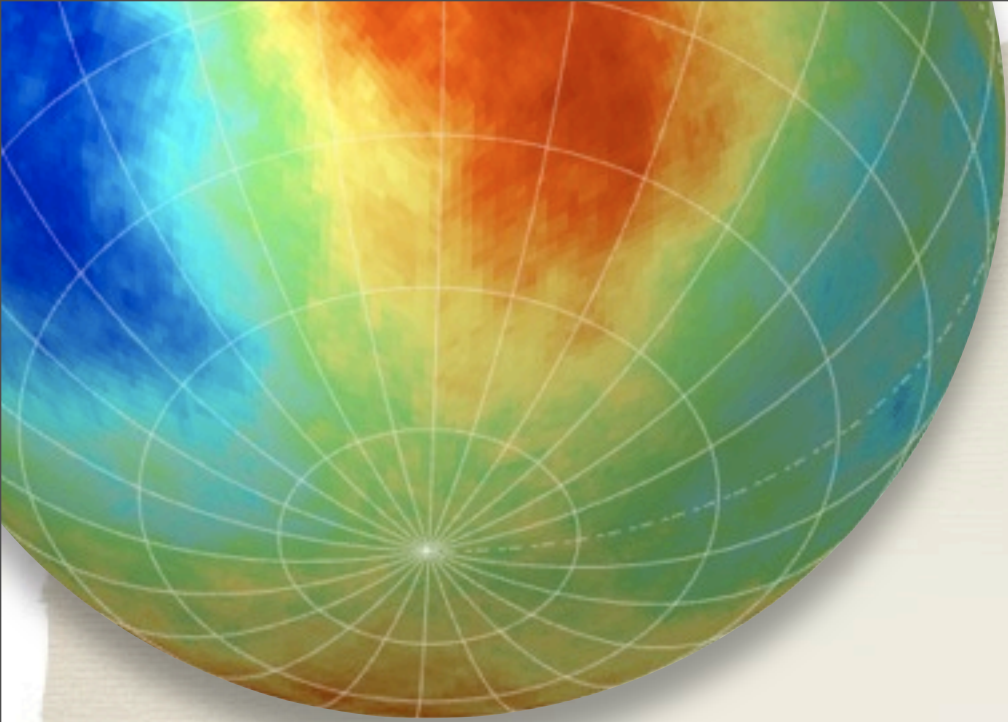
OBSERVATION OF COSMIC RAY ANISOTROPY ABOVE TEV ENERGIES IN ICECUBE

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

RICAP 11

3rd Roma International Conference on Astro-particle Physics

25-27 May 2011 Roma Italy



Outline

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

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LBNL, Berkeley, USA
UC Berkeley, USA
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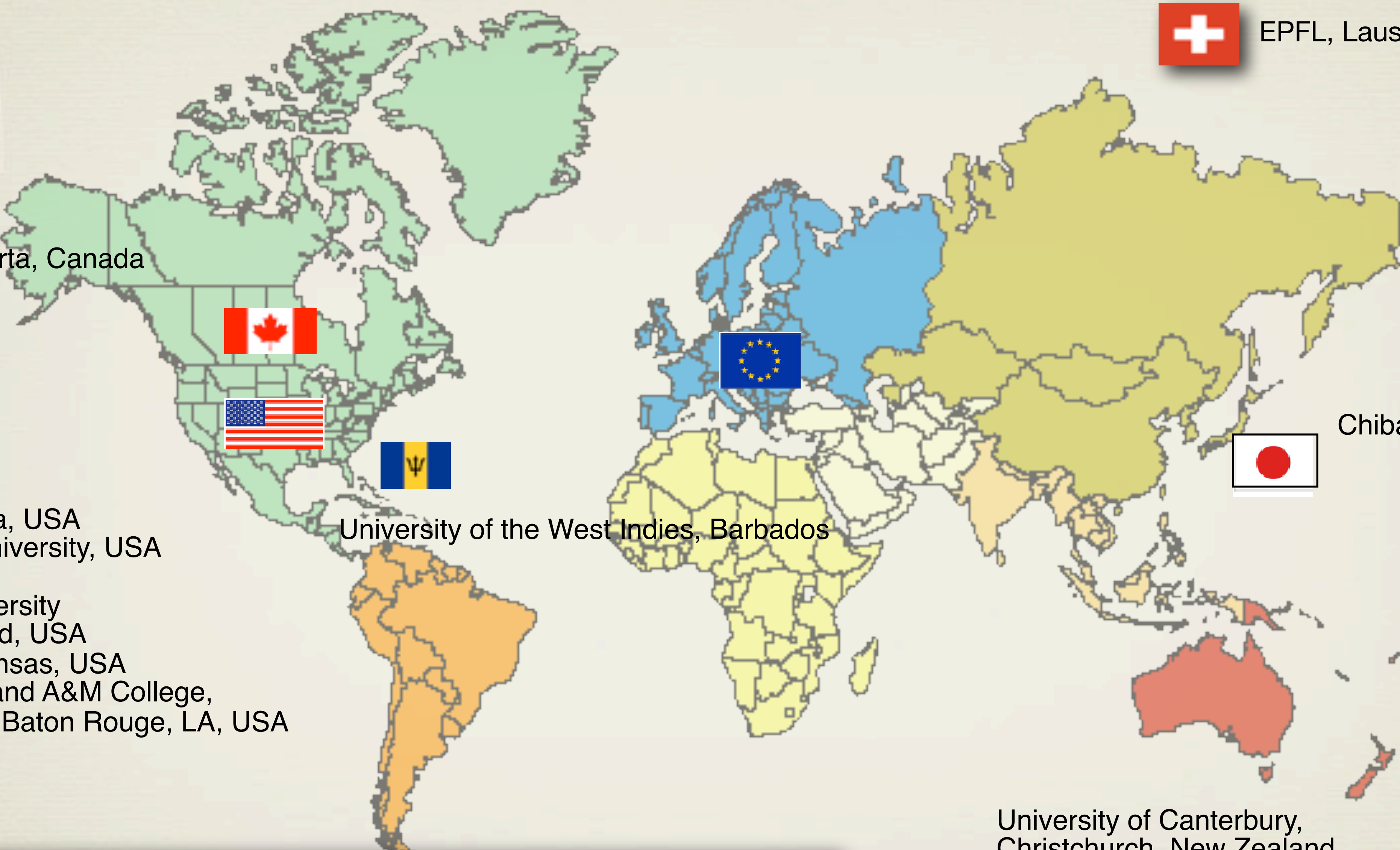

Chiba University, Japan

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

University of Canterbury,
Christchurch, New Zealand

IceCube Collaboration

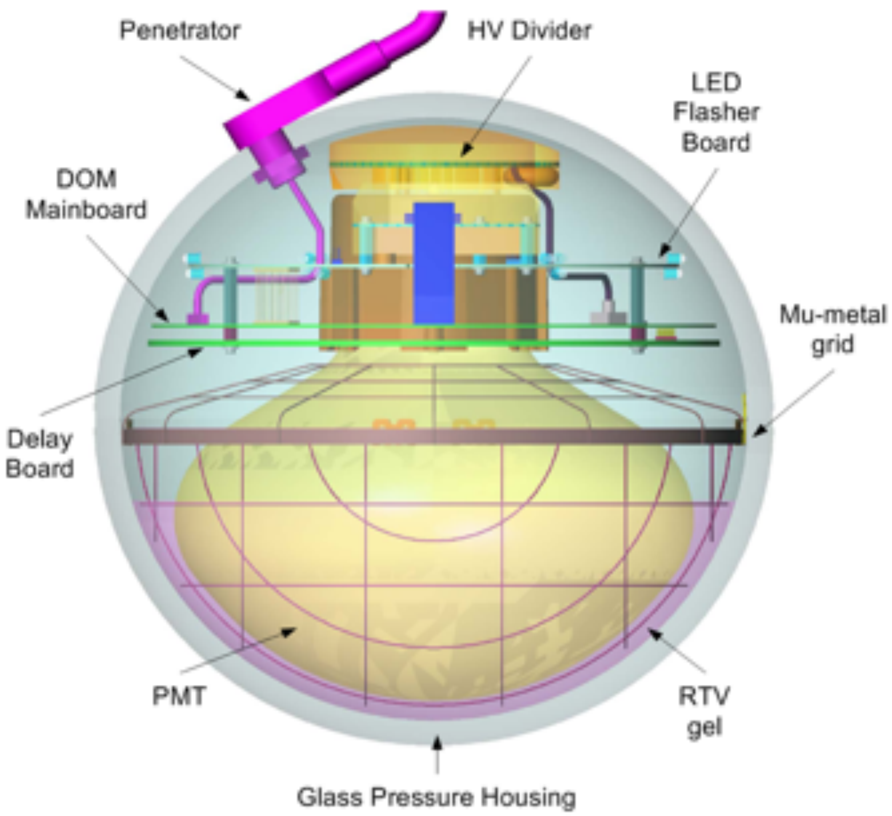
10 countries
36 institutions
~260 collaborators

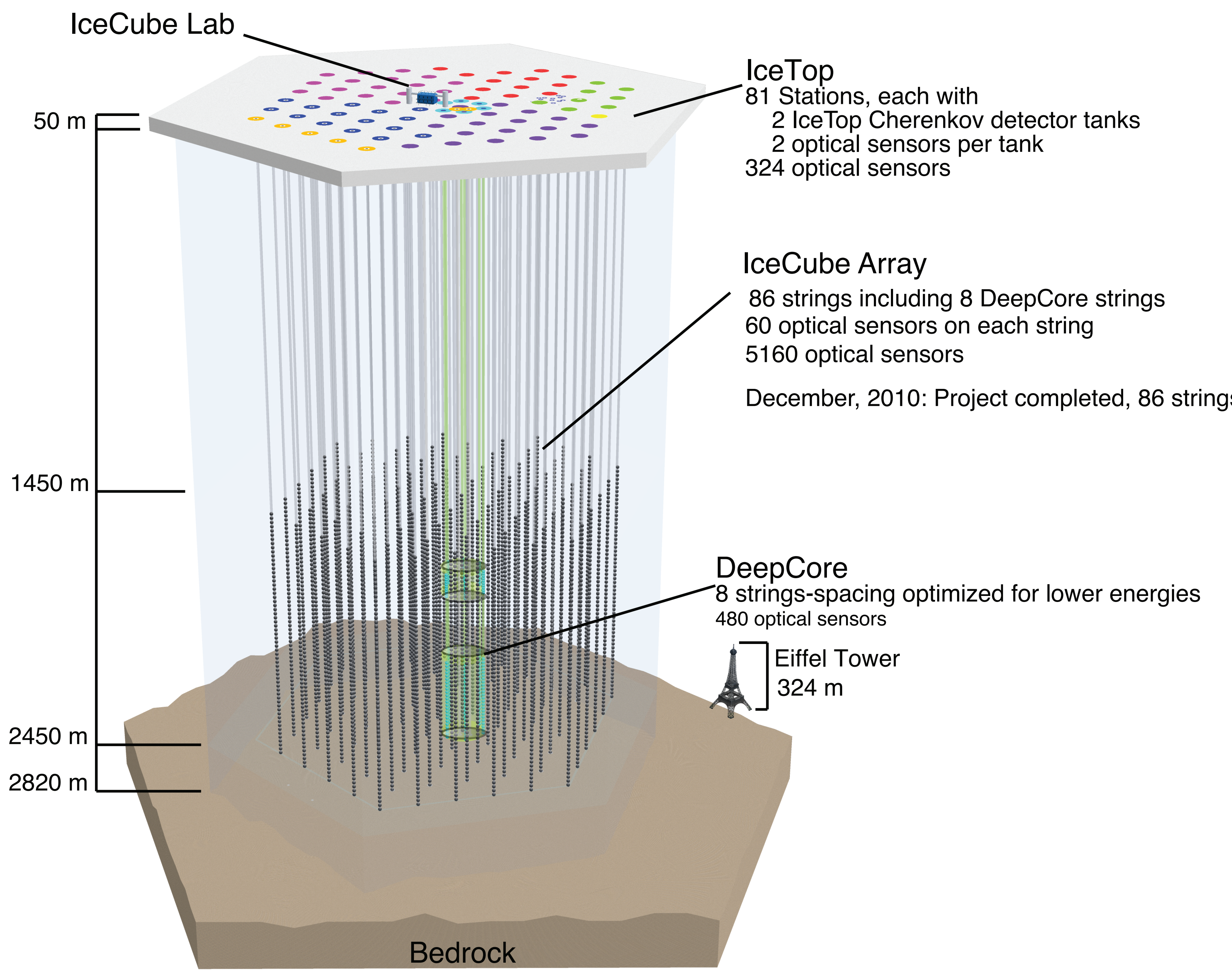
The IceCube detector

➡ **G. Sullivan** - *Status and Recent Results from the IceCube km^3 Neutrino Detector* (tomorrow Plenary)
➡ **T. DeYoung** - *Particle physics in ice with IceCube DeepCore* (today next Parallel session)

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

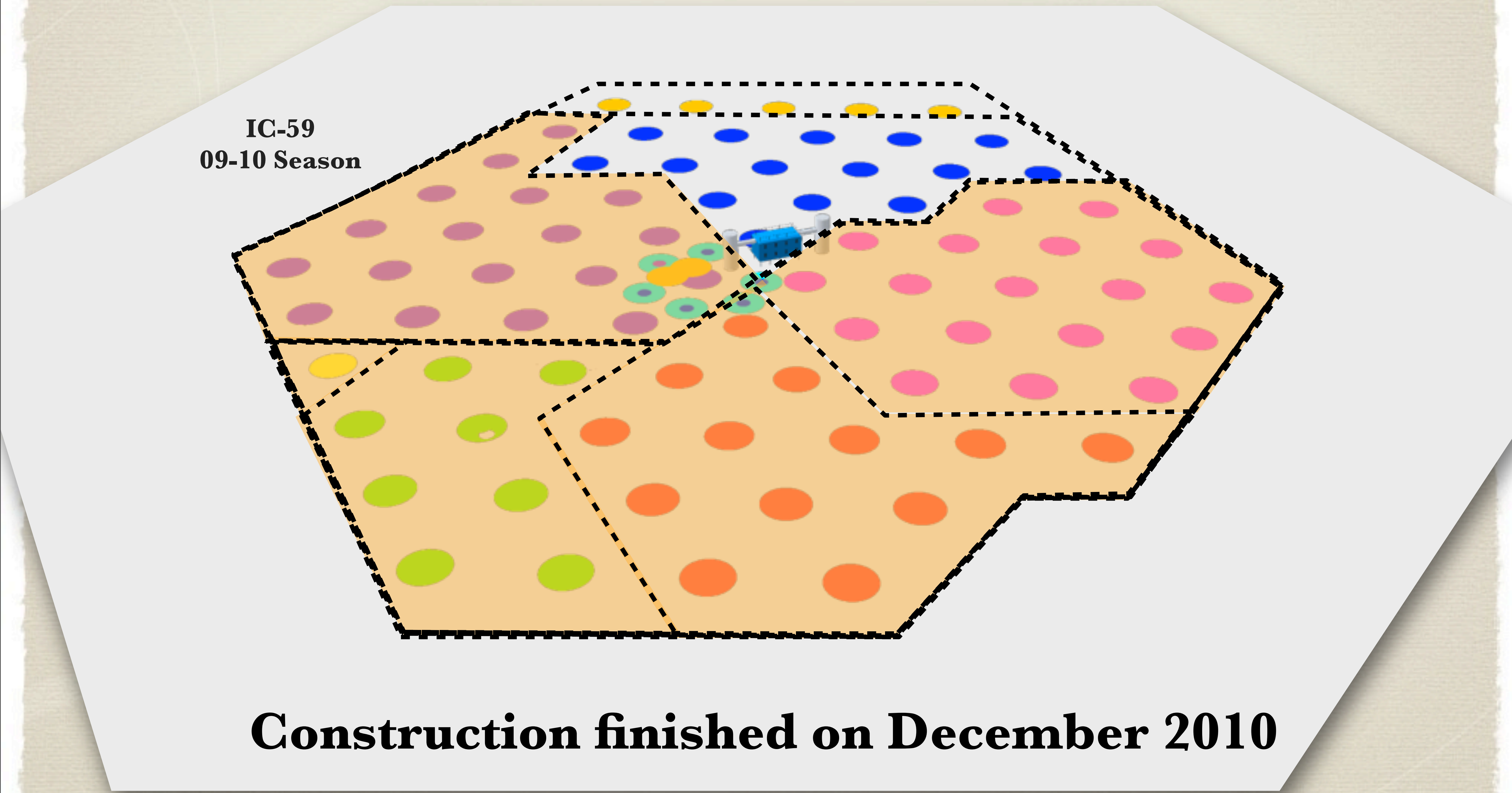
Digital Optical Module





IC59 configuration

Season 2009-2010

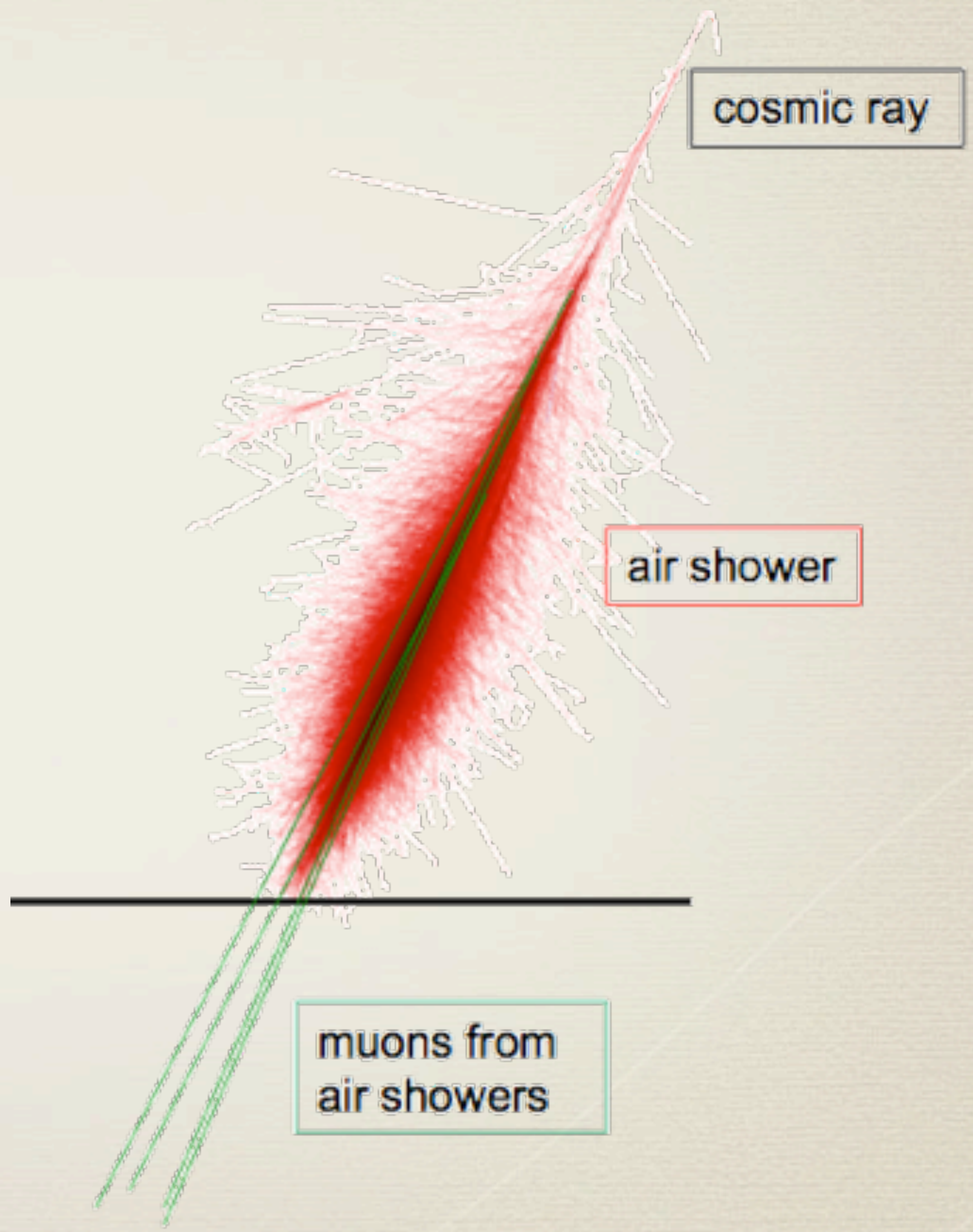


Construction finished on December 2010

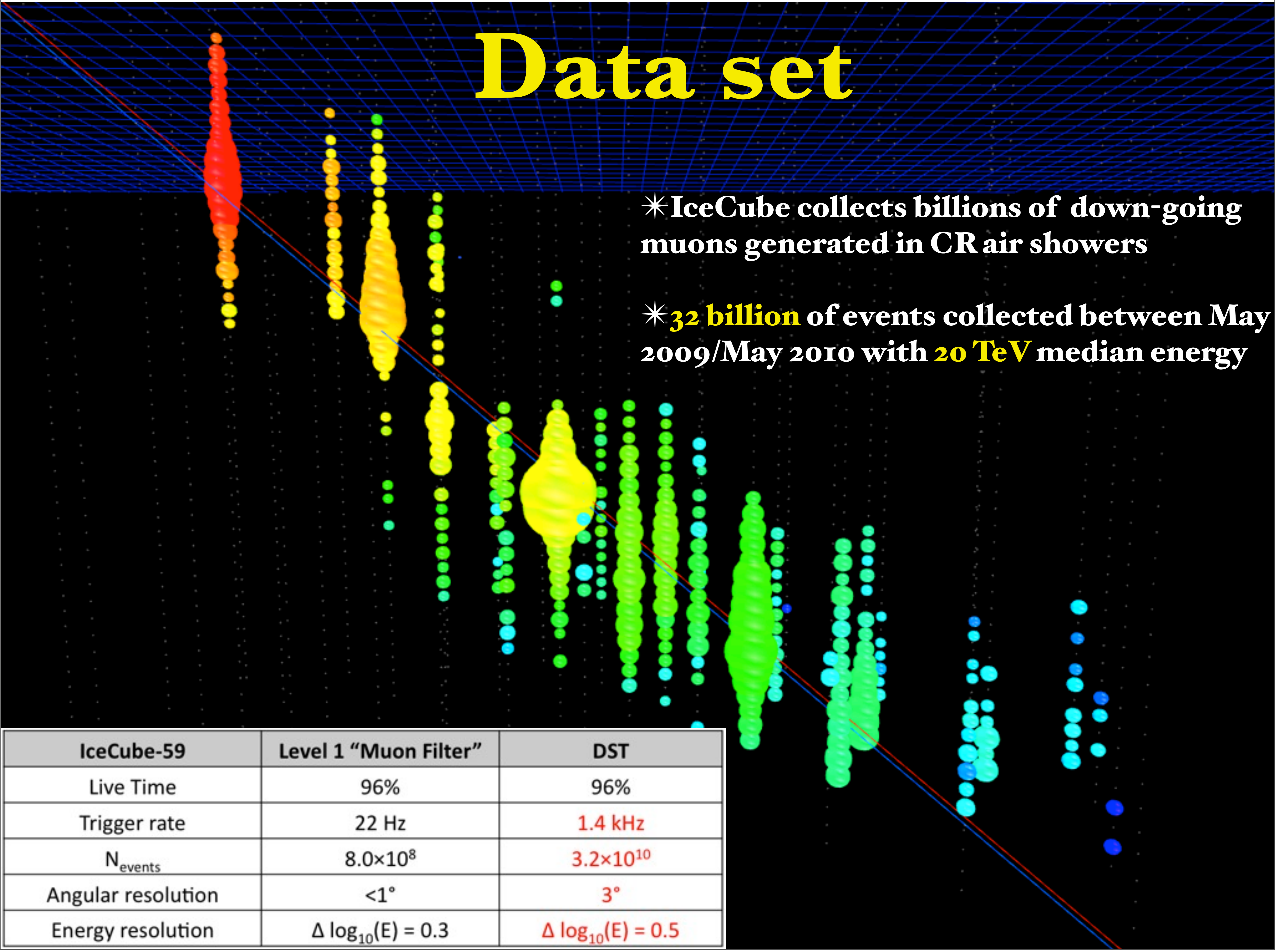
Cosmic rays in IceCube

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

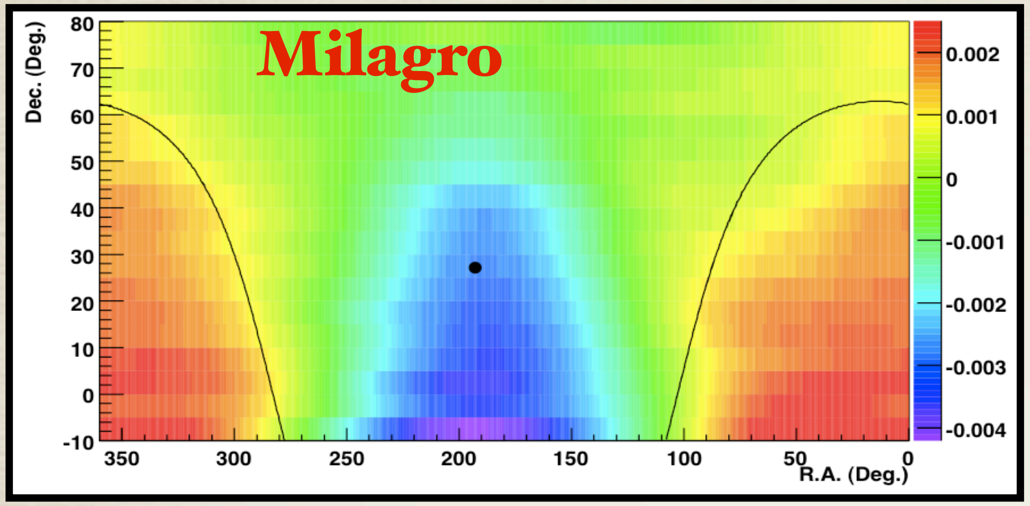


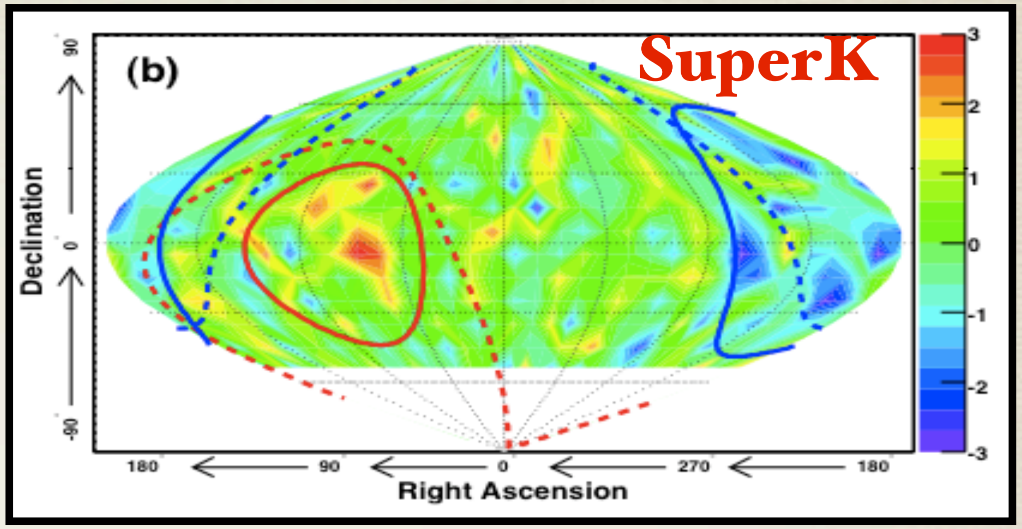
- IceCube collects billions of down-going muons generated in CR air showers
- **32 billion** of events collected between May 2009/May 2010 with **20 TeV** median energy

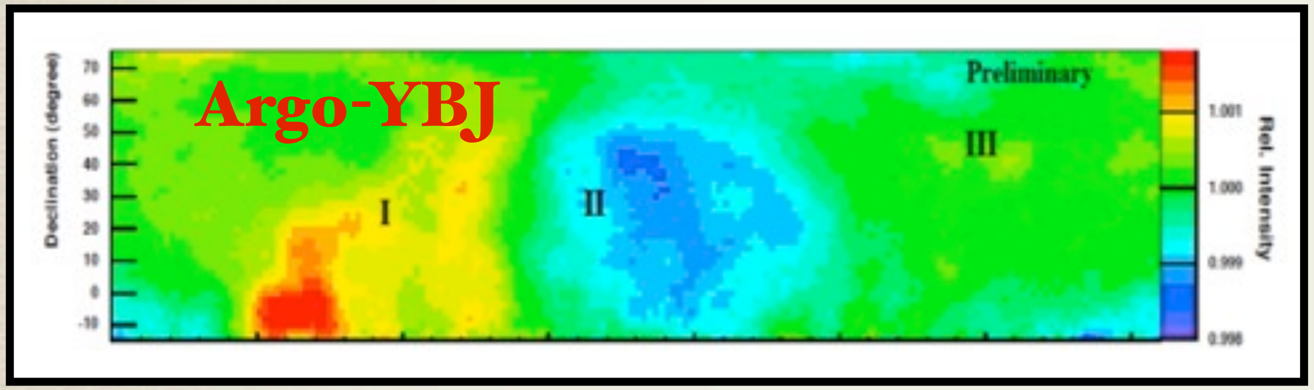
IceCube-59	Level 1 "Muon Filter"	DST
Live Time	96%	96%
Trigger rate	22 Hz	1.4 kHz
N_{events}	8.0×10^{8}	3.2×10^{10}
Angular resolution	<1°	3°
Energy resolution	$\Delta \log_{10}(E) = 0.3$	$\Delta \log_{10}(E) = 0.5$

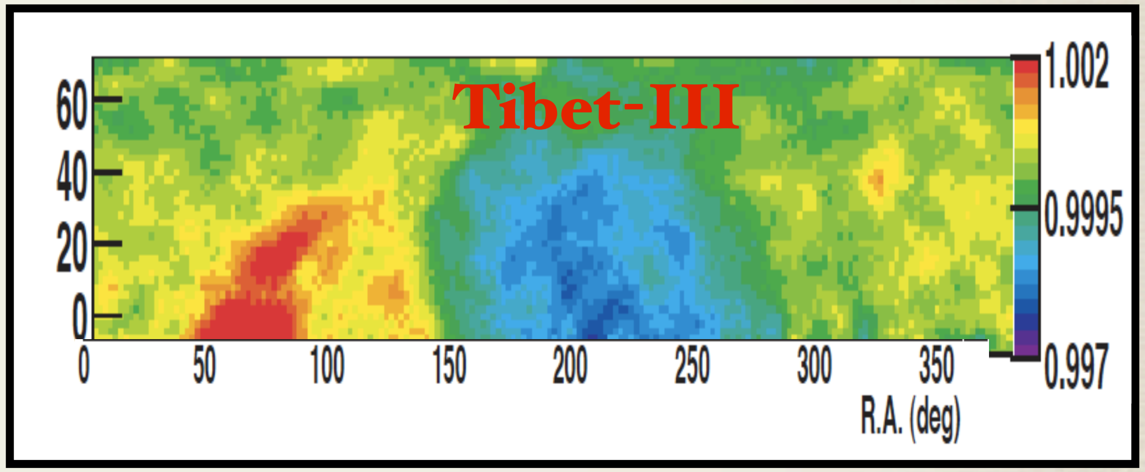
Observation of the CRs large scale anisotropy

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

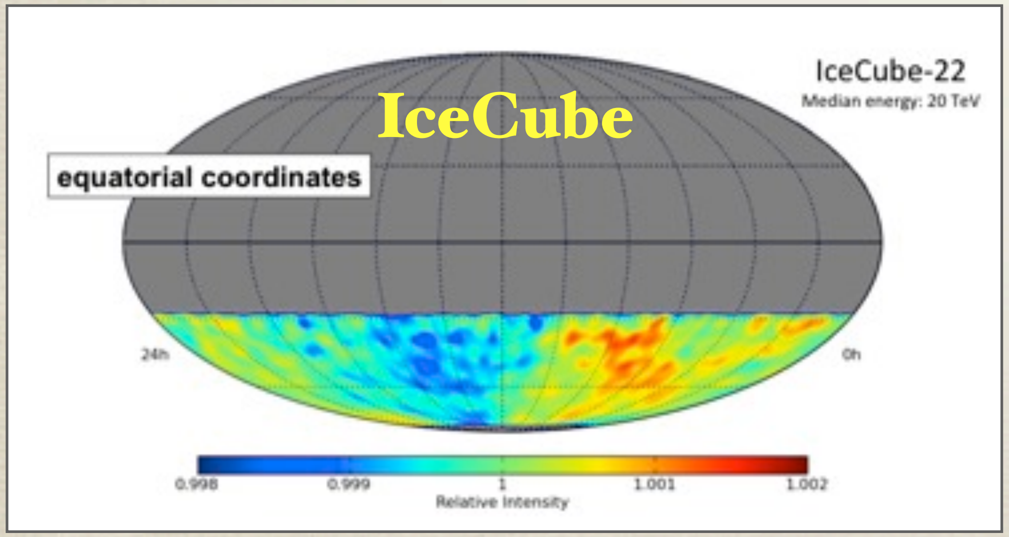








Northern Sky



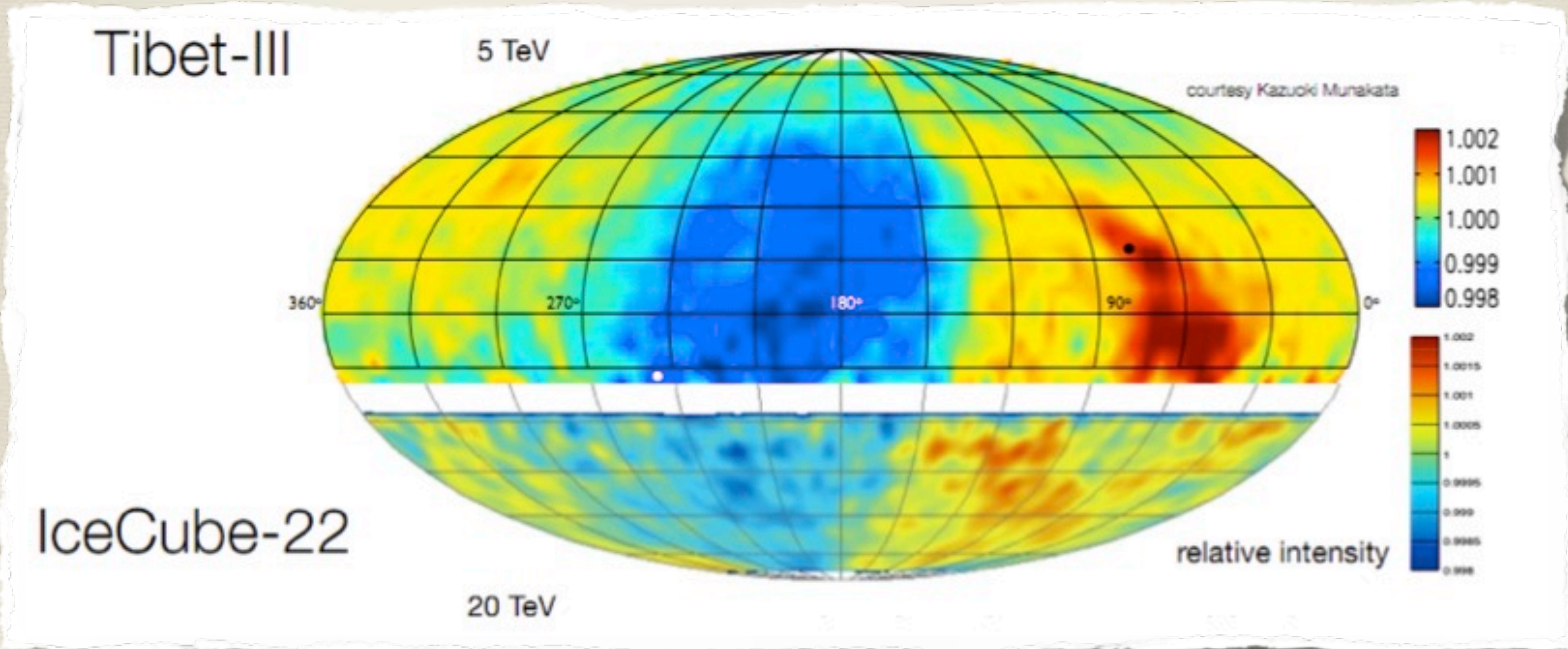
Southern Sky

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.

