Cosmic Ray Astrophysics with AMS-02

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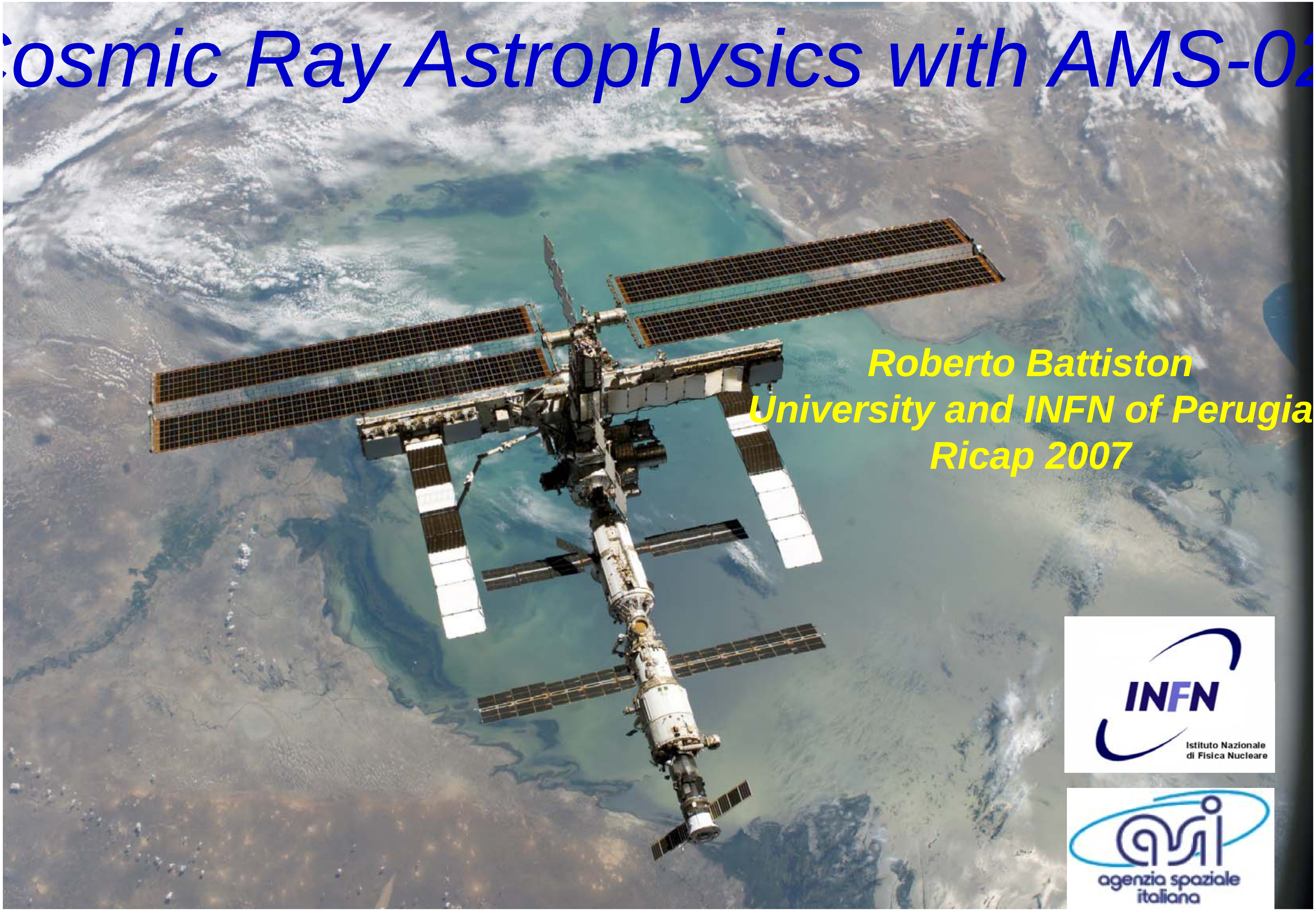
Ricap 2007



INFN
Istituto Nazionale di Fisica Nucleare

asi
agenzia spaziale italiana

The Standard Cosmological Model

This model tell us that the Universe is:

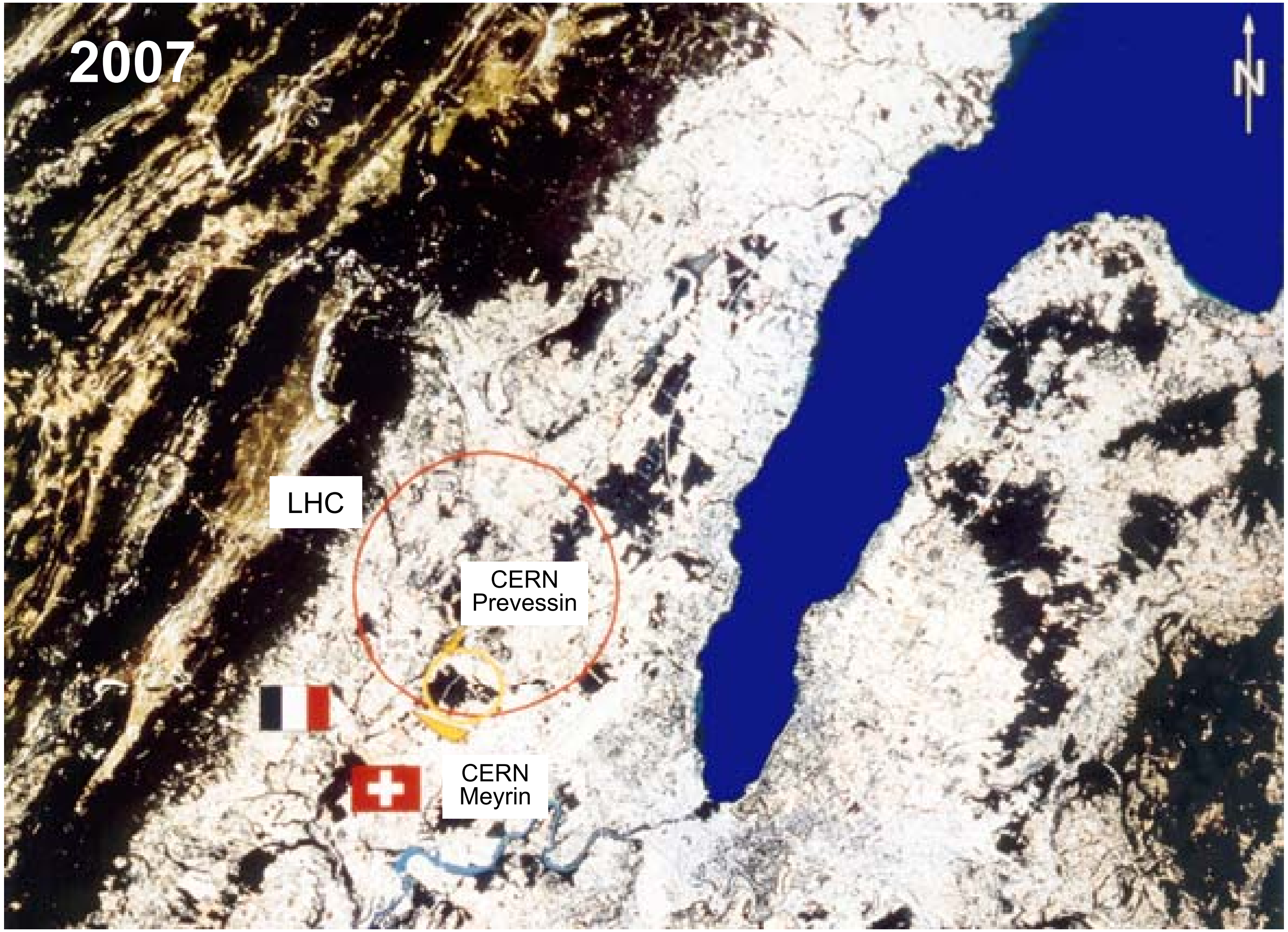
- Spatially flat, homogeneous and isotropic on large scales
- Composed of
  - Radiation, ordinary matter → 4.4 %
  -
  -
  -

Never before we have been so knowingly ignorant about Nature

- Galaxies and large scale structures born from tiny adiabatic Gaussian fluctuations of matter and fields

  which we know nothing about

Development of Accelerators



Energy: 0.0001 *eV*

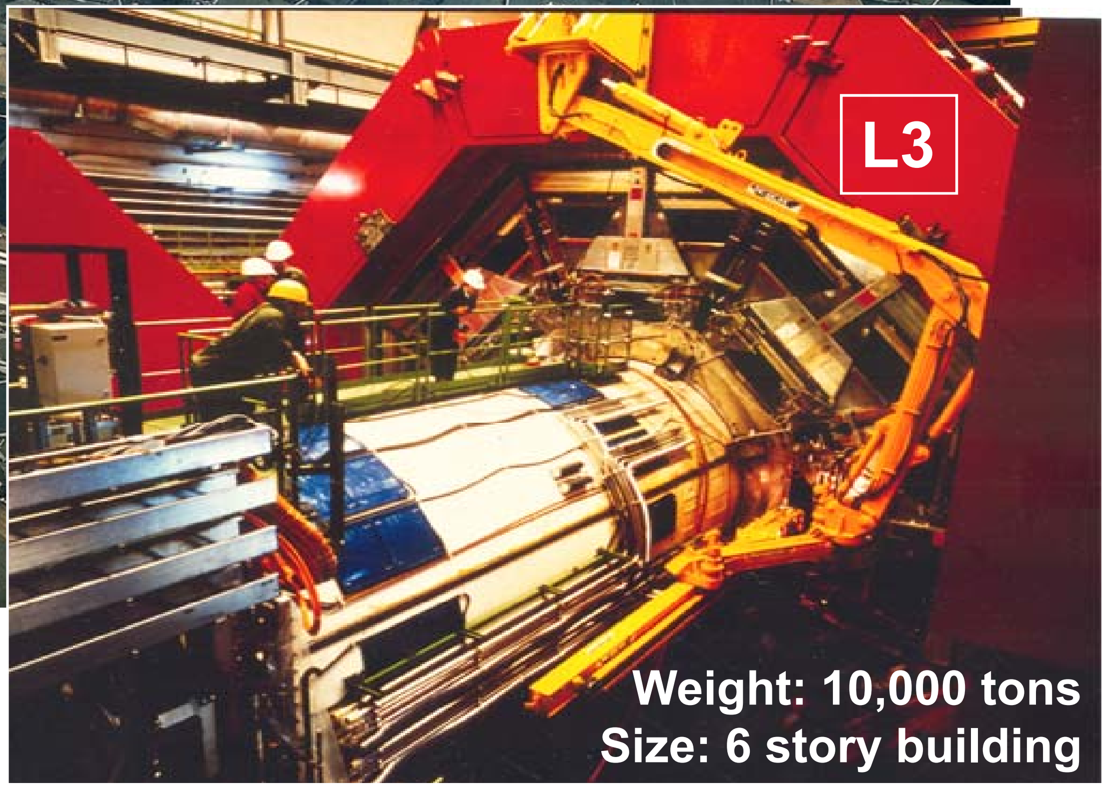
Galileo's work on Gravity

Energy: 100,000,000,000,000,000 *eV*

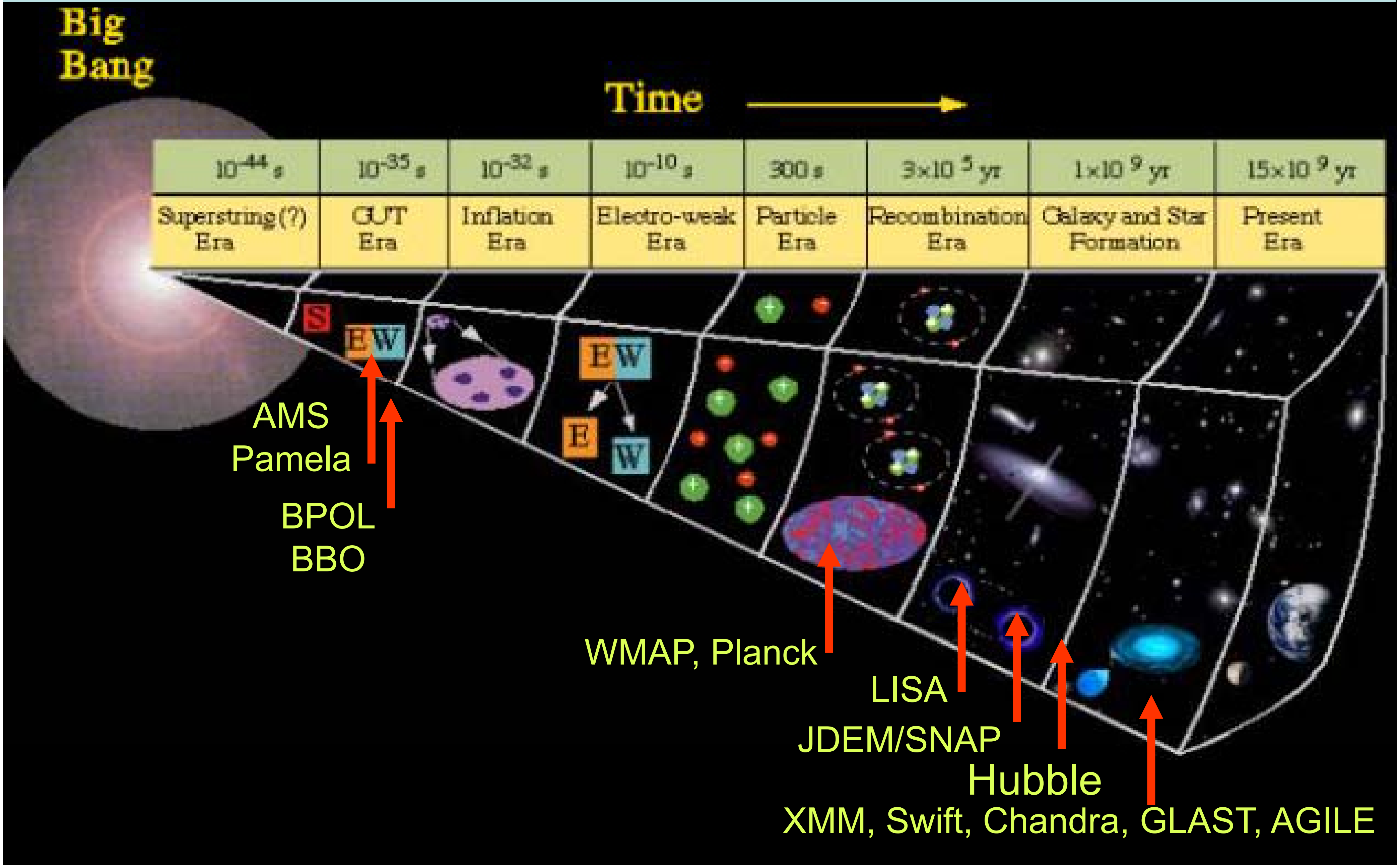
Study fundamental building blocks of nature

Example of study the basic elements of Matter

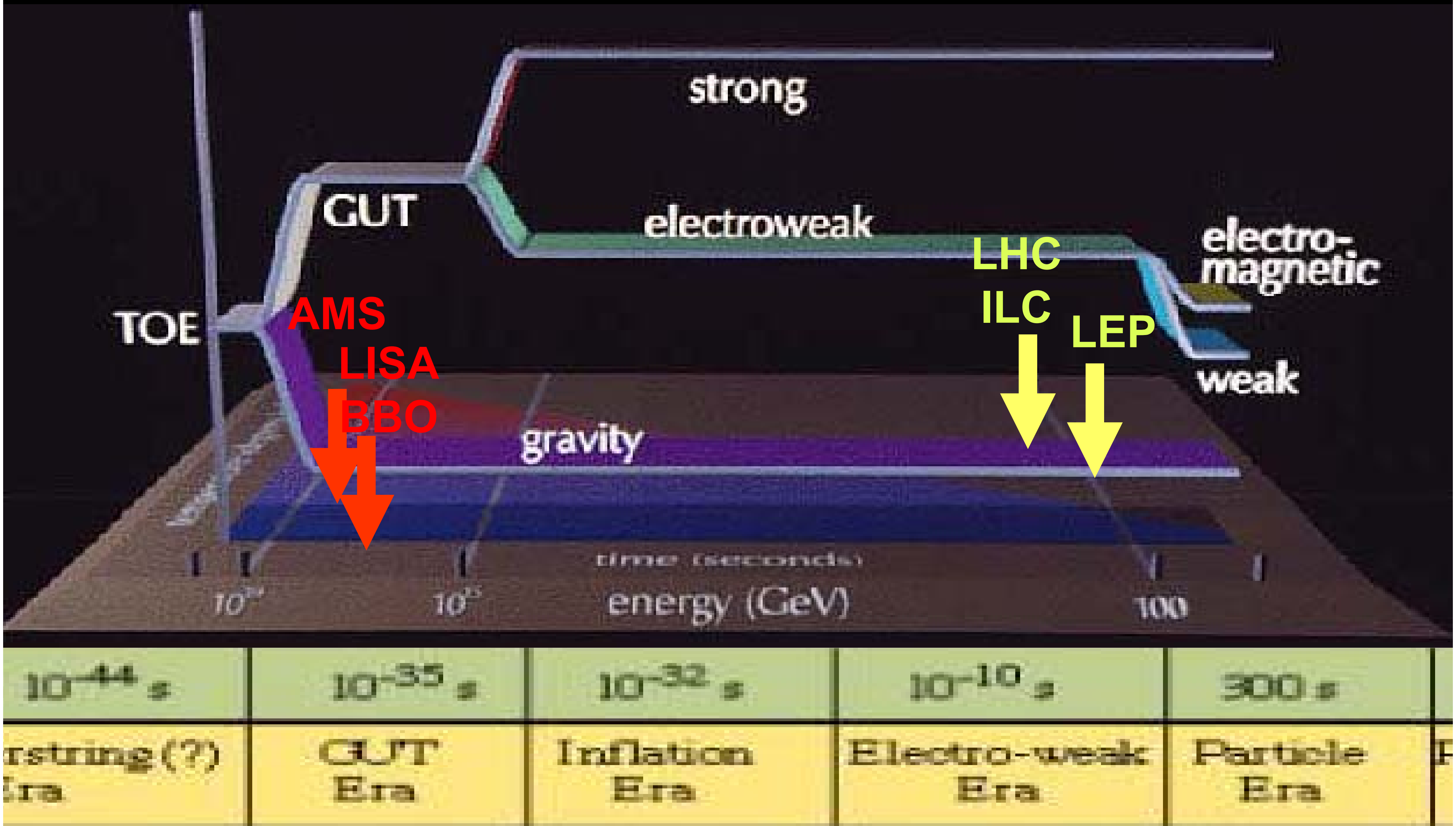
1981-2003
600 Physicists
20 Countries

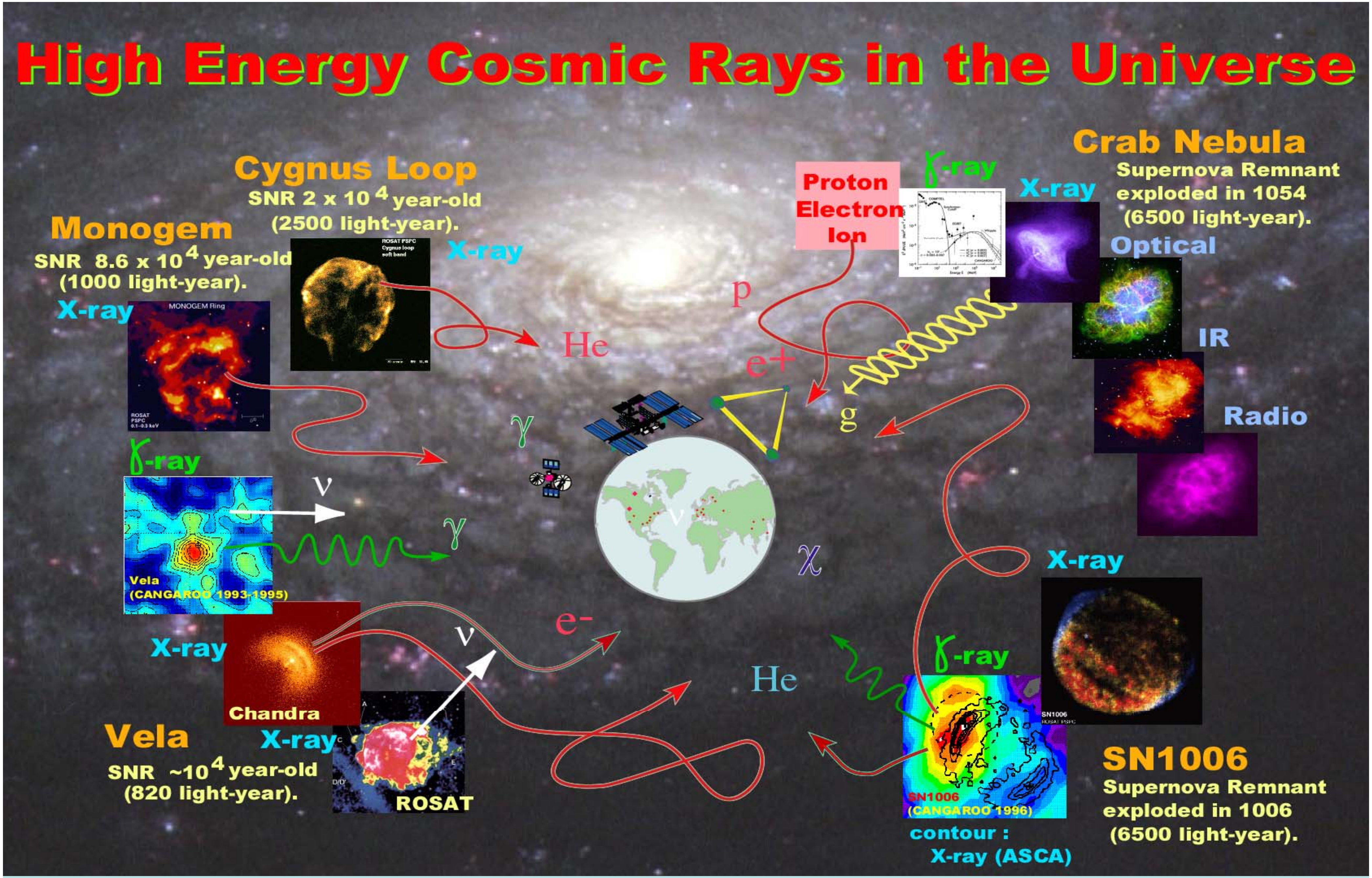


The universe is the ultimate laboratory to study fundamental physics…….



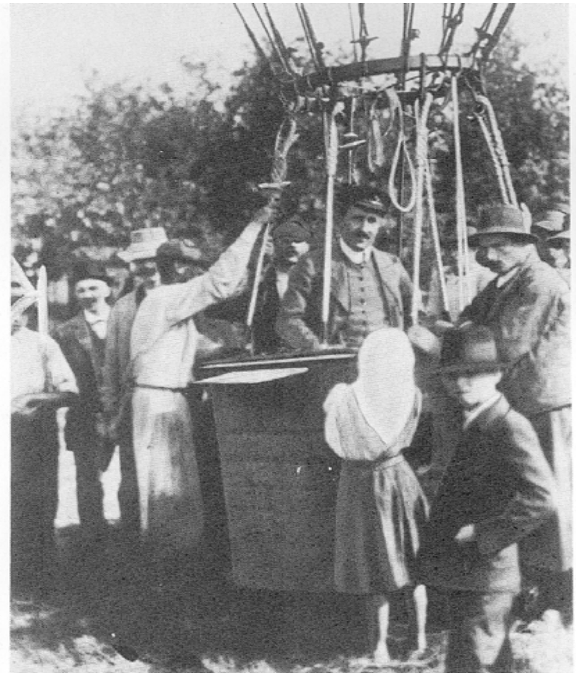
…….reaching energies which cannot be studied at accelerators………



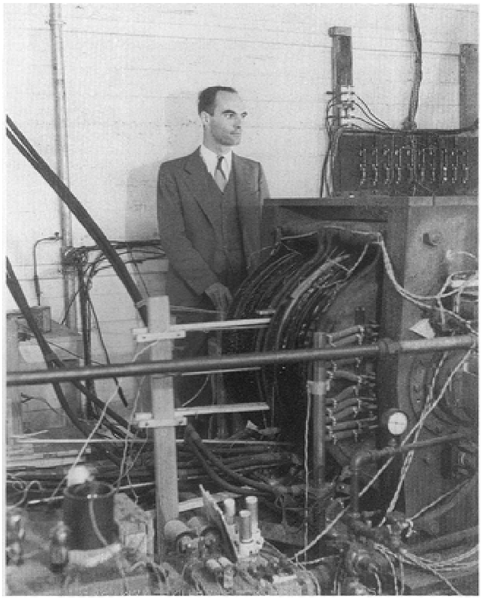


….or charged/neutral particles, gravitational waves…….

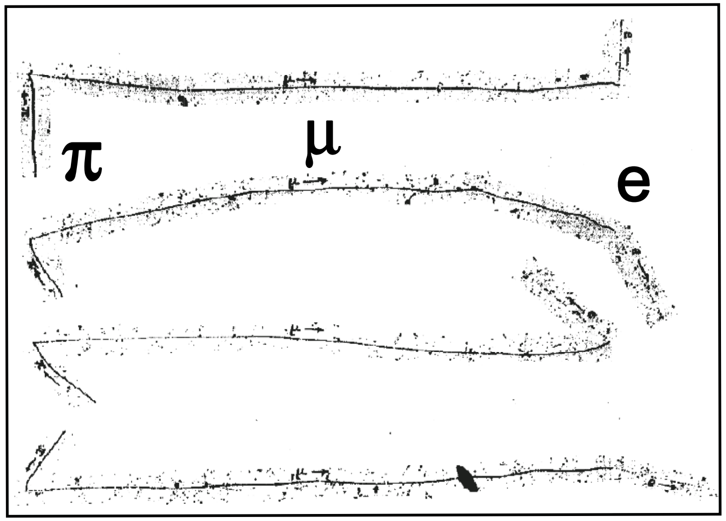
Physics of Charged Cosmic Rays



1912: Discovery of Cosmic Rays
V. Hess



1932: Discovery of positron
C.D. Anderson



1947: Discovery of pions
C. Powell

Discoveries of

1936: Muon (μ)

1938: 10^{15} eV CR

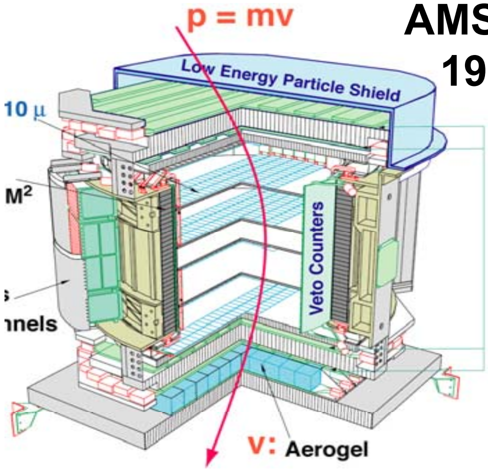
1949: Kaon (K)

1949: Lambda (Λ)

1952: Xi (Ξ)

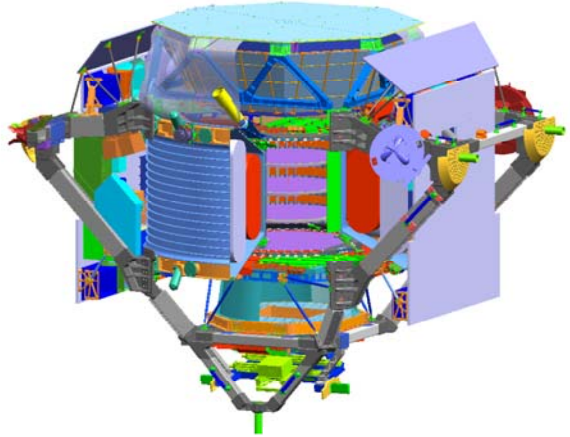
1953: Sigma (Σ)

