A close correlation of filaments of galaxies with ultra-high-energy cosmic rays observed by Telescope Array experiment

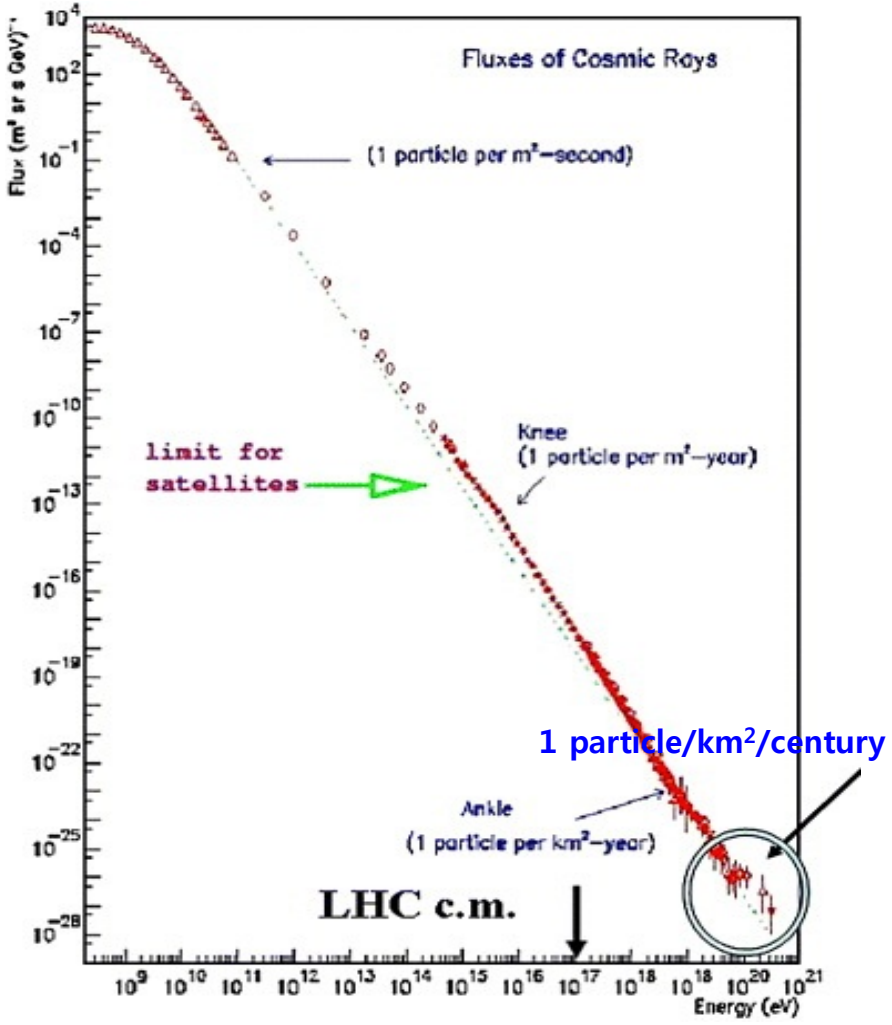
Jihyun Kim*(UNIST), Dongsu Ryu (UNIST/KASI),
Suk Kim (KASI), Soo-Chang Rey (CNU),
and Hyesung Kang (PNU)

2017-07-05
APRIM 2017 @ Taipei

Contents

- Introduction to ultra-high-energy cosmic rays
- Clustering feature of UHECR events observed by TA experiment
- UHECR model
- Statistical test method
- Results
- Conclusion

Ultra-High-Energy Cosmic Rays (UHECRs)



- Cosmic Rays

  : energetic particles originated from outer space that impinge on Earth's atmosphere.

