Observation of Structure in the Arrival Directions of Cosmic Rays at TeV with IceCube

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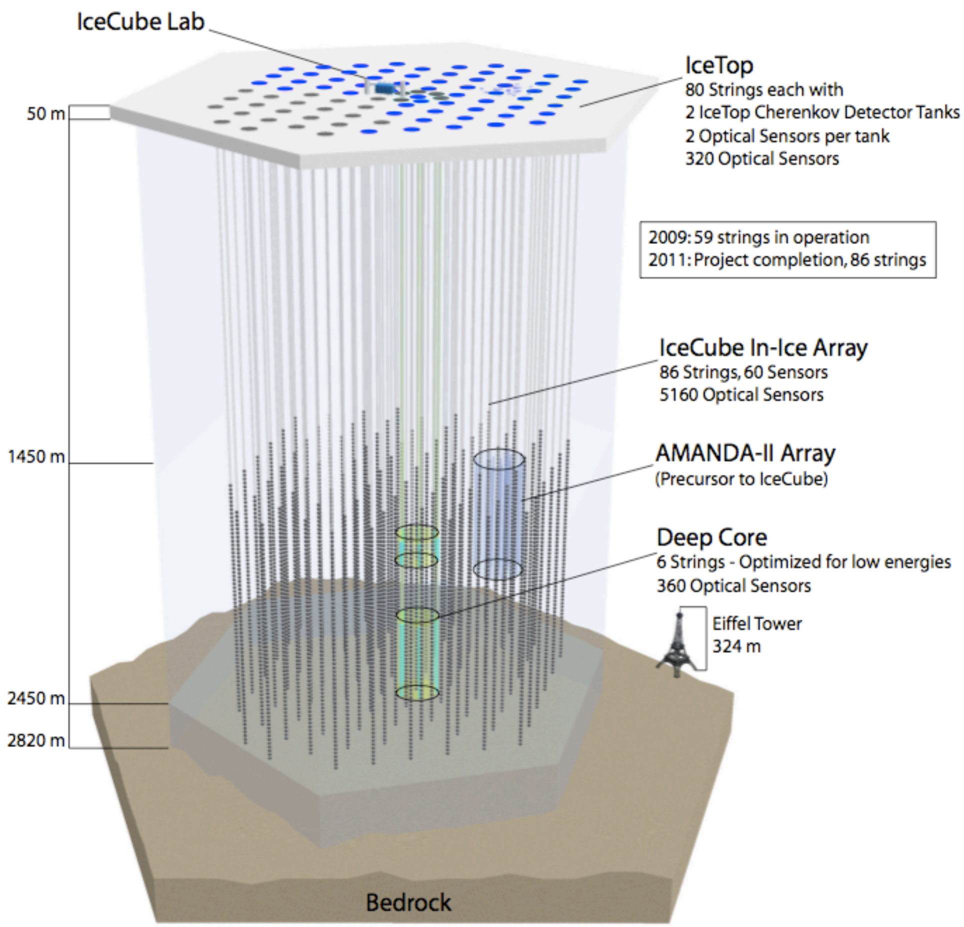
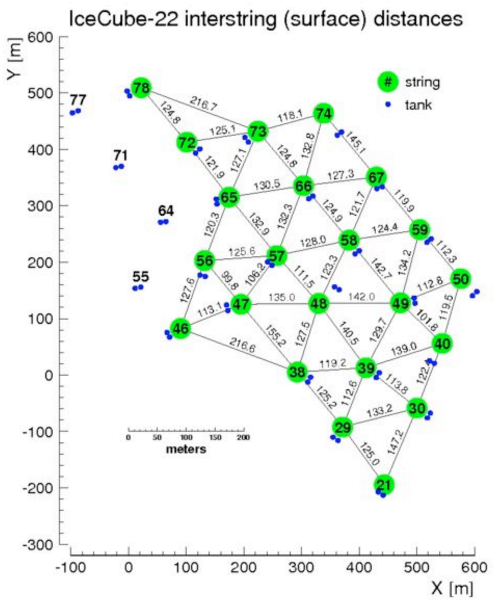
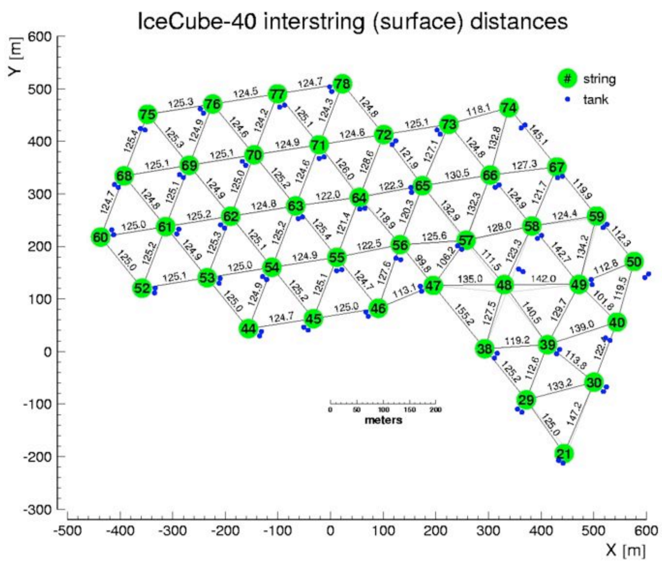
Downgoing Muons in IceCube



- Muons produced in air showers are detected in IceCube. Event rate is 1.4 kHz (IceCube 59)
- Events are reconstructed using an online likelihood fit
- Data stored in DST files:
  - Arrival directions
  - Event times
  - Number of hits
- Median primary energy: 20 TeV
- Median angular resolution: 3° (not optimized for point sources)

Available Datasets





- IceCube 22 (2008)
  - Live time: 226 days
  - Rate (after likelihood reconstruction): 240 Hz
  - 4.3×10^9 events after quality cuts

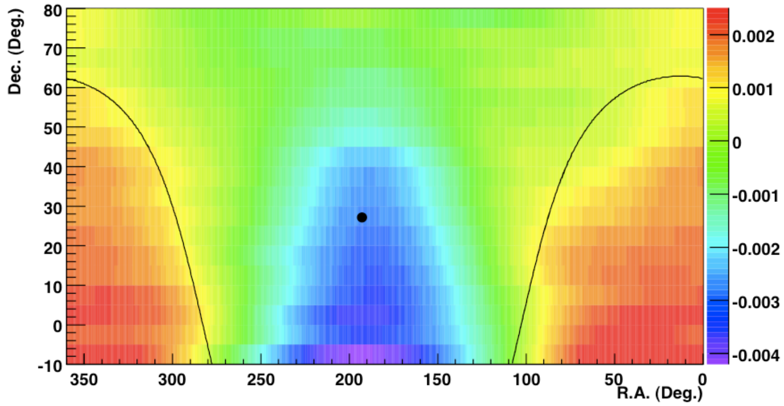
- IceCube 40 (2009)
  - Live time: 324 days
  - Event rate: 760 Hz
  - 15.0×10^9 events after quality cuts

Large Scale Anisotropies

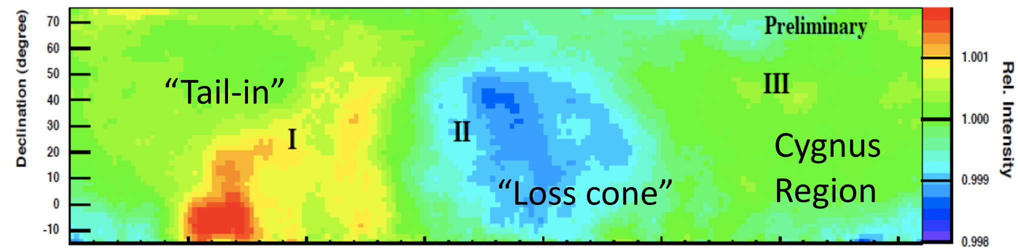
(> 40° in right ascension)

Large Scale Anisotropies

Milagro



ARGO-YBJ



- Cosmic ray showers observed in IceCube are about 1 to 100 TeV in energy

- An arrival direction anisotropy in charged cosmic rays is not expected at these energies due to interactions with the galactic magnetic field. Predicted Larmor radius: 0.1 pc

- Nevertheless, there have been several observations of large-scale, part-per-mille anisotropies in cosmic ray arrival directions between 0.1 and 100 TeV. For example,
  - Tibet: M. Amenomori *et al.*, Science **314** (2006) 439 - 443
  - Milagro: A. Abdo *et al.*, ApJ **698** (2009) 2121 - 2130

Large Scale Anisotropies

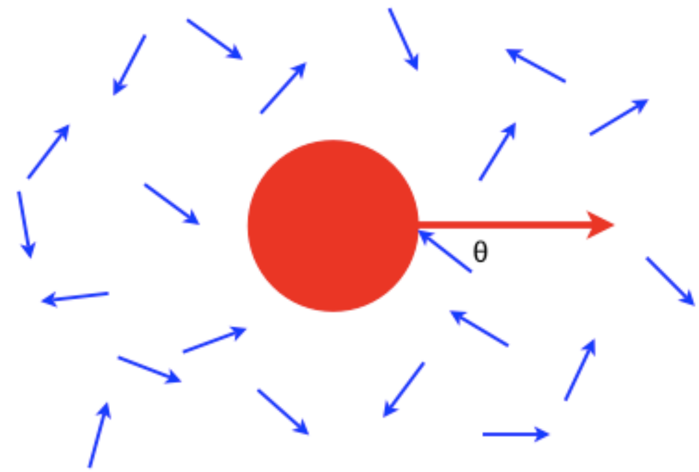
- Large scale anisotropy might be produced in several ways:
  - The motion of the Earth
  - Large scale or local magnetic field configurations
  - The heliosphere (up to about 1 TeV)
  - Discrete diffuse cosmic ray sources (at higher energies)

