Ultra-High Energy Cosmic Rays Observed by the Telescope Array Experiment

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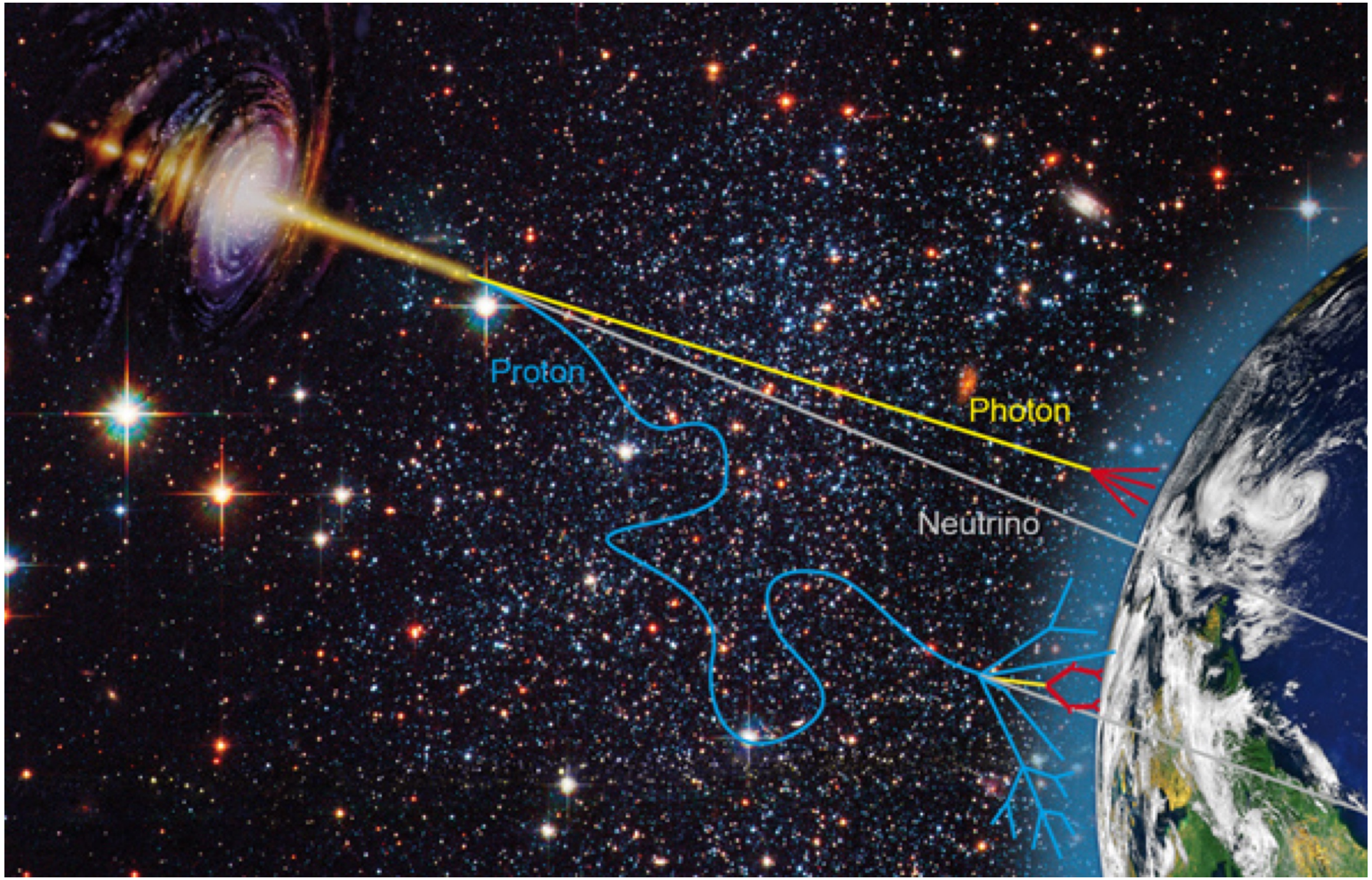
Outline

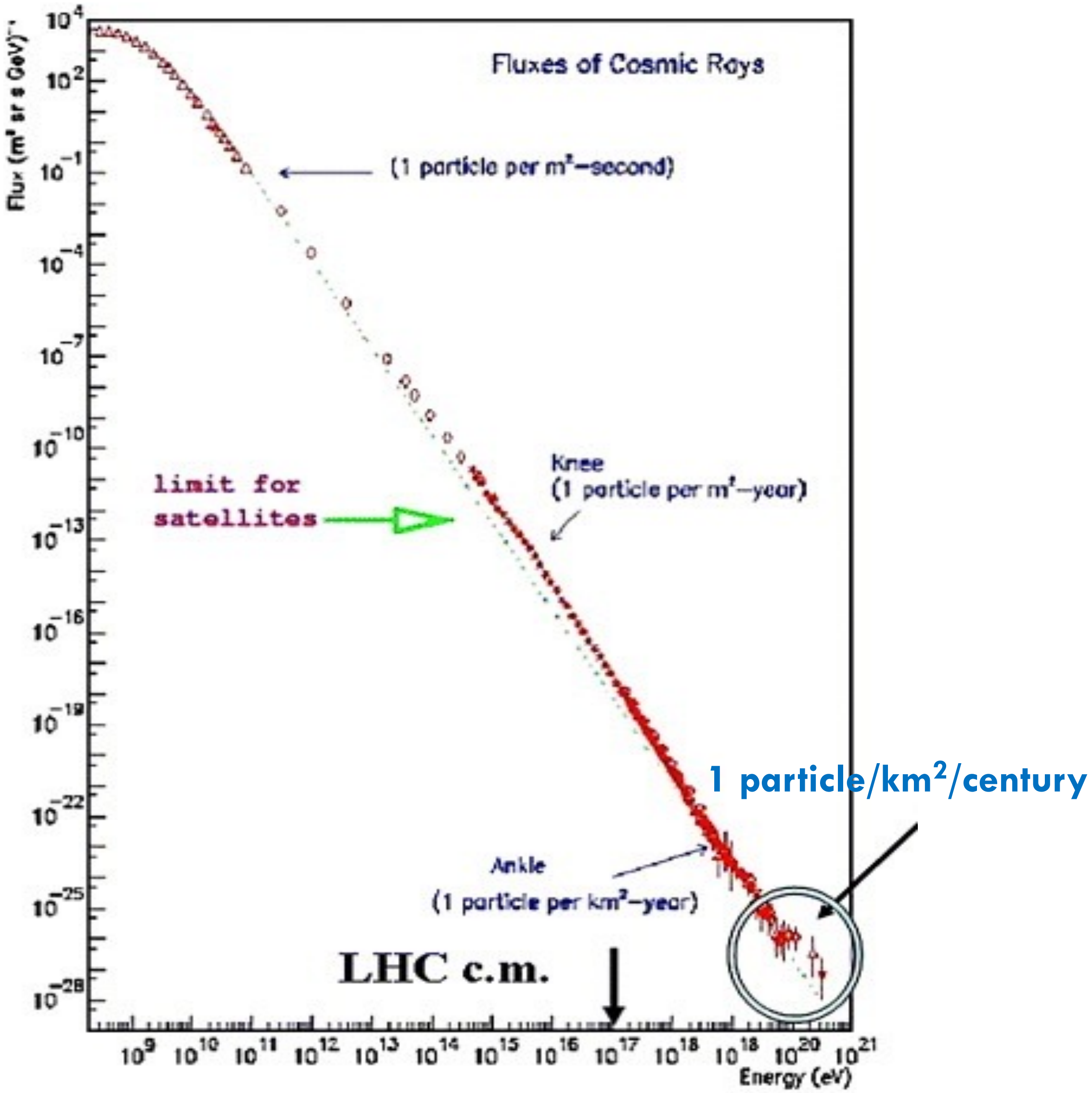
- Ultra-high energy cosmic rays
- Telescope Array experiment
  - Surface detectors
  - Fluorescence detectors
  - Recent results
- Intermediate-scale anisotropy in arrival direction distribution
  - Telescope Array Hotspot
  - New excess of events in the direction of the Perseus-Pisces supercluster
- Future prospects

Ultra High Energy Cosmic Rays



- Cosmic rays (CRs): Energetic charged particles that impinge on Earth's atmosphere from outer space
- Ultra-high energy cosmic rays (UHECRs): Cosmic rays with energies greater than 10^{18} eV

Fluxes of cosmic rays



- Overall, the flux of CRs appears to follow a single power law $\sim E^{-3}$.
- In the ultra-high-energy regime ($E>10^{18}$ eV), direct detection is not feasible due to the extremely low flux.
- **Indirect observation** is necessary!
- A **gigantic observation facility** is essential to collect sufficient data.

Why are these energetic particles interesting?

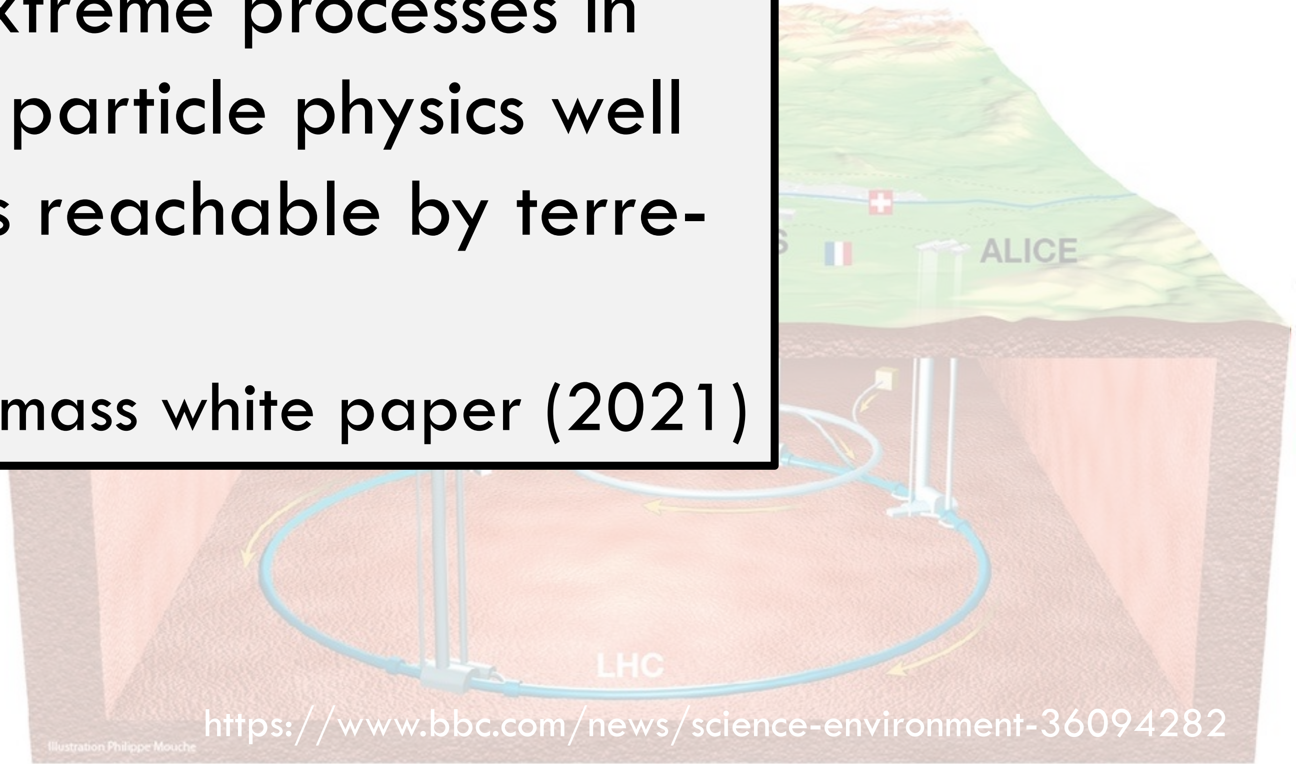
UHECRs' energies are much higher than those scientists can accelerate in the lab, like t[…] collider (LHC).

- How do they achieve such high energy?

[…]ming from?

> "They can simultaneously inform our knowledge of the most extreme processes in the Universe and of particle physics well beyond the energies reachable by terrestrial accelerators."
>
> Snowmass white paper (2021)

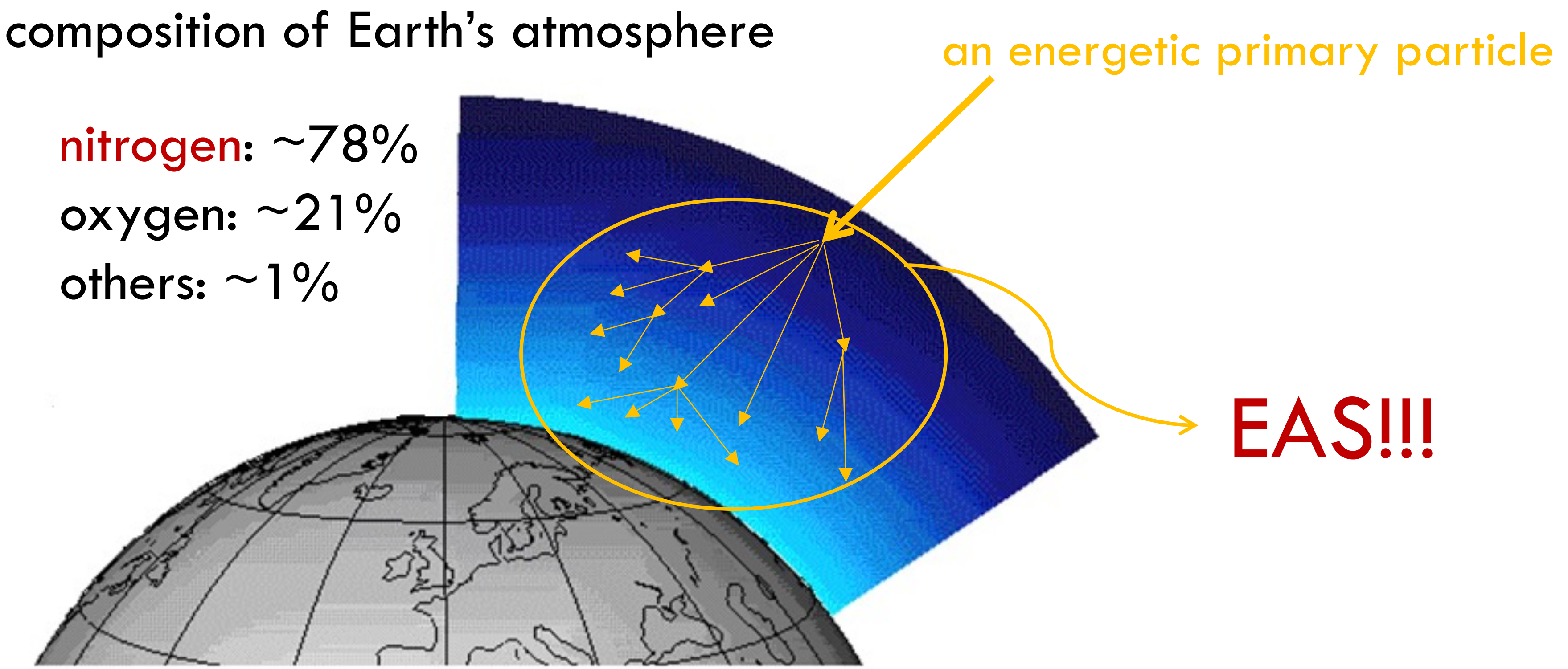

CMS collaboration



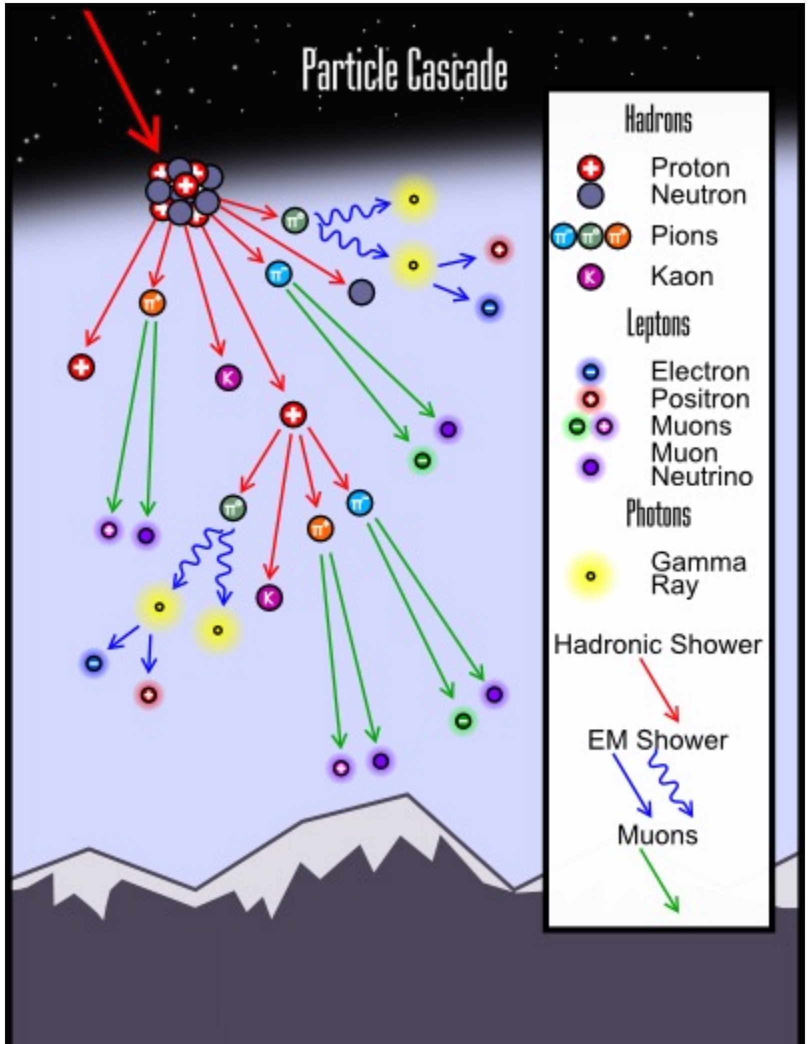
https://www.bbc.com/news/science-environment-36094282

How can we detect UHECRs?

- **Extensive Air Shower (EAS):** A cascade of millions of subatomic particles initiated when a single UHECR collides with a nucleus in the atmosphere



How can we detect UHECRs?



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

- Fluorescence detectors (FDs):

- Telescopes observe nitrogen fluorescence lights in the atmosphere emitted by when charged particles pass through the atmosphere

- Clear, moonless nights: ~10% on-time

- Measure the longitudinal development of the EAS

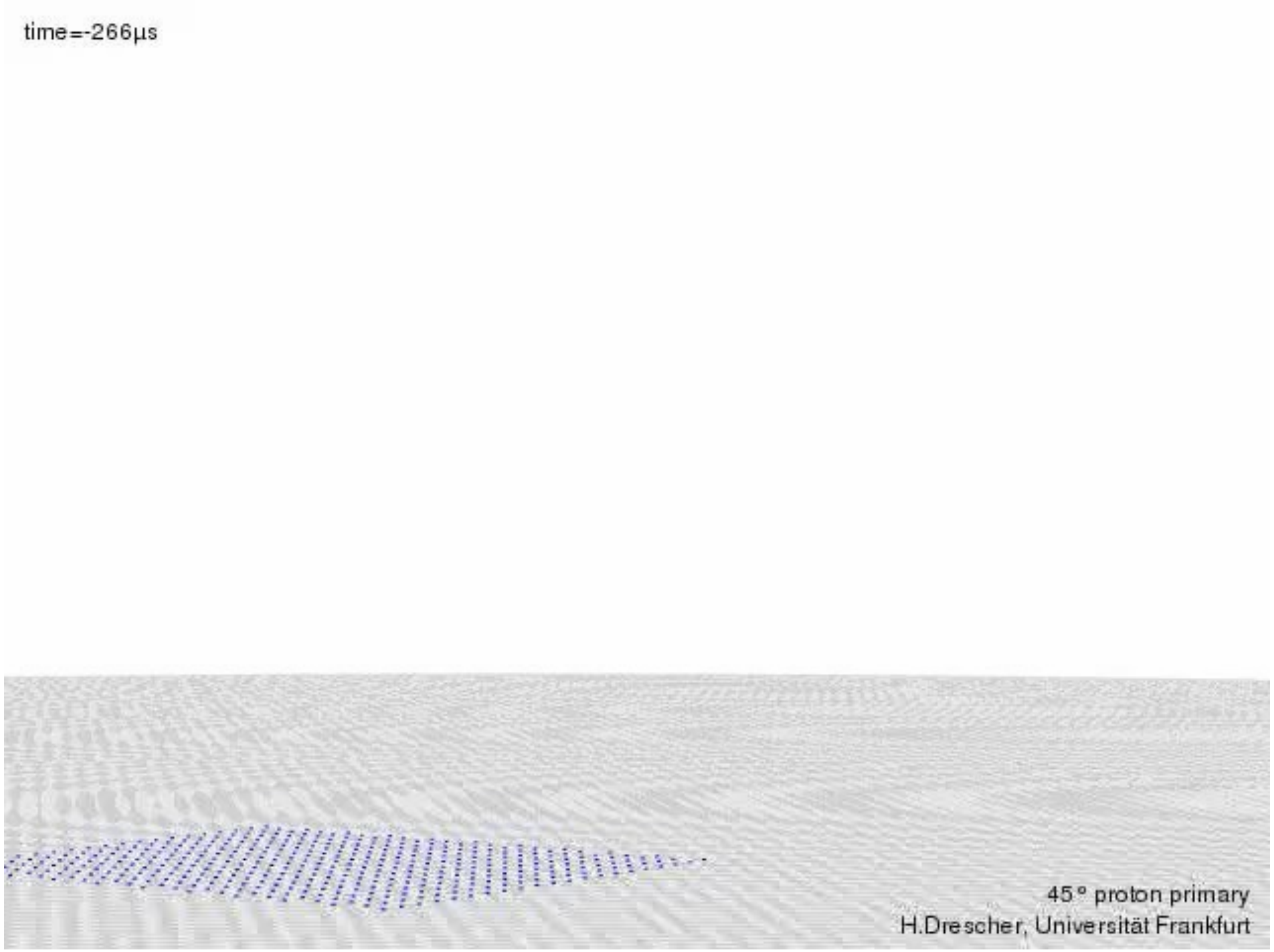
- Surface detectors (SDs):

- Scintillators sample the density of charged particles in the shower when it reaches the Earth's surface

