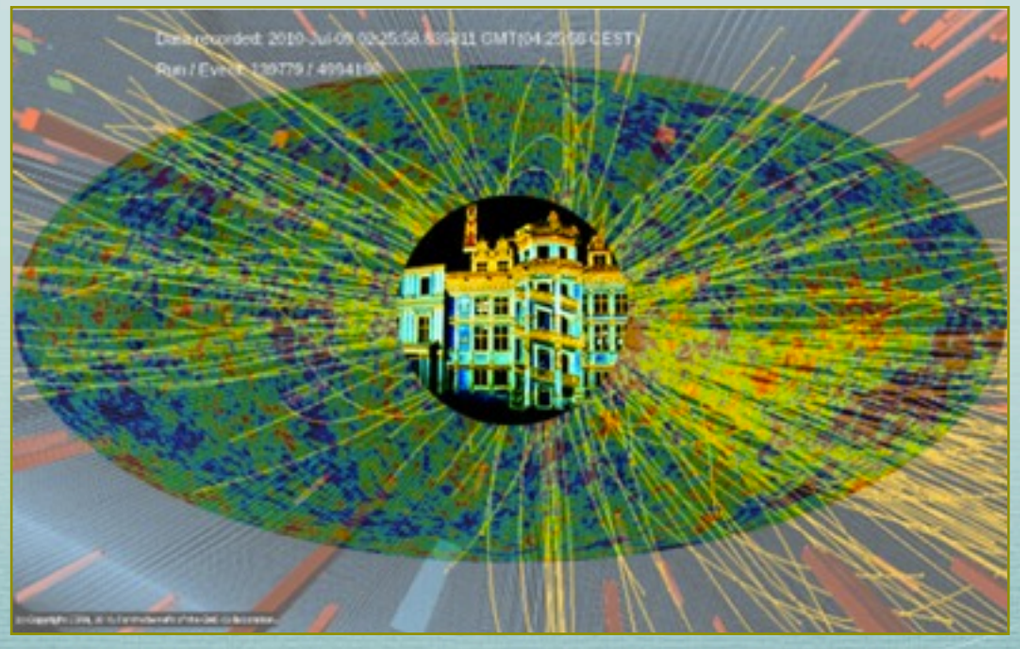
OBSERVATION OF COSMIC RAY ANISOTROPY ABOVE TEV ENERGIES IN ICECUBE

Simona Toscano *on behalf of the* **IceCube collaboration**

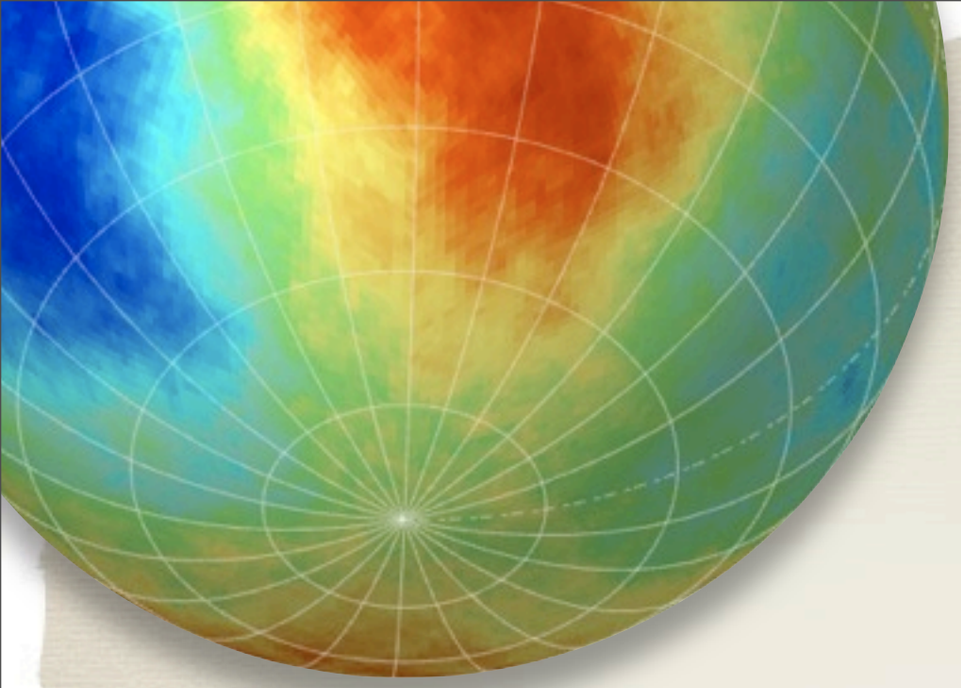
23rd Rencontres de Blois

Particle Physics and Cosmology



Château Royal de Blois

May 29-June3 2011



Outline

- The **IceCube** detector
- Energy dependence of the **large scale anisotropy** *(paper in preparation)*:
  - preliminary results at 20 and 400 TeV.
- **Medium and small scale** structures (submitted to ApJ, **arXiv:1105.2326**):
  - analysis
  - results
- Conclusions

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TWTH Aachen, Germany
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Ohio State University
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College,
Baton Rouge, LA, USA

University of the West Indies, Barbados

University of Canterbury,
Christchurch, New Zealand

IceCube Collaboration

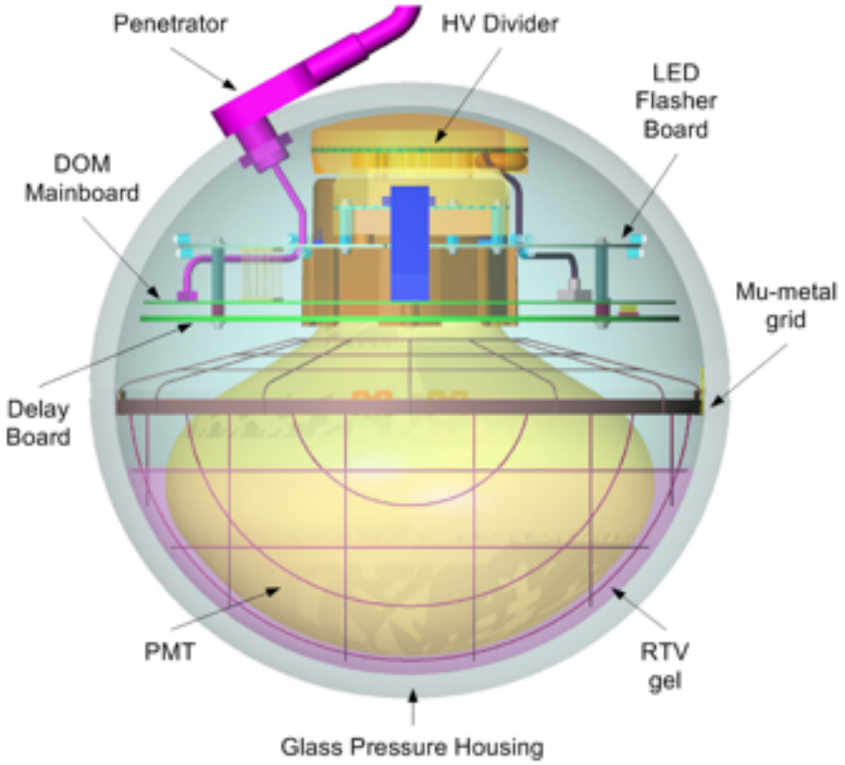
10 countries
36 institutions
~260 collaborators

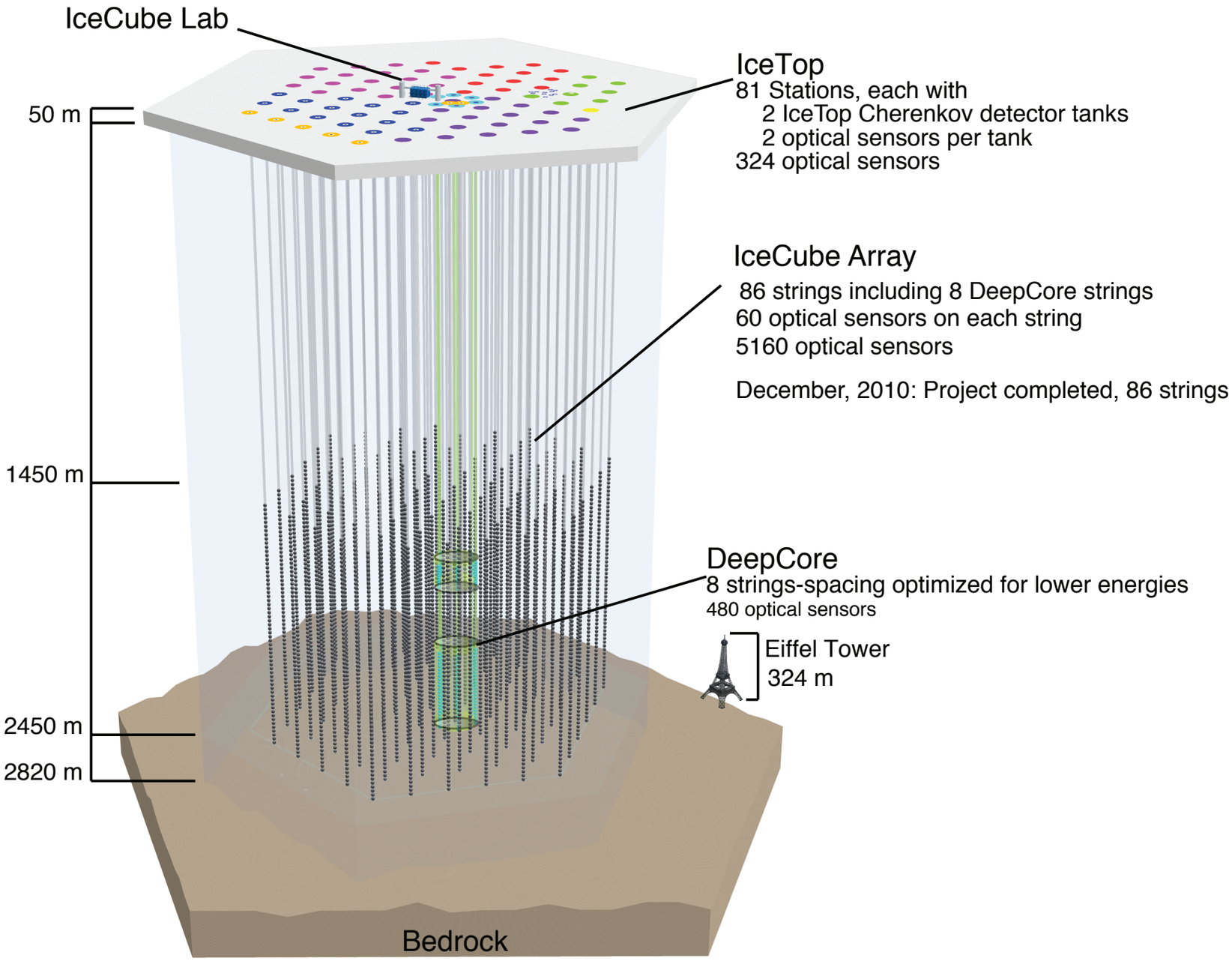
The IceCube detector

IceCube is a km^3-scale neutrino detector "frozen" into the South Pole ice.

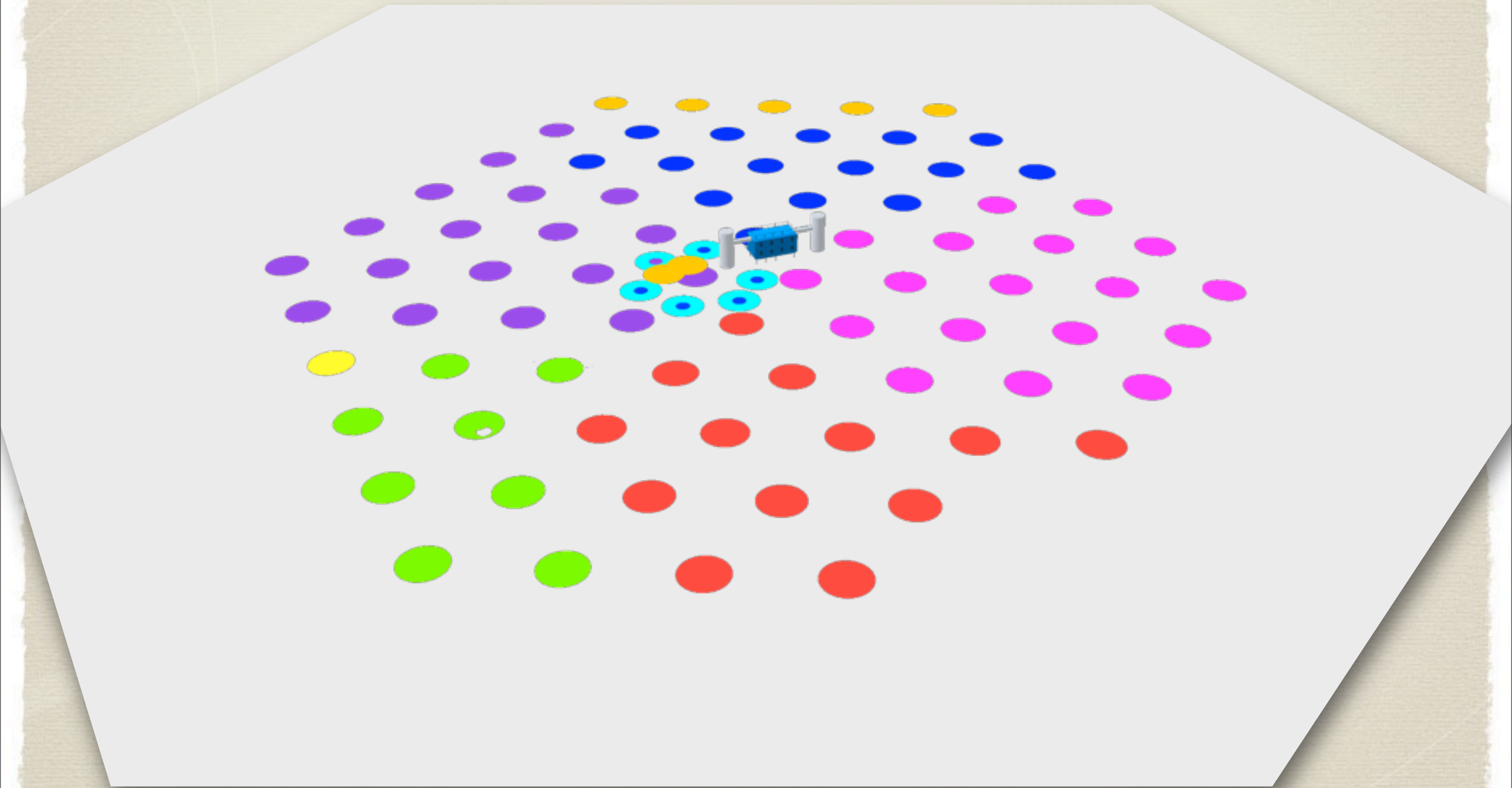
- **86 strings**
- **5160 DOMs**
- **17 m vertical spacing**
- **125 m between strings**

Digital Optical Module

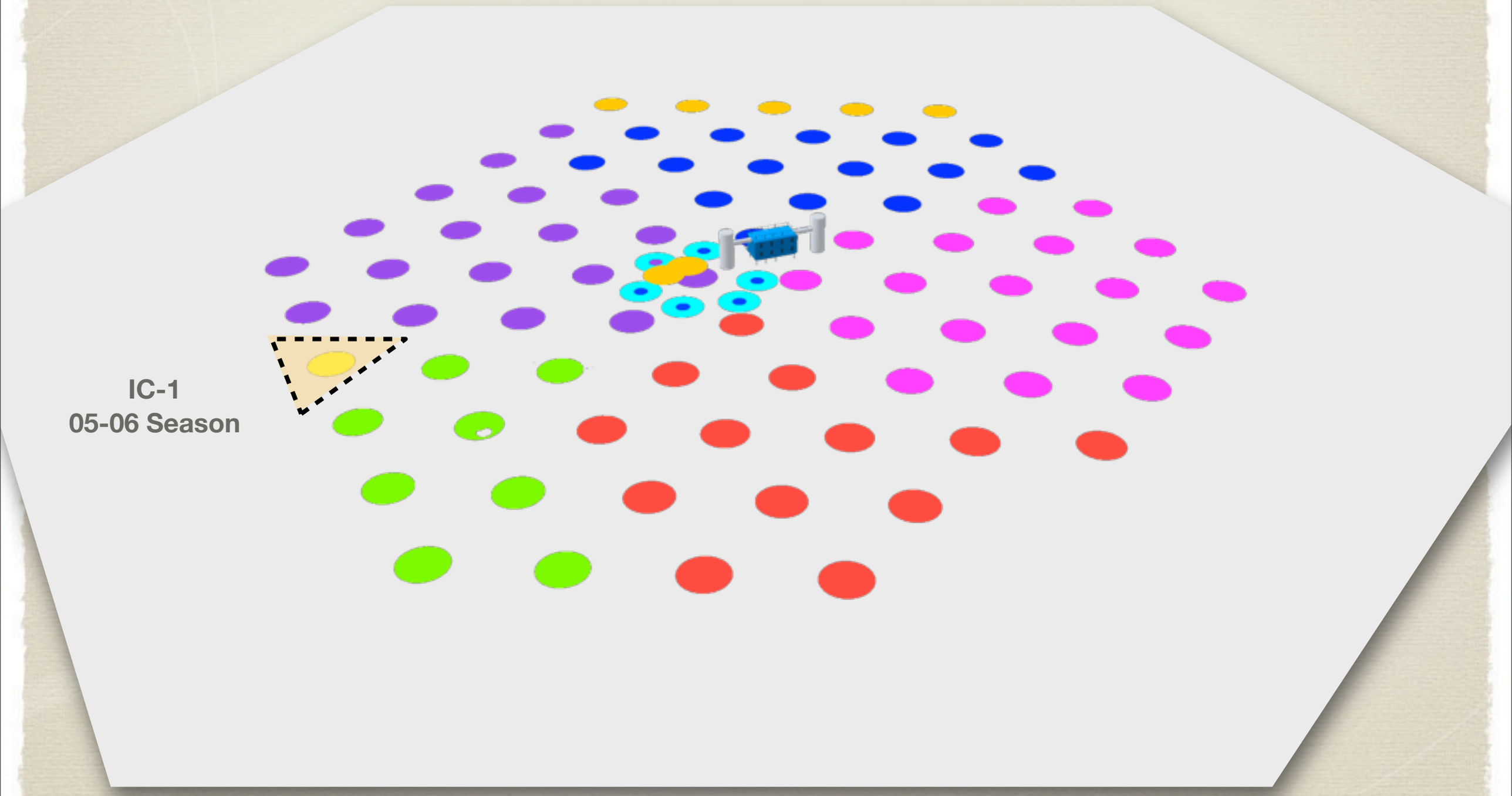




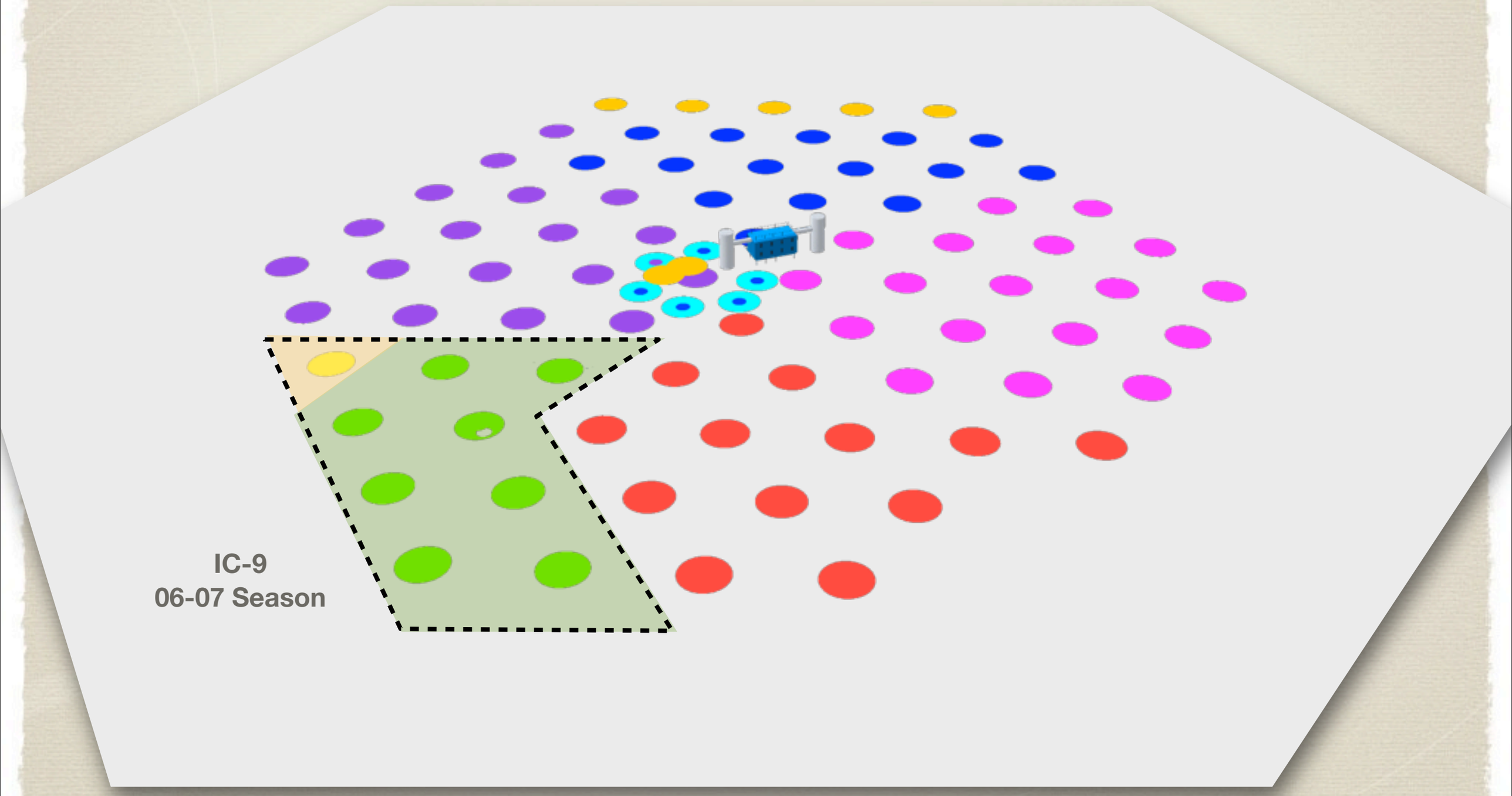
IceCube configurations



IceCube configurations



IceCube configurations



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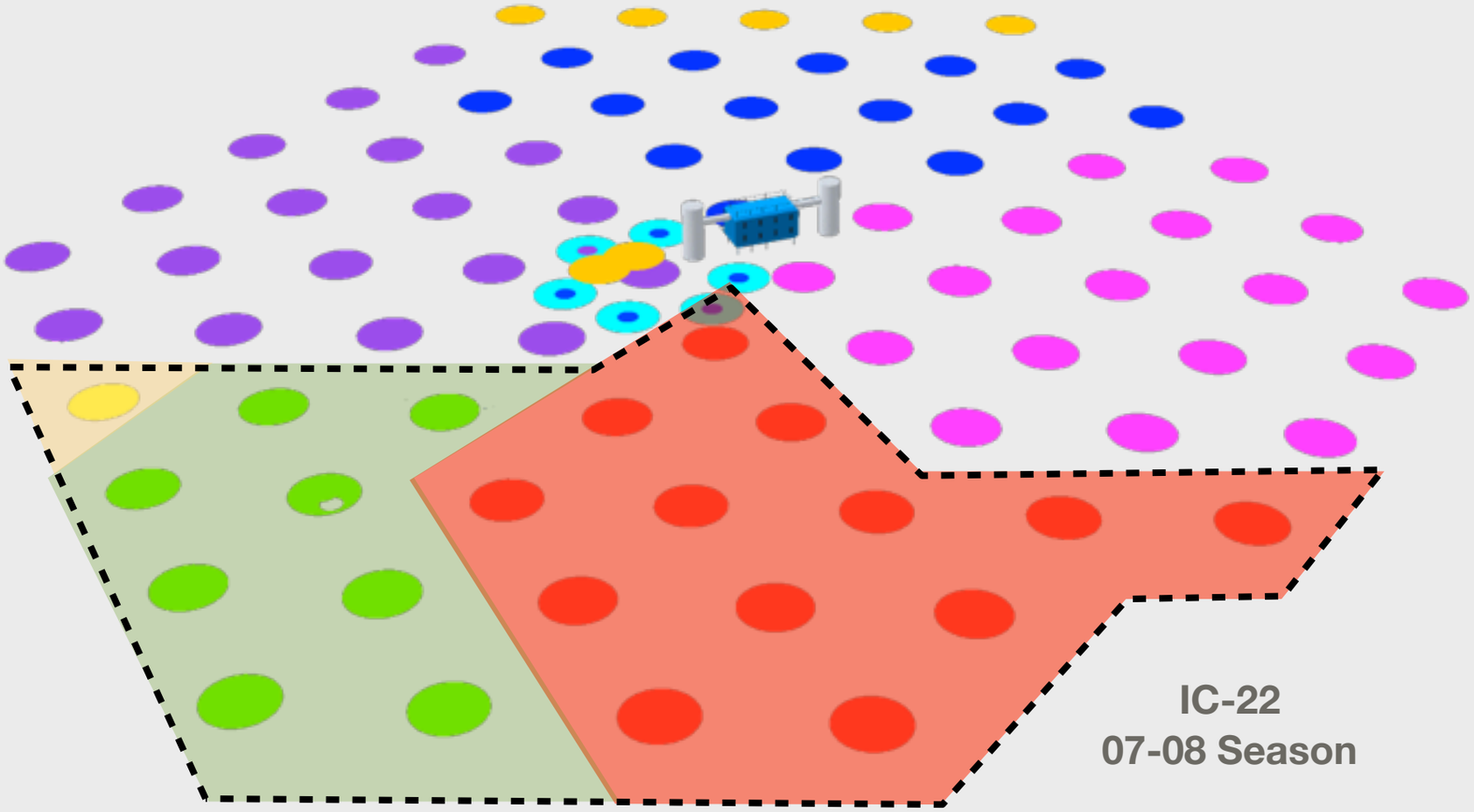
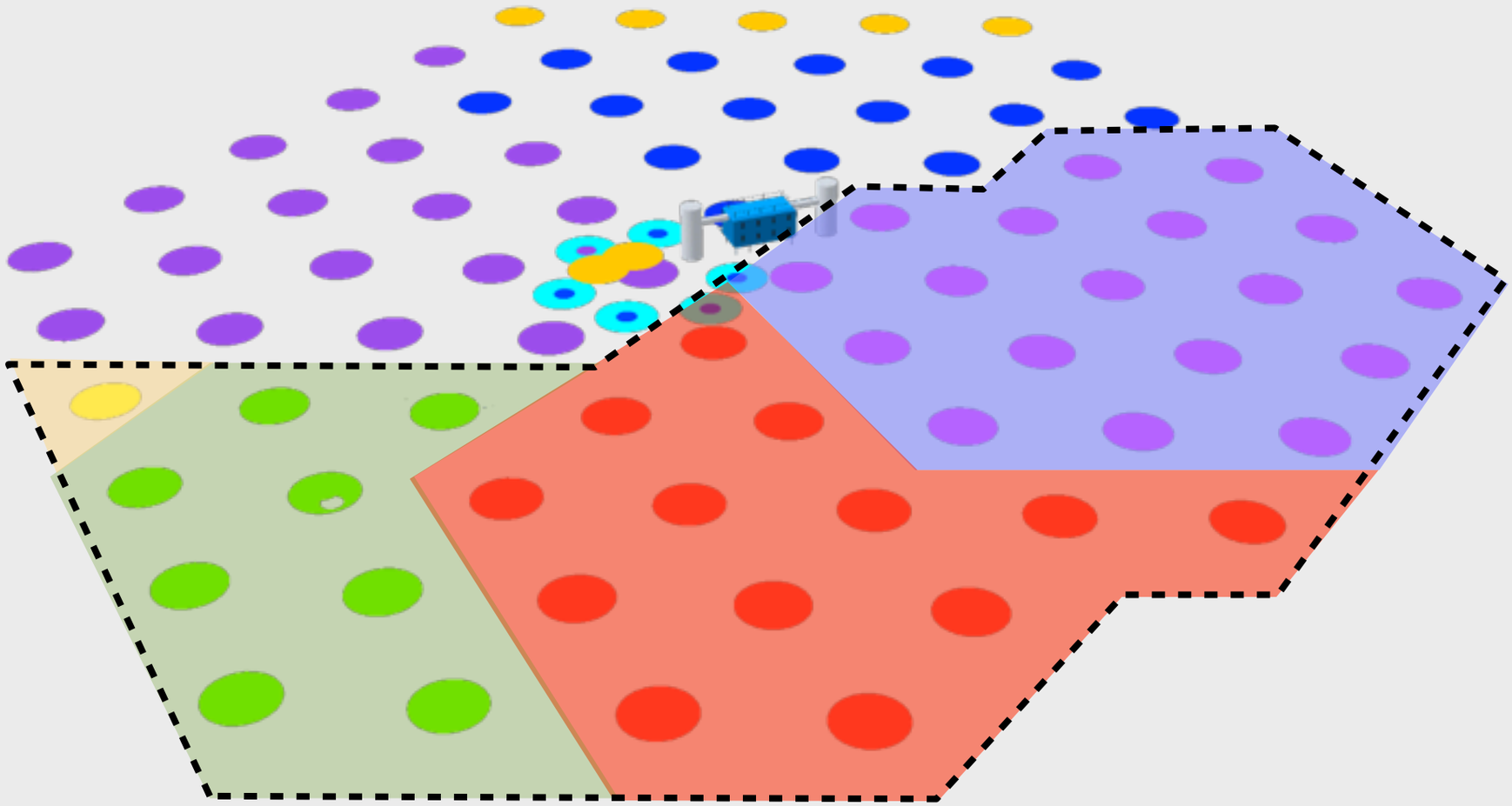
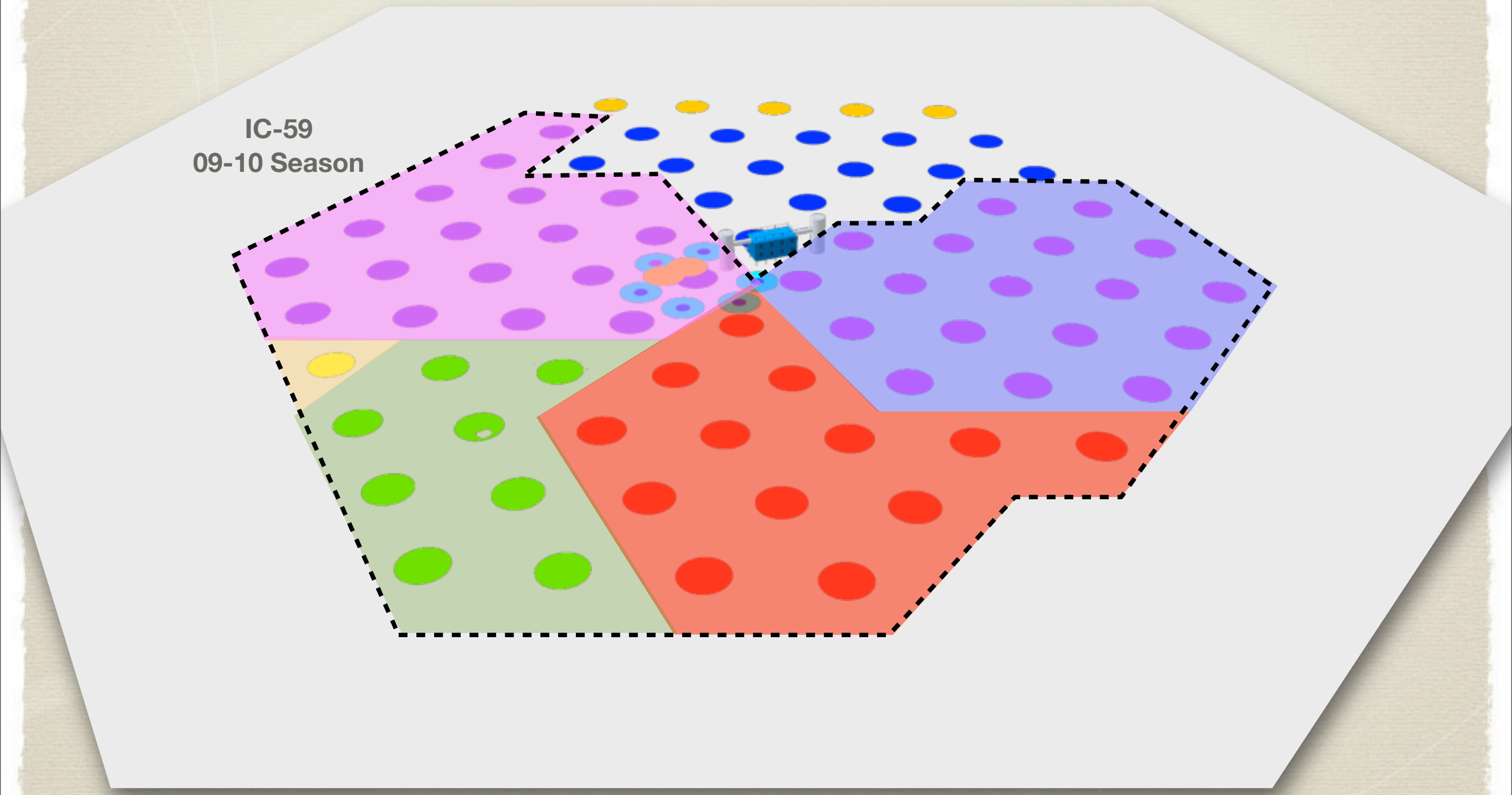


