Observation of Anisotropy in the Galactic Cosmic Rays at TeV Energies with the IceCube Detector

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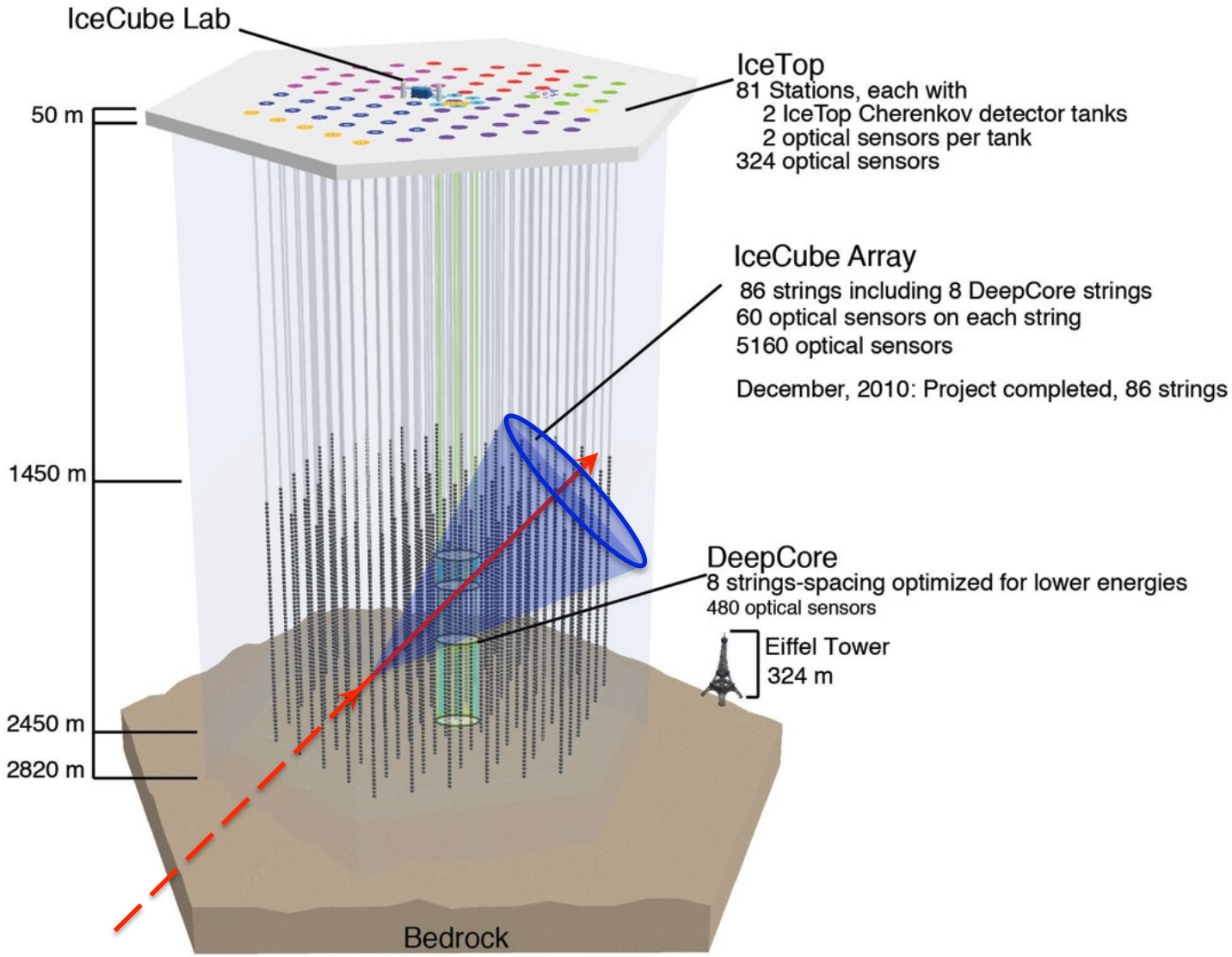
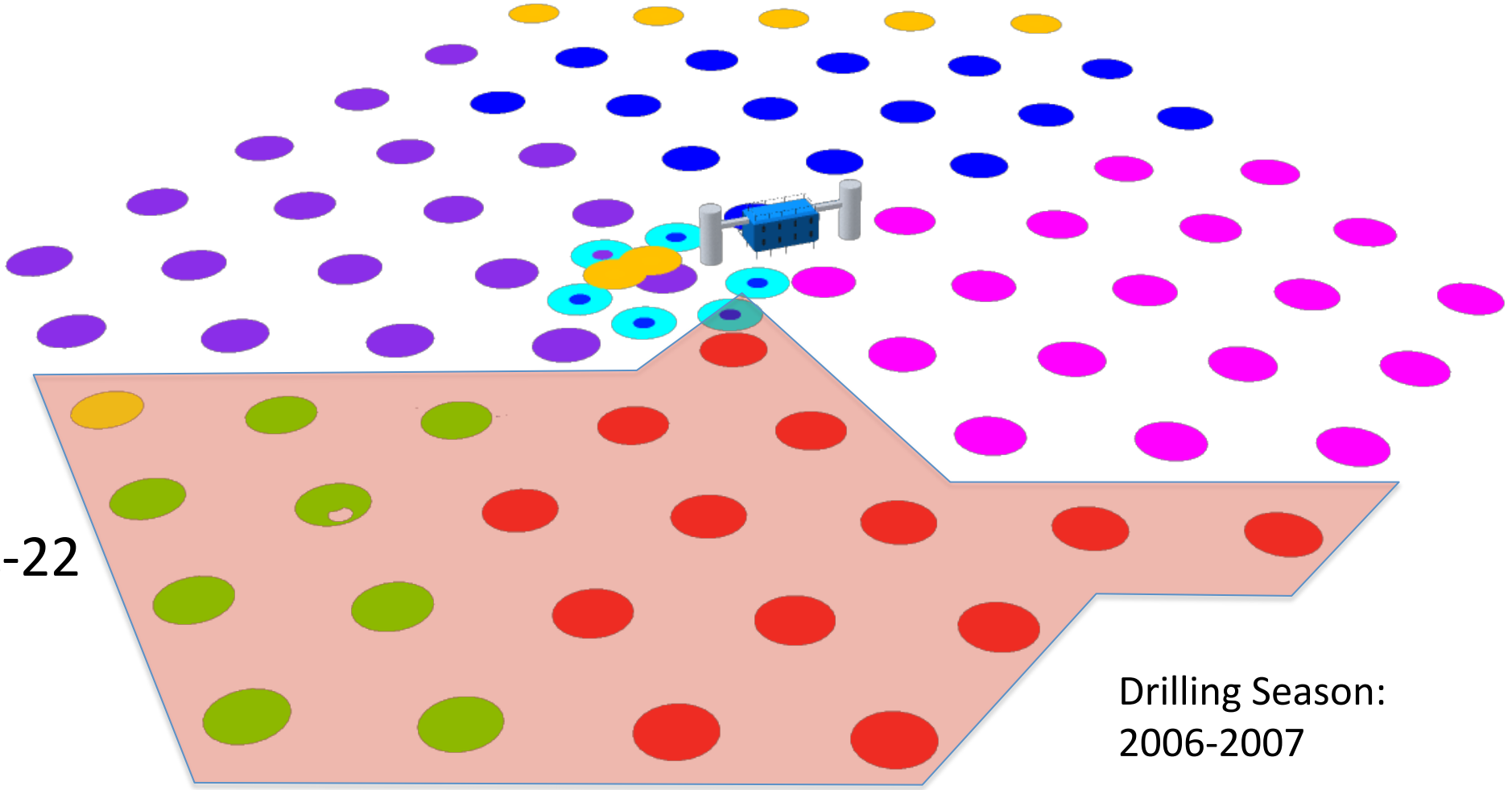
IceCube Detector



