



OBSERVATION OF COSMIC RAY ANISOTROPY ABOVE TEV ENERGIES IN ICECUBE

Simona Toscano on behalf of the IceCube collaboration



3rd Roma International Conference on Astro-particle Physics 25-21 May 2011 Doma Italy

Outline

- * The **IceCube** detector
- * Energy dependence of the **large scale anisotropy** (*paper in preparation*):
 - preliminary results at 20 and 400 TeV.
 - solar dipole

* Medium and small scale structures (submitted to ApJ, arXiv:1105.2326):

- analysis
- systematics
- * Conclusions



University of Oxford, UK

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

Bartol Inst, Univ of Delaware Penn State UW-Madison UW-River Falls LBNL, Berkeley UC Berkeley UC Irvine Univ. of Alabama Clark-Atlanta University Univ. of Maryland University of Kansas Southern Univ. and A&M College University of Alaska, Anchorage Georgia Tech Ohio State

University of West Indies Barbados

Universität Mainz, Germany DESY Zeuthen, Germany Universität Wuppertal, Germany Universität Dortmund, Germany Humboldt Universität, Germany MPI, Heidelberg, Germany Ruhr-Universität, Bochum, Germany Universität, Bonn, Germany

RWTH Aachen, Germany

EPFL, Lausanne, Switzerland

Uppsala Universitet, Sweden Stockholm Universitet, Sweden

Chiba University, Japan

University of Canterbury, Christchurch, New Zealand

IceCube Collaboration 10 countries

36 institutions ~260 collaborators

The IceCube detector

G. Sullivan - Status and Recent Results from the IceCube km^3 Neutrino Detector (tomorrow Plenary)
 T. DeYoung - Particle physics in ice with IceCube DeepCore (today next Parallel session)





IC59 configuration Season 2008-2009





Cosmic rays in IceCube

IceCube tries to identify cosmic ray sources by their neutrino signal, but it also allows for a study of the *cosmic ray flux* itself, as the detector is sensitive to *downward going muons* produced in cosmic ray air showers in the southern hemisphere.

By detecting downgoing muons, IceCube can study the *arrival direction distribution of cosmic rays* in the energy range ~10 TeV to several 100 TeV and produce a cosmic ray sky map of the southern sky.



Data set

*****IceCube collects billions of down-going muons generated in CR air showers

***32 billion** of events collected between May 2008/May 2009 with 20 TeV median energy

IceCube-59	Level 1 "Muon Filter"	DST	
Live Time	96%	96%	
Trigger rate	22 Hz	1.4 kHz	
N _{events}	8.0×10 ⁸	3.2×10 ¹⁰	
Angular resolution	<1°	3°	
En annu na a duti an		$\Delta \log_{10}(E) = 0.5$	

Observation of the CRs large scale anisotropy

There have been several observations of *large-scale*, *part-per-mille anisotropy* in cosmic ray arrival directions between 0.1 and 100 TeV.





Large scale anisotropy

*IceCube observed a large scale anisotropy at 10-3 level for the first time in the Southern Sky.
*The anisotropy appears to be a continuation of large scale structures observed in the Northern Hemisphere.



Relative intensity of the cosmic ray event rate in equatorial coordinates: for each declination belt of width 3°, the plot shows the number of events relative to the average number of events in the belt.

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Relative Intensity

Equatorial sky maps in HEALPix with NSide= 16, pix resol - 3°



Wednesday, May 18, 2011

ICECUBE





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Energy dependence of the Solar dipole

* IceCube observes the Solar dipole in both energy bins. The observed amplitude is compatible with the expectations within the stat. and sys. uncertainties.

* The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction.





Small scale anisotropy

Several experiments have discovered anisotropies on scales of about 10°

***** Milagro observes two localized regions with **significance** > 10σ in the total data set of 2.2 10¹¹ events recorded over 7 years. The "hot" regions have fractional excesses of order several times 10^{-4} relative to the background.

* Same structures observed by ARGO-YBJ.





Relative Intensity map

Equatorial sky maps in HEALPix: equal area pixel (size ~ 0.9°)



Sky map created using the background estimation technique from real data:

N_i: number of data events in the *ith* pixel. *<N_i>*: expected number of events in an isotropic sky (time scrambling in 24 hr) in the *ith* pixel.

