Cosmic Ray Astrophysics with AMS-02: Expected Performances

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CIEMAT

Astroparticle Seminar

Dip. di Fisica – Università di Bologna

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Outline

- Introduction to Galactic Cosmic Rays
- GCR Detection: Present Results
- AMS-02 Spectrometer
- AMS-02 Expected Performances
- Summary

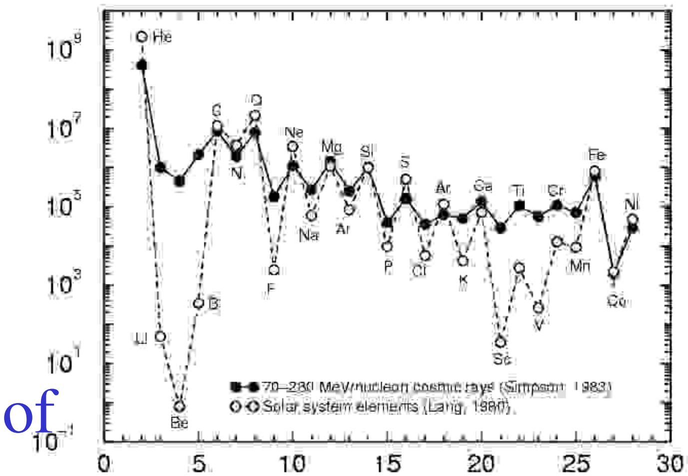
Introduction

- Since their detection in 1912, Cosmic Rays have been a powerful tool for discovery
- From their study μ, e^+, π, K… were first detected
- Nowadays we look back into space to search for faint signals of new physics not yet found in our labs
- The understanding of the mechanisms governing the production and propagation of cosmic rays is needed to disentangle the possible backgrounds

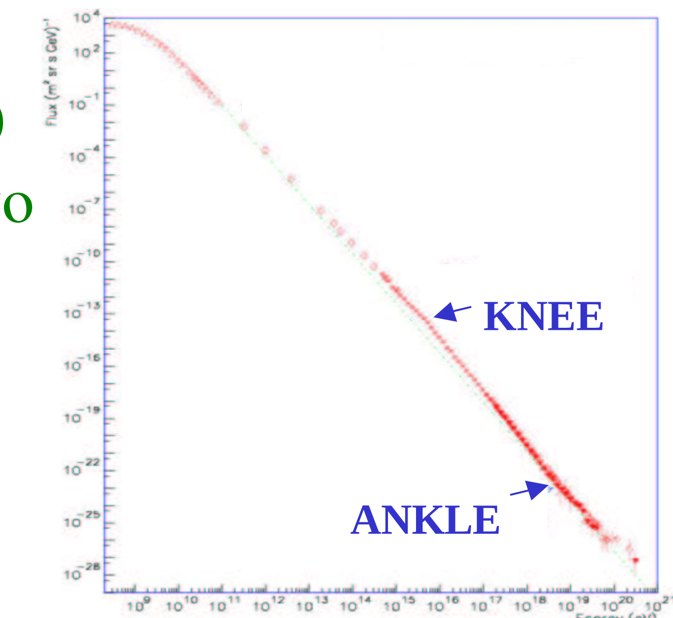
Introduction

- Isotropic & constant for all species
- Composition: 99% hadrons, 1% $e^{\pm}$
- Hadrons: 87% p, 12% He, 1% Z>2
- Similar composition as Solar System

  ⇒ Stellar origin
- Secondary species arise from interactions of the stellar synthesized nuclei with the interstellar medium



- Overwhelming energy range (10^8-10^{20} eV)
- Smooth power spectrum in energy with two breaks (Knee ~ 10^{15} eV & Ankle ~10^{19} eV).
- Fermi acceleration at shocks driven by SN blast waves efficient up to the knee region
- GCR ⇒ EGCR for E > 10^{18} eV



GCR: Propagation Models

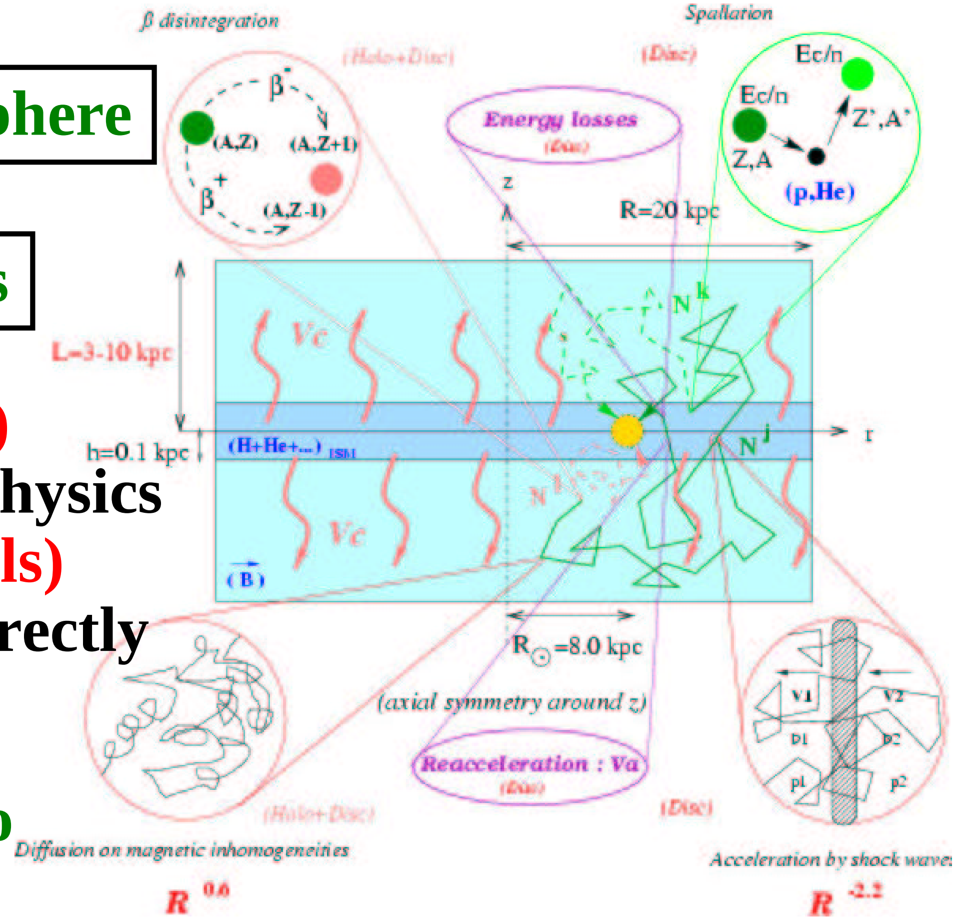
AIM: achieve a reliable physical description of the CR propagation through the Galaxy

Observed CR fluxes in the heliosphere

⇓

Sources, Galactic Parameters

Though simple models (leaky box) account for many observations, physics motivated models (diffusion models) make use of physical quantities directly linked to galactic parameters

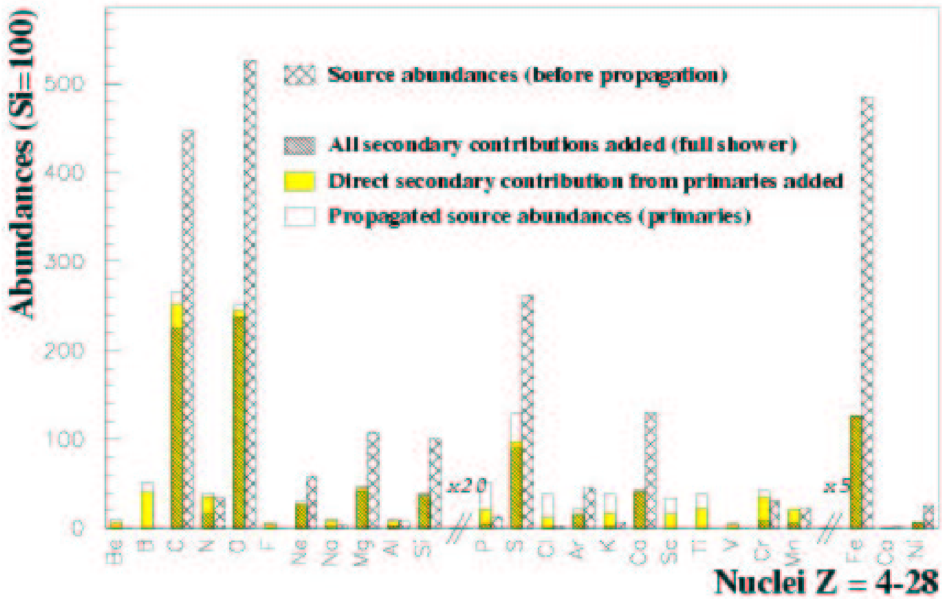


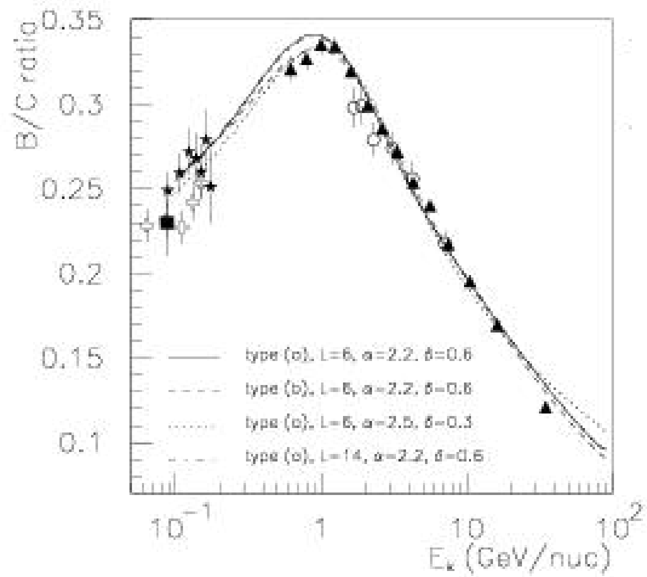
Galaxy: thin disk & diffusive halo

Sources: composition & spectra

Processes: E loss, fragmentation, decay, convection & reacceleration

Propagation Models: Parameter Fit



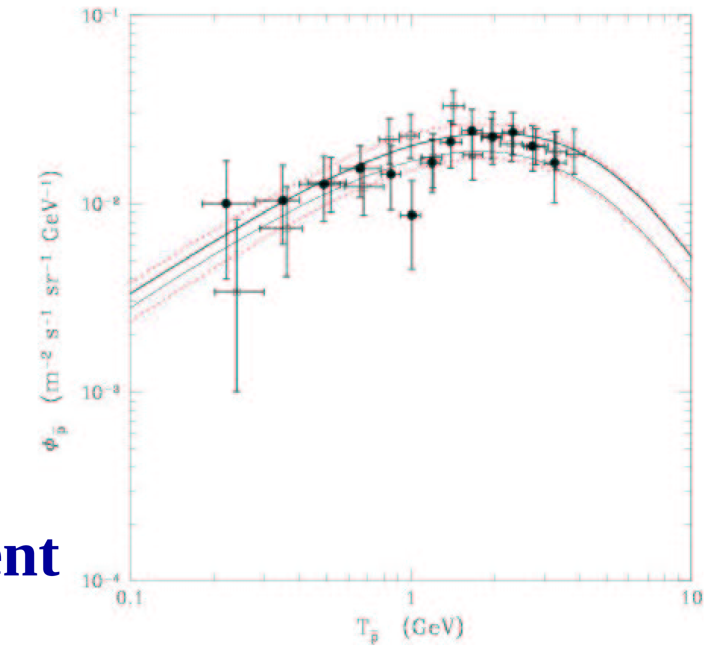


Free parameters in the model are adjusted to reproduce measured "reference" distributions.

1. **Measured abundances at the heliosphere at a given Energy**
2. **Secondary over primary (B/C) ratio as a function of Energy**

The model prediction on other distributions for the sets in the acceptable parameter space region are compared to measurements

Propagation Models: results & needs

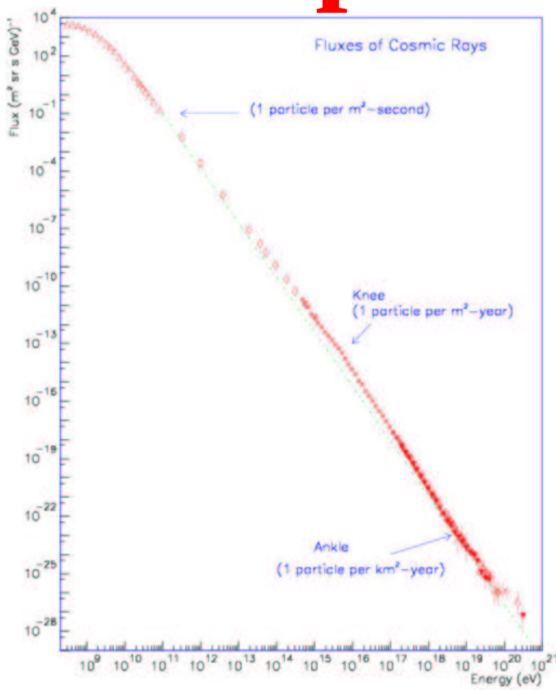


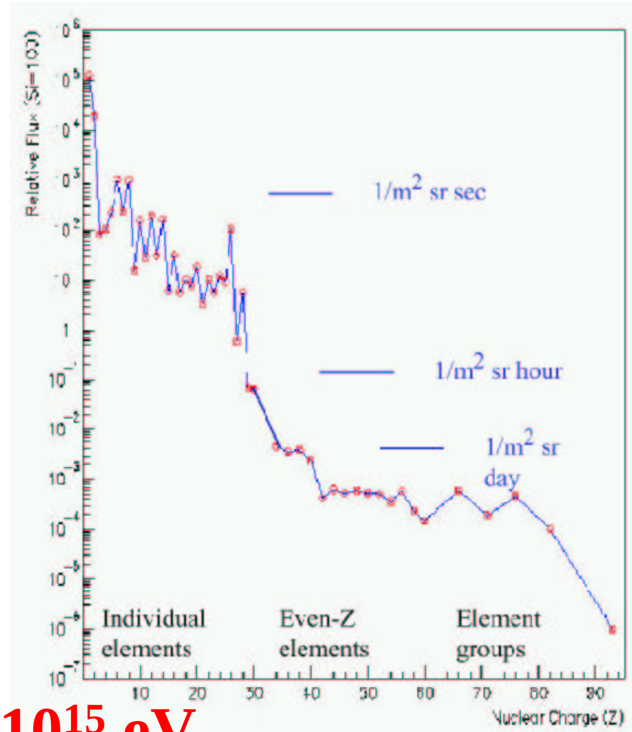
Most of the observations are successfully reproduced, in particular, the antiproton flux (computed as pure secondary from CR interaction with the ISM) nicely agrees with the present measurements.