AMS 01
1998

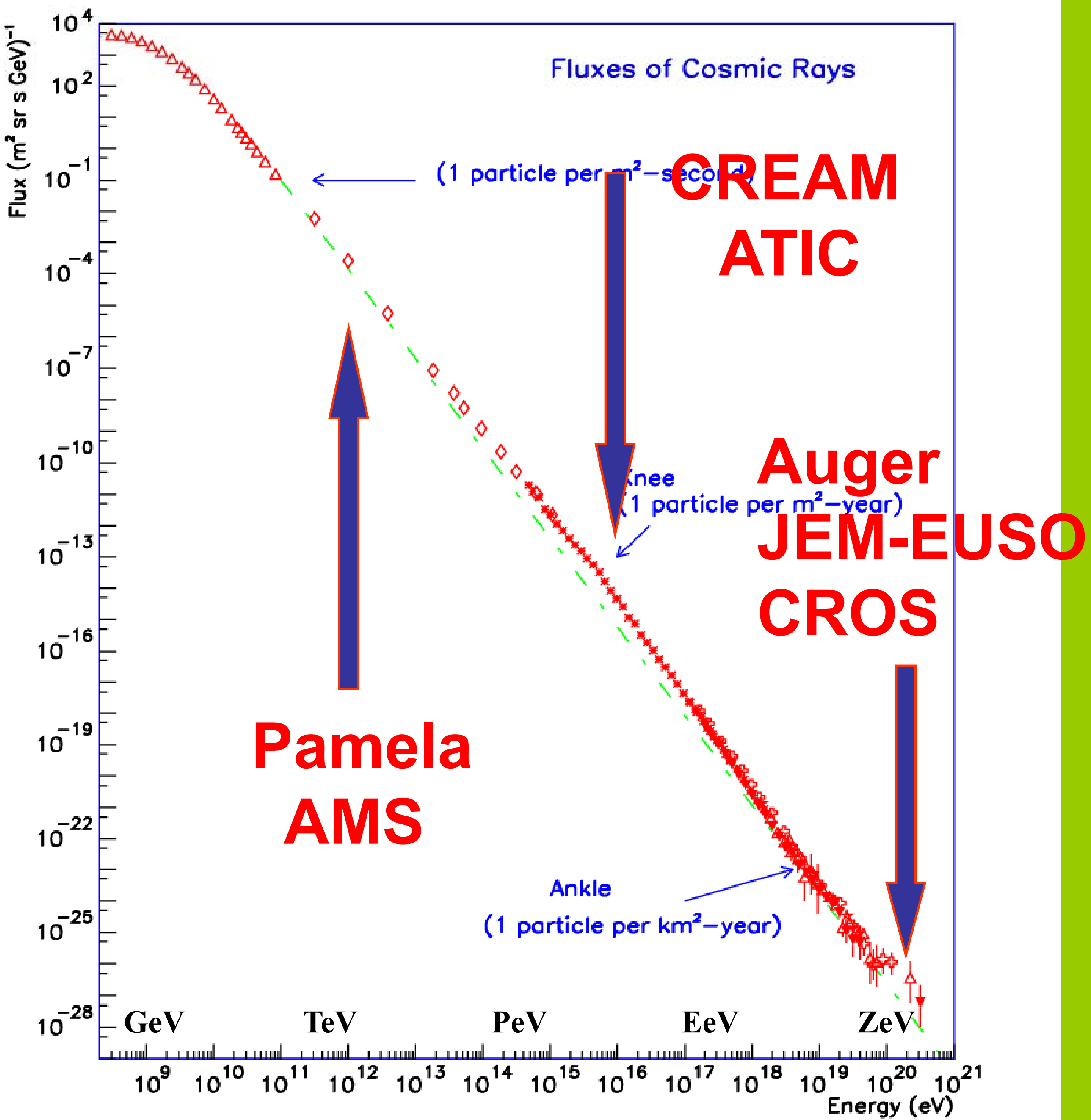


PAMELA
2006

AMS 02
2009



Precision magnetic spectrometers in Space



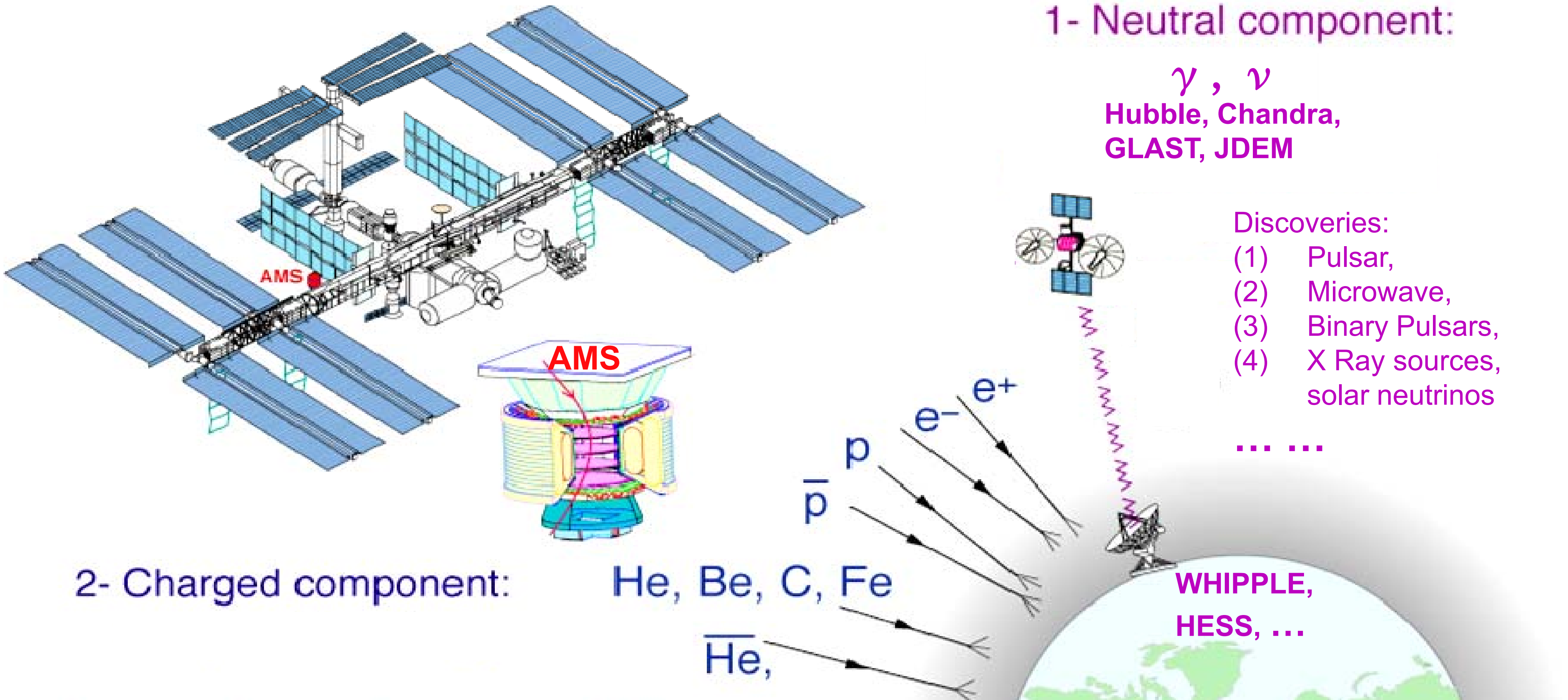
Very Accurate Measurement of the Charged CR Spectrum and Composition

Absence of Antimatter → CP violation, GUT

Dark Matter → SUSY, Axions

Atmospheric neutrinos → Neutrino mass

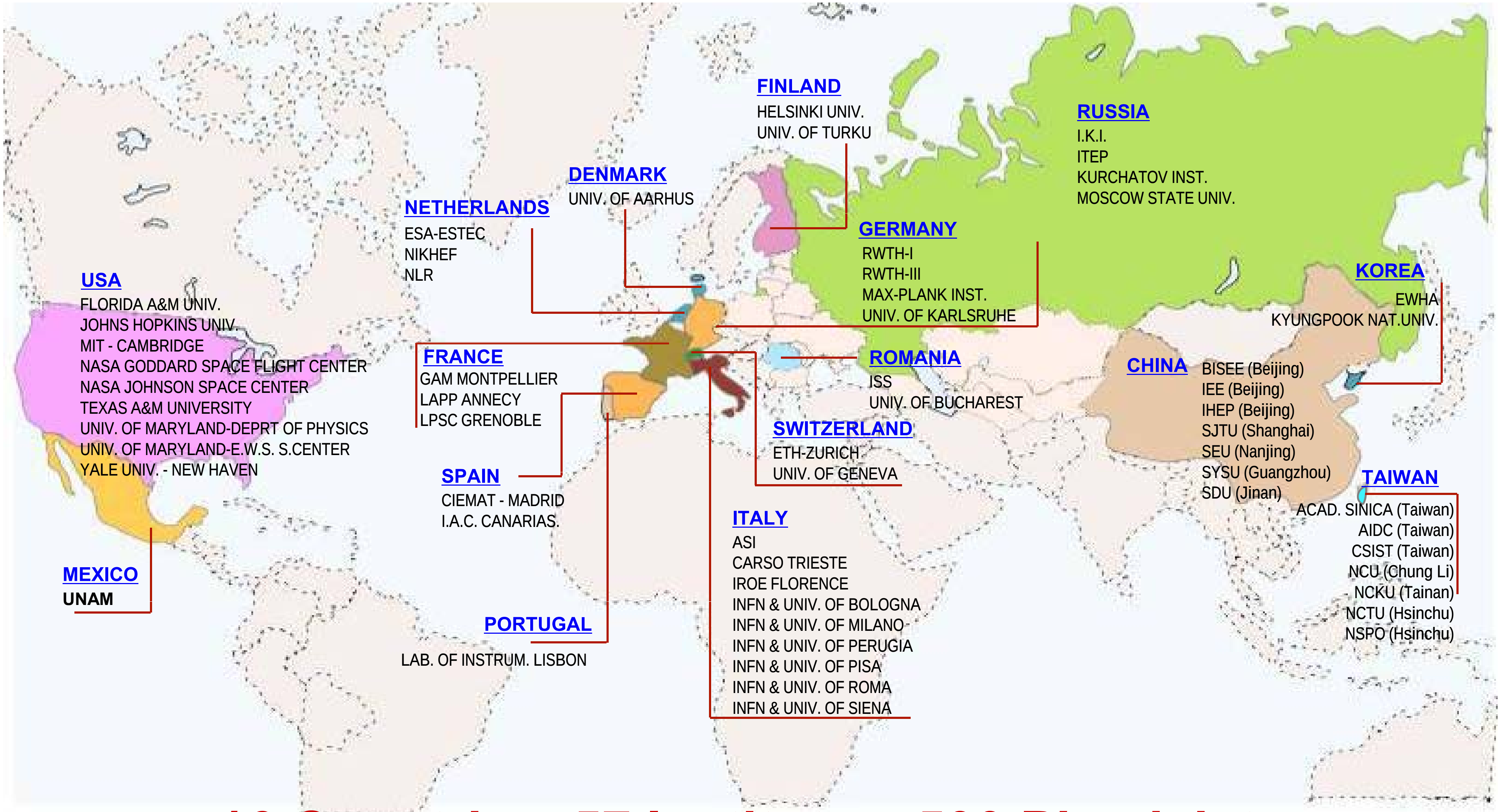
Fundamental Science on the International Space Station



The highest energy particles are produced in cosmic rays.

On Earth we live under 60 miles of air, which is equivalent to 30 feet of water. This absorbs all the charged particles.

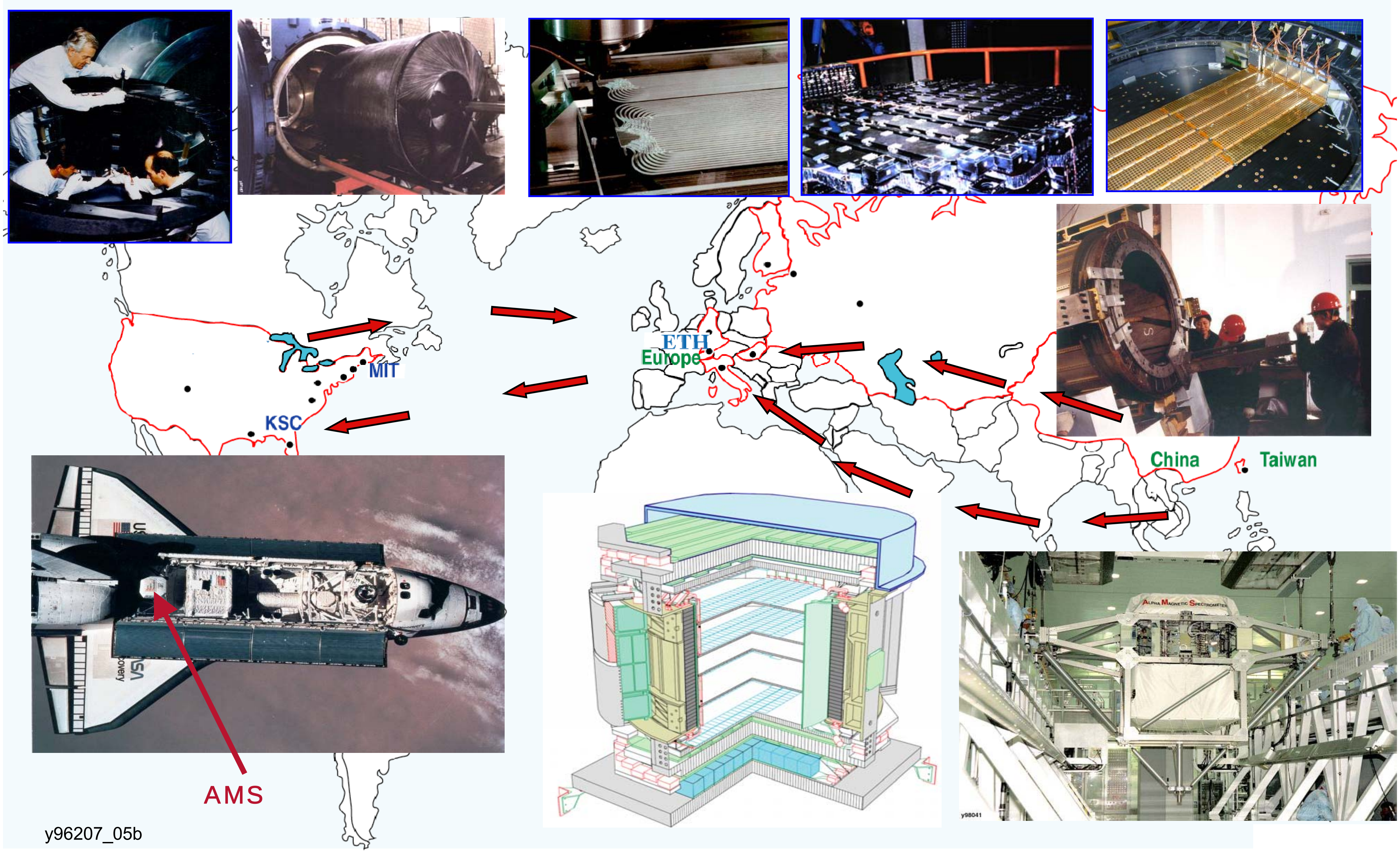
Alpha Magnetic Spectrometer (AMS) is an example of the type of research that can only be carried out on the ISS.



16 Countries, 57 Institutes, 500 Physicists

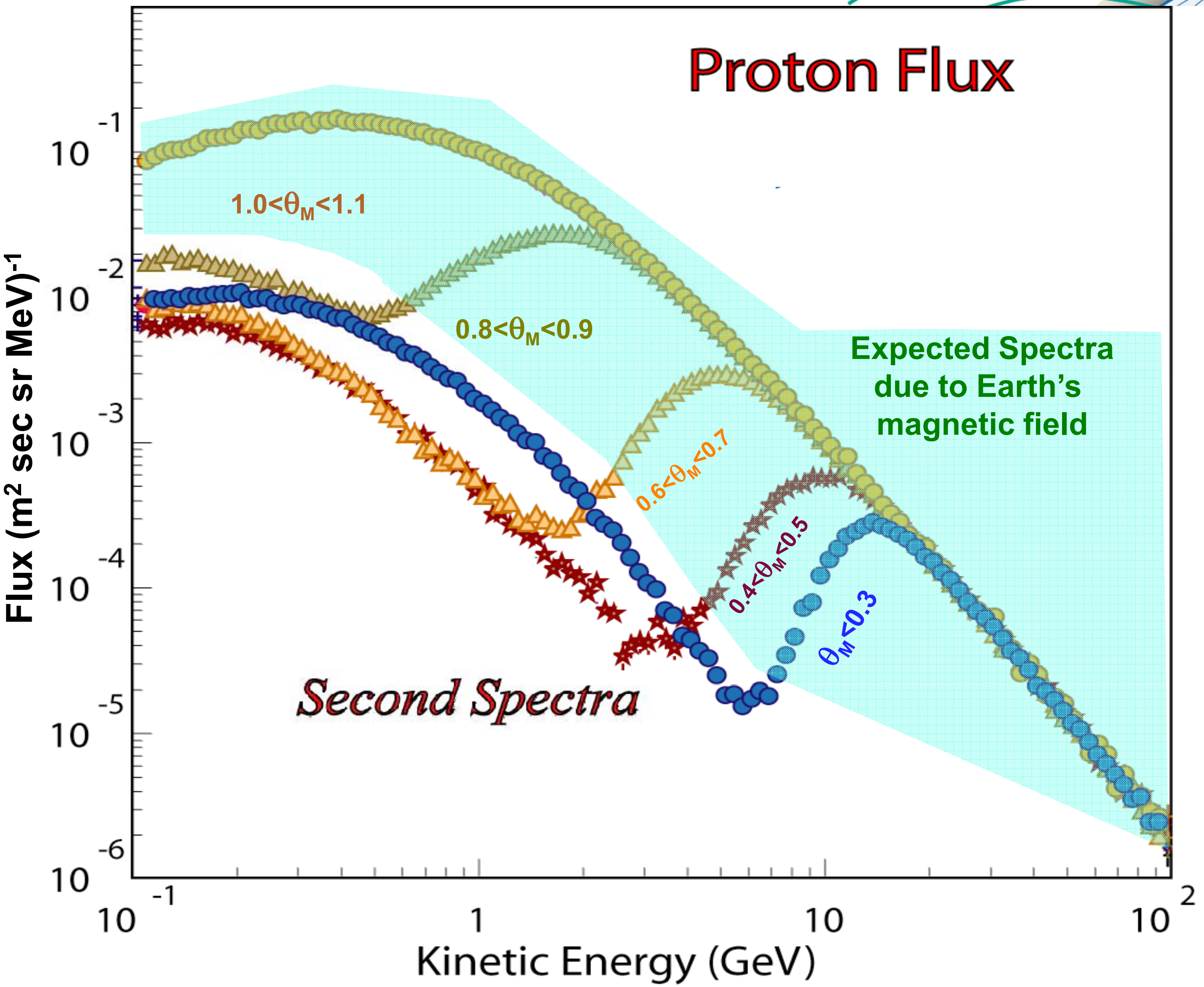
First flight AMS-01

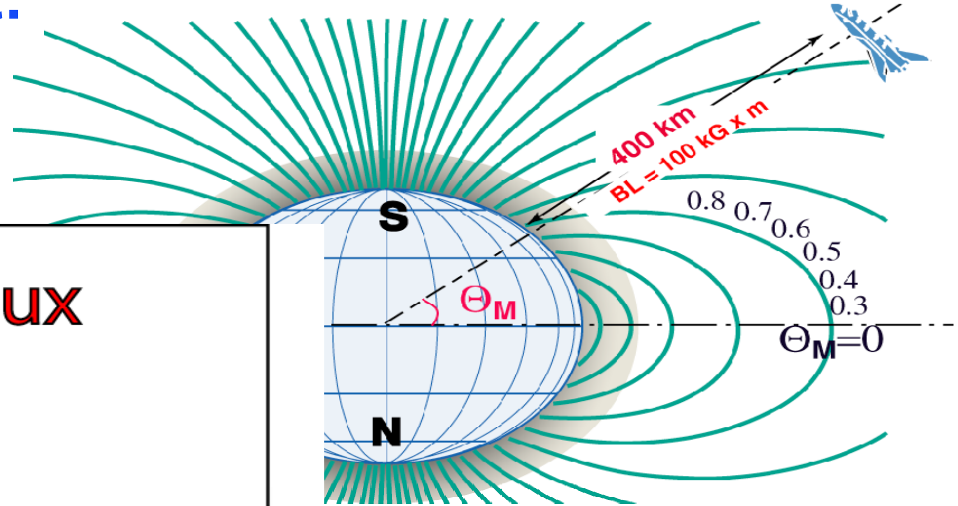
Approval: April 1995, Assembly: December 1997, Flight: 10 days in June 1998



Unexpected results from first flight:

1- the existence of two Spectra in proton flux

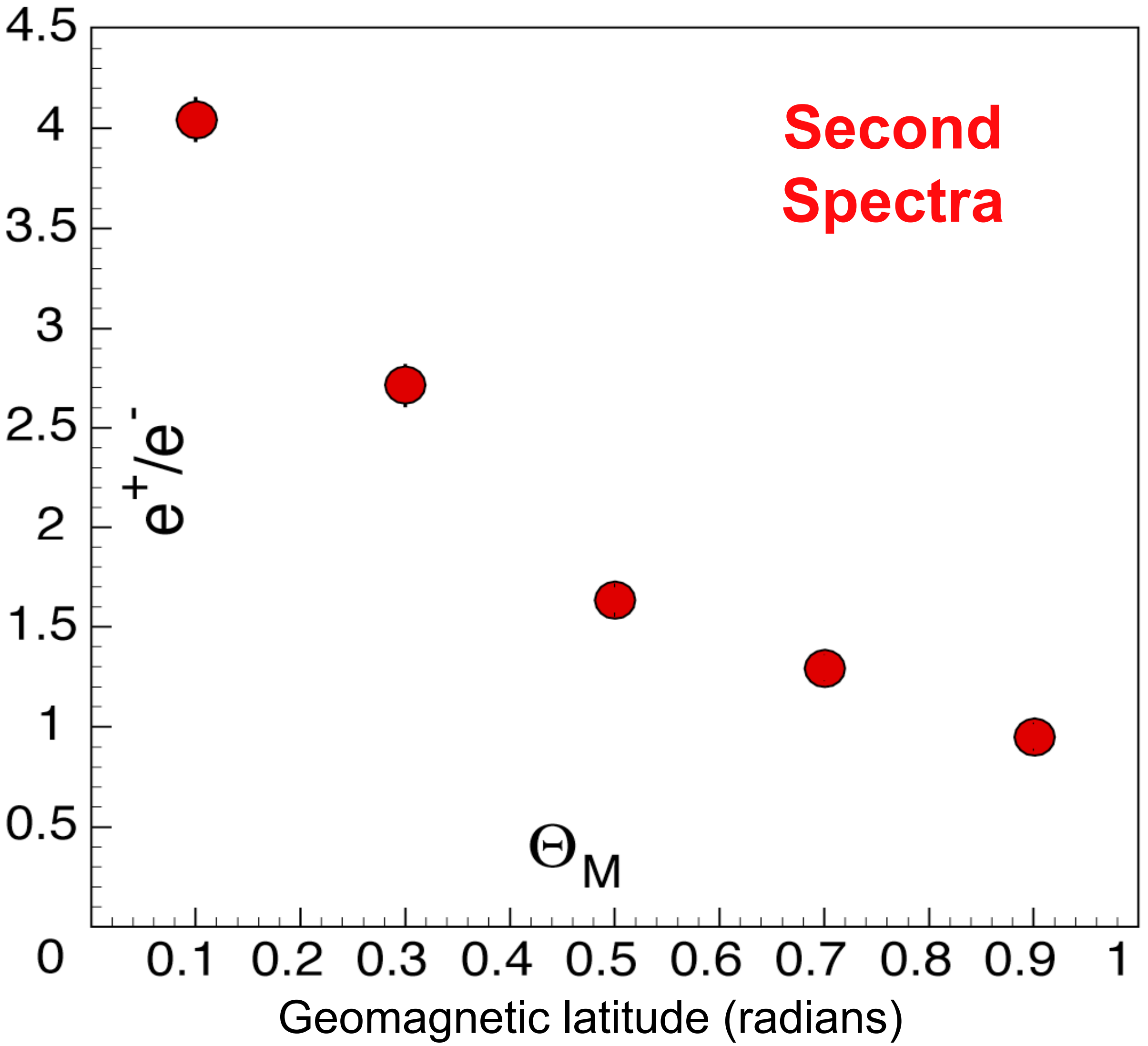




B472 (26 Jan 2000) 215-226

Unexpected results from first flight:

2- There are many more positrons (e^+) than electrons (e^-)

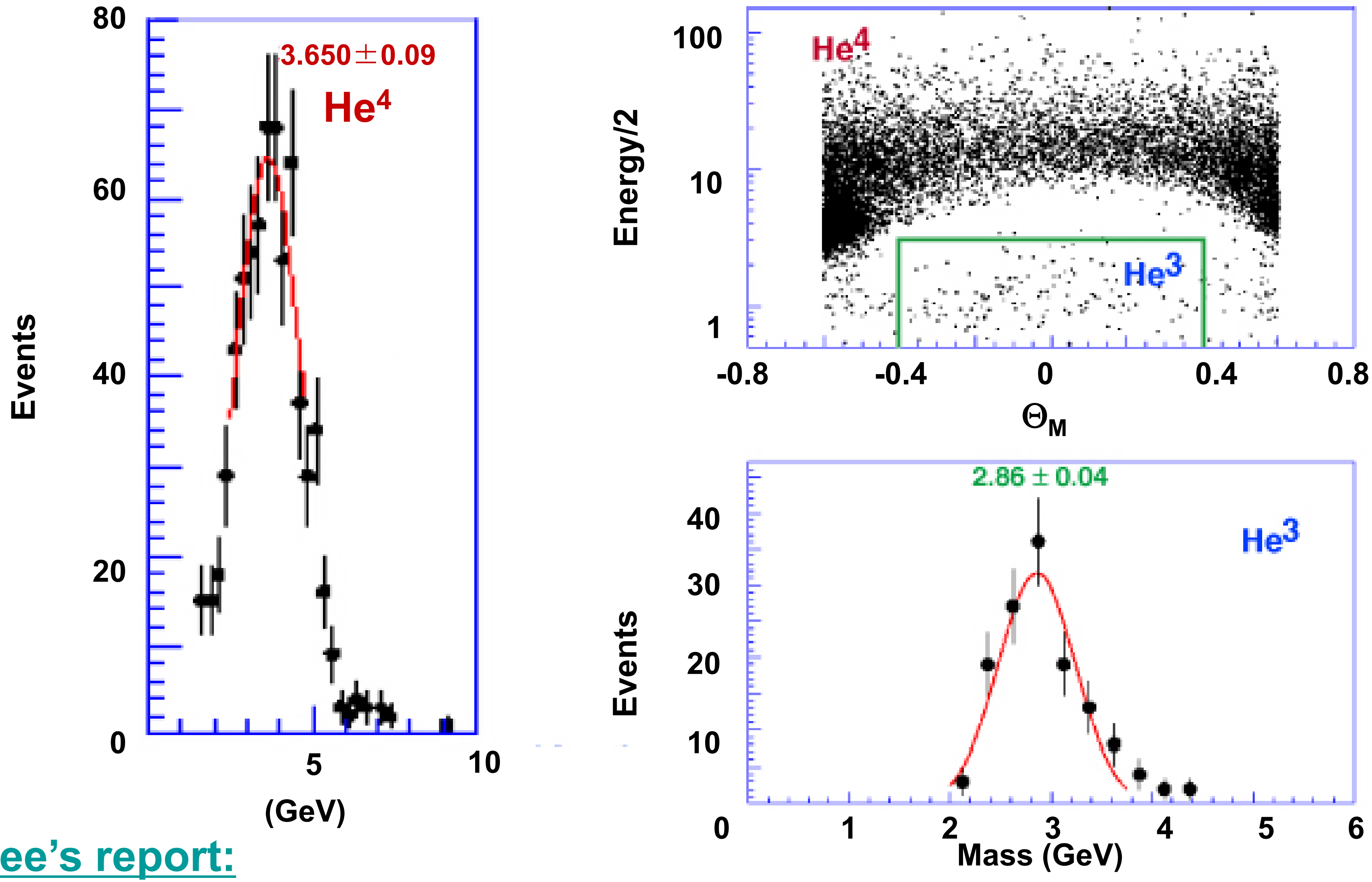


Referee's report:

This paper supplies entirely new data of the highest quality on electrons and positrons of cosmic rays …

Phys. Lett. B484 (27 Jun 2000) 10-22

Unexpected results from first flight:
3- He^4 and He^3 isotopes are completely separated in space



<u>Referee's report:</u>
This is an exciting and important paper …

Phys. Lett. B494 (2000) 193-202

These results were not predicted by any cosmic ray model

Available online at www.sciencedirect.com
ScienceDirect

Physics Letters B 646 (2007) 145–154

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Cosmic-ray positron fraction measurement from 1 to 30 GeV with AMS-01

AMS-01 Collaboration

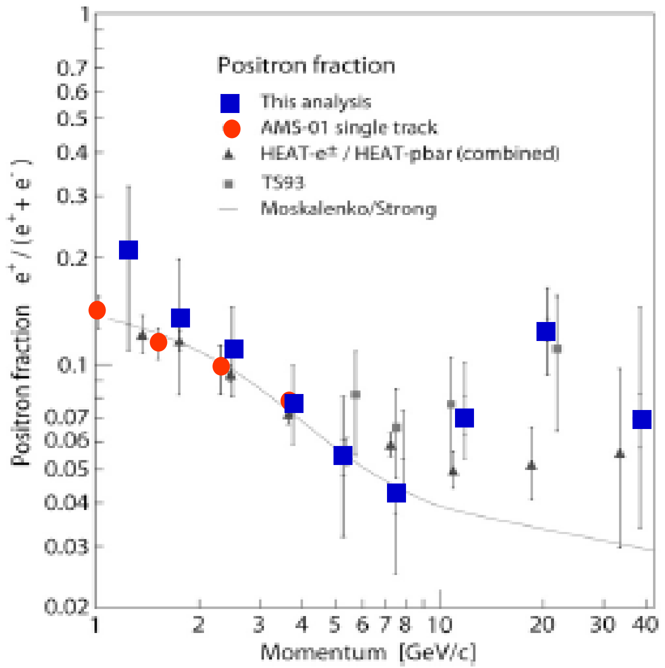


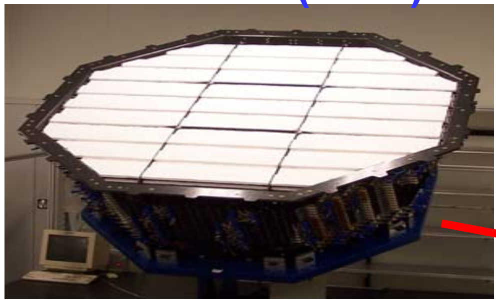
Fig. 4. The positron fraction $e^+/(e^+ + e^-)$ measured in this analysis (filled circles), compared with earlier results from AMS-01 (open circles) [12], TS93 (squares) [13], the combined results from HEAT-$e^{\pm}$ and HEAT-pbar (triangles) [14], together with a model calculation for purely secondary positron production from [15] (solid line). The total error is given by the outer error bars, while the inner bars represent the systematic contribution to the total error.

