
# *Evolution of the Cosmic Ray Anisotropy above 100 TeV as Observed by IceCube*

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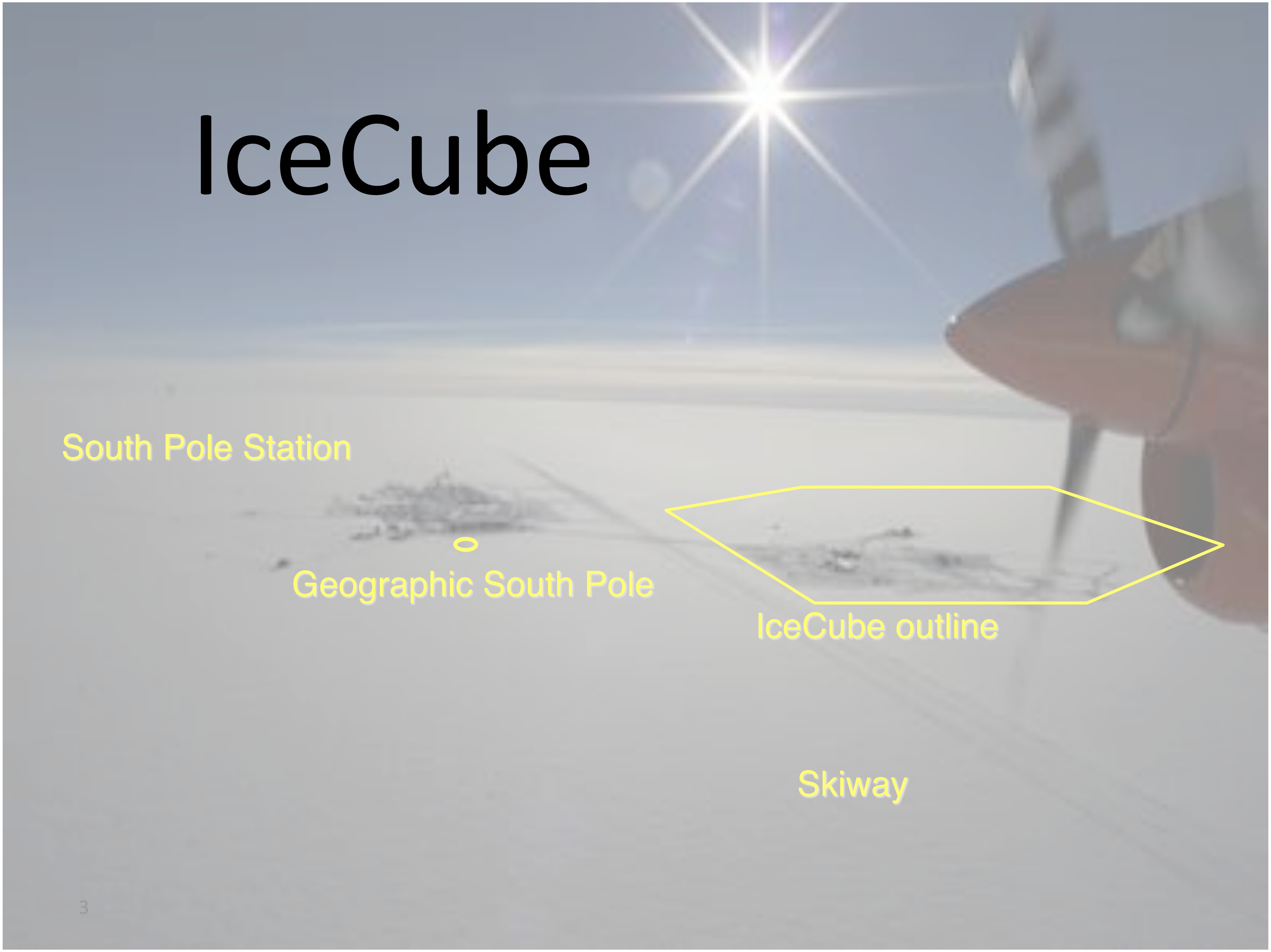
*(for the IceCube collaboration)*
*University of Wisconsin-Madison*

# *Overview*

- The IceCube Neutrino Observatory
- Searching for point like sources of Neutrinos
- Cosmic Ray Anisotropy with IceCube
- Evolution of the cosmic ray anisotropy above 100 TeV
- Possible interpretations
- Conclusion

# IceCube

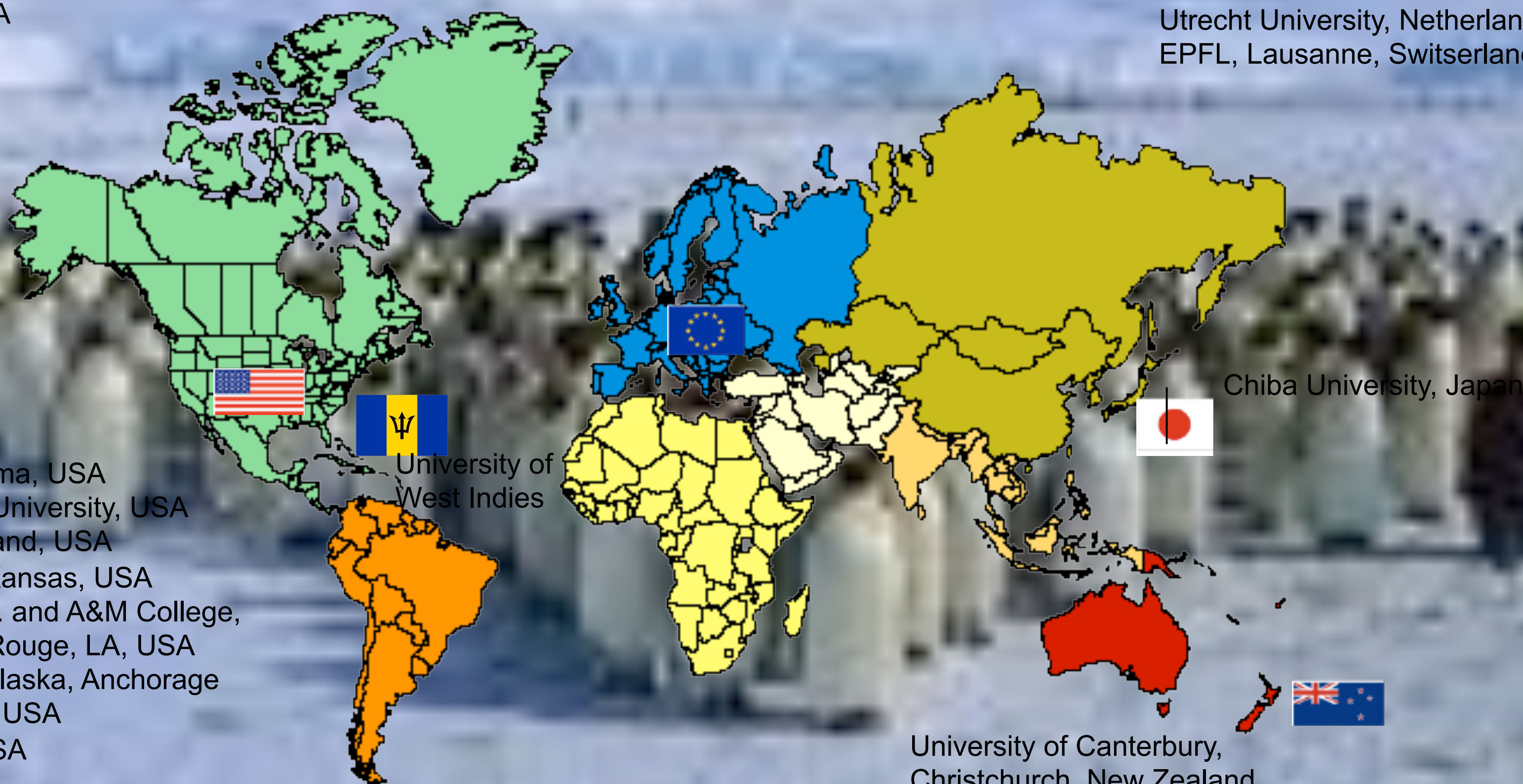

South Pole Station
Geographic South Pole
IceCube outline
Skiway

# IceCube Collaboration

Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg
Ruhr-Universität, Bochum
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands
EPFL, Lausanne, Switserland




Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
University of Alaska, Anchorage
Georgia Tech, USA
Ohio State, USA

University of Canterbury, Christchurch, New Zealand

36 collaborating institutions

# IceCube Detector

→ 1 km3 instrumented volume

→ IceCube is now completed

→ IceCube detector: 86 strings

→80 strings ~125 m apart

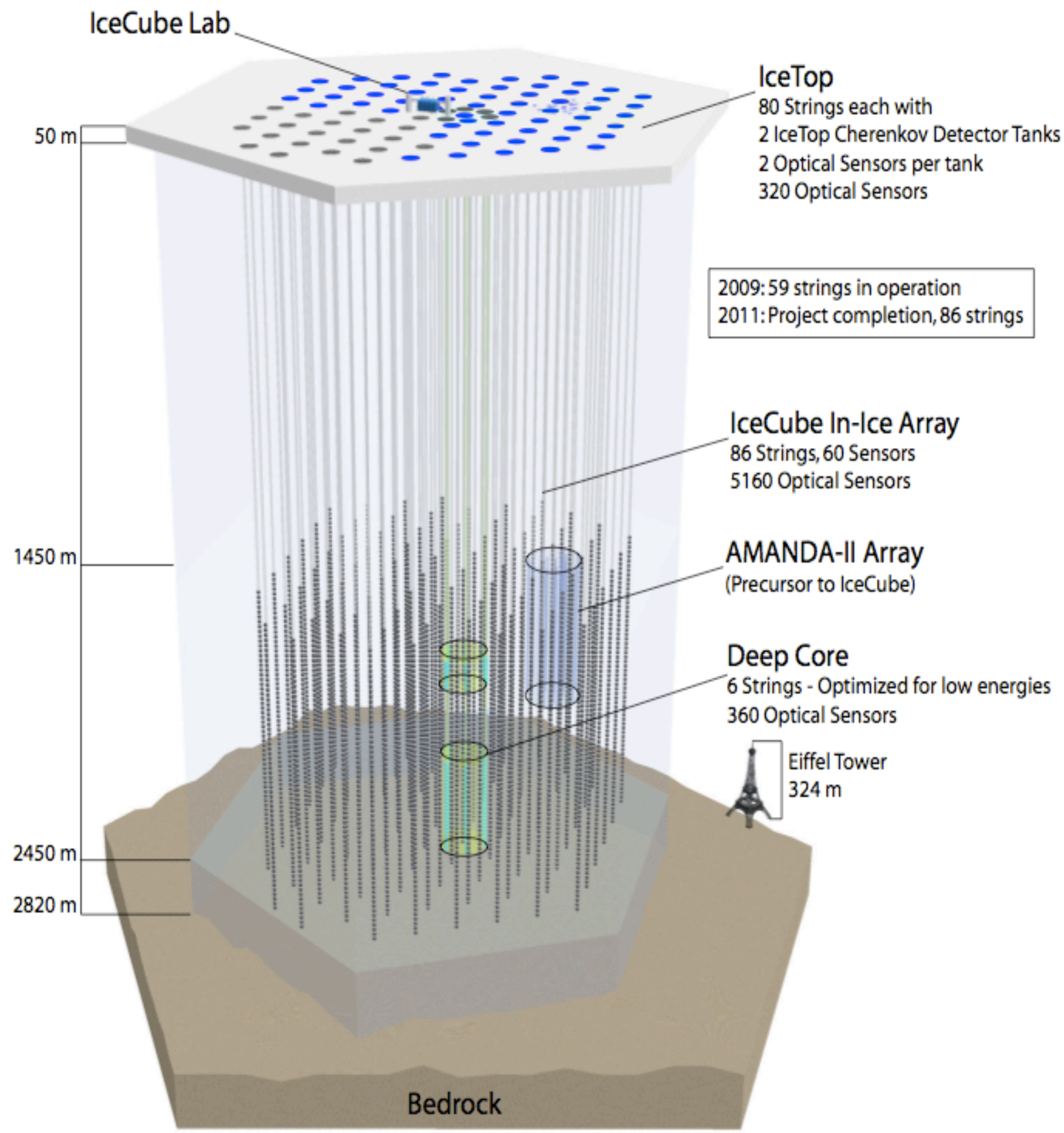
→60 doms per string at 17 m vertical space.

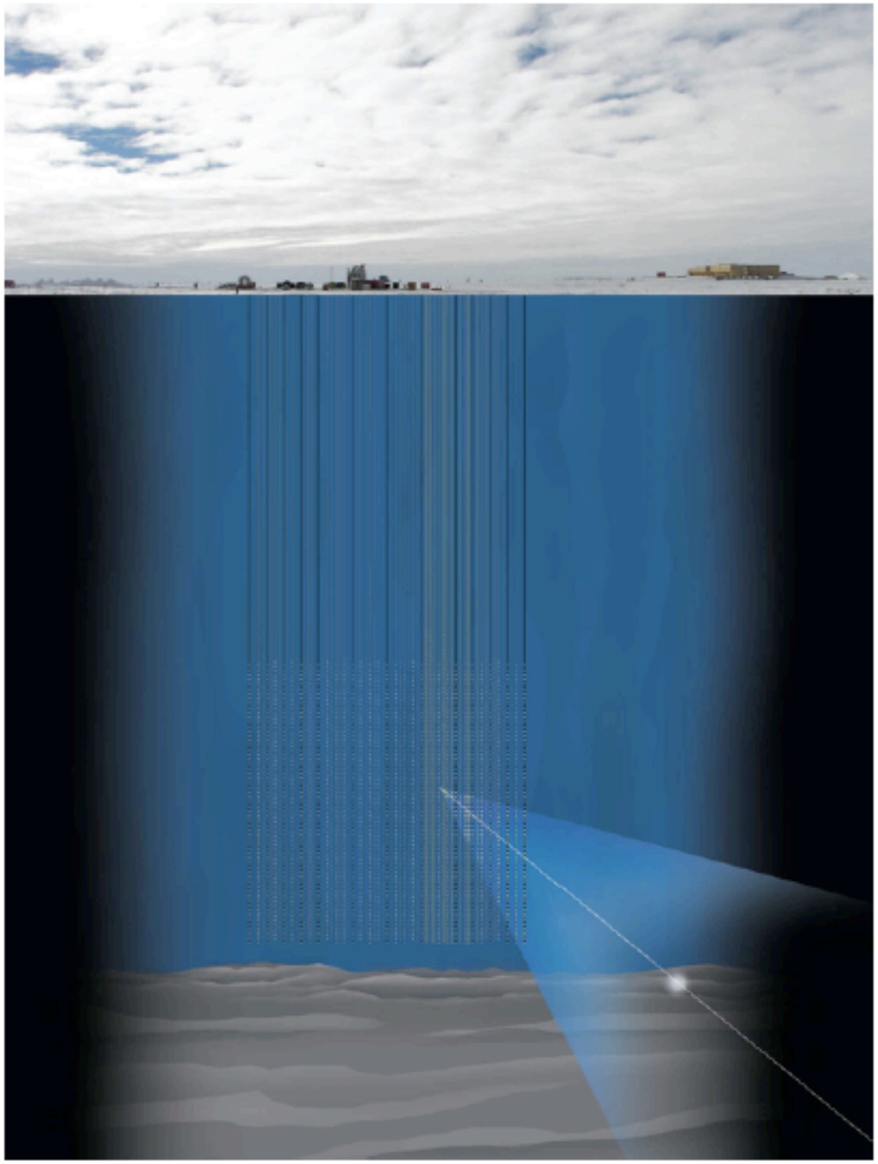
→ Deep Core: 6 string, 72 m Apart, 7 m vertical spacing.

