Cosmic ray detection in space

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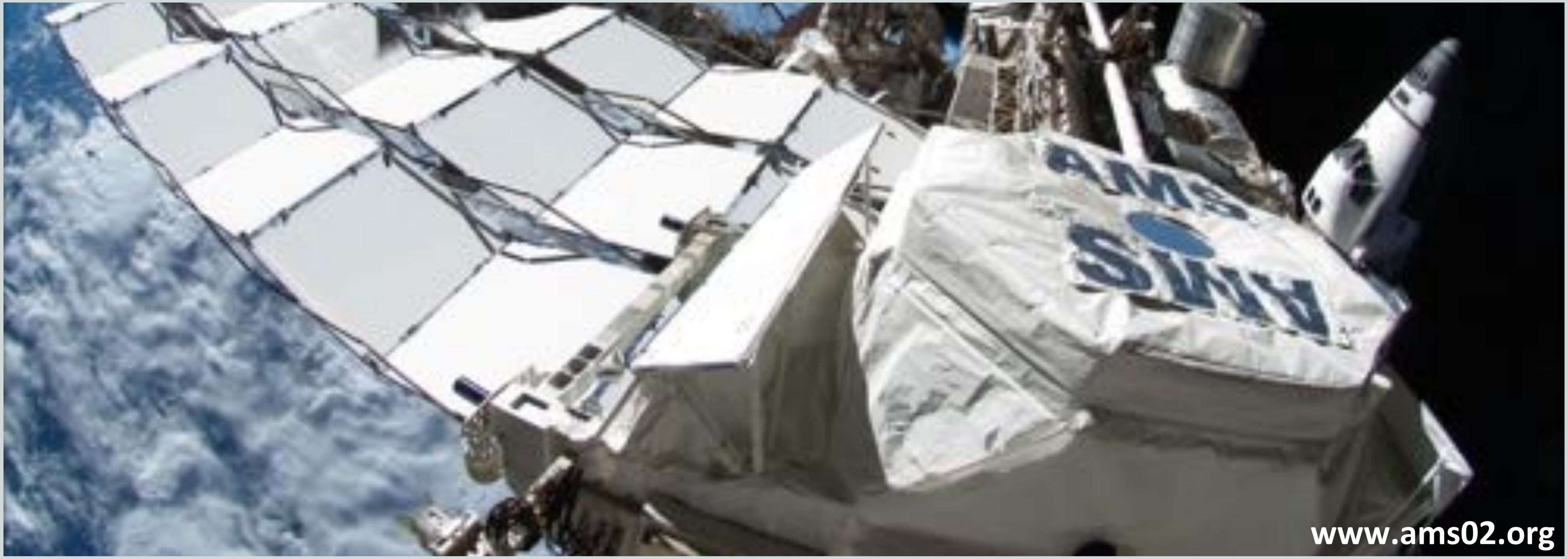

i) Introduction to Cosmic Rays
ii) Space Borne Experiments
iii) The AMS-02 detector

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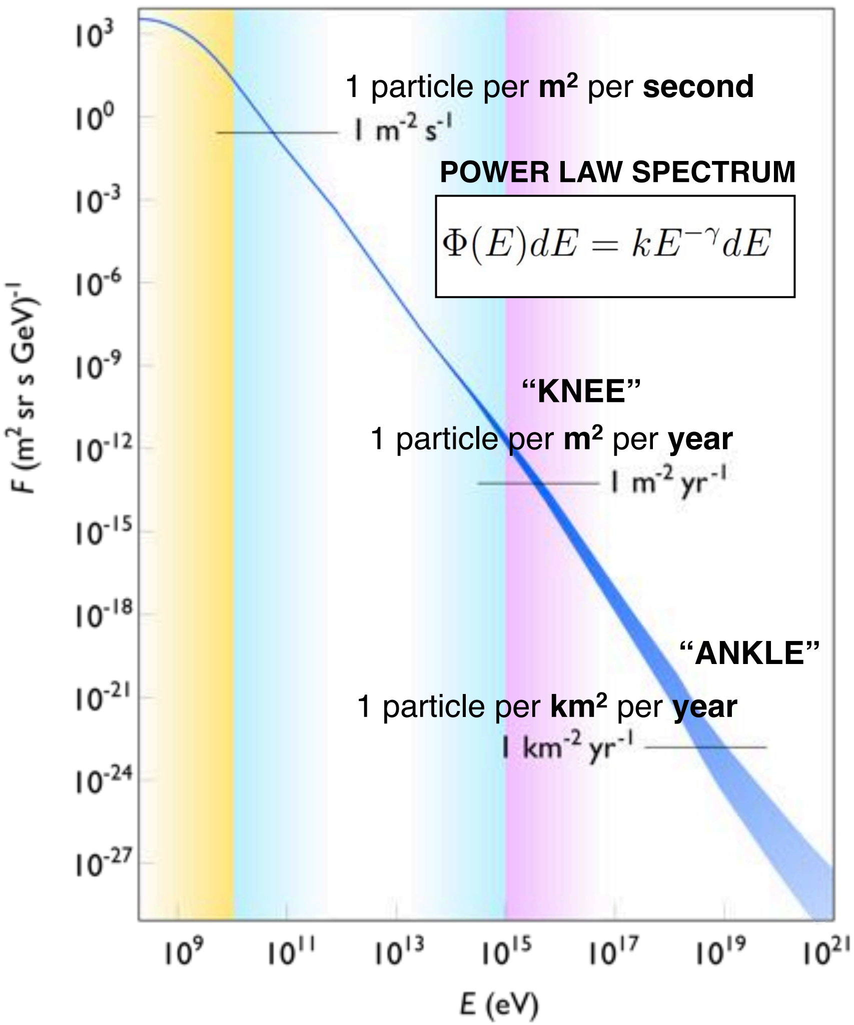
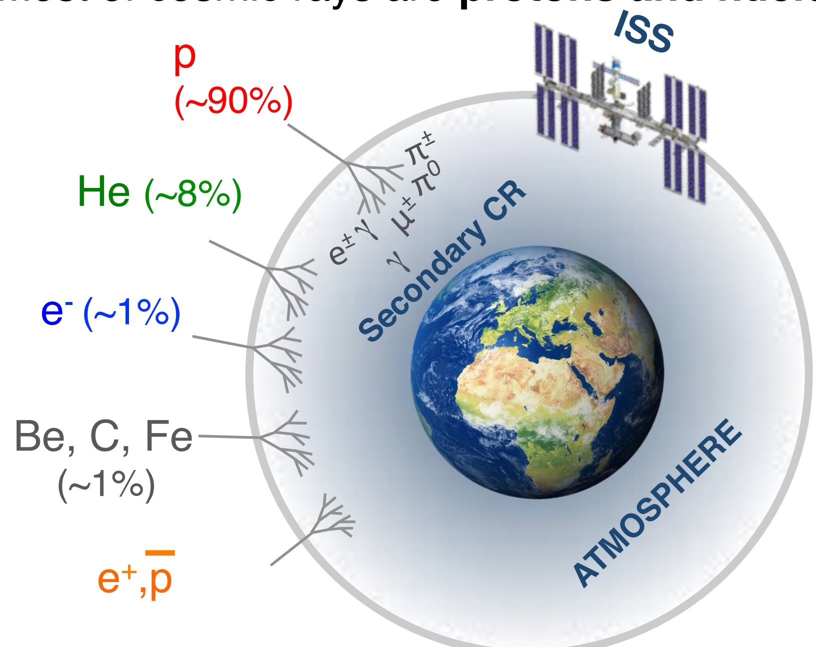
Cosmic Rays

Cosmic ray flux at Earth



- Cosmic ray Flux: Intensity of CR in space per **unit of area, solid angle, time and energy**
- Energy range up to **10^{20} eV**
- Intensities spanning **30 orders of magnitude**
- Most of cosmic rays are **protons and nuclei**

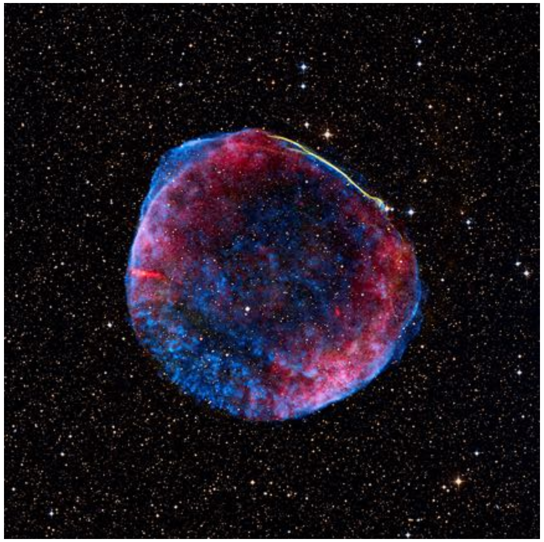


Cosmic Ray Physics

- **ASTROPHYSICS**
  - Origin of cosmic rays
  - Acceleration of charged particles up to PeV energies (“Pevatrons”)
  - Peculiar sources (pulsars, quasars, black holes, ….)
  - Star and solar system evolution
  - Solar physics
  - ……
- **PARTICLE PHYSICS & COSMOLOGY**
  - Hadronic interactions and X-sections (above LHC energies)
  - Matter/Antimatter asimmetry
  - Dark Matter searches
  - ……

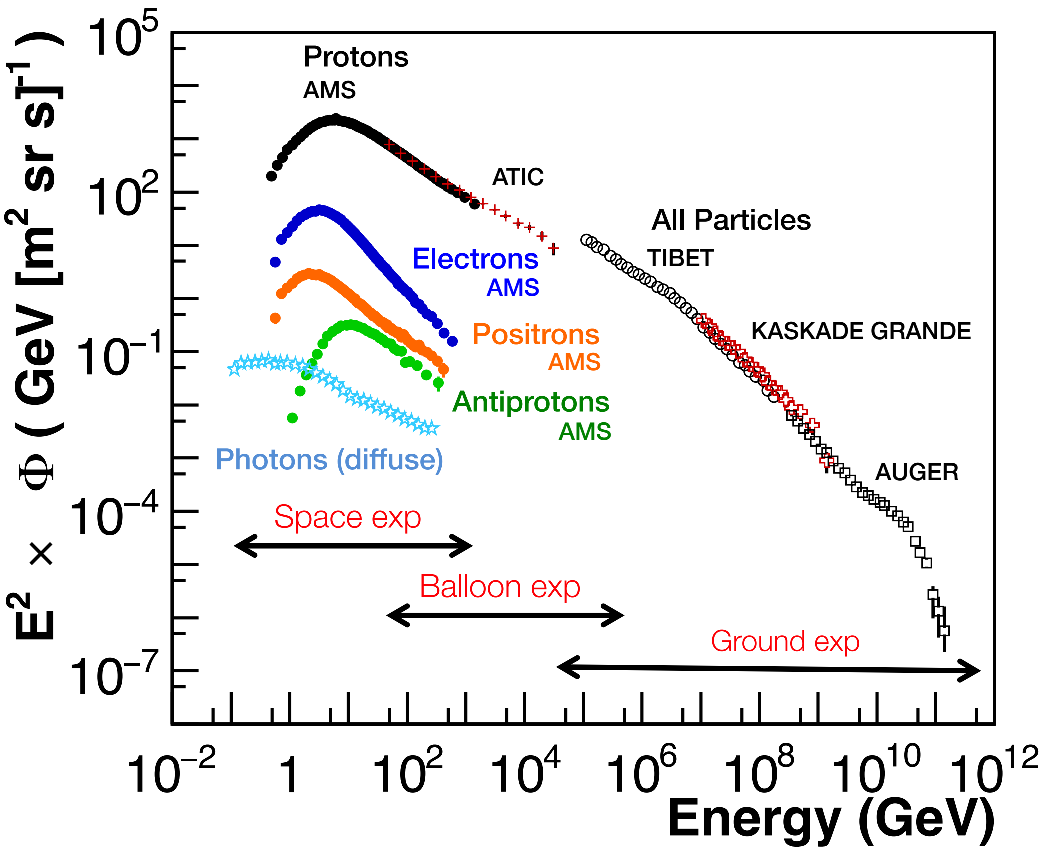
CMS experiment @ LHC

COSMIC RAYS
Intimate connection between very small and very high distances



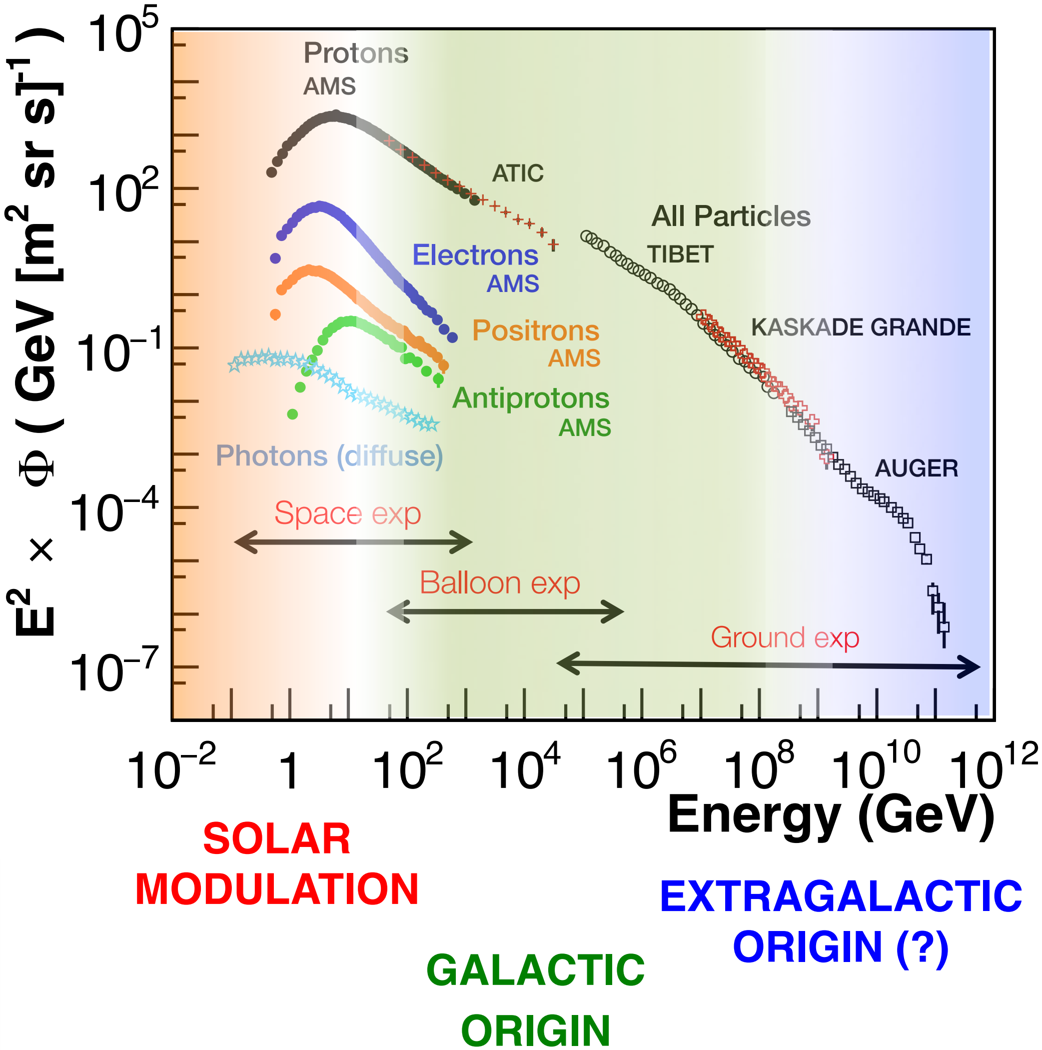
Supernova SN 1006

Cosmic Rays and Particle Physics



- Origin of very high energy CRs still not clear
- Many discussions about the origin of the “knee” and of the “ankle”
- Chemical composition above 1 TeV unknown
- Clear evidence of PeVatrons in the Universe

Cosmic Rays and Particle Physics



- Origin of very high energy CRs still not clear
- Many discussions about the origin of the “knee” and of the “ankle”
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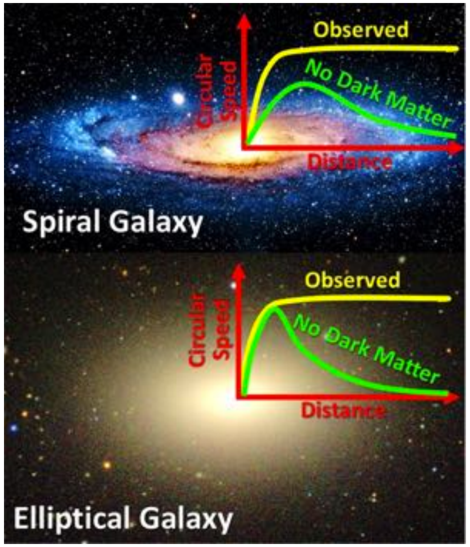
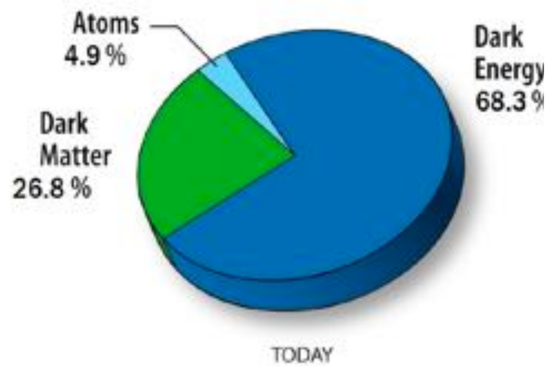
- Clear evidence of PeVatrons in the Universe

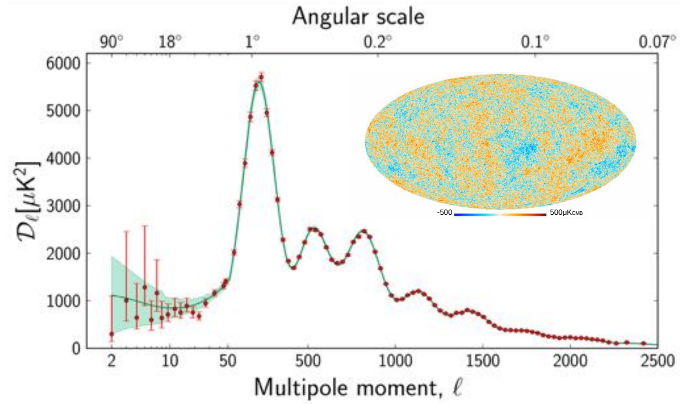
Physics topic example: Dark Matter



Galaxy rotation curves
(more grav. matter than what is observed electromagnetically)

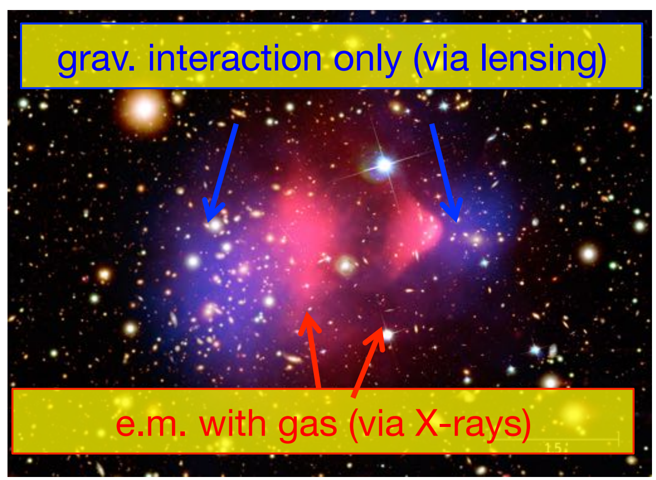


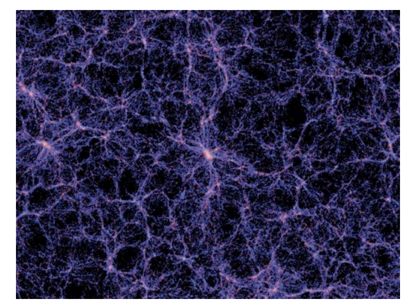
Dark Matter Exists!



Anisotropies of the residual microwave background
(requires Dark Matter and Dark Energy to represent observations)

The “bullet” cluster
(matter that interacts only gravitationally)



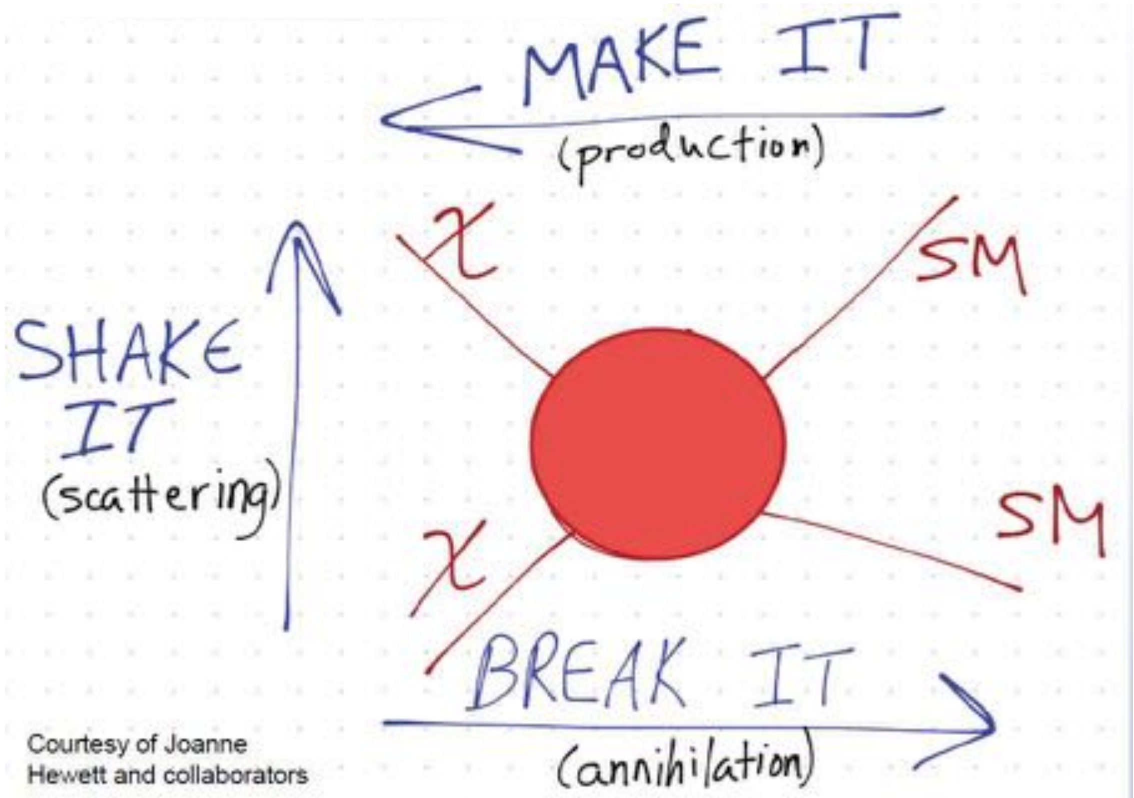


Universe structure formation
(requires Dark Matter and Dark Energy to represent observations)

The quest for Dark Matter

LHC + future colliders

Underground nuclear recoil experiments (DAMA, CRESST, Edelweiss, LUX, …)

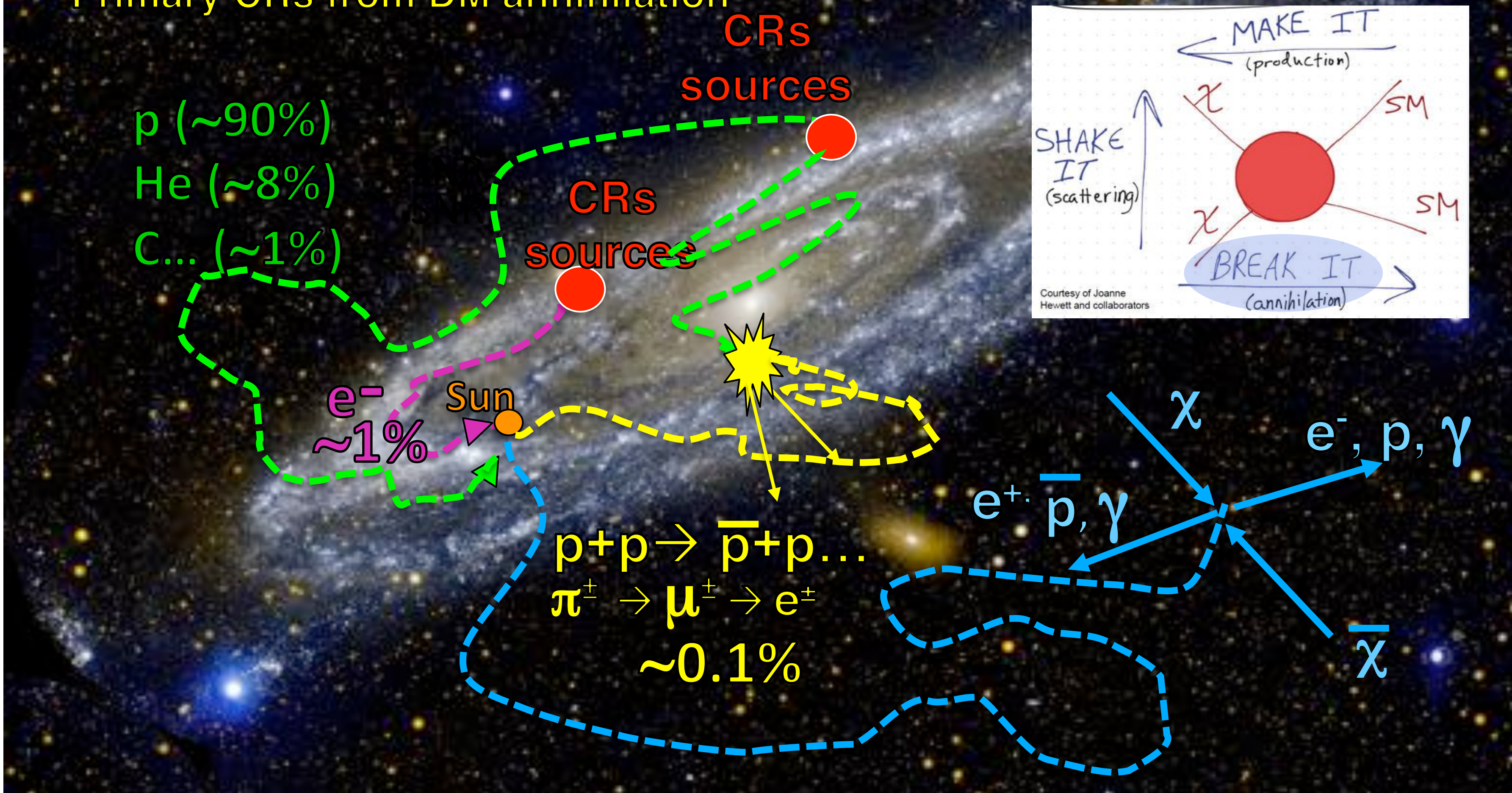


Cosmic Ray Experiments
(Fermi, Pamela, AMS-02, DAMPE, Gaps,….)

The “Standard Model” of Cosmic Rays

“Standard Model” of origin and propagation of Cosmic Rays

- Primary CRs diffuse through interstellar magnetic fields
- Interaction with insterstellar gas (H) produce secondary CRs
- Primary CRs from DM annihilation



The quest for Dark Matter

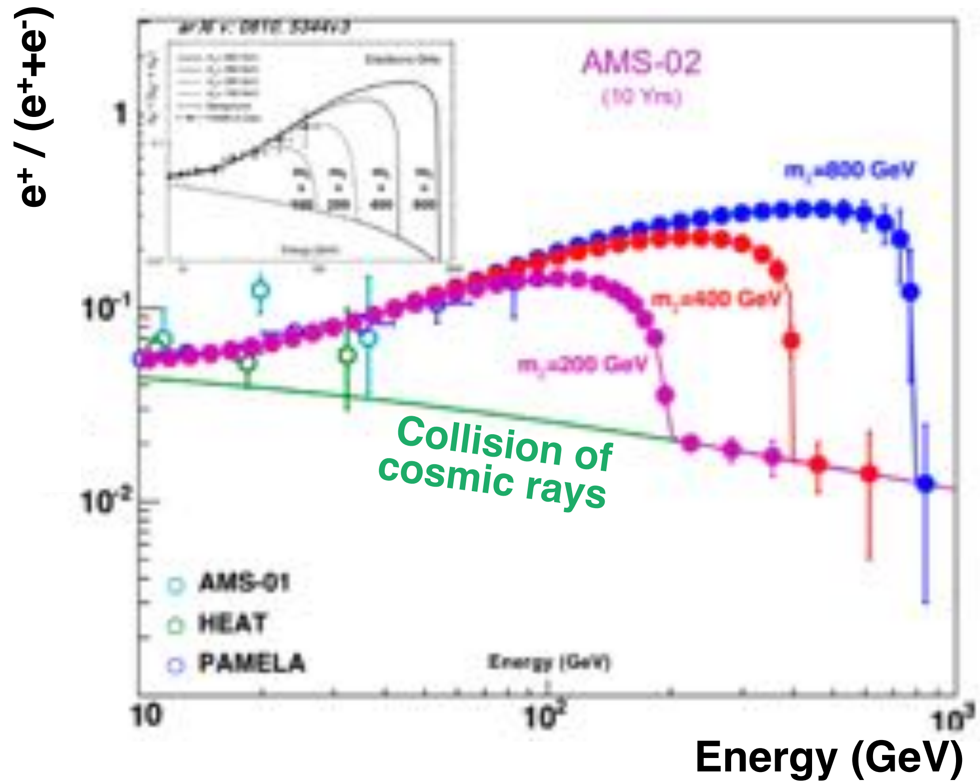
The most sensitive channels to indirect DM searches are the the **rare components in cosmic rays**, for which the

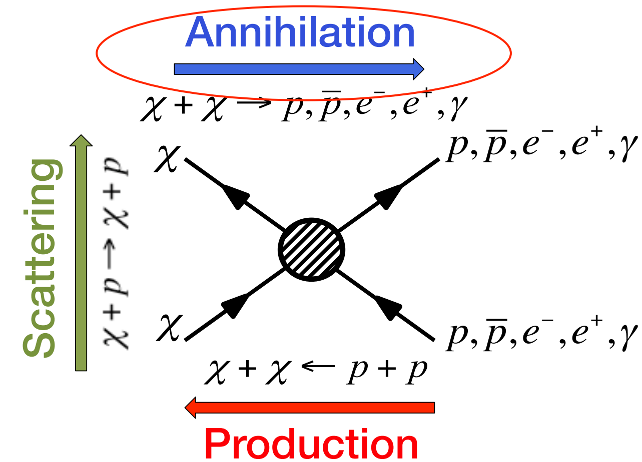
signal / noise

DM origin / astrophysical origin

is more convenient

Positron fraction





Increase in the positron fraction possible hint of DM annihilation

The quest for Dark Matter

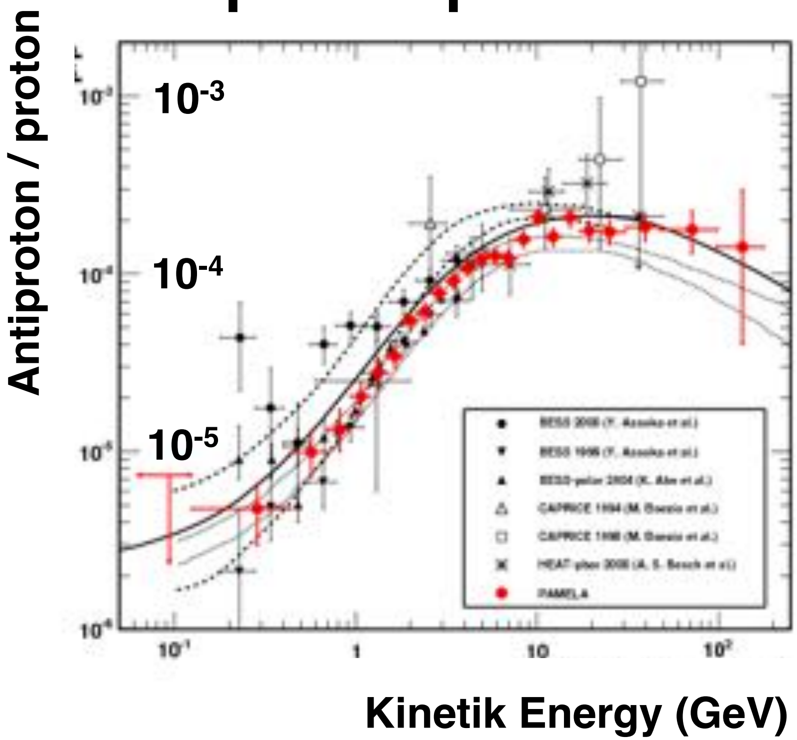
The most sensitive channels to indirect DM searches are the the rare components in cosmic rays, for which the

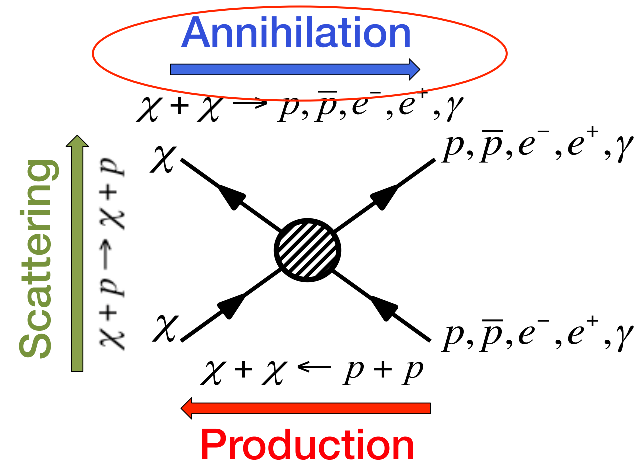
signal / noise

DM origin / astrophysical origin

is more convenient

Antiproton/proton ratio





No antimatter overabundance observed in the antiproton channel

Strong contraints set on the DM mass/interactions

The quest for Dark Matter

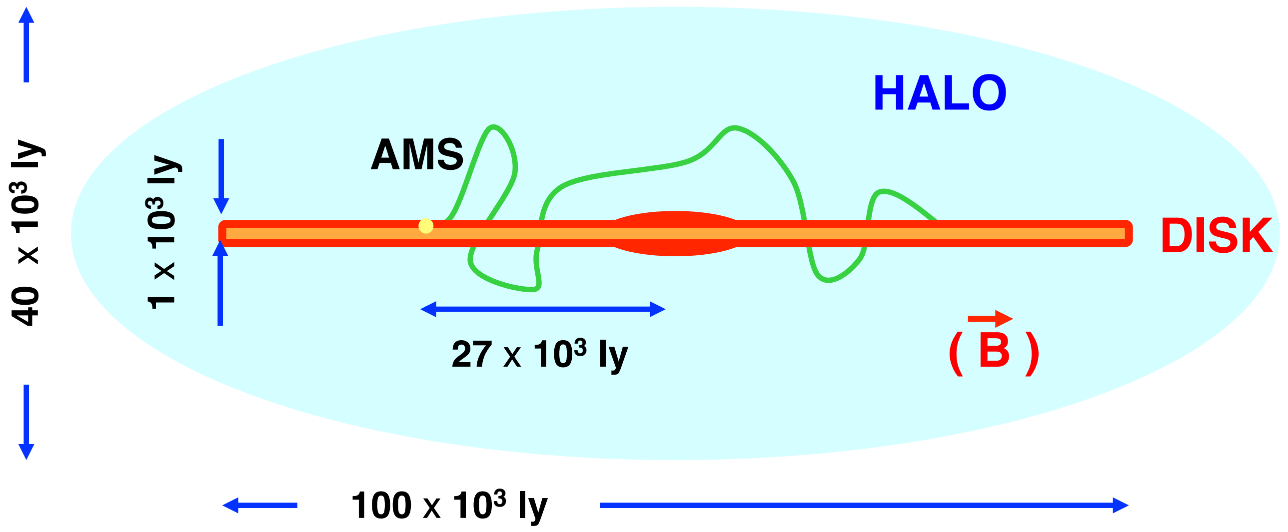
In the search for antimatter overabundances, the main issue is

KNOW YOUR BACKGROUND (expected secondary production)

→ primary fluxes

→ cross sections

→ solar modulation (at low energies)

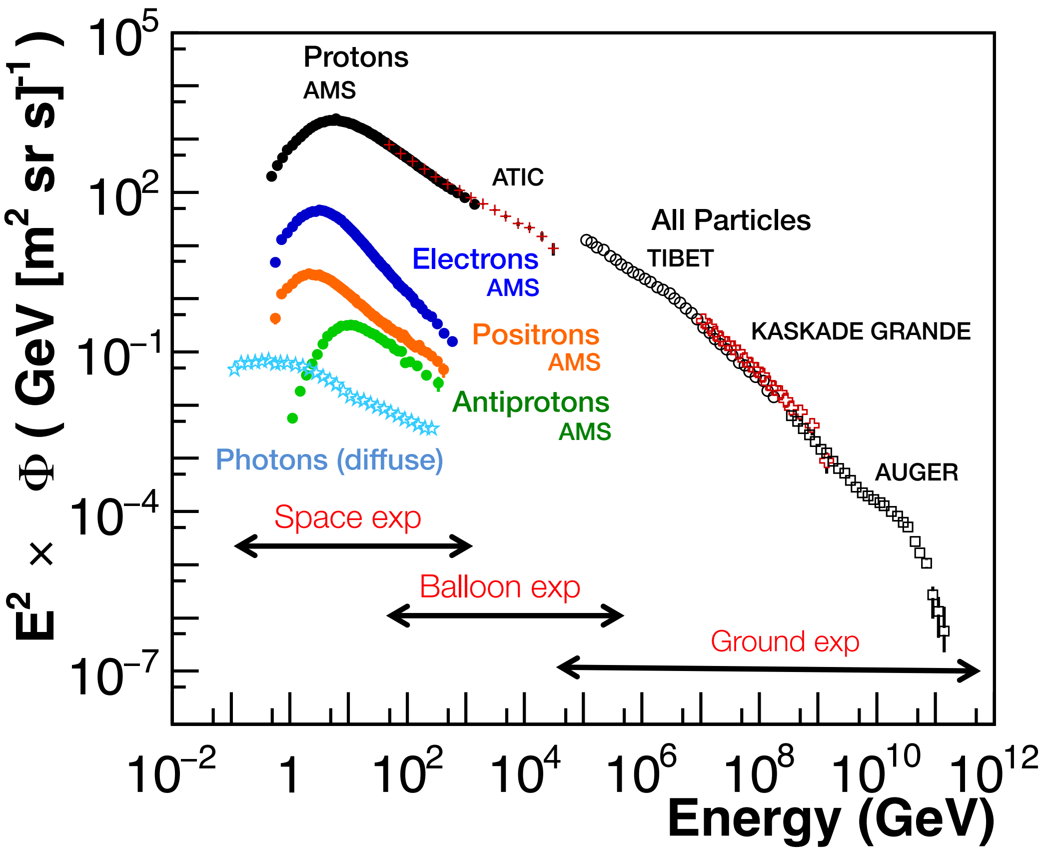


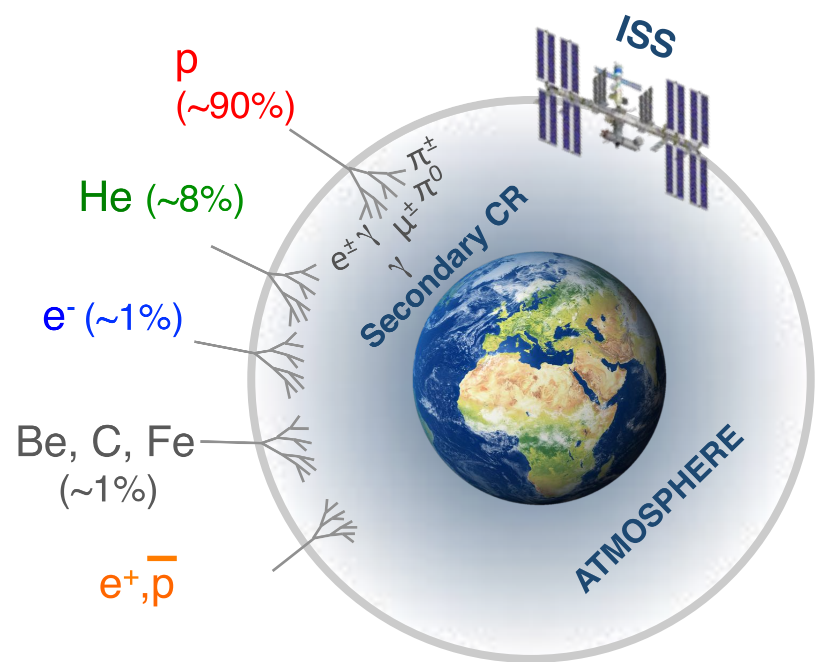
Diffusion
Convection
Reacceleration

Interactions with the Interstellar Medium (ISM):
- Fragmentation
- Secondaries
- Energy loss

Efforts to measure the flux of protons, Helium, Lithium, Carbon, Boron, …..