Neutrinos and cosmic rays are detected using Cherenkov emission in ice sheet

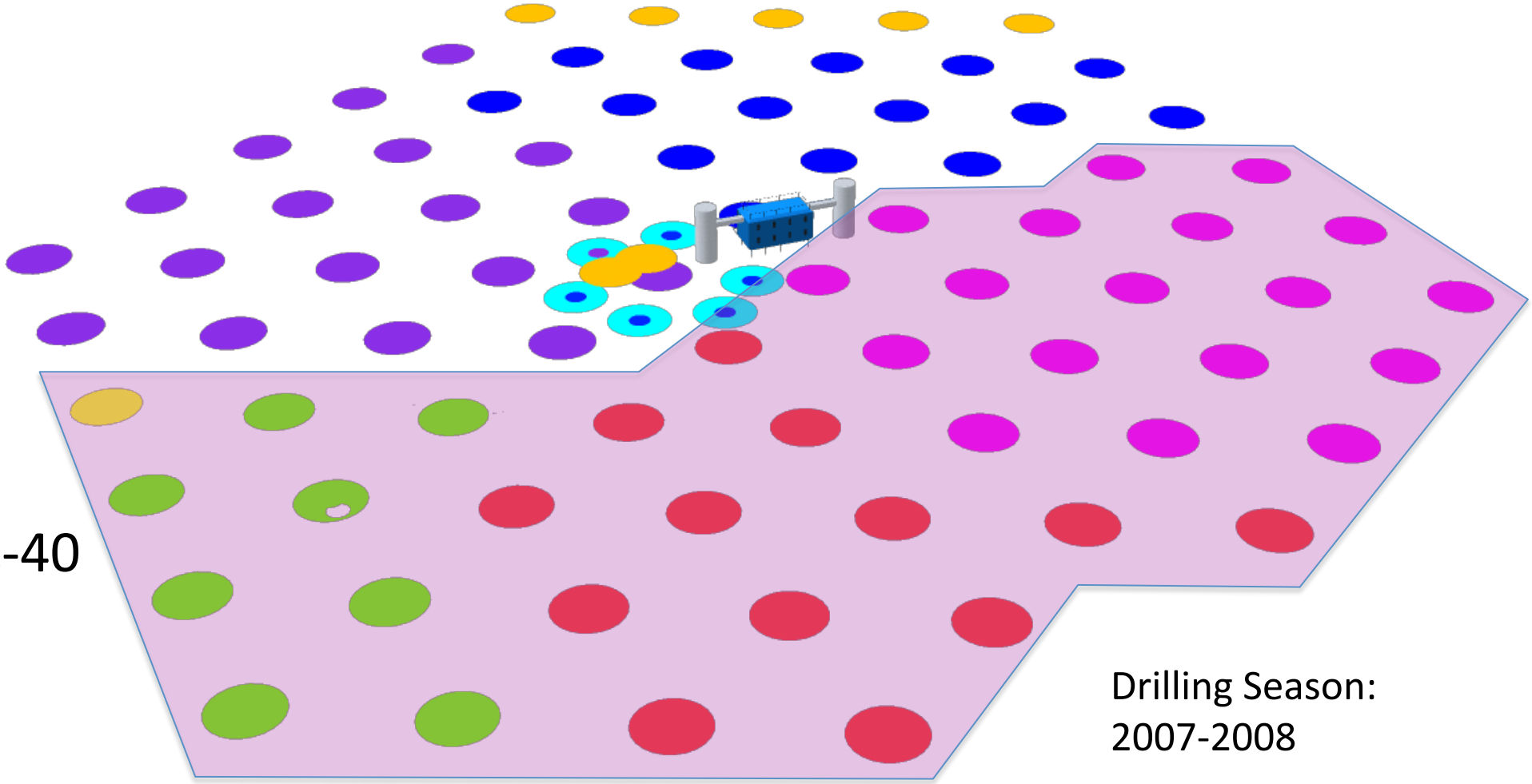
Staged Deployment



IC-22

Drilling Season:
2006-2007

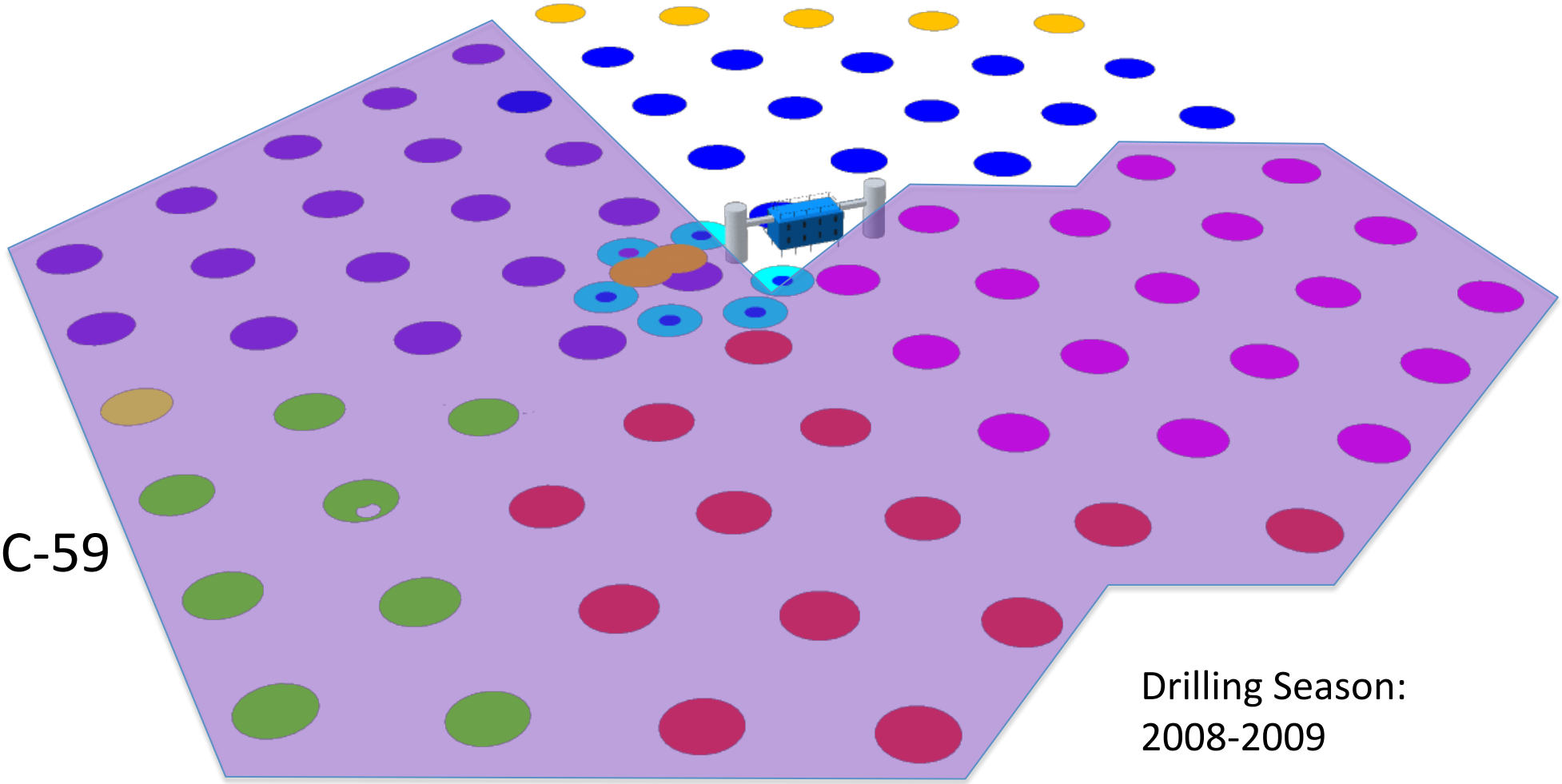
Staged Deployment



IC-40

Drilling Season:
2007-2008

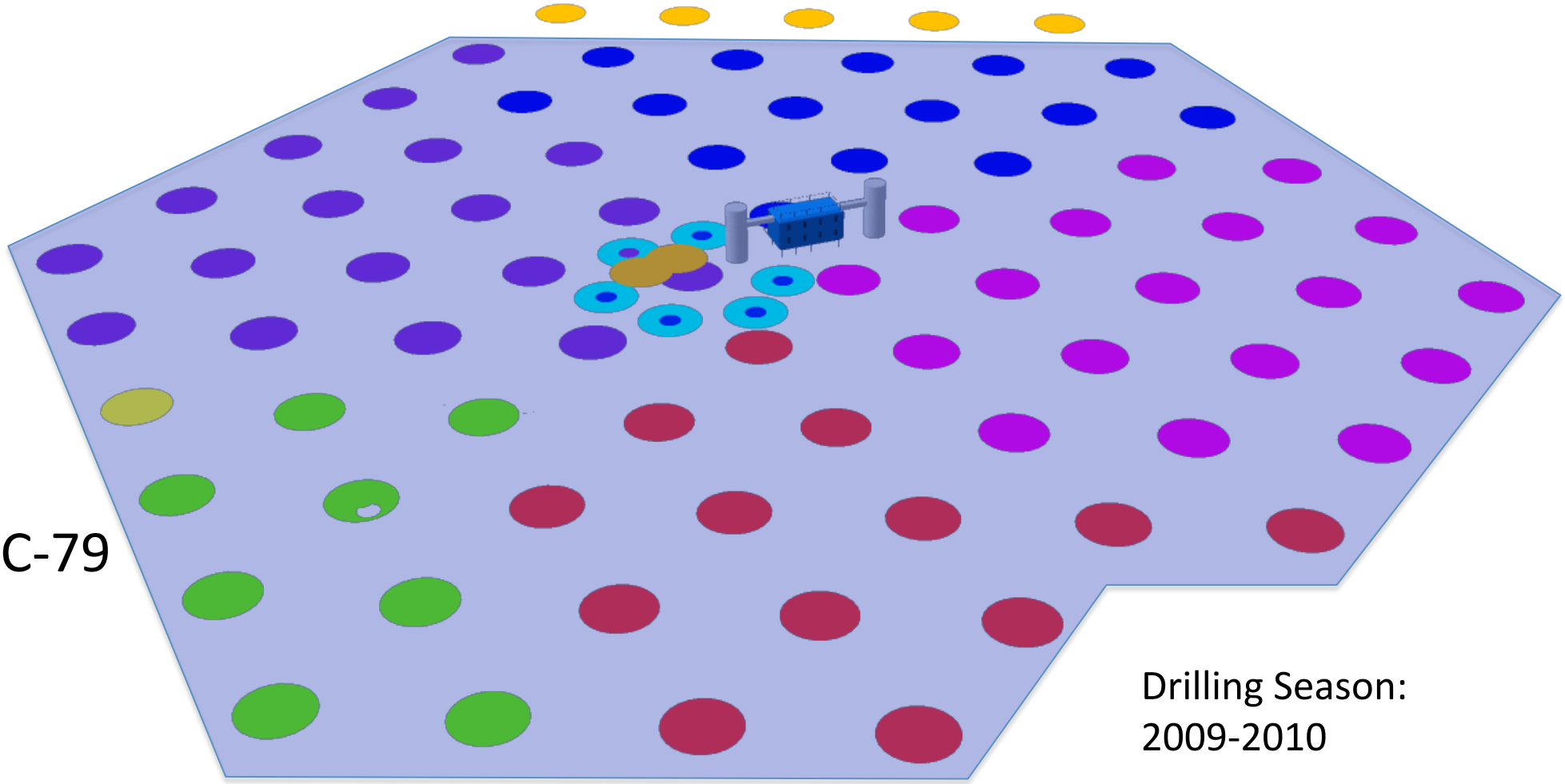
Staged Deployment



IC-59

Drilling Season:
2008-2009

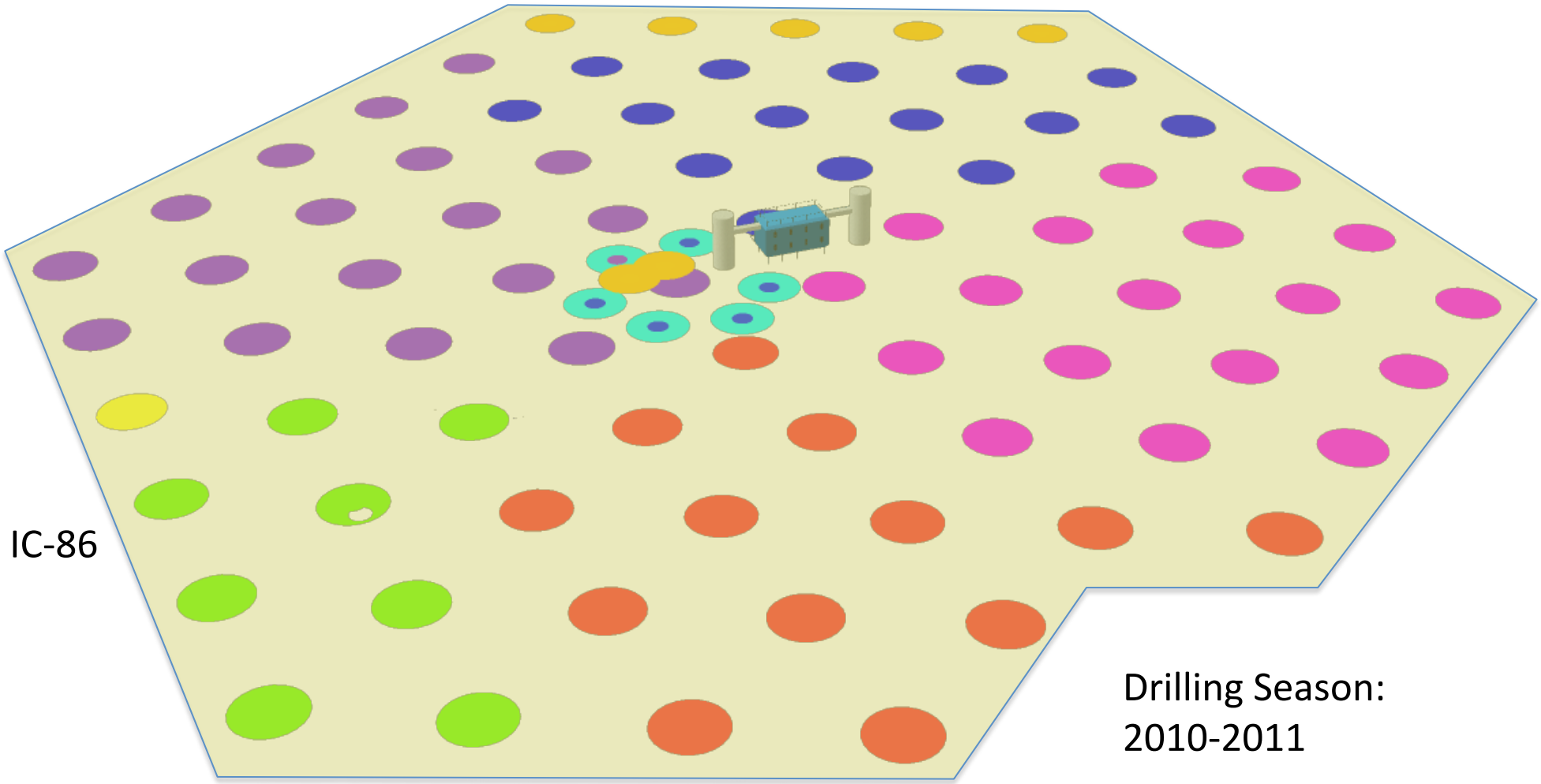
Staged Deployment



IC-79

Drilling Season:
2009-2010

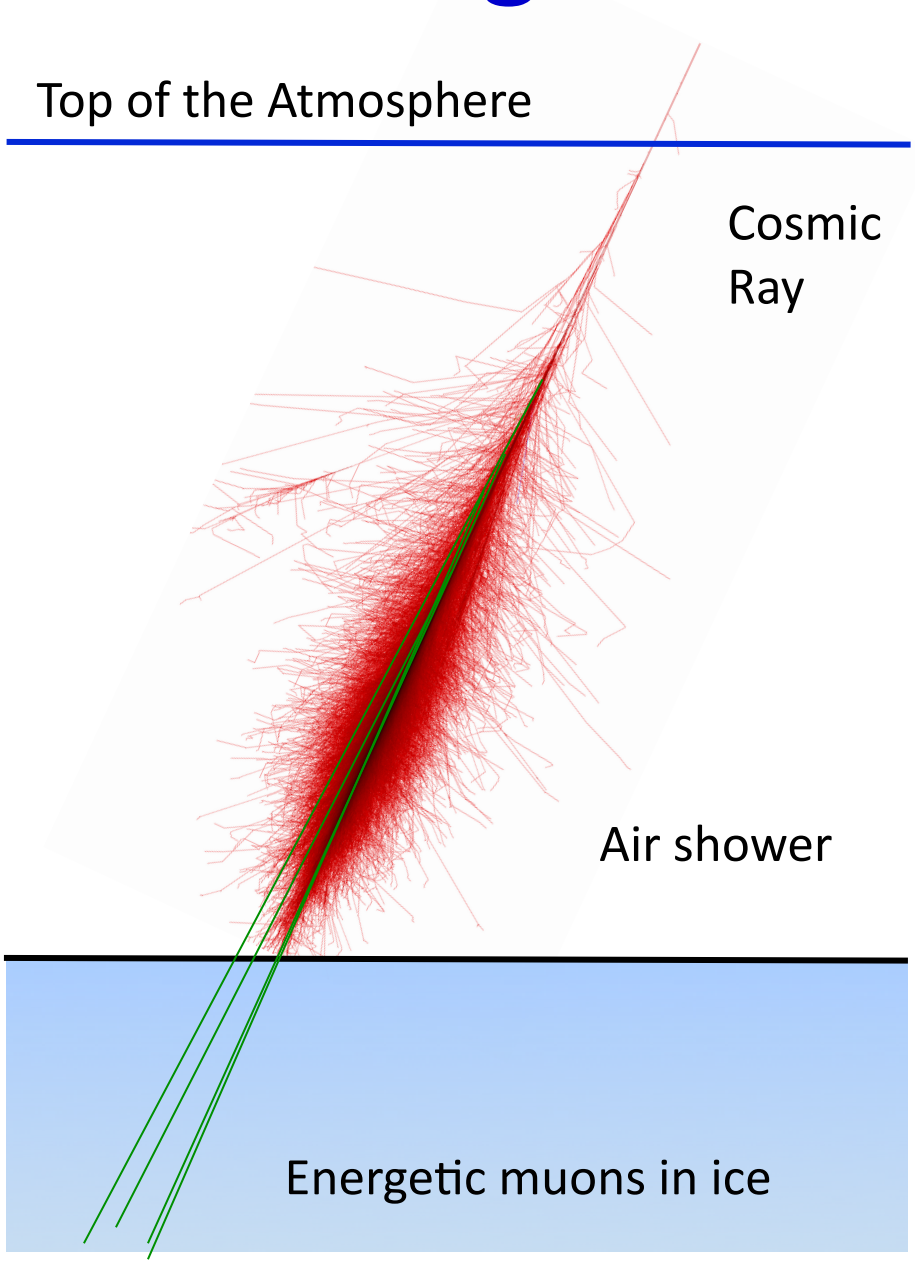
Staged Deployment



IC-86

Drilling Season:
2010-2011

Observing Cosmic Rays with IceCube



- IceCube has proven to be an excellent cosmic ray detector
- Muons from cosmic ray air showers trigger the in-ice detector at >1 kHz
- Sensitivity to cosmic rays from southern hemisphere between 1 TeV – 1 PeV (median = 20 TeV)
- We can build a cosmic ray skymap with high statistics
  - 3.2×10^{10} events in IC59
  - 3.7×10^{10} events in IC79

Map Building

- **Time scrambling algorithm** to estimate expected counts:

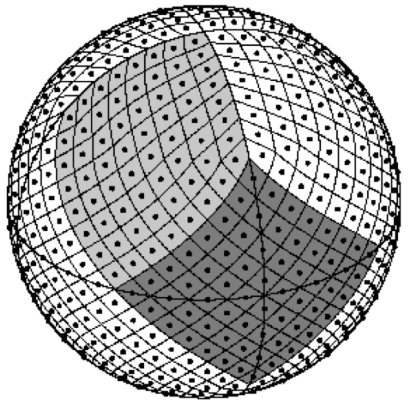
$$dN(\Omega,t) = A(\Omega) \cdot R(t)\, d\Omega\, dt$$

1. Bin the arrival directions in equal-area sky map: HEALPix library N_{side}=64 (0.9°/pixel). Note: 3° resolution for cosmic ray tracks

2. Resample local coordinates of events recorded during a fixed time period Δt (2h to 24h). Randomly reassign event times to local coordinates to get new, randomized celestial coordinates

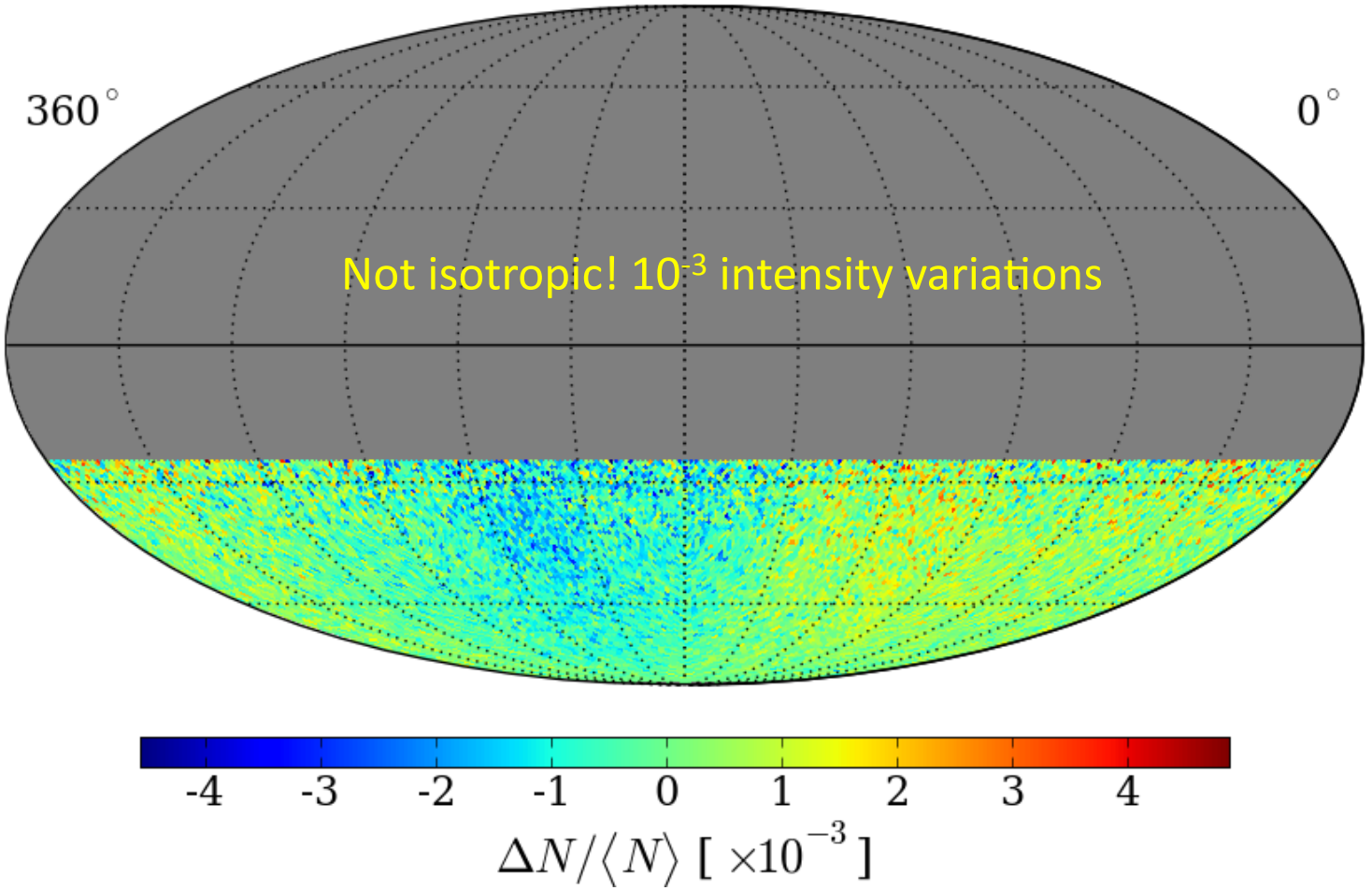
3. Sum over all time periods Δt to get a "reference" or "expected count" map $\langle N \rangle$ for the full data set

4. Subtract expected counts from data:
   1. Relative intensity map: $\delta I = (N - \langle N \rangle) / \langle N \rangle$
   2. Significance map: Li & Ma (ApJ 1983) with $\alpha = 1/(N_{resample})$



IceCube-59 Relative Intensity Map

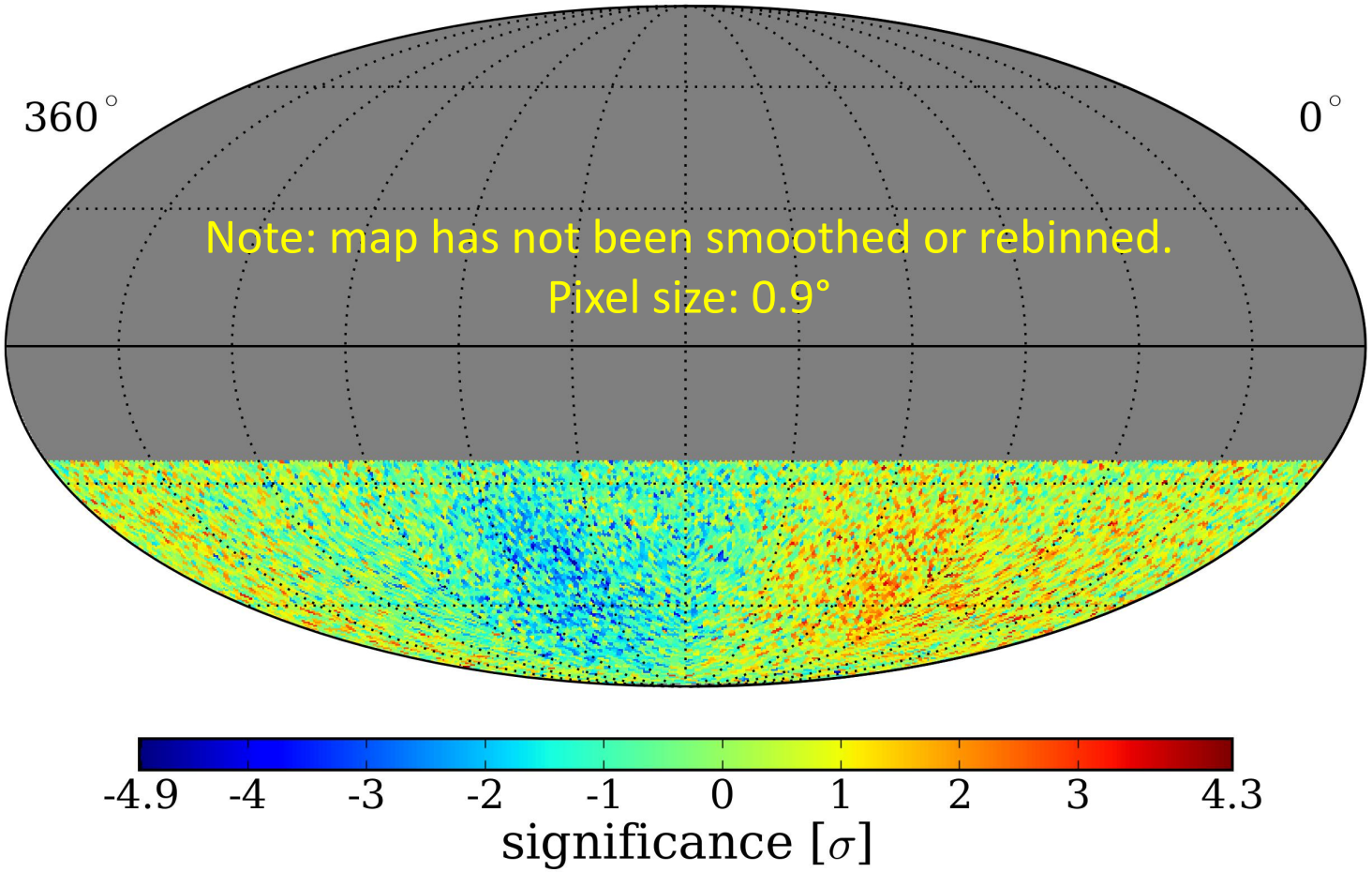
- Relative intensity: $\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta) \rangle}{\langle N_i(\alpha,\delta) \rangle}.$



