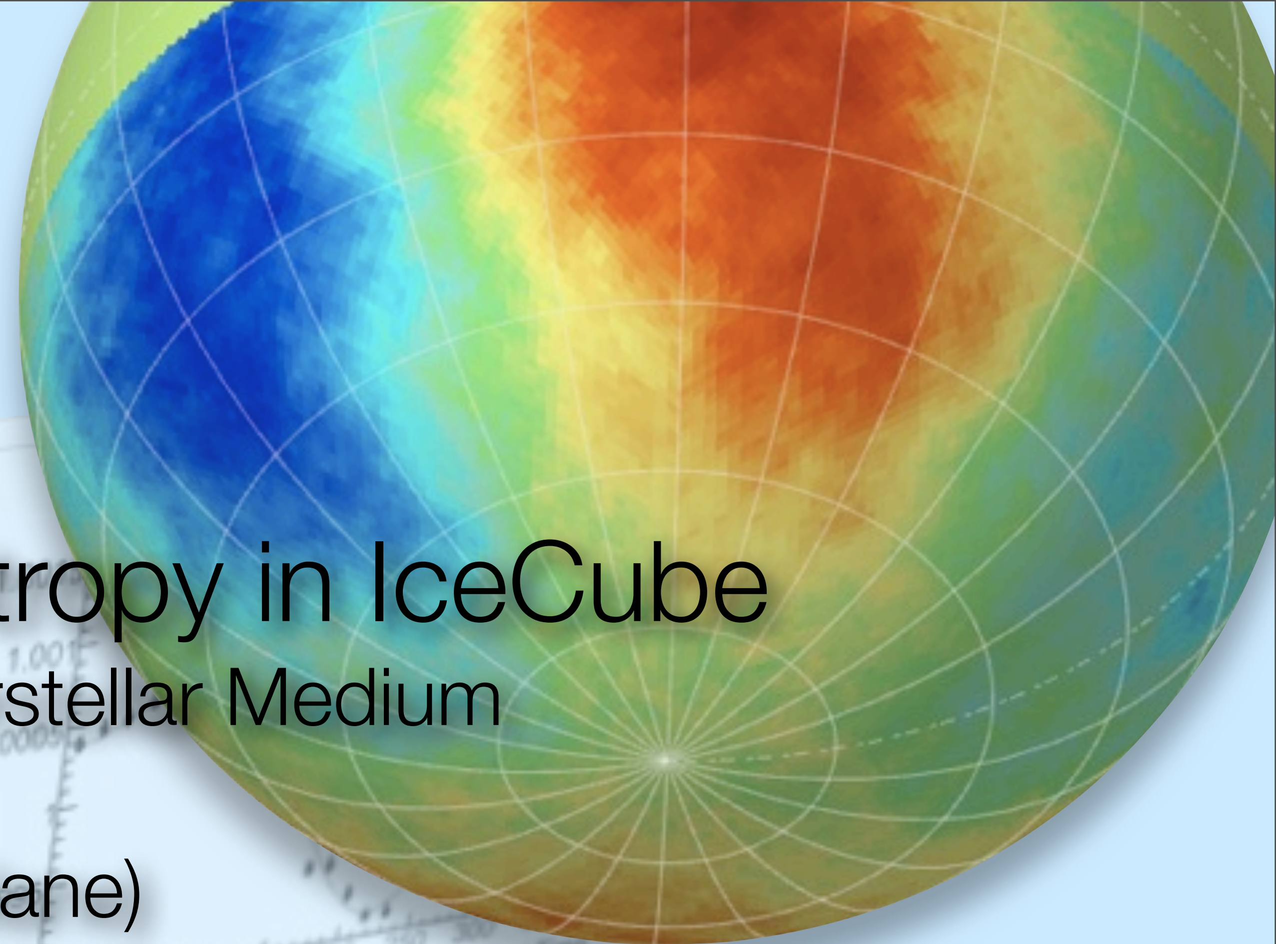

Galactic Cosmic Ray Anisotropy in IceCube

and Propagation Properties in the Interstellar Medium

(and neutrino emission from galactic plane)

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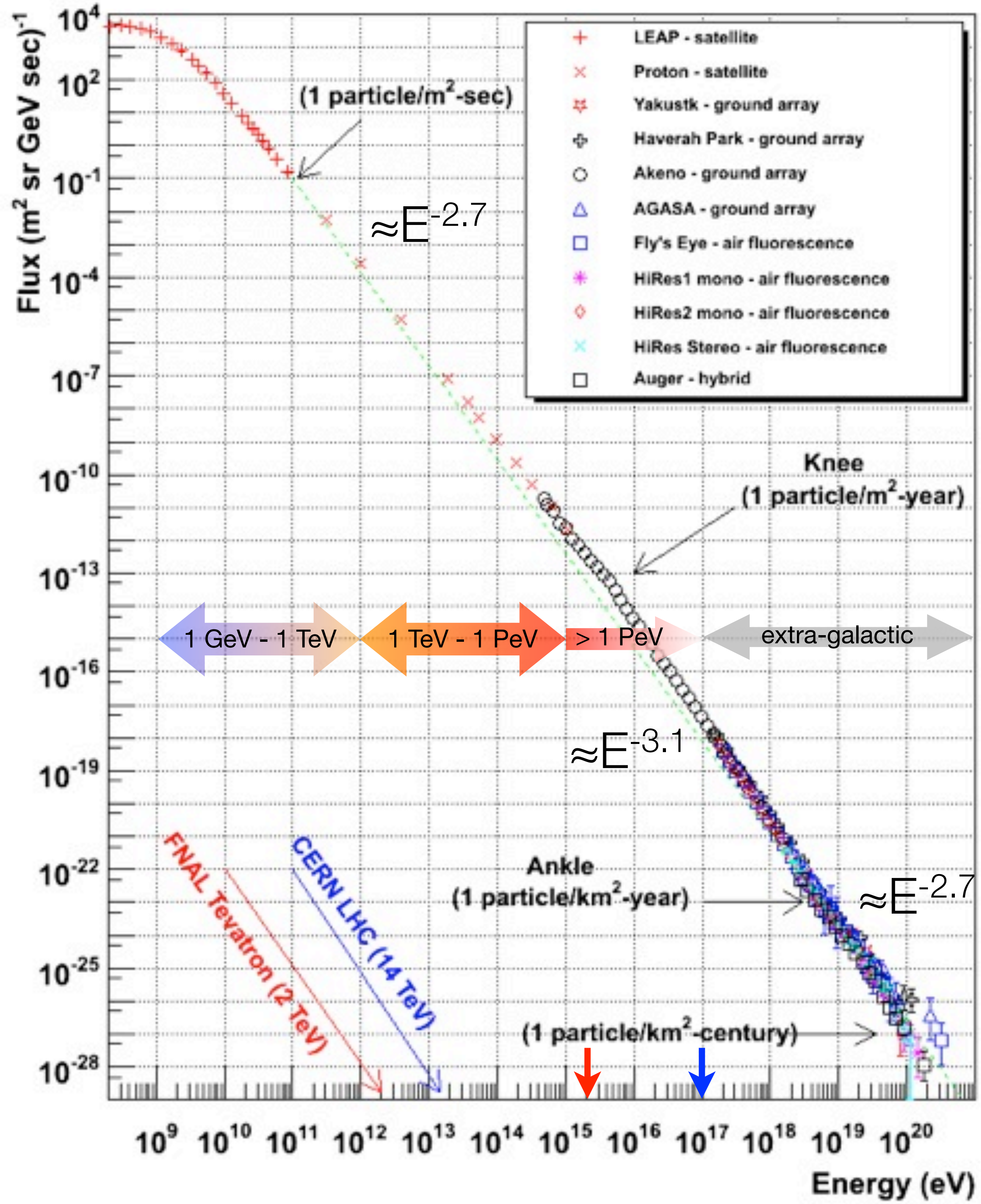
GALPROP Workshop 2011 - Stanford University
December 5-6th, 2011

cosmic rays spectrum

- spectral structure & mass composition hold information on
  - **origin** of cosmic rays and
  - **propagation** from *sources* to Earth
- **anisotropy** in arrival distribution
  - spectral structure
  - origin & propagation



cosmic ray acceleration in supernova remnants

- diffusive shock acceleration in galactic SNR (Baade & Zwicky, 1934 & Fermi, 1949)

$$n_{CR}(E) \approx \frac{E^{-\gamma} R_{SN}}{2\pi R_d^2} \cdot \frac{H}{D(E)}$$ density of cosmic rays

$$D(E) \propto E^{\delta}$$ diffusion coefficient

$$\phi_{CR} = \frac{c n_{CR}(E)}{4\pi}$$ cosmic ray flux

$$\phi_{CR} \approx 2.4 \cdot \left(\frac{E_{SN}}{10^{51} erg}\right)$$ energy emitted by one SN

$$\cdot \epsilon_{CR}$$ cosmic ray acceleration efficiency

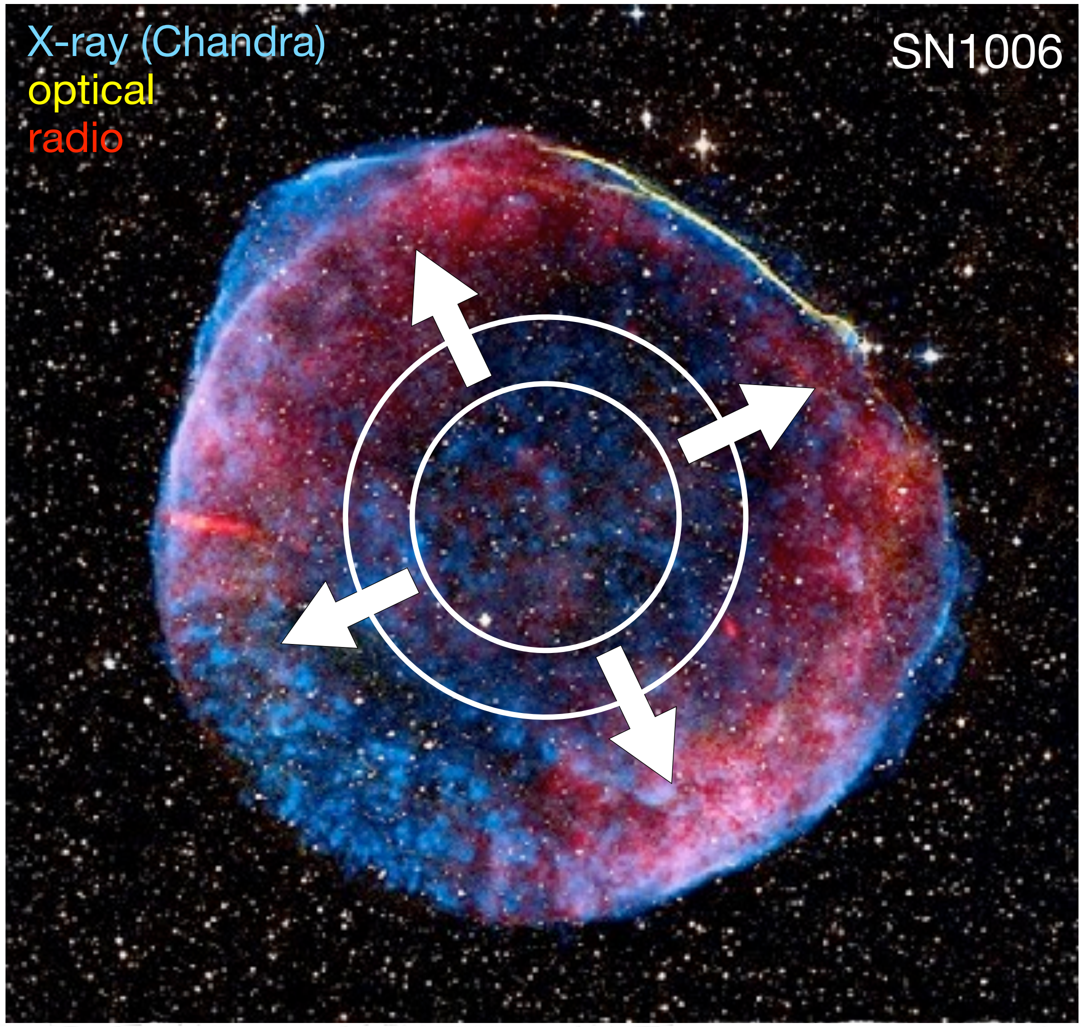
$$\cdot \left(\frac{15kpc}{R_d}\right)^2$$ radius of galactic disk

