Evidence of an energy dependent intermediate-scale anisotropy has been found in the arrival directions of ultra-high energy cosmic rays in the northern hemisphere, using 7 years of TA surface detector data. The previously reported “hot spot” excess $E \geq 10^{19.75}$ EeV is found to correspond to a deficit, or “cold spot,” of events for $10^{19.2} \leq E < 10^{19.75}$ EeV. This feature suggests energy dependent magnetic deflection of cosmic-rays.

The global post-trial significance of the energy spectrum deviation is found to be 3.74σ.
INTRODUCTION

- Telescope Array Hotspot study showed an excess of events with a $3.4\sigma$ post-trial significance. (ICRC 2015 update $3.4\sigma$)
- Part of Energy Spectrum Anisotropy with a $3.74\sigma$ post-trial significance.
- At lower energies there is an event deficit at this location.
  - Could be a signature of energy dependent magnetic deflection of cosmic rays.
7-YEAR DATA HOTSPOT RESULT

Period: 2008 May – 2015 May Surface Detector data

Cuts:
- # of used detectors ≥ 4
- Zenith angle < 55°
- Pointing Error < 10°
- Energy ≥ 57EeV

Resulting Data: 109 events

3.4σ post-trial significance

Max significance 5.1σ
R.A 148.5°, Dec. 44.5°
(17° from SGP)

Tighter Cuts, 20° bin

Energy distribution at this point shows an overall deficit of events.

Max significance 5.1σ
R.A 148.5°, Dec. 44.5°
(17° from SGP)
ENERGY ANISOTROPY

Is there a location on the sky which has a significantly different overall spectrum?

**FINAL RESULT**

Max. local $\sigma = 6.17$
Data:

- 7 years SD data *(from ICRC2015 hotspot by Kawata-san).*
  # Detector $\geq 4$, Zenith angle $< 55^\circ$, Pointing Error $< 10^\circ$
  - Additional cuts *(for low energy theoretical zenith distribution agreement)*:
    - Pointing error $< 5^\circ$, boundary $> 1.2$ km , Lateral fit $\chi^2 < 10$
    - $E \geq 10^{19.2}$ eV - 1332 events *(cut with highest significance)*

Monte Carlo:

- $f (\theta) = \sin(\theta) \cdot \cos(\theta)$ Zenith, uniform Azimuth, simulated detector on-time, energy interpolated from fully reconstructed MC *(from D. Ivanov).*
- 20,000,000 set for exposure ratio binning
- 50,000,000 for background alpha
METHOD
**ISOTROPIC MONTE-CARLO COMPARISON**

- Sin(θ)*cos(θ) – Zenith distribution from detector geometry
- Uniform Azimuthal angle distribution
- On-time simulated – sampling 250,000 event times (E ≥ 0.5 EeV).
- Energy sampled from reconstructed HiRes spectrum.

![Graphs showing comparisons](image)

**Uniform Azimuth**

**Time taken from data**

**Reconstructed HiRes Spectrum**

\[ E \geq 10^{19.0} \text{ eV comparisons} \]
**OVERSAMPLING GRID**

0.5°x0.5° in RA and Decl.

Changing sampling -- declination bias

*0.3°+/-0.2° Opening Angle
Median 0.32°*

Histograms of closest grid distance

Sky is sampled equally

*0.52°+/-0.03°
Median 0.50°*

Used here

Over-sampling grids

ESTIMATED BACKGROUND – EQUAL EXPOSURE

• Likelihood and $\chi^2$ tests are sample size biased
  • Need to control statistics

• Equal exposure binning samples the sky equally.
  • “On” exposure with bin size average = 15°, 20°, 25°, 30°
  • Bin size is function of R.A. and Dec.

