

Correlation of ultra-high energy cosmic rays with large-scale structure of the universe

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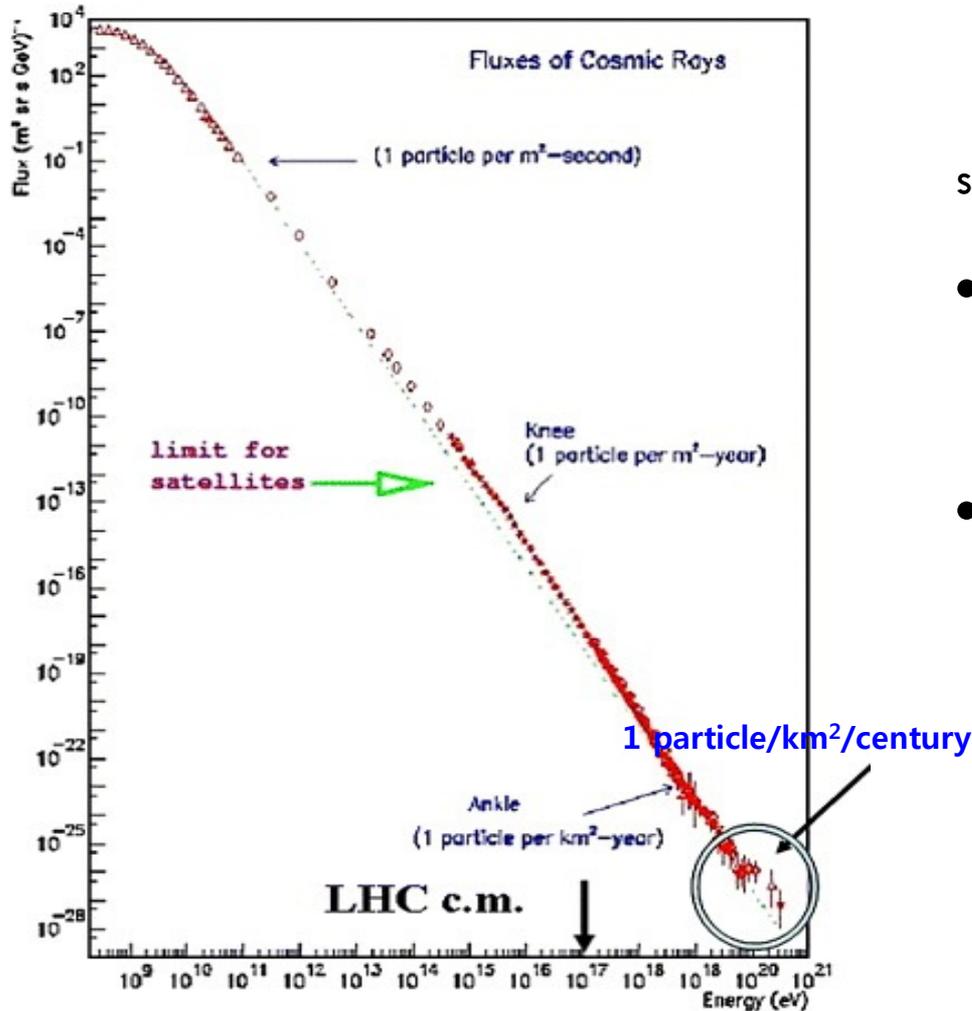
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2. Recent observatories for UHECRs
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Introduction to Ultra-High Energy Cosmic Rays



- 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

- The mysteries of UHECRs

- What are their components?

- mass composition

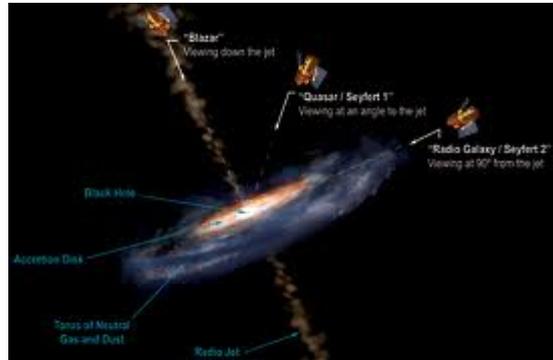
- Do they get through the GZK?

- spectrum

- Where do UHECRs come from?

- arrival direction

From production to observation



Production

- Acceleration of charged particles
- Decay of superheavy particles

Propagation

Cosmic background

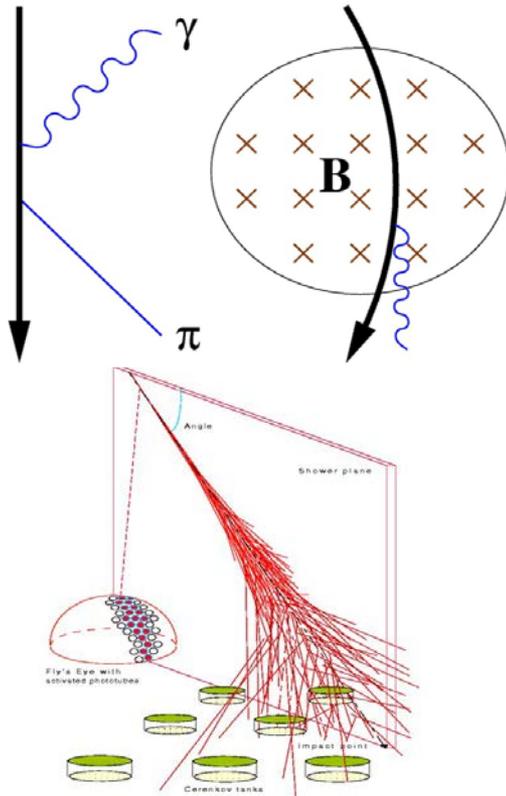
Microwave, Radiowave, Magnetic fields

- Energy loss
- Secondary CR production
- Deflection

Observation

Atmosphere as calorimeter/ scintillator

- Composition
- Energy
- Arrival Direction



Confinement in some plausible accelerators

- The maximum energy attainable by the diffusive acceleration in a certain astrophysical objects can be written by

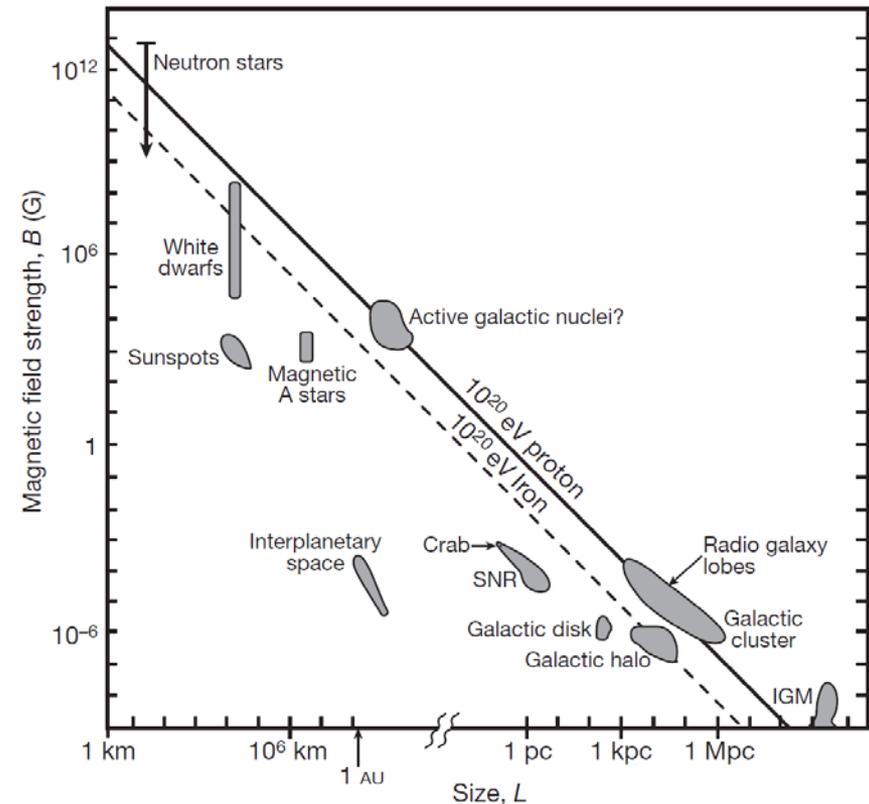
$$E_{\max} = 4 \times 10^{20} Z \left(\frac{B}{100 \mu\text{G}} \right) \left(\frac{\beta_1}{0.3} \right) \left(\frac{D}{100 \text{ kpc}} \right) \text{ eV}.$$

where Z is the atomic number

B is the magnetic field

β_1 is the Lorentz factor

D is the size of the astrophysical objects



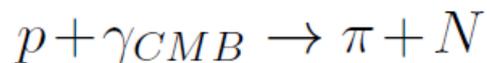
Propagation: energy loss

- When UHECRs propagate in the universe, they undergo attenuations.

