The Puzzles of UHECR: Anisotropy Studies

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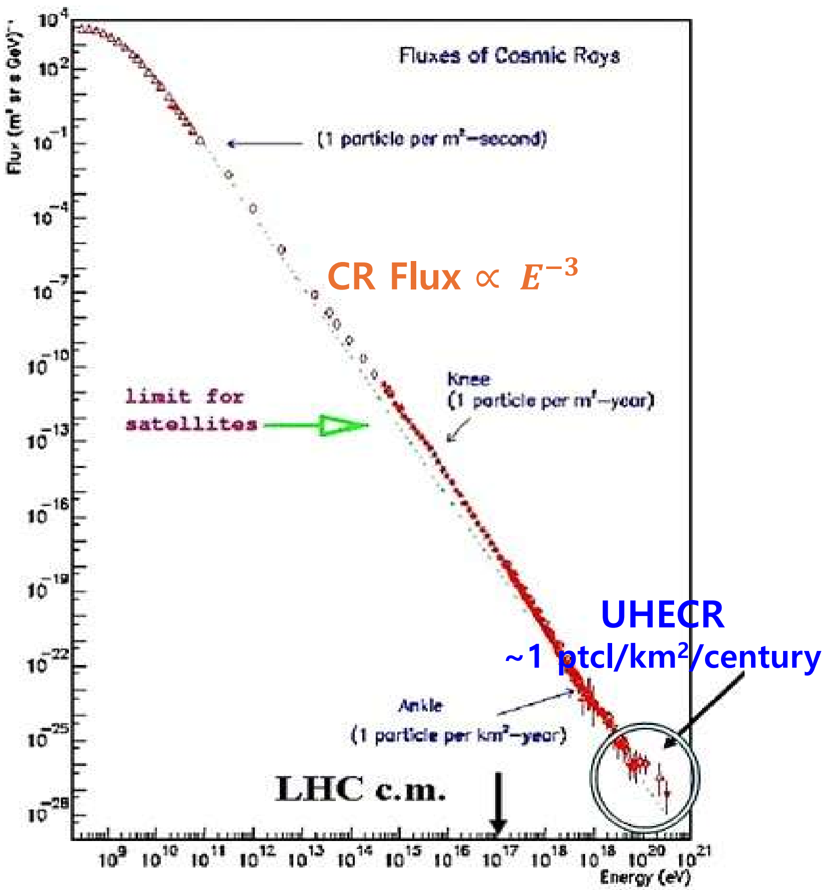
CUBES 2026, 2026.04.26

Ultra-High Energy Cosmic Rays (UHECR)



- Cosmic rays
  - Energetic particles reaching Earth from outer space
  - Energies up to $\sim 10^{20}$ eV
  - Flux decreases as $\sim E^{-3}$ with some features
- Ultra-high energy cosmic rays (UHECR)
  - Cosmic rays with energy $\boldsymbol{E \gtrsim 10^{18}}$ **eV**
  - 1962, CR with $E > 10^{20}$eV at Volcano Ranch
  - 1991, CR with $E = 3.2 \times 10^{20}$eV at Fly's eye
    – **Oh-My-God** particle –
  - 2021, CR with $E = 2.4 \times 10^{20}$eV at TA SD
    – **Amaterasu** particle –
  - A single particle (proton?) having the kinetic energy of a baseball (macroscopic object) with speed of 100 km/h
  - Cannot be trapped by the galactic magnetic fields
    → Extragalactic origin

The main puzzle of UHECR

- **Where and How can elementary particles attain such extremely high energies?**

Oh-My-God particle

23 languages

Article Talk Read Edit View history Tools

From Wikipedia, the free encyclopedia Coordinates: $5^h\ 40^m\ 48^s$, +48° 0′ 0″

Not to be confused with the "God Particle", or Higgs boson.

The **Oh-My-God particle** (as physicists dubbed it[1]) was an ultra-high-energy cosmic ray detected on 15 October 1991 by the Fly's Eye camera in Dugway Proving Ground, Utah, United States.[2][3][4] As of 2026, it is the highest-energy cosmic ray ever observed.[5] Its energy was estimated as $(3.2 \pm 0.9) \times 10^{20}$ eV (320 exaelectronvolt). The particle's energy was unexpected and called into question prevailing theories about the origin and propagation of cosmic rays.

Amaterasu particle

11 languages

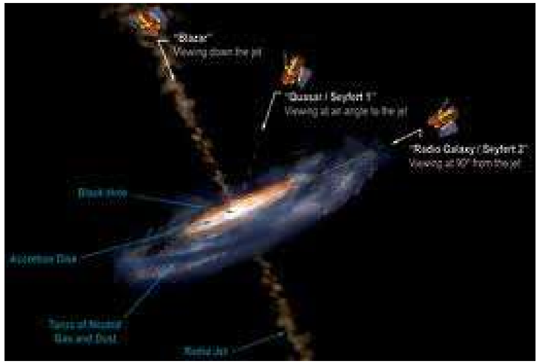
Article Talk Read Edit View history Tools

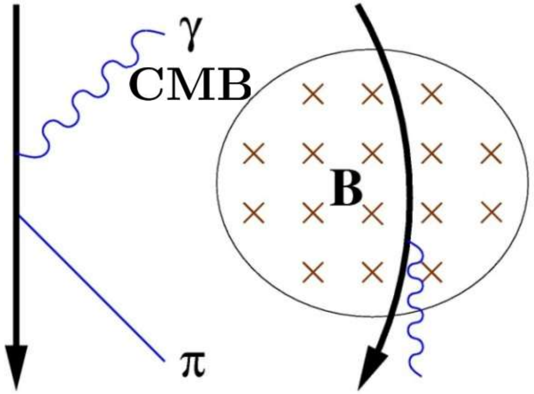
From Wikipedia, the free encyclopedia

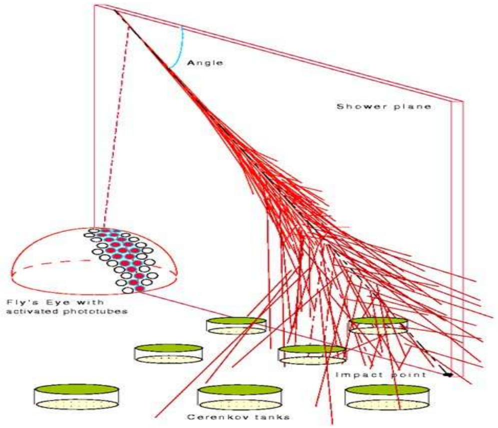
The **Amaterasu particle**, named after the sun goddess in Japanese mythology, was an unexpected ultra-high-energy cosmic ray detected in 2021 and later identified in 2023,[1] using the Telescope Array Project observatory in Utah, United States. It had an energy exceeding 240 exa-electronvolts (EeV) and was inferred through the two dozen particles it sent toward ground detectors. This single particle appears to have emerged, inexplicably, from the Local Void, an empty area of space bordering the Milky Way galaxy.[2] The single subatomic particle held energy roughly equivalent to a brick dropping to the ground from waist height.[3]

> Contemporary astrophysics is faced by a number of acute problems. One of them concerns dark matter, which one might (perhaps mischievously) qualify as the study of particles which should exist. . . but until farther notice, don't. Ultra high energy cosmic rays constitute the inverse problem: particles which do exist. . . but perhaps shouldn't.
>
> —Ludwik M. Celnikier (1996, p. 453)

UHECR – Production, Propagation, Observation







Production

Acceleration of charged particles, Decay of super-heavy particles

- Location (source distribution)
- CR Injection
  - Composition
  - Energy spectrum

Propagation

Interactions with cosmic backgrounds (microwaves, radio waves, magnetic fields)

- Energy loss
- Deflection and Time lag
- Secondary CR production

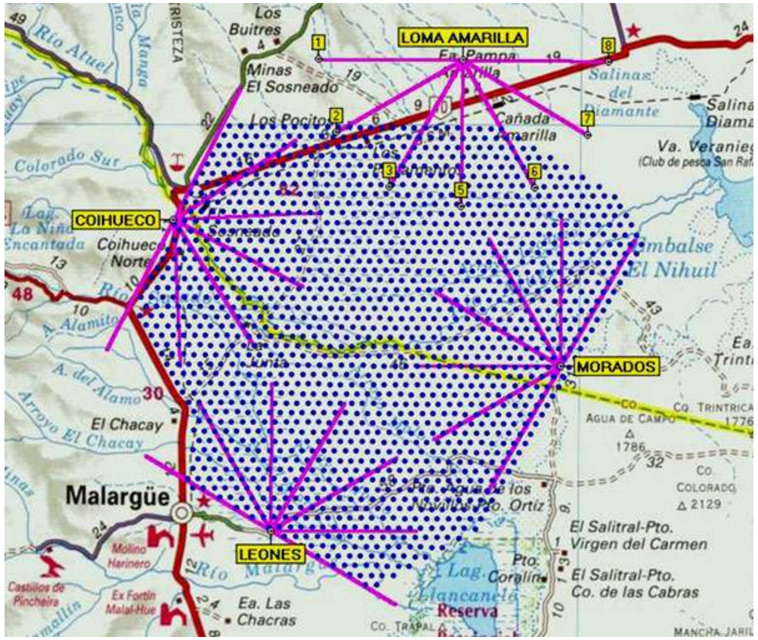
Observation

Extensive air showers, using the atmosphere as a calorimeter or scintillator

- Energy
- Direction
- Composition

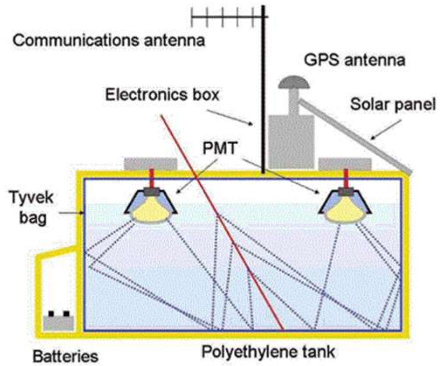
Pierre Auger Observatory (Auger)

