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SEARCH FOR EXOTIC FEATURES IN COSMIC RAY SHOWERS

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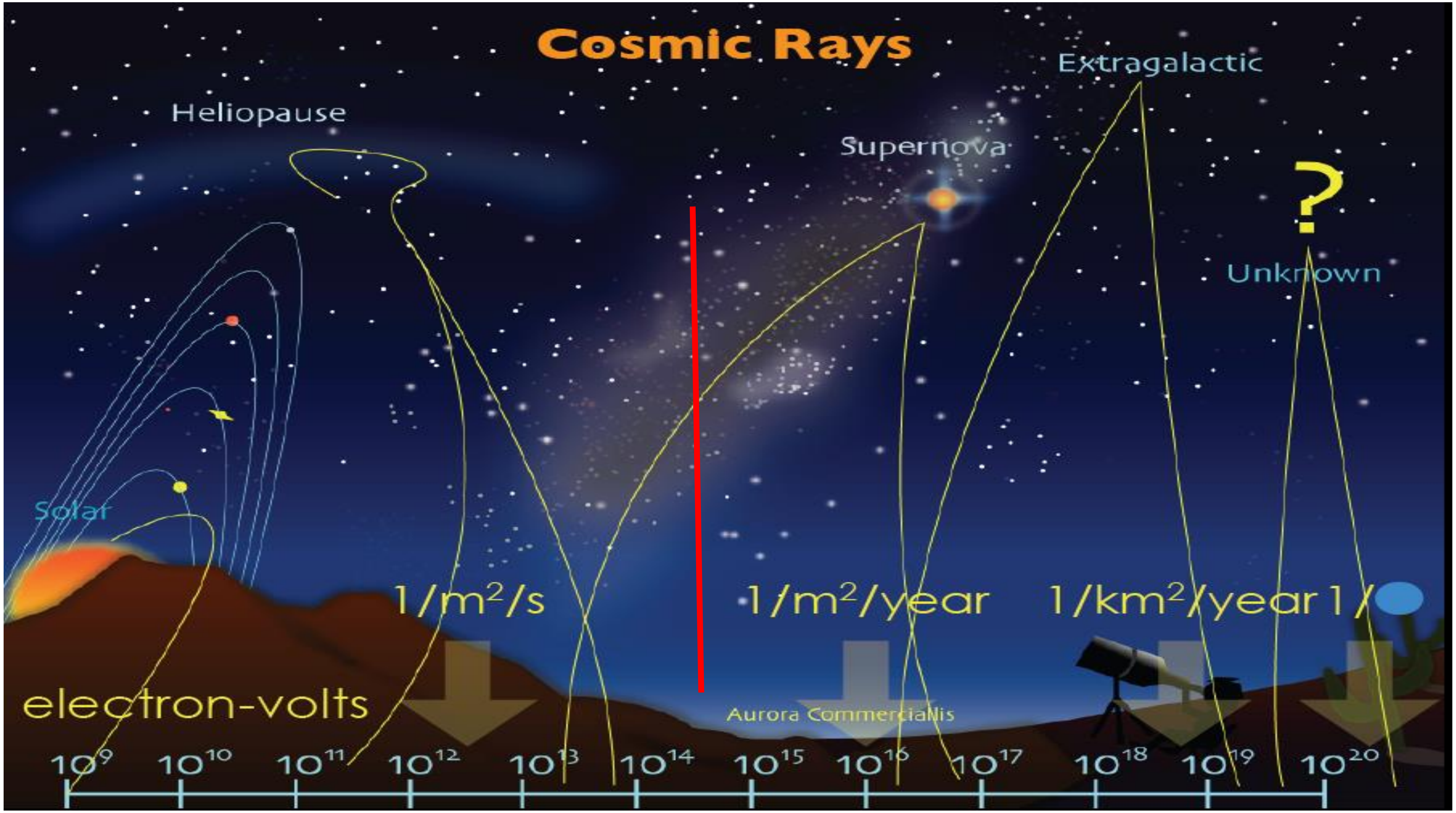
Use of Sparse Cosmic Ray Arrays

Two cosmic ray arrays have been running in tandem, one located at Messiah College, USA, and one at University of Tirana.

- Goals:
  - **Educational**:
  - To increase participation of students at University of Tirana in experimental particle physics,
  - Johan finished his master's thesis on "Cosmic Ray flux Studies at University of Tirana site"
  - **Research:**
  - Sparse cosmic ray arrays fill a niche between the luminosity experiments on one hand and single location cosmic ray experiments on the other
  - The use of precision GPS times allows for correlation of different astrophysical events, looking for rare global events
  - Probe the evolution and diffusion of cosmic rays in Interstellar Medium and our galaxy

Cosmic Ray Sources

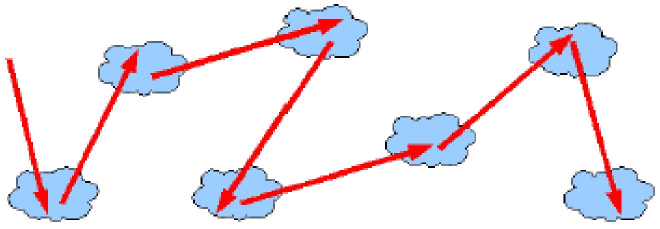


Courtesy: H Takai

Acceleration of Cosmic Rays

Diffusive Shock Acceleration, in regions of high intensity magnetic field

$$\varepsilon_d \simeq \frac{3}{2}\frac{m^4}{q^4}B^{-2}R^{-1} \ .$$



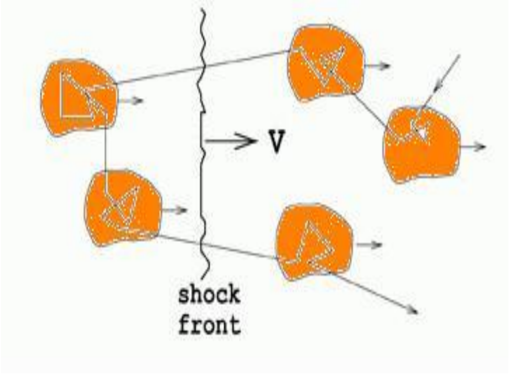
(b)

First Order Fermi Acceleration

The average energy gain per collision:

<ΔE/E> = V/c

Particles undergo the process on crossing a *shock* from upstream to downstream and back again (*Supernovae shocks*)

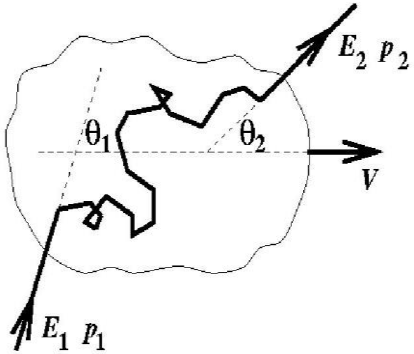


Second Order Fermi Acceleration

The average energy gain per collision:

<ΔE/E> = $(V/c)^2$

Particles are reflected by 'magnetic mirrors' associated with irregularities in the galactic magnetic field. →*Net energy gain*.

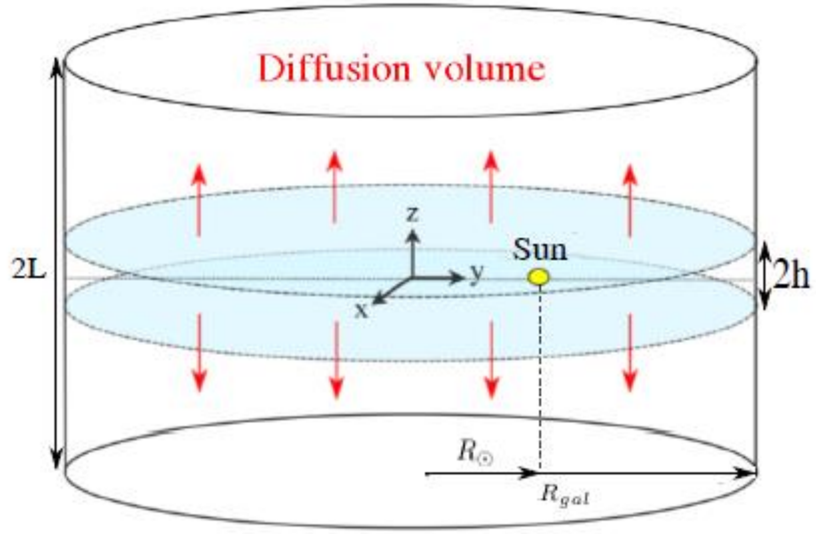


Propagation of cosmic rays in galaxy

The propagation of nuclei of type k is described by the transport equation:

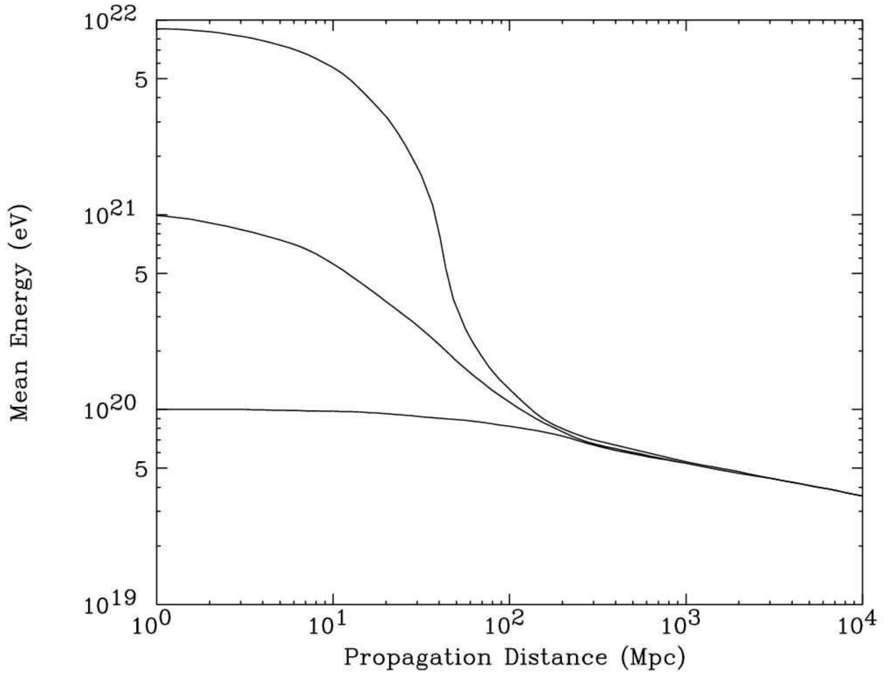
$$\frac{\partial n_k(E,\vec{r},t)}{\partial t} = \nabla\left[D_k(E)\nabla n_k(E,\vec{r},t)\right] - \Gamma_k^{sp}(E) n_k(E,\vec{r},t) + N_k(E)\delta(t-t_s)\delta^3(\vec{r}-\vec{r}_s)$$

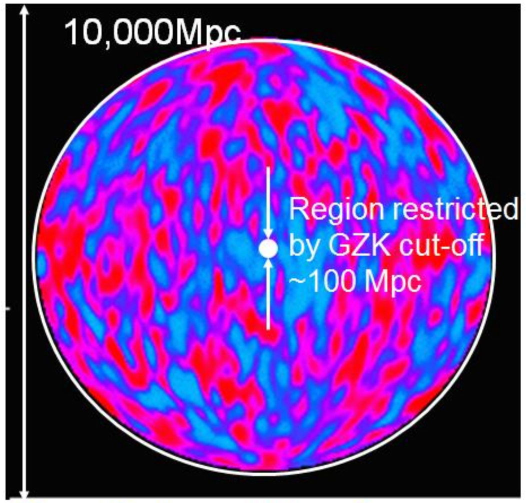
DIFFUSION SPALLATION INJECTION



Cylindrical model. The radius of
the Galaxy is taken as Rgal = 20 kpc. The thickness of the Galactic disk is 2h with h = 100 pc.

