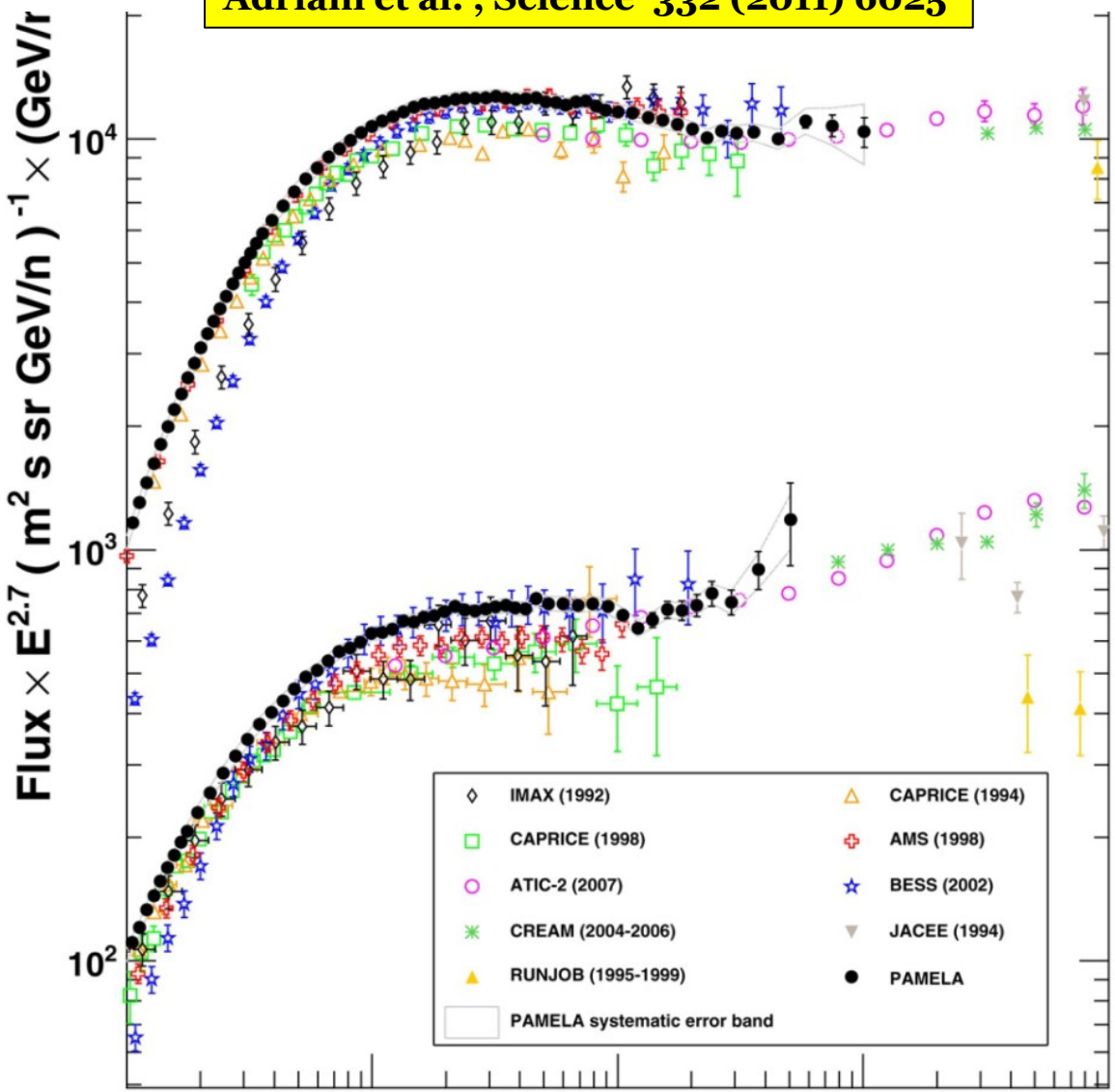


GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

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 (ϕ = 450÷550 GV)
- **High-energy**
  → a complex structure of the spectra emerges…

Adriani et al. , Science 332 (2011) 6025



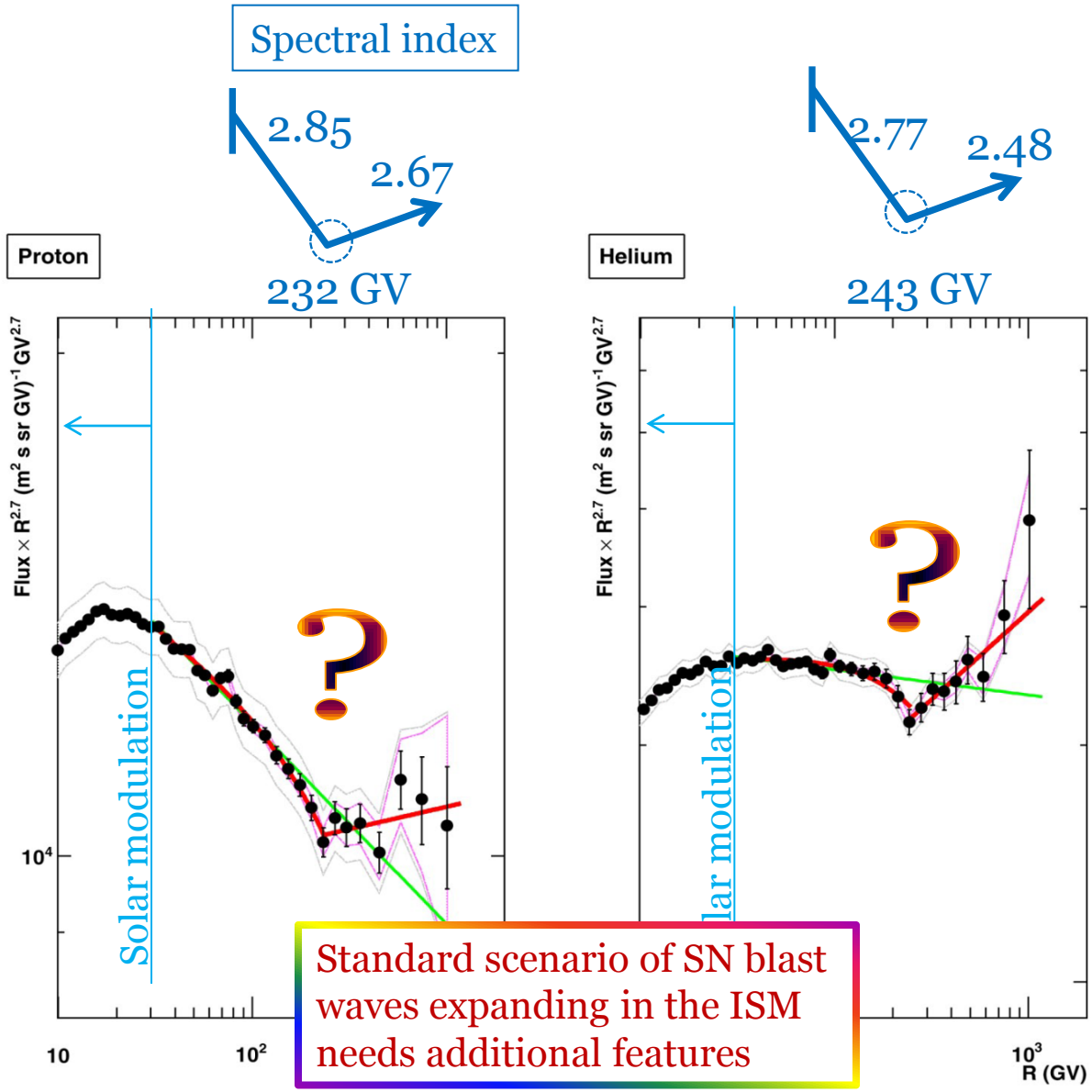
P & He absolute fluxes @ high energy

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



Standard scenario of SN blast waves expanding in the ISM needs additional features

H/He ratio vs R

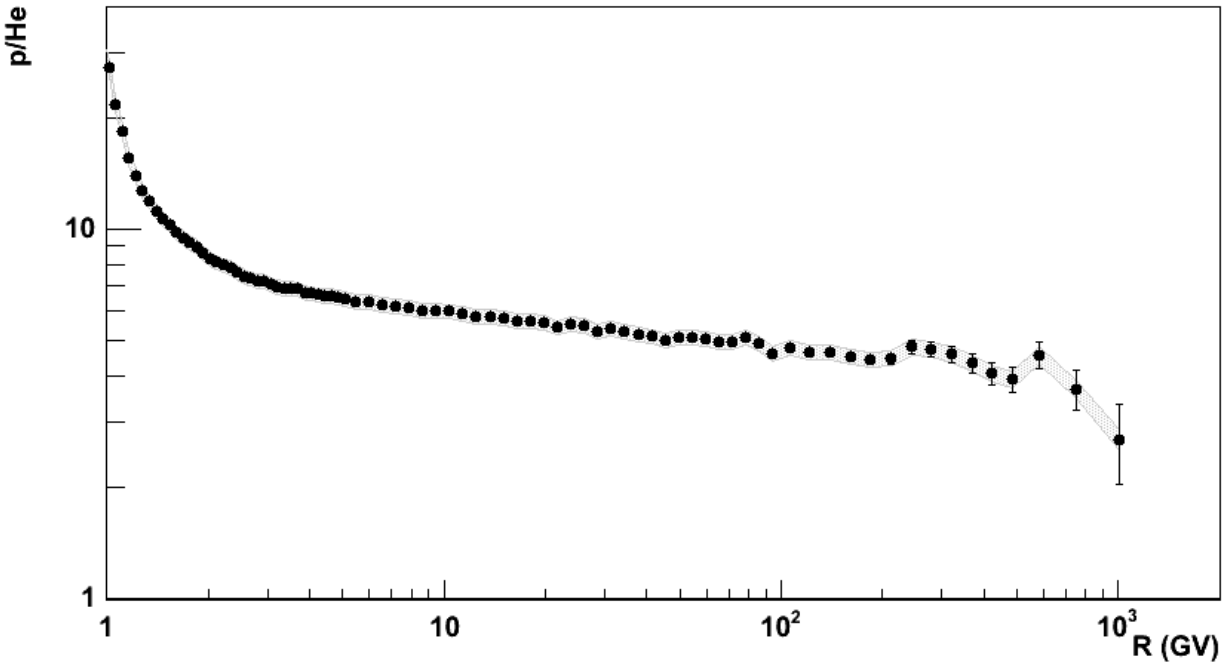
Instrumental p.o.v.

- Systematic uncertainties **<u>partly cancel out</u>** (livetime, spectrometer reconstruction, ...)

Theoretical p.o.v.