- See also: Abbasi et al., ApJ **718** (2010) L194

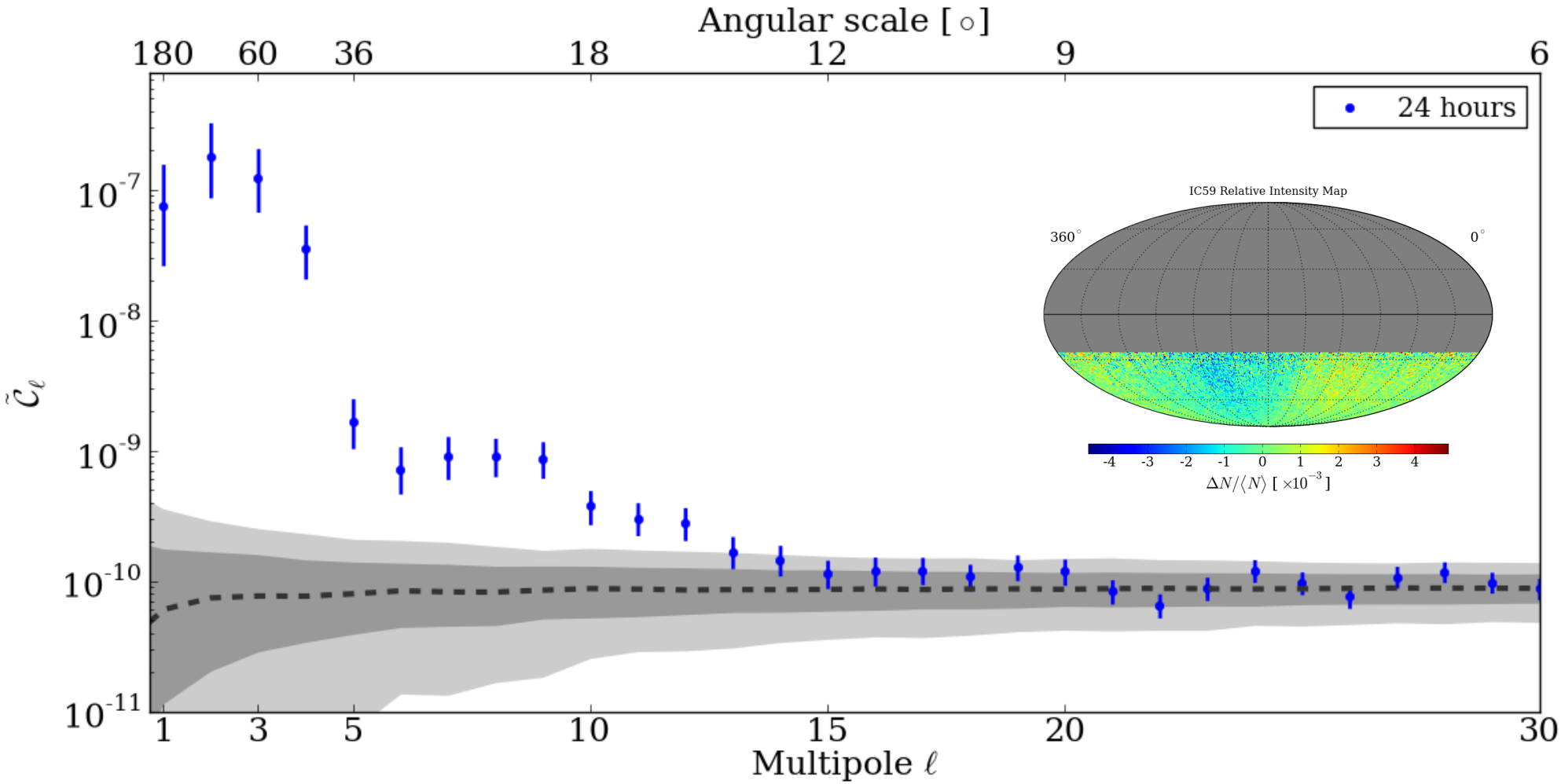
IceCube-59 Significance

- Significance: $$s = \sqrt{2}\left\{ N_{\mathrm{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2}$$



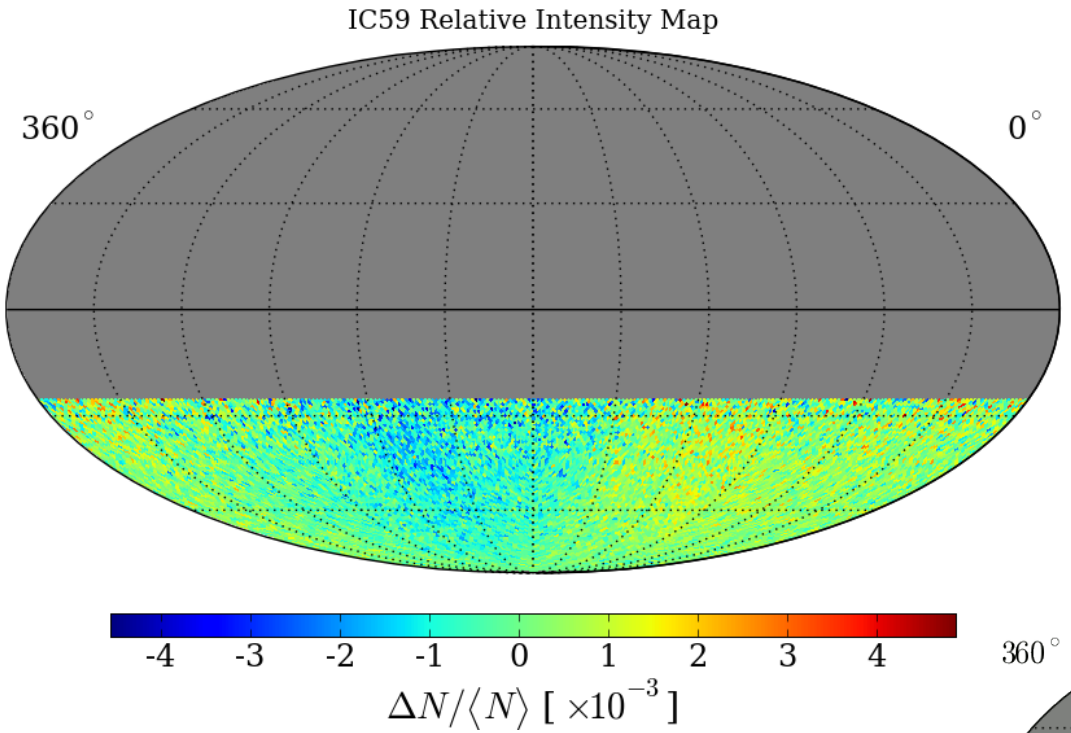
- Do correlations exist on small angular scales as well?

IceCube-59 Power Spectrum



- Sky map contains correlations at several angular scales
- Gray bands: 68% and 95% bands of simulated isotropic maps

Remove Dipole + Quadrupole

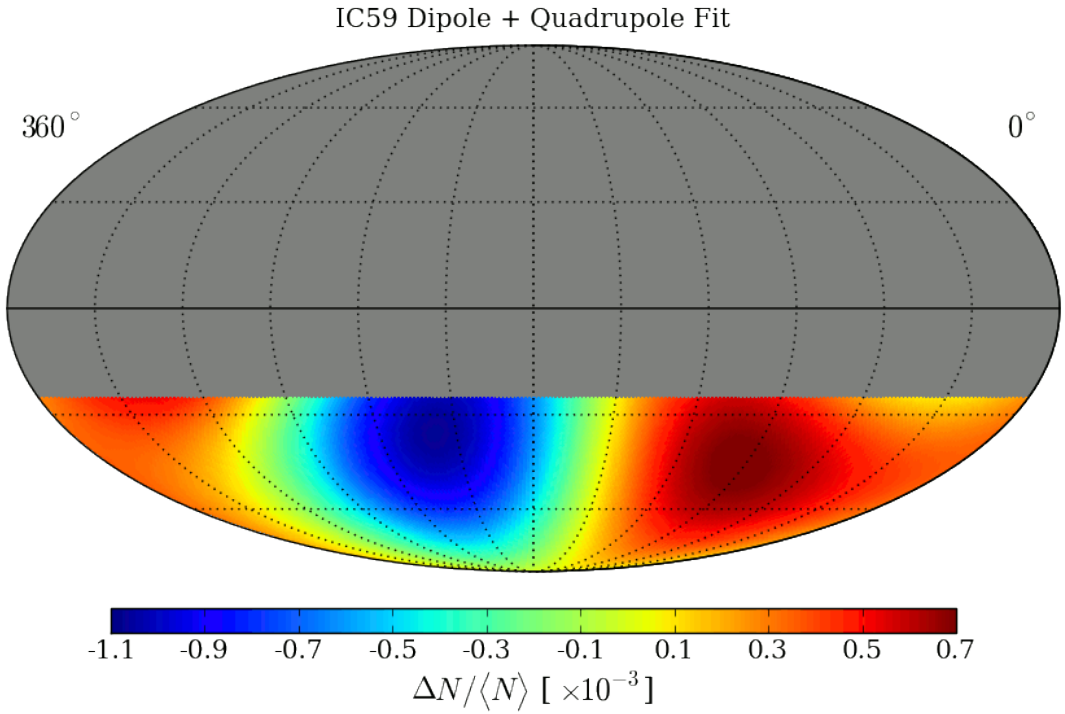


Fit dipole + quadrupole…

Best fit D+Q moments:

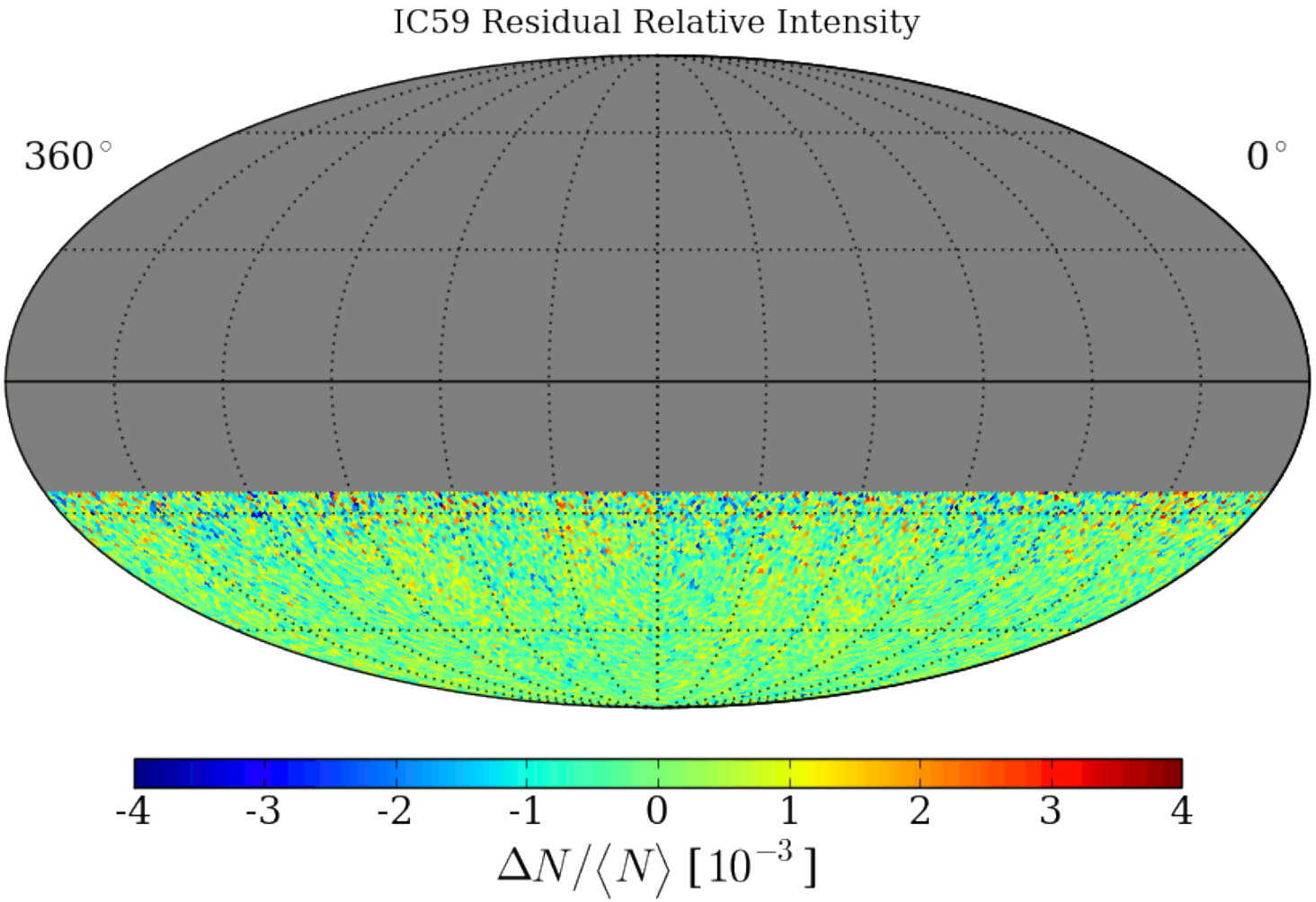
χ^2/ndf = 14743.4 / 14187

Pr(χ^2|ndf) = 0.05%



IC59 Residual Map

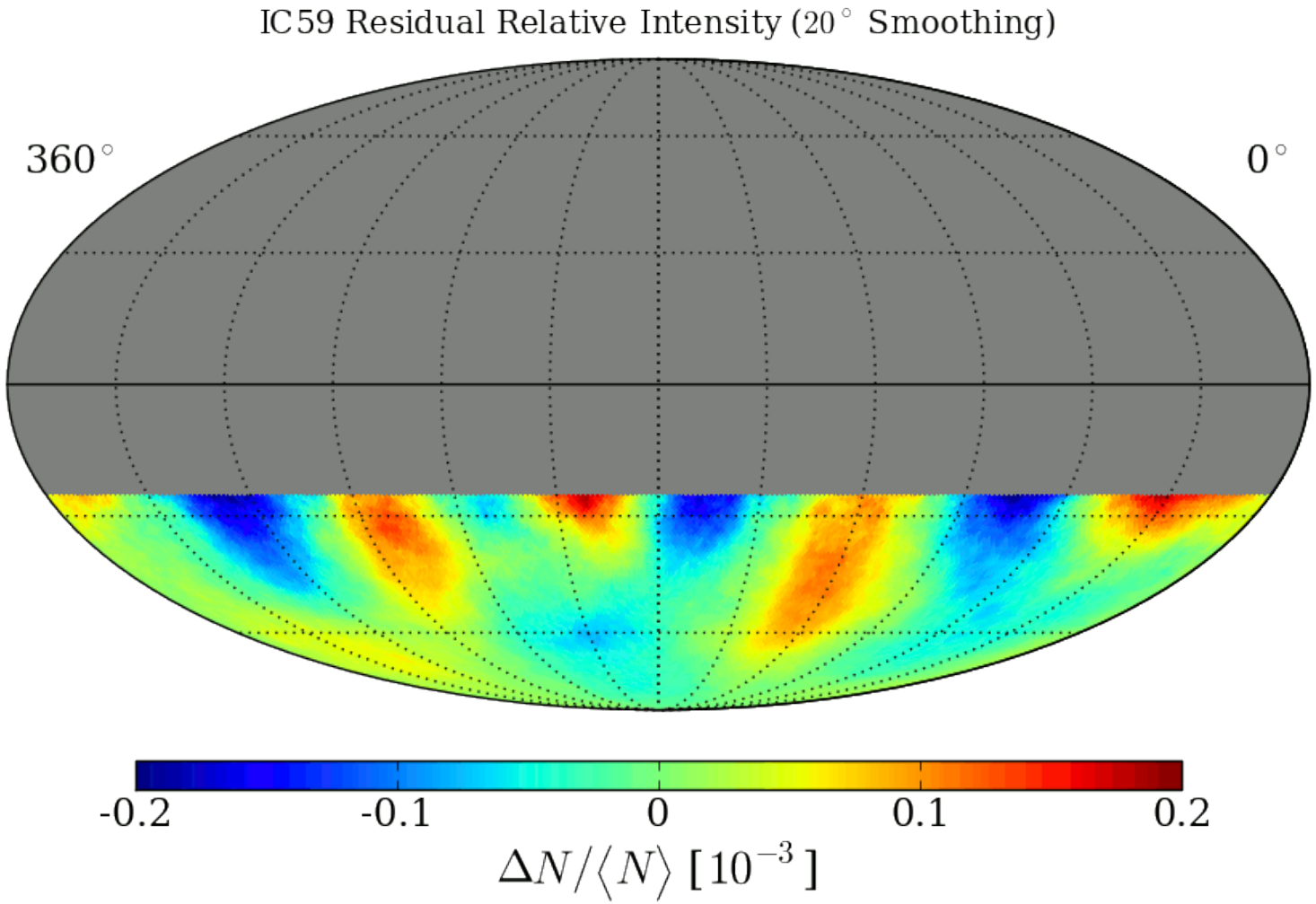
- Subtract D+Q fit from relative intensity map, and you get this:



- To see more structure, we have to rebin (or "smooth") the map

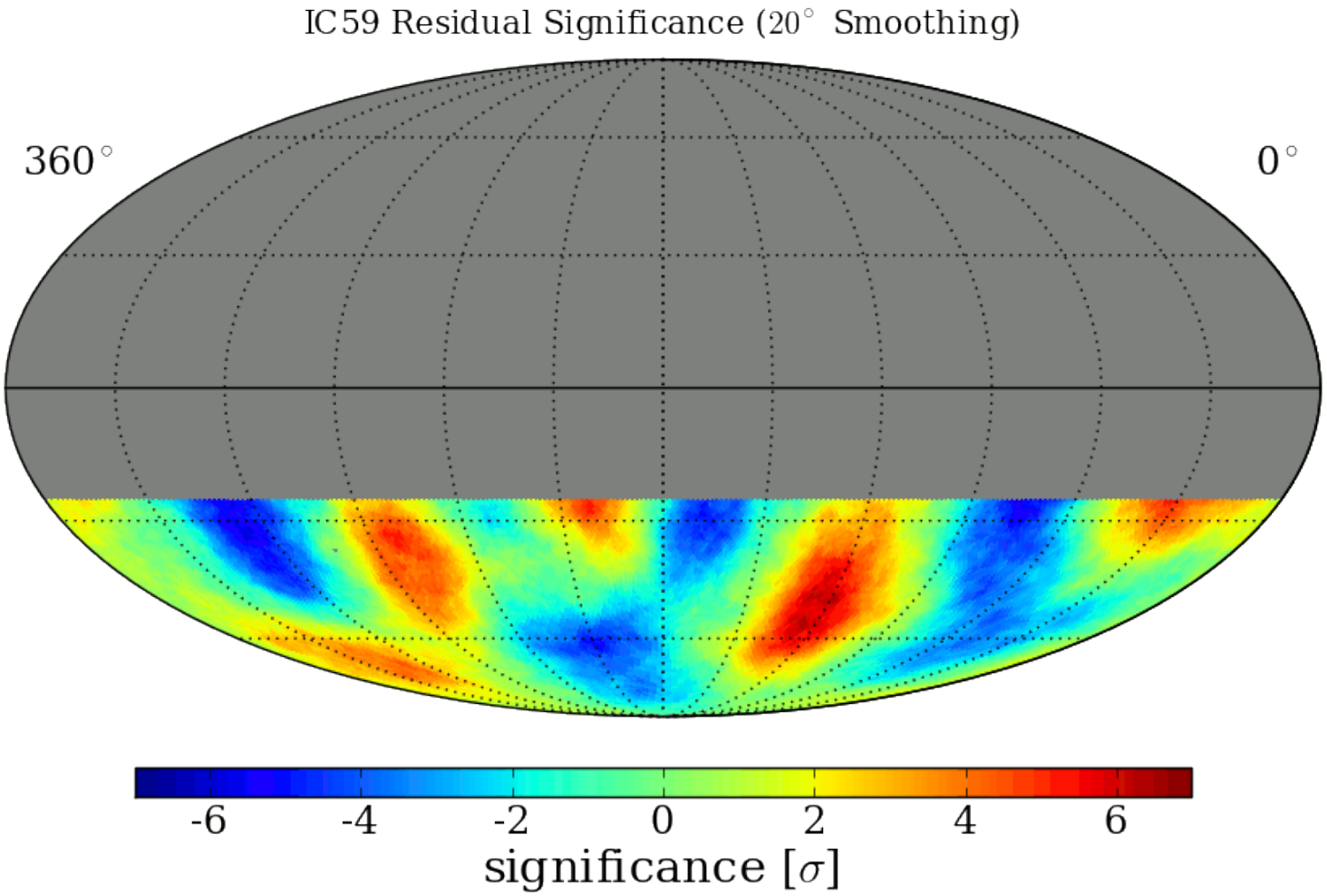
IC59 Smoothed Residual Map

- Example: structures visible after 20° smoothing:



IC59 Residual Significance

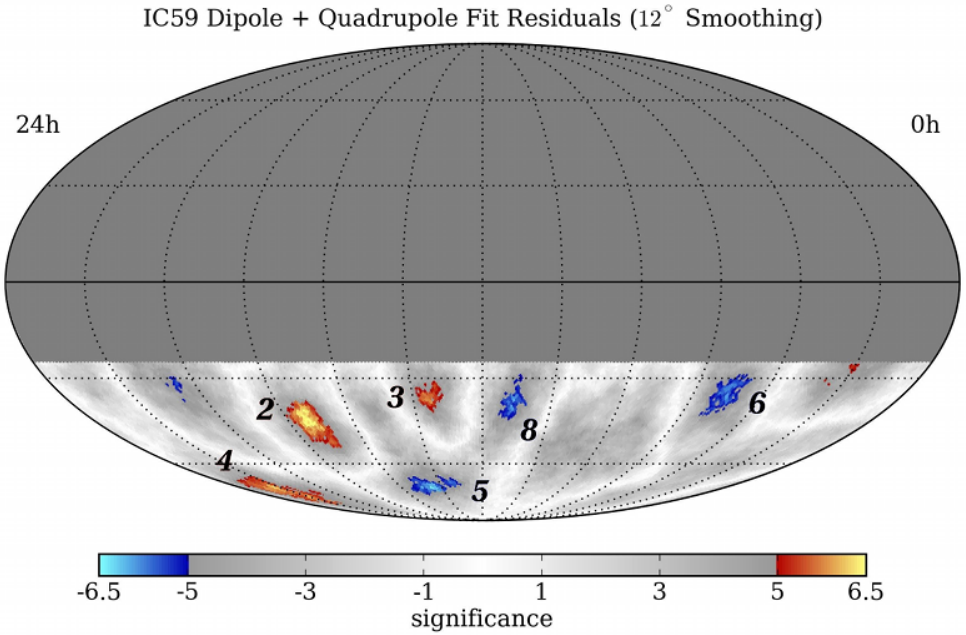
- Li and Ma significance: several “hot” spots (>5σ before trials)

