Catching the Universe's most energetic particles

Ultra-High Energy Cosmic Rays

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Lecture 2

LA-CoNGA Physics - Courses 21B
Astropartículas y Cosmología
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Last Class' Summary

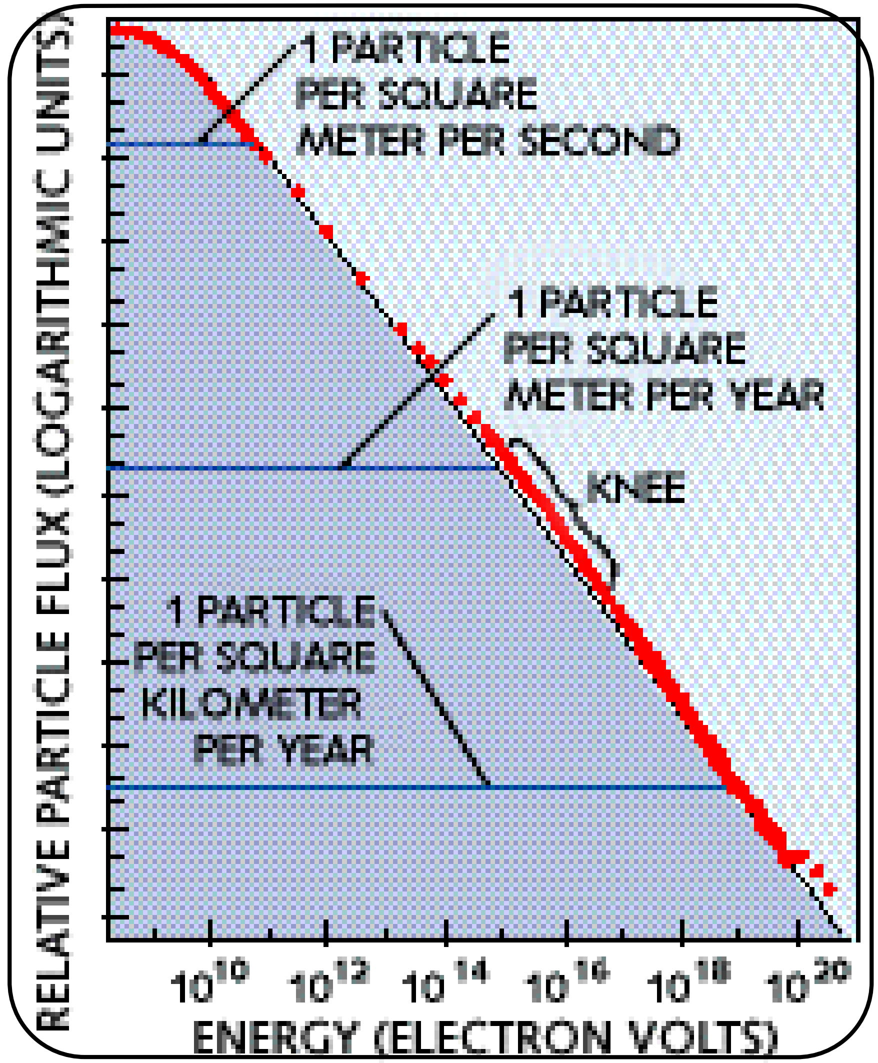
- Introduction to Cosmic Rays
- History
- Scientific Motivation

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

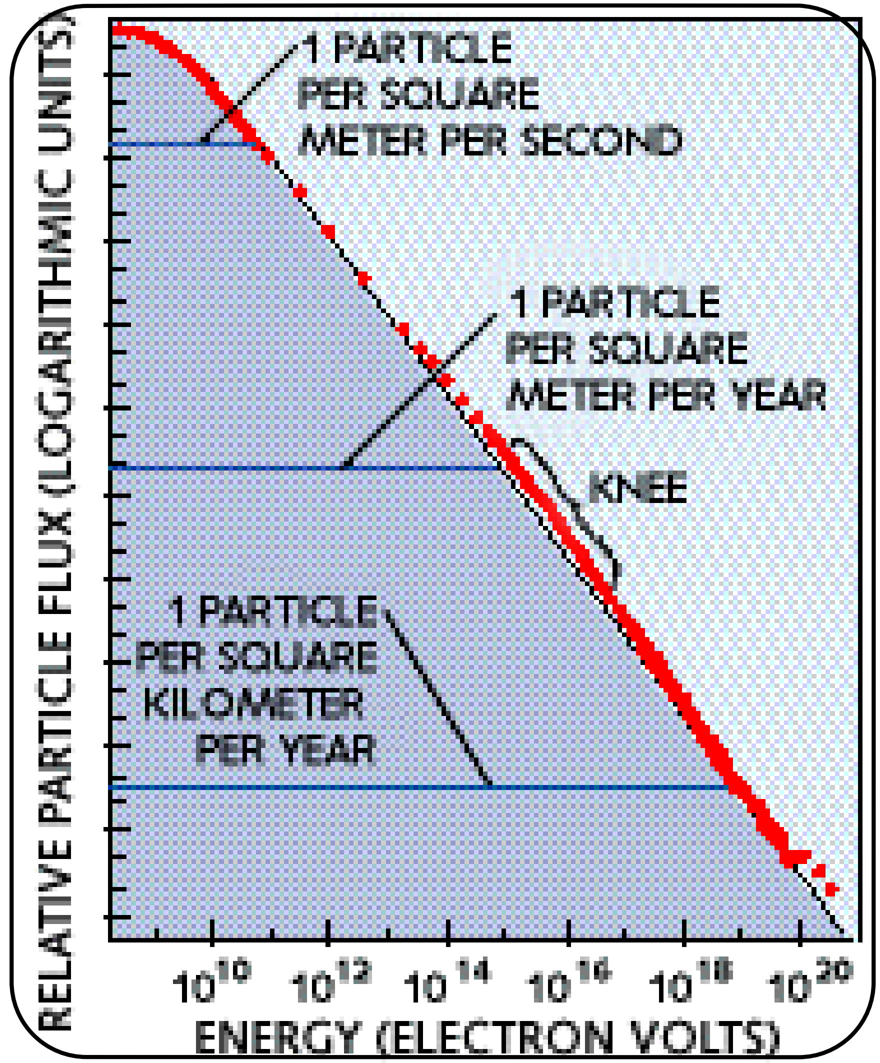
- To measure the primary cosmic rays directly, the detection equipment must be placed above the atmosphere.

- 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.

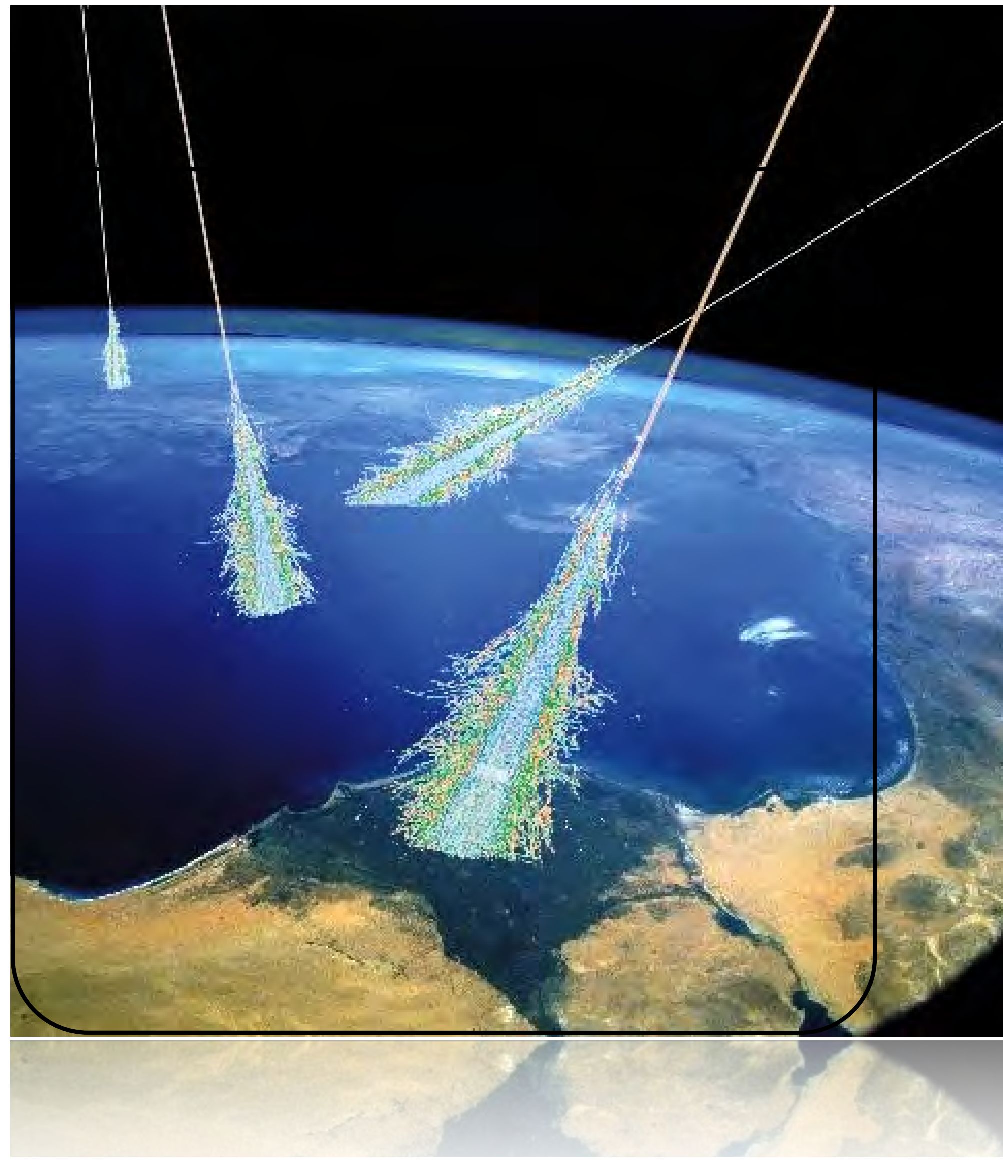
Energy Spectrum

- 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.



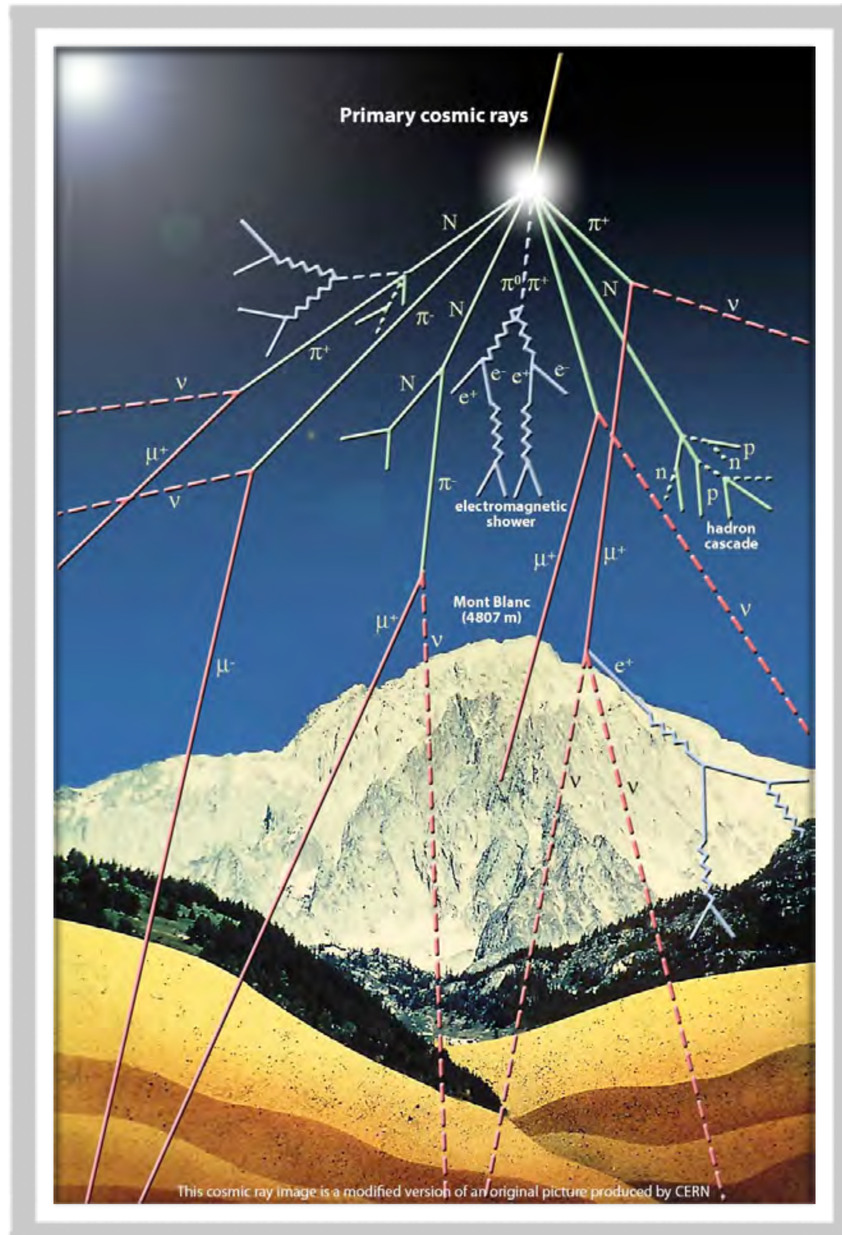
Cosmic Rays

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



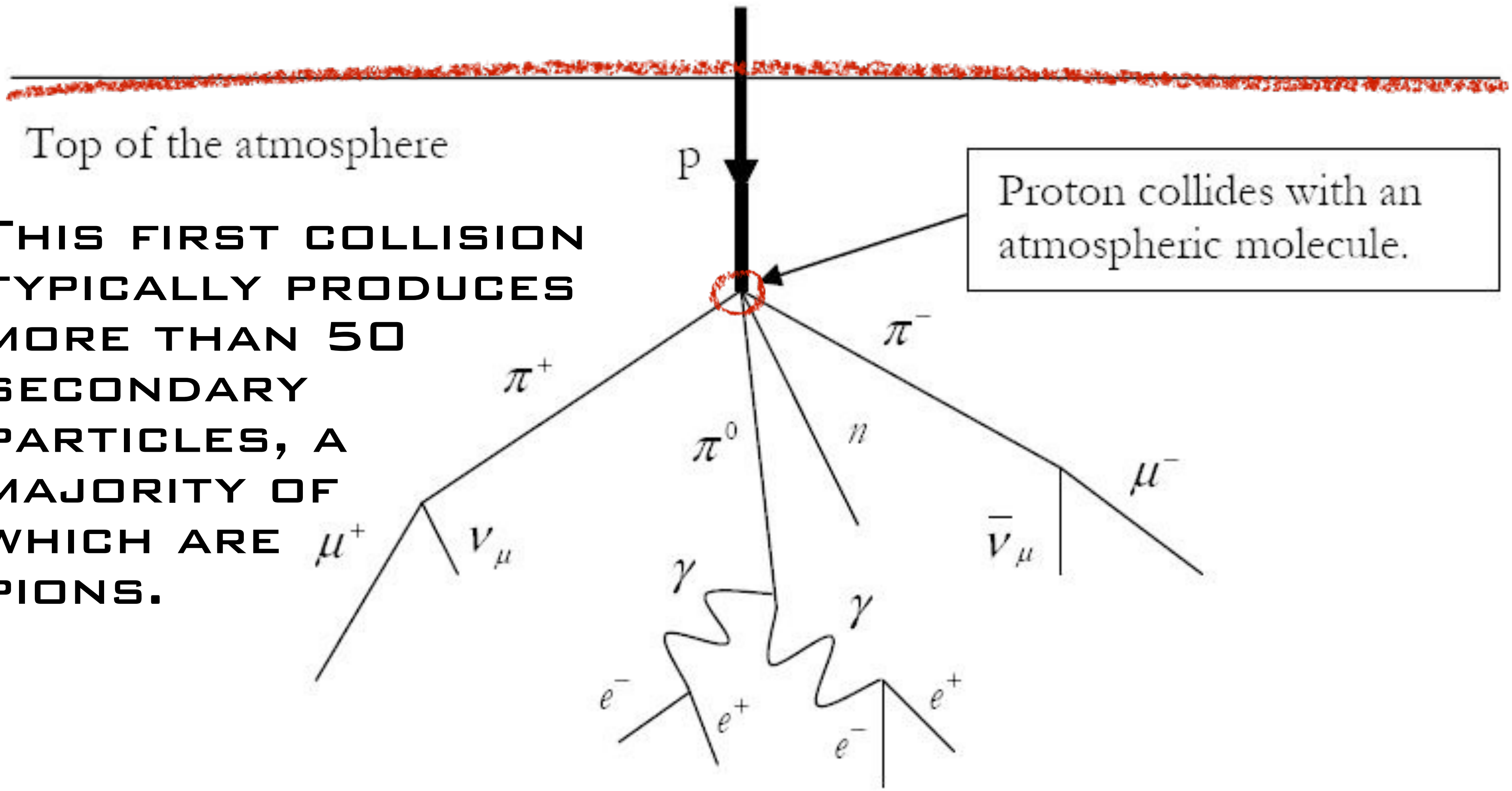
Particle Cascade

- 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

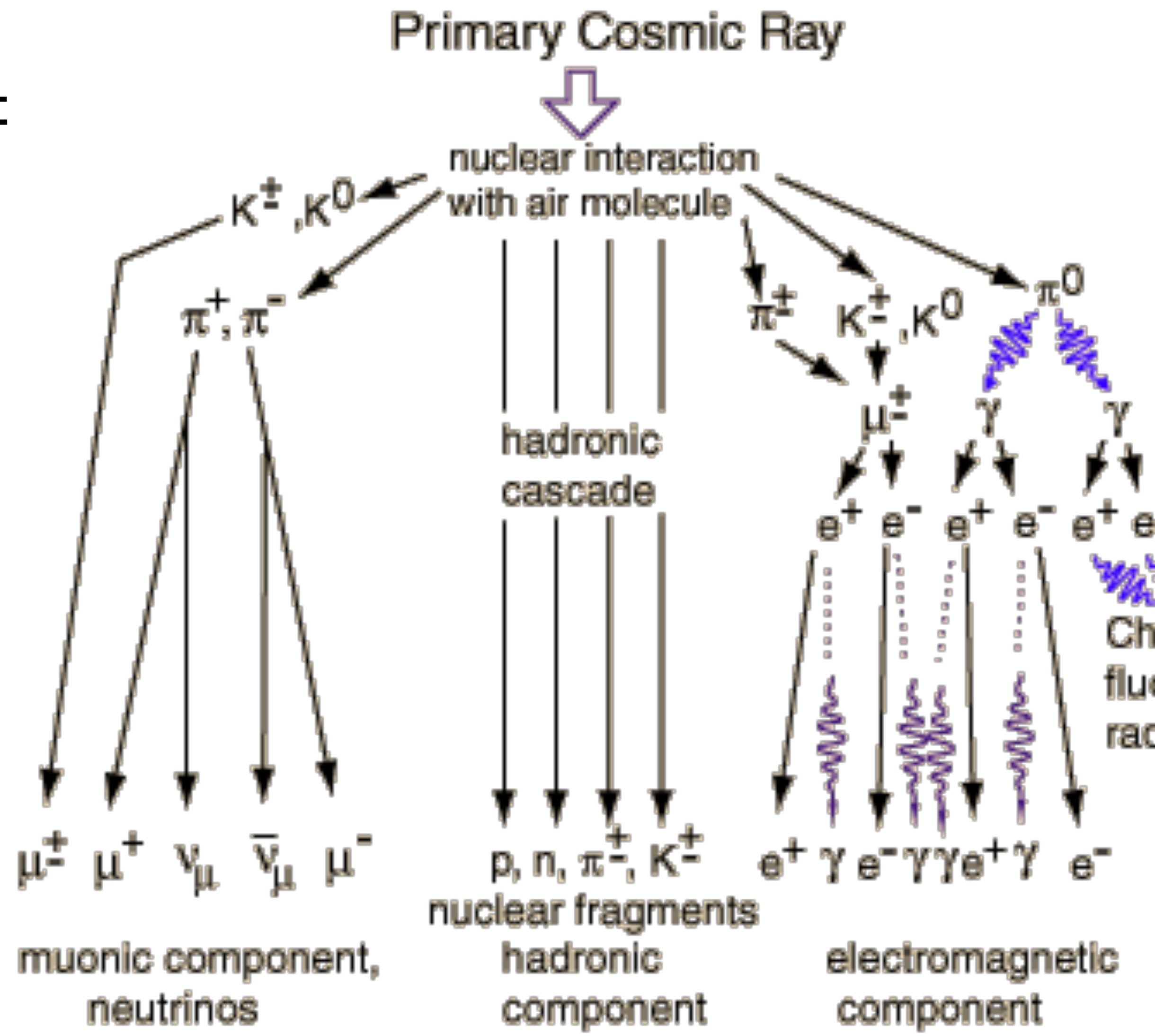
- The process begins with the collision of the primary cosmic ray with a nucleus near the top of the atmosphere.



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

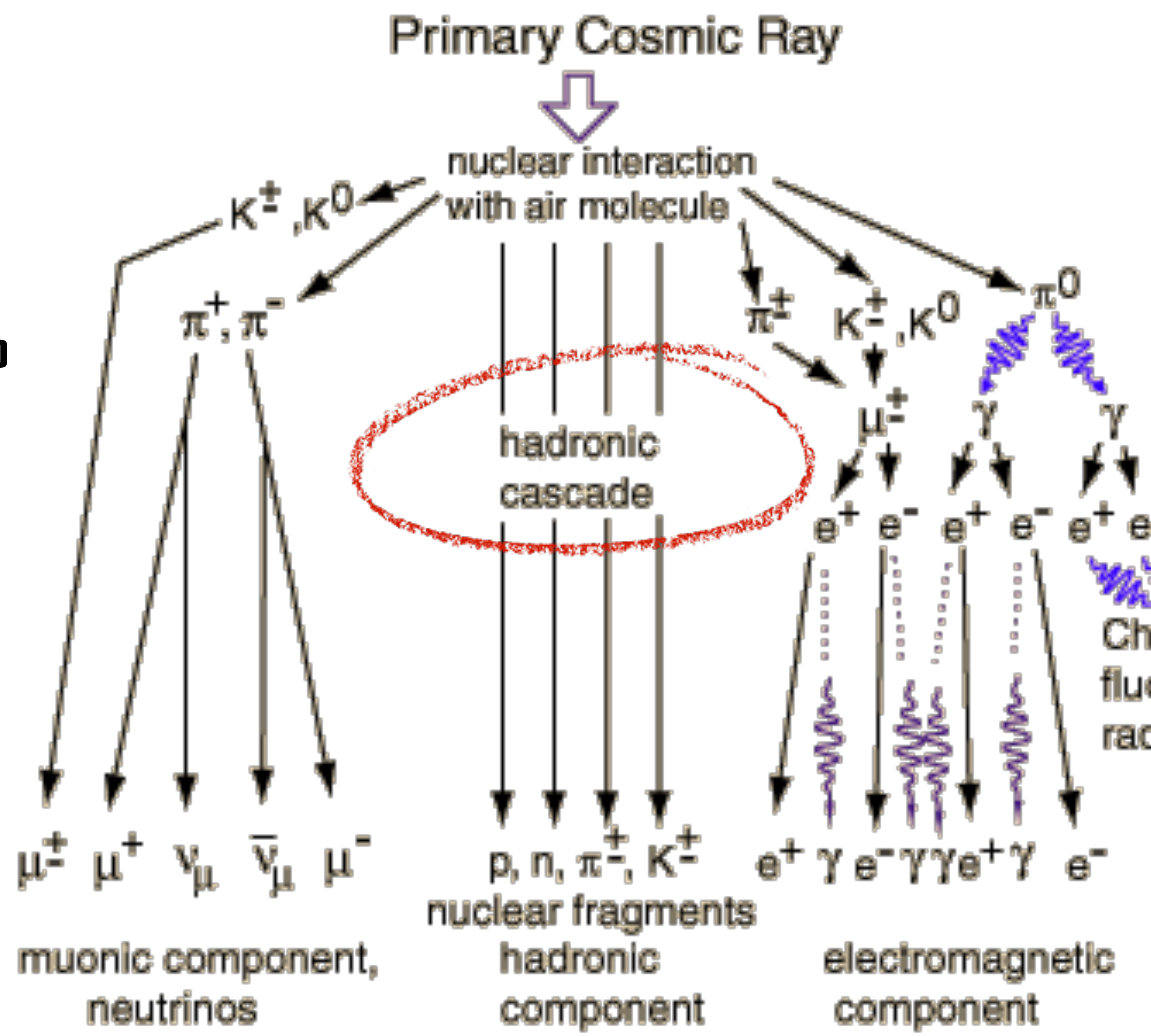
Particle Cascade

- 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.



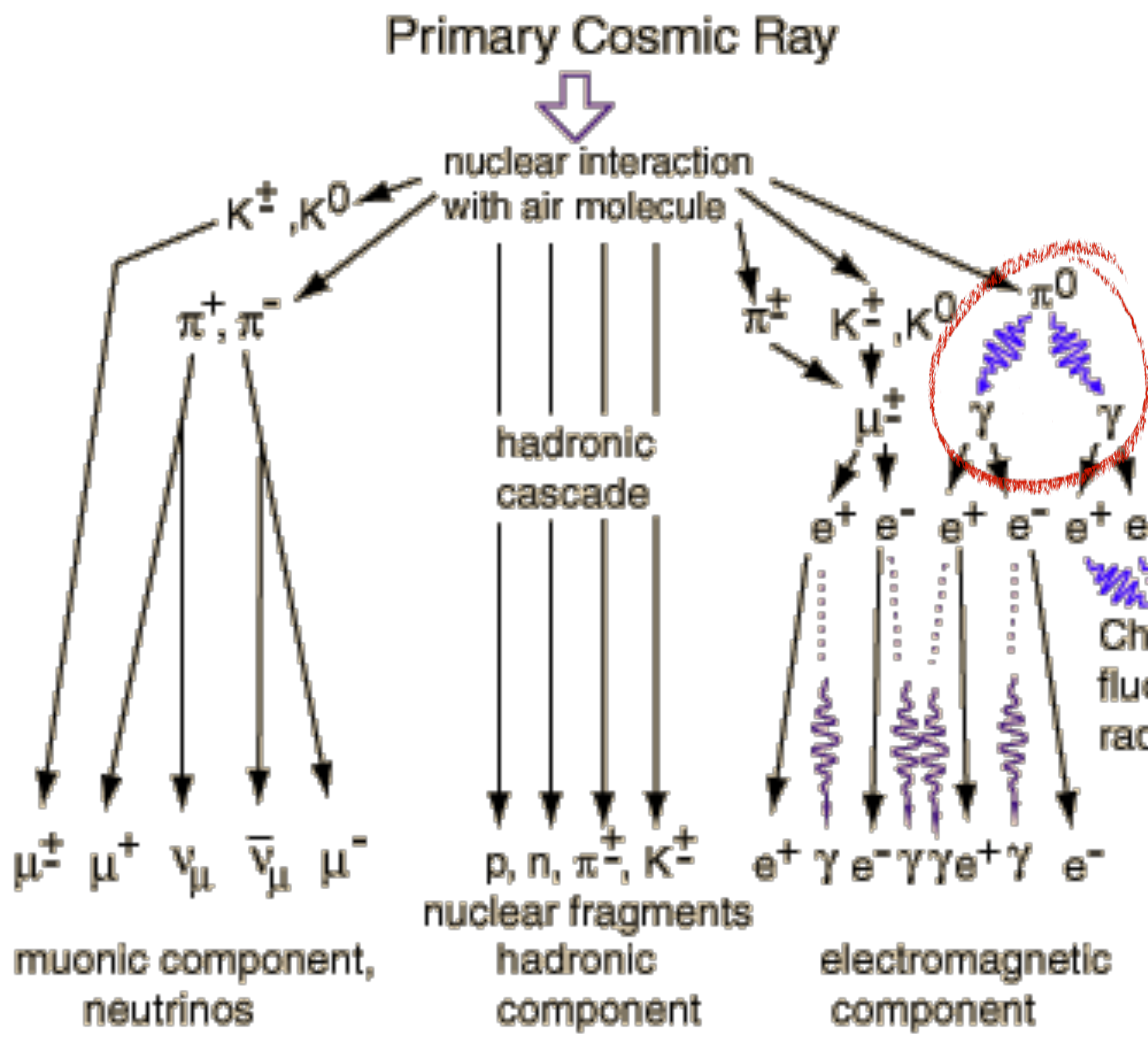
Particle Cascade

- 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".