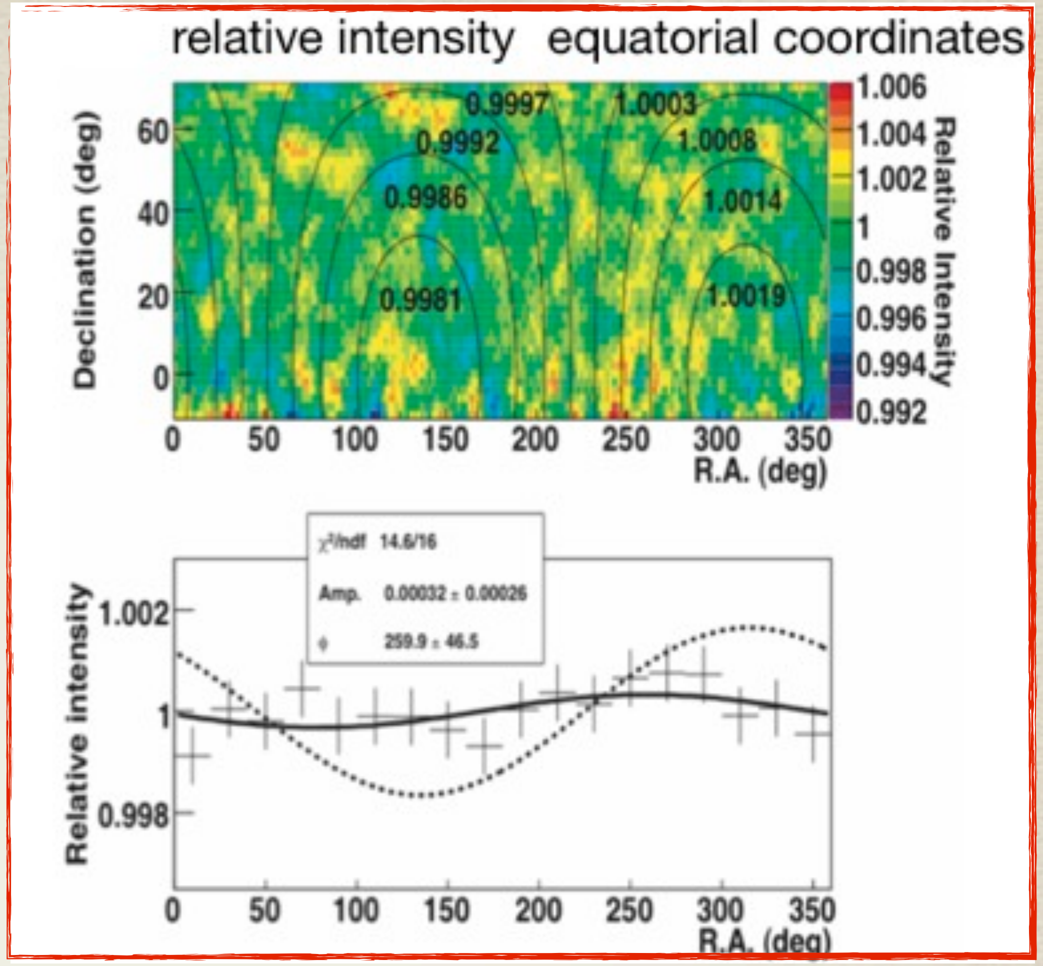
✳The anisotropy appears to be a continuation of large scale structures observed in the Northern Hemisphere.



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

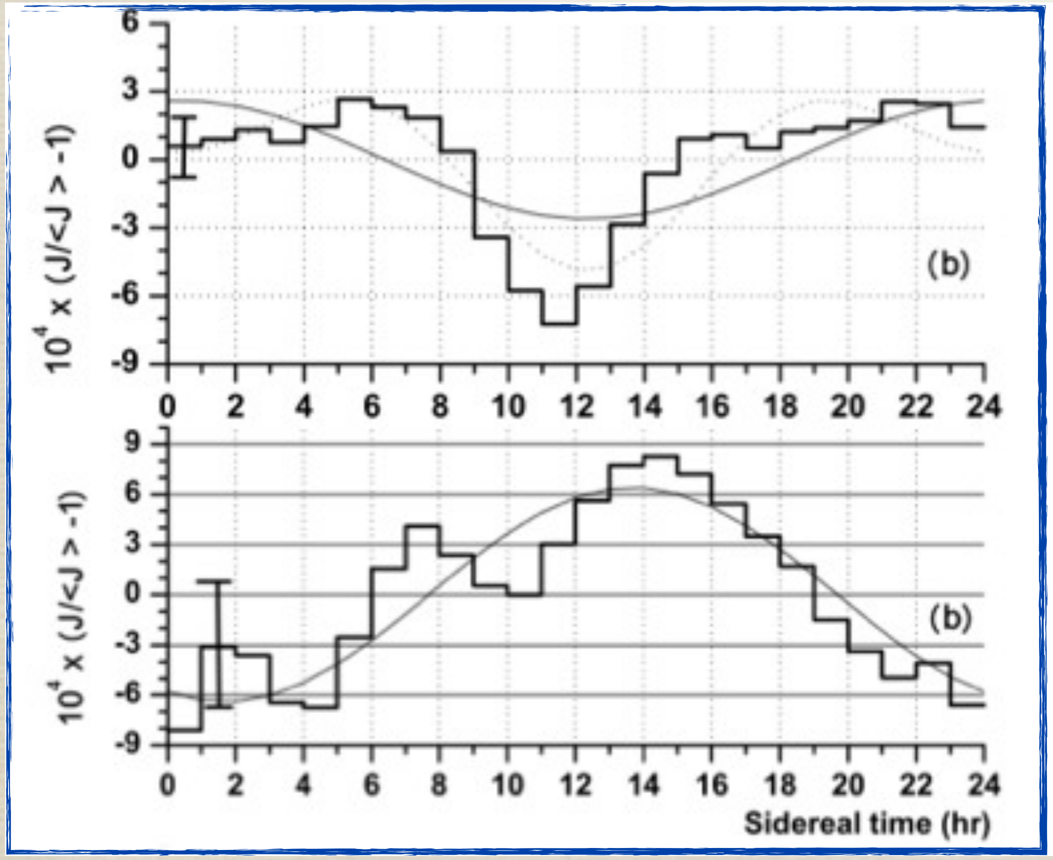


Tibet - III

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

Amplitude: (3.2±2.6)×10^{-4}

consistent with **no anisotropy**



110 TeV

370 TeV

EAS-Top

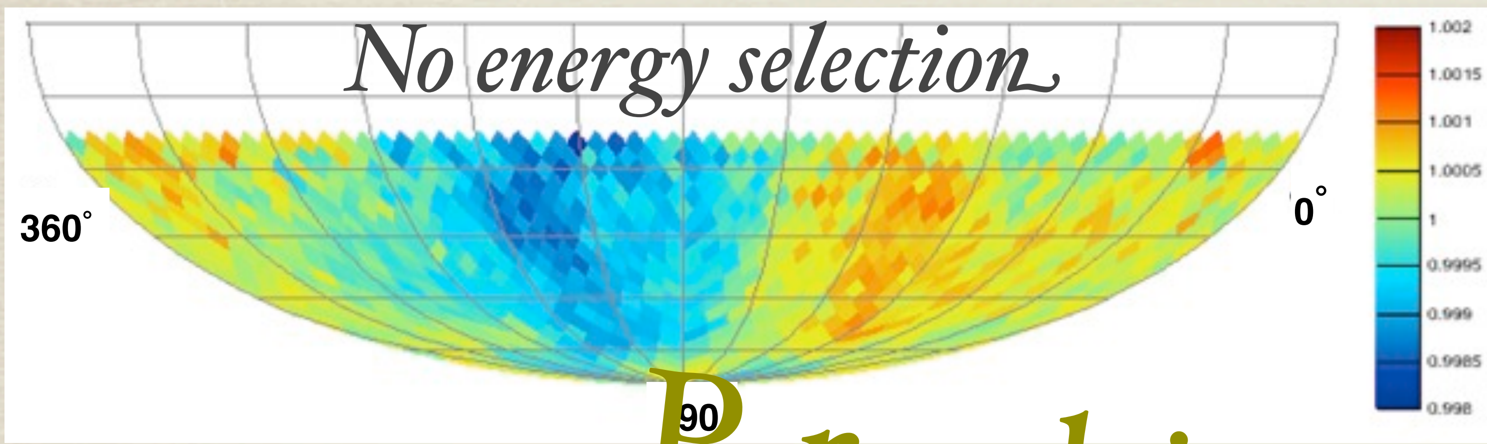
Aglietta et al., ApJ 692, L130, 2009

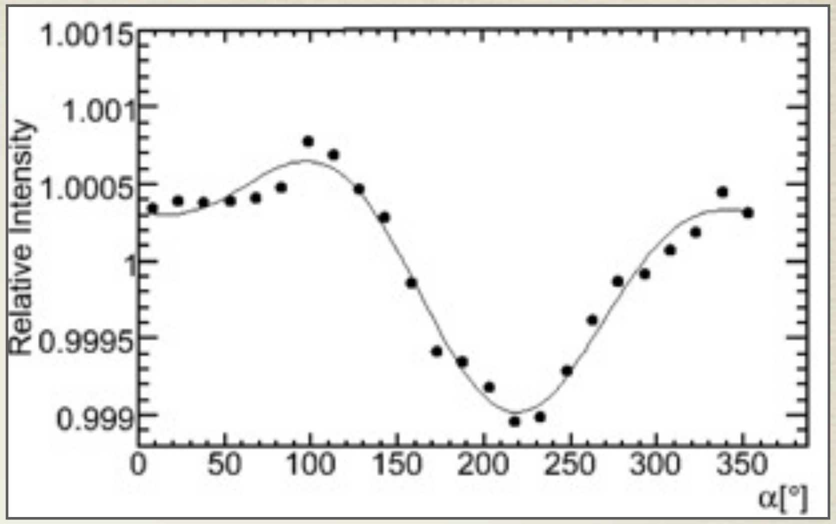
Amplitude (370 TeV): (6.4±2.5)×10^{-4}

low significance, still not conclusive.

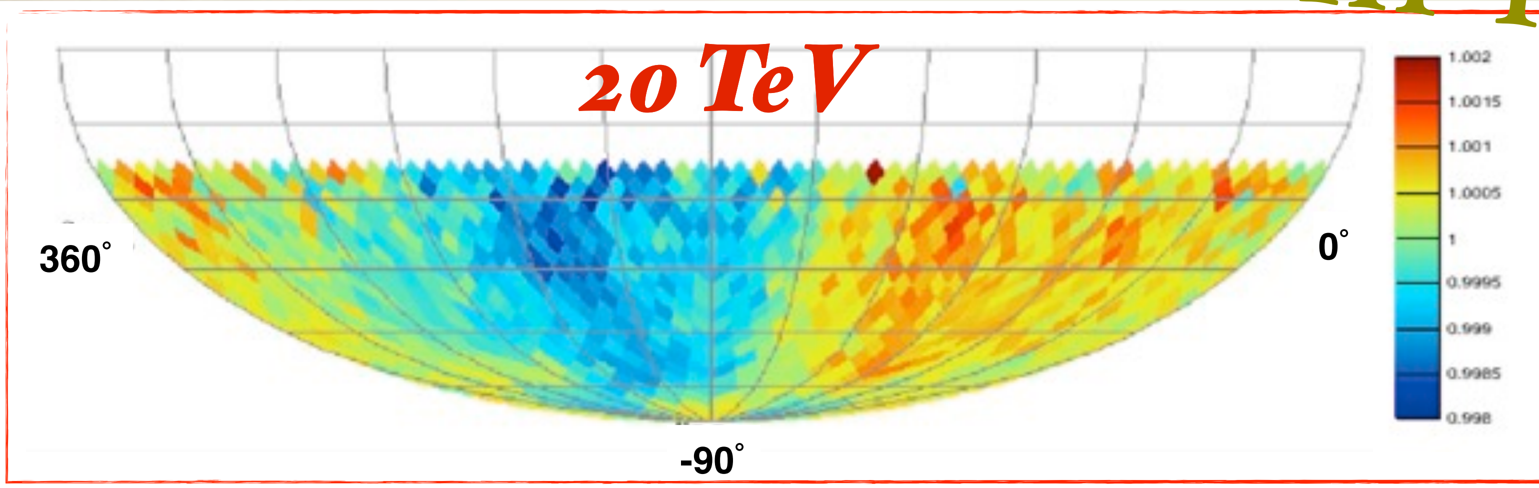
Relative Intensity

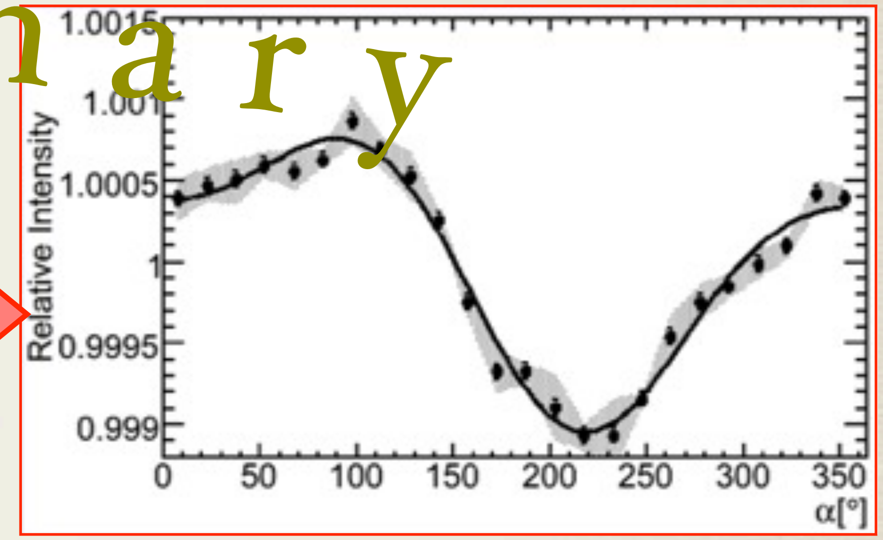
*Equatorial sky maps in HEALPix with NSide= 16, **pix resol ~ 3°***

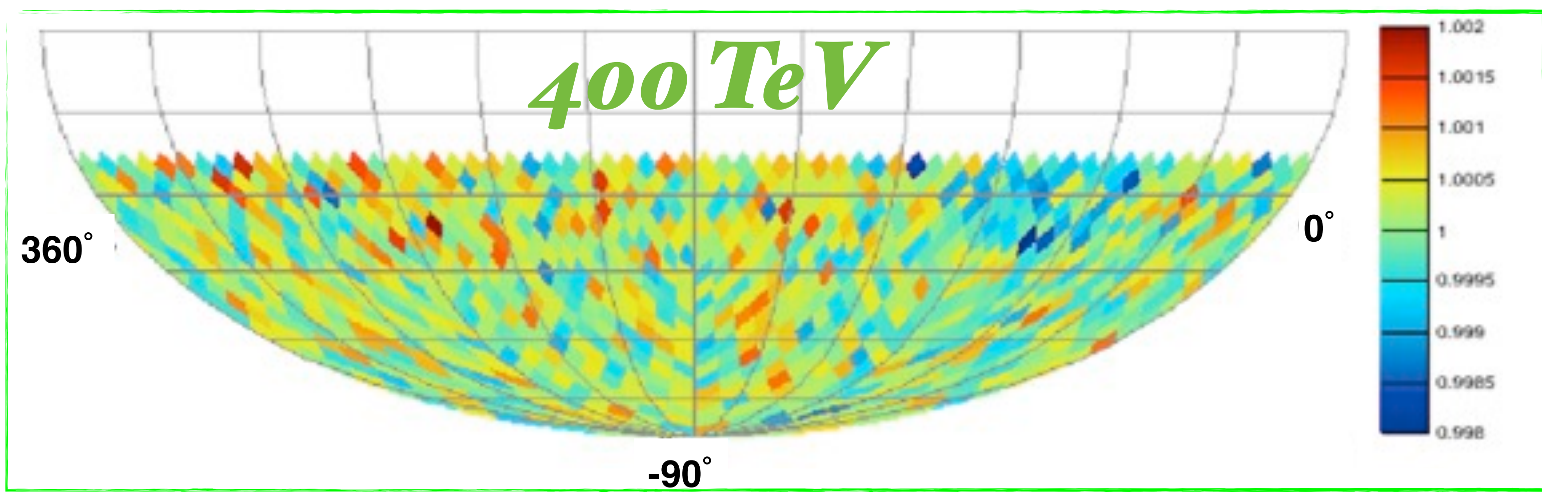


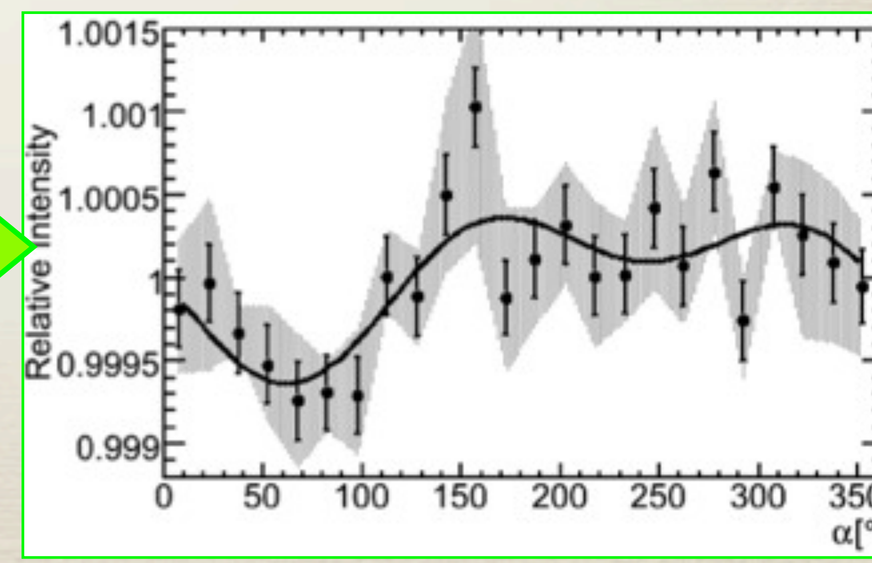


Preliminary

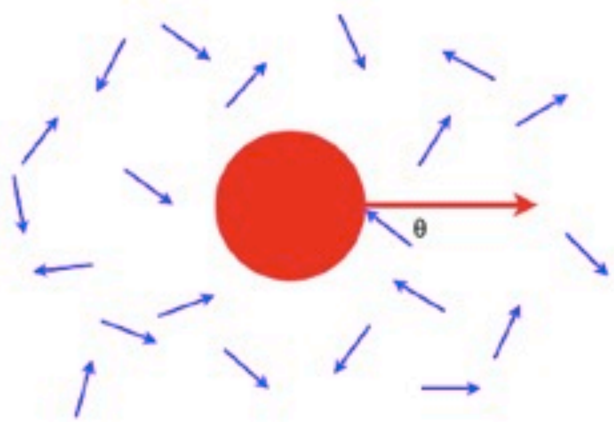






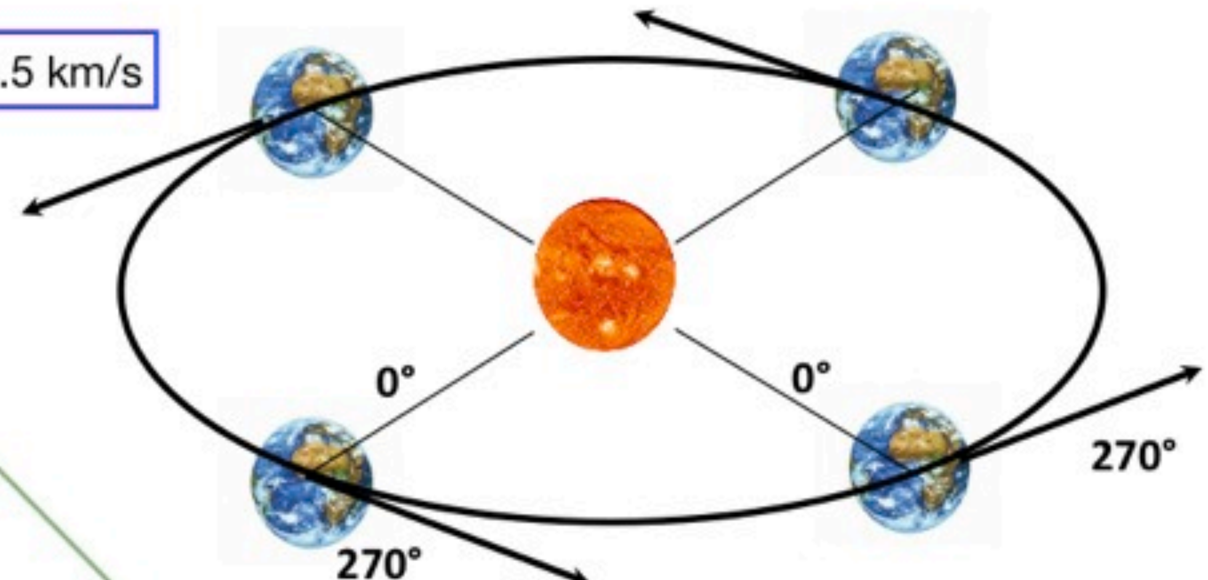


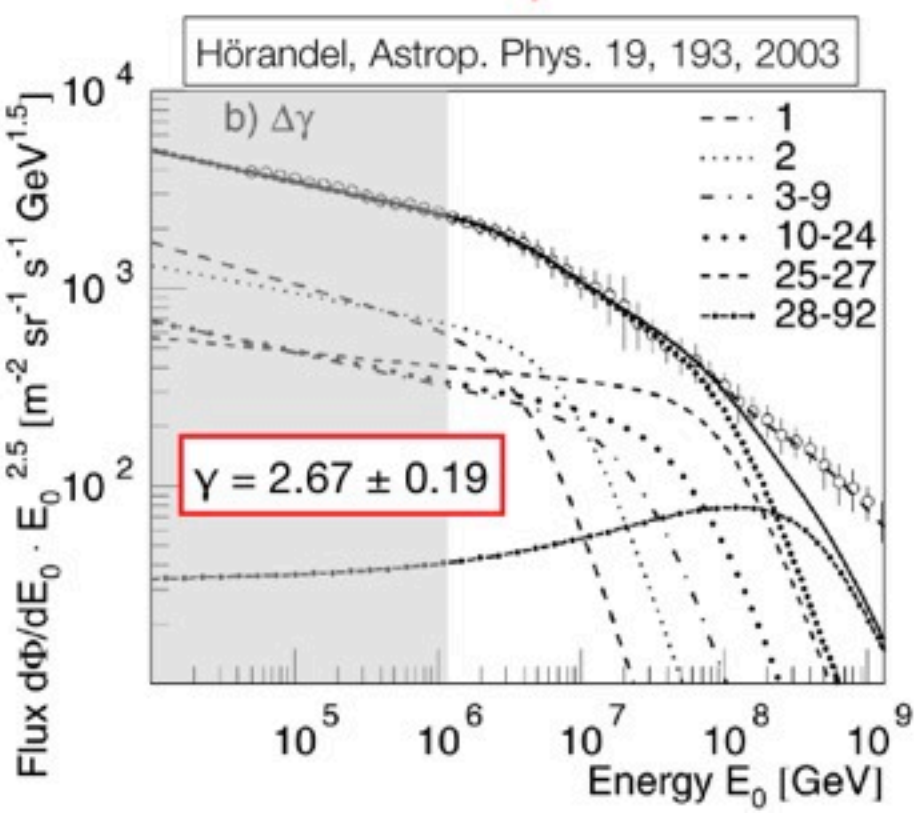
Earth's motion around the Sun: the **Solar dipole**

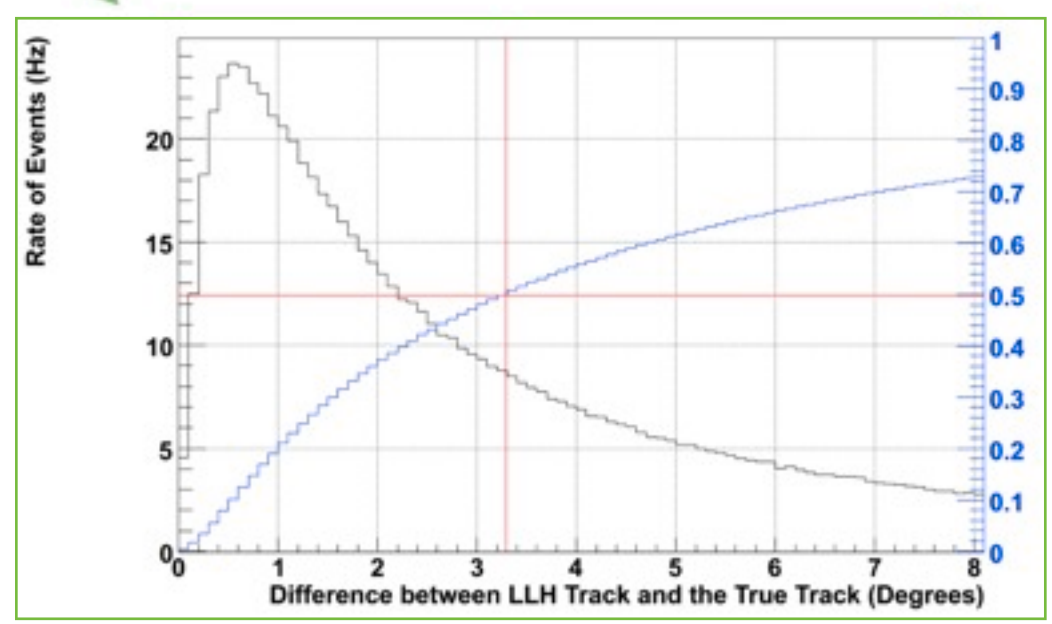


$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

v = 29.8 ± 0.5 km/s



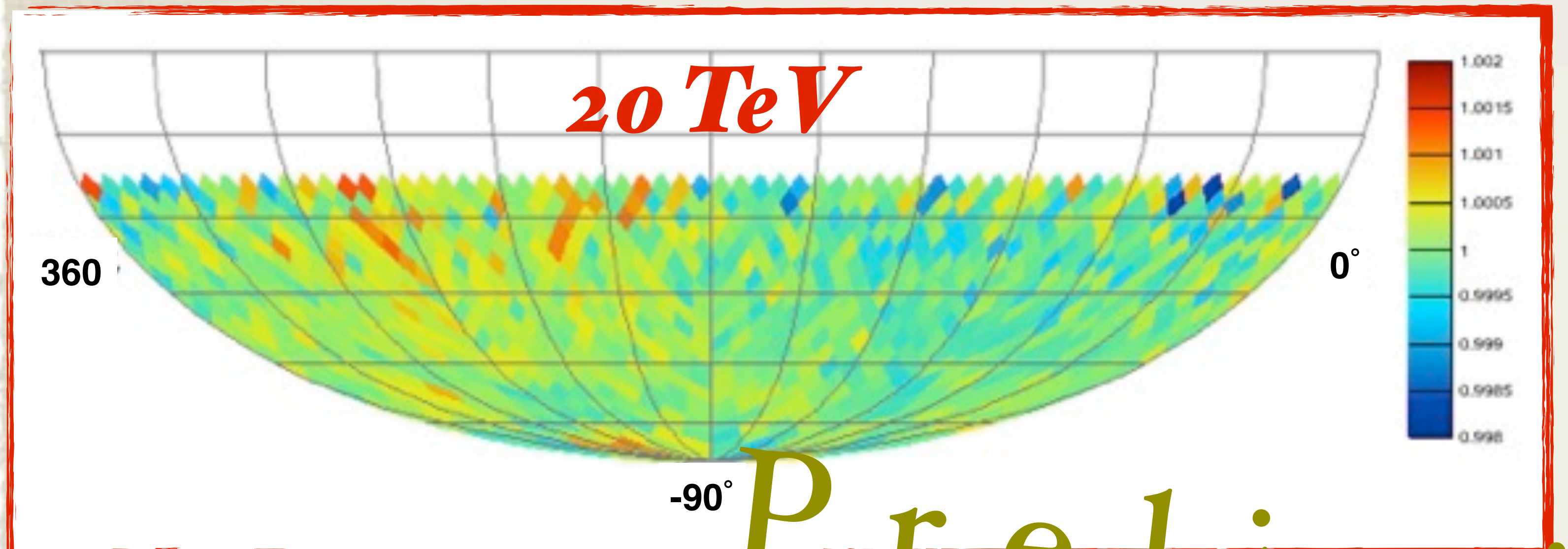


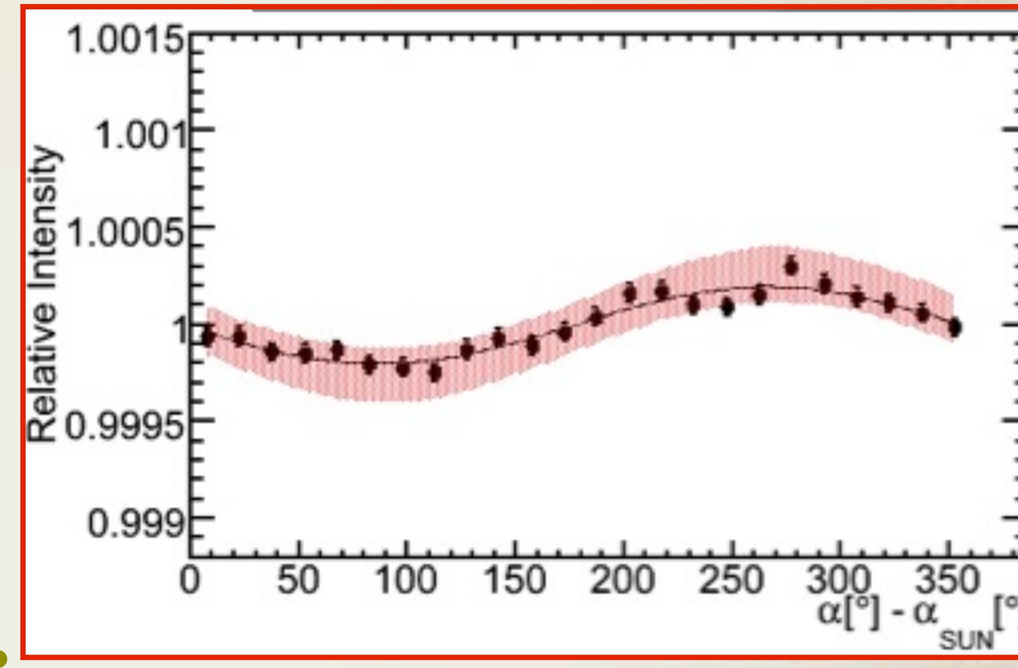


Energy dependence of the Solar dipole

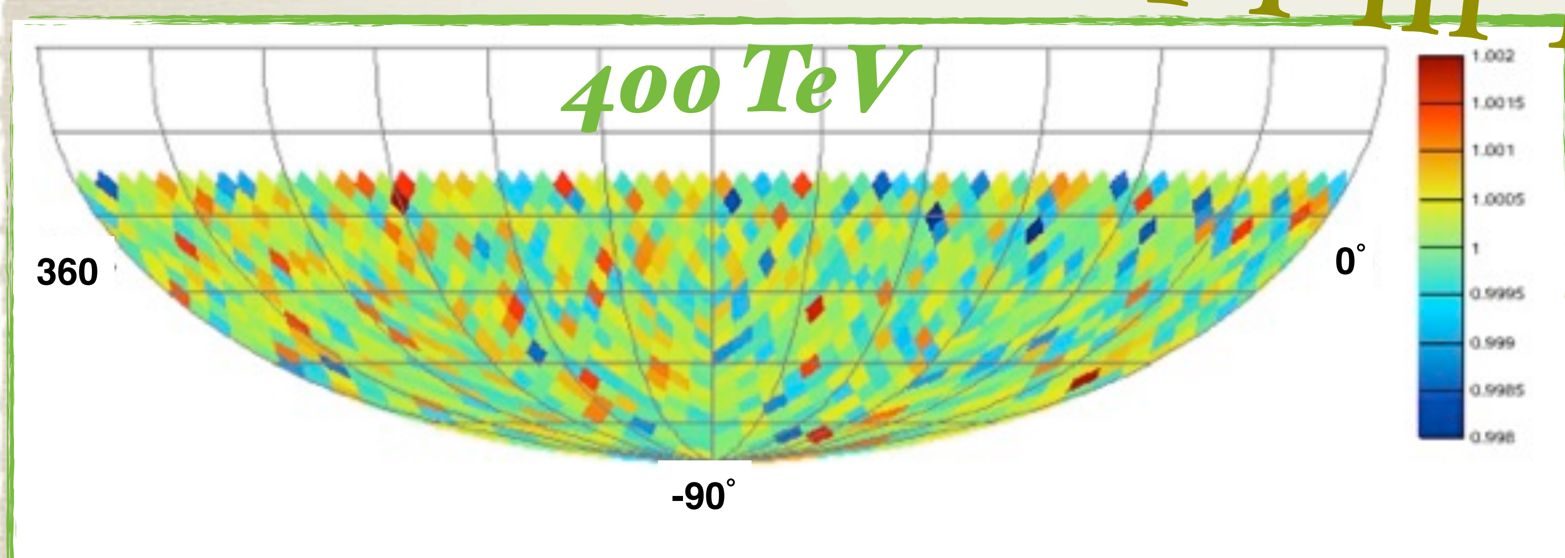
✳ IceCube observes the Solar dipole in both energy bins. The observed amplitude is compatible with the expectations within the stat. and sys. uncertainties.
✳ The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction.

