Inclined Air Showers at the Pierre Auger Observatory

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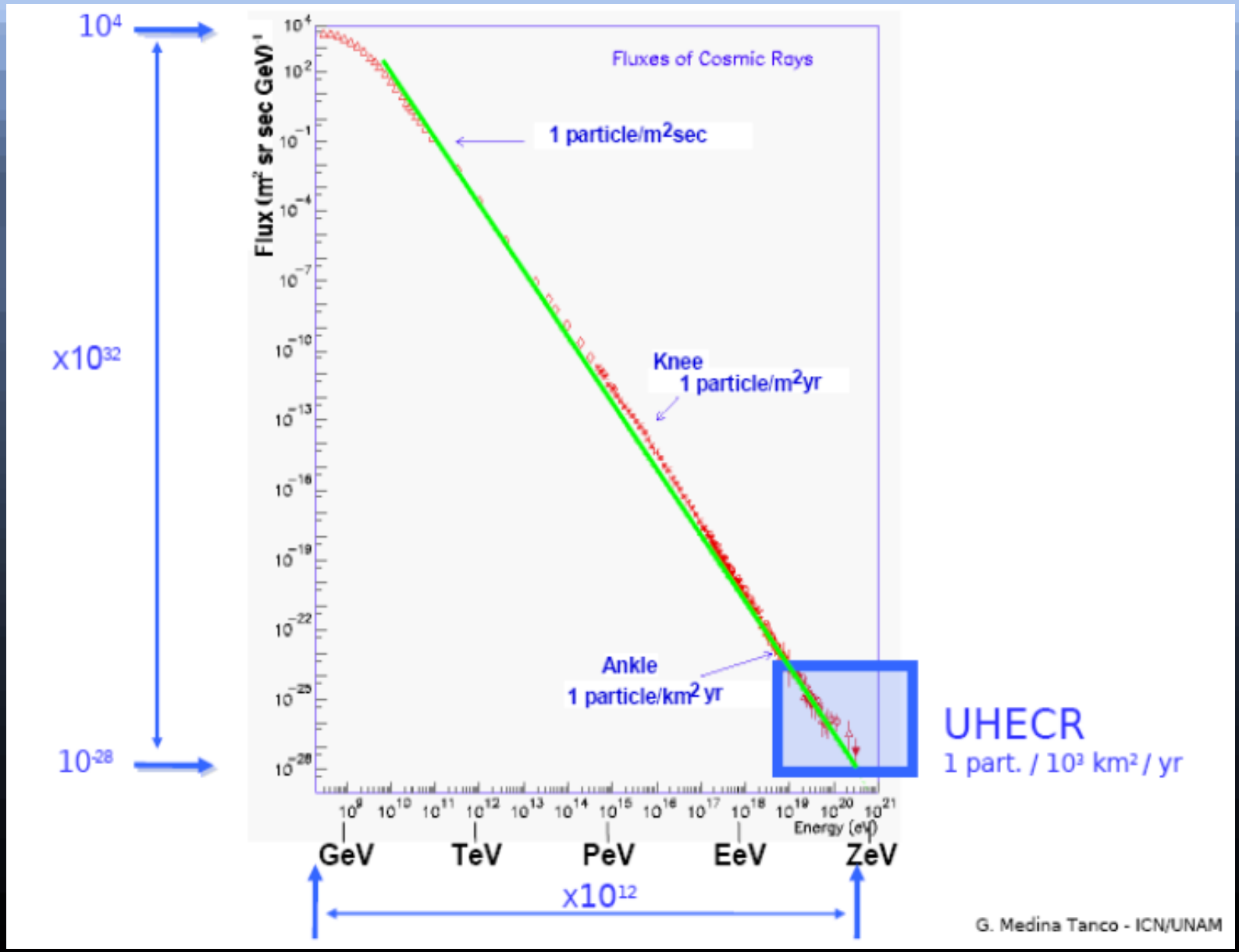
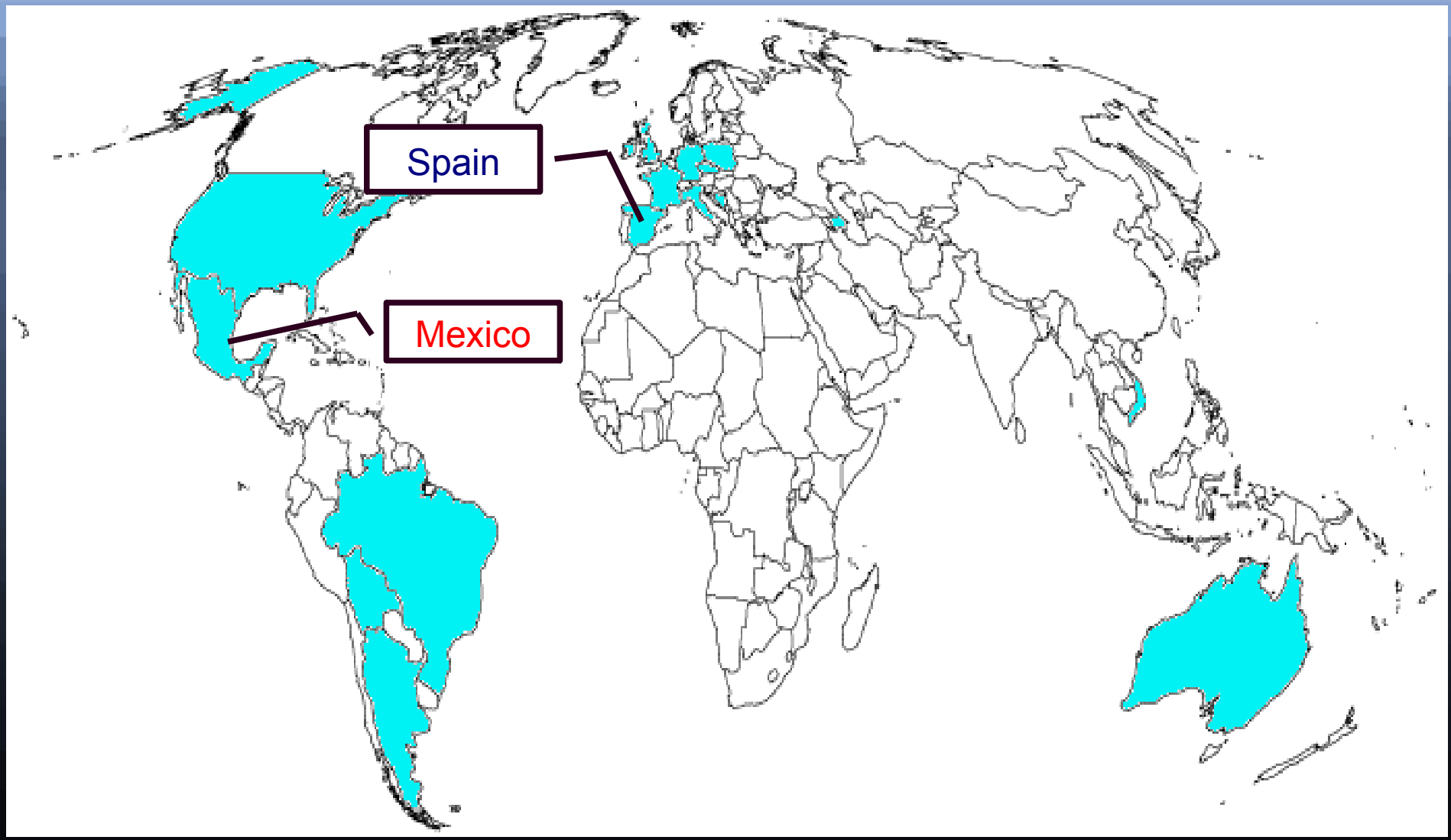
Ultra High Energy Cosmic Ray Spectrum