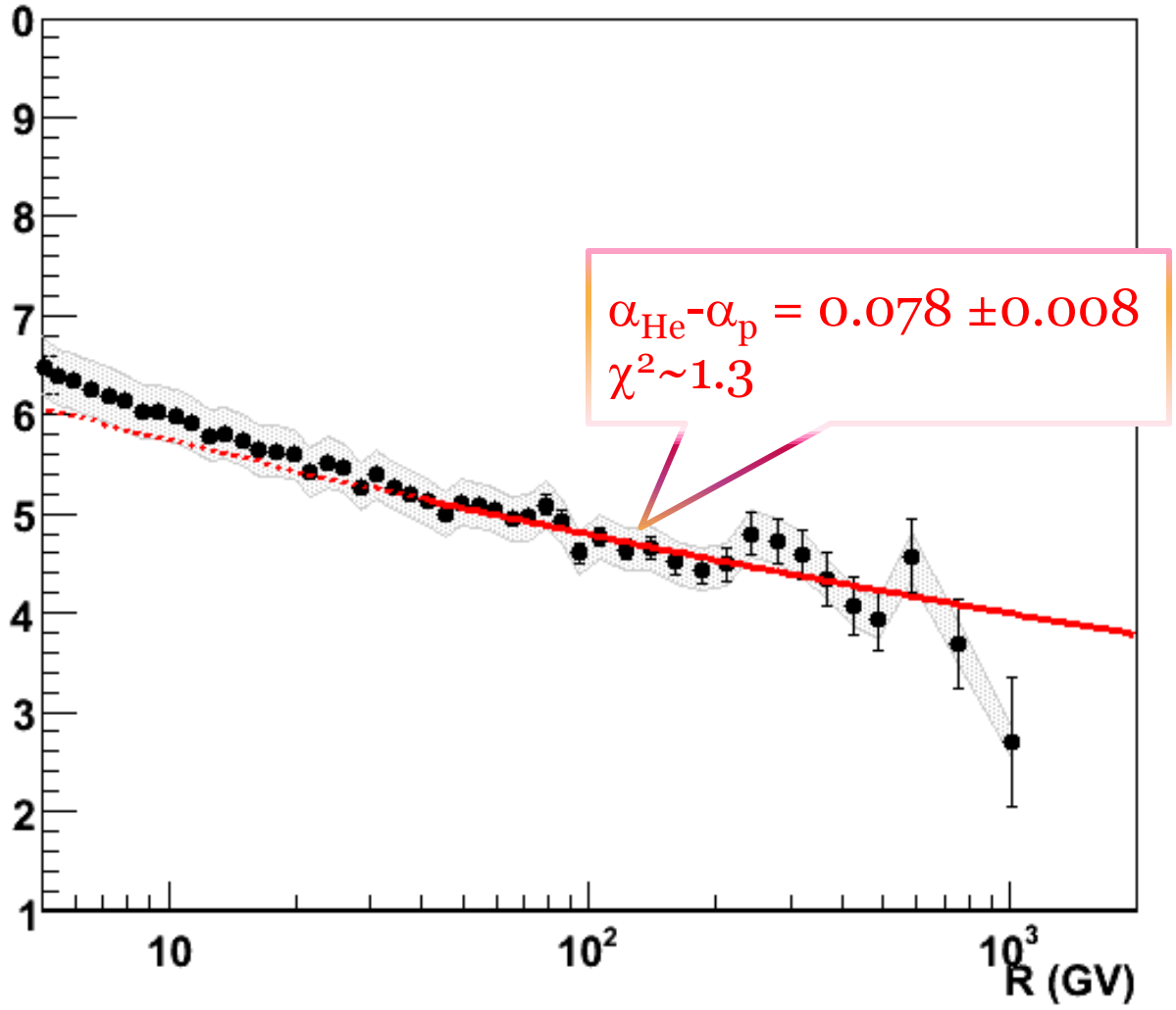
- Solar modulation negligible → information about IS spectra down to GV region
- Propagation effects (diffusion and fragmentation) negligible above ~100GV → information about source spectra

(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)



Electron energy measurements

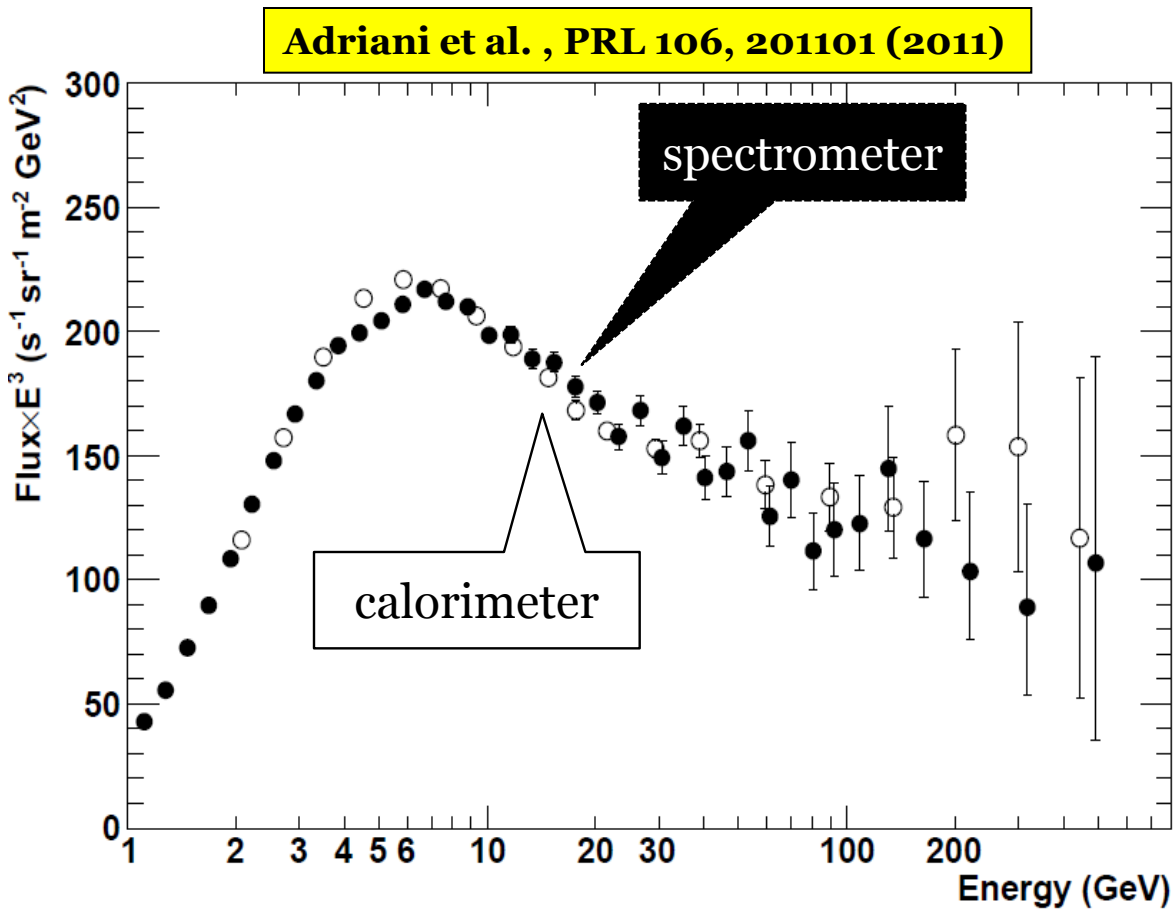
Two independent ways to determine electron energy:

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

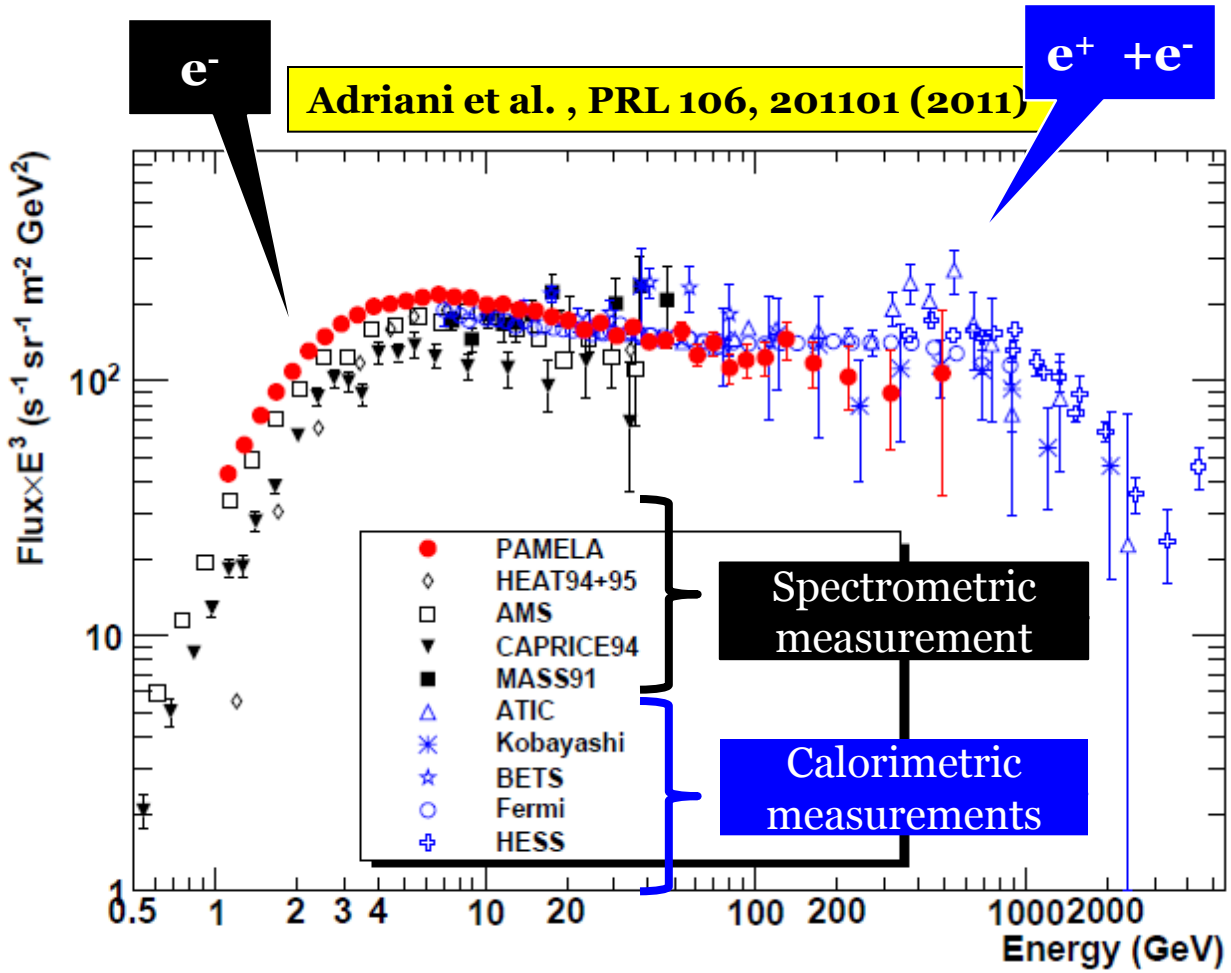


Electron identification:

- Negative curvature in the spectrometer
- EM-like interaction pattern in the calorimeter

Electron absolute flux

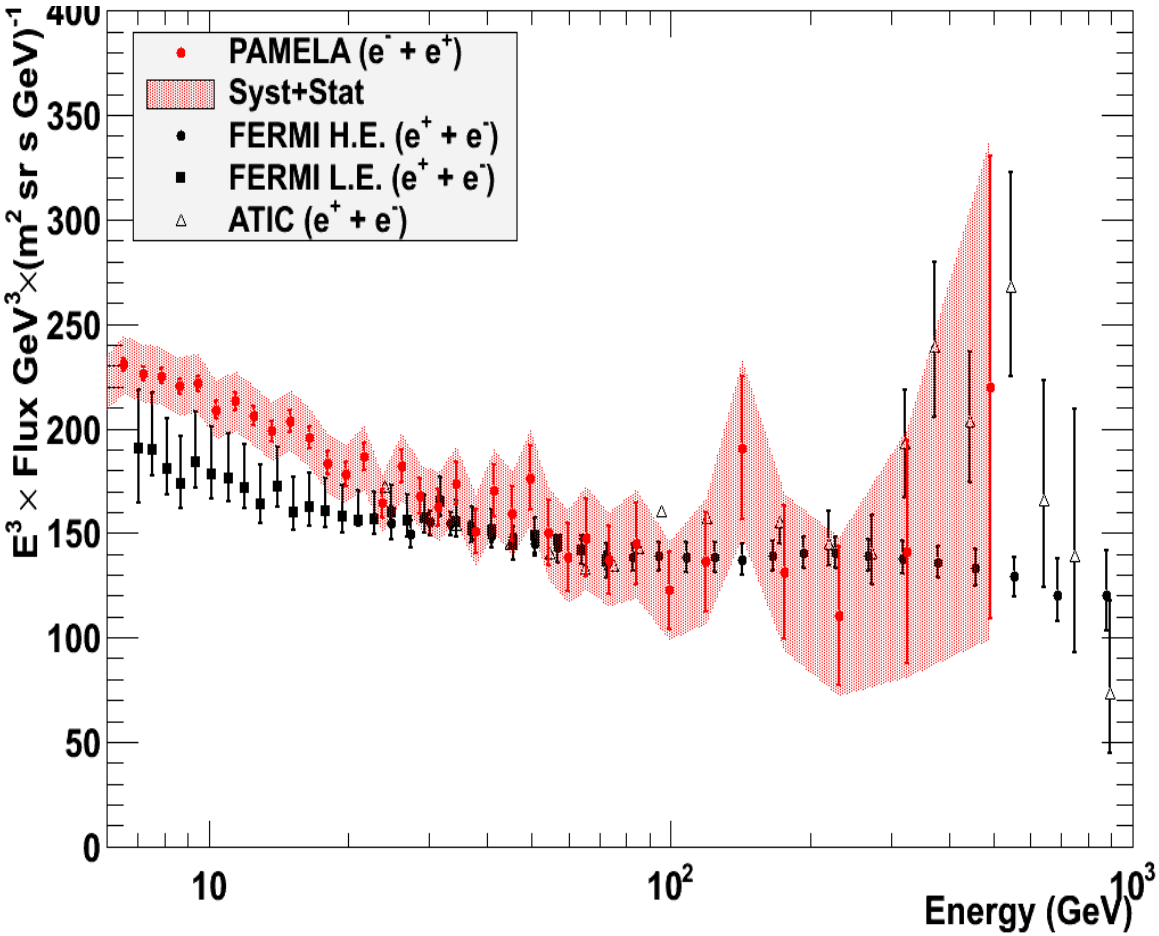
- Largest energy range covered in any experiment hitherto with no atmospheric overburden
- **Low energy**
  - minimum solar activity (ϕ = 450÷550 GV)
- **High energy**
  - No significant disagreement with recent ATIC and Fermi data
  - Softer spectrum consistent with both systematics and growing positron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



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

ONLY AN EXERCISE .....

