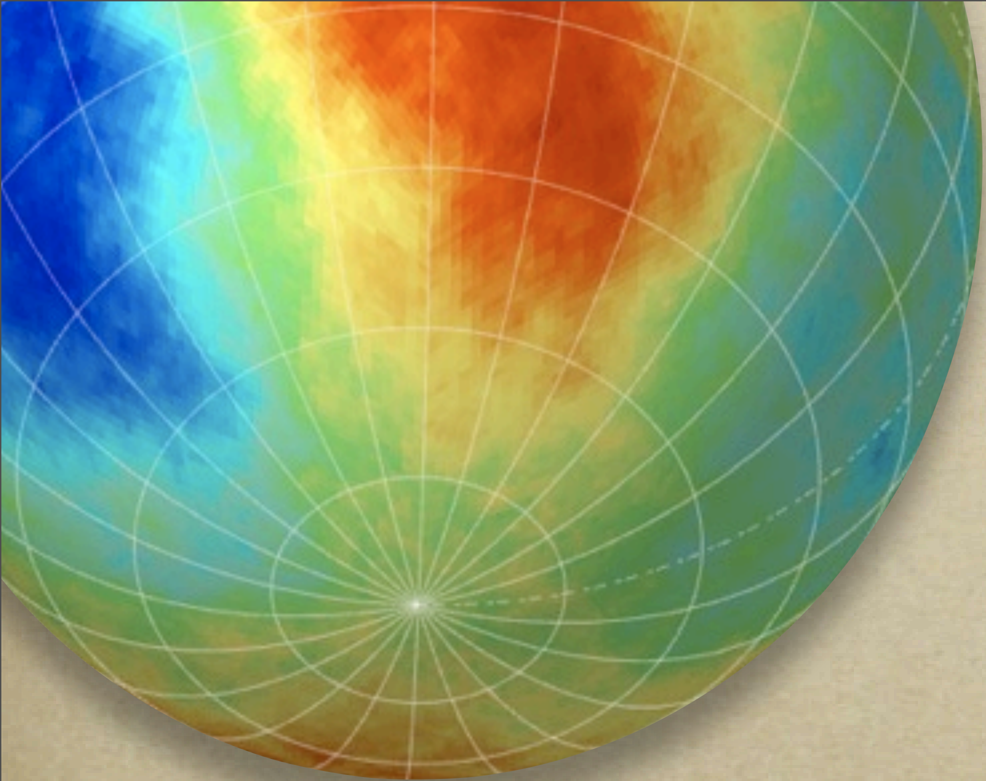

Observation of Anisotropy in the arrival direction distribution of Cosmic Rays above TeV with IceCube and IceTop

Simona Toscano

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University of Wisconsin-Madison

toscano@icecube.wisc.edu

Outline

- *Cosmic Ray* ***Anisotropy****: an introduction*
- *Cosmic Rays in* ***IceCube***
- ***Energy evolution*** *of Anisotropy*
- ***Angular scale*** *of Anisotropy*
- *Preliminary results from* ***IceTop***
- *Possible* ***interpretation***

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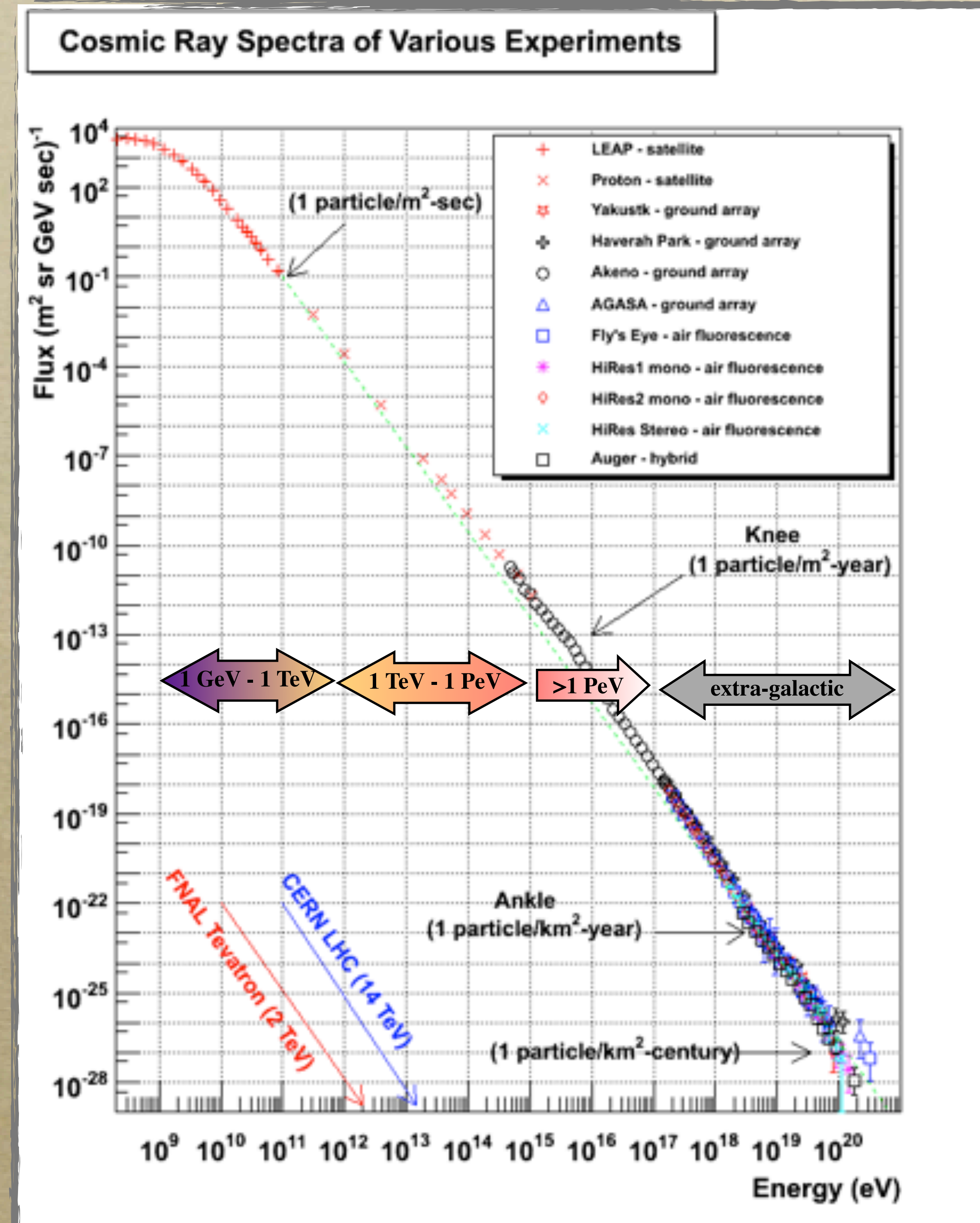
Cosmic Ray Spectrum

- CR below the knee (<10^{15} eV) believed to be galactic
- CR above ~ 10^{18}-10^{19} eV believed to be extra-galactic
- Galactic CR believed to be accelerated in expanding shock waves initiated by SN explosions
- Spectral structure and mass composition hold information
  - origin of cosmic rays
  - propagation from sources to Earth
- Anisotropy in arrival direction (expected from discrete sources distribution & propagation in heterogenous IM and turbulent LIMF)
  - **energy dependence**
  - **angular scale**
  - **origin and propagation**

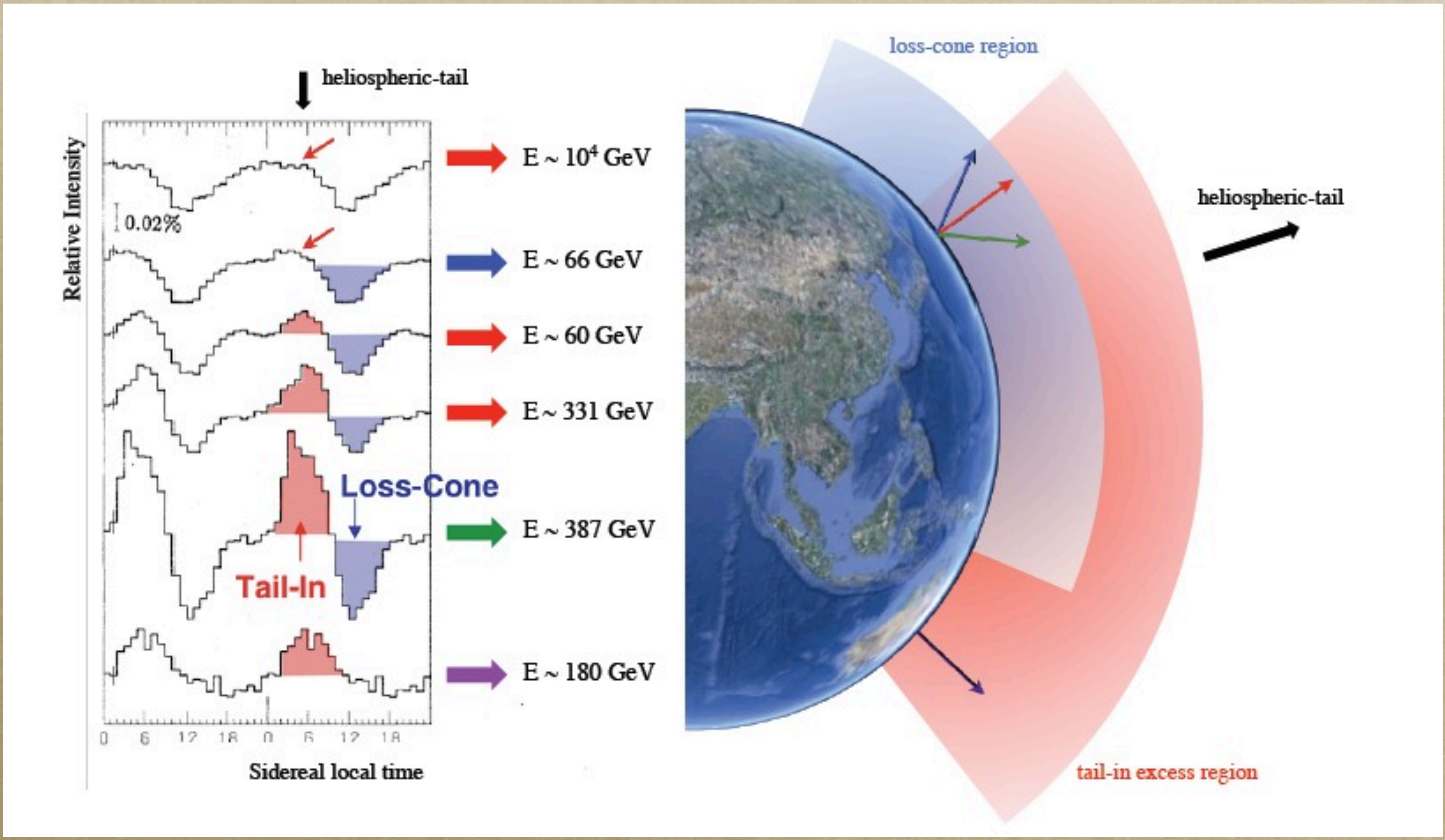


Large scale anisotropy

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

Cosmic ray anisotropy

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)



Dipole anisotropy due to Earth's motion

- Large scale anisotropies can be caused by the motion of the Earth through the cosmic ray rest frame:

  -The intensity of cosmic rays should be higher coming from the direction in which Earth is moving, causing a **dipole anisotropy** if we choose a coordinate frame where the direction of Earth's motion is fixed.

- Earth's motion through space is complex and a superposition of several motions. Two dipole anisotropies due to Earth's motion have been postulated:

  - A **solar dipole anisotropy** due the Earth's motion around the Sun.

  -The **Compton-Getting Effect** due to the motion of the solar system around the Galactic center. In certain scenarios, this effect should be strong enough to be detectable by modern detectors.

Cosmic Ray Anisotropy vs Energy

J.L. Zhang et al., 31st ICRC Łódź - Poland, 2009

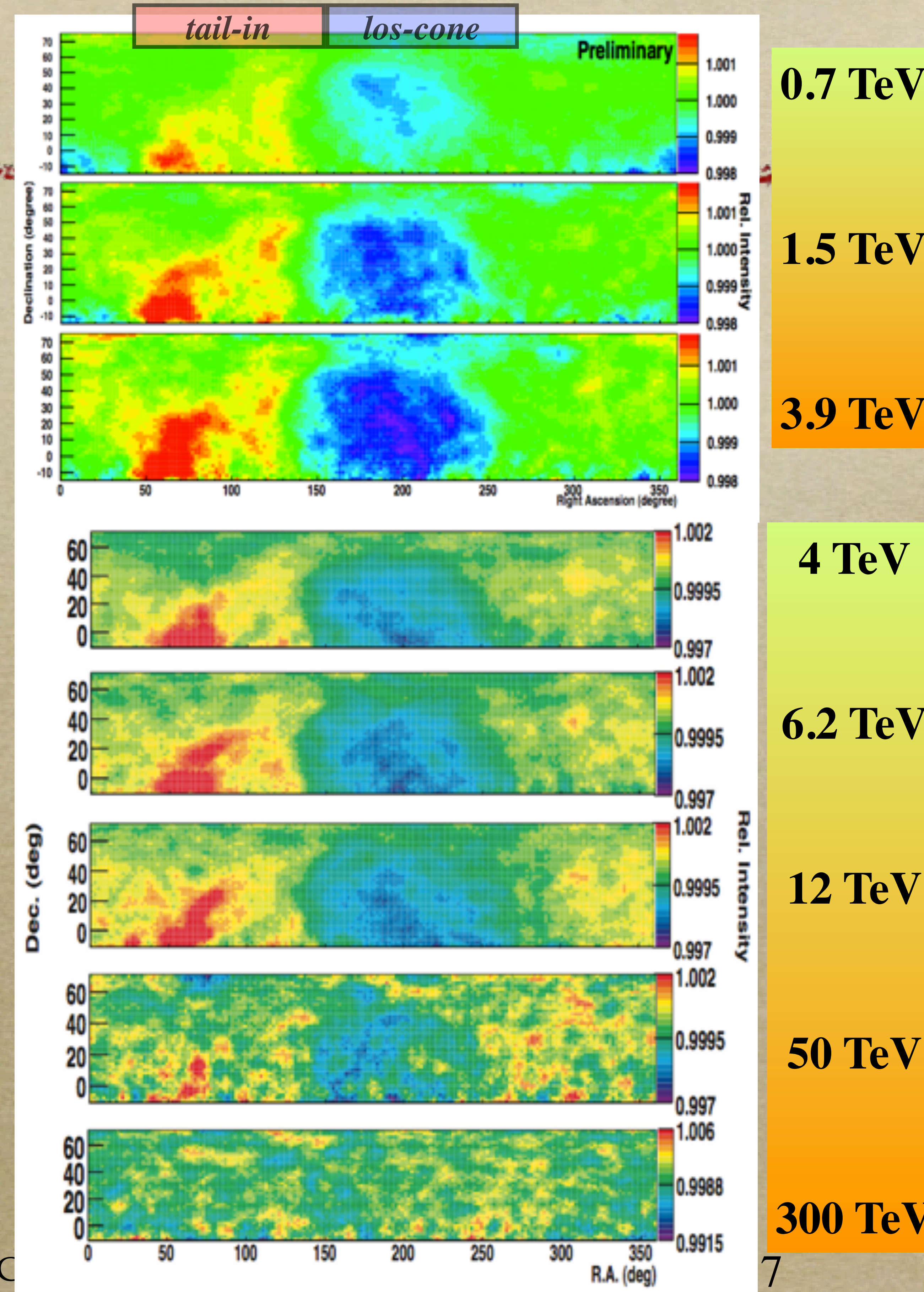
ARGO-YBJ

- data from 2008
- 365 days livetime
- 6.5×10^{10} events
- median CR energy ~ 1.1 TeV

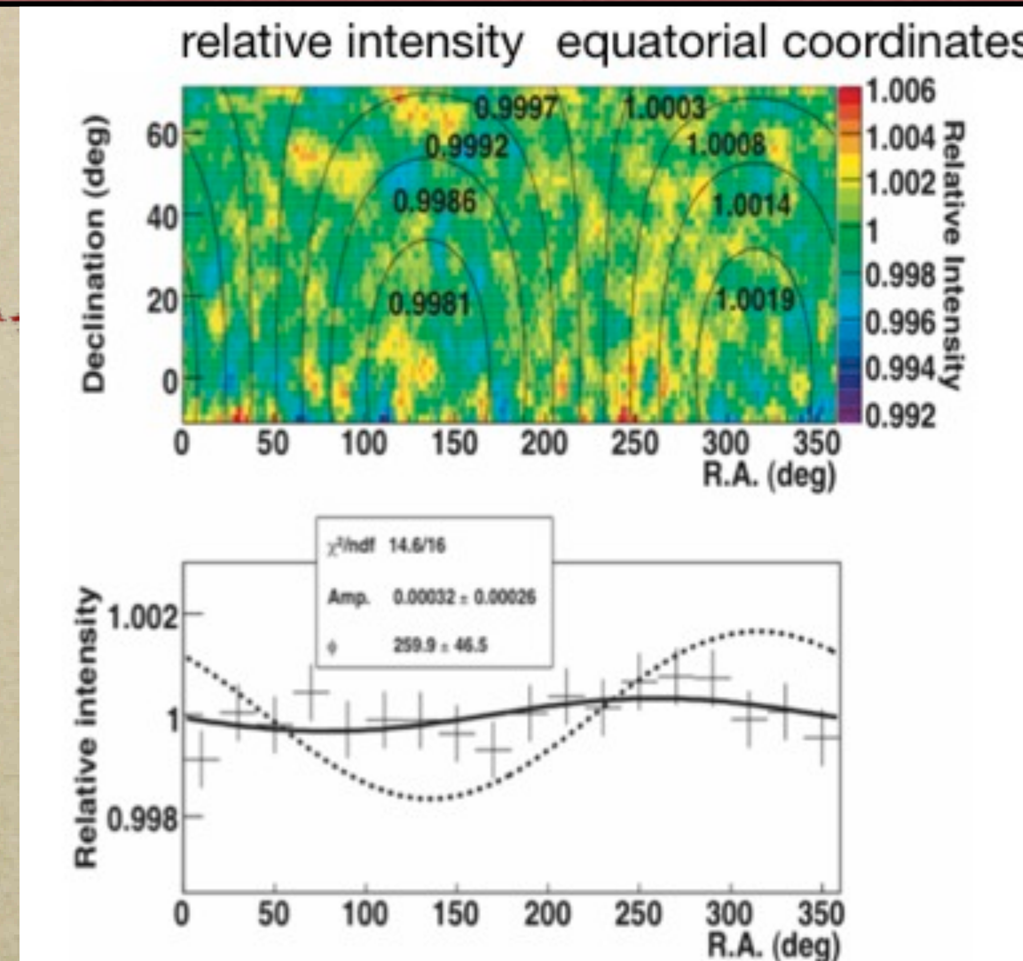
Anemori et al, Science Vol. 314, pp 439, 2006

Tibet-III

- data from 1997 to 2005
- 1874 days livetime
- 3.7×10^{10} events
- modal CR energy ~ 3 TeV
- angular resolution ~ 0.9°



Cosmic Ray Anisotropy vs Energy



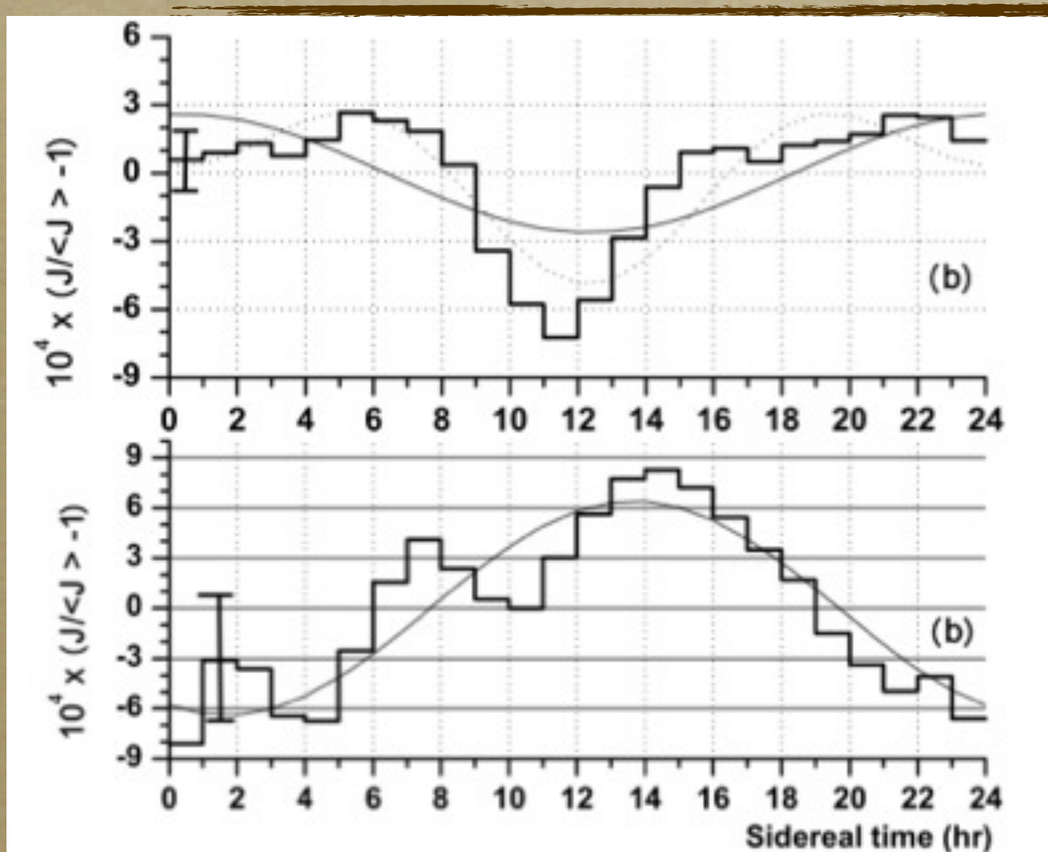
300 TeV

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

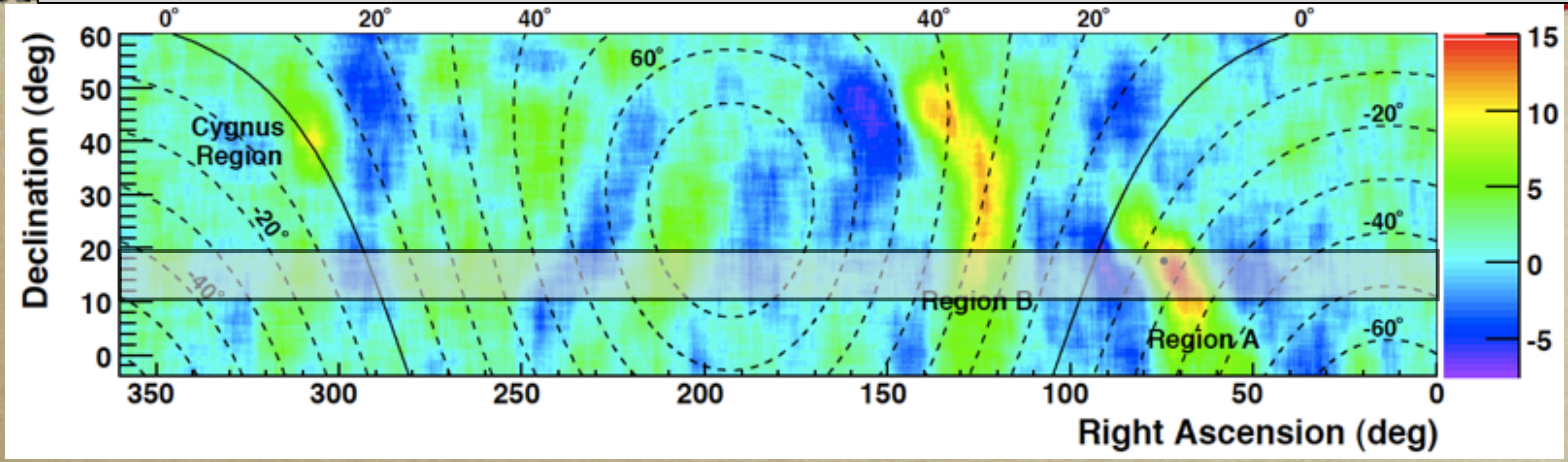
Aglietta et al., ApJ 692, L130, 2009

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

low significance, still not conclusive.

Cosmic ray anisotropy vs angular scale

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.



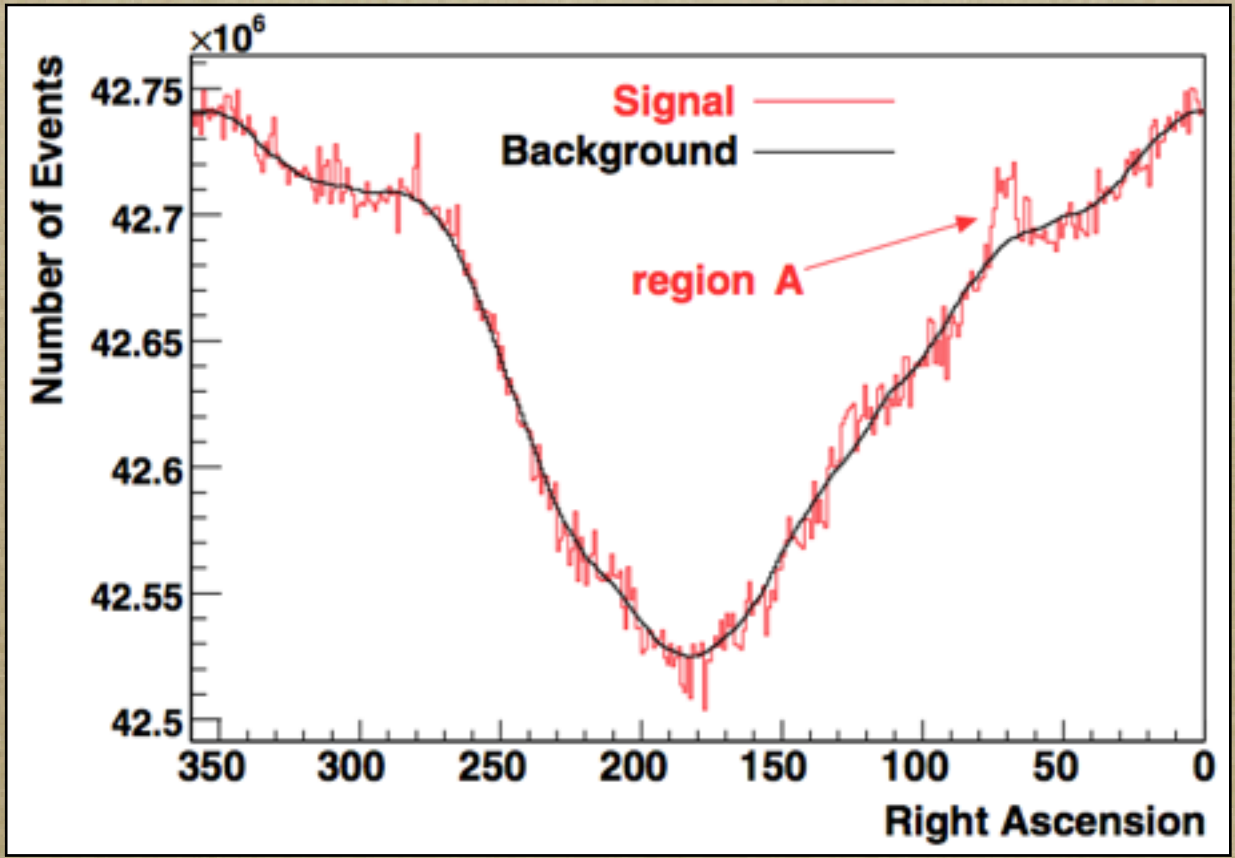
Milagro

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

- 2.2 x 10^{11} events
- median CR energy ~ 1 TeV = 10^{12} eV
- average angular resolution < 1°

Direct Integration:
2hr time window
10° smoothing

- filter all angular features > 30°
- technique used in gamma ray searches

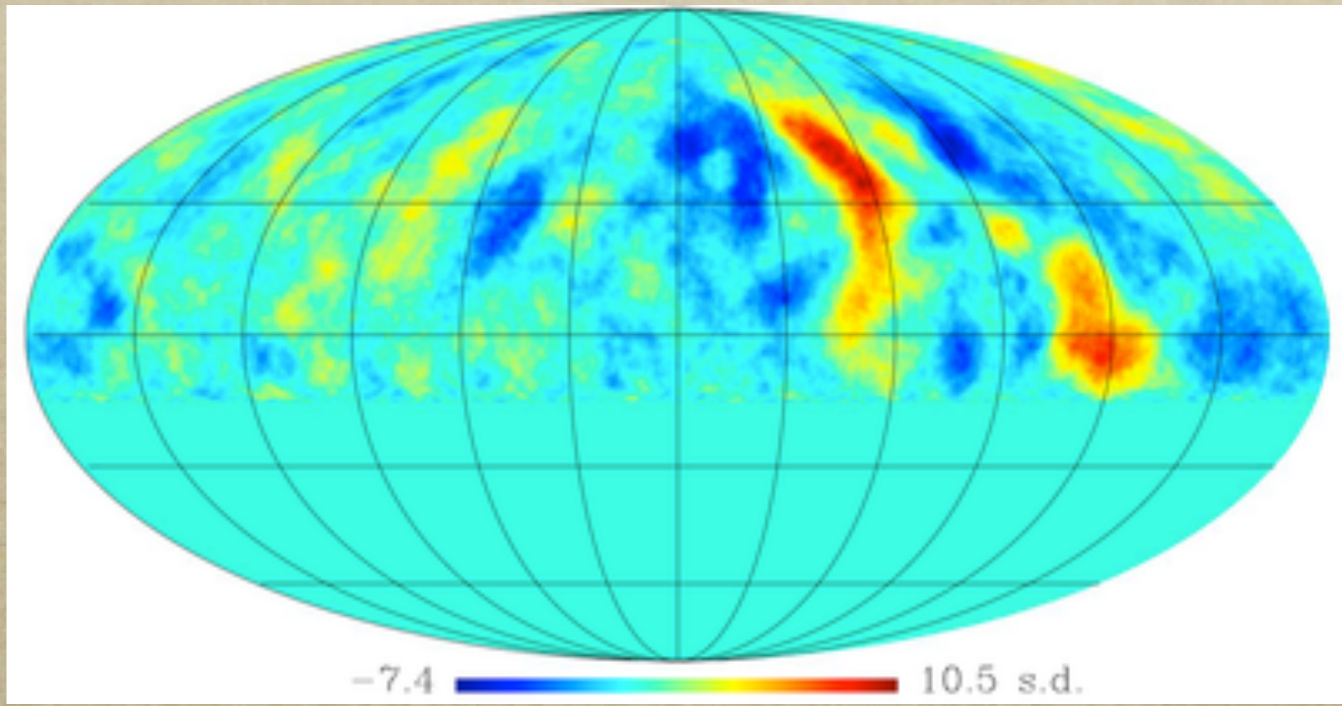


Cosmic ray anisotropy vs angular scale

ARGO-YBJ

(time scrambling)

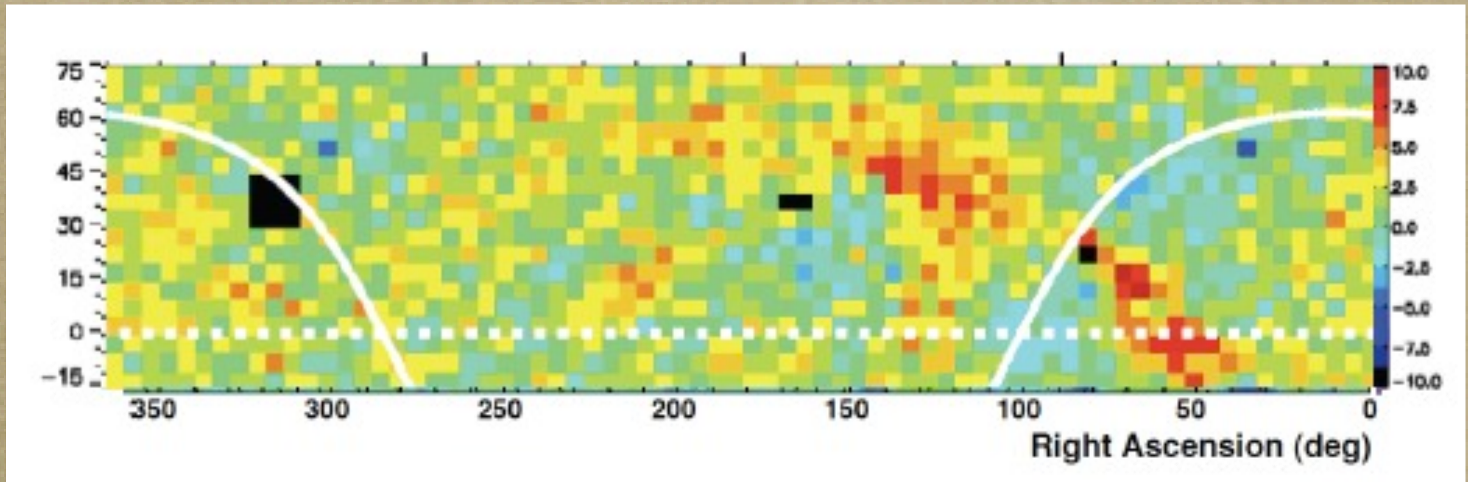
S. Vernetto, Proc. 31st ICRC, 2009



Tibet - III

(global fit)

Amenomori et al., ICRC 2007, Mérida (Mexico)



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Fédérale de Lausanne
University of Geneva
Chiba University
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
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Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
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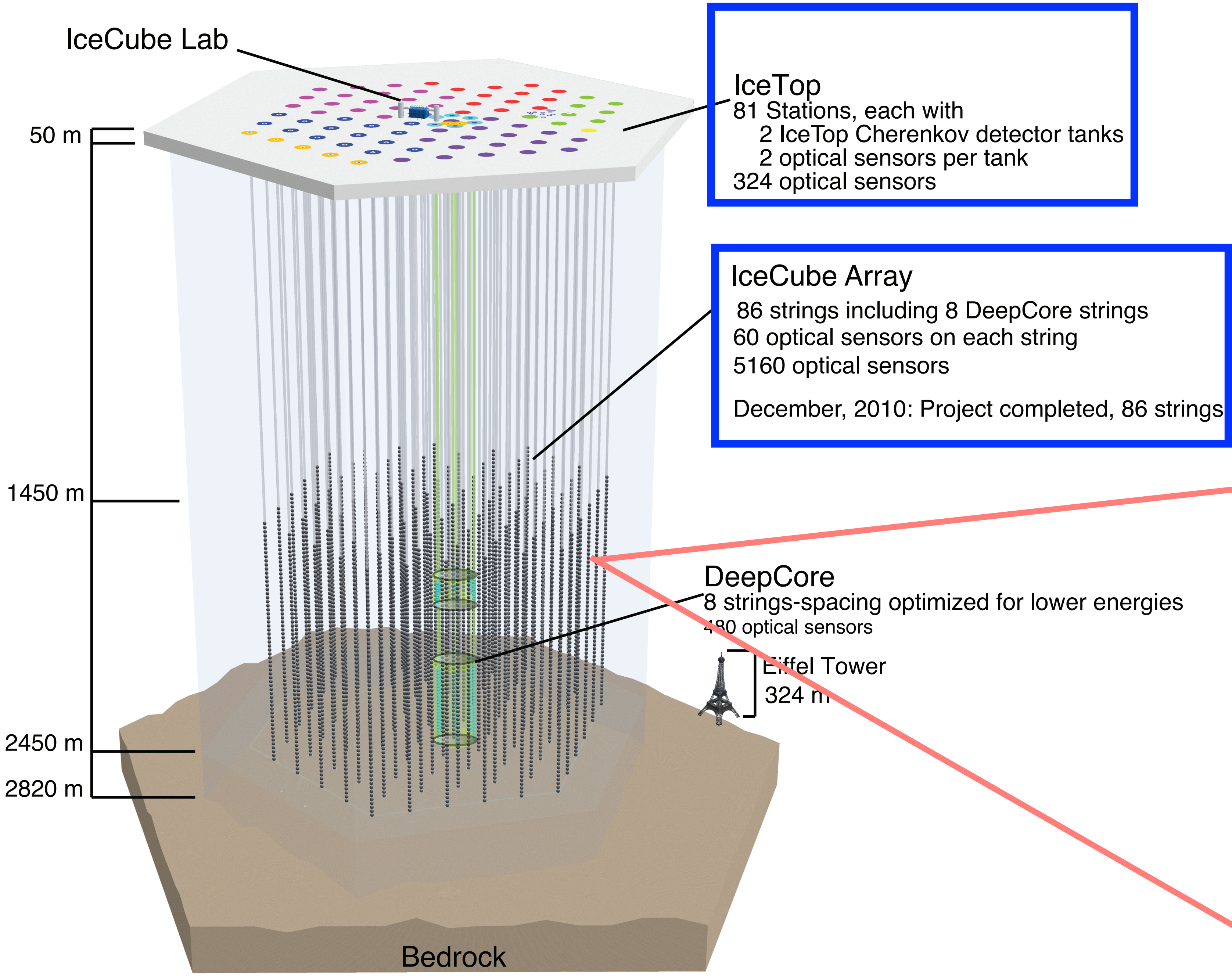
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

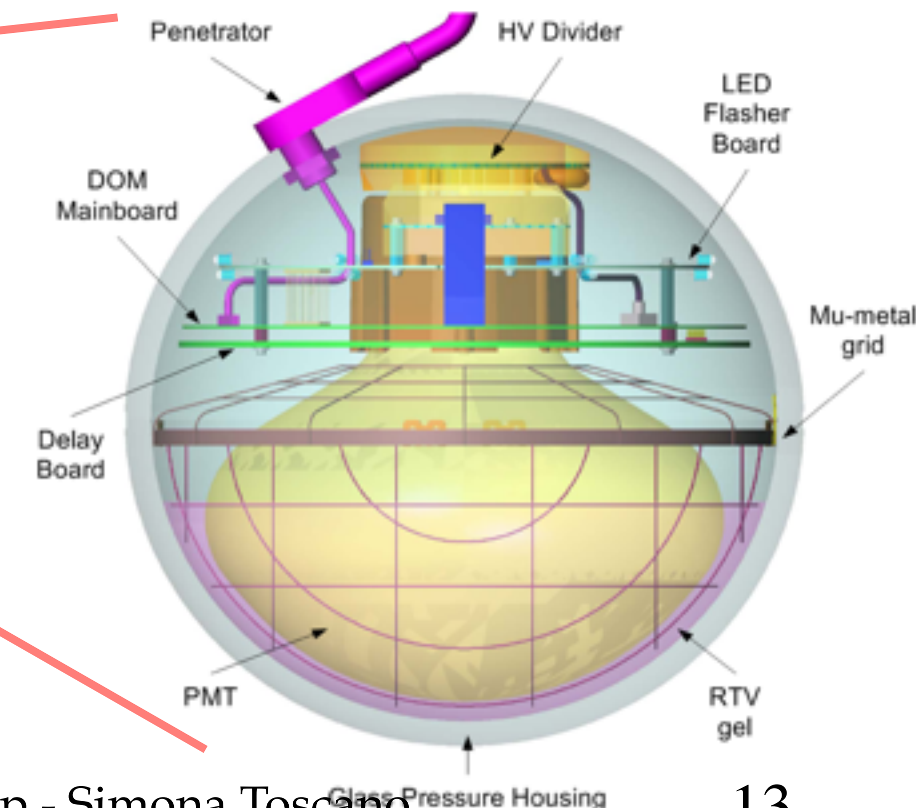
IceCube Observatory

IceCube is a km³-scale neutrino detector "frozen" into the South Pole ice.