- IceCube is the first detector able to measure TeV anisotropies from the southern hemisphere

- IceCube records $>10^{10}$ cosmic ray events per year, so 10^{-4} anisotropies are certainly accessible

Dipole Anisotropies due to Earth's Motion

- Dipole anisotropies can be created by the motion of the Earth through the "rest frame" of cosmic rays:
  - Excess along direction of motion
  - Deficit away from direction of motion

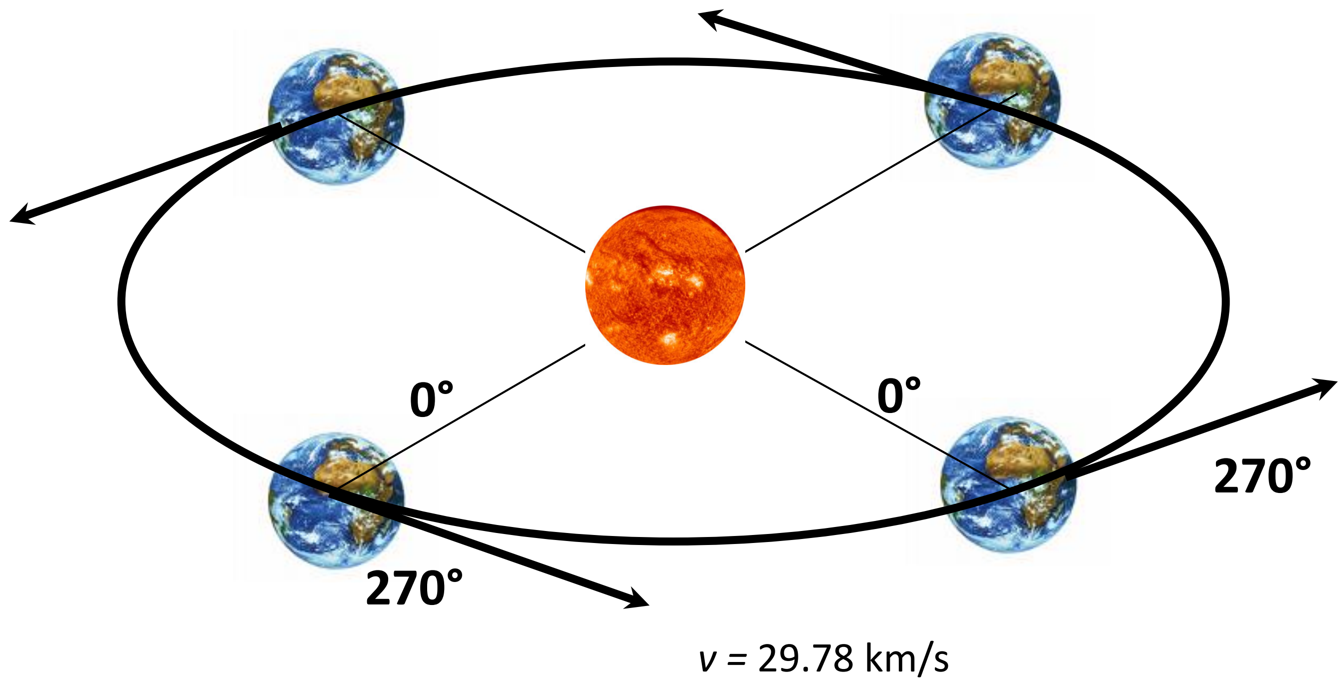


- The Earth's motion through space is a superposition of several motions, and so several dipole anisotropies have been postulated:

1) Solar dipole anisotropy due to Earth's motion about the sun (observed by Milagro, Tibet AS-γ, and IceCube)
2) Compton-Getting Effect due to solar system motion about the galactic center

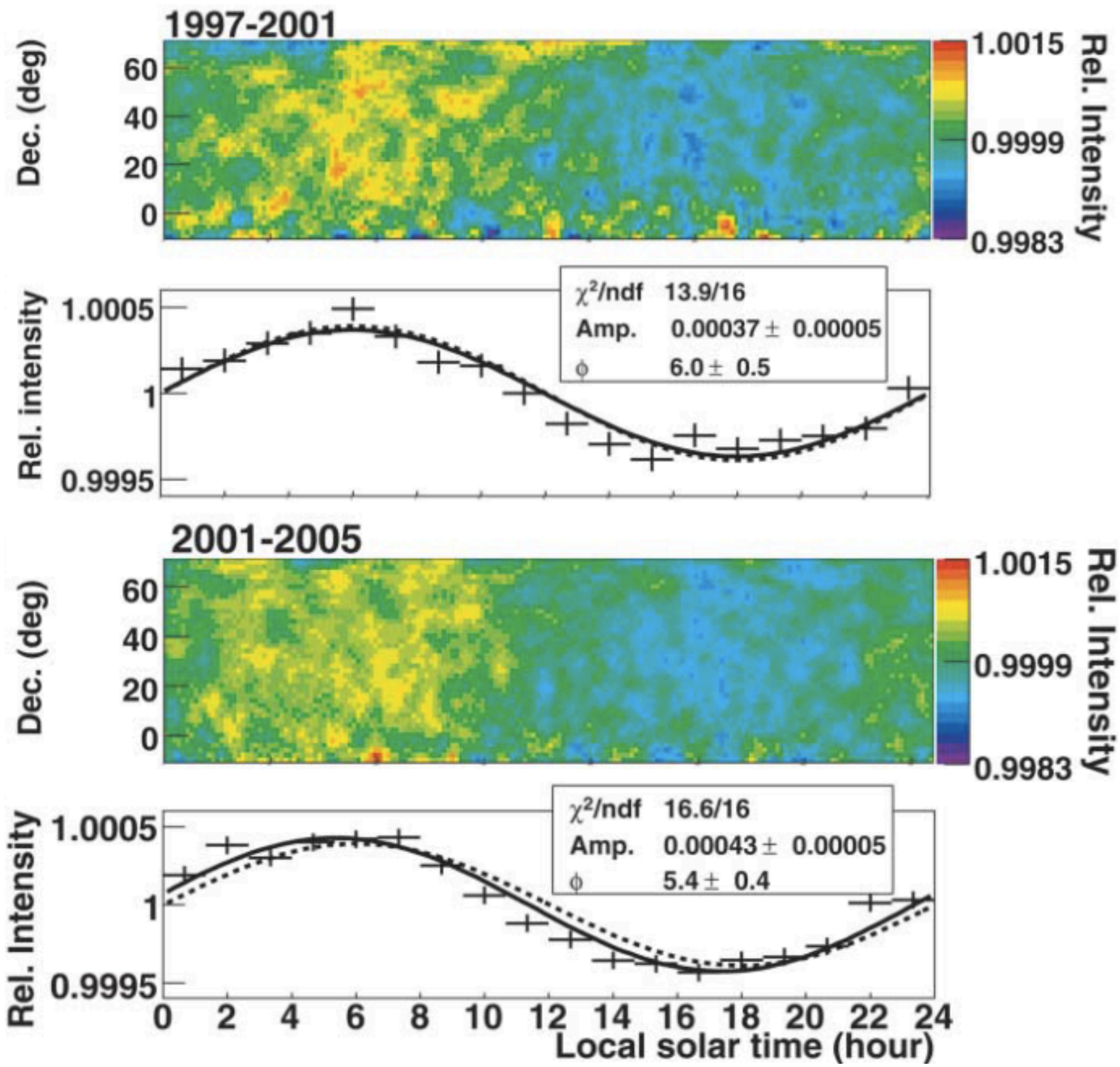
Solar Motion Dipole

- The effect caused by Earth's motion about the sun is visible when the arrival directions are plotted in a frame where universal time (UT) is used to calculate the sky coordinates



- The expected anisotropy is of order 10^{-4}, based on the orbital velocity of the Earth

