Measurements of Cosmic-Ray Anisotropy

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Outline

• Introduction to TeV-PeV CR Anisotropy

• Explanation of Detection Methods

• Experimental Results
Cosmic-Ray Anisotropy

- Cosmic rays $< 10$ PeV are well confined within our Galaxy by $\sim \mu$G magnetic fields.

- A sidereal anisotropy at the $10^{-3} – 10^{-4}$ level has been observed by ground-based air shower detectors from 1 TeV to 1 PeV (reconstructed energy).

Anisotropy measure:

Relative intensity $=$ flux observed / flux expected from isotropy

Differential relative intensity $=$ Relative intensity $– 1$
Why only at TeV-PeV?

< 10 GeV: Solar modulation of flux, Geomagnetic cutoff, Local and time-dependent

> 1 PeV : Particle flux $\approx$ 1 per m$^2$ per year, Extragalactic? Evidence, no discovery

From R. Shellard & S. Swordy

From J.M. Santander (2013 thesis)
Producing Anisotropy

• Simple cosmic-ray gradient
  – inhomogeneous source distribution in our Galaxy and local magnetic fields.

• Compton and Getting (1935)
  Motion through inertial frame of cosmic-ray gradient.
  – Maximum in direction of motion (pure dipole)
    • Cosmic rays are swept up by motion
    • Doppler shift pushes cosmic rays above/below $E_{\text{thresh}}$
  – Solar System around Galaxy
    • RA=315°, Dec 49°
    • Amplitude of 0.35%. NOT OBSERVED
  – Earth around Sun
    • Theta = 270° in Solar frame
    • Amplitude of 0.02%. OBSERVED
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• Introduction to TeV-PeV CR Anisotropy

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Ground-based Mid-Latitude Air-shower Observatories

- Sensitive to $\theta < 50^\circ$ due to atmospheric attenuation & falling CR spectrum
- Scan the sky in Right Ascension along the line Declination = Latitude

Path to anisotropy measurement:
1 - Estimate detector response to isotropic flux
   - Changing rate
   - Changing signal contamination (constant in sidereal sky)
   - Use 24-hour observing periods (for $10^{-4}$ precision)
2 - Interpret partial sky measurement
3 - Interpret partial signal sensitivity
Count map (in equatorial coordinates)

Example:
Right-Ascension Averaging (Direct Integration)

Significance of the Excess (in equatorial coordinates)

*For demonstration purposes only. Background found using a simplified, low resolution algorithm.*
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RA Projection effect

Right-Ascension Averaging is only sensitive to anisotropies along RA. This affects all signals which extend in RA.

![Graphs showing true injected signal and observed signal with differential relative intensity.](image)
RA Projection effect

Right-Ascension Averaging is only sensitive to anisotropies along RA. This affects all signals which extend in RA.
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The High Altitude Water Cherenkov Observatory

- Array of 300 large water-Cherenkov detectors (WCDs) at high altitude observing extensive cosmic-ray air showers
- Partial operation
  - 2012 to 2013, 30 WCDs
  - 2013 to 2015, 100 WCDs
- Full operation since March 2015
  - 1 trillion event triggers

For gamma-ray summary
See T.Weisgarber talk
Previous Results – HAWC-100

HAWC-100 anisotropy paper (ApJ) reported only small-scale ($\leq 60^\circ$) features. arXiv:1408.4805

1. Started with map sensitive to features $\leq$ HAWC Field-of-view.

2. Subtracted dipole/octupole/quadrupole moments to remove any angular power from large-scale ($\leq 60^\circ$) anisotropy.

3. Observed 3 significant excesses.
   Region A: Harder than background
   Energy-dependent morphology
Improve to Large-scale Sensitivity

Old Method: Direct Integration

Standard method for HAWC

Sensitive only to features ≤ HAWC FOV
SNRs and AGN are OK

Improved upon this algorithm by iteratively correcting the all-sky rate for the influence of the large signals

New Likelihood-based Method

Large-scale features are enhanced by over a factor of 2.

Low-moments become stronger because of correction to all-sky exposure as a function of sidereal time.
Improvement to CR Energy Estimation

Z. Hampel (Wisconsin)

Simulation-based likelihood function of detector observables and Bayesian unfolding

Verified by the cosmic-ray all-particle energy spectrum and Moon shadow deflection

\[ \Delta \alpha = \frac{1.6^\circ}{Z \times E[\text{TeV}]} \]

Used to create energy bins for cosmic-ray maps
HAWC

241 stable sidereal days, $E_{\text{med}} = 6.7$ TeV
Restrictive cuts for energy estimation ($19 \times 10^9$ events)
Uneven coverage throughout the year (sys. err.)

Large-scale anisotropy

360°

PRELIMINARY

Amplitude from dipole moment as part of multipole fit
(large errorbars). Dipole-only usually reported.