Aim of the experiment

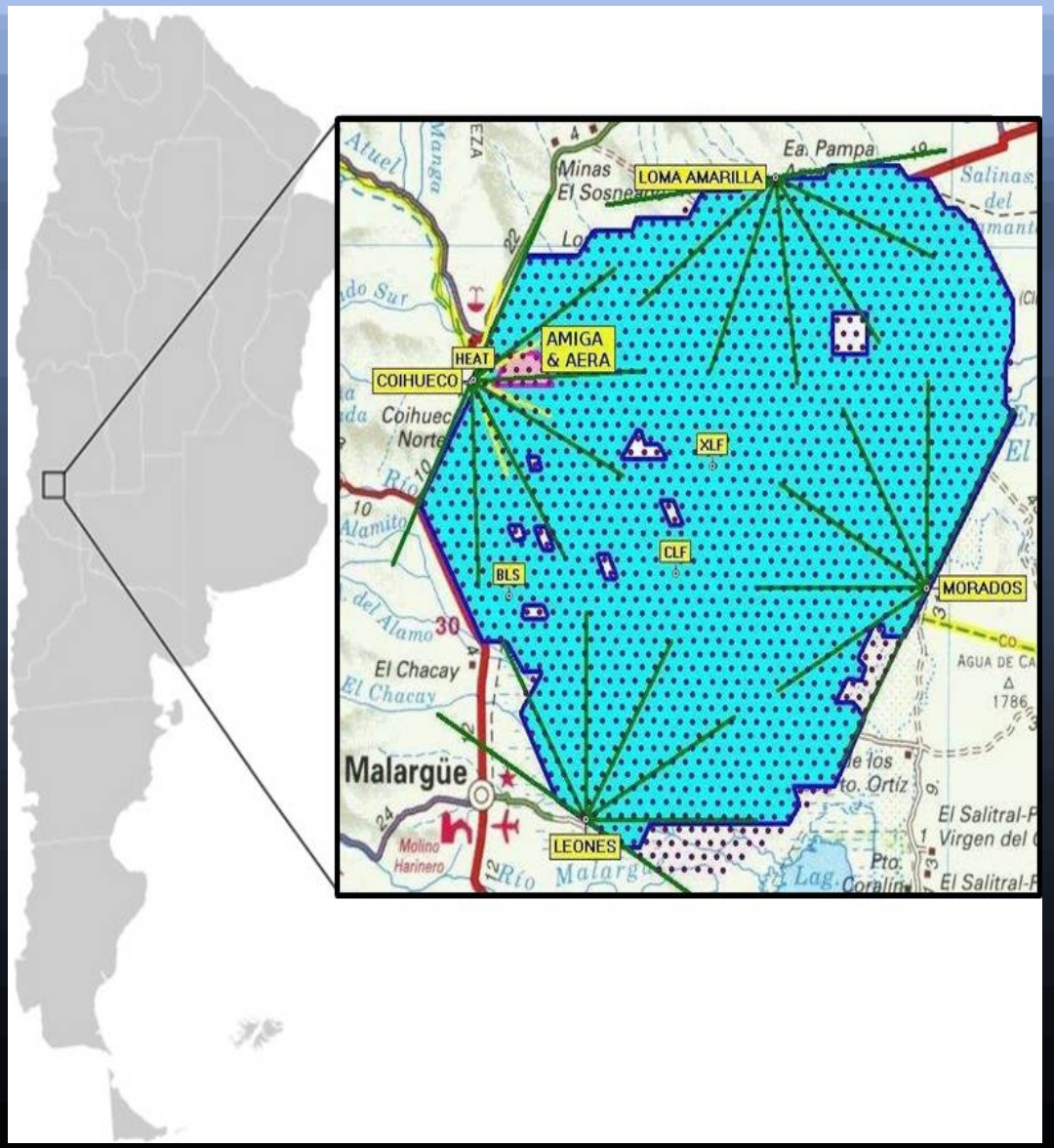
- Study of the highest energetic cosmic rays.
- Determine the sources of these cosmic rays.
- Determine the element composition of cosmic rays.
- Measure the energy spectrum up to energies of 10^{20} eV.

Participants Countries

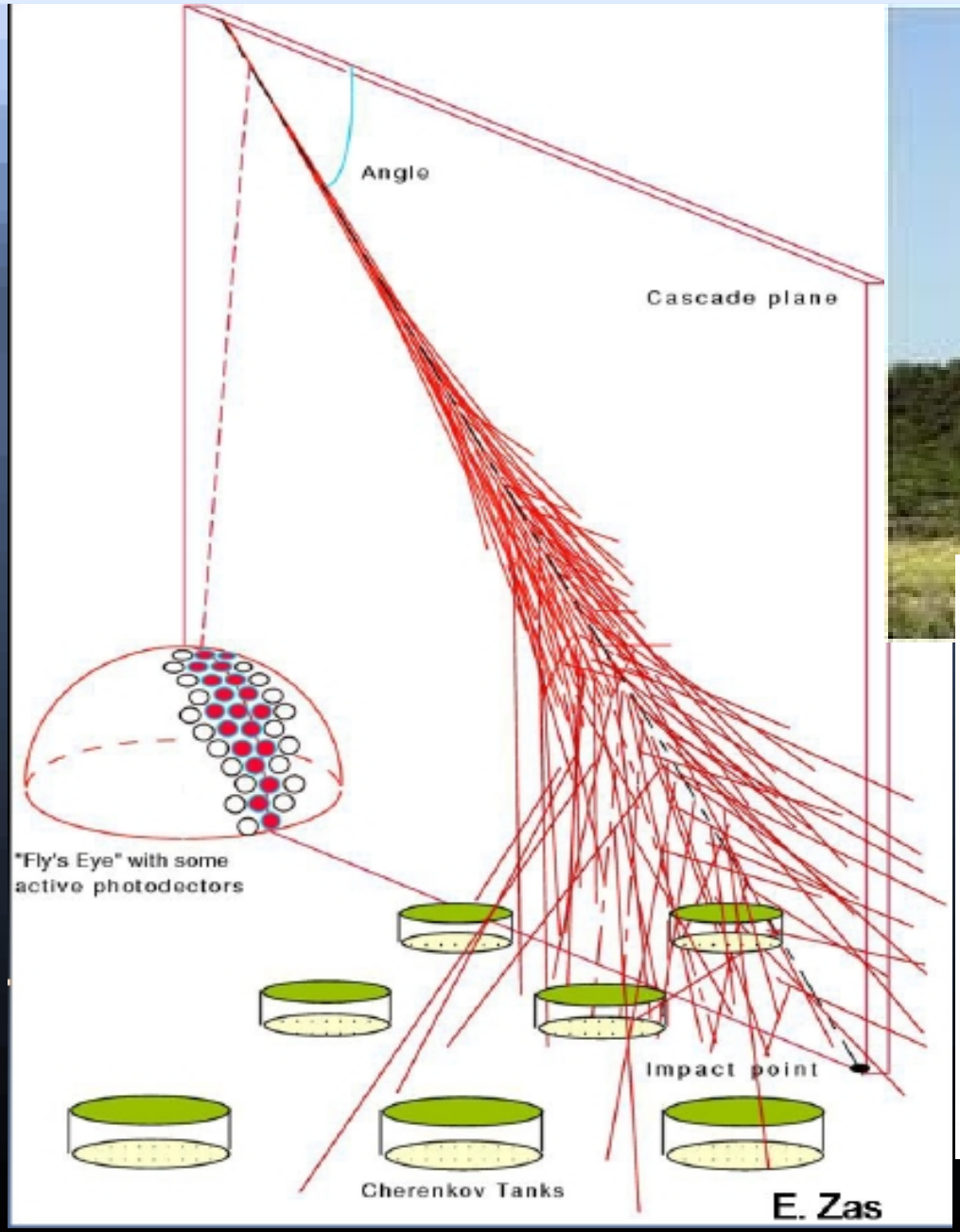


The Pierre Auger Observatory (PAO)

- Located at Malargüe, Argentina, covering an area of 3000 km^2
- 4 buildings wiht 6 Fluorescence Telescopes each one of them.
- 1600 surface detectors (1.5 km spacing)
- Taking data since 2004, PAO completed in 2008

