



Anisotropy of TeV cosmic rays in IceCube and IceTop

Marcos Santander

University of Wisconsin-Madison

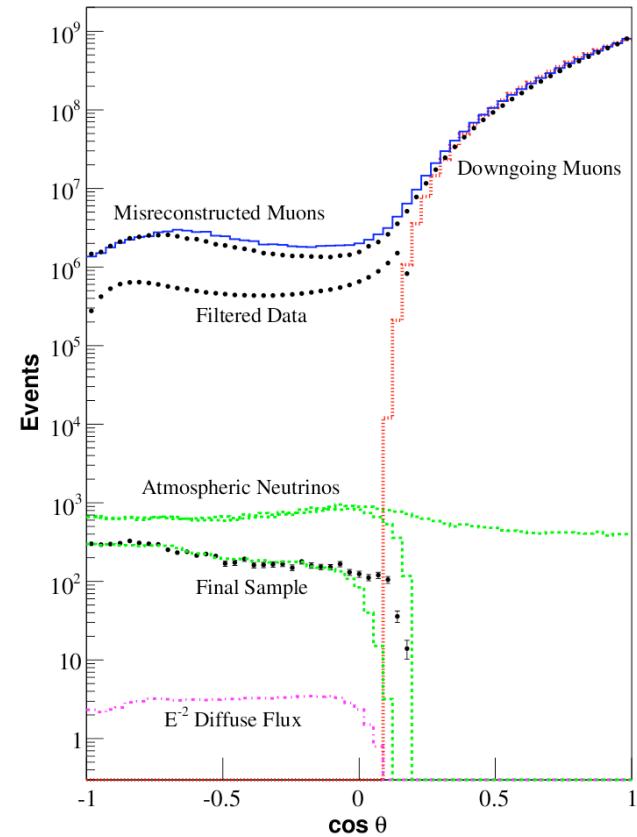
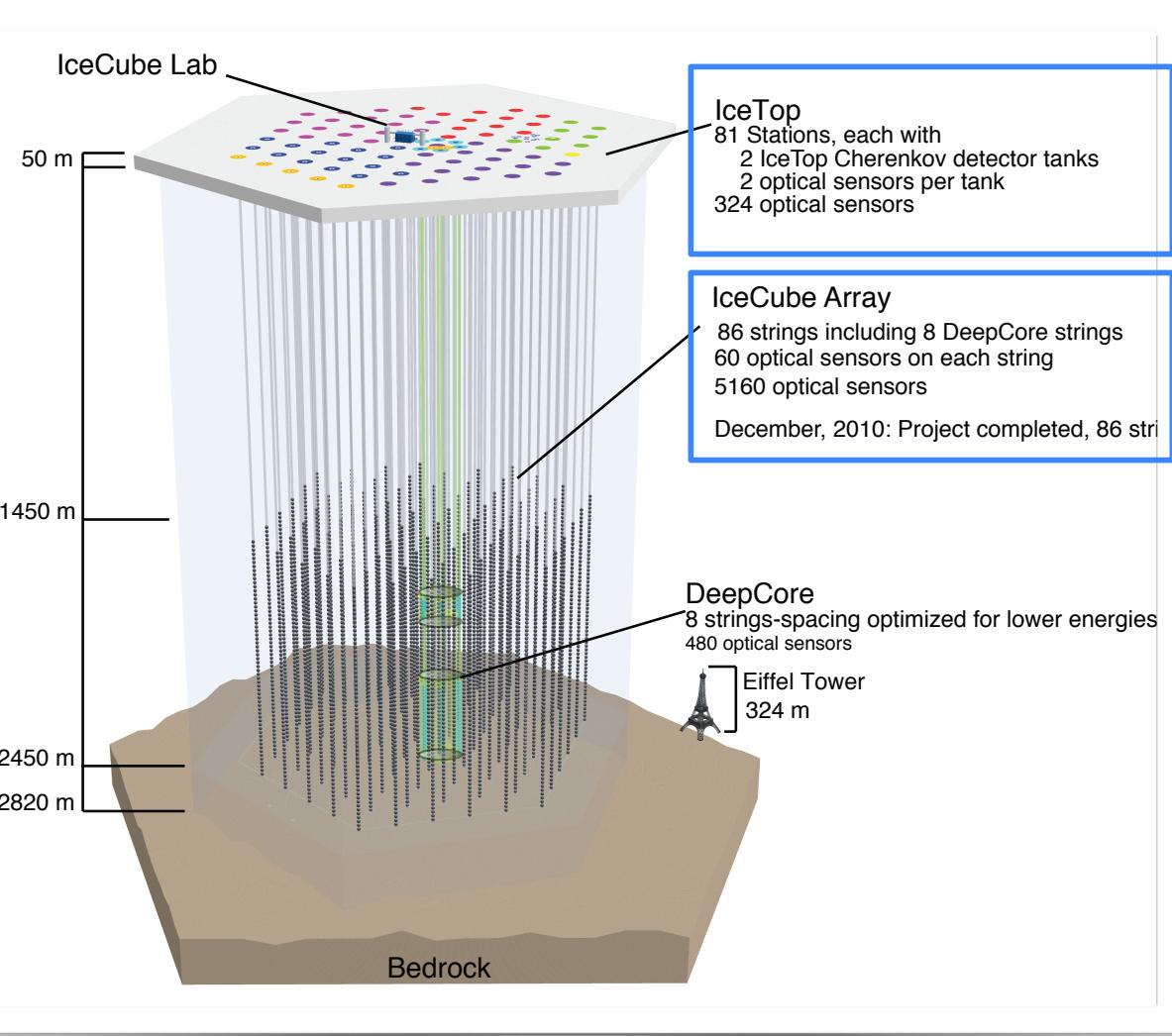


Outline

- Cosmic rays & IceCube
- Large scale and small scale anisotropy
- Anisotropy at high energies with IceCube
- Preliminary anisotropy results from IceTop



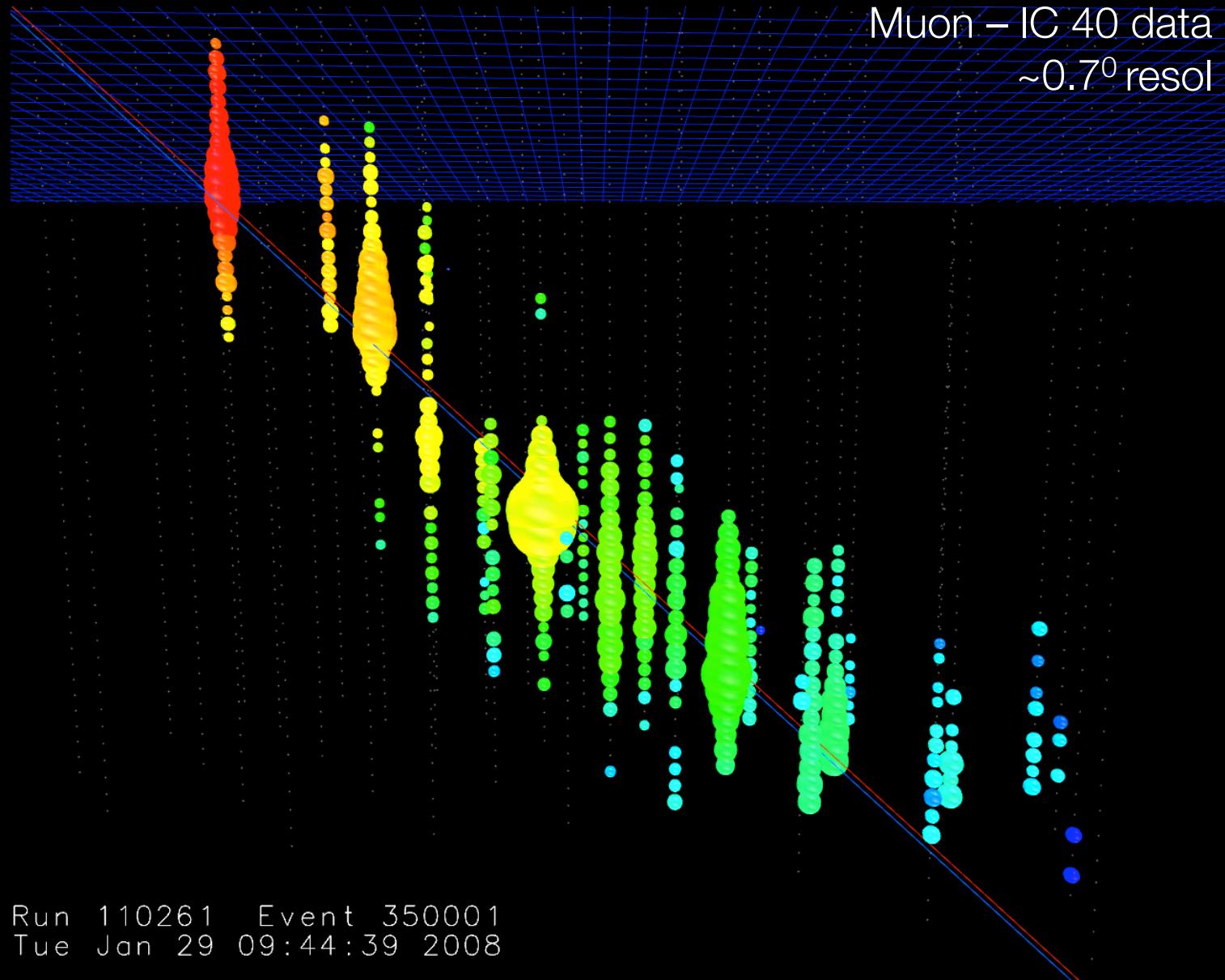
Cosmic rays in IceCube



IC86 μ rate = 2 kHz
($\sim 10^6$ ν rate)