Greisen–Zatsepin–Kuzmin (GZK) Limit





Size of observable universe

Interaction of protons with Microwave Cosmic Background photons→

$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0$

$\rightarrow n + \pi^+$

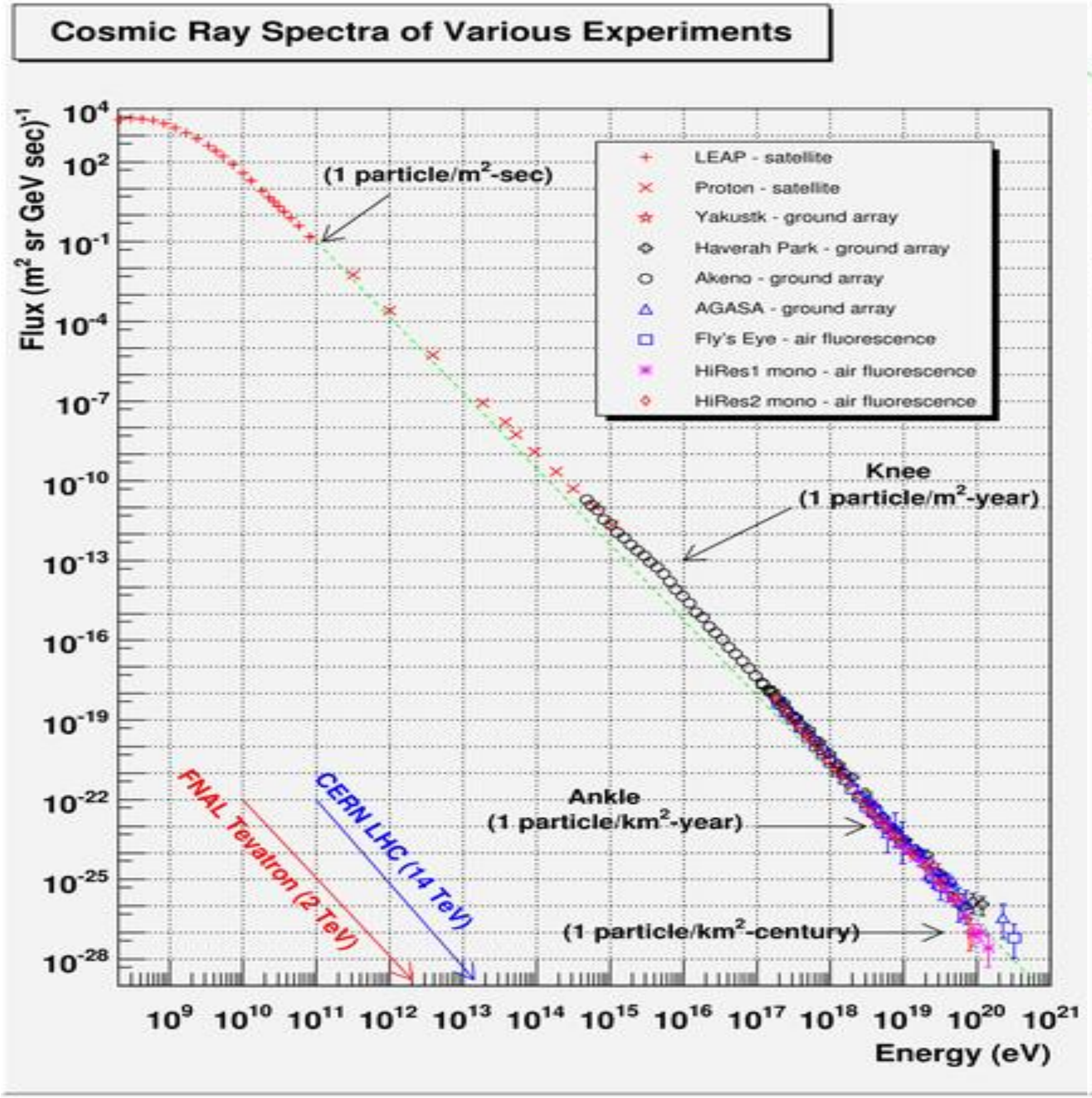
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$

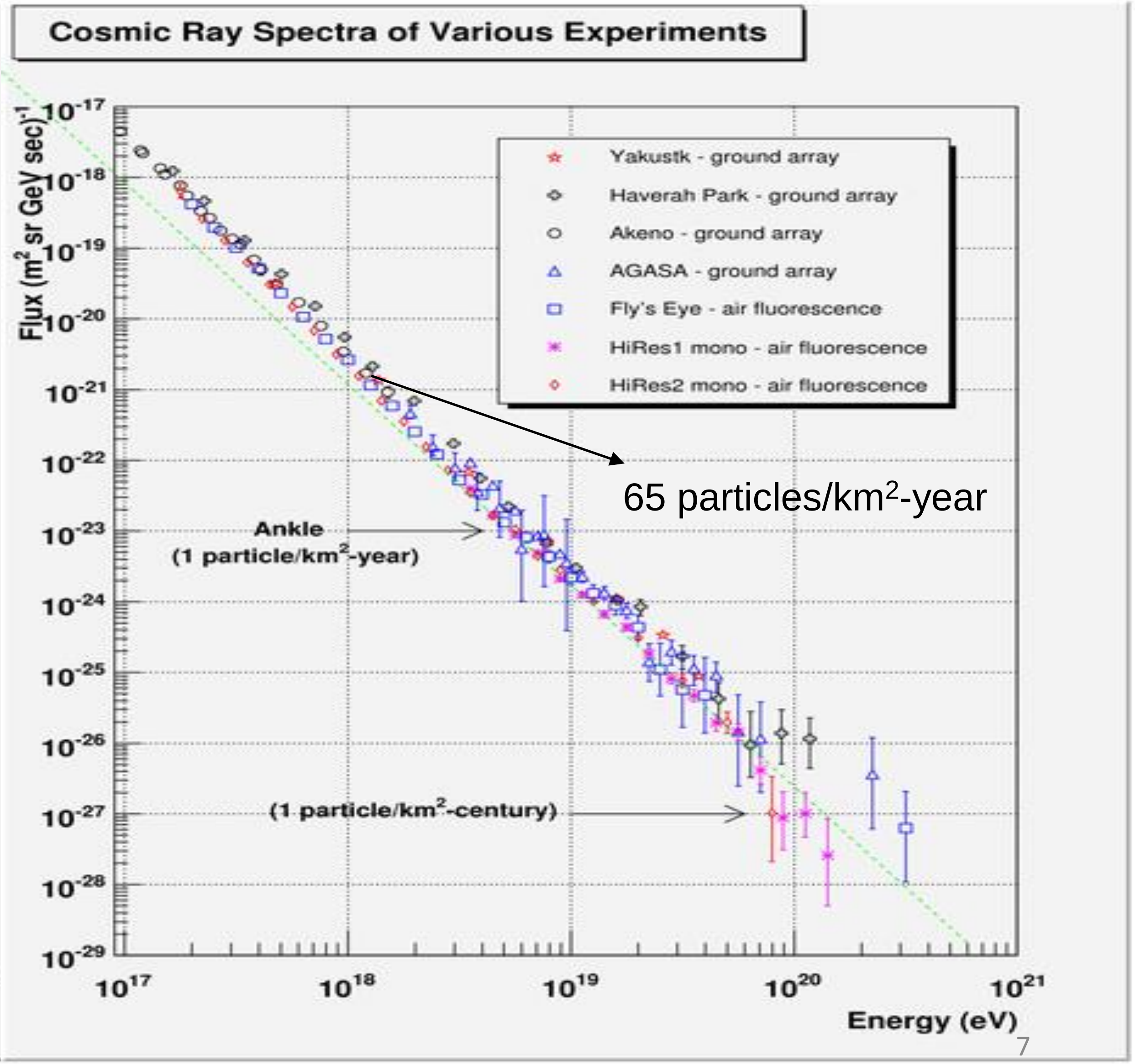
- **Above ~ 4 x10^{19} eV, space becomes opaque to cosmic ray protons**