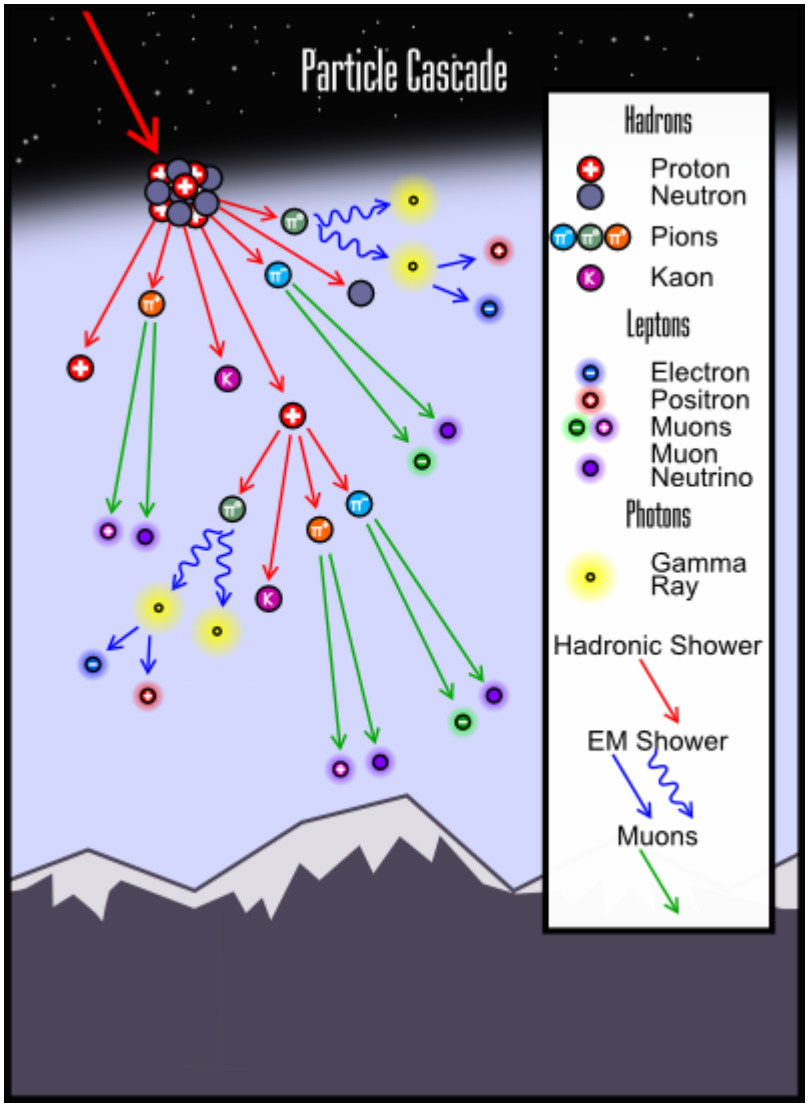
- Ultra-High-Energy Cosmic Rays

  : cosmic rays with energies above 10^{18} eV

- Overall, the flux of CRs appears to follow a single power law ~ E^{-3}.

  → In the Ultra High Energy regime, direct detection using satellites or balloons is not feasible because of the extremely low rates.

How can we observe UHECRs?



Source: http://www.telescopearray.org/

- Extensive Air Shower (EAS):

A cascade of millions of subatomic particles initiated when a single UHECR collides with a nucleus in the atmosphere

- Fluorescence detectors (FD):

observe fluorescence light generated in the atmosphere by charged electromagnetic particles

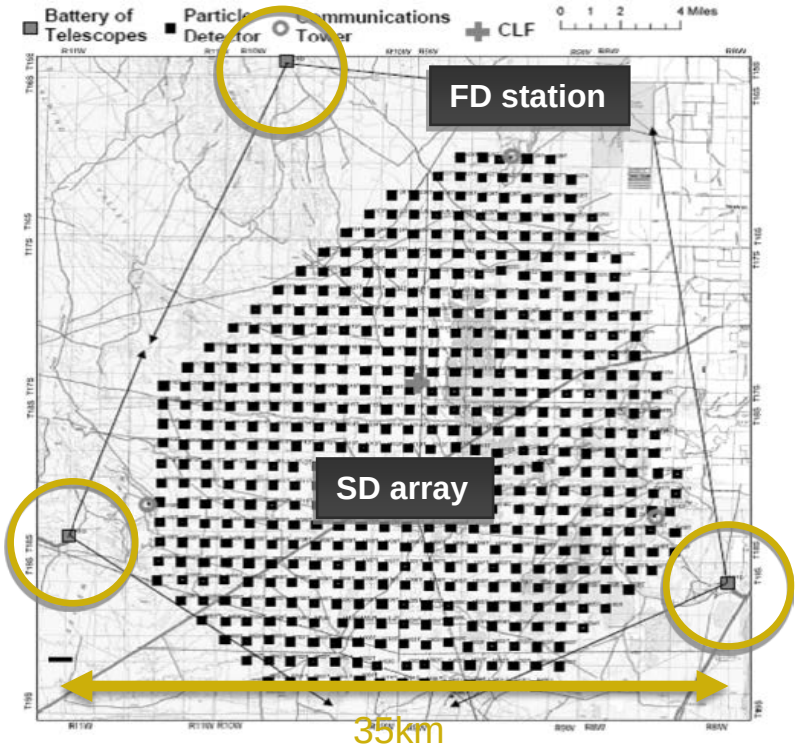
→ estimate the mass composition of the primary particle