Experimental detection

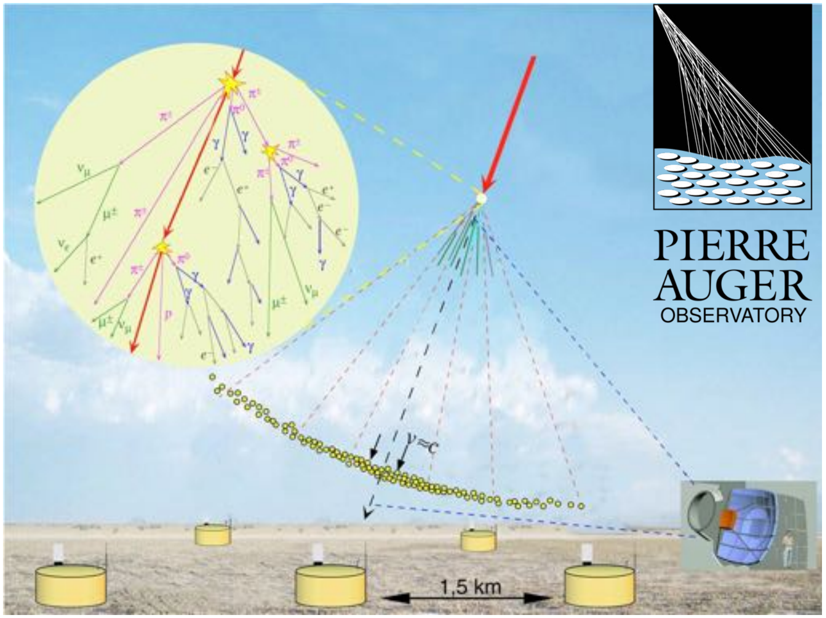




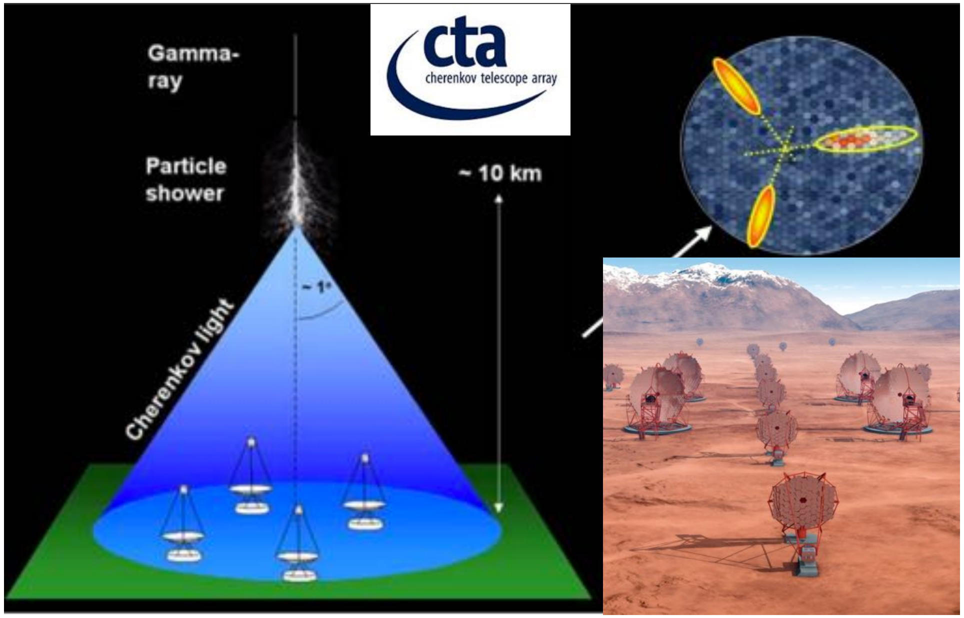
- Primary cosmic rays interact with atmosphere. Only secondary CRs from interactions reach the ground.
- Flux steeply falling as function of energy. Need large collection areas

Ground based experiments

Charged CRs

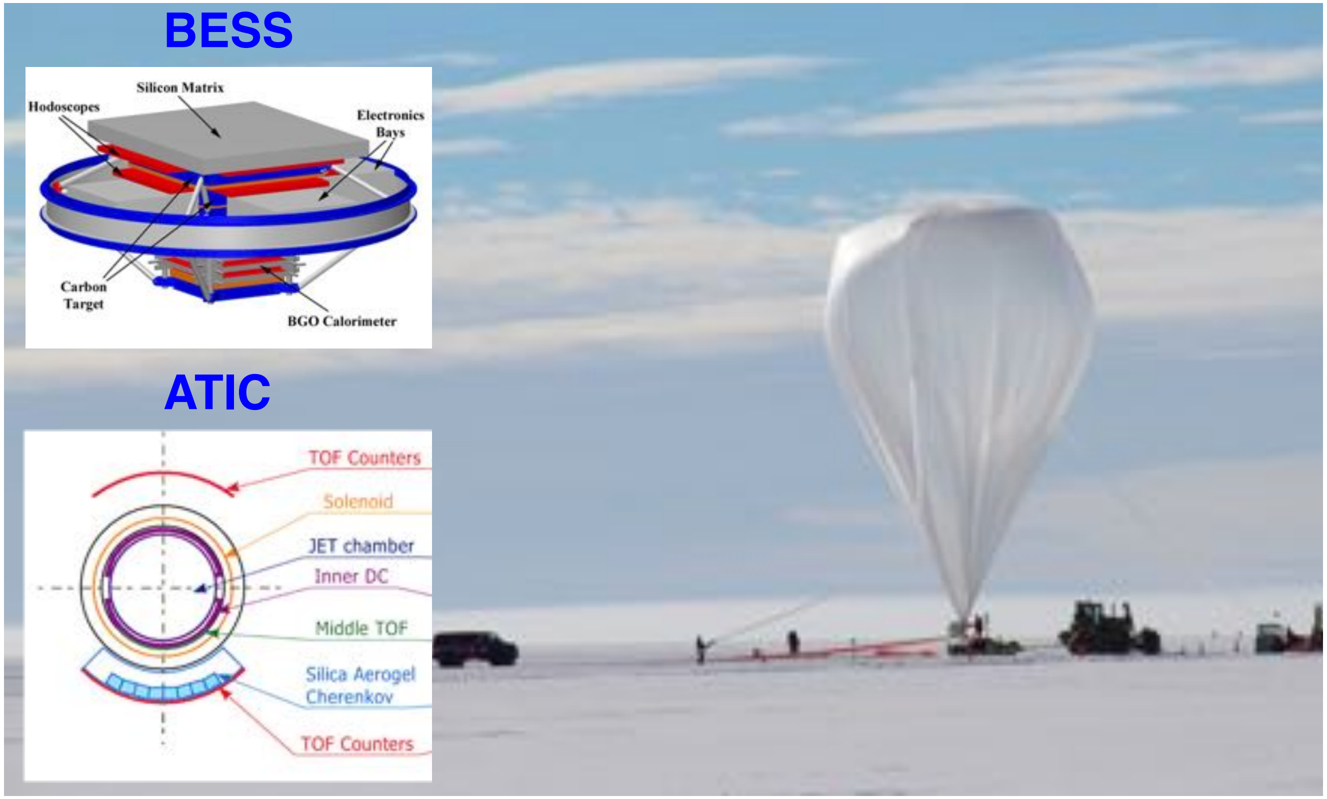


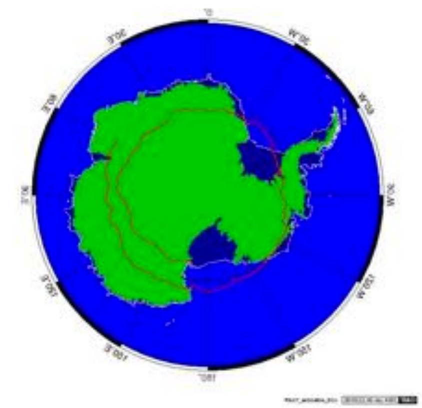
Gamma Rays



- √ Large collection areas → probe CR energies TeV –Eev ranges
- X Indirect measurements
  - Primary CR identified via the analysis of shower shapes and composition at ground (highly rely on MonteCarlo simulations)
  - Main systematics are the parametrization of X-sections at very high energies

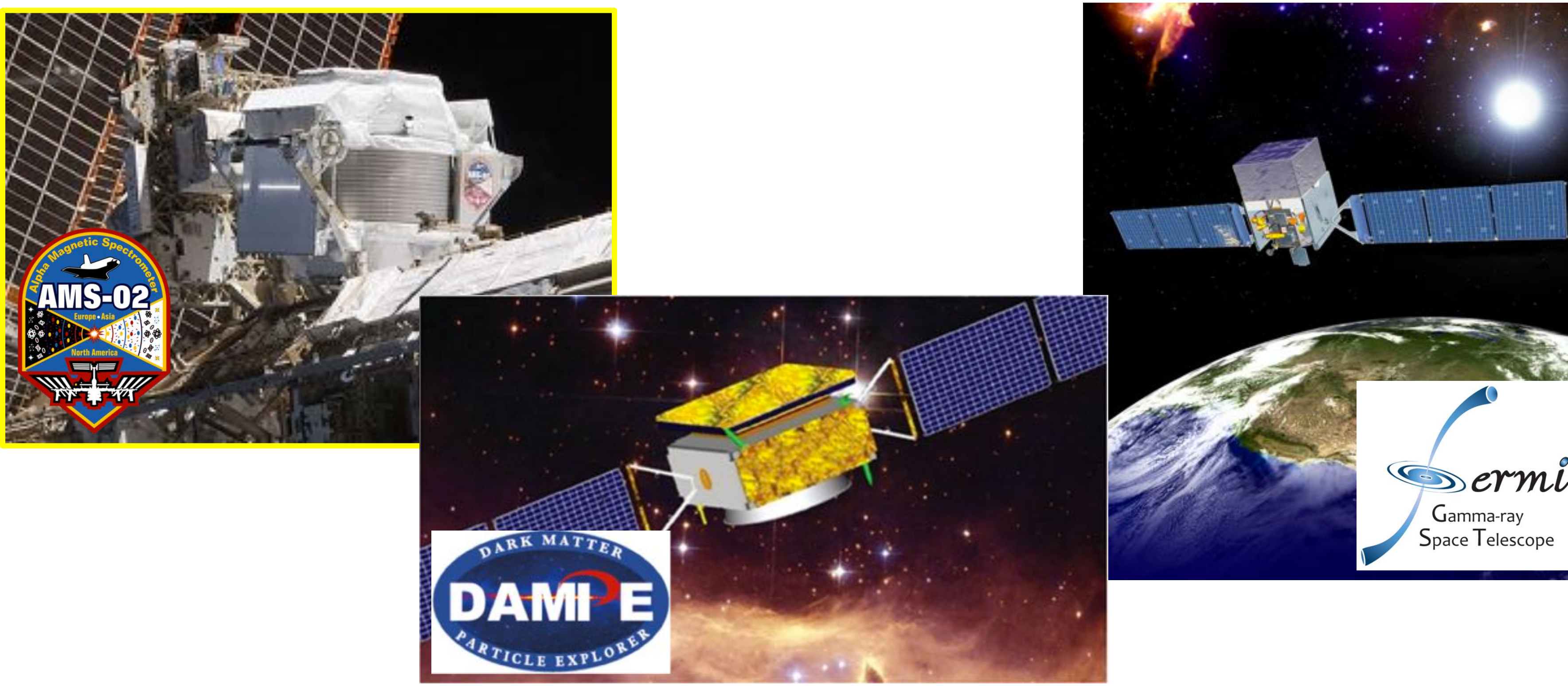
Balloon experiments



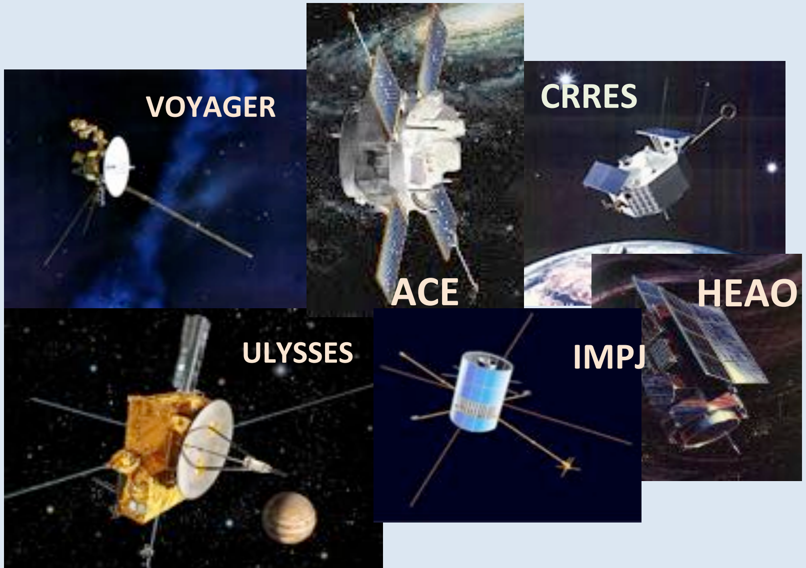


- √ Larger acceptances than space borne experiments
- √ Direct measurements
- X Orbit limited at North poles for maximum 1 month
- X Residual atmosphere above the payload

Space Borne experiments



- √ Direct measurements outside atmosphere
- √ Continuous duty cicles, tipically many years of lifetime
- √ Field of view covering the whole sky
- X Smaller acceptances
- X Operation in space and communications not trivial
- X “Use once and destroy”



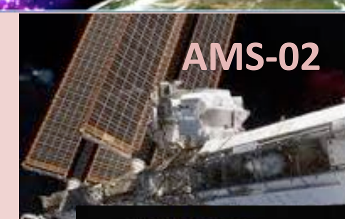
Long missions (years)
Small payloads
Low energies..

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

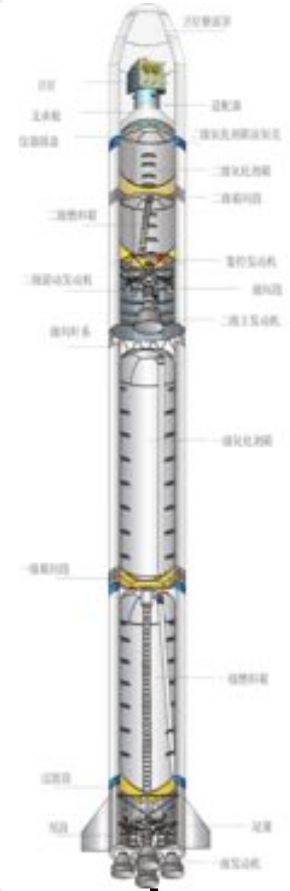
CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)



Long missions
Large payloads

Operations in Space

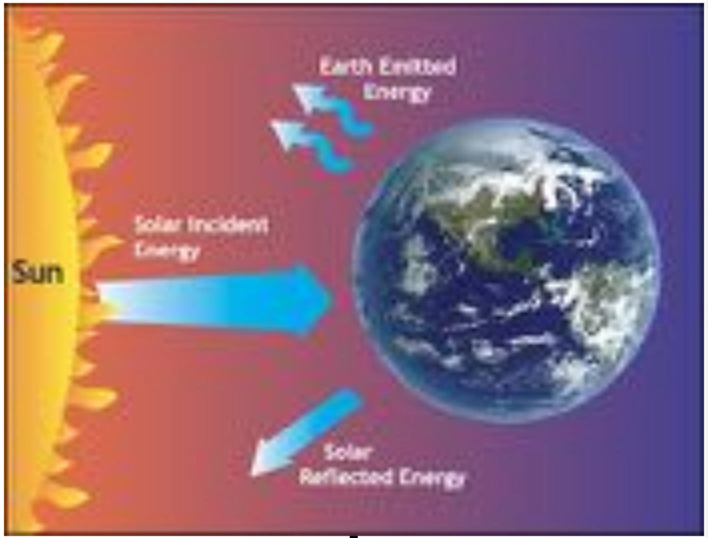


Mechanical stress at launch:

- **Static acceleration**
- **Random vibration**
- **Sinusoidal vibration**
- **Pyroshock**

Life in space:

- **Thermal stresses due to Sun-light (seasonal / day-night effects)**
- **Vacuum**



Careful Design, Model validation and Qualification are needed to ensure *highest possible reliability*

Operations in Space

Space is a harsh environment

Full space qualification sequence before launch:

- Operational tests after stress
- Verification of dynamical behaviour
- Verification of thermal model

Thermal Stress → Functional check → Mechanical Stress → Functional check

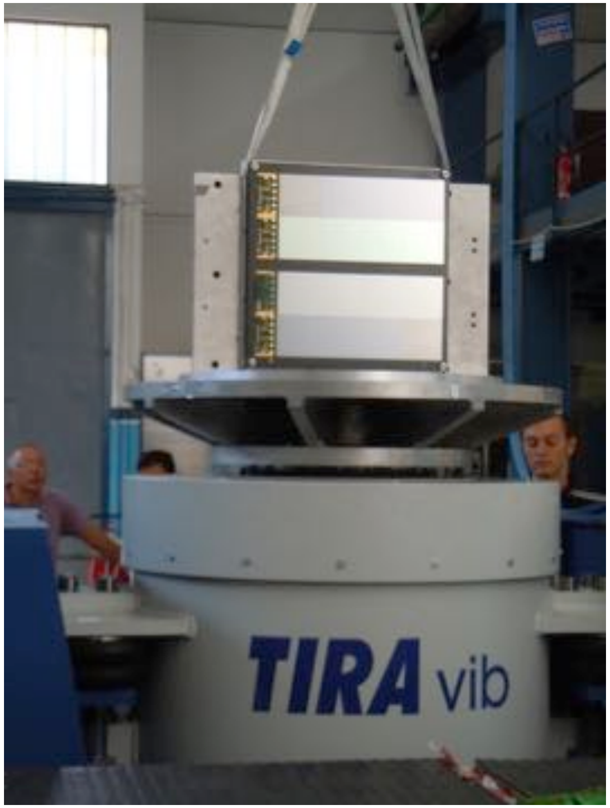
Thermal cycles in Vacuum → Functional check

→ EMC

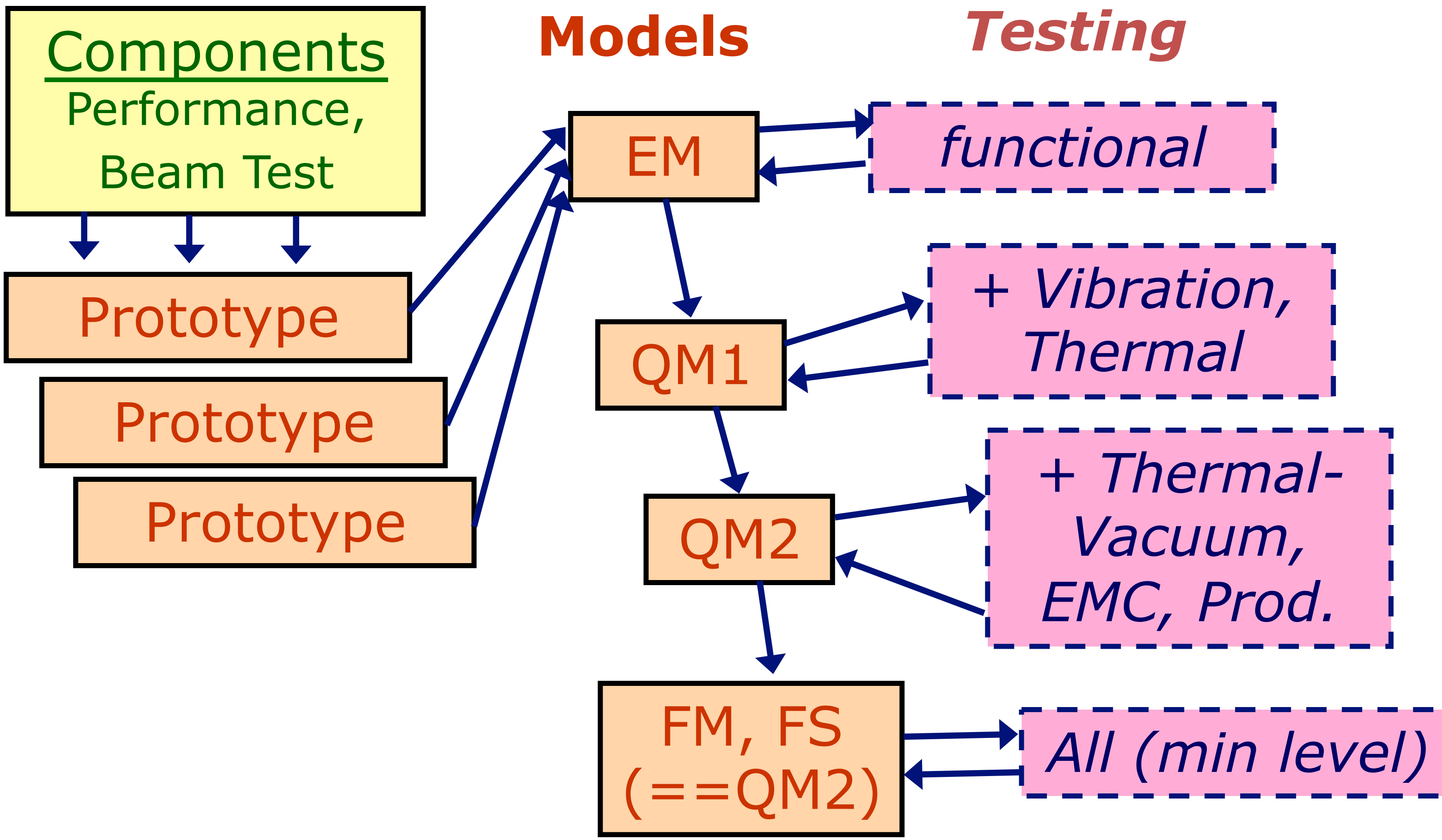
Operations in Space

Space is a harsh environment

Typically 3 step for test procedure:
Thermal, Vibration, Thermo-Vacuum

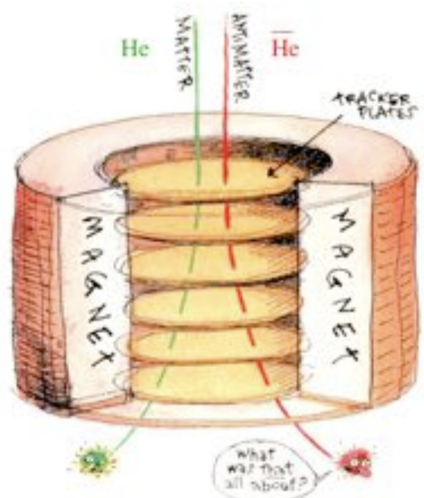


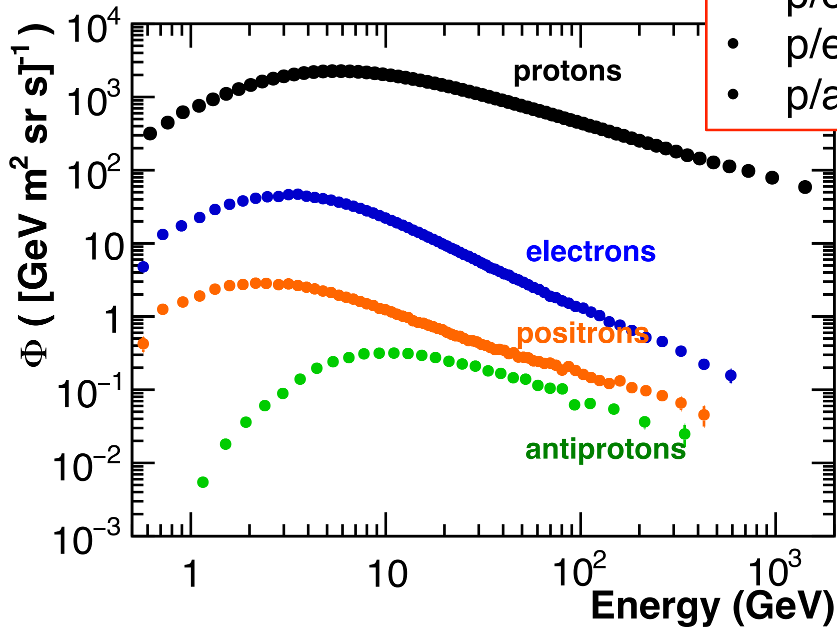
The long process to fly….



Particle Identification (in space)

- Direct identification of the cosmic rays via measurement of their
  - **Velocity** (Time of Flight systems, Cherenkov Radiation detectors)
  - **Charge** (dE/dX detectors, Cherenkov Radiation detectors)
  - **Energy or Rigidity** (Calorimeters, Spectrometers)
  - **Sign of the charge** (Spectrometers)
  - **Peculiar Interactions** (TR detectors, Calorimeters, Neutron detectors, …)
  - **Incoming Direction** (Tracking detectors)





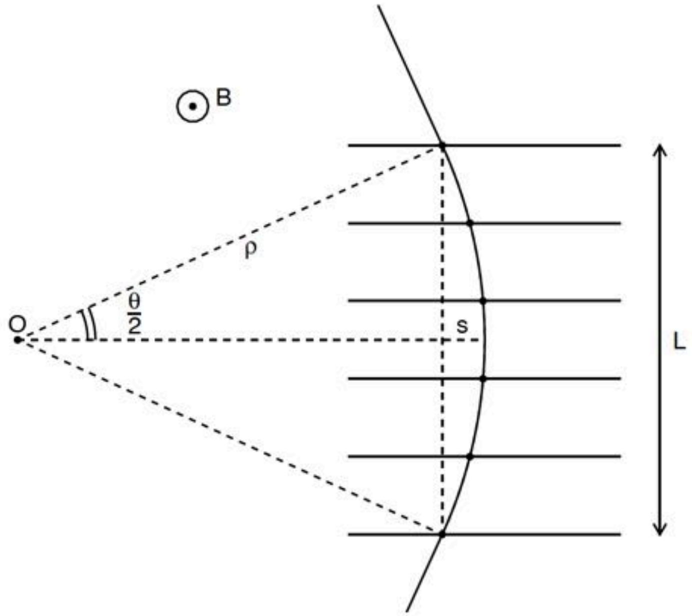
- p/e$^-$ ~ 10^2
- p/e$^+$ ~ 10^3
- p/antip ~ 10^4

Particle identification is fundamental for antimatter measurements

Spectrometers

Magnetic Spectrometers

Simple 2D sagitta model



- Charged particle bent in magnetic field
- The sagitta is measured by sampling the particle trajectory through different planes
- The particle rigidity is inferred via

$$R = \frac{cBL^2}{2s} = \frac{37.5\ B\ [\mathrm{T}]\ L^2\ [\mathrm{m}^2]}{s\ [\mathrm{mm}]}\ \mathrm{GV}$$

- Rigidity resolution scale linearly as

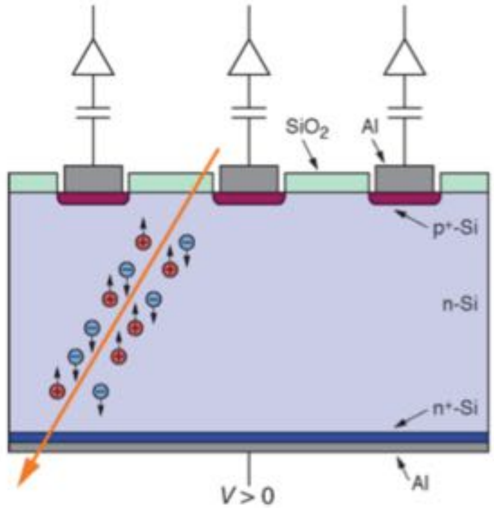
$$\frac{\sigma_R}{R} = \frac{\sigma_s}{s} \propto R$$

- Maximum Detectable Rigidity MDR

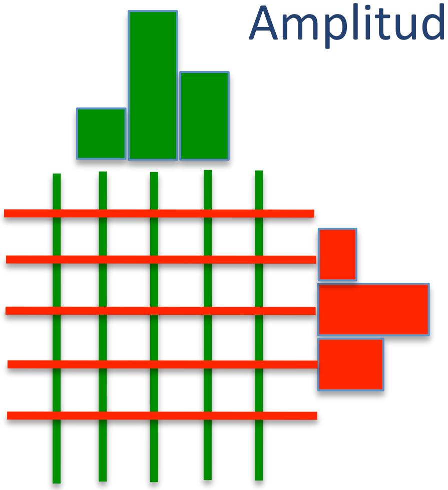
$$\frac{\sigma_R}{R} = 1 \Rightarrow R^{(\mathrm{MDR})} \propto \frac{L^2 B}{\sigma_s}$$

- L ~ Spectrometer dimensions, limited by the space constraints
- B, limited by magnet size and technology (superconducting magnet in space?)
- σ_S ~ position resolution → experimental effort to achieve resolutions below 10μm

Silicon Microstrip Detectors

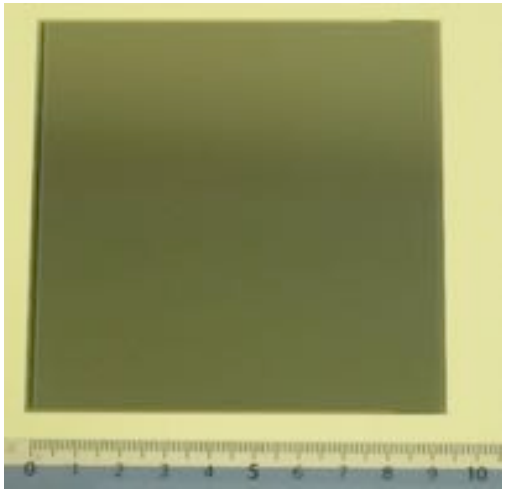


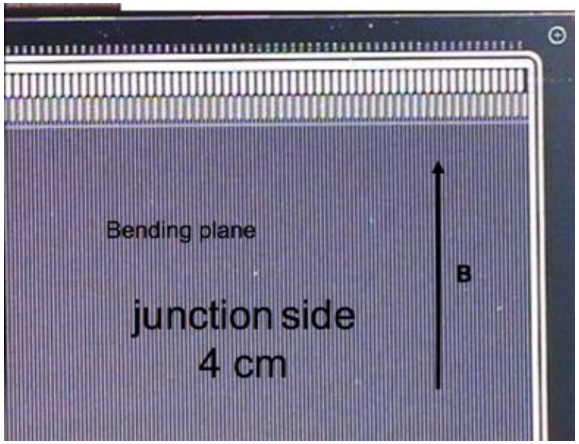
Amplitude → Z^2



Position from the center of gravity of the signal released on adiacent strips (50-200 μm)

Single sensor ≈ 10x10cm^2 … or less





Silicon Microstrip Tracking

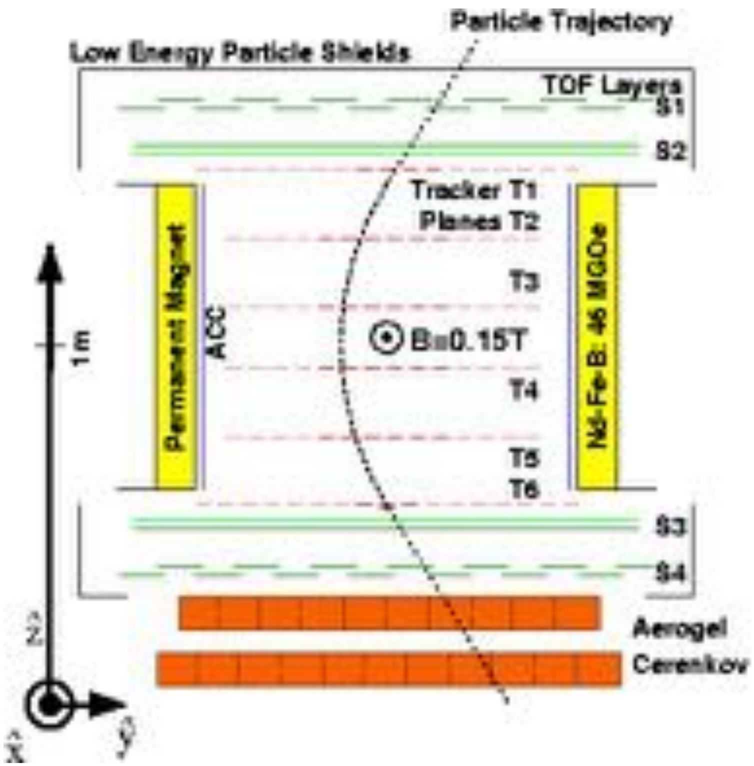
Heritage from microvertex detectors developed in the ‘80s for HEP experiments at accelerators (L3 @ LEP → AMS),

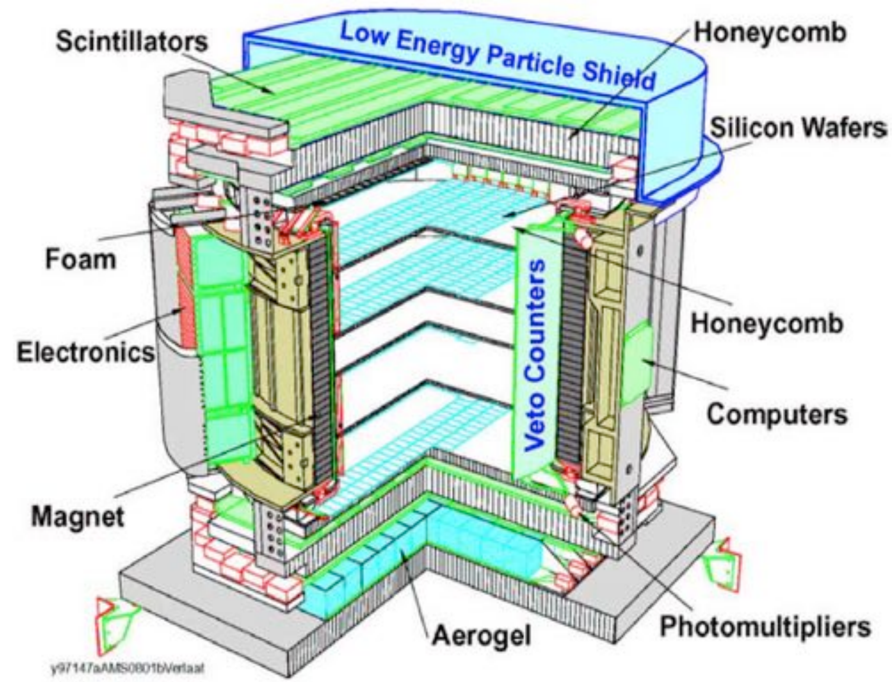
→ Precisions of O(μm)
→ Lightweight: thickness of ≈ 300 μm
→ No consumables (e.g. gas)
→ No High Voltage (≈ 70 V)

Questions in 1995:

→ Never operated in space
→ 300 μm thick detectors will survive the stress of the launch?
→ Assembly precision should match the resolution: do we really know their position ? Alignment after launch?
→ Many readout channels: electronics?

AMS-01: First magnetic spectrometer with a silicon tracker in space

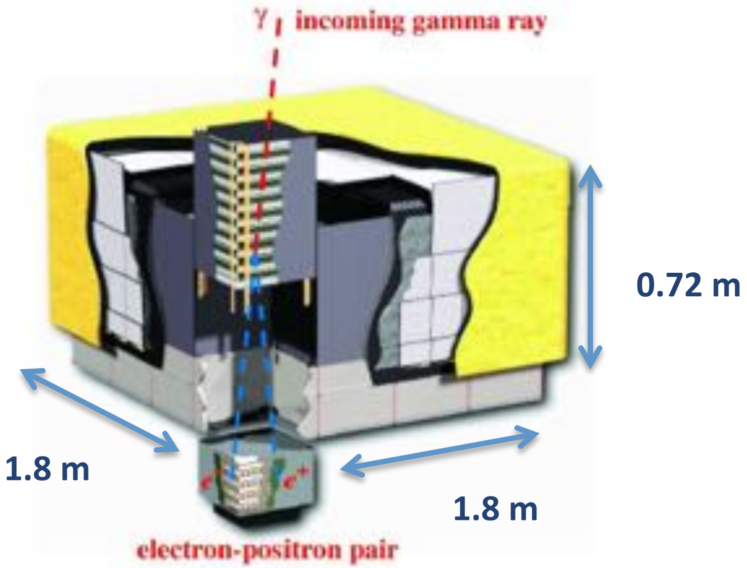


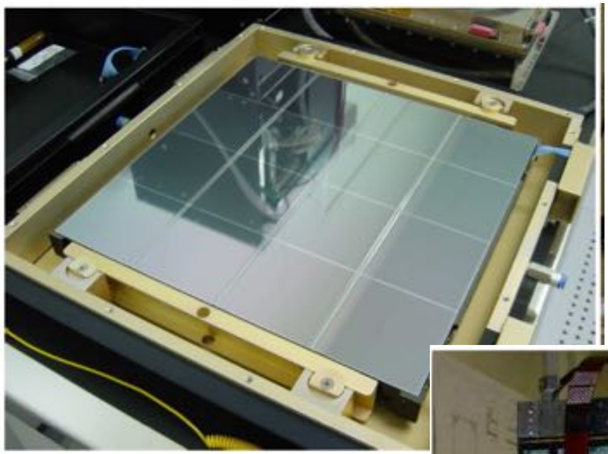


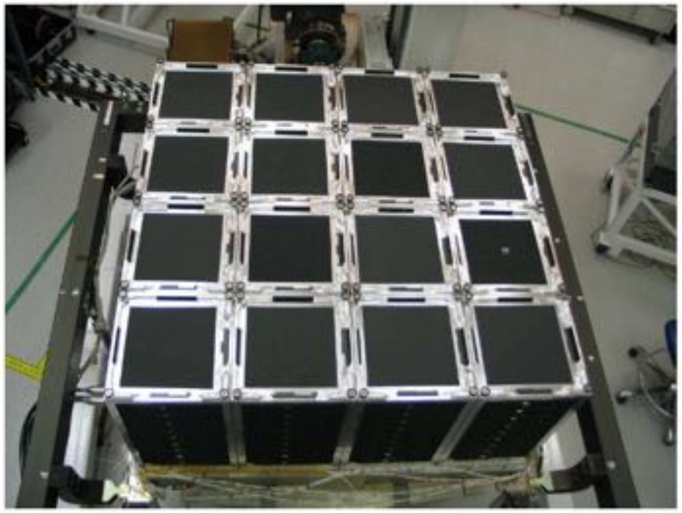
Time Of Flight : measure time → velocity, arrival direction, dE/dX → Z
Magnet: 2.2 Ton of Nd-Fe-B blocks providing a 15kGauss field inside, < 2 Gauss outside
Tracker: 2m^2 of silicon sensors arranged in 6 planes
Aerogel Cerenkov threshold counter: discrimination of e/p based on Cherenkov emission

Fermi (2008)

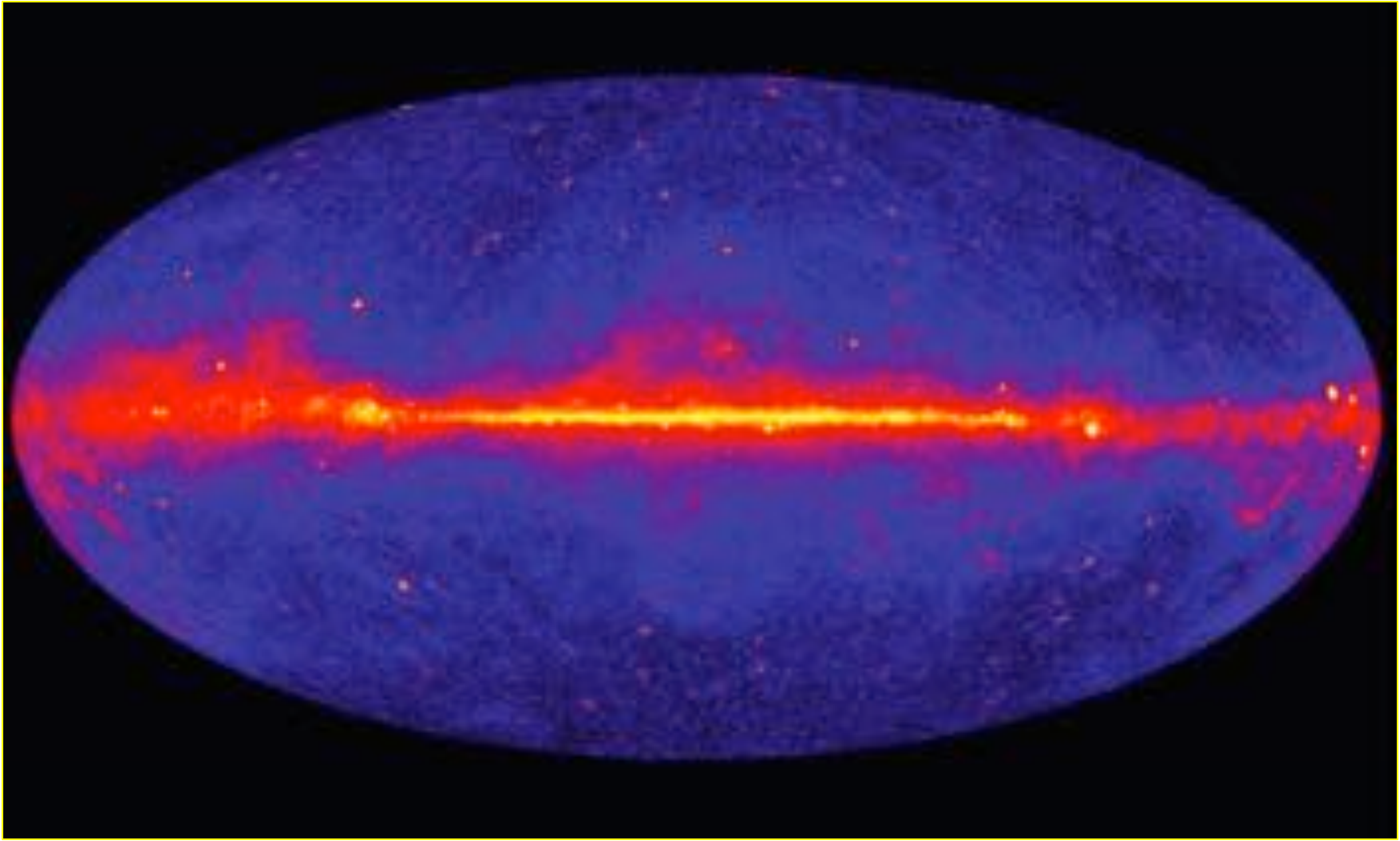
73m^2 of silicon sensors in space







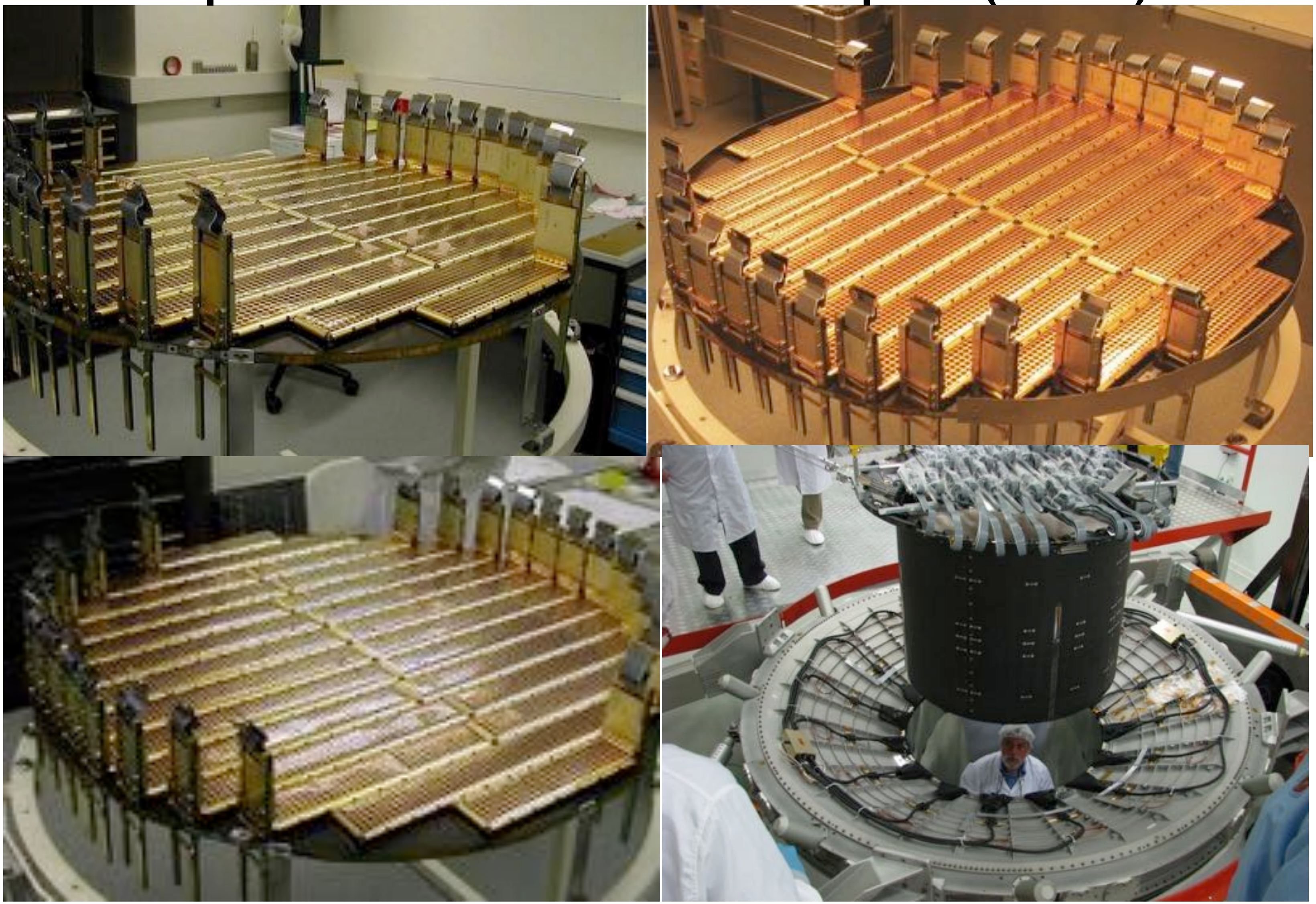
The Fermi sky



More than 3000 sources identified (too crowded to discuss here…)

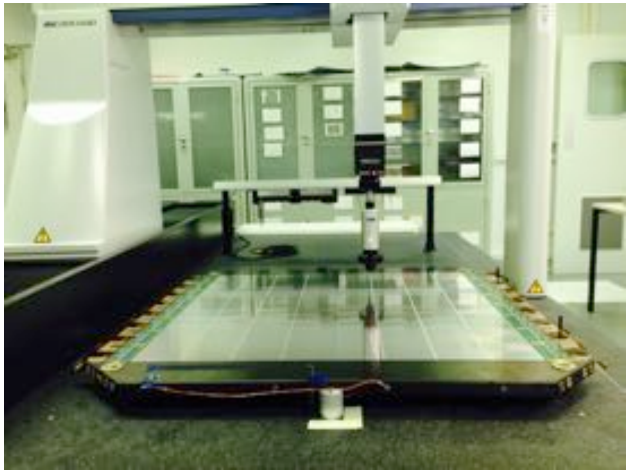
AMS-02 (2011)

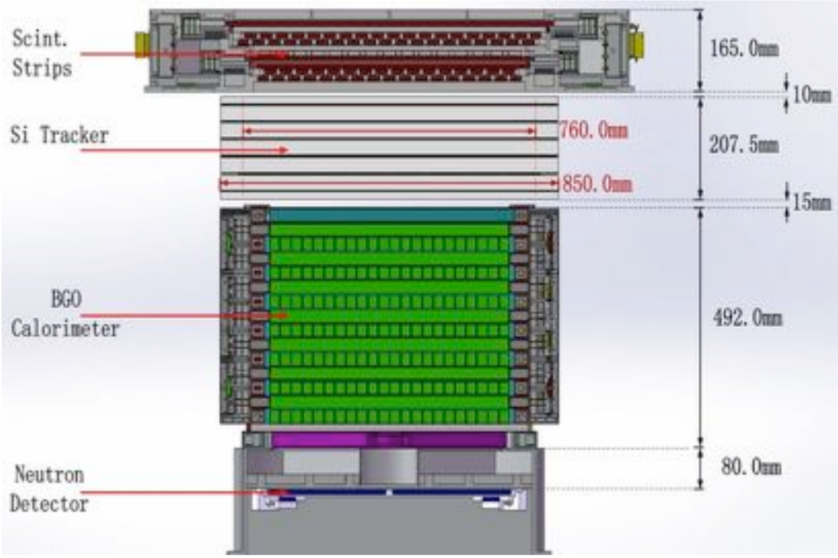
9 planes of silicon sensors in space (6.4 m^2)

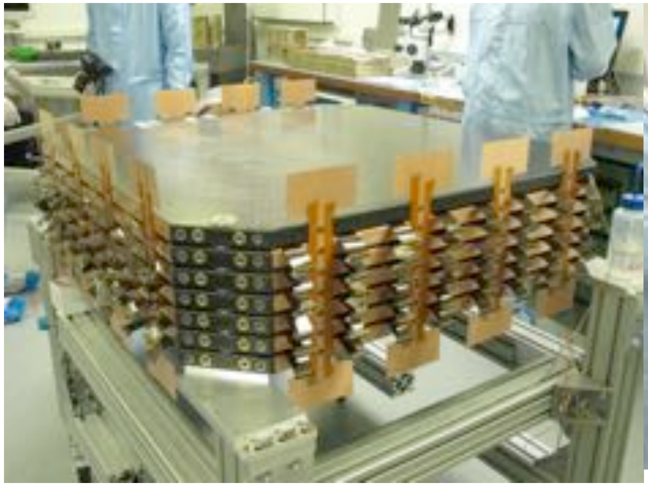


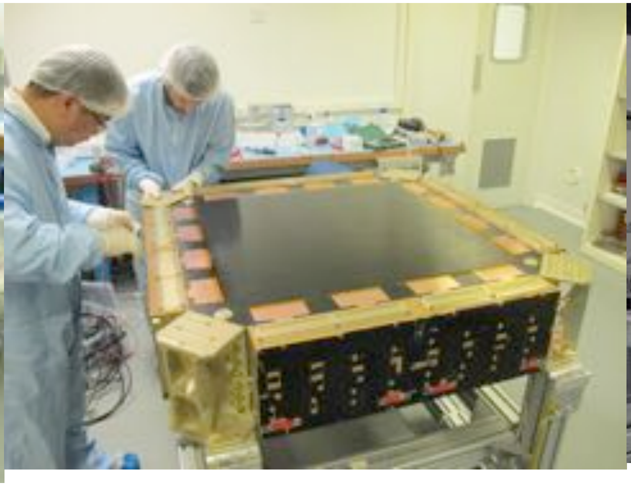
DAMPE (2015)

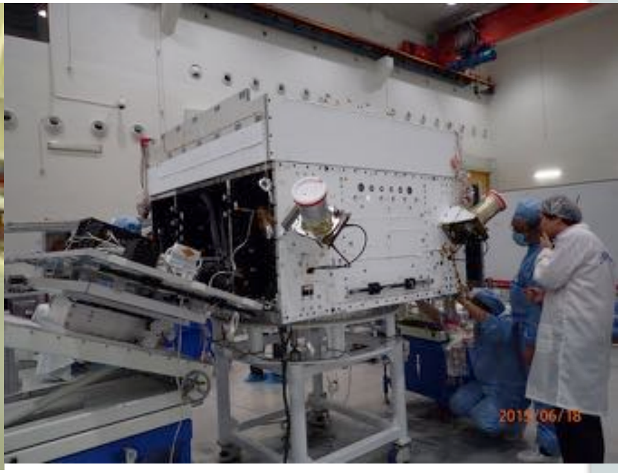
6 planes of silicon sensors in space (7.7 m^2)



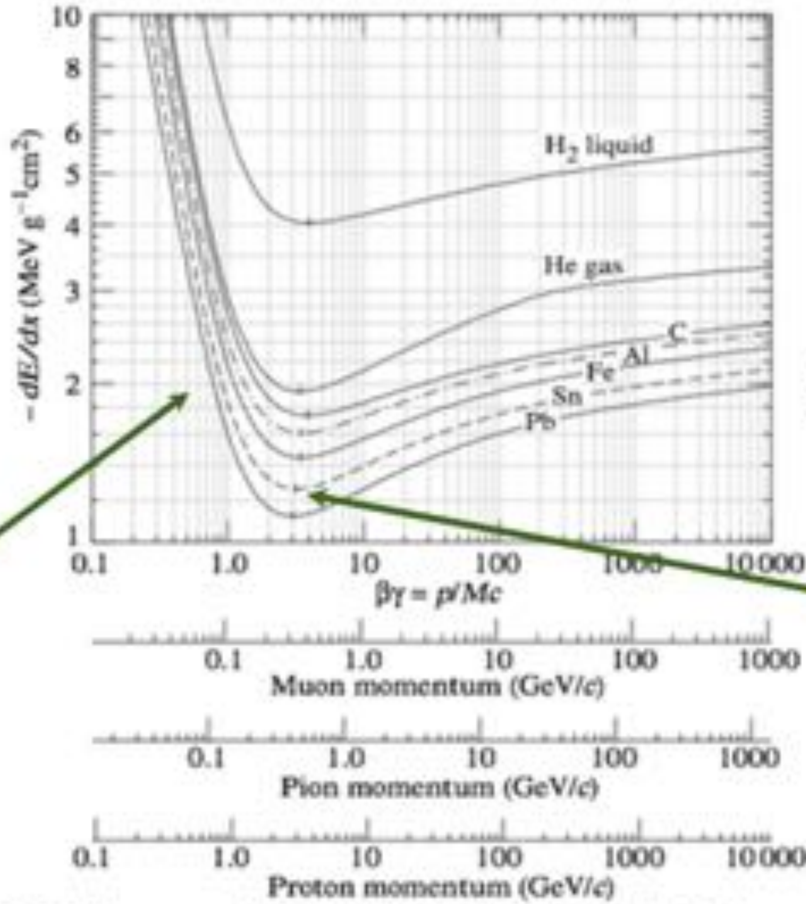








Ionization energy losses



$1/\beta^2$

Figure 27.3: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 27.21.

