Catching the Universe's most energetic particles

Ultra-High Energy Cosmic Rays

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Lecture 2

LA-CoNGA Physics
Curso Internacional de Astropartículas y Cosmología
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Last Class' Summary

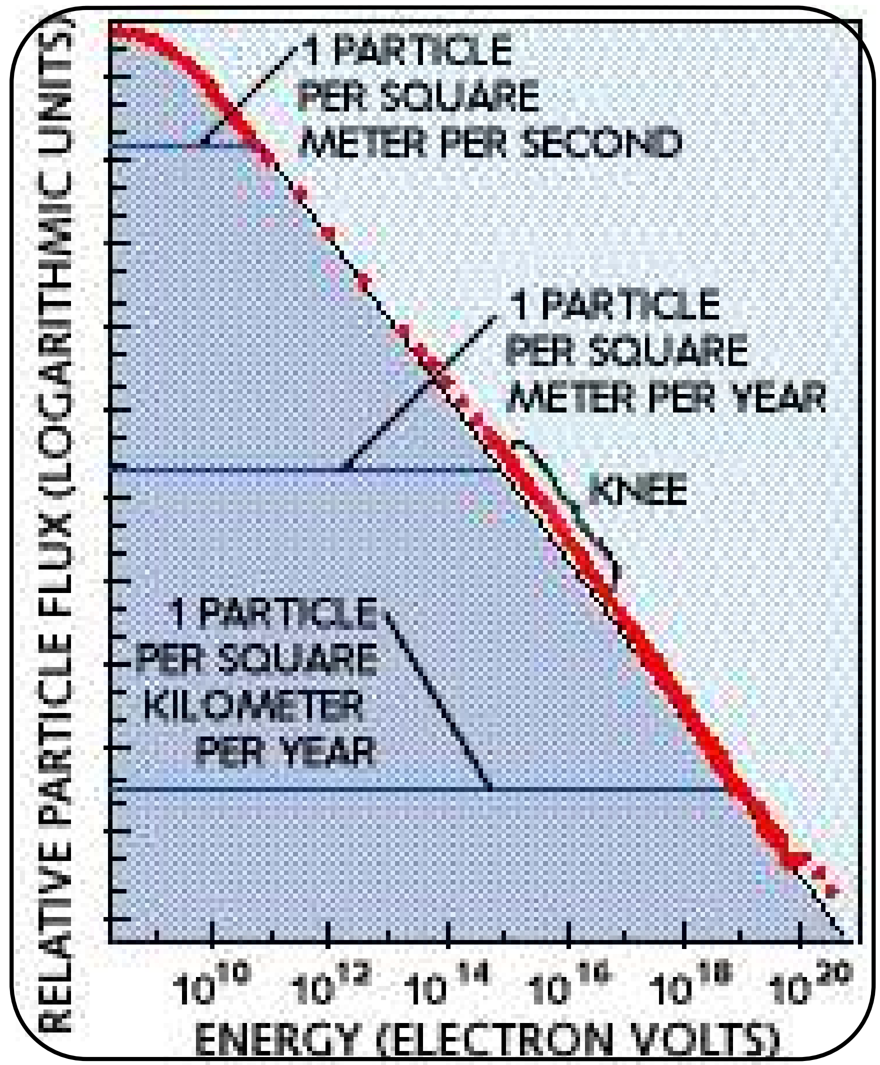
- Introduction to Cosmic Rays
- History
- Scientific Motivation

Today's Program

- Extensive Air Showers
- Detection Techniques
- The Pierre Auger Observatory

Energy Spectrum

- The techniques by which cosmic rays in a given energy range are detected depend critically on the rate of arrival.
- The atmosphere absorbs most of the cosmic rays (as was demonstrated by Hess's original experiments).
- Radiation detected at ground level are actually secondary particles.

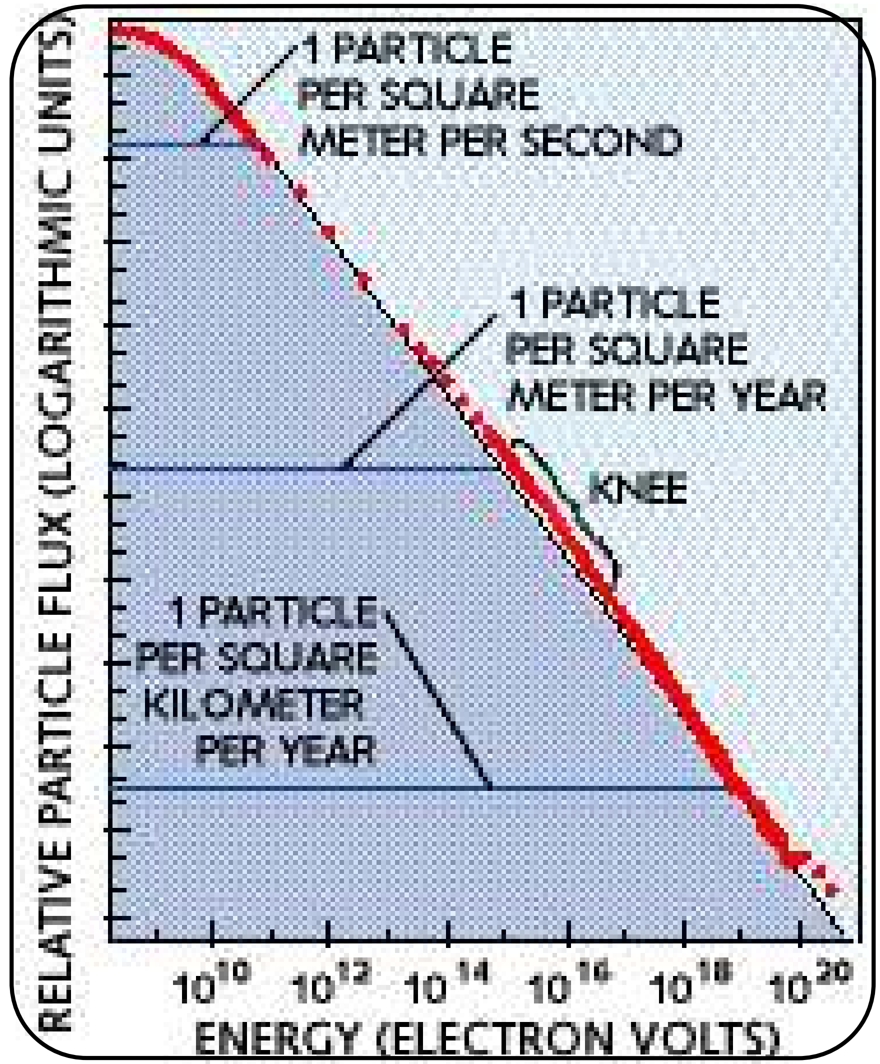


Spectrum & Detection

- To measure the primary cosmic rays directly, the detection equipment must be placed above the atmosphere.
- This is accomplished by carrying the instrument aboard high-altitude balloons flying at above 100,000 feet, on Earth-orbit satellites, or in the future aboard the International Space Station (ISS).
- A good example of a detector deployed on the ISS is the Alpha Magnetic Spectrometer (AMS), which was designed to search for nuclear antimatter in cosmic rays.

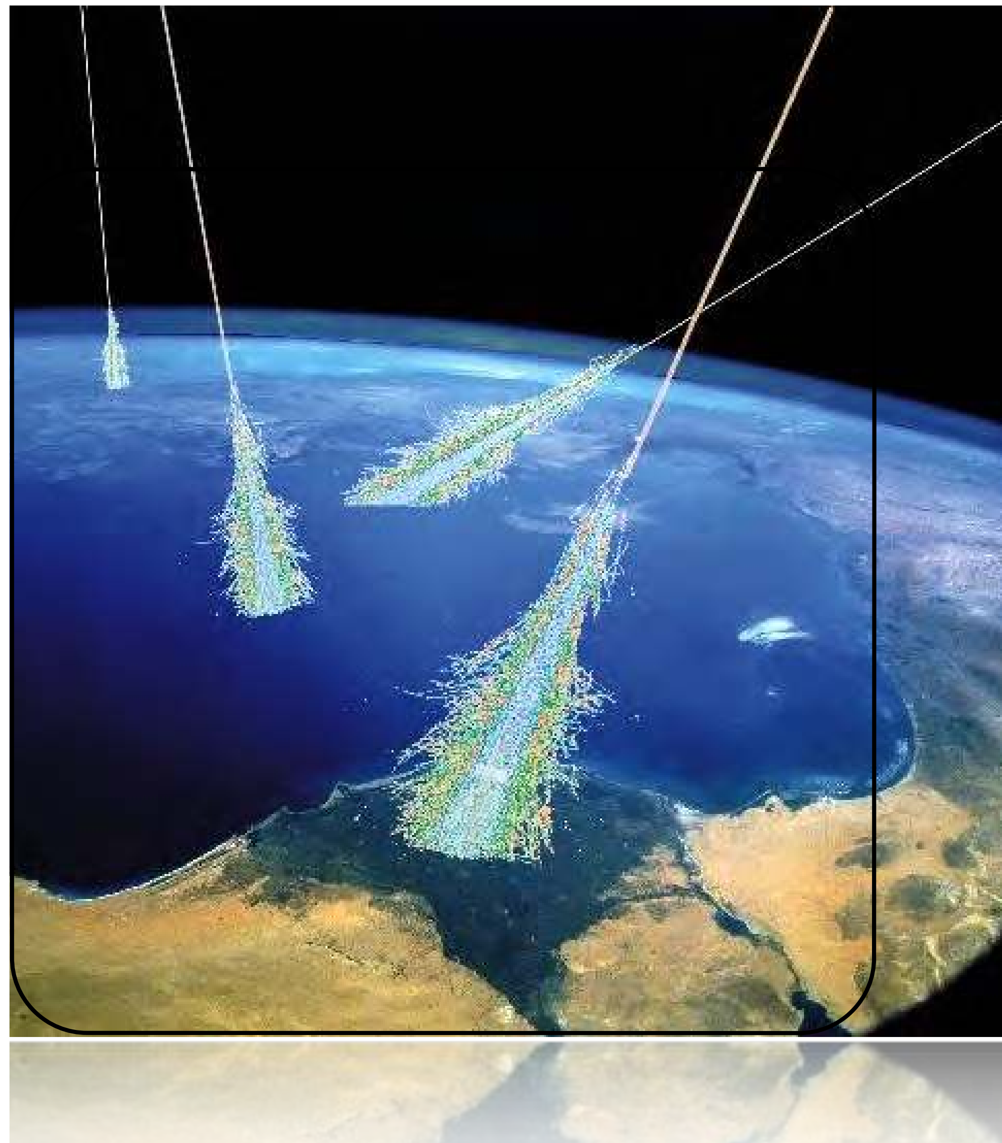
Energy Spectrum

- At above 10^{15} eV, the flux of cosmic rays drops to below one particle per square meter per year.
- This rate makes direct measurements impractical, as it would require flying very large detectors in order to collect sufficient number of particles.
- A different method is required.



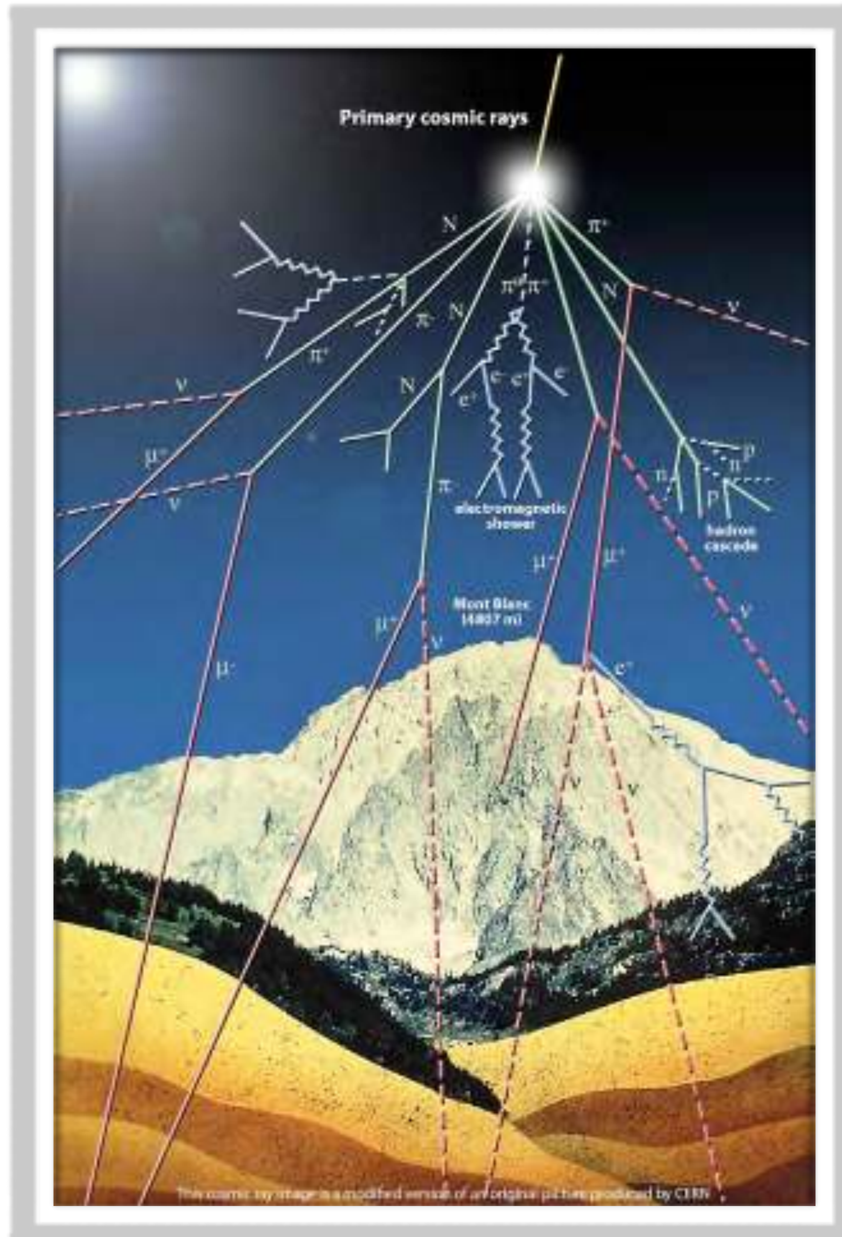
Cosmic Rays

- Over 70 years, physicists have studied cosmic rays with energies in excess of $\sim 10^{14}$ eV by using the Earth's atmosphere itself as part of the detection equipment.



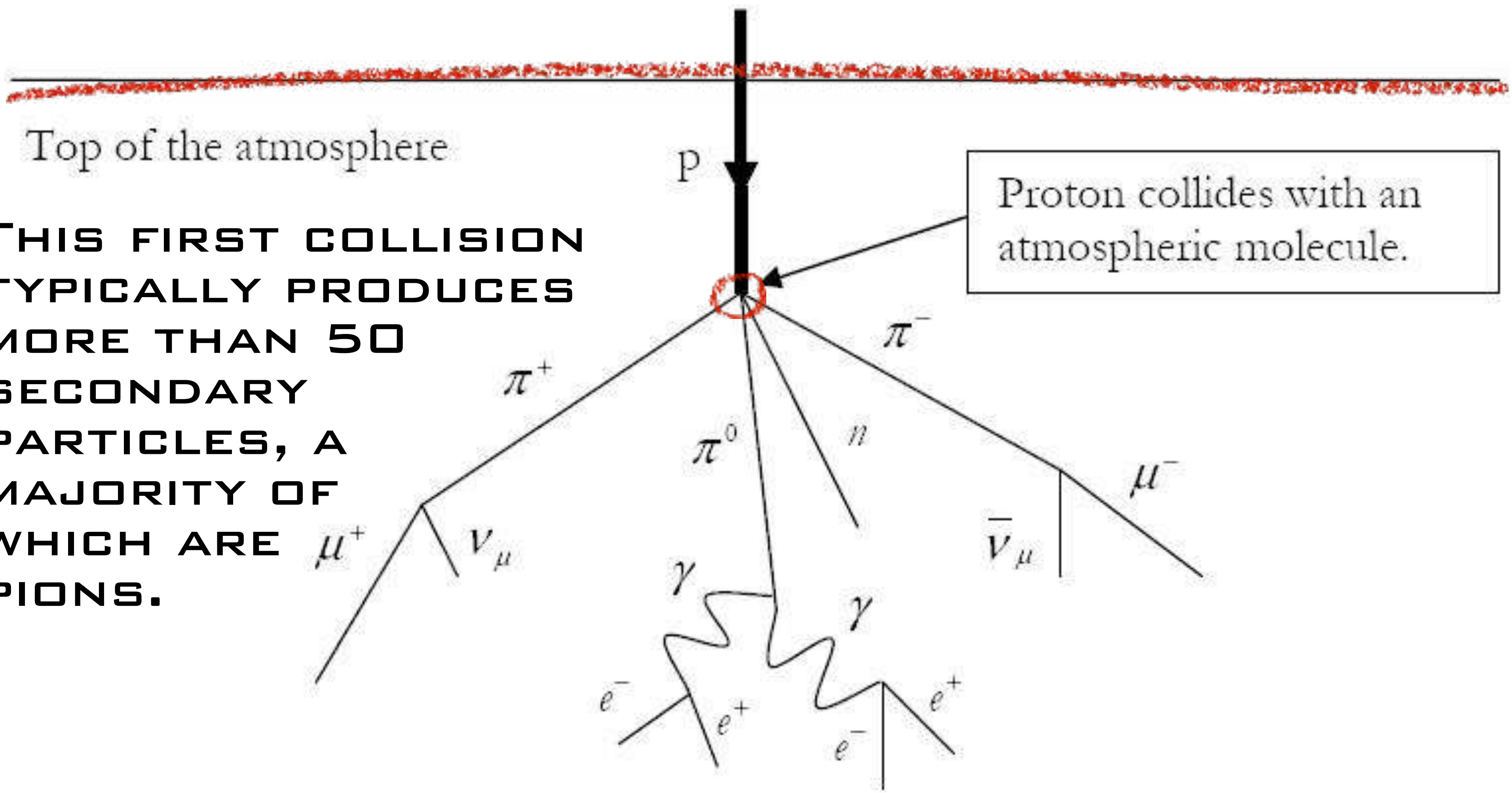
Particle Cascade

- This takes advantage of the interaction between a high-energy cosmic ray and the air, which produces a correlated cascade of secondary particles.



Particle Cascade

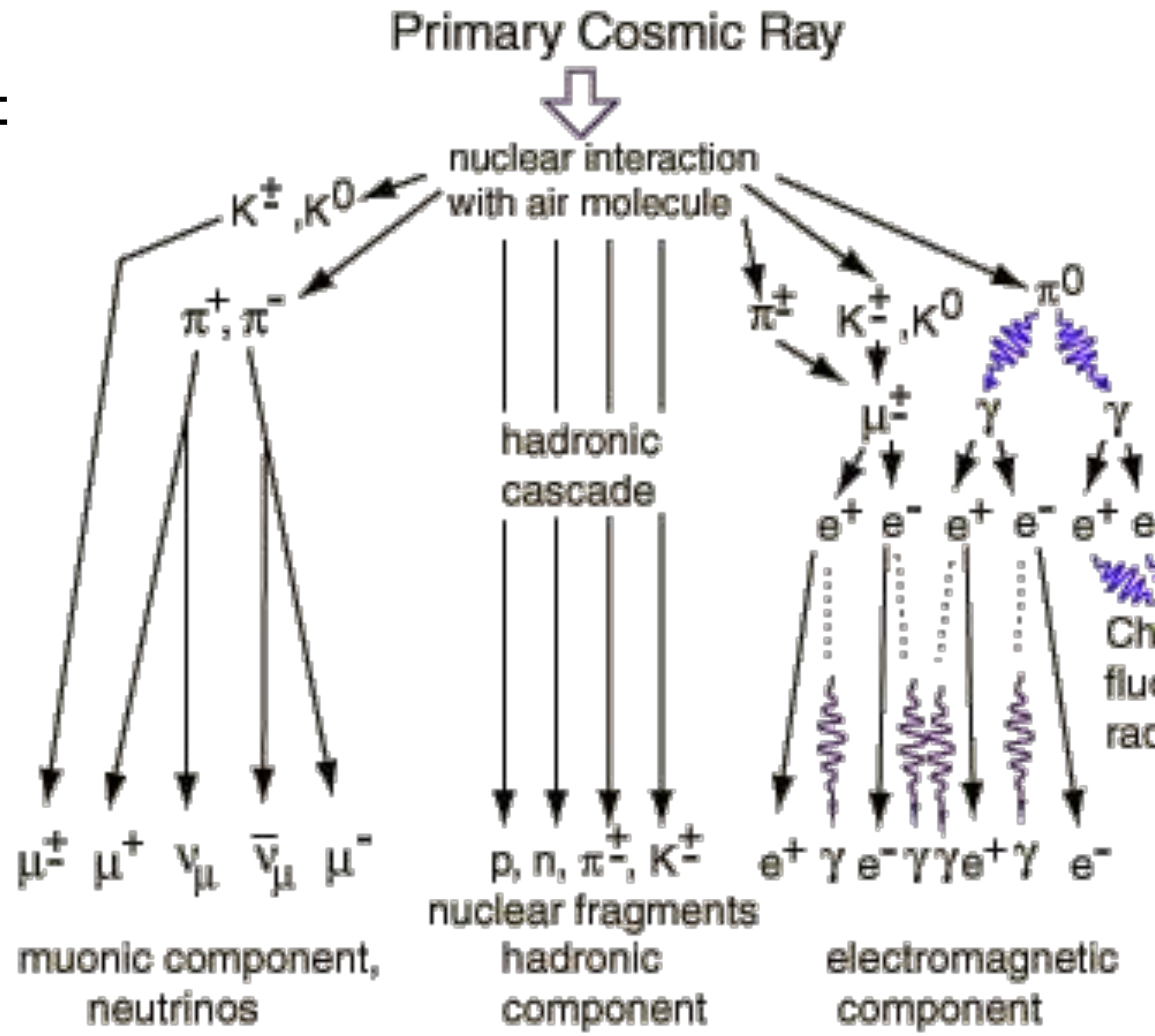
- The process begins with the collision of the primary cosmic ray with a nucleus near the top of the atmosphere.



- This first collision typically produces more than 50 secondary particles, a majority of which are pions.

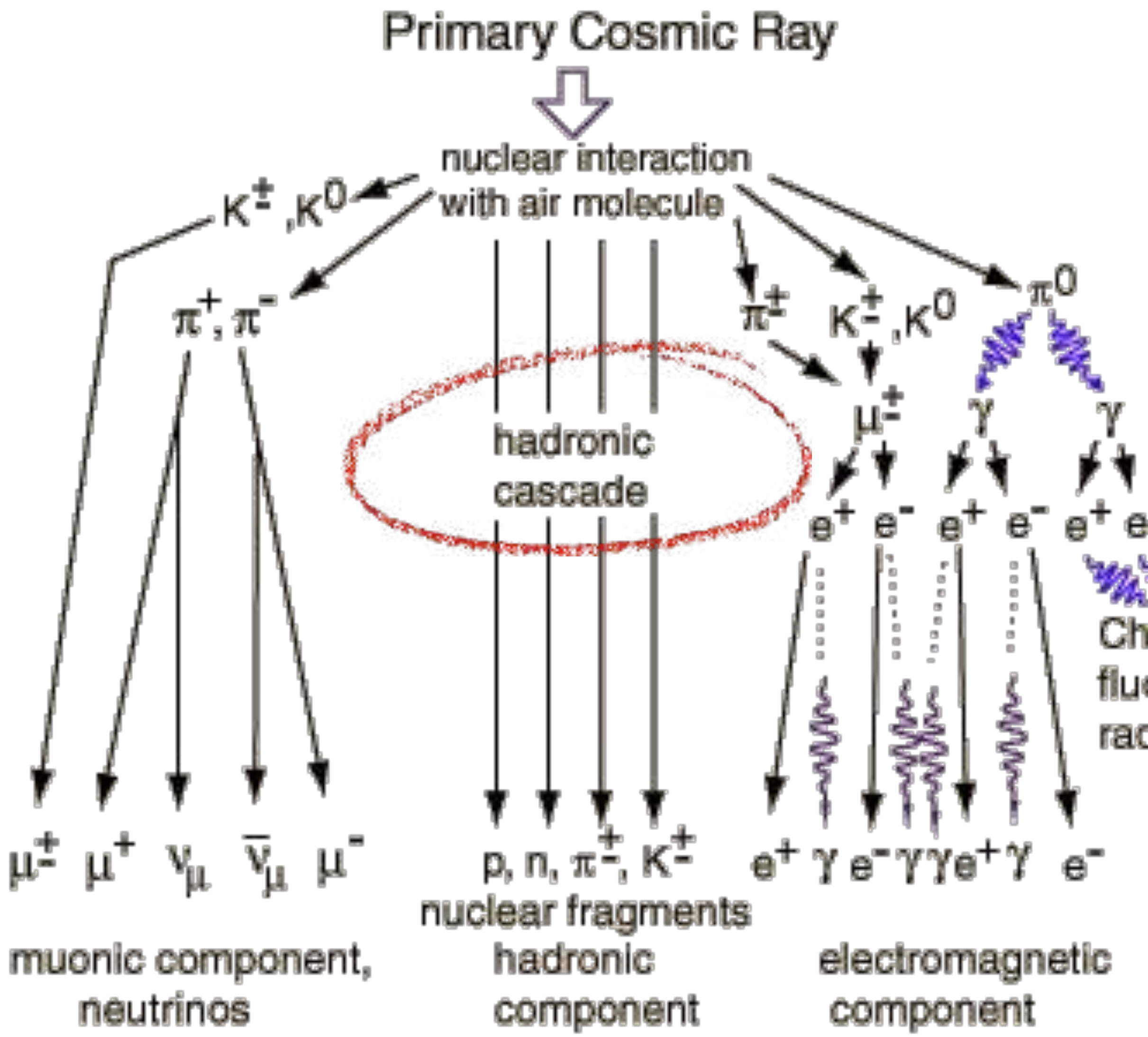
Particle Cascade

- Pions come in three different flavors: positively charged, negatively charged, and neutral.
- All pions are unstable, but the charged pions are relatively long-lived and will most probably collide with another nucleus before decaying.