- Location : Mendoza, Argentina (35°.20S)
- SD : 1600 water Cherenkov detectors,
  1.5 km square grid, 3000 km^2 area
- FD : 24 telescopes in 4 stations

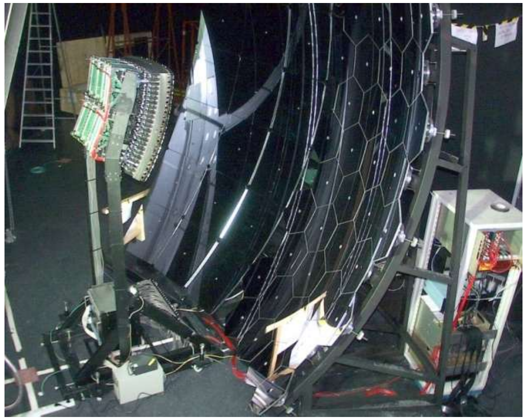


60 km

Surface Detector
Water Cherenkov



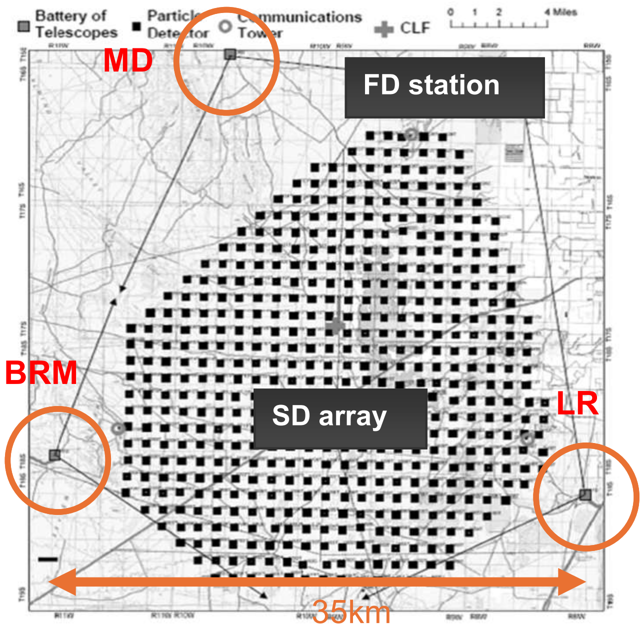
Fluorescence Detector
PMT pixel camera



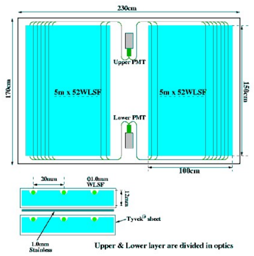
- Duty cycle
  - SD : ~100%
  - FD : ~10-15%

Telescope Array (TA)

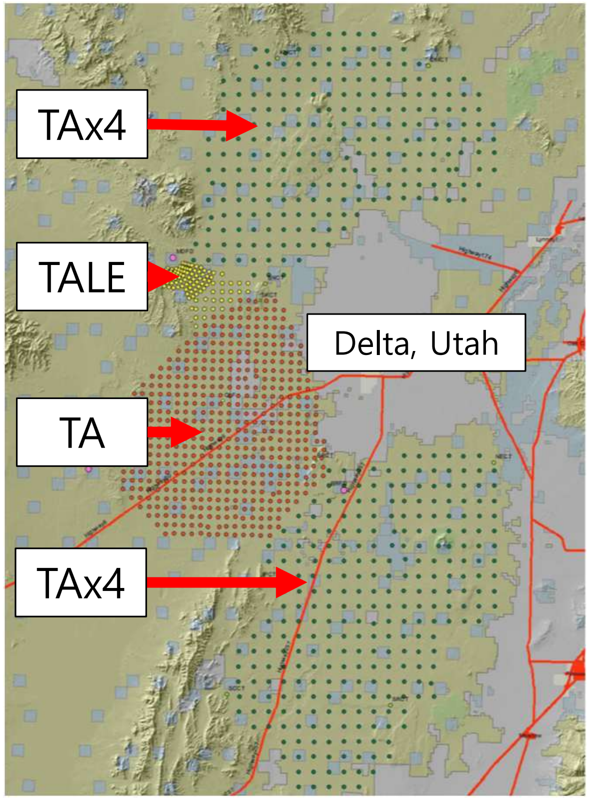
- Location : Utah, USA (39°.30N, 112.9°W)
- SD : 507 plastic scintillation detectors,
  1.2 km square grid, 678 km^2 area
- FD : 18 telescopes in 3 stations



Surface Detector
Plastic scintillator



Fluorescence Detector
PMT pixel camera

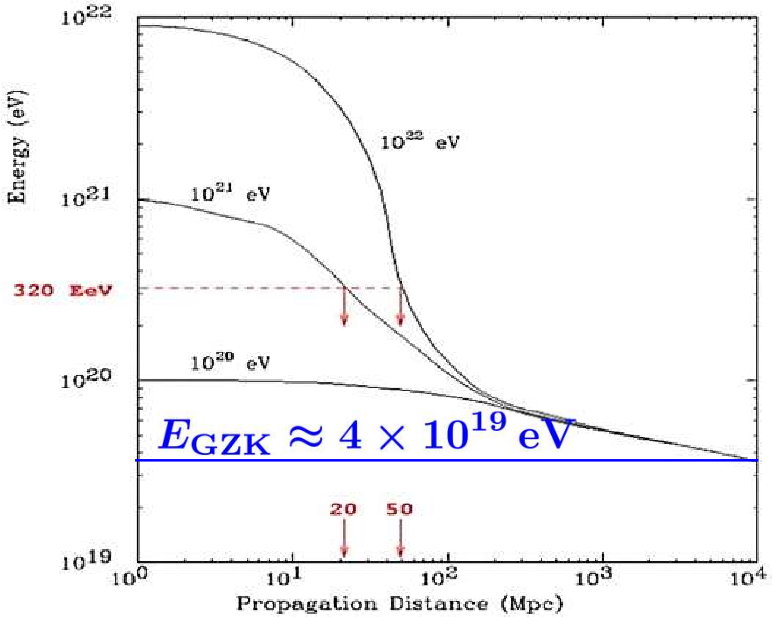


- TALE (TA Low Energy)
- TAx4 (under construction)

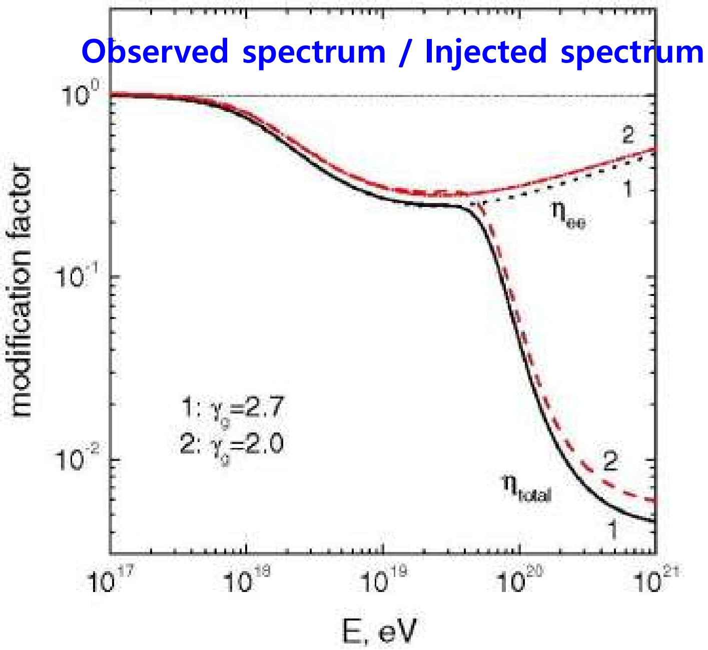
Propagation – Energy loss

- UHECR p, A, γ interact with CMB photons.

$$N + \gamma \rightarrow N + \pi \quad \text{(photo-pion production)}$$
$$E_{\text{th}} \approx 6.8 \times 10^{19} \left(E_{\gamma B}/10^{-3}\,\text{eV}\right)^{-1} \text{eV} \quad \text{(threshold energy)}$$



The energy of protons as a function of the propagation distance.



Change in the energy spectrum

- GZK suppression
  - If the sources are uniformly distributed …
  - Suppression of flux above the GZK energy ~ 4×10^{19} eV
  - GZK radius – attenuation length for super-GZK CR 100Mpc for proton
  - Excessive super-GZK CR may come from the sources within the GZK radius.