• Relative Intensity:

 $\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha, \delta) - \langle N_i(\alpha, \delta) \rangle}{\langle N_i(\alpha, \delta) \rangle}.$

Relative intensity map is *not isotropic*. In IceCube-59, the *strong large scale structure* already observed in IceCube-22 data is visible in the "raw" data.



Significance map

Significance calculation:

$$s = \sqrt{2} \left\{ N_{\rm on} \ln \left[\frac{1+\alpha}{\alpha} \left(\frac{N_{\rm on}}{N_{\rm on} + N_{\rm off}} \right) \right] + N_{\rm off} \ln \left[(1+\alpha) \left(\frac{N_{\rm off}}{N_{\rm on} + N_{\rm off}} \right) \right] \right\}^{1/2} \qquad \alpha = 1/20$$

Li, T., & Ma, Y. 1983, ApJ, 272, 317



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Power spectrum



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Dipole and quadrupole fit

 $\delta I(\alpha,\delta) = m_0$

monopole

 $+p_x \cos \delta \cos \alpha + p_y \cos \delta \sin \alpha + p_z \sin \delta$

dipole

 $+\frac{1}{2}Q_1(3\cos^2\delta-1)+Q_2\sin 2\delta\cos\alpha+Q_3\sin 2\delta\sin\alpha+Q_4\cos^2\delta\cos 2\alpha+Q_5\cos^2\delta\sin 2\alpha$ quadrupole

Coefficient	Fit Value
m_0	0.320 ± 2.264
p_x	2.435 ± 0.707
p_{y}	-3.856 ± 0.707
p_{z}	0.548 ± 3.872
Q_1	0.233 ± 1.702
Q_2	-2.949 ± 0.494
Q_3	-8.797 ± 0.494
Q_4	-2.148 ± 0.200
Q_5	-5.268 ± 0.200

 $\chi^2/\text{ndf} = 14743.4/14187$ $\Pr(\chi^2|\text{ndf}) = 5.5 \times 10^{-4}$





































































Identification of significant structures

region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^{\circ}$	$(-47.4^{+7.5}_{-3.2})^{\circ}$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^{\circ}$	$(-44.1^{+5.3}_{-5.1})^{\circ}$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^{\circ}$	$(-37.0^{+2.2}_{-1.9})^{\circ}$	11°	6.3σ	4.4σ
4	$(332.4^{+9.5}_{-7.1})^{\circ}$	$(-70.0^{+4.2}_{-7.6})^{\circ}$	12°	6.2σ	4.2σ
5	$(217.7^{+10.2}_{-7.8})^{\circ}$	$(-70.0^{+3.6}_{-2.3})^{\circ}$	12°	-6.4σ	-4.5σ
6	$(77.6^{+3.9}_{-8.4})^{\circ}$	$(-31.9^{+3.2}_{-8.6})^{\circ}$	13°	-6.1σ	-4.1σ
7	$(308.2^{+4.8}_{-7.7})^{\circ}$	$(-34.5^{+9.6}_{-6.9})^{\circ}$	20°	-6.1σ	-4.1σ
8	$(166.5^{+4.5}_{-5.7})^{\circ}$	$(-37.2^{+5.0}_{-5.7})^{\circ}$	12°	-6.0σ	-4.0σ







Systematics: previous data sets



Different geometries, same structure Signal grows with statistics









Milagro + IceCube combined map

IceCube map contains all data from IC22, IC40 and IC59 data sets





Conclusions

* IceCube detector was completed in December 2010 and is now taking data in its final configuration (86 strings).

*** Large scale anisotropy**:

- First observation of sidereal anisotropy @ 400 TeV in southern hemisphere.
- Sidereal anisotropy at 20 TeV confirms previous observation.
- Indication of a persistence of anisotropy @ 400 TeV: evidence of a "dip".

* Small and medium scale structures:

- Southern sky in TeV cosmic rays shows significant anisotropy across a wide range of angular scales (10-180 degrees).
- Features similar to what observed in the Northern Sky