There is still a lot of room for improvement both on the

- **Theoretical side : no consensus on the diffusion parameters**
- **Experimental side:**
  - **Nuclear cross-sections (currently known to a 10%)**
  - **Precise measurement of GCR's elemental and isotopic composition and energy spectra**

Experimental Status





- **Direct detection for E < 10^{15} eV**
- **Individual charge measurement for Z < 60**
  Only Even-Z elements for 30 < Z < 60
- **Strategies to overcome the low expected flux**
  1. **Large Acceptance (Balloons)**
  2. **Long Duration (Space)**

Balloons vs Space

	BALLOONS	SPACE-BORNE
Geometrical Acceptance	✓ (green)	✓ (red)
Flight duration	✓ (red)	✓ (green)
Redundancy	✓ (green)	✓ (red)
Atmospheric Corrections	✓ (red)	✓ (green)
Detector Accessibility	✓ (green)	✓ (red)
Flight Control	✓ (red)	✓ (green)
Price	✓ (green)	✓ (red)

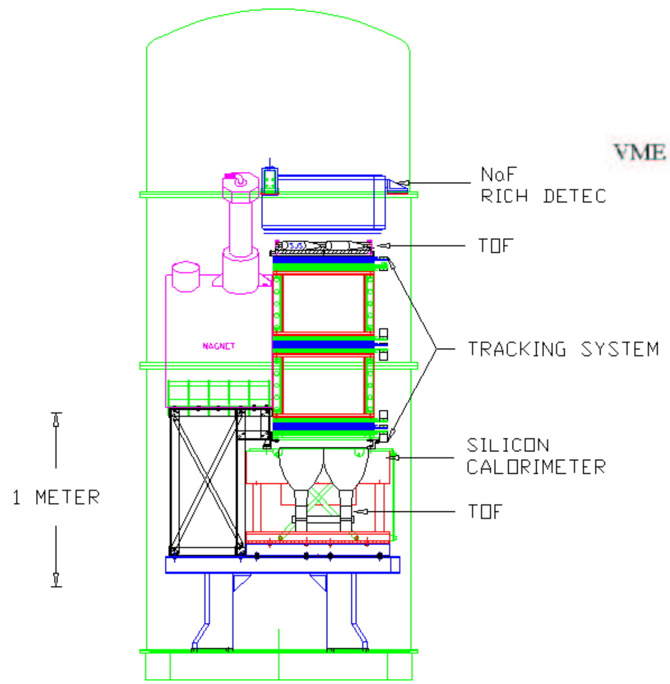
- **“NEW” Experiments:**

Large Acceptance & Long Duration

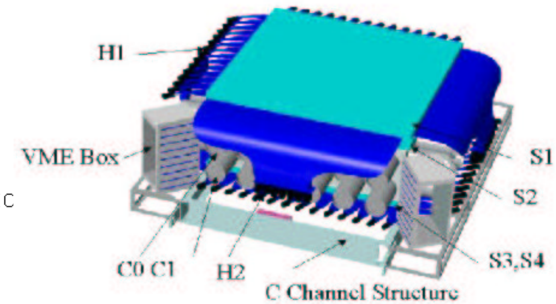
Balloons

- **Magnetic Spectrometers (R, β, Z)**
- **Charge Identifiers (Z, β)**
- **Calorimeters (Z, E)**
- **Emulsion Chambers (Z, E)**

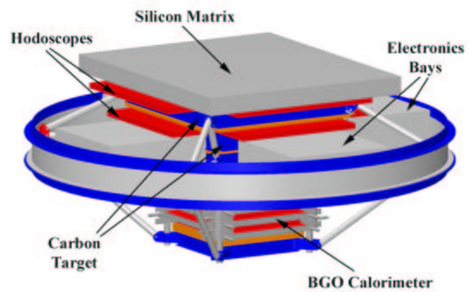
CAPRICE



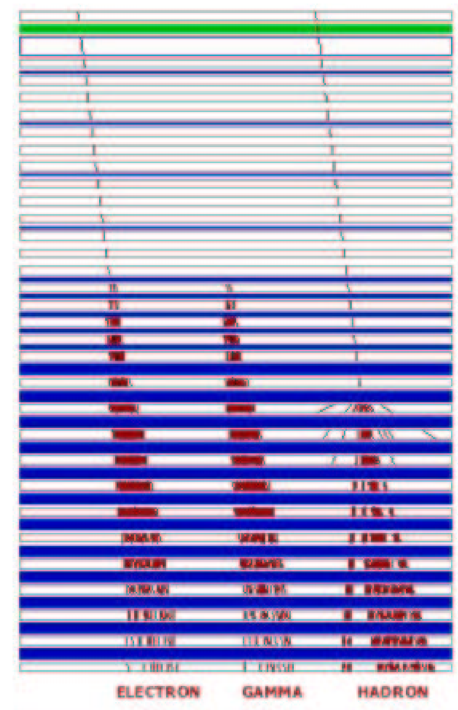
TIGER



ATIC



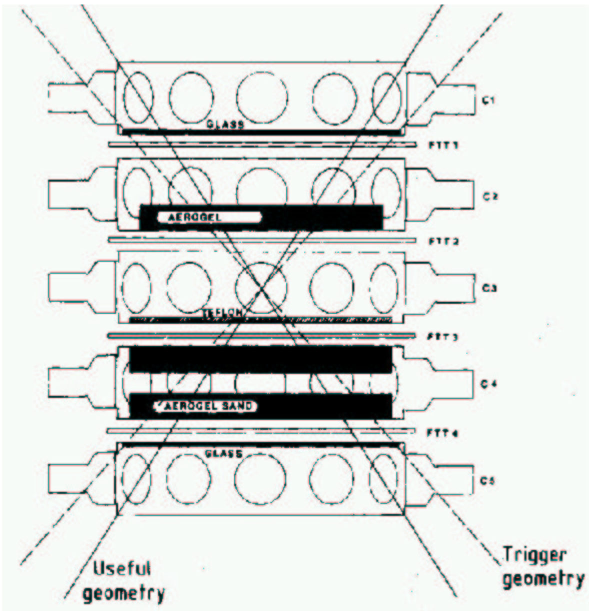
JACEE



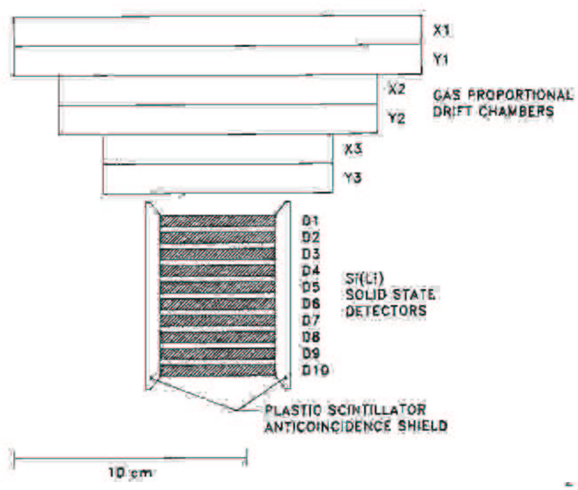
Space-Borne

- Double Cerenkov (Z, β)
- Spectrometers dE/dx ⊕ Total E (Z^2M)
- Magnetic Spectrometers (R, β, Z)

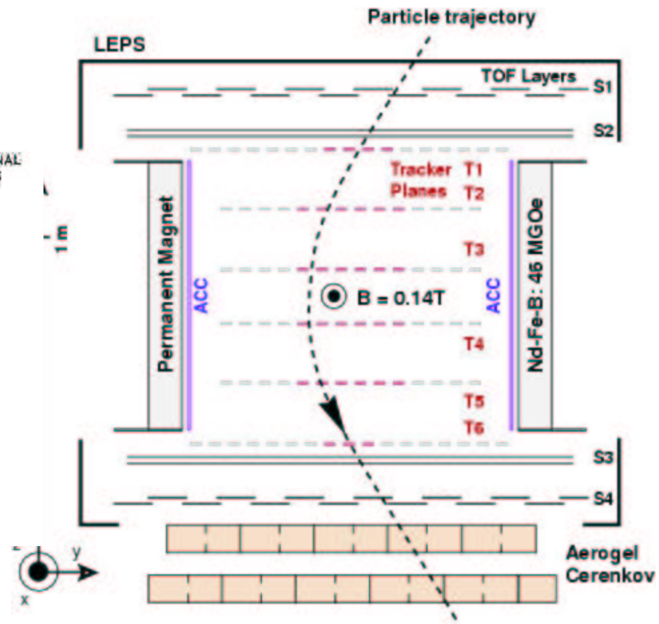
HEAO-3



ISEE-3



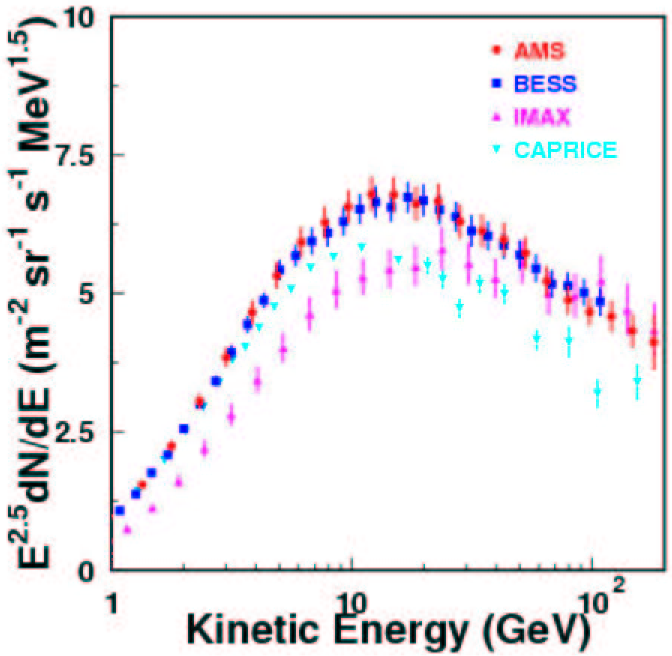
AMS-01



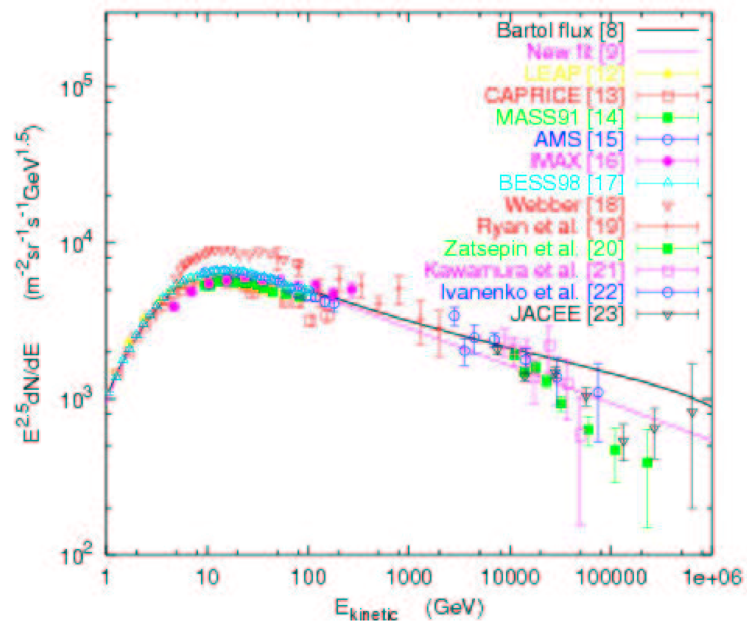
Hydrogen

• 0.1 GeV < E < 100 GeV	Spectrometers	5%
• 100 GeV < E < 1 TeV	Calorimeters	25%
• 1 TeV < E < 1000 TeV	Emulsion Chambers	25%