IceCube configurations

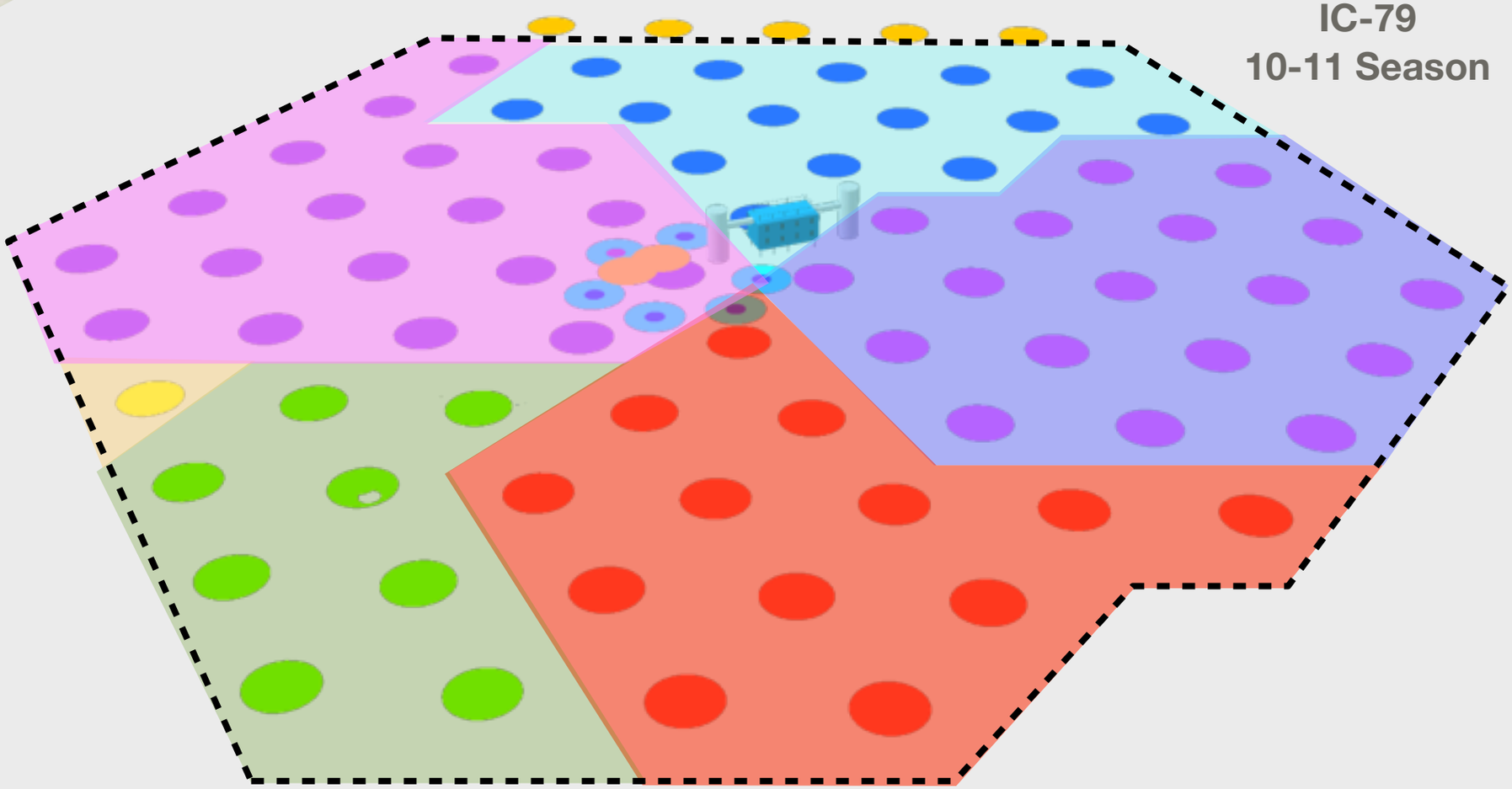


IC-40
08-09 Season

IceCube configurations



IceCube configurations



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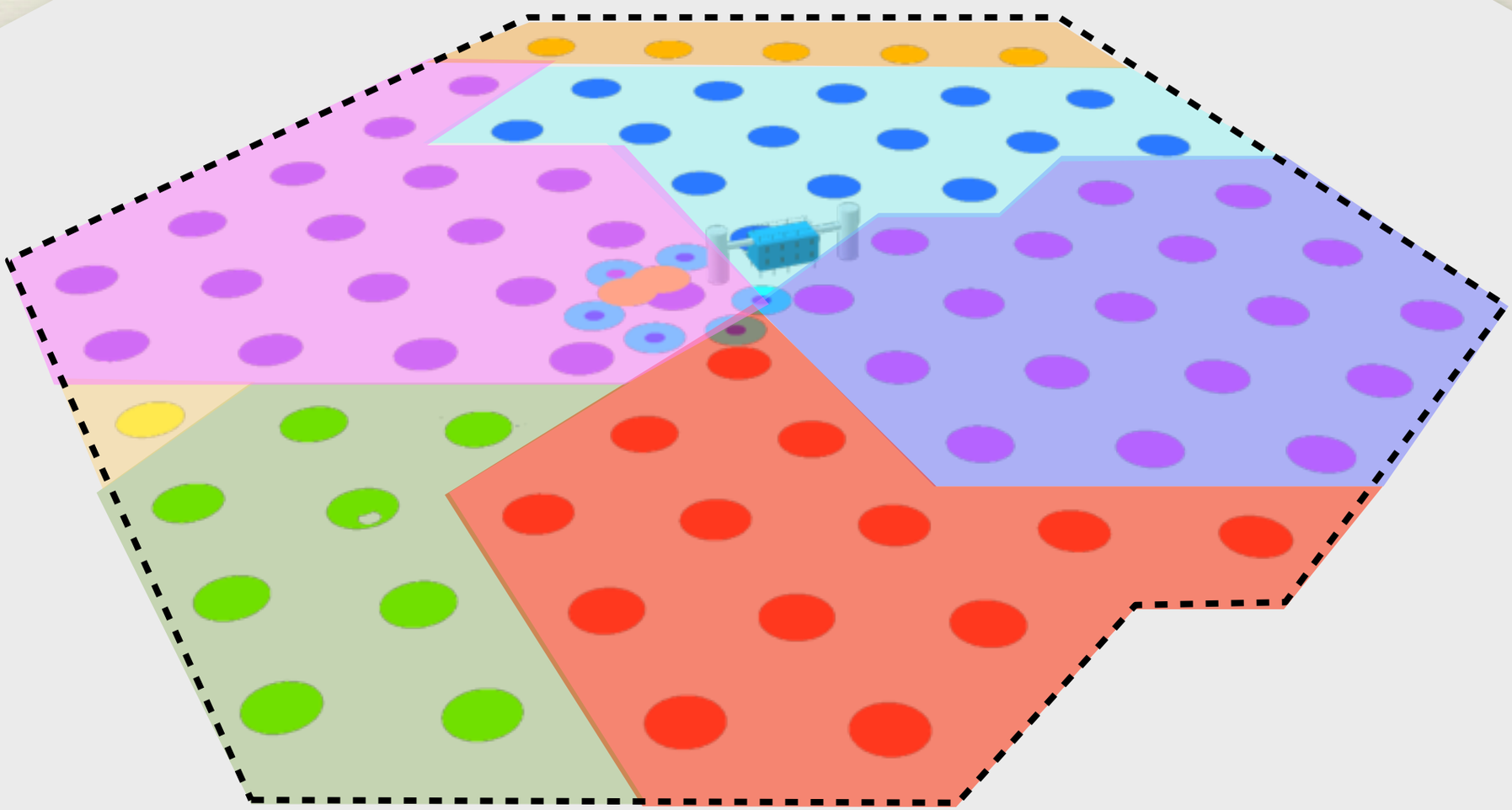
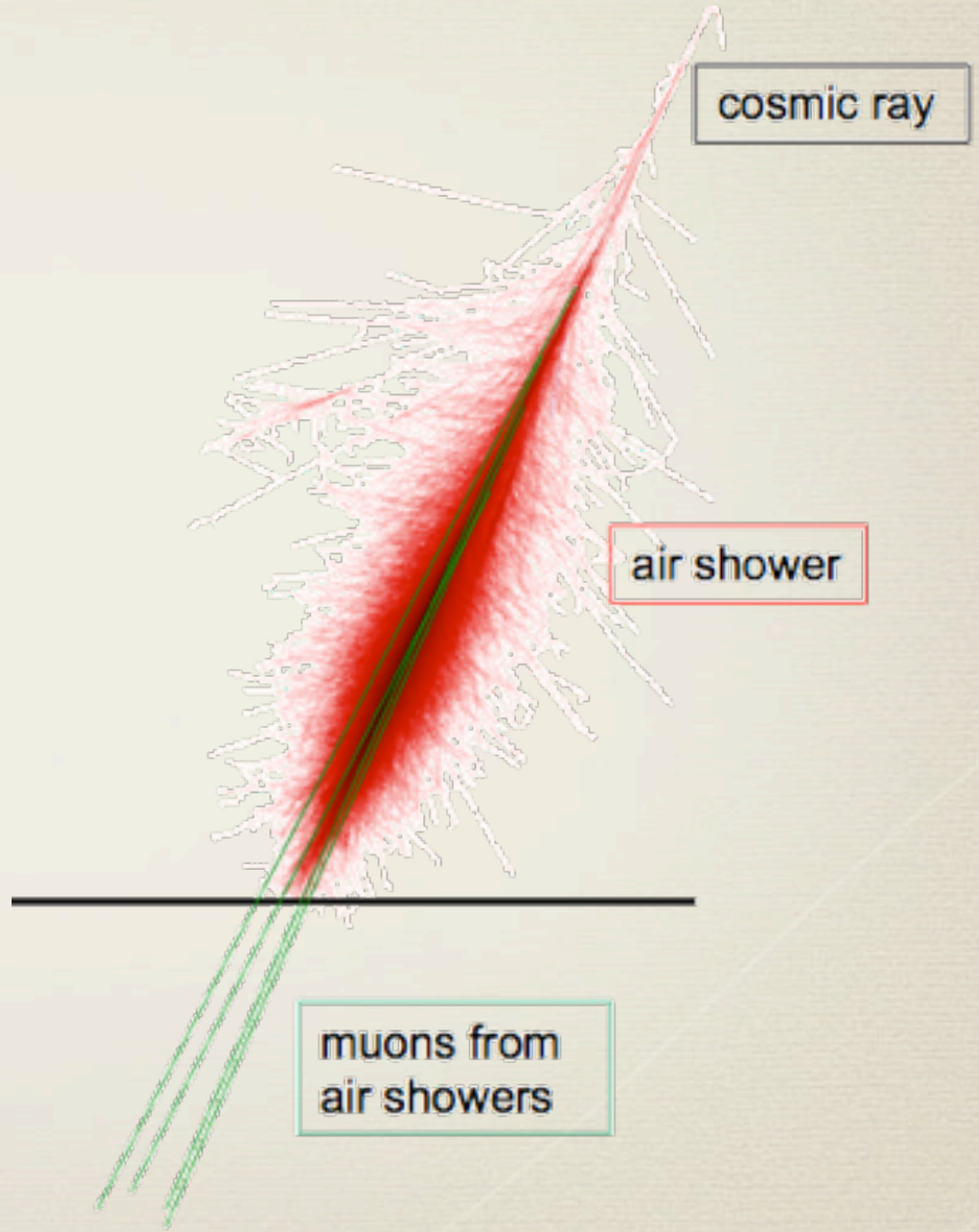


Construction finished on December 2010

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.



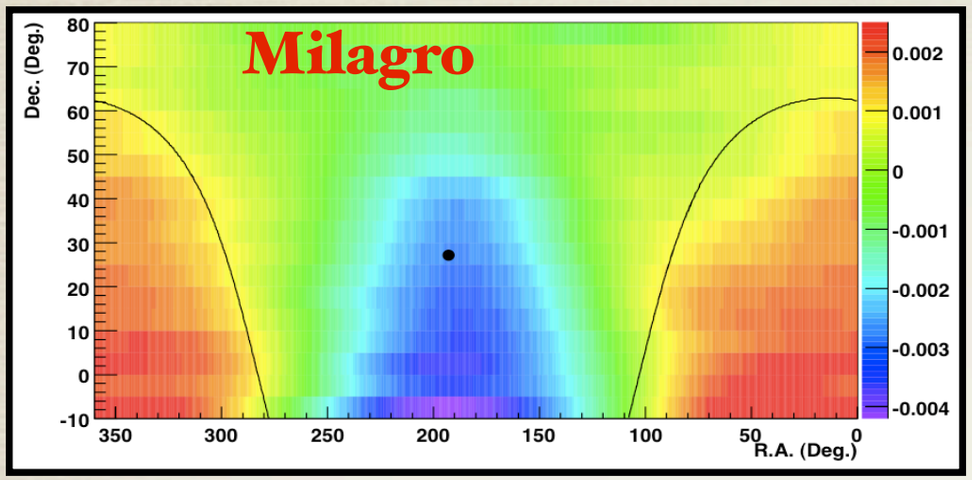
Data set

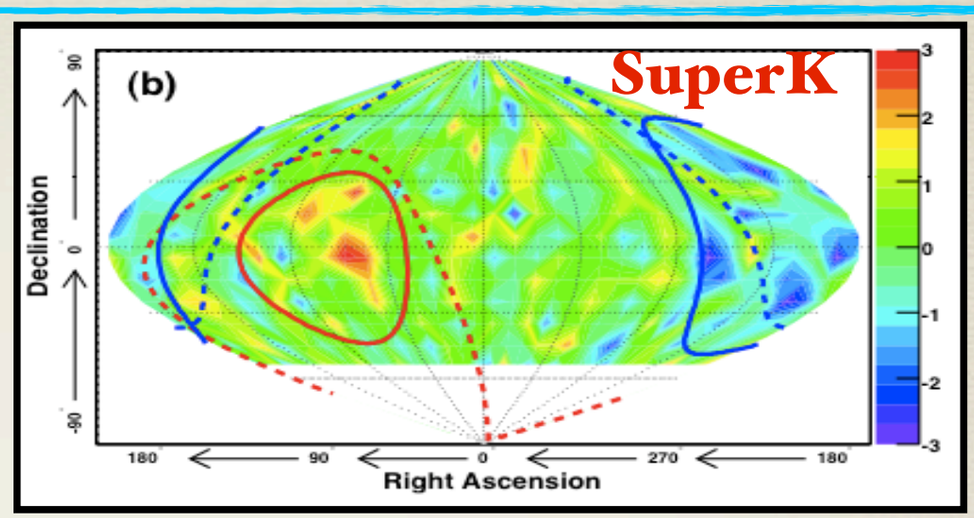
- IceCube collects billions of down-going muons generated in CR air showers
- 32 billion of events collected between May 2009/May 2010 with 20 TeV median energy

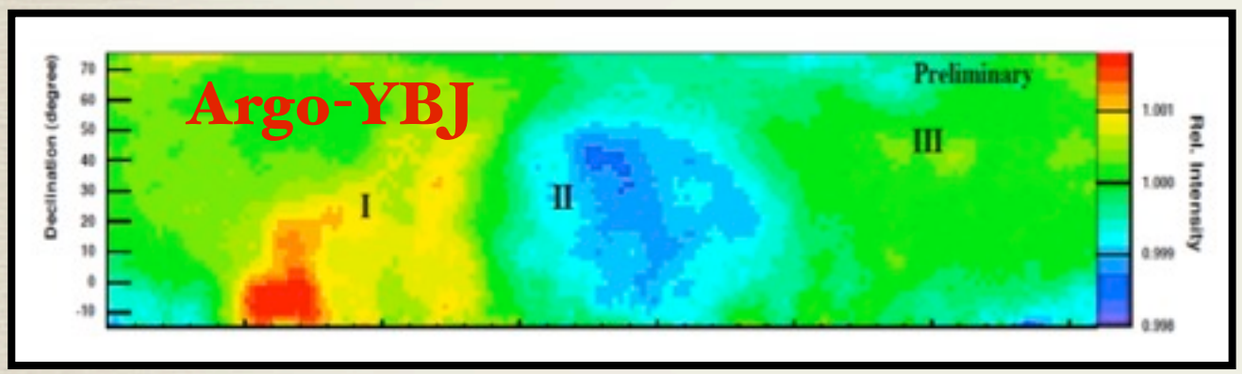
IceCube-59	Level 1 "Muon Filter"	DST
Live Time	96%	96%
Trigger rate	22 Hz	1.4 kHz
N_{events}	8.0×10^{8}	3.2×10^{10}
Angular resolution	<1°	3°
Energy resolution	$\Delta \log_{10}(E) = 0.3$	$\Delta \log_{10}(E) = 0.5$

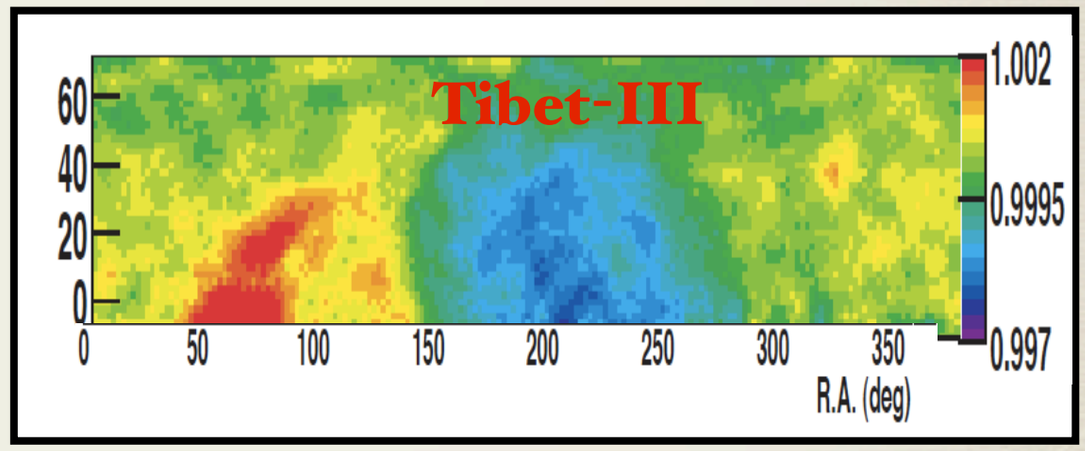
Observation of the CRs large scale anisotropy

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

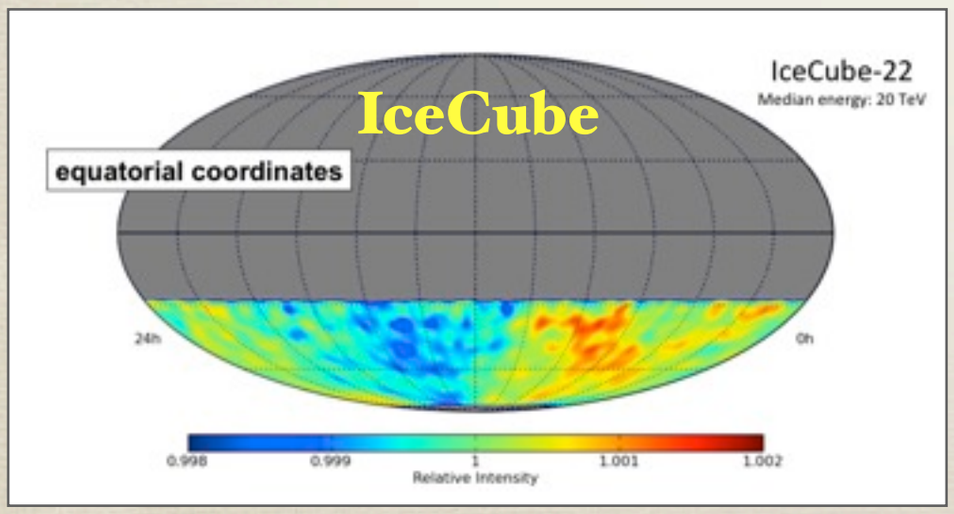








Northern Sky



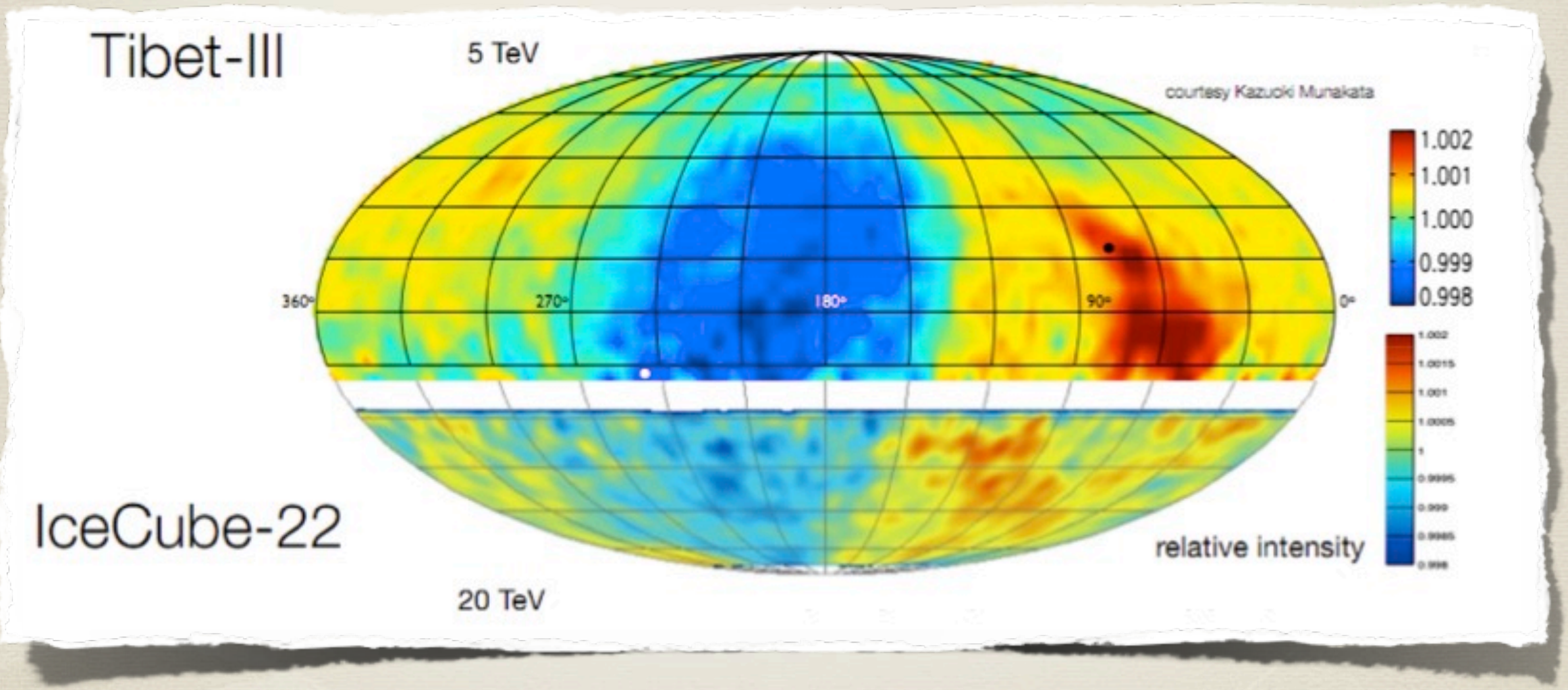
Southern Sky

Tibet ASγ	M. Amenomori et al., Astrophys. J 626 (2005) L29
SuperK	G. Guillian et al., Phys. Rev. D 75 (2007) 062003
Milagro	A. Abdo et al., Astrophys. J. 698 (2009) 2121
ARGO-YBJ	S. Vernetto, Proc. 31st ICRC, 2009
EAS-Top	M. Aglietta, Astrophys. J. 692 (2009) L130
IceCube	R. Abbasi *et al*, Astrophys. J. 718 (2010) L194

Large scale anisotropy

✳IceCube observed a large scale anisotropy at 10^{-3} level for the first time in the Southern Sky.