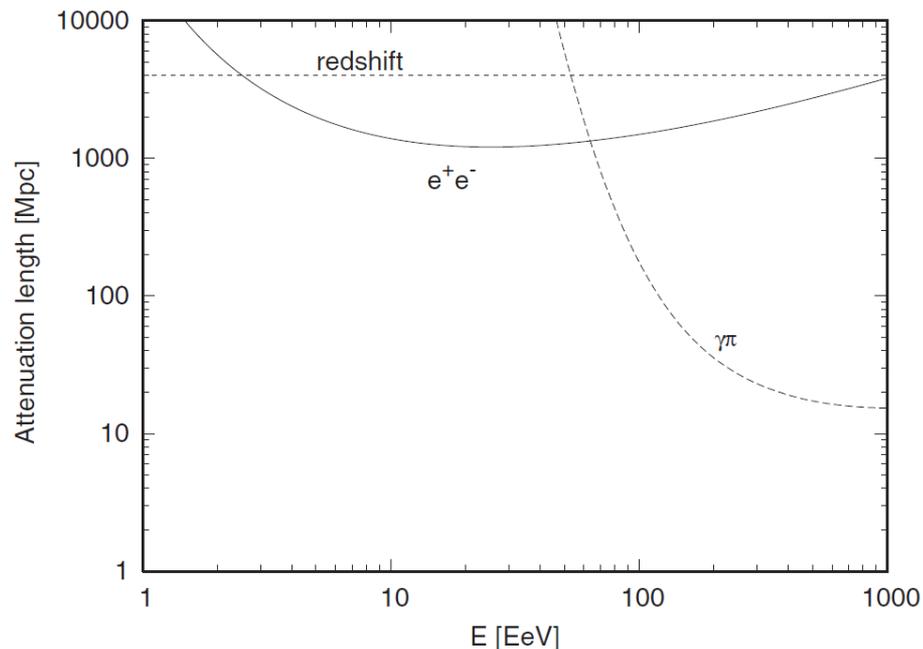
If we assume proton as a primary particle, we need to consider the energy losses by

$$\lambda^{-1} \equiv -\frac{1}{E} \frac{dE}{dx} = \lambda_z^{-1} + \lambda_{ee}^{-1} + \lambda_{\gamma\pi}^{-1}$$

- redshift
- pair production
- photo-pion production
(with CMB photon)



→ The sources of UHECRs would be located in the local universe.



Harari et al. (2006)

Propagation: deflection

- Because UHECRs are charged particles, they can be deflected by galactic magnetic fields and extragalactic magnetic fields. The typical deflection using random patches of magnetic field is given by

$$\delta\theta = 0.8^\circ Z \left(\frac{E}{10^{20} \text{ eV}} \right)^{-1} \left(\frac{dl_c}{10 \text{ Mpc}^2} \right)^{1/2} \left(\frac{B}{10^{-9} \text{ G}} \right)$$

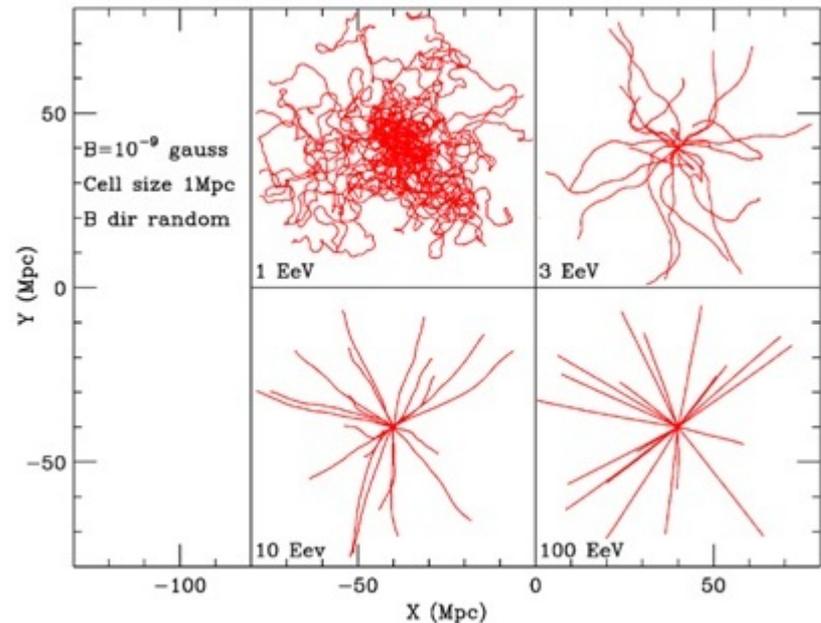
where Z is the atomic number

E is the energy of UHECR

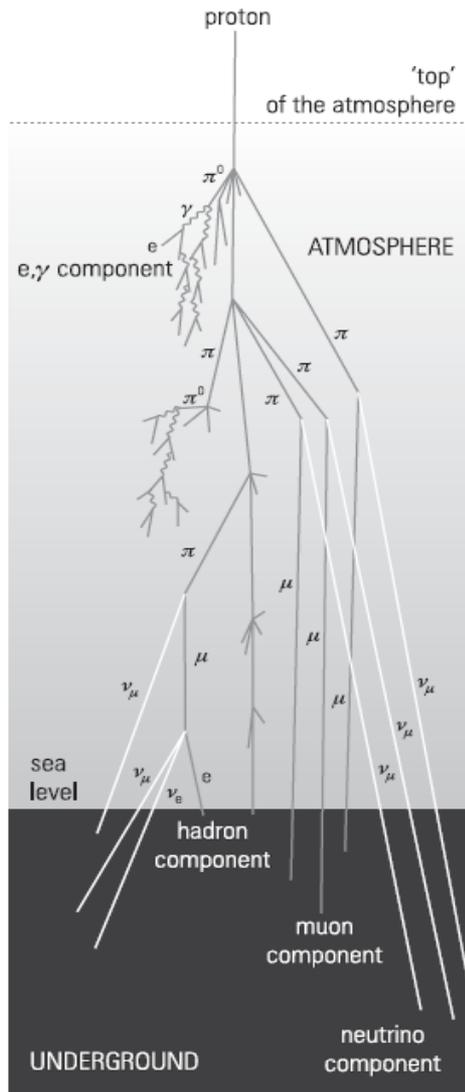
d is the distance

l_c is the average size of patches

B is the magnetic field



Extensive Air Showers



Extensive air showers (EAS):

- hadronic components
- muonic components
- electromagnetic components

Fluorescence detectors (FD):

observe fluorescence light generated in the atmosphere by charged electromagnetic particles

→ longitudinal distribution

→ estimate the mass composition of the primary particle

Surface detectors (SD):

detect the secondary particles of EAS survived at ground level

→ lateral distribution

→ estimate the energy of the primary particle

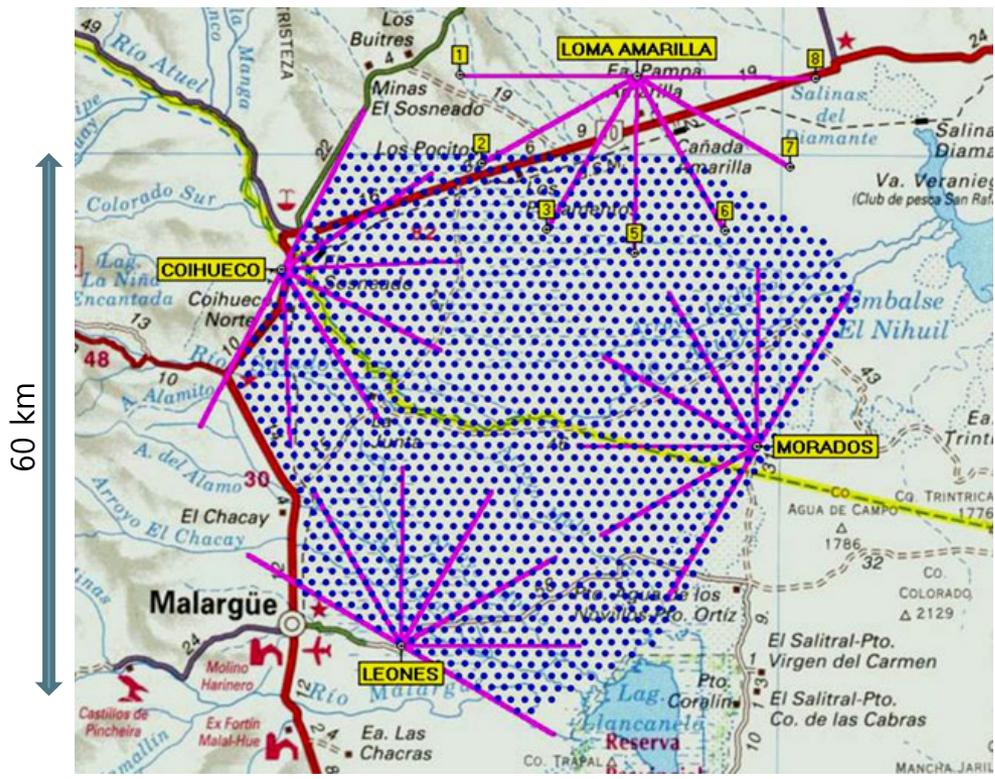
Recent observatories for UHECRs

Recent Experiments

- Since Volcano Ranch experiment observed an EAS in 1962, there have been many huge projects to observe UHECRs.
- Pierre Auger Observatory (PAO)
- Telescope Array (TA)