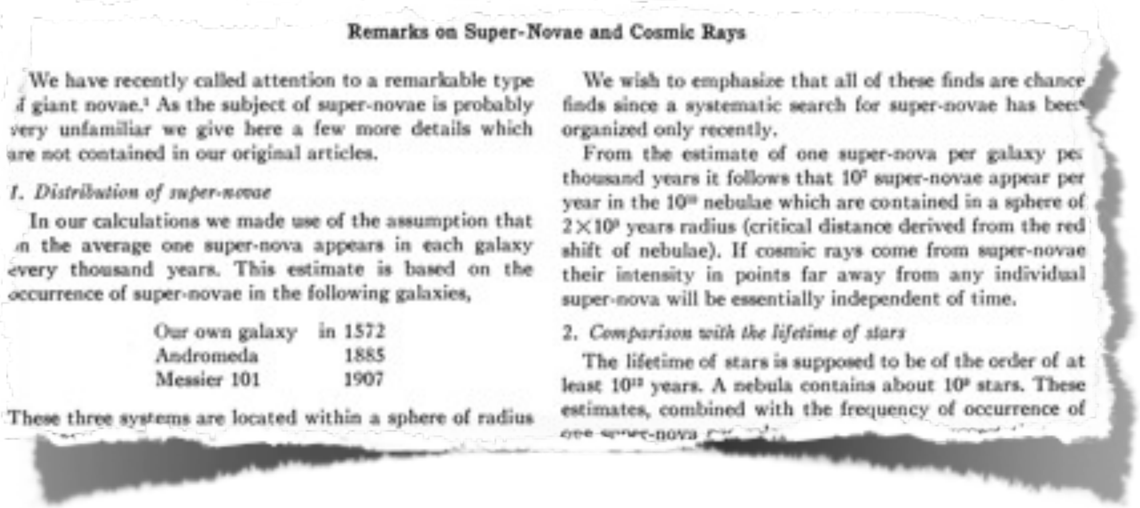
$$\cdot \left(\frac{R_{SN}}{30yr}\right)$$ rate of supernovae in the Galaxy

$$\cdot (\gamma - 2) \cdot 3^{-\delta}$$ propagation term

$$\cdot \left(\frac{E}{1TeV}\right)^{-\gamma-\delta} \quad [TeV^{-1} m^{-2} s^{-1} sr^{-1}]$$

W. Baade & F. Zwicky, Physical Review 46, 76, 1934





Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius

We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

From the estimate of one super-nova per galaxy per thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

2. Comparison with the lifetime of stars

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of one super-nova ...

cosmic ray anisotropy vs energy

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

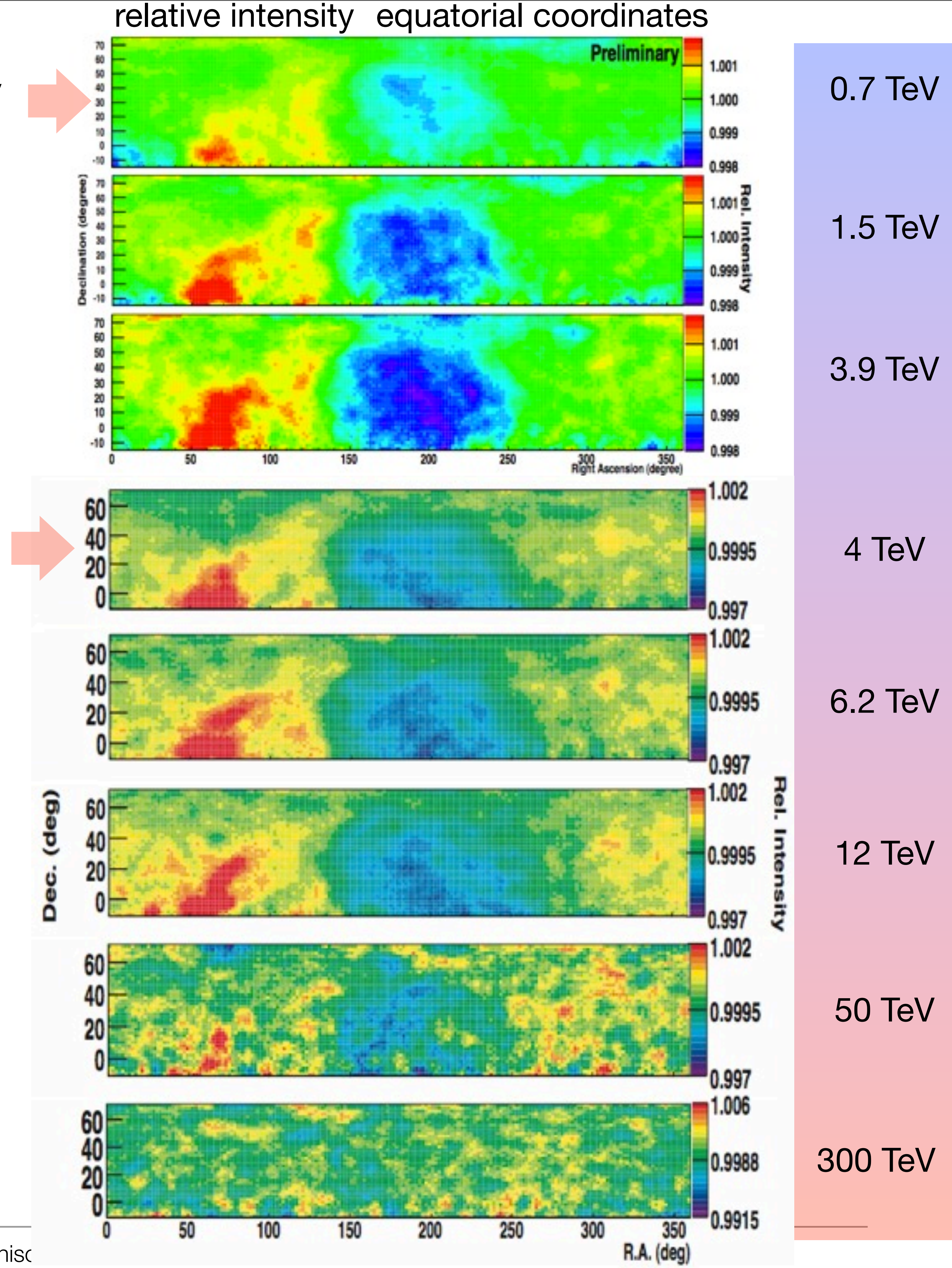
ARGO-YBJ

- data from 2008
- 365 days livetime
- $6.5 \cdot 10^{10}$ events
- median CR energy ~ 1 TeV

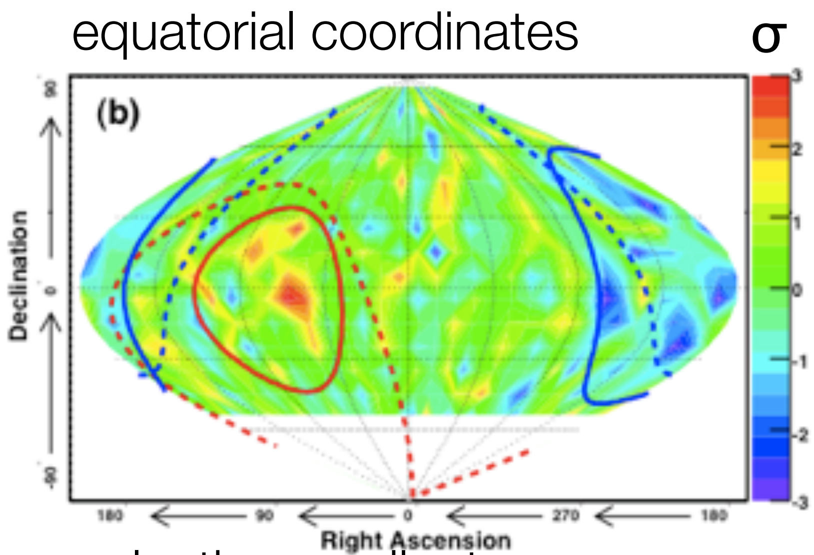
Amenomori et al., Science Vol. 314, pp. 439, 2006

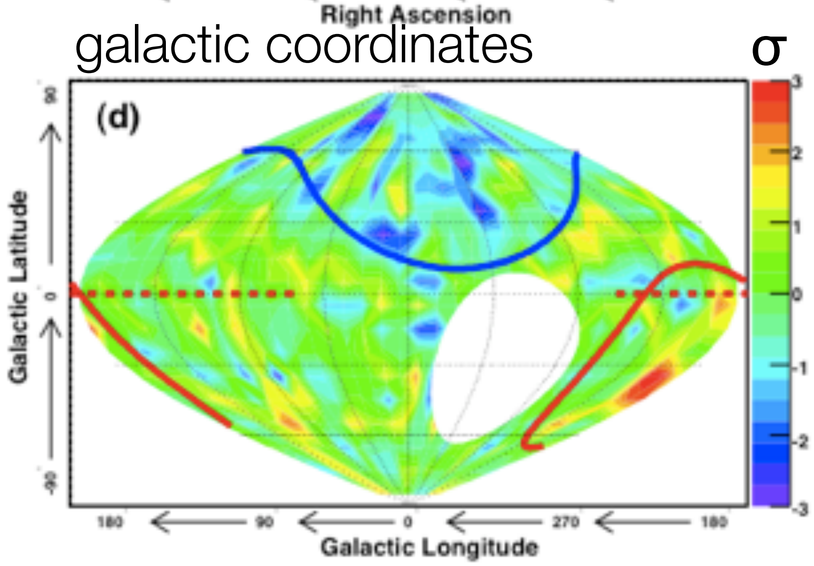
Tibet-ASγ

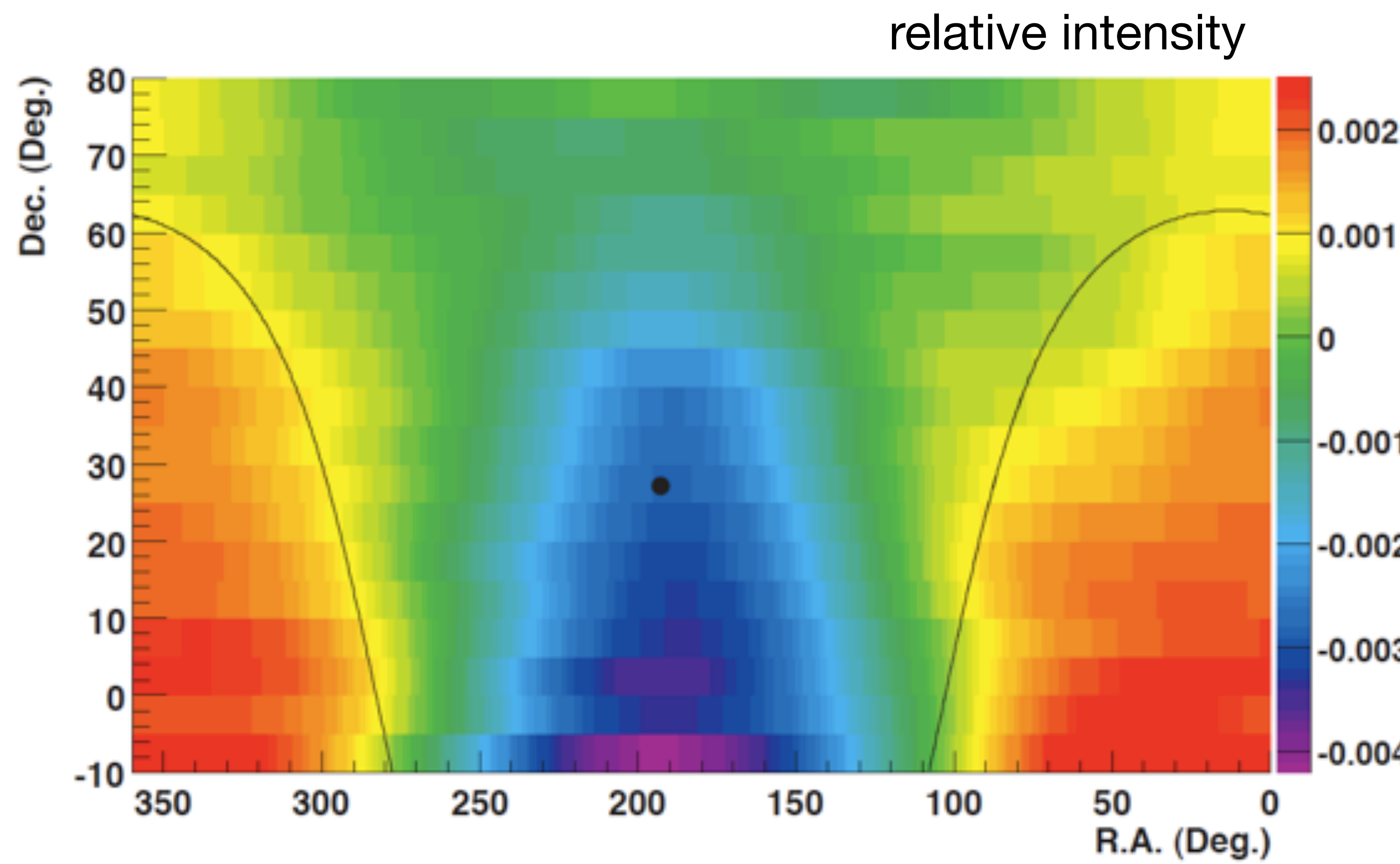
- data from 1997 to 2005
- 1874 days livetime
- $3.7 \cdot 10^{10}$ events
- angular resolution ~ 0.9°
- modal CR energy ~ 3 TeV