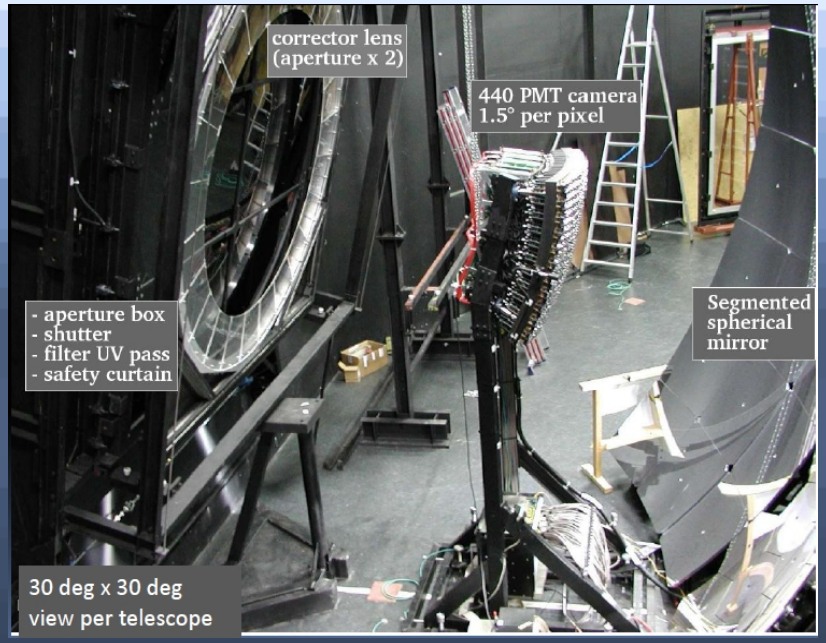


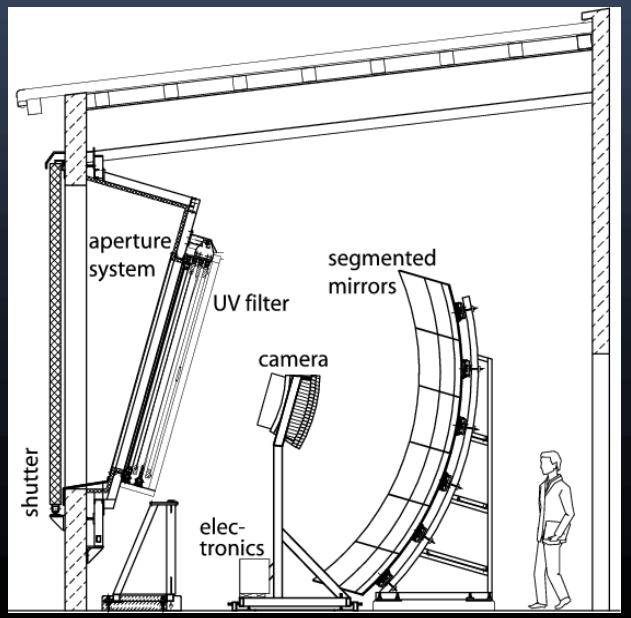
Hybrid Detector



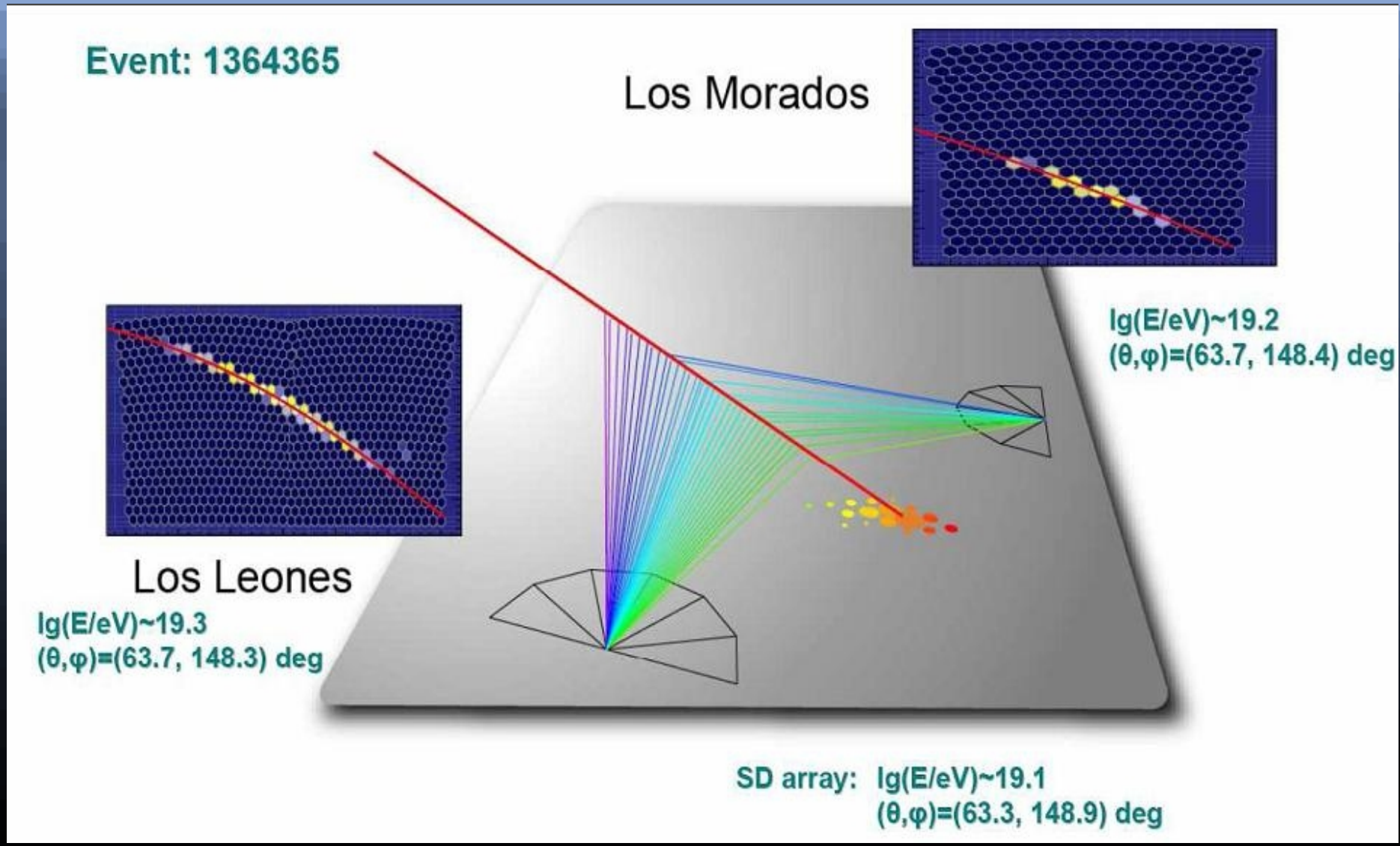
Flurescence Detector

- Charged particles from the air shower interact with the nitrogen molecules of the atmosphere.
- Emitted ultraviolet light via a fluorescence process.
- We can determine the longitudinal profile of the air shower.
- Calorimetric measuremet of the air shower energy.
- Clear and moonless nights.