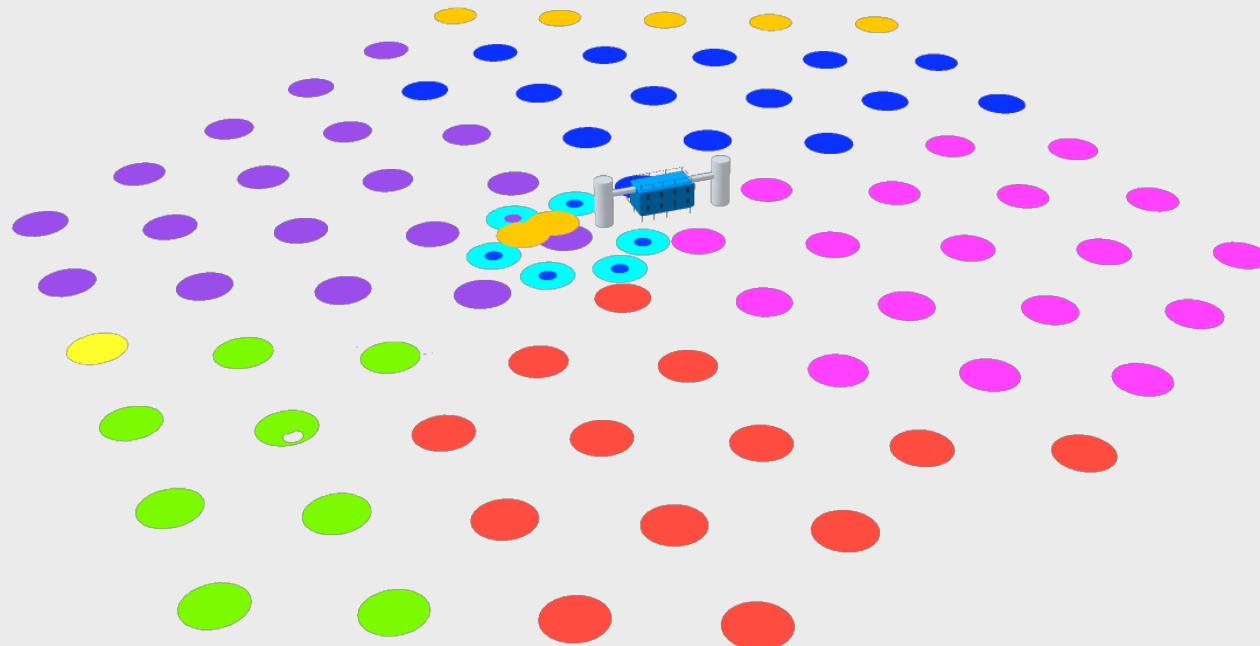


Muon event in IceCube





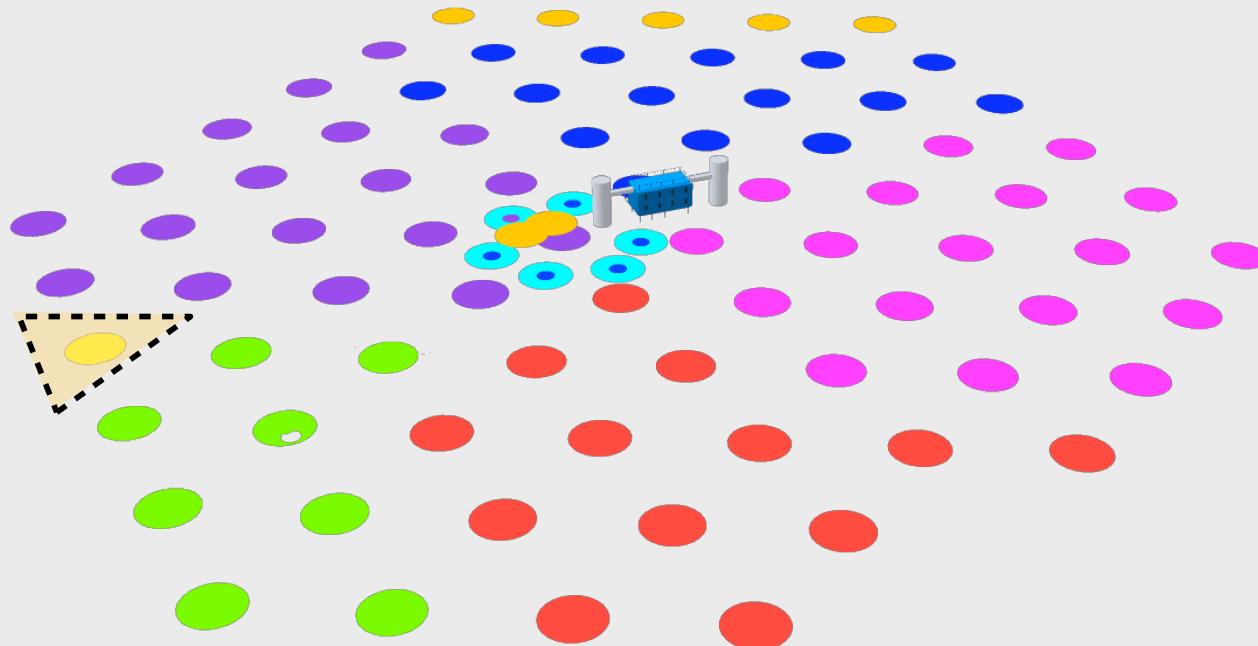
IceCube configurations





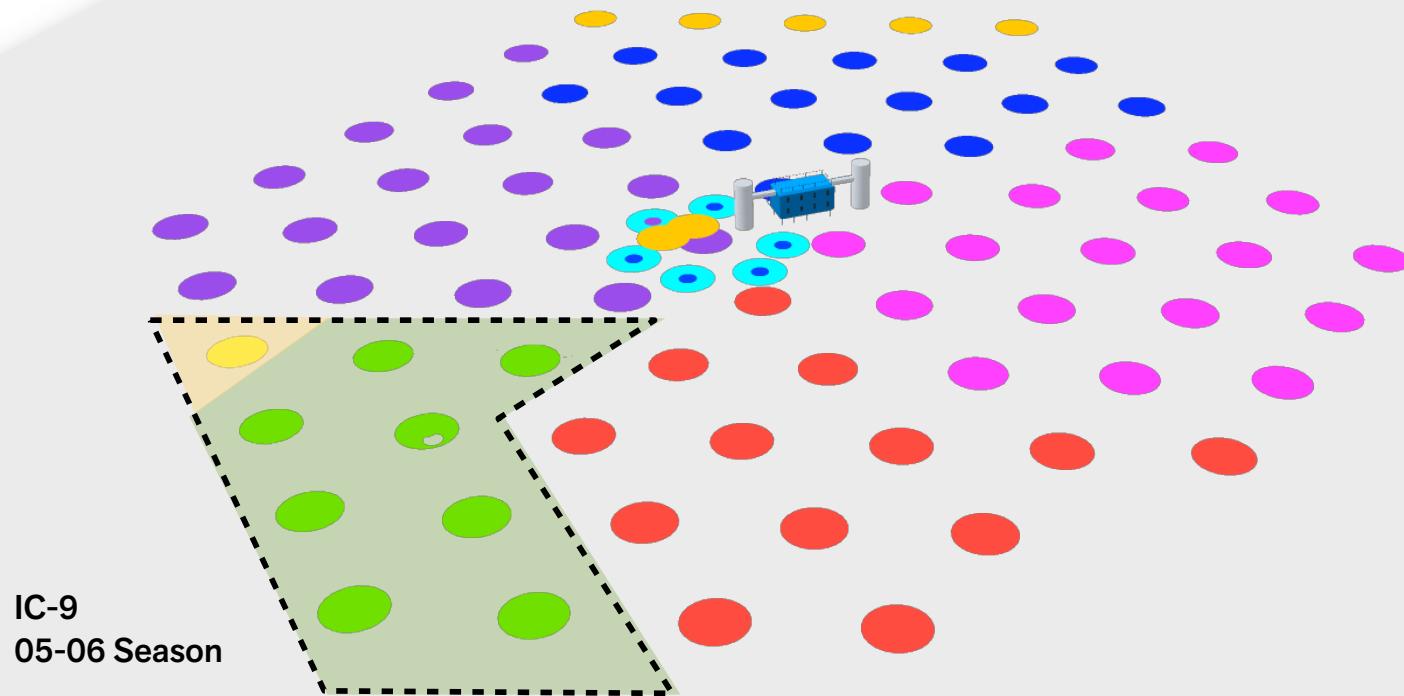
IceCube configurations

IC-1
04-05 Season



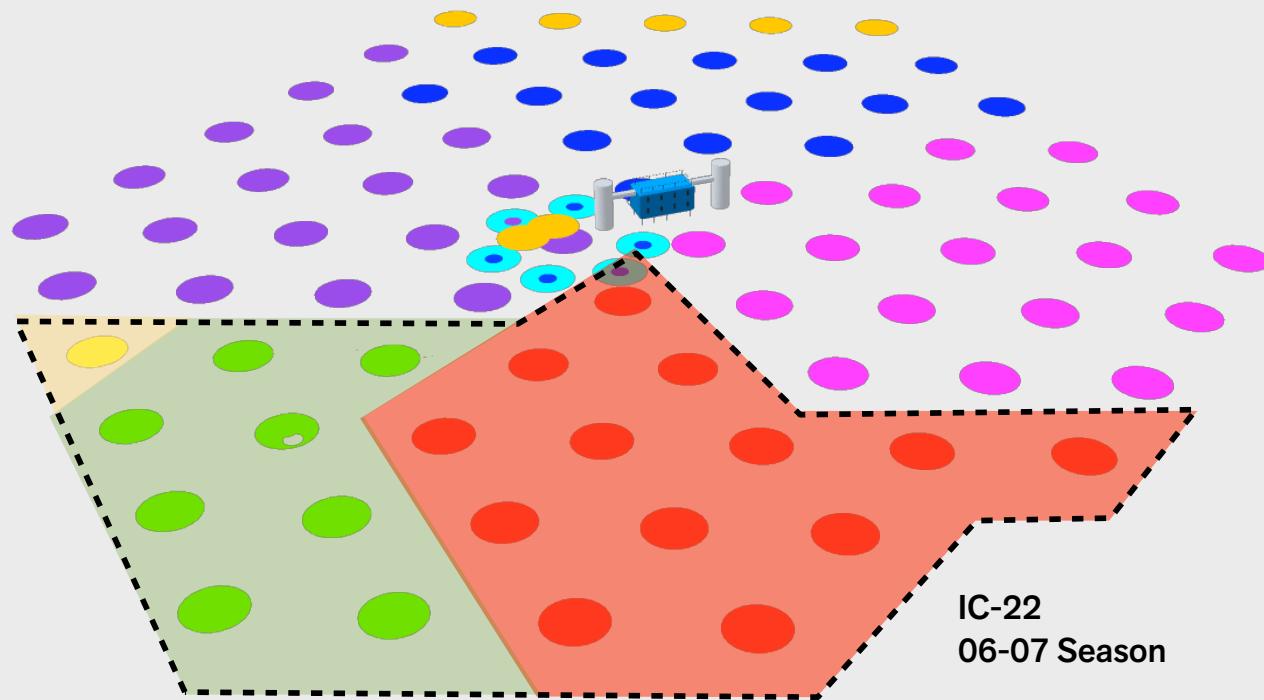


IceCube configurations



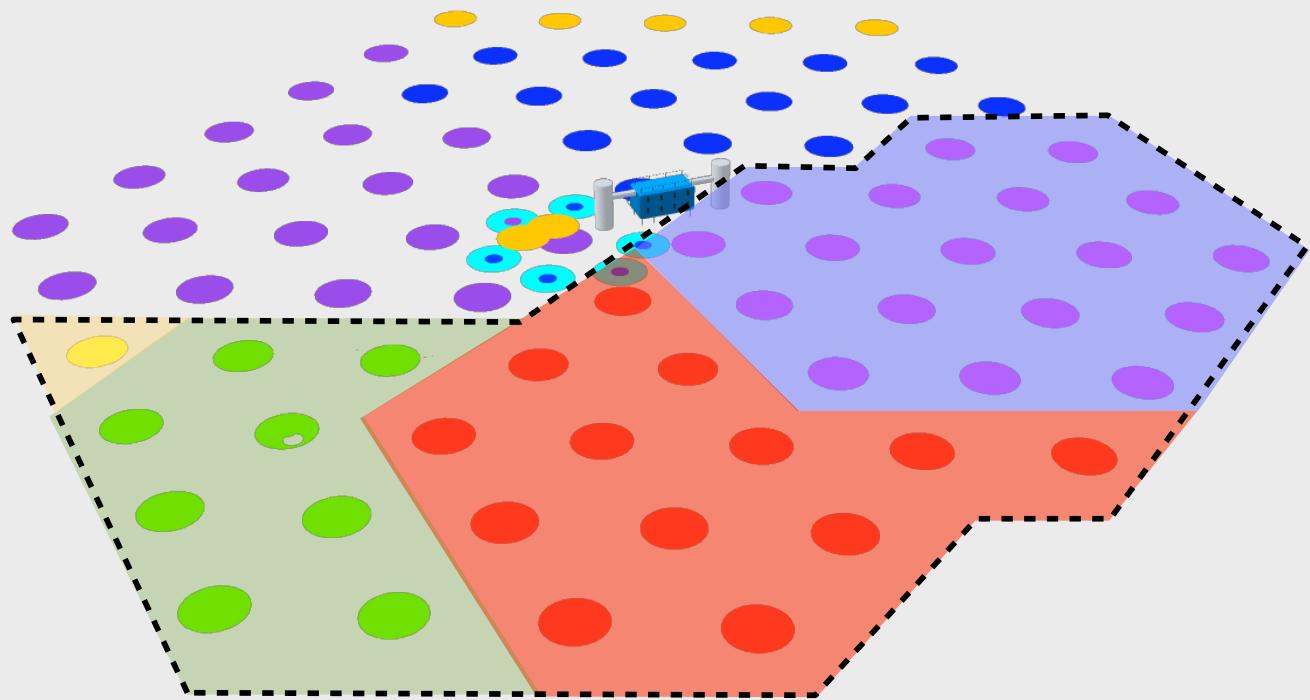


IceCube configurations





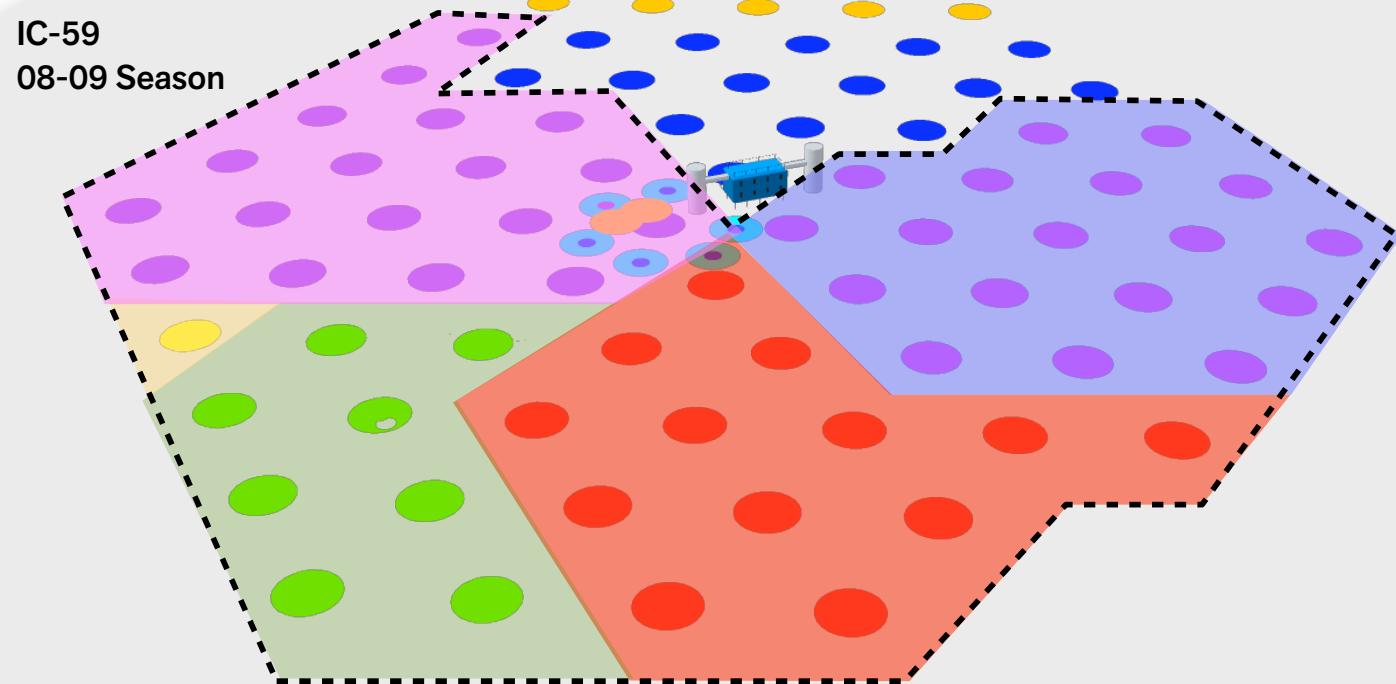
IceCube configurations



IC-40
07-08 Season

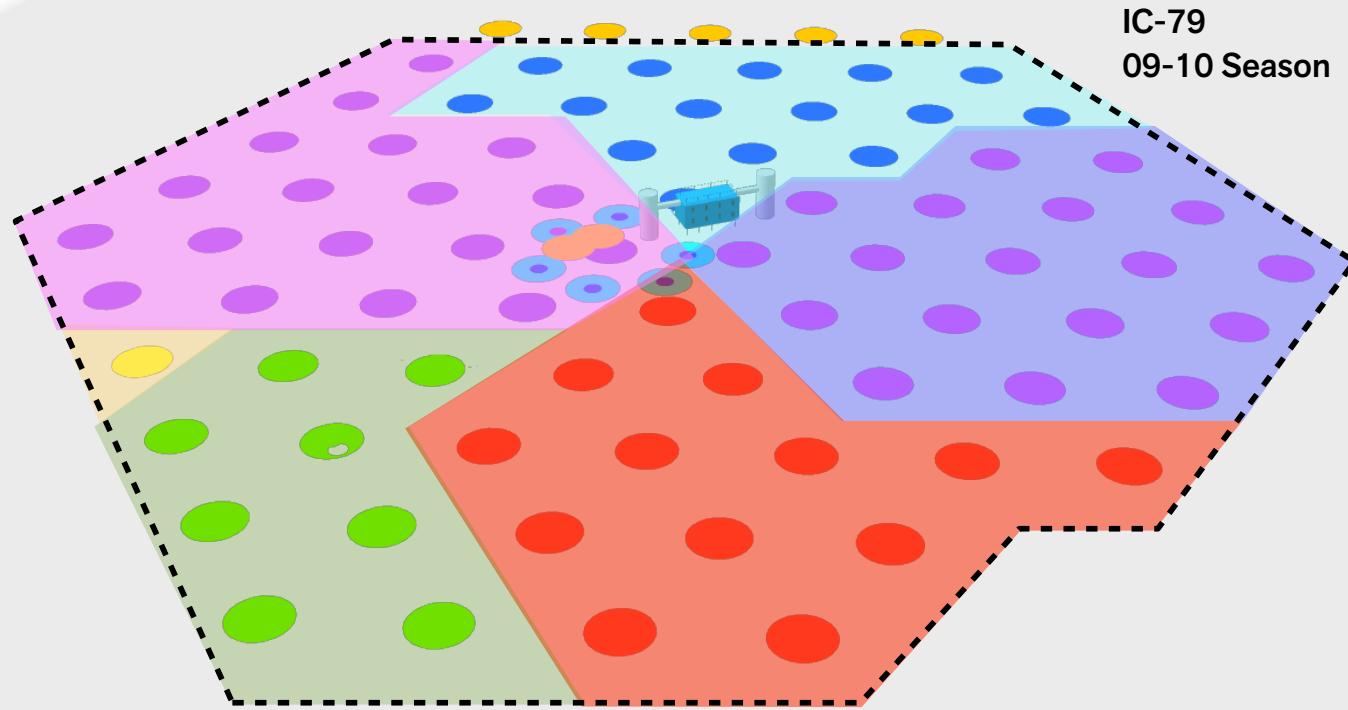


IceCube configurations



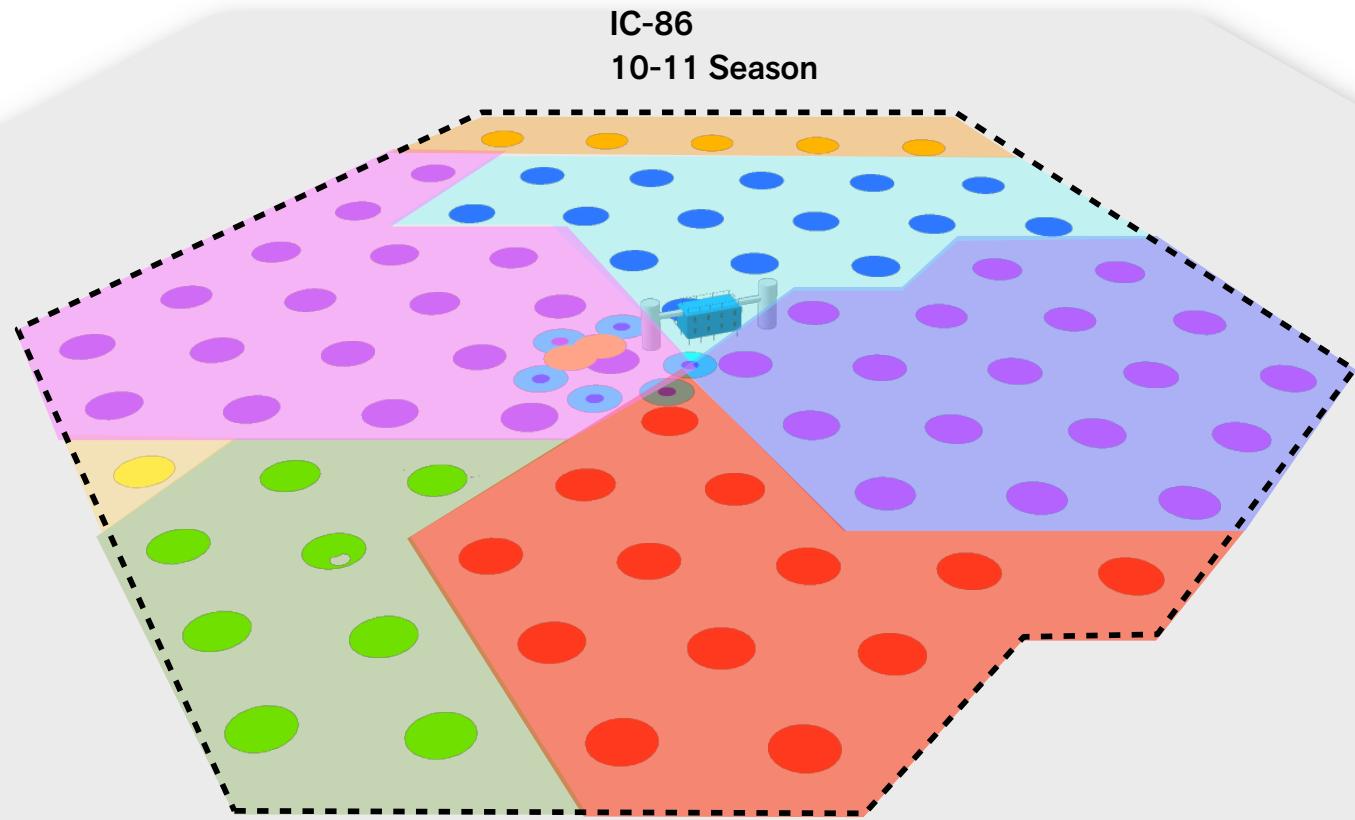


IceCube configurations





IceCube configurations



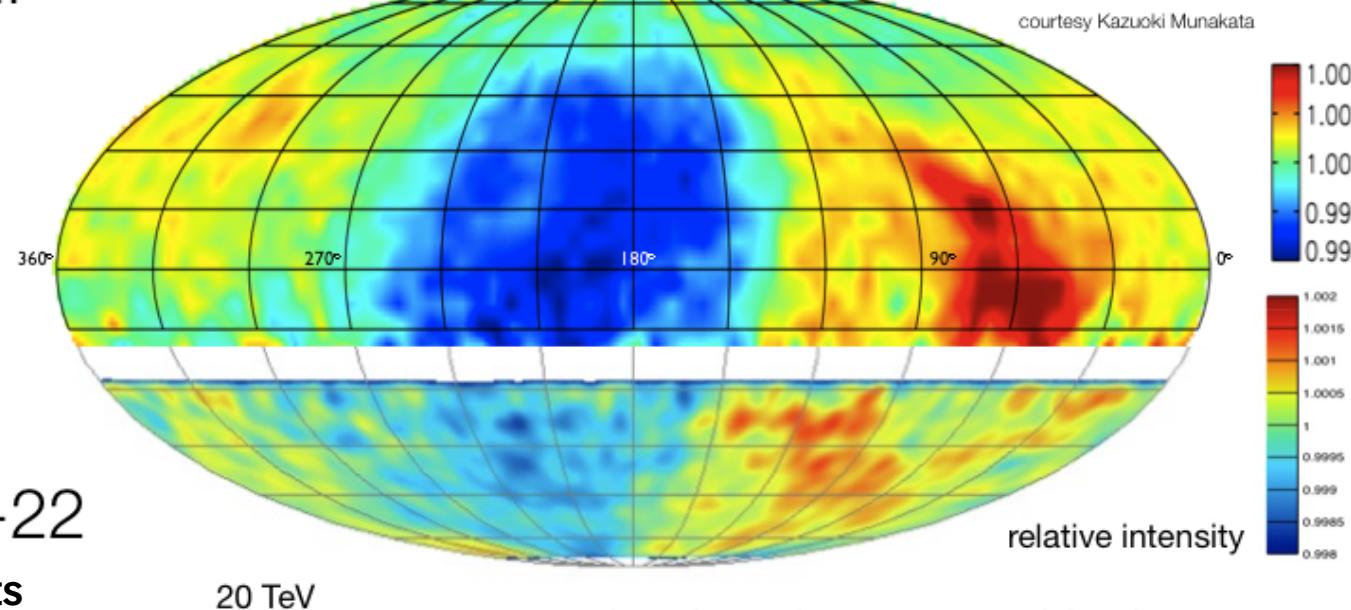


Large scale anisotropy with IceCube

Tibet-III

5 TeV

courtesy Kazuoki Munakata



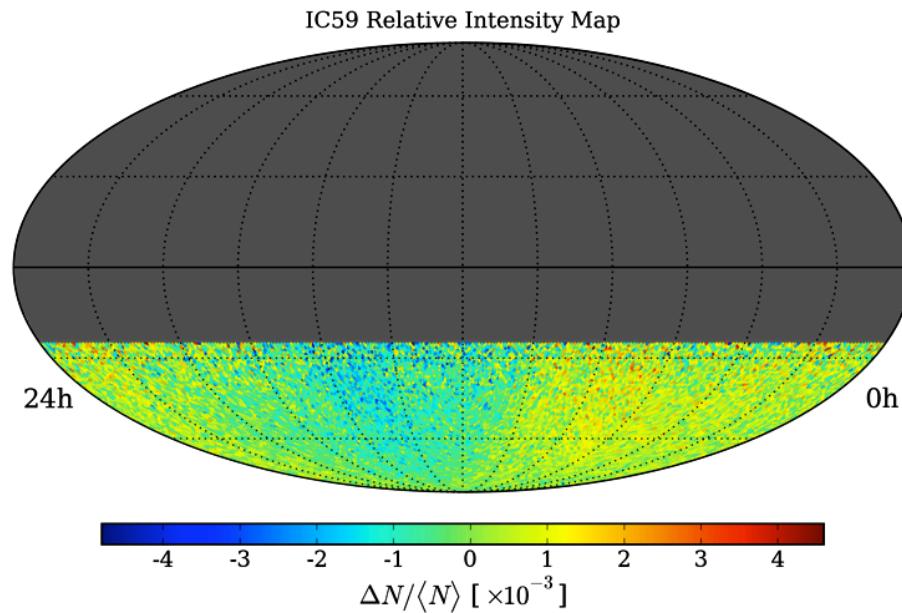
Abbasi et al., ApJ, 718, L194, 2010
arxiv/1005.2960

- $\sim 10^{-3}$ anisotropy observed in the South
- Good match to observations in the North

IC59 relative intensity map

HealPix map