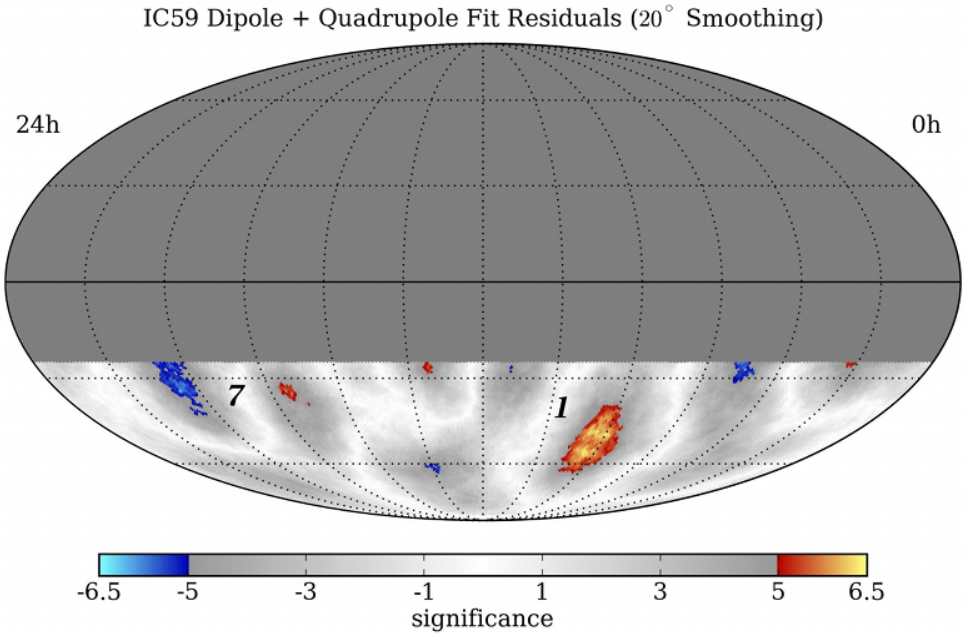


Identification of Significant Hot Spots

IC59 data: R. Abbasi et al., ApJ (in press), arXiv:1105.2326

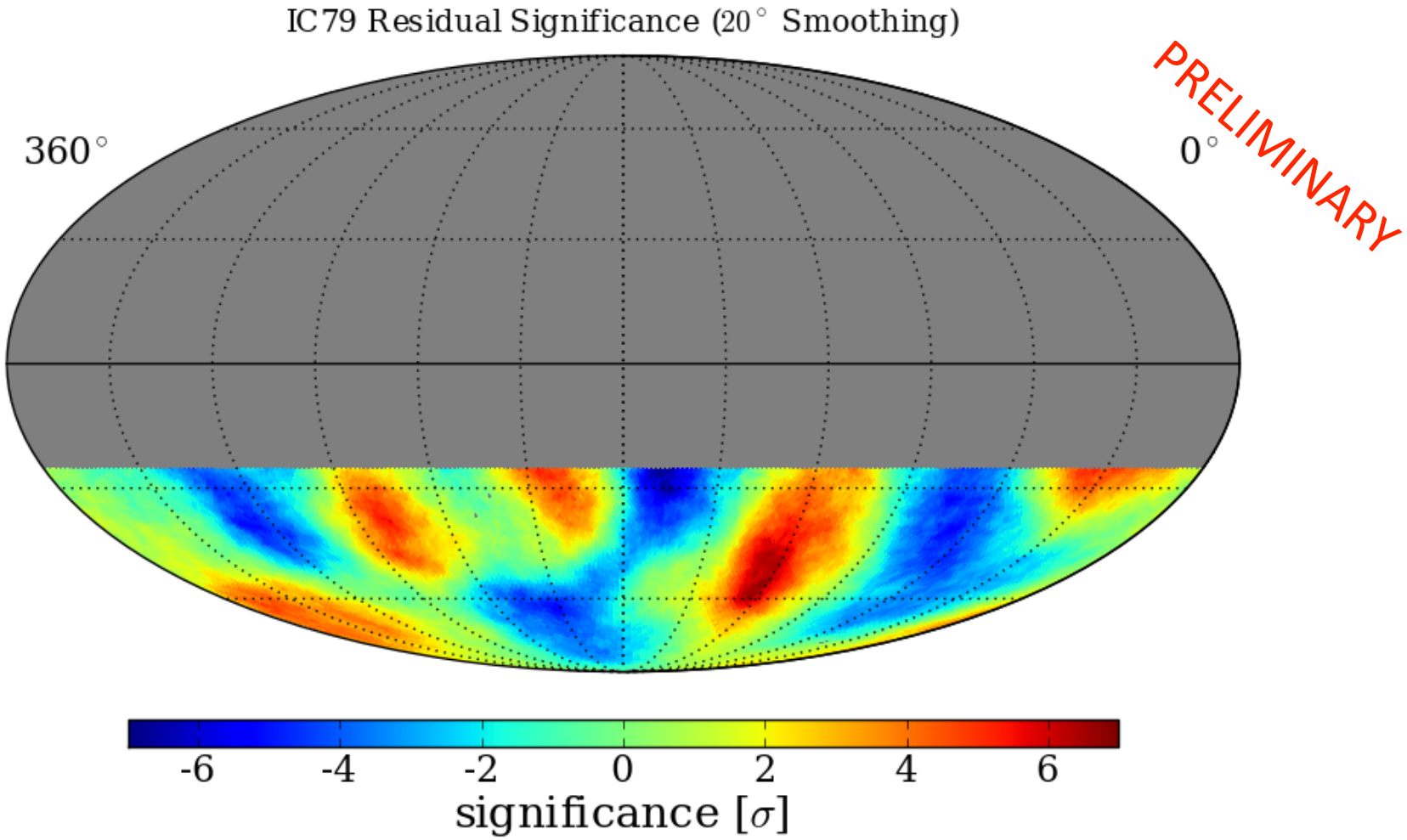
region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	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





Update: IC79 Residual Significance

- Li and Ma significance after 20° smoothing:

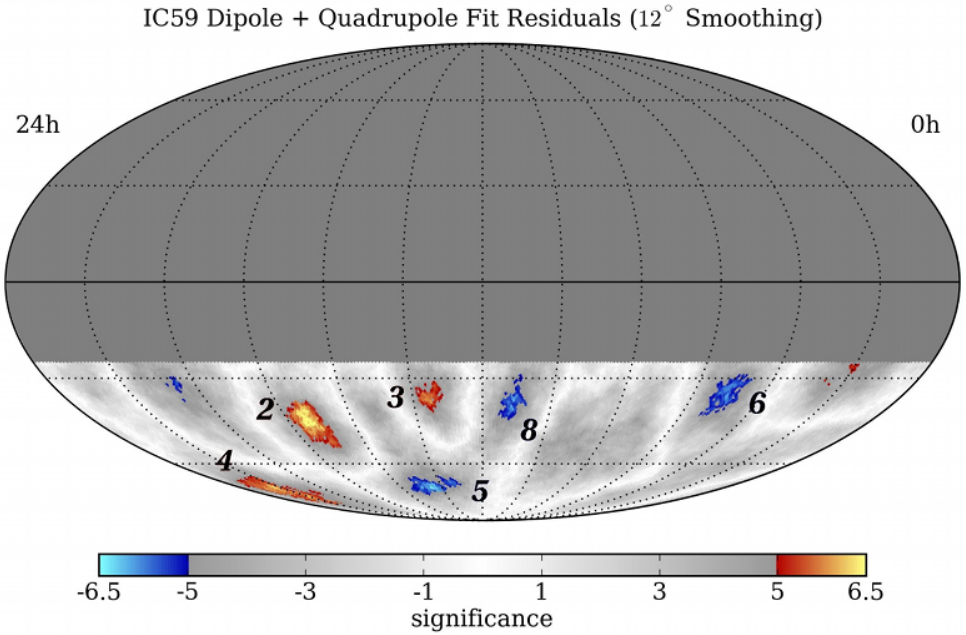


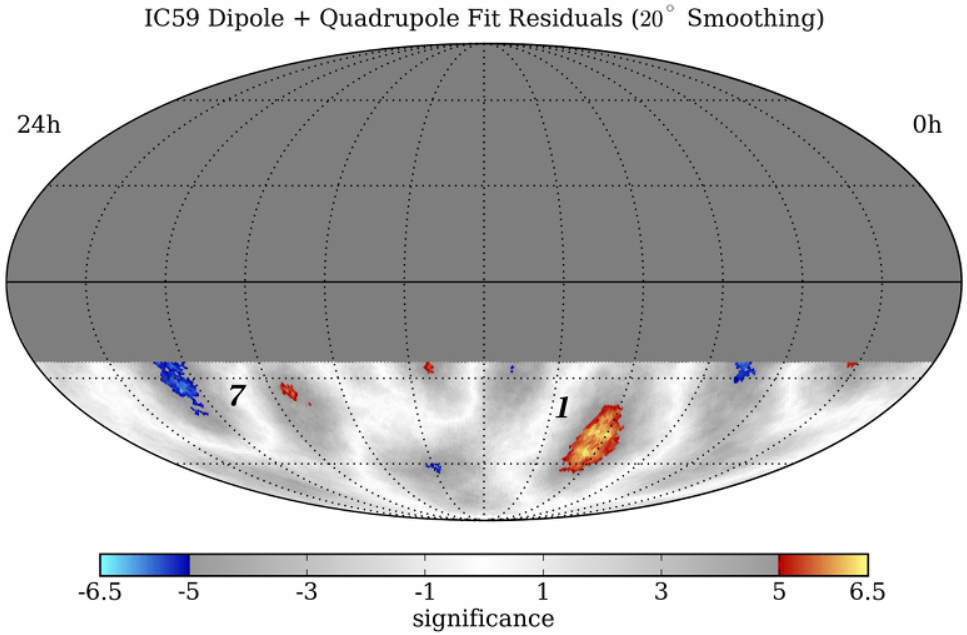
Identification of Significant Hot Spots

IC59 data: R. Abbasi et al., ApJ (in press), arXiv:1105.2326

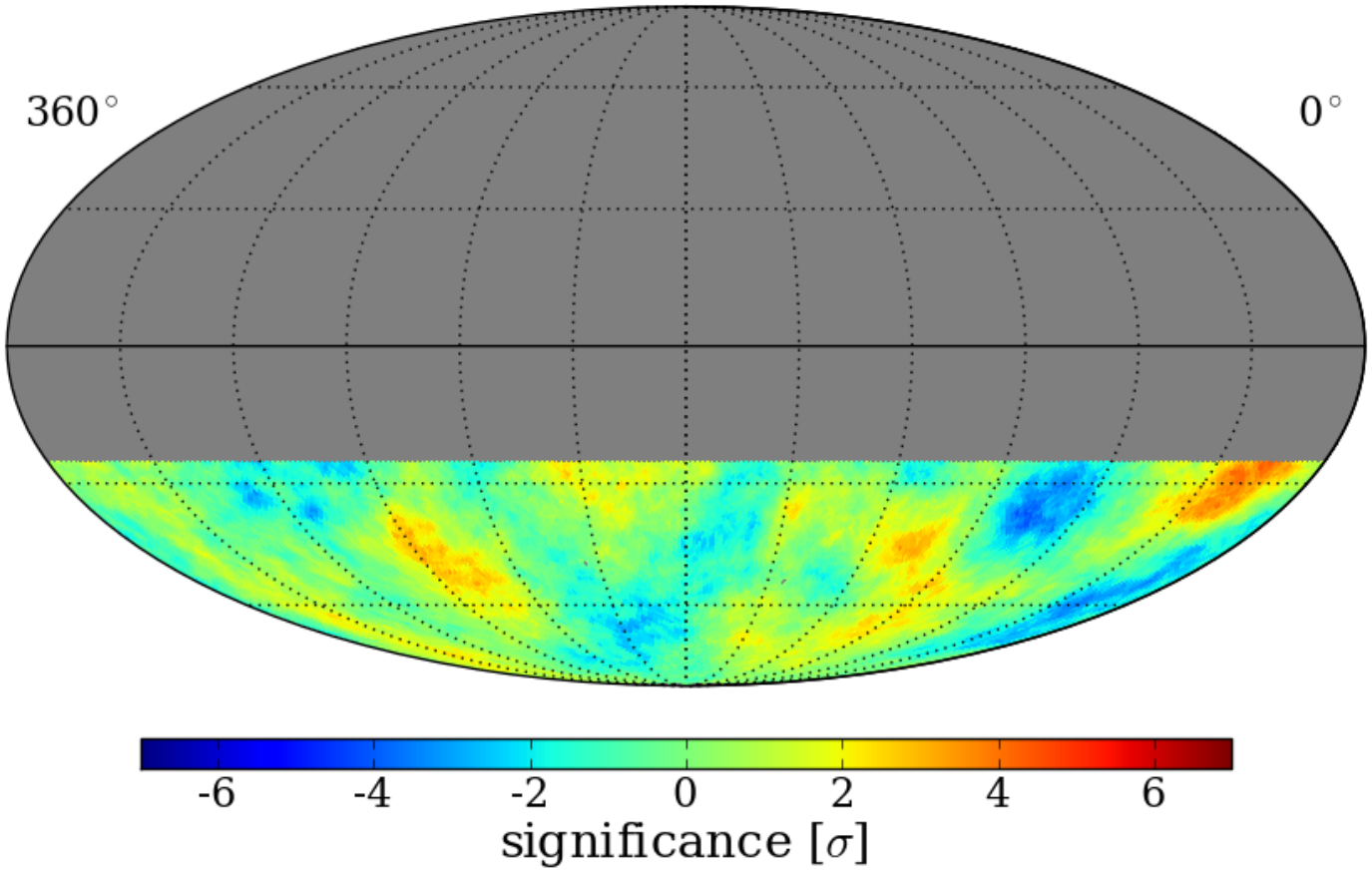
PRELIMINARY

region	right ascension	declination	optimal scale	peak significance	post-trials	IC79 (post-trials)
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ	6.8σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ	5.4σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	4.4σ	6.4σ
4	$(332.4^{+9.5}_{-7.1})^\circ$	$(-70.0^{+4.2}_{-7.6})^\circ$	12°	6.2σ	4.2σ	6.1σ
5	$(217.7^{+10.2}_{-7.8})^\circ$	$(-70.0^{+3.6}_{-2.3})^\circ$	12°	-6.4σ	-4.5σ	-6.1σ
6	$(77.6^{+3.9}_{-8.4})^\circ$	$(-31.9^{+3.2}_{-8.6})^\circ$	13°	-6.1σ	-4.1σ	-4.3σ
7	$(308.2^{+4.8}_{-7.7})^\circ$	$(-34.5^{+9.6}_{-6.9})^\circ$	20°	-6.1σ	-4.1σ	-4.4σ
8	$(166.5^{+4.5}_{-5.7})^\circ$	$(-37.2^{+5.0}_{-5.7})^\circ$	12°	-6.0σ	-4.0σ	-6.4σ

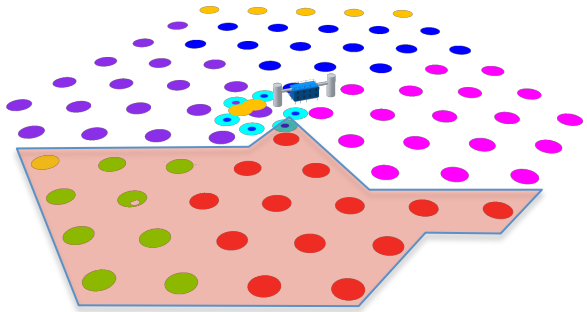




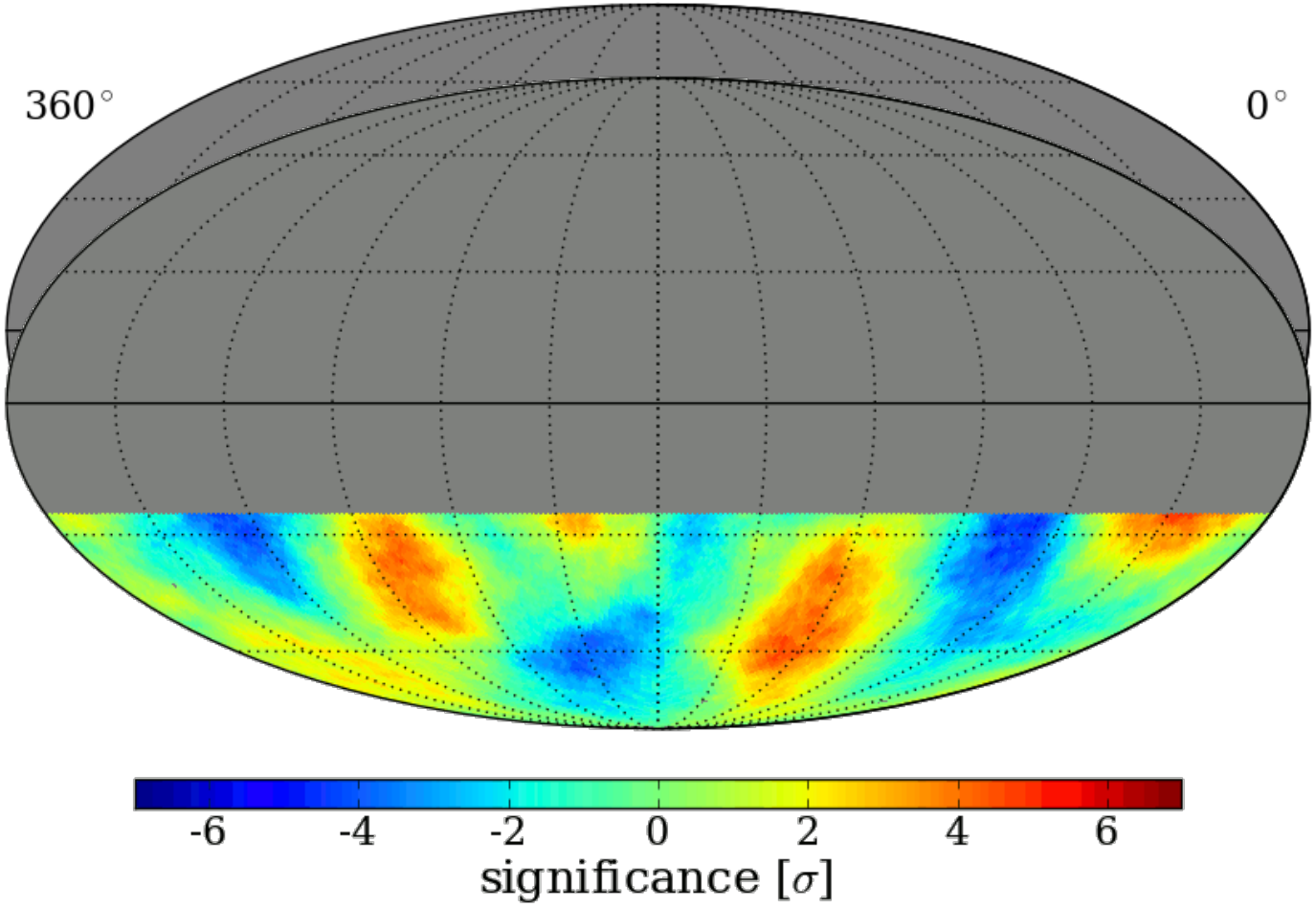
Comparison of IceCube Data Sets



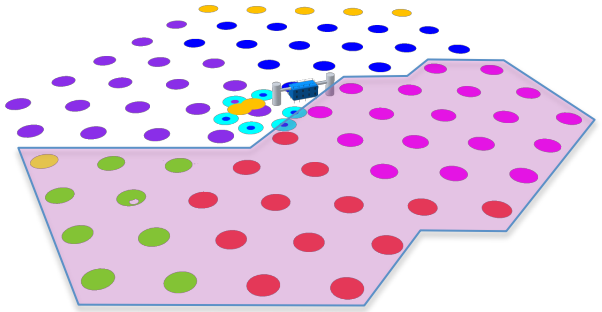
IC22 (2007-2008)



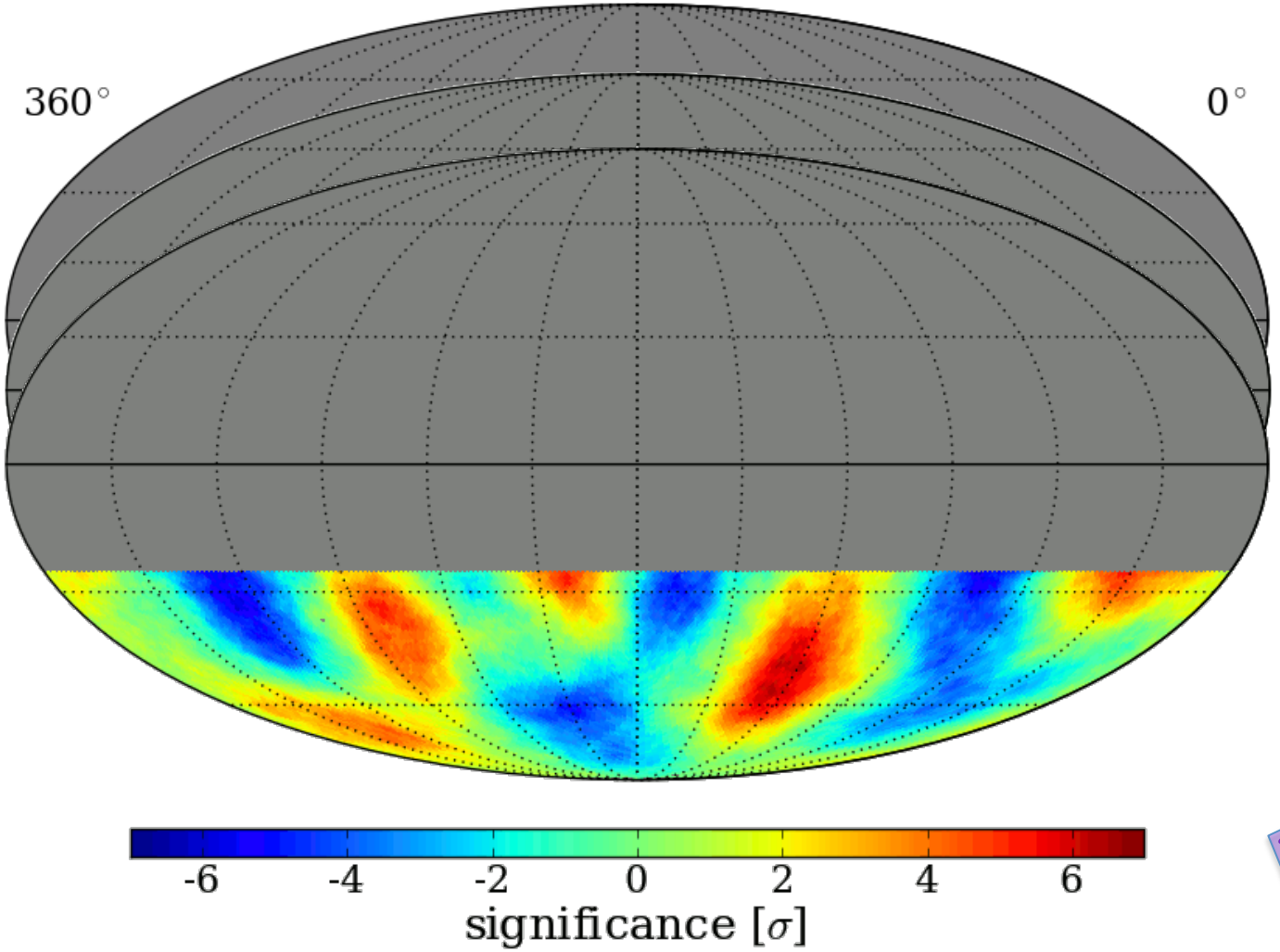
Comparison of IceCube Data Sets



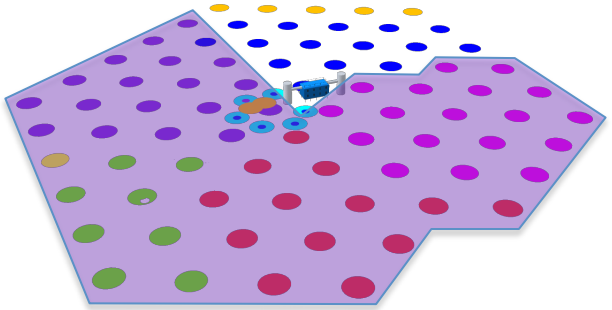
IC40 (2008-2009)



