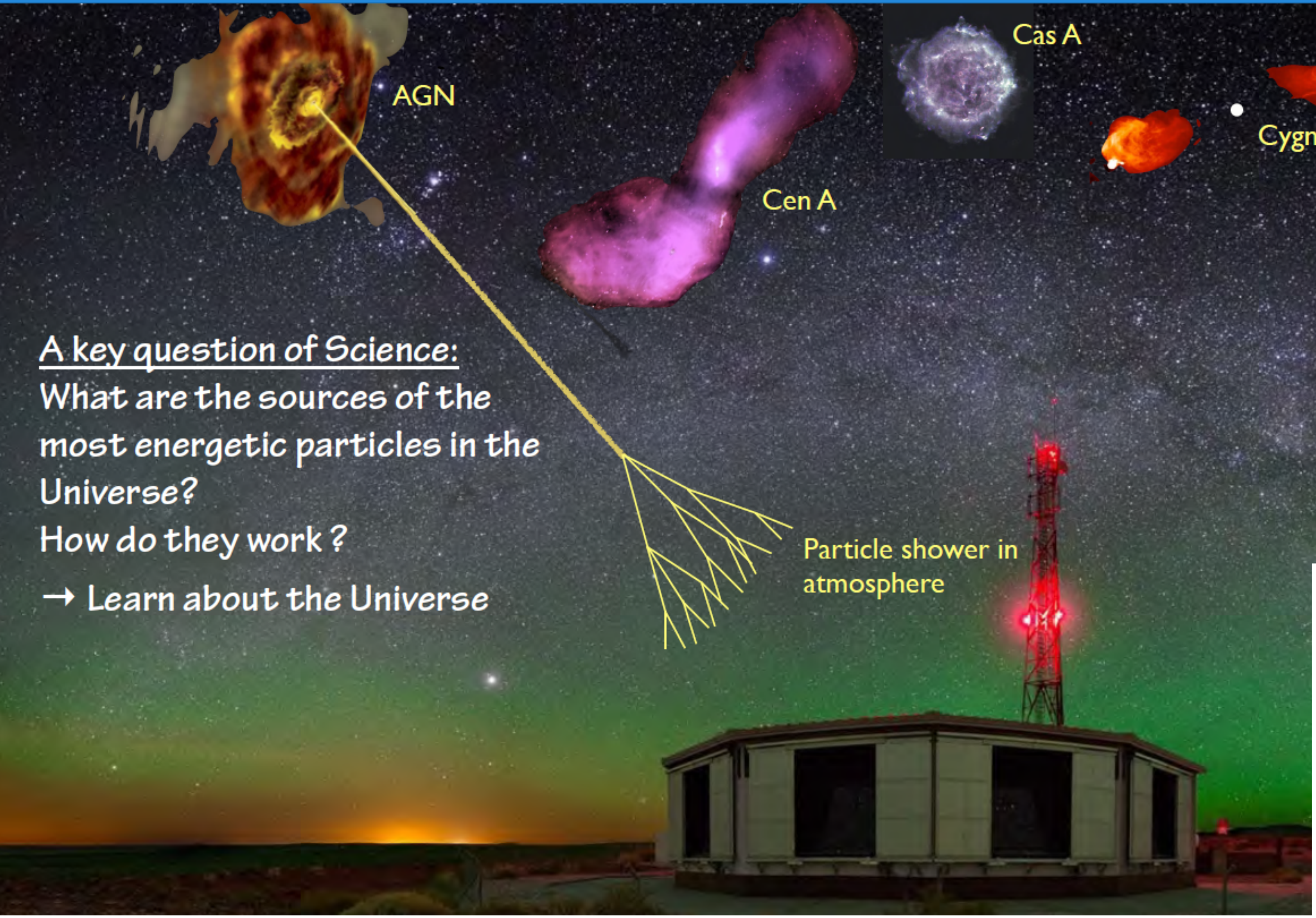
The Pierre Auger Observatory

Recent results and Auger Prime upgrade

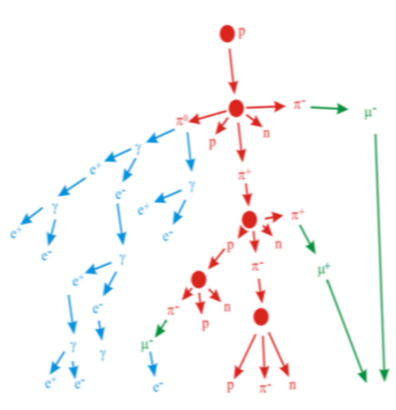
Humberto Salazar

DRC 2019

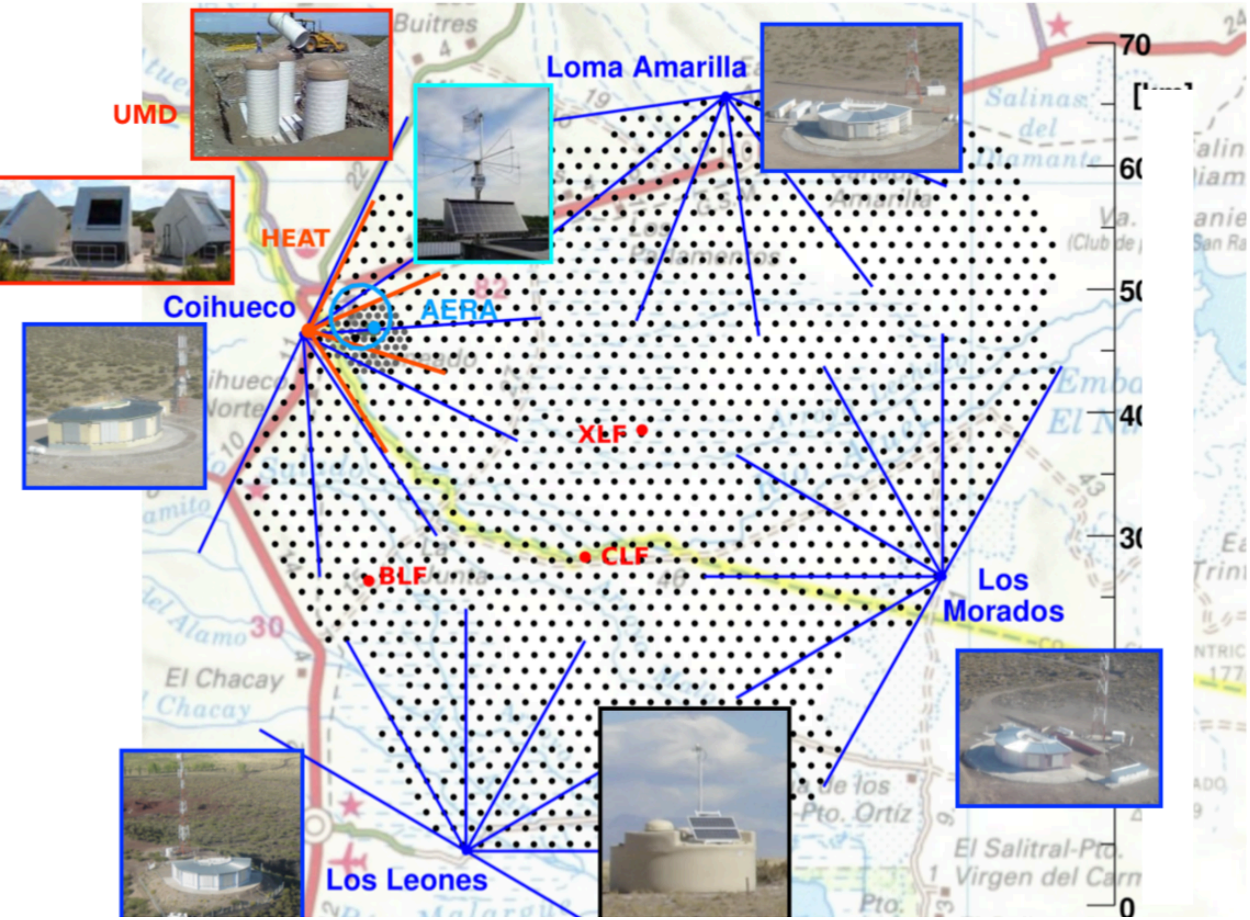
UHECR



AGN
Cen A
Cas A
Cygnus A
A key question of Science:
What are the sources of the most energetic particles in the Universe?
How do they work ?
→ Learn about the Universe
Particle shower in atmosphere



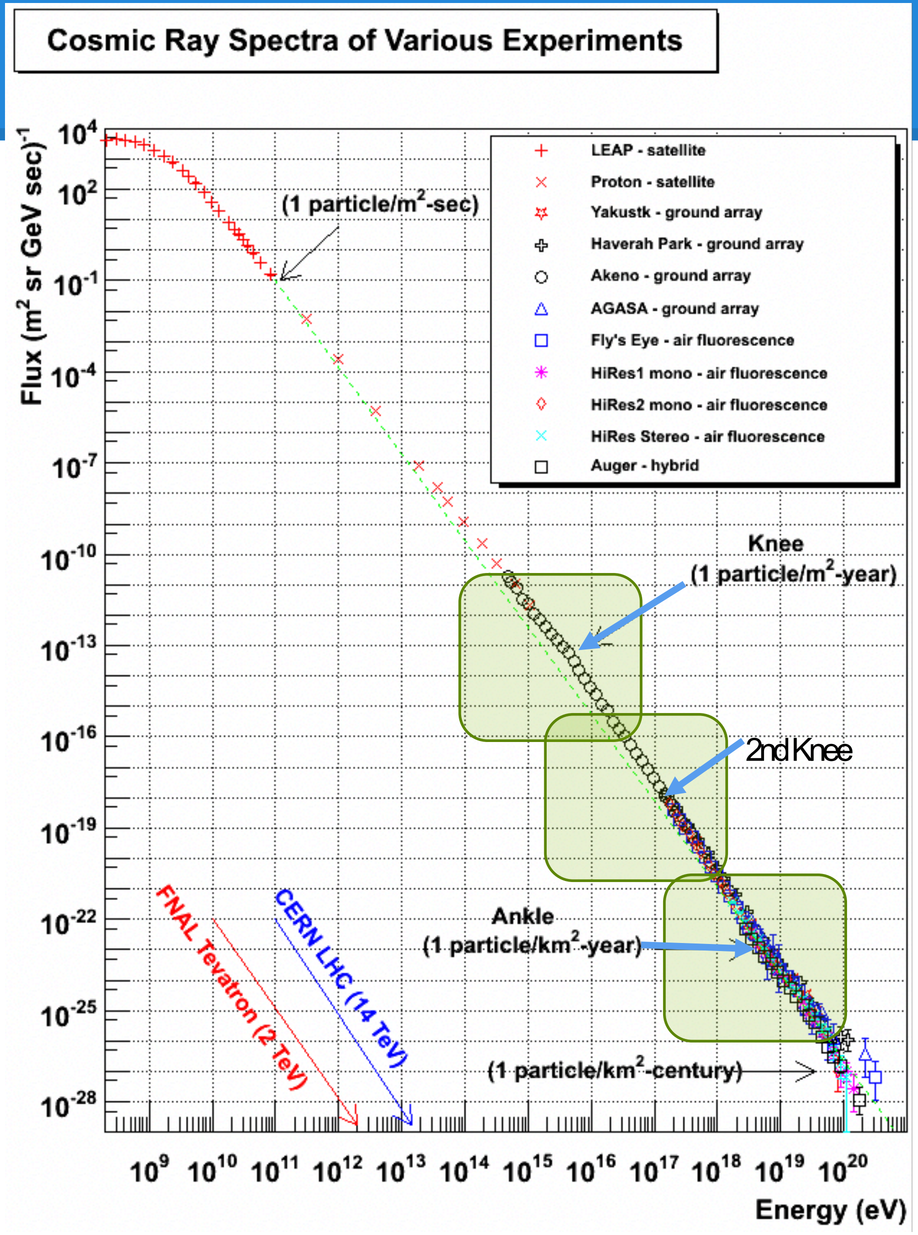
The PA Observatory



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km²
  - ➡SD750 : 61, 0.75 km grid, 25 km²
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30⁰ FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60⁰ FoV
- AERA radio antennas
  - ➡153 graded 17 km²