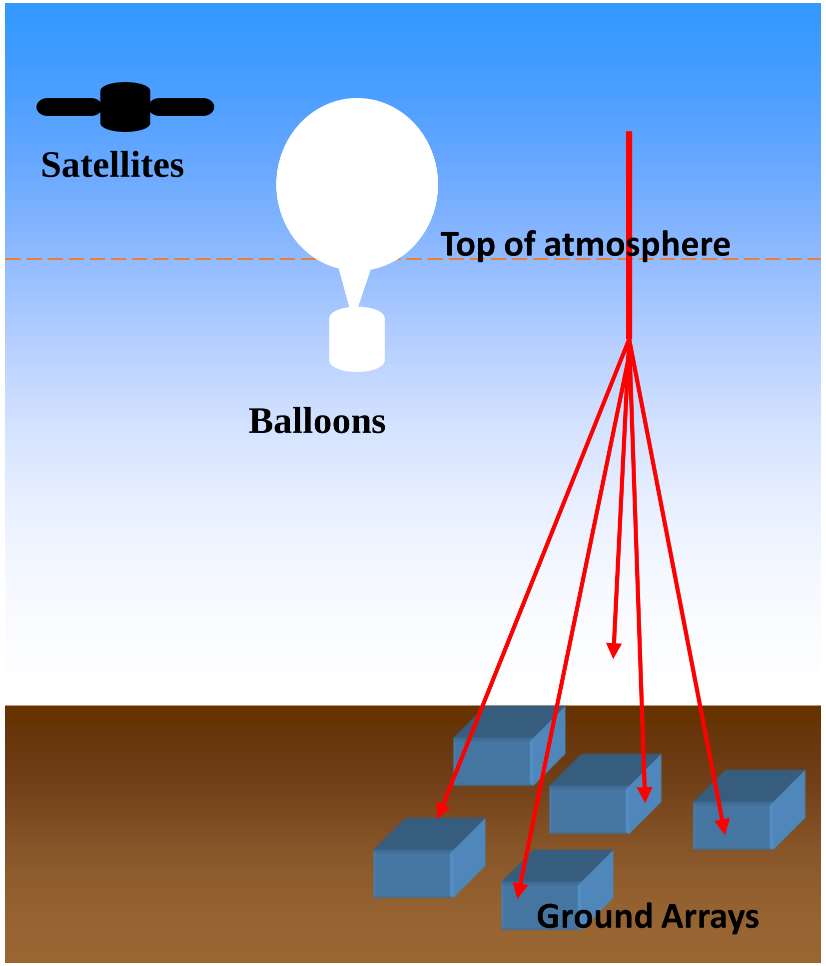
•Sources of CR with energies above the GZK limit must be 'close', < 100 Mpc

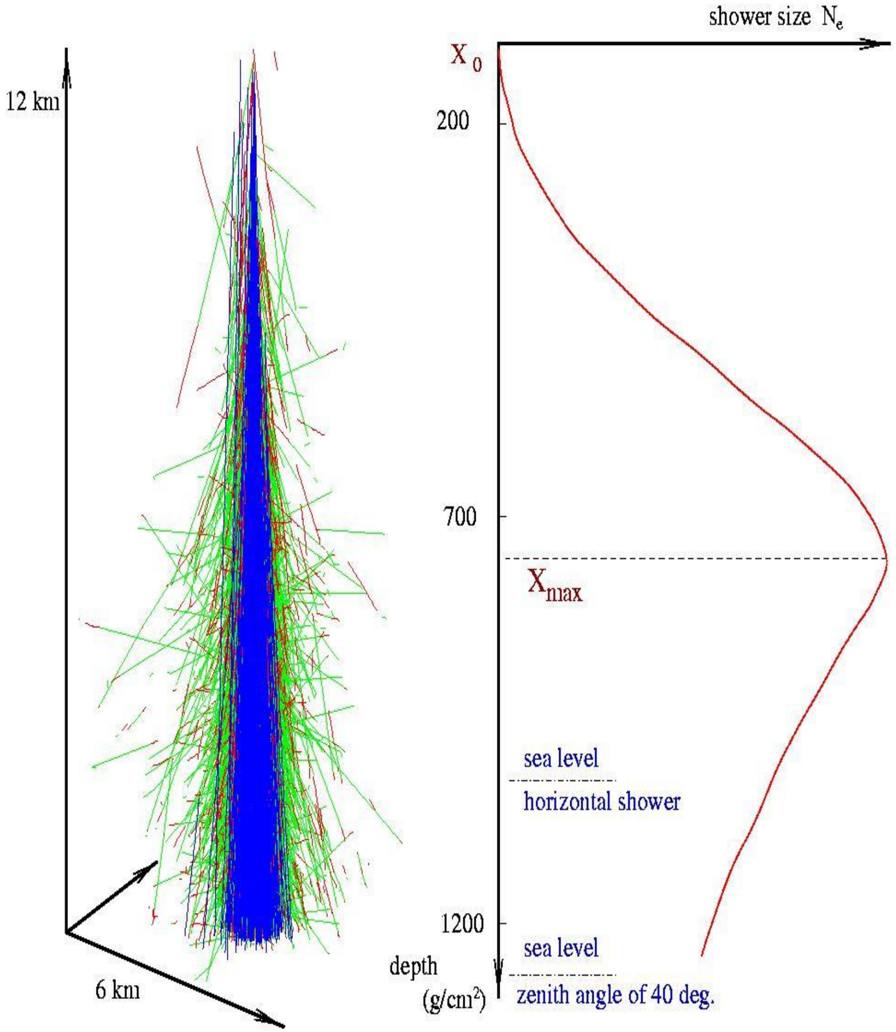
•No definite acceleration sites for such high energies established

Energy Spectrum

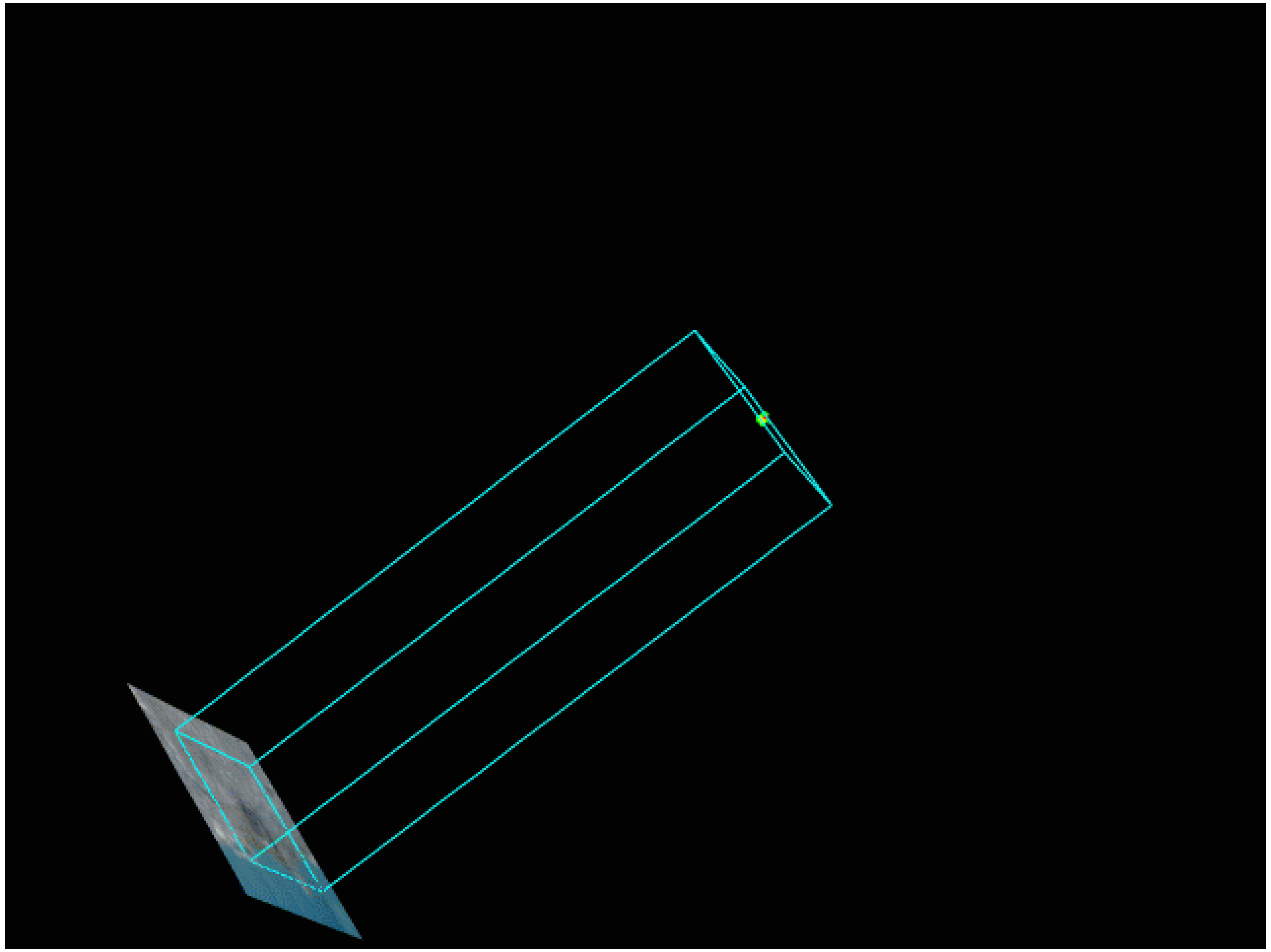




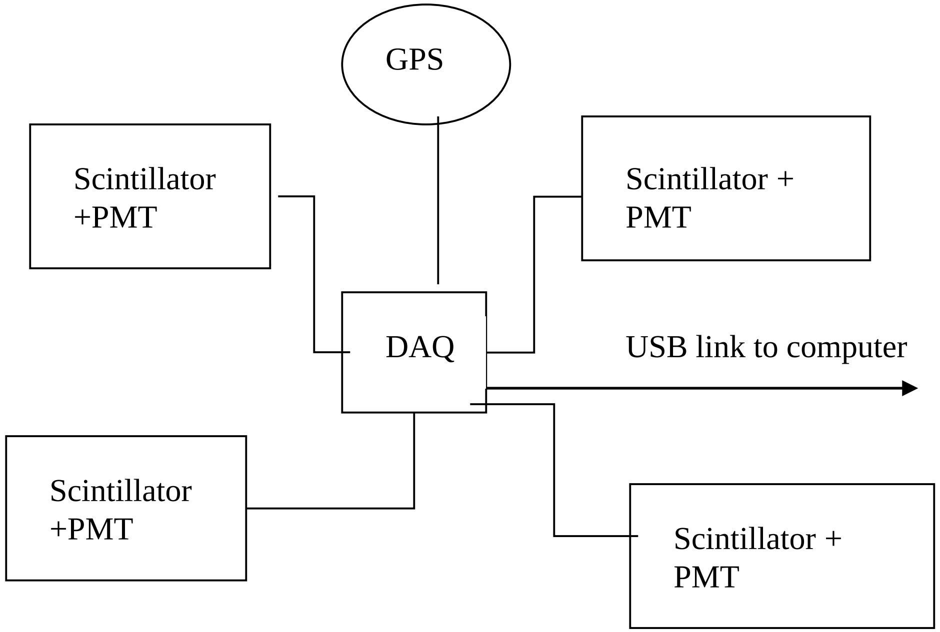

Satellites
Balloons
Top of atmosphere
Ground Arrays


12 km
6 km
shower size N_e
X_0
200
700
X_{max}
sea level
horizontal shower
1200
sea level
zenith angle of 40 deg.
depth
(g/cm^2)