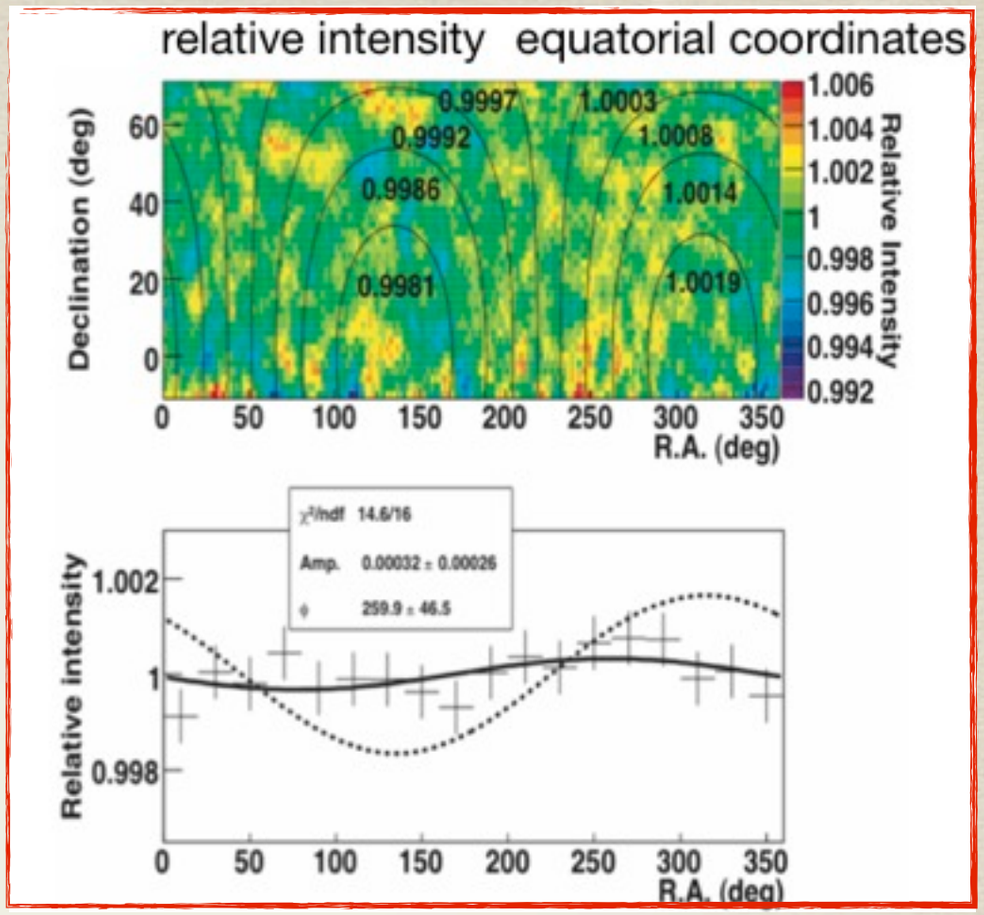
✳The anisotropy appears to be a continuation of large scale structures observed in the Northern Hemisphere.



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.

Energy dependence of the anisotropy

300 TeV

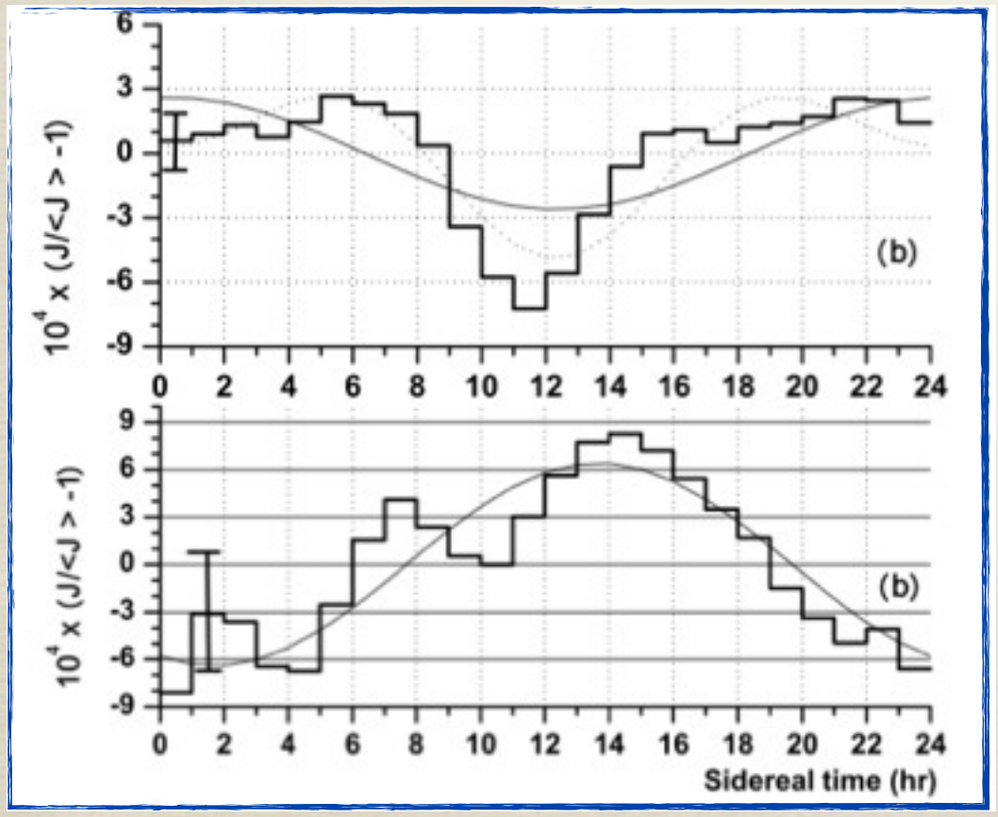


Tibet - III

Amenomori et al., Science Vol. 314, pp. 439, 2006

Amplitude: $(3.2\pm2.6)\times10^{-4}$

consistent with **no anisotropy**



110 TeV

370 TeV

EAS-Top

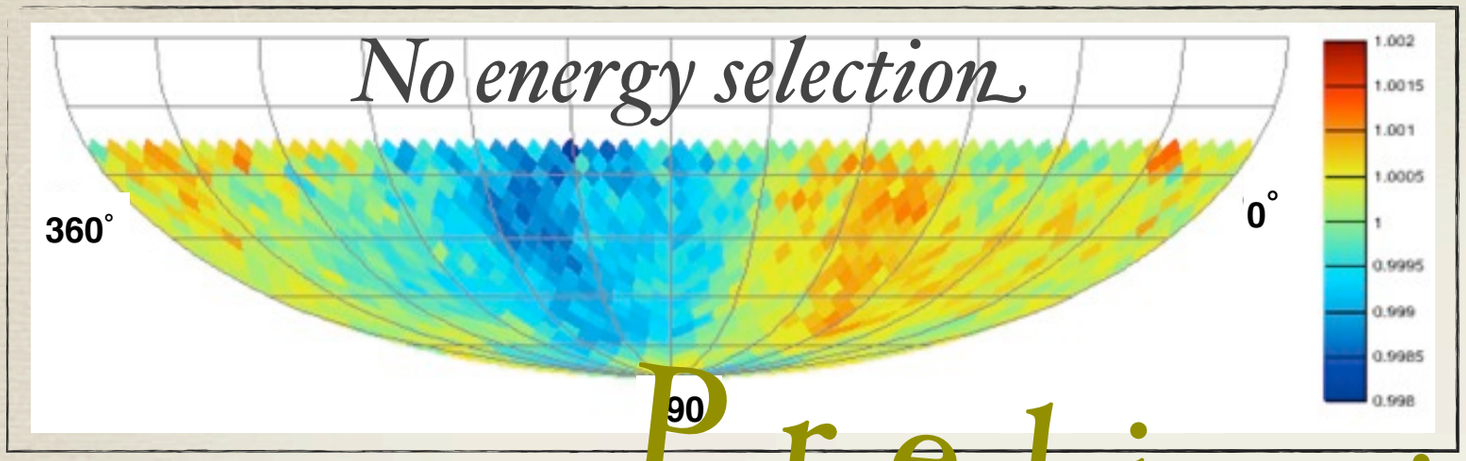
Aglietta et al., ApJ 692, L130, 2009

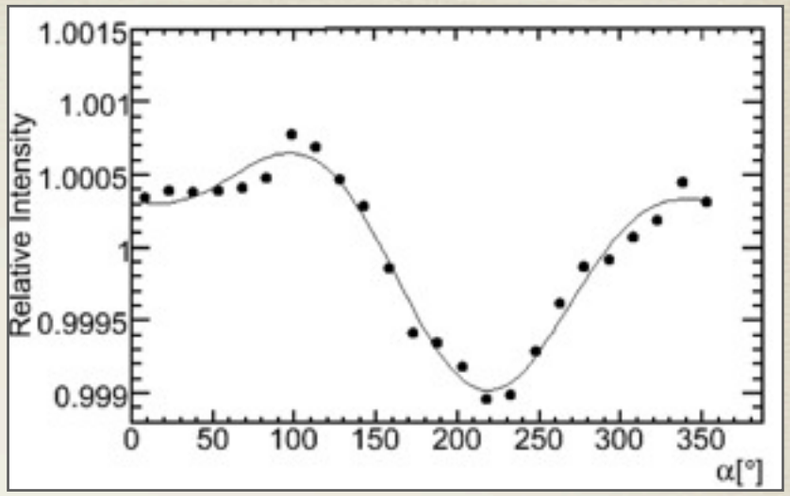
Amplitude (370 TeV): $(6.4\pm2.5)\times10^{-4}$

low significance, still not conclusive.

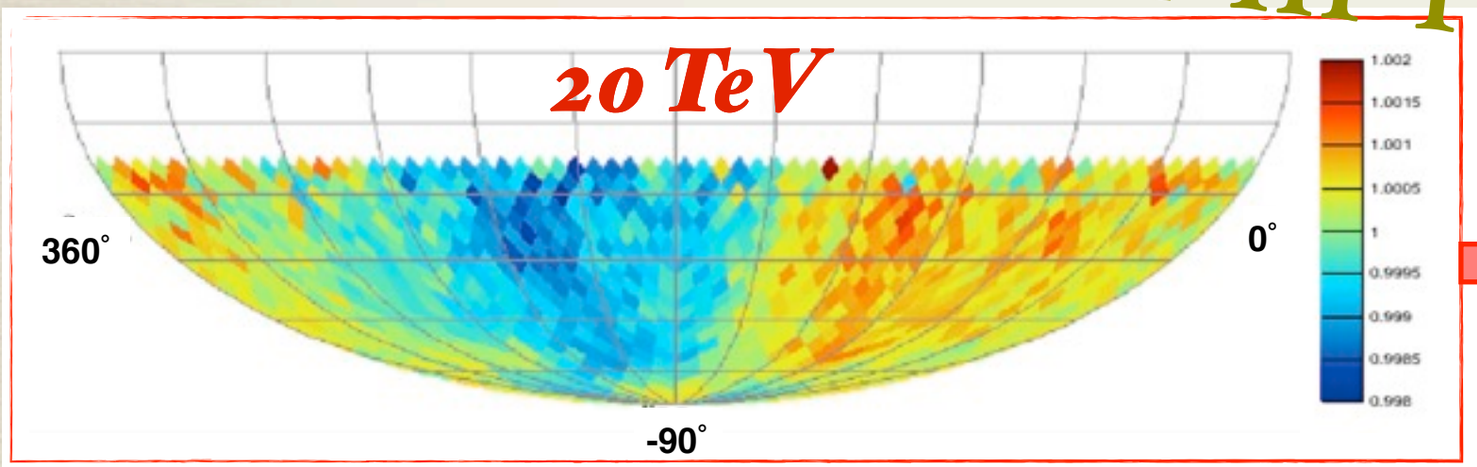
Relative Intensity

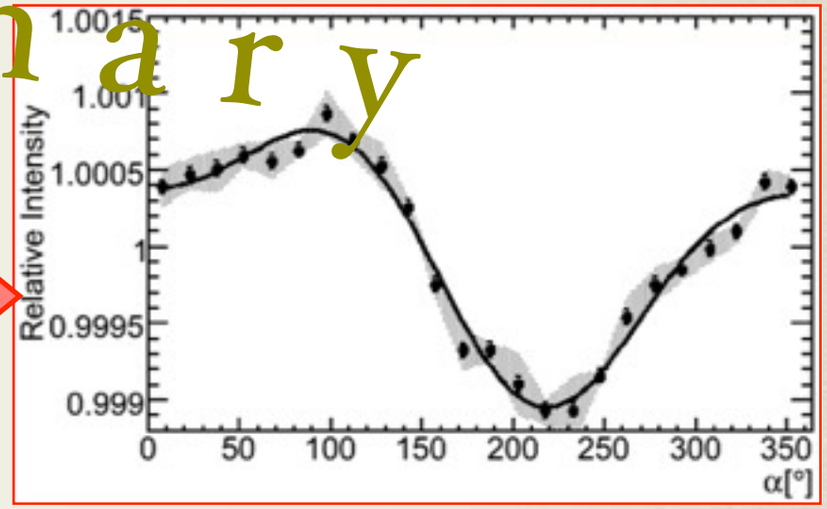
Equatorial sky maps in HEALPix with NSide= 16, ***pix resol ~ 3°***

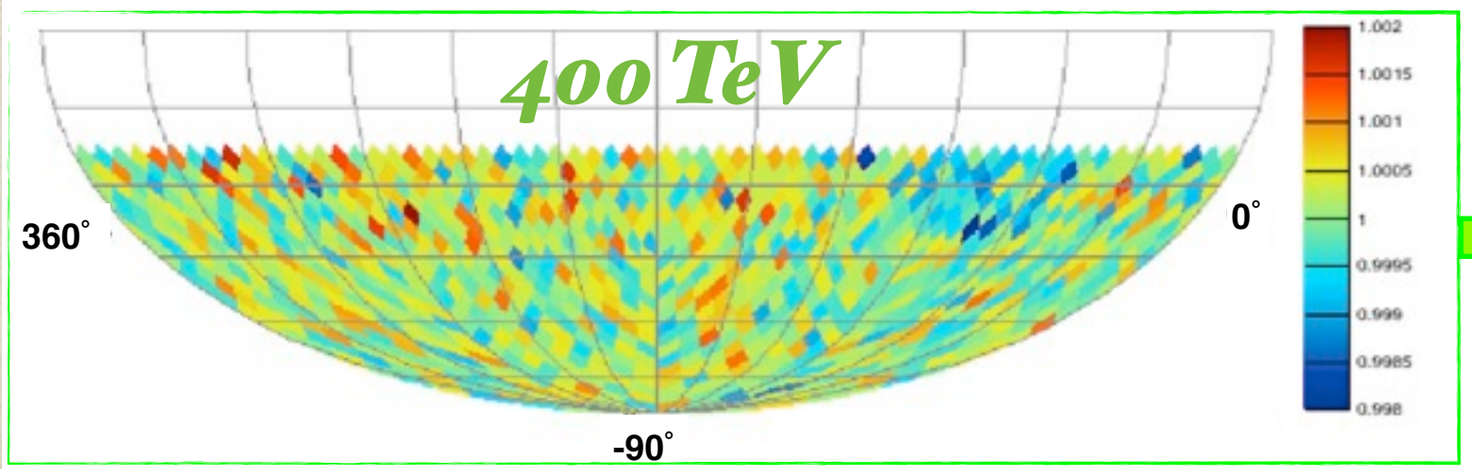


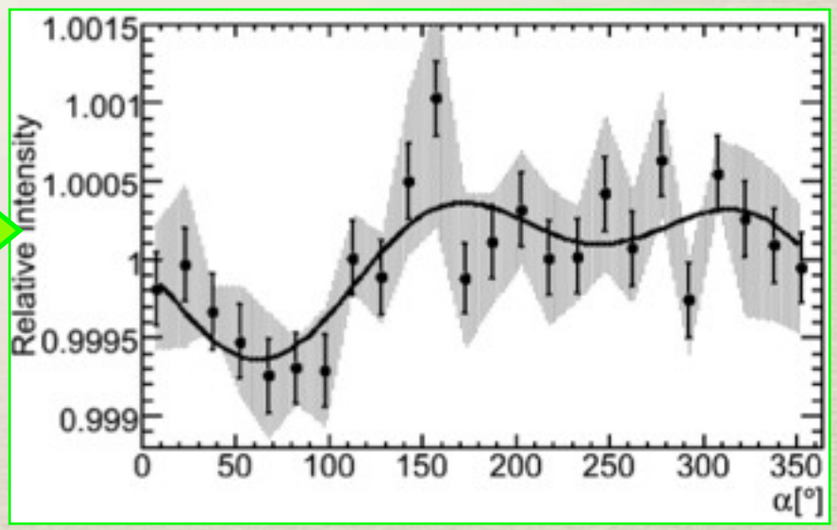


Preliminary







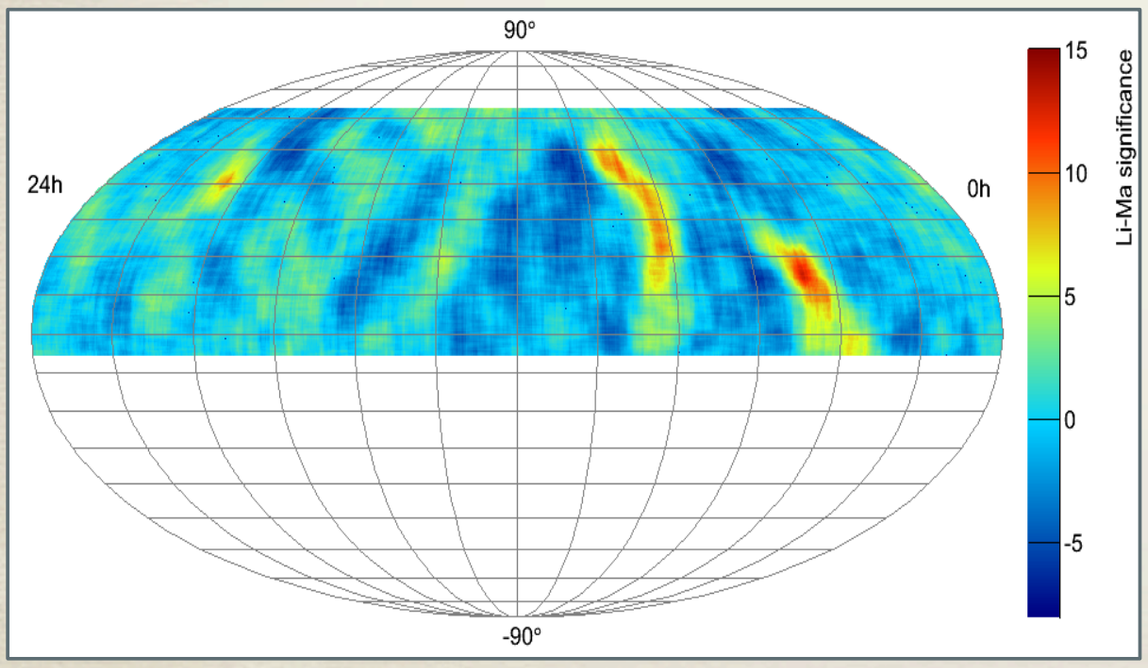


Small scale anisotropy

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 10^{11} events recorded over 7 years. The "hot" regions have fractional excesses of order several times **10^{-4}** relative to the background.

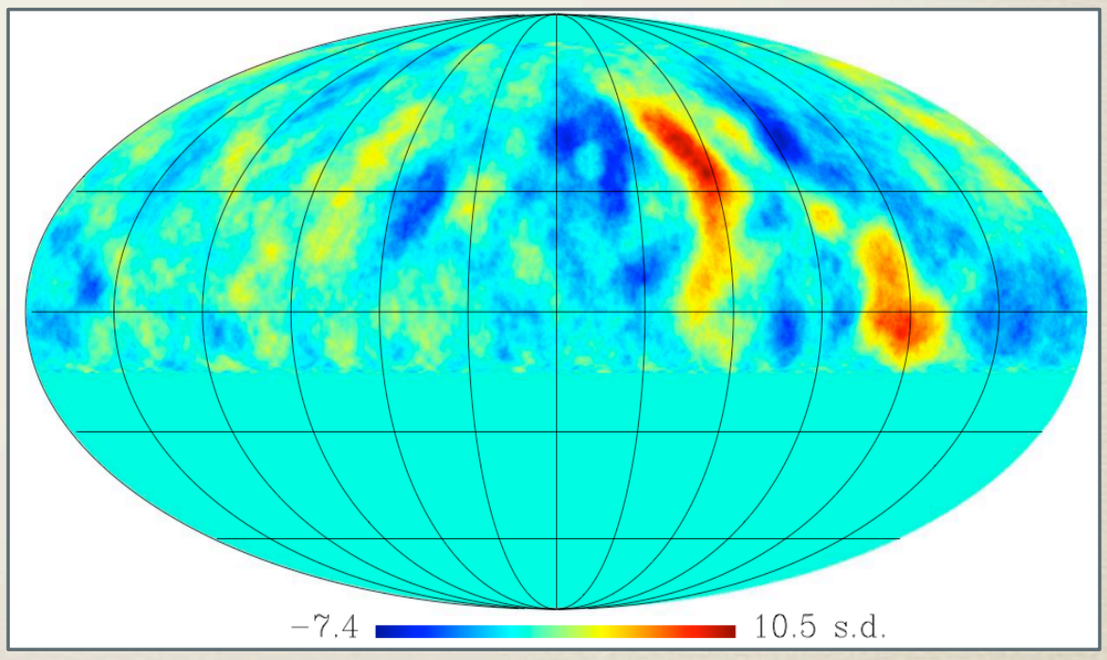
✳ Same structures observed by ARGO-YBJ.



A. Abdo et al., PRL 101 (2008) 221101

Milagro

Median Energy: 1 TeV



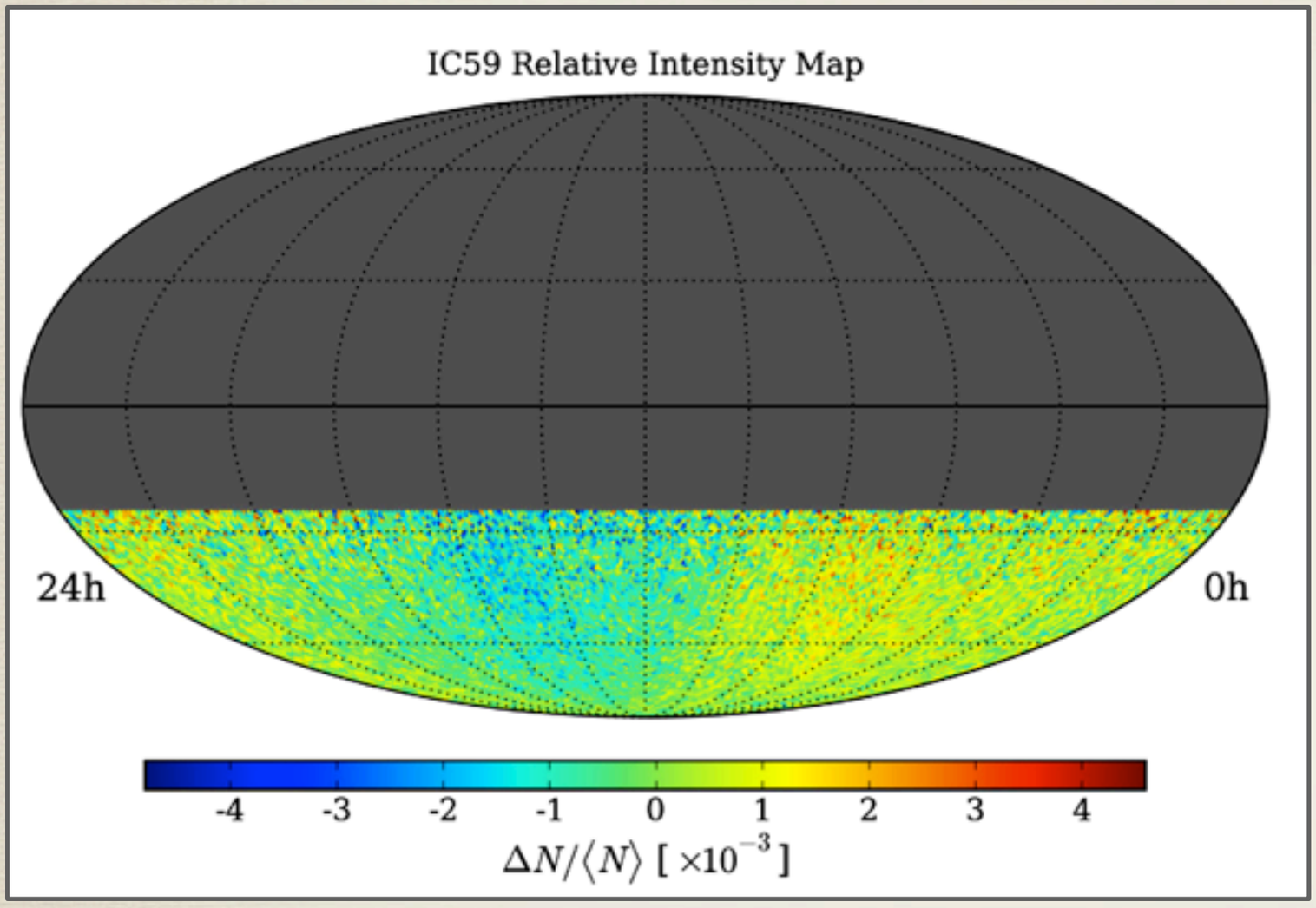
S. Vernetto, Proc. 31st ICRC, 2009

ARGO-YBJ

Median Energy: 2 TeV

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 i^{th} pixel.
- $\langle N_i \rangle$**:** expected number of events in an isotropic sky (time scrambling in 24 hr) in the i^{th} pixel.
- Relative Intensity:

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

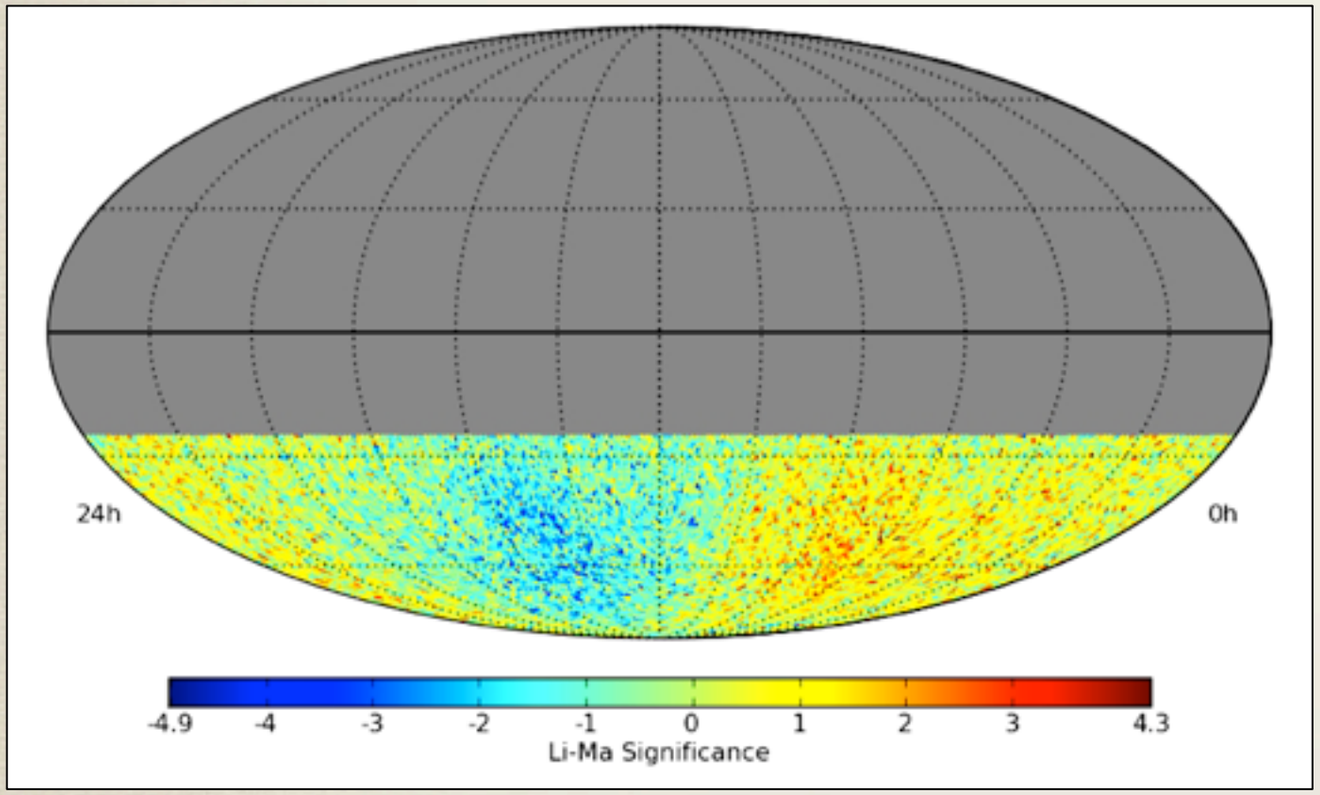
Relative intensity map is *not isotropic*. In IceCube-59, the *strong large scale structure* already observed in IceCube-22 data is visible in the "raw" data.

