# Direct cosmic-ray detection

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# Cosmic-ray energy spectrum

## Direct detection

Energy Range: $10^3 - 10^{15}$ eV

Particles mostly absorbed in Earth's atmosphere

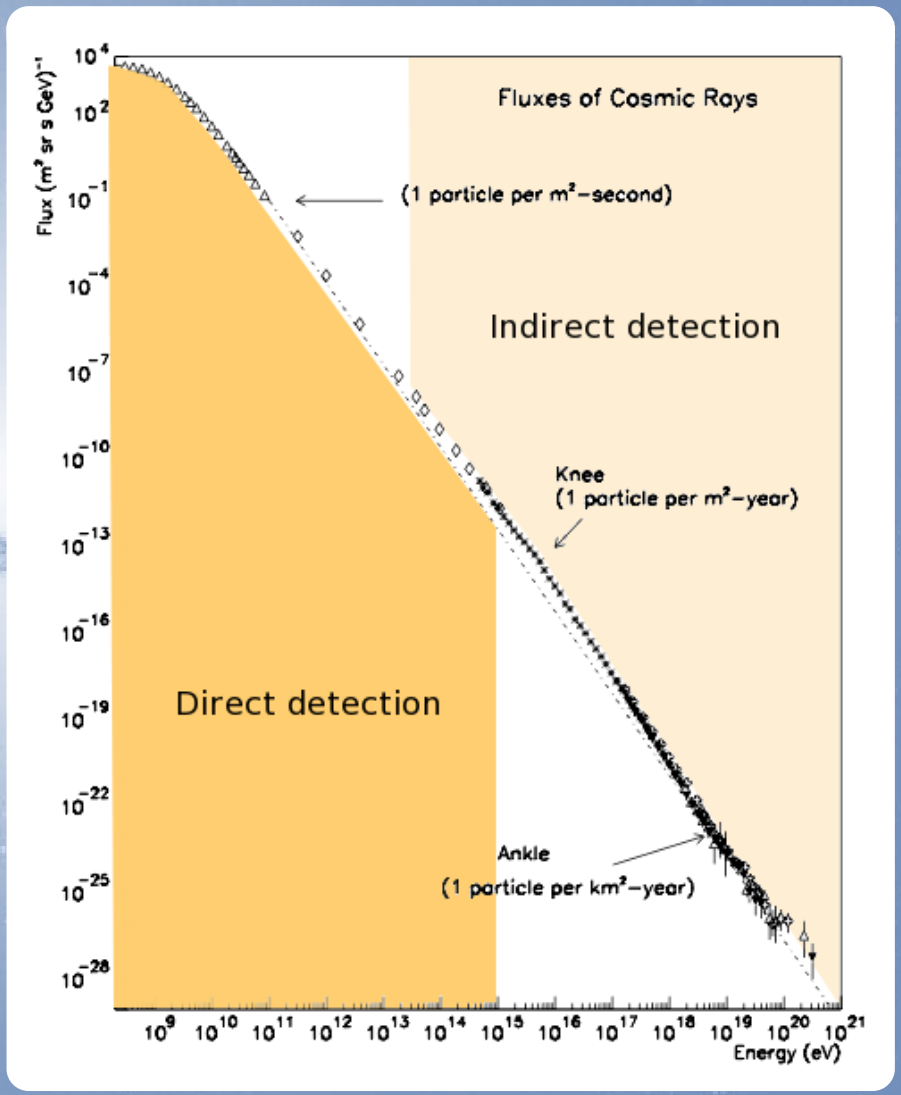
$\Longrightarrow$ space- and balloon-borne experiments

## Indirect detection

Energy Range: $10^{13} - 10^{22}$ eV

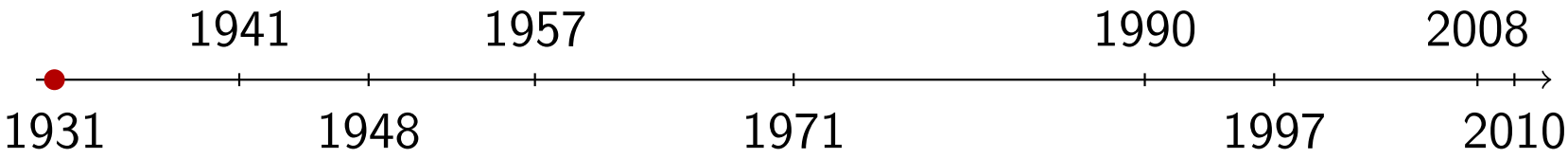
low flux, but interaction in the atmosphere (atmospheric air showers)

$\Longrightarrow$ ground-based experiments

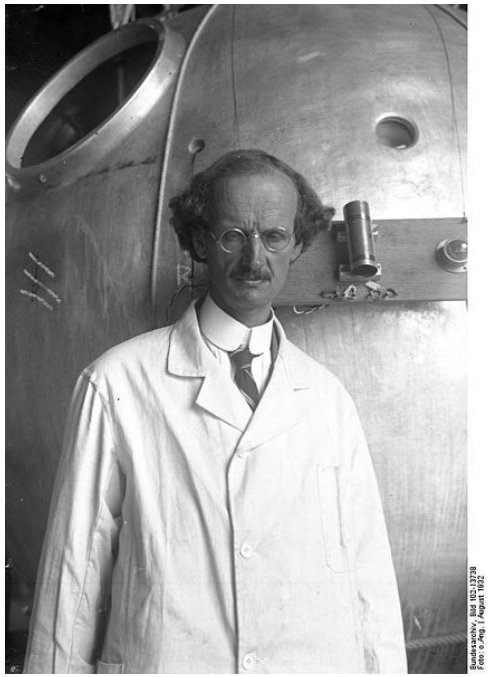


# All started with Viktor Hess 1911/1912

## Some major milestones




## Auguste Piccard: First stratospheric balloon flight at $\sim 16\,\mathrm{km}$



[Bundesarchiv, 1932]

[Les aventures de Tintin]

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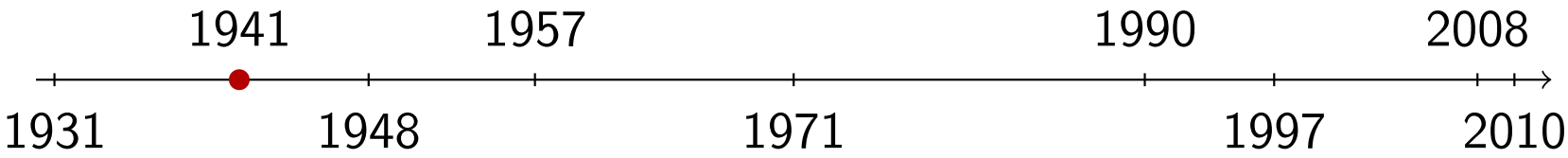
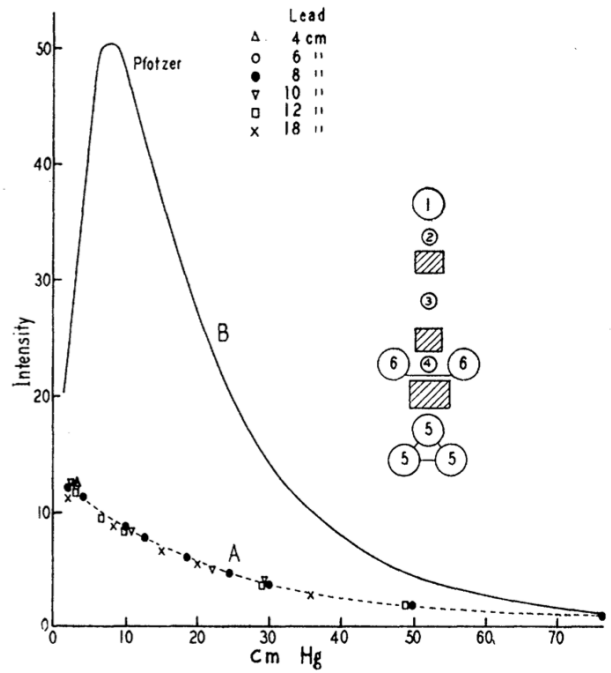
## Some major milestones



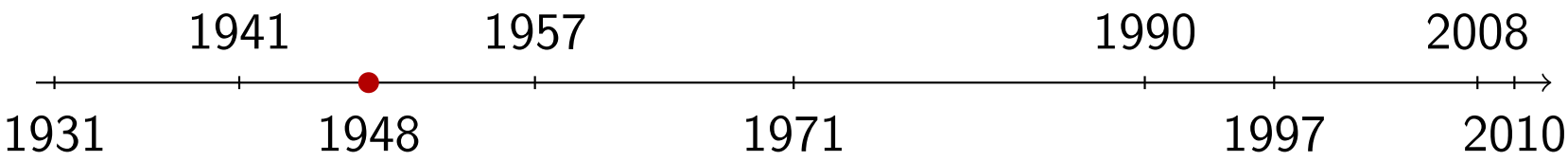

## Marcel Schein: Cosmic rays are primarily protons




[Schein *et al.*, Phys. Rev. **59** (1941), 615]

# All started with Viktor Hess 1911/1912

## Some major milestones




## Phyllis Freier: Evidence for heavy nuclei in primary cosmic rays


[Freier *et al.*, Phys. Rev. **74** (1948), 1818]

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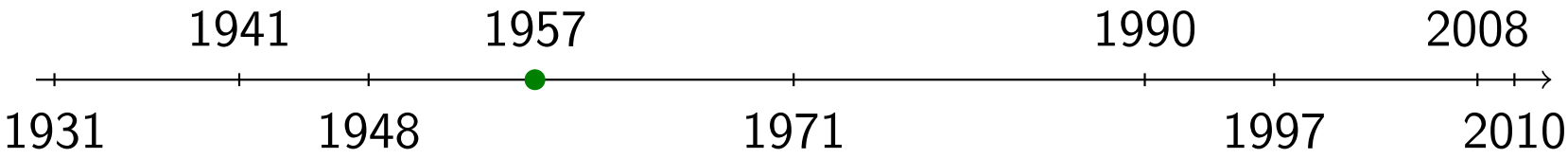
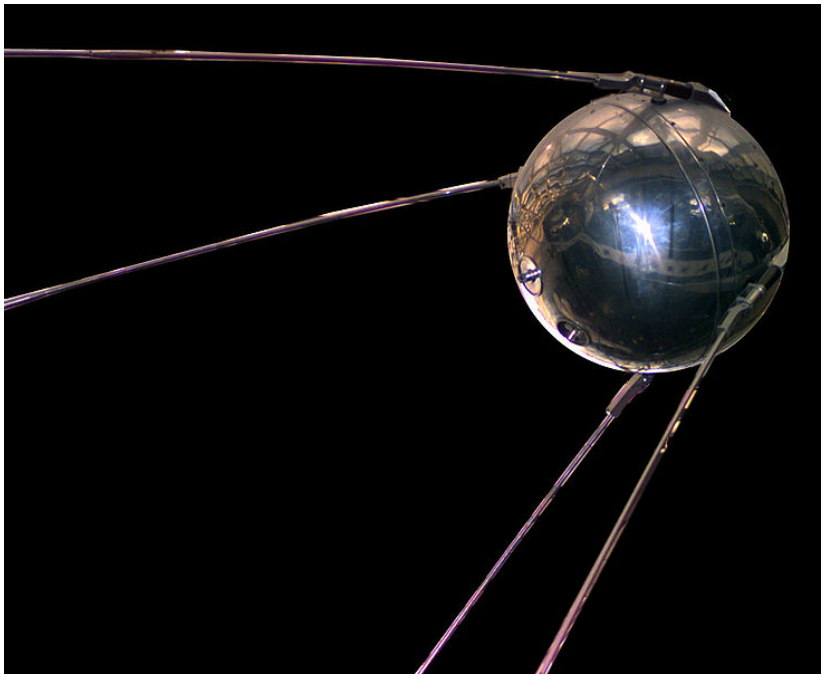
## Some major milestones




## Sputnik 1: First satellite orbiting Earth



[NASA]