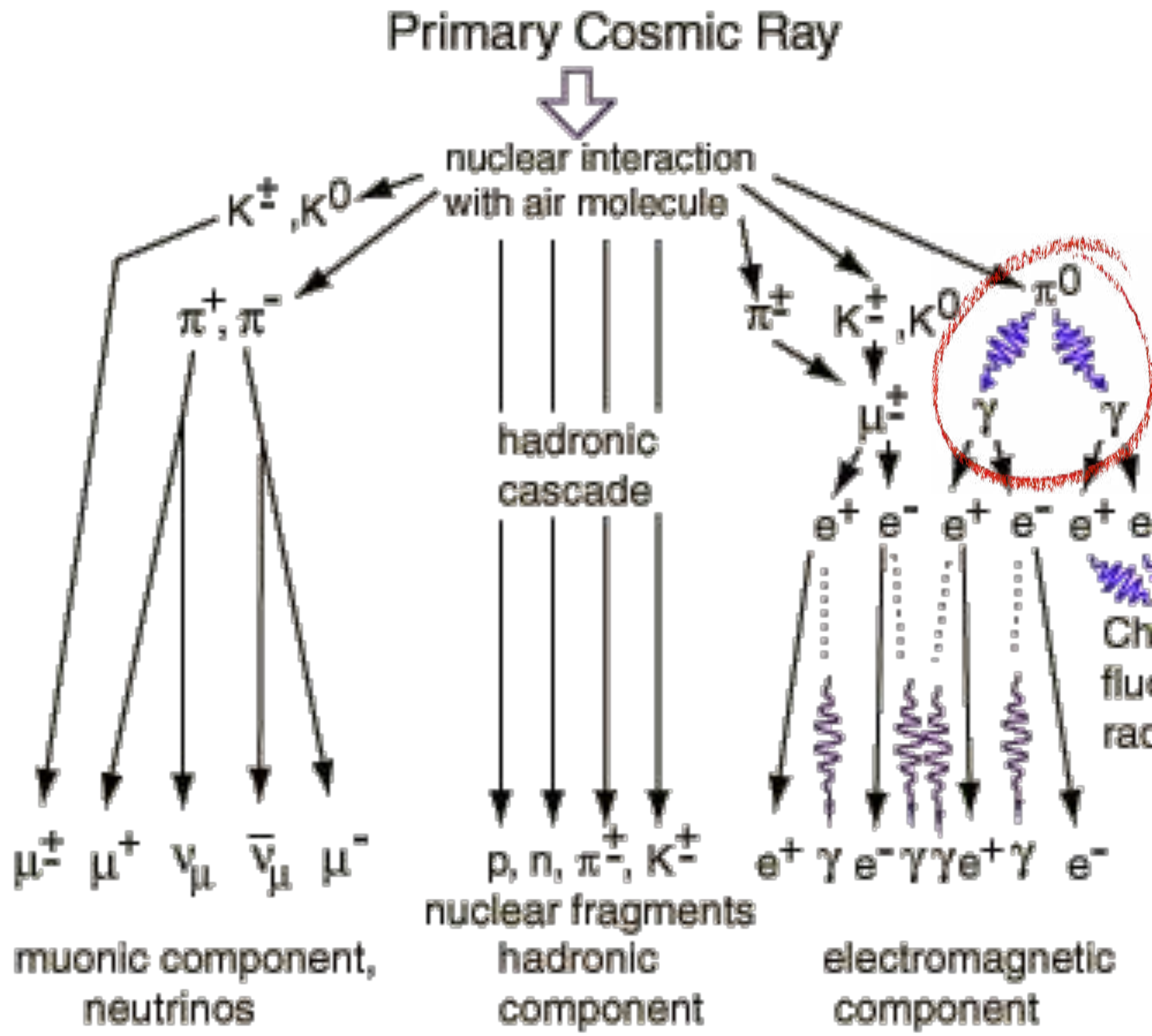
Particle Cascade

- The subsequent collisions are similar in nature to the primary collision.
- This process then leads to a cascade of particles which is referred to as a "hadronic shower".



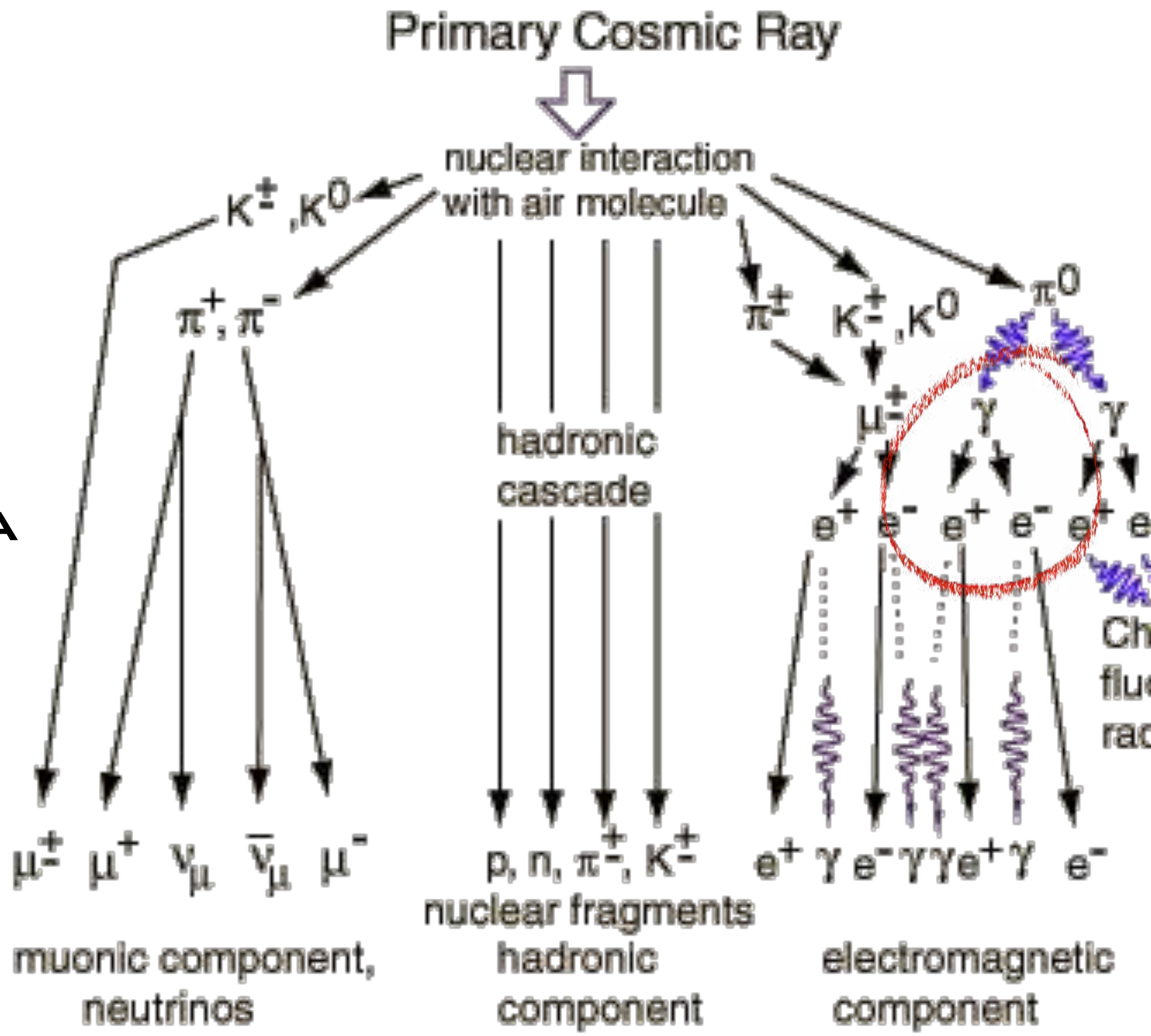
Particle Cascade

- One third of the pions produced are neutral.
- The neutral pions are very short-lived and will almost all decay into a pair of photons before interacting with nuclei in the atmosphere.



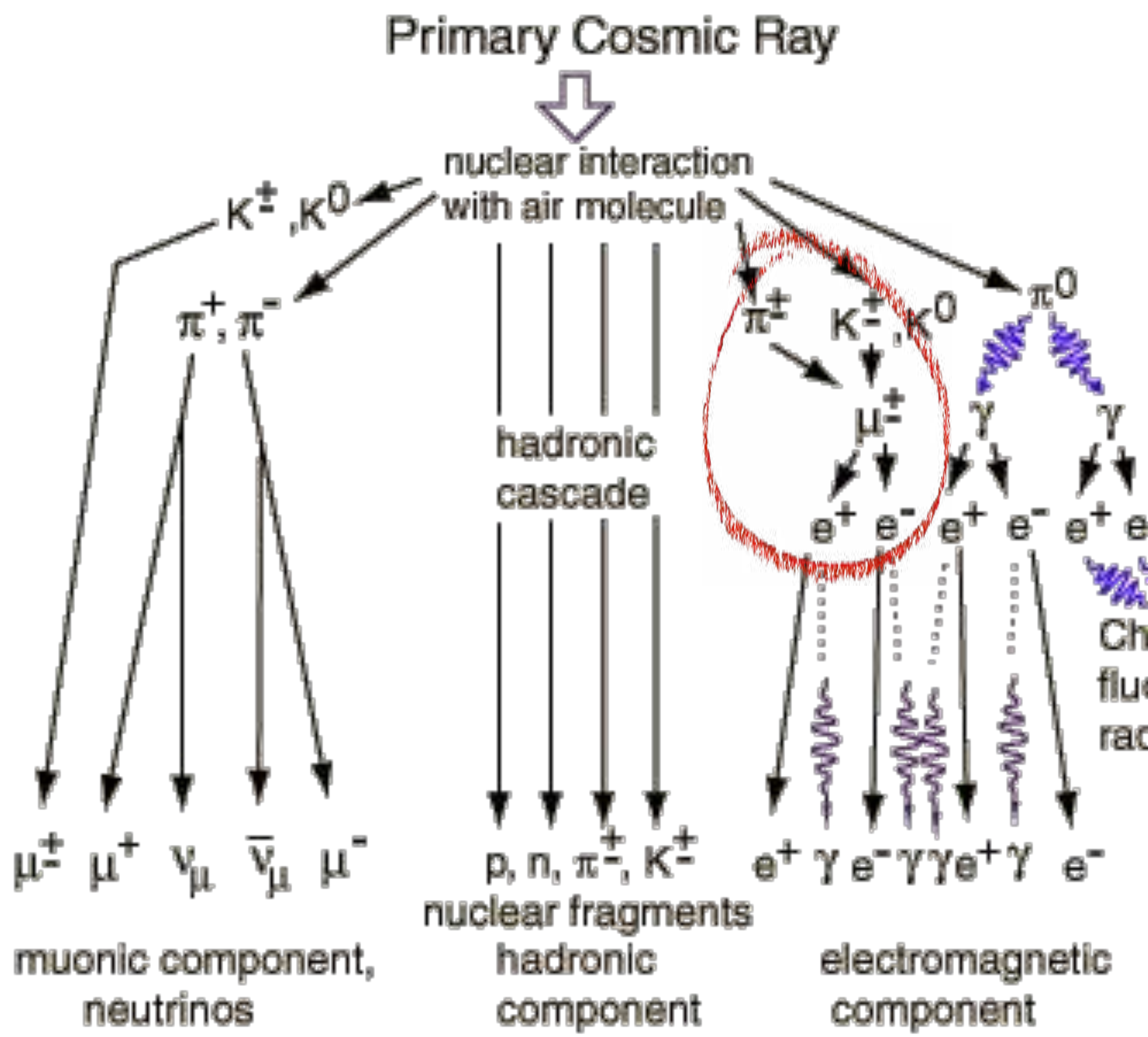
Particle Cascade

- The photons interact with the nuclei in the air to produce electron-positron pairs,
- which in turn will produce photons via "bremsstrahlung".
- This cascading process leads to the formation of an "electromagnetic shower".



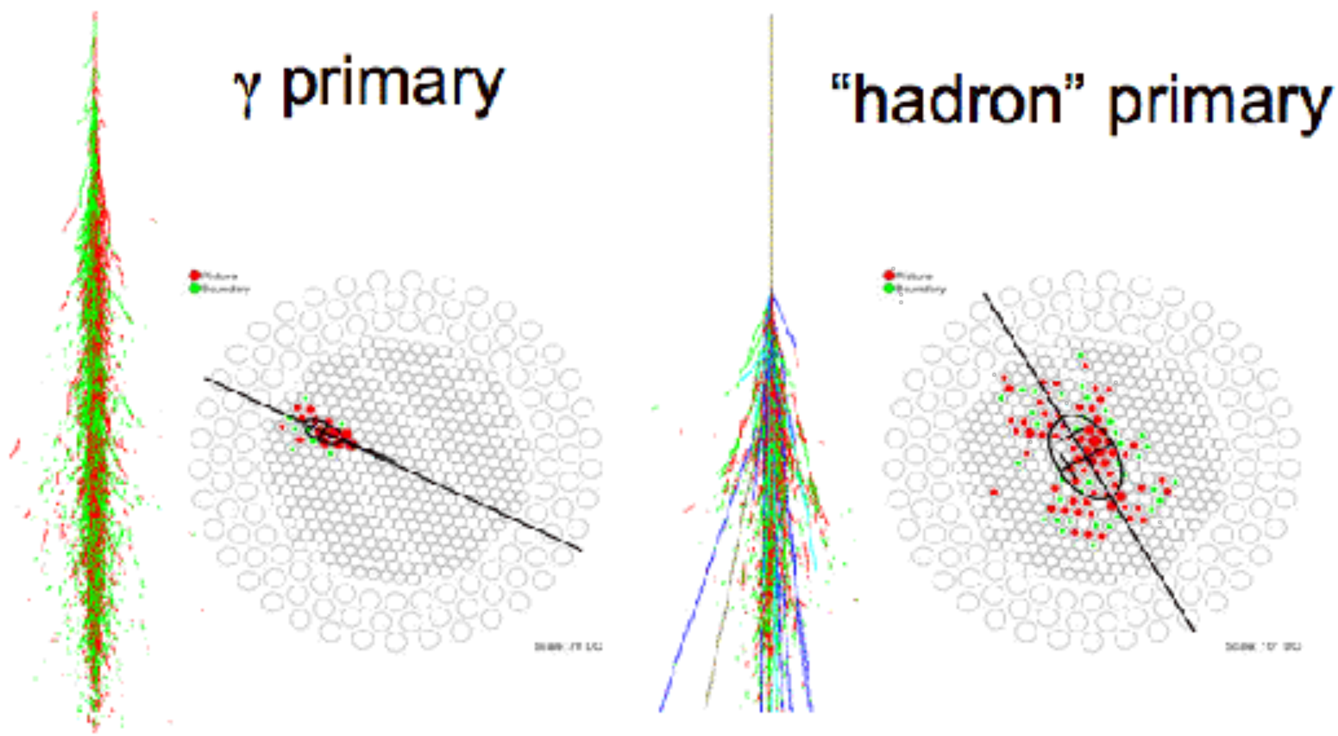
Particle Cascade

- The hadronic shower itself is continuously producing neutral pions and thus initiating secondary electromagnetic showers along its path.



Particle Cascade

- High-energy cosmic rays are believed to consist mostly of charged nuclei.



- Gamma rays have been observed with energies as high as $\sim 10^{12}$ eV.

- both types of cascades are called "extensive air showers" (EAS).

Discovery of EAS

- Extensive air showers were discovered in the 1930's by French physicist Pierre Victor Auger.

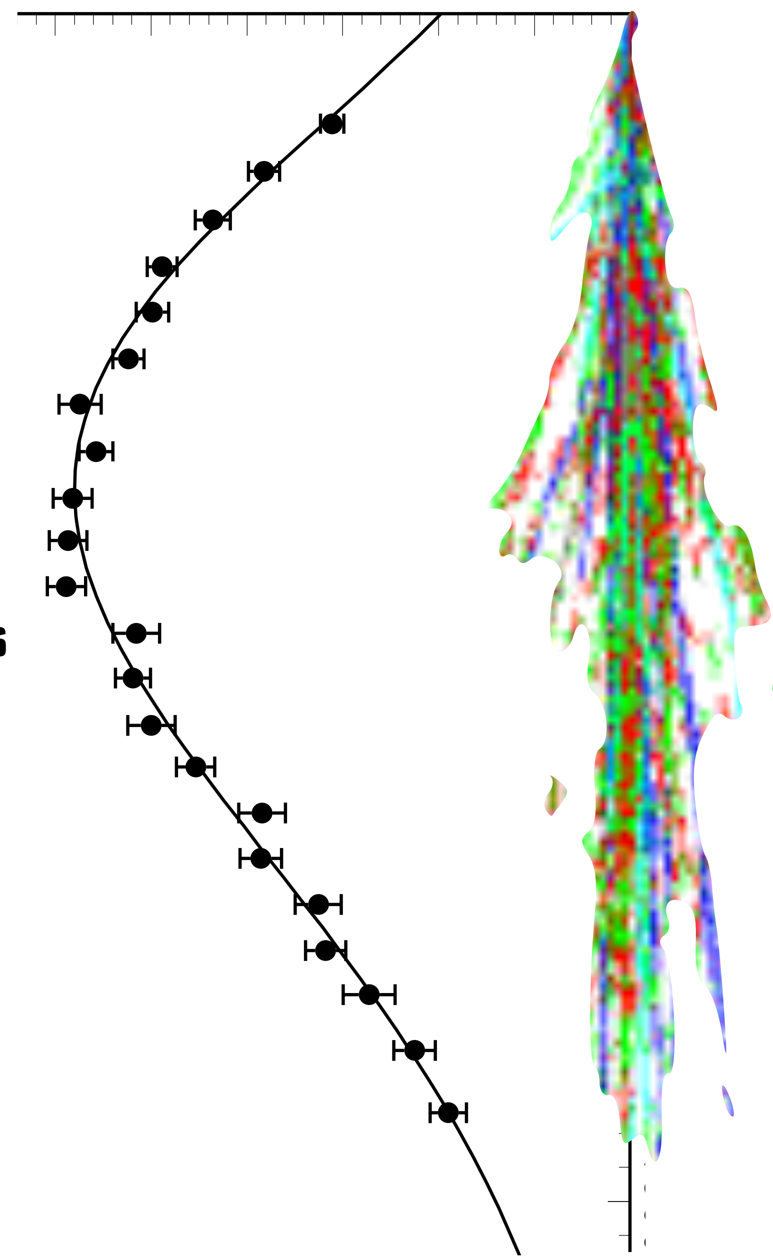
EAS development

- As an EAS develops into the atmosphere, more and more particles are produced.

- A small fraction of the kinetic energy of the primary particle is converted into mass energy.

- The remaining kinetic energy is then distributed over the shower.

- The process of multiplication continues until the average energy of the shower particles is insufficient to produce more particles in subsequent collisions.

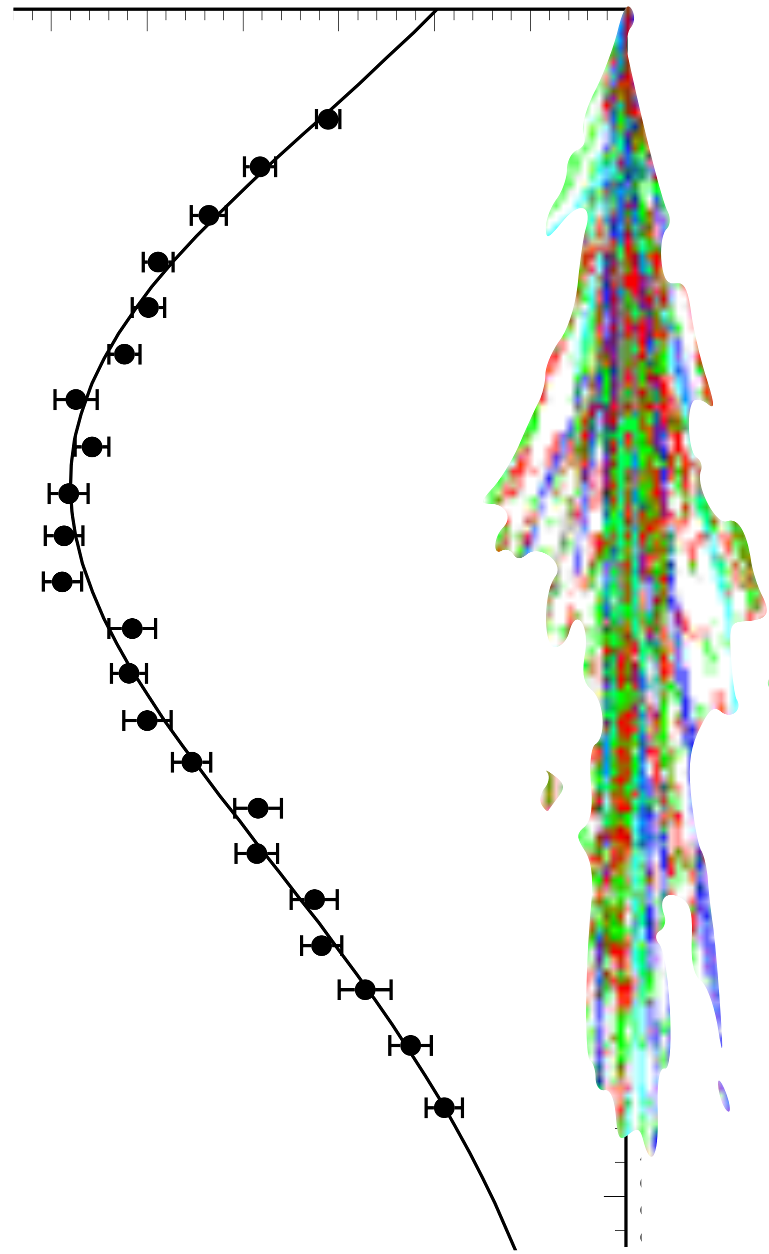


EAS development

- This point of the EAS development is called the "shower maximum".

- Beyond the maximum, the shower particles are gradually absorbed with an attenuation length of ~200 g/cm².

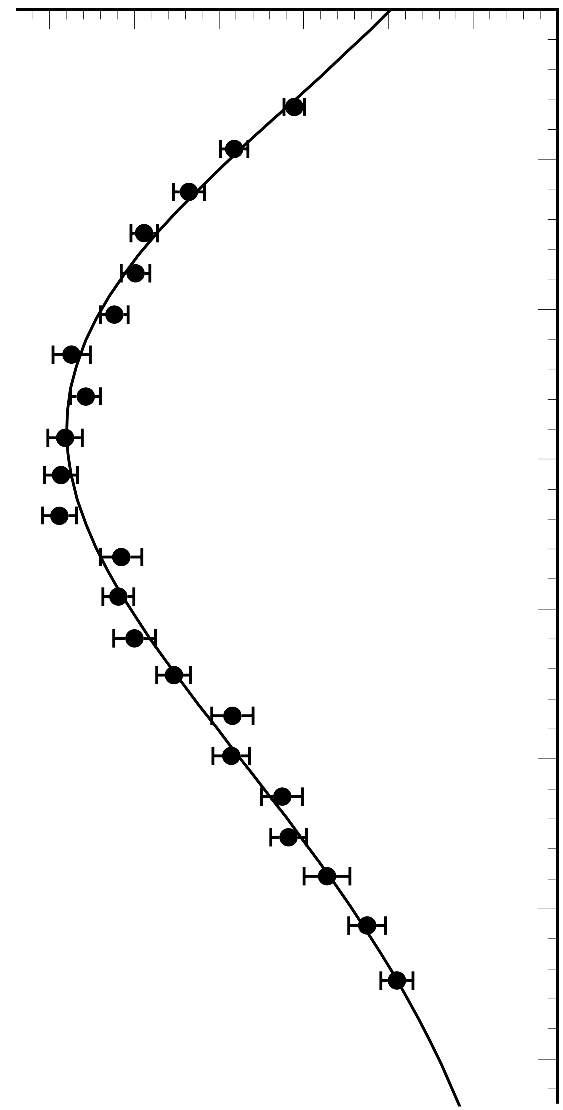
- Rigorously this is a measure of the depth of material penetrated by the shower. (More on this later.)



Properties of Shower Max

- Two properties of the shower maximum are important to note:

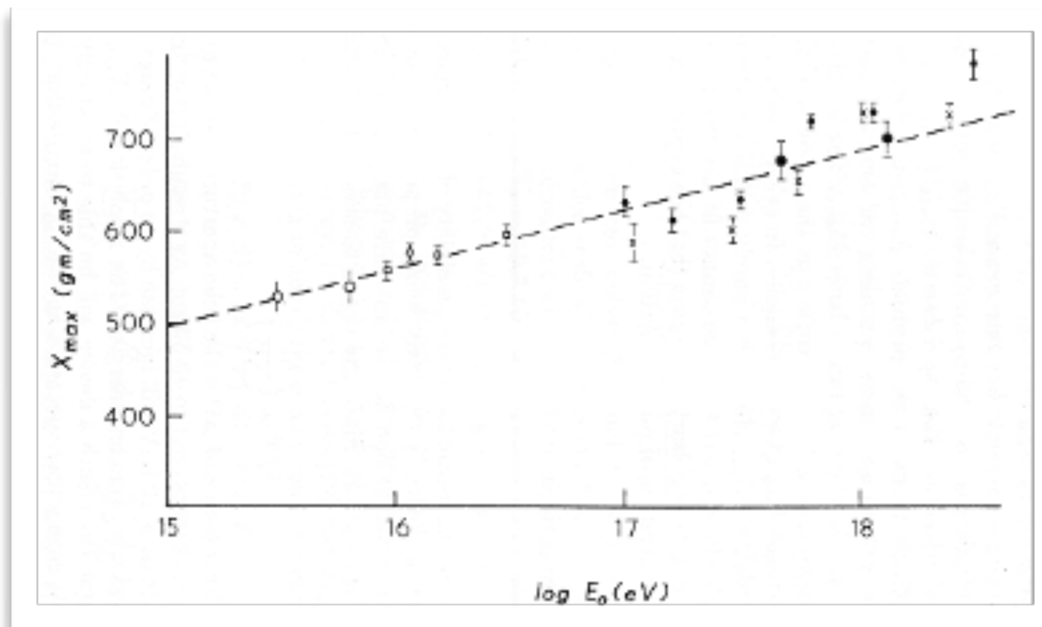
1. at maximum, an EAS typically contains ~1-1.6 particles for every GeV (10^9 eV) of energy carried by the primary cosmic ray.



Properties of Shower Max

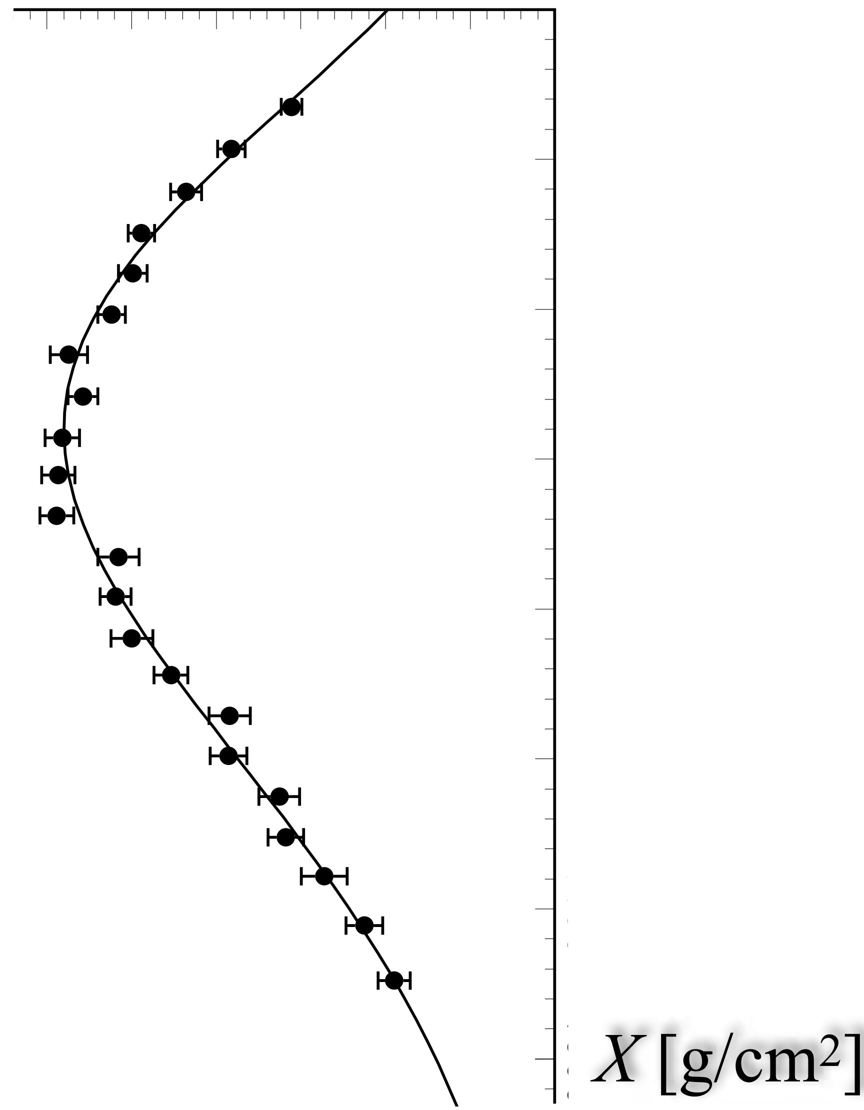
- Two properties of the shower maximum are important to note:

2. The average "slant depth" at which the shower maximum occurs, varies logarithmically with the energy of the primary cosmic ray.