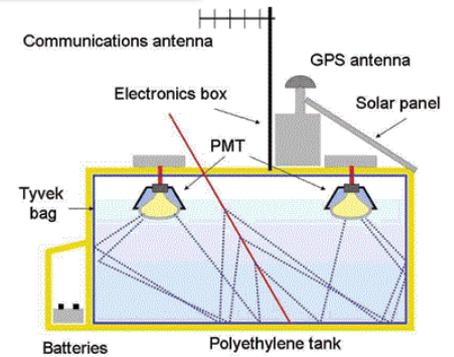
| | PAO | TA |
|-----------|---|---|
| operation | 2004-present | 2008-present |
| location | Argentina | USA |
| detectors | 1600 SDs with 1.5 km spacing + 4 FD stations ~ 3000 km ² | 507 SDs with 1.2 km spacing + 3 FD stations ~ 700 km ² |

Pierre Auger Observatory

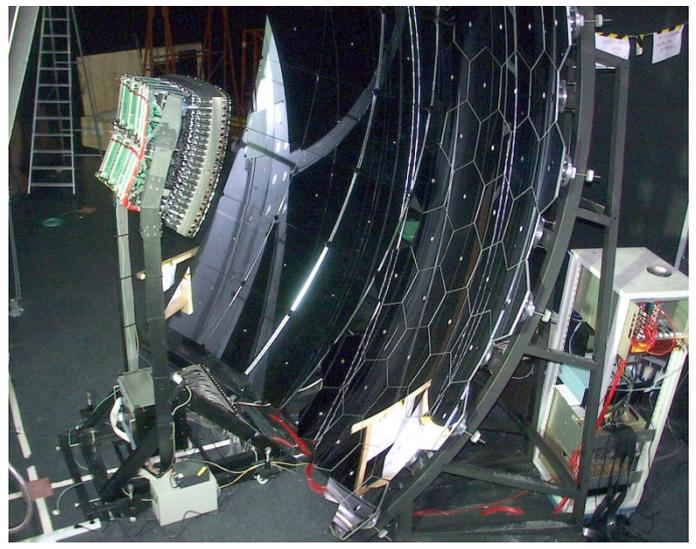


- Location : Mendoza, Argentina
- SD : 1600 water Cherenkov detector, 1.5 km spacing, $\sim 3000 \text{ km}^2$
- FD : 24 telescopes in 4 stations

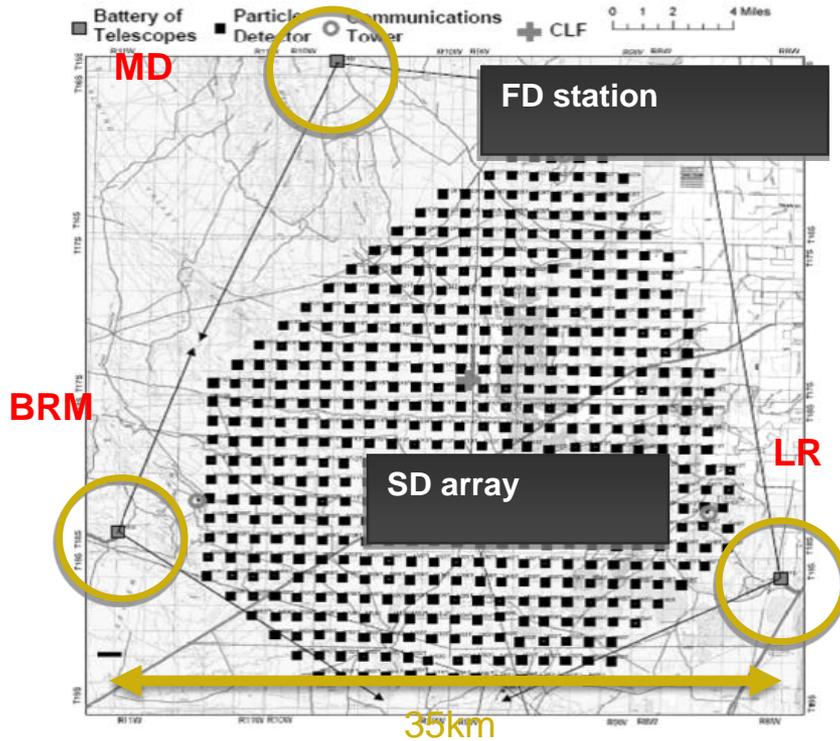
Surface Detector – Water Cherenkov



Fluorescence Detector – PMT

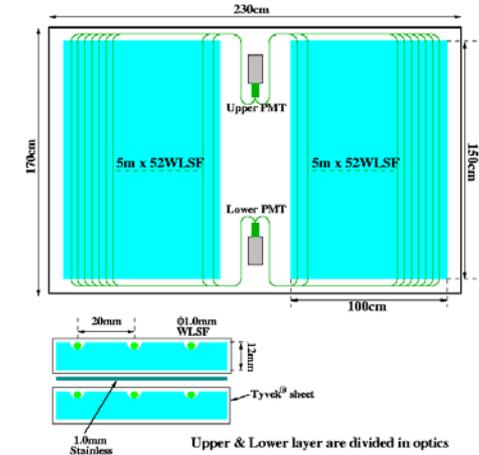


Telescope Array experiment



- Location : Utah, USA
- SD : 507 plastic scintillation detector, 1.2 km spacing, $\sim 700 \text{ km}^2$
- FD : 18 telescopes in 3 stations

Surface Detector – Plastic Scintillation



Fluorescence Detector – PMT



Recent Experiments

| | PAO (2015) | TA (2014) |
|-------------------------------|---|--------------------------|
| energy threshold | 5.2×10^{19} eV | 5.7×10^{19} eV |
| latitude and zenith angle cut | 35.1°S, 80° (44.9°N-90°S) | 39°N, 55° (90°N-16°S) |
| # of events | 231 events | 72 events |
| spectrum | GZK suppression | GZK suppression |
| composition | proton + iron | proton |
| arrival direction | No significant correlation with any astrophysical objects | Hotspot |