Tuesday, December 6, 2011







Super-Kamiokande

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

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

Milagro

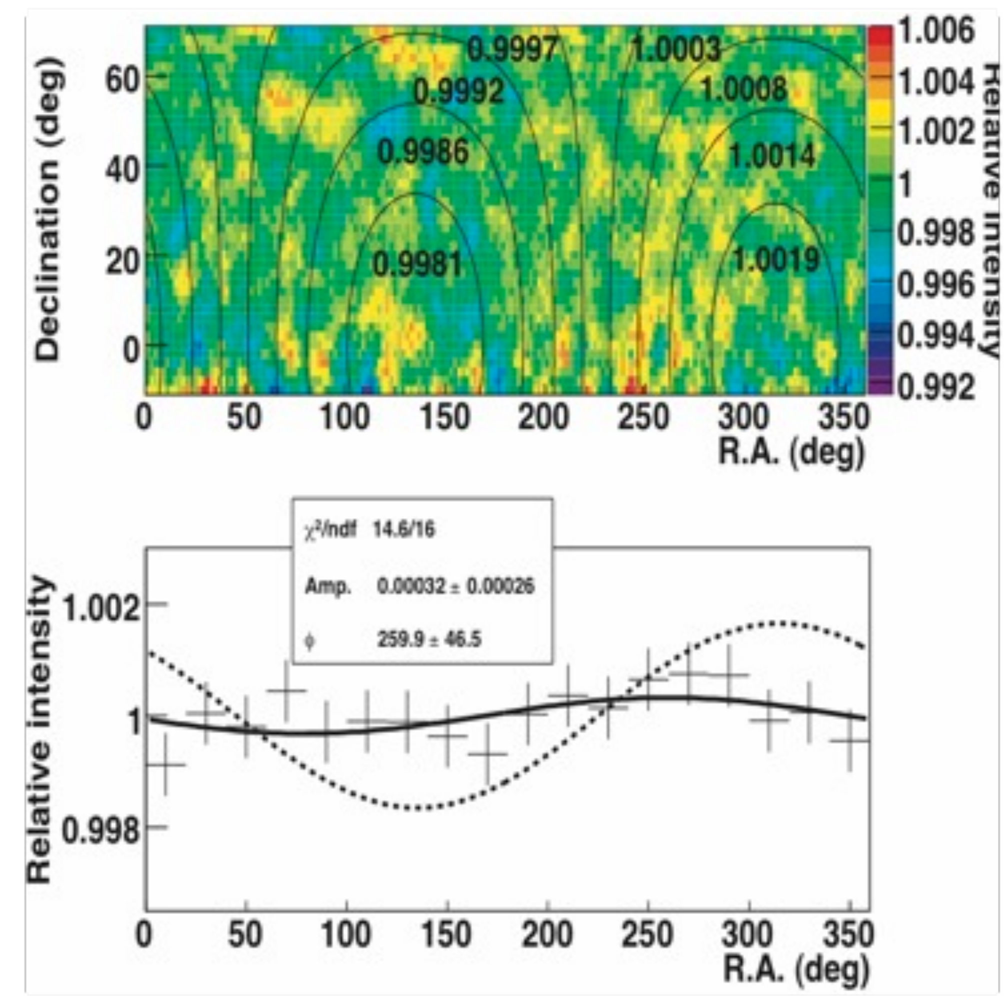
Abdo et al., ApJ, Vol 698-2, pag 2121 (2009)

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

cosmic ray anisotropy vs energy

relative intensity

equatorial coordinates

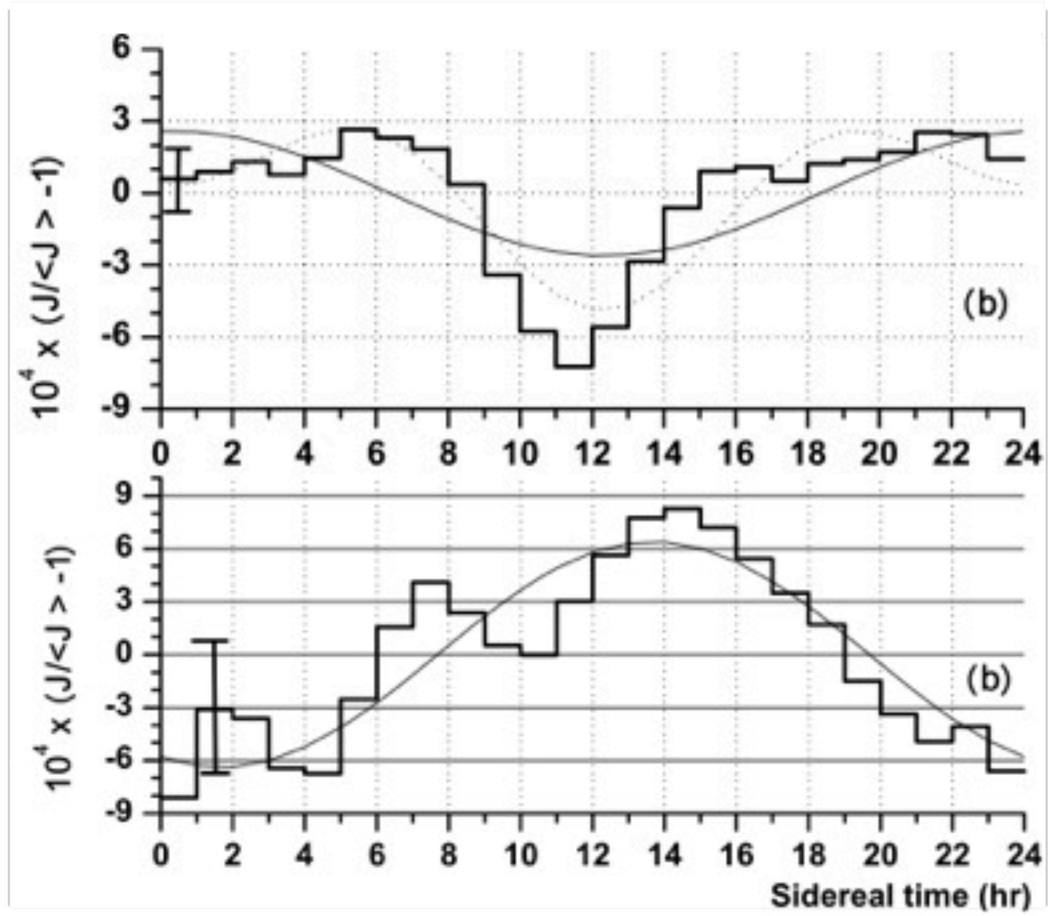


300 TeV

Tibet-ASγ

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

relative intensity



110 TeV

370 TeV

EAS-TOP

Aglietta et al., ApJ 692, L130, 2009

Internationl Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)

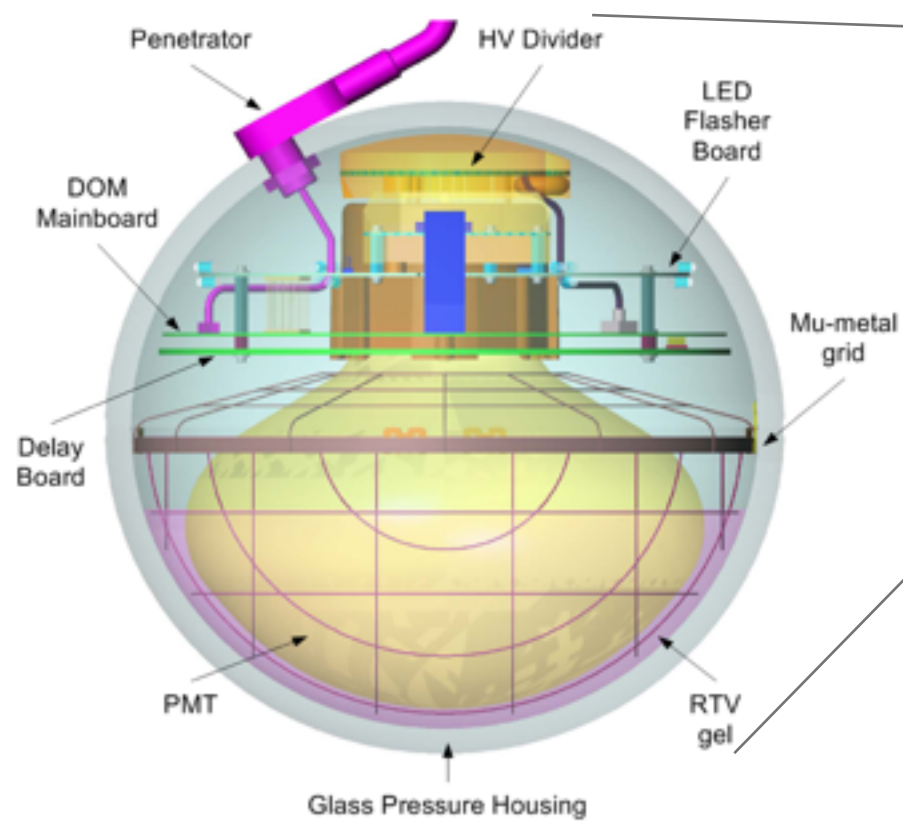
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