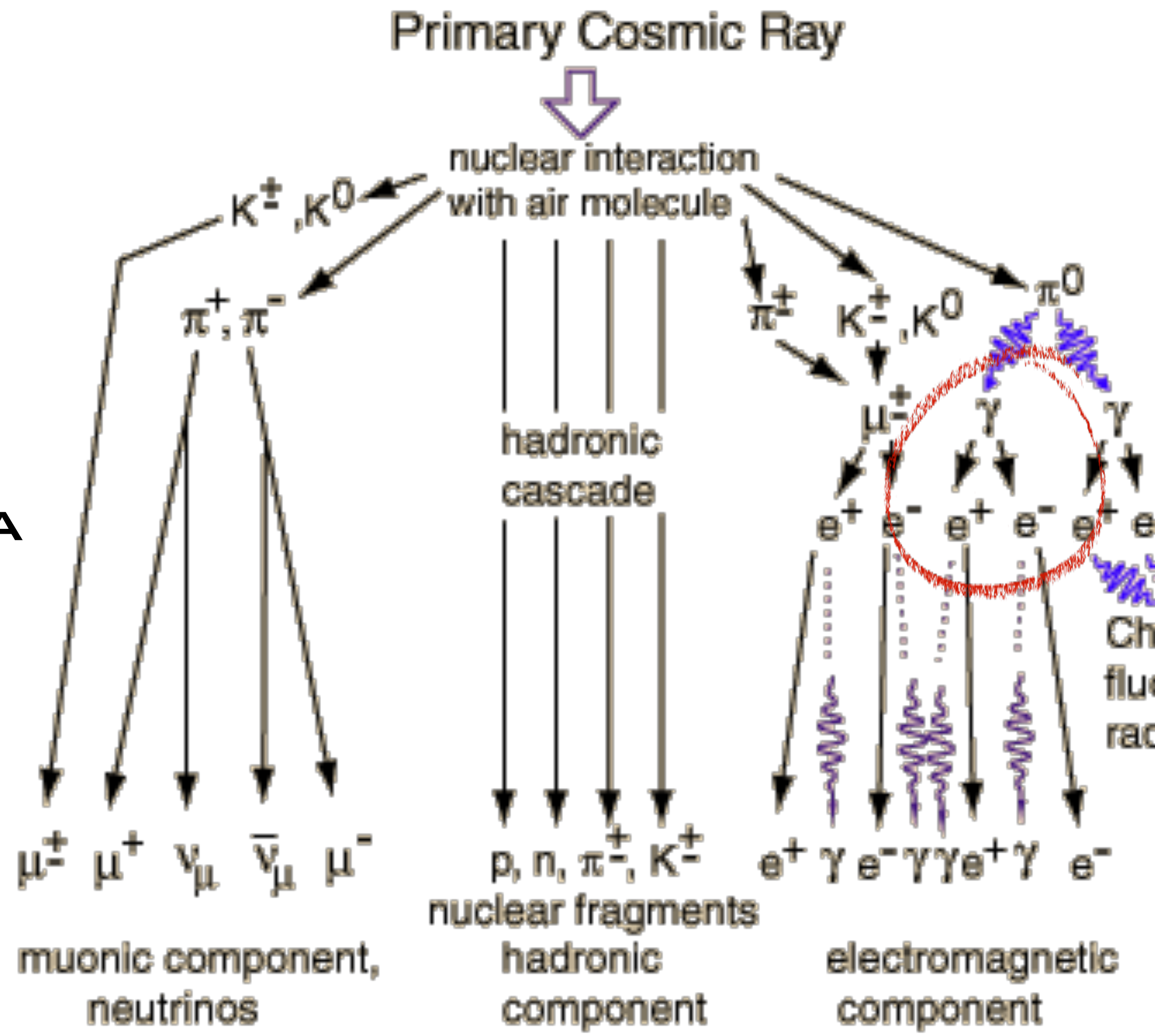
Particle Cascade

- 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.



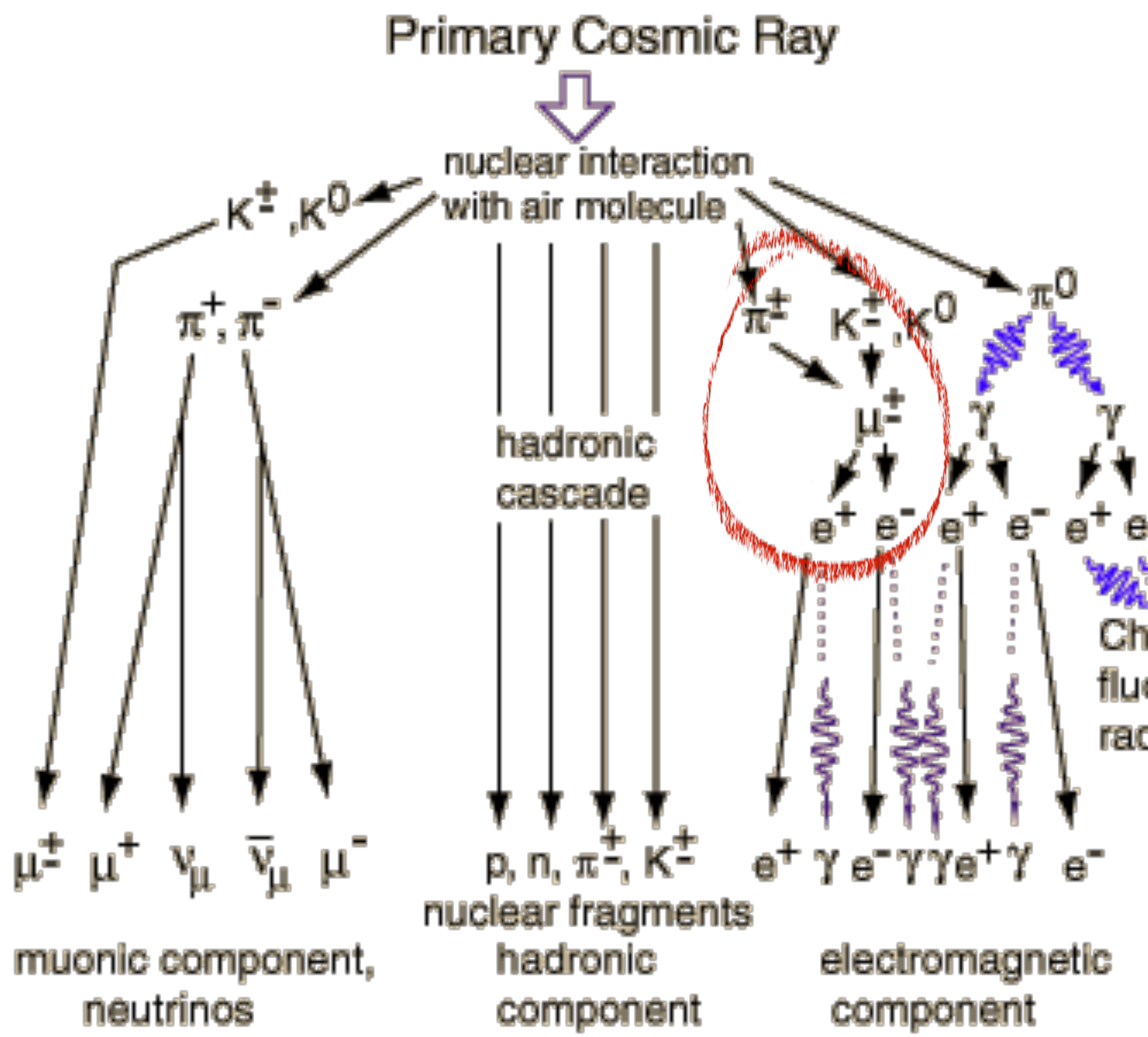
Particle Cascade

- 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".



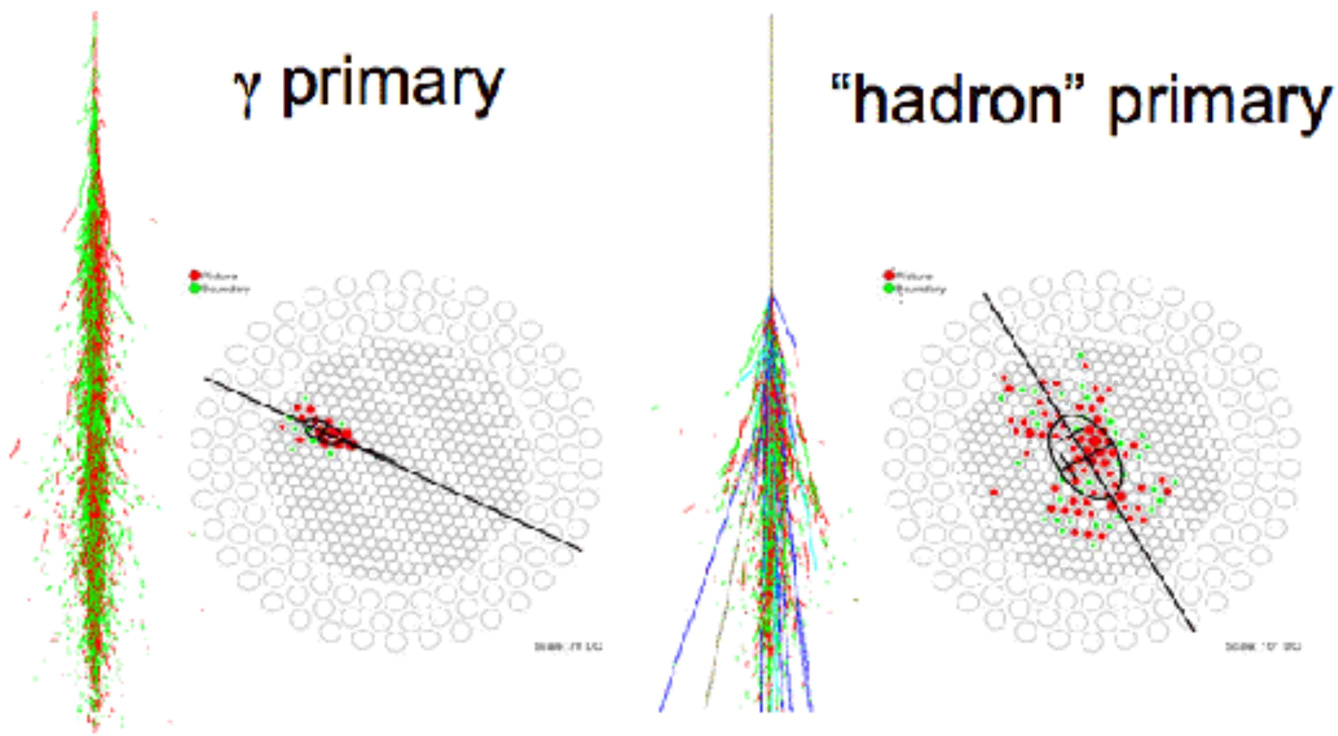
Particle Cascade

- 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 ~10^{12} eV.

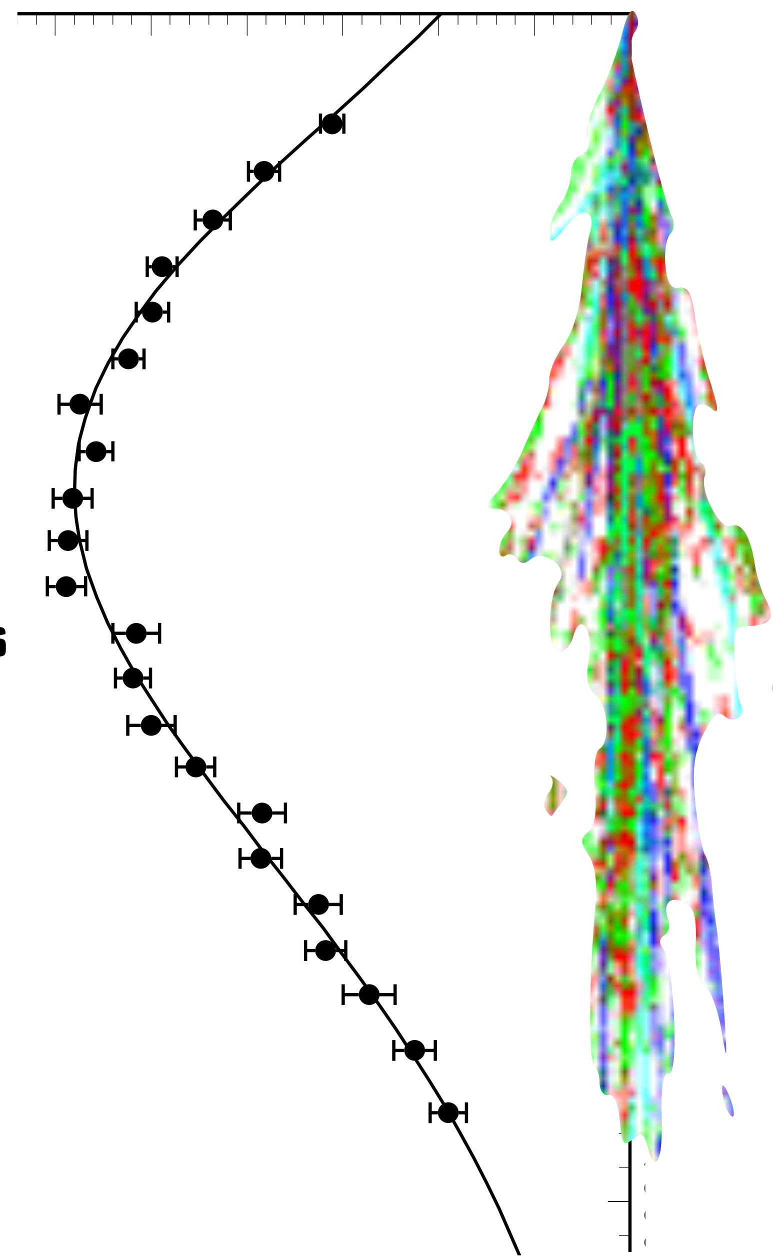
- both types of cascades are called "extensive air showers" (EAS).

Discovery of EAS

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

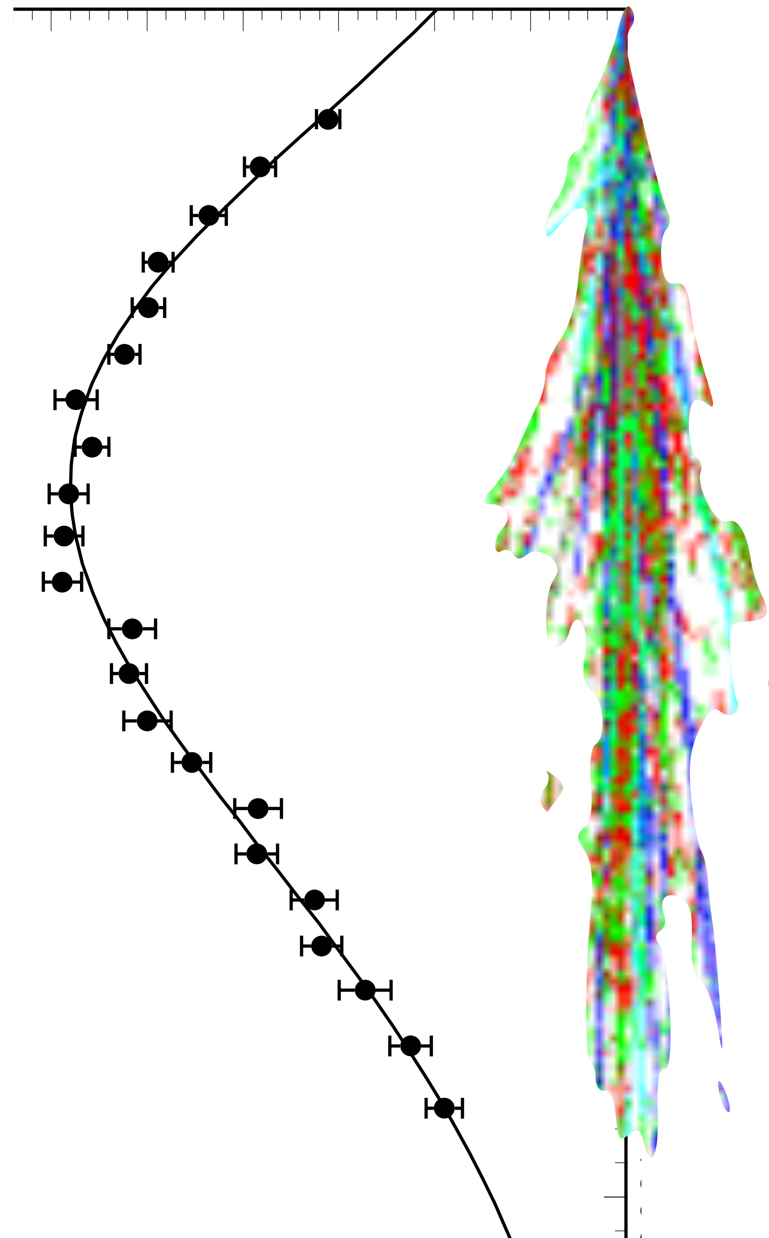
EAS development

- 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

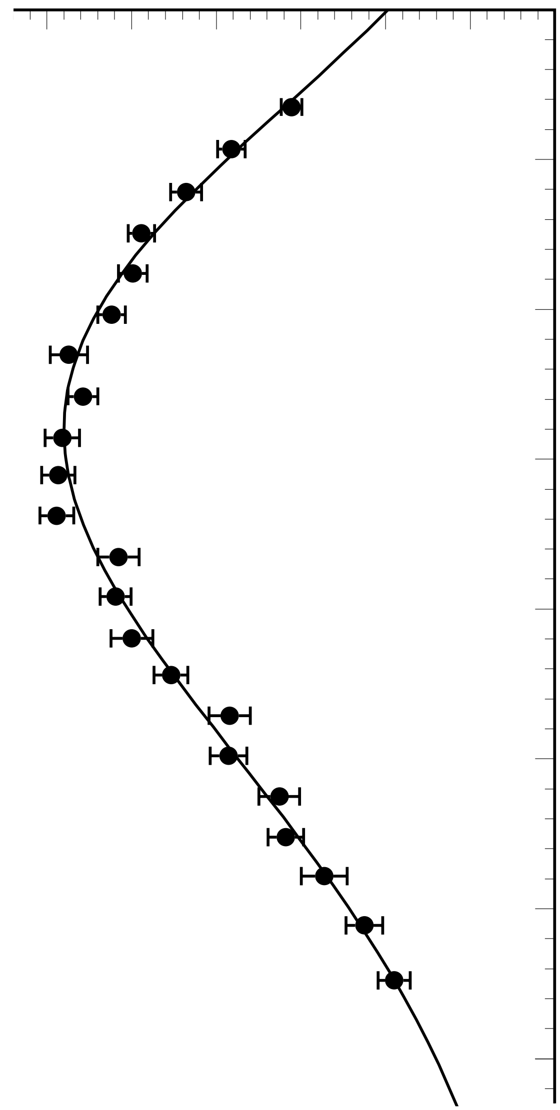
- This point of the EAS development is called the "shower maximum".
- Beyond the maximum, the shower particles are gradually absorbed with an attenuation length of ~200 g/cm².
- Rigorously this is a measure of the depth of material penetrated by the shower. (More on this later.)



Properties of Shower Max

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

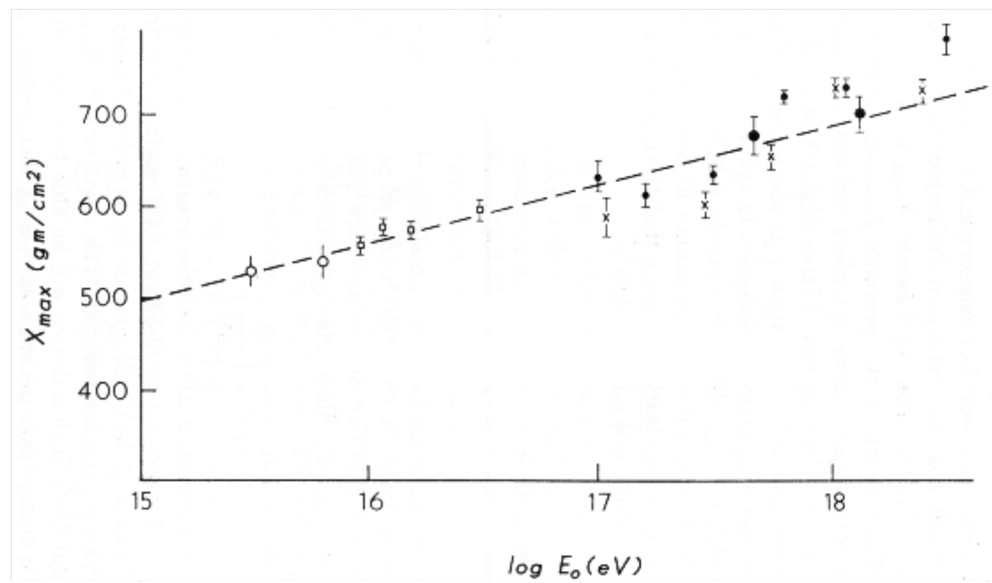
1. at maximum, an EAS typically contains ~1-1.6 particles for every GeV (10^9 eV) of energy carried by the primary cosmic ray.



Properties of Shower Max

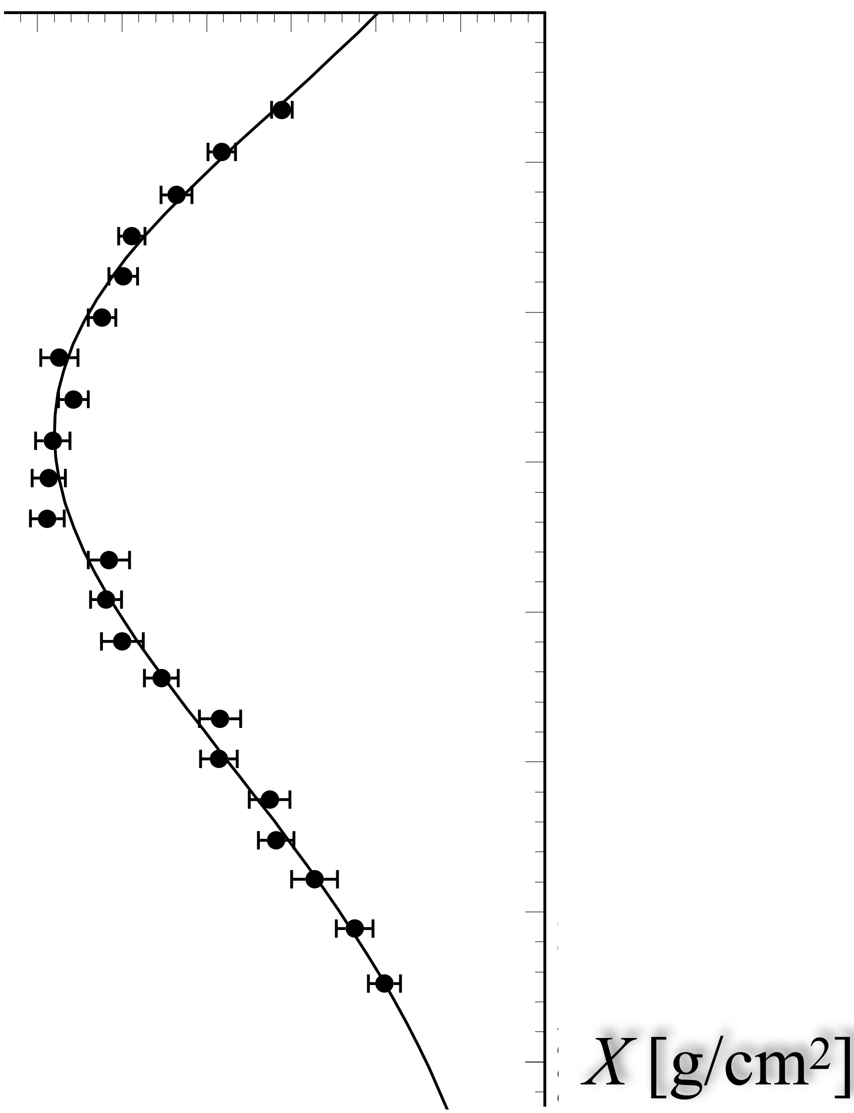
- Two properties of the shower maximum are important to note:

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.

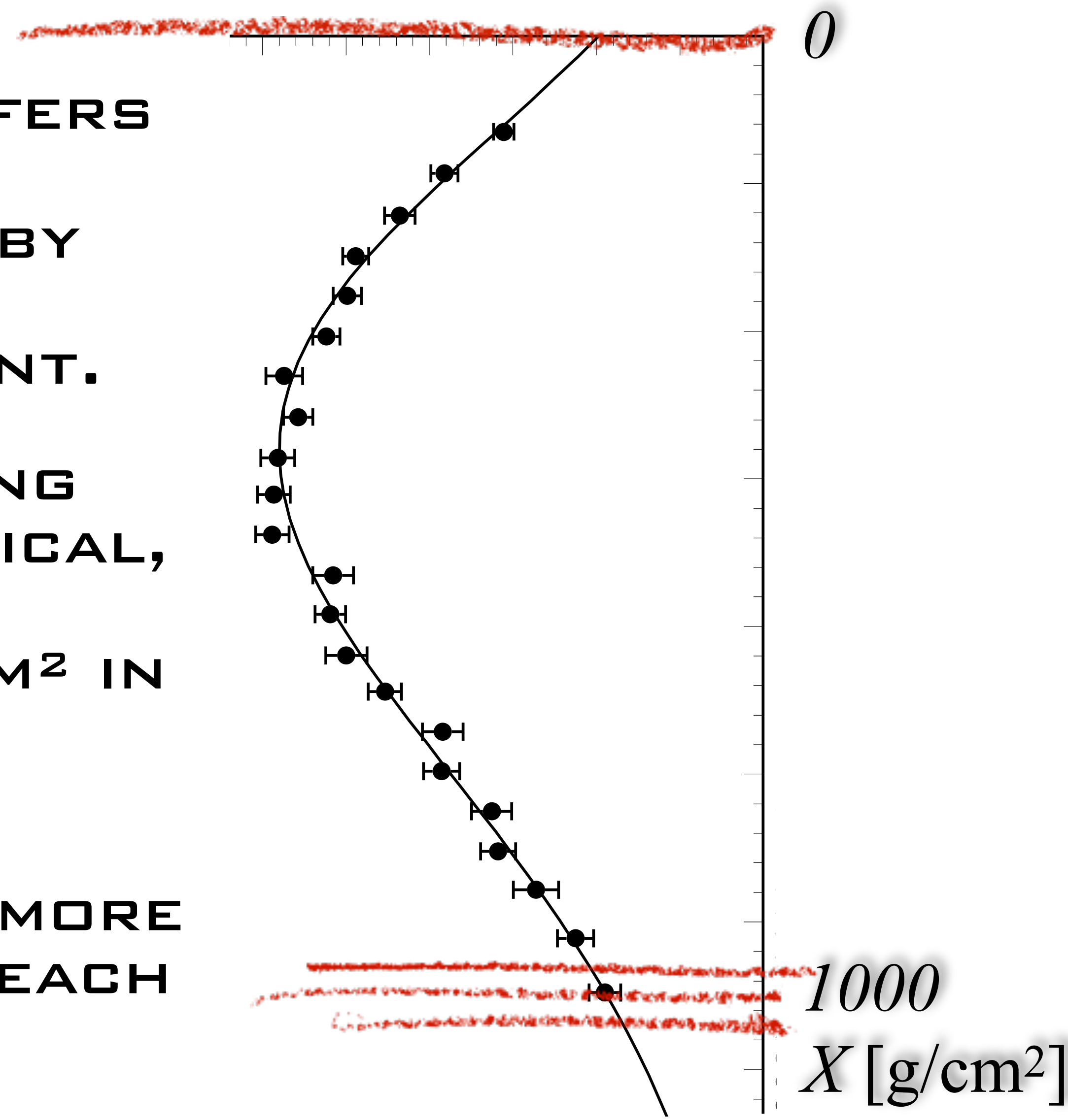


Properties of Shower Max

- The "slant depth" X refers to the amount of materials penetrated by the shower at a given point in its development.