PDG 2008

Bethe-Bloch formula:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

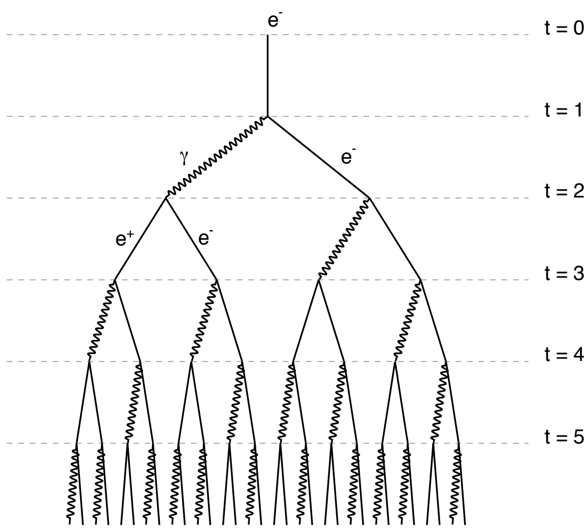
Except in hydrogen, particles of the same velocity have similar energy loss in different materials.

The **minimum in ionisation** occurs at $\beta\gamma$ = 3.5 to 3.0, as Z goes from 7 to 100

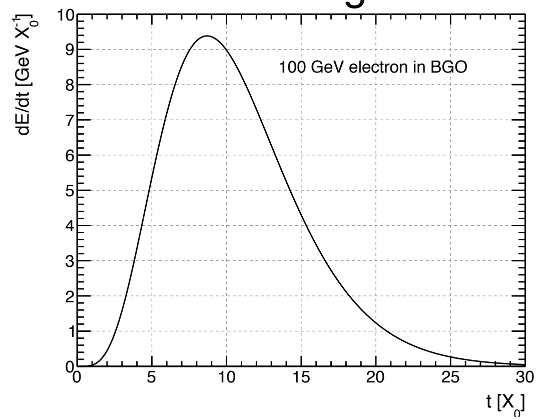
Space born calorimeters

Calorimeters

Simple electromagnetic shower profile



- Calorimeters measures the energy releases of the particle
  - Homogeneous / Sampling
  - Electromagnetic / Hadronic



$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- The energy resolution improves as the energy increases

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Statistical fluctuations (a)

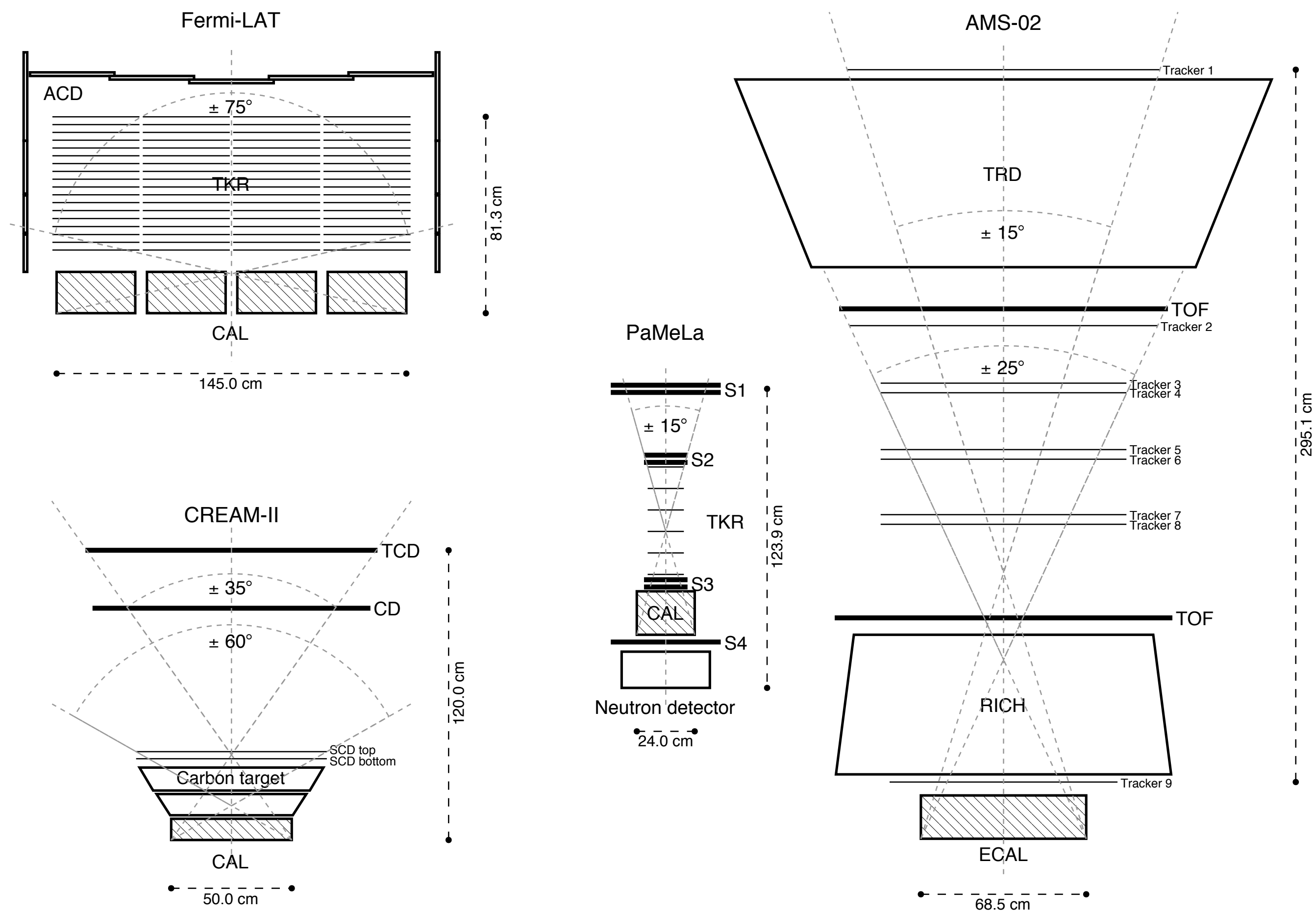
Electronics (b)

Inhomogenities, calibration, energy leaks,… (c)

- BUT: energy resolution is not everything. Tipically the dominant systematic is the knowledge of the energy scale!!
  - Resolution → Symmetric smearing of measured energy
  - Energy scale → Systematic shift of measured energy

Instrument Acceptance

ACCEPTANCE: measurement of the collection capabilities of the detector



Instrument Acceptance

ACCEPTANCE: measurement of the collection capabilities of the detector

The acceptance (or geometric factor) is formally defined as the integral of the effective area over the solid angle:

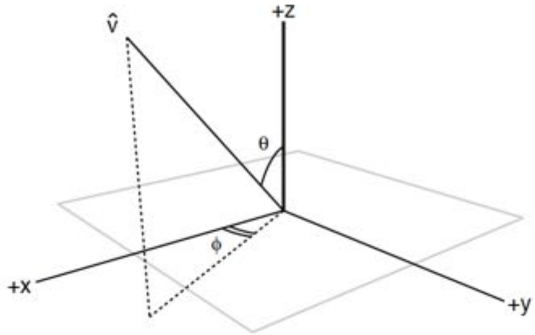
$$G(E) = \int_{\Omega} A_{\text{eff}}(E, \theta, \phi) d\Omega, \quad (77)$$

and the field of view as the ratio between the geometric factor and the effective area at normal incidence:

$$\text{FoV}(E) = \frac{G(E)}{A^{\perp}_{\text{eff}}(E)} = \frac{\int_{\Omega} A_{\text{eff}}(E, \theta, \phi) d\Omega}{A^{\perp}_{\text{eff}}(E)}. \quad (78)$$

(Note that when the angular dependence of the effective area is different at different energies, the field of view does depend on energy, see, e.g., [78].)

A simple planar detector



In this case the effective area at normal incidence is simply the geometrical area of the detector $S = l^2$. It is clear that A_{eff} only depends on the polar angle θ:

$$A_{\text{eff}}(E, \theta, \phi) = S \cos\theta, \quad (79)$$

and the acceptance reads:

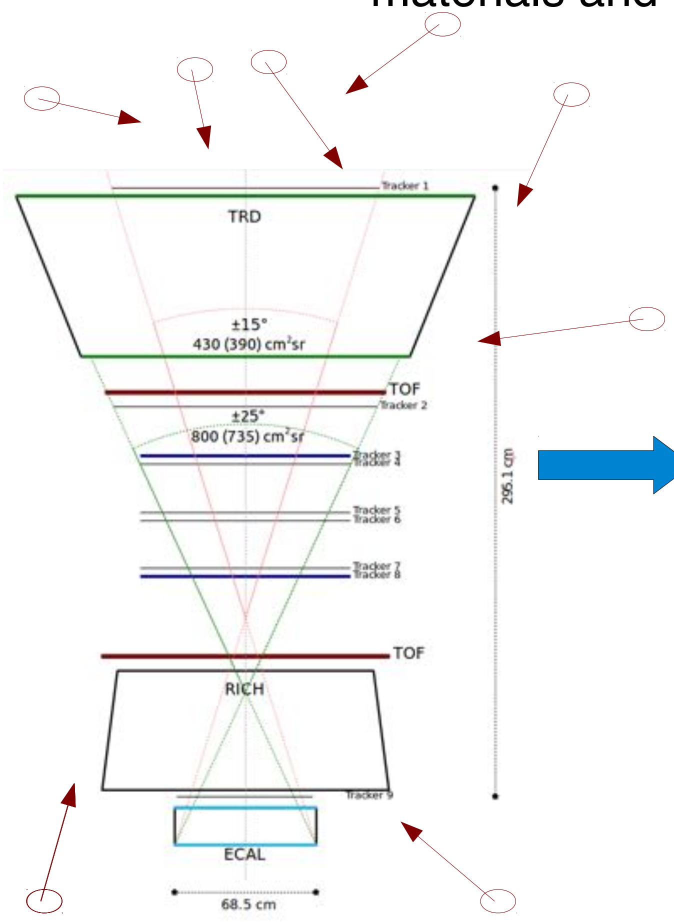
$$G = S \int_0^{2\pi} d\phi \int_0^{\pi} \cos\theta \sin\theta d\theta = \pi S. \quad (80)$$

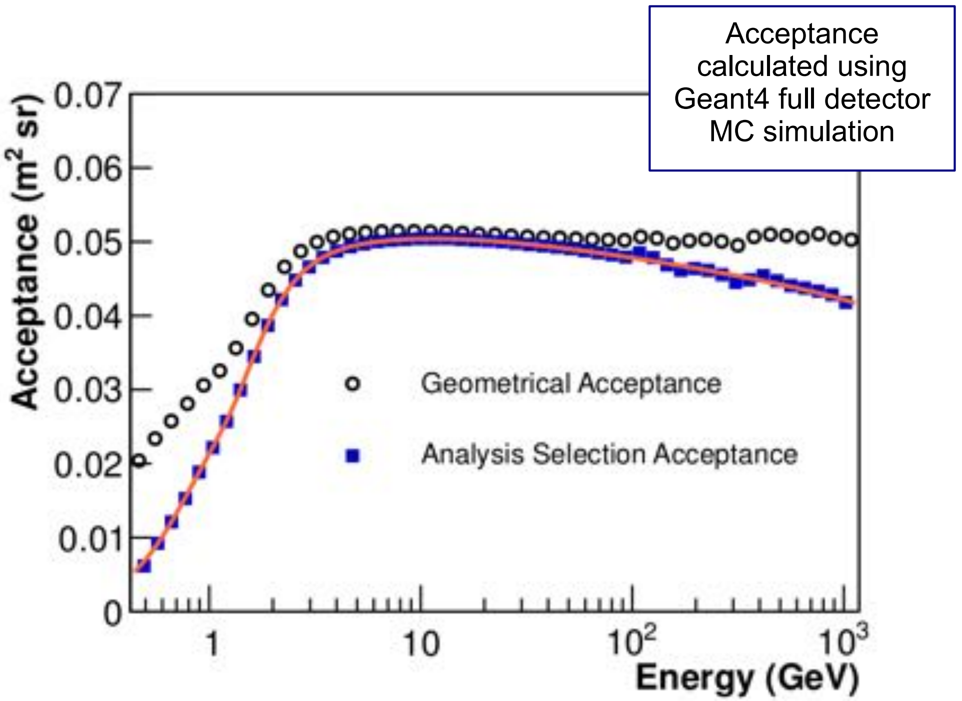
The field of view, finally, is

$$\text{FoV} = \frac{G}{S} = \pi. \quad (81)$$

Instrument Acceptance

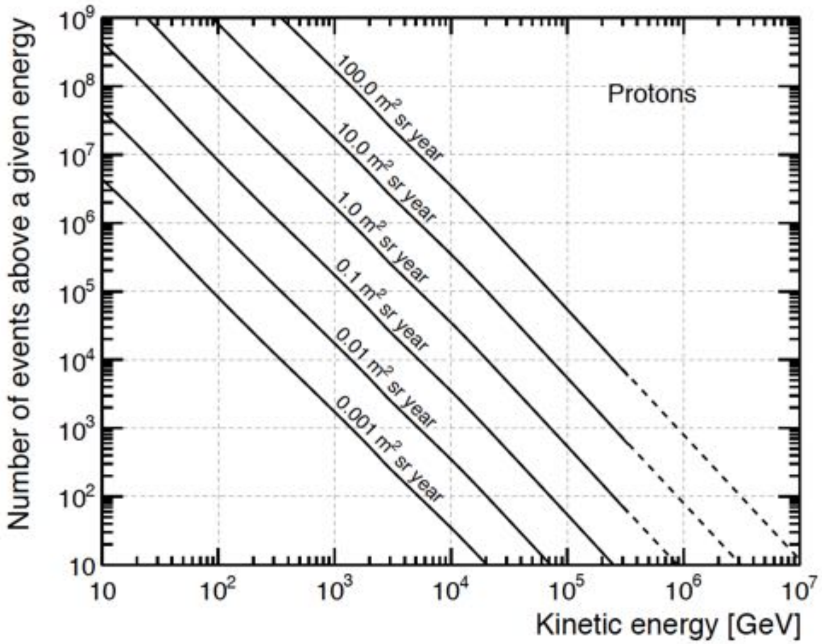
ACCEPTANCE: measurement of the collection capabilities of the detector
Tipically measured with MonteCarlo simulations including the detector geometry, materials and interactions with the detector

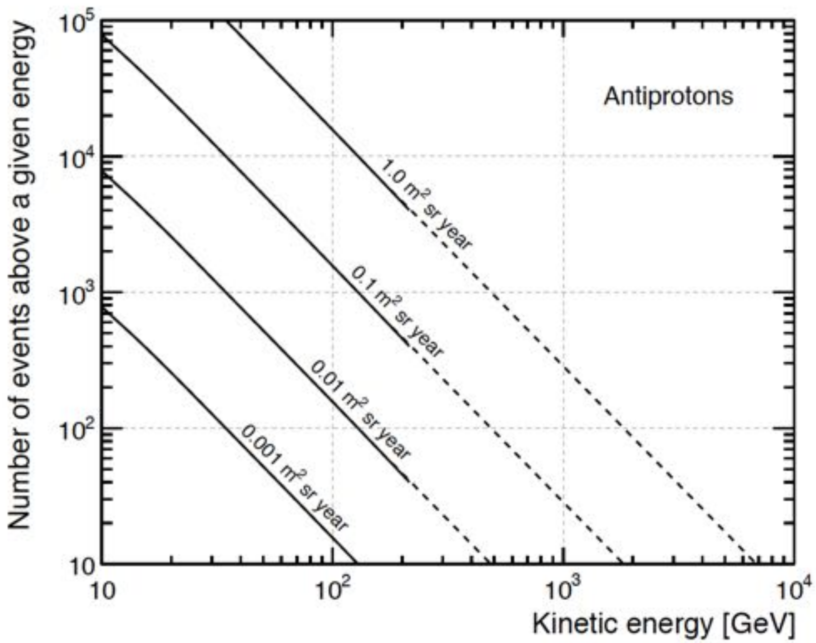




Instrument Gathering Power

GATHERING POWER: measurement of the collection capabilities of the mission (it includes the detector lifetime)





Statistical Error on Flux measurement ~ $1/\sqrt{(N)}$

Maximize Statistics < -- > Minimize statistical uncertainties

- Large acceptances
- Long duration missions

Typical quantities

- Cosmic ray physics is (almost) all about **FLUXES**

- **DIFFERENTIAL FLUX**: number of CRs per unit of time and energy (*) crossing the unit vector area towards a given direction in the sky
  - Measured in [$GeV^{-1}\ m^{-2}\ s^{-1}$]
  - Used for point source studies (like gamma rays)

- **FLUX or INTENSITY**: number of CRs per unit of time, energy (*) and solid angle crossing the unit vector area
  - Measured in [$GeV^{-1}\ m^{-2}\ s^{-1}\ sr^{-1}$]
  - Used for isotropic measurements (charged cosmic rays)

(*) Fluxes can be expressed as function of different improper definition of “energy”
  - Kinetik energy (calorimeters)
  - Kinetik energy per nucleon (calorimeters)
  - Rigidity (spectrometers)

Typical quantities

$$E_{\mathrm{k}} = E - mc^2$$

Kinetik Energy: defined by the acceleration due to electrostratic fields at the sources. Measured with calorimeters

$$\mathcal{E}_{\mathrm{k}} = \frac{E_{\mathrm{k}}}{A}$$

Kinetik Energy per Nucleon: defined by the spallation processes during propagation in the ISM medium. Quantity conserved in spallation processes. Measured with calorimeters (and hypothesis on the isotope composition)

$$R = \frac{pc}{Ze}$$

Rigidity: defines the motion in magnetic fields (for example, during diffusion through turbolent fields or curvature in homogeneuos fields). Measured with spectrometers

β

E	Energy	[GeV]
E_{k}	Kinetic energy	[GeV]
$\mathcal{E}_{\mathrm{k}}$	Kinetic energy/nucleon	[GeV/A]
p	Momentum	[GeV/c]
R	Rigidity	[GV]

Typical quantities

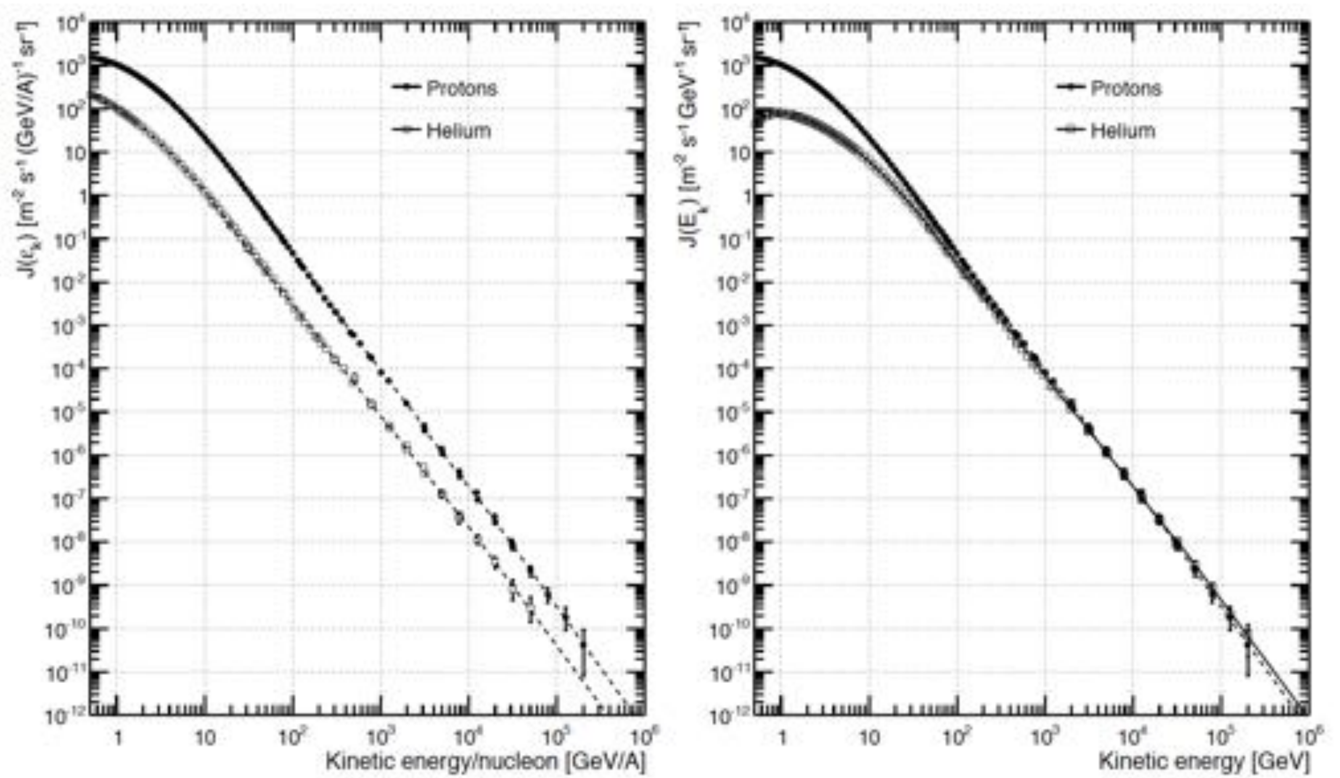


FIG. 2: Differential intensities, plotted as a function of kinetic energy per nucleon (left) and total kinetic energy (right) for the two most abundant CR species: protons and He nuclei. While the He intensity is a factor of ~ 10 smaller than that of protons at, say, ~ 1 TeV/nucleon, the two are comparable, at ~ 1 TeV, when binned in total kinetic energy. See next section for more

Beware: Fluxes are differential quantities (see units). Transformations from different unit on the X axis require the use of the Jacobian on the Y axis

The Flux Measurement

Precision knowledge of the detector acceptance, response and resolution, and of the data acquisition in space.

FLUX

Number of cosmic rays collected

$$\Phi(E) = \frac{N}{\Delta E \, \Delta T \, Acc \, \varepsilon_{sel} \, \varepsilon_{trig}}$$

Trigger Efficiency

Acceptance (m^2 sr)
usually calculated using MC sims

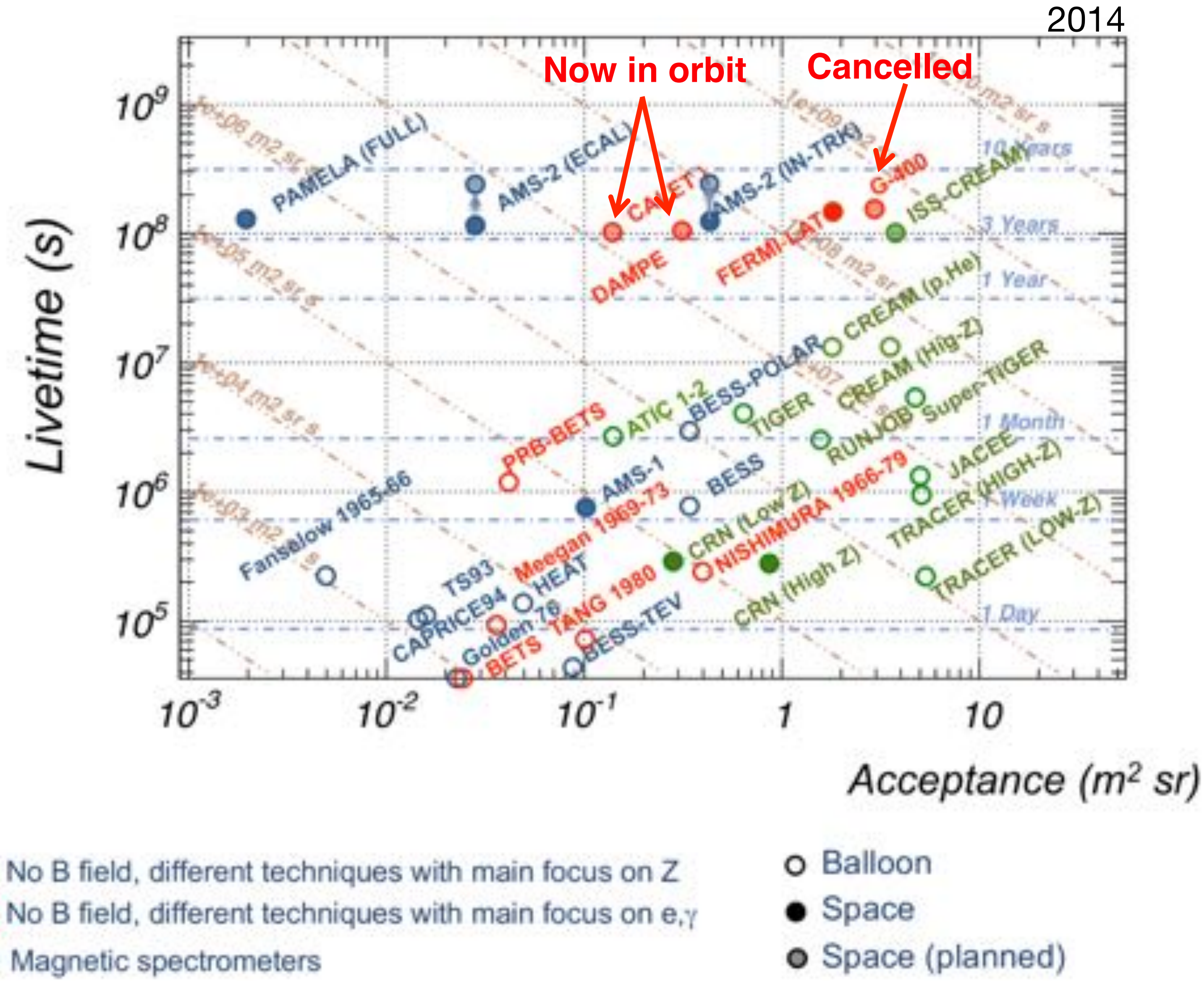
Energy/Rigidity (GeV)
size of the bin

Exposure Time (s)
also called “Livetime”

Particle selection efficiency
based on the statistical techniques employed to extract N

Each factor uncertainty contributes equally to the final measurement.
Systematic uncertainty studies for each factor are fundamental

Future experiments

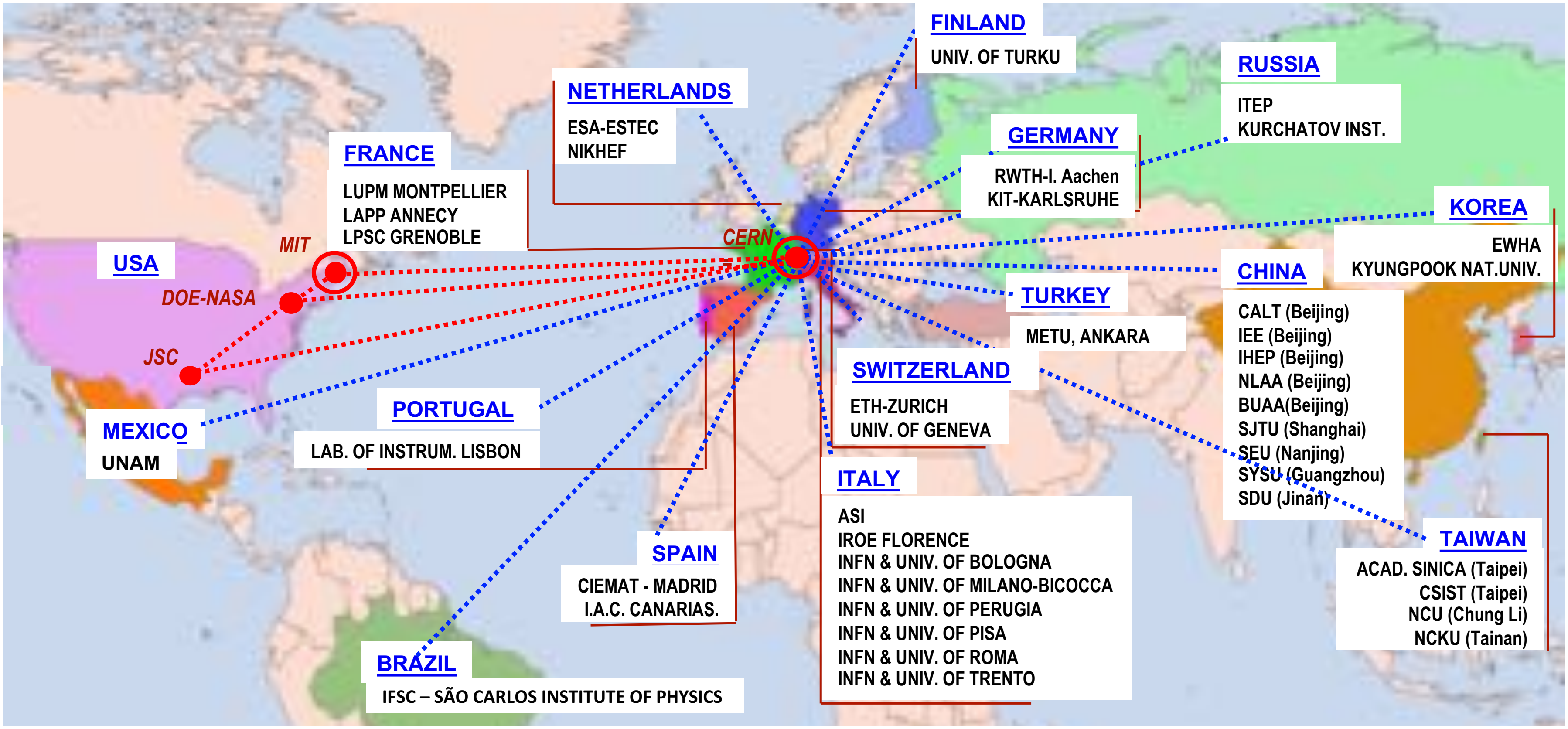


AMS-02 will be the unique magnetic spectrometer in space able to distinguish matter from antimatter for the next 10 years.

The AMS-02 detector

- **Size** 5 x 4 x 4 m, 7500 kg
- **Power** 2500 W
- **Data Readout** 300,000 channels
- **<Data Downlink>** ~ 12 Mbps
- **Magnetic Field** 0.14 T
- **Mission duration** until the end of the ISS operations (currently 2024)

The AMS-02 Collaboration

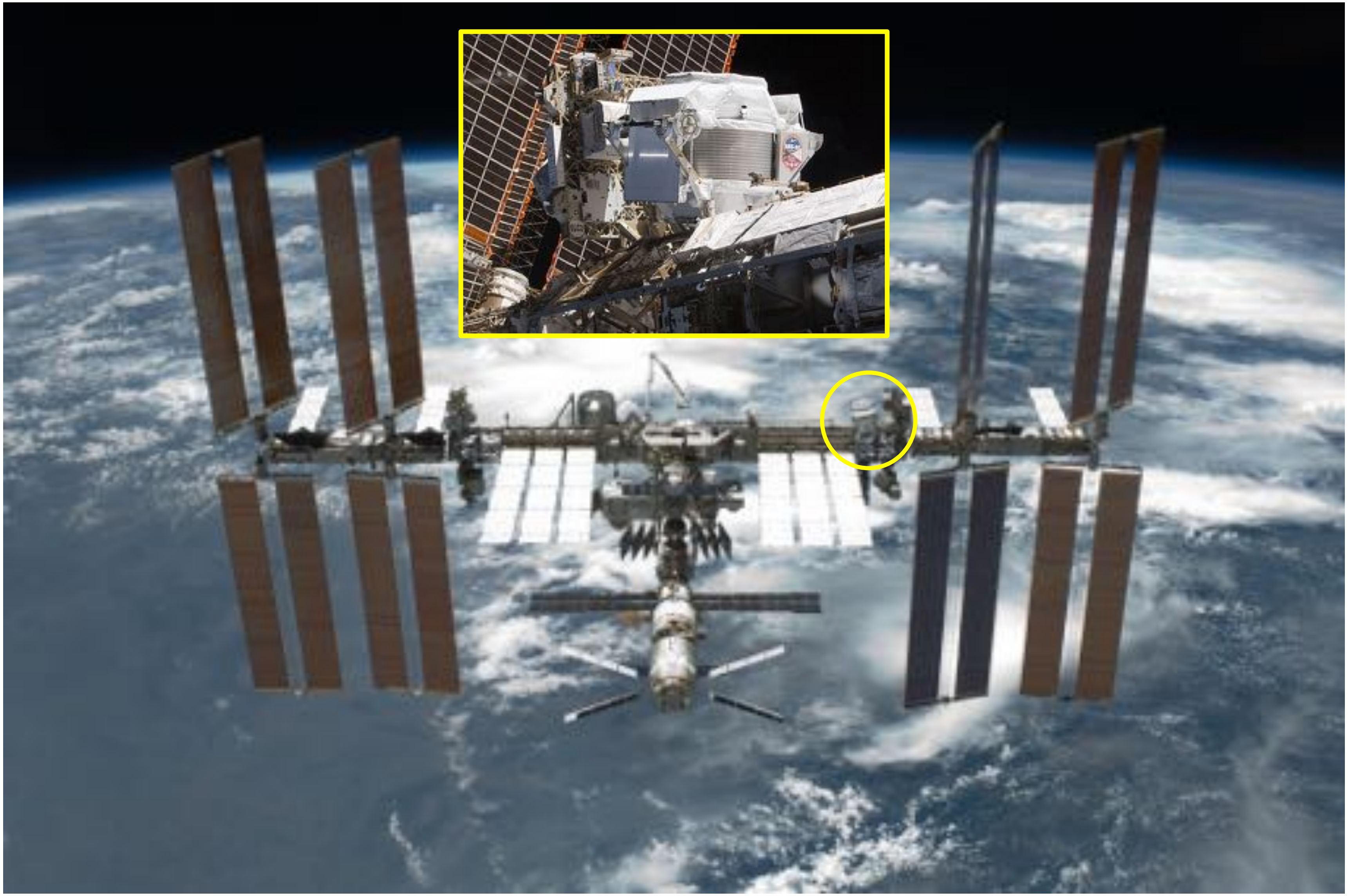


The AMS-02 detector

The AMS-02 detector

The AMS-02 detector

AMS-02 on the ISS



AMS-02 Physics

FUNDAMENTAL PHYSICS

- Indirect search for Dark Matter (e^+, anti-p,….)
- Search for primordial antimatter (anti-He)

COSMIC RAY COMPOSITION AND ENERGETICS

- Precise measurement of the energy spectra of H, He, Li, B, C

to provide information on CR interactions and propagation in the galactic environment

TO ACHIEVE THIS…..