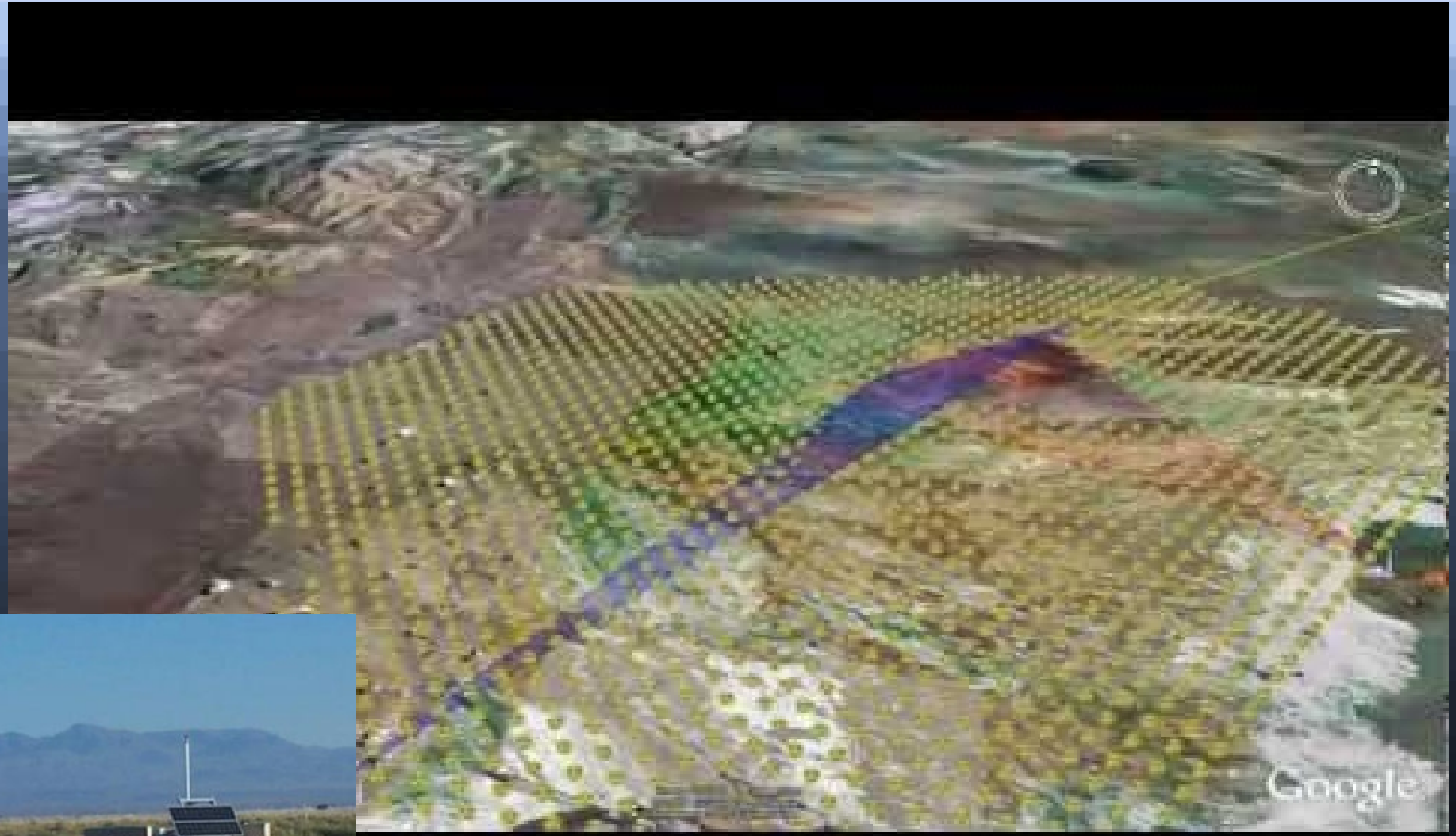




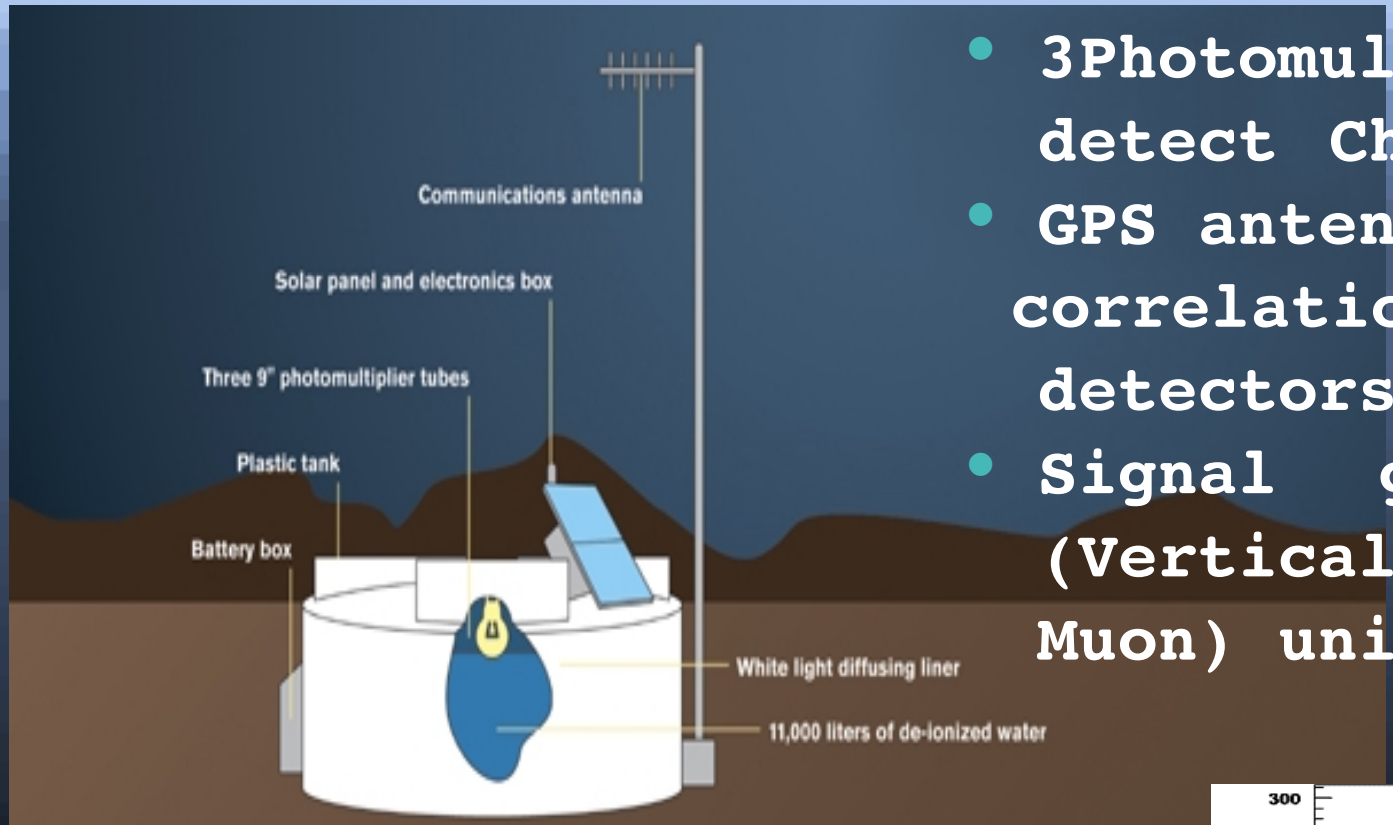
Hybrid Event Example



Surface Array Detector



SD Tank station



- 3Photomultipliers detect Cherenkov light.
- GPS antenna high time correlation to different detectors.
- Signal given in VEM (Vertical Equivalent Muon) units

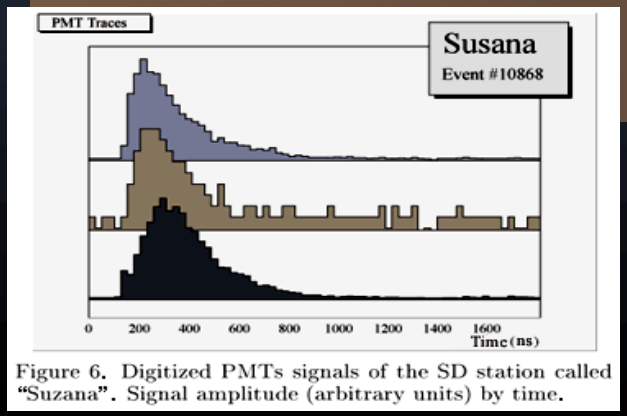
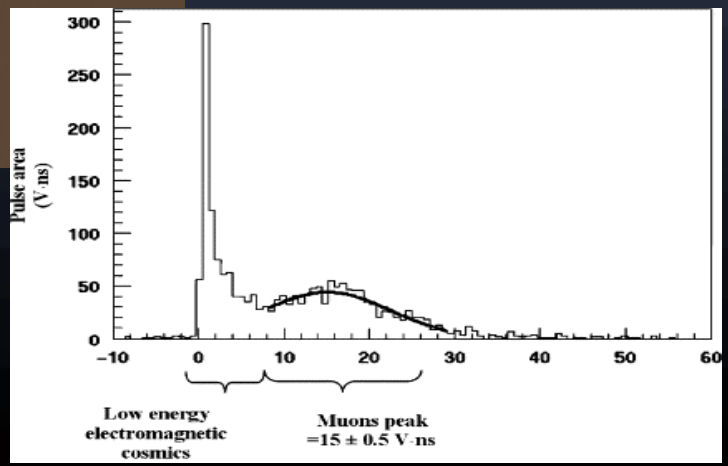
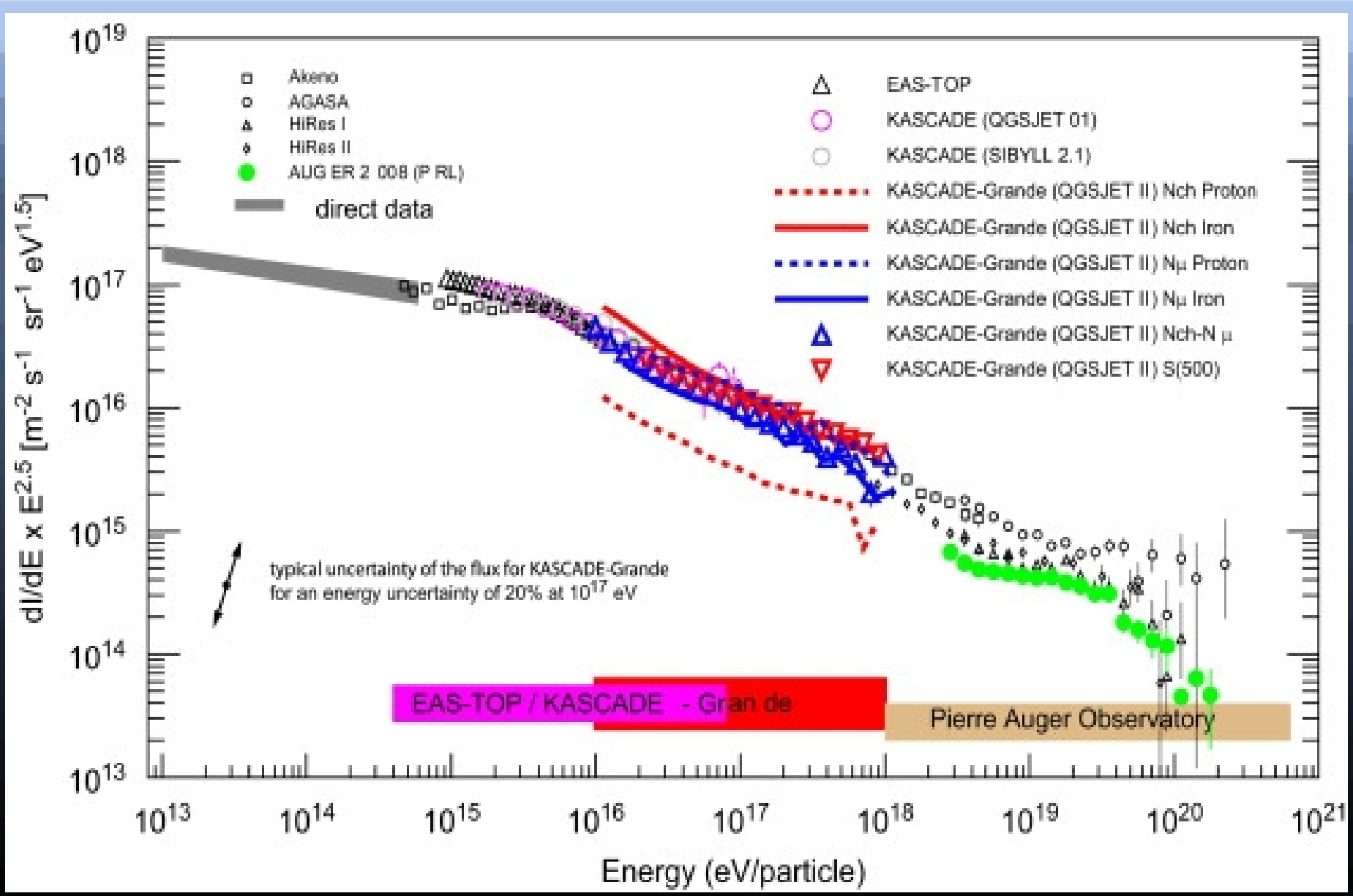


Figure 6. Digitized PMTs signals of the SD station called "Suzana". Signal amplitude (arbitrary units) by time.