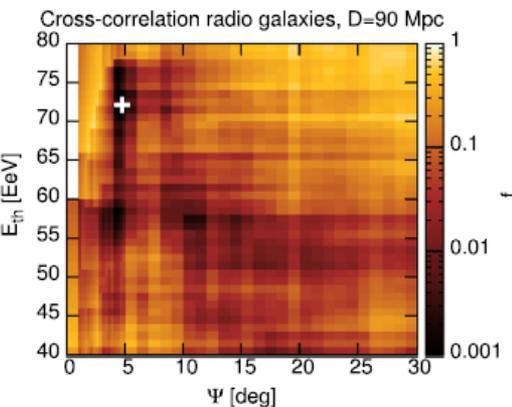
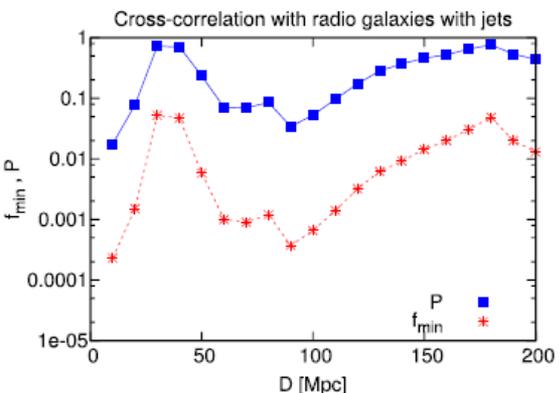
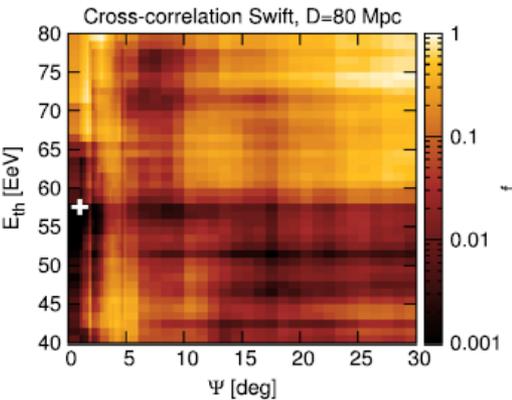
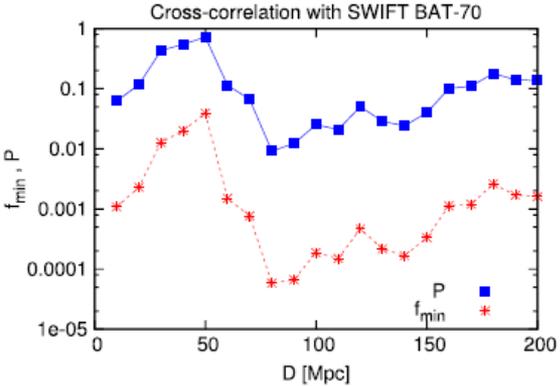
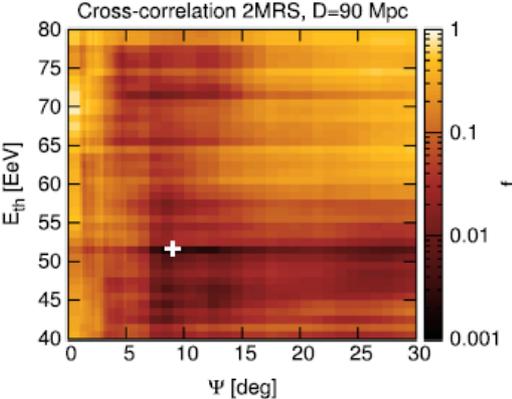
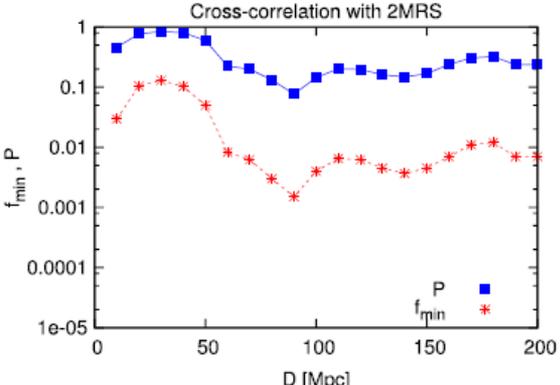
Methodology for studying the correlation with large-scale structure of the universe

Results of PAO [ApJ 804, 15 (2015)]

PAO examines their correlation with different populations of nearby extragalactic objects:

- galaxies in the 2MRS catalog
- AGNs detected by Swift-BAT
- radio galaxies with jets

None of the tests show statistically significant evidence of anisotropy.



Results of TA [ApJ 777, 88 (2013)]

TA examines their correlation with different populations of nearby extragalactic objects:

- galaxies
- AGNs

No statistically significant correlations are found for searching in several catalogs are taken into account.

Table 1
Configurations of the Used Catalogs

| Catalog | Range | N_{all} | N_{target} |
|---------|---------------------------------|------------------|---------------------|
| 3CRR | Compilation of radio surveys | 173 | 16 |
| 2MRS | IR (1–2 μm) | 43533 | 13547 |
| SB-58M | X-ray (14–195 keV) | 1092 | 161 |
| SB-AGN | X-ray (15–55 keV) | 428 | 102 |
| 2LAC | γ -ray (100 MeV–100 GeV) | 1126 | 6 |
| VCV | Compilation of AGNs | 168941 | 762 |

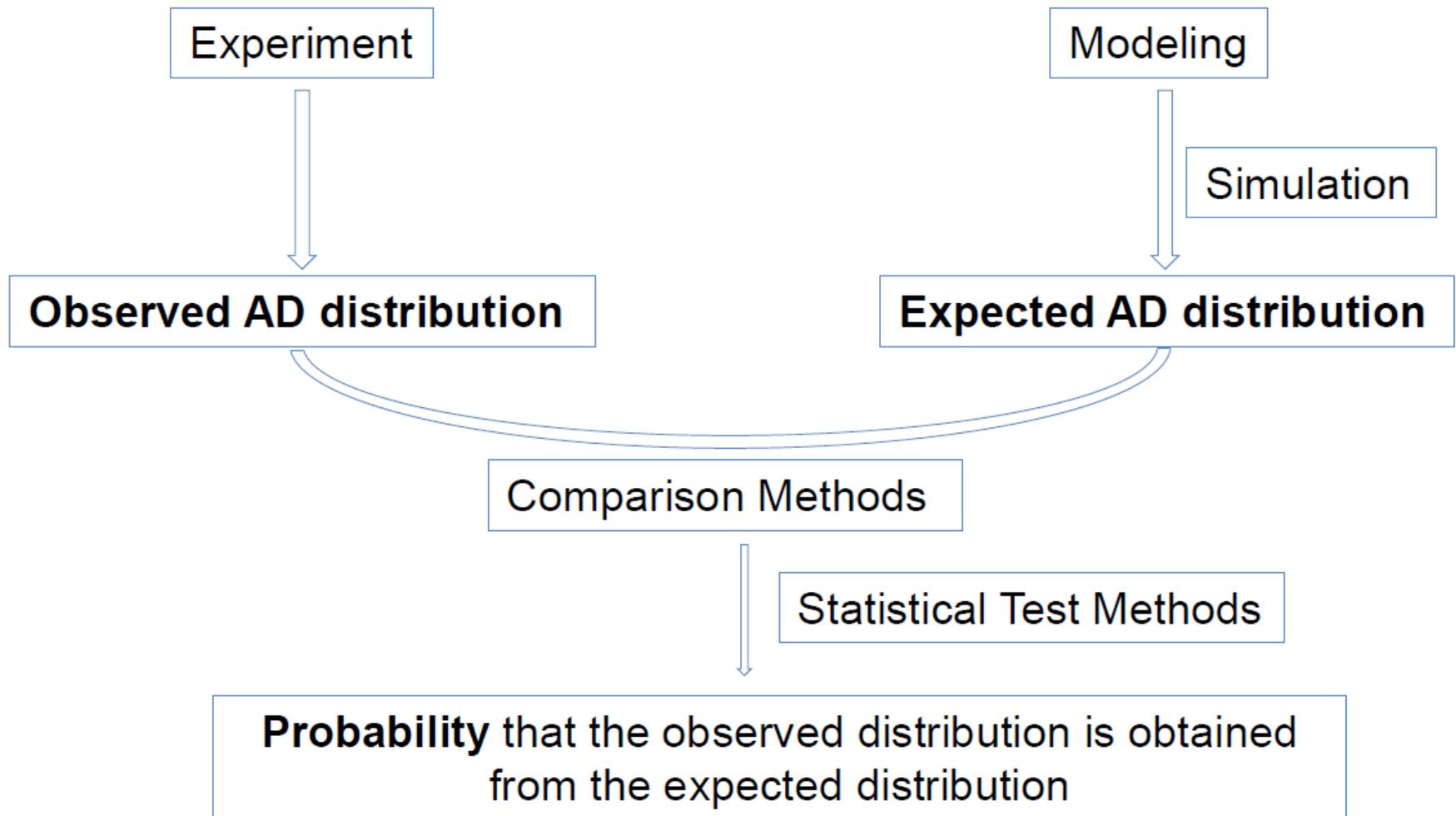
Note. N_{all} : number of all objects contained within the catalog, N_{target} : number of objects with the redshift $z < 0.03$ within the TA FOV.

