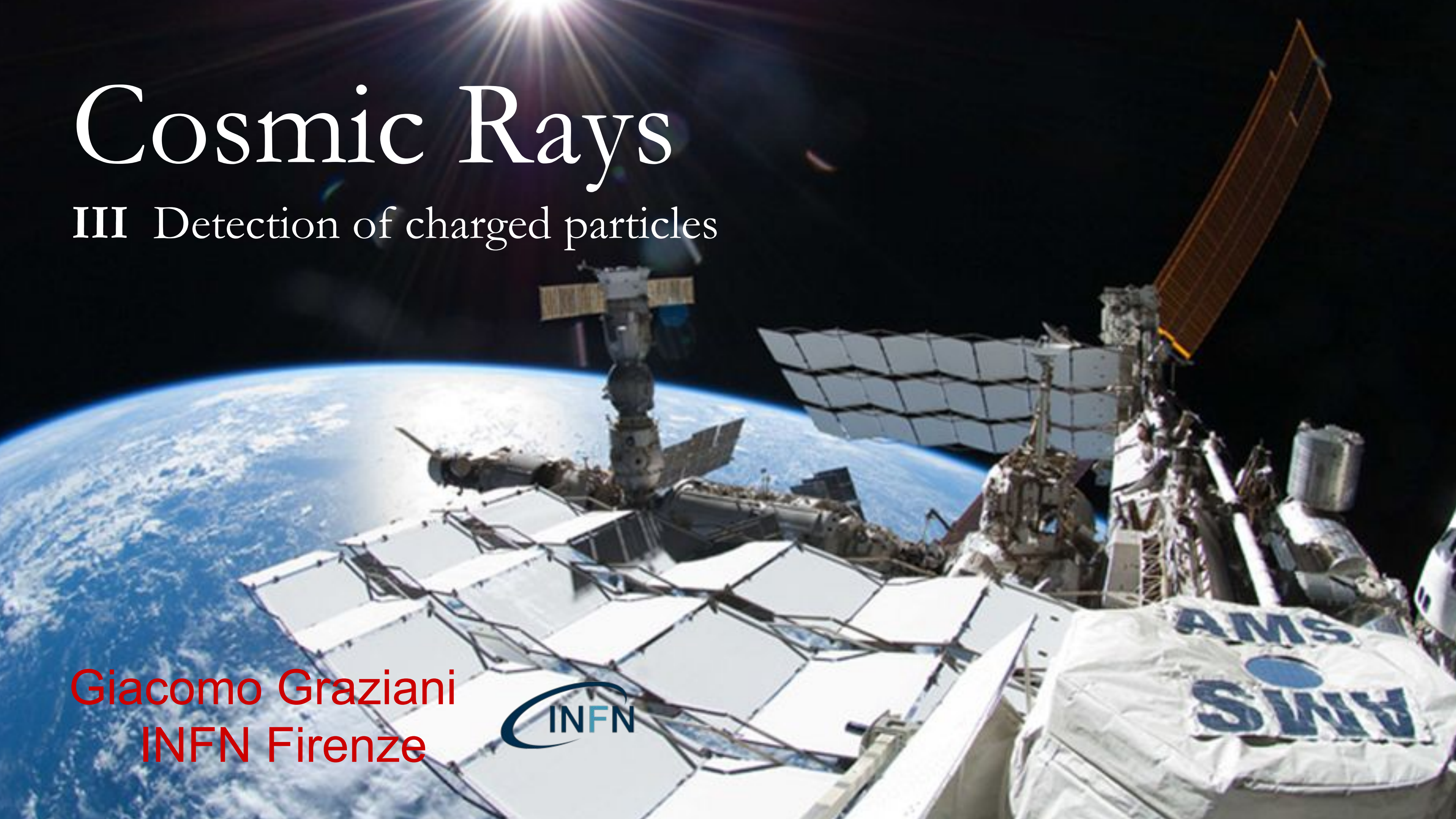
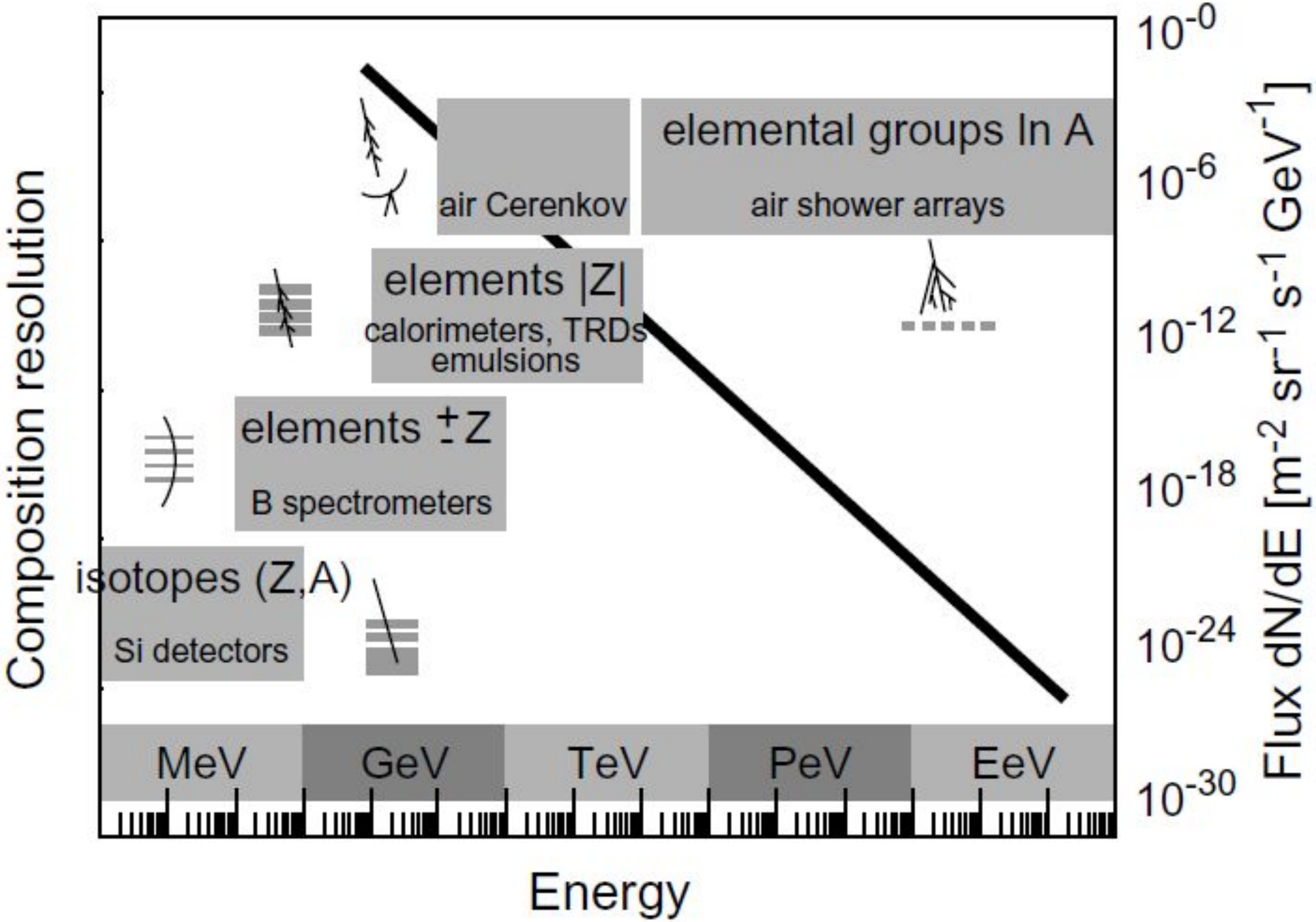
Cosmic Rays

III Detection of charged particles



Giacomo Graziani
INFN Firenze

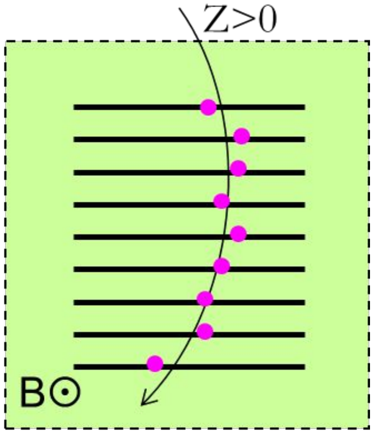
Techniques for different energy scales



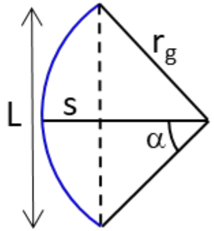
Magnetic Spectrometers

- Exploit bending of charged particles in uniform magnetic field to measure particle **rigidity**

$$\mathbf{R = p/Ze = B\, r_g}$$



- Charge sign can be determined (important to distinguish **matter from antimatter**)
- The gyroradius r_g is measured from the sagitta s



$$\alpha \sim \frac{L}{2r_g}$$

$$s \sim r_g \frac{\alpha^2}{2} = \frac{L^2}{8r_g}$$

$$s[mm] = 38 \cdot L[m]^2 \frac{B[T]}{|R|[GV]}$$

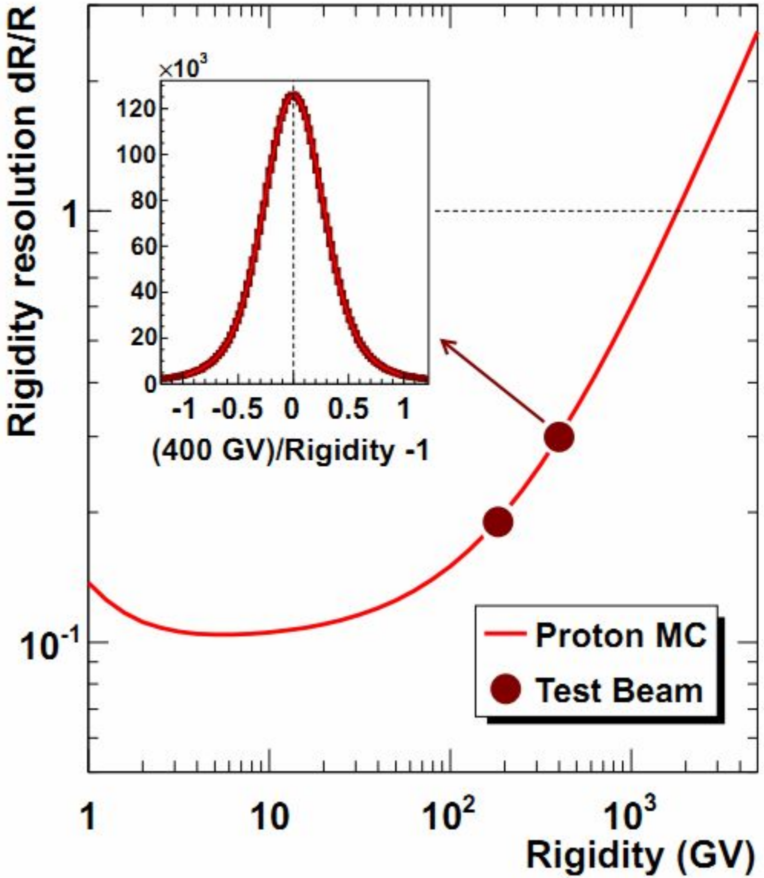
Resolution of Magnetic Spectrometers

- Assuming N equidistant measurements with space resolution σ, the relative error on the rigidity is $$\left(\frac{\Delta R}{R}\right)_{res} = \frac{R}{B}\frac{\sigma}{L^2}\sqrt{\frac{720}{N+4}}$$