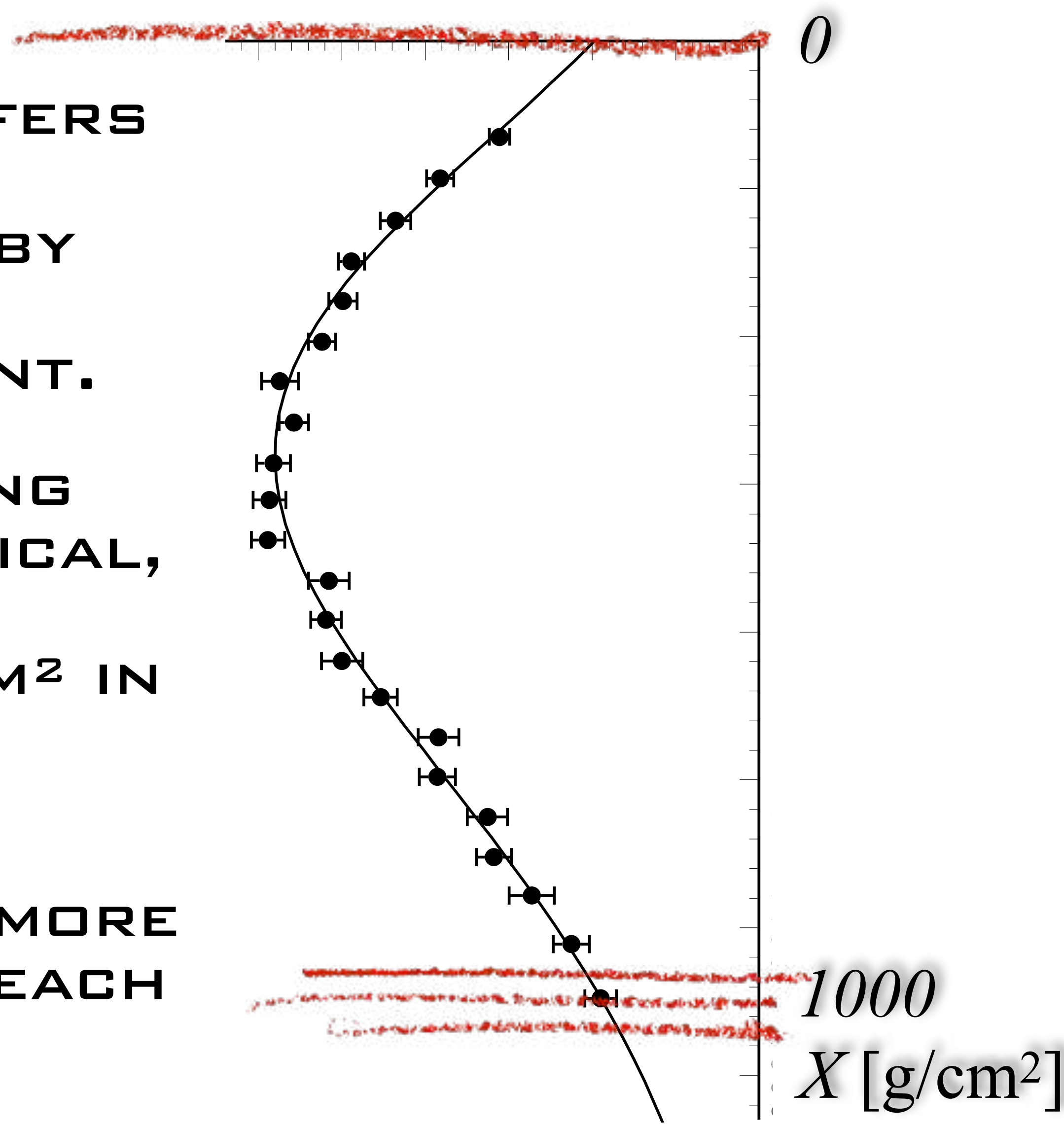
Properties of Shower Max

- The "slant depth" X refers to the amount of materials penetrated by the shower at a given point in its development.
- X is calculated by integrating the density of air from the point of entry of the air shower at the top of the atmosphere, along the trajectory of the shower, to the point in question.



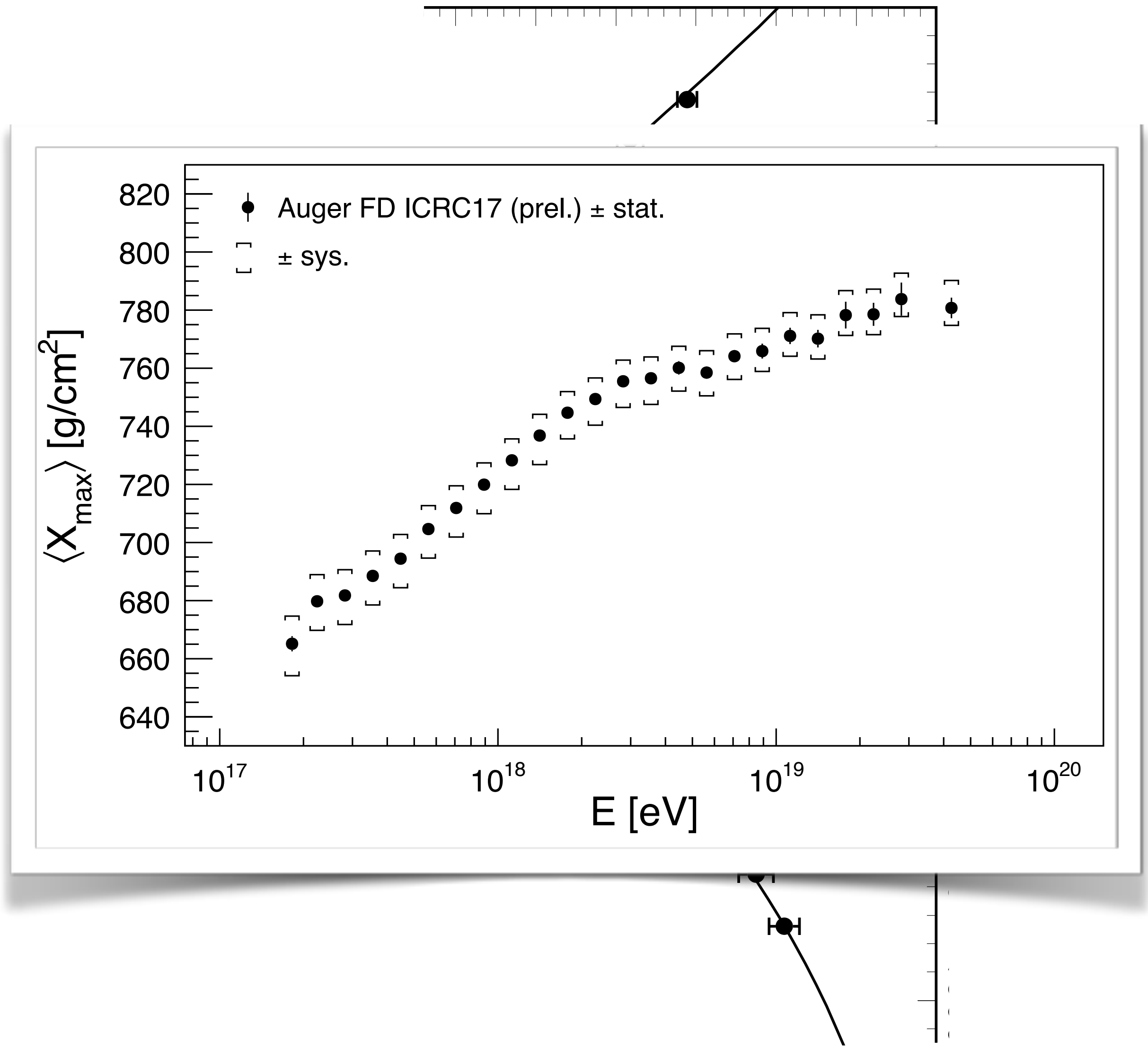
Properties of Shower Max

- The "slant depth" X refers to the amount of materials penetrated by the shower at a given point in its development.
- An air shower traveling along an exactly vertical, downward trajectory traverses ~1,000 g/cm^2 in reaching sea-level.
- Obviously, an inclined shower will traverse more than 1,000 g/cm^2 to reach sea-level.

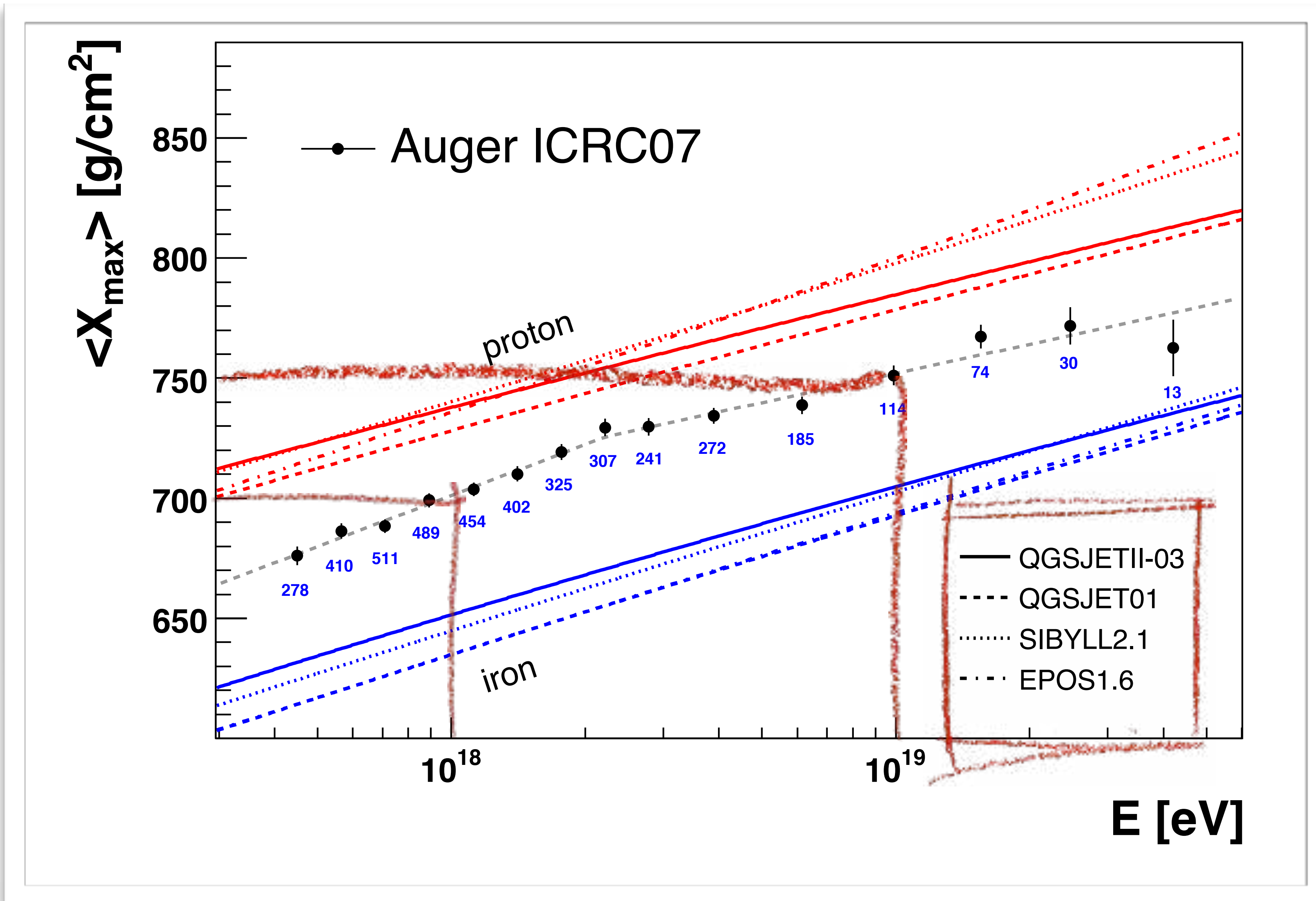


Properties of Shower Max

- the depth of shower maximum is denoted "X_{max}".
- This figure shows a measurement of the average X_{max} as a function of energy.

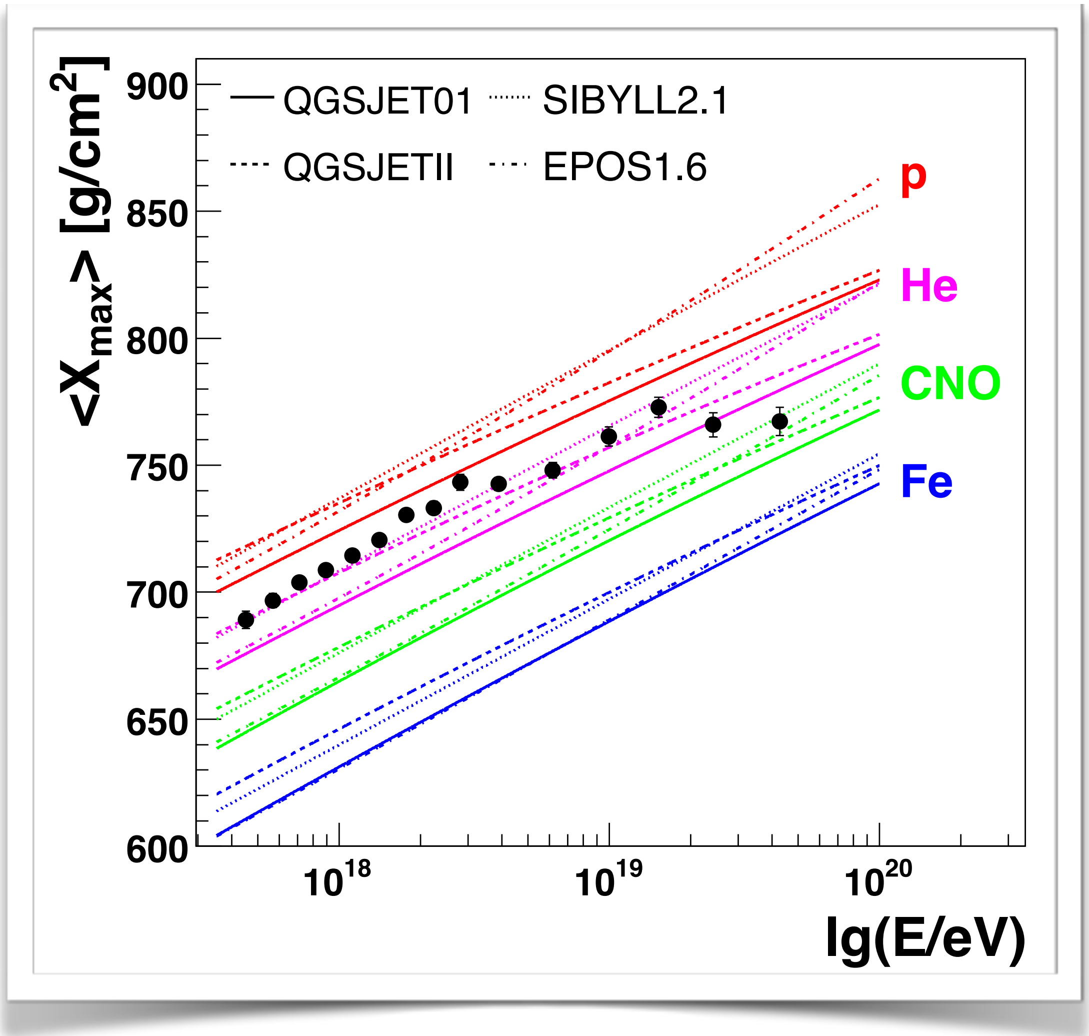


Properties of Shower Max



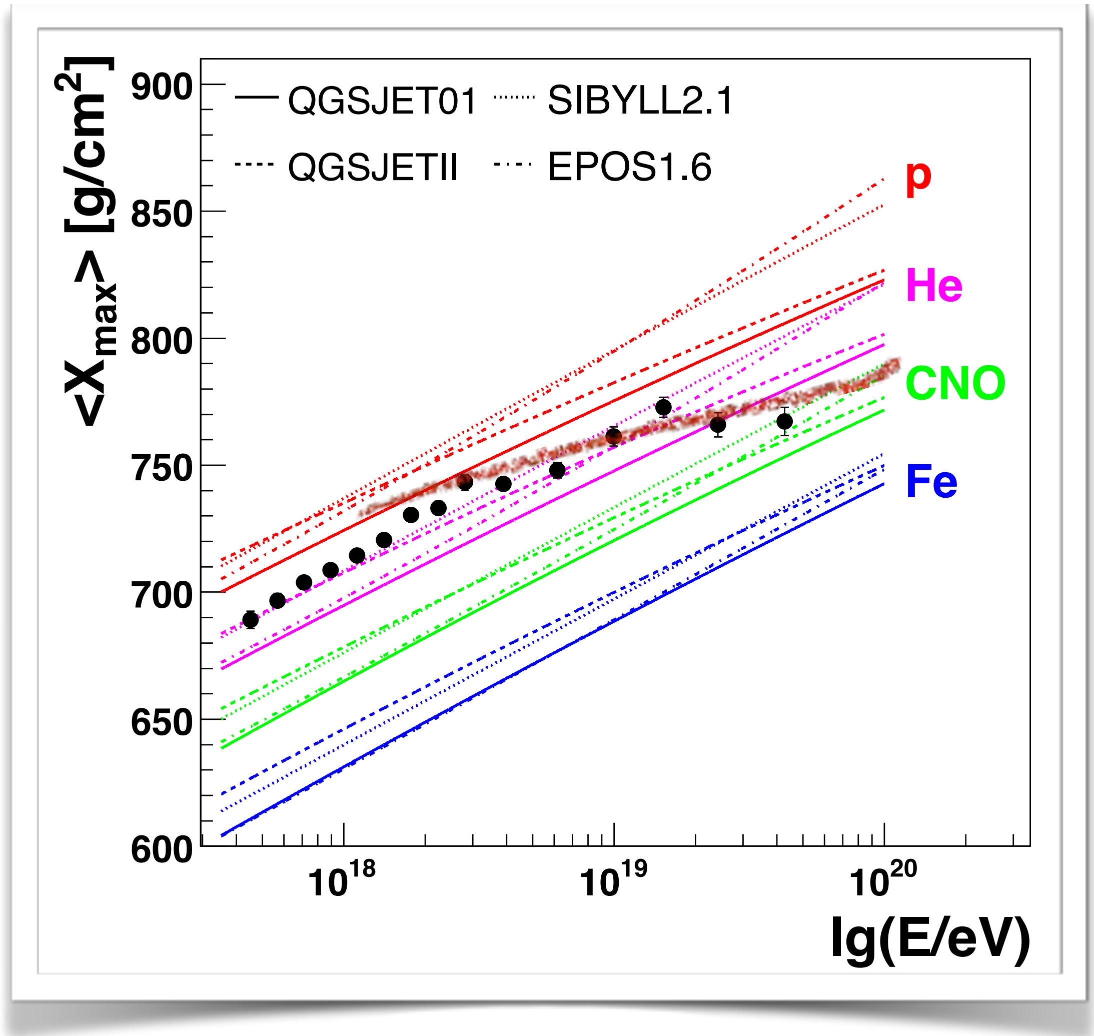
Properties of Shower Max

- Hadronic models predict different absolute values for average X_{max}.
- However, nearly all the models predict:
  - the same slope
  - roughly the same separation between heavier and lighter elements.

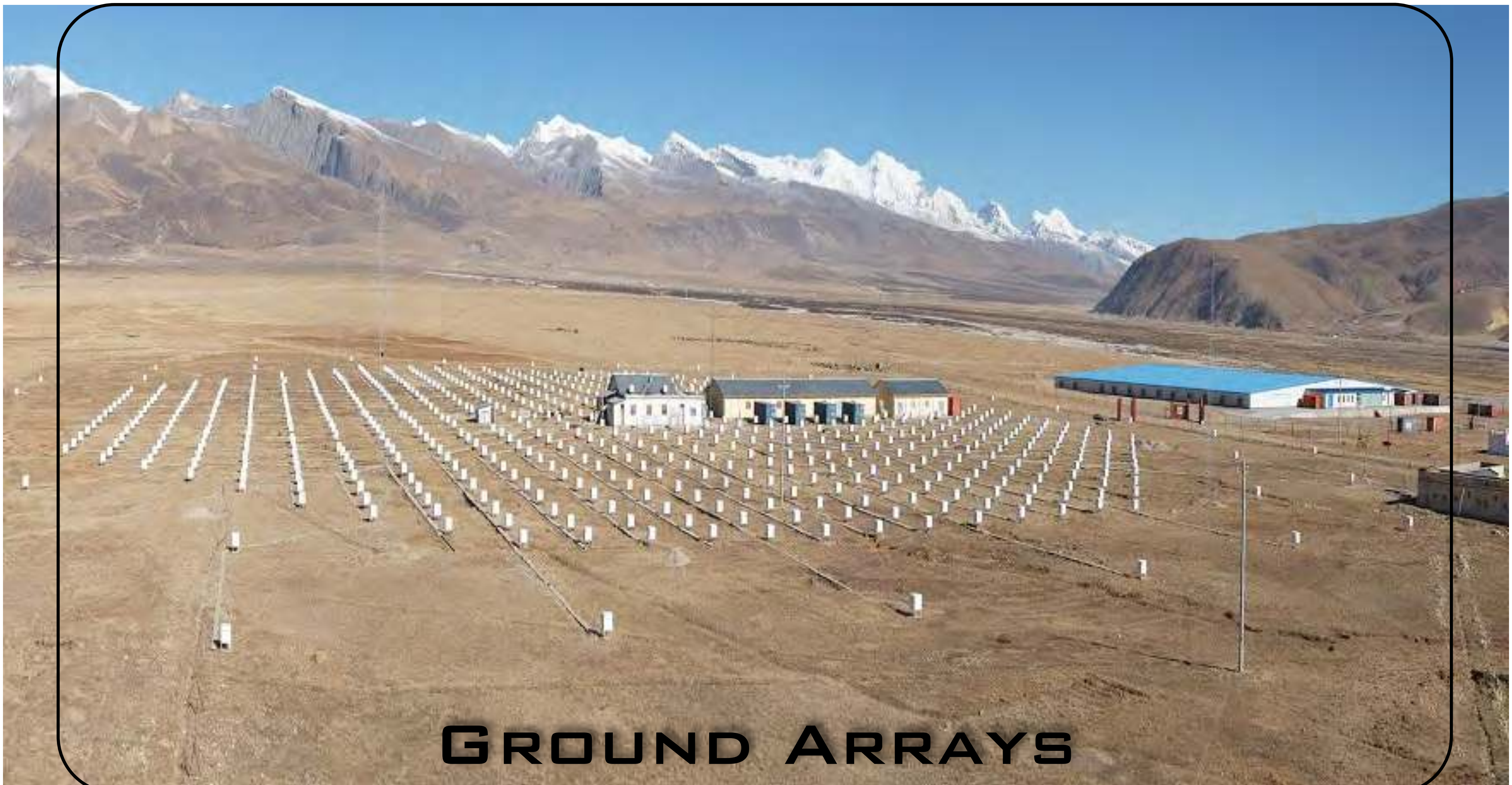


Properties of Shower Max

- UHECRs seem to get heavier at the highest energies.
- Is there a change in particle physics?
- Wrong picture?



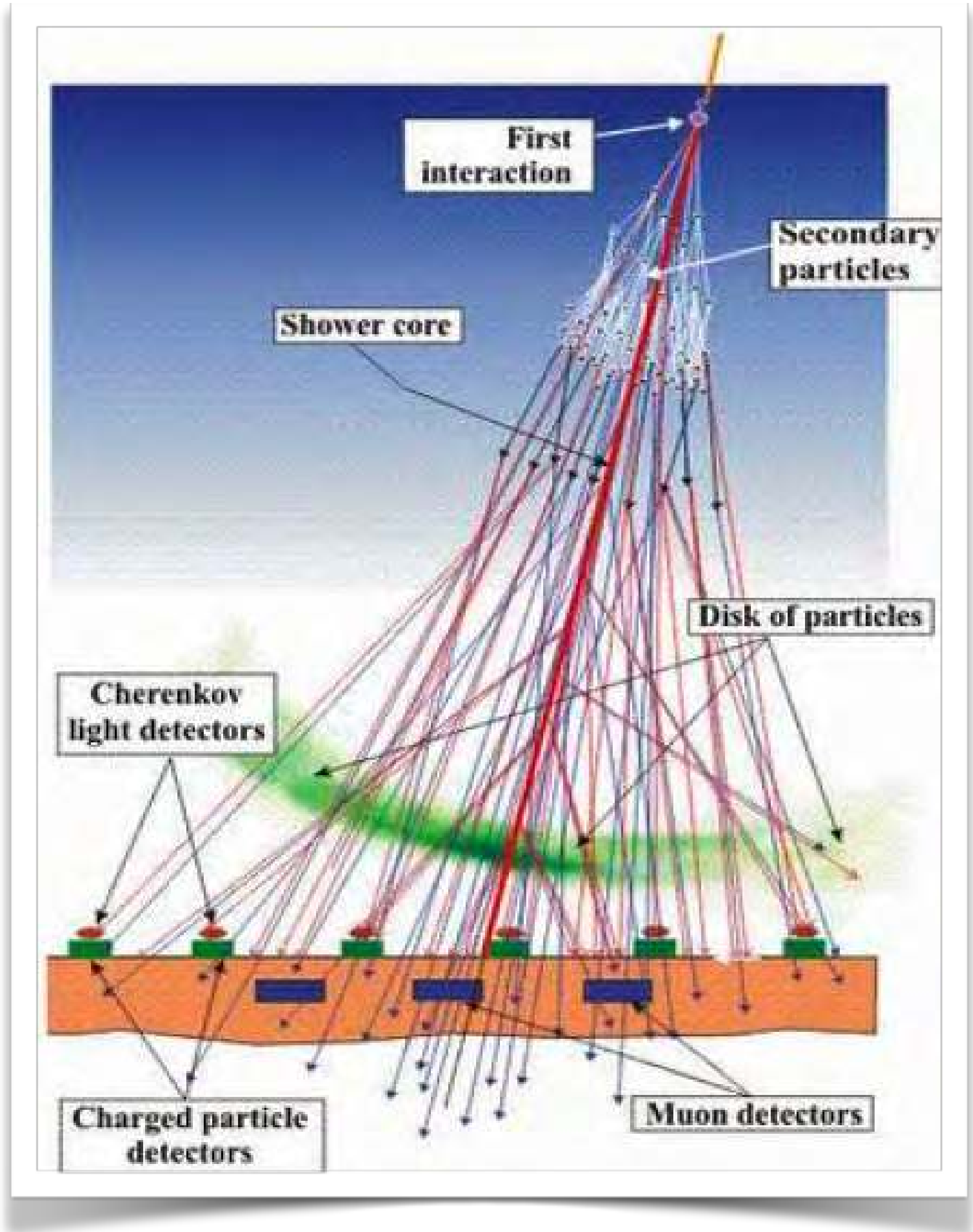
Detection of UHECRs



Ground Arrays

Ground Arrays

- Showers with energy above 10^{15} eV can penetrate to half the vertical atmospheric depth.
- There is also sufficient number of particles in the cascade such that the remnant of the shower can be detected as a correlated event by an array of individual particle detectors on the ground.