+Atmospheric monitoring devices CLF, XLF, Lidars, …

Motivación



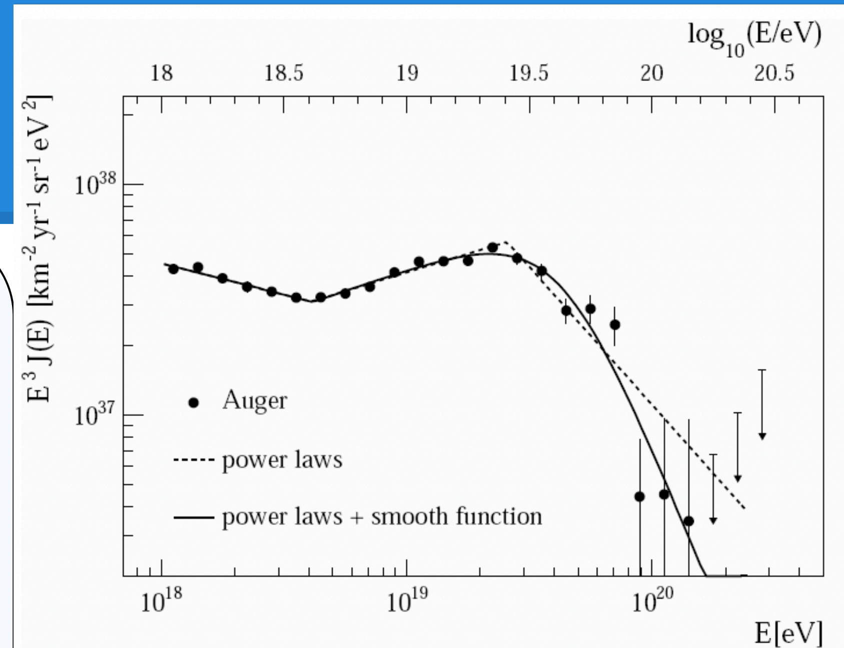
Espectro de Energía

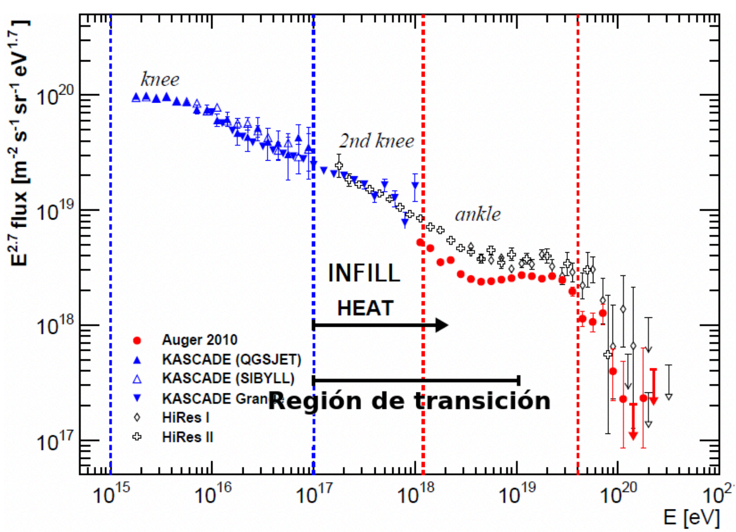
- Sigue una ley de potencias $dN/dE \propto E^{-\gamma}$
- (Knee) ~ 5×10^{15} eV, γ: 2.7-3.1
- (2nd Knee) ~ 4×10^{17} eV, γ: 3.1-3.3
- (Ankle) ~ 4×10^{18} eV, γ: 3.3-2.7

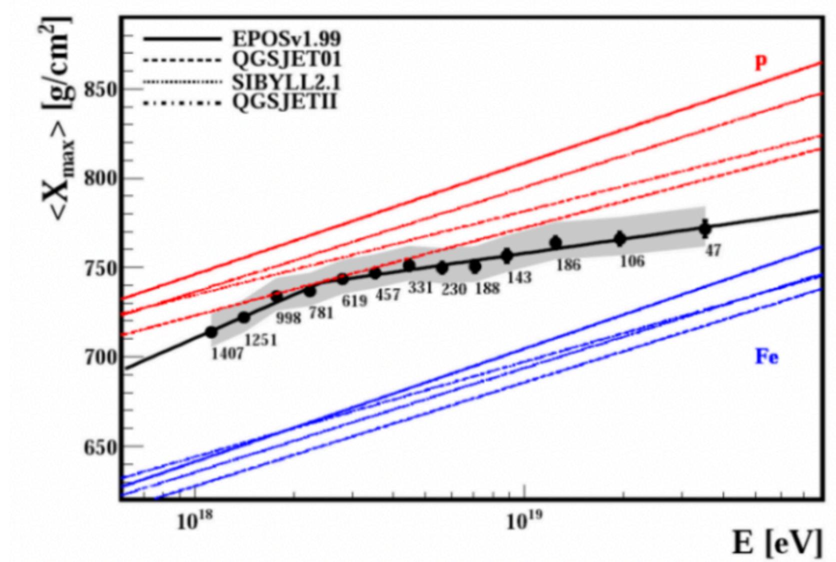
Motivación

Pierre Auger (Extensión 10^{17} eV)

- Inicialmente estudiar el Espectro y $\langle X_{max} \rangle$ para energías > 10^{18} eV
- Mejoras (2010) extender observaciones desde 10^{17} eV
- Incluir región donde "está sucediendo" la transición de fuentes galácticas a extragalácticas



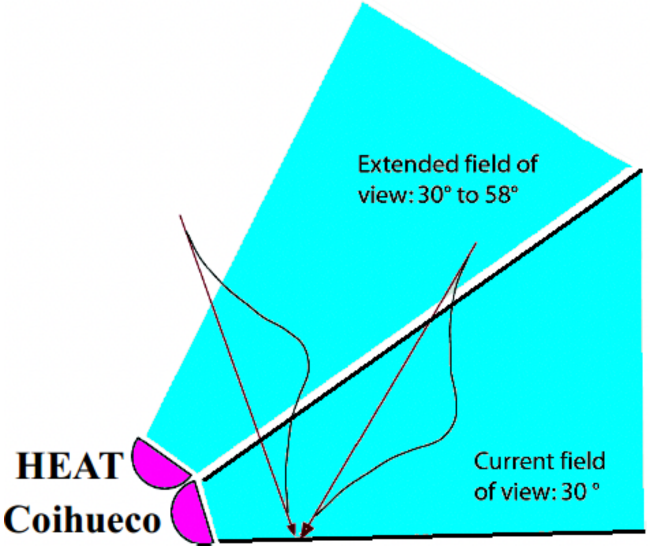


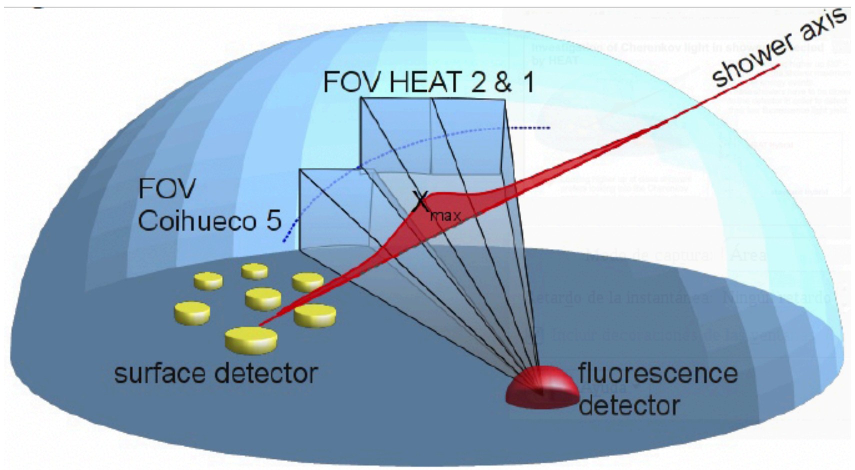


Extensiones FD

High Elevation Auger Telescopes
HEAT

- 3 Telescopios con FOV de 30⁰-60⁰
- A 180 m del sitio Co y en el campo de visión de la extensión del SD
- 2 modos de operación

