Large Scale Cosmic Ray Anisotropy With IceCube

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The IceCube Collaboration

USA:
- Bartol Research Institute, Delaware
- University of California, Berkeley
- University of California, Irvine
- Pennsylvania State University
- Clark-Atlanta University
- Ohio State University
- Georgia Tech
- University of Maryland
- University of Alabama, Tuscaloosa
- University of Wisconsin-Madison
- University of Wisconsin-River Falls
- Lawrence Berkeley National Lab.
- University of Kansas
- Southern University and A&M College, Baton Rouge
- University of Alaska, Anchorage

Sweden:
- Uppsala Universitet
- Stockholm Universitet

UK:
- Oxford University

Switzerland:
- EPFL

Belgium:
- Université Libre de Bruxelles
- Vrije Universiteit Brussel
- Universiteit Gent
- Université de Mons-Hainaut

Germany:
- DESY-Zeuthen
- Universität Mainz
- Universität Dortmund
- Universität Wuppertal
- Humboldt Universität
- MPI Heidelberg
- RWTH Aachen
- Universität Bonn
- Ruhr-Universität Bochum

Japan:
- Chiba University

New Zealand:
- University of Canterbury

34 institutions, 250 members
http://icecube.wisc.edu
IceCube Detector

- When completed (2011) IceCube volume will reach 1 km$^3$ (80 strings + 6 additional strings for Deep Core).
- 2009: 59 strings
  Livetime: 96 %
  Neutrino rate: 160/day

2009: 59 strings in operation
2011: Project completion, 86 strings
• Data is dominated by a large background of cosmic ray muons.
• Data used in this analysis are the downward going muons collected with IceCube 22 strings in 2007.
Large scale cosmic ray anisotropy
Heliomagnetic sphere and heliomagnetotail.

Compton Getting Effect

Local structure of interstellar magnetic field.

Nearby young sources of cosmic rays?

Science Vol. 314. no. 5798, pp. 439 - 443
Data Analysis:

- Downward going muons.
- Data collected June 07-March 08.
- Course line fit estimate of arrival direction: $5.2 \times 10^9$ events.
- A range of selection Criteria (LLH): $4.3 \times 10^9$ events.
- Median angular Resolution (angle bet. reconstructed muon and primary particle): $3^\circ$ degrees.
- Median energy per cosmic ray particle: 14 TeV.
Looking for a 0.1% effect

Possible Anisotropy causes:

- Diurnal variations
  - need a whole day to scan the entire sky
  - day night effect
- Seasonal variation
- Detector Asymmetry
- Non uniform time coverage

IceCube:

- No diurnal variations
  - one day and one night per year
  - Whole sky is fully visible to the detector at any given time
- Seasonal variation
  - Seasonal variation is slow
    (>>one day)
- Detector Asymmetry
- Non uniform time coverage
Azimuthal Normalizing

Trigger and reconstruction biases toward the long axis of the detector.
Looking for a 0.1% effect; don’t want local asymmetry to show up in final skymap
Solution: reweight each event to flatten the azimuth distribution
**IceCube 22 string Skymap**

- 1-d projection of the *Equatorial relative intensity skymap*

- The fitting function is the first and second order harmonic function in the form of $Amp \times \cos (RA - \phi)$
Comparison with Tibet array and Milagro

Anisotropy is a continuation of previously measured large scale anisotropy observed in northern locations.
Source of the observed anisotropy?
Energy Estimation

- Energy is not directly measured.
- Energy is estimated using Energy proxy from simulation.

<table>
<thead>
<tr>
<th>Median Energy</th>
<th>Number of events</th>
<th>68% of events lie between</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 TeV (E1)</td>
<td>$3.3 \times 10^9$</td>
<td>12 - 60 (TeV)</td>
</tr>
<tr>
<td>126 TeV (E2)</td>
<td>$9.6 \times 10^8$</td>
<td>25 - 500 (TeV)</td>
</tr>
</tbody>
</table>
Energy Dependence skymaps

<table>
<thead>
<tr>
<th>Median Energy</th>
<th>Number of events</th>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 TeV (E1)</td>
<td>$3.3 \times 10^9$</td>
<td>7.3±0.3</td>
<td>63.4±2.6</td>
</tr>
<tr>
<td>126 TeV (E2)</td>
<td>$9.6 \times 10^8$</td>
<td>2.9±0.6</td>
<td>93.2±12</td>
</tr>
</tbody>
</table>
In the energy range 10-100 TeV Amplitude shows a decrease in value at higher energies.
Toward Explanation
Possible Sources?

- Heliospheric magnetotail
- Magnetic field structure: Local Interstellar Cloud
- Nearby sources of CR: SNR Vela (128 α, −45 δ).

\[ R_{\text{gyro}} \approx 1 \text{kpc} \frac{1}{z} \frac{E}{10^{18} \text{eV}} \frac{\mu \text{G}}{B} \]
Local Interstellar Magnetic Field

\[ I_{n,m} = a_{1 \perp} \cos \chi_{1} (n,m : \alpha_{1}, \delta_{1}) + a_{1 \parallel} \cos \chi_{2} (n,m : \alpha_{2}, \delta_{2}) + a_{2} \cos^{2} \chi_{2} (n,m : \alpha_{2}, \delta_{2}) \]

M. Amenomori et. al. ICRC 2007 Proceedings
Tibet Array Model Fit to Data

Data

Model

Residual skymap

M. Amenomori et. al. ICRC 2007 Proceedings
Nearby sources of Cosmic Ray

Milagro (1 TeV)
Abdo et. Al. Arxiv:0801.3827

Tibet Array residual skymap (5 TeV)
M. Amenomori et. al. ICRC 2007 Proceedings

Argo (2 TeV)
S. Vernetto et. al. ICRC 2009 Proceedings
Galactic coordinates

Nearby sources of cosmic rays effect on the anisotropy?
Conclusion

- First skymap reporting a significant large scale anisotropy in the southern hemisphere sky.
- IceCube skymap is consistent with Large scale anisotropy results reported by previous experiments looking at the northern hemisphere sky.
- Source for large scale anisotropy is unknown
- Investigating the possibilities of:
  - LIC structure and intensity.
  - medium and small scale anisotropy
First look at IceCube 40 string 08-09
Event Topologies

Muon neutrino

a) $E_\mu = 10$ TeV $\sim 90$ hits

$E \sim dE/dx$, $E > 1$ TeV

Energy Res. $\log(E) \sim 0.3$
Angular Res. $0.8 - 2$ deg

b) $E_\mu = 6$ PeV $\sim 1000$ hits

Electron neutrino

$E = 375$ TeV

Energy Res. $\log(E) \sim 0.1 - 0.2$
Poor Angular Resolution

Tau neutrino

$E = 10$ PeV

$\nu_\tau + N \rightarrow \tau + ...$

Double-bang signature above $\sim 1$ PeV
Very low background
Pointing capability
Best energy measurement