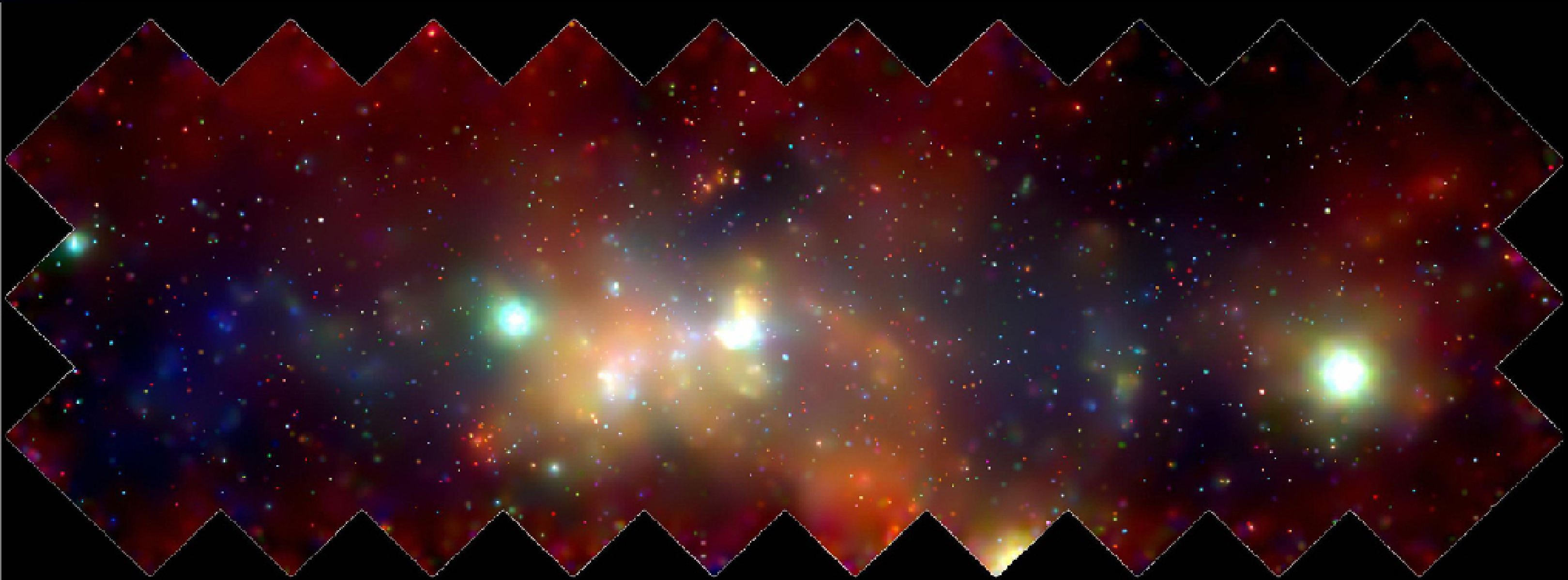
ASTROPARTICLE PHYSICS FROM SPACE

THE AMS EXPERIMENT

Eusebio Sánchez Álvaro
CIEMAT



CONTENTS

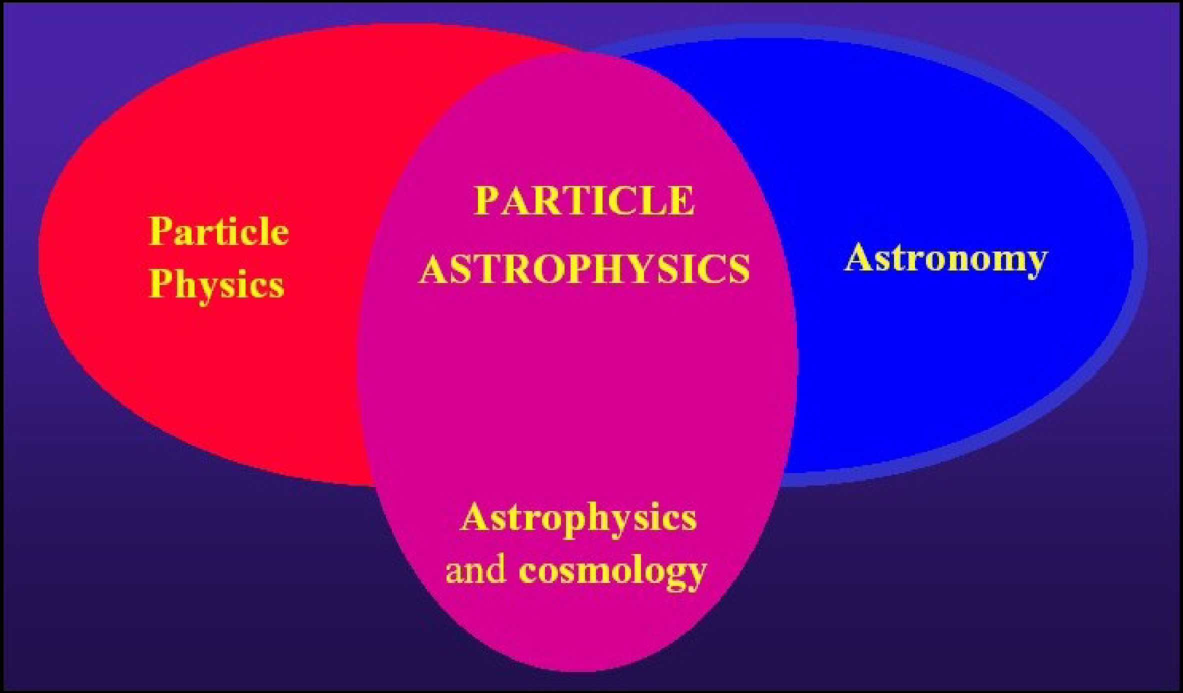
Introduction to Astroparticle Physics
- *Astrophysics: cosmic rays*
- *Particle Physics: Dark Matter, Antimatter, Exotica*
- *Cosmic Ray Detection*

The AMS Experiment
- *Description*
- *Goals*

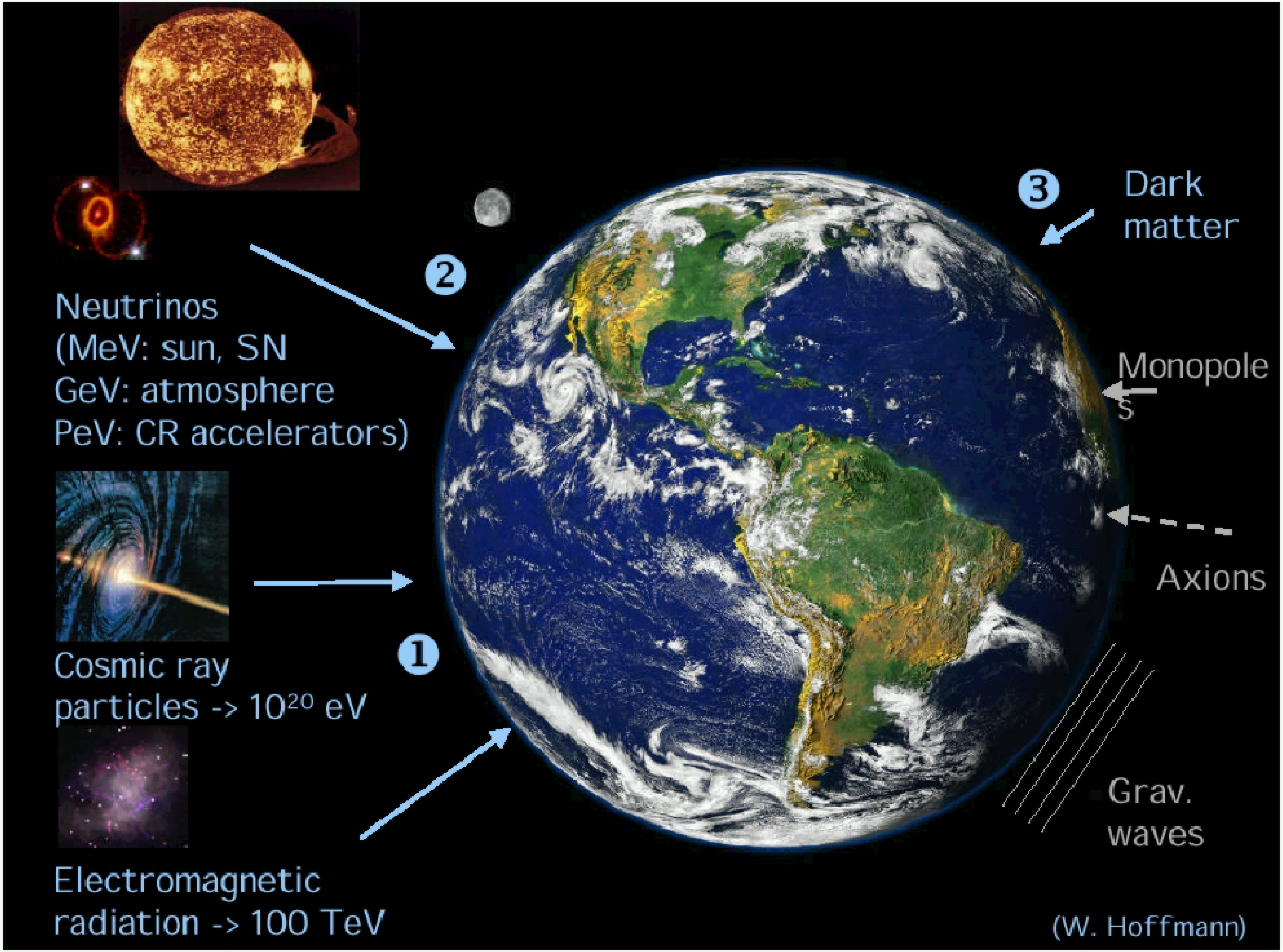
Current Results and Perspectives

Conclusions

Introduction: Astroparticle Physics



Use Particle Physics Theories to explain the Universe.
Use Particle Physics techniques in Astronomy.
Use Particles coming from space in your experiment.



Astroparticle Physics

Cosmic rays studies give results in two different fields

Astrophysics: Origin and propagation of the cosmic rays, abundances, isotopes, spectrum features.

Particle Physics: Dark Matter, Antimatter, Exotics

To study new physics effects it is very important to know the standard physics of cosmic rays.

WHAT DO WE KNOW ABOUT COSMIC RAYS?

Composition: 98% nuclei, 2% electrons.
Photons, neutrinos, antiprotons and positrons.

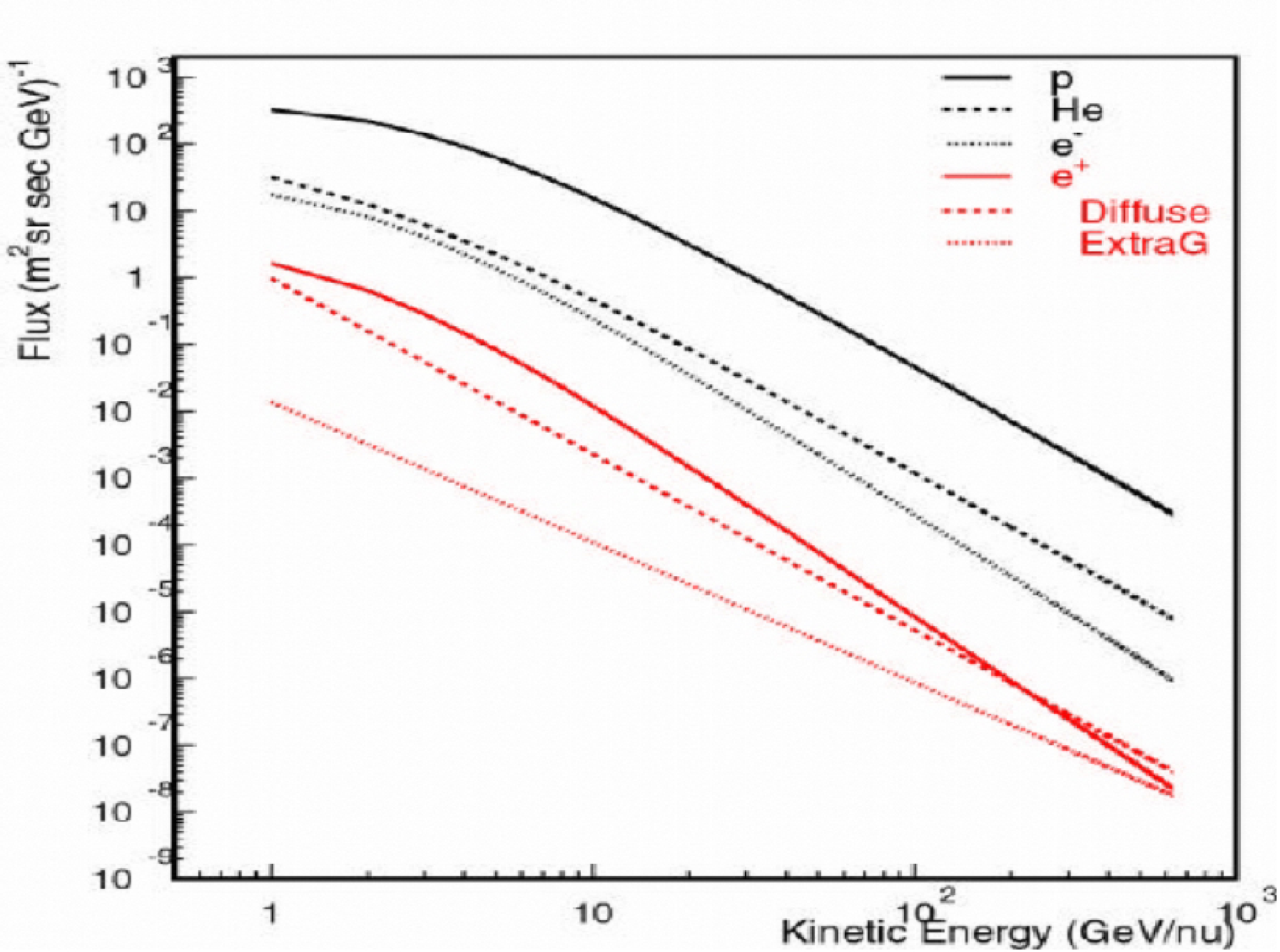
They are the only sample of matter coming from distant regions of the galaxy (and possibly of the Universe) that can be observed in the Solar System.

The Energy Range is Huge.

Where do they come from? Which is their source and their acceleration mechanism? Which is their composition and how does it change with energy? What do they say us about interstellar medium?

New technologies (coming from particle physics) allow new studies of high statistics and precision.