Table 1
The number of electron (N_{e^-}) and corrected positron (N_{e^+}) candidates and the positron fraction as a function of momentum. Systematic errors are given separately for background ($\sigma_{sys,b}$) and livetime ($\sigma_{sys,l}$) correction

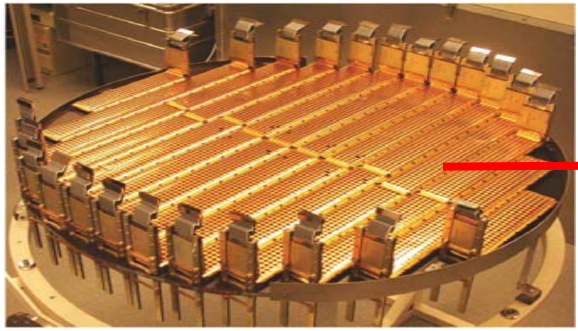
Momentum [GeV/c]	N_{e^-}	N_{e^+}	Positron fraction	σ_{stat}	$\sigma_{sys,b}$	$\sigma_{sys,l}$
1.0–1.5	11	3.0	0.210	$^{+0.11}_{-0.1}$	±0	±0
1.5–2.0	31	4.8	0.133	$^{+0.064}_{-0.051}$	$^{+0.002}_{-0}$	±0.006
2.0–3.0	85	10.7	0.112	$^{+0.034}_{-0.031}$	$^{+0.001}_{-0.003}$	±0.004
3.0–4.5	186	15.8	0.078	$^{+0.021}_{-0.018}$	$^{+0.001}_{-0.003}$	±0.004
4.5–6.0	172	10.0	0.055	$^{+0.025}_{-0.022}$	$^{+0.006}_{-0.007}$	±0.001
6.0–8.9	198	9.0	0.043	$^{+0.029}_{-0.017}$	$^{+0.01}_{-0.004}$	±0.004
8.9–14.8	195	14.5	0.069	$^{+0.03}_{-0.014}$	$^{+0.01}_{-0.002}$	±0.006
14.8–26.5	109	15.4	0.124	$^{+0.038}_{-0.03}$	$^{+0.009}_{-0.003}$	±0.007
26.5–50.0	39	2.9	0.070	$^{+0.075}_{-0.034}$	$^{+0.01}_{-0.01}$	±0.007

The Completed AMS Detector on ISS

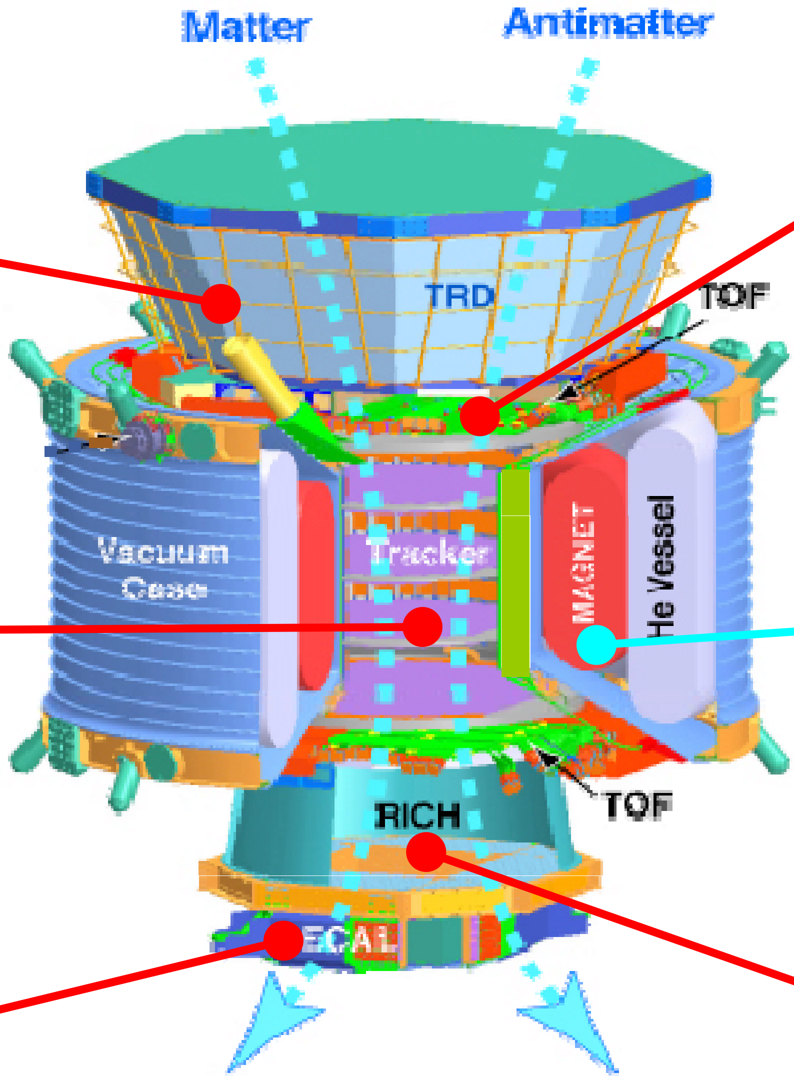
Transition Radiation Detector (TRD)



Silicon Tracker

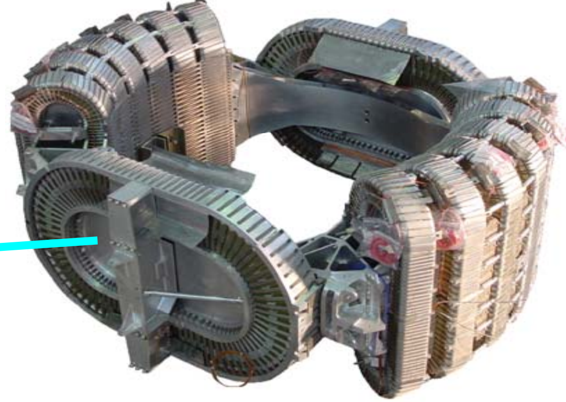


Electromagnetic Calorimeter (ECAL)

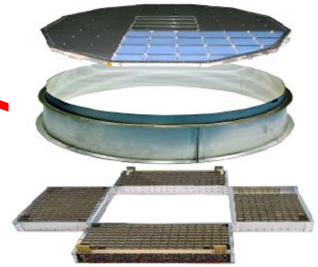


Time of Flight Detector (TOF)

Magnet



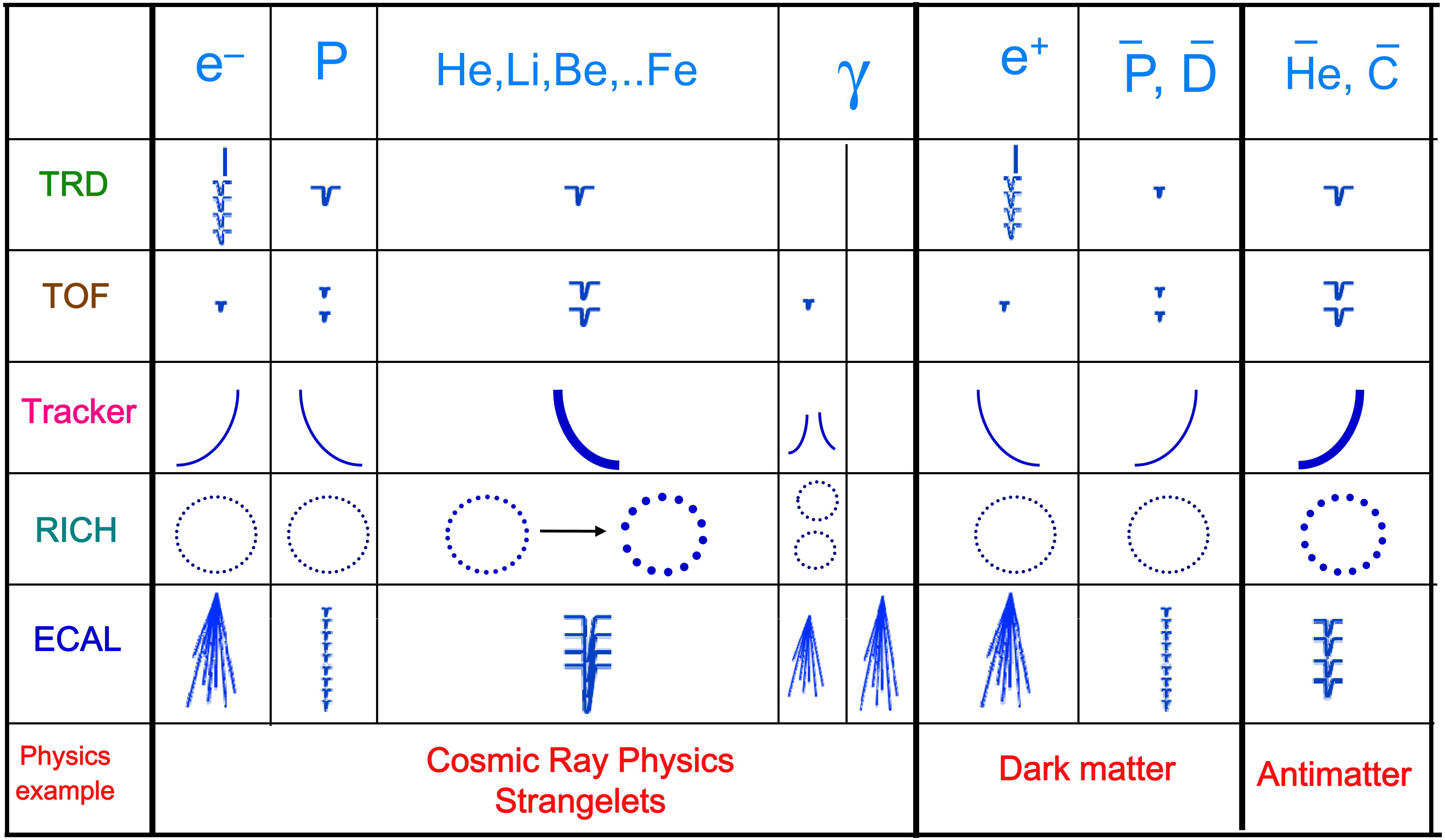
Ring Image Cerenkov Counter (RICH)



Size: 3m x 3m x 3m
Weight: 7 tons

Characteristics of AMS-02

Δ t = 100 ps, Δx = 10 μm, Δv/v = 0.001



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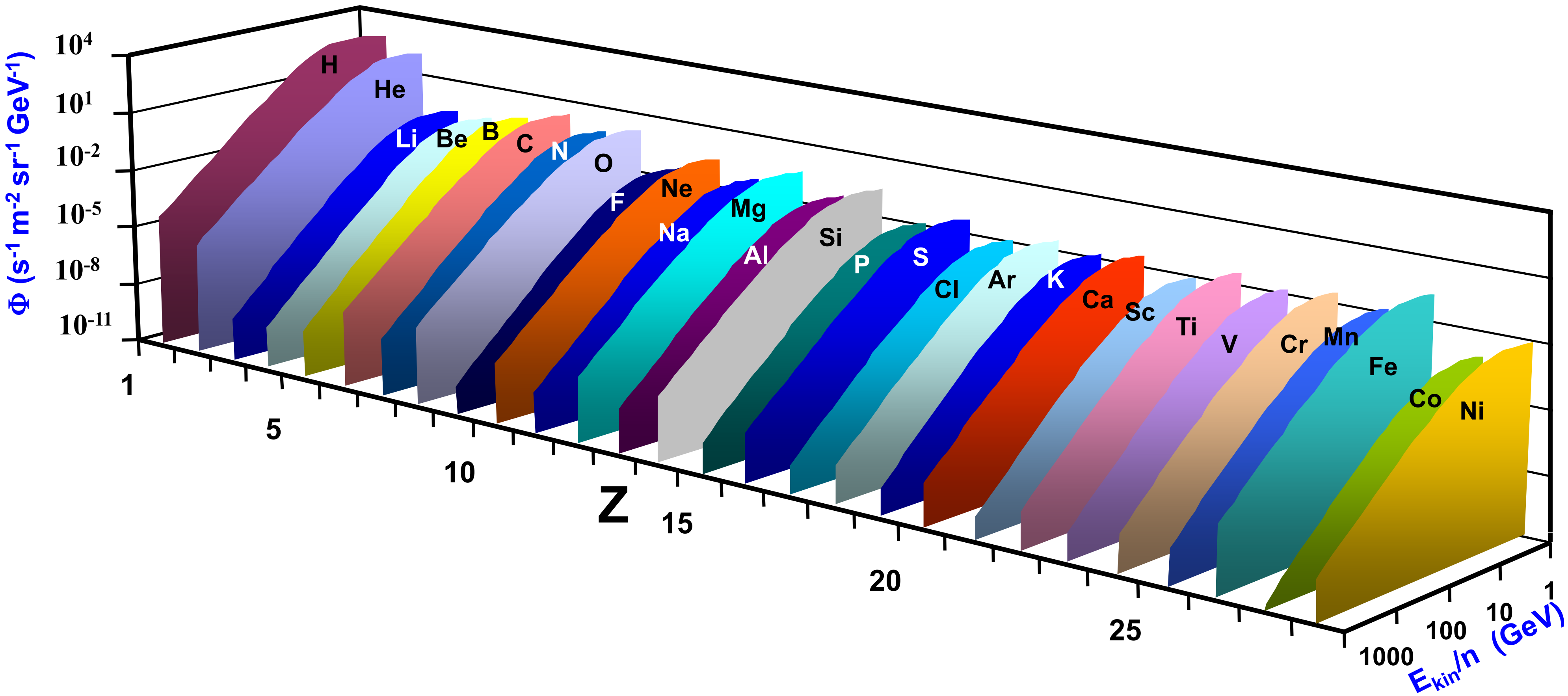
AMS Physics examples

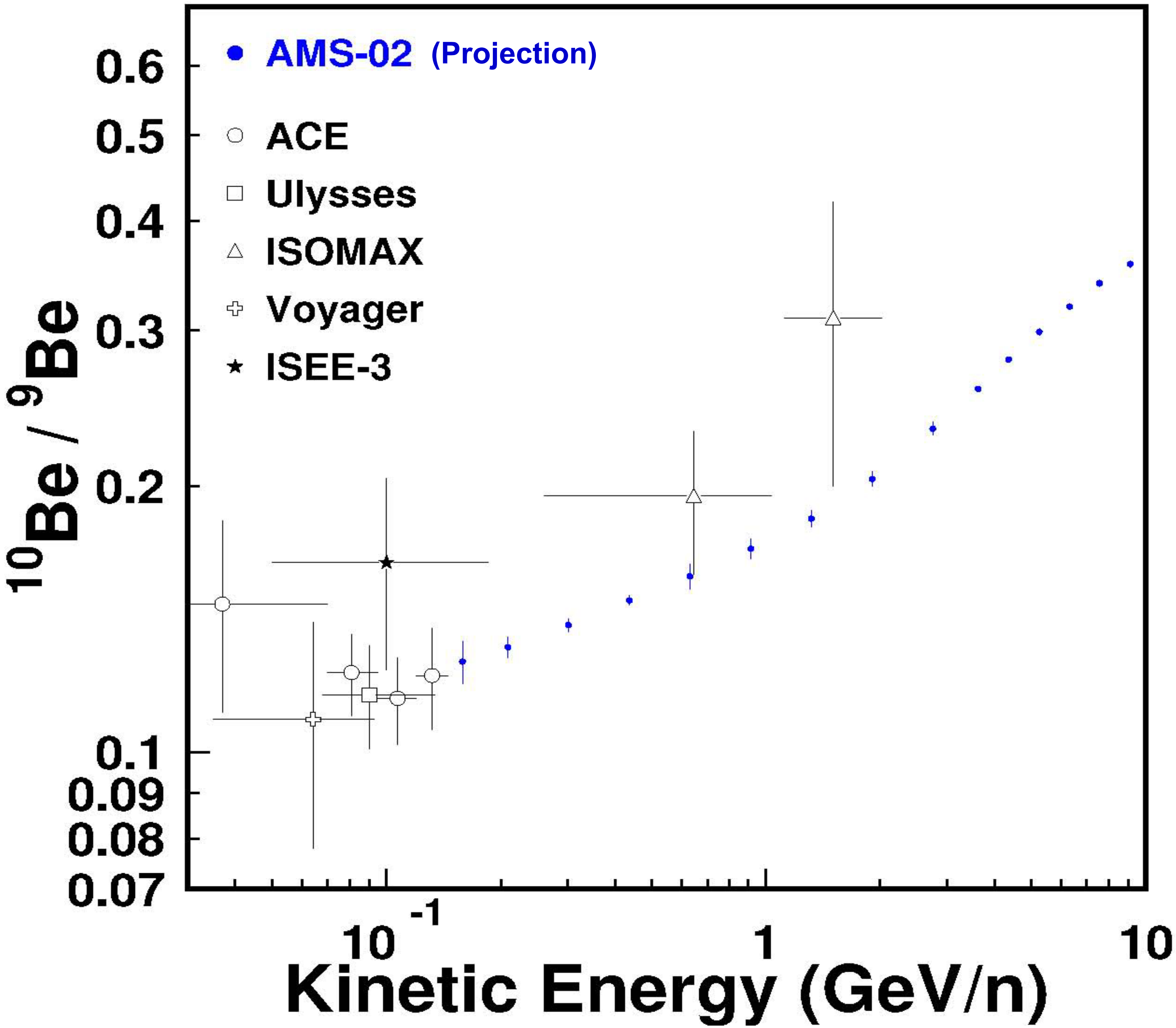
Precision study of the properties of Cosmic Rays

Composition at different energies (1 GeV, 100 GeV, 1 TeV)



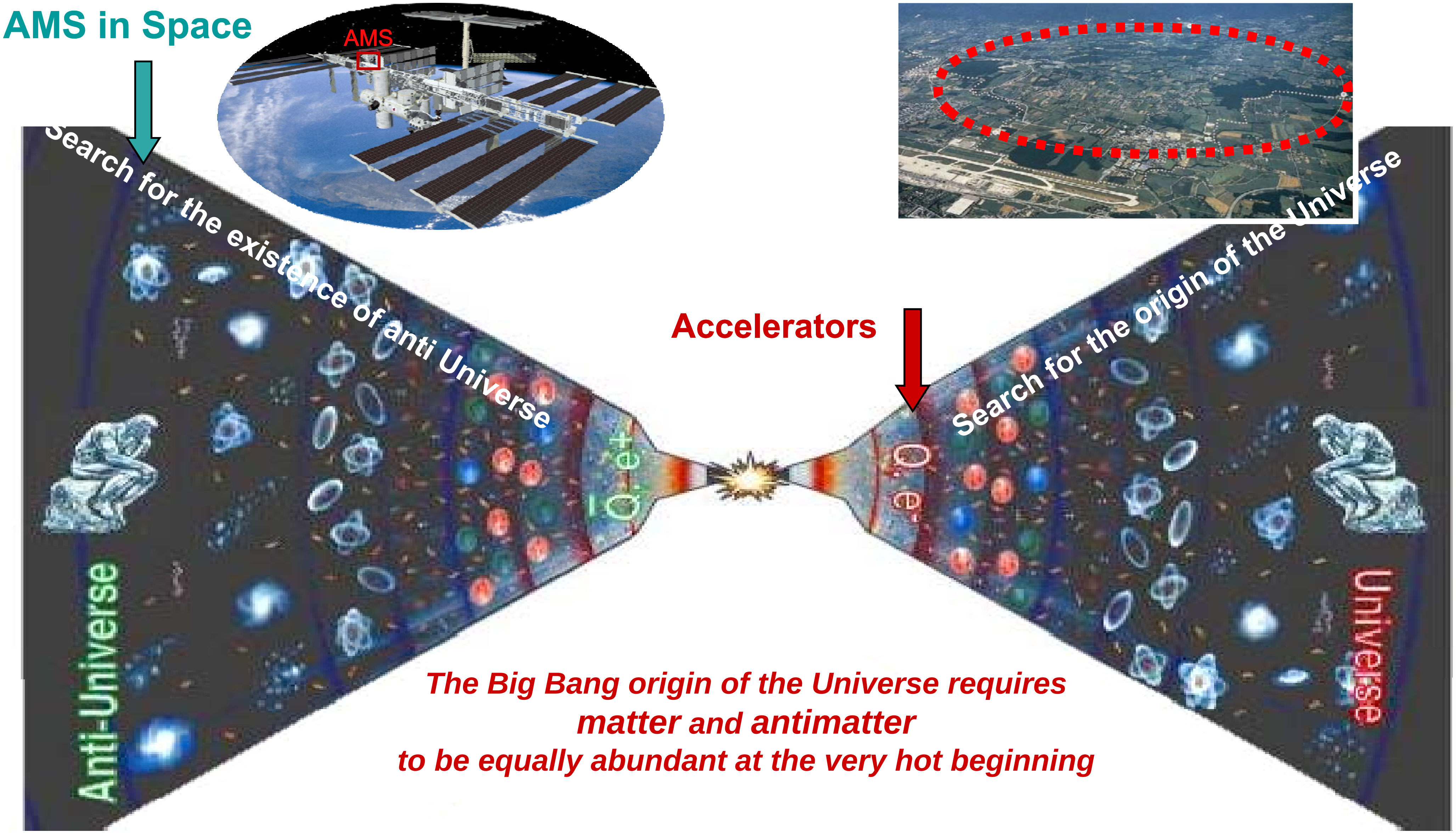
Precision study of the properties of Cosmic Rays

Cosmic Ray confinement time

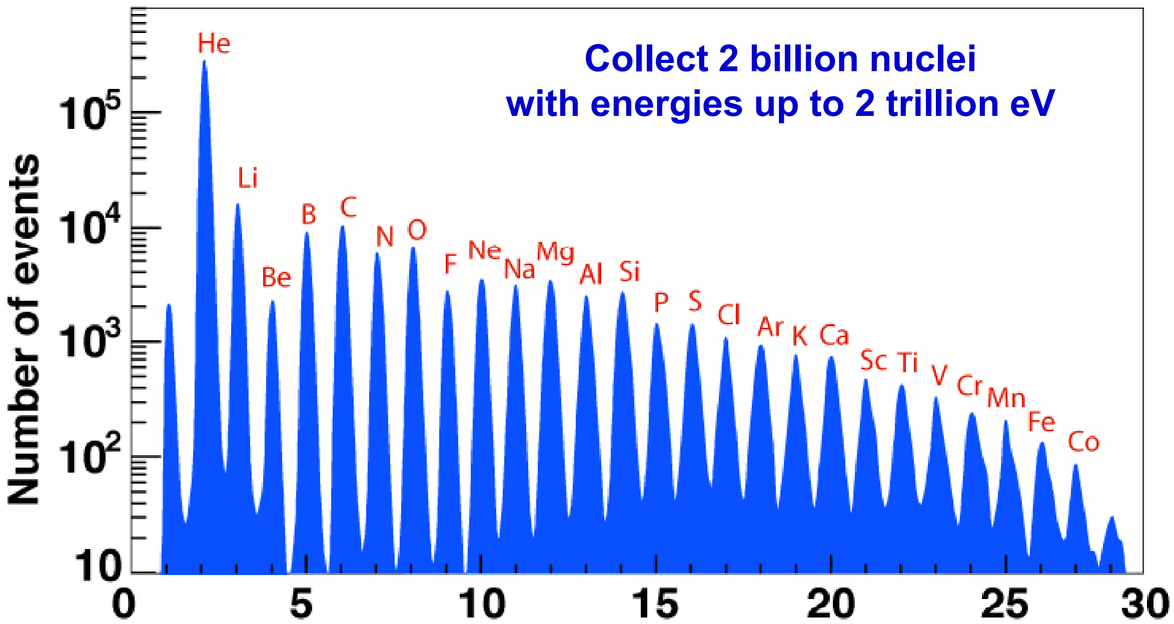


Physics example

Search for the existence of Antimatter in the Universe



Direct search for antimatter: AMS on ISS



Sensitivity of AMS: If no antimatter is found => there is no antimatter to the edge of the observable universe (~ 1000 Mpc).

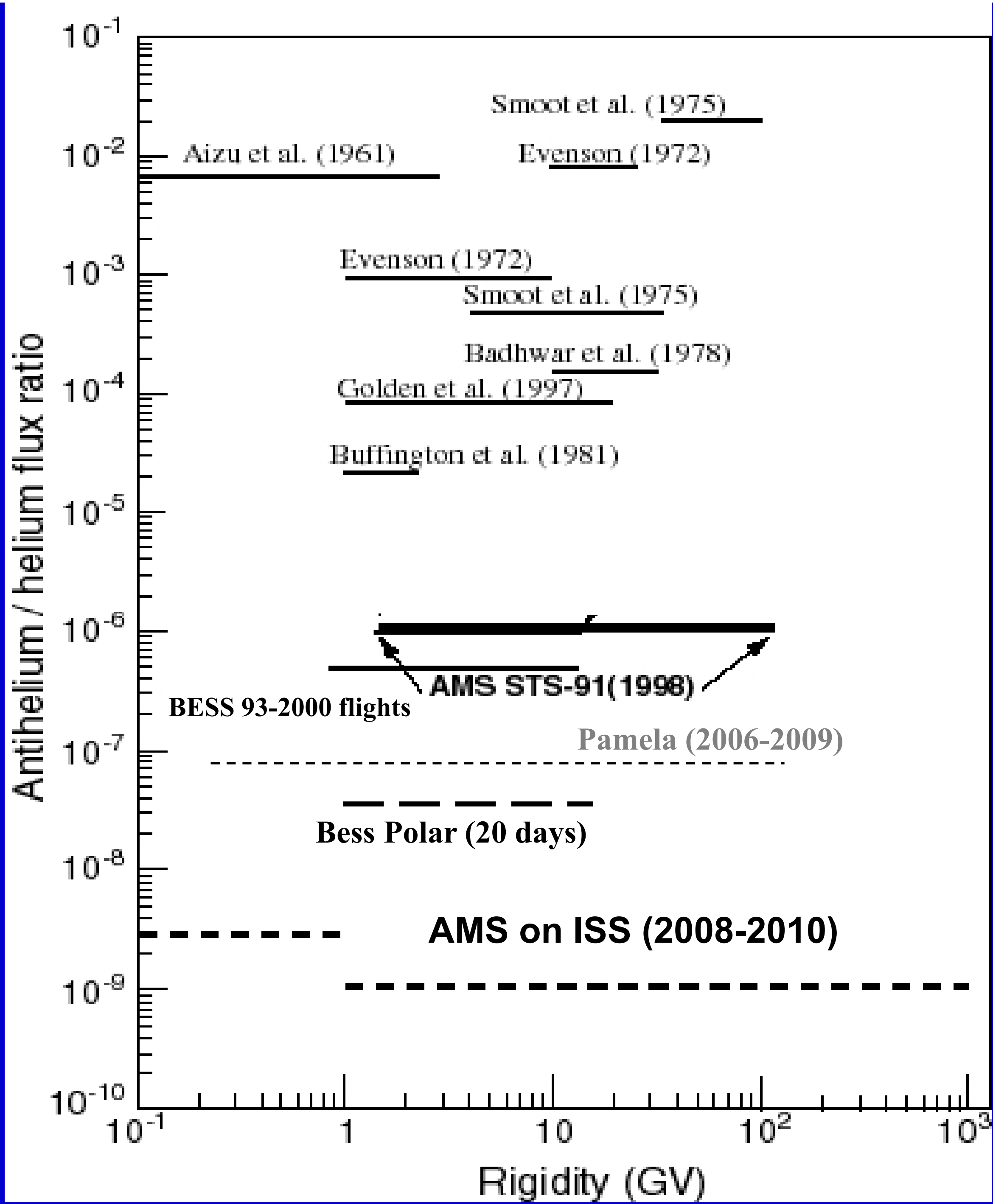
The physics of antimatter in the universe is based on:

- **The existence of a new source of CP Violation**
- **The existence of Baryon, Lepton Number Violation**
- **Grand Unified Theory**
- **Electroweak Theory**
- **SUSY**

} **the Foundations of Modern Physics**

These are central research topics for the current and next generation of accelerators world wide

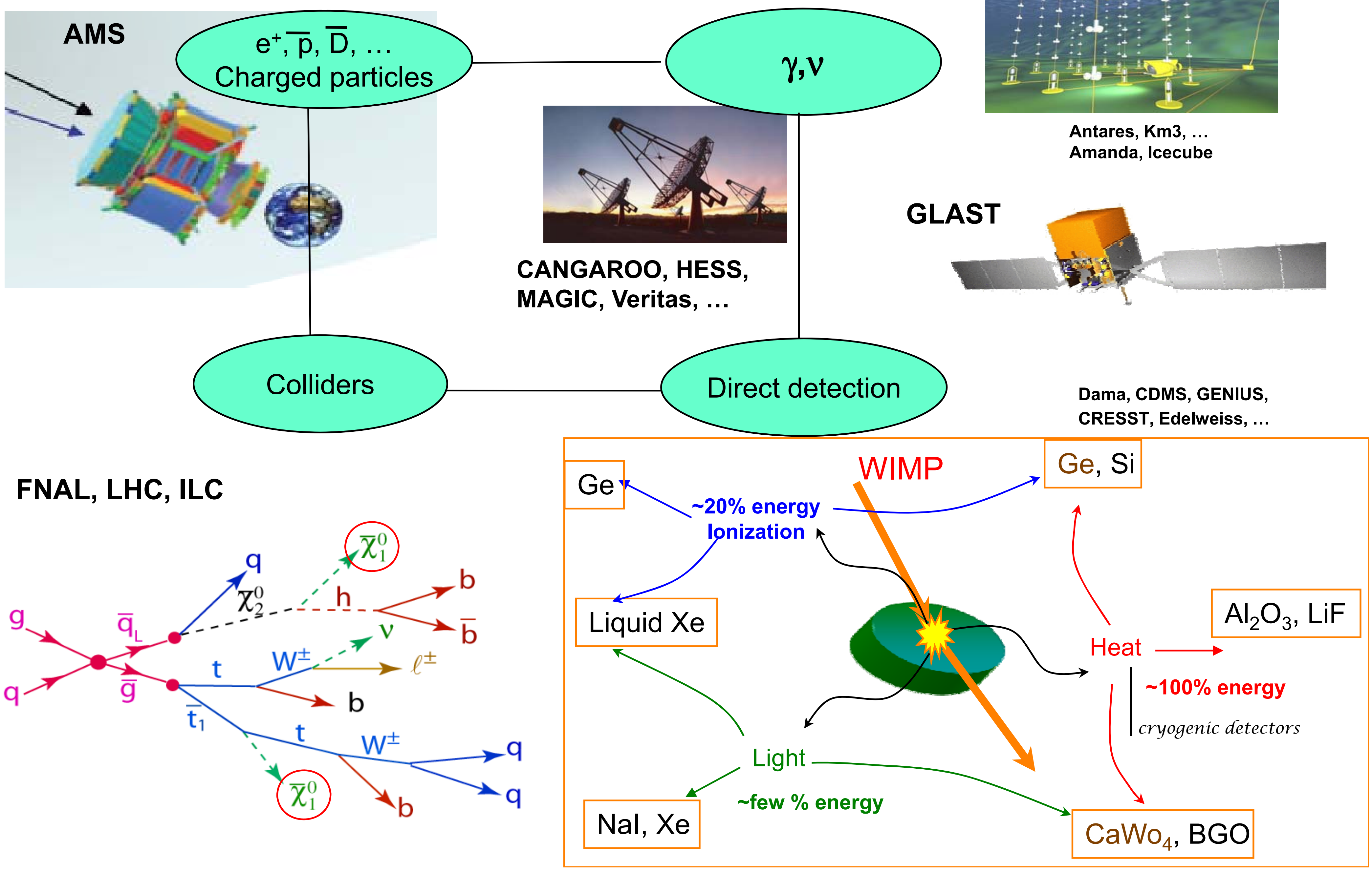
Search for antimatter at the 10^{-9} level of sensitivity with AMS-02 on the ISS