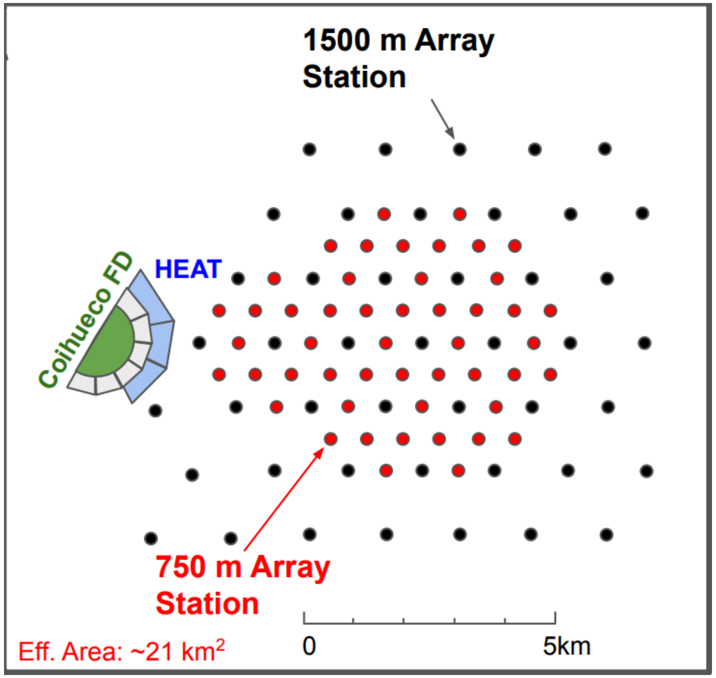


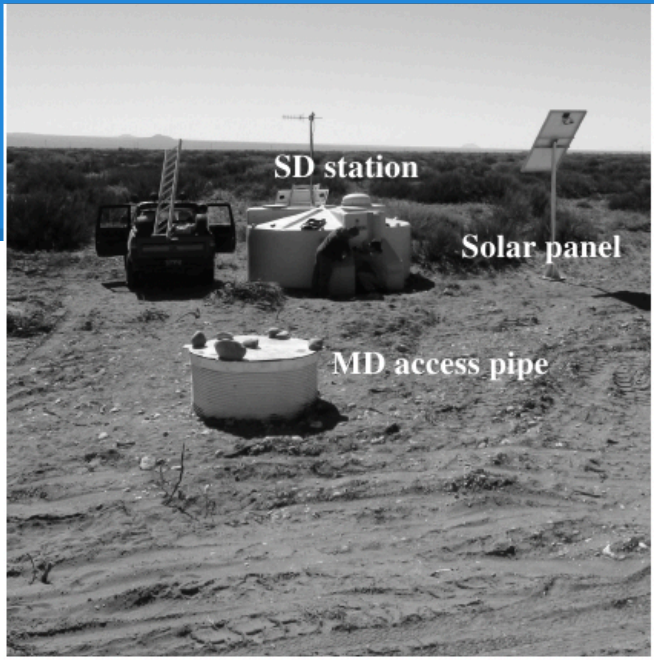


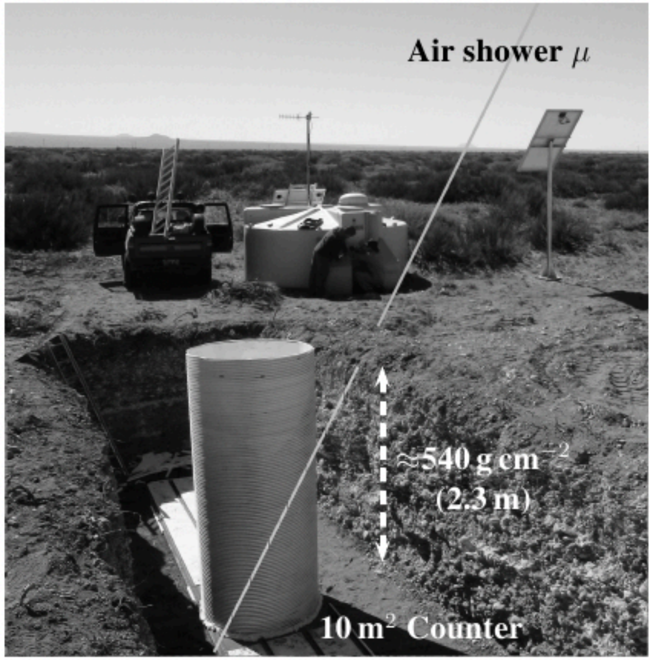
Extensiones SD

Auger Muons for the Infill Ground Array
AMIGA

- 66 WCD, con una separación a 750 m
- Muon Detector (MD), 7 en la fase del arreglo de ingeniería
- Infill cerca y en el FoV de HEAT ➡ Eventos híbridos de baja energía

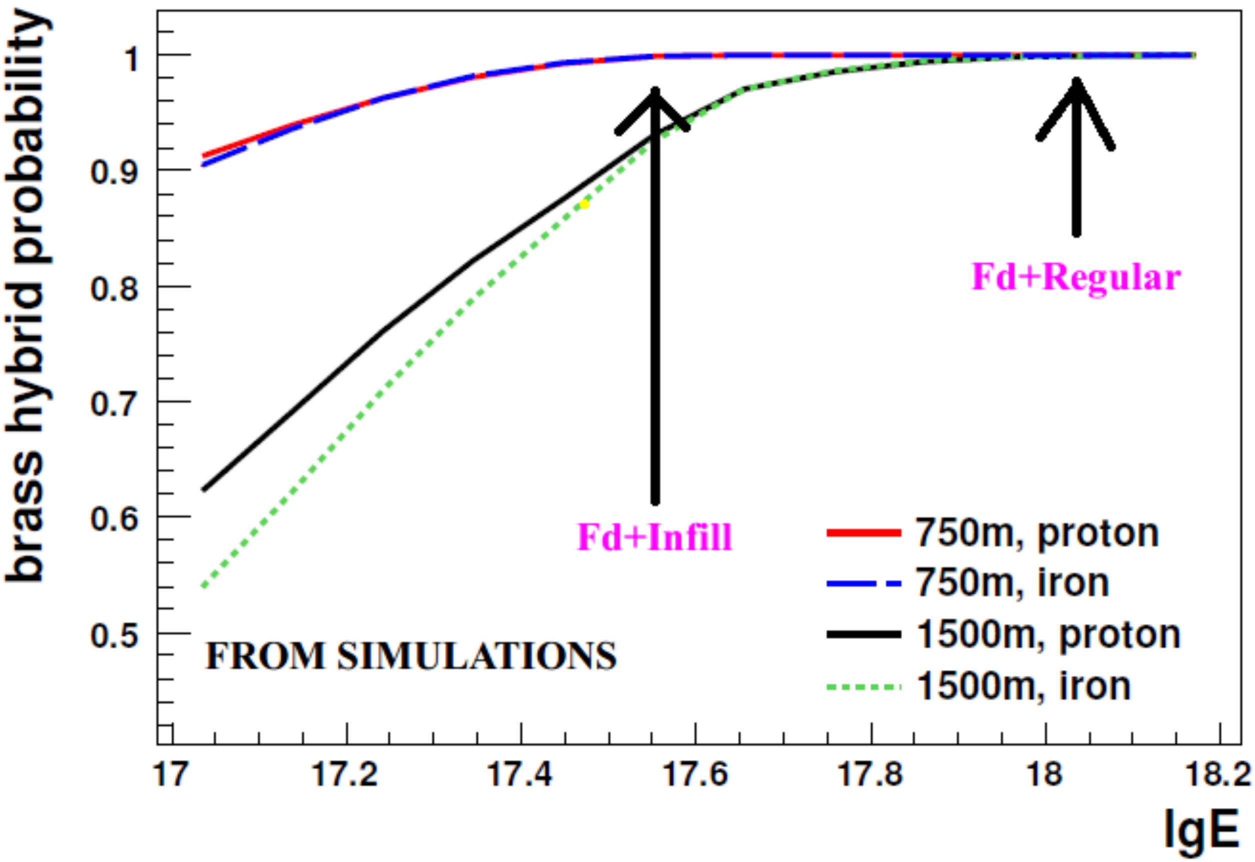






Eficiencia de disparo de eventos híbridos

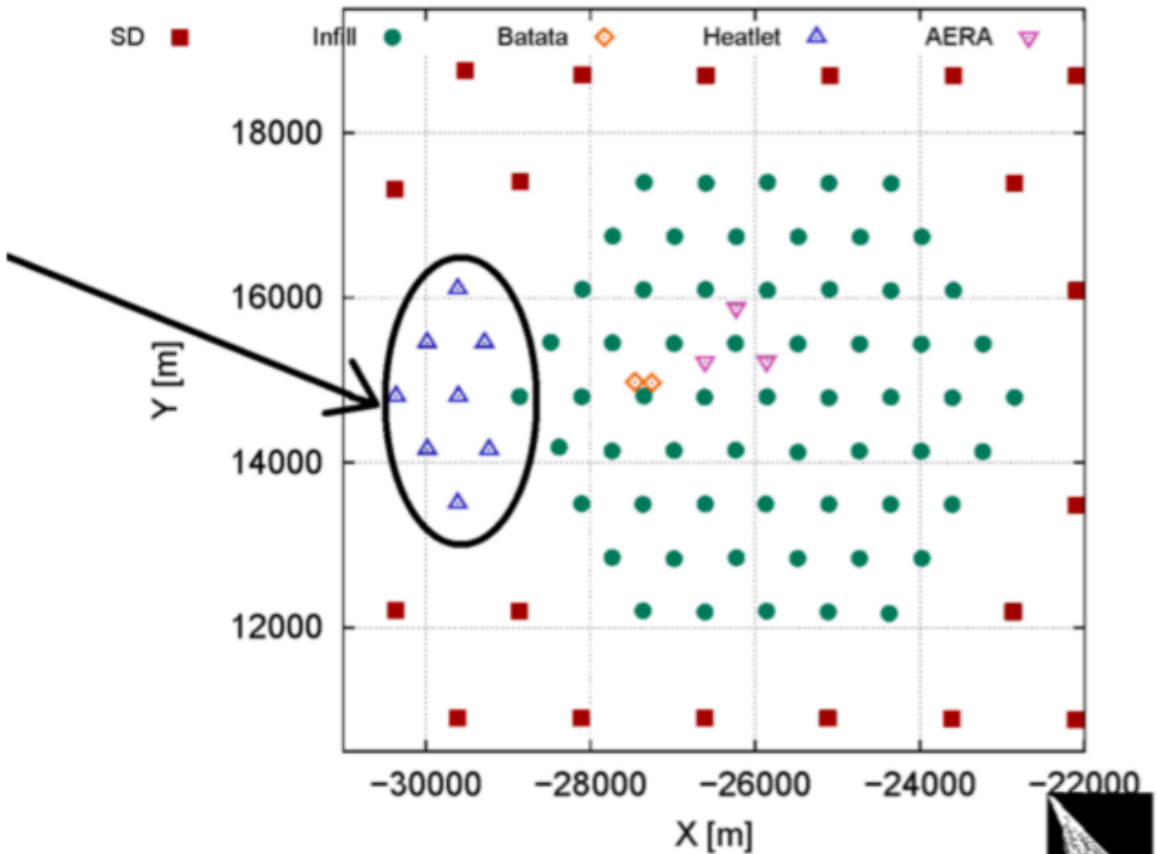
Un evento híbrido es medido con el FD y al menos UNA estación del SD



Añadiendo estaciones más cerca de HEAT podemos aumentar la eficiencia a energías más bajas