  ⇨ at thigh energy, resolution is proportional to momentum, one defines a Maximum Detectable Rigidity (MDR) when ΔR/MDR=1

- while the error from multiple scattering is
$$\left(\frac{\Delta R}{R}\right)_{ms} = \frac{0.053\ \mathrm{T\ m}}{B\beta\sqrt{LX_0}}$$

  dominant at low energy

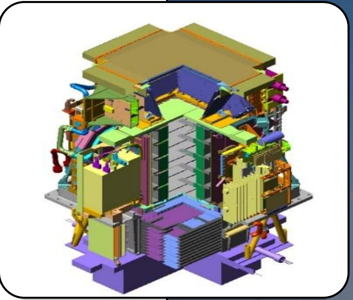


The present generation: PAMELA & AMS

Aiming to extend the antiparticle measurements at high energy

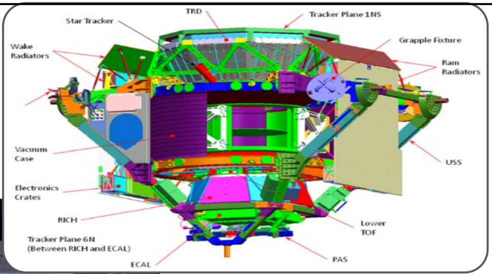
- Instruments placed in **space**
  - GCR path-length @20GeV ~ atmosferic grammage @balloon altitude (~ 5 g/cm^2)
- Tracking system based on **microstrip Si technology**
  - Improved tracking capabilities

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



Launched in 2006
End 2016

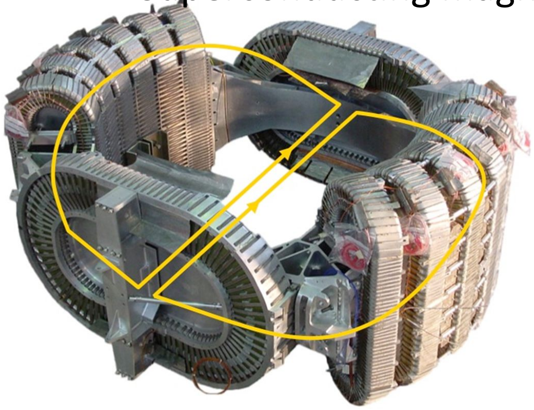
The Alpha Magnetic Spectrometer



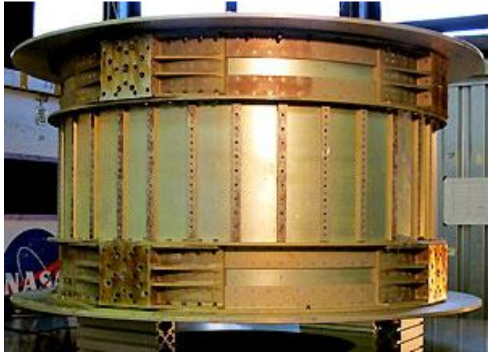
First test flight in 1991
On board the ISS since 2011

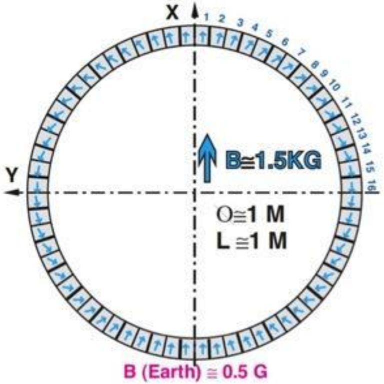
The AMS-02 magnet

Superconducting magnet



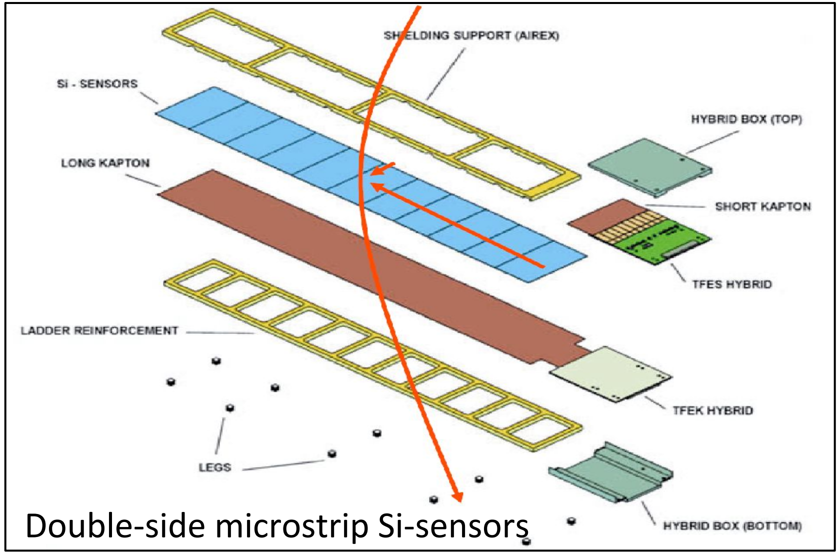
Permanent magnet



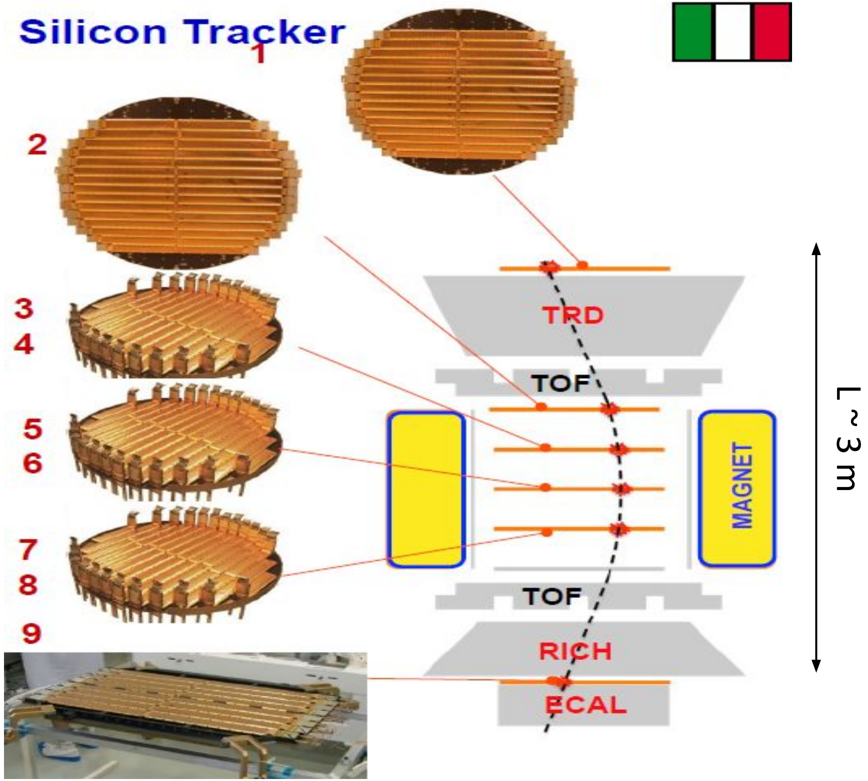


- Both permanent (Nd-Fe-B alloy) and superconducting (Ni-Ti) magnets developed.
- Permanent one chosen, in the perspective of long-duration mission (>3 years)
  - 0.15 T @ center
  - Large cavity 1m ∅ × 1m

The AMS-02 tracking system



Double-side microstrip Si-sensors

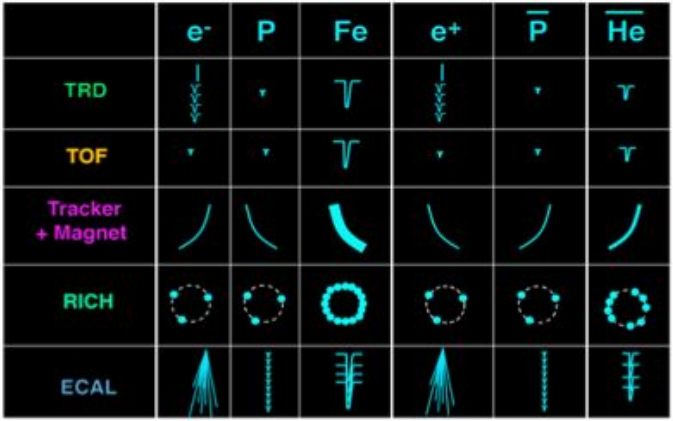


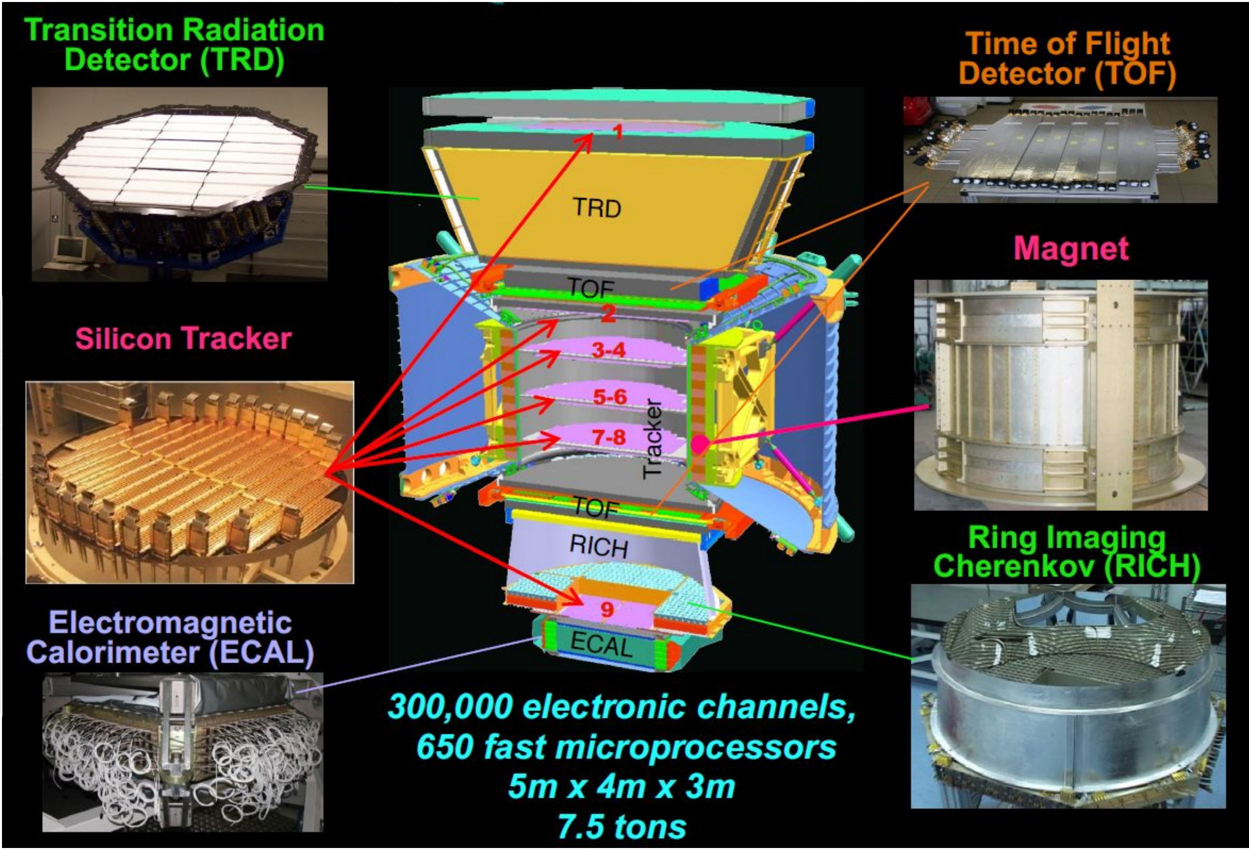
- 0.15 T magnetic field @ center
- **~ 10 μm** resolution on the bending direction
- ~ 3 m track-length