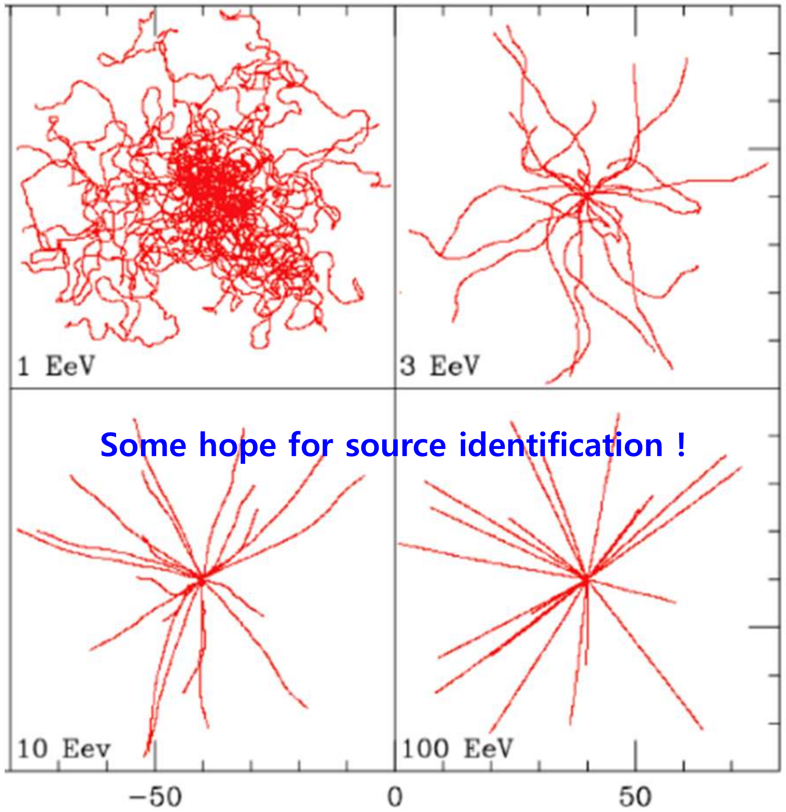
Propagation – Deflection and Time lag

- Magnetic fields → Deflection and Time lag
- Deflection angle – Regular fields and Turbulent fields

$$\delta\theta = 0.5^\circ Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

$$\delta\theta_{\mathrm{rms}} \approx 0.4^\circ Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{\sqrt{d\cdot\ell}}{1\,\mathrm{Mpc}}\right) \left(\frac{B_{\mathrm{rms}}}{10^{-9}\,\mathrm{G}}\right)$$

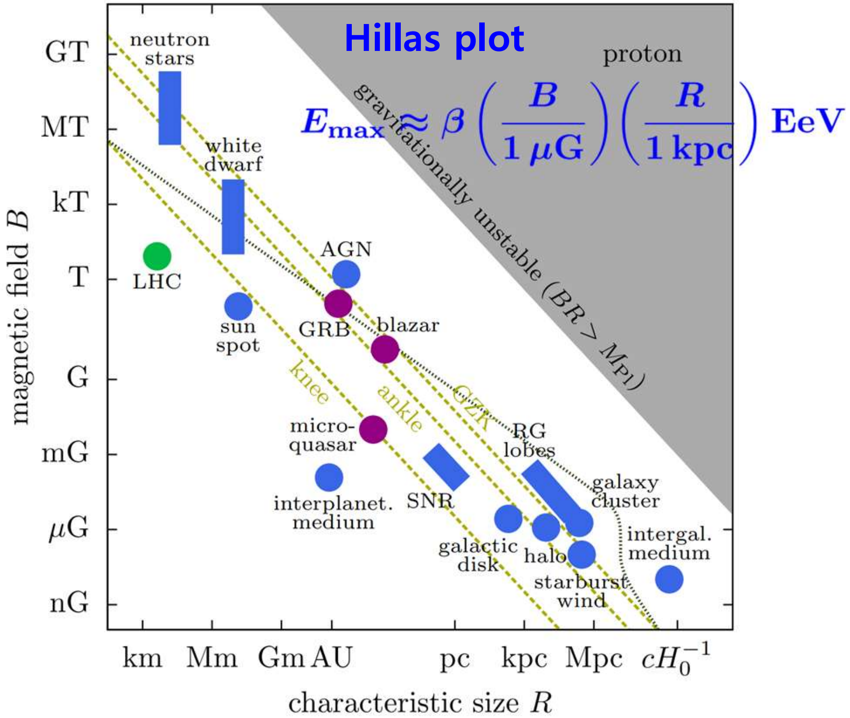
- Galactic magnetic fields (GMF)
  - $B_{\mathrm{G}} \sim 10^{-6}$ G, $R_{\mathrm{G}} \sim 10$ kpc → $\delta\theta \lesssim (0.5^\circ \sim 5^\circ)\, E_{20}^{-1}$
- Extragalactic magnetic fields (EGMF)
  - $B_{\mathrm{EG}} \sim (10^{-9} \sim 10^{-6})$ G (very uncertain)



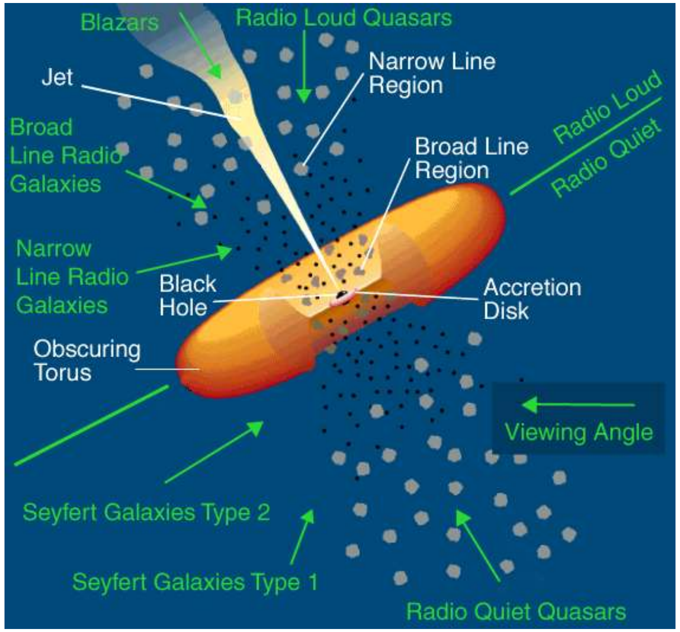
Proton, Turbulent fields of 10^{-9} G, 1 Mpc

Production – Bottom-up – Cosmic Accelerators

- Acceleration mechanisms
  - Diffusive shock acceleration
  - Unipolar induction / direct electric-field acceleration



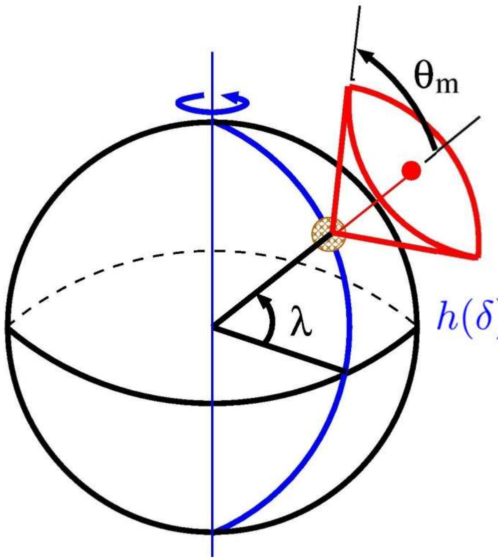
- Acceleration sites - Candidates
  - **AGN** – SMBH, accretion disk, jets and lobes
  - **SBG** – containing GRBs, Magnetars



Data Analysis – Exposure

- The detector array fixed at a given latitude does not cover the sky uniformly. We must consider its efficiency as a function of the arrival direction.
- Exposure function – Geometrical exposure and Detector efficiency

Geometrical exposure



Arrival Direction: (α, δ)
(Right Ascension, Declination)

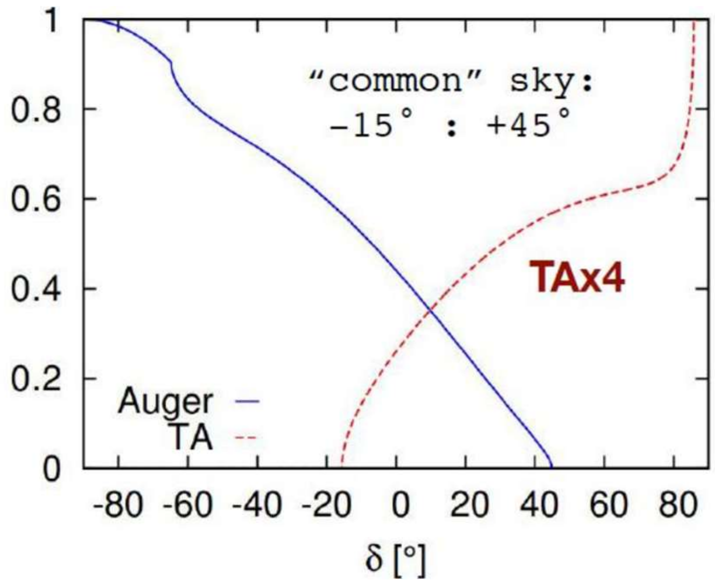
Detector Geometry: $(\lambda,\ \theta_m)$
(Lattitude,Zenith angle cut)

$$h(\delta) = \frac{1}{\pi}\left[\sin\alpha_m \cos\lambda\cos\delta + \alpha_m \sin\lambda\sin\delta\right]$$