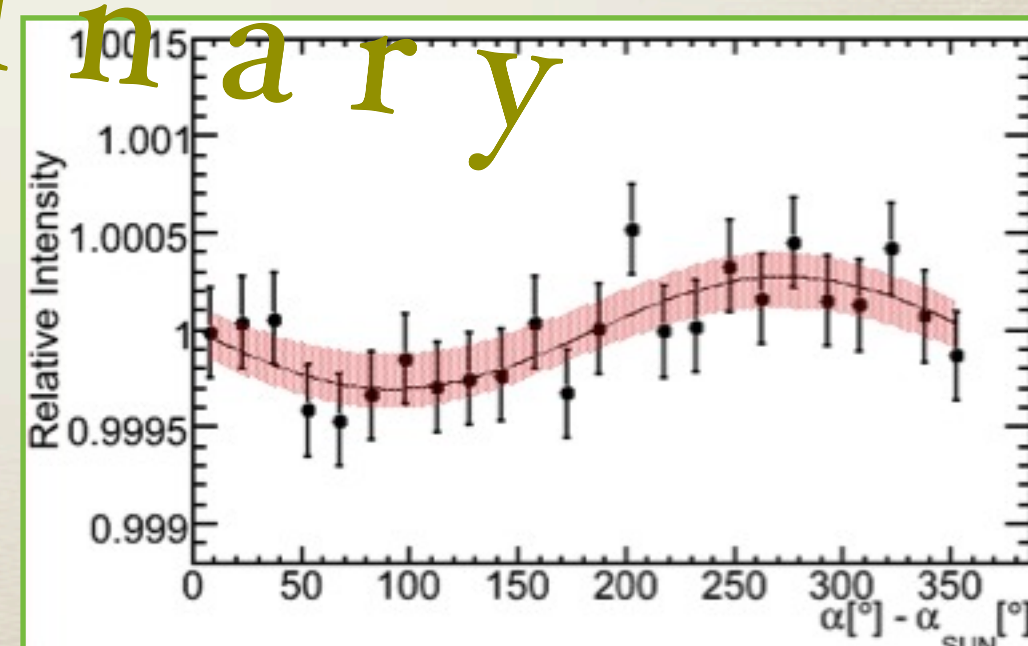
relative intensity Vs. ($\alpha[^\circ]$ - $\alpha_{SUN}[^\circ]$)





Preliminary



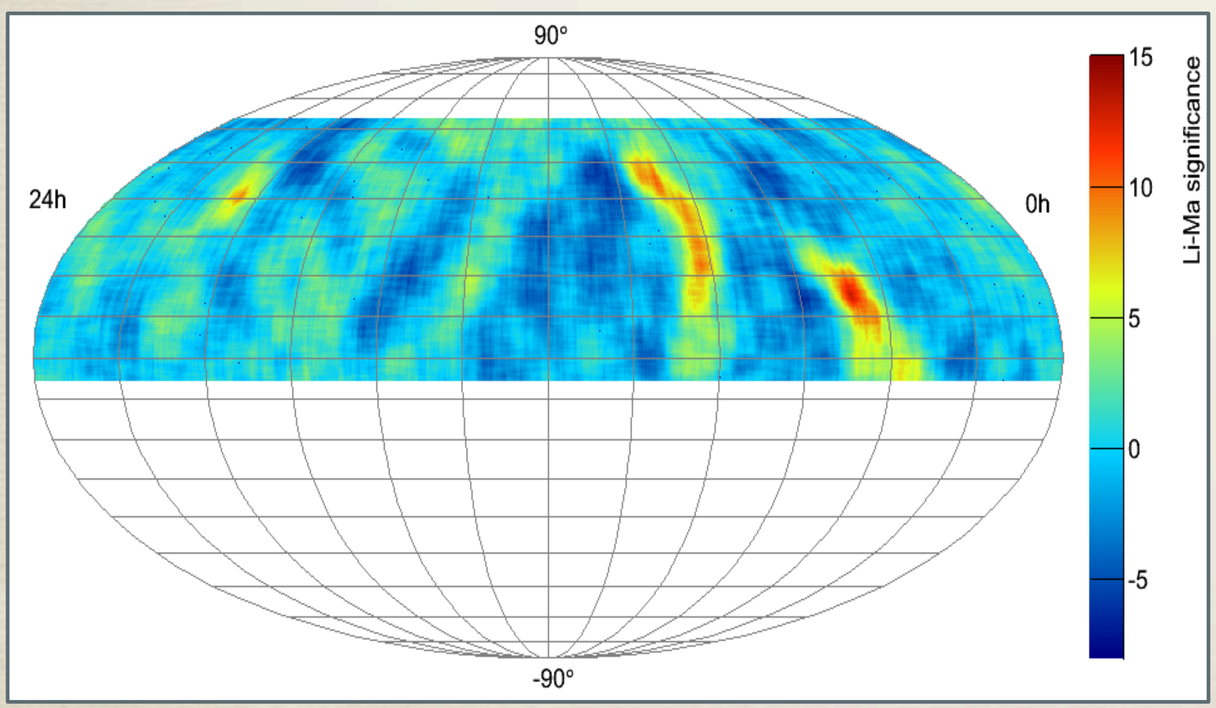


Small scale anisotropy

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.

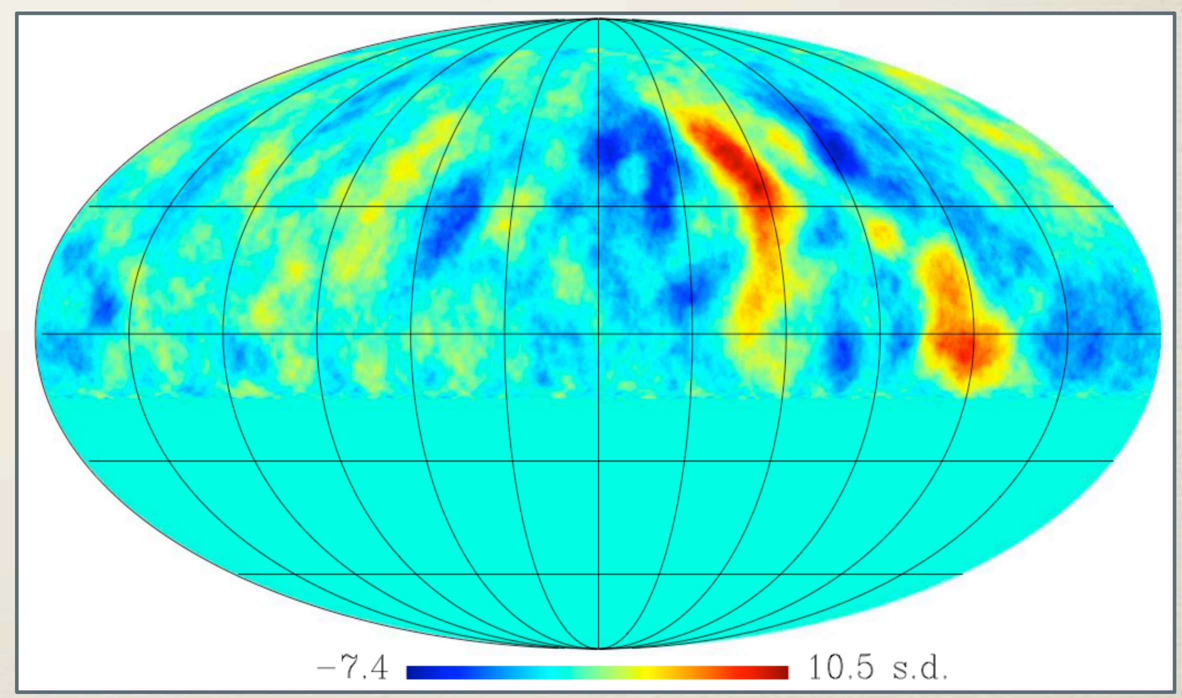
✳ Same structures observed by ARGO-YBJ.



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

Milagro

Median Energy: 1 TeV



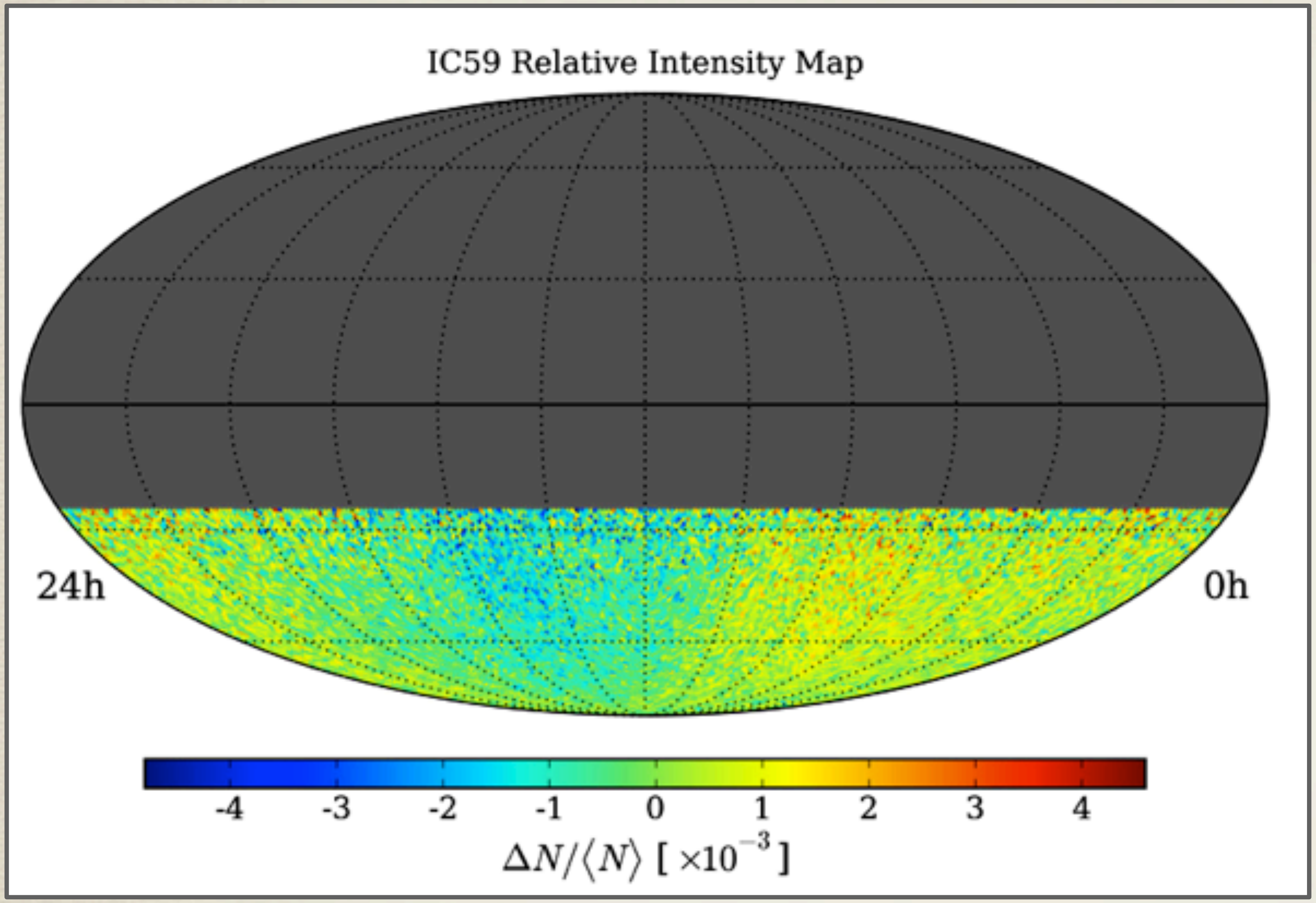
S. Vernetto, Proc. 31st ICRC, 2009

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

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

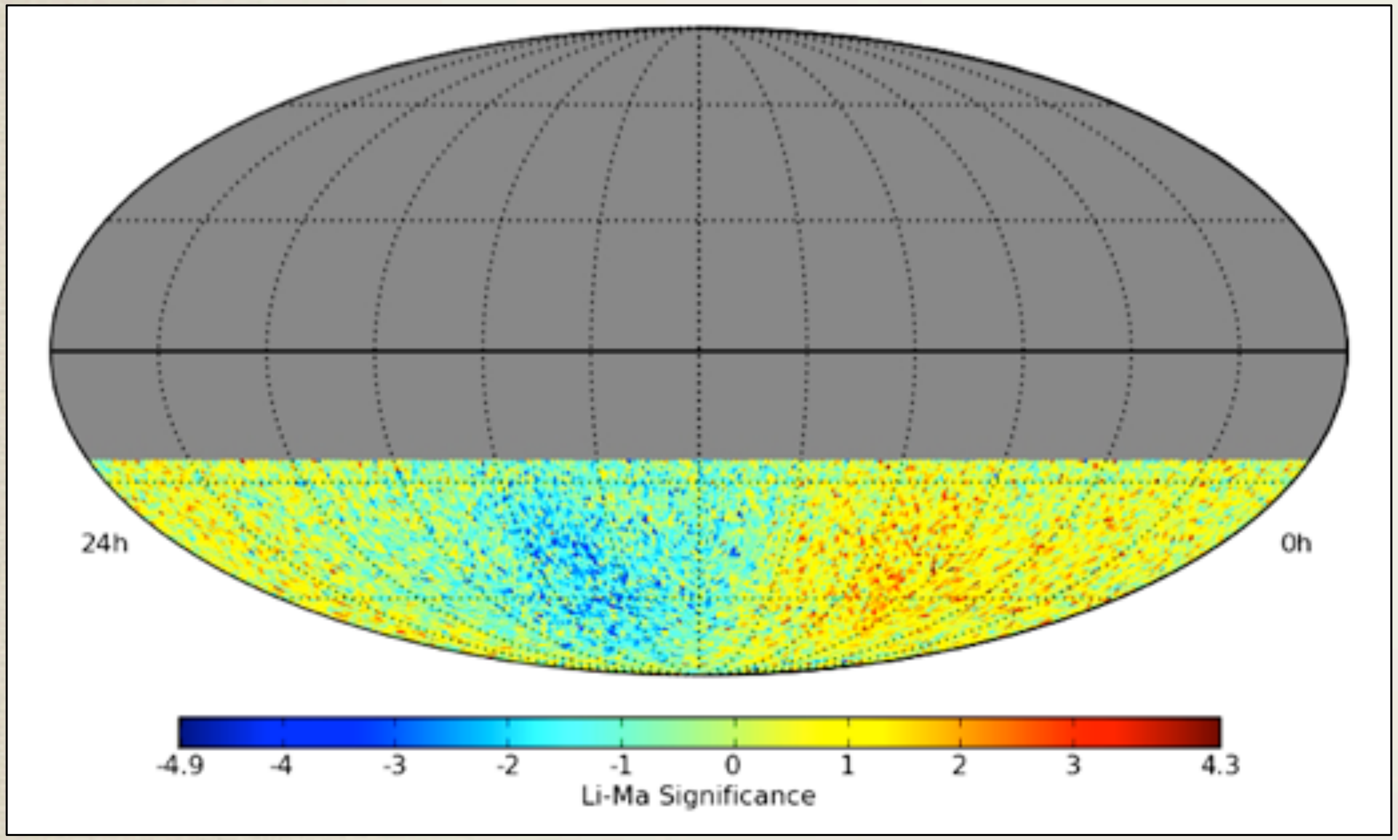
Relative intensity map is *not isotropic*. In IceCube-59, the *strong large scale structure* already observed in IceCube-22 data is visible in the "raw" data.

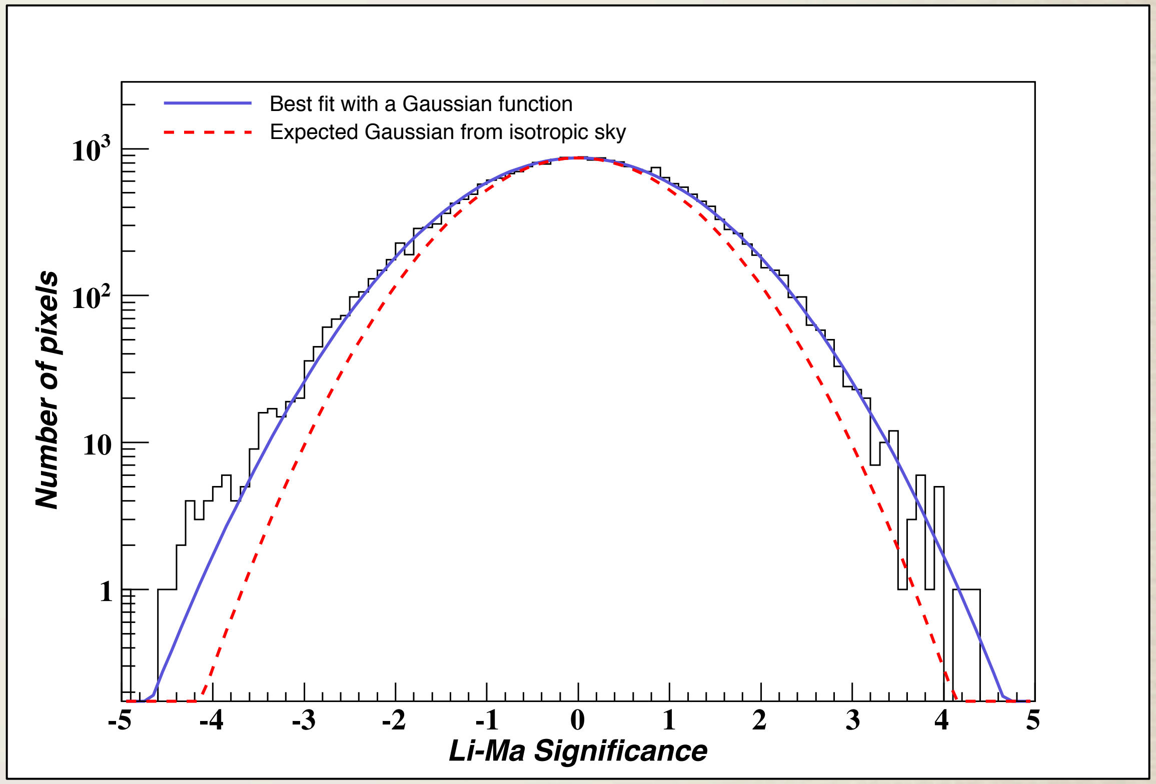
Significance map

Significance calculation:

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

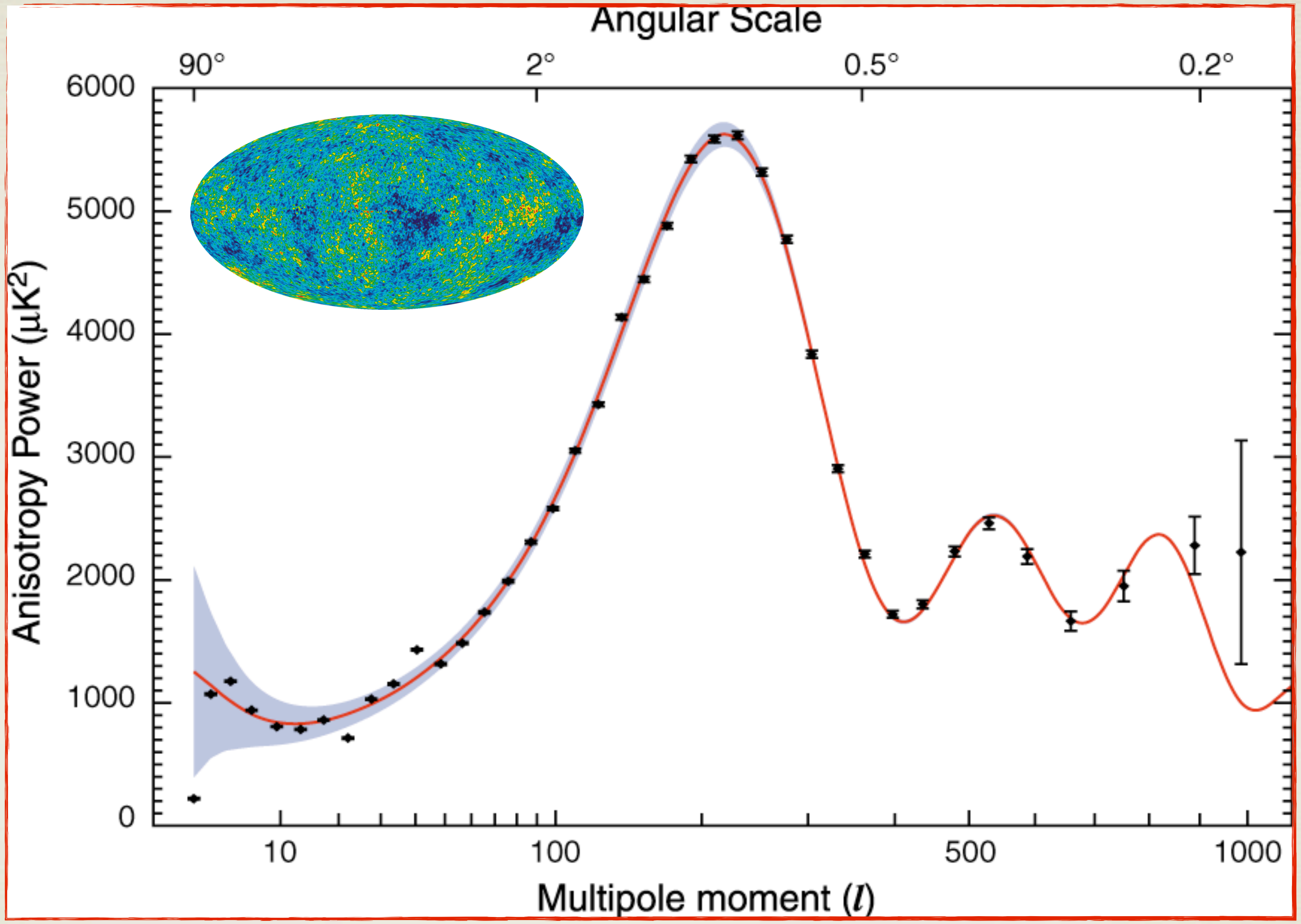
Li, T., & Ma, Y. 1983, ApJ, 272, 317





Power spectrum

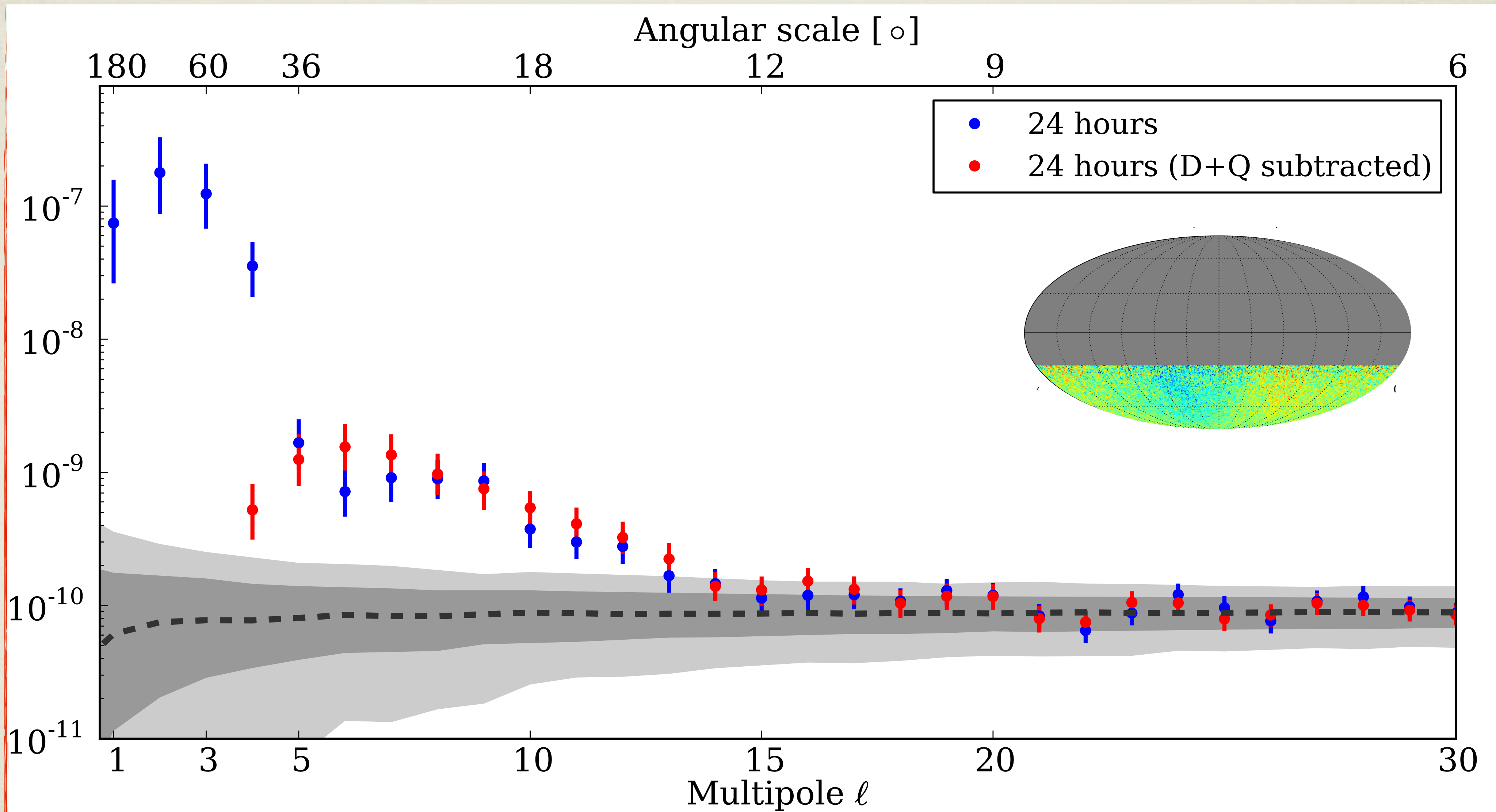
Angular size $\theta \sim \dfrac{180^\circ}{\ell}$



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

Power spectrum

Angular size $\theta \sim \frac{180°}{\ell}$



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

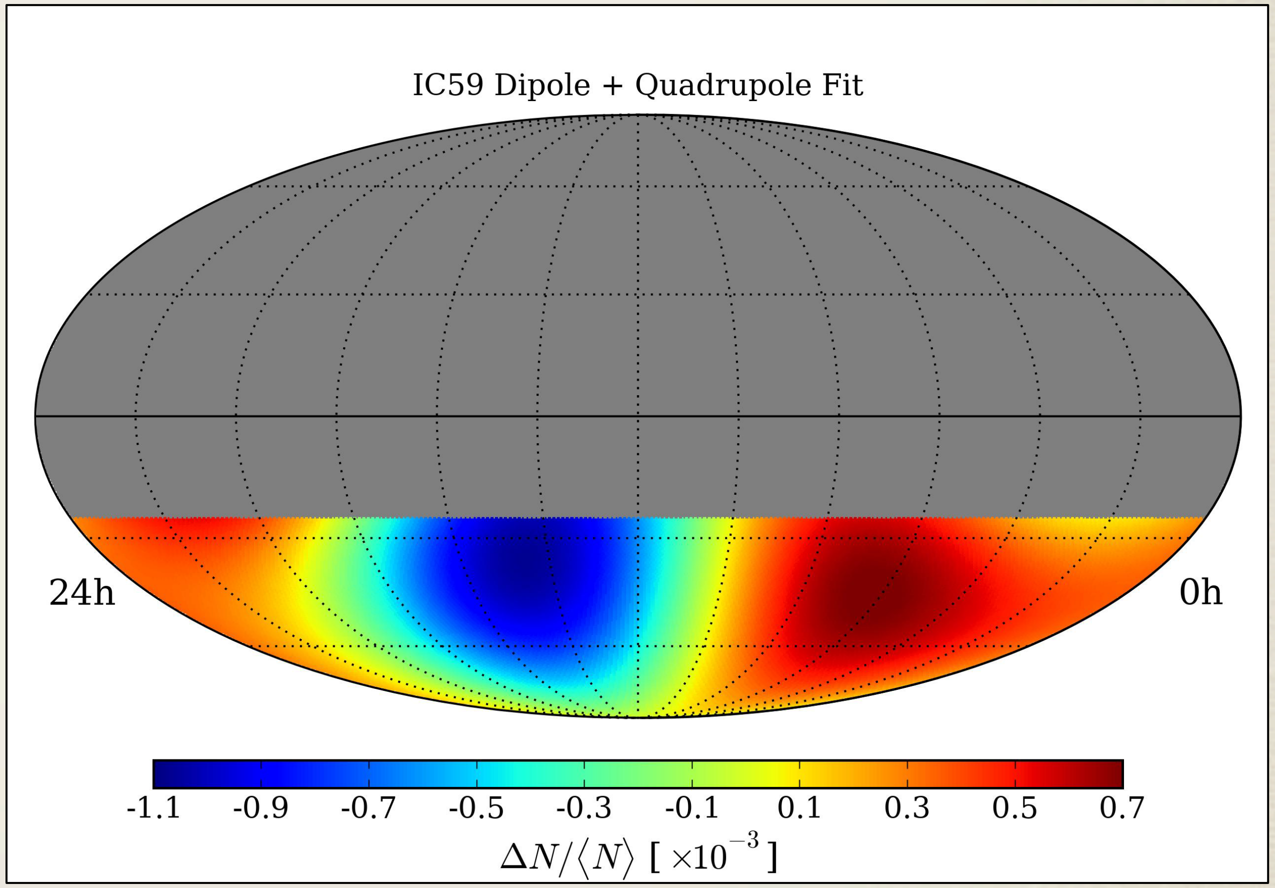
Dipole and quadrupole fit

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

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

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

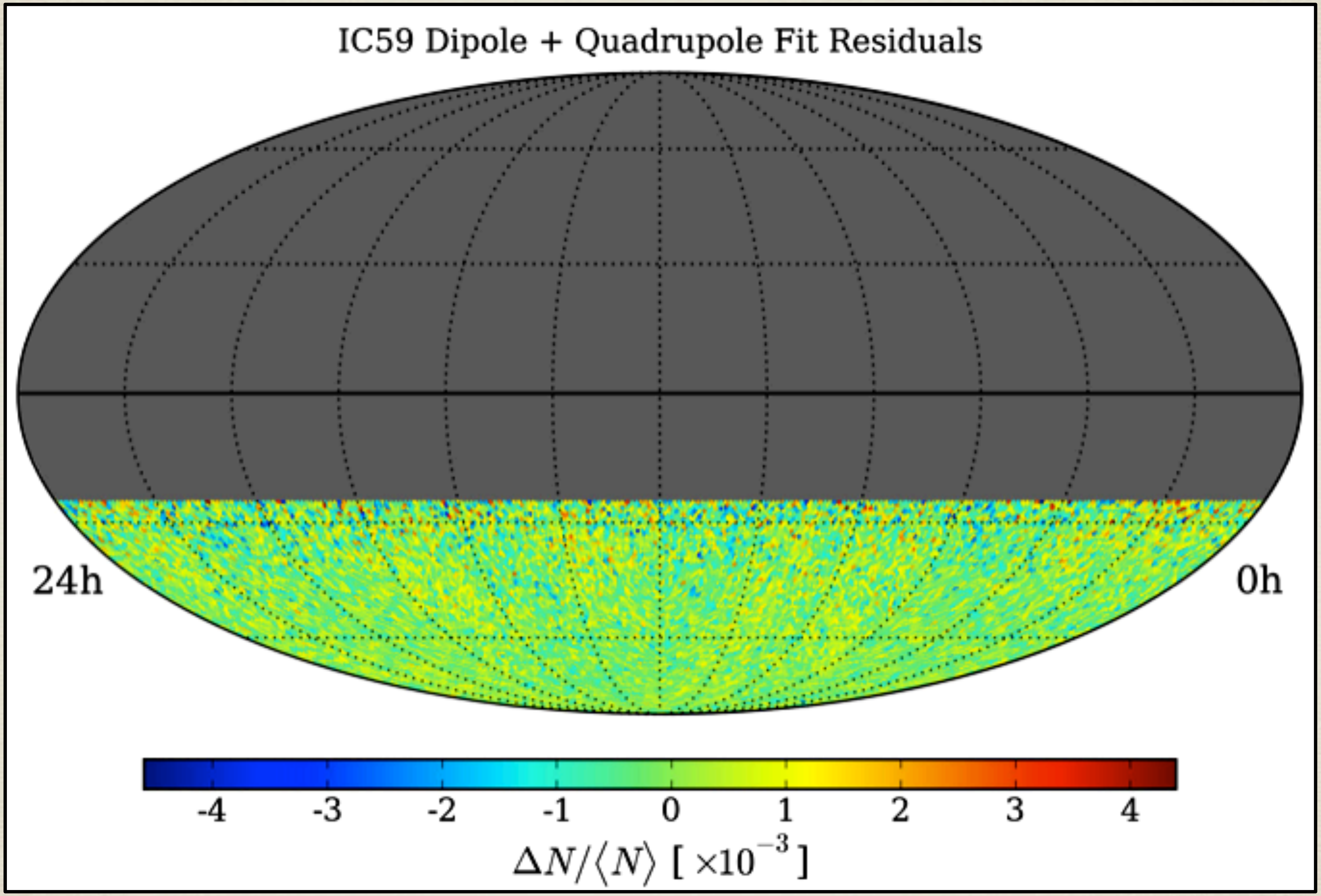
Coefficient	Fit Value
m_0	0.320 ± 2.264
p_x	2.435 ± 0.707
p_y	-3.856 ± 0.707
p_z	0.548 ± 3.872
Q_1	0.233 ± 1.702
Q_2	-2.949 ± 0.494
Q_3	-8.797 ± 0.494
Q_4	-2.148 ± 0.200
Q_5	-5.268 ± 0.200



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

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

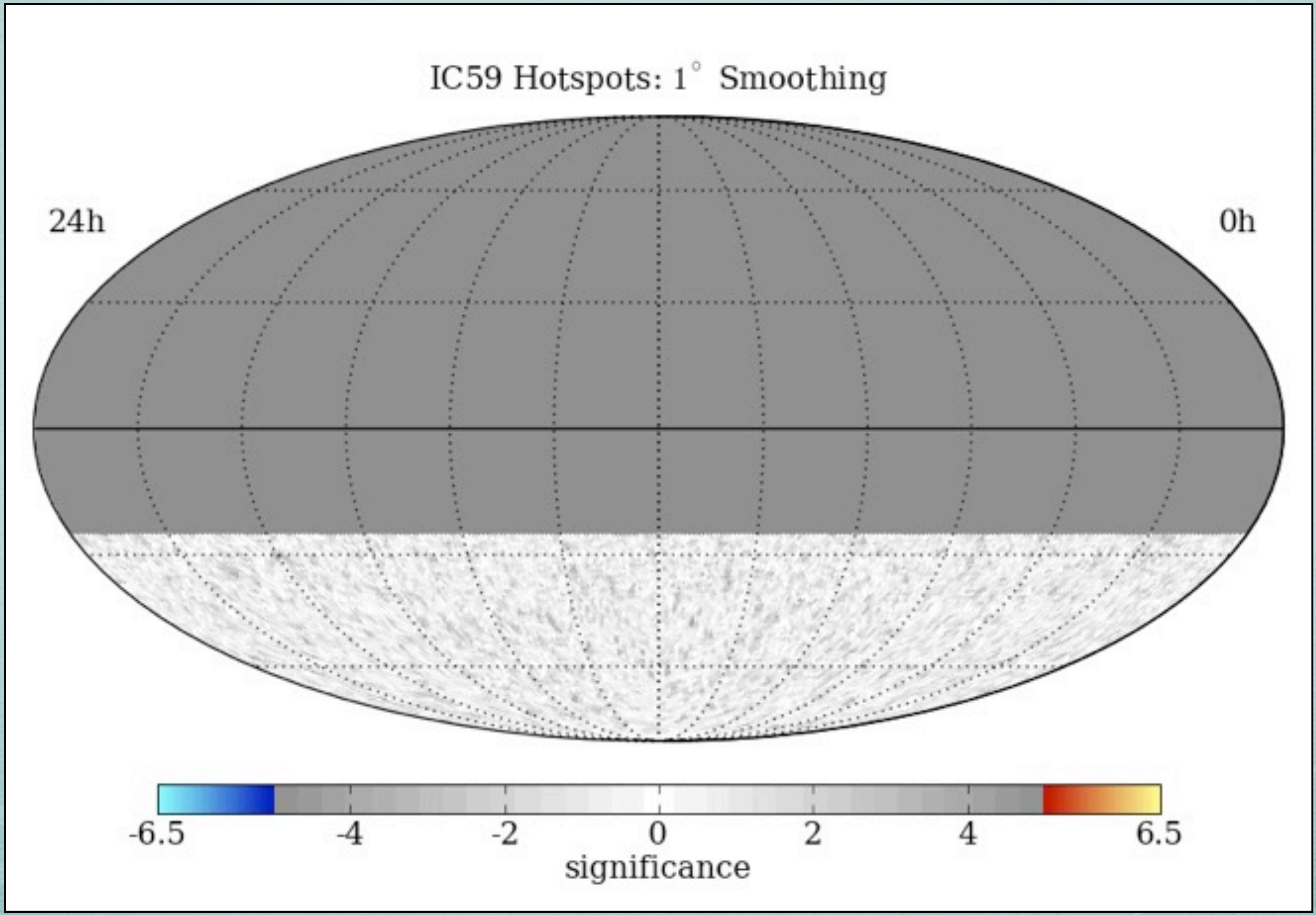
Residual map



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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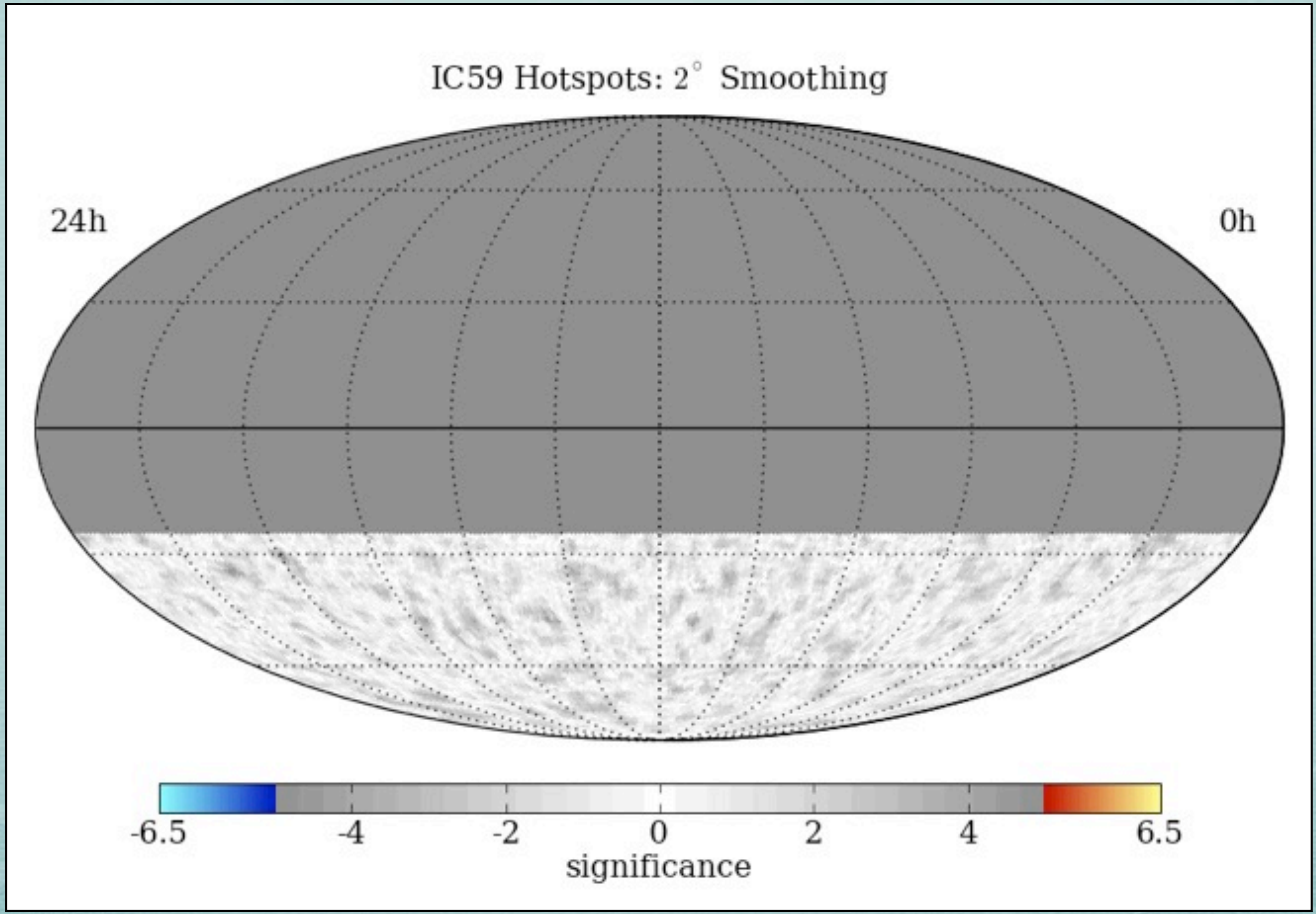