→ **Maximum Detectable Rigidity (ΔR/R=1) ~ 2 TV**

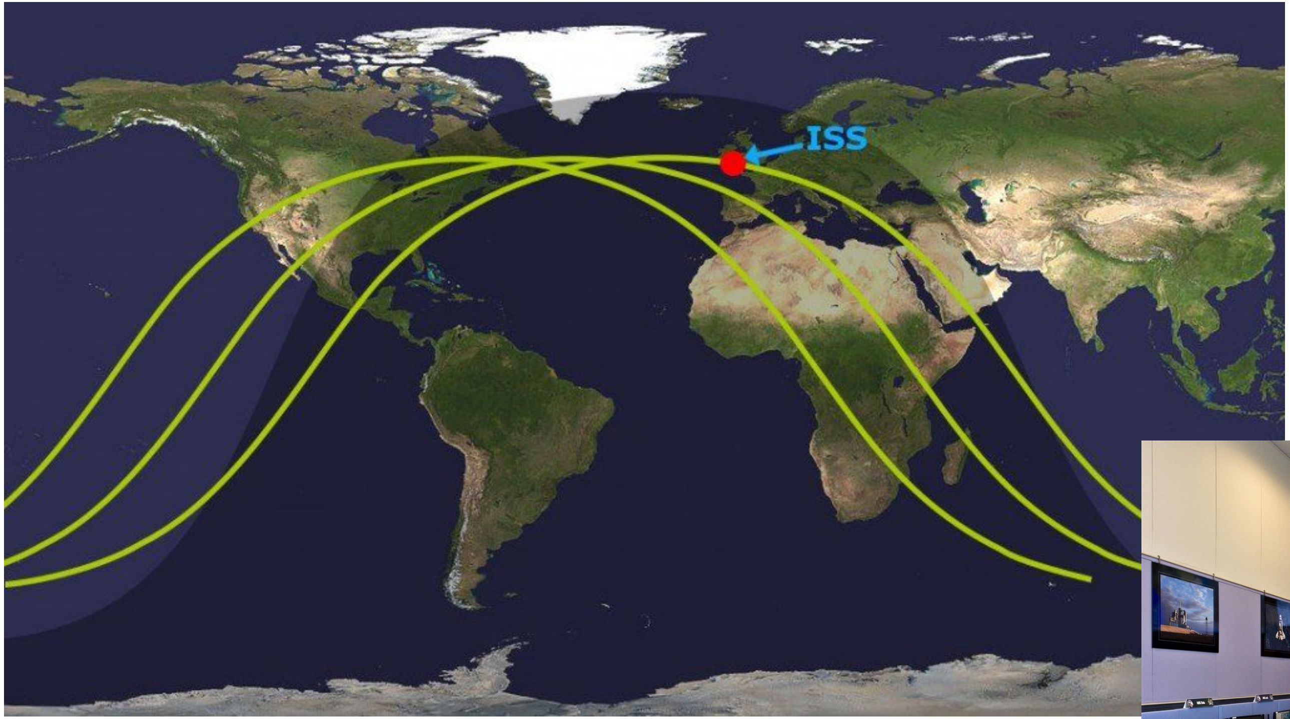
The AMS-02 detectors

- Spectrometer measures rigidity
- Charge and mass distinguished by a set of **redundant** particle identification detectors:





ISS Orbit



ISS "low" Earth orbit:
inclination 52 degrees
350 - 450 Km altitude
15.5 orbits/day !

Reaches high latitudes with low geomagnetic cutoff (good for low-energy cosmic rays)

Control Room at CERN!

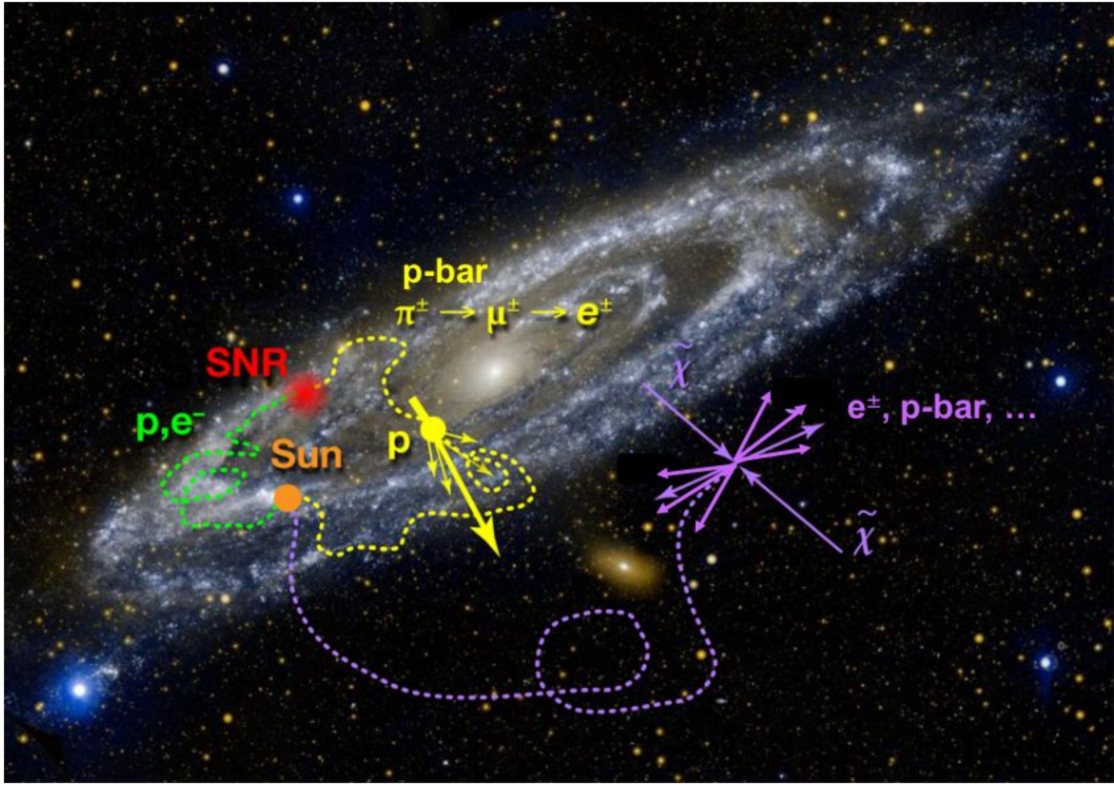
Cosmic Antimatter

- Antimatter in cosmic rays is a sensitive probe for the unknown:
  - Are there anti-galaxies in a matter/antimatter symmetric Universe?

    (now excluded from missing annihilation gammas)
  - Any signal from annihilation or decay of **dark matter?**
- Background to these searches from secondary production of antimatter in interactions of primary CR with the interstellar gas, e.g.

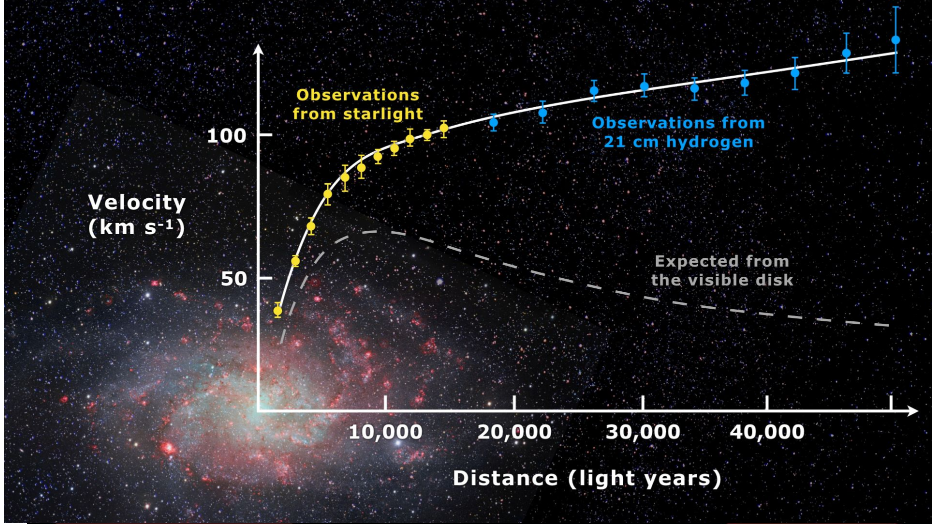
$$pp \to ppp\bar{p}$$

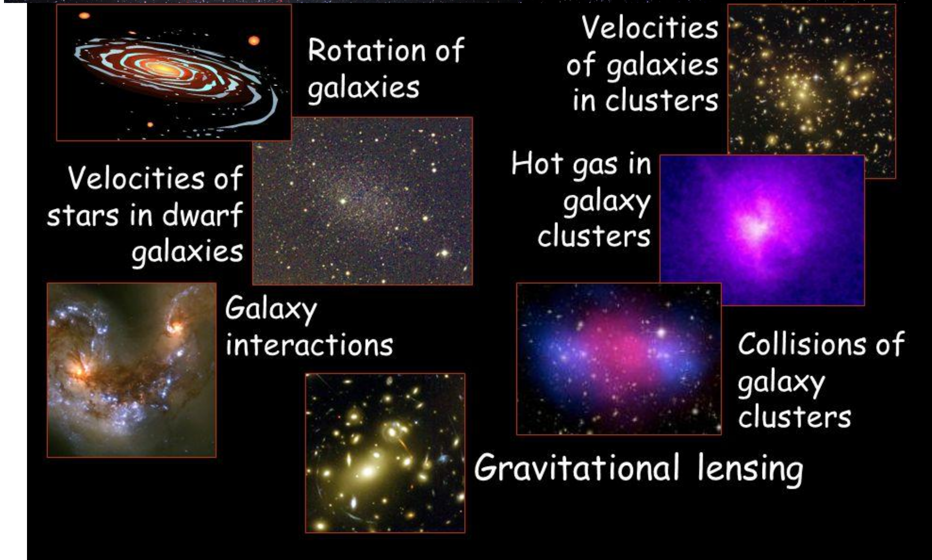
(threshold 5.6 GeV)