$\alpha = \frac{N_{on}^{MC}}{N_{off}^{MC}} = \text{constant}$

$\langle N_{on} \rangle = 163 \pm 12$

$30^\circ < \text{bin}, \ E \geq 10^{19.2} \text{ eV}$

$\langle \alpha \rangle = 0.14028 \pm 9e - 05$

$\langle \text{Radius} \rangle = 30 \pm 3$
POISSON LIKELIHOOD GOODNESS-OF-FIT

- Compare energy distribution “On” (inside) to “Off” (outside)
  - “Off” Normalized to $N_{bg}$ (expectation)

- Energy bins of 0.05 $\log_{10}(E/eV)$
  - Less than mean energy resolution

\[ \chi_k^2 \approx 2n_{on} \log \frac{n_{on}}{n_{bg}} + n_{bg} - n_{on} \]

- $n_{on}$ # data in bin
- $n_{bg}$ expectation
- Degrees of freedom:
  - # bins
  - +1 fluctuating background
  - +1 variable number of bins

\[ \sum n_k^{bg} = N_{bg} = \alpha N_{off} \]

$N_{off}$ Normalized to expectation

Test Used Previously by T.A. In:

- Good reference [http://www.fysik.su.se/~conrad/James/james.5.gof.pdf](http://www.fysik.su.se/~conrad/James/james.5.gof.pdf) or Particle Data Group book
RESULT
ENERGY SPECTRUM ANISOTROPY – 30° <BIN>

- σ deviation — “On” data compared to “Off” data

- Maximum: 6.17σ
- 138.8° R.A., 44.8° Dec.
- Bin size: 28.43°
- # Events: 147
- 6.8° from “hot spot”

0.5° × 0.5° equal angle grid, 30° <bin>, E ≥ 10^{19.2} eV
ENERGY COMPARISON – MAX. LOCAL SIGMA

- Max. local $\sigma$ (6.17)
  location — 138.8° R.A., 44.8° Decl.

- 28.43° radius cap bin
- $E \geq 10^{19.2}$ eV
- Expected Background: $N_{bg} = 166.2$

$$\chi_k^2 \approx 2n_{on} \log \frac{n_{on}}{n_{bg}} + n_{bg} - n_{on}$$
HOT/COLDSPOTS AND SUPERGALACTIC PLANE

Low energy events appear deflected from source changing spectrum

Li-Ma statistics used in previous hotspot analysis

Green line is linear in SG weighted by energy anisotropy $\sigma^2$ of Hot/Cold points.

Result is SGP shifted -16°

Current result
Sky positions where there is hot/cold behavior
GLOBAL SIGNIFICANCE

• Count MC $\sigma \geq 6.17$ (Data $30^\circ$ <bin> and $E \geq 10^{19.2}$ eV)

• **PENALTY MC TEST** *(parameters scanned bounded by statistics)*
  • Bin scan penalty - $15^\circ$, $20^\circ$, $25^\circ$, $30^\circ$ average bin sizes with constant exposure ratios.
    • Low # events inside bins $< 15^\circ$
    • Low # events outside bins $> 30^\circ$

• Energy cut scan penalty - $10^{19.0}$, $10^{19.1}$, $10^{19.2}$, $10^{19.3}$ eV.
  • Number of events is the same as data for each energy cut.
  • Low # events for $E > 10^{19.4}$ eV

• Max. $\sigma$ of $4*4 = 16$ maps is counted as 1 MC set.

Result: 2,500,000 MC sets $232$ passed for $3.74\sigma_{global}$
*One sided with 16 times scan penalty*
GLOBAL SIGNIFICANCE

MC trials maximum distribution

Local sigma to Global post-trial sigma
SPECTRUM ANISOTROPY – GLOBAL $\sigma$

138.8° R.A., 44.8° Decl. Local sigma: 6.17$\sigma$

Global sigma: 3.74$\sigma$

0.5° x 0.5° grid, 30° <bin>, $E \geq 10^{19.2}$ eV

Rough estimate of radius: 1659 grid points $\sigma > 0.7$. $\sqrt{(1659\times0.5)/\pi} \approx 15°$
INTEGRAL DAY SIGNIFICANCE

- Blue line is linear fit

- $\sigma_{\text{local}}$ at 7 year max location — $+1 \sigma$/year
  - Linear correlation 0.989

- Maximum $\sigma_{\text{local}}$ on map
  - Linear correlation 0.976

$30^\circ < \text{bin}$, $E \geq 10^{19.2}$ eV
POSSIBLE CAUSE

• Possible sources:
  • M82 starburst galaxy most likely source
    • “A Monte Carlo Bayesian Search for the Plausible Source of the Telescope Array Hotspot”
      https://arxiv.org/abs/1411.5273
    • “Ultra-high-energy-cosmic-ray hotspots from tidal disruption events”
      https://arxiv.org/abs/1512.04959