Particle Types in the Cosmic Rays



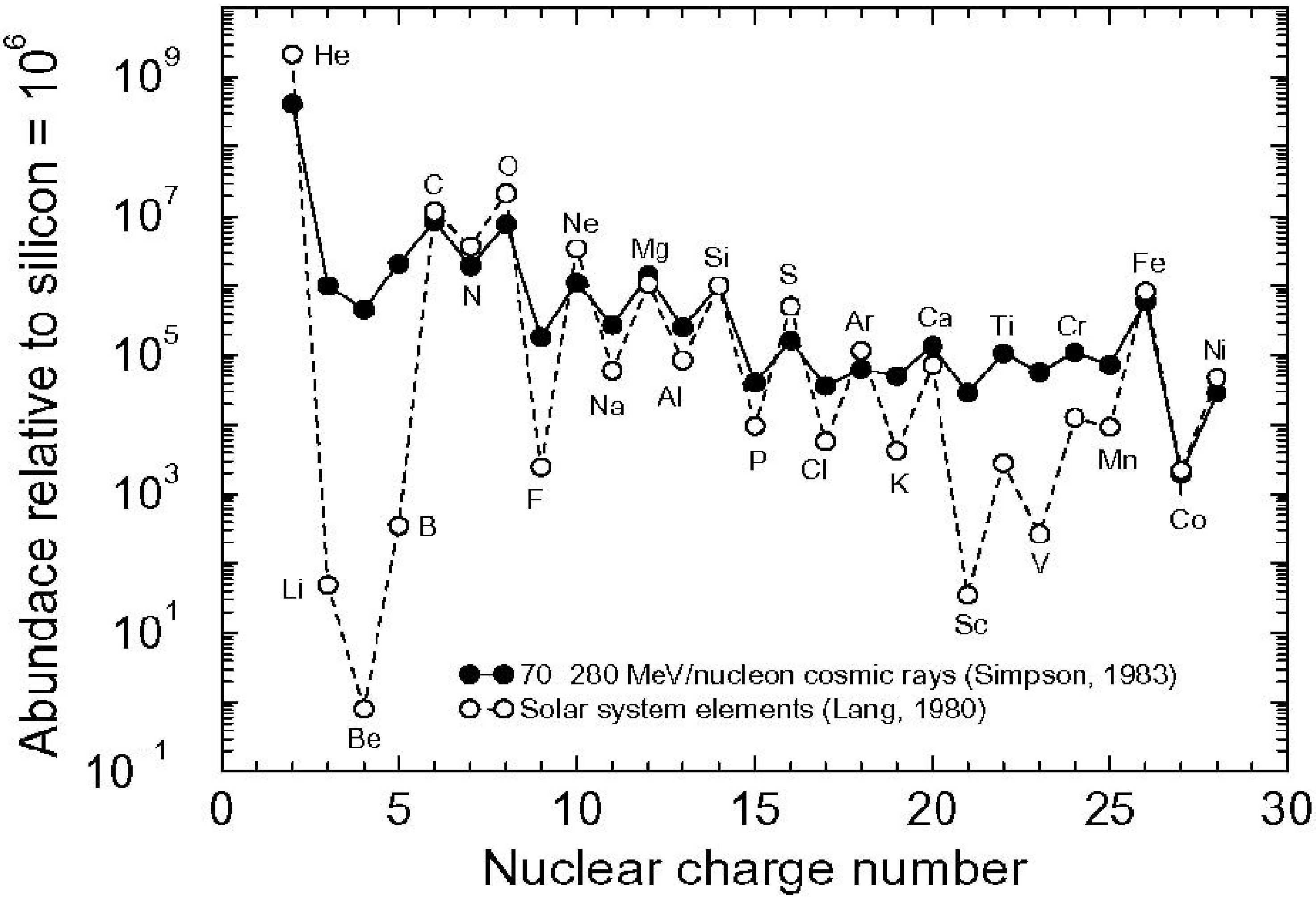
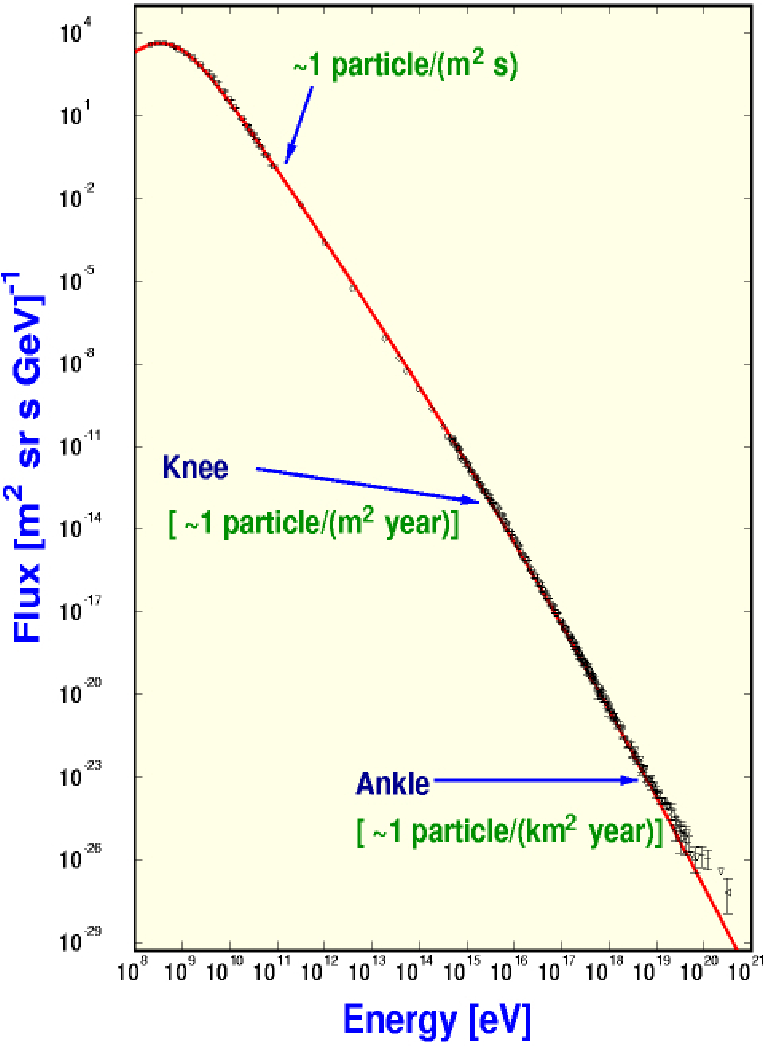
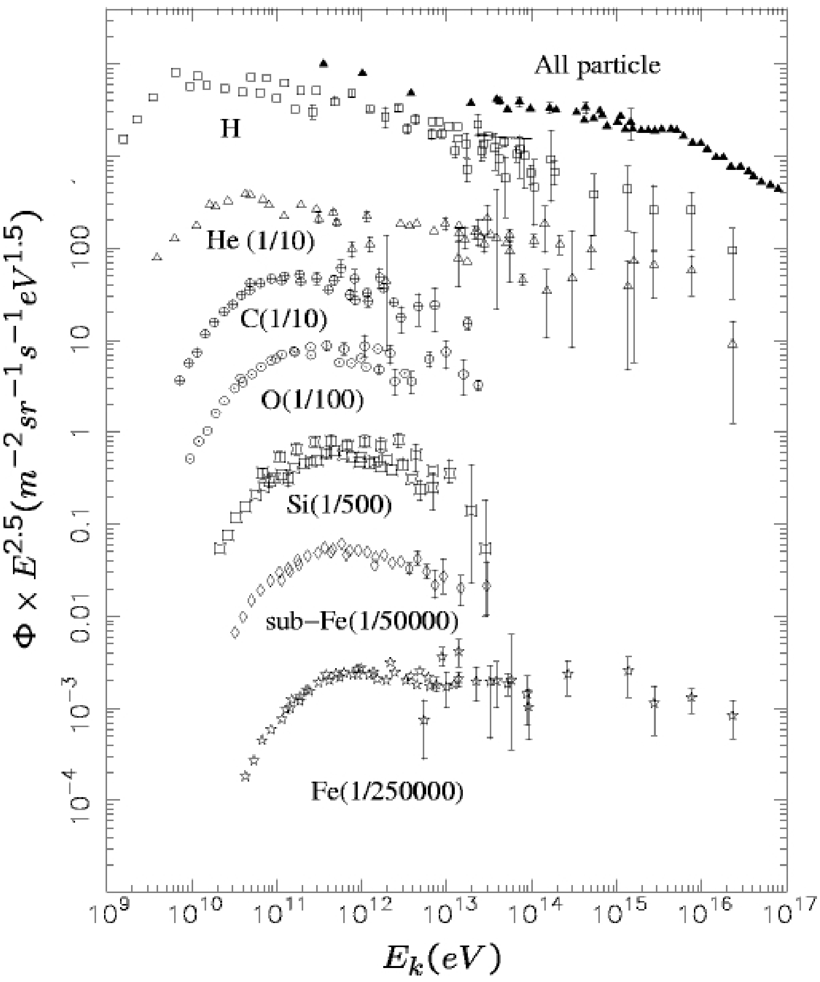


Fig. 2.— The relative elemental abundances of 70-280 Mev/nucleon cosmic rays (closed circles, taken from Tab. 2 by Simpson, 1983) compared to the solar system abundances (open circles, taken from Tab. 38 by Lang, 1980) normalized to Si $= 10^6$.

Energy Spectrum

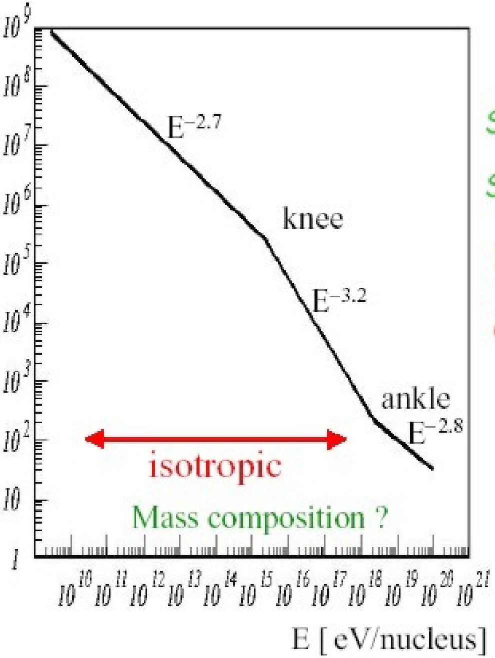




Features of the spectrum and composition are the basis of the current model of cosmic rays

Several components: Galactic, Extragalactic, Ultra High Energy

Features of Cosmic Ray Spectrum



Ingredients of models:

source propagation

$$dN/dE \sim E^{\alpha + \delta}$$

Source acceleration: $\alpha = -2.0$ to -2.2,..

Source cut-off $E < 10^{18} Z \left[\frac{R}{\mathrm{kpc}}\right]\left[\frac{B}{\mu G}\right]$ eV

Diffusion models $\delta = -0.3$ to -0.6

GZK cut-off on CMB γ $E \approx 7\ 10^{19}$ eV

'Conventional Wisdom':

Galactic SNR	$E < 3\ 10^{18}$ eV
Galactic losses	$E > 4\ 10^{14}$ eV
Extragalactic	$E > 3\ 10^{18}$ eV
exotic	$E > 7\ 10^{19}$ eV

Galactic Cosmic Rays:

- Origin in Supernovae
- Composition similar to the Sun, but more Li, Be, B and other elements below Fe. This is due to the spallation processes in the interstellar medium, that produce elements which are not products of nuclear fusion.

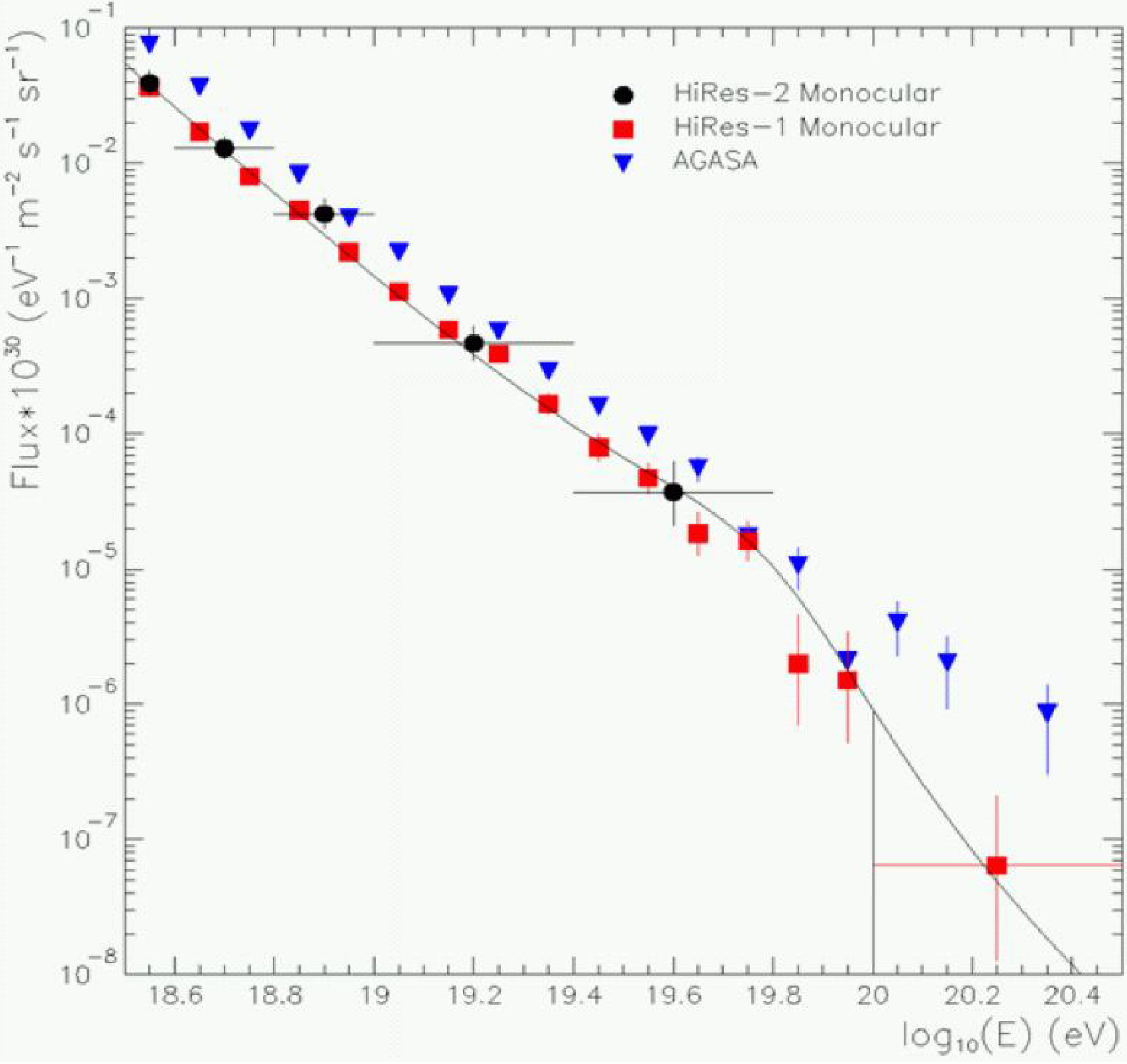
The spallation cross sections are well known from nuclear physics. The element abundances, that depend on the production in primary interactions and the production by spallation, are directly linked to the amount of matter crossed.

Extragalactic Cosmic Rays

- Origin in violent phenomena: AGNs, GRBs ...

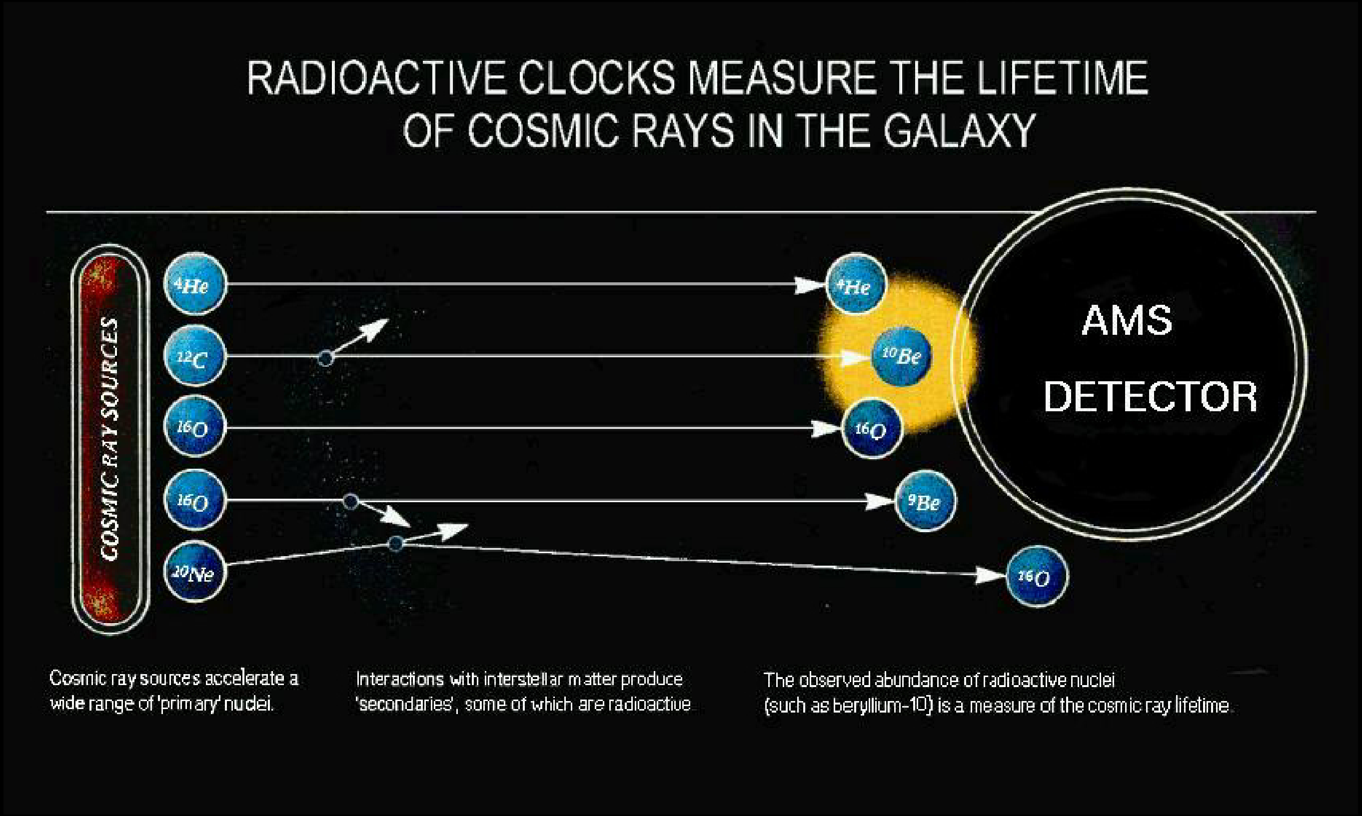
UHE Cosmic Rays

- GZK?



HiRes−2 Monocular
HiRes−1 Monocular
AGASA
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Flux∗10^{30} (eV^{-1} m^{-2} s^{-1} sr^{-1})
18.6
18.8
19
19.2
19.4
19.6
19.8
20
20.2
20.4
$\log_{10}(E)$ (eV)

Propagation: Diffusion galactic models, spallation



RADIOACTIVE CLOCKS MEASURE THE LIFETIME OF COSMIC RAYS IN THE GALAXY

Cosmic ray sources accelerate a wide range of 'primary' nuclei.

Interactions with interstellar matter produce 'secondaries', some of which are radioactive.

The observed abundance of radioactive nuclei (such as beryllium-10) is a measure of the cosmic ray lifetime.

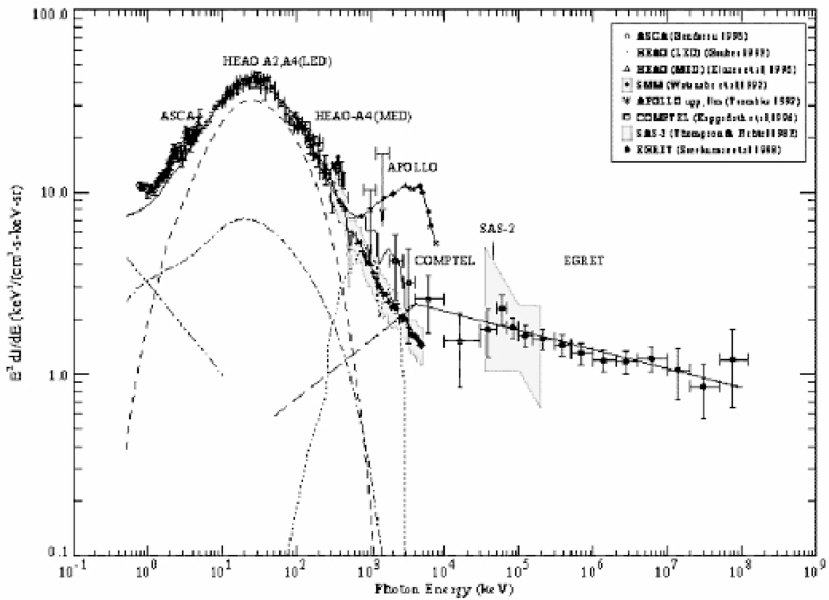
The long lifetime of some isotopes allows to use them as cosmic clocks. Example: Lifetime of Be10 = 4 My. Measuring the ratio Be10/Be9 we know how much Be10 has been converted to Be9 in its way through the galaxy. Other processes contributing are the scape from the galaxy or the loss of energy due to other interactions.