- ~100% on-time

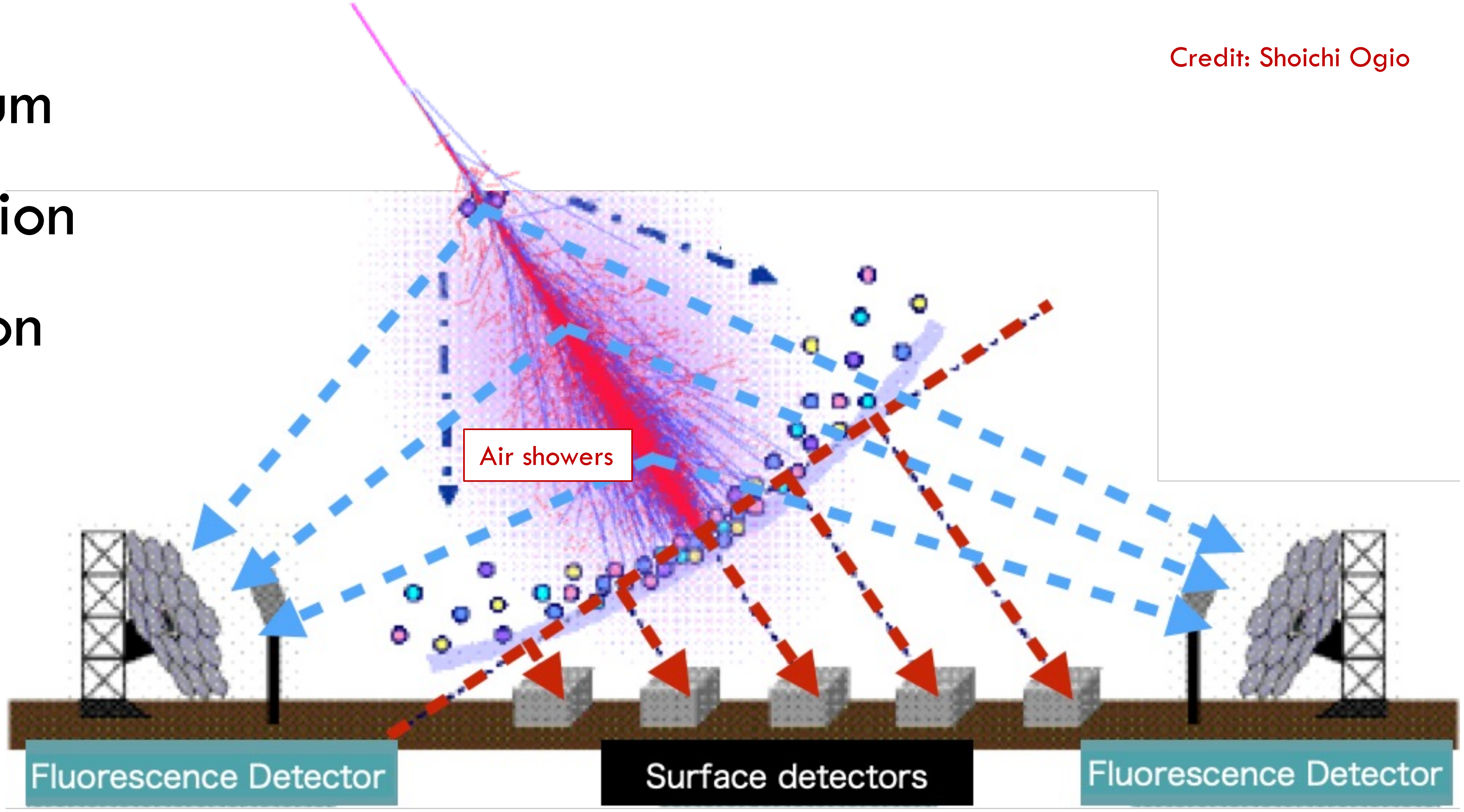
- Measure the lateral footprint of the EAS

Simulation of an extensive air shower



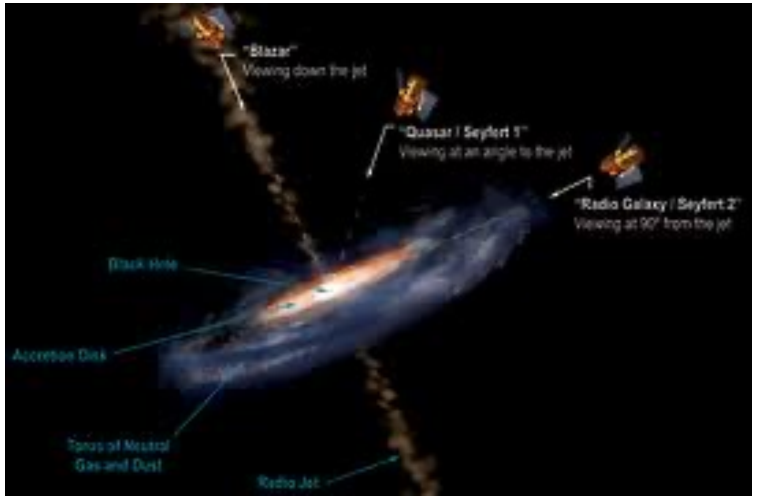
Main observables of UHECRs

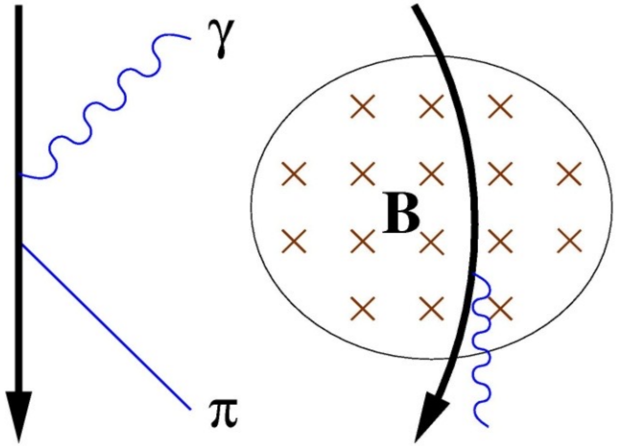
- Energy spectrum
- Mass composition
- Arrival direction

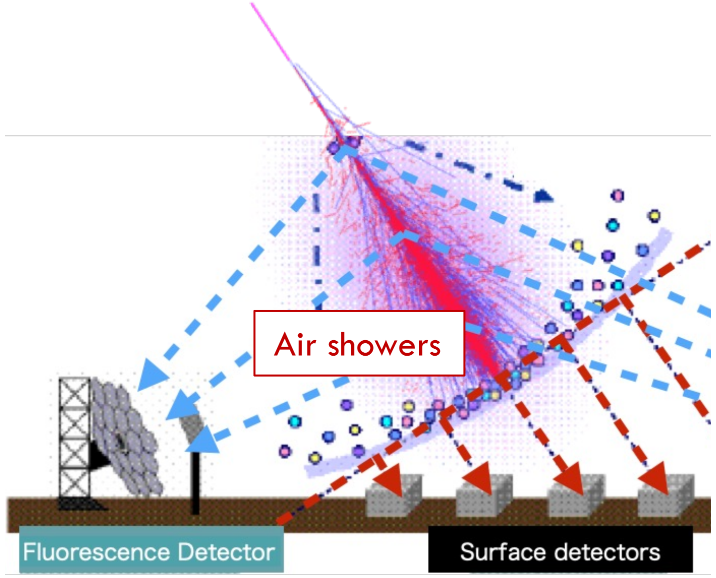


Astrophysics of UHECRs

From production to observation: Astrophysics + Particle physics







Production

- Acceleration of charged particles
- Decay of superheavy particles

Propagation

Cosmic microwave background photons, Cosmic magnetic fields, …

- Energy loss
- Secondary CR production
- Deflection

Observation

Atmosphere as calorimeter

- Composition
- Energy
- Arrival Direction

Production: Source candidates

- Source candidates are required to be capable of confining particles up to E_{max}, which translates into a simple selection criterium for candidate sources with magnetic field strength *B* and size *D*,

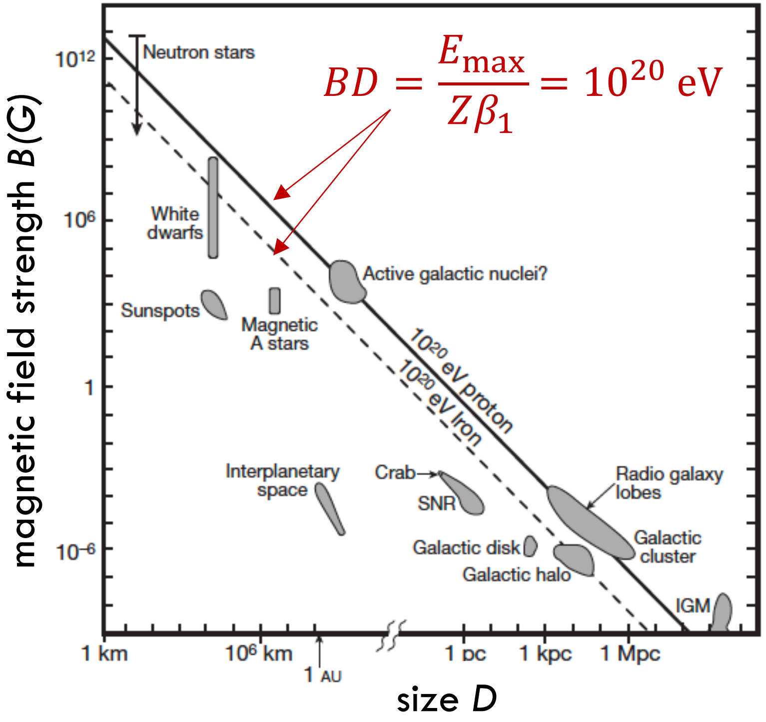
$$E_{\max} = 4 \times 10^{20}\, Z \left(\frac{B}{100\mu\mathrm{G}}\right)\left(\frac{\beta_1}{0.3}\right)\left(\frac{D}{100\,\mathrm{kpc}}\right) \mathrm{eV}.$$

where Z is the atomic number

B is the magnetic field

β_1 is the Lorentz factor

D is the size of the astronomical objects



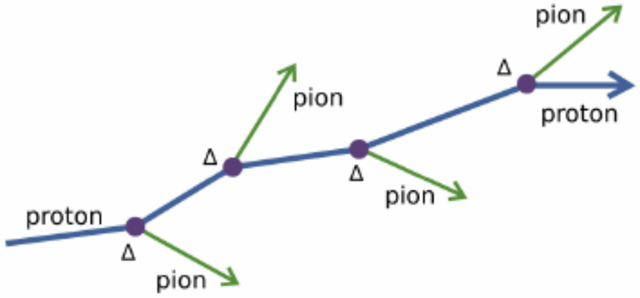
Bauleo and Martino (2009)

Propagation: Distance limitation

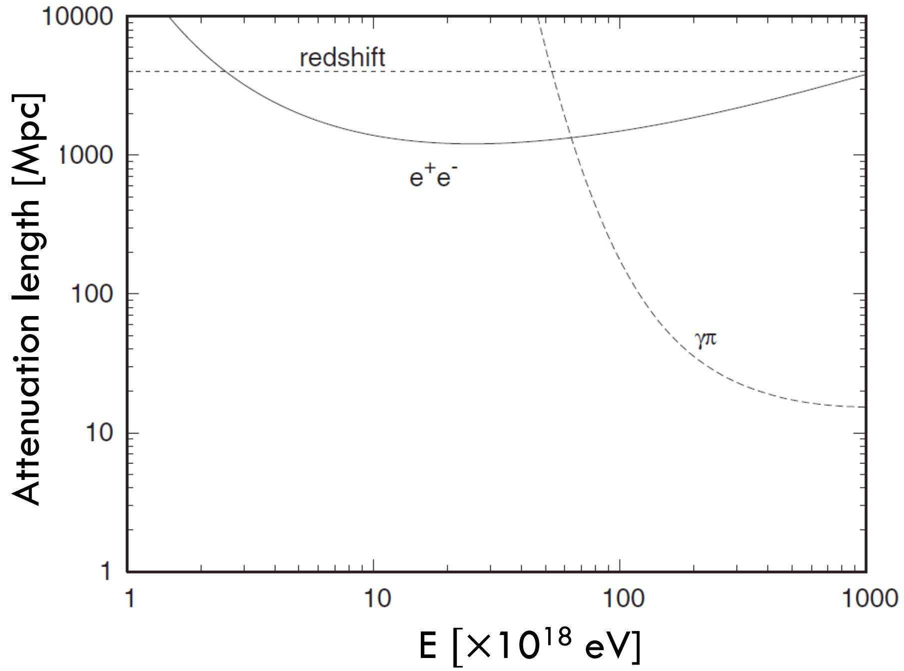
- When UHECRs propagate in the universe, they undergo attenuations. If we assume a proton as a primary particle, the energy losses can be described by

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

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



$$p + \gamma_{CMB} \rightarrow \pi + N$$



Harari et al. (2006)

Propagation: Deflection by magnetic fields

- Since UHECRs are charged particles, their trajectories would be deflected by cosmic magnetic fields. The typical deflection angle using random patches of magnetic fields is given by

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

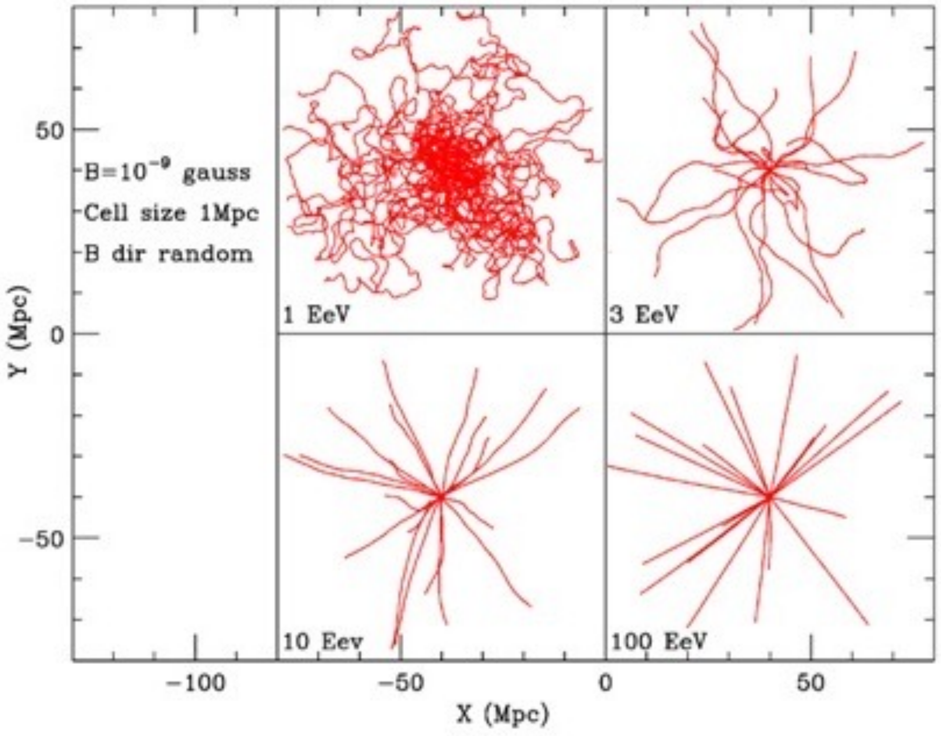
where Z is the atomic number

E is the energy of UHECR

d is the distance

l_c is the average size of patches

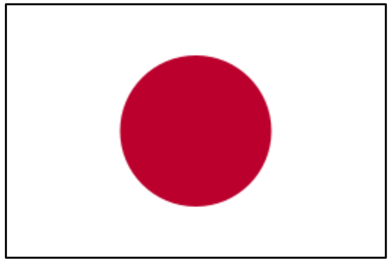
B is the magnetic field



Observatory for UHECRs

Telescope Array Collaboration

USA



Japan

Korea

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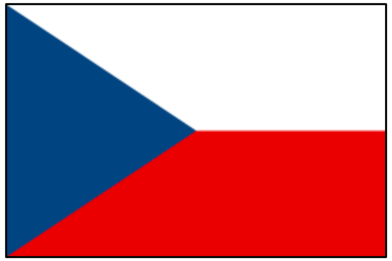
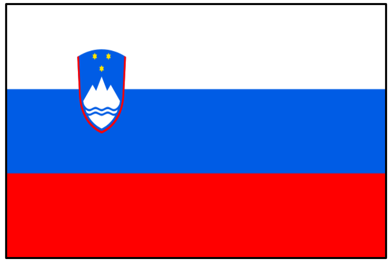
140 members, 32 institutes, 7 countries

Russia

Belgium



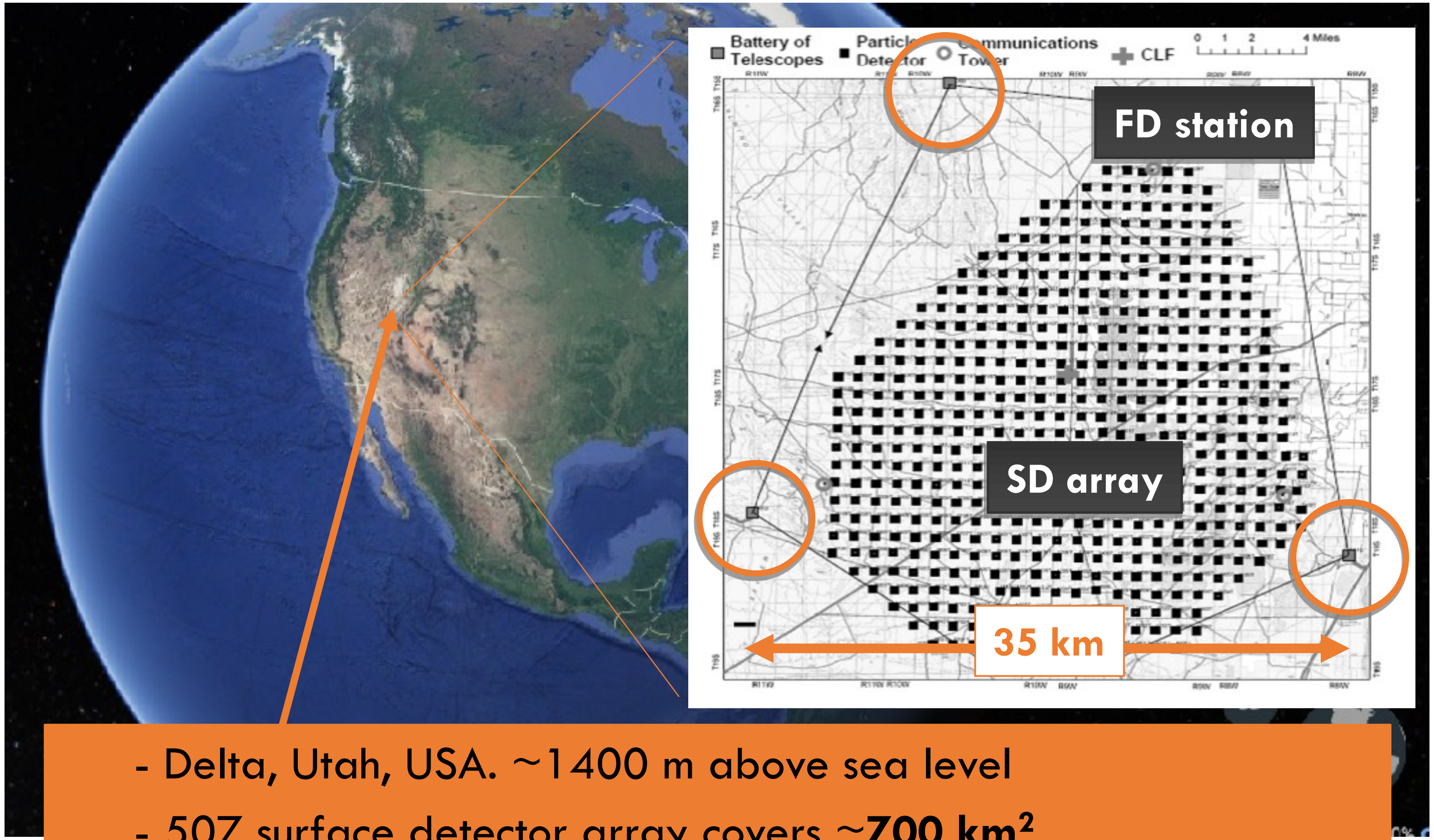
Czech Republic



Slovenia

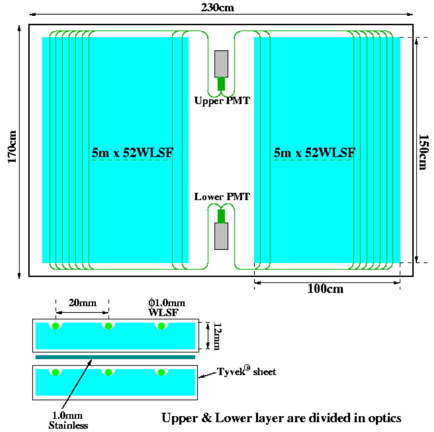
Telescope Array (TA) experiment

- The largest cosmic ray observatory in the northern hemisphere



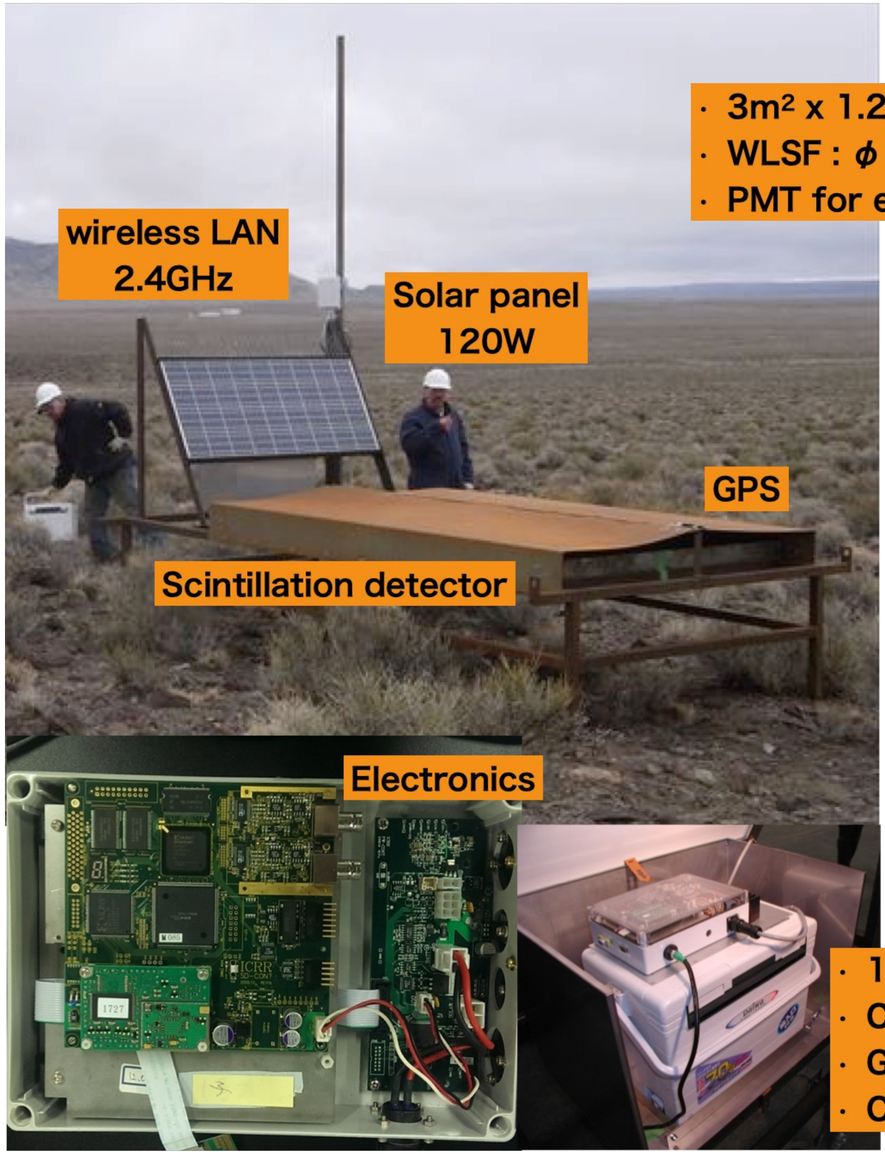
- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km^2**
- 38 telescopes in 3 stations look over the array