Particle identification and Energy measurement up to TeVs

- Matter/antimatter separation using magnetic field
- e/p separation using independent subdetectors

Maximize the data sample

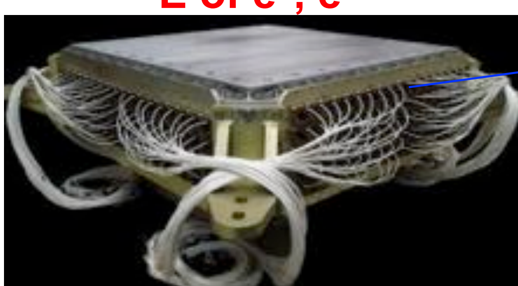
- Detector size (acceptance)
- Exposure time: ISS in space

AMS: TeV precision spectrometer

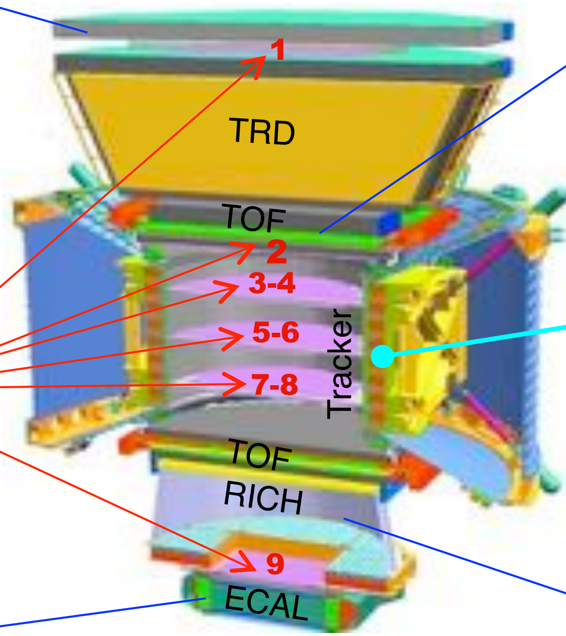
TRD
Identifies e^+, e^-

Silicon Tracker
Z, P

ECAL
E of e^+, e^-



Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



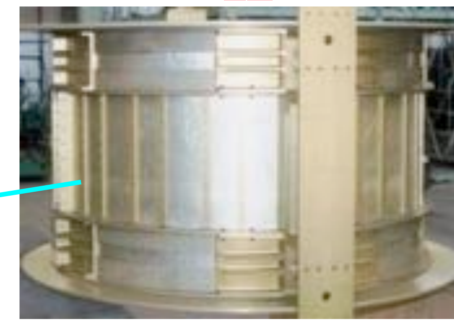
Z and P ~ E

are measured independently by the

Tracker, RICH, TOF and ECAL

TOF
Z, E

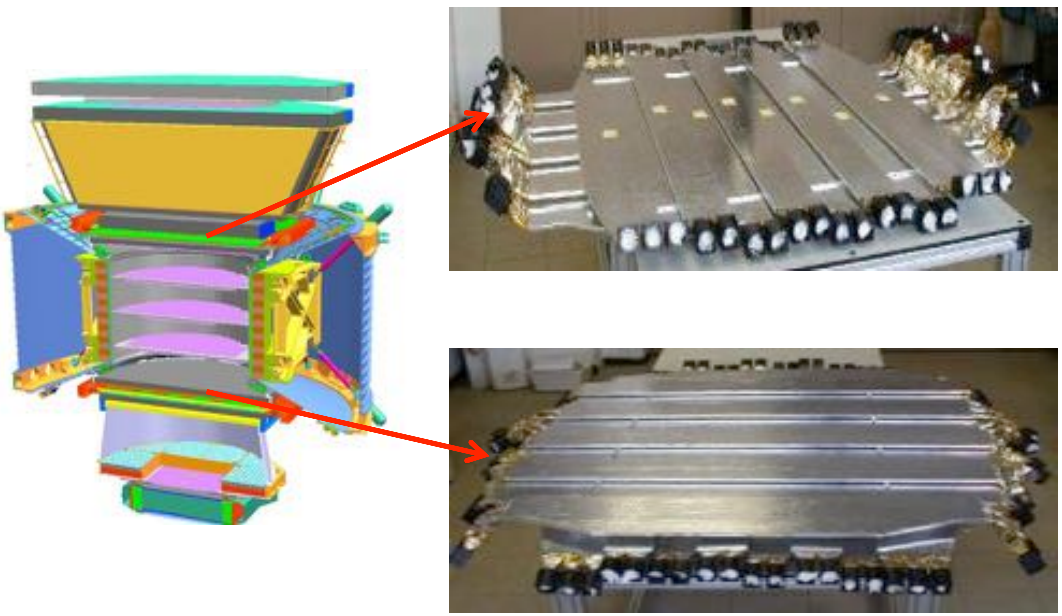
Magnet
±Z

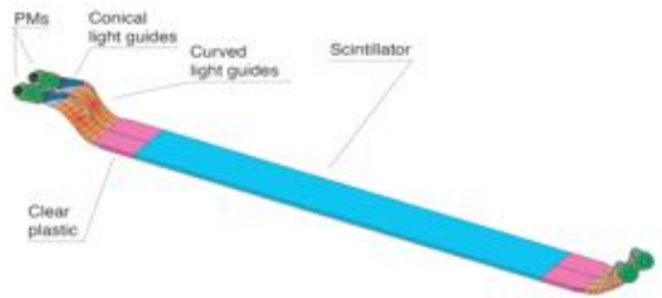


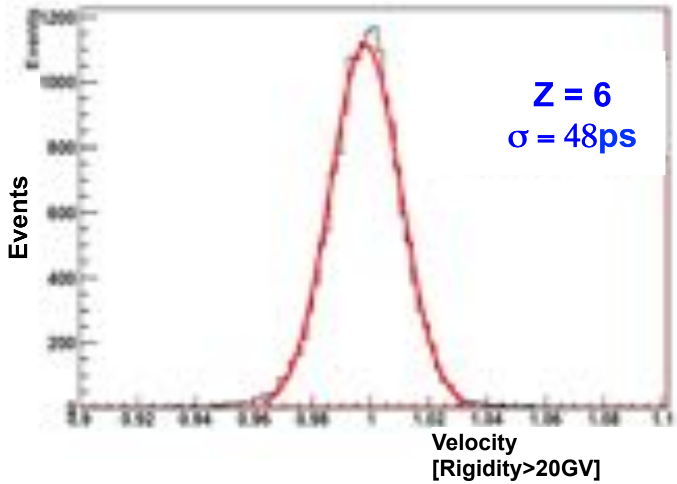
RICH
Z, E

Time of Flight TOF

Fast scintillator planes coupled with PMTs for fast light readout
Time of flight resolutions ~ 160 ps → $d\beta/\beta^2$ ~ 4% for Z=1 particles, better for higher charges



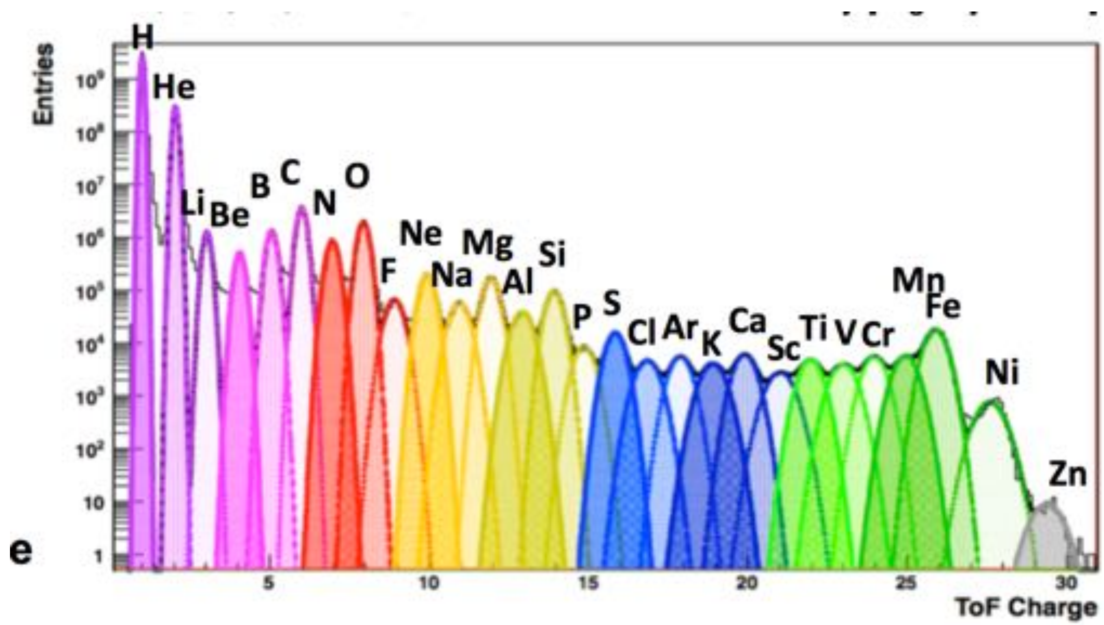




Fast signal used to provide the experiment trigger to charged particles

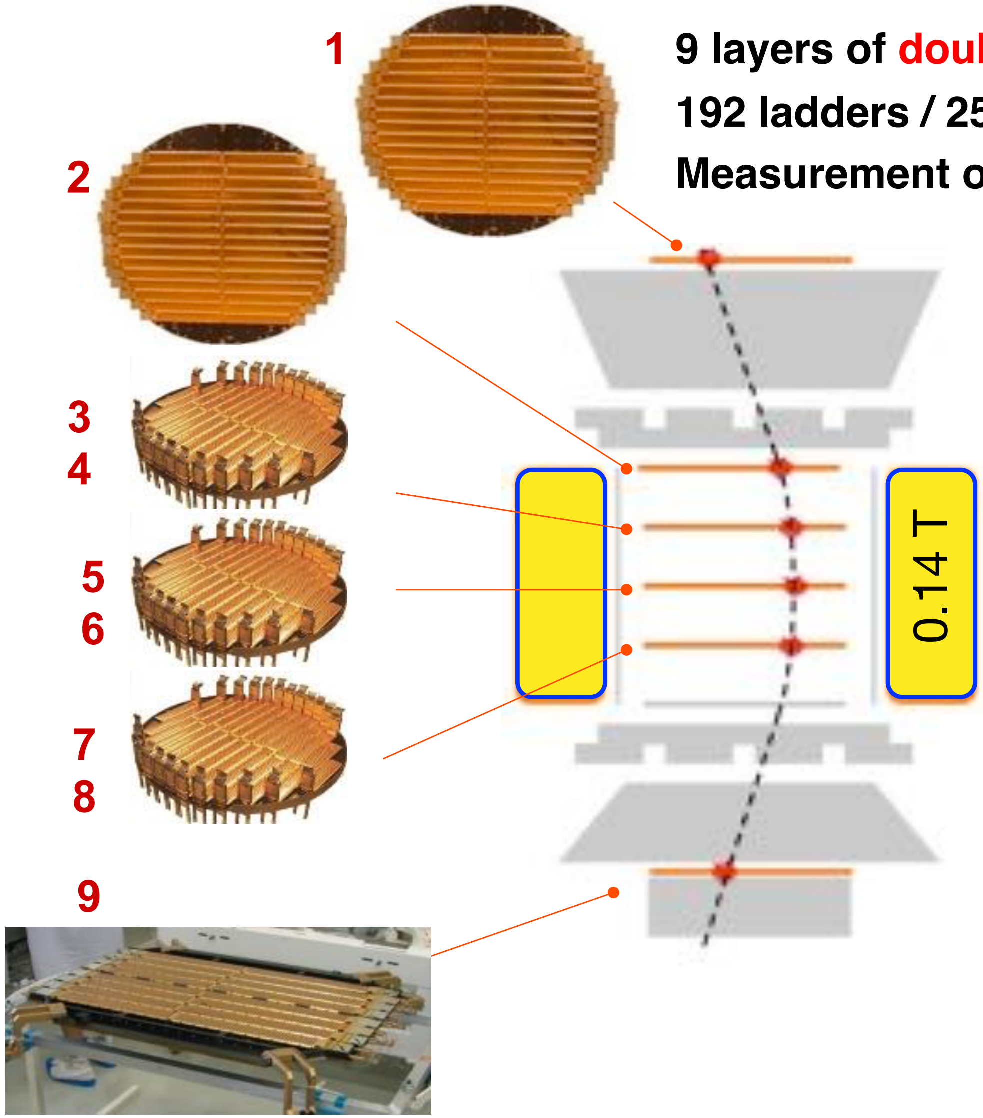
Time of Flight TOF

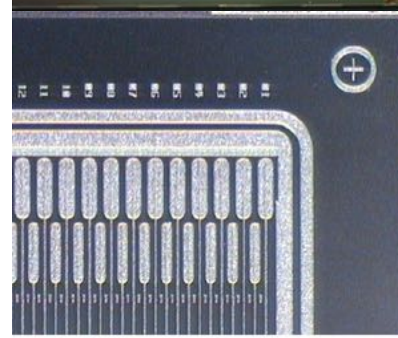
Fast scintillator planes coupled with PMTs for fast light readout
Energy deposit sampled in 4 layers → Particle charge reconstruction using dE/dX



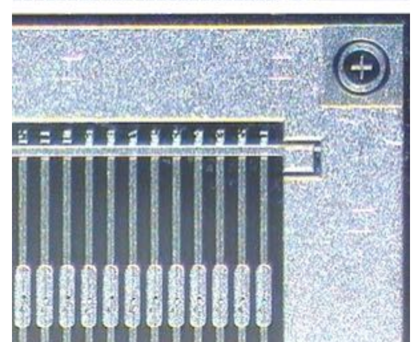
Magnetic Spectrometer

9 layers of double sided silicon microstrip detectors
192 ladders / 2598 sensors/ 200k readout channels
Measurement of the coordinate with 10μm accuracy





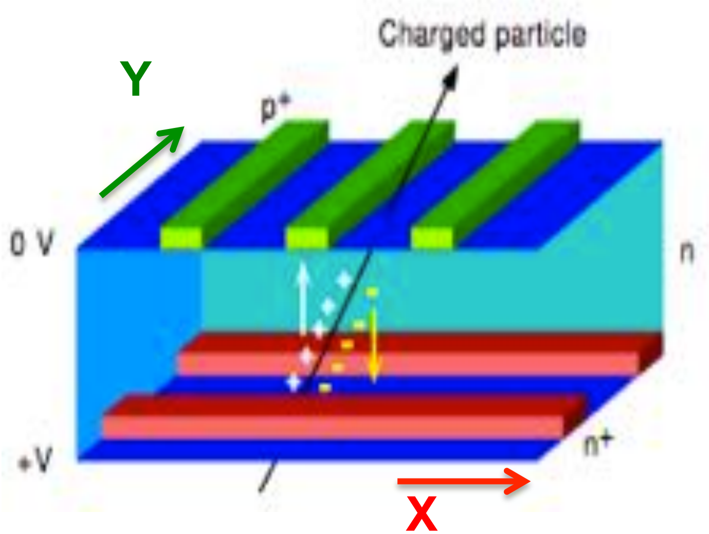
P-side (bending dir)
27.5 µm pitch
104 µm readout

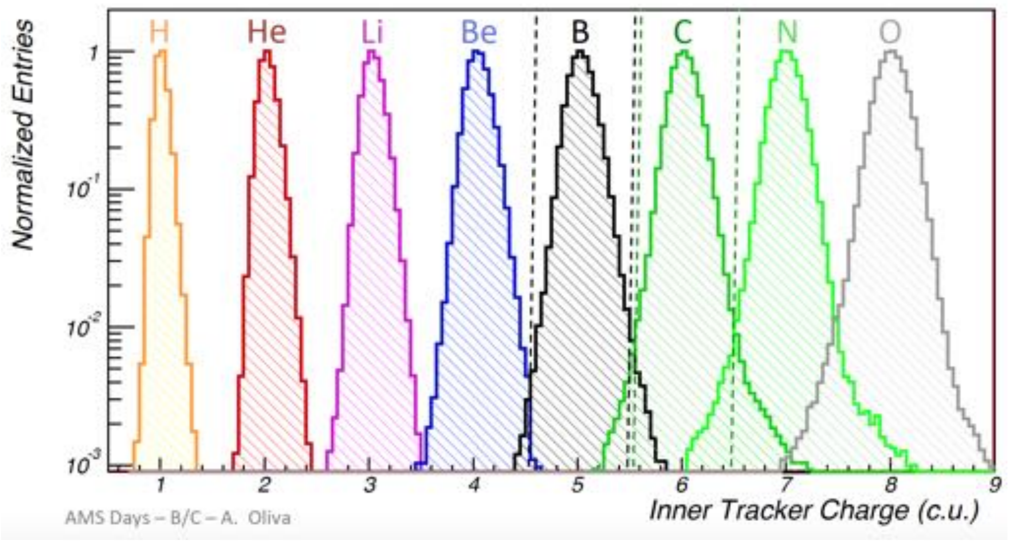


N-side
104 µm pitch
208 µm readout

Magnetic Spectrometer

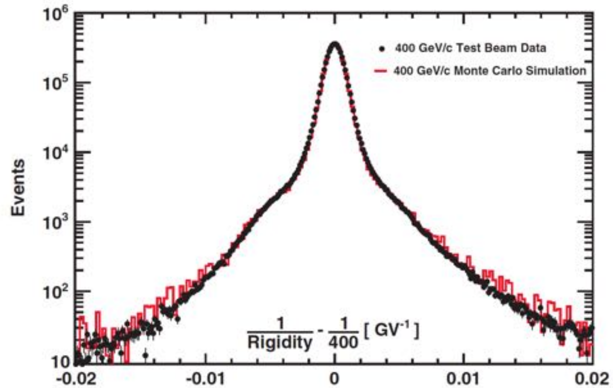
14 dE/dX samples in Inner Tracker
4 dE/dX samples in external planes

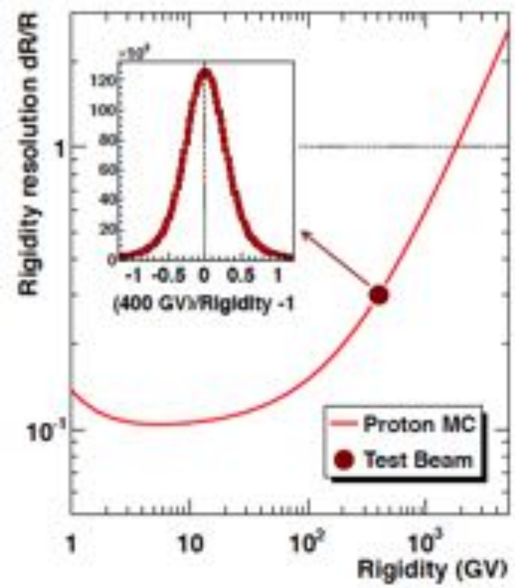




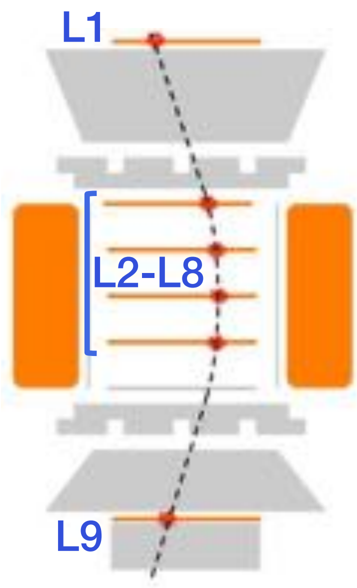
Magnetic Spectrometer

The spectrometer resolution is studied using test beam particles and MC simulations





Magnetic Spectrometer



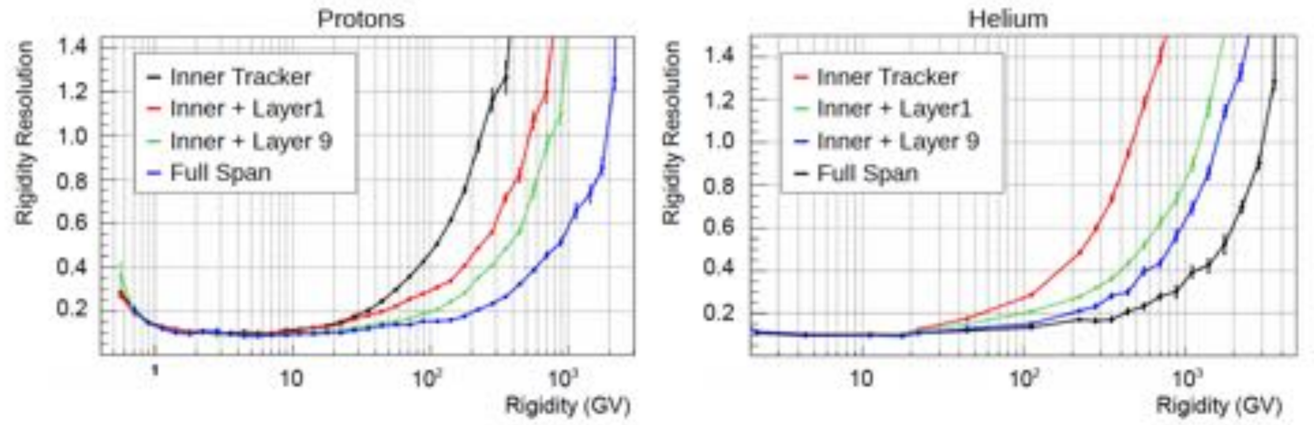


Figure 2.12: Rigidity measurement resolution for protons (**Left**) and Helium (**Right**) estimated from MC. Different colors identify different Tracker spans. The presence of the external layers used to increase the trajectory lever of arm allows to measure the rigidity of particles crossing the Tracker layers up to the TeV range

At low energies, the rigidity measurement resolution is dominated by the multiple scattering in the tracker material (dR/R ~ R).
At high energies, the resolution is defined by the curvature measurement (dR/R ~ R).

The maximum detectable rigidity is defined as the rigidity when the resolution is 100% (Cannot distinguish between negative and positive curvatures)

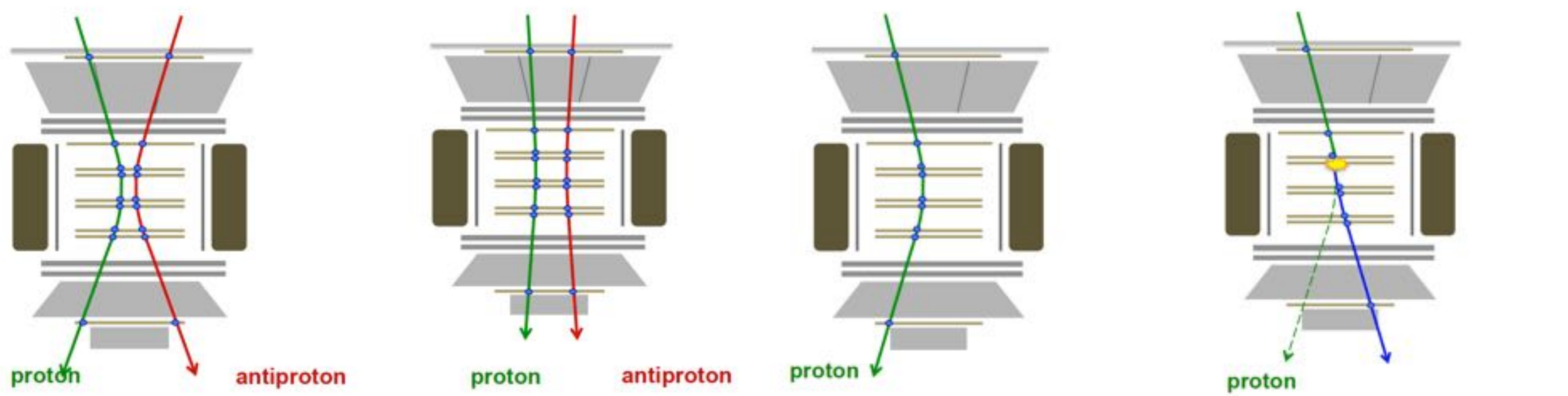
Magnetic Spectrometer

Charge Confusion (or Flip)

Tracker Resolution (statistical)

Interactions with the material

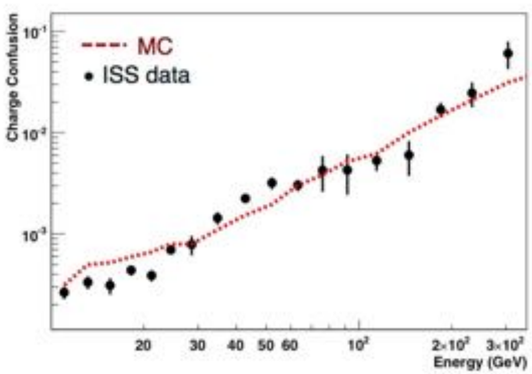
Trajectories at low energy | high energy | Clean proton trajectory | Occurrence of nuclear scattering



Larger is the energy, straighter is the particle's trajectory
(straighter is the trajectory, higher is the confusion…)

→ well-reconstructed proton

→ distorted trajectory
→ fake antiproton



The amount of charge confusion increases with energy, limiting the capabilities to correctly measure the fraction of antimatter in cosmic rays

Space born detectors

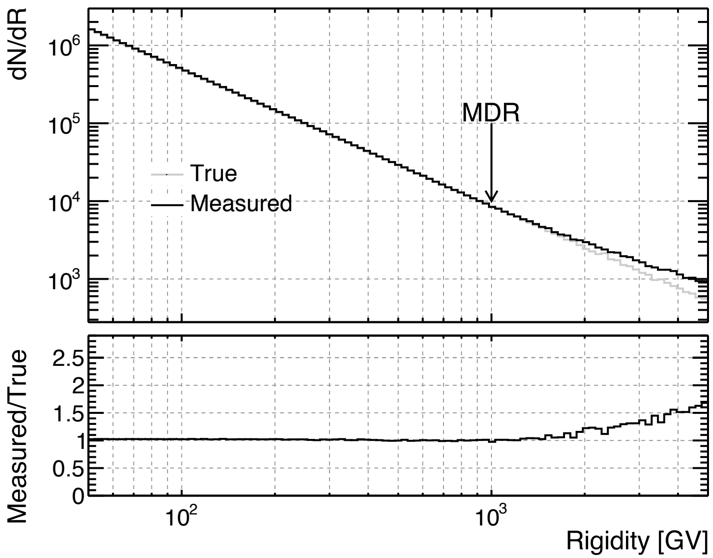


FIG. 62: Effect of a finite rigidity resolution on a toy Monte Carlo power-law spectrum with index 2.75, mimicking the primary cosmic-ray proton spectrum, for a maximum detectable rigidity of 1 TV. (For completeness, the smearing used for this illustration is gaussian in $1/R$. Though the relative fluctuation in R and $1/R$ are the same, the result would have been somewhat different if the smear was done in the rigidity space—we stress, however, that the point of the exercise was not to develop a realistic model of the rigidity dispersion.)

- Distortion of the flux measurement above ~MDR
- The flux can be corrected if the smearing/ migration matrix is known (tipically from MonteCarlo simulations)

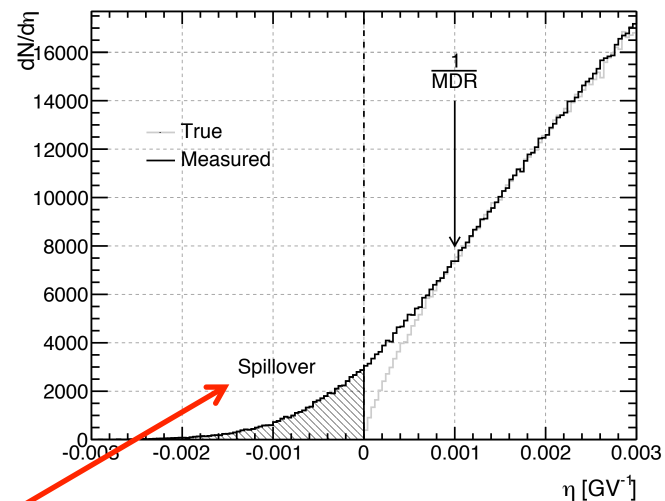
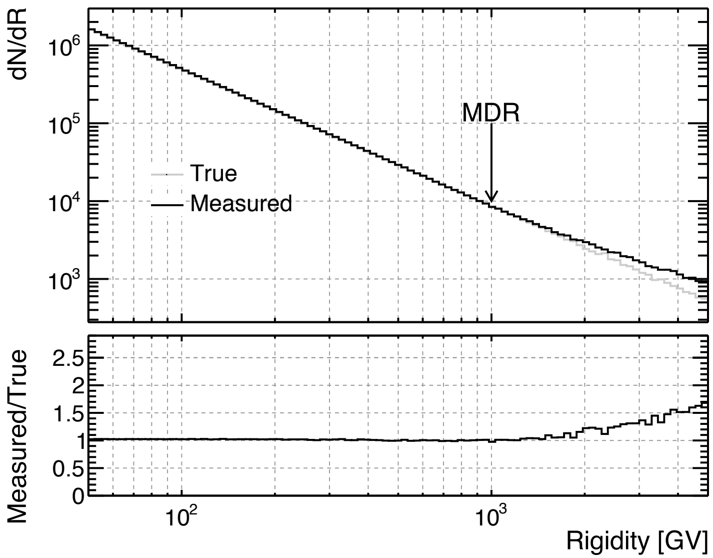


FIG. 63: Illustration of the spillover effect. Here the same (true and measured) spectra in figure 62 are shown in the η space. We remind again that for this toy simulation the smearing is gaussian in η, assuming a MDR of 1 TV.

- Charge flip probability increases as the energy increases
  - SPILLOVER or CHARGE CONFUSION

Space born detectors

- Distortion of the flux measurement above ~MDR
- The flux can be corrected if the smearing/ migration matrix is known (tipically from MonteCarlo simulations)



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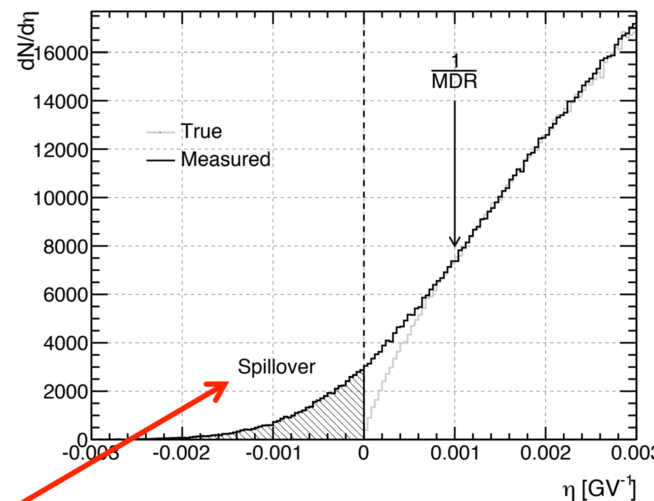

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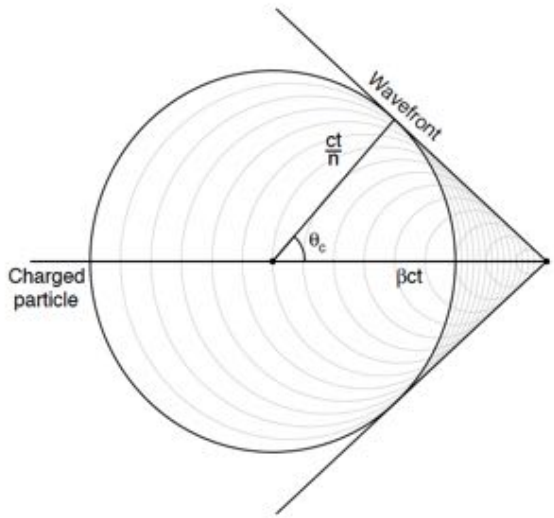
- Charge flip probability increases as the energy increases
  - SPILLOVER or CHARGE CONFUSION

Ring Imaging Cherenkov RICH



Cherenkov radiation is emitted when a charged particle moves in a medium at a speed greater than the speed of light *in that medium*

$$\beta > \frac{1}{n}. \tag{52}$$

$$\cos\theta_c = \frac{1}{n\beta}$$

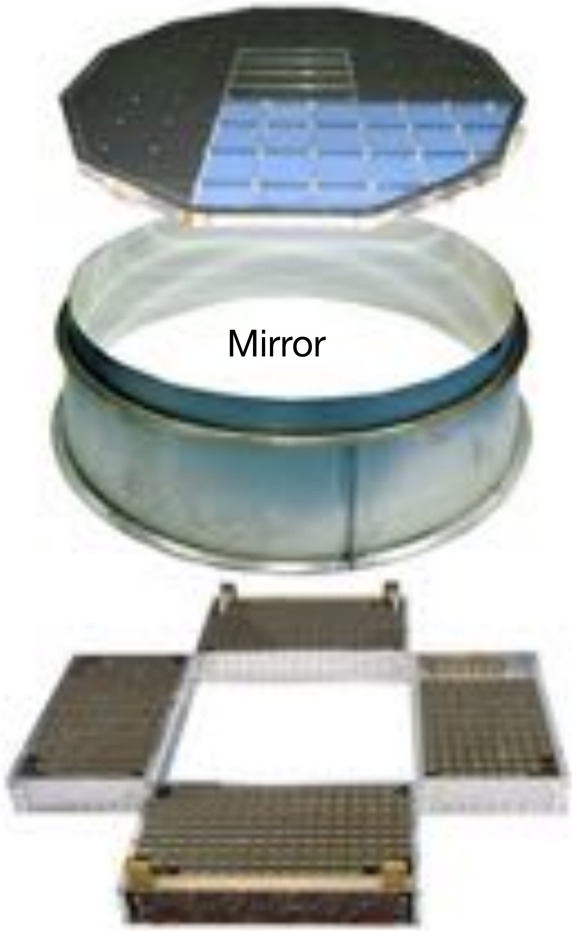
$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Geometry: Cherenkov ring aperture used to measure the particle velocity

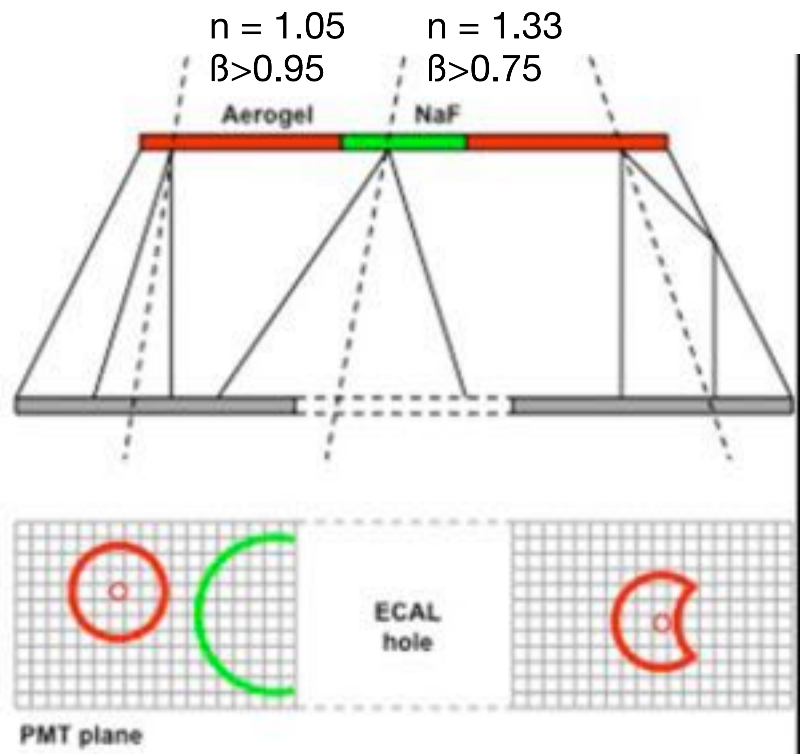
Intensity: number of UV photons proportional to particle charge

Ring Imaging Cherenkov RICH

Radiator

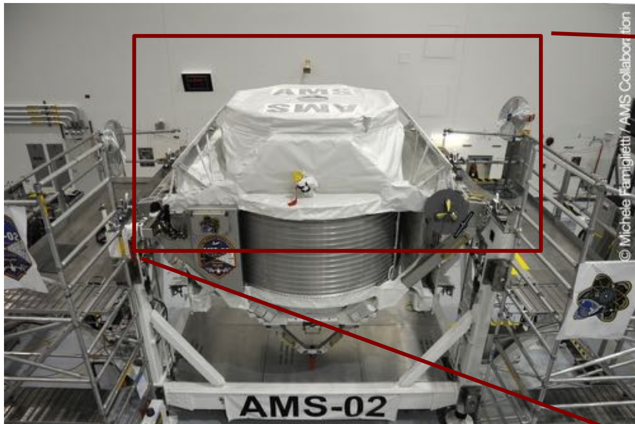


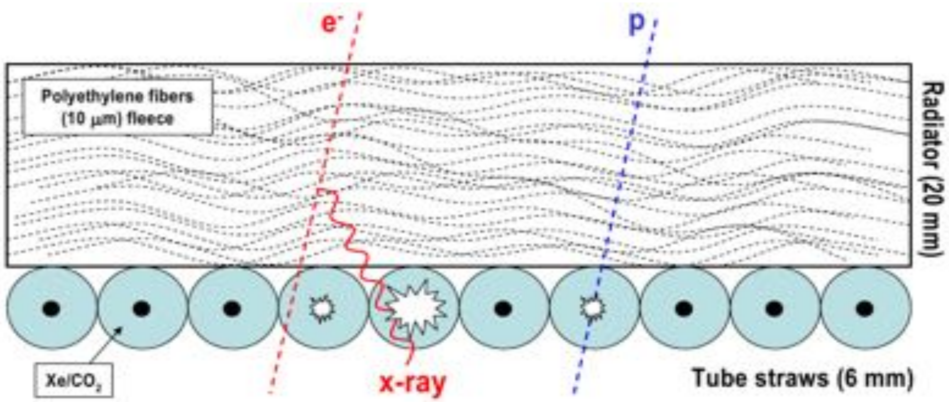
10,880 photosensor plane



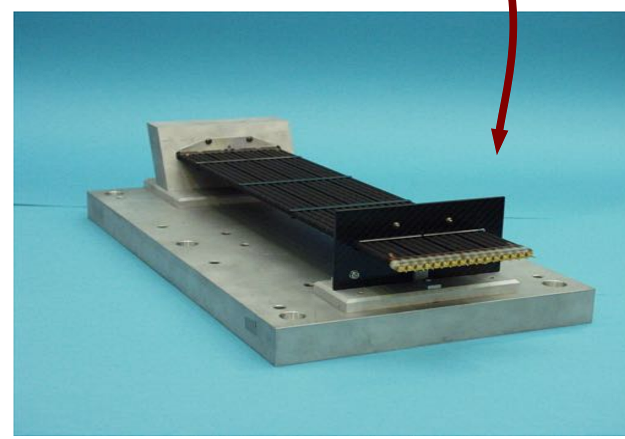
Measurement of velocity with dß/ß~0.1%

Transition Radiation Detector TRD



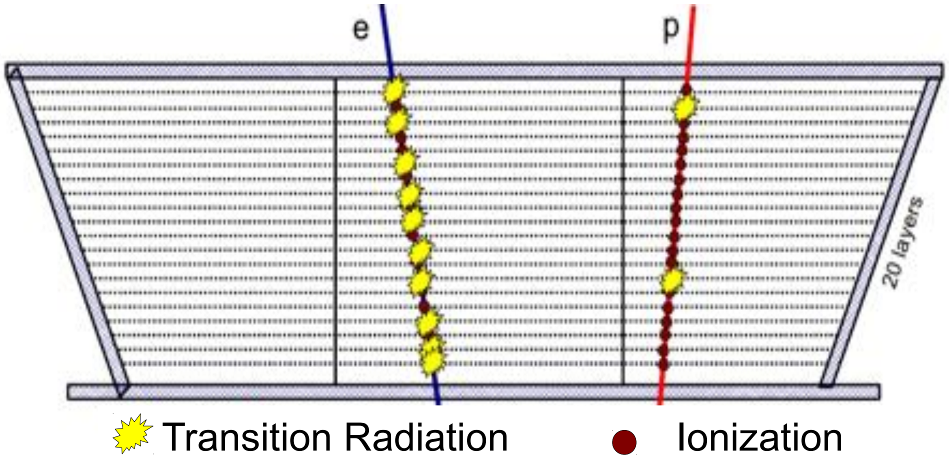


$$\mathcal{P}_{TR} \propto \gamma = E/m$$



20 Layers of radiator (fleece) to induce X ray radiation
Straw tubes for ~KeV xray detection (Xe/C02 gas)

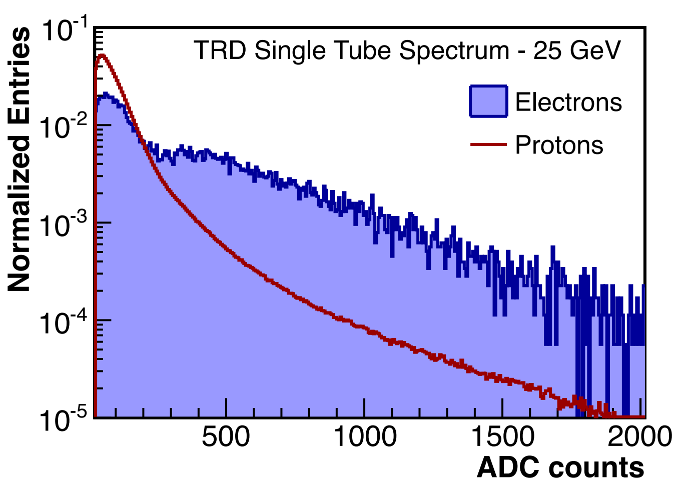
Transition Radiation Detector TRD



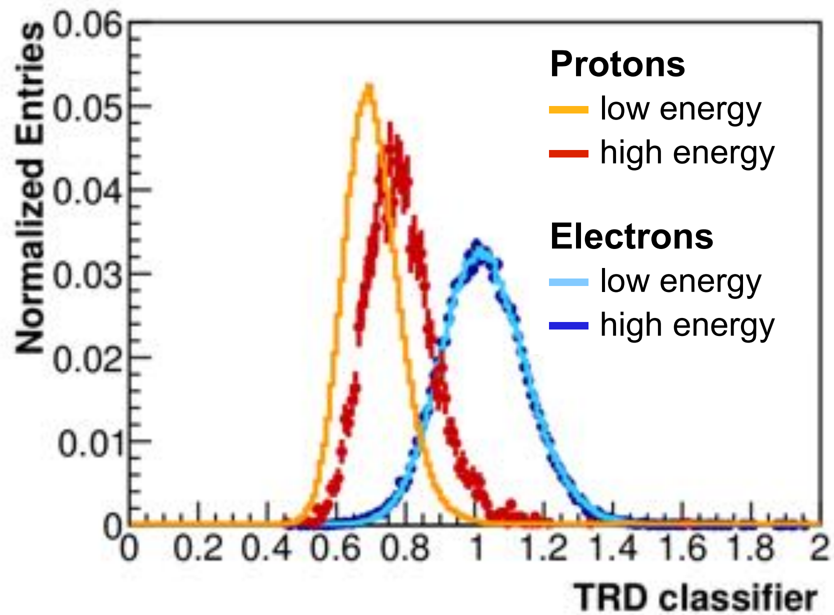
$$\mathcal{P}_{TR} \propto \gamma = E/m$$

For same Rigidity or Energy particles

$$\mathcal{P}_{TR}\left(e^{\pm}\right) \gg \mathcal{P}_{TR}\left(p\right)$$



$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$



Electromagnetic Calorimeter ECAL

SAMPLING CALORIMETER

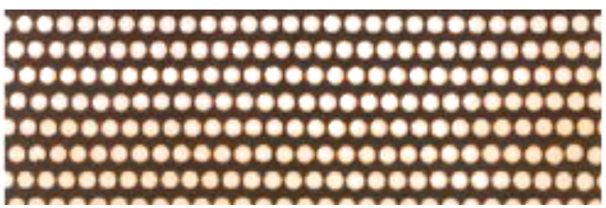
Lead + Scintillating fibers

66 x 66 x 17 cm^3

1296 readout cells

17 X_0, 0.6 λ_{nucl}

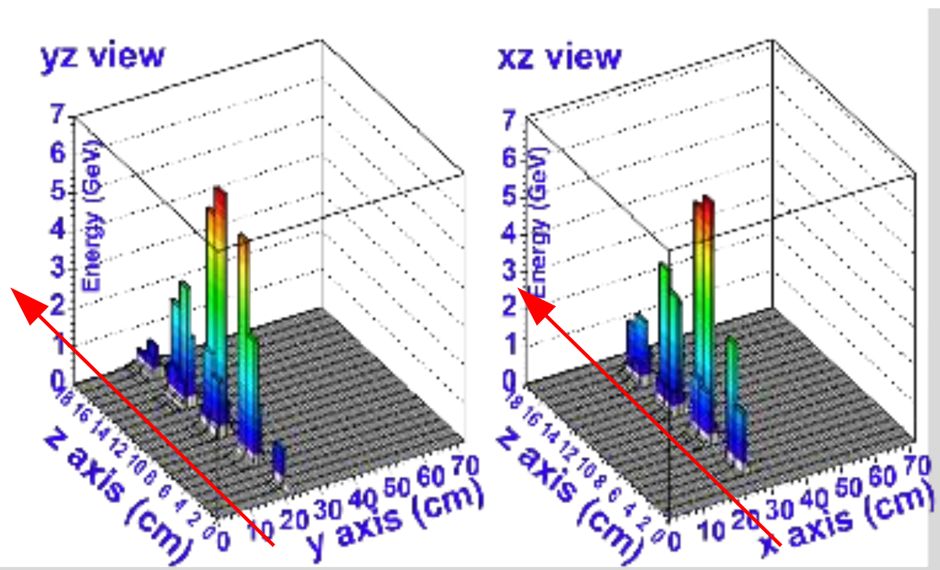
1 superlayer



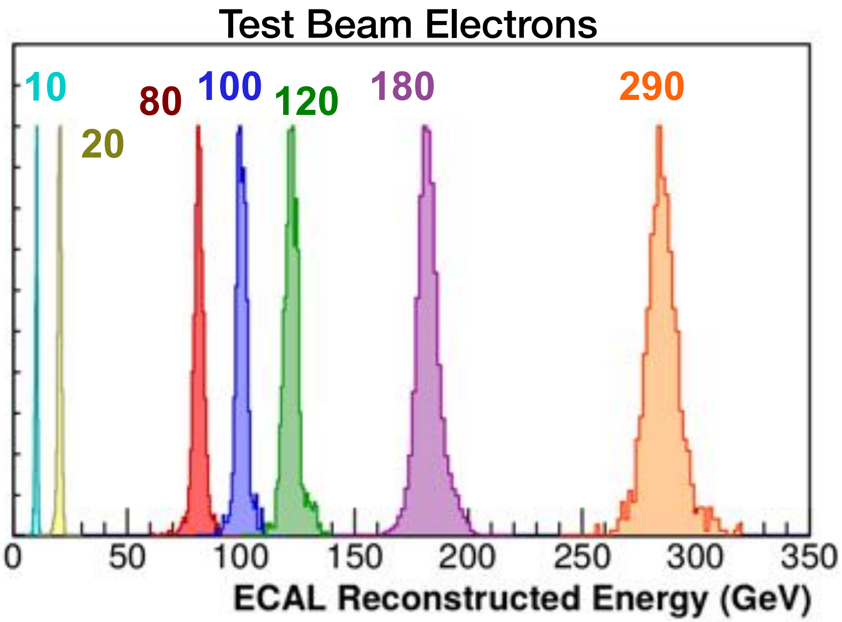
50,000 fibers, Φ=1mm

Uniformly distributed in 600 kg of lead

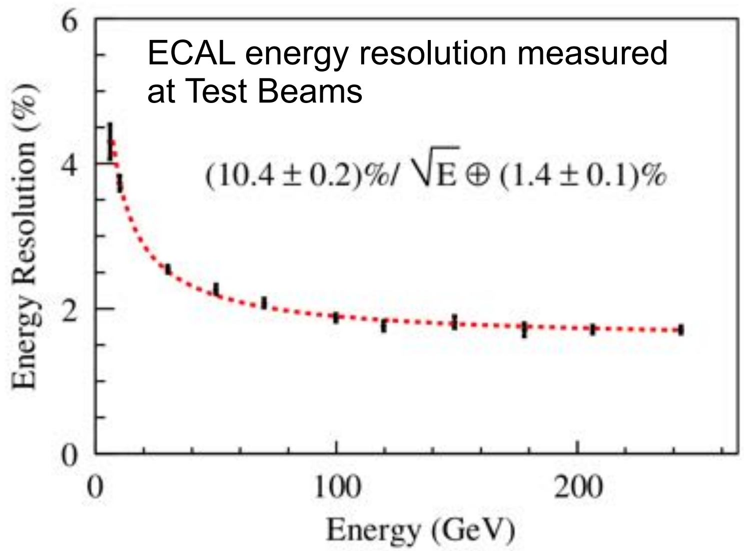
Energy and **arrival direction** measurement of electrons and photons up to 1 TeV