1 GeV < E < 100 GeV



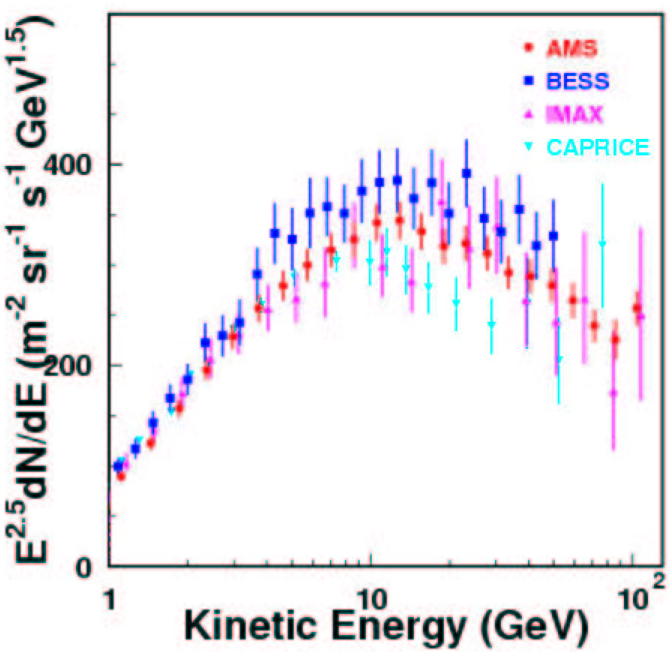
1 GeV < E < 1000 TeV



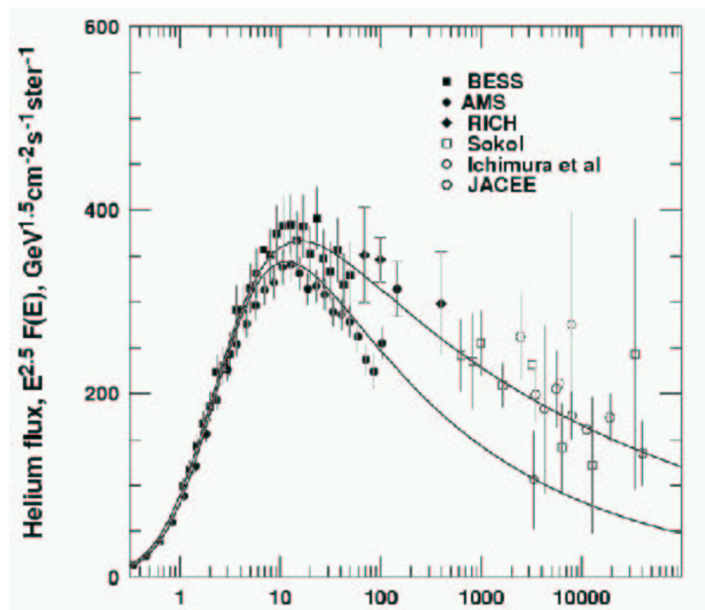
Helium

- 0.1 GeV/n < E < 100 GeV/n   Spectrometers   10%
- E > 100 GeV/n   Emulsion Chambers   Poor statistics

E < 100 GeV/n



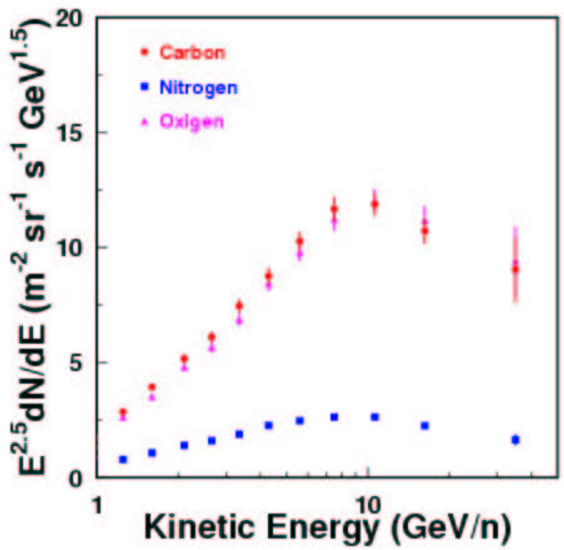
E < 100 TeV/n



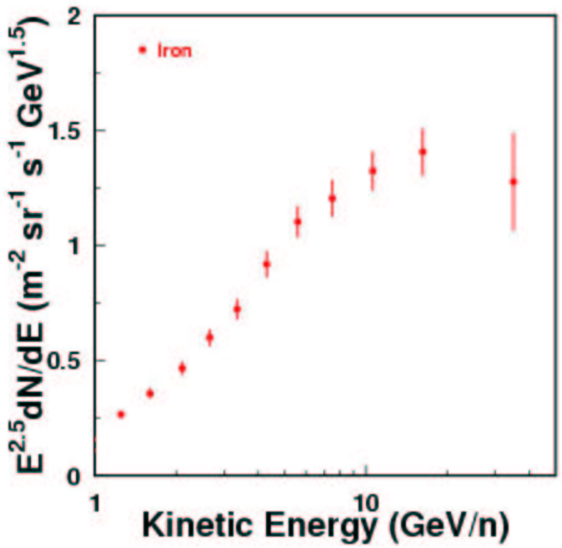
Z > 2

- Most precise measurements from HEAO-3 C2 instrument
- Operated for 8 months in 1979 – 1980
- 7 million events with $4 \leq Z \leq 28$
- Charge resolution 0.12 – 0.2 units
- Absolute fluxes from 0.6 to 35 GeV/n
- Systematic Errors ~ 5%

C N O



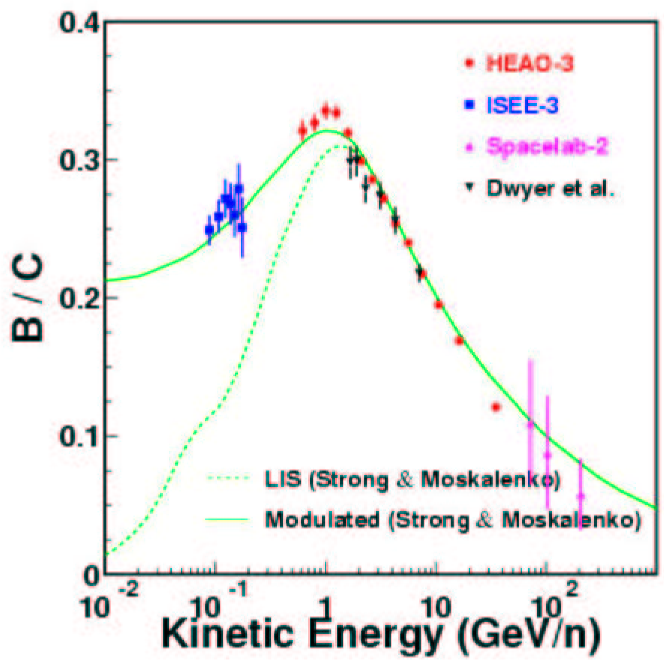
Fe



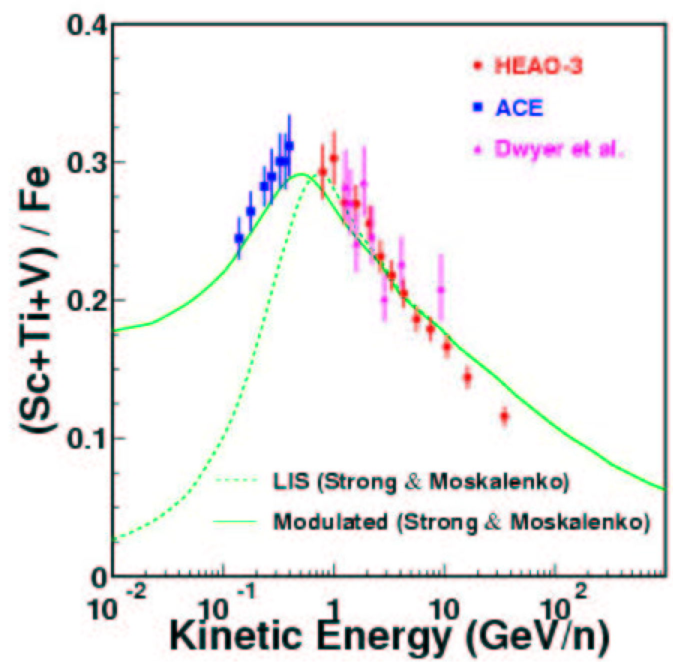
Secondary CR

- **B/C and sub(Fe)/Fe measured for 0.1 GeV/n < E < 35 GeV/n**
- **Precision of ~ 5% for B/C and 10% for sub(Fe)/Fe**
- **Data consistent with ~ 5 g cm^{-2} crossed by primary CR**

B/C



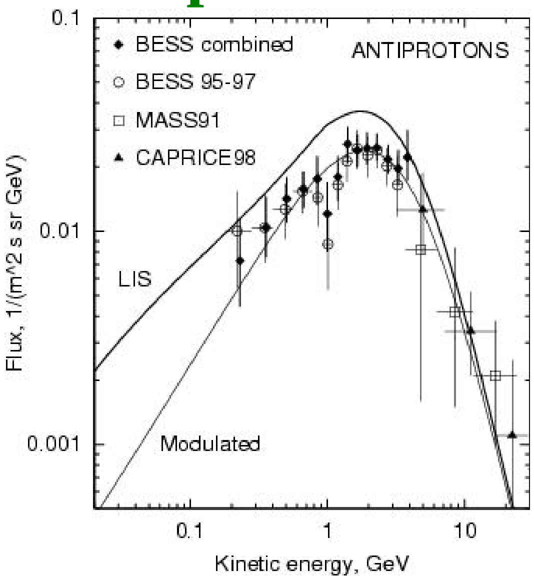
(Sc+Ti+V)/Fe



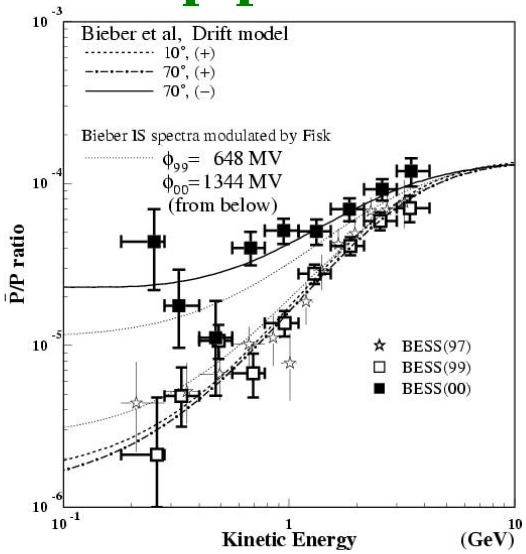
Antiprotons

- **Main hadronic antimatter expected in CR**
- **Deviations from secondary spectrum ⇒ new physics**
- **World statistics ≈2000**
- **Energy range 0.2 GeV < E < 50 GeV**

$\bar{p}$ flux



$\bar{p}$/p ratio

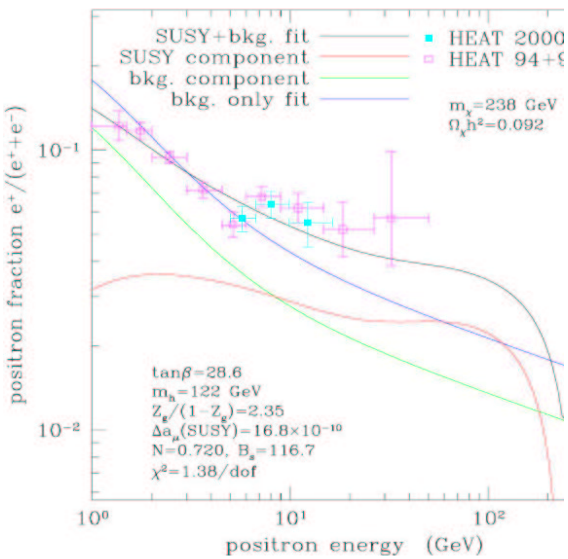


⇒ Data consistent with secondary production

Electrons & Positrons

- Small (~1%) but important component in CR's
- e^- (~ 90%) directly injected at sources
- e^+ produced by CR interactions with ISM ($\pi \to \mu \to e$)
- Deviations from secondary spectrum ⇒ new physics
- e^- measured for E < 1 TeV
- e^+ measured for E < 50 GeV
- Measurements differ by a 50% even for E < 50 GeV
- Some systematics cancel in the $e^+/(e^+ + e^-)$ ratio…

$e^+/(e^+ + e^-)$



⇒ Data inconclusive

Light Isotopes (1/2)

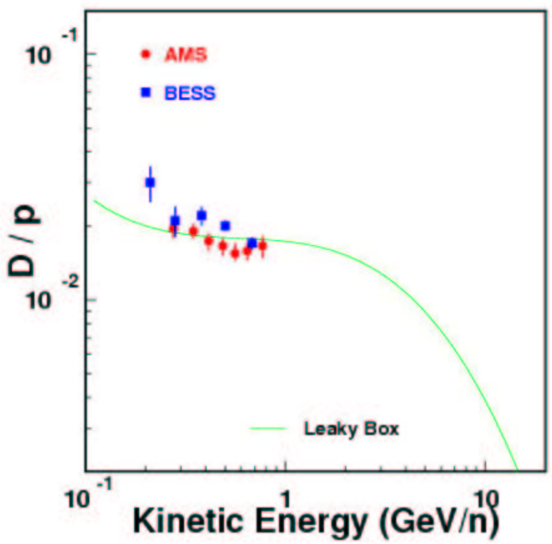
- Magnetic spectrometer measurements in the energy range

  D/p: 0.2 GeV/n < E < 0.8 GeV/n

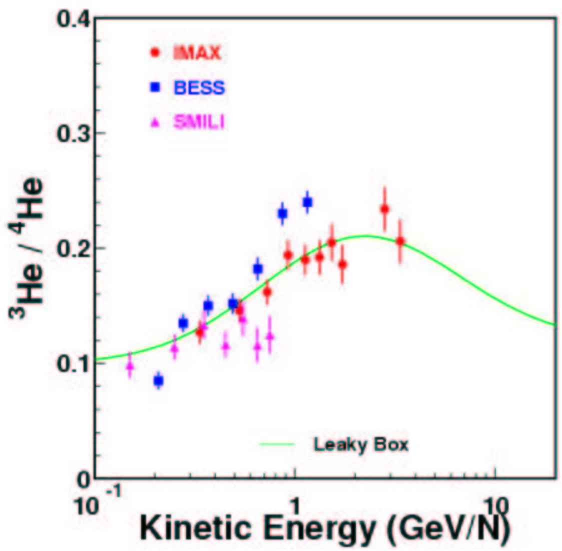
  $^3He/^4He$: 0.1 GeV/n < E < 3.4 GeV/n