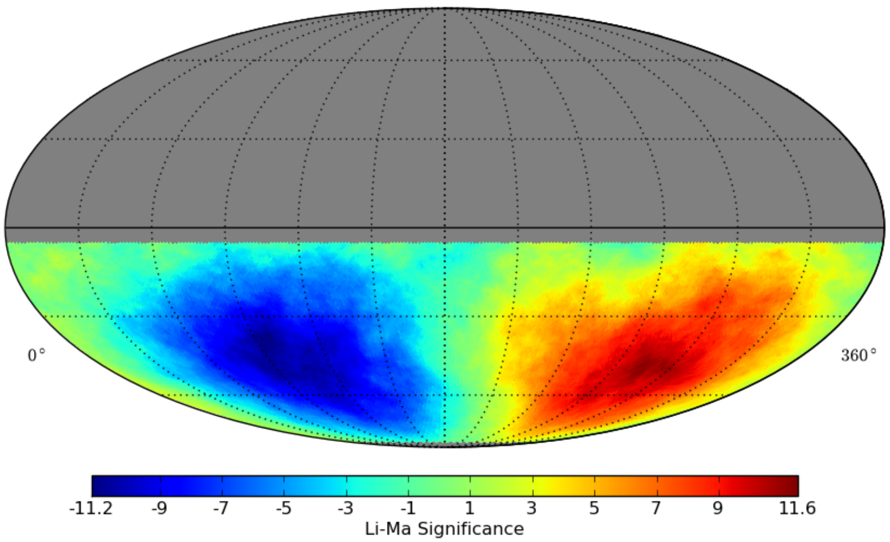
Solar Dipole: Northern Hemisphere

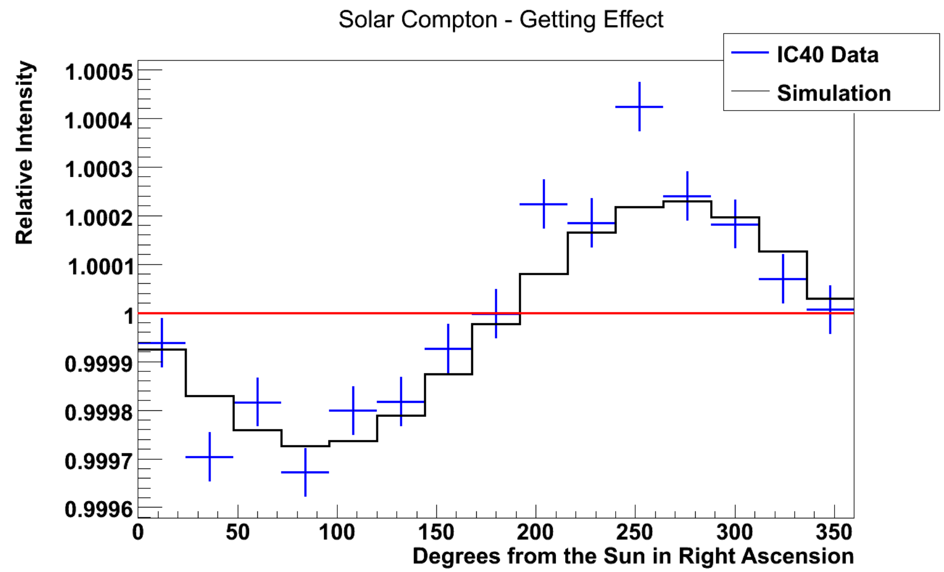


From M. Amenomori *et al.*, Science **314** (2006) 439 - 443

Solar Dipole: Southern Hemisphere

- IC40 data: solar motion dipole is observed with the expected strength

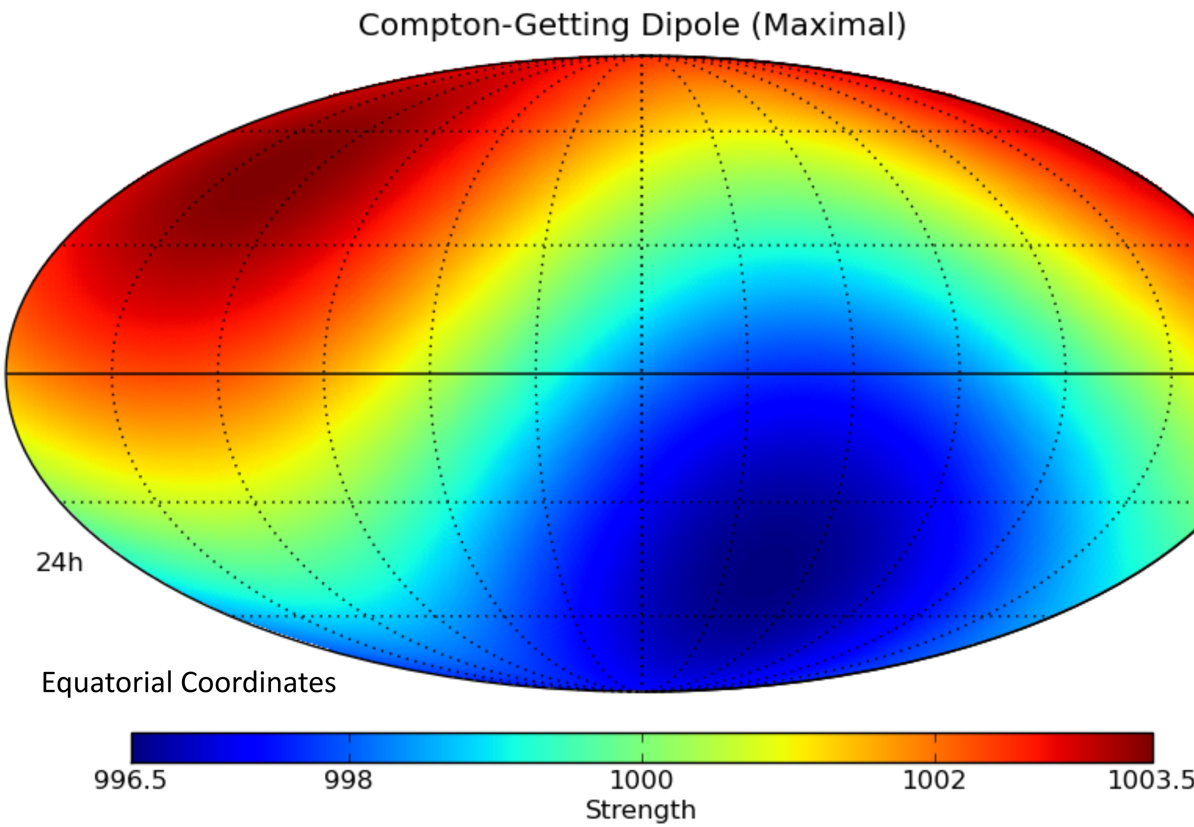




- Note: this skymap was created in UT and is plotted in degrees from the sun, not in equatorial coordinates.
- Note: over the course of one year, the solar motion effect will be washed out in sidereal time

Compton-Getting Dipole

- If galactic CRs do not co-rotate with us about the galactic center, the galactic motion of the solar system create a dipole anisotropy in equatorial coordinates



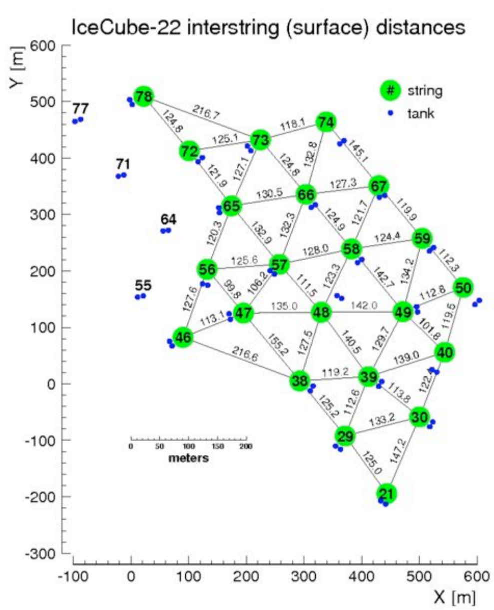
$$\frac{I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos\theta$$

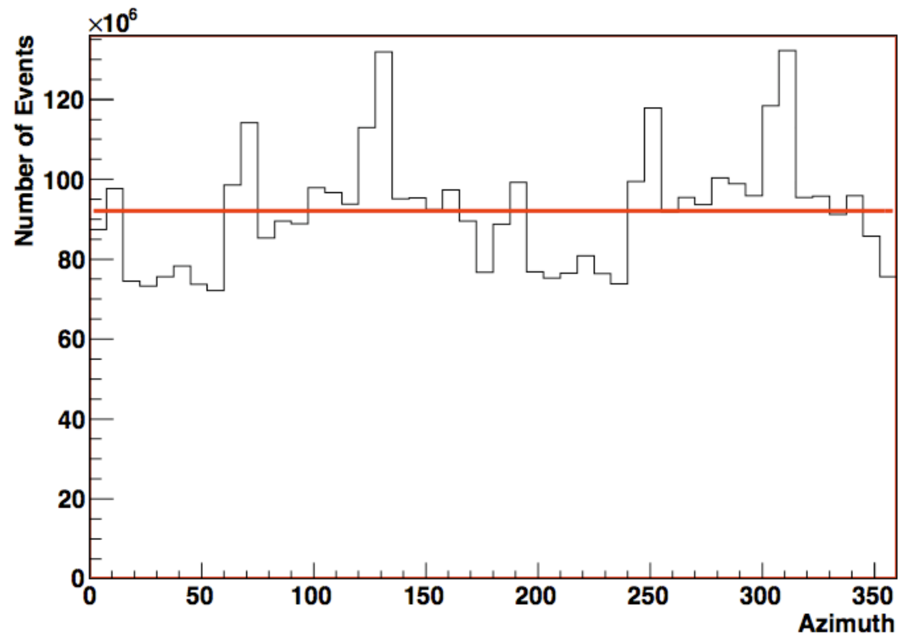
$$\gamma = 2.7 \text{ (spectral index)}$$

$$v = 220 \text{ km s}^{-1}$$

- Motion of cosmic ray plasma is not known… but assuming cosmic rays are at rest w.r.t. the galactic center, we should observe a dipole of 0.35%, inclined relative to the equatorial plane