Surface Detector: Plastic Scintillator

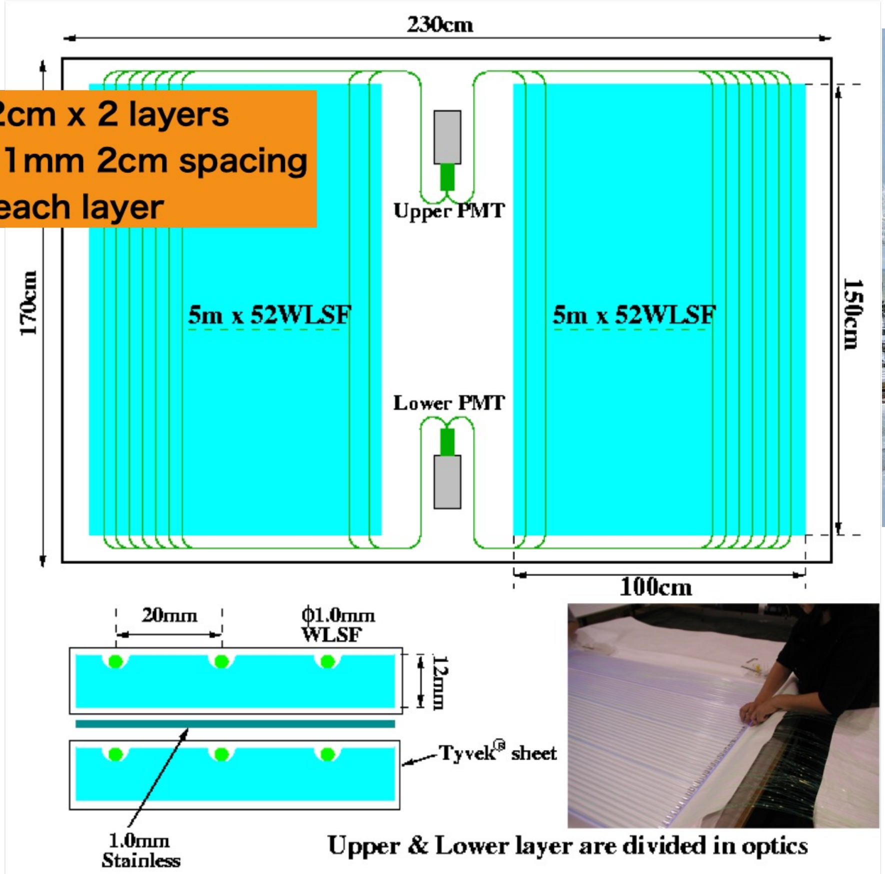


Fluorescence Detector: PMT camera

Scintillator Surface Detectors (SDs)



- $3m^2$ x 1.2cm x 2 layers
- WLSF : ϕ1mm 2cm spacing
- PMT for each layer

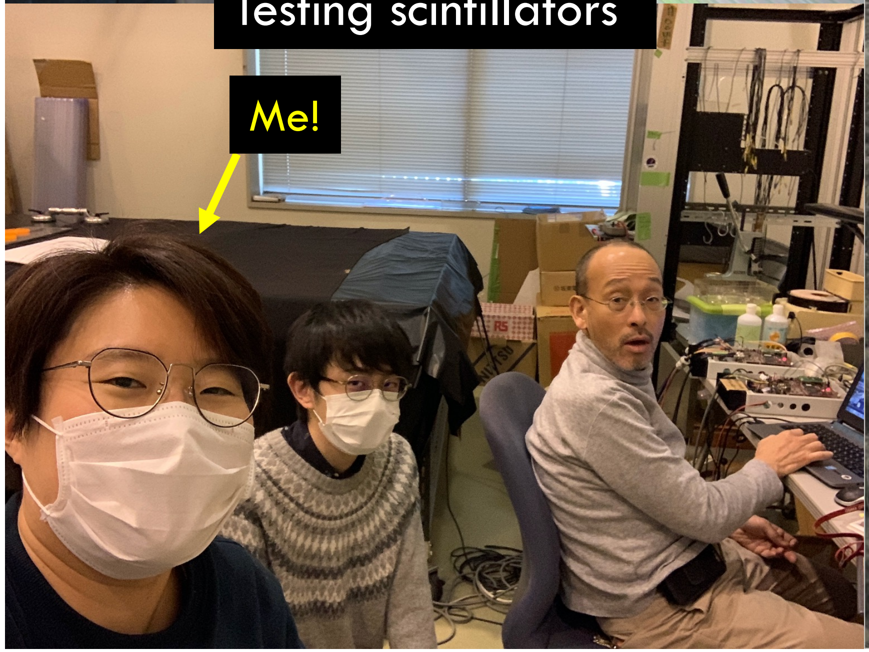


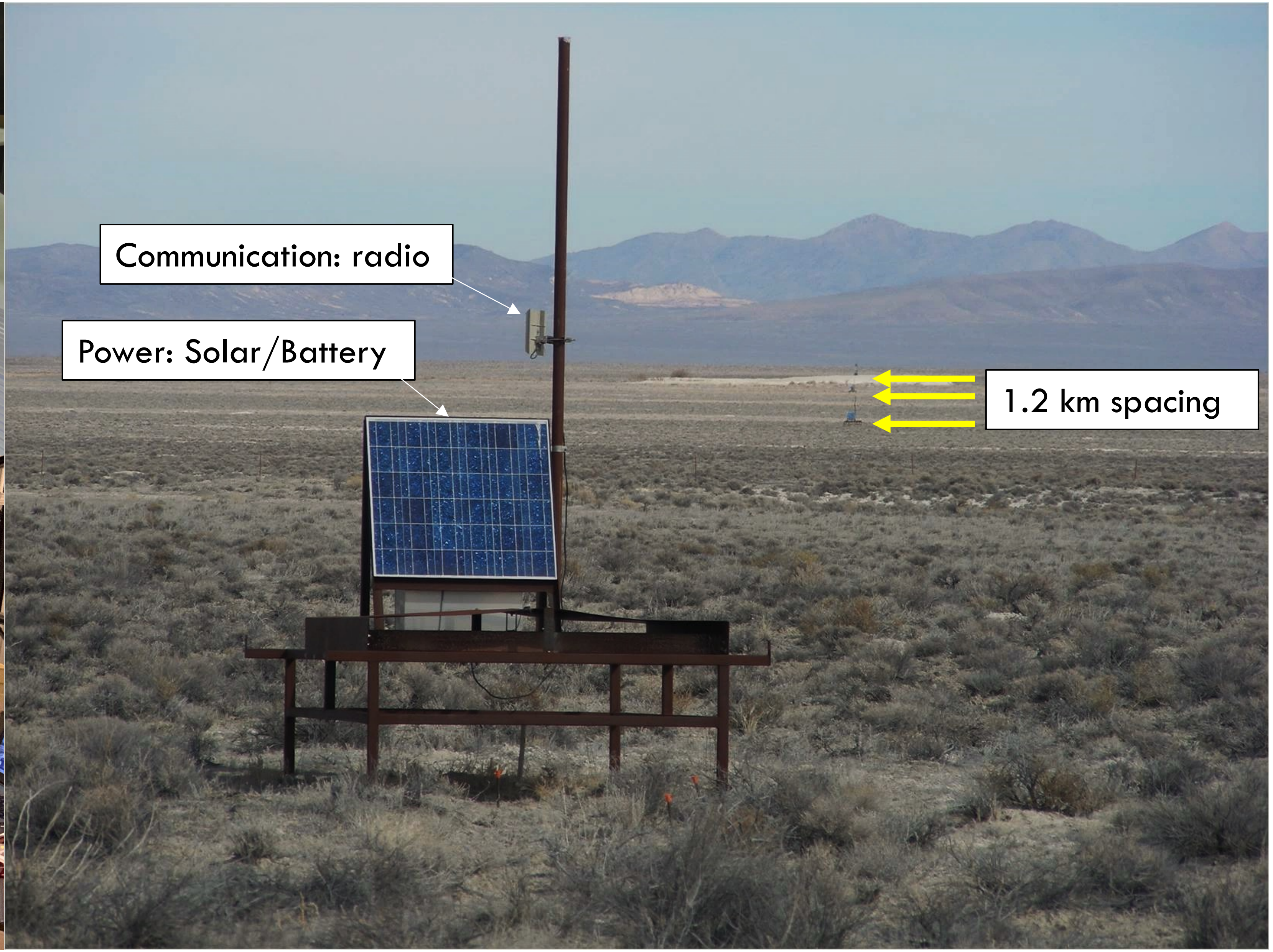
- 12bit 50MHz FADC x 2 layers
- CPU : Renesas SH4(25MHz)
- GPS, WLAN-modem
- Charge controller

- 507 plastic scintillation counters
- 2 layers, 1.2 cm thick, 3 m^2 area
- 1.2 km square grid spacing covering

~700 km^2

Scintillator Surface Detectors (SDs)

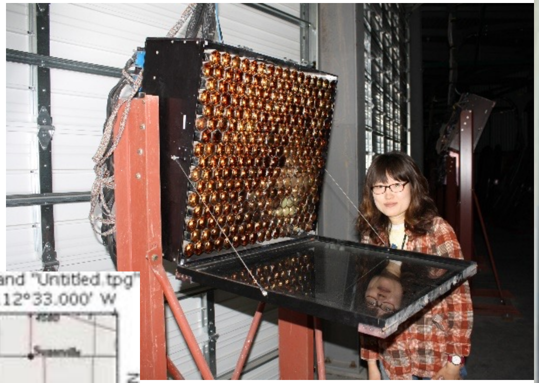




Fluorescence Detectors (FDs)

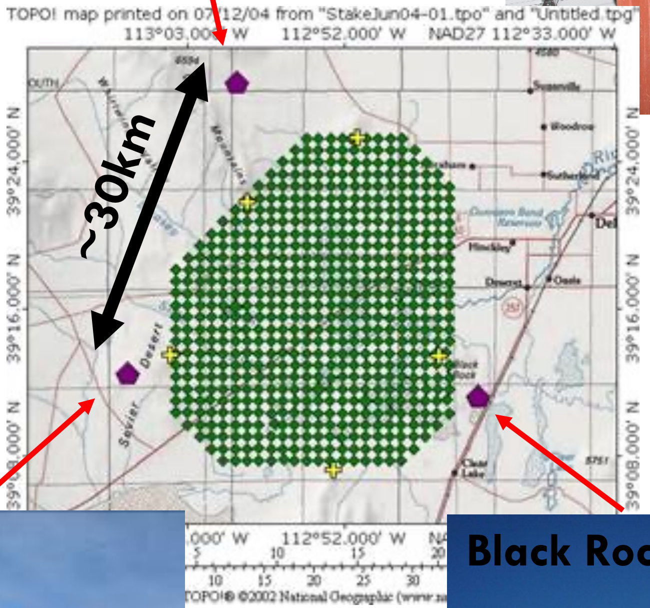
Middle Drum

14 telescopes @ station
256 PMTs/camera

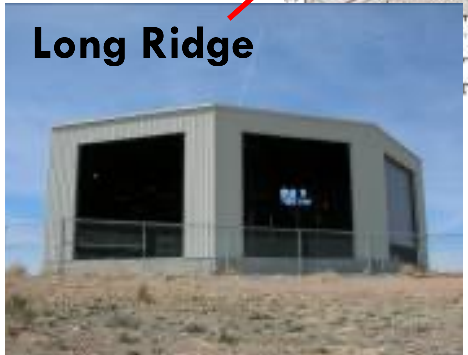


5.2 m^2

Reutilized from HiRes-I



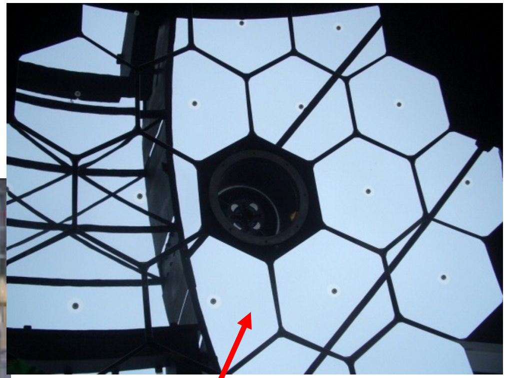
Long Ridge



Black Rock Mesa

12 telescopes/station
256 PMTs/camera

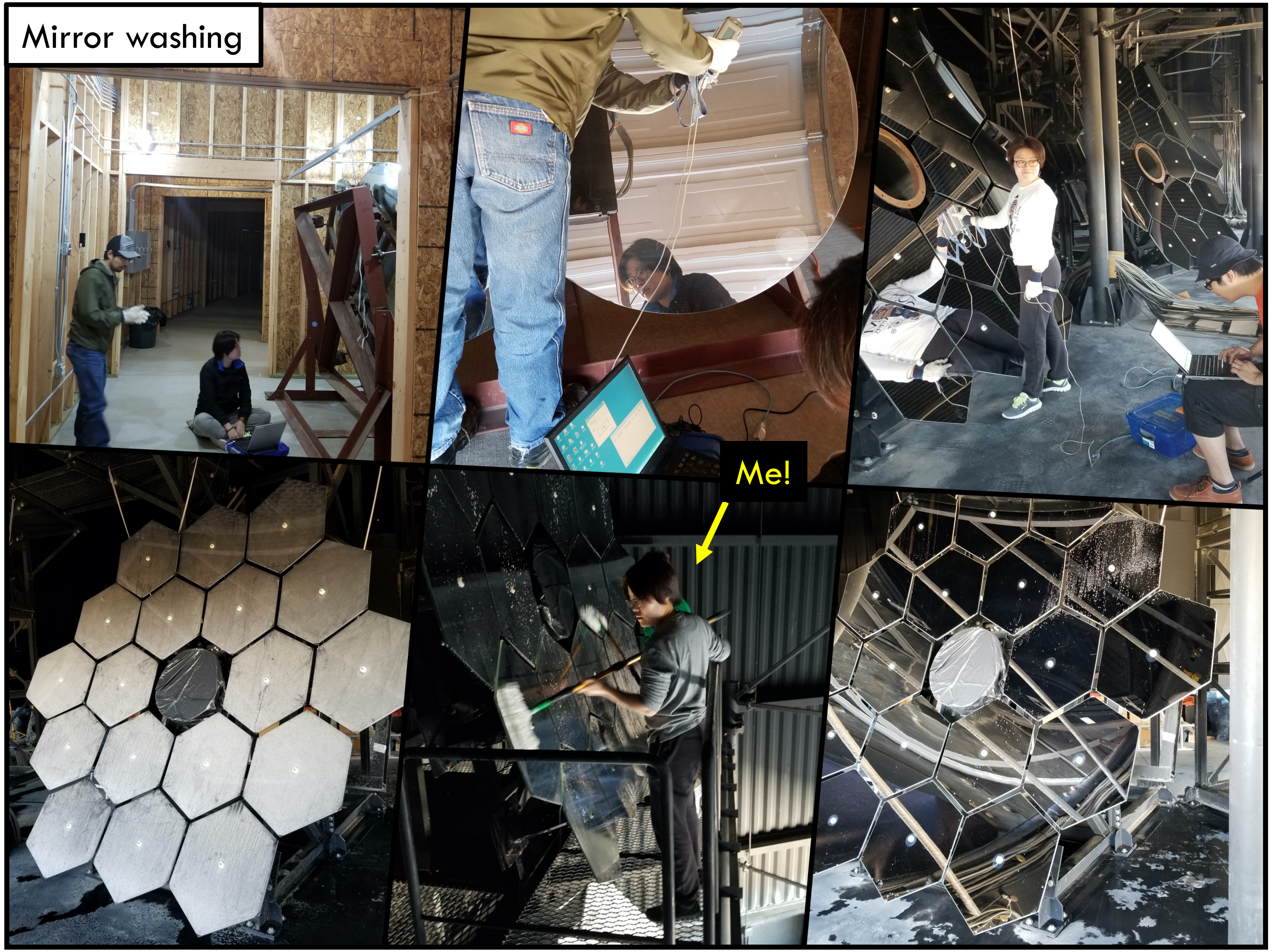
New Telescopes



6.8 m^2

- 3 stations
- 12–14 telescopes
- 256 hexagonal PMTs per camera
- 3°–31° elevation
- Look over the SD array for hybrid observation

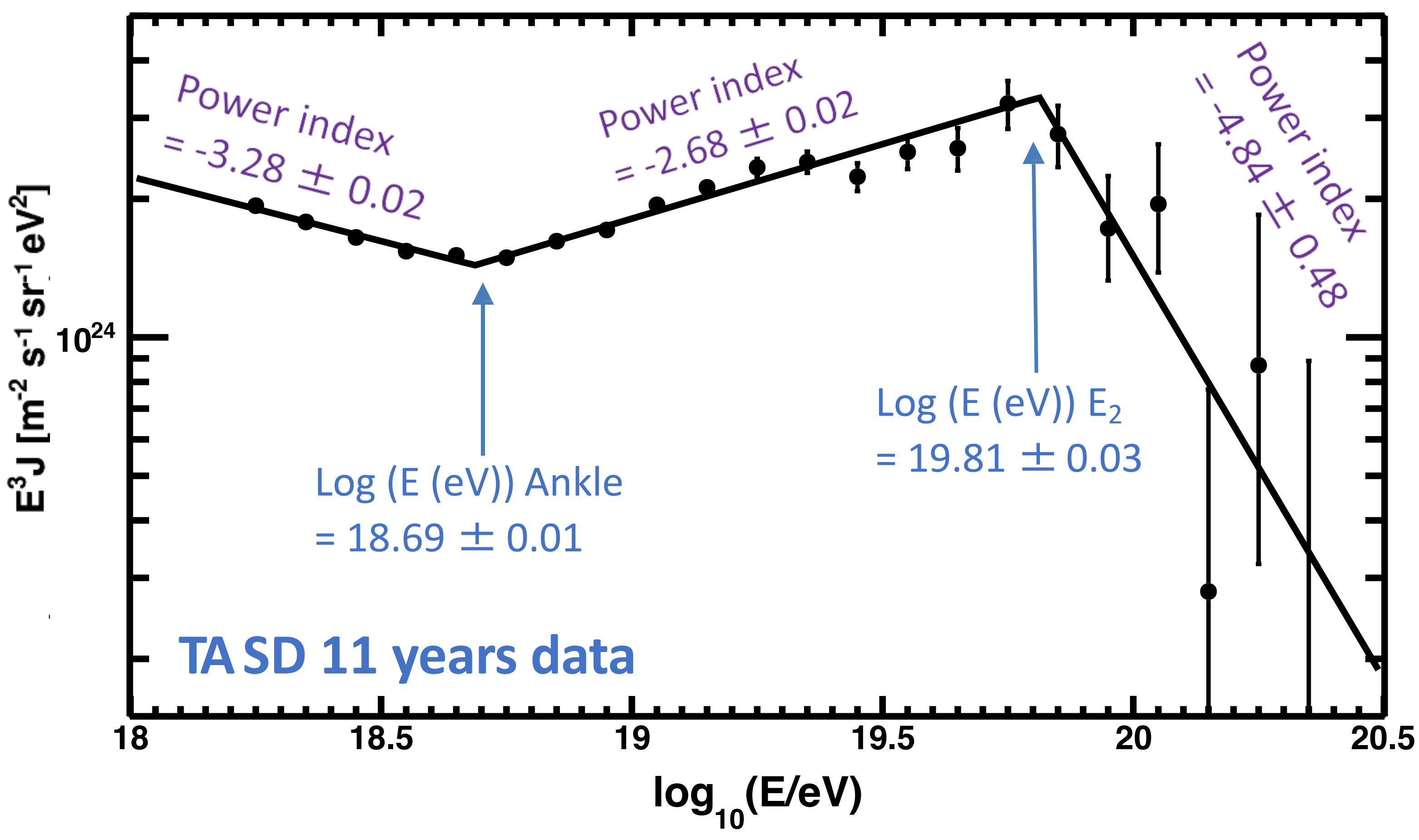
Fluorescence Detectors (FDs)

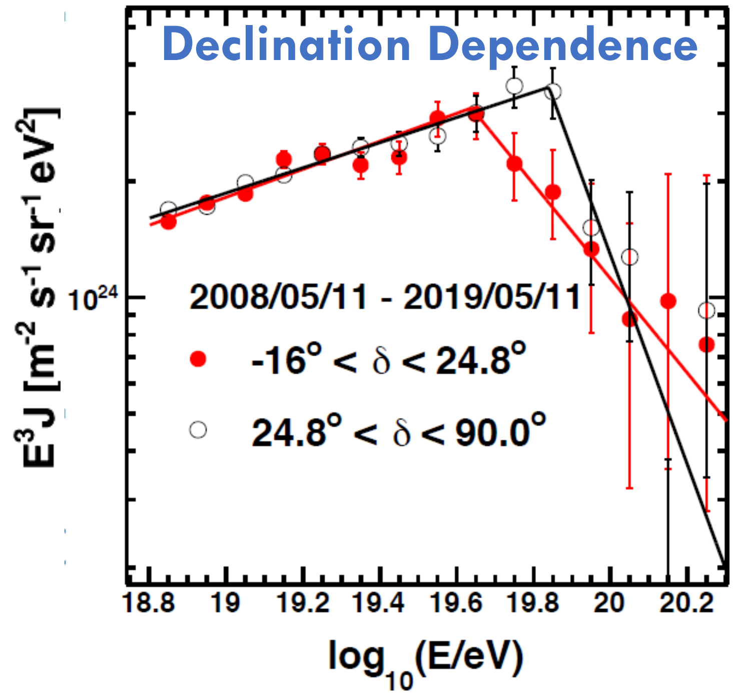


Recent results from Telescope Array

Energy spectrum: What happened during propagation?