Air shower simulation, 200 GeV Iron shower



Detectors



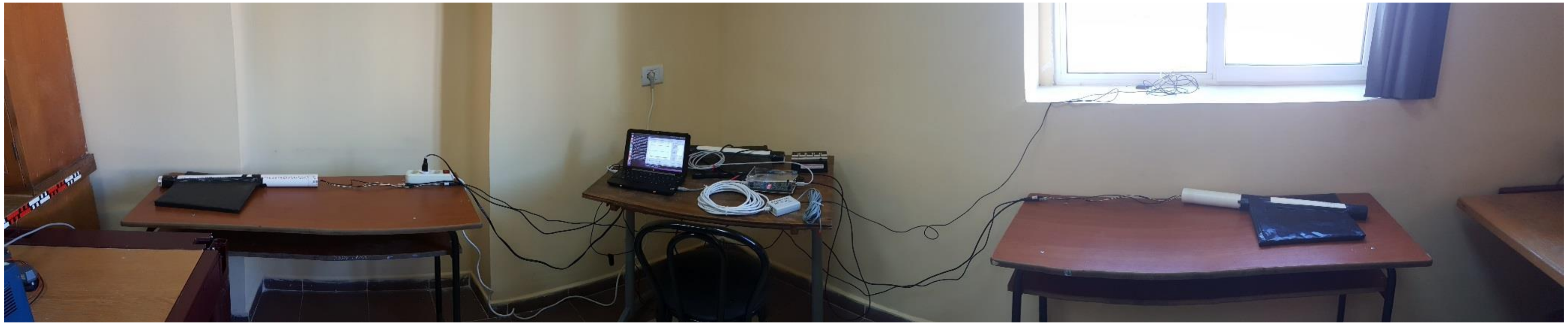
Developed by Fermi National Laboratory for the QuarkNet Program

Each DAQ card accommodates up to 4 channels

Three were used for each of our arrays

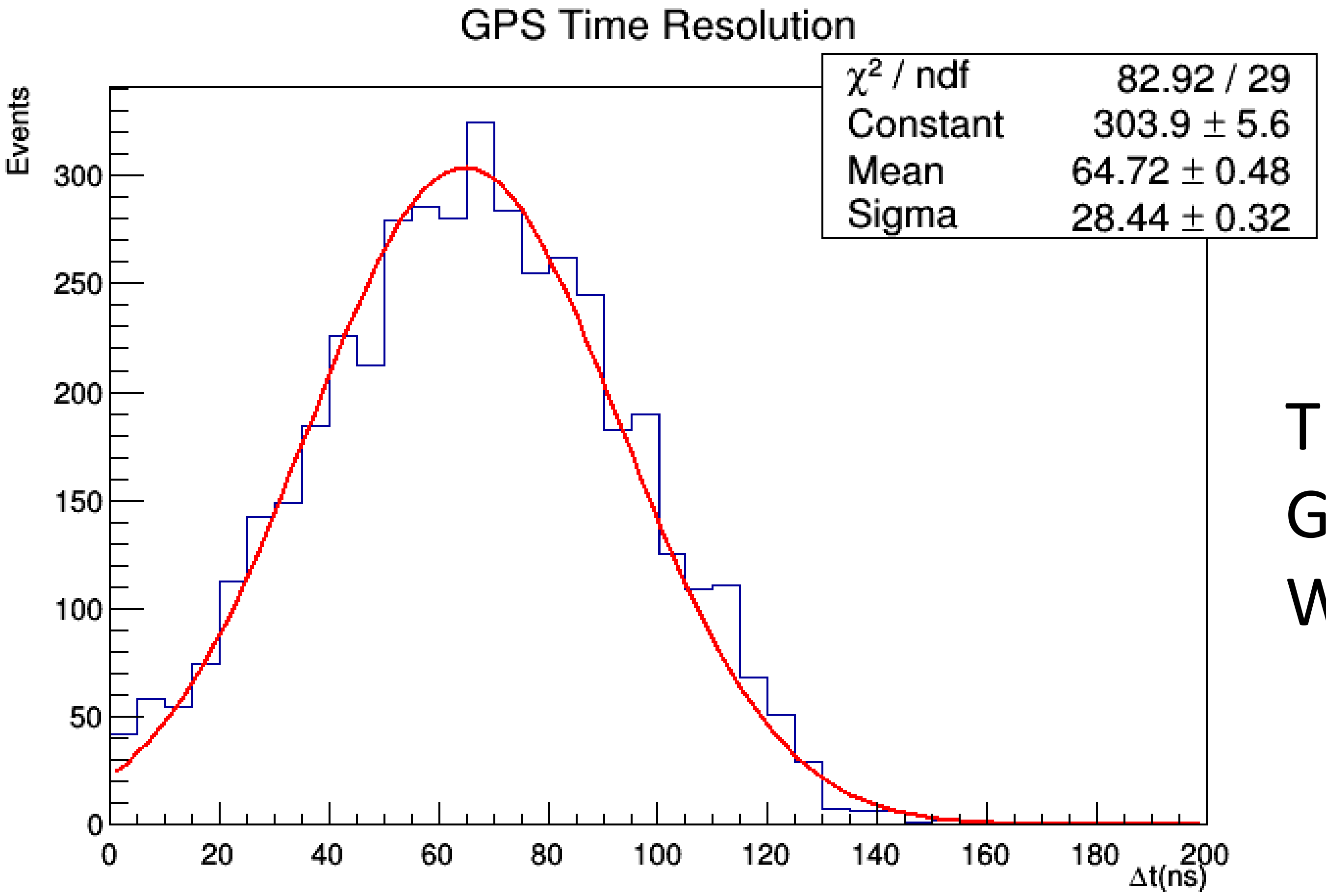
Measure ToT (Time over threshold) and time

Time resolution of individual channels σ_t ~1 ns



UT site

GPS Time Resolution for correlation studies of different arrays

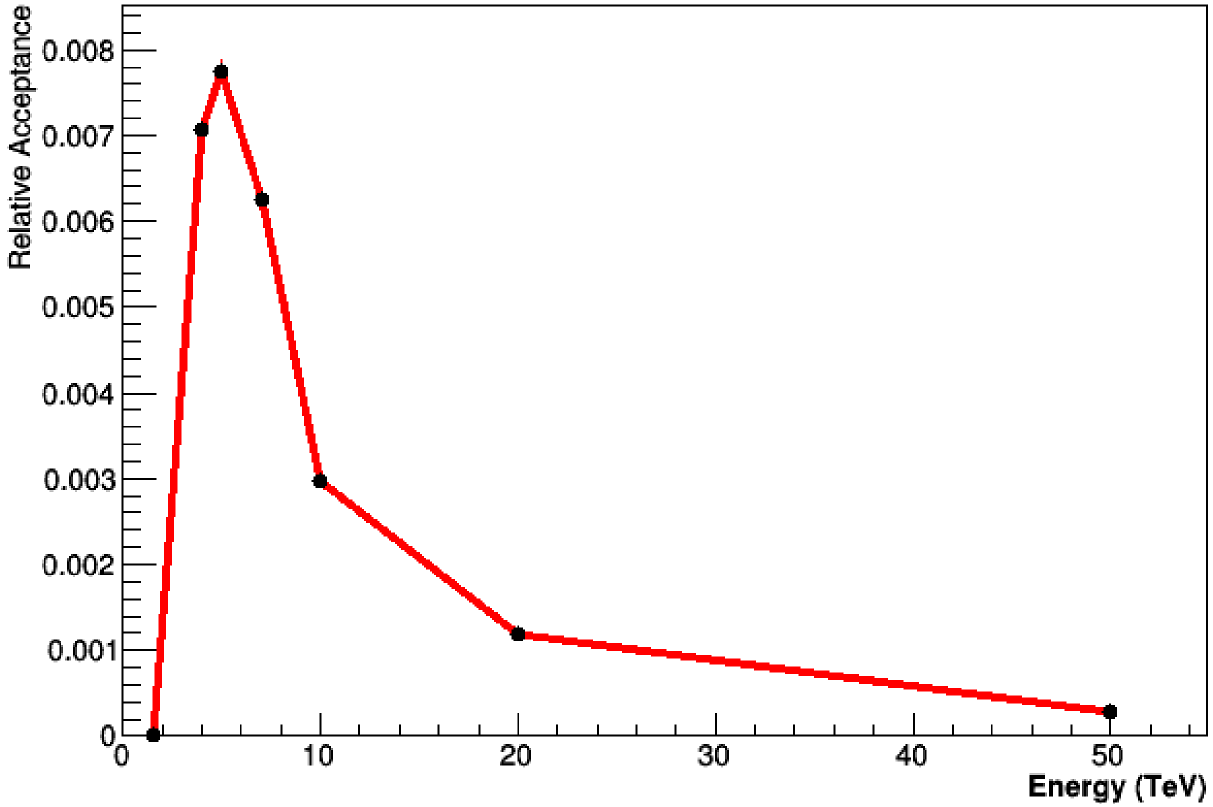


$$Mean = (64.72 \pm 0.48\ )ns$$

$$\sigma_t = (28.4 \pm 0.3\ )ns$$

The Mean represents the GPS drift time
While σ_t the resolution.