- Statistical errors ≥ 5 – 10%
- Sensitive to propagation history of p and ^4He

D/p



$^3He/^4He$



Light Isotopes (2/2)

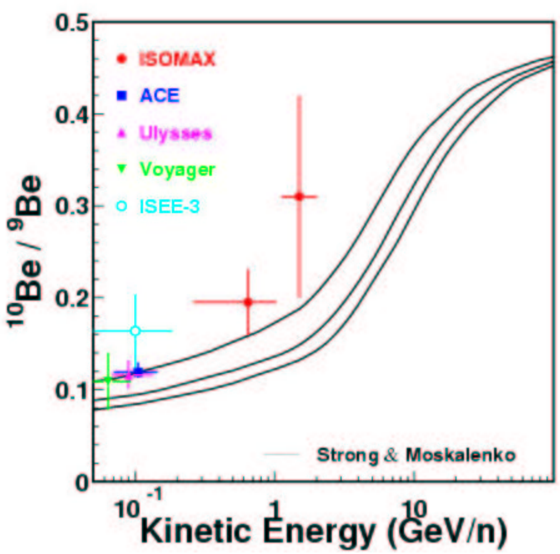
- **Radioactive nuclei** ≡ *Cosmic Ray Chronometers*

  ^{10}Be $t_{1/2} = 1.51$ Myr

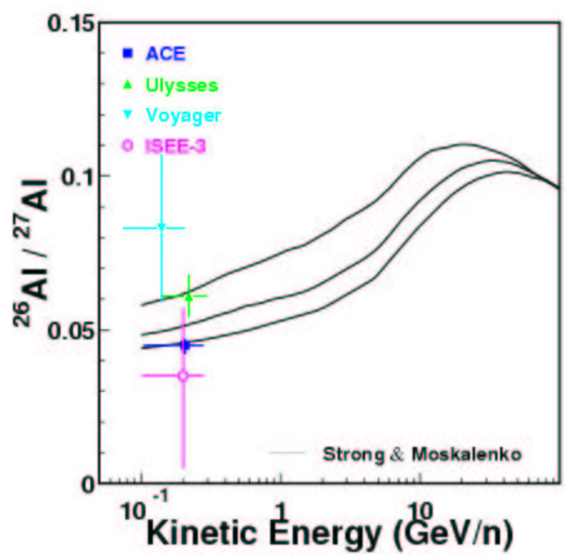
  ^{26}Al $t_{1/2} = 4.08$ Myr

- **Measurements in space** $E \approx 100$ MeV/n
- **Balloon measurement** 0.3 GeV/n $< E < 2$ GeV/n

$^{10}Be/^{9}Be$



$^{26}Al/^{27}Al$



Experimental Status: Summary

- **CR spectra are determined with precision in the range**

  $E < 100$ GeV/n & $Z < 30$

- **CR abundances are accurately measured for**

  $Z < 30$ and Even-Z for $30 < Z < 60$

- **Light Isotope Spectra are measured for**

  $E < 1$ GeV/n

⇒ In order to overcome current limitations

Long Duration & Large Acceptance & Precise Experiments

Future Experiments

BALLOONS

- **Long Duration Flights (LDB)**

  ATIC (2000, 2002)

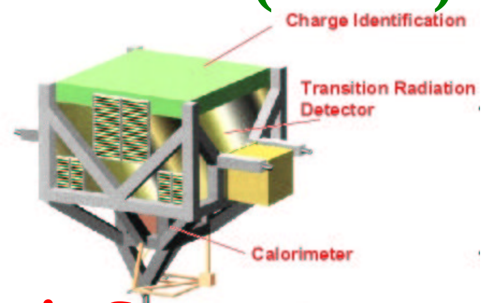
- **Ultra Long Duration (ULDB)**

  CREAM (2003?)

SPACE-BORNE

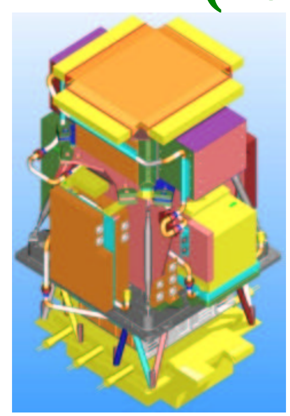
- **Calorimeter**

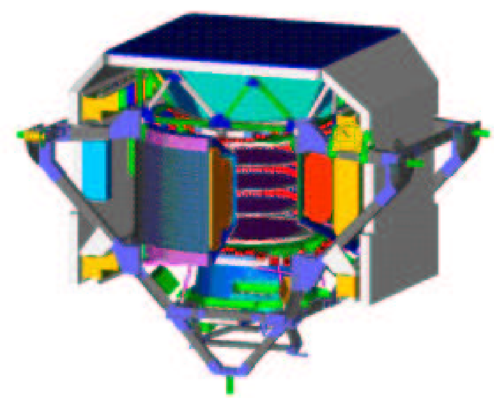
  ACCESS (2007?)



- **Magnetic Spectrometers**

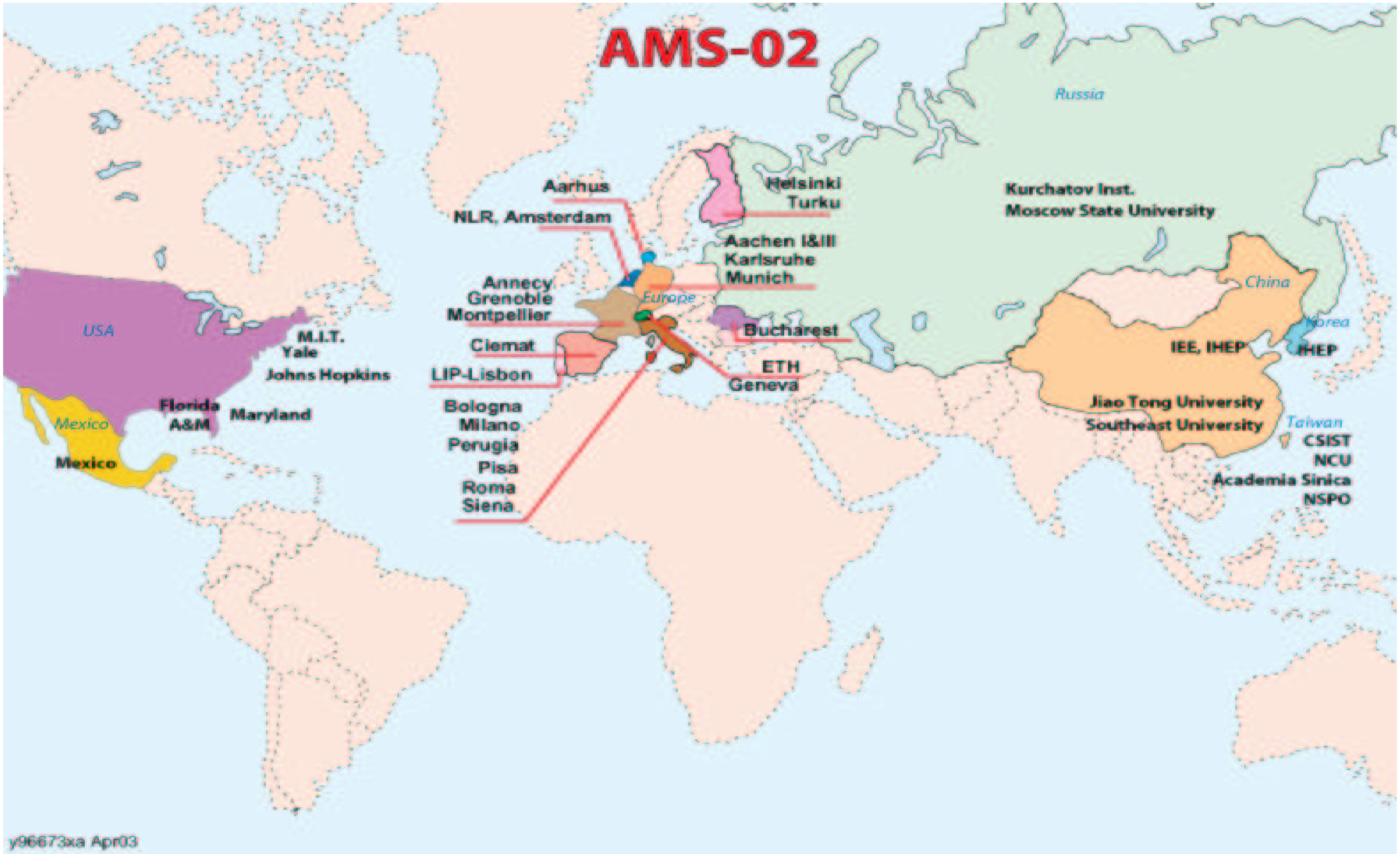
PAMELA (2003) AMS-02(2005)





AMS Experiment

- **AMS is a fundamental physics experiment in space**
- **The AMS experiment is mostly built in Europe**
- **The use of the Space Shuttle and the Space Station is based on a NASA – US DOE MOU (1995)**
- **The AMS collaboration has the responsibility for assessing the experiment's quality and merit and for the construction of AMS**
- **NASA is not involved in the construction of AMS**


AMS-02
Russia
Helsinki
Turku
Kurchatov Inst.
Moscow State University
Aarhus
NLR, Amsterdam
Aachen I&III
Karlsruhe
Munich
Annecy
Grenoble
Montpellier
Europe
China
Korea
USA
M.I.T.
Yale
Johns Hopkins
Ciemat
LIP-Lisbon
Bucharest
IEE, IHEP
IHEP
ETH
Geneva
Bologna
Milano
Perugia
Pisa
Roma
Siena
Florida
A&M
Maryland
Mexico
Mexico
Jiao Tong University
Southeast University
Taiwan
CSIST
NCU
Academia Sinica
NSPO
y96673xa Apr03

International Collaboration

~200 scientists

U. of Aarhus (DK); Academia Sinica (Taiwan); U. of Bucharest (RO); Chinese Academy of Sciences, Inst. of High Energy Physics IHEP (Beijing); Chinese Academy of Sciences, Inst. of Electrical Engineering IEE (Beijing); Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT (Madrid, ES); Chung Shan Inst. of Science and Technology CSIST (Taiwan); EHWA Women's University (Seoul, KR) ETH Zurich (CH); Florida A&M U. (Tallahassee, FL); U. of Geneva (CH); Helsinki U. of Technology (FI); INFN Bologna & U. Bologna (IT); INFN Milano (IT); INFN Perugia, (IT); & U. Perugia (IT); INFN Pisa & U. Pisa (IT); INFN Roma & U. Roma (IT); INFN Siena & U Siena (IT); Inst. Superior Technico (Lisbon, PT); Inst. di Ricerca sulle Onde Elettromagnetiche IROE (Florence, IT); Inst. des Sciences Nucleaires de Grenoble ISN (FR); Inst. for Theoretical and Experimental Physics ITEP (Moscow, RU), Jiao Tong U. (Shanghai); Johns Hopkins U. (Baltimore, US); U. of Karlsruhe (DE); Kurchatov Institute (Moscow, RU); Kyungpook National University CHEP (Taegu, KR); Laboratoire d'Annecy-le-Vieux de Physique des Particules LAPP (FR); Laboratório de Instrumentaço e Física Experimental de Partículas LIP (Lisbon, PT); U. Maryland (College Park, US); Max Planck Inst. (Garching, DE) ; Massachusetts Inst. of Technology MIT (Cambridge, US); U. Montpellier (FR); Moscow State University (RU), Nat'l Aerospace Laboratory NRL (Amsterdam, NL); U. Nacional Autonoma de Mexico (MX); Nat'l Space Program Office (Taiwan); Nat'l Central University NCU (Taiwan); Nat'l Inst. for Nuclear Physics and High Energy Physics NIKHEF (Amsterdam, NL) I. Physikalisches Inst., RWTH Aachen (DE); III. Physikalisches Inst., RWTH Aachen (DE); Southeast U. (Nanjing); U. of Turku (FI); Yale U. (New Haven, US); Lockheed Martin, USA; Space Cryomagnetics LTD, UK; Arde, Inc., USA; CAEN Aerospace, IT; Carlo Gavazzi Space SpA, IT; ISATECH Engineering GmbH, DE; OHB GmbH, DE; Linde; NASA; ESA