GAMMA RAYS

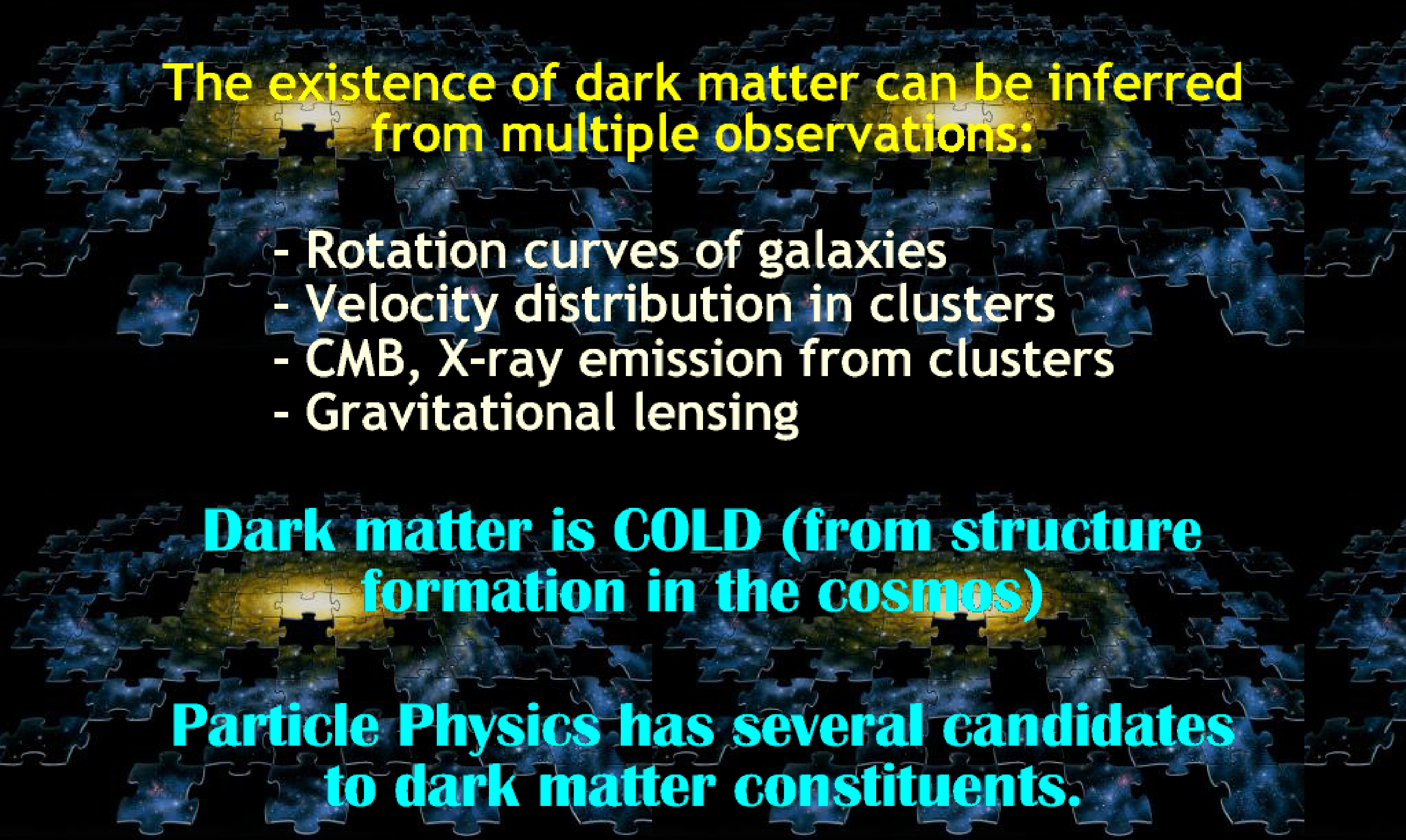
Gamma Rays are not deviated by the magnetic fields. They can be associated to their sources.

Gamma rays from the galactic disk are produced by the decays of neutral pions coming from the interactions of the cosmic rays with the interstellar medium.

It is possible to obtain the cosmic ray density by measuring the diffuse gamma ray from the galactic plane. It is necessary to know the background in order to search for rare events.



Dark Matter



The existence of dark matter can be inferred from multiple observations:

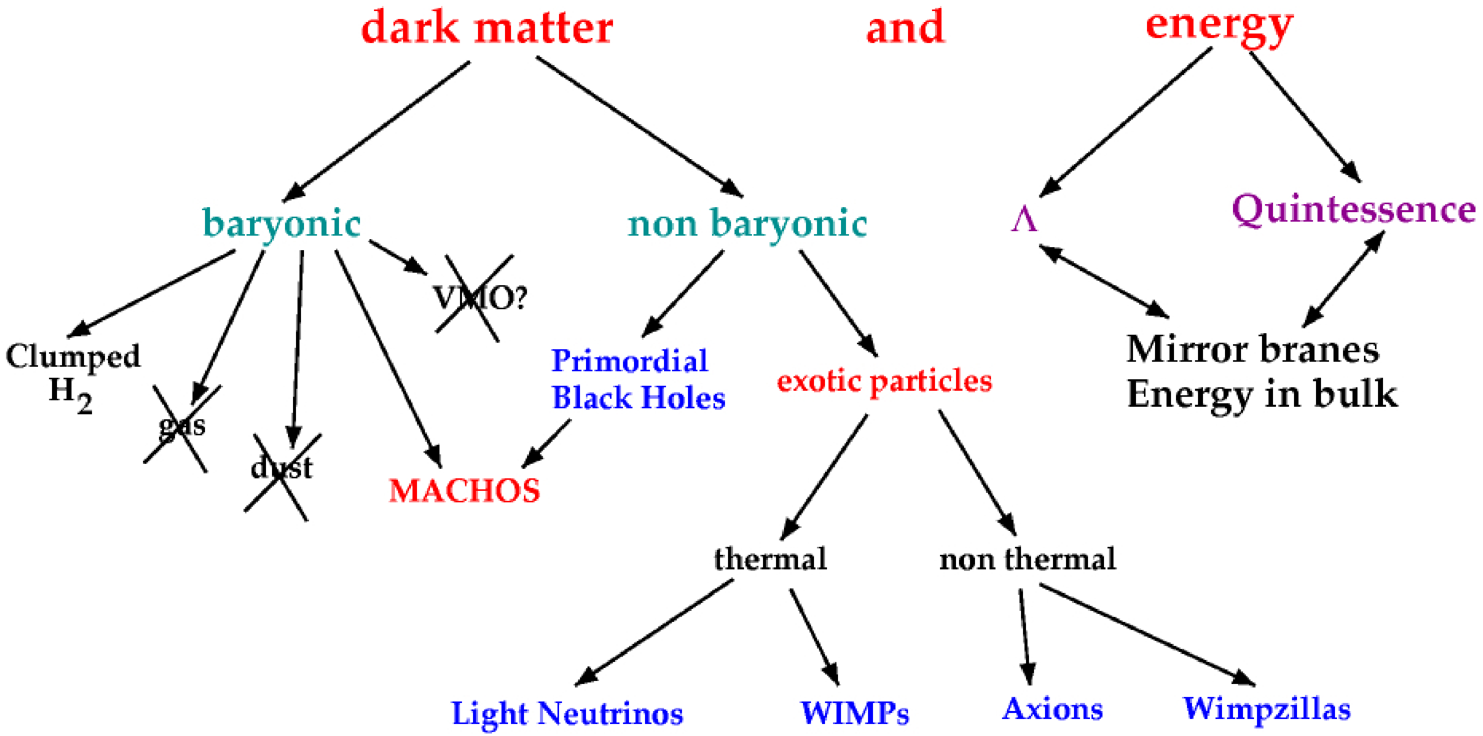
- Rotation curves of galaxies
- Velocity distribution in clusters
- CMB, X-ray emission from clusters
- Gravitational lensing

Dark matter is COLD (from structure formation in the cosmos)

Particle Physics has several candidates to dark matter constituents.

DARK MATTER

A complex territory to map experimentally: high priority



dark matter and energy

baryonic

non baryonic

Λ

Quintessence

Clumped H_2

~~gas~~

~~dust~~

MACHOS

~~VMO?~~

Primordial Black Holes

exotic particles

Mirror branes
Energy in bulk

thermal

non thermal

Light Neutrinos

WIMPs

Axions

Wimpzillas

Why Ω_b , Ω_m , Ω_Λ , Ω_k ?

Likely to be related to fundamental properties of forces

Dark Matter

The LSP is a relic:

If R-parity is conserved, then LSP (Lightest Supersymmetric Particle) is stable.

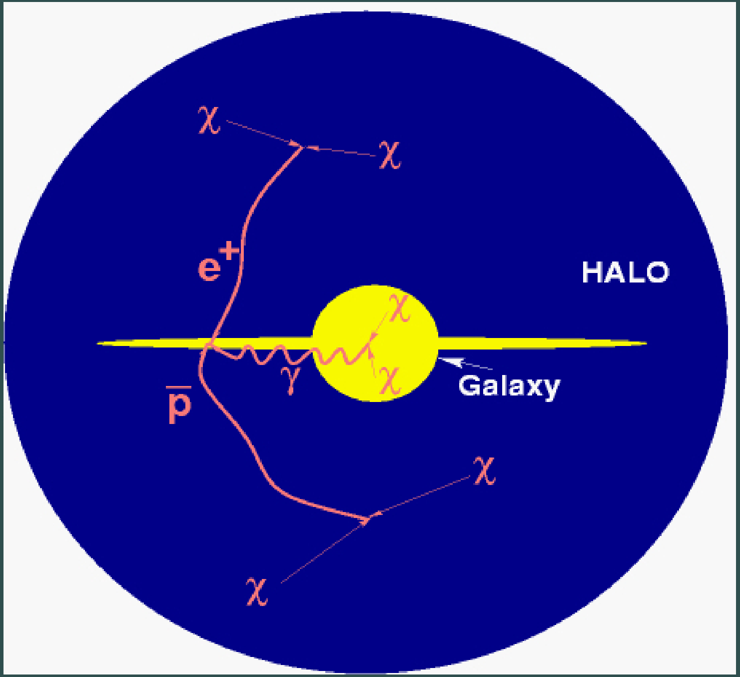
If it has no colour and no charge, it is a nice realization of a WIMP (Weakly Interacting Massive Particle)

Too much freedom in the SUSY models:

The LSP nature depends on the SUSY breaking mechanism and on the region of the parameter space it implies.

Here we consider the "MSSM-gravity mediated" SUSY breaking mechanism and parameter space regions where the χ is the LSP

Dark Matter



$\chi\bar{\chi} \to q\bar{q} \to$ ANTIPROTONS

$\chi\bar{\chi} \to q\bar{q} \to$ ANTIDEUTERIUM

$\chi\bar{\chi} \to W^+W^-, ZZ \to$ POSITRONS

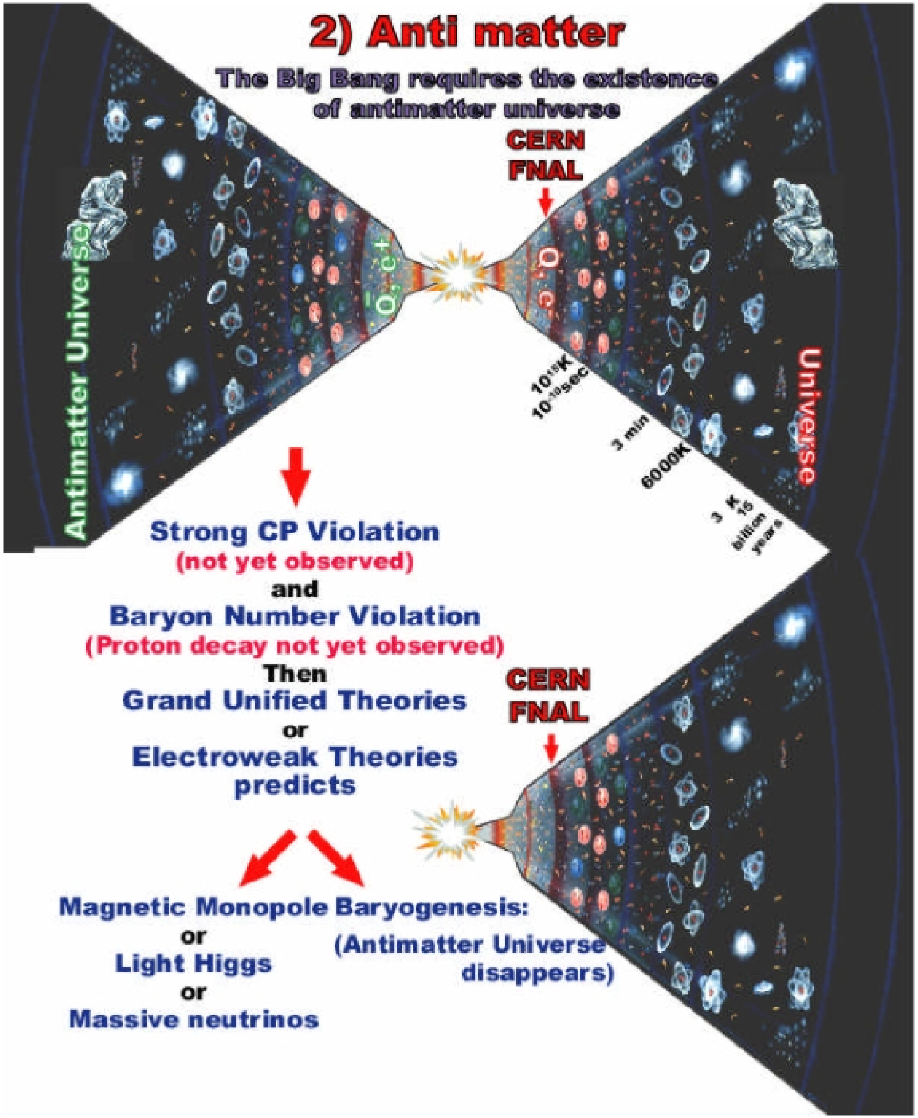
$\chi\bar{\chi} \to \tau^+\tau^-, b\bar{b}, t\bar{t} \to$ POSITRONS

$\chi\bar{\chi} \to \gamma\gamma, Z\gamma \to$ PHOTONS

Charged particles contribute to cosmic ray fluxes.

Neutral particles keep directionality, what makes them detectable if they are produced in regions with high density of neutralinos (Astronomy of γ, ν)

Fluxes grow if WIMPs distribution is clumpy.



2) Anti matter

The Big Bang requires the existence of antimatter universe

Strong CP Violation
(not yet observed)
and
Baryon Number Violation
(Proton decay not yet observed)
Then
Grand Unified Theories
or
Electroweak Theories
predicts

Magnetic Monopole
or
Light Higgs
or
Massive neutrinos

Baryogenesis:
(Antimatter Universe disappears)

ANTIMATTER

Unlikely, but not absolutely excluded yet.

The detection of a single anihelium nucleus (or a even more negative one) would imply the existence of antistars or antigalaxies.

Experimental information about baryogenesis.

Strange Quark Matter, Strangelets

Normal Matter is made up of nucleons (neutrons, protons) each with 3 *up* and *down* quarks

Carbon Nucleus

Lumps of strange quark matter (Strangelets) are a single “super nucleon” with many *up*, *down* and *strange* quarks.

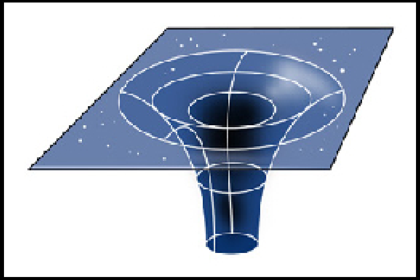
Strangelet

- Low charge to mass ratio
- Mass from ~100 to ~10^{57} times proton mass
- Many interesting, unusual properties

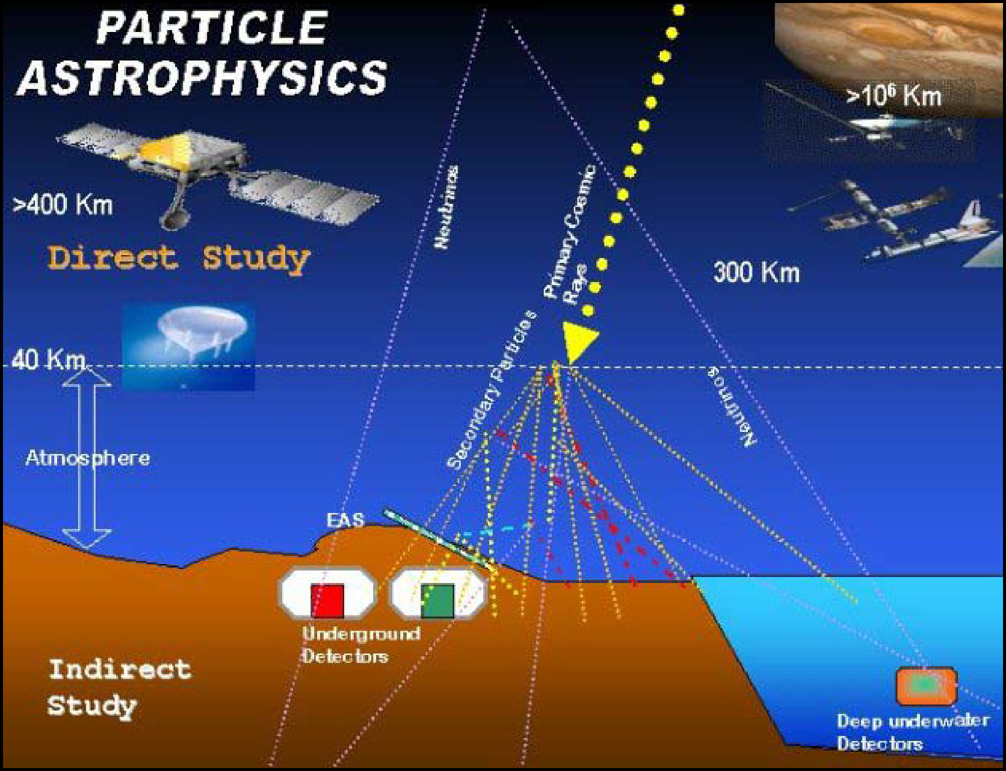
Primordial Black Holes

They are detectable through the antiproton and antiduteria fluxes.

Mainly at very low energies.