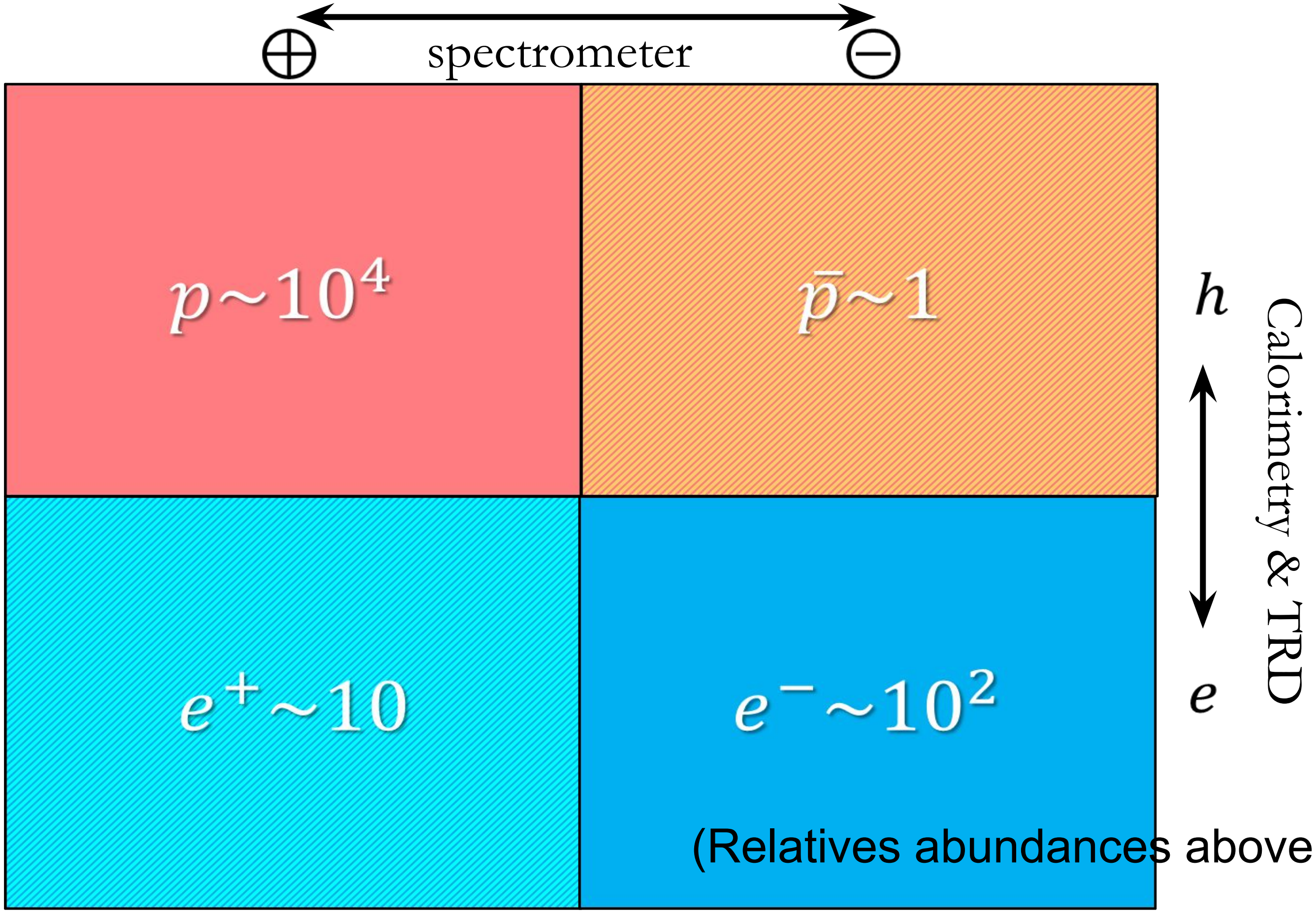
Dark Matter

- Many independent observations, most notably the rotation curves for spiral galaxies, show the gravitational effect of matter not interacting electromagnetically, the dark matter
- Thought to account ~ 85% of the matter in the Universe
- Its nature is still unknown

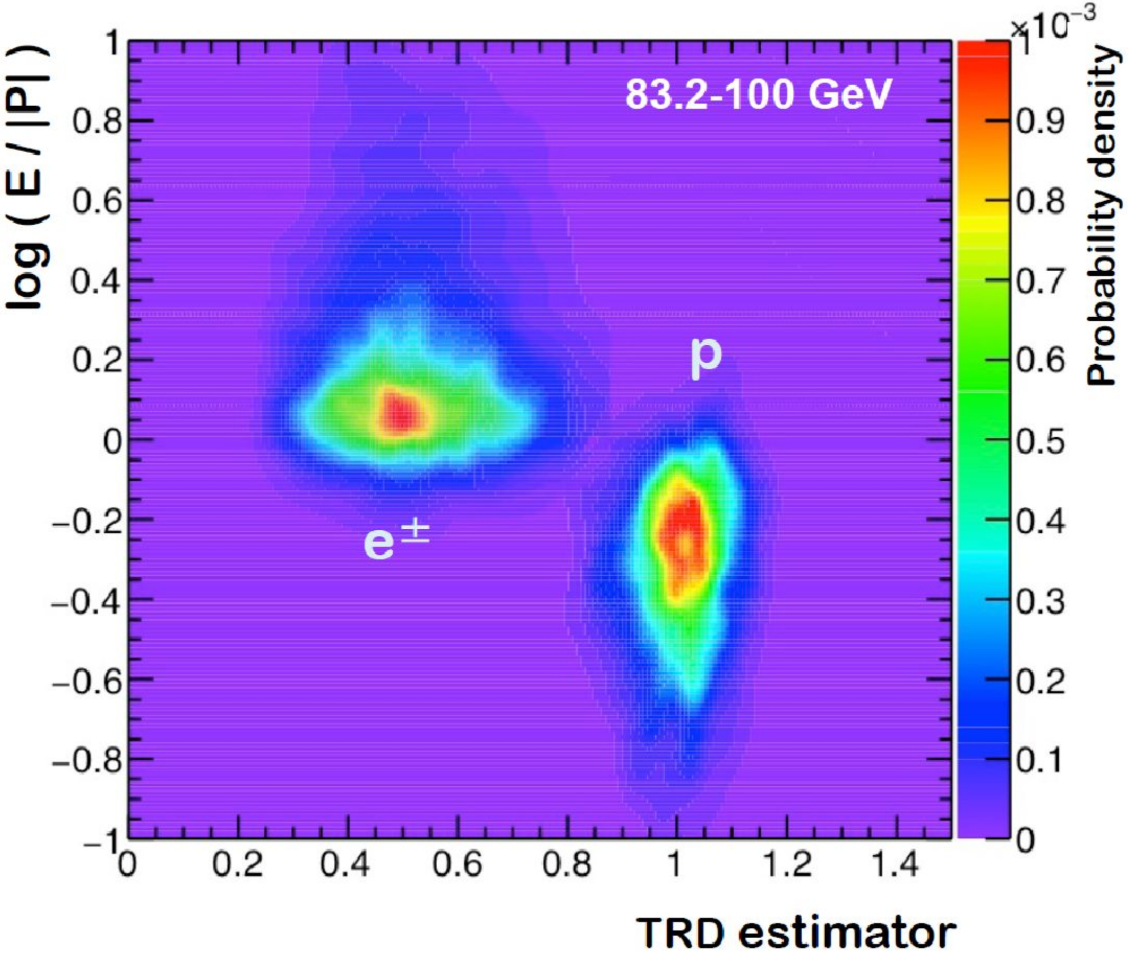




Identification performance

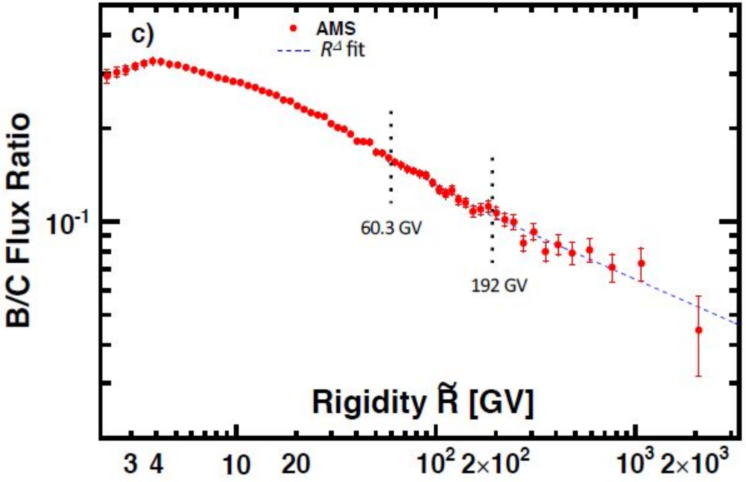


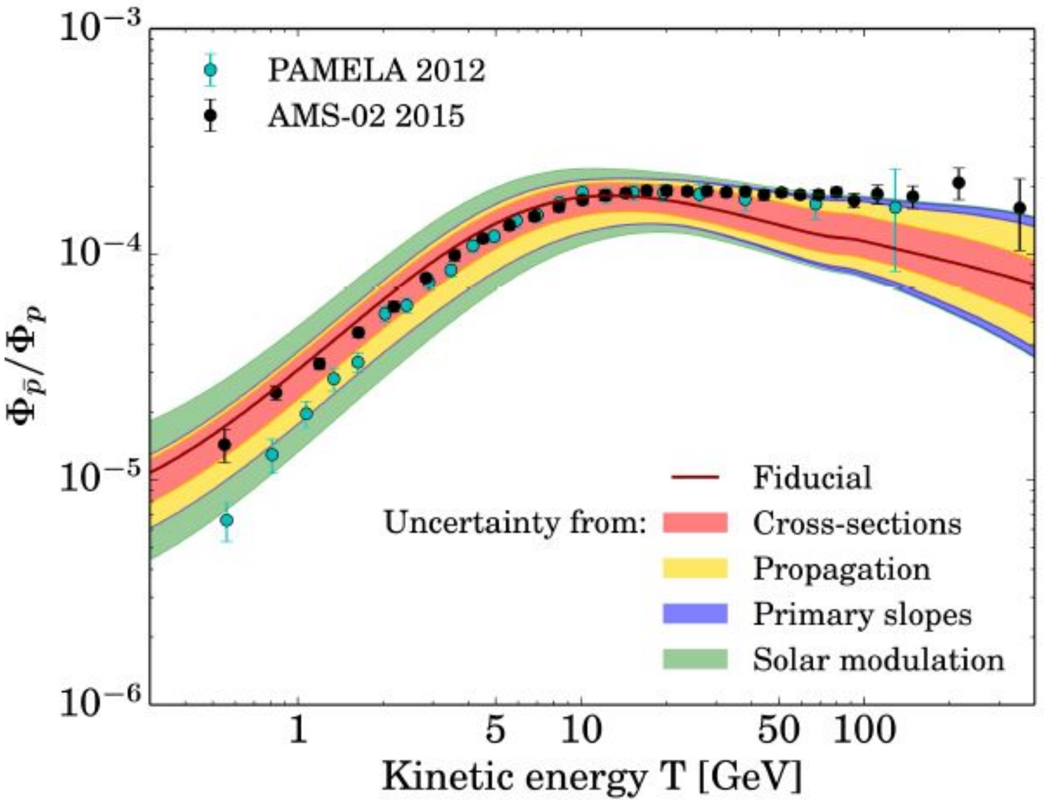
(Relatives abundances above ~ 1 GeV)


83.2-100 GeV
e±
p
log (E / |P|)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
TRD estimator
×10⁻³
Probability density
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Result for antiproton/proton ratio

- Result is consistent, within uncertainties, with expected secondary antiproton flux
- Uncertainty on propagation model improved by better measurement of B/C ratio (and other secondary/primary)