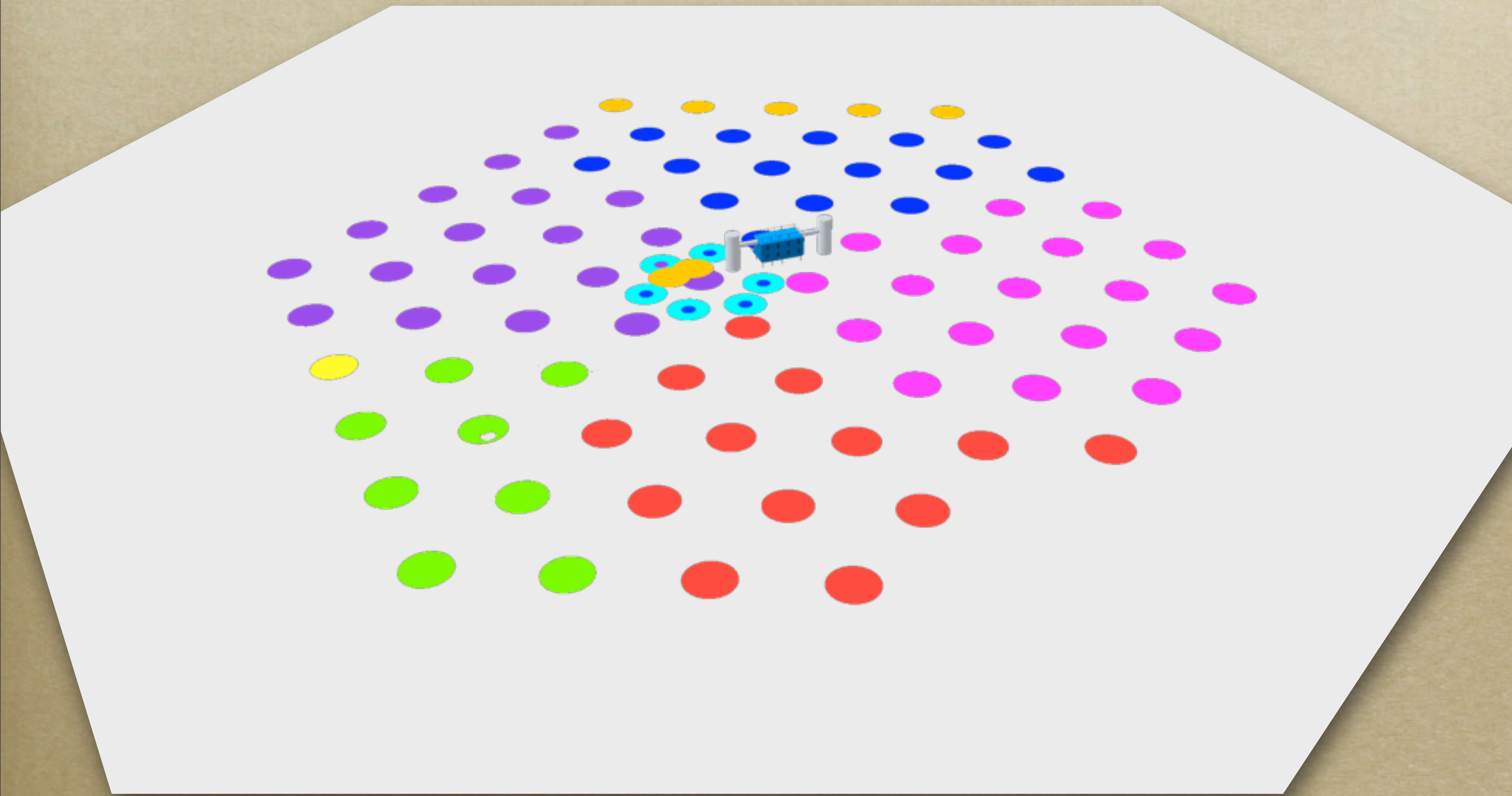
- **86 strings**
- **5160 DOMs**
- **17 m vertical spacing**
- **125 m between strings**