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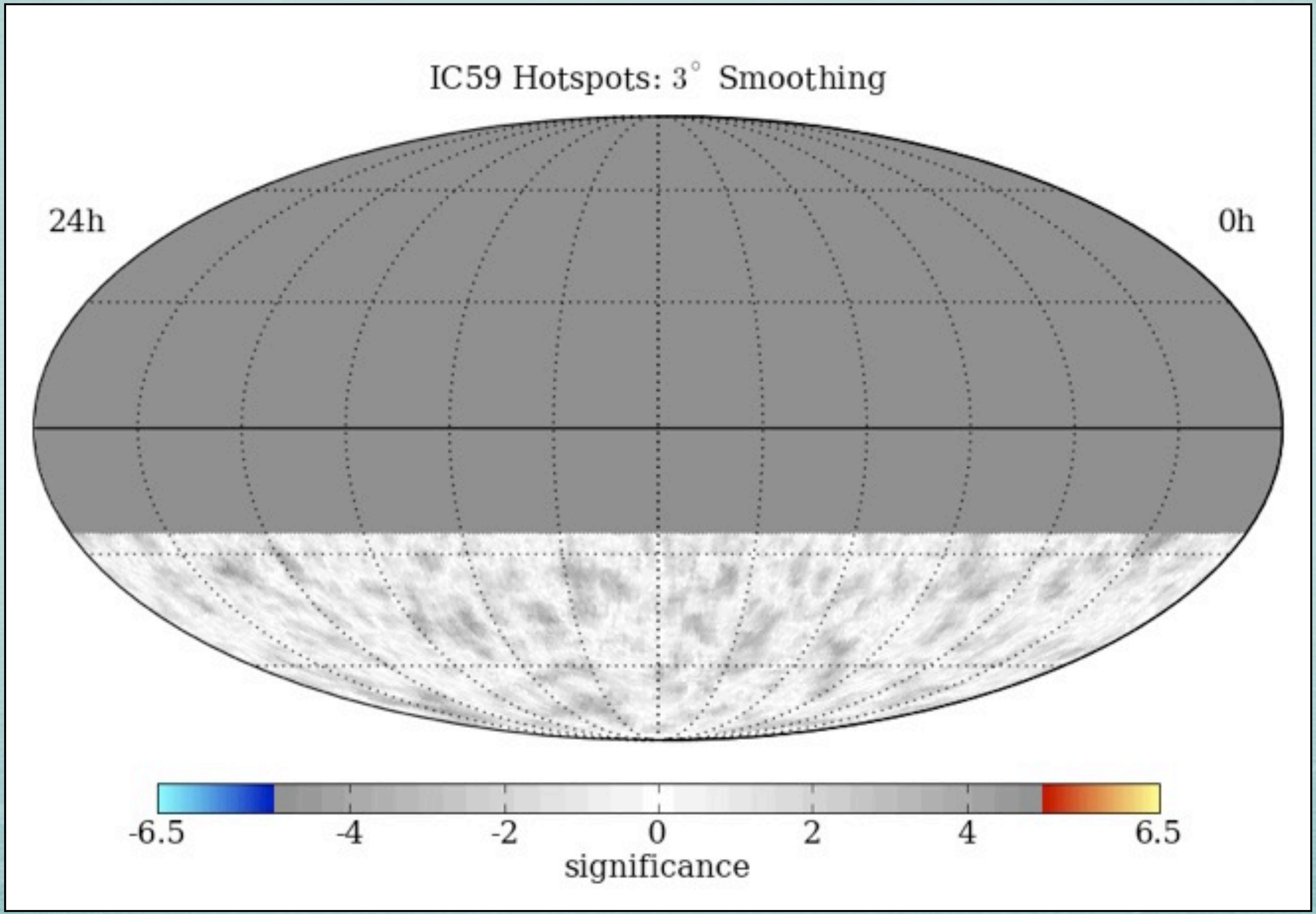

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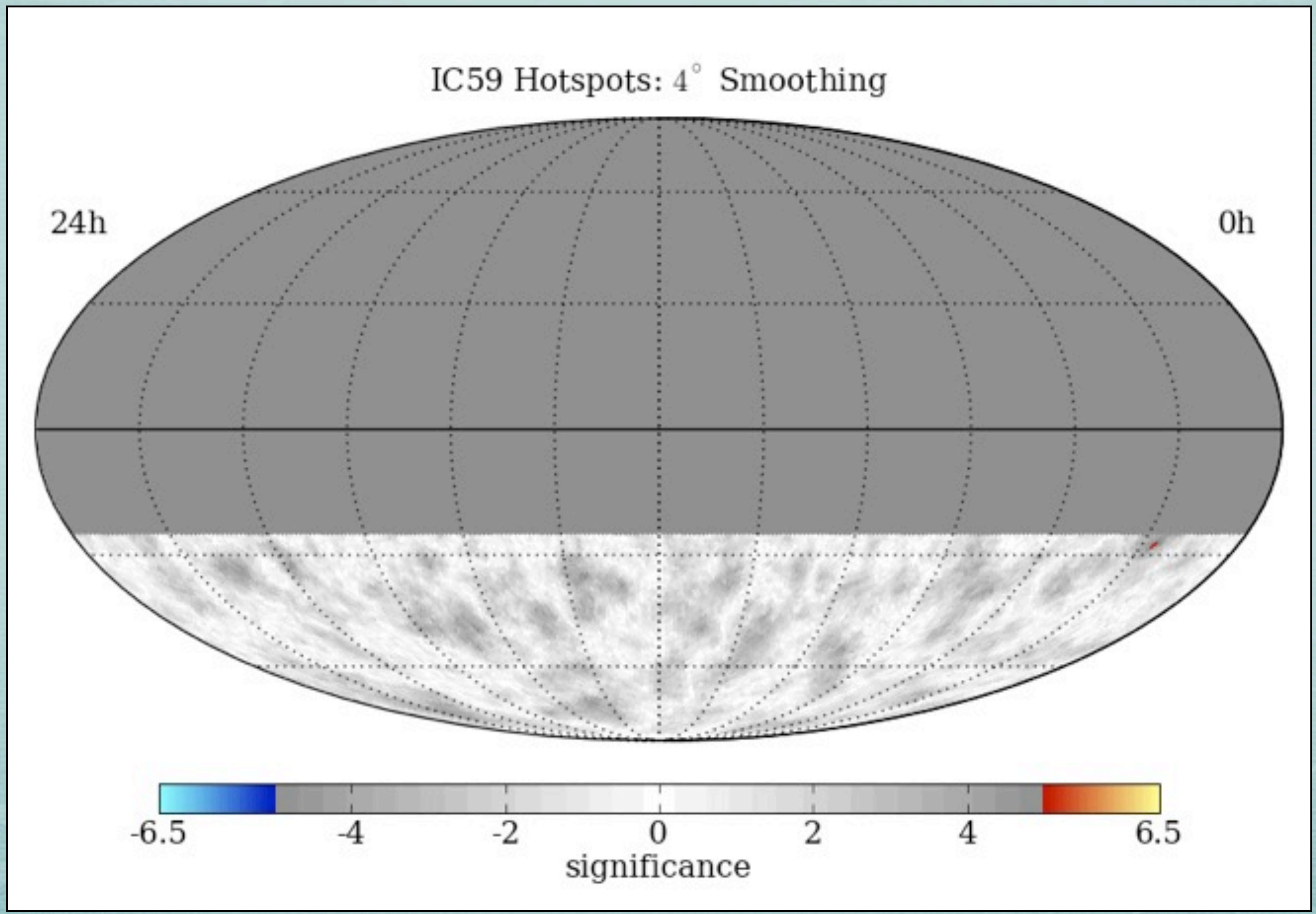

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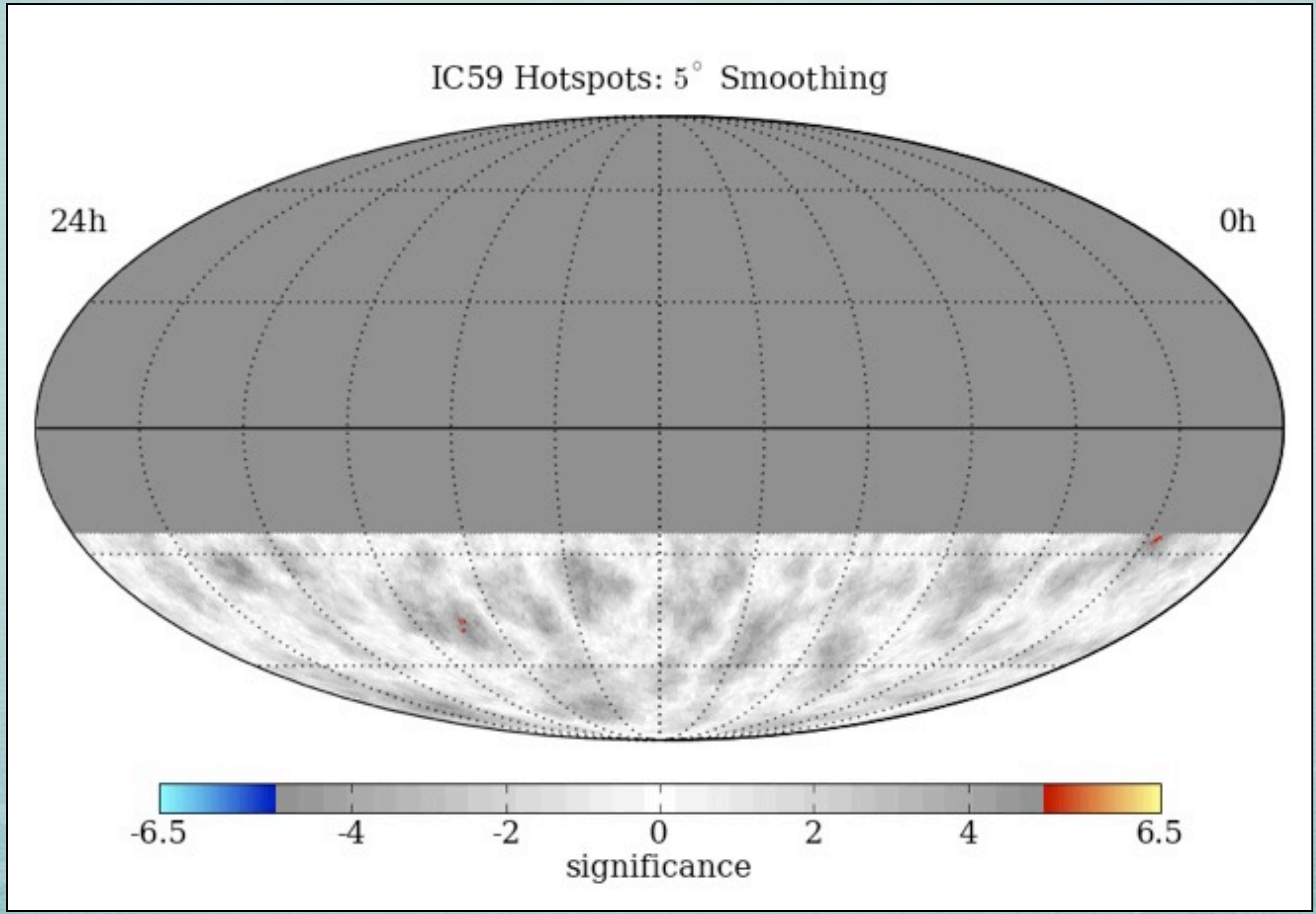

Thursday, May 26, 2011

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Scan from 1 - 30° in smoothing
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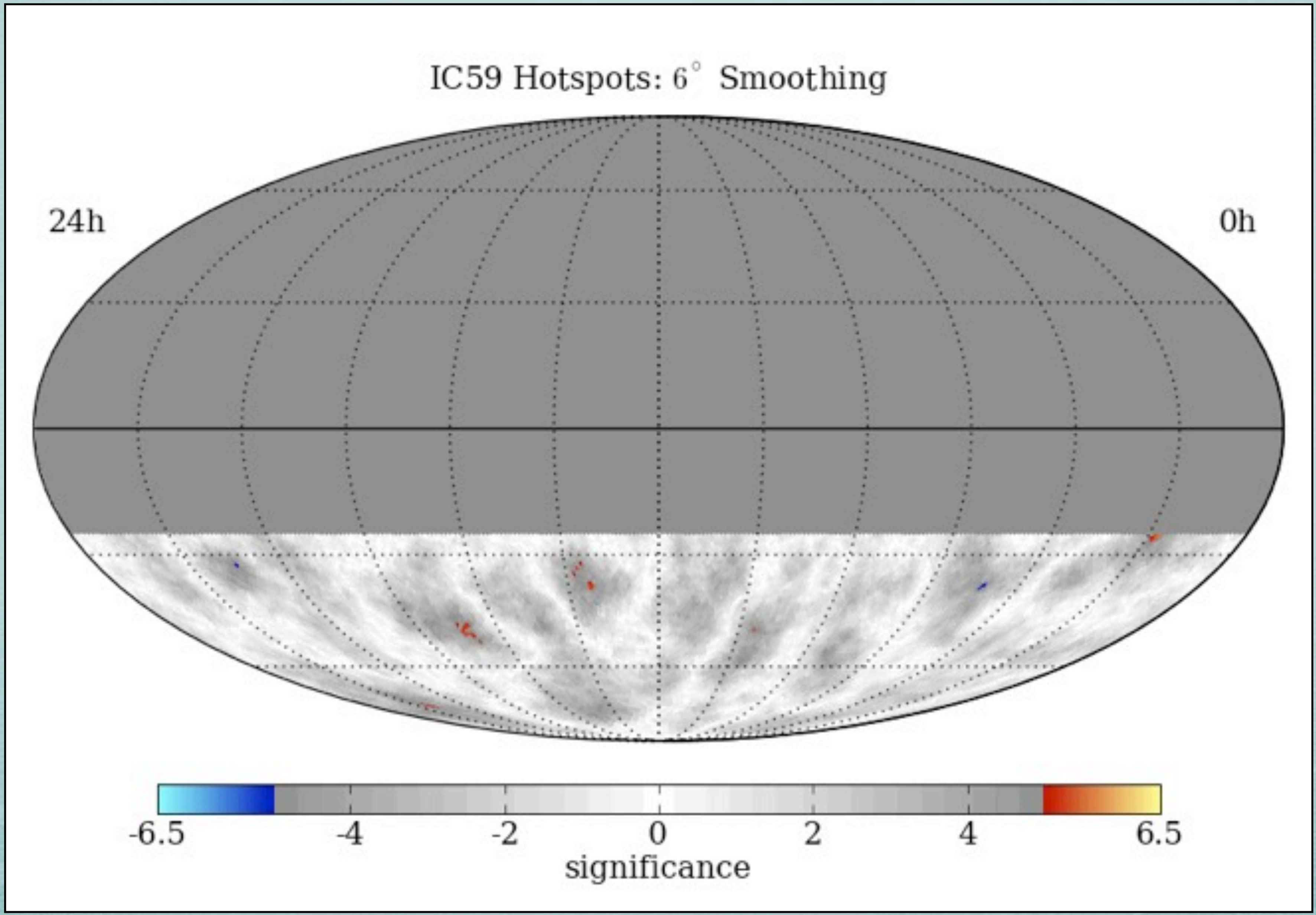

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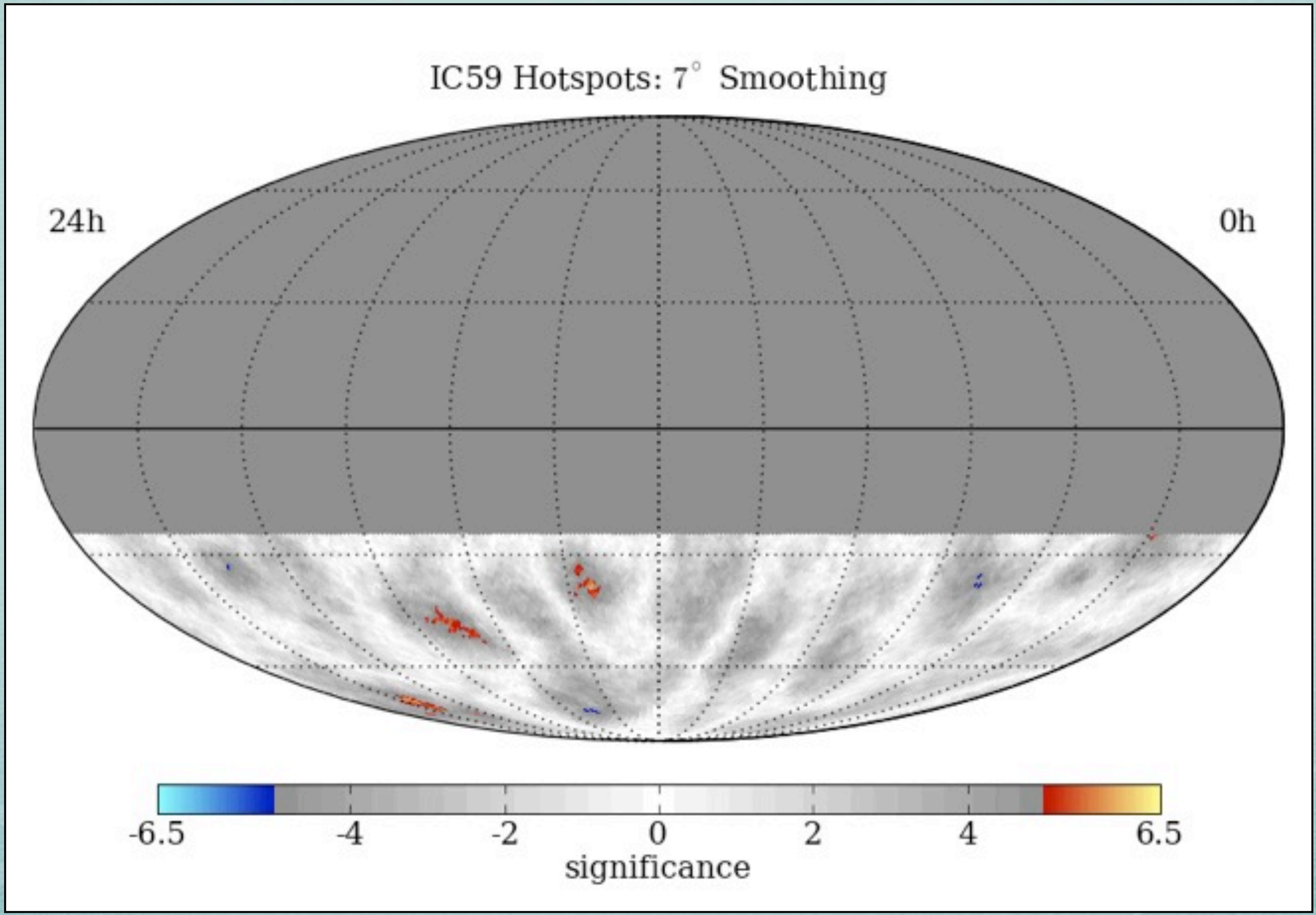

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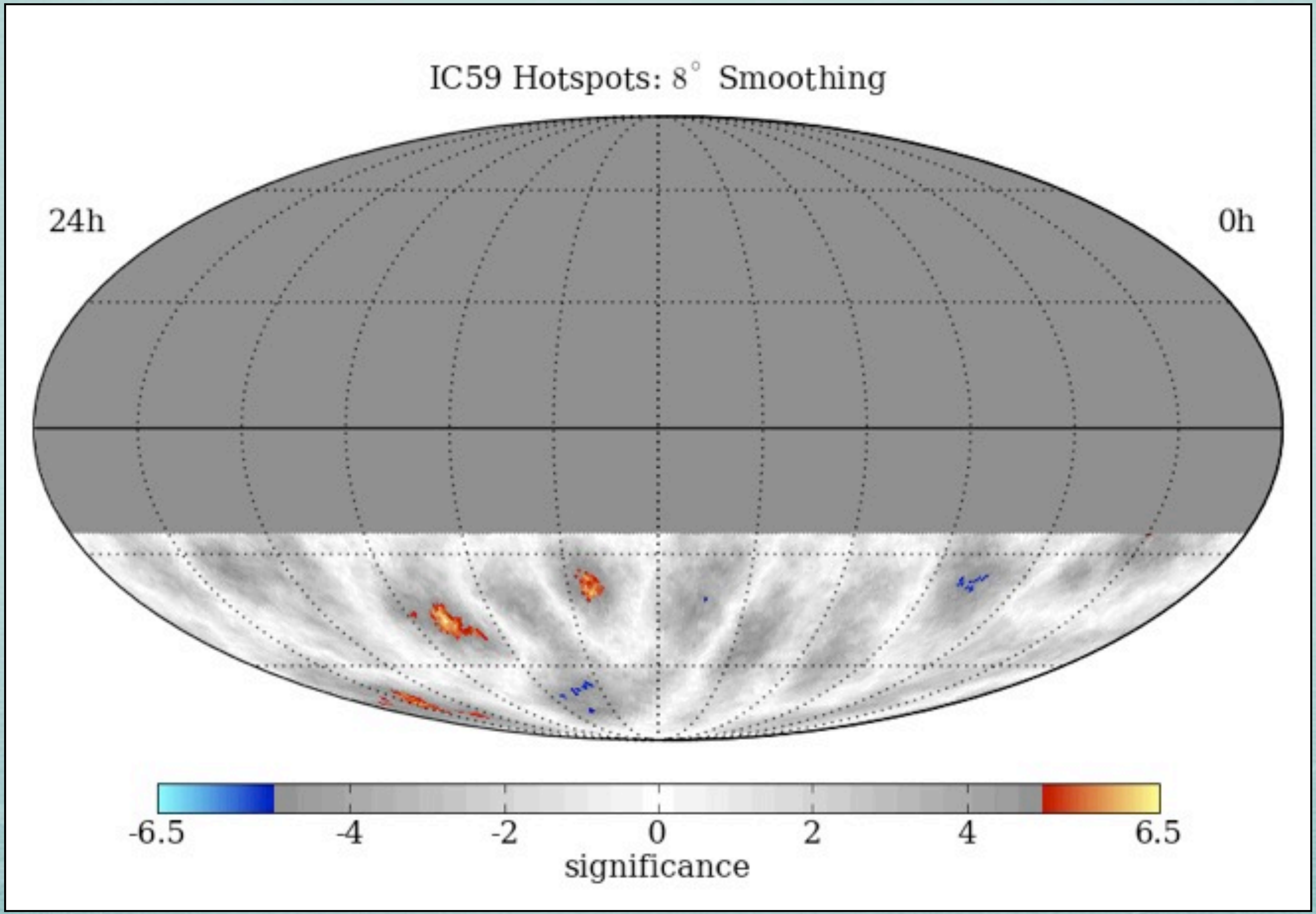

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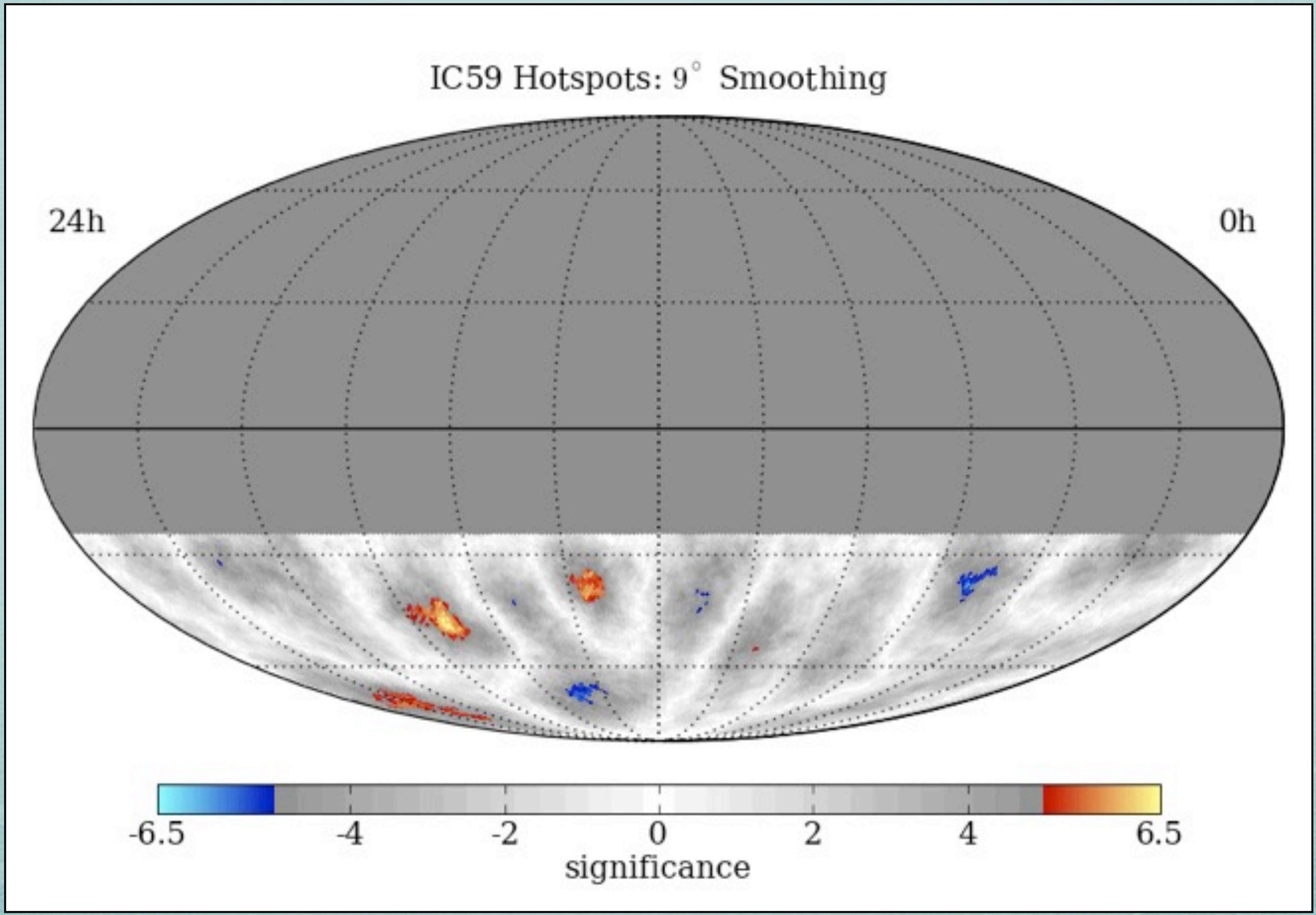

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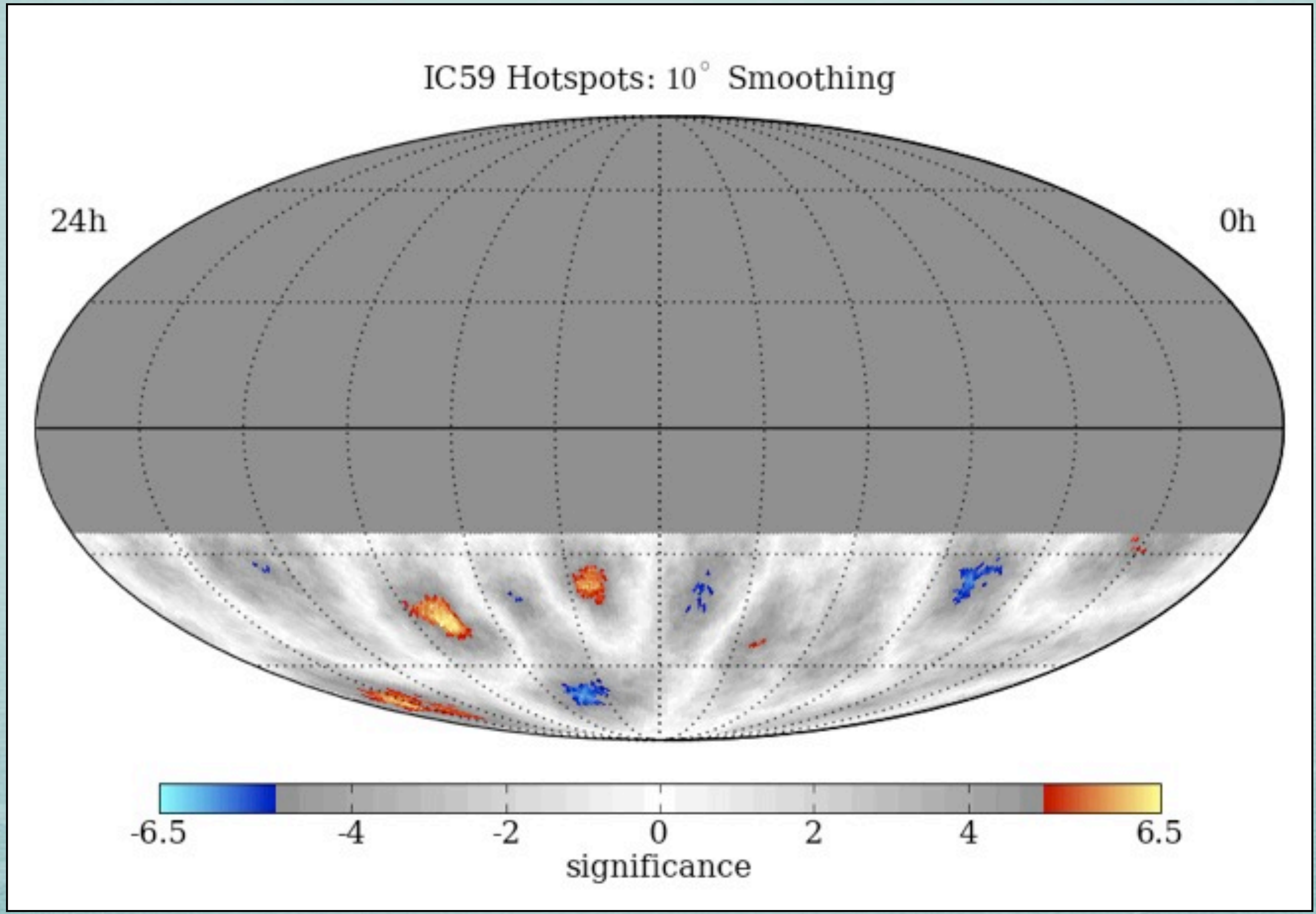

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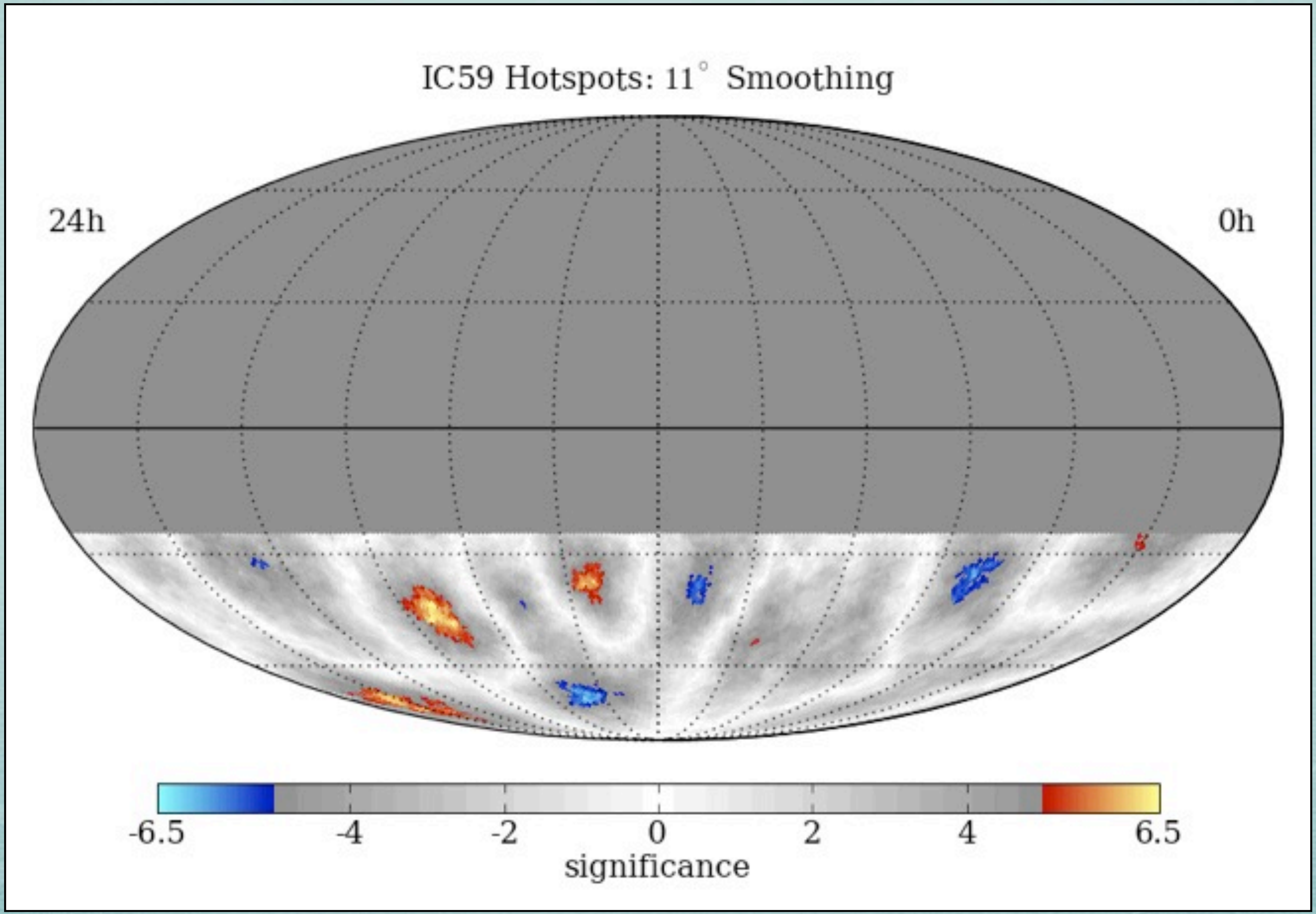