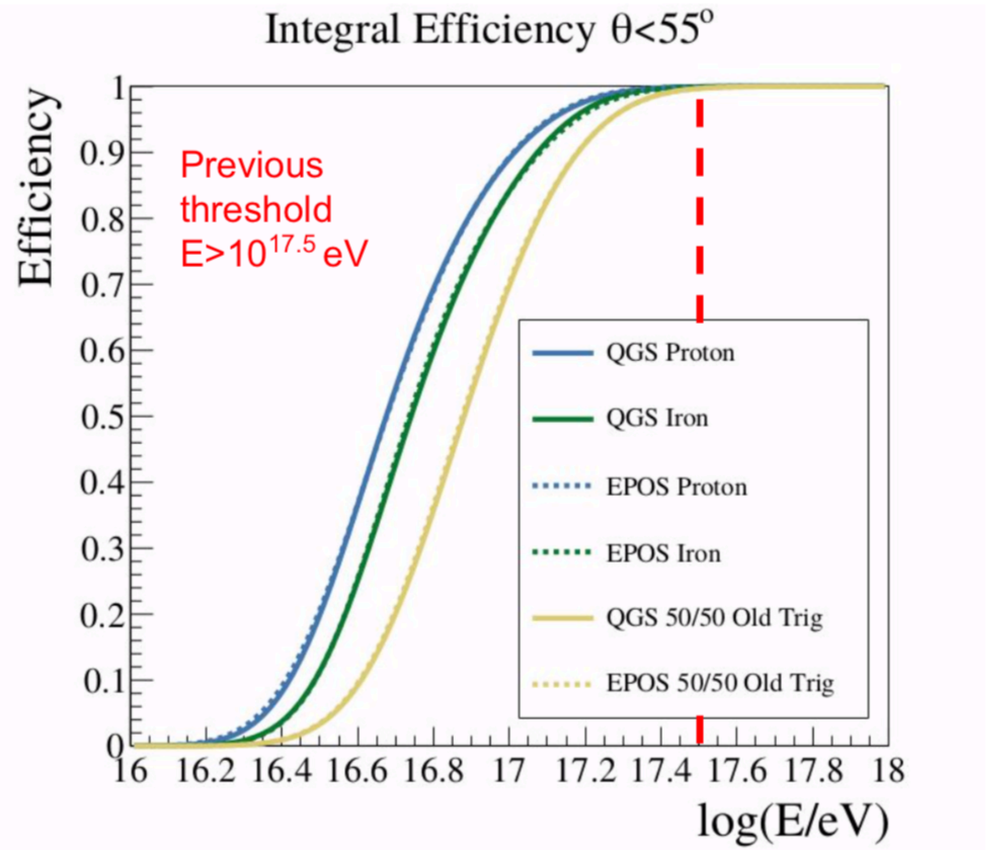
HEATLET

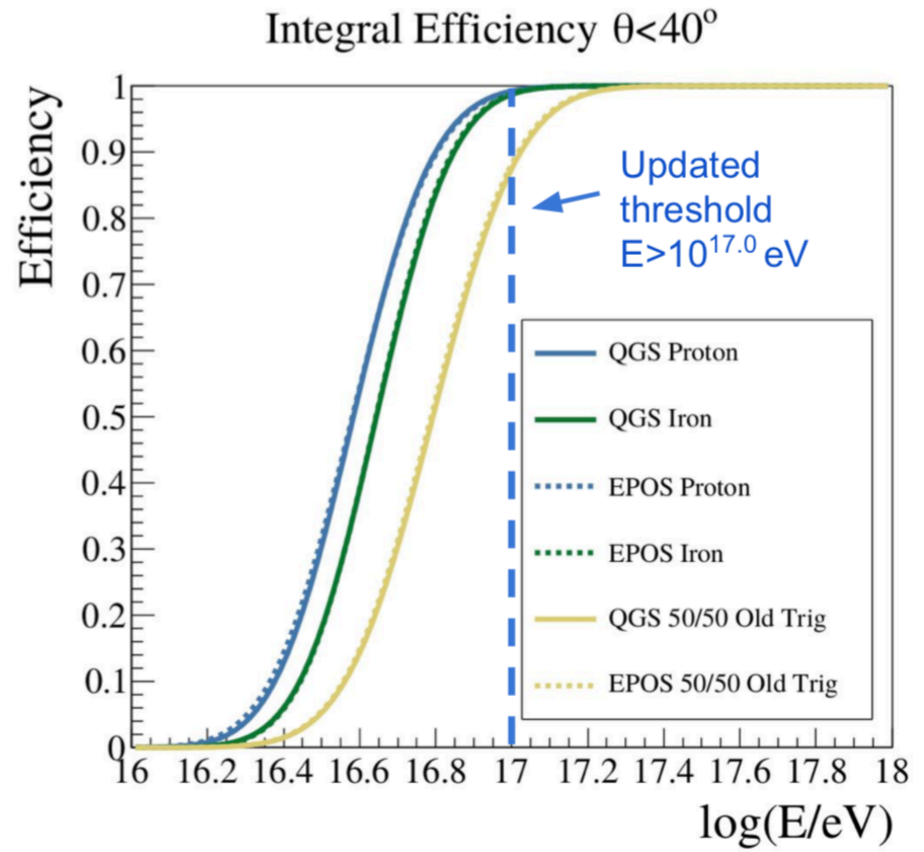
- HEAT Low Energy Trigger ⟹ Aumento de de la eficiencia de detección híbrido, sin necesidad de Corrección con Simulaciones
- Arreglo de 9 tanques (750 m separación)
- HEATLET muy cerca y en el FoV de HEAT ⟹ eventos híbridos de muy baja energía.



Resultados: Espectro de energía

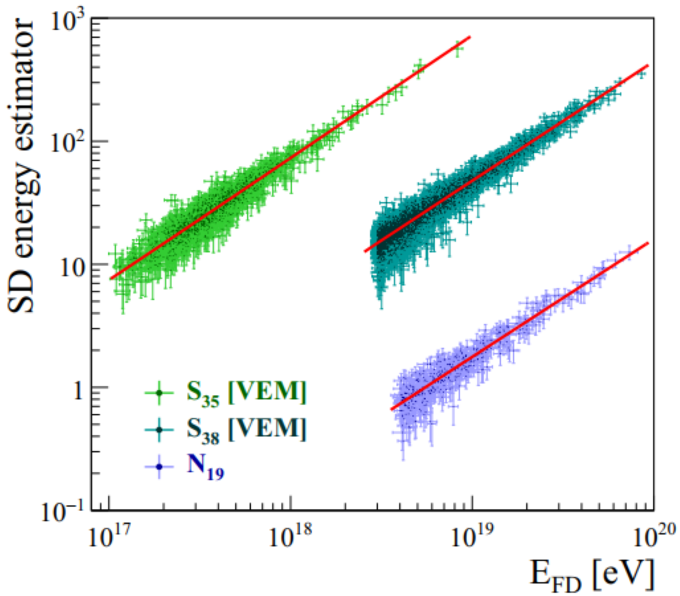
Cambio de umbral de eficiencia $(\theta < 55^o, E > 10^{17.5}\,eV)$ to $(\theta < 40^o, E > 10^{17.0}\,eV)$



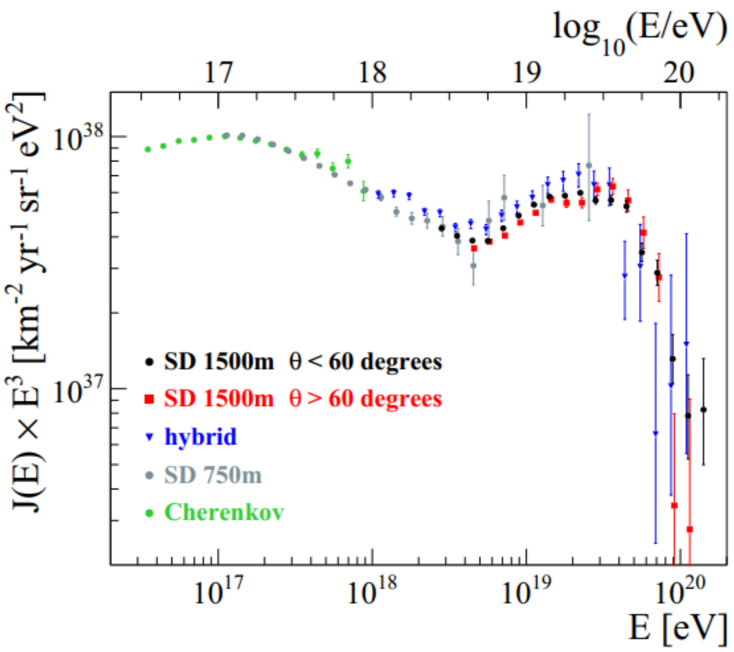


Astrophysics of UHE cosmic rays

Energy spectrum



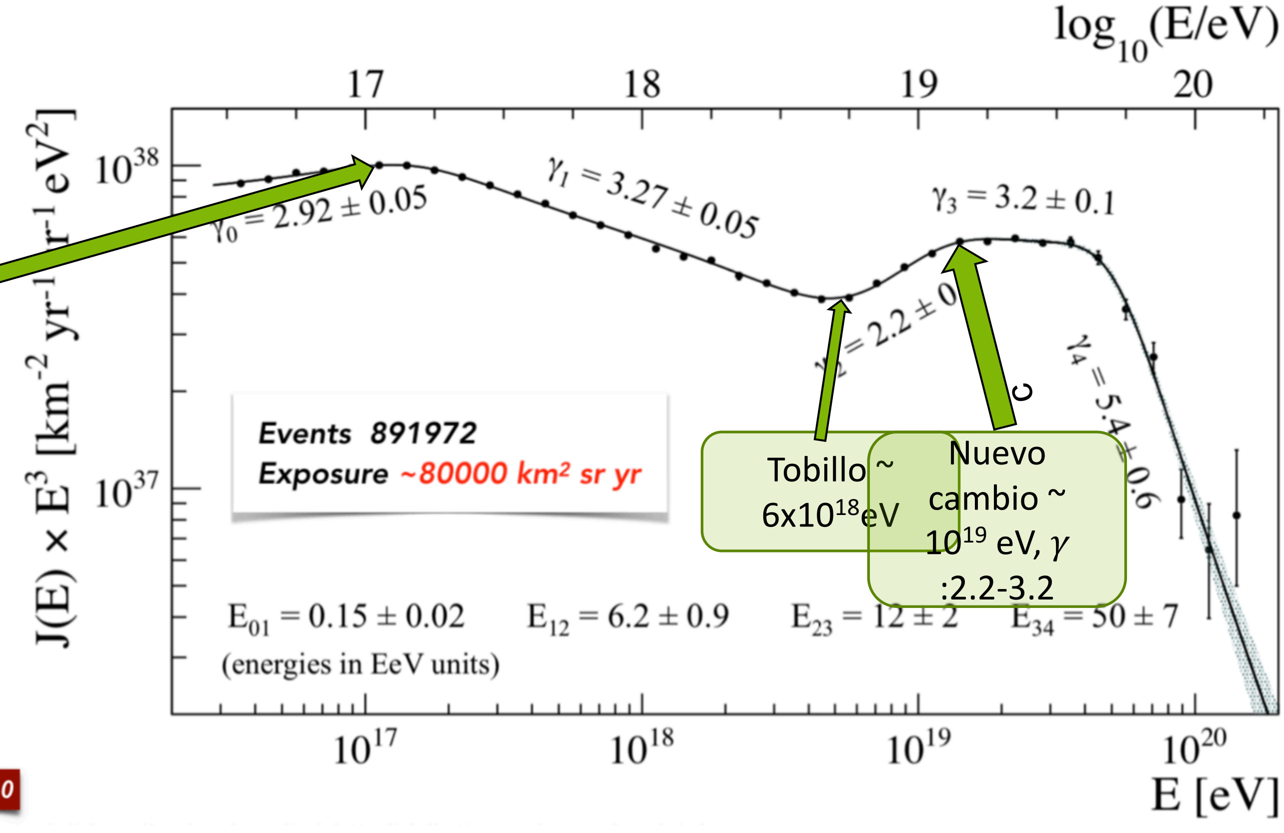
Correlation between the FD energy and the SD energy estimators as measured using the different data sets