Harmonic Analysis



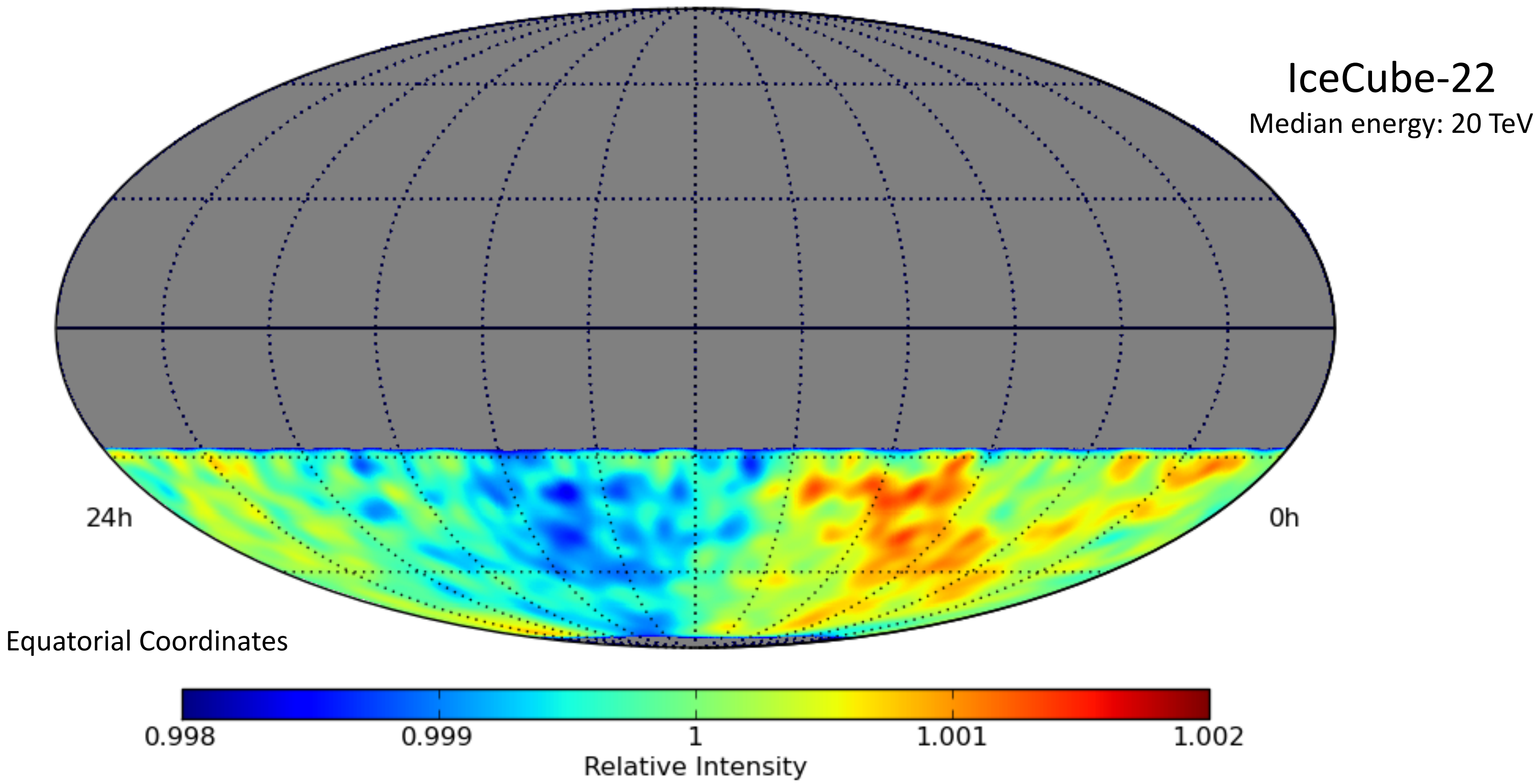


- Anisotropies like the Compton-Getting dipole are identified by fitting harmonics to the event distribution in right ascension.

- We want to find 10^{-4} effects in the presence of:
  - ~~Diurnal~~ and seasonal variations in atmospheric conditions
  - Asymmetries in the detector geometry (see plot)
  - Gaps in the data due to quality cuts and non-uniformities in the uptime

IC22 Harmonic Analysis

- IC22: relative intensity in 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 in the belt

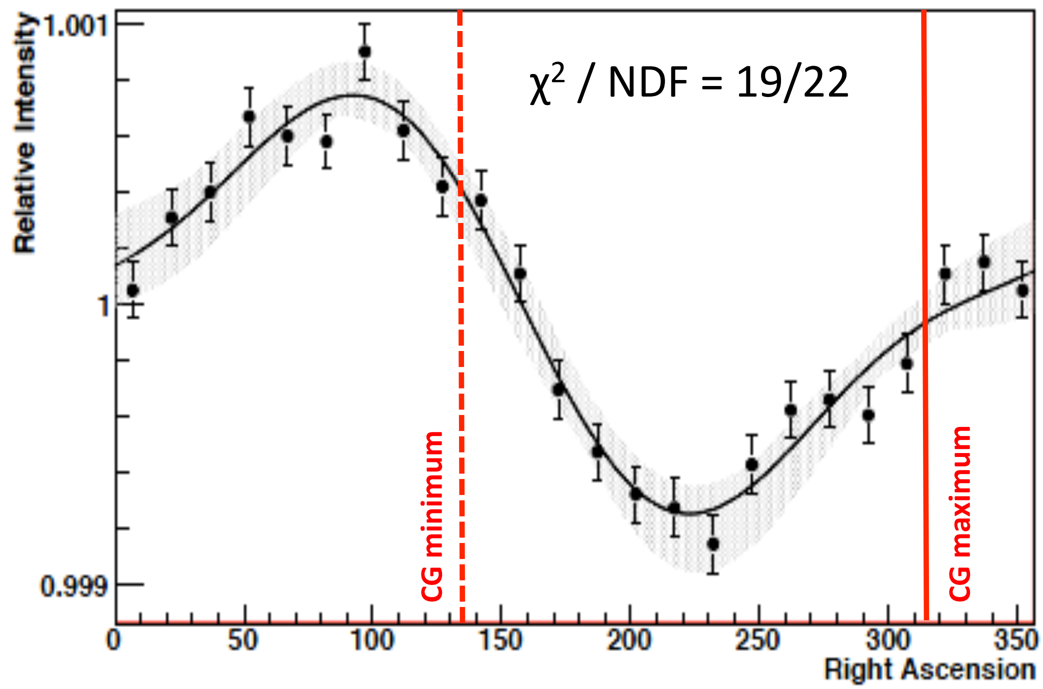
IC22 Harmonic Analysis

- Fit the RA distribution with the function

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

- From R. Abbasi *et al.*, ApJ Lett. (in press):

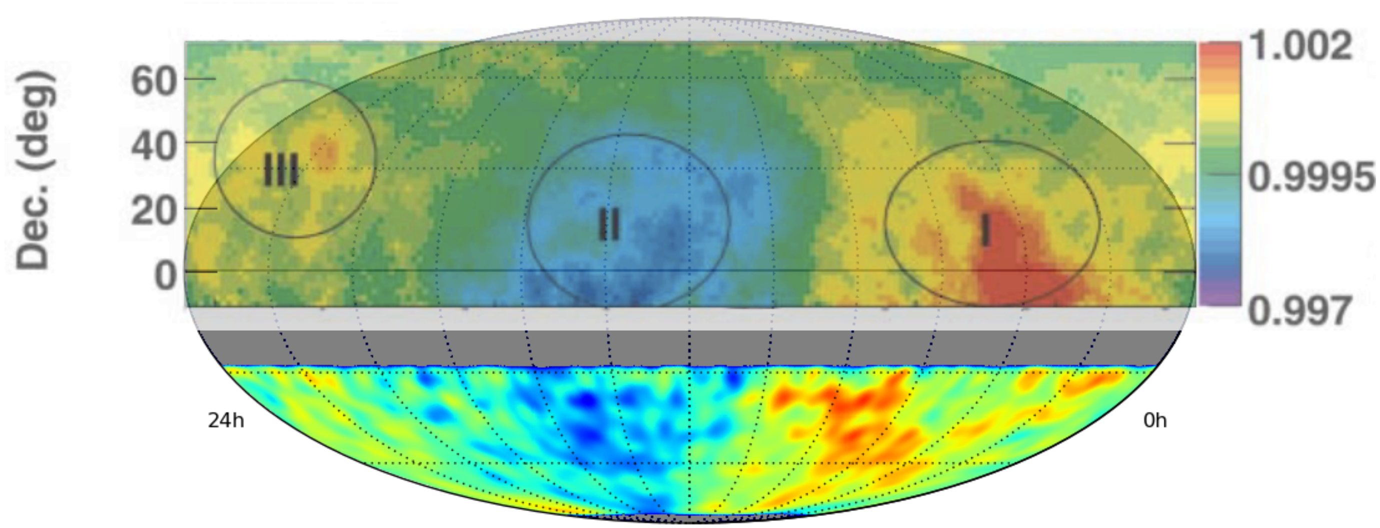
$$A_1 = (6.4 \pm 0.2 \pm 0.8) \times 10^{-4}$$
$$A_2 = (2.1 \pm 0.3 \pm 0.5) \times 10^{-4}$$
$$\varphi_1 = 66.4^\circ \pm 2.6^\circ \pm 3.8^\circ$$
$$\varphi_2 = -65.6^\circ \pm 4.0^\circ \pm 7.5^\circ$$