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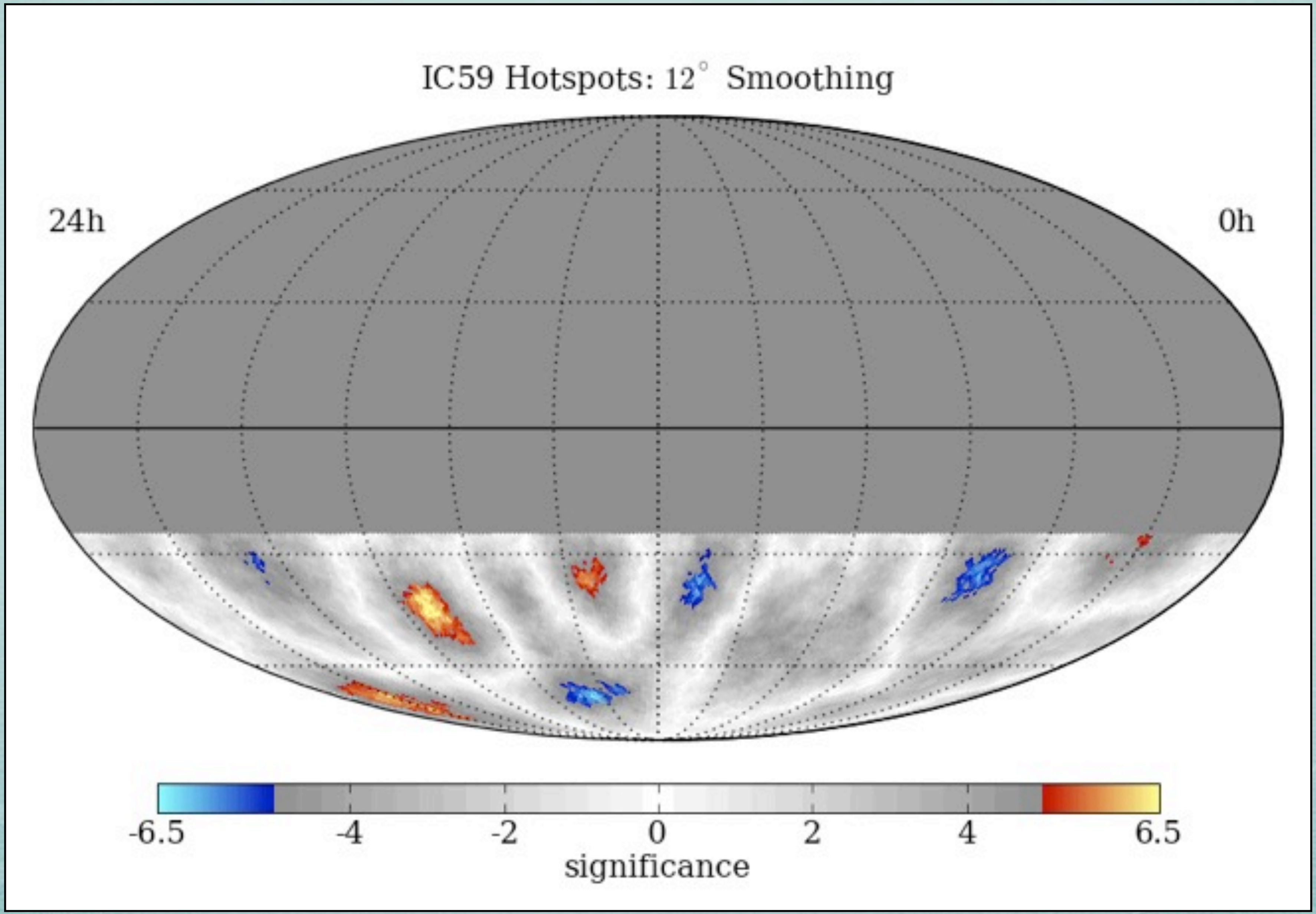

MAP SMOOTHING SCAN

Scan from 1 - 30° in smoothing
Different regions have different optimal angular smoothing
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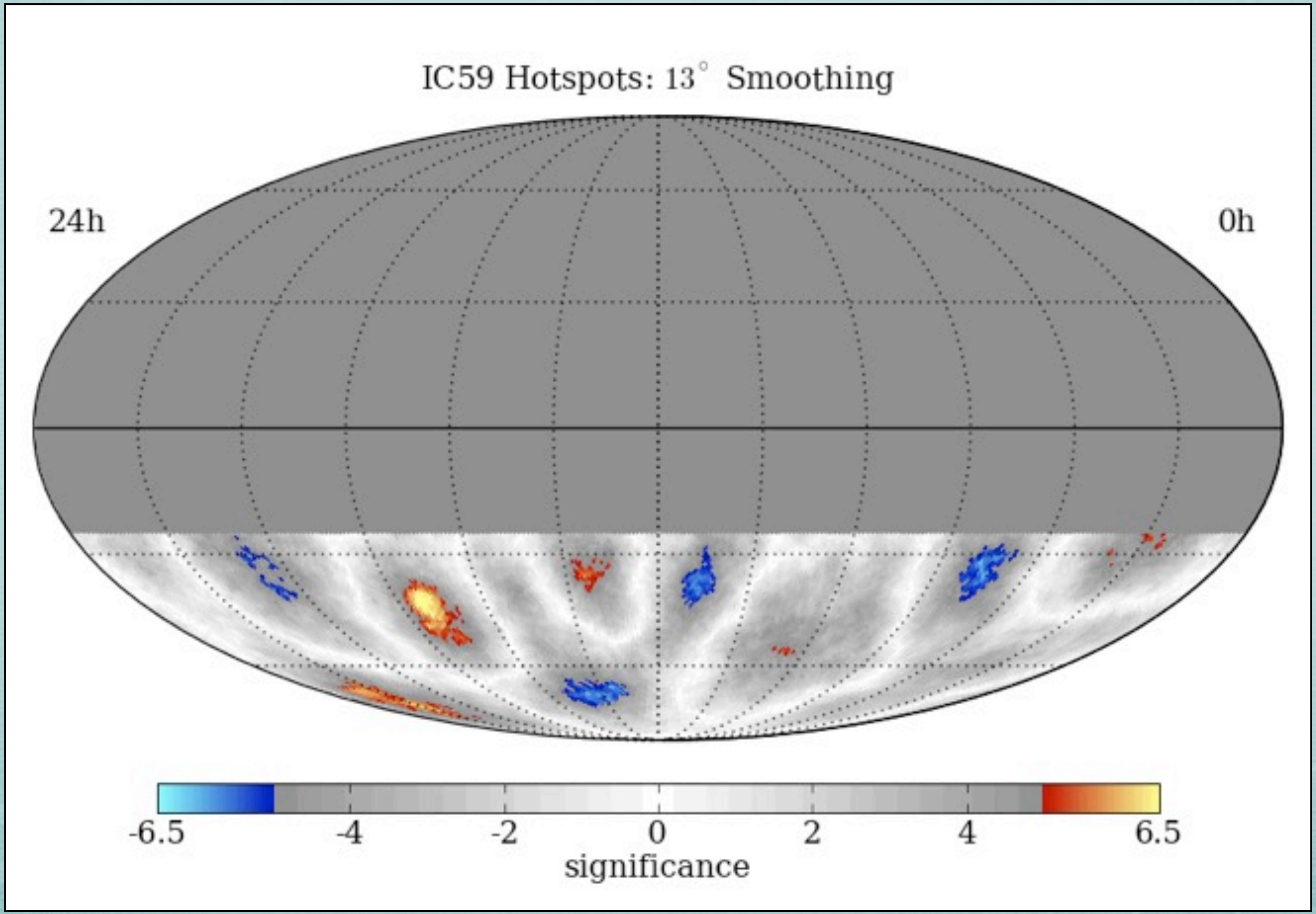

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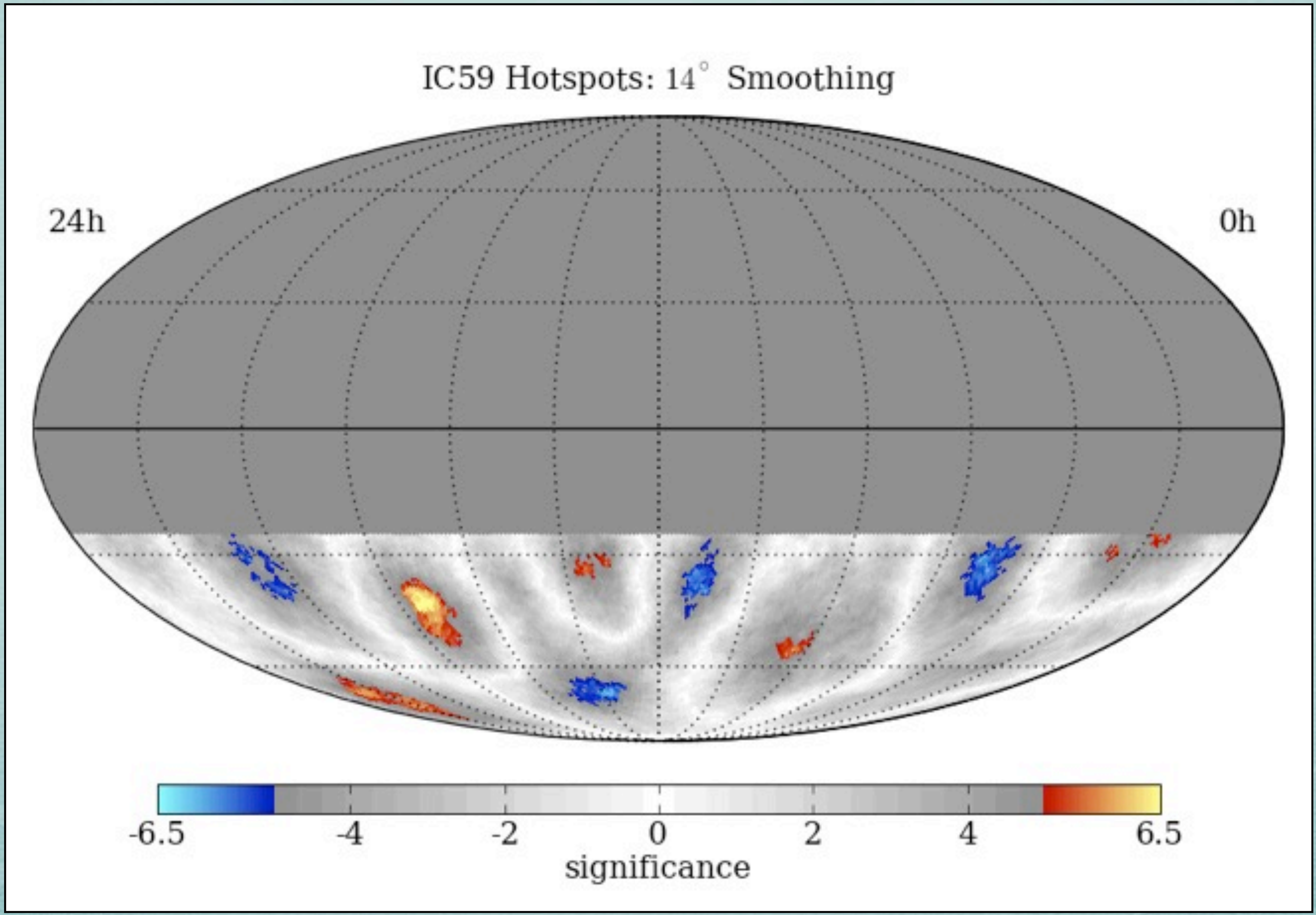

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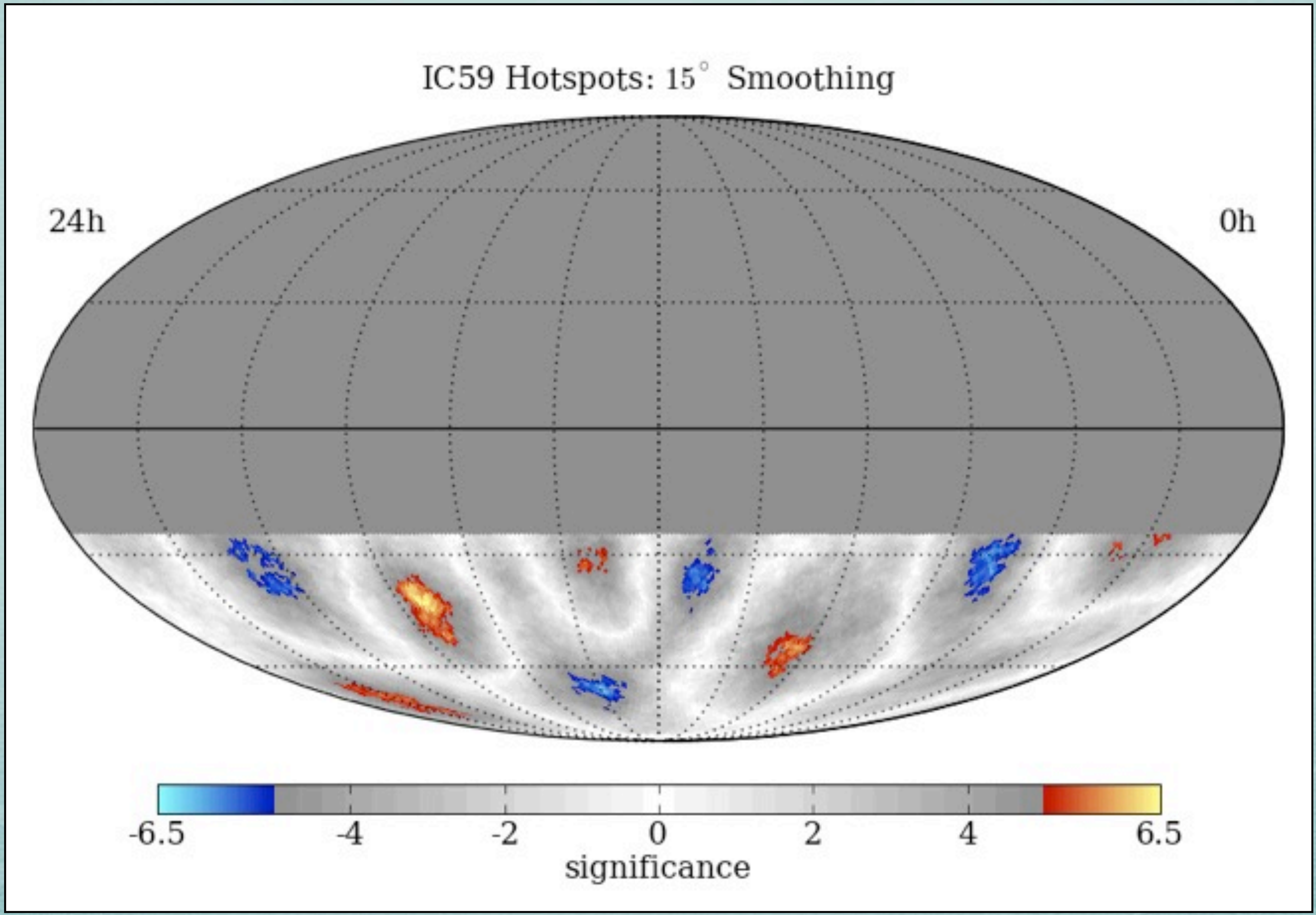

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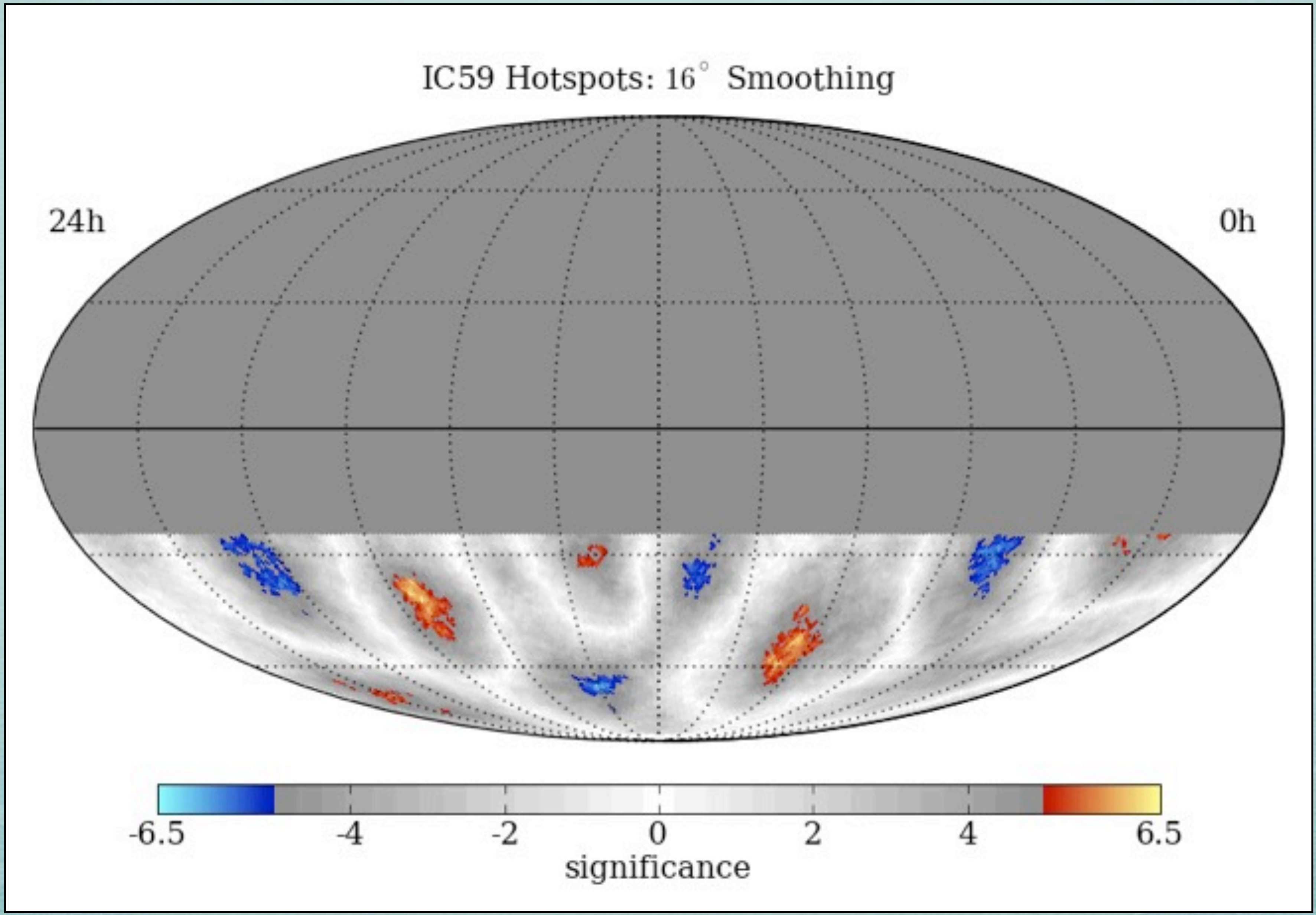

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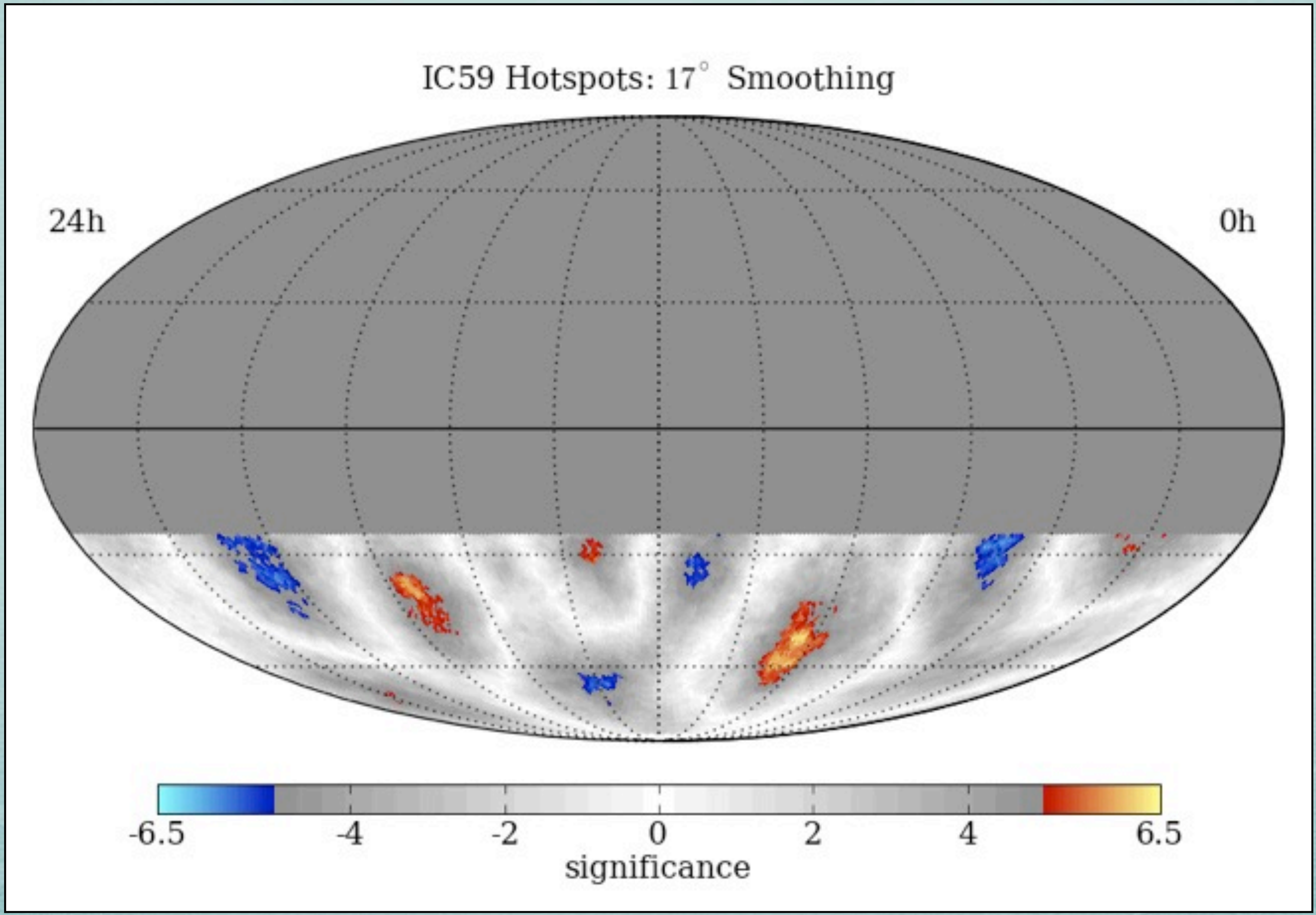

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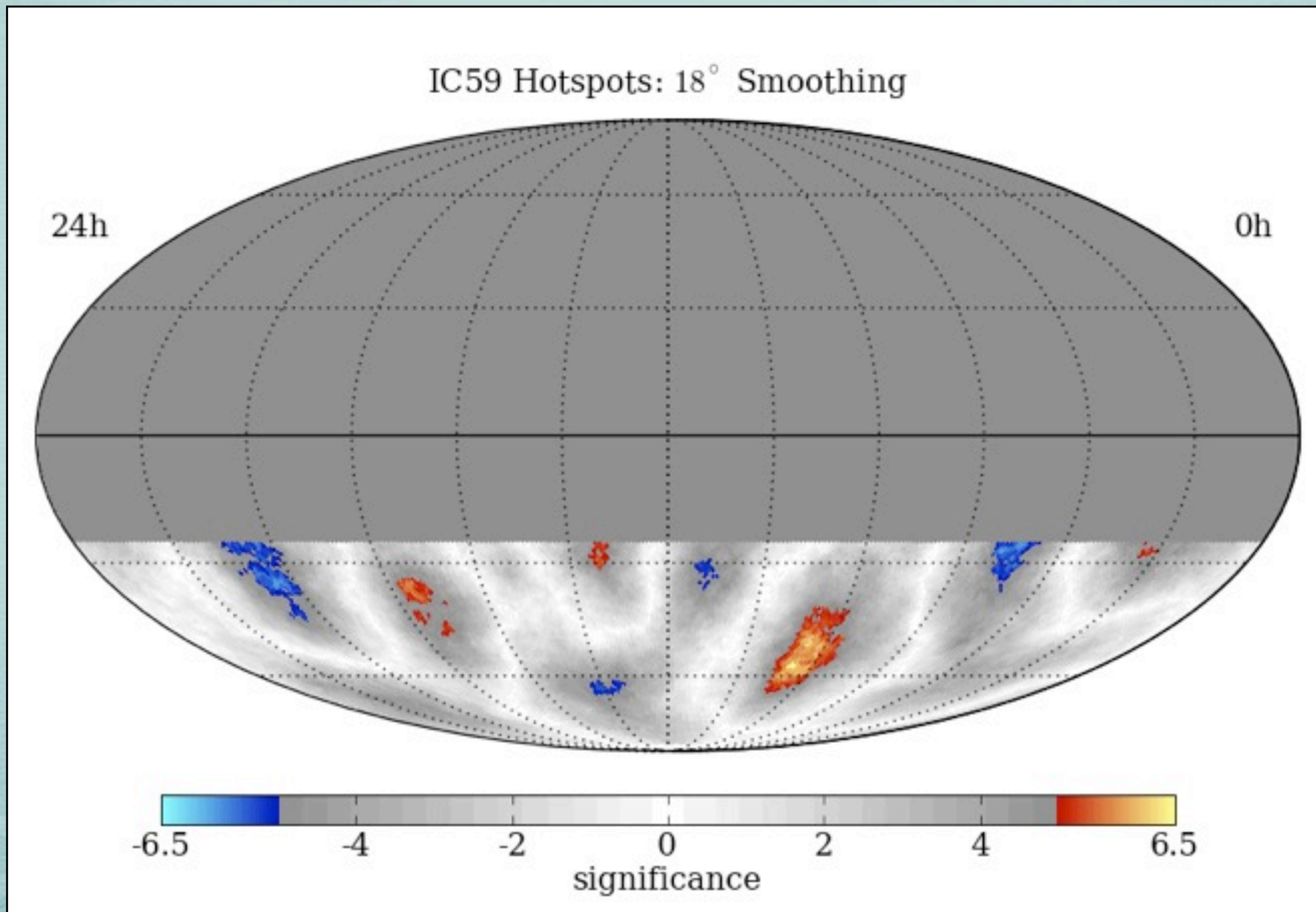

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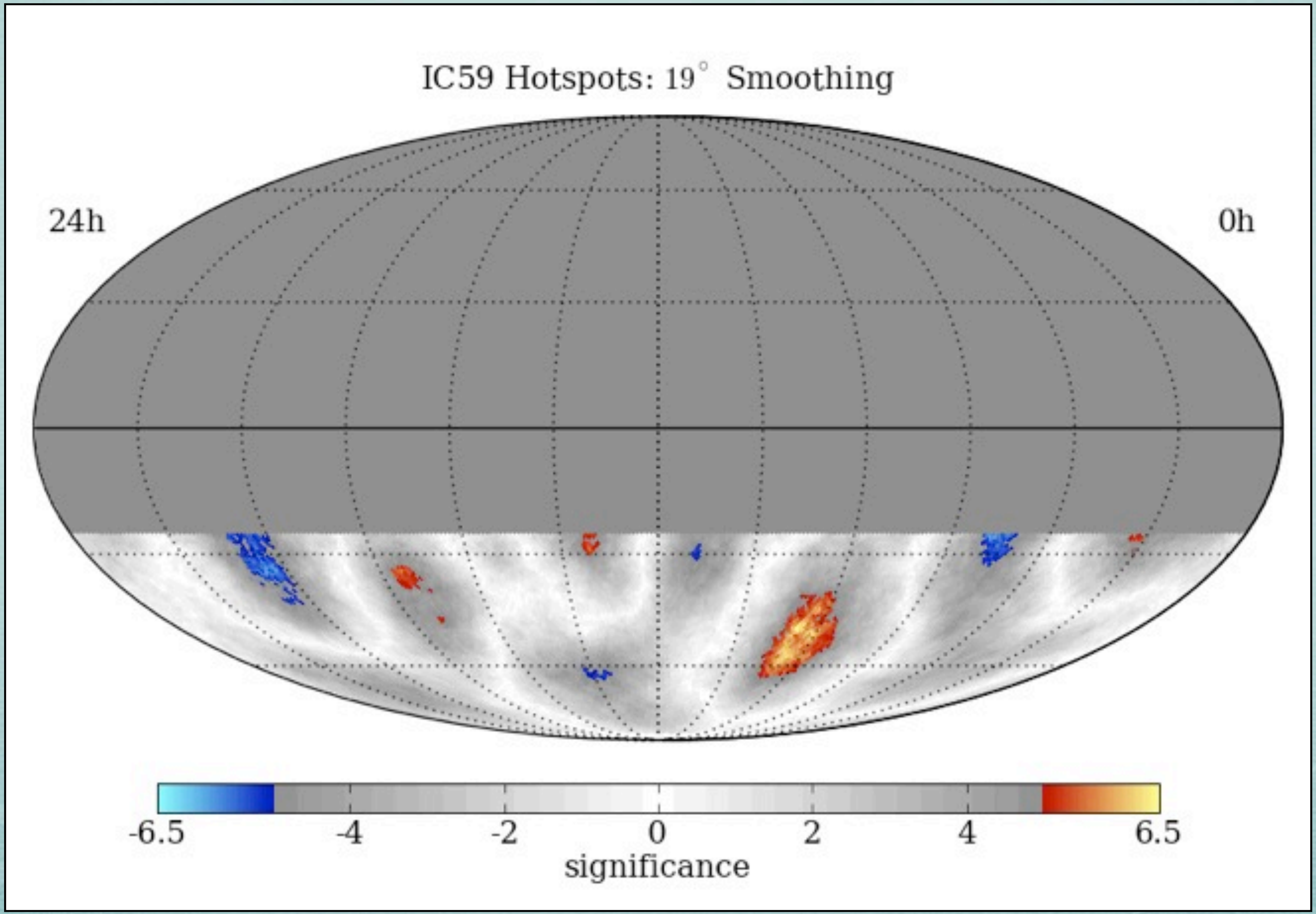

Thursday, May 26, 2011

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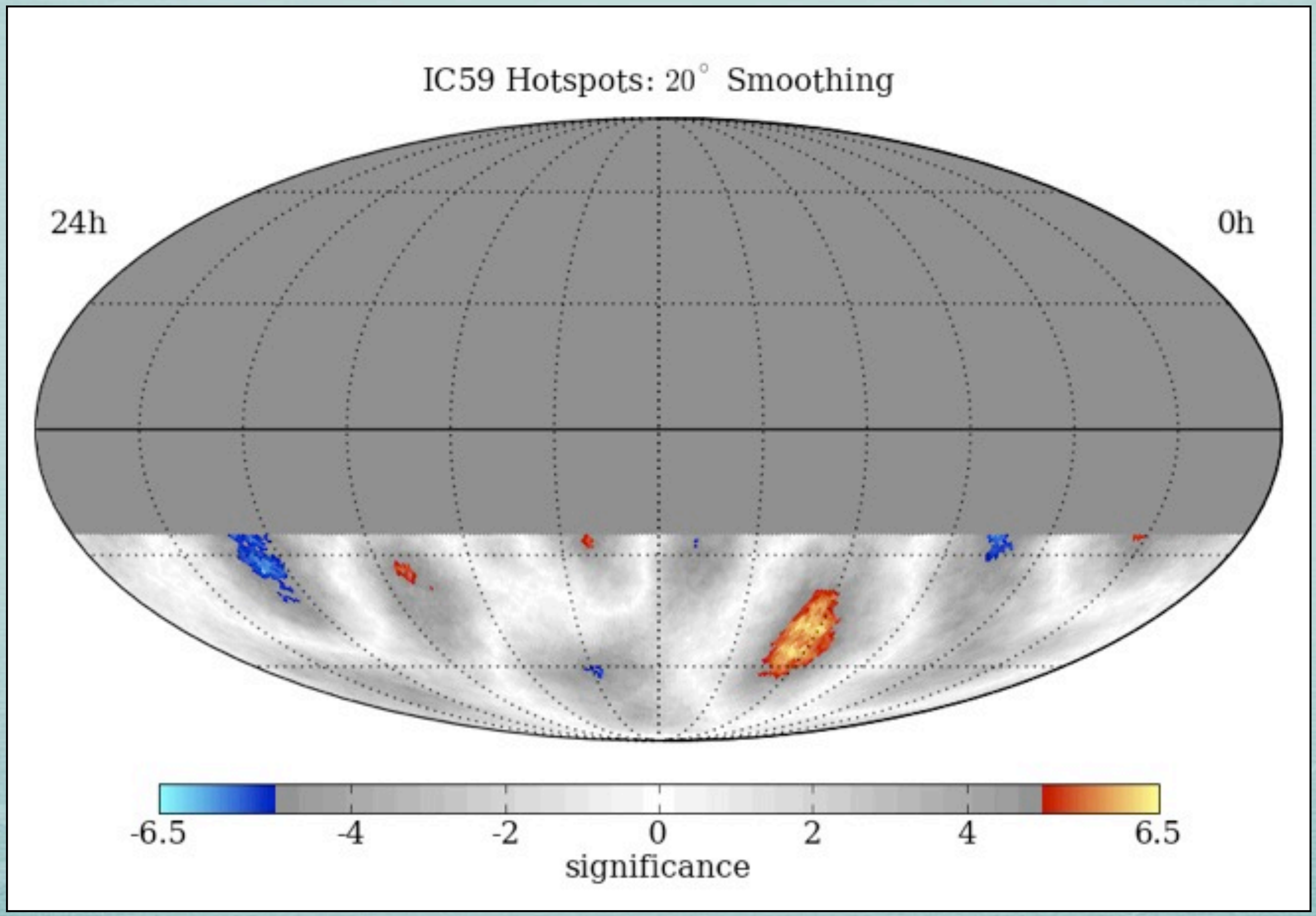