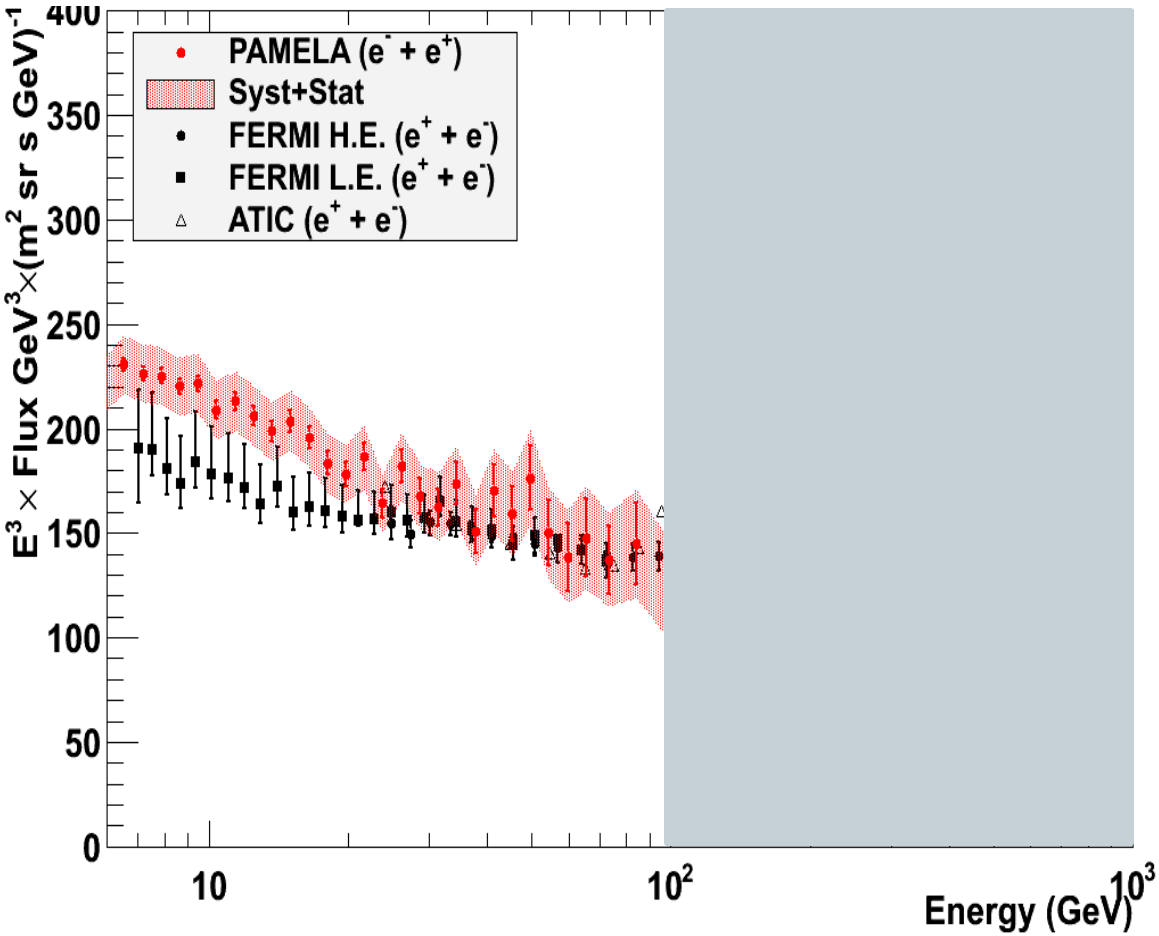
- Compatibility with FERMI (and ATIC) data
- Beware: positron flux not measured but **extrapolated** from PAMELA positron flux!
- Low energy discrepancies due to solar modulation



$(e^+ + e^-)$ 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

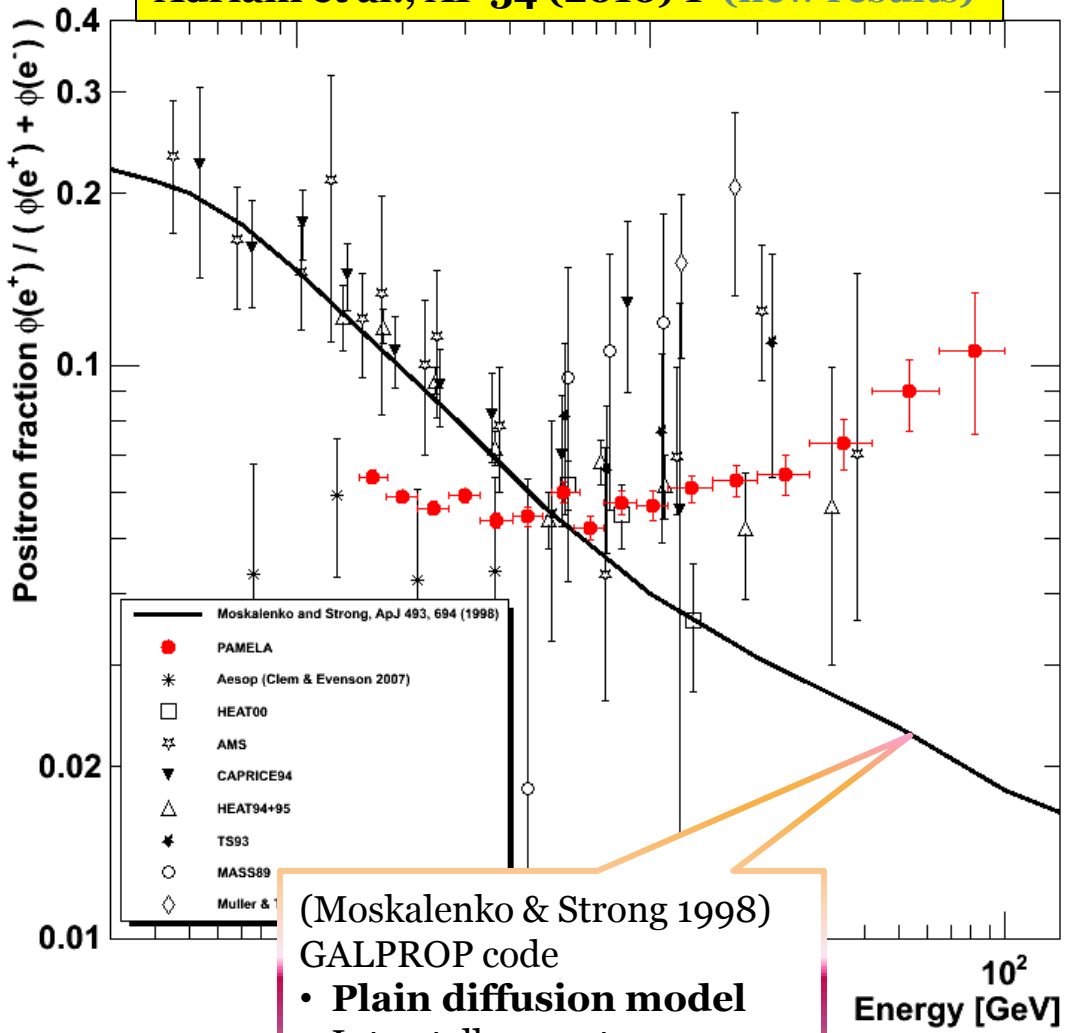
ONLY AN EXERCISE .....



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

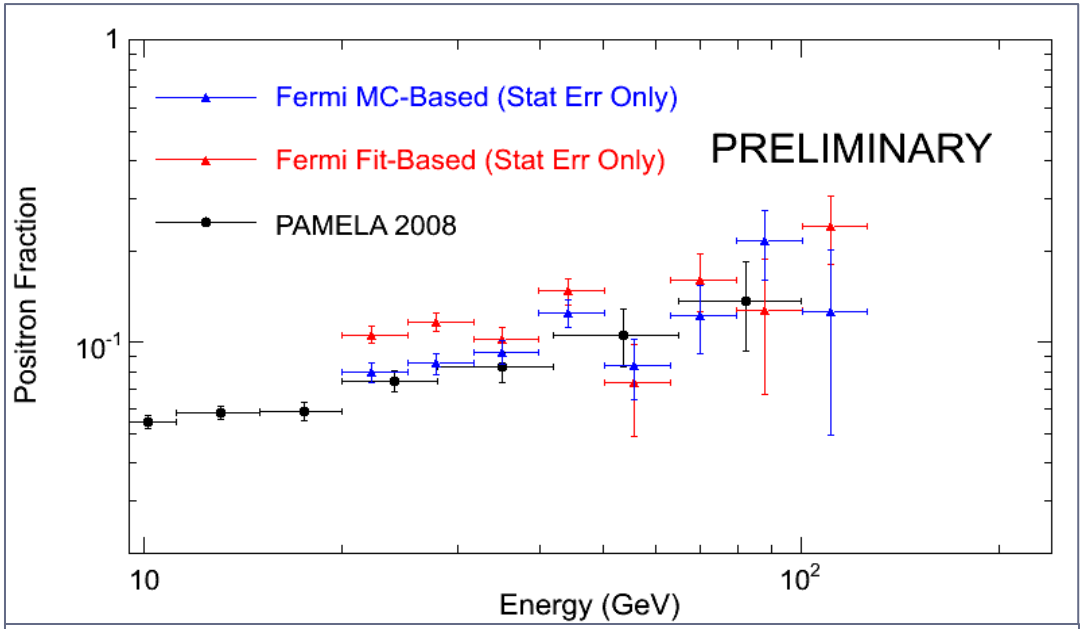
FERMI positron/electron ratio

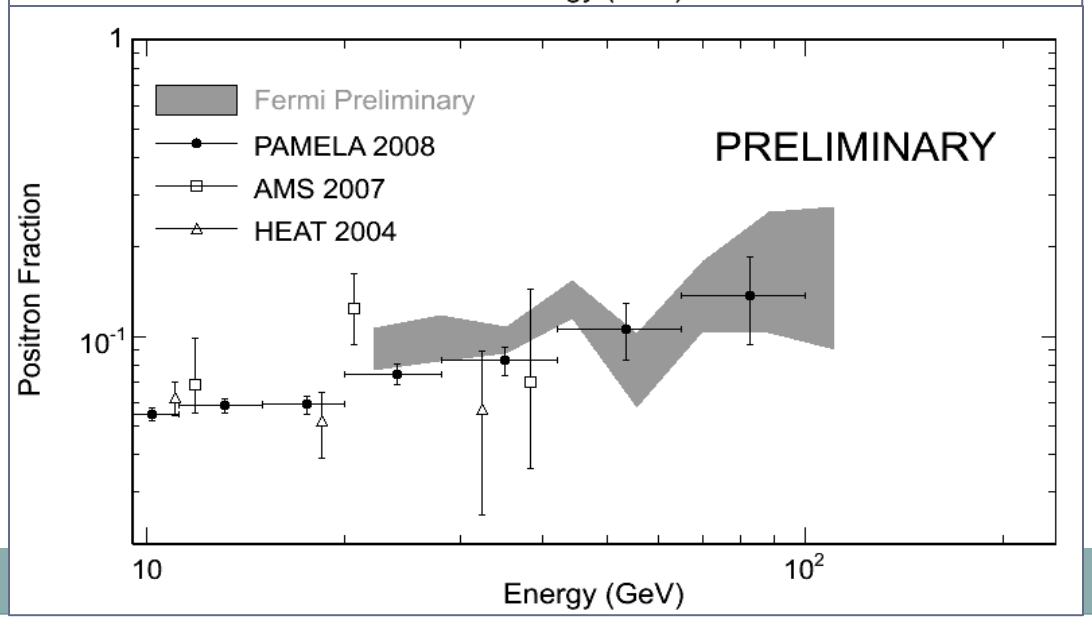
The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth's magnetic field as a charge discriminator