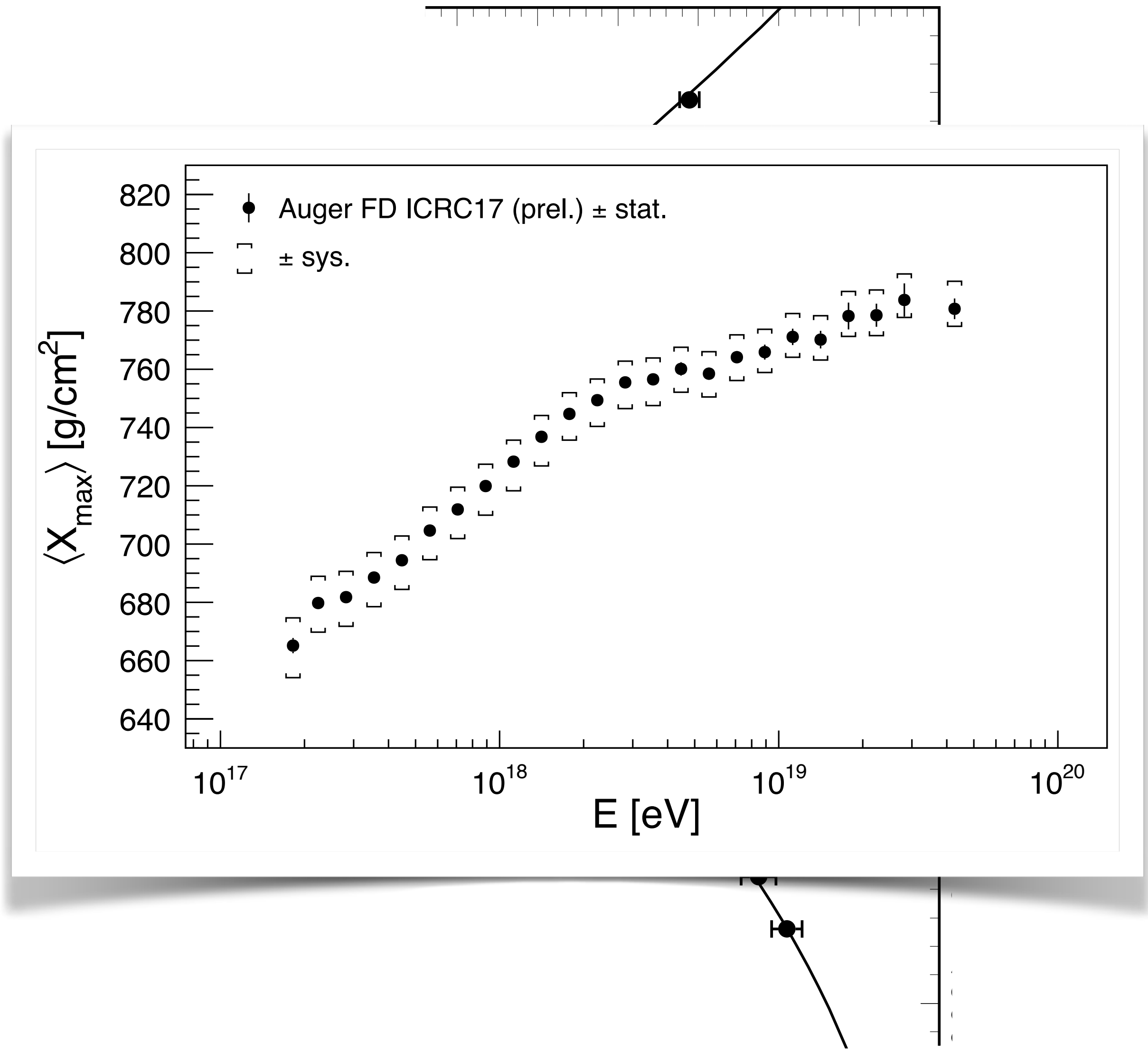
- An air shower traveling along an exactly vertical, downward trajectory traverses ~1,000 g/cm² in reaching sea-level.

- Obviously, an inclined shower will traverse more than 1,000 g/cm² to reach sea-level.

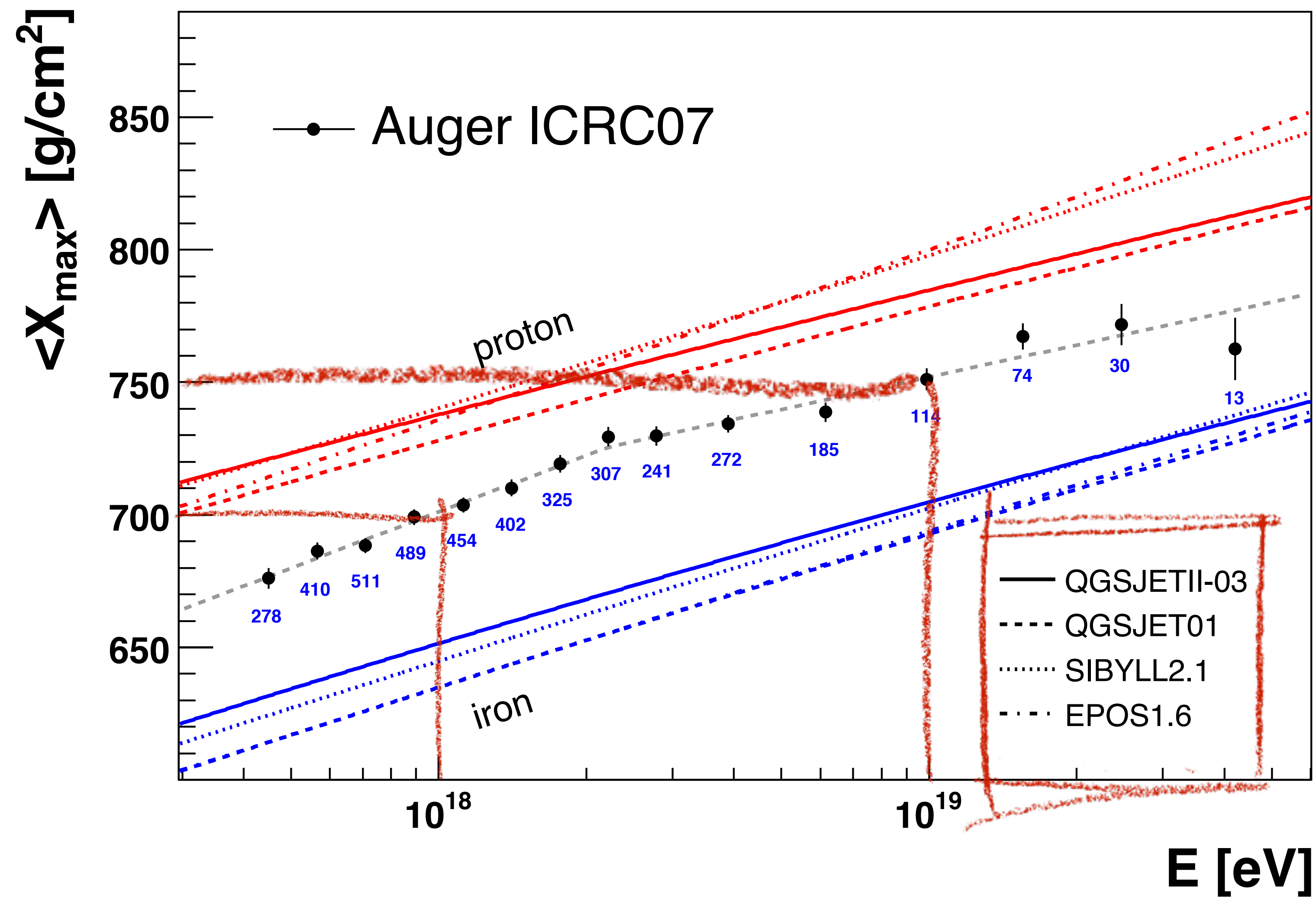


Properties of Shower Max

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

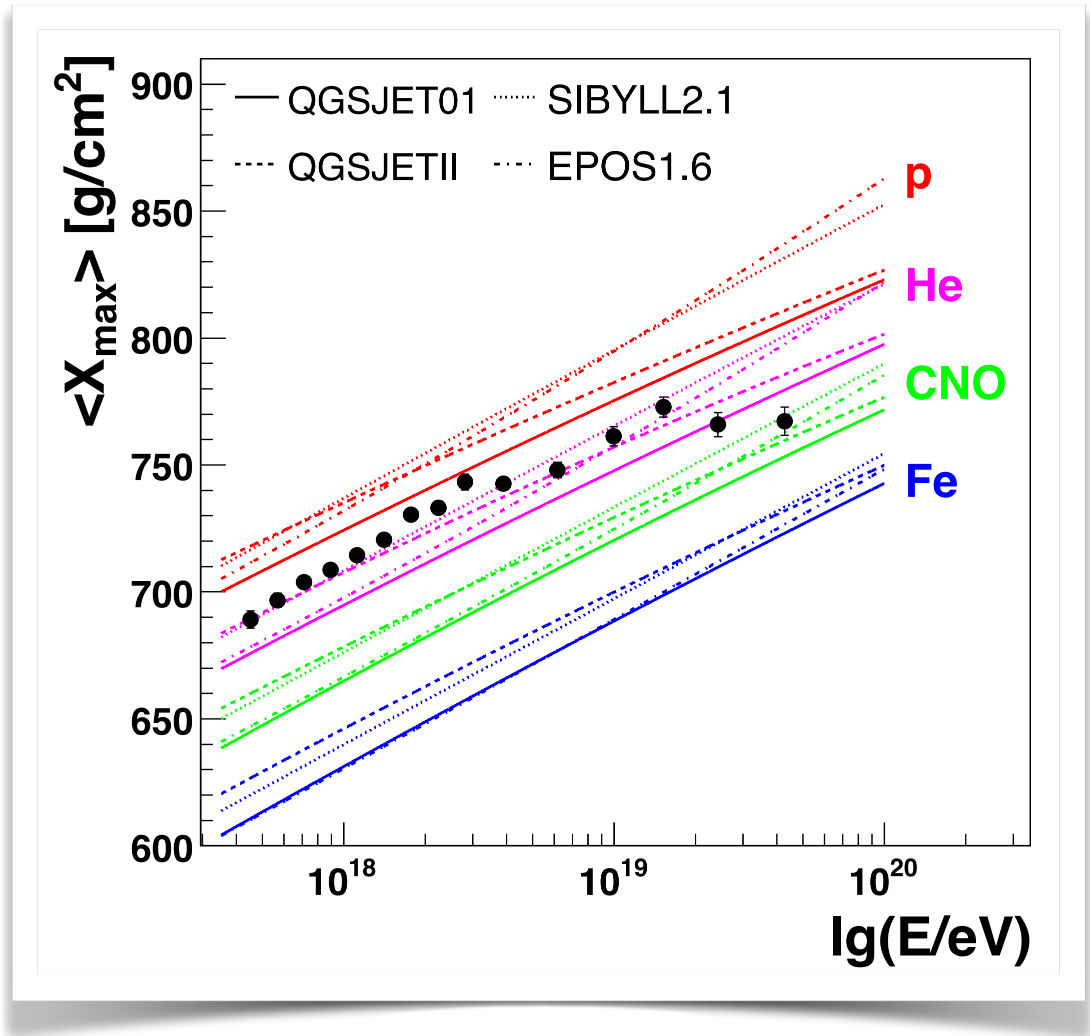


Properties of Shower Max



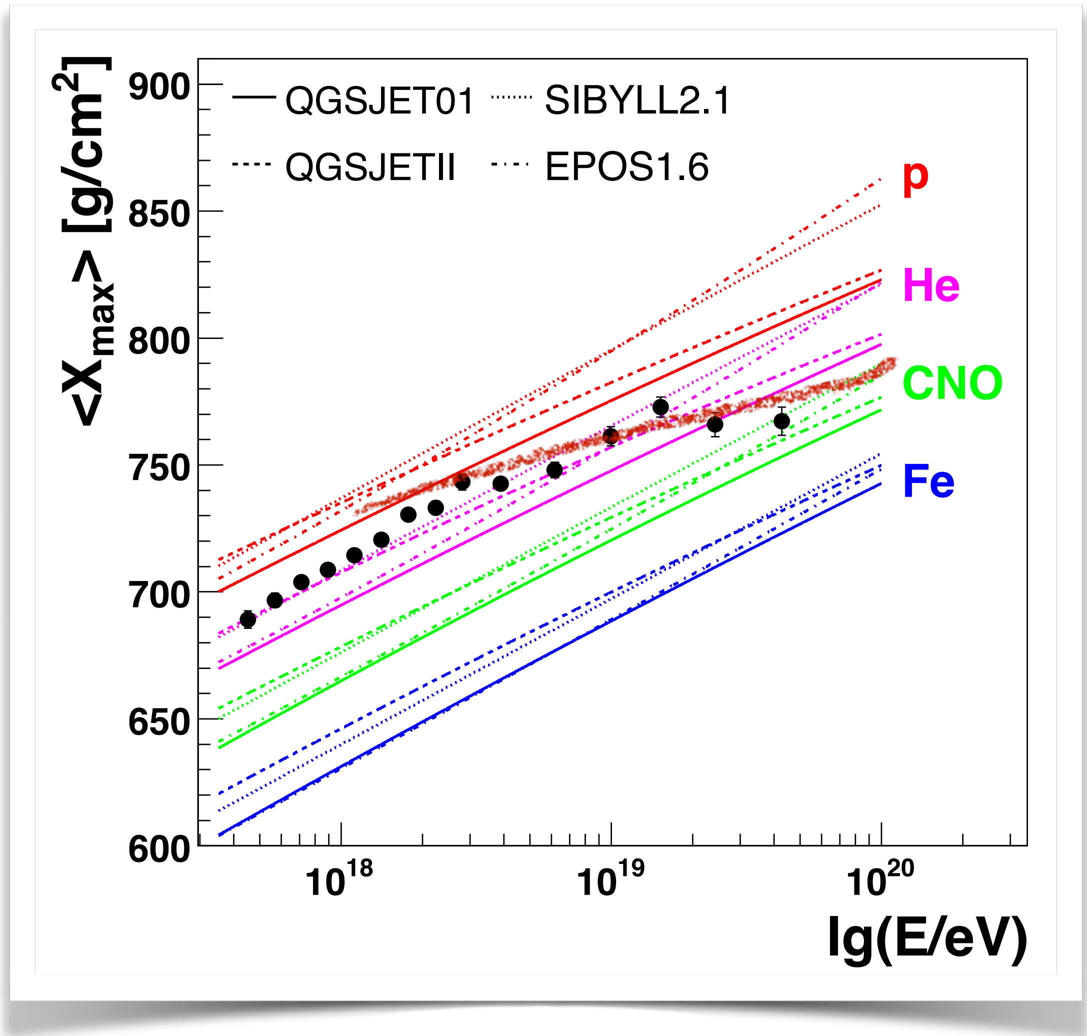
Properties of Shower Max

- 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.

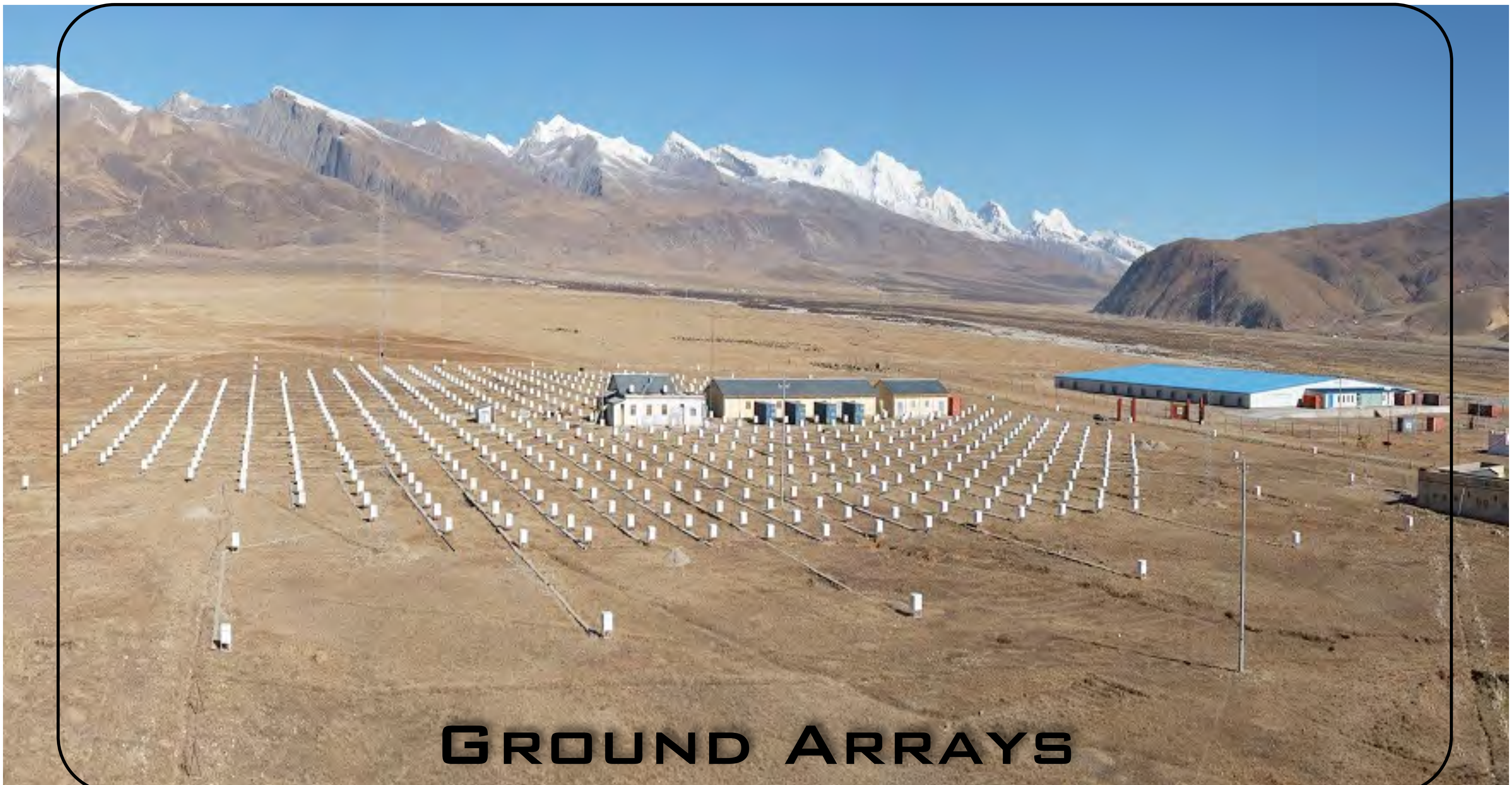


Properties of Shower Max

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



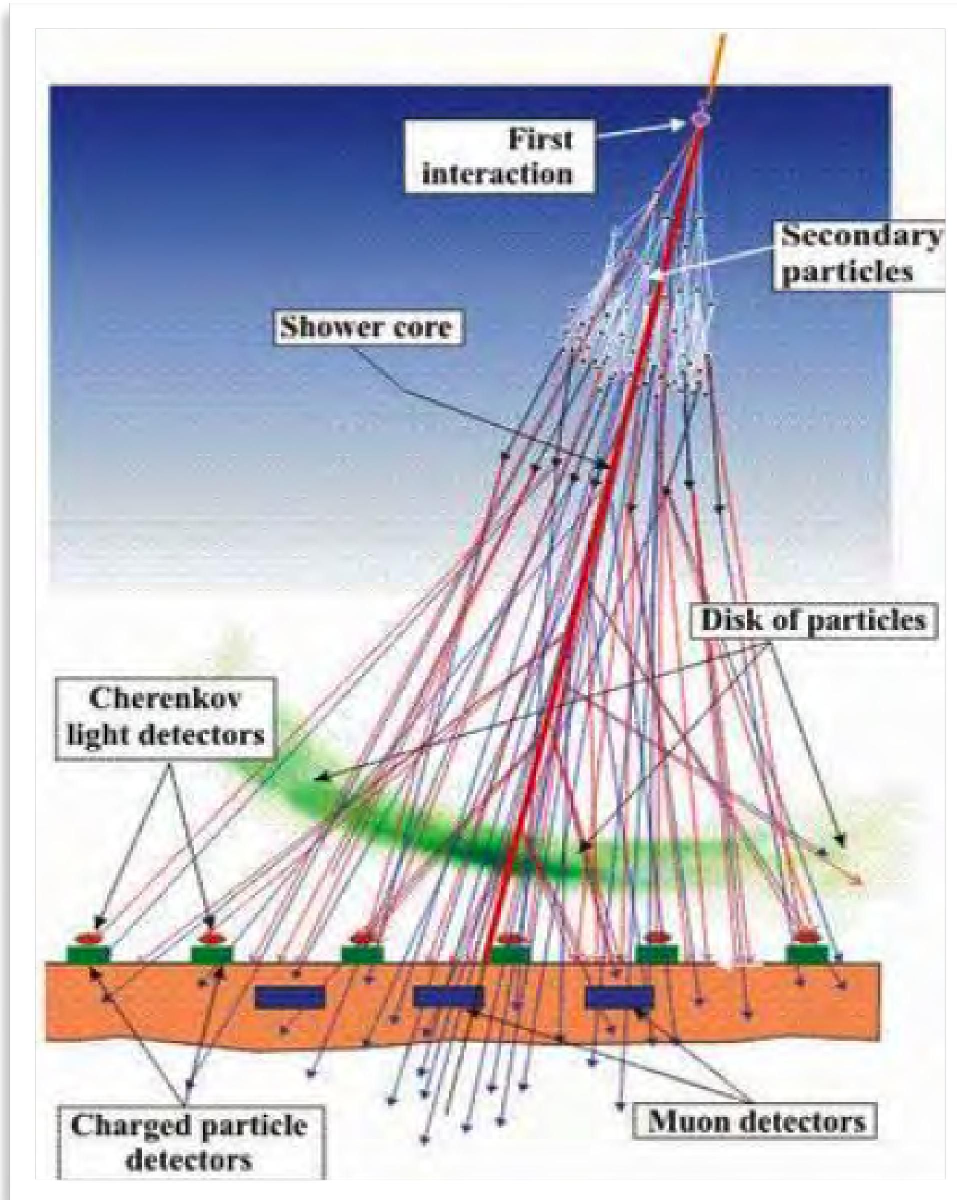
Detection of UHECRs



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.

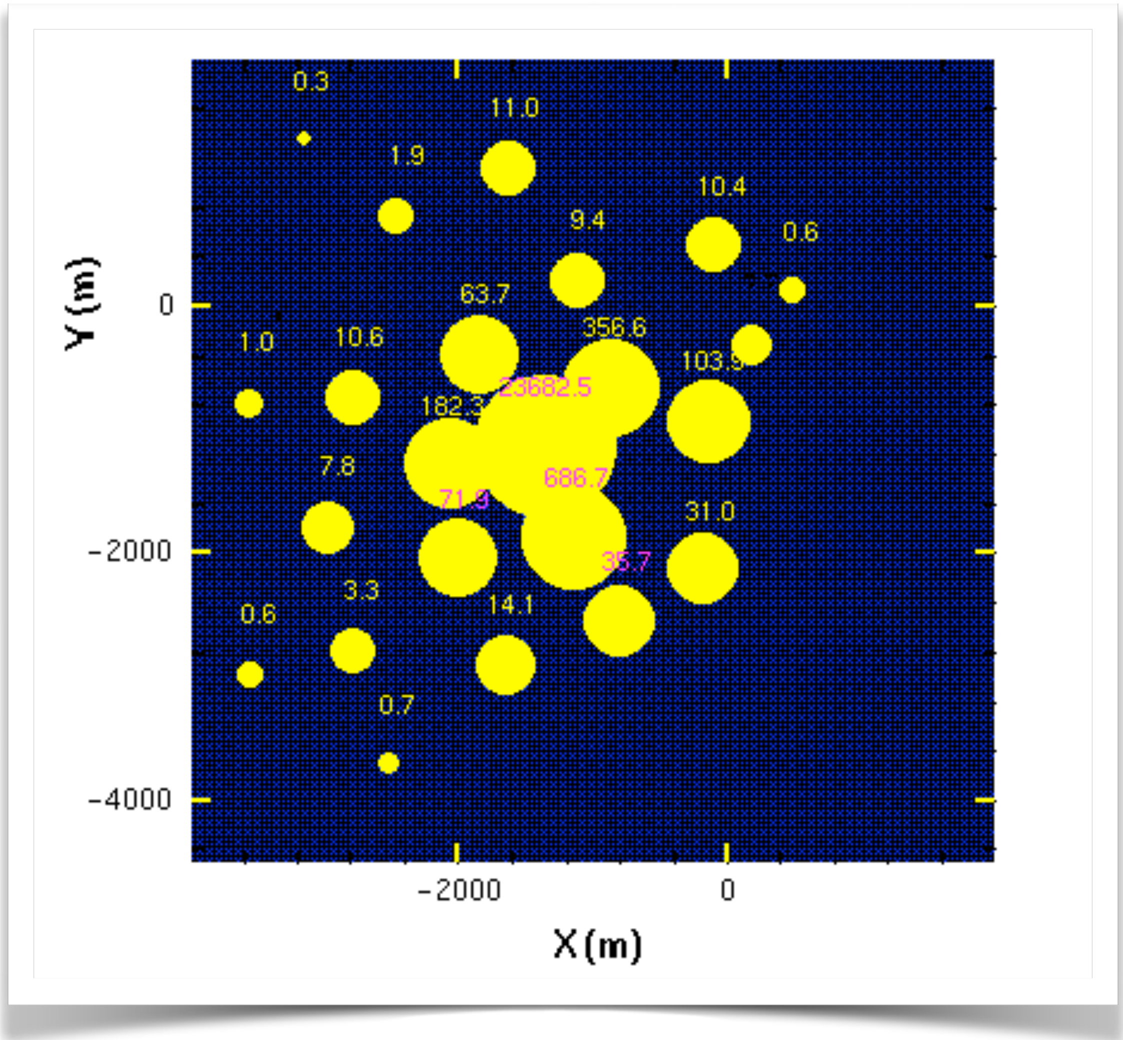


Ground Arrays

- 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.