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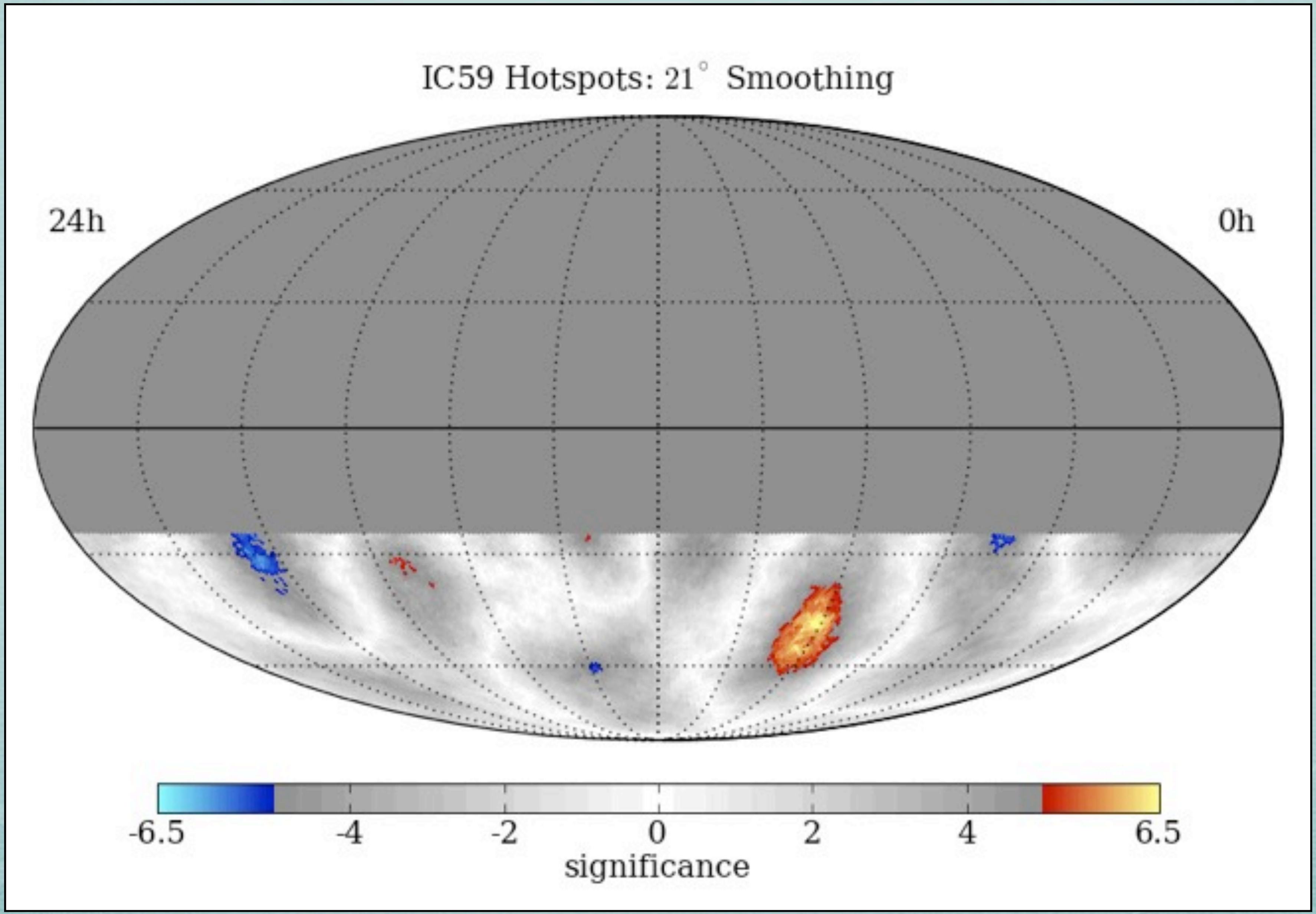

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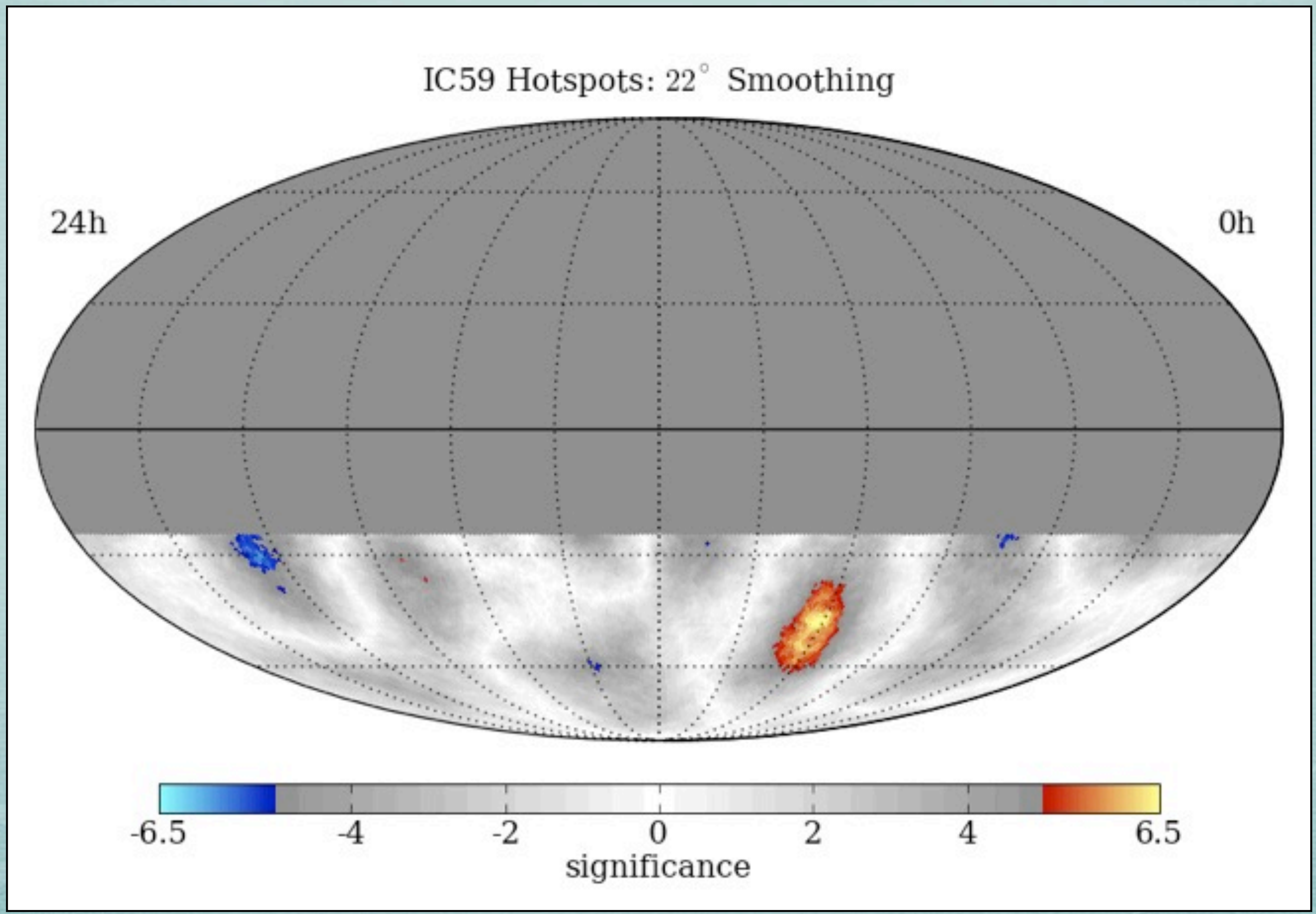

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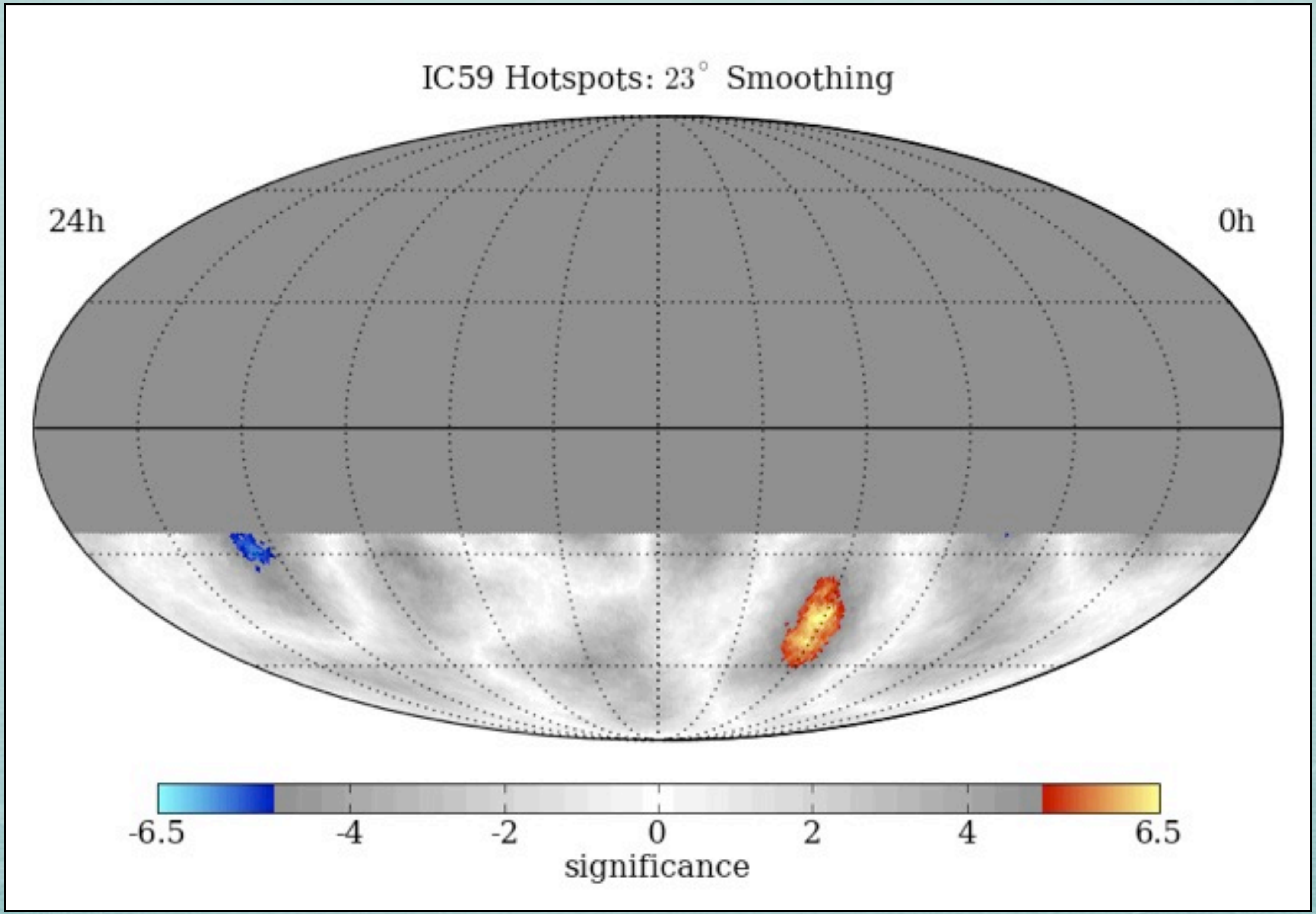

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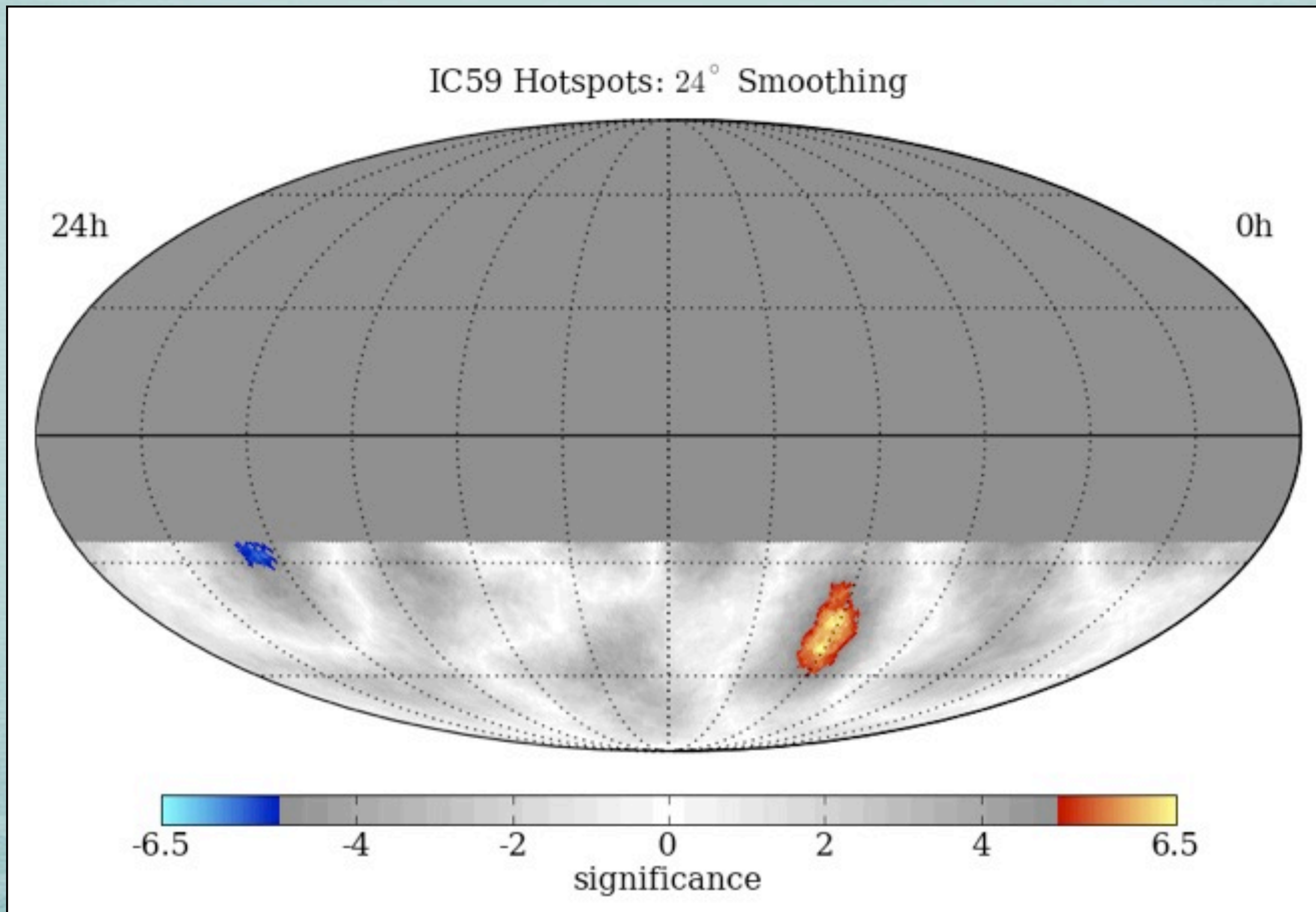

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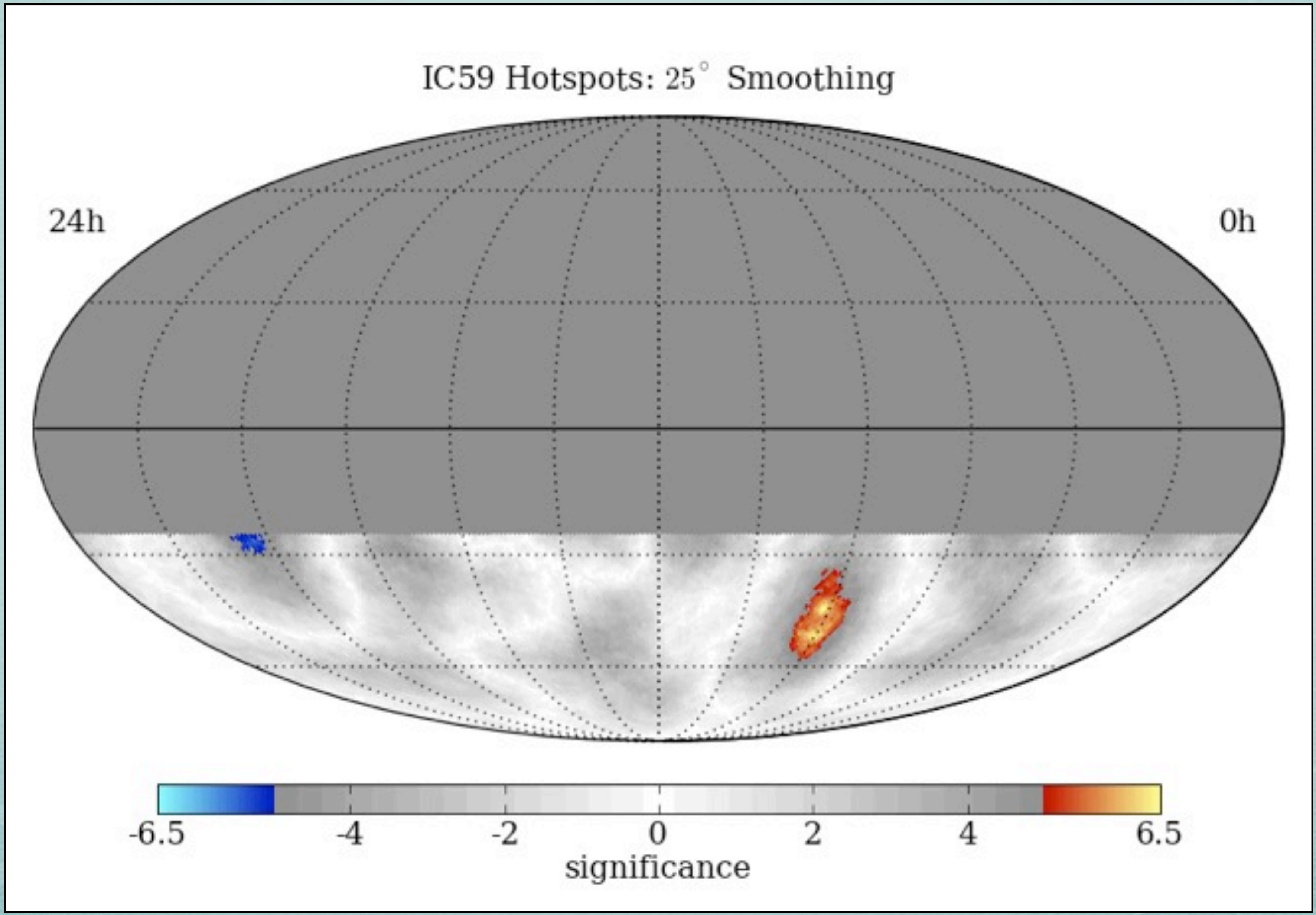

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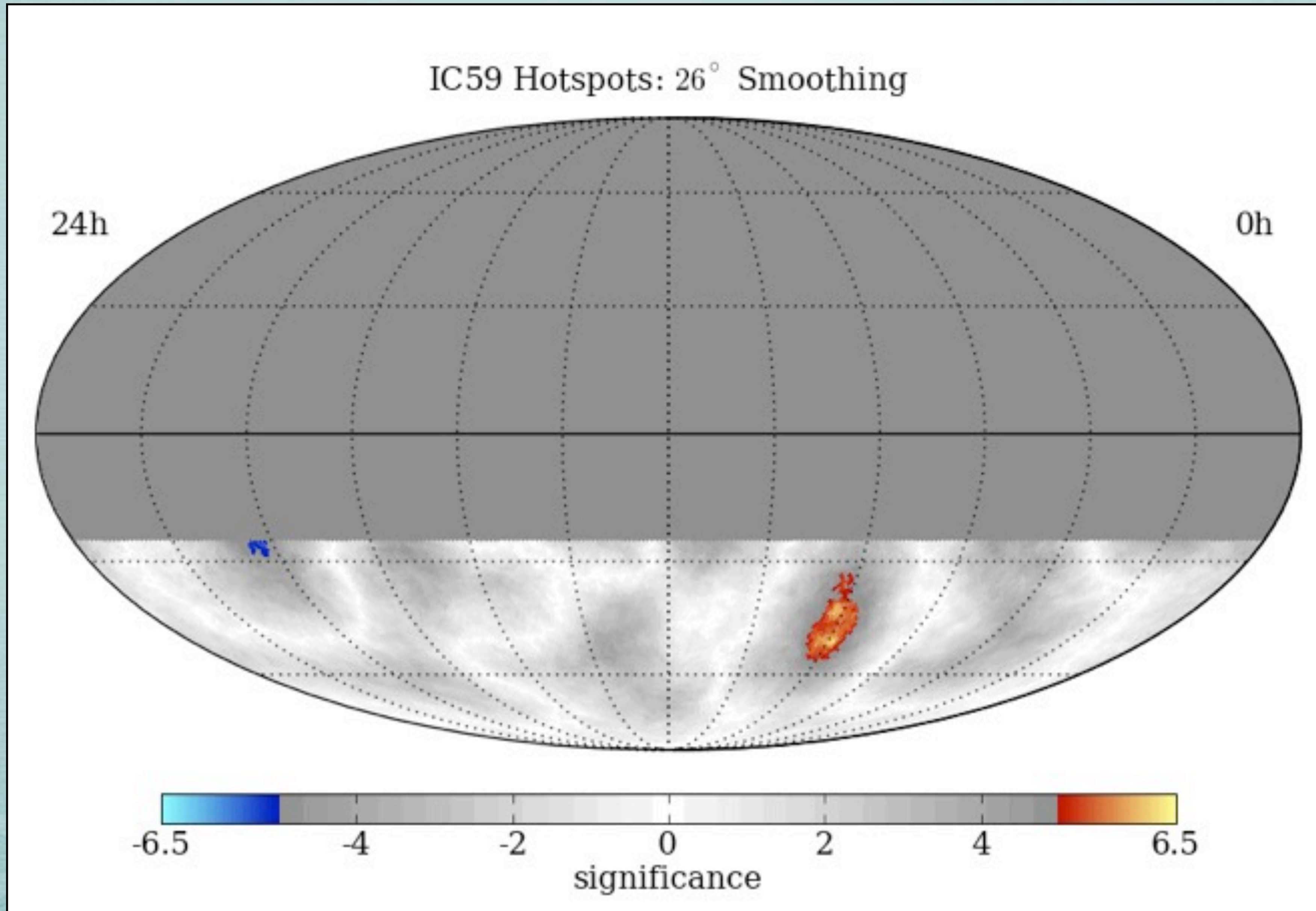

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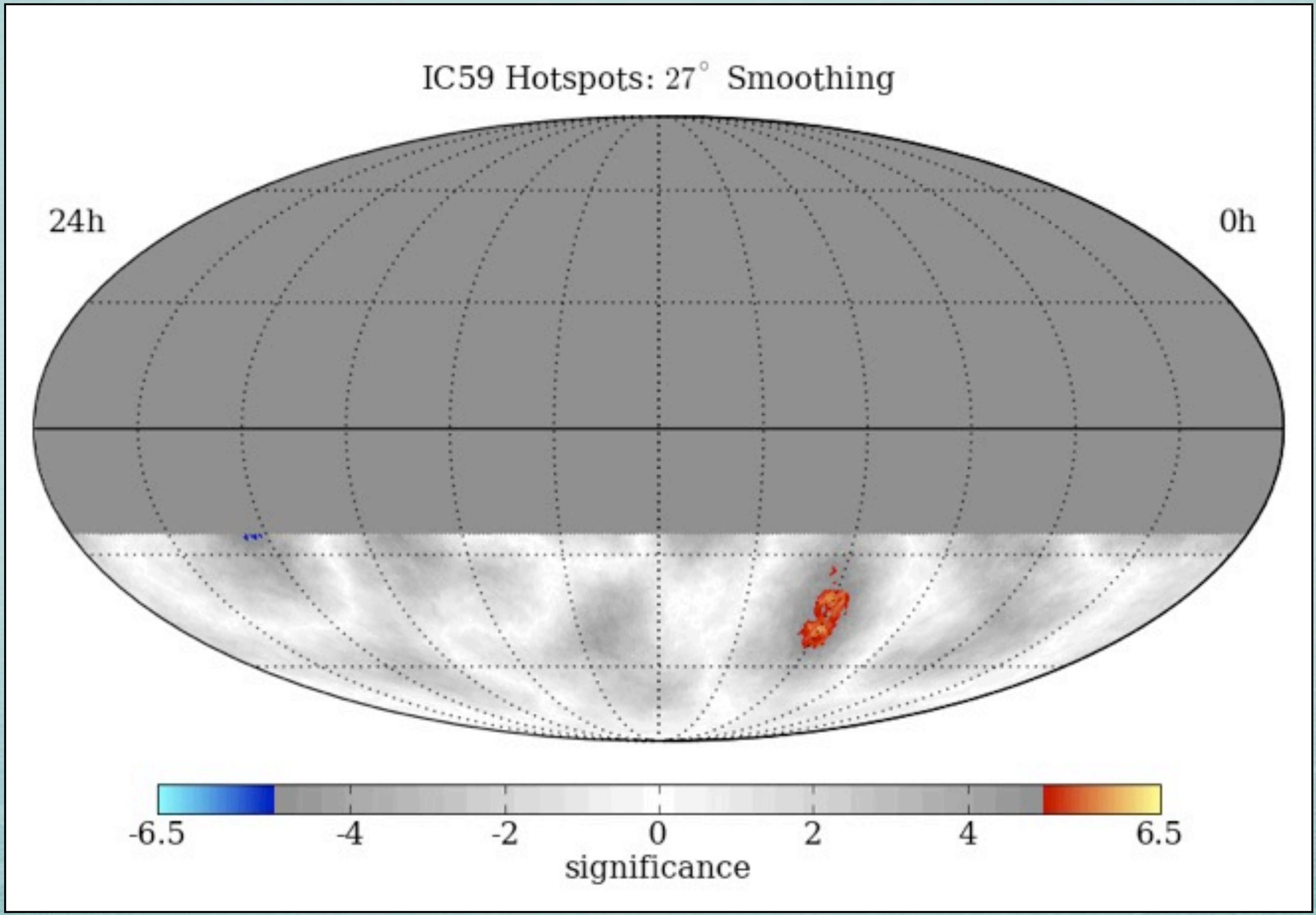

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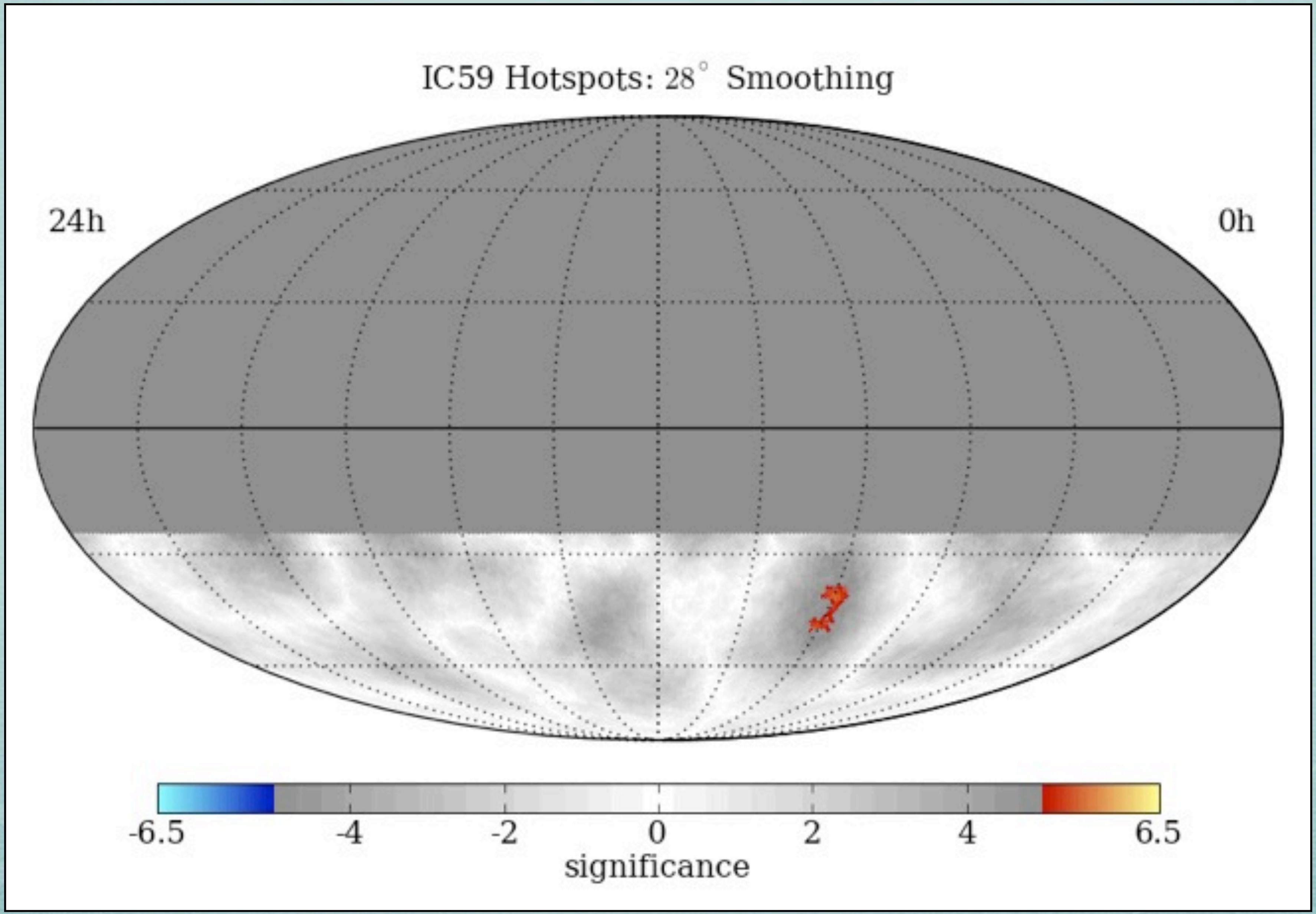

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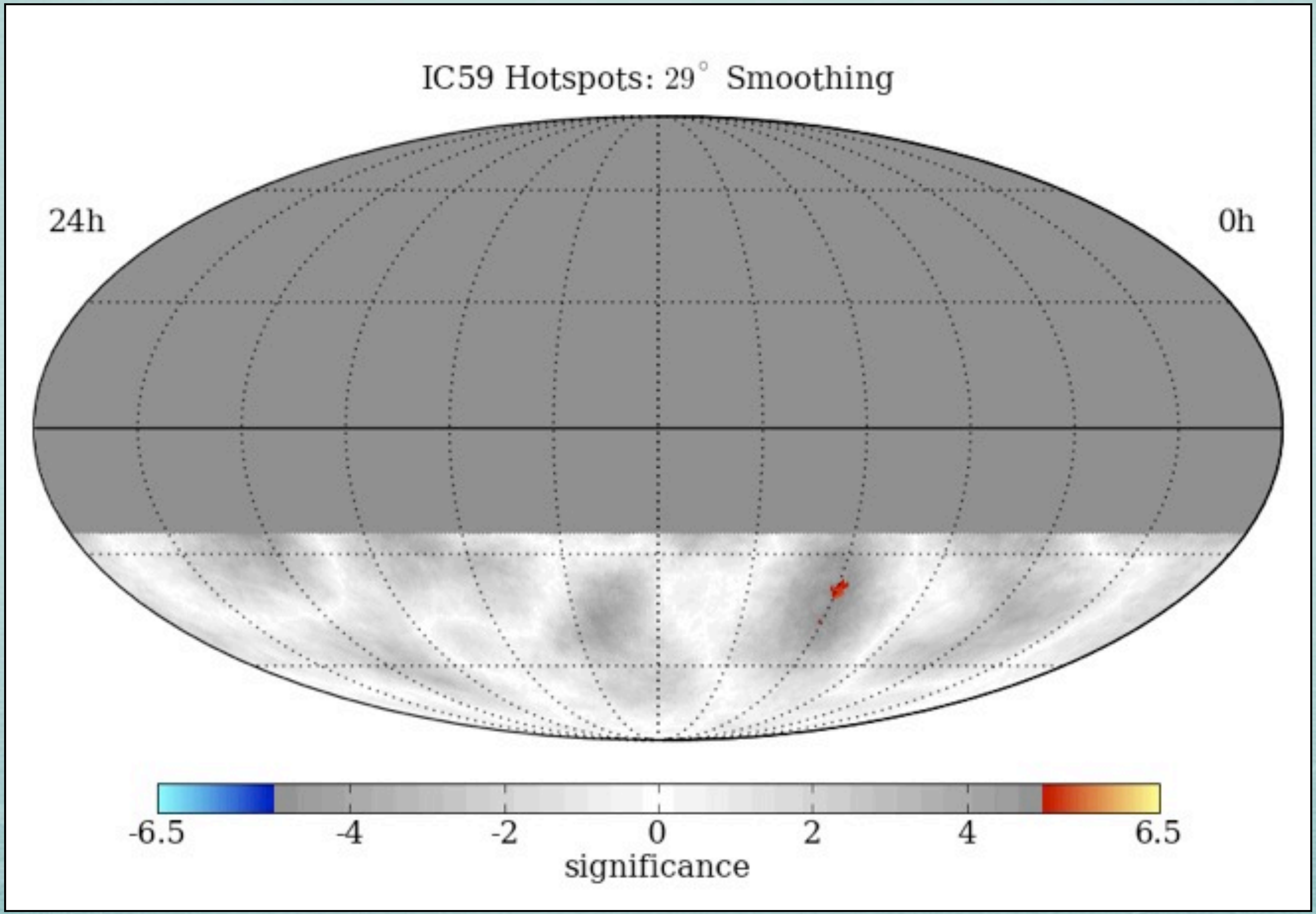