Table 4
Summary of Correlations with the Best Parameter Set (Minimum Threshold, Window Size, Maximum Redshift) for Each Catalog

| Catalog | E_{min} (EeV) | ψ (deg) | z_{max} (z) | A | N | k | p | P_{min} | P_{PPS} |
|---------|---------------------------|-----------------|-----------------------------|-----|-----|-----|--------|----------------------|------------------|
| 3CRR | 66.77 | 2.0 | 0.017 | 4 | 11 | 1 | 0.0020 | 2.2×10^{-2} | 0.75 |
| 2MRS | 51.85 | 6.5 | 0.005 | 660 | 31 | 29 | 0.62 | 8.5×10^{-5} | 0.21 |
| SB-58M | 57.46 | 11 | 0.017 | 79 | 25 | 25 | 0.68 | 6.1×10^{-5} | 0.04 |
| SB-AGN | 62.20 | 10 | 0.020 | 58 | 17 | 17 | 0.52 | 1.3×10^{-5} | 0.01 |
| 2LAC | 55.41 | 12 | 0.018 | 3 | 23 | 3 | 0.069 | 2.1×10^{-1} | 0.83 |
| VCV | 62.20 | 2.1 | 0.016 | 288 | 17 | 8 | 0.14 | 8.6×10^{-4} | 0.25 |

Notes. A : number of objects with the redshift $\leq z_{\text{max}}$, N : number of observed cosmic ray events with the energy $E \geq E_{\text{min}}$, k : number of events correlated with objects, p : probability of correlation for a single event from an isotropic distribution, P_{min} : the cumulative binomial probability to obtain k or more estimated from an isotropic distribution, and P_{PPS} : the probability after including the penalties from parameter scanning.

Strategy



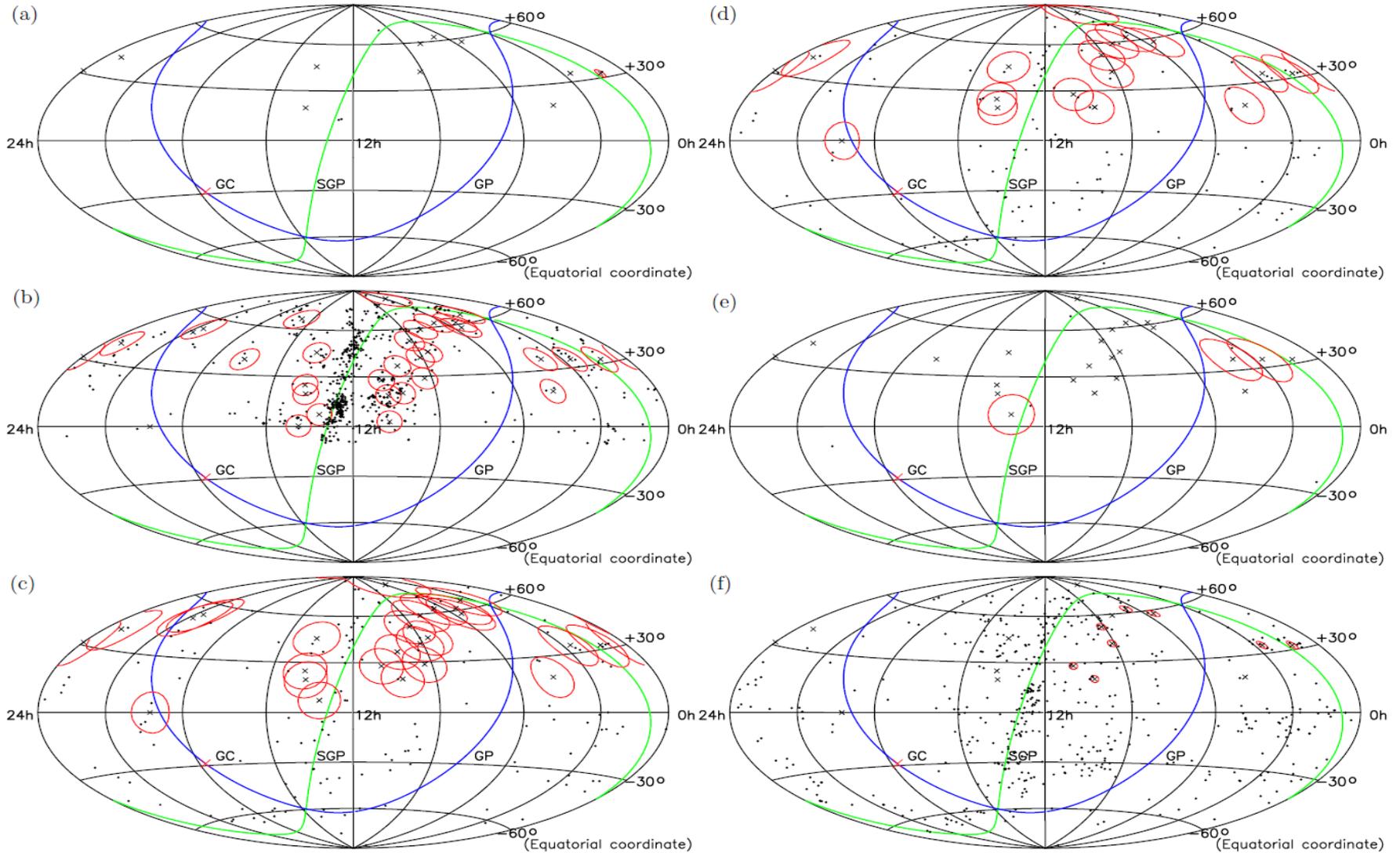
Exploratory analysis for correlation search

- 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

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

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. \rightarrow correlation angle



Close correlation between TA events and local galaxy filaments

Clustering feature of TA UHECR events [ApJL 790, L21 (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 ($N_{\text{on}} = 19, N_{\text{bg}} = 4.49$). We calculated the probability of such a hotspot appearing by chance in an isotropic cosmic-ray sky to be 3.7×10^{-4} .