- Surface detectors (SD):

detect the secondary particles of EAS survived at ground level

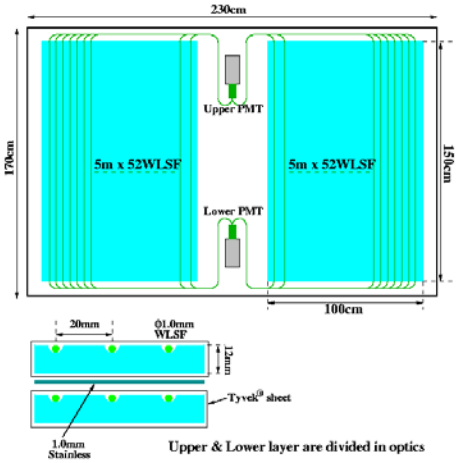
→ estimate the energy of the primary particle

Telescope Array experiment



- Location : Utah, USA
- SD : 507 plastic scintillation detectors,
  1.2 km spacing, ~700 km^2
- FD : 18 telescopes in 3 stations

Surface Detector – Plastic Scintillation



Fluorescence Detector – PMT

Clustering feature of TA UHECR events (TA collaboration 2014)

- "For 72 UHECR events having energies above 57 EeV, collected over five years with the TA SD, TA has observed a cluster of events with a statistical significance of 5.1σ ($N_{on} = 19$, $N_{bg} = 4.49$). We calculated the probability of such a hotspot appearing by chance in an isotropic cosmic-ray sky to be 3.7×10^{-4}."