Thursday, May 26, 2011

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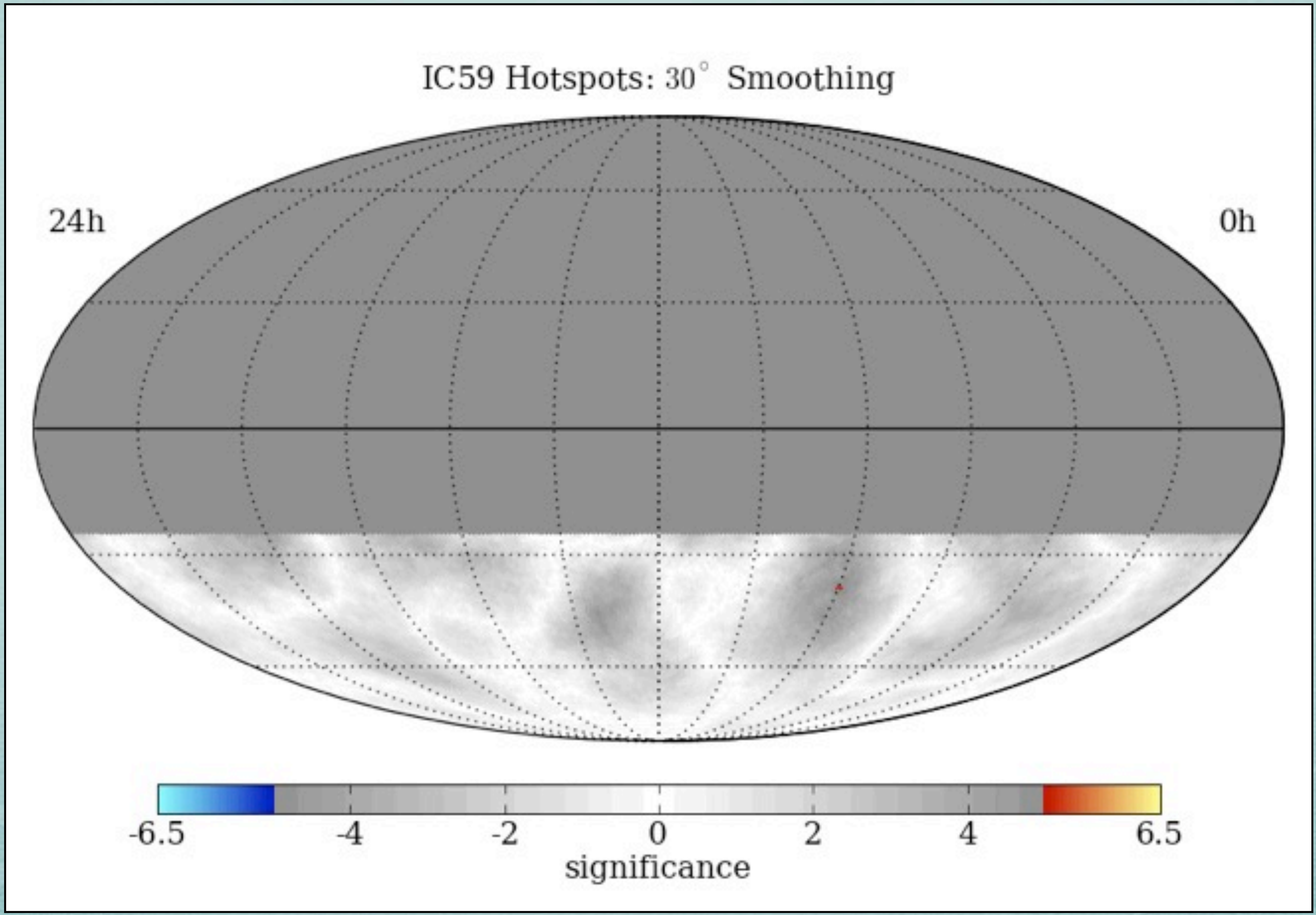
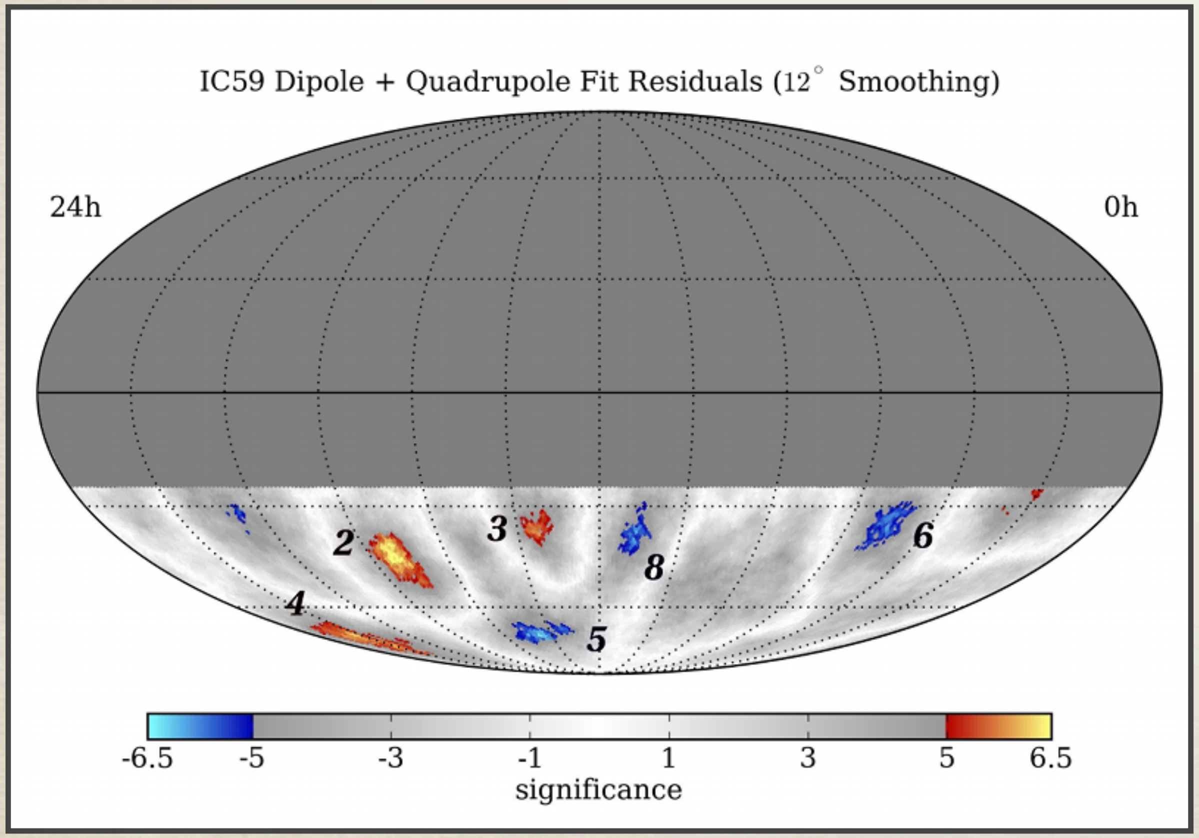
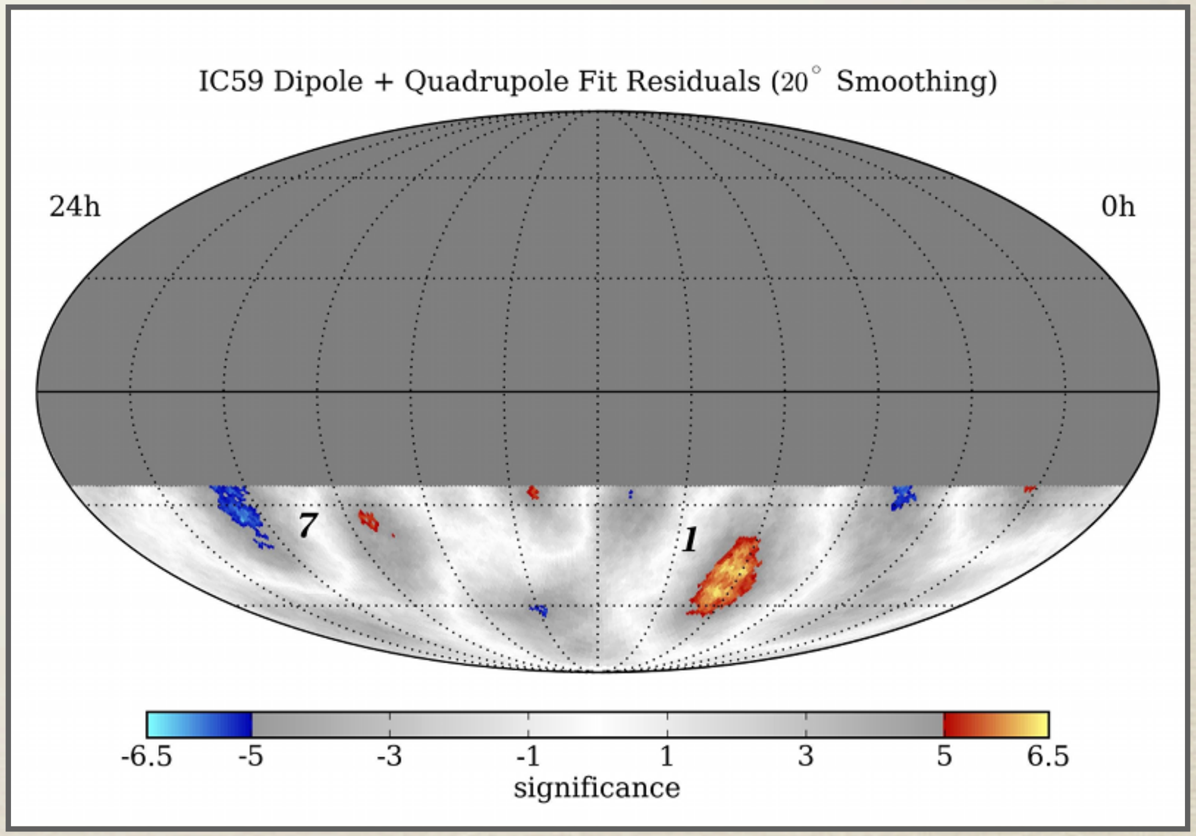


Identification of significant structures

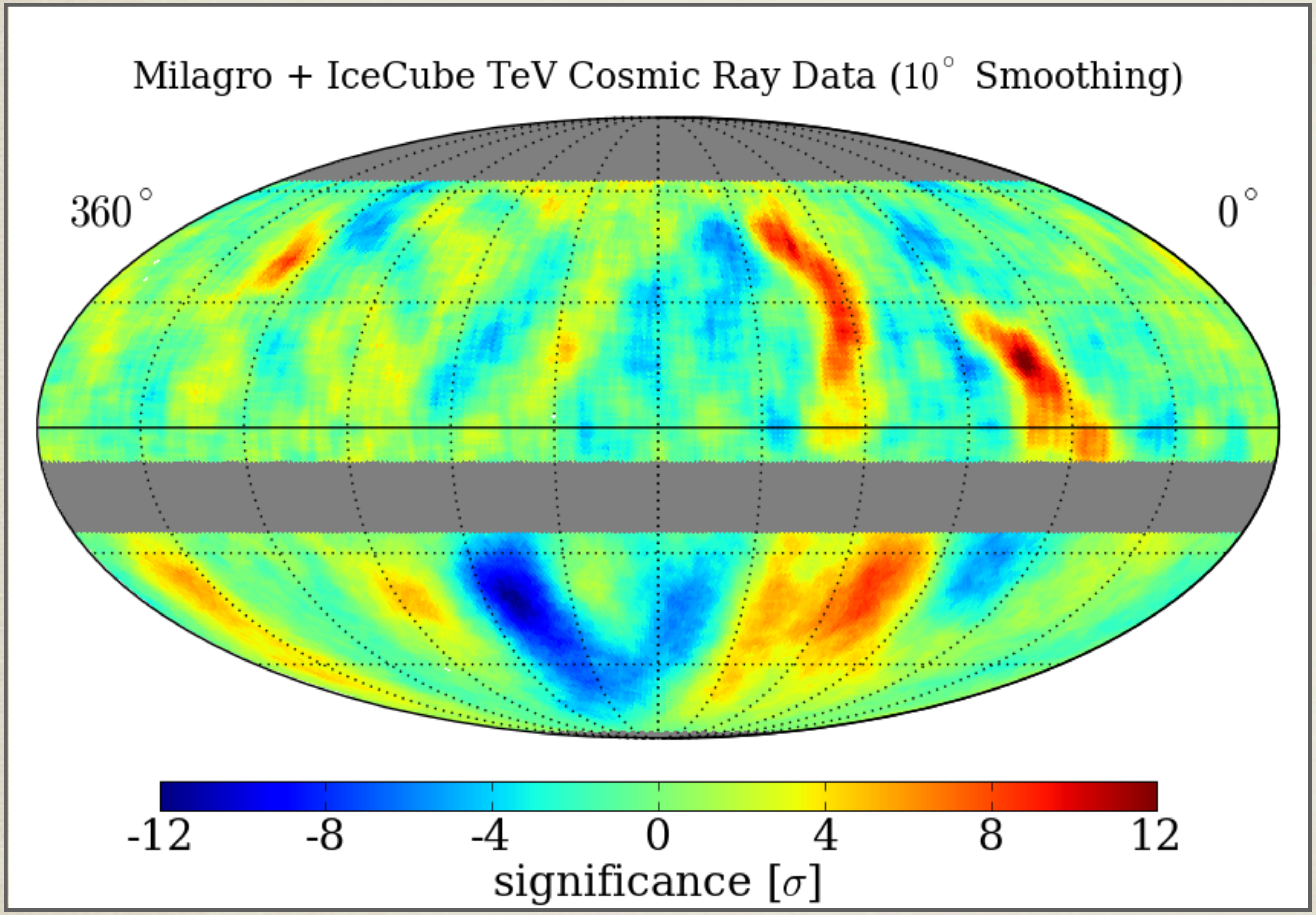
region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ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



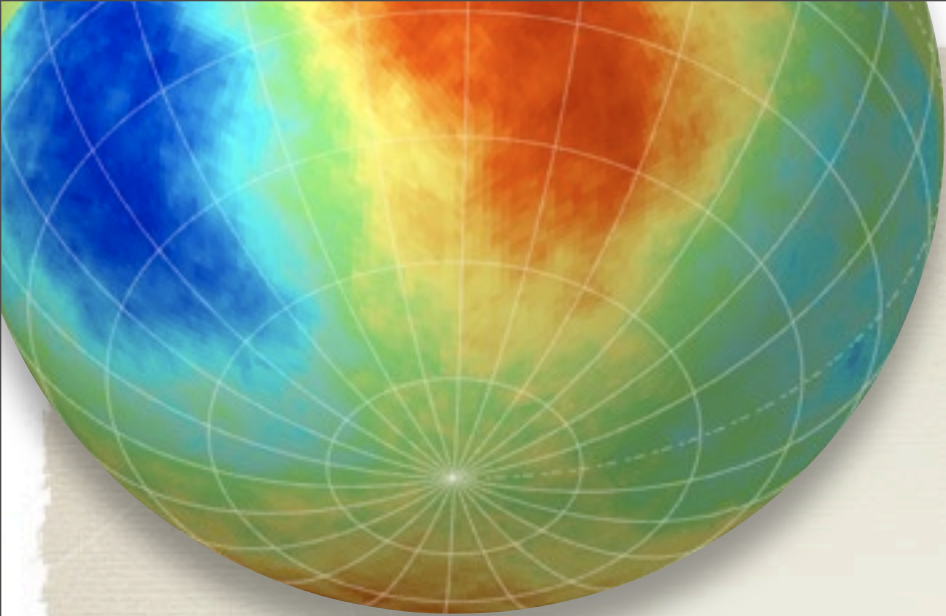
Milagro map:

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

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

IceCube map:

- **5.6×10^{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.**

BACKUP SLIDES

MAP SMOOTHING SCAN

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

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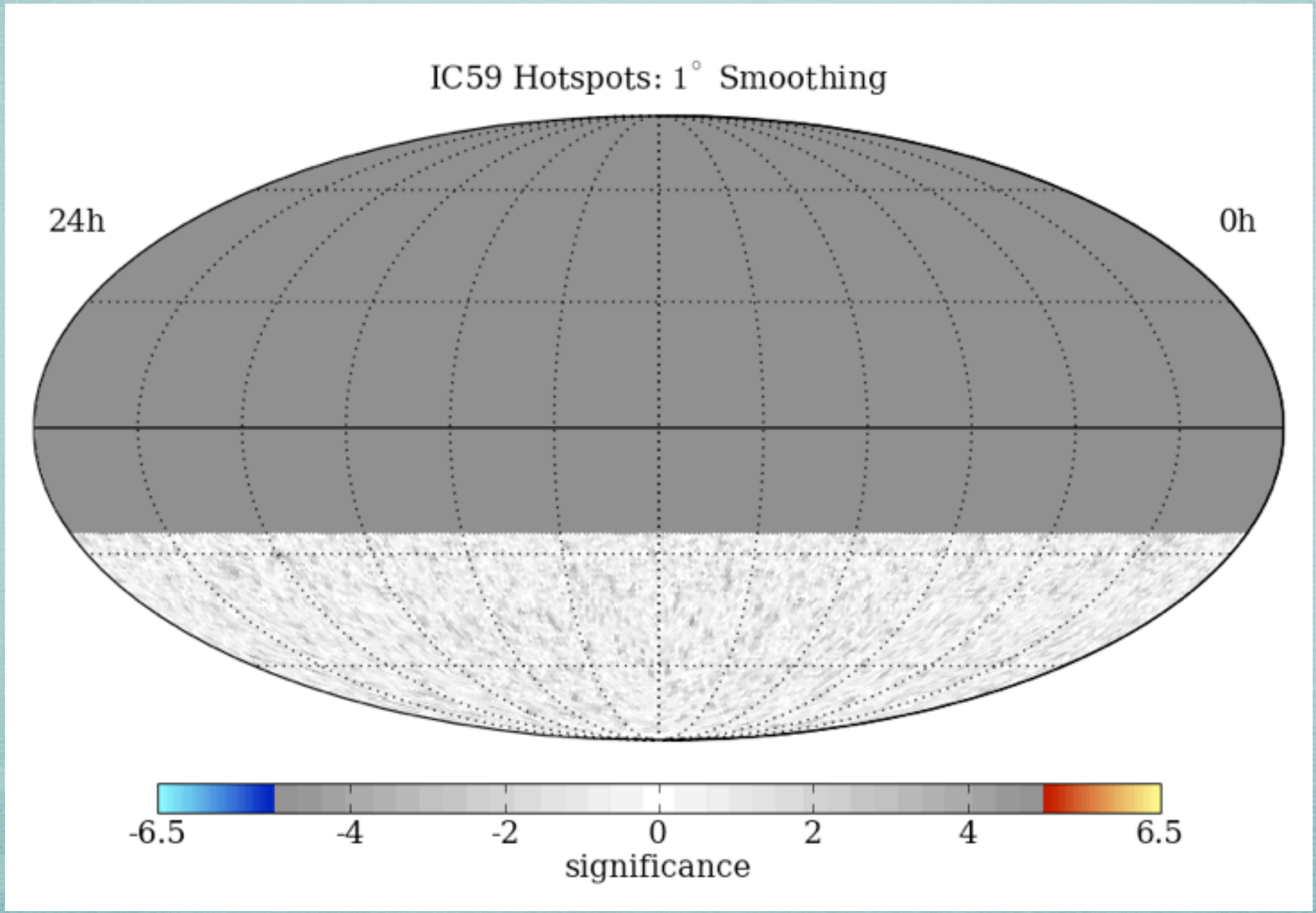
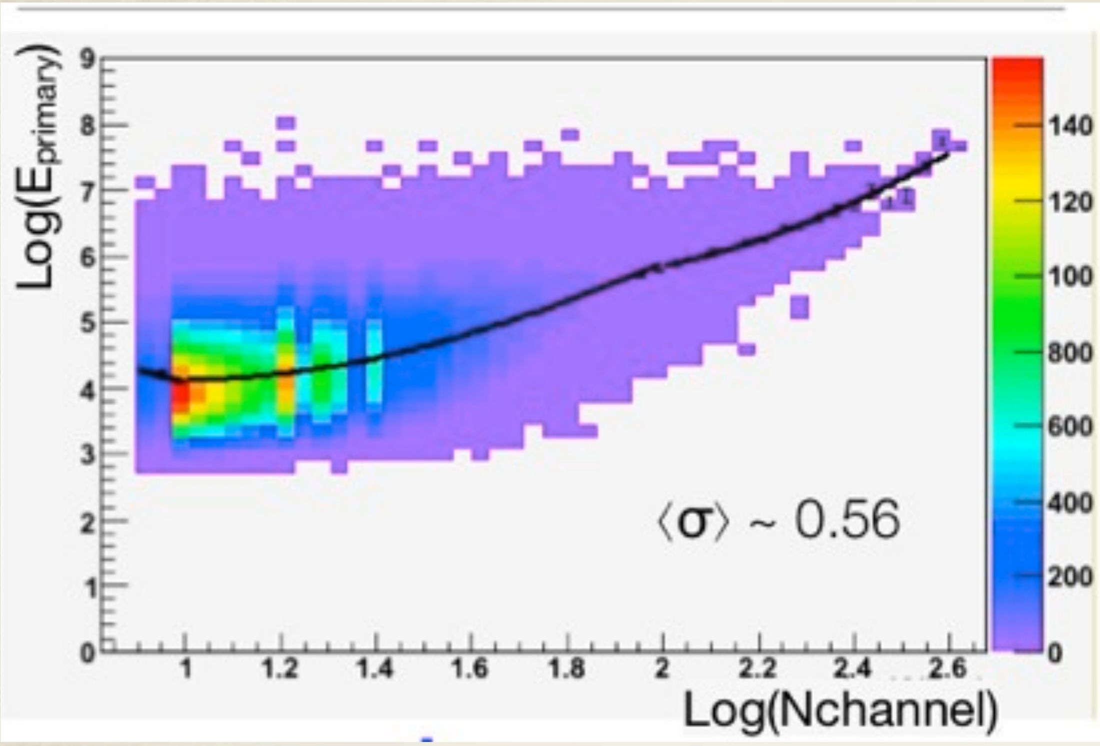
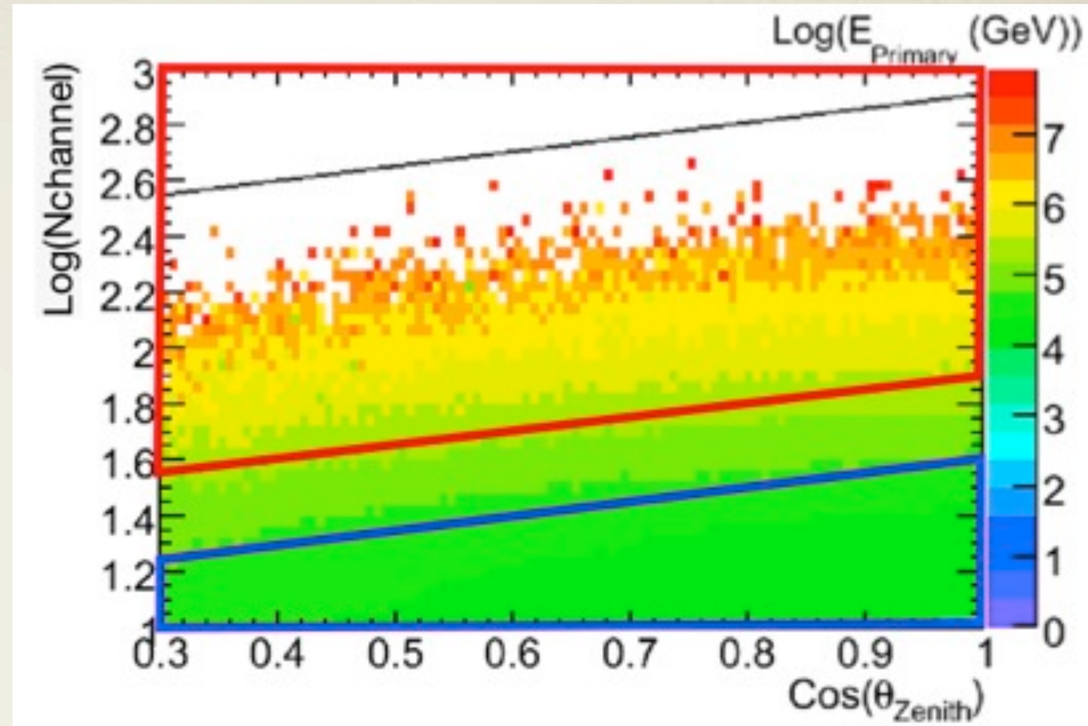
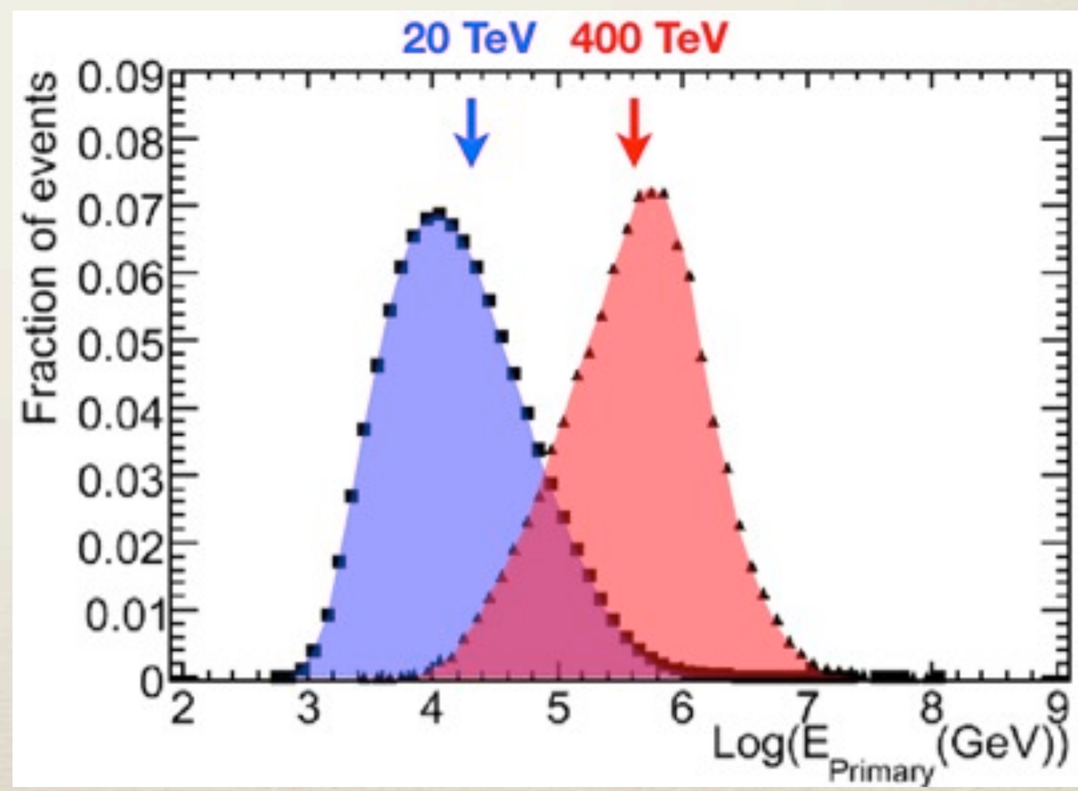


Energy estimation

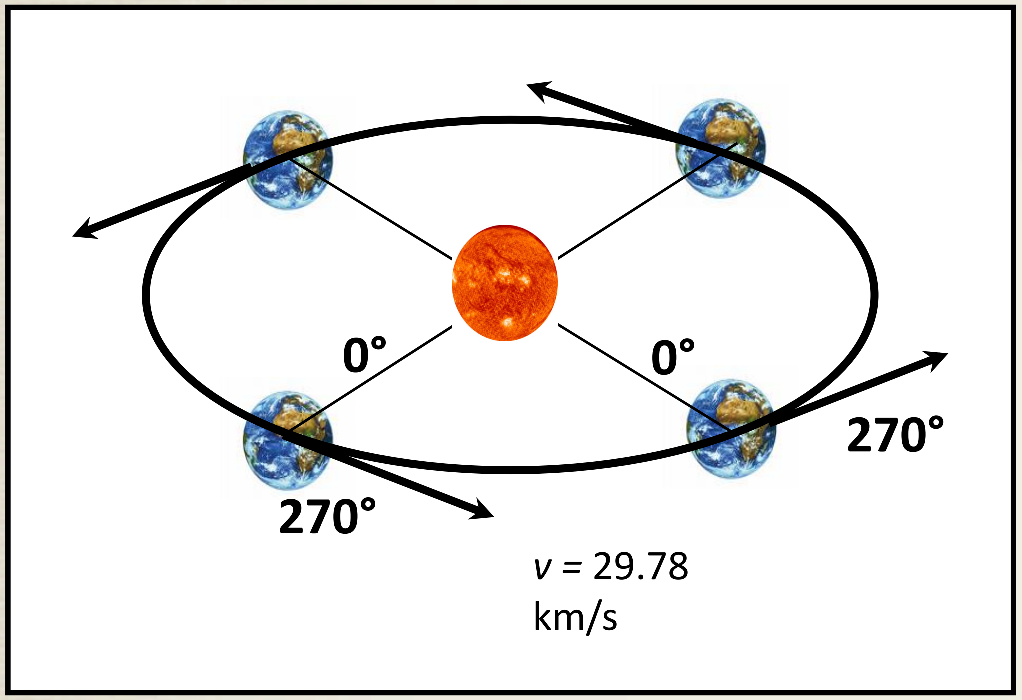


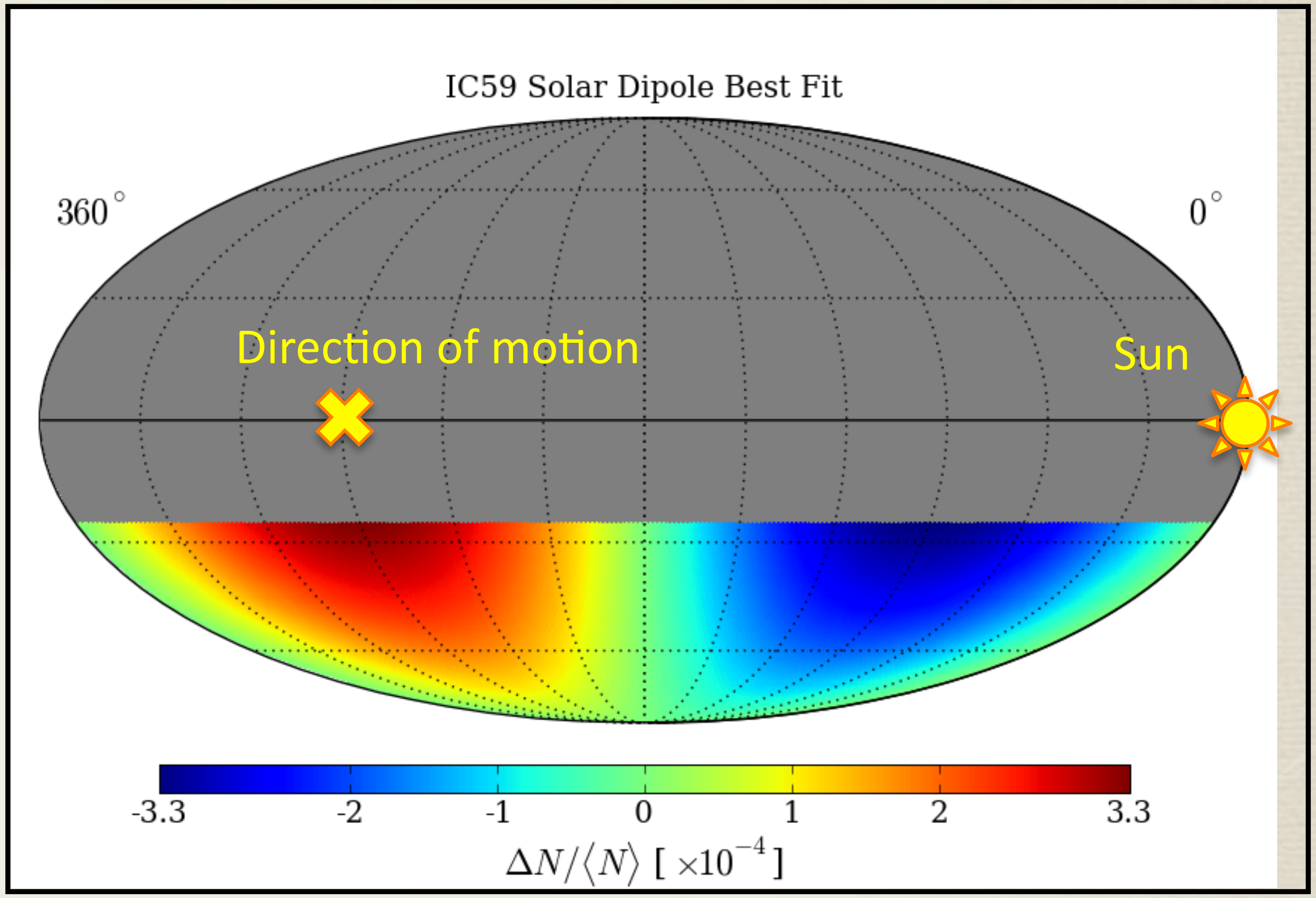




Systematics: Solar Dipole

We are sensitive to the motion of the Earth around the Sun (10^{-4} effect is expected):
visible when UT is used in local-celestial coord. transformation.