- Spectral shape is indicative of collisions of the UHECR en route to us at Earth.

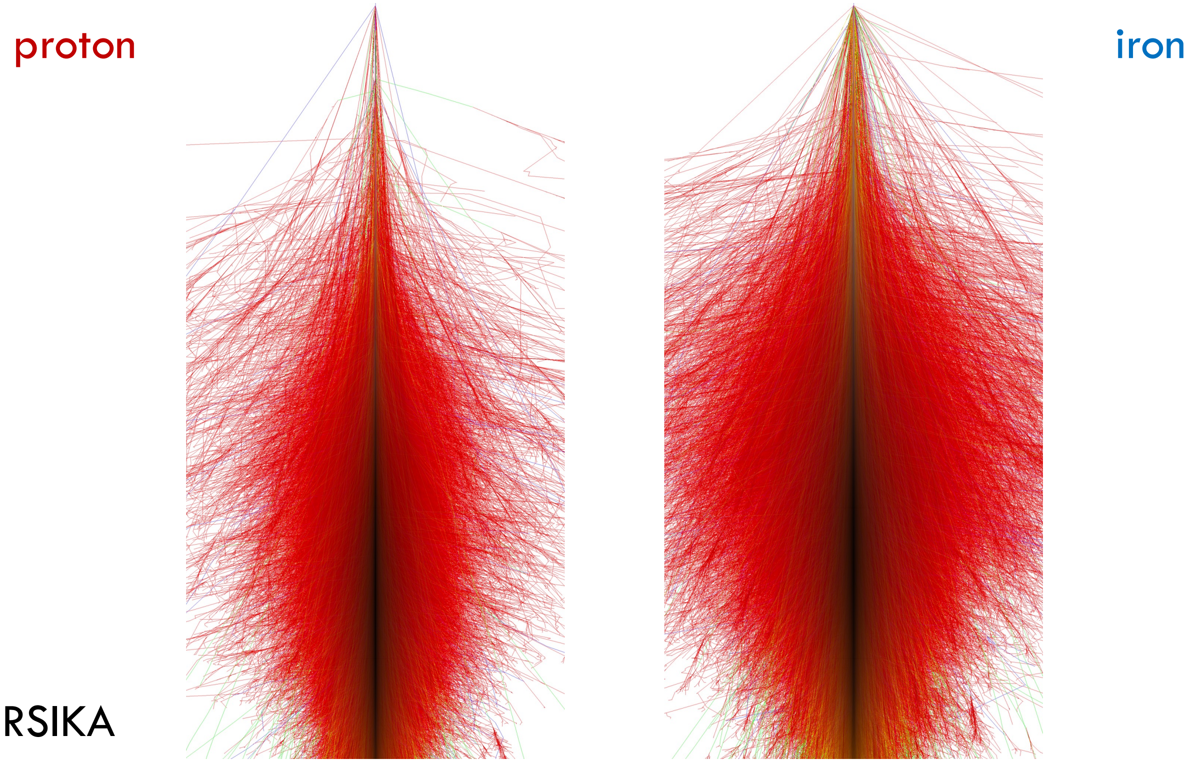




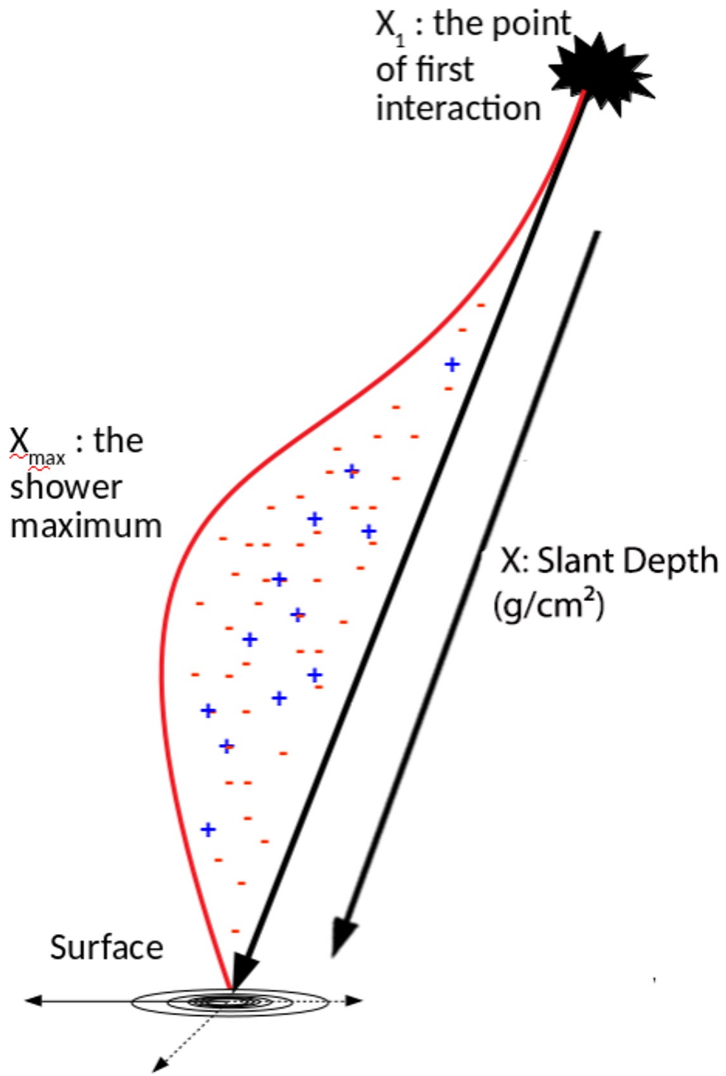
- Differences in the cutoff energies
  - log(E/eV)=**19.64 ±0.04** for (-16°–24.8°)
  - log(E/eV)=**19.84 ±0.02** for (24.8°–90°)
  - The global significance of the difference is estimated to be **4.3σ.**

Mass composition: What kind of particle are they?

- The slant depth, X, is the amount of materials penetrated by the shower at a given point in its development.
- The shower maximum, X_{max}, depends on the primary particle of the shower.

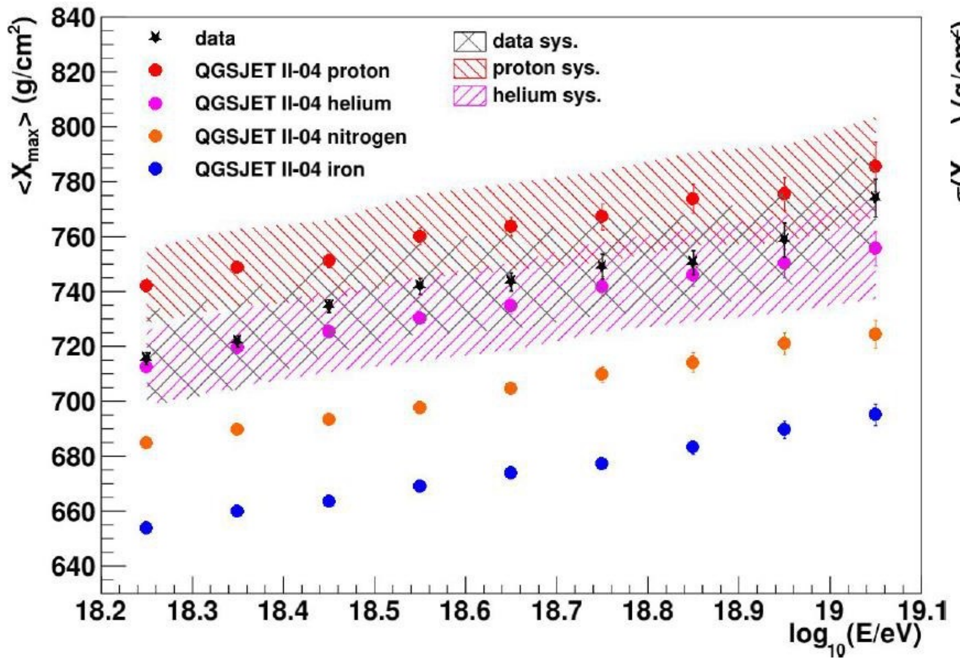


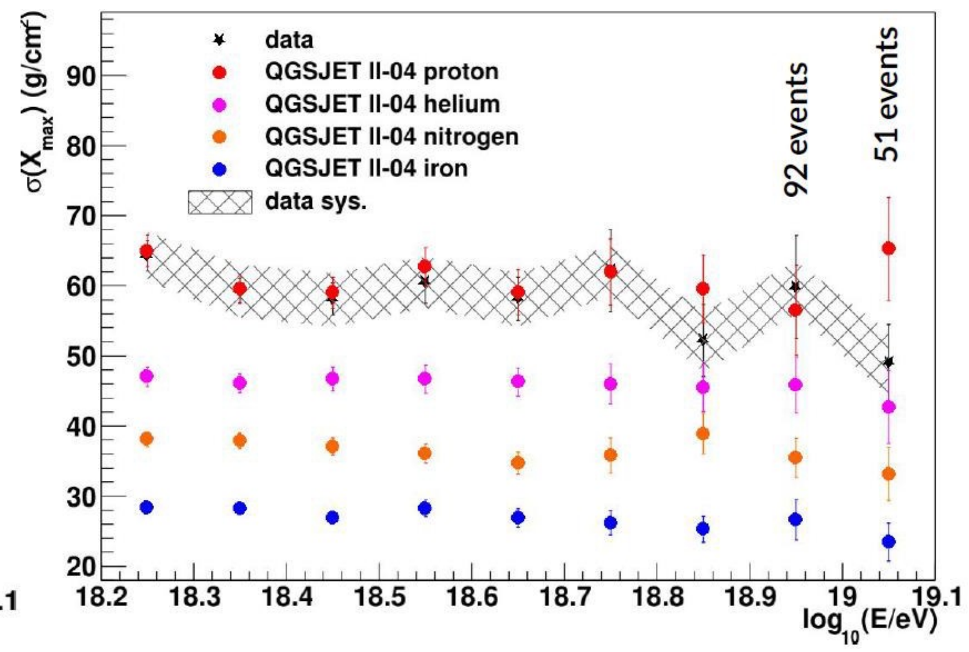
Credit: CORSIKA



Mass composition: What kind of particle are they?

10 years SD and FD hybrid data





- Energy Range: $10^{18.2}$–$10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 g/cm2
- QGS jet II-04 interaction model was compared with the data
  → agreement with the light composition
- More events are needed to study the highest energies

Arrival direction distribution: What are their sources?

- Anisotropy search is critical to narrowing down source candidates of UHECRs.

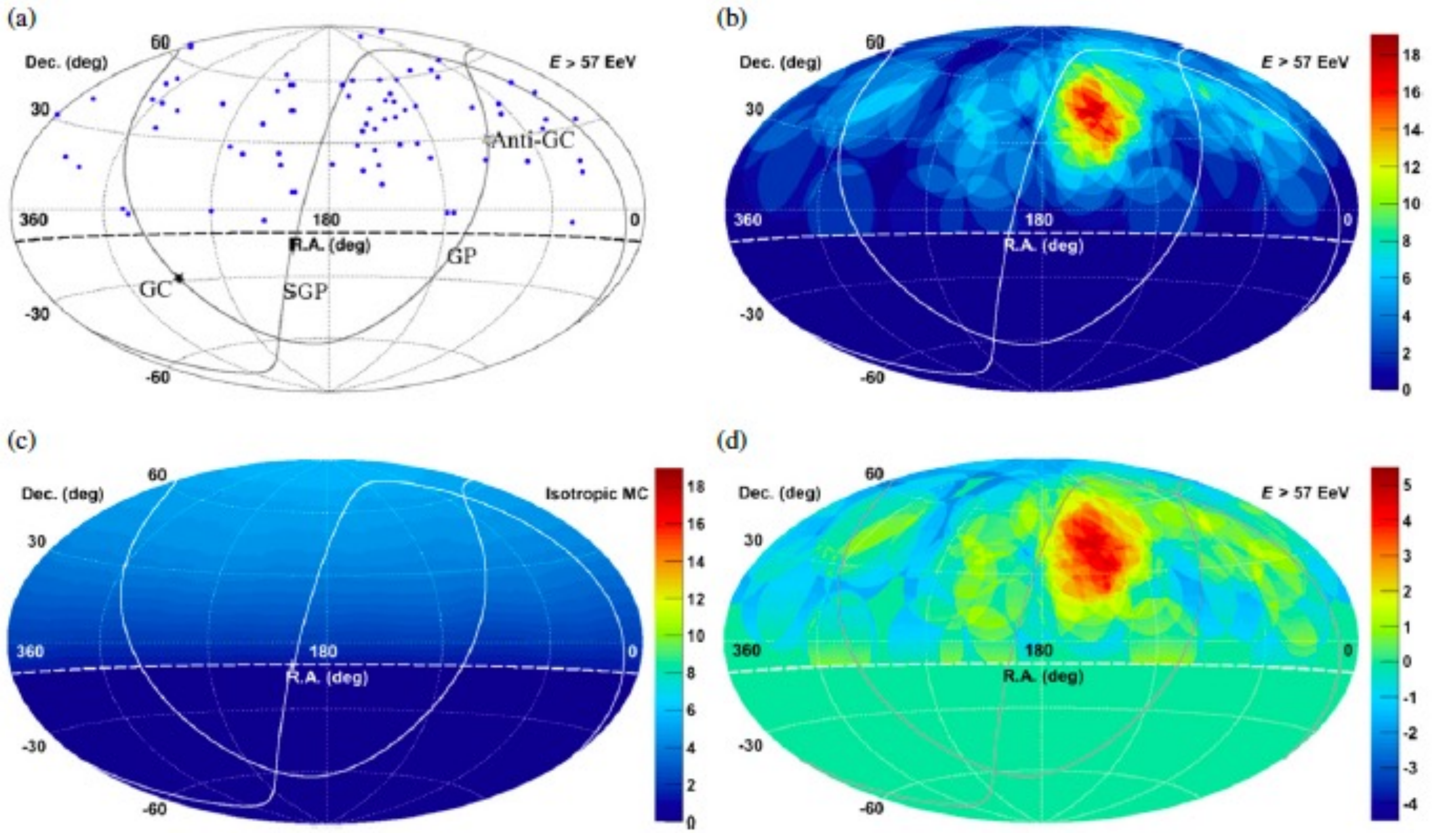


Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. = −10°. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by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

- We perform **intermediate scale anisotropy** searches.
- 72 events with E $> 5.7\times10^{19}$ eV (5-year TA SD data)
- Maximum local significance: 5.1σ

  Observed: 19 events

  Expected from iso.: 4.5 events
- Post-trial probability:

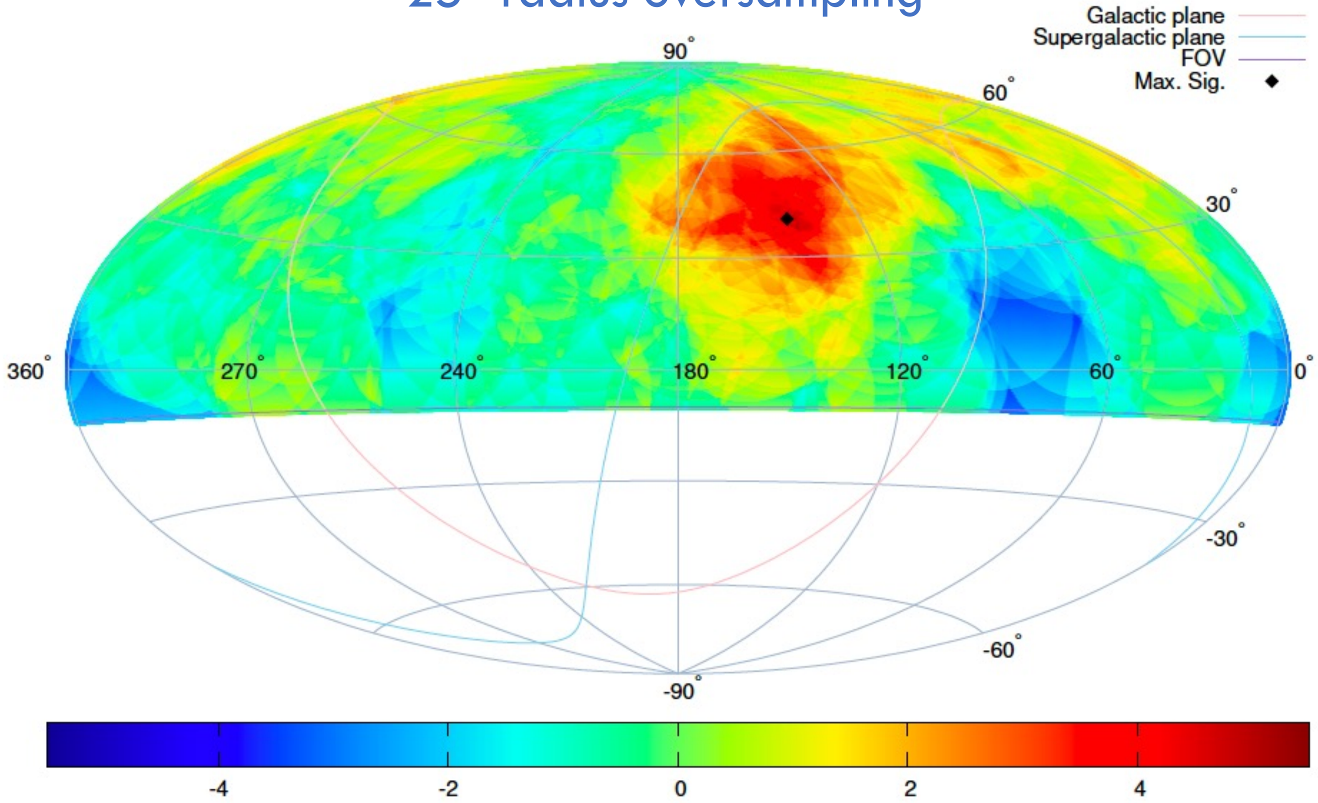
$P(\mathrm{p_{pre}} > 5.1\sigma) = 3.7\times10^{-4}$

→ **3.4σ**

Abbasi et al. (2014)

Update on the TA Hotspot

25°-radius oversampling



Deficit Li-Ma significance Excess

- 179 events with E > 5.7×10^{19} eV (12-year SD data)
- Maximum local Li-Ma sig.: 5.1σ

  Observed: 40 events

  Expected from iso.: 14.6 events

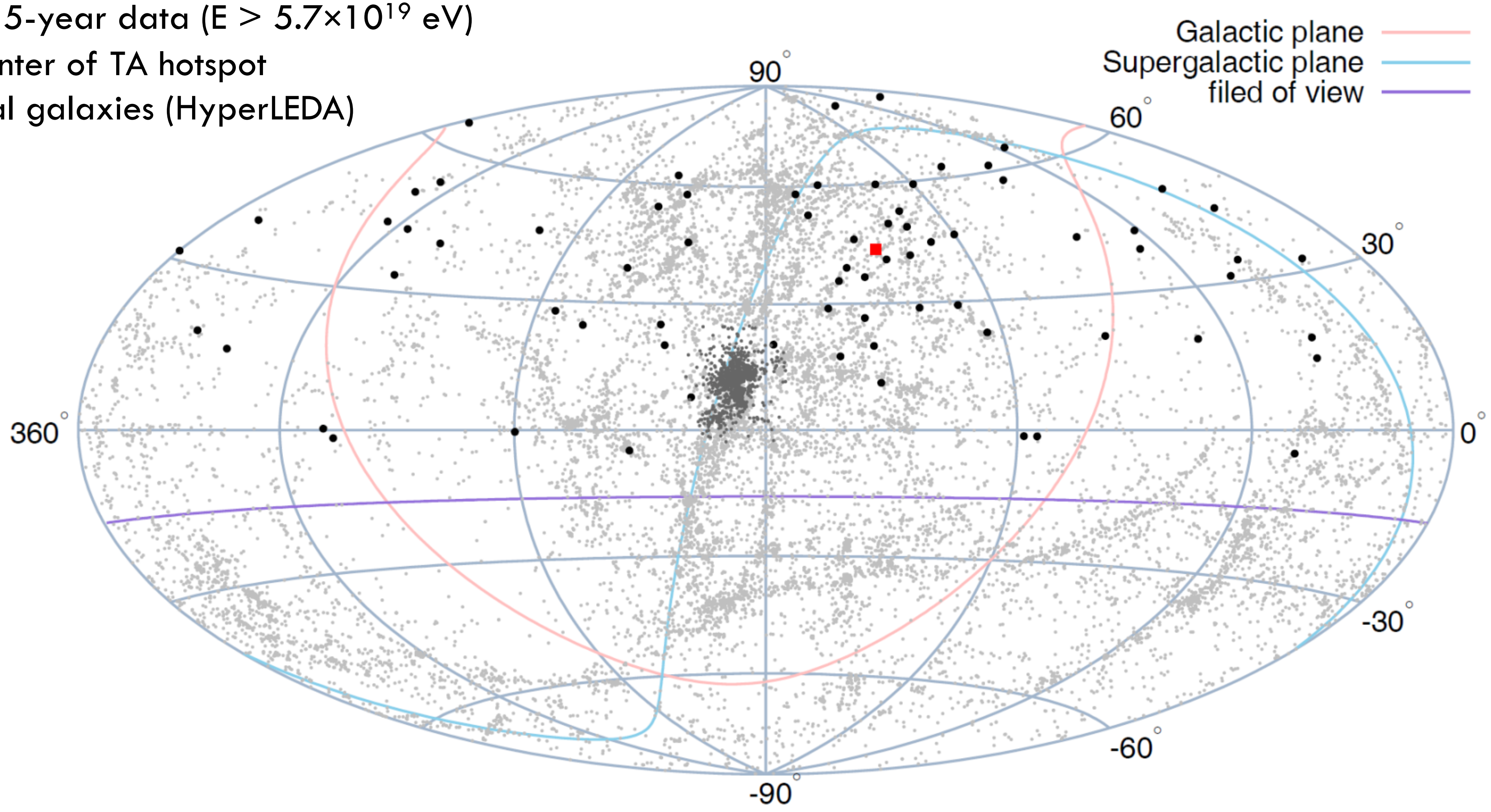
- **Post-trial probability:**

$$P(S_{\mathrm{MC}} > 5.1\sigma) = 6.8\times10^{-4}$$

$$\rightarrow 3.2\sigma$$

What is the origin of the TA hotspot? JK+ Sci. Adv., 5, eaau8227 (2019)

black dots: TA 5-year data (E > 5.7×10^{19} eV)
red square: center of TA hotspot
gray dots: local galaxies (HyperLEDA)



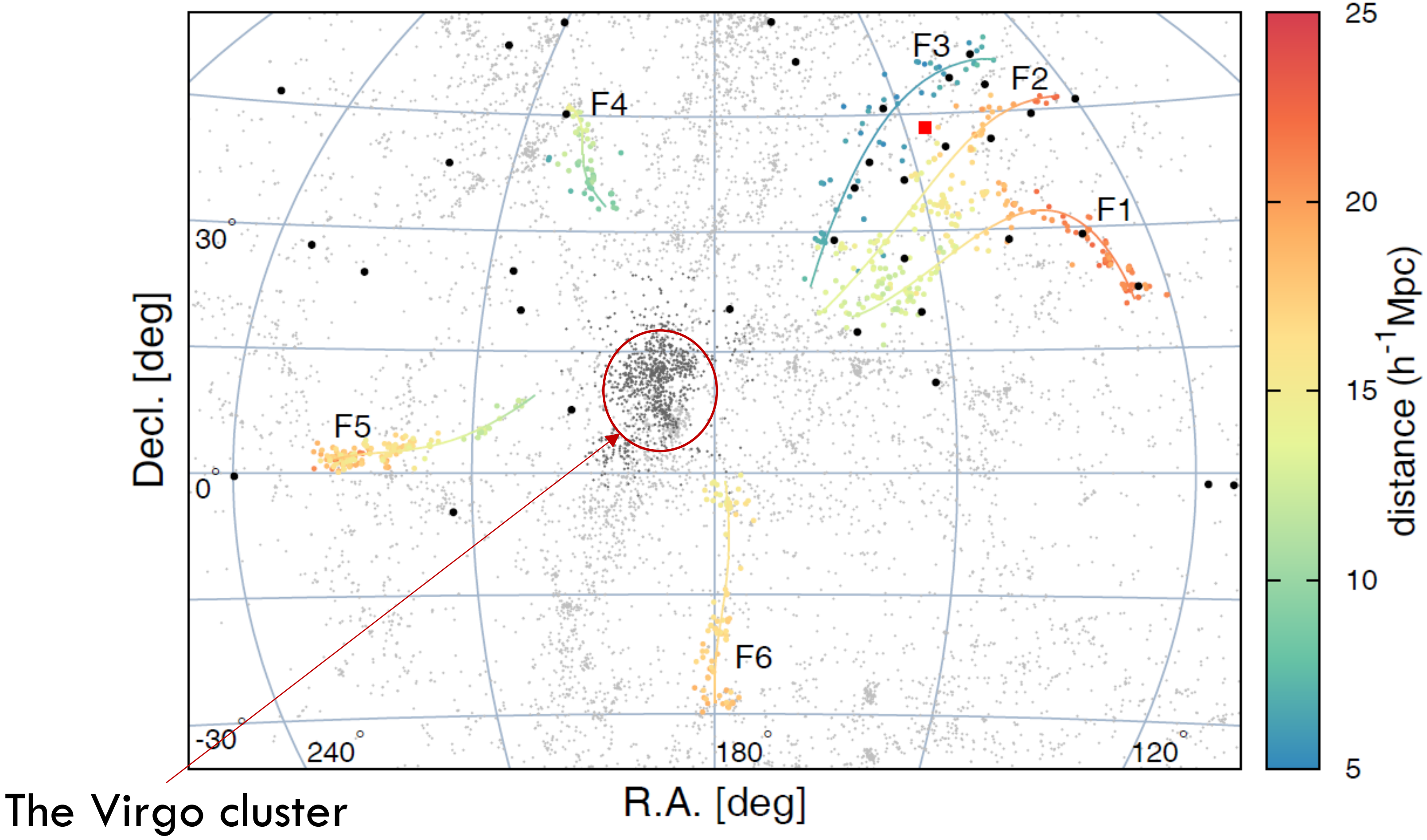
Are TA hotspot events coming from a single source?