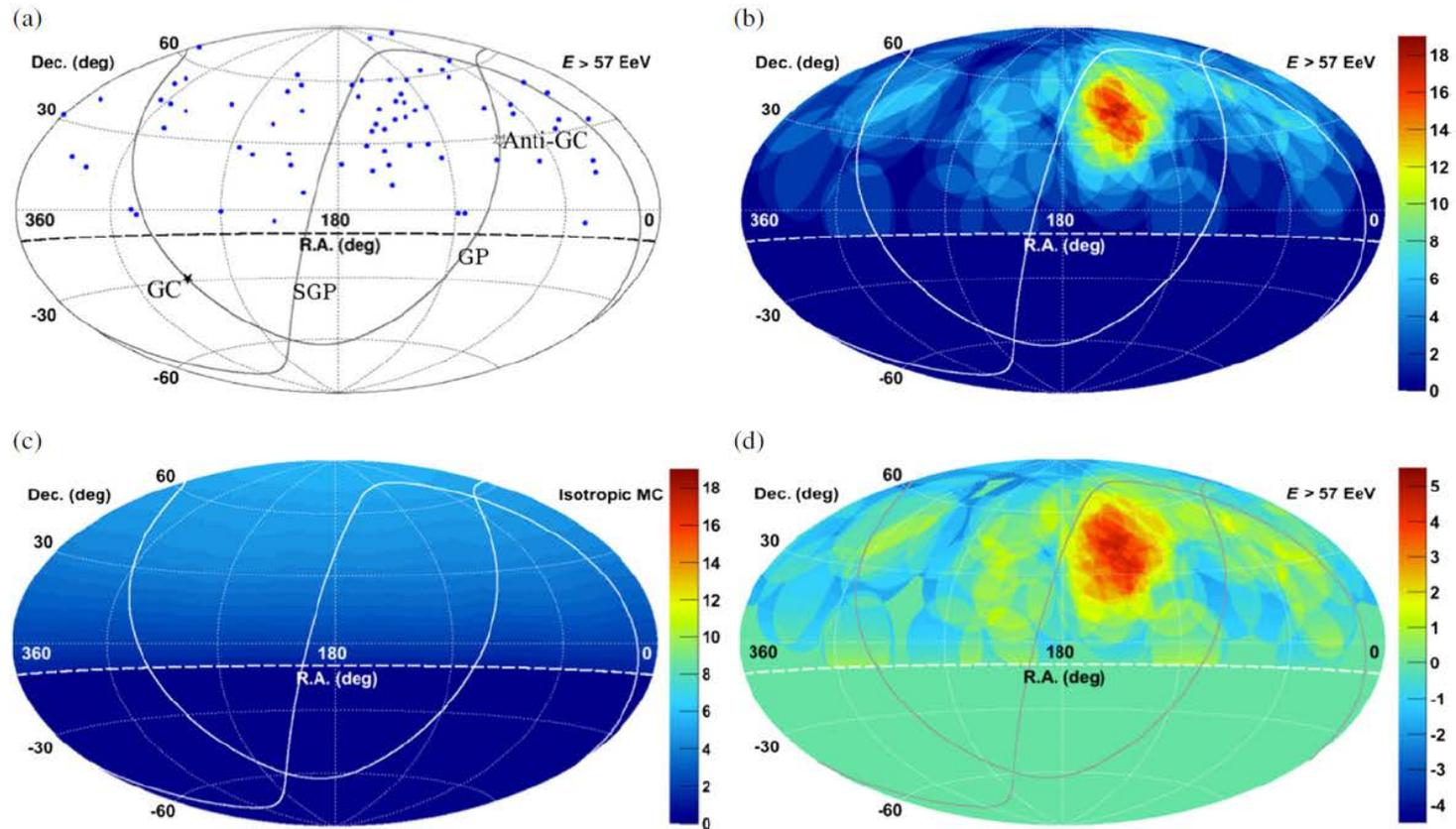
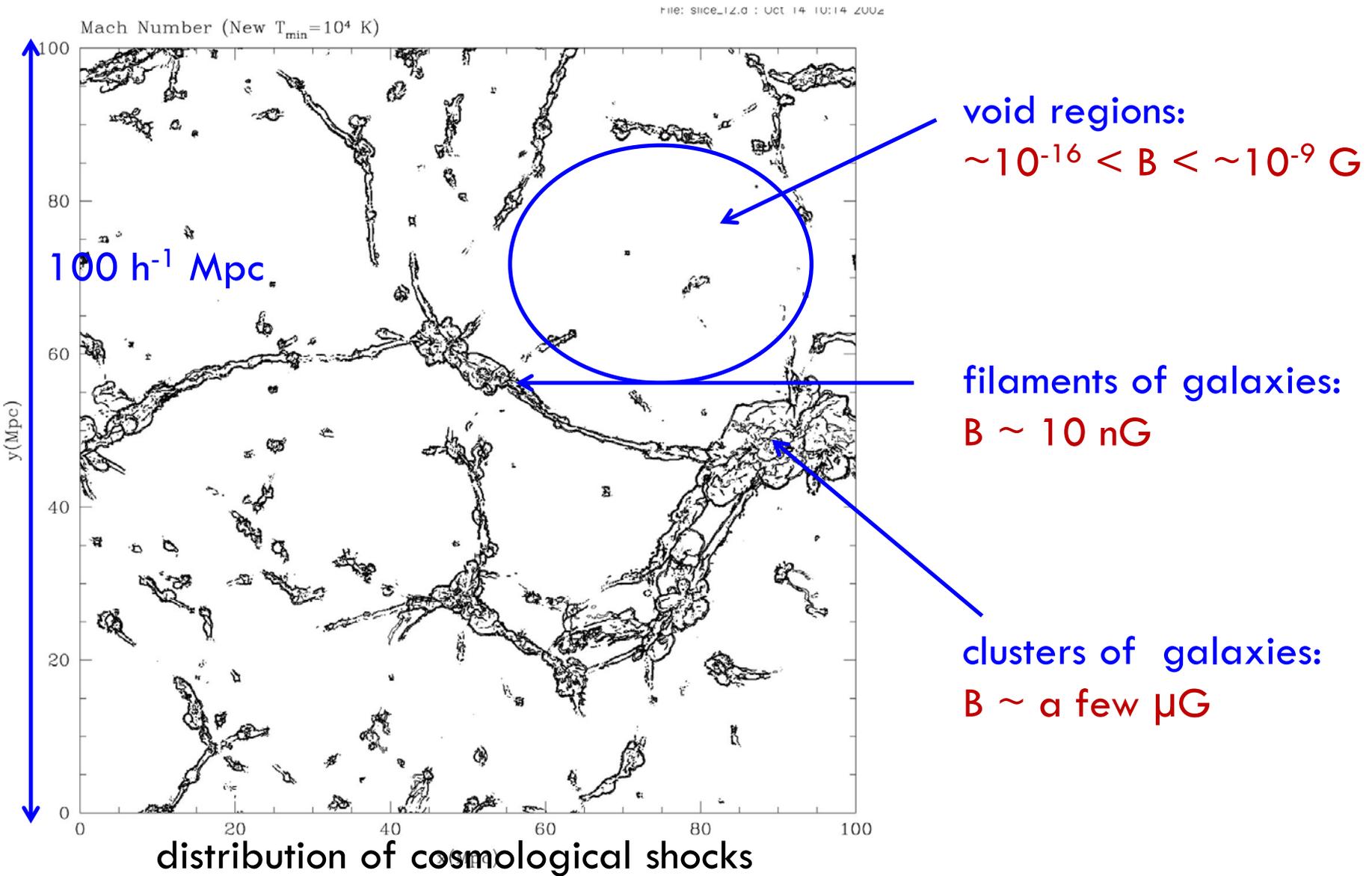


Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. = -10° . (a) The points show the directions of the UHECRs $E > 57$ EeV observed by 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).

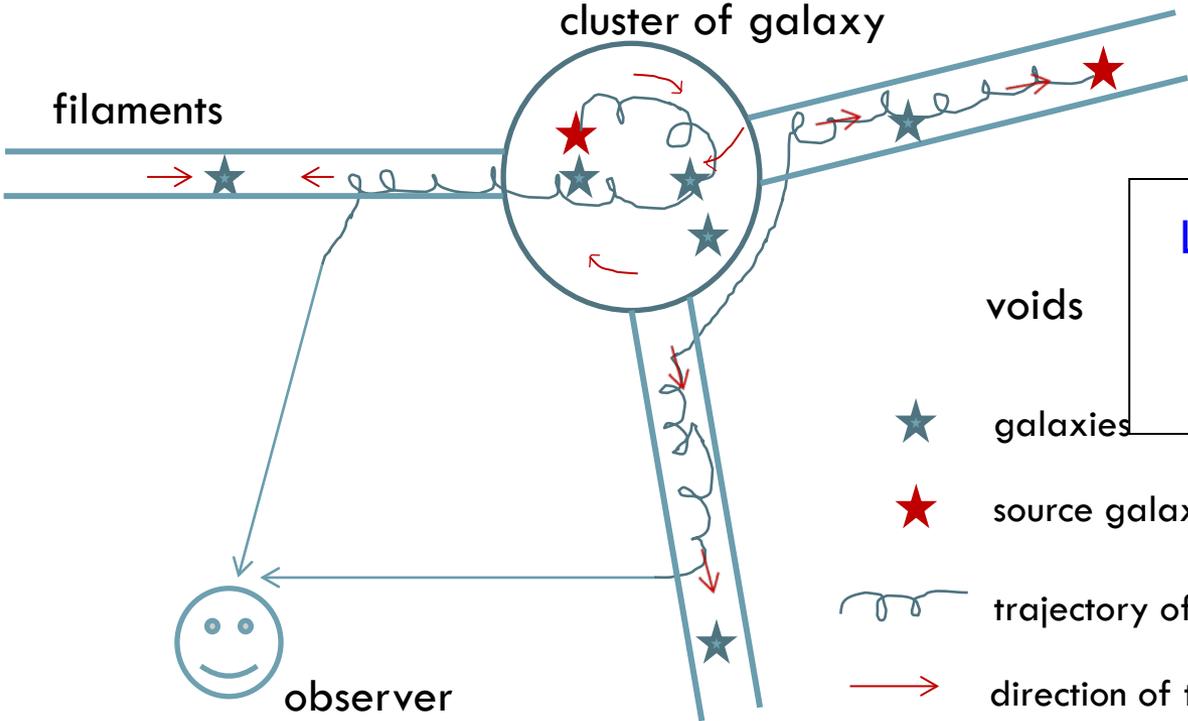
LSS and intergalactic magnetic field



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 leave 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 $D \sim$ a few Mpc and magnetic field of $B \sim 10$ nG can confine UHECRs of $E \sim 50$ EeV !