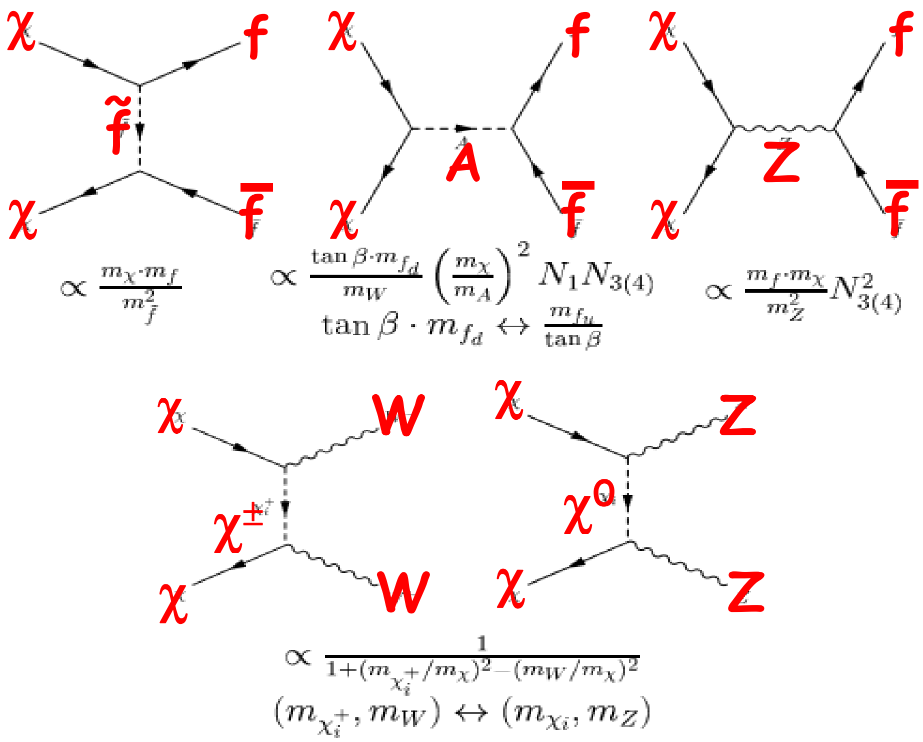
Dark Energy = 73 %

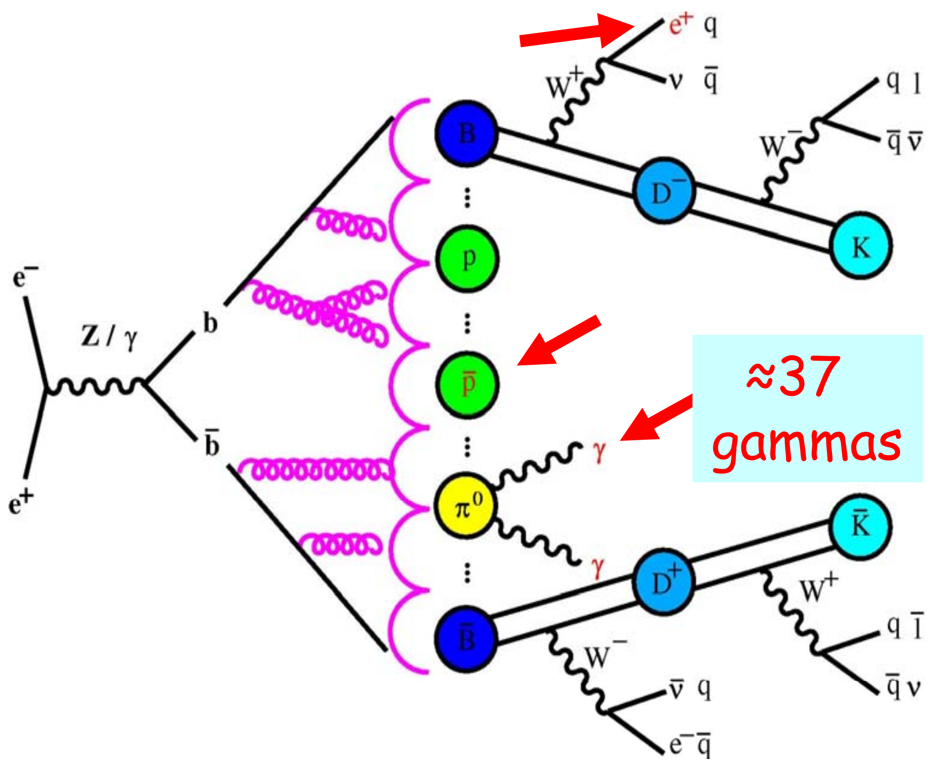
Dark Matter = 23 %

Dark Matter Searches



DM Annihilation in Supersymmetry

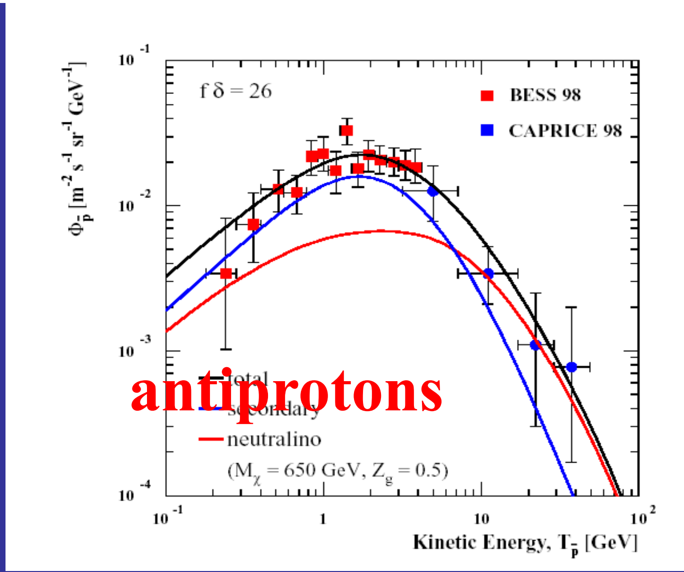




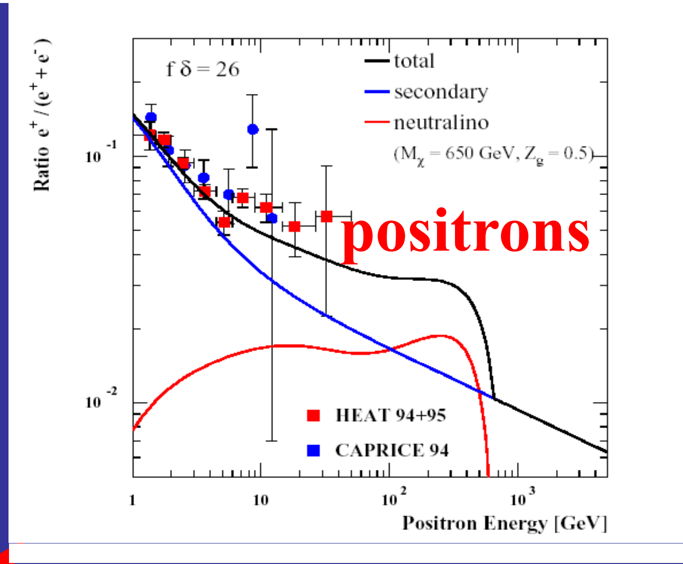
Dominant
χ + χ ⇒ A ⇒ b bbar quark pair

B-Fragmentation known!
Hence Spectra of Positrons, Gammas and Antiprotons known!

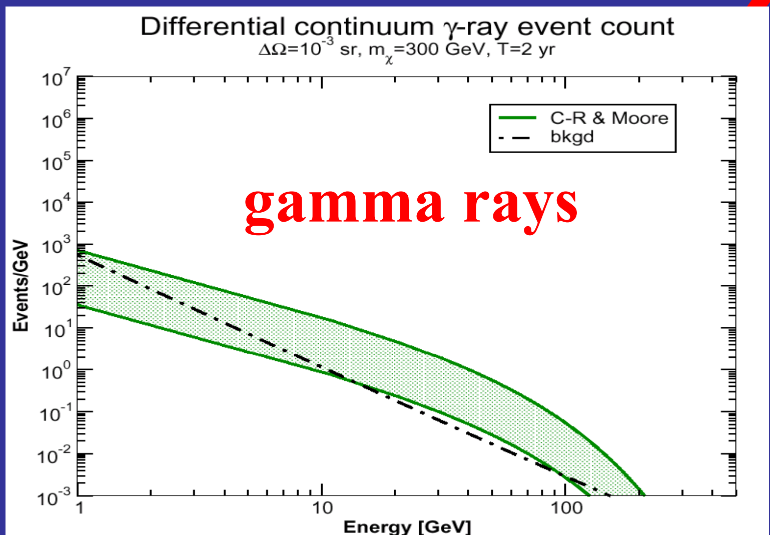
Galaxy = Super B-Fabrik with rate 10^{40} x B-Factory

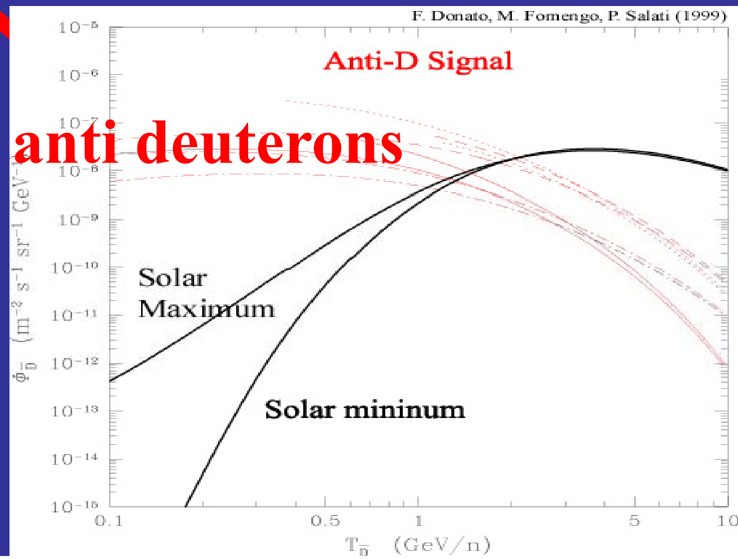


Unique Feature Of AMS



Combining searches in different channels could give (much) higher sensitiviy to SUSY DM signals



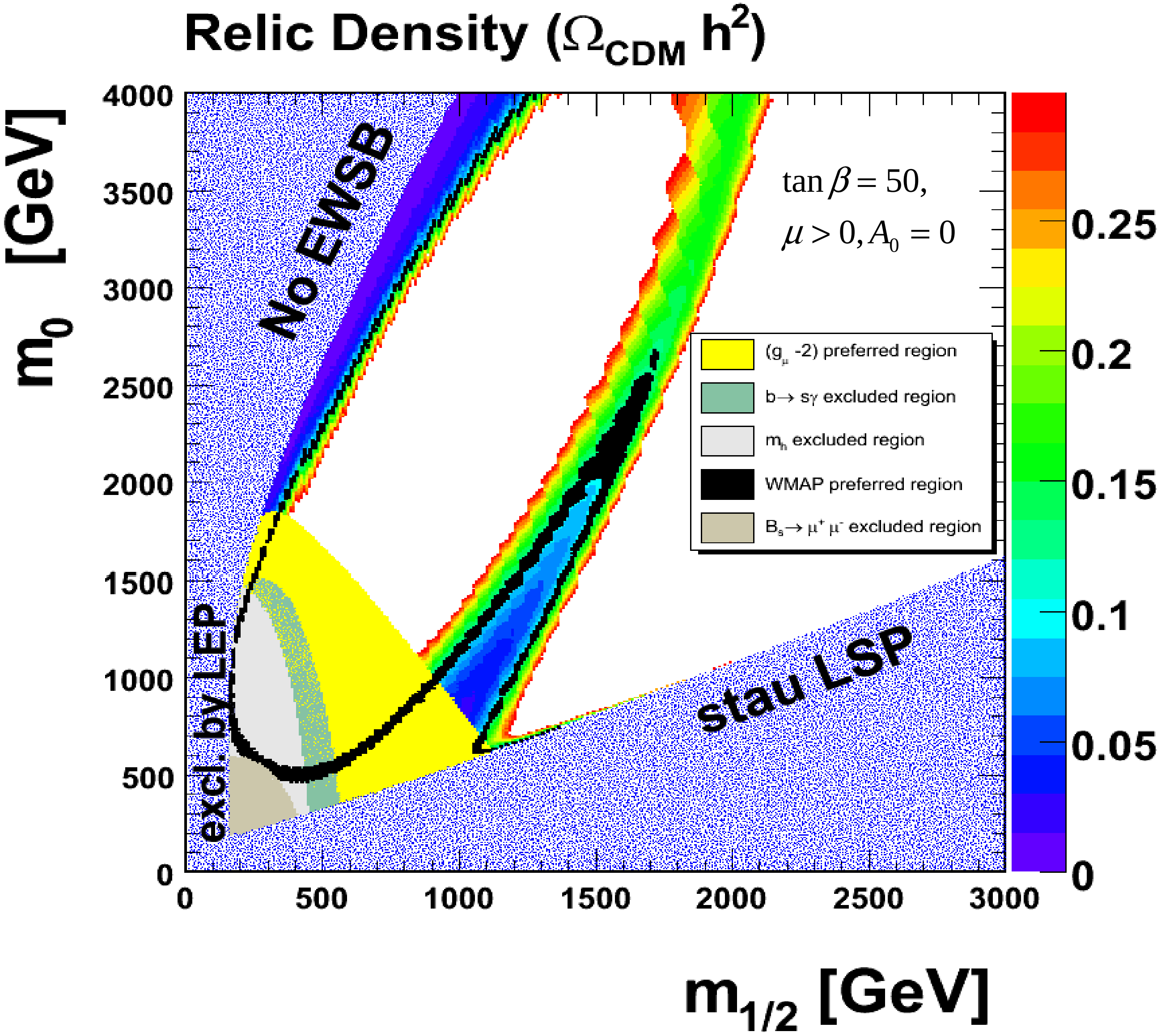


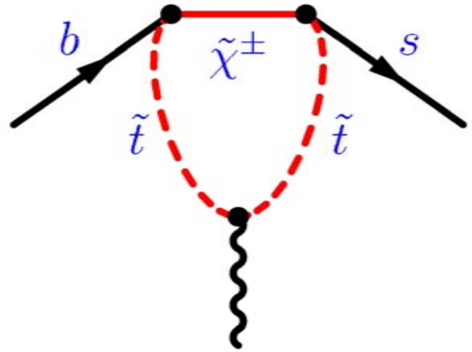
- From astrophysics and cosmology we get:

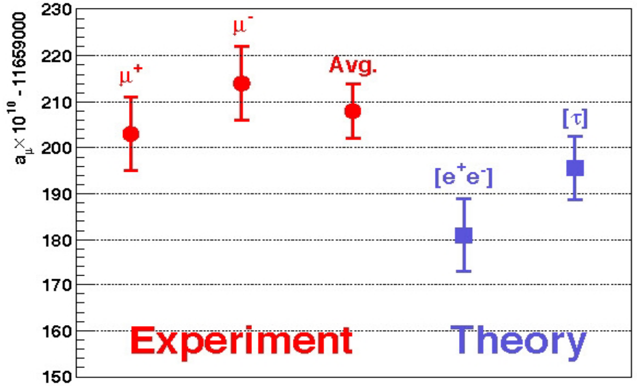
$$\Omega_{CDM} h^2 = 0.120 \pm 0.005$$

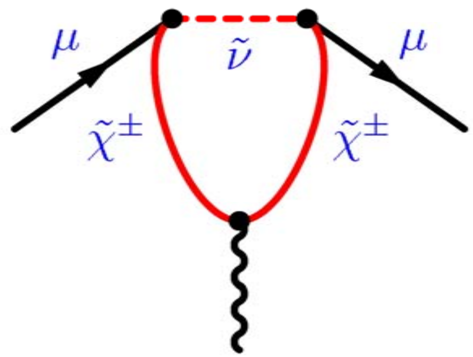
$$BR(B \to X_s \gamma)_{\exp} = (3.39^{+0.30}_{-0.27}) \cdot 10^{-4}$$

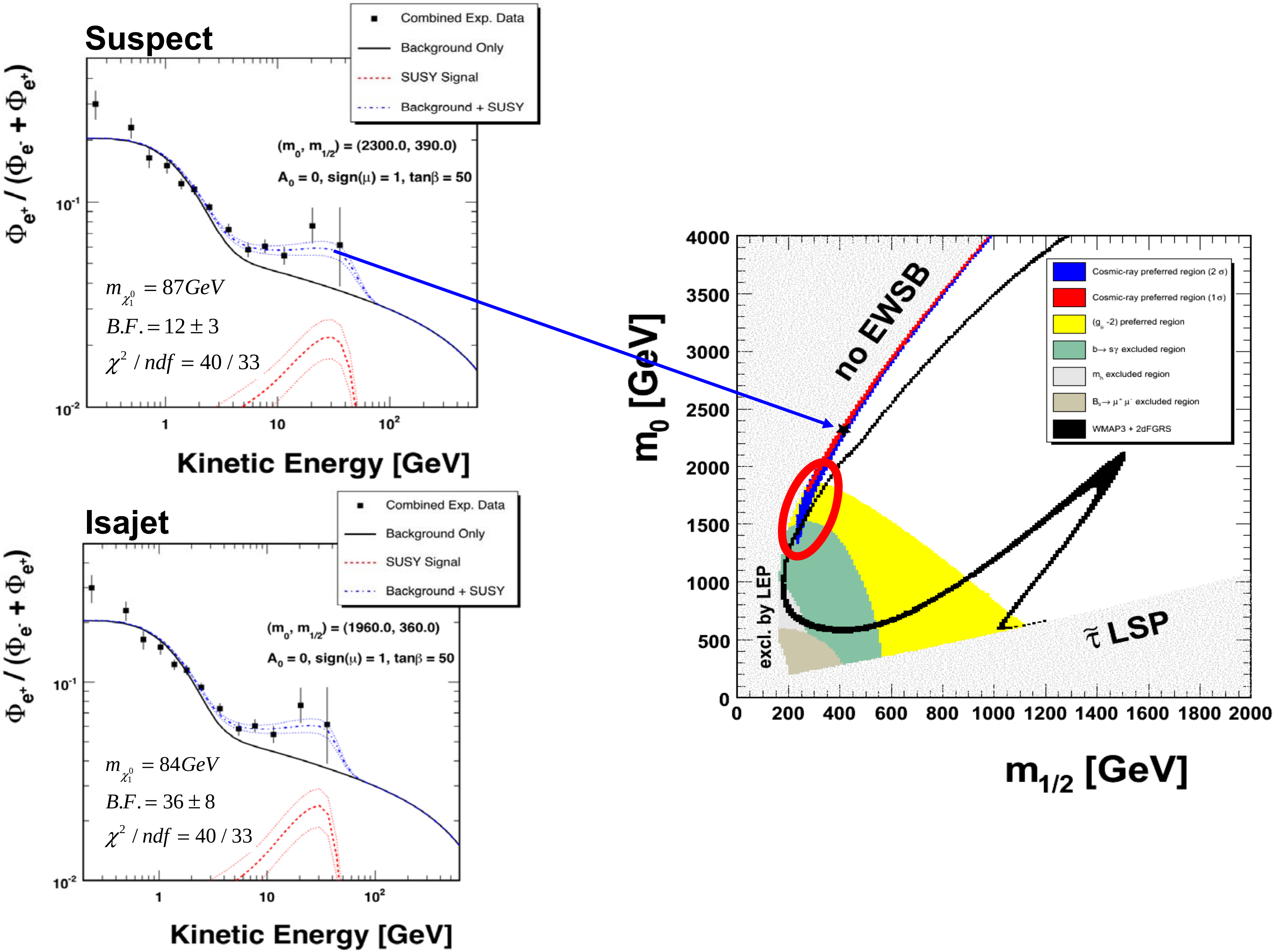
$$BR(B \to X_s \gamma)_{SM} = (3.70 \pm 0.30) \cdot 10^{-4}$$







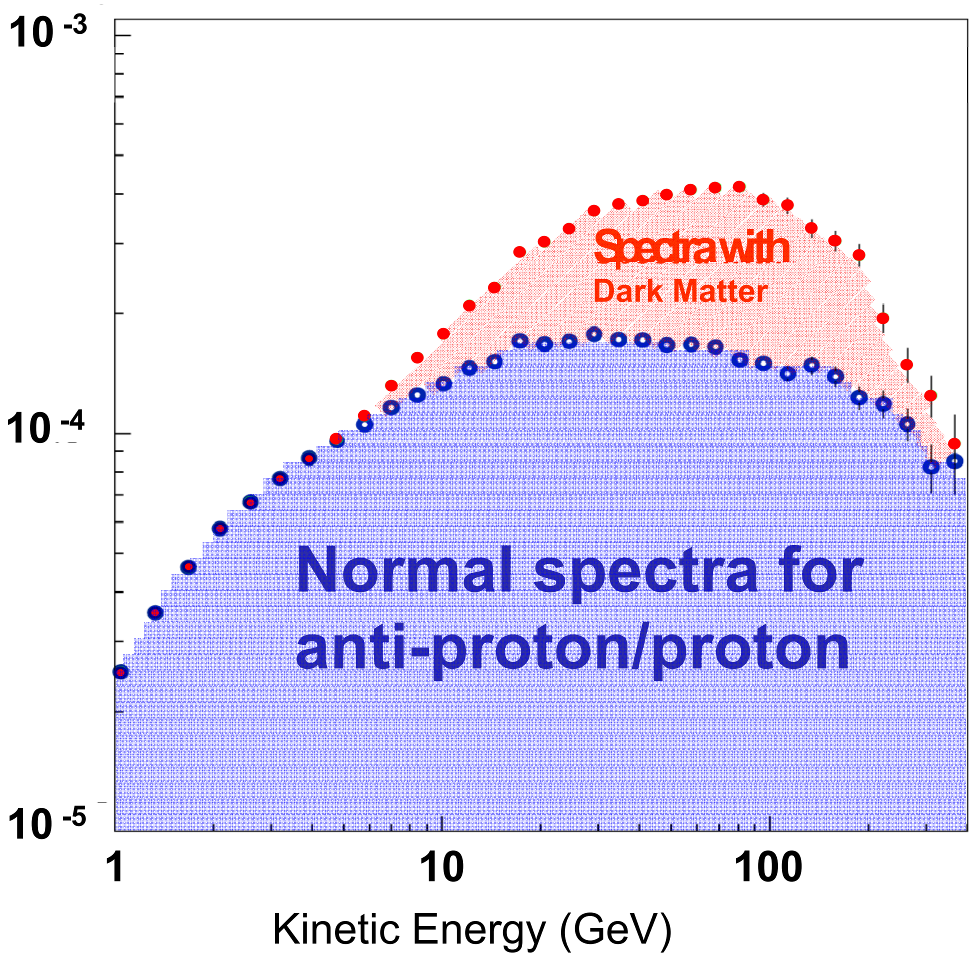




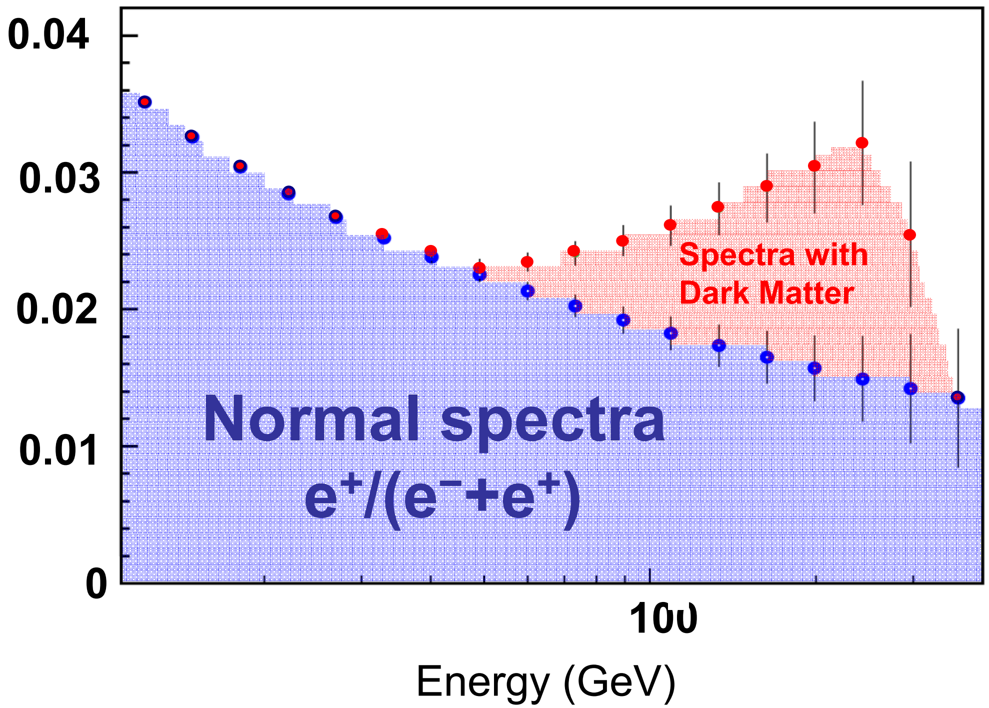
Suspect
Combined Exp. Data
Background Only
SUSY Signal
Background + SUSY
(m0, m1/2) = (2300.0, 390.0)
A0 = 0, sign(μ) = 1, tanβ = 50
$m_{\chi_1^0} = 87 GeV$
$B.F. = 12 \pm 3$
$\chi^2 / ndf = 40 / 33$
$\Phi_{e^+} / (\Phi_{e^-} + \Phi_{e^+})$
Kinetic Energy [GeV]
Isajet
Combined Exp. Data
Background Only
SUSY Signal
Background + SUSY
(m0, m1/2) = (1960.0, 360.0)
A0 = 0, sign(μ) = 1, tanβ = 50
$m_{\chi_1^0} = 84 GeV$
$B.F. = 36 \pm 8$
$\chi^2 / ndf = 40 / 33$
$\Phi_{e^+} / (\Phi_{e^-} + \Phi_{e^+})$
Kinetic Energy [GeV]
no EWSB
Cosmic-ray preferred region (2 σ)
Cosmic-ray preferred region (1 σ)
(gμ-2) preferred region
b→ sγ excluded region
mh excluded region
Bs→ μ+ μ- excluded region
WMAP3 + 2dFGRS
excl. by LEP
τ̃ LSP
m_0 [GeV]
$m_{1/2}$ [GeV]

Two leading theoretical candidates

Dark Matter is a supersymmetric particle with Mχ = 840 GeV.
This is not accessible to the next accelerator (LHC)

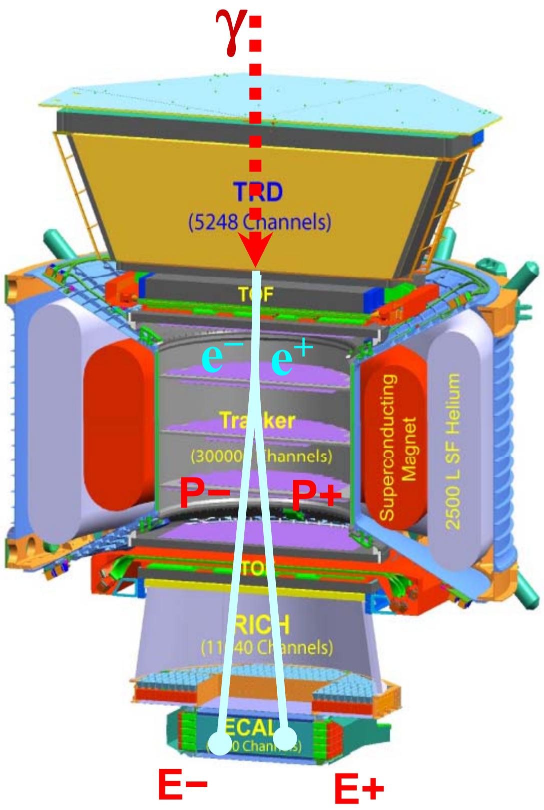


Dark Matter is a Kaluza-Klein Boson (B)
- assumes extra dimensions -
with a typical mass of M_B = 300GeV