No plausible nearby point source behind TA hotspot on the sky!

Six filaments of galaxies connected to the Virgo cluster

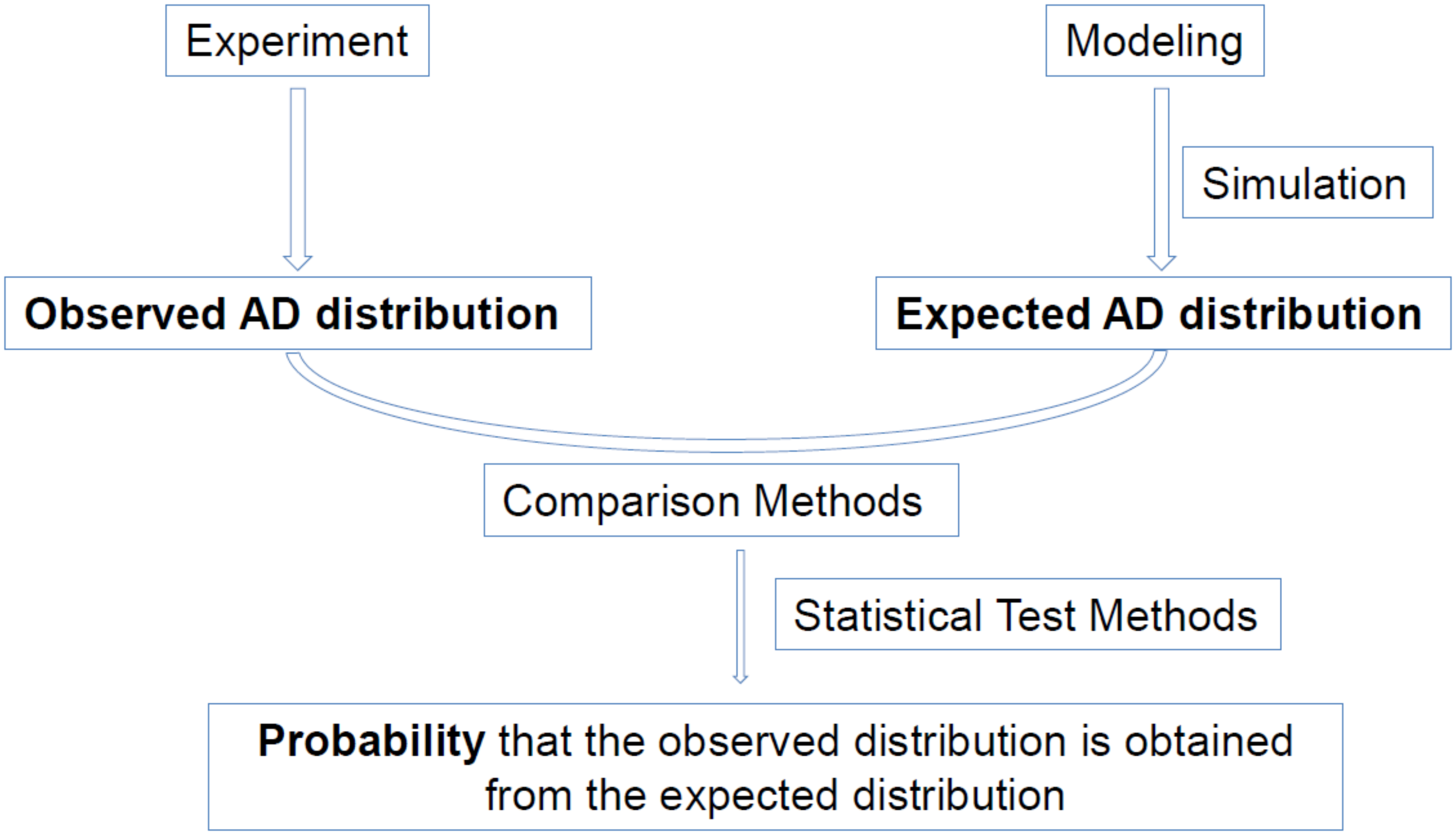
black dots: TA 5-year data TA (2014)
color dots: filaments of galaxies S. Kim+ (2016)
gray dots: local galaxies Makarov+ (2014)

JK+(2019)

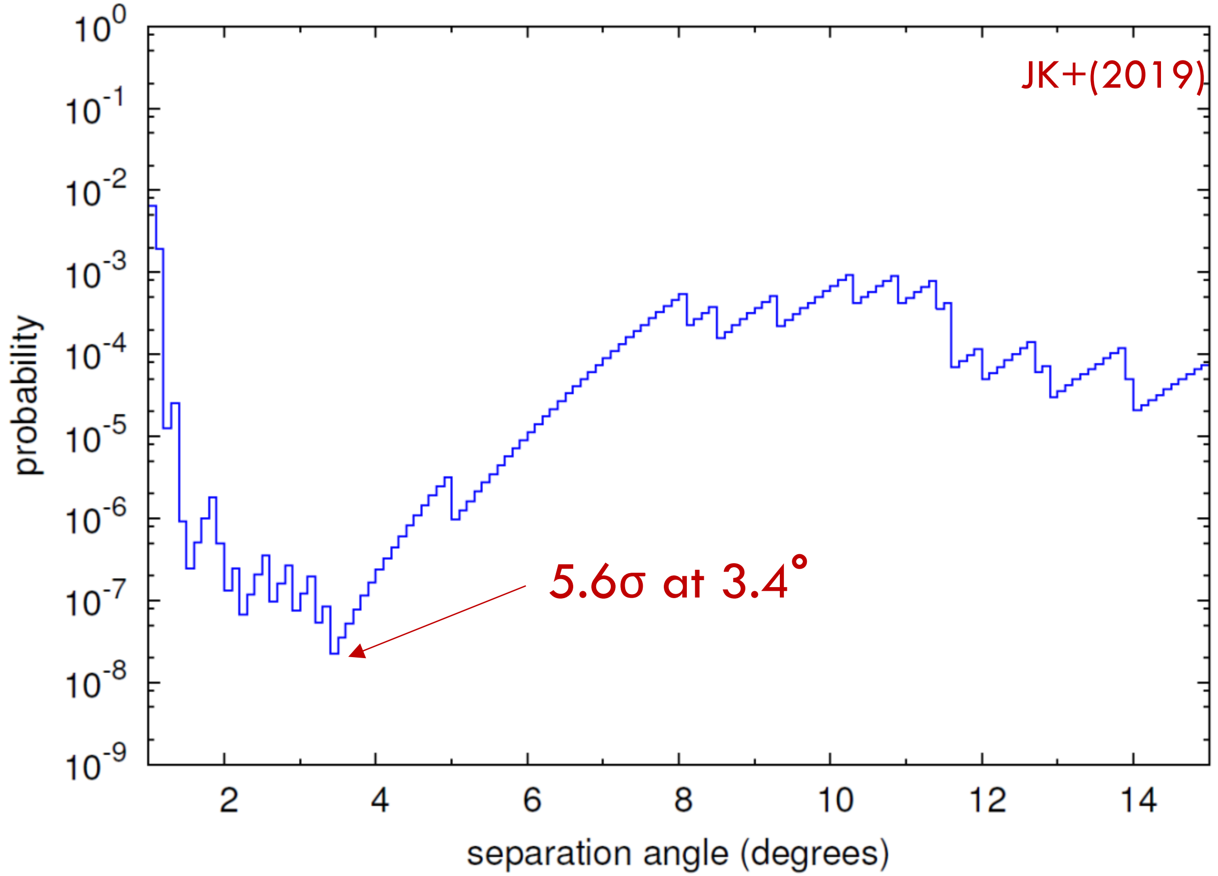


Correlation analysis using arrival direction distribution

AD: arrival direction



Close correlation between TA events and filaments



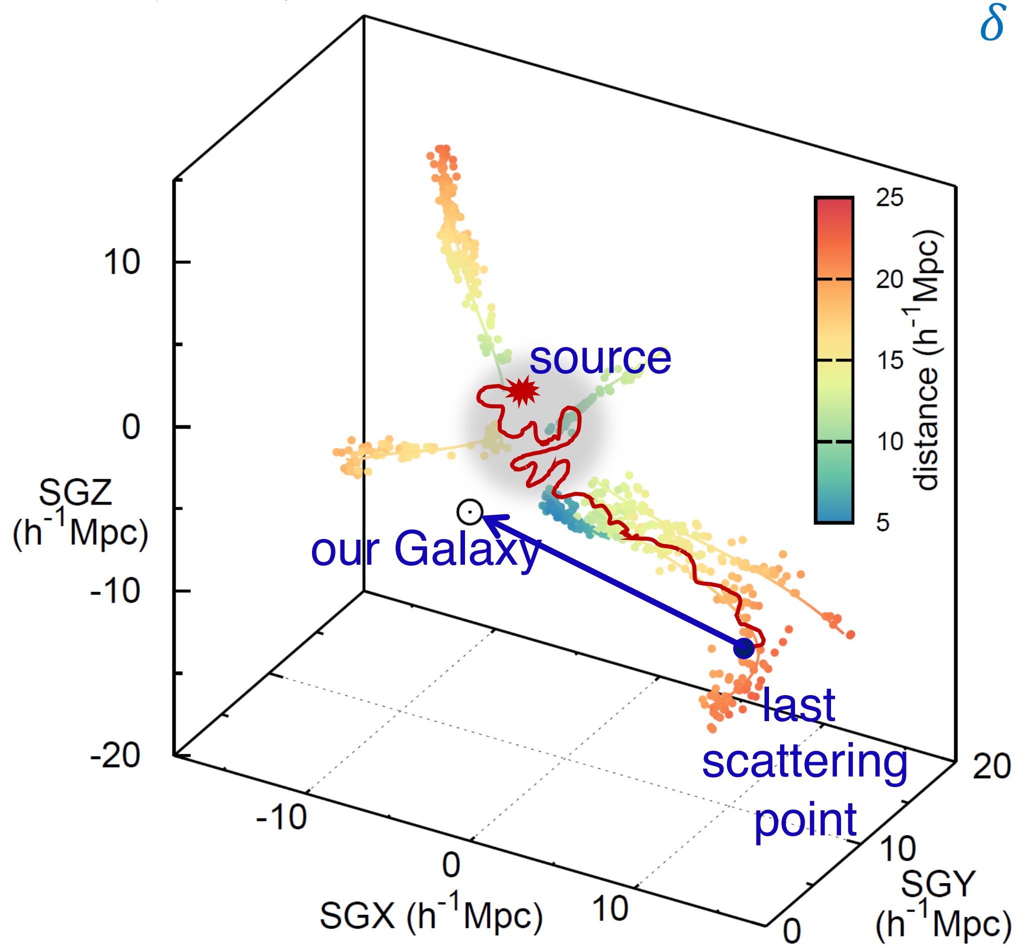
- 72 events with E > 5.7×10^{19} eV (5-year TA SD data)
- Maximum local significance: 5.6σ
  - Observed: 19 events
  - Expected from iso.: 4.2 events

  } ~350% excess
- Post-trial probability: $P(\mathrm{p_{pre}} > 5.6\sigma) = 5.1\sigma$

→ The estimated mass composition of UHECRs and the strength of galactic magnetic fields are consistent with observations.

A plausible model for the origin of TA hotspot

JK+(2019)



$$\delta \sim f \times \frac{\pi}{2} \left(\frac{5 \times 10^{19}\ \mathrm{eV}}{E/Z} \right) \left(\frac{L}{25\ \mathrm{Mpc}} \right)^{1/2} \left(\frac{l_c}{1\ \mathrm{Mpc}} \right)^{1/2} \left(\frac{B_{\mathrm{random}}}{20\ \mathrm{nG}} \right)$$

- UHECRs are postulated to be produced at a source (sources) inside the Virgo cluster. They roam around for a while because of cluster magnetic fields. Then, some of them escape through connected filaments.
- This picture requires
  - B >~1 μG in clusters
  - B > ~20 nG in filaments
  - (Size of cluster/filament ~ a few Mpc)

Is it possible for UHECRs to propagate like this way in the cosmic web?

Numerical simulation of magnetized cosmic web

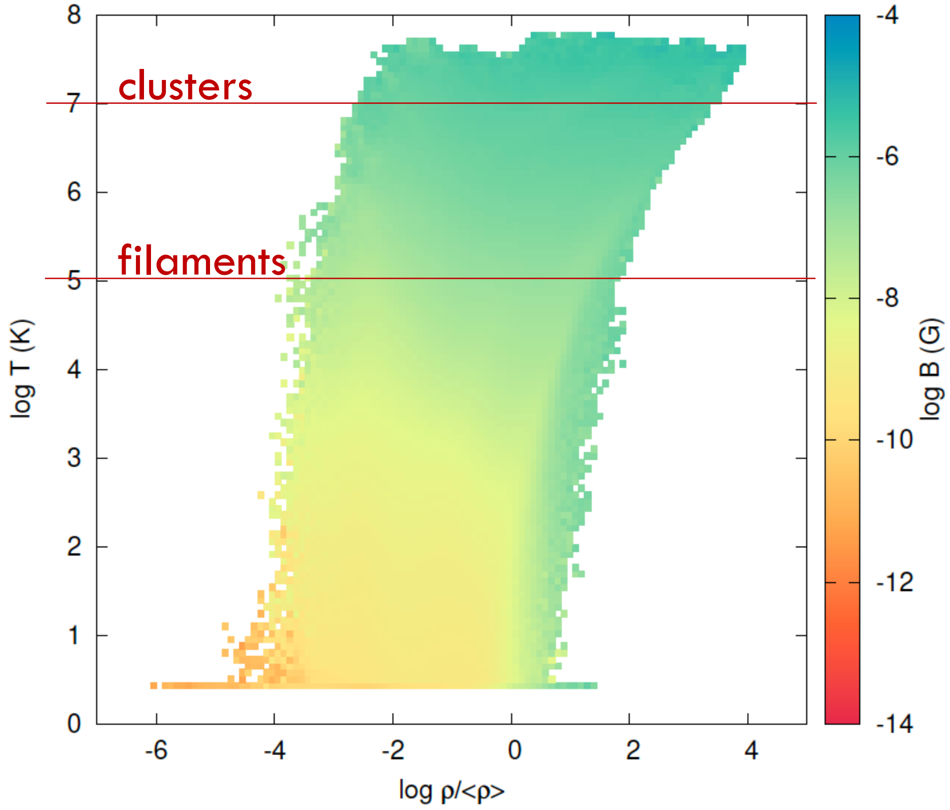
- The model universes are generated through numerical simulations for the LSS formation using a particle-mesh/Eulerian cosmological hydrodynamics code (Ryu+1993).
- Assuming a ΛCDM cosmological model, the following parameters were used:

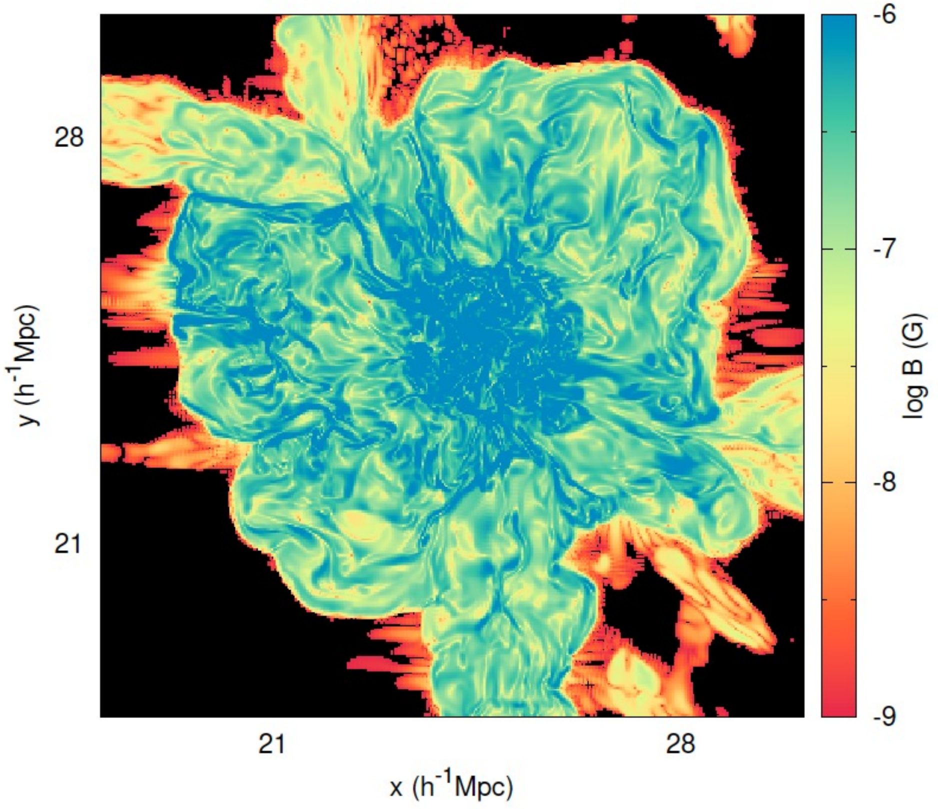
$$\Omega_\Lambda = 0.72,\ \Omega_{DM} = 0.236,\ \text{and}\ \Omega_{BM} = 0.044,$$

$$h = 0.7,\ \sigma_8 = 0.82,\ \mathrm{n} = 0.96.$$

- The generation of intergalactic magnetic field is seeded by the Biermann battery mechanism at cosmological shocks (Ryu+1998).
- The overall strength of magnetic field is rescaled to reproduce the observed values of clusters. The core value within 1 h^{-1}Mpc from the X-ray center is rescaled to 2 μG and 3 μG.