Digital Optical Module

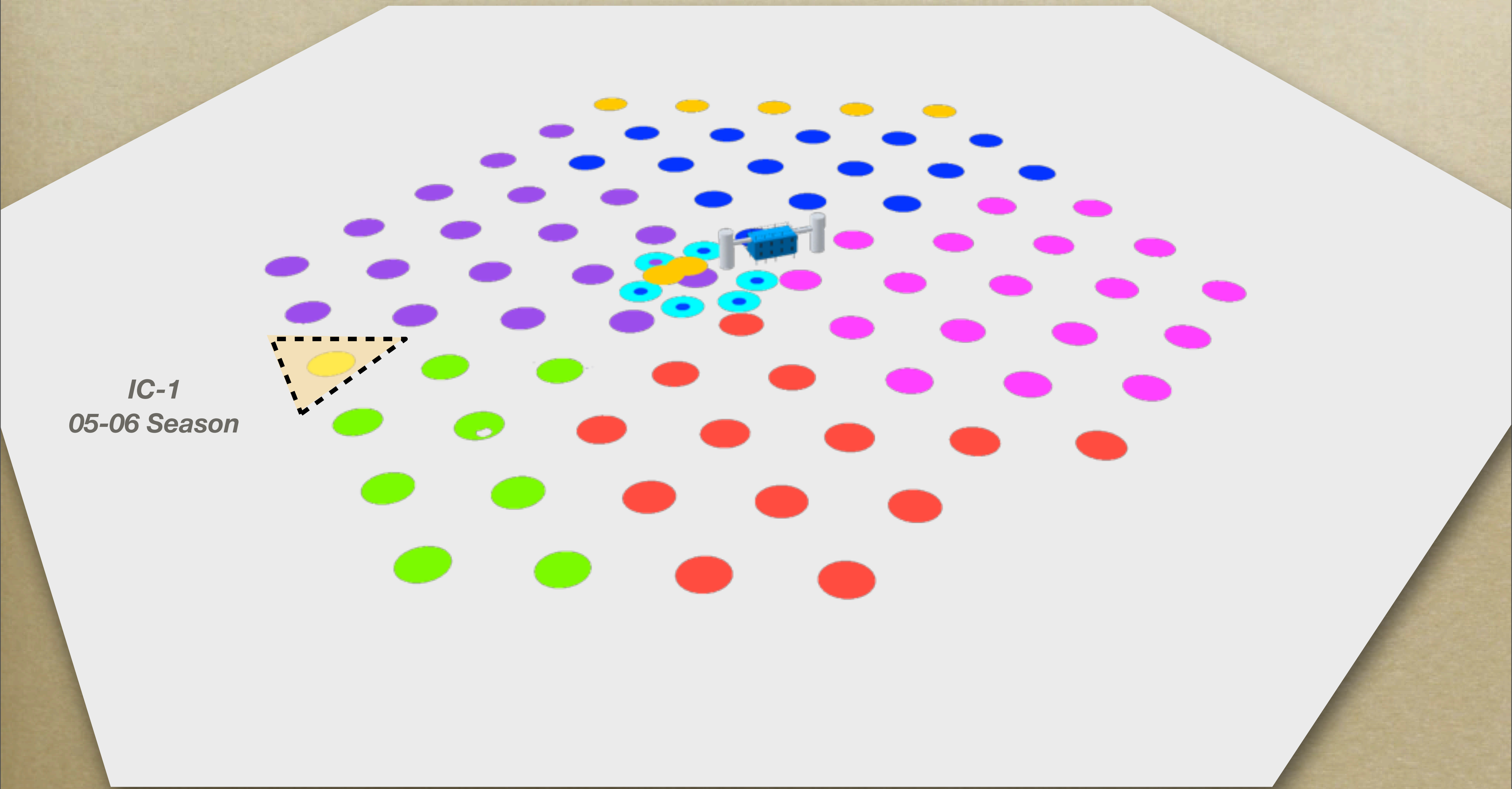


Wednesday, April 18, 2012

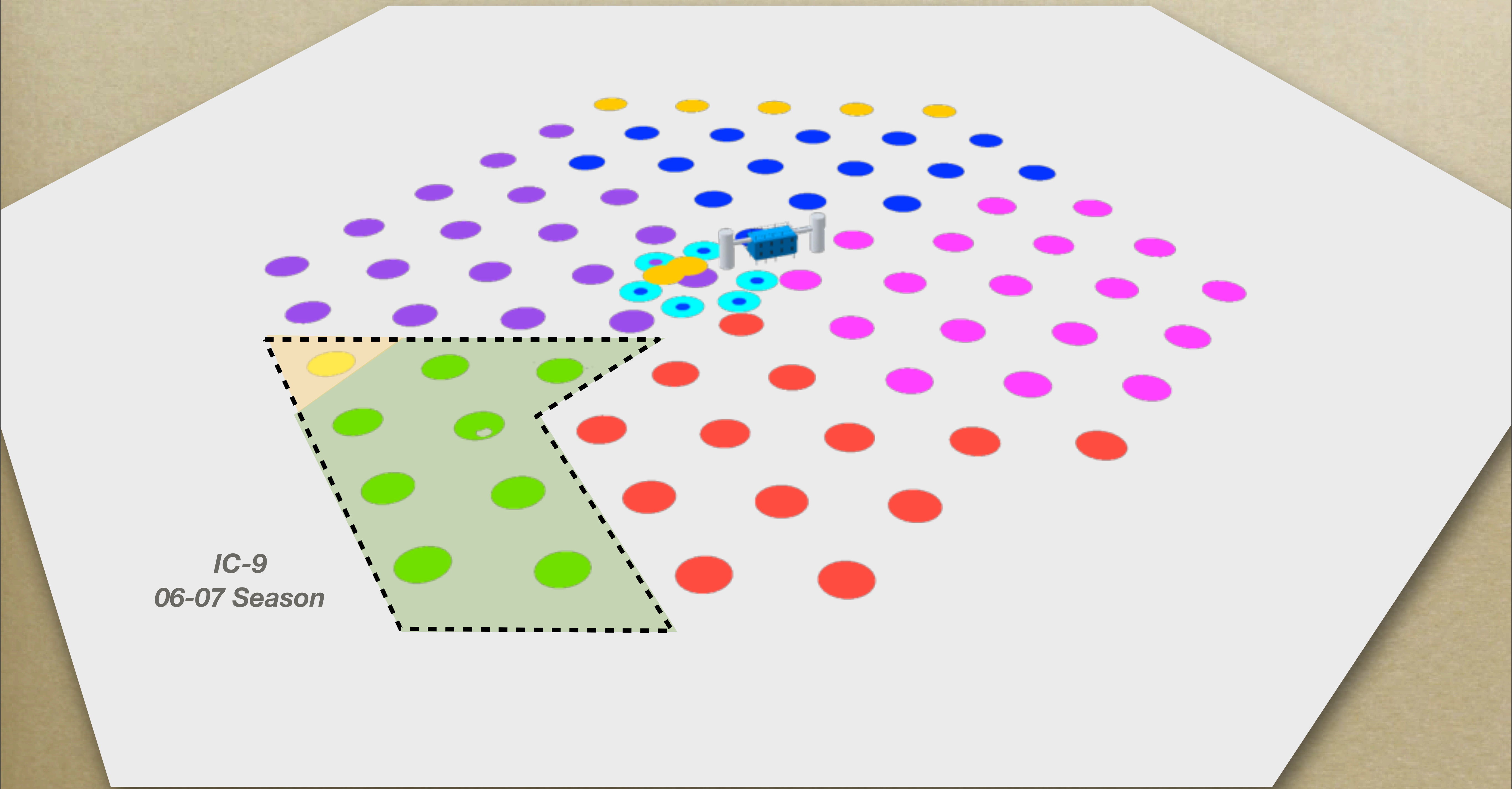
IceCube configurations



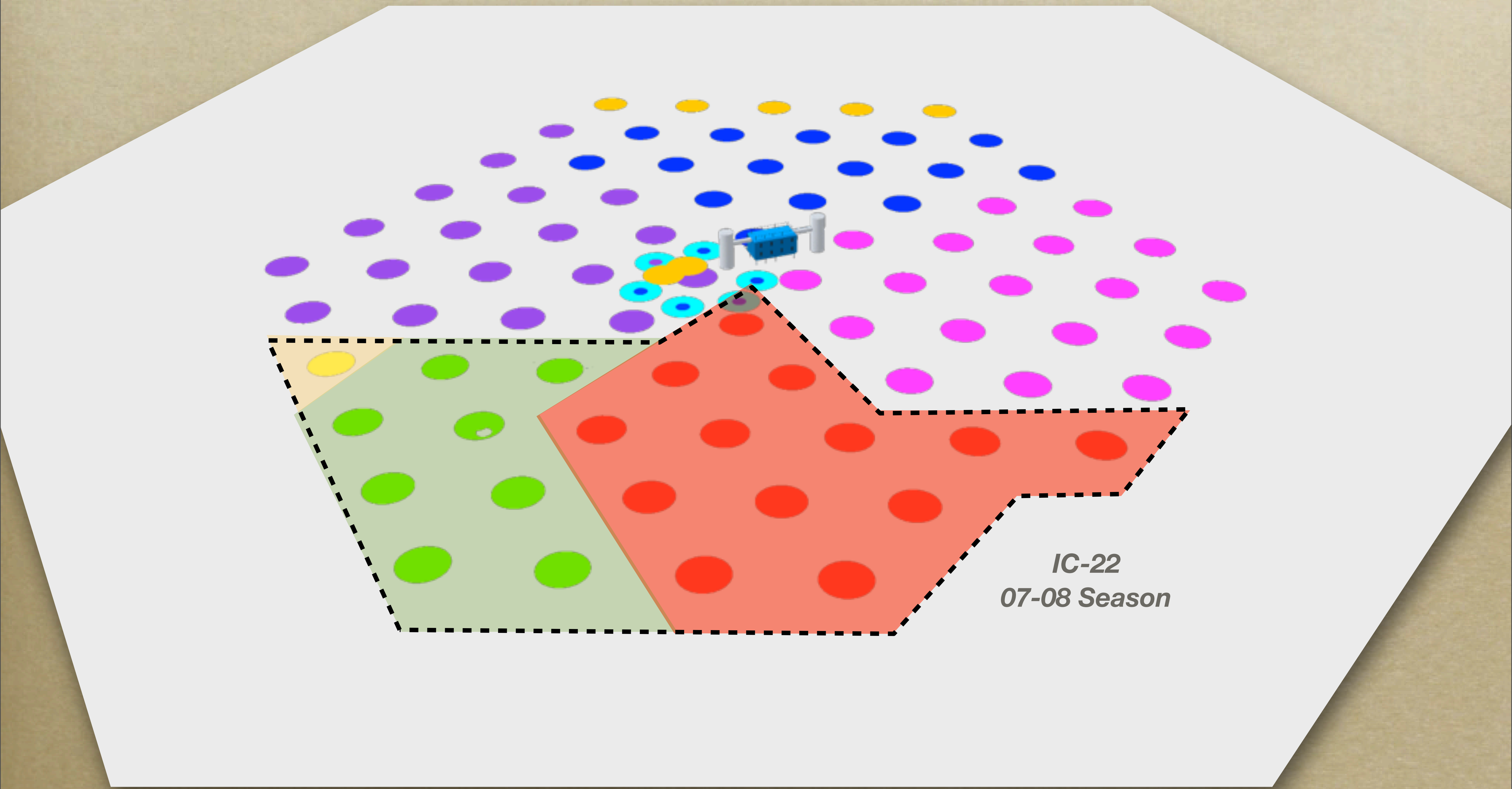
IceCube configurations



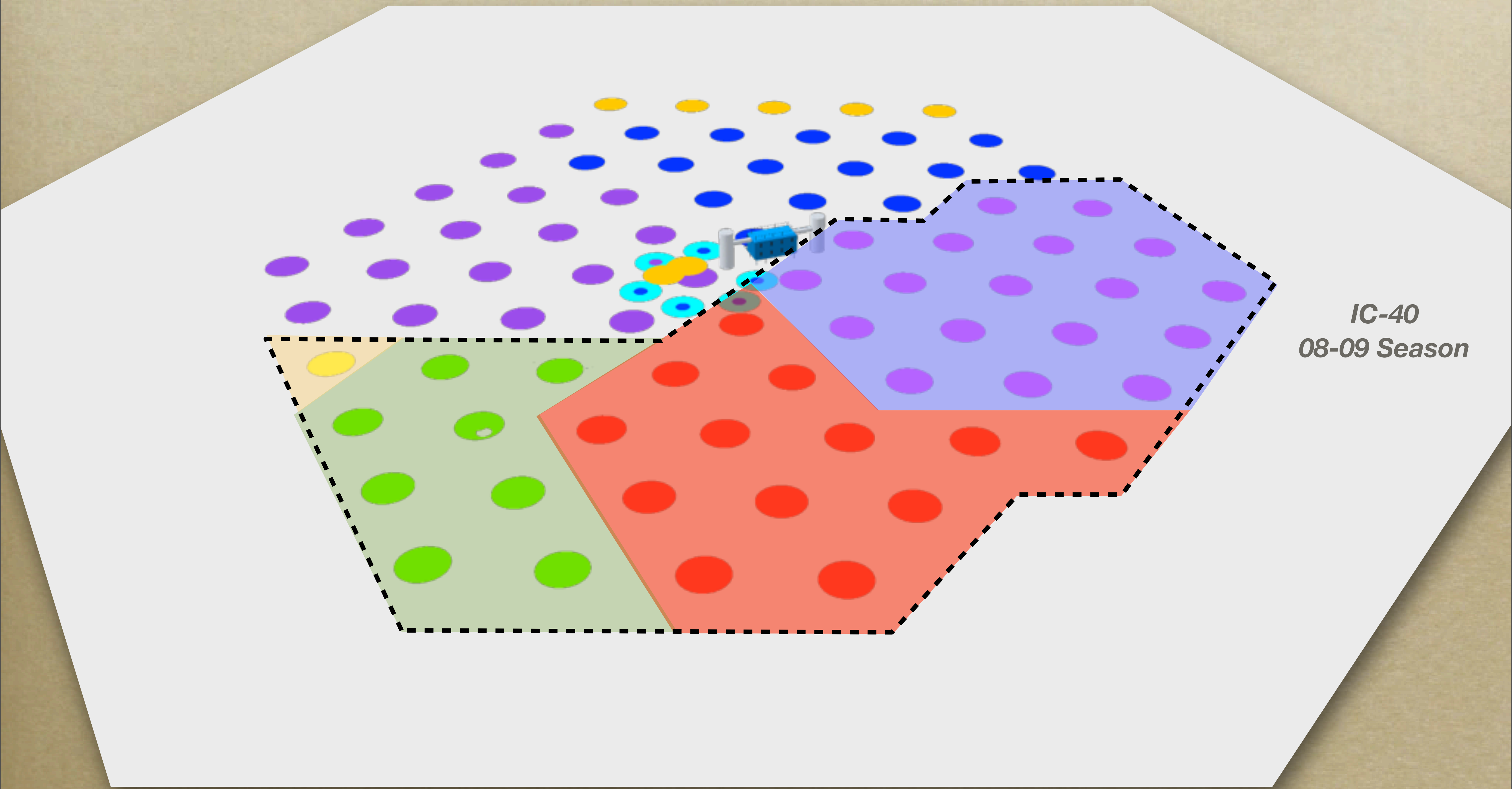
IceCube configurations



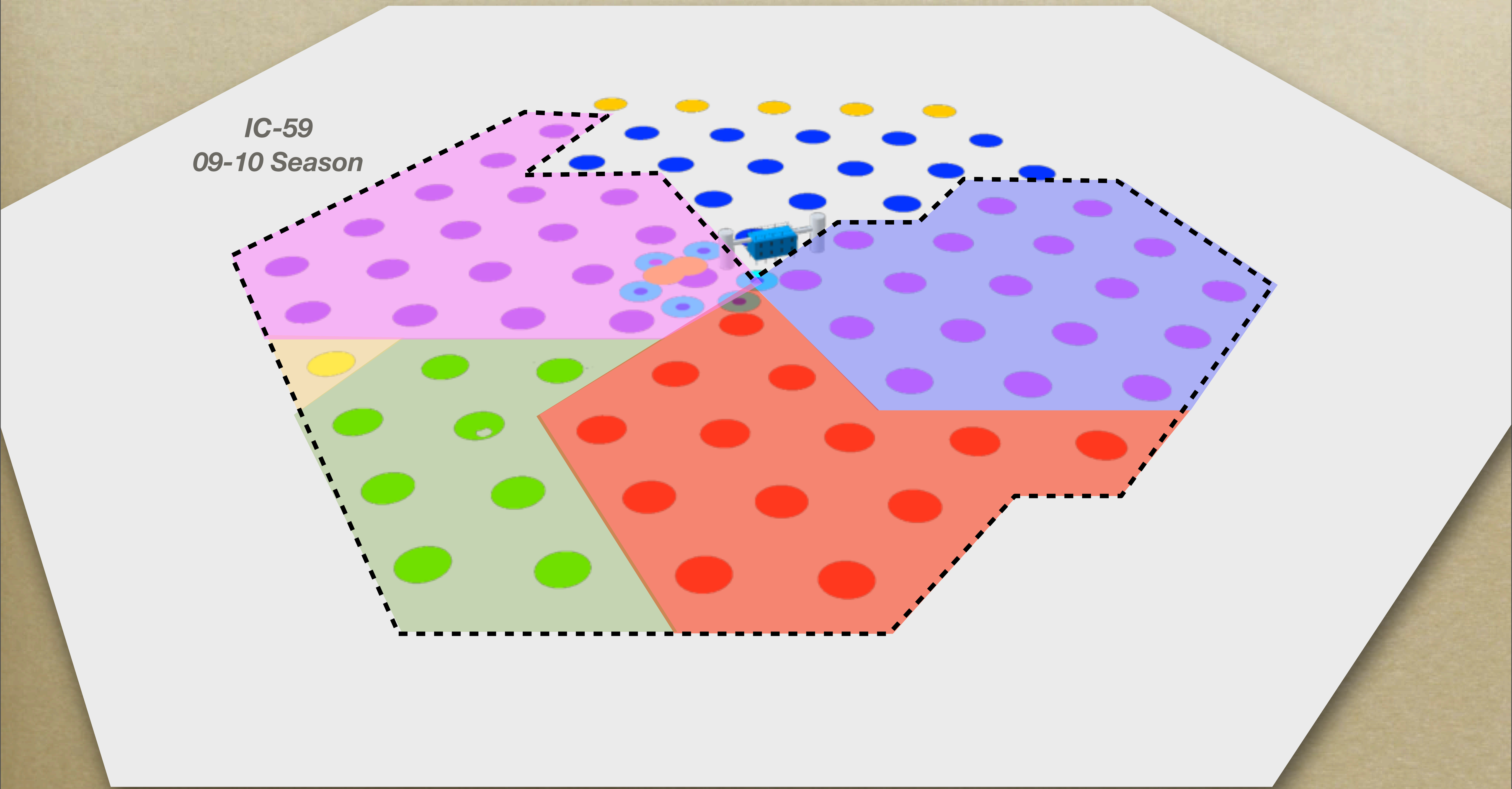
IceCube configurations



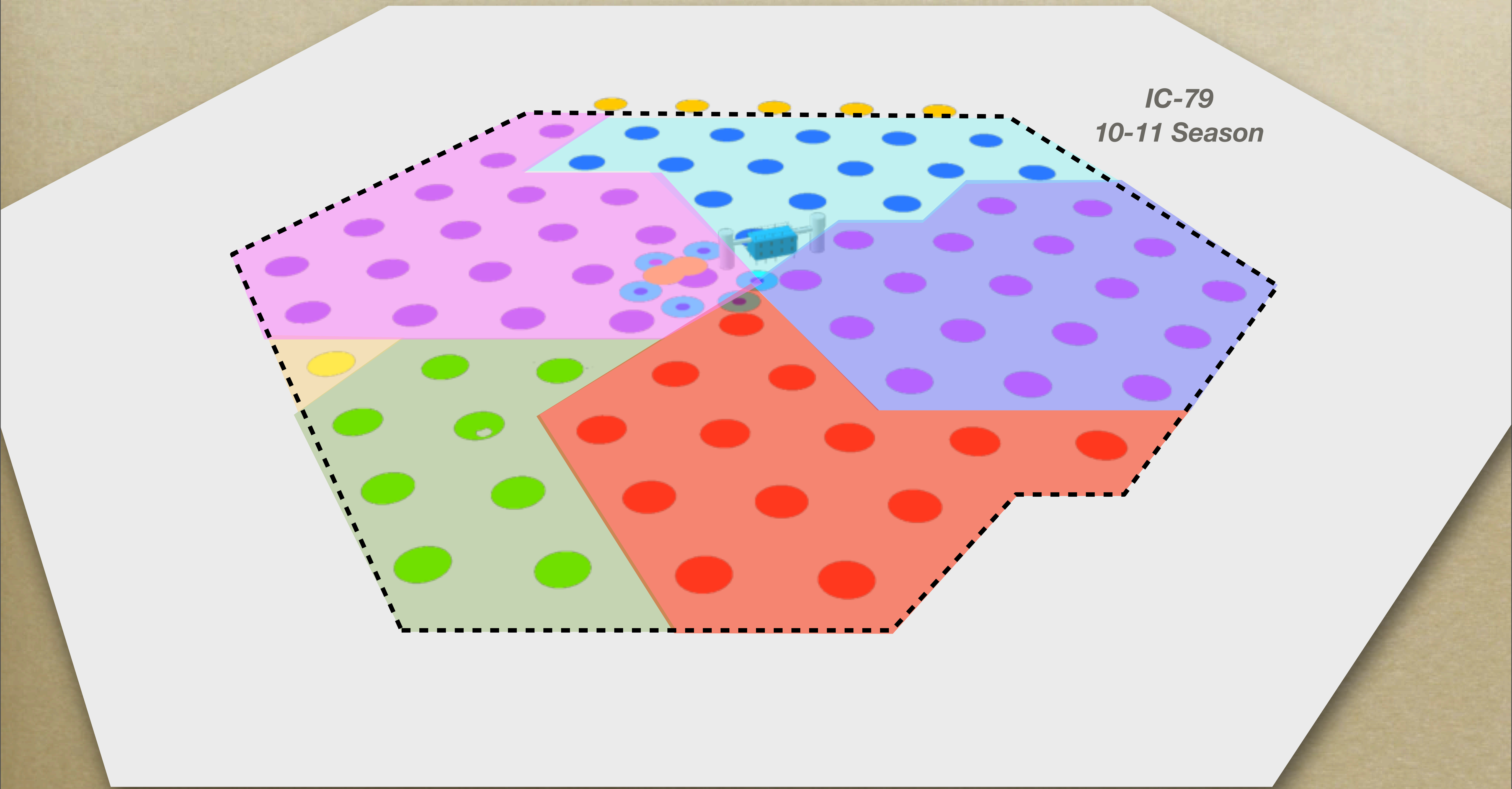
IceCube configurations



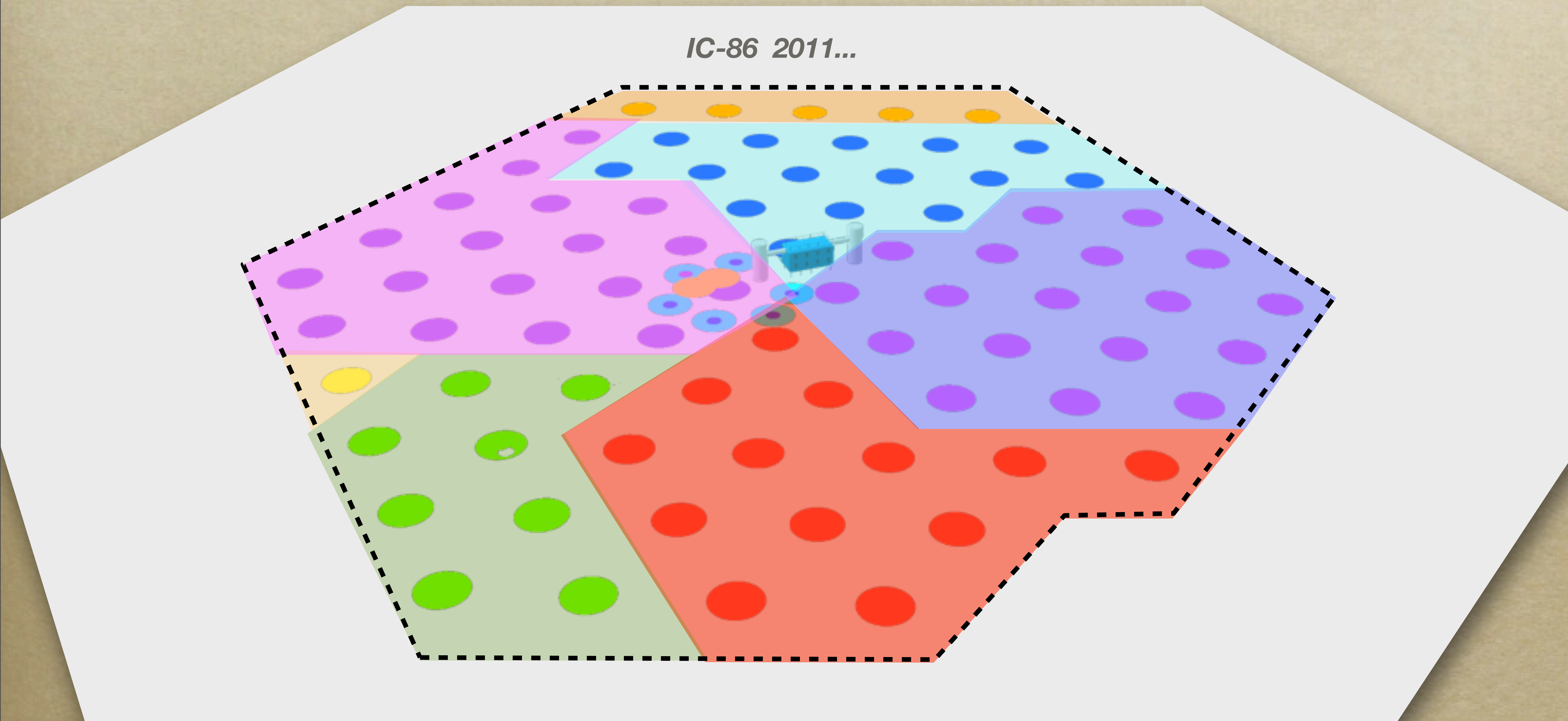
IceCube configurations



IceCube configurations

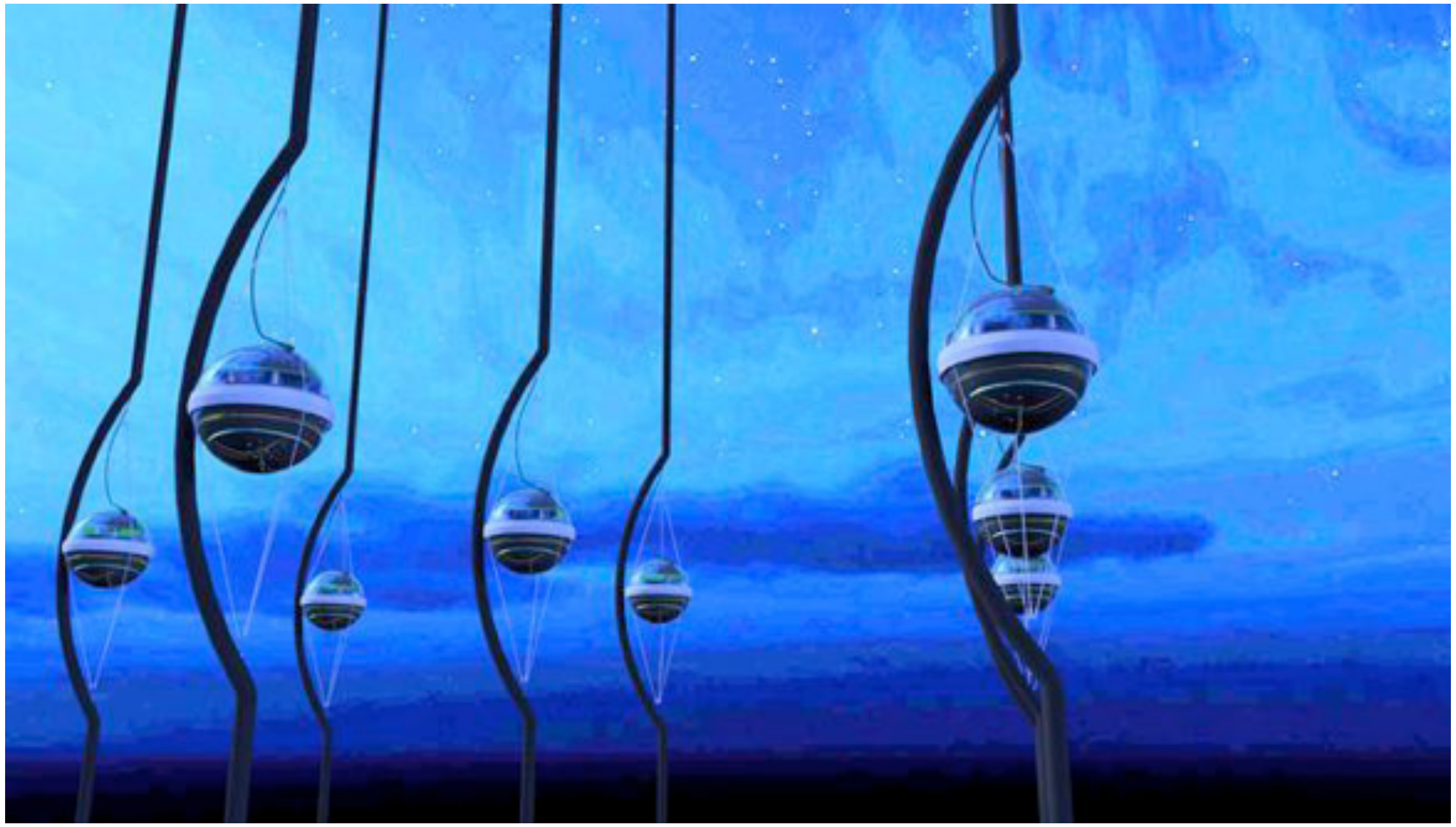


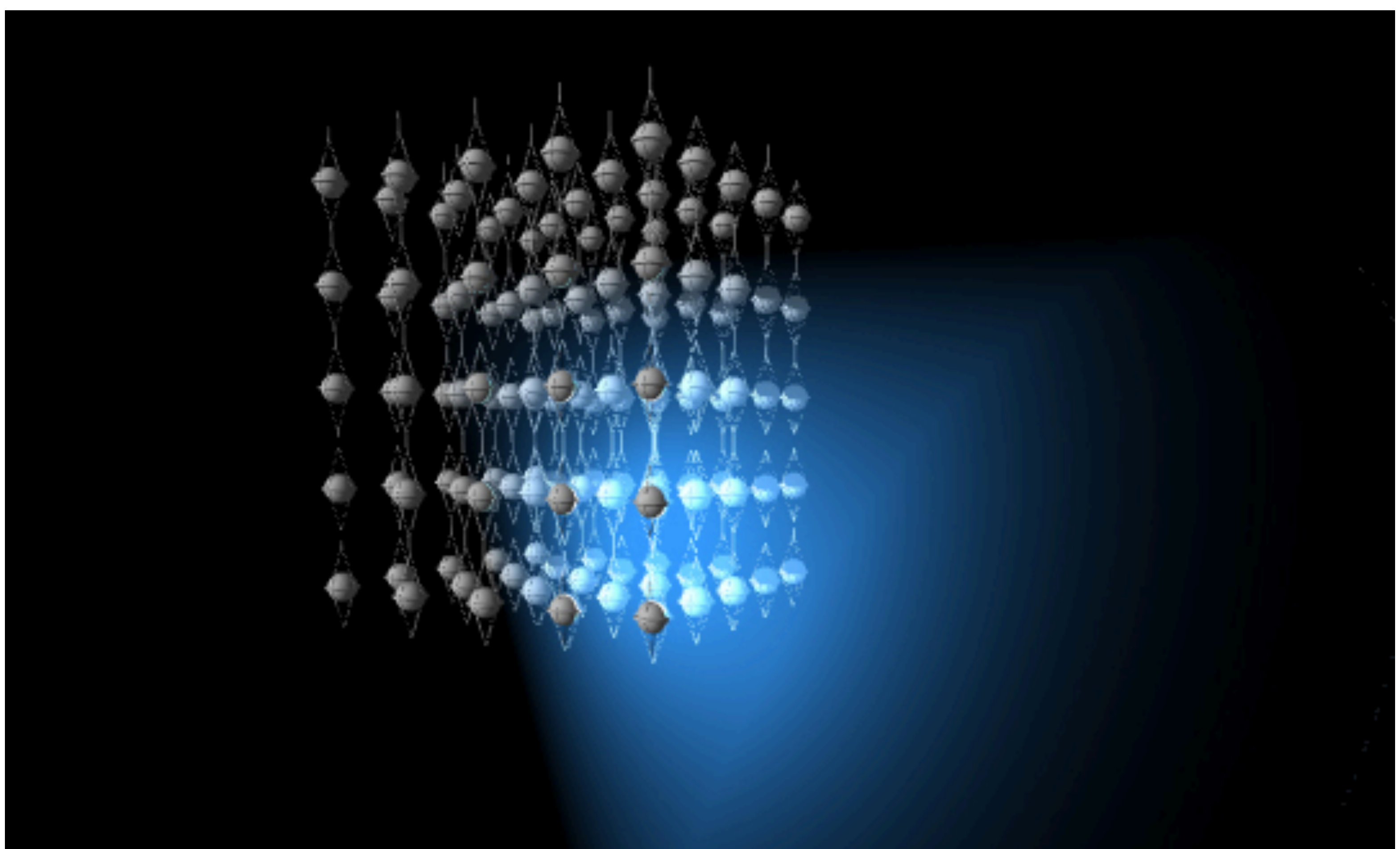
IceCube configurations

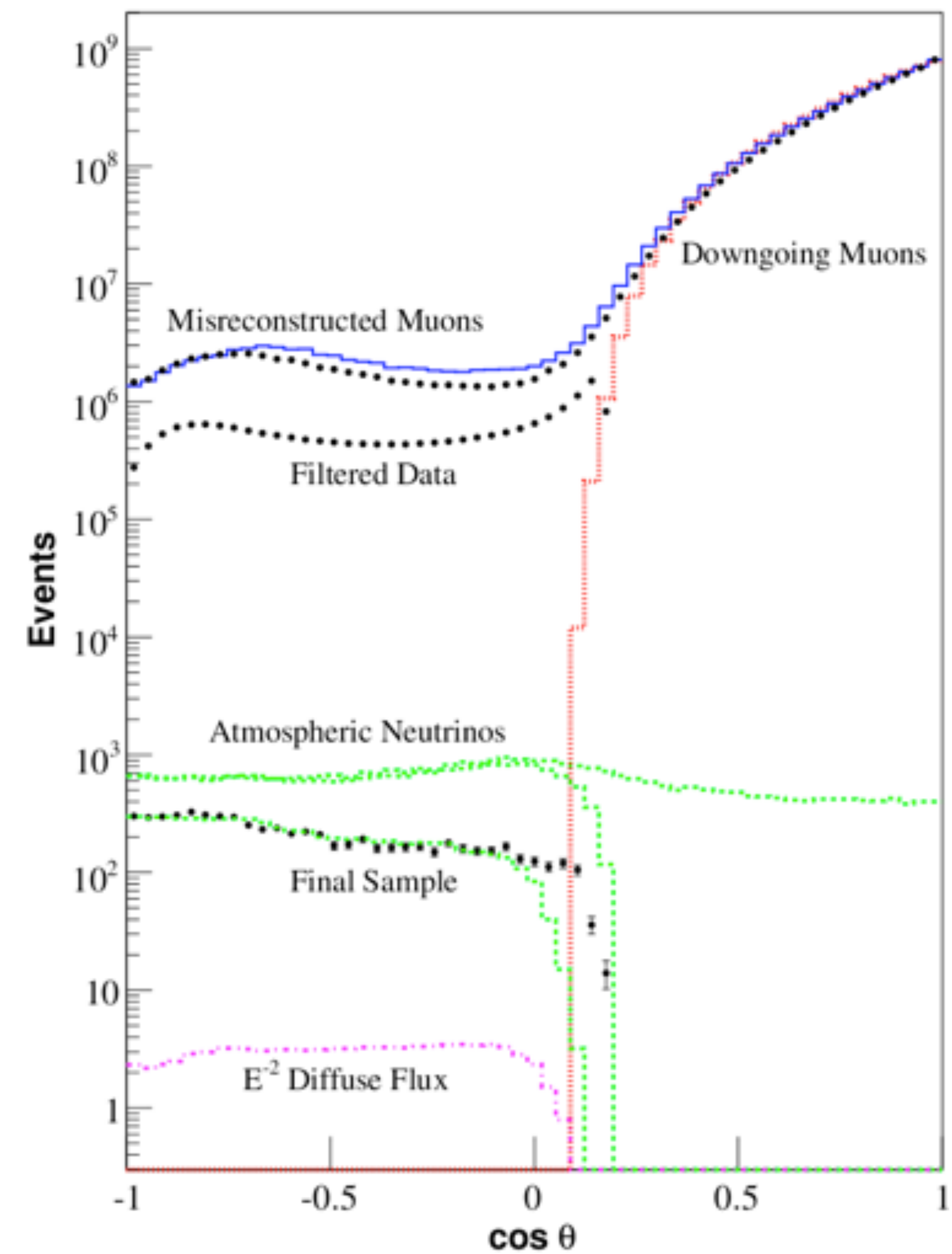


Construction finished on December 2010

Detection technique



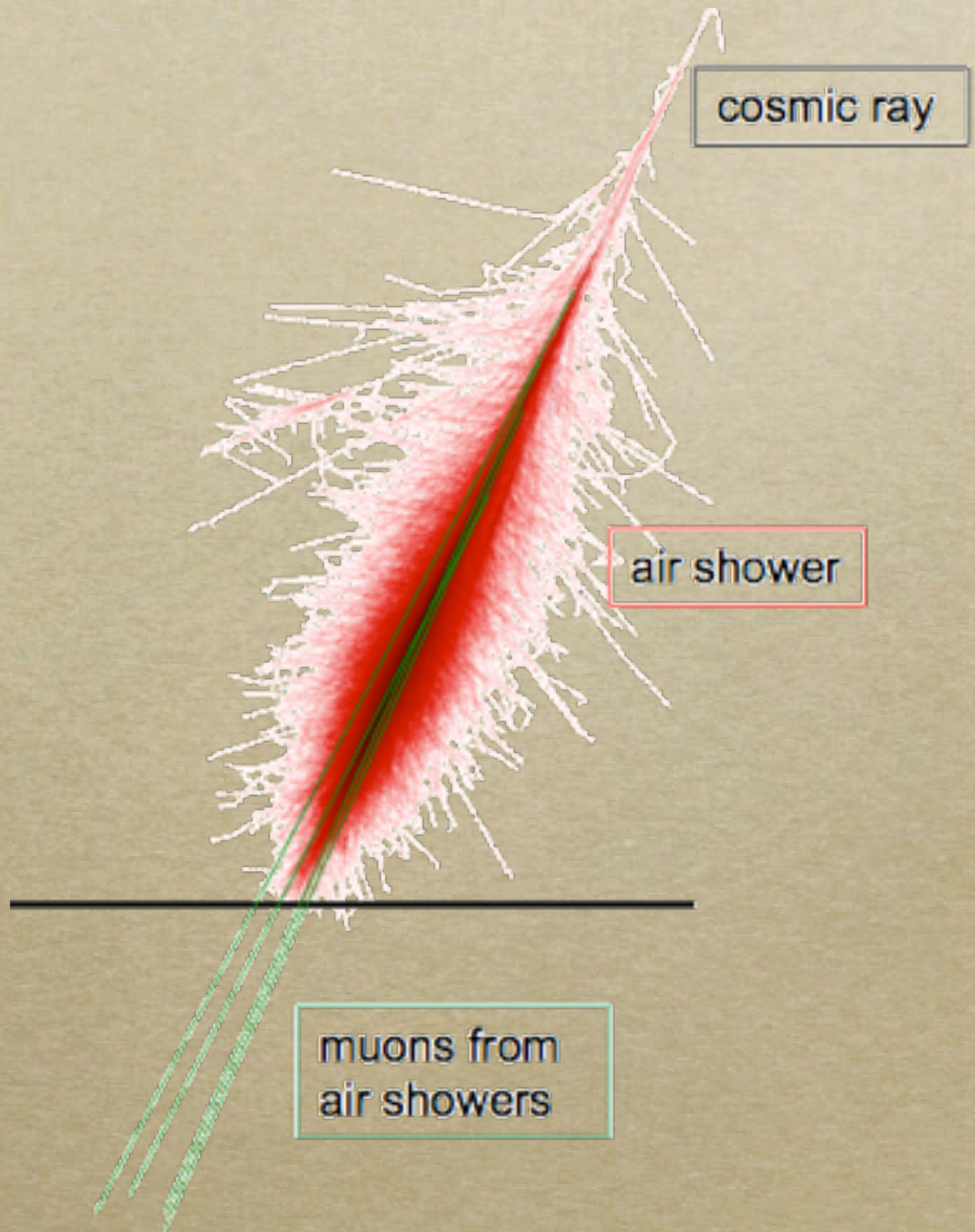




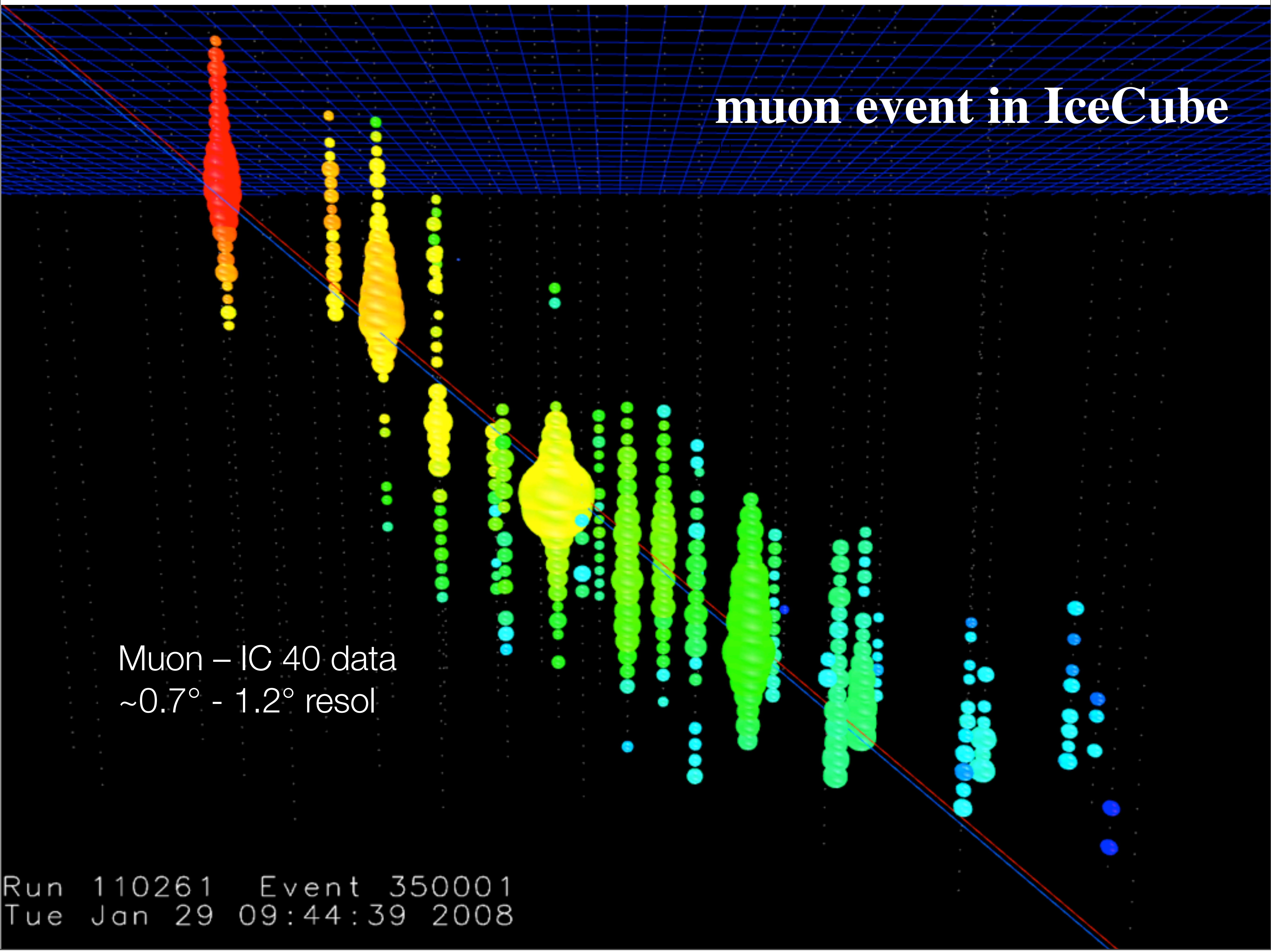
IC86 μ rate = 2 kHz
(~ 10^6 ν rate)

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.



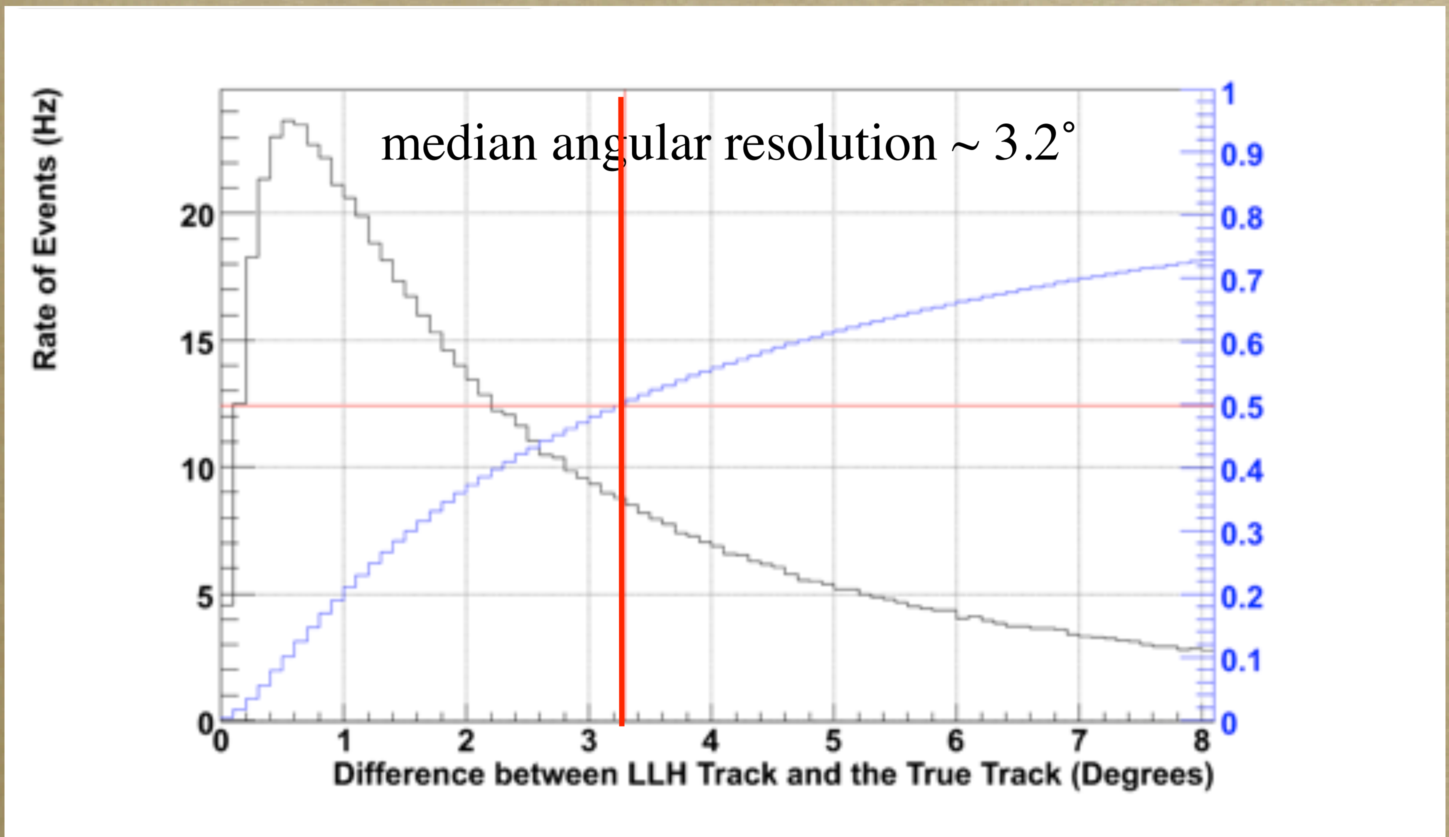
By detecting downgoing muons, IceCube can study the *arrival direction distribution of cosmic rays* in the energy range ~10 TeV to several 100 TeV and produce a cosmic ray sky map of the southern sky.

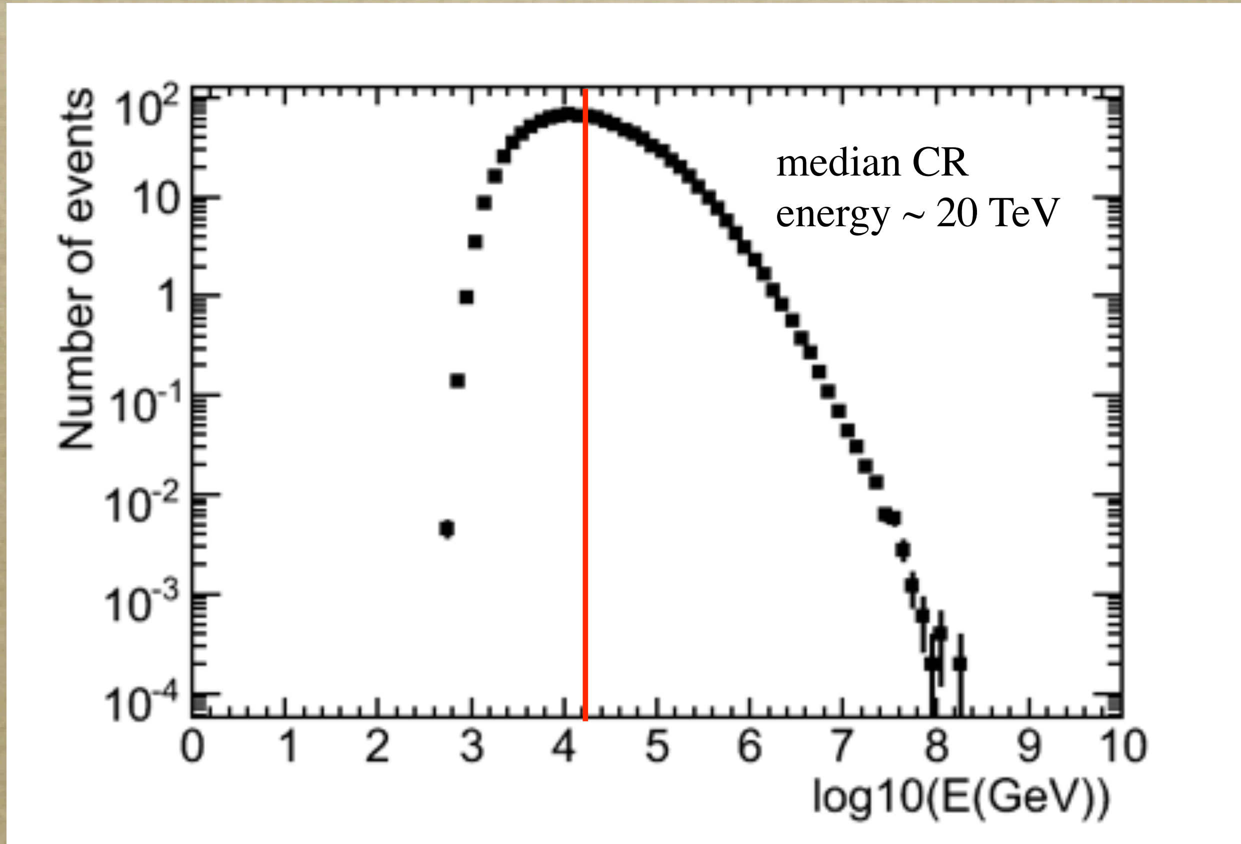

muon event in IceCube
Muon – IC 40 data
~0.7° - 1.2° resol
Run 110261 Event 350001
Tue Jan 29 09:44:39 2008

IceCube muon (bundles) data

detector	trigger rate (Hz)	actual time (days)	livetime (days)	number of events(*)
IceCube-22	500	300	226	5.4×10^9
IceCube-40	1,100	358	324	19×10^9
IceCube-59	1,700	367	334.5	34×10^9
IceCube-79	2,000	344	320	39×10^9
IceCube-86	2,500	365	365	50×10^9

(*) number of events with LLH reconstruction from online-filter collected by DST





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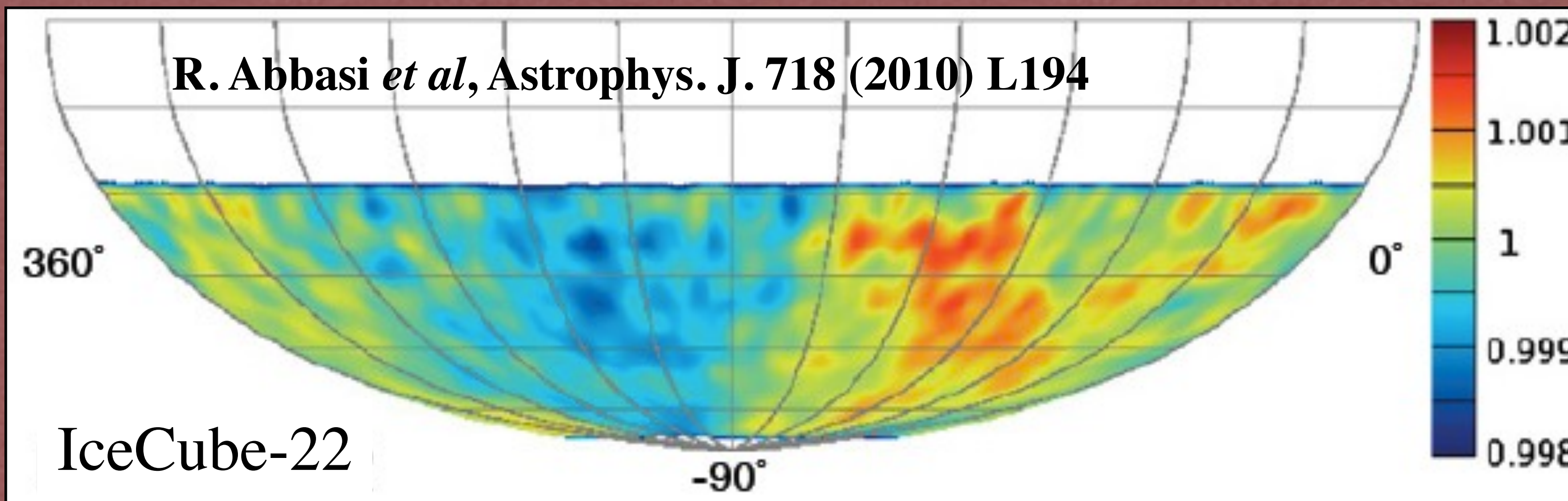
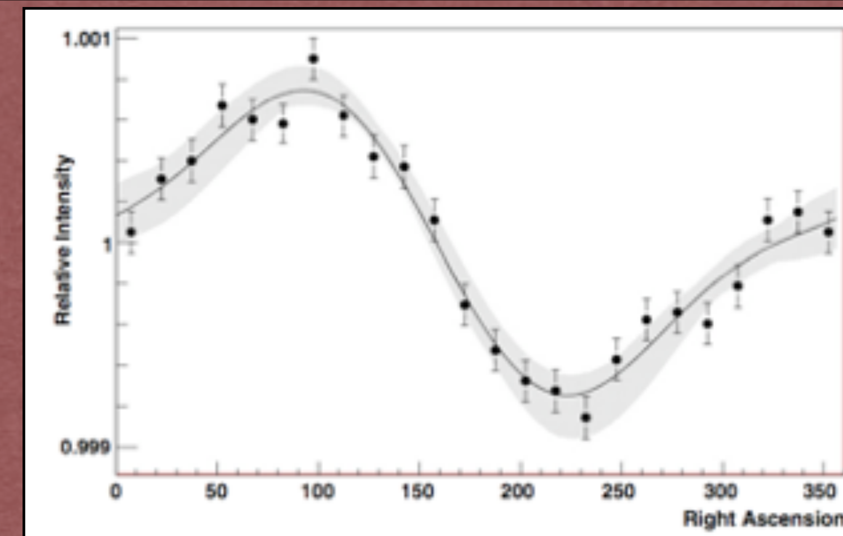
Cosmic ray anisotropy in IceCube

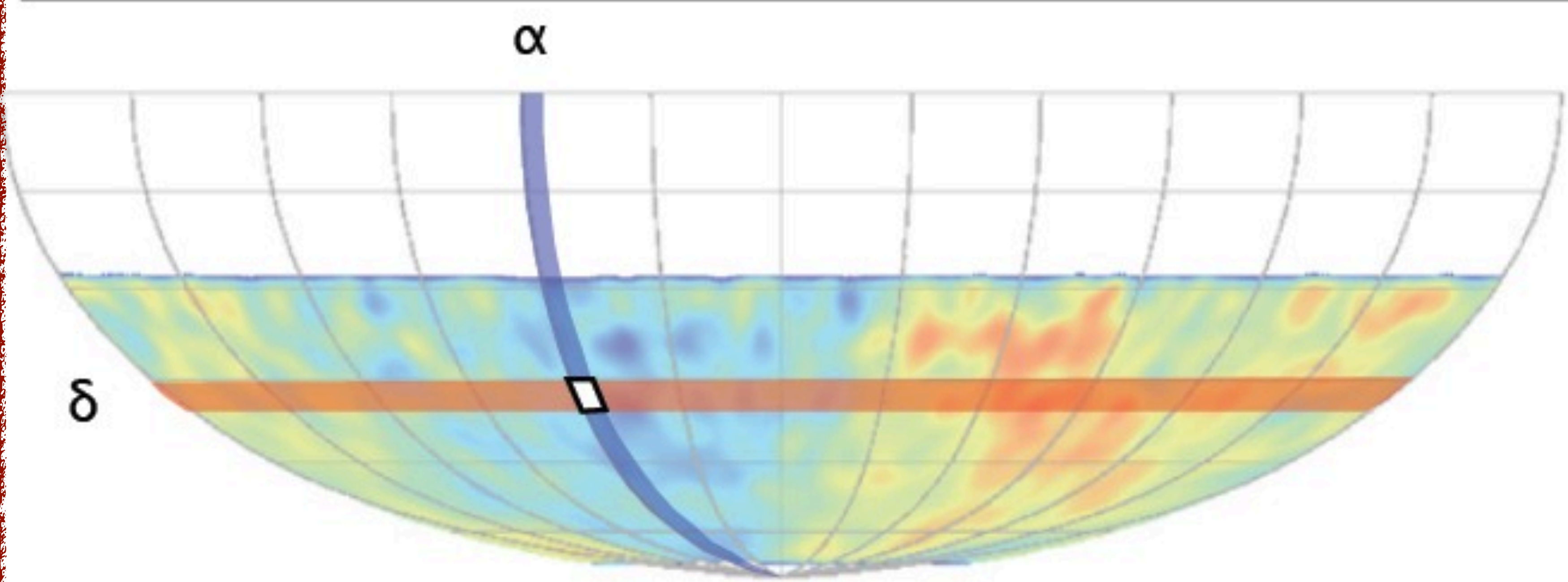
Relative Intensity - Equatorial coordinates





global fit on 1D RA with *dipole* + *quadrupole* terms

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



relative intensity

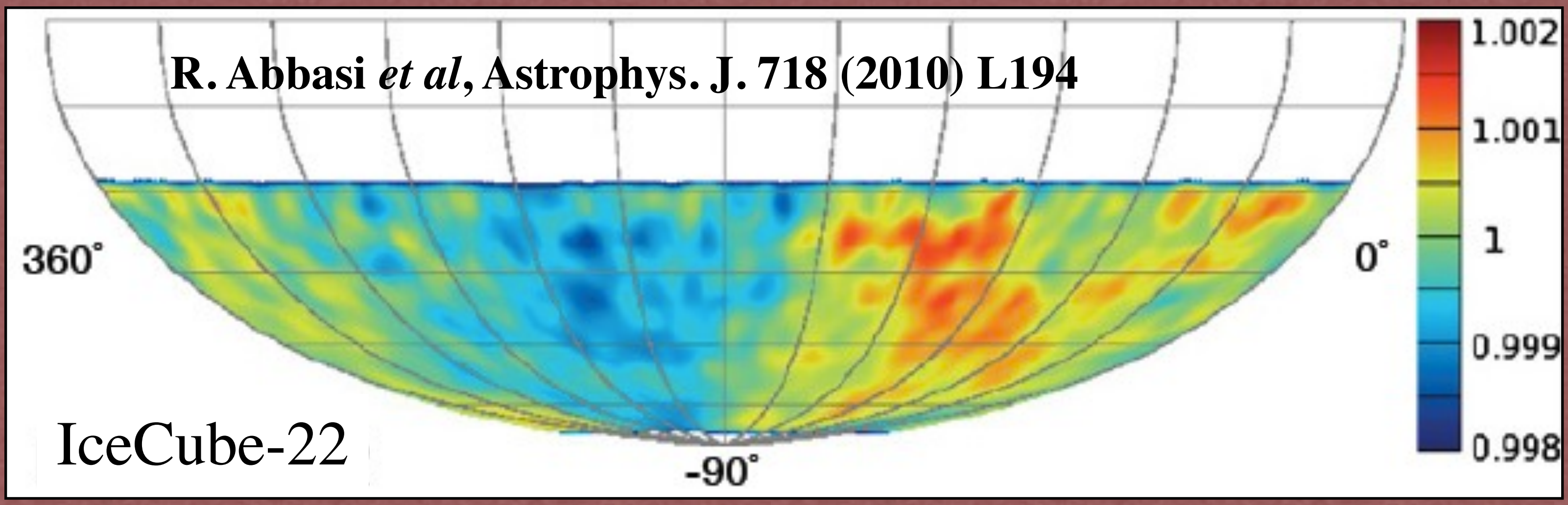
$$I_i = \frac{N_i(\alpha, \delta)}{\langle N_i(\delta) \rangle_\alpha}$$

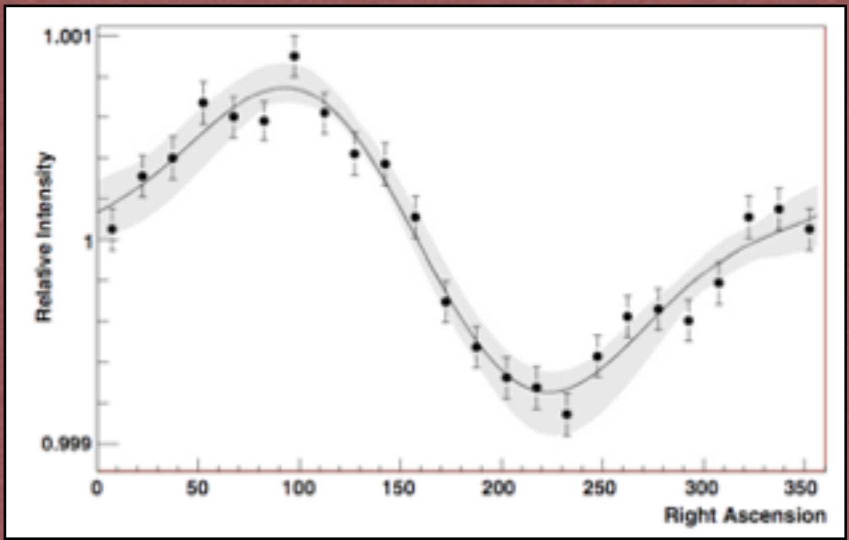
Wednesday, April 18, 2012

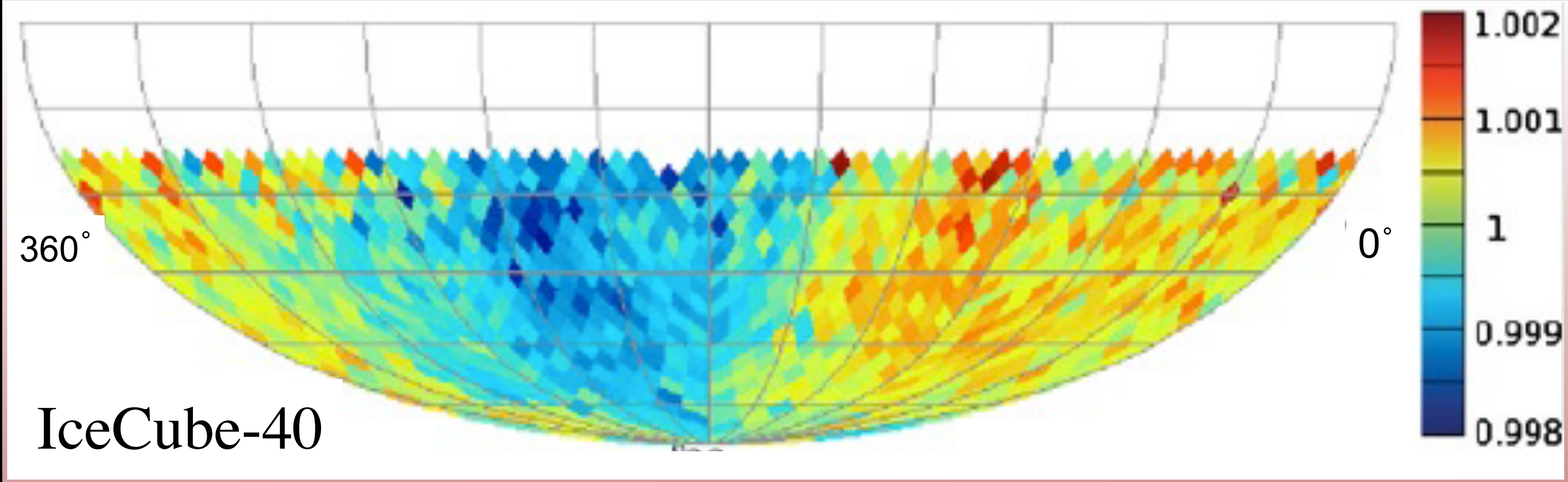
Cosmic ray anisotropy in IceCube

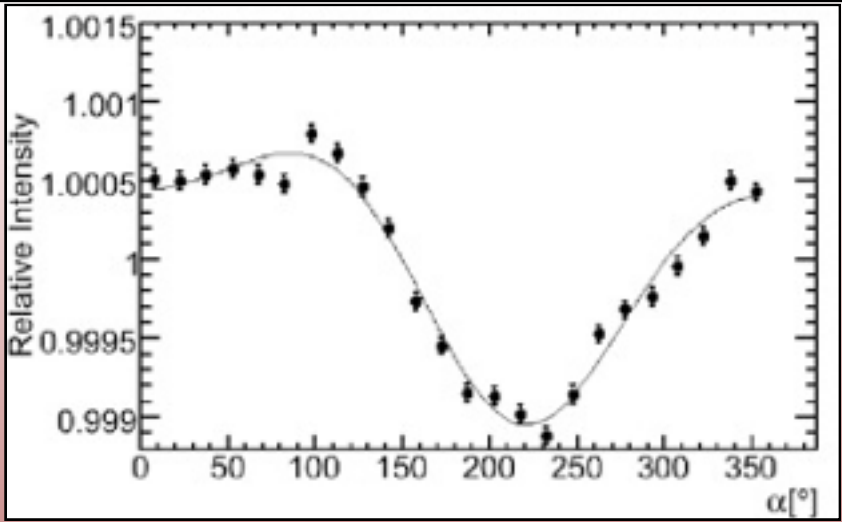
Relative Intensity - Equatorial coordinates

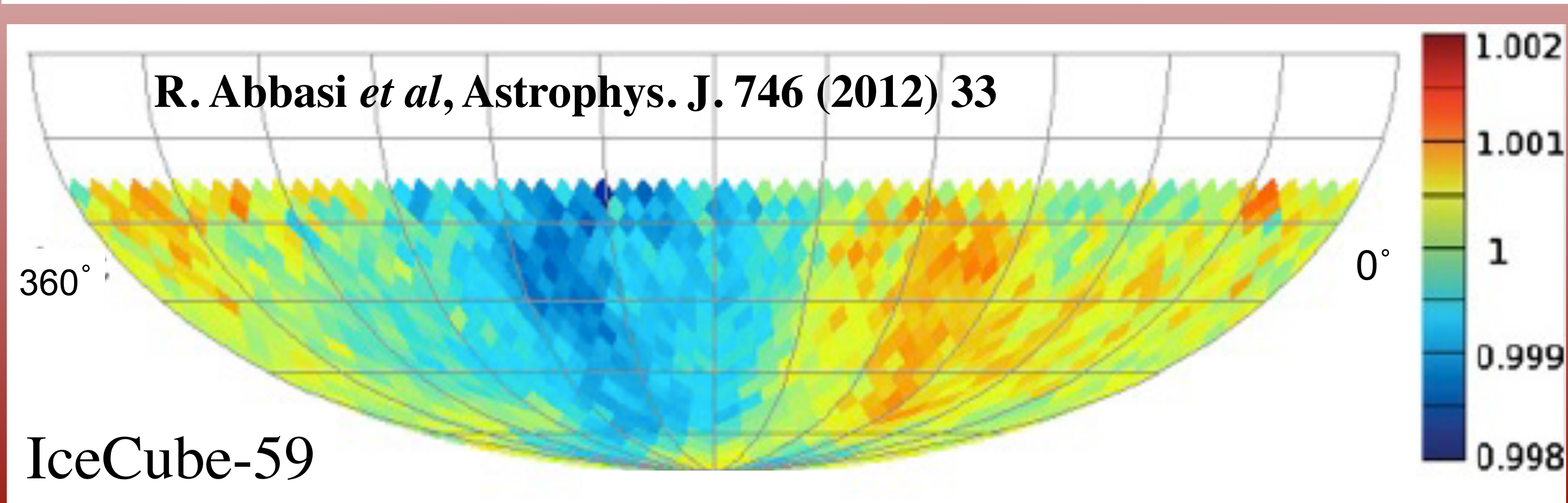
Maps in HEALPix with NSide= 16, **pix resol ~ 3°**