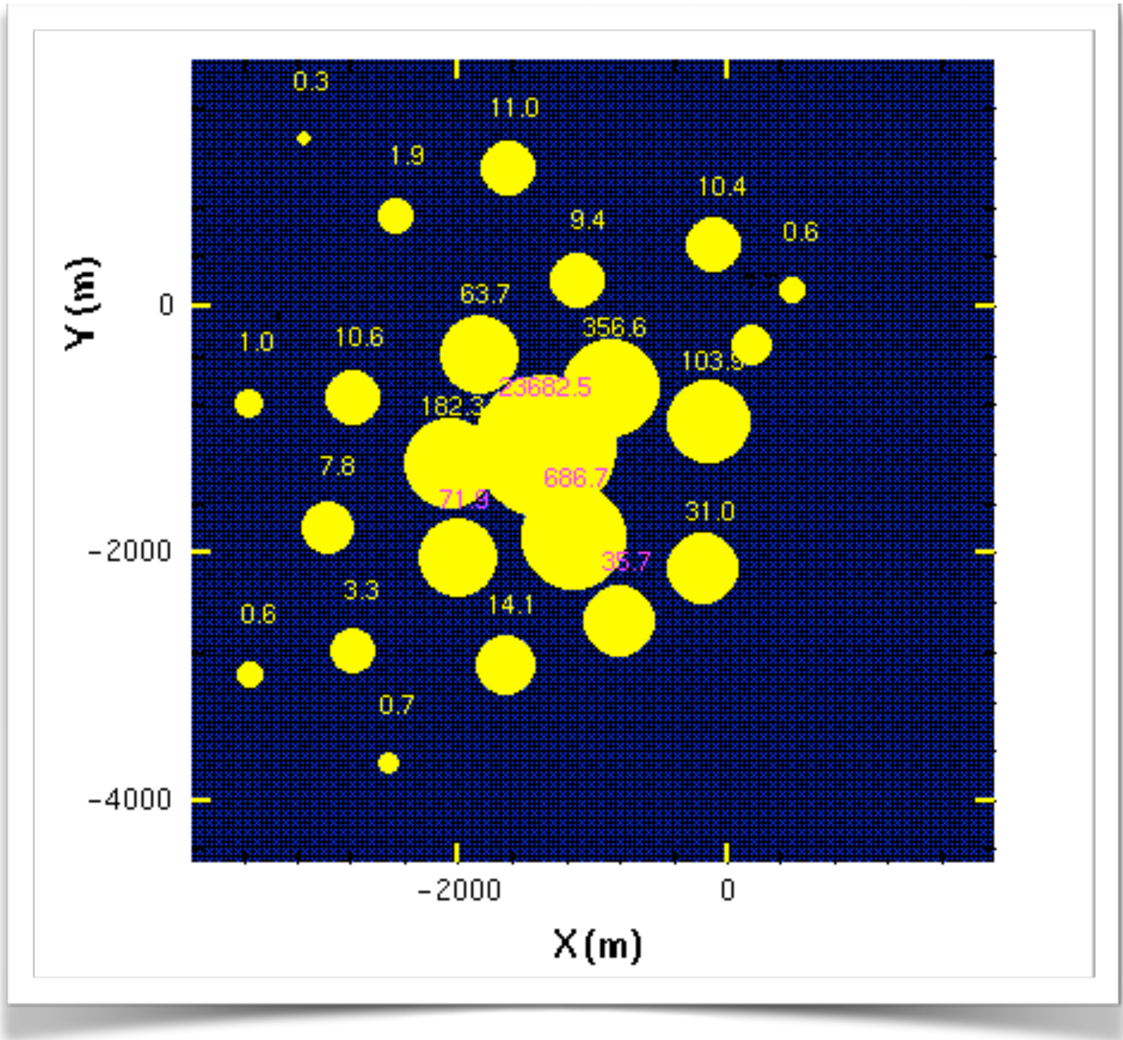


Ground Arrays

- The threshold (the lowest energy detectable by an instrument) of such a "Ground Array" depends on the altitude of the array, and the separation between detectors.

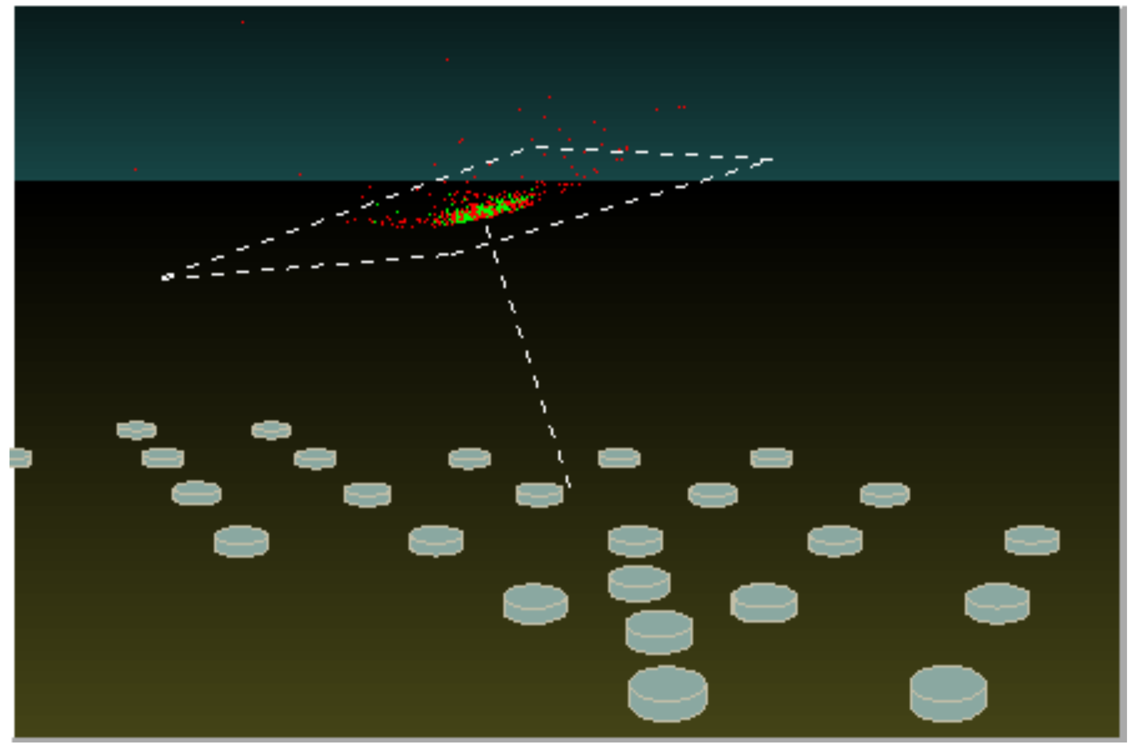
Ground Arrays

- Each station of the array samples the density of particles in its neighborhood of the shower.
- The footprint of air showers typically can extend for several kilometers.



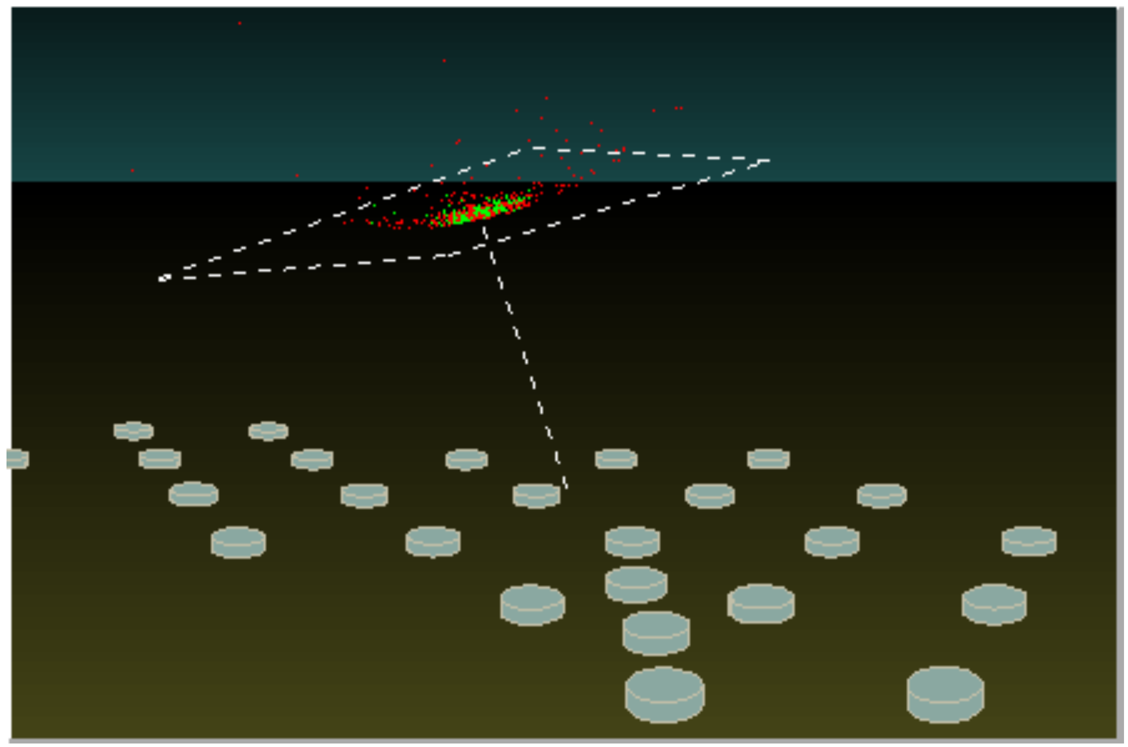
Ground Arrays

- Particles in the air shower arrive in the form of a thin pancake traveling at essentially the speed of light.
- By measuring the time of arrival of the shower front at the individual stations, the direction of the primary cosmic rays can be calculated.



Ground Arrays

- Conventionally, the energy is deduced from the density measured at a given distance from the core of the shower at ground level.
- This distance is chosen to minimize the uncertainties.



Ground Arrays

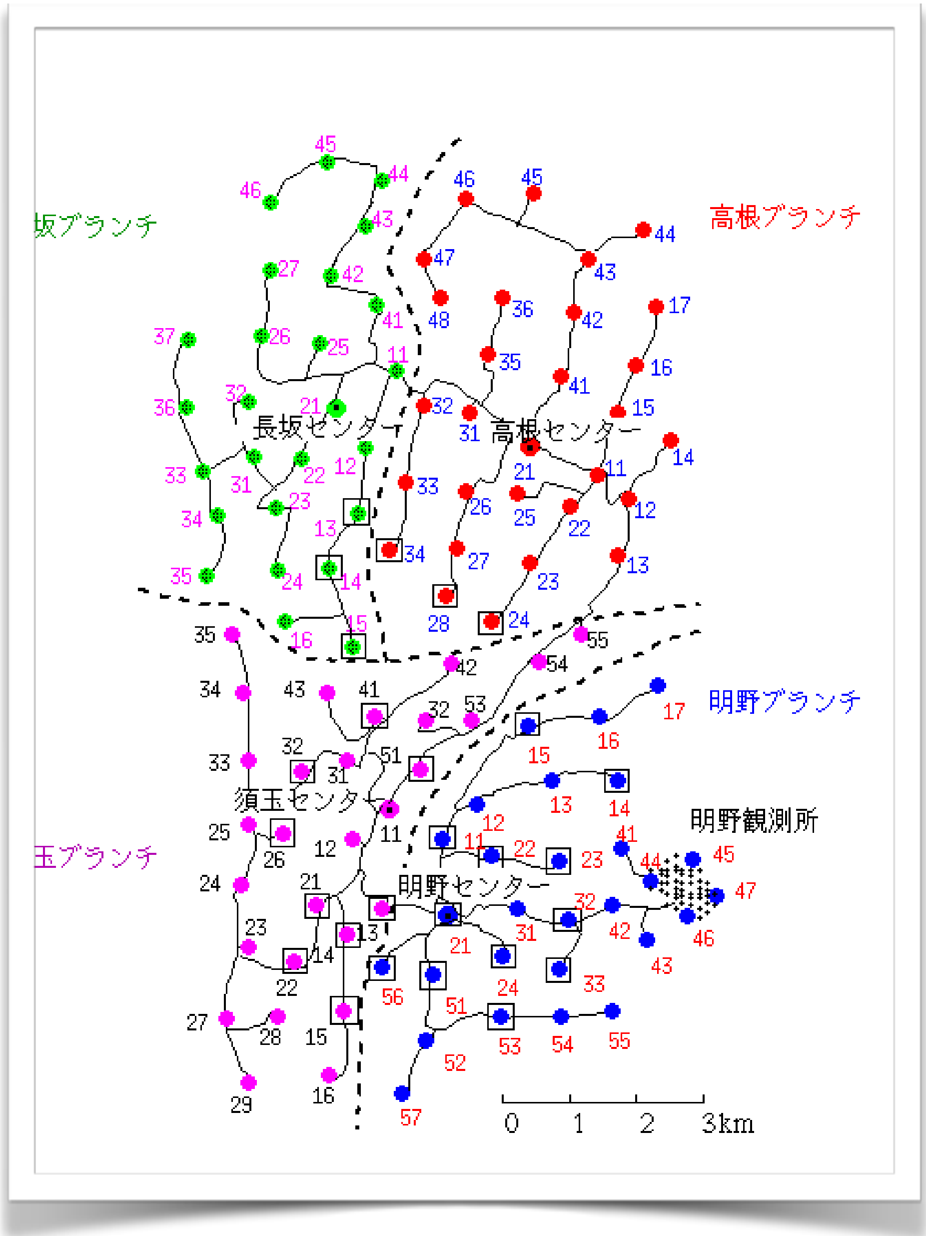
1946: Rossi & Zatsepin build first array

Ground Arrays

1962: John Linsley sees first $E > 10^{20}$ eV

Ground Arrays

- AGASA:
  - 100 km²
  - plastic scintillators



Detection of UHECRs

Air Fluorescence Technique

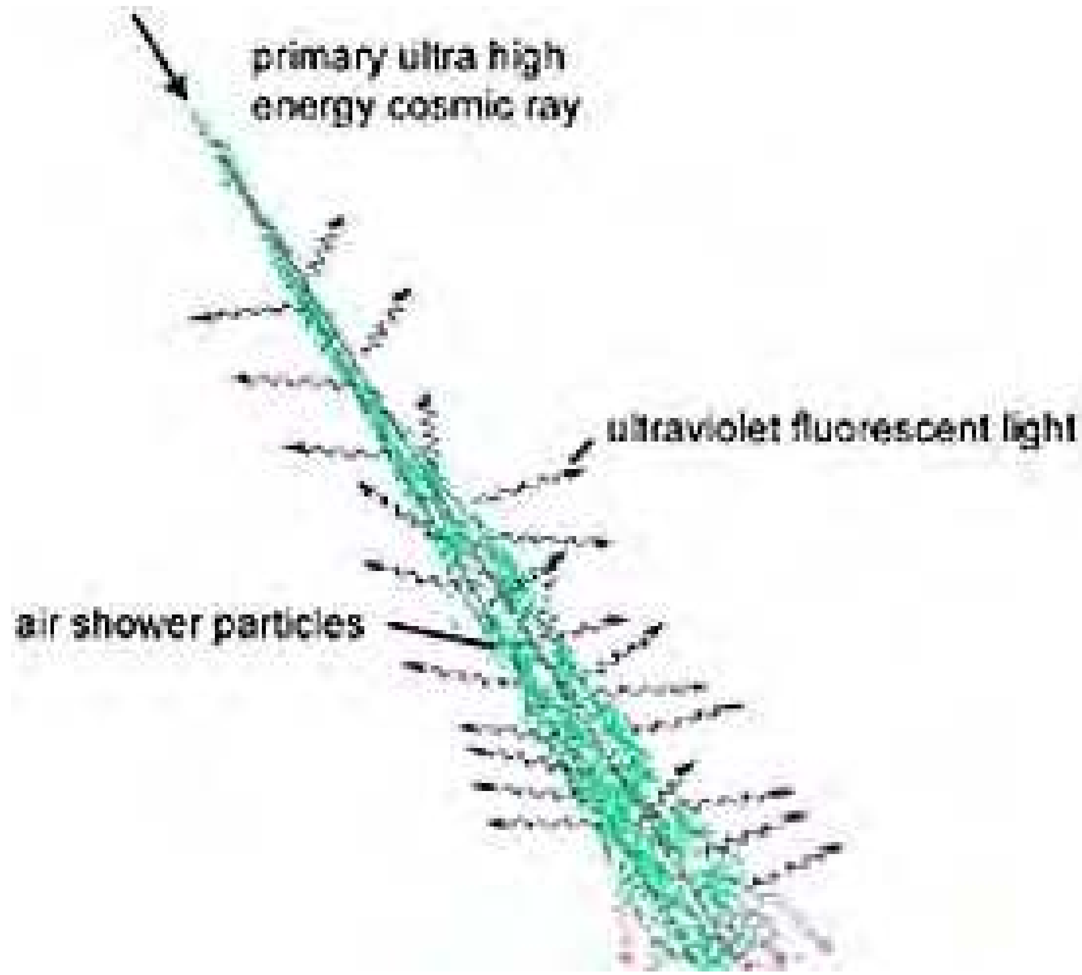
Air Fluorescence

- "fluorescence": process by which atoms absorb photons of one wavelength and emits photons at a longer wavelength.
  - e.g. fluorescence lights

1. An electric current passes through an elongated bulb, colliding with mercury atoms.
2. The collision process excites the mercury atoms, which then emits ultra-violet (UV) light.
3. This emission is actually referred to as "luminescence". These UV photons are then absorbed by the phosphor coating of the bulbs, which re-emits in the visible. It is of course the re-emission process which is properly called "fluorescence".

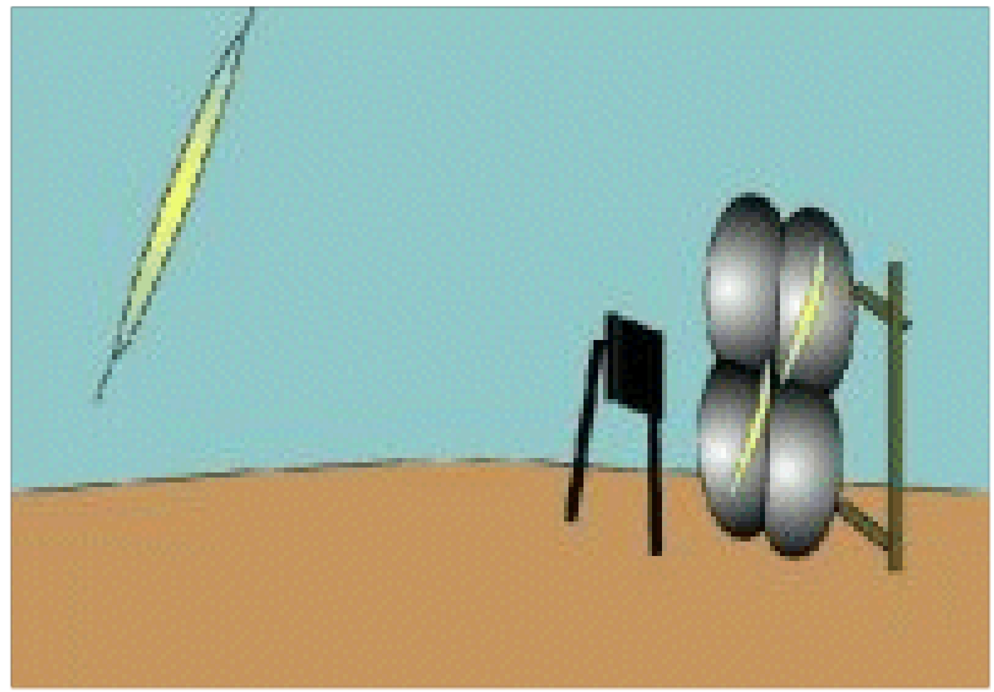
Air Fluorescence

- The passage of charged particles in an extensive air shower through the atmosphere results in the ionization and excitation of the gas molecules (mostly nitrogen).
- Some of this excitation energy is emitted in the form of UV radiation.



Air Fluorescence

- The scintillation light is collected using a lens or a mirror and imaged on to a camera.
- The camera "pixelizes" the image and records the time of arrival of light along with the amount of light collected at each pixel.
- This can be made on clear, moonless nights, using very fast camera elements to record light flashes of a few microseconds.



Air Fluorescence

- Air fluorescence was studied in the early 60's in LANL.

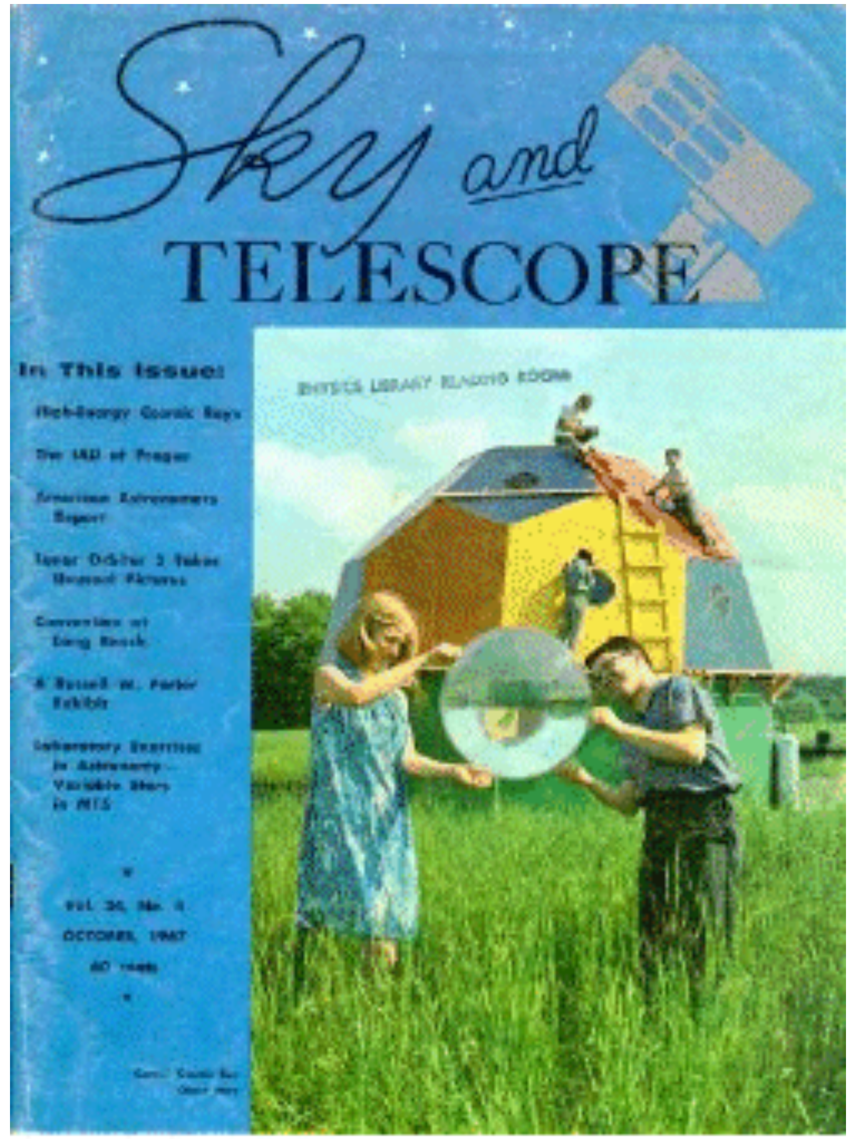
- It was a method for detecting the yield of nuclear explosions in tests.

- Many charged particles are expelled from a nuclear explosion, and these particles will also produce scintillation light as they pass through air.

- The amount of light can be used to estimate the total amount of energy released from the device.

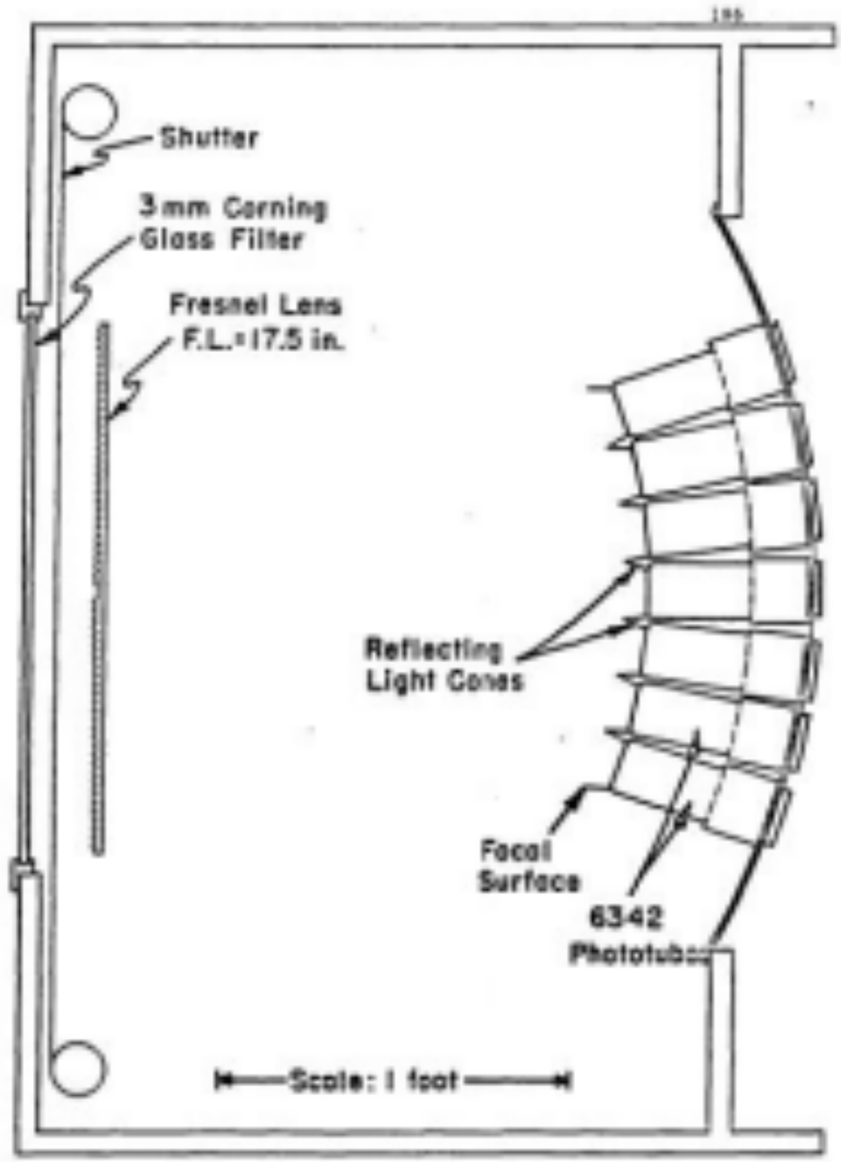
Air Fluorescence

- In 1967, Greisen's group constructed a full-scale fluorescence experiment.
- The Cornell detector images the nigh-sky using 500 photo-multiplier tubes (PMT), divided into 10 modules.
- Each PMT is a pixel covering a solid angle of ~6 deg by 6 deg.
- Each module is equipped with a 0.1 m^2 Fresnel lens.