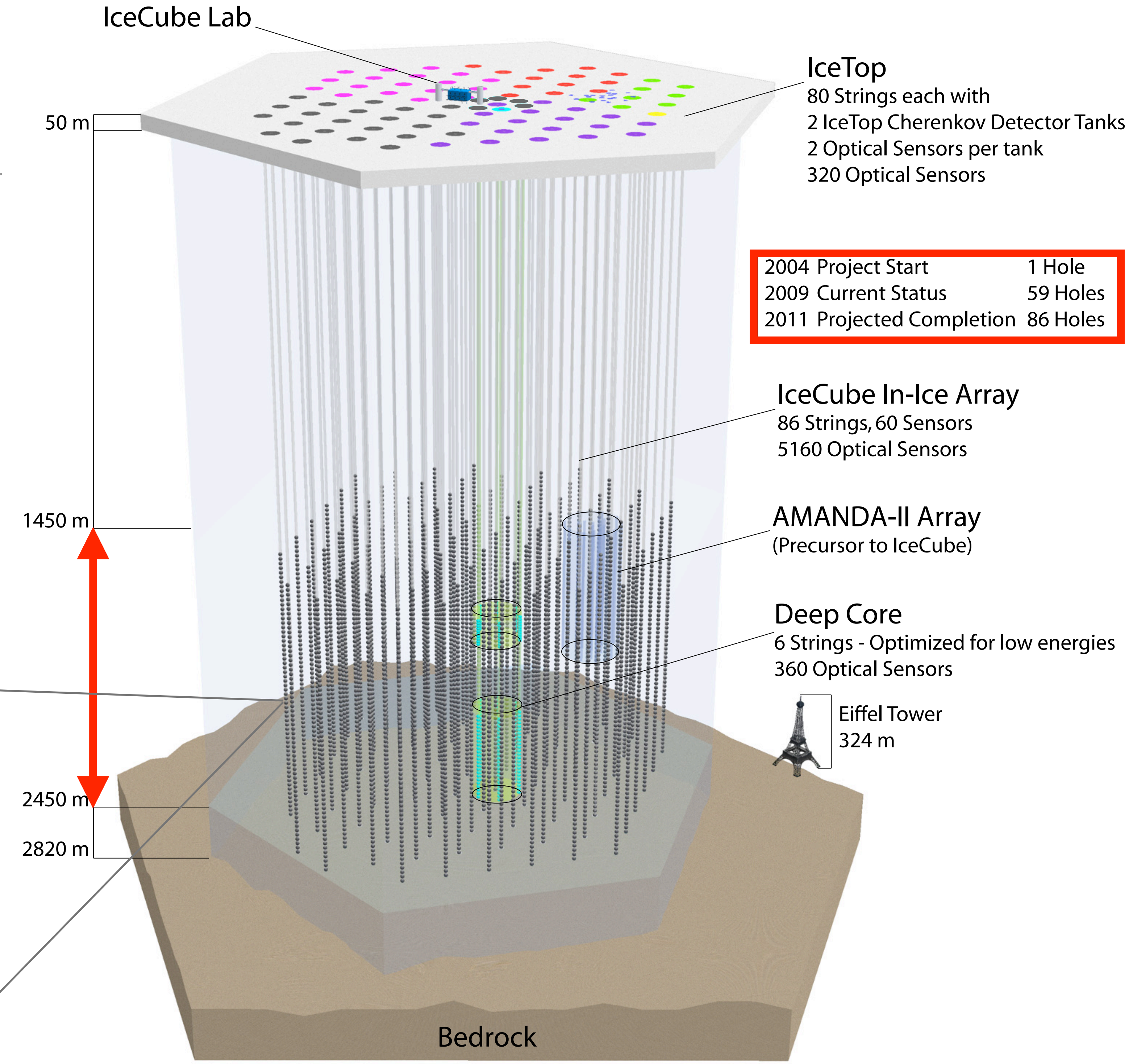
IceCube Observatory

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

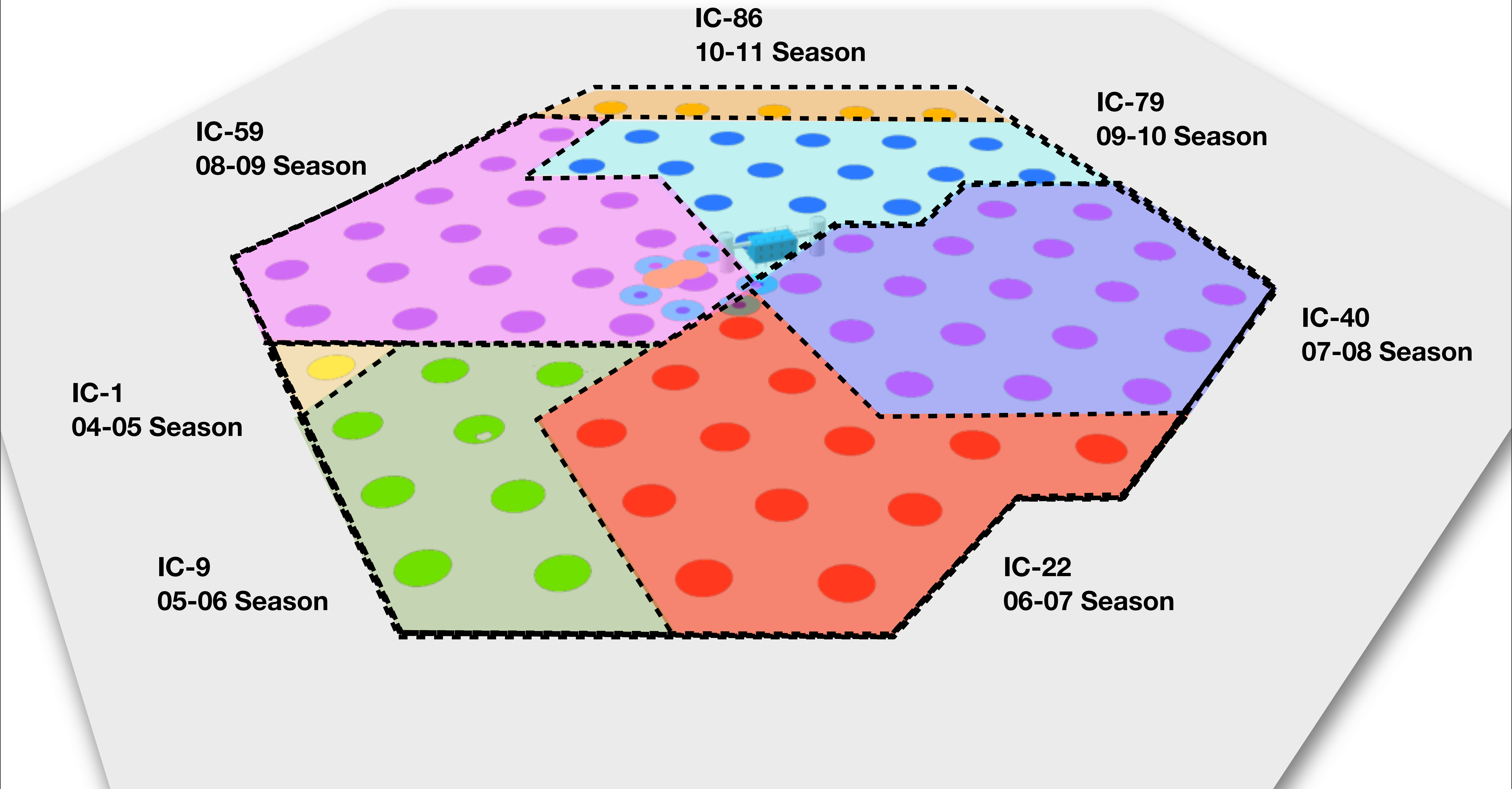
Digital Optical Module - DOM



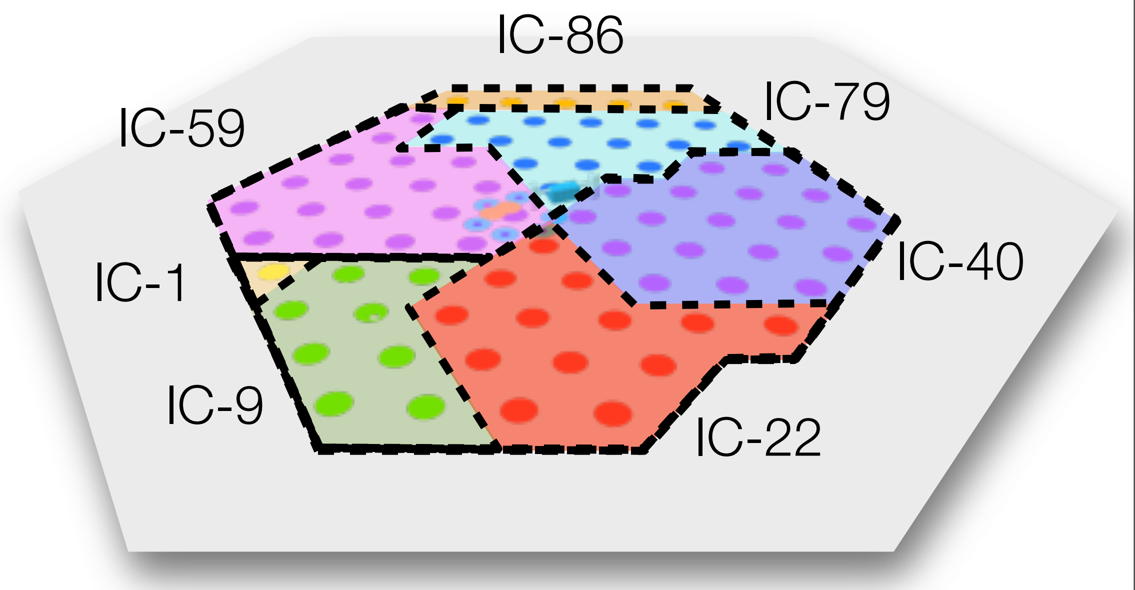
IceCube

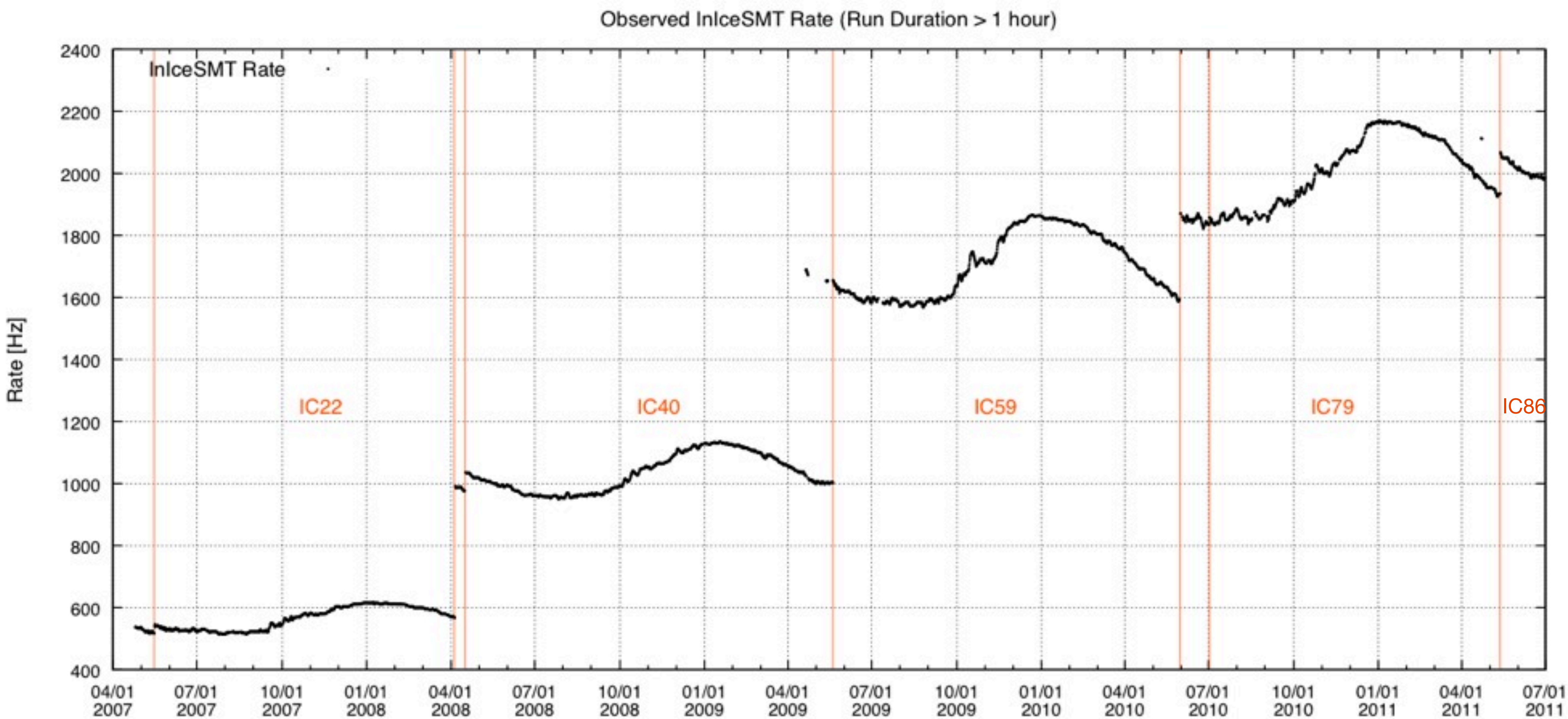


IceCube configurations



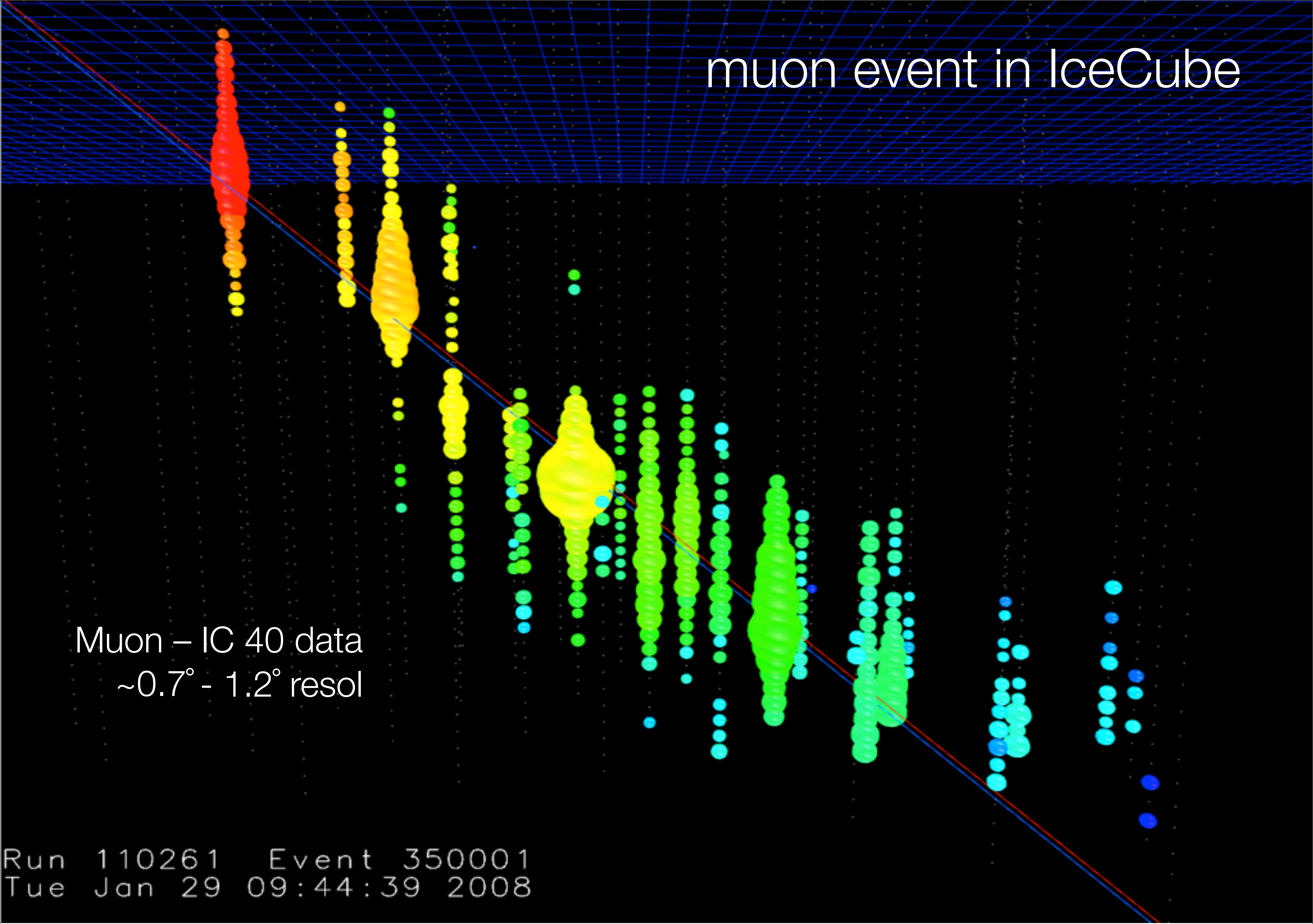
growing IceCube & temperature correlations