CORSIKA Monte Carlo Simulation



Energy sensitivity of our arrays was simulated with CORSIKA Monte Carlo

Energy threshold is ~2TeV

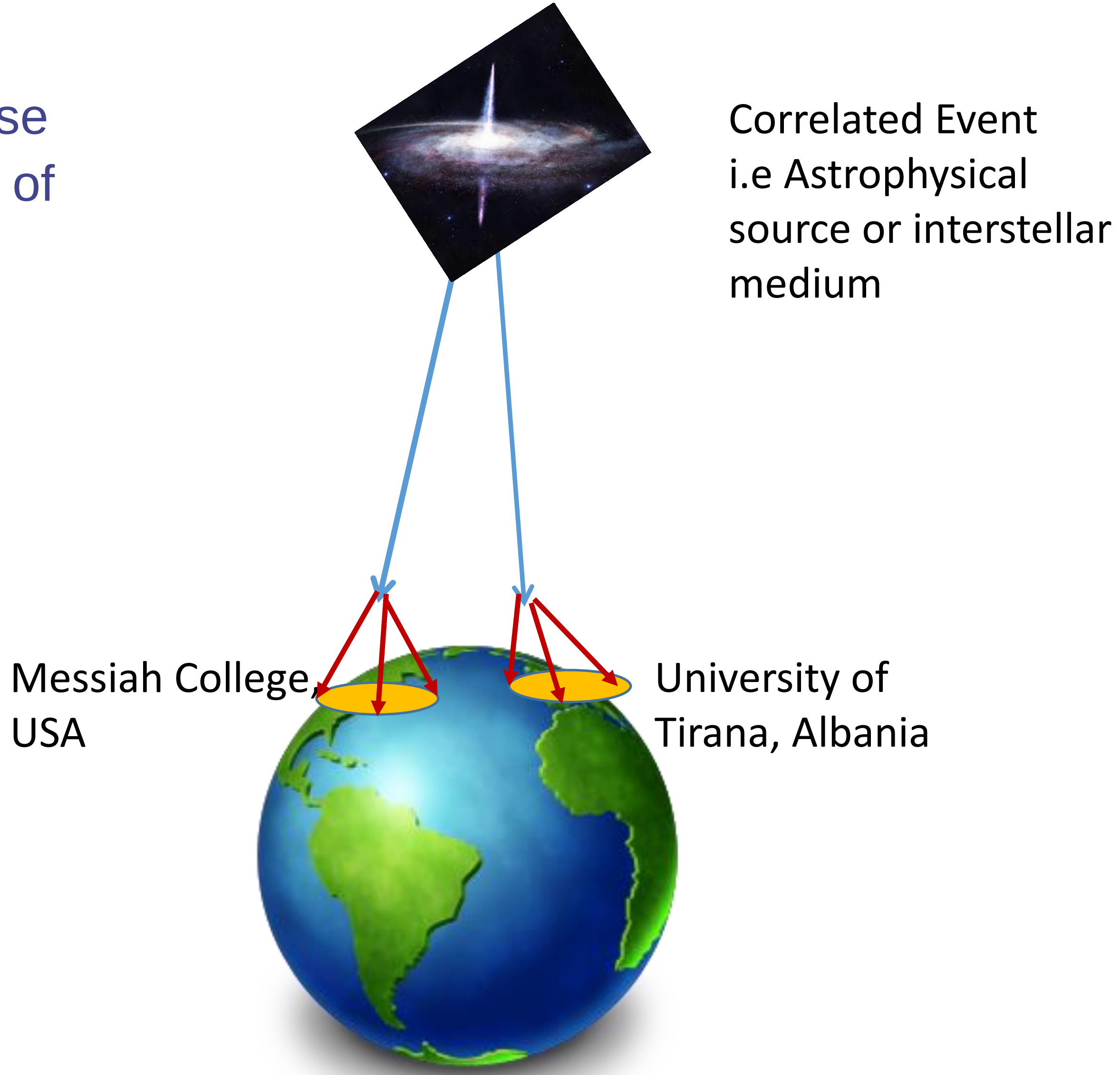
Most probable value is ~6 TeV

Sparse detector arrays

- Detectors are located far away each other as this case
- System of distant detectors can study different kinds of phenomena:
  - simultaneous detection of showers on large distance, enabling search for global events
  - simultaneous increase of event rate

- Potential sources of simultaneous showers:
  - Photodisintegration of nuclei in the Solar system or interstellar medium
  - - Gerazimova-Zatsepin (GZ) effect
  - Decay of massive exotic objects

???



Distance between the two sites, 4740 miles/7630 km

Search for time correlated events

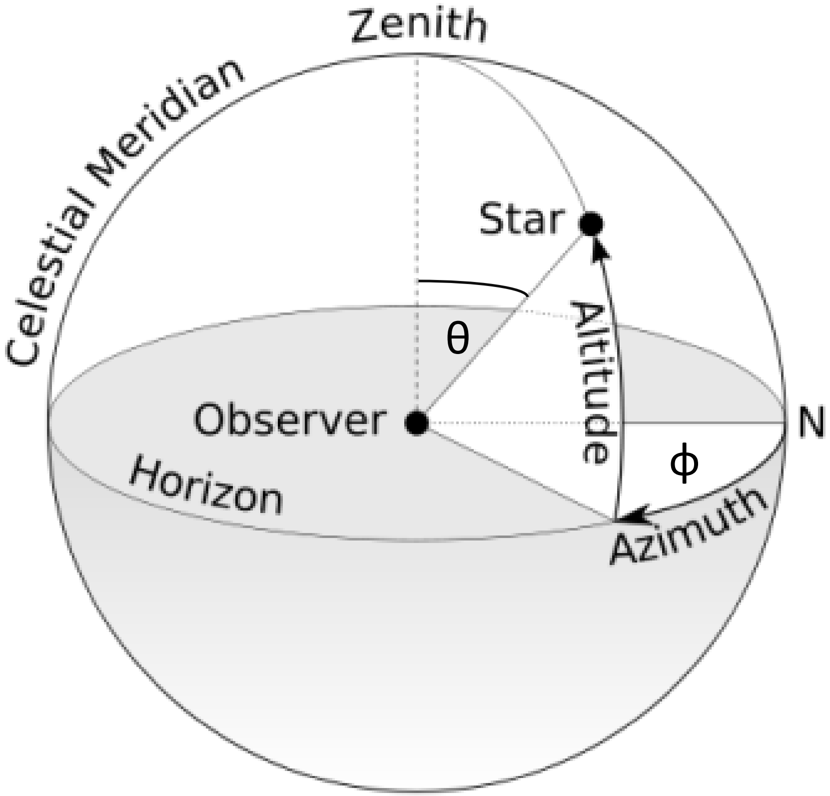
- Collected about one year worth of data at a rate of 200 cosmic ray shower events per day
- The number of coincident events observed in a time window τ~23 ms ($c\tau$ distance between two sites) is 12.
- The number of expected random coincidences during this time is

  $$2 n_1 n_2 \tau = 11$$
- Based on Poisson distribution the observed number is consistent with being random combinatoric and not anything physical

Anisotropy study

- Galactic cosmic rays expected to be almost isotropic due to interaction with magnetic field over long distance to Earth as yielded from the diffusion model
- Anisotropy may be caused however irregular magnetic field features
- The sensitivity of our arrays to TeV range cosmic rays is ideal for probing interstellar magnetic fields close to our solar system
- Several Collaboration have indicated anisotropy including Auger and TA covering the ultra high energy range

Arrival direction of Cosmic ray Showers



The arrival direction angles θ and ϕ are reconstructed from arrival time difference in the detectors of the array

With t_0 , t_1, and t_2 times of arrival at the detectors $d_1=c(t_1-t_0)$, $d_2=c(t_2-t_0)$ and with

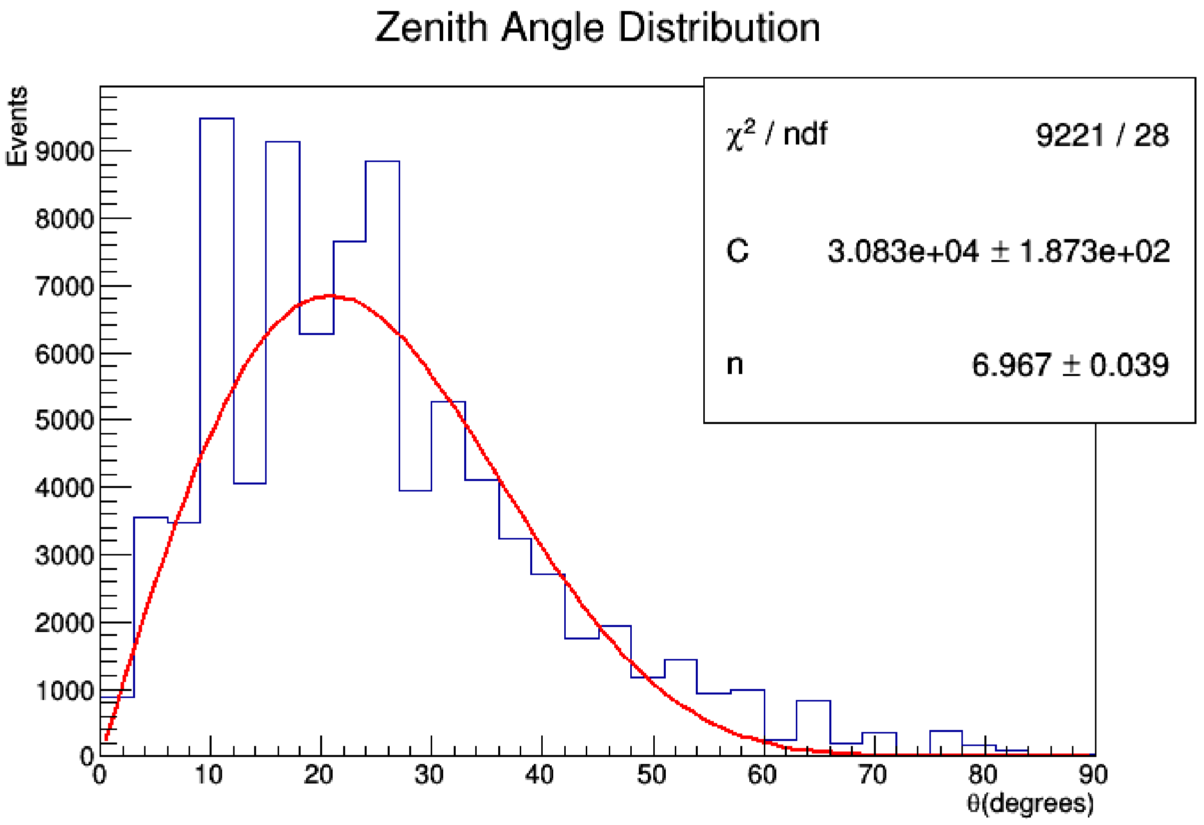
$$a = \frac{d_2 - d_1 \frac{y_2 - y_0}{y_1 - y_0}}{(x_2 - x_0) - (x_1 - x_0)\frac{y_2 - y_0}{y_1 - y_0}}$$

$$b = \frac{d_2 - d_1 \frac{x_2 - x_0}{x_1 - x_0}}{(y_2 - y_0) - (y_1 - y_0)\frac{x_2 - x_0}{x_1 - x_0}}$$