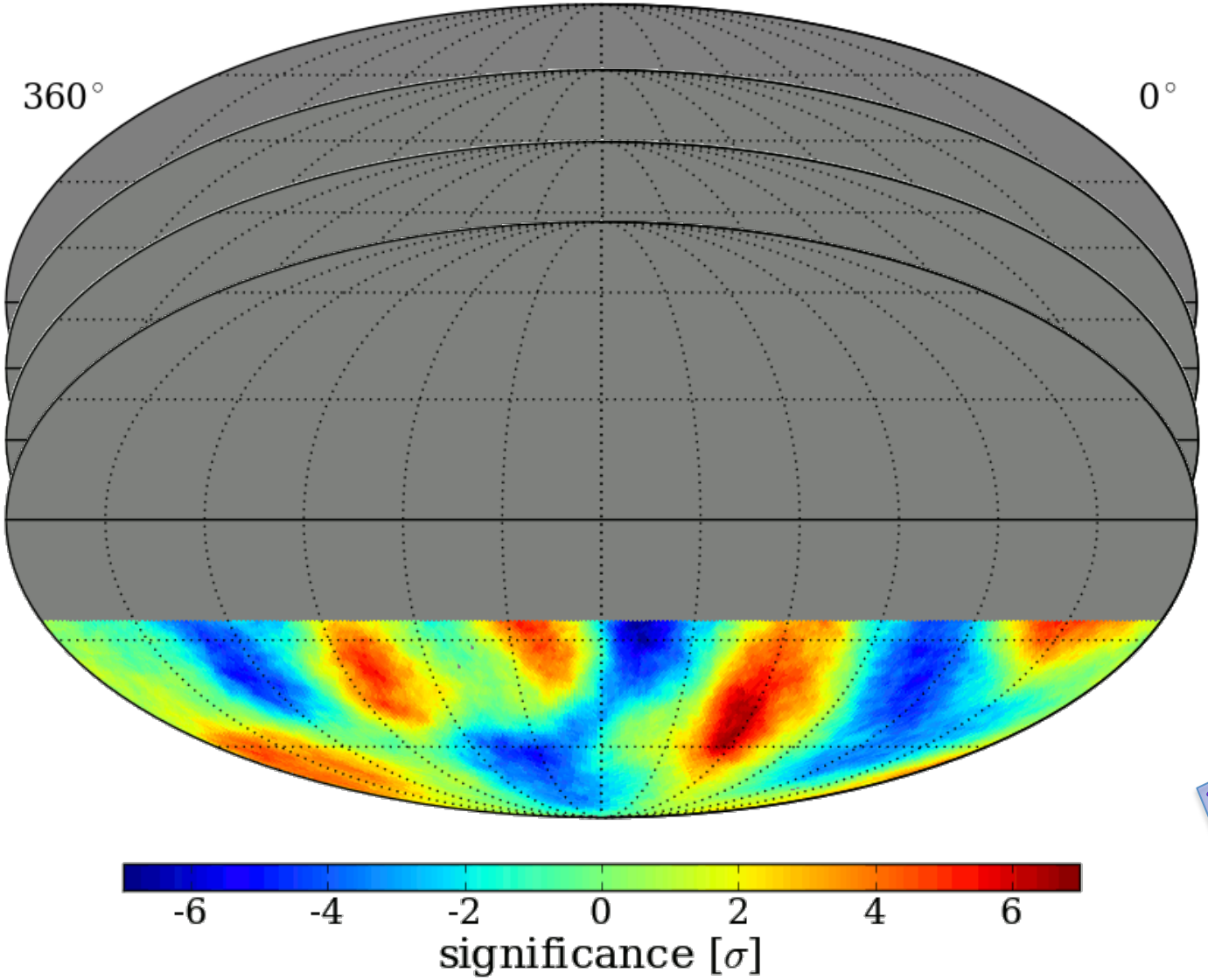
Comparison of IceCube Data Sets



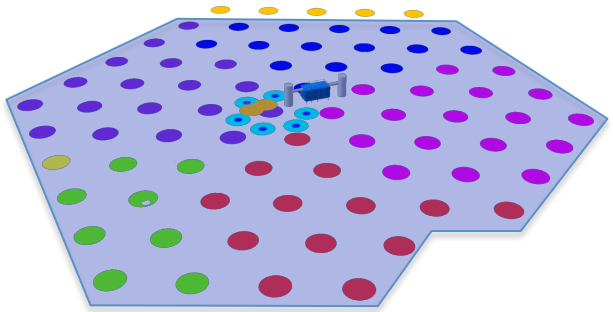
IC59 (2009-2010)



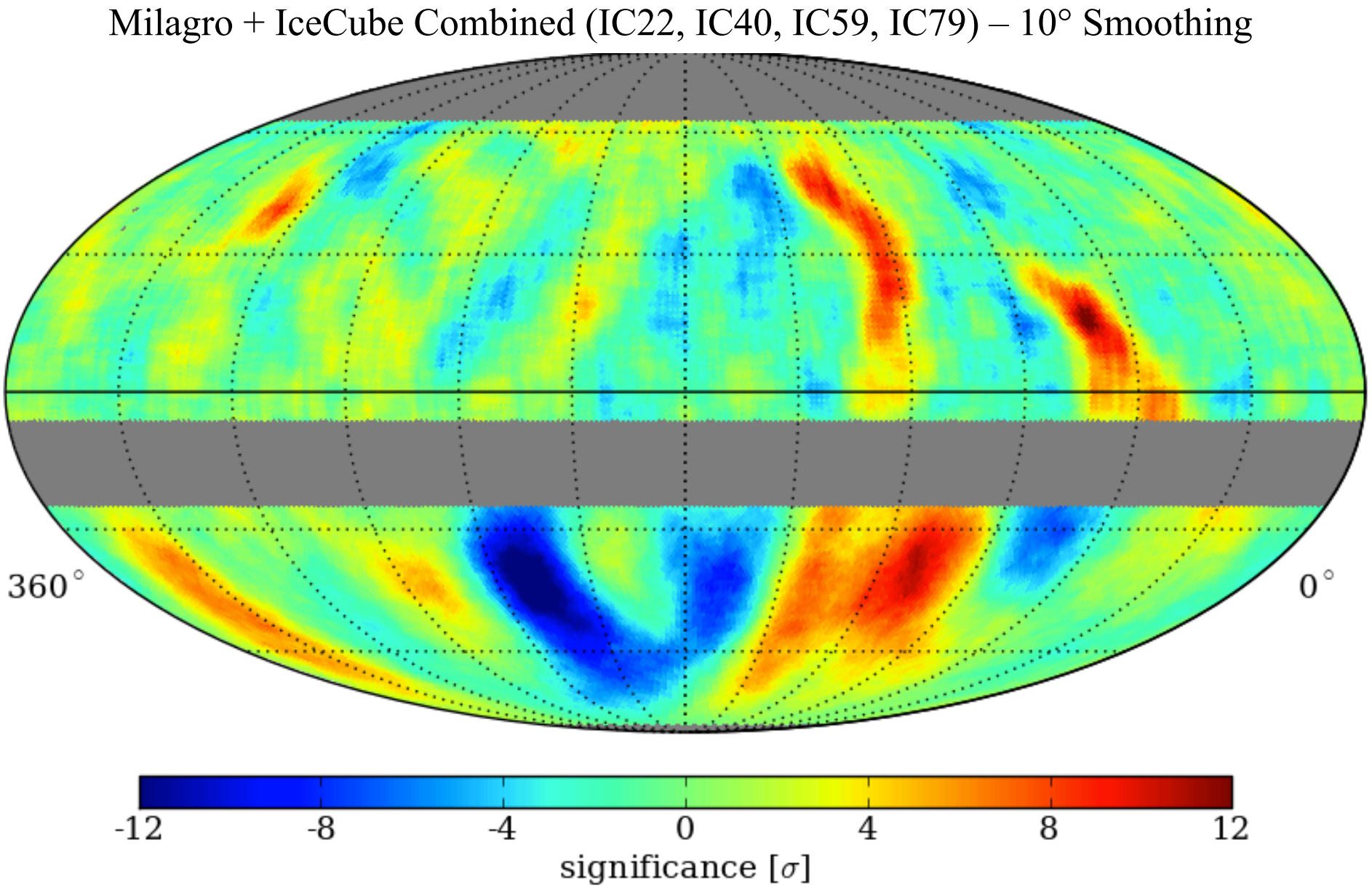
Comparison of IceCube Data Sets



IC79 (2010-2011)



Comparison to Northern Hemisphere



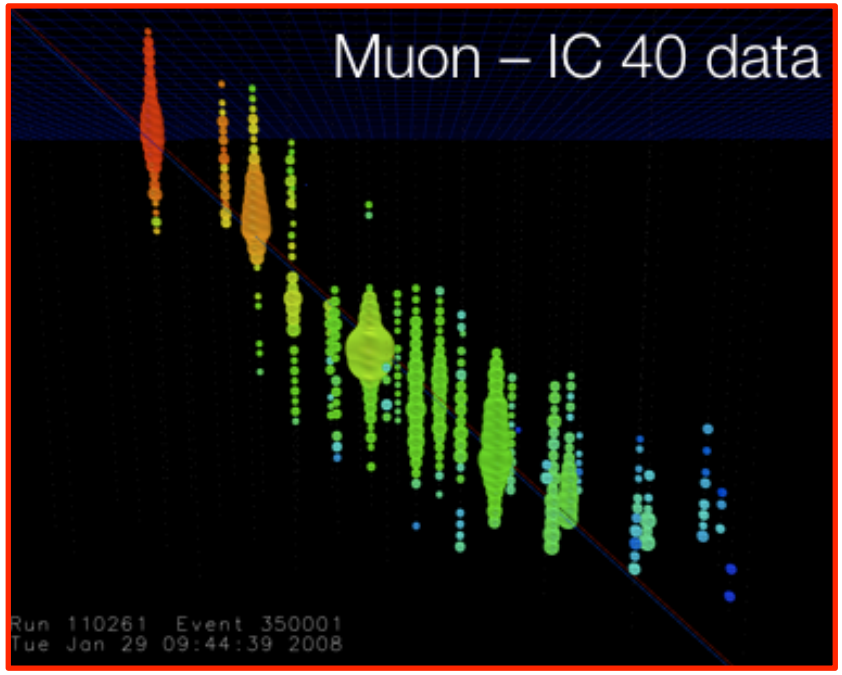
Summary

- IceCube data indicate the presence of a significant and persistent anisotropy at large and small angular scales
  - Features are similar to observations in northern sky
  - Signal is present in all data sets and grows with statistics
  - IC59 results are in press (ApJ): see also arXiv:1105.2326

- Origin: galactic or heliospheric?
  - IceCube will operate for most of the next solar cycle and is well-positioned to search for heliospheric effects

- The energy-dependence of the anisotropy has also been investigated. See talk by R. Abbasi (HE 1.1, Aug. 13)

The Cosmic Ray Data Set



- **D**ata **S**ummary and **T**ransfer (DST) filter: fast online reconstruction of events passing simple majority trigger (mostly muons)
- Trade-off: quality of reconstruction for large statistics

IceCube-59	L1 Muon Filter	DST
Live Time	96%	96%
Trigger rate	35 Hz	1.4 kHz
N_{events}	8.0×10^{8}	3.2×10^{10}
Angular resolution	<1°	3°
Energy resolution	$\Delta \log_{10}(E_{\mu}) = 0.2 - 0.3$	$\Delta \log_{10}(E_{CR}) = 0.5$