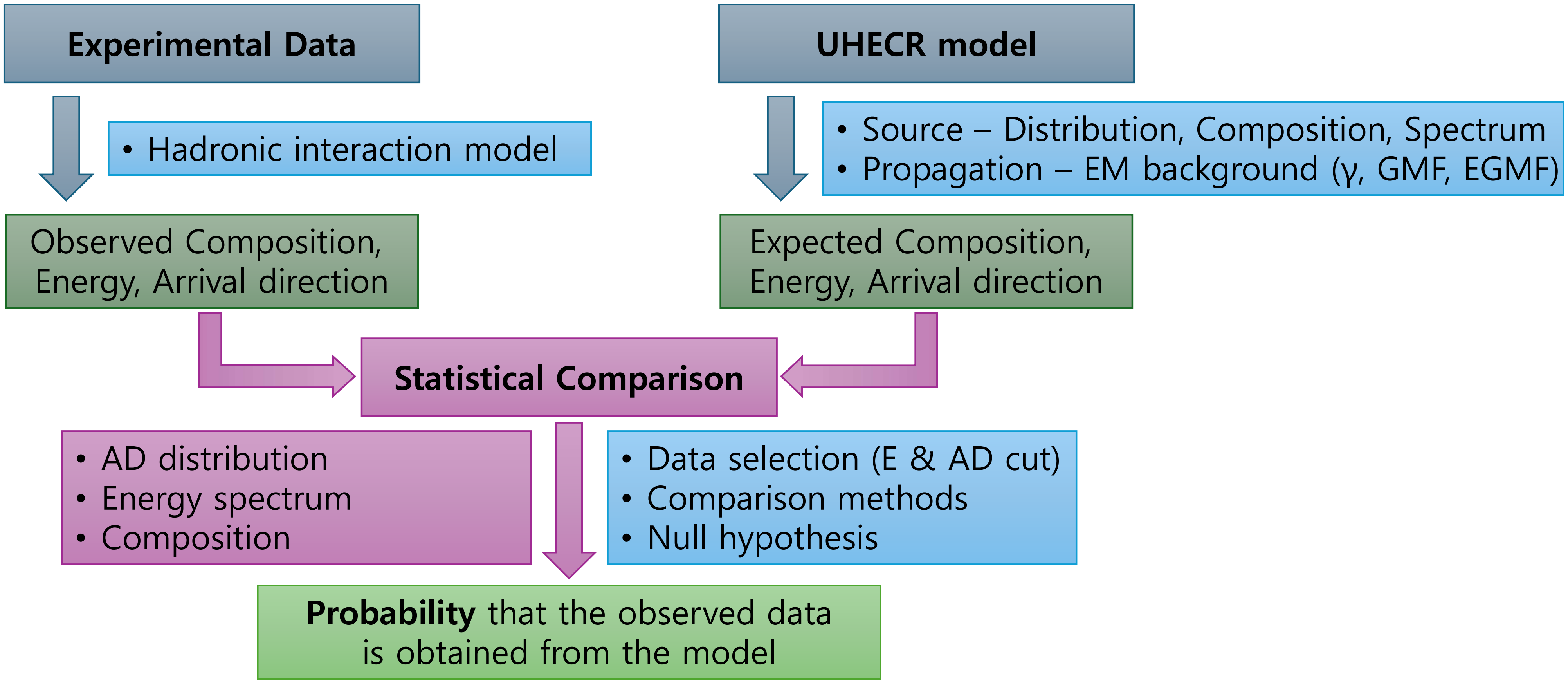
$$\alpha_m = \begin{cases} 0, & \text{for } \xi > 1, \\ \pi, & \text{for } \xi < -1, \\ \cos^{-1}\xi, & \text{otherwise} \end{cases}$$

$$\xi = \frac{\cos\theta_m - \sin\lambda\sin\delta}{\cos\lambda\cos\delta}$$

$$\text{PAO}: \lambda = -35.20^\circ,\ \theta_m = 60^\circ$$
$$\text{TA}: \lambda = +39.30^\circ,\ \theta_m = 55^\circ$$

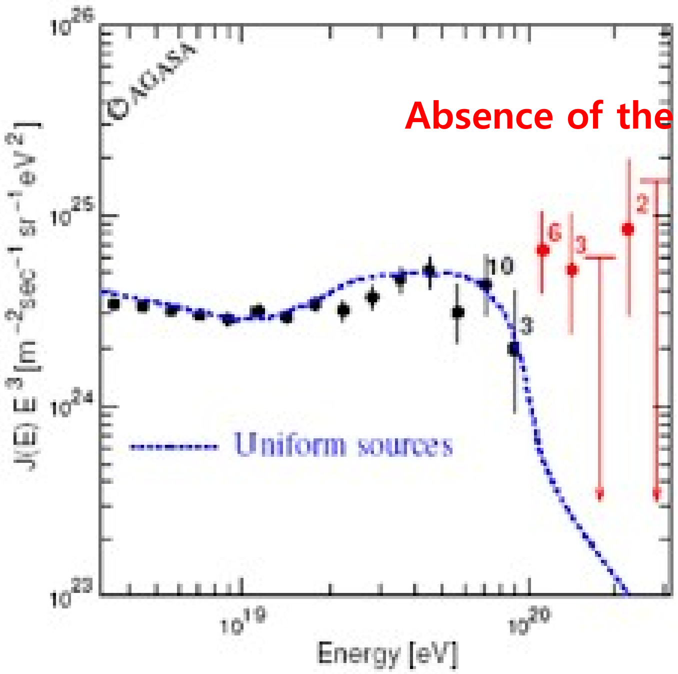


Data Analysis – modeling and statistical test



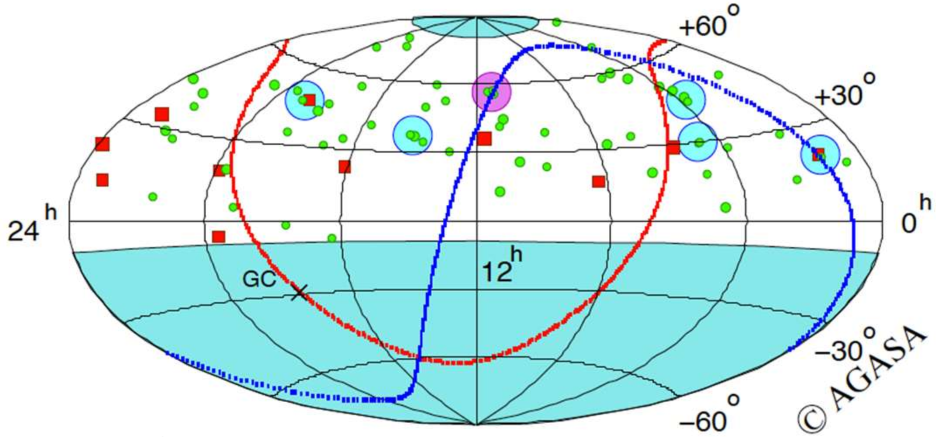
Issues – AGASA results

- AGASA (Hayashida et al. 2000)



Absence of the GZK cutoff

Isotropic with small clustering



- **Big puzzles of AGASA results**
  - Excessive super-GZK CR → Sources within the GZK radius
  - Galaxy (~ matter) distribution within the GZK radius – concentrated along the supergalactic plane.
  - Isotropic distribution of CR → Sources beyond GZK radius → Violation of GZK physics?

Issues – Crazy ideas & New experiments

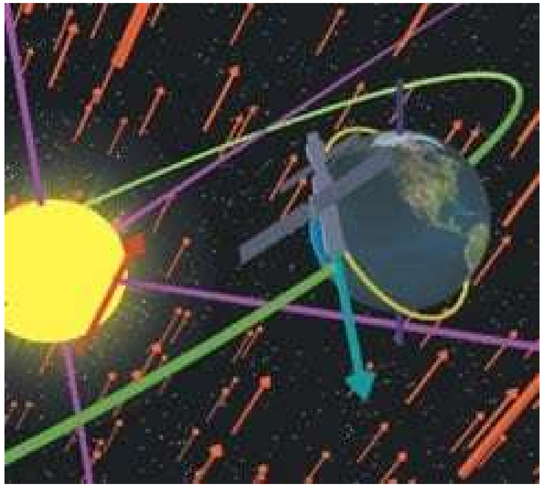
- Super-heavy dark matter

Figure 7. Dark matter may be much more massive than usually assumed, much more massive than wimpy WIMPS, perhaps in the WIMPZILLA class.

In perhaps the greatest image every to make it into a scientific paper, Figure 7 of Kolb, Chung, and Riotto's paper from 20 years ago highlights what a WIMPzilla might look like. The illustration is not to scale.

KOLB, CHUNG AND RIOTTO, 1998

- Lorentz symmetry violation

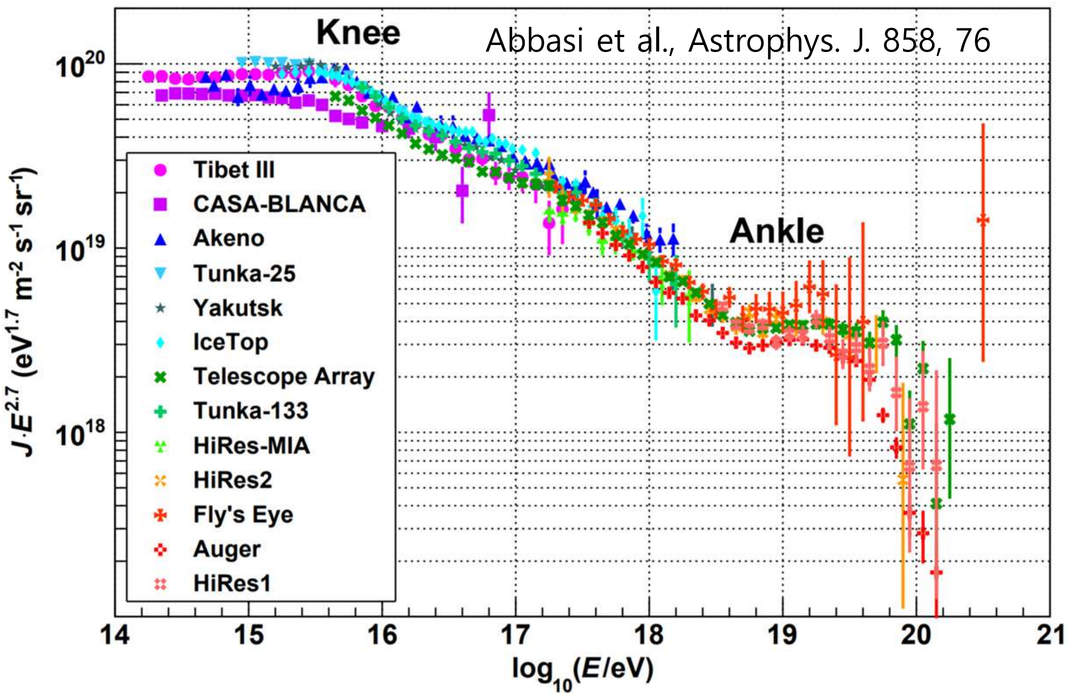


- New experiments launched
  - Pierre Auger Observatory (2005)
  - Telescope Array (2008)