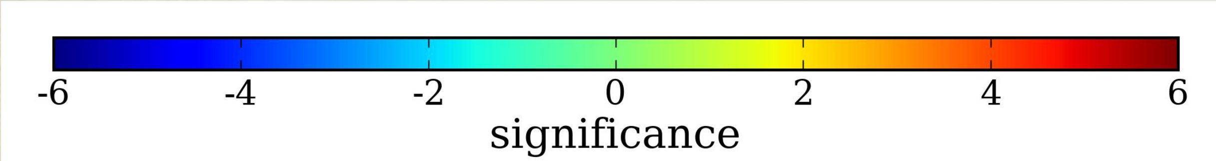




Coefficient	Fit Value ($\times 10^{-4}$)
m_0	-0.029 ± 0.058
p_x	0.017 ± 0.142
p_y	-3.661 ± 0.142
p_z	-0.027 ± 0.072

$$\chi^2/\mathrm{ndf} = 14206.8/14192$$
$$\Pr(\chi^2|\mathrm{ndf}) = 0.416$$

Systematics: previous data sets

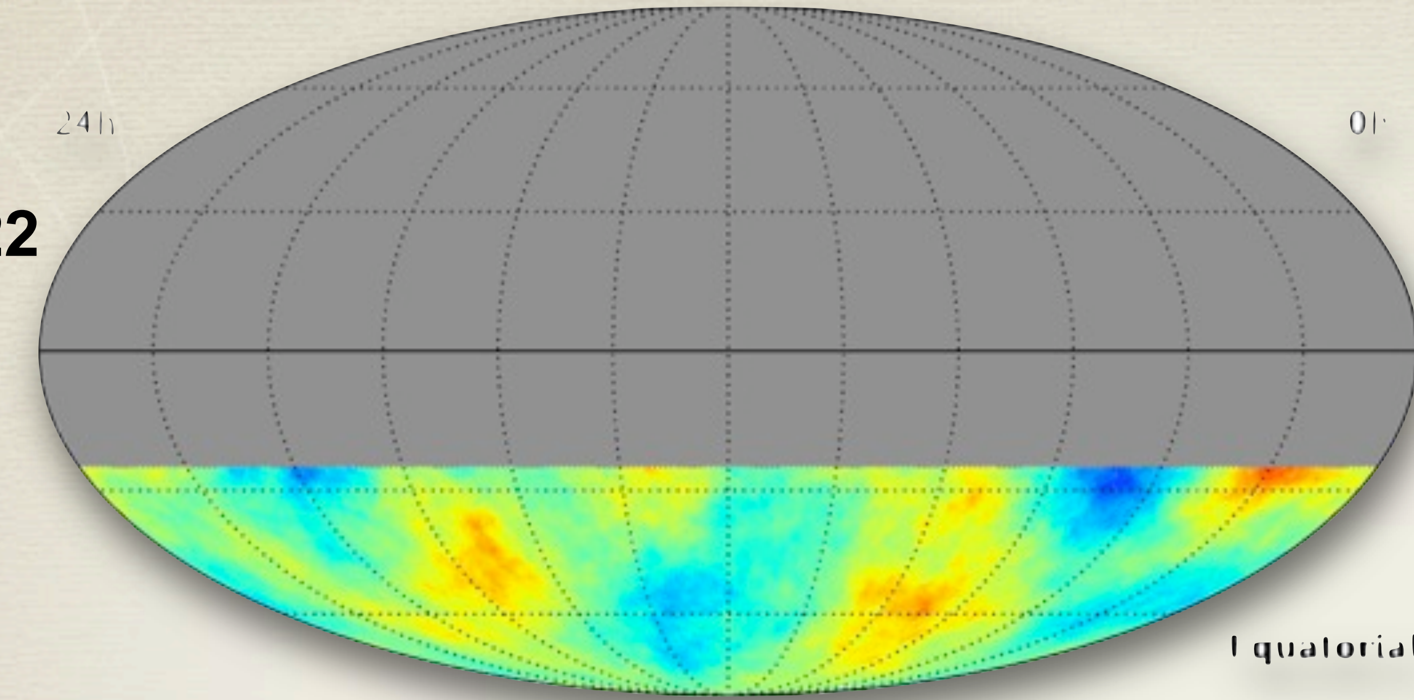


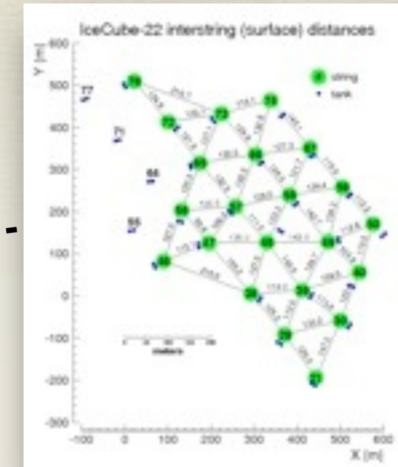
Different geometries, same structure

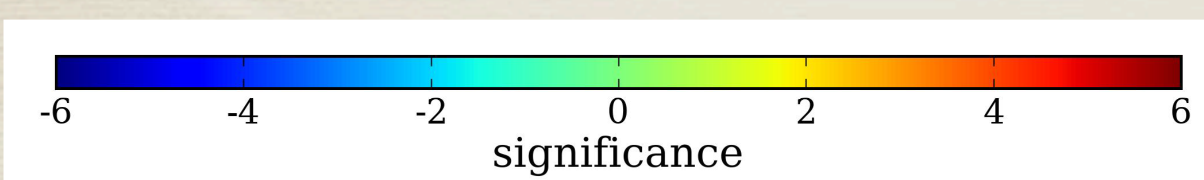
Signal grows with statistics

Systematics: previous data sets

IC22







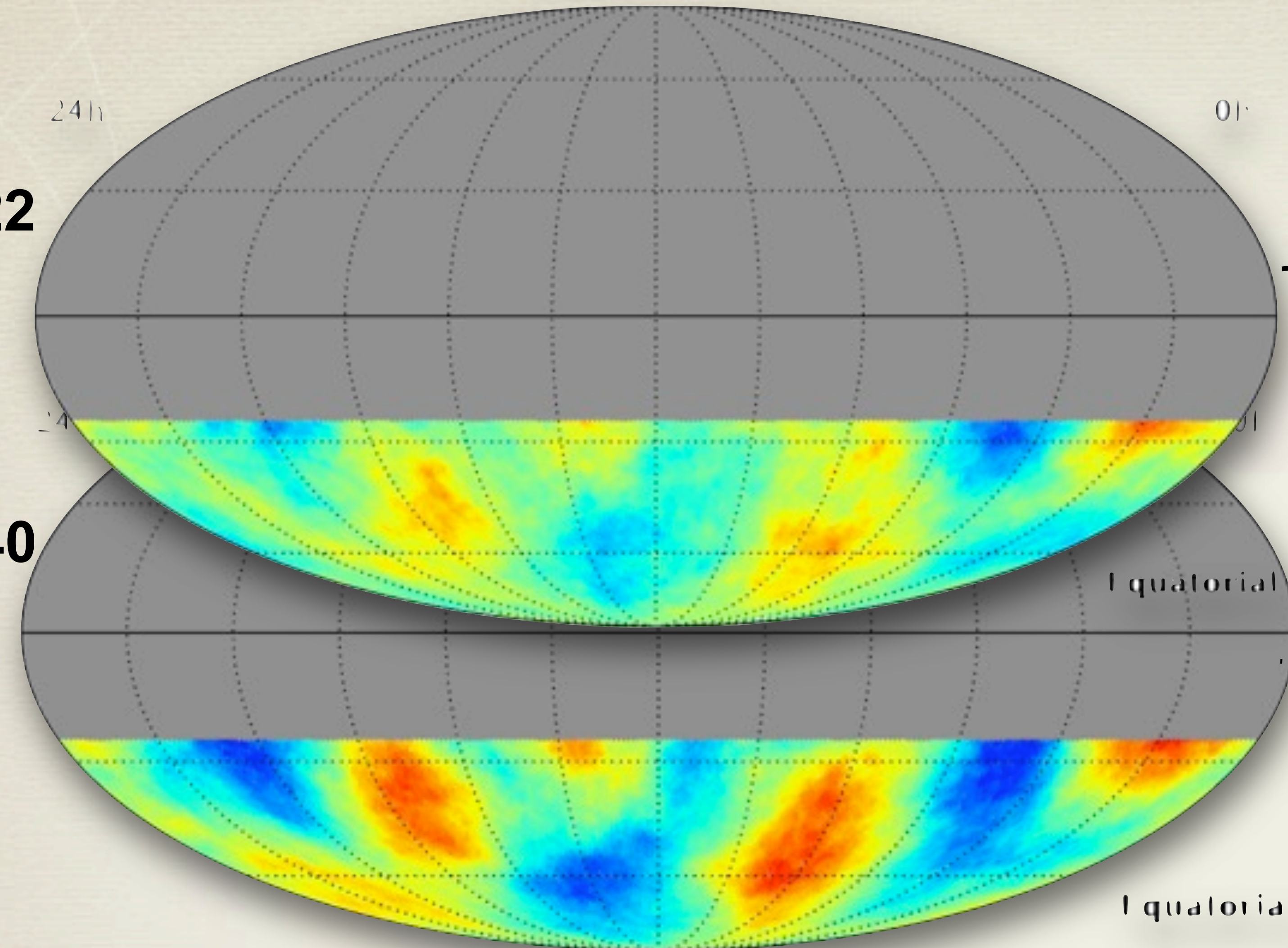
Different geometries, same structure

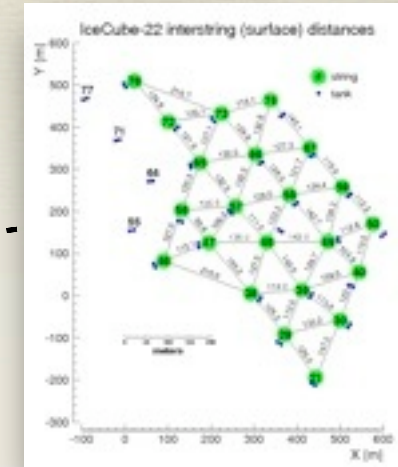
Signal grows with statistics

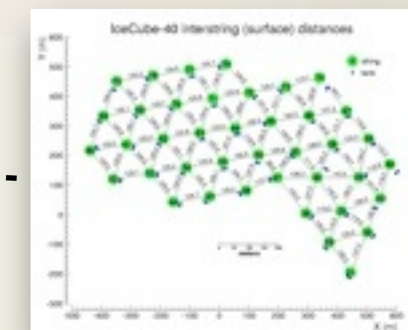
Systematics: previous data sets

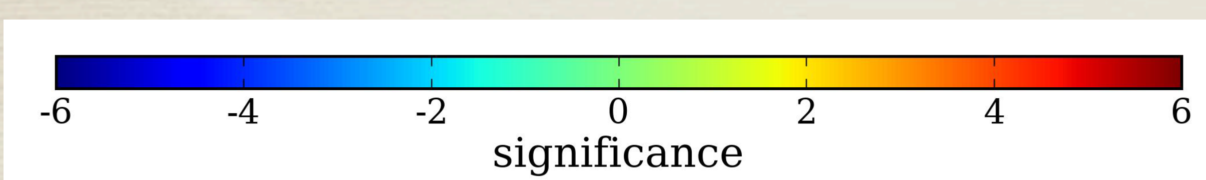
IC22

IC40









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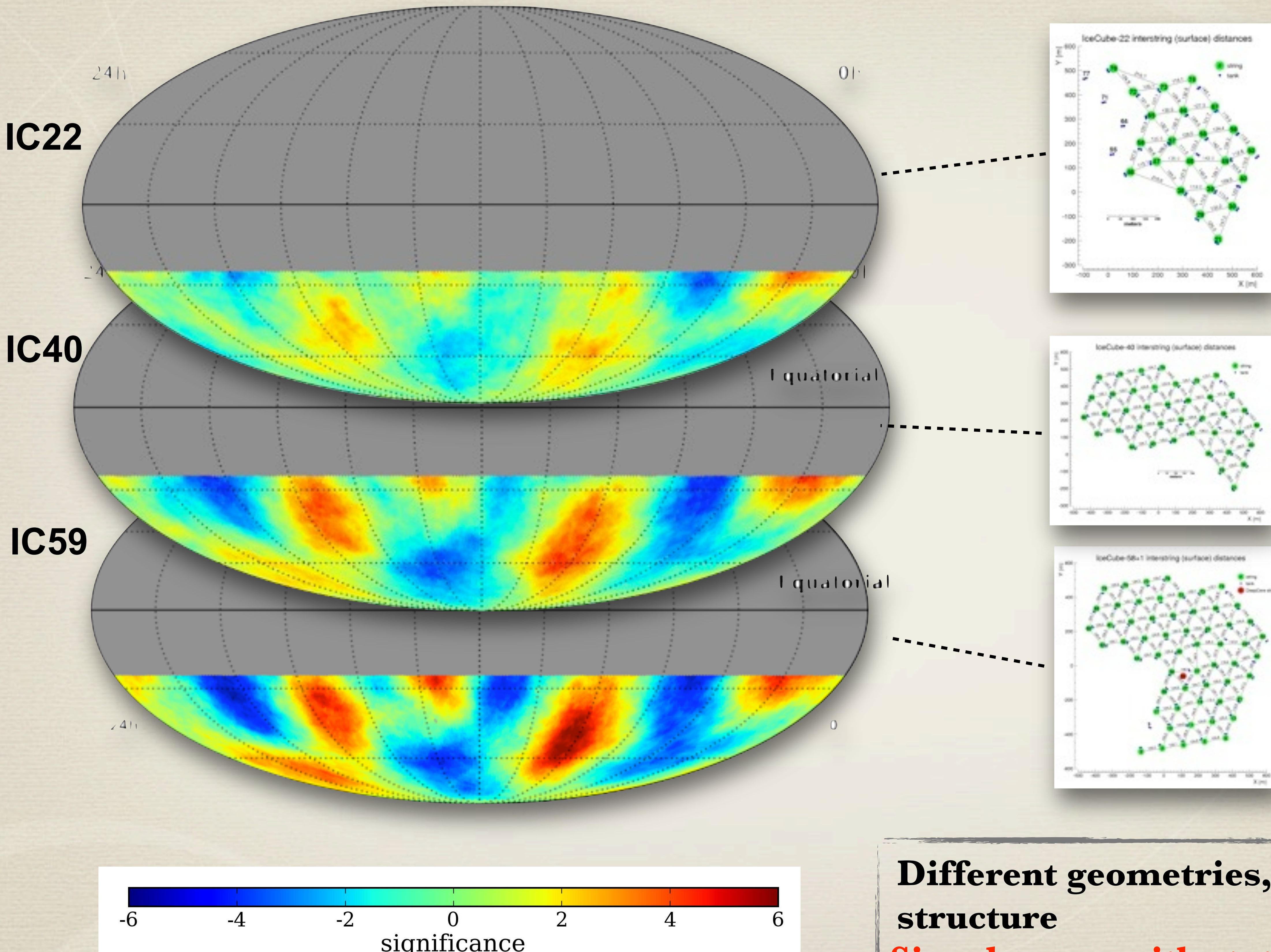


Different geometries, same structure

Signal grows with statistics

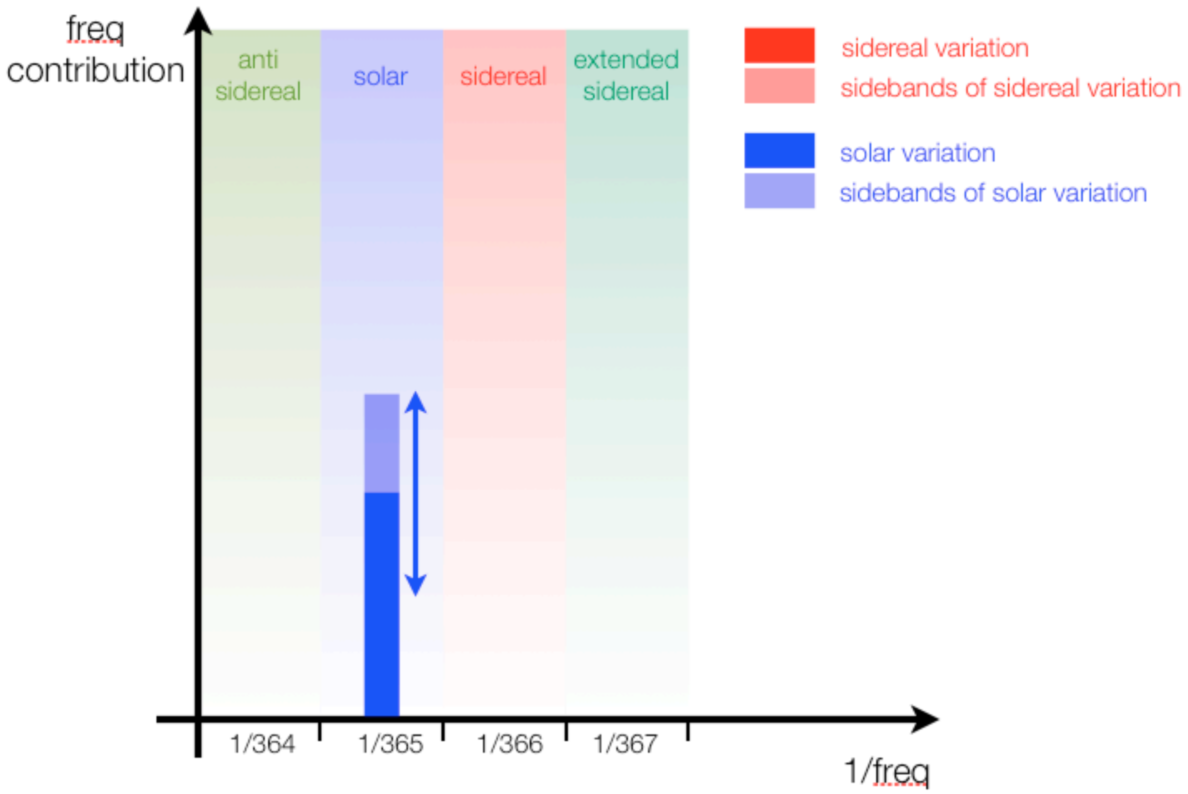
Farley, & Storey, Proc. Phys. Soc., 67, 996, 1954

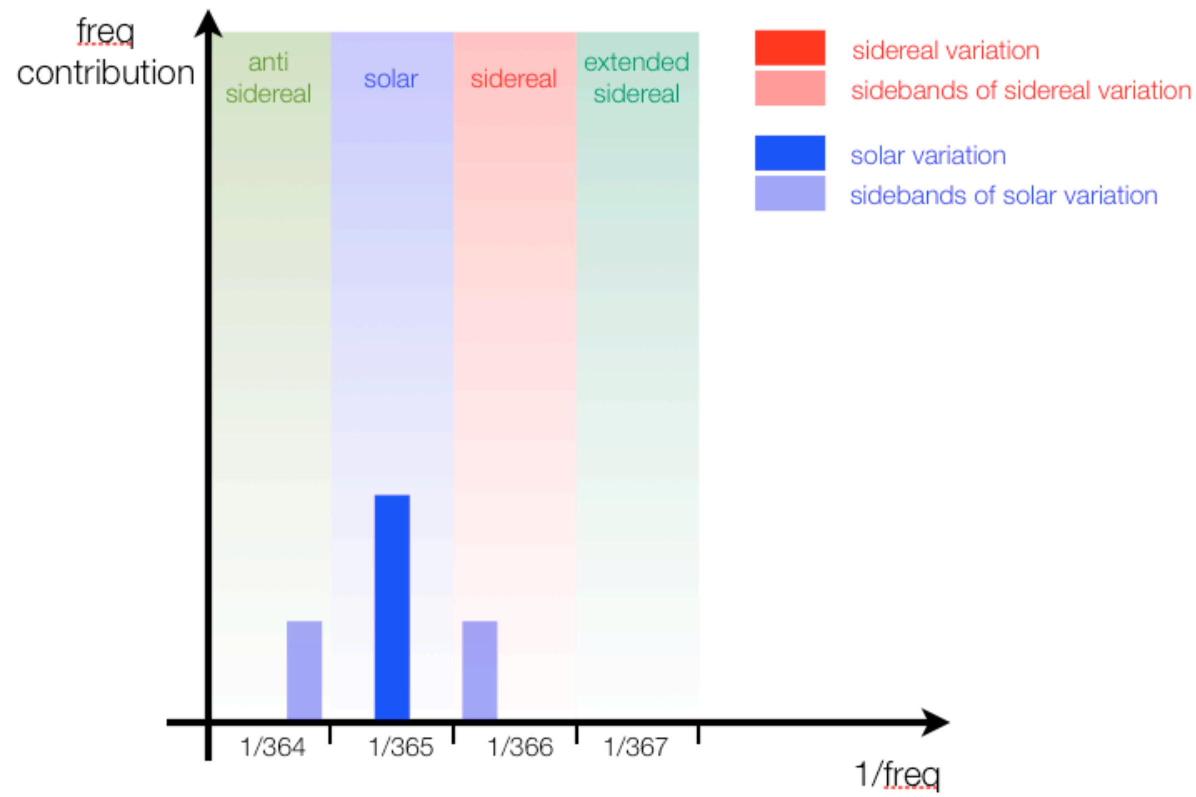
Nagashima, et al., Nuovo 907 Cimento C, 6, 550, 1983

anti- / extended-sidereal reference frames

A static distribution in **solar** (sidereal) reference frame averages to zero in **sidereal** (solar) frame after one year

An annual modulation of the **solar** (sidereal) distribution does not compensate and produces distortions on the **sidereal** (solar) anisotropies





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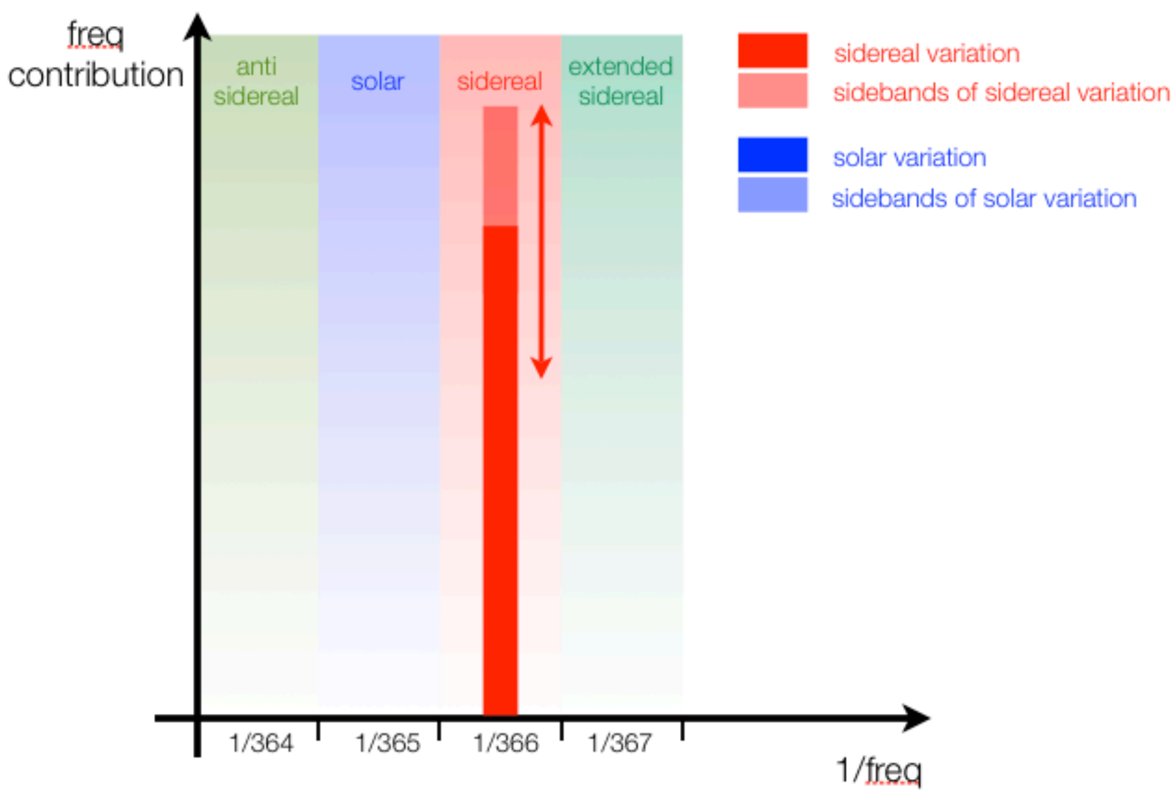
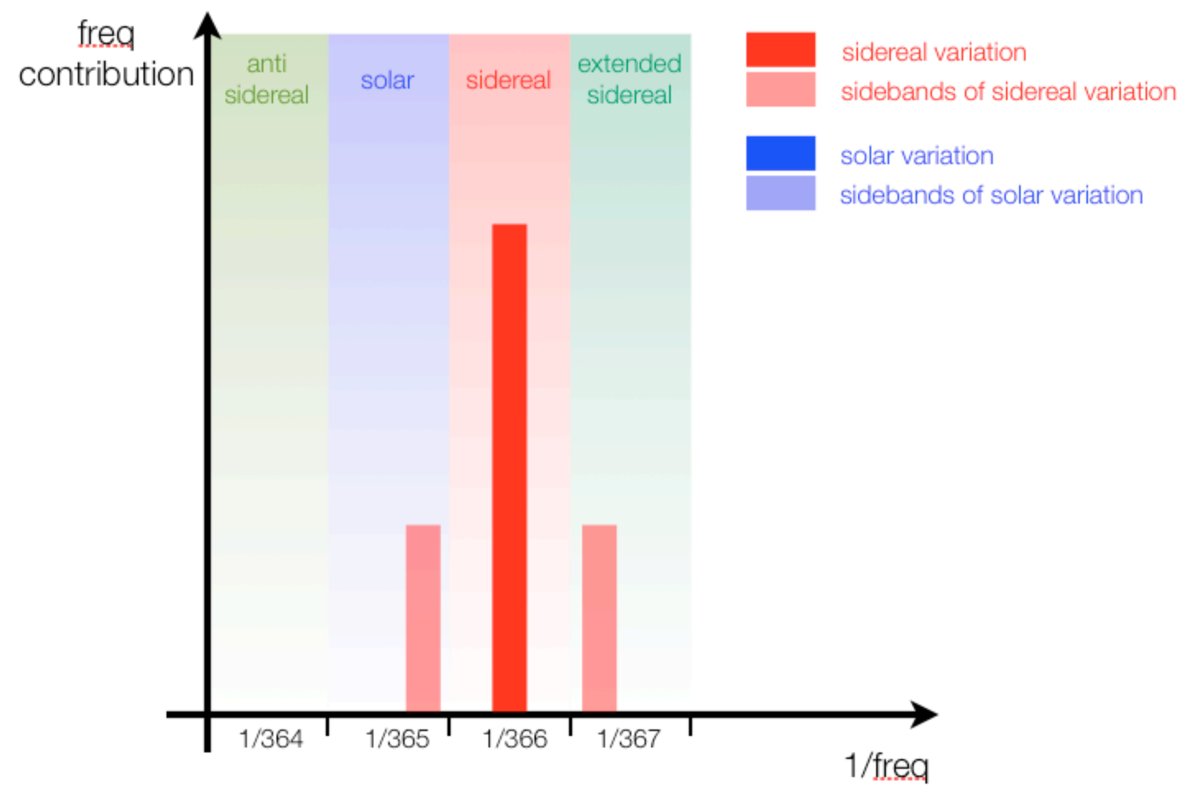




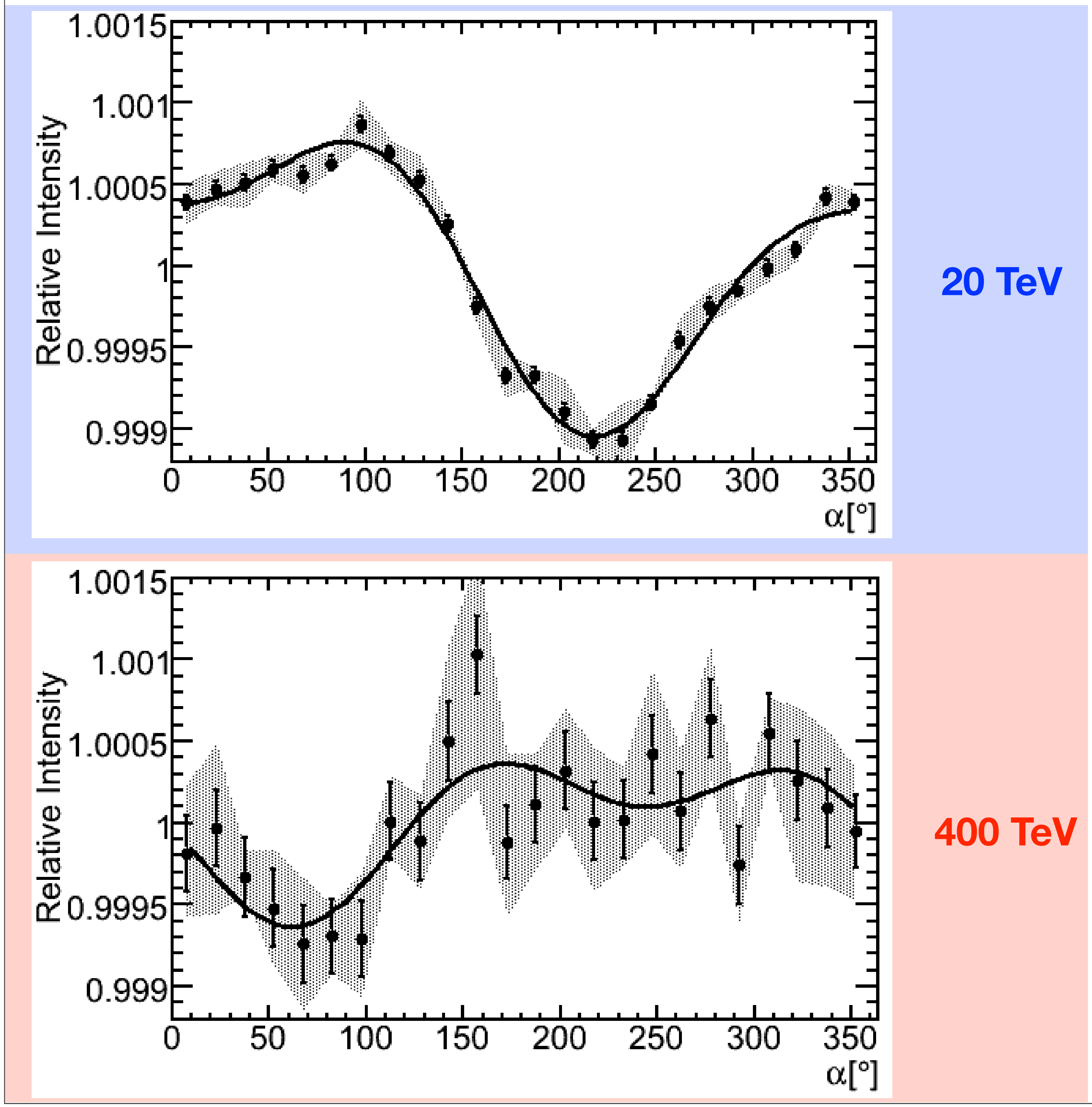
Summary of measurements for IC59

$$\sum_{j=1}^{n=2} A_j \cos[i(\alpha - \phi_j)] + B$$

	$E_{primary}$ (TeV)	events (10^9)	A_1 (10^{-4})	φ_1 (°)	A_2 (10^{-4})	φ_2 (°)	χ^2/ndf
sidereal	20	17.9	7.9 ± 0.1 ± 0.4	50°.5 ± 1°.0 ± 1°.1	2.9 ± 0.1 ± 0.4	299°.5 ± 1°.3 ± 1°.5	95/19
	400	0.5	3.7 ± 0.7 ± 0.7	239°.2 ± 10°.6 ± 10°.8	2.7 ± 0.7 ± 0.6	152°.7 ± 7°.0 ± 4°.2	34.19
solar	20		1.9 ± 0.1 ± 0.6	267°.1 ± 3°.8 ± 7°.5			23/21
	400		2.9 ± 0.7 ± 1.0	272°.1 ± 13°.3 ± 5°.0			12/21
anti-sidereal	20		0.4 ± 0.1	1°.5 ± 18°.5			29/21
	400		0.5 ± 0.7	324°.6 ± 75°.4			17/21
extended-sidereal	20		0.7 ± 0.1	165°.7 ± 10°.3			29/21
	400		0.7 ± 0.7	212°.9 ± 54°.5			23/21

Systematic uncertainties IceCube-59

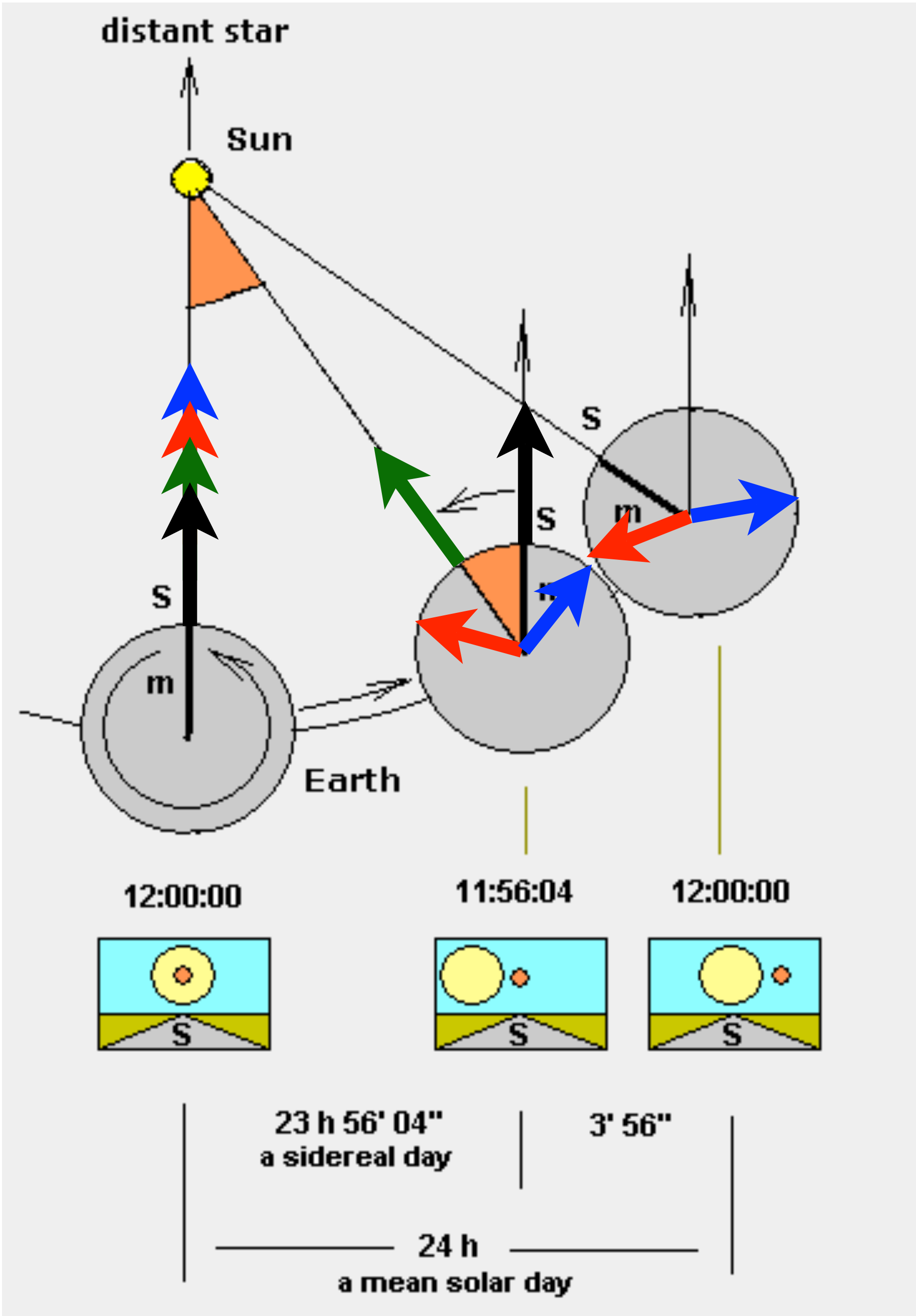
statistical stability tests + anti-sidereal effect



statistical stability tests:

- summer/winter season datasets
- rate ≳ median daily rate
- even/odd sub-runs (2 mins data)
- random sub-run selection
- use ~20hr full days (214/324 d)

anti- / extended-sidereal reference frames



The anti- / extended-sidereal reference frames are unphysical and no anisotropy is expected

An anisotropy in anti-sidereal (extended-sidereal) frame is to be associated to the corresponding distortion of the sidereal (solar) arrival distributions

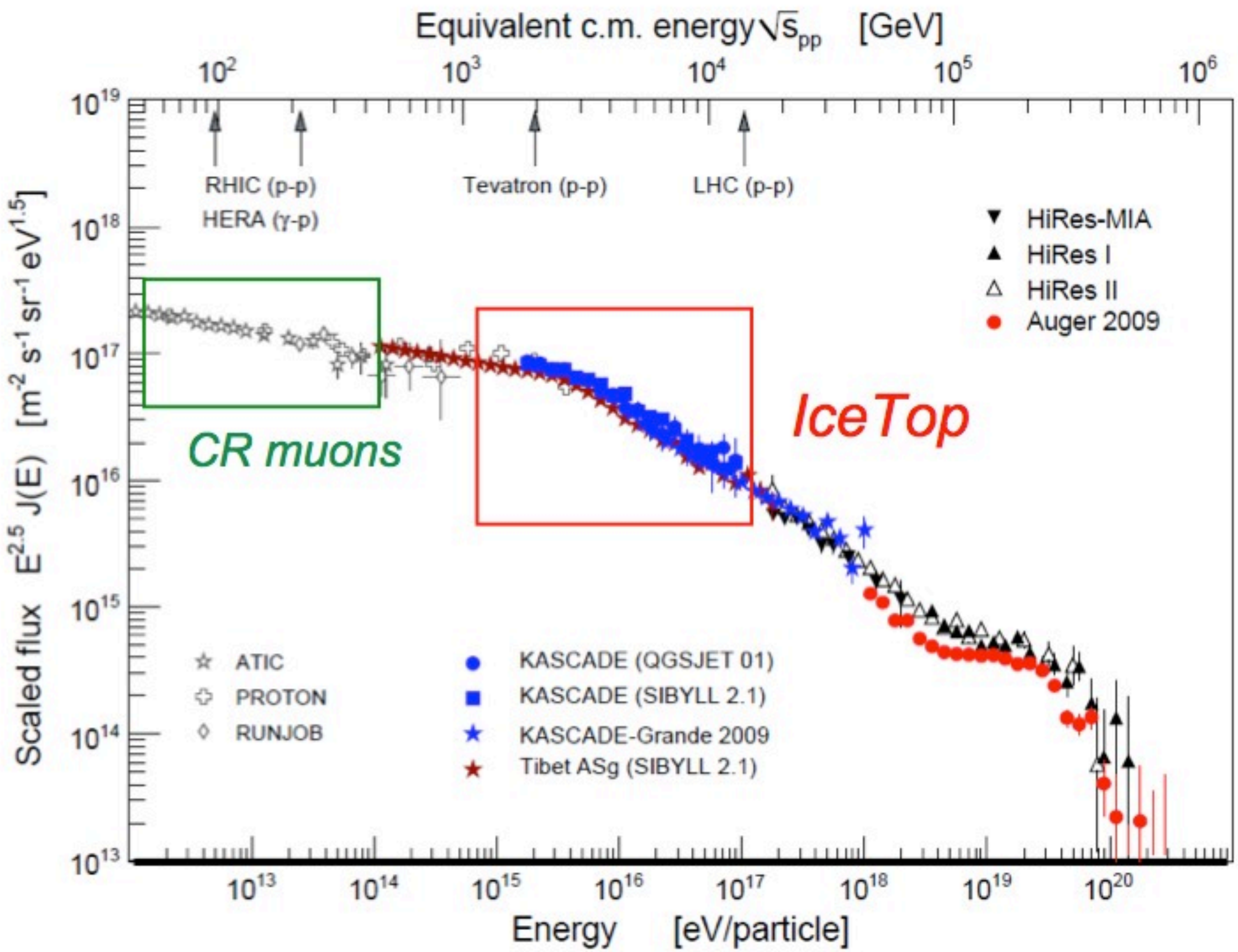
solar time

sidereal time

anti-sidereal time

extended-sidereal time

Cosmic Ray Energy Spectrum



IceCube-59 DST data

- Data taken between May 20, 2009 and May 30, 2010. Integrated livetime 335.5 days.

- 3.4×1010 events stored in a special format suitable for high data rate.

- Simulations: median energy and angular resolution depend on zenith angle.

- Zenith angle cut: accept events < 65°.