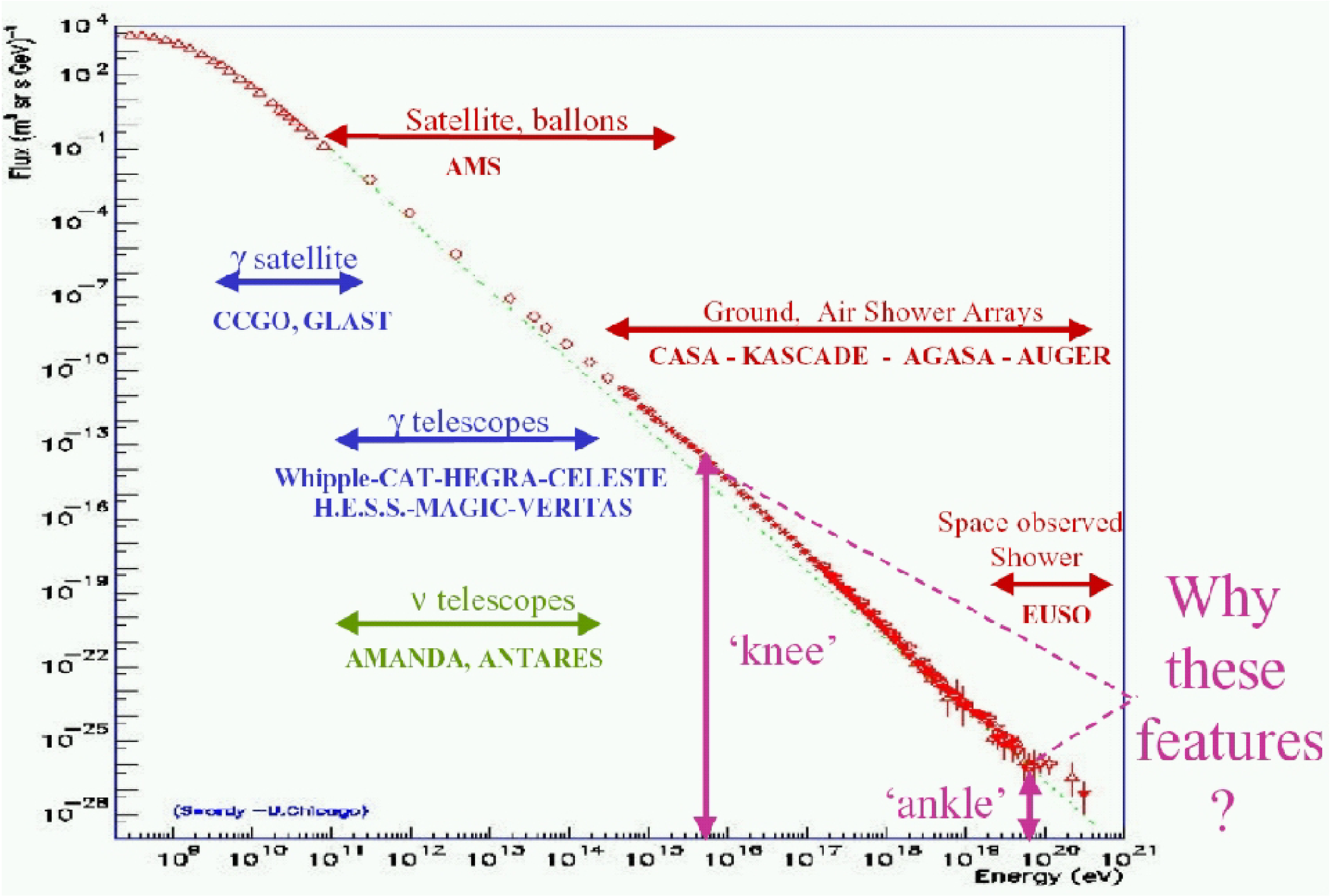


COSMIC RAY DETECTION



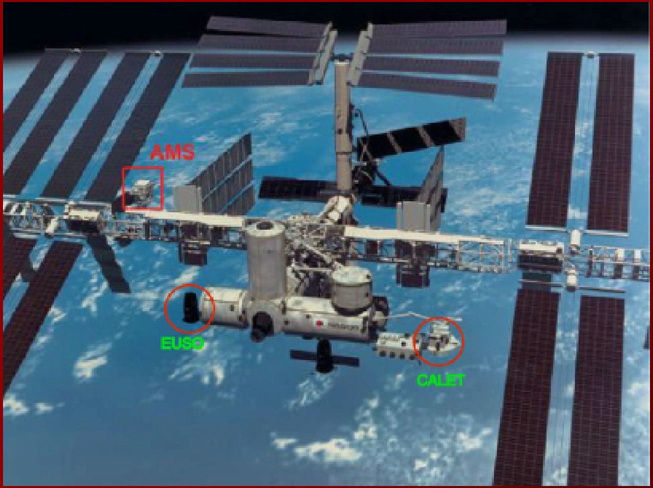
Detectors on earth, in balloons and in space are complementary.

COSMIC RAY DETECTION

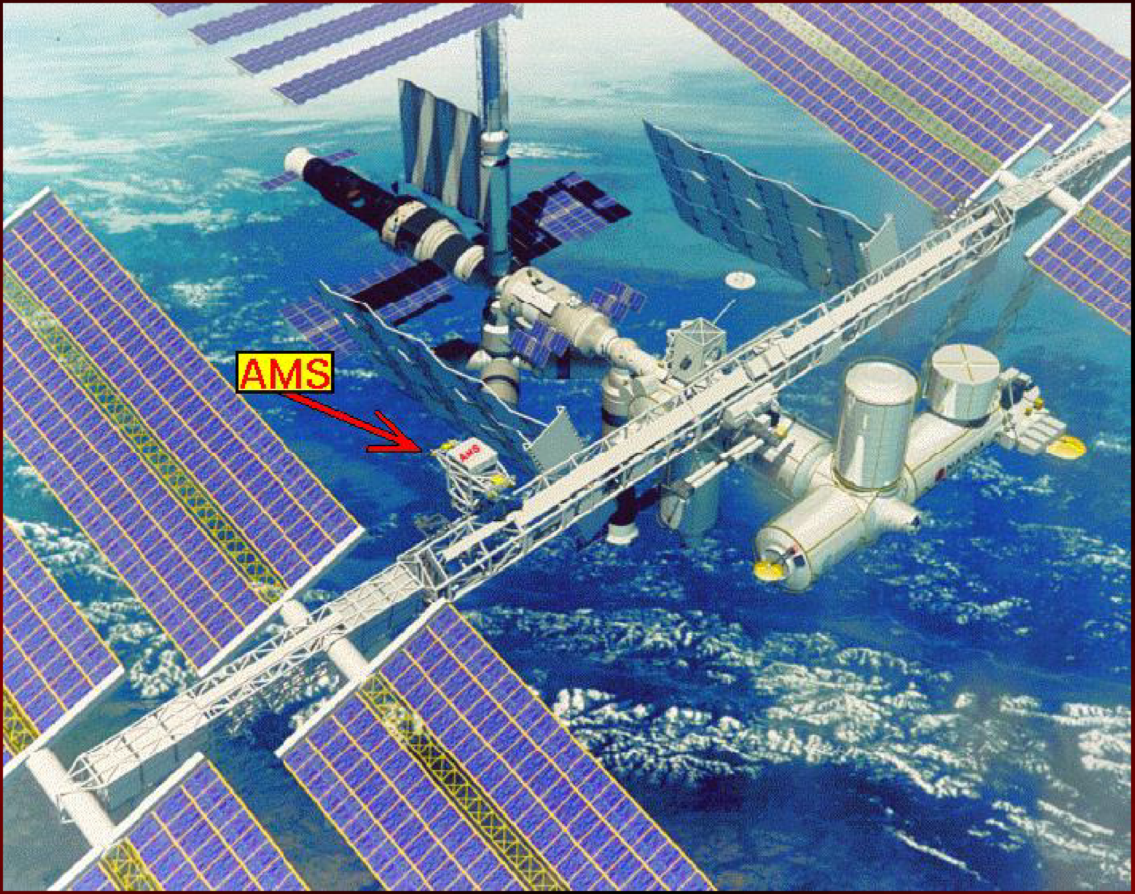


Why these features ?

THE AMS EXPERIMENT

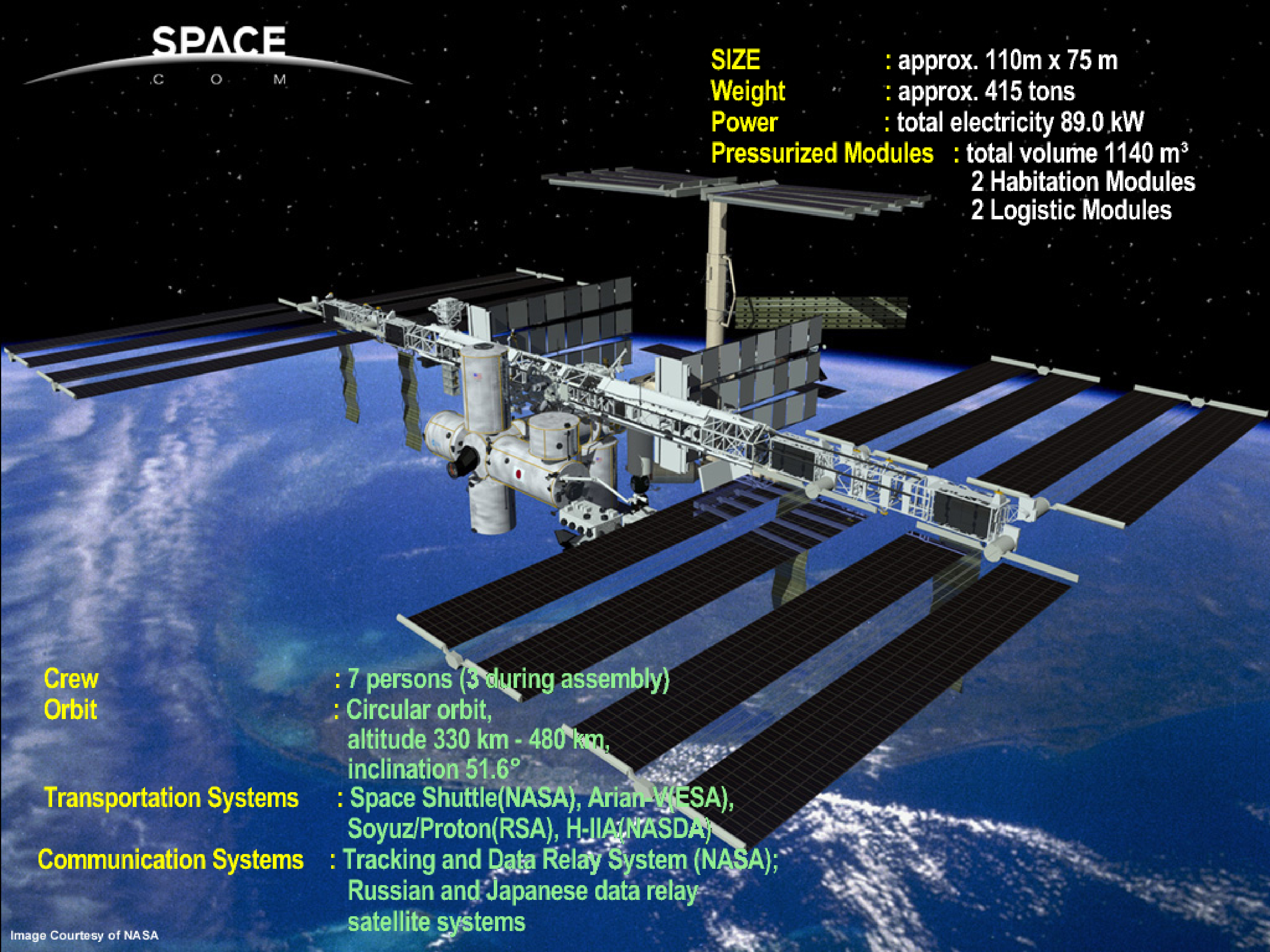


THE AMS EXPERIMENT



AMS will be located on the International Space Station (ISS)

SPACE.COM



SIZE : approx. 110m x 75 m

Weight : approx. 415 tons

Power : total electricity 89.0 kW

Pressurized Modules : total volume 1140 m^3
2 Habitation Modules
2 Logistic Modules

Crew : 7 persons (3 during assembly)

Orbit : Circular orbit,
altitude 330 km - 480 km,
inclination 51.6°

Transportation Systems : Space Shuttle(NASA), Arian-V(ESA),
Soyuz/Proton(RSA), H-IIA(NASDA)

Communication Systems : Tracking and Data Relay System (NASA);
Russian and Japanese data relay
satellite systems

Image Courtesy of NASA

THE AMS EXPERIMENT

AMS is in the scientific program of the ISS

It is the ONLY particle physics experiment approved for the ISS

Approval date (NASA-DOE MoU) 1995 (rev. 1999)

The AMS collaboration (trough DOE) is the responsible of the construction and operation of the detector

NASA offers two flights in the space shuttle:

PHASE 1: Test flight

test of the detector operation

Study of background and data rate in real conditions

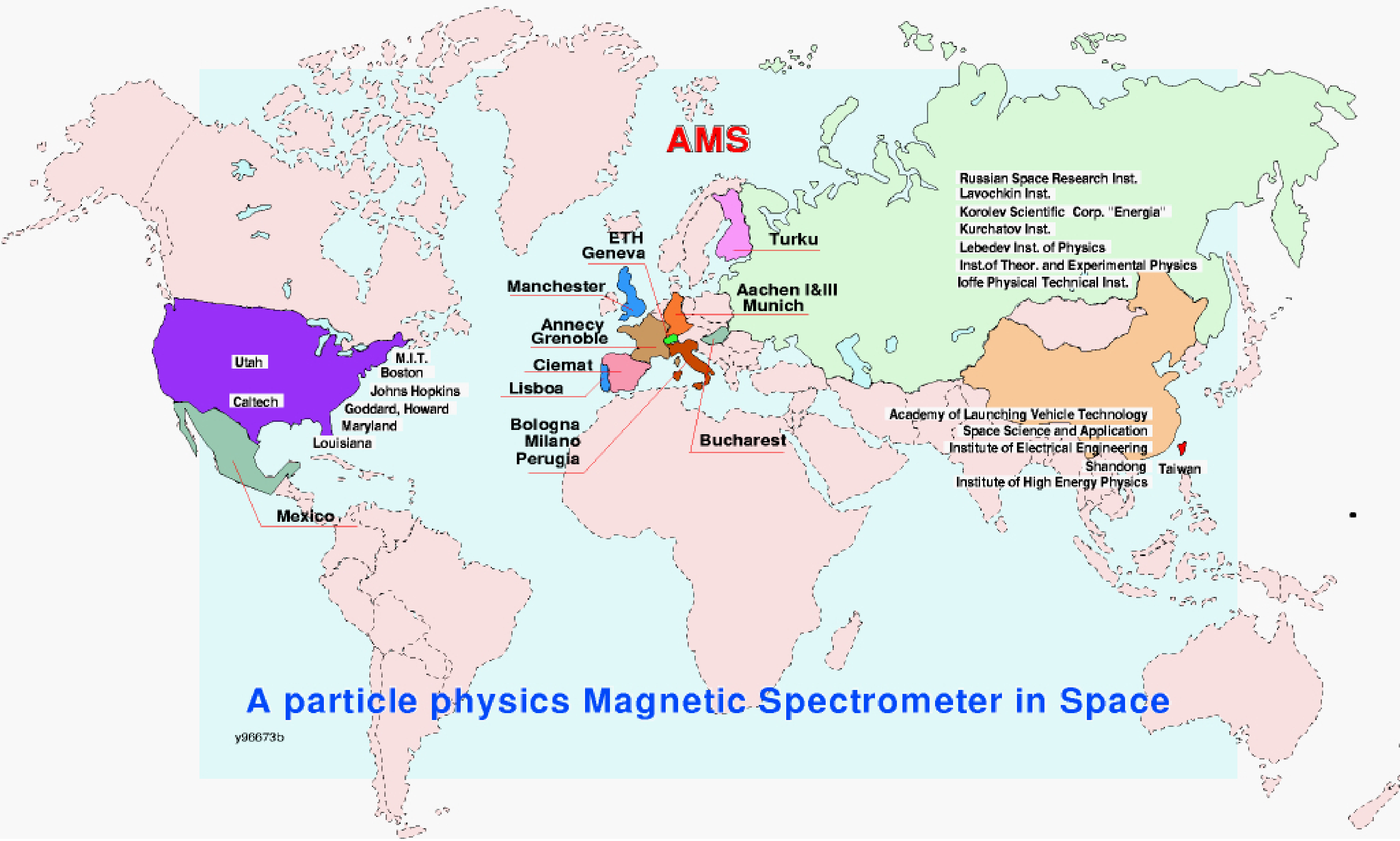
June 1998
STS-91 Mission:10 days

PHASE 2: Transport and installation on the ISS

3 years data taking to cover the physics program

Flight UF4.1 (end of 2005)
N.E.T. september 2007

THE AMS EXPERIMENT



A particle physics Magnetic Spectrometer in Space

THE AMS EXPERIMENT

AMS is a particle physics detector

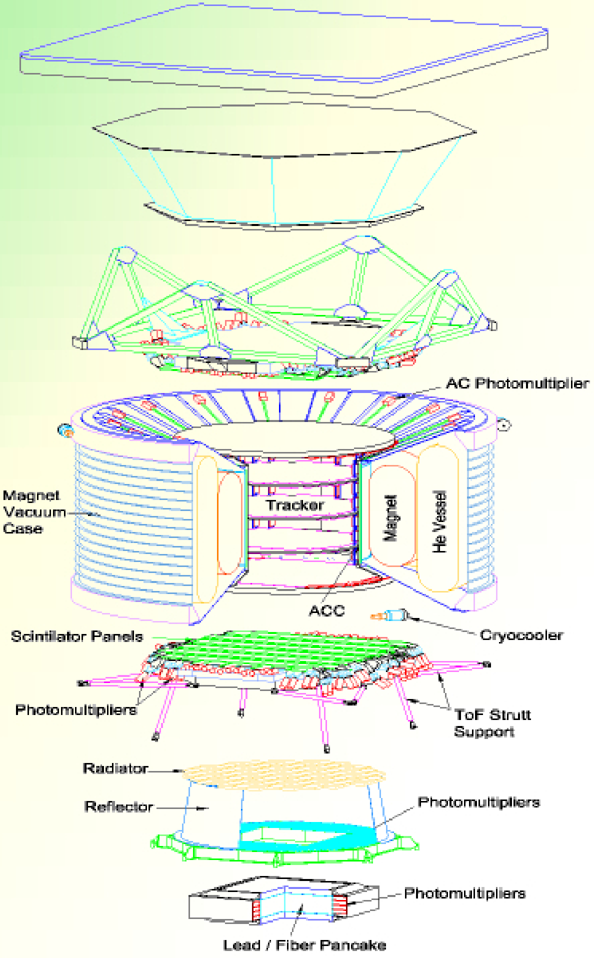
Geometrical acceptance 0.45 m^2 sr

Approximate dimensions 3x1.8x1.8 m^3

Total weight 6T

AMS 02

(Exploded View)



TRD:
Transition Radiation Detector

Truss Structure
TRD,ToF Support

ToF: (s1,s2)
Time of Flight Detector

TR:
Silicon Tracker

ACC:
Anticoincidence Counter
(veto Counter)