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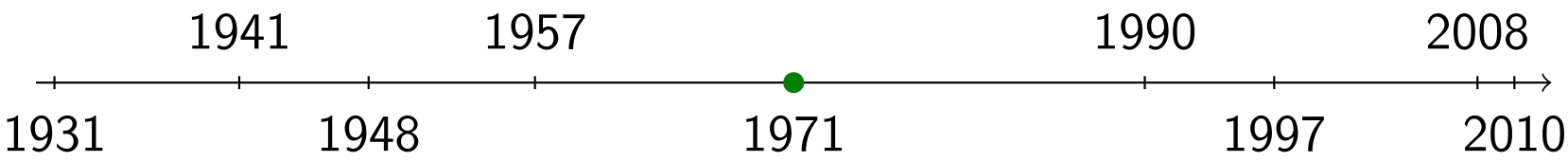
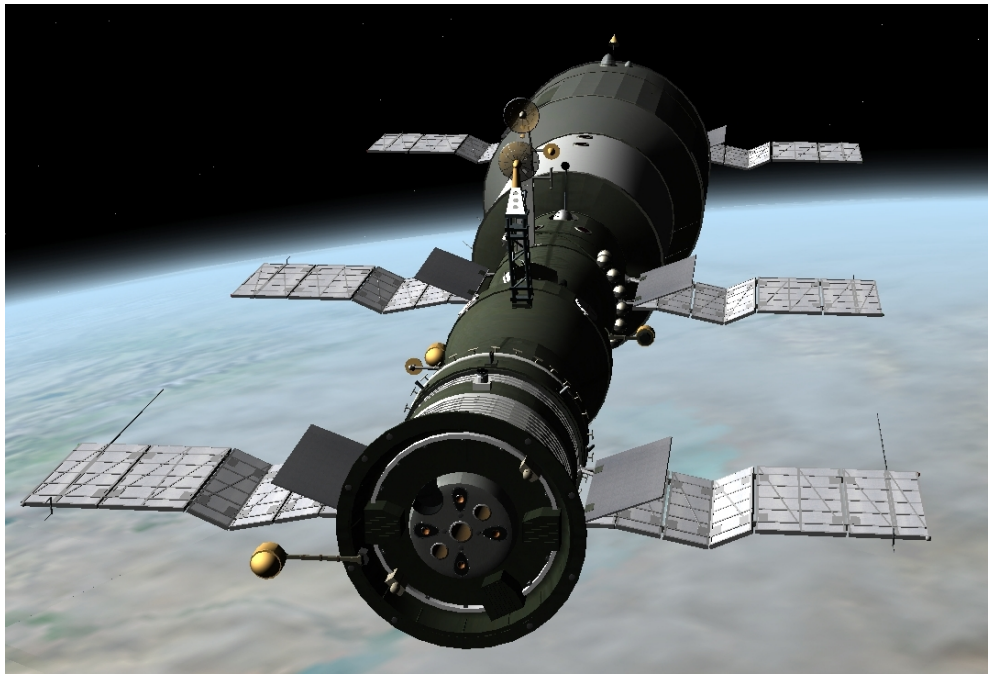
## Some major milestones



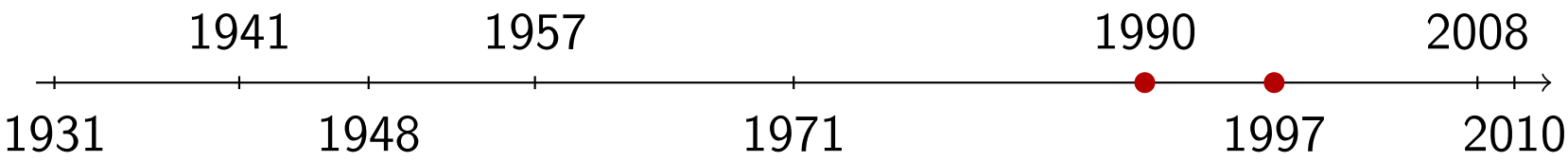

## Salyut 1: First space station



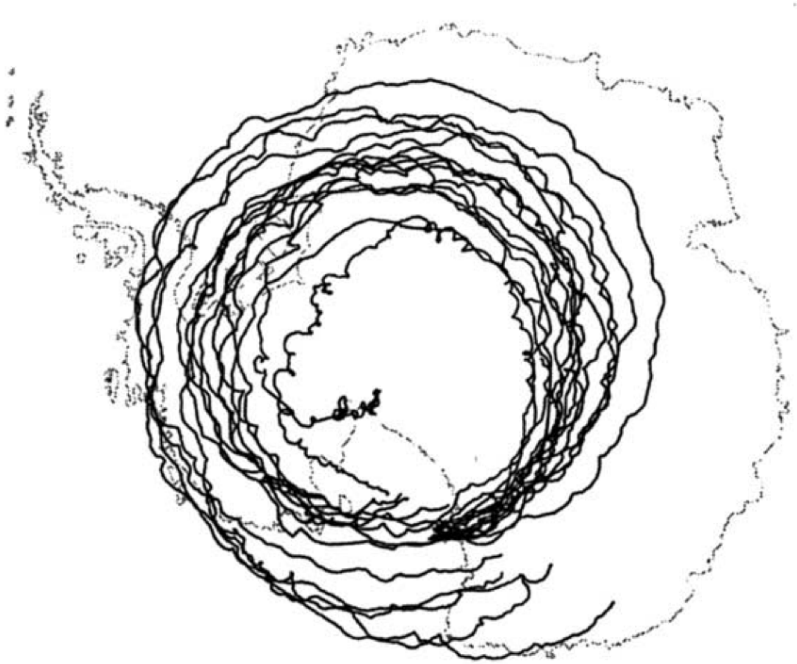
[3D Simulation]

# All started with Viktor Hess 1911/1912

## Some major milestones




## First circumpolar LDB flights (1990: South Pole; 1997: North Pole)



[Gregory & Stepp, Adv. Sp. Res. **33** (2004), 1608]

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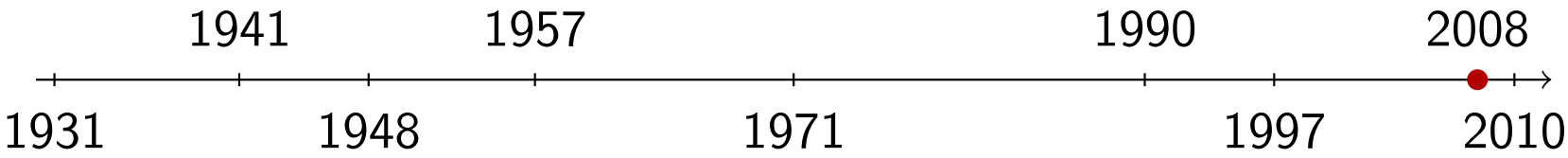
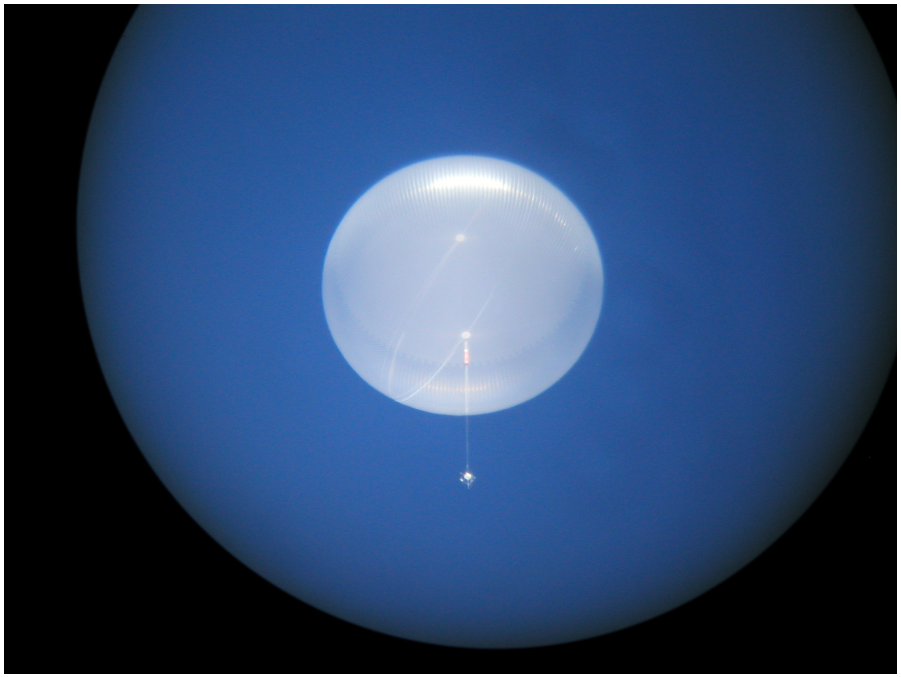
## Some major milestones




## First Super-Pressure Balloon (SPB) flight



[NASA]

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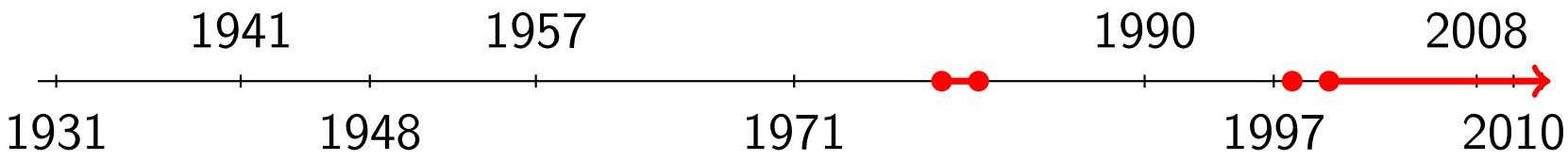



## Balloon- and space-borne experiments in this talk

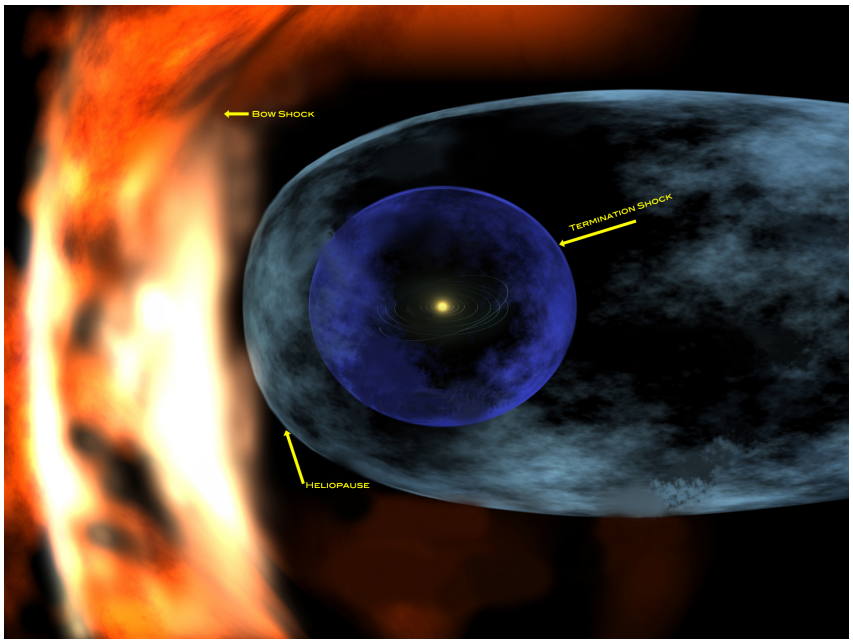
Space-borne experiments:

- High Energy Astronomy Observatory 3 (HEAO 3);
- Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA);
- Alpha-Magnetic Spectrometer (AMS).

Balloon-borne experiments:

- Advanced Thin Ionization Calorimeter (ATIC);
- Trans-Iron Galactic Element Recorder (TIGER);
- Cosmic-Ray Mass And Energetics (CREAM).

# Scientific challenges




Heliosphere (artistic view)

[NASA]

## Solar Physics

Solar modulation of CRs, solar energetic particles, solar cosmic rays, Jovian electrons

## Cosmic ray sources and acceleration

nearby sources ($e^+$), source abundances (FIP vs. volatility)

## Cosmic-ray propagation

propagation mechanisms (elemental spectra, secondary-to-primary ratios)

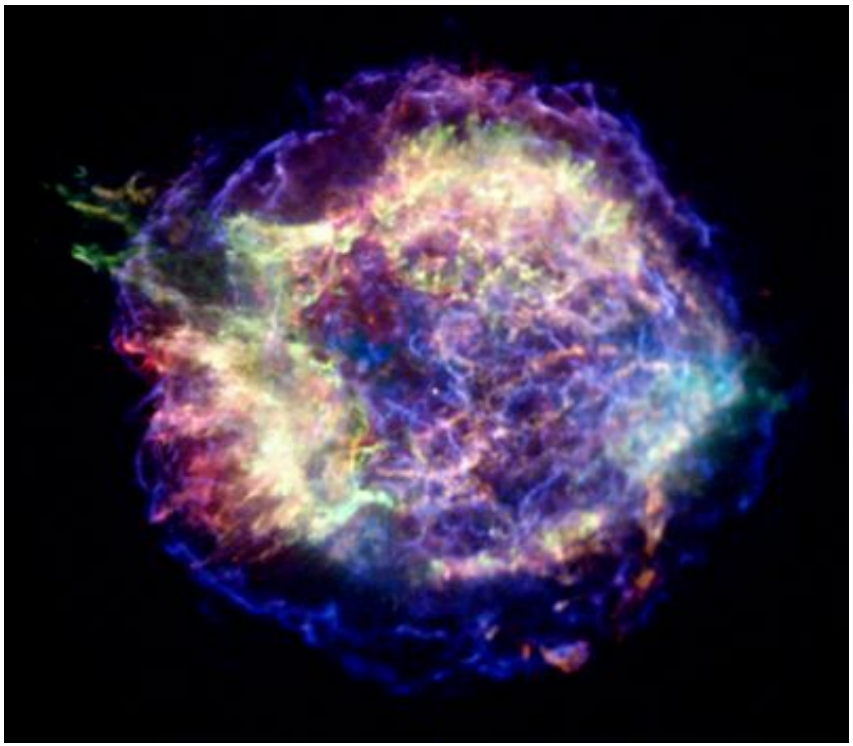
## Dark matter

Annihilation ($e^{\pm}$, $p\bar{p}$)

## Antimatter

Baryonic asymmetry ($Z < -2$)

# Scientific challenges



Cassopeia A (Chandra, X-rays)

[NASA/CXC/MIT/UMass Amherst/M.D.Stage *et al.*]