TELESCOPE ARRAY PROJECT

PIERRE AUGER OBSERVATORY

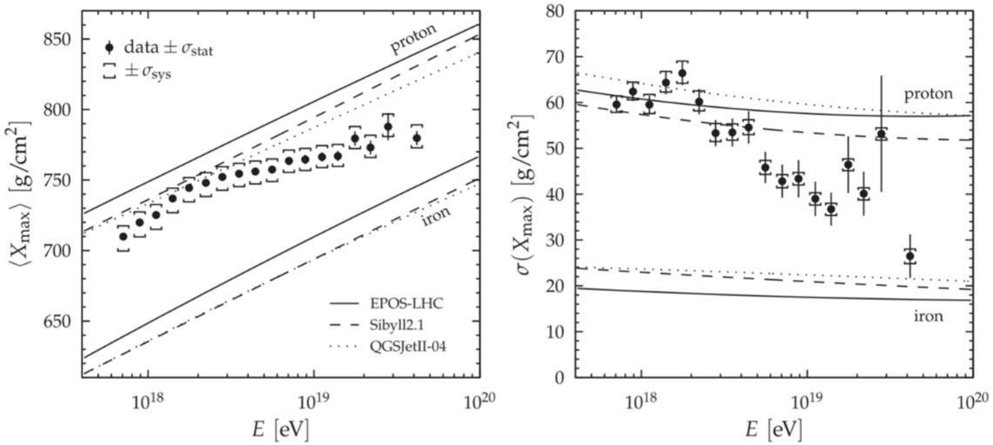
Issues – Energy spectrum

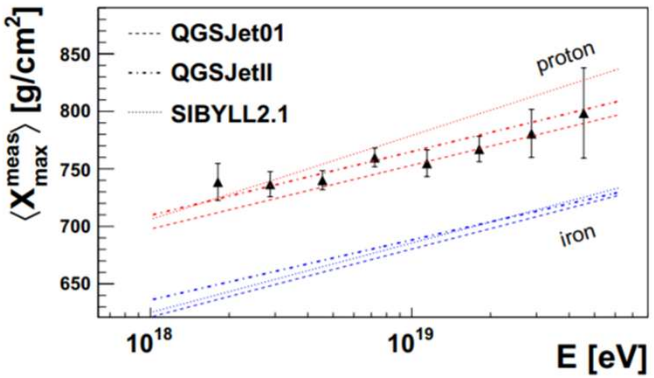


- Auger / TA – Energy scale difference
- Knee
  - Steep Fall → End of injection spectrum?
  - Astrophysical model – light to heavy nuclei
  - Leaky box model – Leakage of GCR
  - Interaction model – New physics in the interaction with the atmosphere
- Ankle
  - Rise → New component?
  - Ankle model – GCR → EGCR transition
  - Dip model – Pile up of GZK secondary
- **GZK suppression**
  - 1990s, AGASA – No GZK suppression
  - **Confirmed by 2010s, HiRes, Auger, TA**

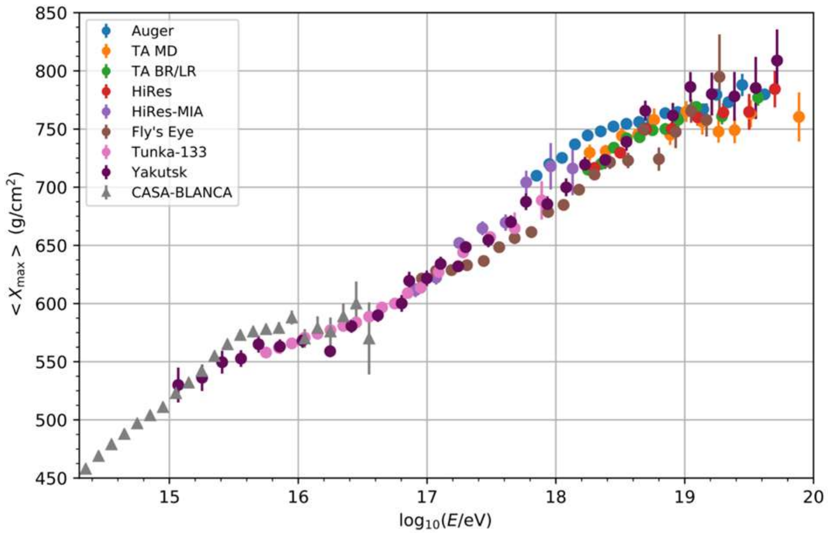
Issues – Composition

- $X_{\mathbf{max}}$ – Auger vs TA



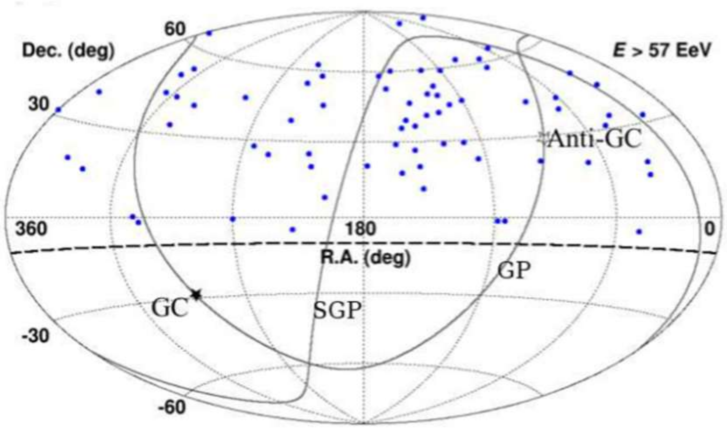


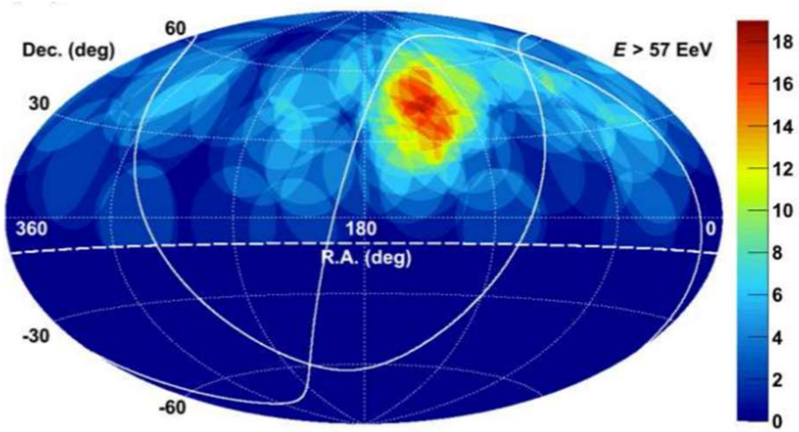
- Composition
  - Auger data favor heavy elements, while TA data stay at proton at high energies.
  - All $X_{\mathbf{max}}$ results are compatible within statistical errors.



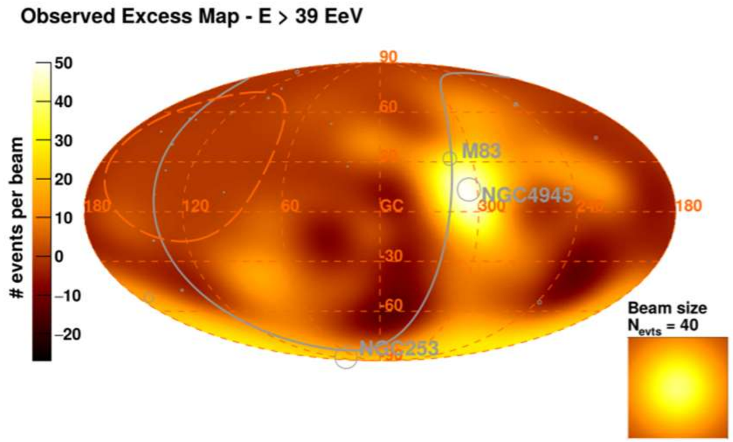
Issues – Arrival directions

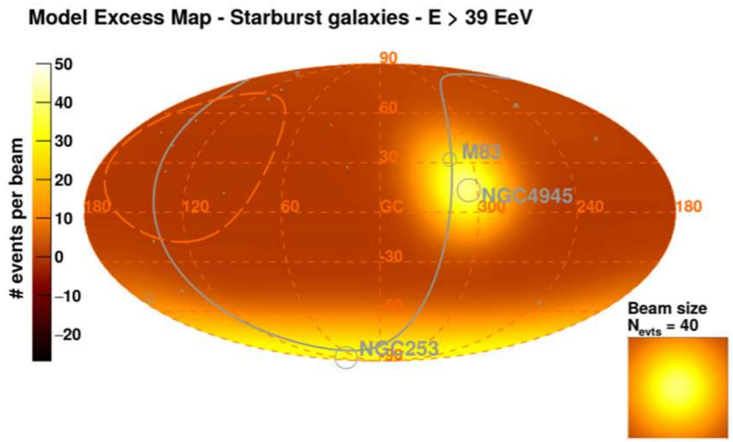
- **TA – Hot Spot :** $E \geq 57\ \mathrm{EeV}$