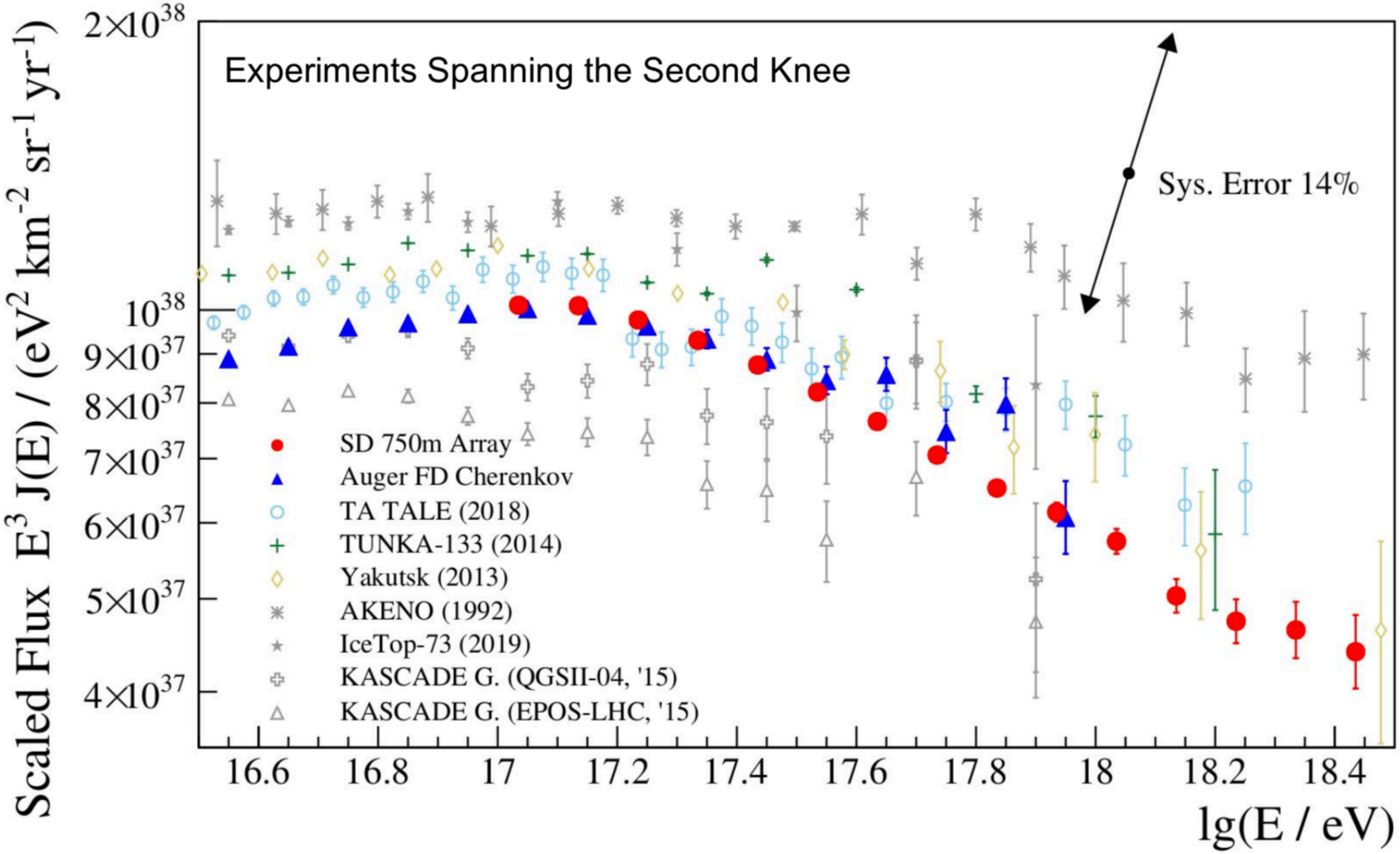
Energy spectra measured at the Pierre Auger Observatory

Resultados: Espectro de energía

- Combinando resultados del nuevo espectro cherenkov, es posible ver la 2da rodilla alrededor de $10^{17.15}$ eV
- El espectro se ha medido desde $10^{16.5}$ eV hasta $10^{20.2}$ eV.

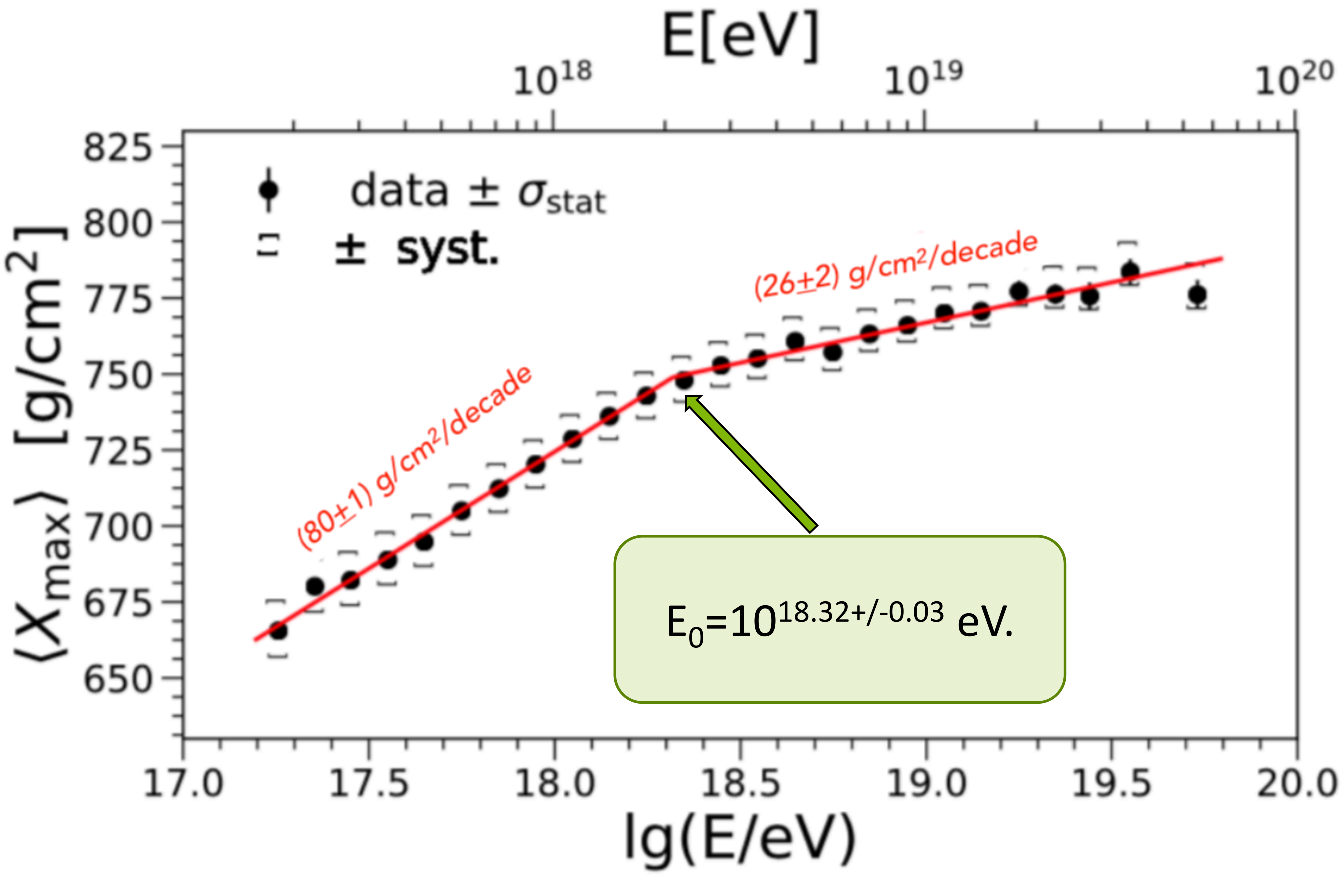


Resultados: Espectro de energía (2a rodilla)

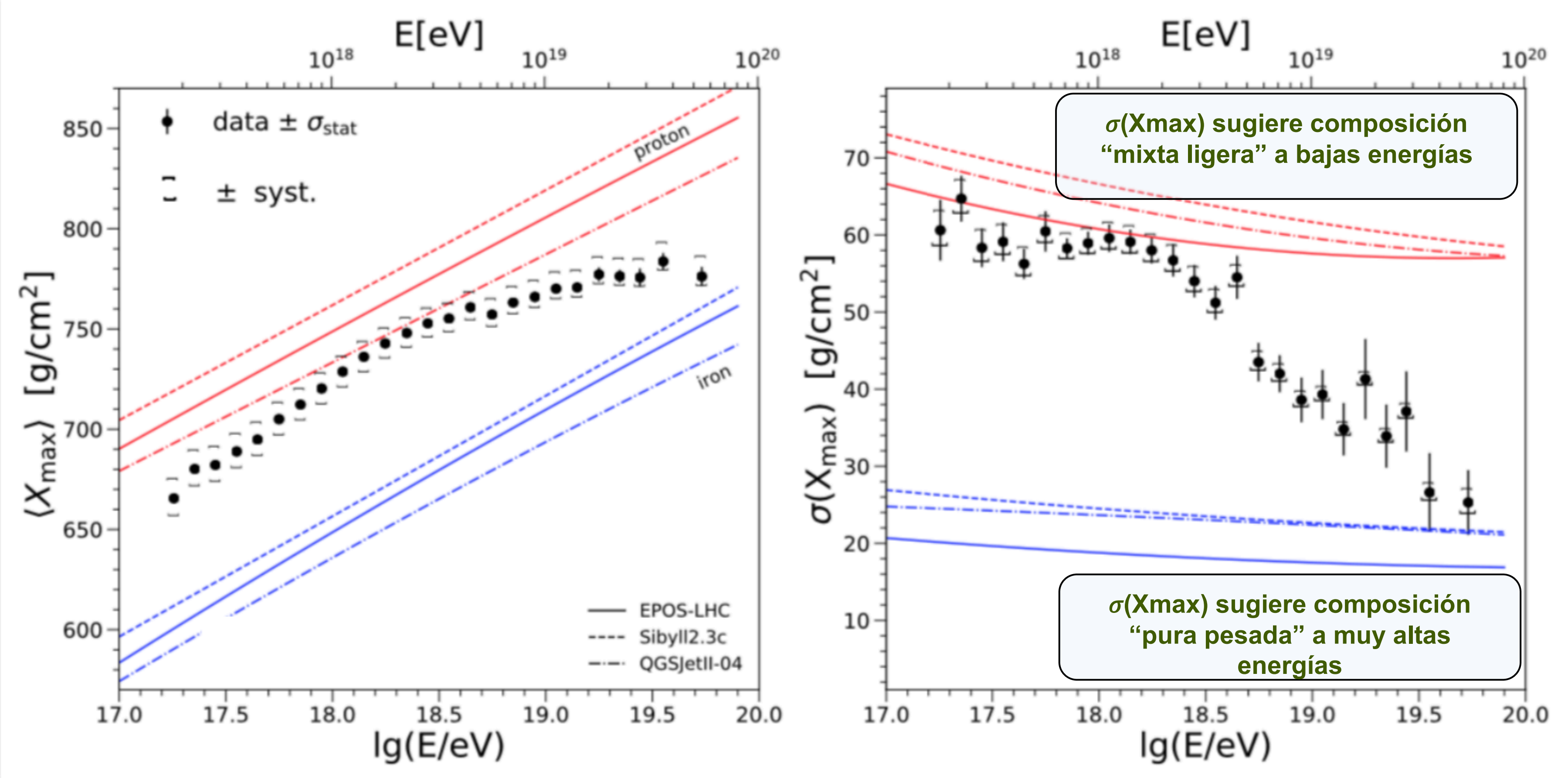


Resultados: Evolución de <X_{max}> con la Energía

- **Tendencia de Composición ligera hasta E_0**
- **Tendencia de composición intermedia-pesada por arriba de E_0**