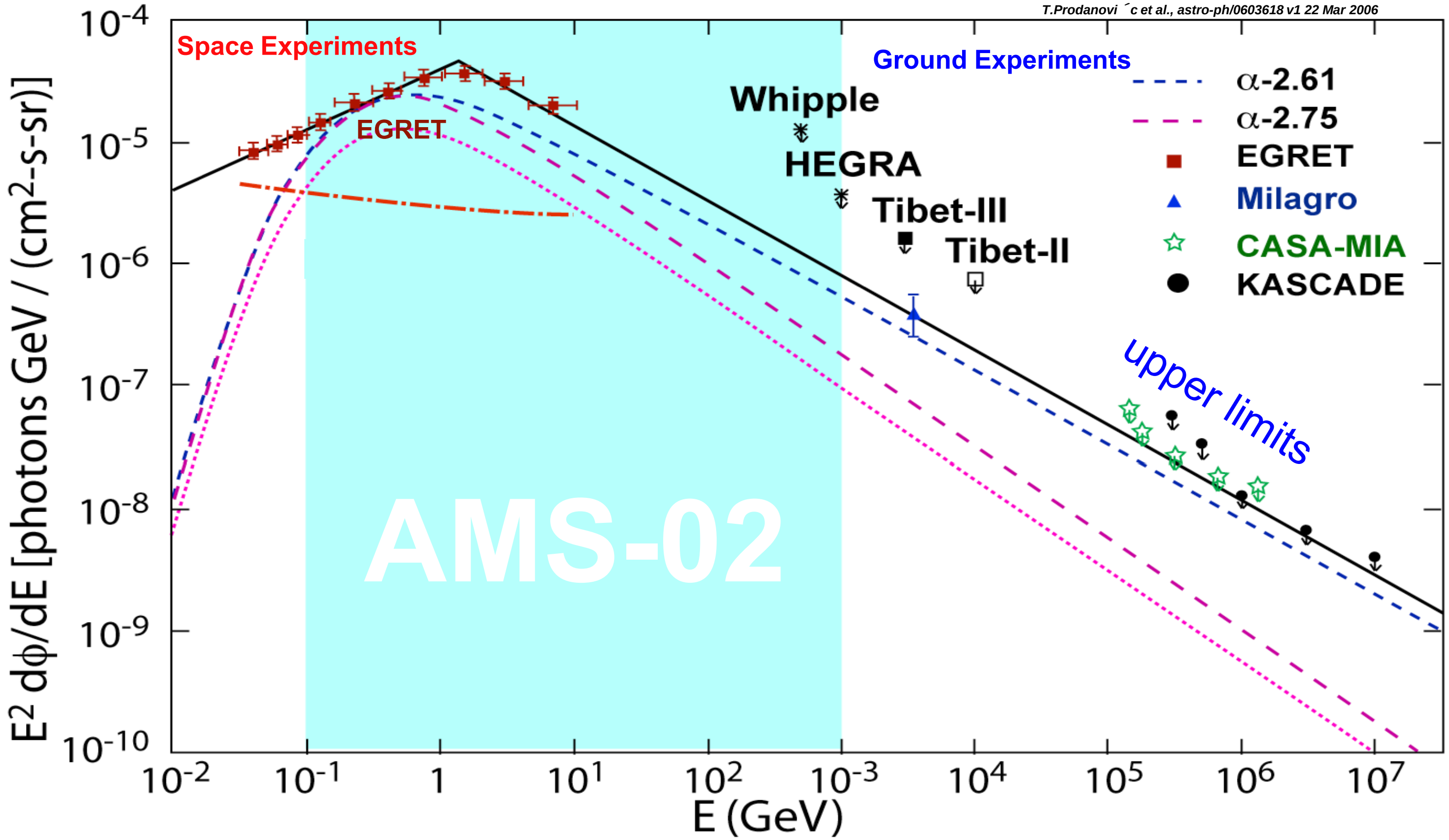


AMS Physics example

Study of high energy (0.1 GeV – 1 TeV) diffuse gammas



Unique constraints
$P^+ = E^+ = P^- = E^-$



The diffuse gamma-ray spectrum of the Galactic plane
$40^o < 1 < 100^o$, $|b| < 5^o$

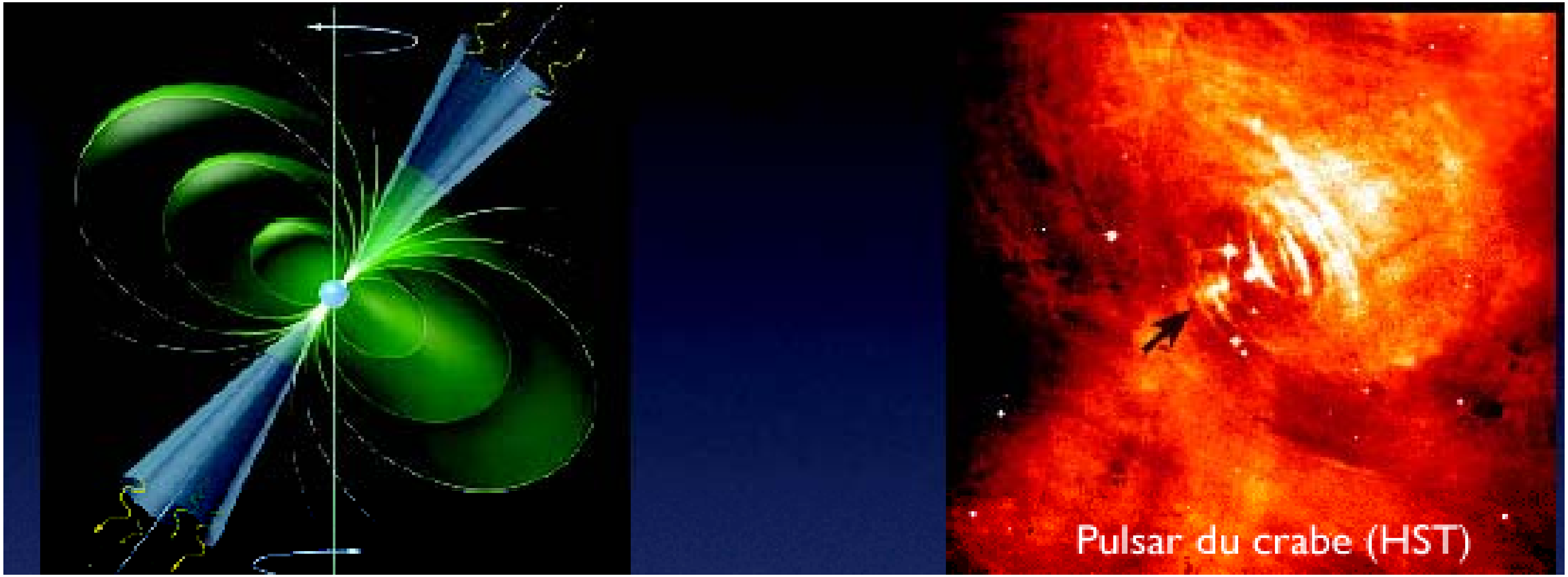
1. **Pointing precision of 2 arcsec**
2. **UTC time (from GPS, μsec accuracy) allows to relate AMS measurements with other missions**

Pulsars in the Milky Way:

Pulsar: neutron star sending radiation in a periodic way, not yet detected > few GeV
Emission in radio, visible, X and gamma

(G. Bignami – Fundamental discoveries of X-, gamma-rays from neutron stars 1973-1976)

AMS: energy spectrum for pulsars in the 100 MeV – 1 TeV and
pulsar periods measured with µsec time precision
(currently measured to millisec precision)



Similar studies can be made for Blazers and Gamma Ray Bursters

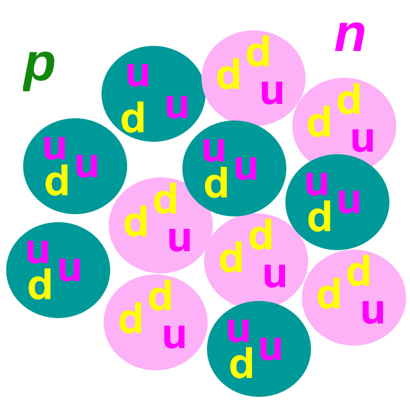
Physics Example
Search for New Matter in the Universe

There are six types of Quarks found in accelerators (u, d, s, c, b, t).

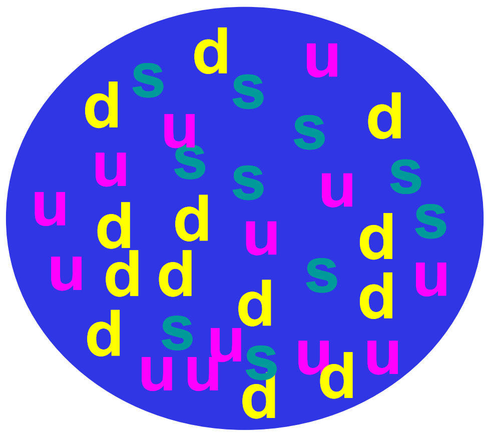
All matter on Earth is made out of only two types (u, d) of quarks.

"Strangelets" are new types of matter composed of three types of quarks (u, d, s) which should exist in the cosmos.

Carbon Nucleus



Strangelet



i. A stable, single "super nucleon" with three types of quarks

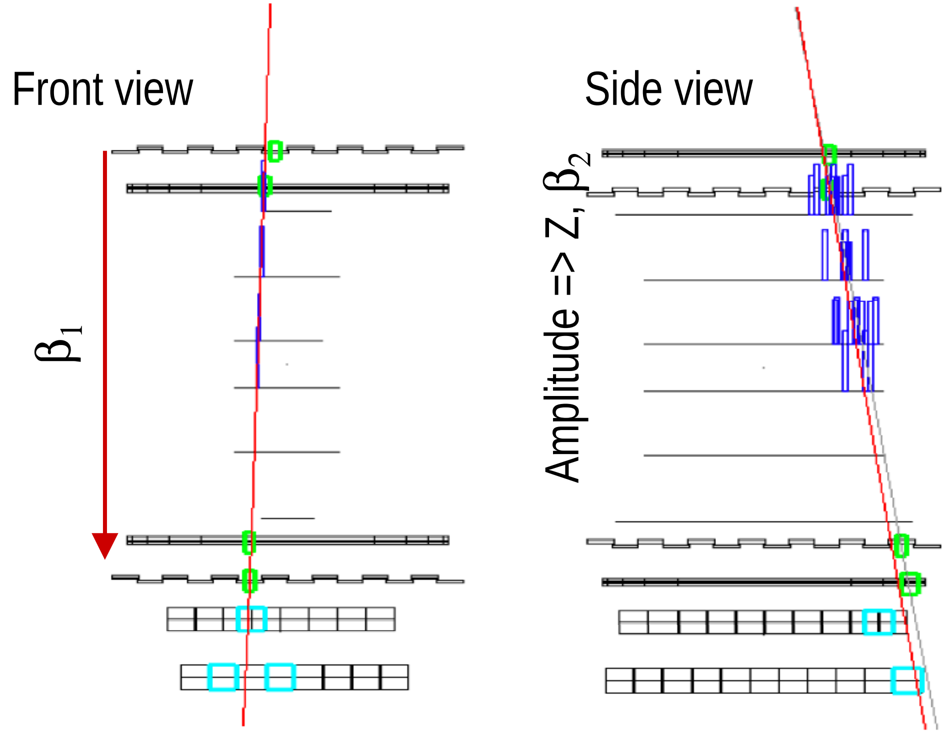
ii. "Neutron" stars may be one big strangelet

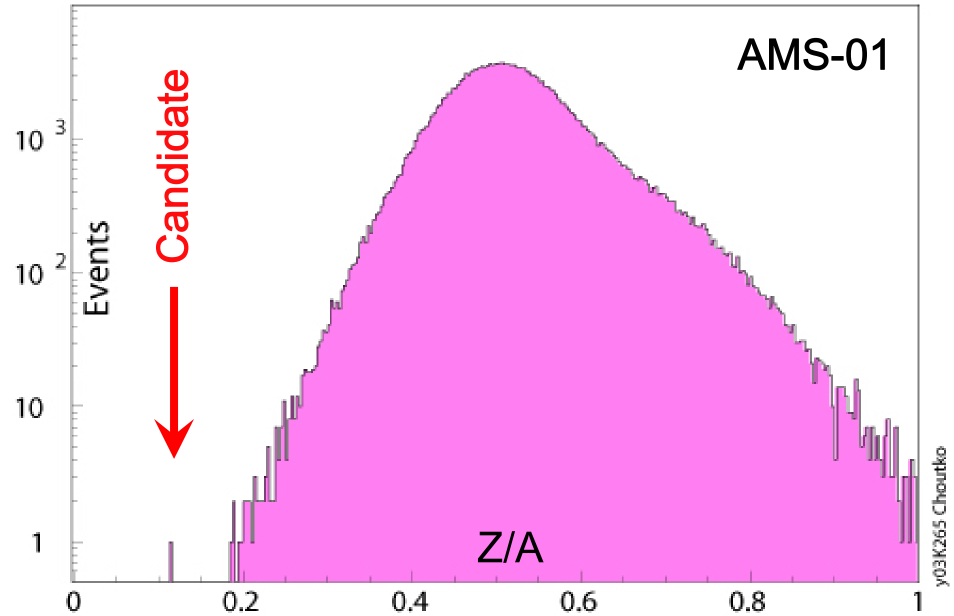
AMS will provide a definitive search for this new type of matter.

Strangelet candidate from AMS-01

Observed 5 June 1998 11:13:16 UTC

Lat/Long= -44.38° /+23.70° , Local Cutoff 1.95±0.1 GV, Angle= 77.5° from local zenith





Rigidity = 4.31 ± 0.38 GV

Charge Z = 2

$\beta_1 = \beta_2$ = 0.462 ± 0.005

Mass = 16.45±0.15 GeV/c^2

Z/A = 0.114 ± 0.01

Flux (1.5 < E_K < 10 GeV) = 5×10^{-5} (m^2 sr sec)$^{-1}$

Background probability < 10^{-3}

The AMS Experiment

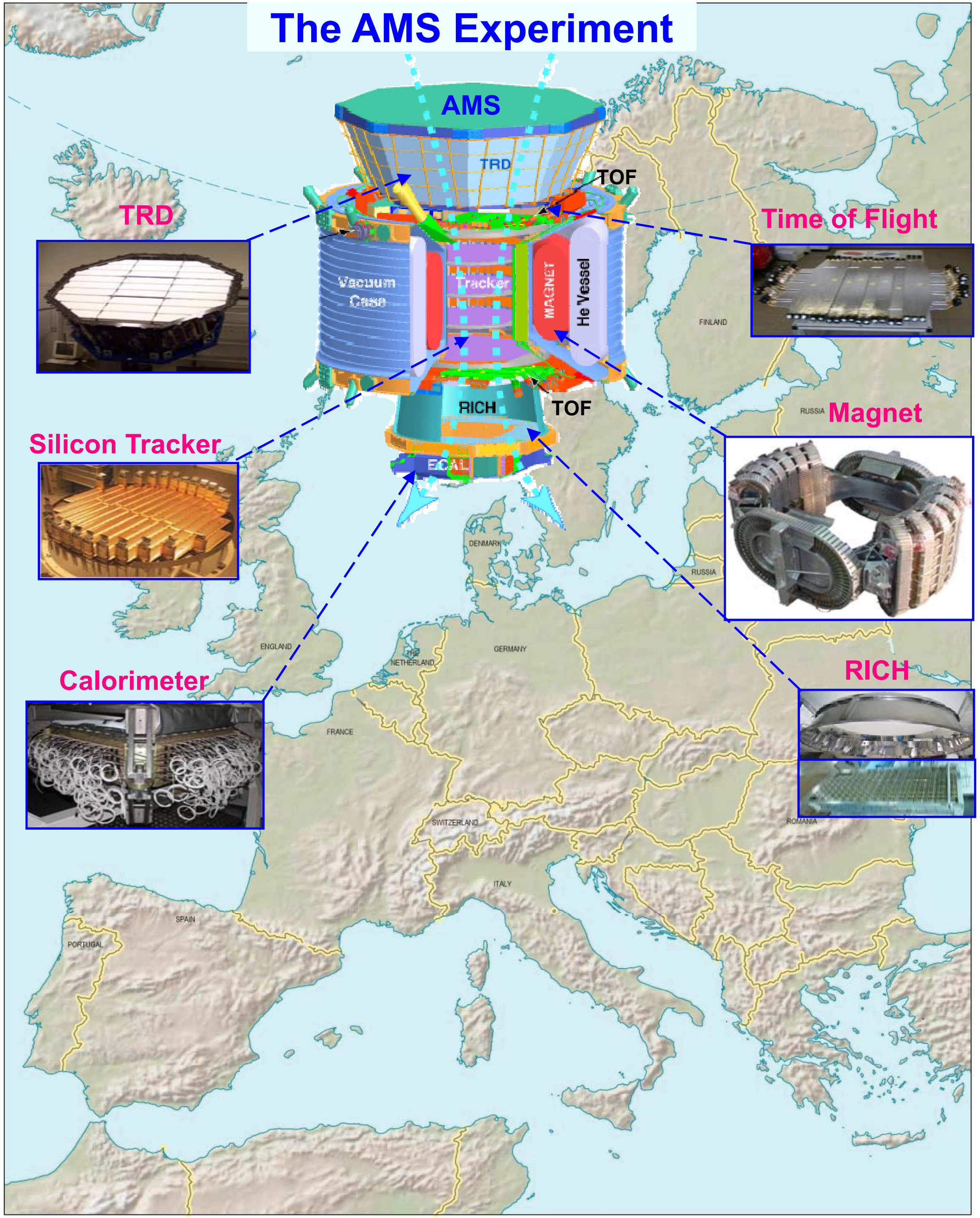
S.C.C. Ting

R. Battiston

M. Pohl

J. Torsti

F. Barao



K. Lübelsmeyer

M. Aguilar

J.P. Vialle

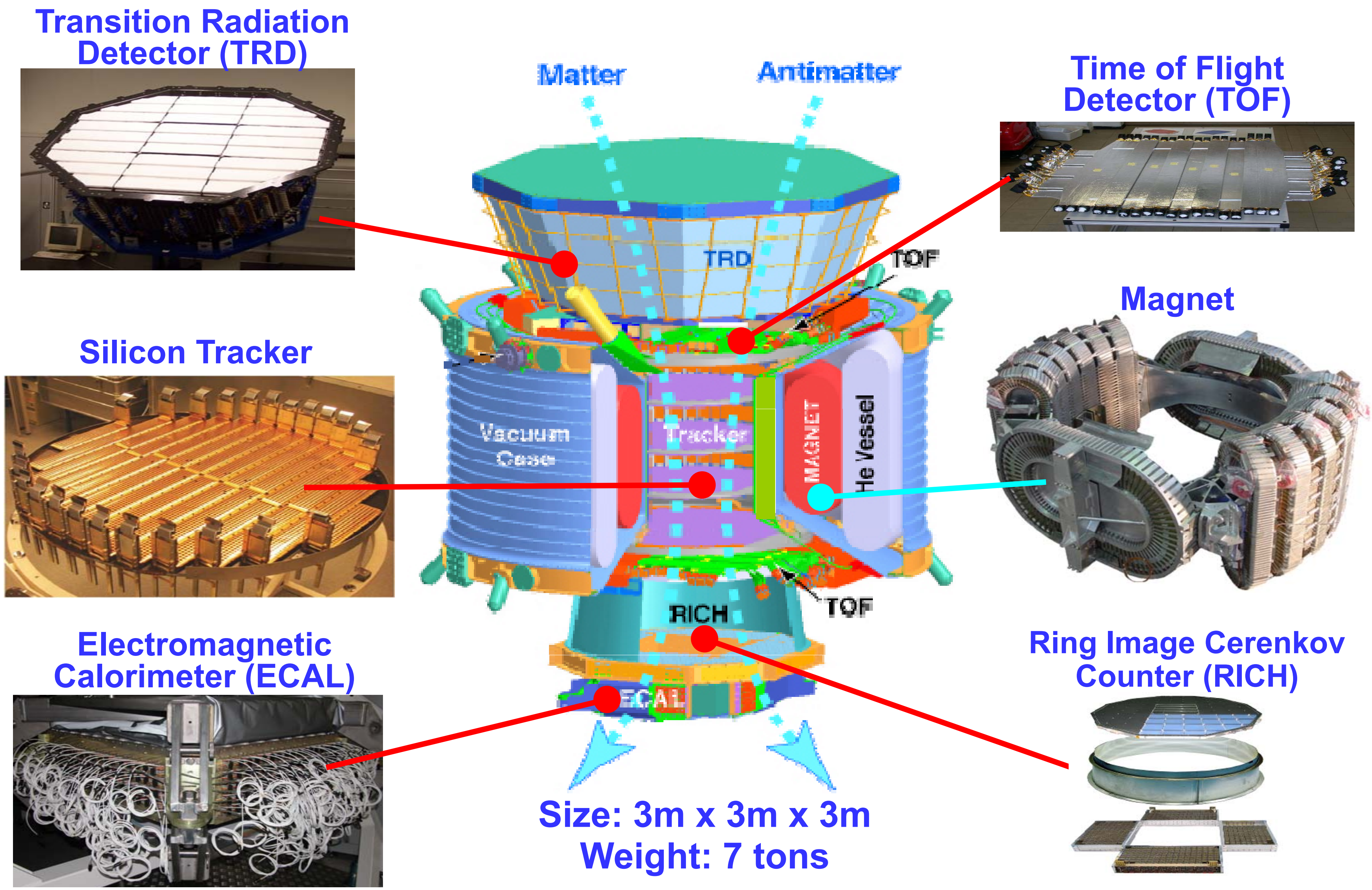
J. Madsen

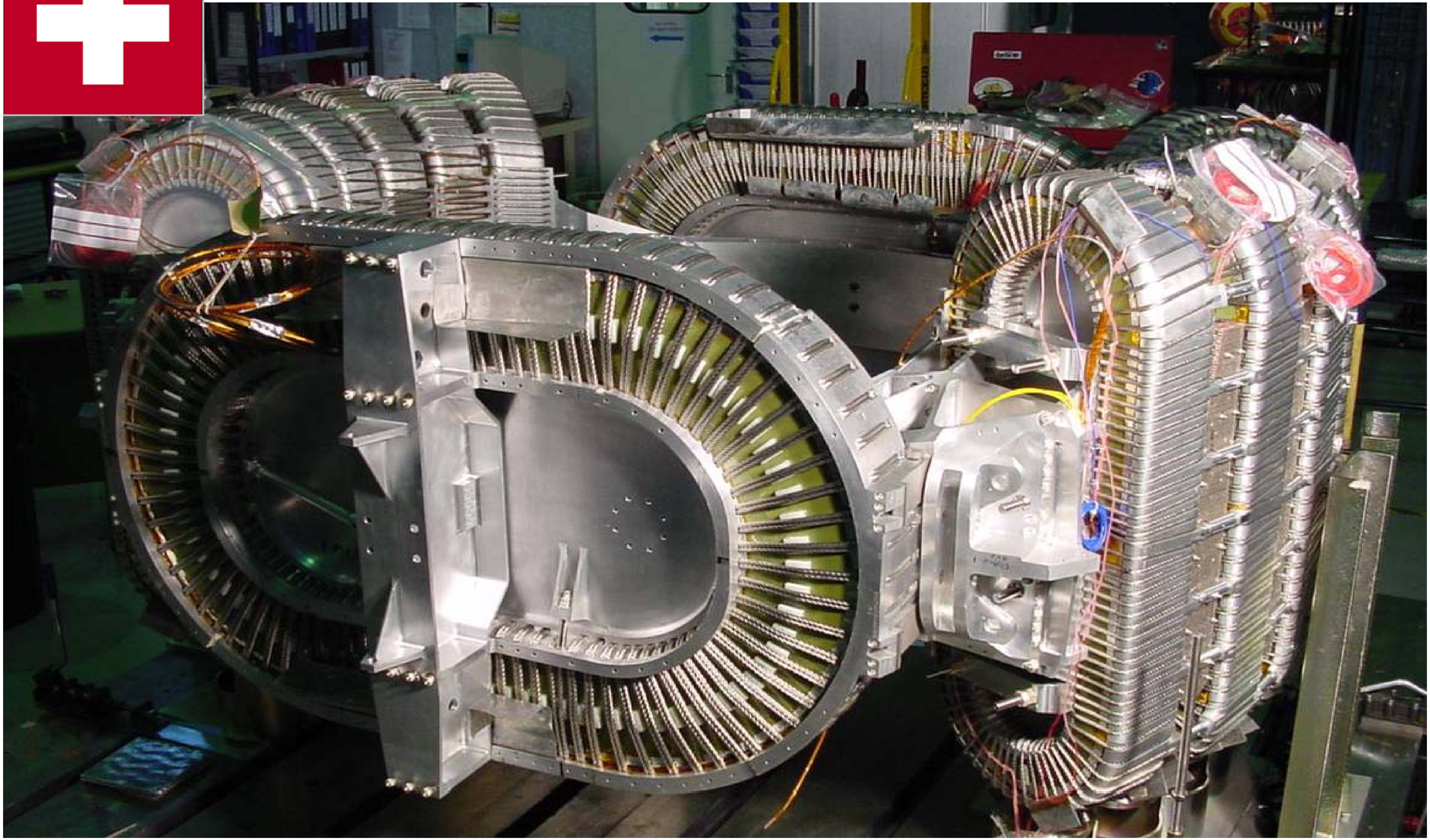
B. Verlaat

Italy in AMS

The AMS experiment is the largest scientific participation on the ISS in Italy and it has the highest priority within ASI and INFN

