TA Anisotropy Summary

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For the TA Collaboration
Outline

• Telescope Array experiment
• Recent results
  – Correlation with LSS
  – Hotspot in the northern sky
  – Spectral anisotropy at Hotspot
  – Small-scale cluster search
  – Correlation with starburst galaxies
  – Supergalactic structure of multiplets
• TAx4 Project
Study of muons from ultrahigh energy cosmic ray air showers measured by the Telescope Array Collaboration


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The TA is the largest aperture hybrid cosmic ray detectors in the northern hemisphere.
700km with 1.2km spacing - 2 layer Scintillators + WLS fibers + 2 PMTs - Solar power system - Communication antenna - DAQ 50MHz FADC - Communication array

→ Stand-alone detector

SD Event Display

Distance North, [1200m]

Distance East, [1200m]

Onset time, [1200m]
UHECR Anisotropy Search

Possible particle astronomy?
Correlation with LSS

- Large-Scale Structure model 2MASS Galaxy catalog (XSCz)
- Grey Pattern: flux model with 6° radius circle smearing angle → Matter density \(\propto\) Cosmic-ray luminosity

We investigate correlation between arrival directions of the UHECRs and the LSS model (and isotropic model).

From ICRC2017 S. Troitsky
Correlation with LSS

E > 10 EeV

E > 40 EeV

E > 57 EeV

x-axis: smearing angle
Y-axis: compatibility between the expected and the data

E ≥ 5.7 × 10^{19} eV
Consistent with LSS
Inconsistent with isotropy
(9-year data)

ICRC2017 S. Troitsky
Hotspot (>57EeV, 5 years)

- 5-year observation by the TA SD
- Observed 72 events with E>57 EeV
- Indication of UHECR hotspot
- Local significance 5.1σ

- Assuming 5 search window radii (15°, 20°, 25°, 30°, 35°), Global significance 3.4σ

10-year observation ➔ double exposure

Angular Scan
(>57EeV, 10 years)

Preliminary

O.S. : oversampling radius

From JPS2018 meeting S. Ogio & K. Kawata
Results of the Angular Scanning for 10 years

<table>
<thead>
<tr>
<th>O.S. radius</th>
<th>15°</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Significance for 10 years (σ)</td>
<td>4.1</td>
<td>4.6</td>
<td>5.0</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Location of Maximum Significance</td>
<td>RA: 140.4° Dec: 53.2°</td>
<td>RA: 149.4° Dec: 49.0°</td>
<td>RA: 144.3° Dec: 40.3°</td>
<td>RA: 152.8° Dec: 39.8°</td>
<td>RA: 157.4° Dec: 38.5°</td>
</tr>
</tbody>
</table>

Hotspot position published in ApJL2014 → RA: 146.7° Dec: 43.2°

From JPS2018 meeting S. Ogio & K. Kawata
Independent Analysis (>57EeV)

1st-half 5 years: 72 events
Hotspot position = 5.0σ

2nd-half 5 years: 85 events
Hotspot position = 2.0σ

From JPS2018 meeting S. Ogio & K. Kawata
Differential Time Variation of the Hotspot

**Table:**

<table>
<thead>
<tr>
<th>Hotspot position</th>
<th>Search radius</th>
<th>ON</th>
<th>$\alpha^{*}$OFF (OFF)</th>
<th>ON/OFF ratio ($\alpha$)</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA: 144.3° Dec: 40.3°</td>
<td>25°</td>
<td>36</td>
<td>12.6 (121)</td>
<td>0.10435</td>
<td>5.0</td>
</tr>
</tbody>
</table>

$\chi^2 / \text{ndf}$: 5.577 / 9

$\text{Const.}$: 3.669 ± 0.7734

From JPS2018 meeting S. Ogio & K. Kawata
Integral Time Variation of the Hotspot

Deviation from the linear increase for 10 years

→ Consistent with linear increase within $2\sigma$

From JPS2018 meeting S. Ogio & K. Kawata
Spectral Anisotropy at Hotspot


Comparison of spectra between inside and outside of hotspot

→ Probabilities of spectral anomaly are calculated in the all sky.

"cold spot" at lower energies, same place as the hot spot at high

$>10^{19.2} \text{ eV}$

3.7$\sigma$ post-trial significance
Cluster Events $>100\text{EeV}$

2 doublets above 100 EeV.

$\to$ the probability to have $\geq 2$ doublets at $\leq \sqrt{2}$ deg is

$P = 0.30\% \ (2.8\sigma)$

Ta 9 years (23 events)

Auger 6 years (6 events)

No correction for E scale difference b/w TA and Auger!
Correlation of UHECRs with catalogs

- Scanning the following parameters
  - Energy threshold $E_{TH}$
  - Search radius $\psi$
  - Anisotropic fraction $f_{ani}$

Results (Post-trial significances)
- Starburst galaxies : $4.0\sigma$
- $\gamma$-ray AGNs : $2.7\sigma$
- Swift-BAT (X-ray) AGNs : $3.2\sigma$
- 2MASS galaxies : $2.7\sigma$

Northern sky?
→ Test the Auger best-fit parameter model
Auger hypothesis for Starburst Galaxy Correlation

- SBG selected for $\gamma$-ray studies
  - 63 sources (within 250Mpc), 4 detected in $\gamma$
  - Radio flux@1.4GHz > 0.3Jy
    Proxy for UHECR flux
  -> 23 sources remain

- Local Group
  Not included
  - Milky way, LMC, SMC, M33 and M31
Search for Correlation with SBG by TA in the Northern Sky