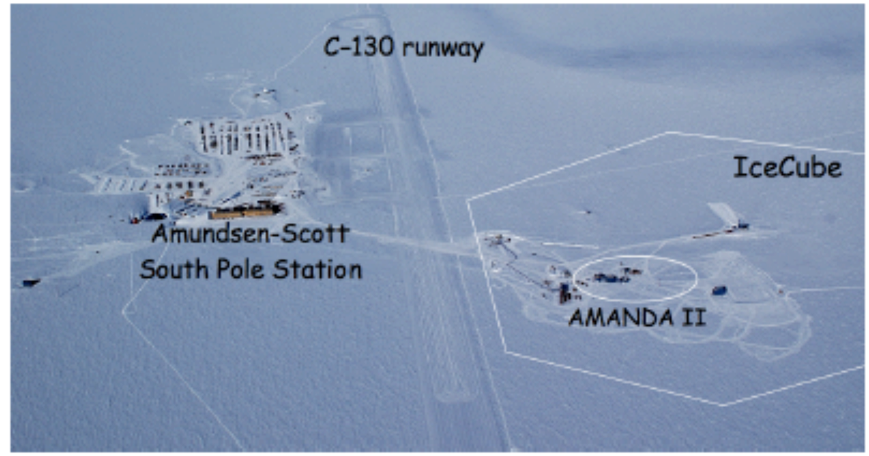
→IceTop:

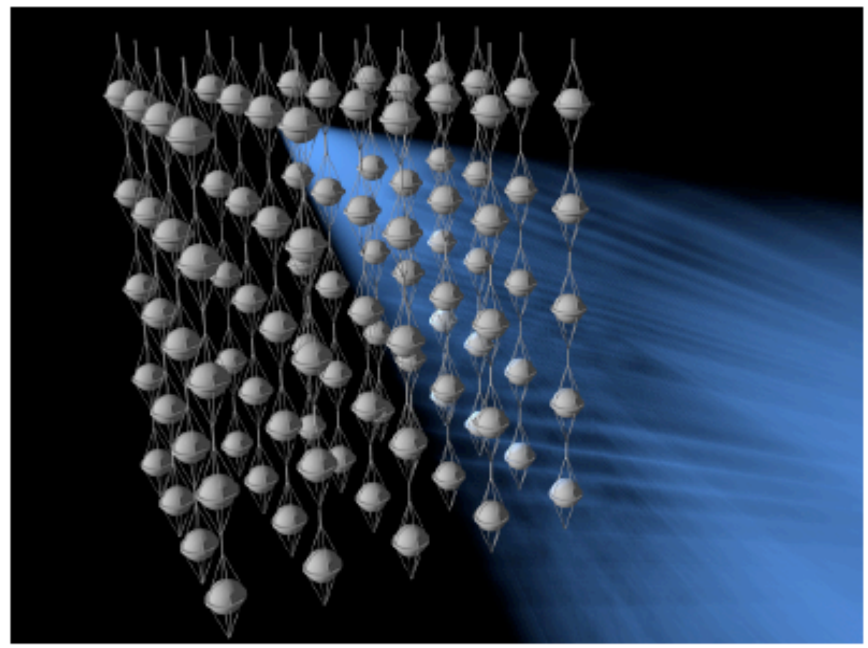
→2 Cherenkov Tank per string.

→2 optical sensors per tank.



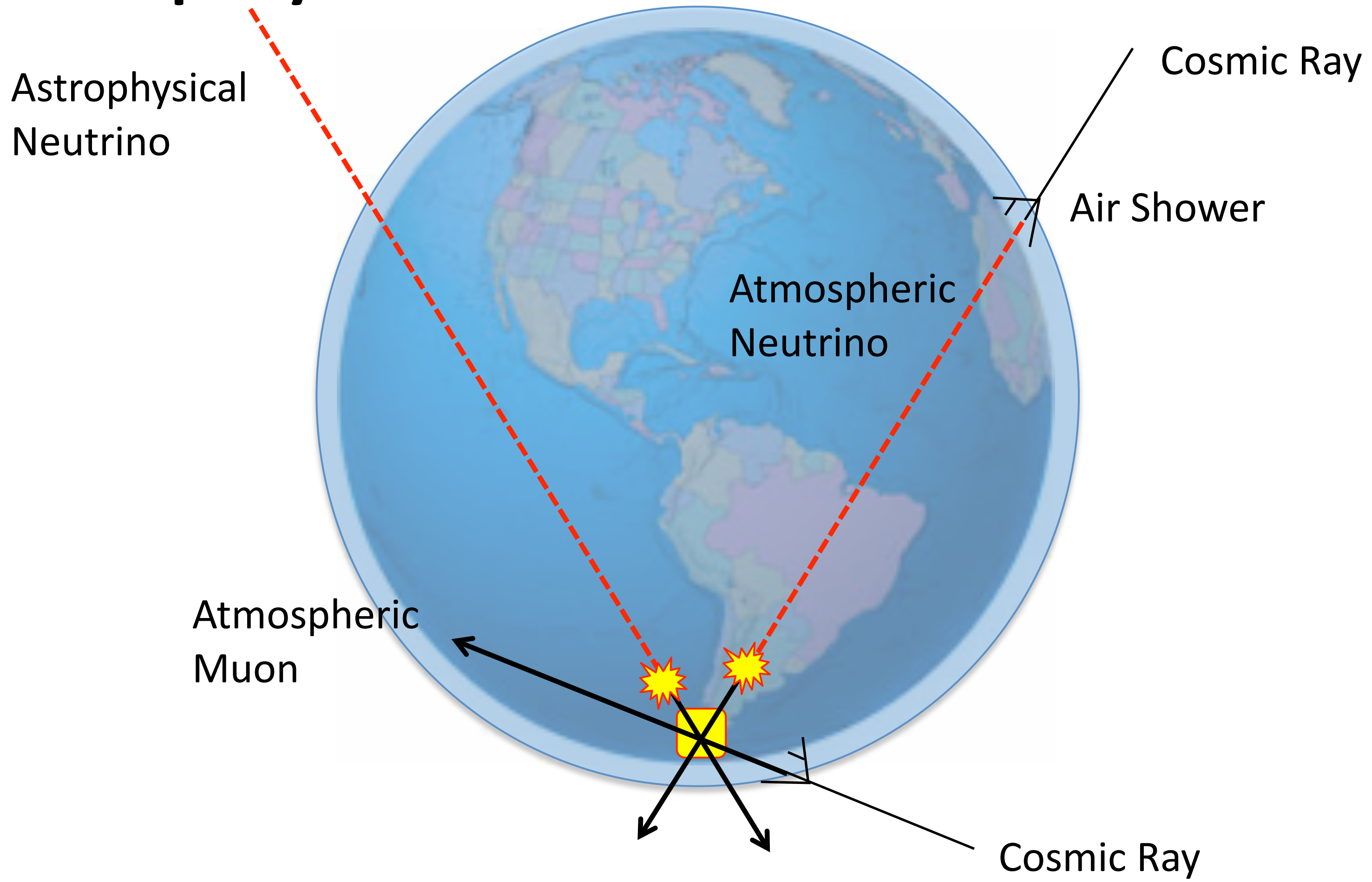




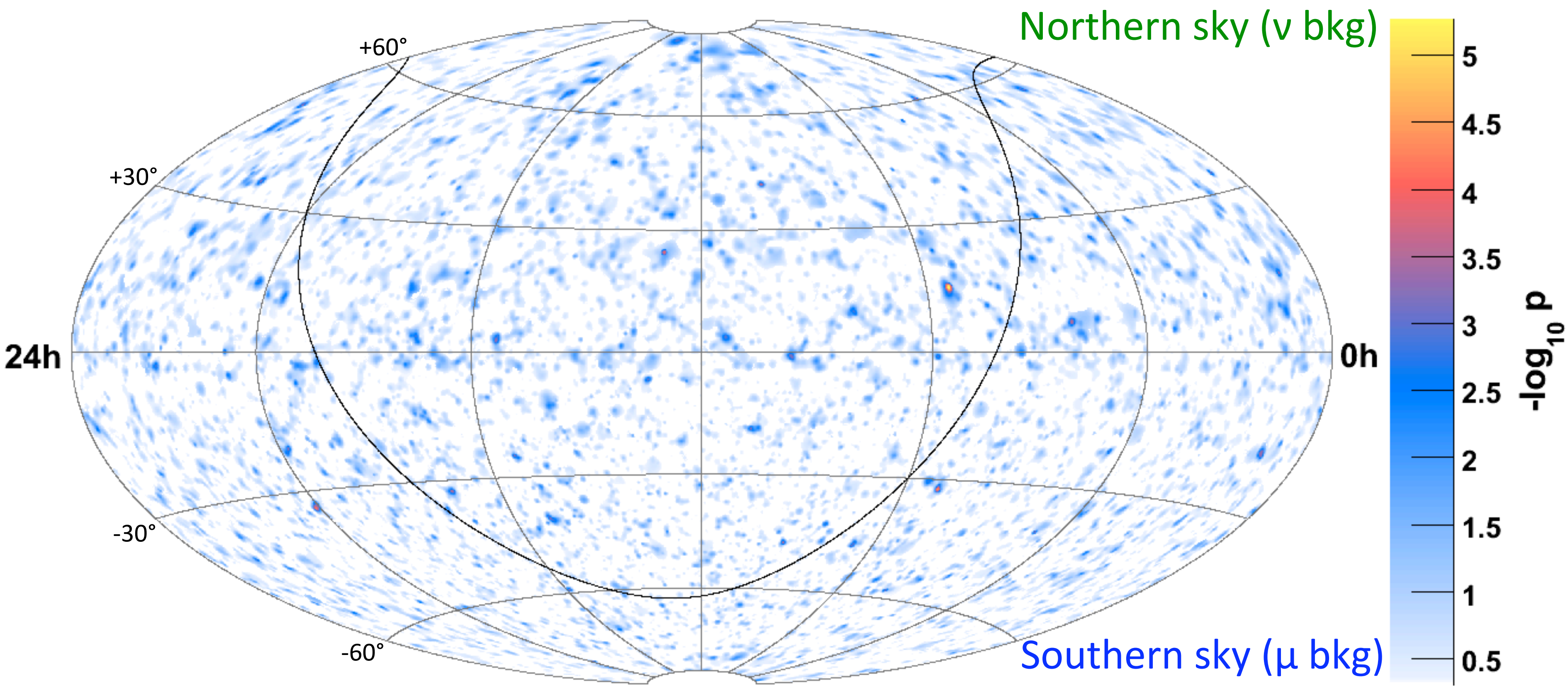
# Detection Technique

# Astrophysical Neutrino Detection




- Use large volume of material (~1 $km^3$ of rock, water, or ice) to improve chance of neutrino interaction inside the detector
- Use the Earth as a filter: build underground to reduce backgrounds, look for upgoing events to remove cosmic ray events.
- Data is dominated by a large background of cosmic ray muons. But they are useful in their own right.

# IC40 All-Sky Point source search: Likelihood approach

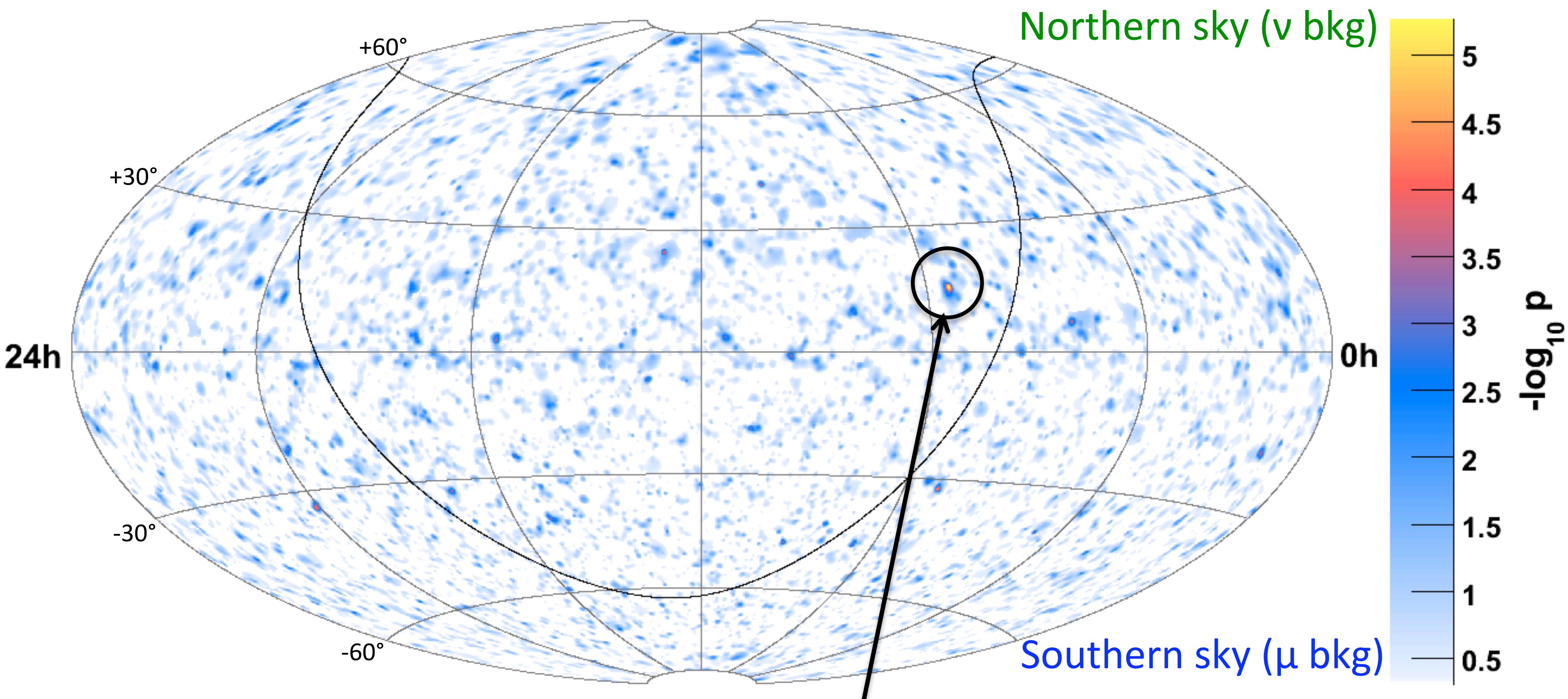



Hottest location in the all-sky search is:
Ra=113.75°, Dec=15.15°

Livetime = 375.5 days

# Events = 36900
(14121 up-going,
22779 down-going)

# IC40 All-Sky Point source search: Likelihood approach




Hottest location in the all-sky search is:

Ra=113.75°, Dec=15.15°

Livetime = 375.5 days

# Events = 36900
(14121 up-going,
22779 down-going)

In background simulated trials (scrambling data in r.a.), an equal or greater excess occurs by chance 1817/10000 times.
=> **all-sky final p-value is 18%, not significant**



Submitted to Astrophysical Journal

# IC40 All-Sky Point source search

## Northern Sky **Sources:**

Highest significance comes from southern sky (see next slide)

P-values >=0.5 (downward fluctuations) are given as "---"

22-string hottest spot is now a downward fluctuation →

| Source Name | Ra , Dec (deg) | | p-value |
|---|---|---|---|
| Cyg_OB2 | (308.083, 41.510) | : | --- |
| MGRO_J2019+37 | (305.220, 36.830) | : | 0.44 |
| MGRO_J1908+06 | (286.976, 6.269) | : | --- |
| Cas_A | (350.850, 58.815) | : | --- |
| IC443 | ( 94.179, 22.529) | : | --- |
| Geminga | ( 98.476, 17.770) | : | 0.48 |
| Crab_Nebula | ( 83.633, 22.014) | : | --- |
| 1ES_1959+650 | (299.999, 65.149) | : | --- |
| 1ES_2344+514 | (356.770, 51.705) | : | --- |
| 3C66A | ( 35.673, 43.043) | : | 0.24 |
| H_1426+428 | (217.136, 42.672) | : | --- |
| BL_Lac | (330.680, 42.278) | : | 0.23 |
| Mrk_501 | (253.468, 39.760) | : | 0.42 |
| Mrk_421 | (166.114, 38.209) | : | 0.14 |
| W_Comae | (185.382, 28.233) | : | --- |
| 1ES_0229+200 | ( 38.202, 20.287) | : | 0.18 |
| M87 | (187.706, 12.391) | : | --- |
| S5_0716+71 | (110.473, 71.343) | : | --- |
| M82 | (148.967, 69.680) | : | 0.40 |
| 3C_123.0 | ( 69.268, 29.671) | : | 0.44 |
| 3C_454.3 | (343.491, 16.148) | : | --- |
| 4C_38.41 | (248.815, 38.135) | : | 0.46 |
| PKS_0235+164 | ( 39.660, 16.620) | : | 0.14 |
| PKS_0528+134 | ( 82.735, 13.532) | : | --- |
| PKS_1502+106 | (226.104, 10.494) | : | --- |
| 3C_273 | (187.278, 2.052) | : | --- |
| NGC_1275 | ( 49.951, 41.512) | : | --- |
| Cyg_A | (299.868, 40.734) | : | 0.44 |
| IC-22_maximum | (153.375, 11.375) | : | --- ← |