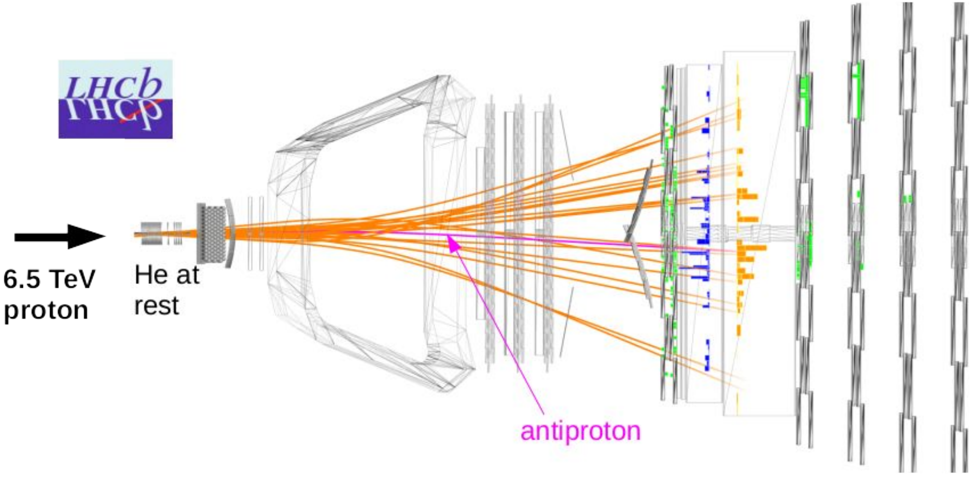


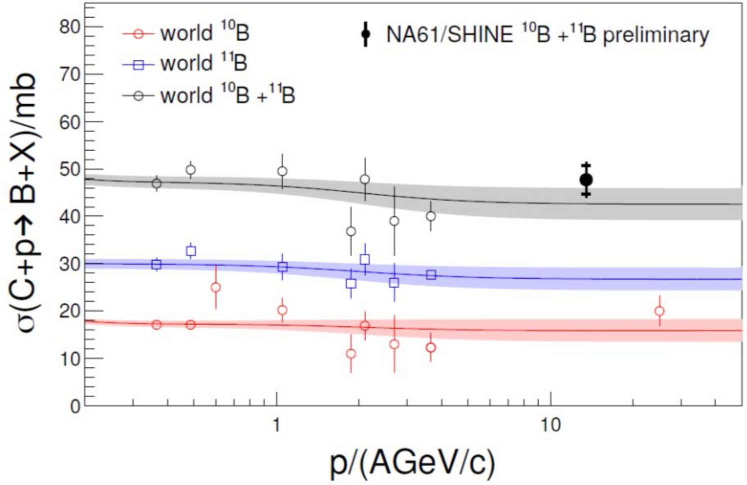


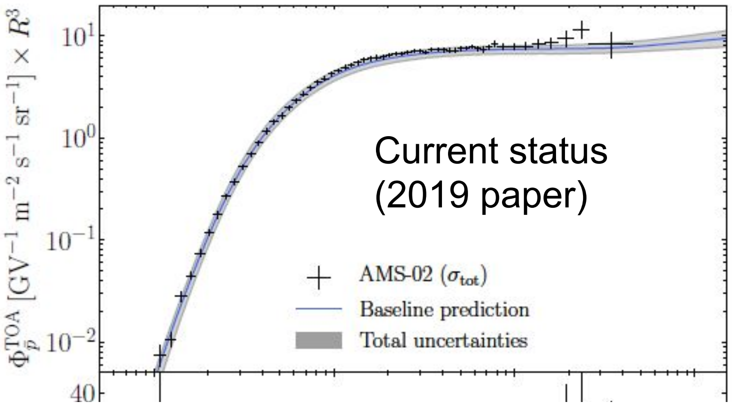
- Still sizeable error from cross-sections

Help from accelerators!

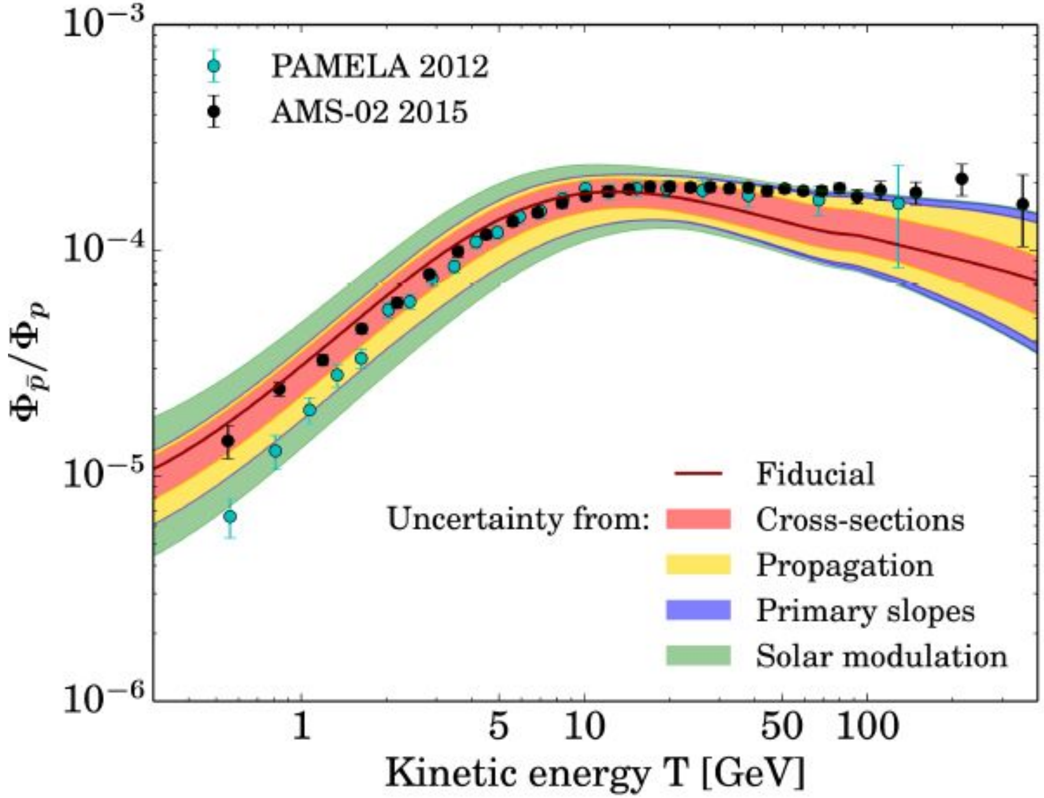
- Recent cross-section measurements made at CERN, both for antiproton production in pp and pHe collisions and spallation processes (like C->B)
- Prediction as of 2019 has smaller uncertainty and is closer to data. Cosmic ray physics getting a precision science!





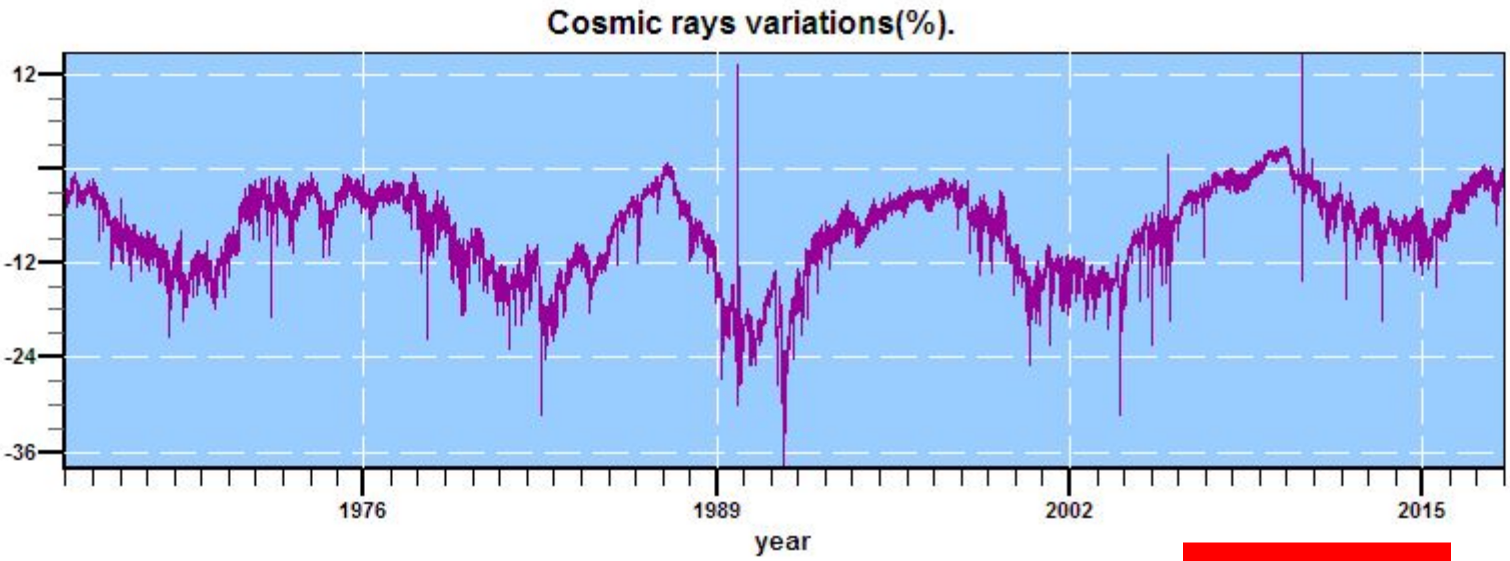


Current status (2019 paper)



is one of the two experiments wrong below 10 GeV ??

Time-dependent solar modulation!



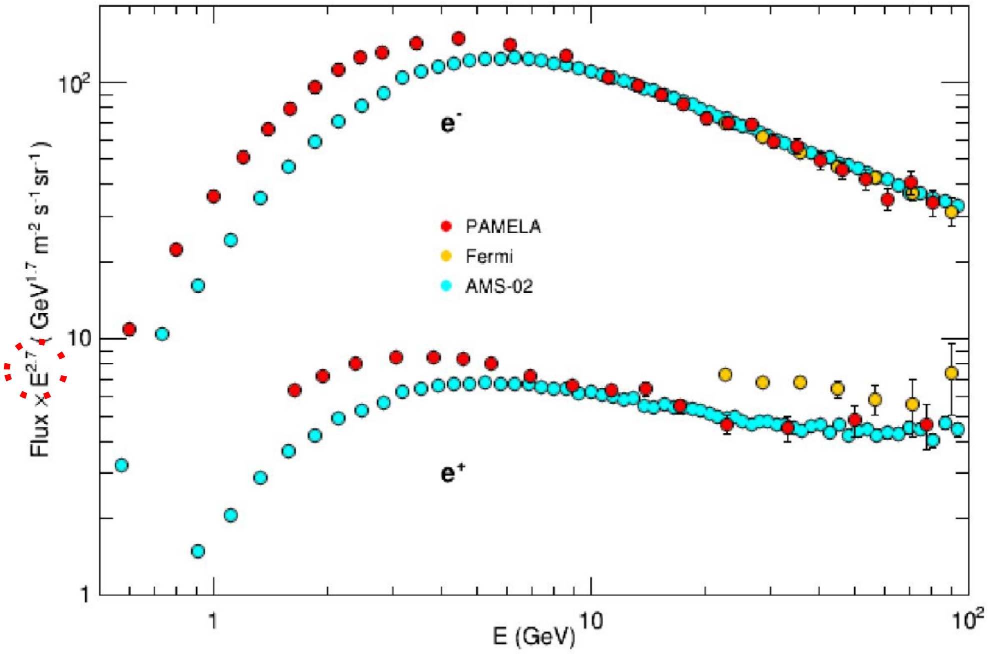
PAMELA

AMS02

Electron and Positron spectra

- ❑ At the acceleration sites, primary electrons and protons are expected to have a similar energy spectrum.
- ❑ But in the propagation electrons are affected by much larger energy losses, due to **synchrotron radiation** due to the interaction with the galactic field