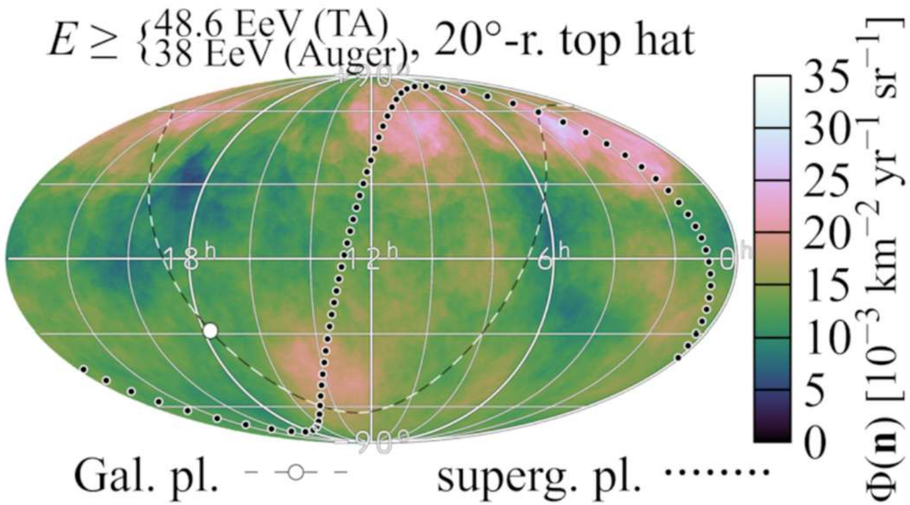


- **Auger – Correlation with SBG :** $E \geq 39\ \mathrm{EeV}$

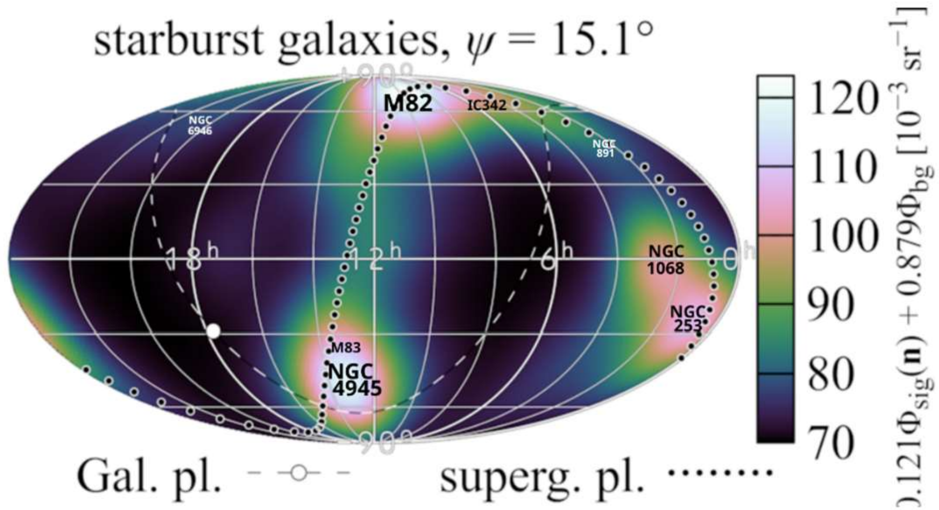




Correlation with SBG – TA & Auger



The observed UHECR flux
above 38 EeV (Auger) / 49 EeV (TA)



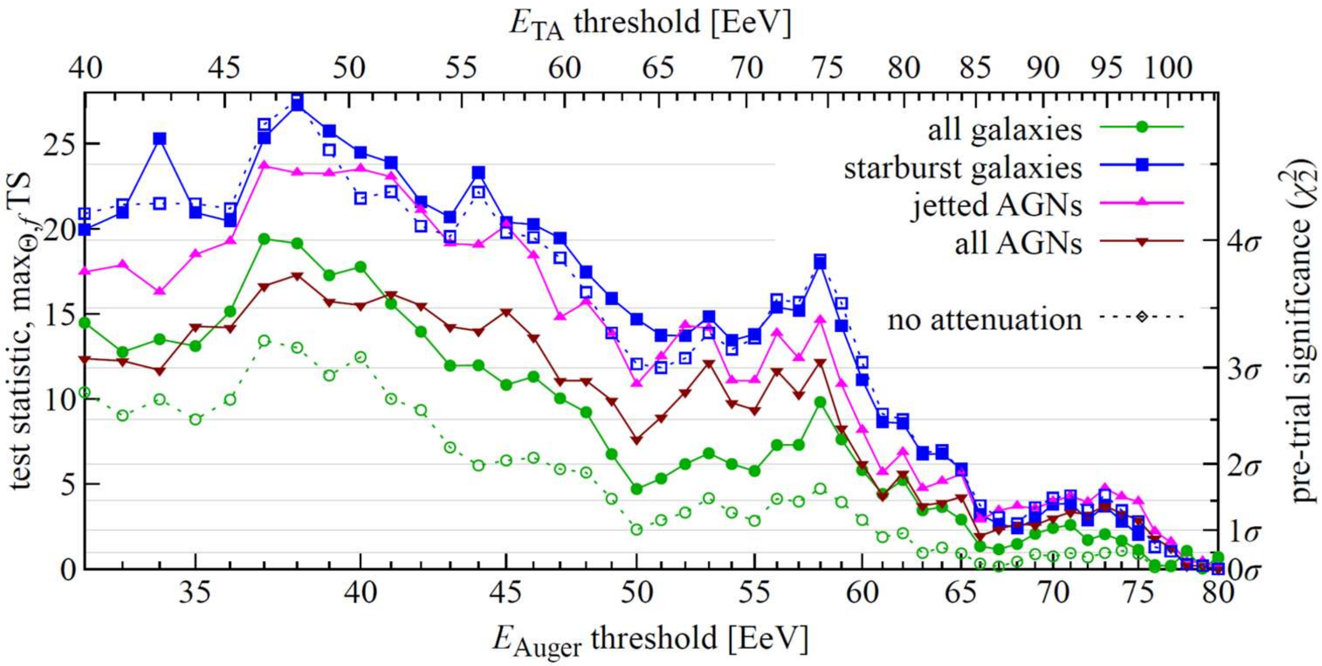
The starburst galaxy model predictions

UHECR with $E \geq 38(\text{Auger})[49(\text{TA})]$ EeV

SBG fraction 12.1%, Smearing angle 15.1°

4.7σ post-trial significance

Correlation with SBG & AGN – Auger



A. Gálvez Ureña, ICRC2025

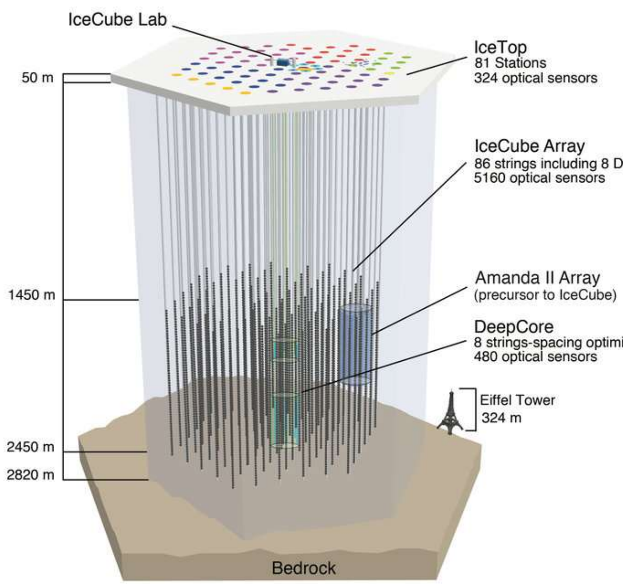
- Correlation with starburst galaxies: 4.2σ (post-trial)
- Correlation with jetted AGNs: 3.8σ (post-trial)

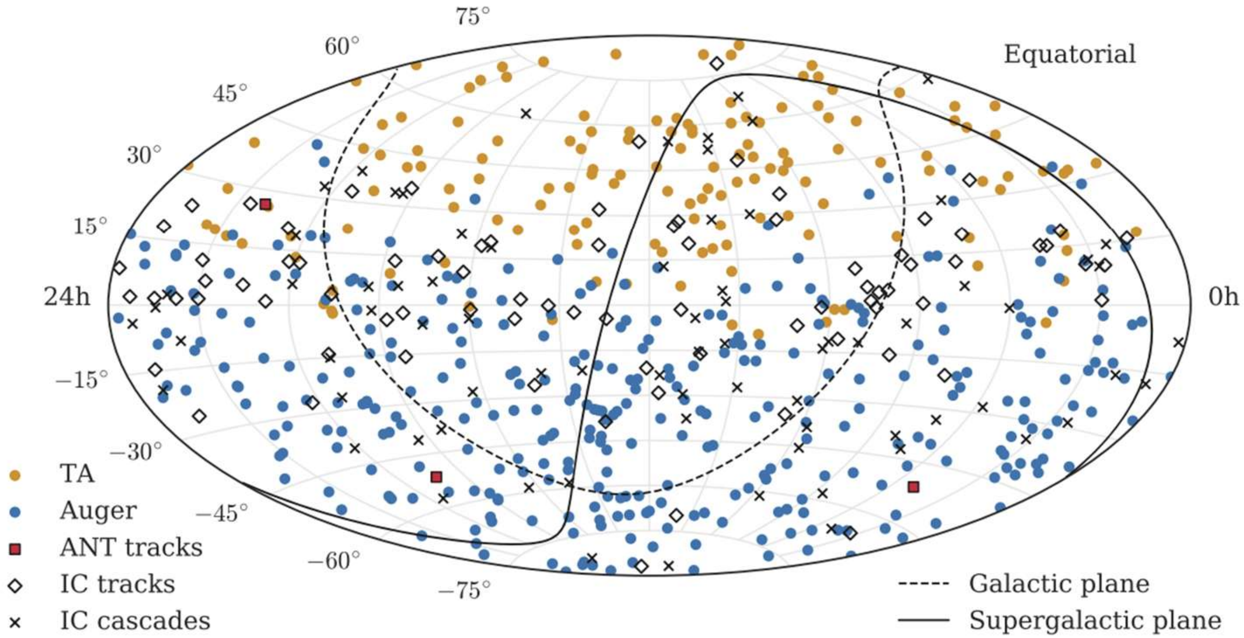
Multi Messengers – UHECR & Neutrinos

- Coincidence of high-energy neutrinos and UHECR
  - Observed data from (ANTARES+IceCube)+(Auger+TA)
  - JCAP 01 (2016) 037 : Correlation – 3σ at 22°
  - ApJ 934, 164 (2022) : No significant correlation

❖ UHECR-produced γ and ν

- Pion decay → ν (PeV~EeV)
- IceCube ν, Fermi γ background
  → Ruling out pure proton scenarios





TA hot spot – Energy spectrum anisotropy

- Energy spectrum anisotropies
  - TA 7-year data with $E \geq 10^{19.2}$ eV
  - Scan the sky with circular window of equal exposure (14% – adjusted)
  - Comparison method for energy spectrum
    - Binned Poisson likelihood ratio goodness of fit (GOF) test
  - Maximum significance at $(\alpha = 139°, \delta = 45°)$ with $p = 9 \times 10^{-5}$ (3.74σ)