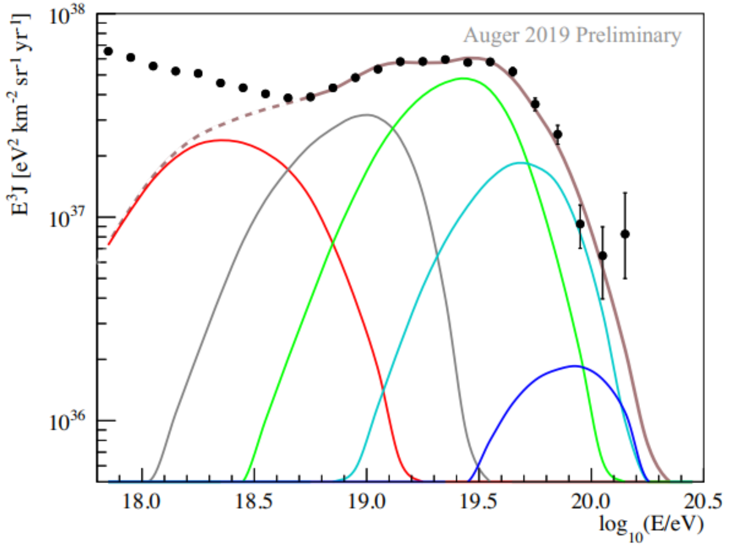


Resultados: <X_{max}> y sus fluctuaciones

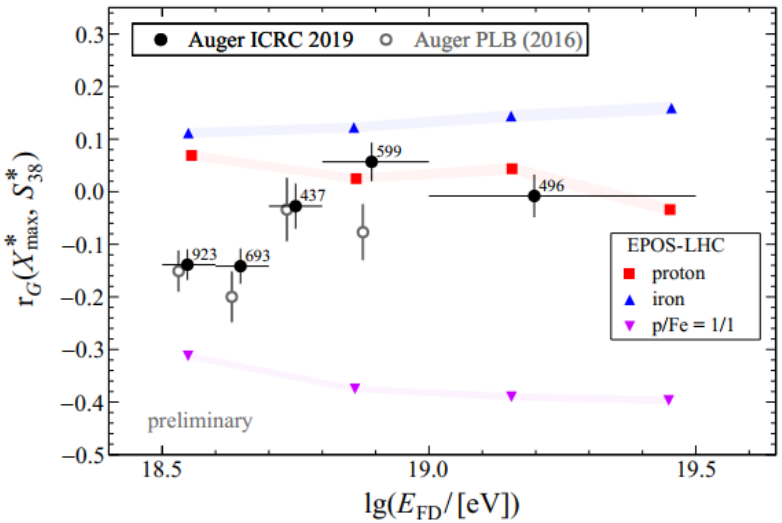


Astrophysics of UHE cosmic rays

Multi-messengers



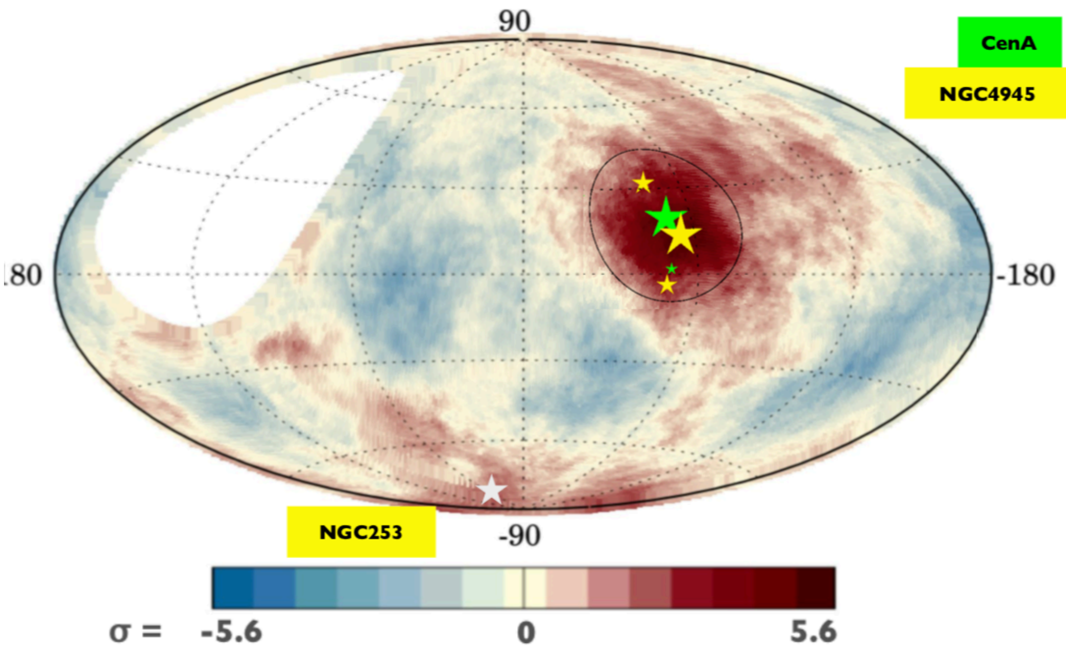
The simulated energy spectrum (multiplied by E^3) at the top of the Earth's atmosphere obtained with the best fit parameters: all-particle (brown curve), $A = 1$ (red), $2 \leq A \leq 4$ (grey), $5 \leq A \leq 22$ (green), $23 \leq A \leq 38$ (cyan), $A \geq 39$ (blue). The combined energy spectrum as measured by Auger is shown for comparison with the black dots.



The first two moments of the X_{max} distributions as predicted for the model (brown curve) versus pure compositions. Only the energy range indicated by the solid brown line is included in the fit. The measured mean X_{max}^{SD} are shown with purple triangles for comparison

Resultados: Anisotropias

Total SD events with E>32 EeV : 2157
Total exposure 101,400 km² sr yr



Blind search

Scan ranges:
32 EeV ≤ Eth ≤ 80 EeV (1 EeV steps)
1° ≤ ψ ≤ 30° (1° steps)

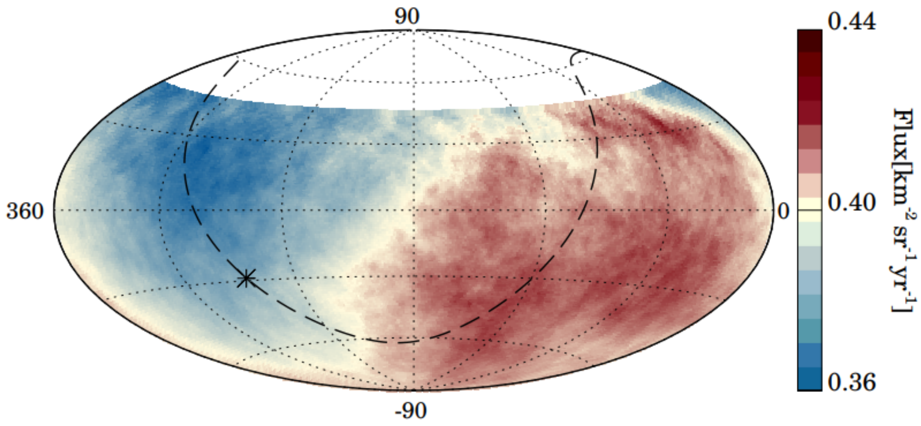
Most significant excess for E>38 EeV
(α=202°, δ= -45°) ~2° from CenA

Centaurus A

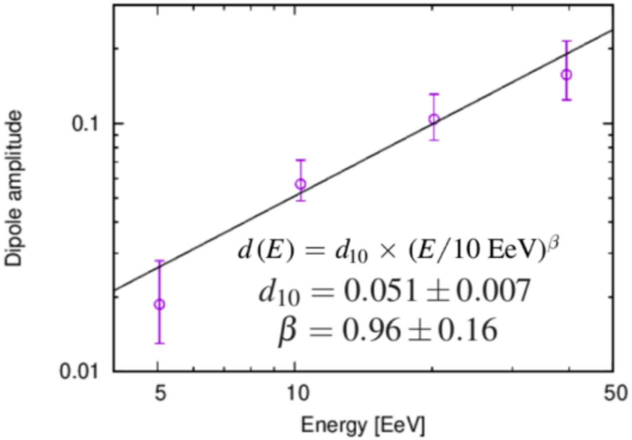
3.9 σ effect (post-trial)
for E>37 EeV, 28° window

Astrophysics of UHE cosmic rays

Arrival directions



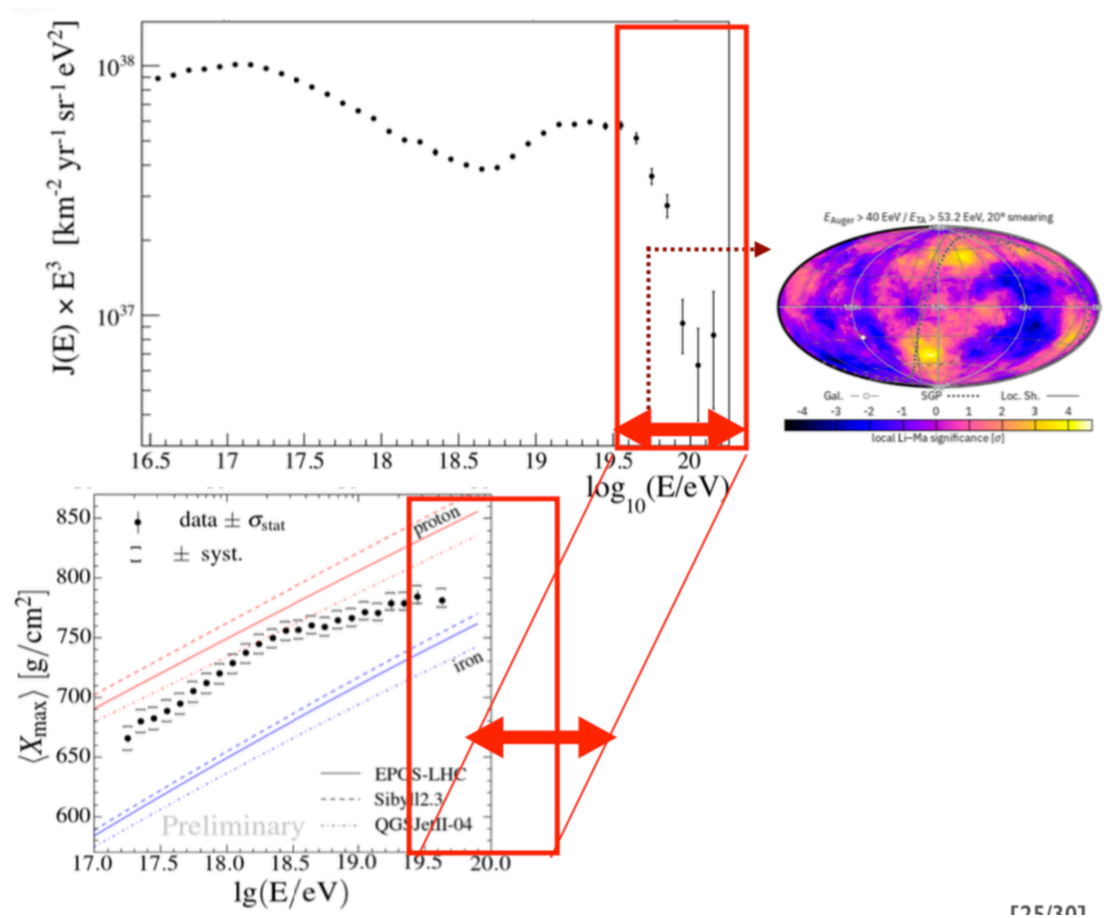
The CR flux above 8 EeV, averaged on top-hat windows of 45◦ radius (equatorial coordinates). The Galactic plane and the Galactic center are indicated by a dashed line and a star respectively.