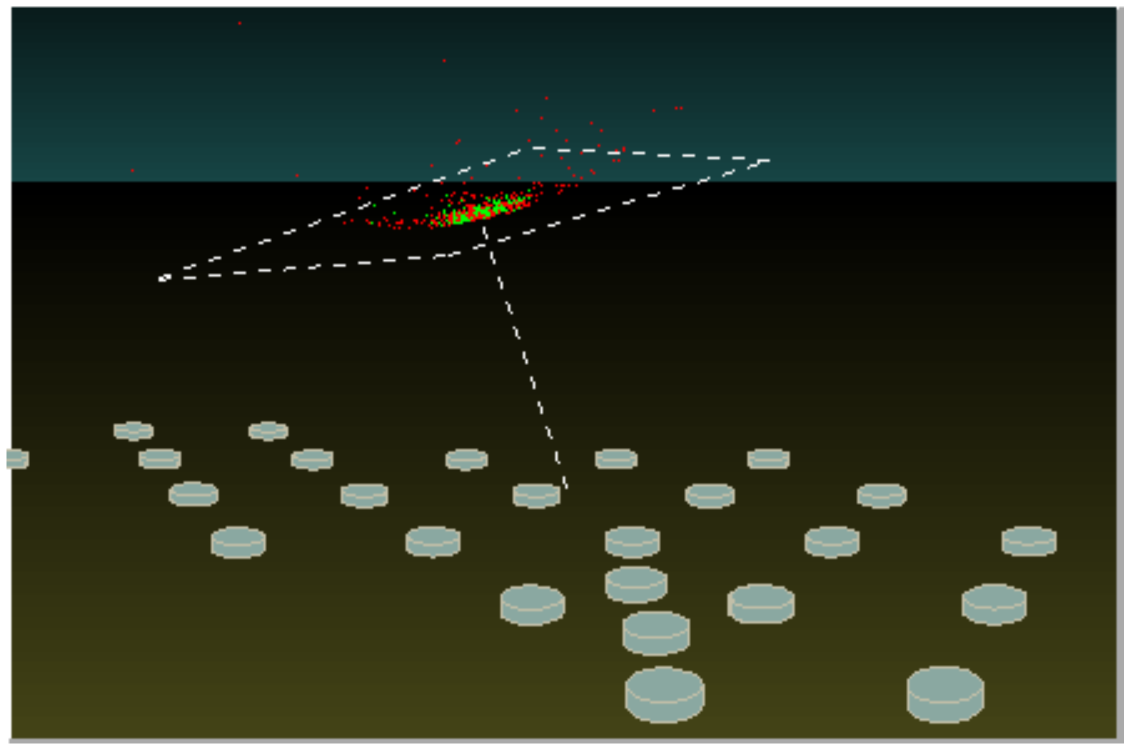
Ground Arrays

- 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.



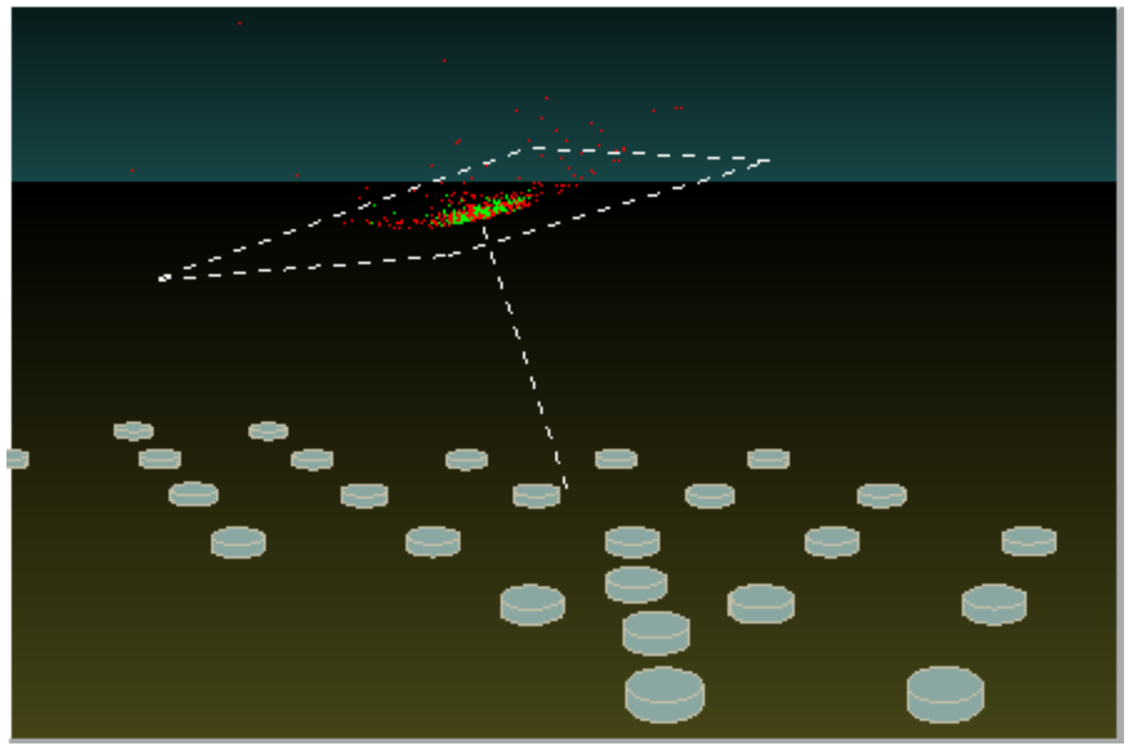
Ground Arrays

- 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

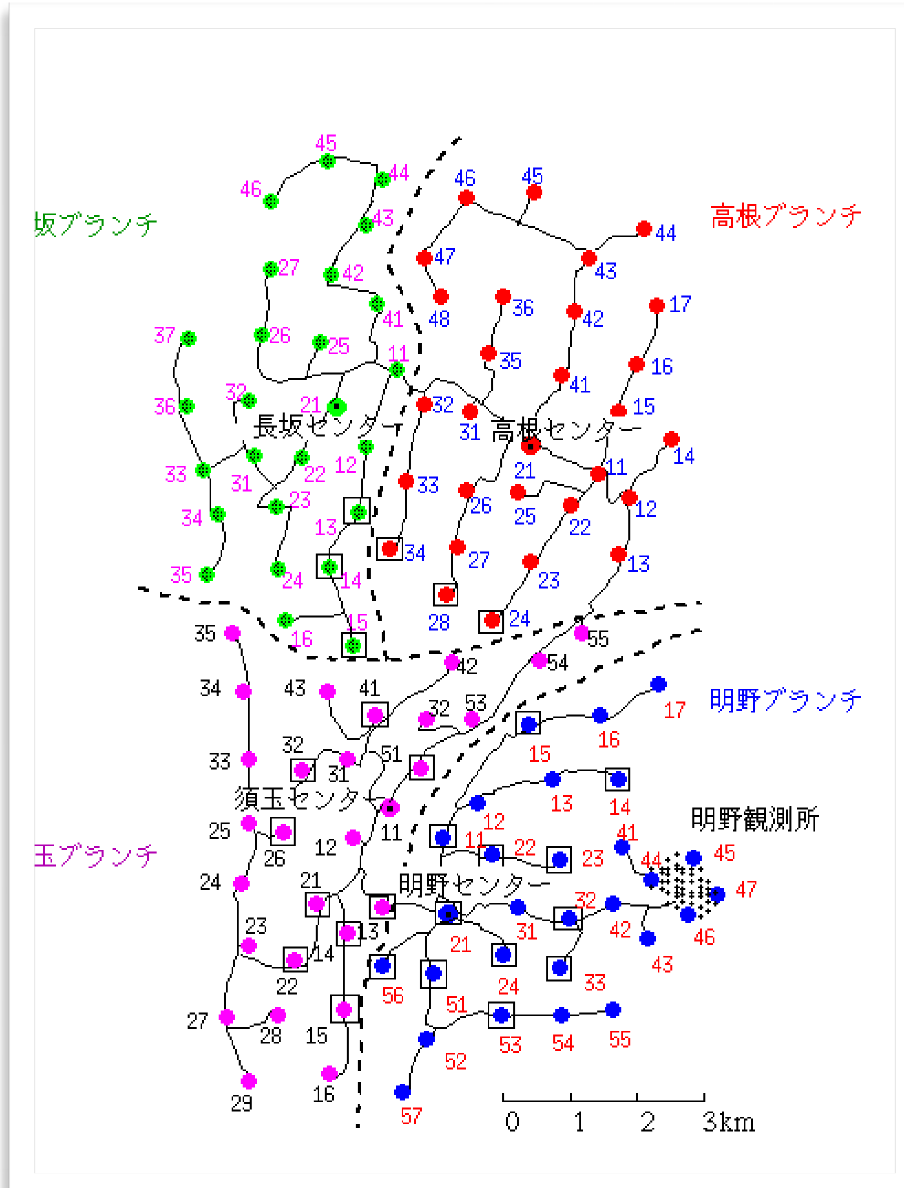
1946: Rossi & Zatsepin build first array

Ground Arrays

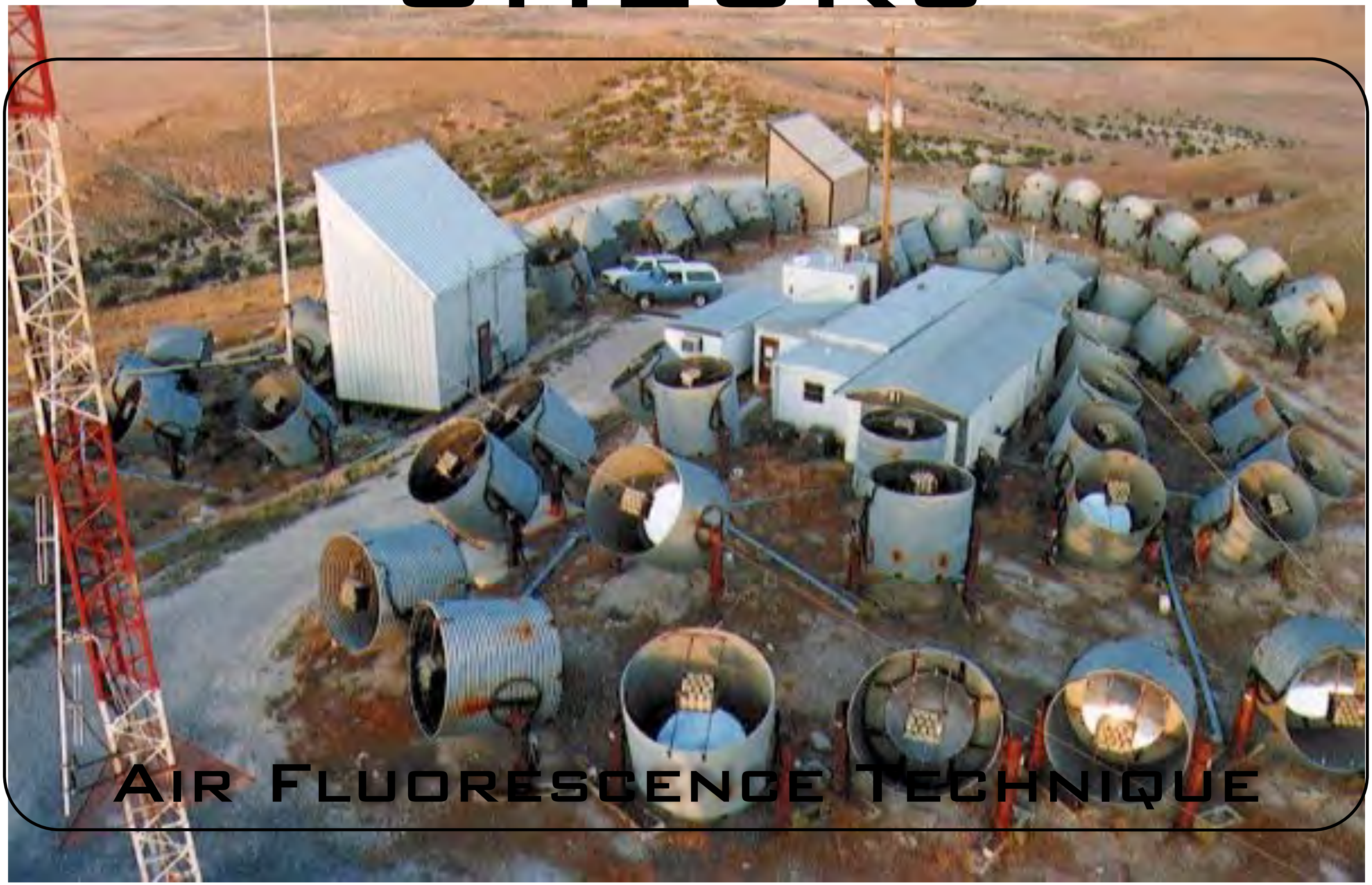
1962: John Linsley sees first $E>10^{20}$ eV

Ground Arrays

- AGASA:
  - 100 km²
  - plastic scintillators



Detection of UHECRs



Air Fluorescence Technique

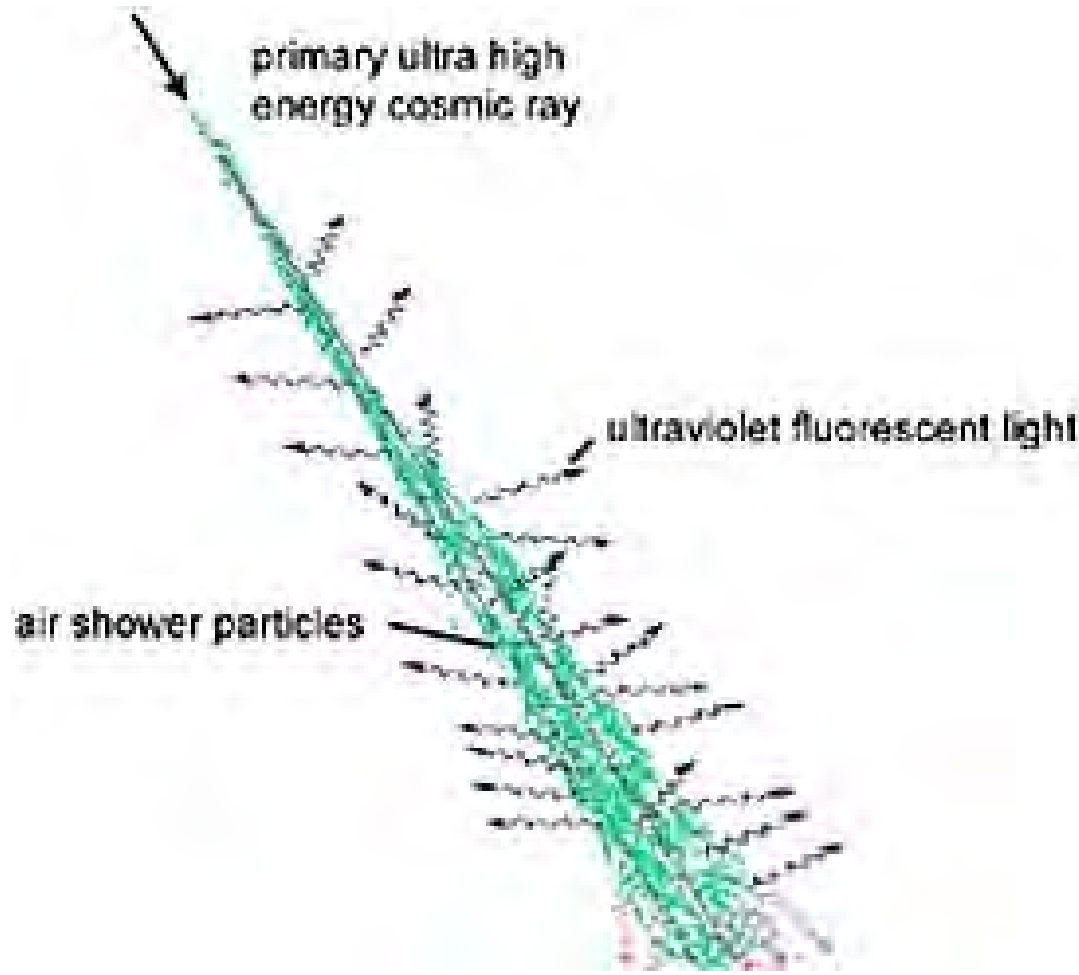
Air Fluorescence

- "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".

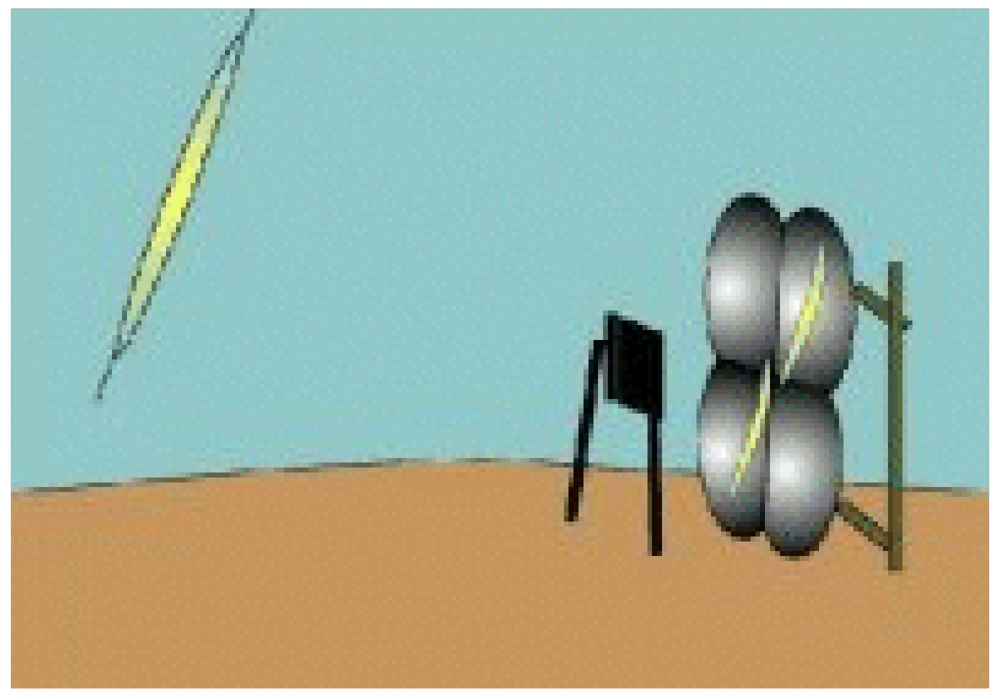
Air Fluorescence

- 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.

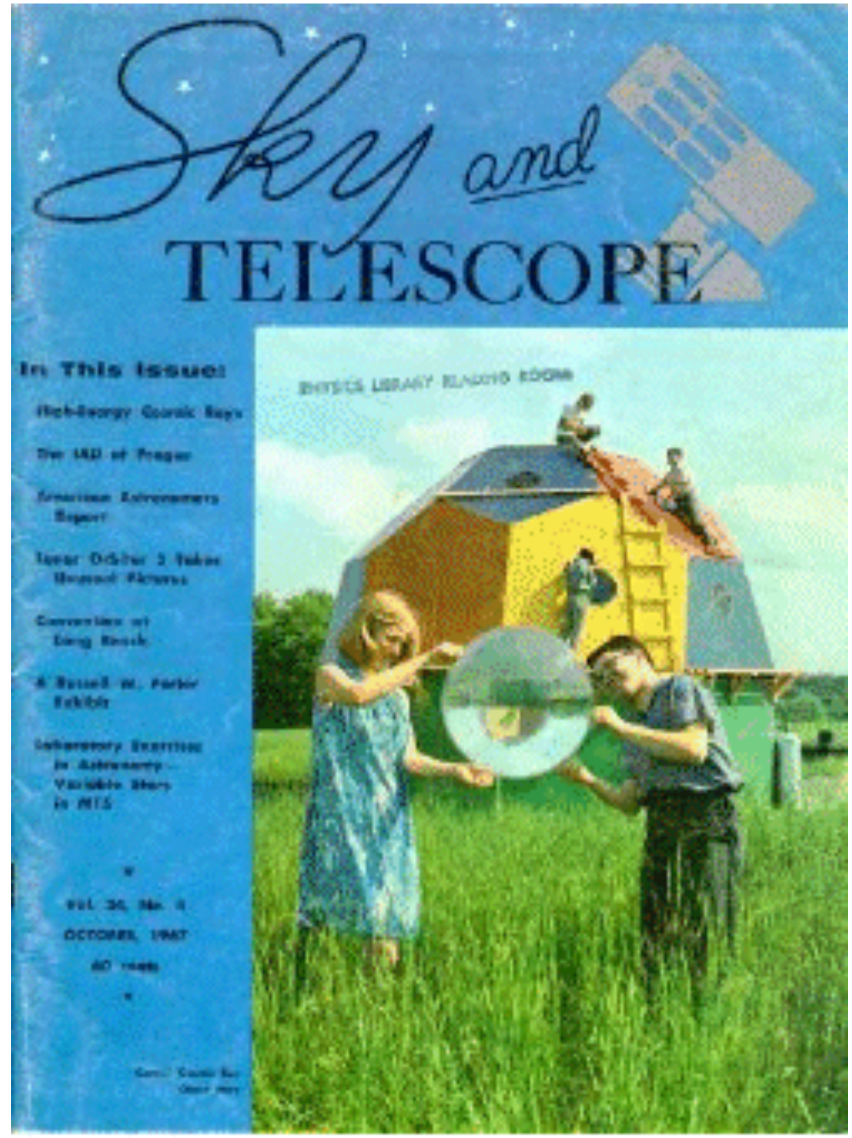
- It was a method for detecting the yield of nuclear explosions in tests.

- 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.

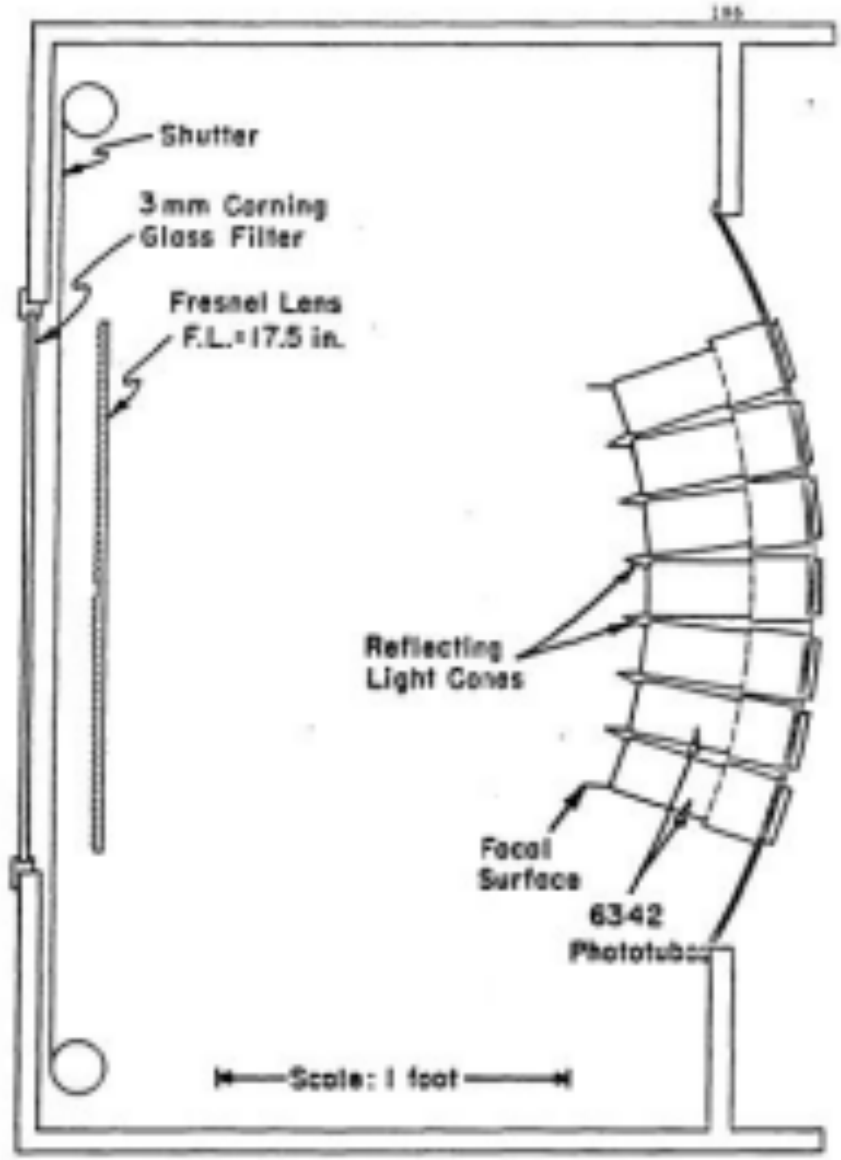
Air Fluorescence

- 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.



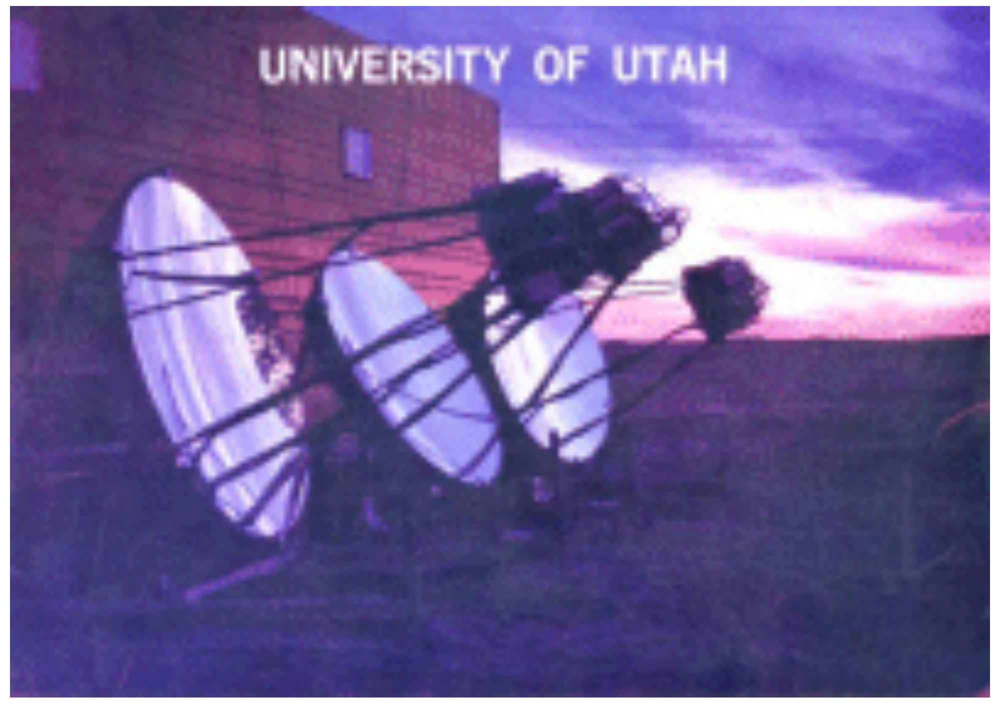
The Cornell Experiment

- 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.