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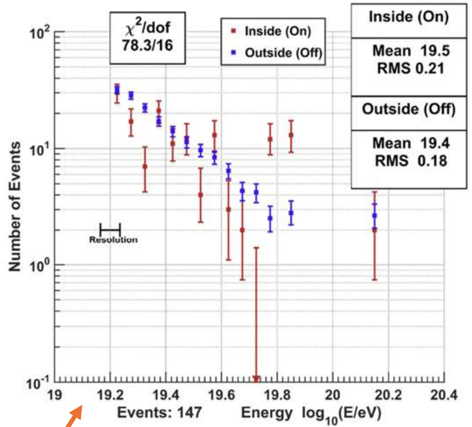

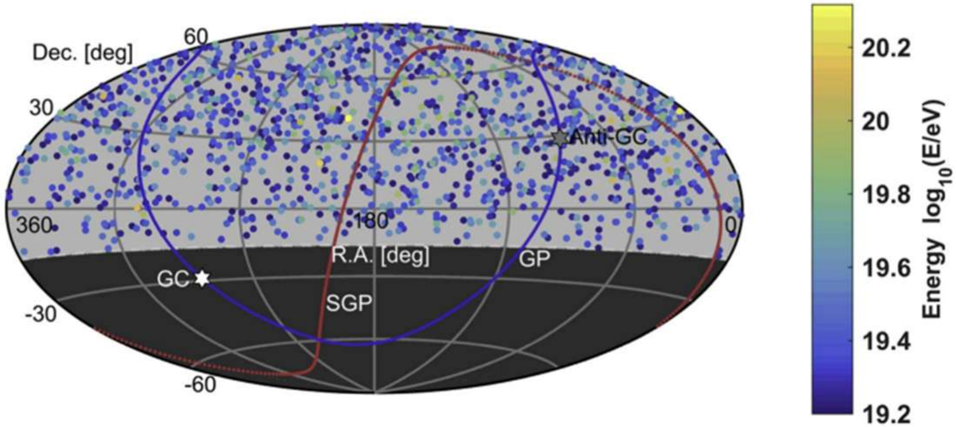

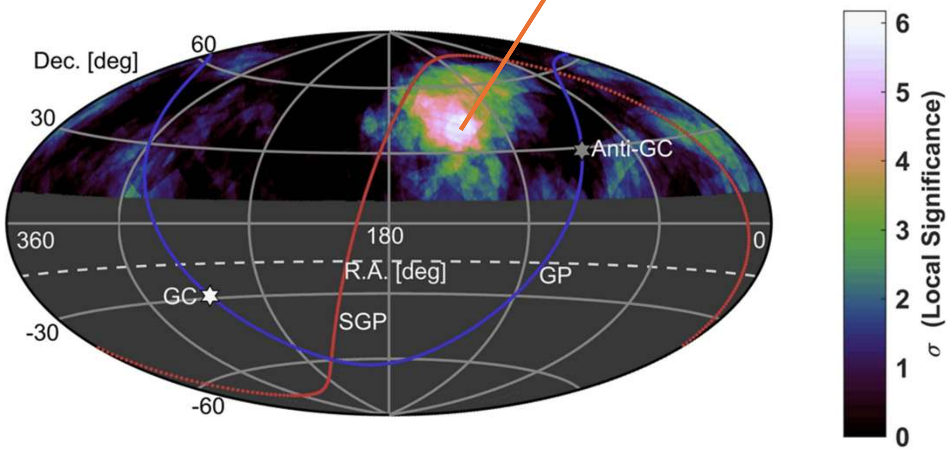

Combined analysis – TA – AD & E correl.

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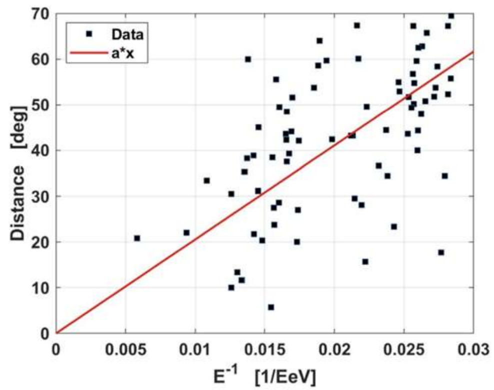
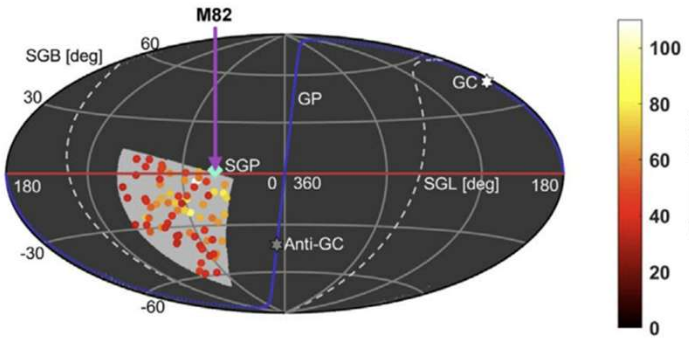
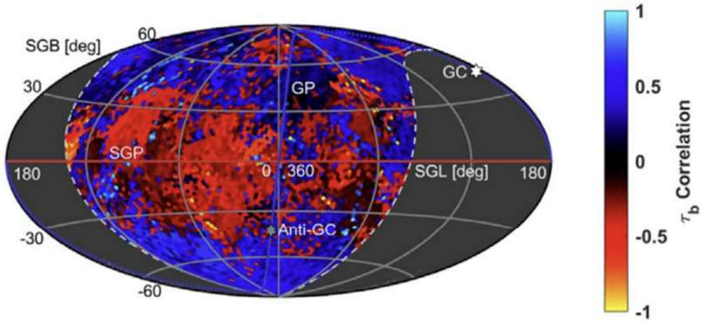
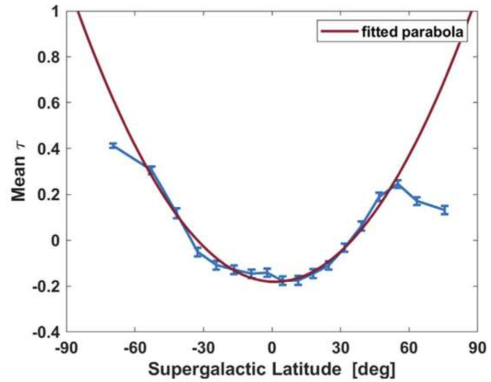
- Correlation between arrival directions and energy inverses
  - TA 7-year and 10-year data
  - Blind search for magnetic multiplets (point-like sources) – Scan the sky with wedge windows (shape adjusted) to examine the correlation between the angular distance from the source (position adjusted) and the energy inverse of CR
  - Comparison method for correlation – Kendal's τ ranked correlation
  - Supergalactic cosmic-ray multiplet Significant correlations along the supergalactic plane







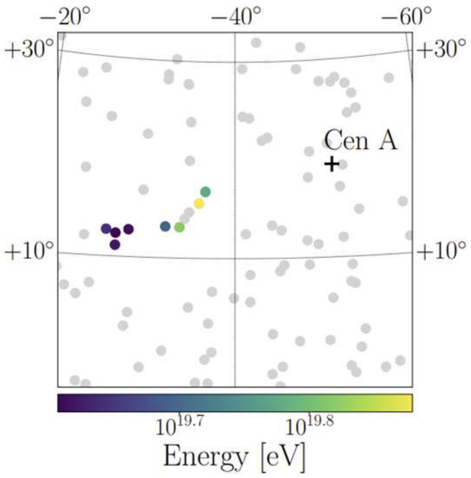


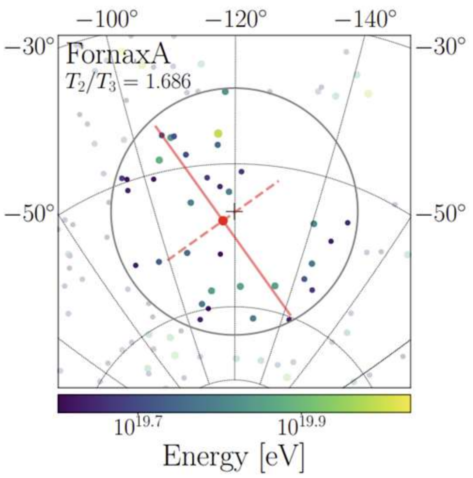
Combined analysis – Auger – AD & E correl.