Energy dependence of the dipolar amplitude measured in four energy bins above 4 EeV

Perspectivas Upgrade

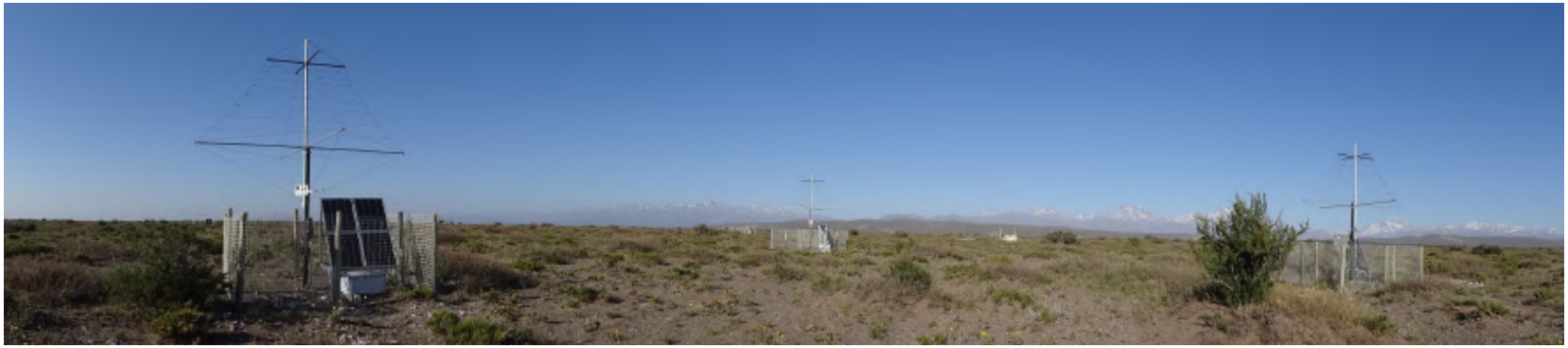
- Estudiar el origen de la supresión
- Estudio de interacciones hdrónicas a UHE, busqueda de física “no estandar”
- Separación componente muónica-electromagnética (composición)
- Extender operaciones hasta 2025 (más estadística)



Detectors and AugerPrime Upgrade

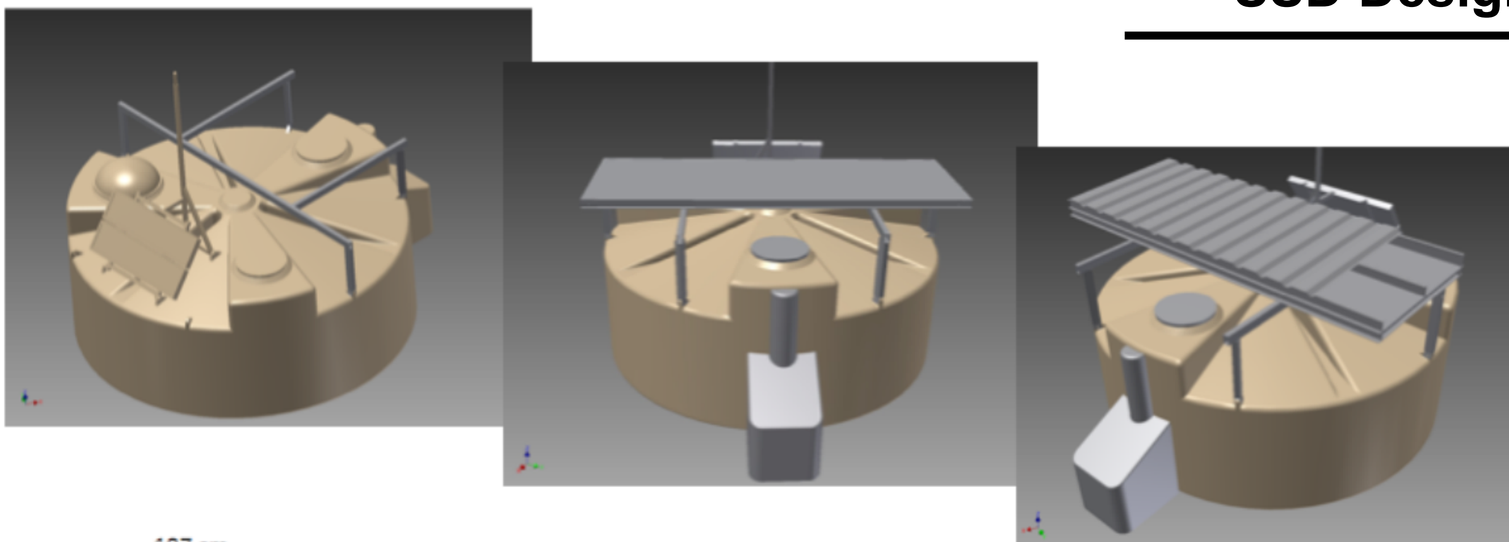
Prototype detectors

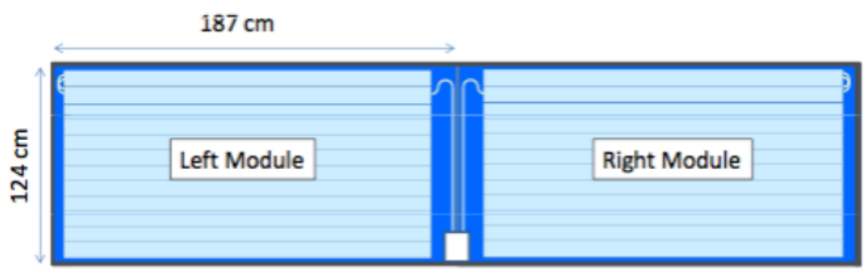
7 detector planes (2 m^2) in operation since April 2014 (5+1 double)



Detectors and AugerPrime Upgrade

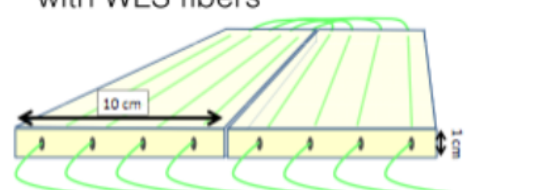
SSD Design





Two modules in one box per station, readout by one PMT, area ~4 m^2

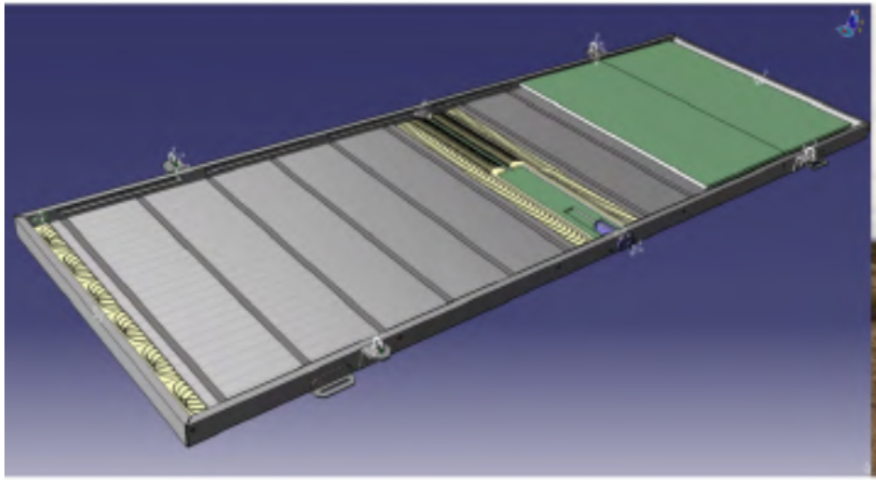
Read-out of scintillators with WLS fibers



Detectors and AugerPrime Upgrade

New detectors to get composition event by event

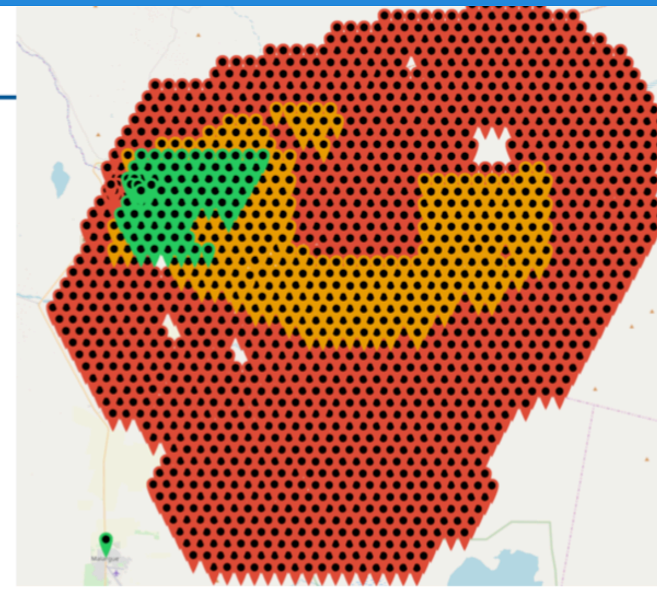
- $3.8\ \mathrm{m}^2$ scintillators (SSD) on each 1500-m array station
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750-m array (AMIGA)
- increased FD uptime



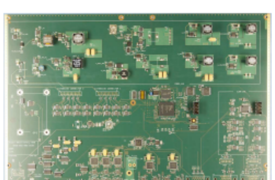
Upgrade

AugerPrime : the Upgrade

a large exposure detector with composition sensitivity above ~4 10^{19} eV



Electronics prototypes (120 MHz)



- **12 upgraded stations (Engineering Array)** since 2016 with new electronics, higher sampling, large dynamic range
- the SSD preproduction array: **80 stations** (since March 2019)
- 356 SSD stations already deployed
- Underground Muon detector
- the largest radio detector (3000 km^2)

Detectors and AugerPrime Upgrade

Real-time Measurements with Atmospheric Instruments at the Pierre Auger Observatory

The state of the atmosphere regarding the air density profile, the vertical distribution of aerosols, and the location of clouds is closely monitored at the Pierre Auger Observatory because the troposphere serves as a giant calorimeter for the air fluorescence technique. We present an overview of the atmospheric monitoring instruments at our disposal, with a focus on their capabilities for real-time measurements and their importance to extensive air shower reconstruction. We detail the improvement of our database of aerosol attenuation measurements that has been extended by two more years to the end of 2017 and fully recalculated with new software that brings a range of enhancements. We also address the importance of using hourly measurements of aerosol distributions for analyses rather than static models of average atmospheric conditions.