Equal area pixels ($\sim 0.9^\circ$ spacing)



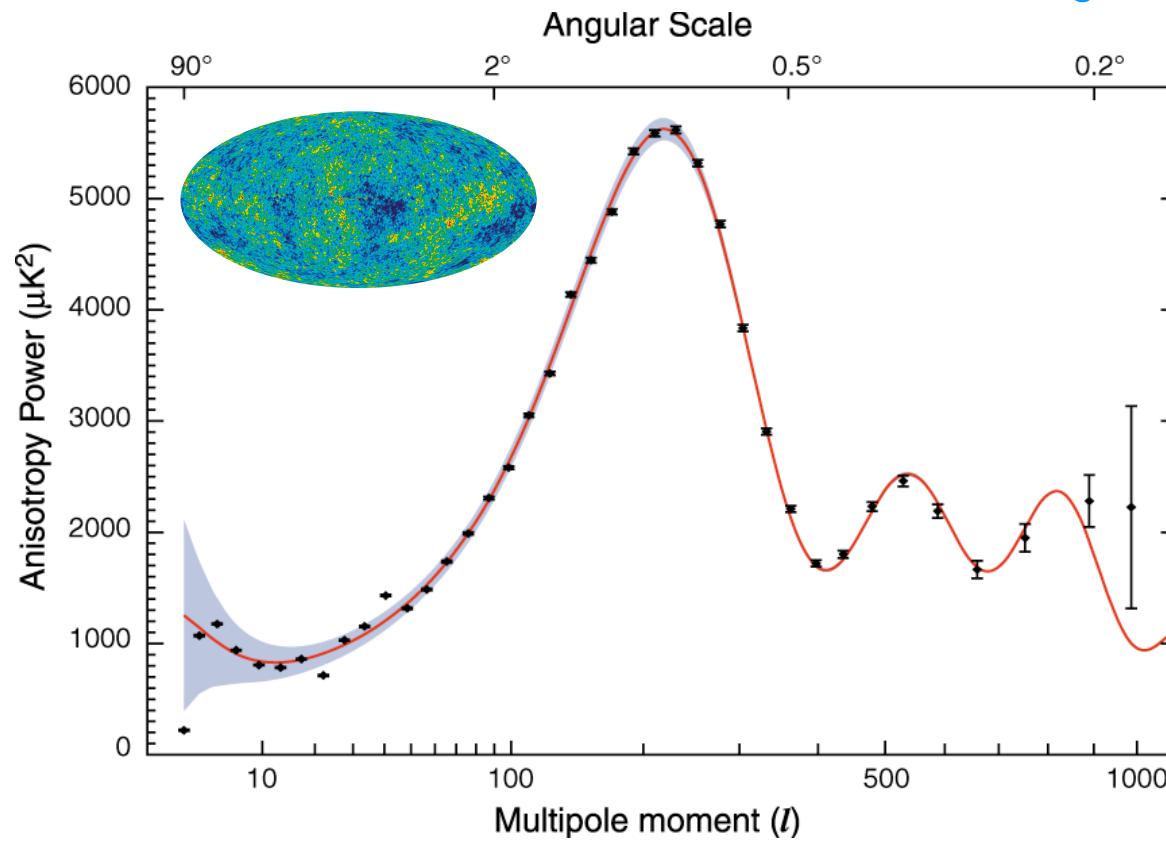
- IC59 data (5.6×10^{10} events, 20 TeV)
- N_i events in the i th pixel
- $\langle N_i \rangle$ expected number of events for an isotropic sky (24 hr time scrambling)
- Relative intensity:

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

> Relative intensity map is **not isotropic** (IC 22 large scale structure)

Power spectrum

Angular size $\theta \sim \frac{180^\circ}{\ell}$

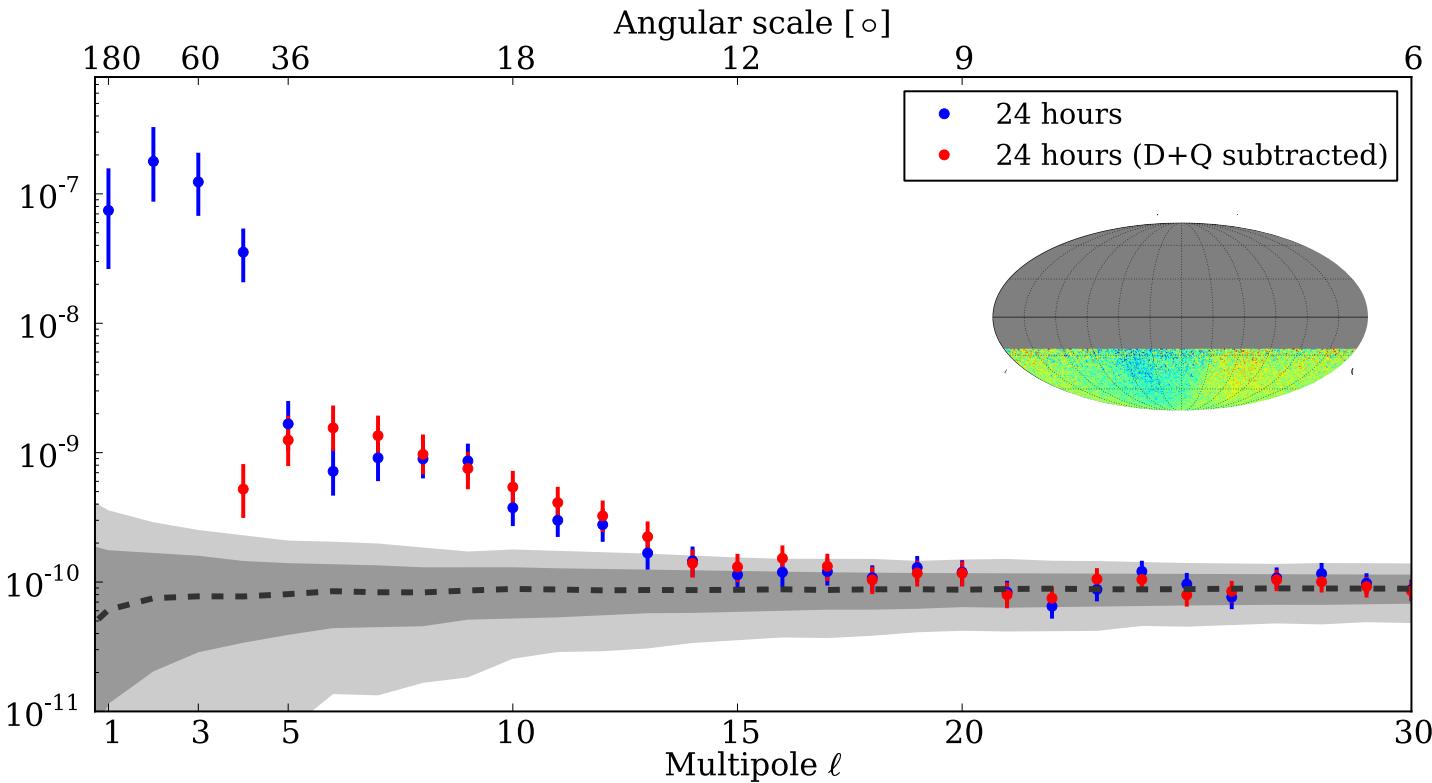


Multipole expansion

$$\delta I(\mathbf{u}_i) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{u}_i) \quad \mathcal{C}_{\ell} = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

Power spectrum

Angular size $\theta \sim \frac{180^\circ}{\ell}$



Multipole expansion

$$\delta I(\mathbf{u}_i) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{u}_i) \quad \mathcal{C}_{\ell} = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