Cosmic Ray Spectrum

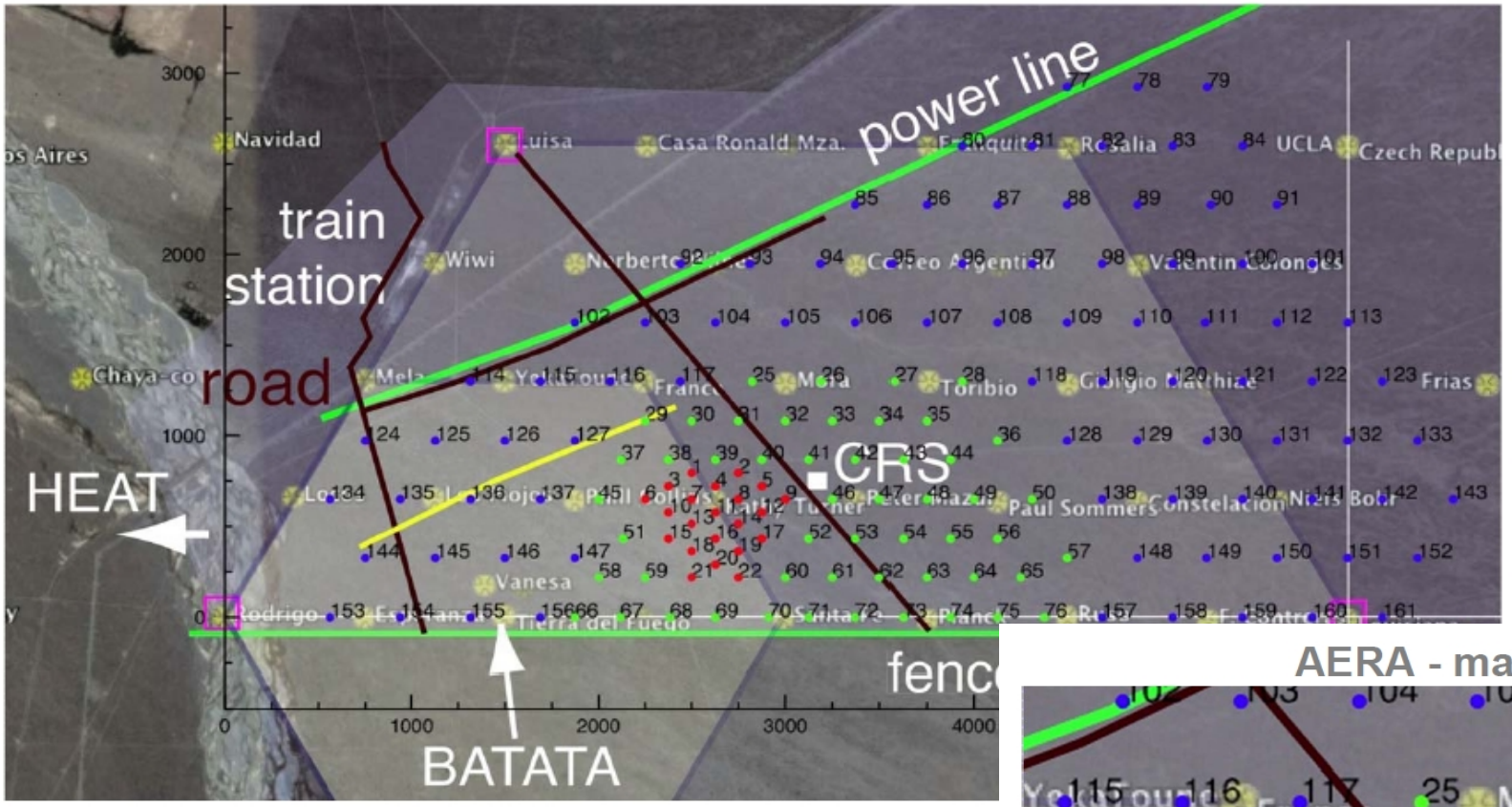


Auger Upgrades

- AERA – Detection of the Cosmic Rays with radio antennas (in Mhz range).
  - Small Black Spider, Butterfly and Salla.

AERA
Auger Engineering Radio Array

AERA - map

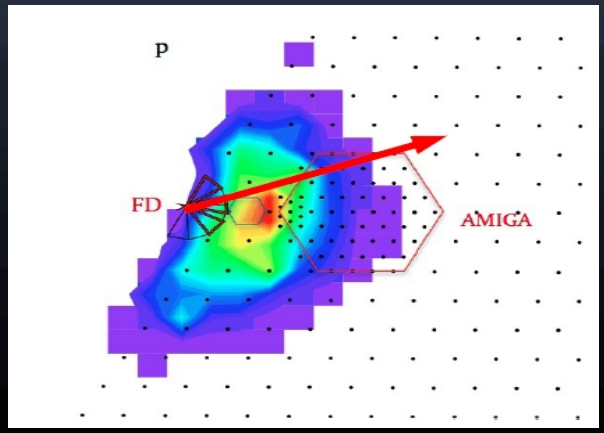


- **Radio threshold at 10^{17} eV**
- **AERA – SD – correlation possible at 10^{17} ev**
- **Large statistics**

AMBER,MIDAS AND EASIER

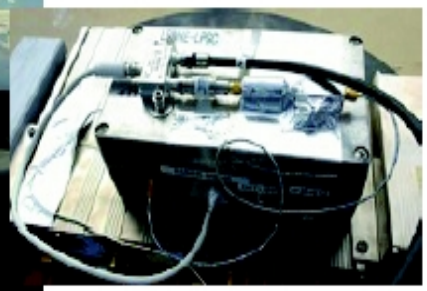
AMBER

- Not optimal overlap with HEAT or Coihueco.
- Crab transit – calibration.
- SD events in AMBER FoV (Infill and regular SD)
- AMBER tests with a 4GHz source.



MIDAS

Antenna



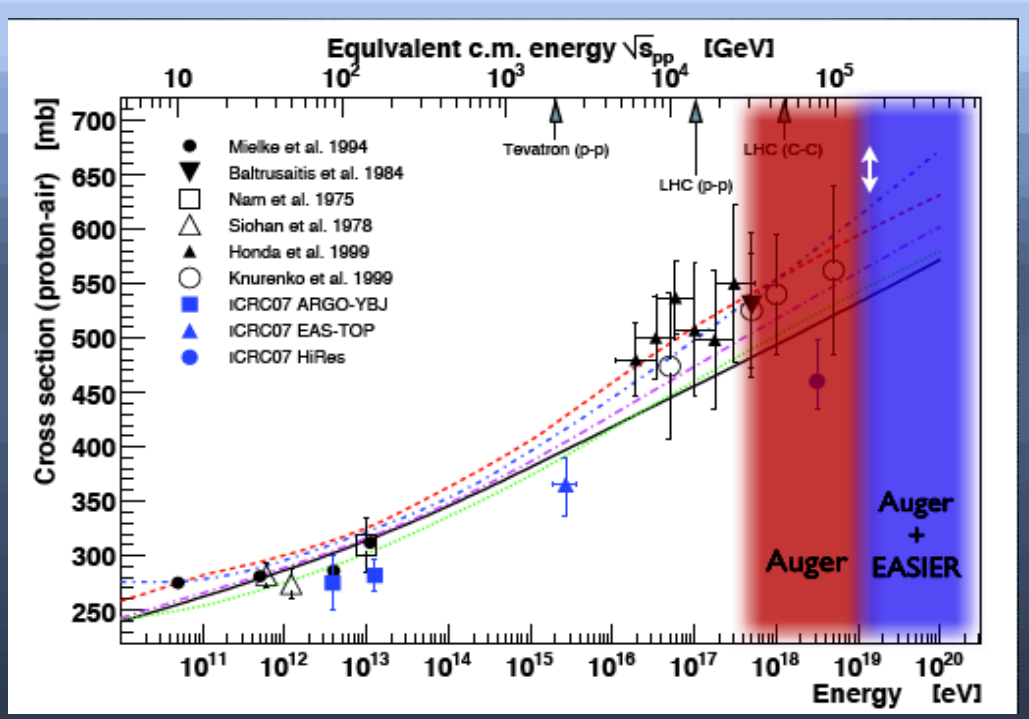
Electronics

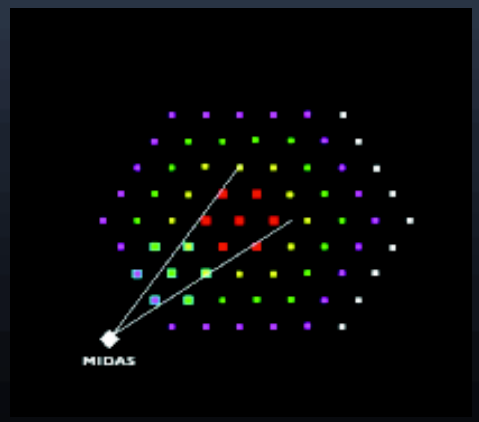
7 Antennas
Taking data since April 2011

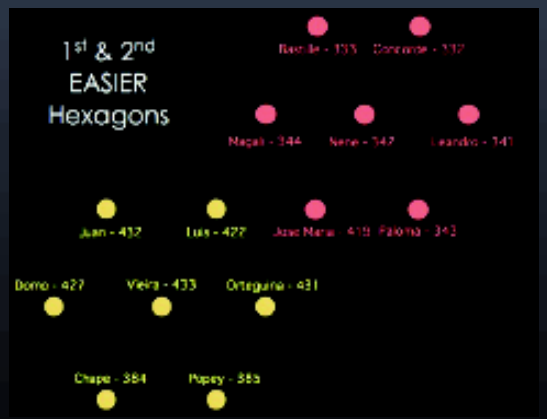
- Stable radio signal.
- No effects on regular array.
- Already working.