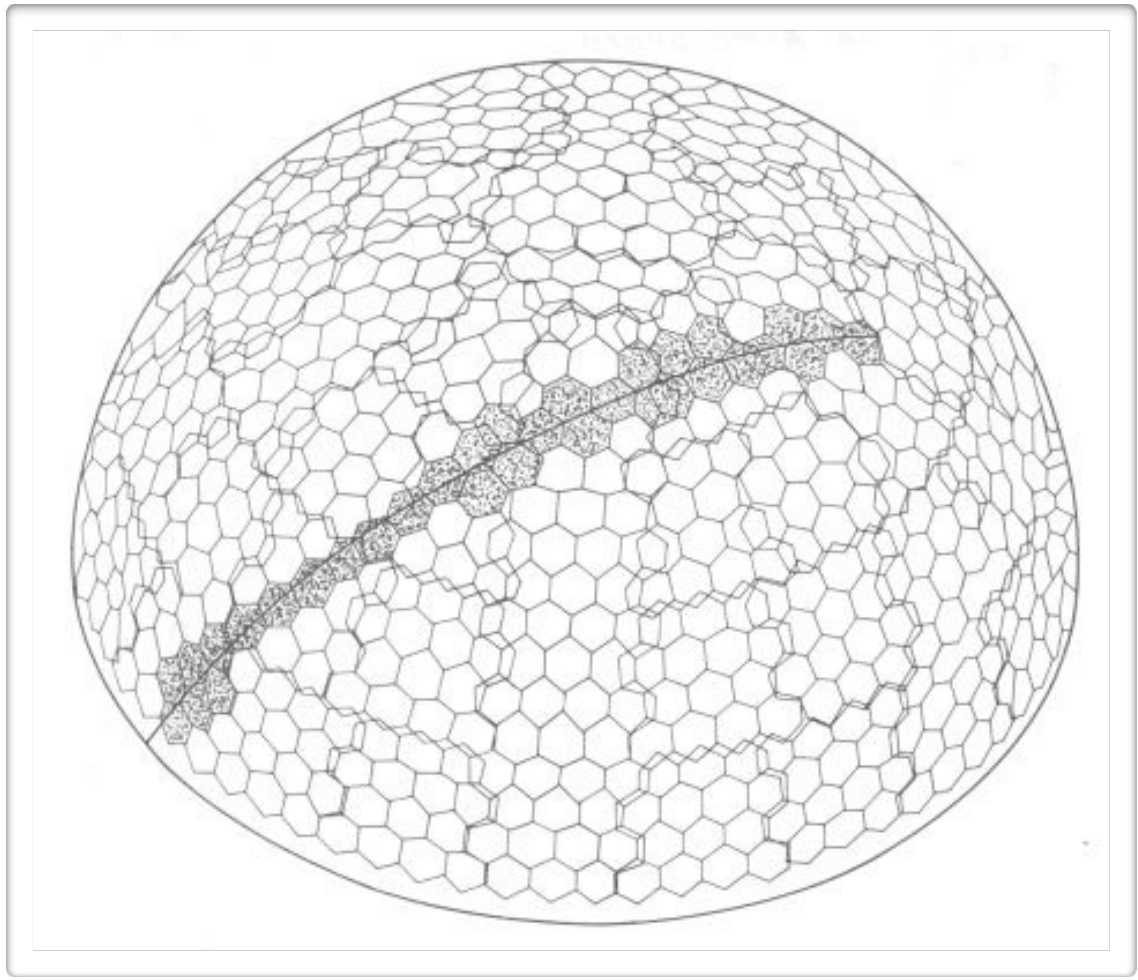


Air Fluorescence

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

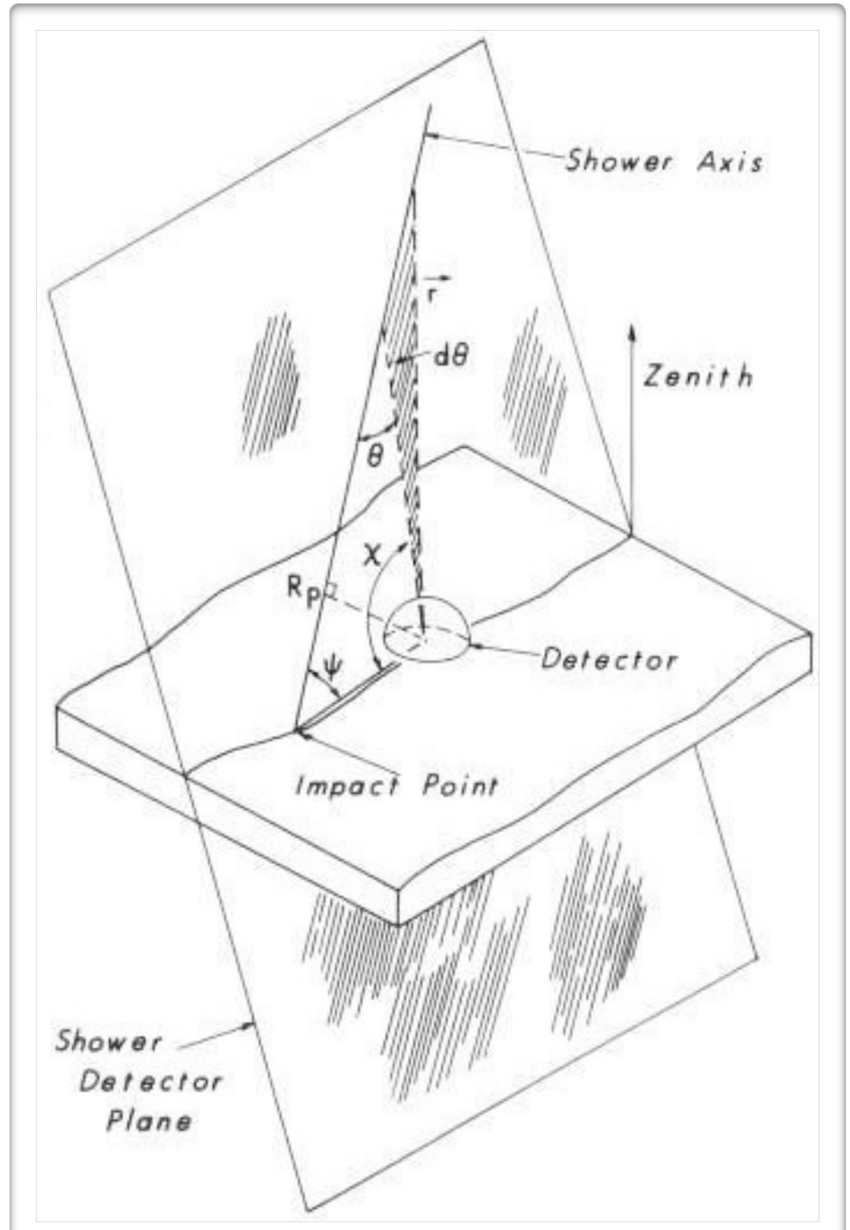
The Fly's Eye

- 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.



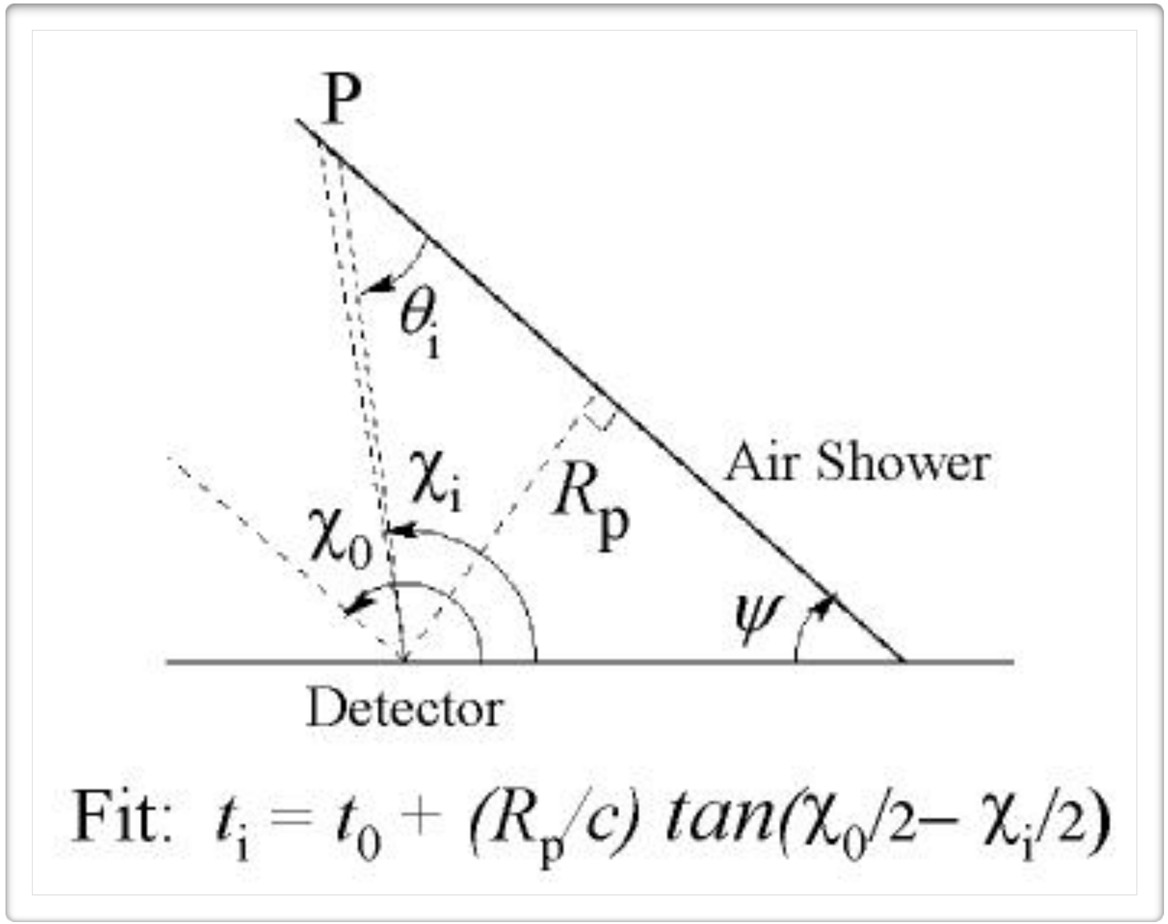
Geometrical Reconstruction

1. Shower Detector Plane (SDP).

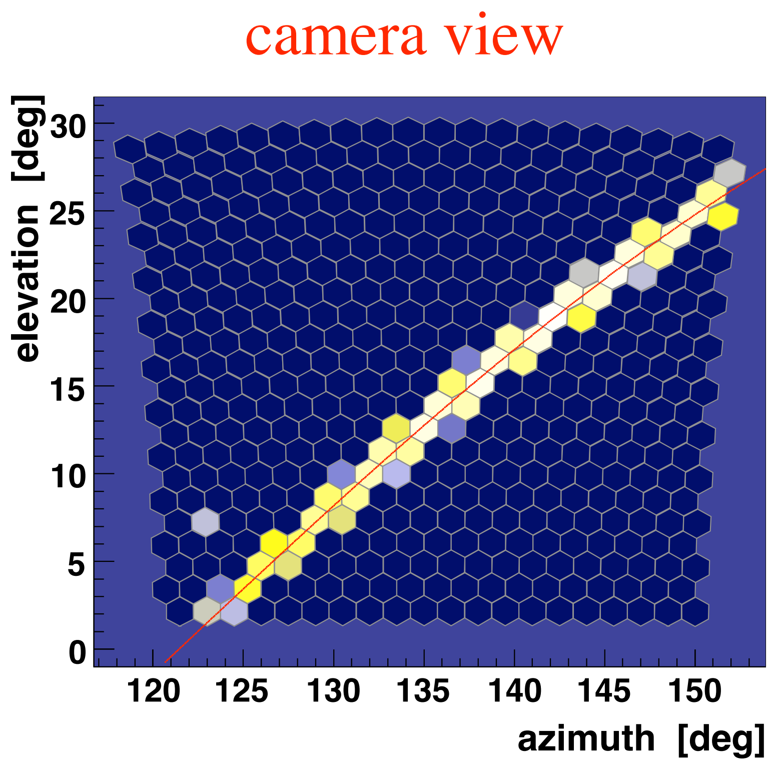


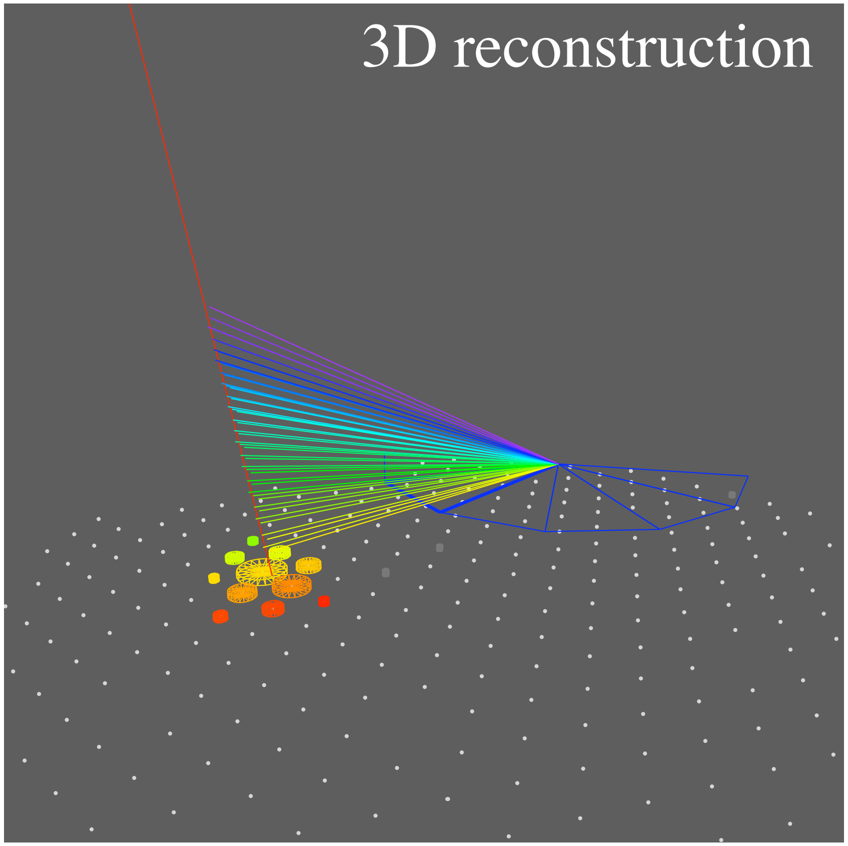
Geometrical Reconstruction

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

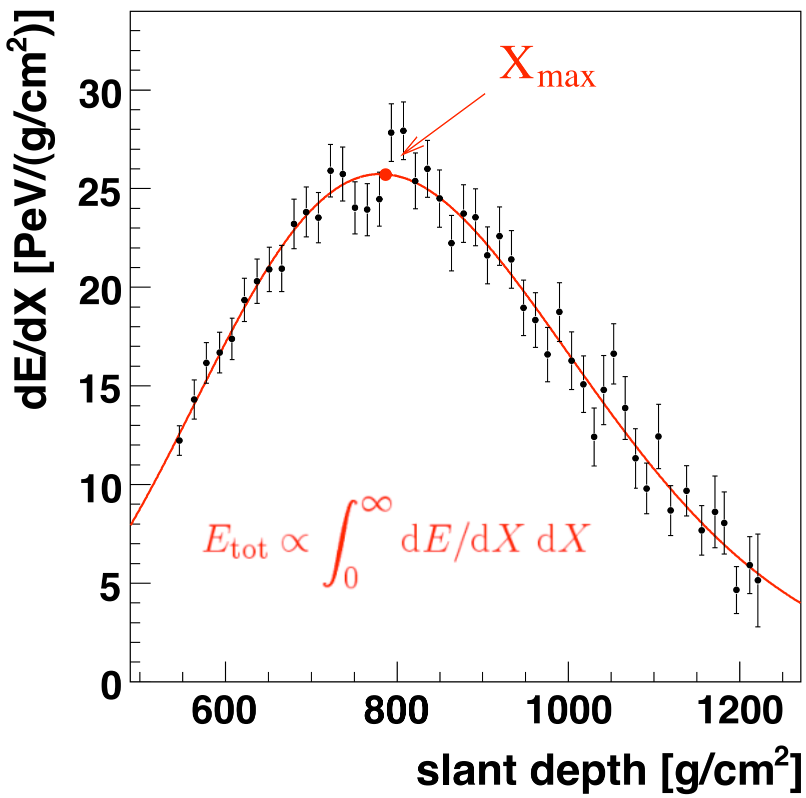


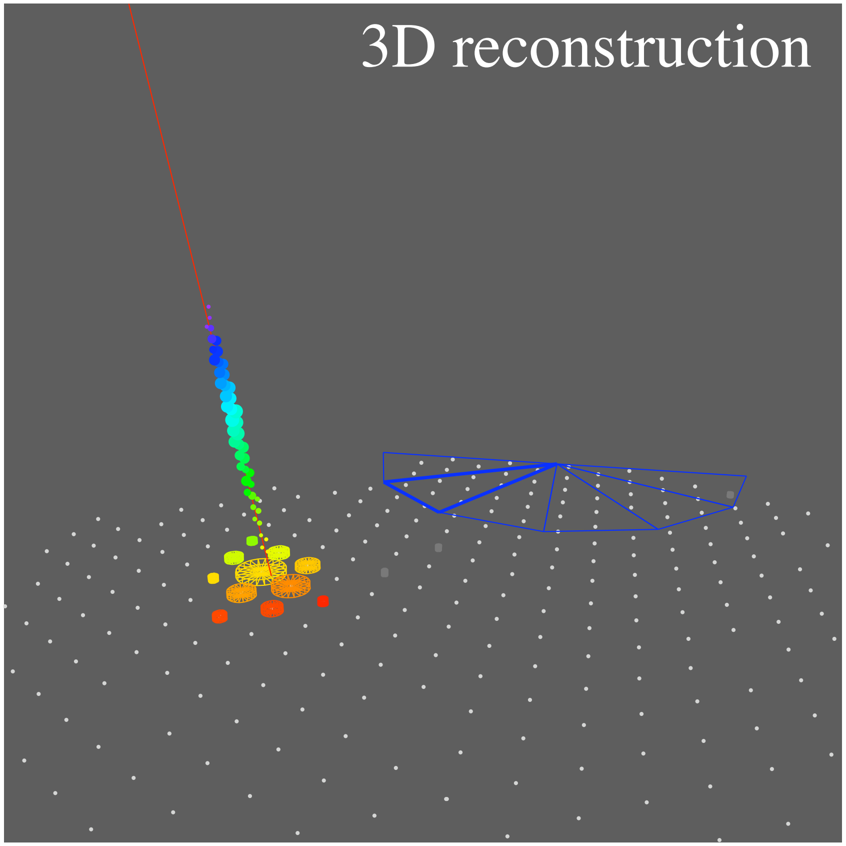
Shower Profile





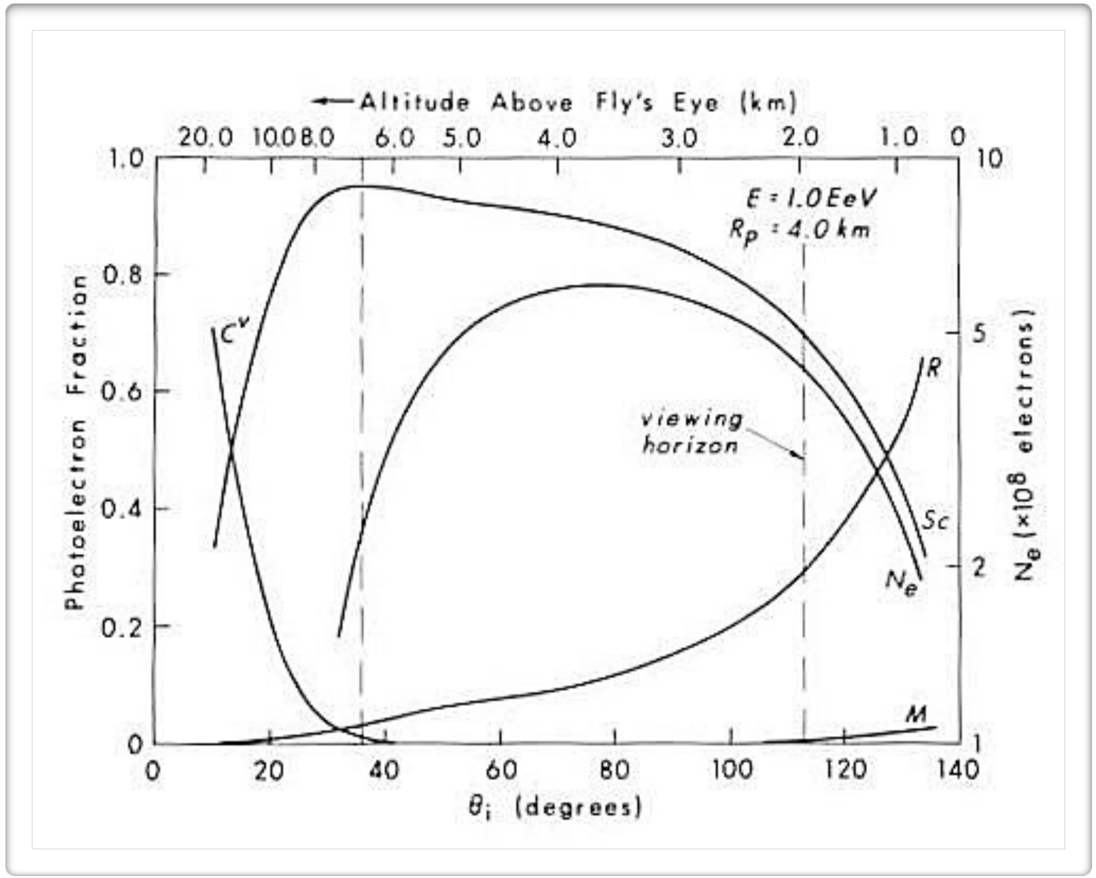
Shower Profile





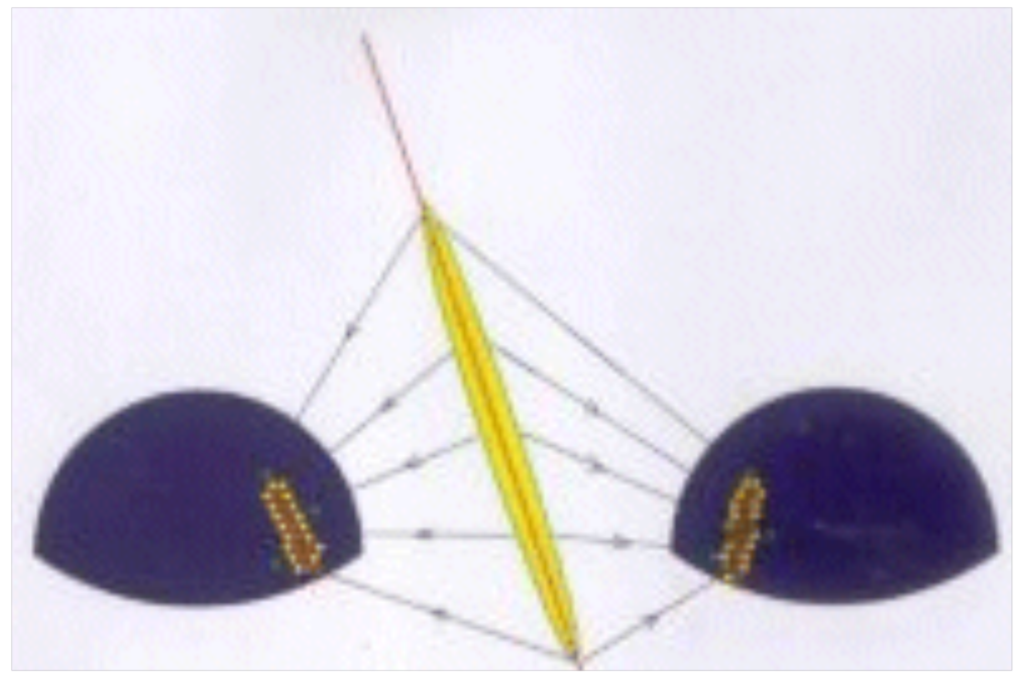
Shower Profile

- 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.



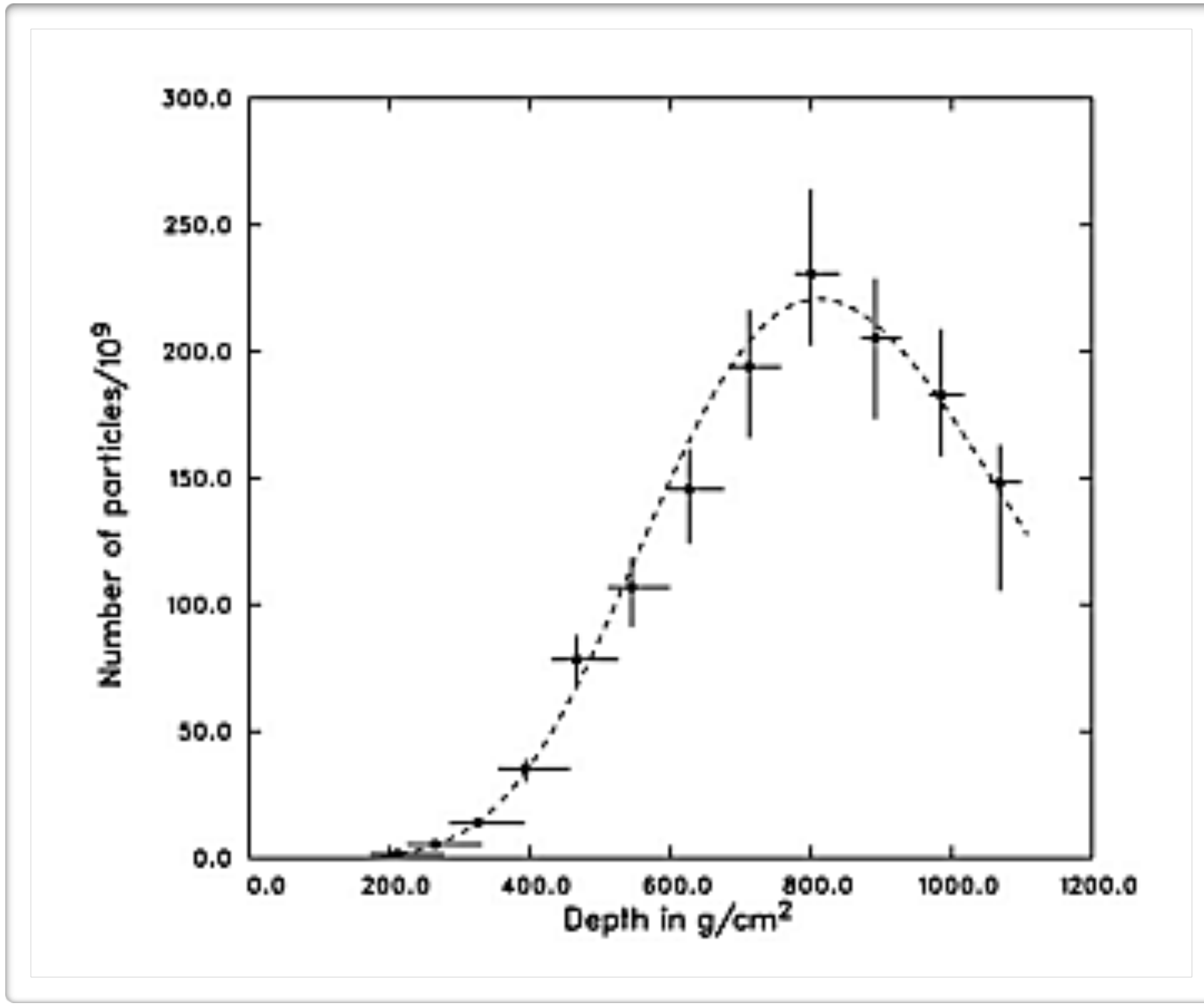
Mono vs. Stereo

- Mono uncertainties.
- Stereo Solution.