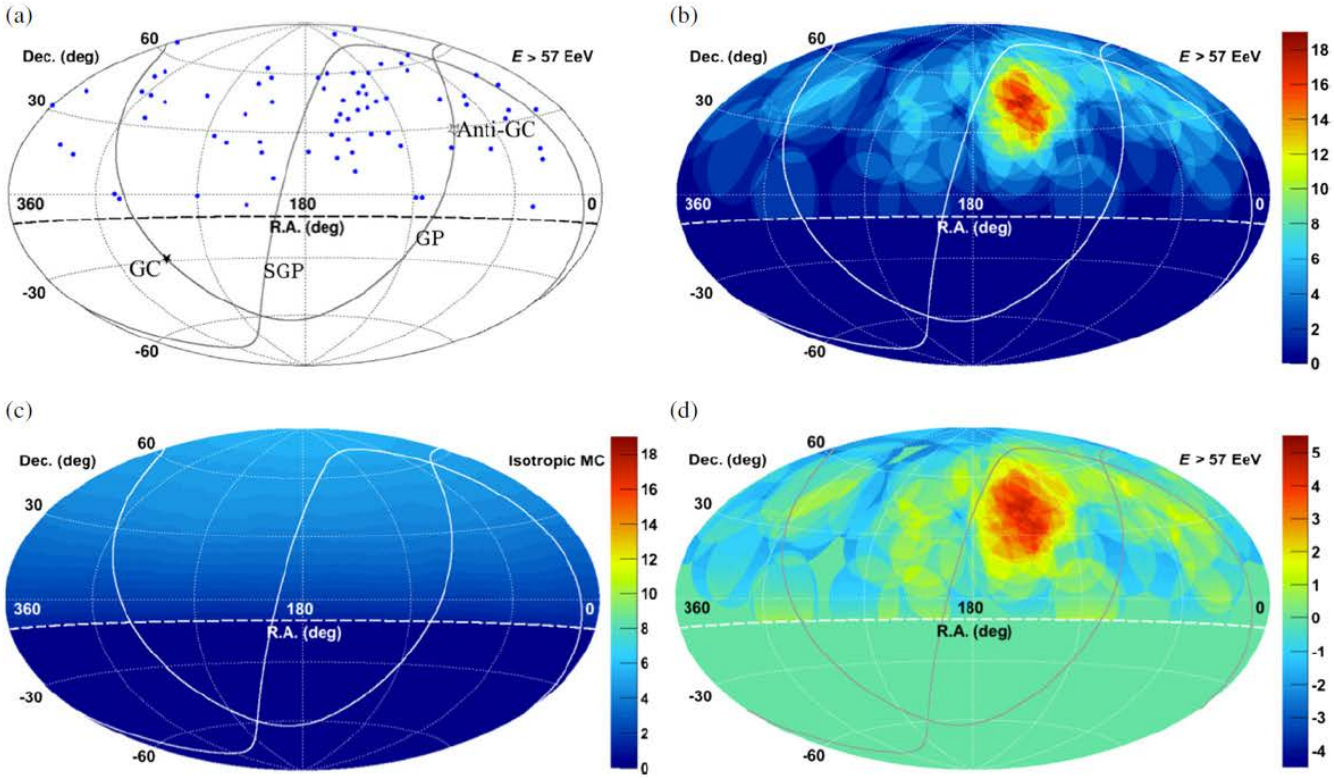
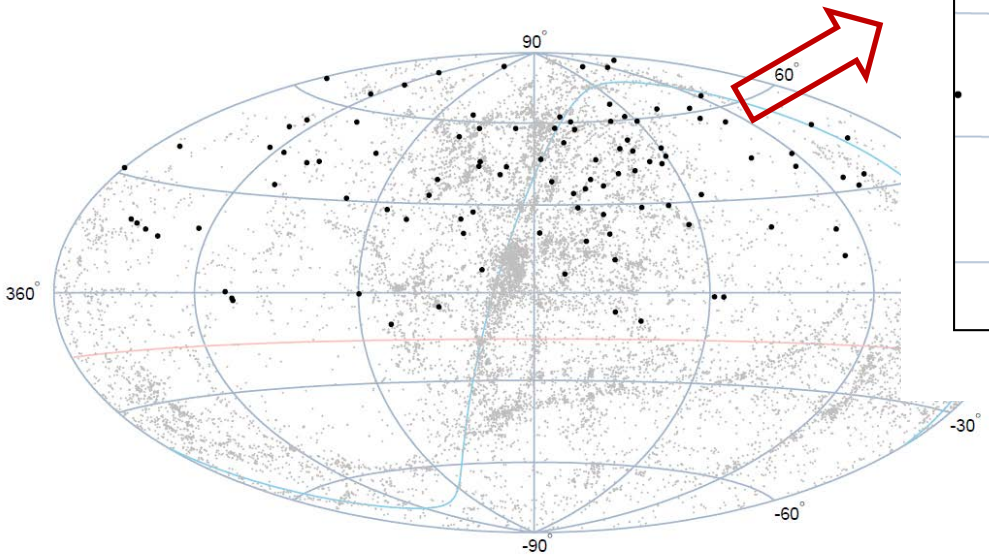


Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. $= -10°$. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by the TA SD array, and the closed and open stars indicate the Galactic center (GC) and the anti-Galactic center (Anti-GC), respectively; (b) color contours show the number of observed cosmic-ray events summed over a 20° radius circle; (c) number of background events from the geometrical exposure summed over a 20° radius circle (the same color scale as (b) is used for comparison); (d) significance map calculated from (b) and (c) using Equation (1).

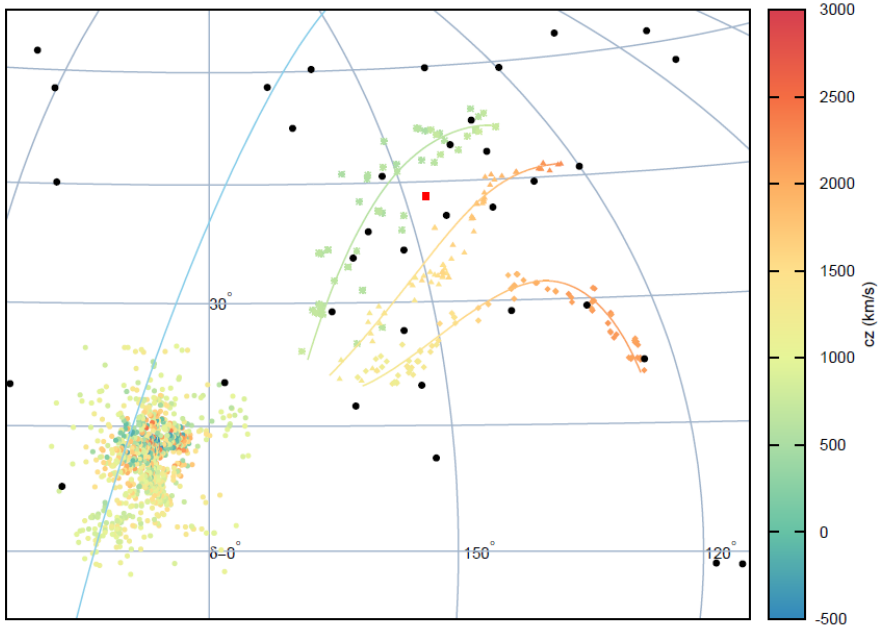
To understand the origin of the TA hotspot