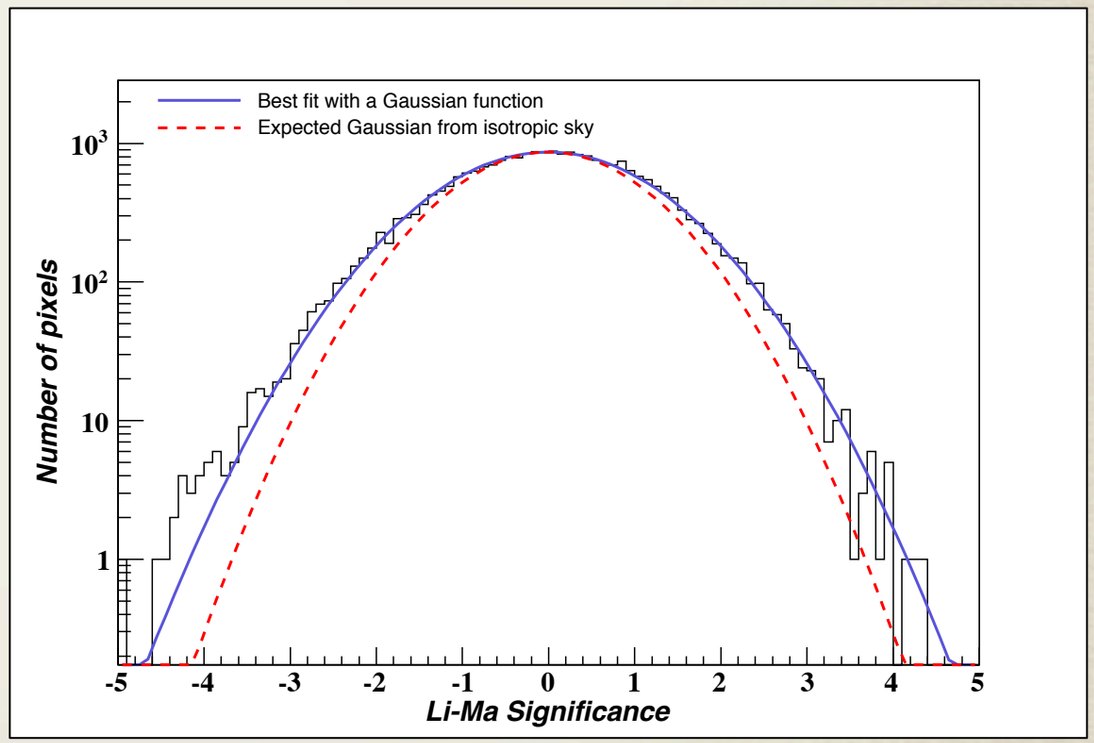
Significance map

Significance calculation:

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

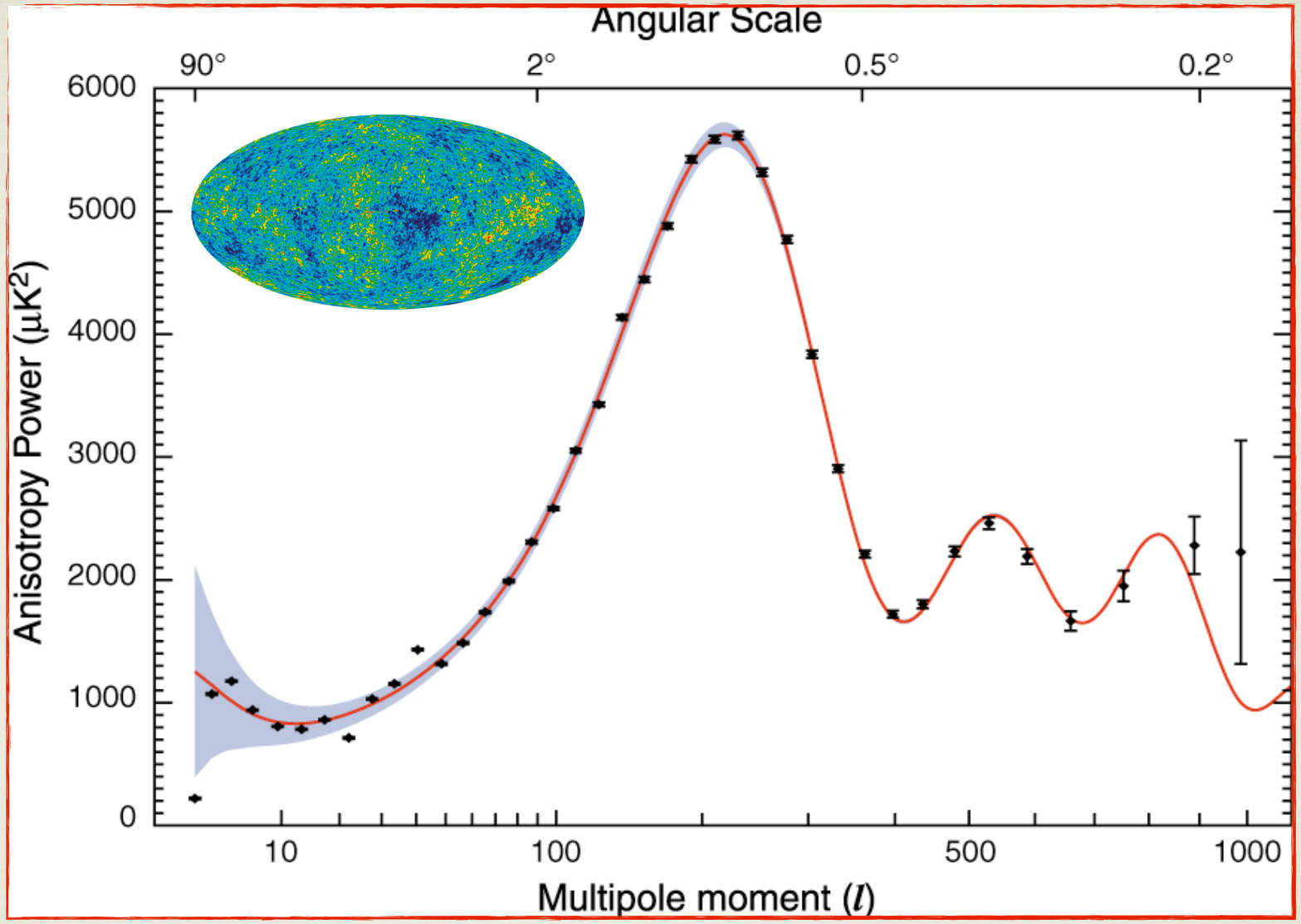
Li, T., & Ma, Y. 1983, ApJ, 272, 317





Power spectrum

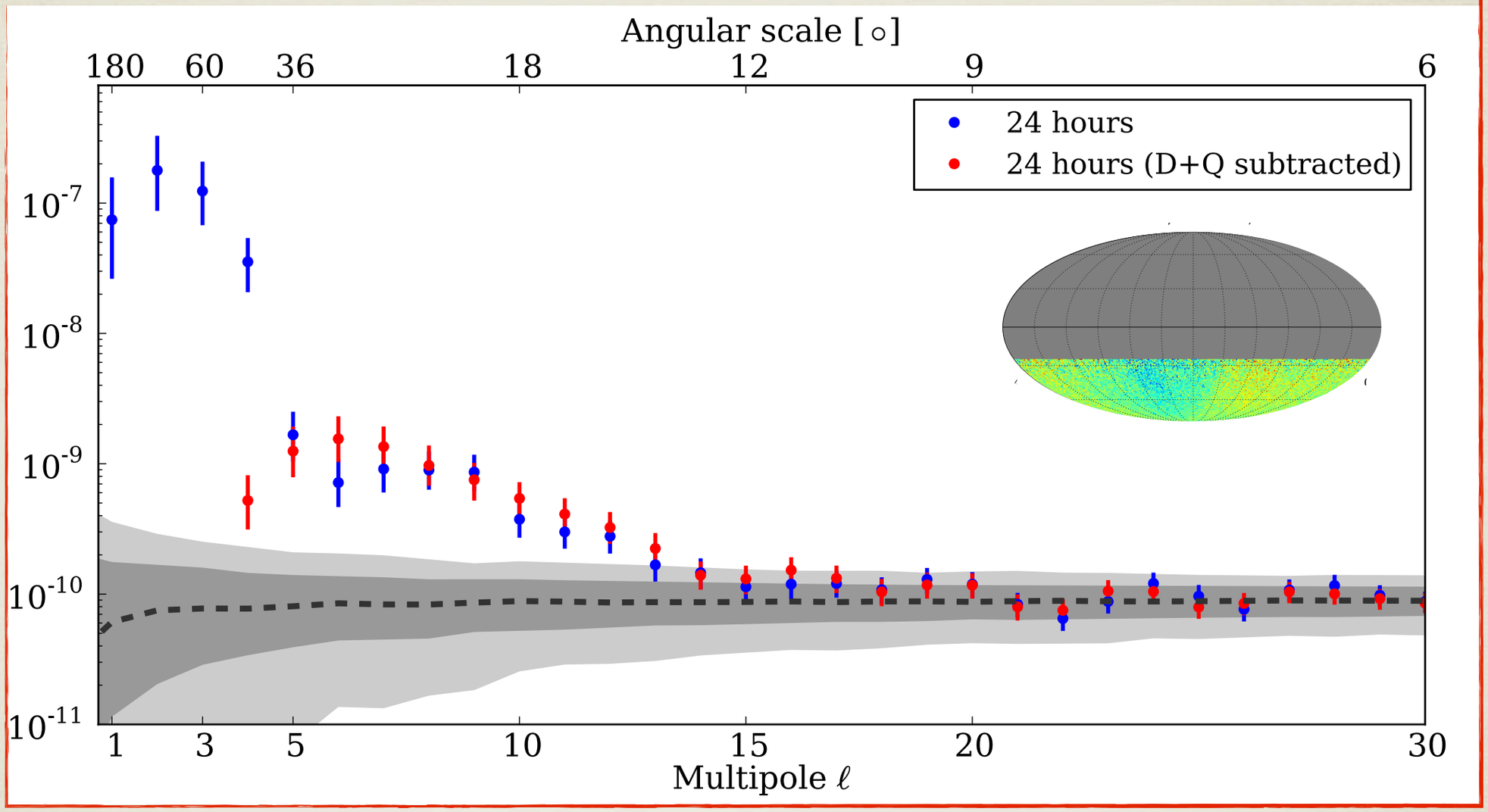
Angular size $\theta \sim \dfrac{180^\circ}{\ell}$



Multipole expansion: $\delta I(\mathbf{u}_i) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{u}_i) \qquad C_\ell = \dfrac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$

Power spectrum

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



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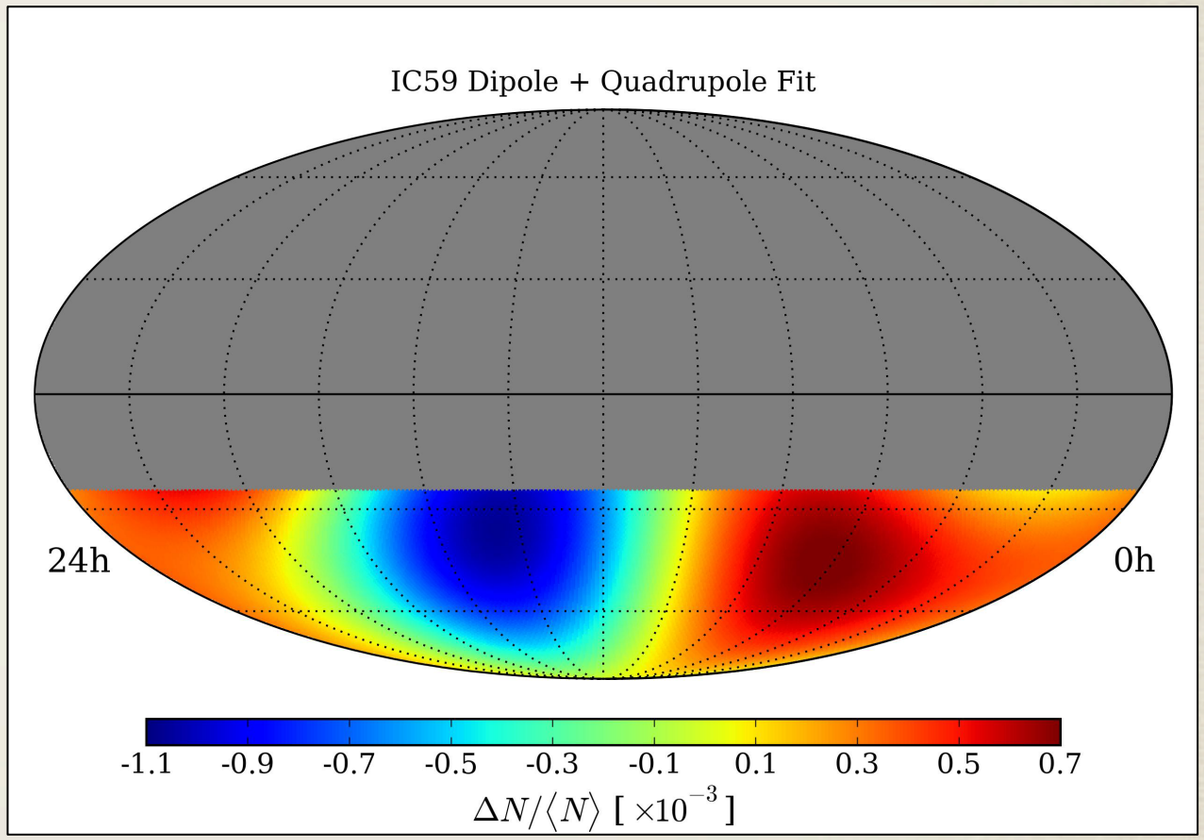
Dipole and quadrupole fit

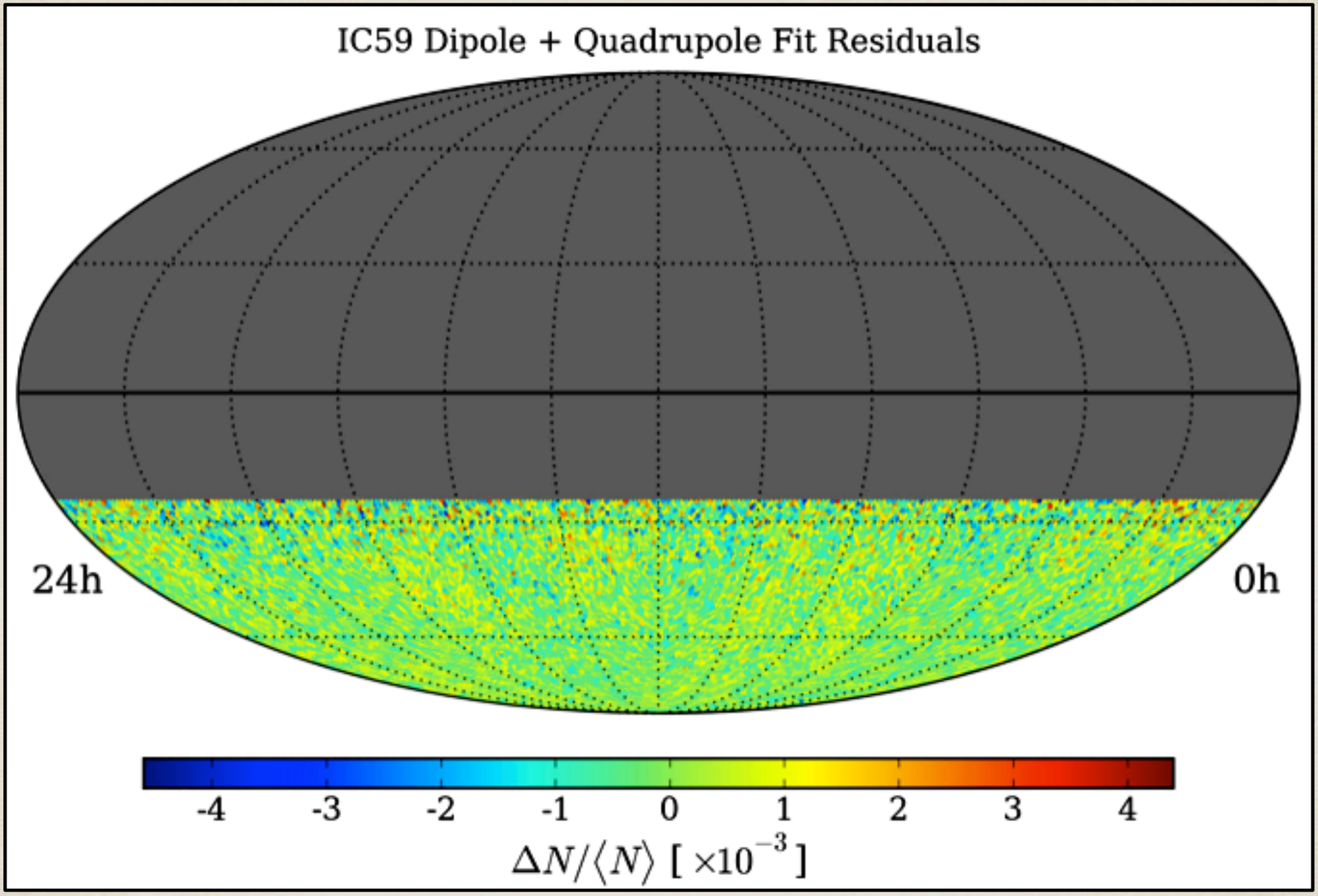
$$\delta I(\alpha,\delta) = m_0 \qquad \textbf{monopole}$$
$$+p_x \cos\delta\cos\alpha + p_y \cos\delta\sin\alpha + p_z \sin\delta \qquad \textbf{dipole}$$
$$+\frac{1}{2}Q_1(3\cos^2\delta - 1) + Q_2 \sin 2\delta\cos\alpha + Q_3 \sin 2\delta\sin\alpha + Q_4 \cos^2\delta\cos 2\alpha + Q_5 \cos^2\delta\sin 2\alpha \qquad \textbf{quadrupole}$$

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

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



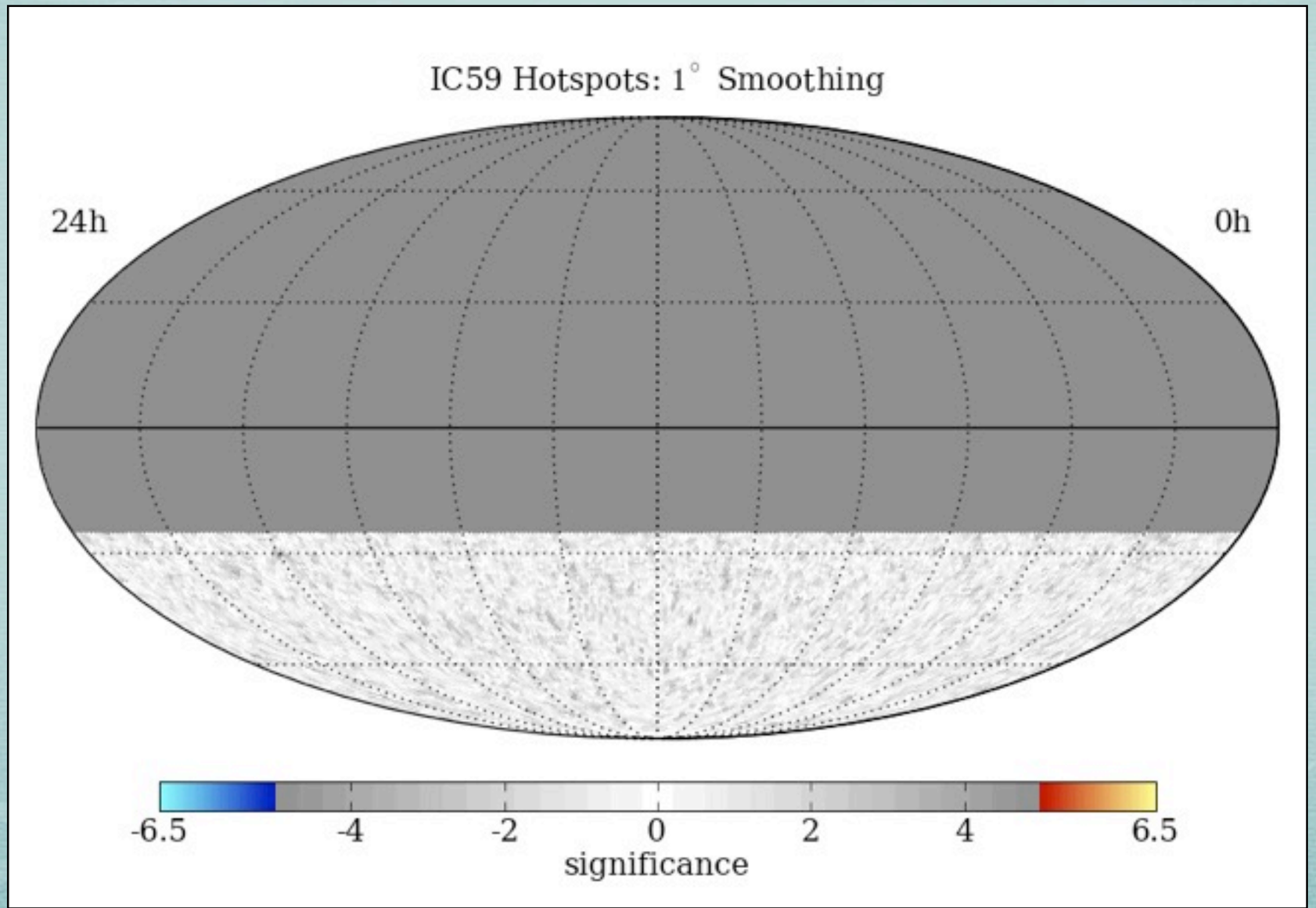
Residual map



No structures seem to be present: we need to smooth the map.

MAP SMOOTHING SCAN

Scan from 1 - 30° in smoothing
Different regions have different optimal angular smoothing
Significances are pre-trial



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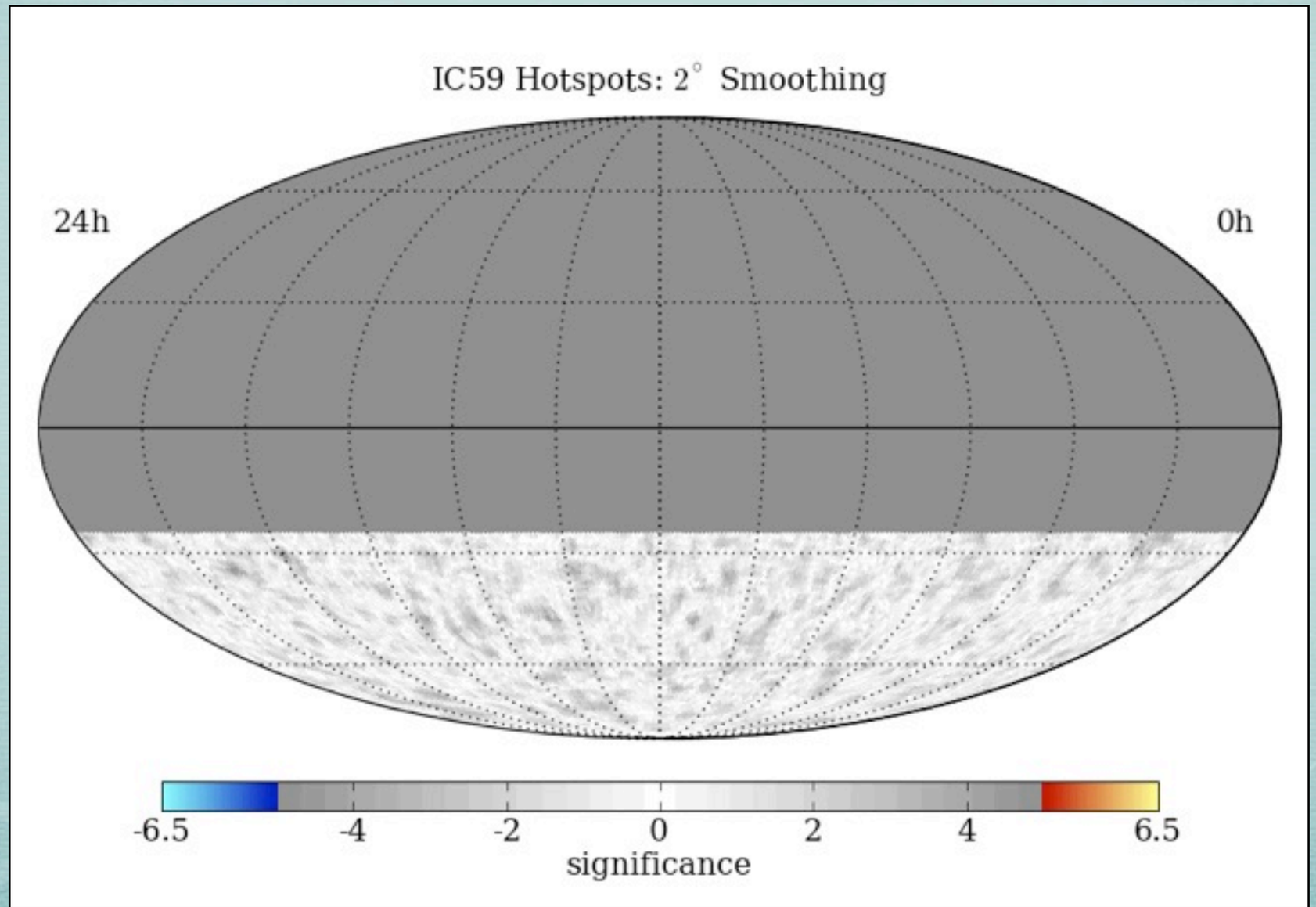

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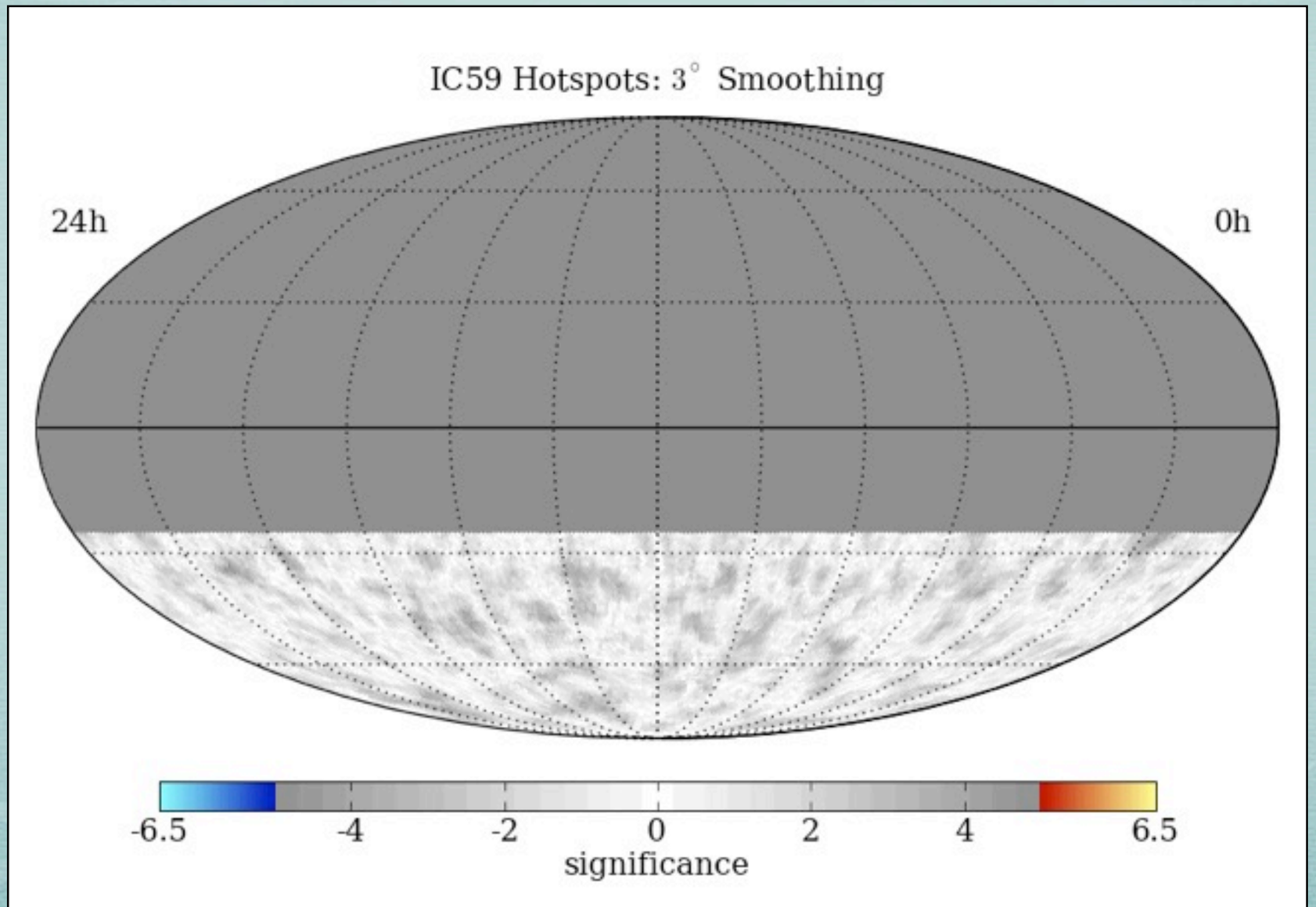