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. @ Fermi Symposium (May 2011)

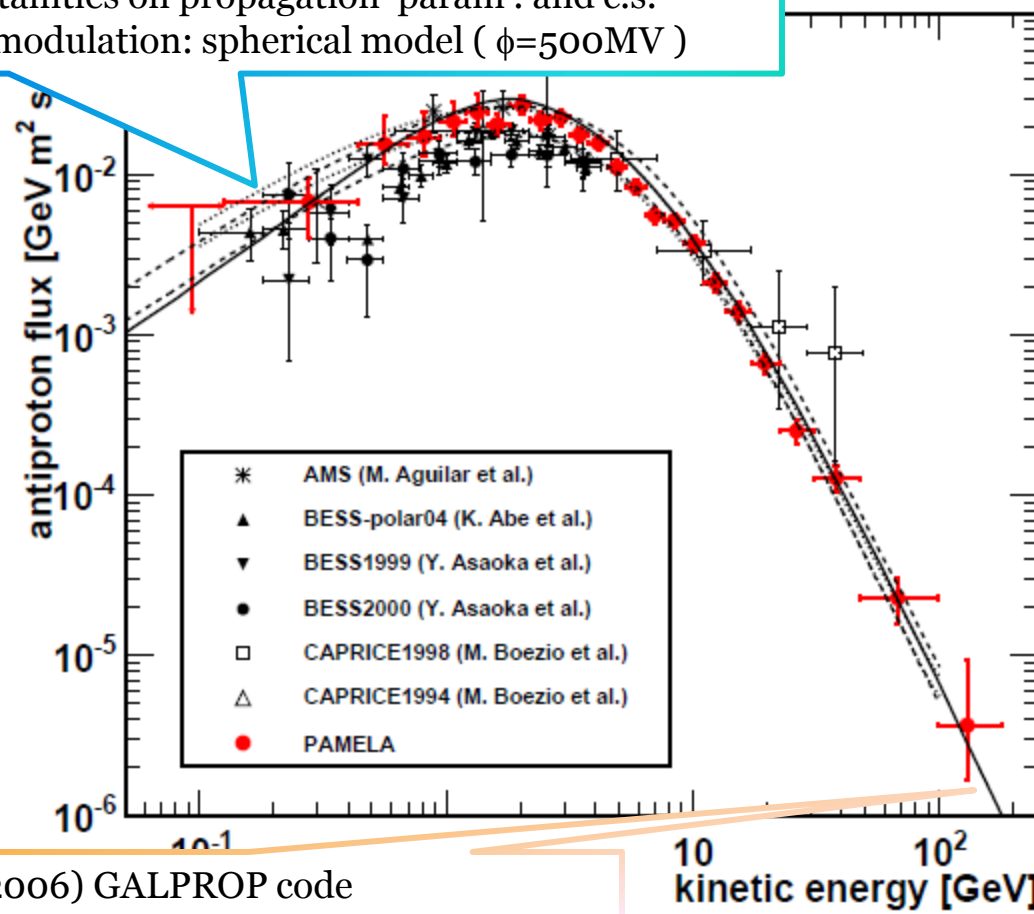




Antiproton flux

- 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)



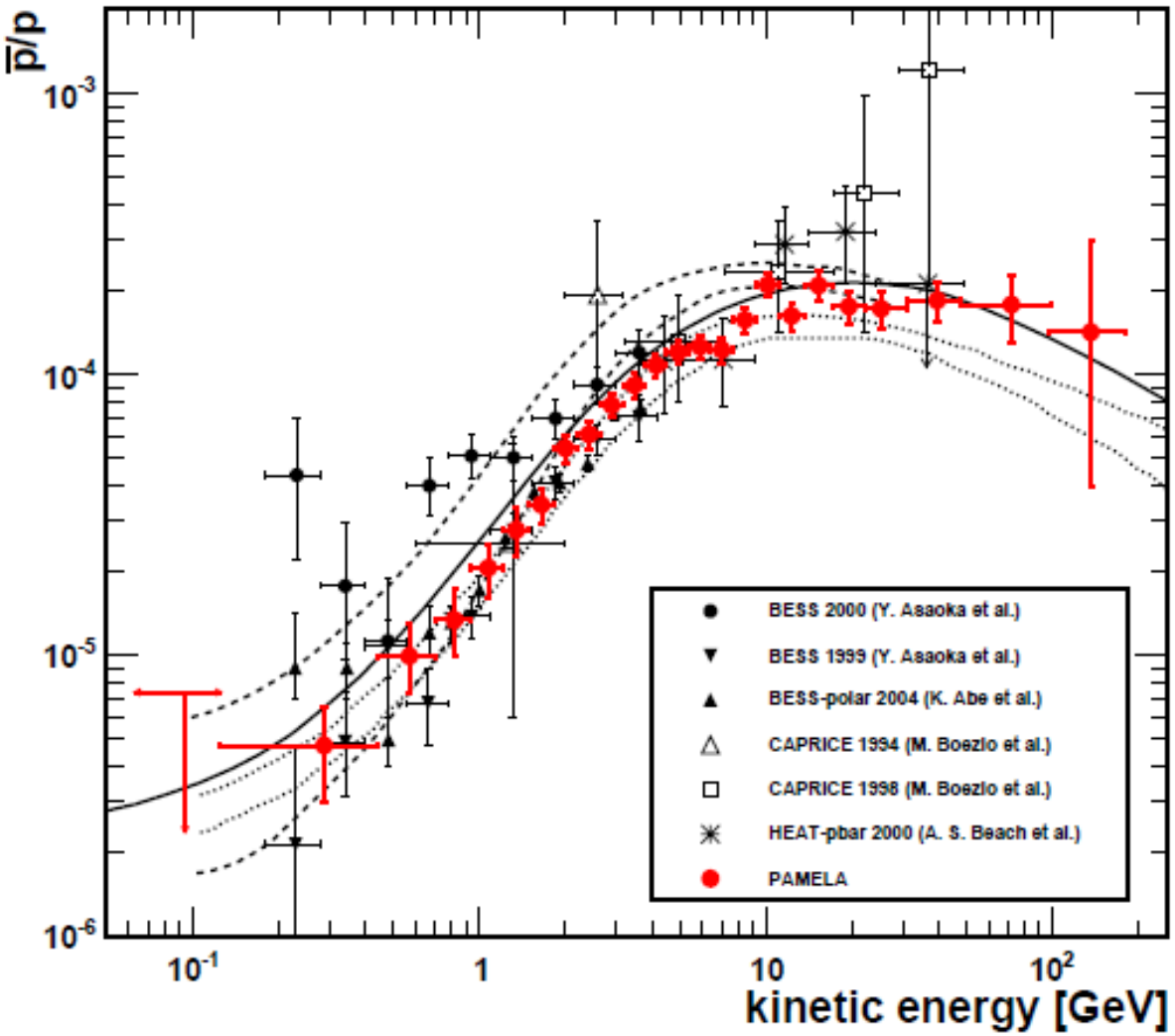
Adriani et al. - PRL 105 (2010) 121101

(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

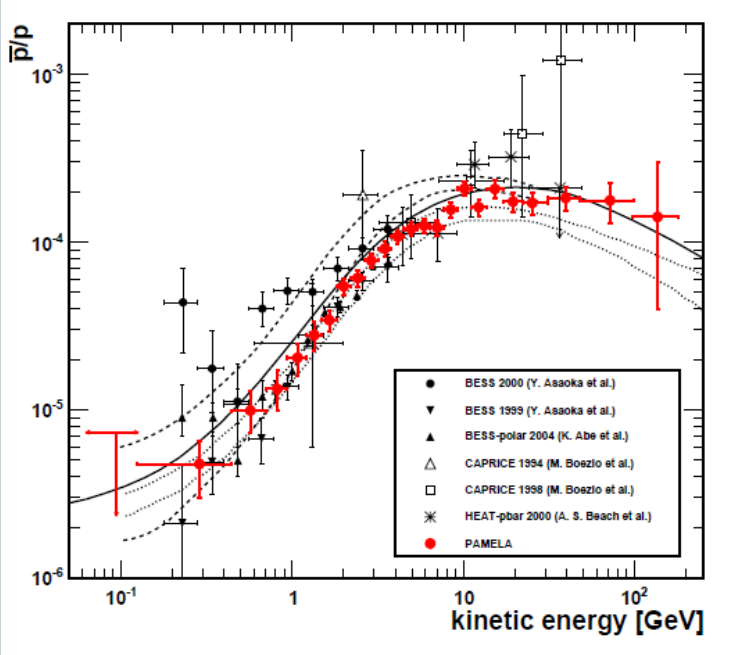
Adriani et al. - PRL 105 (2010) 121101



A challenging puzzle for CR physicists

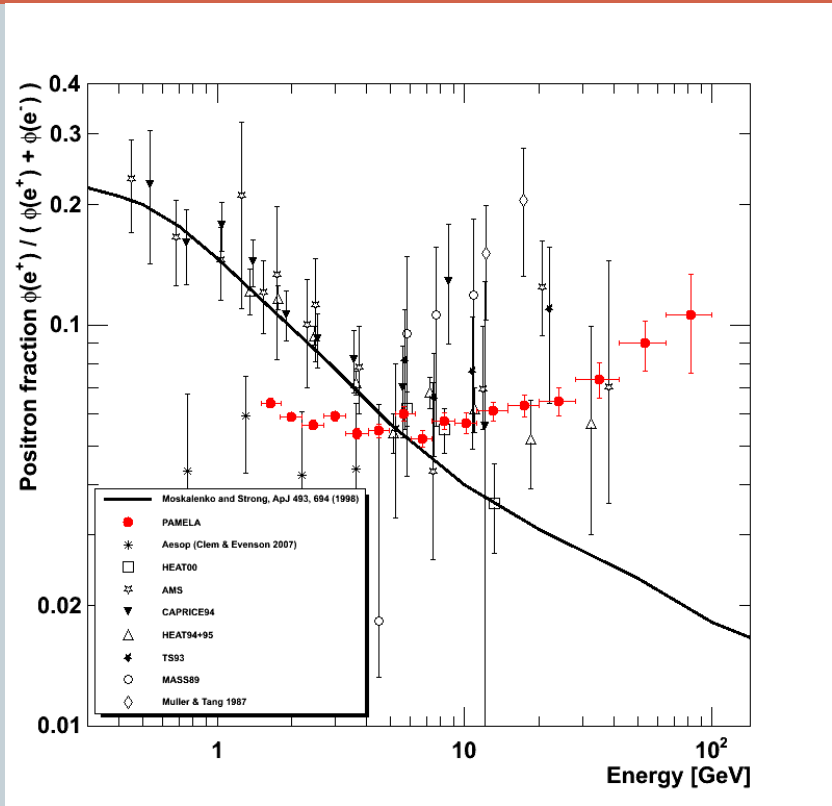
Antiprotons

→ Consistent with pure secondary production



Positrons

→ Evidence for an excess



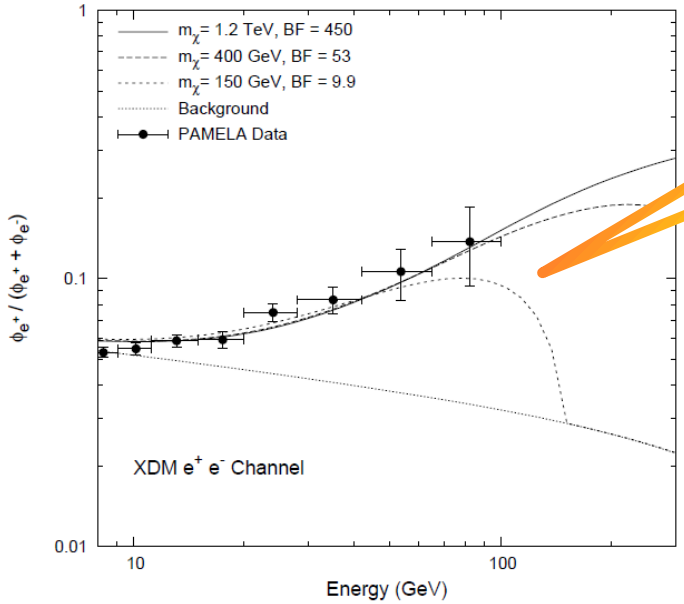
Positron-excess interpretations

Dark matter

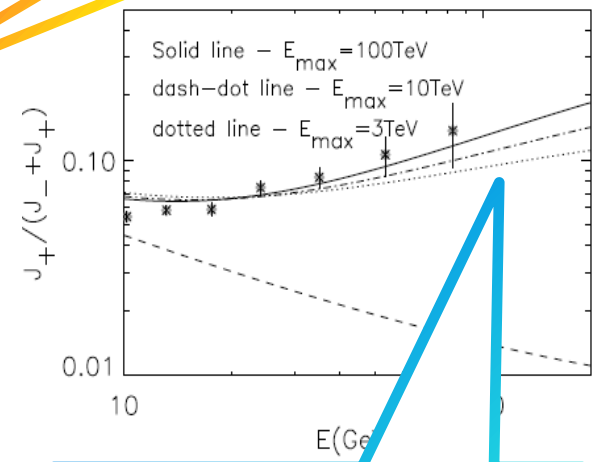
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