Magnetic field strength in LSS of the universe

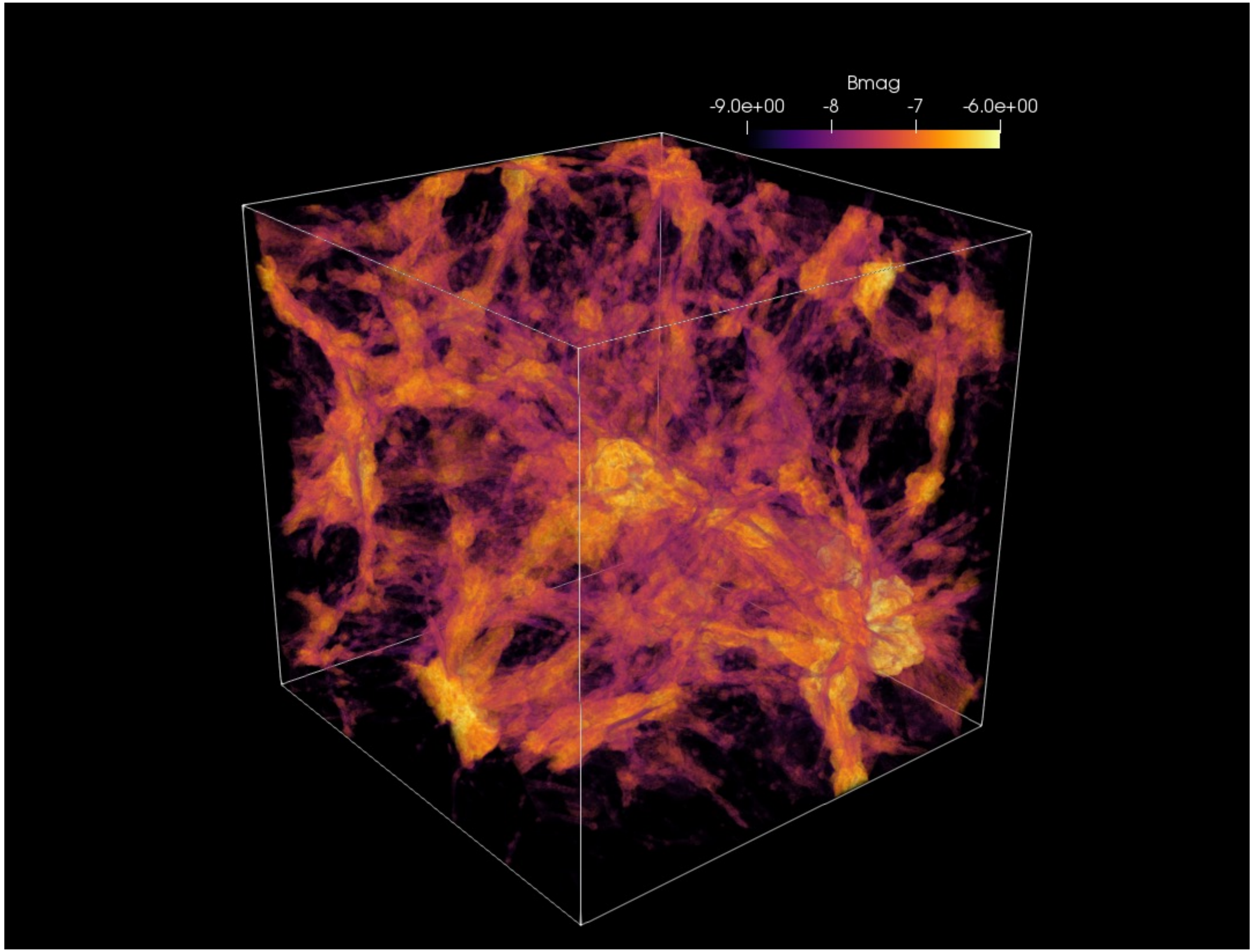




Temp. of intracluster medium: ~10^7 K
Temp. of warm-hot ionized plasma ~10^5–10^7 K

Temp. of the Virgo cluster: ~3.0×10^7 K
Temp. of sample cluster: ~3.2×10^7 K

Particle propagation in magnetized cosmic web



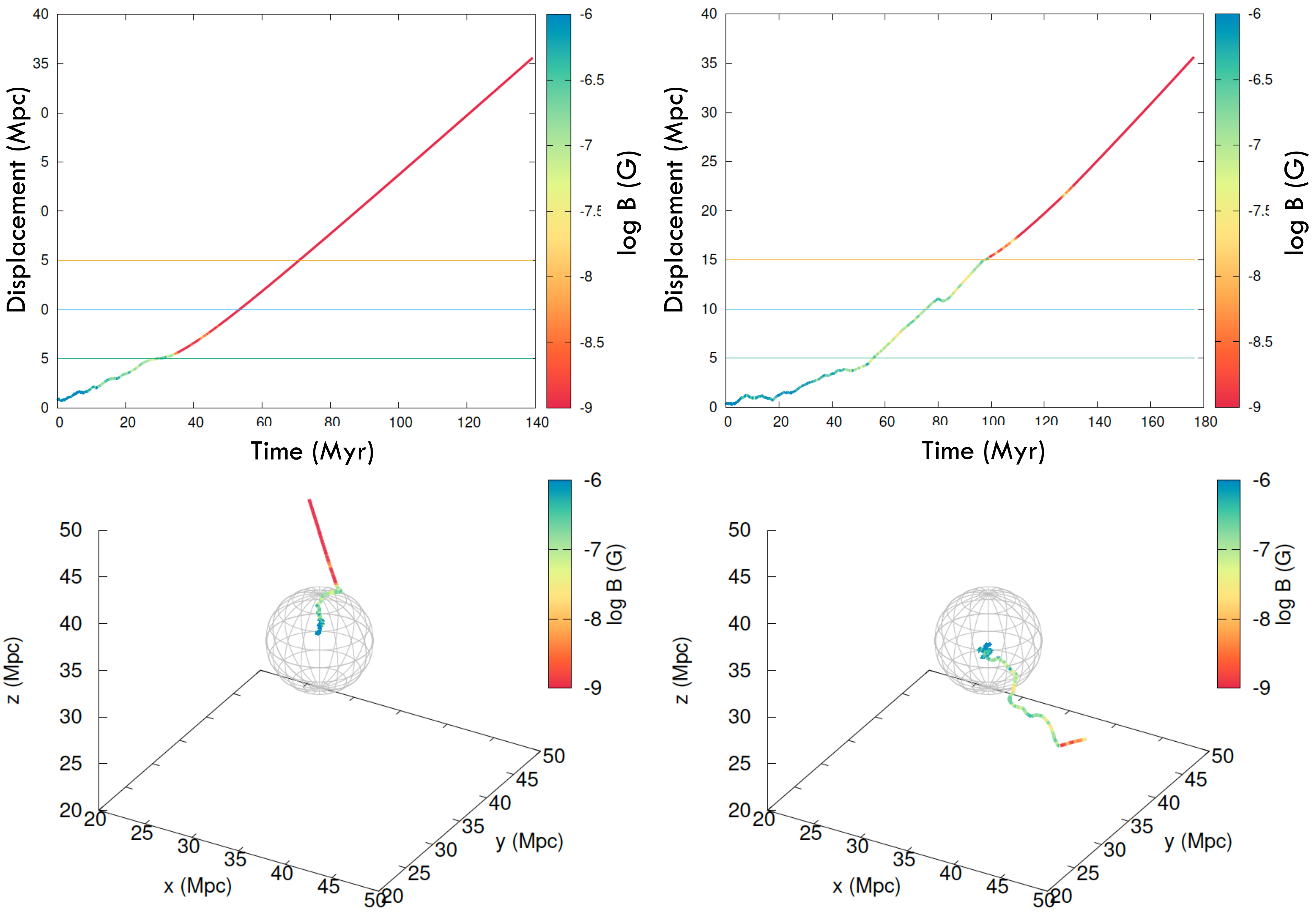
- A cubic box of comoving size of 49 h^{-1}Mpc with periodic boundaries, divided into 1440^3 uniform grid zones.

- The grid resolution is 34.5 h^{-1}kpc, which is smaller than the gyro-radius of UHE protons in most zones.

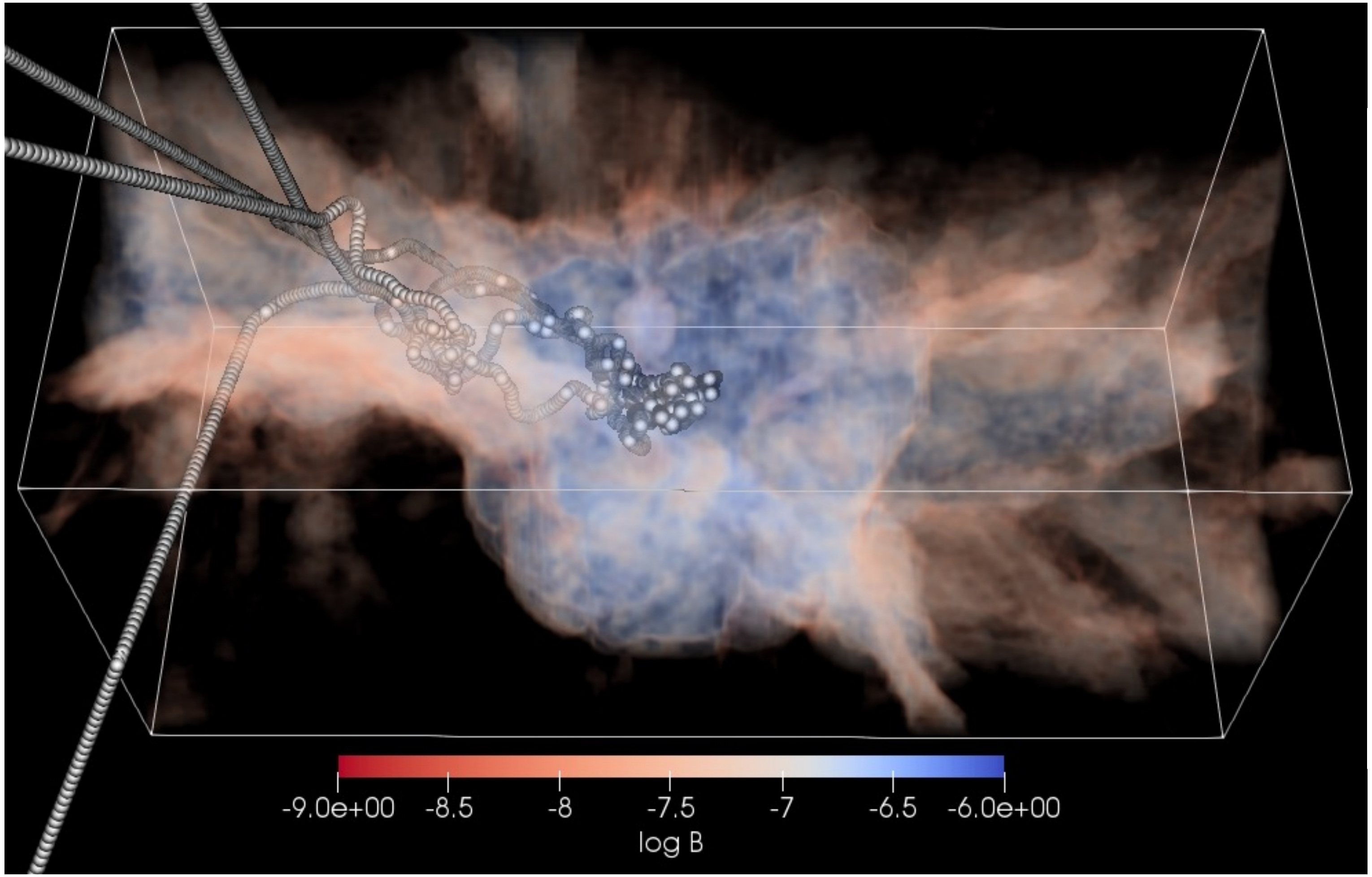
- Inject 10^5 UHE protons with 6×10^{19} eV at random positions within the cluster core toward random directions.

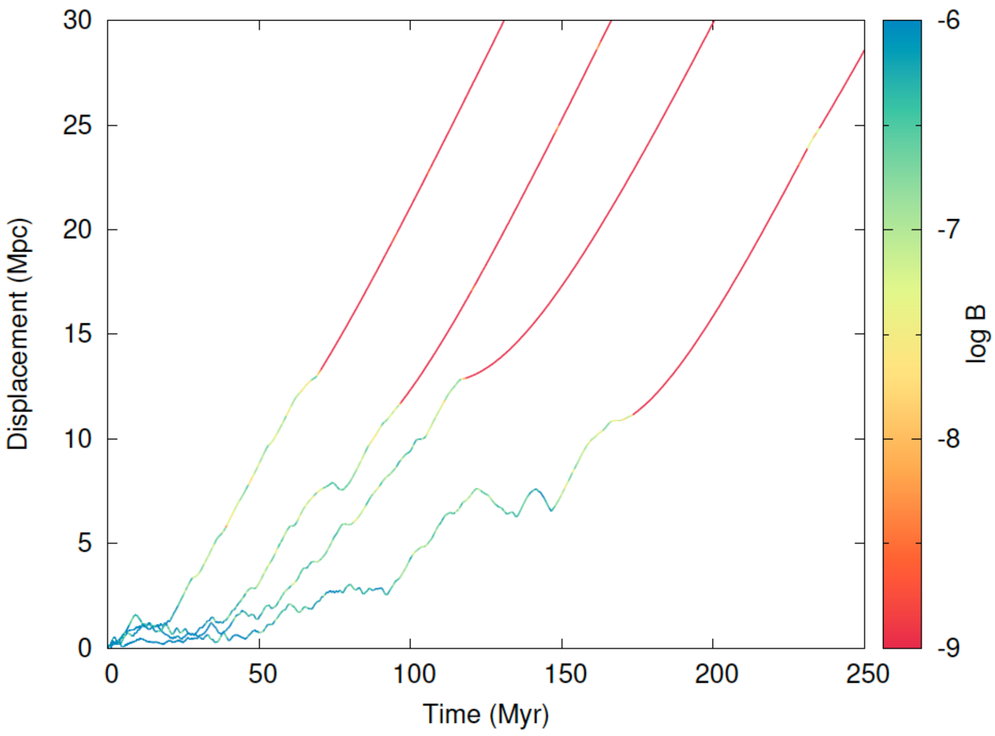
- Trace the trajectories of UHE protons with the relativistic equation of motions.

Examples of particle propagation: Direct escape from cluster (left) + Escape to filament (right)



Examples of particles escaping to filaments w/ magnetic fields

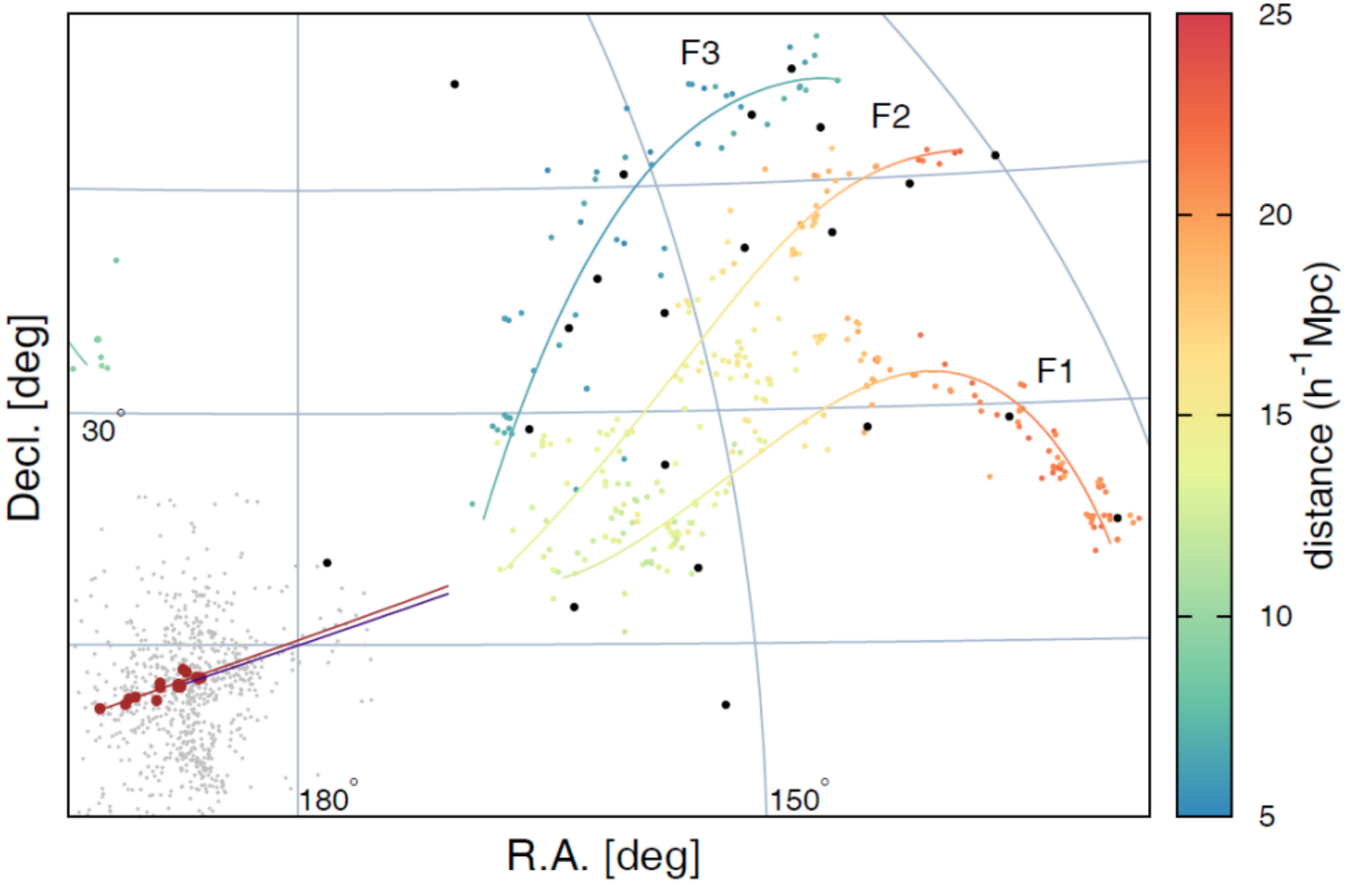




Analysis of 10^5 particles: preliminary

- Core of 2 μG
  - Particles directly escape from the cluster: ~55%
  - Particles escape to the filaments: ~45%
- Core of 3 μG
  - Particles directly escape from the cluster: ~49%
  - Particles escape to the filaments: ~51%
- The results of this study confirm that it is possible for a UHE proton produced from a source in a galaxy cluster to escape through galaxy filaments connected to the cluster.

Intriguing observations in the Virgo cluster



- Brown circles and the brown line plot brightest elliptical galaxies and the extension of the cluster principal axis, respectively, in the Virgo Cluster (West & Blakeslee (2000), S. Kim+ (2018)).
- The extension of M87 jet with the indigo line (Kovalev+ (2007)).

Conclusions of this study

- The results of this study confirm that it is possible for a UHE proton produced inside the cluster to escape toward and propagate along filaments of galaxies connected to the cluster.

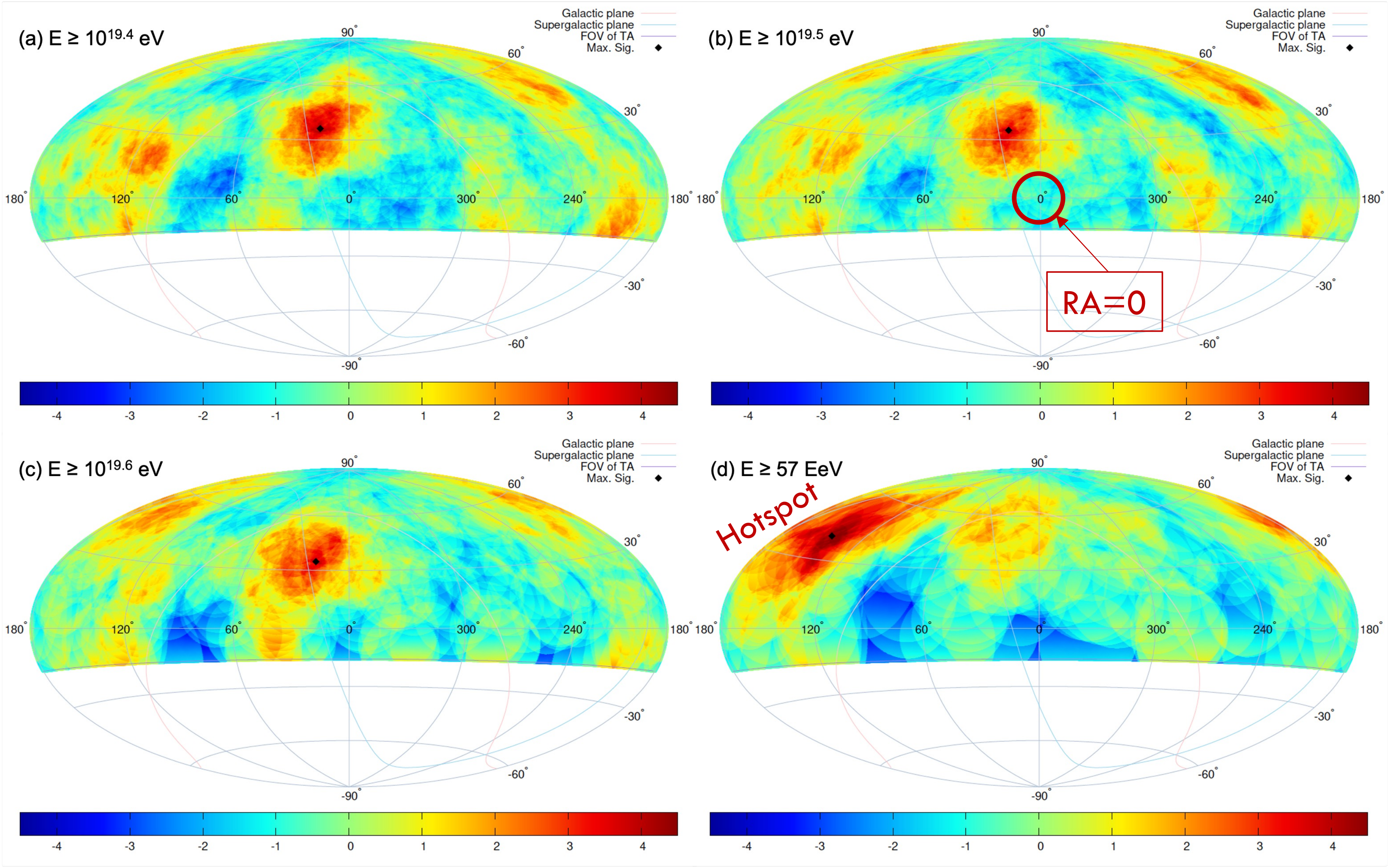
  → Supports the model for the origin of TA hotspot

- The magnetic field distribution in the regions of the Virgo Cluster and the hotspot is required for realistic tests to reproduce the TA hotspot.
- The exploration of IGMF by astronomical projects like SKA can provide better constraints in the near future.
- Under the circumstances, the IGMF model is crucial.

  → More simulations with various IGMF models are in progress.