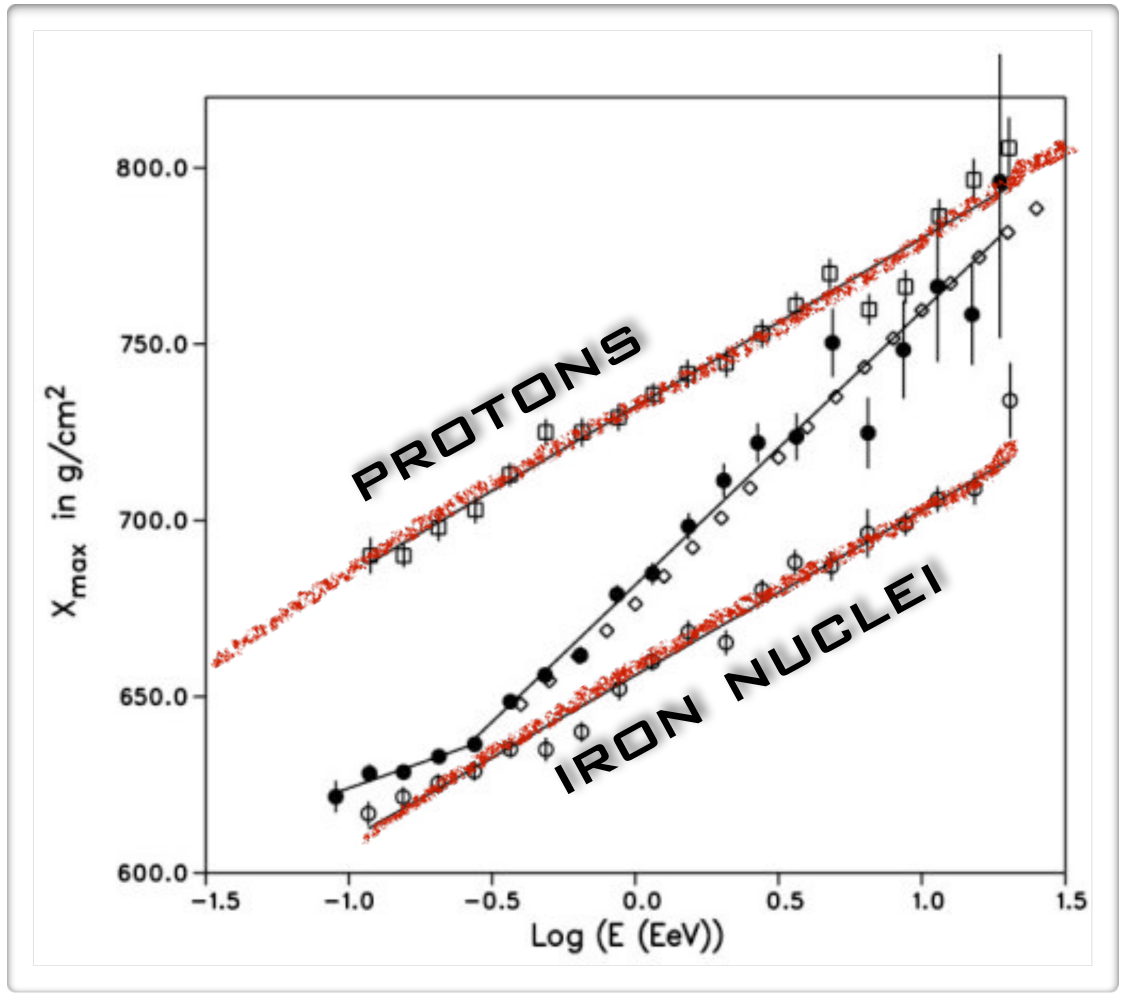
Results from the Fly's Eye

- 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

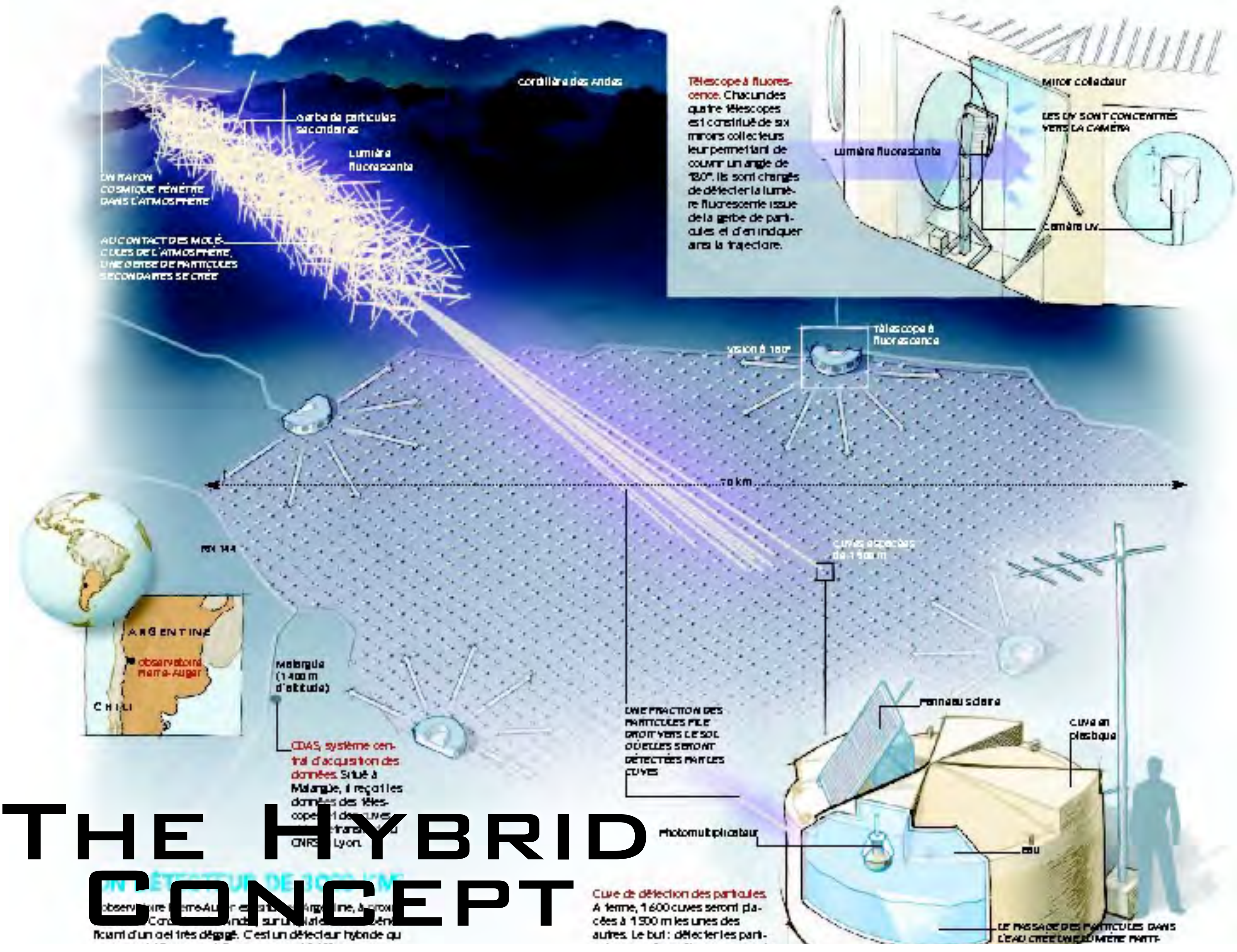
You are here

Auger

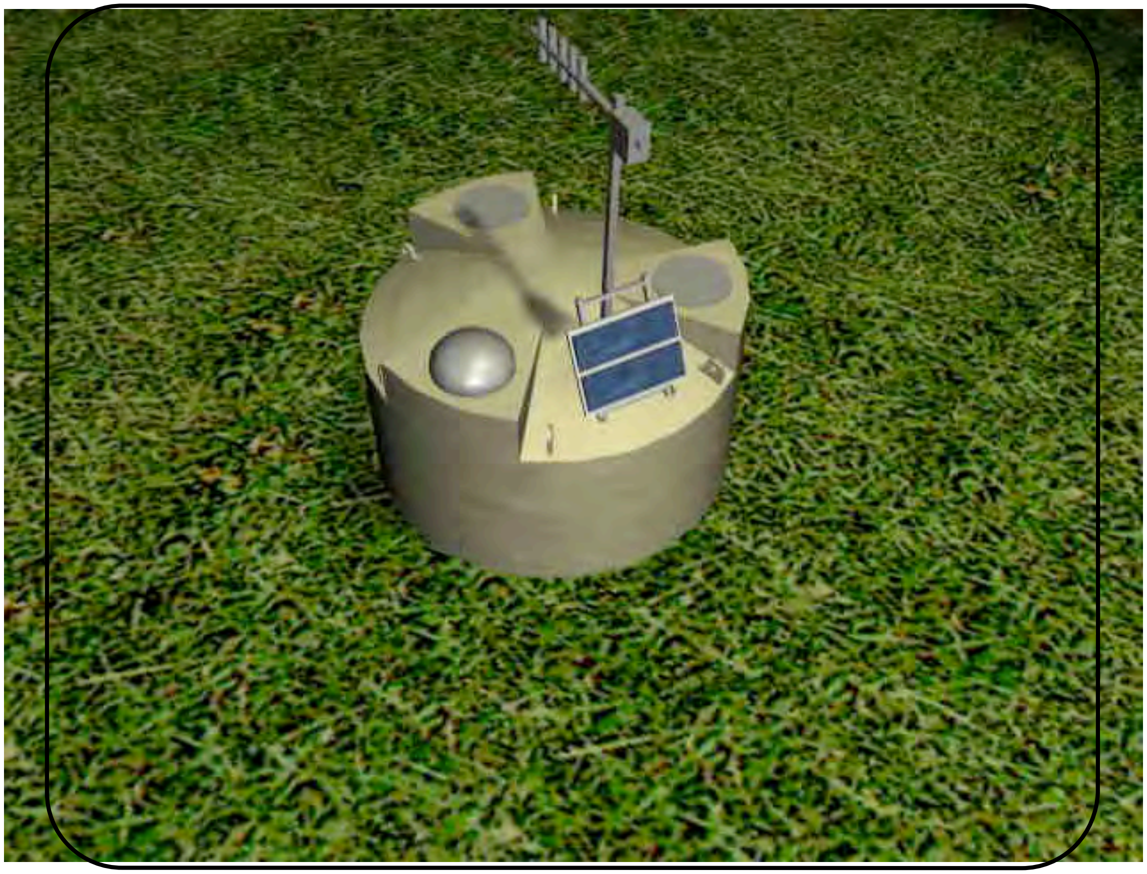
North

The Collaboration

The Hybrid Concept

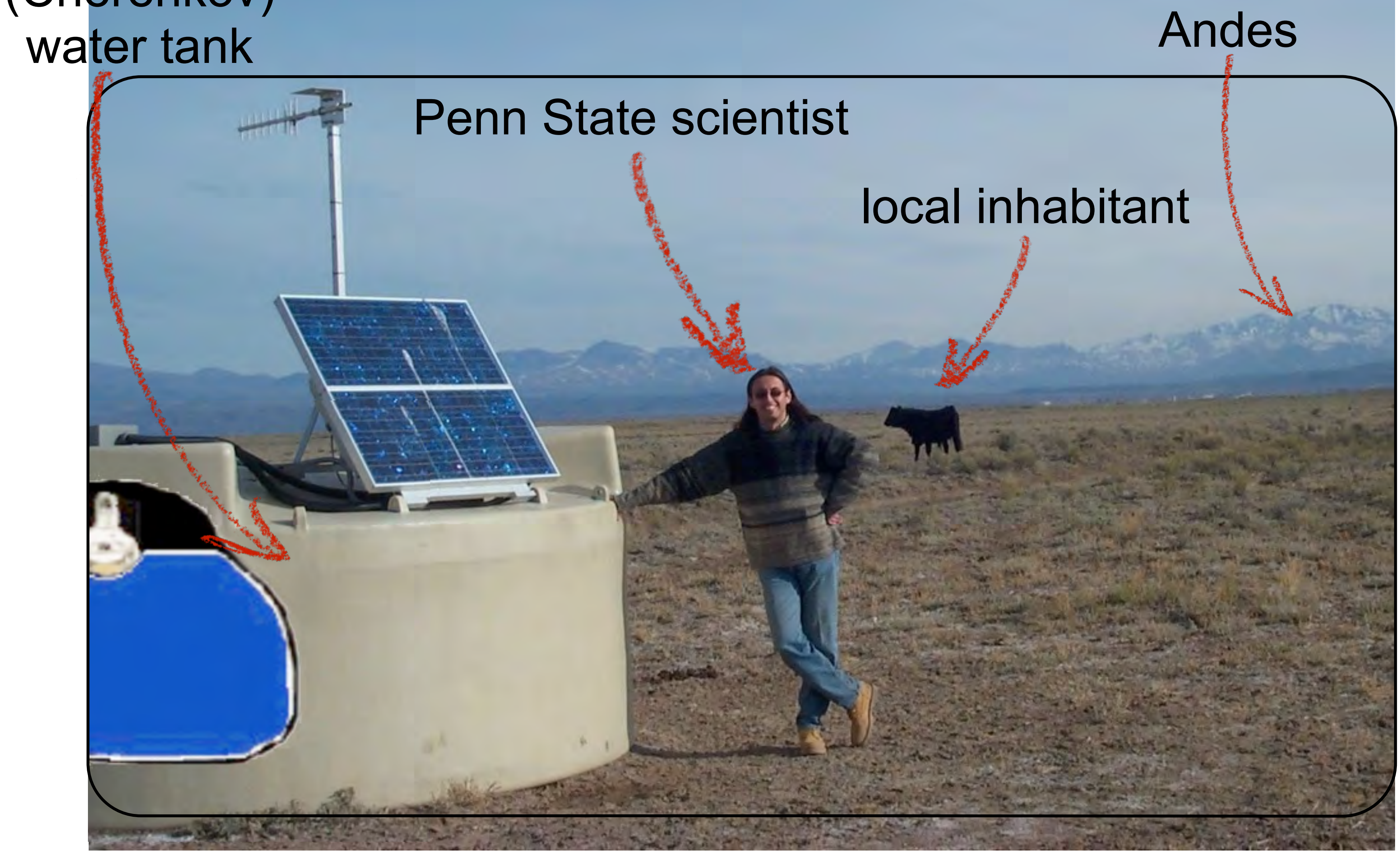


Ground Array

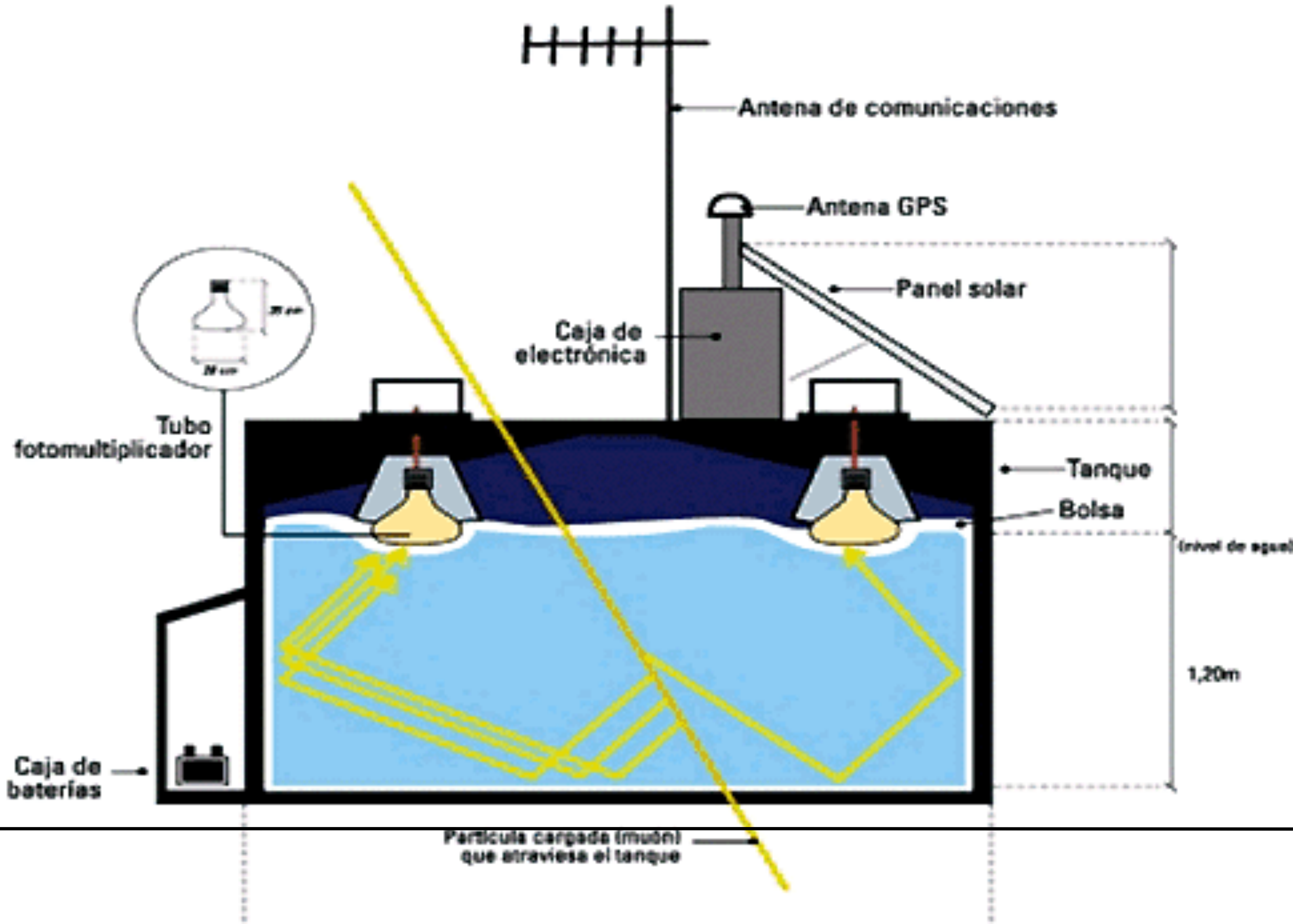


- 1600 stations
- 3000 km^2
- triangular grid
- 1.5 km spacing

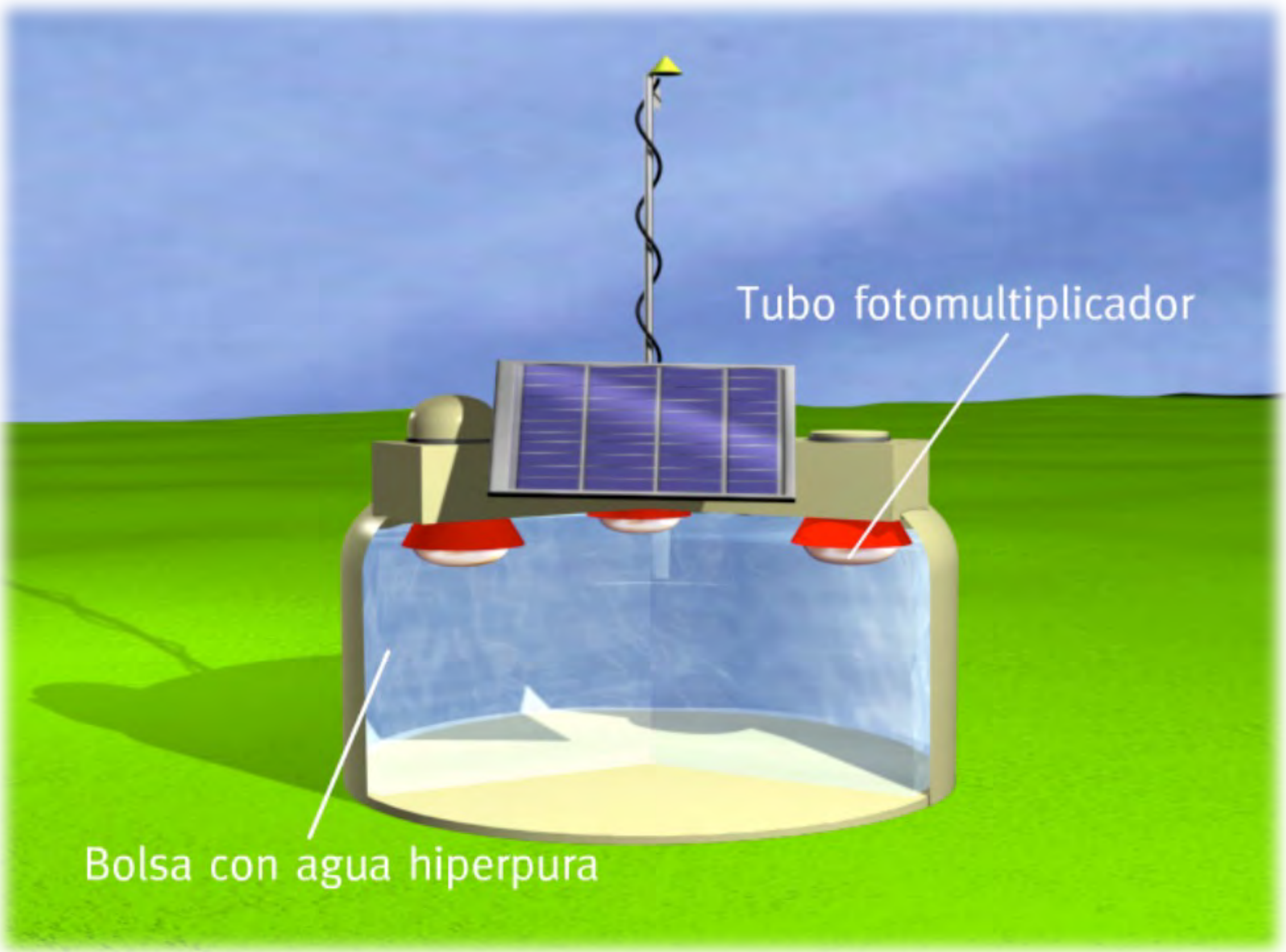
Ground array



THE WATER CHERENKOV TANK

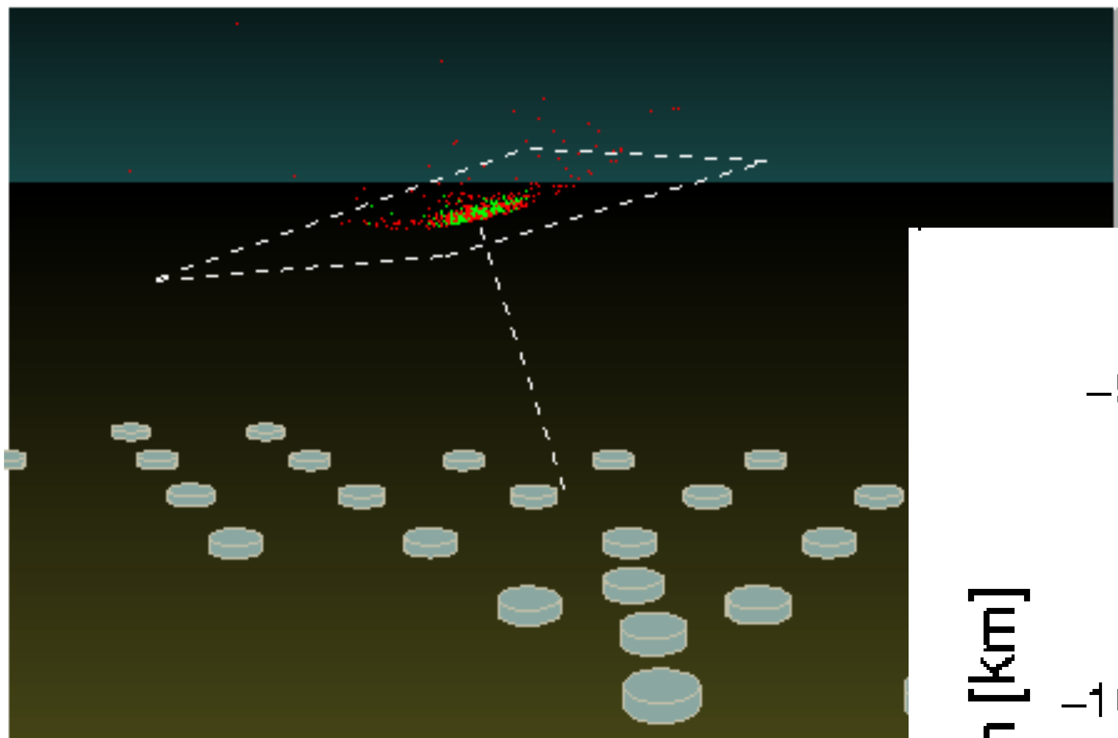


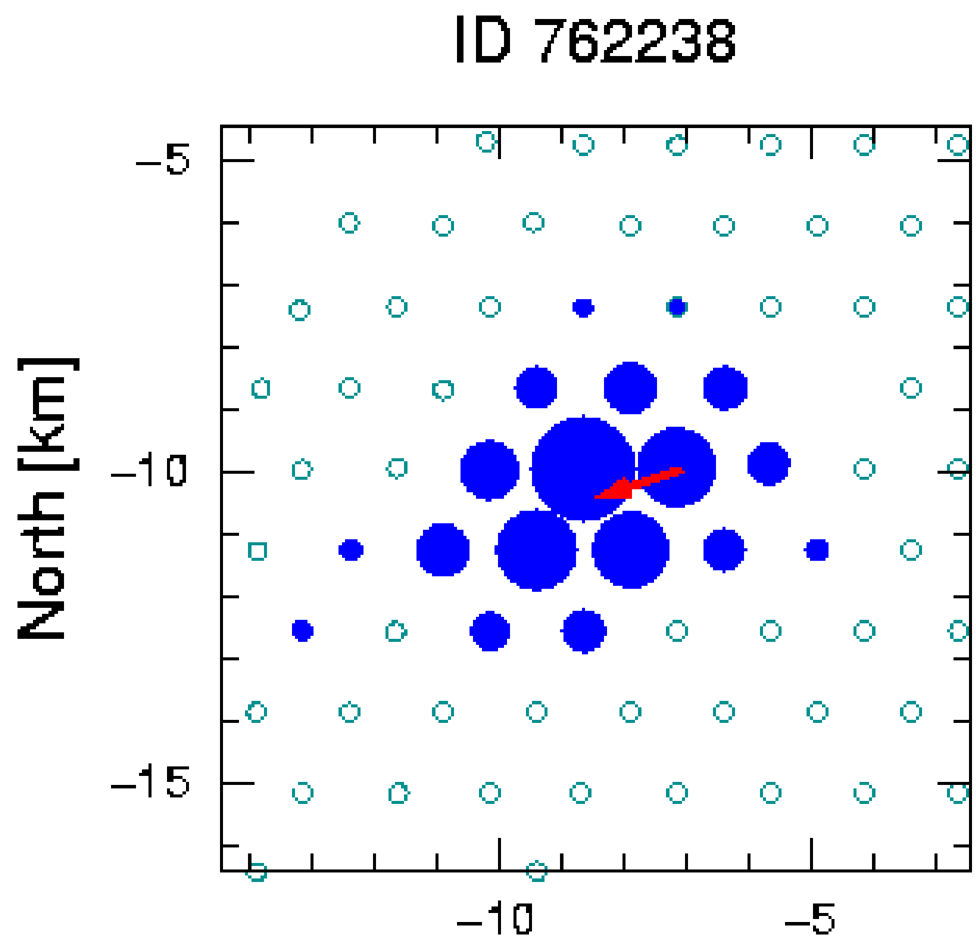
THE WATER CHERENKOV TANK