$A = (1.14 \pm 0.94) \times 10^{-3}$

Amplitude from dipole moment as part of multipole fit
(large errorbars). Dipole-only usually reported.
HAWC Angular power spectrum with / without improved method

New method reveals masked power in lower multipoles

Does not alter small-scale results

Statistical noise level (~10^{-9}) \( \propto \) Events\(^{-1}\)

*calculated using PolSpice
Amplitudes from dipole moment as part of multipole fit (large errorbars). Dipole-only usually reported.

Solar/Geomagnetic effects $E_{\text{med}} = 4$ TeV

Fluctuations take over at $E_{\text{med}} = 82$ TeV
HAWC

Consistent with previous experiments.

Small offset in HAWC data likely due to unaccounted seasonal effect from partial year coverage & Solar Compton-Getting anisotropy.

This will be corrected in future work.
- Observational biases affect interpretation of excess/deficit
  - RA projection effect
    Dipole orientation is not fully constrained
  - Partial sky causes degeneracy in large-scale moments
  - Partial years of data have Solar C-G effect
  - $E \leq 1 \text{ TeV}$: Amp. is affected by Solar activity

- HAWC has a large & still growing data set (1 billion day$^{-1}$)
  - A new reconstruction method (Ahlers et al.)
  - A new cosmic-ray energy estimation method
  - Preliminary results agree well with previous

Ongoing work includes
  - Matching energy/rigidity responses
  - Tests agreement of small-scale anisotropy
  - Leptonic anisotropy search &
  - Gamma-ray diffuse study
    - Both require understanding CR anisotropy
  - Extending measurement to $E \sim 100 \text{ TeV}$

What astrophysics are these excesses/deficits informing us about?
HAWC - Region A

- Relative intensity in 10° circle for 7 energy proxy bins
- Hard spectrum in Region A, compared to off-source regions:

<table>
<thead>
<tr>
<th>Proxy Bin</th>
<th>Median Energy (TeV)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>3</td>
<td>5.6</td>
</tr>
<tr>
<td>4</td>
<td>8.4</td>
</tr>
<tr>
<td>5</td>
<td>9.8</td>
</tr>
<tr>
<td>6</td>
<td>14.1</td>
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<td>7</td>
<td>19.2</td>
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$4.3 \sigma$ effect
<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HAWC</strong></td>
<td><img src="image" alt="HAWC Image" /></td>
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<td><img src="image" alt="HAWC Image" /></td>
<td><img src="image" alt="HAWC Image" /></td>
</tr>
<tr>
<td>Bin0:</td>
<td>1.7 (±0.6/±1.3) TeV</td>
<td>3.2 (±1.9/±2.4) TeV</td>
<td>5.6 (±1.2/±3.9) TeV</td>
<td>14.1 (±28.7/±9.8) TeV</td>
</tr>
<tr>
<td>Milagro Hotspot (square)</td>
<td>HAWC Hotspot (star)</td>
<td>Milagro Hotspot (square)</td>
<td>HAWC Hotspot (star)</td>
<td>Milagro Hotspot (square)</td>
</tr>
<tr>
<td><strong>ARGO</strong></td>
<td><img src="image" alt="ARGO Image" /></td>
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<td><img src="image" alt="ARGO Image" /></td>
</tr>
<tr>
<td>Bin0:</td>
<td>25-39 hits = 0.66 TeV</td>
<td>40-99 hits = 1.4 TeV</td>
<td>100-249 hits = 3.5 TeV</td>
<td>250-629 hits = 7.3 TeV</td>
</tr>
</tbody>
</table>

Region A: Energy Dependence

HAWC–ARGO Comparison
Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)

Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)


2015, February 3
Daniel Fiorino, PhD Thesis Defense
Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)
## Comparing Small-scale Regions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Region A</th>
<th>Region B</th>
<th>Region C (Region 4)</th>
<th>Region D (Region 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ARGO-YBJ</strong></td>
<td>(57°, -10°)</td>
<td>(125°, 45°)</td>
<td>(208°, 29°)</td>
<td>(240°, 45°)</td>
</tr>
<tr>
<td></td>
<td>10 x 10⁻⁴, 16σ</td>
<td>5 x 10⁻⁴, 15σ</td>
<td>1.6 x 10⁻⁴, 6σ</td>
<td>2.3 x 10⁻⁴, 7σ</td>
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<tr>
<td><strong>HAWC</strong></td>
<td>(59°, -9°)</td>
<td>(125°, 46°)</td>
<td>(206°, 24°)</td>
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<tr>
<td></td>
<td>8.8 x 10⁻⁴, 21σ (pre)</td>
<td>5.3 x 10⁻⁴, 16σ (pre)</td>
<td>2.6 x 10⁻⁴, 11σ (pre)</td>
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<tr>
<td><strong>Milagro</strong></td>
<td>(69°, 14°)</td>
<td>(136°, 45°)</td>
<td></td>
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<tr>
<td></td>
<td>6 x 10⁻⁴, 15σ (pre)</td>
<td>4 x 10⁻⁴, 13σ (pre)</td>
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