$$\cos(\theta) = \sqrt{a^2 + b^2}$$

$$\tan(\phi) = \frac{a}{b}$$

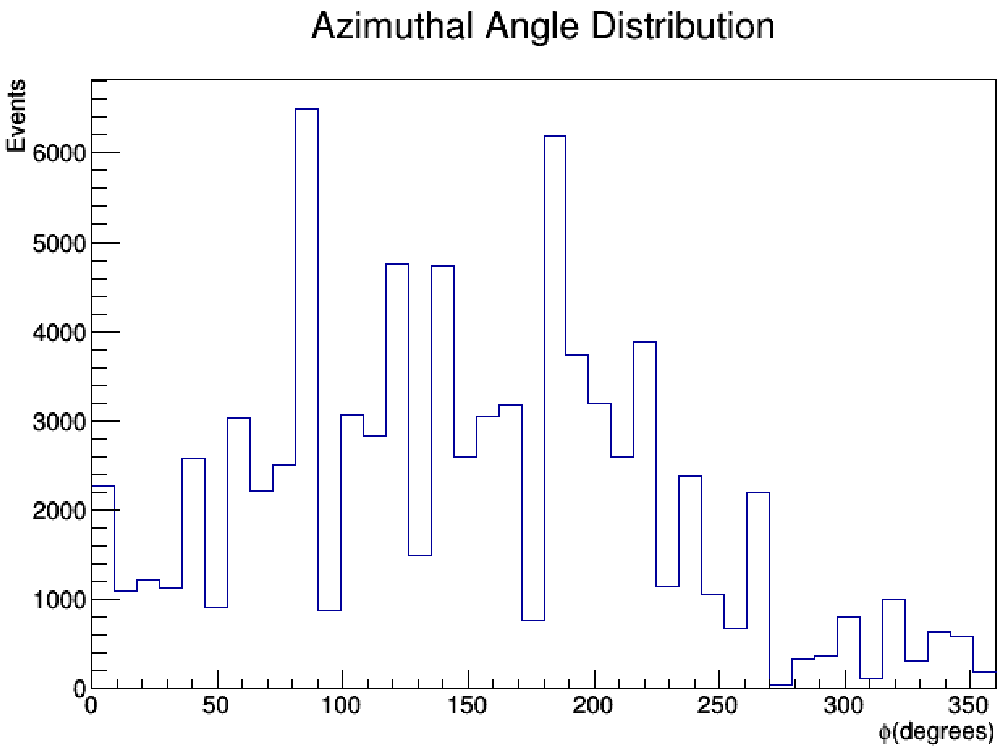
Horizontal coordinates distribution for US site



Zenith angle distribution is fitted with:

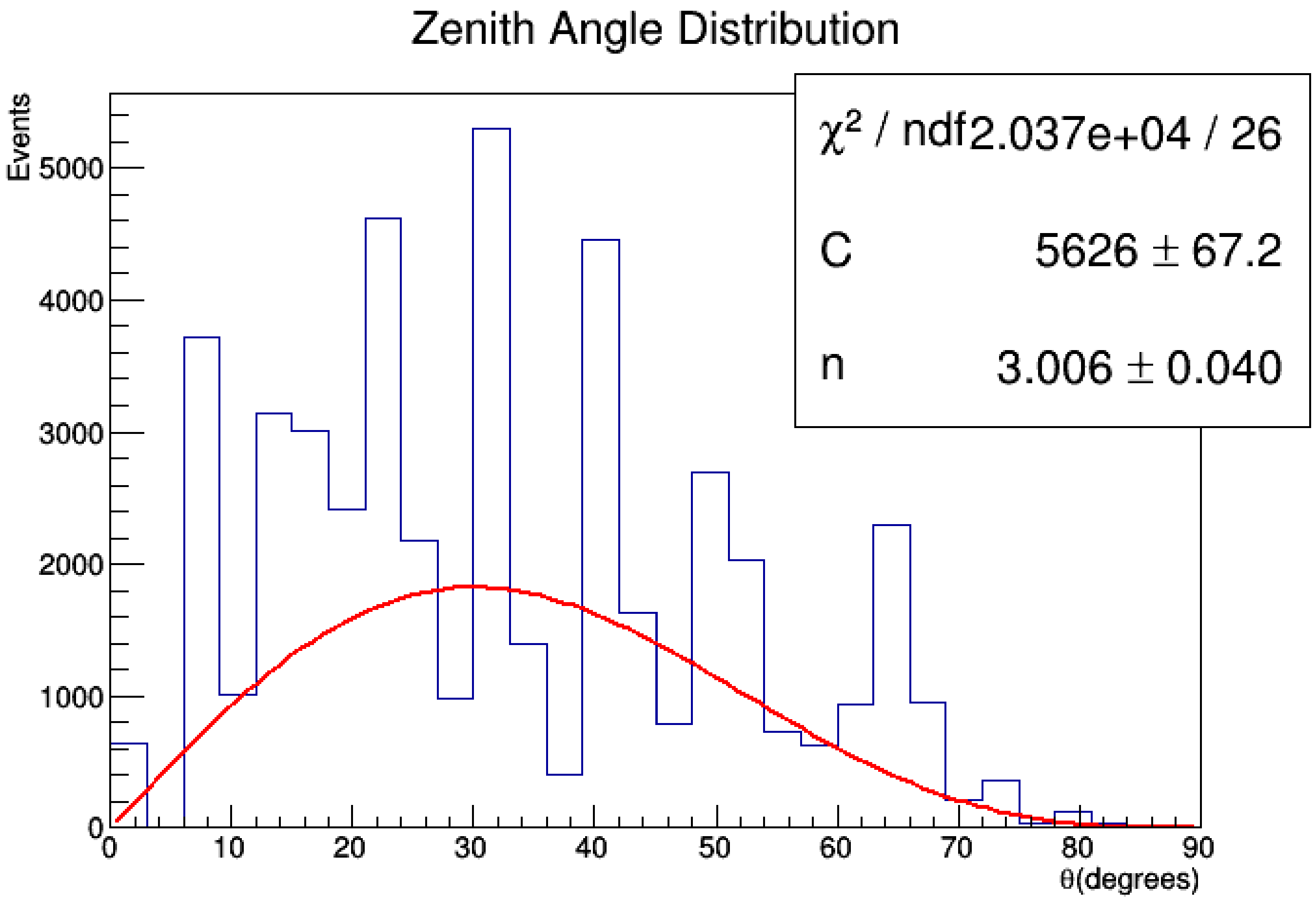
$$F(\theta) = C \cdot cos^n(\theta)$$

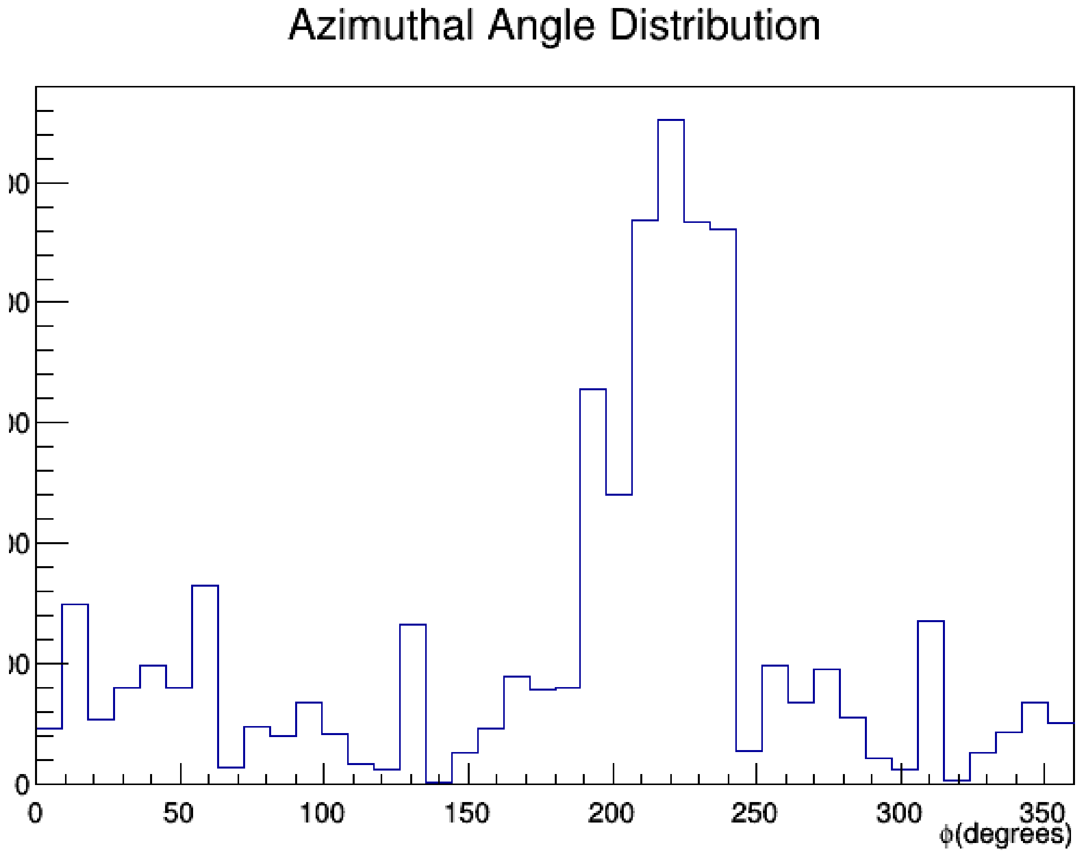
n=6.97±0.04 is consistent with quoted exponents in literature ranging from n=5 -10.