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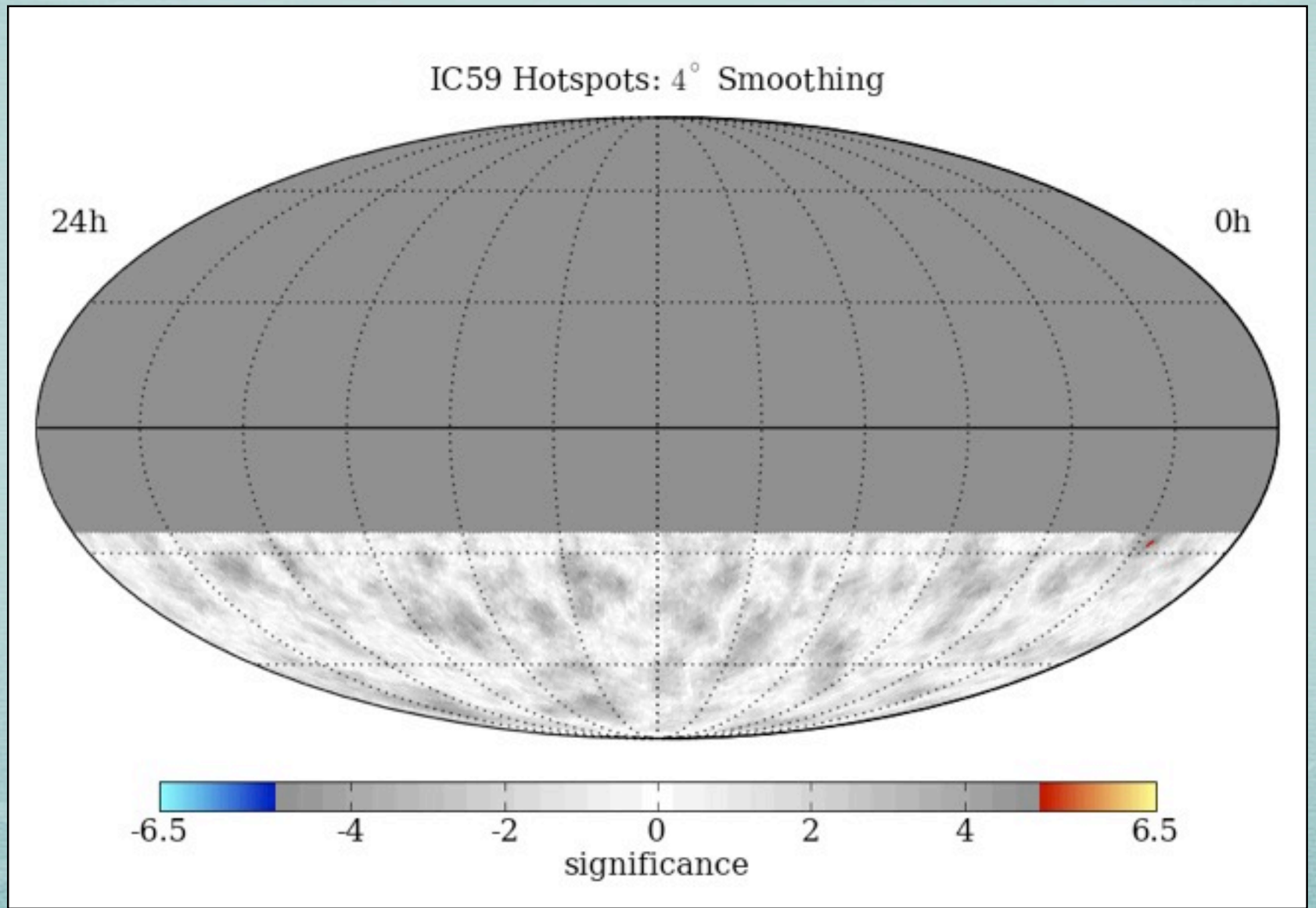

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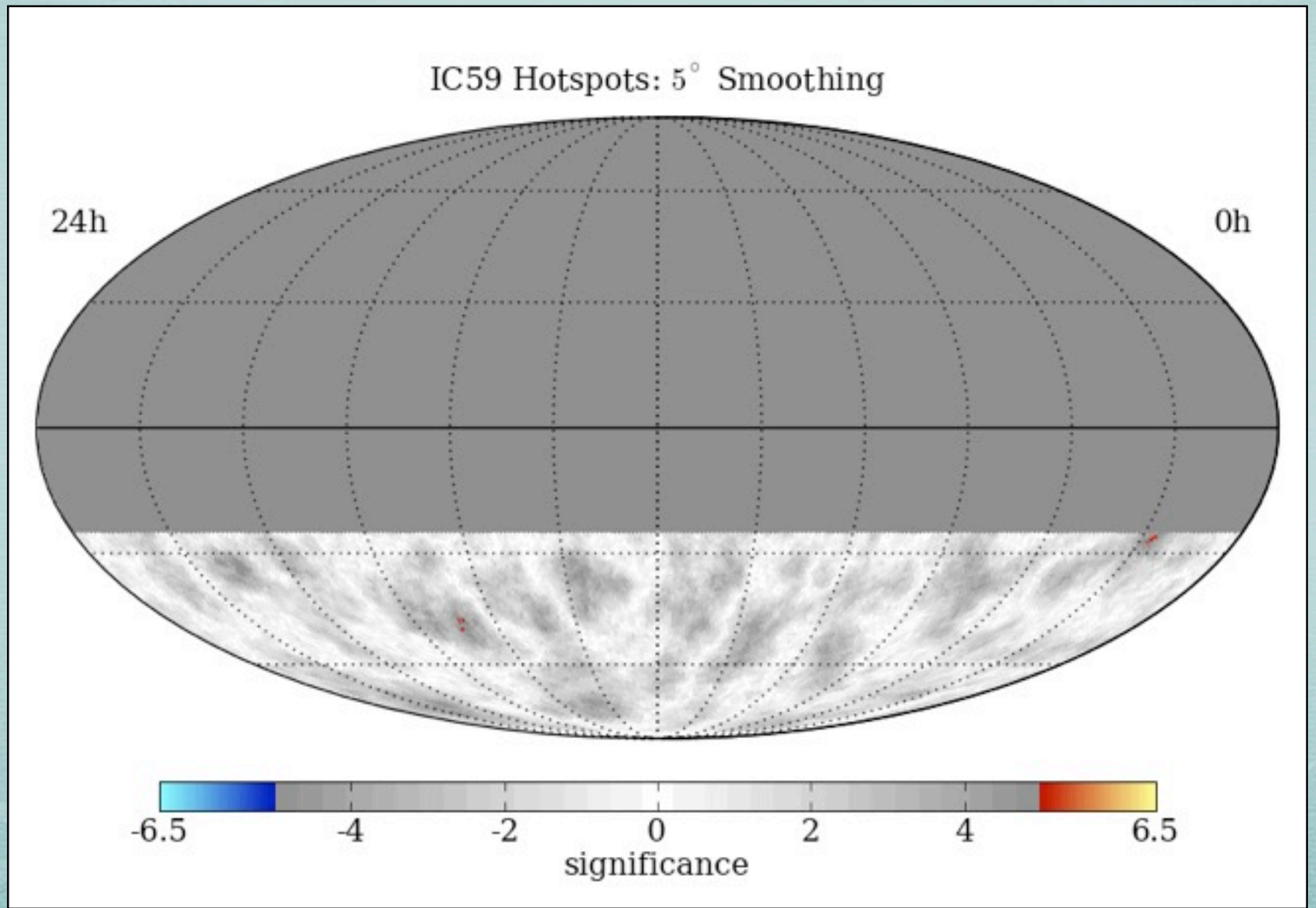

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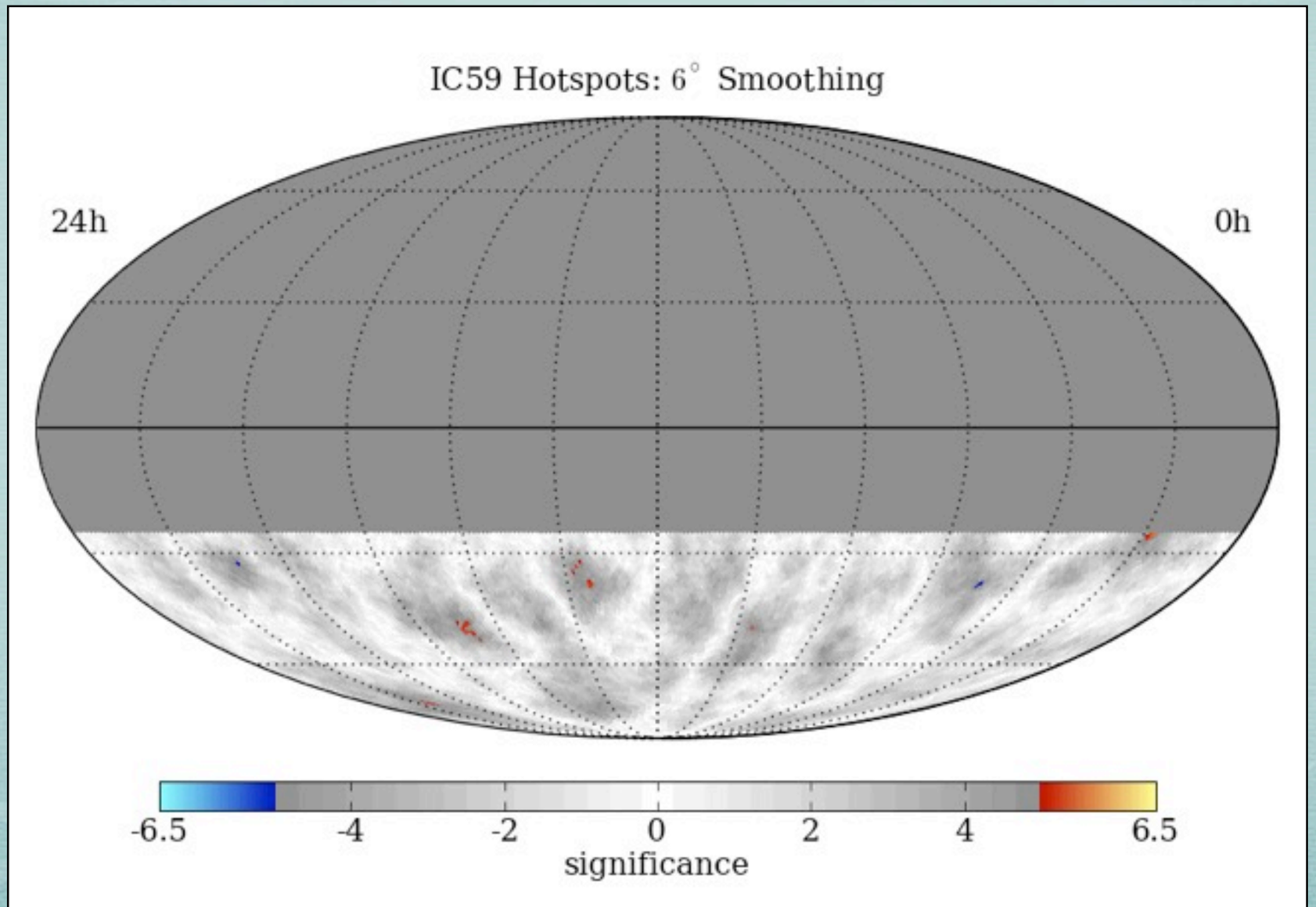

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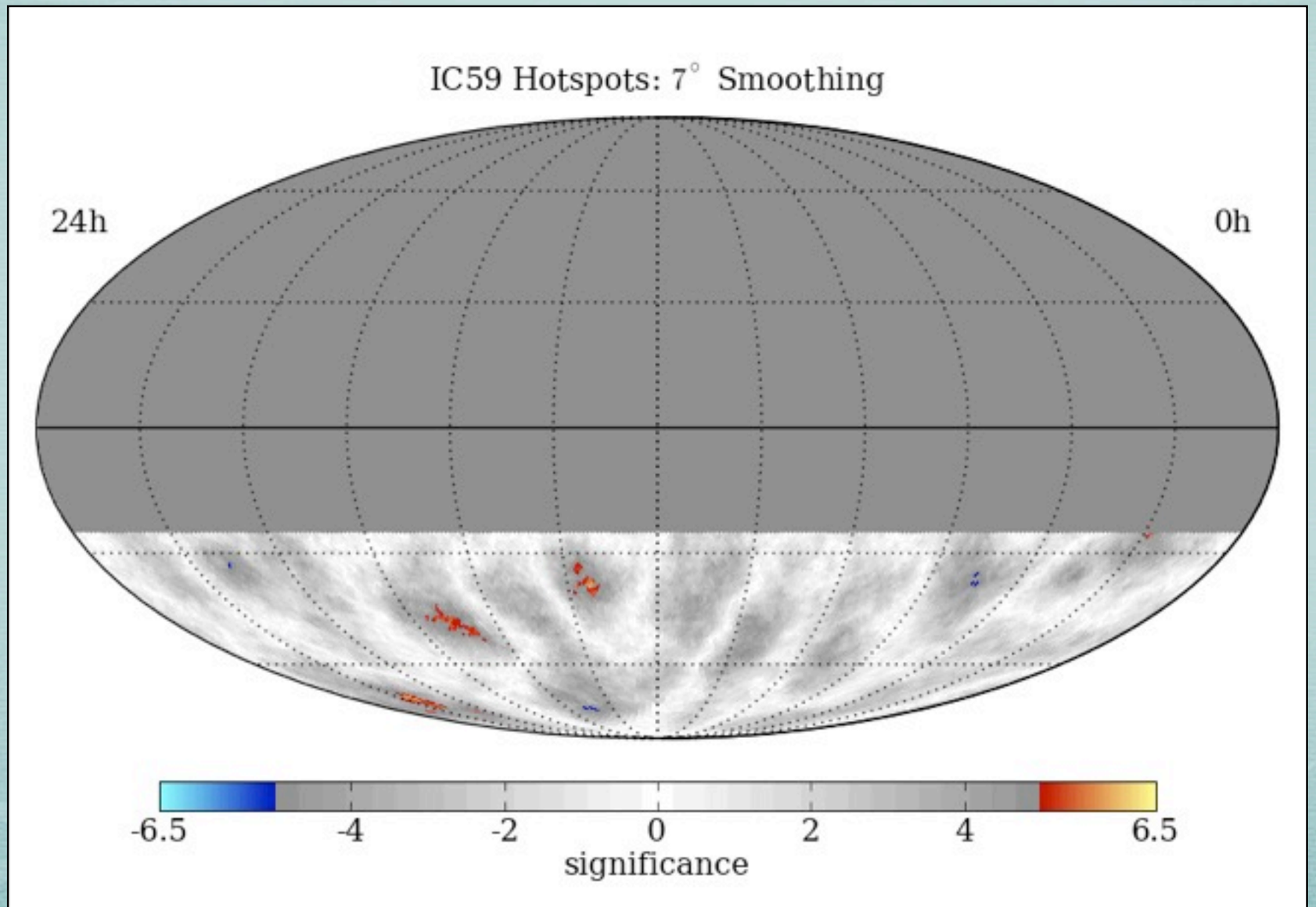

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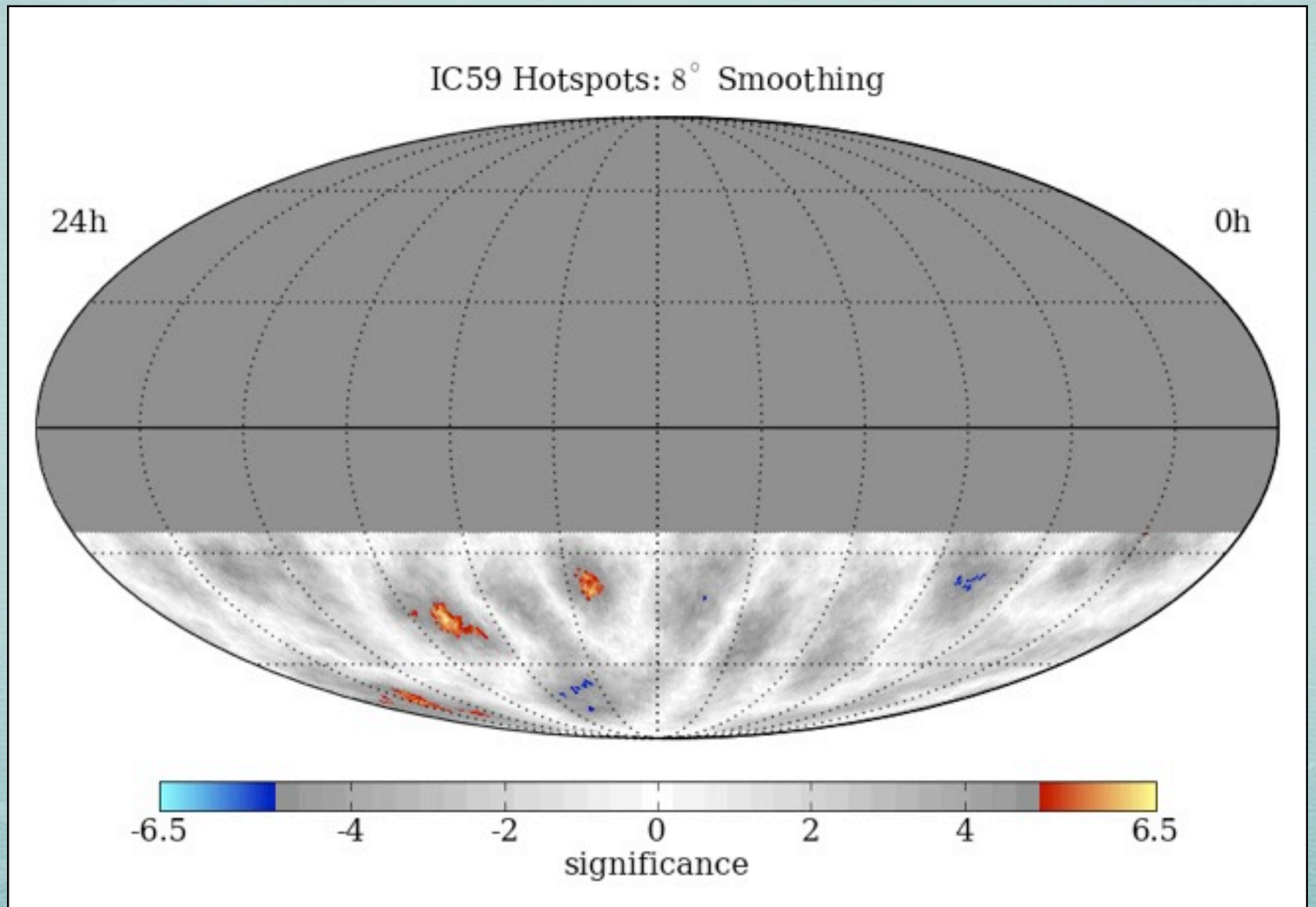

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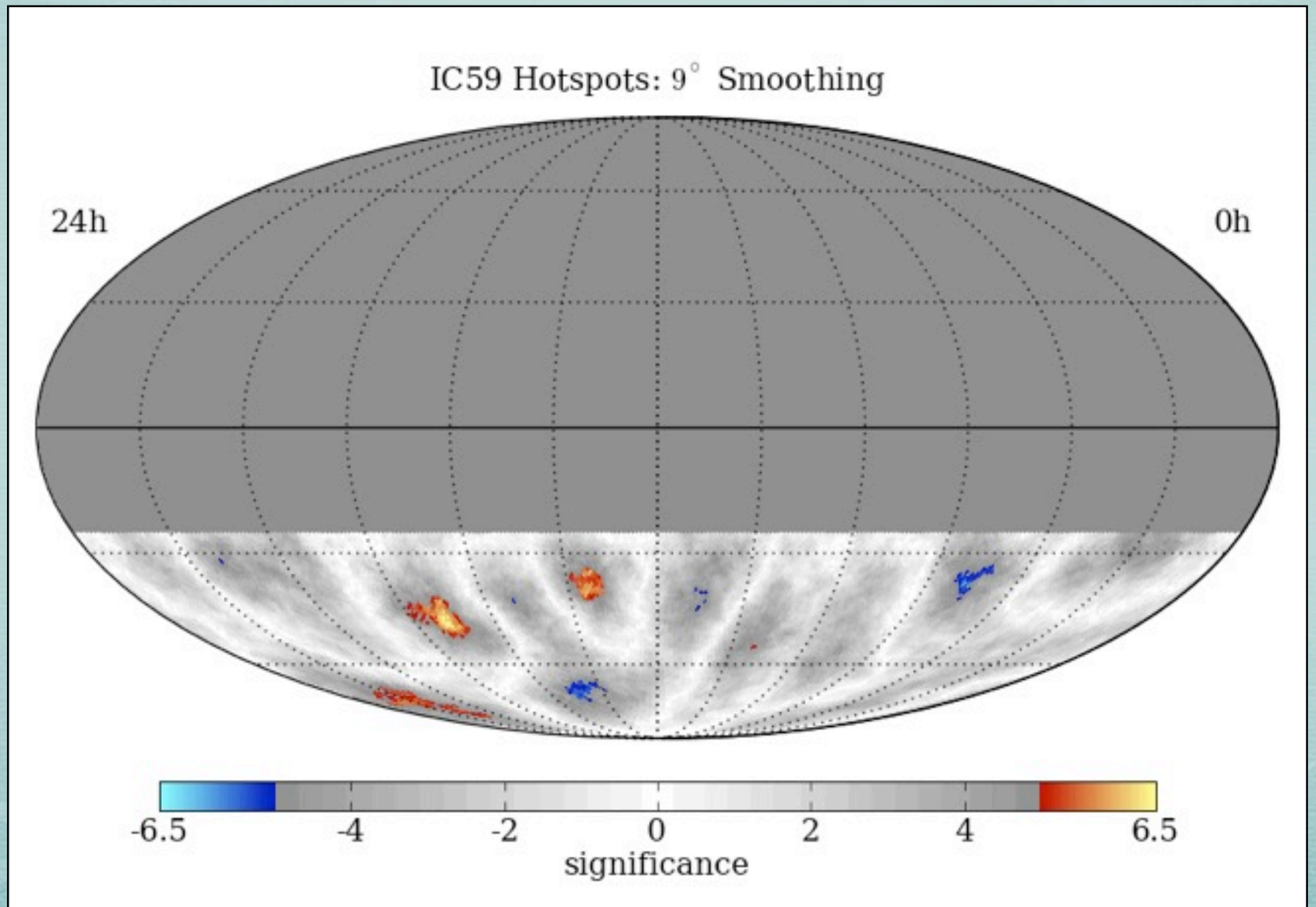

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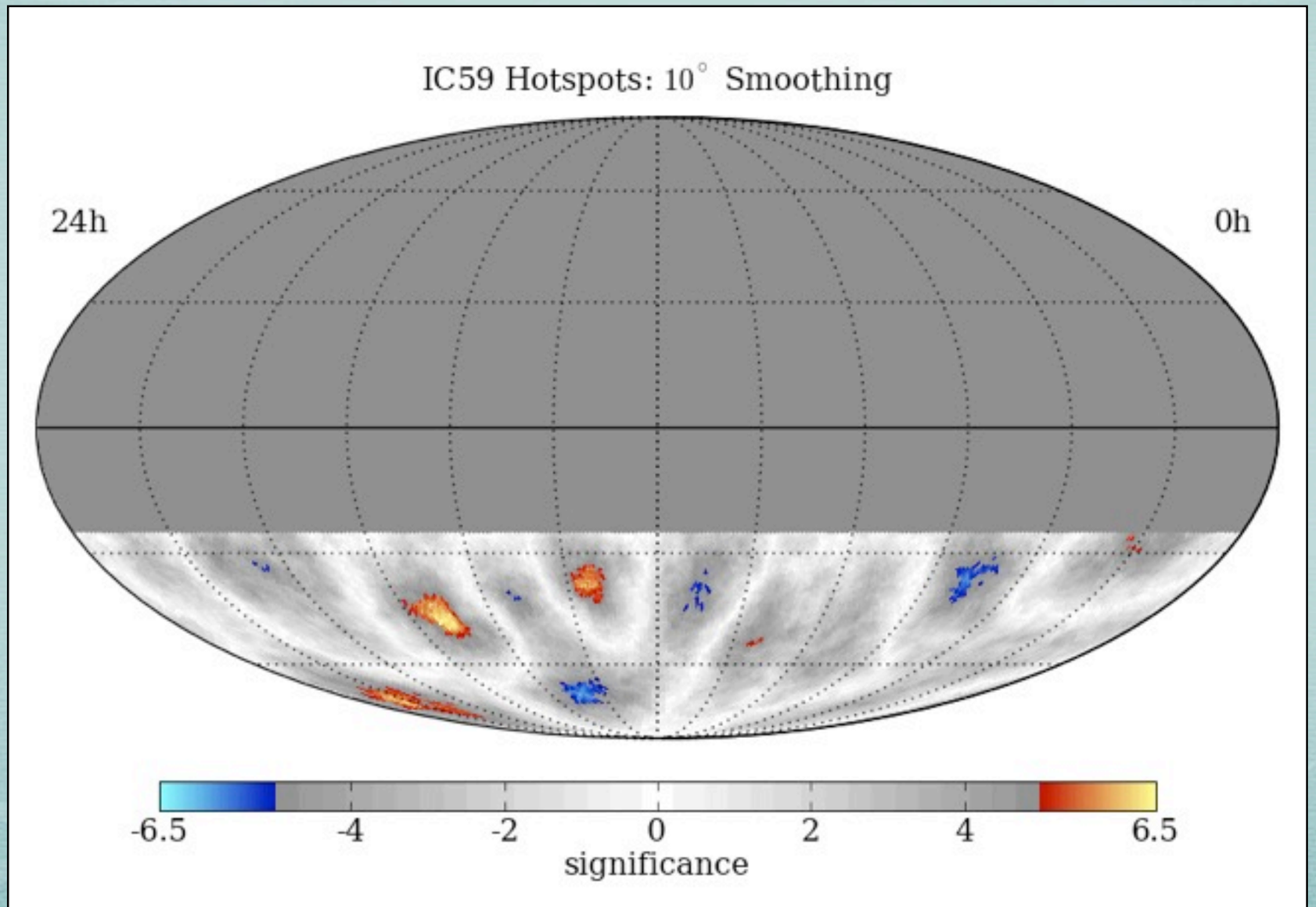