- We examine the sky distribution of the TA UHECR arrival direction and that of galaxies in the local universe.

Grey dots: Hyper LEDA galaxies ($v \leq 3500$ km/s)
Black dots: 110 TA events ($E \geq 57$ EeV)
Pink line: Boundary of TA exposure
Skyblue line: Supergalactic plane



Equatorial coordinates

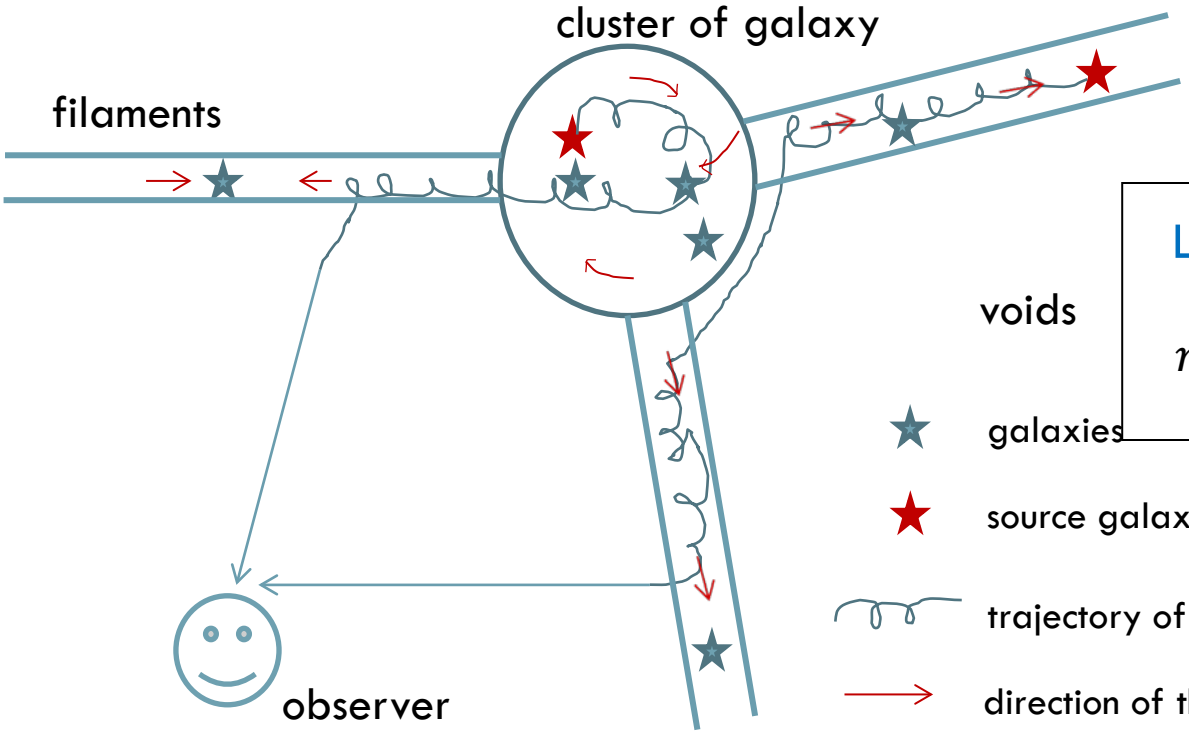


Toward the TA hotspot, no specific astrophysical sources like active galactic nuclei are found.
We found filaments of galaxies connected to the Virgo cluster. (Kim et al. 2016)

Confinement of UHECRs by filaments of galaxies

- Assuming UHECRs are generated at sources inside clusters or filaments, they would be captured by the magnetic fields in the cosmic web and escape toward open fields, possibly to filaments, before travel to us. Then, the arrival direction of UHECR events would be correlated with the distribution of filaments on the sky.