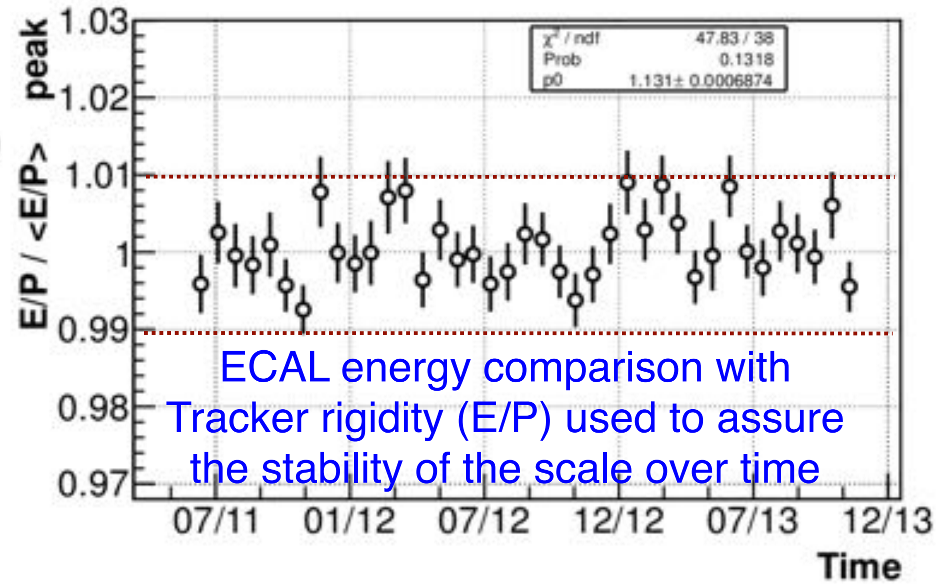


Energy Measurement



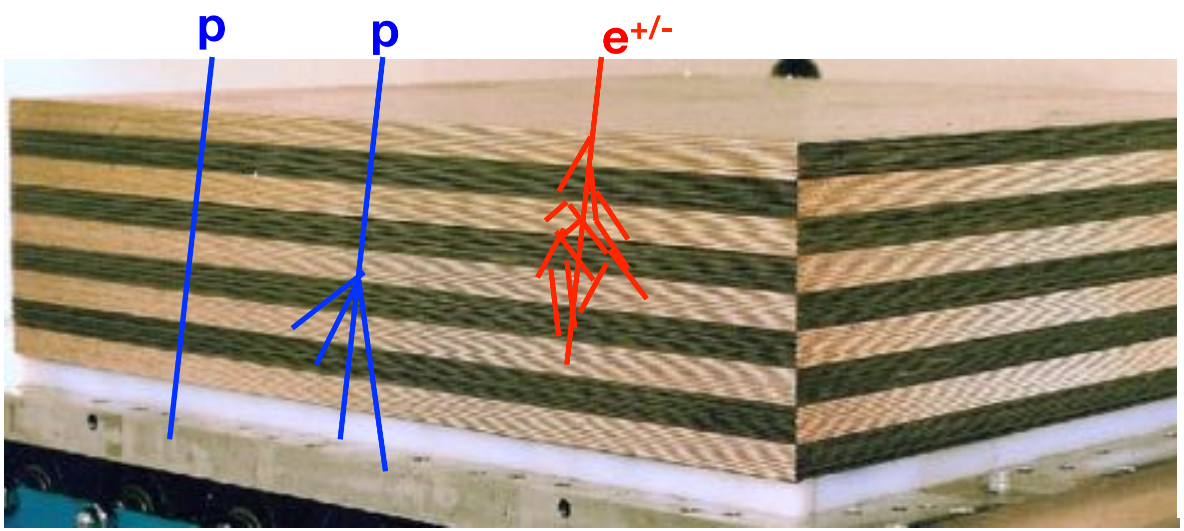
- ECAL energy resolution ~2%
- ECAL energy absolute scale tested during test beams on ground
- We have no line in space (as in collider exp.) to calibrate the energy scale in orbit!
  - MIP ionization used to cross-calibrate the energy scale in orbit





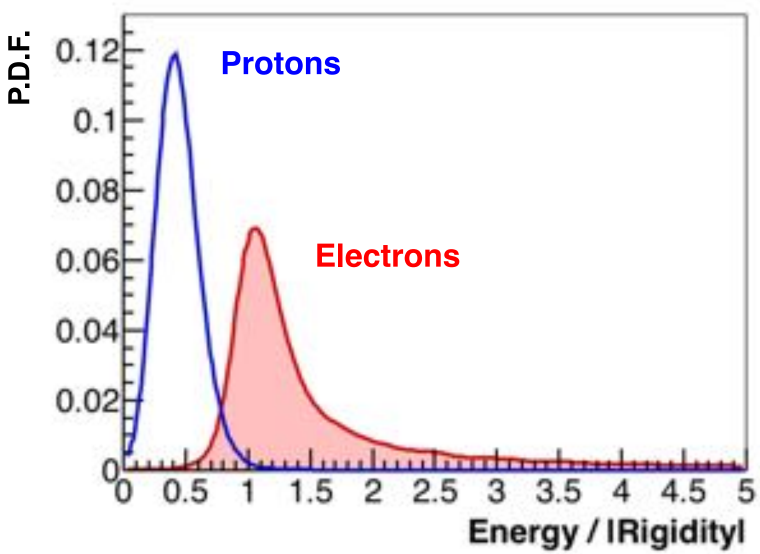
Calorimeter resolution impreves at high energy (compare with spectrometer)

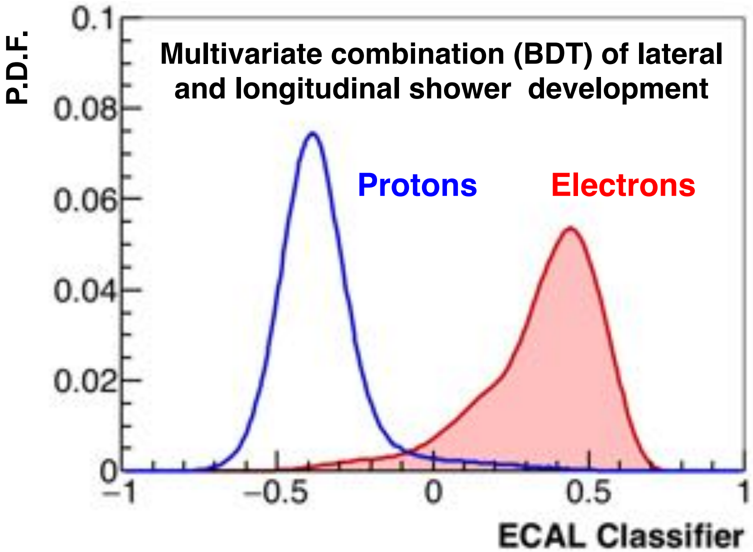
Electromagnetic Calorimeter ECAL



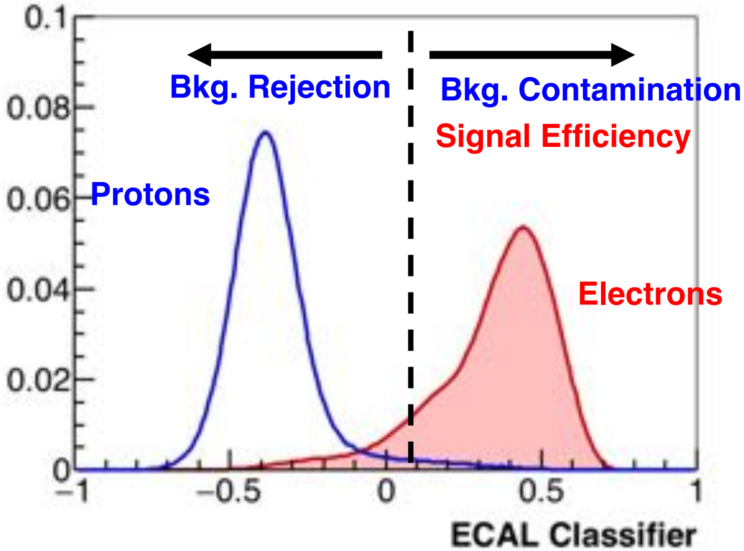
Electrons
Electromagnetic Shower
Energy contained
$E_{ECAL} \sim P_{TRACKER}$

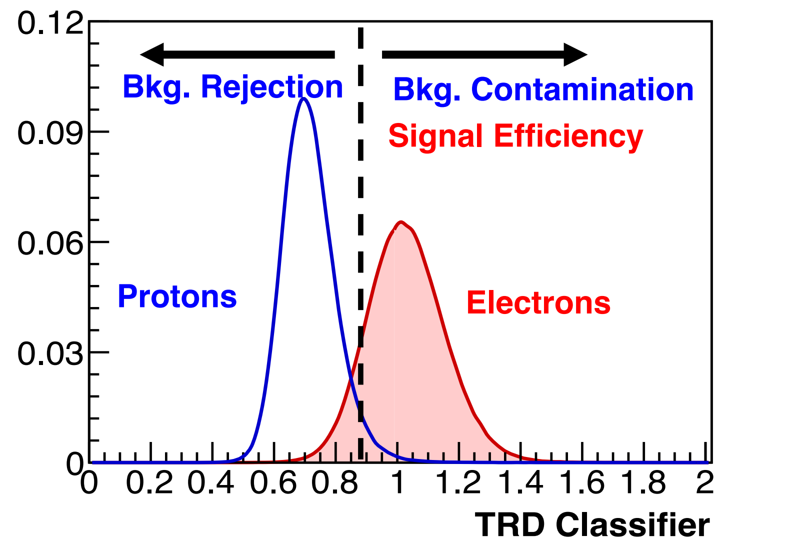
Protons
MIP or Hadronic Shower
Irregular shower
$E_{ECAL} << P_{TRACKER}$

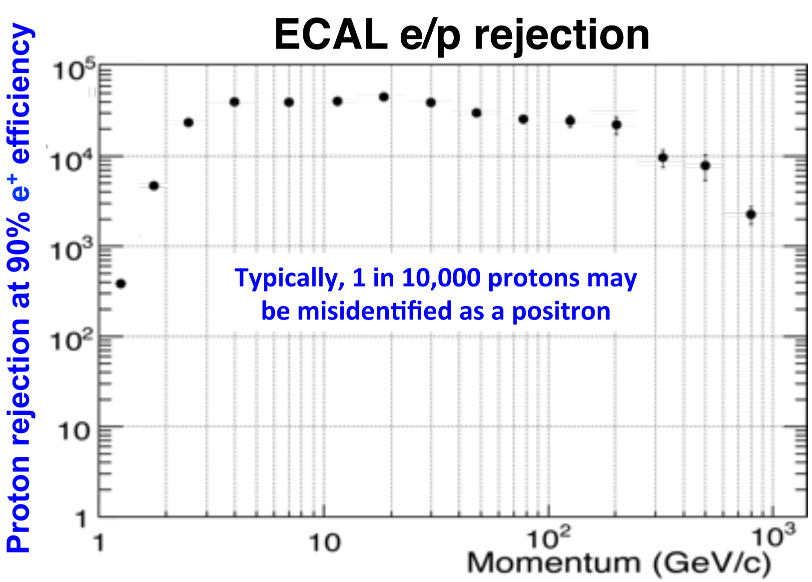


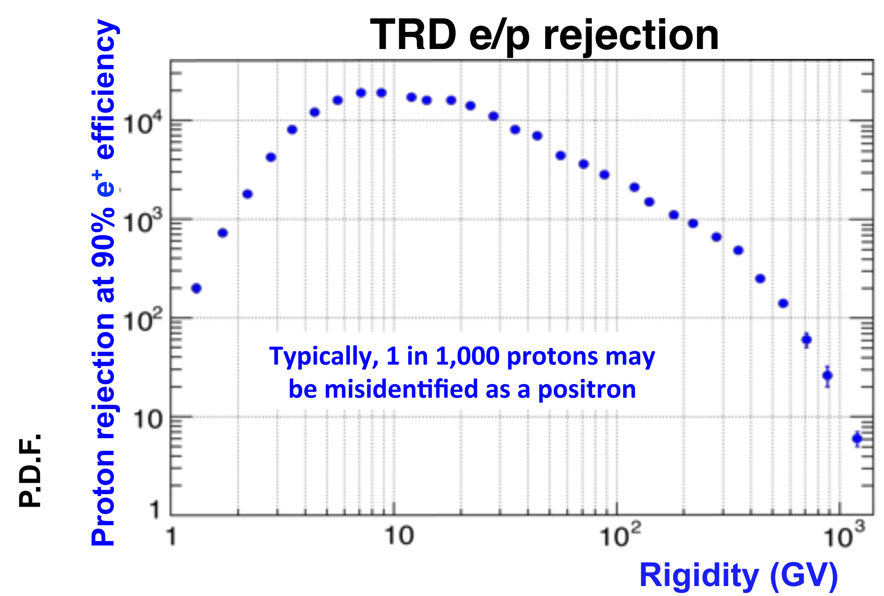


ECAL and TRD e/p separation



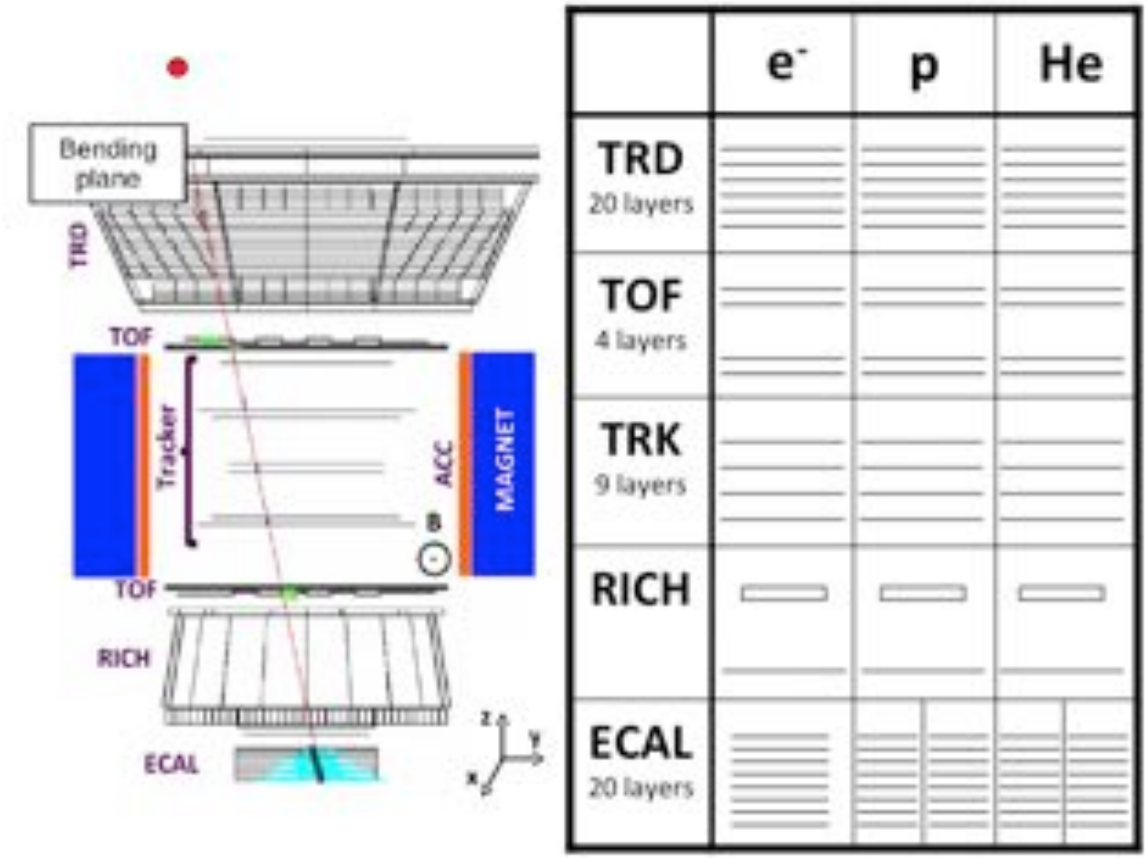






AMS: TeV precision spectrometer

Full coverage of anti-matter and CR physics



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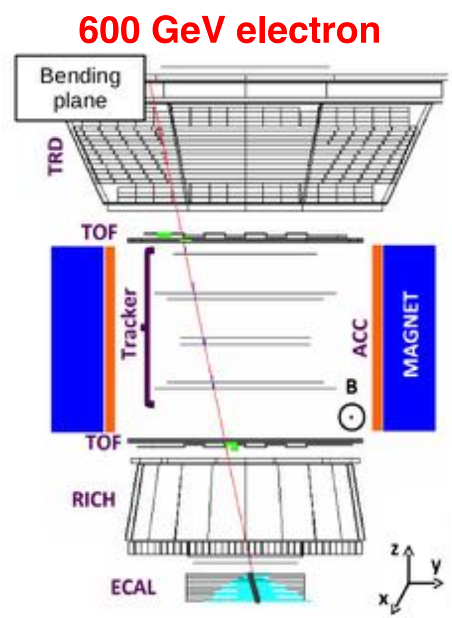
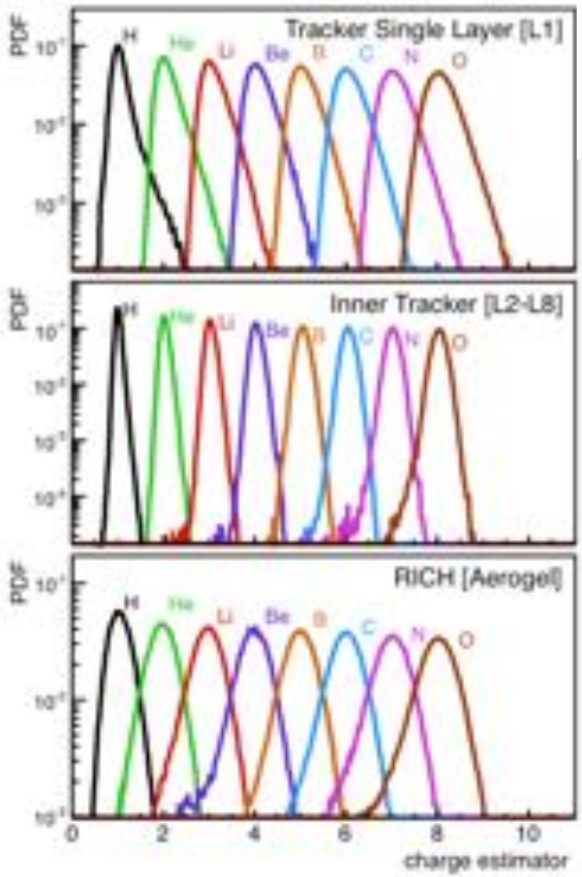
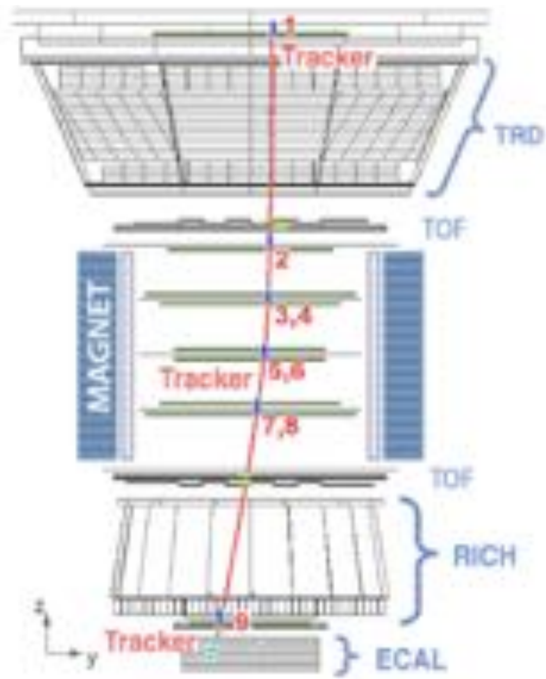


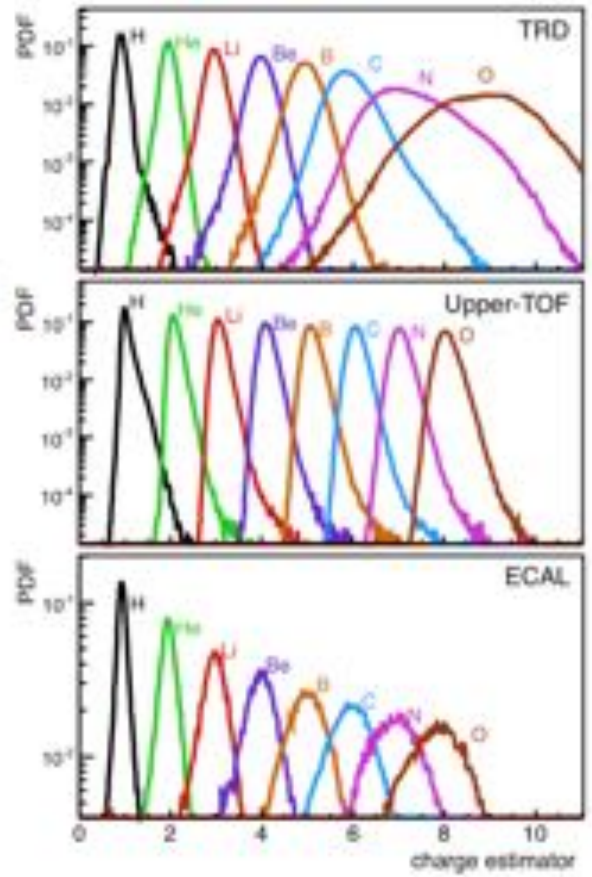
	e^+	e^-	p	$\bar{p}$	He	$\overline{He}$	
TRD 20 layers							e/p separation, charge (|Z|)
TOF 4 layers							trigger, velocity (β), charge (|Z|)
TRK 9 layers							momentum (p), sign (±Q), charge (|Z|)
RICH							velocity (β), charge (|Z|)
ECAL 18 layers							$e^\pm$ energy, e/h separation, γ trigger

AMS-02 Charge Measurement



Charge Measurements of Light CR Nuclei





Redundant measurements of the nuclear charge at different depths of the detector.

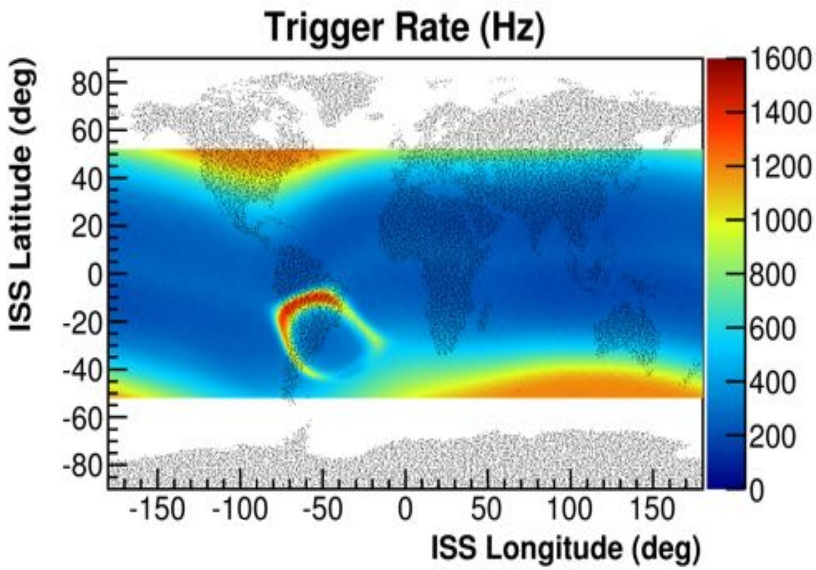
Precise understanding of nuclear fragmentation in the materials.

AMS orbit

ISS orbit period ~ 90min
+/- 50 deg latitude covered

DAQ operations depend on orbit position

Increase of trigger rate in polar region (low magnetic field and trapped particles) and in the South Atlantic Anomaly



Detector operated continuously around the clock since May 2011 with no major interruptions

Trigger

Each time a detector decides to save the information of a particle crossing, the electronics freezes the analog information on all the sensors (~300,000 for AMS), digitizes them and package them to send to ground. This procedure lasts O(100 μs – 1 ms).

The flux of cosmic rays through the detector volumes is typically higher than the digitization capabilities. Only a fraction of the total cosmic rays crossing the detector volumes has to be recorded (typically, particles crossing the interesting detector fiducial volume and above a certain energy threshold)

The **trigger** is a system that decides whether the instrument should freeze the analog information and save the **event**. It is based using information from fast detectors and combining it in a simple AND-OR logic.

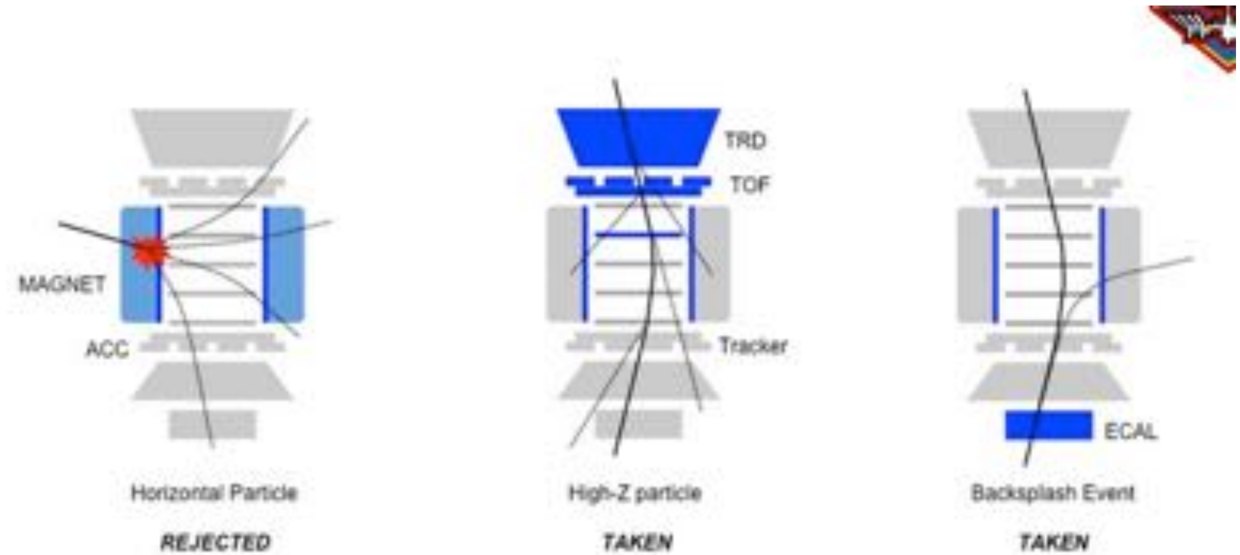
The trigger represent a very delicate system. If an interesting event is not triggered, it will be lost forever. Typically, the trigger selection it is a compromise between the maximum numberof events stored with respect to the capabilities of data storage and transfer and event pileup.

Trigger

AMS uses the fast information of the TOF the trigger charged particles, the external anticoincidence to veto cosmic rays outside the acceptance, and the fast ECAL information to trigger photons (that do not leave energy in the TOF)

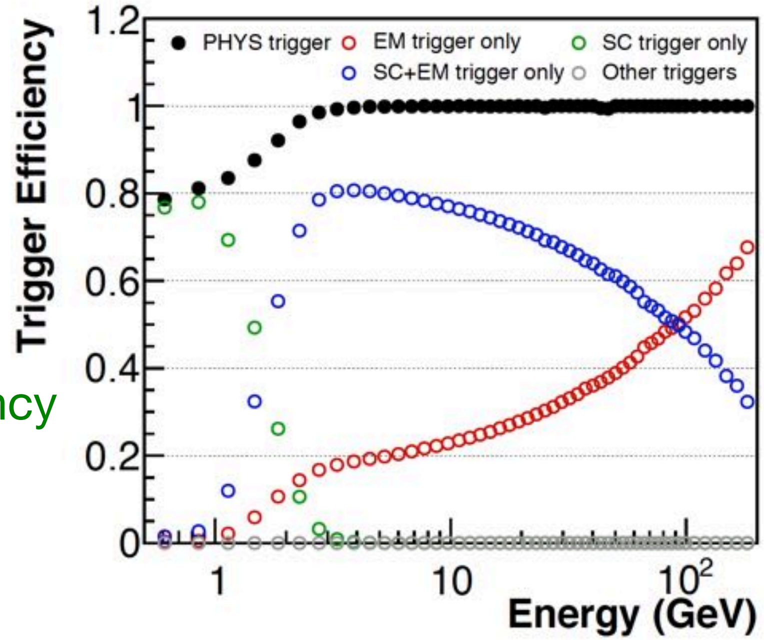
AMS-02 Triggers:

- Unbiased 3/4
- Charged Z=1
- Charged Ions
- “Slow” ions
- Electrons
- Photons
- Unbiased em



If any of these conditions is satisfied, the event is triggered

Example: electron trigger



TOTAL trigger efficiency

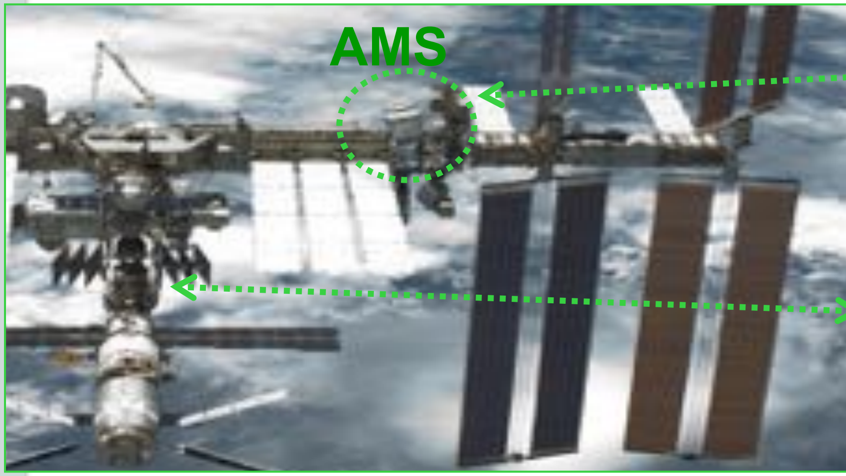
ECAL only efficiency

ECAL&TOF efficiency

TOF only efficiency

Below 3 GeV, efficiency<100% because the calorimeter energy deposit is not above the threshold

Data transfer



Ku-Band
High Rate (down):
Events <10Mbit/s>
≈30 billion triggers
70 TB of raw data

Flight Operations

Ground Operations

S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN

AMS Computers at MSFC, AL

White Sands Ground Terminal, NM

AMS physics results

LEPTONS / ANTIMATTER

- Positrons fraction $e^+/(e^+ + e^-)$
- Electron and Positron fluxes (e^+, e^-)
- Electron plus Positron flux ($e^+ + e^-$)
- Antiprotons/protons

Sensitive to Dark Matter signal

HADRONS

- Proton and Helium (p, He)
- Lithium, Boron, Carbon (Li, B, C)

Probes to improve the astrophysical background knowledge

AMS-02 is providing precise data to search for new physics in the Cosmic Ray channels while improving the understanding of the astrophysical background with a coherent set of data

AMS physics results

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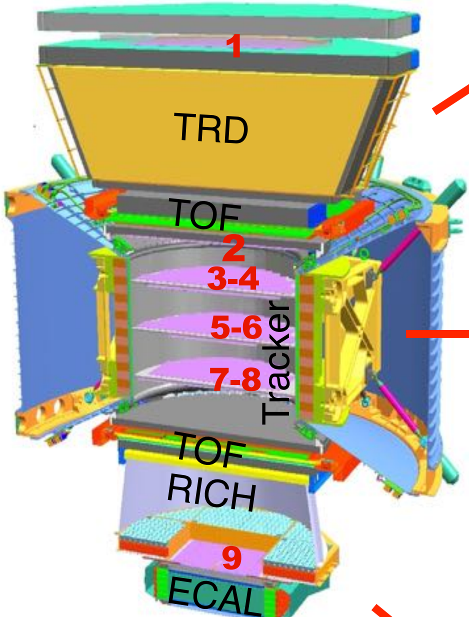
Probes to improve the astrophysical background knowledge

AMS-02 is providing precise data to search for new physics in the Cosmic Ray channels while improving the understanding of the astrophysical background with a coherent set of data

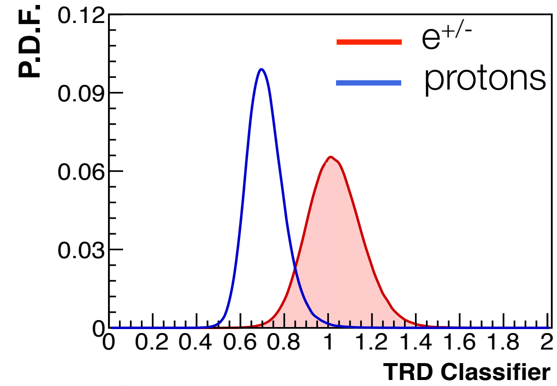
Identification of $e^{+/-}$



TRD

Transition Radiation

to identify $e^{+/-}$

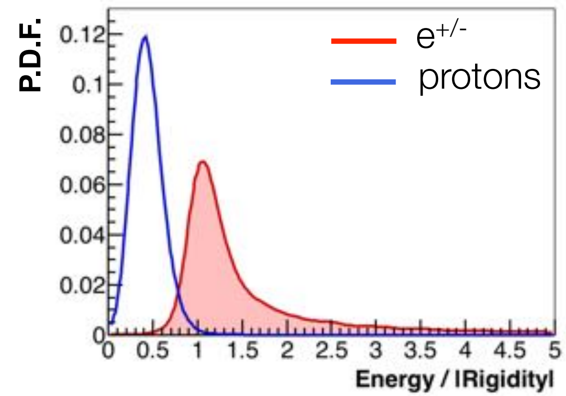


TRACKER

Momentum P

$e^{+/-}$: $P_{TRK} = E_{ECAL}$

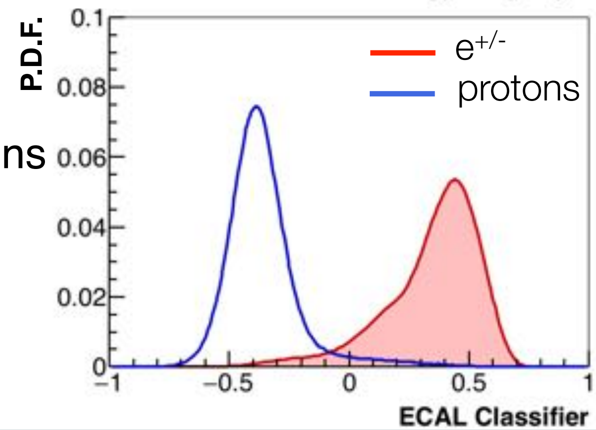
Protons: $P_{TRK} >> E_{ECAL}$



ECAL

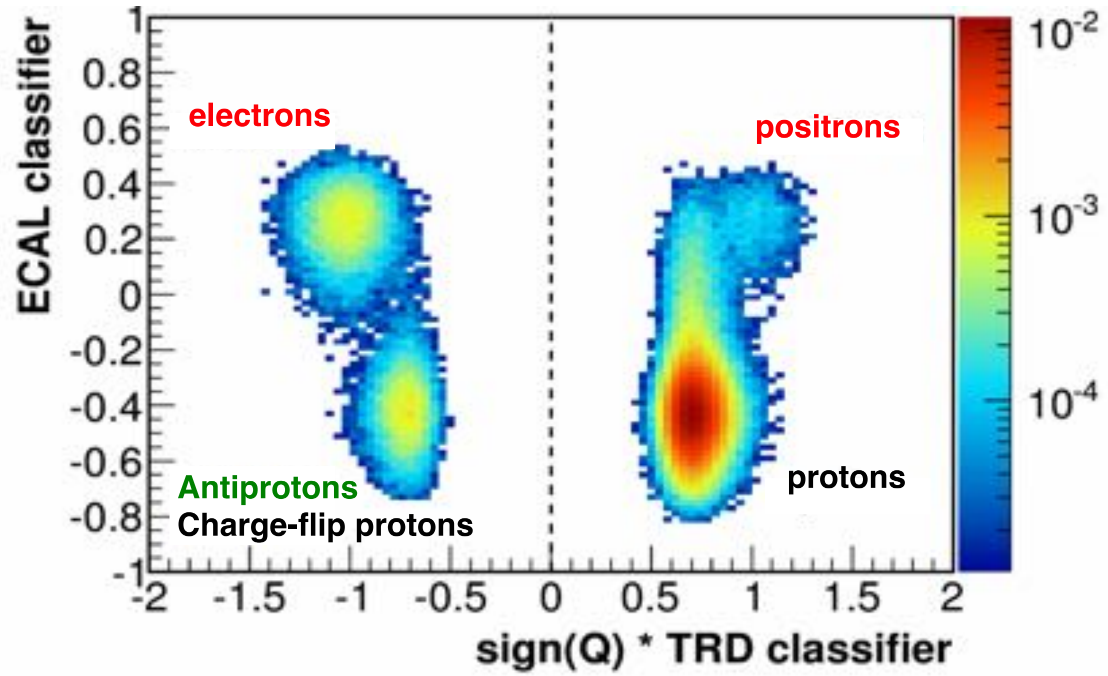
Shower Topology

to separate $e^{+/-}$ from protons



Identification of $e^{+/-}$

The whole ECAL and TRD subdetector information is gathered in the so called "classifier" 1-D variables, trained to reject protons.

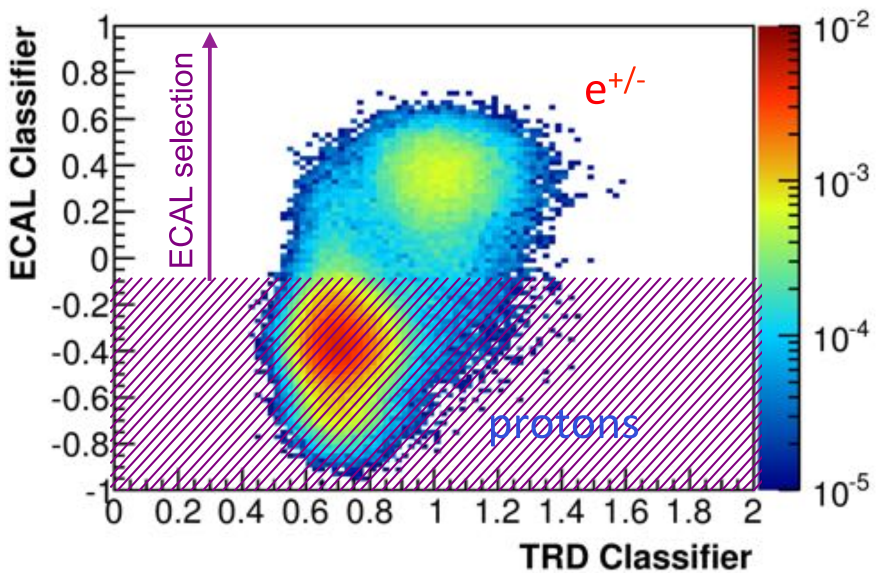


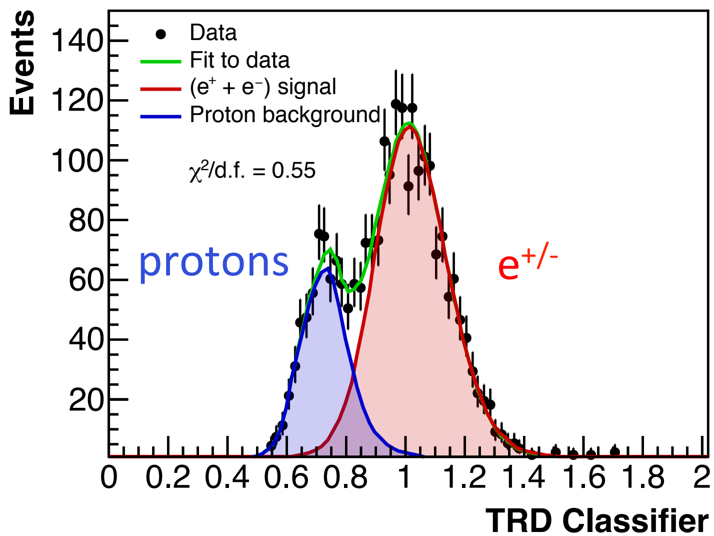
ECAL and TRD, separated by the magnet, efficiently and independently discriminate the signal ($e^{+/-}$) from the background (protons)

Identification of $(e^+ + e^-)$

TRD Classifier template fit

Reference spectra for the signal and the background are fitted to data as a function of the TRD classifier for different cuts on the ECAL BDT estimator

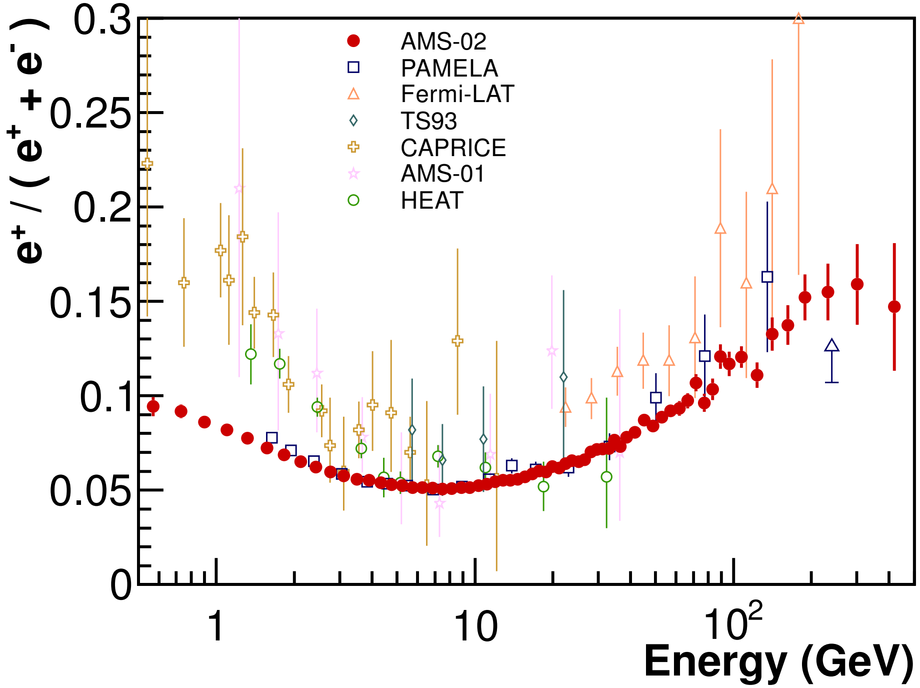


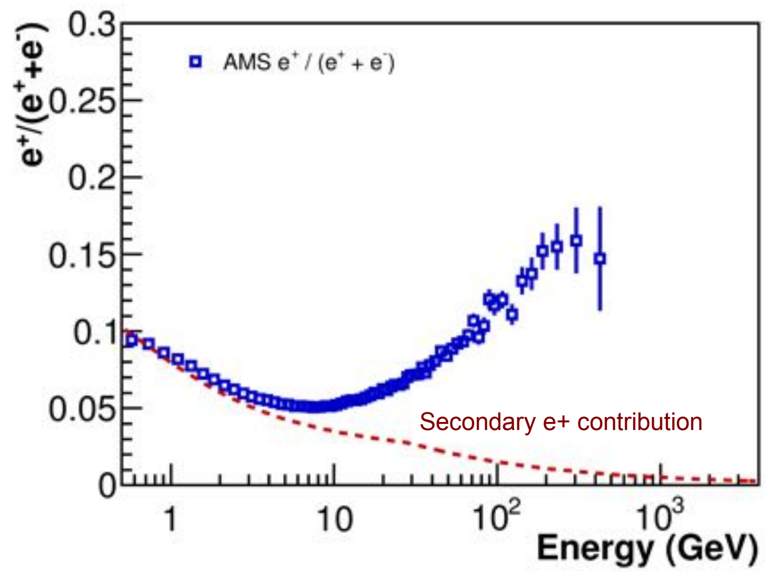


1. ECAL efficiently removes the majority of background protons
2. TRD independently evaluates the tiny remaining protons in the selected $e^{+/-}$ sample

Positron Fraction

Rise in the fraction of positrons (antimatter) over electrons (matter) not expected by the current Standard Model of CR origin and propagation