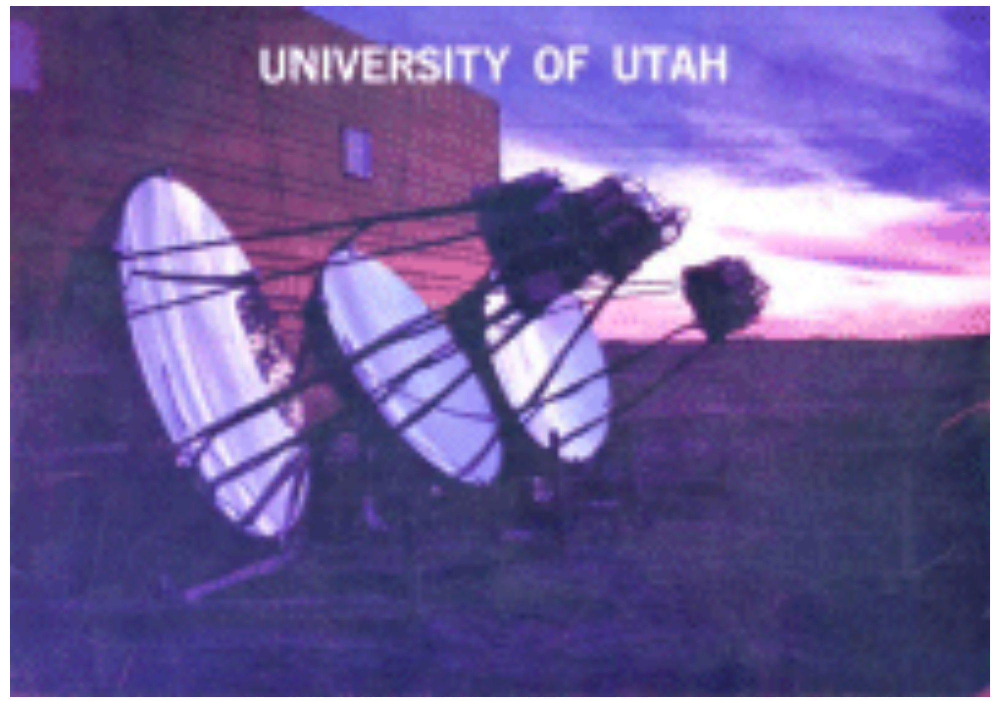
The Cornell Experiment

- PMT's were arranged at the focal surface (roughly spherical).
- An optical filter was placed before the lens at the aperture.
- It operated for several years but was not sensitive enough.
  - Lenses were too small to collect sufficient light, and
  - the atmosphere in upstate New York was too contaminated.



Air Fluorescence

- In 1976, Physicists from Utah detected fluorescence light from cosmic ray air showers.
- Three prototype modules were used in a test at Volcano Ranch.
- Each prototype had a 1.8 m diameter mirror for light collection. x20 increase!
- The clear desert air also provided much improved visibility over the Cornell experiment.

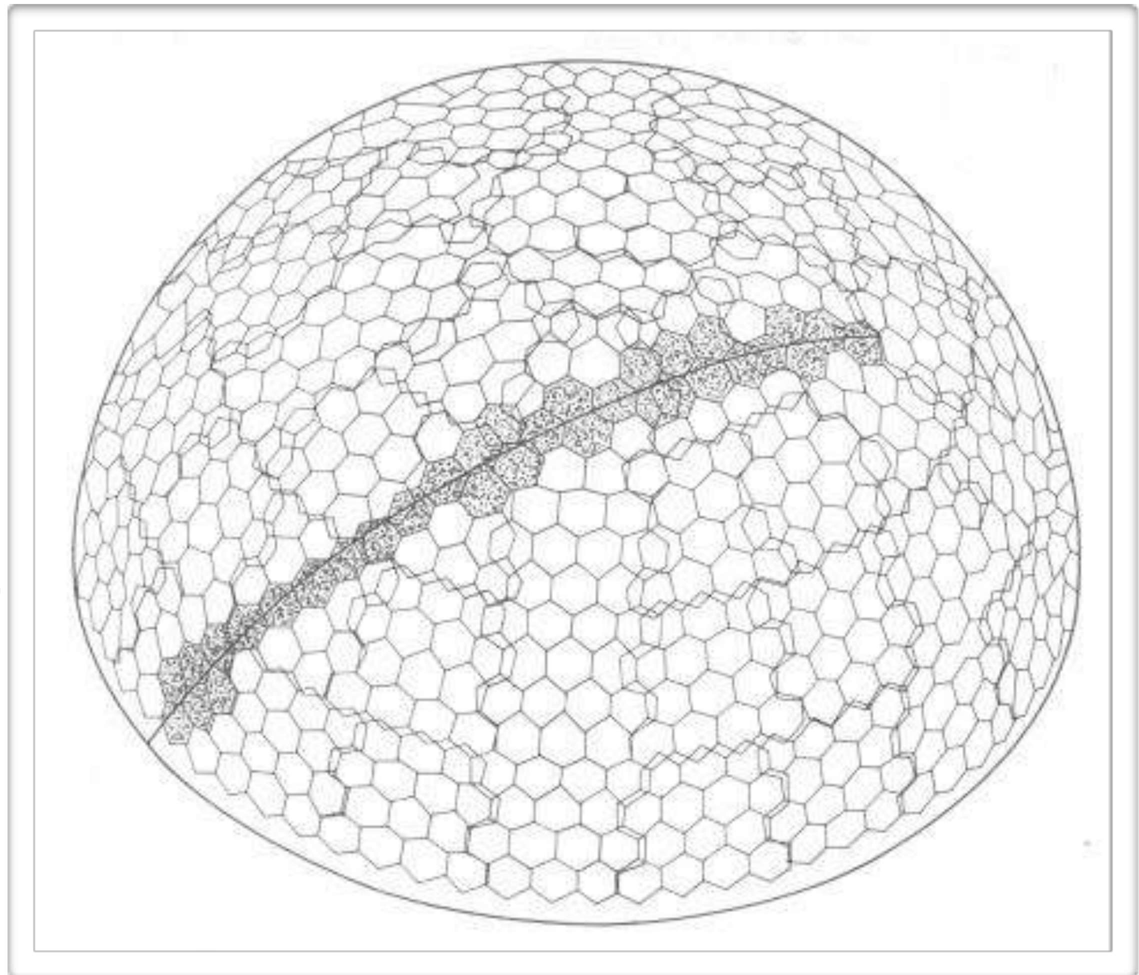


Air Fluorescence

- The Utah group constructed a full-scale detector.
- The Fly's Eye began observations in 1981 and was operated until 1993.

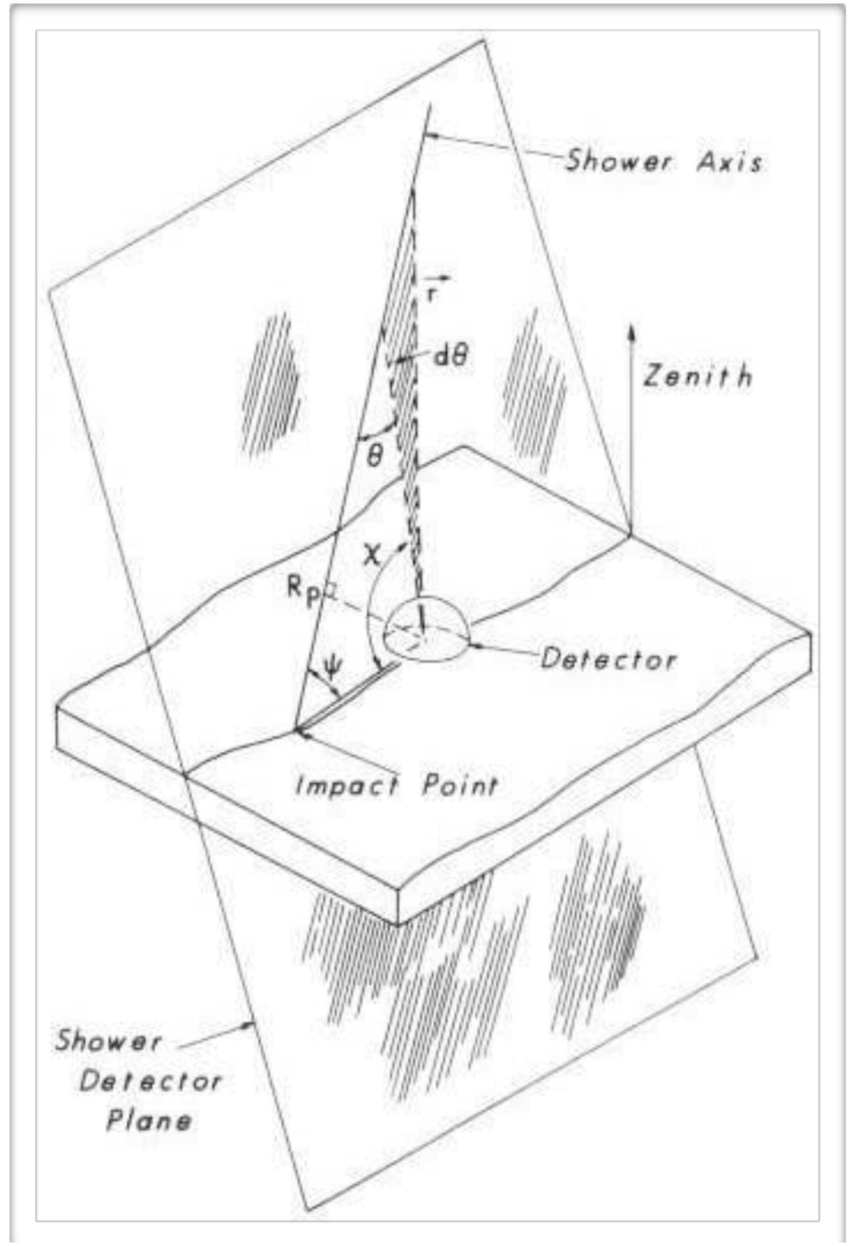
The Fly's Eye

- The detector array at Dugway comprised of 67 modules.
- Each was housed on corrugated steel barrel on a motor-driven rotary mount.
- During observation, the mirrors divide the sky into 880 pixels.
- The trajectory of an air shower crossing the sky was imaged onto a succession of triggered pixels.



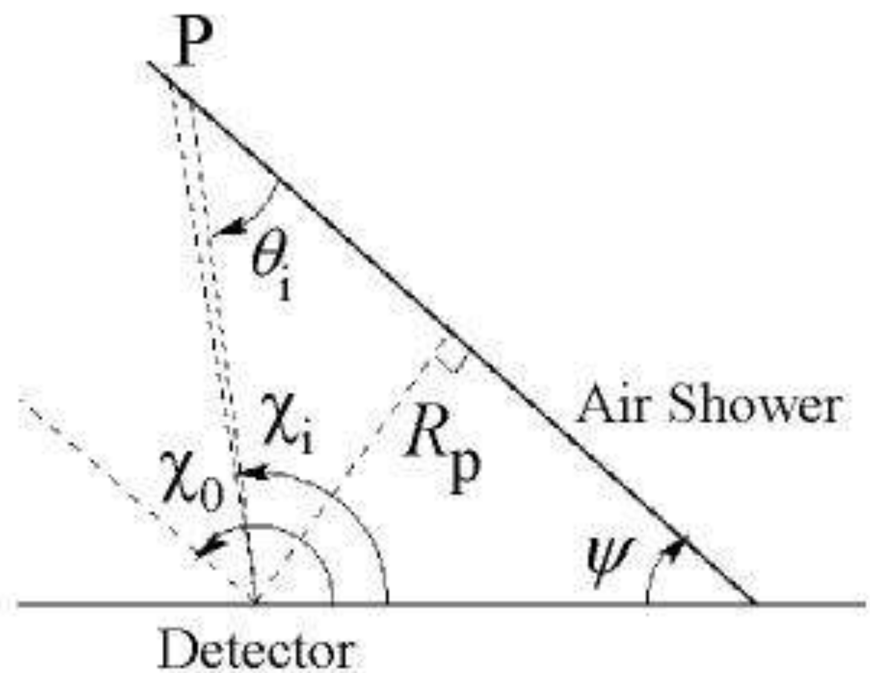
Geometrical Reconstruction

1. Shower Detector Plane (SDP).



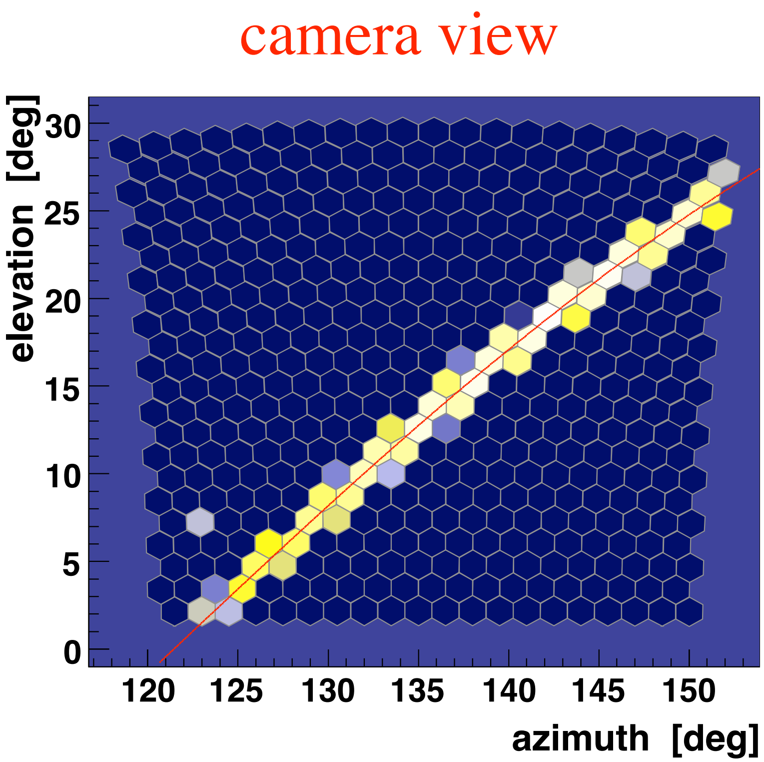
Geometrical Reconstruction

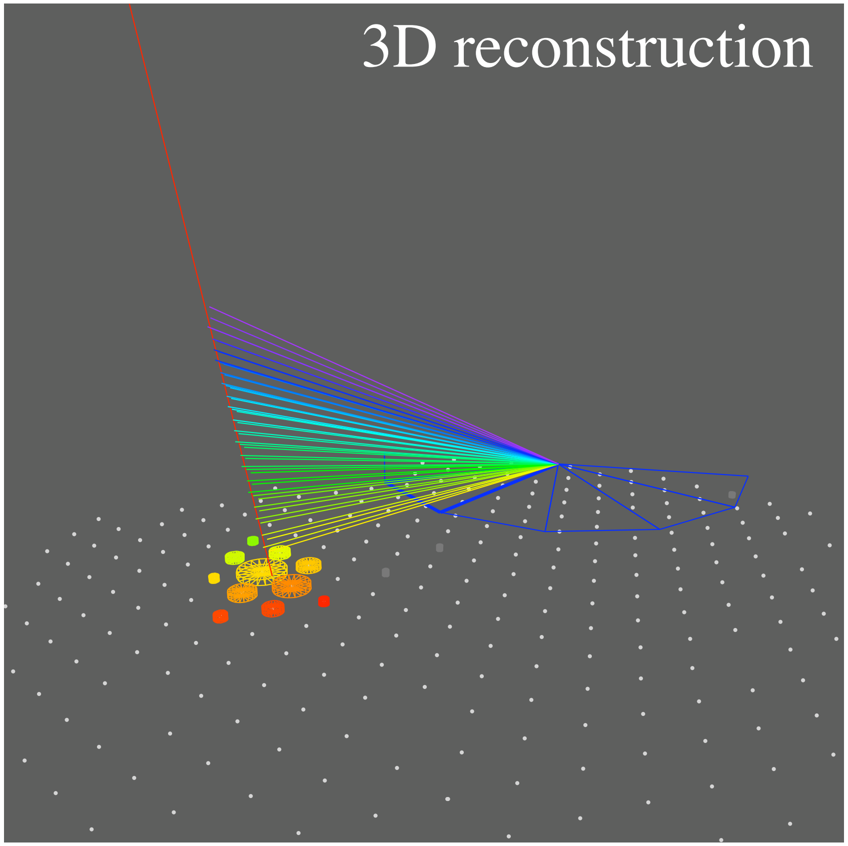
1. Shower Detector Plane (SDP).
2. Axis within the SDP; i.e. time-fit.



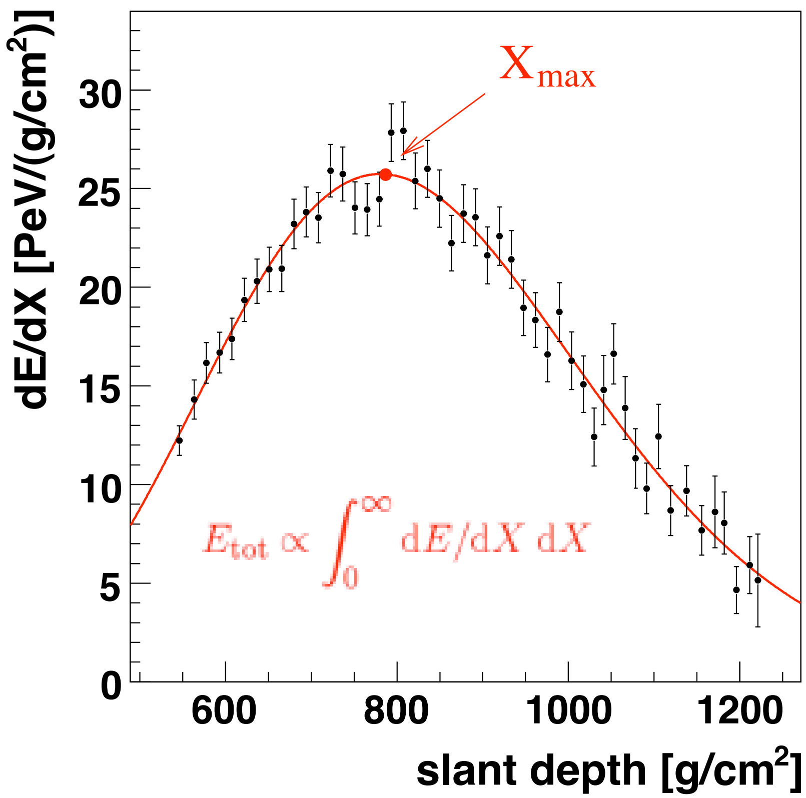
Fit: $t_i = t_0 + (R_p/c)\ tan(\chi_0/2 - \chi_i/2)$

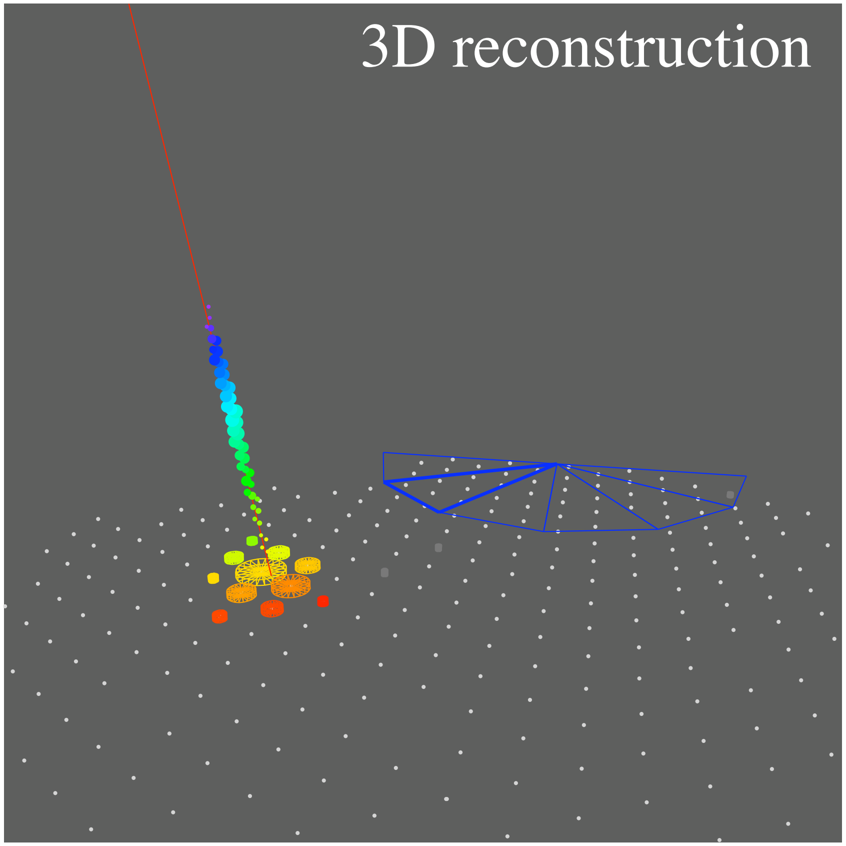
Shower Profile





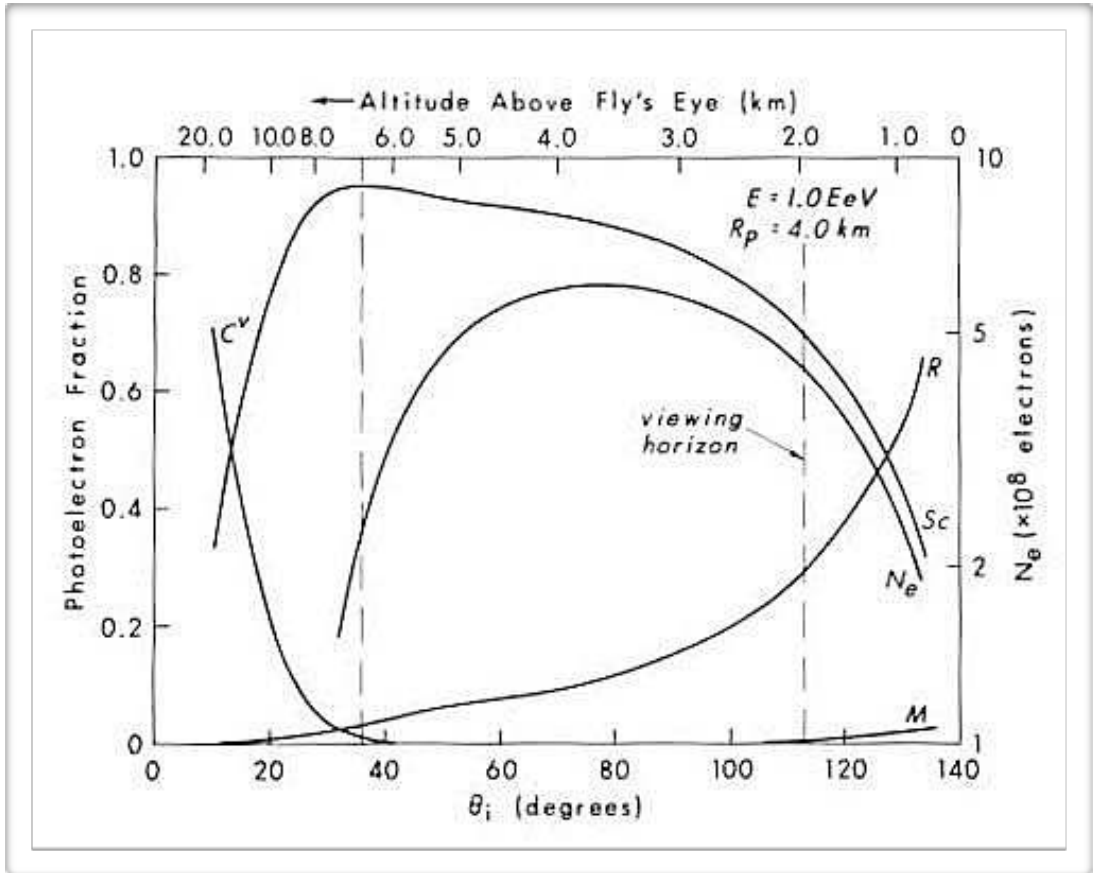
Shower Profile





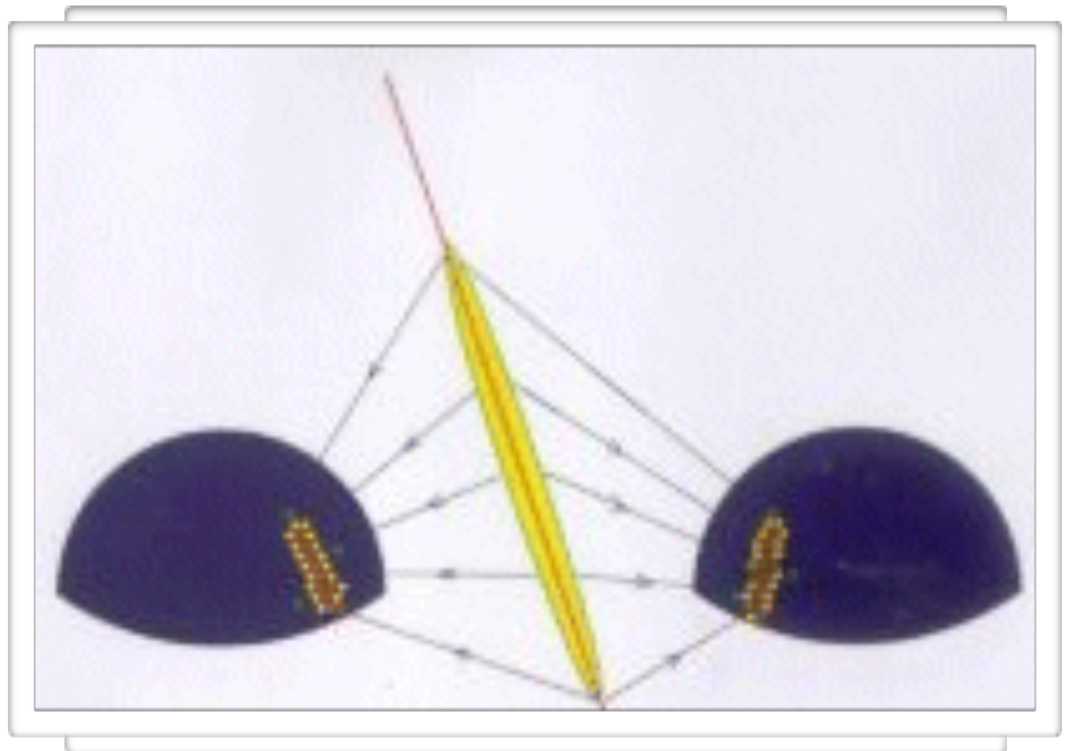
Shower Profile

- N_e shows the shower size as a function of shower development.
- Contributions to amount of light are:
  - C^v: direct Cherenkov light for small viewing angles,
  - Sc: scintillation (fluorescence) light,
  - R: Cherenkov light from molecular (Rayleigh) scattering, and
  - M: Cherenkov light from particulate (Mie) scattering.