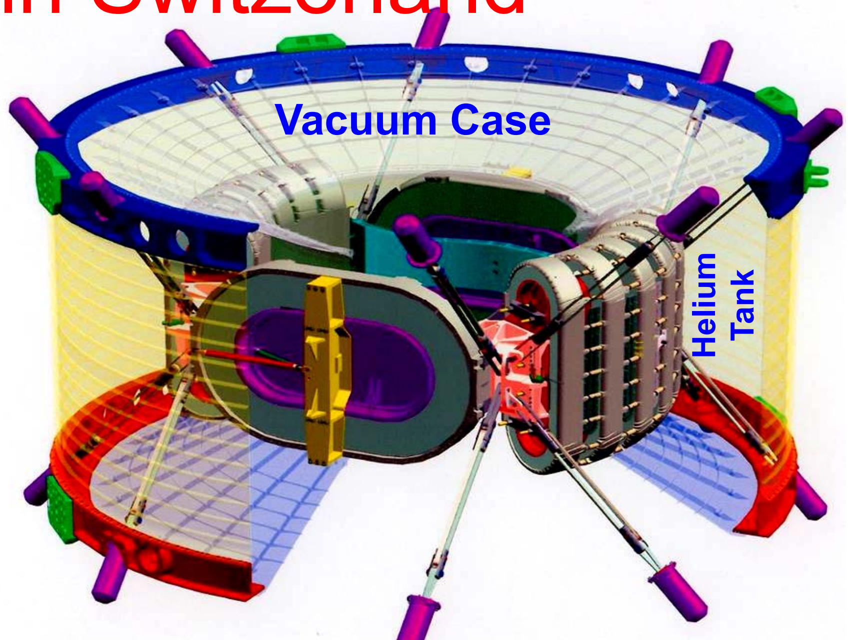
The Completed AMS Detector on ISS

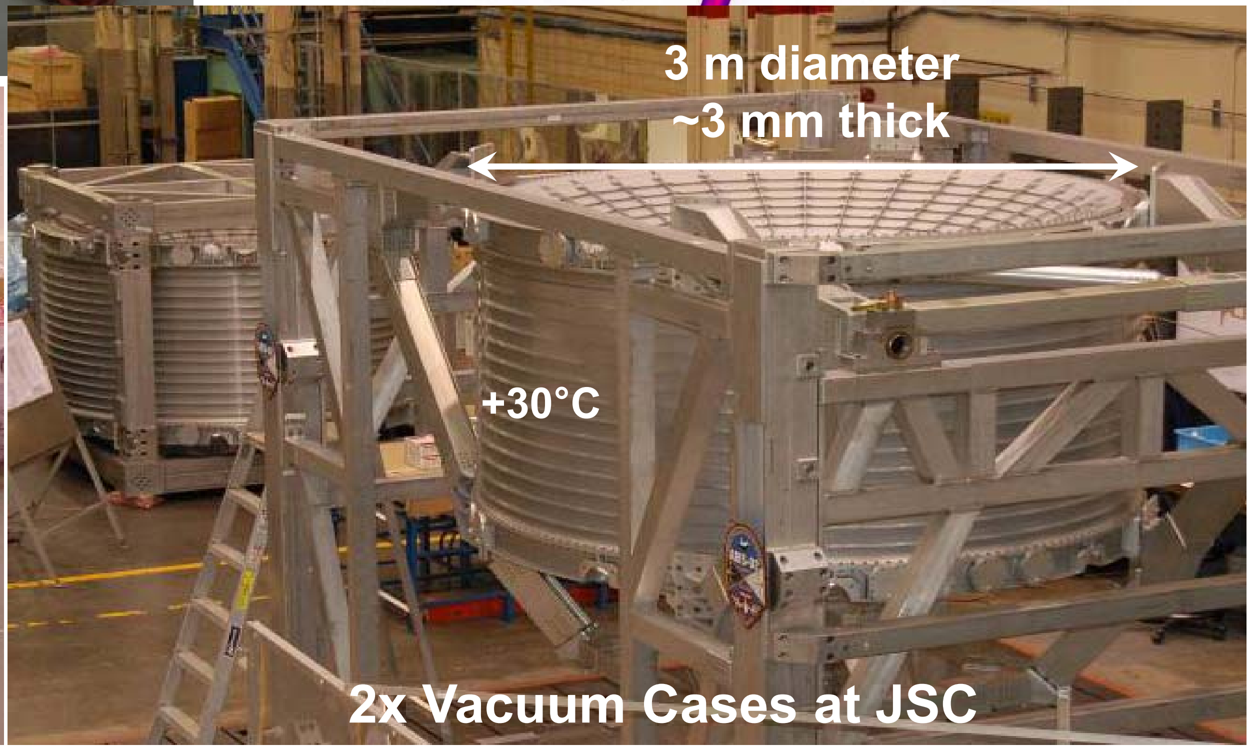




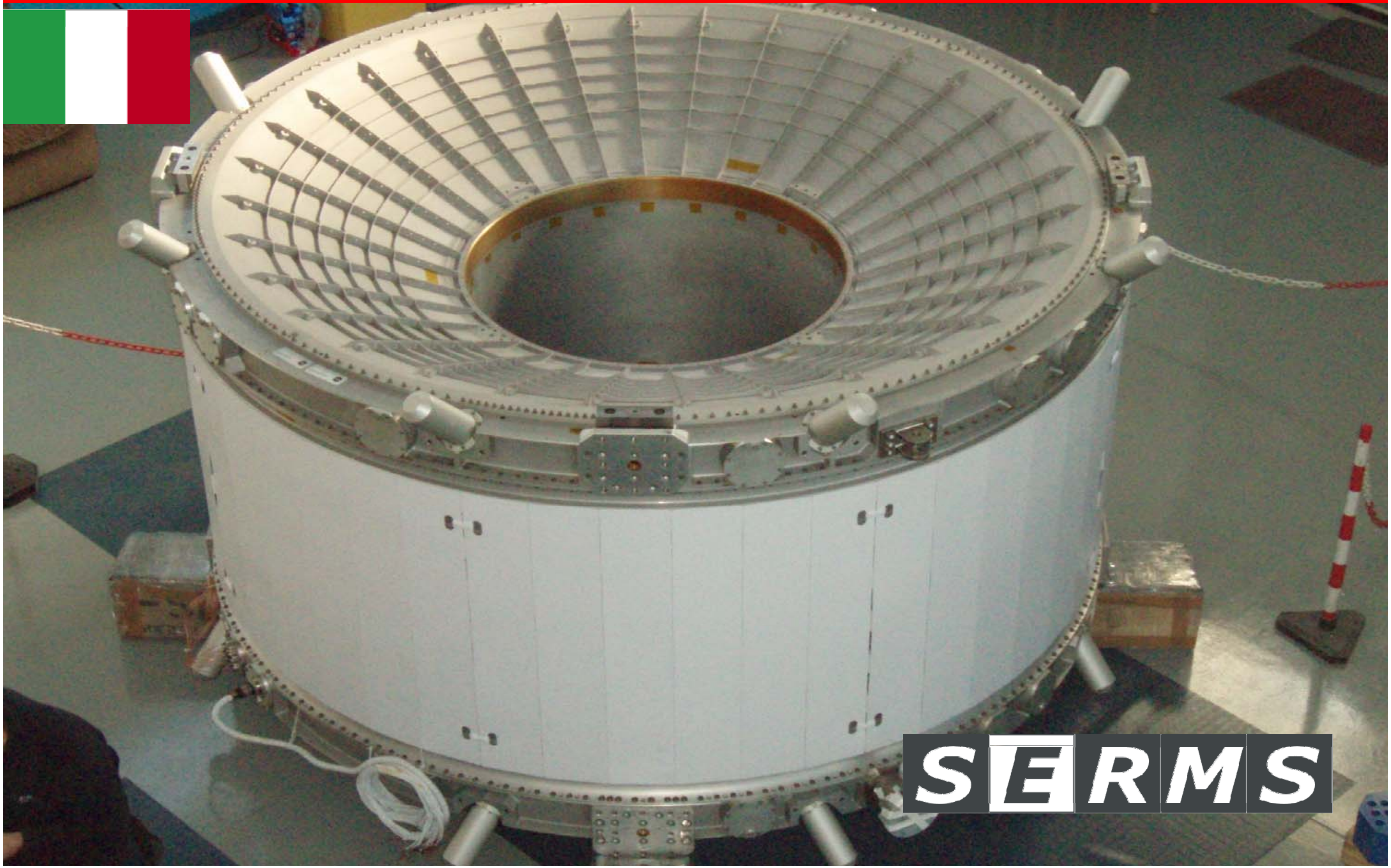
The first Superconducting Magnet in space – operating at 1.8K

Key developments in Switzerland





Vibration tests of Flight Spare Magnet Vacuum Case

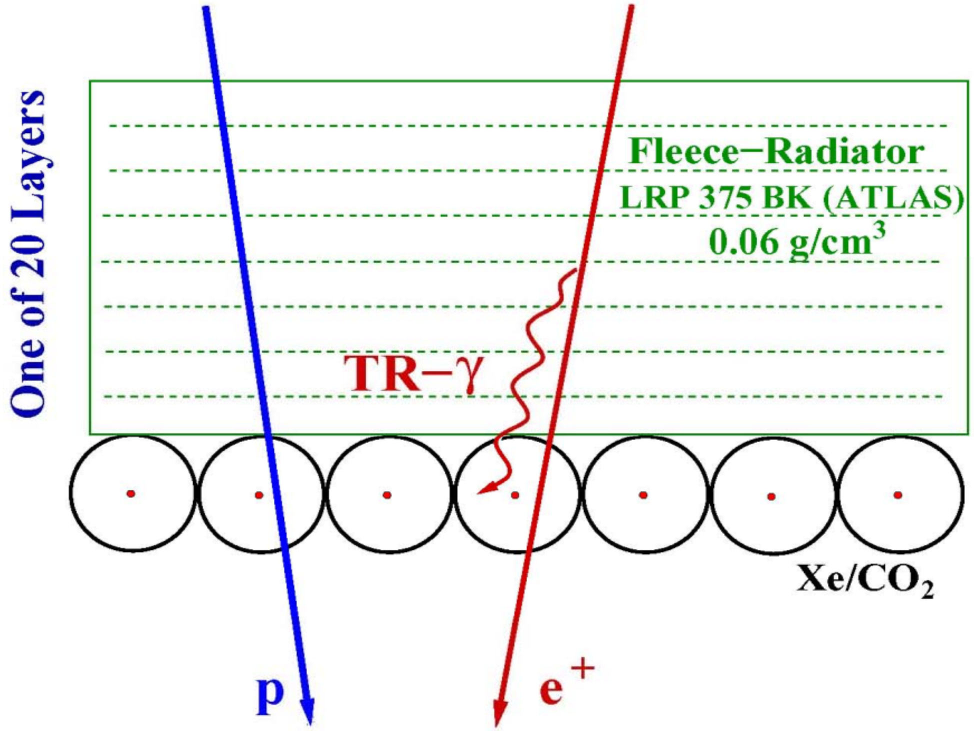


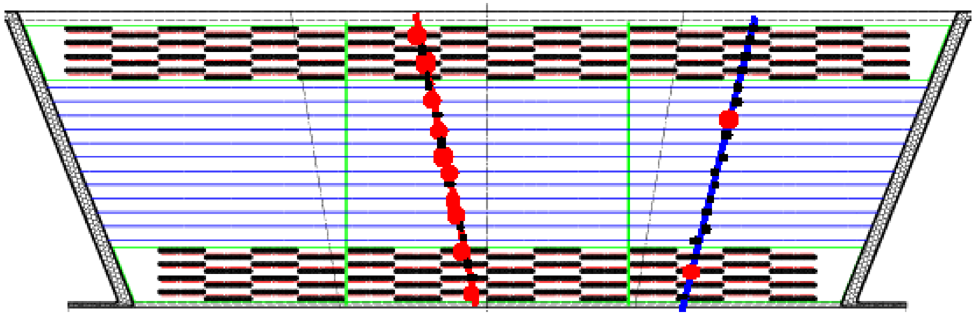
Test of magnet in vacuum at 1.8K

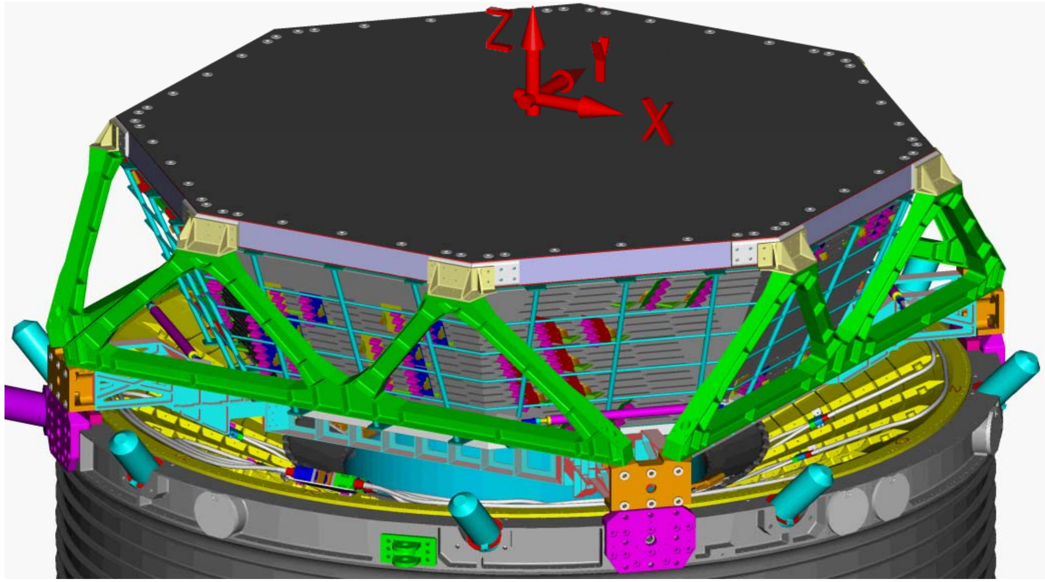
Transition Radiation Detector: TRD

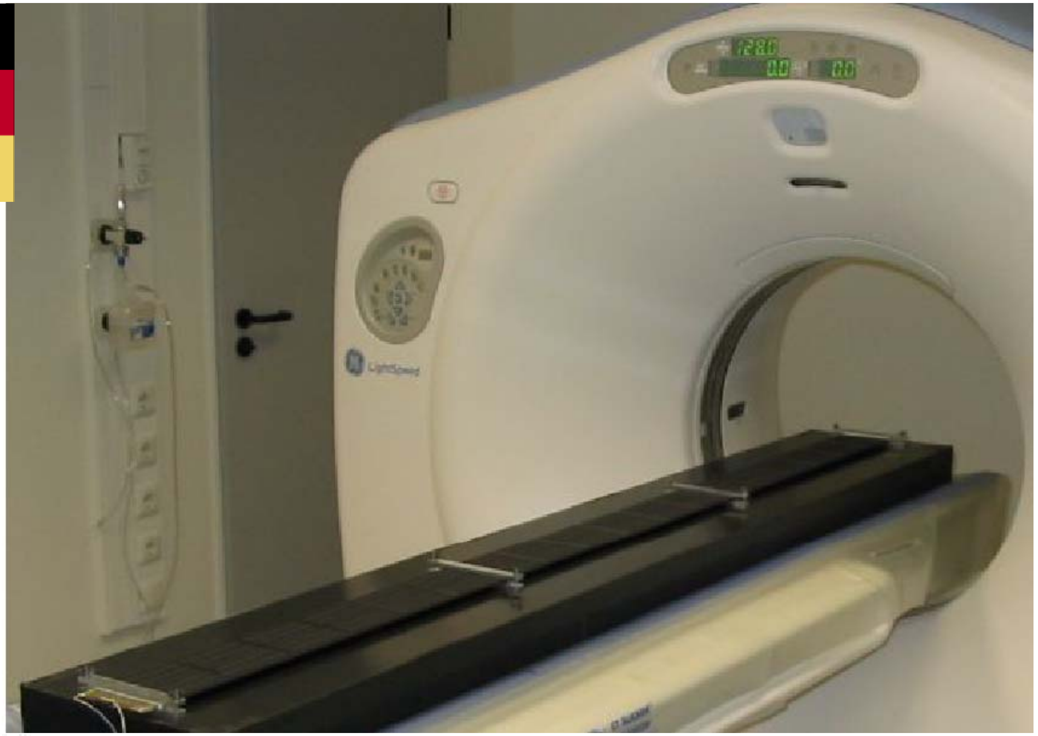
Identify e⁺, reject P

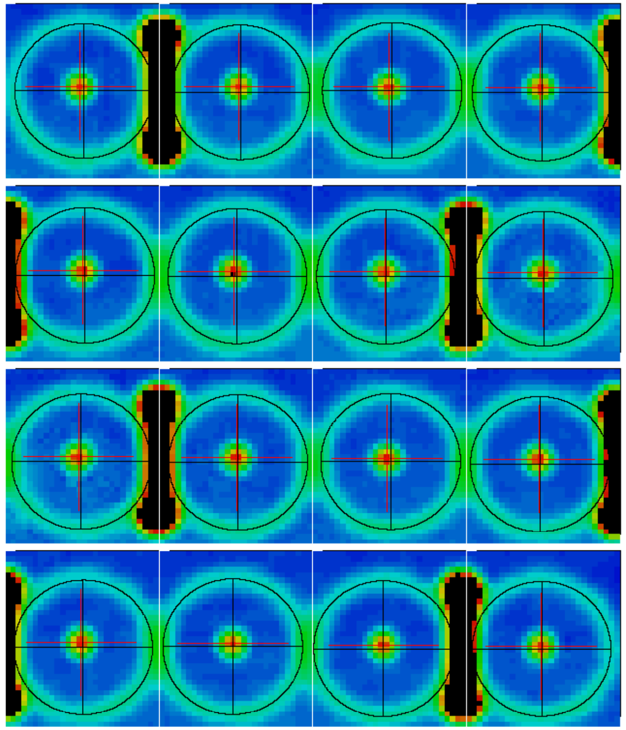
Professor K. Luebelsmeyer



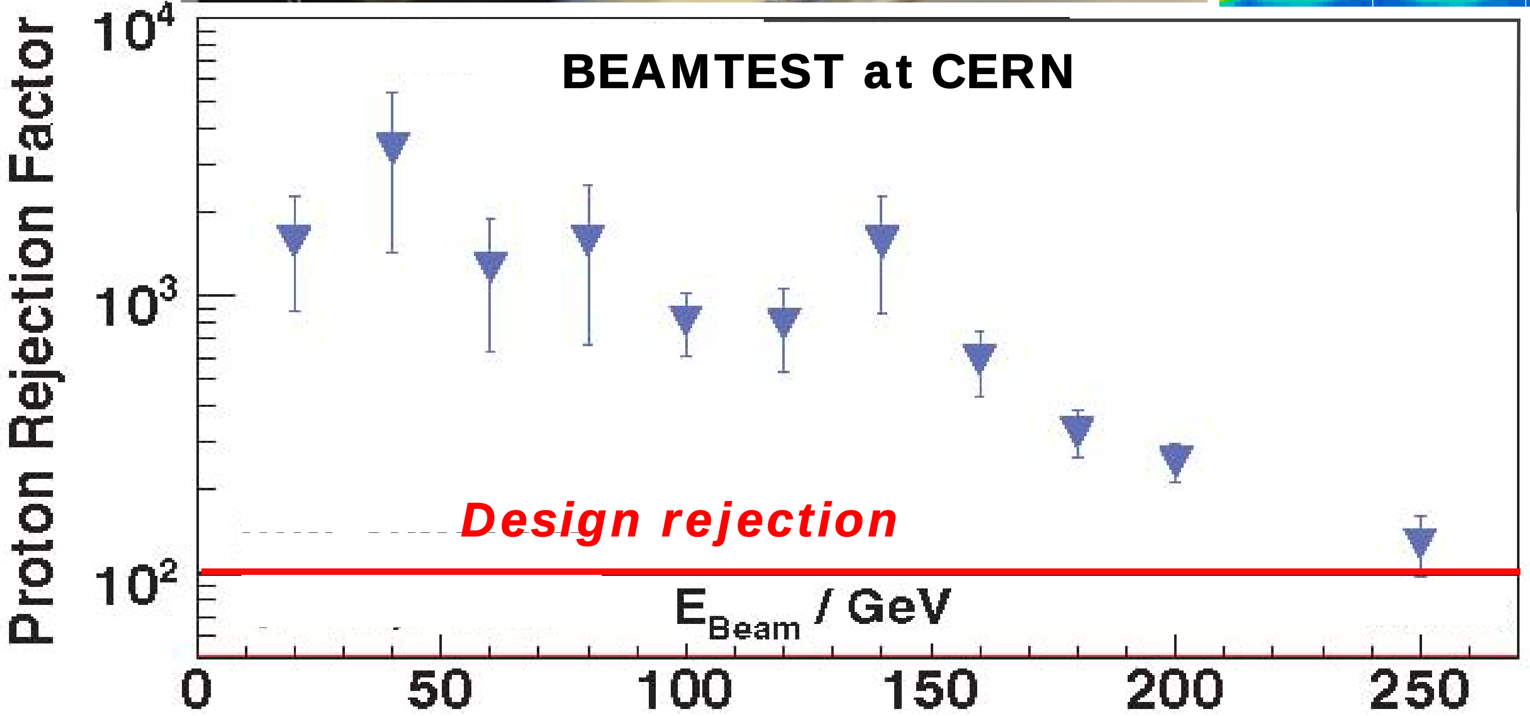






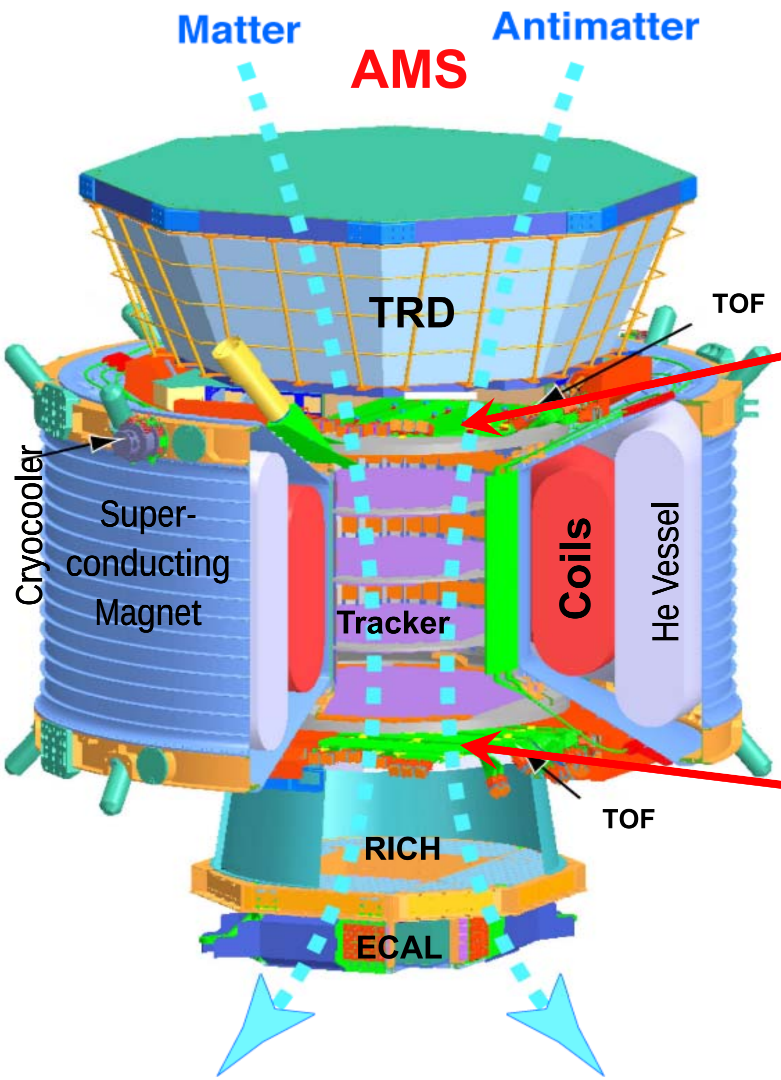


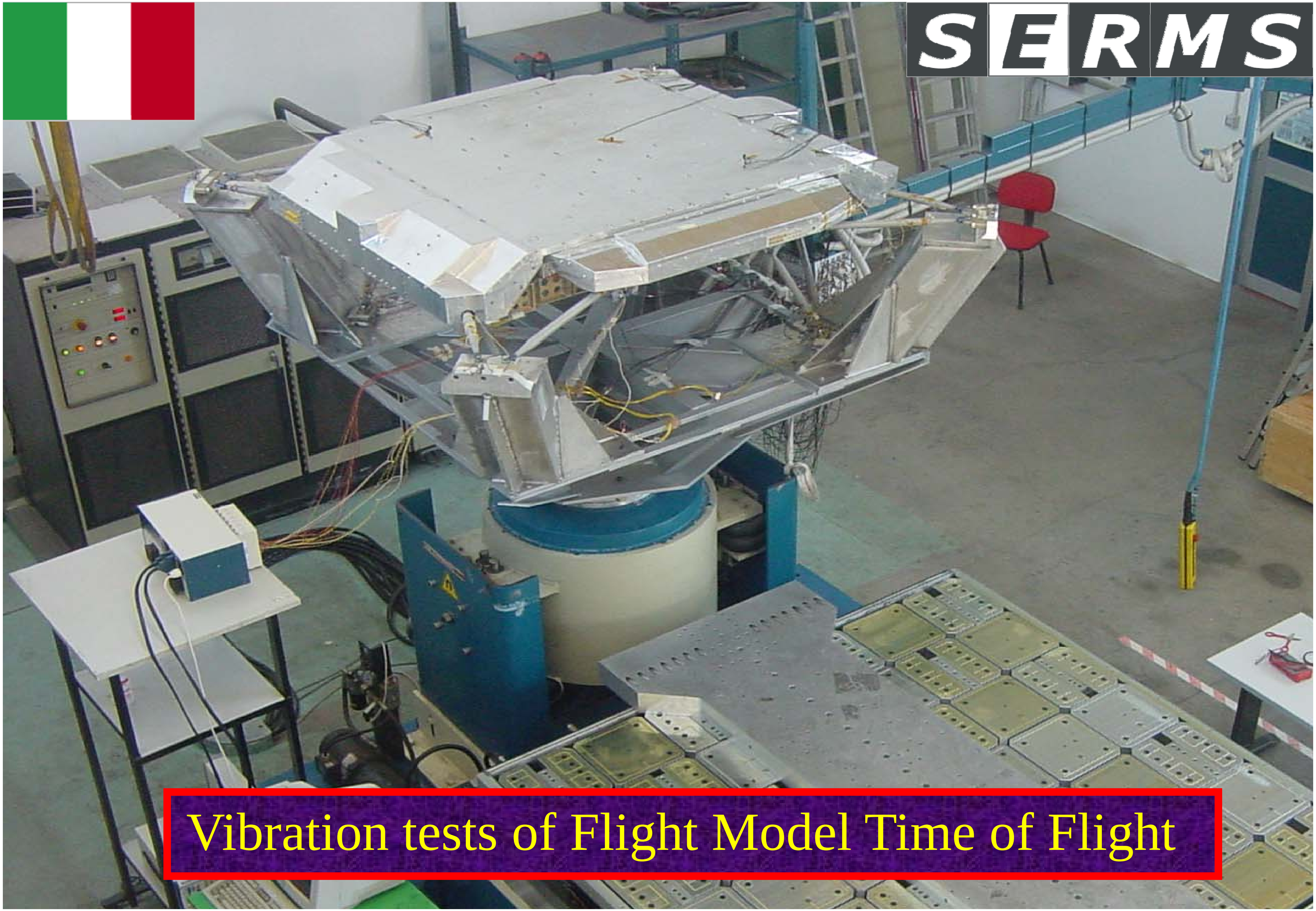
5248 tubes


BEAMTEST at CERN
Design rejection
Proton Rejection Factor
E_Beam / GeV
10^4
10^3
10^2
0
50
100
150
200
250

Time of Flight (TOF)

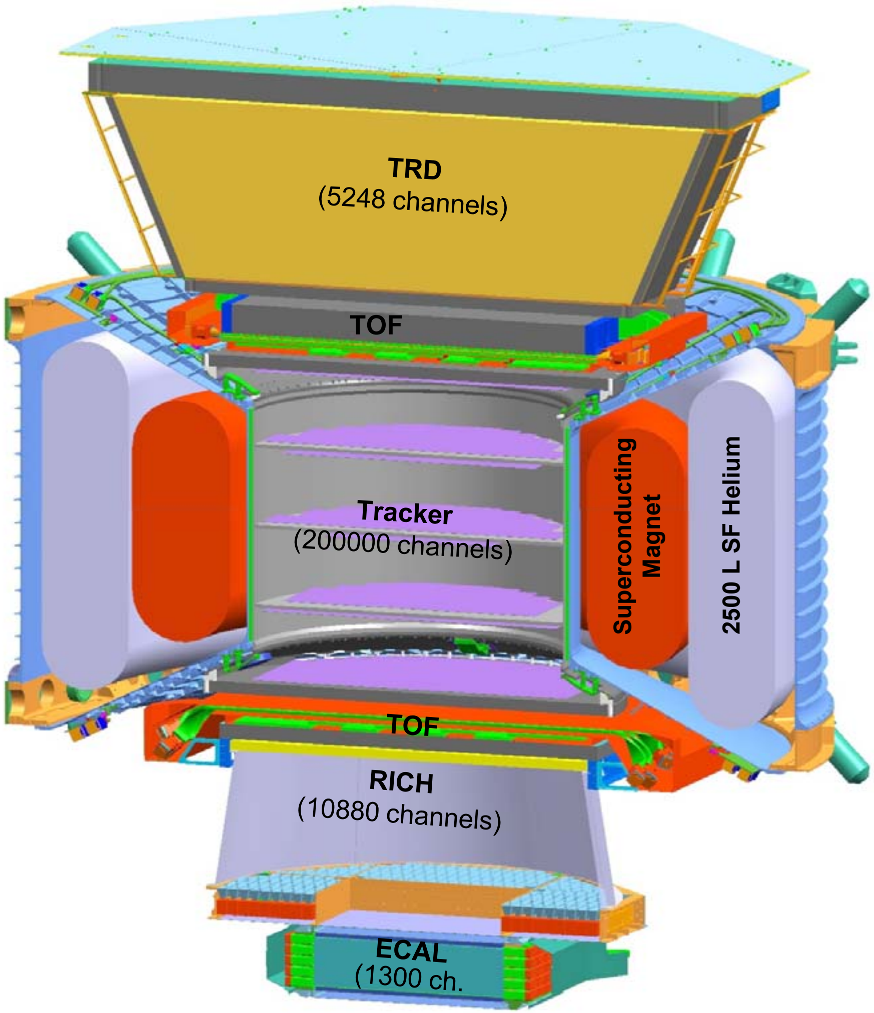
Measures the time of particles to ~ 100 picoseconds