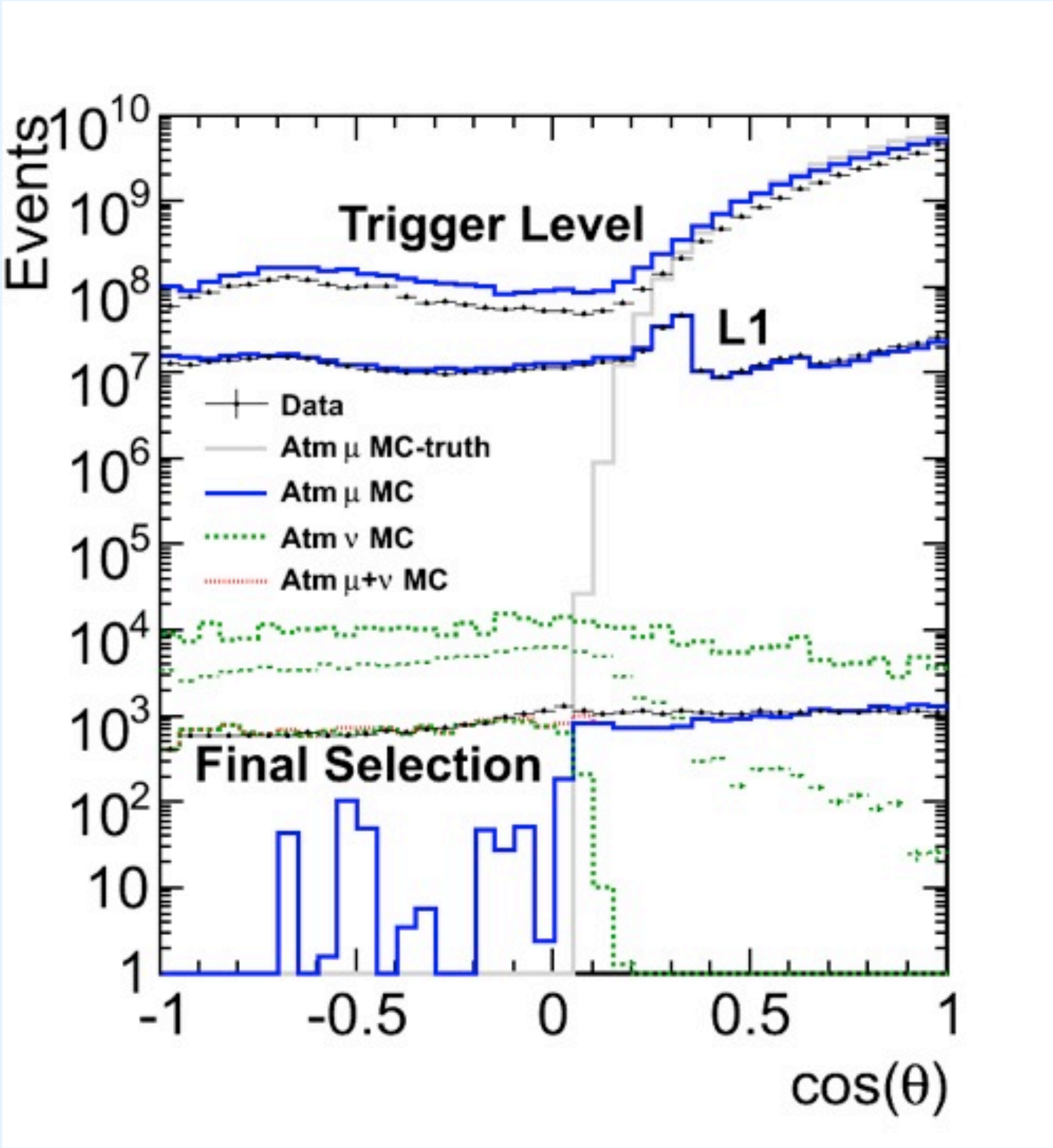
Tuesday, December 6, 2011

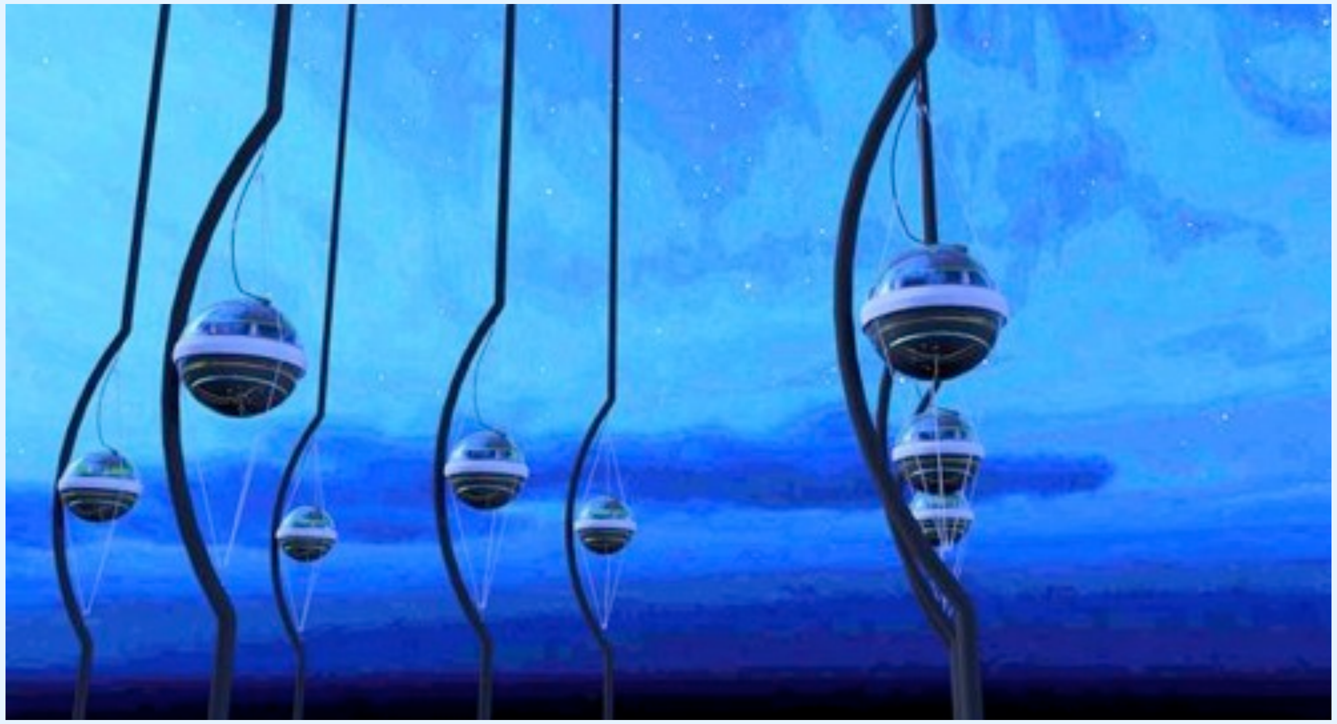
muon event in IceCube

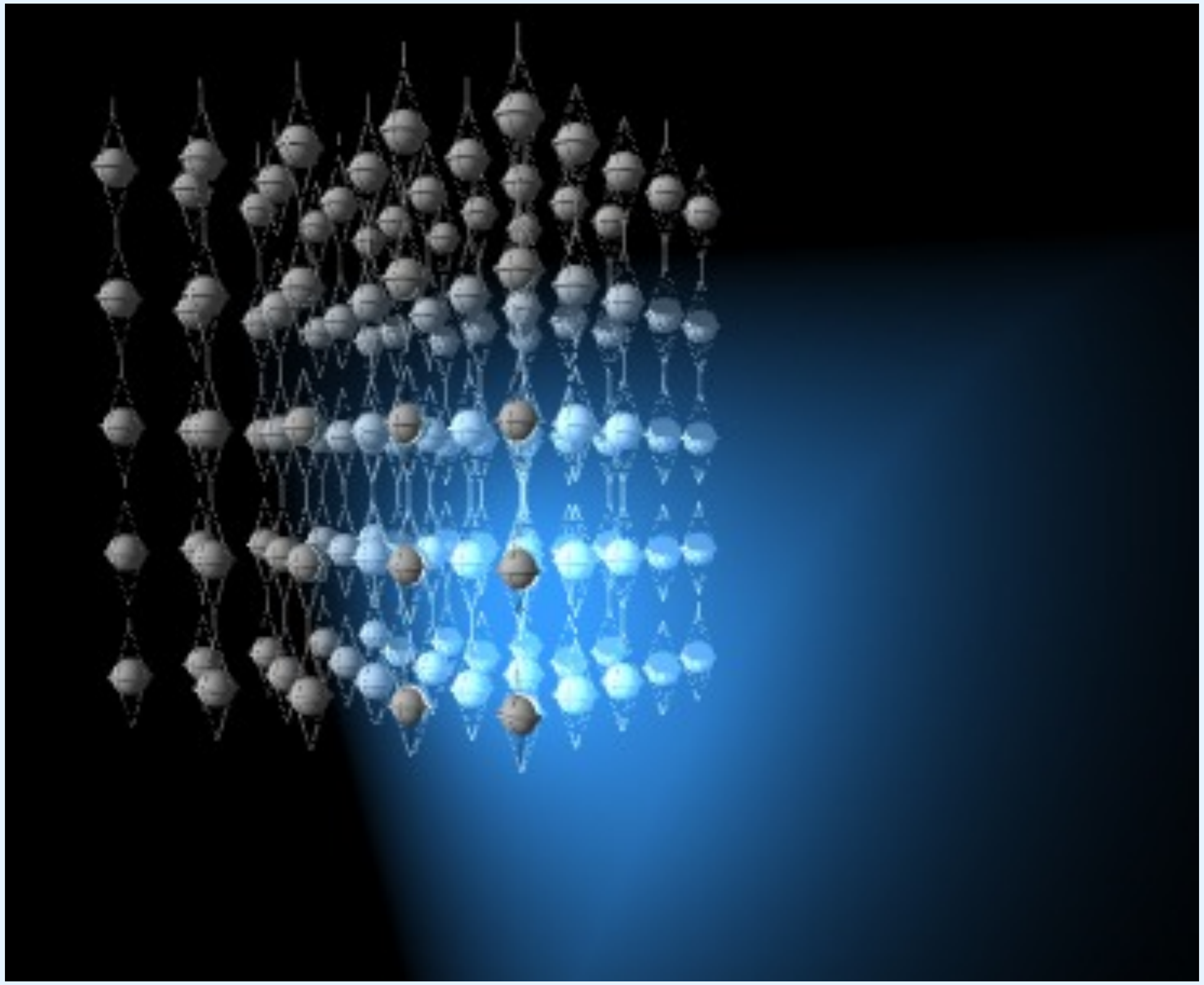


Muon – IC 40 data
~0.7° - 1.2° resol

detection technique

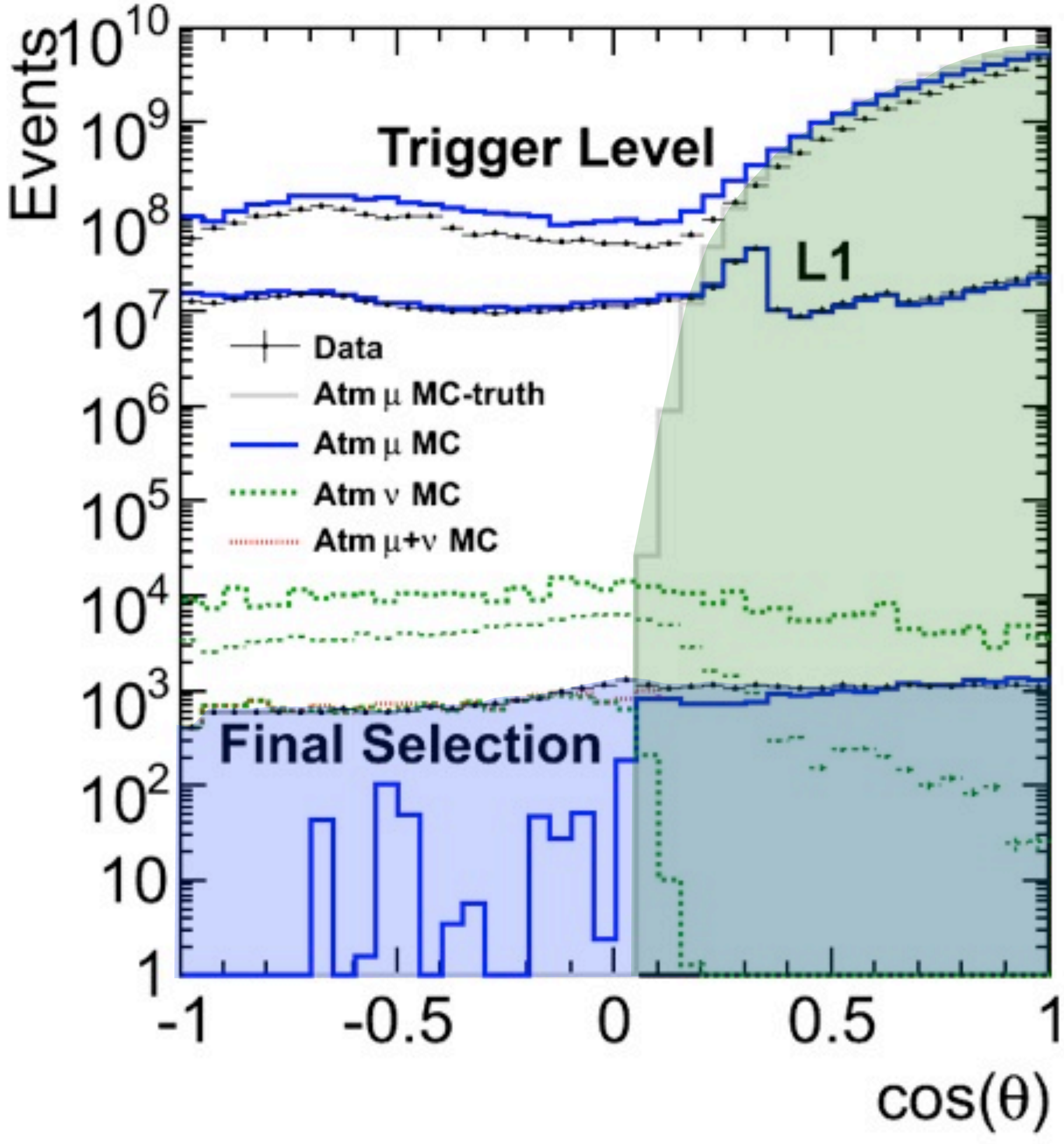


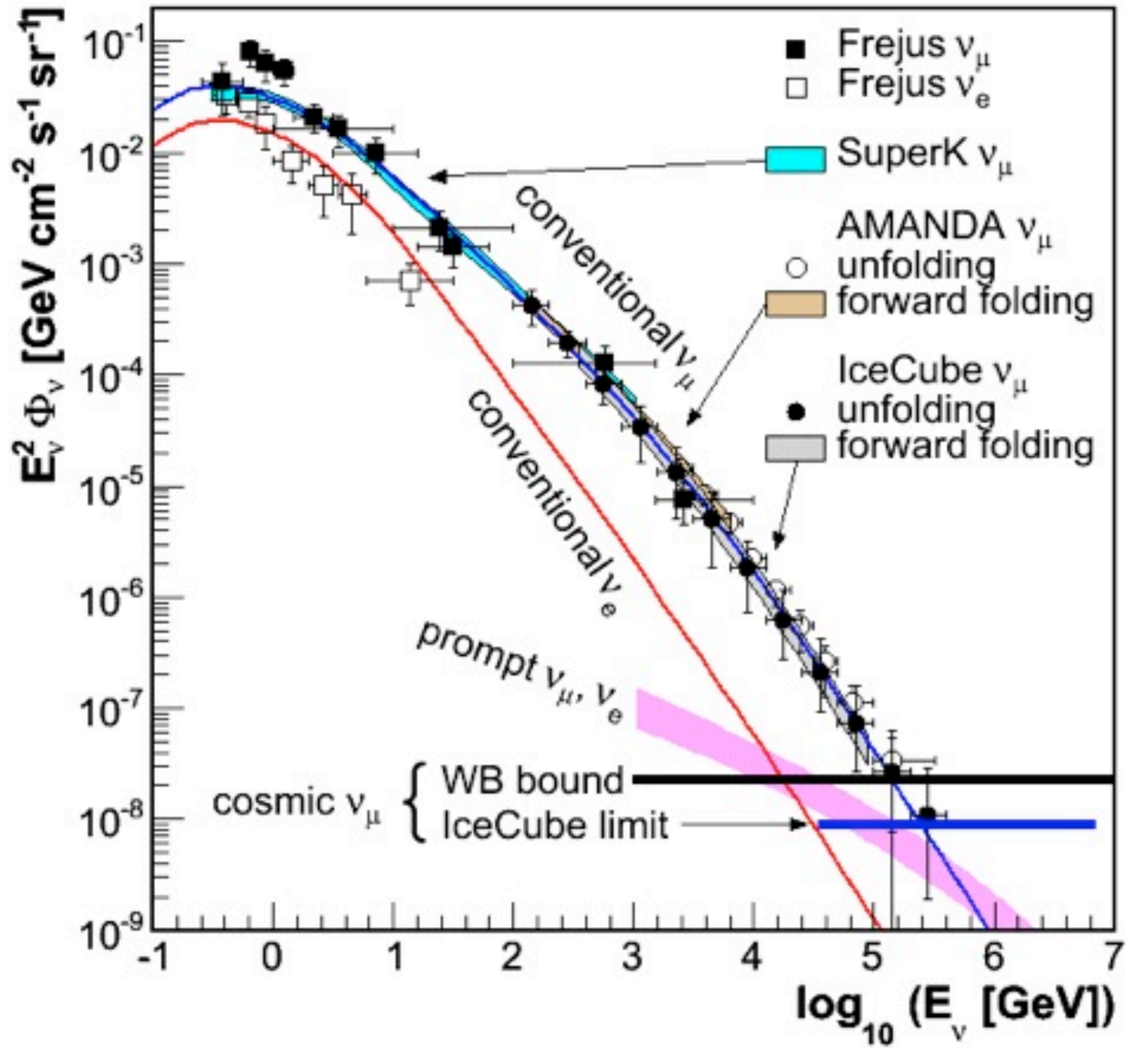




Tuesday, December 6, 2011

selecting high energy neutrinos