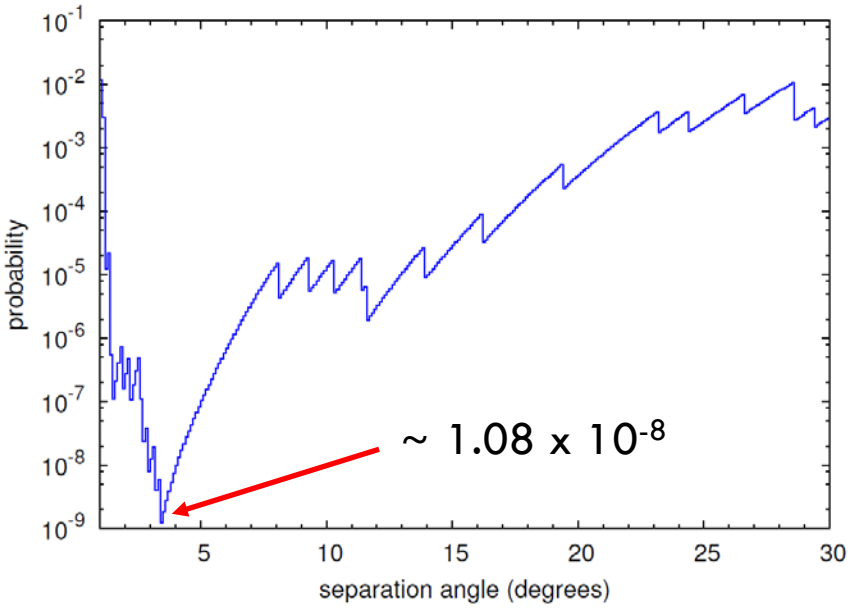
Filaments of thickness D ~ a few Mpc and magnetic field of B ~ 10 nG can confine UHECRs of E ~ 50 EeV !



Larmor radius:

$$r_L \approx \frac{1\ \mathrm{Mpc}}{Z}\left(\frac{E}{10^{19}\ \mathrm{eV}}\right)\left(\frac{B}{10\ \mathrm{nG}}\right)^{-1}$$

Correlation b/w TA events and filaments? (JK et al. in prep.)



Statistical tests for anisotropy:
Binomial probability of the excess of TA events with ≥ 57 EeV around those three filaments within the separation angle ≤ θ

We found that 21 out of 110 events correlated at $3.4°$, while 4.77 events were expected to correlate by chance for an isotropic expectation. The binomial probability of observing by chance in an isotropic expectation an equal, or larger, number of events than that found in the data:

$$P(X \geq 21) = 1.08 \times 10^{-8} = 5.72\sigma$$

To evaluate the significance of this excess, we simulated 10^9 sets of isotropic Monte Carlo UHECR data with the same number of TA UHECR events. We found the post-trial probability is $P = 1.14 \times 10^{-7}$.

Conclusion

- There have been lots of studies to point out the origin of UHECRs by comparing the arrival direction distribution of UHECRs with that of astrophysical objects, such as AGN, radio galaxies, or the large-scale structure of the universe.

  → No statistically significant correlations are found.

- A source (or sources) of the TA hotspot events is likely in the Virgo cluster. The UHECRs would be captured by the magnetic fields in the cosmic web and escape toward open fields, filaments connected to the Virgo cluster, before travel to us.

  → A close correlation between the TA hotspot events and filaments of galaxies connected to the Virgo Cluster was found.

- Deflection angle due to the GMF is a few to several degrees for protons but much larger for irons at $E \geq 57$ EeV. A close correlation with $\theta \sim 3^\circ$ means

  → TA hotspot events are mostly protons, if the correlation is real.

- Further exploration of correlation between UHECR events and galaxy distribution in the local universe is under way.

backup

Estimators for Anisotropy Test

- We can count the number of events, k, out of N that are located within the angular window, θ, from some astrophysical objects, candidates of source of UHECRs.
- The probability P that k or more out of a total of N events from an isotropic flux are correlated by chance is given by

$$\mathrm{P}(X \geq k) = \sum_{x=k}^{N} \binom{N}{x} p^x (1-p)^{N-x}$$

where p is the probability that isotropic background events fall into the angular window.

- For each window, we calculate this cumulative binomial probability of observing by chance in an isotropic flux an equal, or larger, number of events than that found in the data.
- We find out the angle that have the minimum probability. → correlation angle