Dipole and quadrupole subtraction

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

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

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

monopole

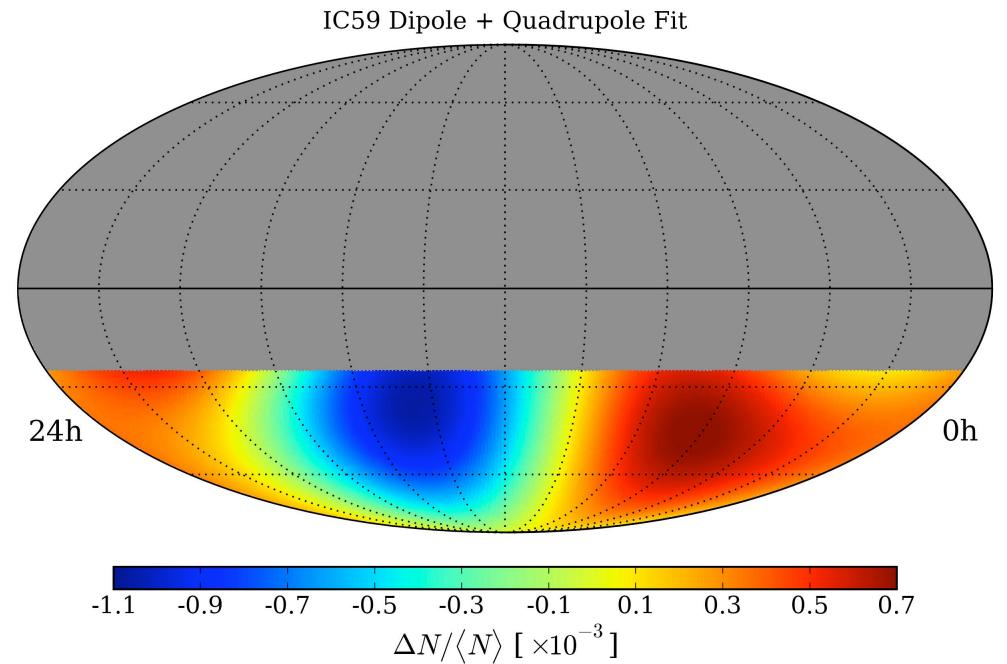
dipole

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

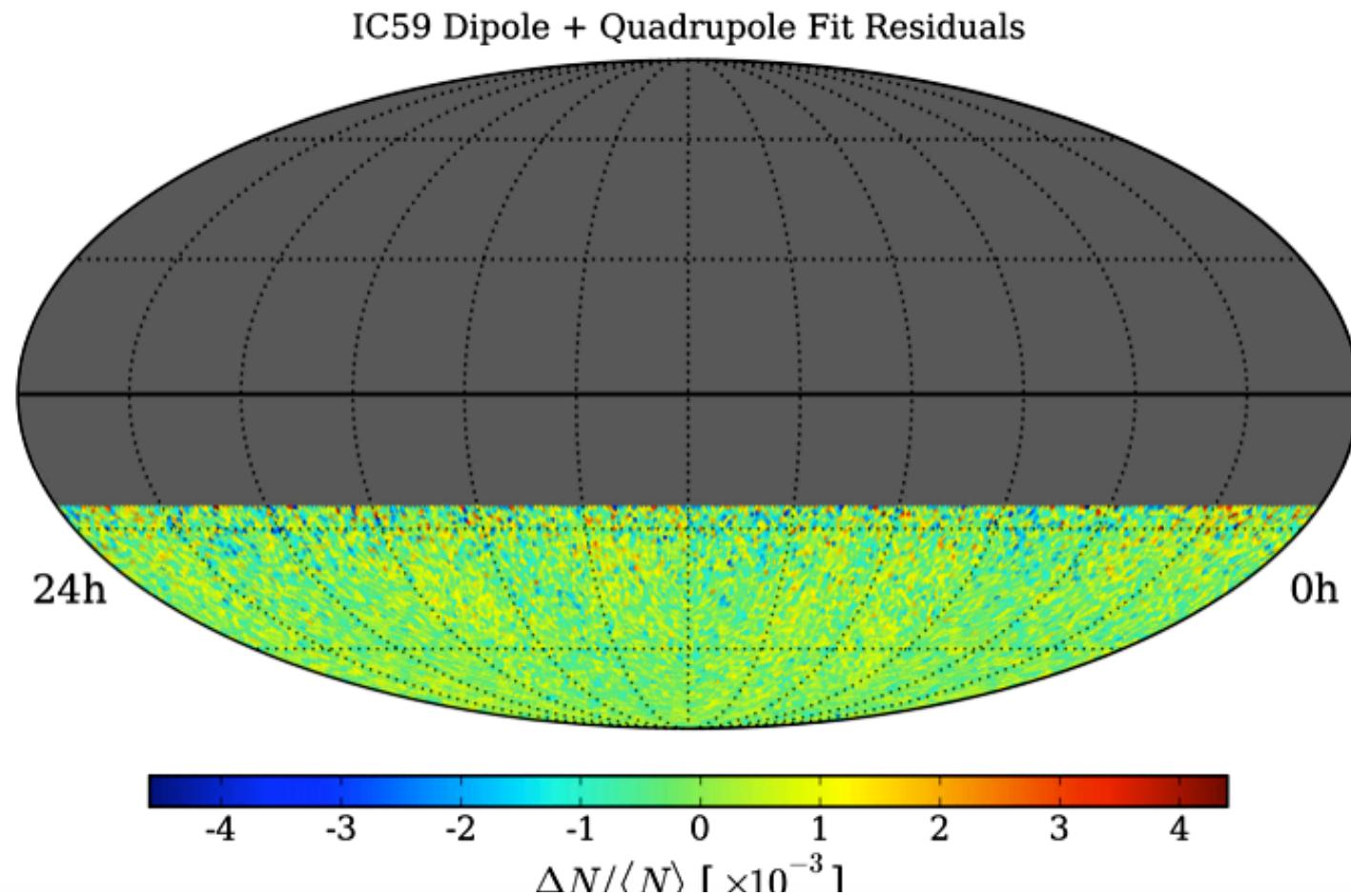
$$\chi^2/\text{ndf} = 14743.4/14187$$

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



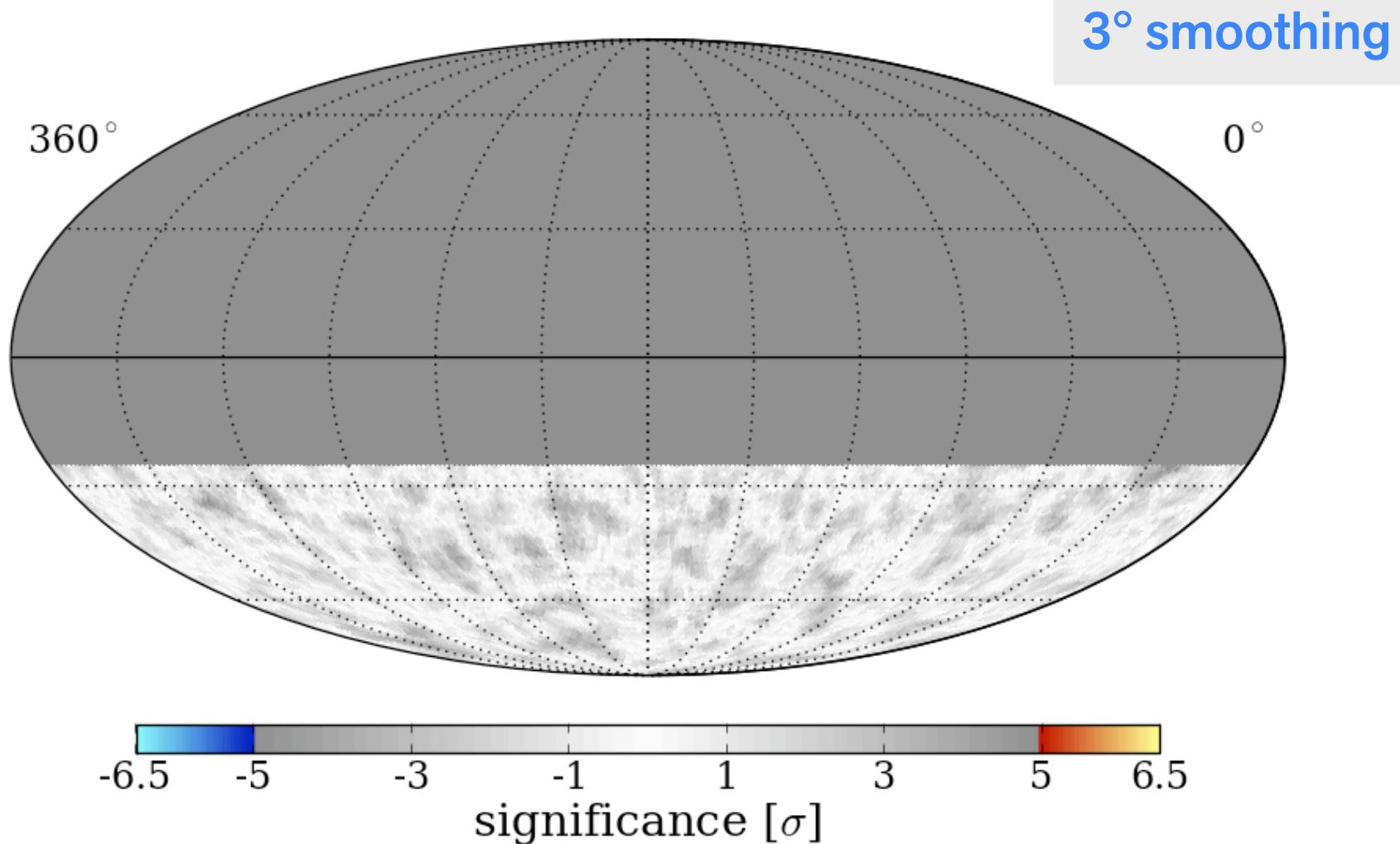


Fit residuals map



> Anisotropy not immediately visible (**smoothing needed**)

Map smoothing scan

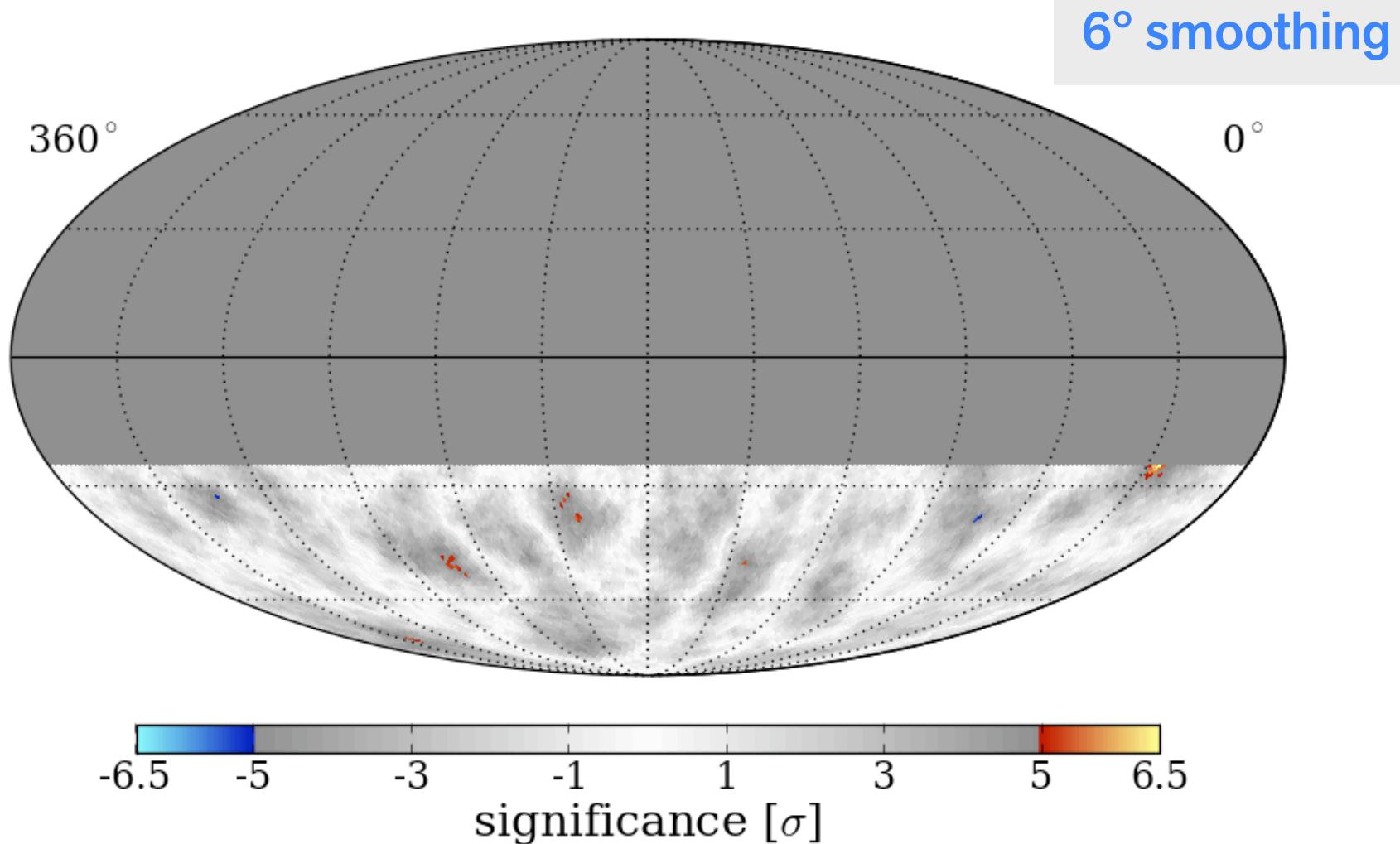


Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

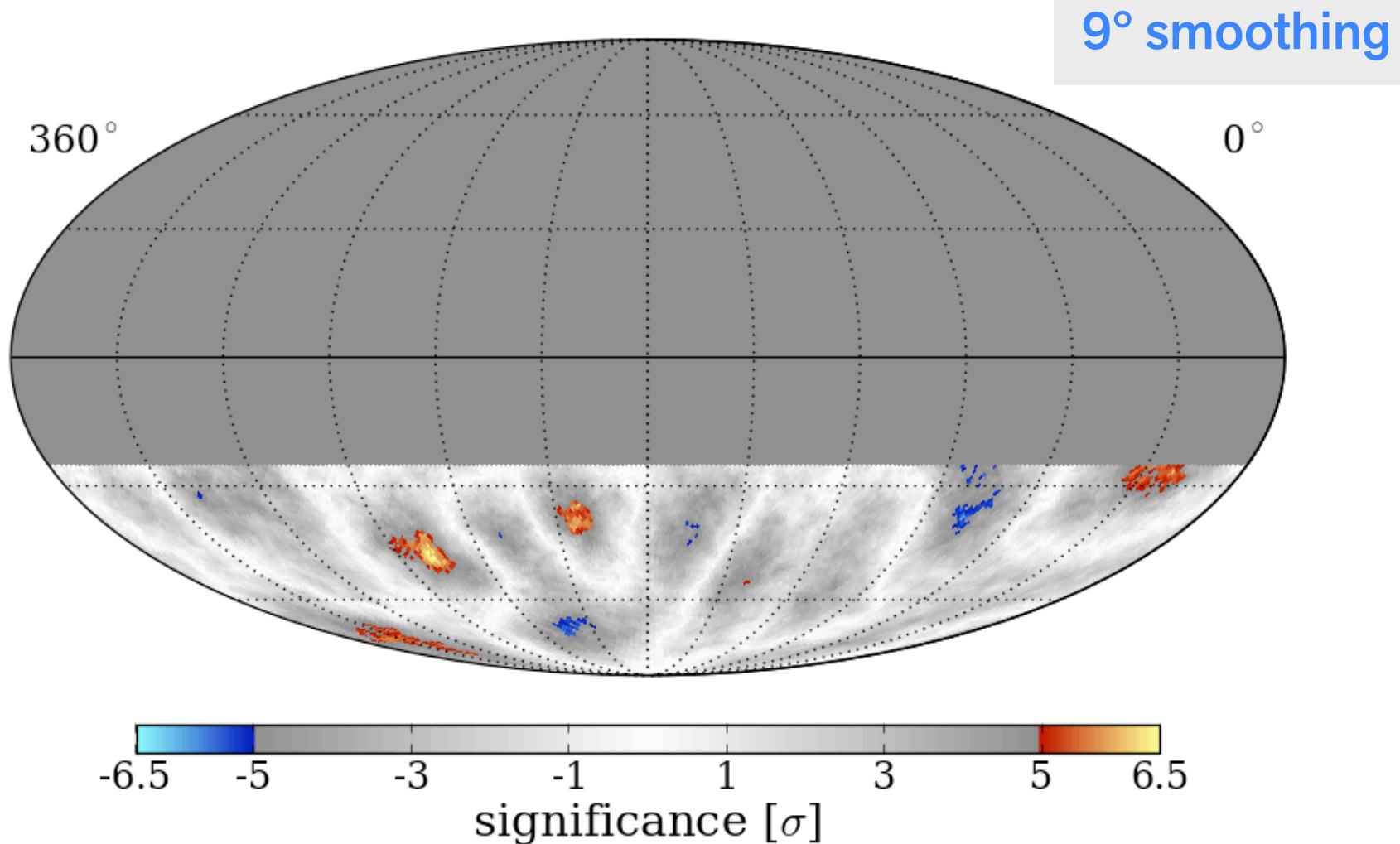


Scan from 1 - 30° in smoothing

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Map smoothing scan



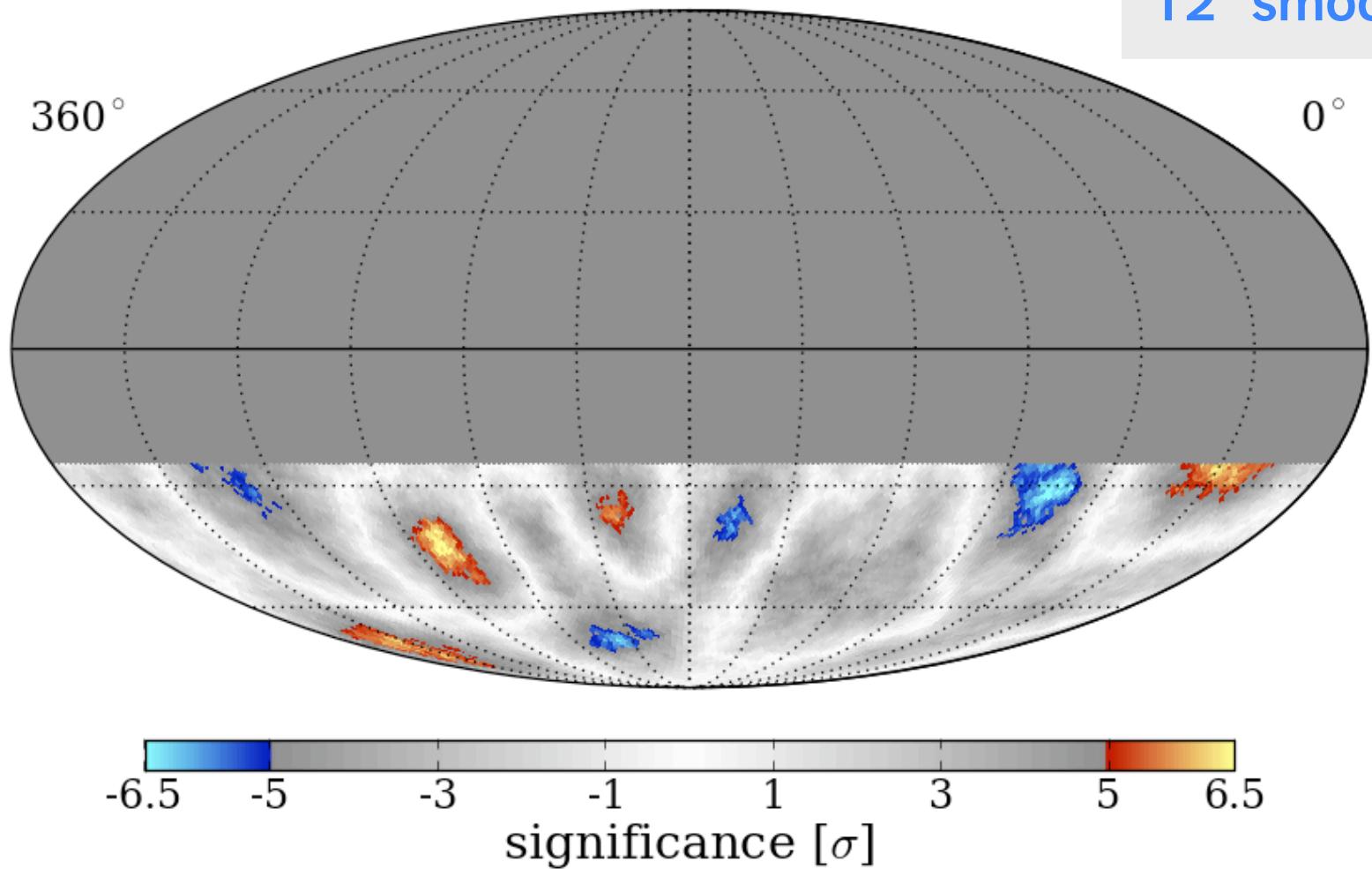
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