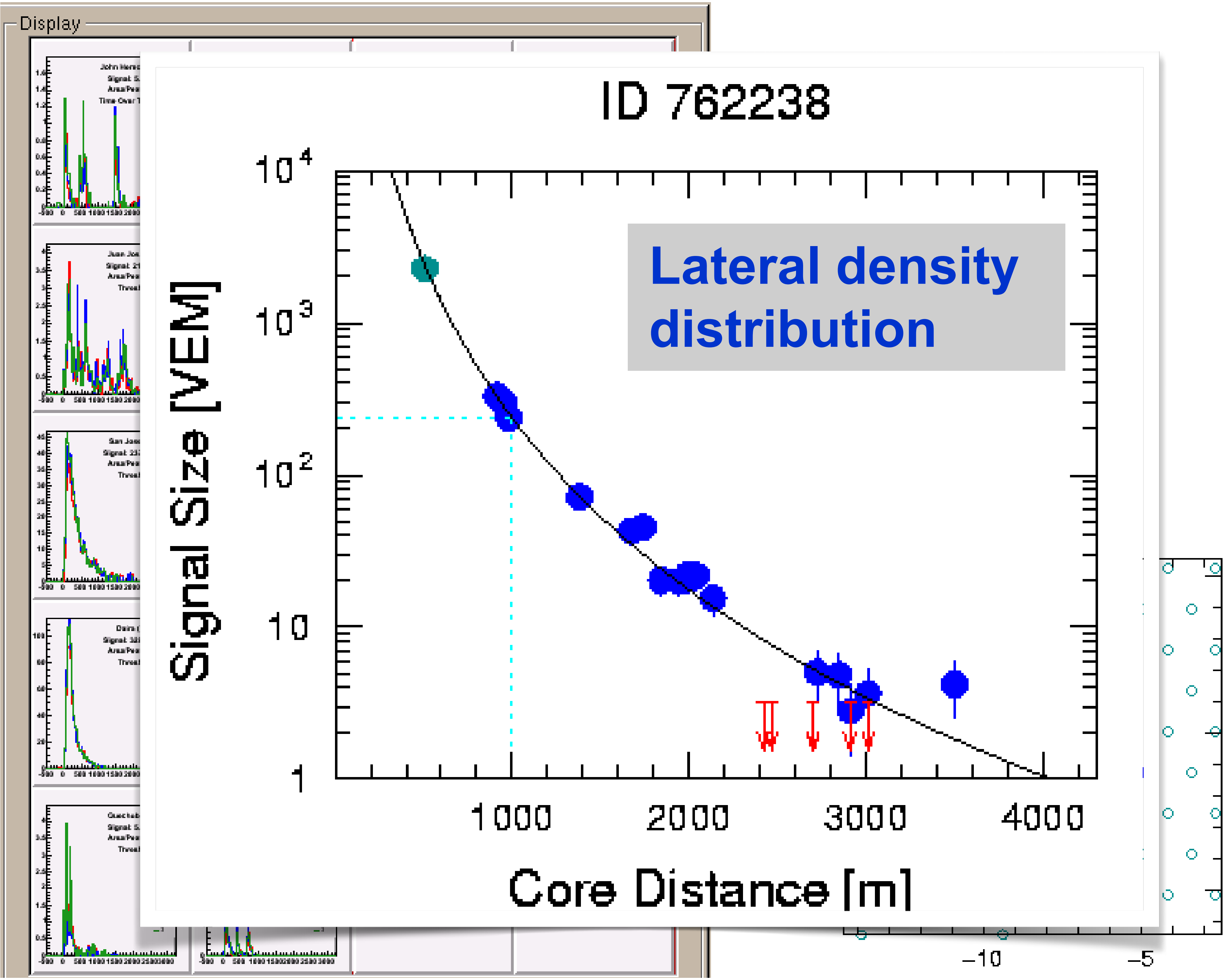


Deploying the largest array ever built

TYPICAL UHECR EVENT

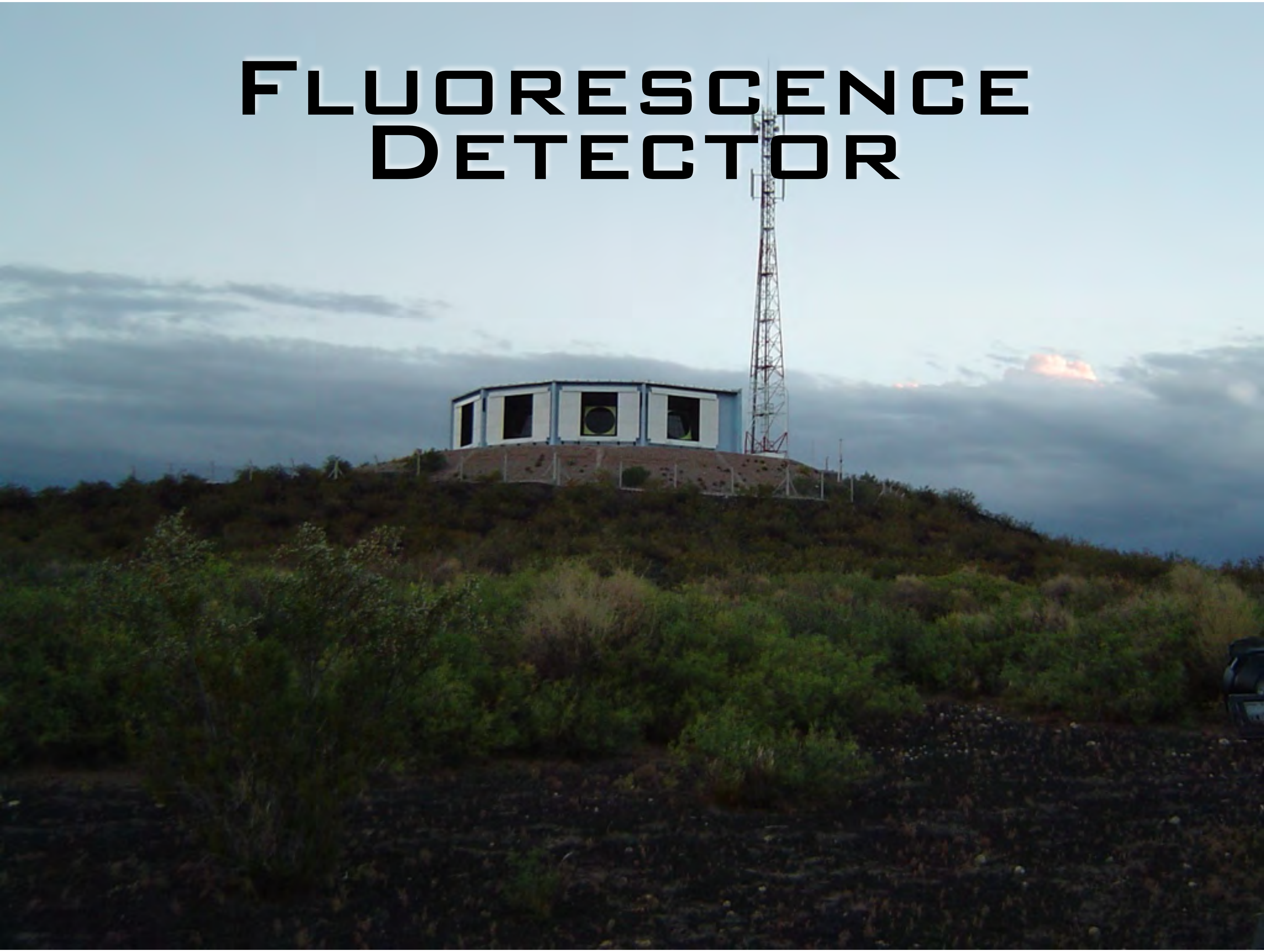




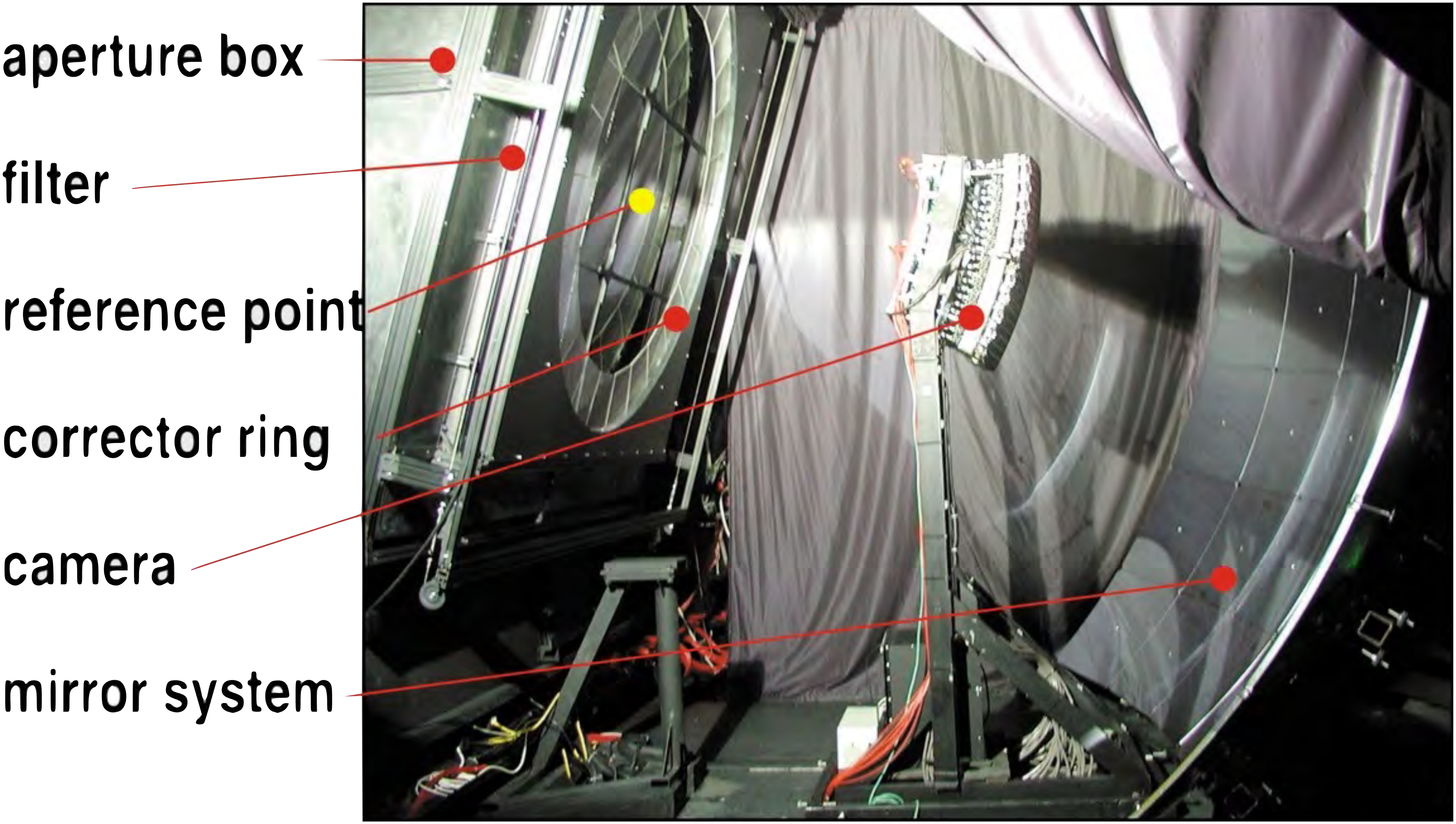

Display
ID 762238
Lateral density distribution
Signal Size [VEM]
Core Distance [m]
1
10
10^2
10^3
10^4
1000
2000
3000
4000
−10
−5

The Hybrid Design

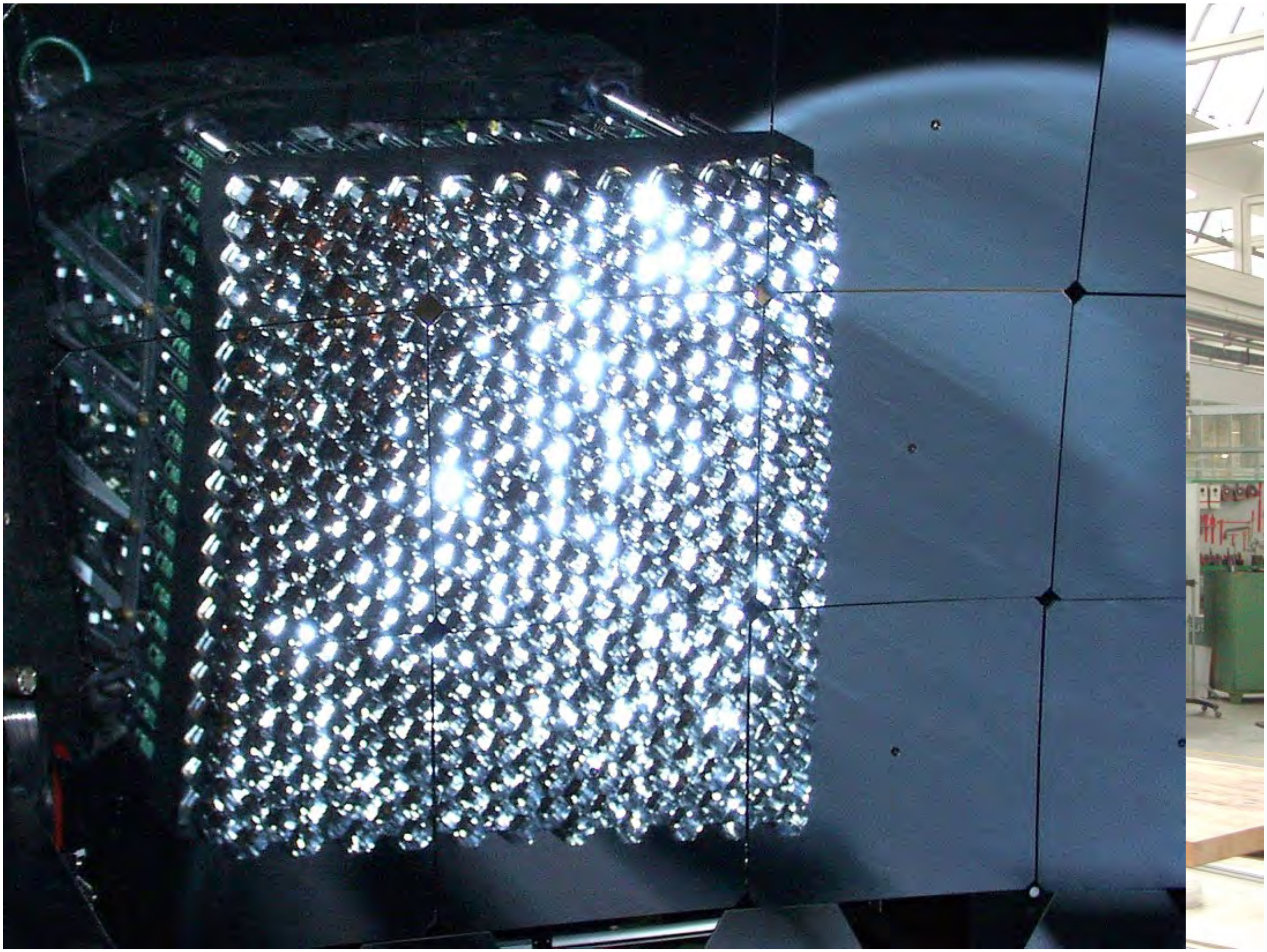
Fluorescence Detector



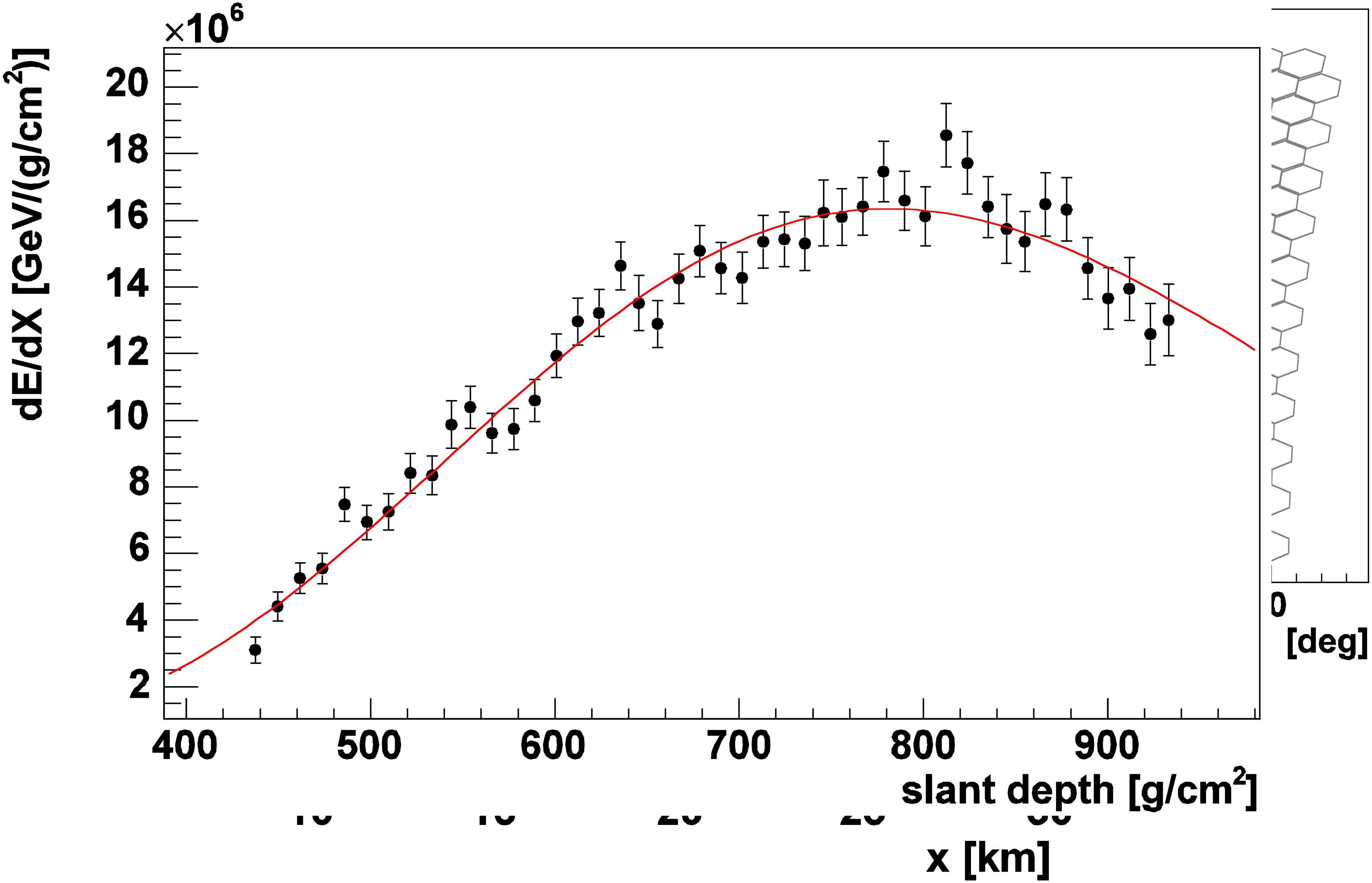
Inside the Building



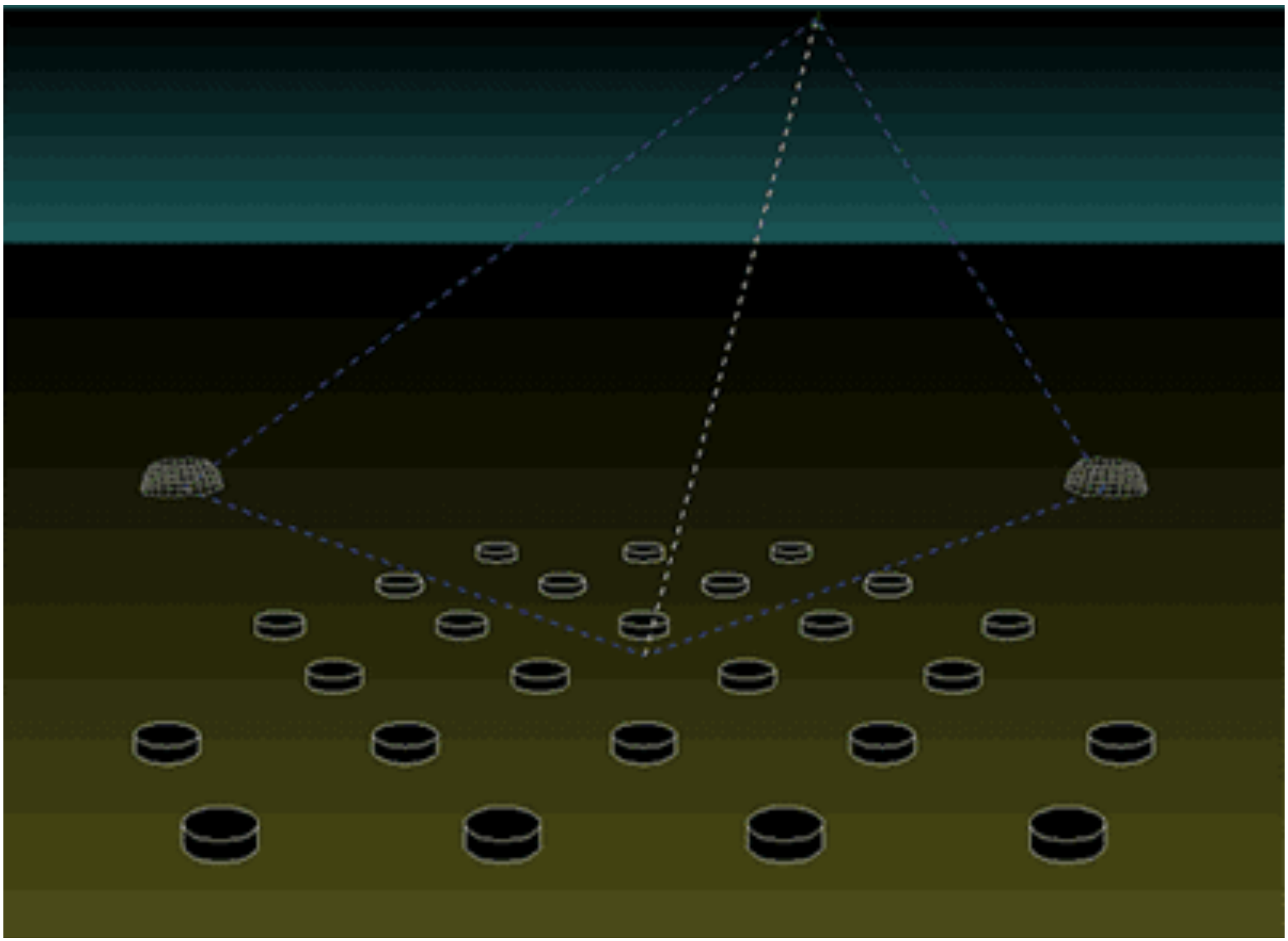
The Fluorescence Detector



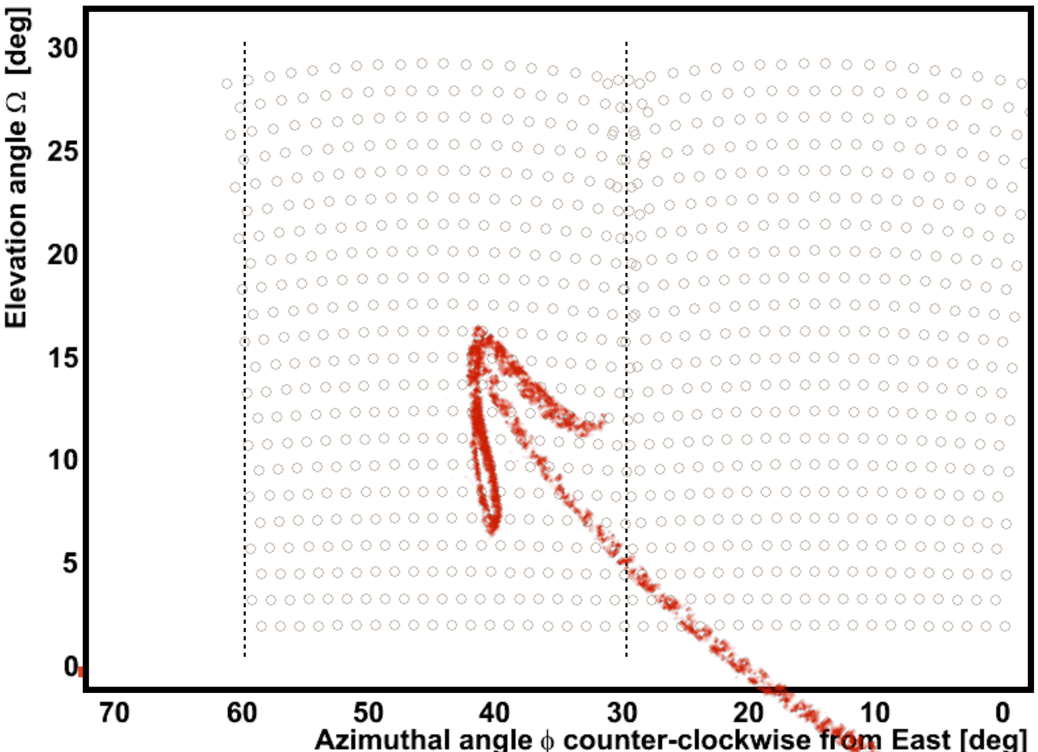
TYPICAL UHECR (FD VIEW)