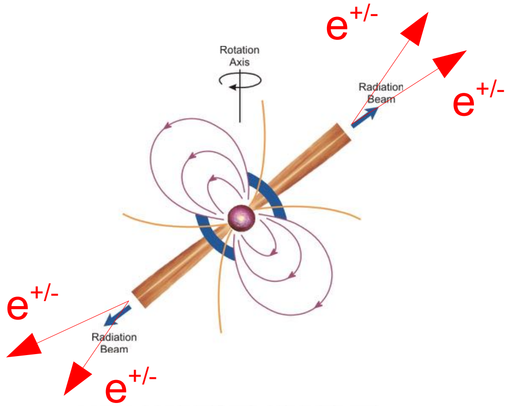


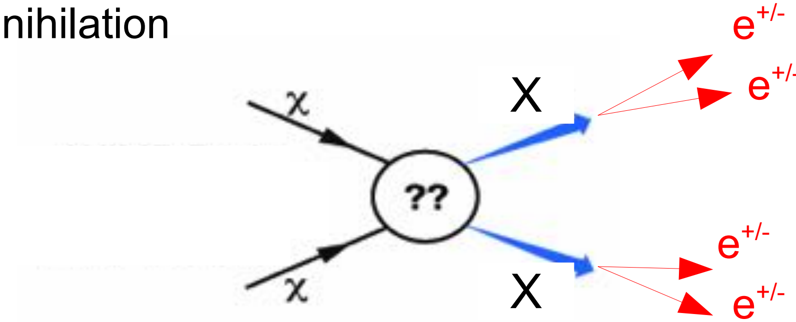


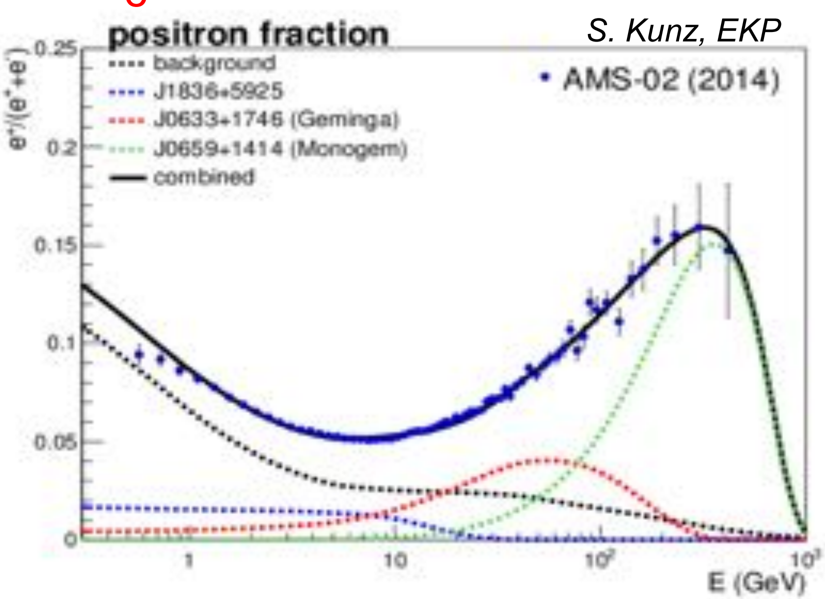
Unprecedented accuracy and energy range allowed a detailed study of the positron fraction behavior with energy

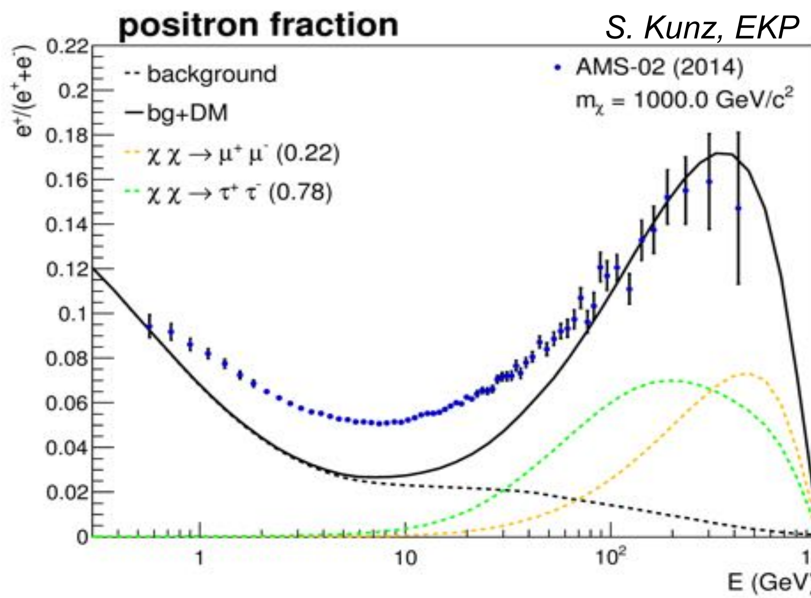
Positron Fraction

- PULSARS
- Dark Matter annihilation



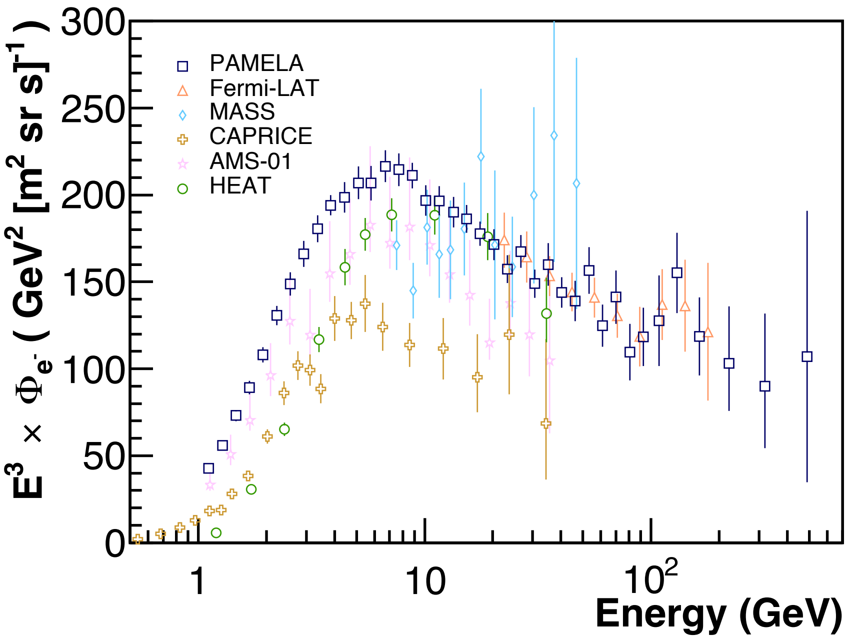


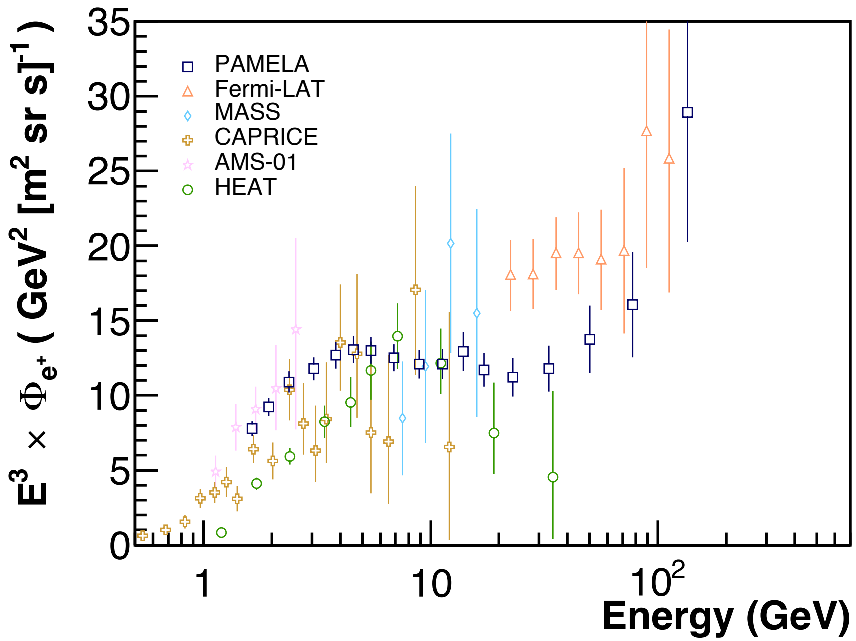




- Both mechanisms can be tuned to explain the data.
- The measurement of the spectral shape alone cannot disentangle between the two sources......

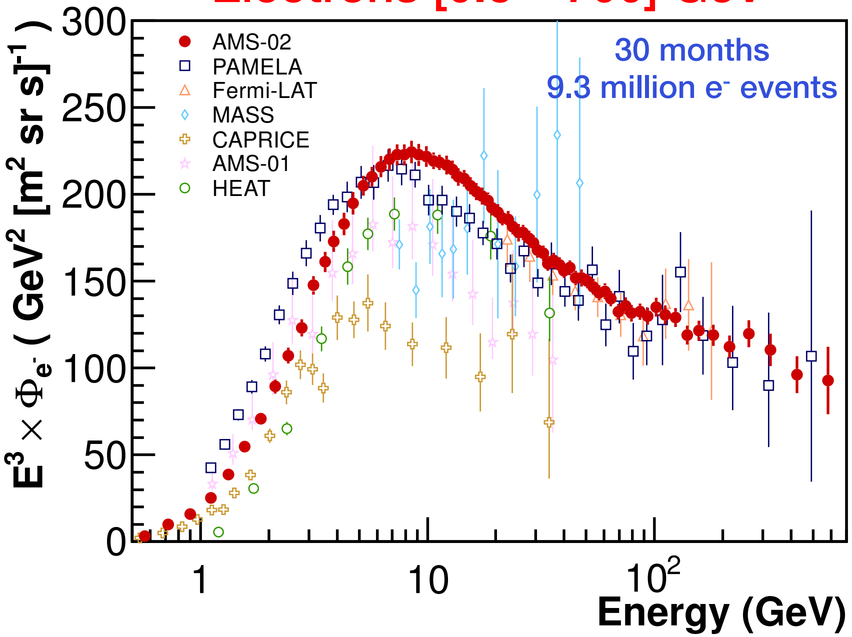
e^+ and e^- Fluxes



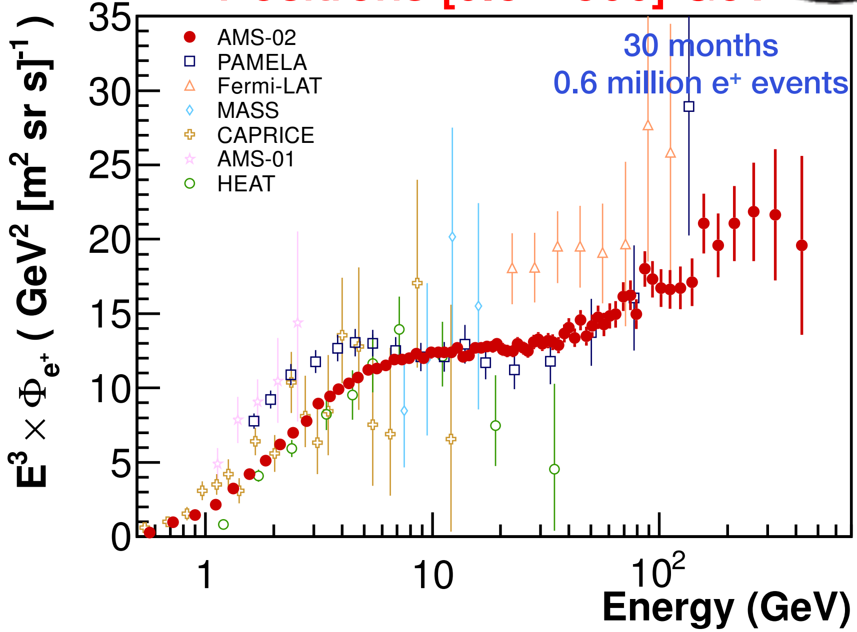


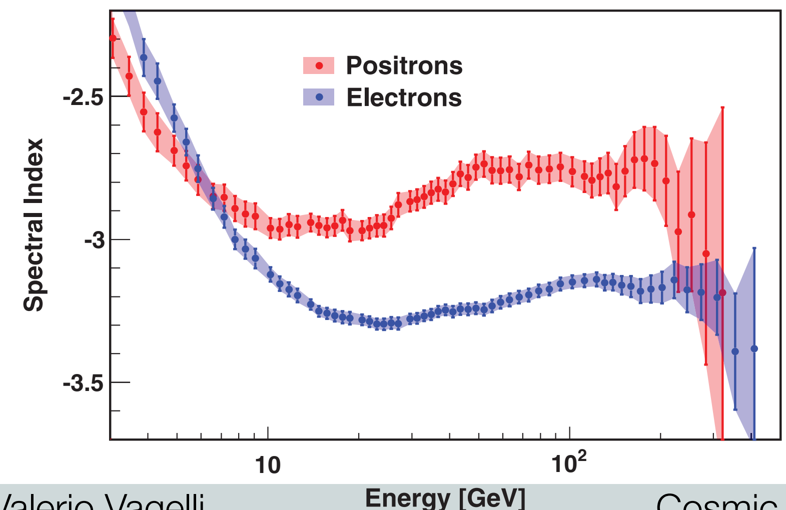
e^+ and e^- Fluxes

Electrons [0.5 – 700] GeV



Positrons [0.5 – 500] GeV



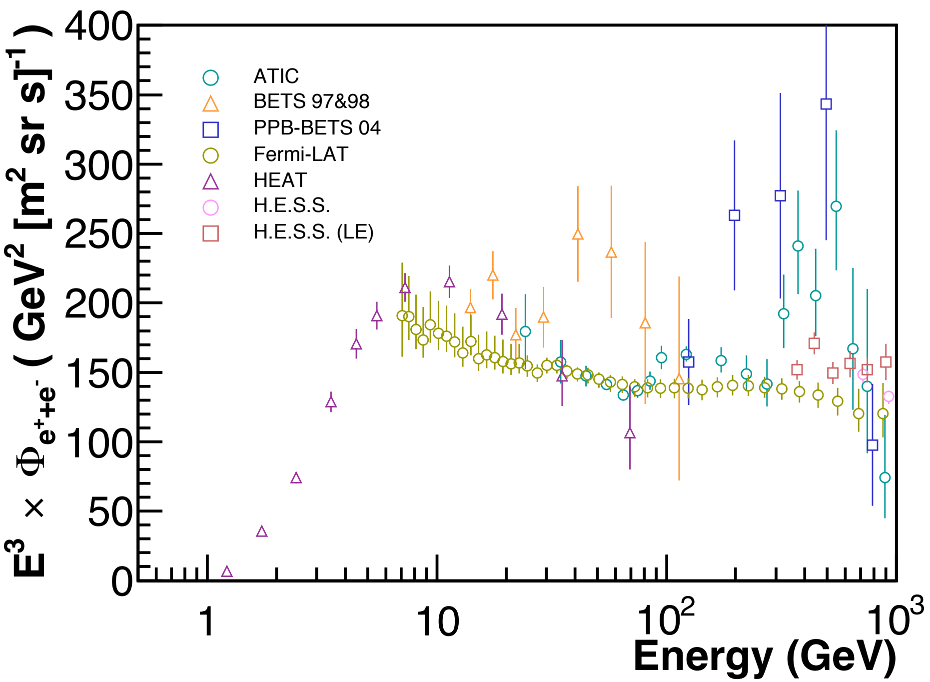


e^+ and e^- flux are significantly different in their magnitude and energy dependence

The positron fraction rise is due to an **excess of positrons**, not due to a unpredicted decrease of electrons.

$(e^+ + e^-)$ Flux

Independent measurement of the total $e^{+/-}$ flux without identification of the charge sign.
Higher energy reach and improved accuracy due to looser selection.

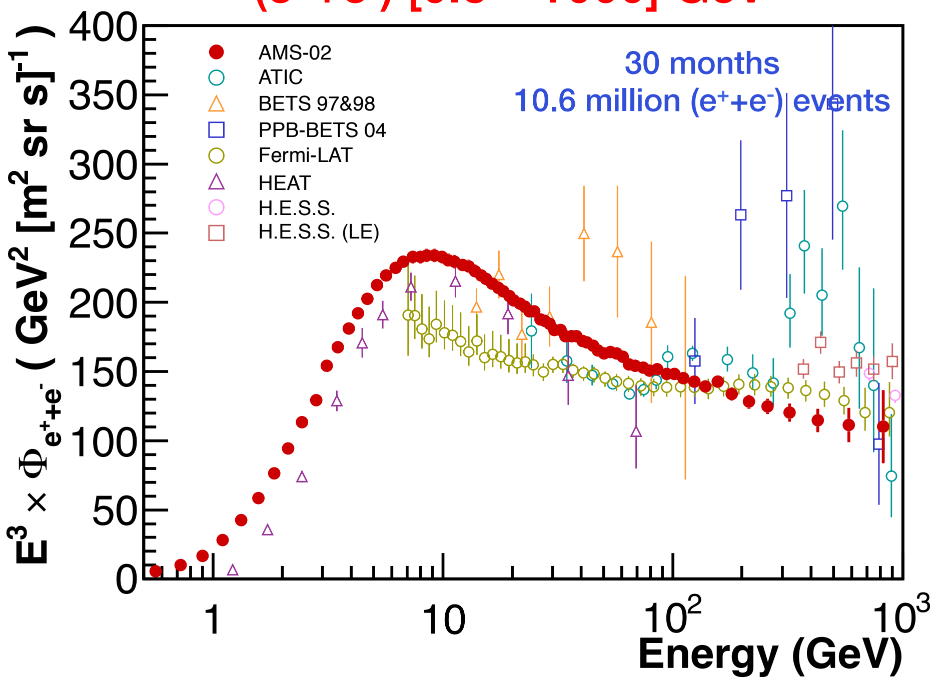


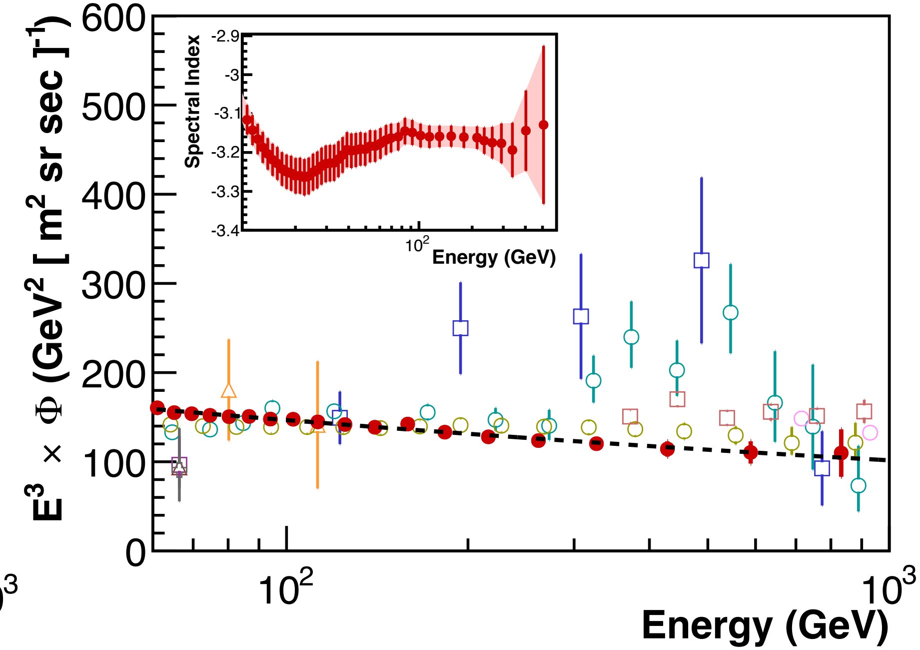
$(e^{+}+e^{-})$ Flux

Independent measurement of the total $e^{+/-}$ flux without identification of the charge sign.

Higher energy reach and improved accuracy due to looser selection.

$(e^{+}+e^{-})$ [0.5 – 1000] GeV

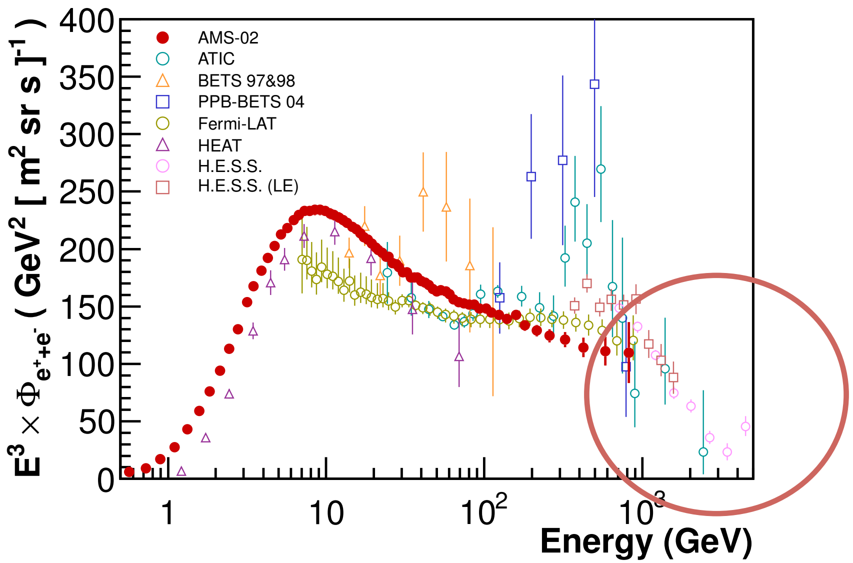




The $(e^{+}+e^{-})$ flux is smooth, and can be described by a single power law starting from 30 GeV up to 1 TeV.

No evidence of fine structures has been observed in the $(e^{+}+e^{-})$ spectrum.

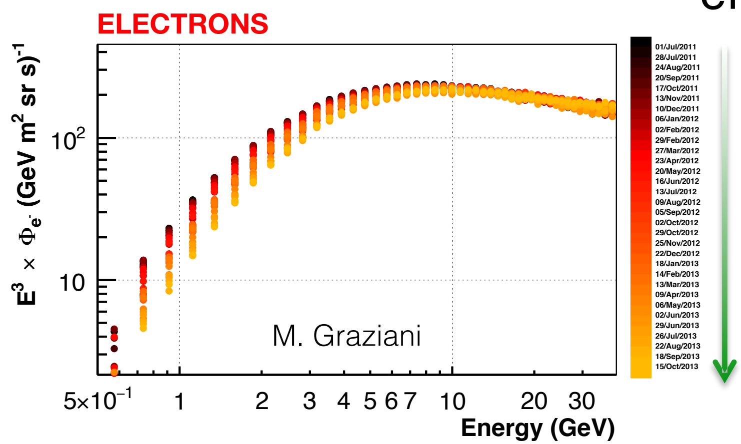
What's next…..

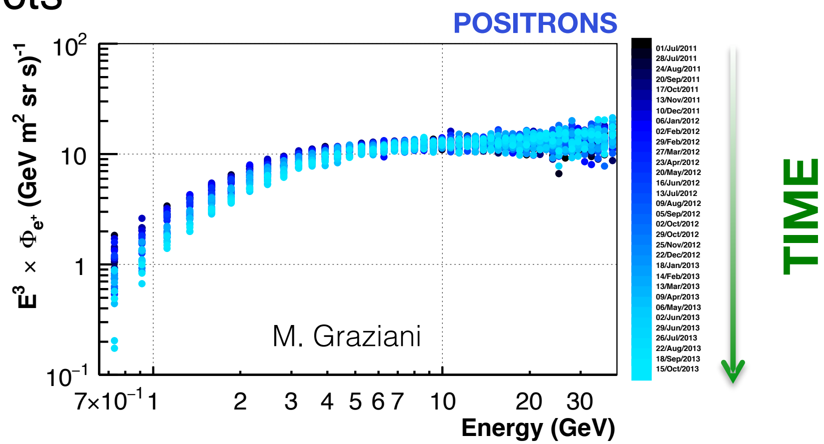


Explore the TeV energy range

- Overlap with ground experiments
- Search for spectral features

Explore the GeV range to study for Solar time dependent modulation and transient effects





What is AMS observing?

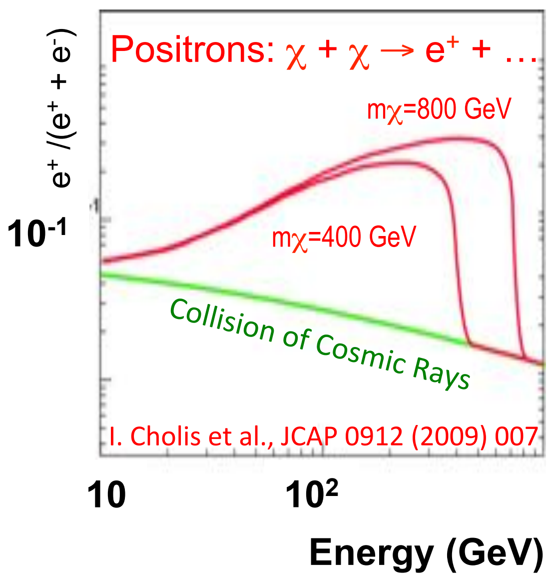
Something “different” with respect to conventional models of e^+ production by collisions of CR hadrons with the interstellar medium (ISM)

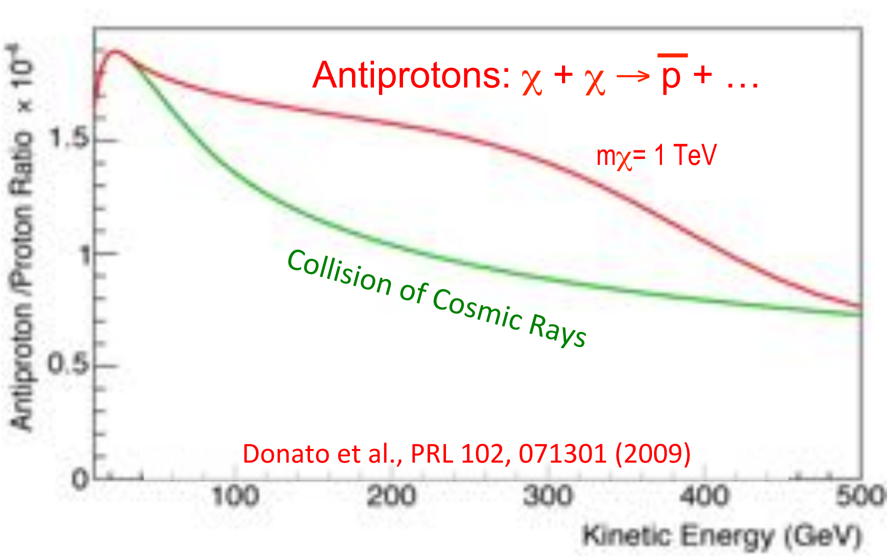
Astrophysical Sources?

- Local sources as pulsars ($e^{+/-}$ only source, anisotropy..)
- Additional acceleration mechanisms (reacceleration of CR hadrons in old SNRs)

Dark matter?

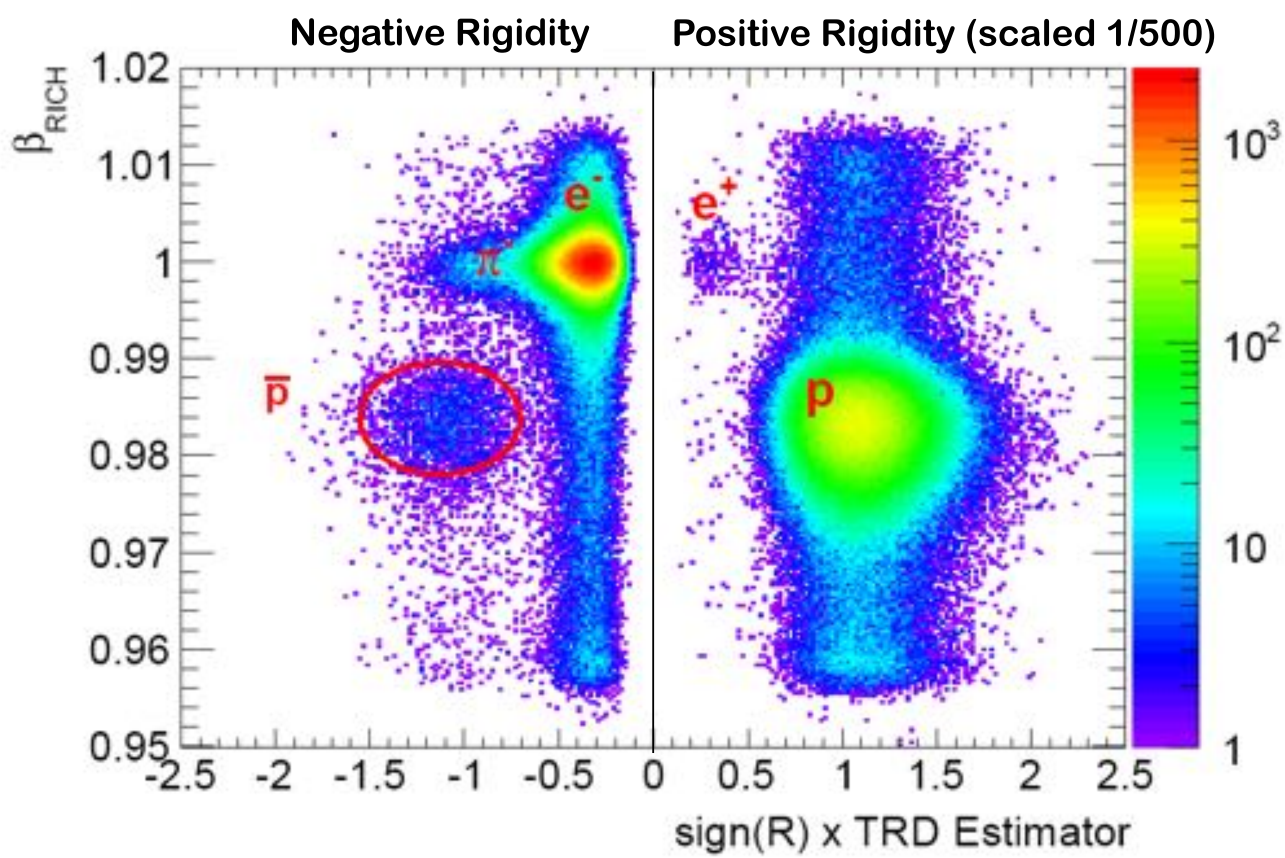
- Isotropic distribution arrival for $e^{+/-}$
- Signatures in other channels (like antiprotons)





Antiprotons

The low energies

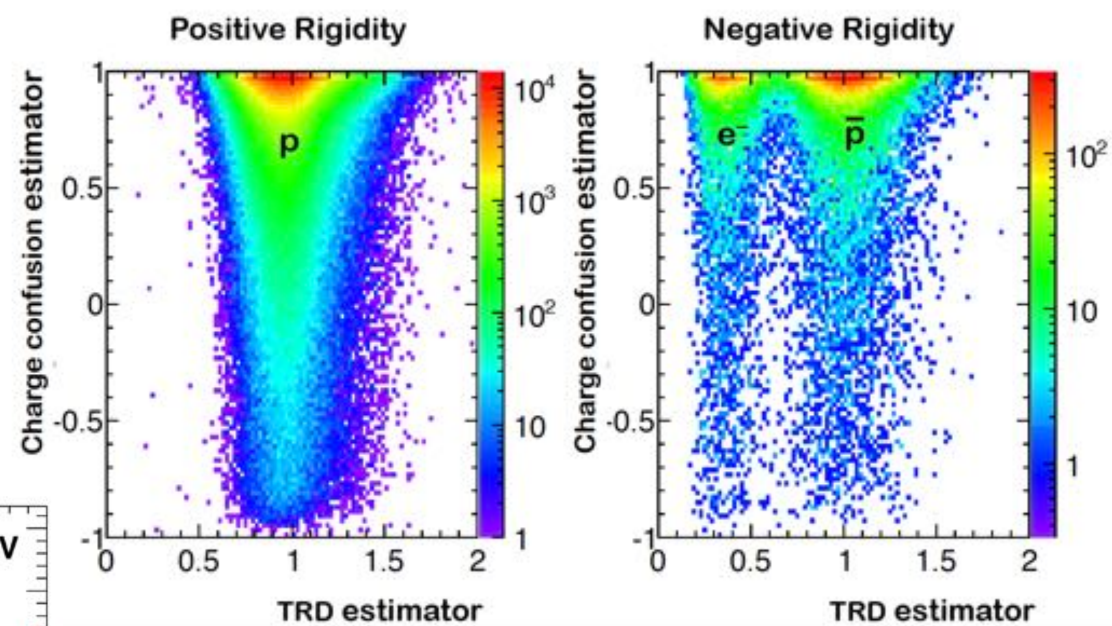


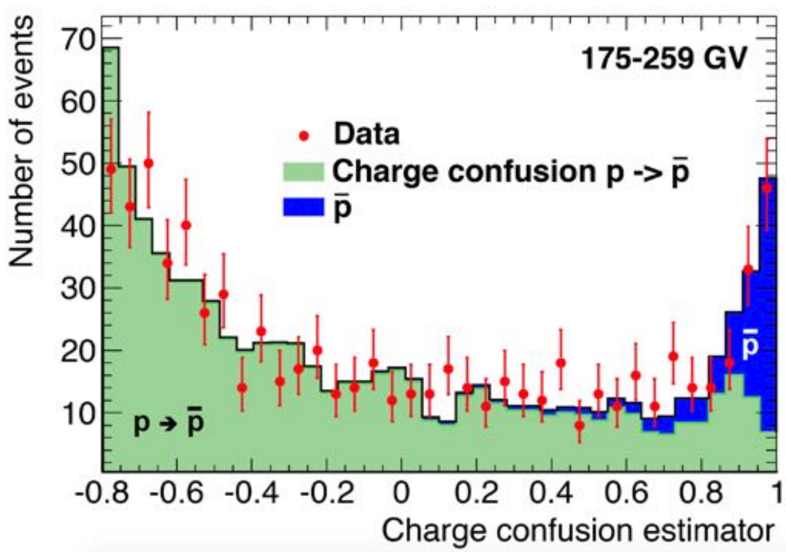
Below 10 GV, the RICH and TRD efficiently separate antiprotons from $e^{+/-}$ and local pions produced by interactions of CRs with the detector material

Antiprotons

Anti-p are 10^4 less abundant than p. Charge sign flip is the dominating systematic

- TRD discriminates e^- / anti-p
- The negative "anti-p" sample is dominated by charge-flip protons

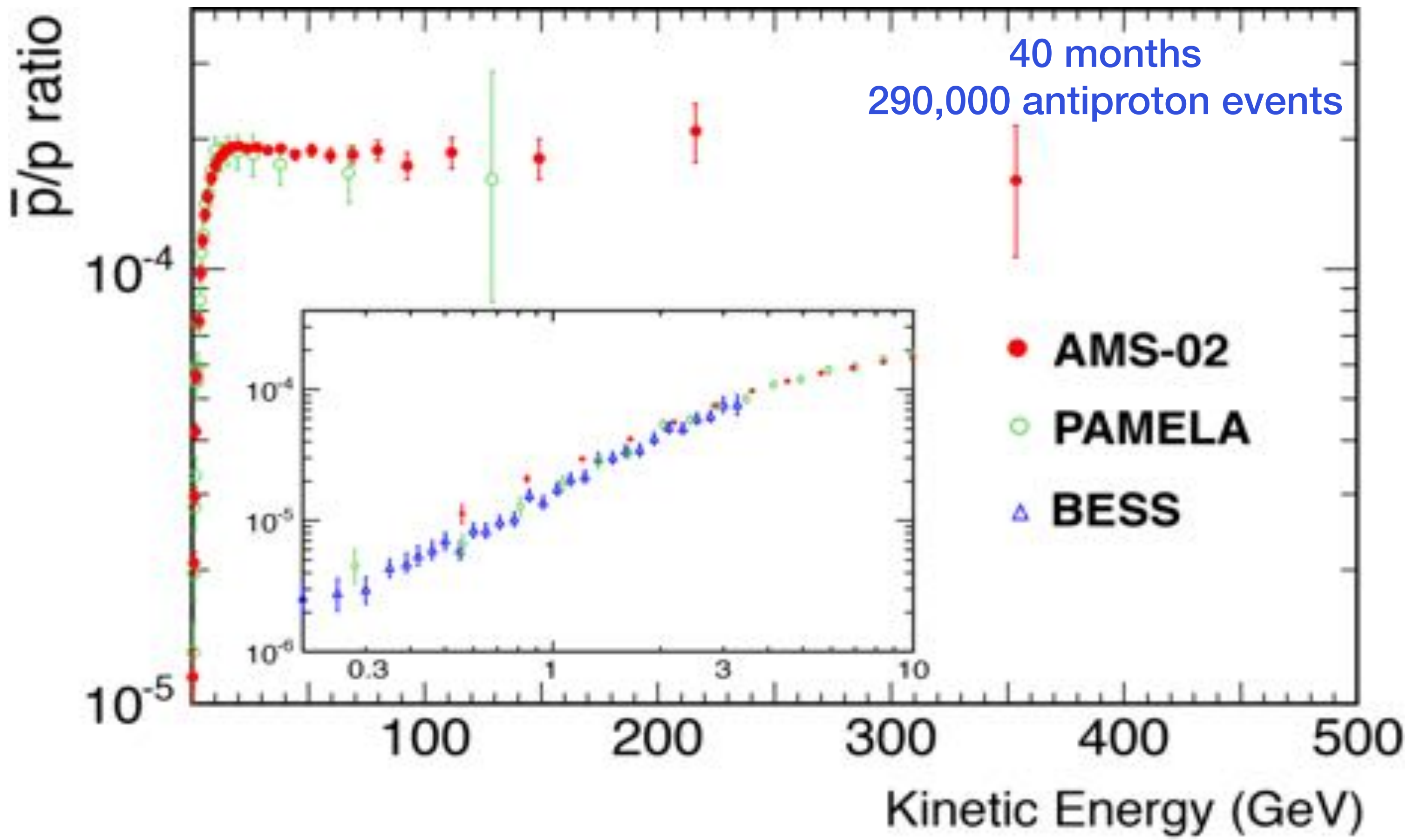




Reference spectra of charge-flip protons and genuine anti-p have been fit to data to estimate the background in the selected "negative-charge" sample

Antiprotons

p̄/p ratio [1 – 450] GeV

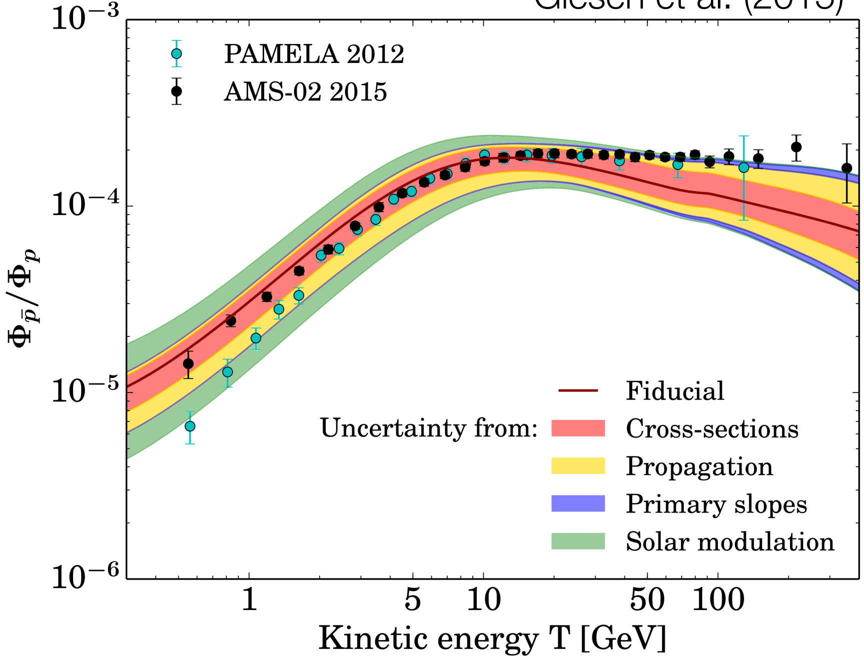


The antiproton ratio does not decrease at high energies. Could this be a hint of Dark Matter annihilation?

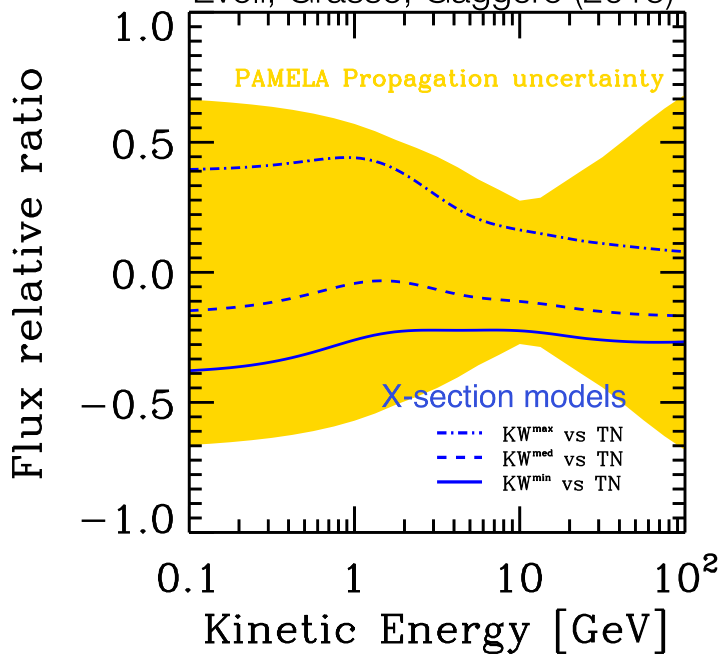
Antiprotons

The accuracy of the AMS measurement challenges the current knowledge of cosmic background

Giesen et al. (2015)



Evoli, Grasso, Gaggero (2015)



Evoli, Grasso, Gaggero (2015)

Upcoming measurements (in particular, from AMS-02 [1], CALET [54], and ISS-CREAM [49]) are expected to significantly improve our knowledge of propagation parameters and then to reduce the associated uncertainties. In that situation, antiproton production cross sections will prevent us to provide predictions for the astrophysical backgrounds as accurate as the forecasted sensitivities.

AMS physics results

LEPTONS / ANTIMATTER

- Positrons fraction $e^+/(e^++e^-)$
- Electron and Positron fluxes (e^+, e^-)
- Electron plus Positron flux (e^++e^-)
- Antiprotons/protons

Sensitive to
Dark Matter signal

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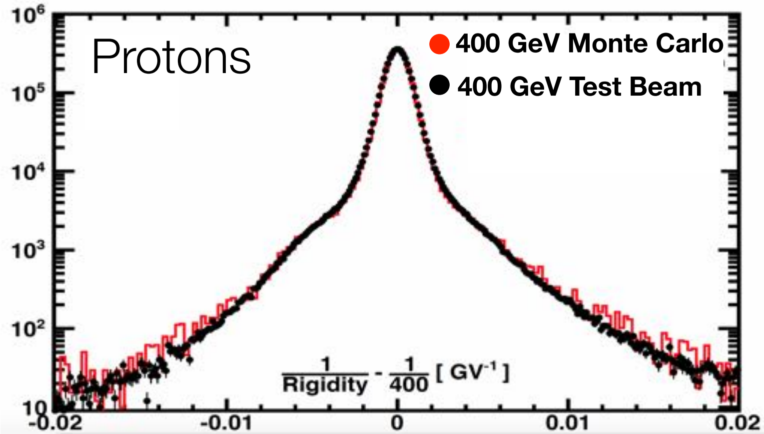
Probes to improve
the astrophysical background
knowledge

AMS-02 is providing precise data to search for new physics in the Cosmic Ray channels while improving the understanding of the astrophysical background with a coherent set of data

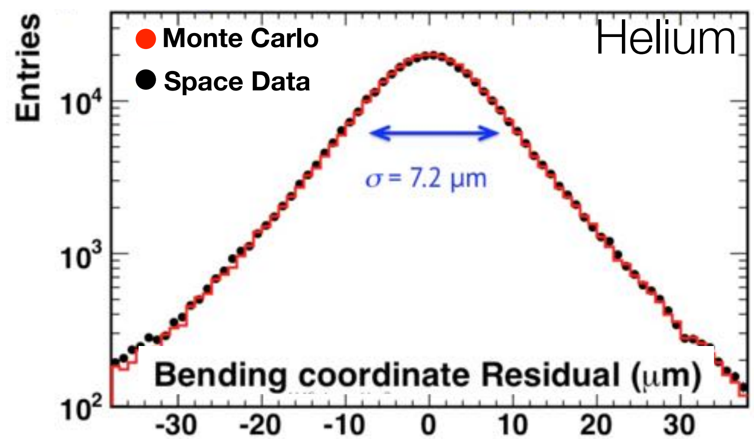
Proton and Helium Fluxes

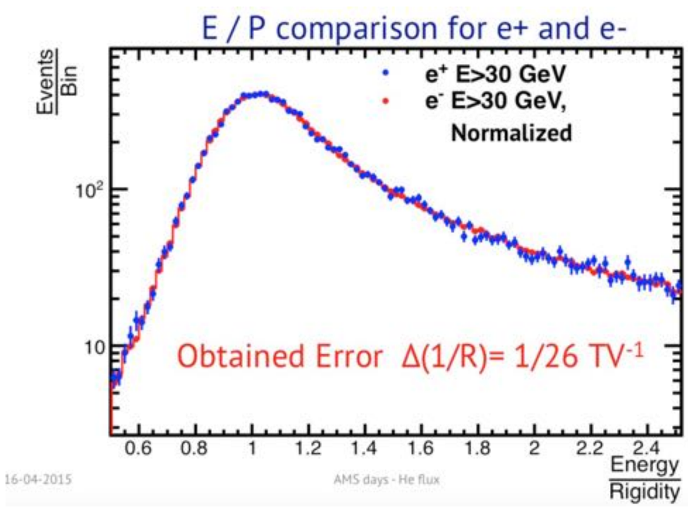
The AMS-02 Tracker Rigidity resolution has been checked comparing Test Beam data and Monte Carlo Simulations to Space data.