12° smoothing



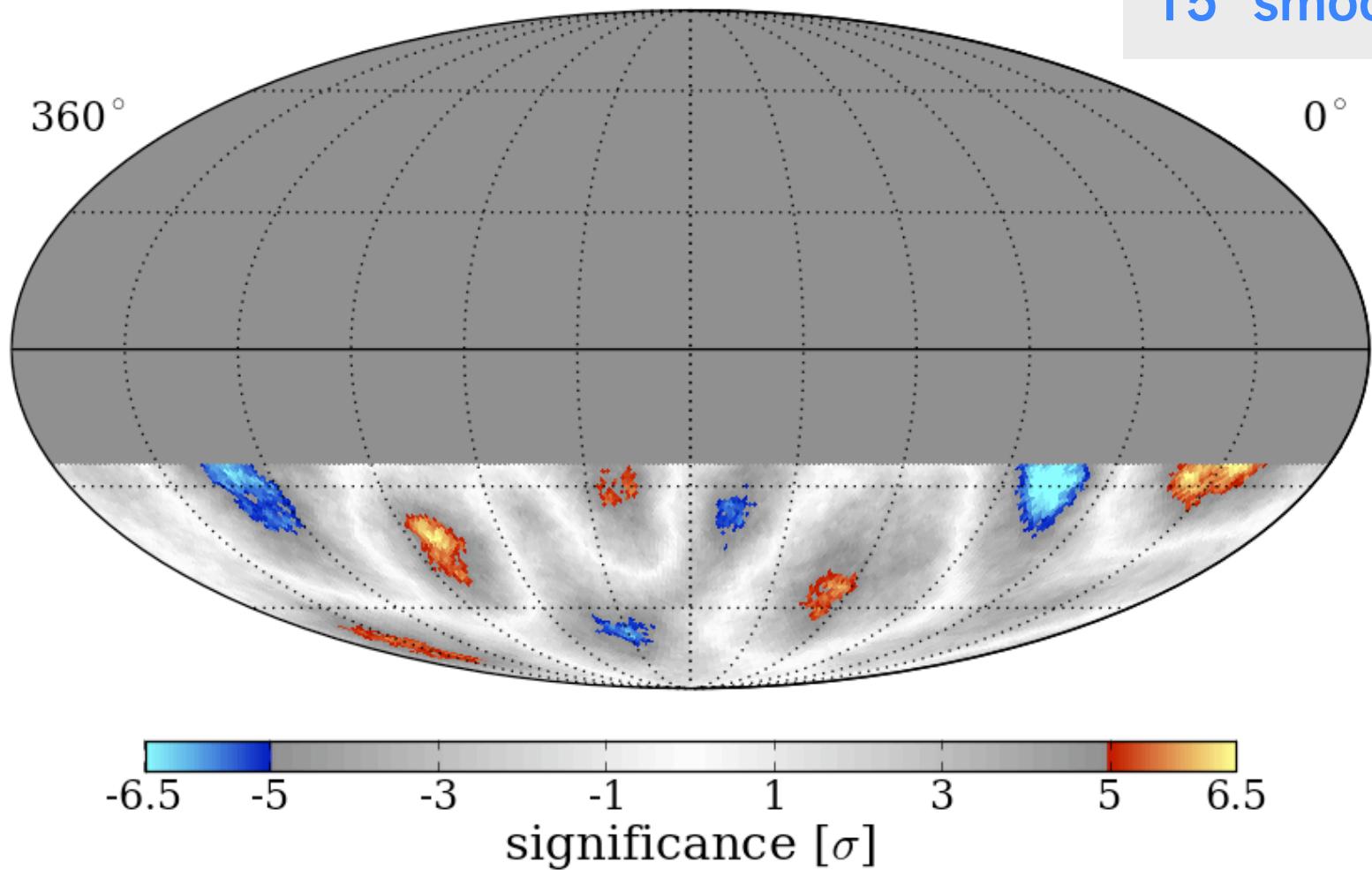
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

15° smoothing



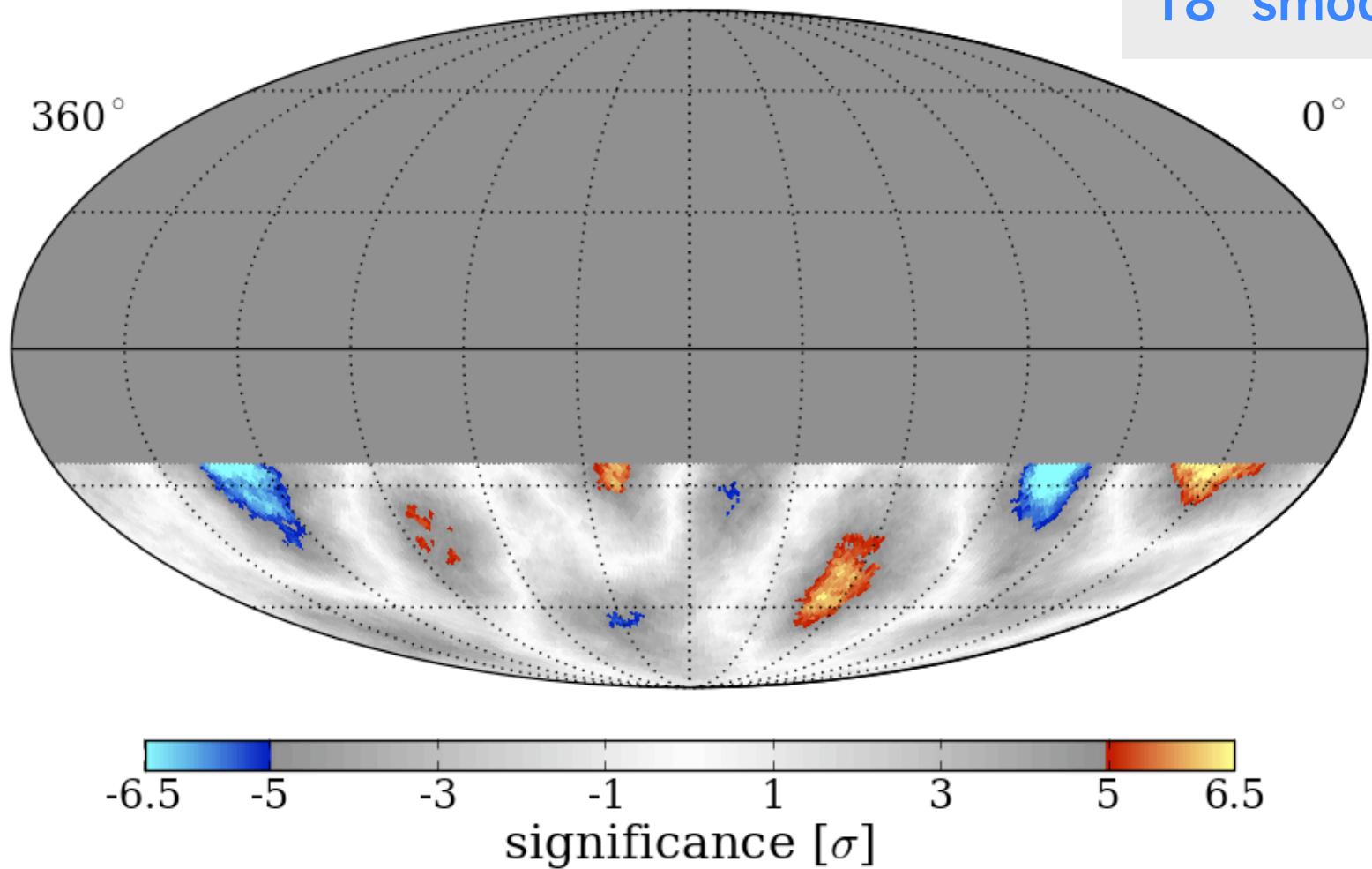
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

18° smoothing



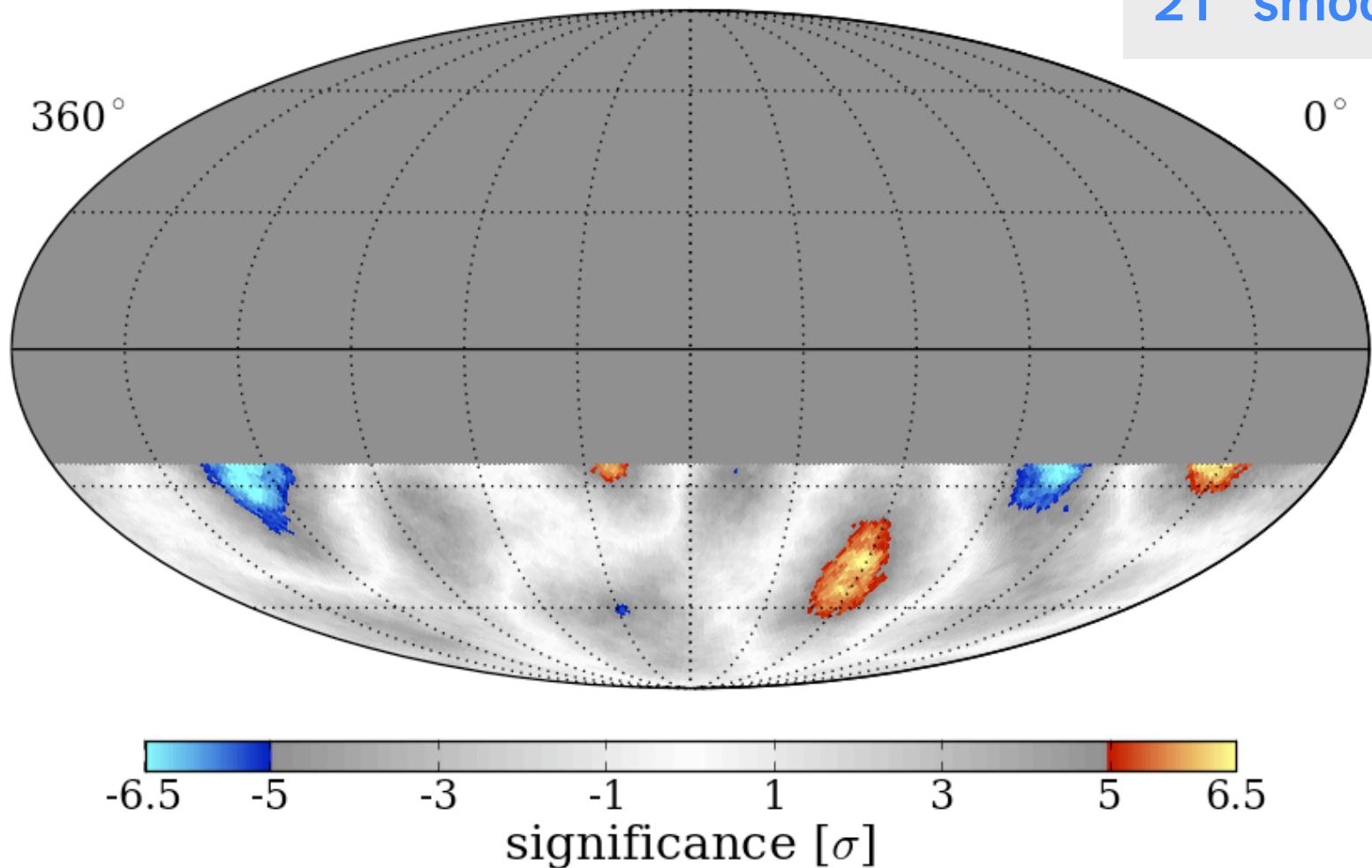
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

21° smoothing



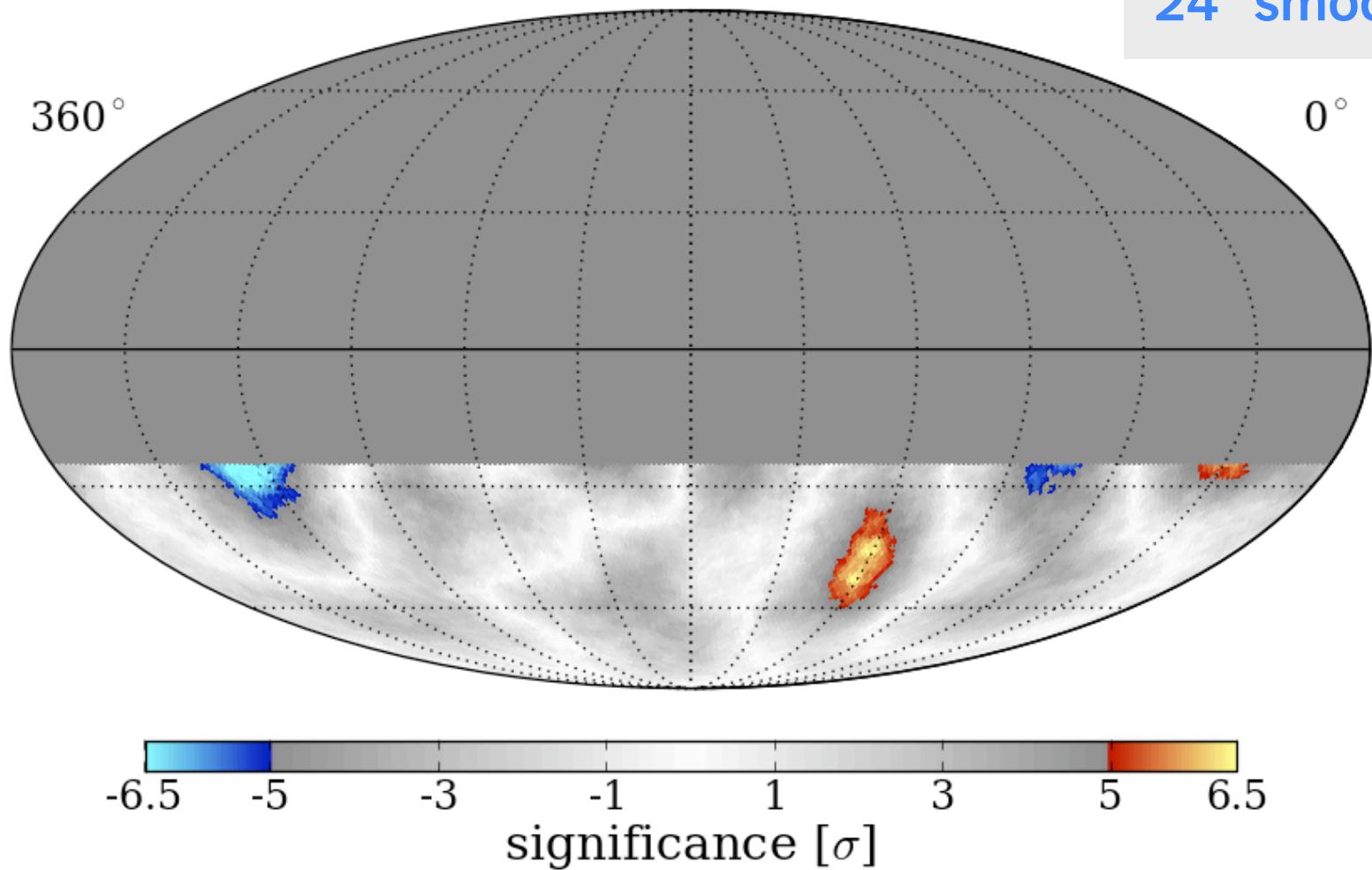
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

24° smoothing



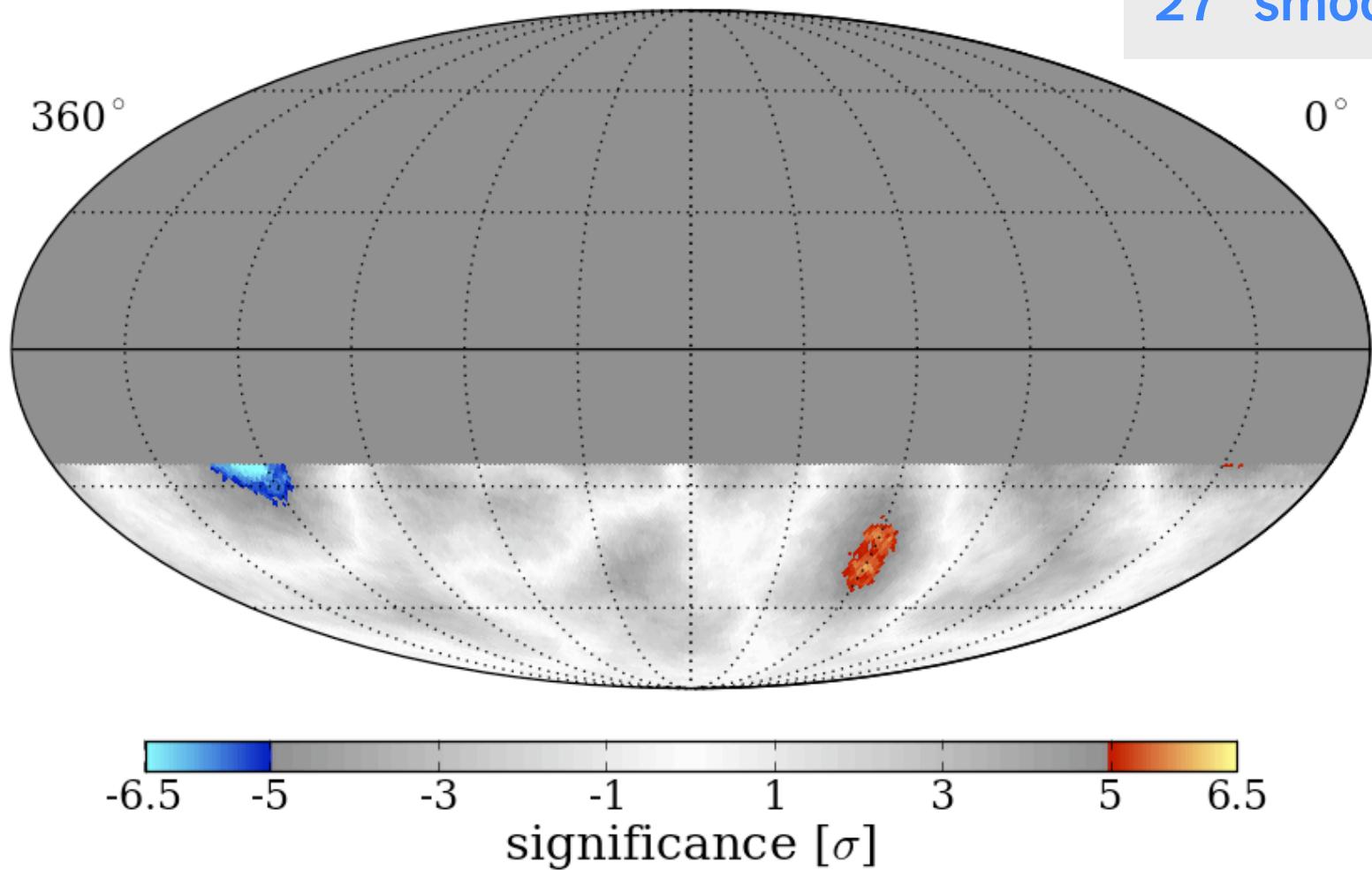
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