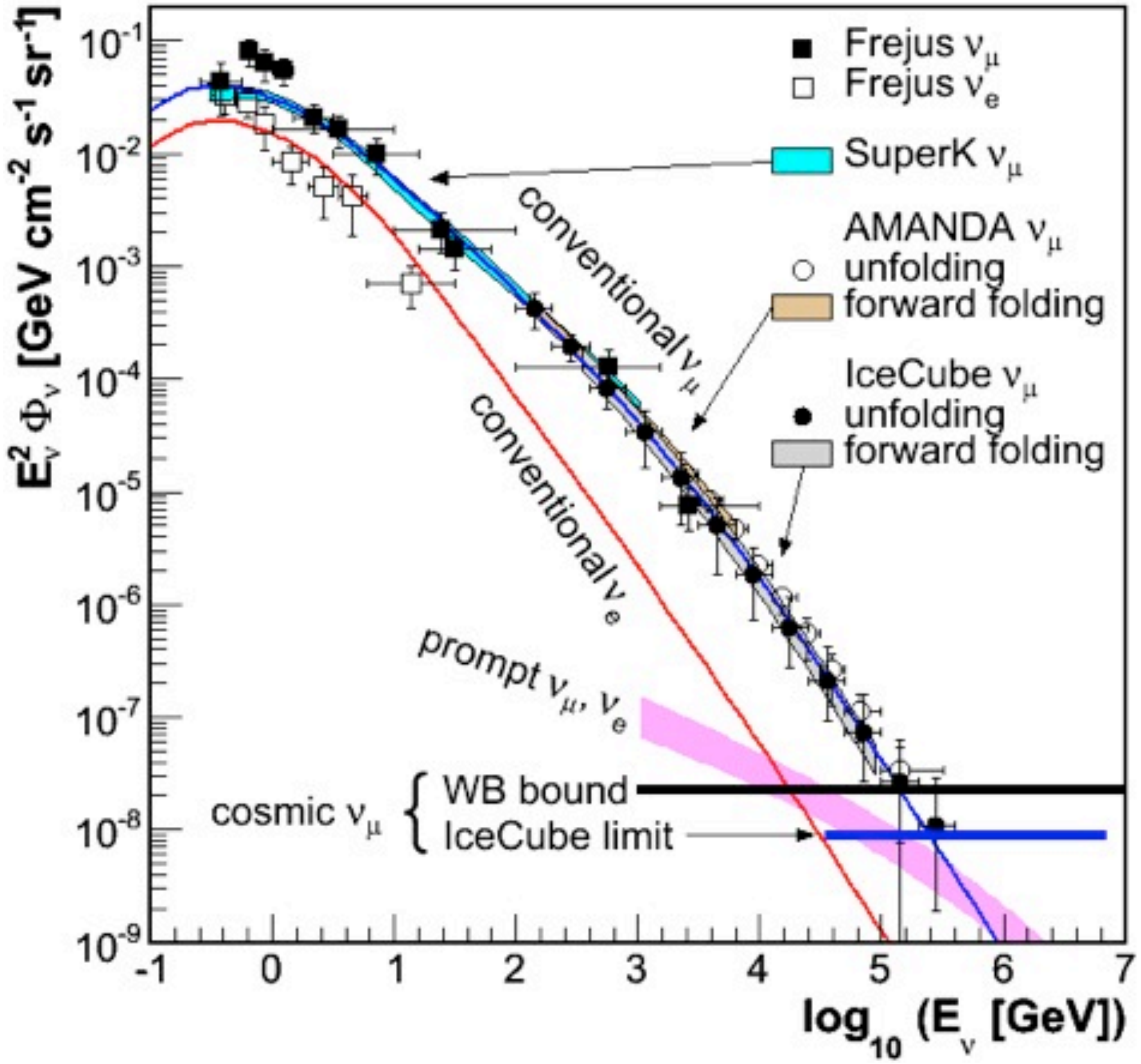


searching for high energy neutrinos

- point (<1°) steady/transient sources
- extended (>1°) sources
- galactic/extragalactic sources
- diffuse sources of HE/EHE neutrinos
  - origin of cosmic rays

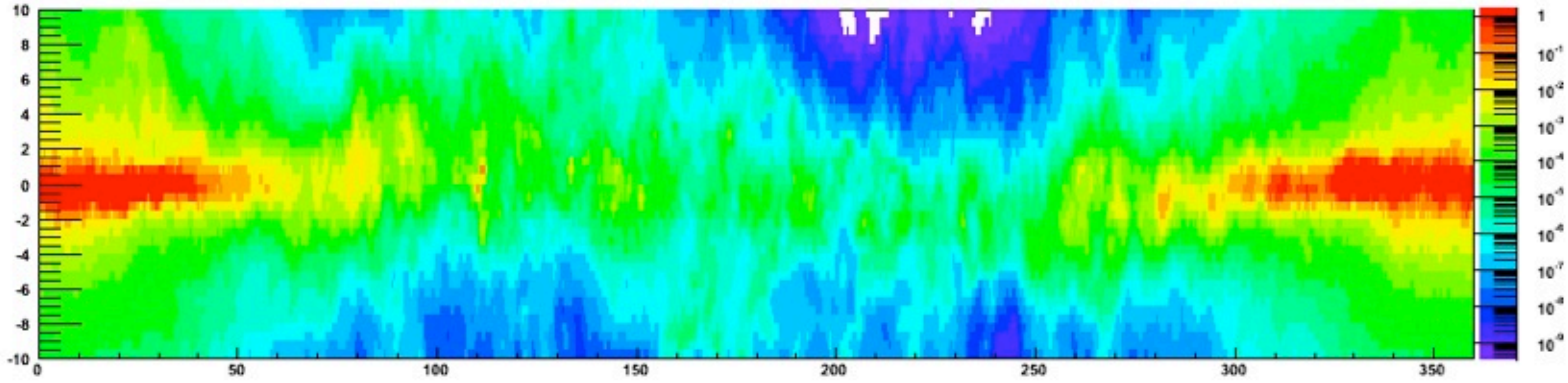
- if gamma ray emission from galactic plane is hadronic, neutrinos are expected as well