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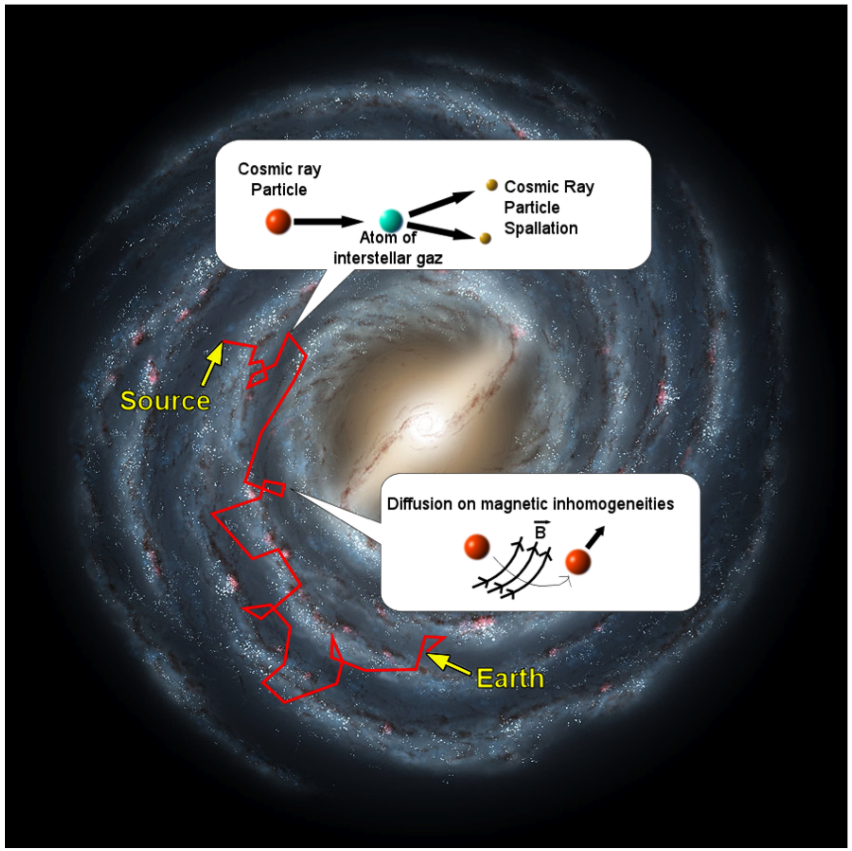


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# Scientific challenges

Bullet Cluster (Chandra, Hubble)

[NASA]

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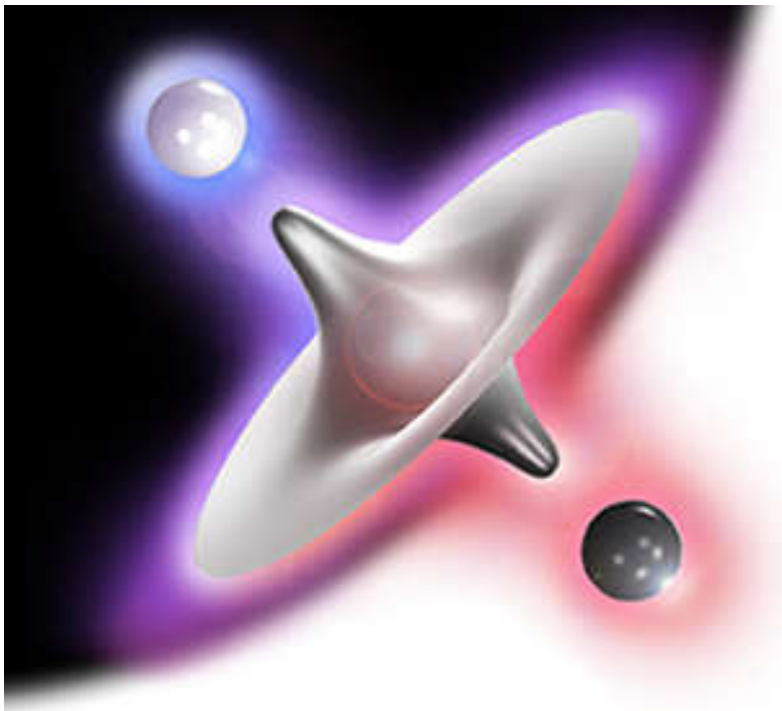

[CERN]

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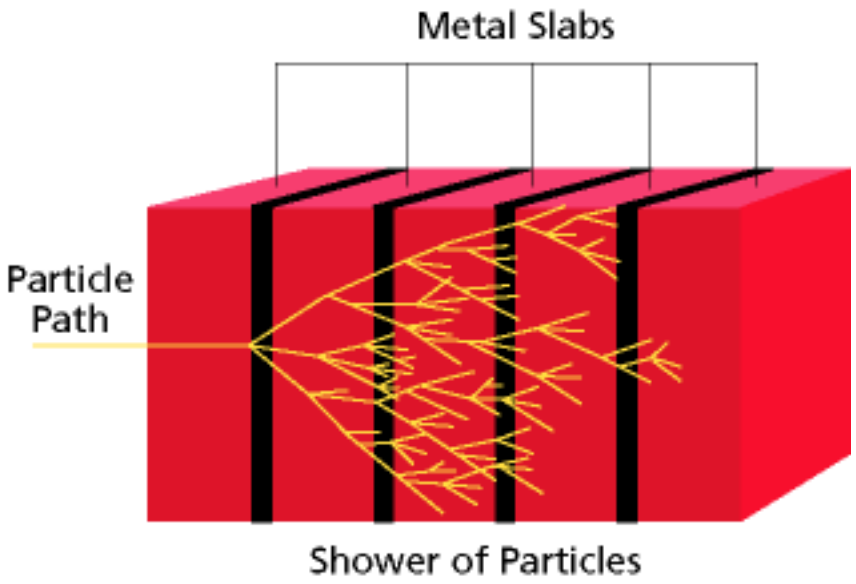
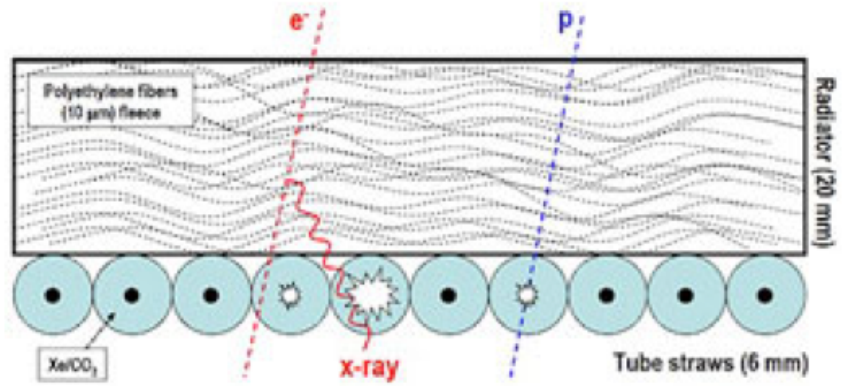
# Measurement techniques: Energy

## Calorimeter




- hadronic and electromagnetic;
- particle shower production using dense material;
- energy measurement through scintillation.

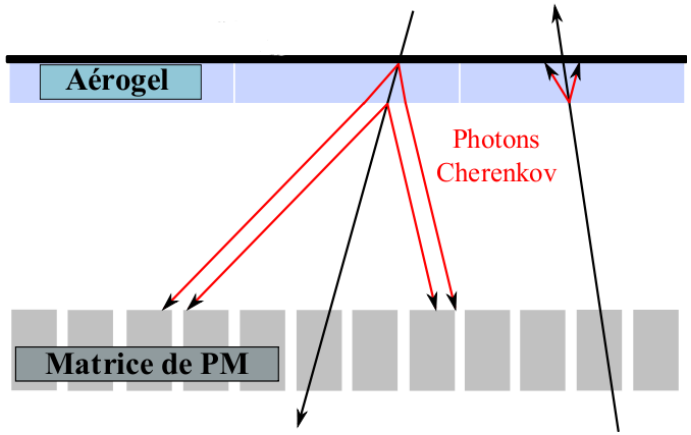
## Transition radiation




- threshold and precision;
- $\gamma$'s produced during passage between materials with differing dielectric constants;
- $W_0 \propto \gamma$ (Lorenz factor);
- energy measurement through ionisation.

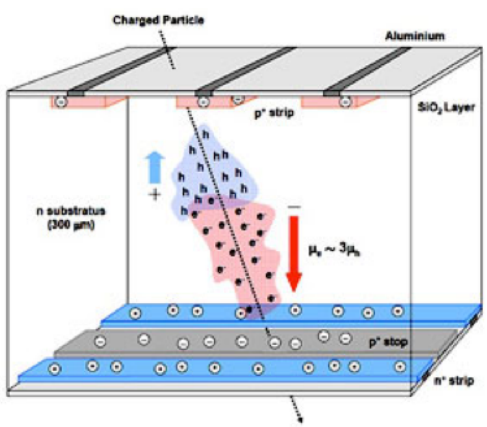
# Measurement techniques: Charge

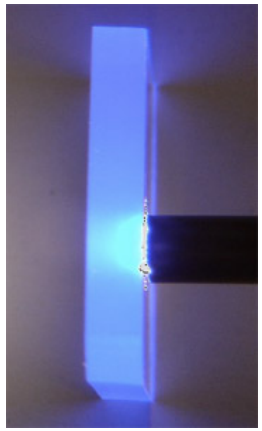
## Cherenkov




- $\gamma$'s produced during the passage through a radiator;
- $N_\gamma \propto Z^2$;
- $\theta = \cos^{-1}(1/\beta n)$.

## d$E$/d$x$ - Energy losses

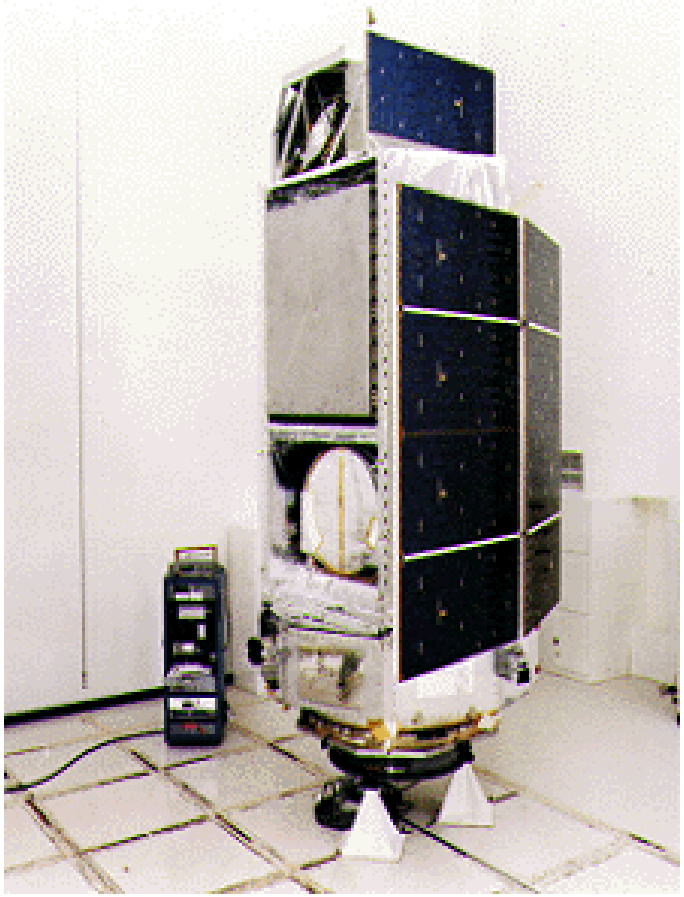


- silicon diodes and plastic scintillators;
- ionisation of the material;
- $-\mathrm{d}E/\mathrm{d}x \propto Z^2$.

A combination of different types or multiple detectors of the same type allows to infer also other particle characteristics!

# High Energy Astronomy Observatory 3 (HEAO 3)



[NASA]

## Lifetime

20 September 1979 - 29 May 1981

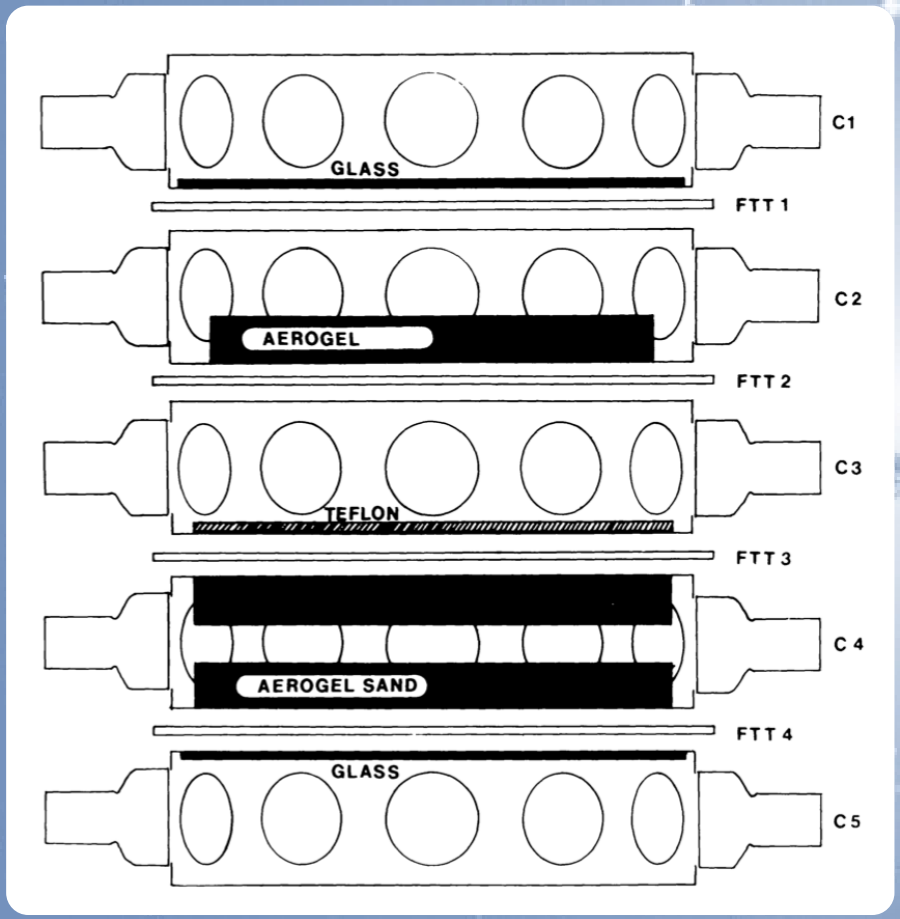
## Instruments

- High Resolution Gamma Ray Spectrometer (HRGRS / C1);
- Cosmic Ray Isotope Experiment (C2);
- Heavy Nuclei Experiment (C3).