$$-\frac{dE}{dt} = 2\sigma_T c \gamma^2 U_B \beta^2 \sin^2\theta$$

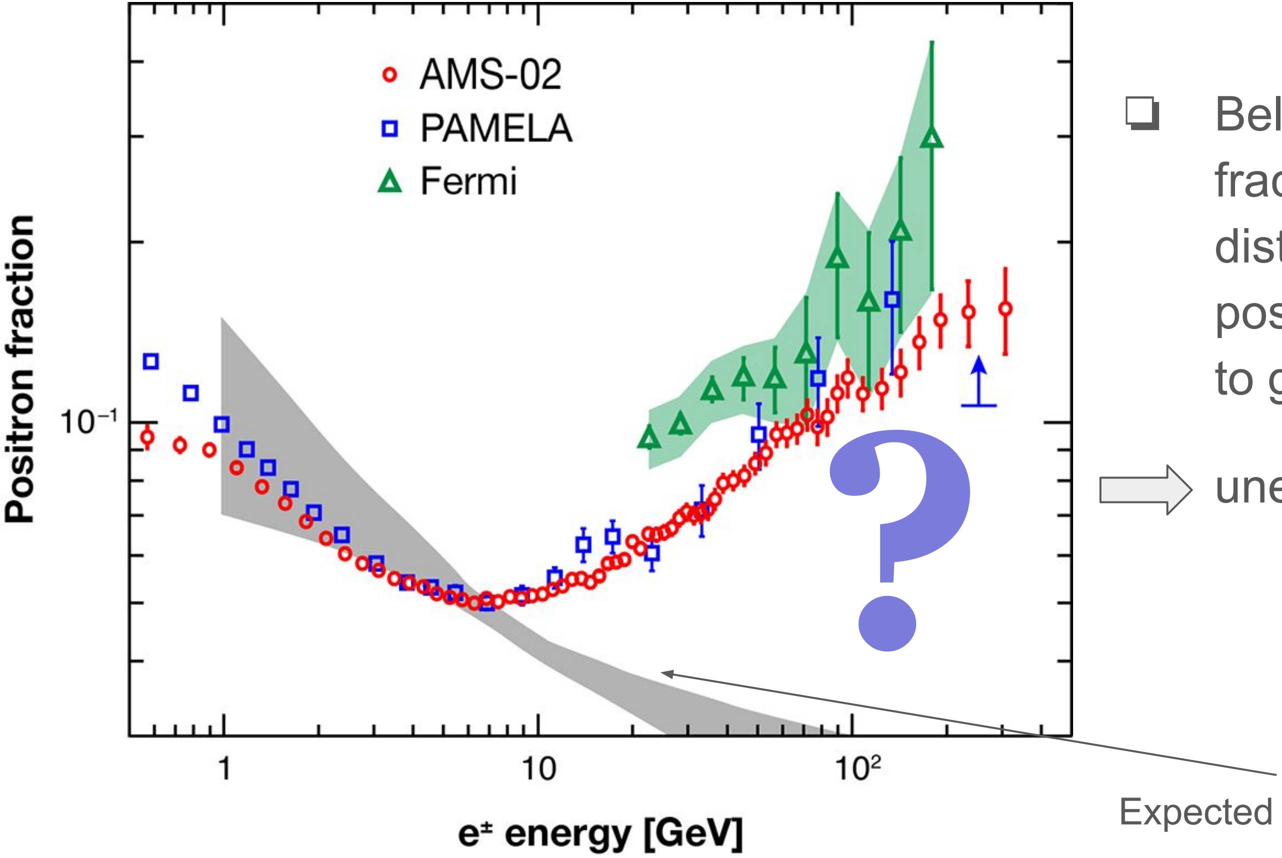


- ❑ For a given particle energy, loss is proportional to $\gamma^2 \propto 1/m^2$

⇨ e- spectrum is softer that protons

- ❑ Positrons are expected to be produced in secondary collisions, as a result of decays of positive mesons (π+,K+ -> μ+ -> e+)

Positron fraction: surprise!



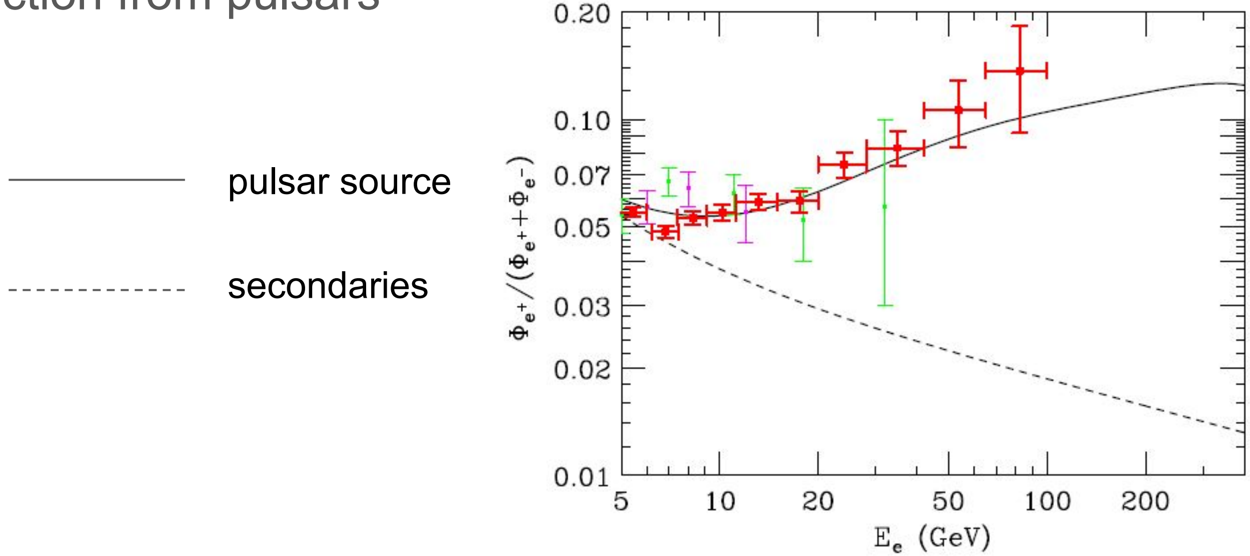
- ❏ Below 10 GeV the e+ fraction has the expected distribution for secondary positrons, but above it starts to grow

⇨ unexpected new source

Expected for secondary positrons

Positrons: interpretation

- Hard to explain with dark matter contribution without a corresponding antiproton signal
- There are astrophysical explanations, as high energy positrons are not so difficult to produce at sources: e+e- pair creation on top of electron acceleration, several models proposed (with large uncertainties)
- Example: production from pulsars

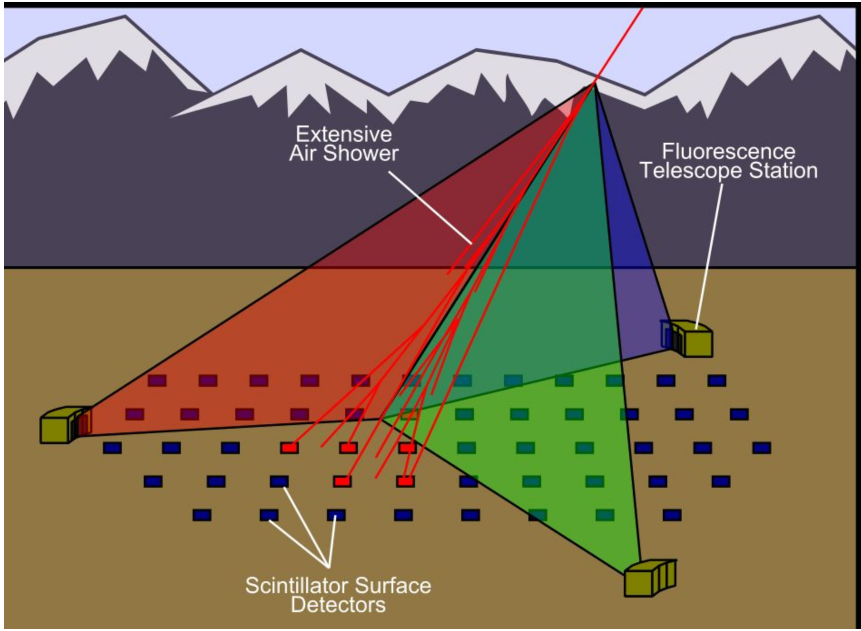


Extensive Air Showers (EAS)

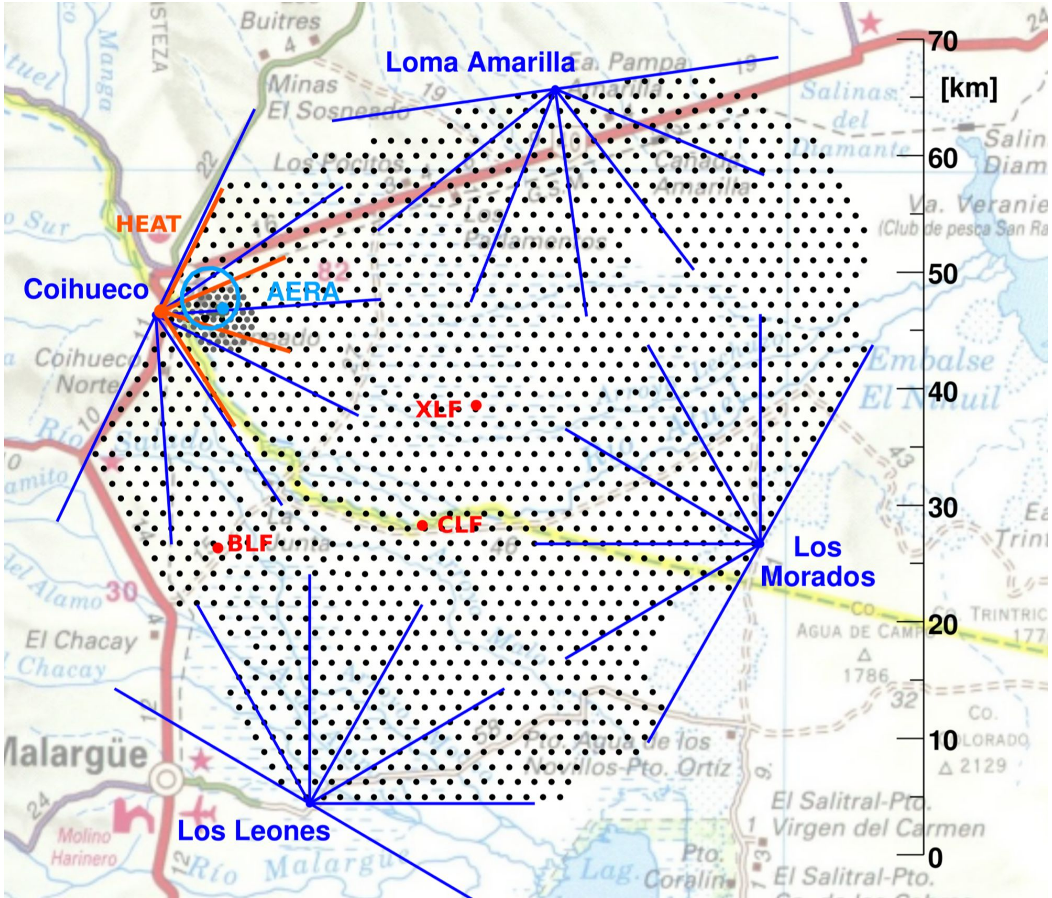
- Highest energy CR, above the knee, are the most interesting to understand the sources. Presently, they can be studies only observing the huge showers produced by their interaction with the atmosphere
- Several techniques:
  - Ground-level **arrays** of detectors (possibly at high altitude), measuring coincident signals of shower charged particles over large areas

    → sensitive to charged particles in the tail of the shower
  - Measure **fluorescence light** (mostly UV) emitted by the ionised air (during clear nights)

    → sensitive to the total electromagnetic energy released in the atmosphere
  - measure radio waves emitted by showers (less accurate technique, being improved recently)