Resolution Function



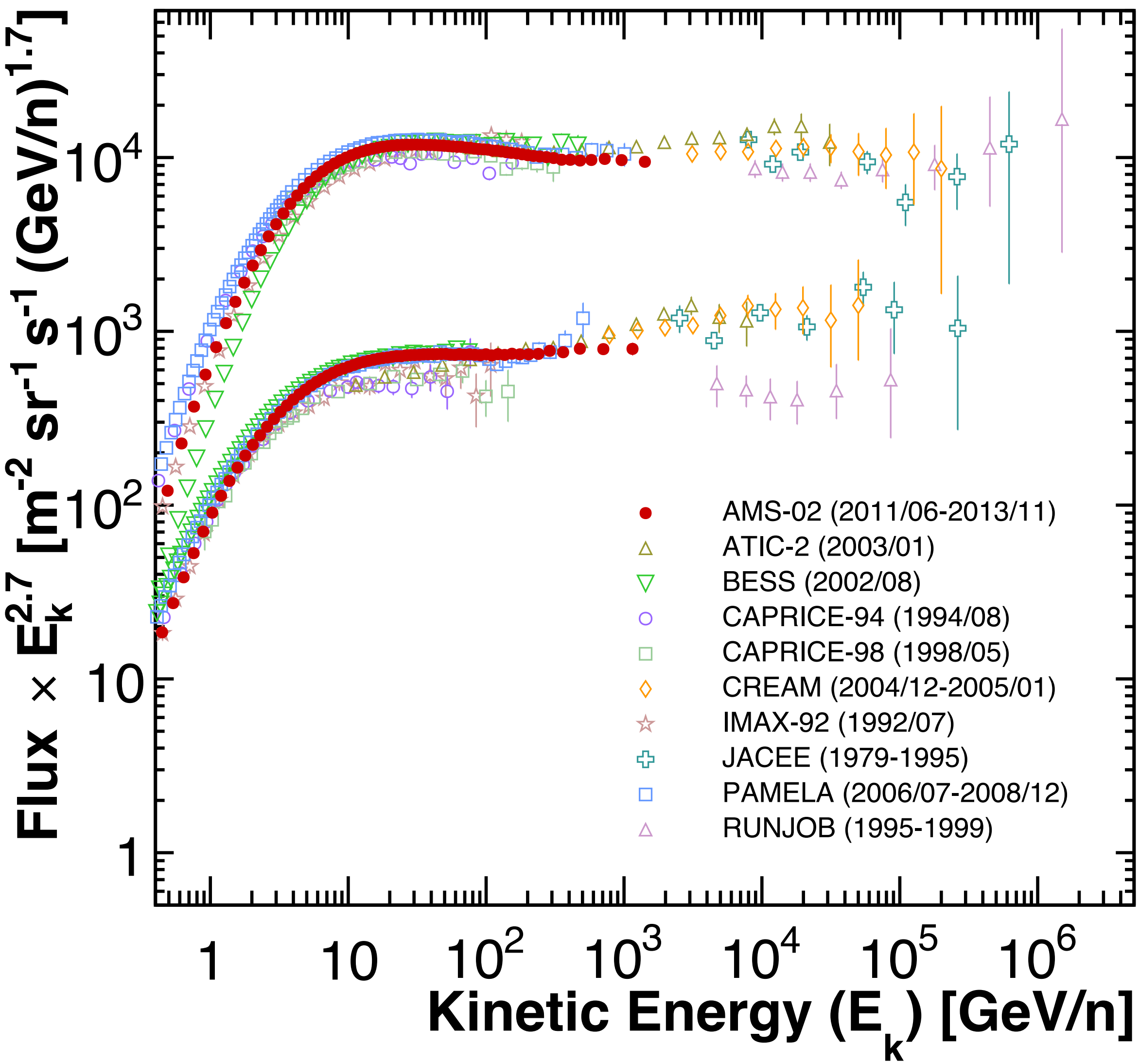
Coordinate resolution





The redundant measurement of the $e^{+/-}$ energy with the ECAL is used to further control the Tracker rigidity scale

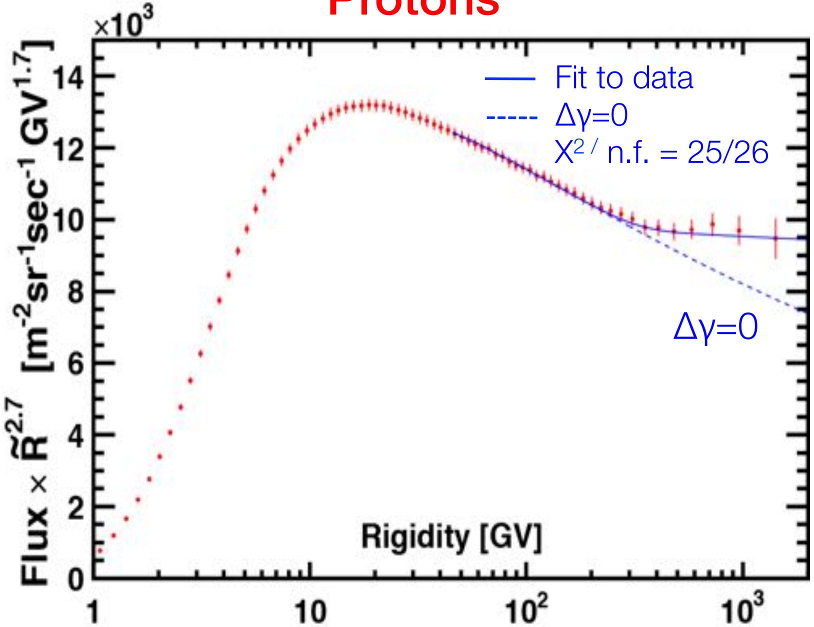
Proton and Helium Fluxes



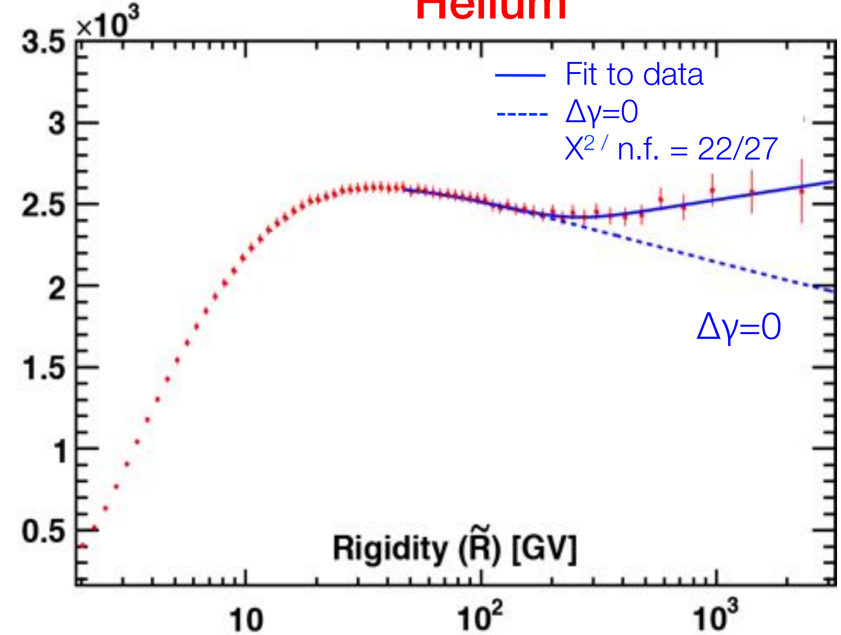
Proton and Helium Fluxes

$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

Protons



Helium

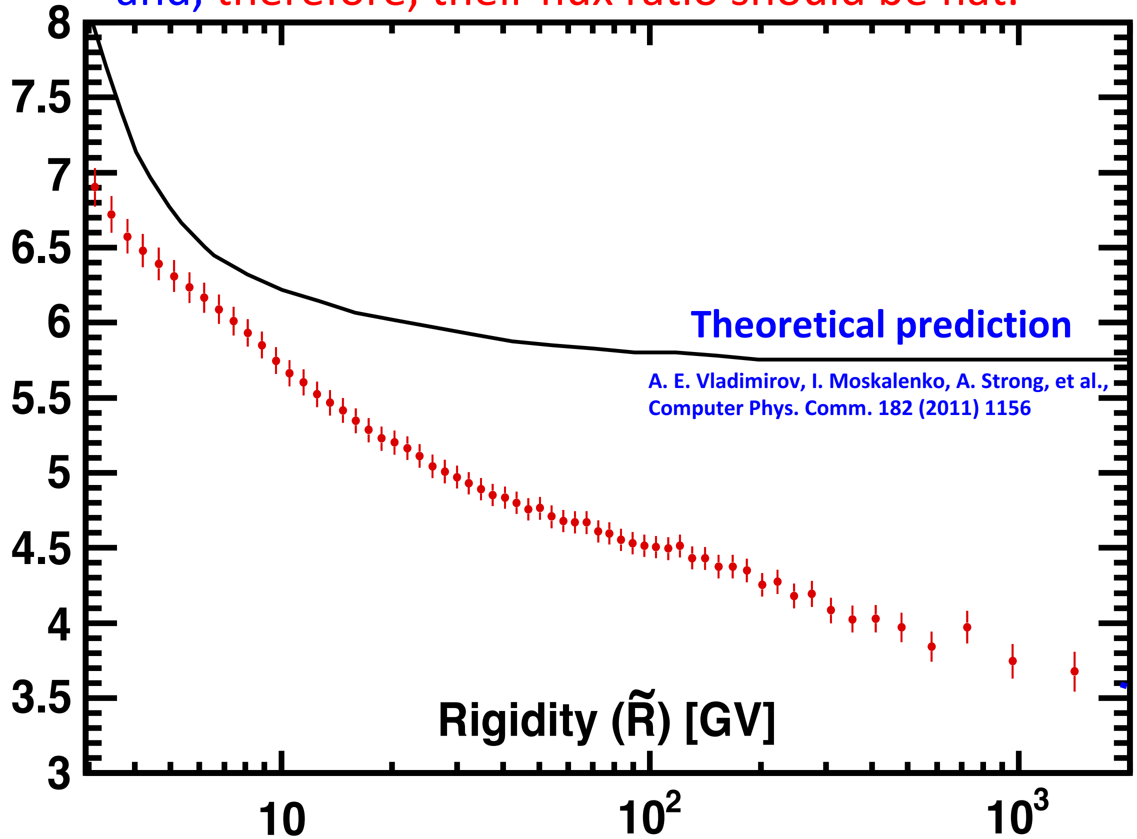


The H and He spectra harden with increasing rigidity

Both fluxes cannot be described by single power laws (traditional assumption).
A break in the power law at R~300 GV is required to describe the data.

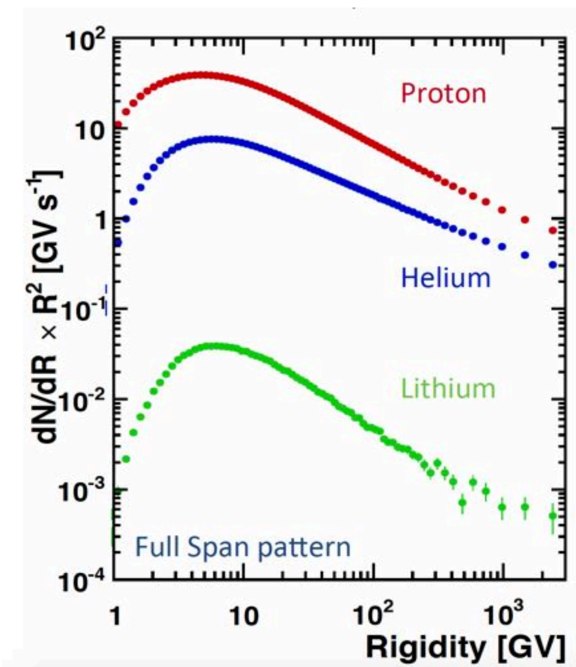
Proton and Helium Fluxes

Protons and helium are both “primary” cosmic rays.
Traditionally, they are assumed to be produced in the same sources and, therefore, their flux ratio should be flat.

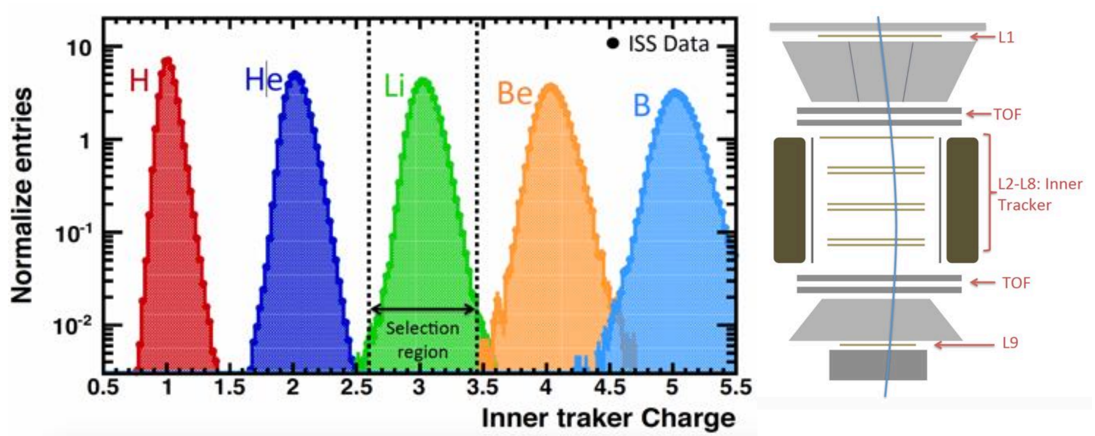


The H/He spectrum shows an unexpected energy dependence.
This may hint to unpredicted phenomena in the primary CR propagation or acceleration

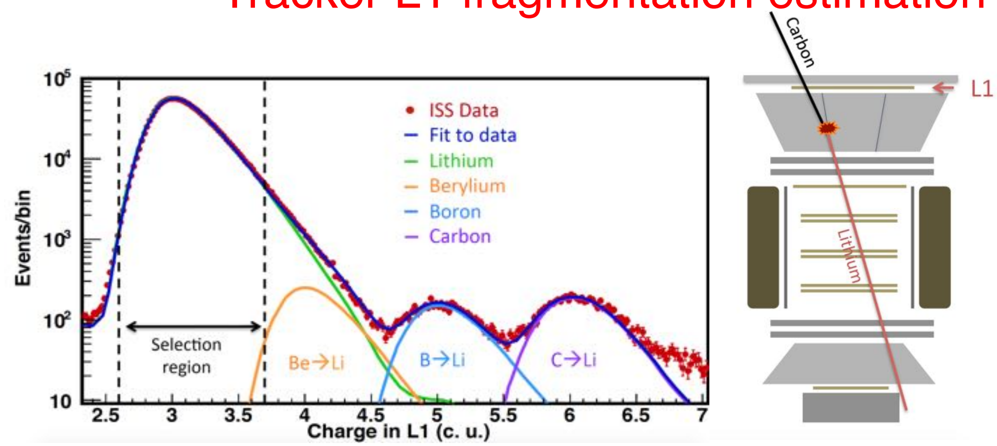
Lithium



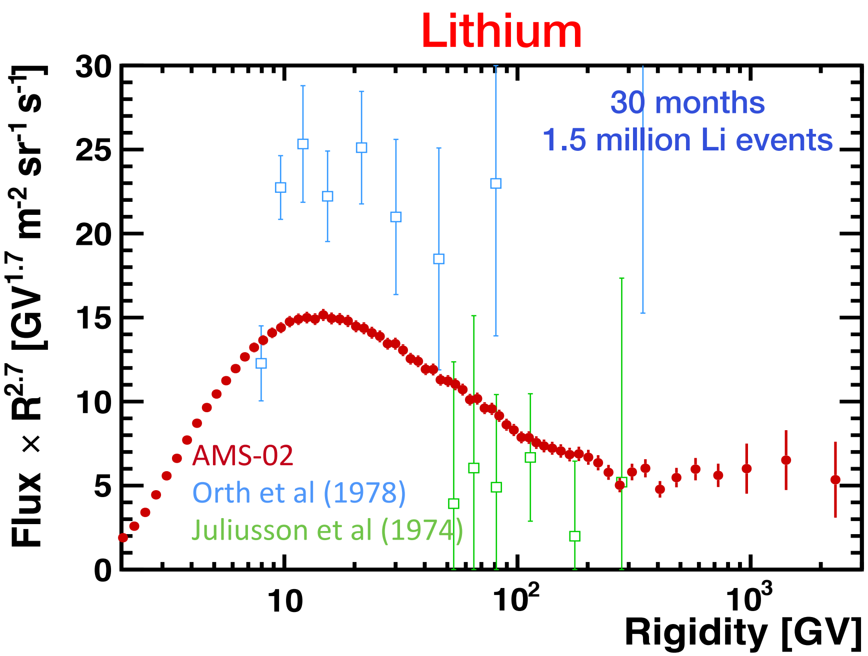
Inner Tracker IZI selection



Tracker L1 fragmentation estimation

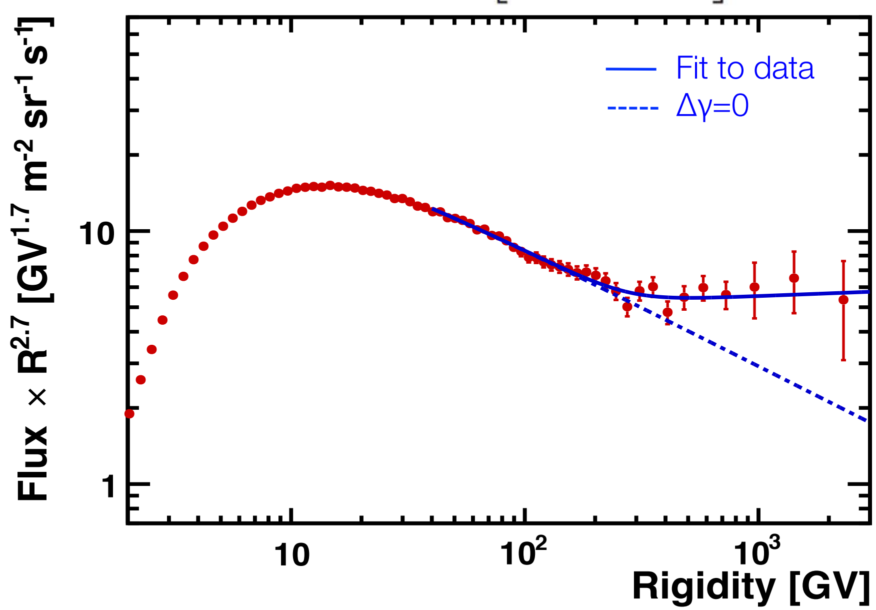


Lithium Flux

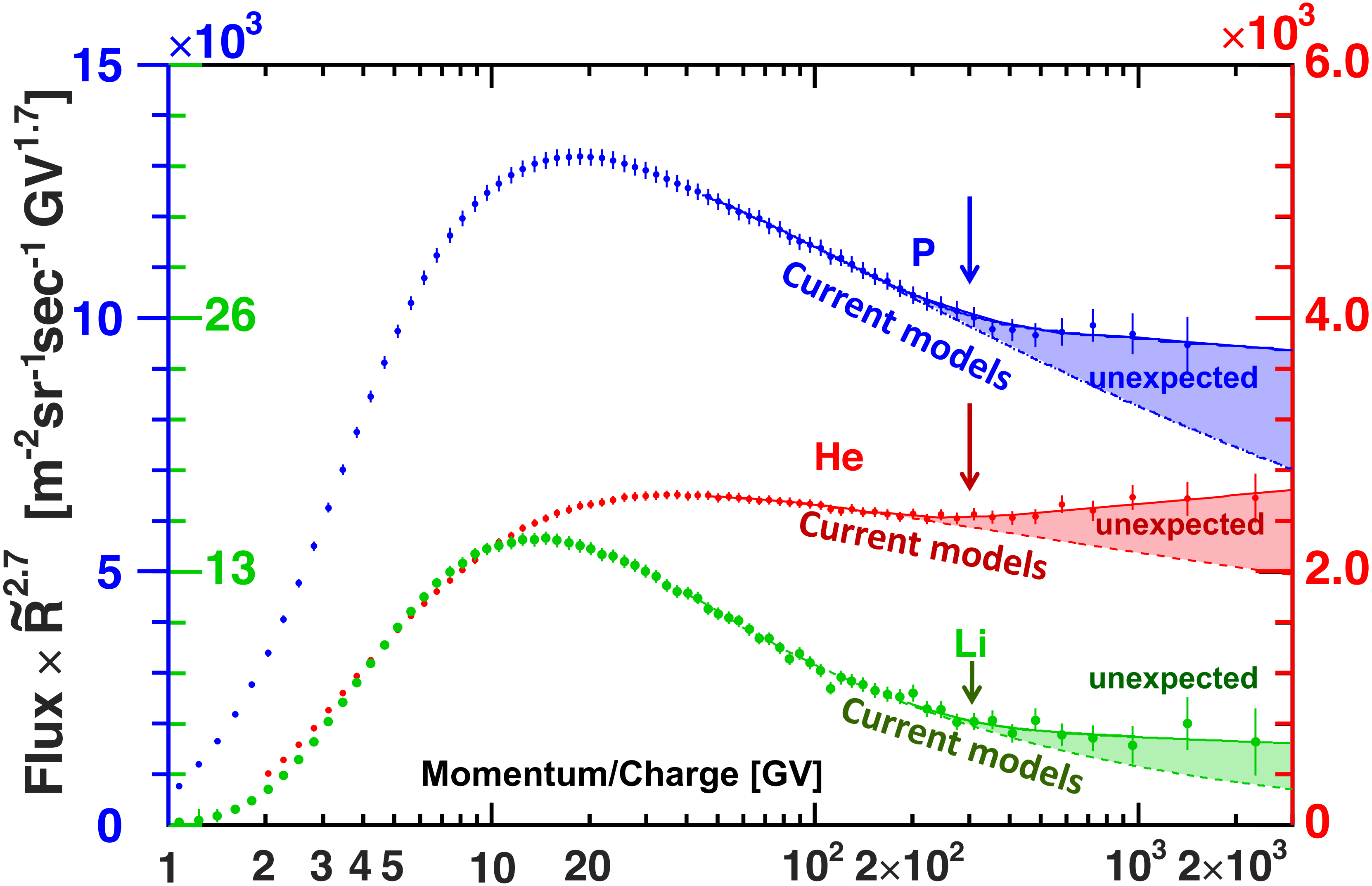


The large size of the collected statistics and the charge identification capabilities of AMS allow to measure the Li flux with unprecedented precision.

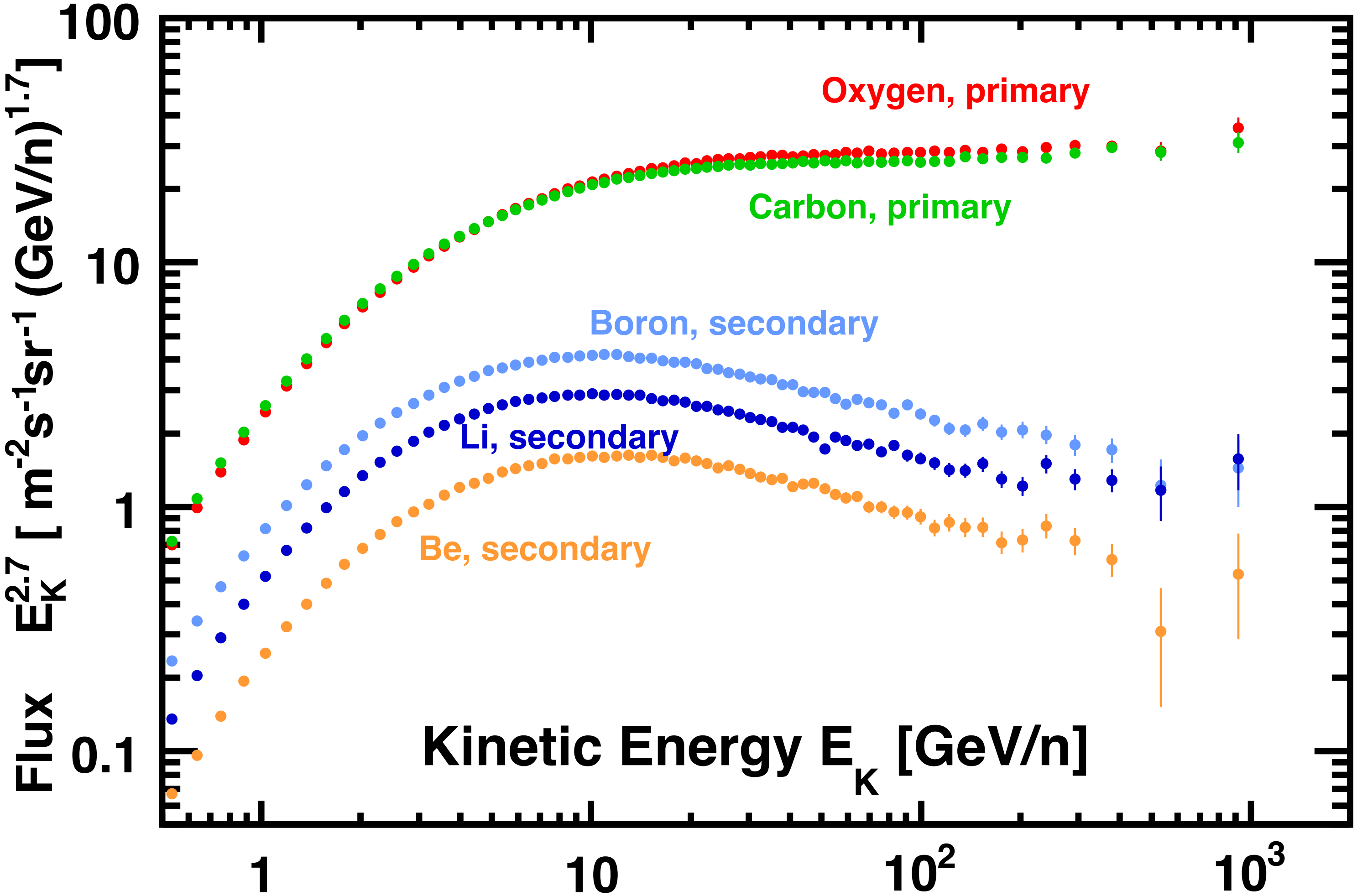
$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$



Light Nuclei



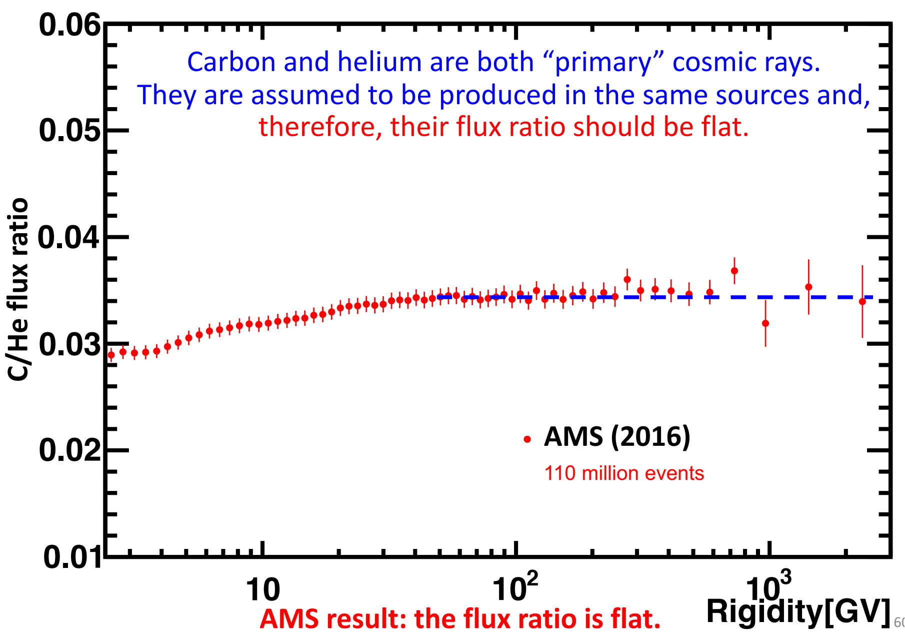
Heavier Nuclei



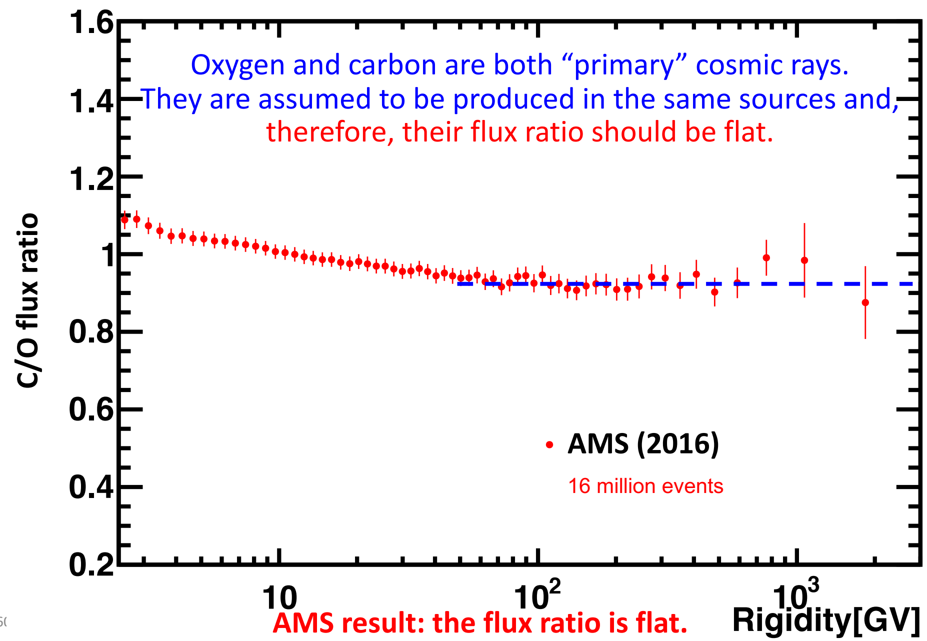
Primary and secondary cosmic rays have characteristically different rigidity dependencies

Heavier Nuclei

Carbon / Helium

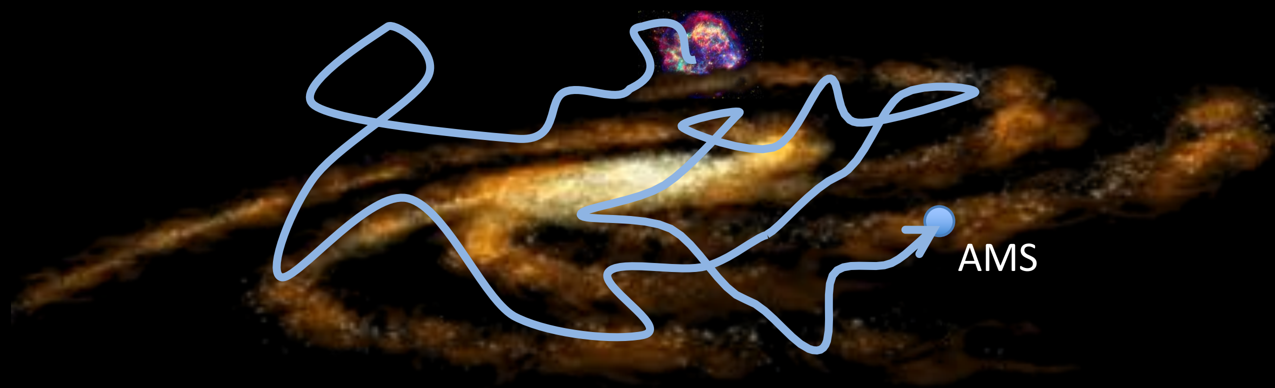


Carbon / Oxygen



Current acceleration and propagation model well explain the relative rigidity spectra of <u>primary</u> cosmic rays for CNO elements and for He, but not for protons

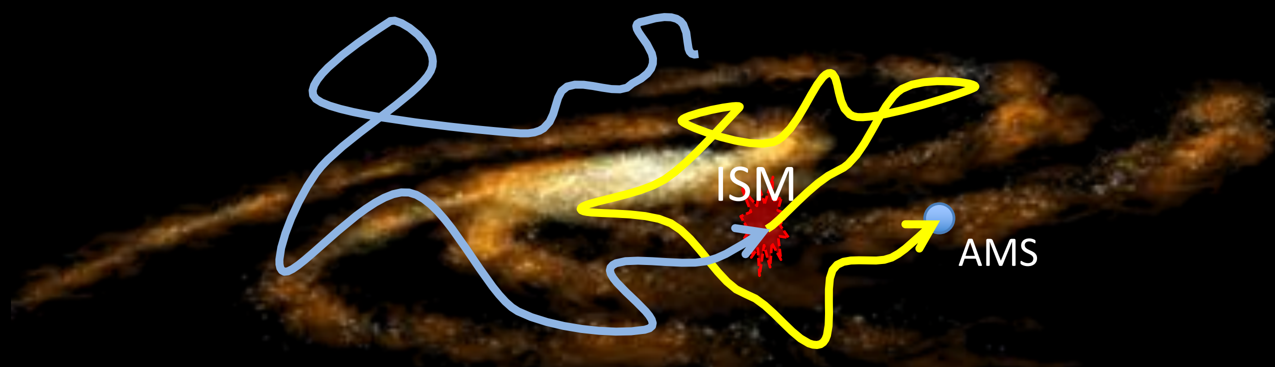
Primary Cosmic Rays (p, He, C, O, …)



Primary cosmic rays carry information about their original spectra and propagation.

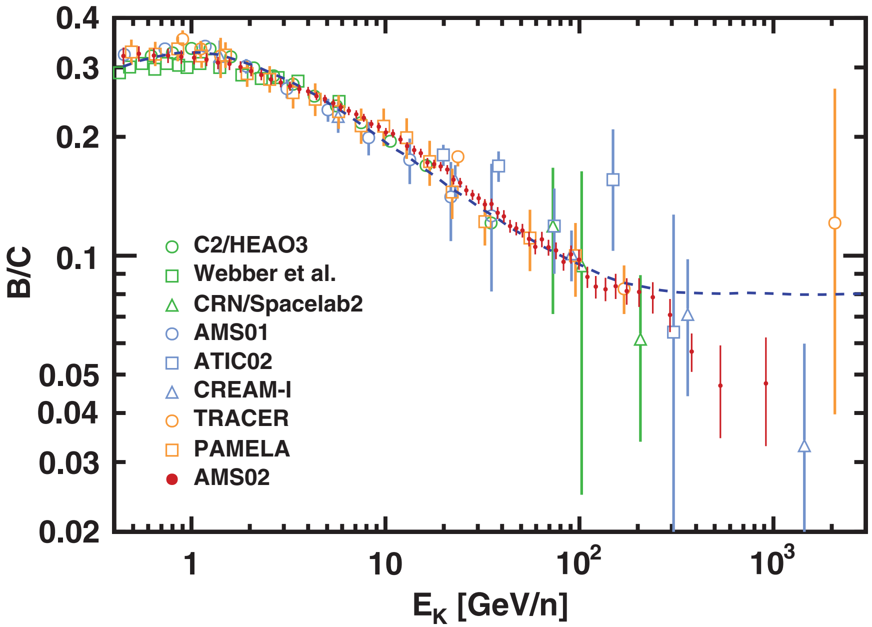
Secondary Cosmic Rays (Li, Be, B, …)

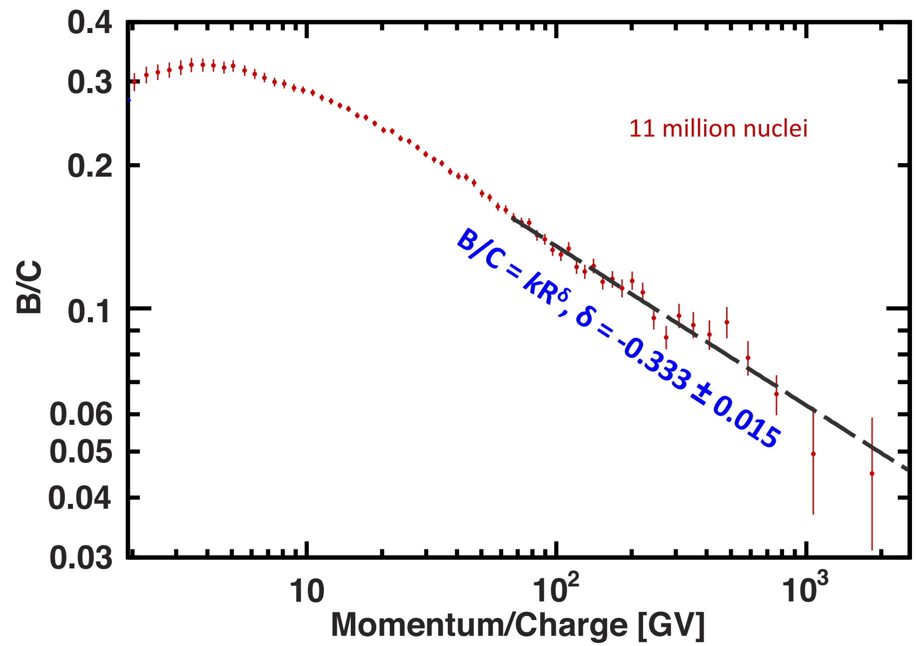
C, O, …, Fe + ISM → Li, Be, B + X



Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

Heavier Nuclei

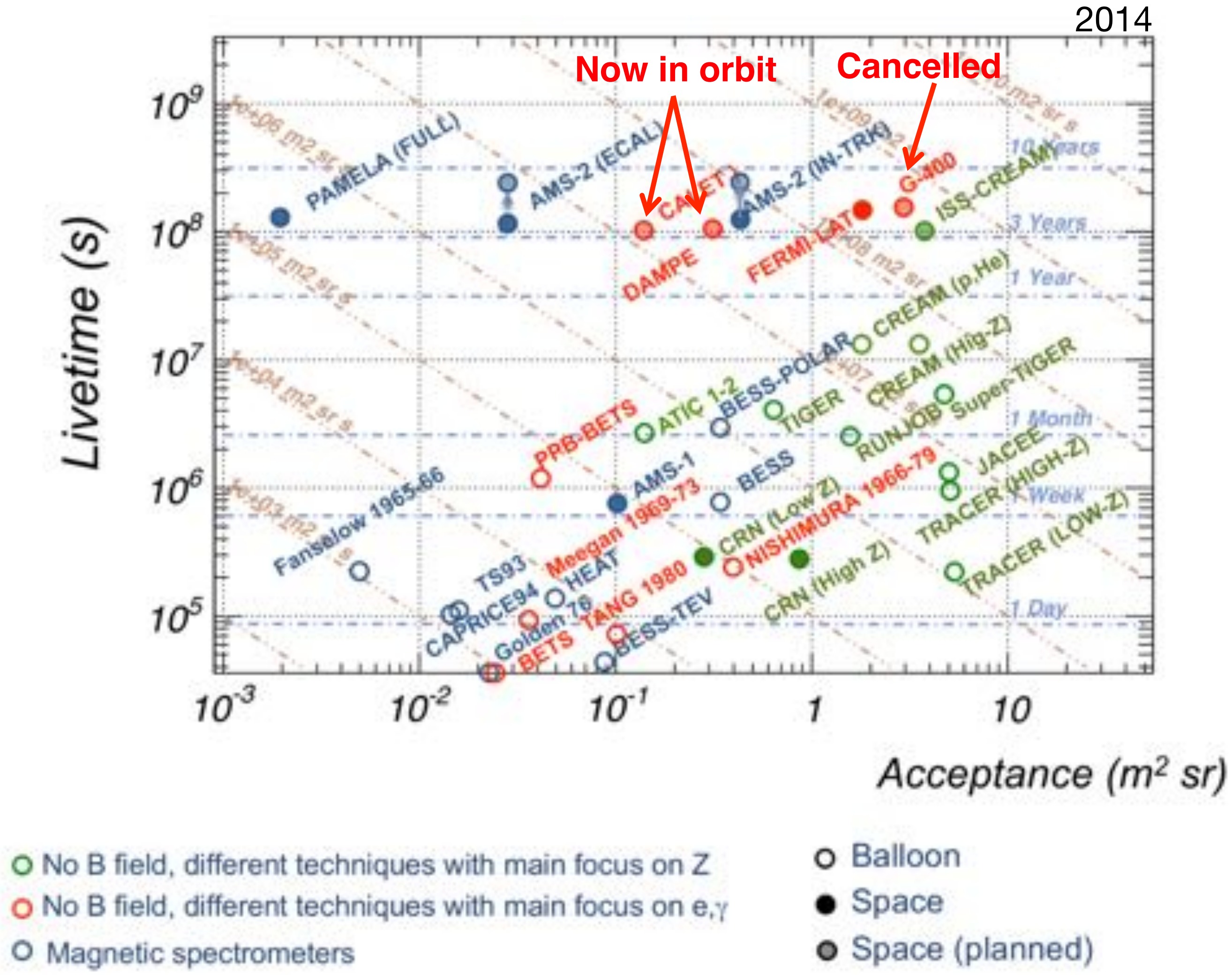




Secondary/primary ratios are sensitive to propagation mechanisms.

AMS results are in agreement with Kolmogorov turbolence model of magnetized plasma

Future experiments



AMS-02 will be the unique magnetic spectrometer in space able to distinguish matter from antimatter for the next 10 years.

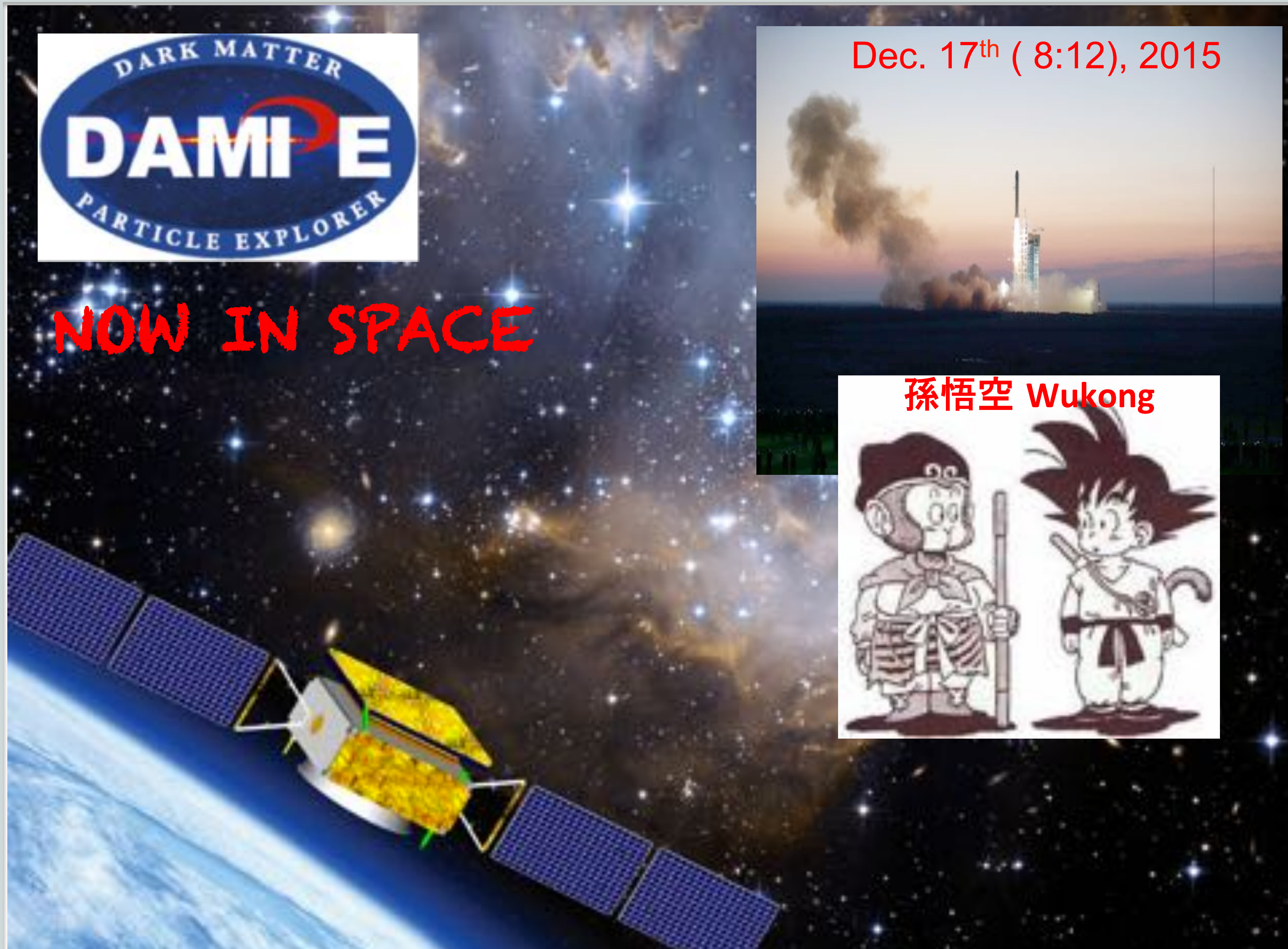
AMS is a unique, large acceptance, multipurpose magnetic spectrometer on the International Space Station.