Astrophysical processes

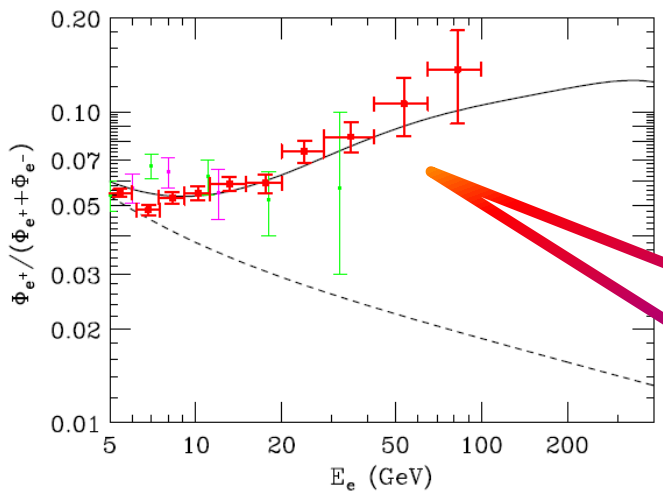
- known processes
- large uncertainties on environmental parameters



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



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

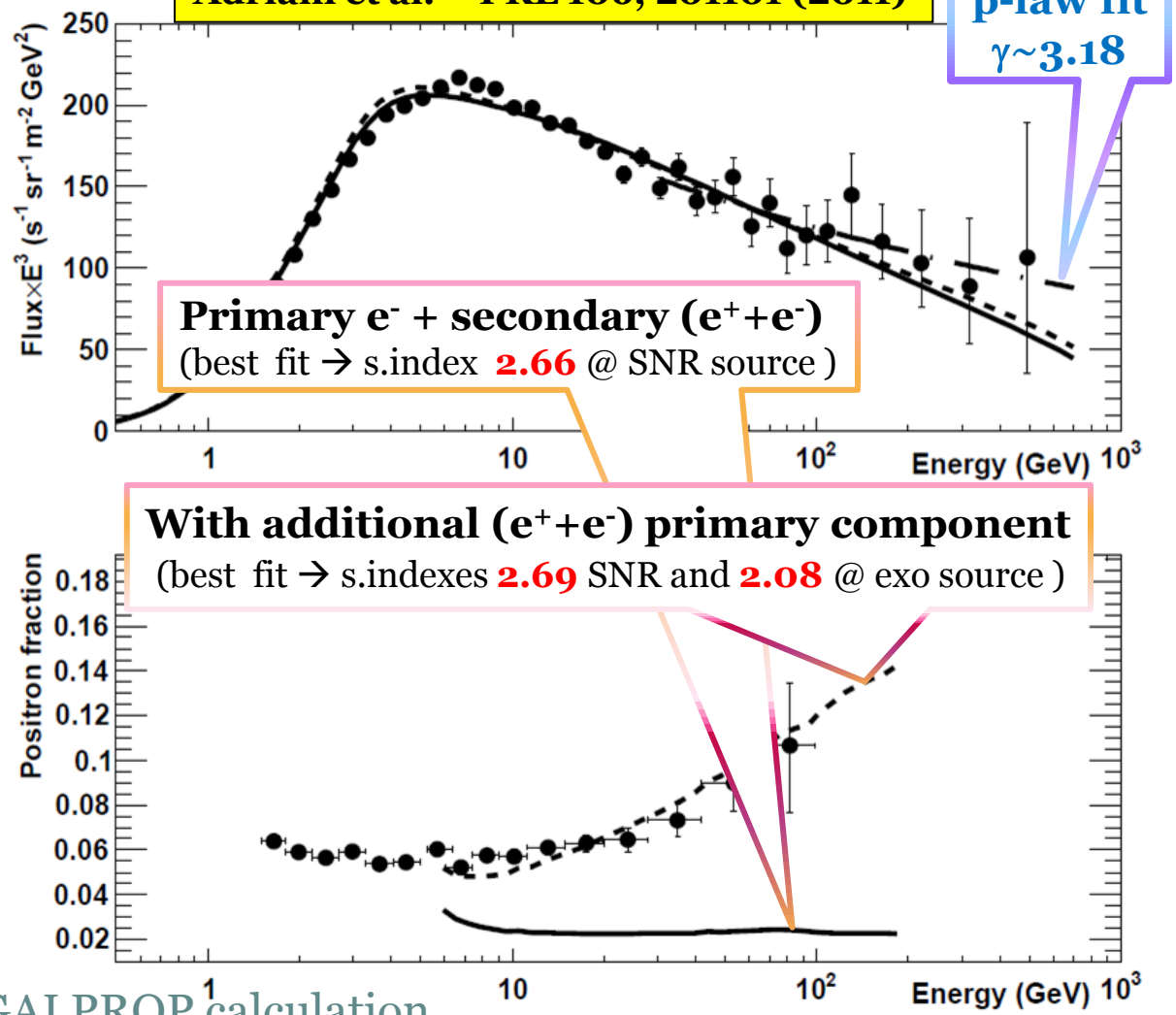


(Hooper, Blasi and Serpico, 2009)
contribution from diffuse mature & nearby young **pulsars**.

Positrons vs electrons

- Fit of electron flux
- Two scenarios:
  1. **standard** (primary+secondary components)
  2. **additional primary** e^- (and e^+) component
- Electron data are not inconsistent with standard scenario, but…
- …an additional component better reproduces positron data

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



GALPROP calculation

diffusion + reacceleration (Ptuskin et al. 2006)

H and He primary spectra from best fit of propagated spectra to PAMELA results

Orbiting Space Station

ALPHA MAGNETIC SPECTROMETER

→Search for primordial anti-matter

→Indirect search of dark matter

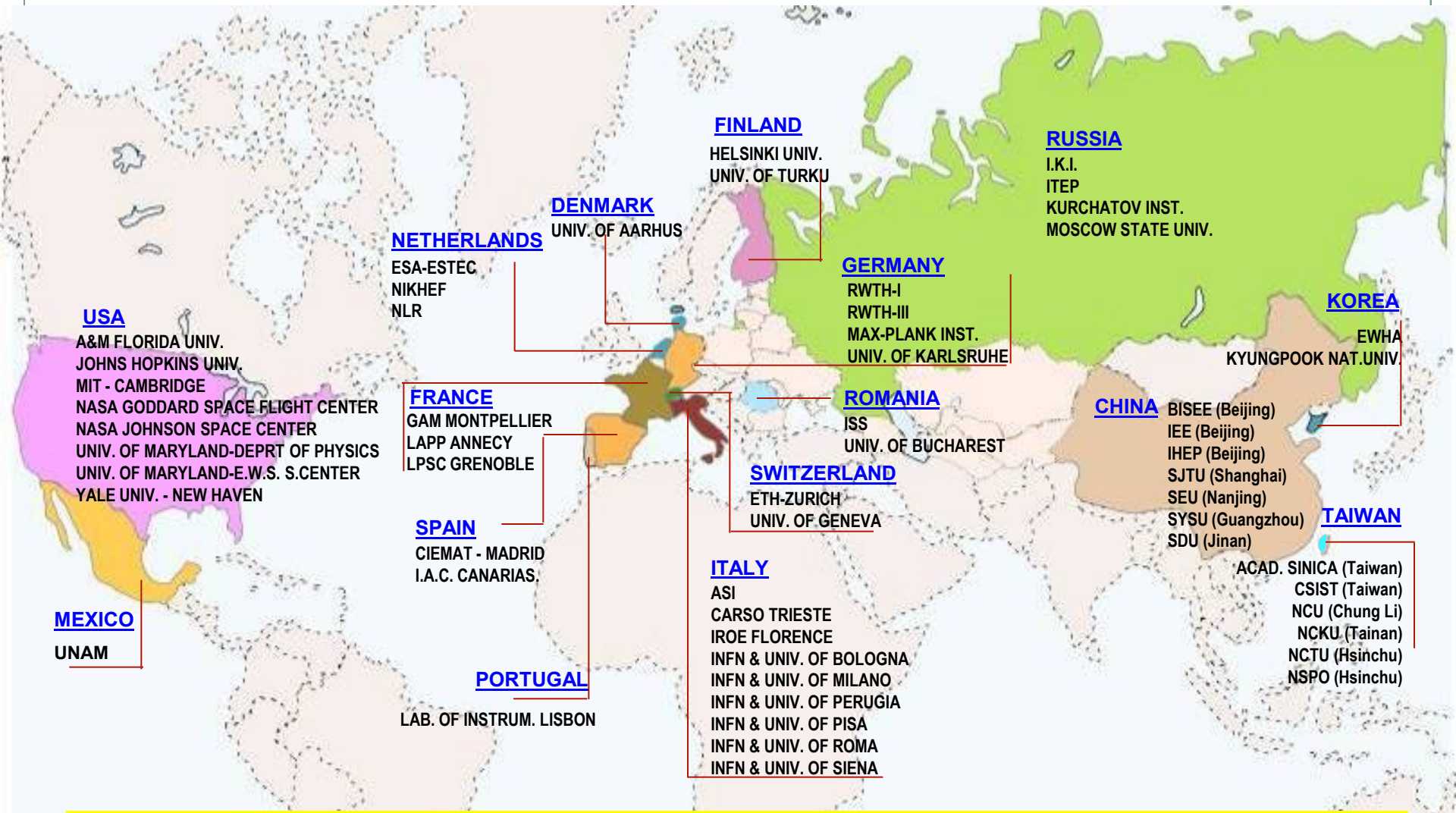
→High precision measurement of the energetic spectra and composition of CR from GeV to TeV