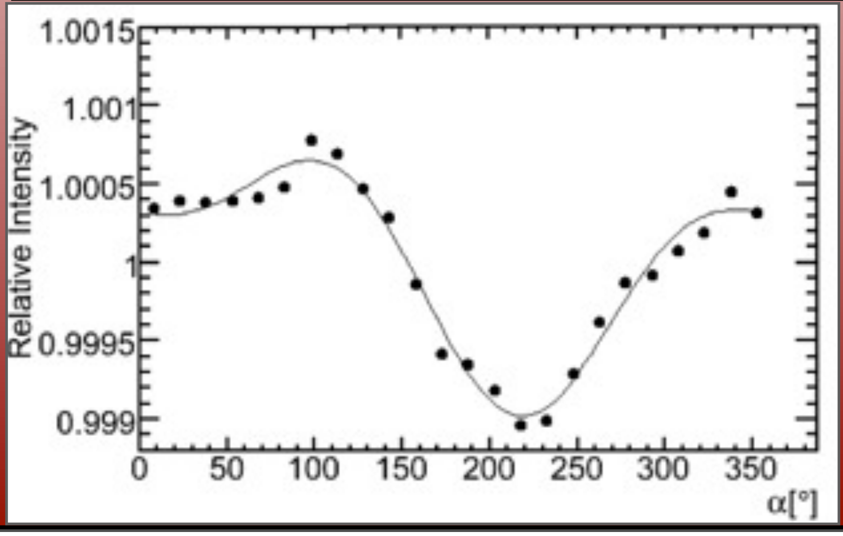








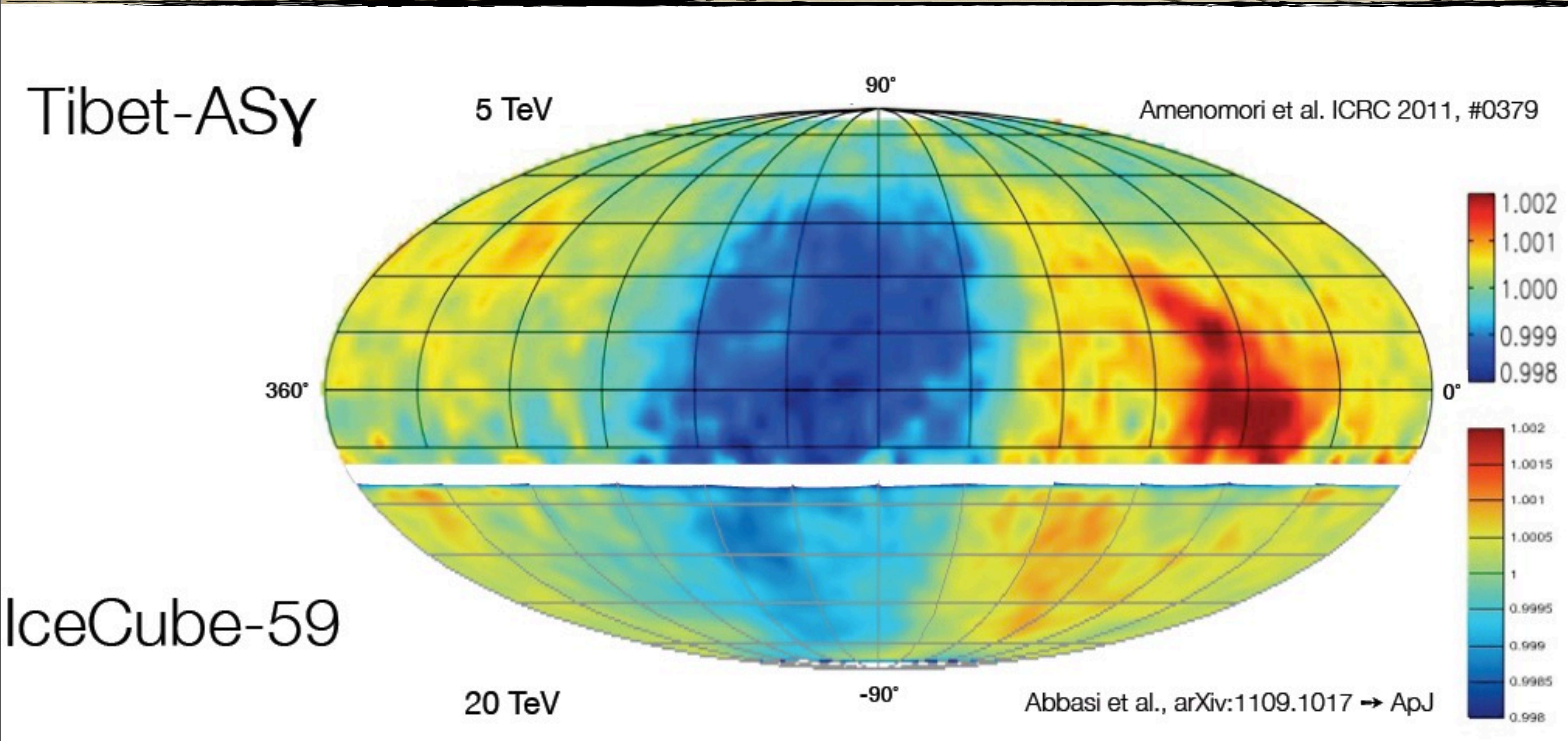




time

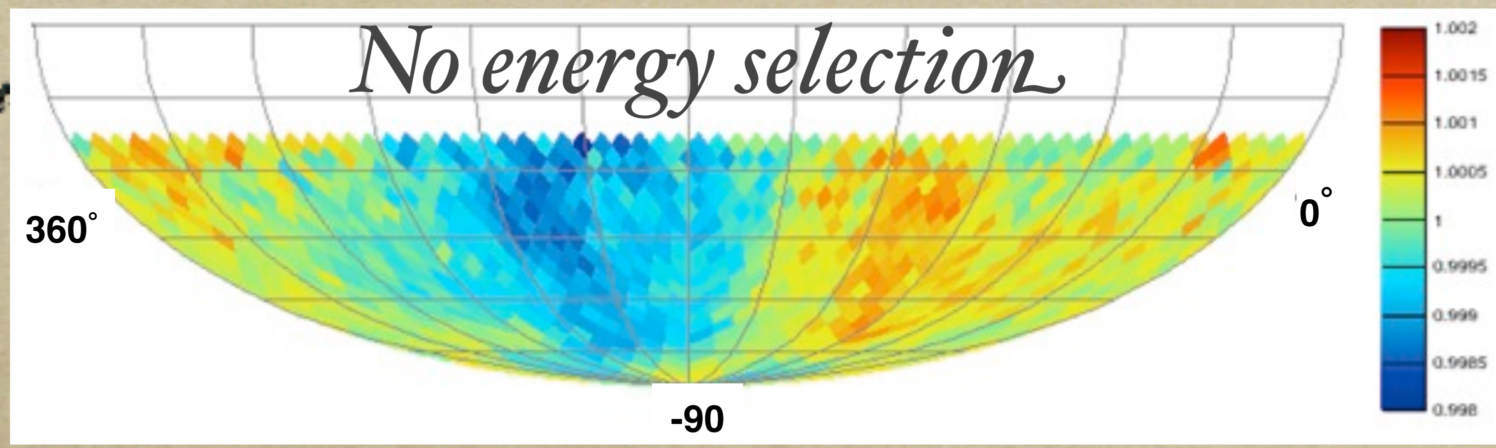
Large scale anisotropy

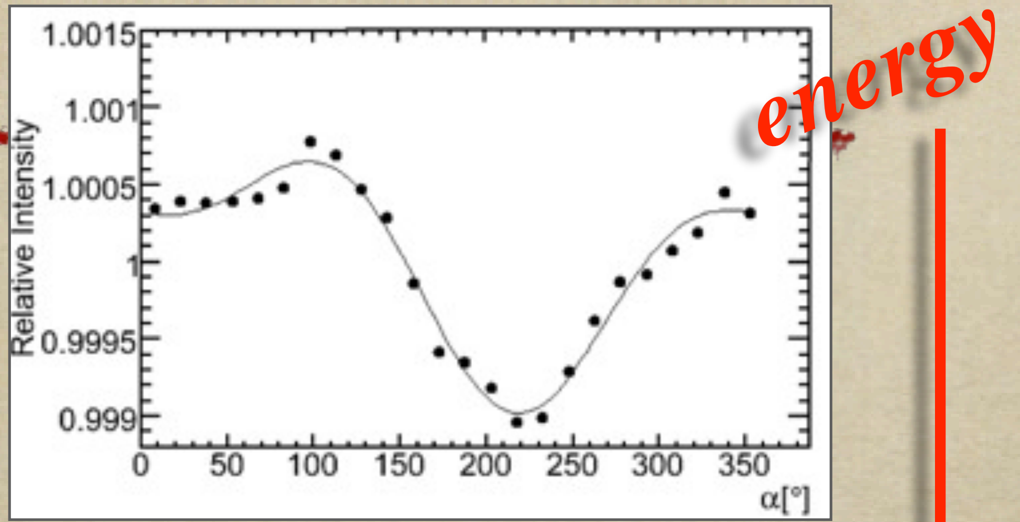
- 10^{-3} anisotropy observed in the Southern sky.
- Good match with the observations in the North

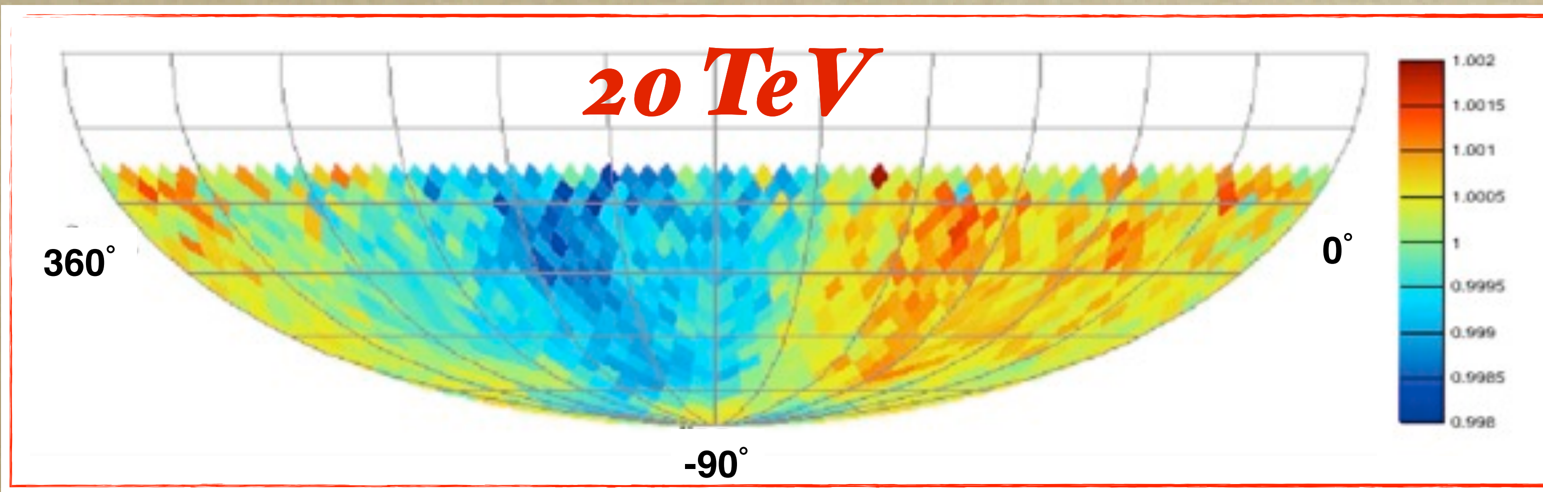


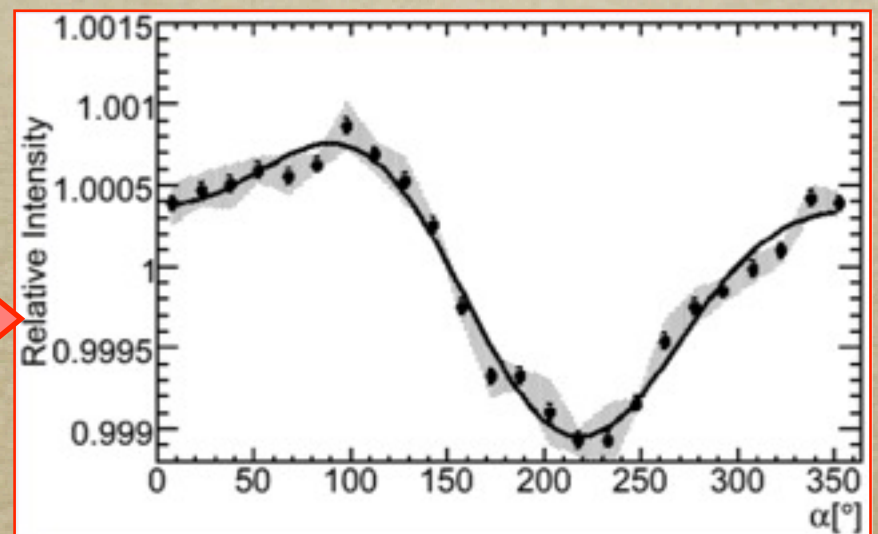
Cosmic ray anisotropy vs energy in IceCube-59

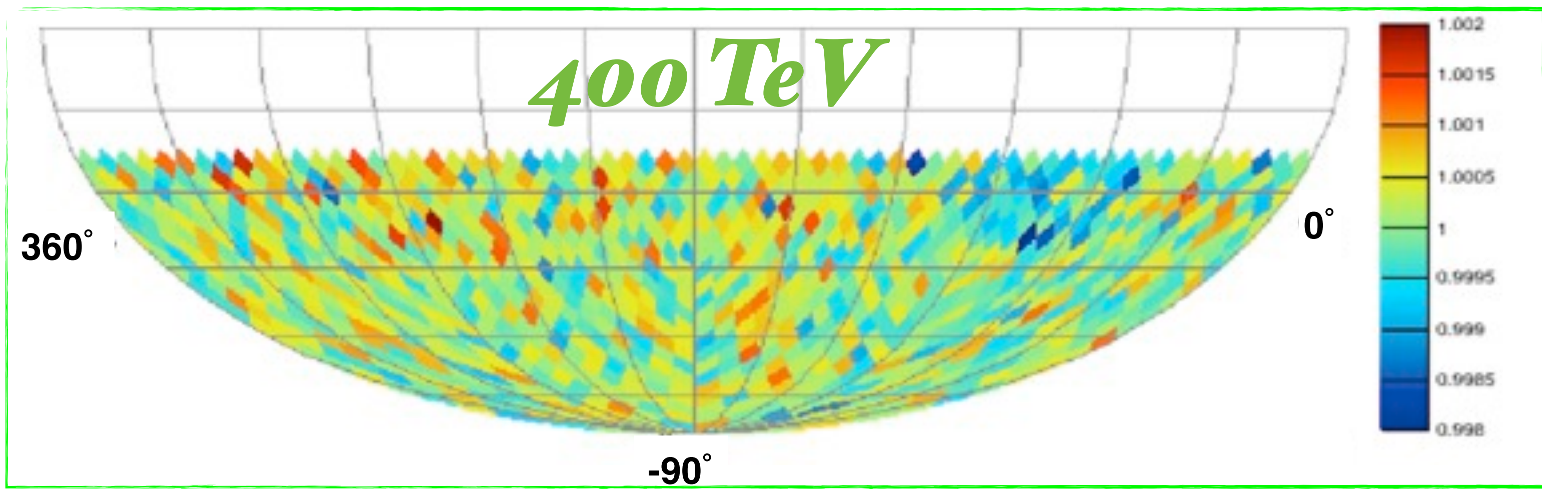
R.Abbasi et al., Astrophys.J. 746 (2012) 33

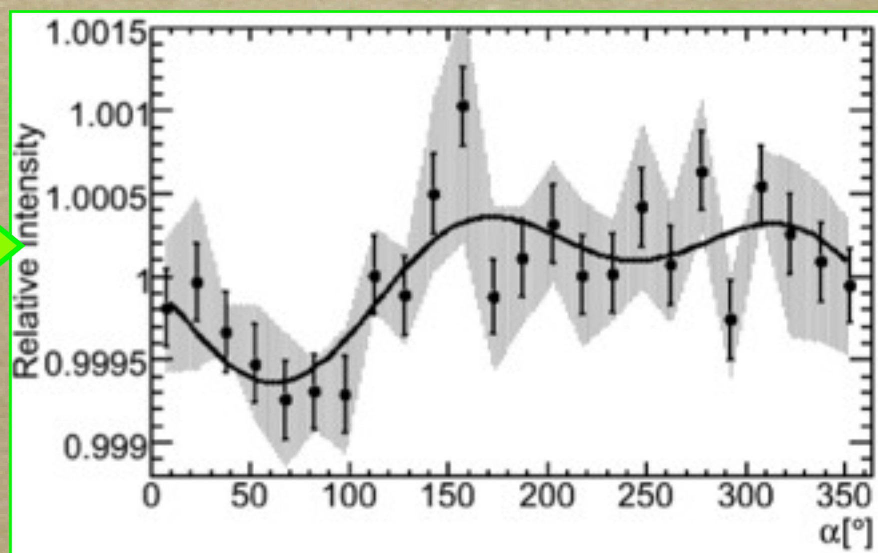












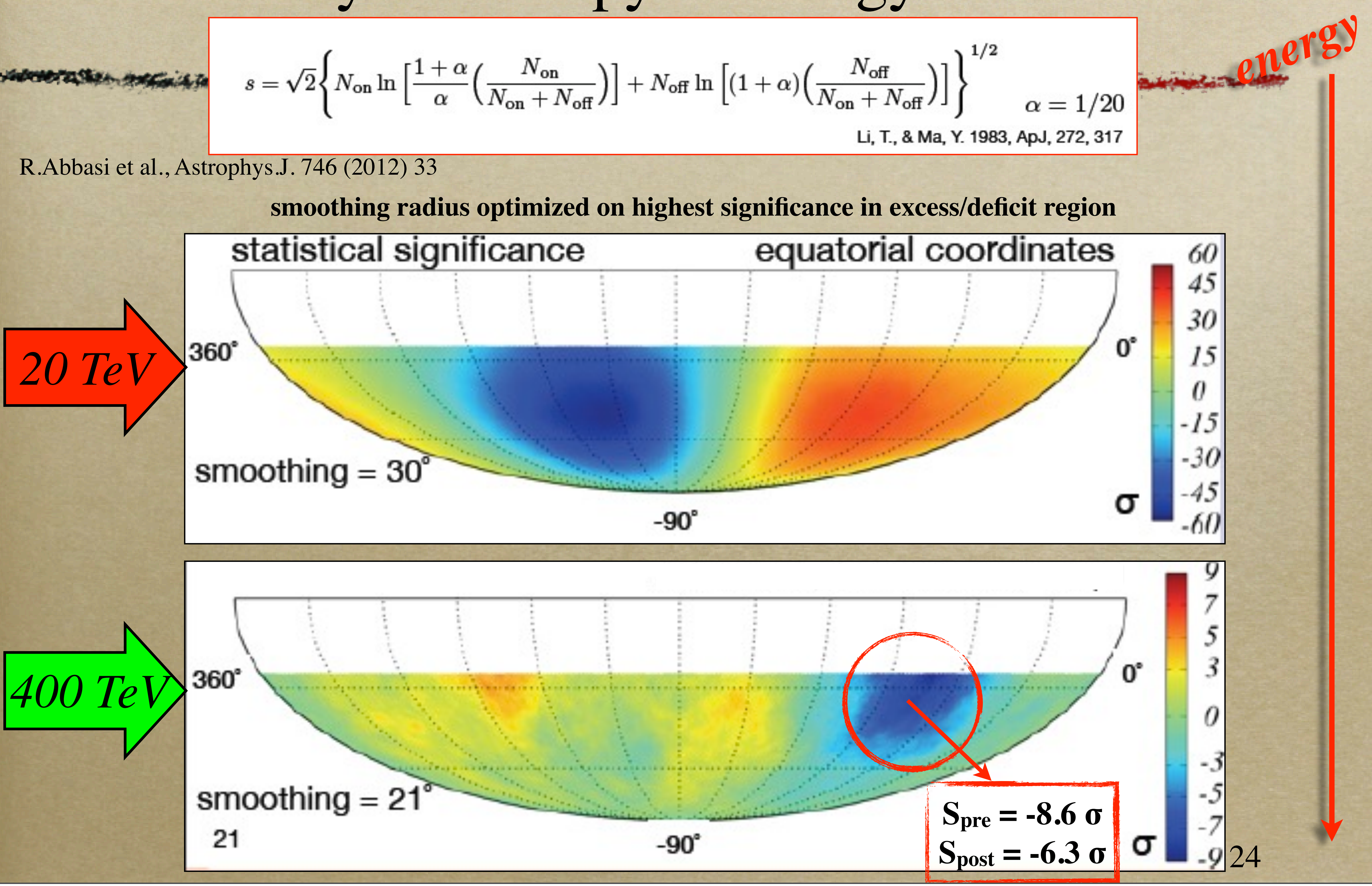
Cosmic ray anisotropy vs energy in IceCube-59

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

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

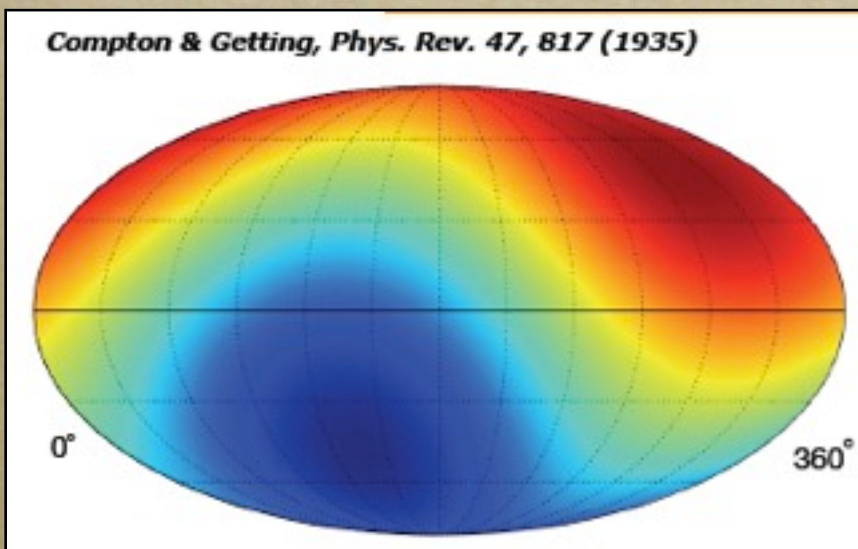
R.Abbasi et al., Astrophys.J. 746 (2012) 33

smoothing radius optimized on highest significance in excess/deficit region

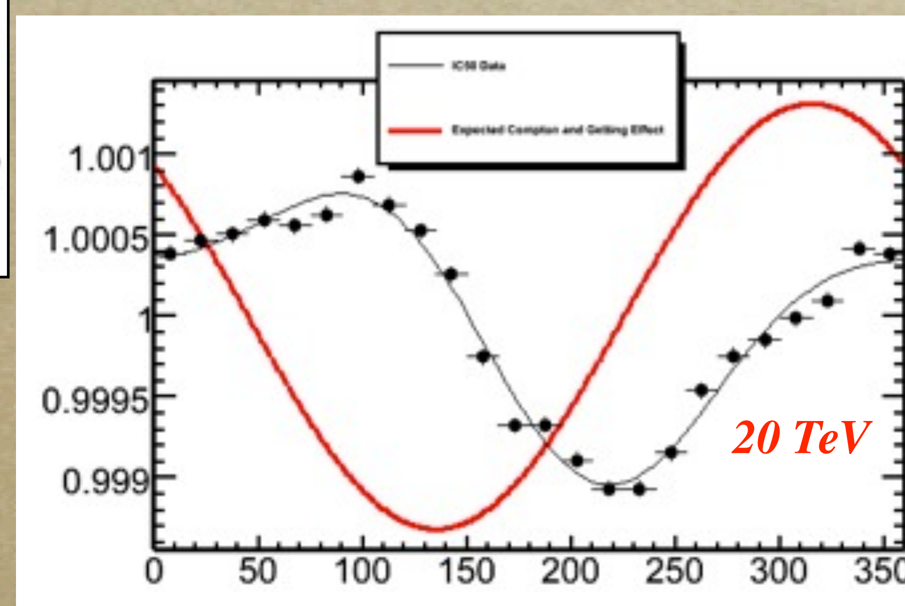


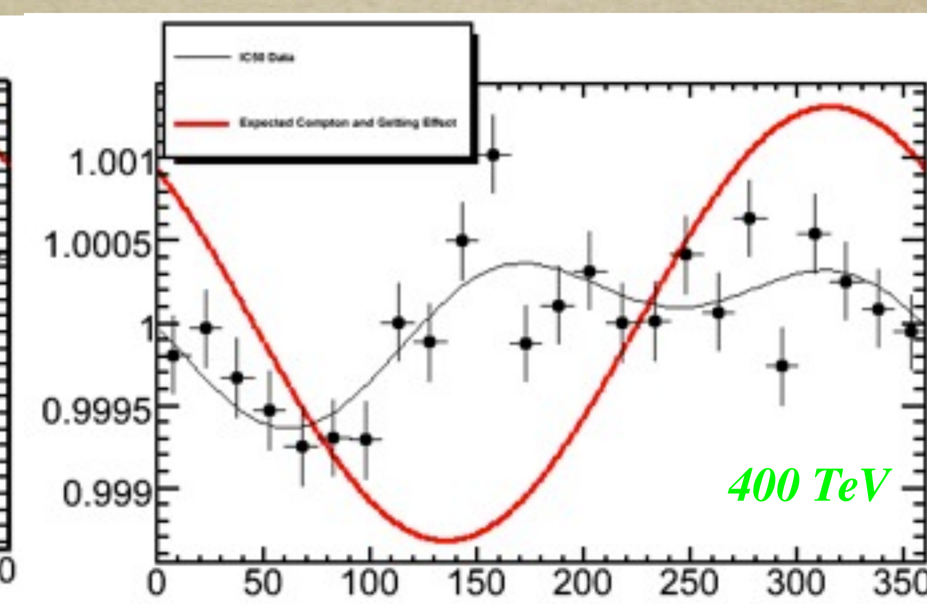
The Compton-Getting effect

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



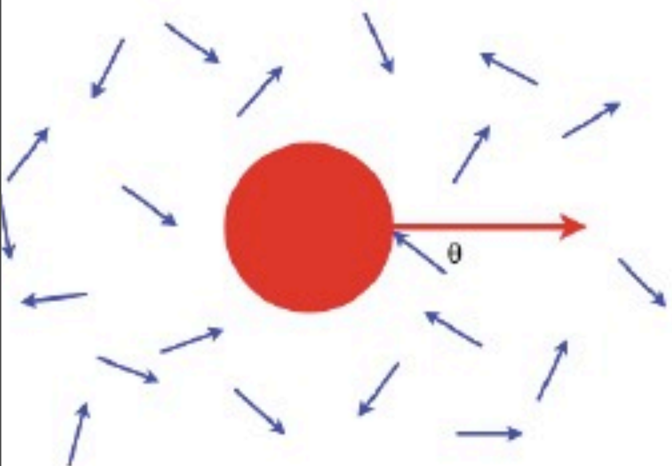
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta \qquad \gamma = 2.7 \quad \text{cosmic ray spectral index} \qquad v = 220 \text{ km/s} \quad \text{speed}$$





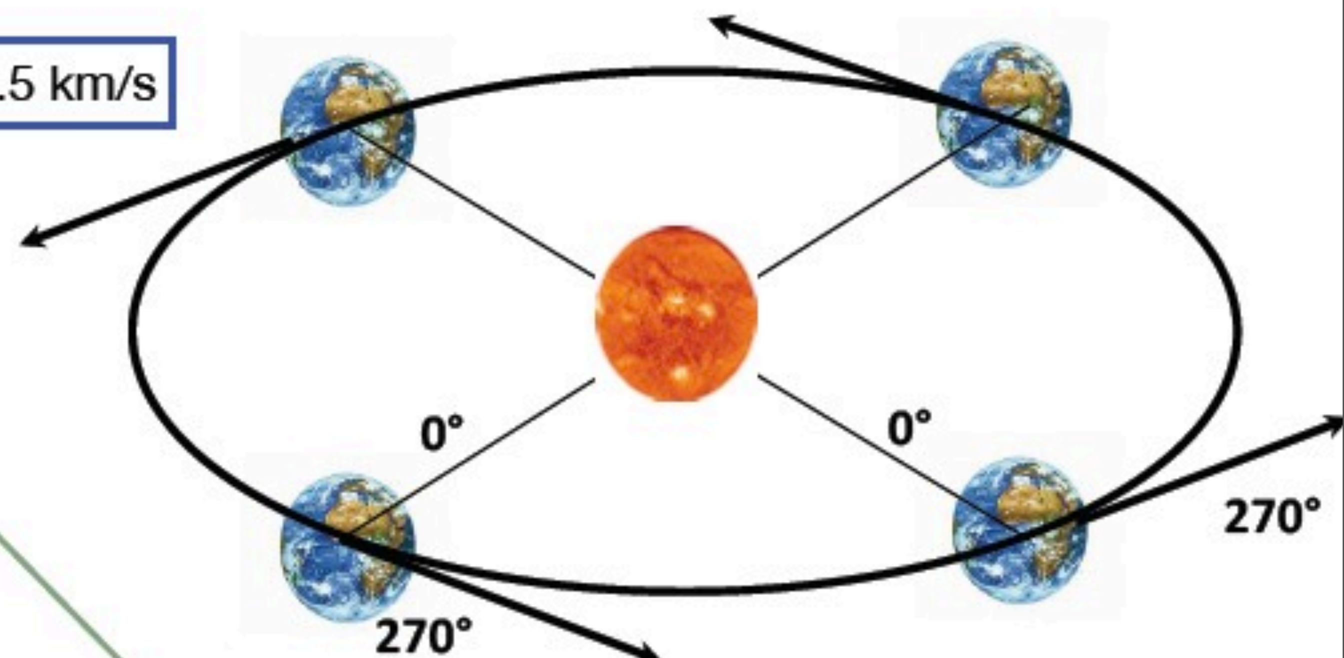
- Motion of cosmic ray plasma is **not known**... but assuming cosmic rays are at rest with respect to the galactic center, we should observe a dipole of 0.35%, **inclined relative to the equatorial plane**.
- The **anisotropy** does **NOT** have the right phase to be explained by the Compton-Getting effect.

Earth motion around the Sun: the Solar Dipole

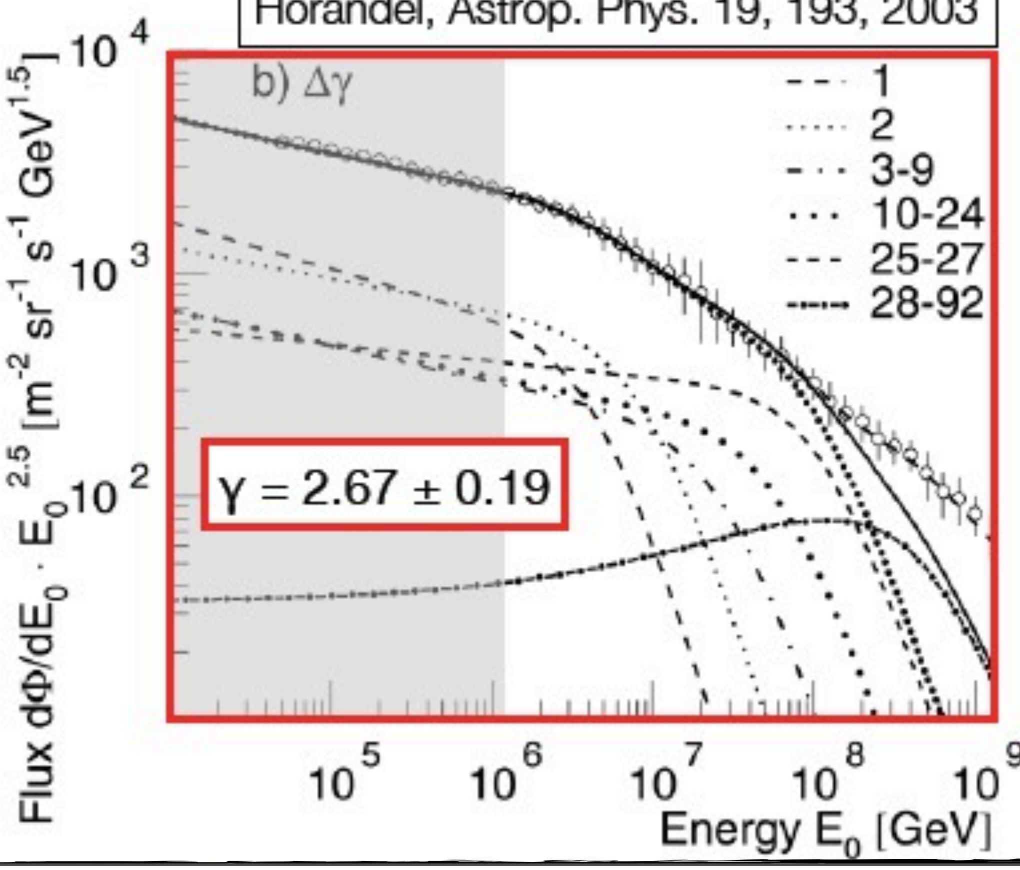


v = 29.8 ± 0.5 km/s

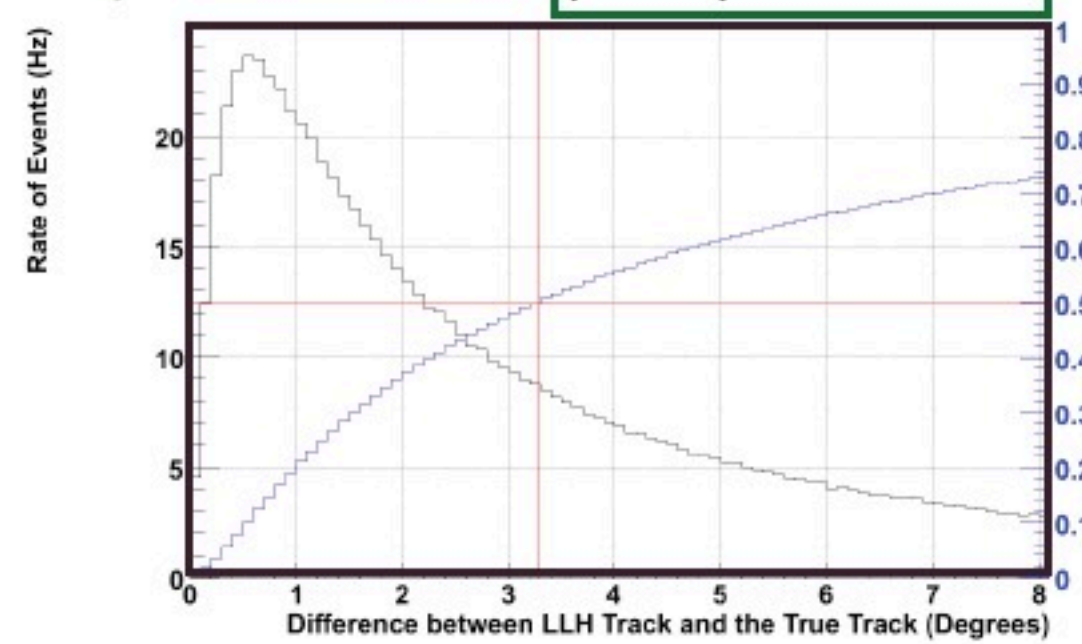
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003



point spread function



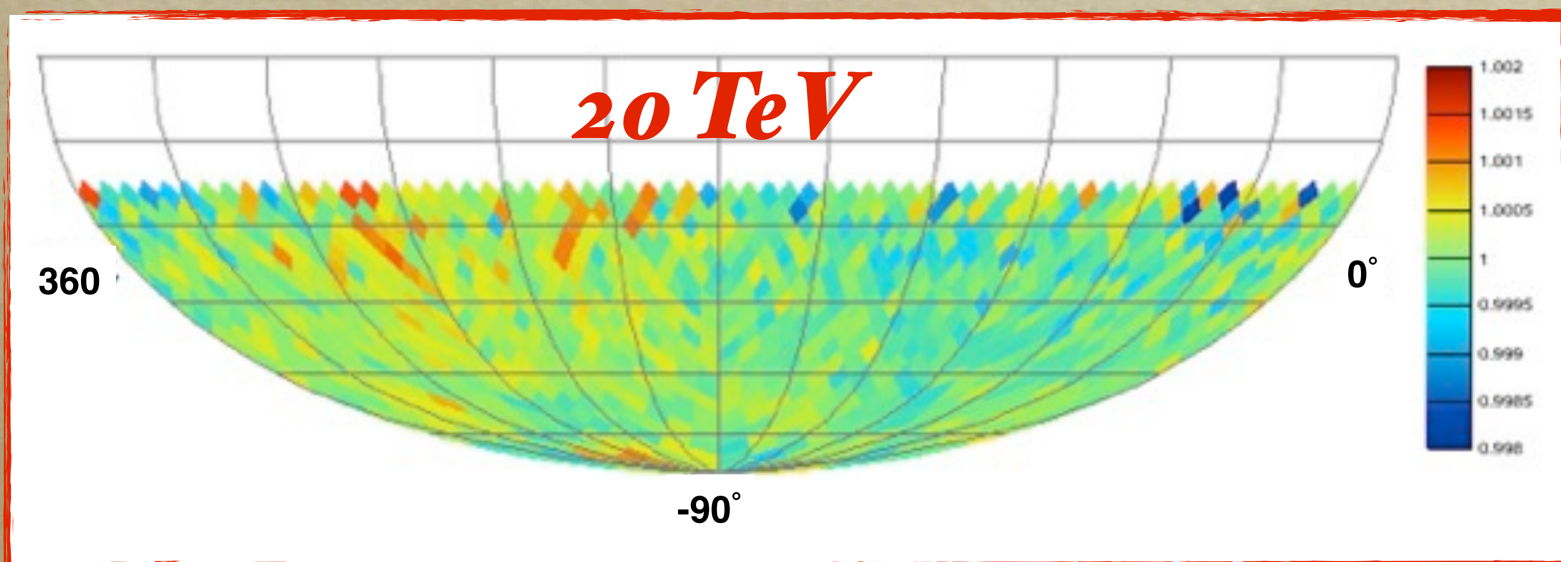
Solar dipole anisotropy vs energy in IceCube-59

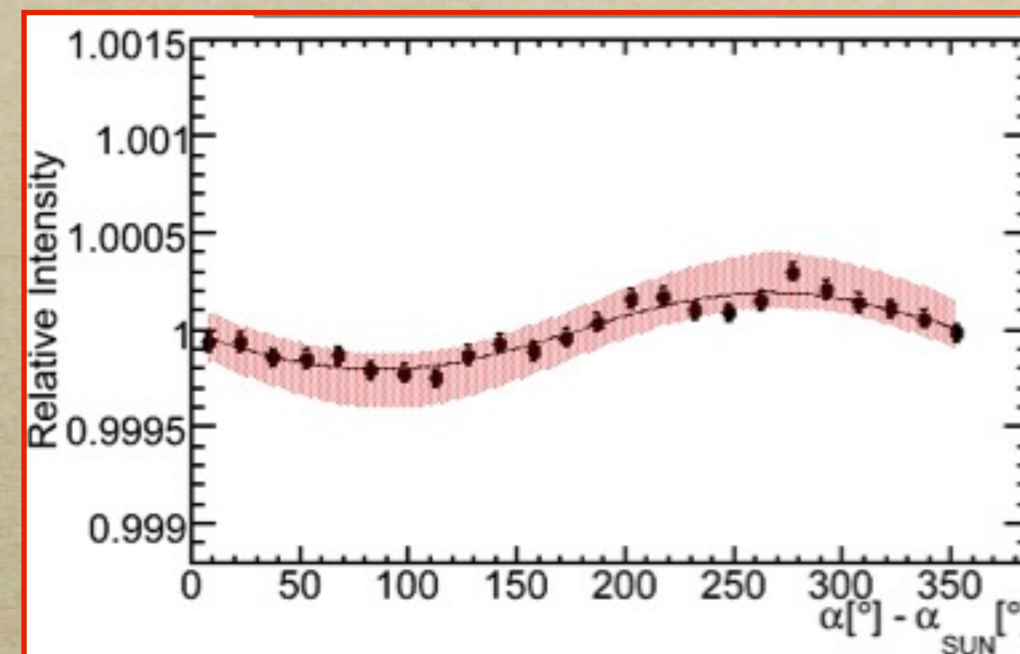
✳ IceCube observes the Solar dipole in both energy bands. The observed amplitude is compatible with the expectations within the stat. and sys. uncertainties.