27° smoothing



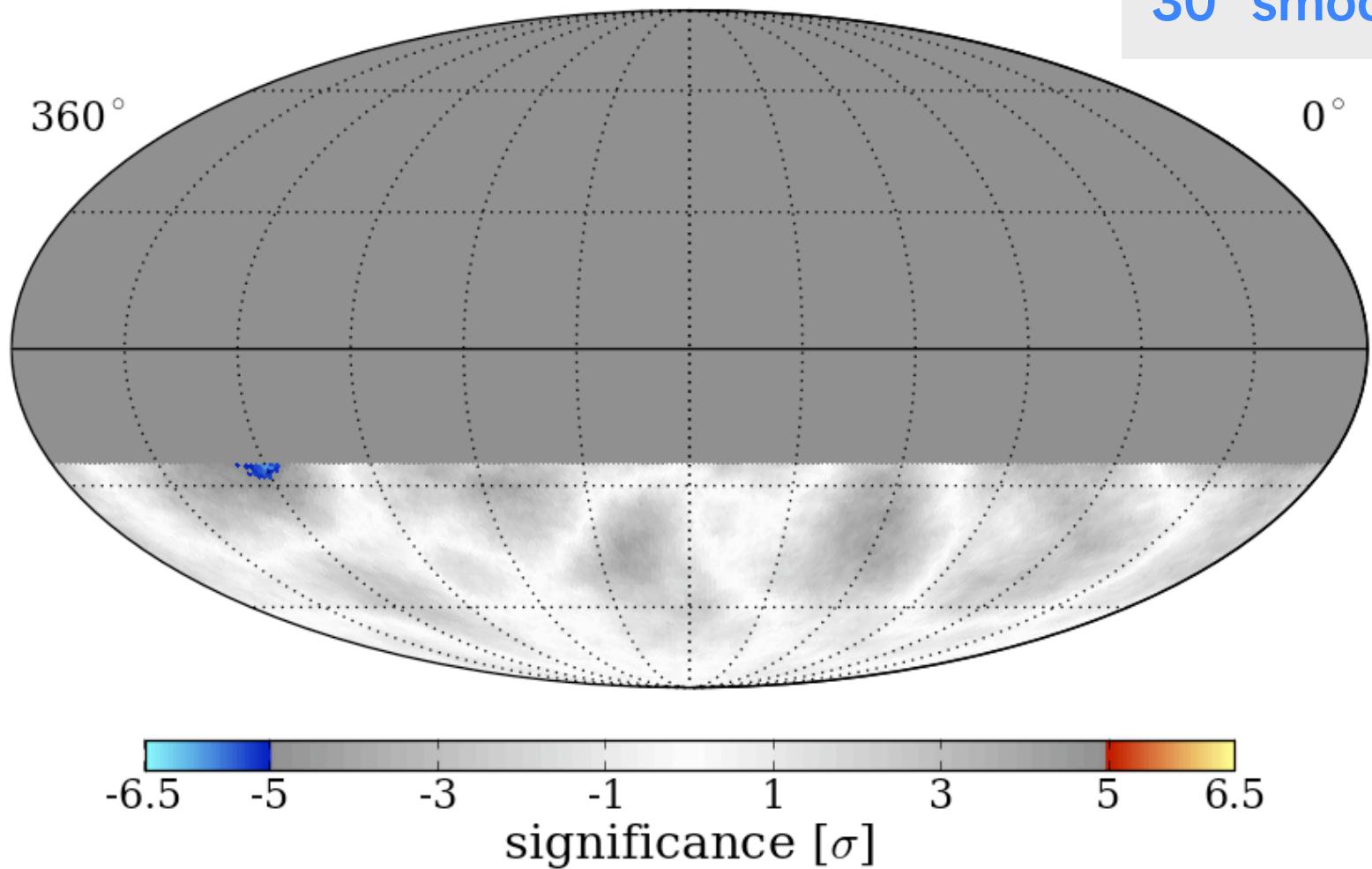
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Map smoothing scan

30° smoothing



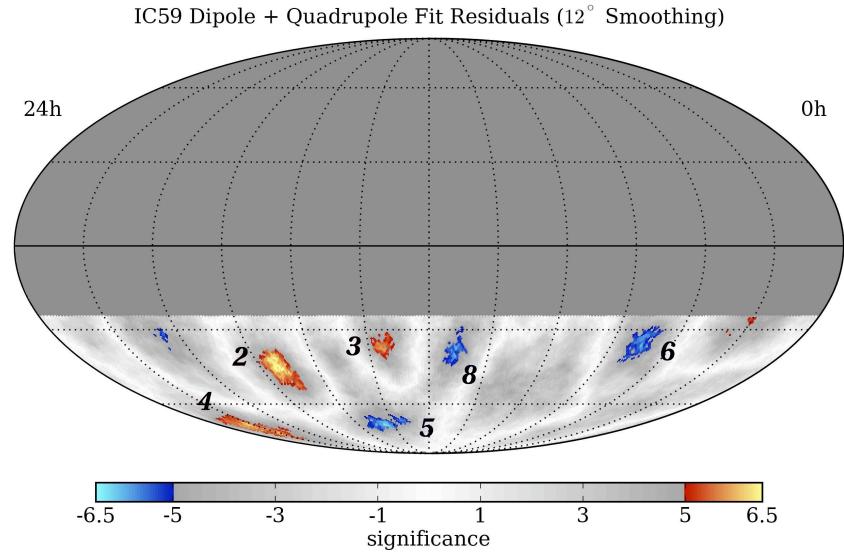
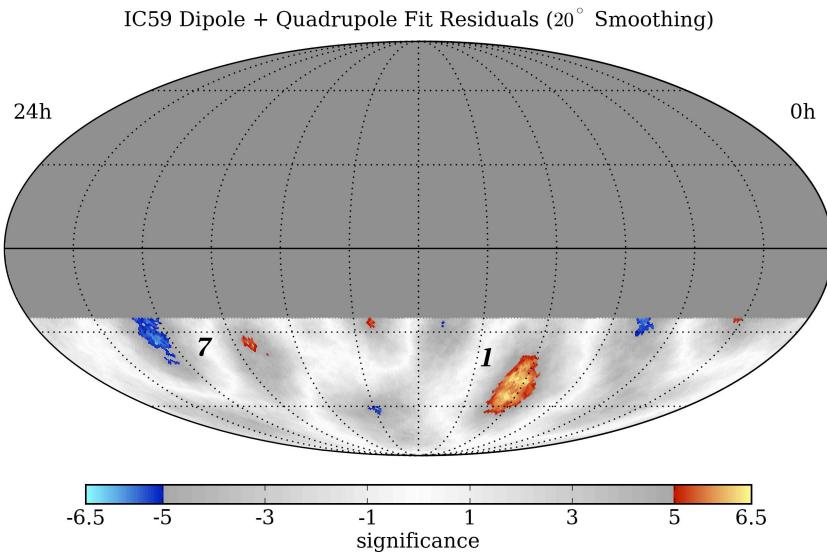
Scan from 1 - 30° in smoothing

Different regions have different optimal smoothings

Significances are pre-trial

Smoothing scan results

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



Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326

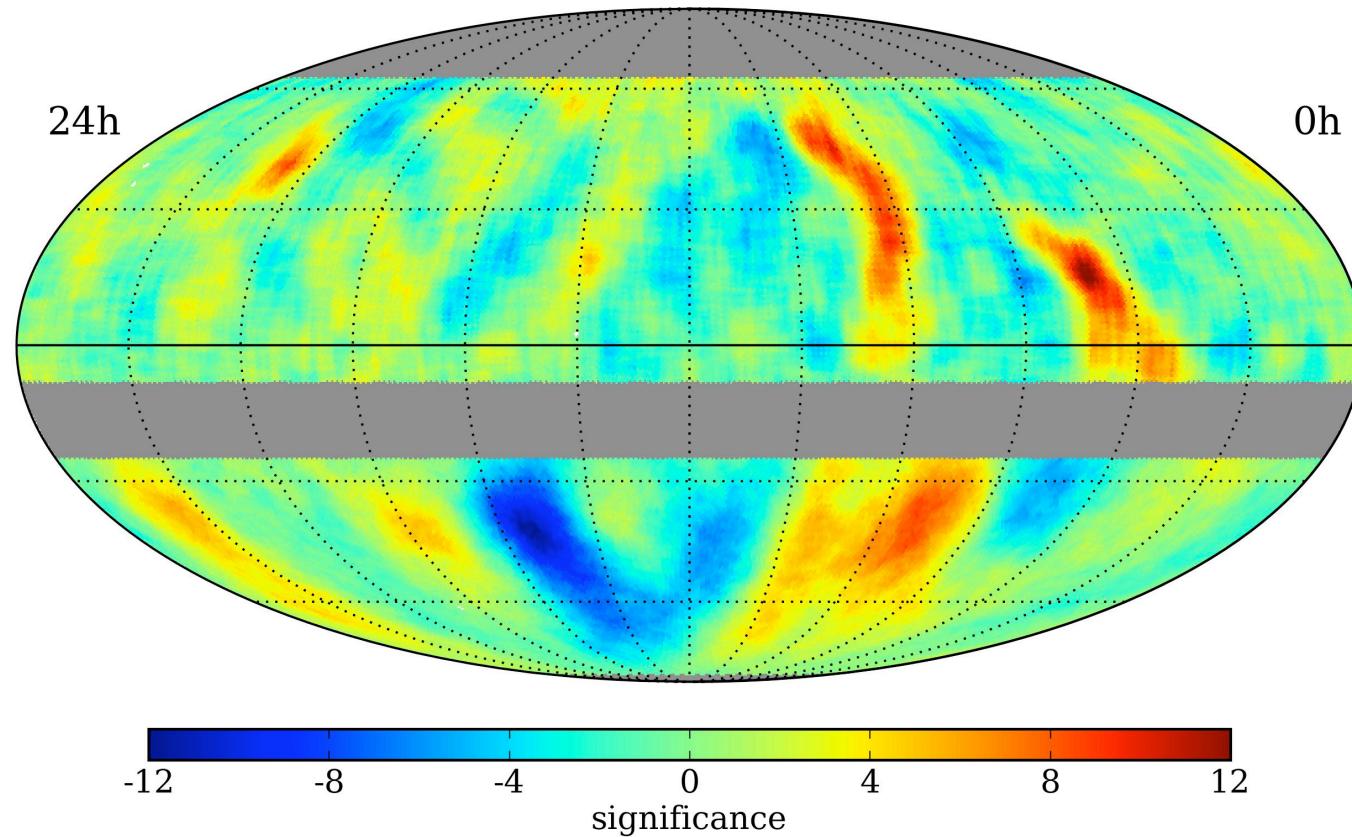


Milagro + IceCube combined skymap

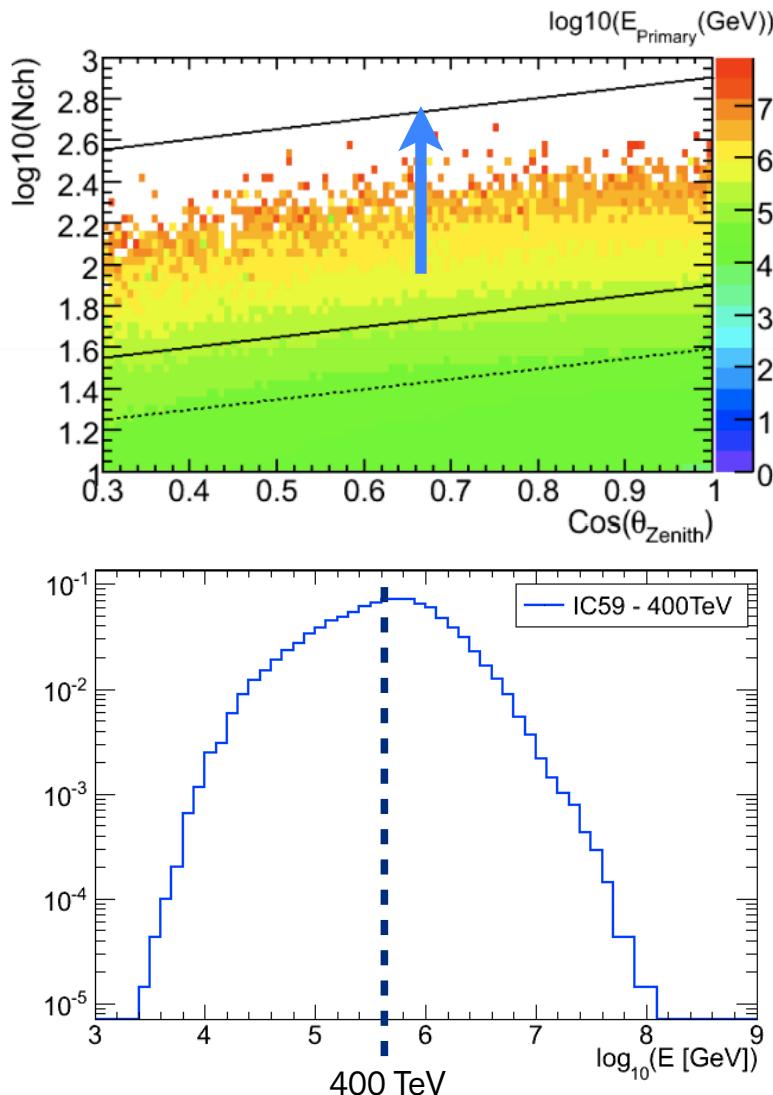
Milagro median energy ~ 1 TeV

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

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)



Anisotropy at high energies - IceCube

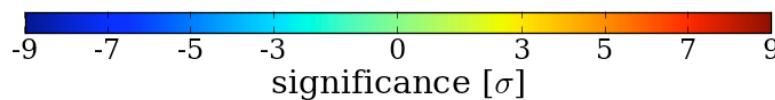
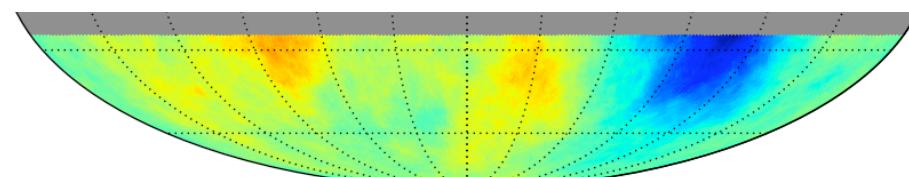
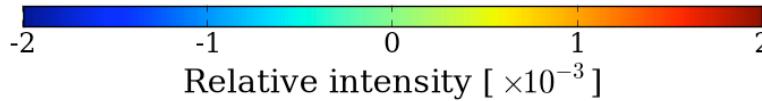
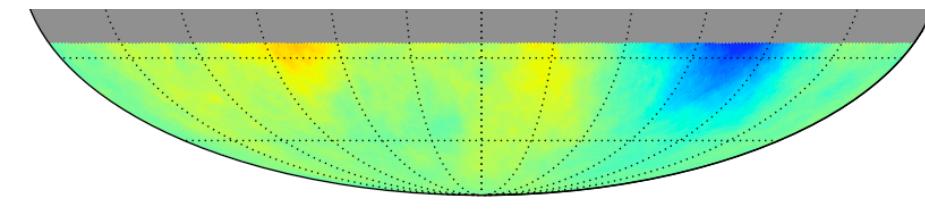


- Cut on number of triggered DOMs and on reconstructed zenith angle
- Final sample: 6.1×10^8 events
- Median energy: 400 TeV

Abbas et al., submitted to ApJ, arxiv/1109.1017



Anisotropy at high energies - IceCube

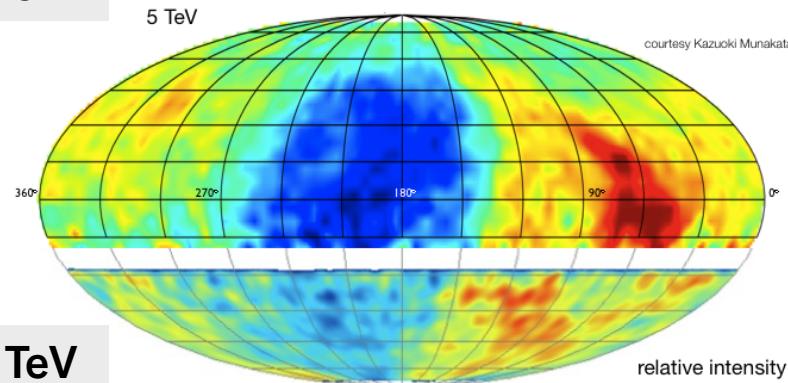


- Optimal smoothing of **21°**
- Strength of **~10⁻³**
- Minimum significance: **-8.6 σ**
(-6.3 σ post-trial)