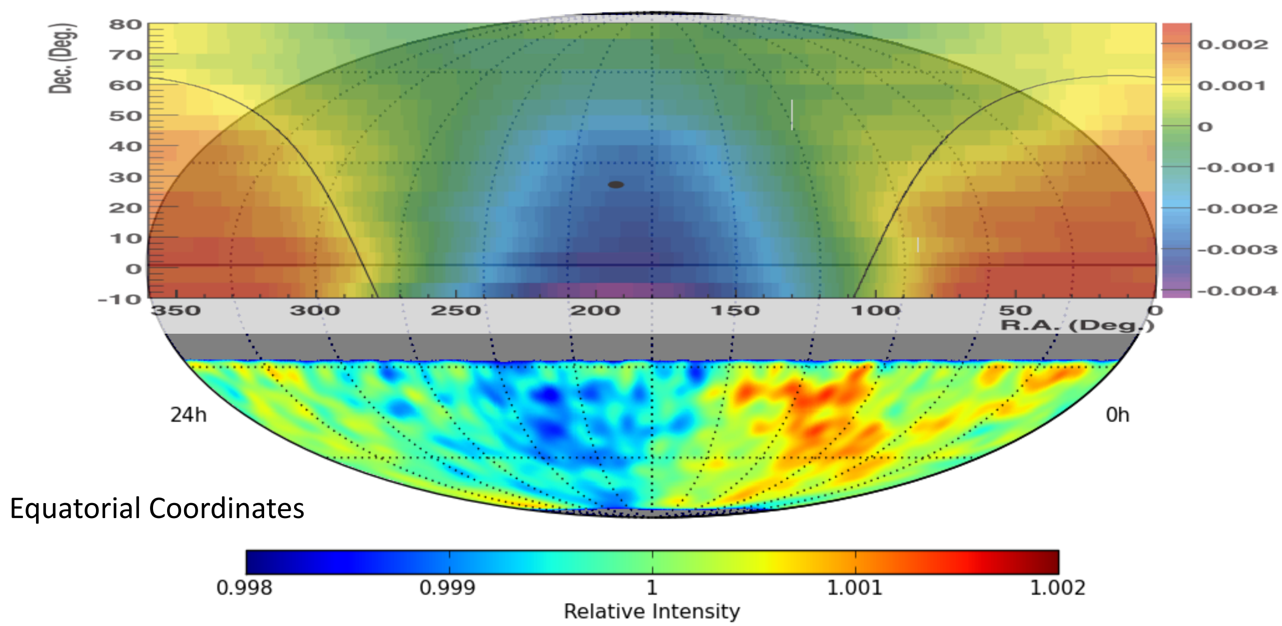
- The anisotropy is not a pure dipole and does not have the right phase to be explained by the Compton-Getting effect

- There may be a Compton-Getting component, but it seems to be overwhelmed by other effects

Comparison to Northern Hemisphere



IceCube & Tibet Array
(3 TeV)



IceCube & Milagro
(10 TeV)

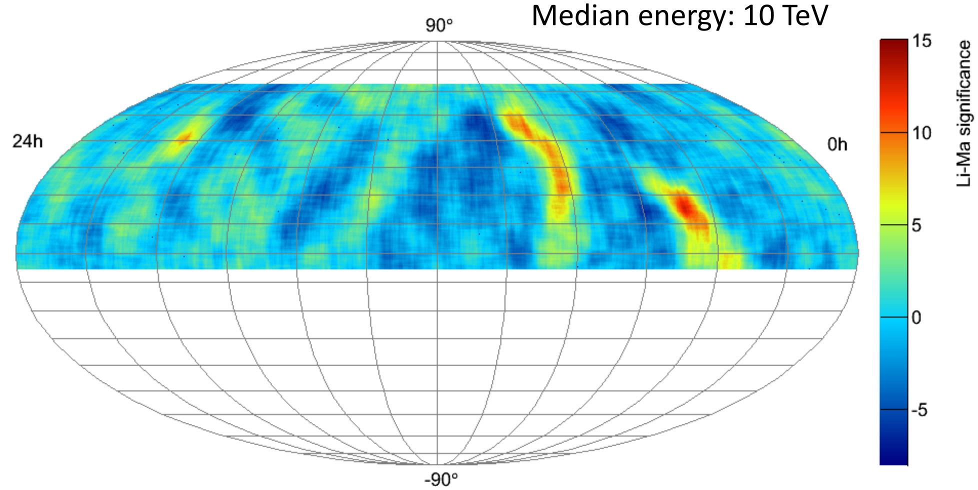
Anisotropies on Smaller Scales

Anisotropies on Smaller Scales

- Several experiments have discovered anisotropies on scales of about 10°
- Milagro: >10σ hotspots seen with 7 yr of data (amplitude is a few 10^{-4})
- Also observed by Tibet AS-γ and ARGO-YBJ
- Origin: magnetic funneling? Diffusion from nearby SNR?
- IceCube can search for similar anisotropies in the southern sky

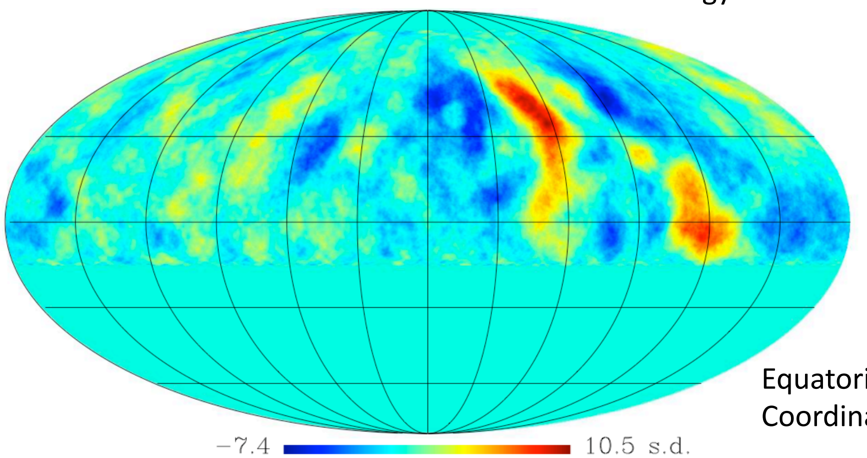
Milagro

Median energy: 10 TeV



ARGO-YBJ

Median Energy: 2 TeV



Equatorial Coordinates

Analysis Technique

- We create a signal map from the arrival directions of events, and we calculate a background map from the data themselves

- Expected background counts, estimated from data:

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

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

R event rate (as a function of time t)

ε 1 if event is in ra and δ bin under consideration, 0 otherwise

- This equation can be "integrated" numerically by randomly assigning detected event times to local arrival directions. This automatically accounts for event rate fluctuations, and ensures the preservation of the local arrival direction distribution

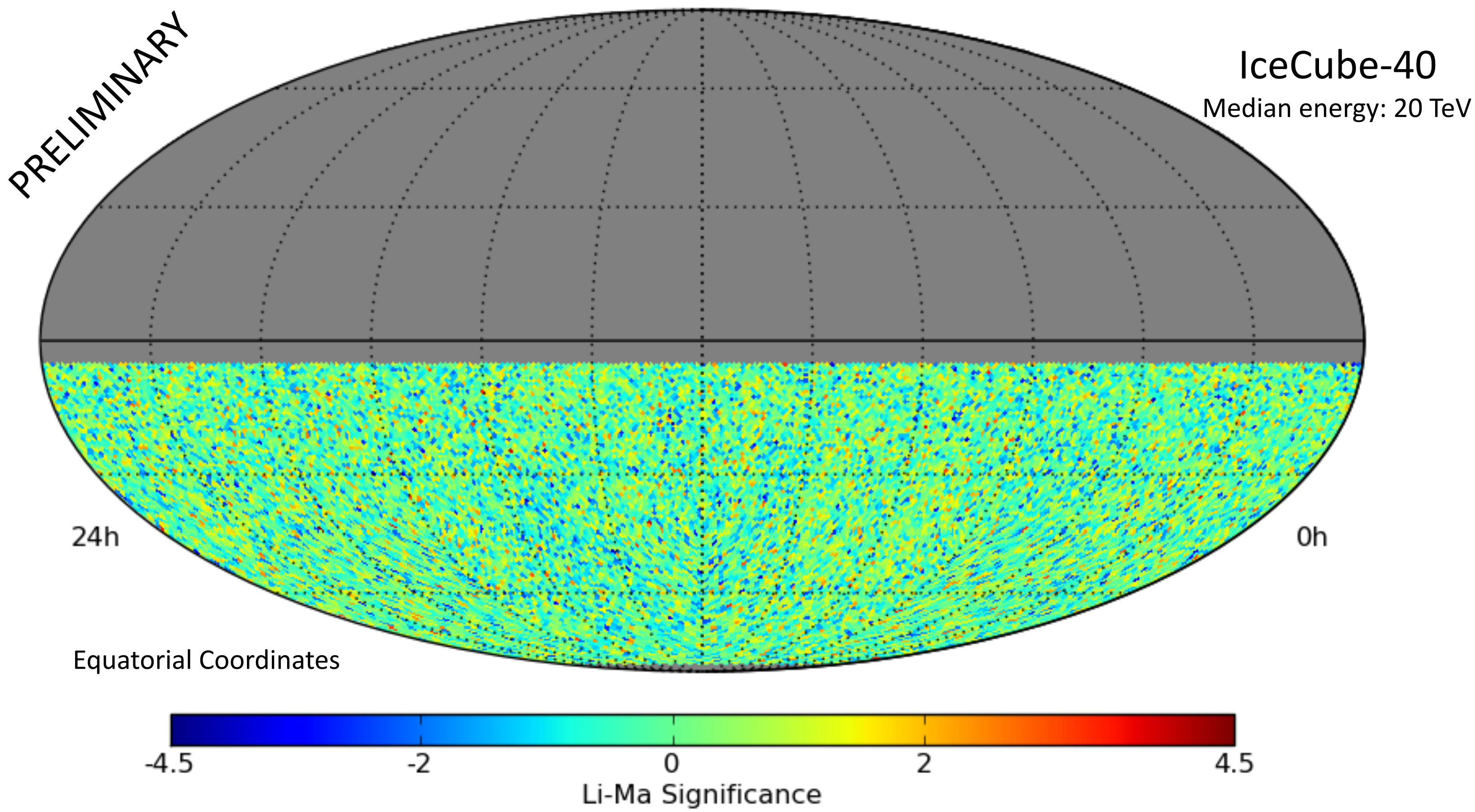
- Note: integration assumes a stable detector acceptance function. We use integration times of 2 – 4 hours to ensure detector stability