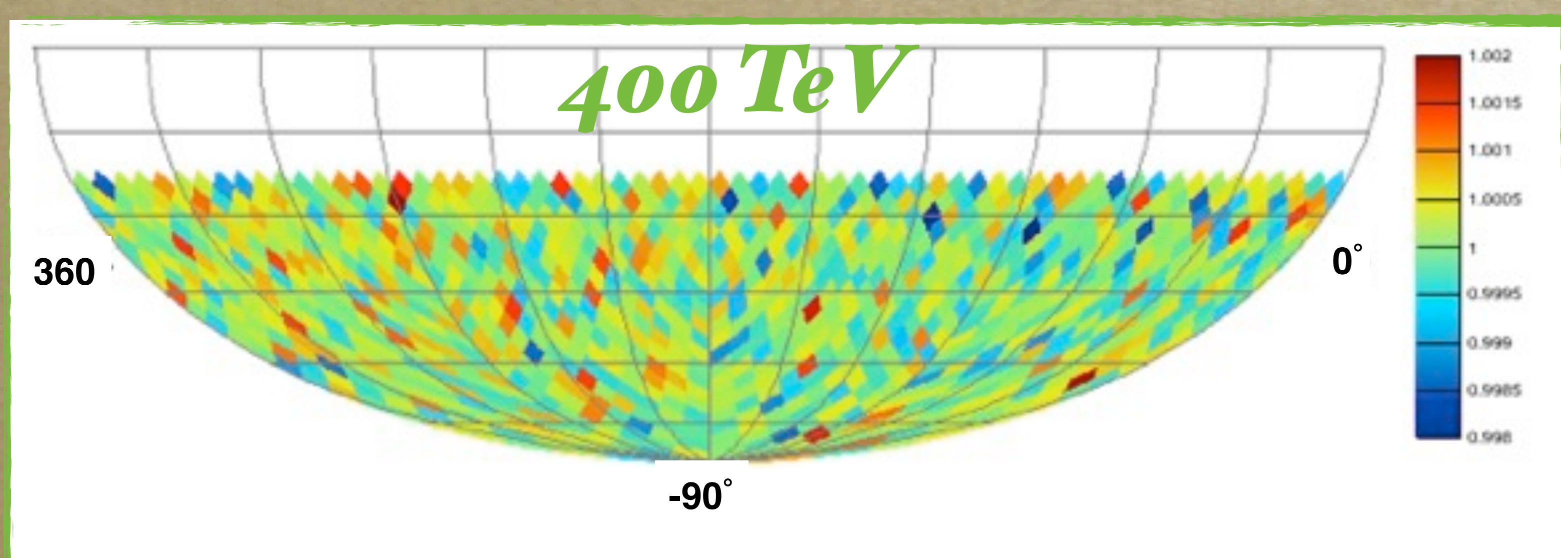
✳ **The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction.**

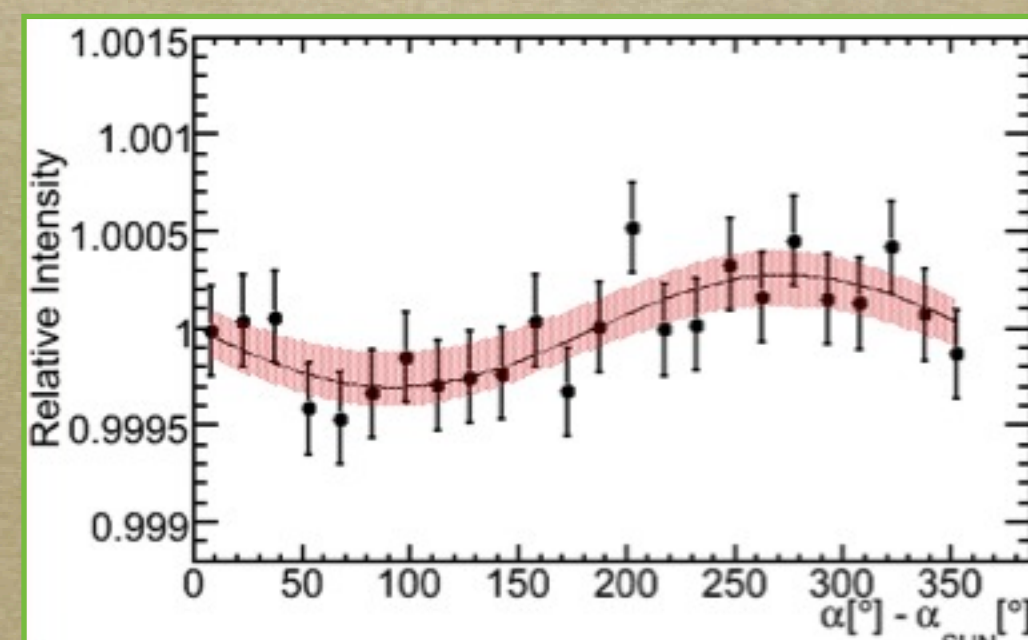
R.Abbasi et al., Astrophys.J. 746 (2012) 33

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

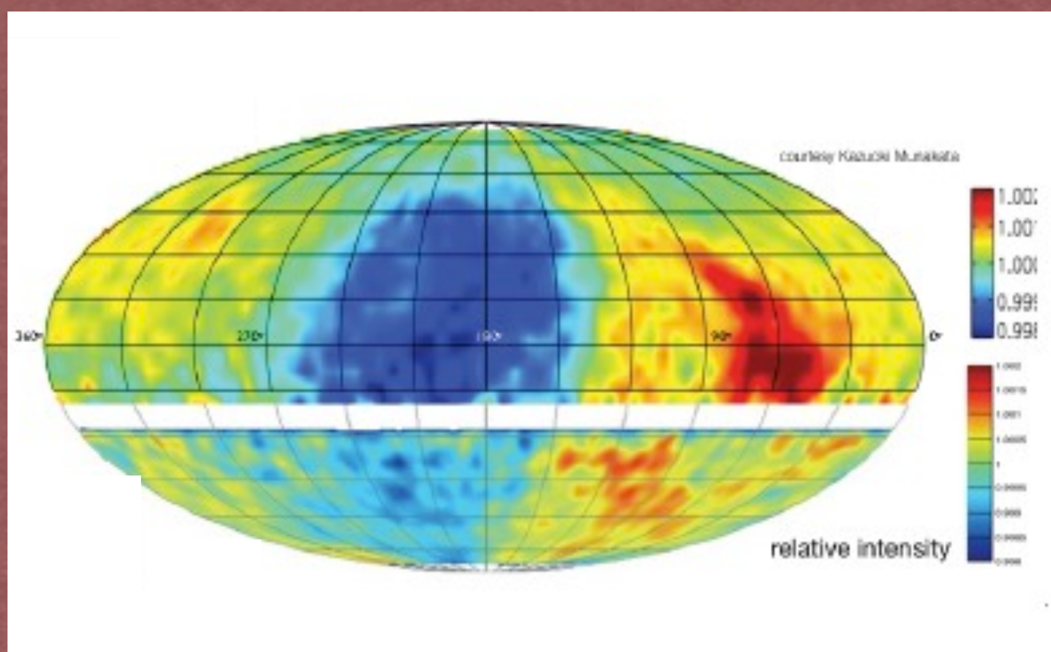






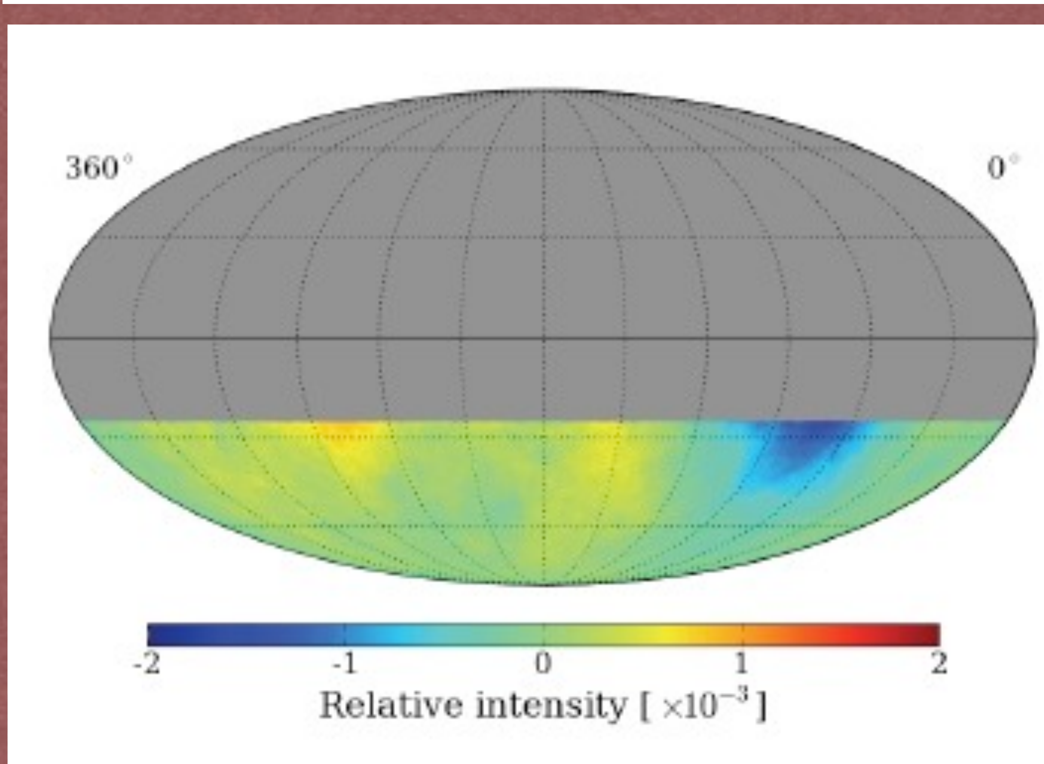


Cosmic ray anisotropy vs energy

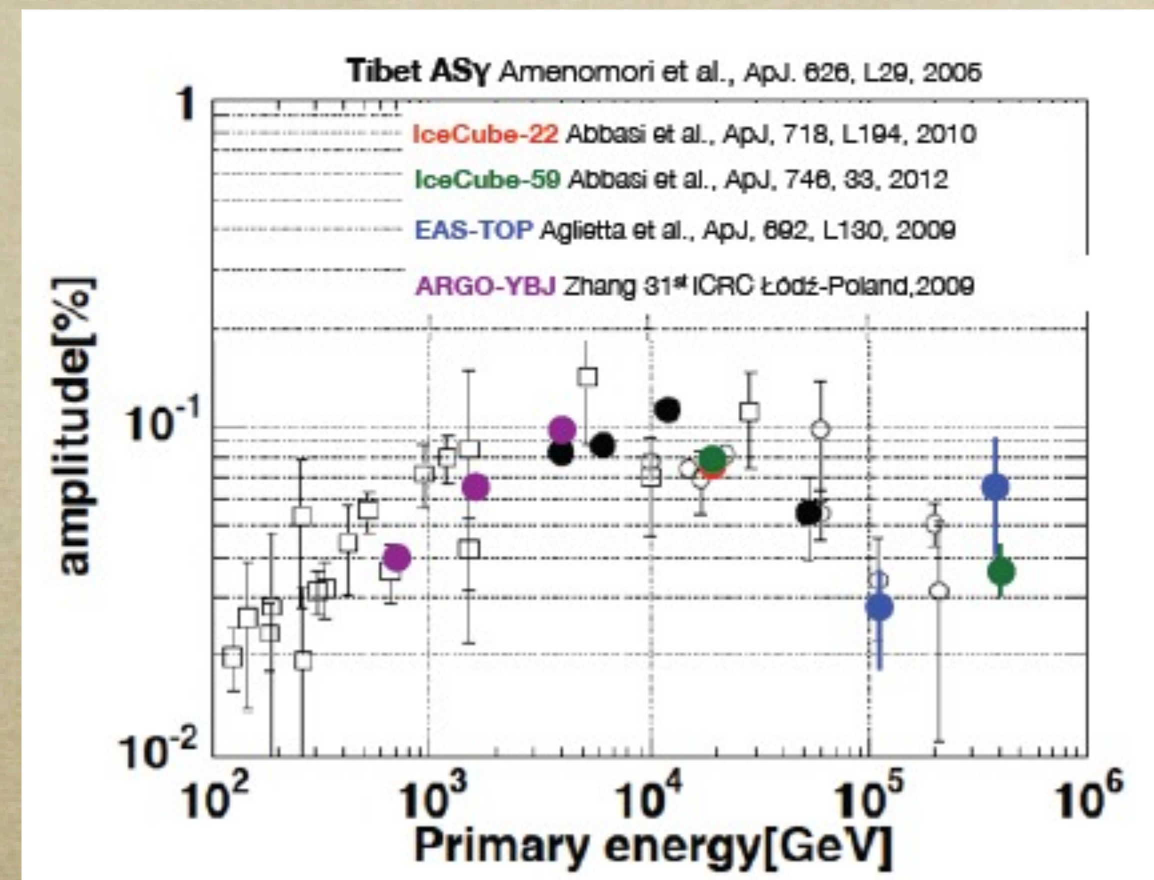


5 TeV

20 TeV



400 TeV



- The anisotropy changes phase at ~ 100 TeV
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

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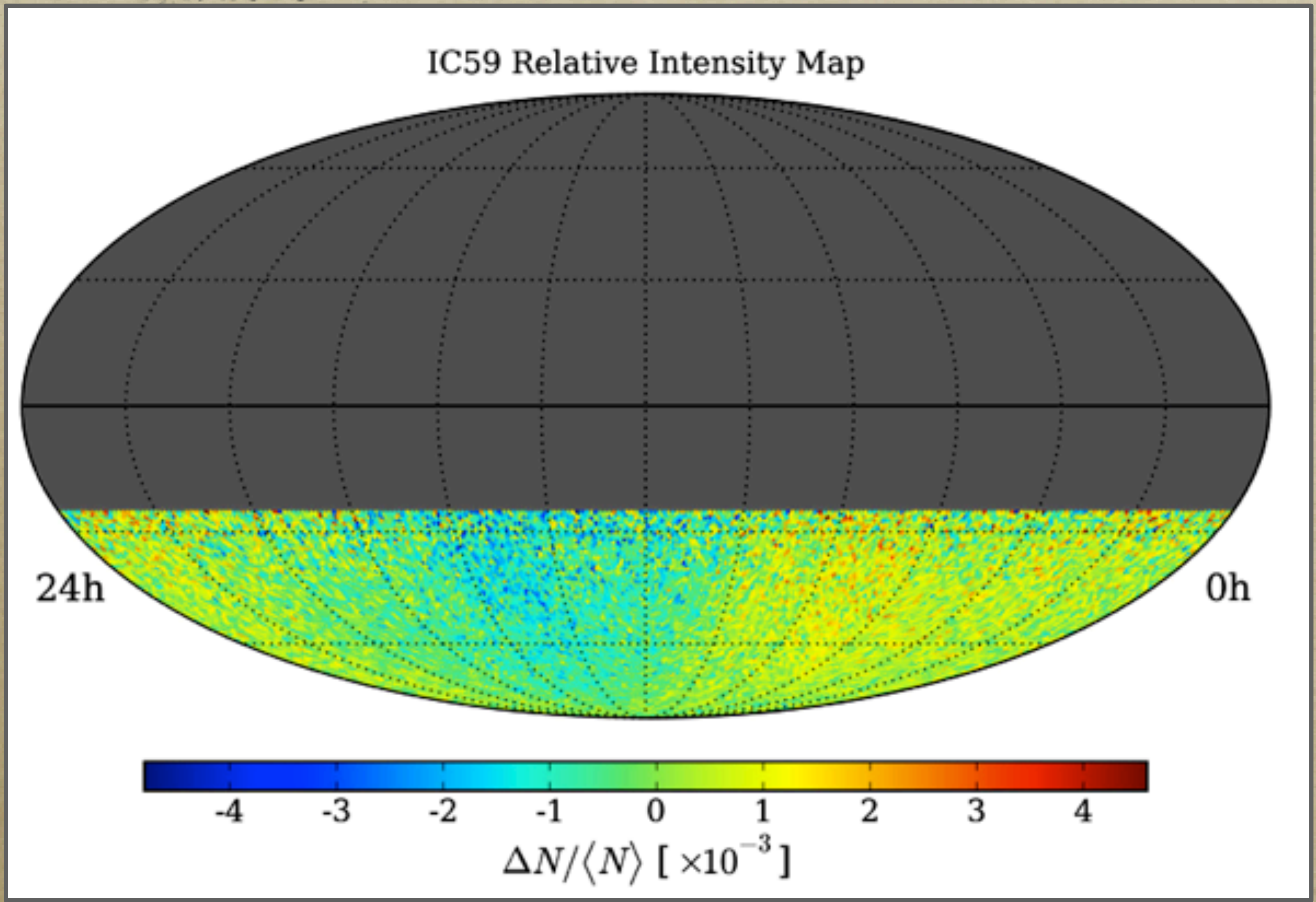
IceCube-59 relative Intensity map

R. Abbasi et al., Astrophys.J. 740 (2011) 16

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*. The *strong large scale structure* is visible in the "raw" data.

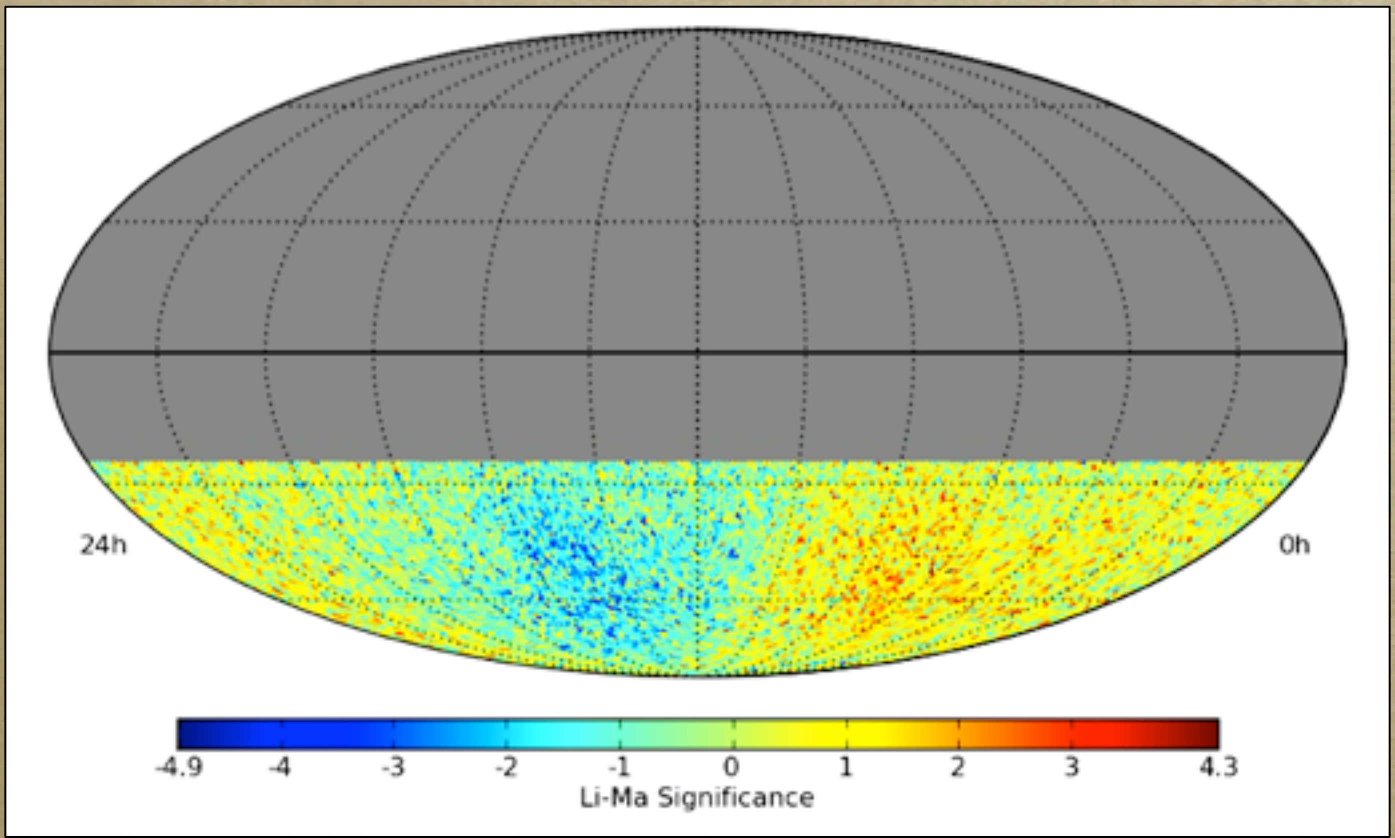
Significance map

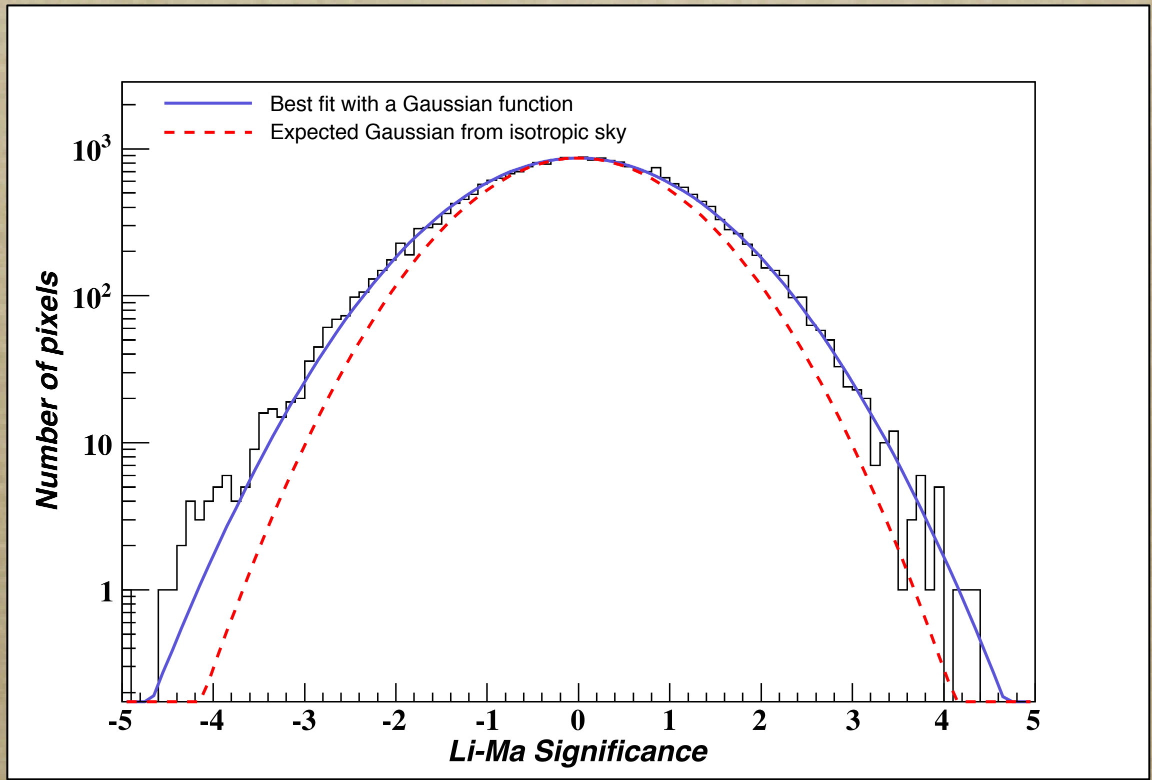
R. Abbasi et al., Astrophys.J. 740 (2011) 16

Significance calculation:

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

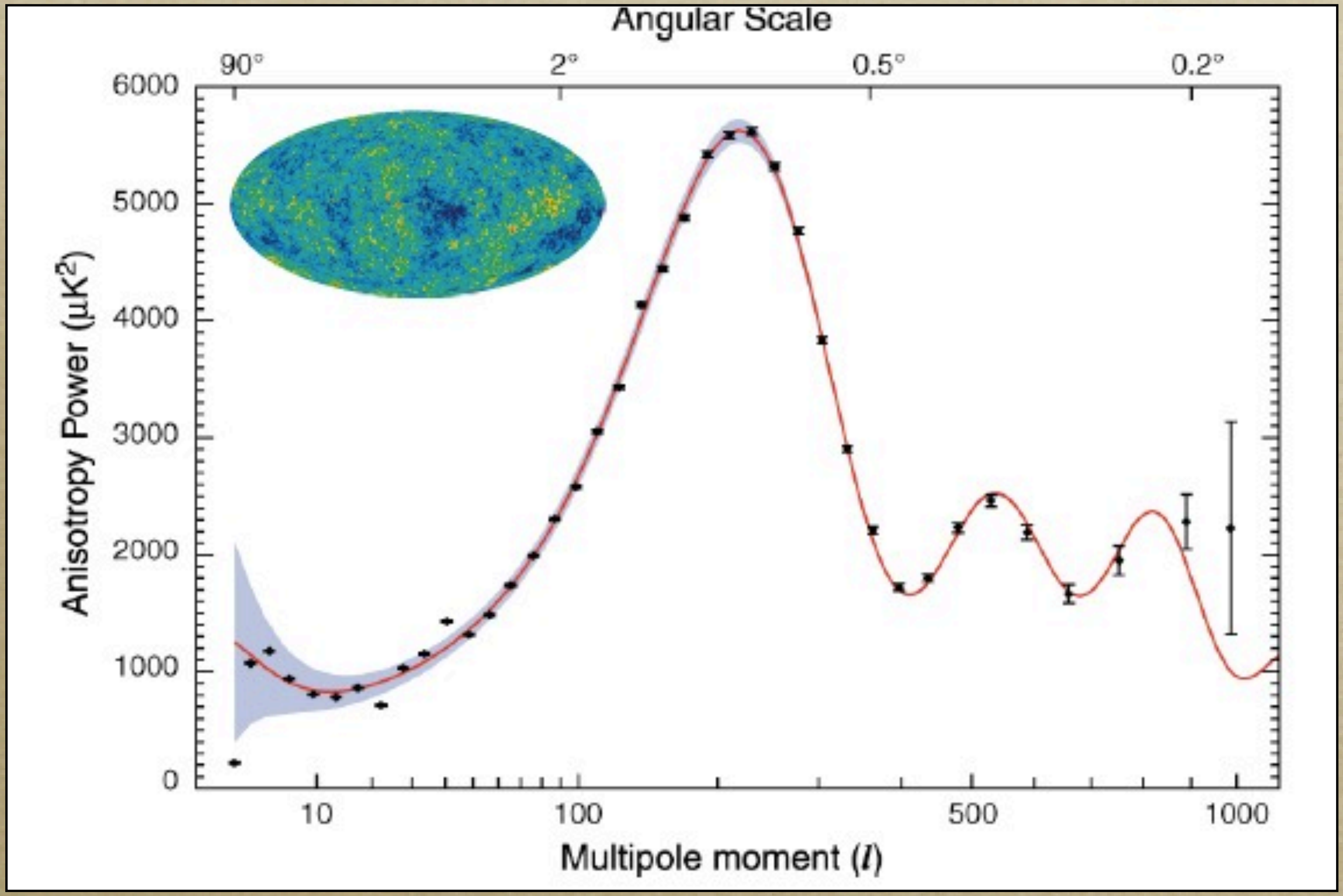
Li, T., & Ma, Y. 1983, ApJ, 272, 317





Angular power spectrum

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

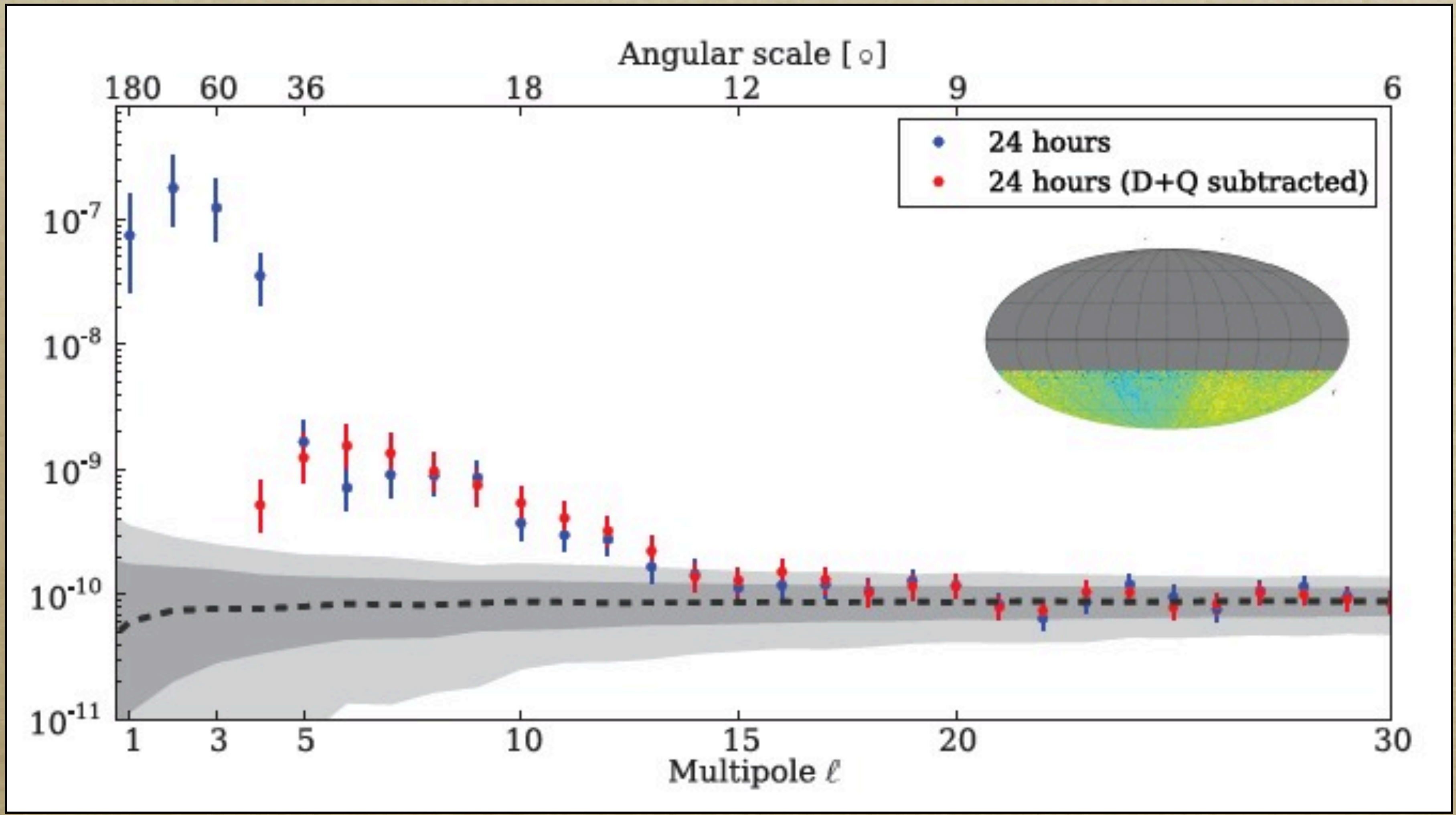


Multipole expansion: $\delta I(\mathbf{u}_i) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{u}_i)$ $\quad \mathcal{C}_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$

Angular power spectrum

R. Abbasi et al., Astrophys.J. 740 (2011) 16

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



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

Dipole+quadrupole subtraction

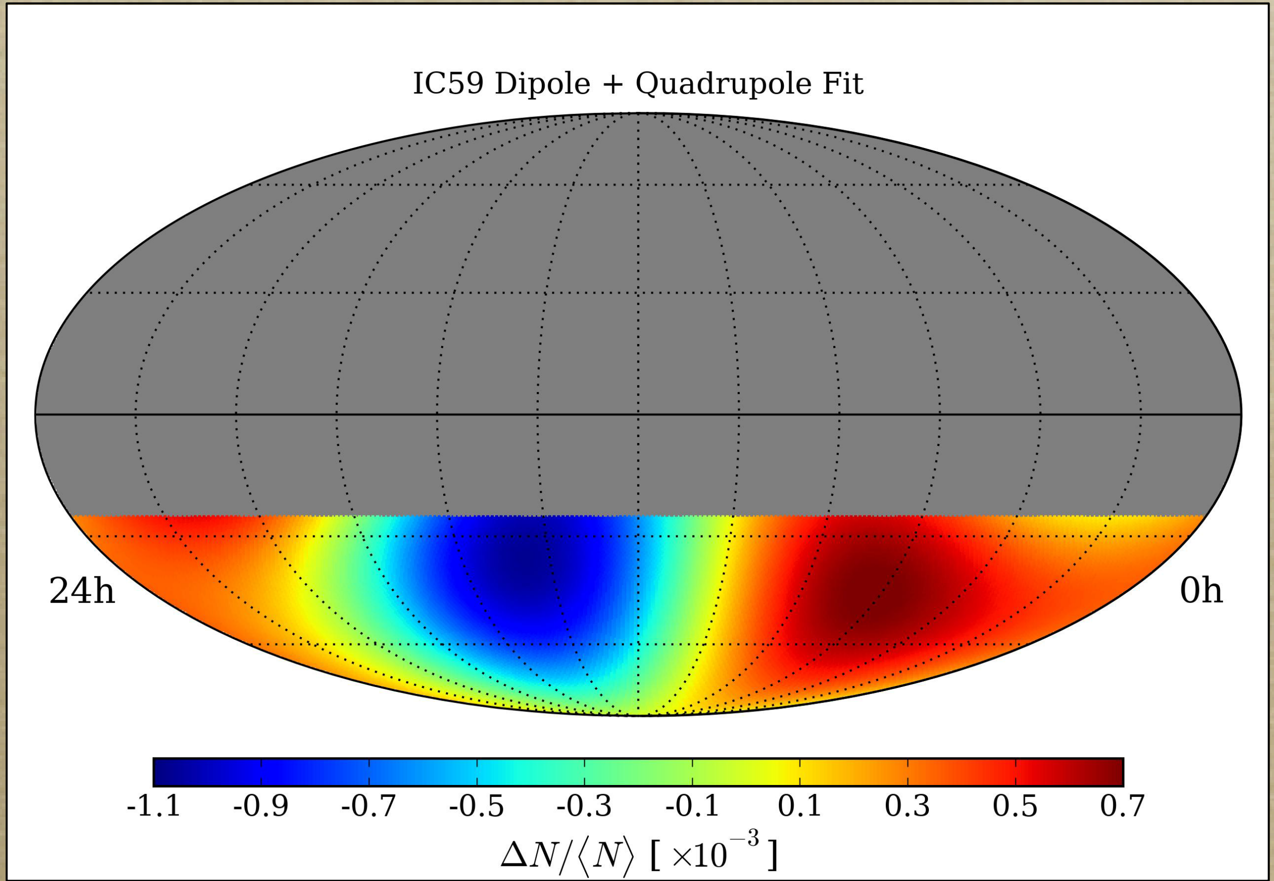
R. Abbasi et al., Astrophys.J. 740 (2011) 16