There is no other magnetic spectrometer in space in the foreseeable decades.

The results from AMS to date are unexpected and contradict traditional understanding of cosmic rays.

We need to work closely with the theoretical community to develop a comprehensive model to explain all of our observations.

AMS will stay on ISS for the lifetime of the Station. By then (2024) we should be able to determine the origin of many of these unexpected phenomena.


DARK MATTER
DAMPE
PARTICLE EXPLORER
NOW IN SPACE
Dec. 17th (8:12), 2015
孫悟空 Wukong

DAMPE Science

Satellite for high energy cosmic ray direct detection

- Indirect search for Dark Matter with $e^{+/-}$ and gamma-rays
- Precise measurement of the cosmic ray spectrum and composition
- High energy gamma-ray astronomy

- Detection of 5 GeV - 10 TeV e/γ
- Measurement of 100 GeV – 100 TeV cosmic rays
- Excellent energy resolution and tracking precision

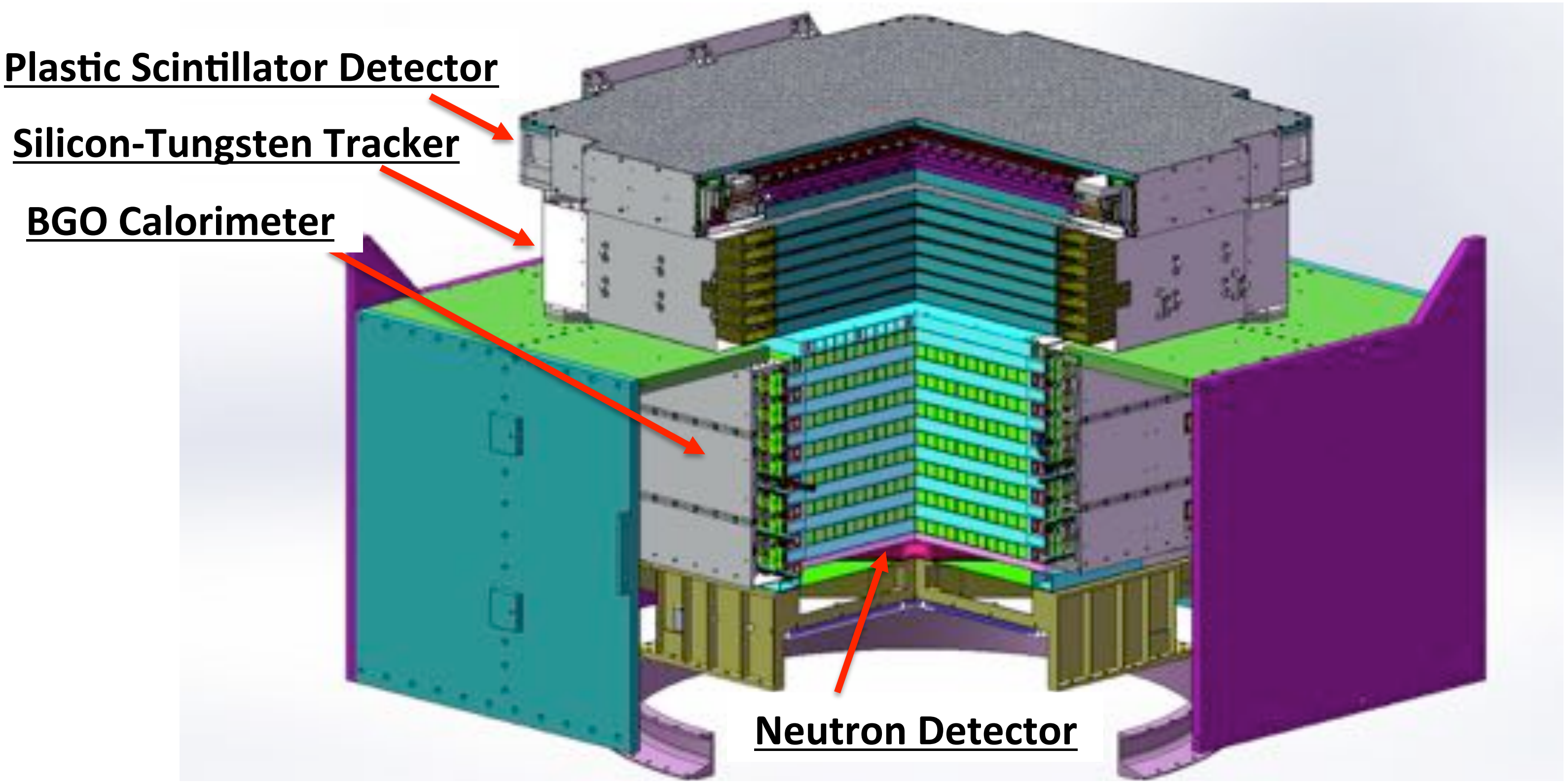
Follow-up mission to AMS-02 and Fermi-LAT

- Extend the energy range above th TeV region with improved energy resolution
- Overlap with Fermi for some time

University and INFN of Perugia
University and INFN of Lecce
University and INFN of Bari

The Dark Matter Particle Explorer

The DAMPE Detector

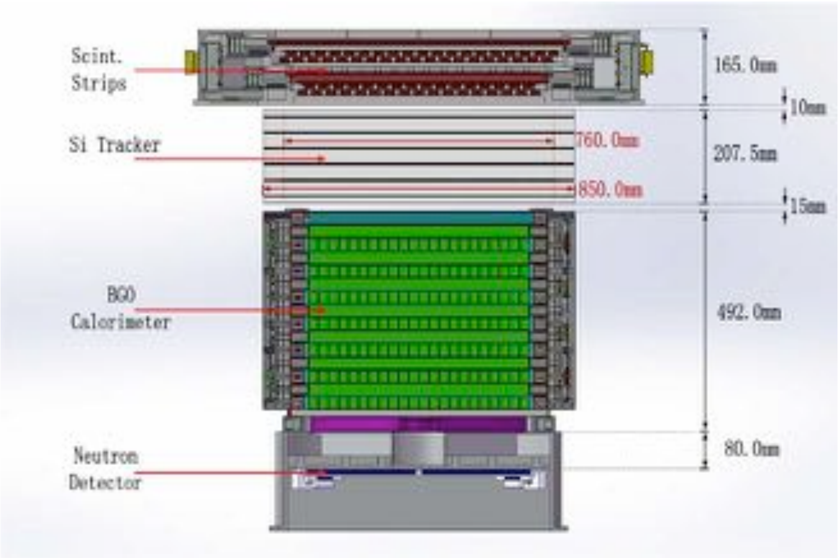


W converter + thick calorimeter (total 33 X0) + precise tracking + charge measurement ➠ high energy γ-ray, electron and CR telescope

The Dark Matter Particle Explorer

	DAMPE	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	1.5	3	10
e/γ Angular res.@100 GeV (°)	0.1	0.3	0.1
e/p discrimination	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	31	17	8.6
Geometrical accep. (m^2sr)	0.29	0.09	1

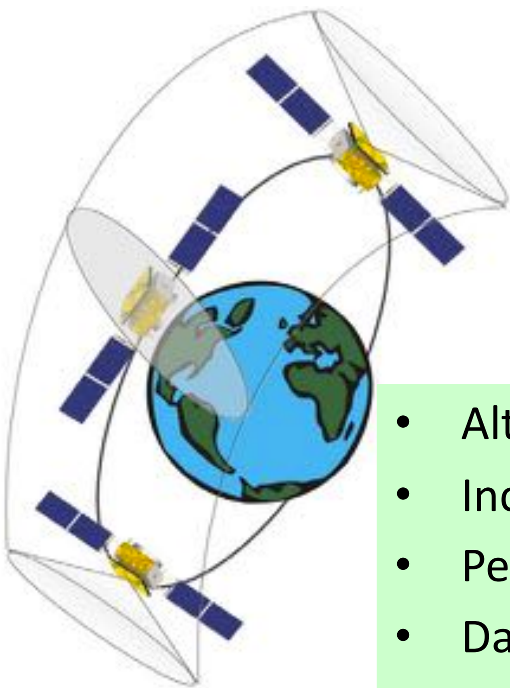
- **Geometrical acceptance with BGO alone: 0.36 m^2sr**
  - **BGO+STK+PSD: 0.29 m^2sr**
  - **First 10 layers of BGO (22 X_0) +STK+PSD: 0.36 m^2sr**



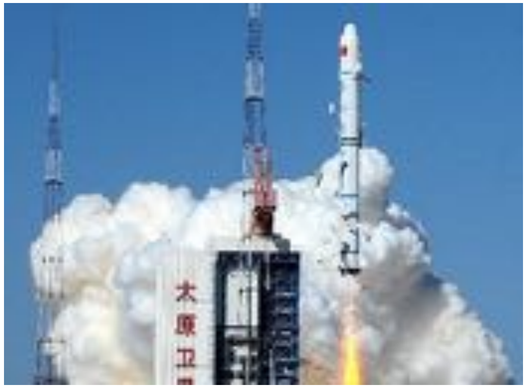
The Dark Matter Particle Explorer

- One of the 5 satellite missions of the Strategic Priority Research Program in Space Science of CAS
  - Approved for construction (phase C/D) in Dec. 2011
  - Scheduled launch date **December 17, 2015** from Jiuquan Satellite Launch Center in the Gobi desert

- Satellite < 1900 kg, payload ~1340kg
- Power consumption 640W (400 W)
- Lifetime > 3 years
- Launched by CZ-2D rockets

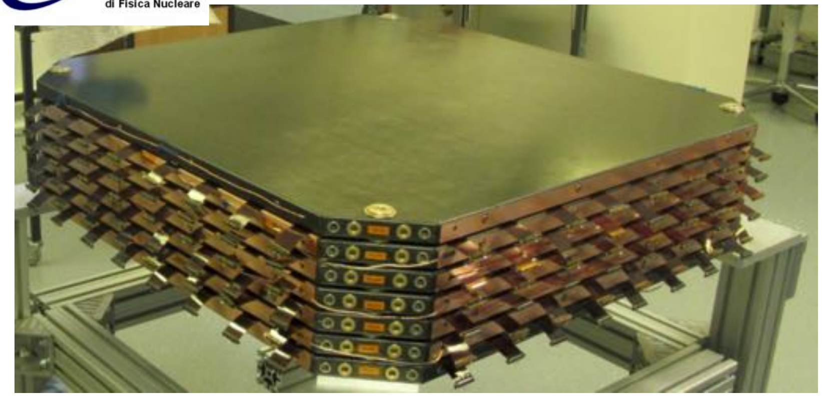


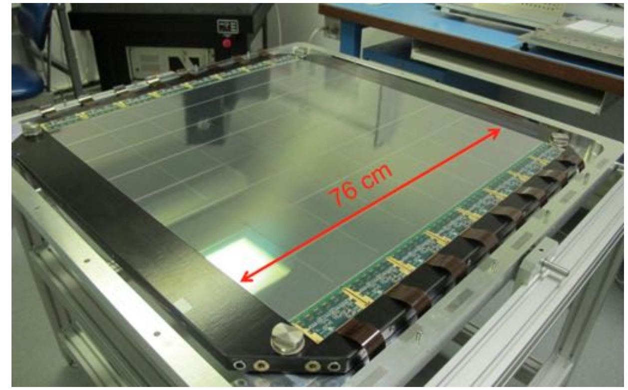
- Altitude 500 km
- Inclination 87.4065°
- Period 90 minutes
- Dawn/dusk (6:30 AM) sun-synchronous orbit



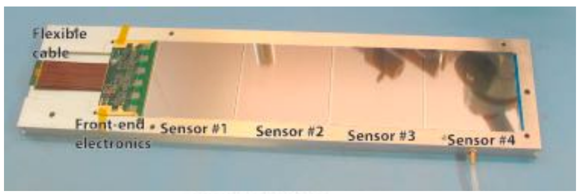
9

Silicon Tracker STK

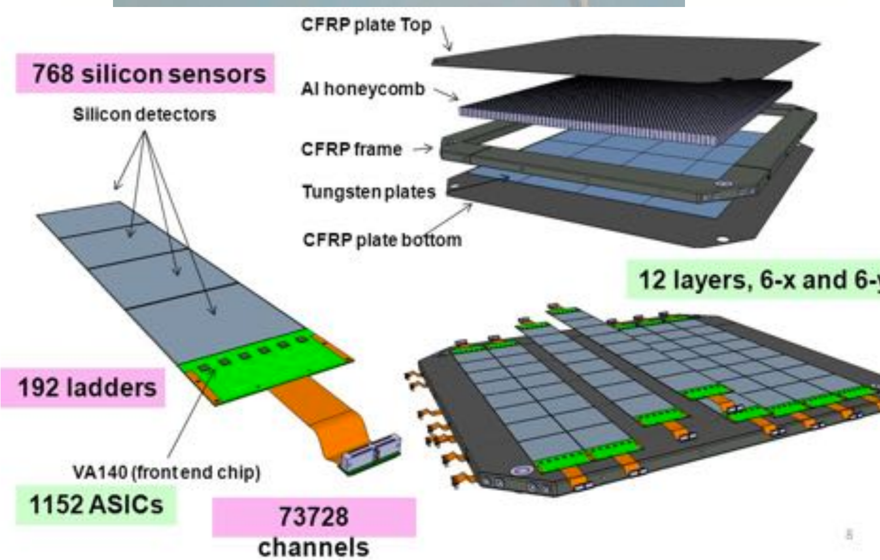


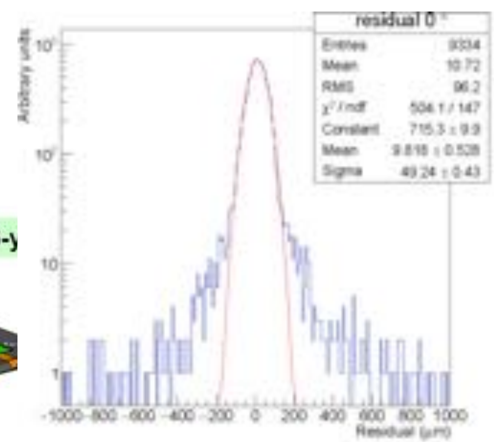


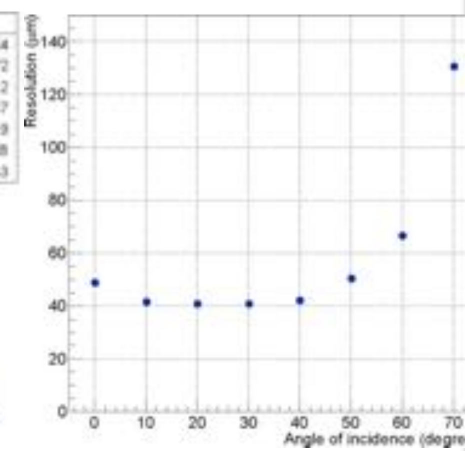
6 planes of Si micro-strip detector interleaved with W converter layers.



768 sensors with 121 µm pitch / 242 µm readout







Tracker tested at CERN test beams.
Calibration/alignment using flight data ongoing

BGO Calorimeter

14 layers of BGO bars
22 bars/layers, 308 total
X_0=32, λ=1.6 for high e/p separation


Carbon Fiber Structure

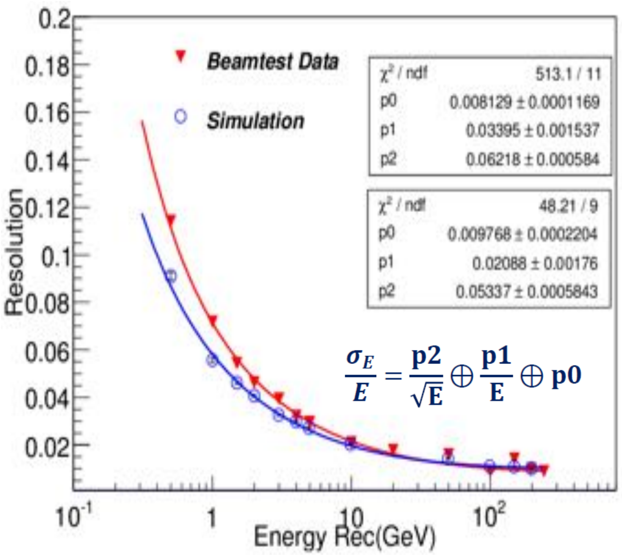

BGO crystal installation

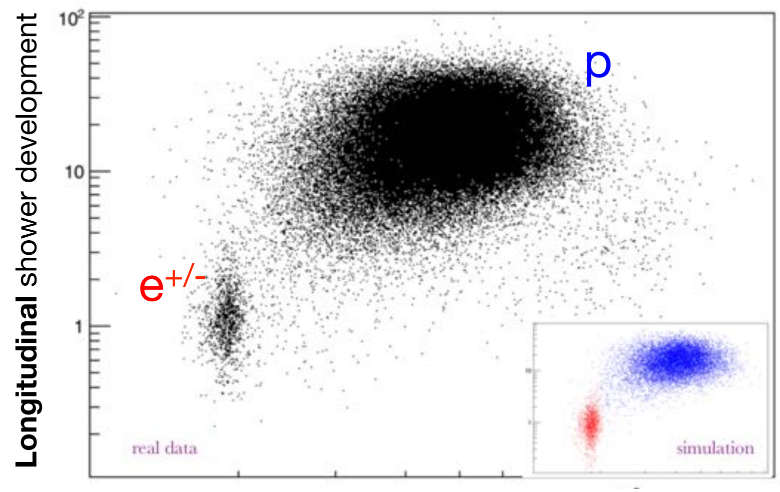

PMT installation


Cableing

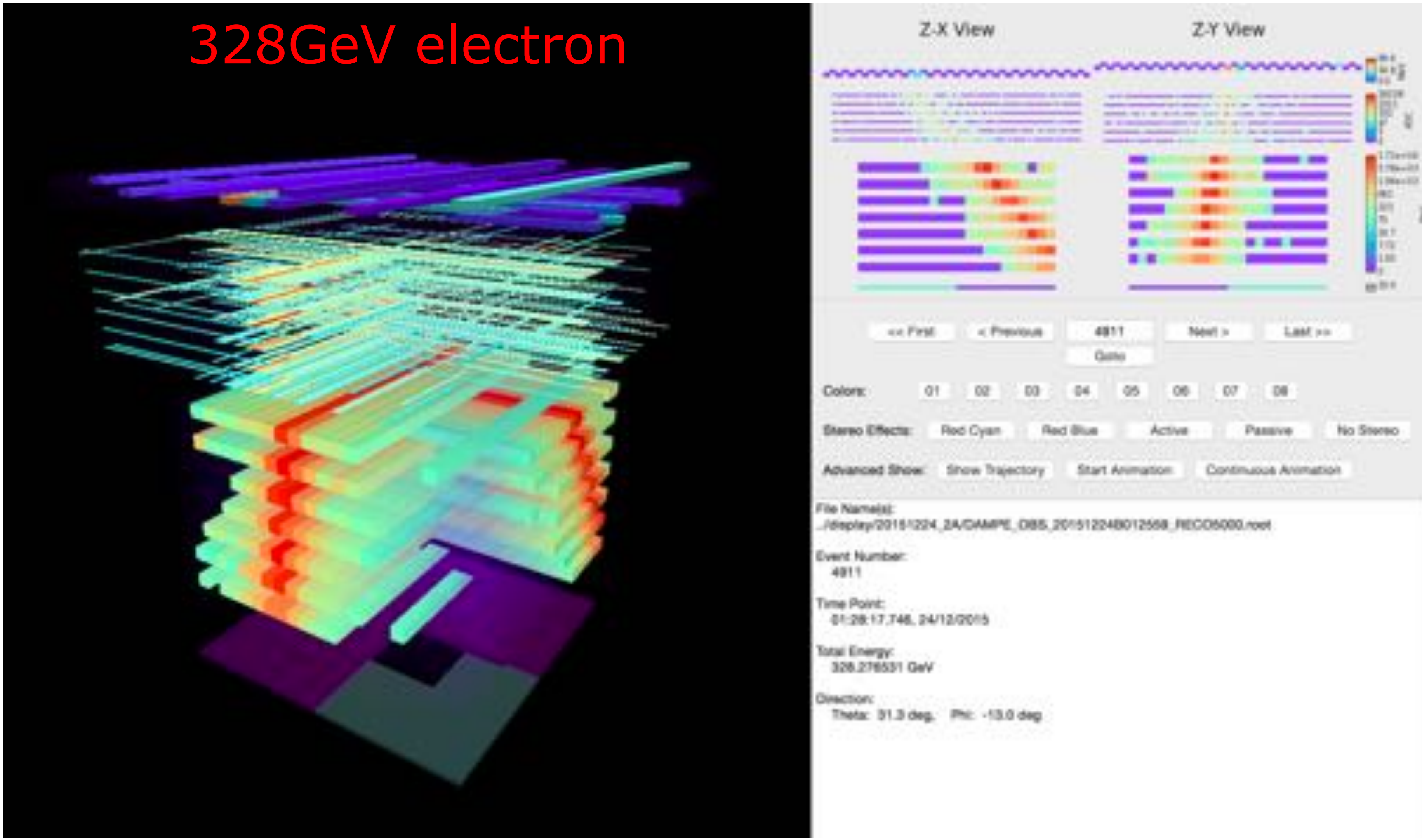

Cable connector


BGO Calorimeter

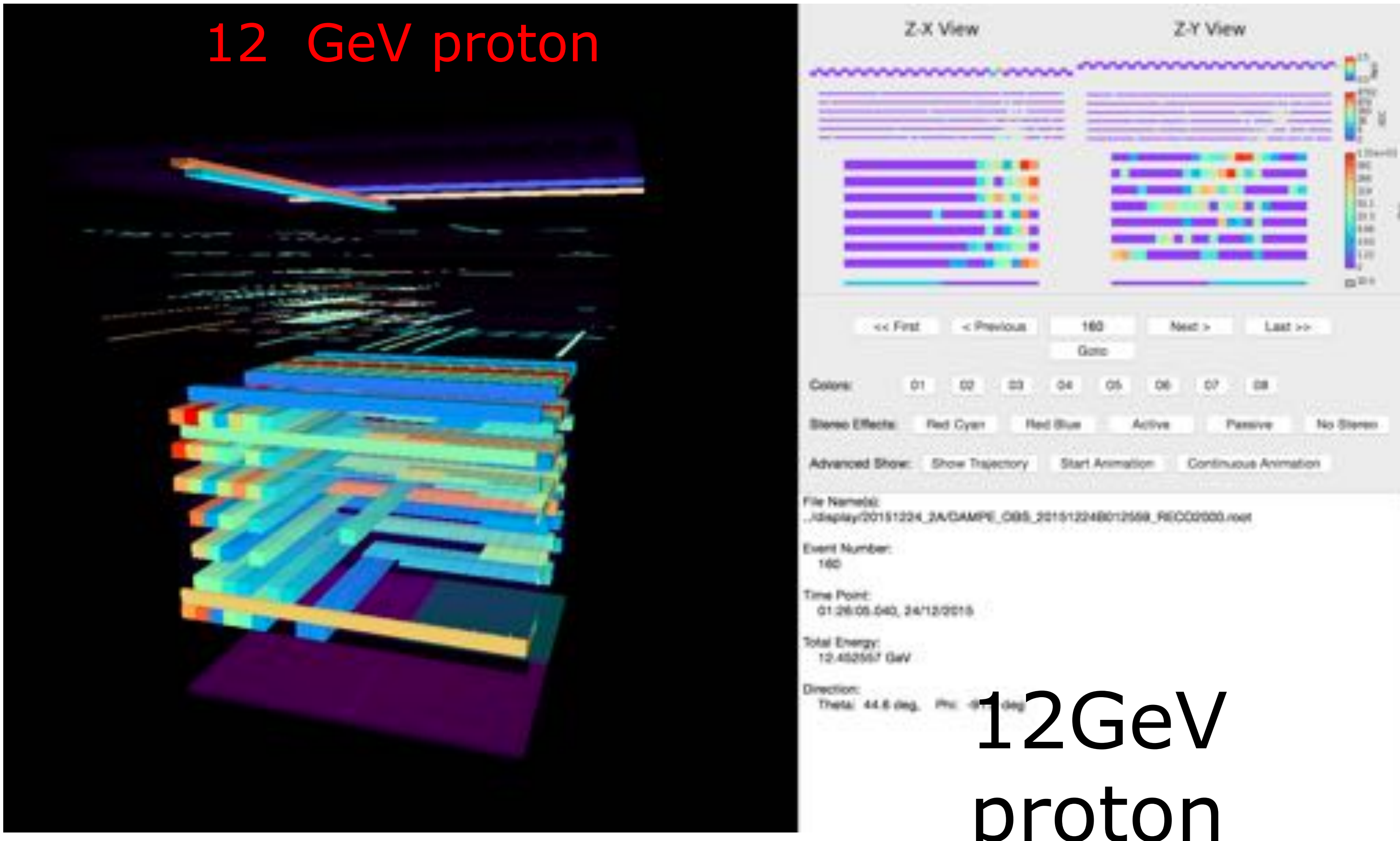




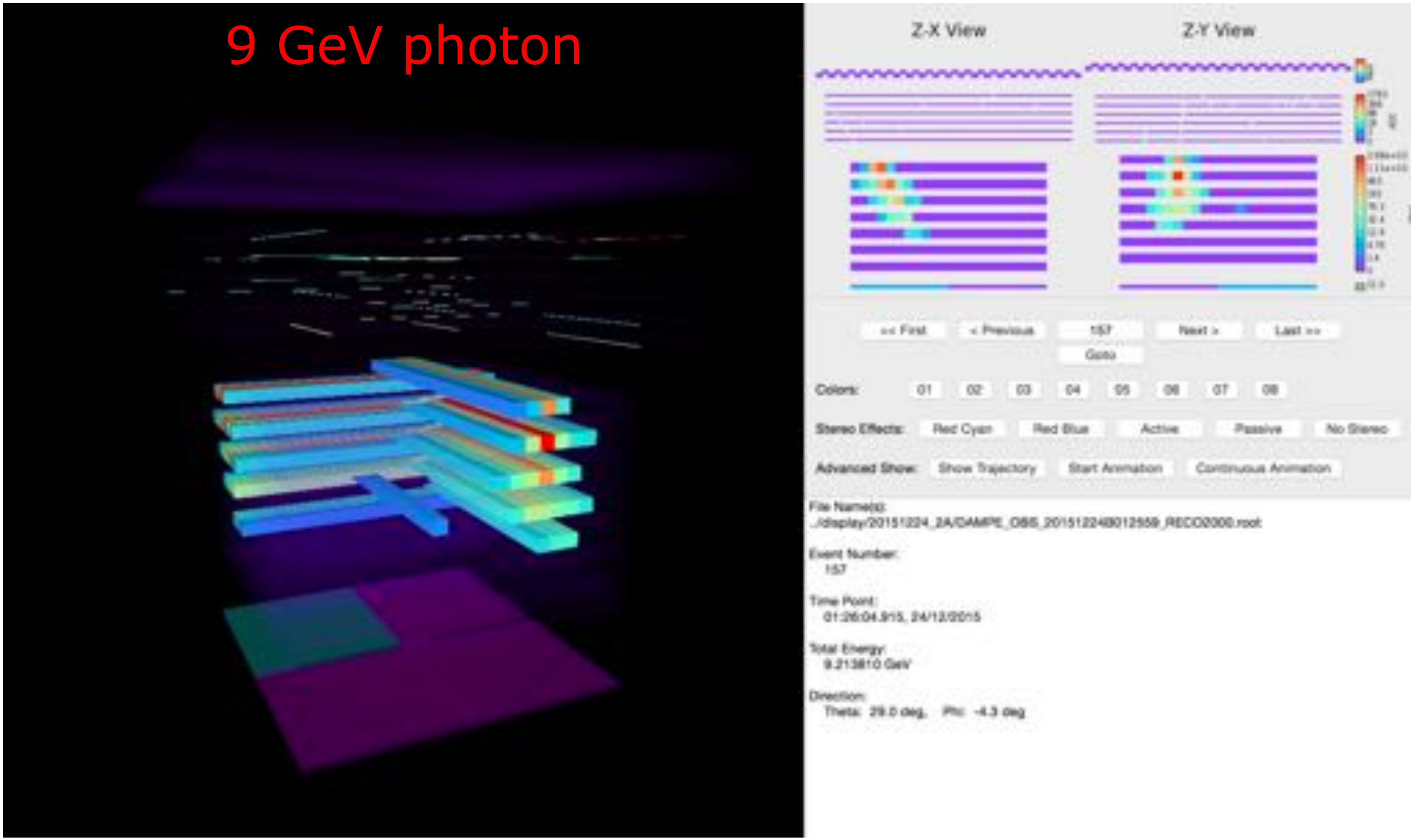
First Space events



First Space events

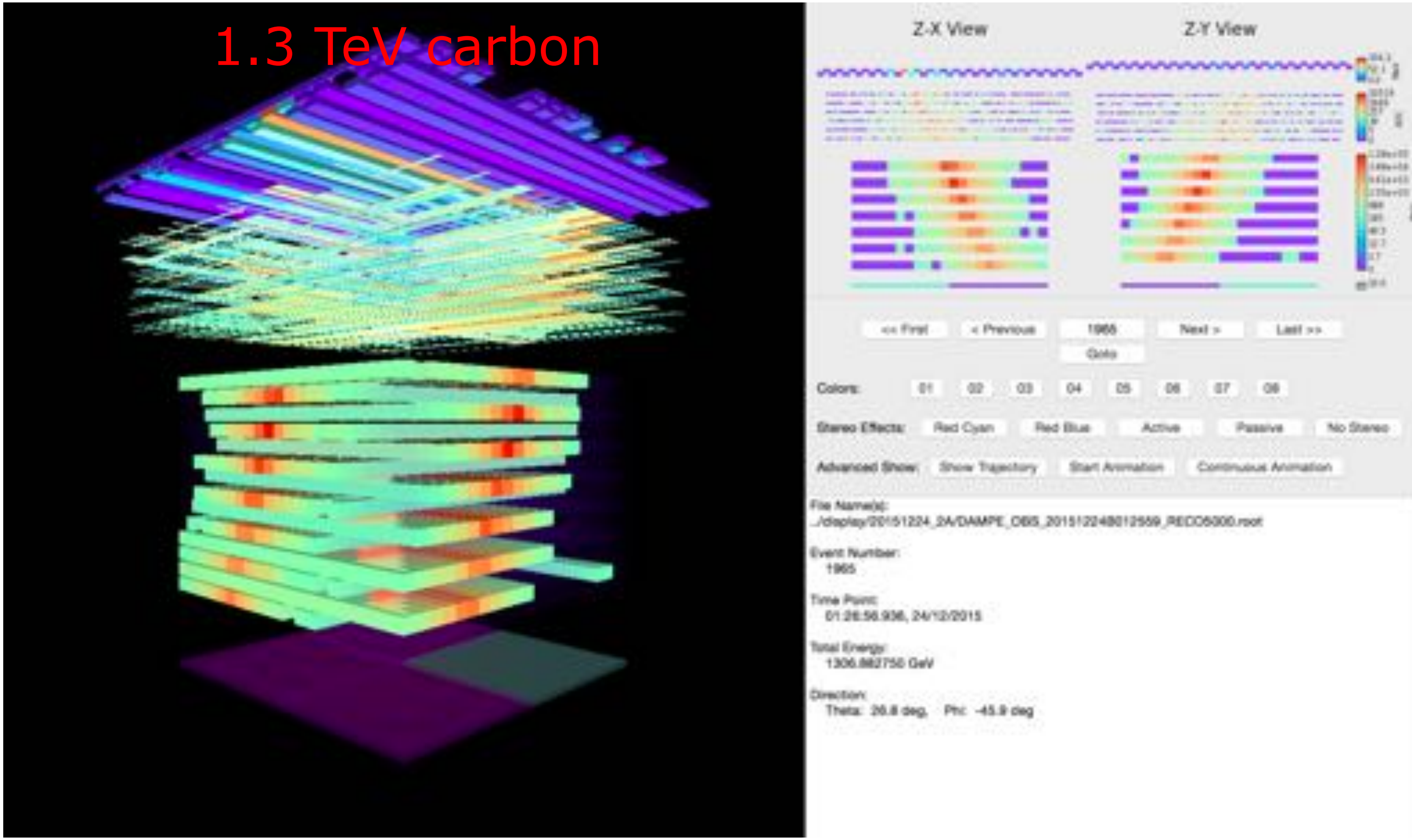


First Space events



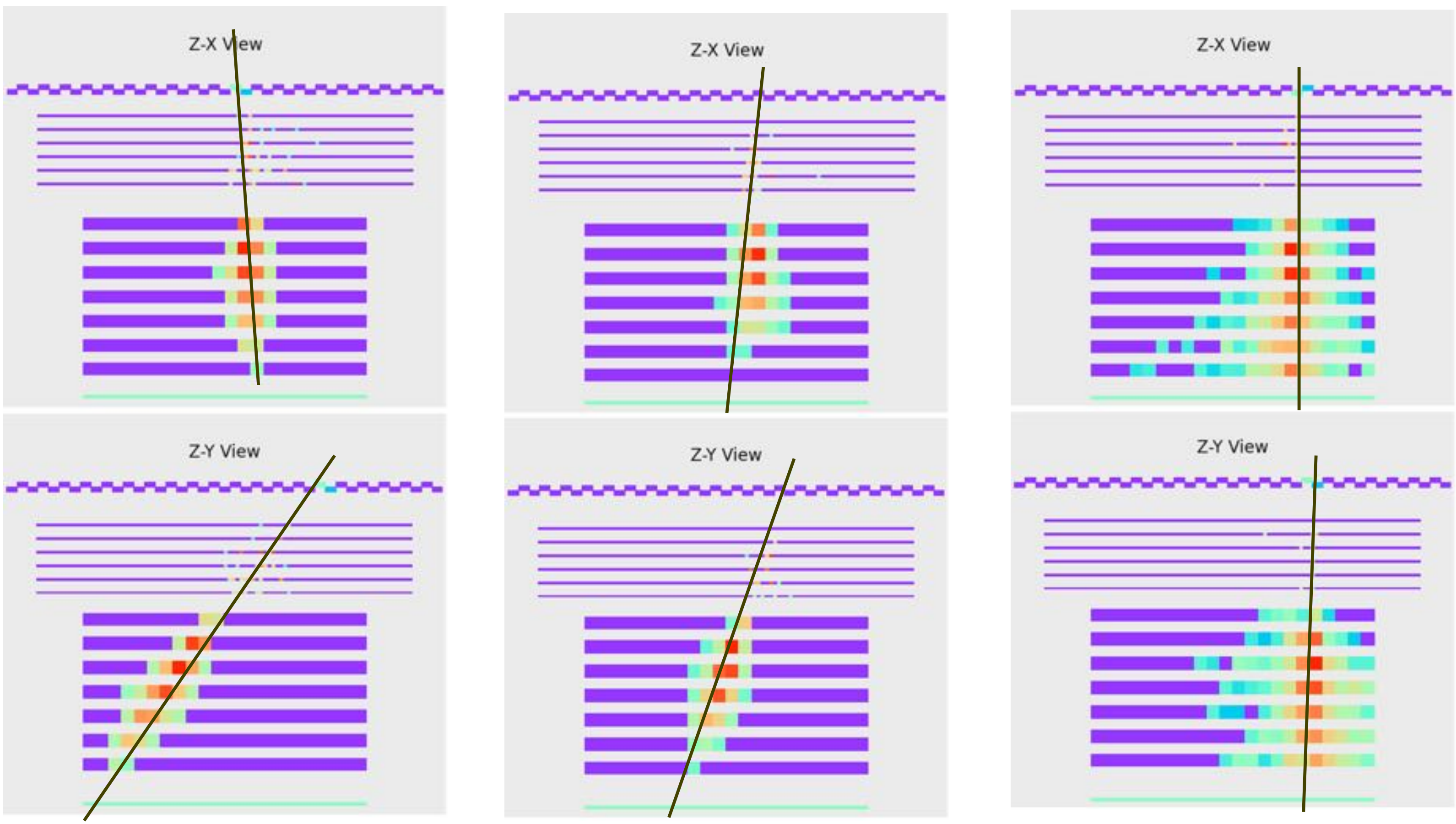
9GeV gamma-ray

First Space events



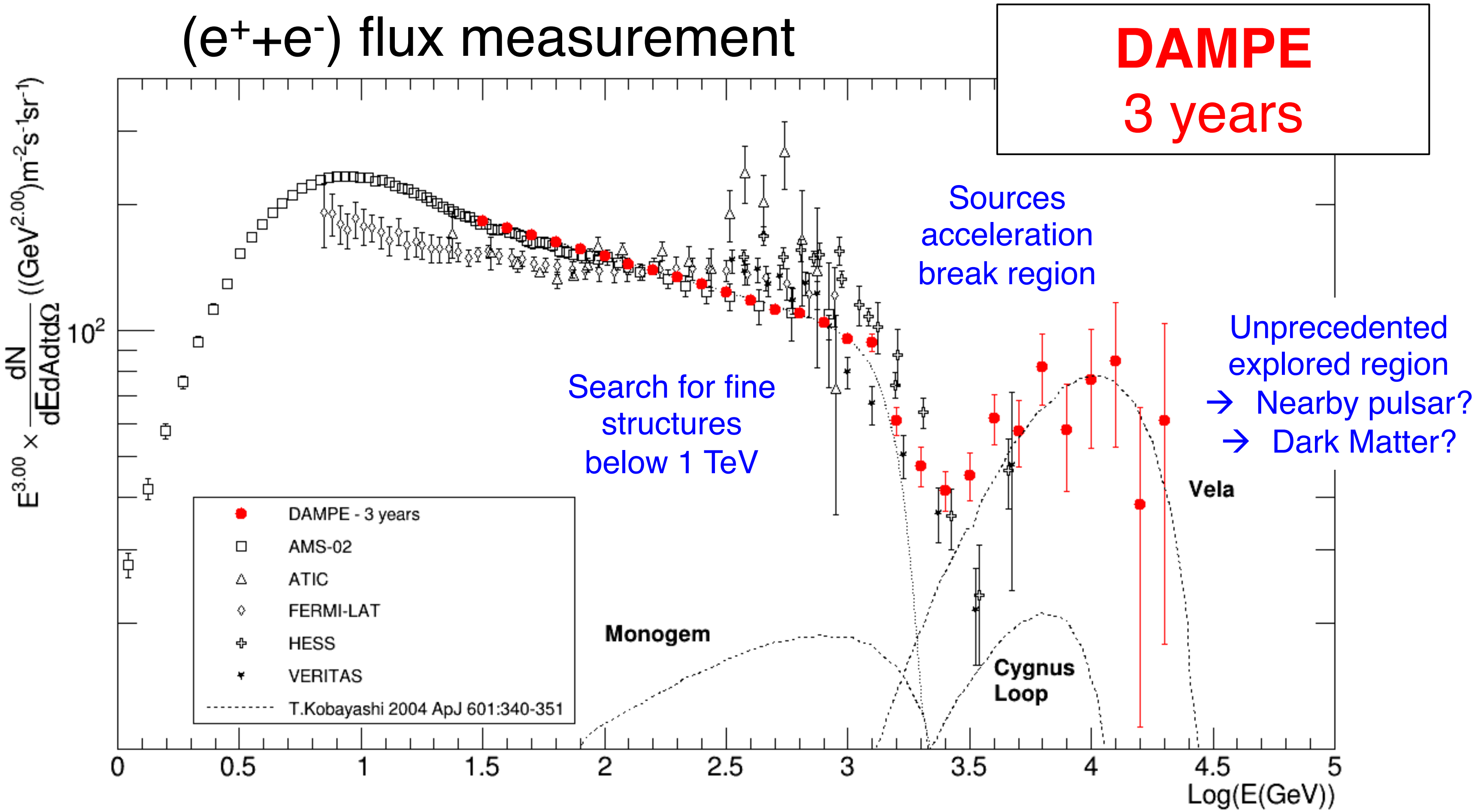
First Space events

electron gamma-ray Proton

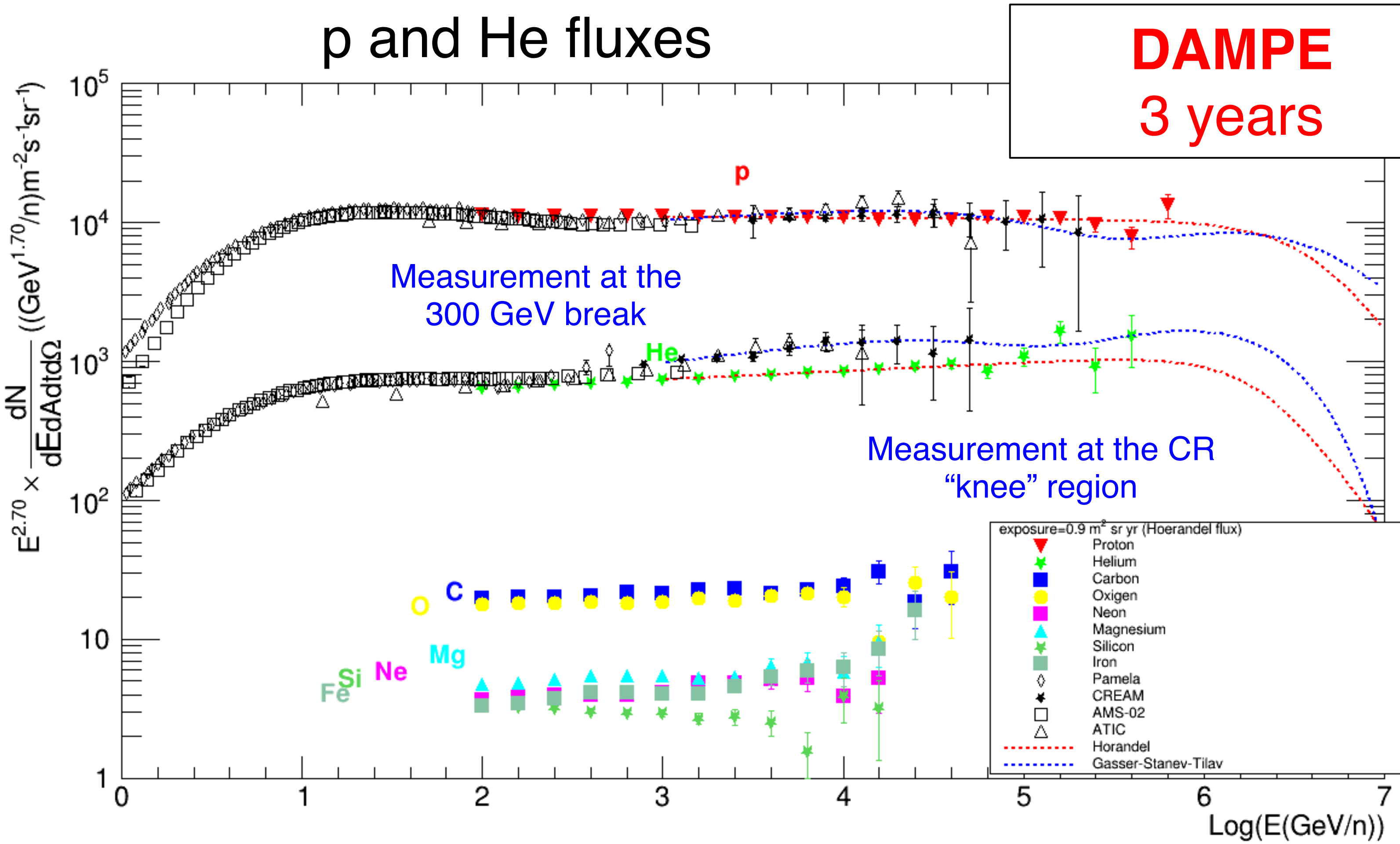


Science Prospects

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



Science Prospects



DAMPE is working properly, as expected, and collecting data

Currently many efforts to calibrate the detector (tracker alignment, calorimeter e/p, charge calibration, MonteCarlo tuning…)

Physics results will come soon. Stay tuned!