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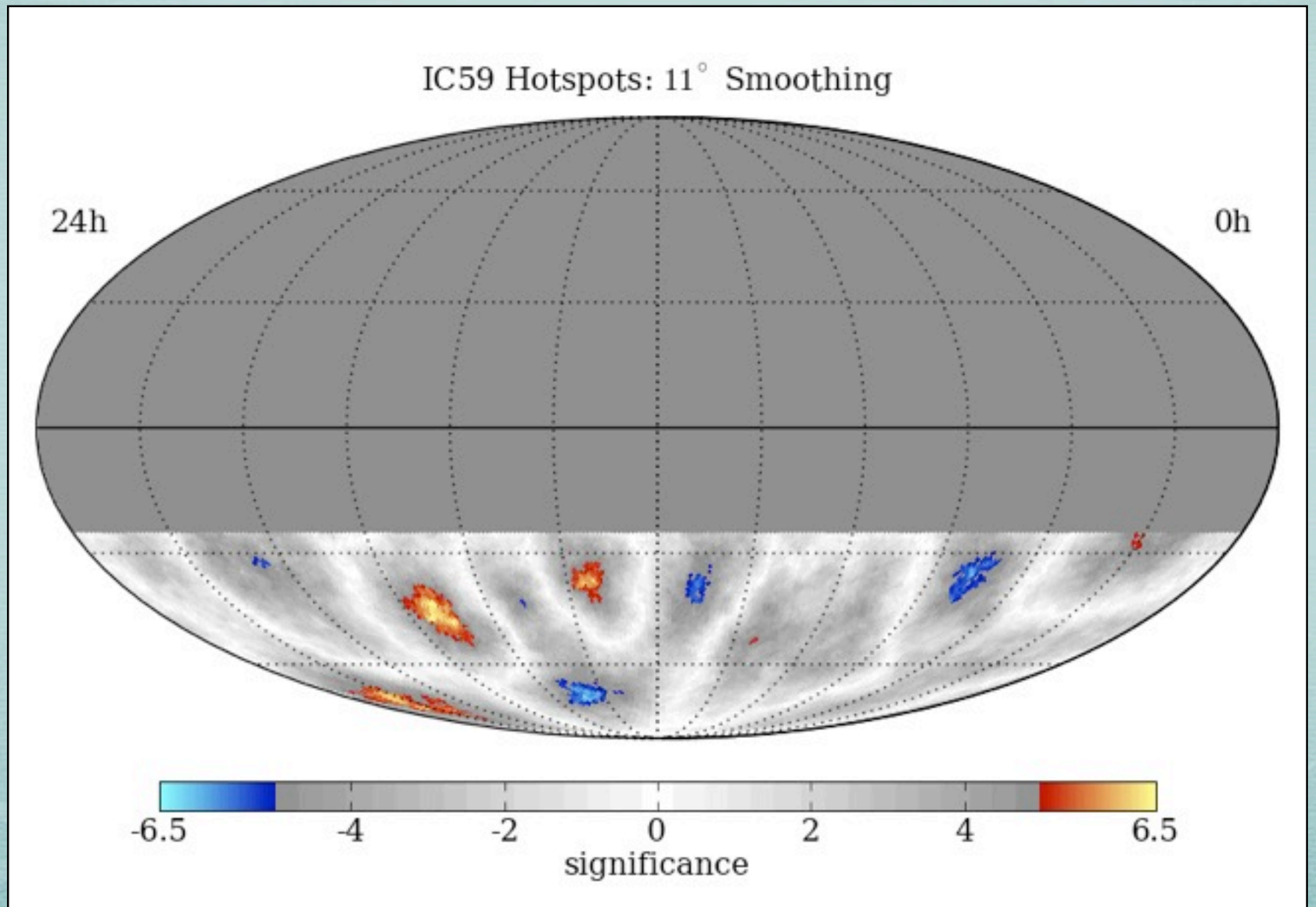

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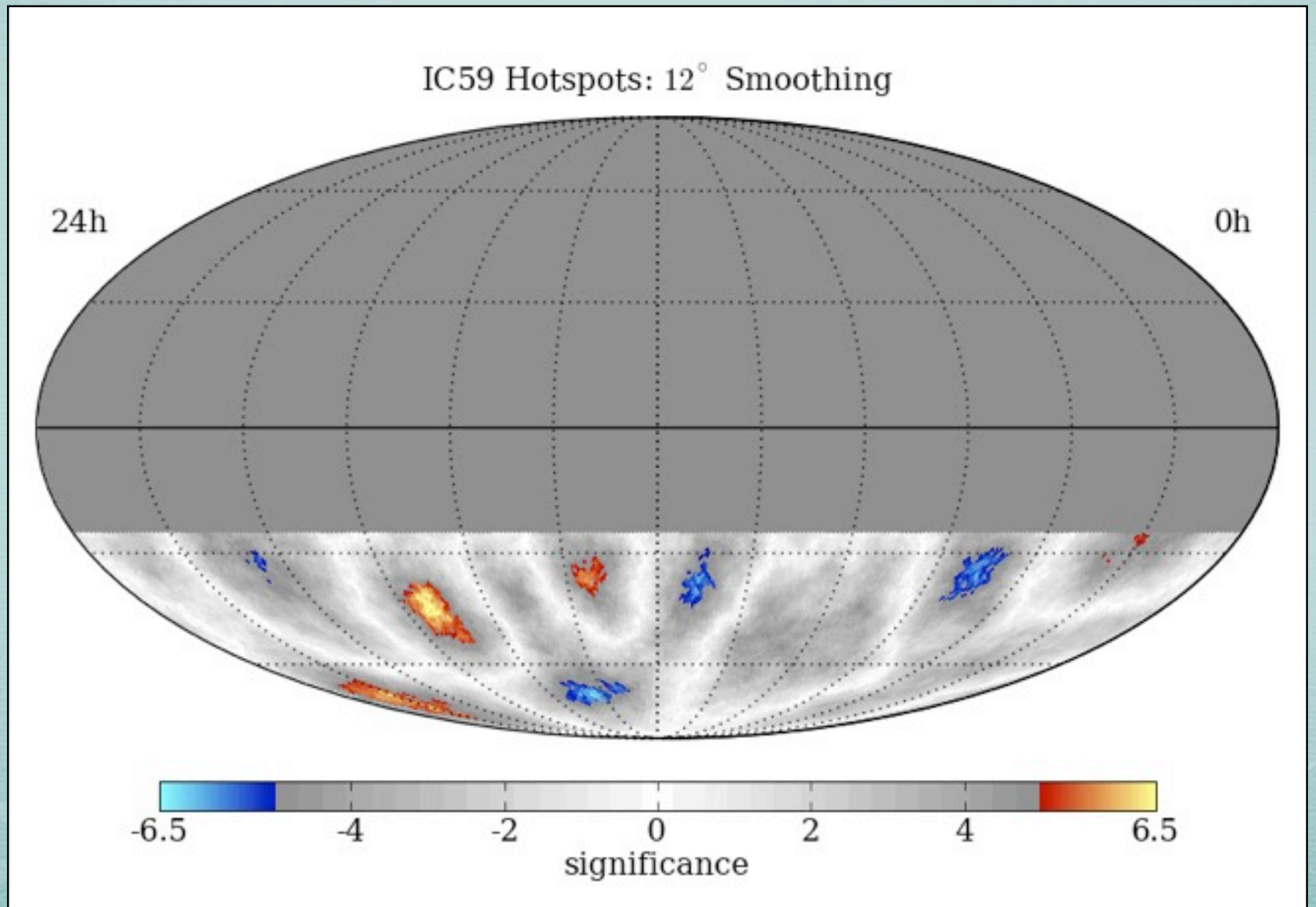

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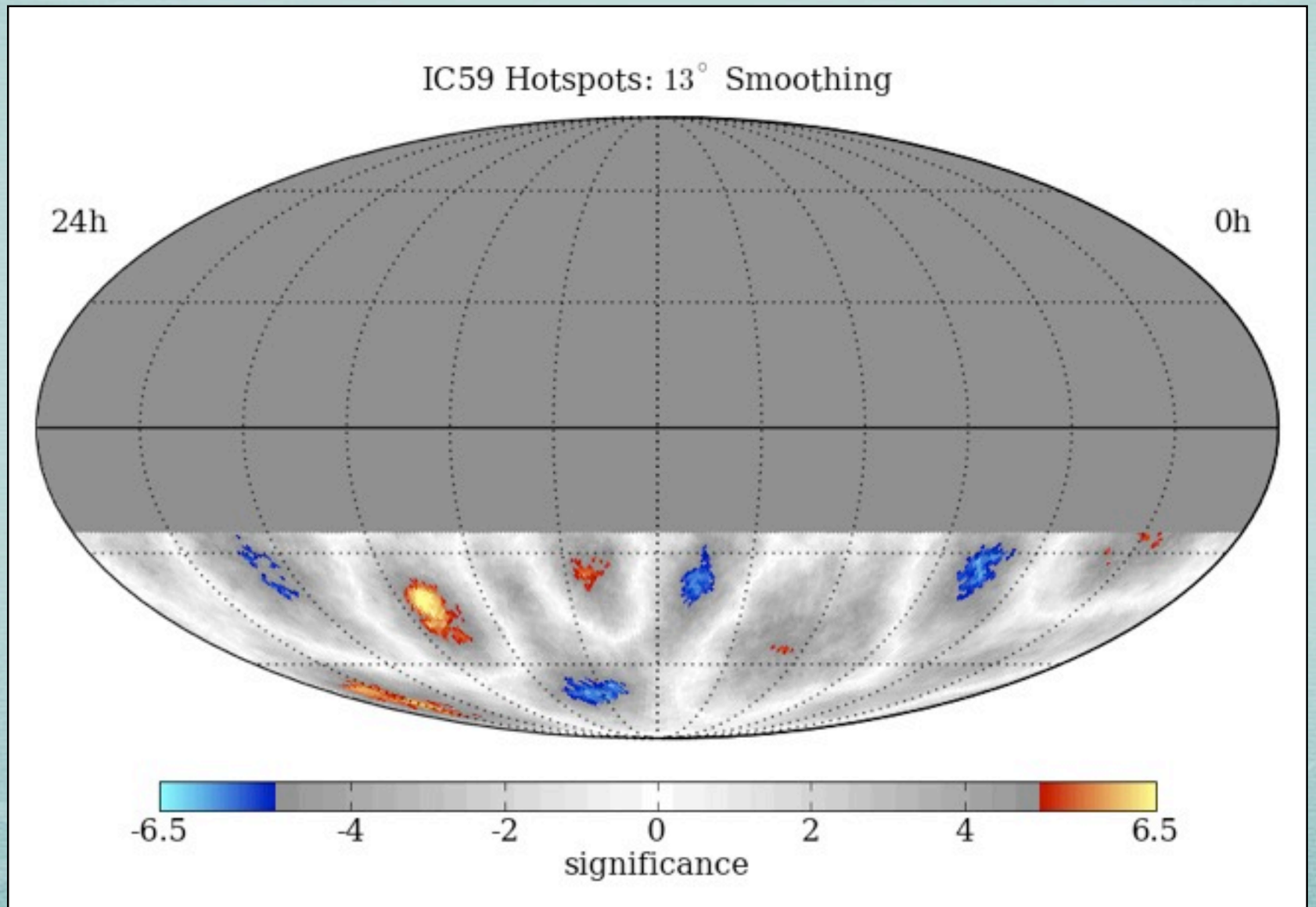

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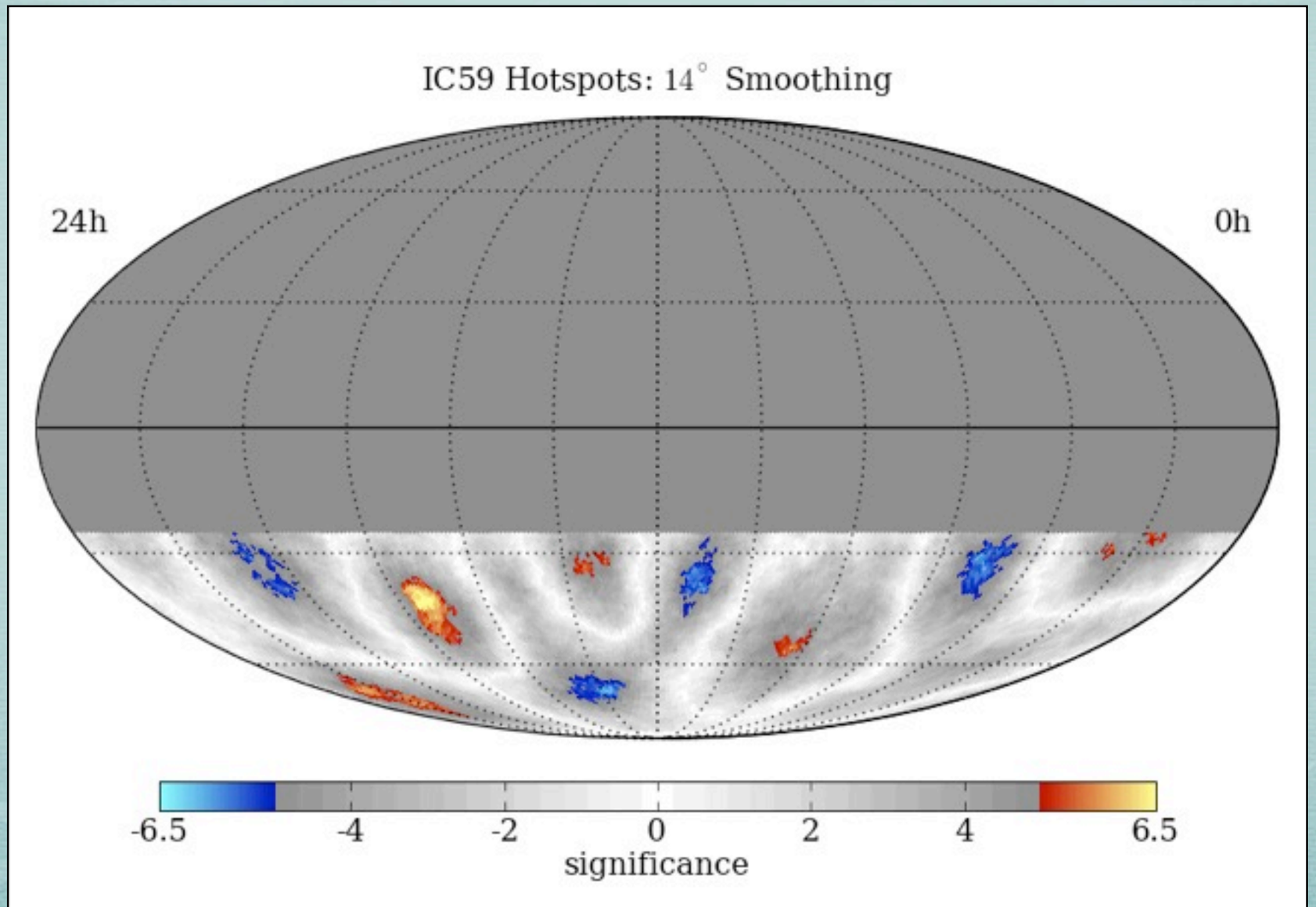

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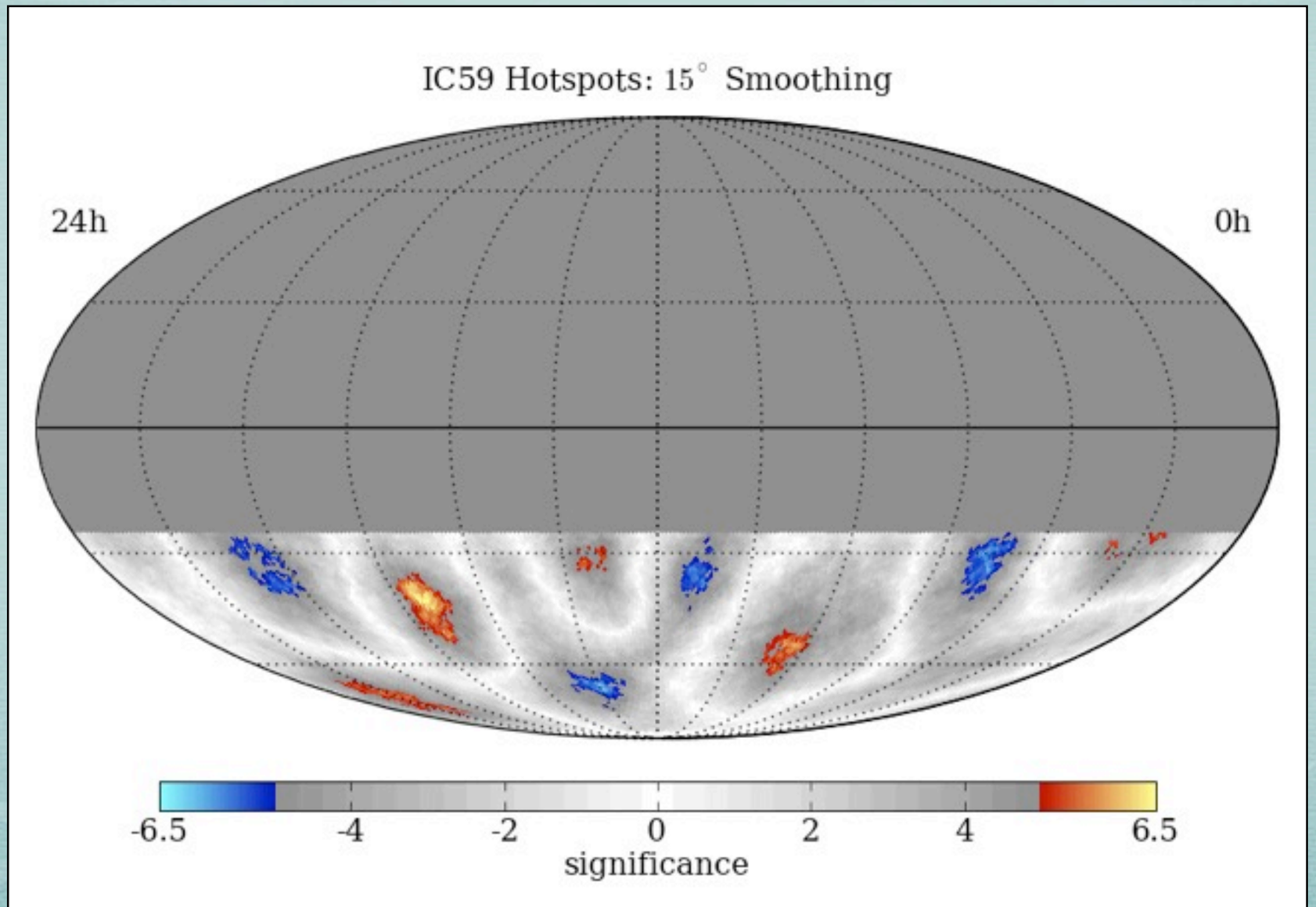

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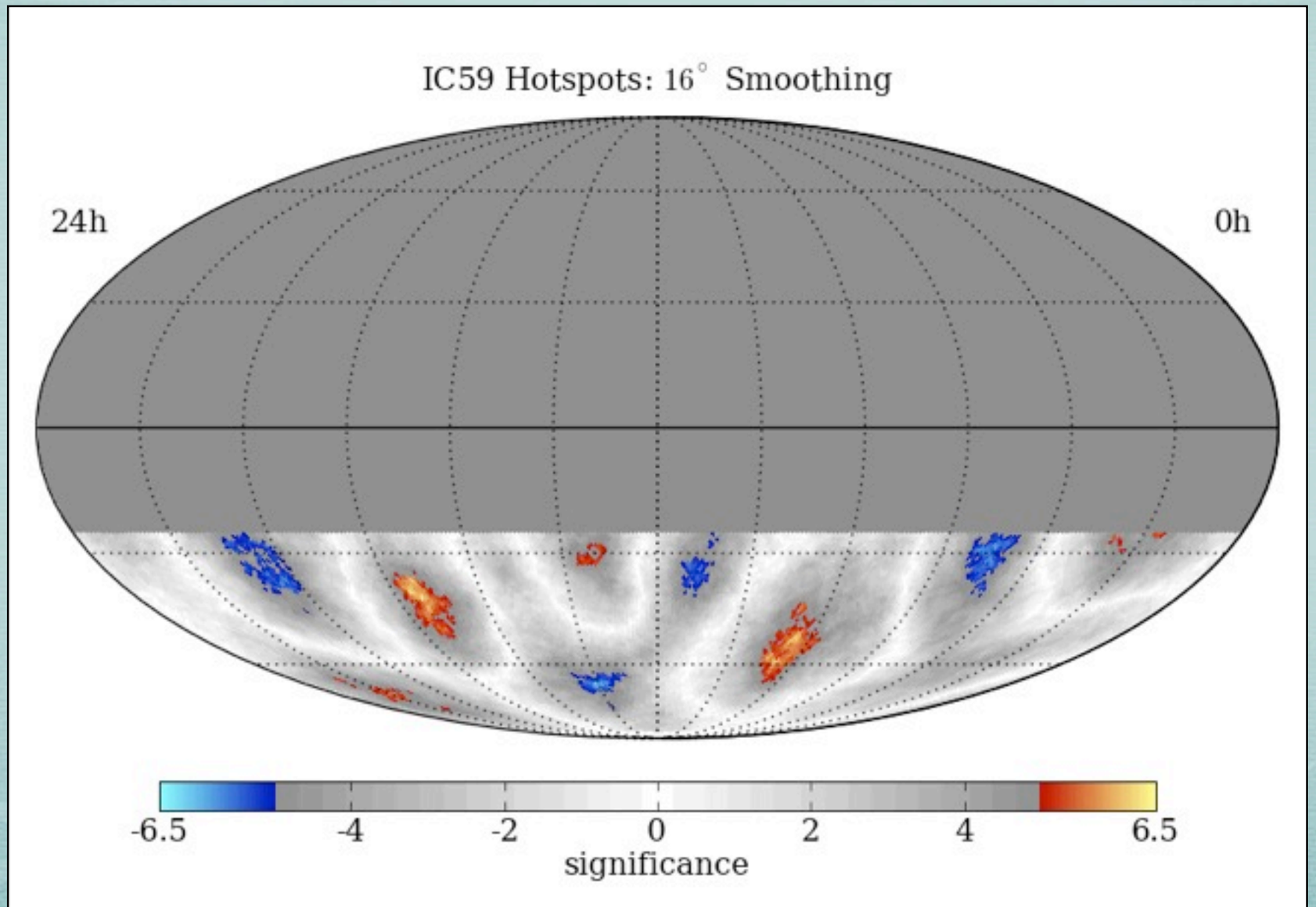

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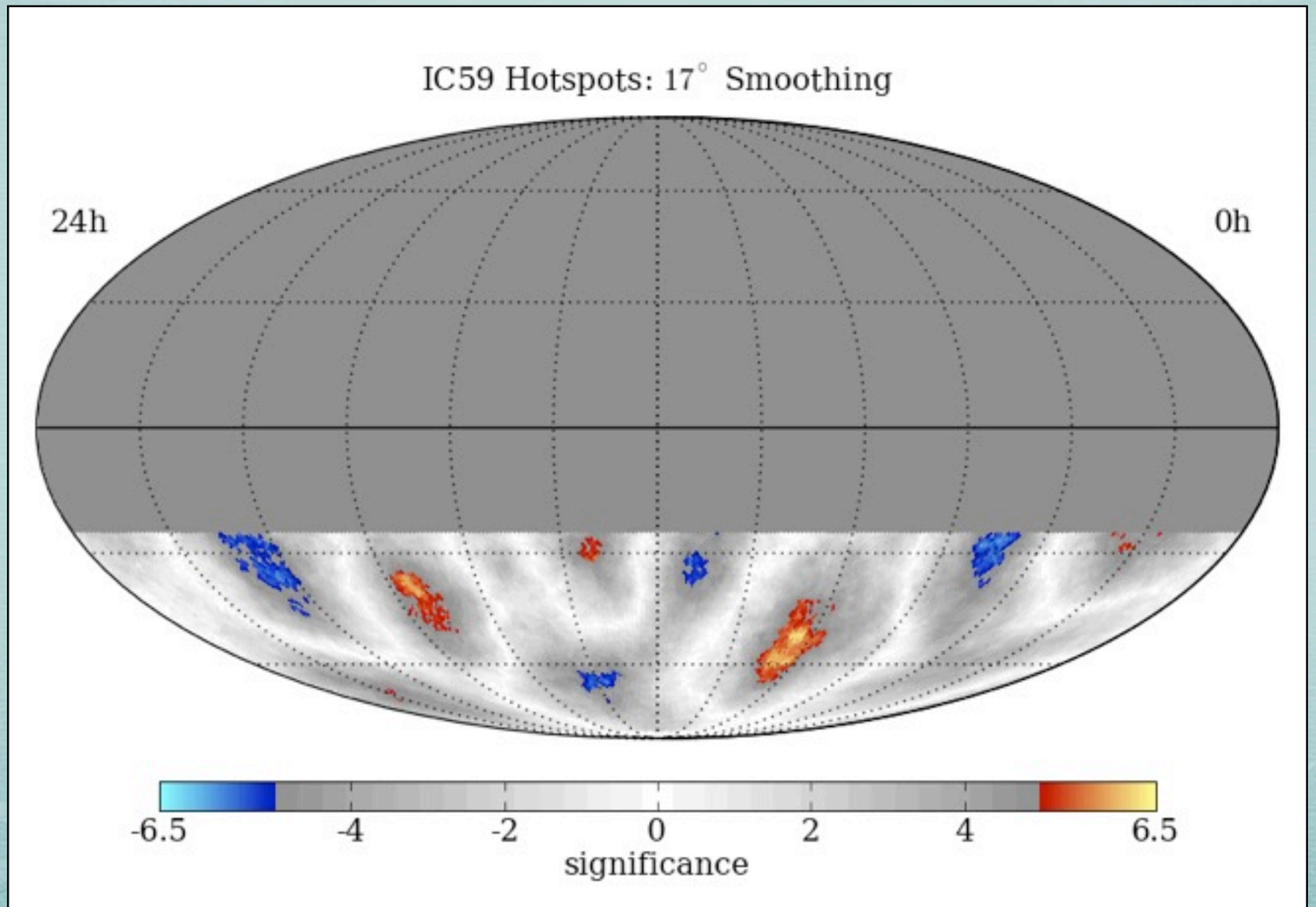

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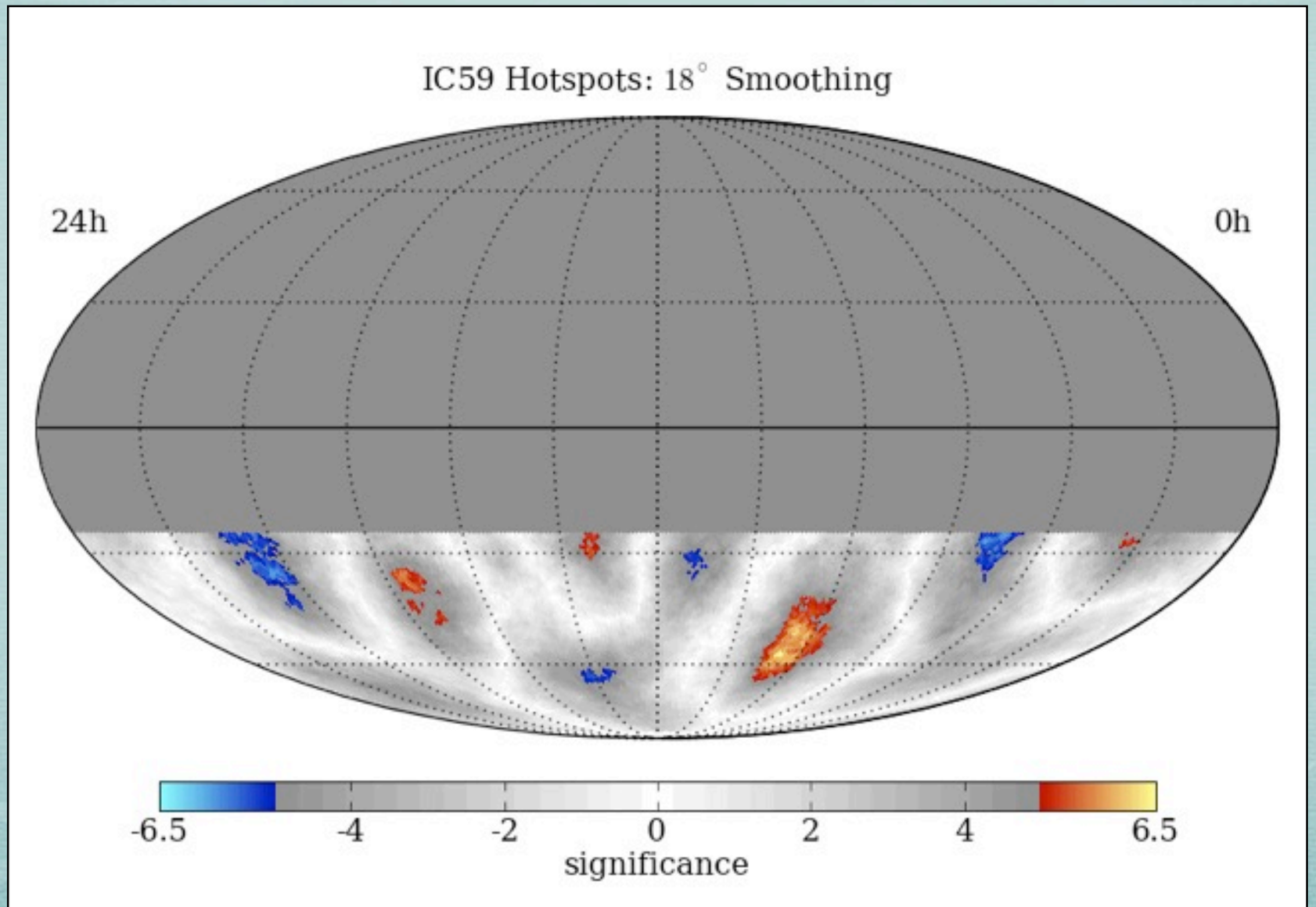