AMS Physics Goals

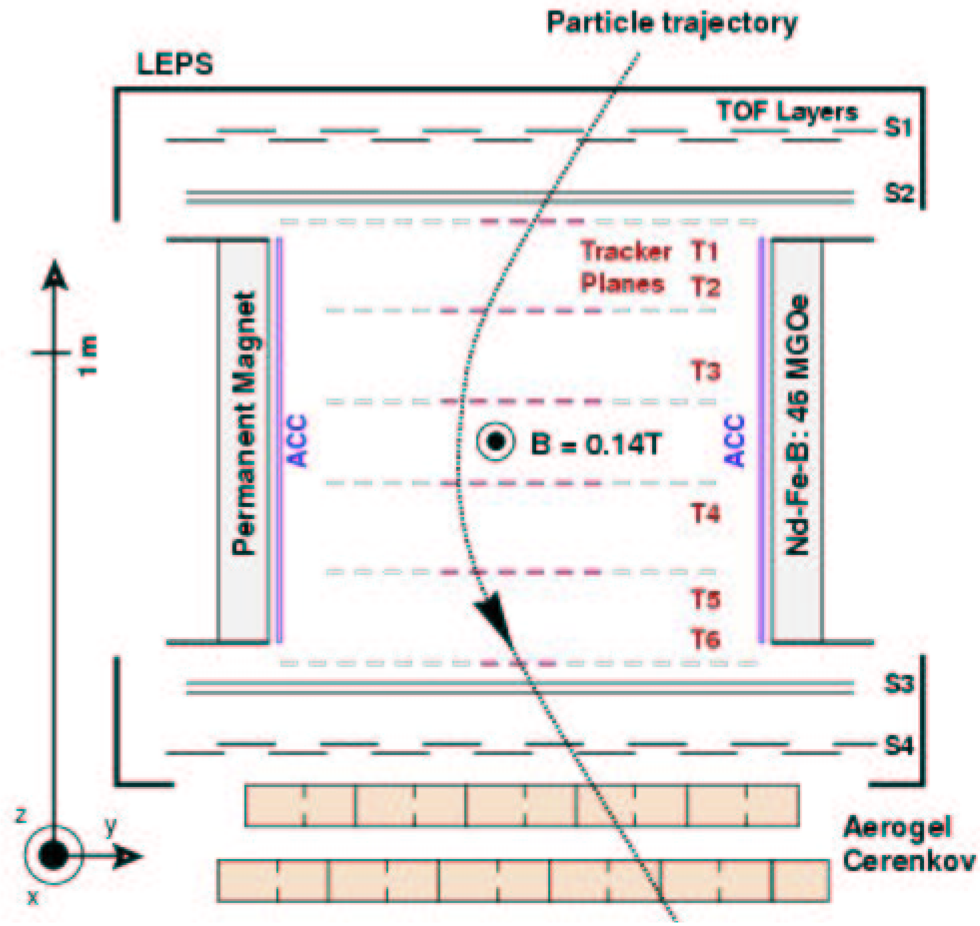
- Antimatter search ($\overline{\mathrm{He}}$,$\overline{\mathrm{C}}$) with a sensitivity 10^3 to 10^4 better than current limits.
- Dark Matter search
  - High statistics precision measurements of $e^{\pm}$, $\overline{p}$ and γ spectra
- Astrophysics studies
  - High statistics precision measurements of light isotope spectra

AMS Experimental Program

- Precursor flight aboard the Space Shuttle
  - ► Instrumental
  - ► Background Studies

- Long duration (3-year) mission at the International Space Station (ISS)

AMS-01 Spectrometer

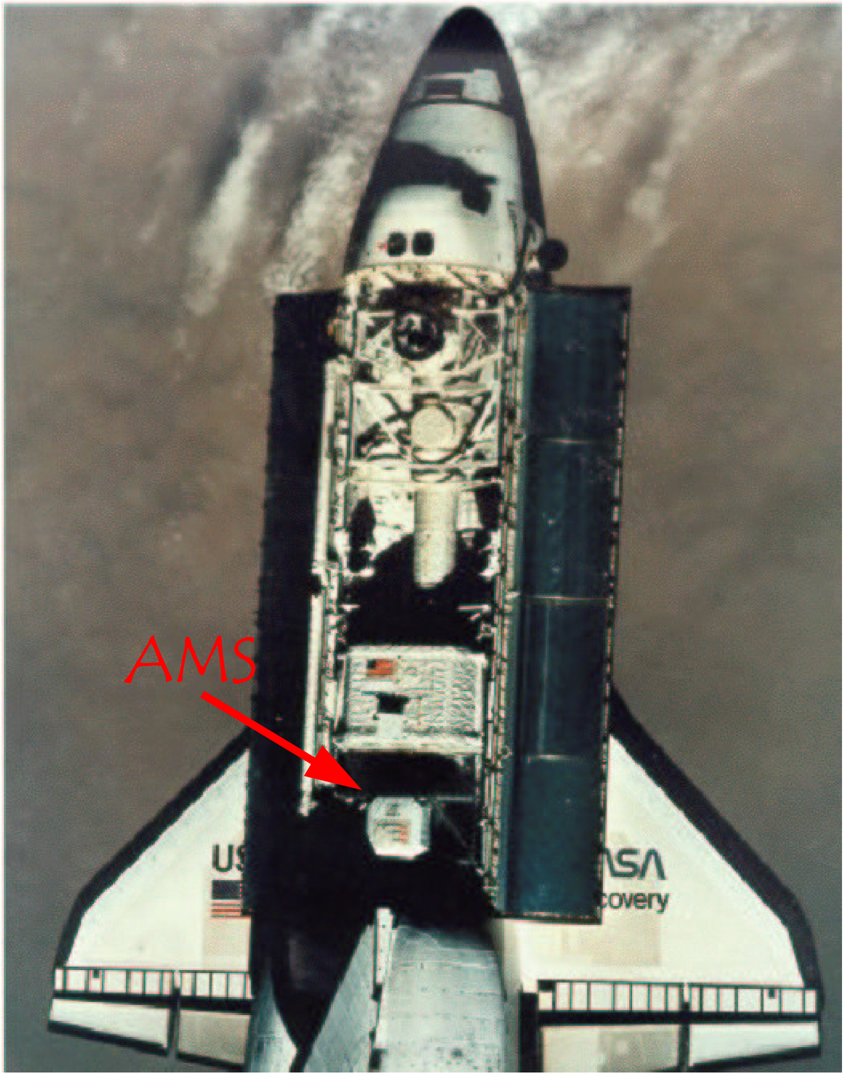


- Permanent Magnet
- Silicon Tracker
- Scintillator System
- Threshold Cerenkov

Weight	3 t
Power	1 kW

Acceptance: 0.3 m^2sr

STS-91 Flight



June 2-12, 1998

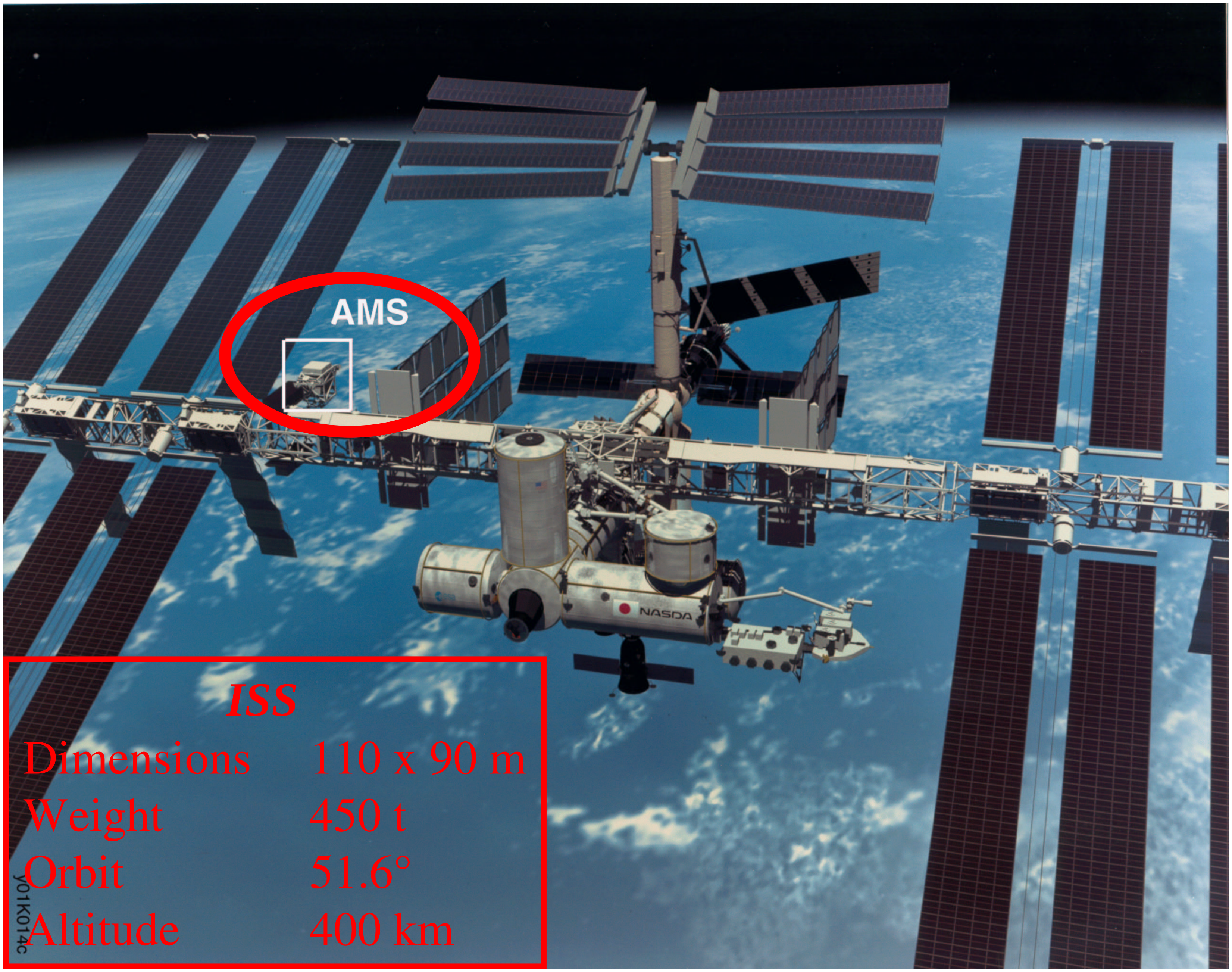
Orbital Parameters

Inclination	51.7°
Altitude	320-390 km
Period	91 min

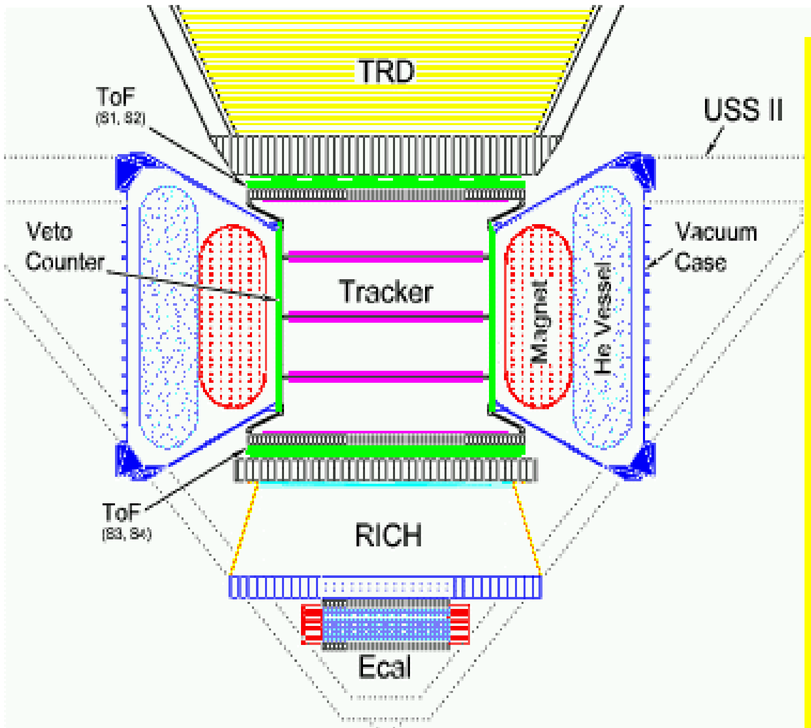
AMS

Trigger rate 100 – 700 Hz

100 Million events on tape


AMS
NASDA
ISS
Dimensions 110 x 90 m
Weight 450 t
Orbit 51.6°
Altitude 400 km
y01K014c

AMS-02 Spectrometer



- Superconducting Magnet
- Silicon Tracker
- Scintillator System
- Transition Radiation Detector
- Ring Imaging Cerenkov
- Electromagnetic Calorimeter