EASIER

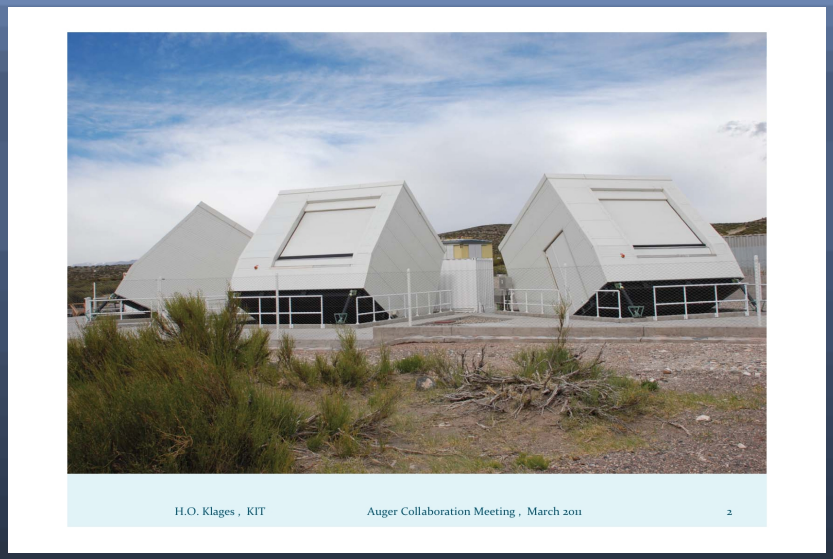
- 61 antennas.
  - 7 installed in april 2011
  - 54 installed in abril 2012
- EASIER hexagons in MIDAS FoV
- Physics outcomes:
  - Hadronic cross sections
  - Detection of ultra high energy neutrinos and photons.
  - Constraints and parametrizations of interaction models.
  - Indentification of astrophysical sources.



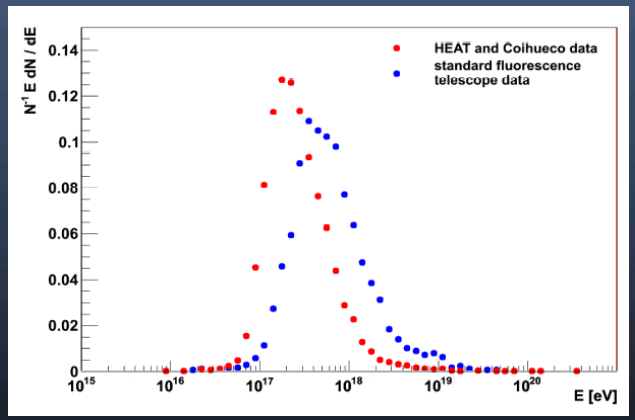


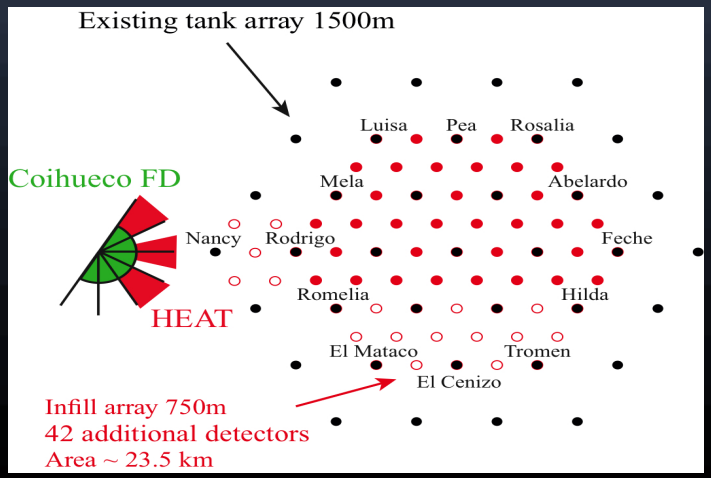


Auger extensions to lower energies: HEAT and AMIGA (Infill + Muon Detectors)

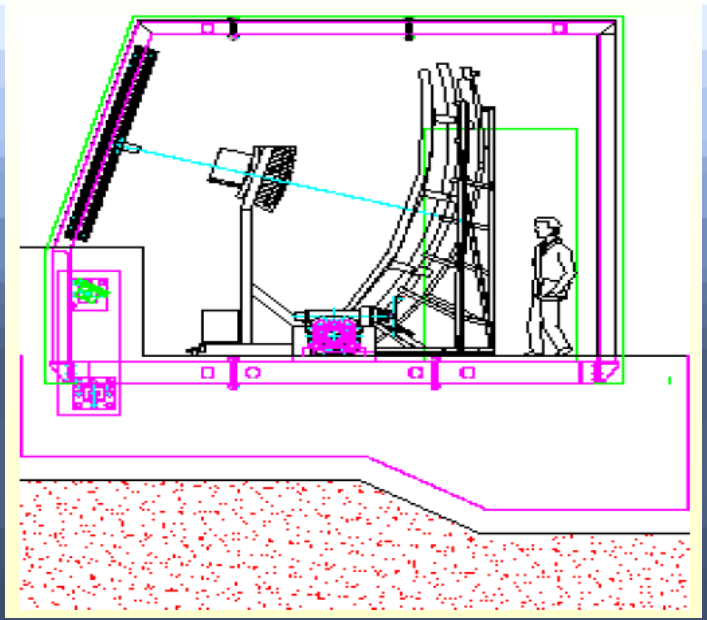


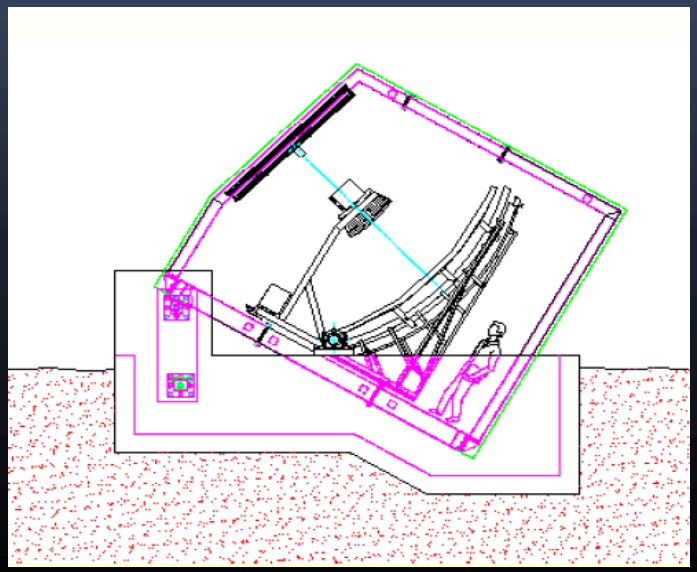
- HEAT + Coihueco is capable to measure hybrid showers (10^{17} eV)





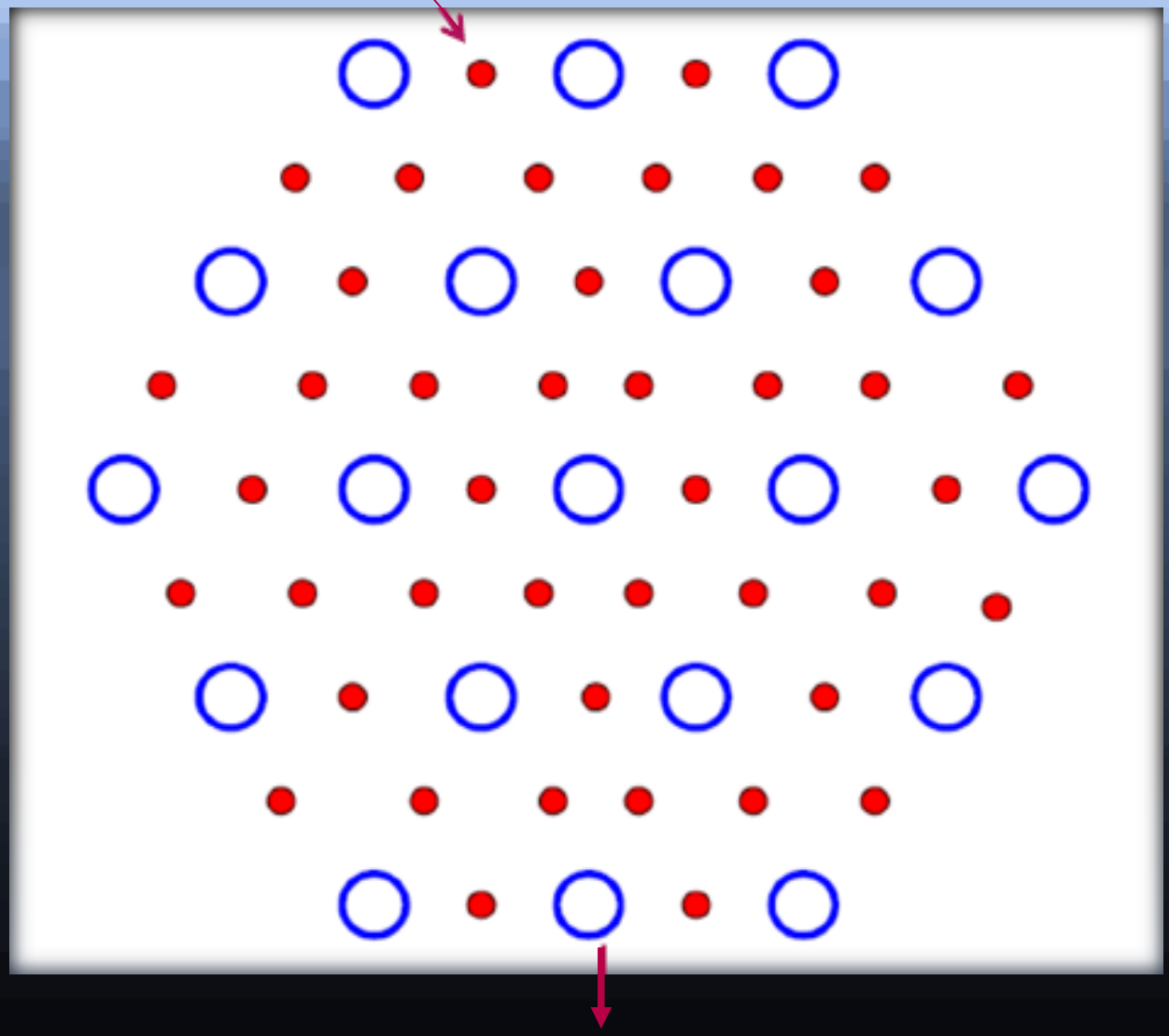
- FOV 30º X 30º
- Full overlap with Coihueco FOV
- Cross-checks with Coihueco
- Hydraulic tilting system
- Monitored by inclination and distance sensors.