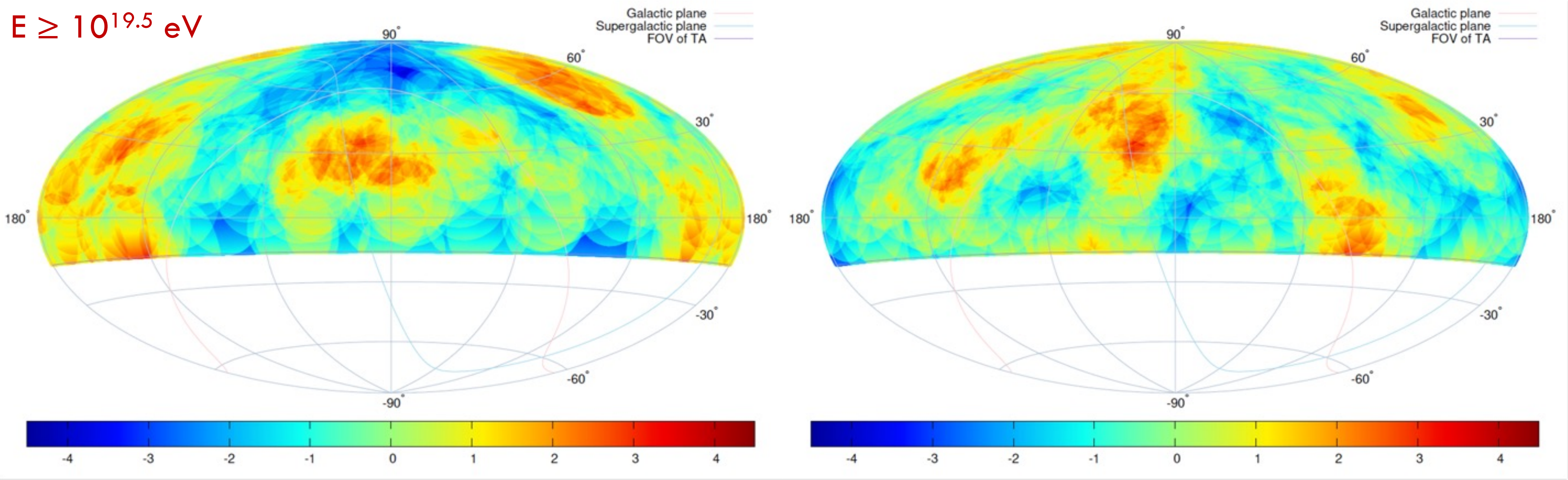
New excess of events

New excess in slightly lower energy events



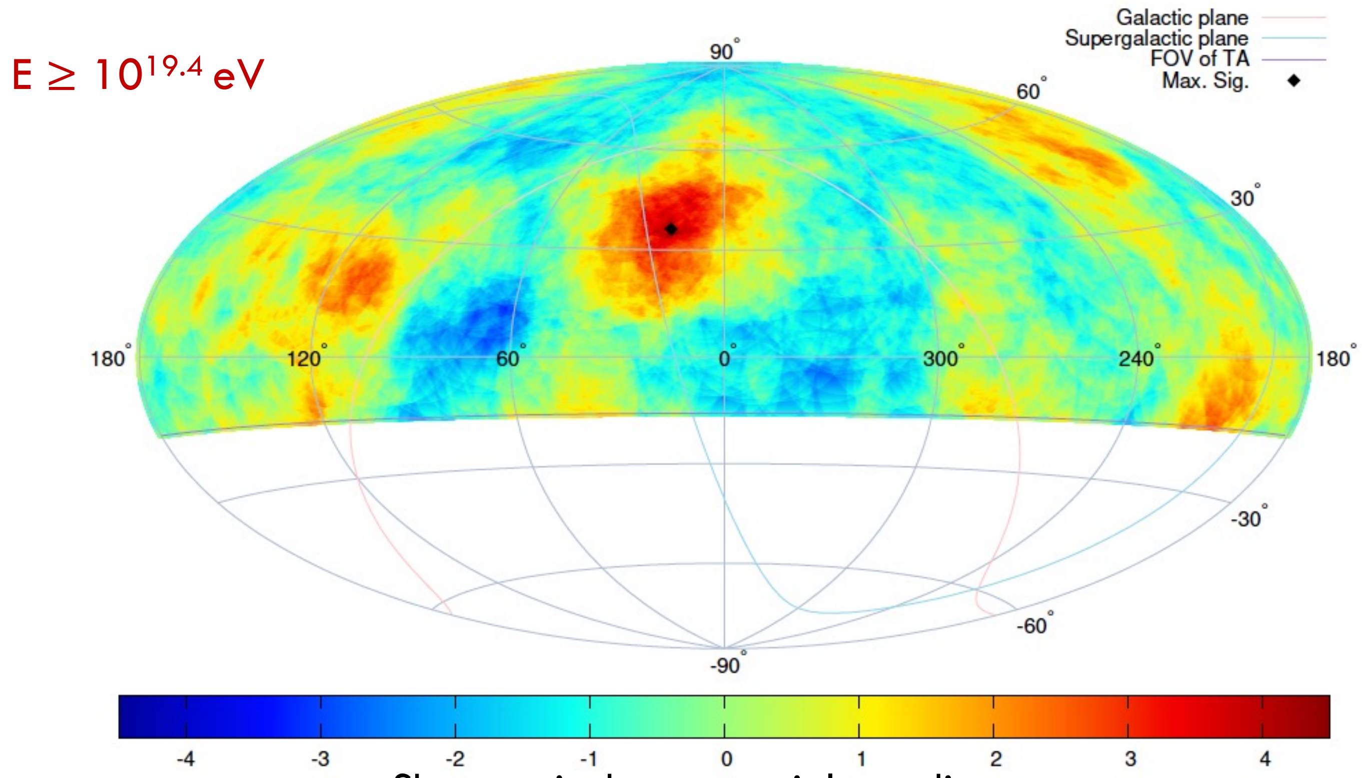
- Li-Ma significance map: excess (red) / deficit (blue) of events compared to isotropy
- Black diamond (◆): the maximum Li-Ma significance position
- Equatorial coords. having RA=0 at center

Independent analysis for the new excess



- It is found that there is no apparent difference between the first 5- and last 6-year data. Both of them have similar local significances toward the new excess region, which are around 3σ. It indicates that steady excesses have been observed in this region.

Li-Ma analysis with 20° oversampling: $E \geq 10^{19.4}$ eV



Skymaps in the equatorial coordinates

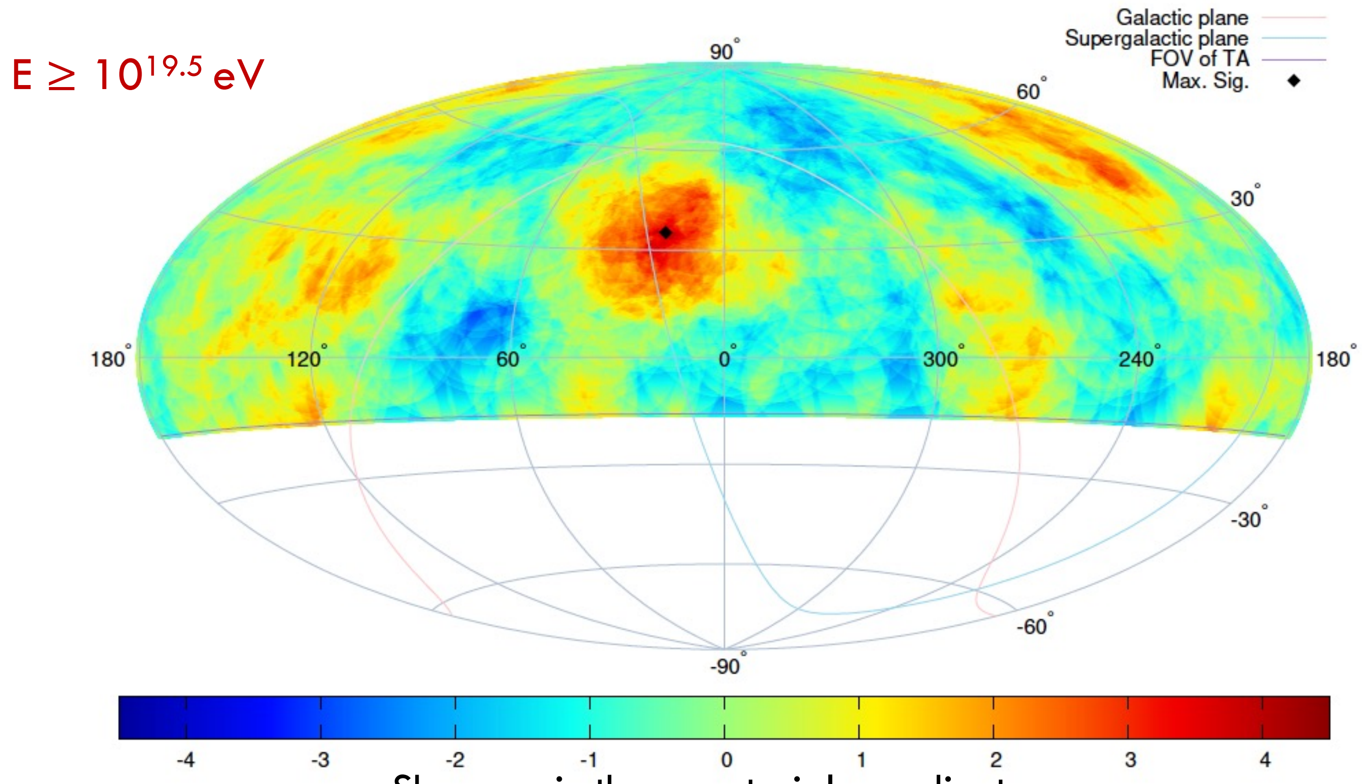
- 864 events with $E \geq 10^{19.4}$ eV (11-year TA SD data)
- Maximum local significance: 4.4σ at (17.4°, 36.0°)

  Observed: 85 events

  Expected from isotropy: 49.5 events

  ~72% excess to the isotropy

Li-Ma analysis with 20° oversampling: $E \geq 10^{19.5}$ eV



Skymaps in the equatorial coordinates

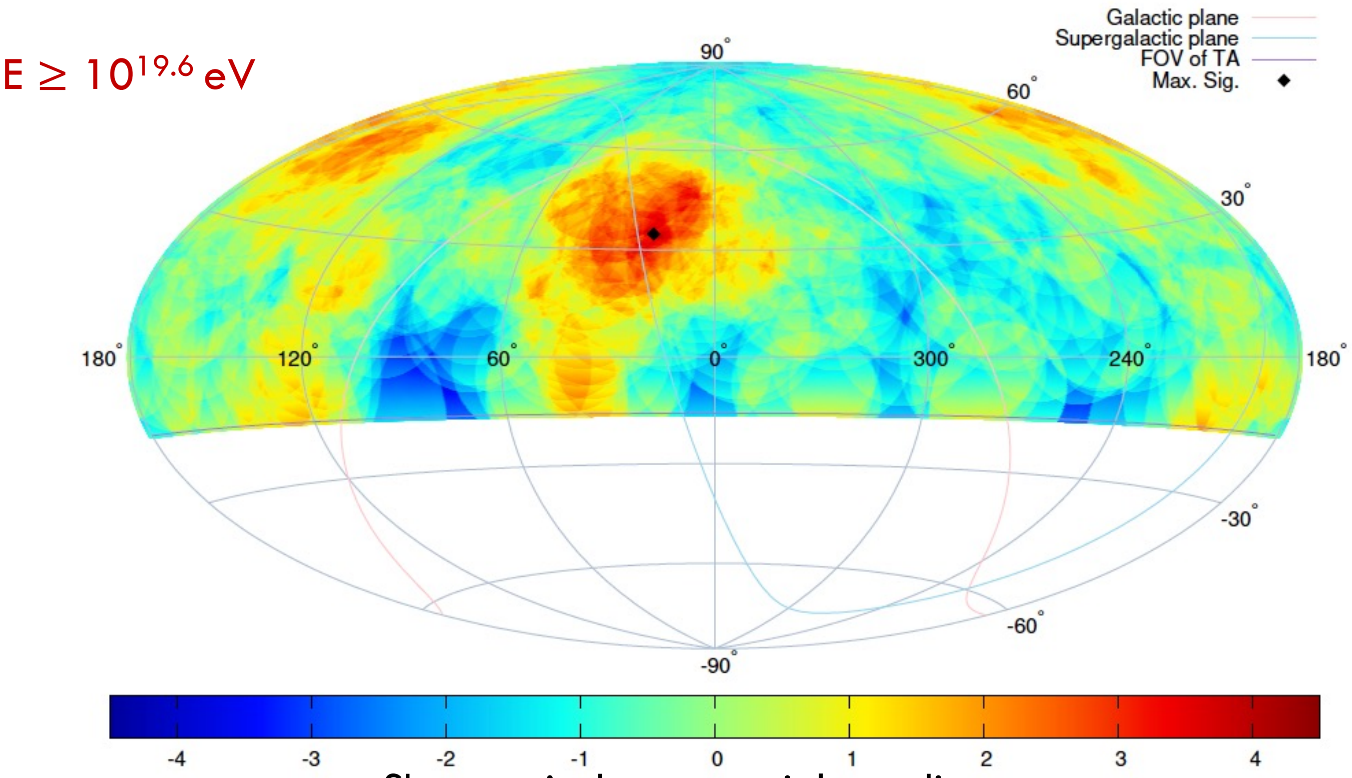
- 558 events with $E \geq 10^{19.5}$ eV (11-year TA SD data)
- Maximum local significance: 4.2σ at (19.0°, 35.1°)

  Observed: 59 events

  Expected from isotropy: 31.5 events

  ~87% excess to the isotropy

Li-Ma analysis with 20° oversampling: $E \geq 10^{19.6}$ eV



Skymaps in the equatorial coordinates

- 335 events with $E \geq 10^{19.6}$ eV (11-year TA SD data)
- Maximum local significance: 4.0σ at (19.7°, 34.6°)

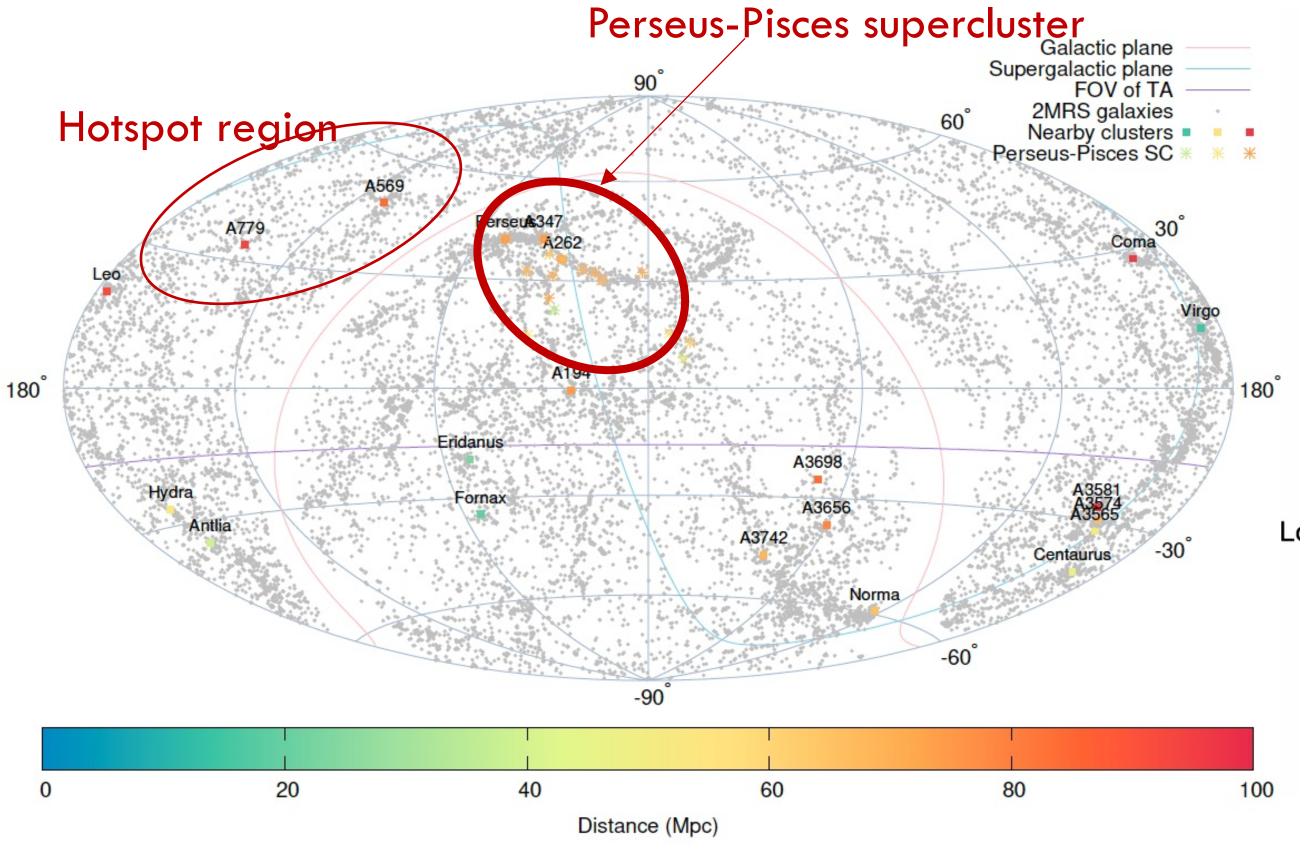
Observed: 39 events

Expected from isotropy: 18.6 events

~110% excess to the isotropy

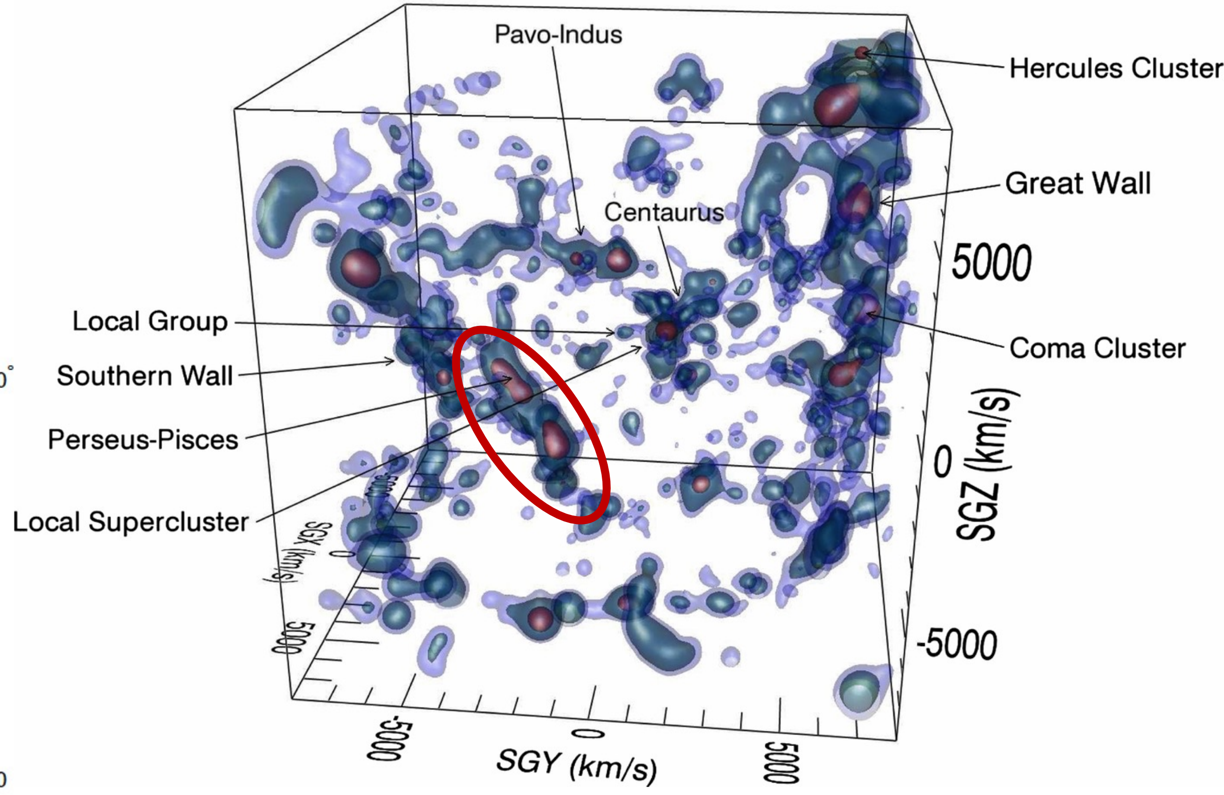
What is behind the new excess?

Sky map with nearby galaxies and clusters of galaxies



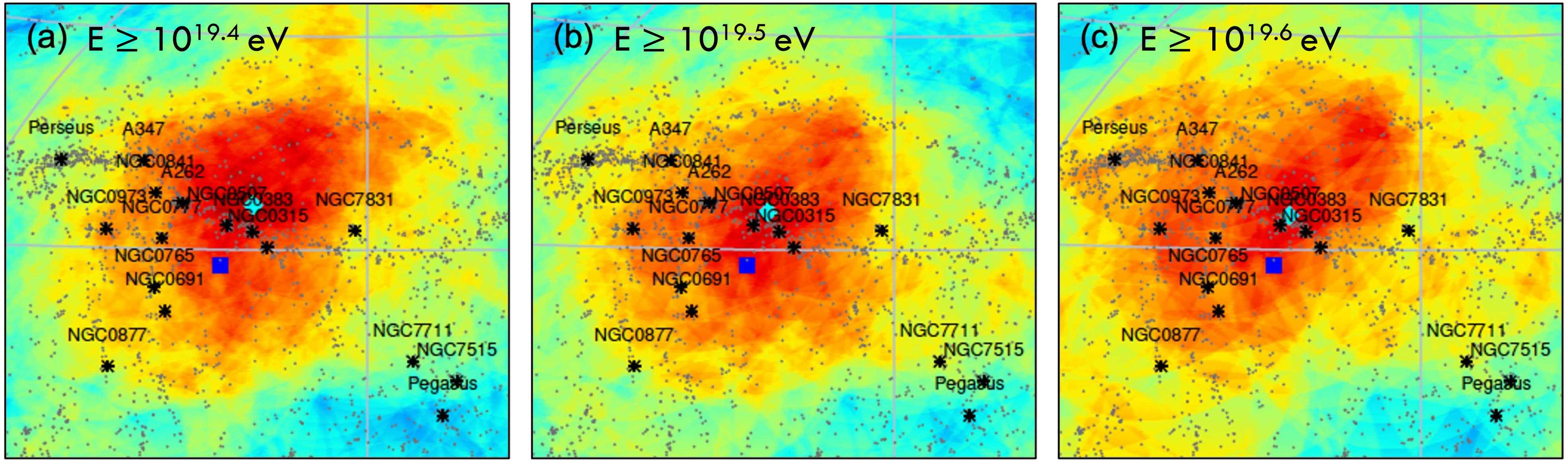
Equatorial coordinates

3-dimensional density maps



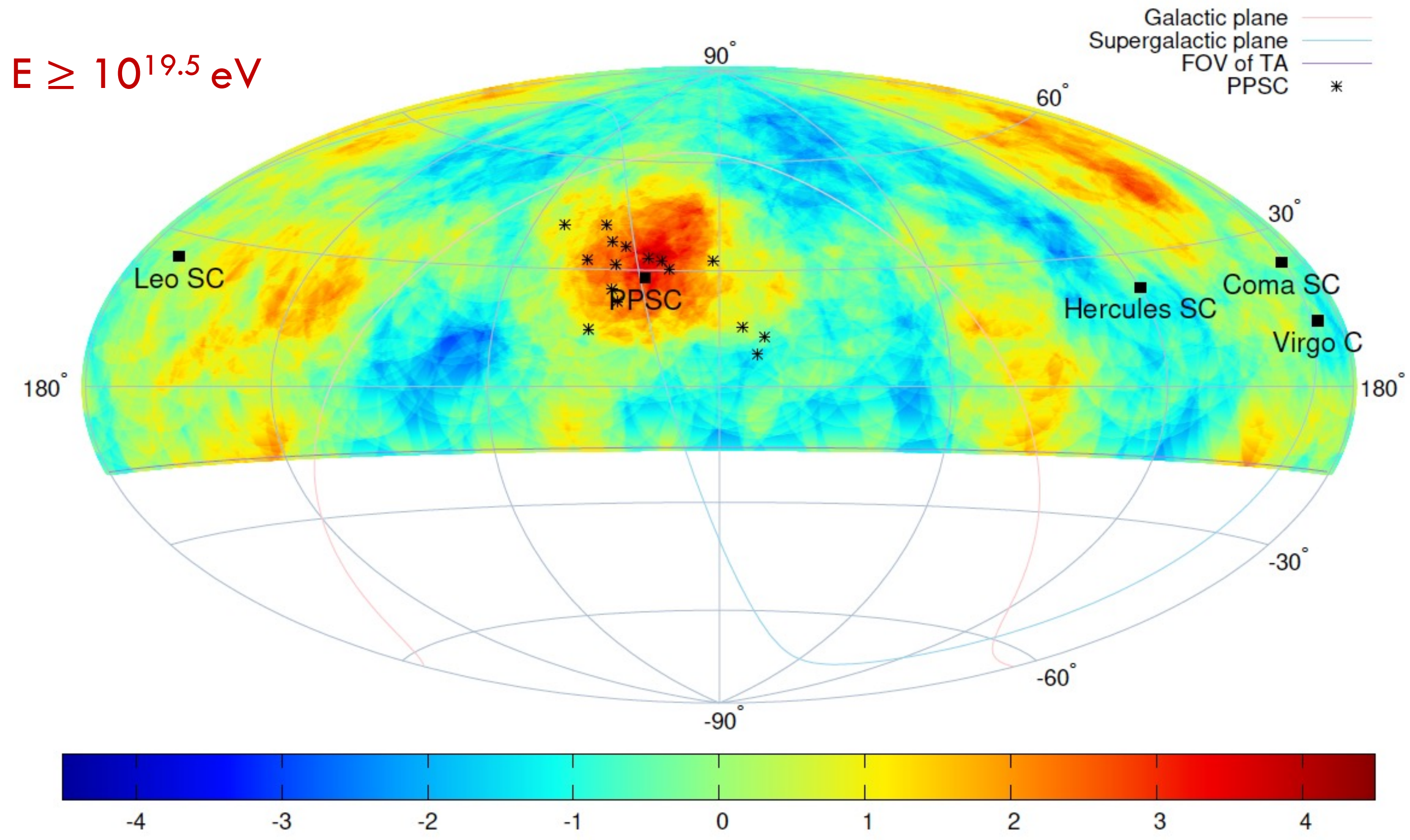
Courtois et al. (2013). AJ **146**(3).