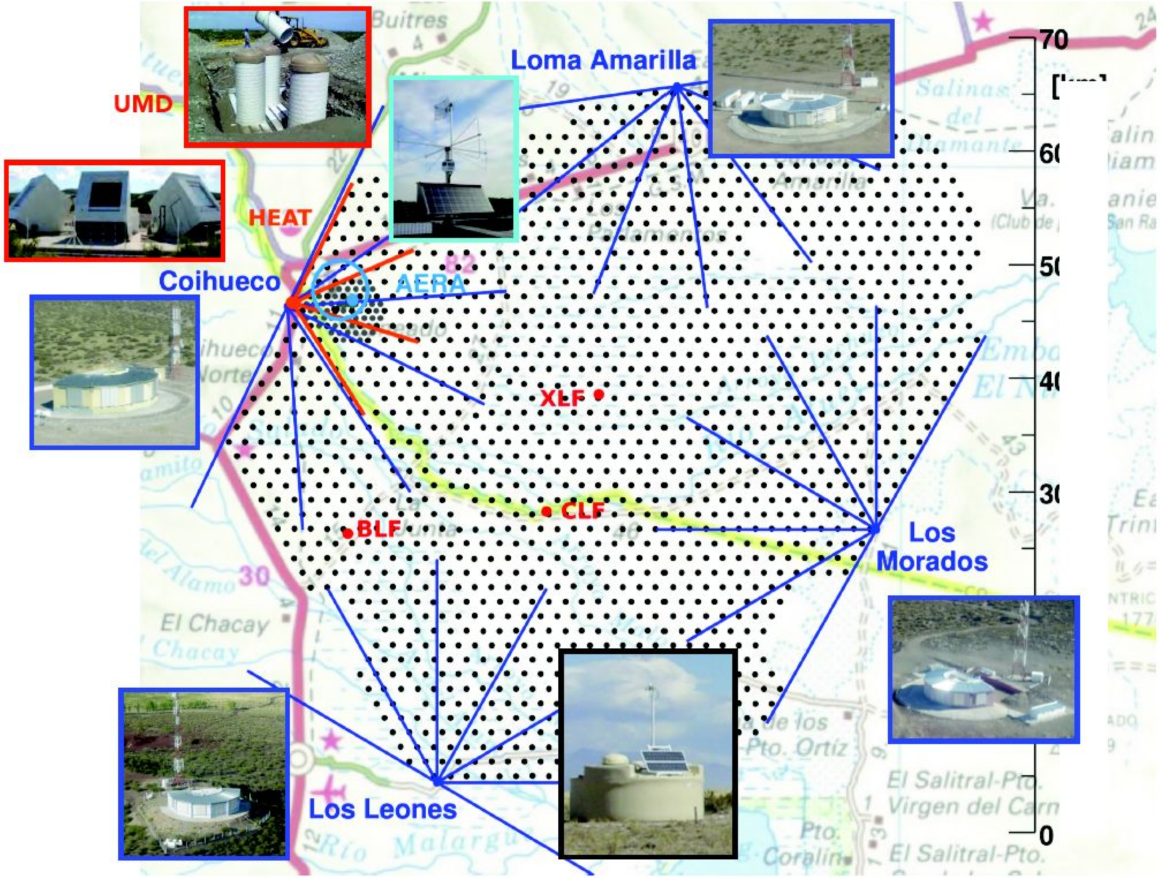


The Pierre Auger Observatory



- Observing extensive air showers from Ultra-High Energy (UHE) cosmic rays (E>0.1 EeV) simultaneously with two techniques:
  - **Water Cherenkov surface detectors**
  - **Fluorescence detectors**
- Covered area of **3000 Km^2**
- Located in a plateau in Argentina, ~ 1400m altitude
- Aims of combined measurements:
  - Distinguish hadron, electron, photon, neutrino-induced showers
  - Determine energy and composition with reduced systematic uncertainty

The Auger Detectors

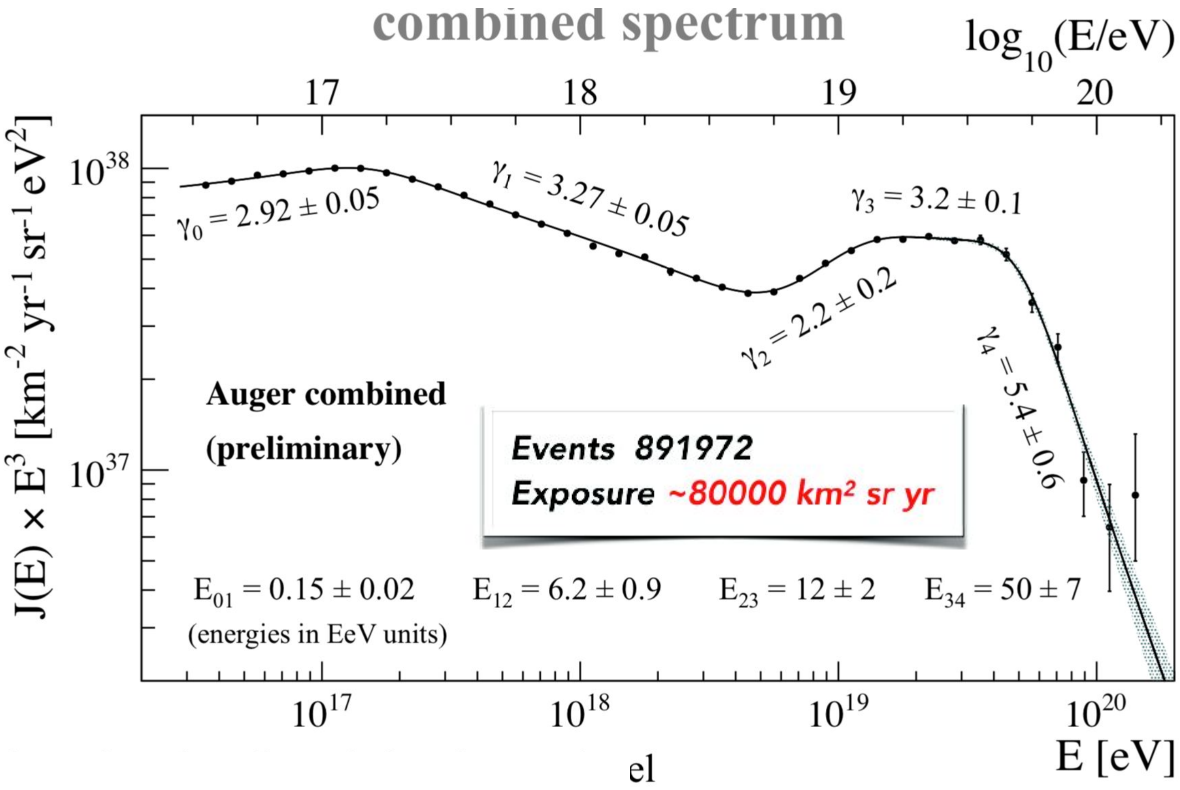


- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km^2
  - ➡SD750 : 61, 0.75 km grid, 25 km^2
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30^0 FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60^0 FoV
- AERA radio antennas
  - ➡153 graded 17 km^2

+Atmospheric monitoring devices
CLF, XLF, Lidars, …

Latest energy spectrum

- ❑ Energy reconstruction heavily relies on simulation. The different measurement techniques cross-checking each-other
- ❑ Systematic error on the energy scale ~ 14%
- ❑ Best determinations so far of the discontinuities in the spectrum: “knees”, “ankle”, and clear confirmation of the GZK cutoff



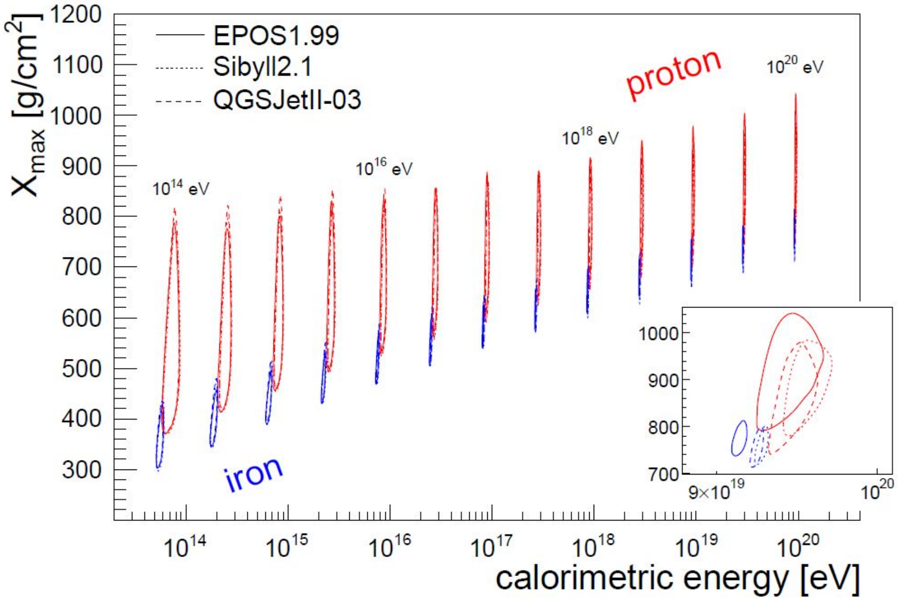
Composition: The Xmax method

- The depth of the shower maximum Xmax and its fluctuation depend on the particle mass number A: protons go deeper into the atmosphere and fluctuate more than heavy nuclei

$$\langle X_{max}\rangle = \langle X_{max}\rangle_p + f_E\langle lnA\rangle$$

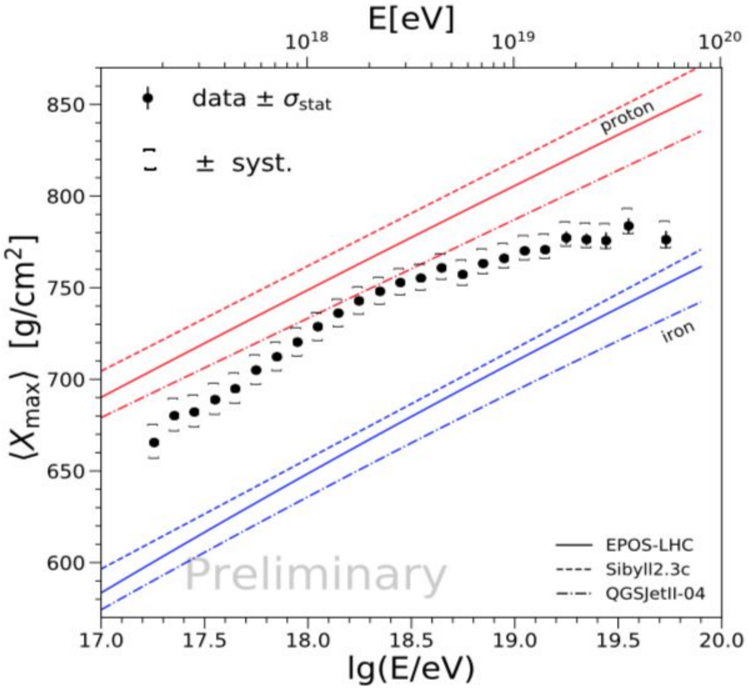
$$\sigma^2(X_{max}) = \langle\sigma^2_{sh}\rangle + f_E\sigma^2(lnA)$$