MG: Magnet
CC: Cryocooler

ToF: (s3,s4)
Time of Flight Detector

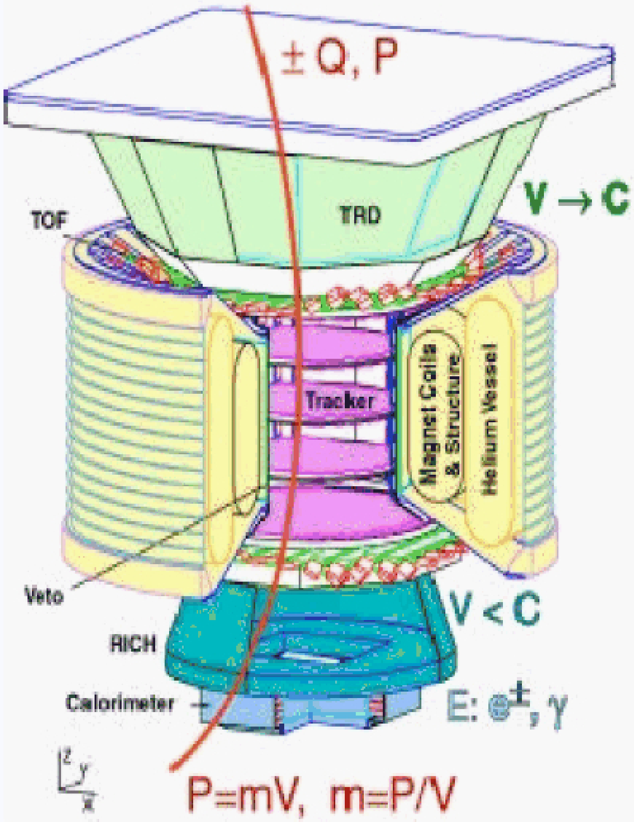
RICH:
Ring Image Cherenkov Counter

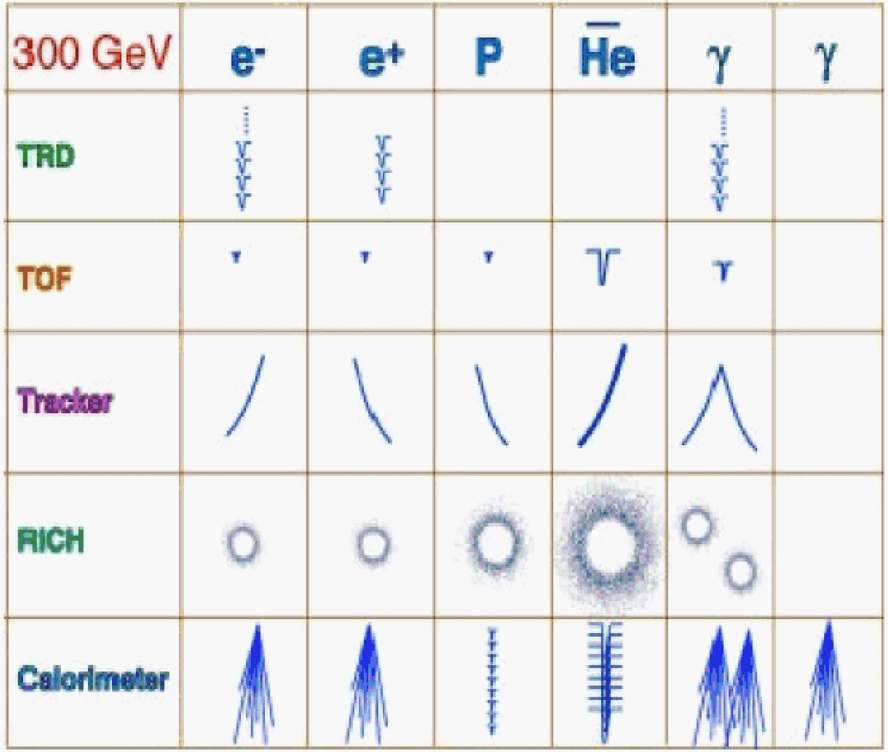
EMC:
Electromagnetic Calorimeter

R. Becker
August 13, 2000

THE AMS EXPERIMENT

AMS-02





300 GeV	e^-	e^+	P	$\overline{He}$	γ	γ
TRD						
TOF						
Tracker						
RICH						
Calorimeter						

THE AMS EXPERIMENT

The space is a new (and very hostile) environment for particle physics experiments:

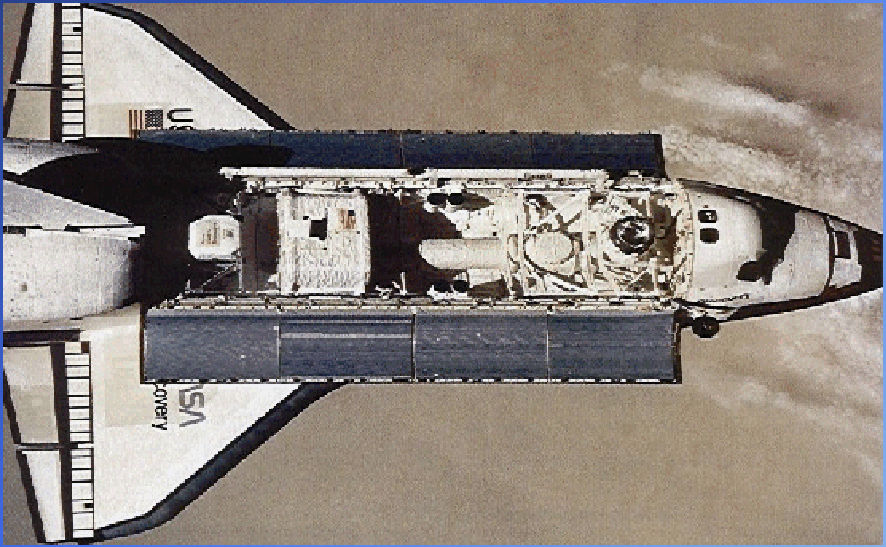
- Limited weight (6 Tons)
- Limited energy consumption (2 kW)
- Extreme temperature variations -60°C y +60°C
- Acceleration up to 9g during lift off and stop at the ISS.
- Limited bandwidth for data transmission.
- Operation in vacuum.

THE AMS EXPERIMENT: AMS01

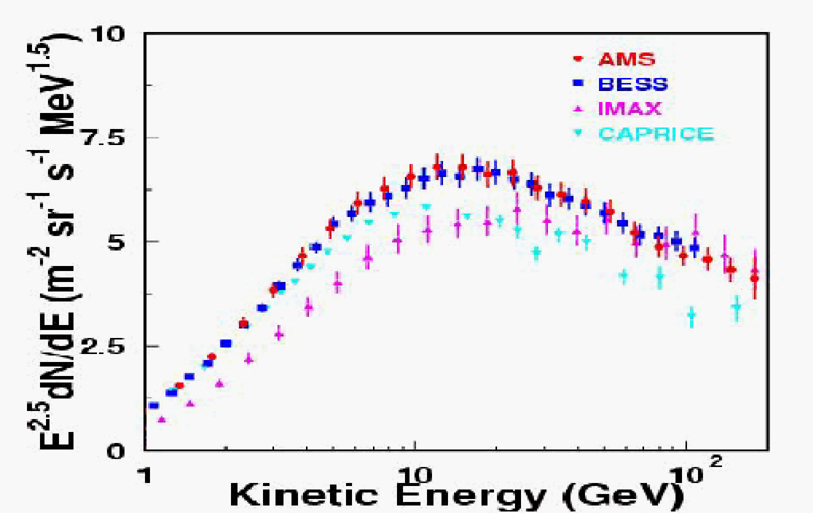
Operation in these conditions has been proved possible: AMS01

Test flight in the shuttle Discovery in 1998.

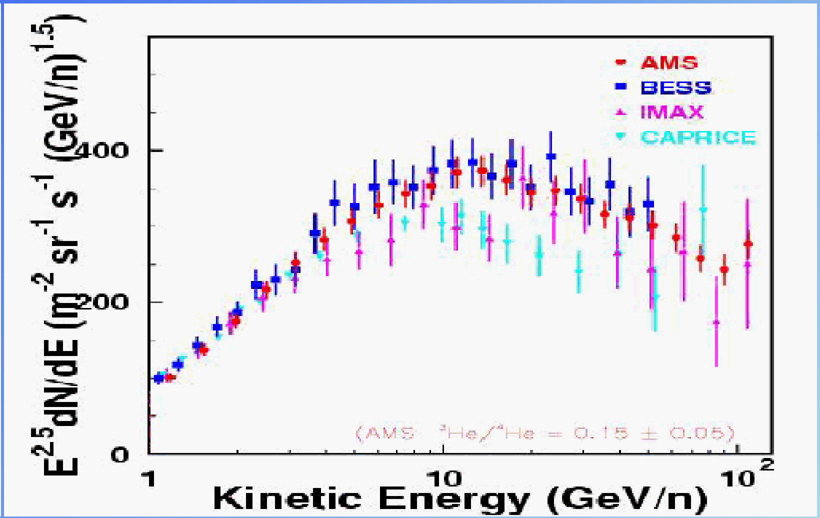
Data taking during 90 hours.



Proton flux



Helium Flux



THE AMS EXPERIMENT: SUPERCONDUCTING MAGNET

It provides the curvature in the particles tracks to distinguish charges up to TeV range of energies.

Some Parameters:

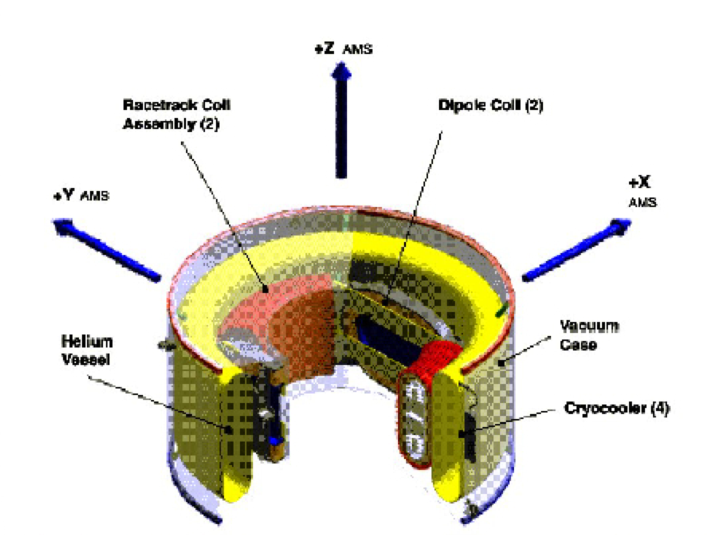
Central Magnetic Field: 0.87 T

Nominal Operating Current: 459 A

Stored Energy: 5.15 MJ

Superconducting Material: NbTi

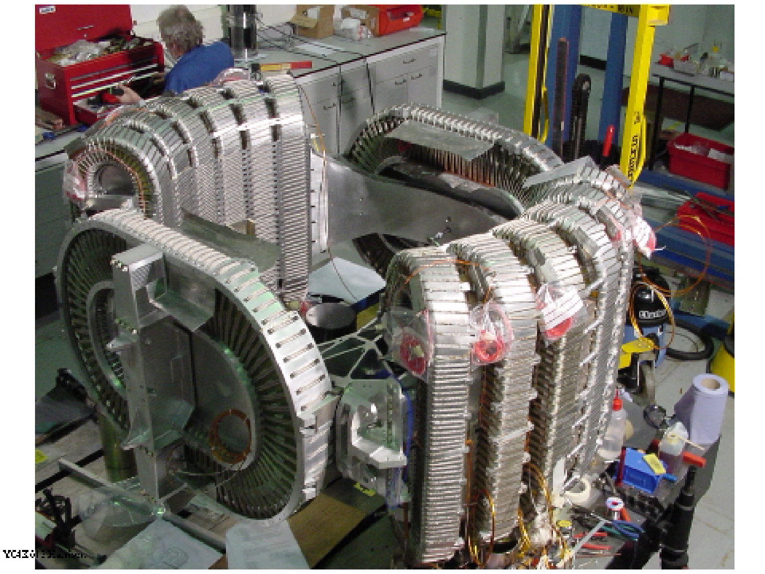
Work Temperature: 1.8 K

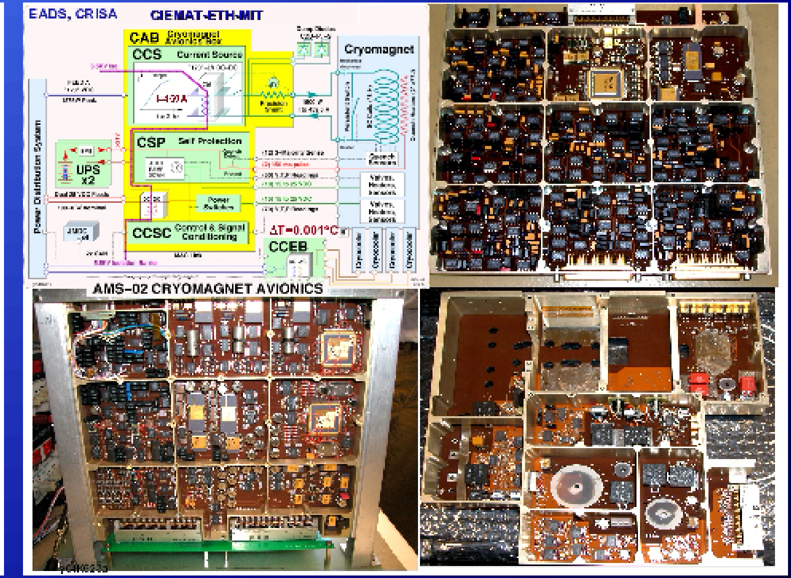


Cooled by 2500 l of superfluid helium

CIEMAT is one of the responsible institutes for the construction of the magnet and of the associated electronics

THE AMS EXPERIMENT: SUPERCONDUCTING MAGNET





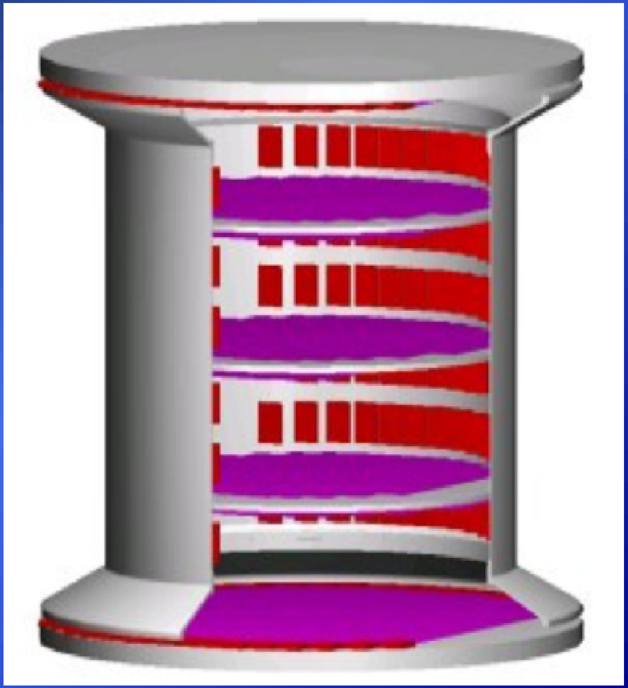
This will be (hopefully) the first large superconducting magnet used in space

THE AMS EXPERIMENT: TRACKER

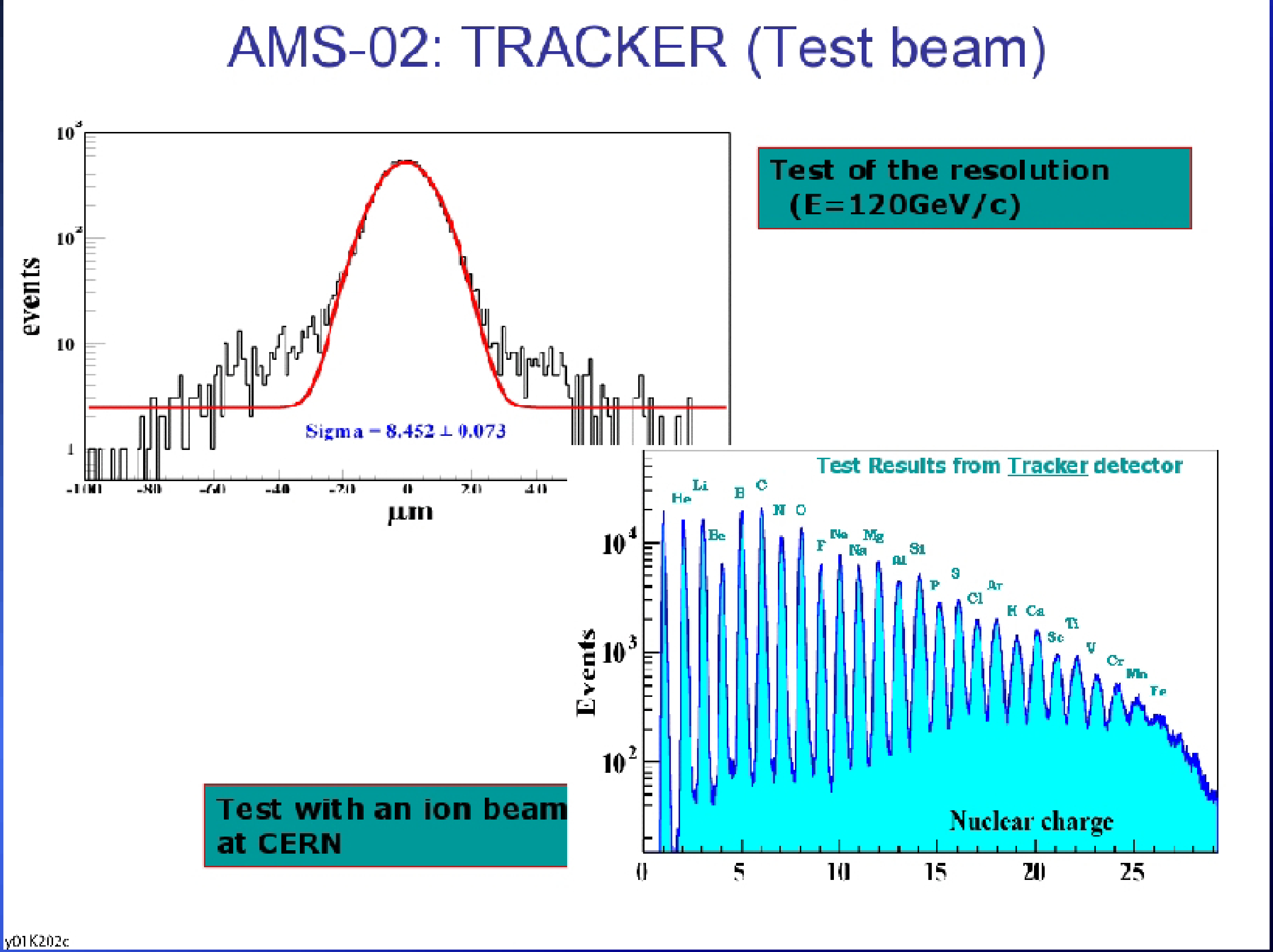
Determination of the track of particles:
Resolution in x coordinate 10 microns, Resolution in y coordinate 30 microns

Determination of the charge (Z) using de measurement of the energy loss

8 planes of silicon sensors ~200000 channels



THE AMS EXPERIMENT: TRACKER



AMS-02: TRACKER (Test beam)

Test of the resolution (E=120GeV/c)