…Southern Sky sources continue on next slide…

# IC40 All-Sky Point source search

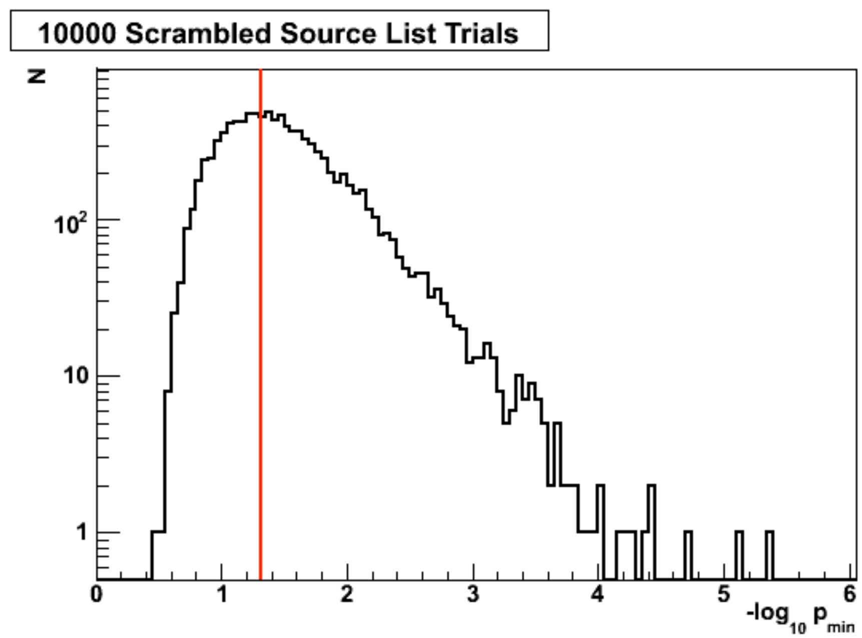
## Southern Sky **Sources:**

Highest significance from list of 39 sources comes from PKS 1622-297 →

| Source Name | Ra , Dec (deg) | | p-value |
|---|---|---|---|
| Sgr_A* | (266.417, -29.008) | : | 0.44 |
| PKS_0537-441 | ( 84.710, -44.086) | : | --- |
| Cen_A | (201.365, -43.019) | : | --- |
| PKS_1454-354 | (224.361, -35.653) | : | --- |
| PKS_2155-304 | (329.717, -30.225) | : | 0.32 |
| PKS_1622-297 | (246.525, -29.857) | : | 0.048 ← |
| QSO_1730-130 | (263.261, -13.08) | : | --- |
| PKS_1406-076 | (212.235, -7.874) | : | 0.39 |
| QSO_2022-077 | (306.420, -7.640) | : | --- |
| 3C279 | (194.050, -5.790) | : | 0.12 |

*Pretrial p-value of 4.8% or less for any of the 39 sources happens in 62% of scrambled skymaps

-> **source list final p-value = 62%**



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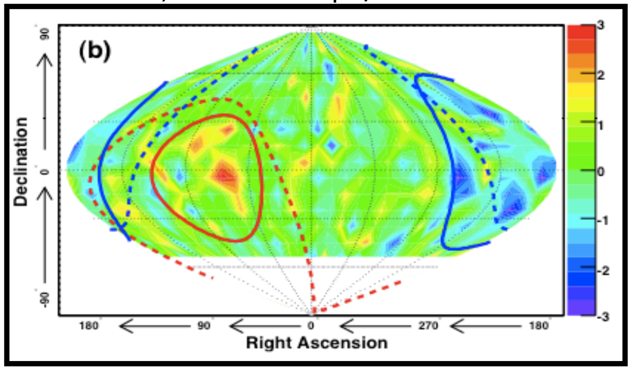
# Large Cosmic Ray Anisotropy Measurements in the Northern sky

## Super-K

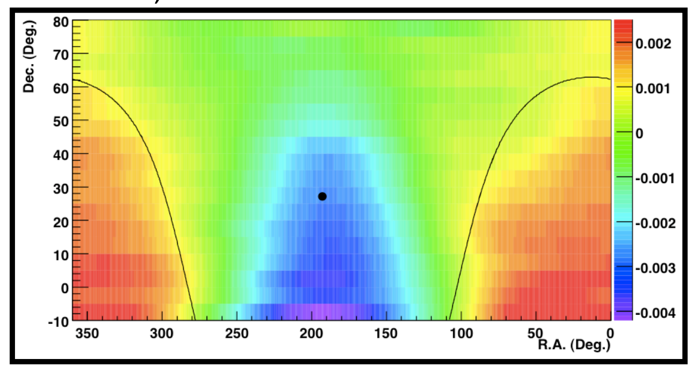
Guillian et al., arXiv:astro-ph/0508468




- 2.1×10$^8$ events bet. 1996 – 2001
- Angular resolution < 2º
- Median energy ~ 10 TeV

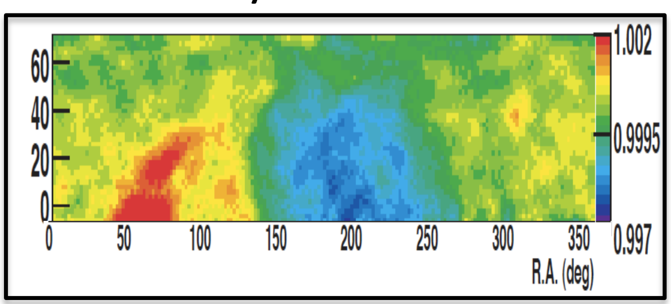
## Milagro

Abdo et al., arXiv:0806.2293



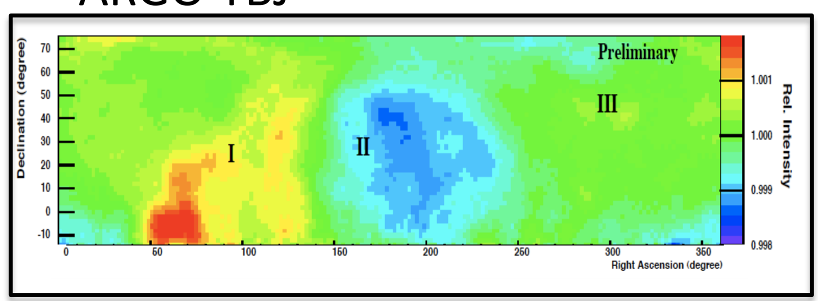

- 9.6×10$^{10}$ events bet. 2000-2007
- Angular resolution < 1º
- Median energy ~ 6 TeV

## Tibet Array




- 3.7×10$^{10}$ events bet. 1997-2005
- Angular resolution < 1º
- Median energy ~ 6 TeV

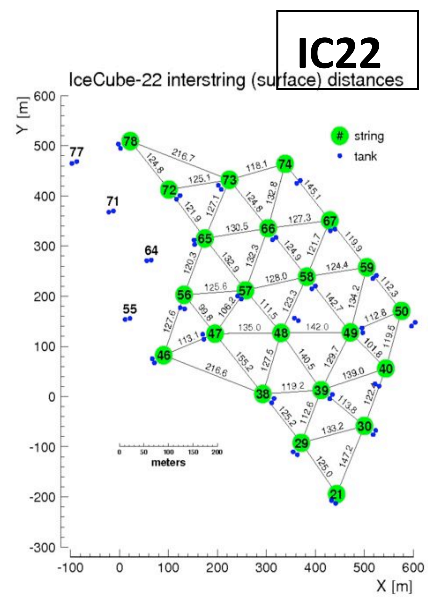
## ARGO-YBJ




- 6.5×10$^{10}$ events on 2008
- Angular resolution < 2º
- Median energy ~ 1 TeV

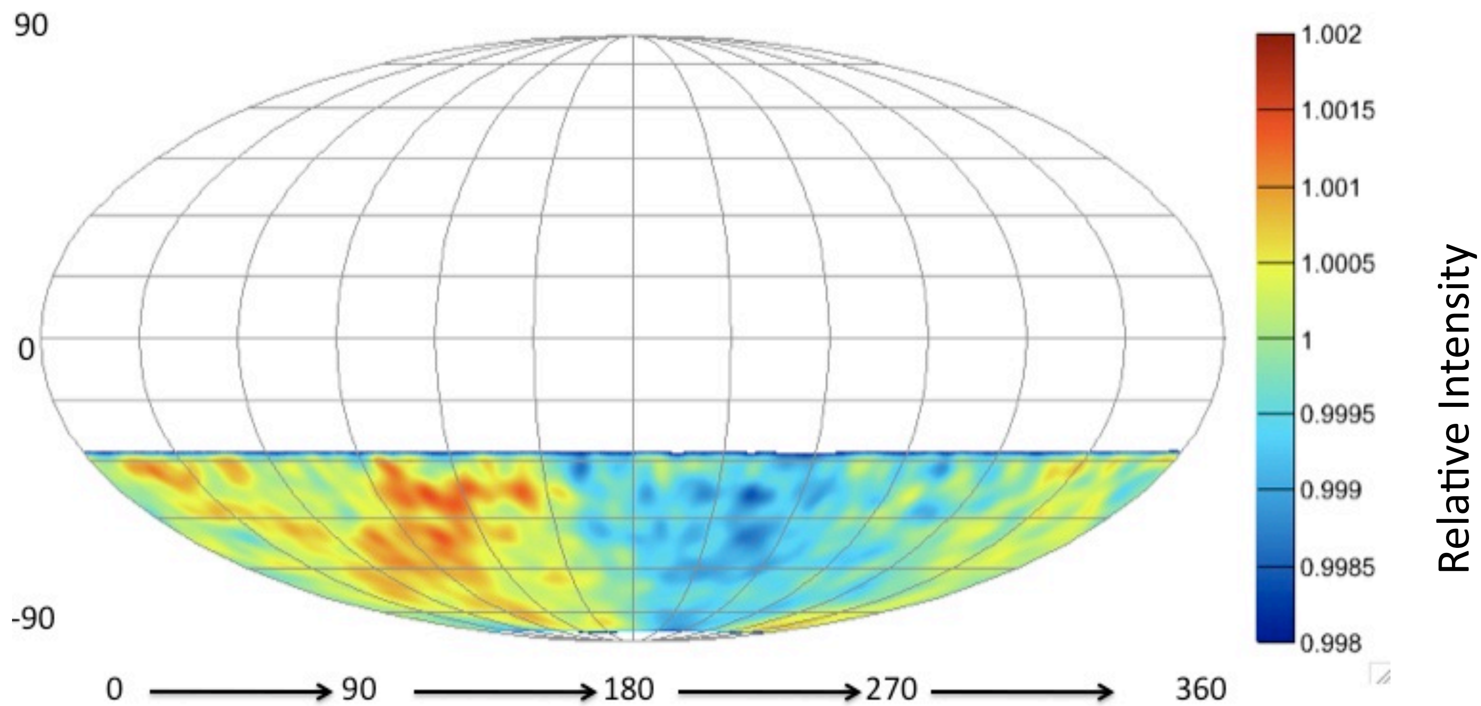
# Cosmic Ray Anisotropy with IceCube

- IceCube records *several $10^{10}$ cosmic ray events per year,* which makes it possible to study anisotropies in the cosmic ray arrival direction distribution at high precision.
- IceCube is the first detector able to measure anisotropies of the *southern sky.*
- The method needs to be sensitive to anisotropies at the $10^{-4}$ level, in the presence of variations due to …
  - Advantage: H*aving the entire half sky uniformly visible at any time*
  - *diurnal* and *seasonal variations* of atmospheric conditions,
  - Disadvantage: asymmetries in the *detector geometry:* non-uniform detector exposure to different regions of the sky due to gaps in the *detector uptime* and an uneven run selection due to quality cuts,
  - *Solution: reweight each event to flatten the azimuth distribution*



## *IceCube 22 string First Observation of the Anisotropy for the southern sky*

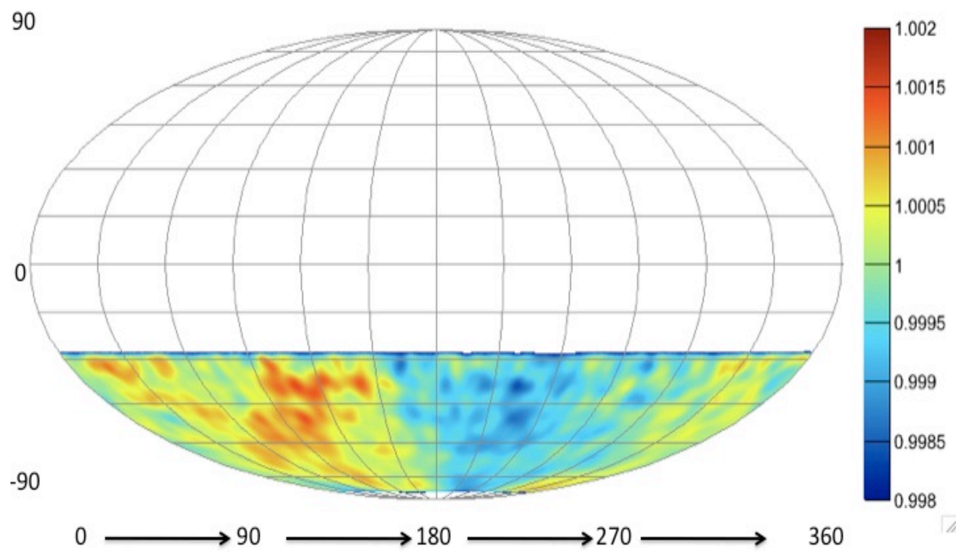
Equatorial coordinates

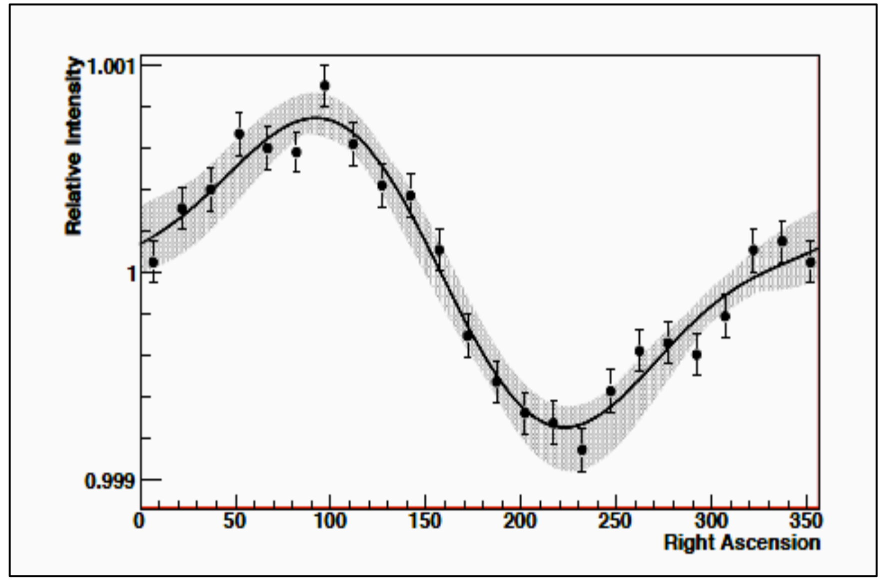



• *Relative intensity* of the cosmic ray event rate:
for each declination belt of width 3°, the plot shows the number of events relative to the average number of events in the belt.