Background Estimate and Smoothing

- Uncertainties in the background can be reduced by repeated resampling of the event times (20x per event).
- The length of the integration time determines the maximum angular scale we can probe. E.g., with 4-hr integration periods, we are insensitive to scales larger than 60°
- Signal and background maps are smoothed to improve our sensitivity to larger features. We smooth on an angular scale that is comparable to the feature size
- Significances are calculated using the method of Li and Ma
- Warning: testing several smoothing angles introduces trial factors. We use the IC22/IC40 data sets to find the optimal smoothing parameters, which we will use as *a priori* inputs when the IC59 data are unblinded

IceCube 40 Skymap

- The southern sky observed with IC40 using a 4-hour integration time



IceCube 40 Skymap

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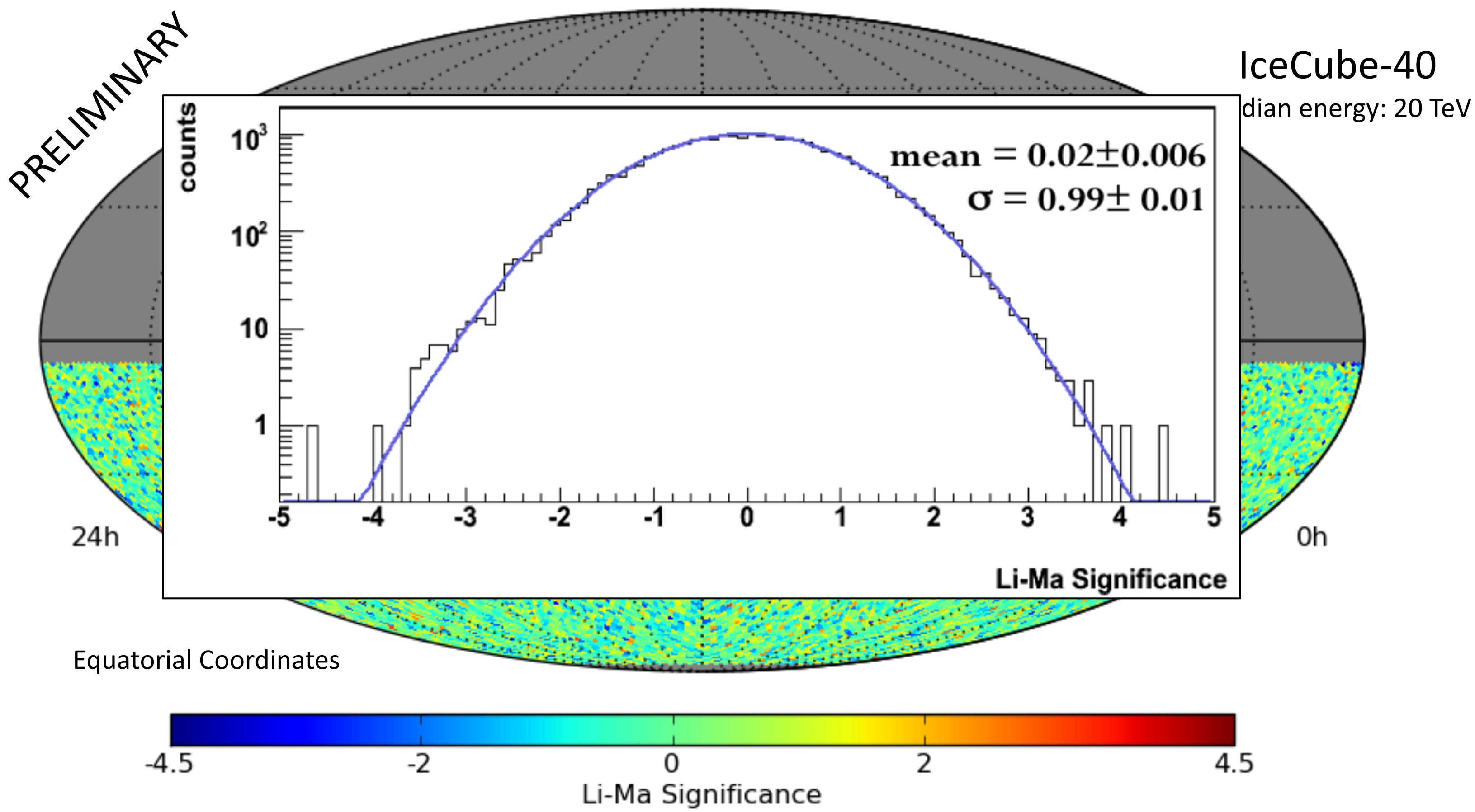
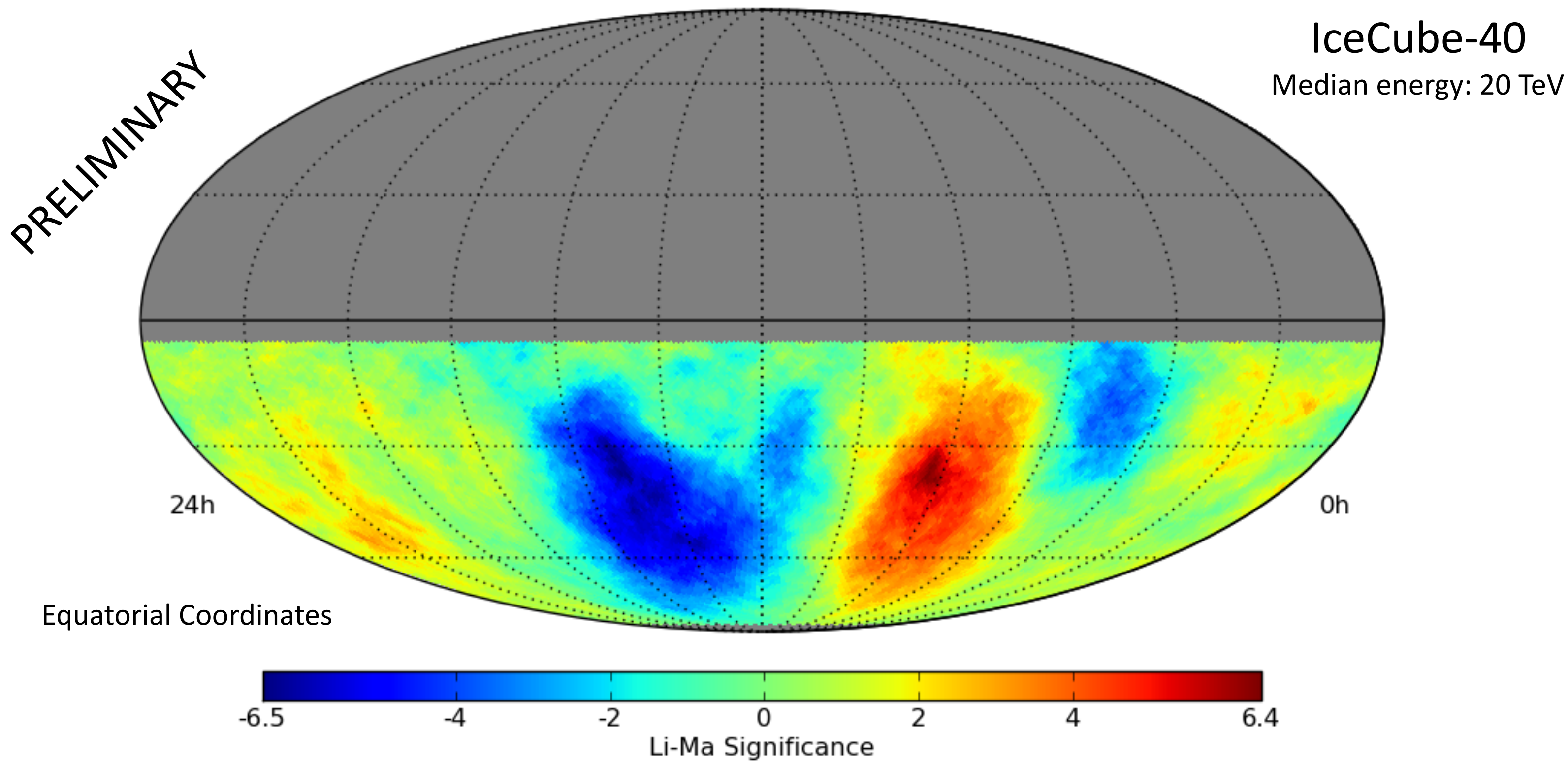


IceCube 40 Skymap

- The southern sky observed with IC40 using a 4-hour integration time and a 20° smoothing radius