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



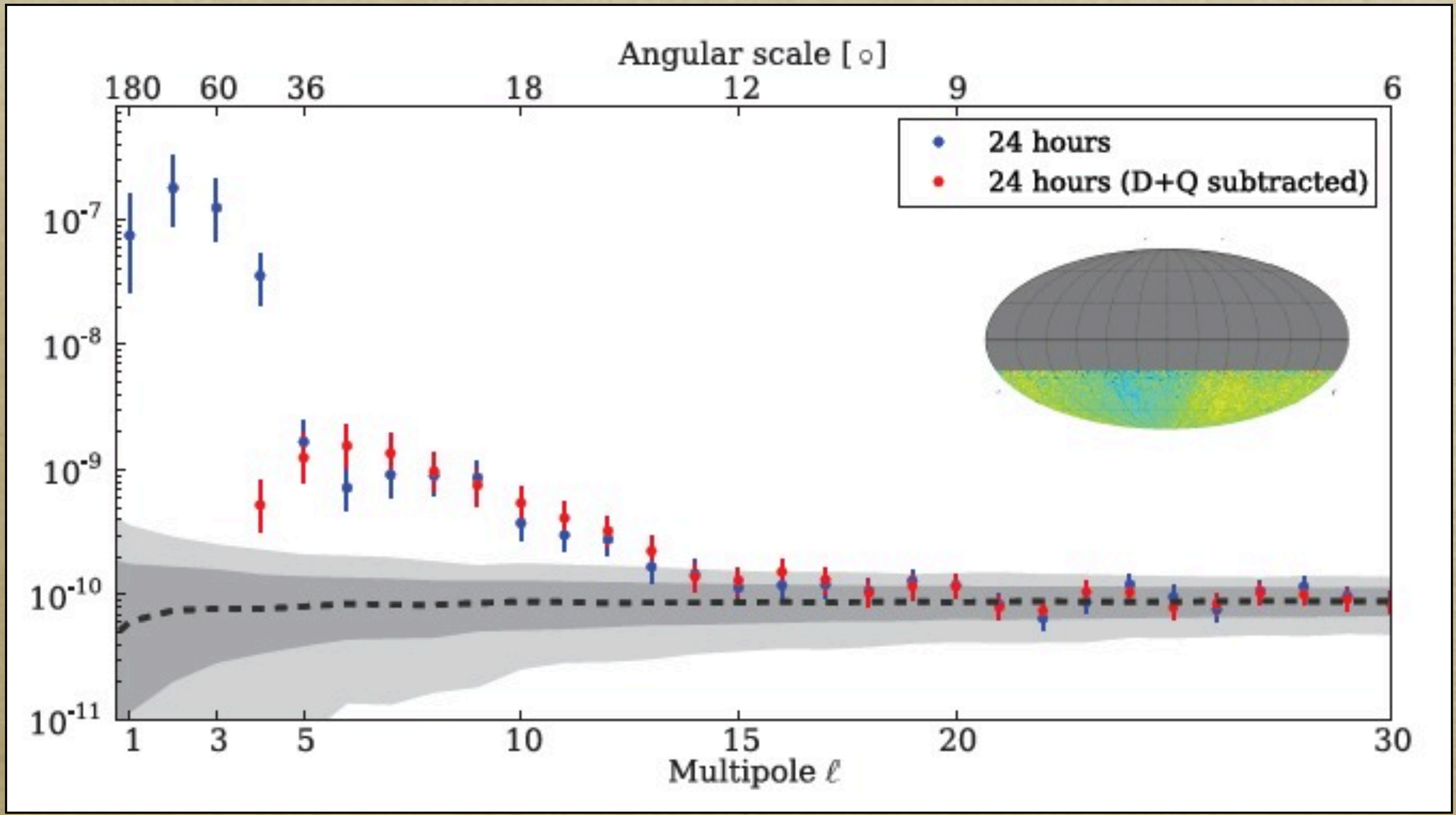
$$\chi^2/\text{ndf} = 14743.4/14187$$

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

Angular power spectrum

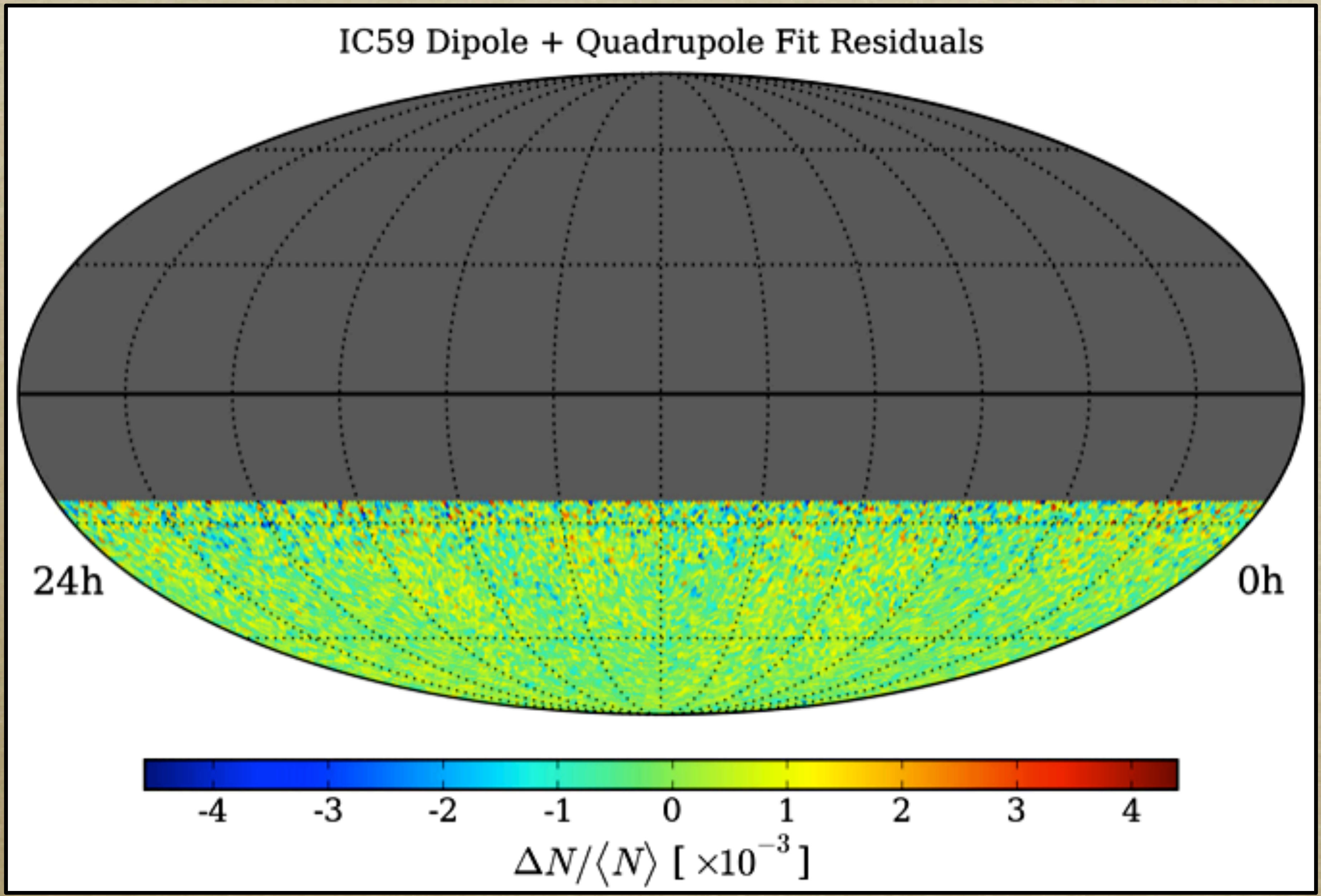
R. Abbasi et al., Astrophys.J. 740 (2011) 16

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



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

Residual map

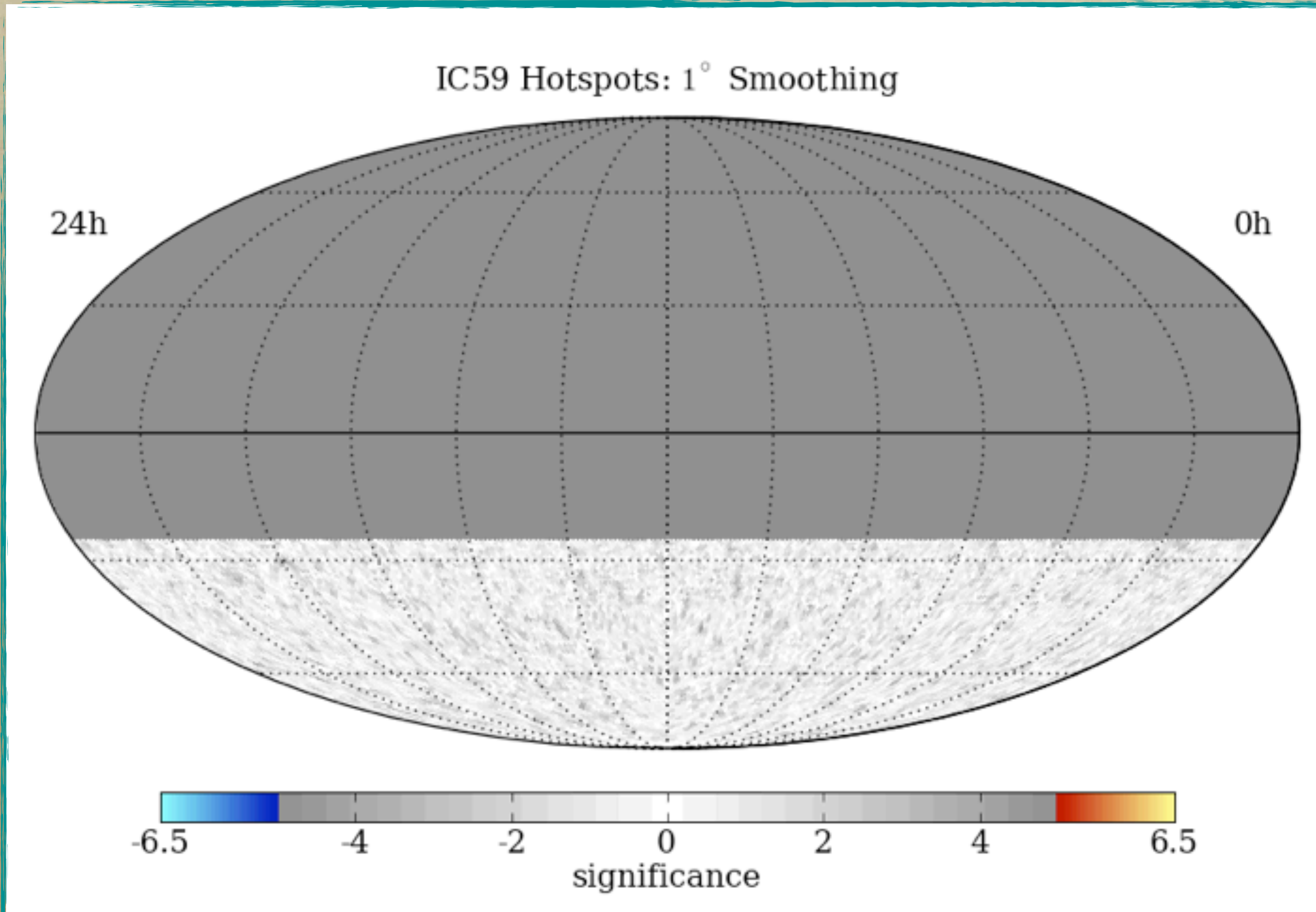


No structures seem to be present: we need to smooth the map.

Map smoothing scan

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

Map smoothing scan

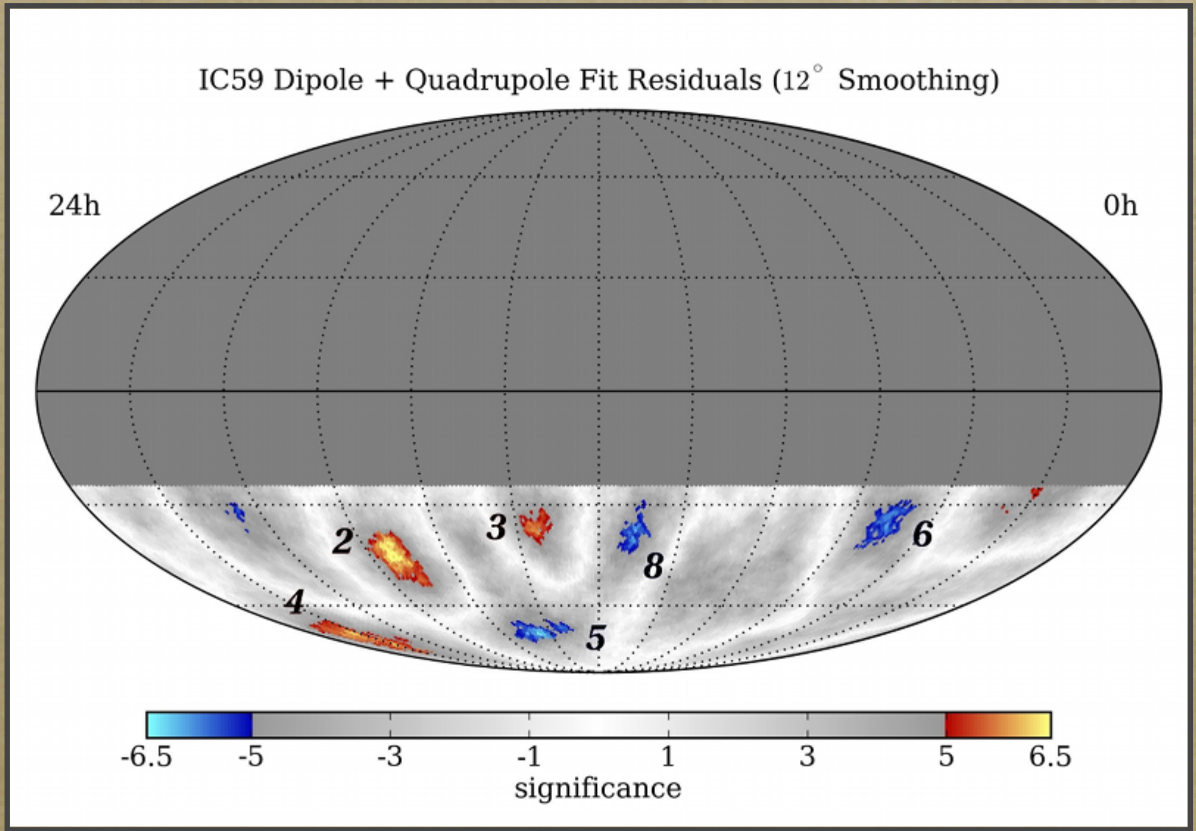


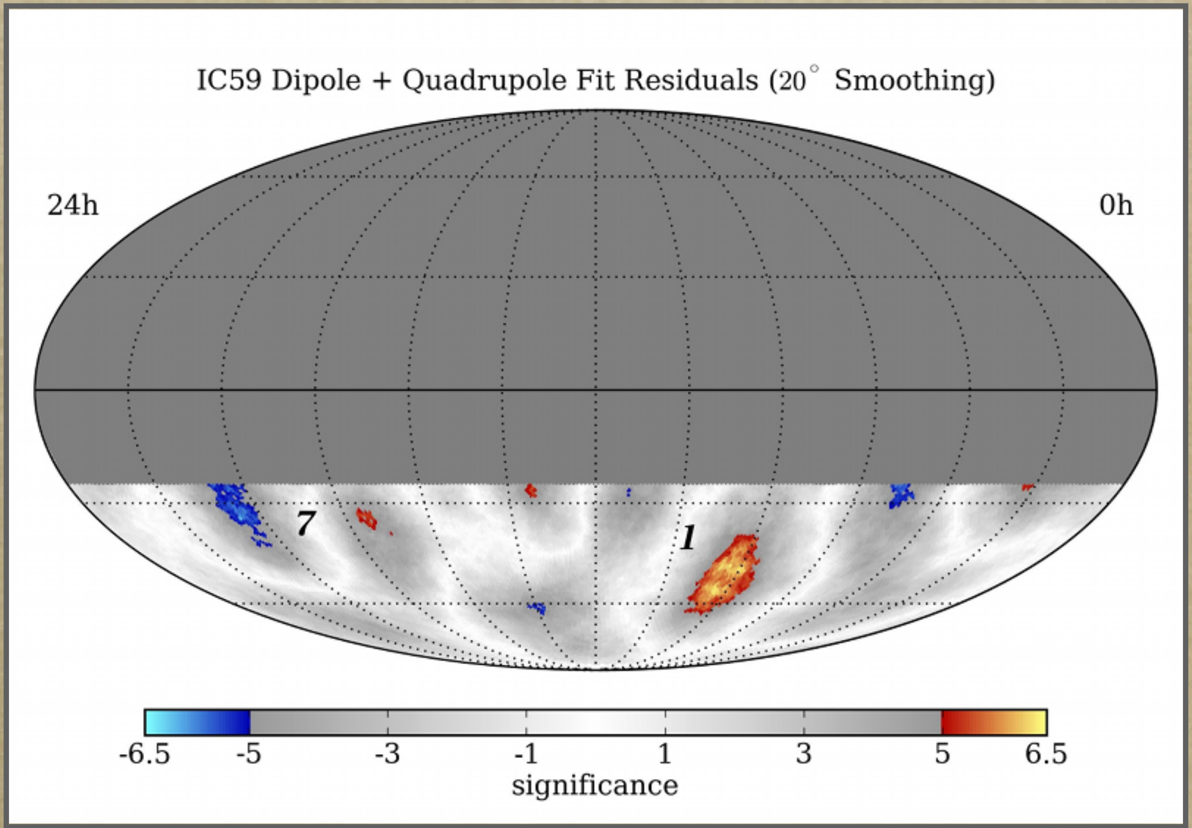
Scan from 1 - 30° in smoothing
Different regions have different optimal angular smoothing
Significances are pre-trial

Identification of significant structures

R. Abbasi et al., Astrophys.J. 740 (2011) 16

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

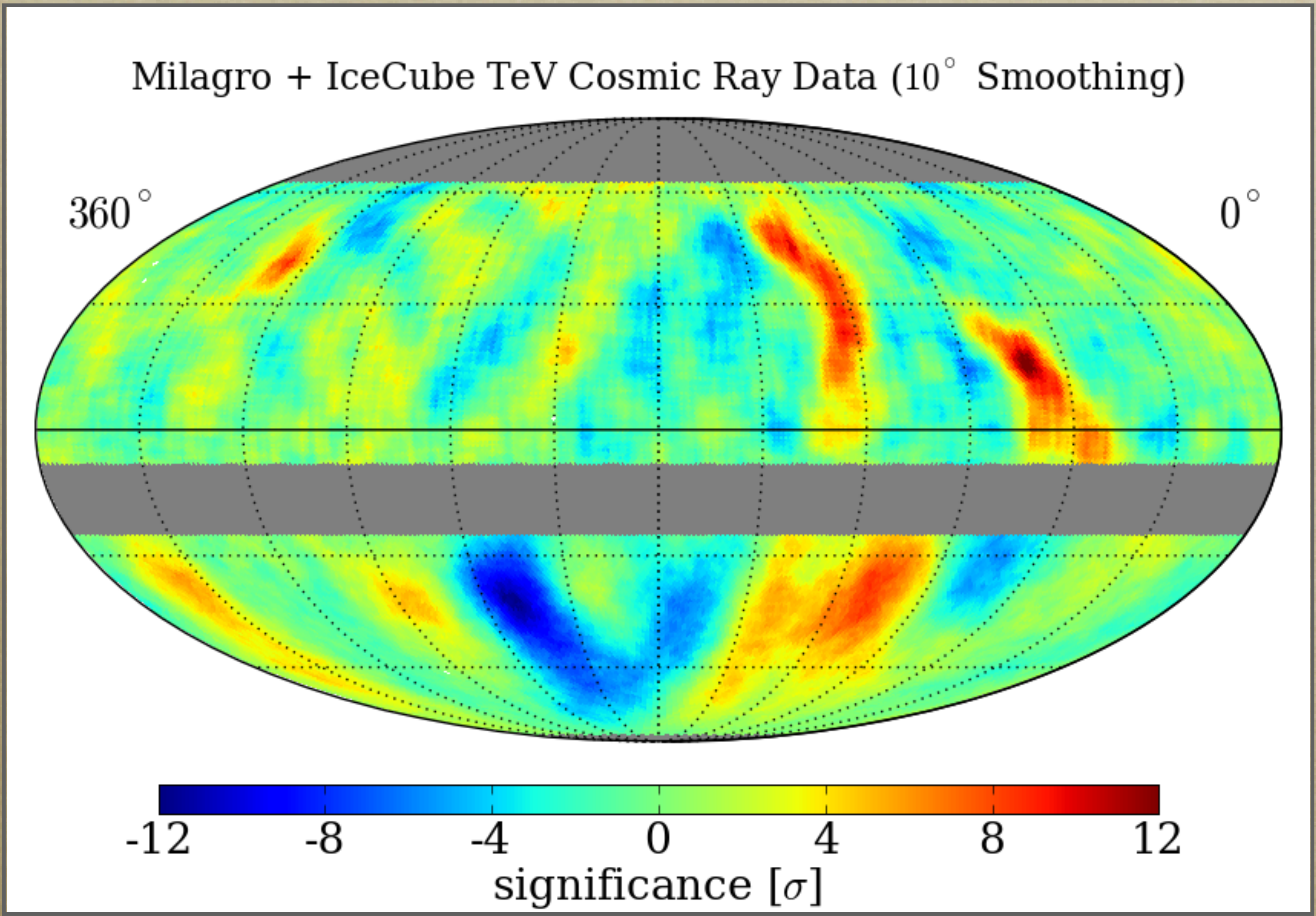




Milagro+IceCube combined map

R. Abbasi et al., Astrophys.J. 740 (2011) 16

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:

[R. Abbasi et al. , Astrophys. J 740 (2011) 16]

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

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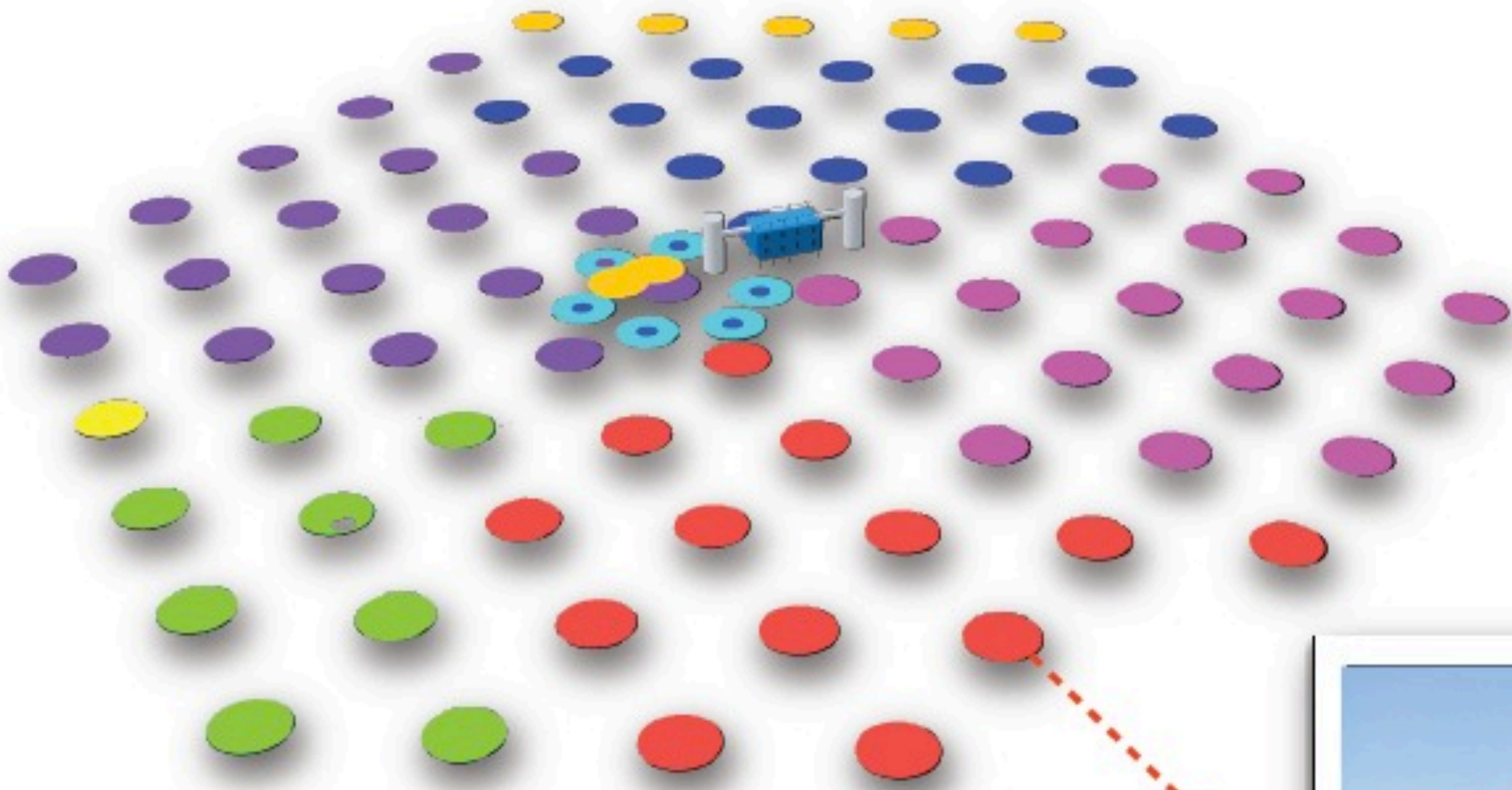
IceTop air shower array

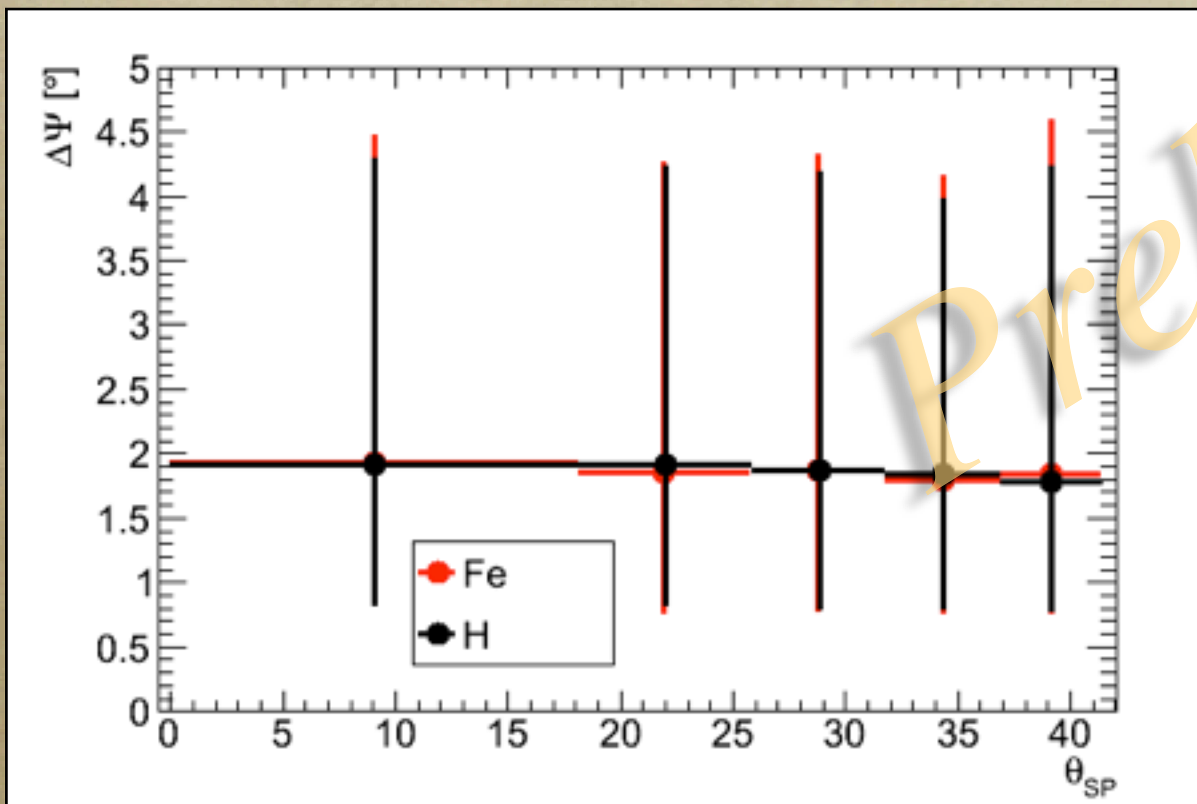


- 81 stations
  - 2 tanks per station
  - 2 DOMs per tank (hi gain, low gain)

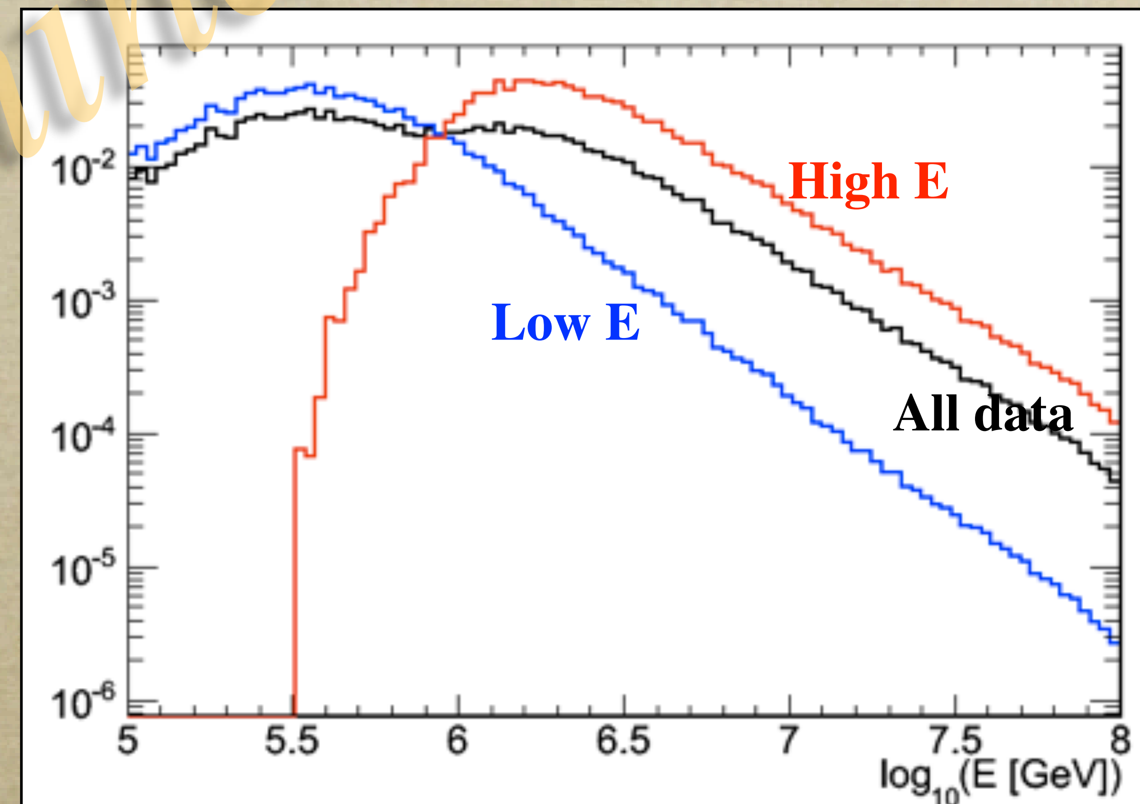
Anisotropy with IceTop

Preliminary

Median Angular resolution (from MonteCarlo)

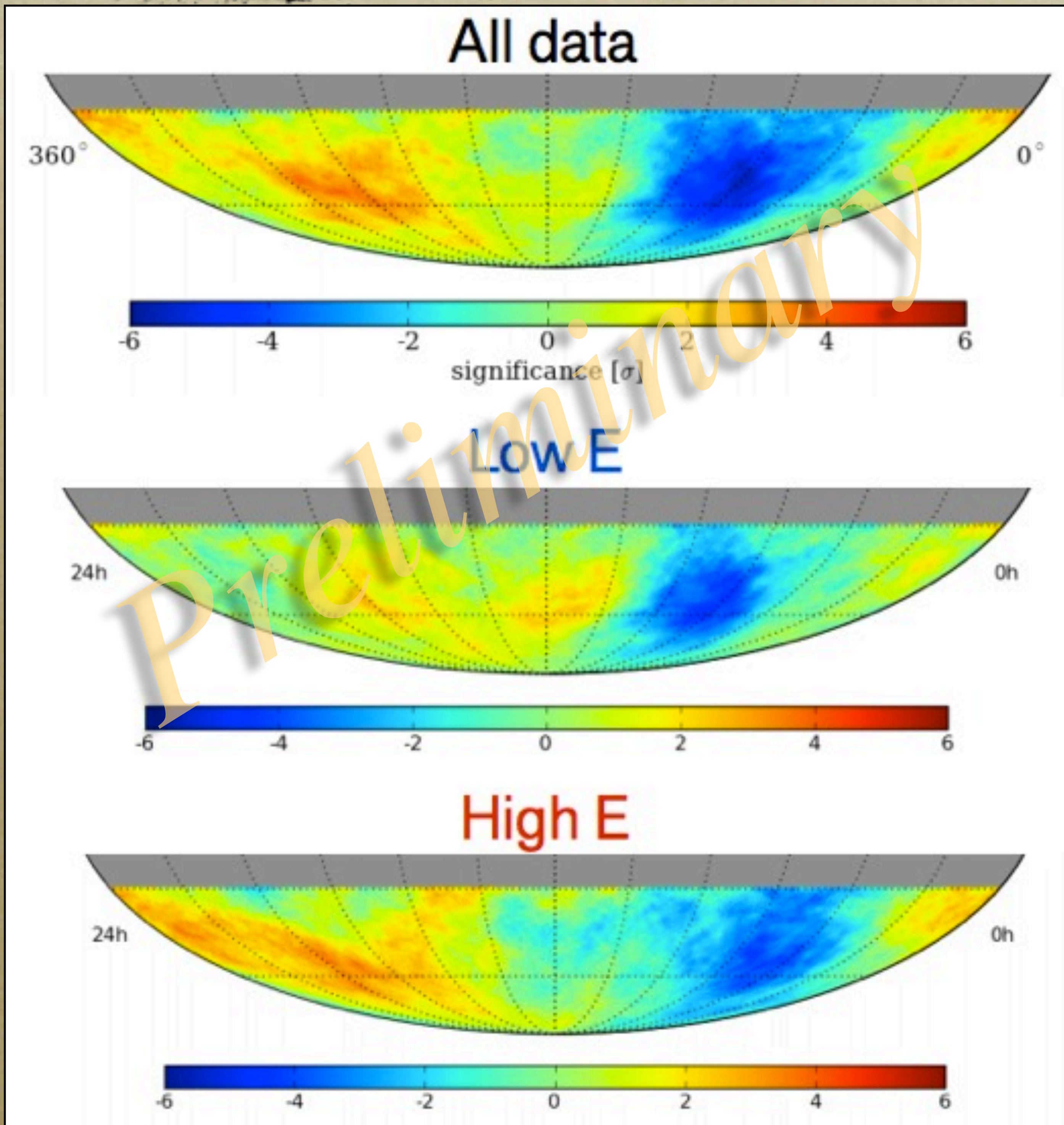


Energy distributions



IceTop stations > 3	**117 x 10^6**	**All data**
3<= IceTop stations < 8	**87 x 10^6**	**Low E**
IceTop stations >= 8	**30 x 10^6**	**High E**

Significance maps for IceTop



- **117 x 10[6]** events
- **500 TeV** median energy
- Minimum significance: **-6.2 σ (pretrial)**

- **87 x 10[6]** events
- **400 TeV** median energy
- Minimum significance: **-5.1 σ (pretrial)**

- **30 x 10[6]** events
- **2 PeV** median energy
- Minimum significance: **-4.9 σ (pretrial)**

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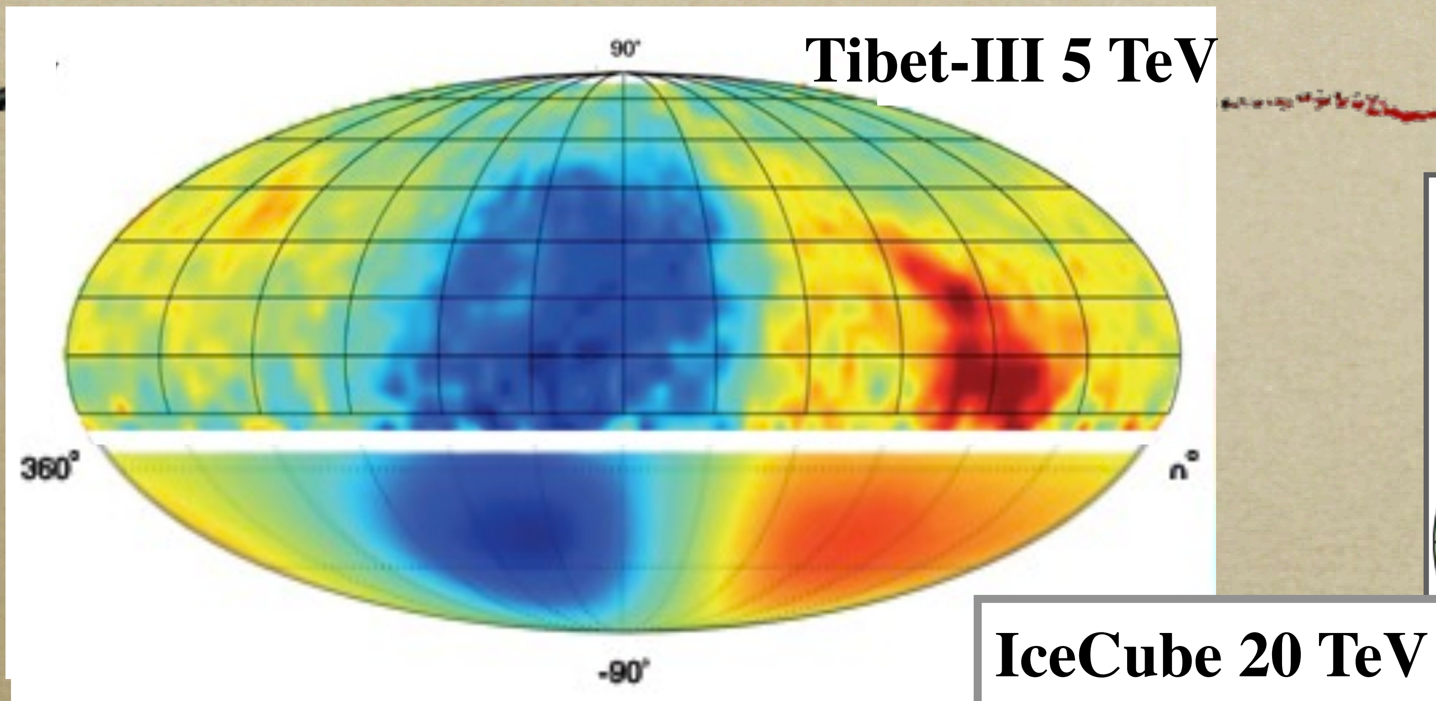
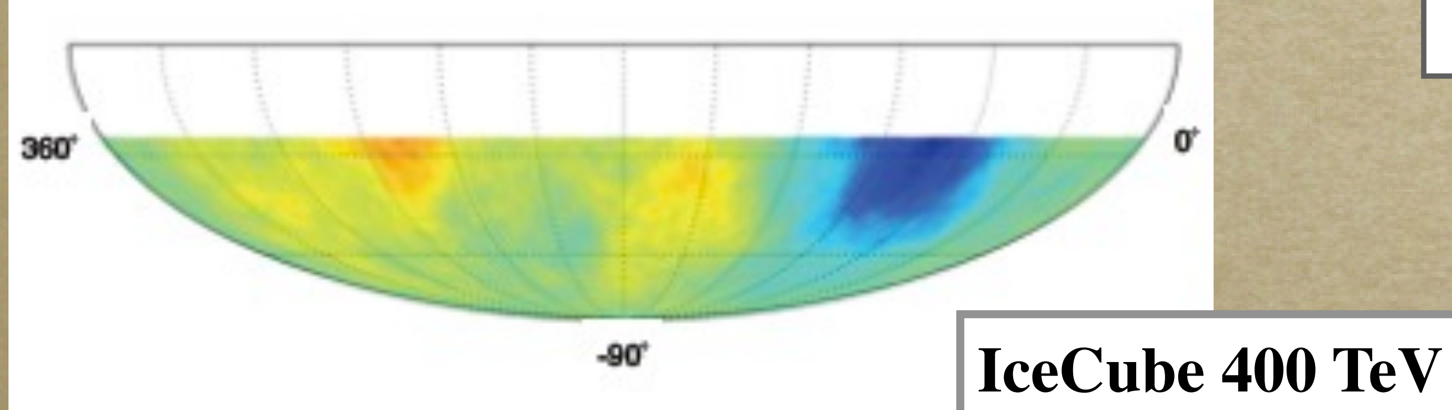
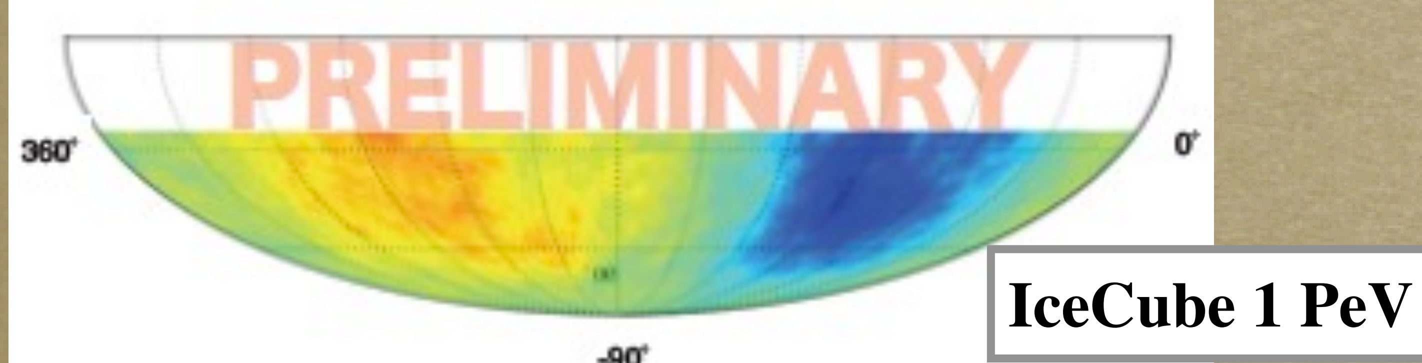
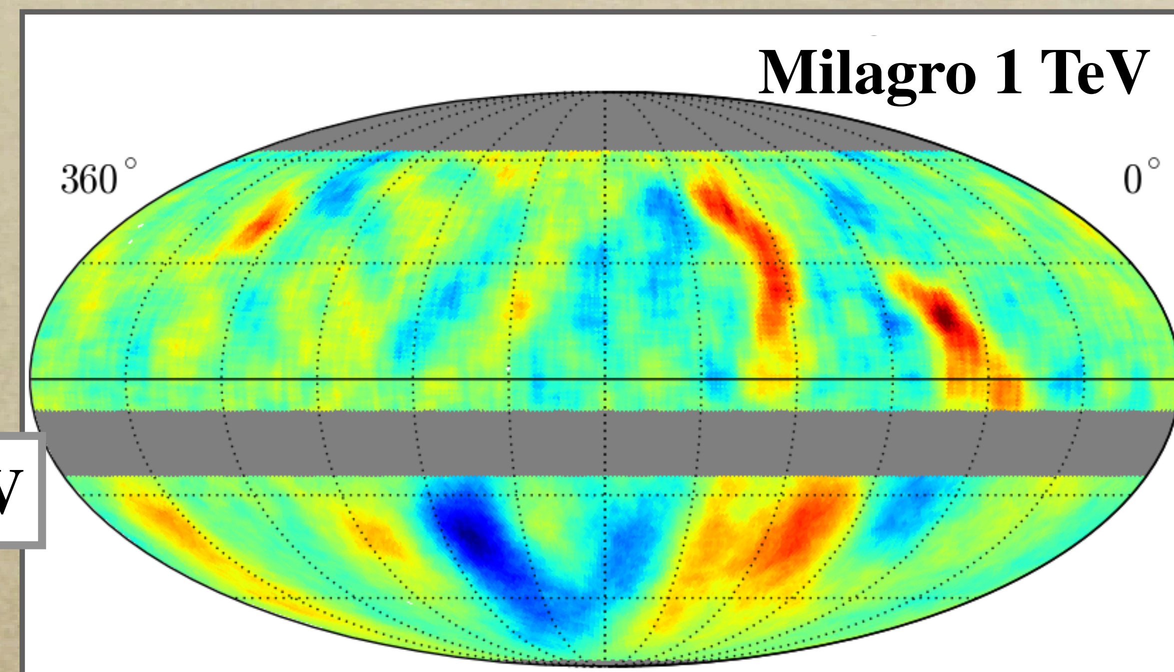
Cosmic ray anisotropy