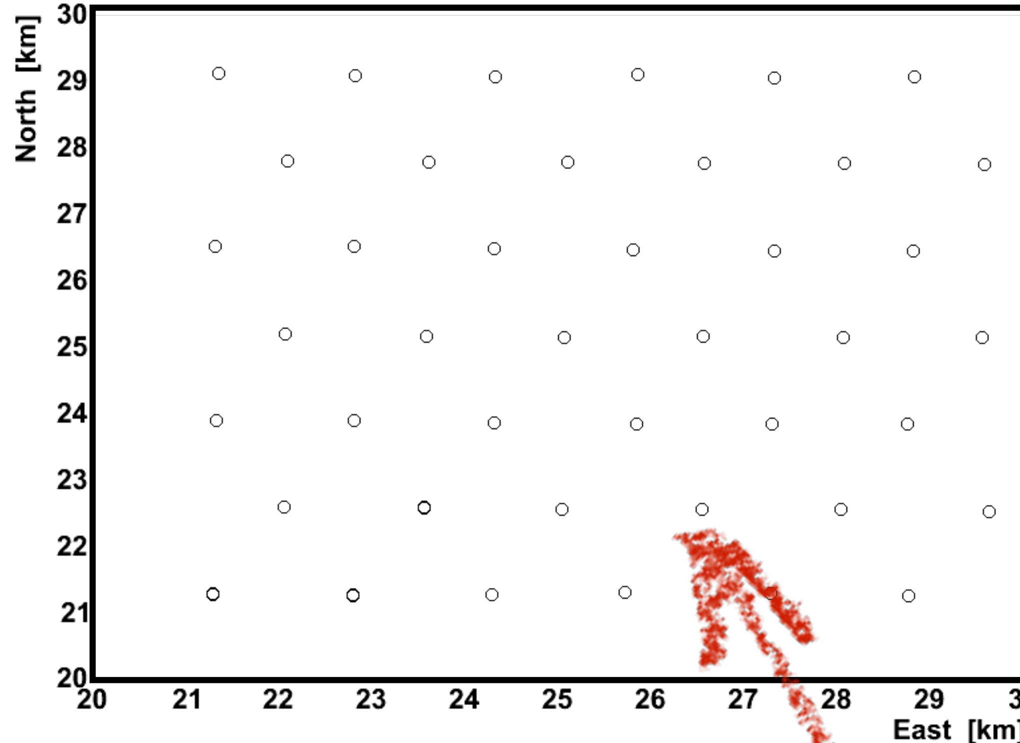


Hybrid Detection



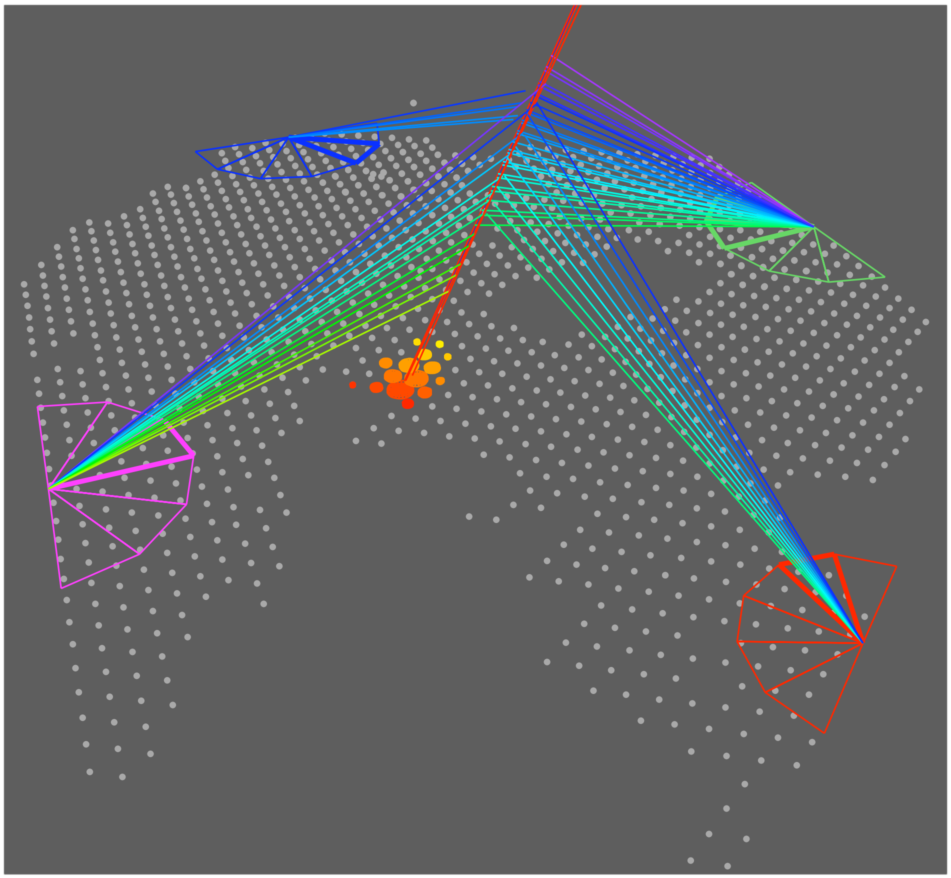
Hybrid Detection

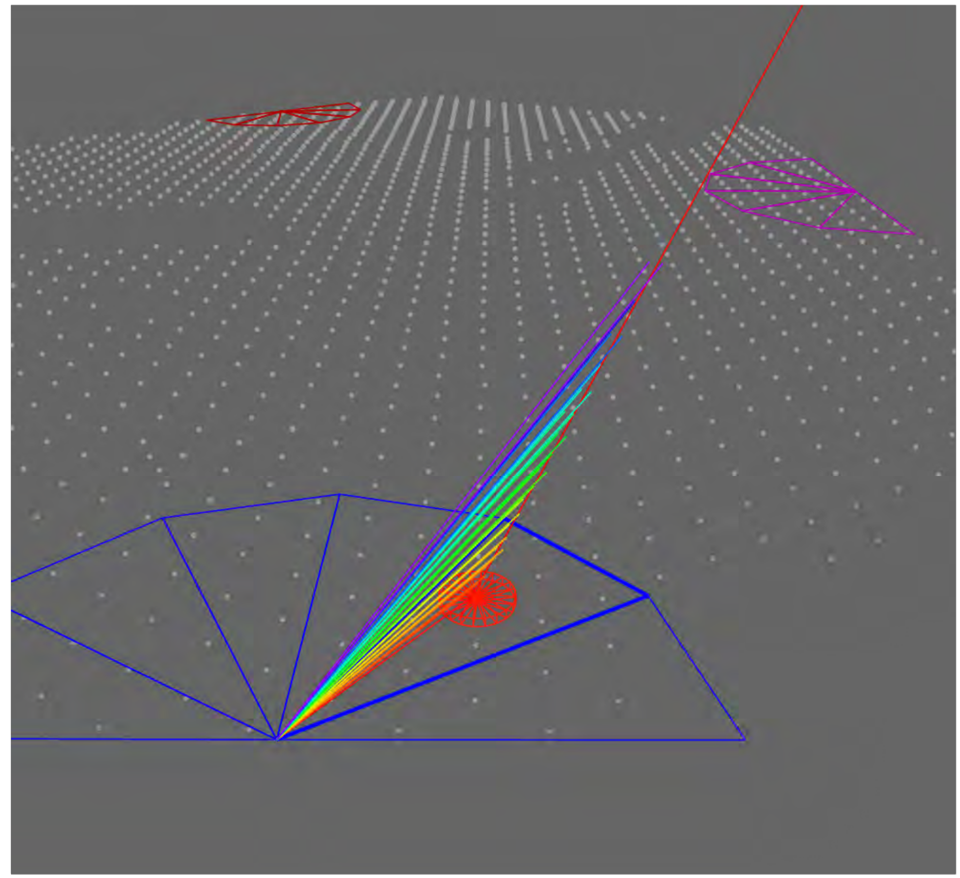




Hybrid reconstruction: use all pixels and tanks

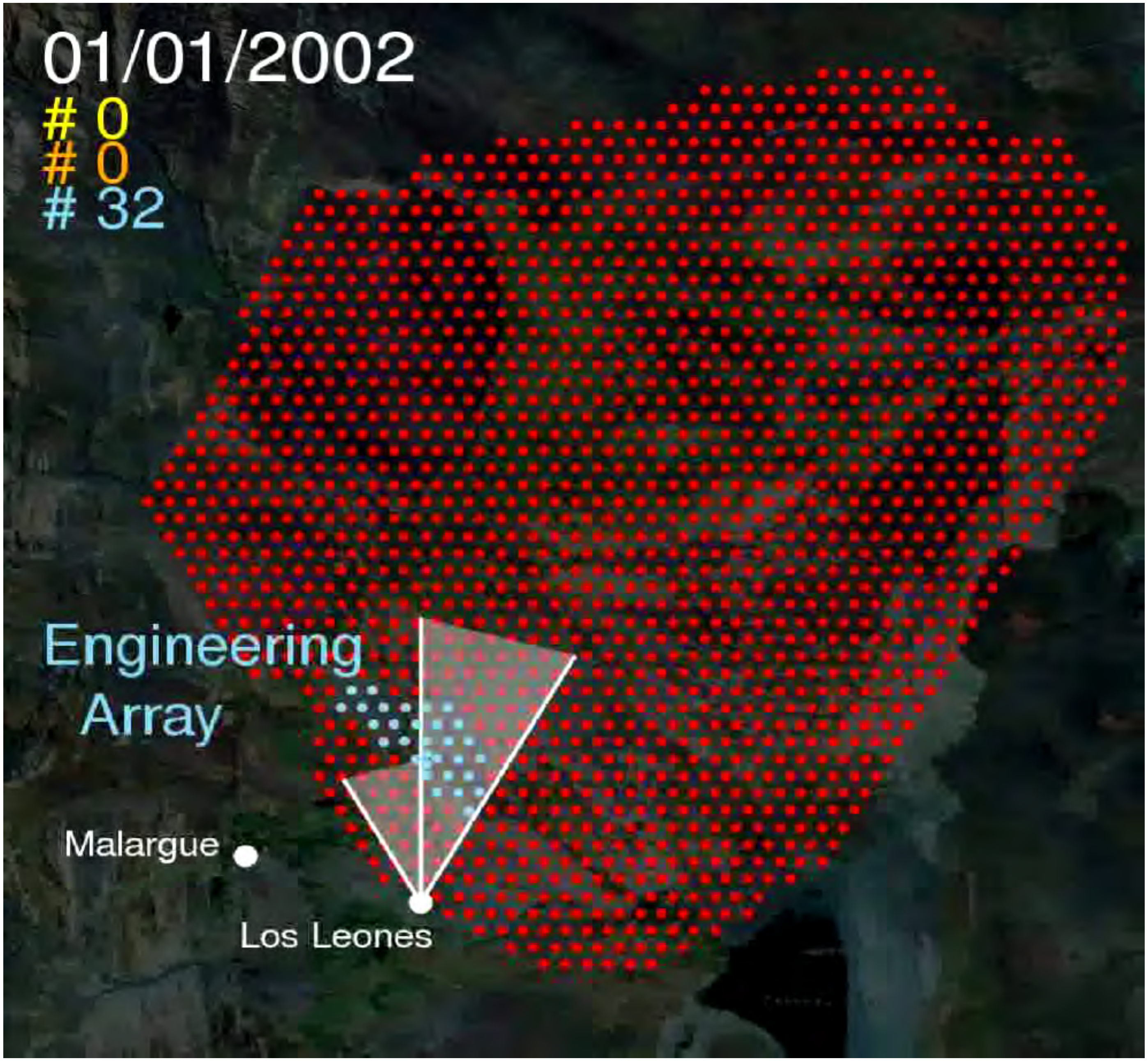
Hybrid Events



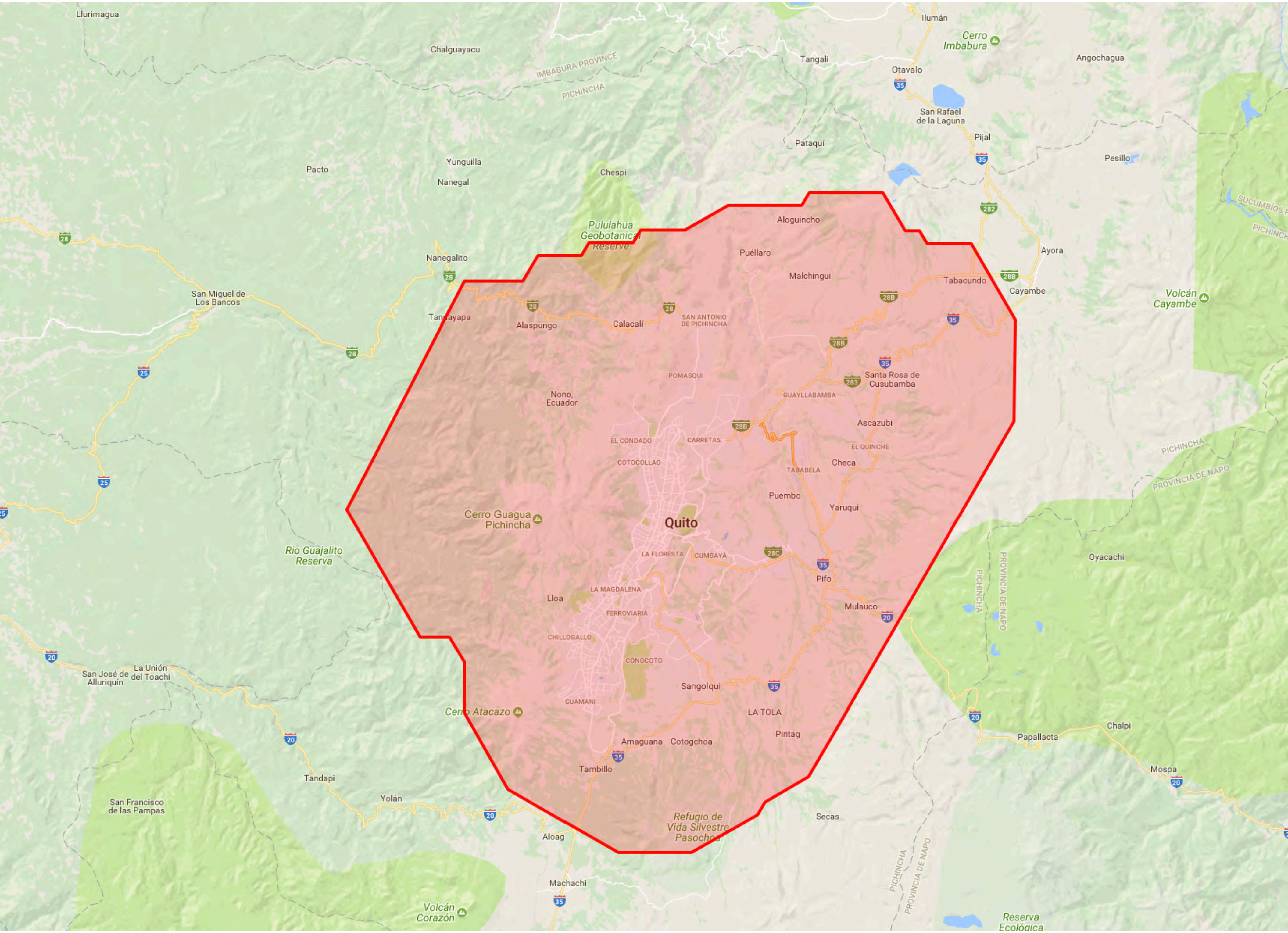


Golden and sub-Threshold hybrid events

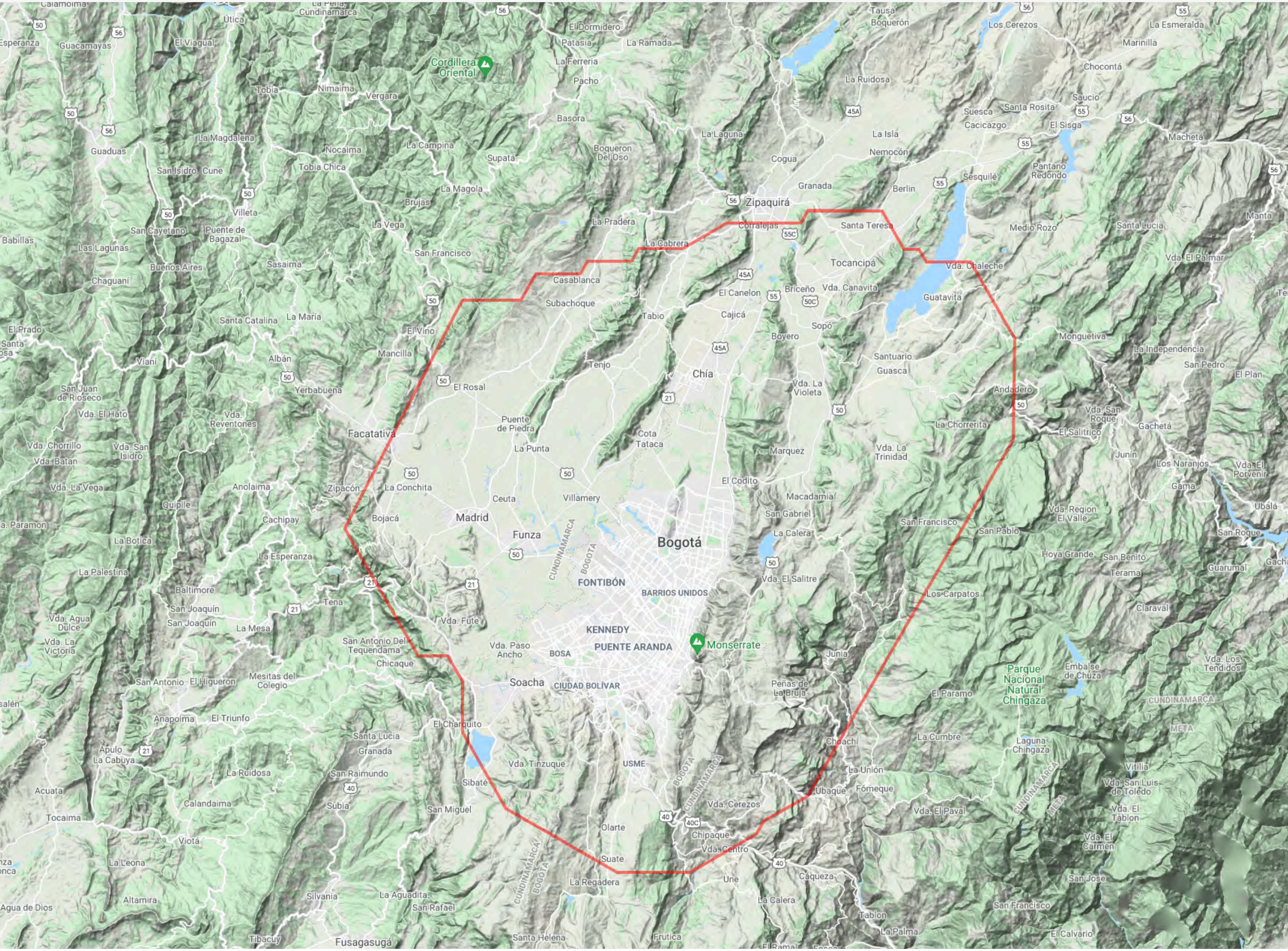
Deployment



WHEN SIZE MATTERS

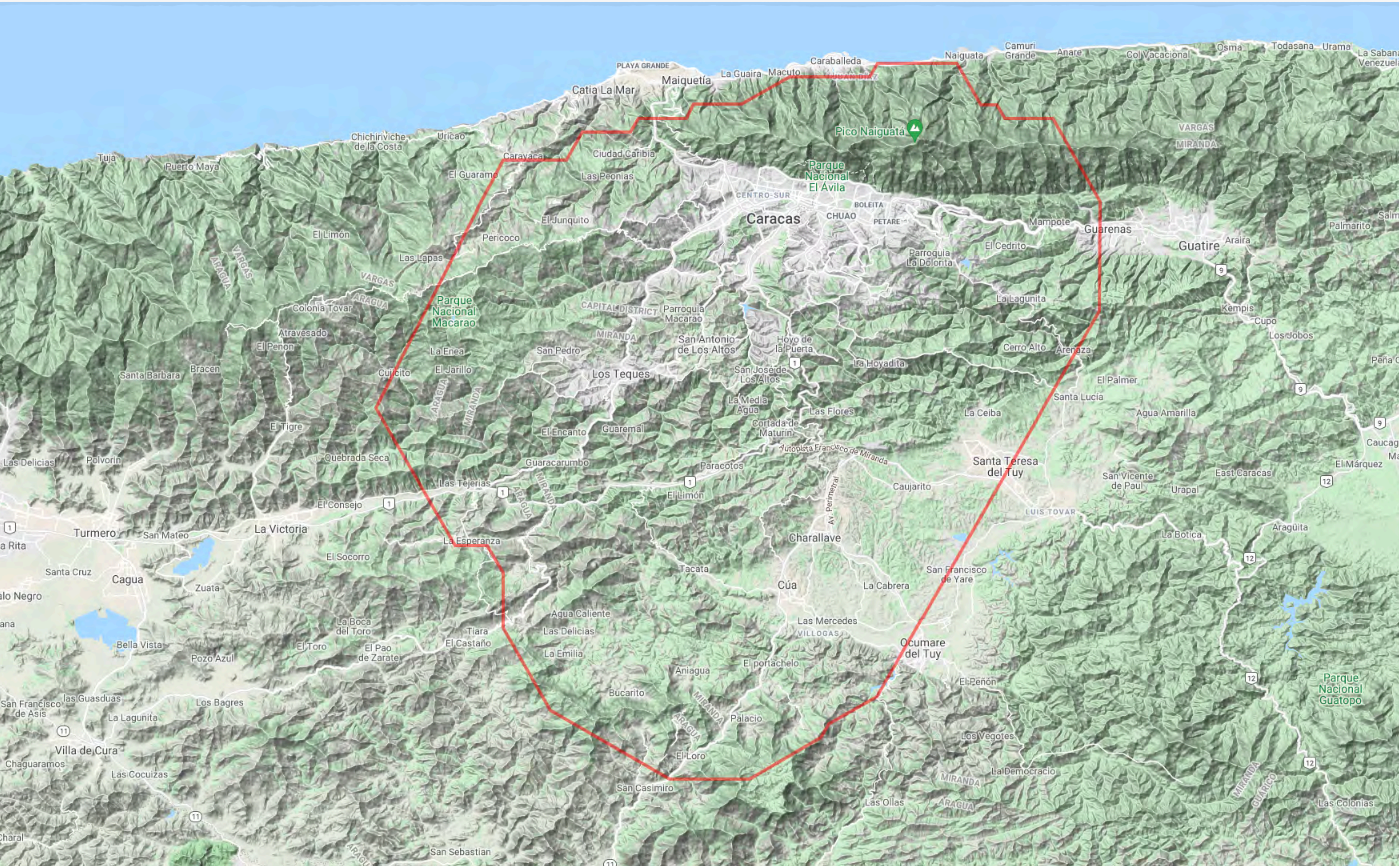


Llurimagua
Chalguayacu
IMBABURA PROVINCE
PICHINCHA
Tangali
Ilumán
Cerro Imbabura
Otavalo
Angochagua
San Rafael de la Laguna
Pijal
Pataquí
Pesillo
Pacto
Yunguilla
Nanegal
Chespi
Pululahua Geobotanical Reserve
Aloguincho
Puéllaro
Malchingui
Ayora
Tabacundo
Cayambe
Volcán Cayambe
Nanegalito
San Miguel de Los Bancos
Tandayapa
Alaspungo
Calacalí
SAN ANTONIO DE PICHINCHA
POMASQUI
Santa Rosa de Cusubamba
GUAYLLABAMBA
Nono, Ecuador
Ascazubi
EL CONDADO
CARRETAS
EL QUINCHE
COTOCOLLAO
Checa
TABABELA
PICHINCHA
PROVINCIA DE NAPO
Puembo
Yaruqui
Cerro Guagua Pichincha
Quito
Rio Guajalito Reserva
LA FLORESTA
CUMBAYÁ
Oyacachi
Pifo
LA MAGDALENA
Lloa
Mulauco
FERROVIARIA
CHILLOGALLO
CONOCOTO
La Unión del Toachi
San José de Alluriquín
Sangolquí
GUAMANI
LA TOLA
Cerro Atacazo
Papallacta
Chalpi
Pintag
Amaguana
Cotogchoa
Tambillo
Tandapi
Mospa
San Francisco de las Pampas
Yolán
Refugio de Vida Silvestre Pasochoa
Secas
Aloag
Machachi
Volcán Corazón
Reserva Ecológica
SUCUMBÍOS

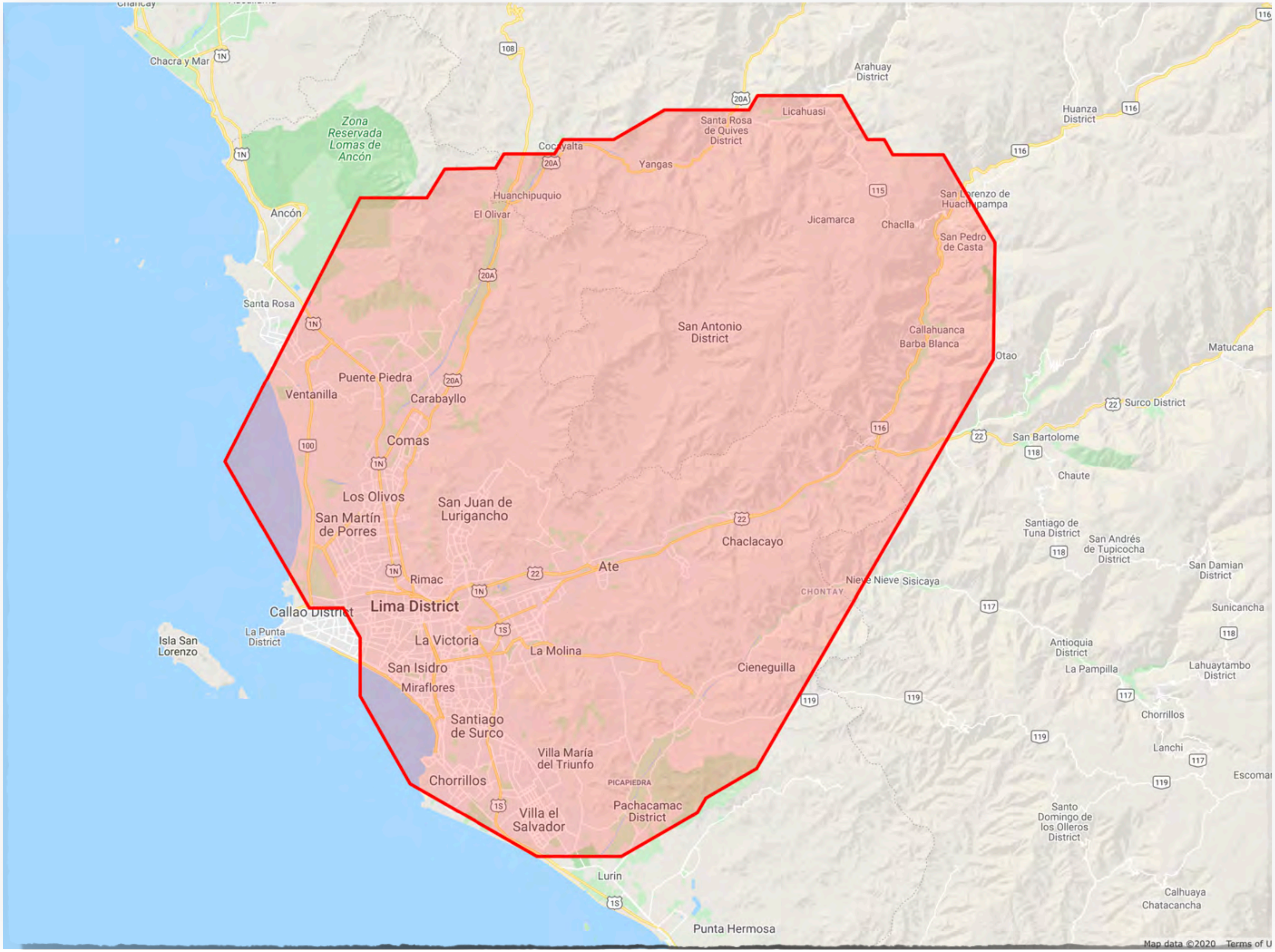


Calamoima
La Peña
Cundinamarca
Utica
El Dormidero
Tausa
Boquerón
Los Cerezos
La Esmeralda
Esperanza
Guacamayas
El Viagual
Cordillera Oriental
Patasia
La Ramada
Marinilla
La Ferreria
La Ruidosa
Chocontá
Pacho
Tobia
Nimaima
Vergara
Saucio
Basora
Suesca
Santa Rosita
Cacicazgo
El Sigua
La Magdalena
La Laguna
La Isla
Machetá
Guaduas
Nocaima
La Campina
Boqueron Del Oso
Cogua
Nemocón
Pantano Redondo
San Isidro
Cune
Supatá
Tobia Chica
Sesquilé
La Magola
Granada
Berlin
Zipaquirá
Villeta
Brujas
Babillas
San Cayetano
Puente de Bagazal
La Vega
La Pradera
Corralejas
Santa Teresa
Medio Rozo
Santa Lucia
Manta
Las Lagunas
La Cabrera
San Francisco
Sasaima
Buenos Aires
Tocancipá
Vda. Chaleche
Vda. El Palmar
Chaguaní
Casablanca
El Canelon
Briceño
Vda. Canavita
Subachoque
Guatavita
Tabio
Cajicá
Santa Catalina
La Maria
El Prado
El Vino
Sopó
Boyero
Santa Rosa
Monguetiva
Mancilla
La Independencia
Albán
Viani
Tenjo
Santuario
Guasca
Chía
San Pedro
El Plan
San Juan de Rioseco
Yerbabuena
El Rosal
Vda. La Violeta
Andadero
Vda. El Hato
Vda. Reventones
Puente de Piedra
Vda. San Roque
Gachetá
La Chorrerita
El Salitrico
Facatativá
Cota
Tataca
Vda. Chorrillo
Vda. San Isidro
La Punta
Marquez
Vda. La Trinidad
Junín
Vda. Batan
Los Naranjos
Vda. El Porvenir
Anolaima
El Codito
Zipacón
La Conchita
Gama
Vda. La Vega
Villamery
Macadamia
Quipile
Ceuta
Vda. Region El Valle
Ubalá
Cachipay
Madrid
San Gabriel
San Francisco
Bojacá
Paramon
Bogotá
San Pablo
San Roque
La Botica
Funza
La Calera
La Esperanza
Hoya Grande
San Benito
FONTIBÓN
Gachalá
La Palestina
Terama
Vda. El Salitre
Guarumal
Baltimore
BARRIOS UNIDOS
Los Carpatos
San Joaquín
Tena
Claraval
Vda. Agua Dulce
Vda. Fute
San Joaquín
La Mesa
KENNEDY
Vda. La Victoria
San Antonio Del Tequendama
Monserrate
Vda. Paso Ancho
PUENTE ARANDA
Junia
Parque Nacional Natural Chingaza
Vda. Los Tendidos
BOSA
Chicaque
Embalse de Chuza
San Antonio
El Higueron
Mesitas del Colegio
Soacha
CIUDAD BOLÍVAR
Peñas de La Bruja
El Paramo
CUNDINAMARCA
Anapoima
El Triunfo
El Charquito
META
Santa Lucia
Choachí
La Cumbre
Laguna Chingaza
Apulo
Granada
La Cabuya
Vda. Tinzuque
USME
La Unión
Vitilla
La Ruidosa
San Raimundo
Vda. San Luis de Toledo
Acuatá
Sibaté
Ubaque
Fómeque
Calandaima
Subia
Vda. Cerezos
Vda. El Paval
Vda. El Tablon
Tocaima
San Miguel
Olarte
Chipaque
Viotá
Vda. Centro
Vda. El Carmen
La Leona
Suate
Cáqueza
San Jose
Une
Altamira
La Regadera
Silvania
La Aguadita
La Calera
San Francisco
Agua de Dios
San Rafael
Tablon
La Palma
El Calvario
Tibacuy
Fusagasugá
Santa Helena
Fruticá
El Ramal

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!