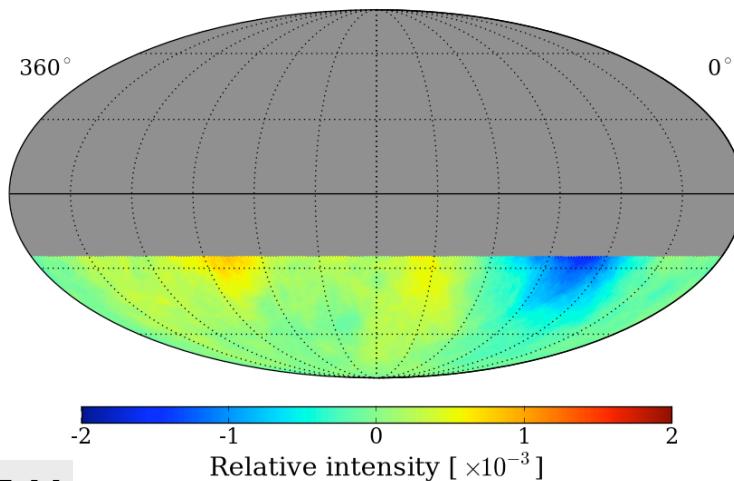
Abbas et al., submitted to ApJ, arxiv/1109.1017

Comparison to low energies

5 TeV



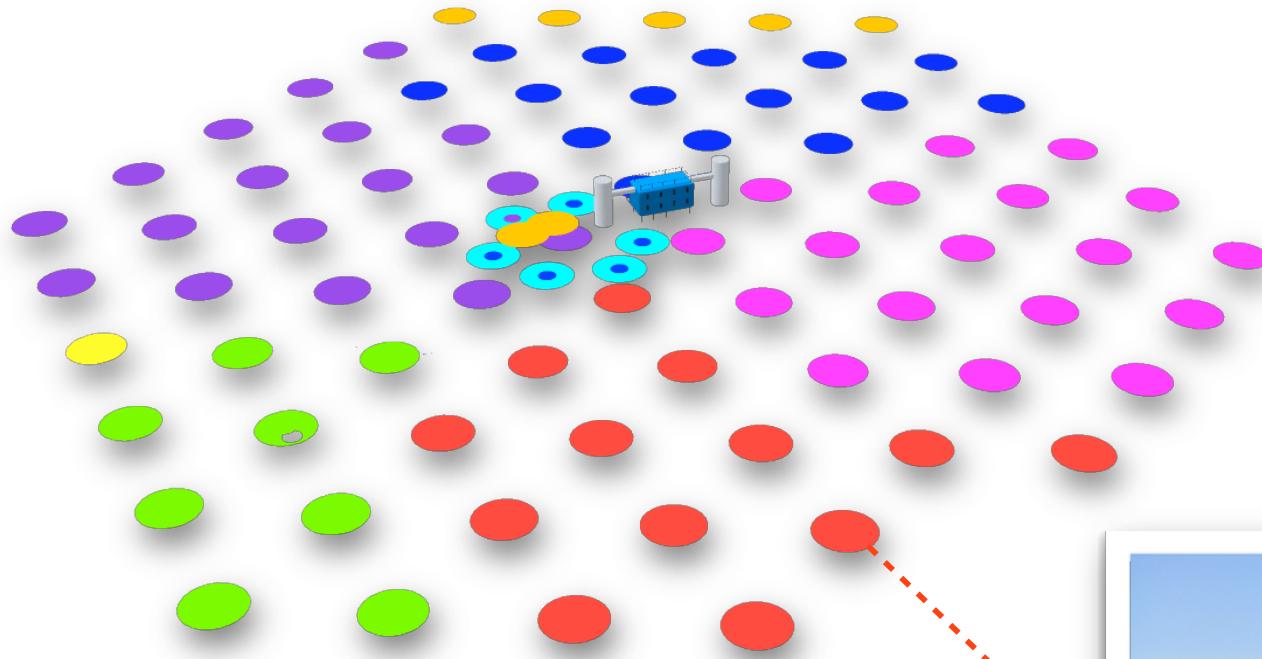
20 TeV



400 TeV

- The anisotropy changes phase
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

IceTop air shower array



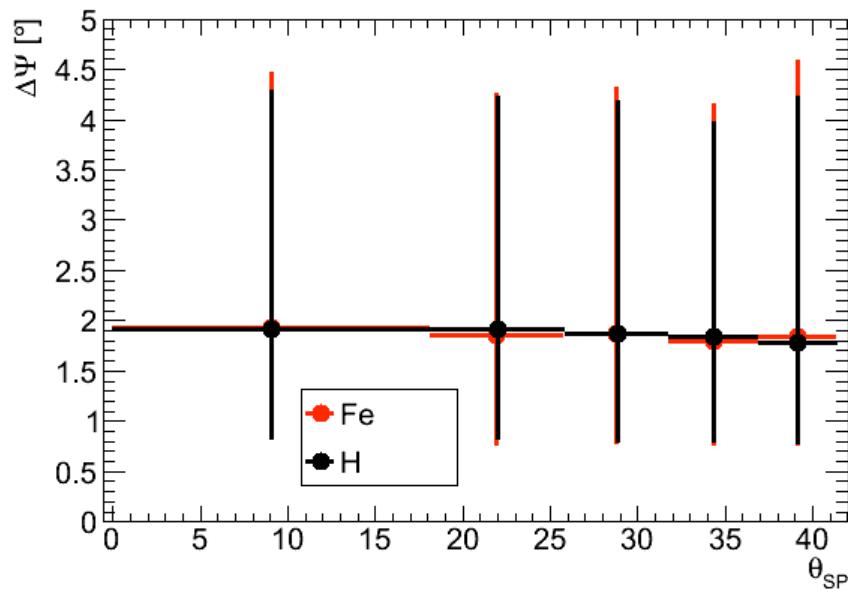
- 81 stations
 - 2 tanks per station
 - 2 DOMs per tank (hi gain, low gain)



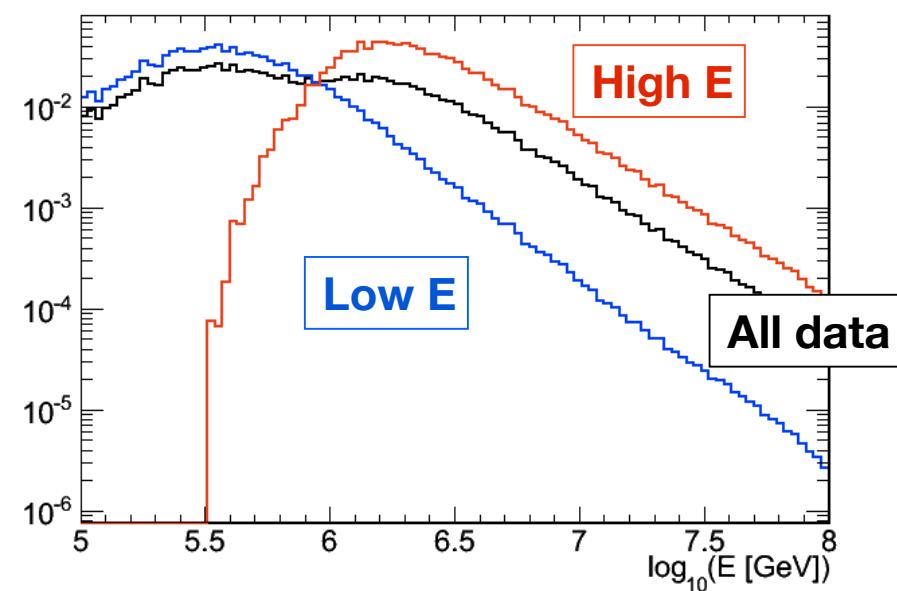
Anisotropy with IceTop

PRELIMINARY

Median angular resolution



Energy distributions



IT59 dataset

Events

IT stations > 3	117×10^6
$3 \leq \text{stations} < 8$	87×10^6
$\text{stations} \geq 8$	30×10^6

All

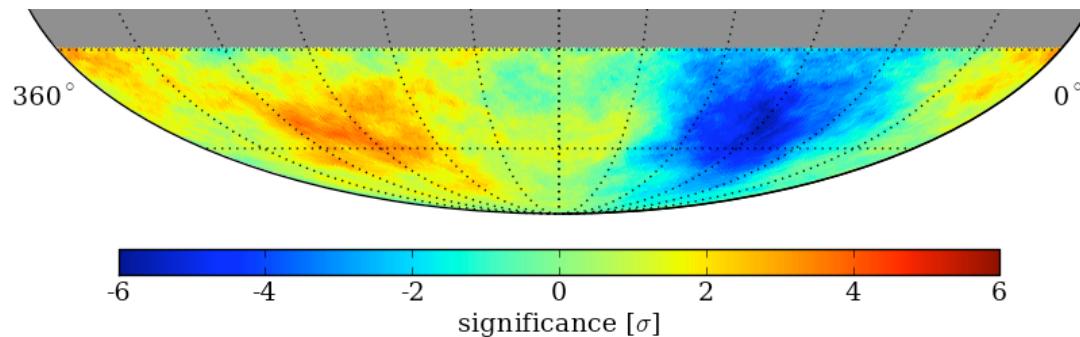
Low E

High E

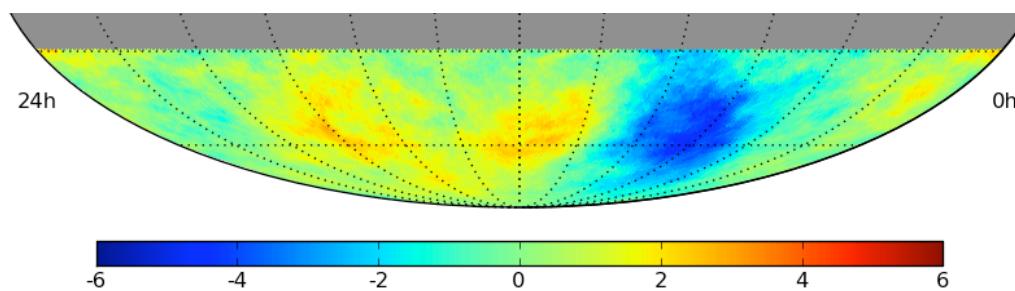
Significance maps for IT59

PRELIMINARY

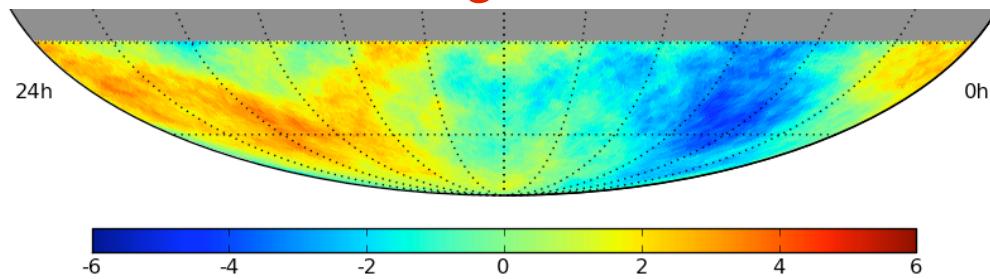
All data



Low E



High E



- 117×10^6 events
- **500 TeV** median energy
- Minimum significance: **-6.2 σ (pretrial)**

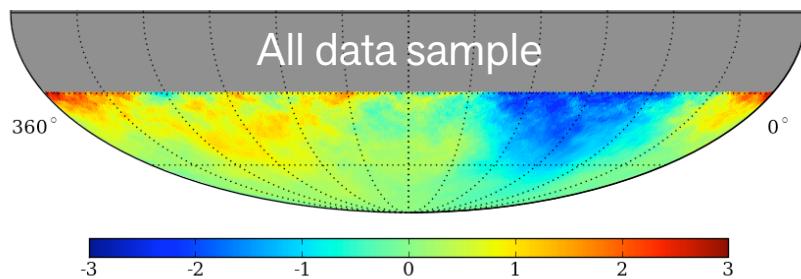
- 87×10^6 events
- **400 TeV** median energy
- Minimum significance: **-5.1 σ (pretrial)**

- 30×10^6 events
- **2 PeV** median energy
- Minimum significance: **-4.9 σ (pretrial)**

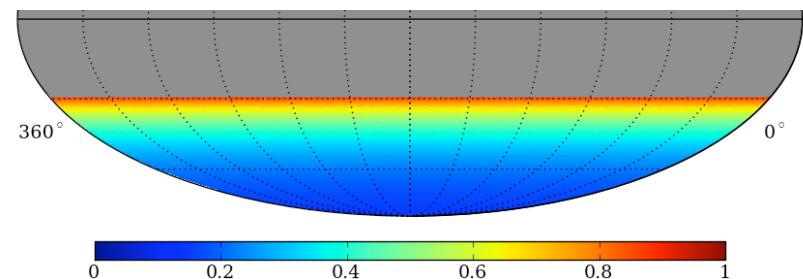
Relative intensity maps

PRELIMINARY

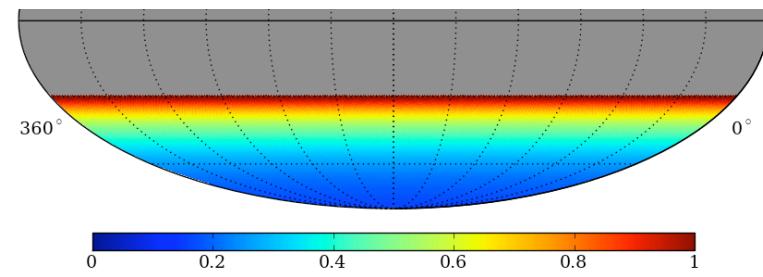
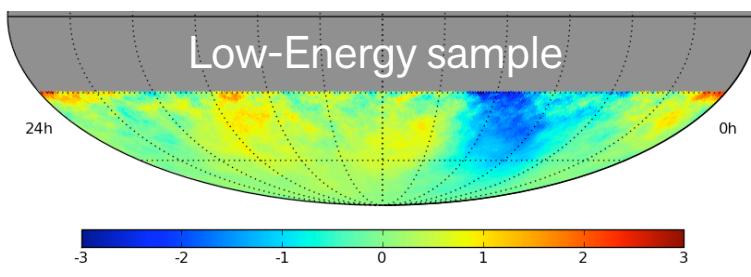
$$\Delta N/\langle N \rangle \times [10^{-3}]$$



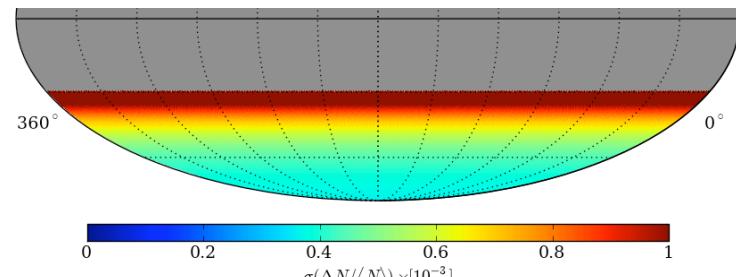
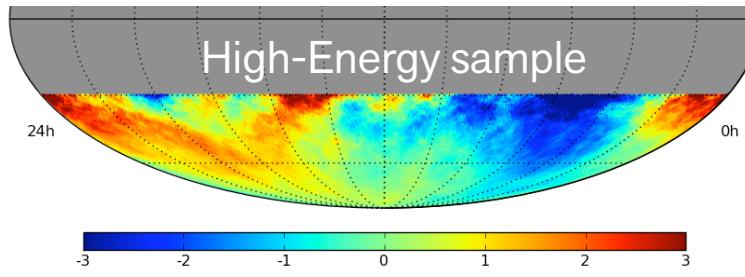
$$\sigma(\Delta N/\langle N \rangle) \times [10^{-3}]$$



Low-Energy sample



High-Energy sample





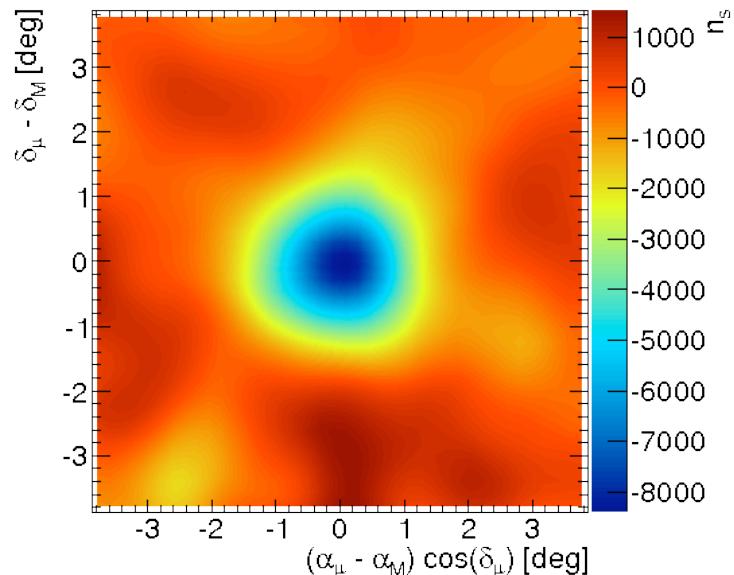
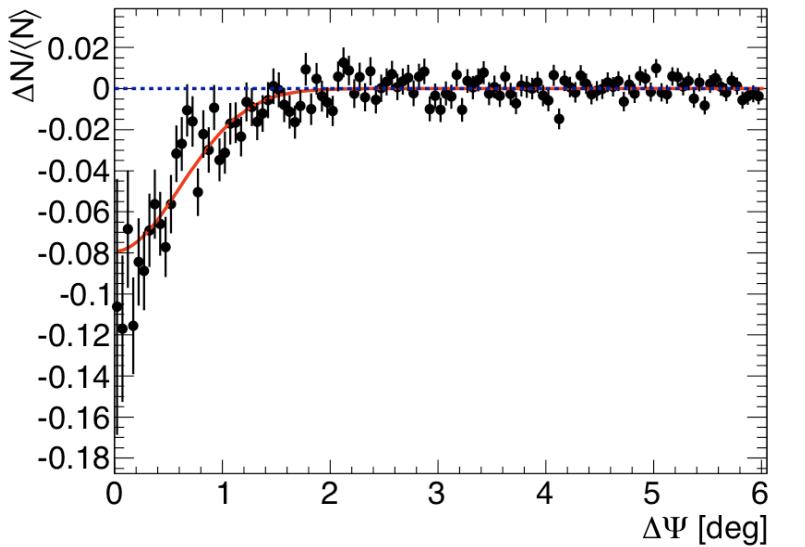
Conclusions