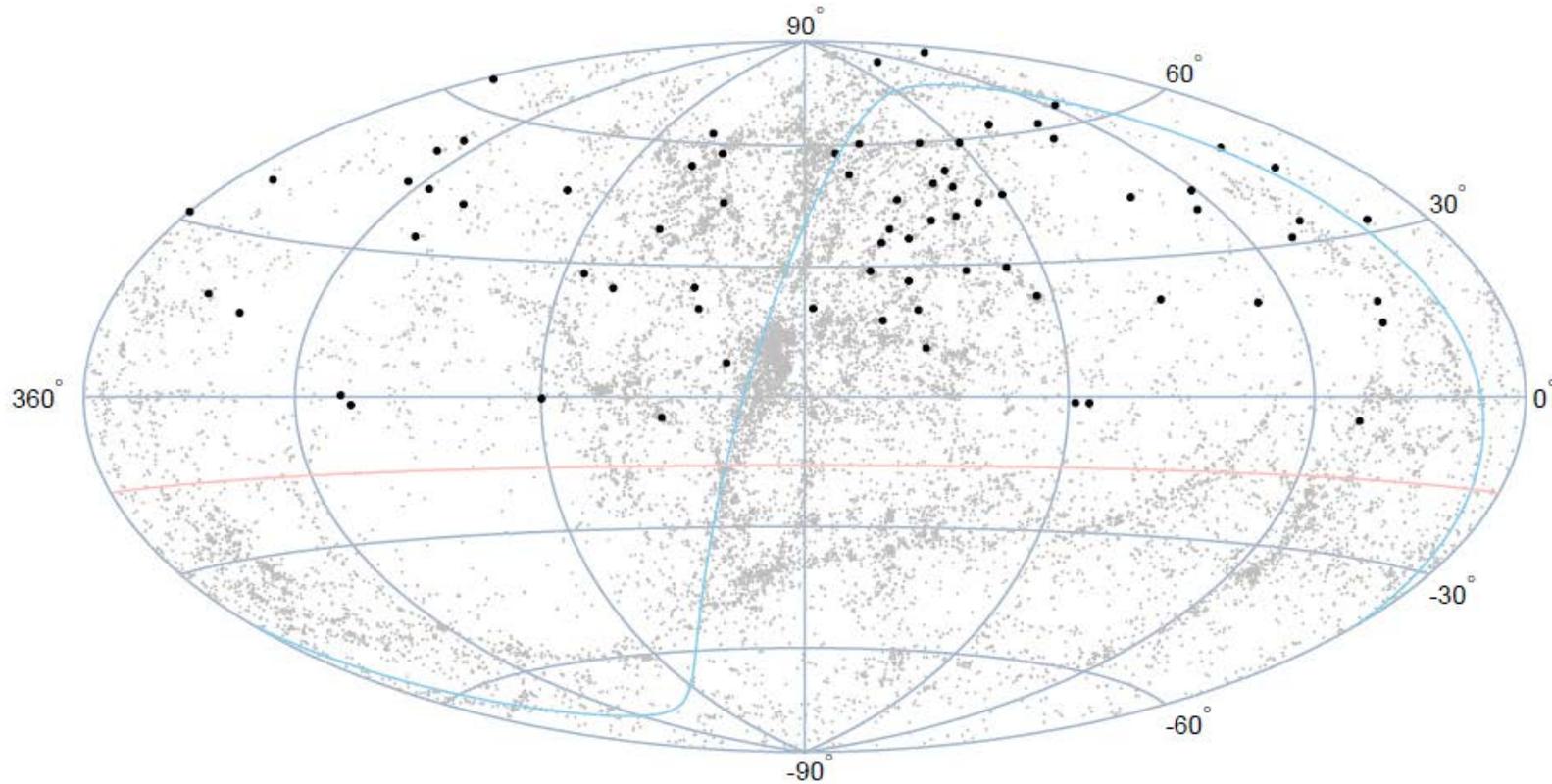


Larmor radius:

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

- voids
- galaxies
- source galaxies
- trajectory of UHECR
- direction of the magnetic fields

72 TA events with ≥ 57 EeV and galaxies with $v \leq 3500$ km/s from HyperLEDA in the equatorial coordinates



Grey dots: Hyper LEDA galaxies with $v \leq 3500$ km/s

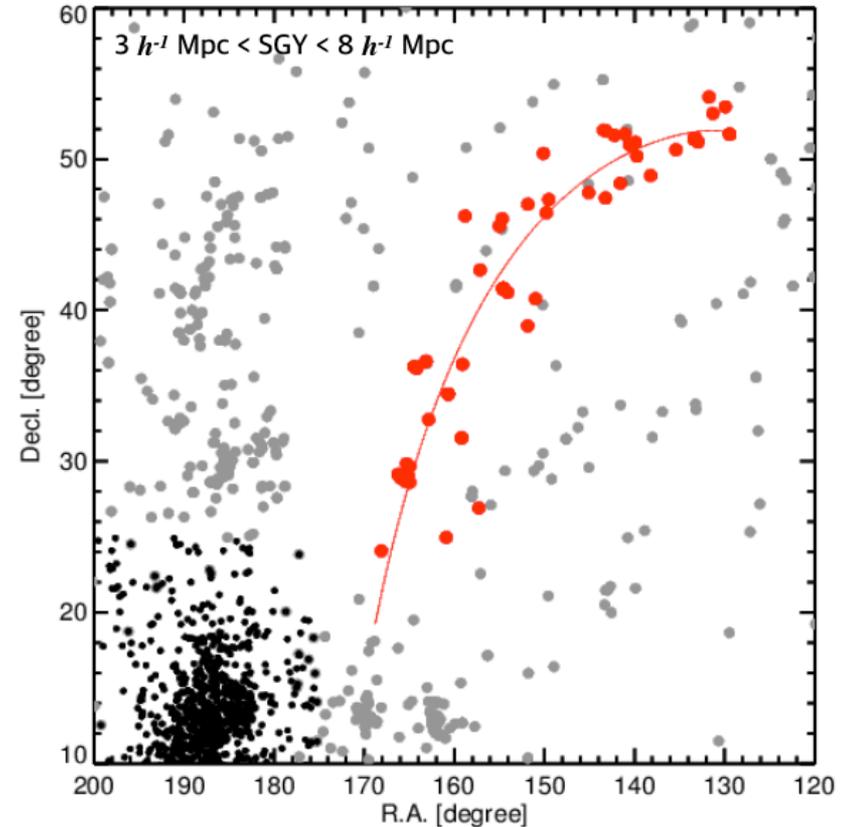
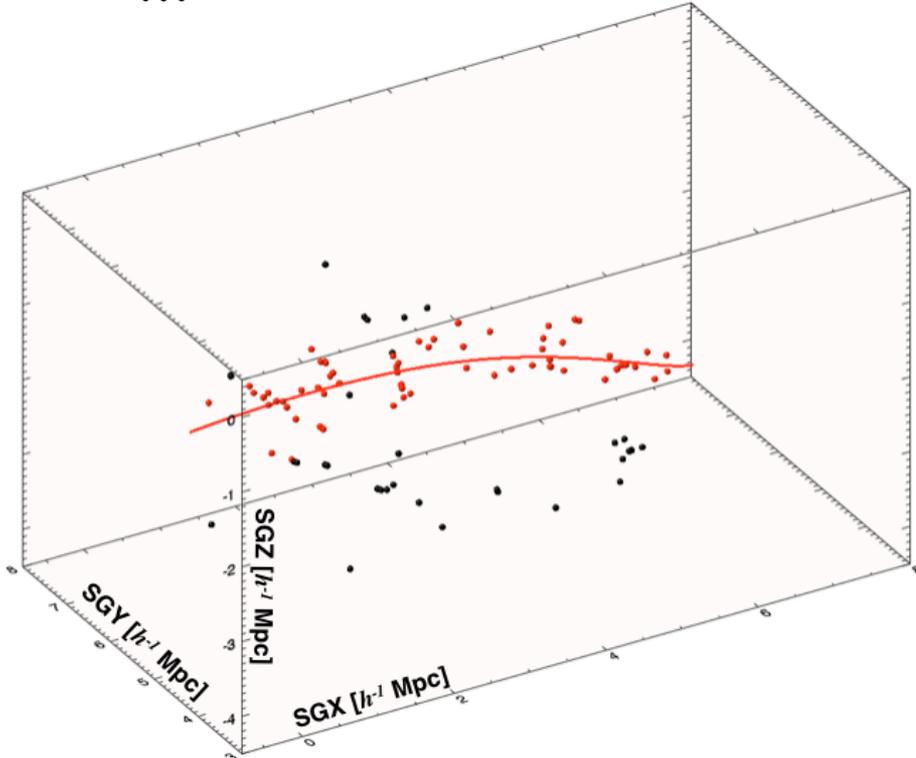
Black dots: TA events