New excess with the Perseus-Pisces supercluster (PPSC)



- Black asterisks (*): the representative elements of the PPSC; Gray dots (·): Galaxies from the 2MASS Redshift Survey catalog (35–100 Mpc); Cyan diamonds (◆): the positions of maximum excesses; Blue squares (■): the center of the PPSC.
- It is seen that the excess is coincident with the overall distribution of the PPSC. The angular separations between the positions of the maximum excesses and the center of the PPSC are less than ~10°.

New excess with PPSC and other major structures



- Choose all the similar major structures to the Perseus-Pisces supercluster in TA's field of view within 150 Mpc.
- Virgo cluster (17 Mpc), Perseus-Pisces supercluster (70 Mpc), Coma supercluster (90 Mpc), Leo supercluster (135 Mpc), and Hercules supercluster (135 Mpc).

Monte Carlo study methods and results

- To quantify how often this happens by chance, we generate many Monte-Carlo event sets, each containing the same number of events as the data, thrown isotropically according to the acceptance of the TA SD.
- We count as successes the number of sets where the point of maximum Li-Ma significance is at least as significant as in the data, and also occurs at least as close to the PPSC as in the data: $(S_{mc} \geq S_{obs})$ and $(\theta_{mc} \leq \theta_{obs})$.
- Chance probability of having equal or higher excess on top of the PPSC / major structures {PPSC, Virgo cluster, Coma SC, Leo SC, Hercules SC}

Summary of the Monte-Carlo studies that estimate the chance probability of having an excess

Energy (eV)	Events	Criteria	PPSC	Major structures
$E \geq 10^{19.4}$	864	$(S_{mc} \geq 4.4\sigma)$ & $(\theta_{mc} \leq 8.6°)$	**3.6σ**	3.1σ
$E \geq 10^{19.5}$	558	$(S_{mc} \geq 4.2\sigma)$ & $(\theta_{mc} \leq 7.4°)$	**3.6σ**	3.0σ
$E \geq 10^{19.6}$	335	$(S_{mc} \geq 4.0\sigma)$ & $(\theta_{mc} \leq 6.8°)$	**3.4σ**	2.9σ

- **This result indicates that a cosmic ray source may exist in the direction of PPSC.**

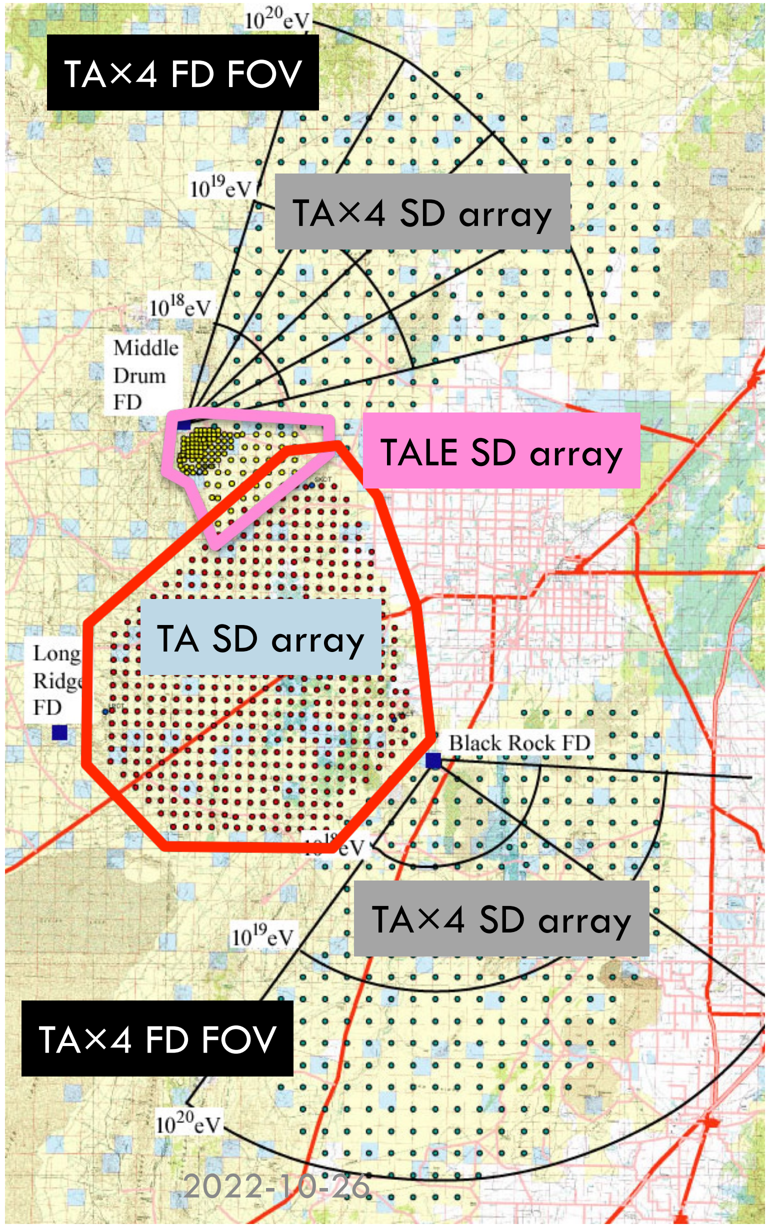
Conclusions

- A new excess appears in slightly lower energy events with the local Li-Ma significance of **4.2σ**.
- Behind the new excess, there is **the Perseus-Pisces supercluster.**
- Having an excess on top of the PPSC by chance is rare (**3.5σ**).
- The chance probability of having an excess on top of nearby major structures (PPSC + Virgo cluster + Coma SC + Leo SC + Hercules SC) is also rare (**3.0σ**).
- The excess of events observed in the direction of the Perseus-Pisces supercluster indicates that **a cosmic ray source may exist in the direction of PPSC**, where there are many interesting astronomical objects, including active galaxies, starburst galaxies, and large-scale shocks, that may be UHECR sources.
- It is important to study these astronomical objects in the supercluster further and to increase the statistical power of northern hemisphere cosmic ray studies.

Summary of TA's recent status

- **Energy Spectrum**
  - Confirm the GZK suppression at E ~ 6.5×10^{19} eV
  - Find a significant difference in the spectra above and below ~25° in declination
- **Mass Composition:** Appears light and steady for E>10^{18} eV
- **Arrival Direction Distribution**
  - Hotspot persists, but significance does not increase very quickly
  - New significant excess at a slightly lower energy in conjunction with the Perseus-Pisces supercluster
- Need more data to improve statistics, especially for anisotropy and mass composition measurement
- Plan to complete the extension of the Telescope Array, **the TA×4 project**, and take more data!!

TA×4 project: Upgraded!!!



- Motivation

  To study more about the highest energies and examine the implications obtained by TA

- Four times TA SD (**~3000 km^2**)

  500 new SDs with 2.08 km spacing

- Two FD stations

  North/South stations were installed now.

- Status

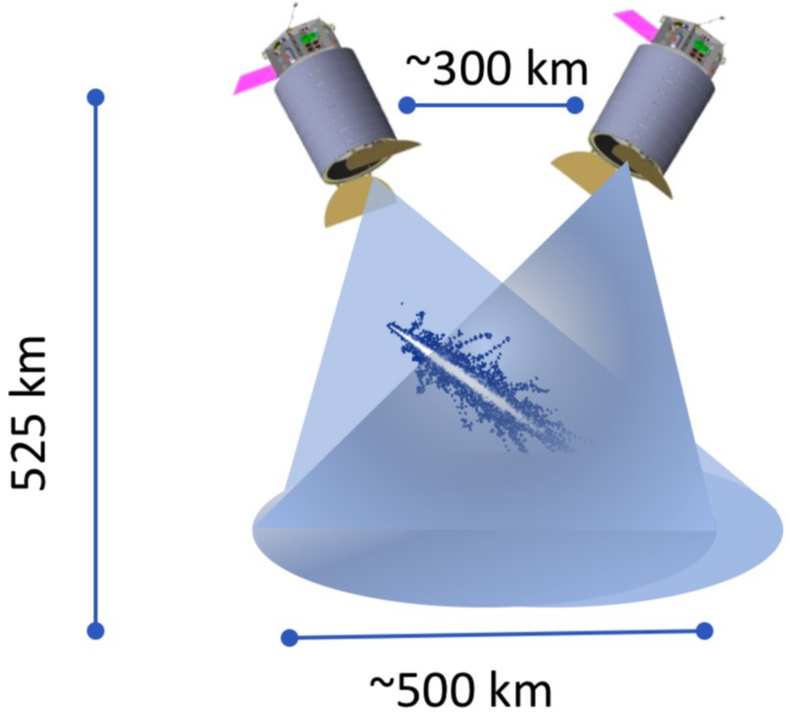
  - ~250 TAx4 SDs were deployed in Mar. 2019.
  - Two TAx4 FD stations were constructed.
  - Data acquisition has been started.

- Prospects

  Gives us a crucial clue to identify UHECR sources with high statistics

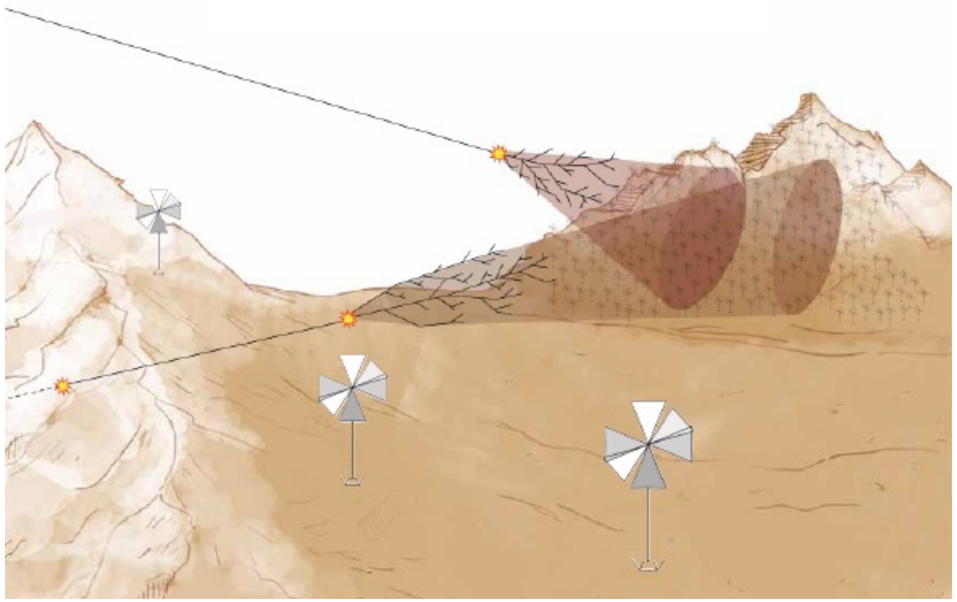
Next generation UHECR observation

POEMMA



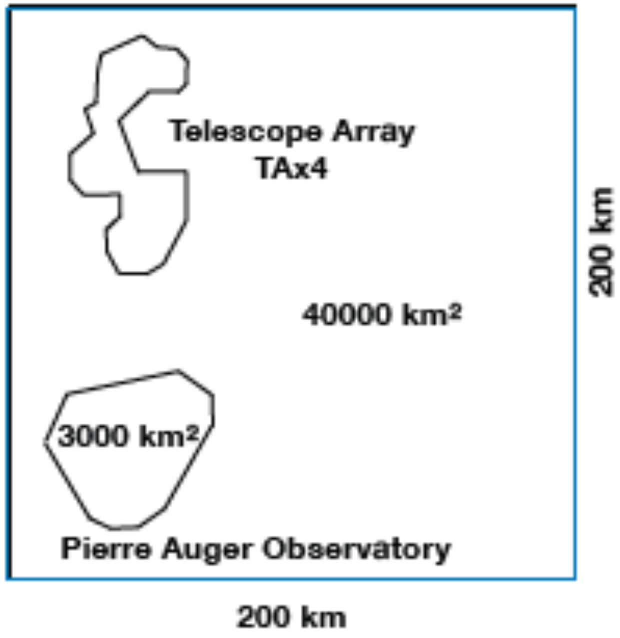
The Probe of Multi-Messenger Astrophysics (POEMMA) observatory is a space-based experiment proposed to identify the sources of UHECRs and to observe cosmic neutrinos both with full-sky coverage.

GRAND



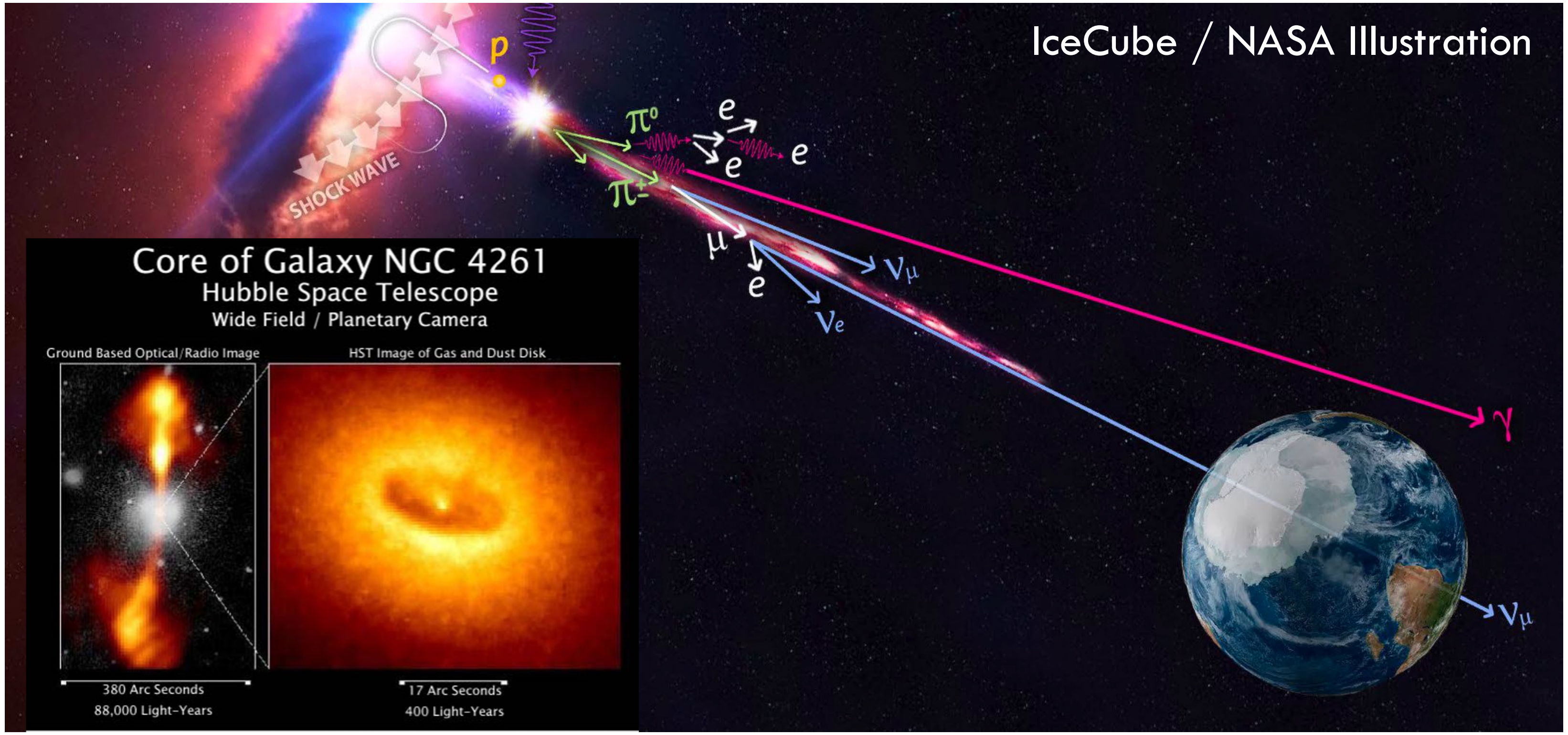
The Giant Radio Array for Neutrino Detection (GRAND) is a proposed experiment to detect the most energetic cosmic particles: neutrinos, cosmic rays, and gamma rays

GCOS

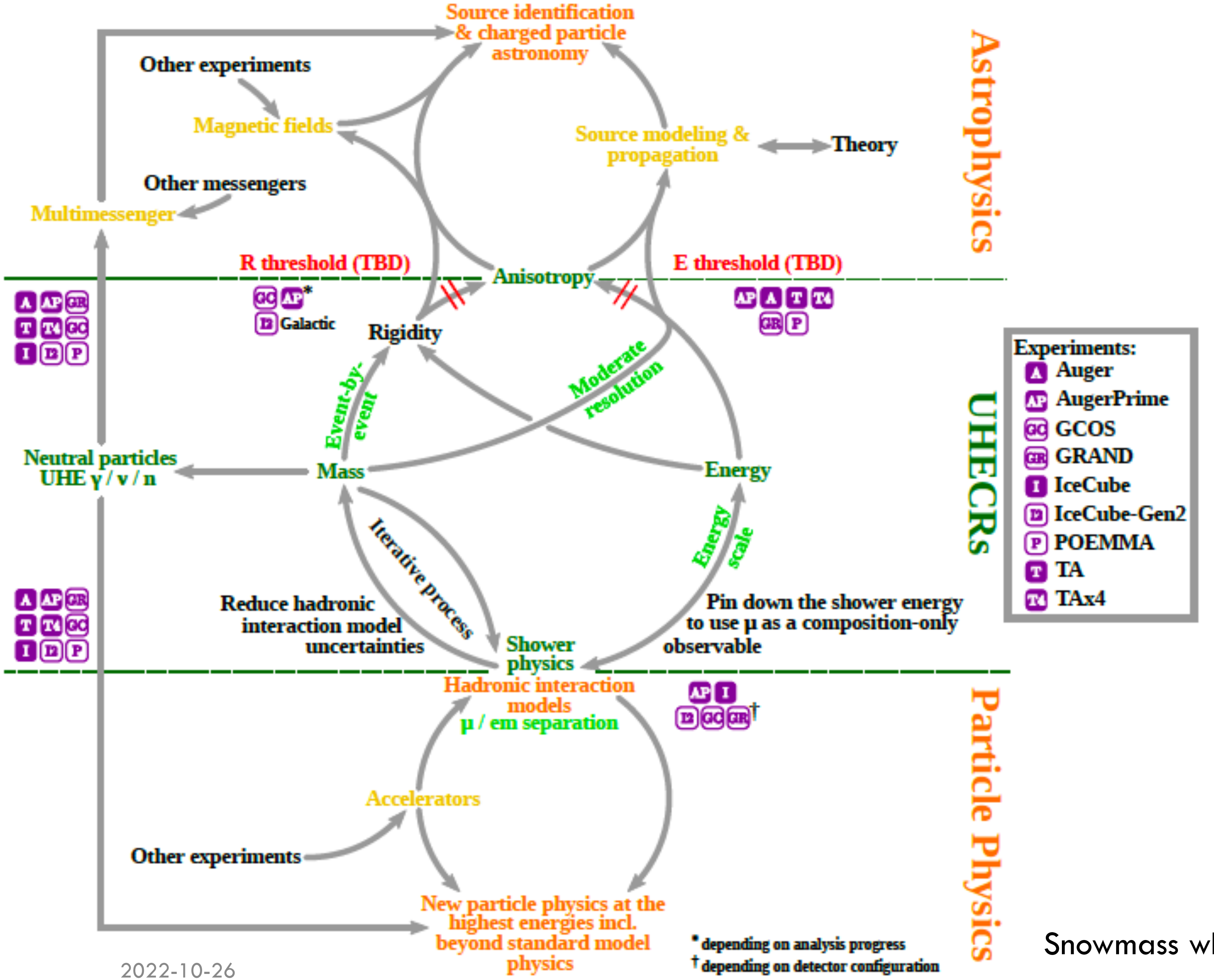


The Global Cosmic Ray Observatory (GCOS) is a set of surface arrays with a total area of about 40,000 km^2 to identify UHECR sources.

High energy astrophysics: Multi-messenger astrophysics



- Includes neutrino and gamma-ray astronomy: Correlations in the arrival directions
- Gamma rays and neutrinos are both secondary products of interactions between primary cosmic rays and matter (possibly near the source site)—they have the advantage of not bending in the ubiquitous magnetic fields in outer space.



Strong connection with

- particle physics
- astrophysics

Snowmass white paper (2021)

We hope to better understand the nature and origin of UHECRs, thereby giving us a window to understanding the universe.

Thank you!