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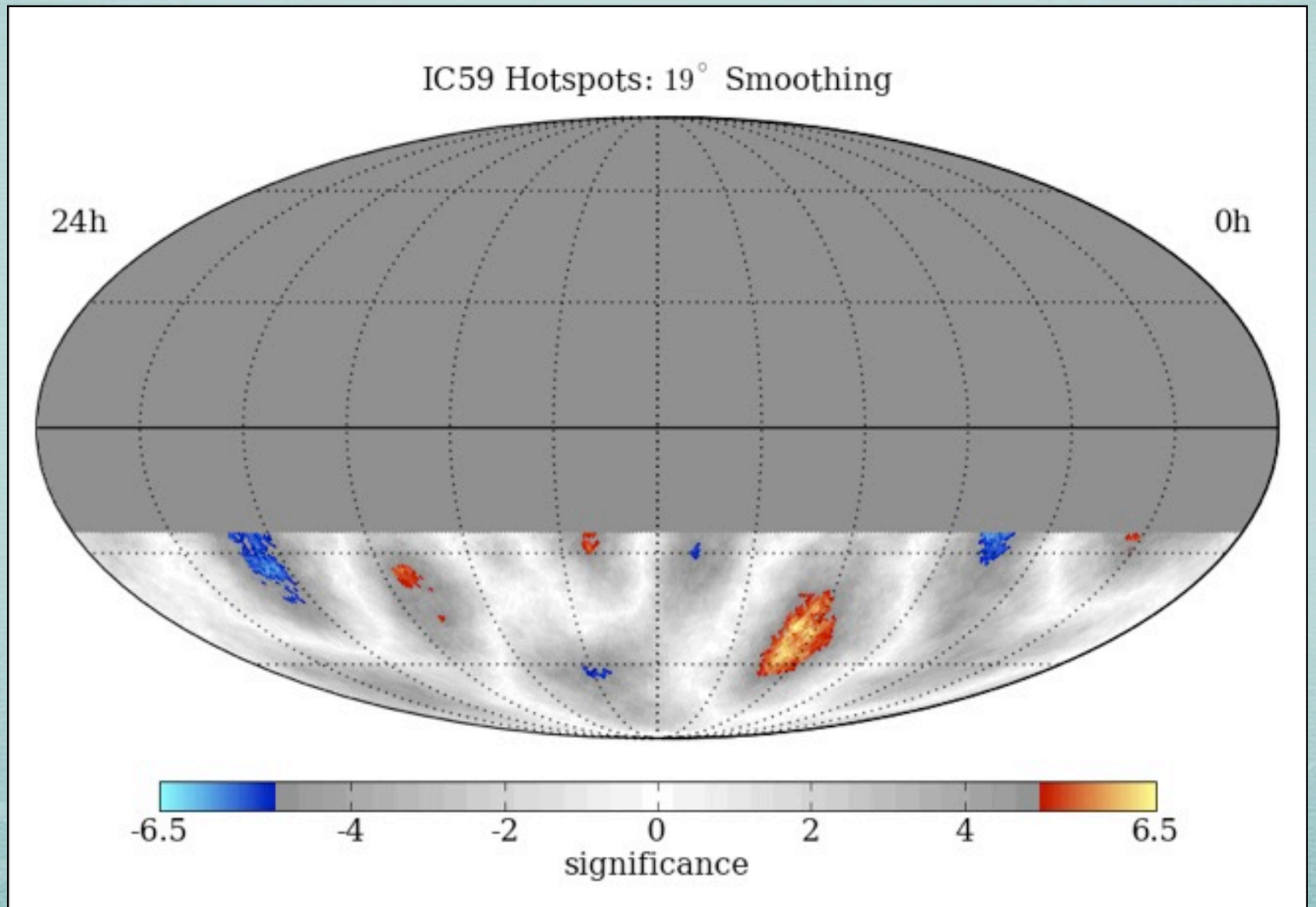

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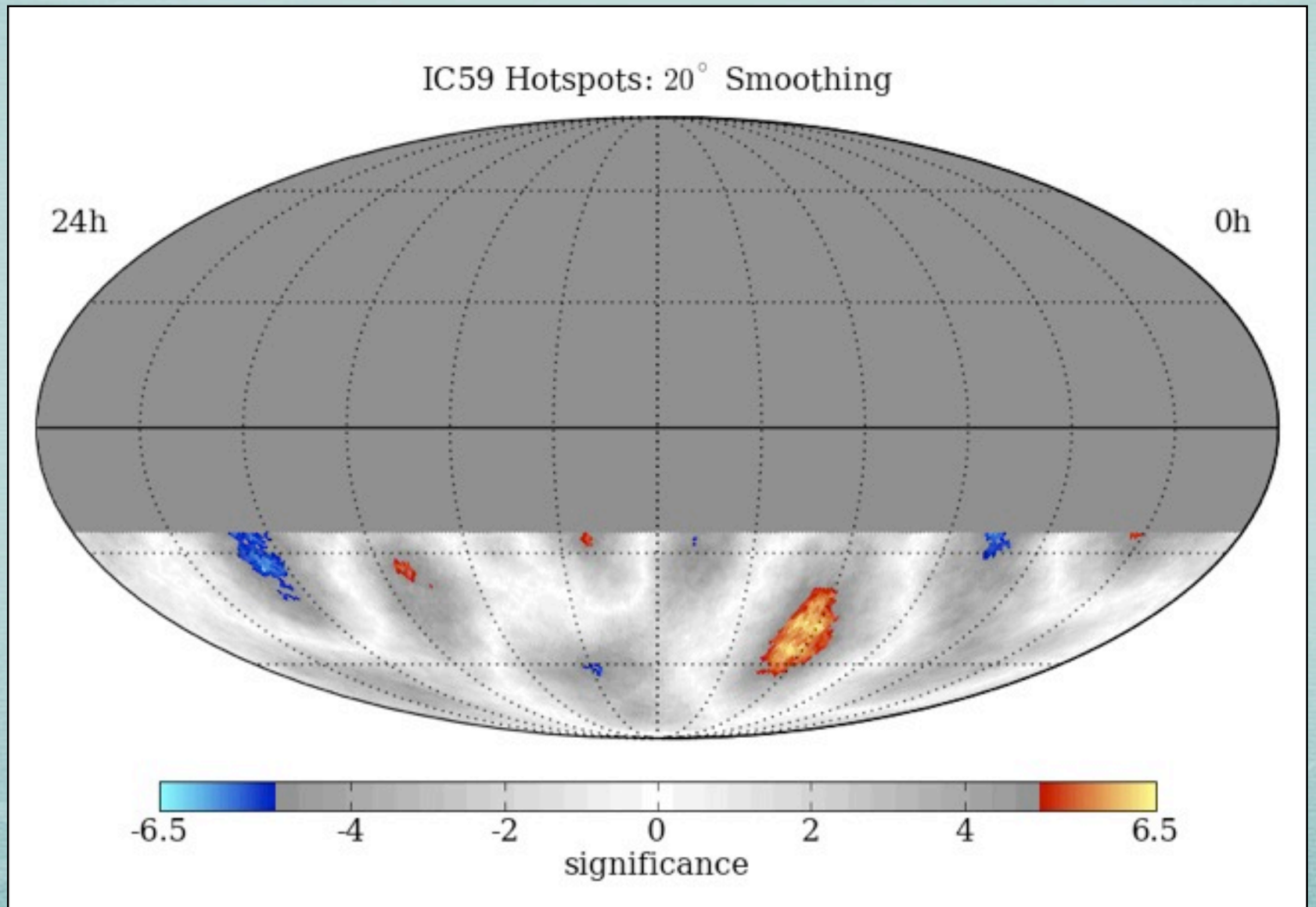

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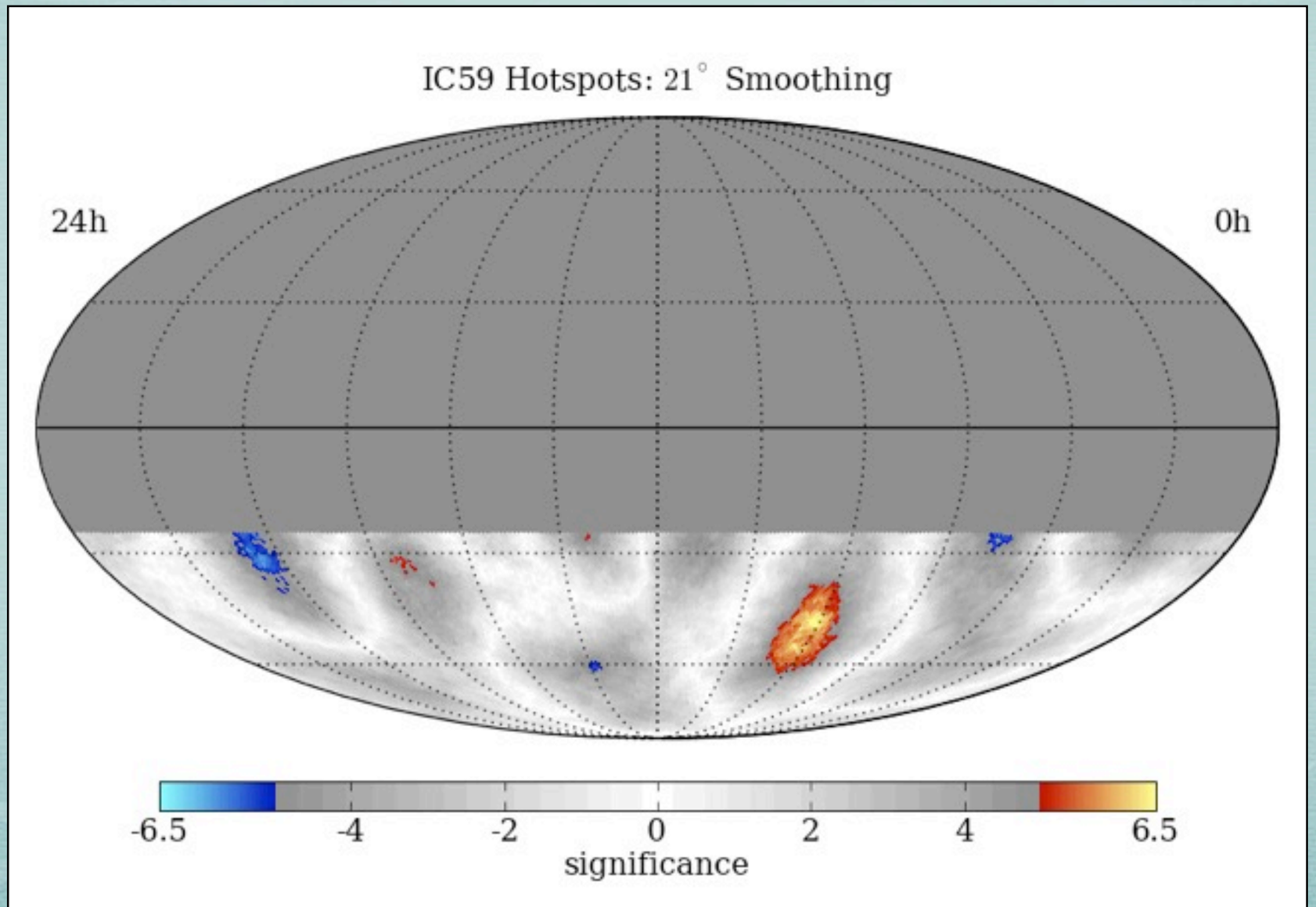

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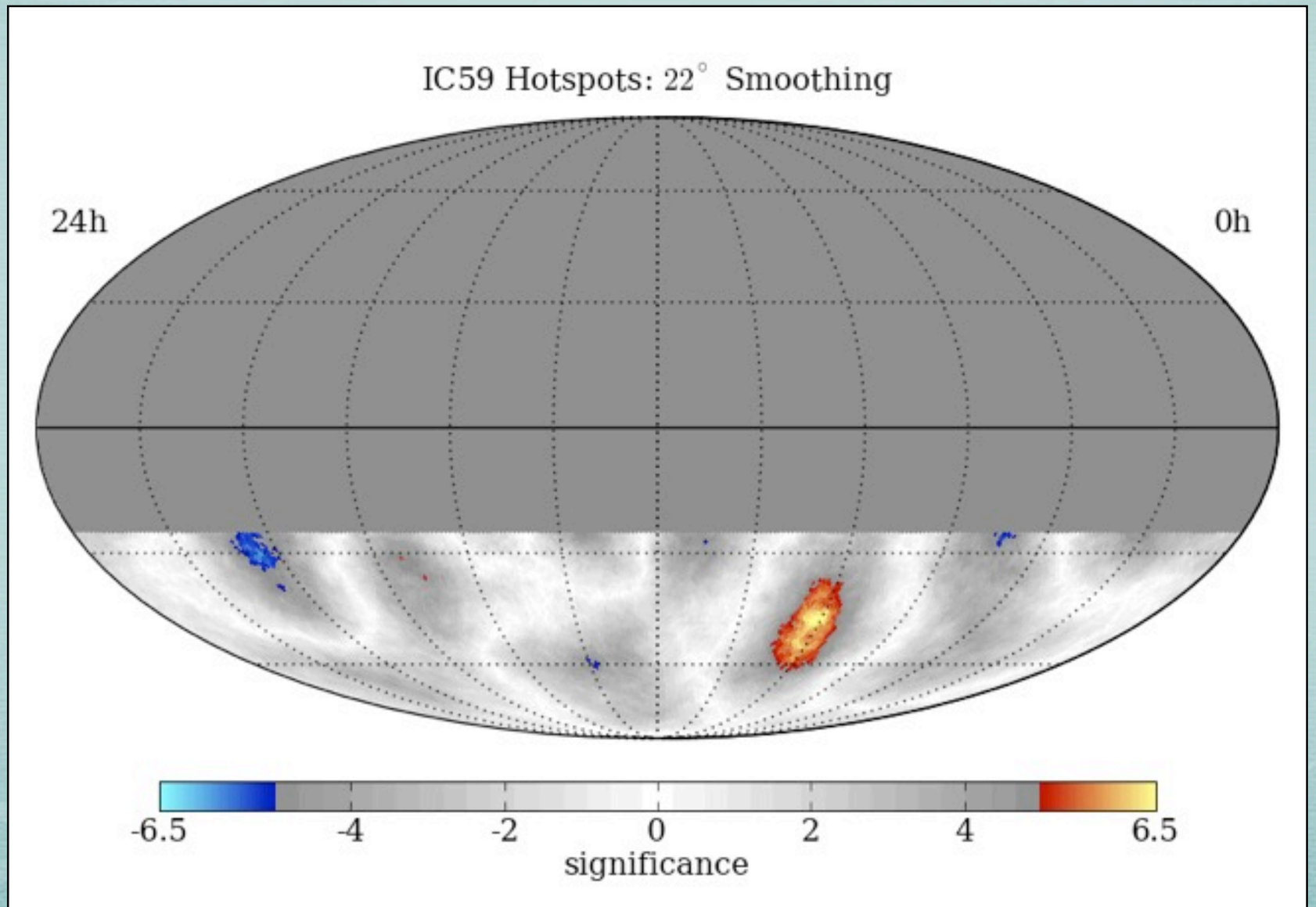

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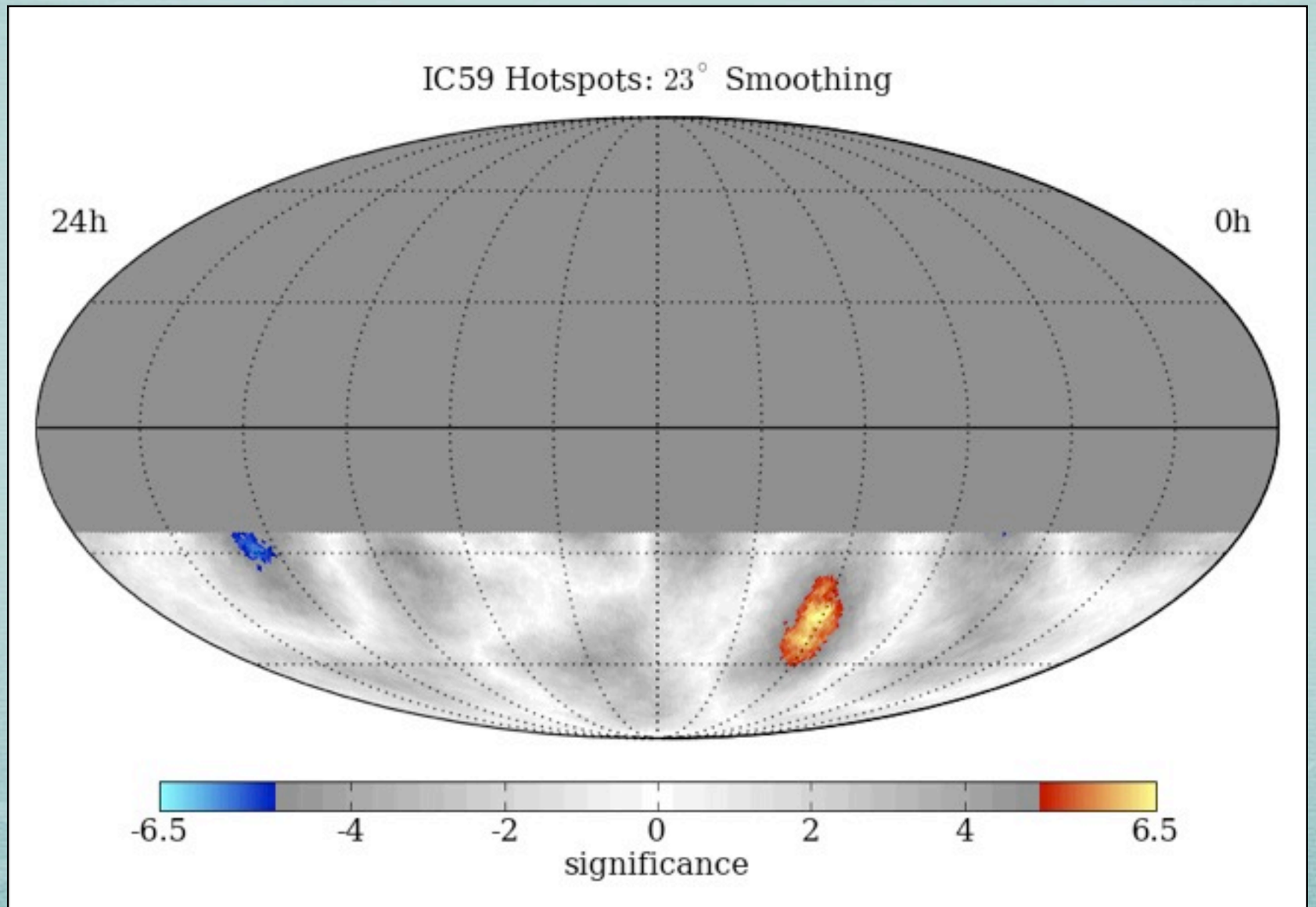

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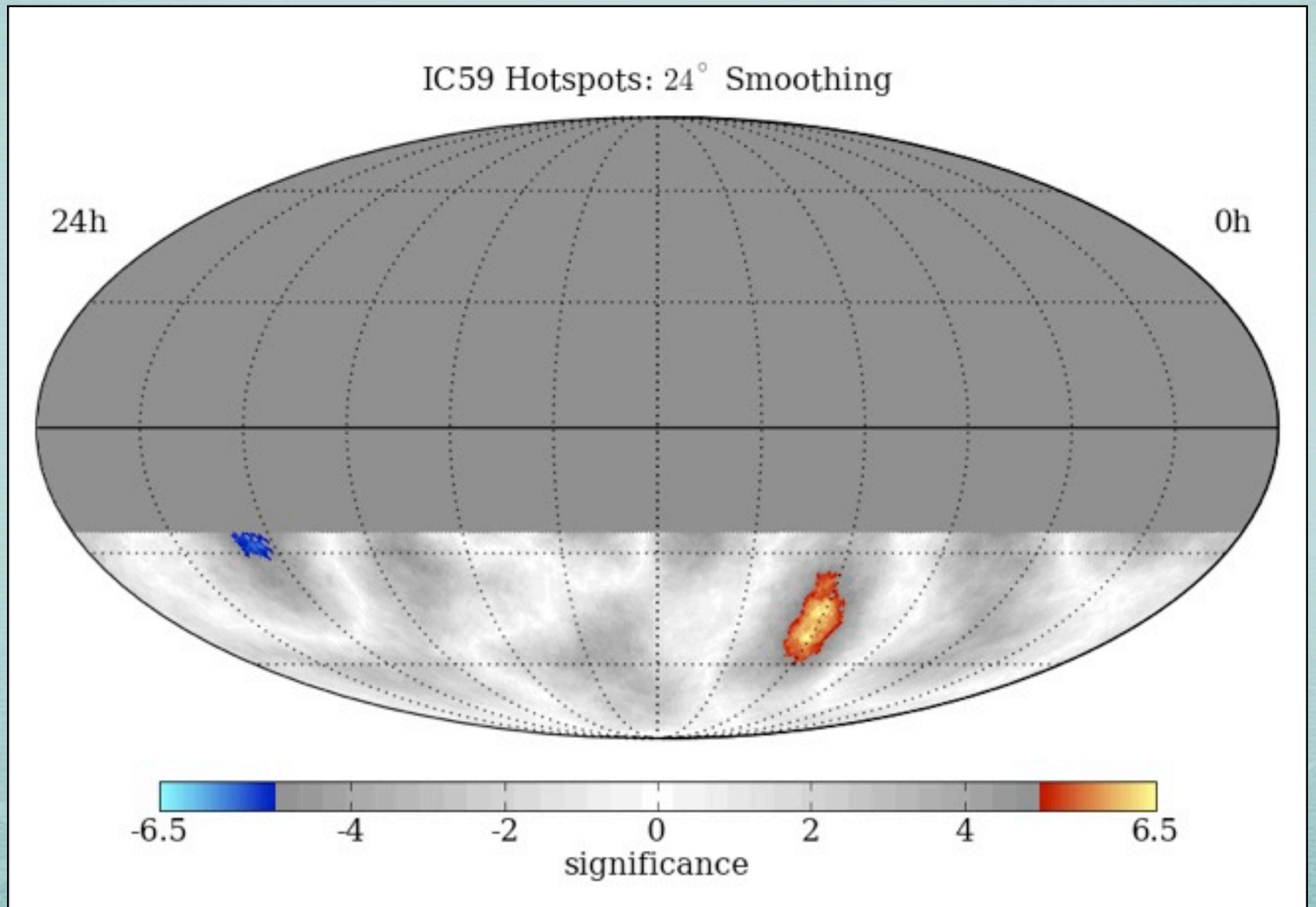

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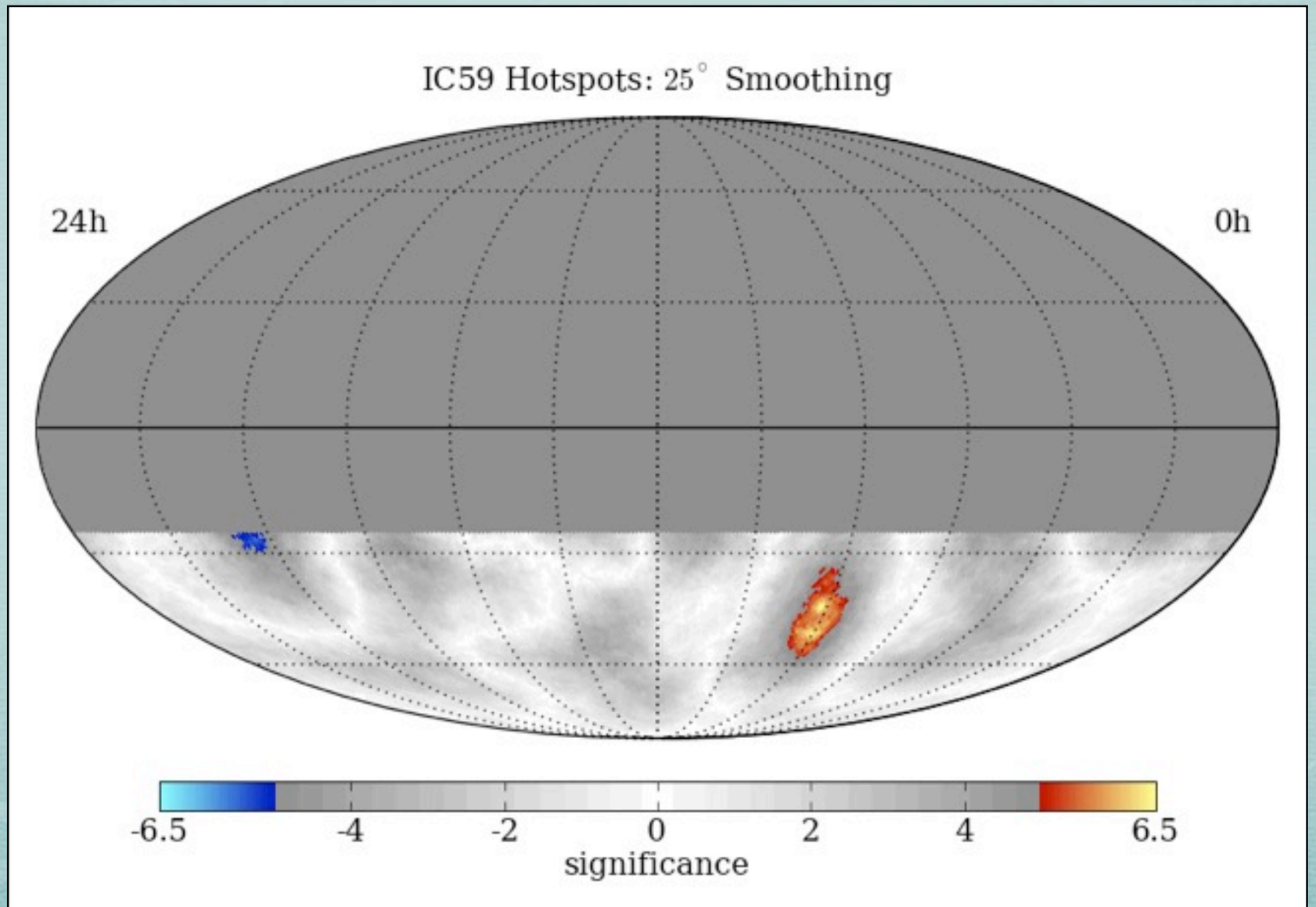

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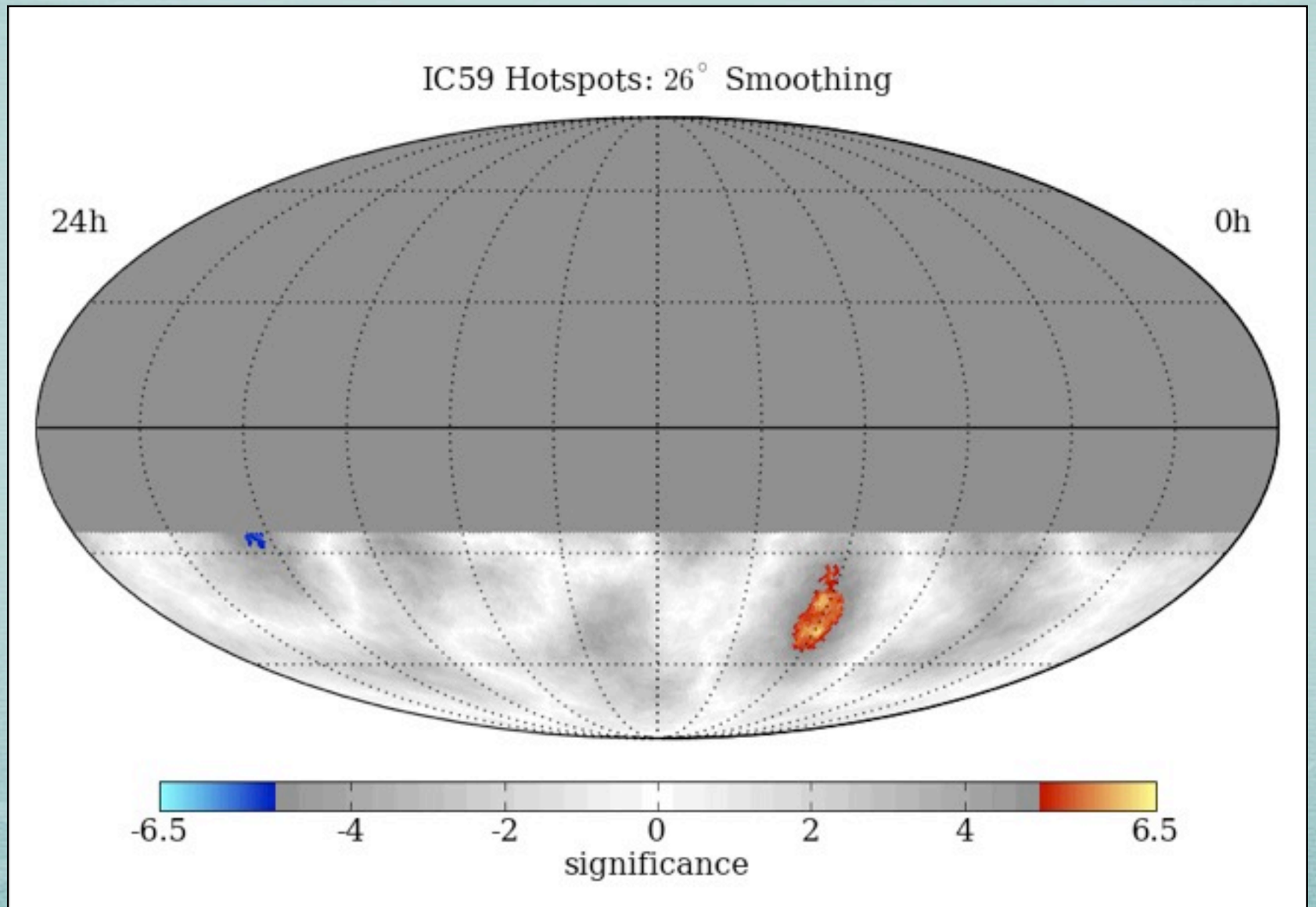