Pink line: Boundary of TA exposure

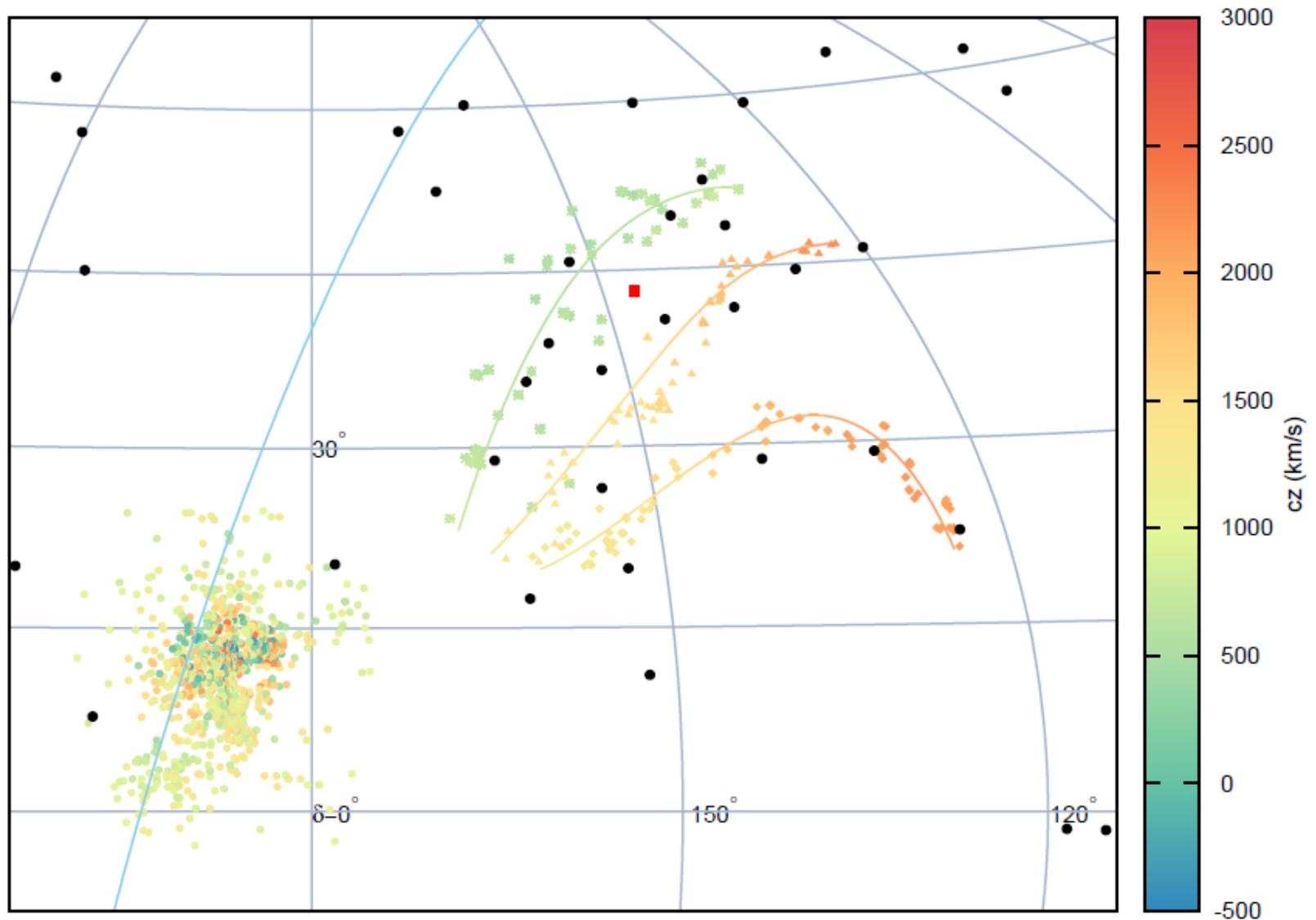
Skyblue line: Supergalactic plane

Finding filaments around the region of TA hotspot

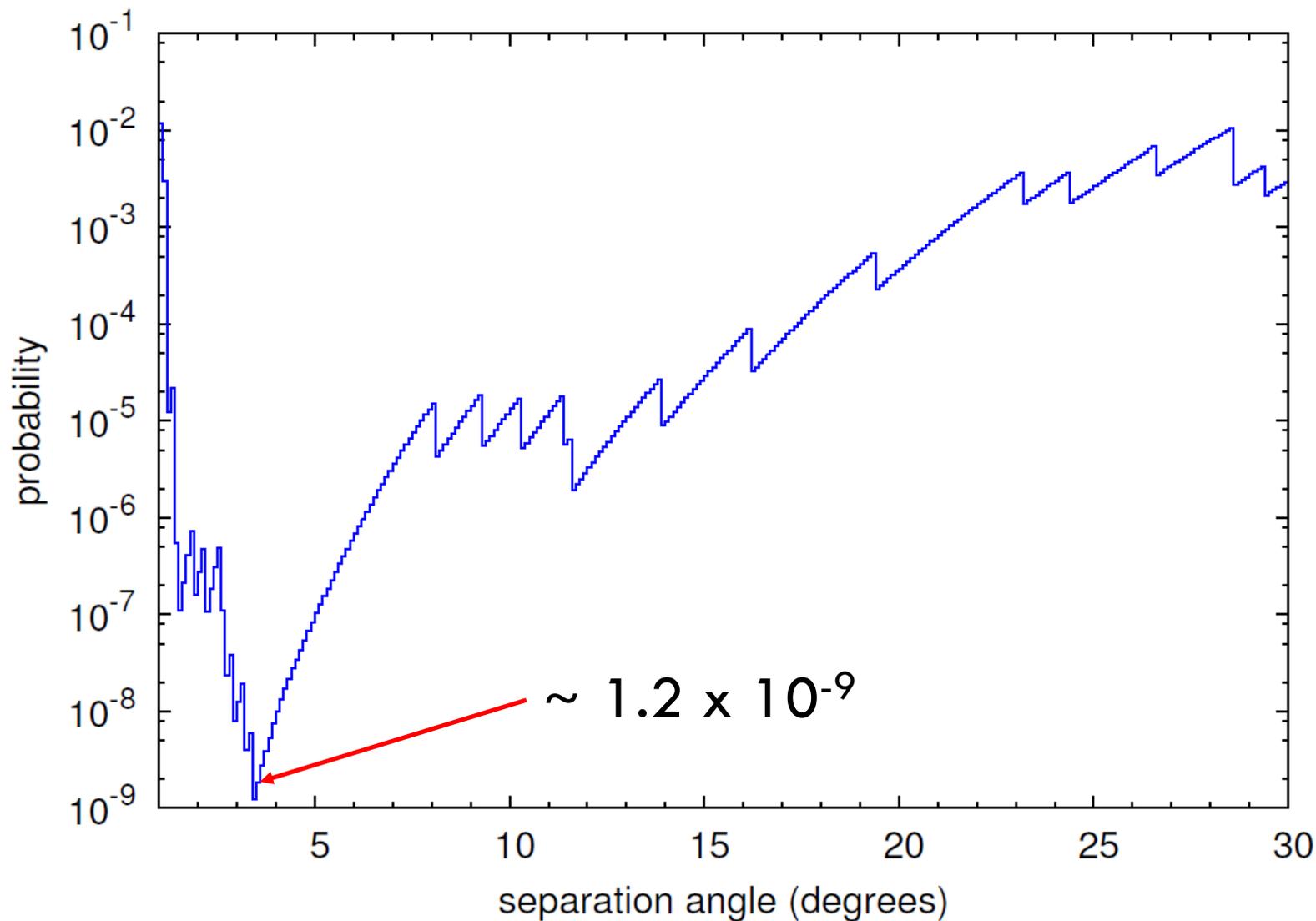
- used galaxies in HyperLEDA and EVCC catalogs
- worked in the supergalactic coordinates
- picked neighboring galaxies using Voronoi tessellation
- constructed filamentary structures
- found three new filaments around the hotspot area
- ...



Correlation between TA events and filaments?



Binomial probability of the excess of TA events with ≥ 57 EeV around the spines of three filaments inside $\leq \theta$



Results of statistical analysis

| reference | angle | cr_num | sim_num | p_sim | iso_num | bino_prob | bino_sig |
|-----------|-------|--------|---------|----------|---------|-----------------------|----------|
| spines | 3.4 | 18 | 43274 | 4.33E-02 | 3.12 | 1.23×10^{-9} | 6.08 |

- We found that 18 out of 72 events correlated at 3.4° , while 3.12 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

$$P(X \geq 18) = 1.23 \times 10^{-9} \rightarrow 6.08\sigma$$

- We simulated 10^9 sets of isotropic arrival directions containing the same number of events as the data set. For the filament spine, we found the post-trial probability is

$$P = 2.0 \times 10^{-8}$$

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 close correlation between TA hotspot events and galaxy filaments attached to the Virgo Cluster was found.
 - Filaments are connected to the Virgo Cluster → the source (or sources) of TA hotspot events is likely in the Virgo Cluster
 - Close correlation with $\theta \sim 3^\circ$ (deflection due to the GMF: a few to several deg for protons but much larger for ions toward the hotspot direction at $E \geq 57$ EV) → TA UHECR events are mostly protons.
- Further exploration of correlation between UHECR events vs galaxy distribution in the local universe is under way.