- search for neutrinos from galactic plane



contact: Naoko Kurahashi <naoko@icecube.wisc.edu>

searching for neutrinos from the galactic plane



Fermi's diffuse gamma-ray emission model

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

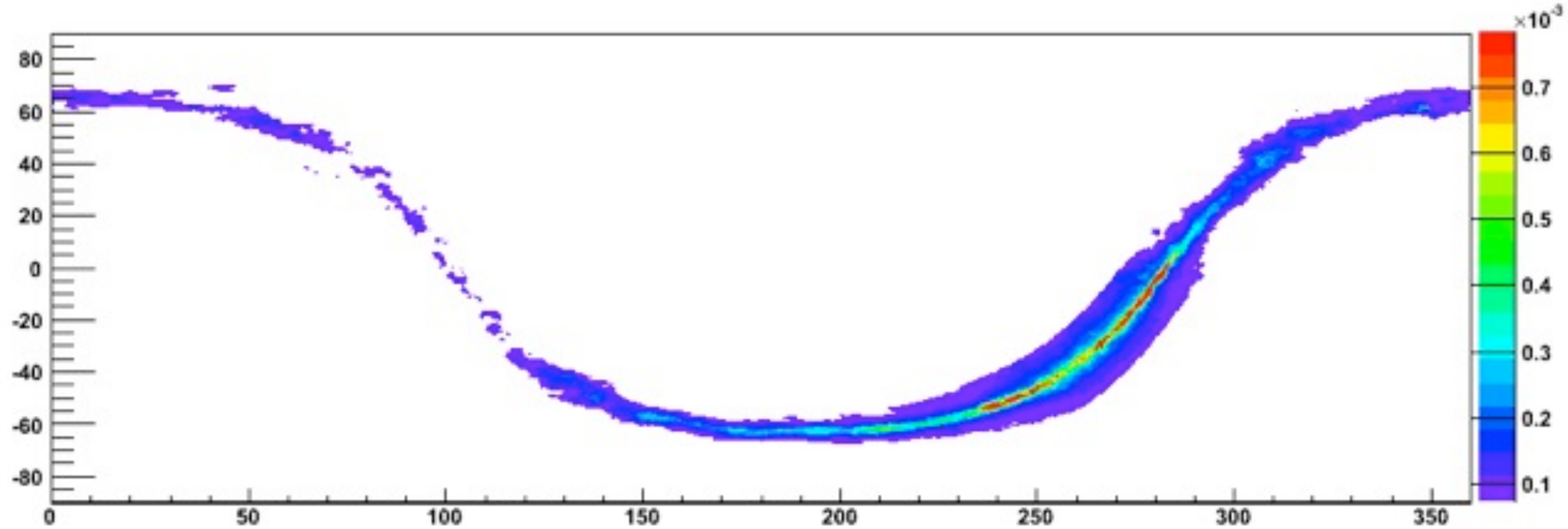
Likelihood analysis of IceCube neutrinos using this model as spacial template

BUT model includes π^0 decay + IC + other leptonic processes

NEW model with $\pi^{\pm}$ (charged meson) decay processes only

contact: Naoko Kurahashi <naoko@icecube.wisc.edu>

searching for neutrinos from the galactic plane



galactic plane emission model in equatorial coordinates

IceCube sensitivity is declination-dependent, more sensitive to up-going events

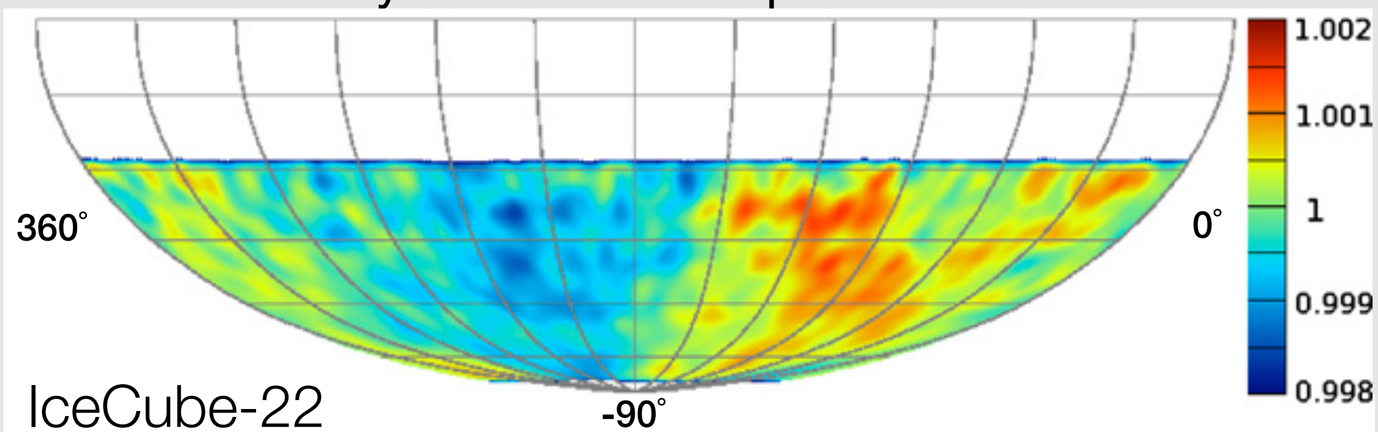
(i.e. northern hemisphere)

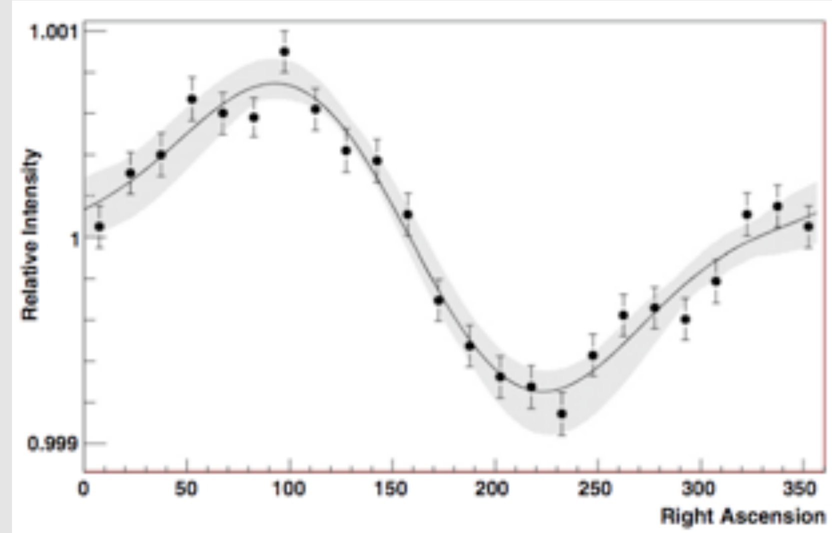
Wish List

- use GALPROP to calculate neutrino emission from CR interaction in the Galaxy
- give absolute flux scale and spectral shape predictions for neutrino emission

cosmic ray anisotropy in IceCube

relative intensity equatorial coordinates





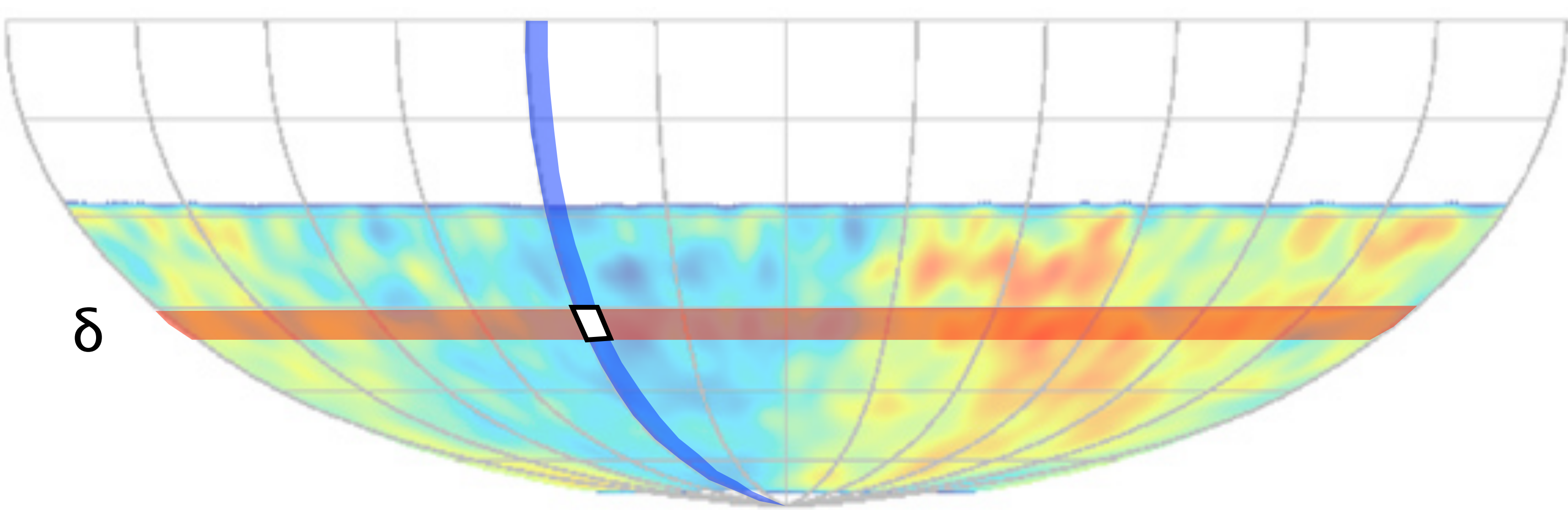
Abbasi et al., ApJ, **718**, L194, 2010

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

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

α

δ



relative intensity

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

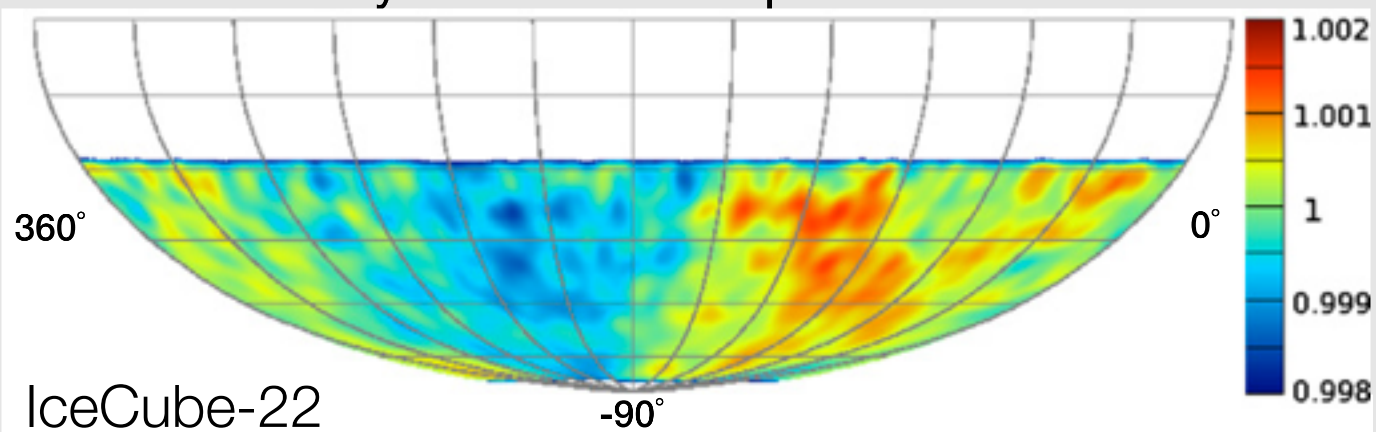
cosmic ray anisotropy in IceCube

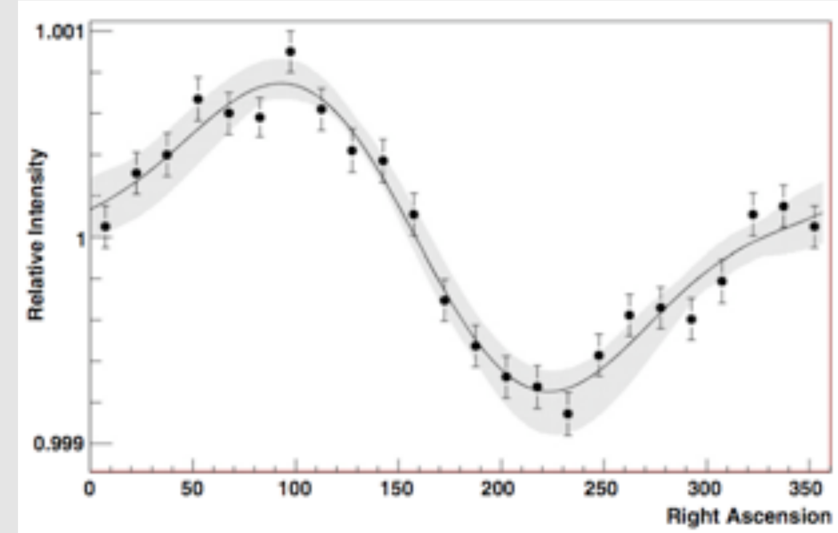
time

relative intensity equatorial coordinates

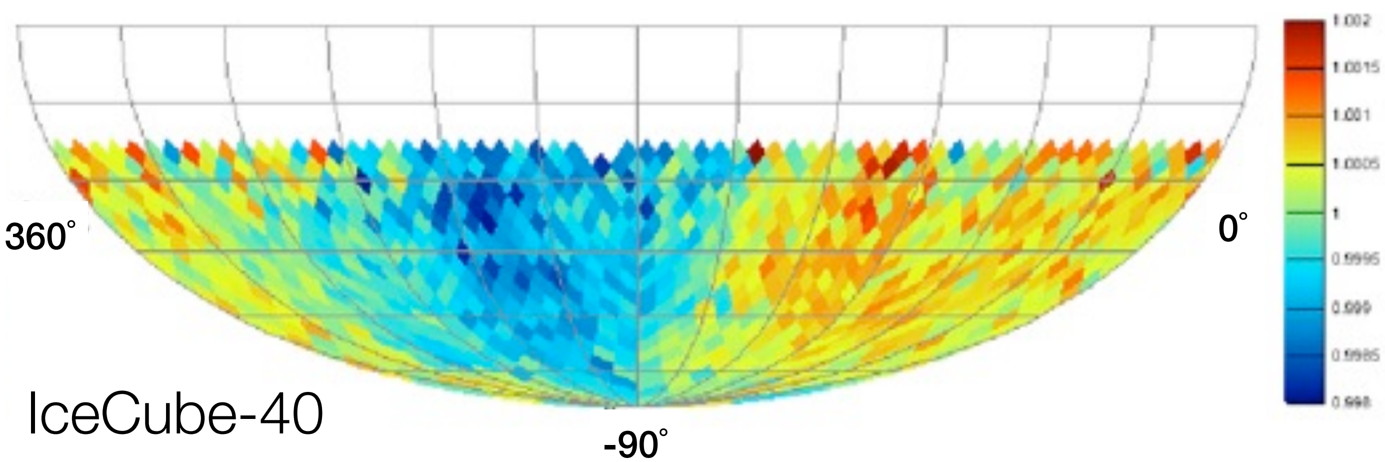
$$I_i = \frac{N_i(\alpha,\delta)}{\langle N_i(\delta)\rangle_\alpha}$$