# *IceCube 22 string First Observation of the Anisotropy for the southern sky*

Equatorial coordinates




- *IceCube 22:*
- data from June 2007 to March 2008
- 226 days livetime
- $4.3 \cdot 10^9$ events
- median angular resolution ~ 3˚
- median CR energy ~ 20 TeV

Abbasi et al., ApJ, **718, L194, 2010**

- Large scale anisotropies are analyzed by fitting *harmonics* to the event distribution in right ascension.
- Fitting the first and second harmonic function to e nsion

$$\sum_{i=1}^{2} A_i \cos(i(\alpha - \phi_i)) + B$$

dipole

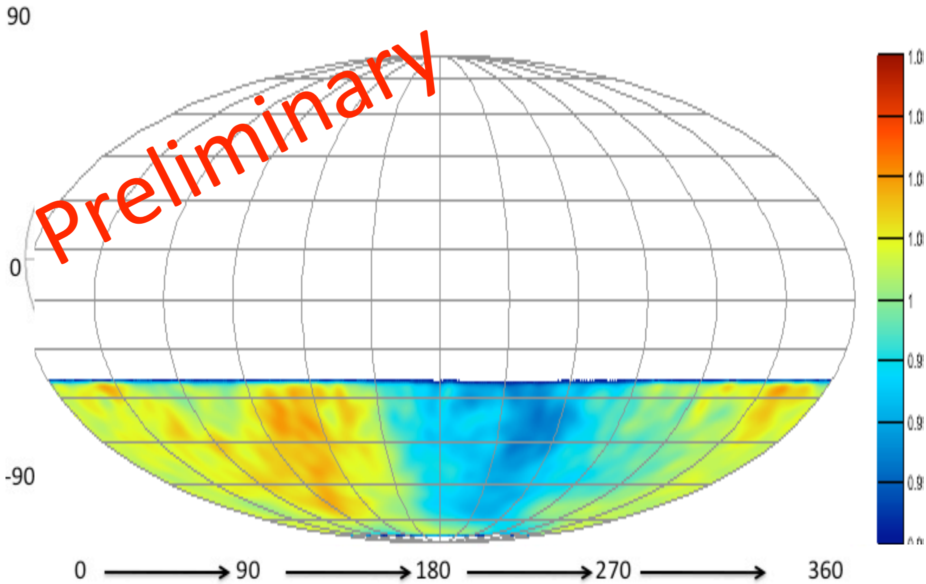
$$A_1 = (6.4 \pm 0.2_{stat} \pm 0.8_{syst}) \times 10^{-4}$$
$$\phi_1 = 66^\circ.4 \pm 2^\circ.6_{stat} \pm 3^\circ.8_{syst}$$

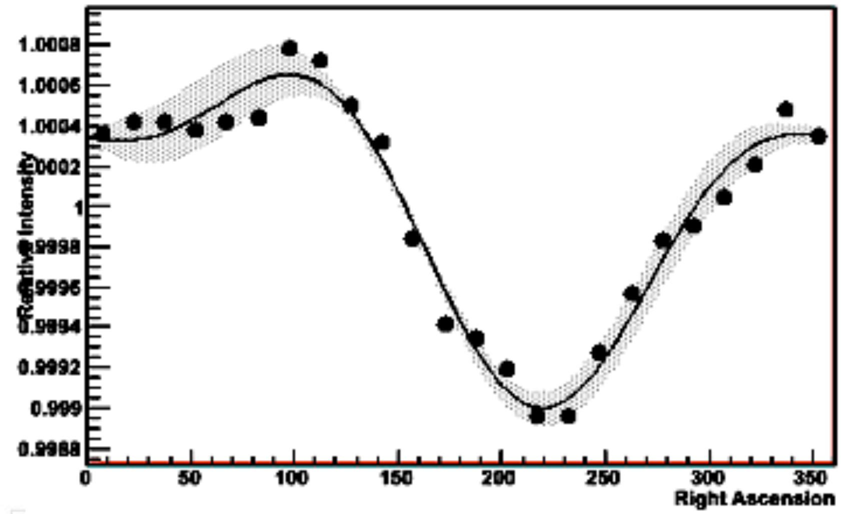
quadrupole

$$A_2 = (2.1 \pm 0.3_{stat} \pm 0.5_{syst}) \times 10^{-4}$$
$$\phi_2 = -65^\circ.6 \pm 4^\circ.0_{stat} \pm 7^\circ.5_{syst}$$

# IceCube 59 string Cosmic ray skymap for the southern sky

Equatorial coordinates




- 1-d projection of the Equatorial relative intensity skymap
- Fitting the first and second harmonic function to event distribution in right ascension

$$\sum_{i=1}^{2} A_i \cos(i(\alpha - \phi_i)) + B$$

*Dipole:*

*$A1 = (7.2 \pm 0.1_{stat} \pm 0.6_{sys}) \times 10^{-4}$*

*$\Phi 1 = (55.1^{o} \pm 0.9^{o}_{stat} \pm 2.1^{o}_{sys})$*

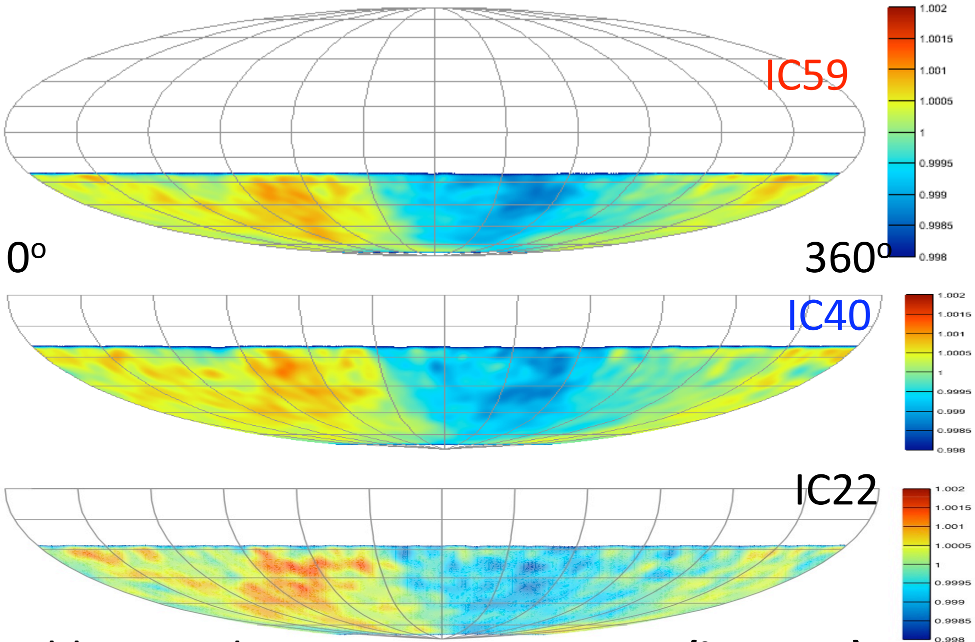
*Quadruple:*

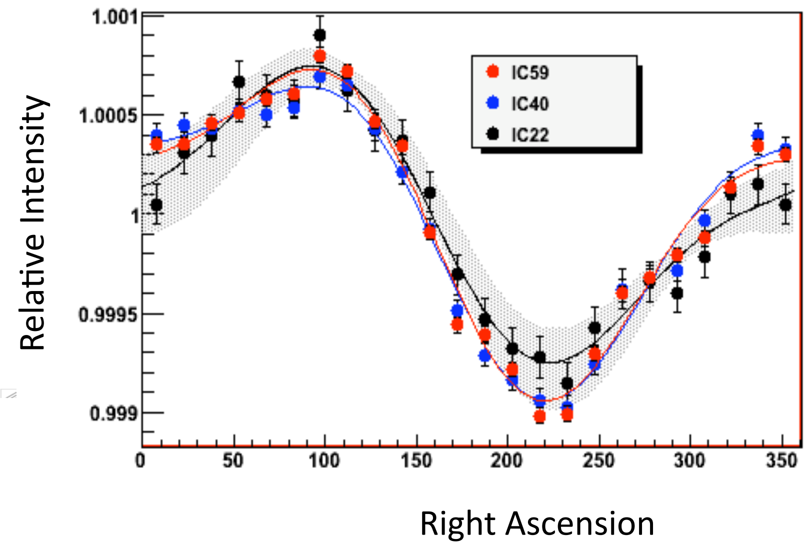
*$A2 = (-2.6 \pm 0.1_{stat} \pm 0.3_{sys}) \times 10^{-4}$*

*$\Phi 2 = (30.5^{o} \pm 1.2^{o}_{stat} \pm 1.6^{o}_{sys})$*

- *IceCube 59:*
- data from May 2009 to May 2010
- 324 days livetime
- $23 \cdot 10^{9}$ events
- median angular resolution ~ 3˚
- median CR energy ~ 20 TeV

# Relative Intensity of Cosmic Rays (IC22, IC40 & IC59)




Abbasi et al., ApJ, **718, L194, 2010 (in press)**

| Year | Rate (Hz) | LiveTime(Days) | CR Median Energy (TeV) | Median Angular Resolution (degrees) | Number of Events (billion) |
|---|---|---|---|---|---|
| 2007-IC22 | 240 | ~226 | ~19 | 3 | ~4 |
| 2008-IC40 | 780 | ~324 | ~19 | 3 | ~15 |
| 2009-IC59 | 1300 | ~324 | ~19 | 3 | ~23 |

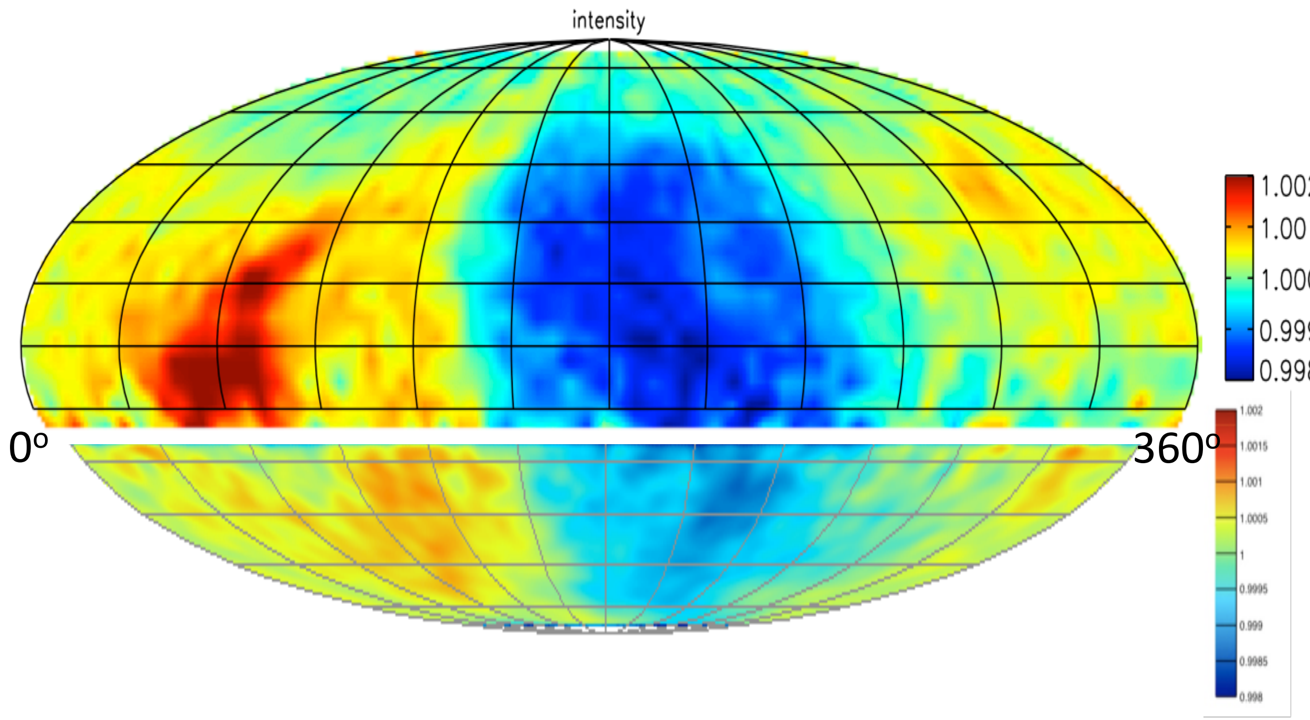
# Comparison to the Northern Hemisphere Tibet Array and IceCube

Tibet Array

5TeV

IceCube-59

20 TeV

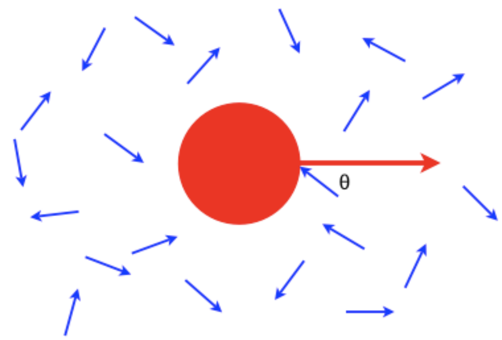



Relative Intensity

Anisotropy is a continuation of previously measured large scale anisotropy observed in northern locations.

# Dipole Anisotropies Due to the observer Motion

# Dipole Anisotropies Due to the observer Motion




- Large scale anisotropies can be caused by our motion through the cosmic ray rest frame:
  - The intensity of cosmic rays should be *higher* coming from the direction in which the observer is moving in causing a *dipole anisotropy*.
  - An Apparent effect on the intensity of cosmic rays

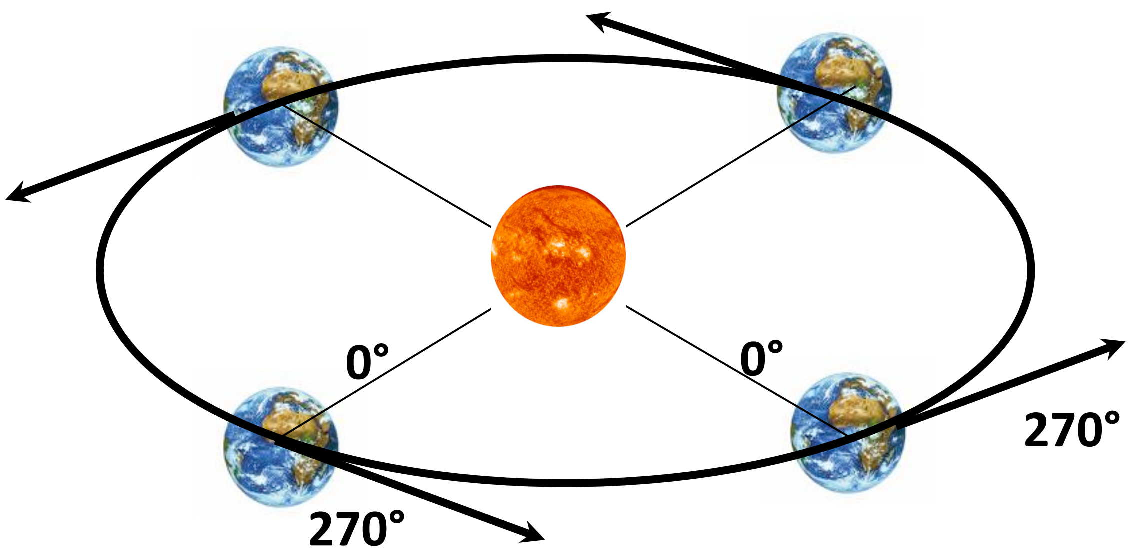
$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

- Earth's motion through space is a superposition of several motions. Two dipole anisotropies due to Earth's motion have been postulated:

  - solar dipole anisotropy due the Earth's motion around the Sun.
  - Compton-Getting Effect due to the motion of the solar system around the Galactic center.

# Solar Dipole Effect

This effect caused by Earth's motion around the Sun is apparent when the skymap is plotted with respect to the sun $O(10^{-4})$.

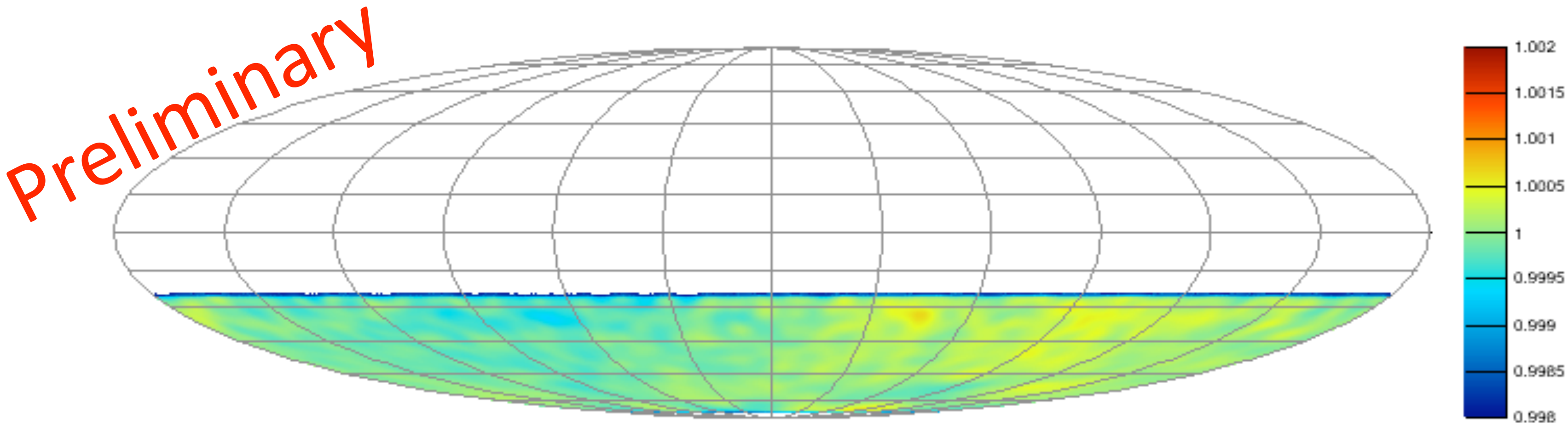



$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

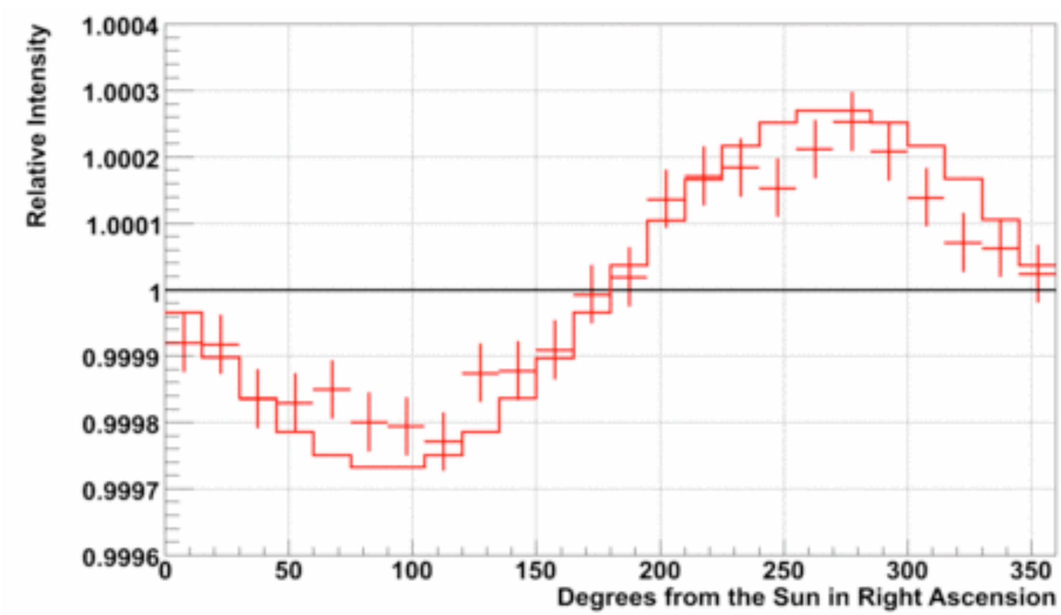
$\gamma = 2.7$ cosmic ray spectral index