JCAP 06 (2020) 017
Eur.Phys.J.C 75 (2015) 269

- Correlation between arrival directions and energy inverses
  - Auger 14.5-year data
  - All-sky blind search and nearby-source-based search
    - ➢ Correlation between their arrival direction and the inverse of their energy → **Multiplet**
    - ➢ Principal axis analysis aimed to detect the elongated patterns → **Thrust**
  - No statistically significant features

Isotropic chance probabilities			
Target	Multiplets (40 EeV)	Thrust ratio (20 EeV)	Thrust ratio (40 EeV)
Cen A	1.2×10^{-2}	0.75	0.42
M 87	0.61	0.44	0.85
Fornax A	0.96	0.21	1.9×10^{-2}
NGC 253	0.54	0.98	0.88
NGC 4945	0.25	2.9×10^{-2}	3.7×10^{-2}
Circinus	0.99	0.82	0.58
M 83	0.20	0.14	0.54
NGC 4631	—	0.59	0.85
NGC 1808	0.61	0.63	0.77
NGC 1068	0.75	6.0×10^{-2}	0.29

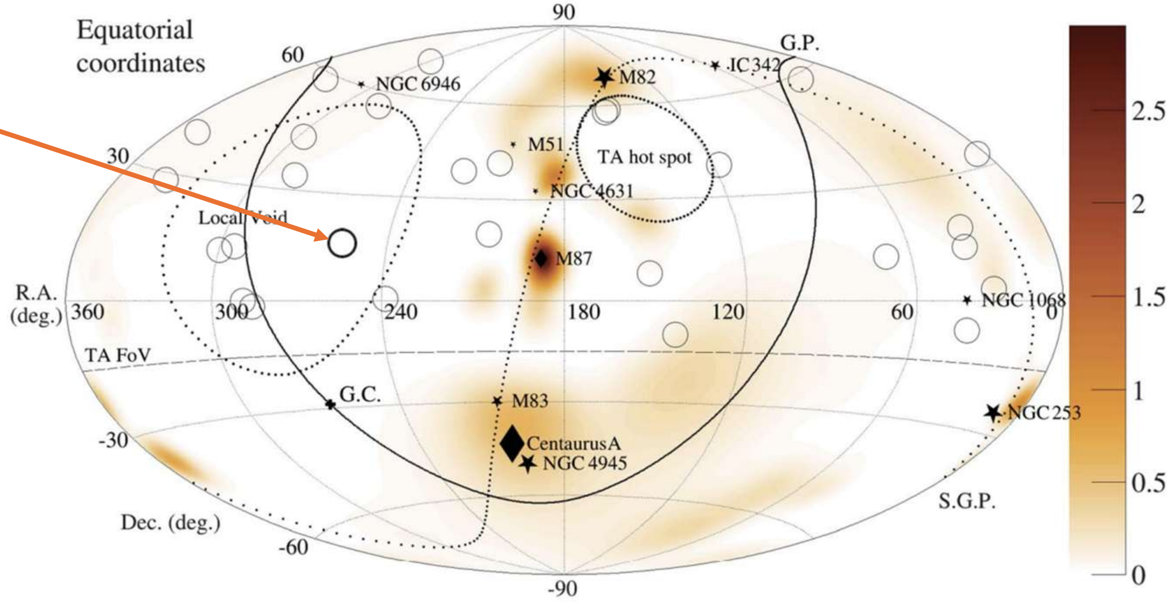




The highest energy event by TA SD

- The highest energy event detected by TA SD Science 382 (2023) 903
  - $E = 2.4 \times 10^{20}$eV
  - **Amaterasu** (天照) particle
  - **No plausible source behind – void region**

TA UHECR with $E \geq 100$ EeV



Composition from AD correlation

- Correlation between UHECR and LSS
  - UHECR – $E > 100\mathrm{EeV}$
  - LSS model – 2Mass catalog, $d < 250\mathrm{Mpc}$
  - Propagation in CMB,
    EGMF (smearing angle), GMF (model)
  - AD distribution – compatible with isotropy
  - **To be compatible with LSS within 2σ**
    - ✓ EGMF – Strong (> 20nG, λ=1Mpc)
    - ✓ Composition – Very heavy mass (> Fe)

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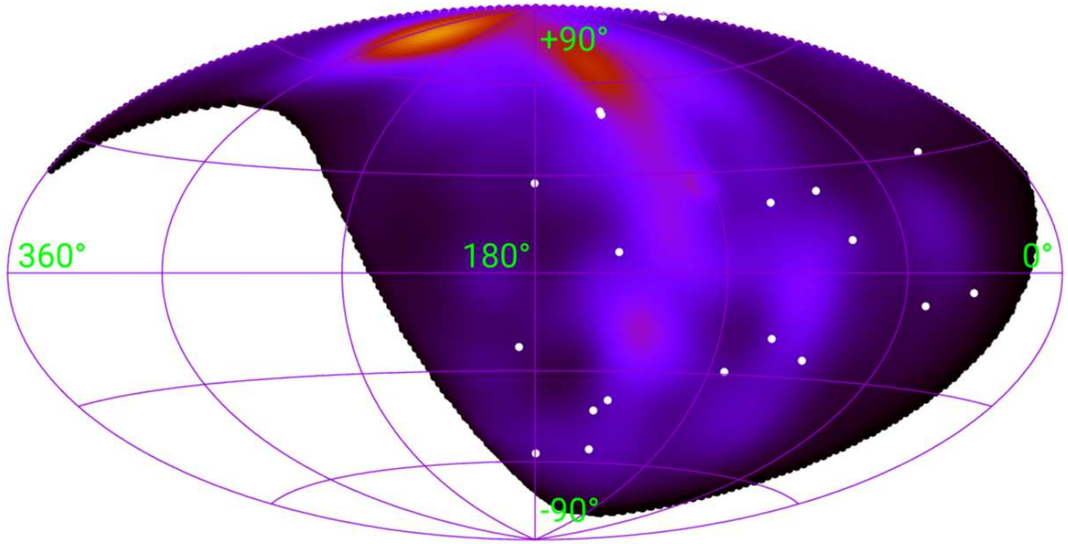
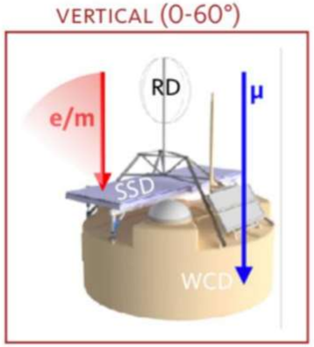
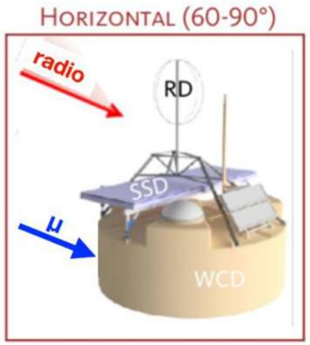
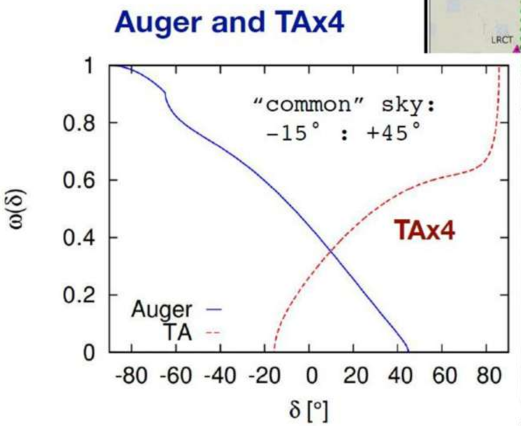


- UHECR with $E > 100\mathrm{EeV}$ – white points
- Flux map – for proton and smearing angle 10°

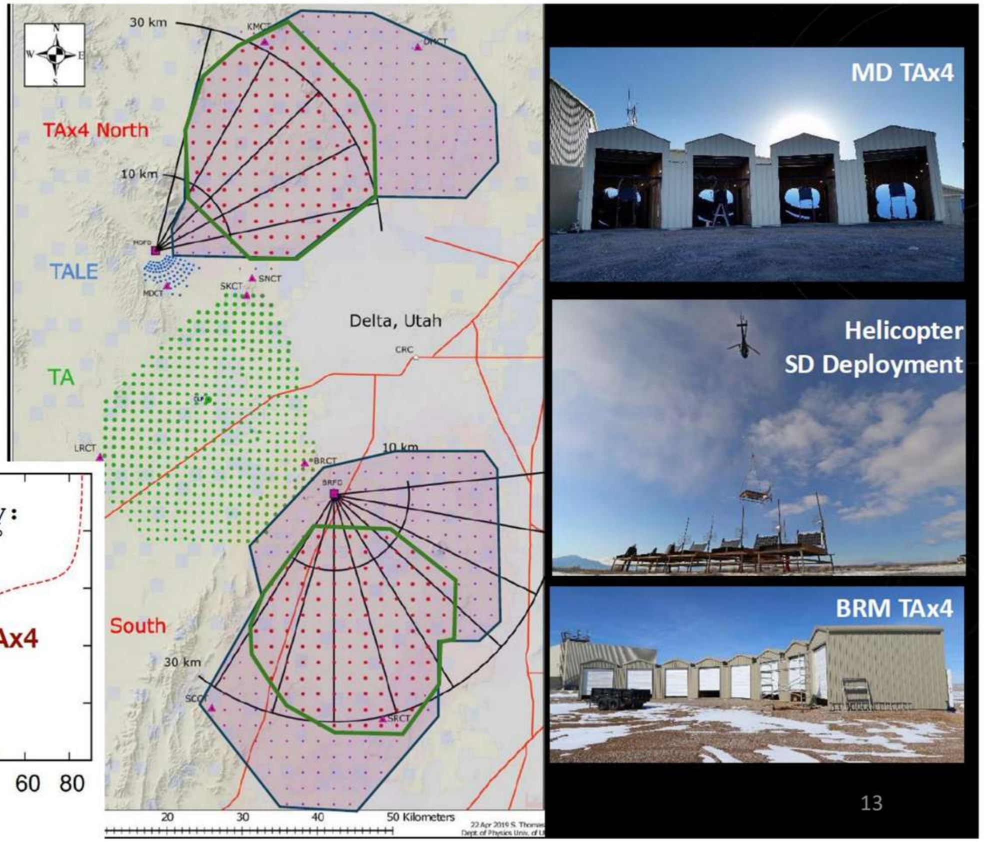
Upgrade – AugerPrime & TAx4







Detector spacing 1.2 km and 2.08 km, 257 out of 500 detectors installed



Discussion and Outlook

- How to pile up sufficient data
  - Northern hemisphere – TAx4 is running.
  - Space-based detector
  - Radio wave detector array
  - **Composition** – AugerPrime, New tech.

- Improvement of analysis
  - Composition from SD data
    - Multiple observables and Deep learning
  - Combined analysis
    - Multi-messenger – Neutrinos, Gamma rays
    - Correlations – Arrival directions, Energy spectrum, and Composition

- Theoretical understanding
  - Hadronic physics at energies beyond LHC
  - Acceleration mechanisms
    - Modeling of AGN and SBG
    - Supermassive black hole engines

- Wishful thinking
  - **New physics at high energy**
  - **UHECR astronomy**
    - Source identification
    - Injected composition and spectrum
    - Probe of GMF and EGMF
  - **Observation of high energy γ and ν**