Non-uniform acceptance in ϕ

Horizontal coordinates distribution for Albania site

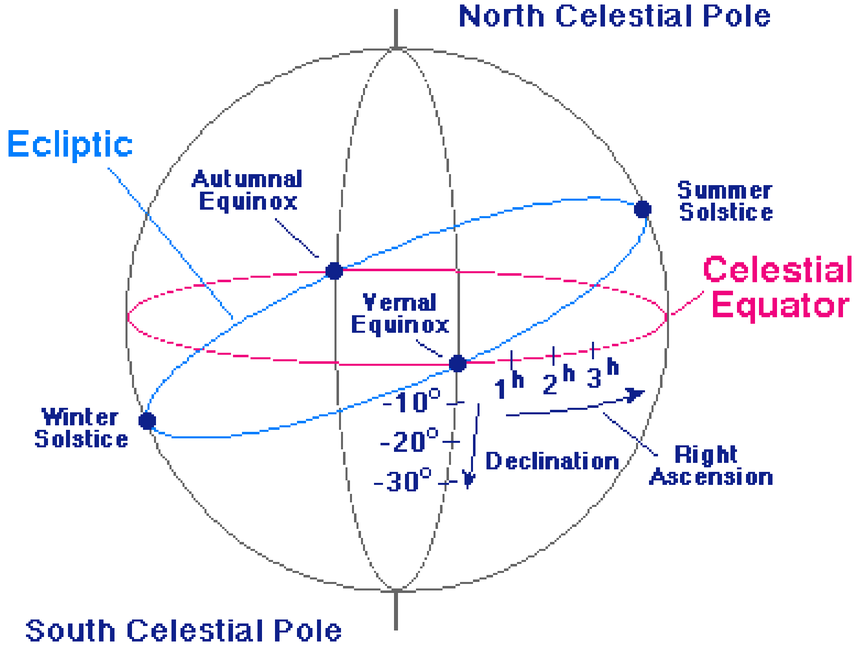


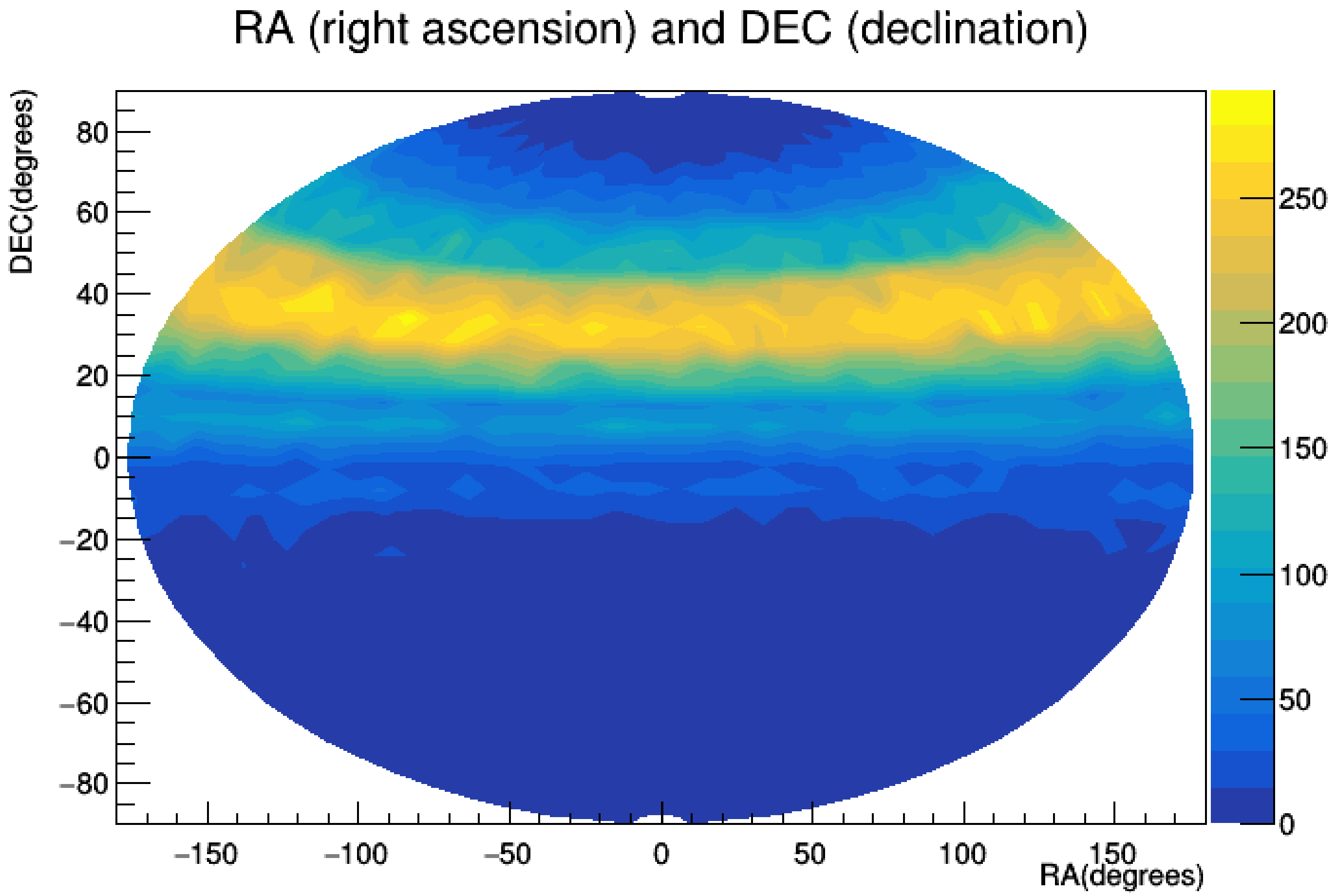


n=3.01±0.04 is lower than quoted exponents in literature ranging from n=5 -10.

Both distributions at UT site are affected by asymmetrical x-span vs y-span of the array

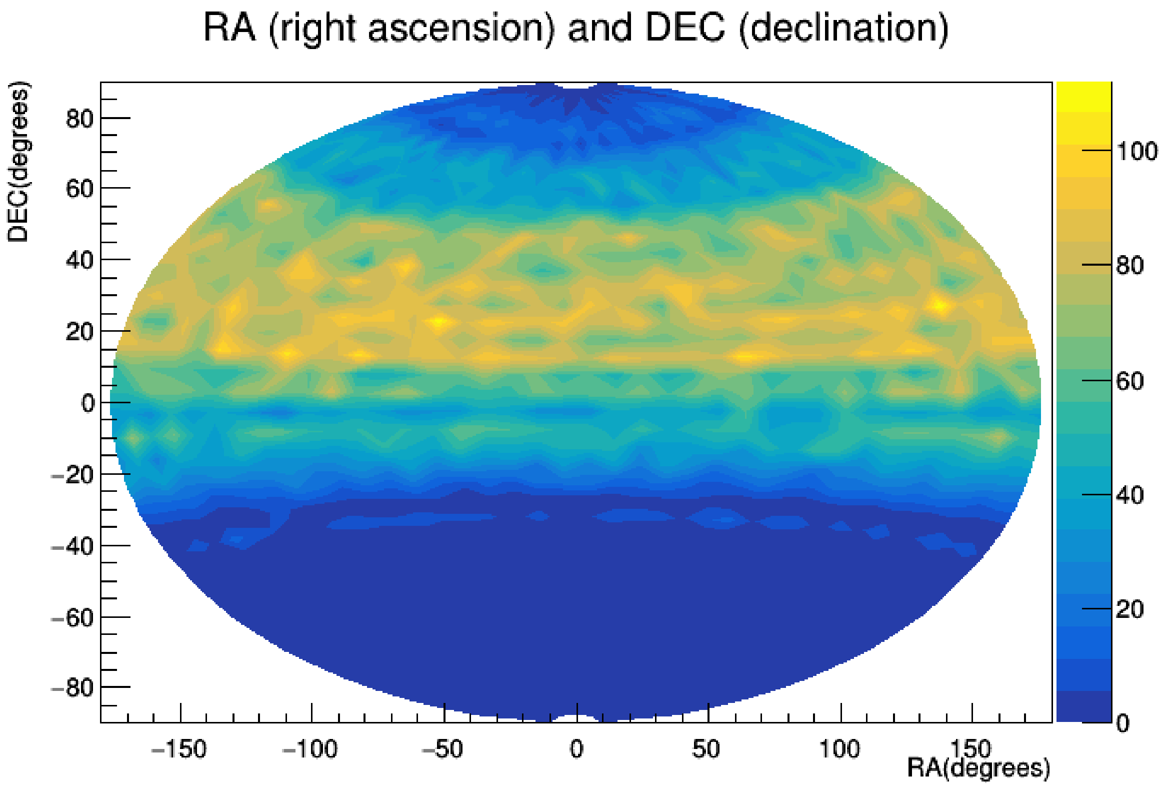
Equatorial Coordinates Map US site



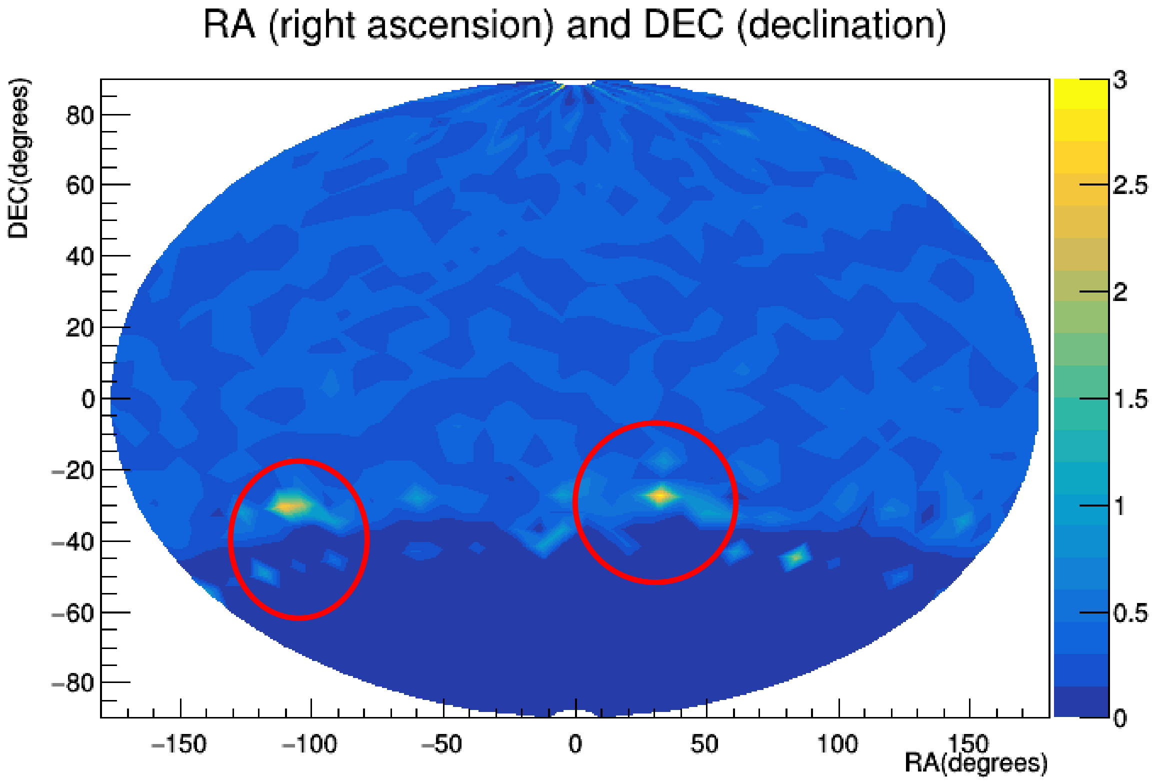


Uncorrected map: Majority of events come from 20-50 degrees Declinations as expected for northern latitudes