## Mission of C2

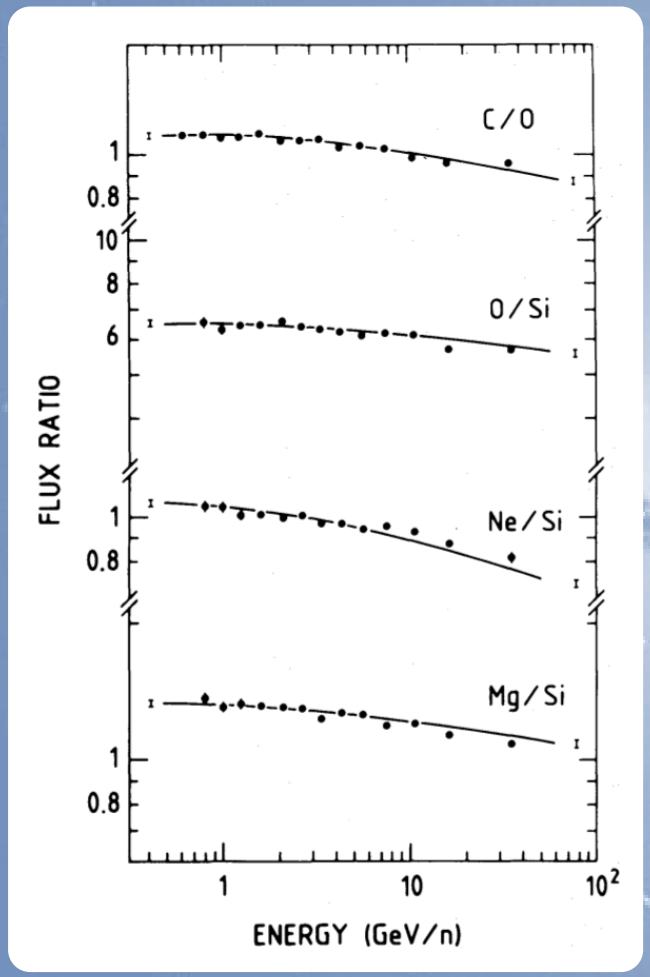
Measurement of elemental spectra and abundances from beryllium to nickel between 0.6 and 35 GeV/n

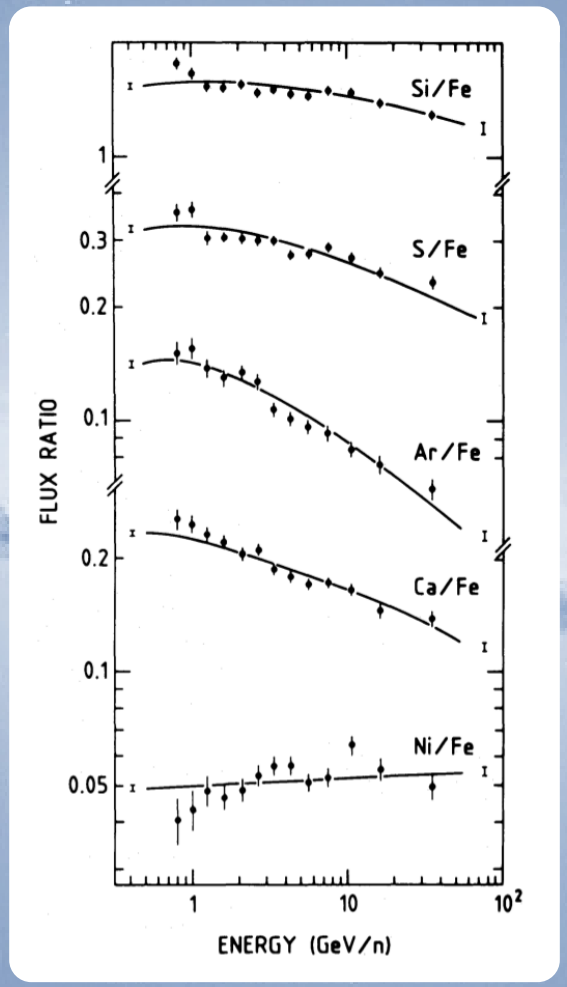
# HEAO 3 (C2) - Cosmic Ray Isotope Experiment

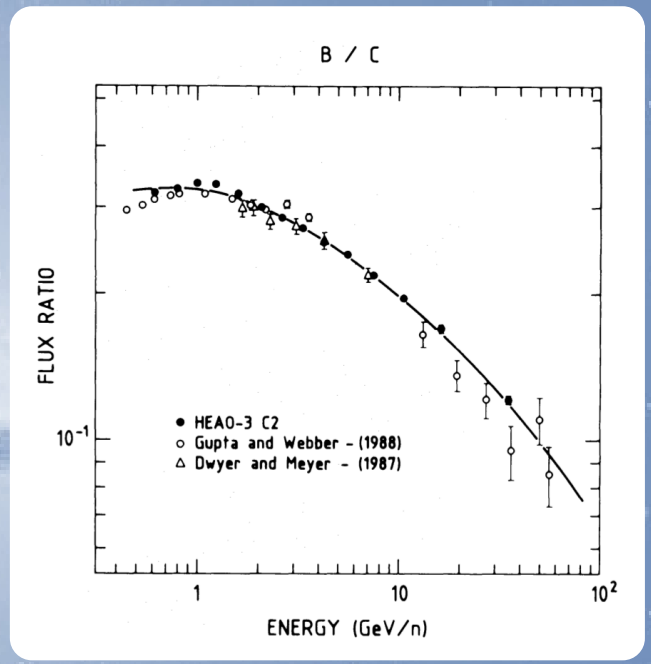



- 5 Cherenkov counters with different refractive index used for velocity and charge determination;
- Flash-tube hodoscope of 4 trays used for particle track reconstruction;
- effective area of $0.07\,\mathrm{m}^2$ for each propagation direction;
- over 7 million events collected of particles with $4 \leq Z \leq 28$ between $0.6$ and $35\,\mathrm{GeV/n}$.

# HEAO 3-C2 results [Engelmann *et al.*, A&A **233** (1990), 96]

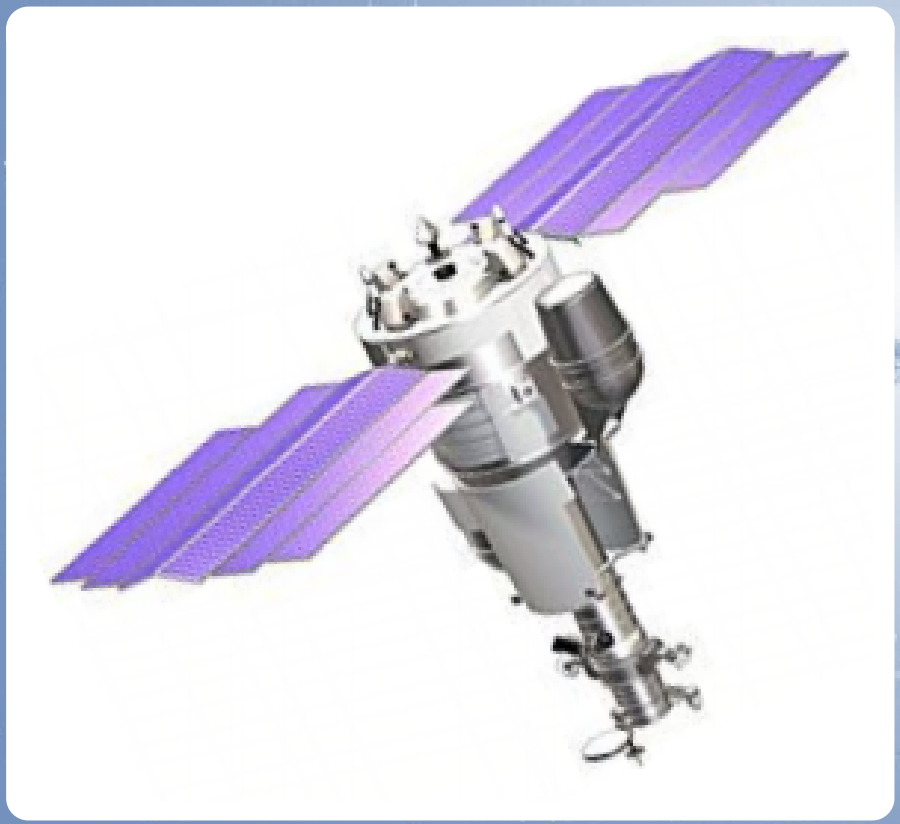



Most precise mesurements of cosmic rays ($4 \leq Z \leq 28$)!

# Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



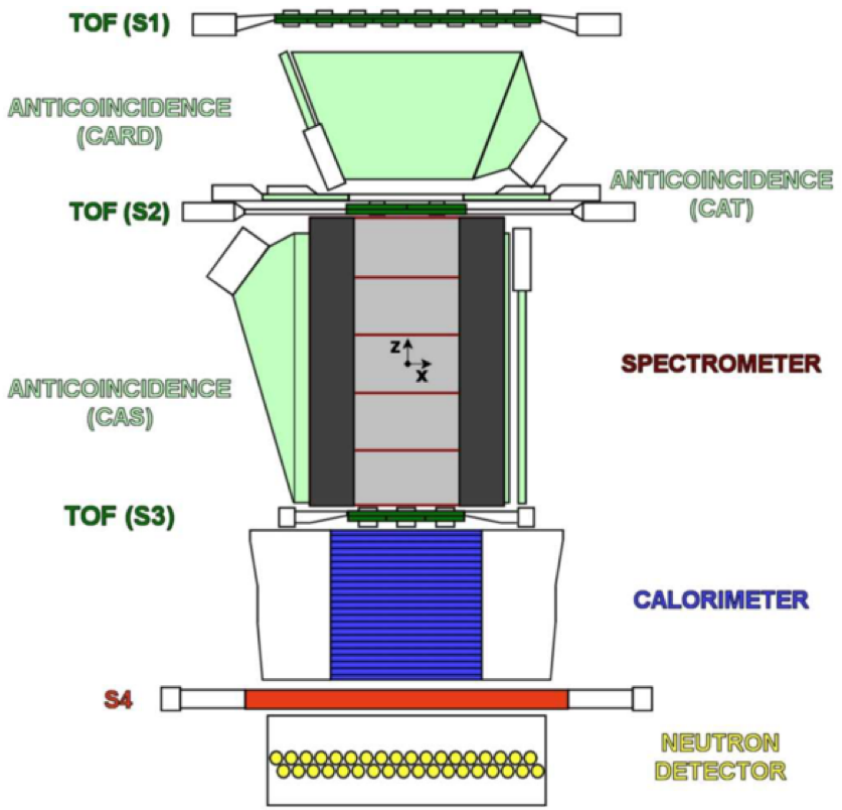
## Lifetime

15 June 2006 - 2010/2011

## Scientific goals

- search for evidence of annihilations of dark matter ($\bar{p}$ and $e^+$ spectra)
- search for antinuclei;
- test propagation models;
- study of solar physics and solar modulation;
- study of possible contribution from local sources to the electron spectrum.