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

AMS-02 goals and capabilities

Cosmic rays spectra and chemical composition up to 1 TeV

Search for Antimatter in Space

Search for Dark Matter

Gamma Rays

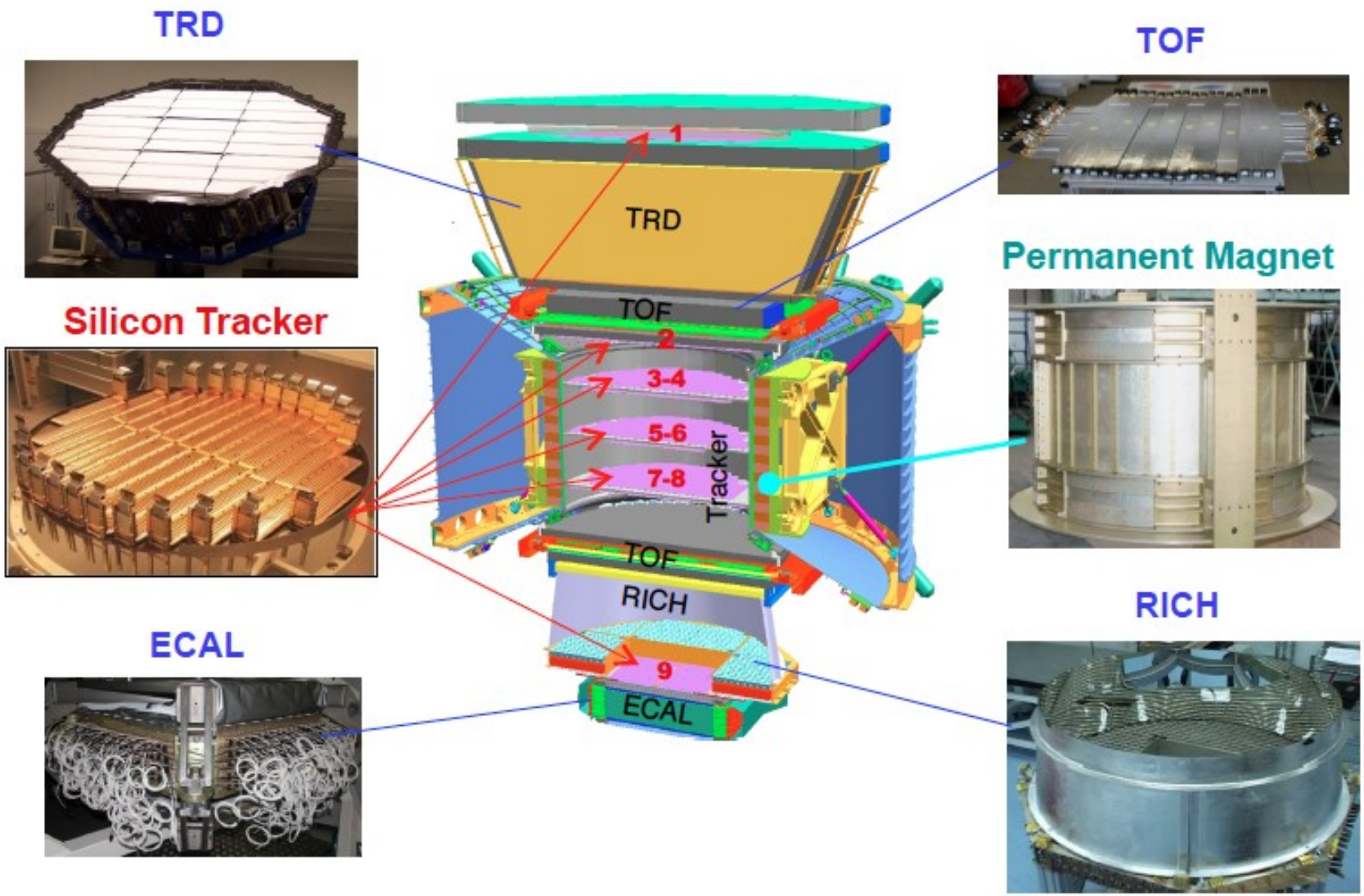
AMS will identify and measure the fluxes for:

- **p for E < 1 TeV with unprecedented precision**
- **e+ for E < 300 GeV and e– for E < 1 TeV (unprecedented precision)**
- **Light Isotopes for E < 10 GeV/n**
- **Individual elements up to Z = 26 for E < 1 TeV/n**

Absolute fluxes and spectrum shapes of protons and helium are important for calculation of atmospheric neutrino fluxes

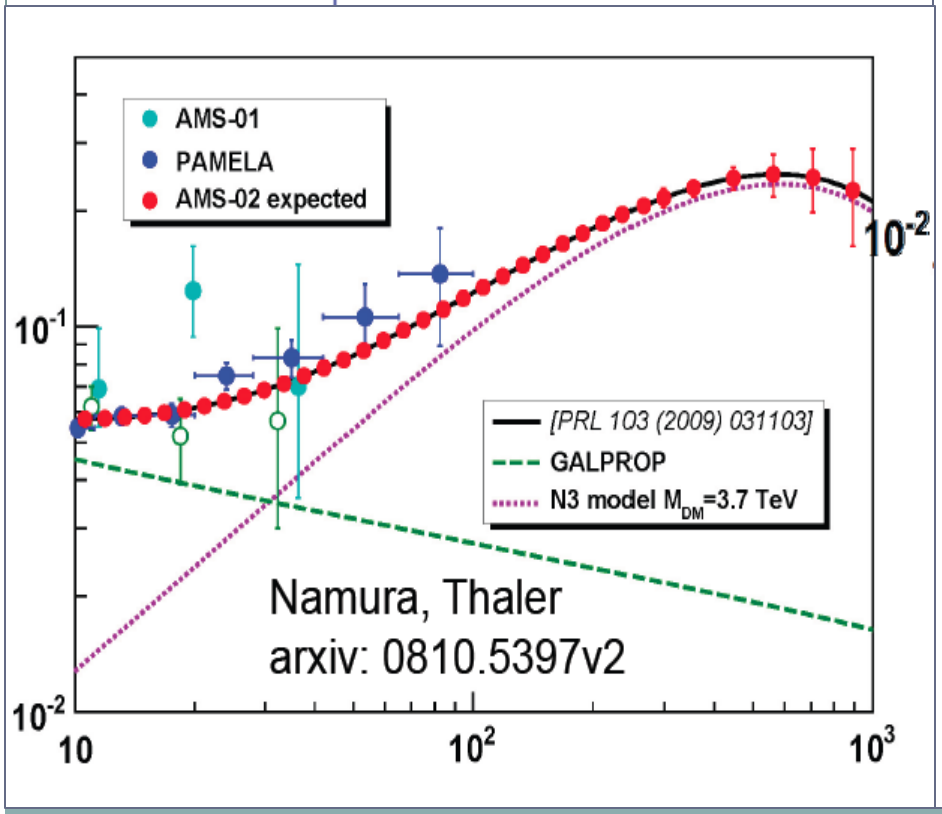
Composition and spectra are important to constraint propagation, confinement, ISM density

The AMS-02 detector

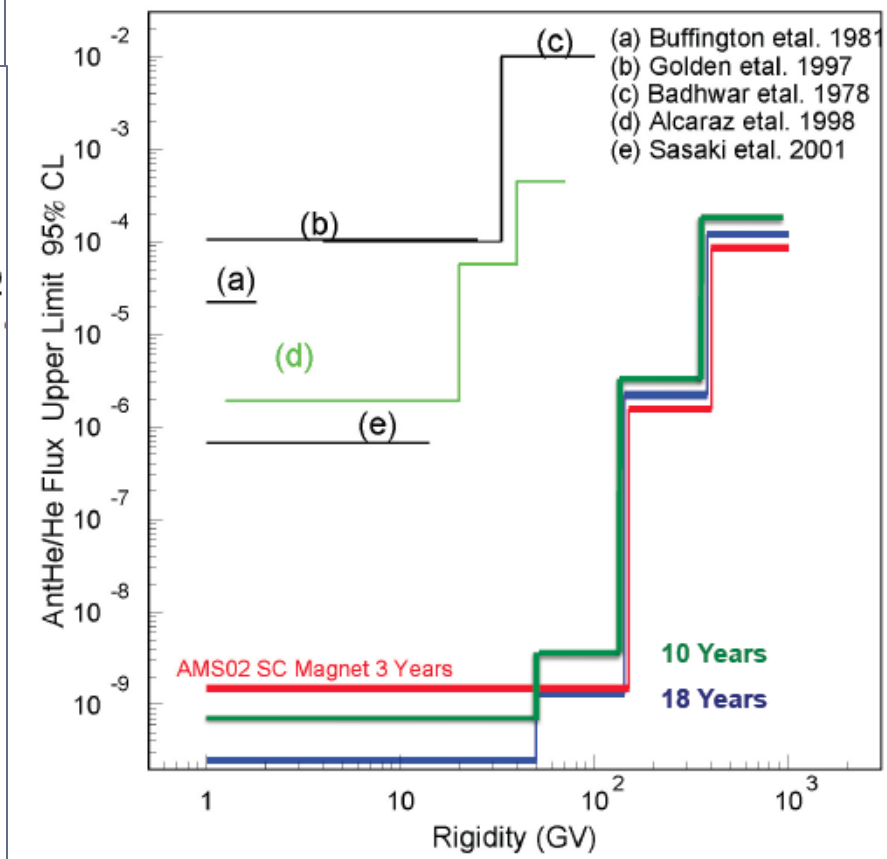


	A (cm^{2}sr)	MDR(TV)
9 Si layers + ECAL	300	2.14
8 Si layers + ECAL	900	0.85
8 Si layers (plane 1N in)		
7 Si layers		