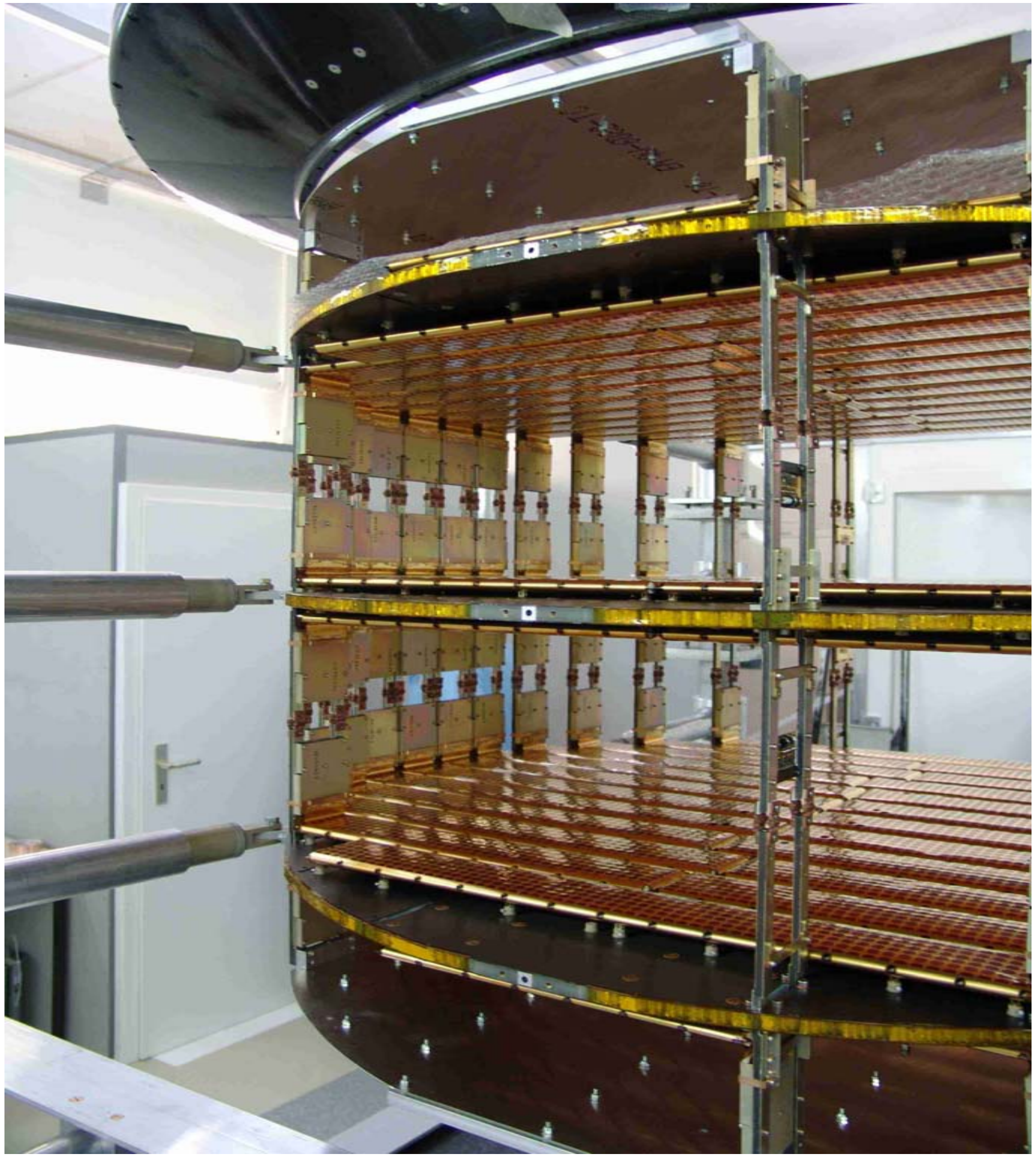




Vibration tests of Flight Model Time of Flight

Silicon Tracker, 8 planes

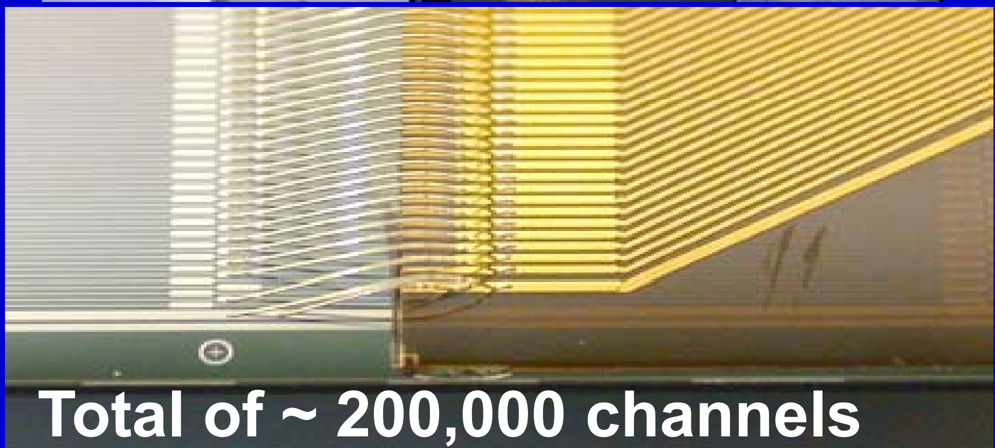




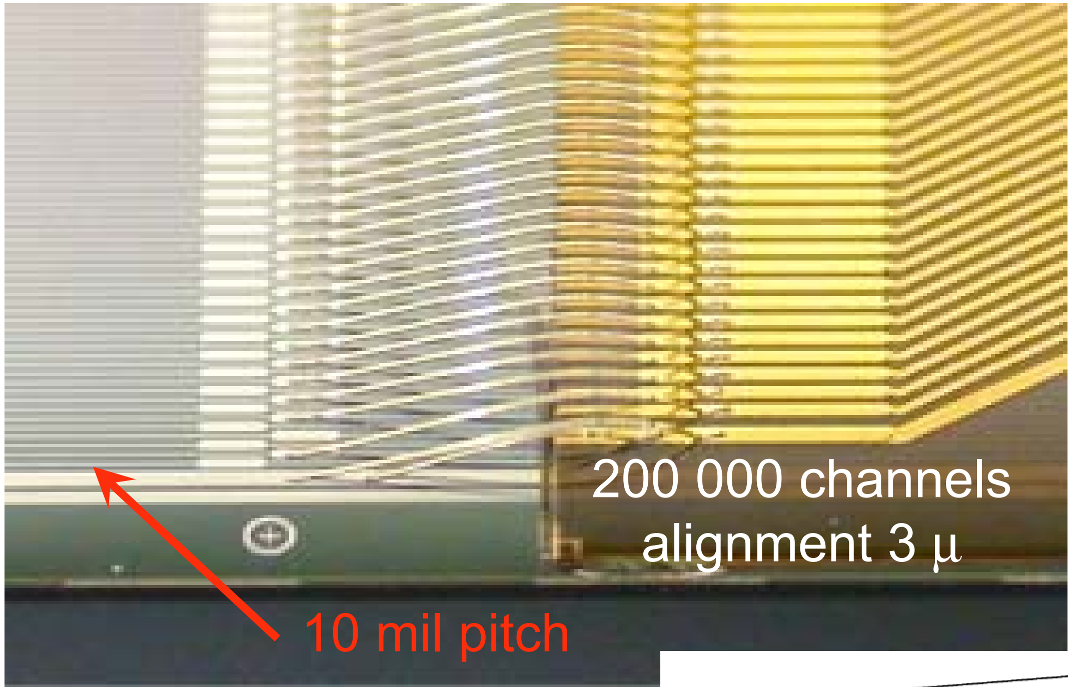
Professor R. Battiston

Precision Construction in Italy

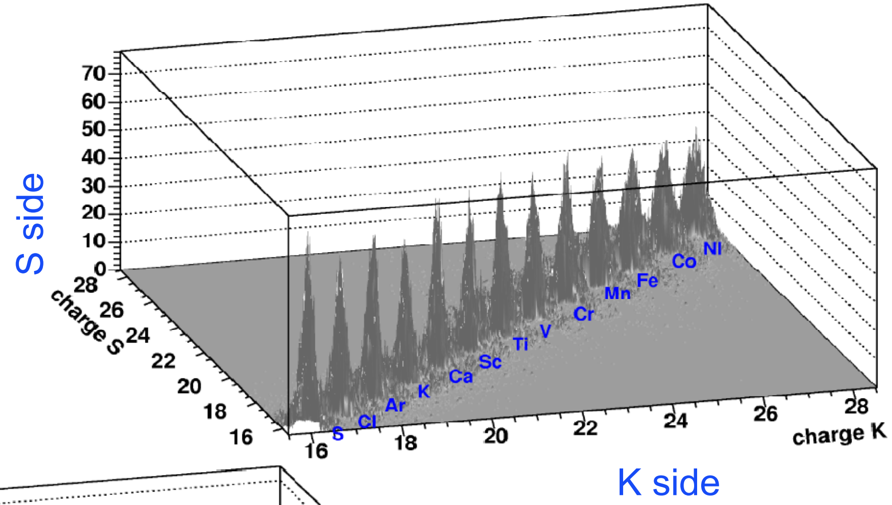
This detector is very complex even by terrestrial standards, totaling ~ 6,7 m^2 of double sided silicon detectors

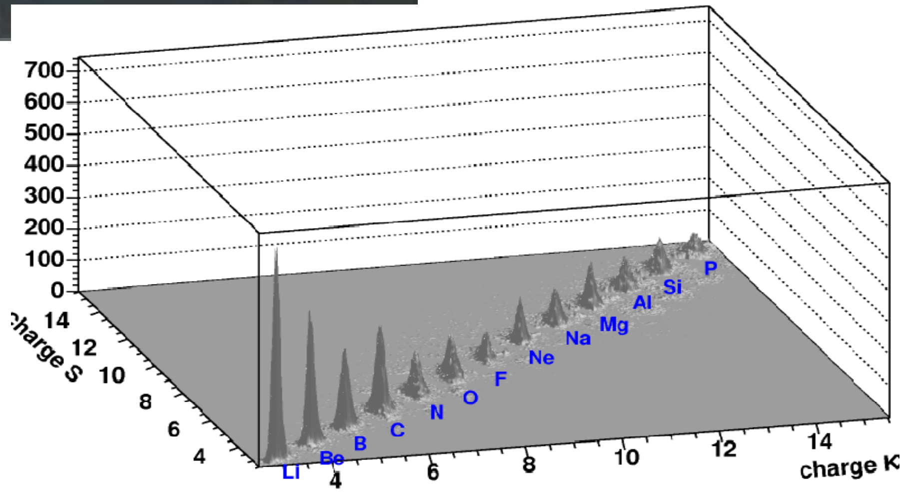


It has taken 50 engineers and technicians three years to complete the detector



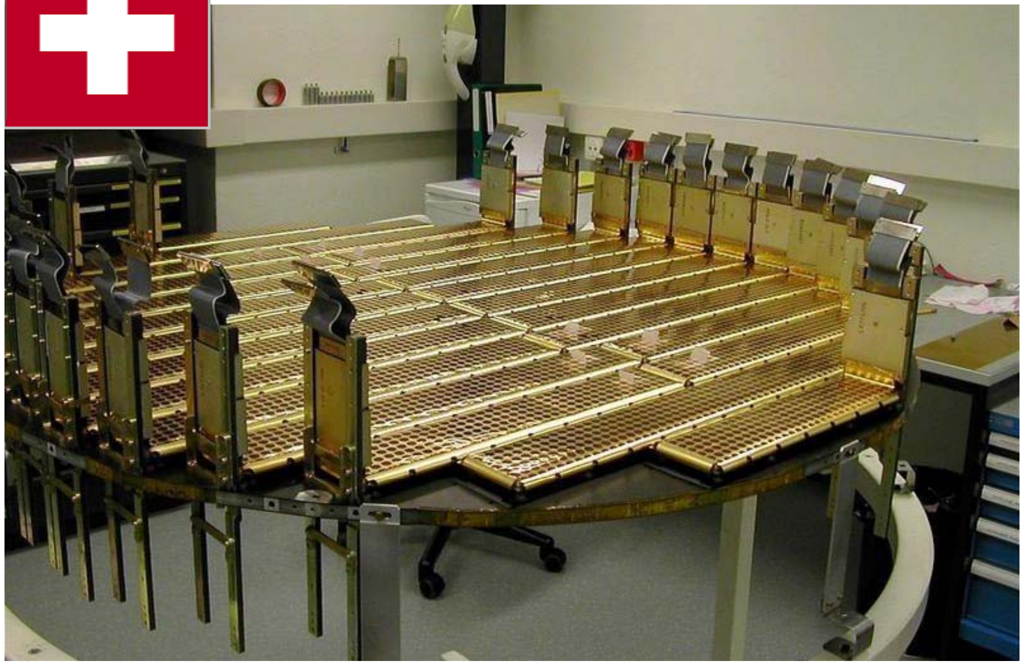
Test results from CERN identify all nuclei simultaneously

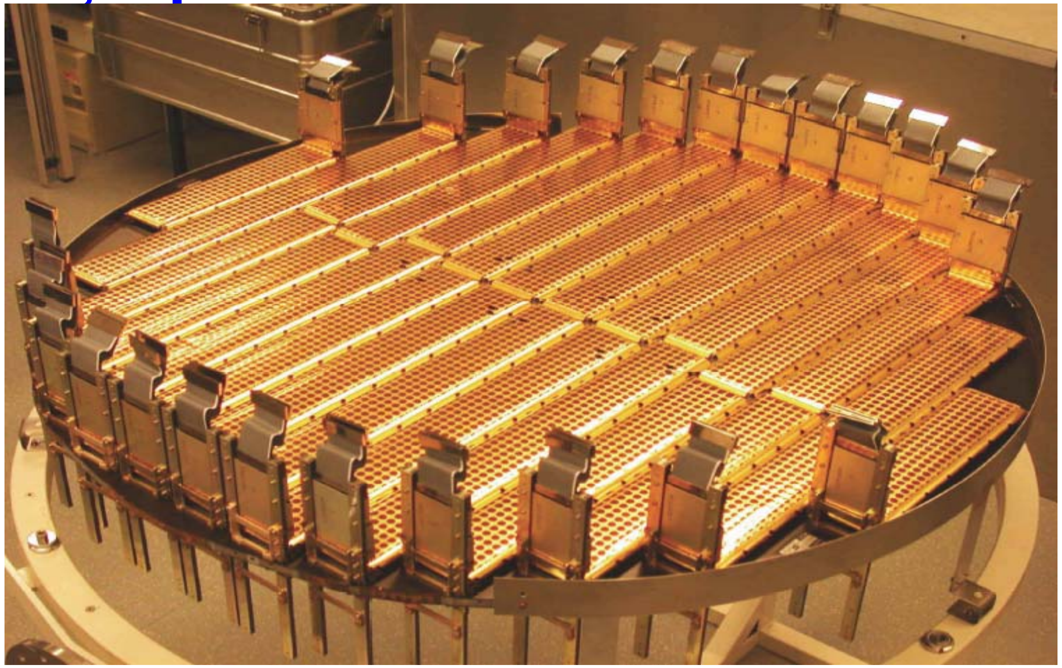


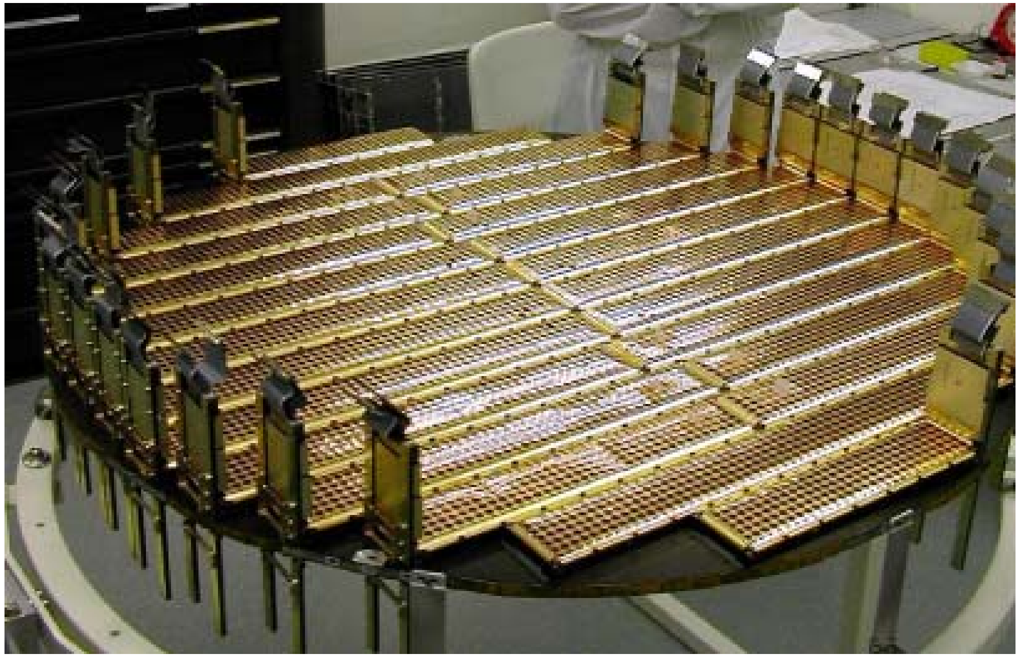


Tracker Assembly Labs in Switzerland

Silicon Tracker, 8 planes

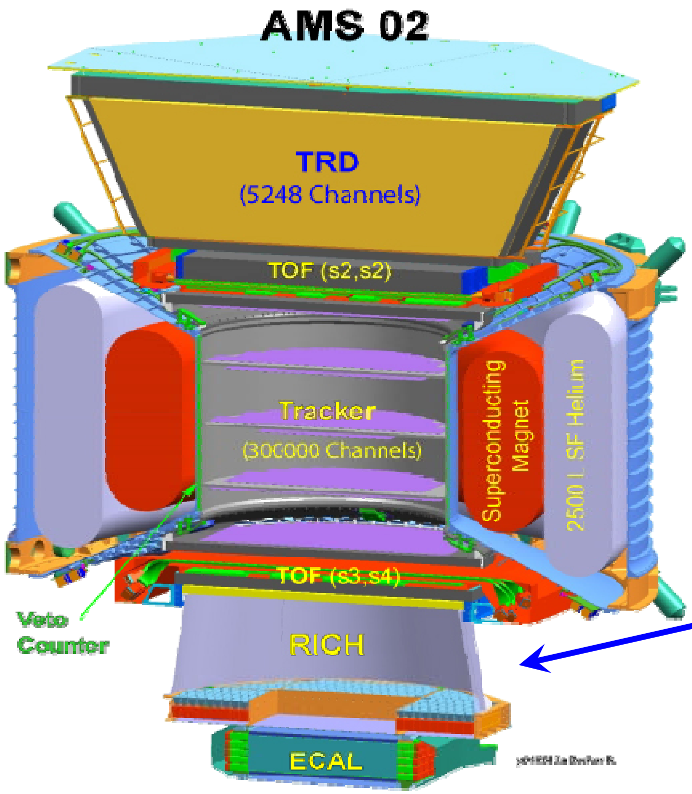




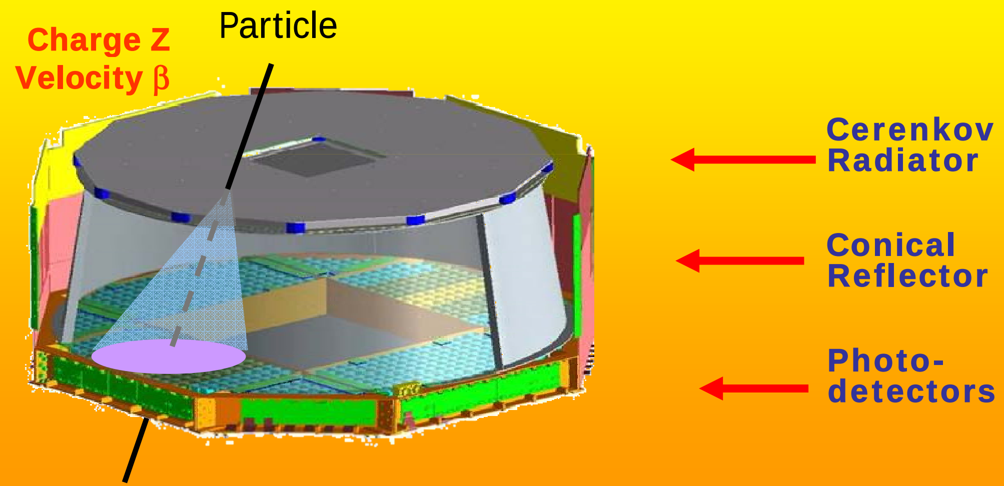


Professor M. Bourquin

AMS Ring Imaging CHerenkov (RICH)



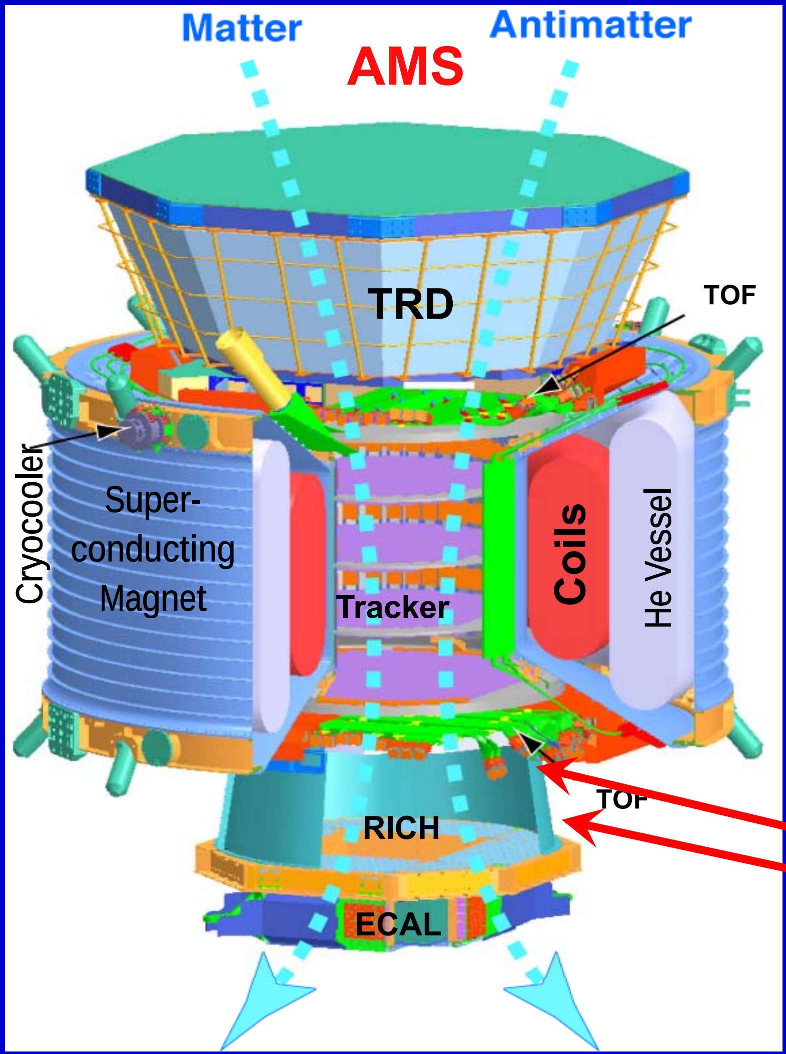
Precise measurement of the velocity & charge

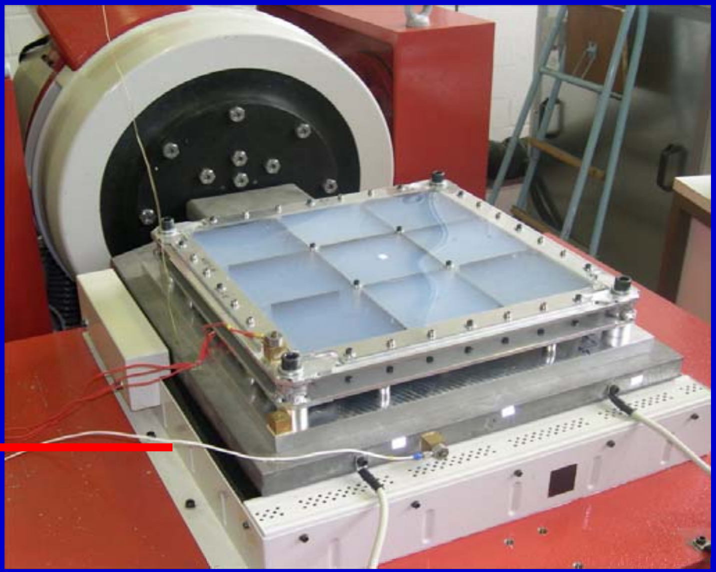


10,880 photodetectors

Professor M. Aguilar, Madrid

Ring Imaging Cerenkov Radiator (RICH)

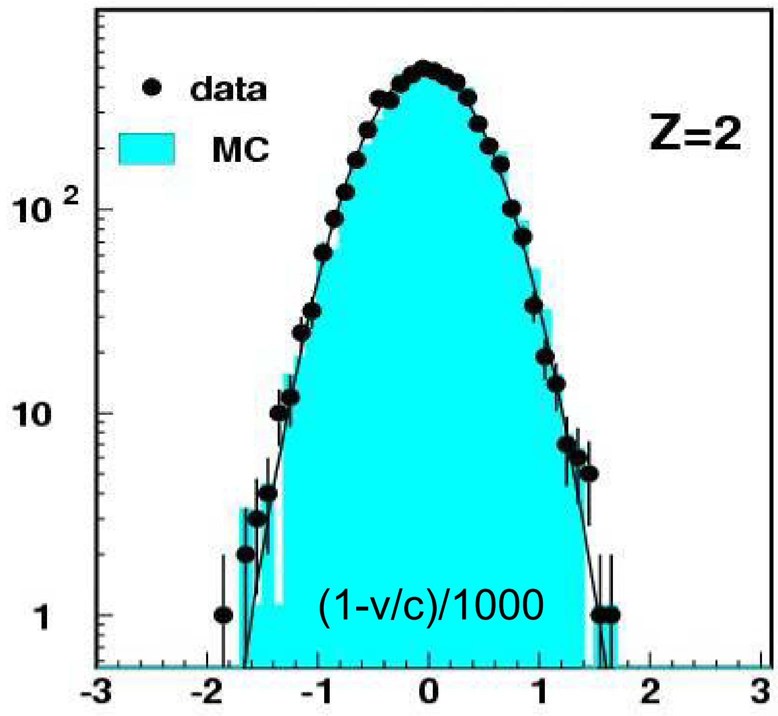


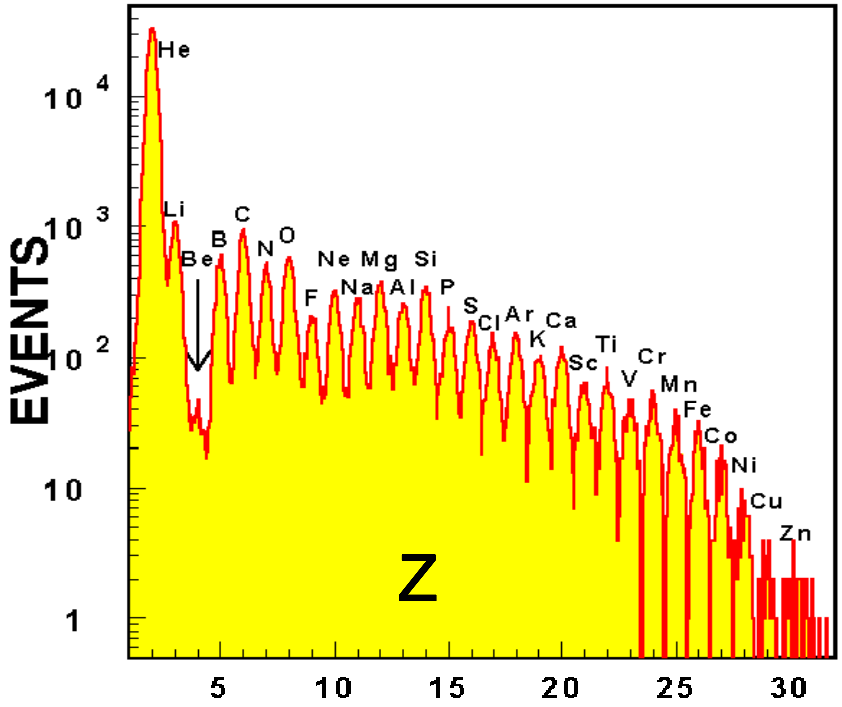


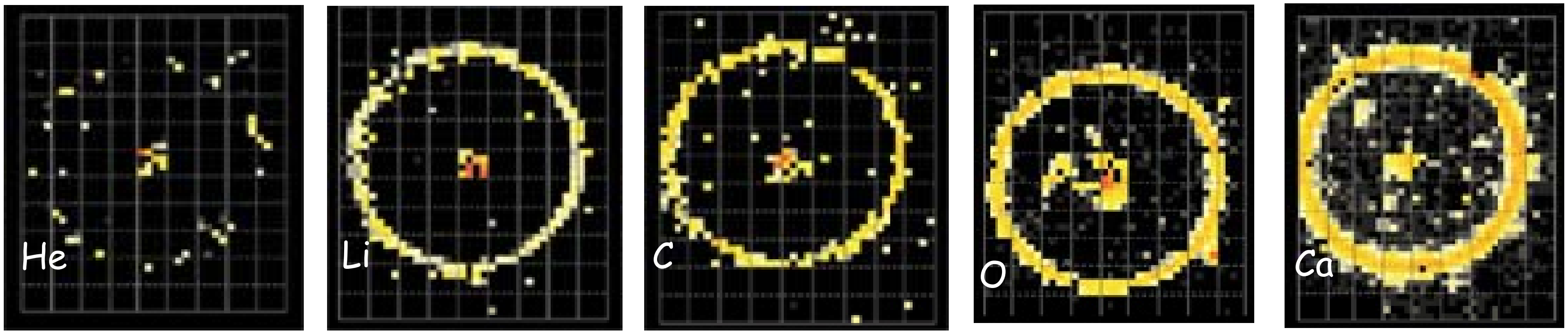
Space Qualified Radiator

Space Qualified Mirror

RICH test beam E=158 GeV/n



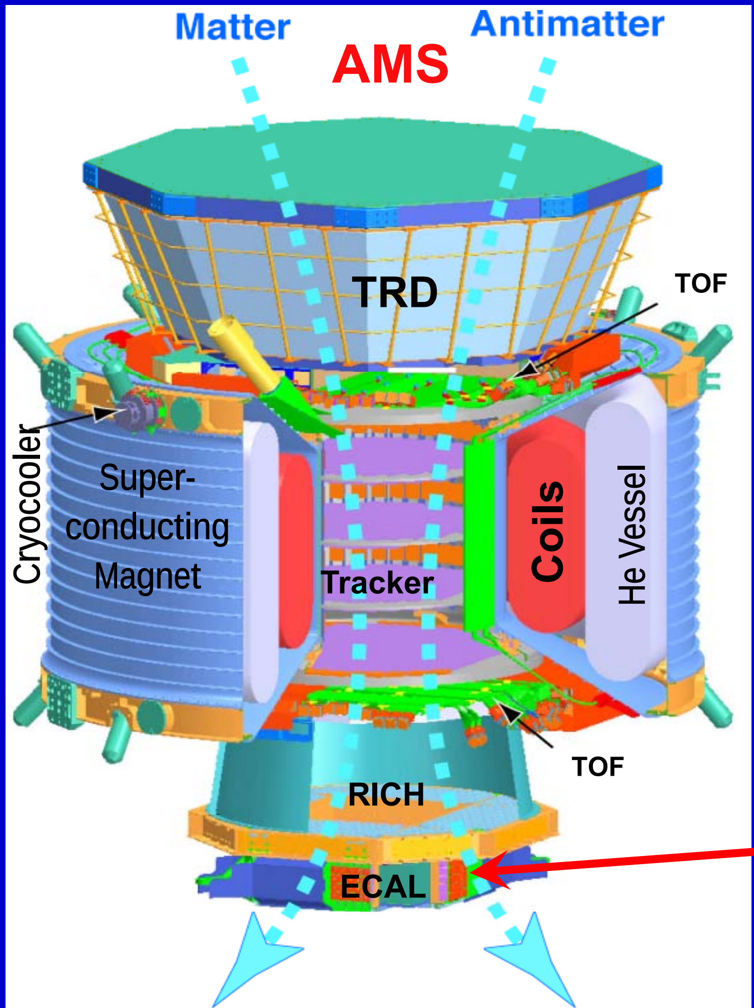




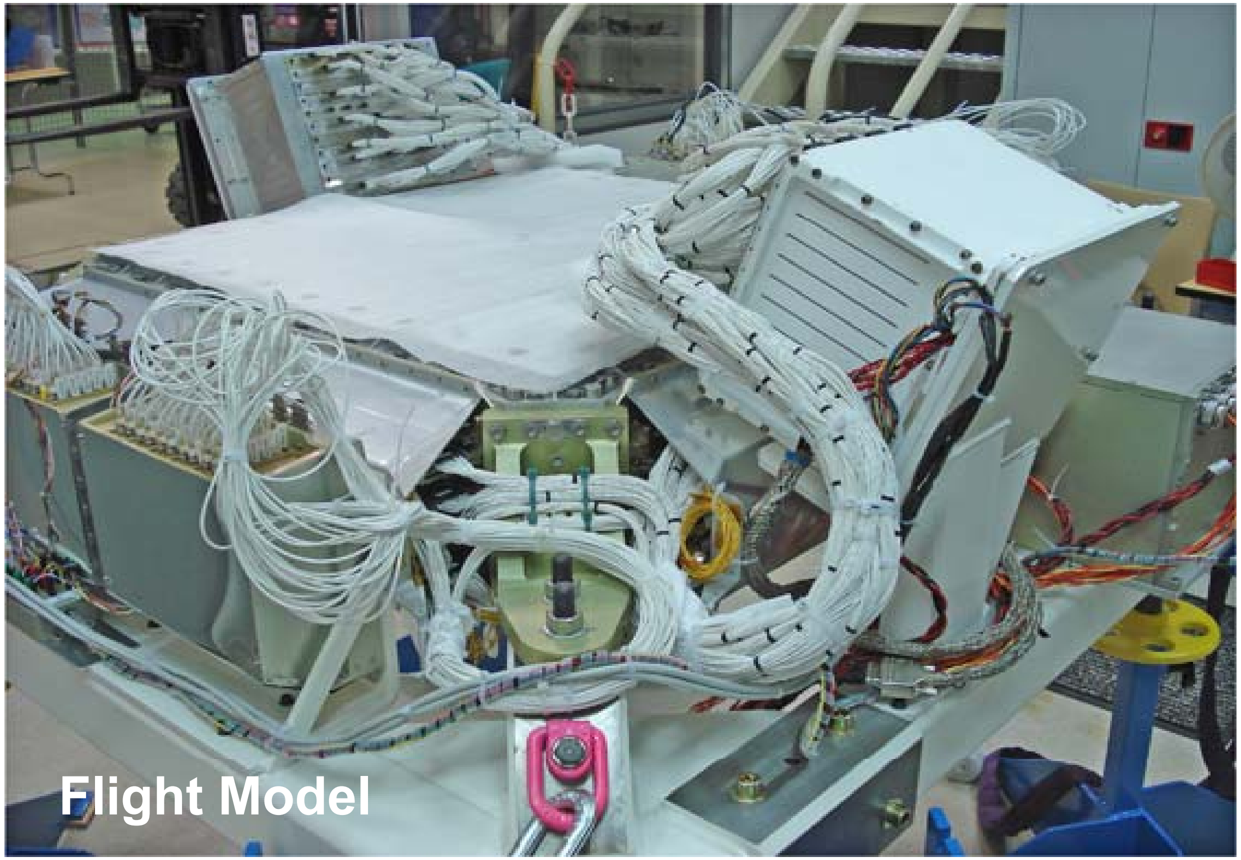
Single Event Displays

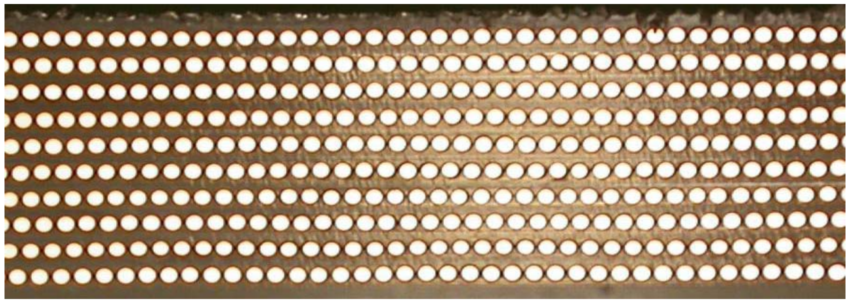
Electromagnetic Calorimeter (ECAL)