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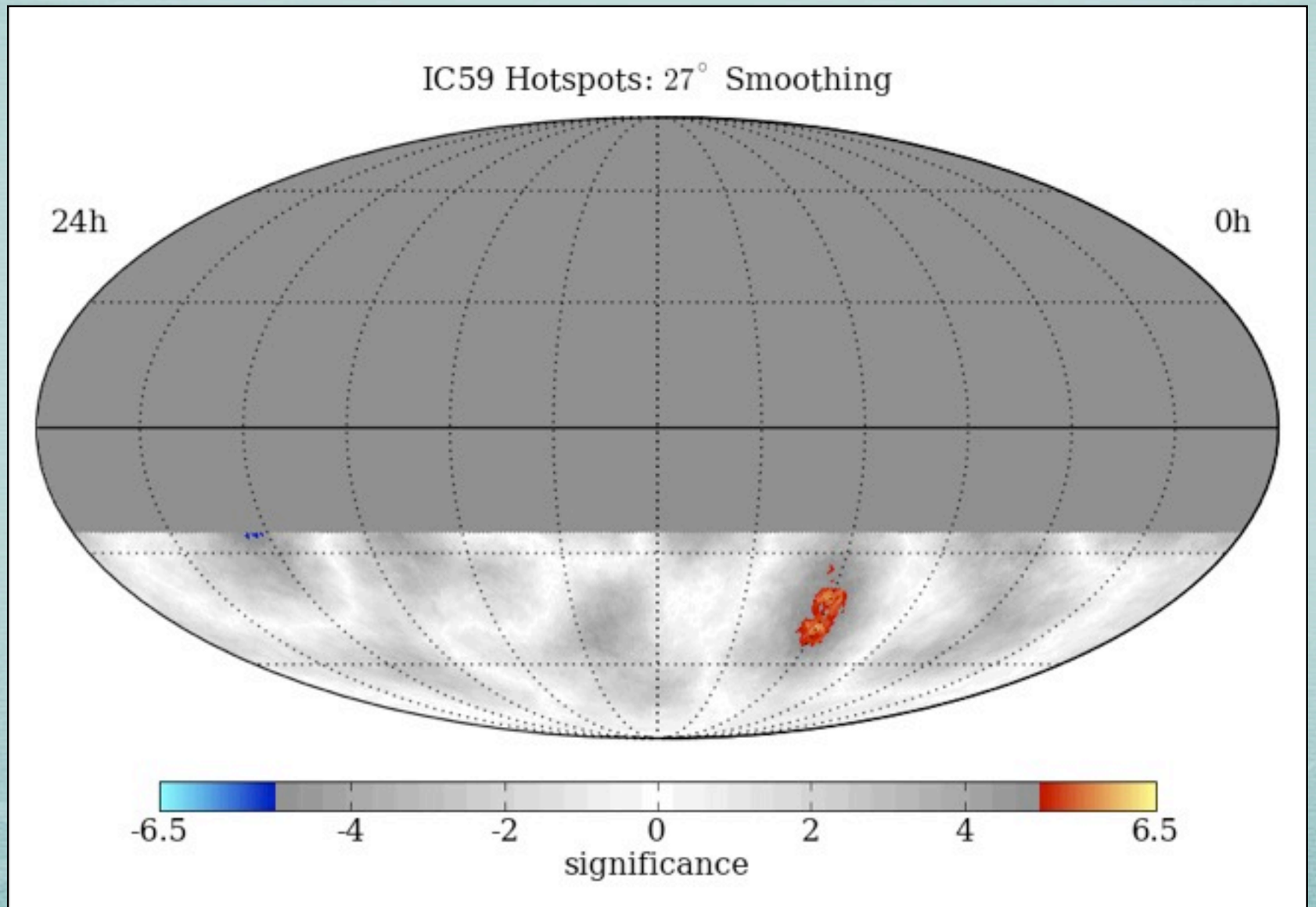

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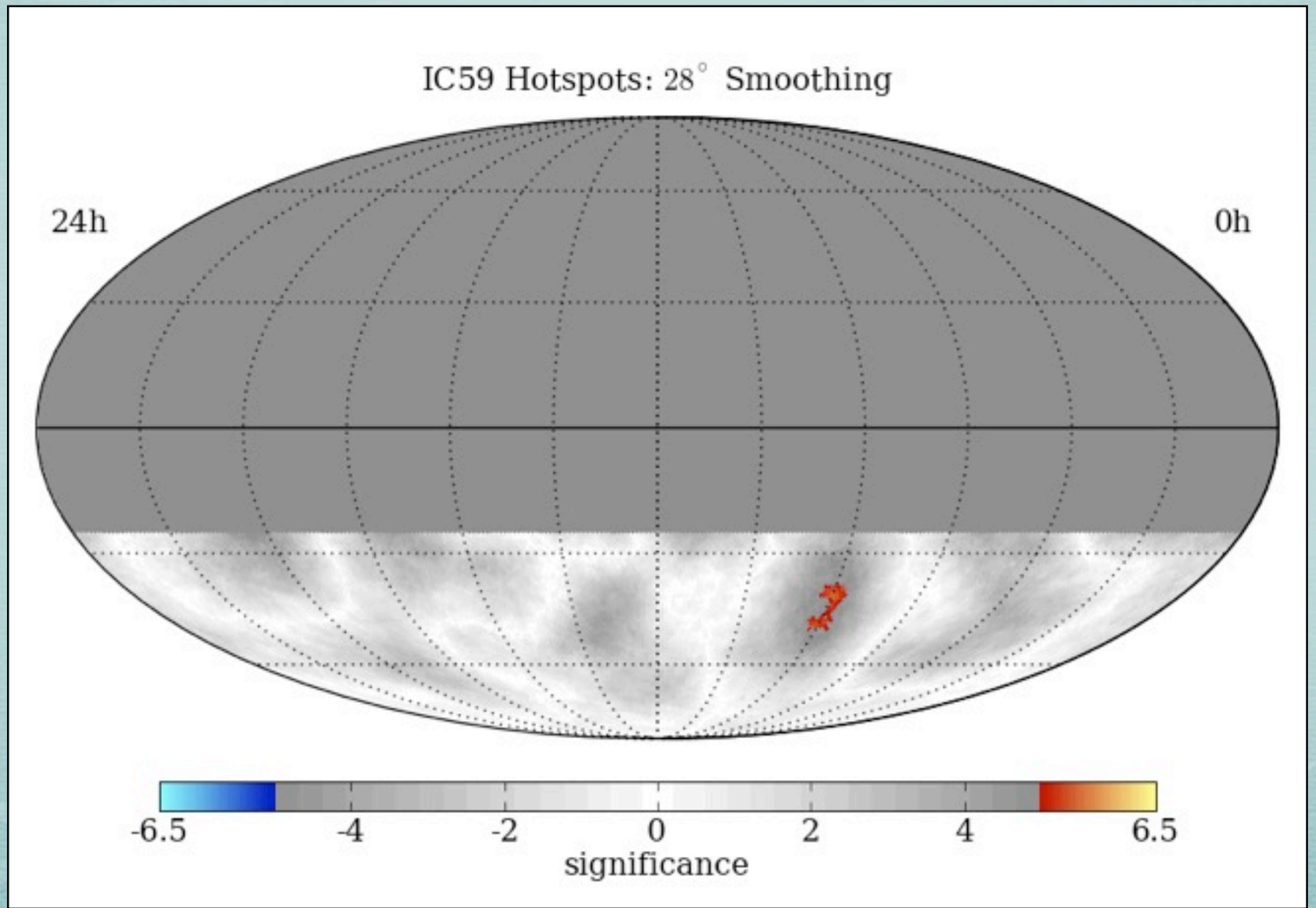

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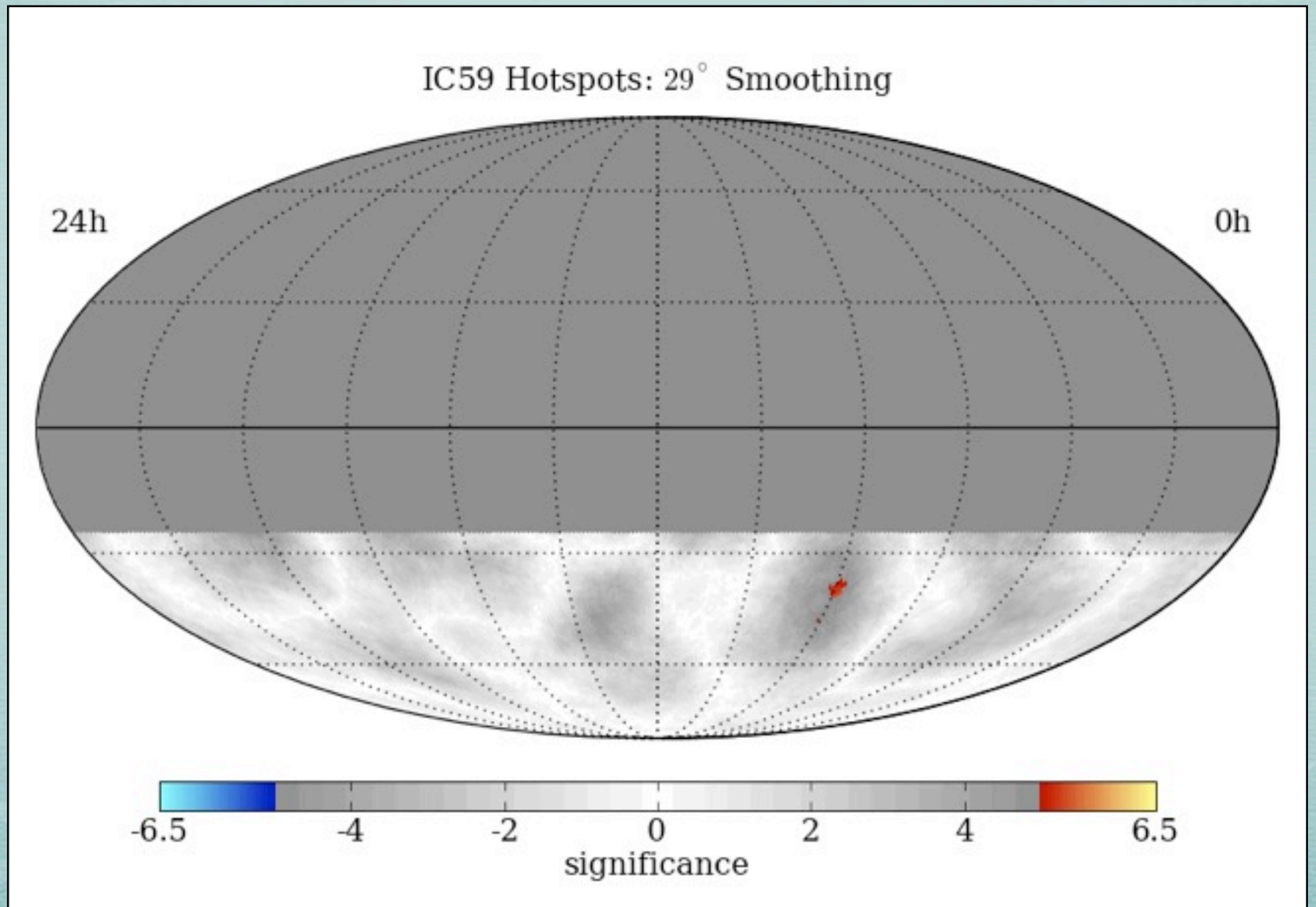

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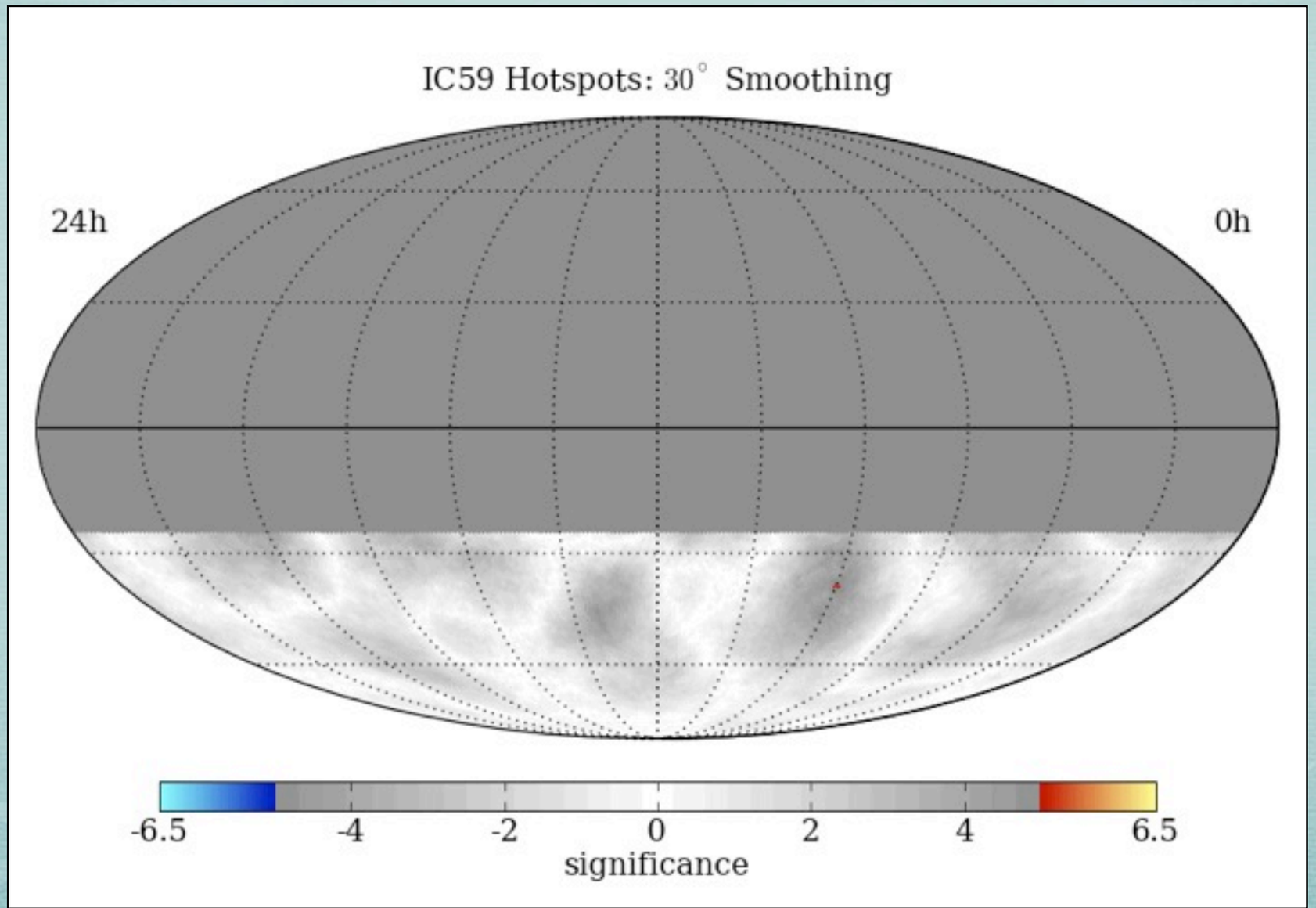
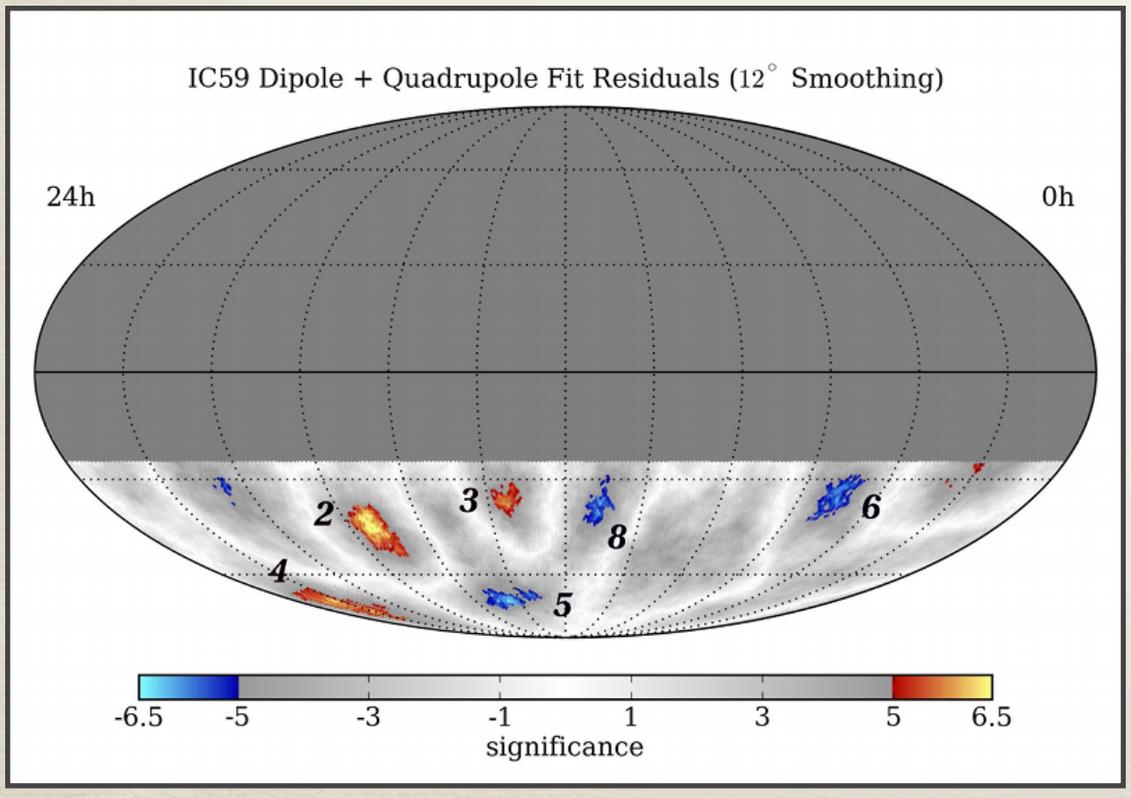
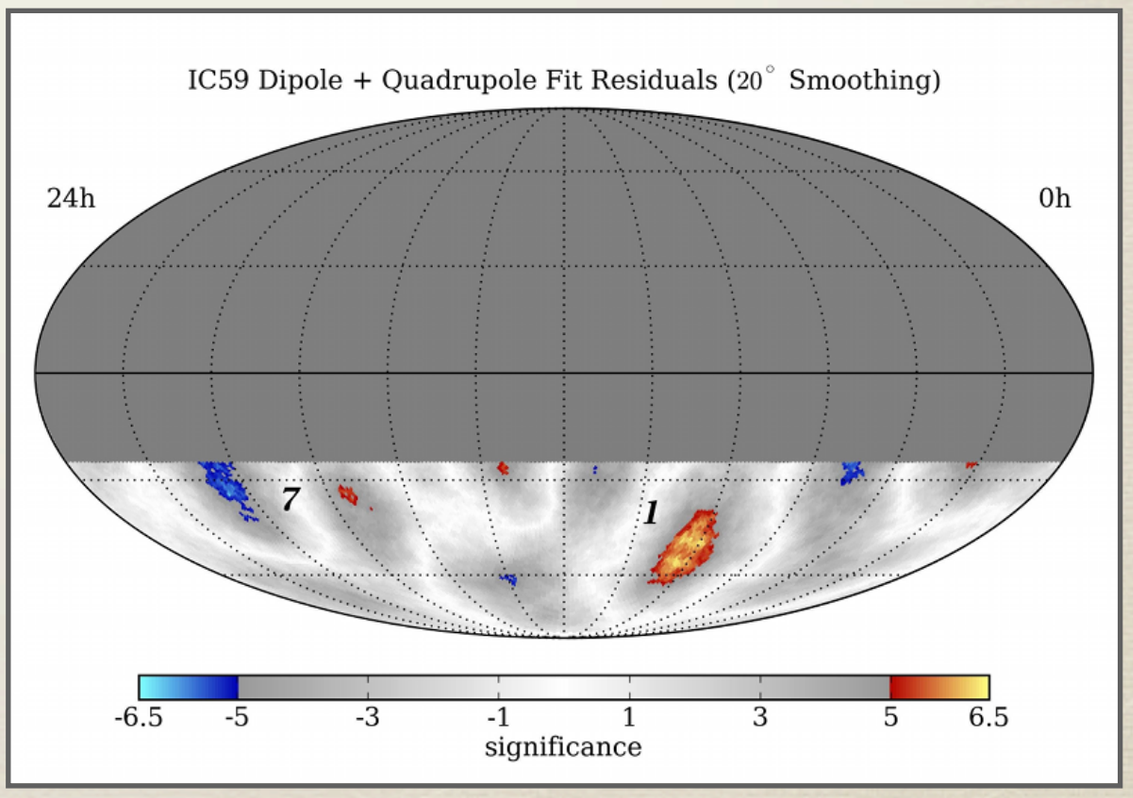


Identification of significant structures

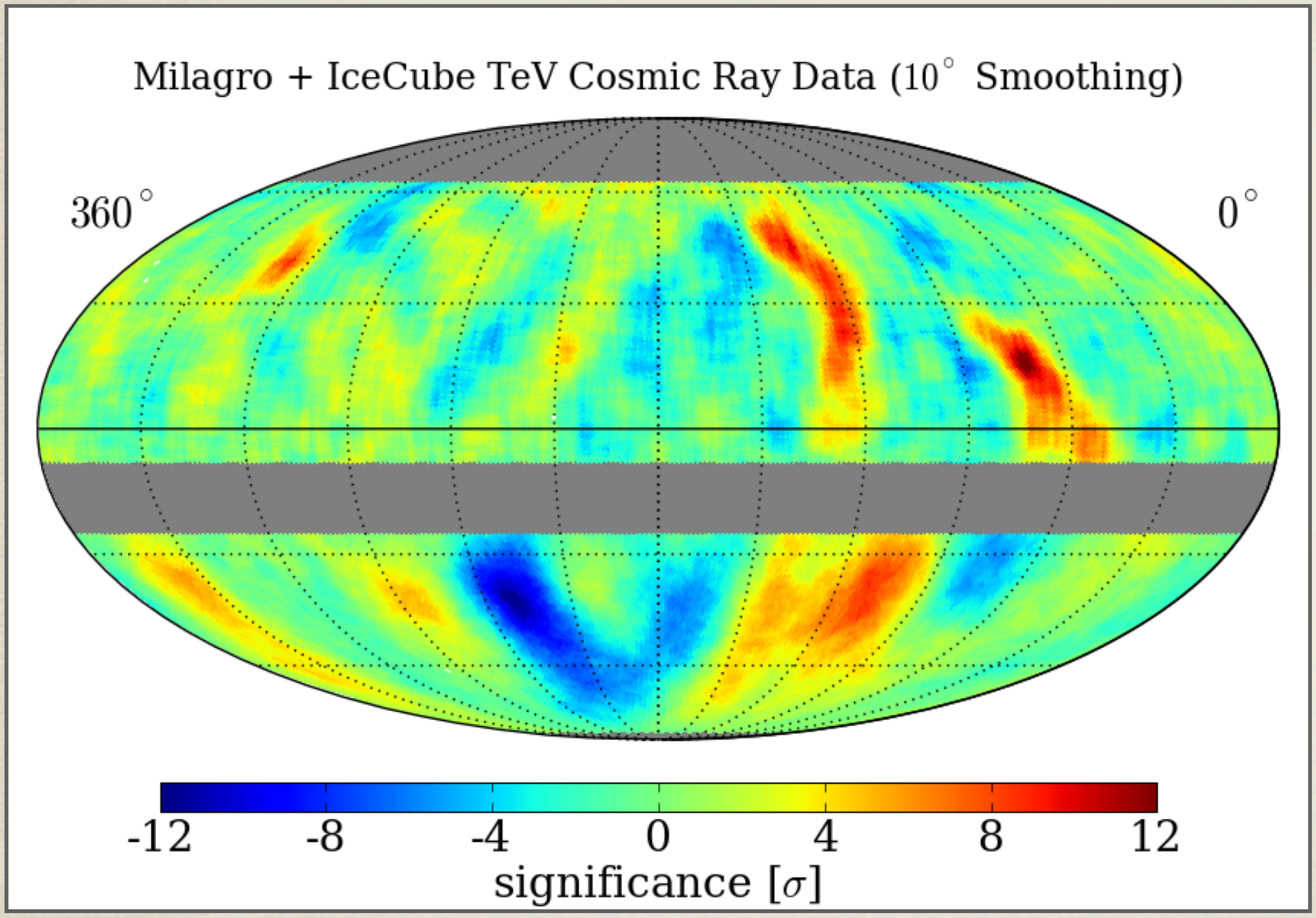
region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ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





Milagro + IceCube combined map

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



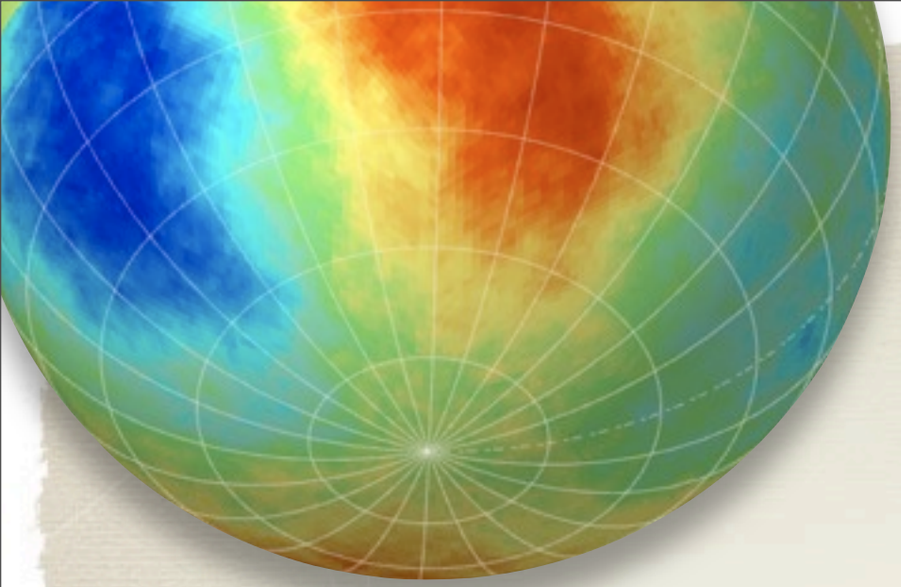
Milagro map:

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

- **2.2 x 10^{11}** events
- direct integration (2 hr)
- 10° smoothing
- median energy **1 TeV**

IceCube map:

- **5.6x10^{10}** events
- time scrambling (4 hr)
- 10° smoothing
- median energy **20 TeV**



Conclusions

- **IceCube** detector was **completed in December 2010** and is now taking data in its final configuration (86 strings).
- **Large scale anisotropy**:
  - Sidereal anisotropy at 20 TeV confirms previous observation.
  - First observation of sidereal anisotropy @ 400 TeV in southern hemisphere.
  - 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).
- **The origin of the anisotropy is still unknown.**