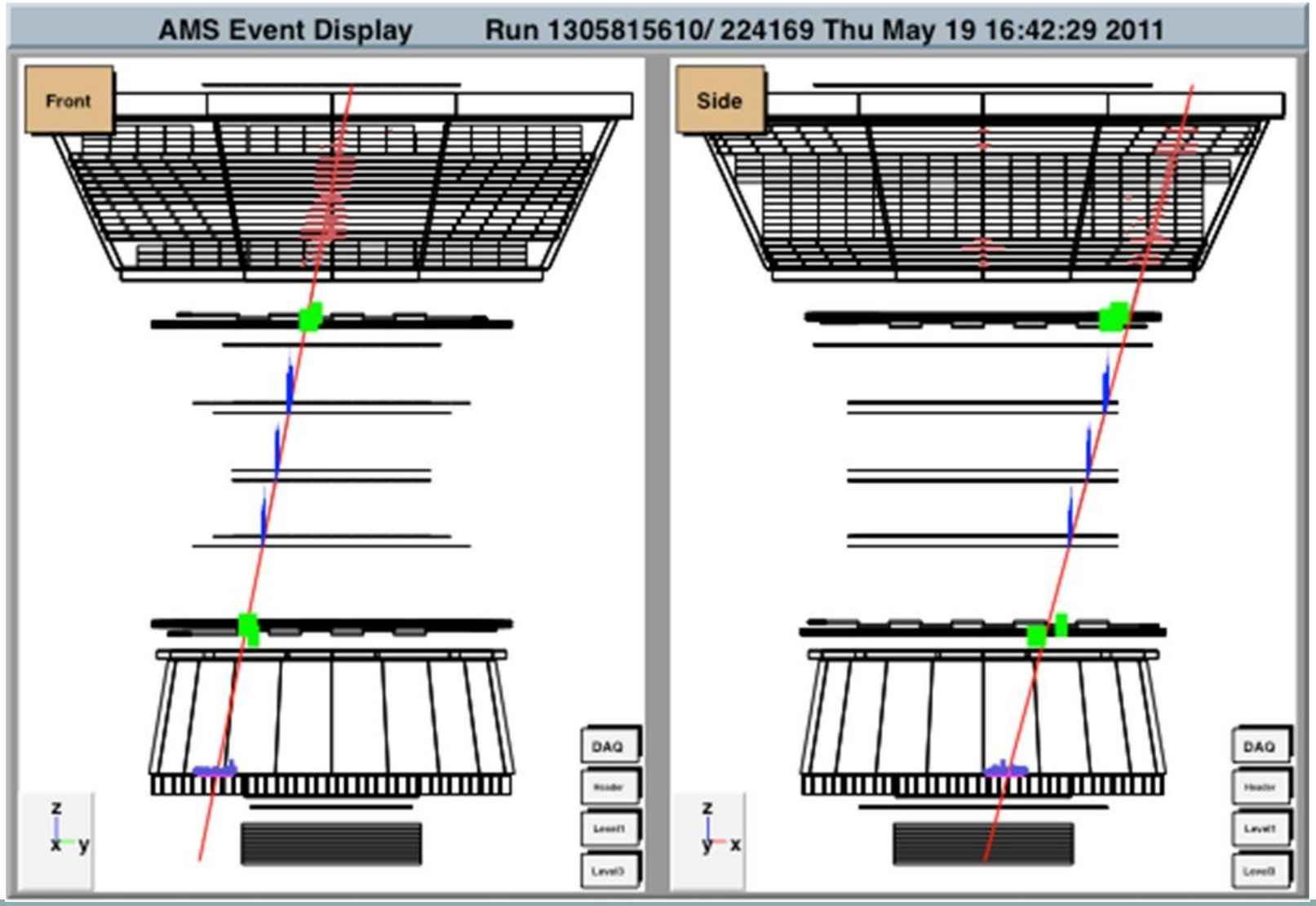
AMS positron fraction



:--) AMS-02 Antihelium Limits :--(



AMS first events

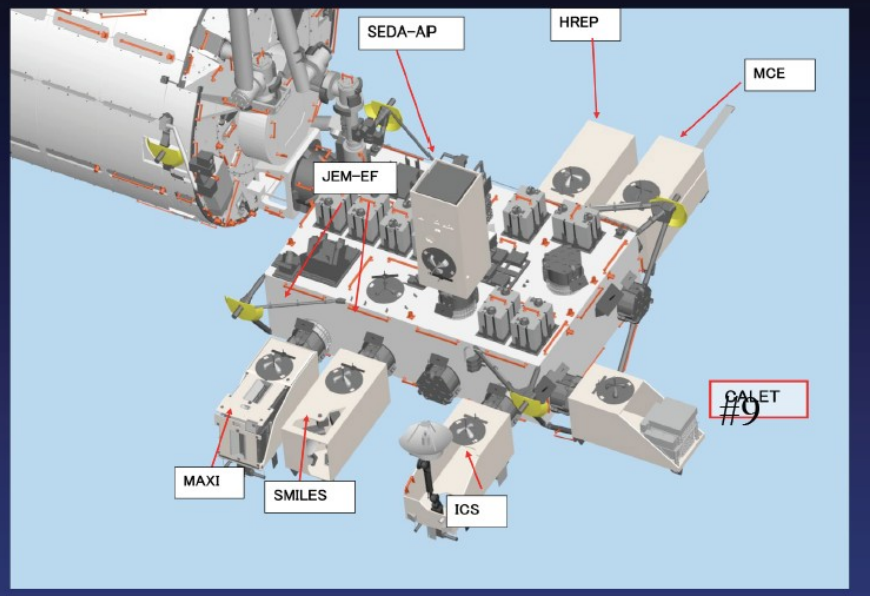


42 GeV Carbon nucleus

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

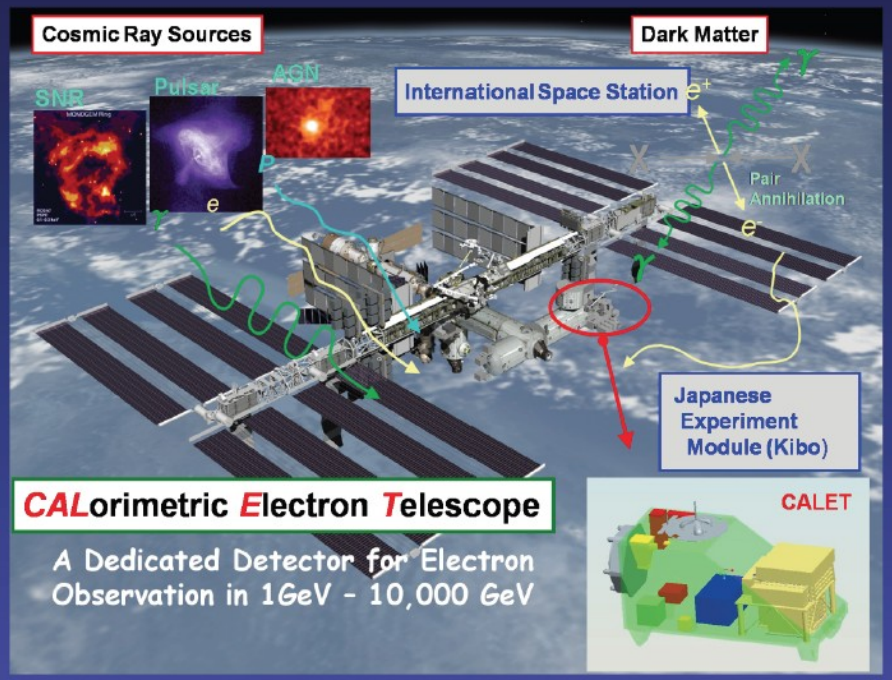
Power Consumption: 640 W

Data Rate: 300 kbps

CALET Overview

□ Observation

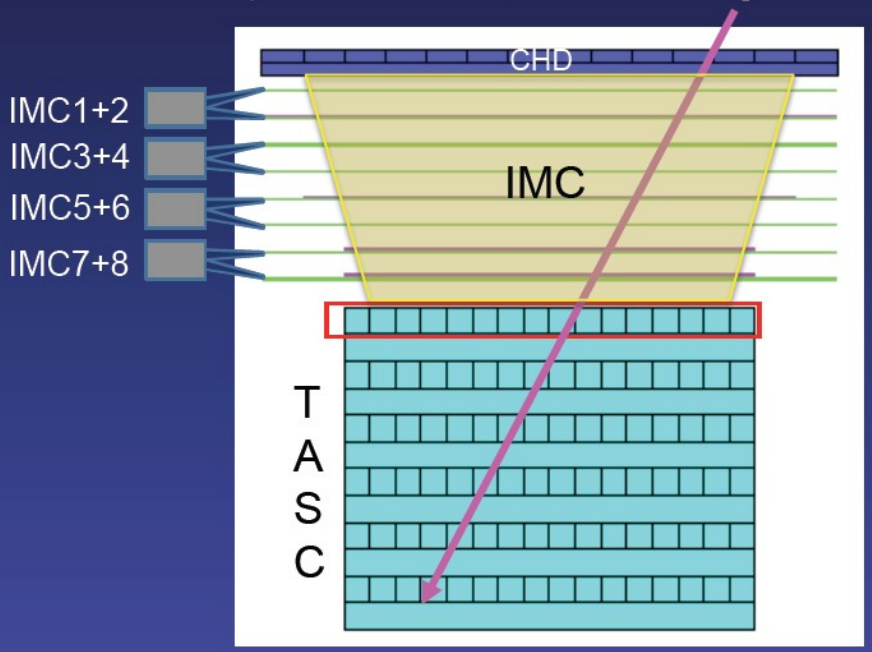
- **Electrons** : 1 GeV - 10 TeV
- **Gamma-rays** : 10 GeV-10 TeV (GRB > 1 GeV)
  + Gamma-ray Bursts : 7 keV-20 MeV
- **Protons, Heavy Nuclei:**
  several 10 GeV- 1000 TeV (per particle)
- **Solar Particles and Modulated Particles in Solar System**: 1 GeV-10 GeV (Electrons)



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

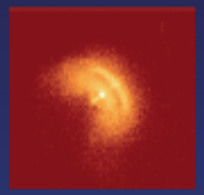


The electron spectrum above 1 TeV

Is there a nearby (< 1 kpc) acceleration source?

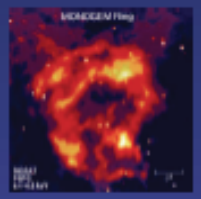
- CALET will explore the **spectral shape beyond 1 TeV** with **low background** (10^5 rejection) and **high energy resolution** (2 - 3%)
- **Anisotropy** measurements to validate possible evidence of nearby source(s)

Nearby Pulsars
or
Dark Matter ?



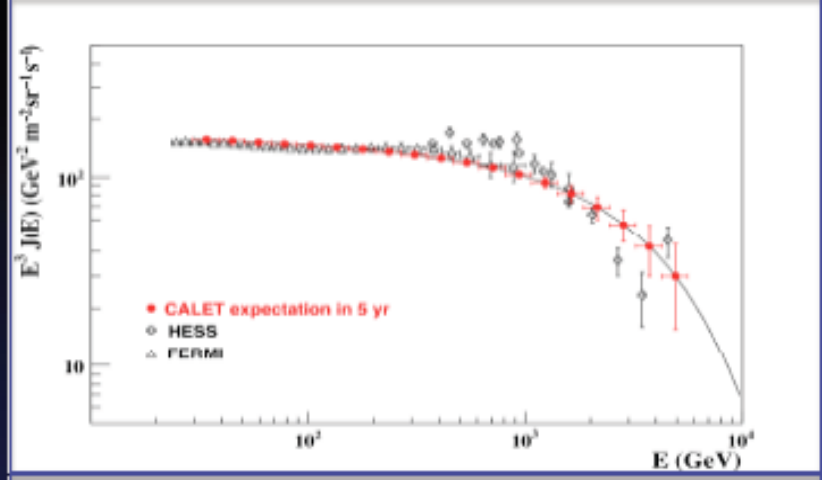
Vela
10,000 years
820 ly
(by CHANDRA)

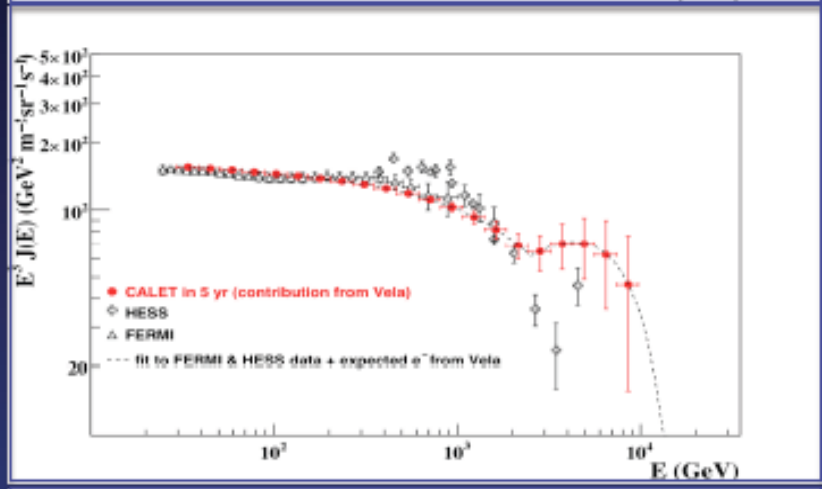
Cygnus Loop
20,000 years
2,500 ly
(by ROSAT)