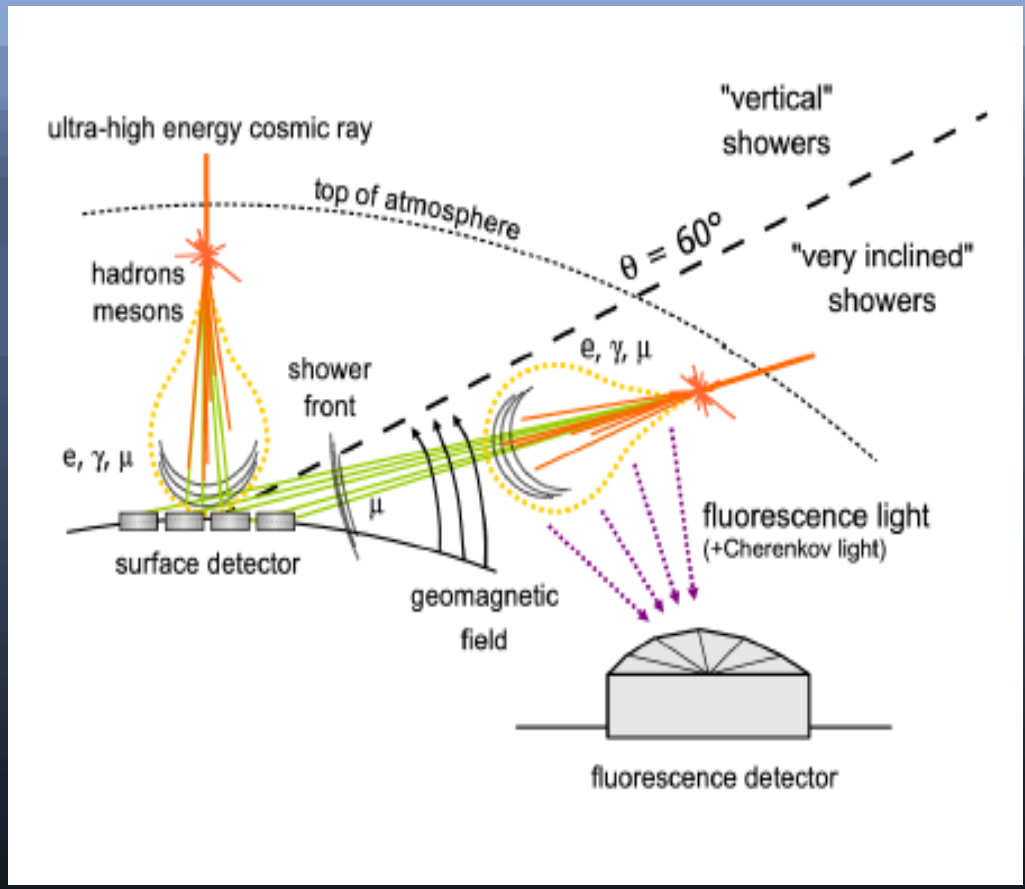
Infill Array

- More sensitive to low energies.
- Hexagonal grid of 0.75 km spacing (half of the regular one).



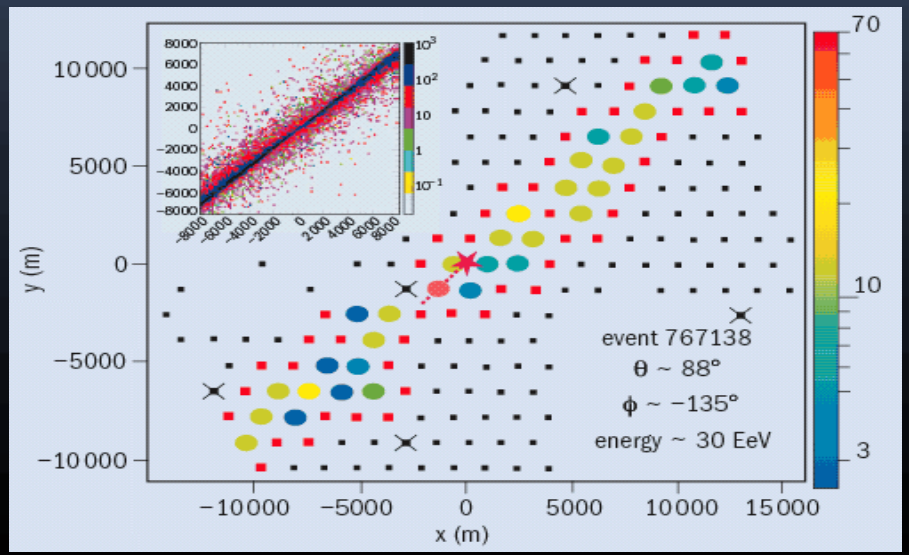
Inclined Showers

- Increases the viewable portion of the sky.
- Enhances the event statistics by 30%.
- Dominance of muons at ground.
- Main background in searches of ultra-high energy neutrinos.
- Muon content useful for mass composition and hadronic models studies.



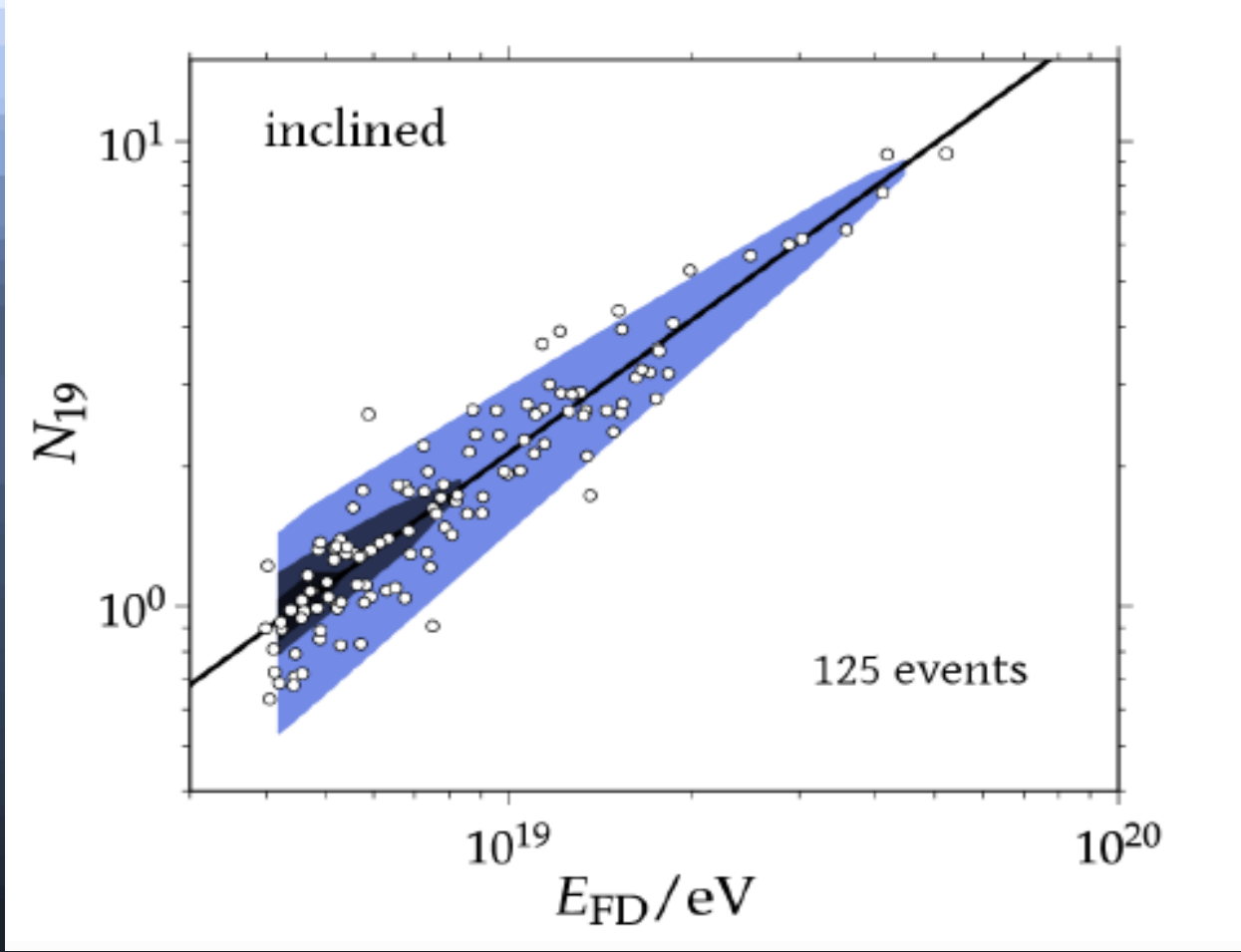
SD Reconstruction

- Inclined showers generate asymmetric and elongated signal patterns in SD
- Event selection: Top Down
- Reconstruction of arrival direction: fit model of shower fron to arrival times at SD triggered detectors.
- Reconstruction of the energy estimator N19: fit model of 2D muon density, profiles at ground to signals.