Test with an ion beam at CERN

yD1K202c

Resolution and charge identification in a test beam at CERN

THE AMS EXPERIMENT: TOF

It gives the trigger
for the experiment

This system was tested
at AMS01

2x2 scintillation planes

Determination of the
particle velocity using
Time of Flight

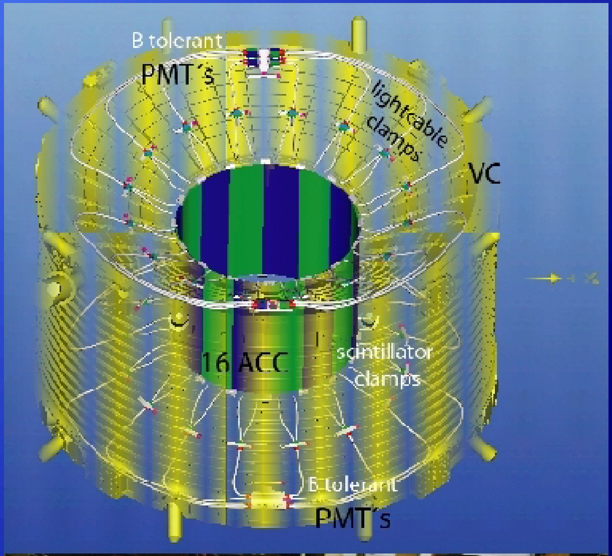
Time resolution ~120 ps;
Lenght ~1m

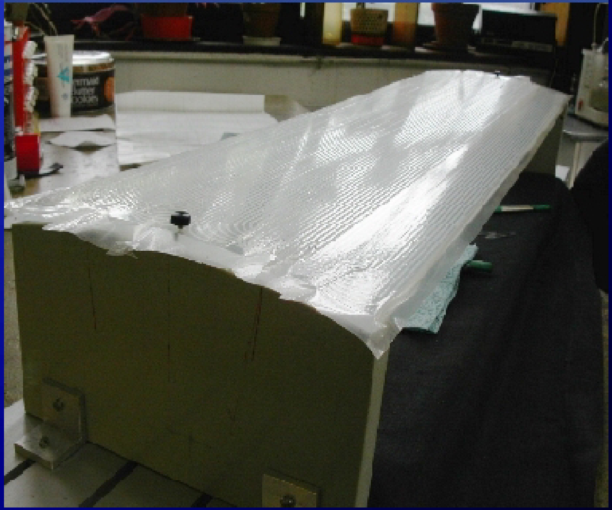
Determination of the charge
using the energy loss dE/dx

THE AMS EXPERIMENT: ANTICOUNTERS

They give a veto at the trigger level to the events produced by secondary interactions in the detector

They need high efficieny and a very fast response inside the magnetic field



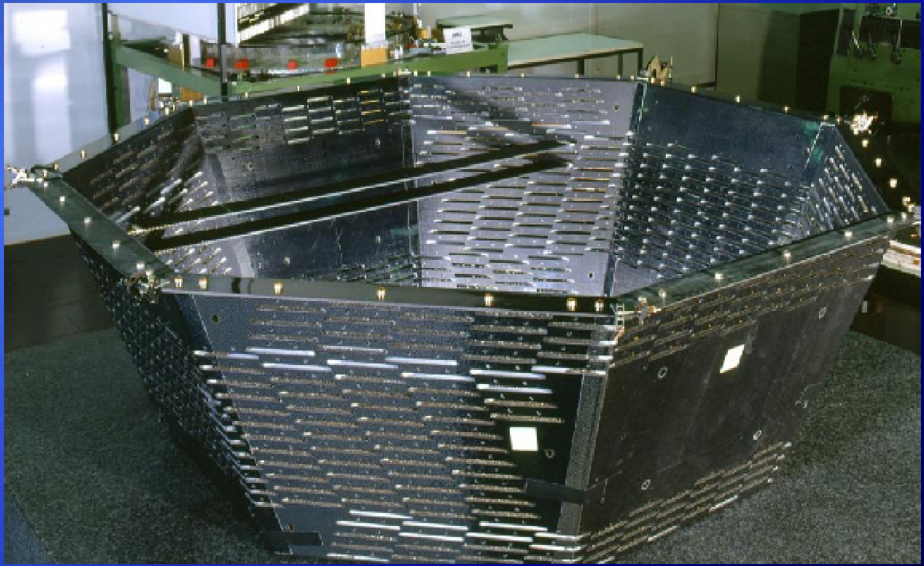


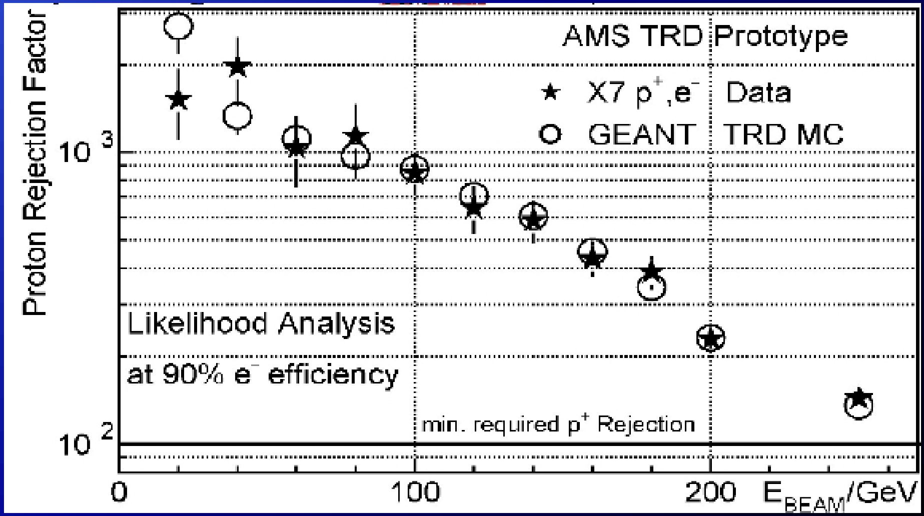
THE AMS EXPERIMENT: TRANSITION RADIATION DETECTOR

Identification of electrons/positrons

Additional tracking (20 points external to the magnetid field)

4 for x + 12 for y + 4 for x





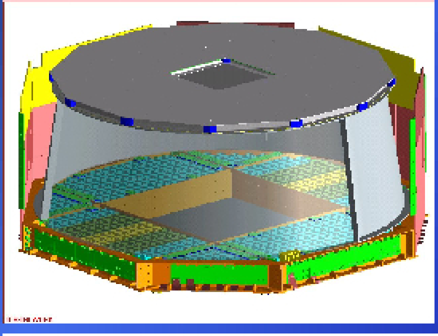
THE AMS EXPERIMENT: RICH

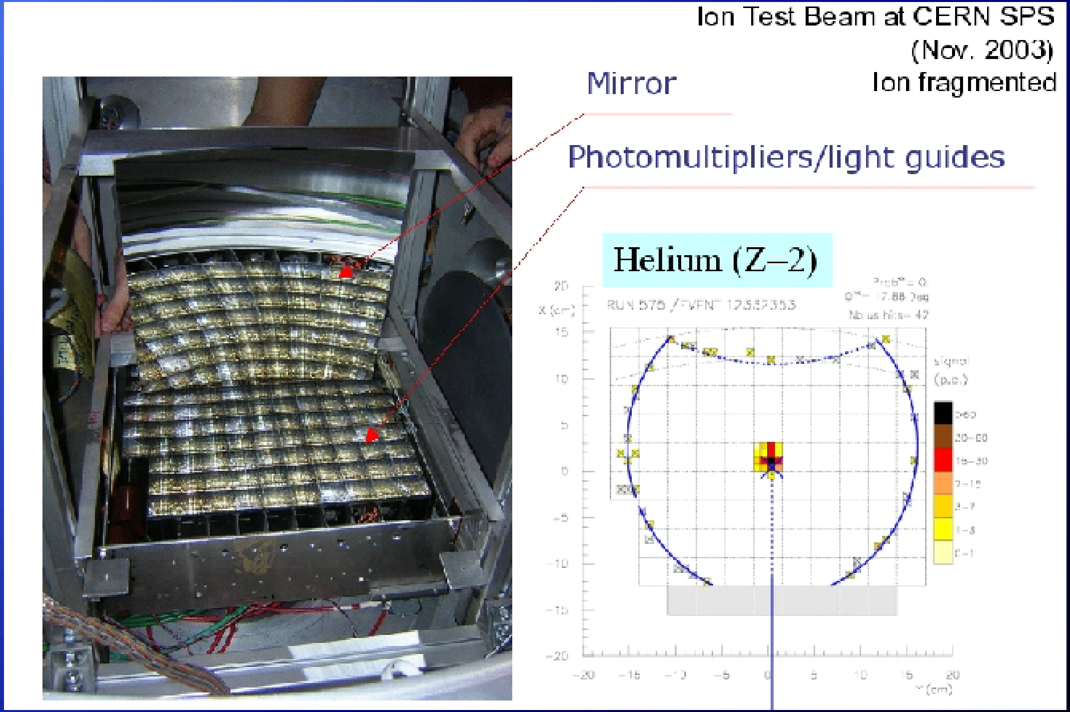
Precise measurement of the particle velocity(b)

Mesurement of the particle charge

CIEMAT is involved in the construction.

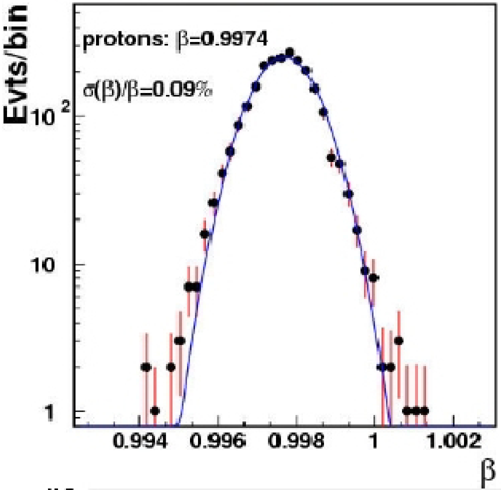
The RICH will be assembled at CIEMAT (starting in a few weeks).



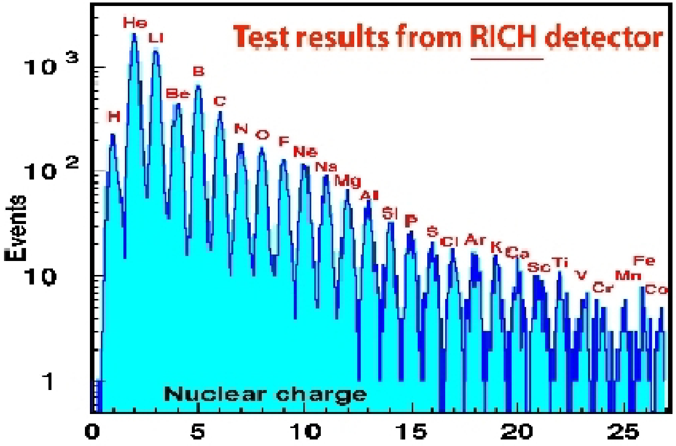

Ion Test Beam at CERN SPS
(Nov. 2003)
Ion fragmented

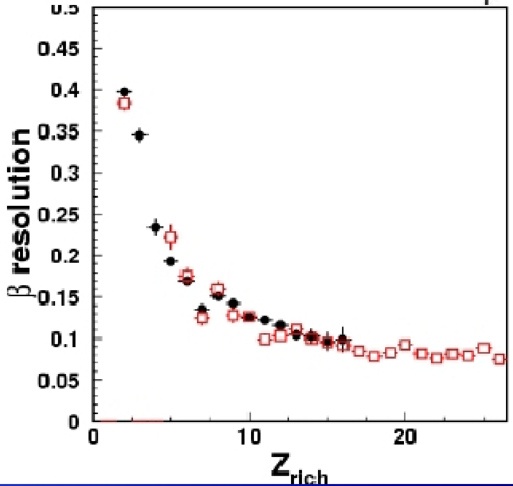
THE AMS EXPERIMENT: RICH

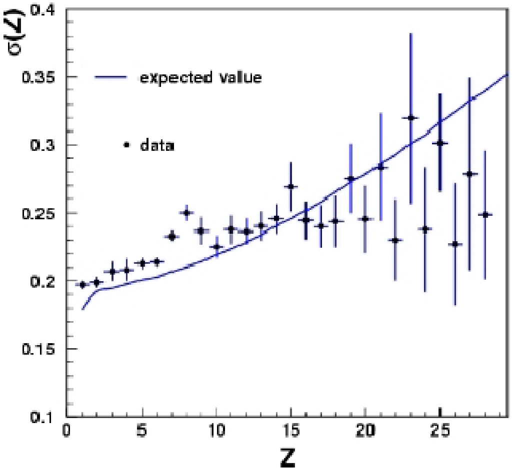
Velocity(Z=1): $\sigma(\beta)/\beta < 1\times10^{-3}$



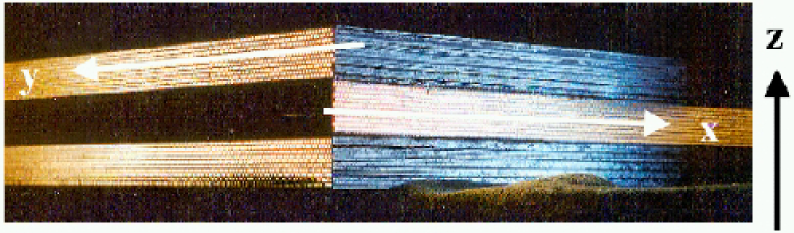
Charge measurement up to Z ~ 25





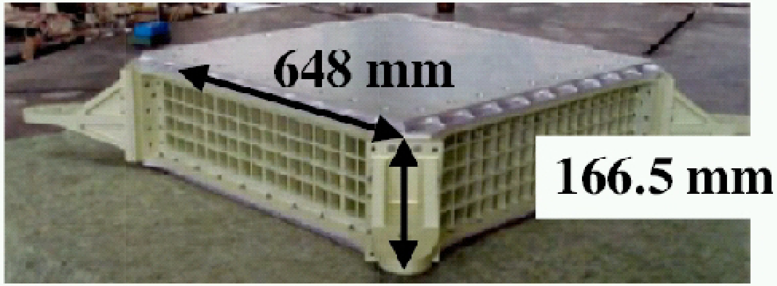


THE AMS EXPERIMENT: ELECTROMAGNETIC CALORIMETER



3 superlayers (out of 9)

1 superlayer = 11 grooved lead foils (thick~1mm) + 10 layers of scintillating fibers (∅ = 1mm)



324 PMT's

1 PMT= 4 anodes + last dynode

dynamic range : MIP → 1TeV

anode granularity :

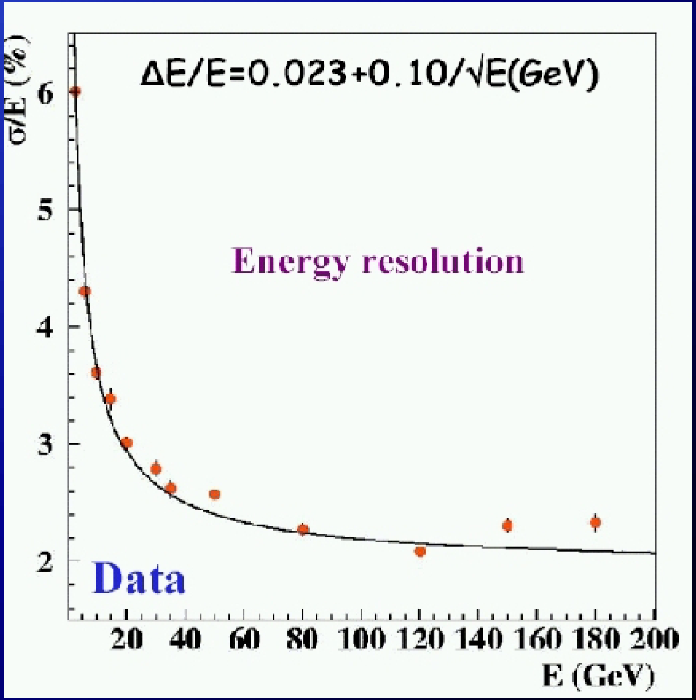
0.5 R_M in X/Y directions

0.9 X_0 in depth, 18 samplings

Identification of electrons, positrons and photons

Measurement of energy and direction of the particle

Trigger for photons



THE AMS EXPERIMENT: Calendar

Final Assembly of subdetectors and qualification tests	2005
Integration and full detector tests at CERN	2006
Thermal Cycles in vacuum at ESTEC (ESA)	2007
Integration at KSC	2007
Launch and Instalation on the ISS	N. E. T. September 2007

ESTEC -- European Spece Research and Technology Center,
Noordwijk, The Netherlands (ESA)
KSC -- Kennedy Space Center, Florida, USA (NASA)

THE AMS EXPERIMENT

GENERAL GOALS OF AMS

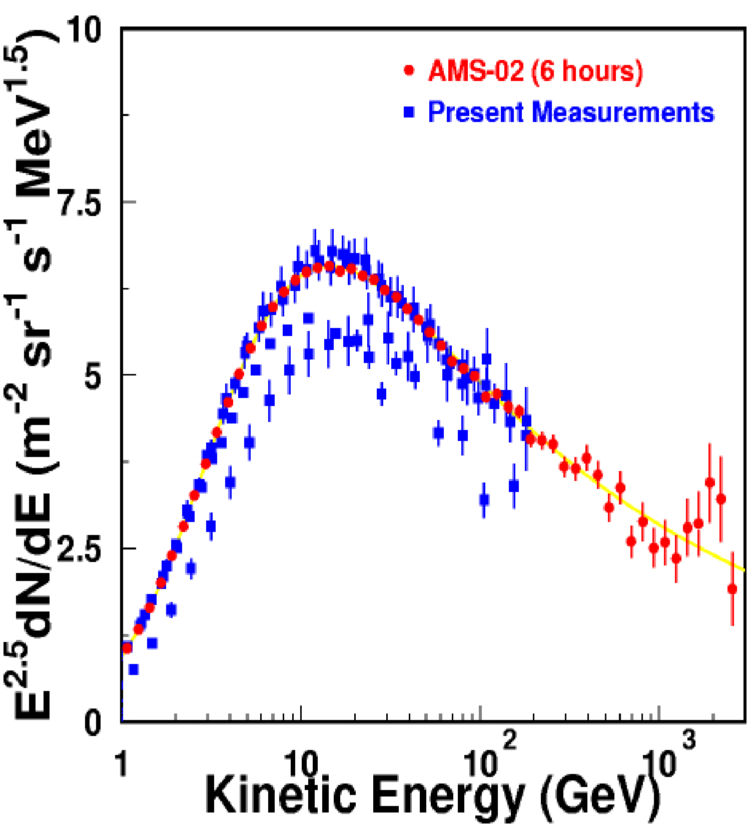
1) Full study of the cosmic ray composition and relative abundance of isotopes of light nuclei
   - Sources composition
   - Acceleration Mechanisms
   - Interactions with the interstellar medium (propagation)

2) Precise measurements of the antiproton spectra, antideuteria, positrons and photons
   - Dark Matter: SUSY candidates