angular scale

energy scale

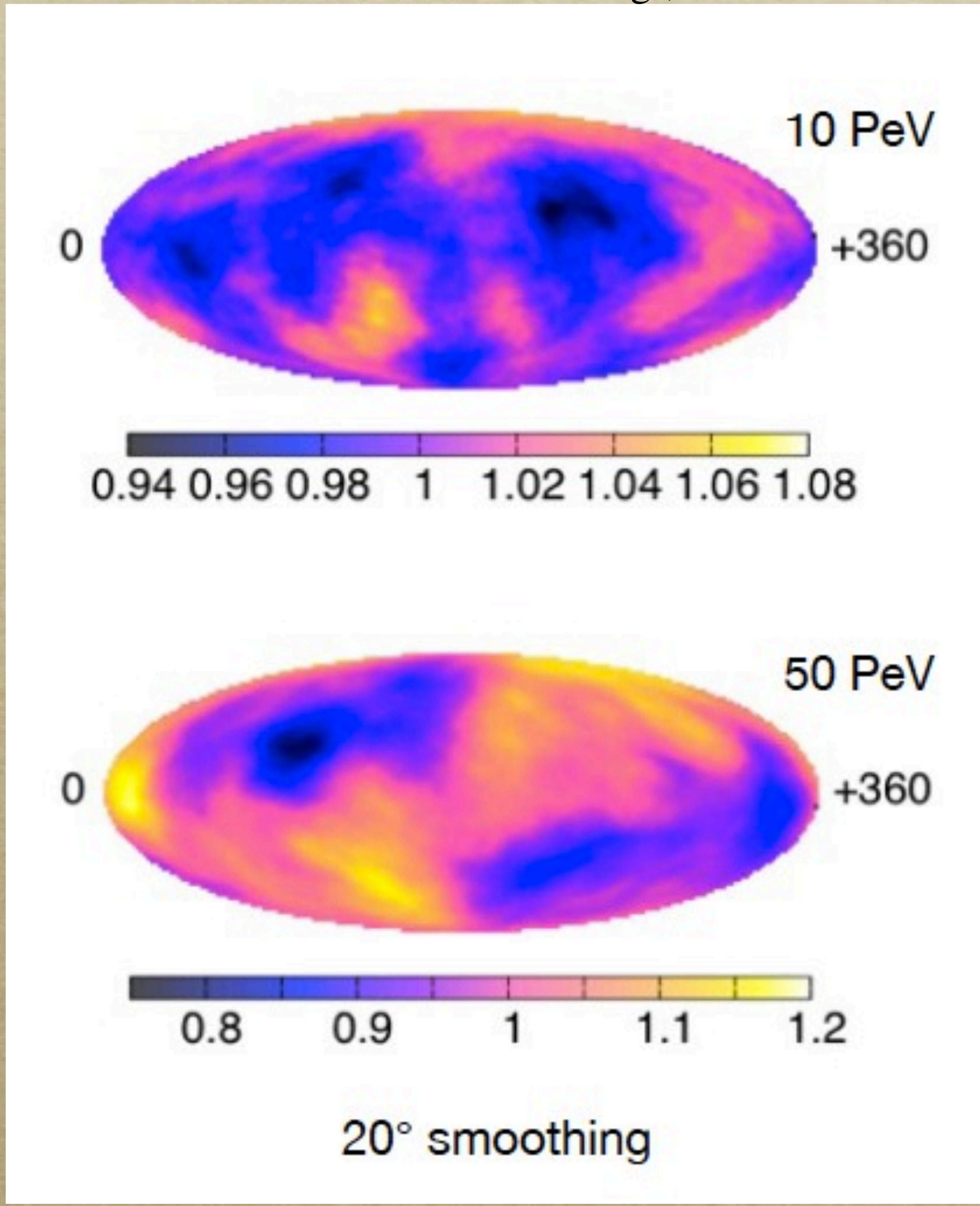
Origin of *large scale anisotropy*

- Stochastic effect from < 0.1-1kpc young SNR & propagation — Erlykin & Wolfendale, Astropart. Phys., 25, 183 (2006); Blasi & Amato, arXiv:1105.4529
  - superposition of dipole anisotropy contributions from nearby sources of cosmic rays;
  - each source contributes at different energy from a different direction (which explains change in phase).
  - These diffusive models can explain only a *pure dipole anisotropy*
- CRs escape from galaxy in a different way (cross different width and environment) from different directions. — Butt, Nature, 460, 701 (2009)
- Combined effect of regular galactic and turbulent IS magnetic field < 10 pc: isotropy broken in our vicinity due to propagation in turbulent magnetic field. — Battaner, Castellano & Masip ApJ, 703, L90 (2009)
- The CR density is different inside and outside the LIC. Effect from Local Intestellar Cloud (LIC) and local IS magnetic field < 1 pc. Interesting since they expect a quadrupole component. — Amenomori et al., ICRC 2007, Mérida, México (2007)

Origin of *small scale anisotropy*

Giacinti & Sigl, arXiv:1111.2536

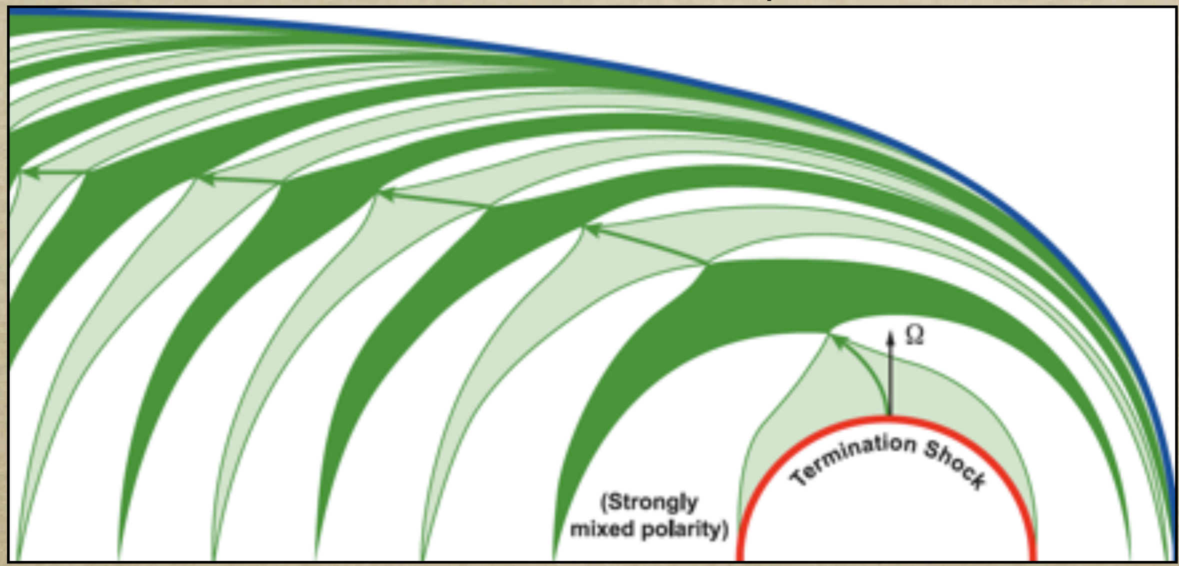
- arise naturally from interaction with turbulent interstellar magnetic field within mean free path
- assuming an underlying dipole anisotropy, fractional localized regions form the effect of magnetic field turbulence
- the residual maps provide an image of magnetic field turbulence < 10's pc
- cosmic ray energy spectra might also be affected by this propagation effects



Origin of *small scale anisotropy*

Small angular features might reveal properties of the boundary region between solar wind and interstellar wind (Heliosphere)

Lazarian & Desiati, ApJ, 722, 188, 2010



- Milagro observes harder than average spectrum from region A. This means that particles have to be accelerated in the heliosphere.
- Magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail
- turbulence makes reconnection fast and not affected by ohmic dissipation
- magnetic tubes contraction leads to increase of particle energy as long as they are within the contracting magnetic loop

$$N(E)dE \sim E^{-5/2}dE$$

first-order Fermi acceleration of test particle in magnetic mirrors

$$E_{max} \approx 10^{13}\ eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right) \quad \sim 10\ \text{TeV}$$

unlikely to expect energies > 10 TeV

Similar to hardening of "diffuse" cosmic rays by Pamela, CREAM, ATIC-2. Milagro may be measuring a propriety of CRs.

Summary-I

- Anisotropy observed with IceCube:
  - energy evolution: **20 TeV to PeV**
  - wide angular scale range (**10˚ - 180˚**)
  - strength in the **10^{-4} -10^{-3}** range
- 20 TeV anisotropy matches observations in the North
- Observation of anisotropy at 400 TeV (change in phase and size)
- Preliminary results from IceTop at ~400 TeV are consistent with IceCube results.
- Anisotropy observed at 2 PeV (near the CR knee) change in composition?

Summary-II

- The origin of large scale anisotropy could be related with:
  - stochastic distribution of SNR and pure diffusion of CRs in the galaxy
  - asymmetry of the galaxy: CRs escape from different directions affected by different local conditions
  - pure effect of CRs propagation and interaction with turbulence of the LIMF.
- The origin of small scale anisotropy could be related with:
  - might be related to effects within mean free path, or resulting from propagation
  - TeV cosmic rays as a new probe for outer heliospheric boundary and ISM

The origin of anisotropy is still unknown

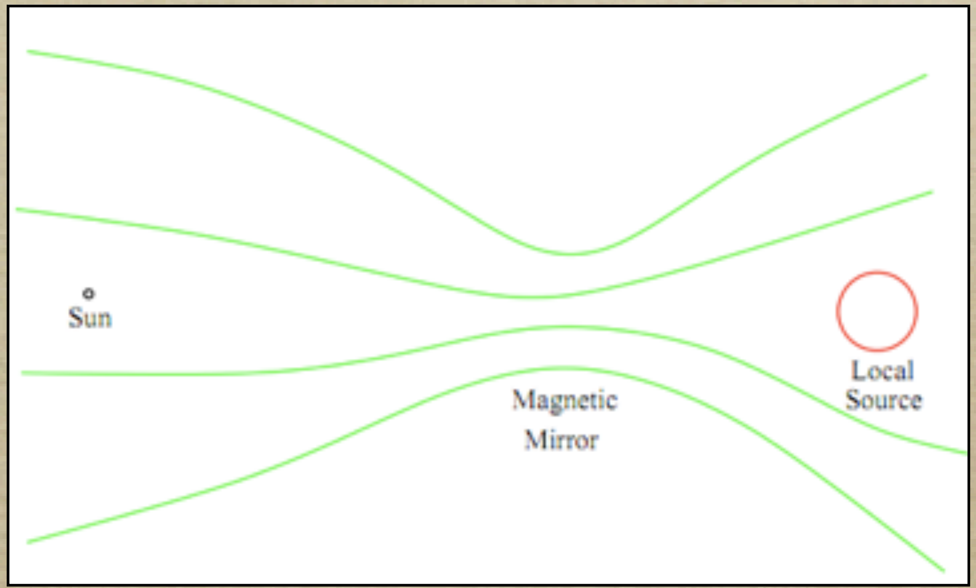
Back-up slides

Origin of *small scale anisotropy*: CR source

Salvati & Sacco, arXiv:0802.2181
Drury & Aharonian, Astropart. Phys. 29, 420 (2008)

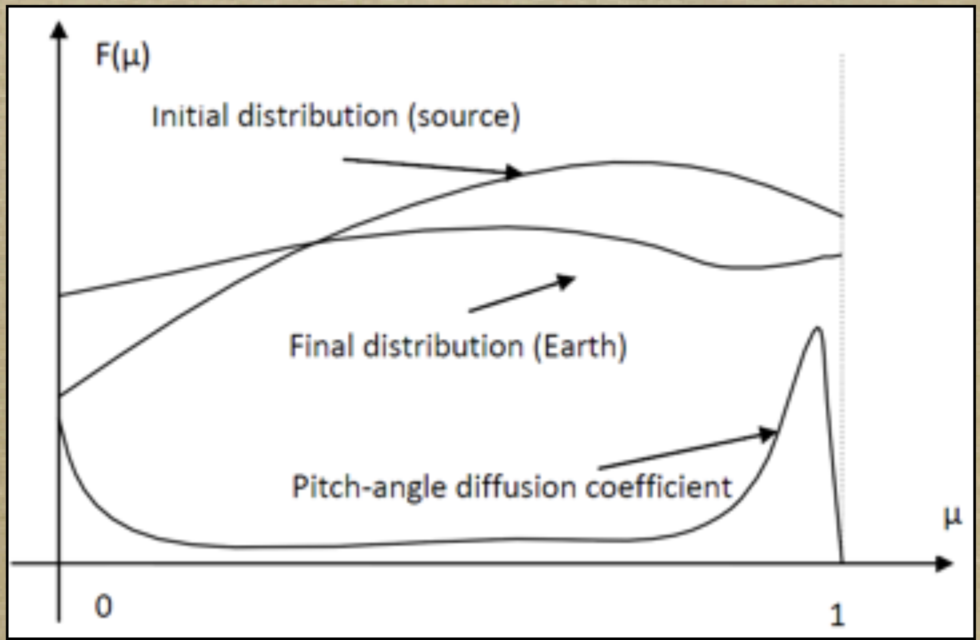
- CR from Geminga: ~90-200 pc, 340,000 yr ago

Salvati, Astron. & Astrophys. arXiv:1001.4947



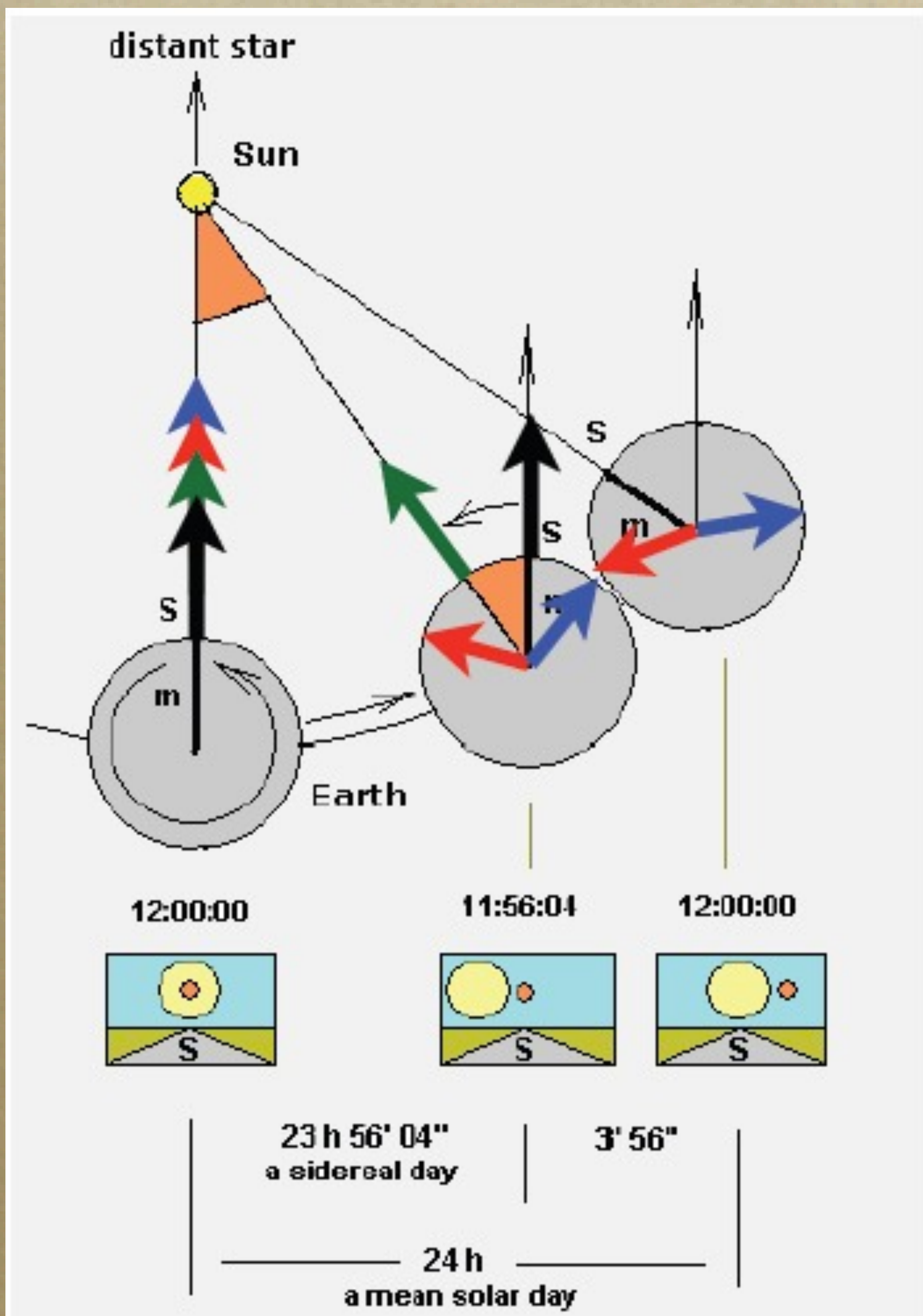
- In order to explain a small scale structure at these distances they need to introduce a magnetic connection between the source and the us. Propagation in turbulent LIMF.

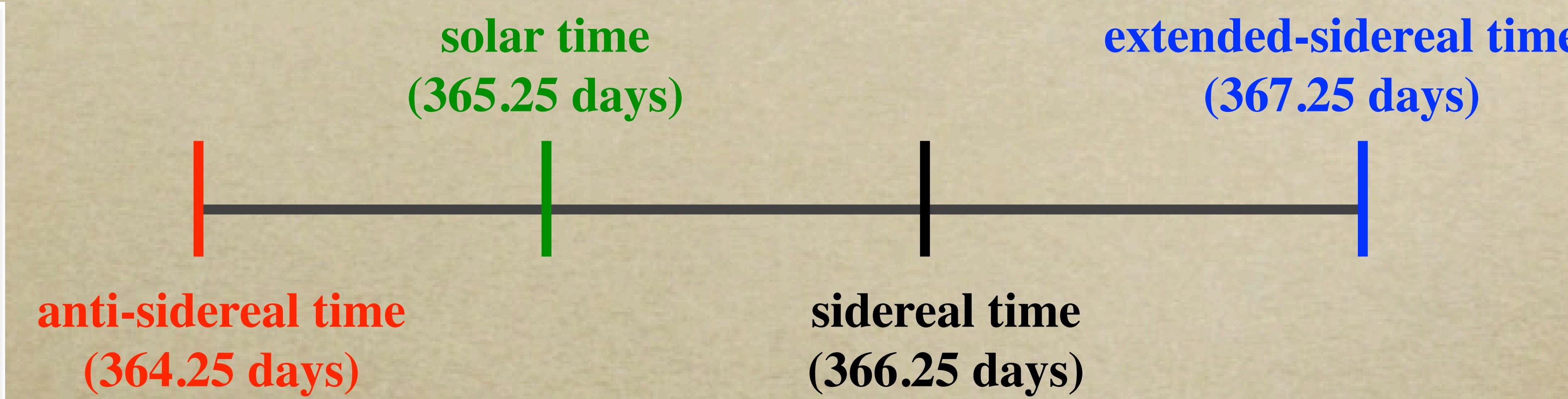
Malkov et al., ApJ 721, 750, 2010



- Effect due to a pure propagation of CR in the galaxy. Anisotropic MHD turbulence in the ISM (incidentally requires magnetic connection to the faraway source)
  - it exist a large scale anisotropy "perturbed" by faint beam of collimated particles along the "magnetic" tube that connects to the source (~100 pc)
  - pitch angle scattering peaked near the direction of LIMF

Systematic uncertainties in IceCube-59



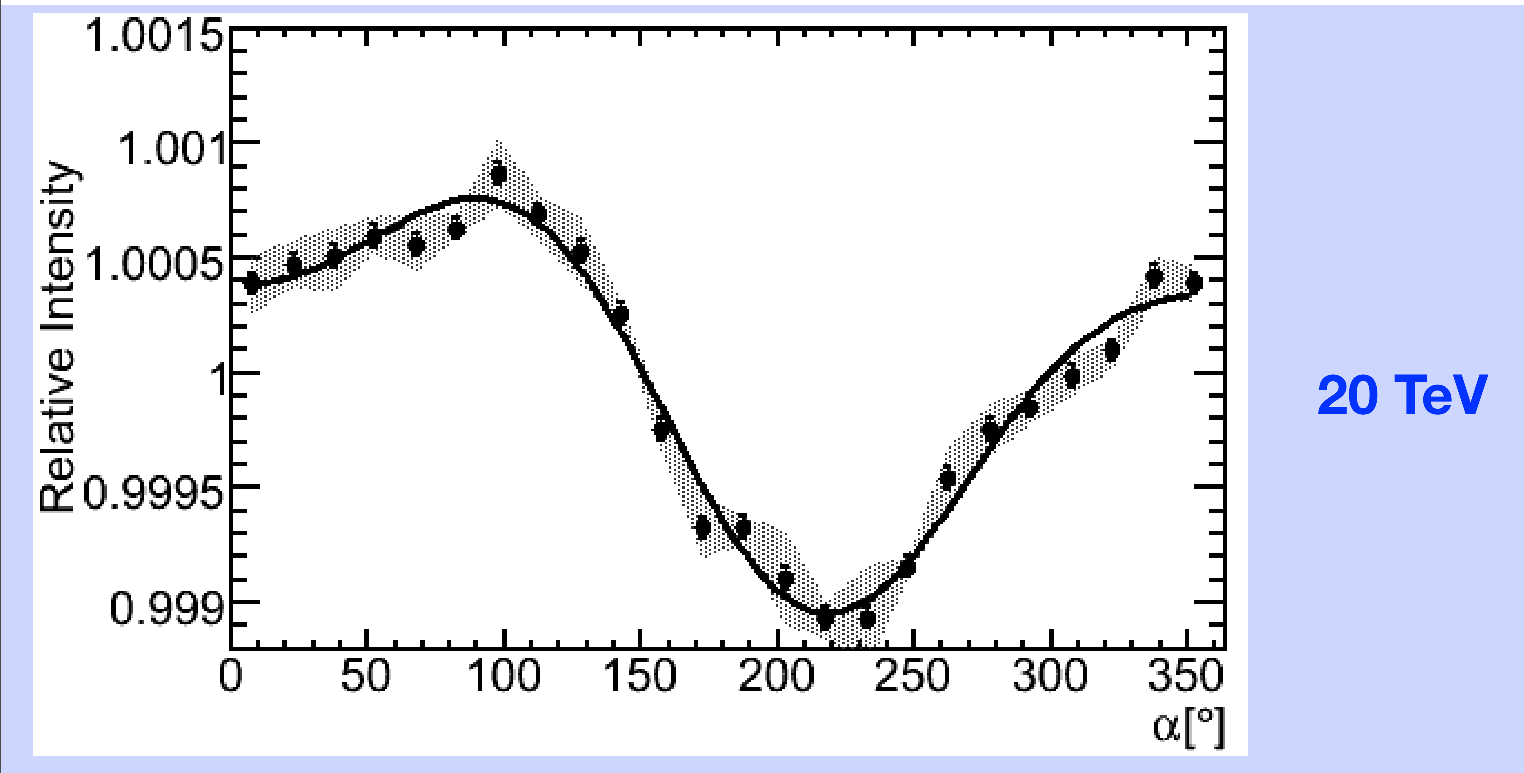


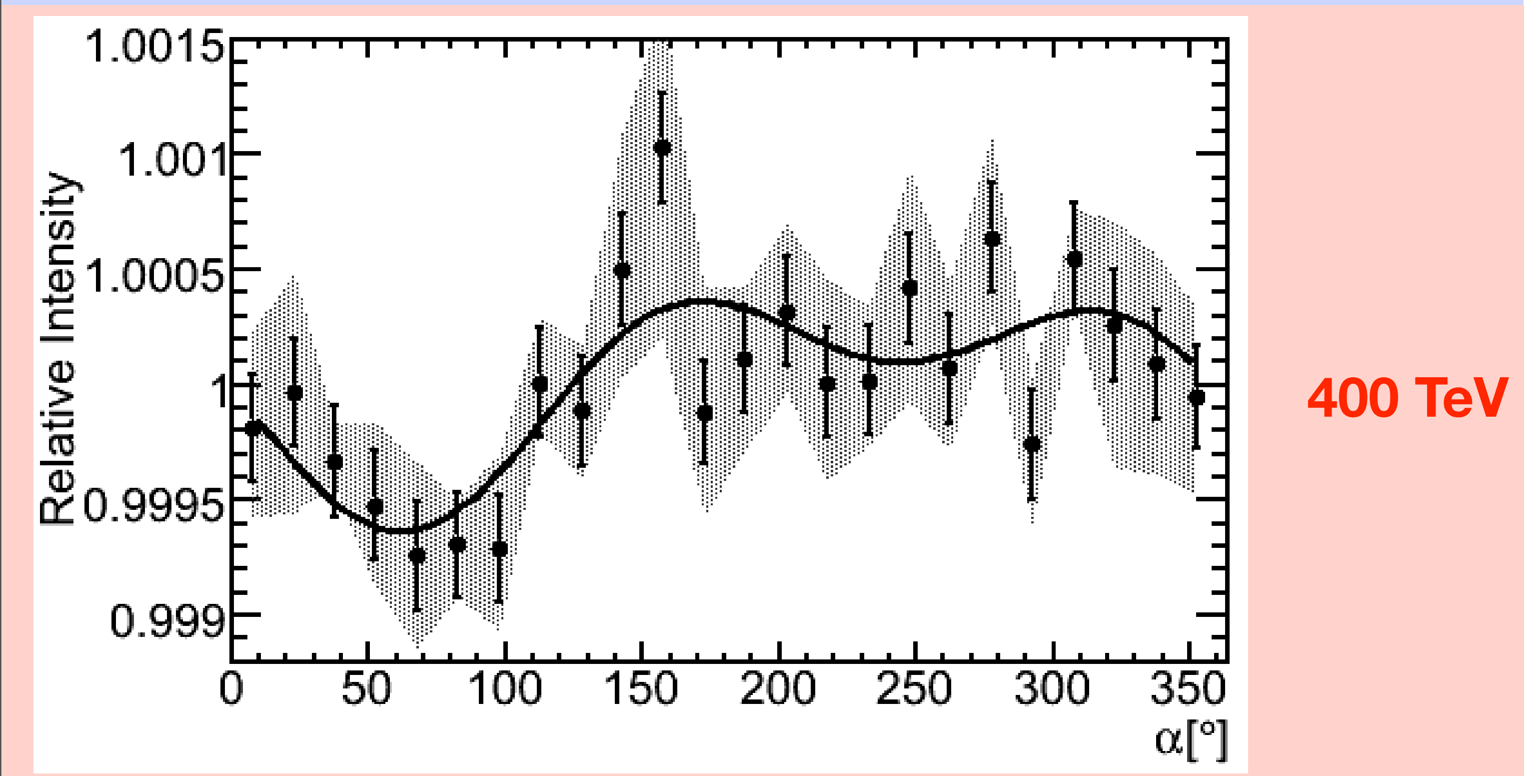
The anti- / extended-sidereal reference frames are unphysical and no anisotropy is expected

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

Systematic uncertainties in IceCube-59

statistical stability tests + anti-sidereal effect

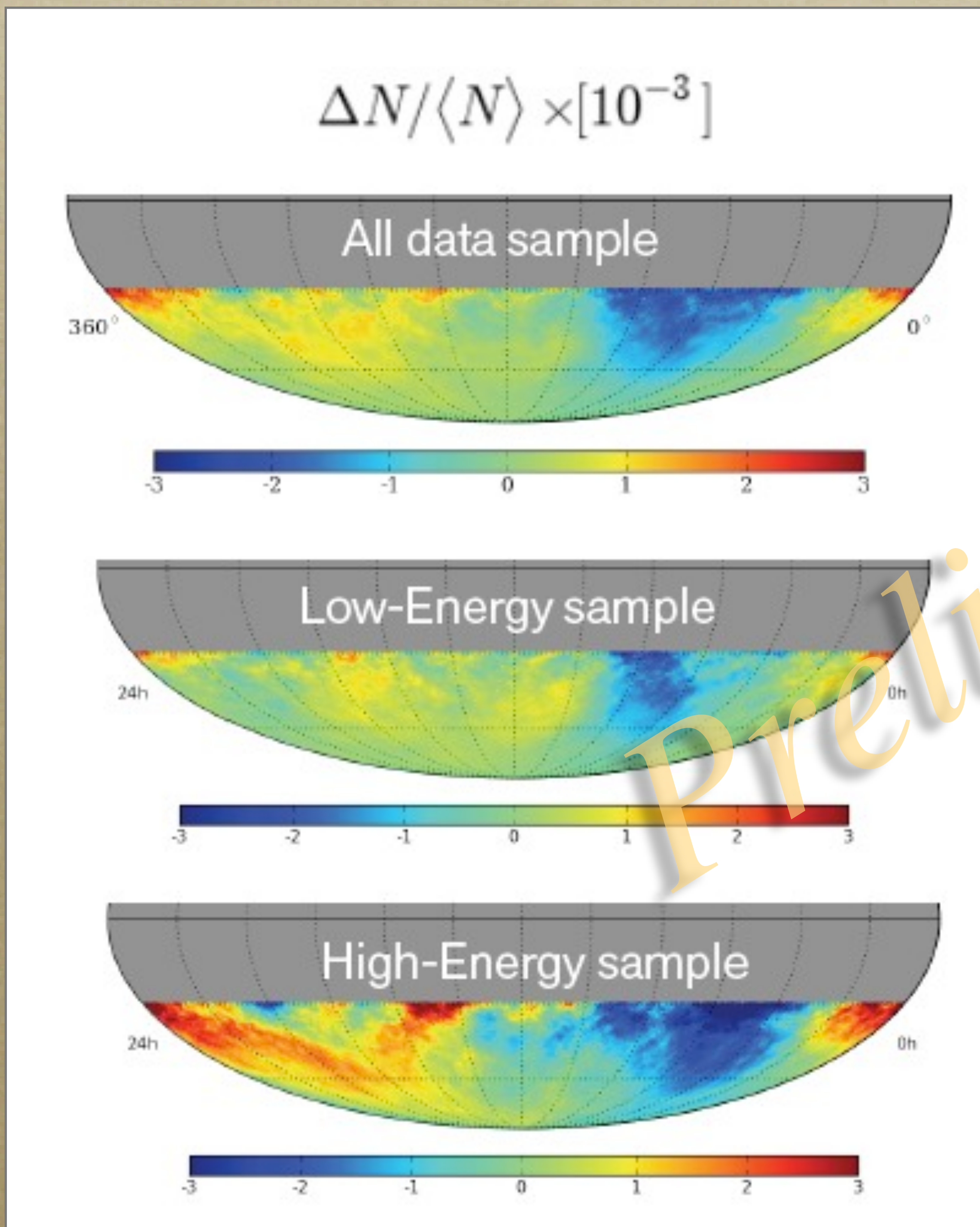


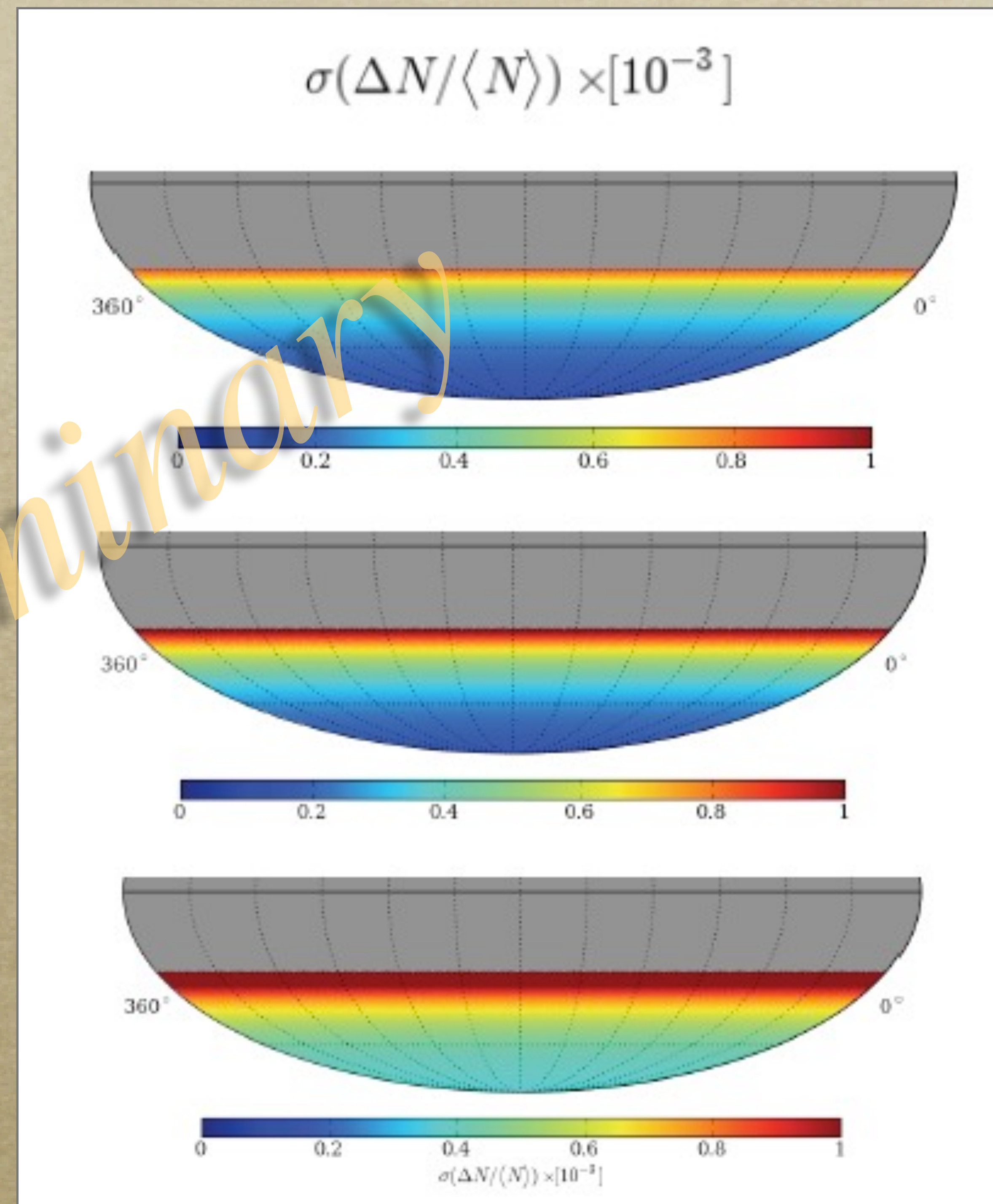


statistical stability tests:

- 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)