$v = 29$ km/s speed

# *IceCube 59 string Observation of the Solar Dipole Anisotropy*




0° 360°




$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

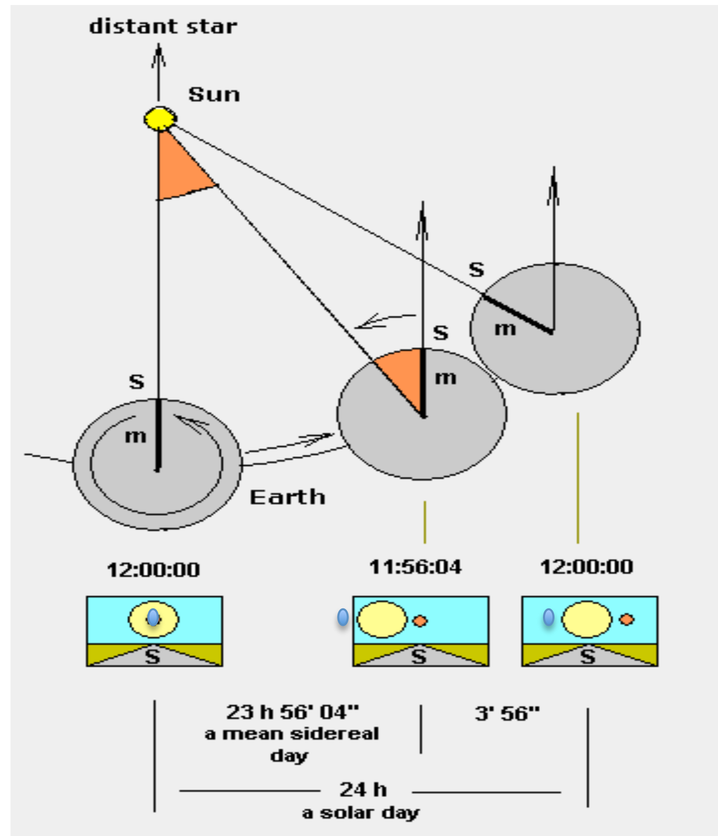
$\gamma = 2.7$ cosmic ray spectral index

$v = 29$ km/s speed

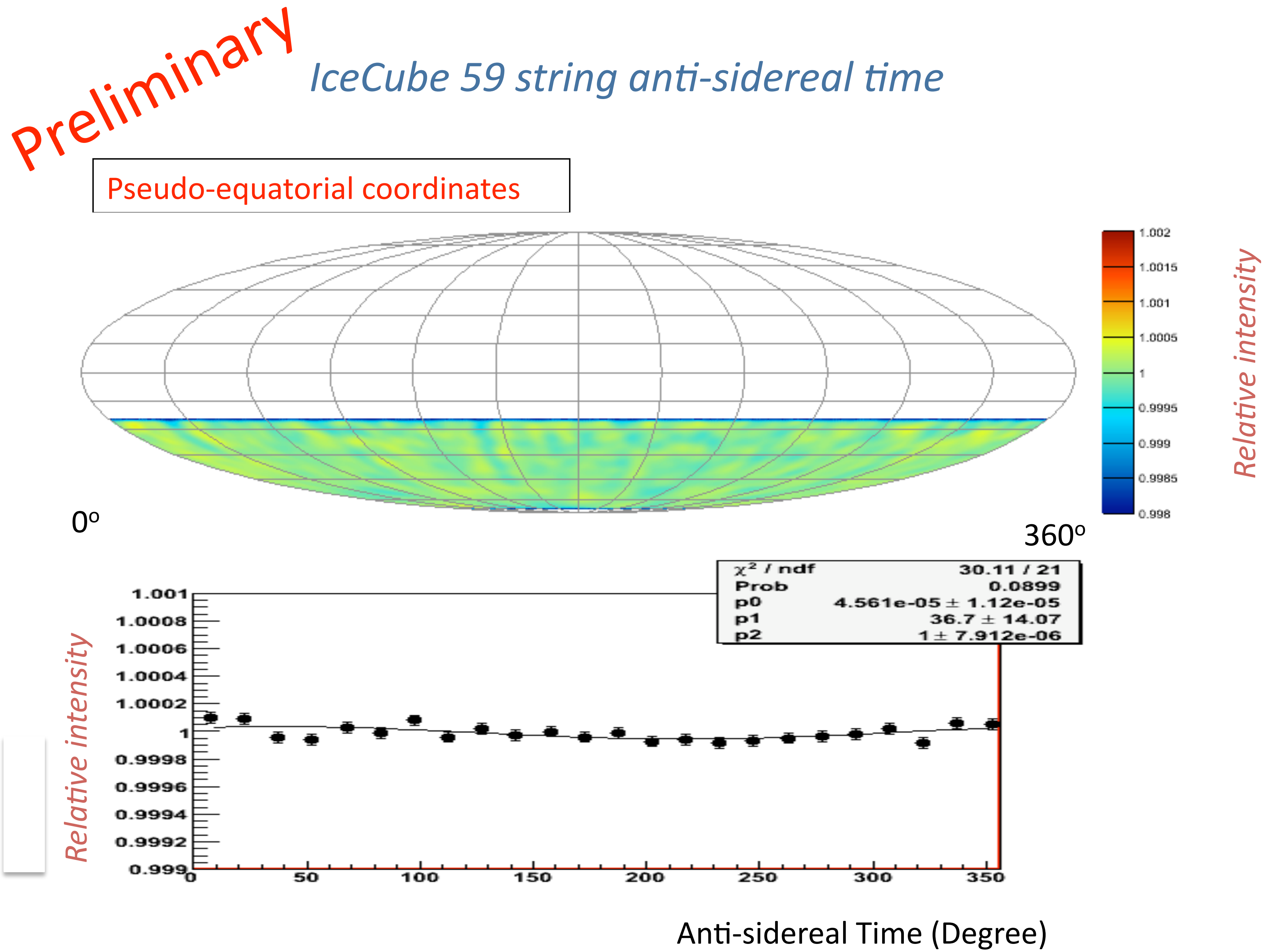
# *Systematic Check*

- As an important systematic check, we use *anti-sidereal time* to estimate the systematic error on the signal due to yearly-modulated daily variations.

- Anti-sidereal time is a nonphysical time frame created by flipping the sign in the transformation from universal time to sidereal time. No signal is expected in this time frame.



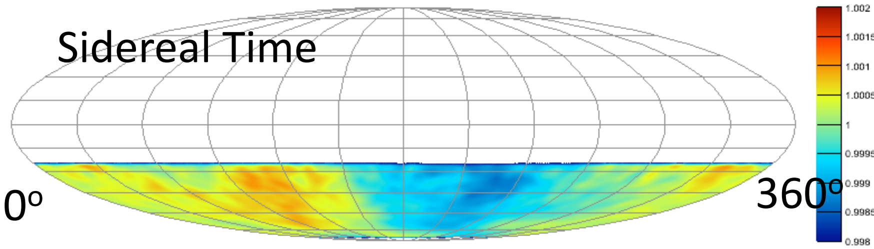
# IceCube 59 string anti-sidereal time

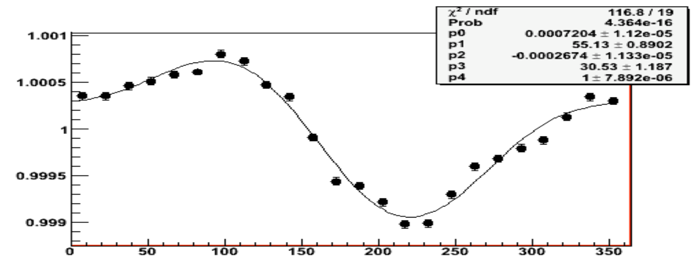


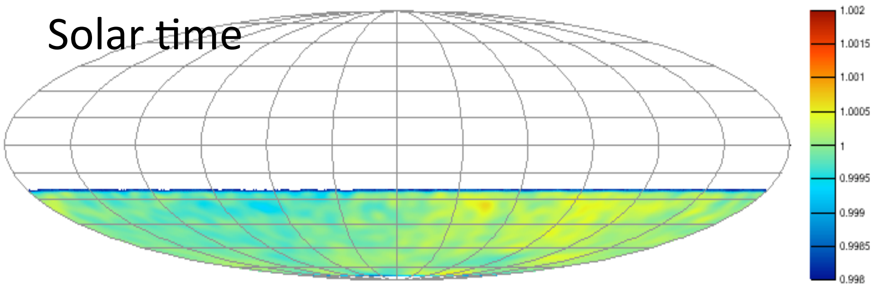
## *IceCube 59 cosmic ray skymaps in sidereal-solar-antisidereal time*

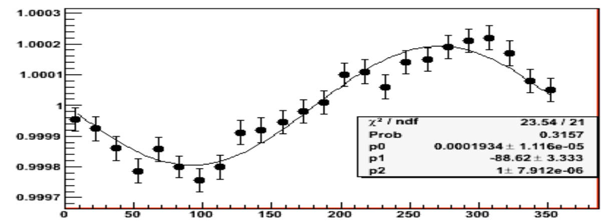
Preliminary

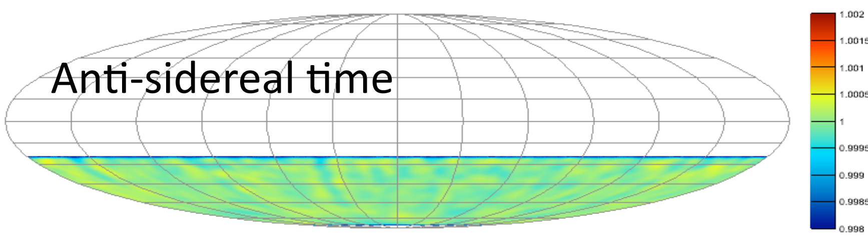
1-d projection

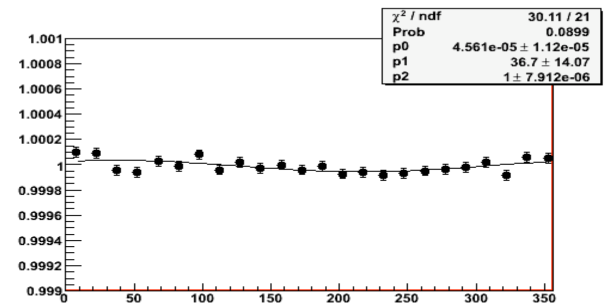



| A1 ($10^{-4}$) (sidereal) | Φ1(deg) (sidereal) | A1 ($10^{-4}$) (solar) | Φ1(deg) (solar) | A1($10^{-4}$) (anti-sidereal) | Φ1(deg) (anti-sidereal) |
|---|---|---|---|---|---|
| 7.2±0.1 | 55.1±0.89 | 1.7±0.1 | 90.9±3.6 | 0.45±0.11 | 36.7±14.1 |

Observation of the solar dipole effect and the absence of the anti-sidereal Signal insures the reliability of the observation.

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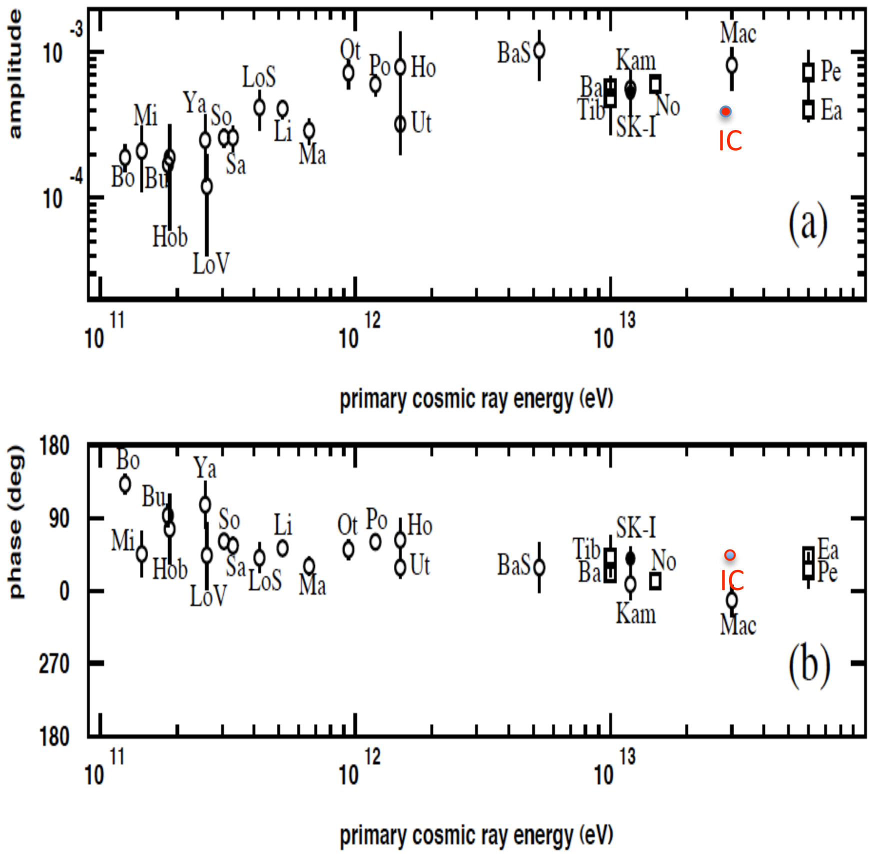
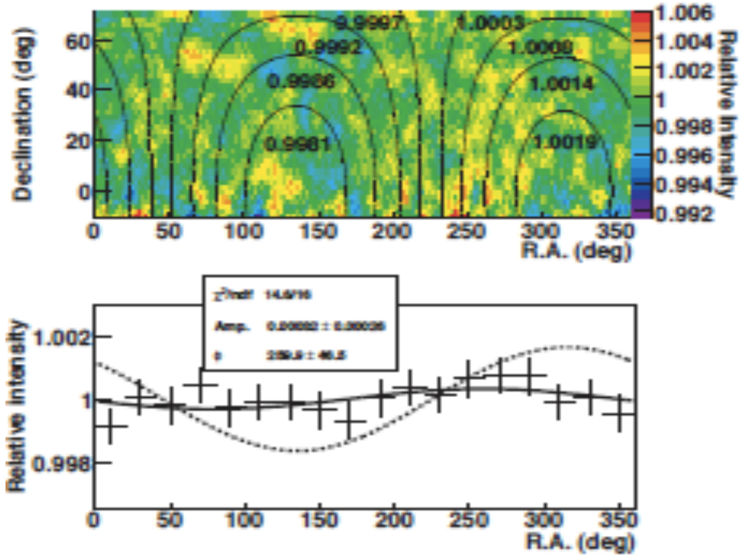
# Evolution of the cosmic ray anisotropy > $10^{14}$ eV




- The amplitude and the phase are well established <$10^{13}$ eV.
- Study of the anisotropy evolution in the energy region >$10^{14}$ eV can provide an insight to the origin and propagation of cosmic rays.