✓ Auger best-fit parameters
- Anisotropic fraction $f_{\text{ani}}=9.7\%$
- Search radius $\psi=12.9^\circ$
- Energy threshold $E_{\text{TH}}=39\text{EeV}$
  (43EeV in the TA energy scale)
✓ Strong radio source: M82 in the northern sky

✓ Same sources and parameters as Auger-best fit
✓ No scan over parameters, no statistical penalty
✓ UHECR attenuation neglected, found negligible by Auger (most of the flux from within a few Mpc)

A. di Matteo, T. Fujii, K. Kawata (UHECR2018 Poster)
Search for Correlation with SBG by TA in the Northern Sky

A. di Matteo, T. Fujii, K. Kawata (UHECR2018 Poster)

\[ TS = 2 \log \left[ \frac{L(\phi, f_{ani})}{L(f_{ani} = 0)} \right] \]

~1.1σ compatible with 100% isotropic
~1.4σ compatible with starbursts
Supergalactic Structure of Multiplets

J.P. Lundquist, UHECR2018
Paper in preparation

Correlation between CR energies and distances in the “Wedge”

- Energy Threshold: 10, 15, 20...100 EeV
- Wedge width: 10°, 20°, 30°...90°
  (steps of 5° on each side of the pointing direction)
- Maximum Distance: 15°, 20°, 25°...90°
- Pointing Direction: 0°, 5°, 10°...355°
Supergalactic Structure of Multiplets

✓ Rank Correlation Analysis
→ All values are ranked 1 to n. Kendall’s correlation is used.

\[
\tau = \frac{(\text{number of concordant pairs}) - (\text{number of discordant pairs})}{\frac{1}{2}n(n-1)}
\]

Negative \( \tau \): Energies are inversely-proportional to distances
Positive \( \tau \): Energies are proportional to distances

Negative correlations of greater significance appear correlated with supergalactic plane (post-trial significance >~4\( \sigma \))
Summary

- Large/intermediate-scale anisotropy (>57EeV)
  - Consistent with LLS, Inconsistent with isotropy 2-3σ
  - Hotspot still exists for 10-year observation
  - Spectral anisotropy 3.7σ (7-year data)
- Small-scale cluster >100EeV
  - 2 doublets : 2.8σ
- Correlation with starburst galaxies:
  Test Auger’s parameters ($E_{TH}=39EeV, \psi=12.9^o, f_{ani}=9.7\%$)
  - No significance so far
- Supergalactic structure of multiplets
  - multiplet-like events do appear correlated with supergalactic plane $>\sim4\sigma$

Hints of UHECR anisotropies in the northern sky

- TA Extension : TAx4 (TA aperture x4)
  - Under construction
Now there is hint of anisotropy at 3σ level for northern sky.

- extend SD array by 4 times (3,000km²)
  1. Add 500 scint. counters with 2.1 km spacing
  2. Add two FD stations
     → Approved and under construction

Science
1. Anisotropy study → Expect >5σ
2. Xmax at highest energy region
3. UHE photon & neutrino search
After matching energy scale at the ankle break, the location of the suppression energy is clear different.

→ Systematics or physics?
Nearby Prominent AGNs

Dermer, et al., arXiv:0811.1160

TA: 2008 May – 2014 May (6.0 years) 87 events
Auger: 2004 May – 2009 Nov (5.5 years) 62 events
Comparison with Large-Scale Structure

Sky map of expected flux at $E > 57$ EeV (Galactic coordinates). The smearing angle is $6^\circ$. The letters indicate the nearby structures as follows: C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); UM: Ursa Major (20 Mpc); and V: Virgo cluster (20 Mpc).

No correction for E scale difference b/w TA and Auger!

TA 7 years + PAO 10 years
Small scale: starburst correlations

\[ TS = 2 \ln \left( \frac{L(\Phi_2)}{L(\Phi_1)} \right), \]

\[ L(\Phi_j) = \prod_i \frac{\Phi_j(\hat{n}_i)\omega(\hat{n}_i)}{\int_{4\pi} \Phi_j(\hat{n})\omega(\hat{n}) \, d\Omega}, \]

\[ \Phi_1(\hat{n}) = \Phi_{iso} = 1/4\pi \]

\[ \Phi_{mod}(\hat{n}) = f_{SBG} \Phi_{SBG}(\hat{n}) + (1 - f_{SBG})\Phi_{iso}, \]

\[ \Phi_{SBG}(\hat{n}) = \frac{\sum_k \phi_k \exp \left( \frac{\hat{n}_k \cdot \hat{n}}{\theta^2} \right)}{\int_{4\pi} \sum_k \phi_k \exp \left( \frac{\hat{n}_k \cdot \hat{n}}{\theta^2} \right) \, d\Omega}. \]
DIRECTION OF CORRELATIONS

Grid points greater than 4.5 sigma

- Sources are correlated with the supegalactic plane.
- Magnetic fields are correlated with sources.
- Multiplets will exhibit a structure indicative of clustering of sources
  - Random fields will diffuse events perpendicular to their average direction. Multiplets should be in ‘wedges’ not rectangles or circles.
Simple simulation

- 1/E supergalactic plane deflection for fraction of events
  - Random “source” position. Gaussian $\sigma=5^\circ$ plus 1/E deflection.
- Isotropic Exposure
- Total energy distribution matches published average

$\delta \approx 0.5^\circ Z \frac{S}{kpc \mu G} \frac{B}{10^{20}eV} \frac{1}{E}$

1/E for 10% of events. $\frac{S}{kpc \mu G} B = 25$

All 3027 events $E \geq 10^{19.0}$
- Isotropic positions
- Published spectrum

Analysis applied to simulation result