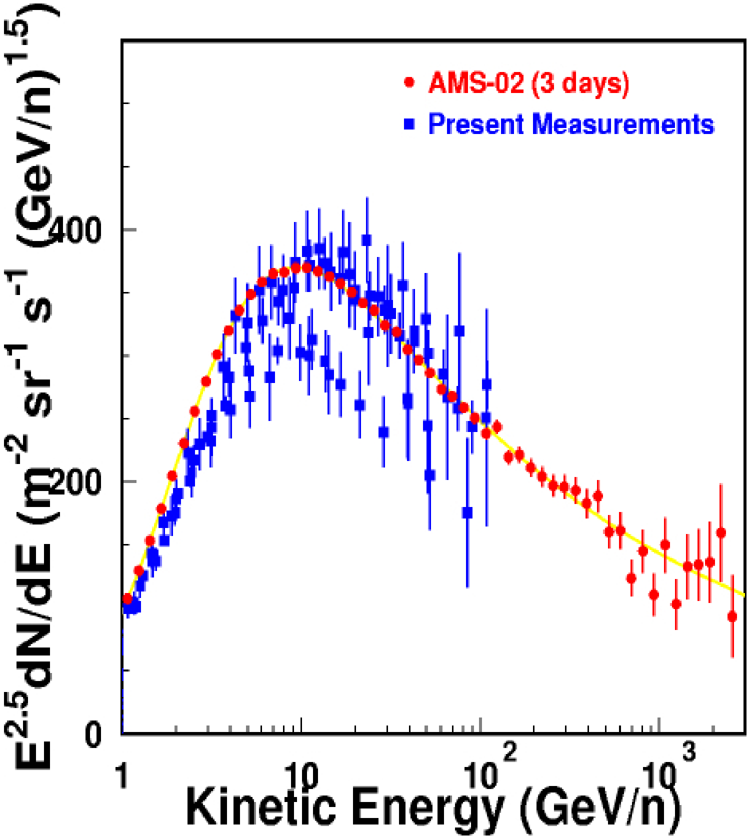
3) Detection of antihelium, anticarbon... with sensitivity 3 or 4 orders of magnitude better than current.
   - Antimatter: No conservation of baryonic number
   - CP violation

4) Exotics
   - Strangelets and other oddities

Results for proton and helium fluxes

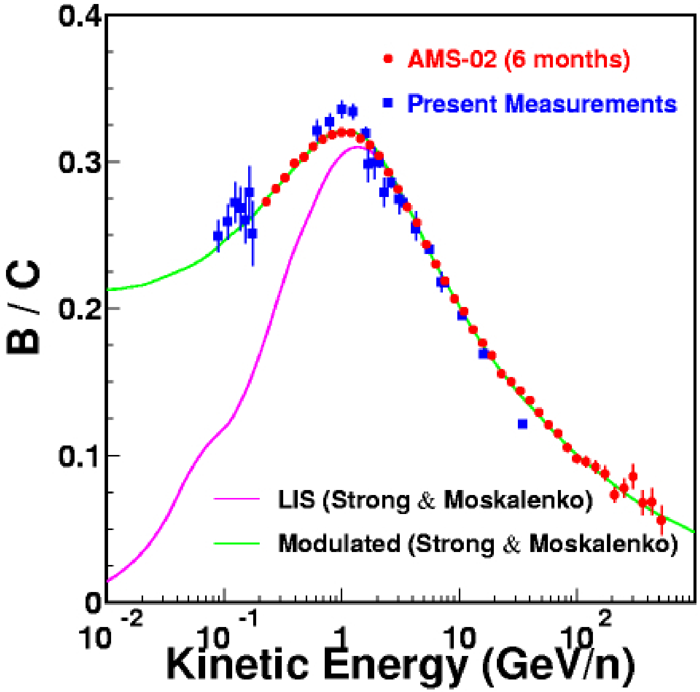


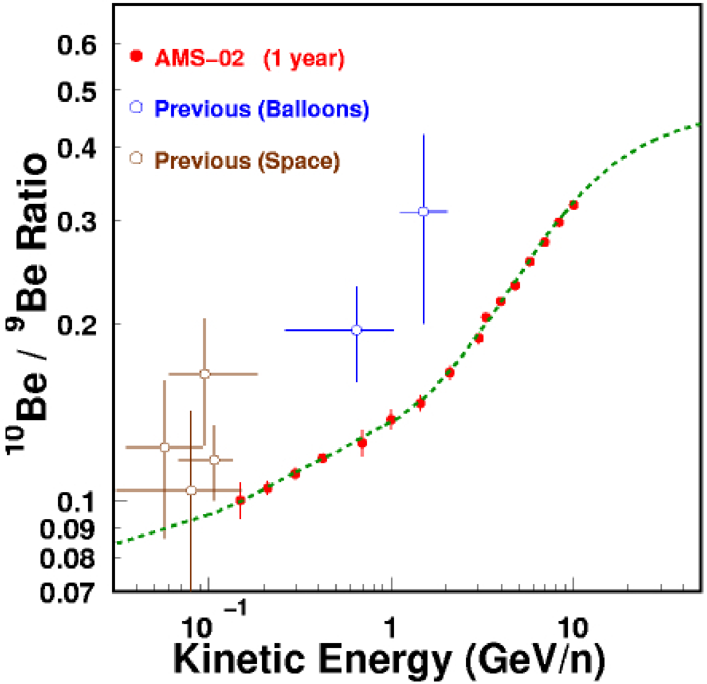
p



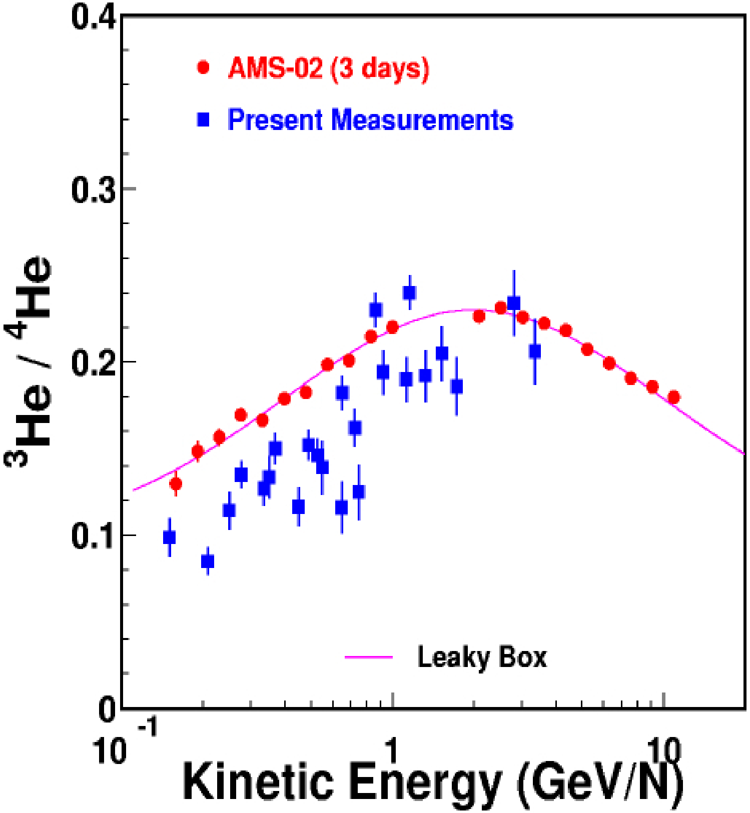
He

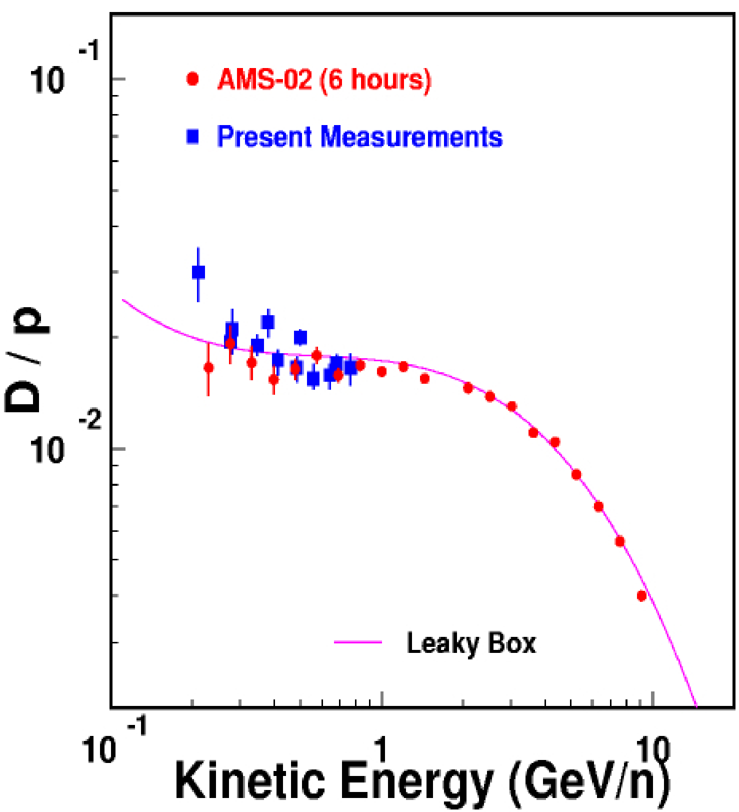
Cosmic Clocks



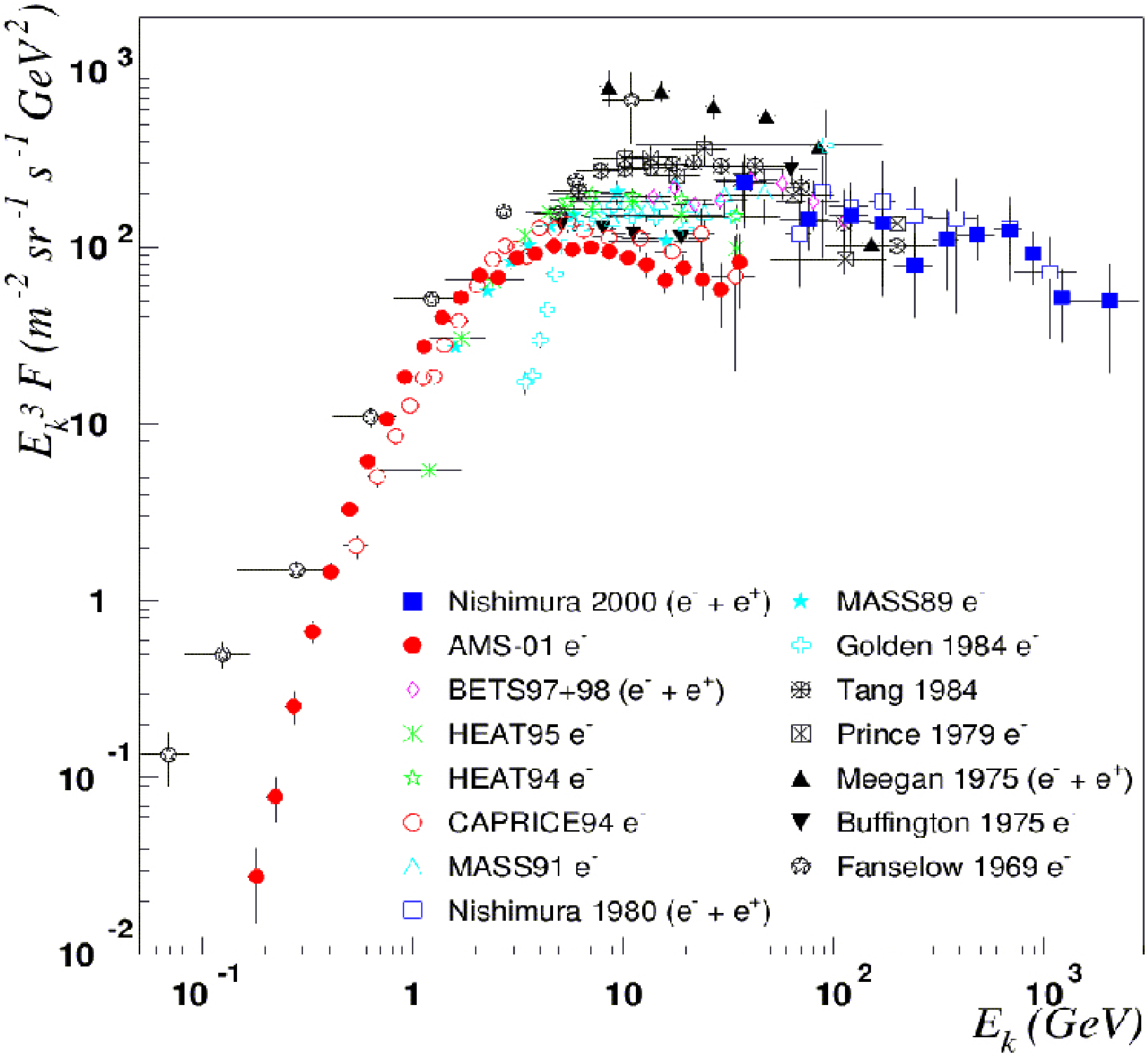


Cosmic Clocks



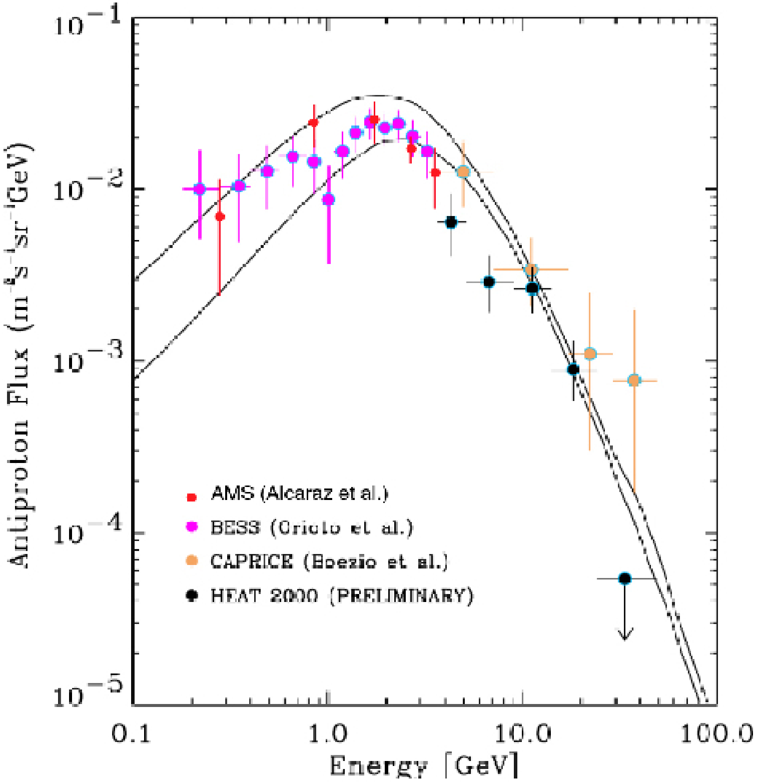


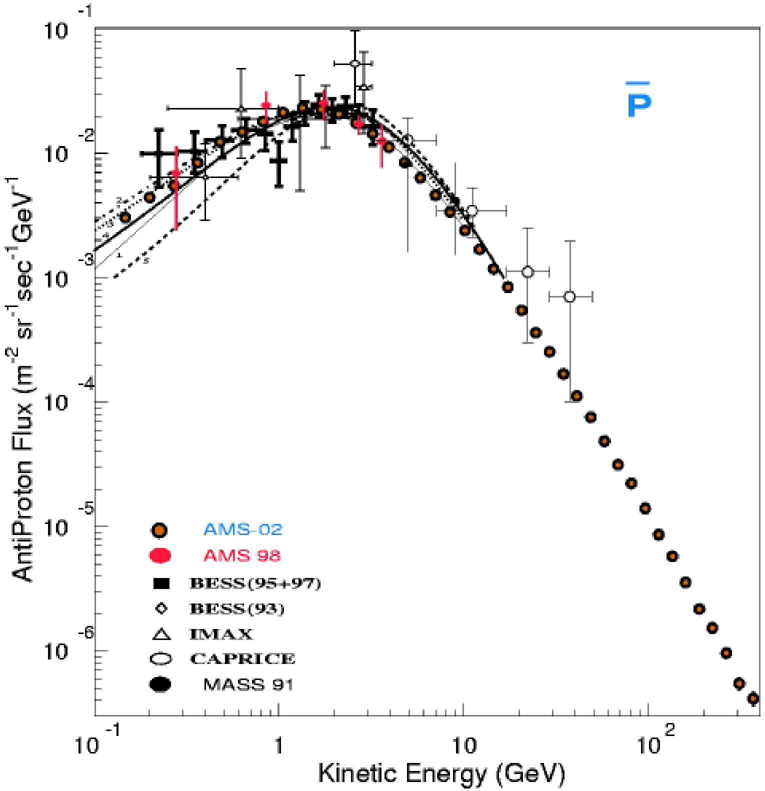
Electrons



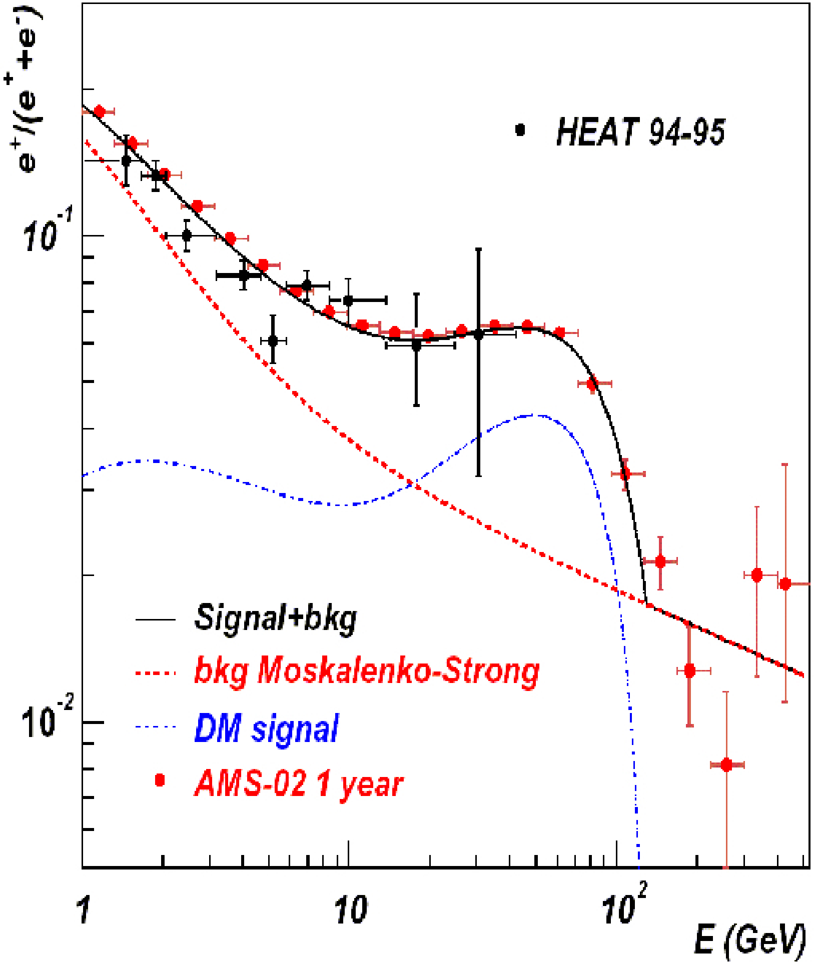
$E_k^3 F\ (m^{-2}\ sr^{-1}\ s^{-1}\ GeV^2)$
10^{-2}
10^{-1}
1
10
10^2
10^3
10^{-1}
1
10
10^2
10^3
$E_k\ (GeV)$
Nishimura 2000 ($e^- + e^+$)
AMS-01 e^-
BETS97+98 ($e^- + e^+$)
HEAT95 e^-
HEAT94 e^-
CAPRICE94 e^-
MASS91 e^-
Nishimura 1980 ($e^- + e^+$)
MASS89 e^-
Golden 1984 e^-
Tang 1984
Prince 1979 e^-
Meegan 1975 ($e^- + e^+$)
Buffington 1975 e^-
Fanselow 1969 e^-