# Previous measurements at > $10^{14}$ eV

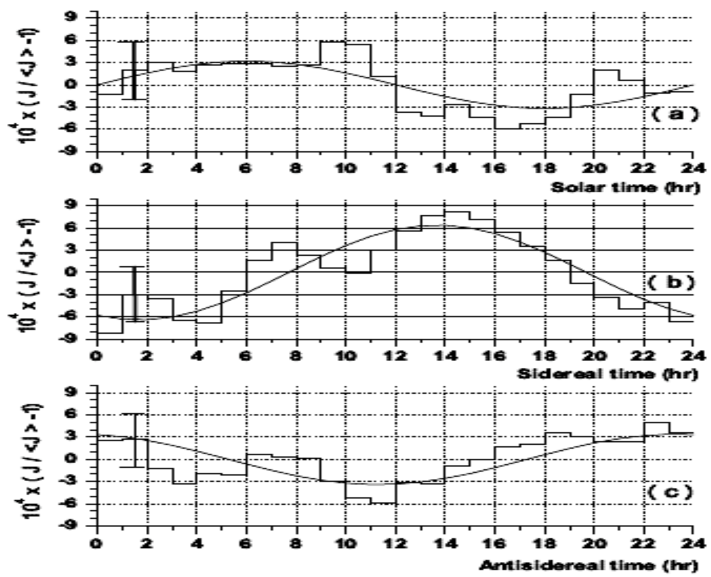
Tibet Array




Science314:439-443,2006

| Energy (TeV) | Amplitude($10^{-4}$) |
|---|---|
| 300 | 3.2±2.6 |

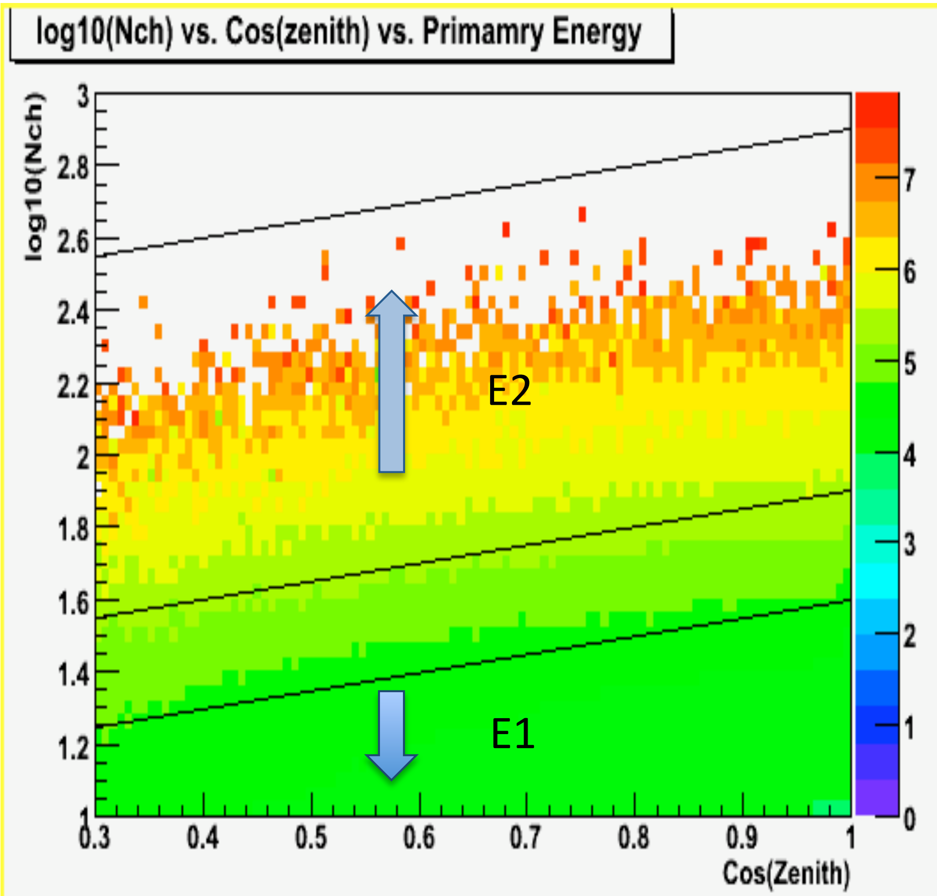
EAS-TOP

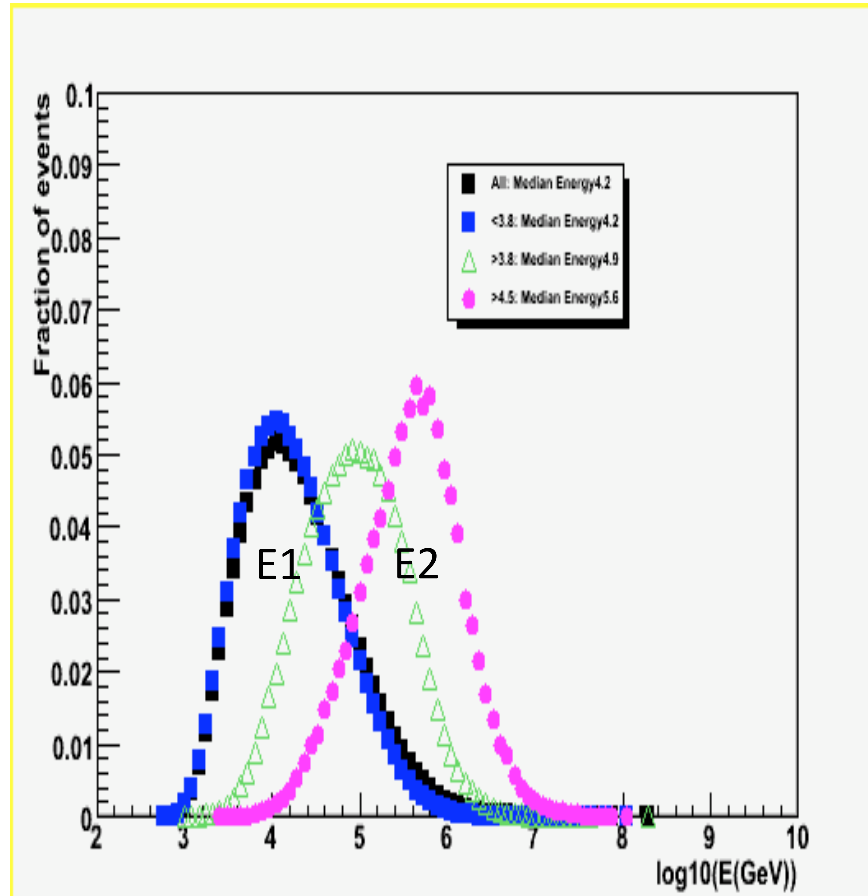



arXiv:0901.2740

| Energy (TeV) | Amplitude($10^{-4}$) |
|---|---|
| 370 | 6.4±2.5 |

# Event selection for the two primary energy regions

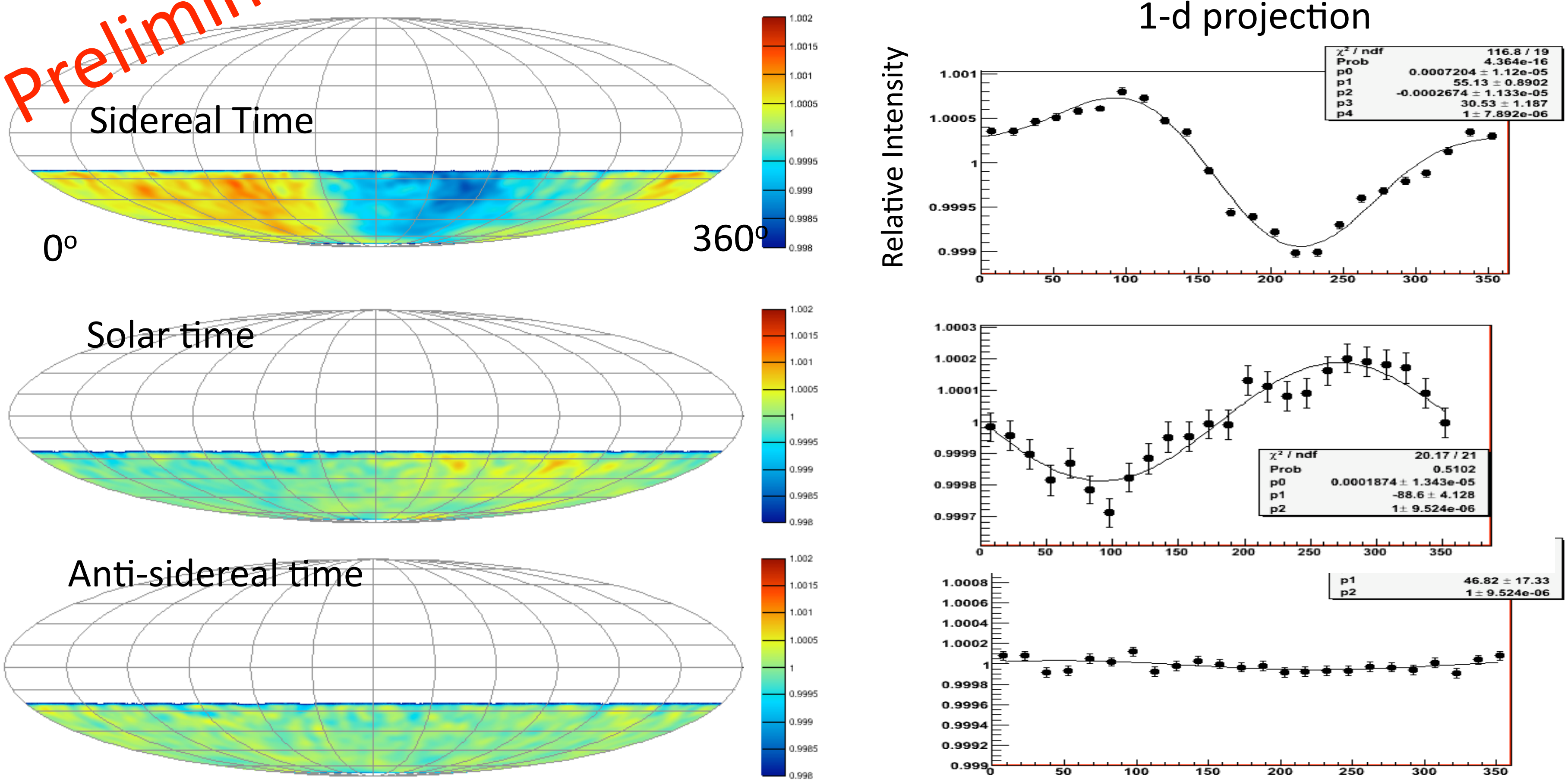



•Convert what is measured, Cherenkov light, to an estimate of the Muon energy.

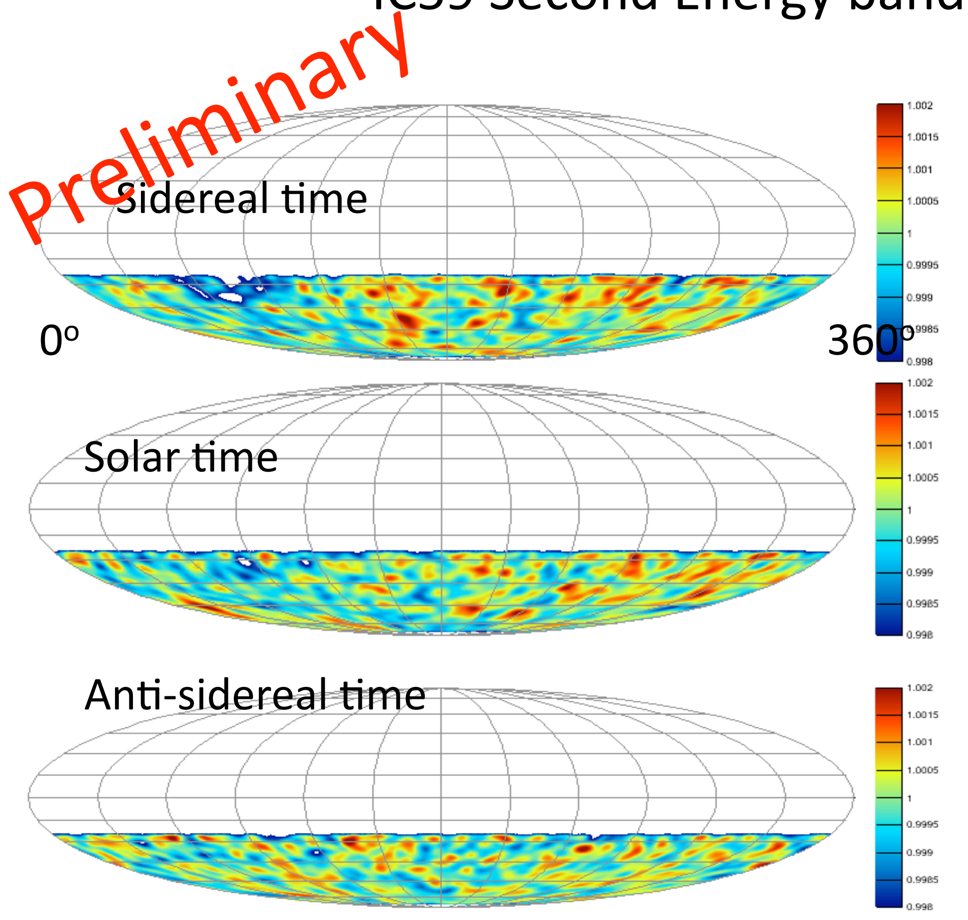
•Simplest estimation: **Number of Triggered Optical Modules (NCh)**

# IC59 First Energy band [Median Energy 19TeV]

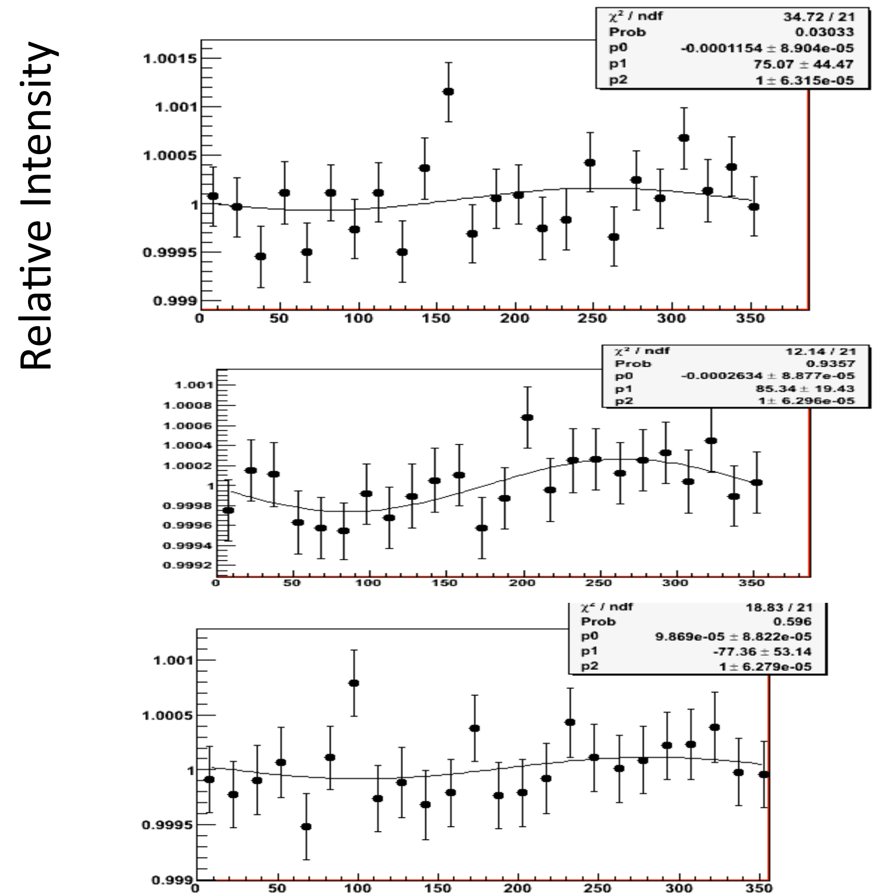



| A1 ($10^{-4}$) (sidereal) | Φ1(deg) (sidereal) | A1 ($10^{-4}$) (solar) | Φ1(deg) (solar) | A1($10^{-4}$) (anti-sidereal) | Φ1(deg) (anti-sidereal) |
|---|---|---|---|---|---|
| 8.1±0.13 | 54.6±0.9 | 1.7±0.1 | 89.5±4.4 | 0.44±0.1 | 46.8±17.3 |

# IC59 Second Energy band [Median Energy 400 TeV]




1-d projection [-42- - 72] in Declination




| A1 ($10^{-4}$) (sidereal) | Φ1(deg) (sidereal) | A1 ($10^{-4}$) (solar) | Φ1(deg) (solar) | A1($10^{-4}$) (anti-sidereal) | Φ1(deg) (anti-sidereal) |
|---|---|---|---|---|---|
| -1.1±0.89 | 75.1±44.5 | 2.7±0.88 | 81.47±18.7 | 0.98±0.88 | -77.3±53.14 |

# *Overview*

- Motivation
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# Compton-Getting Effect

- The motion of the solar system around the Galactic center through the rest frame of the cosmic ray plasma produces a dipole anisotropy with a maximum in the direction of motion.