Weight	6.7 t
Power	2 kW

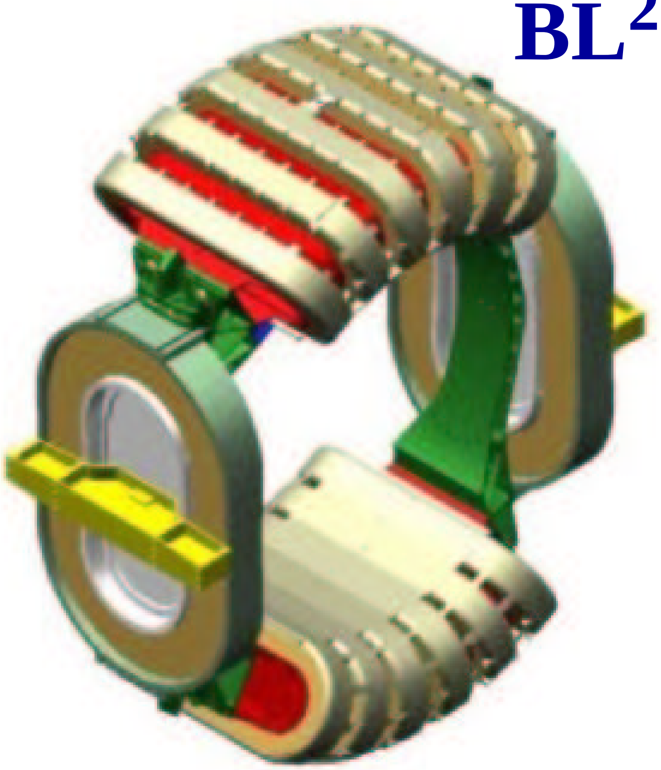
Acceptance: 0.45 m^2sr

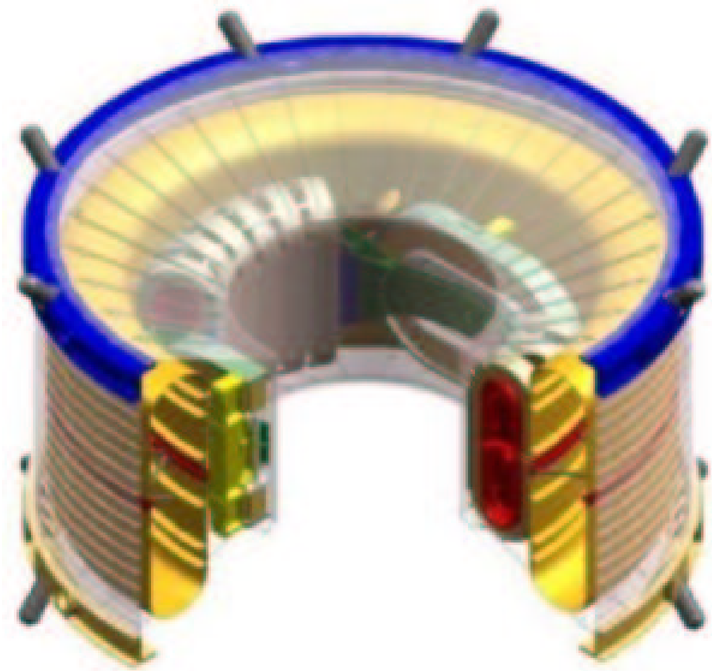
AMS-02 Superconducting Magnet

12 racetrack coils & 2 dipole coils

2500 liters of superfluid helium

$$BL^2 = 0.8\ Tm^2$$



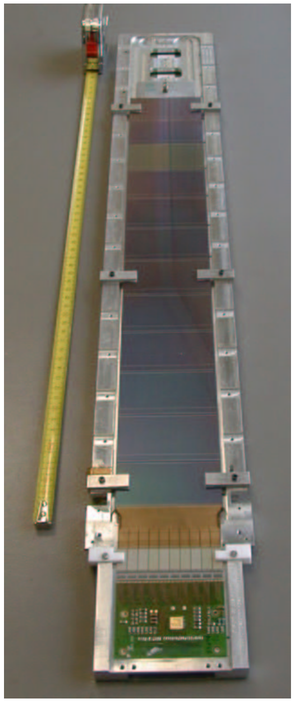


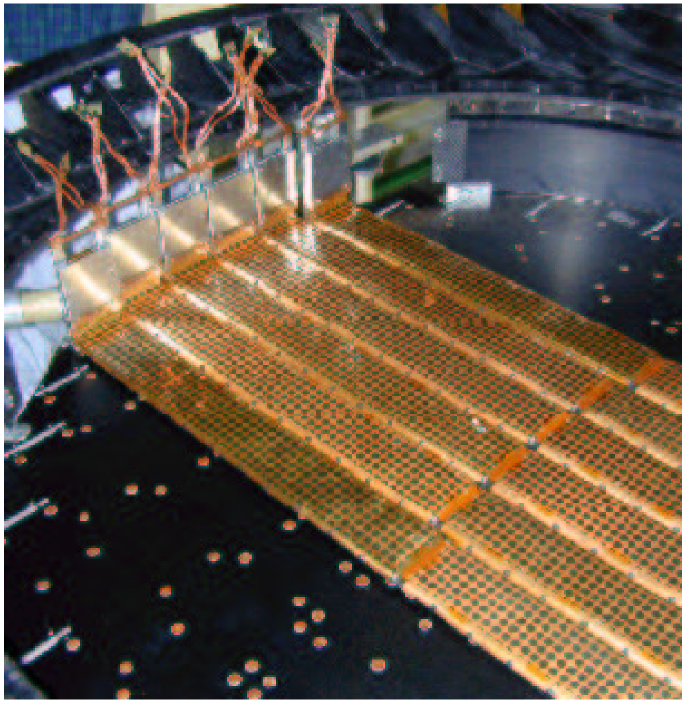
AMS-02 Silicon Tracker

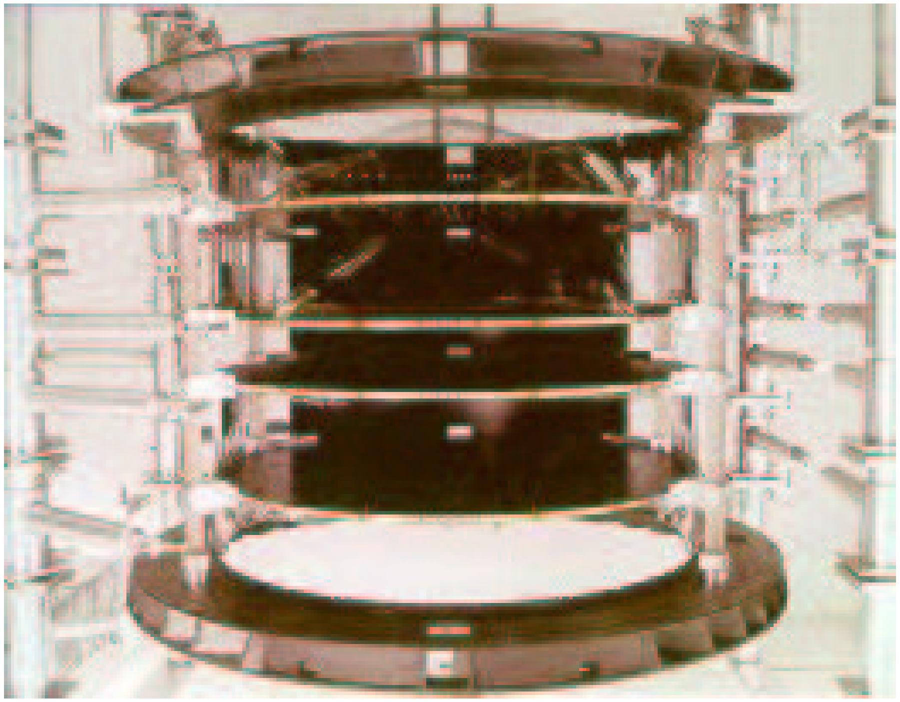
8 layers of double sided silicon sensors

$6.5m^2$ 192 Ladders (196k channels)

$\sigma(p)/p$ = 1.5% @ 10 GeV, MDR = 2 TeV (protons)





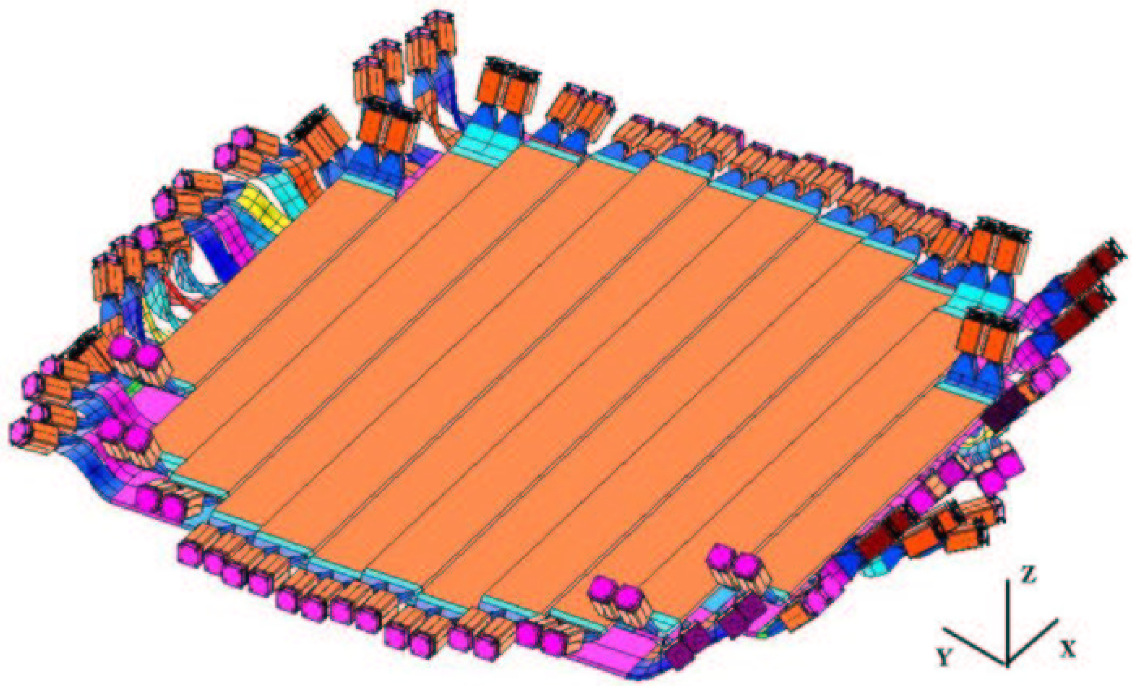


AMS-02 Time of Flight System

4 planes, 34 scintillator paddles

seen by 2 PMTs on each side

$\sigma(\beta)/\beta$ = 3.5% @ Z,β = 1 & Charge (Z<15)

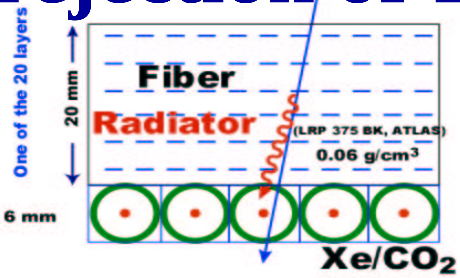


AMS-02 Transition Radiation Detector

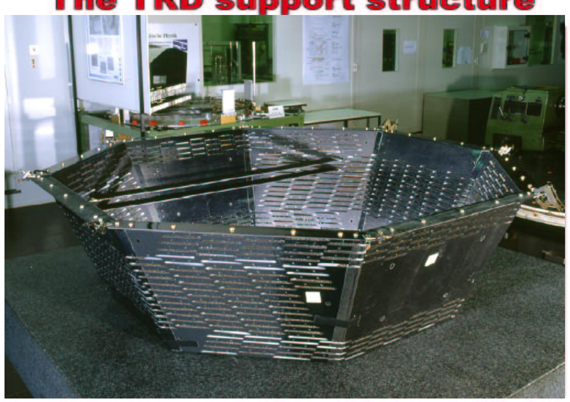
20 layers of TRD

5248 straw tubes

h/e rejection of 10^2– 10^3 in the range 1.5 – 300 GeV

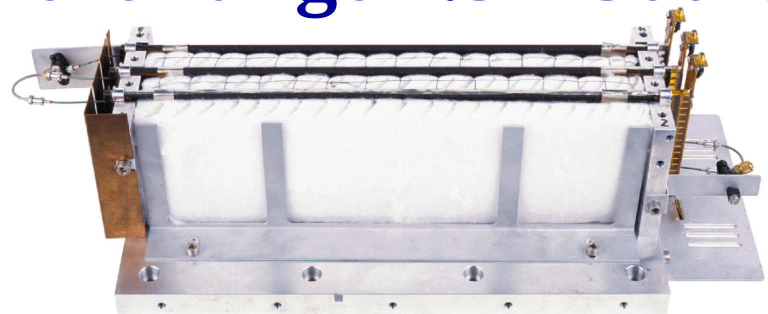


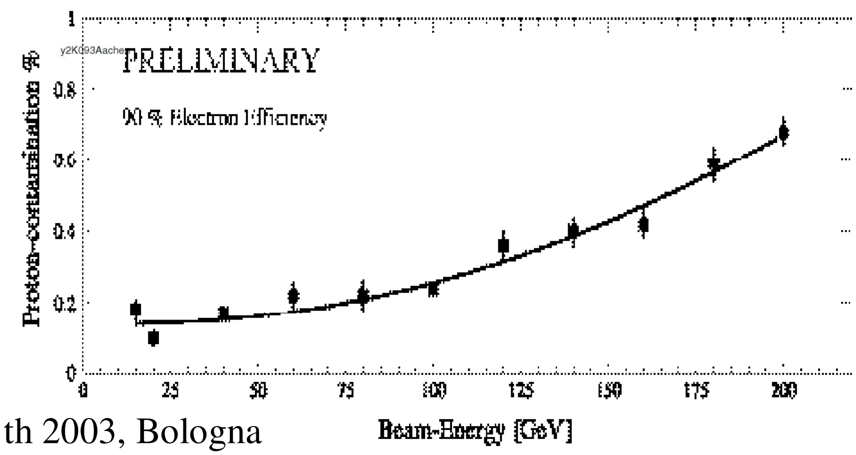
The TRD support structure



Top 4 layers (measure y coordinate), 12 layers (x), 4 layers (y)

y01K142b Figure 146



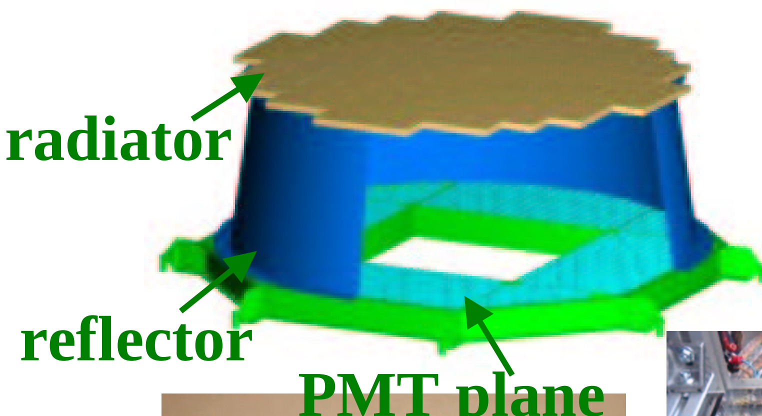


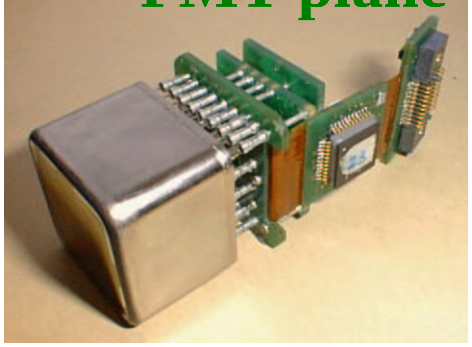
AMS-02 Ring Imaging Cerenkov Counter

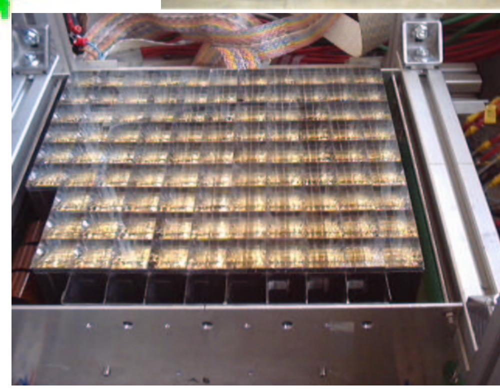
30 mm silica aerogel ⊕ 5 mm NaF radiator