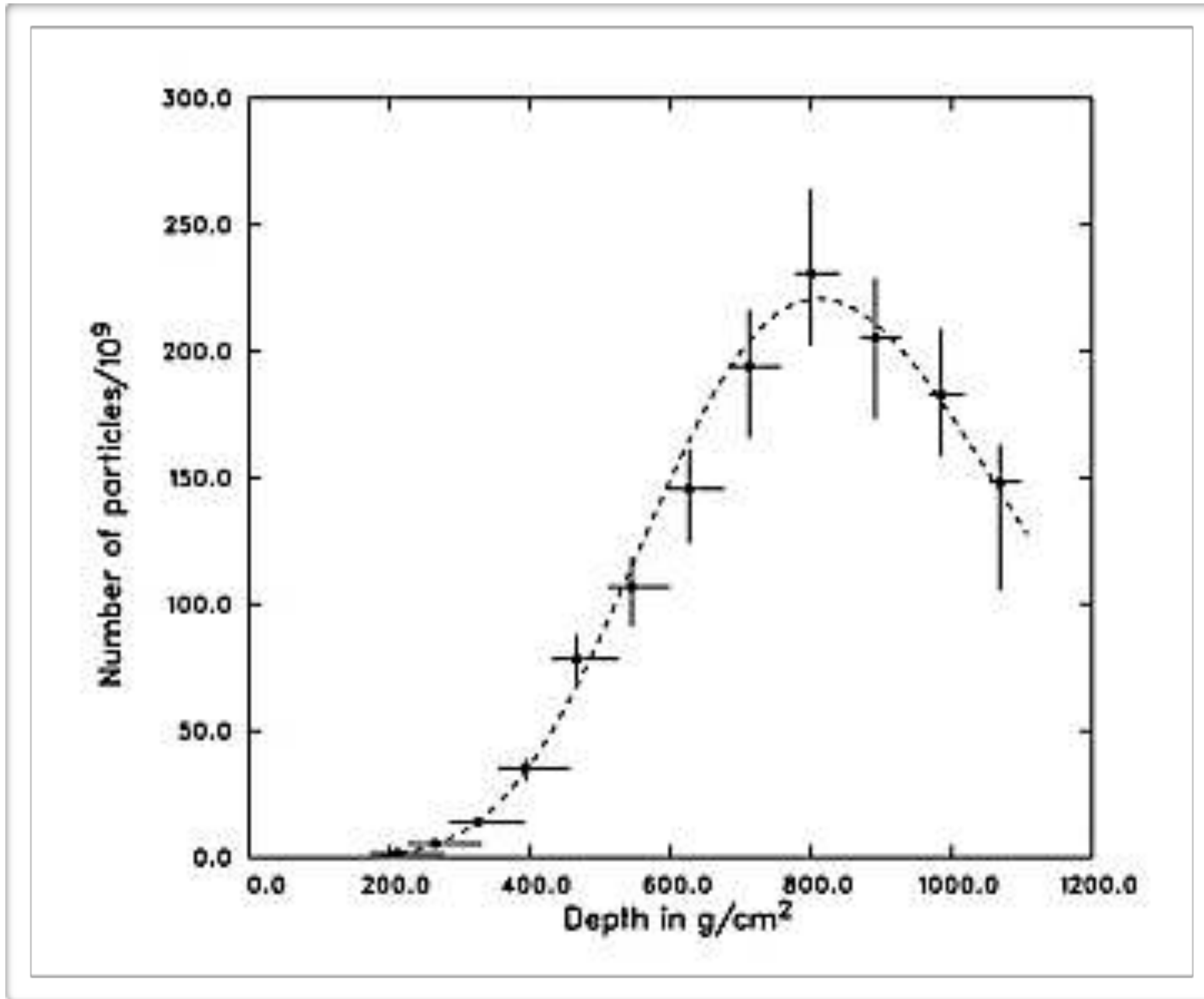
Mono vs. Stereo

- Mono uncertainties.
- Stereo Solution.



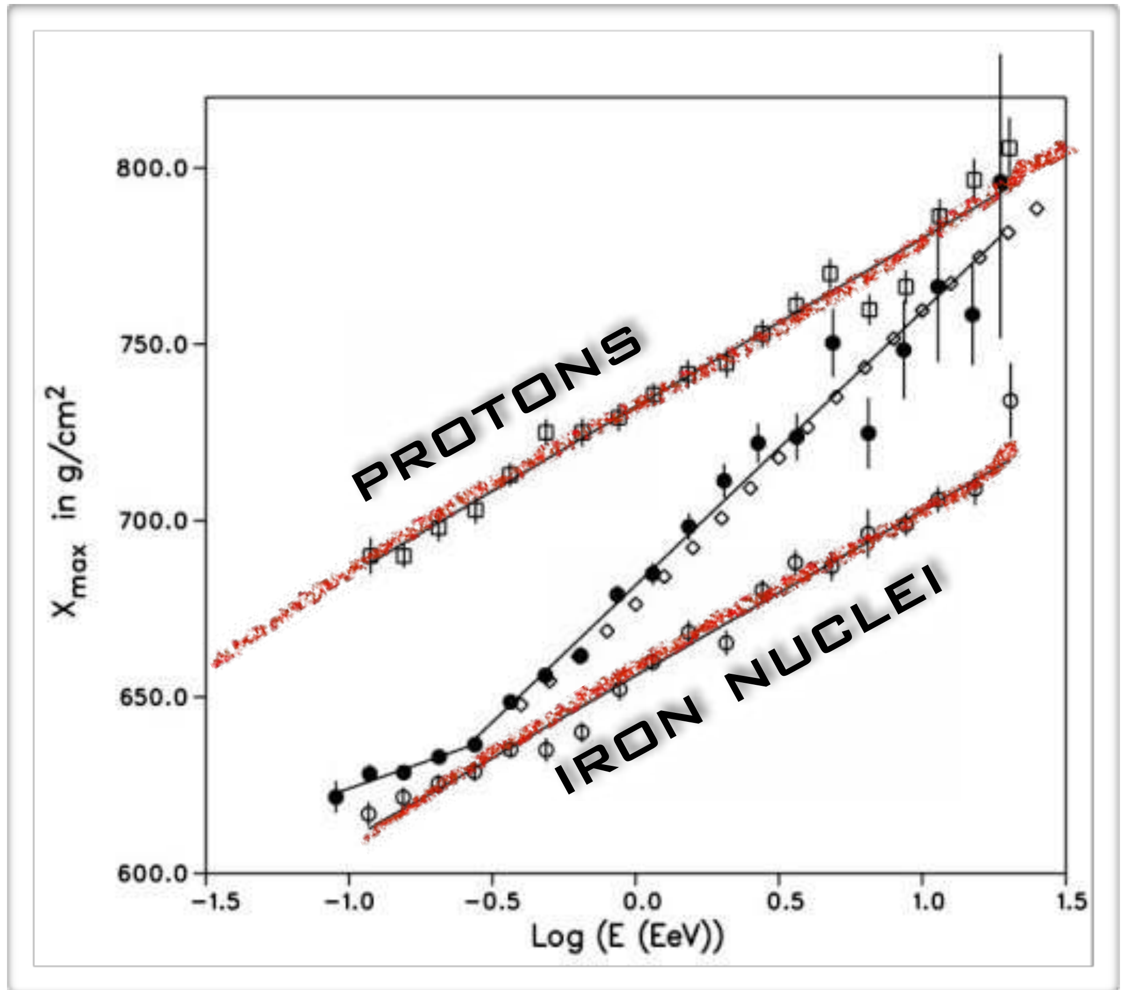
Results from the Fly's Eye

- Highest energy particle ever observed! 3.2×10^{20} eV



Results from the Fly's Eye

- Composition change between ~10^{17} eV and ~10^{19} eV.



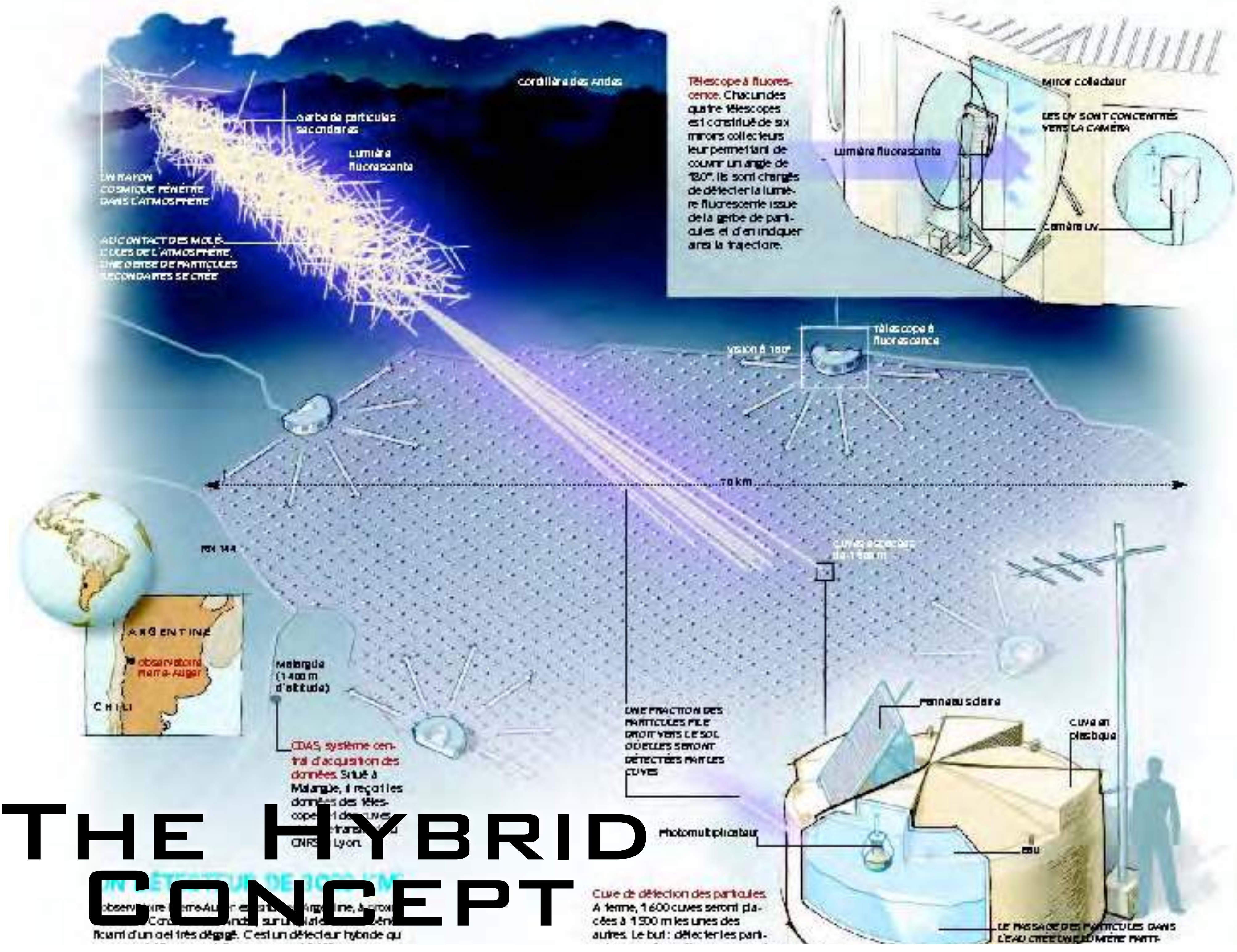
Not long ago in a country far, far away...