# PAMELA detector




[PAMELA homepage]

geometrical acceptance of $0.22\,\mathrm{m}^2\,\mathrm{sr}$

## Time-Of-Flight (TOF)

- 3 plastic scintillators
- $\beta$ and $|Z|$ measurement

## Spectrometer

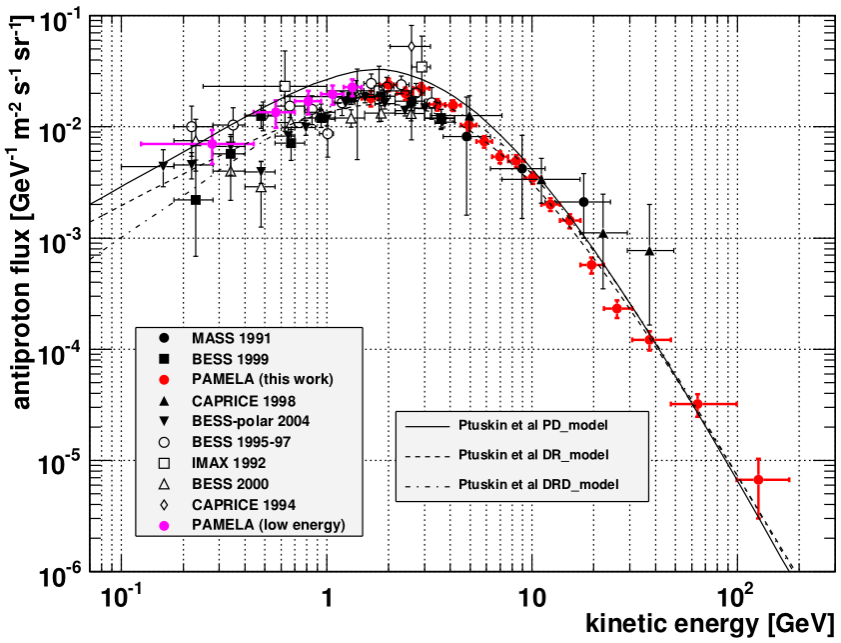
- permanent magnet and 6 layers of silicon microstrips
- $R$ and $Z$ measurement

## Electromagnetic calorimeter

- W/Si sampling
- $E$ measurement and shower topology

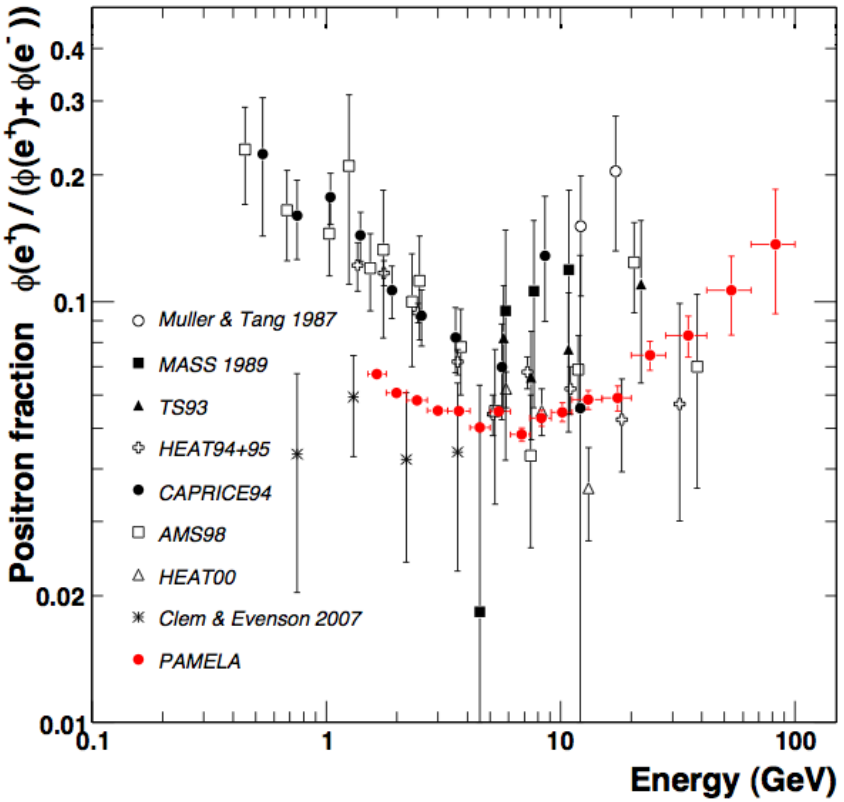
# PAMELA results

## Antiproton flux




[J. Wu, Licentiate Thesis, 2010]

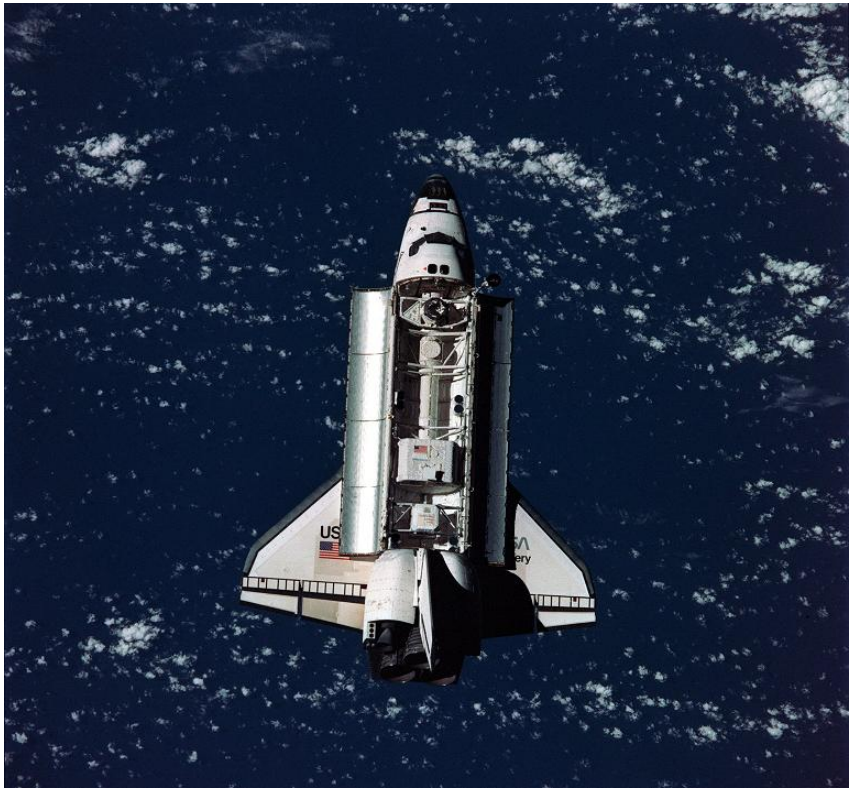
## Positron fraction




[O. Adriani *et al.*, Phys. Rev. L. **102** (2009), 051101]

Data analysis still ongoing: new results will be published soon! Stay tuned!

# Alpha Magnetic Spectrometer - 01



## Lifetime

2 - 12 June 1998 on the space shuttle *Discovery*

## Scientific goals

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- search for antinuclei;
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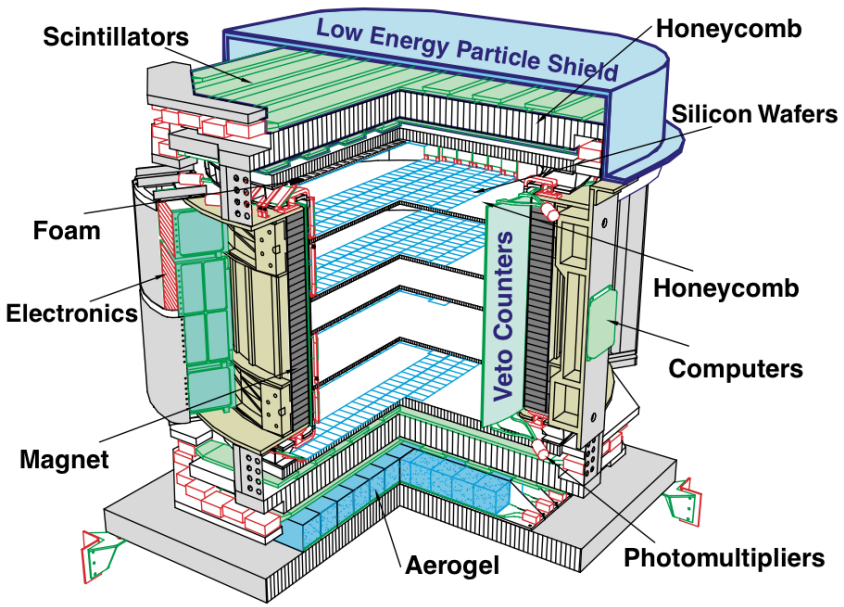
- study of solar physics and solar modulation;
- study of possible contribution from local sources to the electron spectrum.

# AMS-01




[AMS Collaboration, Physics Reports **366** (2002), 331]

geometrical acceptance of 0,82 $m^2$ sr

## Time-Of-Flight (TOF)

- 2 plastic scintillators
- $\beta$ and $|Z|$ measurement

## Spectrometer

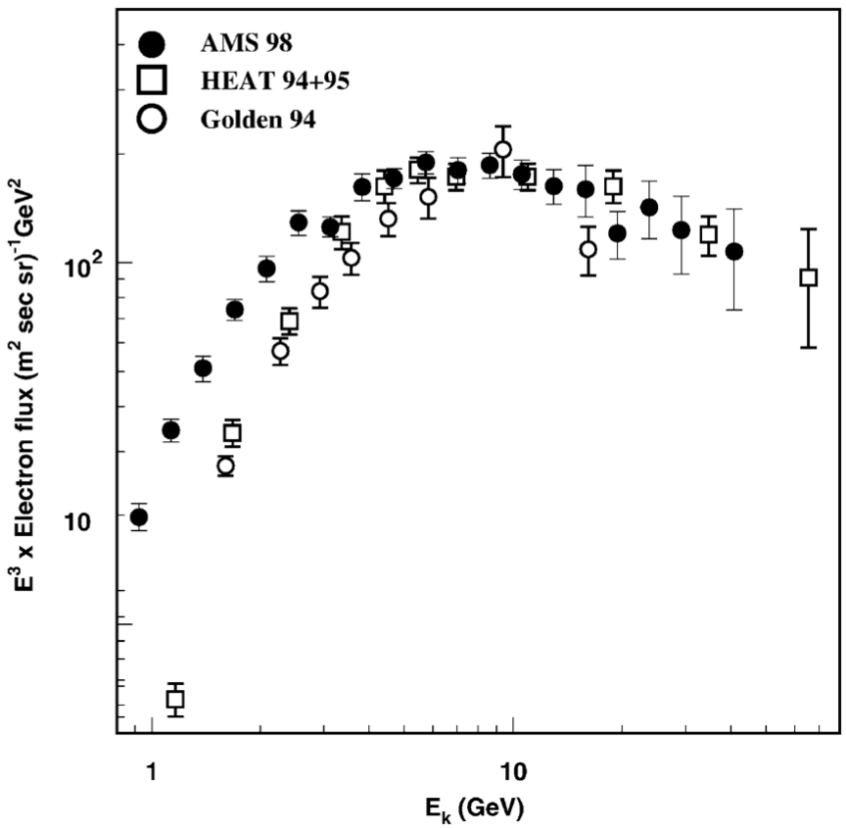
- permanent magnet and 6 layers of silicon microstrip
- $R$ and $Z$ measurement

## Cherenkov counter

- Cherenkov imager with aerogel radiator
- $\beta$ and $|Z|$ measurement

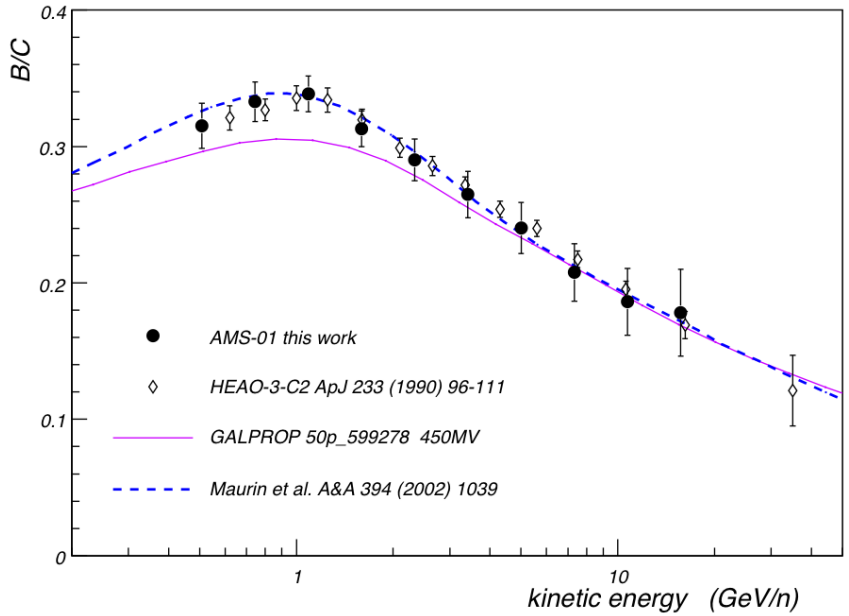
# AMS-01 results

## Electron flux




[AMS Collaboration, Physics Reports **366** (2002), 331]

## B/C ratio




[Tomassetti *et al.*, 31st ICRC (2009), 182]

AMS-02 launch scheduled for november 2010!

# Advanced Thin Ionization Calorimeter

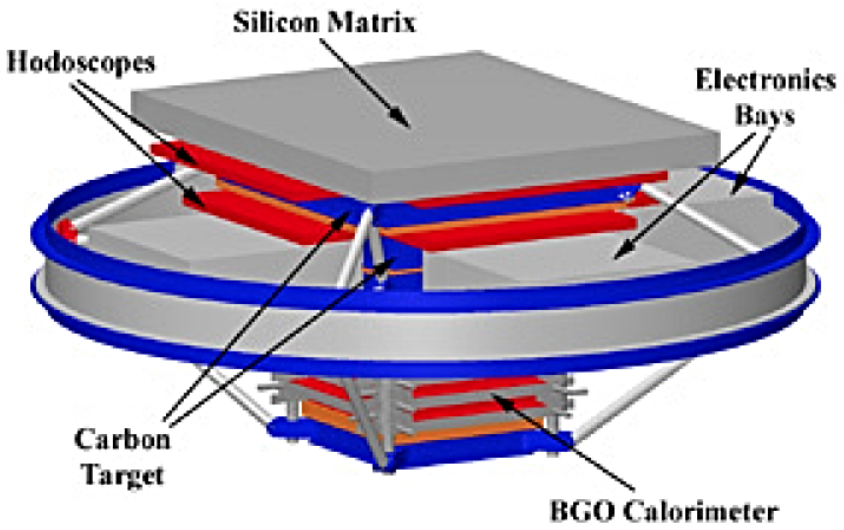
[ATIC homepage]

3 LDB flights (2000, 2002 & 2007), 50 days

## Scientific goals

- measure spectra for individual elements;
- discover "breaks" or "bends" in the spectra;
- measure the H/He ratio;
- determine the spectral differences between elements;
- study the composition of the cosmic-ray matter.