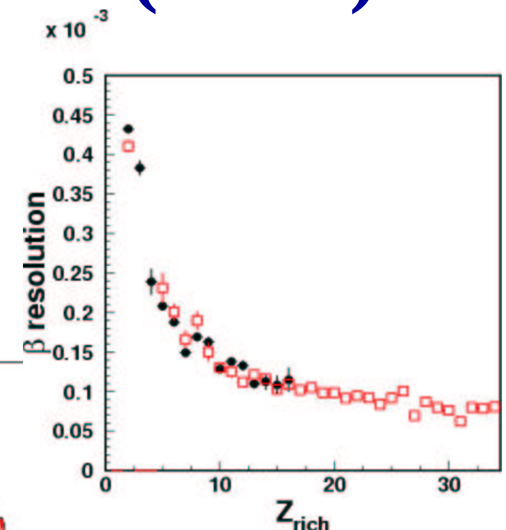
680 multianode (4x4) PMTs

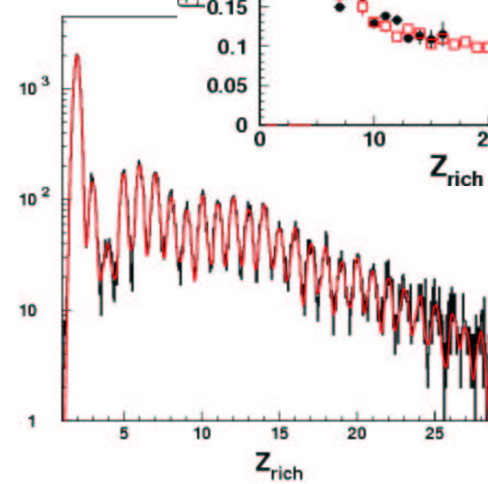
$\sigma(\beta)/\beta$ = 0.1% (Z=1) & Z_{CONF}<10% (Z<26)











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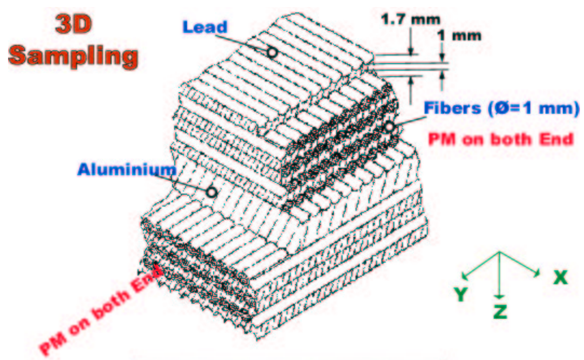
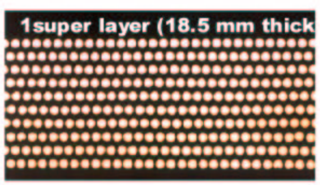
AMS-02 Electromagnetic Calorimeter

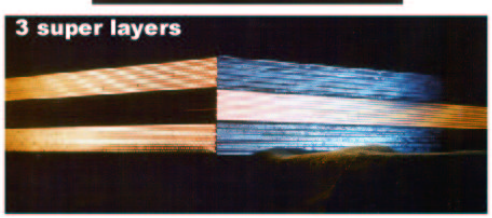
9 super layers of Sci-Fiber/Lead (16.4 Xo)

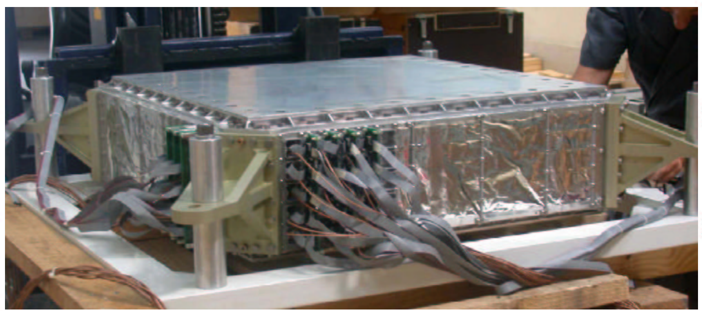
324 multianode (2x2) PMTs

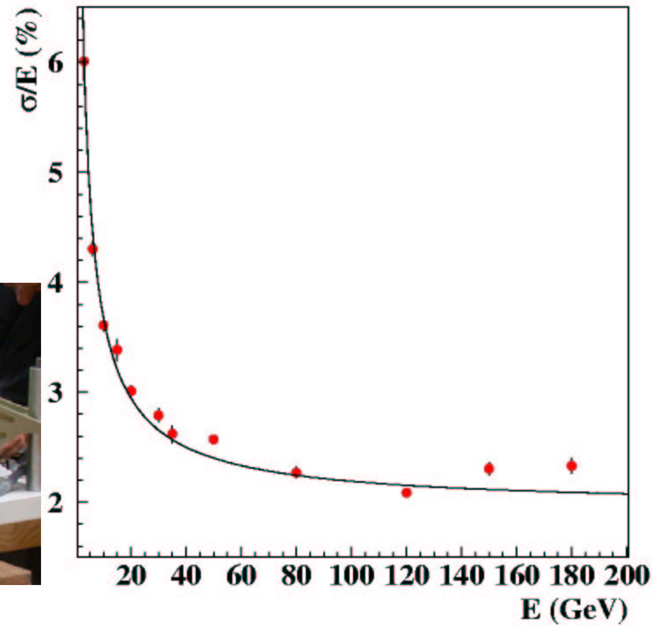
$\sigma(E)/E$ = 2% @ 100 GeV   h/e rejection of 10^3