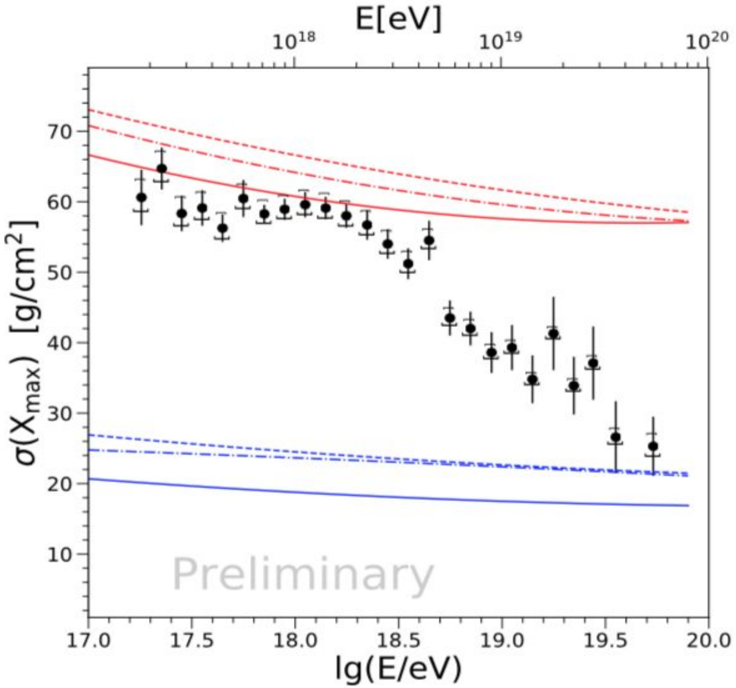
- Not possible to measure A event-by-event, but the average composition can be estimated



Composition Result

- Both the average Xmax and its spread indicate the composition getting lighter below the ankle, and suddenly heavier above the ankle
- Compatible with extragalactic component
- Caveat: large uncertainty due to dependency on shower models

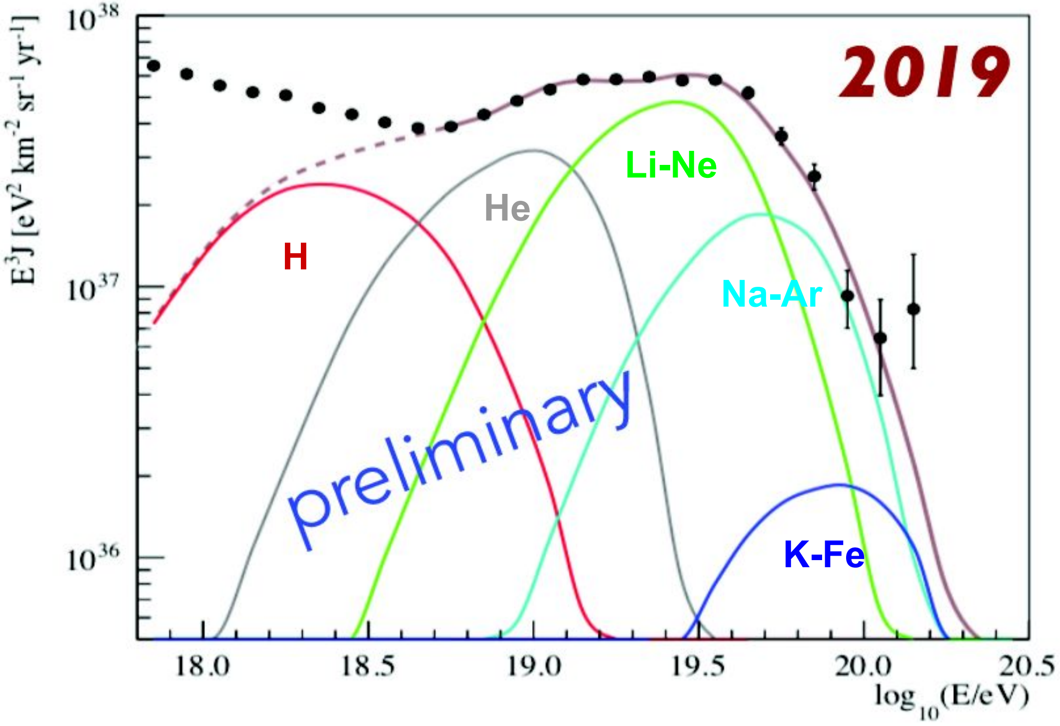




Model-dependent interpretation of UHE CR

- Auger fit their data on energy and composition assuming that CR above the ankle are extragalactic and the acceleration has a rigidity-dependent maximum energy:

$$E_{\max}(Z) = E_{\max}(p)/Z$$



The quest for anisotropy

- The arrival direction of UHE can bring information on the source’s position, if their gyroradius is >~ the source distance
- Auger is trying to identify point sources
- But also large-scale anisotropy, that could be due to the anisotropy of sources, or a dominant source, diffused by extragalactic magnetic fields
- At the lowest order, fit a dipole anisotropy

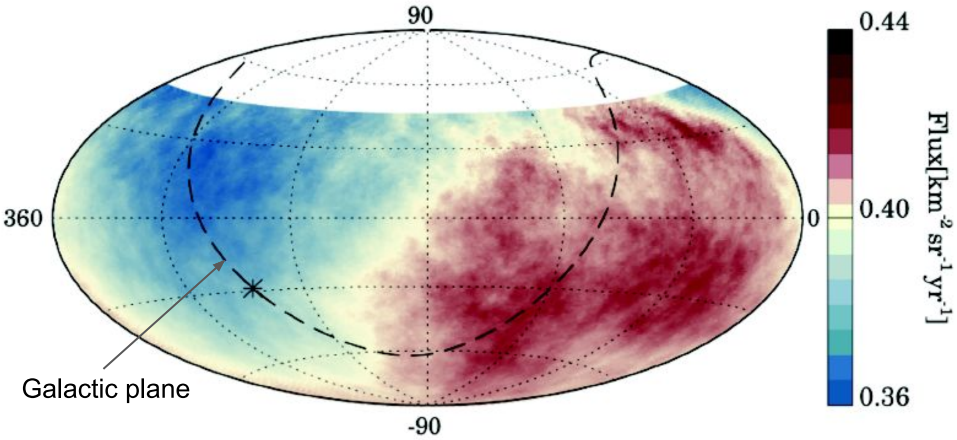
The positive result for the dipole anisotropy announced by Auger in 2017, not related to the galactic plane, is considered to be the **first evidence for the extragalactic origin of UHE cosmic rays**

physicsworld
TOP 10
BREAKTHROUGH
2017

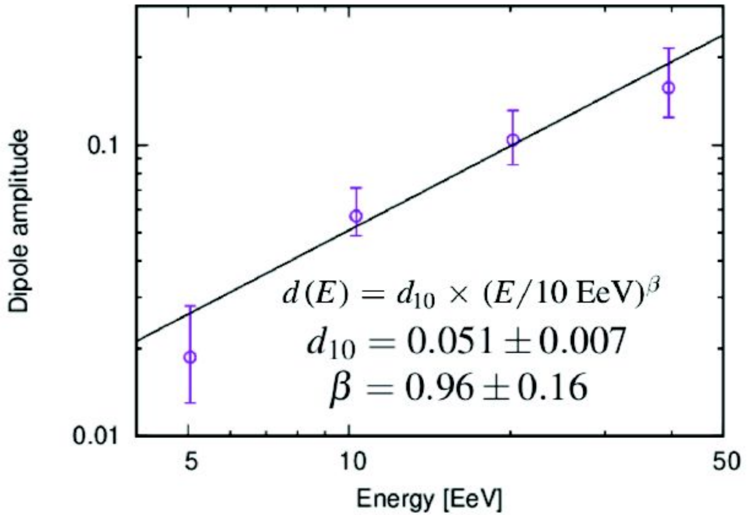
Large scale anisotropy

Energy [EeV] interval	Energy [EeV] median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,317	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	70 ± 34	-57^{+24}_{-20}
≥ 8	11.5	36,924	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11

Exposure >92000 km²sr yr
for events with $\vartheta<80^0$



Equatorial coordinates



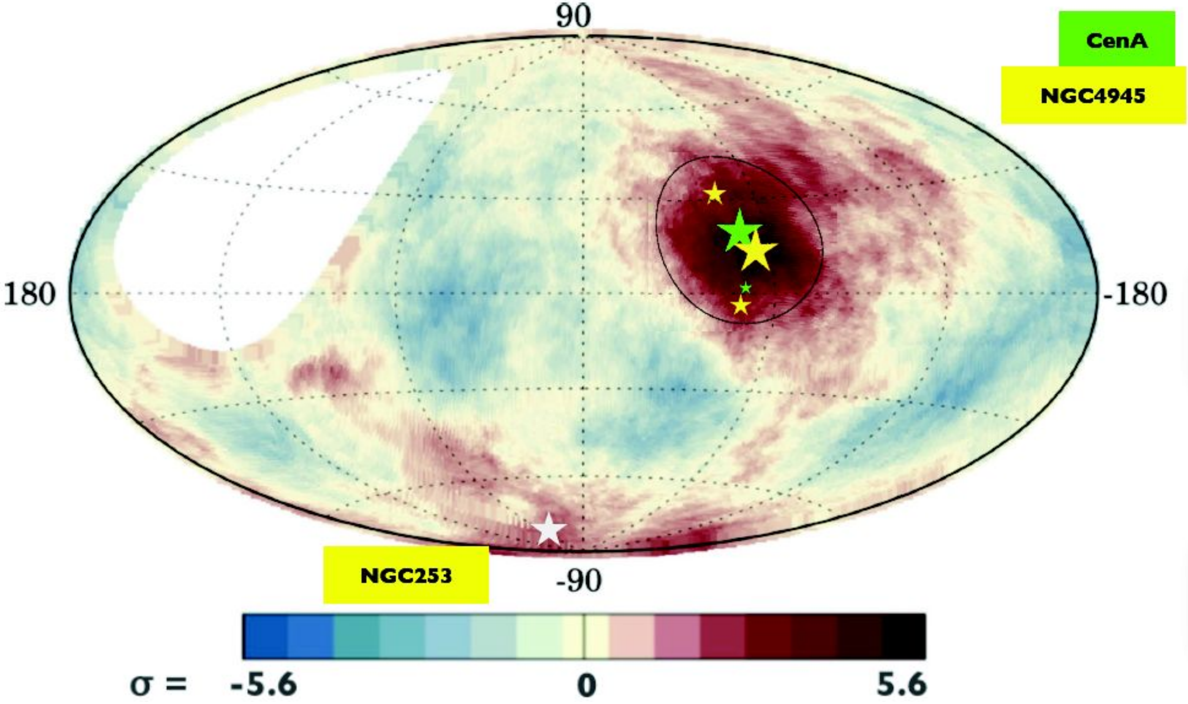
3-D Dipole above 8 EeV at (α,δ) = (98°,-25°) : $(6.6^{+1.2}_{-0.8})\%$
Amplitude increasing with energy

Result for point sources

First significant local excess identified, best match is radio-galaxy Centaurus A

Total SD events with E>32 EeV : 2157

Total exposure 101,400 km^2 sr yr



Blind search

Scan ranges:

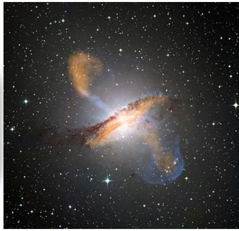
$32 \text{ EeV} \le E_{th} \le 80 \text{ EeV}$ (1 EeV steps)

$1° \le \psi \le 30°$ (1° steps)

Most significant excess for E>38 EeV
($\alpha=202^{0}$, $\delta= -45^{0}$) ~2^{0} from CenA

Centaurus A

3.9 σ effect (post-trial)
for E>37 EeV, 28^{0} window



Summary

- Current generation of space experiments reached % accuracy on energy spectrum and composition between ~0.02 and ~100 GeV
  - precise constraints to acceleration and propagation models
  - high sensitivity to dark matter contributions

- Ultra-High energy cosmic rays start to provide informations on their astrophysical source
  - a novel tool for multi-messenger astrophysics