The Pierre Auger Observatory

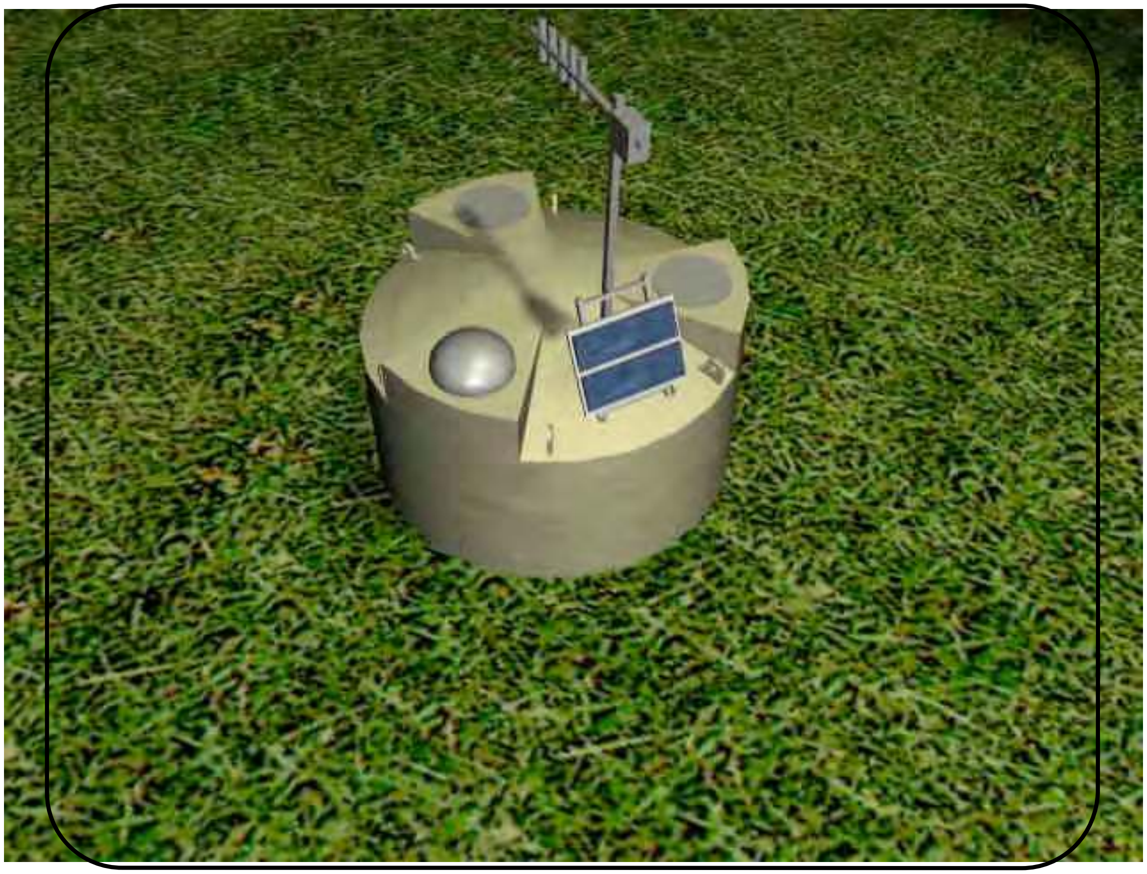
Auger Location

The Collaboration

The Hybrid Concept

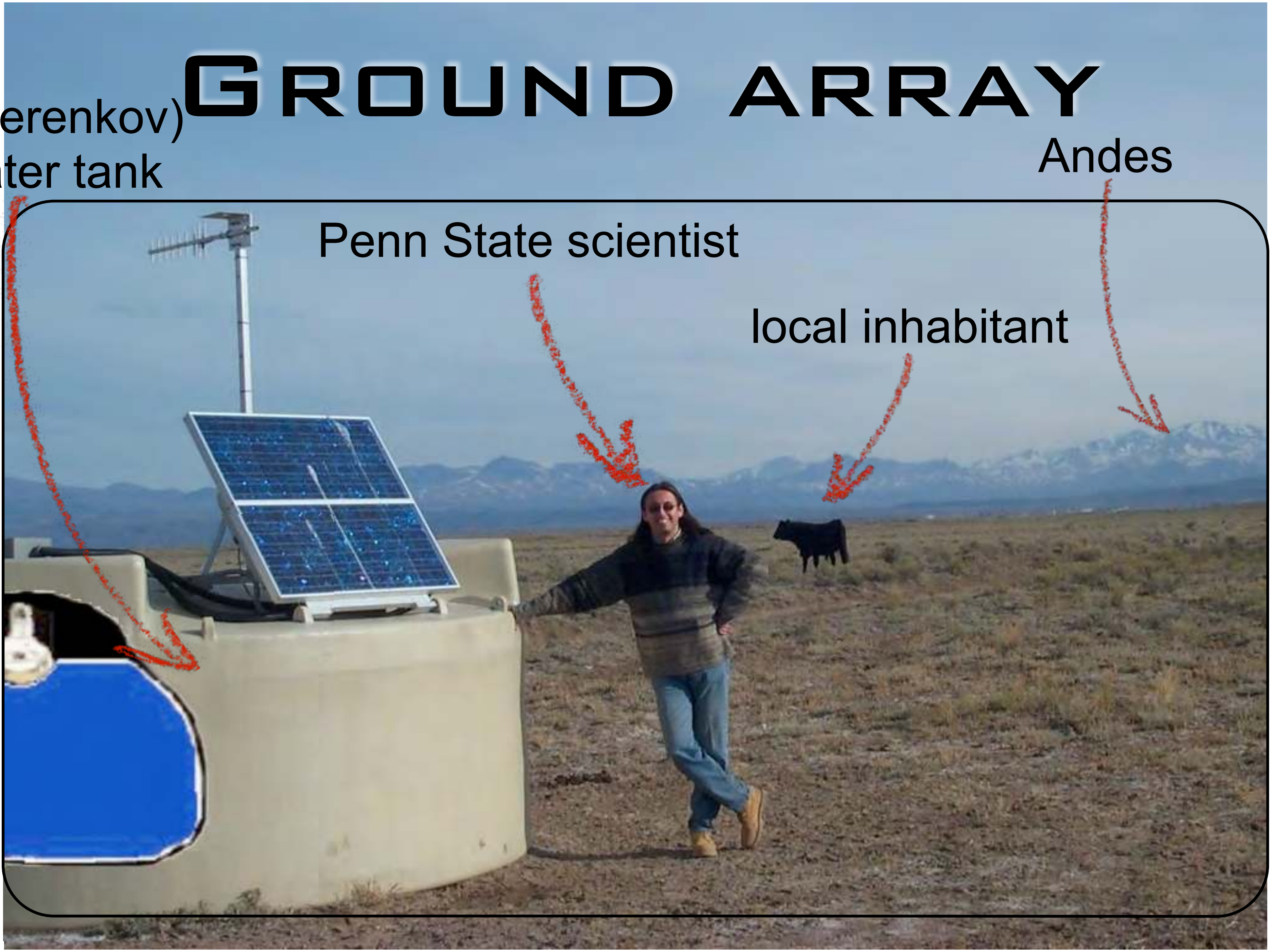


Ground Array

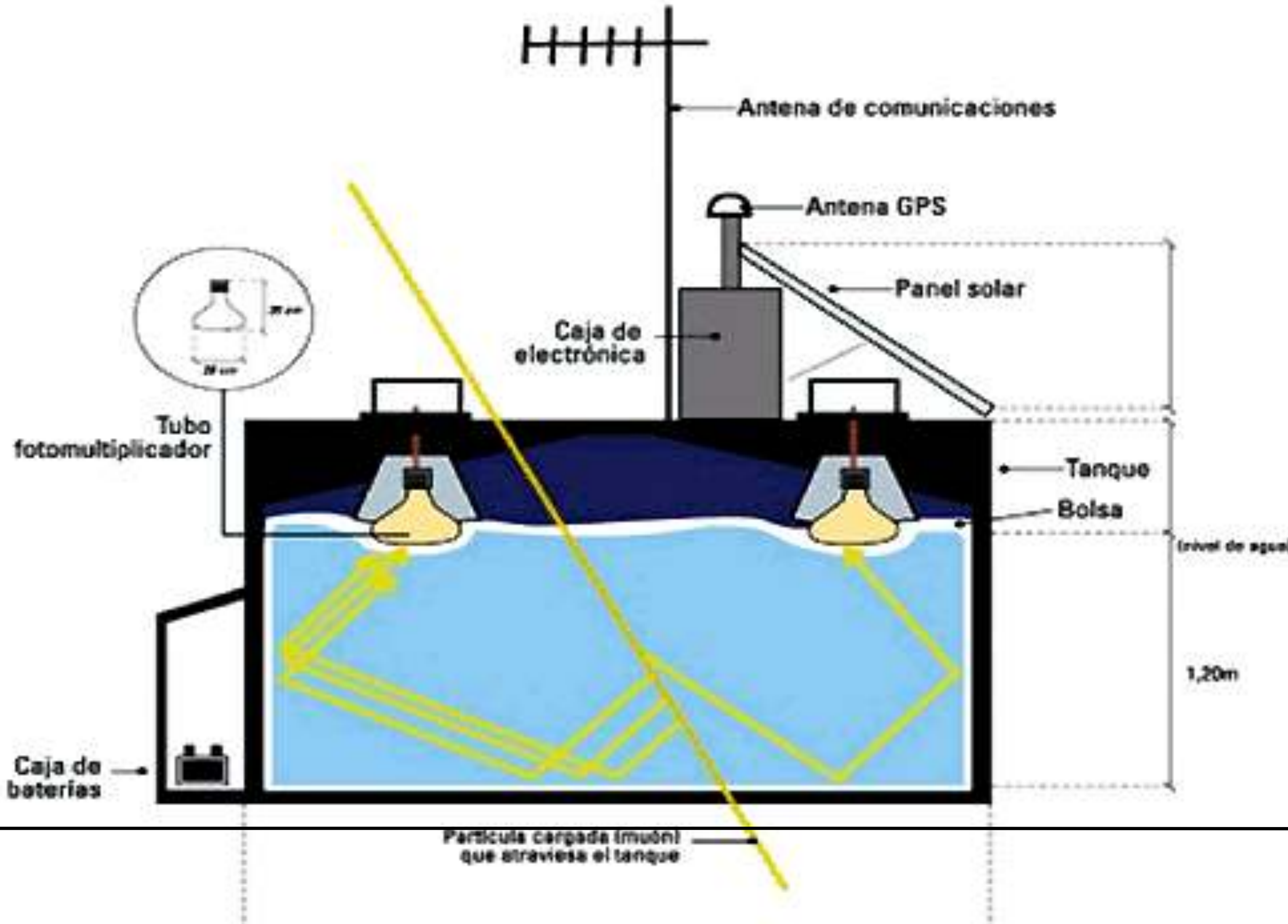


- 1600 stations
- 3000 km^2
- triangular grid
- 1.5 km spacing

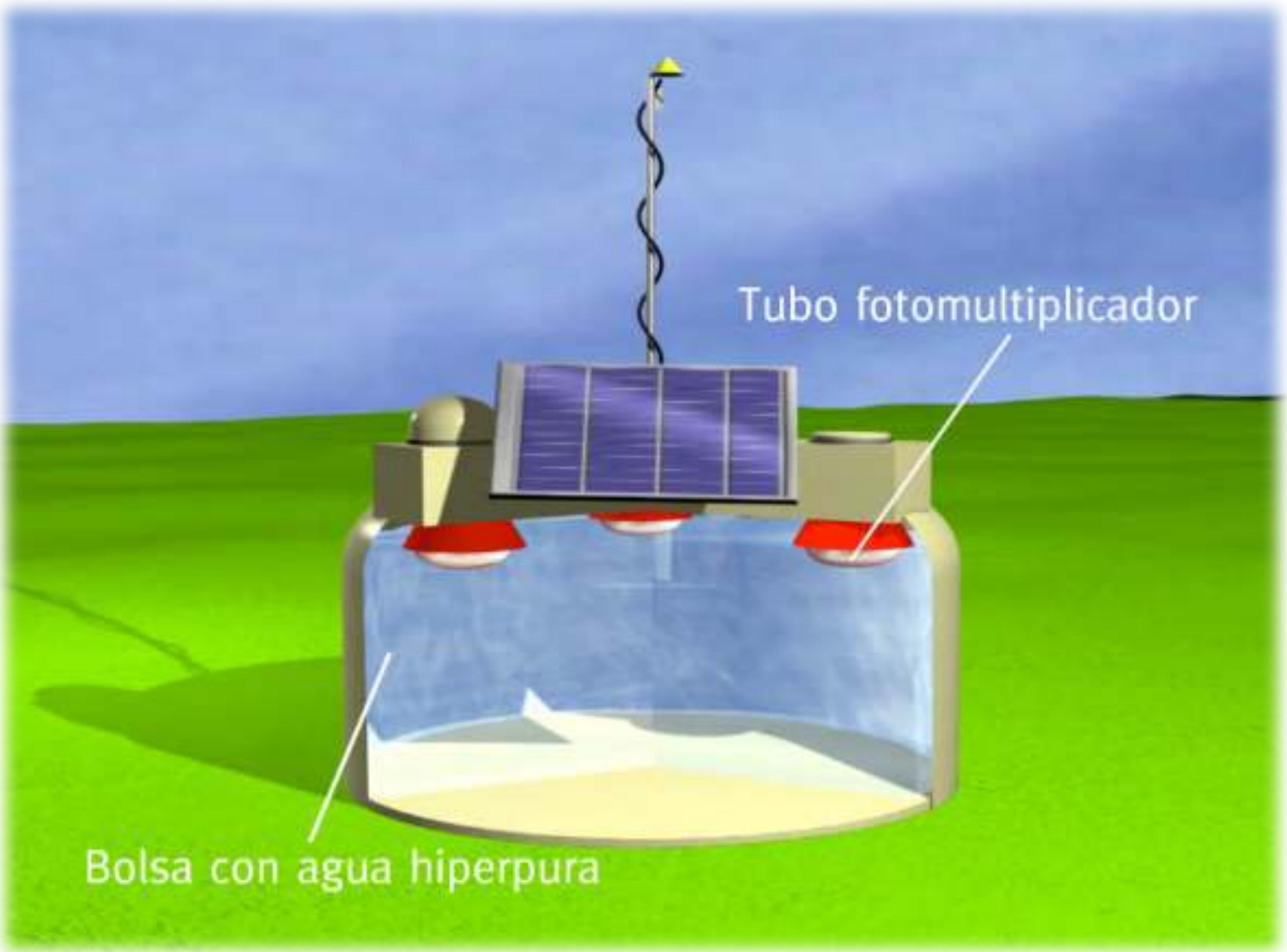
Ground array



THE WATER CHERENKOV TANK

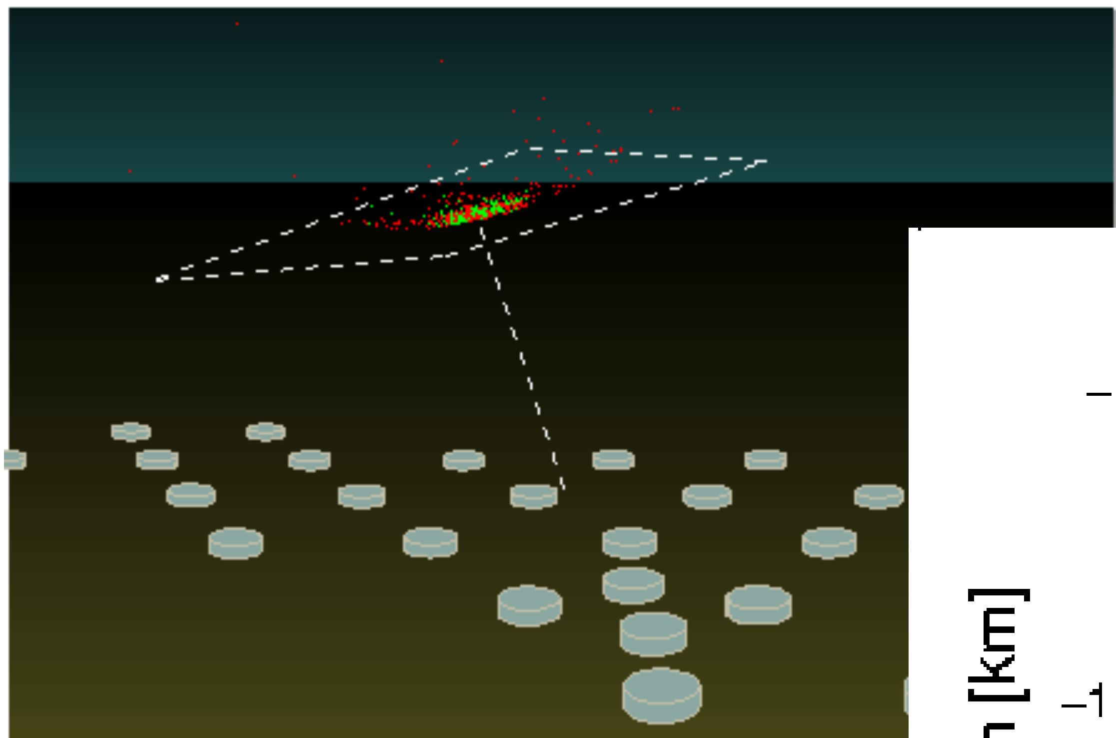


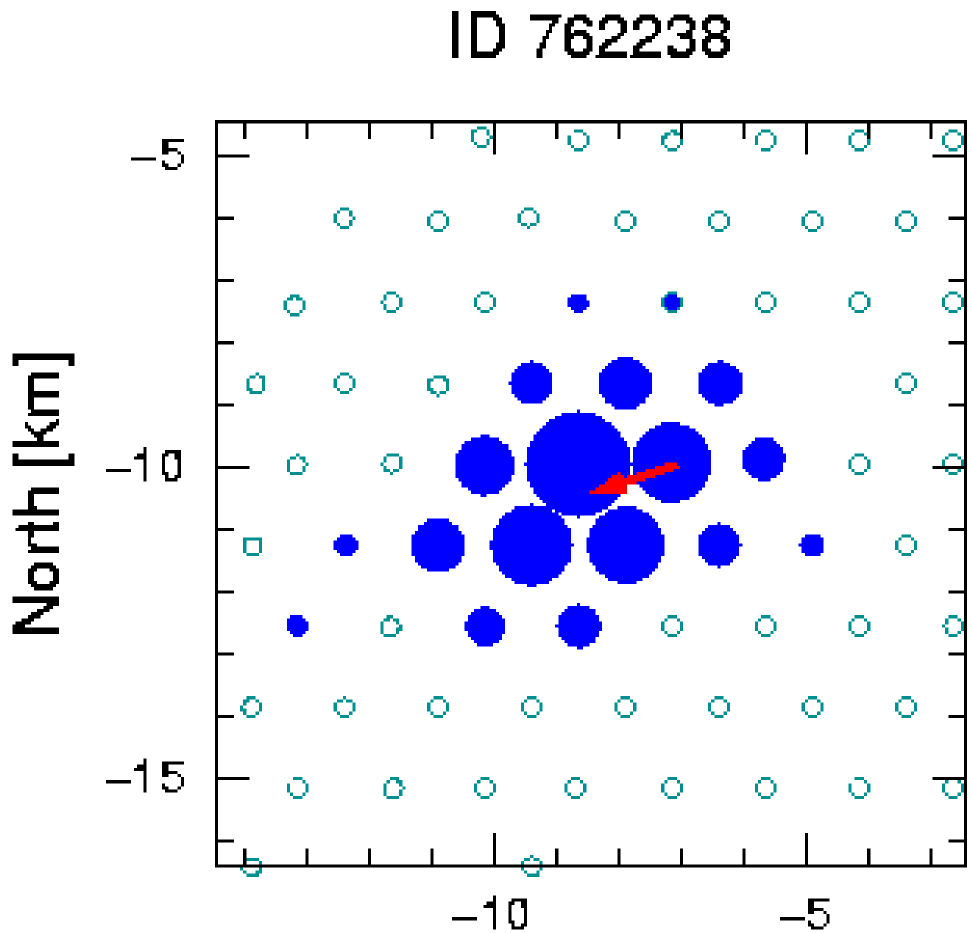
THE WATER CHERENKOV TANK

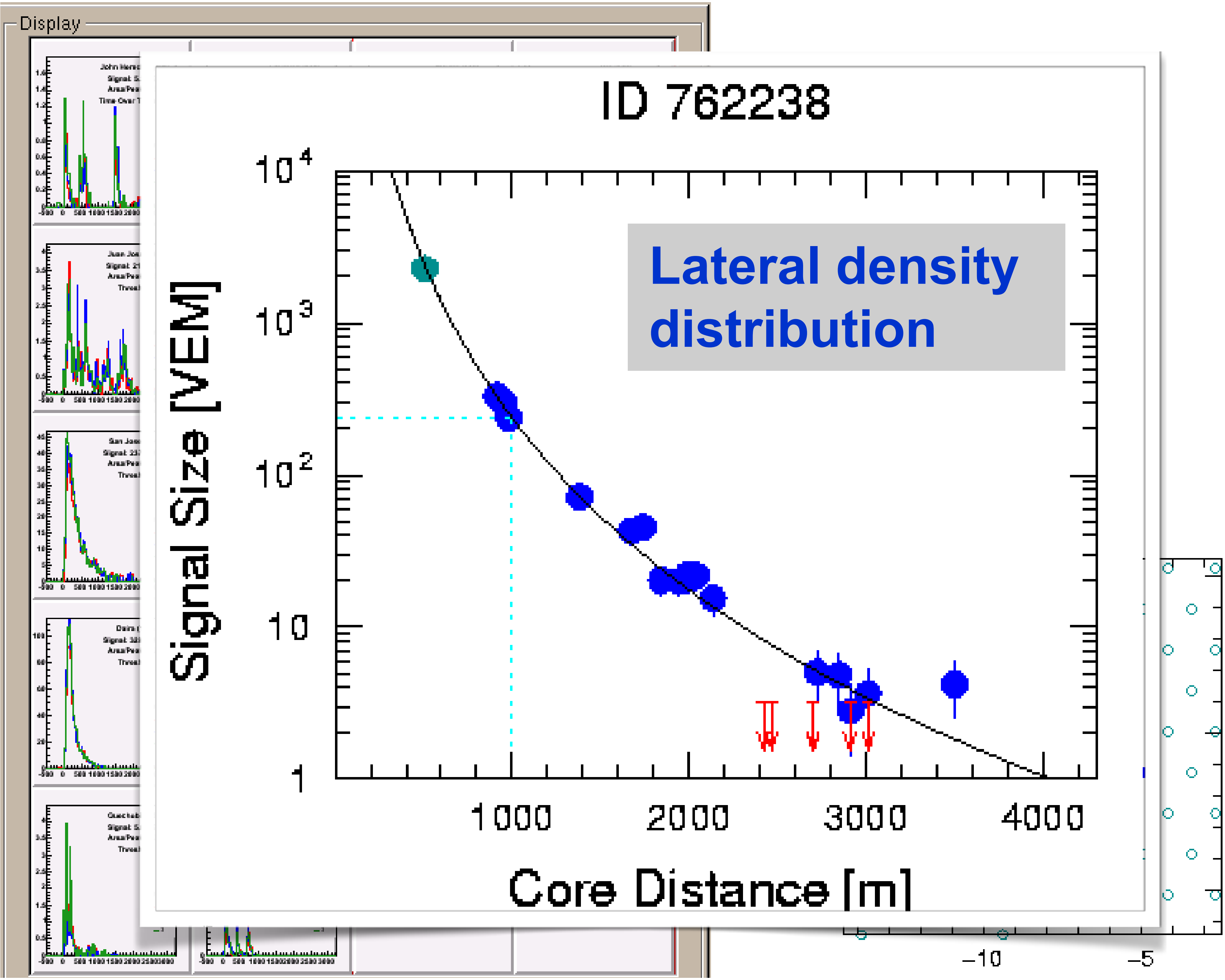


Deploying the largest array ever built

TYPICAL UHECR EVENT



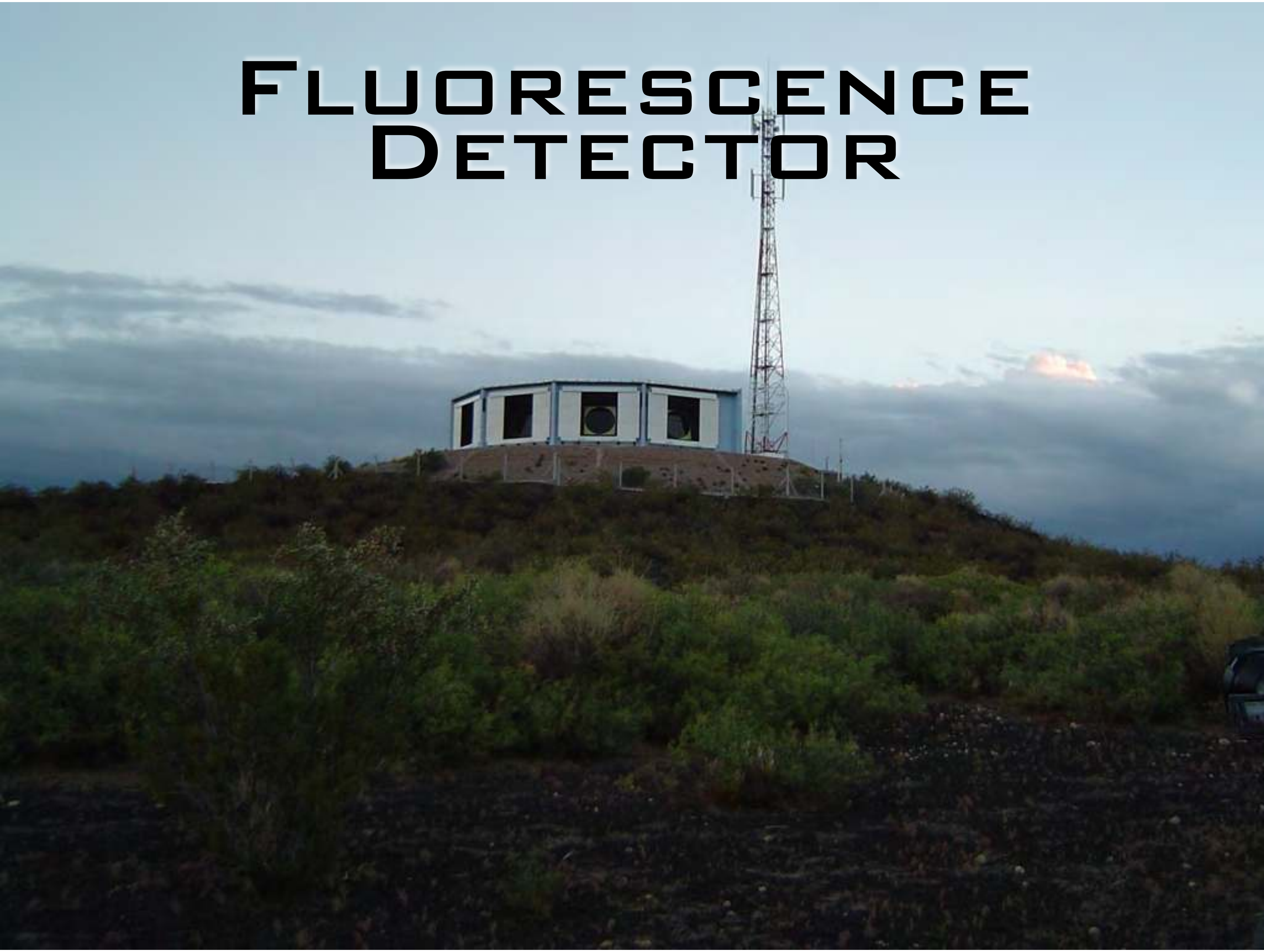




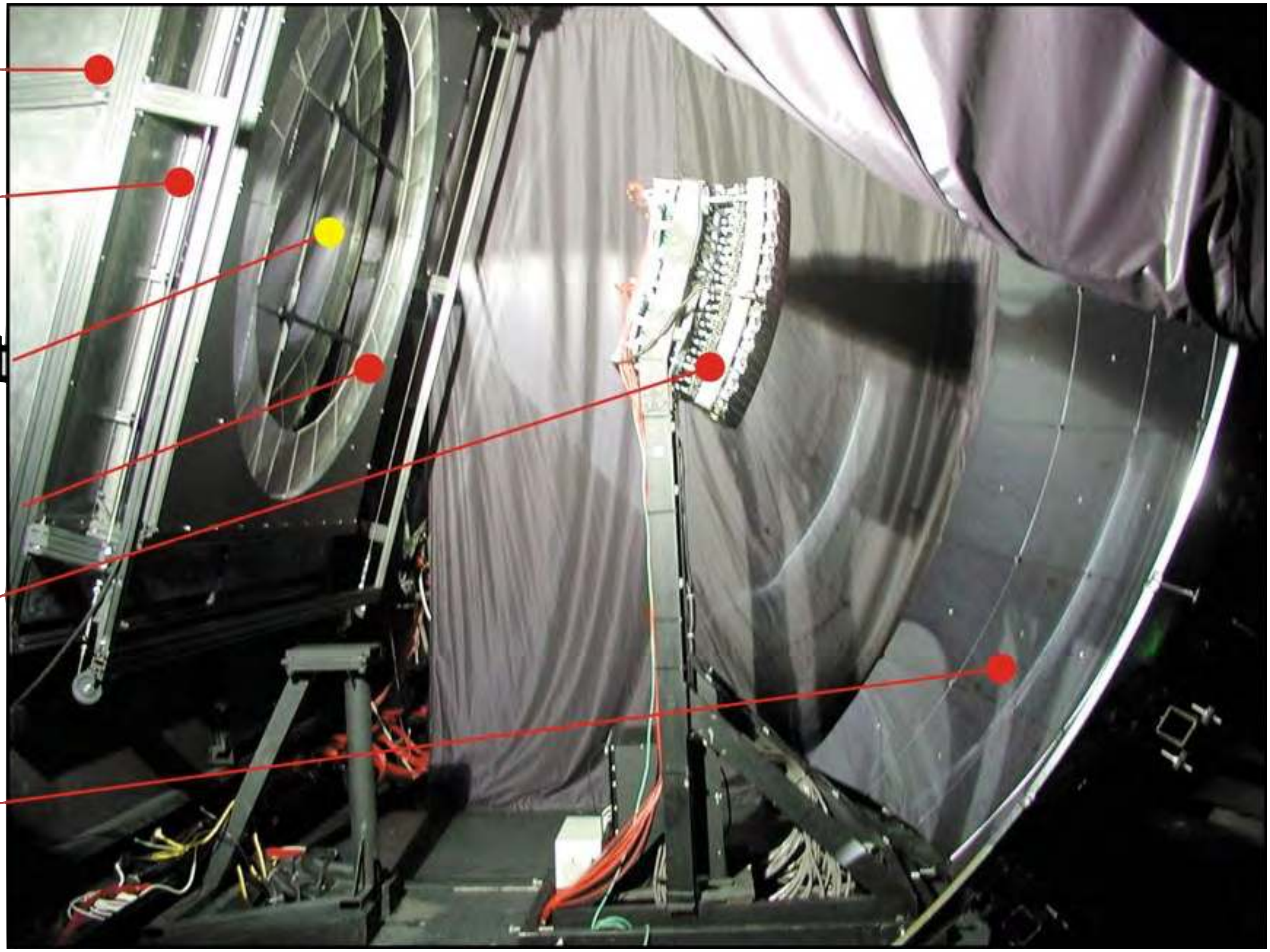
Display
ID 762238
Lateral density distribution
Signal Size [VEM]
Core Distance [m]
10^4
10^3
10^2
10
1
1000
2000
3000
4000
−10
−5

The Hybrid Design

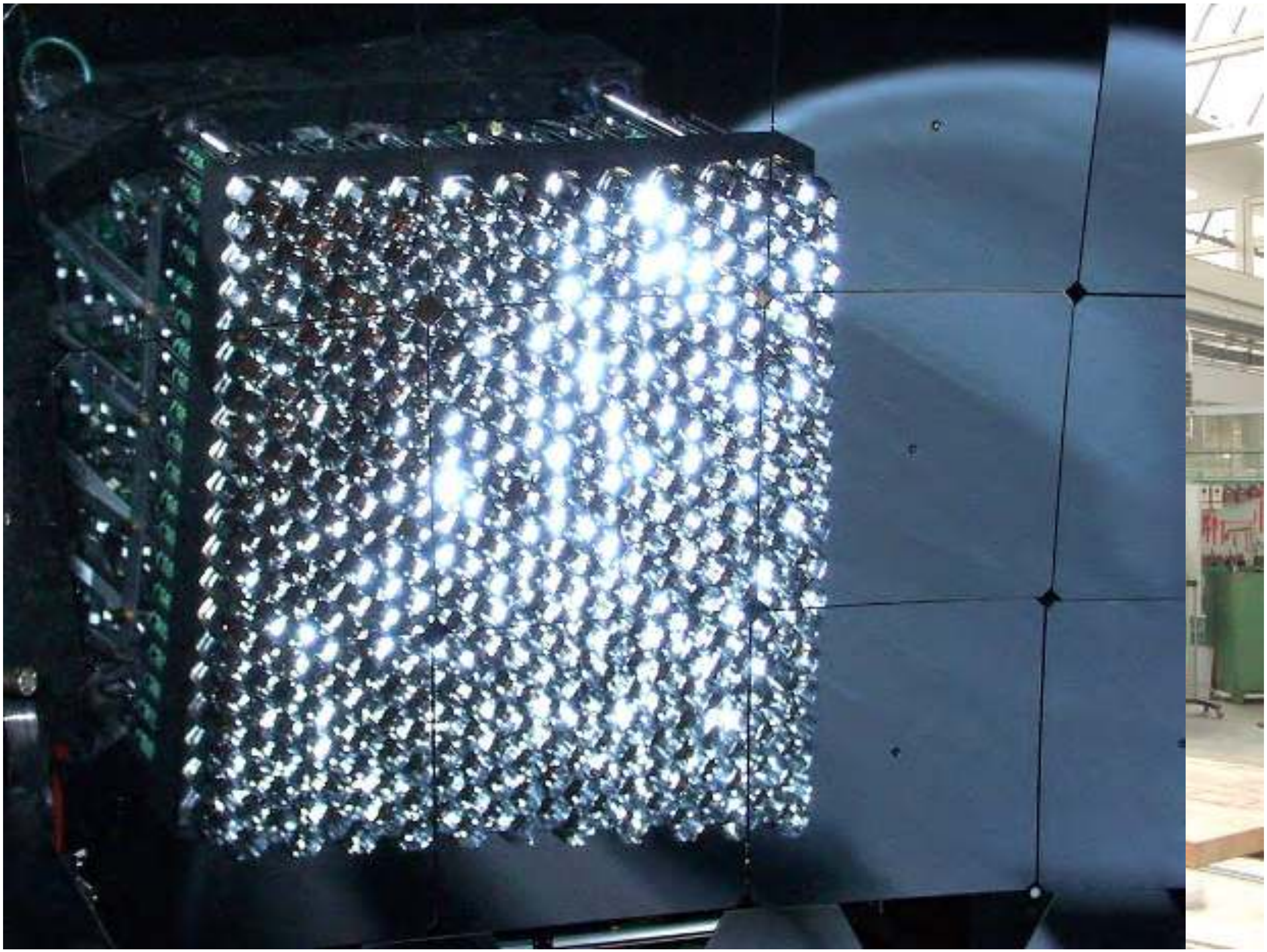
Fluorescence Detector



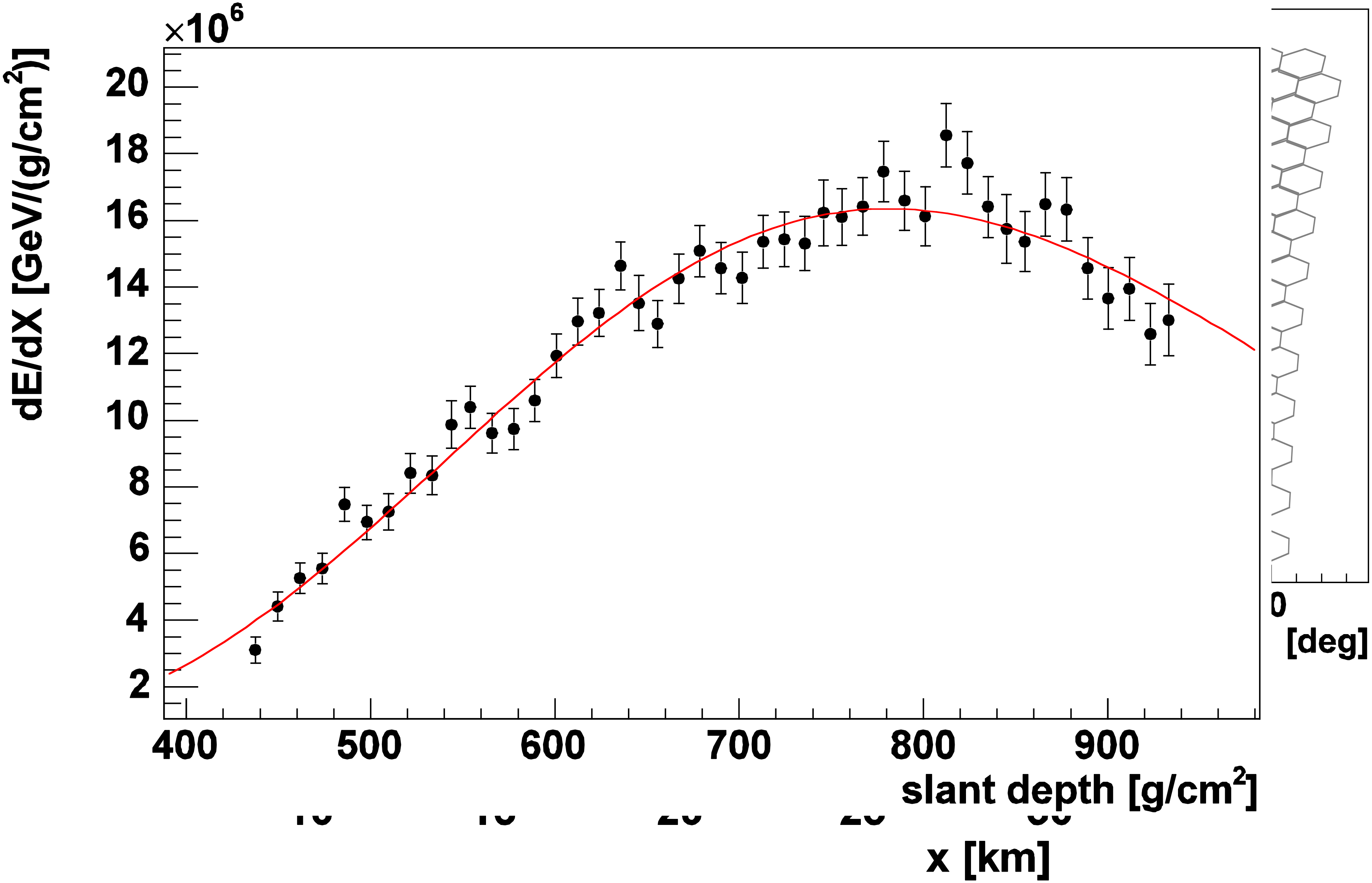
Inside the Building



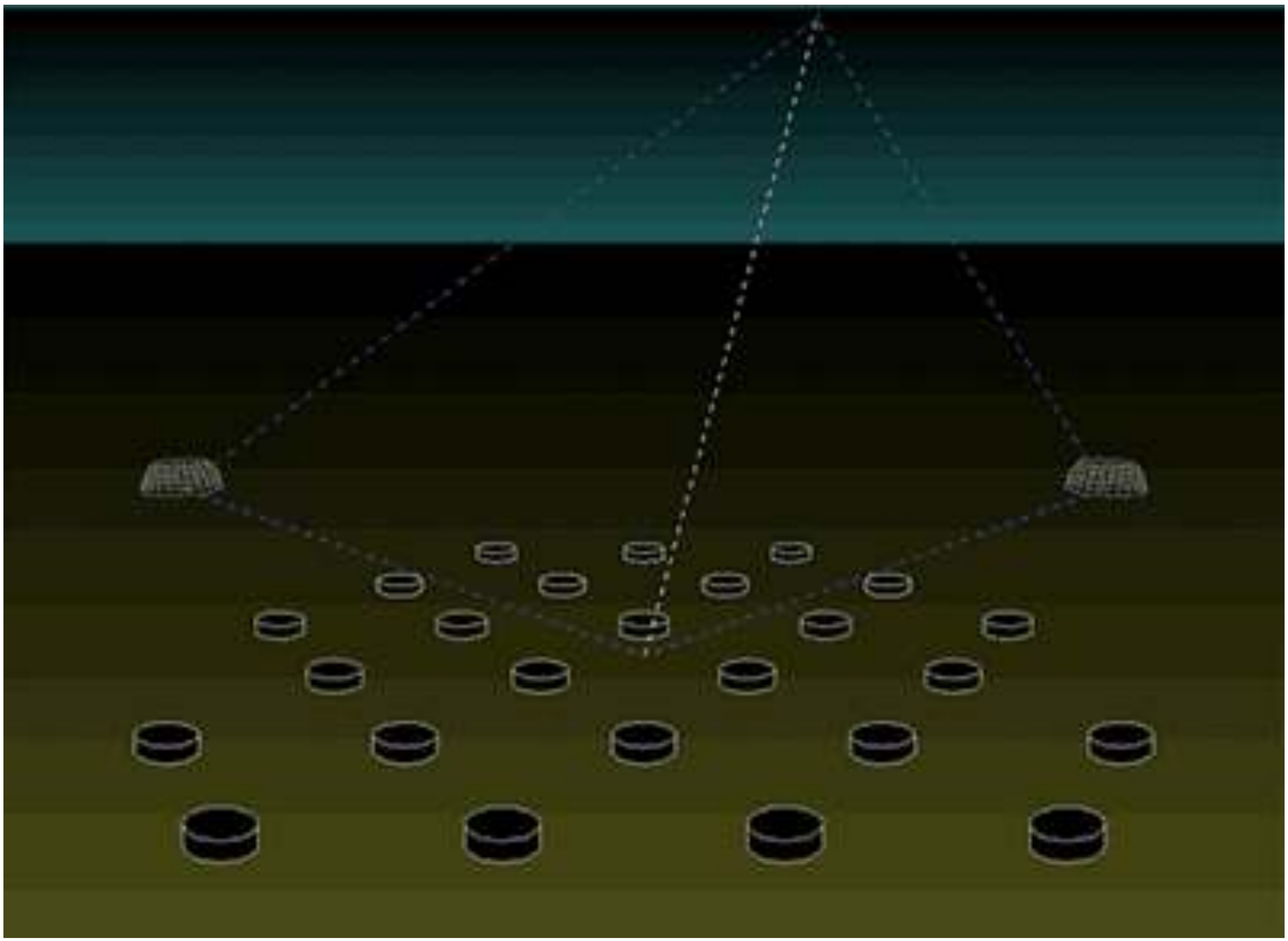
The Fluorescence Detector



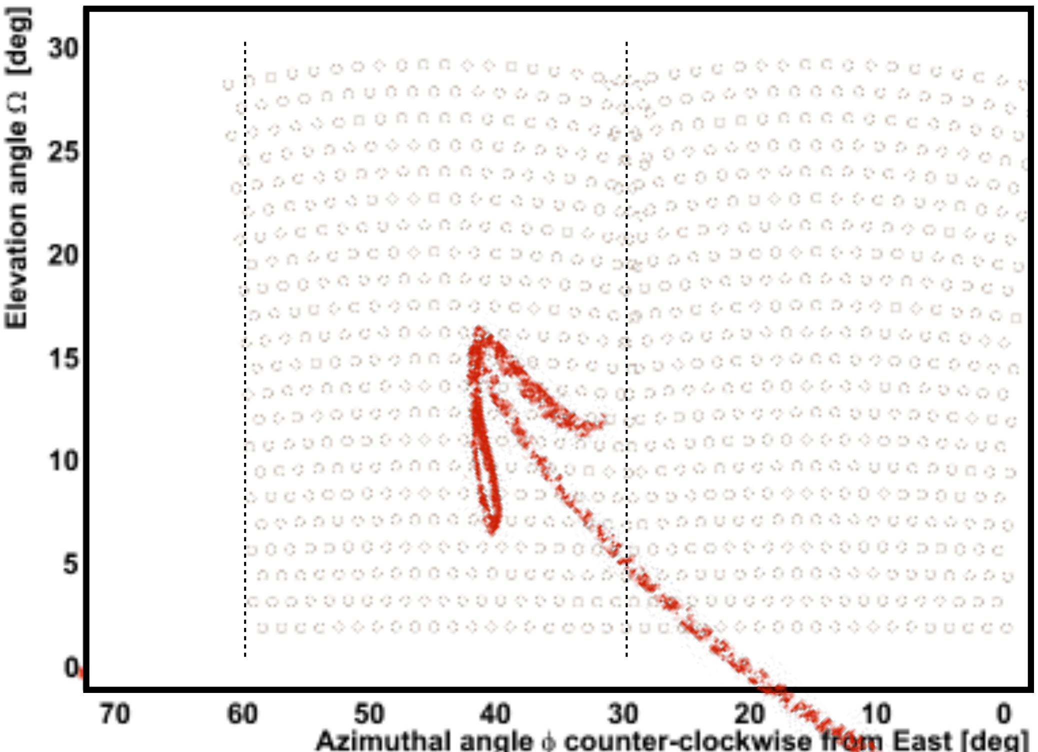
TYPICAL UHECR (FD VIEW)