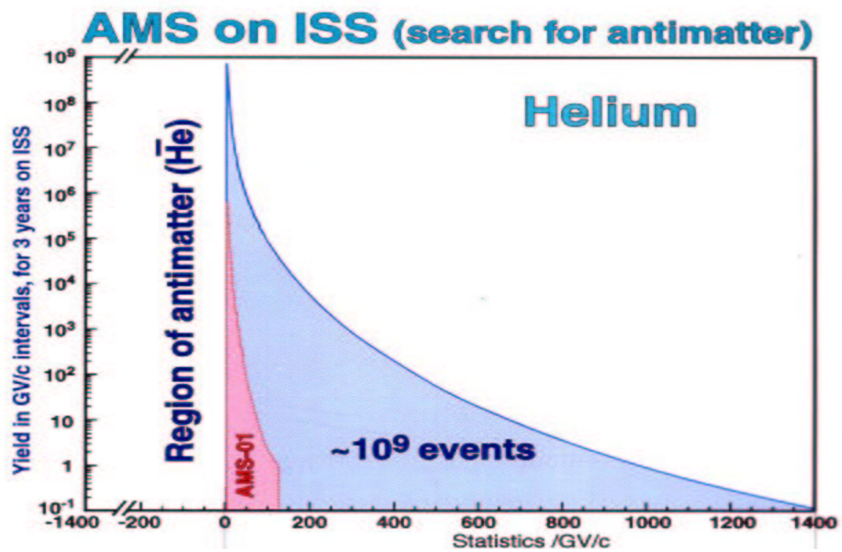


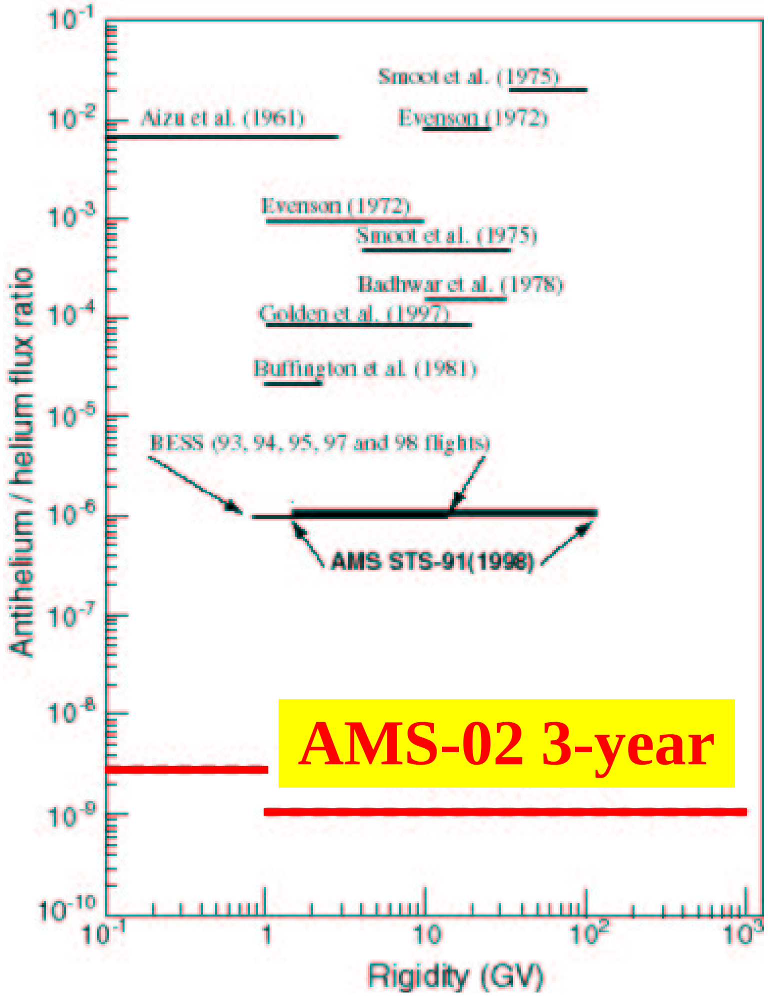




AMS-02 Antimatter Sensitivity

In 3 years AMS will collect 10^9 He with $E \lesssim 1$ TeV

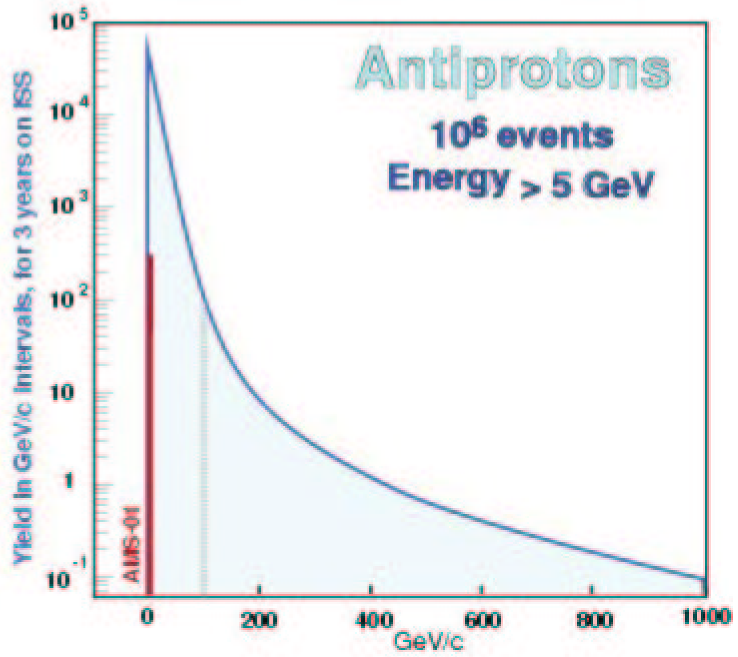




AMS-02 Antiprotons

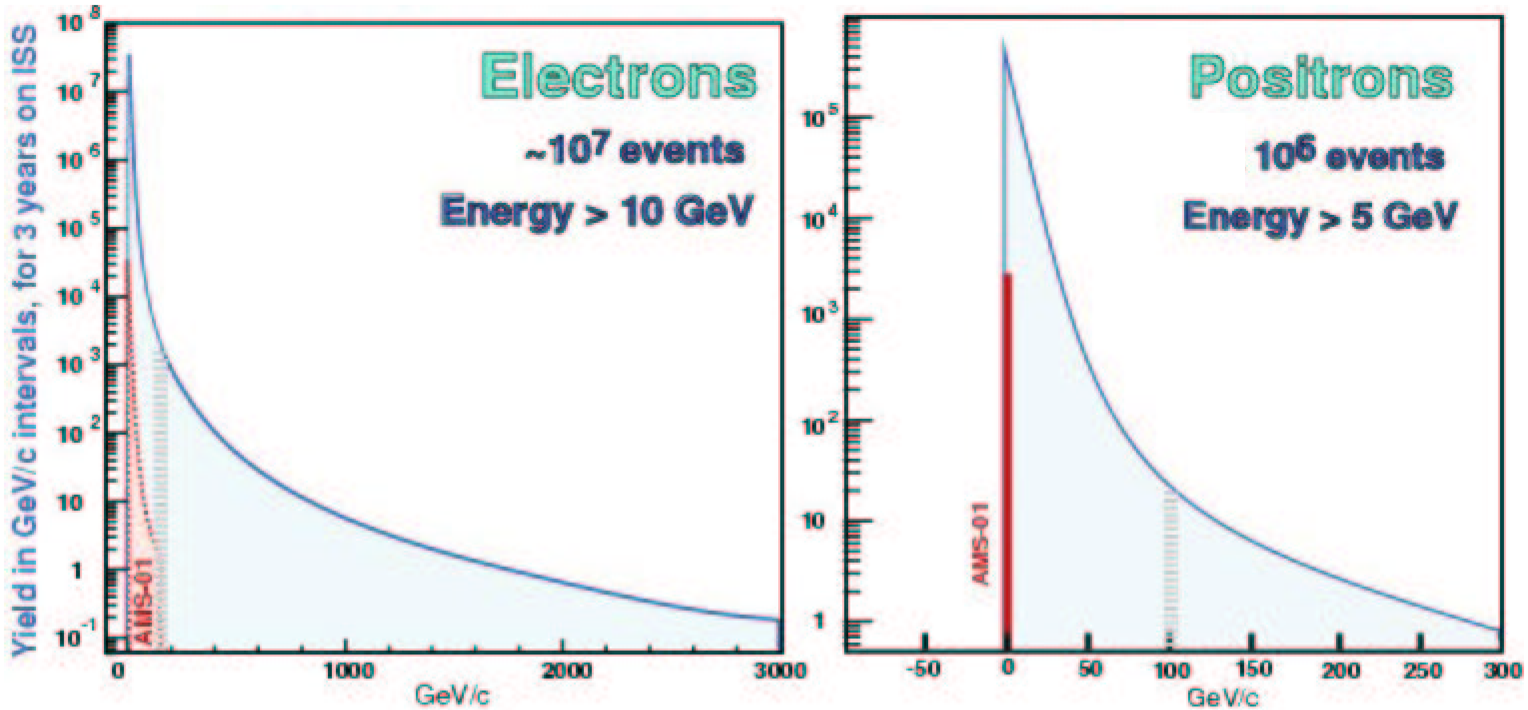
AMS will measure the $\bar{p}$ flux up to 400 GeV

After 3 years will collect $\approx 10^6$ $\bar{p}$



AMS-02 Electrons & Positrons

AMS will measure the e^- flux up to O(TeV) and the e^+ flux up to ≈ 300 GeV

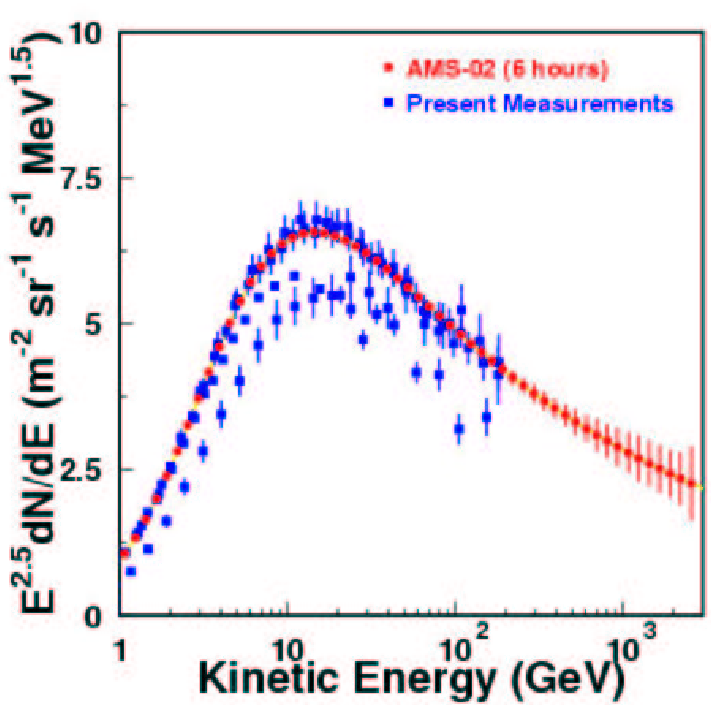


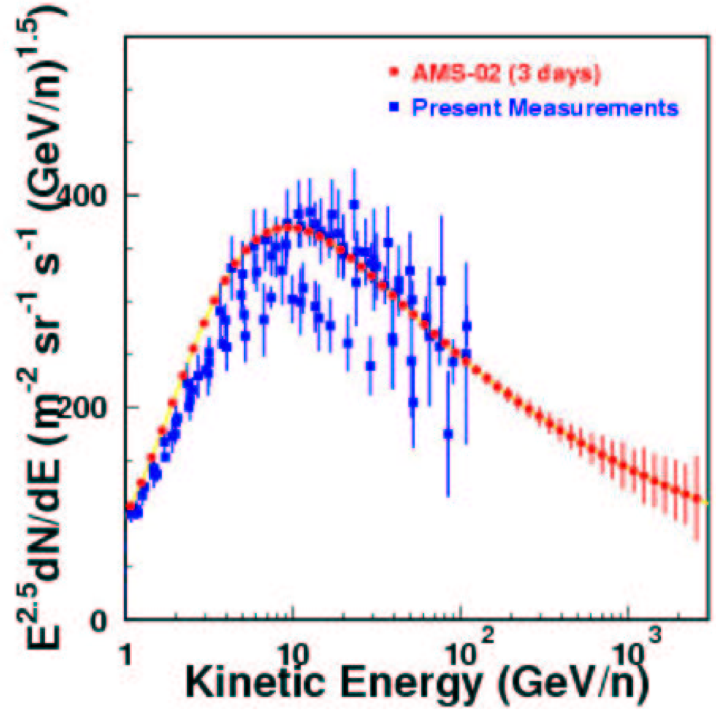
AMS-02 Protons & Helium

AMS will measure H & He fluxes for E≲1 TeV

after 3 years will collect ≈10^8 H with E > 100 GeV

and ≈10^7 He with E > 100 GeV/n



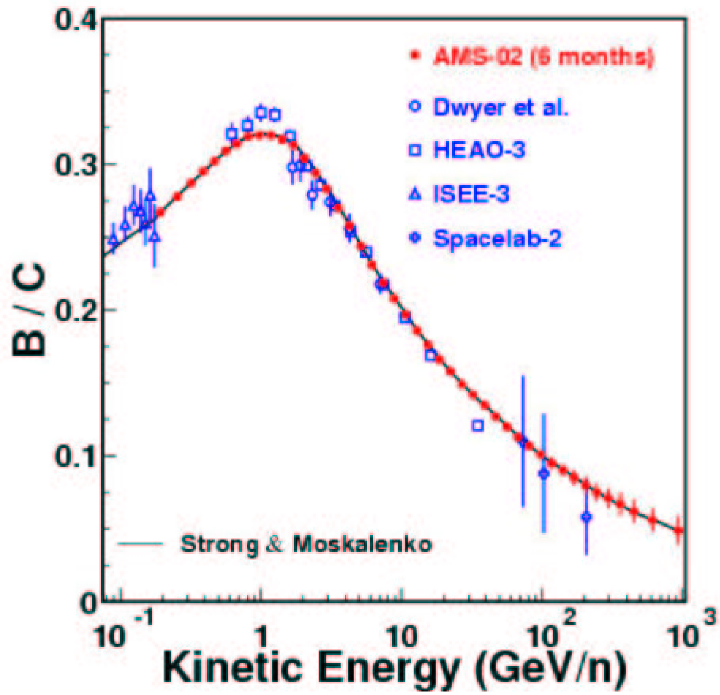


AMS-02 Light Elements

AMS will measure the spectrum for E $\lesssim$ 1 TeV/n

after 3 years will collect $\approx 10^5$ C with E > 100 GeV/n

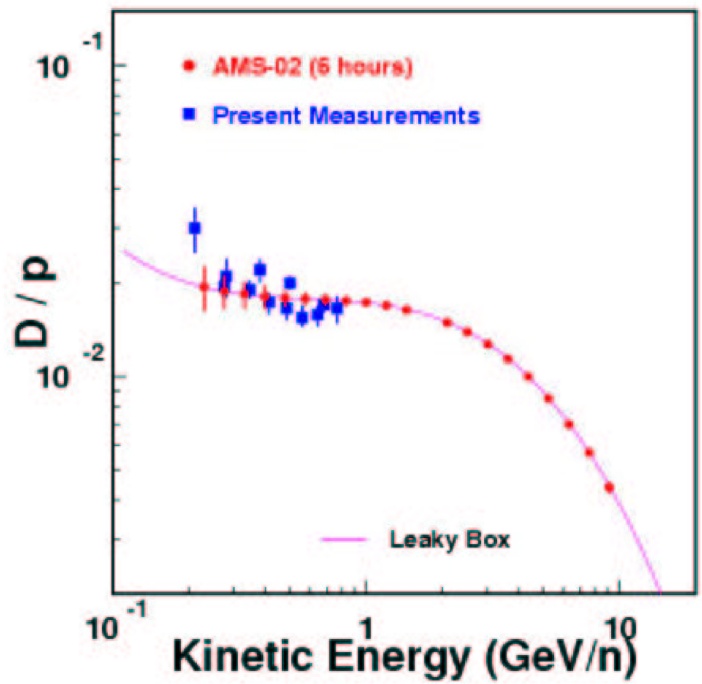
and $\approx 10^4$ B with E > 100 GeV/n



AMS-02 Light Isotopes (1/3)

AMS will identify D up to 10 GeV/n

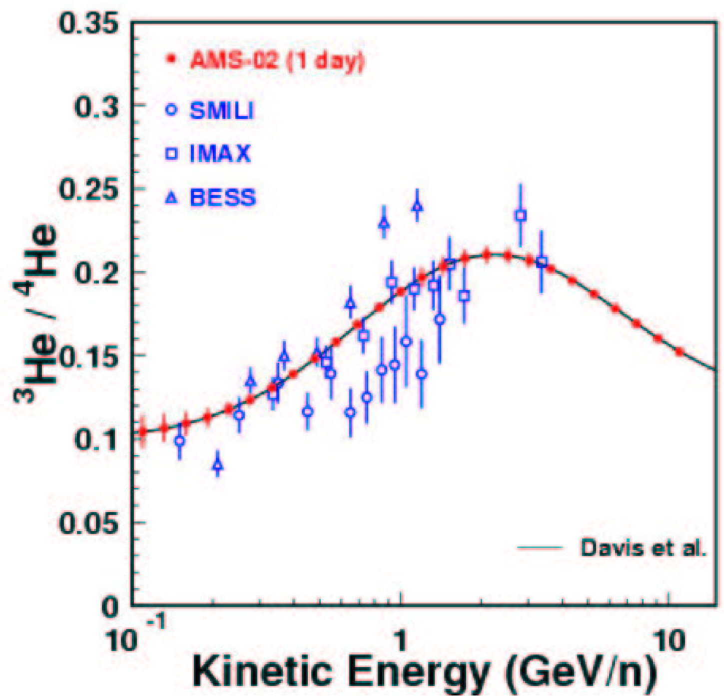
after 3 years will collect $\approx 10^8$ D



AMS-02 Light Isotopes (2/3)

AMS will identify ^{3}He up to 10 GeV/n

after 3 years will collect $\approx 10^8$ ^{3}He

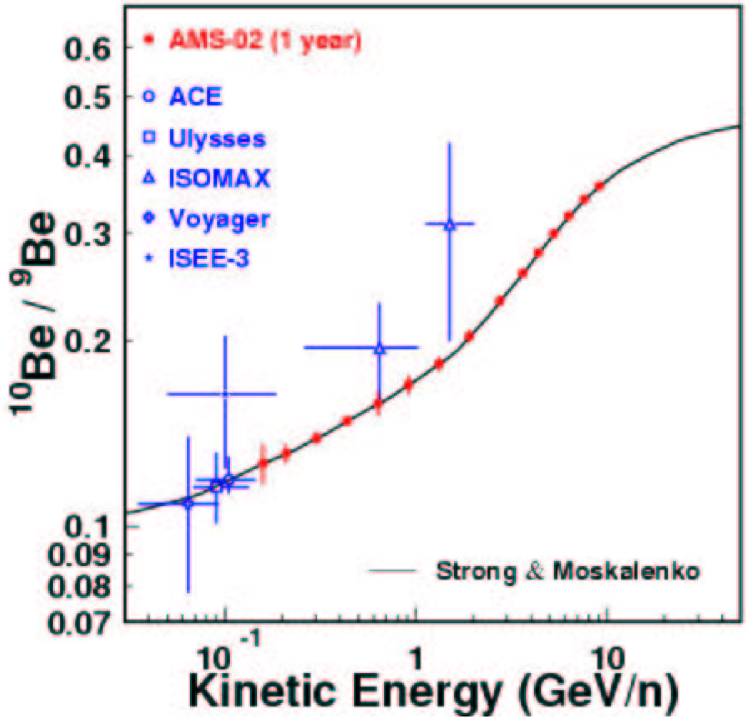


AMS-02 Light Isotopes (3/3)

AMS will separate ^{10}Be from ^{9}Be for

0.15 GeV/n < E < 10 GeV/n

after 3 years will collect $\approx 10^5$ ^{10}Be



Summary

- Good understanding of GCR origin and propagation is needed to constraint the faint signal search in CR
- Propagation models provide us with the framework for that and, in turn, may improve our knowledge of the galactic properties
- Precise experimental inputs are needed to validate an constraint these models
- A new generation of experiments which will take data in the near future will dramatically improve the present measurements
- AMS-02 will certainly contribute to this effort with precise light element and isotope flux measurements

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