- Anisotropy observed with IceCube:
 - Wide angular scale range (**10°-180°**)
 - Strength in the **10⁻⁴-10⁻³** range
 - Different energies: **20 TeV to 400 TeV**
- 20 TeV anisotropy matches that observed in the North
- Observation of anisotropy at 400 TeV (change in phase, size compared to 20 TeV)
- Preliminary results from **IceTop at 400 TeV** are consistent with IceCube results
- Anisotropy observed at 2 PeV (near the CR knee) change in composition?
- Origin of the anisotropy still unknown



Backup slides

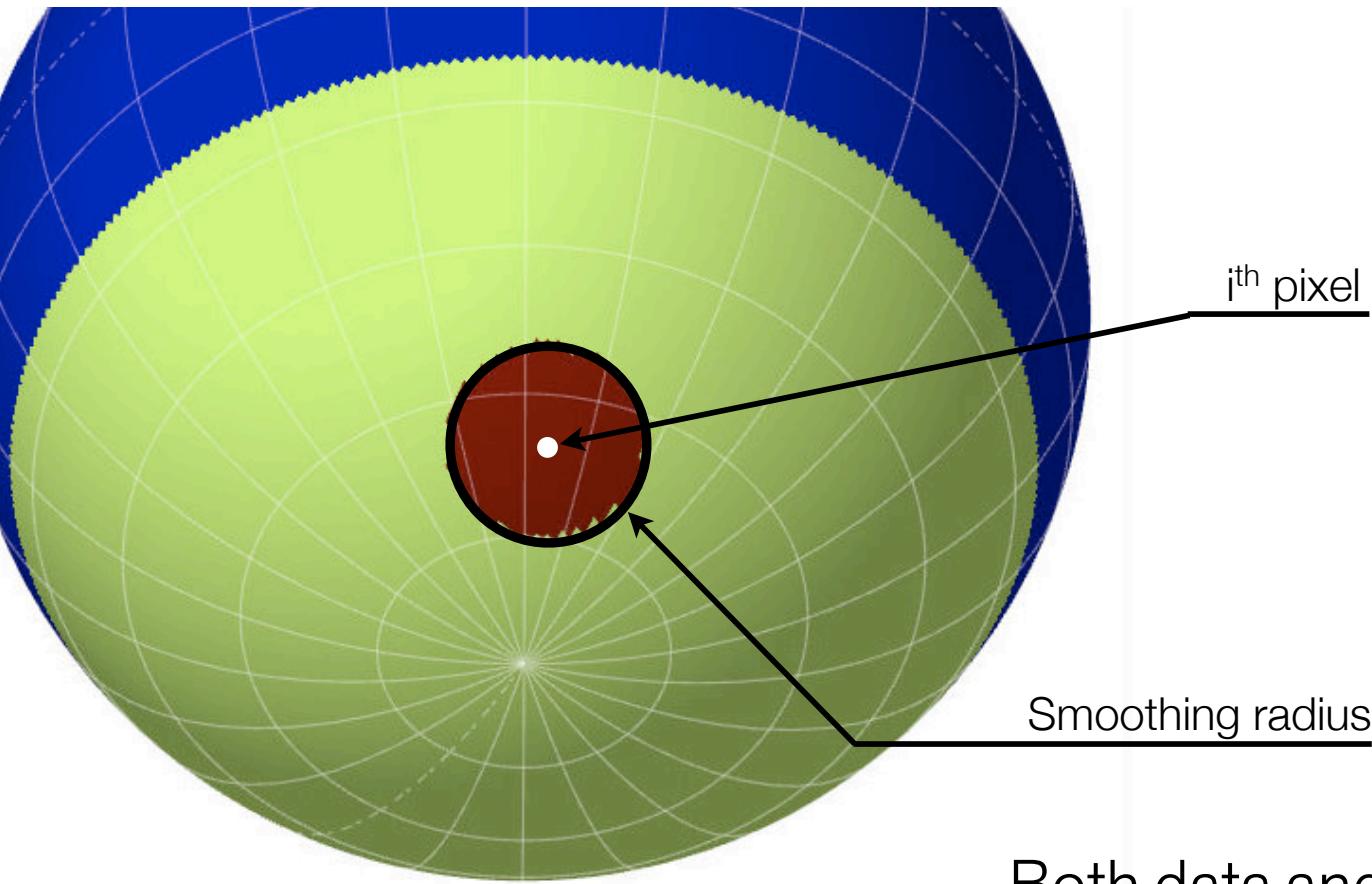
IC59 Moon shadow



● IC59 results

- Optimal integration radius $\sim 0.79^\circ$
- Significance at 0.79° ($\sim -11.8\sigma$)
- Gaussian fit gives 1σ width of $0.61^\circ \pm 0.05^\circ$
- Looks clean in unbinned analysis too

Smoothing scale



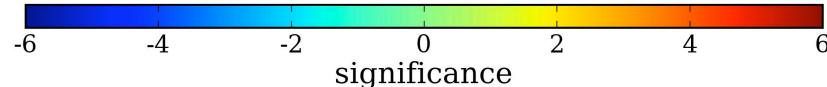
$$N_i = \sum_p N_p$$

p is the pixel #
inside the disc

- Both data and bkg maps are “smoothed” in this way
- “Rebinning” of the map



IC22 and IC40

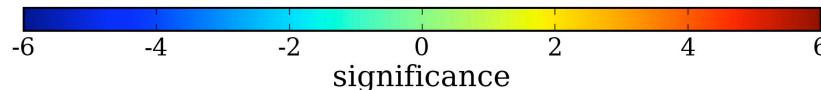
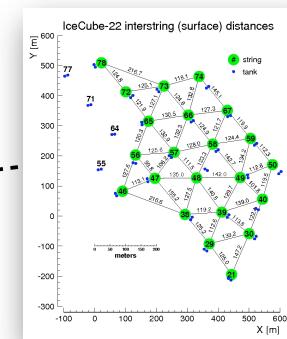
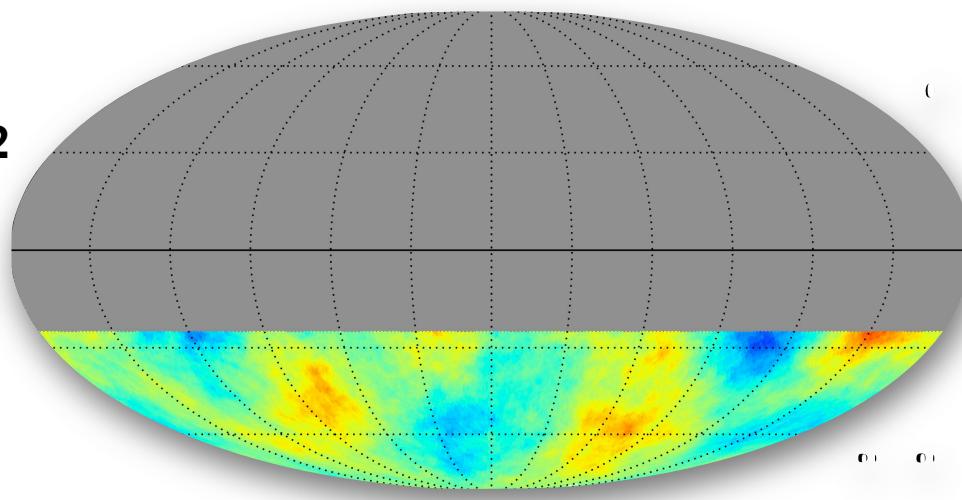


Different geometries, same structure



IC22 and IC40

IC22



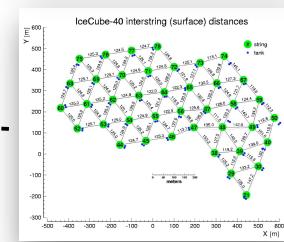
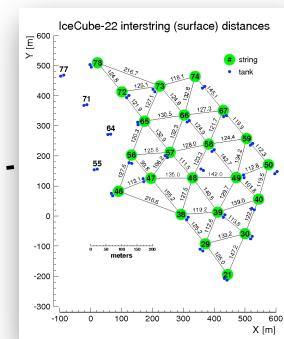
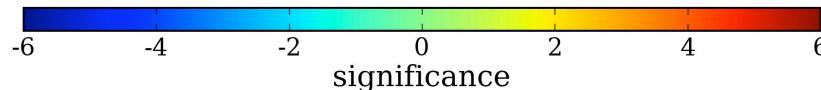
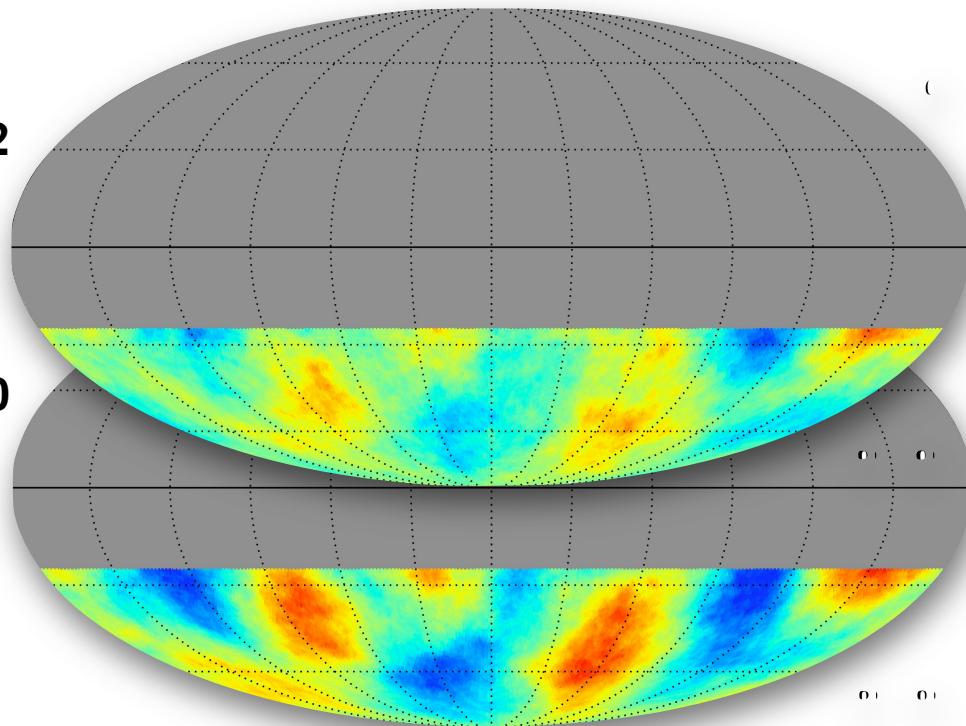
Different geometries, same structure



IC22 and IC40

IC22

IC40

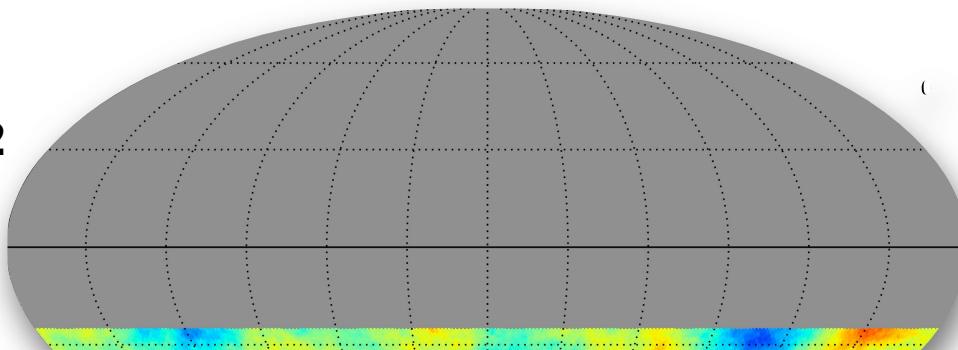


Different geometries, same structure

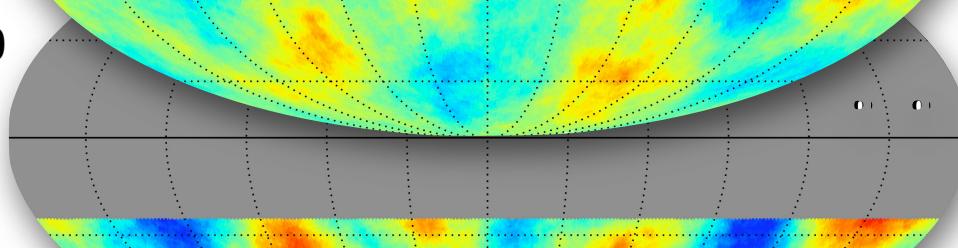


IC22 and IC40

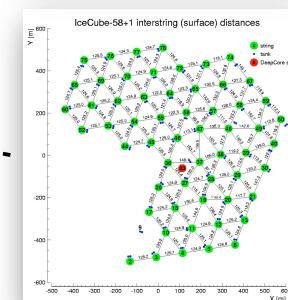
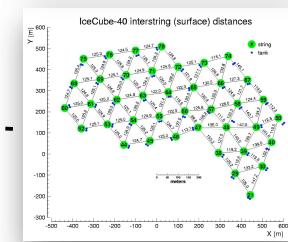
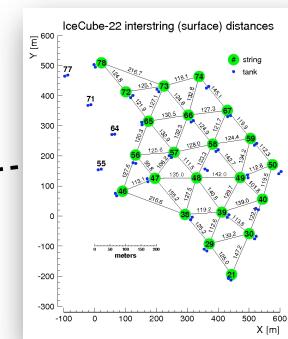
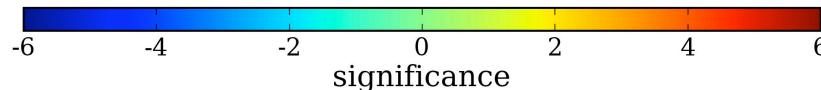
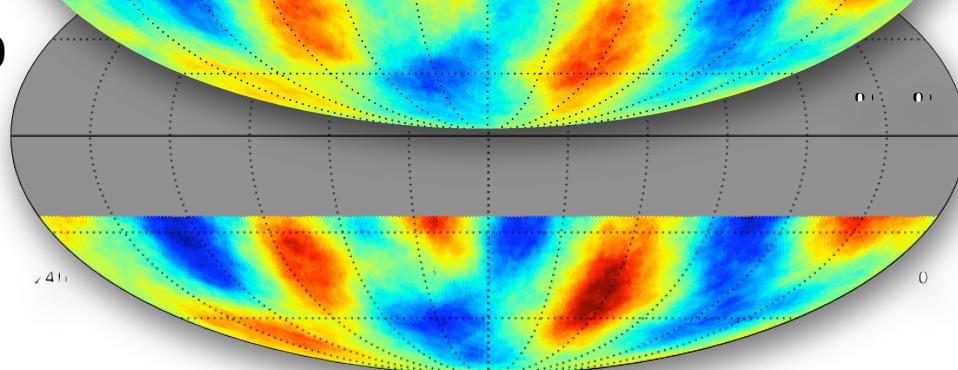
IC22



IC40



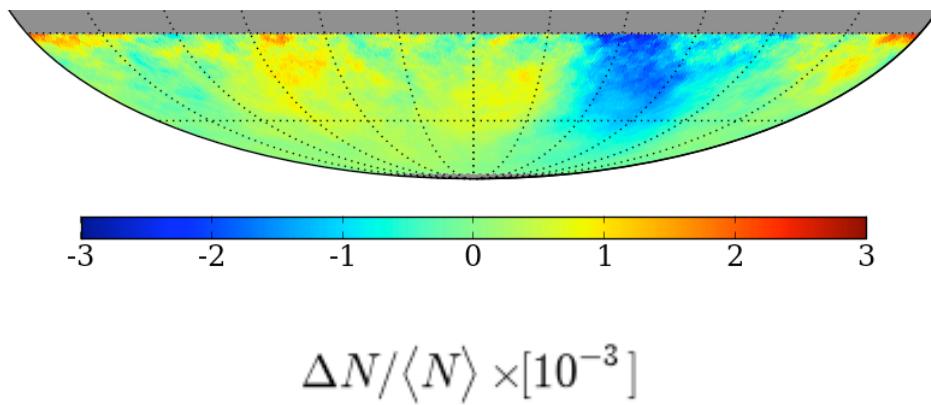
IC59



Different geometries, same structure

Comparison to IC data - Low E

IceTop 59 – Low E



IceCube 59 – 400 TeV