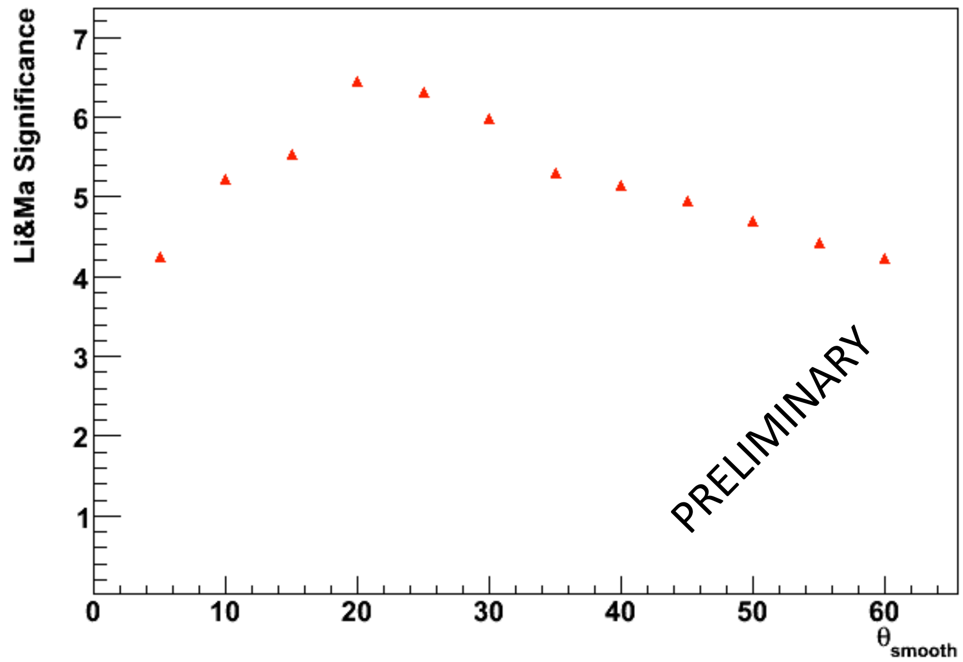


- Note: due to the smoothing, neighboring bins are highly correlated
- Note: indicated significance is pre-trials

Significance vs Smoothing Angle

- **Trial factors**: the location and extent of the excesses were determined by examining the data

- The smoothing radius of 20° maximizes the significance of the "hot spot" and was chosen *a posteriori* for that reason

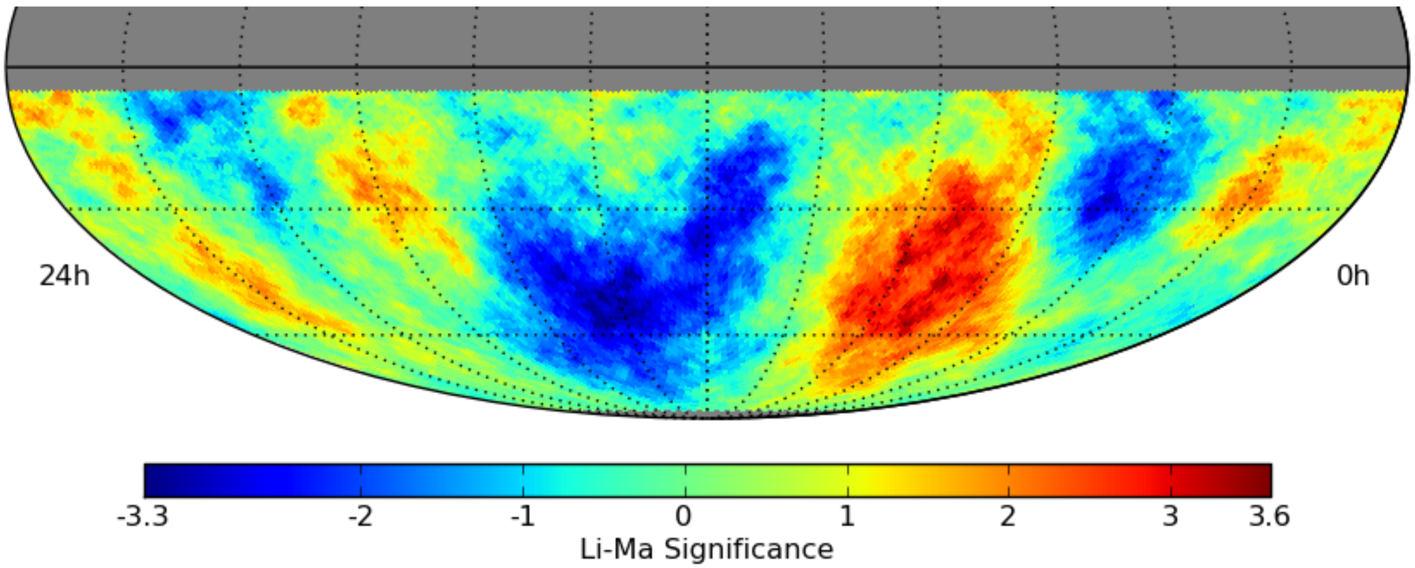


- The parameters that optimize the signal in IC40 are *a priori* for the analysis of data in IC59 and beyond

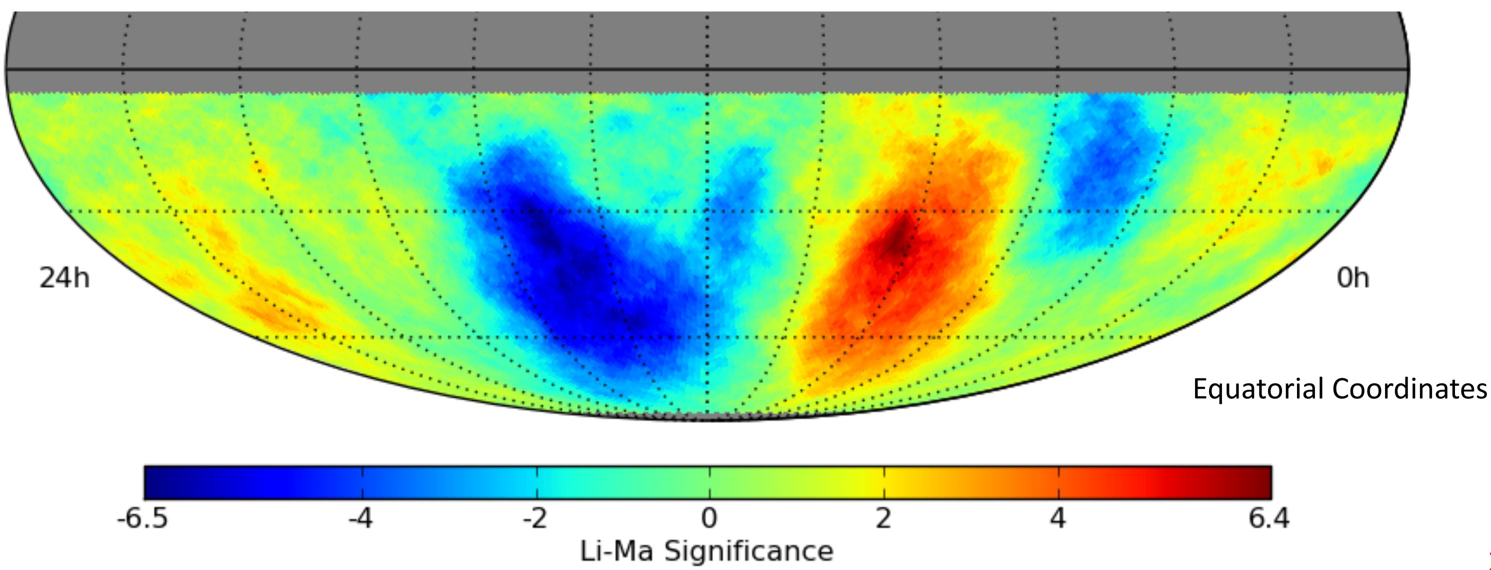
- We will use IC59 to establish the significance of the signal