• Possible magnetic fields:
  • Supergalactic magnetic sheet increases post-GZK flux (E > 50 EeV) and deflects (E < 50 EeV)
    • “The supergalactic structure and the origin of the highest energy cosmic rays”
    • “Cosmic Magnetic Fields in Large Scale Filaments and Sheets”
CONCLUSION

- There is a $3.74\sigma$ Energy Spectrum Anisotropy ($E \geq 10^{19.2}$ eV) at $138.8^\circ$ R.A., $44.8^\circ$ Decl.
  - It is a deficit at low energies and excess at high energies
  - It has been increasing in significance every year.
- Possible indication of magnetic deflection of UHECR
ADDITIONAL MATERIAL
MC DISTRIBUTION OF HITS

Shows small amount of declination bias in the analysis
MC DISTRIBUTION OF HITS

- Distribution of hits in Right Ascension.
- Distribution of hits with Degrees of Freedom.
- Distribution of hits with Energy Cut [EeV].
- Distribution of hits with Bin Size [deg].

23
MC CHI^2 DISTRIBUTION AT DATA MAX SIGMA POINT

“Chi square” distribution of MC sets at single grid point with 14 energy bins

- Closest to chi^2 with 16 degrees of freedom
- There are two additional degrees of freedom:
  - Background Fluctuation
  - Rebinning of low statistic energy bins

138.8 R.A. 44.8 Dec.
E ≥ 10^{19.2} eV
30° <bin>
MC CHI\^2 DISTRIBUTION AT DATA MAX SIGMA POINT

“Chi square” distribution of MC sets with no background fluctuation or rebinning

![Graph showing chi-square distribution]

MC sets with 14 energy bins
Closest to chi\^2 with 14 degrees of freedom

547 MC have infinite chi\^2 due to no rebinning

138.8 R.A. 44.8 Dec.
E ≥ 10^{19.2} eV
30° <bin>
MC DISTRIBUTIONS AT DATA MAX SIGMA POINT

138.8 R.A. 44.8 Dec.
\[ E \geq 10^{19.2} \text{ eV} \]
30° <bin>

MC \( N_{on} \) is Poisson: 163.8 +/- 12.0
\[ (\sqrt{163.8}) = 12.8 \]

MC \( N_{bg} \) background is not Poisson: 163.8 +/- 1.7

Fluctuation is \( \sqrt{N} \times 0.14 \) exposure ratio

This is the same background fluctuation Li-Ma uses
Data fits reconstructed published spectrum well.

Data inside hot/cold spot does not fit spectrum

- Unless hot and cold energy ranges are normalized separately

Power laws are consistent, flux is not

Indication of flux enhancement of post-GZK spectrum (low statistics)

At location of Li-Ma hot/cold maximum

Inside Coldspot – $20 \leq E < 57$ EeV fits MC (normalized to 28 events)

Inside Hotspot – $E \geq 57$ EeV fits MC (normalized to 19 events)
Could systematics cause events to migrate from Coldspot to Hotspot? Energy is reconstructed by Zenith angle and s800 signal:

- Zenith agrees very well. Systematic must come from s800
- s800 would have to be increased by 139% for hotspot to be systematic from the coldspot

E $\geq$ 57 EeV events: $\sim$14 over $N_{bg}$ or 3.6$N_{bg}$

20 $\leq$ E < 57 EeV events: $\sim$21 under $N_{bg}$ or 0.57$N_{bg}$
OTHER SYSTEMATIC CHECKS

- Seasonal and hourly energy corrections result in little change to joint significance
- Anti-Sidereal time results in no significant excesses, deficits or combinations

20 <= E < 57 EeV Anti-Sidereal

E >=57 EeV Anti-Sidereal
Cosmic Ray events produce Extensive Air Showers (EAS) in the atmosphere.

Secondary particles ($e^\pm, \mu^\pm, \gamma, \ldots$) reach the ground level, and are detected by the TA SD counters.

EAS is reconstructed using 2 fits:

- Timing fit -> trajectory of the primary particle
- Counter signal lateral distribution fit -> energy of the primary particle

Each TA SD counter is powered by solar cells and uses radio readout.

Two layers of 1.5m x 2m x 1.2cm plastic scintillator to detect charged particles.

Self-calibration every 10 minutes using atmospheric muons.

Example of hotspot event.