Equatorial Coordinates Map Albania site



Statistical fluctuations: Low number of statistics there



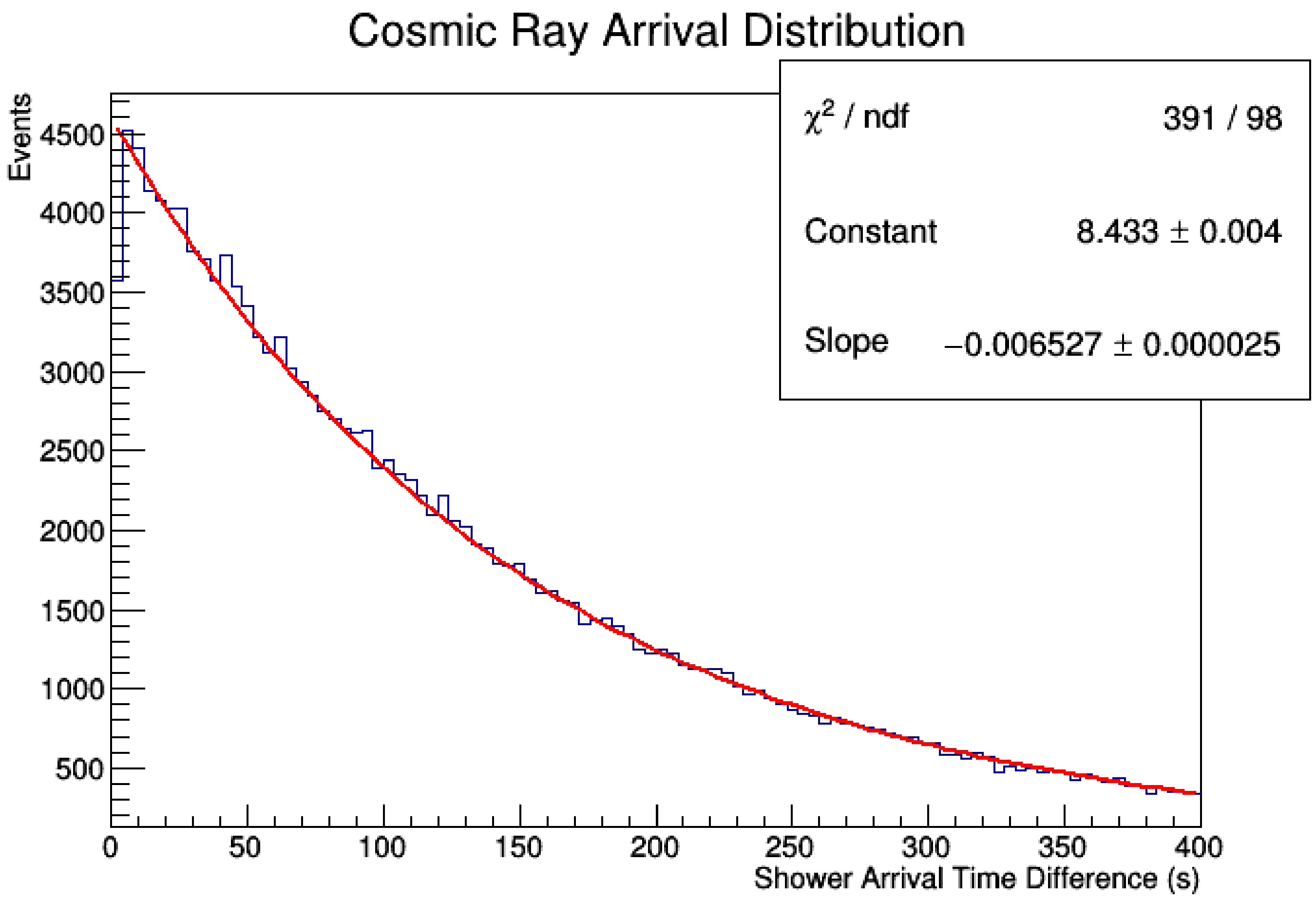
Uncorrected map: Majority of events come from 20-50 degrees Declinations as expected for UT's location

Corrected map: It is reconstructed from the ratio of true events with fake events generated from data using Scrambling technique: it's looking more isotropic

Arrival time of Cosmic Rays

Cosmic Ray Showers arrival times appear to be Poisson distribution as expected from stochastic nature of particle collision with the atmosphere

However if chaotic features are observed, it opens the door for the nature of the astroparticle physics process and the statistical properties of the process causing the deterministic behavior



Chaos Search in time series of Cosmic Ray Showers

Grassberger-Procaccia Method: Correlation dimension

In a time series sample: $\{ x_1, x_2, x_3, \ldots x_N\}$ we construct m-dimensional delay vectors

$\mathbf{X_i} = \{x_i, x_{i+1}, x_{i+2}. ..x_{i+(m-1)\tau} \}$
Where τ is an arbitrary time increment and m is the embedded dimension

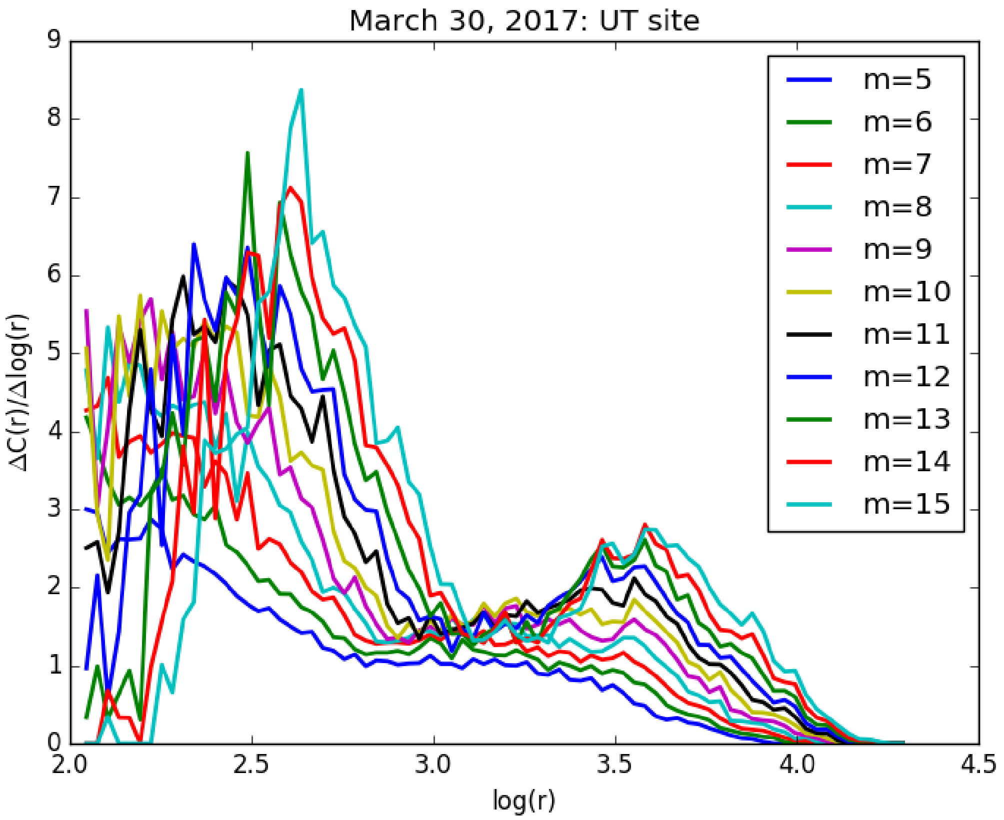
$$C(r) = \frac{2}{(M-W)(M-W+1)} \sum_{i=1}^{M-W} \sum_{j=i+W}^{M} \Theta(r - |\boldsymbol{x_i} - \boldsymbol{x_{j|}}),$$

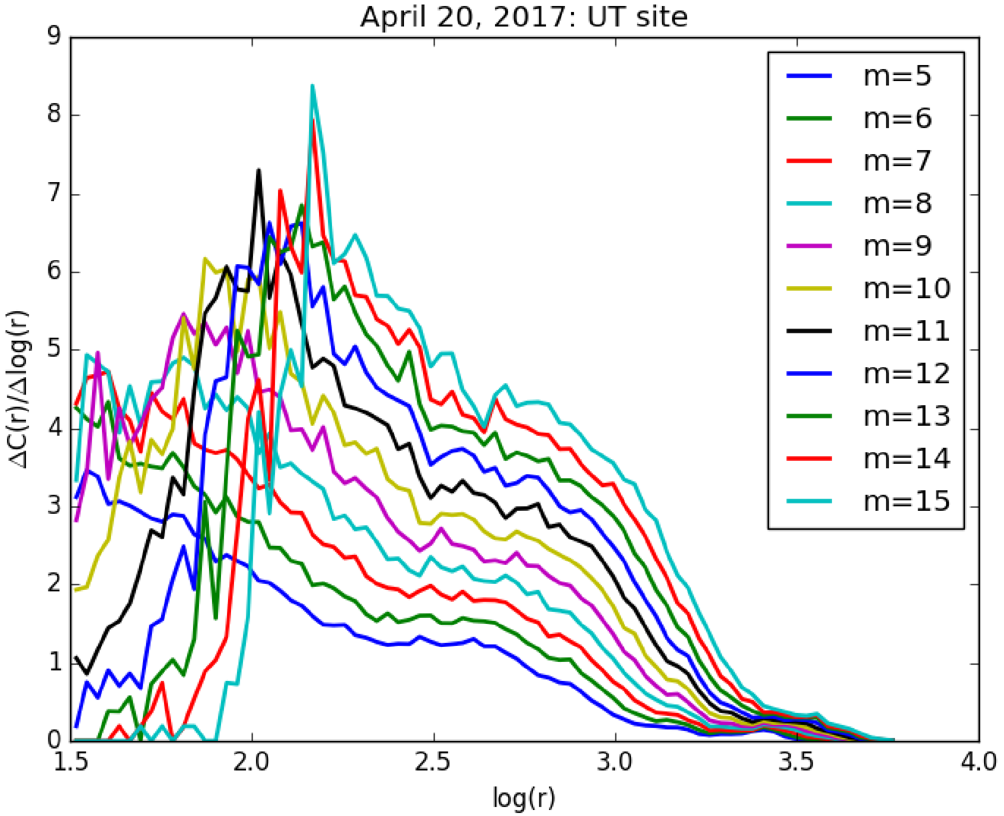
Θ is the Heavyside step function, M=N-(m-1)τ

Look for convergent flat parts in $\frac{d\log C(r)}{d\log(r)}$ vs $\log(r)$

Fractal dimension can be extracted from the plateau

Data is broken into daily clusters for analysis of chaotic vs stochastic behavior





Possible Chaotic events: fractal dimension of 1.5, when events are scrambled the chaos feature disappears Indicating need for more investigation

Stochastic event: No flat regions

Summary & What’s next?

- It’s been a good platform educationally but with challenges mostly at keeping the data going.
- Study of the time correlation of the two arrays reveals consistency with random coincidences.
- The arrays have potential for anisotropy studies.
- One chaotic cluster of events was possibly observed at Tirana site on March 30, 2017
- As next step, collect more data, see any other students are interested at the UT site, particularly to follow through with some of these analysis.