# ATIC detector




[ATIC homepage]

geometrical acceptance of 0.075 – 0.15 $m^2$ sr

## Silicon Matrix

- silicon microstrip
- $Z$ measurement

## Hodoscopes

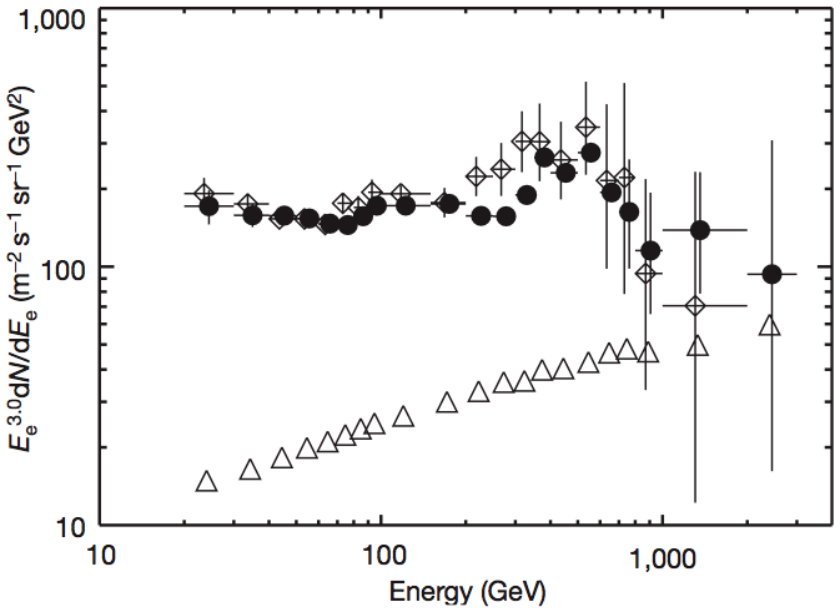
- 3 plastic scintillators
- $Z$ and trajectory measurement

## Ionisation calorimeter

- 3 layers of carbon and 10 layers of BGO crystals
- $E$ measurement

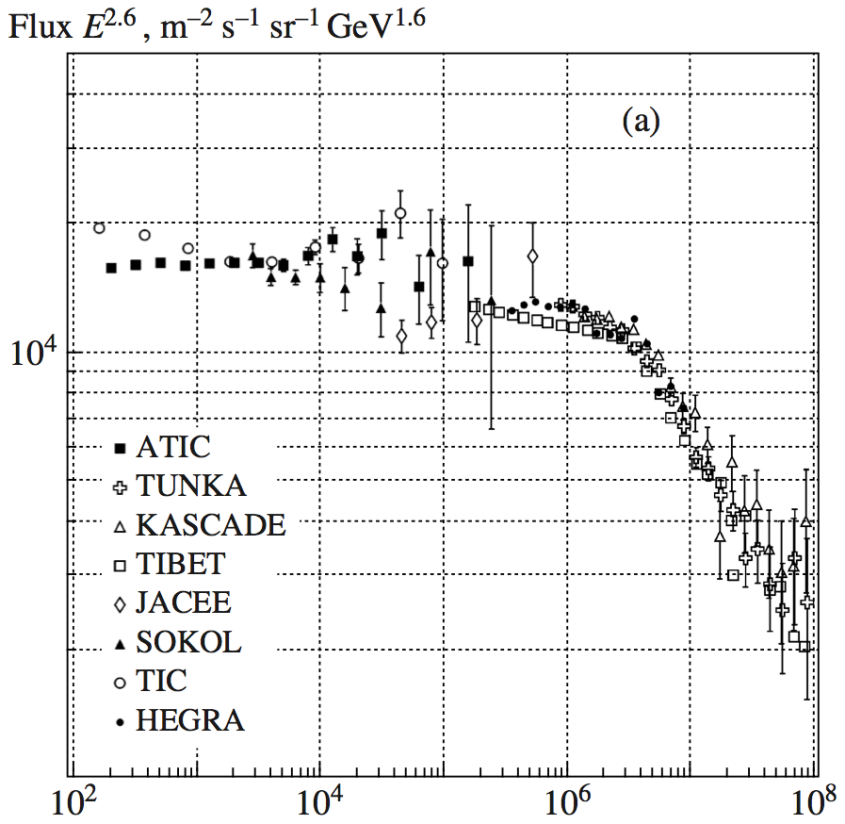
# ATIC results

## Excess of $e^-$ at $E$ of 300 – 800 GeV



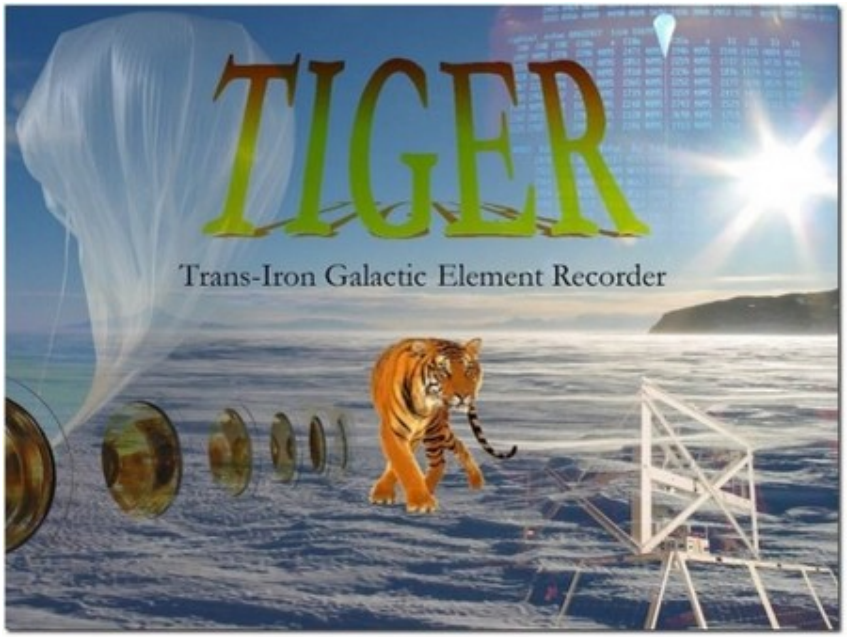

[J. Chang *et al.*, Nature, **456** (2008), 362]

## Inclusive spectrum of ATIC-2




[Panov *et al.*, Bulletin of the Russian Academy of Sciences: Physics, **73** (2009), 564]

# Trans-Iron Galactic Element Recorder

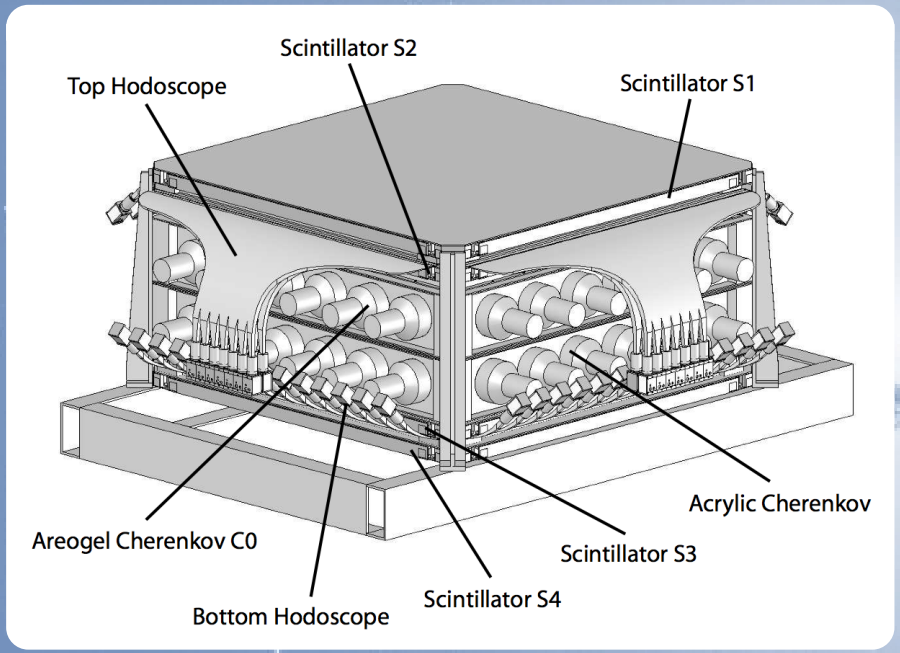



2 LDB flights (2001 & 2003), 50 days

## Scientific goals

- measuring the abundances of particles with $26 \leq Z \leq 38$;
- study acceleration mechanisms;
- identify sources;

# TIGER detector




geometrical acceptance of $1.7\,\mathrm{m}^2\,\mathrm{sr}$

## Scintillators

- 4 layers plastic scintillators
- $E$ and $Z$ measurement

## Cherenkov counters

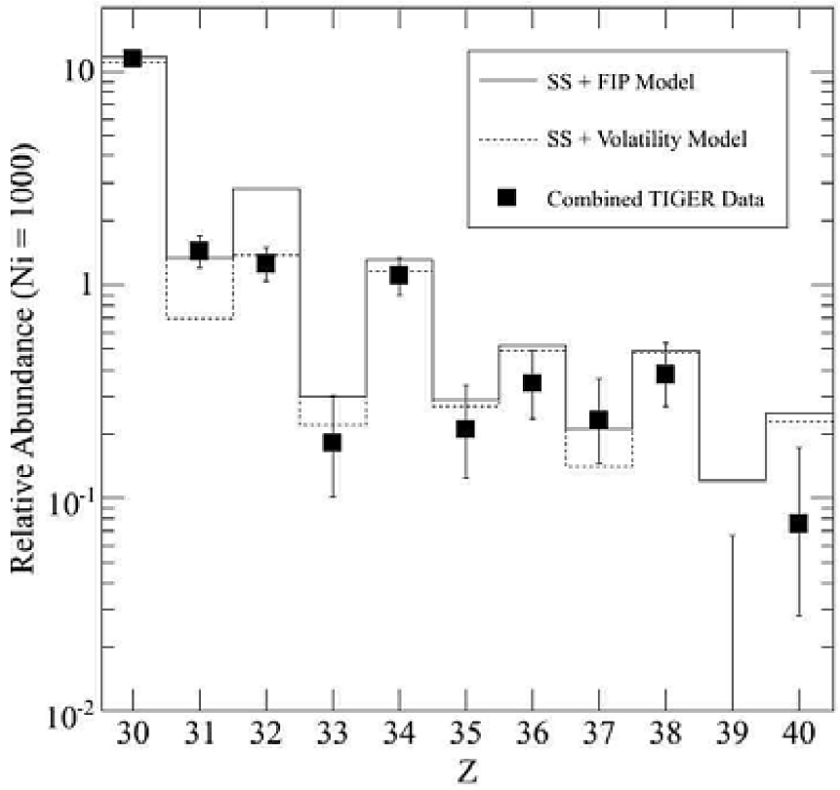
- 2 (acrylic & aerogel) Cherenkov radiators
- $\beta$ and $Z$ measurement

## Hodoscopes

- 2 scintillating fiber hodoscopes
- trajectory measurement

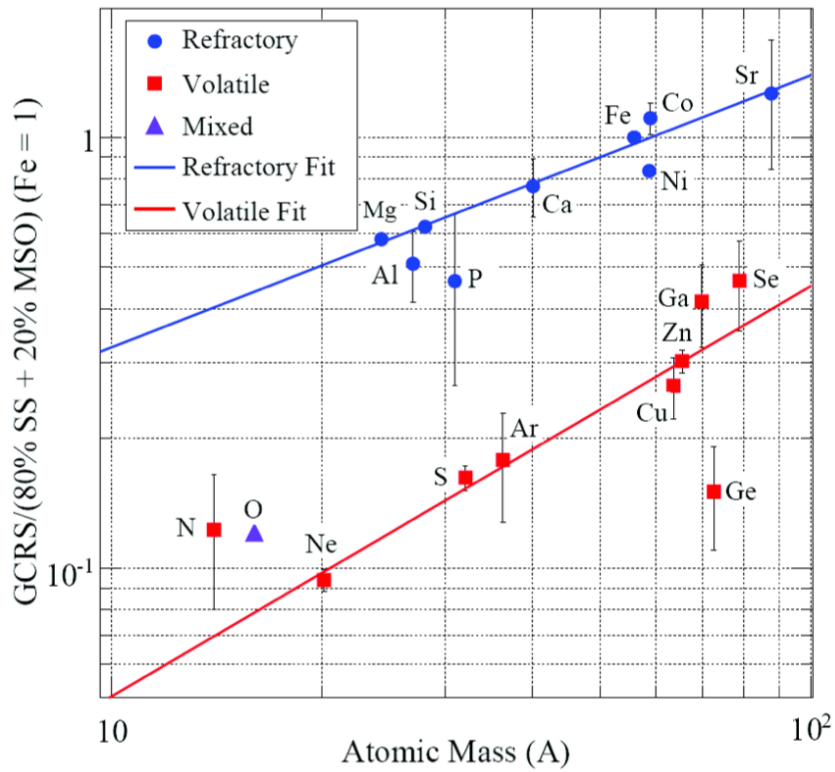
# TIGER results

## Relative abundances




[Rauch *et al.*, 30th ICRC (2007), 187]

## Relative abundances (SS + MSO)




[Link *et al.*, 31st ICRC (2009), 617]