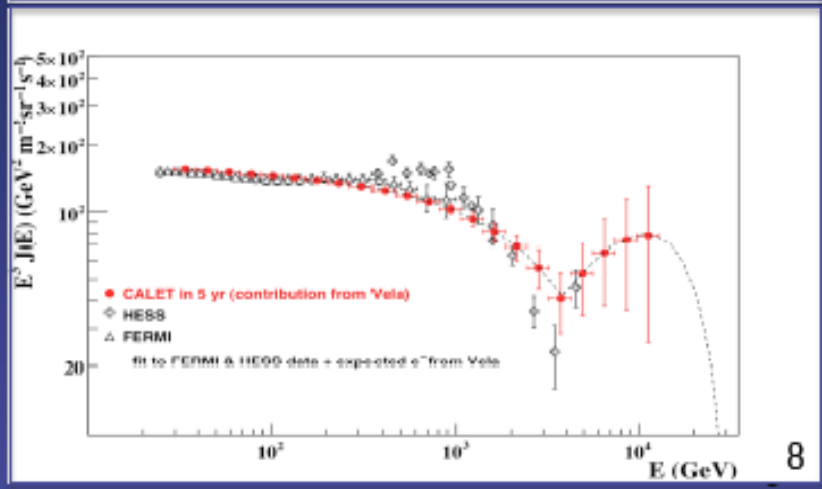


Monogem
86,000 years
1,000 ly

Candidate Nearby Sources
- $T < 10^5$ years
- $L < 1$ kpc

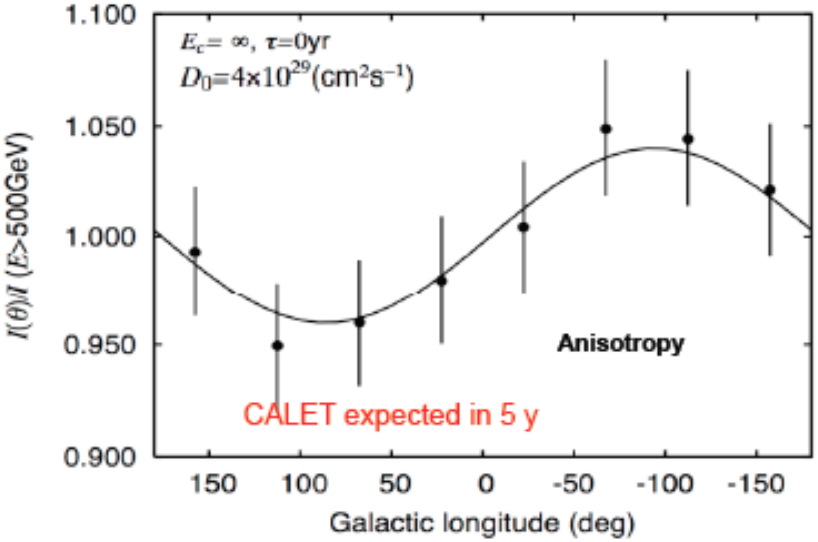


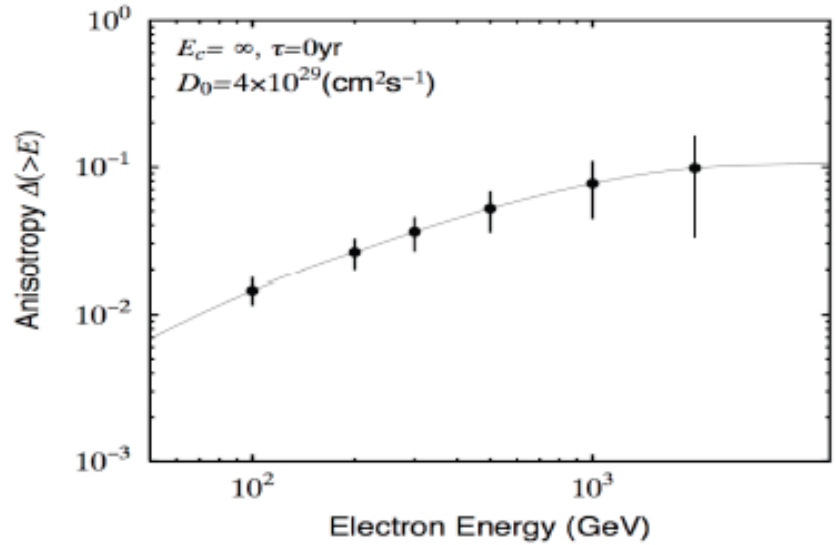


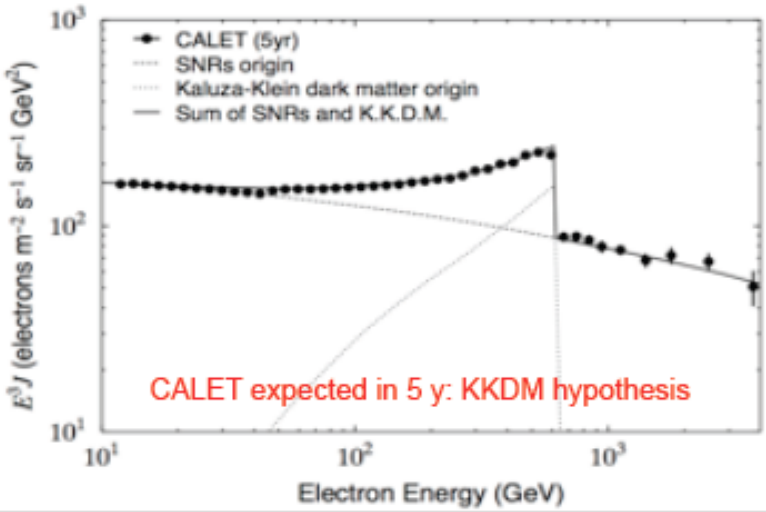


The electron spectrum above 1 TeV

- **CALET will perform Anisotropy** measurements to validate possible evidence of nearby source(s)





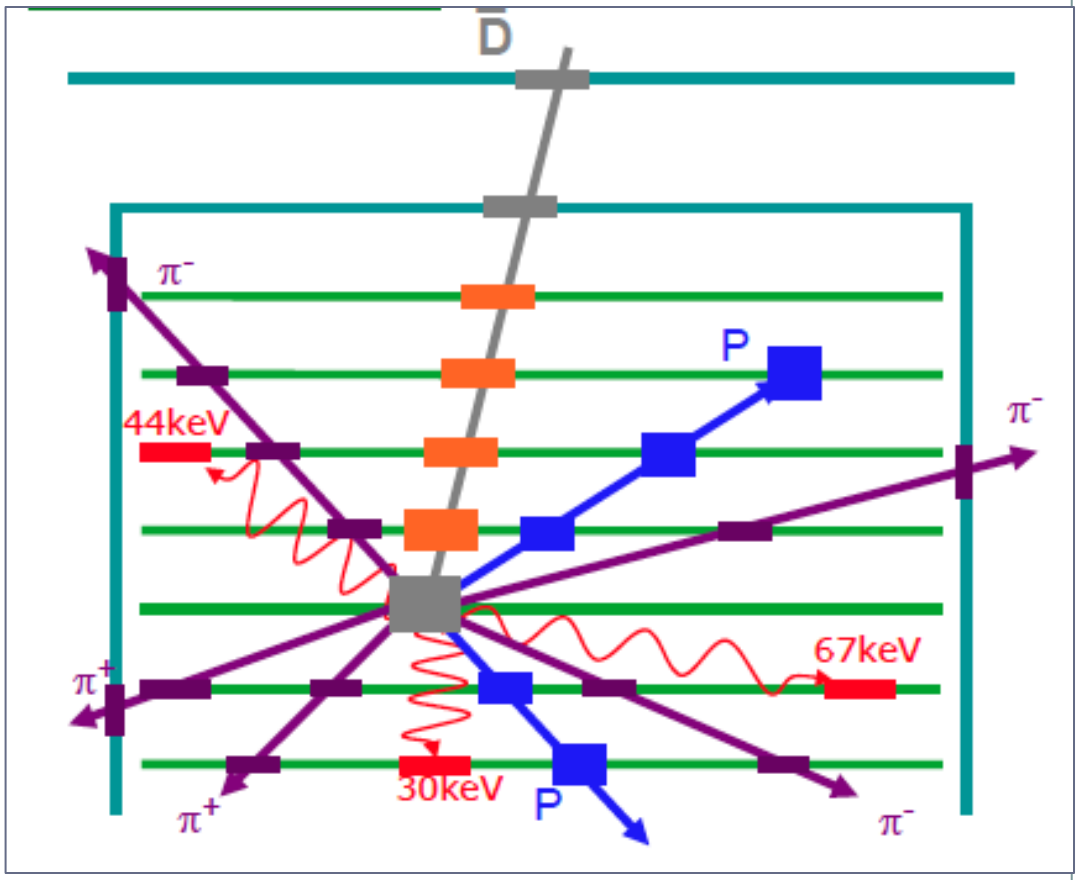


The electron spectrum below 1 TeV

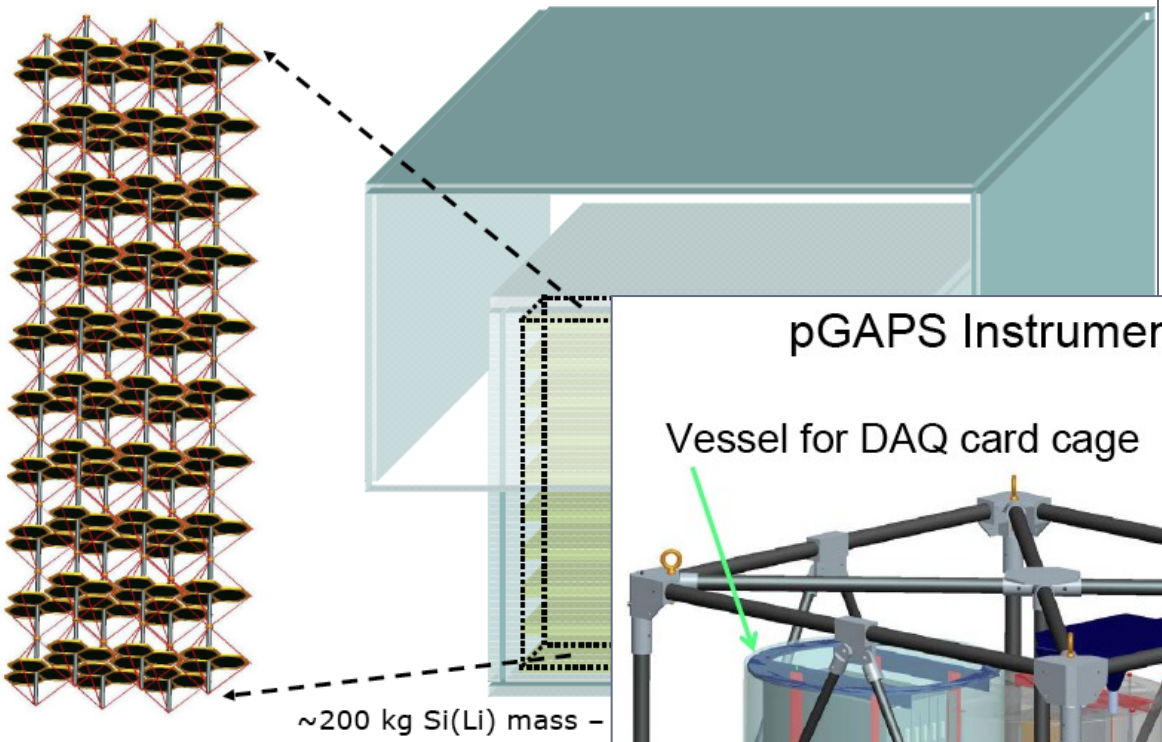
Accurate **spectral shape** measurements in the regionof the 'ATIC anomaly' and of the spectrum down to 1 GeV.

The GAPS experiment

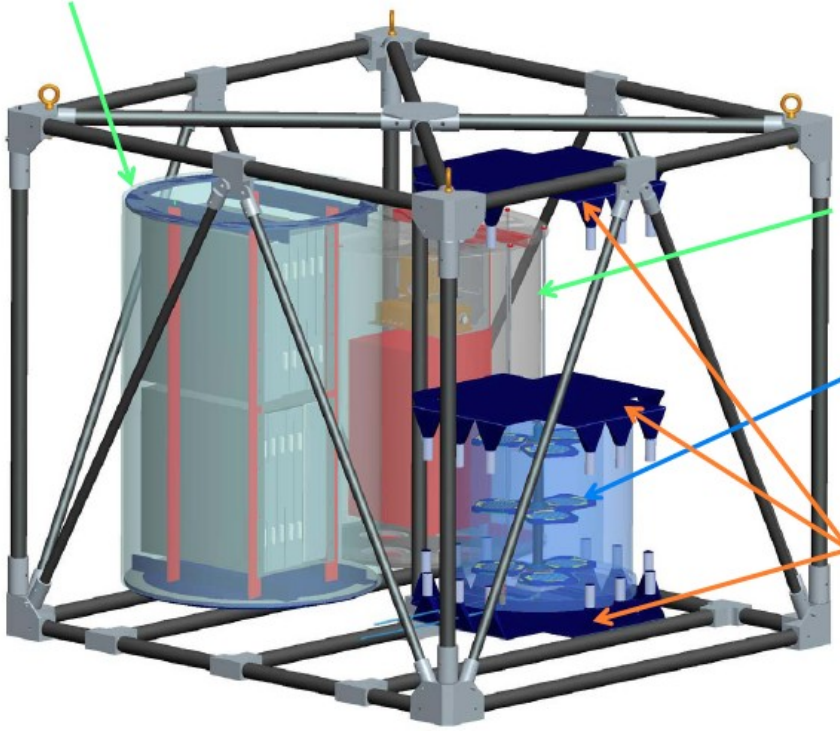
- A time of flight (TOF) system tags candidate events and records velocity
- The antiparticle slows down & stops in a target material, forming an excited exotic atom with near unity probability
- Deexcitation X-rays provide signature
- Pions and protons from annihilation provide added background suppression



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

- Indirect dark matter searches with charged CR are a tool to seek for dark matter, complementary to direct searches and collider experiments;
- Some interesting "signals" in the data created big excitements in the last 2 years, but **no "smoking gun" yet**;
- While searching for dark matter**, new "astrophysics" has been found**, which points towards new mechanisms of production and/or acceleration of charged CR.
- New experiments ready to provide data soon!

PS: I apologize for the experiments I did not have time to mention …