A precision 3-dimensional measurement of the directions and energies of light rays and electrons



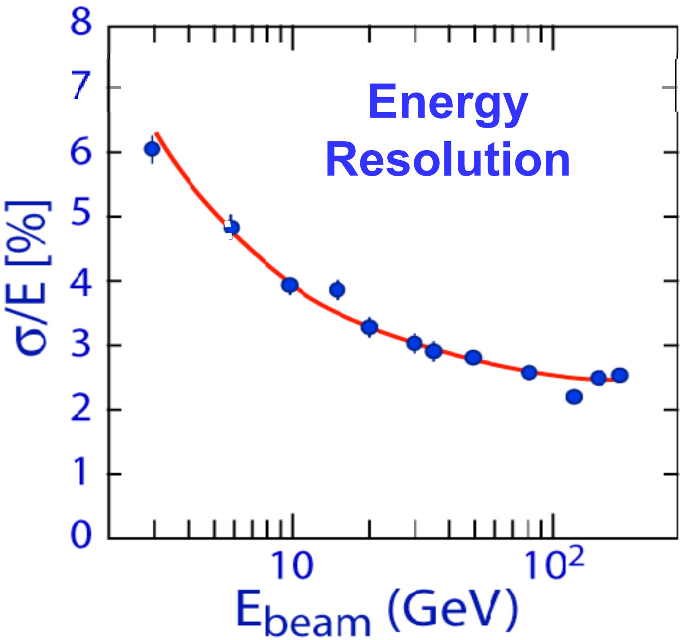
ECAL: A 3 dimensional, 17 X_0 measurement of the direction & energy of gamma rays and electrons

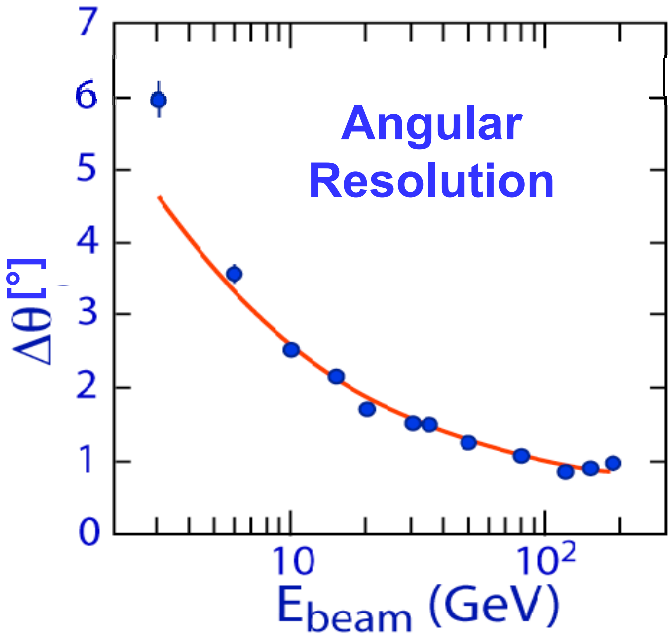




Cut-away view of fibers and lead

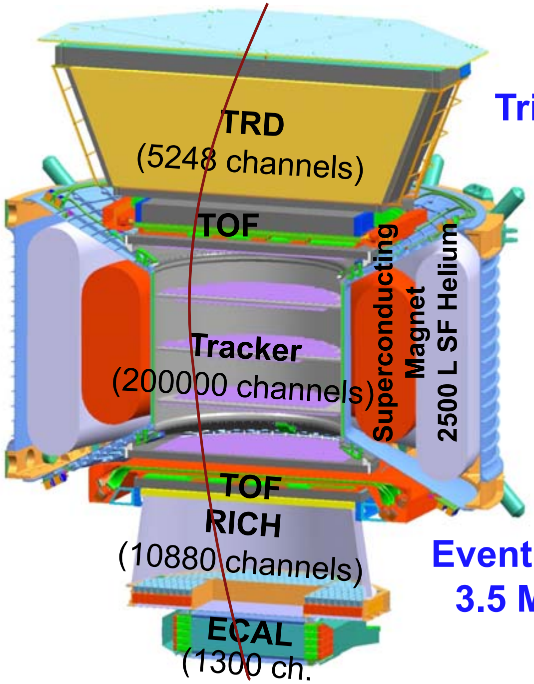
Verified in accelerator





AMS-02 Electronics

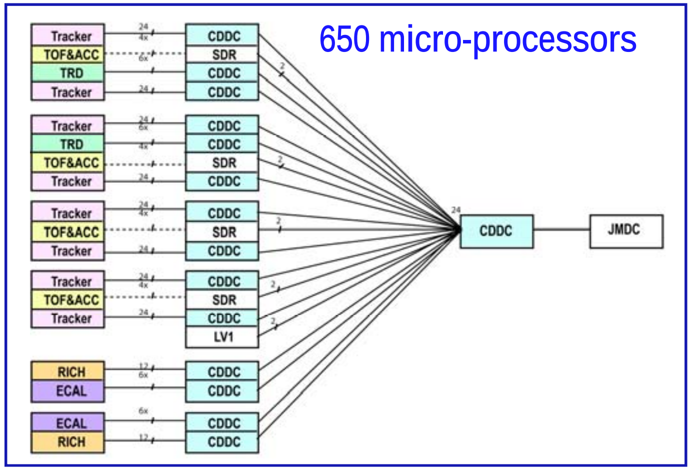
Dr. M. Capell, MIT
Prof. S.C. Lee, AS



Trigger Rate 2000 Hz

Event Size 3.5 Mbit

~ 7 Gbit/sec

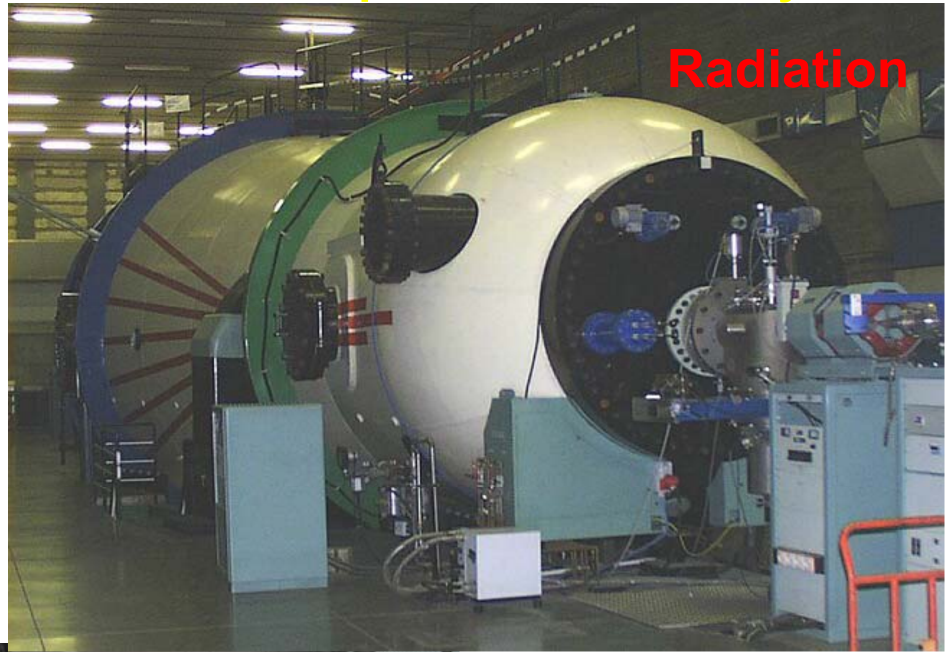


2 Mbit/sec

The AMS electronics is based on Accelerator physics technologies.
It is ~ 10 times faster than commercial space electronics.

Dedicated facilities in Taiwan

Dedicated Space Qualification Facilities have been developed for AMS in Italy

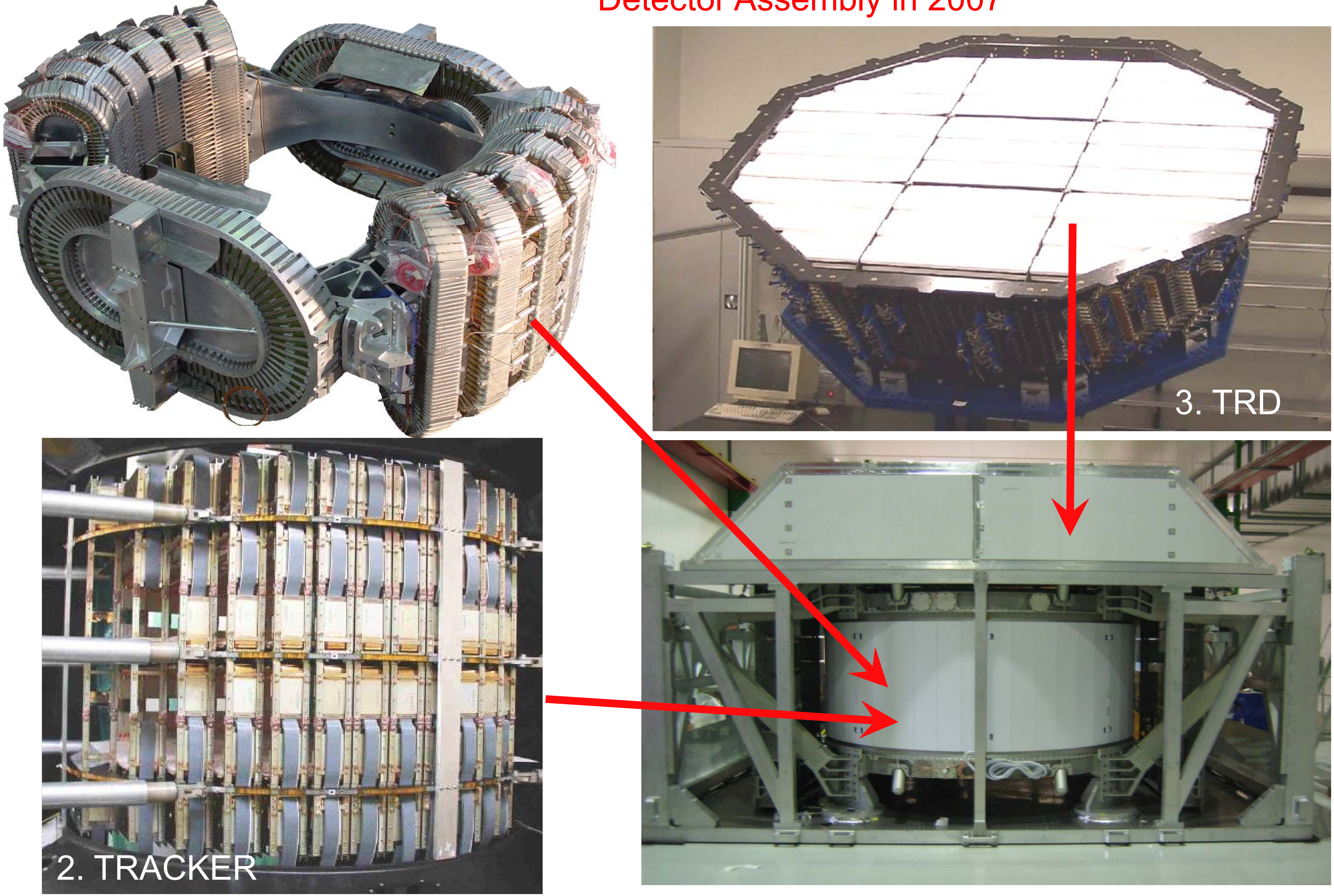


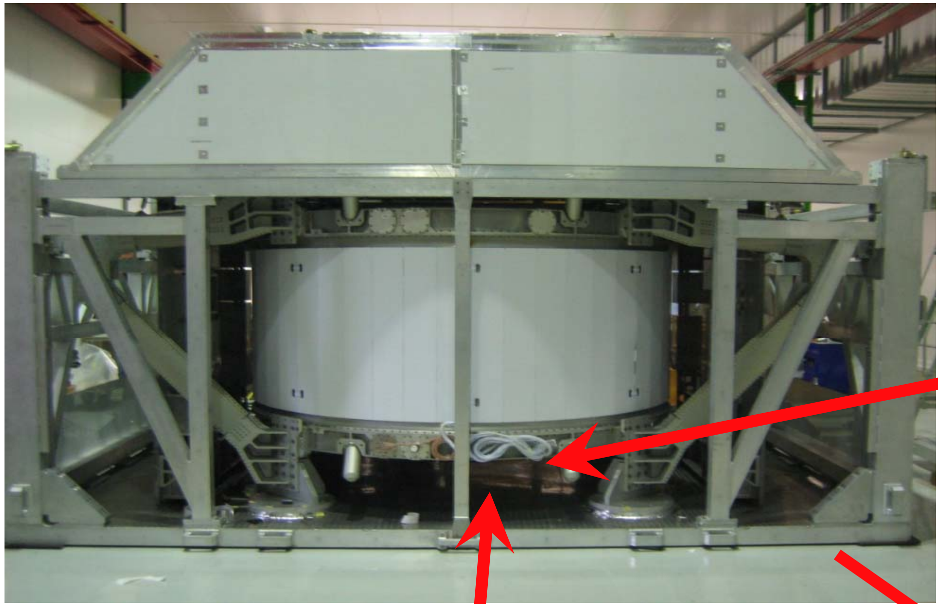
SERMS

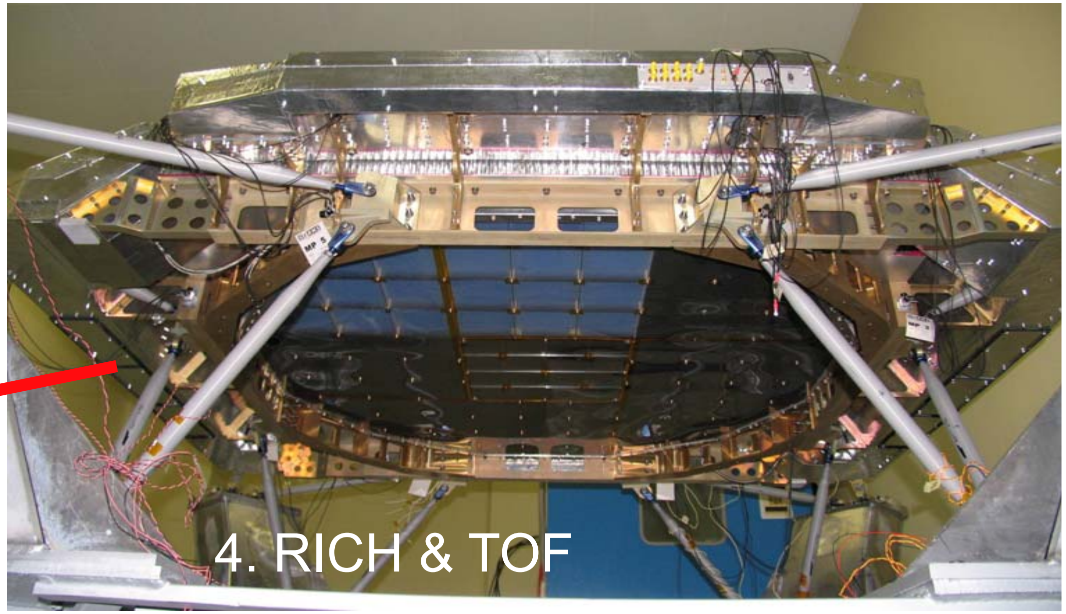
INFN

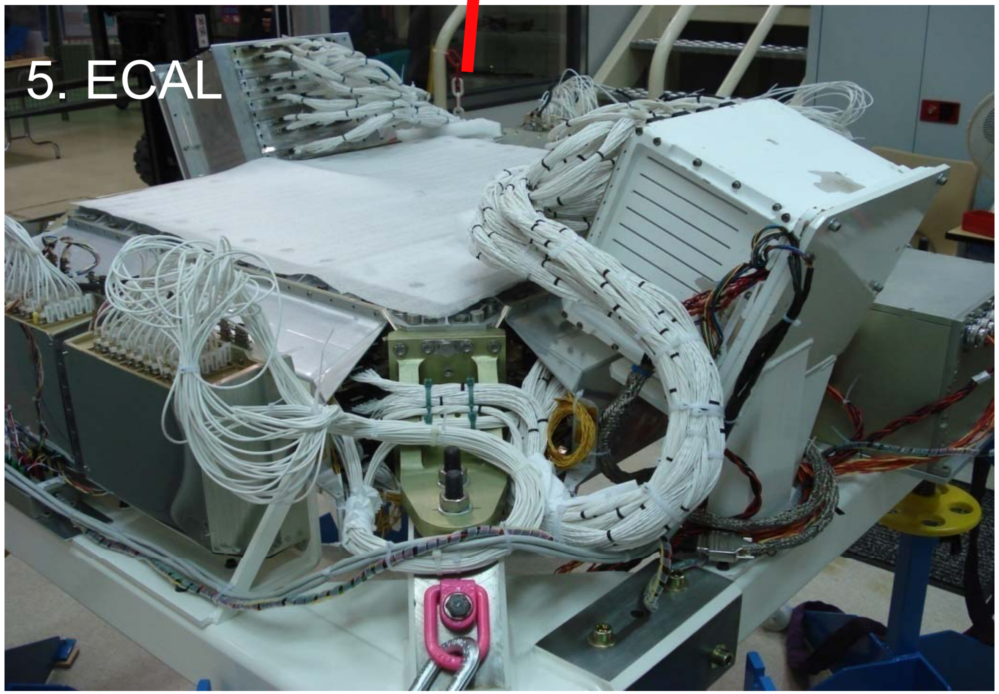
Istituto Nazionale di Fisica Nucleare

Detector Assembly in 2007



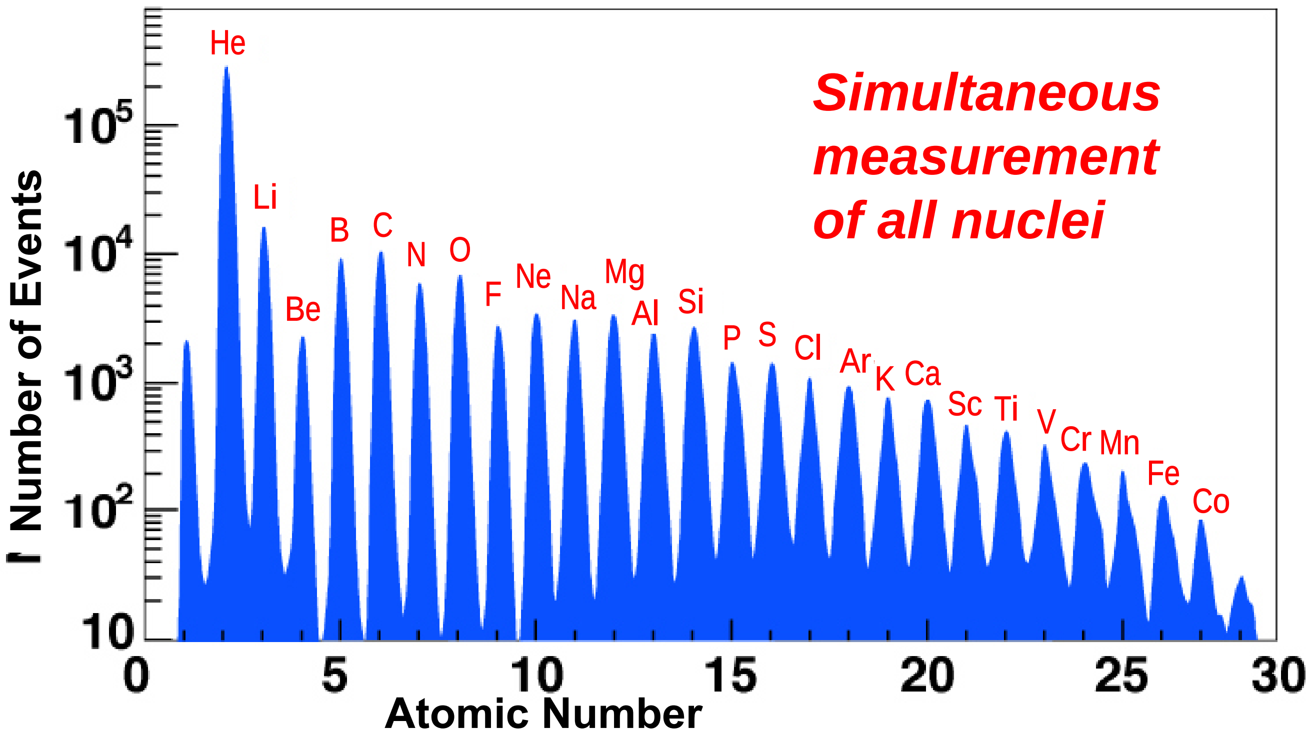


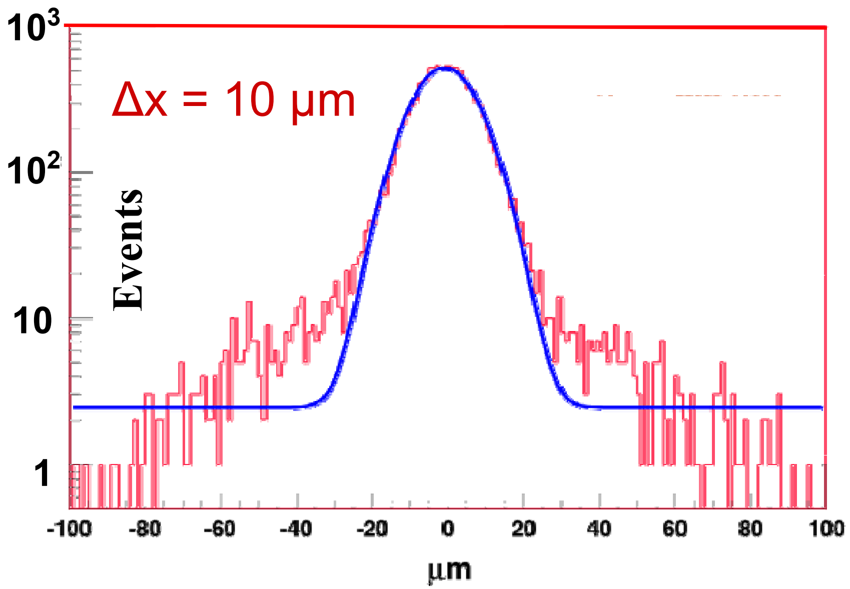


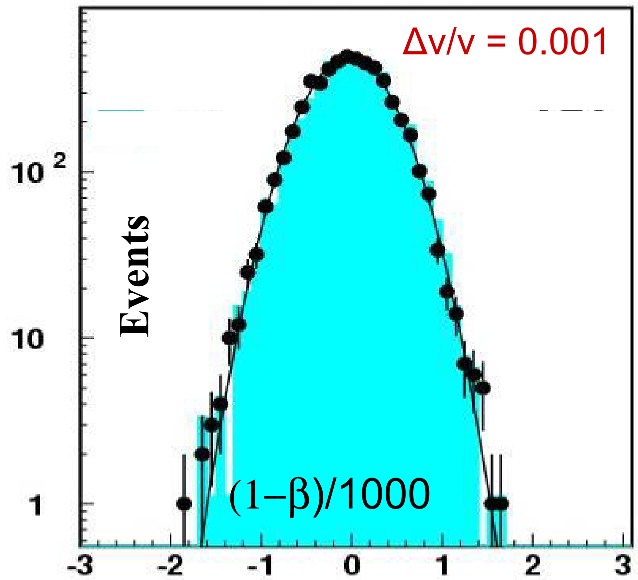


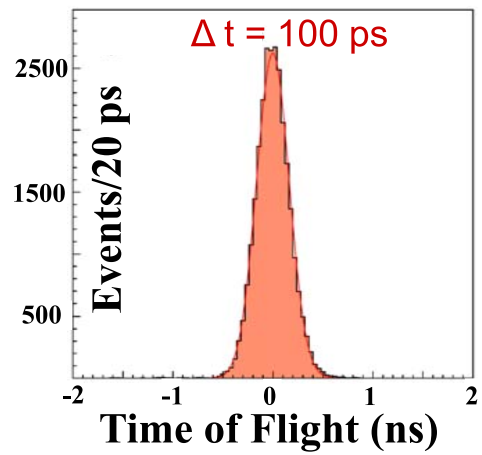
The detector is on schedule to be sent to KSC in December 2008.

Test results from accelerator









y04K513_05

The study of

The very large (Cosmology)

and

The very small (Elementary Particles)

IS

COMING TOGETHER

David N. Schramm

….. and much of the data which is bringing them together <u>are</u> coming and <u>will</u> come from the study of different form of cosmic radiations with increasingly high accuracy !

Discoveries in Physics

Facility		Original purpose, Expert Opinion	Discovery with Precision Instrument
30 BeV Proton Accelerator **Brookhaven**	**(1960's)**	Nuclear force	2 types of neutrinos Break down of time reversal symmetry New form of matter
400 BeV Proton Accelerator **FNAL**	**(1970's)**	Neutrino physics	*5th and 6th types of quark*
Electron Positron Collider **SLAC Spear**	**(1970's)**	Properties of quantum electricity	Quark inside protons 4th family of quarks 3rd kind of electrons
Electron Positron Collider **PETRA**	**(1980's)**	6th kind of quark	*Gluon*
Large Underground Cave **Super Kamiokande**	**(2000)**	Proton life time	Neutrino has mass
Hubble Space Telescope	**(1990's)**	**Galactic survey**	***Curvature of the universe, dark energy***
AMS on ISS		**Dark Matter, Antimatter Strangelets,…**	***?***

Exploring a new territory with a precision instrument is the key to discovery.

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