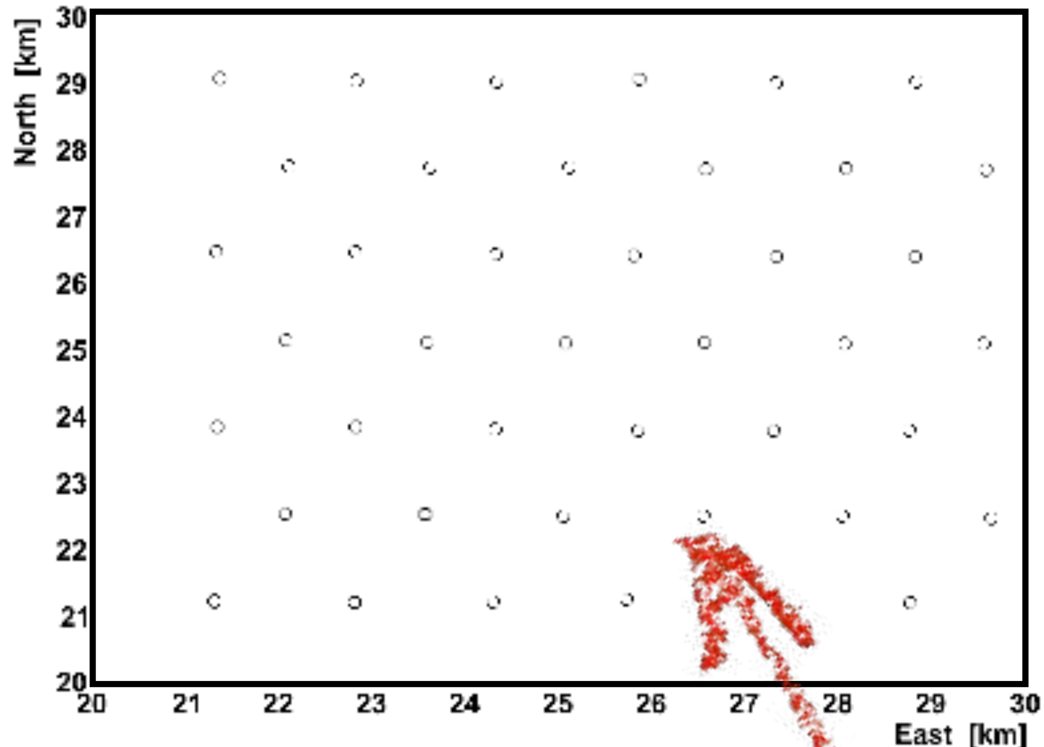


Hybrid Detection



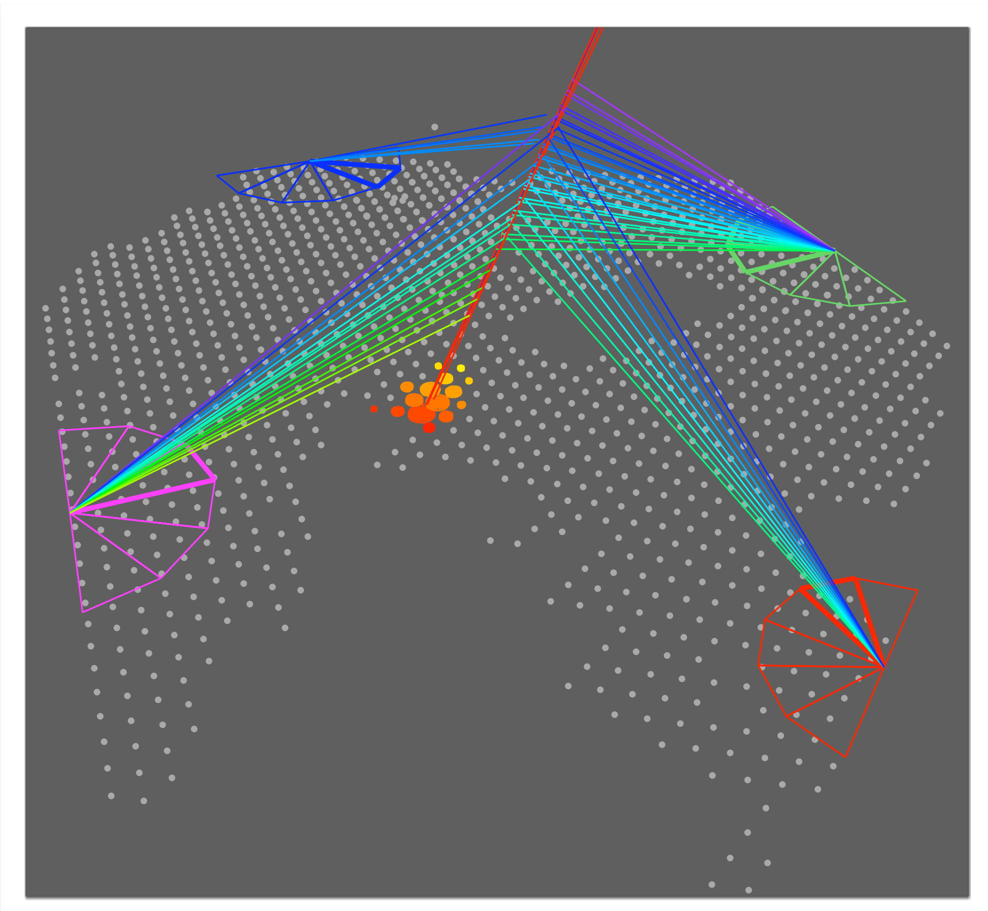
Hybrid Detection

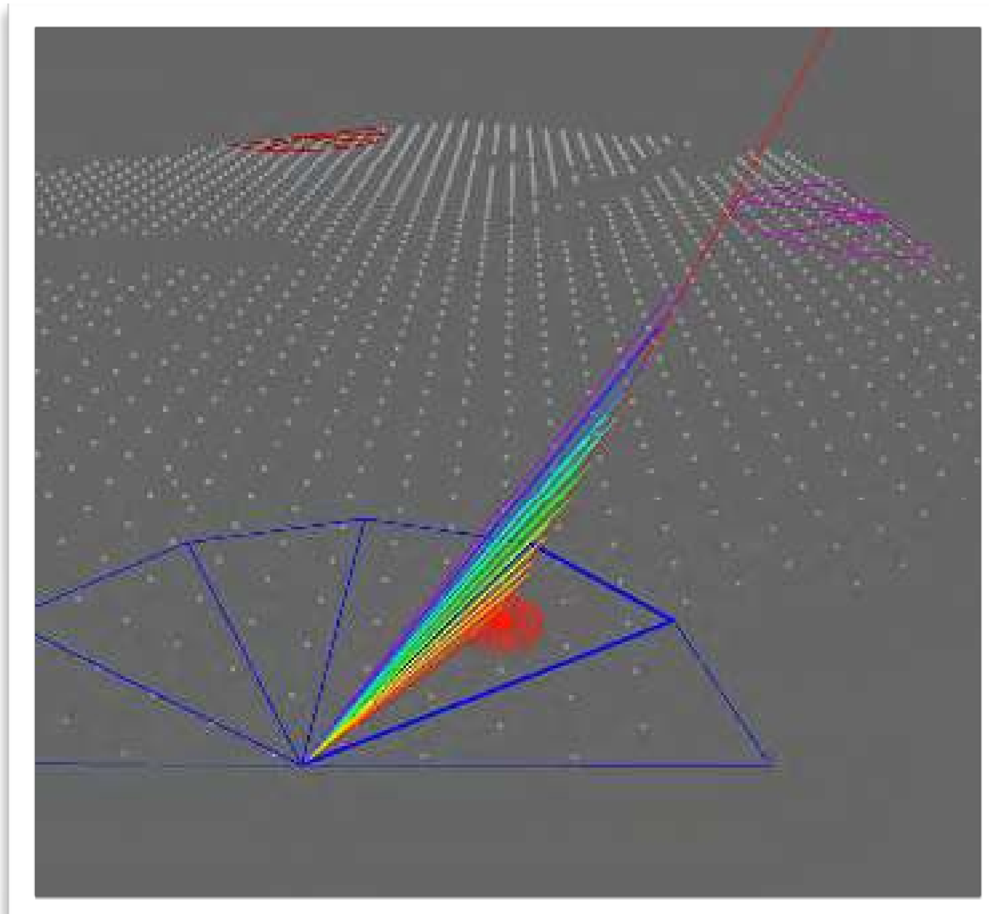




Hybrid reconstruction: use all pixels and tanks

Hybrid Events

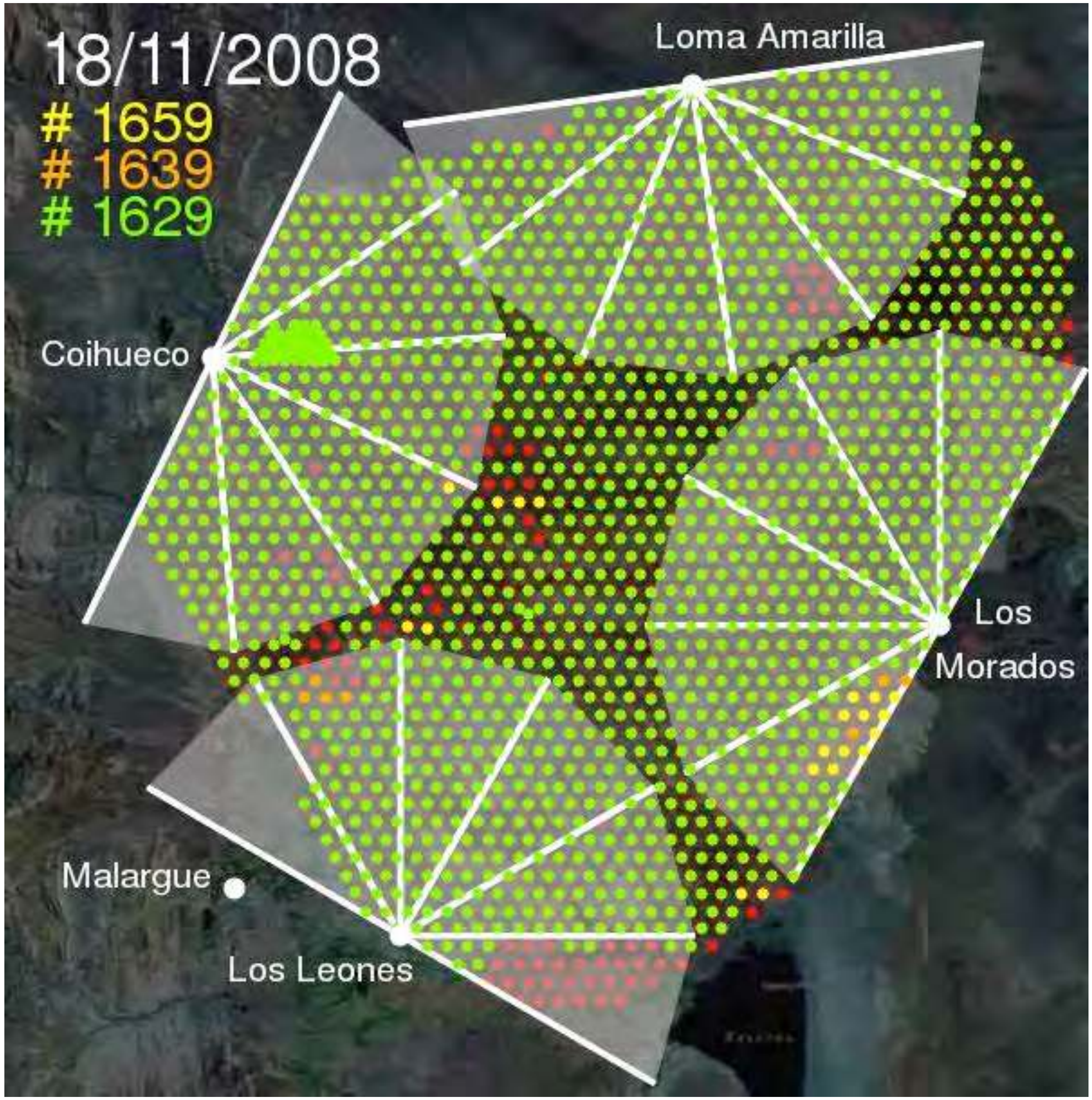


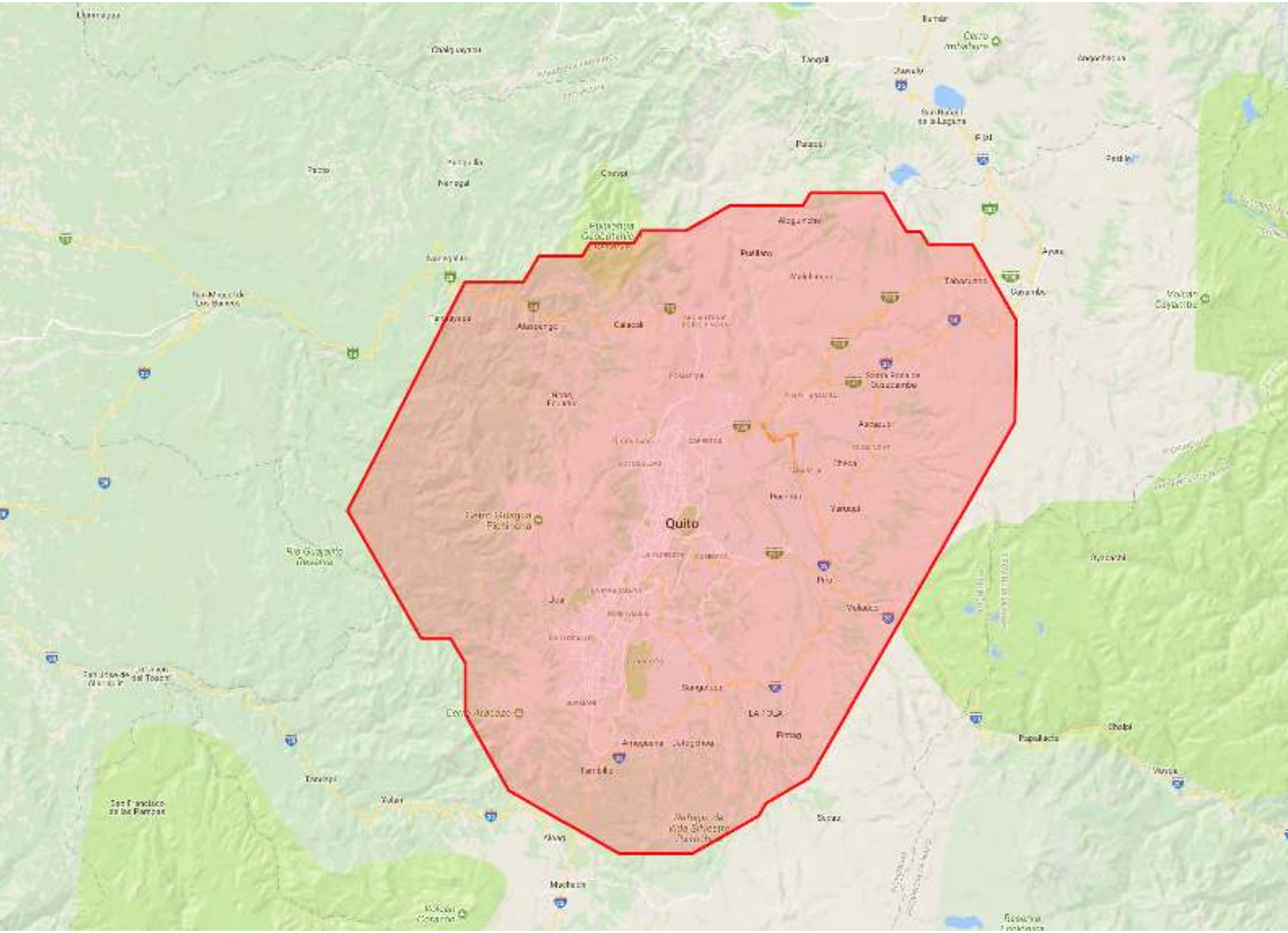


Golden and sub-Threshold hybrid events

Deployment

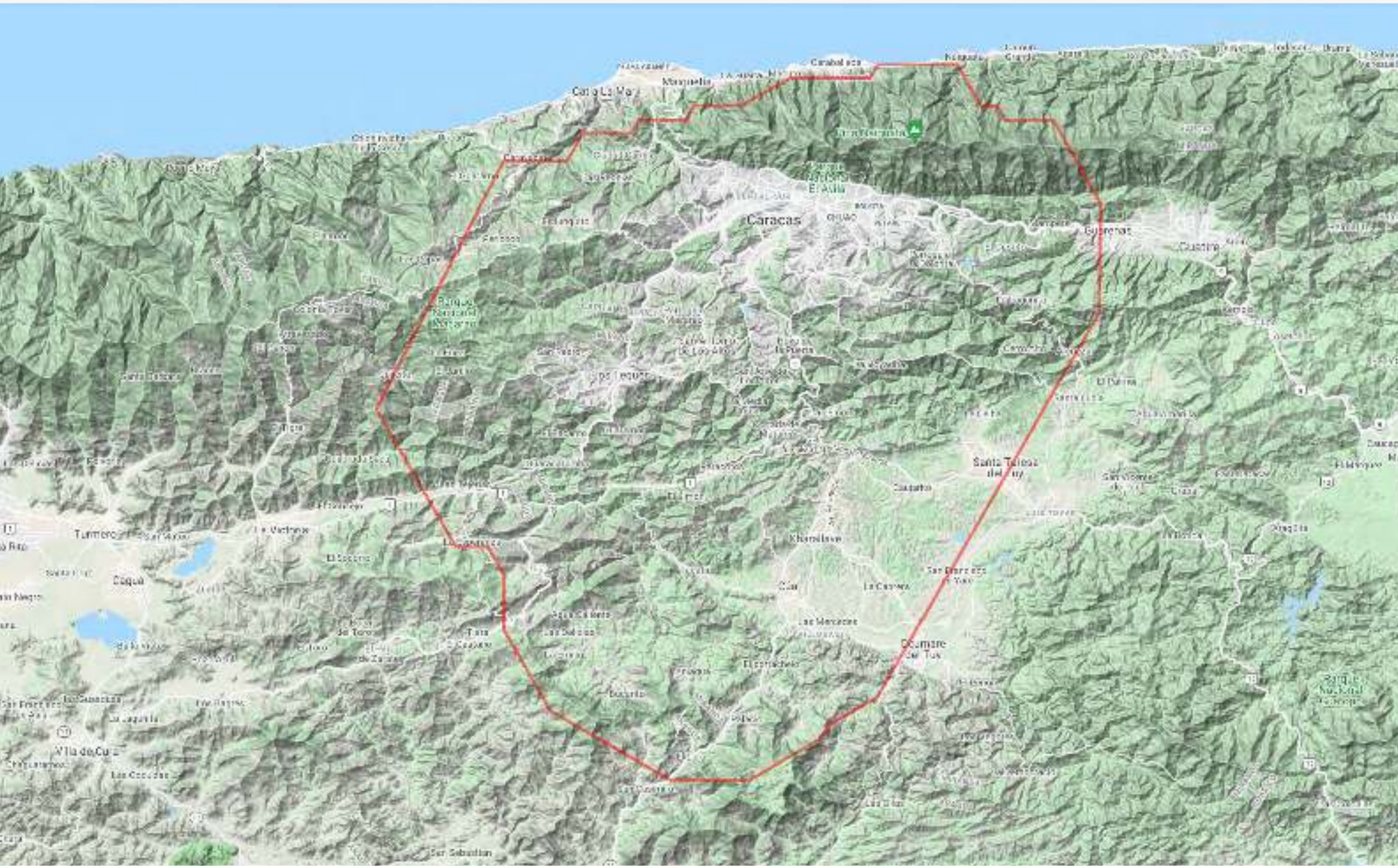
WHEN SIZE MATTERS



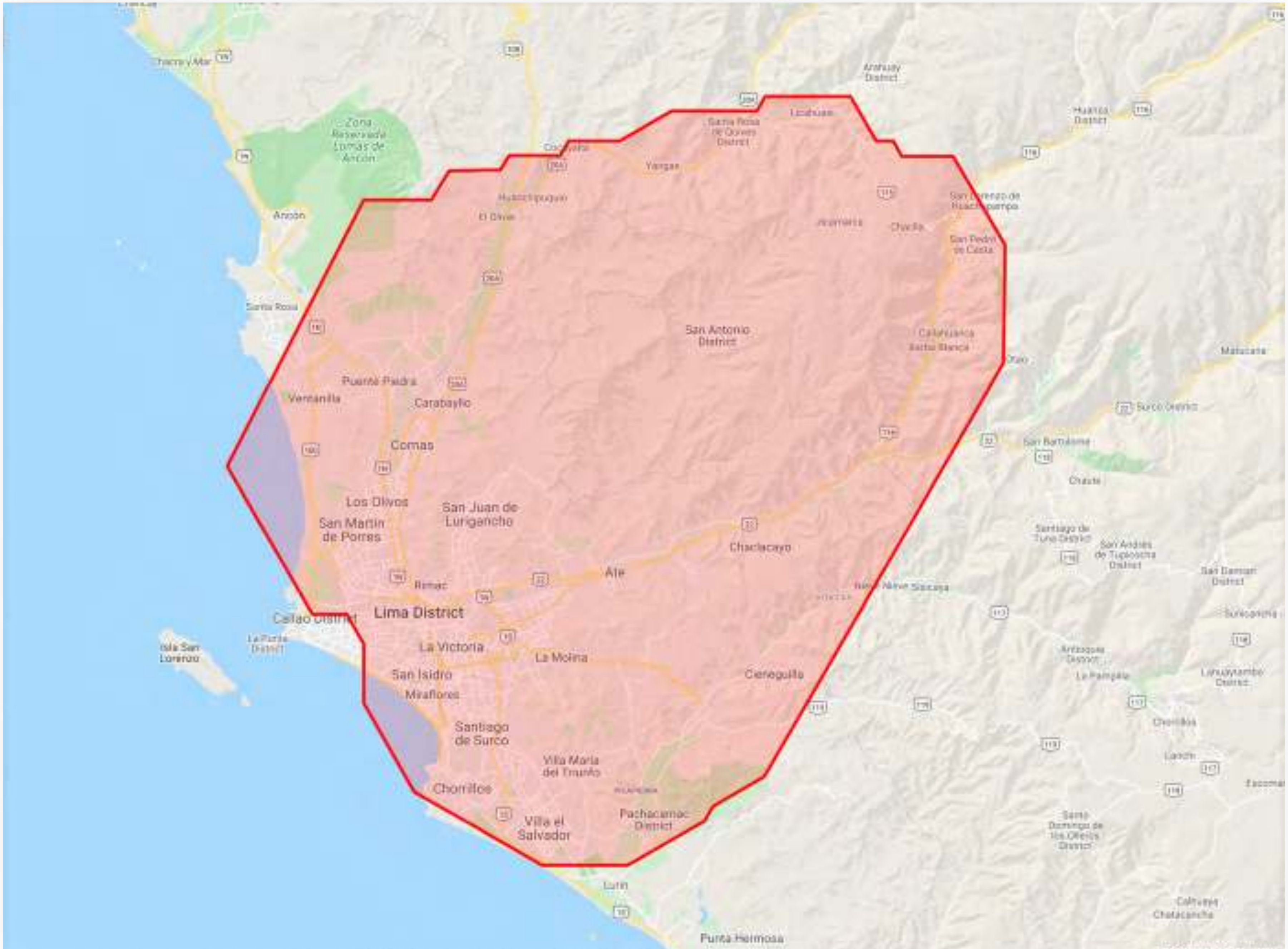

Quito
Papallacta
Machachi


Zipaquirá
Chía
Bogotá
FONTIBÓN
KENNEDY
PUENTE ARANDA
BOSA
Madrid
Funza
Soacha
Usme
Tocancipá
Guatavita
Facatativá
Tenjo
Cajicá
El Rosal

WHEN SIZE MATTERS



WHEN SIZE MATTERS



Summary

- Extensive Air Showers
- Detection Techniques
- The Pierre Auger Observatory

Coming Next

- Data Analysis:
  - Energy
  - Anisotropy
  - Composition

Thank You!