- The effect is difficult to predict, as the isotropic cosmic ray rest frame is not known.

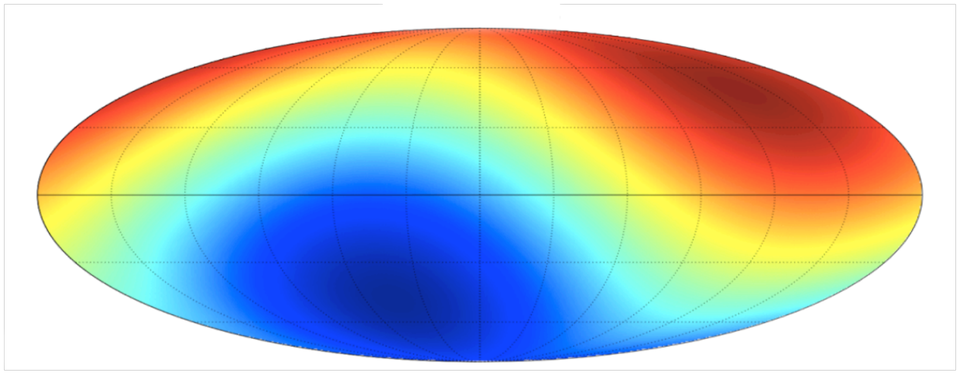
- If cosmic rays do *not* co-rotate with the Galaxy, the magnitude of the effect in relative intensity is

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

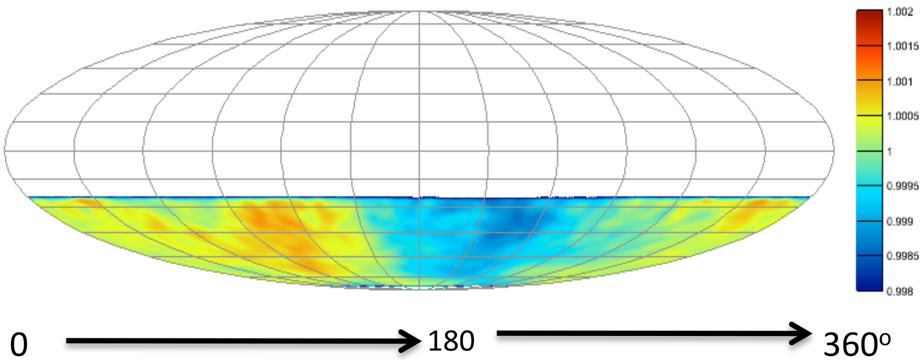
$$\gamma = 2.7 \quad \text{cosmic ray spectral index}$$
$$v = 220\ \text{km/s} \quad \text{speed}$$

- The maximum of the anisotropy is 0.35%, with a maximum at right ascension 315° and declination 48° and a minimum at right ascension 135° and declination - 48°.

# *Galactic Compton Getting*



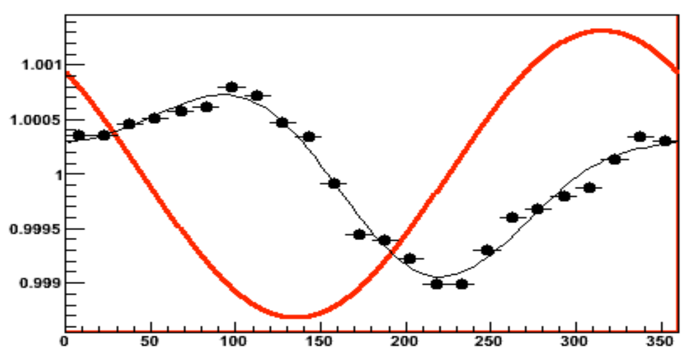
The maximum of the anisotropy is 0.35%, with a maximum at right ascension 315° and declination 48° and a minimum at right ascension 135° and declination - 48°.




$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

$\gamma = 2.7$ cosmic ray spectral index

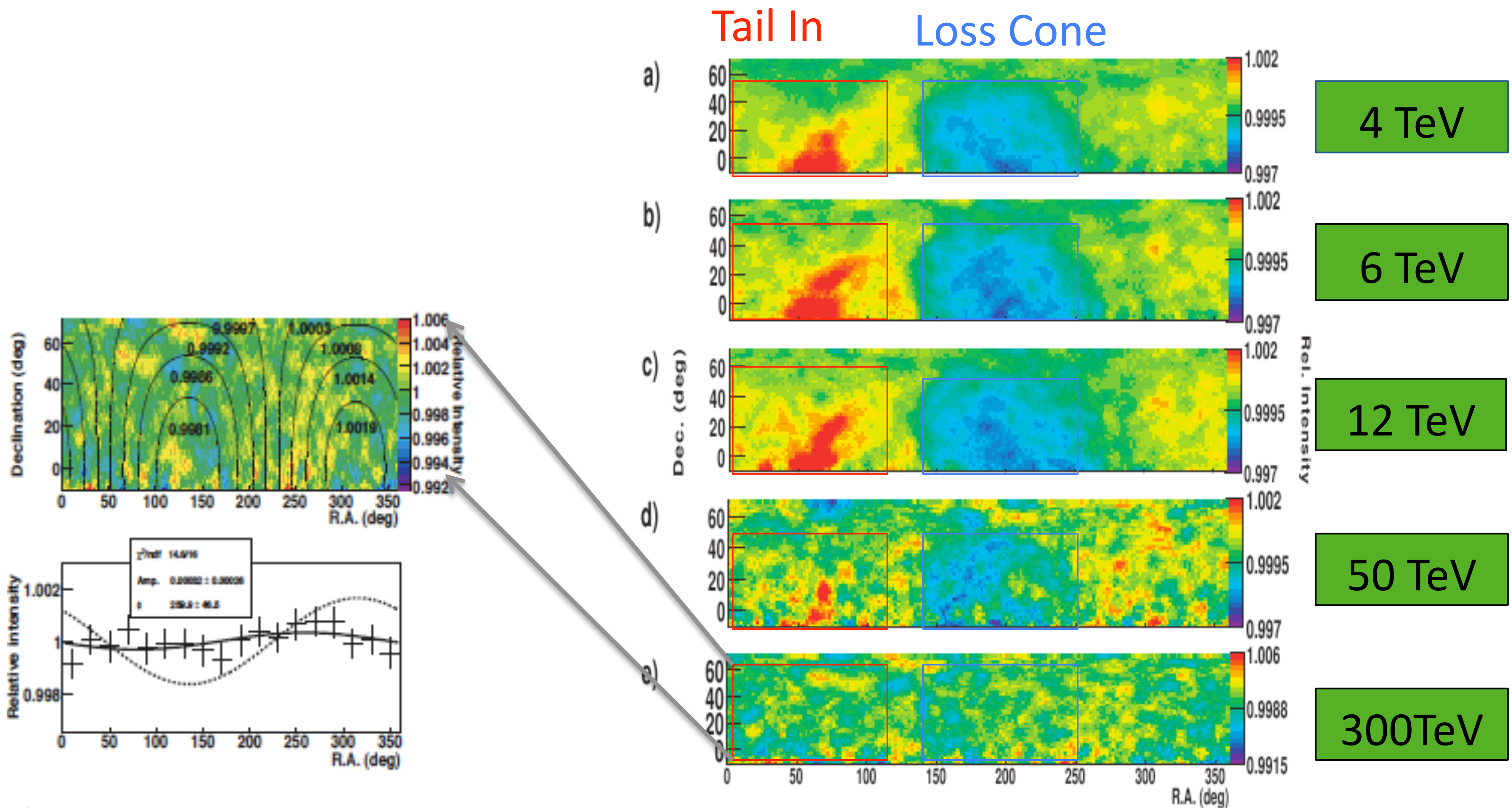
$v = 220$ km/s speed




The anisotropy in IceCube data is *not a pure dipole* and does not have the right phase to be explained by the Compton-Getting effect. If the Compton-Getting effect is present in the data, it is overshadowed by a stronger effect.

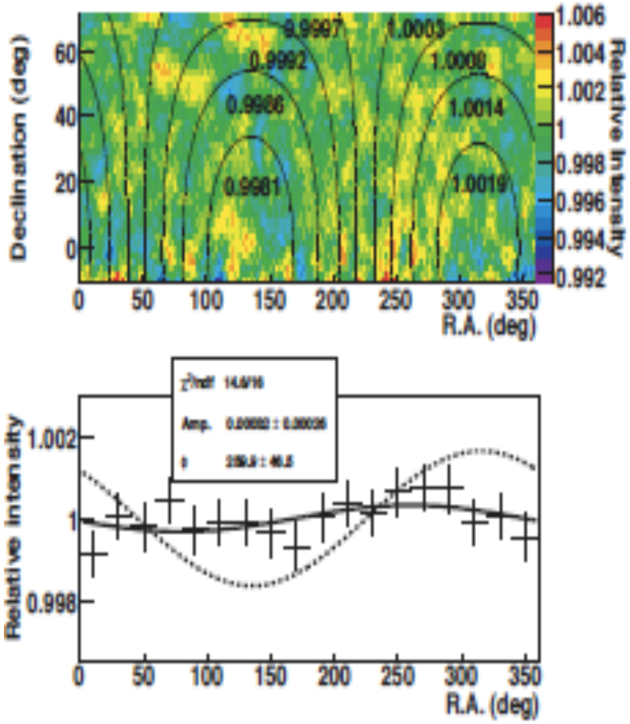
# *Tibet Array*

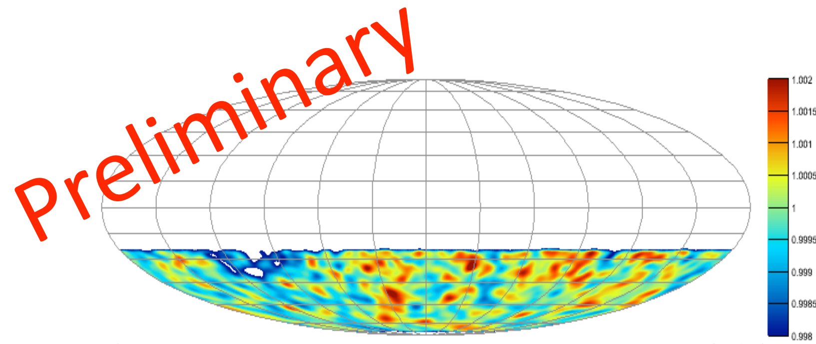
Science Vol. 314. no. 5798, pp. 439 - 443