Super-TIGER (4 TIGER modules) flights are planned for 2012 and 2014

# Cosmic Ray Energetics And Mass

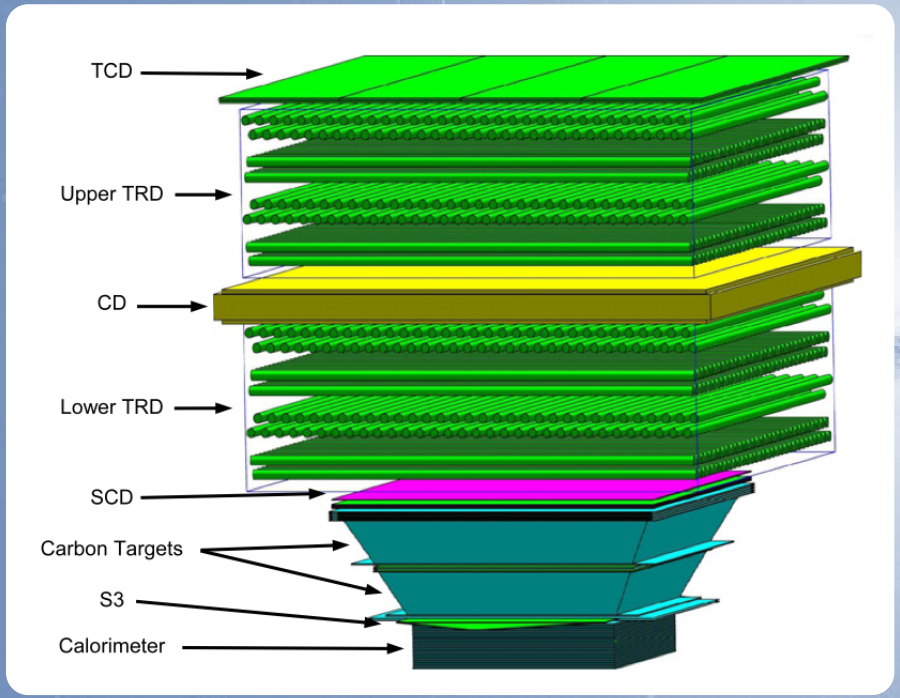
CREAM flight duration exceeds all prior balloon-borne experiments!

5 LDB flights (2004, 2006–2009),
157 days
6th and 7th flight in preparation

## Scientific goals

- measure spectra for individual elements;
- discover “breaks” or “bends” in the spectra;
- determine the spectral differences between elements;
- study the composition of the cosmic-ray matter.

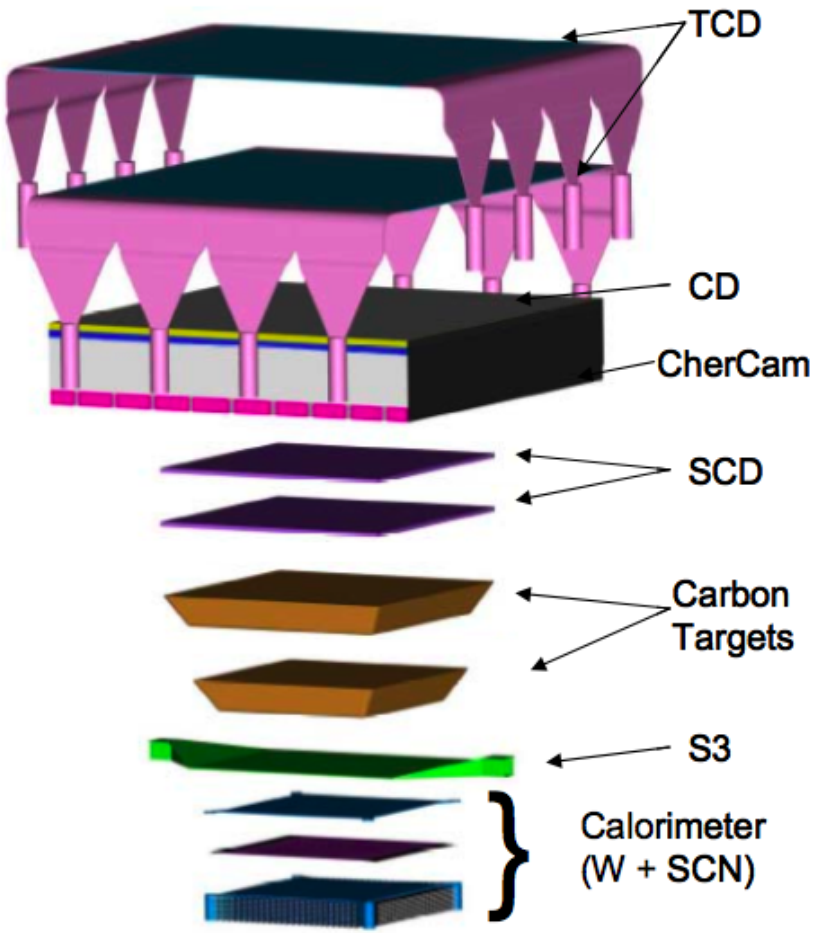
# CREAM sub-detectors




## CREAM-I/II sub-detectors

- *Timing Charge Detector* (TCD):
  Z, vetoes albedo particles
- *Transition Radiation Detector* (TRD) (only CREAM-I):
  $\gamma$
- *Cherenkov Detector* (CD):
  Z, vetoes non-relativistic particles
- *Silicon Charge Detector* (SCD):
  Z
- ionisation calorimeter:
  E

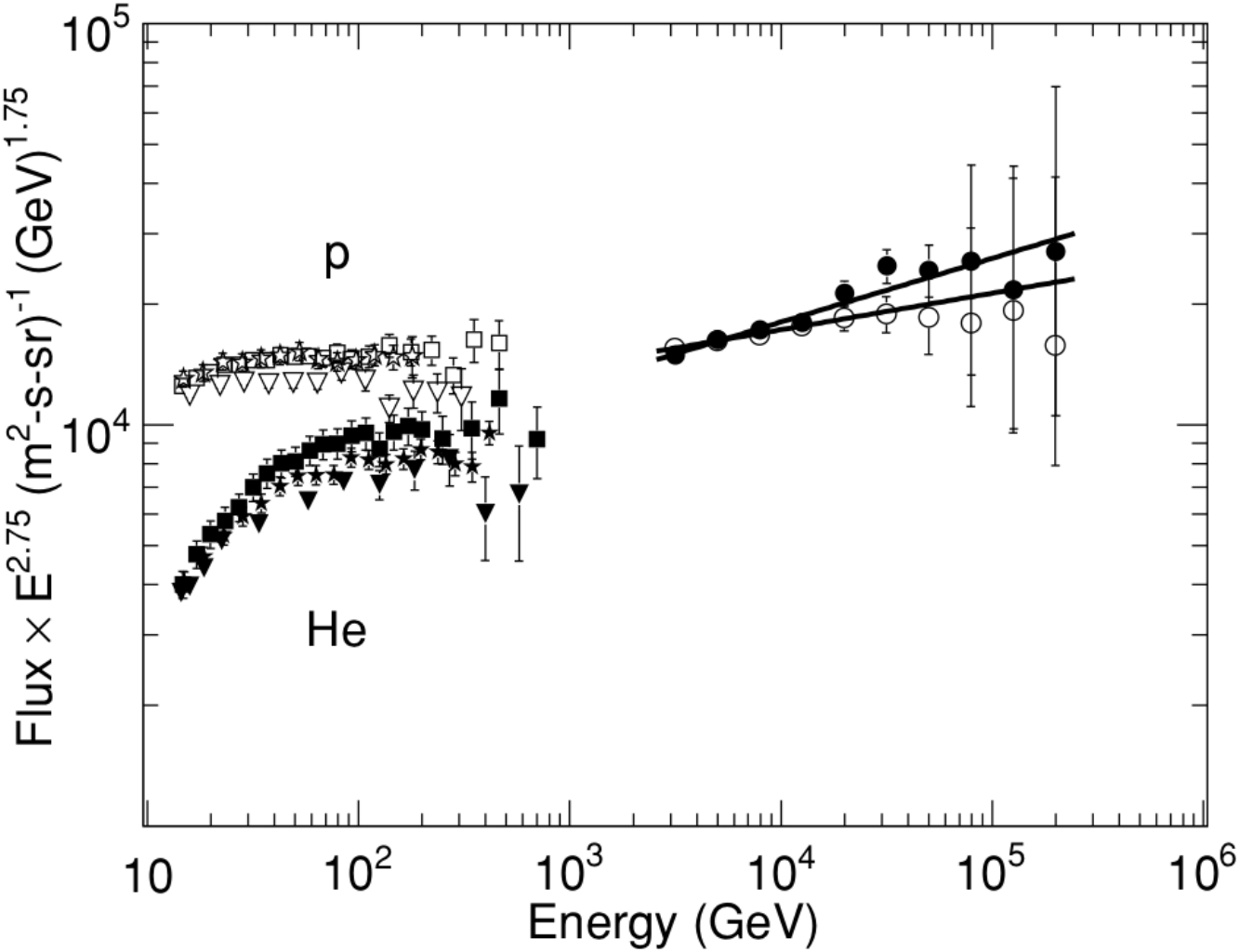
# CREAM sub-detectors




## CREAM-III/IV/V sub-detectors

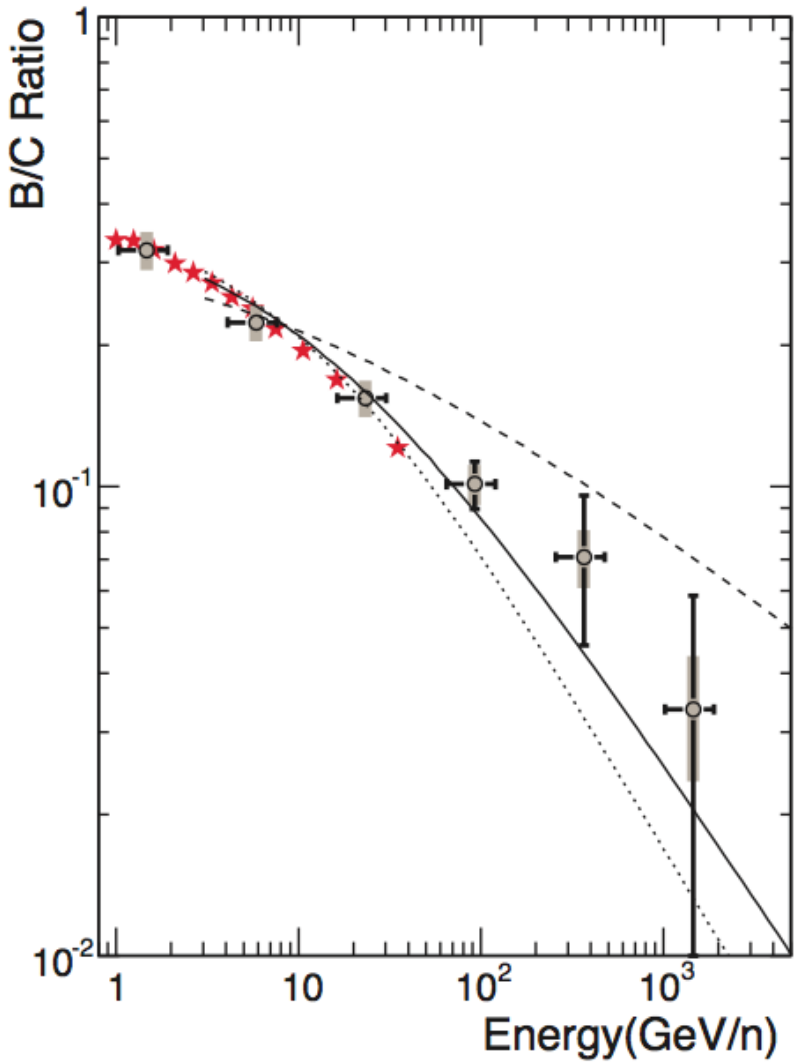
- *Timing Charge Detector* (TCD):
  Z, vetoes albedo particles
- *Cherenkov Detector* (CD):
  Z, vetoes non-relativistic particles
- *Cherenkov Camera* (CherCam):
  Z
- *Silicon Charge Detector* (SCD):
  Z
- ionisation calorimeter:
  E