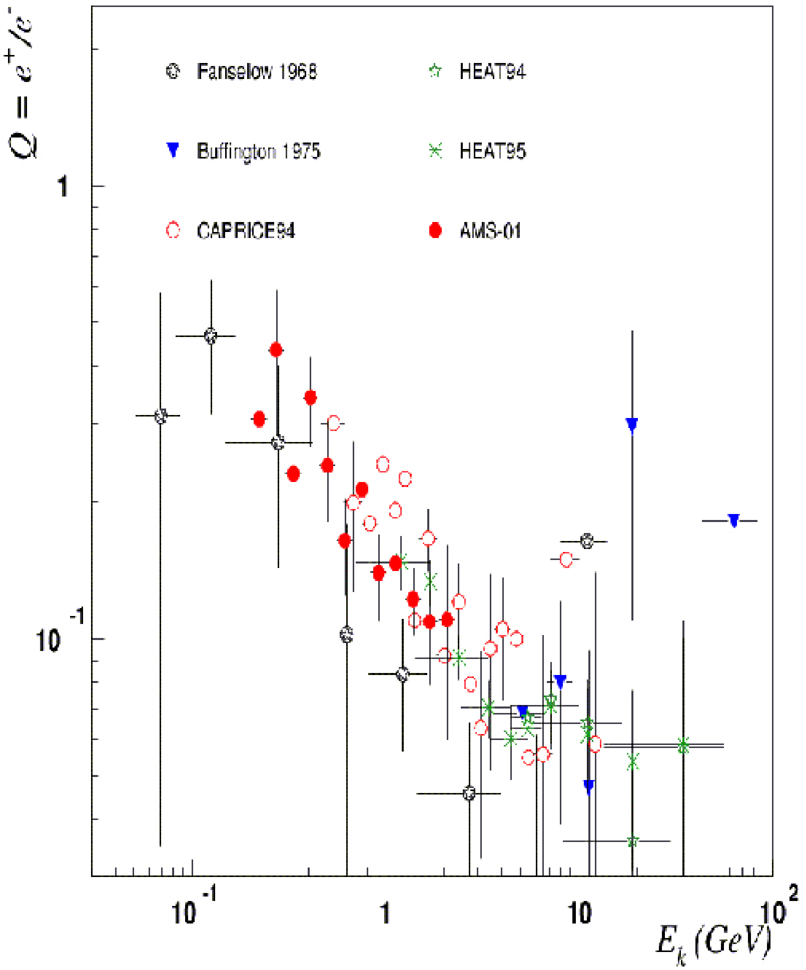
Antiprotons





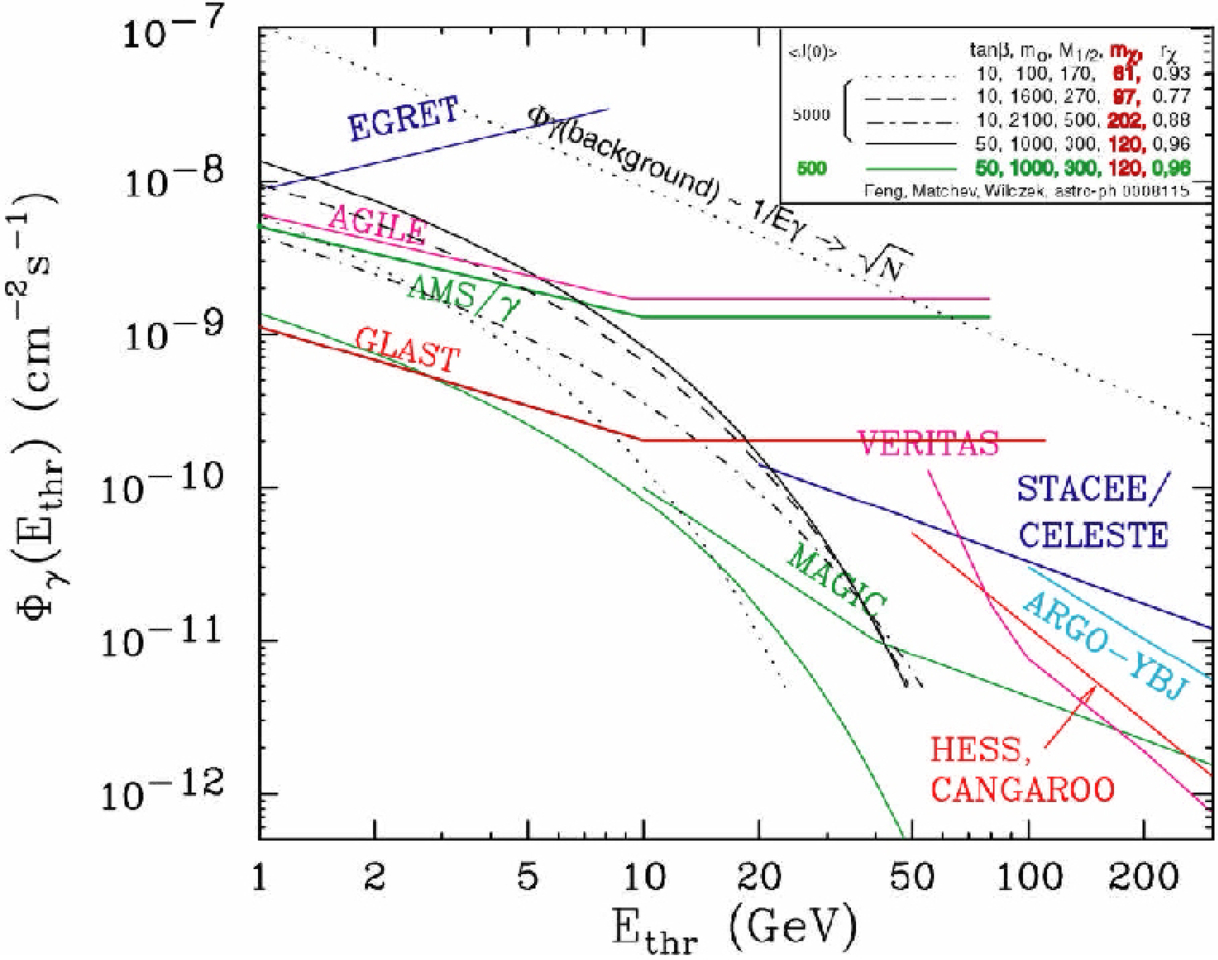
Positrons


e+/(e+ +e-)
10-1
10-2
1
10
10 2
E (GeV)
HEAT 94-95
Signal+bkg
bkg Moskalenko-Strong
DM signal
AMS-02 1 year

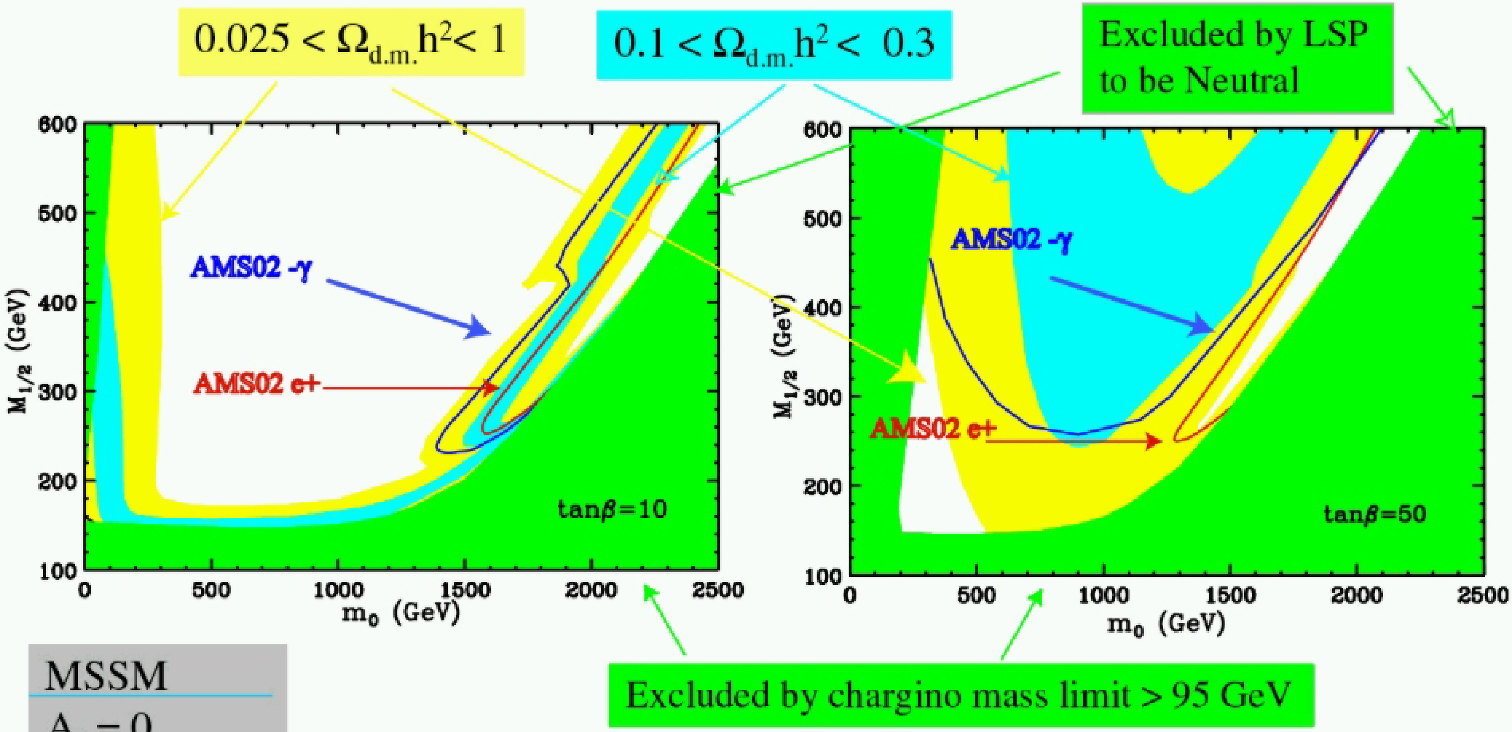

Q = e+/e-
1
10 -1
Fanselow 1968
HEAT94
Buffington 1975
HEAT95
CAPRICE94
AMS-01
10 -1
1
10
10 2
Ek (GeV)

Gamma Rays

SUSY D.M. γ fluxes above E_{thr} vs Point Source Sensitivity



SUSY in AMS



$0.025 < \Omega_{d.m.}h^2 < 1$

$0.1 < \Omega_{d.m.}h^2 < 0.3$

Excluded by LSP to be Neutral

Excluded by chargino mass limit > 95 GeV

MSSM

$A_0 = 0$

$\mu > 0$

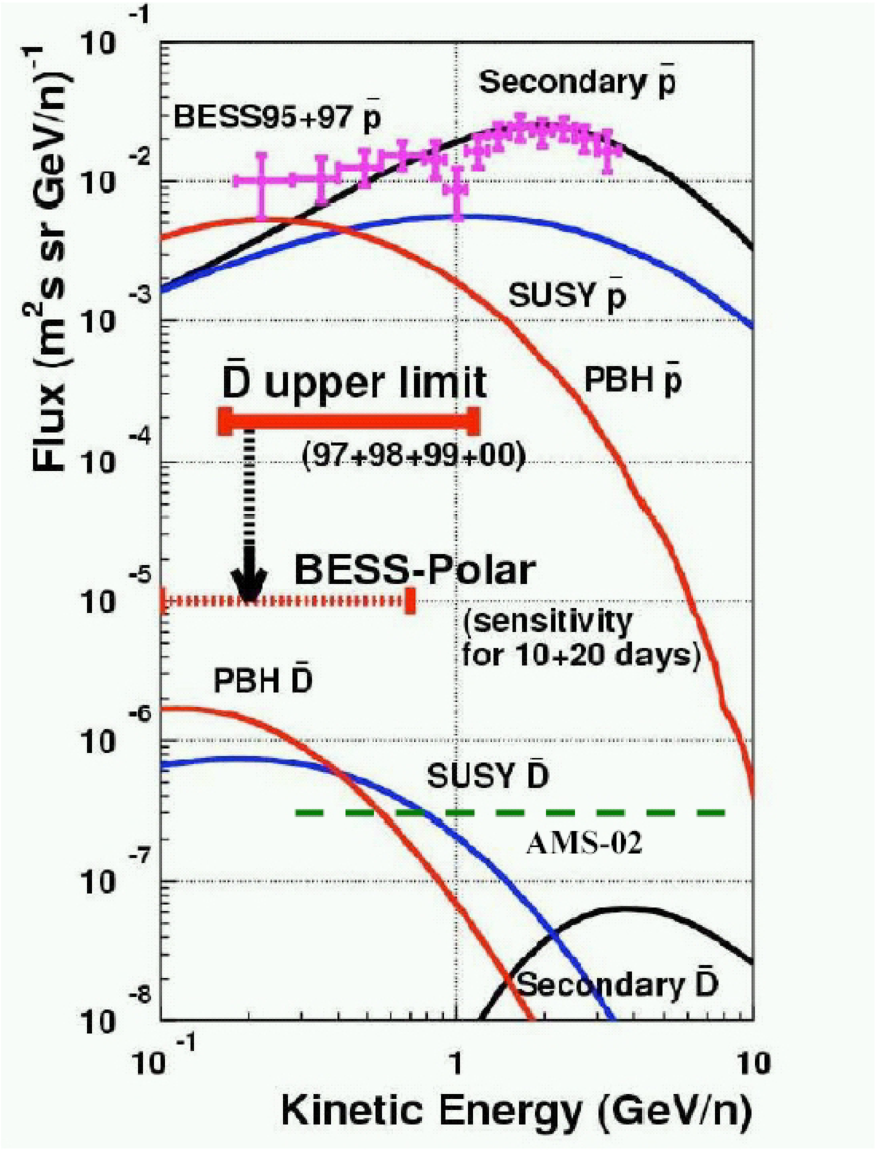
$m_t = 174$ GeV

$\tan\beta = 10$

Fixed Halo profile, indirect limits better if halo is clumpy

adapted from astro-ph 0008115

These results are STRONGLY MODEL DEPENDENT (both of galactic halo and SUSY)

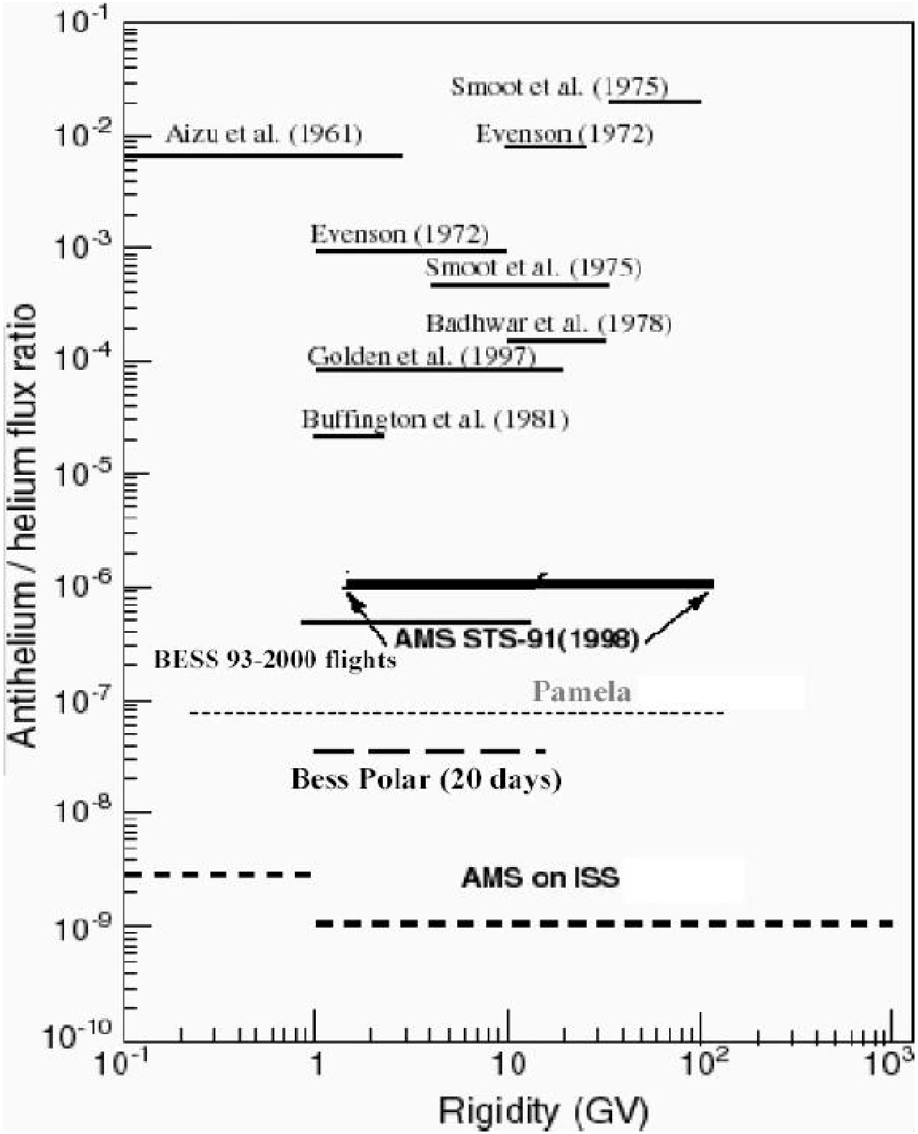


ANTIDEUTERIUM

Not observed to date

It is expected to improve several orders of magnitude

AMS-02 starts to be sensitive to new physics



ANTIMATTER

Searches of antihelium nuclei

Not all the models are already excluded

CONCLUSIONS

The study of cosmic rays has given very interesting results both for astrophysics and for particle physics

Spacial experiments will give in the coming years the most precise measurements ever done in cosmic rays

There are discovery potential for new physics beyond the Standard Model: Dark Matter (SUSY), primordial black holes, primordial antimatter, strangelets…

Mainly in antiproton, positron, antideuterium and gamma rays fluxes.