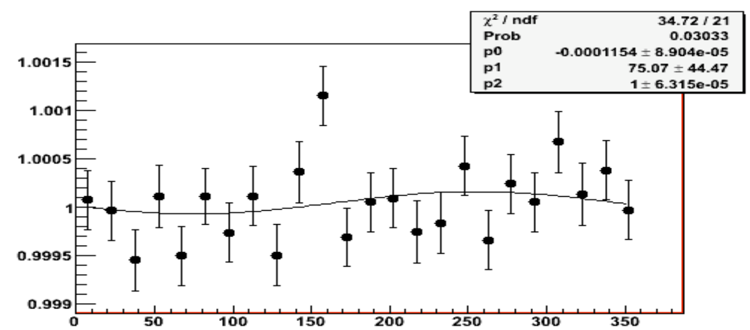
# IC59 and Tibet Array Comparison

Science Vol. 314. no. 5798, pp. 439 - 443



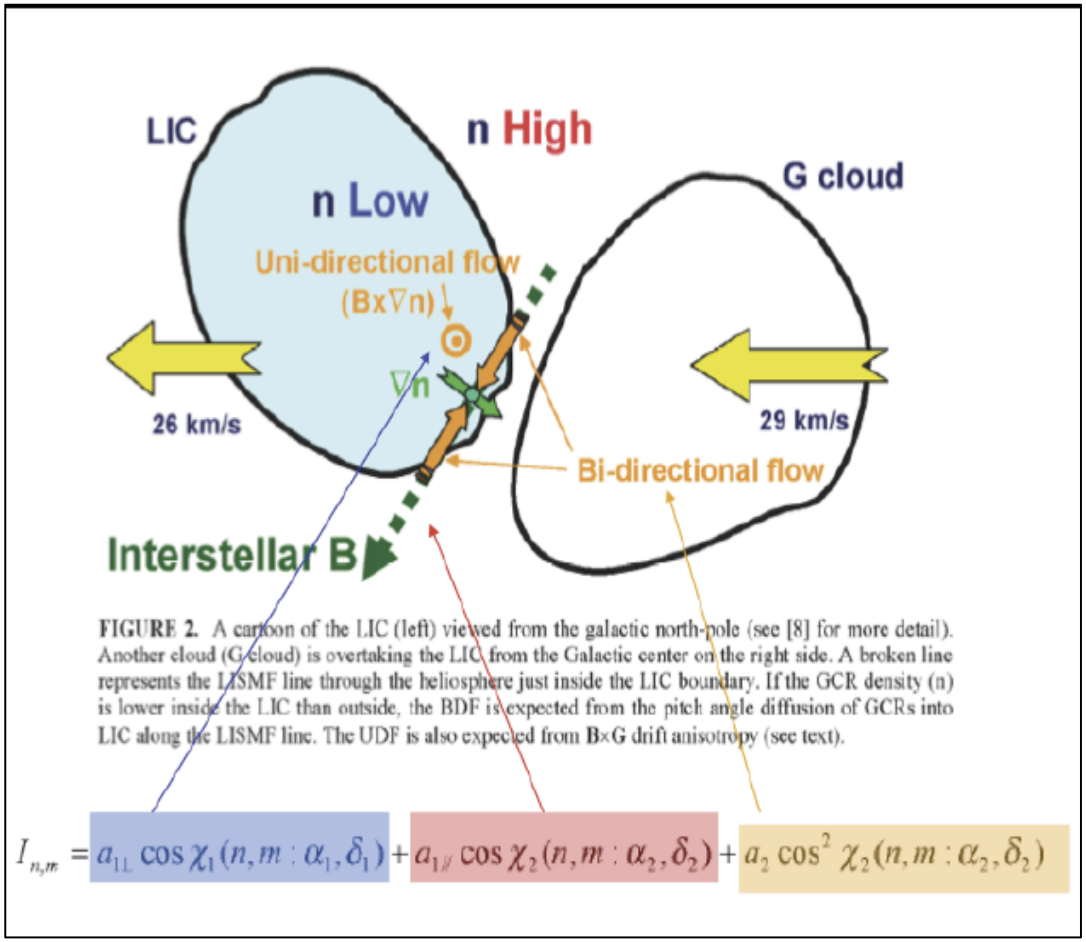

0º 360º

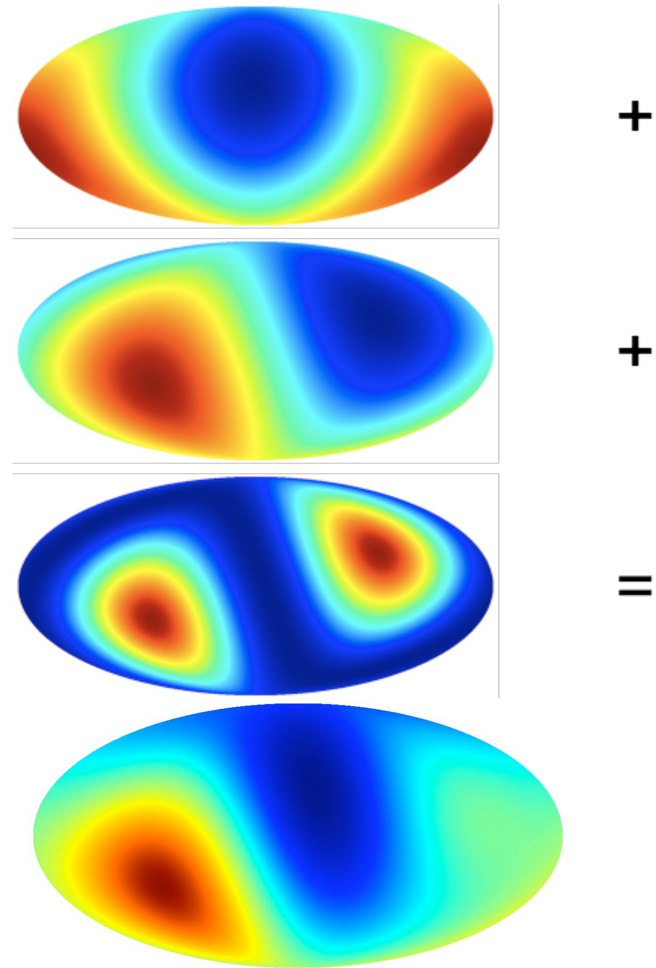



300TeV

400TeV

# Local Interstellar Magnetic Field



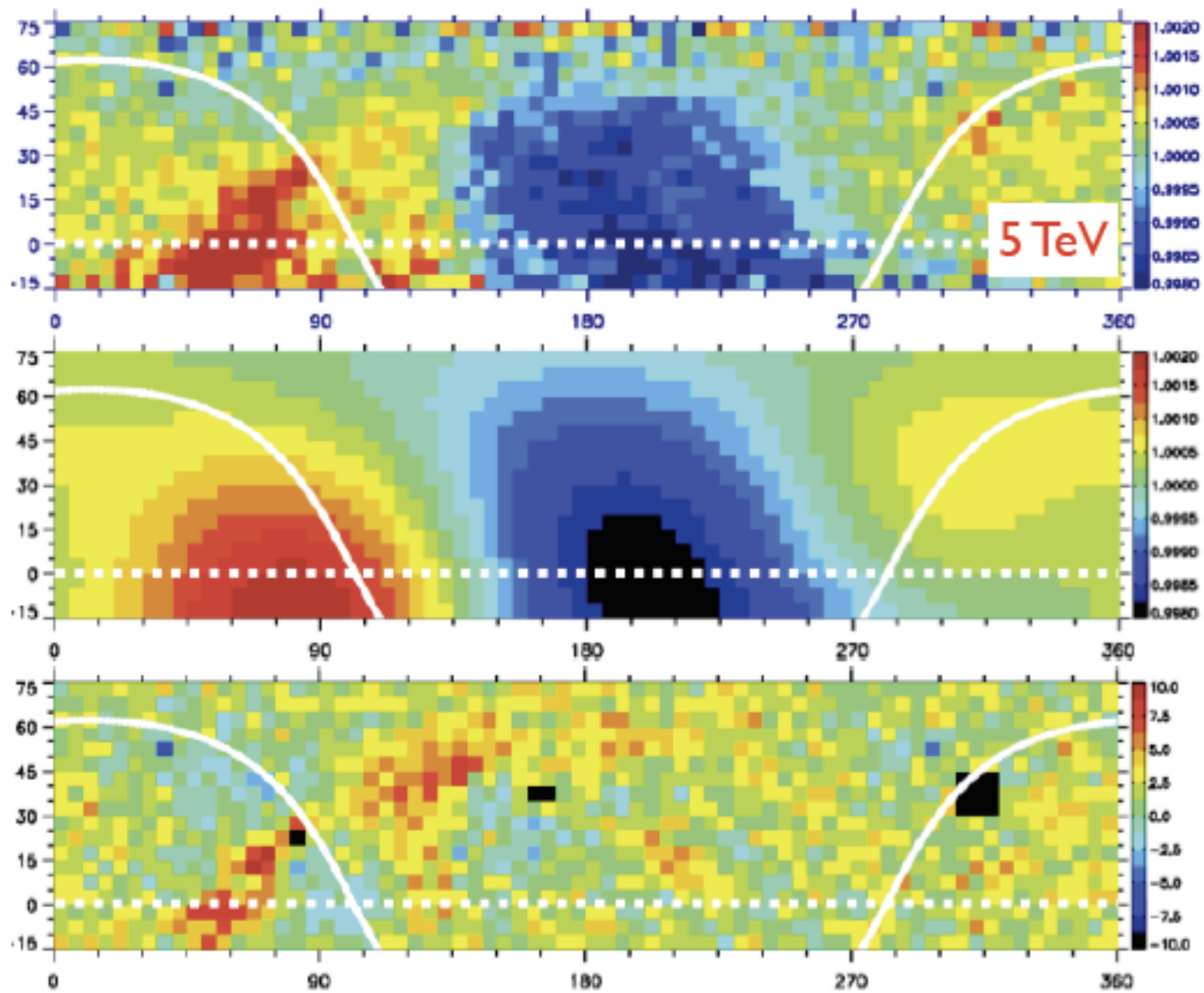

M. Amenomori *et. al*. ICRC 2007 Proceedings

# Tibet Array Model Fit to Data

Data

Model

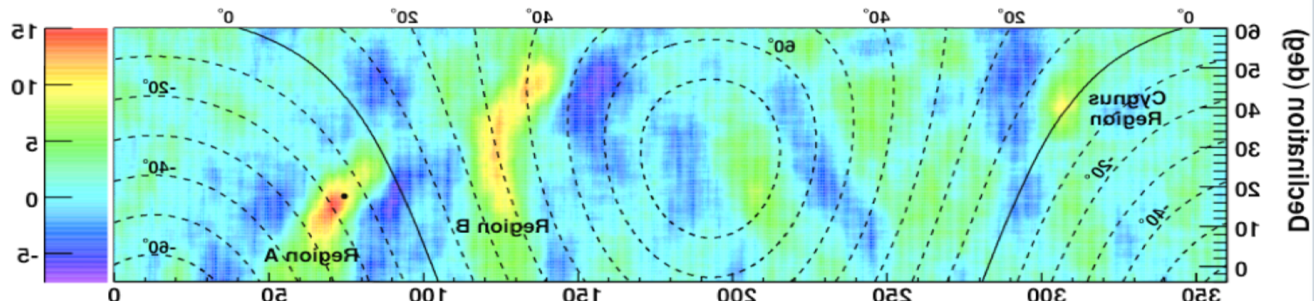
Residual skymap




M. Amenomori *et. al*. ICRC 2007 Proceedings

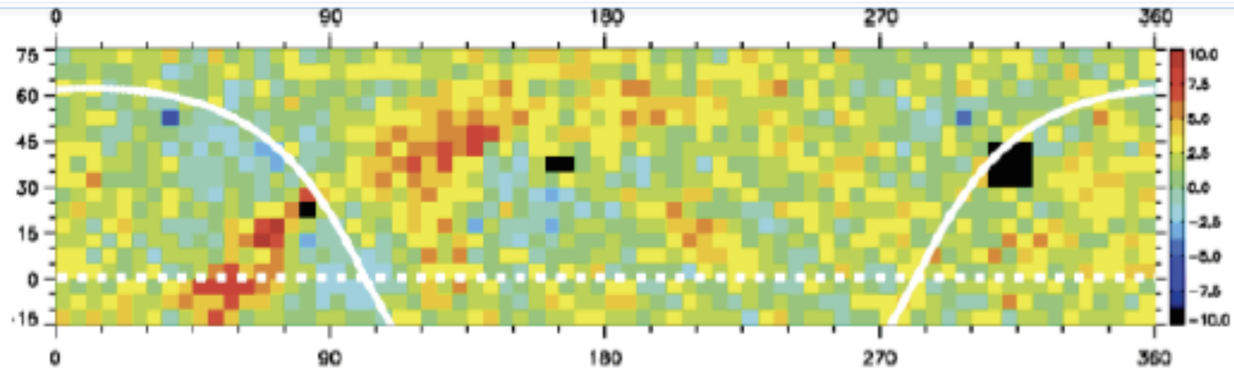
# *Localized Excess in Cosmic Rays*

Milagro
[1 TeV]



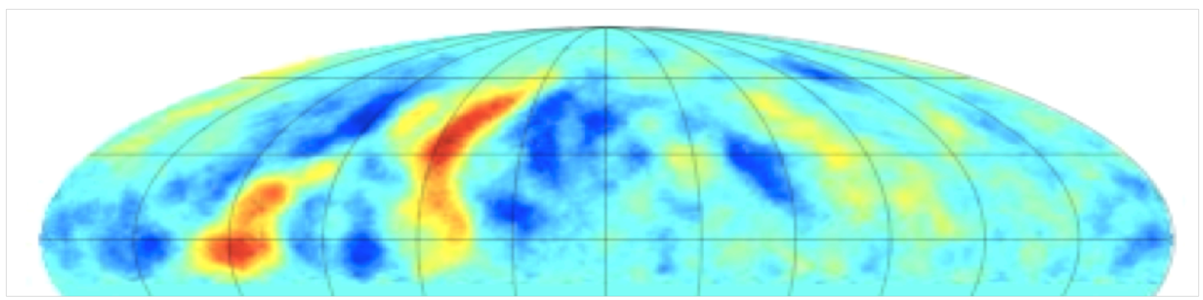
Abdo *et. Al.* Arxiv:0801.3827

Tibet Array
[5 TeV]




M. Amenomori *et. al.* ICRC 2007 Proceedings

Argo
[2 TeV]



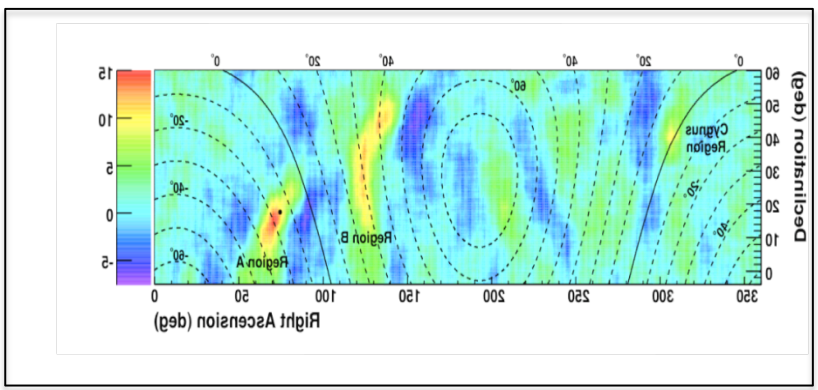
0 S. Vernetto *et. al.* ICRC 2009 Proceedings 360

# Medium Scale Anisotropy

# *Medium/Small Scale Anisotropy*

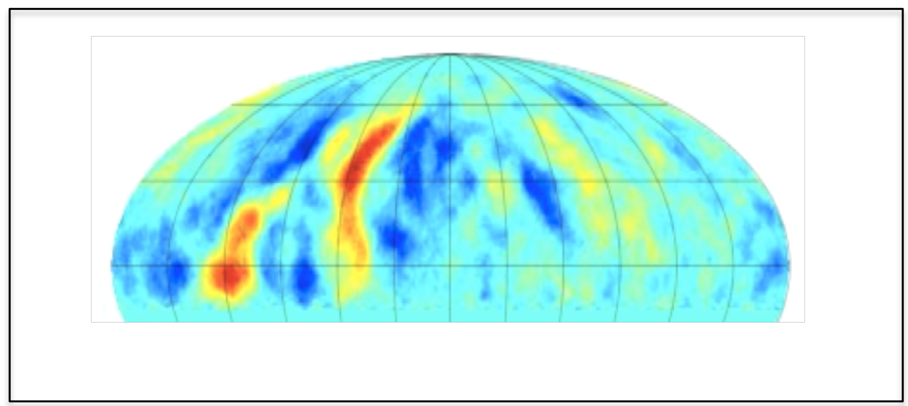
- Milagro observed two localized regions.
- **data set of 2.2 $10^{11}$ events**.
- The "hot" regions have
  - **significance > 10 σ** with a sensitivity to features with an extents smaller than 30°
  - Fractional Excess of region A ~$6\times10^{-4}$, region B~$4\times10^{-4}$ relative to the background.
- Argo also observes the two localized regions.
- Searching for similar structures in the southern sky.

Milagro




Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

Argo



Proceedings from the 31st the ICRC in Lodz

# *IceCube can search for similar structures in the southern sky*

- To produce a skymap of the southern sky, we adopt a method commonly used in large field-of-view gamma ray detectors.
- A signal map is made based on the arrival direction of each event, and a background map is created from the data itself.

$$N_{\exp}(ra,\delta) = \iint E(ha,\delta)\ R(t)\ \varepsilon(ha,ra,t)\ \ dt\ d\Omega$$

$E$ probability that an event comes from angular element $d\Omega$

$R$ event rate (as a function of time $t$)

$\varepsilon$ 1 if event is in $ra$ and $\delta$ bin under consideration, 0 otherwise

- This equation can be integrated "numerically" by randomly assigning detected event times with local arrival directions. This procedure compensates for any event rate variations and ensures that the background events have the same arrival direction distribution in local coordinates as the data.

- Significances are calculated using the method of Li&Ma.

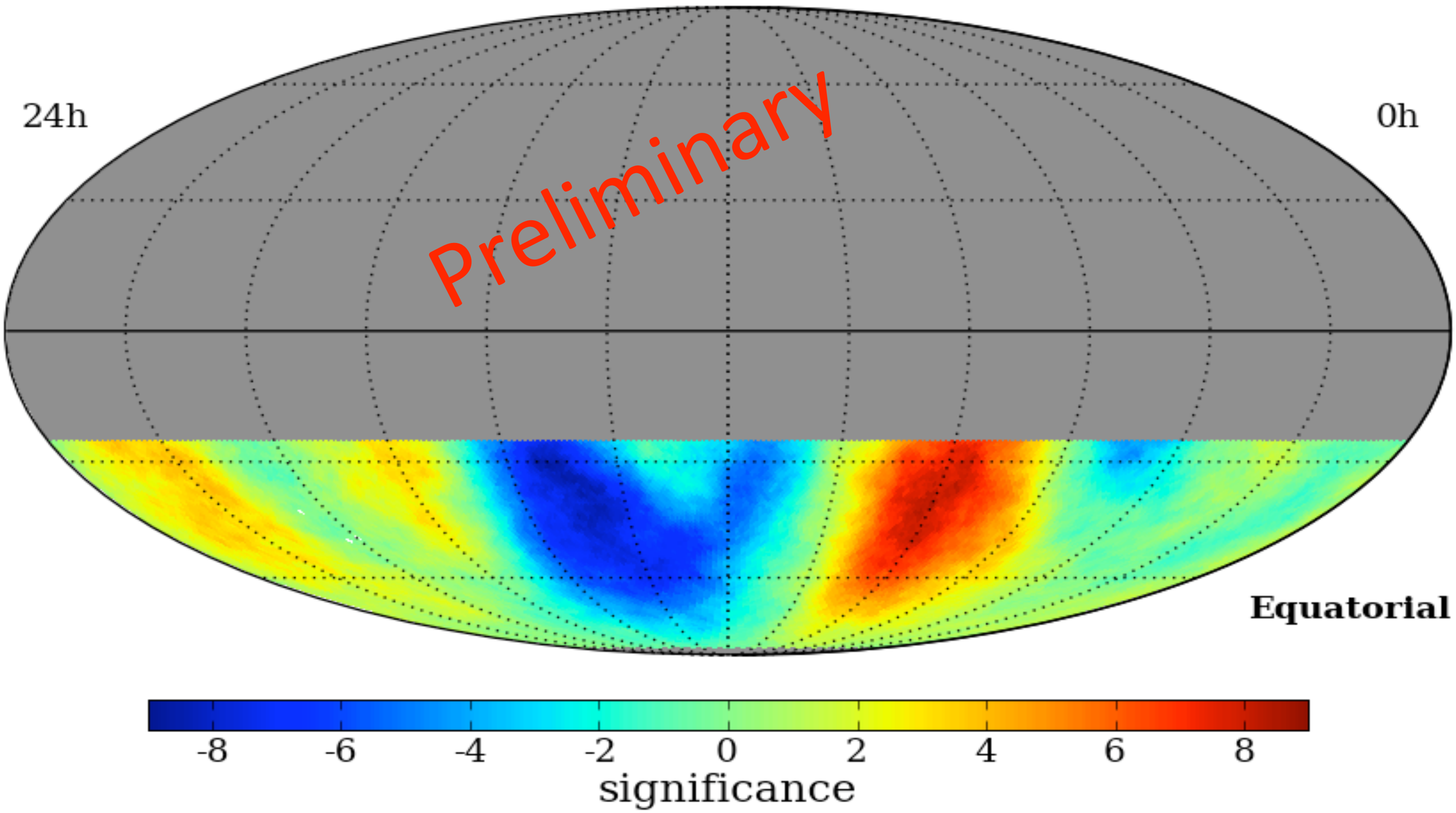
## *Searching for medium scale structures in the southern sky.*

- The length of the time interval used for the background estimate determines the maximum size of features we are sensitive to. For example, with 4 hour integration time, we are insensitive to features of more than around 60°.

- For maximum sensitivity signal and background maps are smoothed on scales that correspond to the feature size.

- Testing several smoothing angles introduces trial factors, but we can use the IC22/IC40 data sets to find optimal parameters. These are then a priori parameters for IC59 analysis (remember that IC59 is already recorded!).

# IceCube-59 cosmic ray skymap (4h scrambling, 20$^o$ smoothing)



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# *Conclusion and Summary*

- IceCube construction is now completed
- First skymap reporting a significant large scale anisotropy in the southern hemisphere sky at 20 TeV.
- The anisotropy is in remarkable agreement with previous measurements in the northern hemisphere.
- The result is also consistent across IC22-IC40 and IC59.
- The result is supported by the observation of solar dipole effect together with the absence of the anti-sidereal signal.
- No significant anisotropy is observed at higher energies (around 400 TeV).
- The result is not consistent with the modulation expected from  Galactic Compton Getting.