Detectors and AugerPrime Upgrade

Long Term Performance of the Pierre Auger Observatory

The Pierre Auger Observatory is the largest detector ever built to measure ultra-high energy cosmic rays. It employs a hybrid technique, combining a surface detector consisting of 1660 water-Cherenkov stations and a fluorescence detector composed of 27 Schmidt telescopes. The construction of the Observatory started in 2004, and since then, it has been continuously taking data in a stable manner. We will present the behavior of the Observatory over more than 14 years and the expected response into the future with the AugerPrime upgrade now underway. Key performance indicators such as the on-time and the event rates will be presented, along with reference to calibration and monitor instruments.

Detectors and AugerPrime Upgrade

Analysis of Data from Surface Detector Stations of the AugerPrime Upgrade

Measuring the different components of extensive air showers is of key importance in reconstructing the mass composition of ultra-high energy cosmic rays. AugerPrime, the upgrade of the Pierre Auger Observatory, aims to enhance the sensitivity of its surface detector to the masses of cosmic rays by installing a 3.8 m^2 plastic scintillator detector on top of each of the 1660 Water-Cherenkov Detectors (WCDs). This Scintillator Surface Detector (SSD) provides a complementary measurement which allows for disentanglement of the electromagnetic and muonic shower components. Another important improvement of AugerPrime are the surface-detector electronics. The new electronics will process signals from the WCD and the SSD with higher sampling frequency and enhanced resolution in signal amplitude. Furthermore, a smaller photomultiplier tube will be added to each WCD, thus increasing its dynamic range. Twelve upgraded surface detector stations have been operating since September 2016. Additionally, seventy-seven SSDs have been deployed and are taking data since March 2019. In this work, the analysis of the data from these detectors is presented.

Detectors and AugerPrime Upgrade

Measurements of Inclined Air Showers with the Auger Engineering Radio Array at the Pierre Auger Observatory

The Auger Engineering Radio Array (AERA) comprises 153 autonomous radio antenna stations distributed over an area of 17 km^2. It is operated in coincidence with the surface detector array and fluorescence telescopes of the Pierre Auger Observatory so that hybrid observations of extensive air showers initiated by cosmic rays in the EeV energy range can be performed. A first analysis of the radio emission of more than 500 inclined air showers with zenith angles between 60° and 84° was published last year. Here, we provide an update of the analysis including recent data, approximately quadrupling the event statistics. For inclined showers, the radio signal is found to be distributed over an area of several km^2, allowing air showers to be measured with radio antennas on a grid as sparse as the 1500 m spacing of the 1600 water-Cherenkov Detector (WCD) stations. For a subset of these inclined events, for which the primary energy can be reconstructed with the data from the WCD array, we verify that the measured radio amplitudes agree with Monte Carlo simulations made using CoREAS. Special challenges of a radio event reconstruction dedicated to inclined air showers will also be discussed.

Detectors and AugerPrime Upgrade

The AMIGA underground muon detector of the Pierre Auger Observatory - performance and event reconstruction

The Auger Muons and Infill for the Ground Array (AMIGA) aims to both lower the detection threshold of the Pierre Auger Observatory down to energies of ~ $10^{16.5}$ eV and to directly measure the muon content of extensive air showers. AMIGA consists of an array of coupled water Cherenkov and buried scintillation detectors deployed in two superimposed triangular grids of 433 m and 750 m spacings. Each underground detector has a total area of 30 m^2 buried at a depth of 2.3 m, to shield it from the shower electromagnetic component. The scintillation plane is segmented in plastic-scintillator strips with embedded wavelength-shifter optical fibers coupled to a common optical sensor. Before proceeding to the construction of the full-size array, an engineering array was operated until November 2017 to validate and optimize the design, and to evaluate the performance of the detection system. During this phase, scintillation areas of 5 m^2 and 10 m^2 and two optical sensors, photomultiplier tubes and silicon photomultipliers, were tested. In this work, we present the status and performance of the array currently equipped with silicon photomultipliers, along with the timing performance and geometry reconstruction of modules equipped with photomultiplier tubes. Analyses and results are based on both laboratory and field measurements. Scintillation areas of 10 m^2 and silicon photomultipliers as readout have been selected as the baseline design for the full-scale AMIGA array.

Detectors and AugerPrime Upgrade

A Large Radio Detector at the Pierre Auger Observatory – Measuring the Properties of Cosmic Rays up to the Highest Energies

High-energy cosmic rays impinging on the atmosphere of the Earth induce cascades of secondary particles, the extensive air showers. Many particles in the showers are electrons and positrons, which due to interactions with the magnetic field of the Earth emit radiation with frequencies of several tens of MHz. In the last years, huge progress has been made in measuring the characteristics of extensive air showers through their radio signal at these frequencies.

The radio technique is now routinely applied to measure the properties of cosmic rays, such as their arrival direction, their energy, and their particle type/mass. Air showers with zenith angles above 60° have a large footprint of the radio emission on the ground which can be detected with sparse arrays with kilometer-scale spacing. With the Auger Engineering Radio Array (AERA) these "horizontal air showers" are measured, demonstrating the feasibility of the radio technique for highly inclined showers.

At present, the Auger Collaboration is upgrading its detectors. The upgrade includes the installation of radio antennas on each of the 1661 water-Cherenkov detectors of the array. The main objective of the radio upgrade (Radio Detector) is to measure horizontal air showers and to determine the properties of cosmic rays up to the highest energies. The combination of water Cherenkov detectors and radio antennas will provide muon-electron separation for horizontal air showers at the highest energies.

Detectors and AugerPrime Upgrade

New Electronics for the Surface Detectors of the Pierre Auger Observatory

The surface detector array of the Pierre Auger Observatory consists of 1660 water-Cherenkov detector stations (WCDs) that sample the charged particles and photons of air showers initiated by energetic cosmic rays. Each station continuously samples signals from photomultiplier tubes (PMTs) viewing the water volume, and records a $\approx 20\ \mu s$ trace whenever a local trigger condition is satisfied. Absolute timing is provided by a GPS receiver on each station, and power is provided by a solar power system. The Observatory is currently implementing an upgrade, "AugerPrime". AugerPrime includes the addition of a small PMT to increase dynamic range, a plastic scintillator above each WCD to enhance the separation of electromagnetic and muon shower components, a radio detector to measure the radio emission of inclined air showers, and an infill of buried muon counters to provide additional cross checks. Consequently, new electronics to support these additional detectors is also being implemented. In addition to more measurement channels, the new electronics includes improved GPS receivers, higher sampling frequency, increased dynamic range, increased processing capability, and improved calibration and monitoring systems. This paper presents the design of the new electronics and discusses performance characteristics observed in laboratory measurements and engineering array data.

Detectors and AugerPrime Upgrade

Test benches for the upgrade of the Pierre Auger Observatory electronics

The Pierre Auger Observatory, the largest cosmic ray detector ever built, has been collecting scientific data since 2004. As part of the AugerPrime upgrade, the Observatory is currently undergoing a modification of the surface detector stations, which involves a replacement of their electronics with a faster and a more powerful system that provides channels for additional detectors as well as increased dynamic range and processing capability, higher sampling frequency, and improved timing, calibration and monitoring systems. The testing of the new electronics boards will be conducted in three stages: the production test performed at the manufacturer site, the climate tests including accelerated ageing executed in a laboratory and finally the full functionality tests effectuated before the deployment at the Observatory in Argentina. A description of the test benches and the testing procedures is given together with some examples of the performance of the prototype.

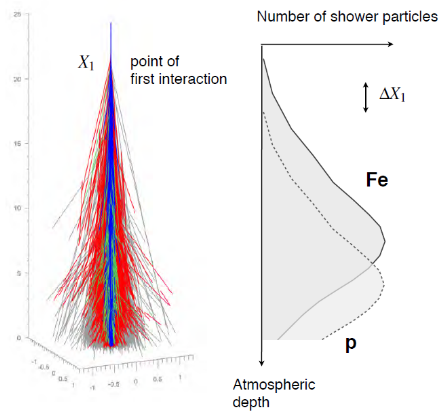
Detectors and AugerPrime Upgrade

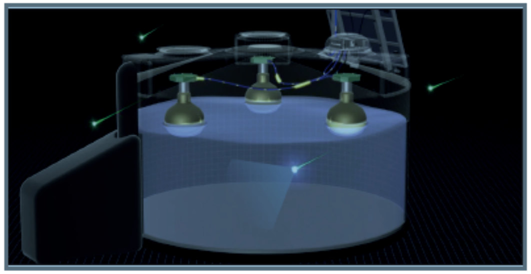
Production and Quality Control of the Scintillator Surface Detector for the AugerPrime Upgrade of the Pierre Auger Observatory

The Pierre Auger Observatory is undergoing a major upgrade, called AugerPrime. One of the goals of this upgrade is to improve the capabilities of the existing stations of the surface detector. The main modification consists in the addition of a new scintillator surface detector (SSD) to each water-Cherenkov detector station. The large-scale production of the SSDs started in 2017. The detector assembly is done in six laboratories with the collaboration of many other institutions providing components. Each institution involved follows common procedures, making sure that all the high standards set by the design are being met. We describe these procedures, which include quality checks of all components and a final certification of each detector with cosmic-ray muons. The deployment of the SSDs at the Observatory is already under way.

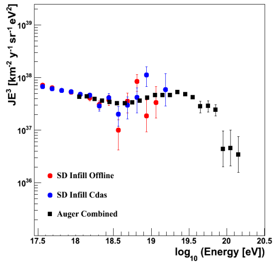
Grupo Auger en Puebla

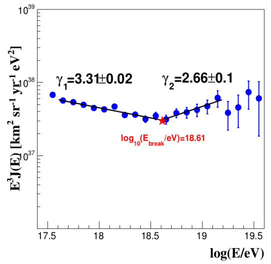
- MC Simulations for HEAT, ASCII using CONEX, CORSIKA, GEANT4
- Reconstruction and Data Analysis
- Electronica

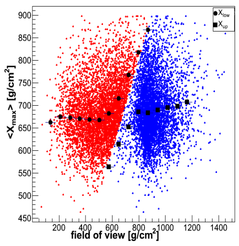


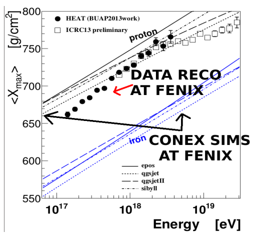


Cherenkov light produced by air-shower particles is detected by three photomultiplier tubes, which view the water volume.

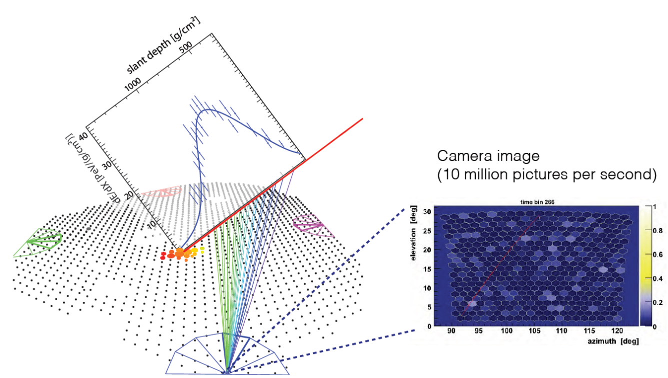








Grupo Auger en Puebla



- Cuarto de Control Remoto, Para toma de datos del FD

Gracias