Relative intensity maps





Preliminary

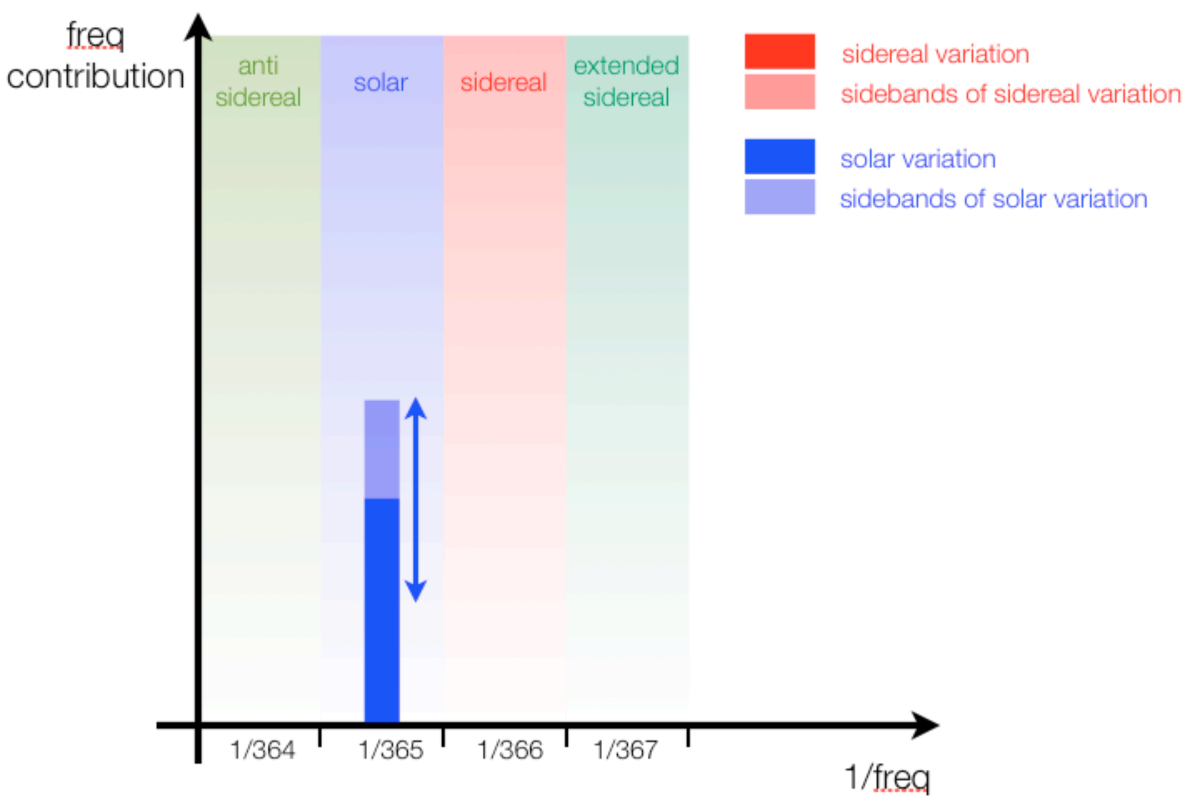
Farley, & Storey, Proc. Phys. Soc., 67, 996, 1954

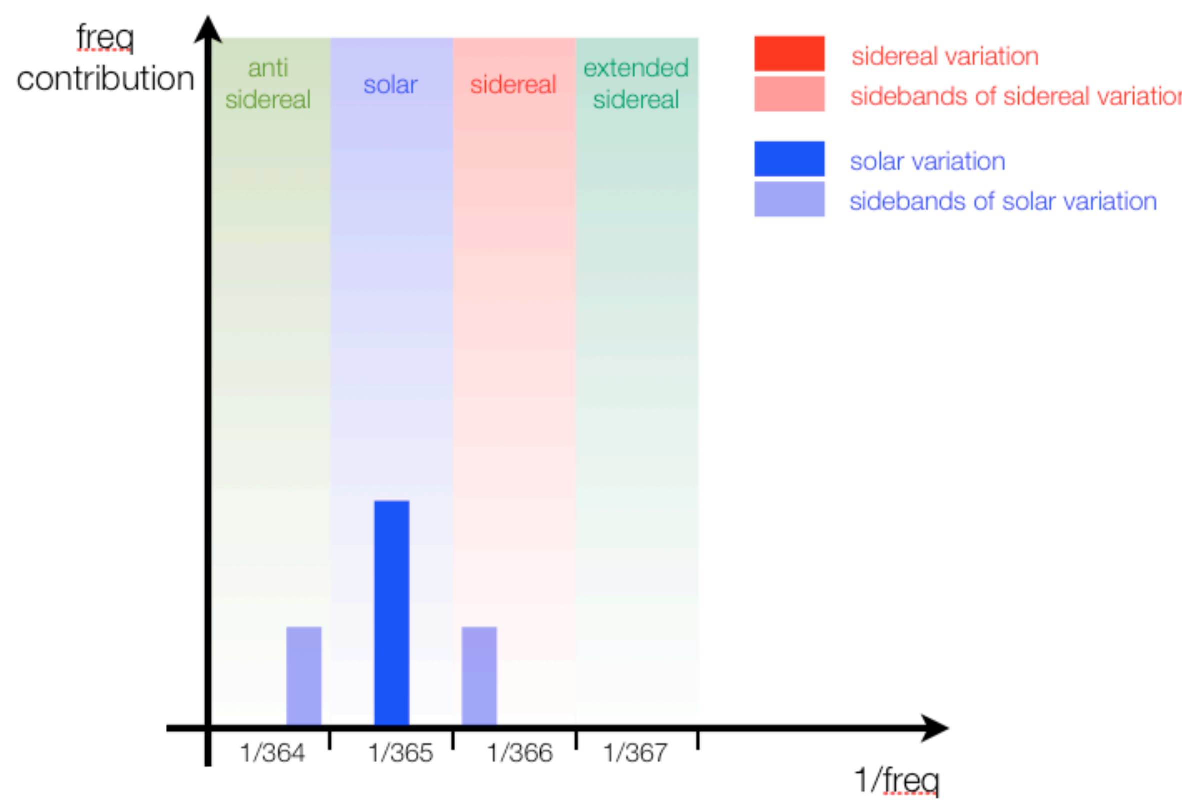
Nagashima, et al., Nuovo 907 Cimento C, 6, 550, 1983

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





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

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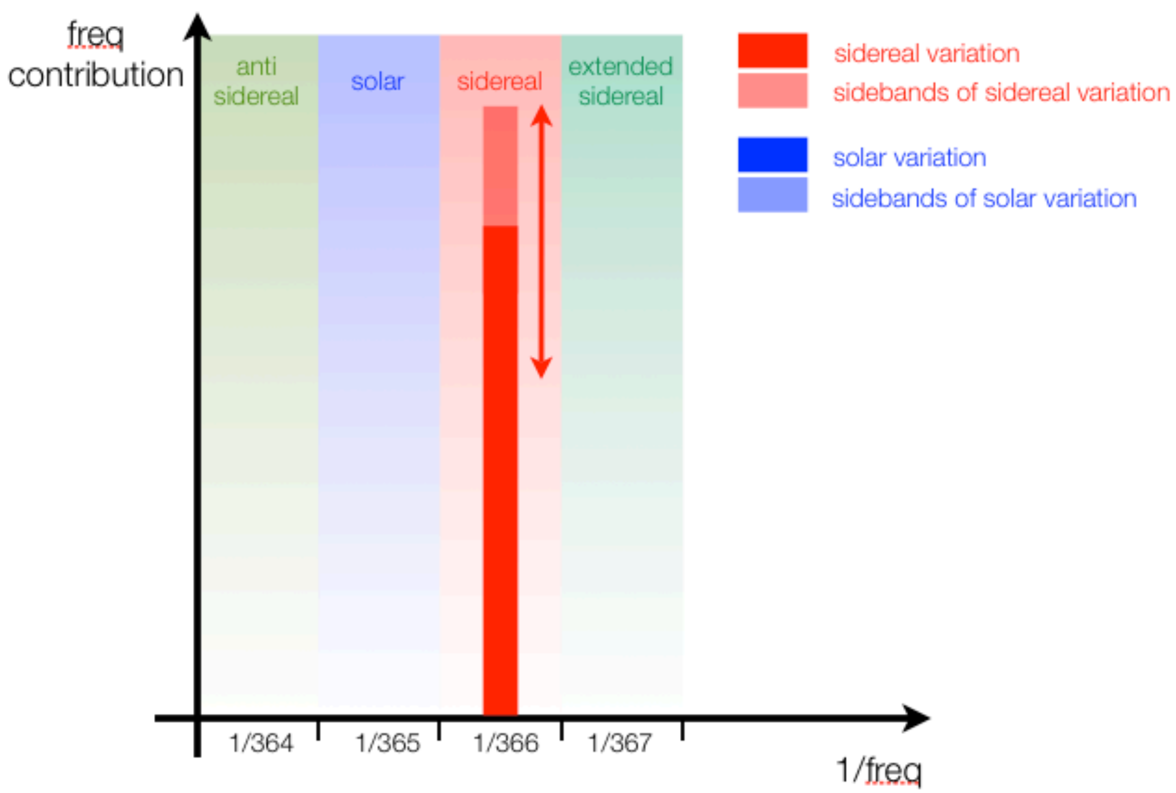
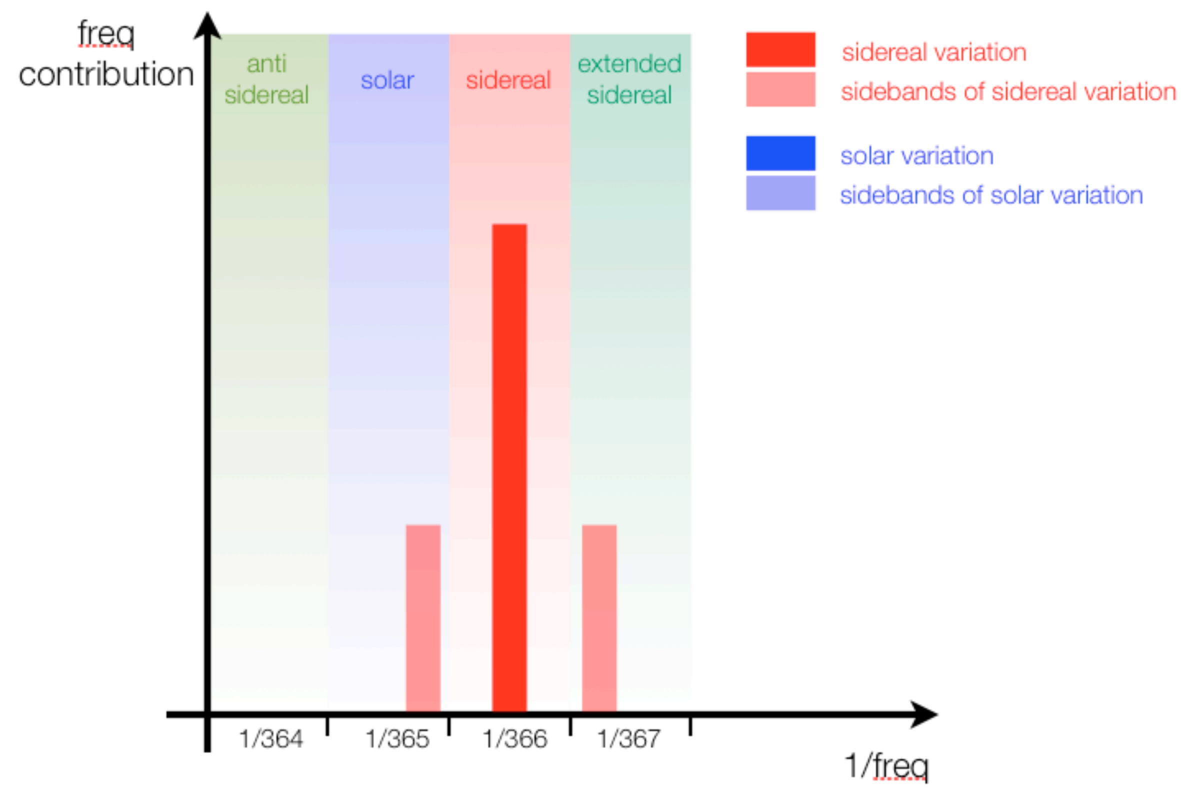
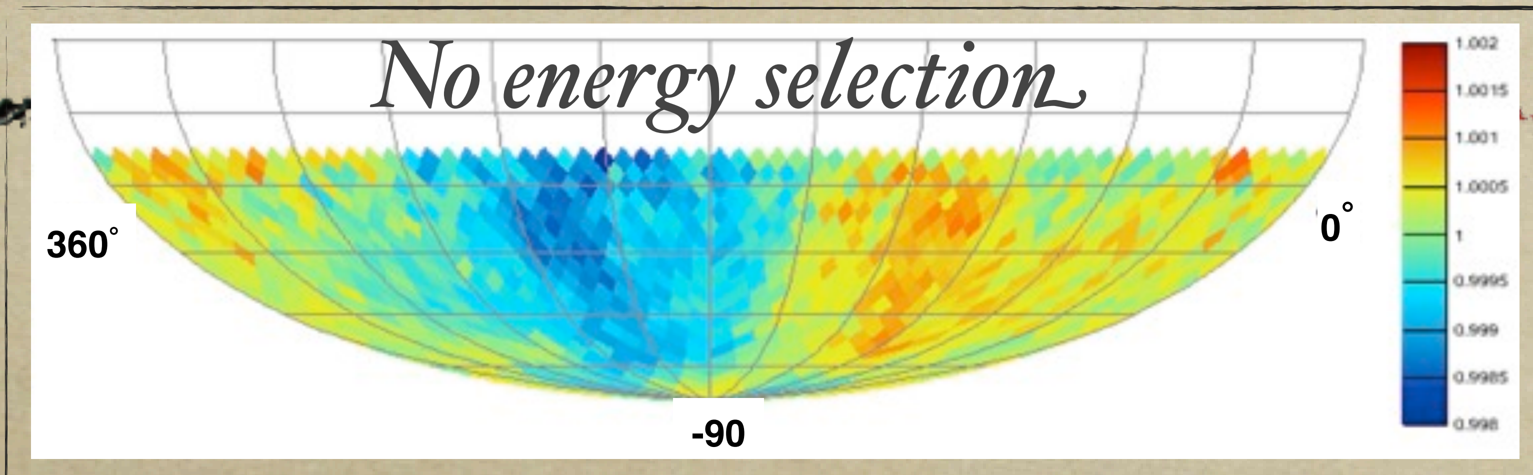
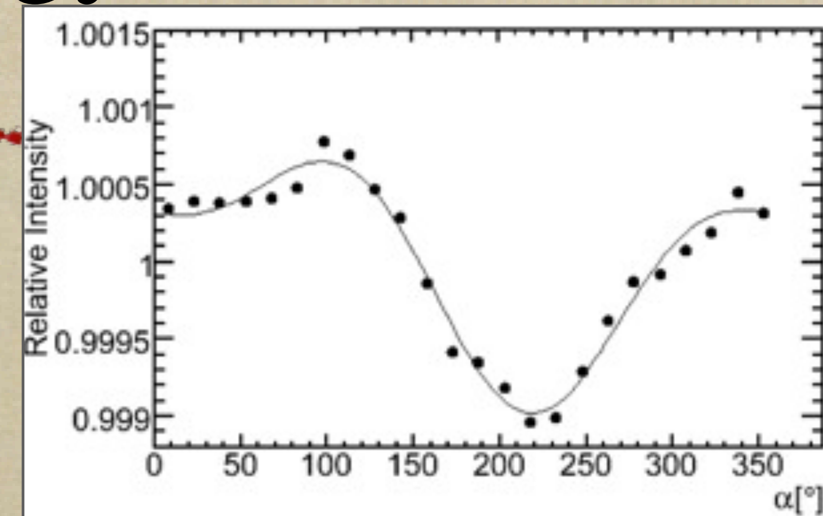
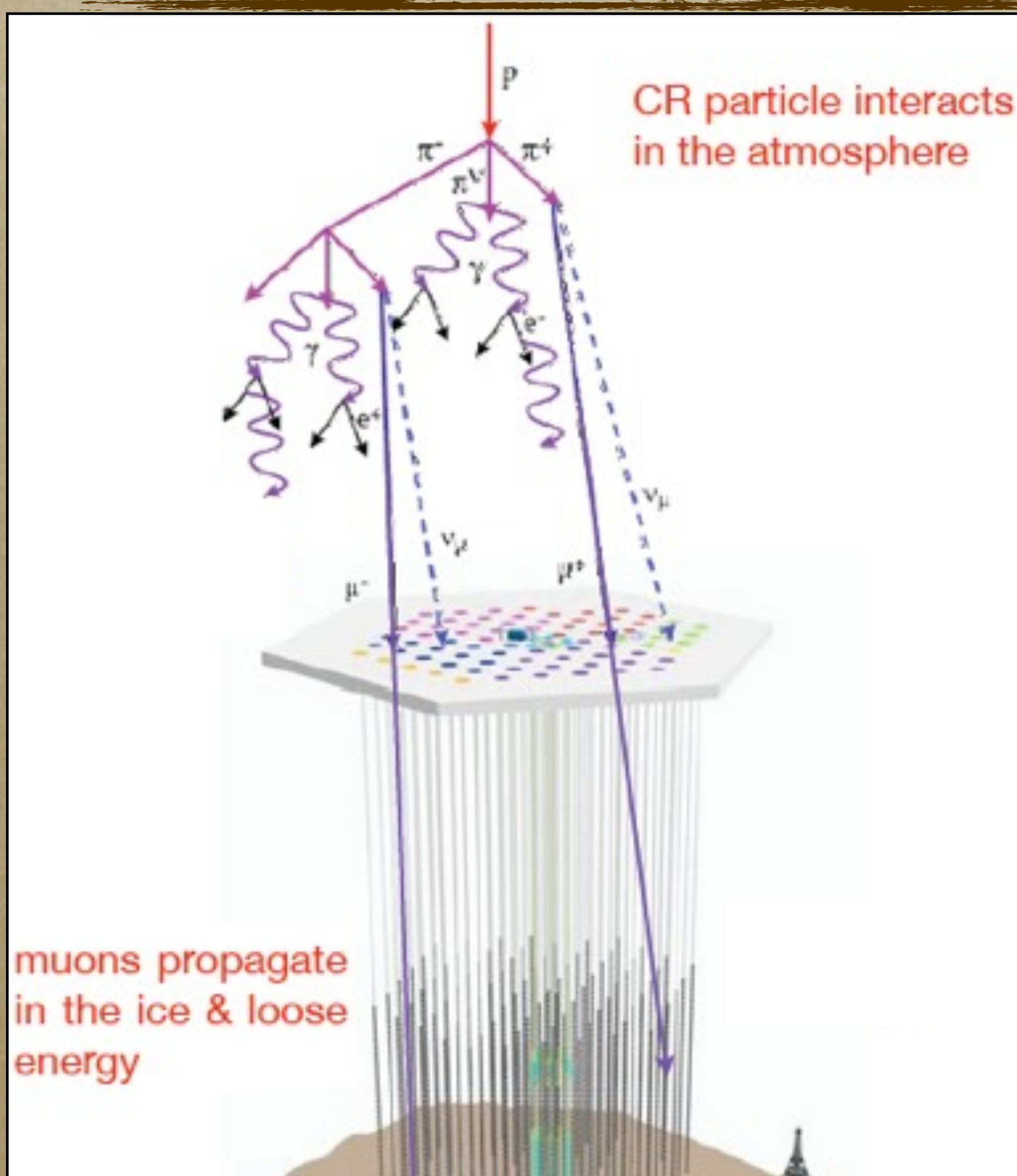


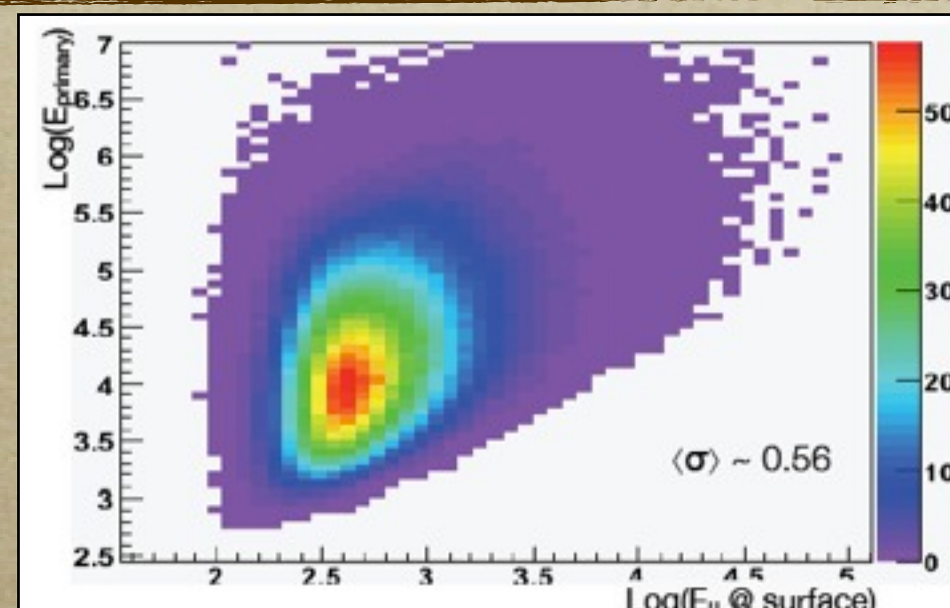


Cosmic ray anisotropy vs energy in IceCube-59



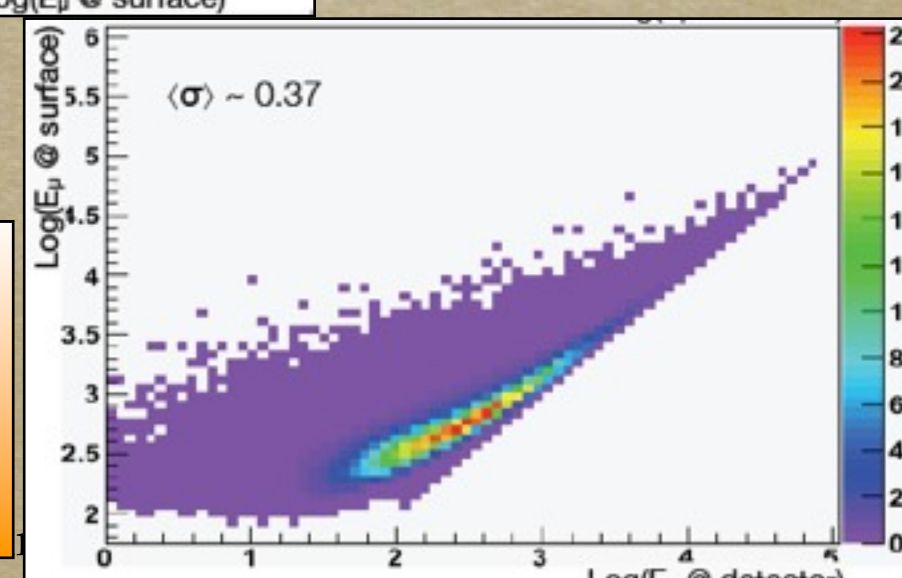




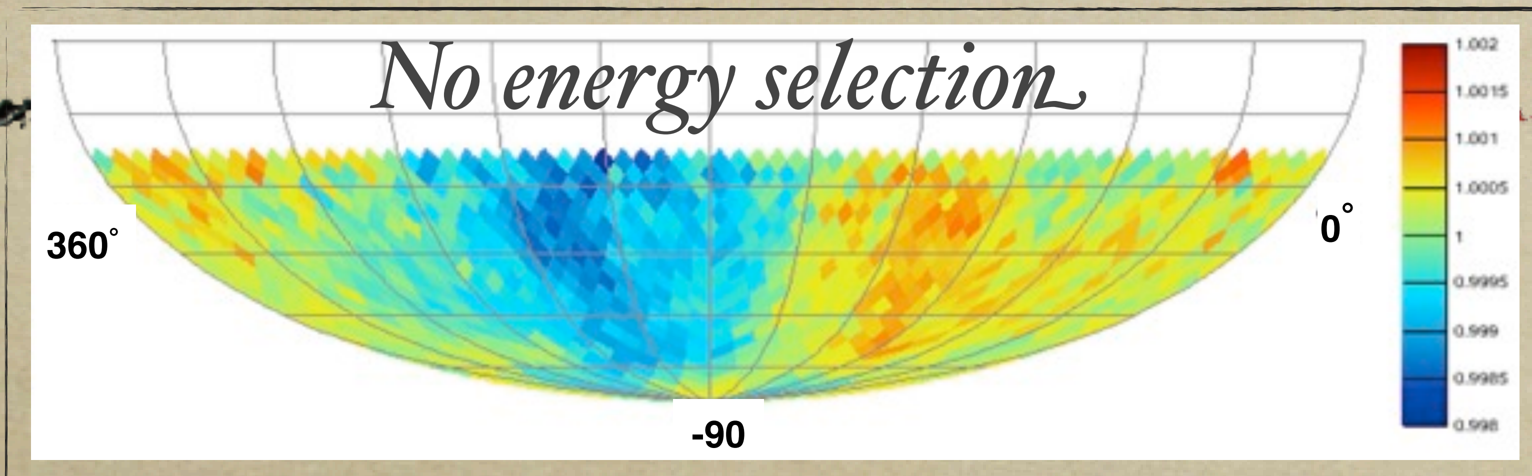


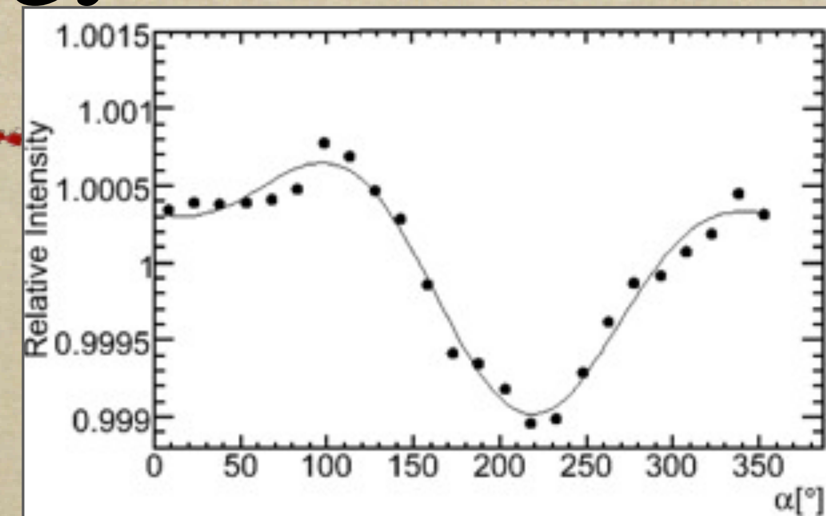
Monte Carlo simulations

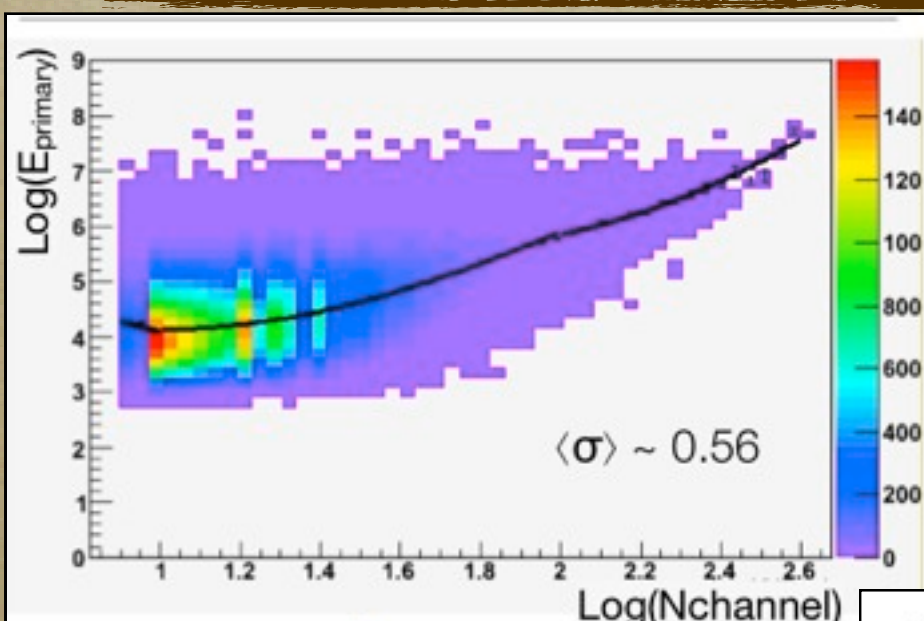
The energy resolution is dominated by the physics of the CR interaction



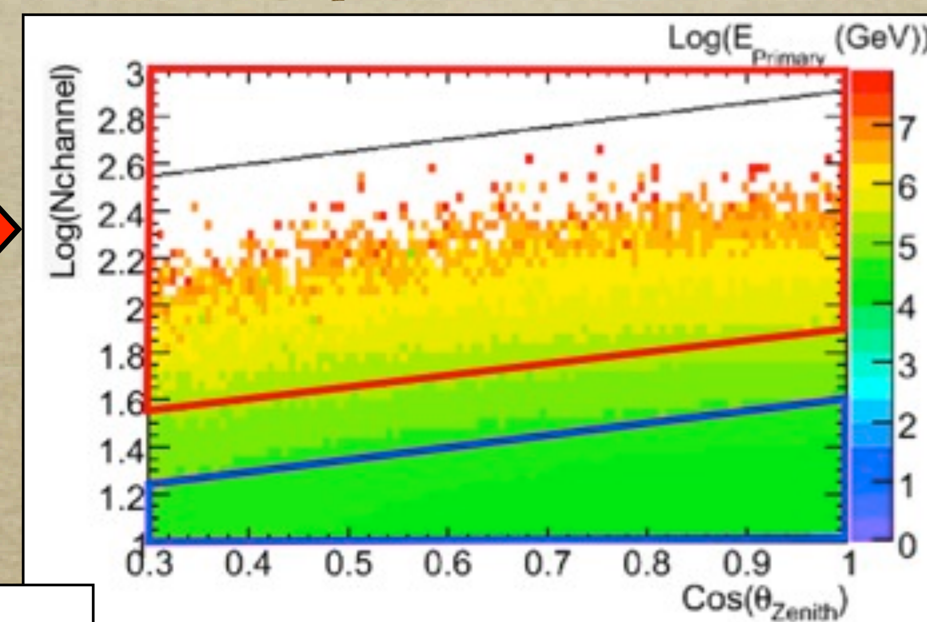
Cosmic ray anisotropy vs energy in IceCube-59



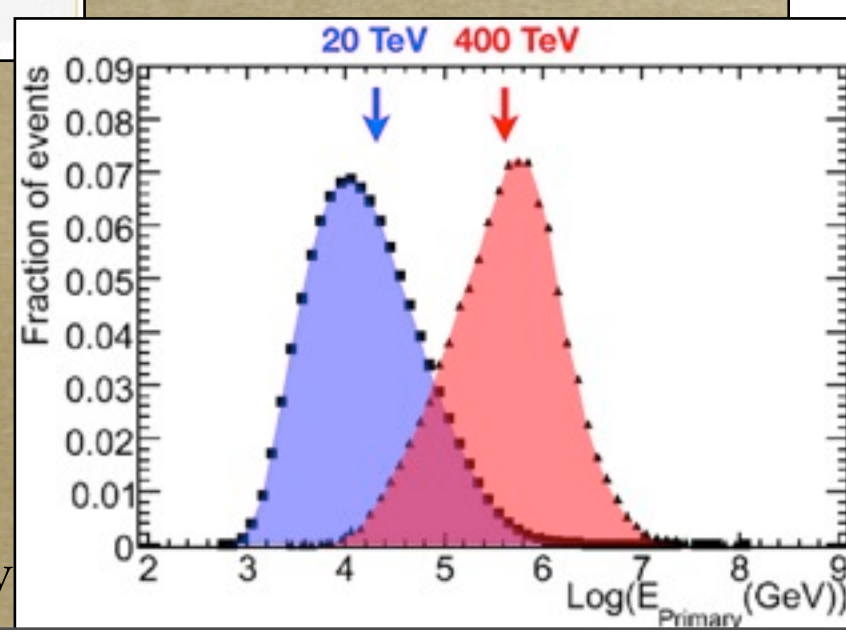




A 2D cut is used to select events of a given median energy

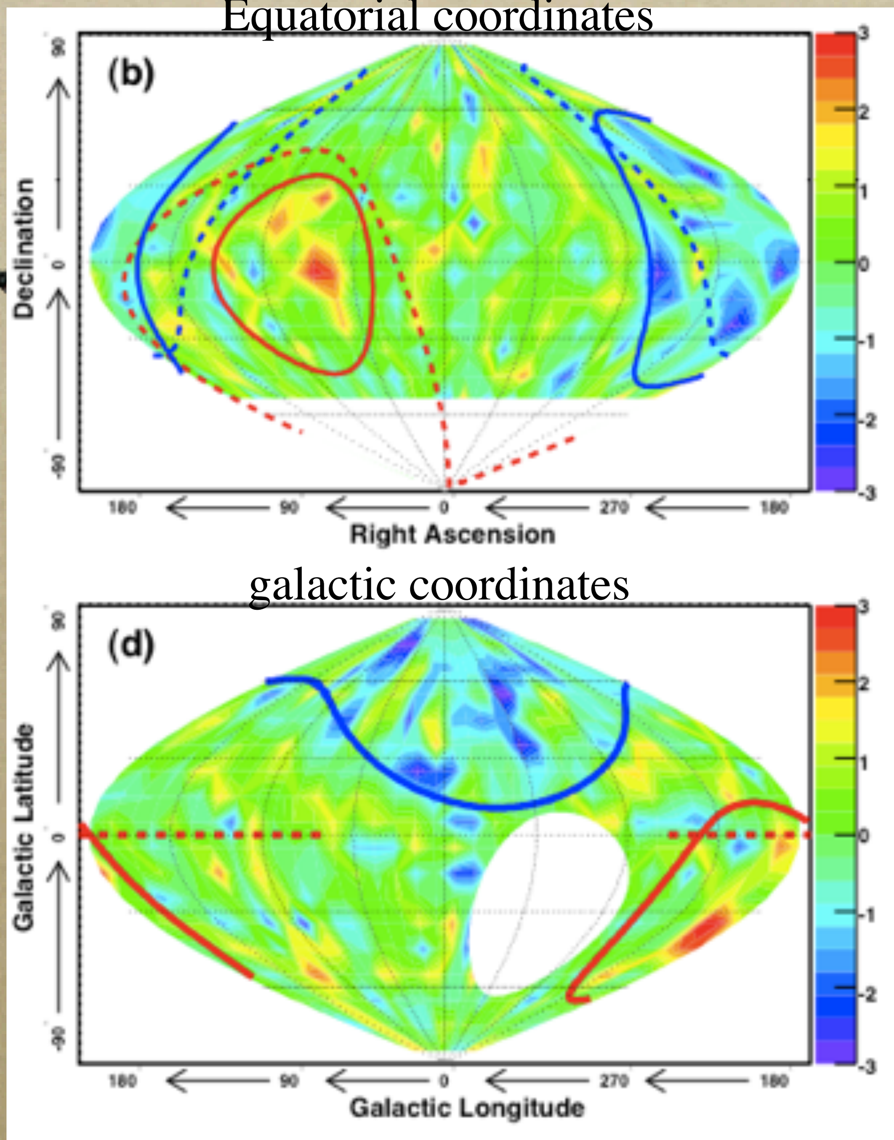


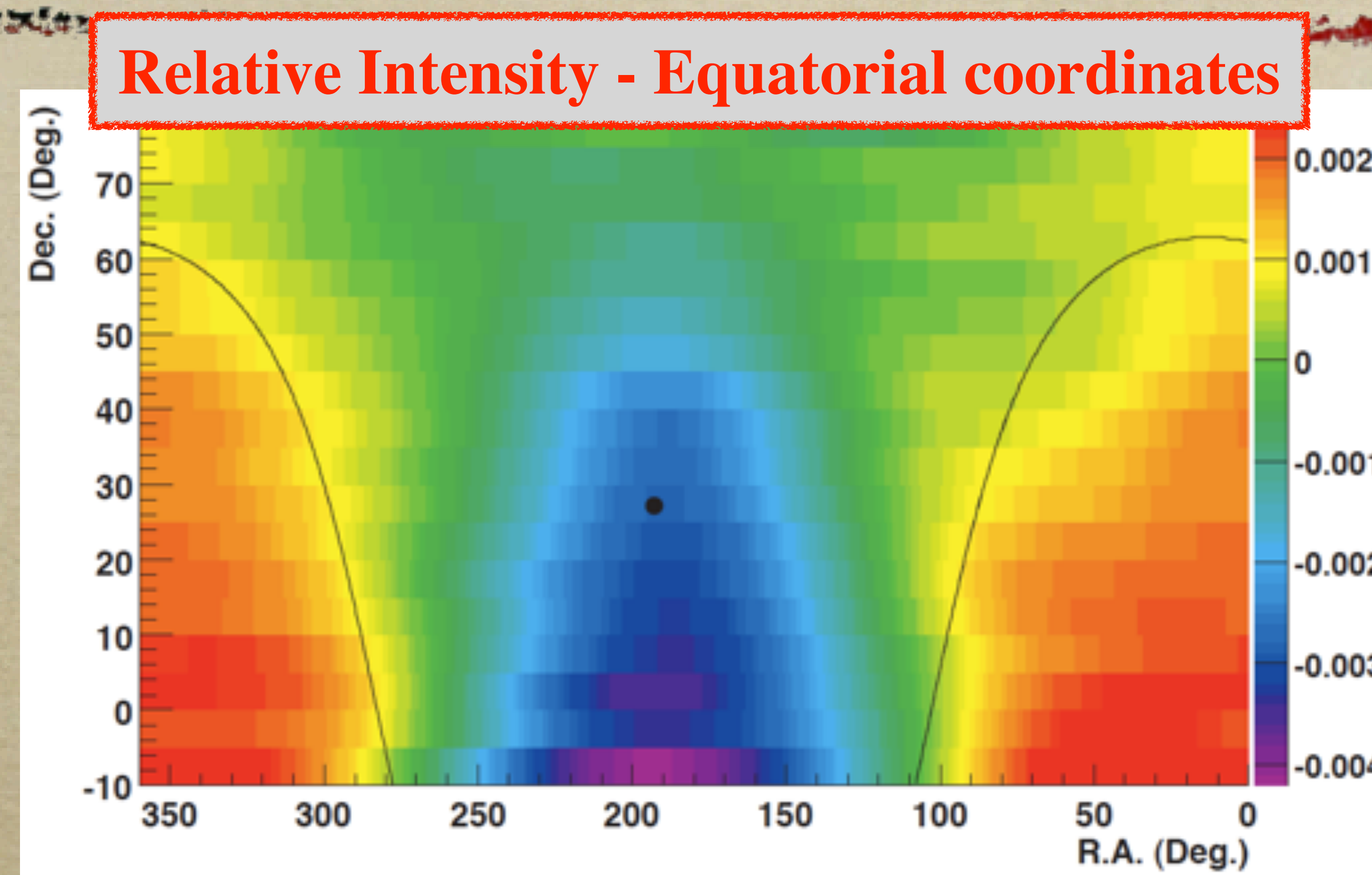
Nchannel is the number of triggered DOMs in IceCube



2 energy samples selected

Cosmic ray anisotropy





Super-Kamiokande

Guillian et al., Phys Rev D, Vol 75, 063002 (2007)

- data from 1996 to 2001
- 1662 days livetime
- 2.1 x 10^8 events
- angular resolution < 2°
- median CR energy ~ 10 TeV

MILAGRO

Abdo et al., ApJ, Vol 698-2, pag 2121 (2009)

- data from 2000 to 2007
- $9.5 \cdot 10^{10}$ events
- angular resolution < 1°
- median CR energy ~ 6 TeV