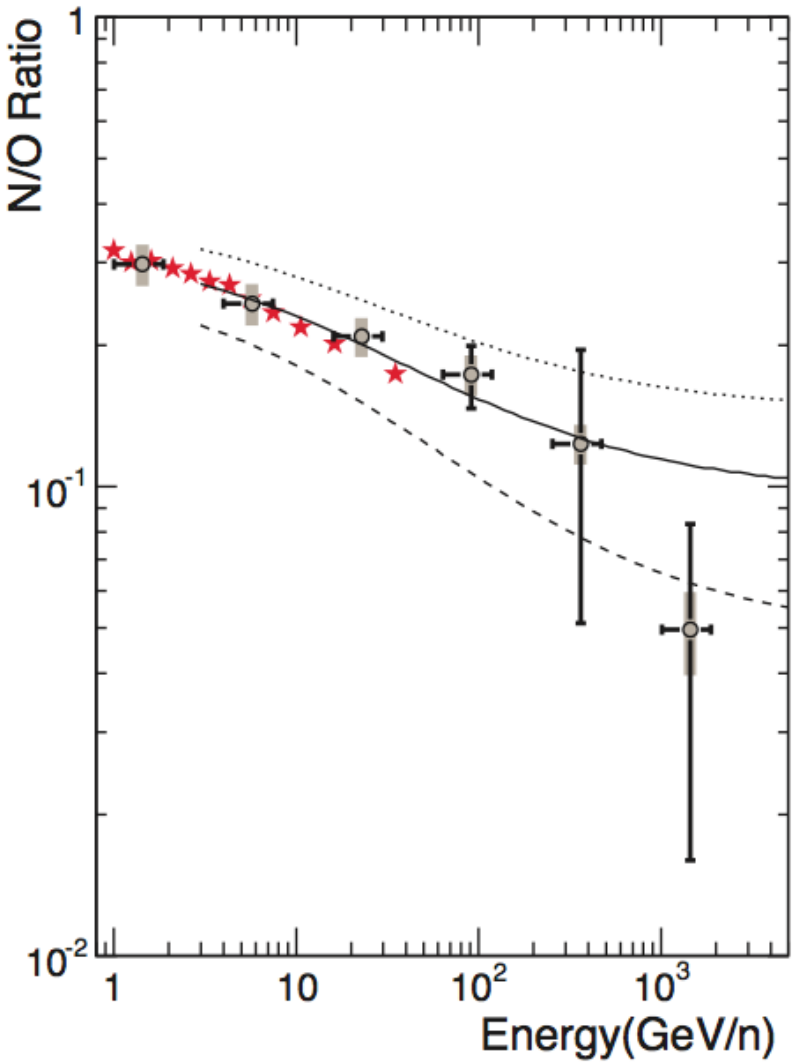
# CREAM-I proton and helium fluxes




[Ahn *et al.*, ApJ Letters **714** (2010), L89]

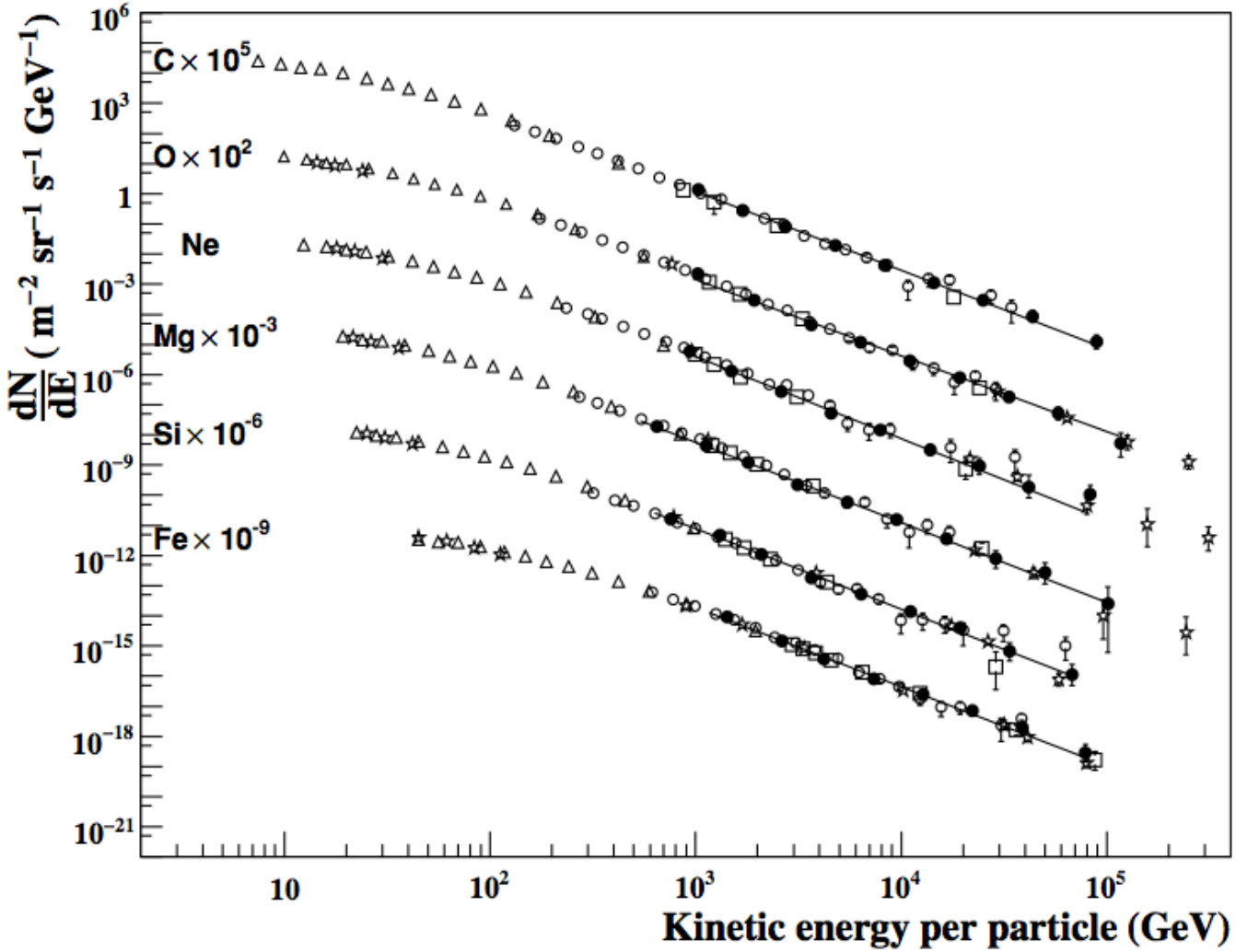
# CREAM-I B/C and N/O ratios



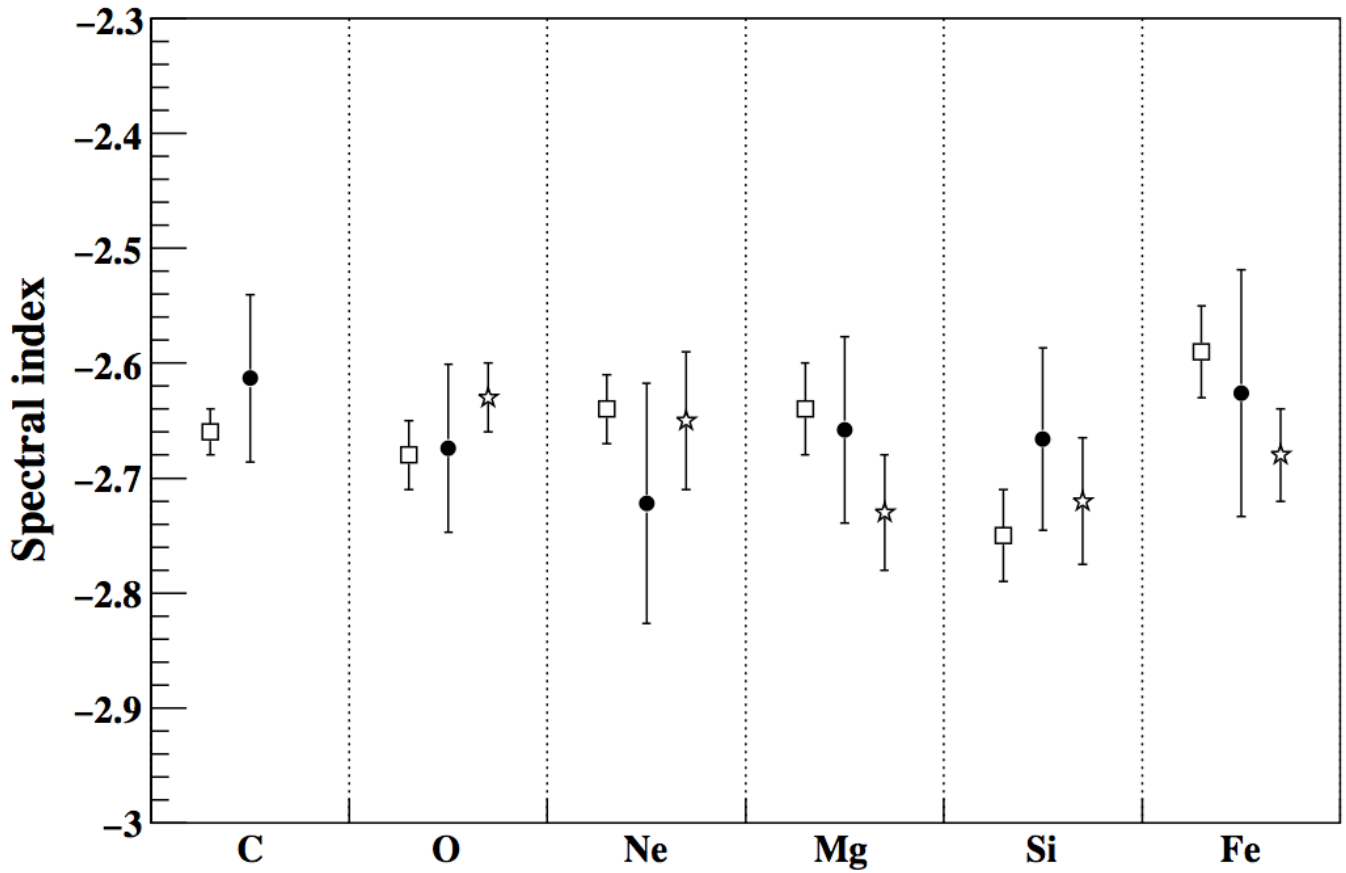

[H. S. Ahn *et al.*, Astropart. Phys. **30** (2008), 133]

# CREAM-II primary fluxes




[H. S. Ahn *et al.*, Astrophys. J. 707:593-603, 2009]

# CREAM-II spectral indices (single power-law fit)




⋆ = CRN + TRACER data, □: direct + indirect measurements, ●: CREAM-II

[H. S. Ahn *et al.*, Astrophys. J. 707:593-603, 2009]

Very similar spectral indices! Average spectral index $\bar{\gamma} = 2.66 \pm 0.04$

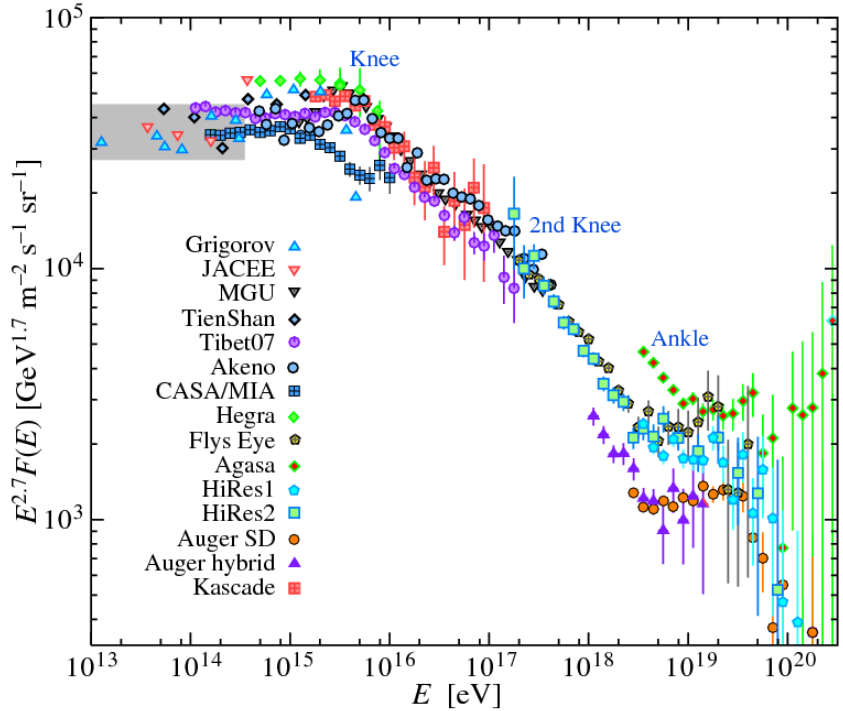
# Link between direct and indirect detection

## Indirect detection

- detection of secondary particles (air showers);
- estimation of primary particle properties based on hadronic model.

## Direct detection can

- measure precisely the elemental fluxes at energies up to the knee;
- calibrate indirect experiments.




[PDG 2009]

# Conclusion

## Direct cosmic-ray detection with space- and balloon-borne experiments

- small background due to secondary particles;
- identification of particle properties (mass, energy, charge);
- large acceptance and long exposure time, but limited through weight and cost;
- addresses a great number of cosmic-ray physics.

## Detectors

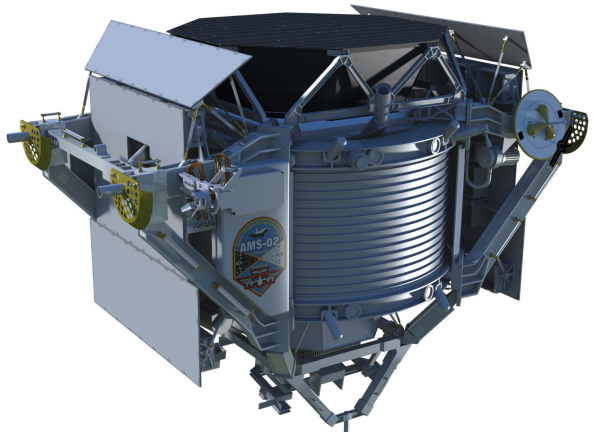
- complex and diverse;
- precision measurements of spectra and abundances on-going;
- extending measurements until energies of indirect detection experiments.

Exciting times! New results coming in the next months...

# Outlook - AMS02

## Modified AMS01 spectrometer

- TRD added;
- Cherenkov counter replaced by Cherenkov imager;
- electromagnetic calorimeter added;
- 3 additional silicon tracker layers.



[AMS homepage]