Energy Calibration

- High Quality hybrid events.
- Calibration of N19 using FD Energy.



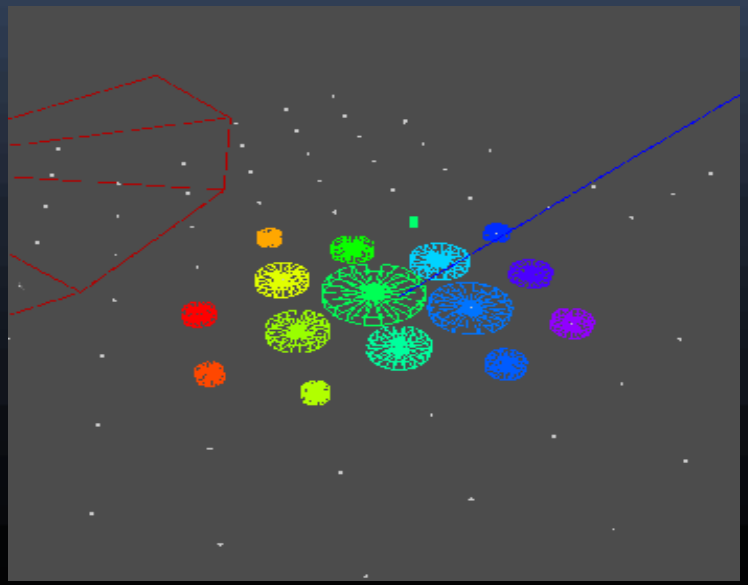
$$E_{SD}^{\text{inclined}} = A \cdot N_{19}^{B}$$
$$A = (4.69 \pm 0.09) \times 10^{18}\text{eV}$$
$$B = 1.05 \pm 0.02$$

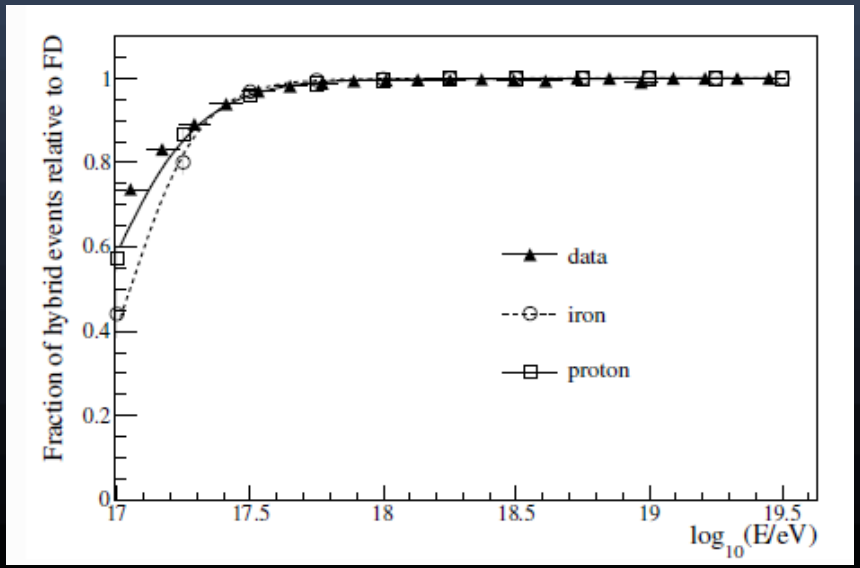
Data Period:
from Jan. 2004 to Sept. 2010

Exposure

- Solid Angle
- Instantaneus Aperture (active cell)
- Full Efficiency for inclined showers: 4 EeV

$$\mathcal{E}(E) = \int_T \int_\Omega \int_{S_{gen}} \varepsilon(E,t,\theta,\phi,x,y)\ \cos\theta\ \mathrm{d}S\ \mathrm{d}\Omega\ \mathrm{d}t = \int_T \mathcal{A}(E,t)\ \mathrm{d}t$$



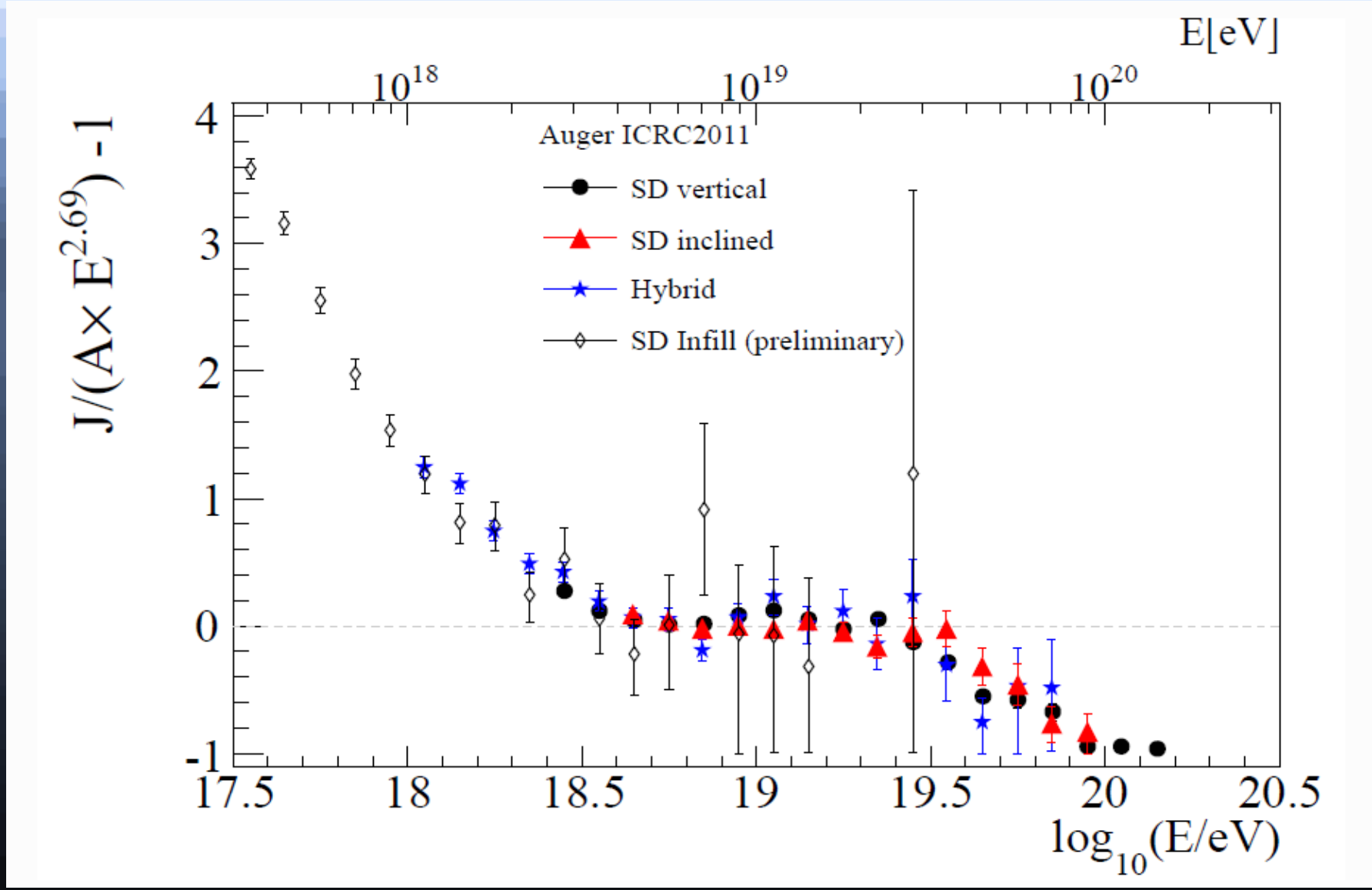


Cosmic Ray Flux

Cosmic Ray Flux = Number of reconstructed events per energy and exposure.

- Data Sample: 1 January 2004 – 30 December 2010
- 5936 events with E > 4 EeV
- Zenith angle between 62° and 80°
- Exposure: 5306 km^2
- Systematic uncertainties from calibration propagates to the flux.
- FD energy scale uncertainty 22%

Energy Spectrum



Plot from the talk "Measurement of the energy spectrum of cosmic rays at highest energies using the Pierre Auger Observatory", UHECR 2012, I. Maris, Pierre Auger Collaboration

Status and Future Work

- Identify the primary cosmic ray nature at the highest energies and investigate high-energy hadronic interaction properties.
- Extended to low energy range, with HEAT and Infill Array.
- Implementation of new detection techniques: radio (MHz) and microwave (GHz) antennas.
- Continue operation and data taking.