Stability Check: IC22 and IC40

IC22

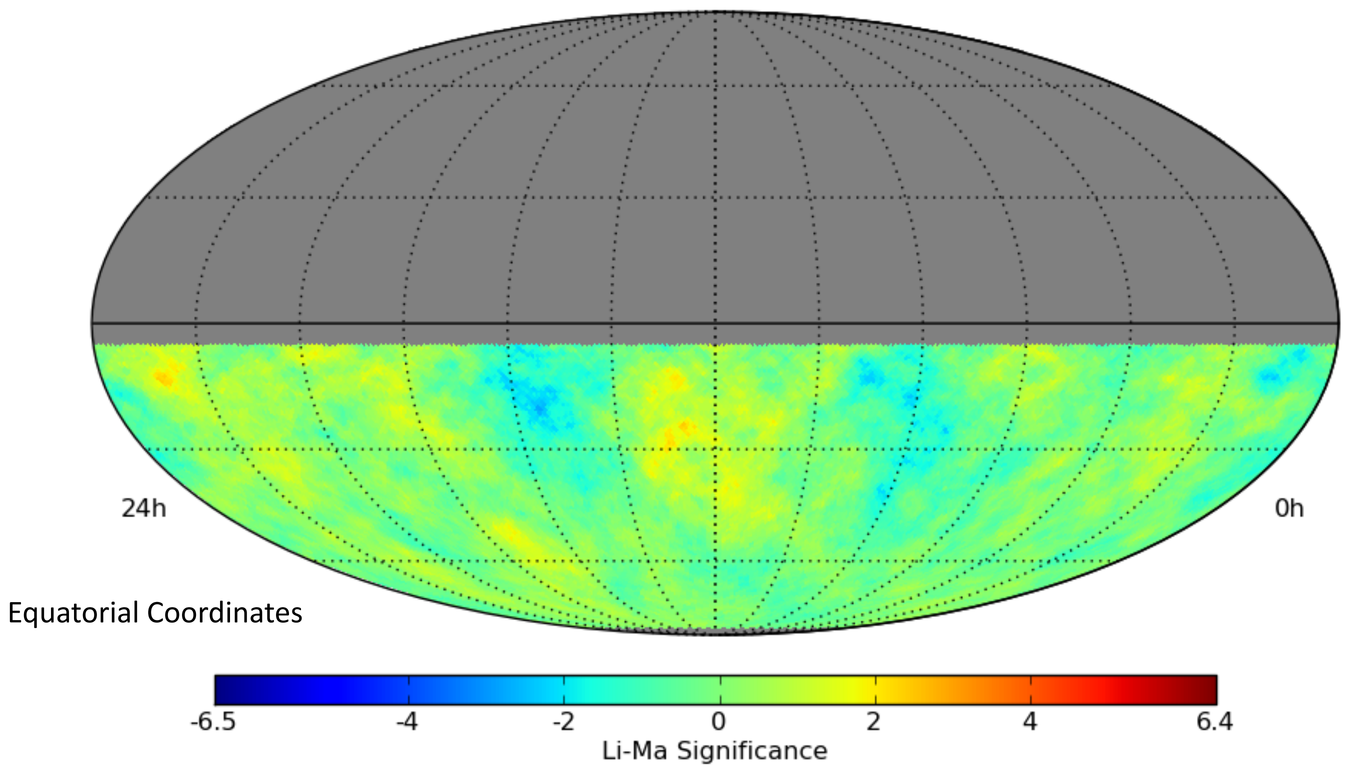


IC40



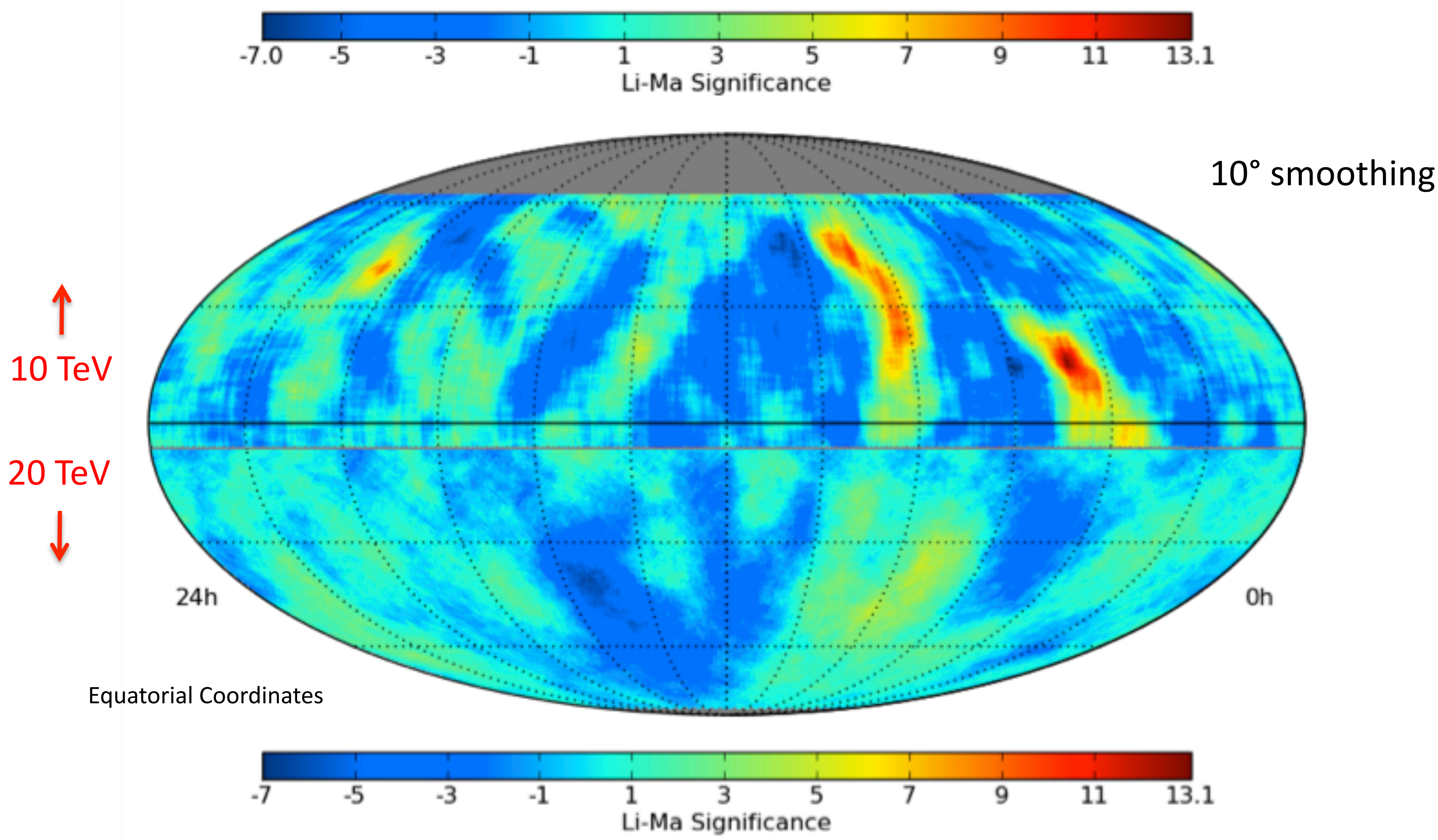
Sanity Check: Antisidereal Time

- Antisidereal time is a non-physical time calculated by flipping the sign in the UT-sidereal time conversion. No signal is expected in this time frame, aside from seasonal effects

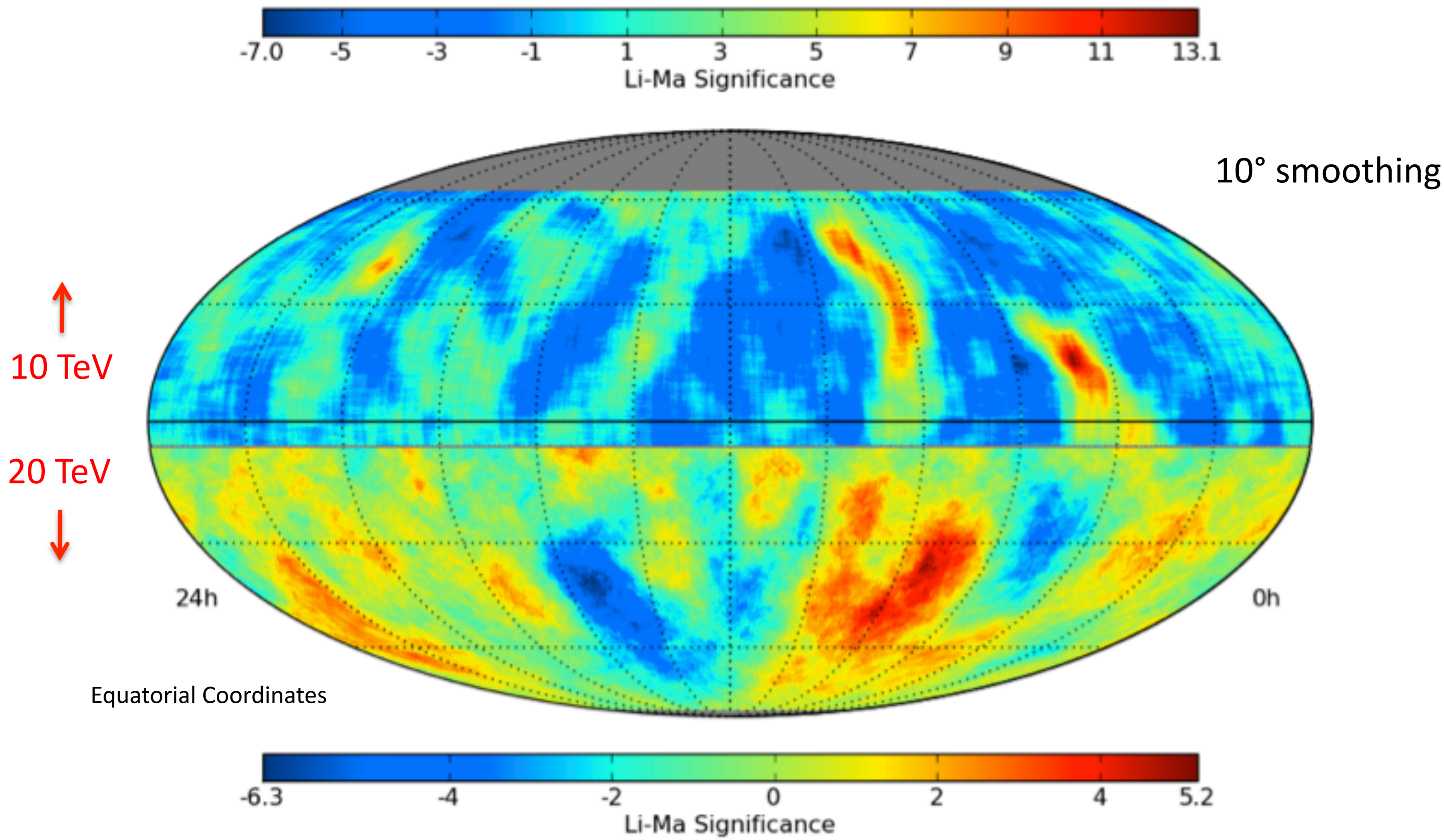


- Result: there is no remaining signal (or seasonal effect) if antisidereal time is used to transform local to equatorial coordinates

IC40 and Milagro



IC40 and Milagro



Conclusions

- IceCube records several 10^{10} cosmic ray events per year, and can observe anisotropies in the cosmic ray arrival directions of 10^{-4}

- The IceCube skymap shows a broad excess region of about 20° around α=120°, and an equally strong deficit around α=220°

- The anisotropy is not a pure dipole, so the Compton-Getting effect is at best a part of the observed signal

- Similar anisotropies have been observed in the northern hemisphere, but their origins are not known. IC59 data will be used to establish the significance of the anisotropy and to determine if it persists at higher energies (>100 TeV)