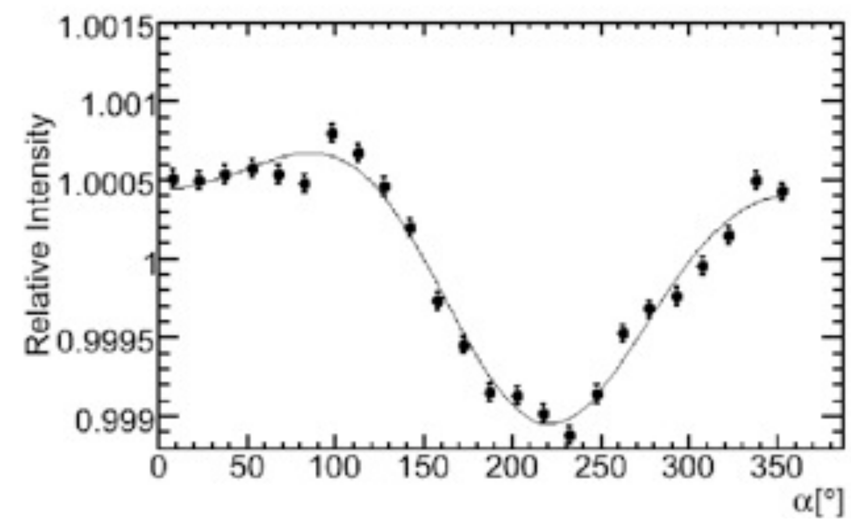
20 TeV



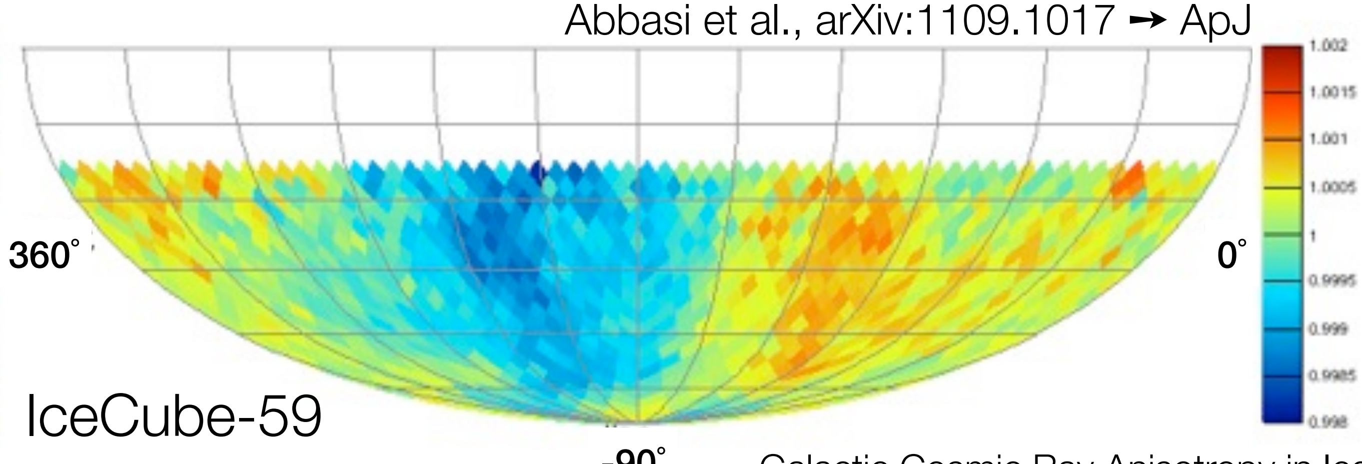


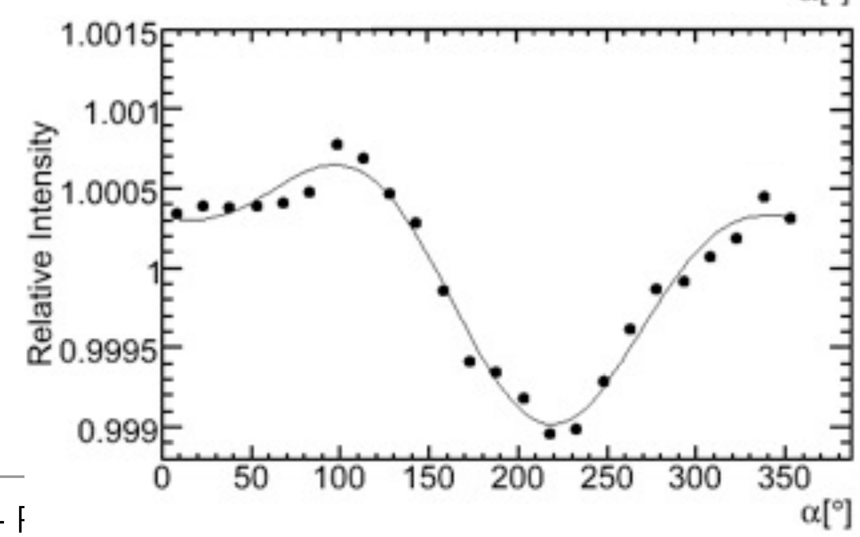
Abbasi et al., ApJ, **718**, L194, 2010



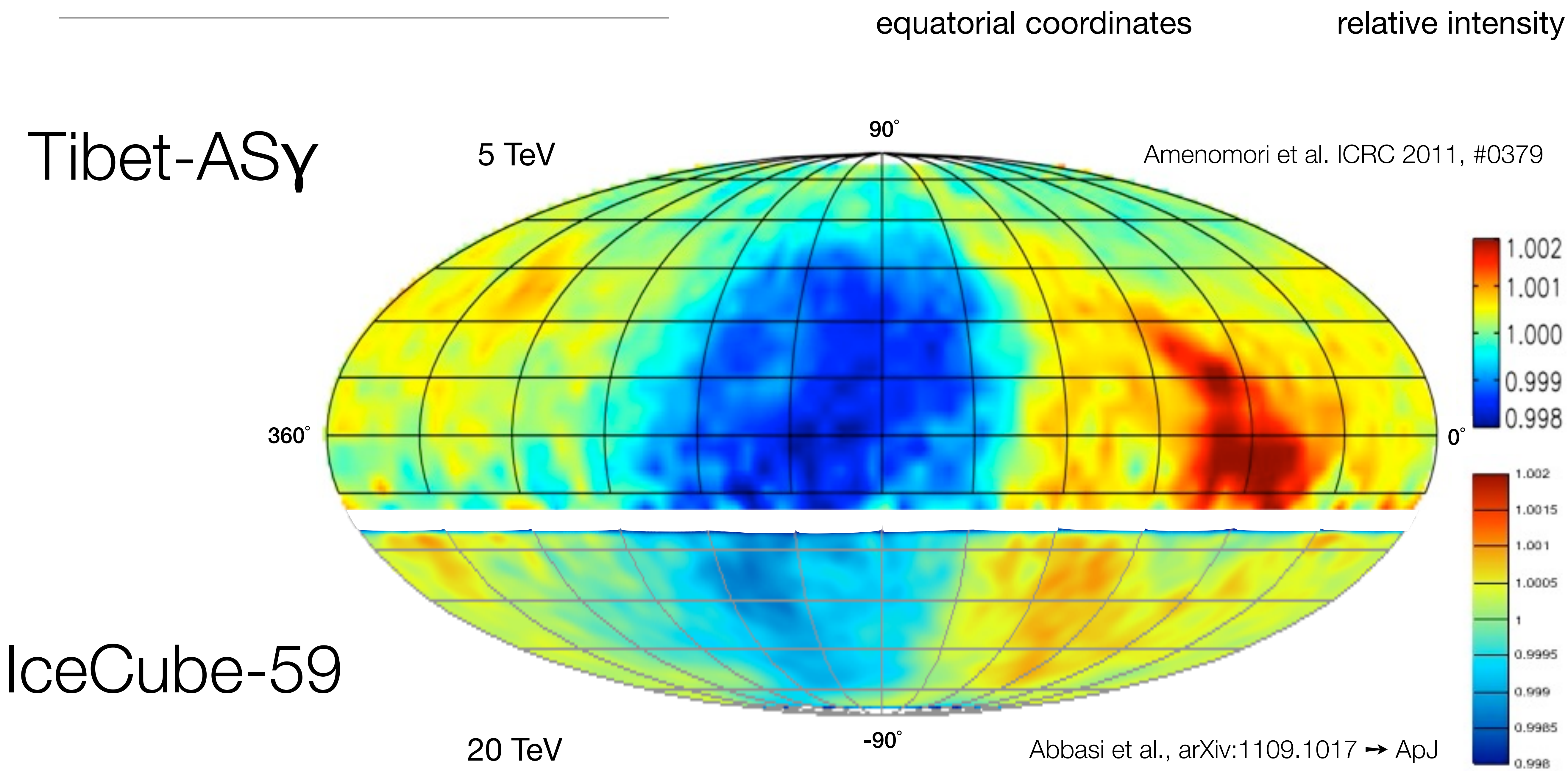


Abbasi et al., arXiv:1109.1017 → ApJ





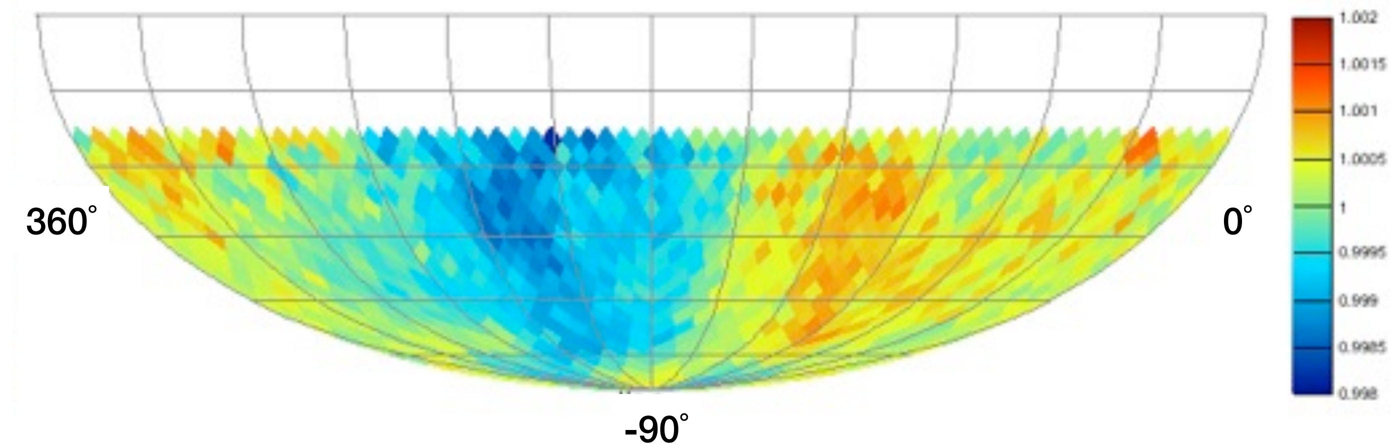
cosmic ray anisotropy in arrival direction



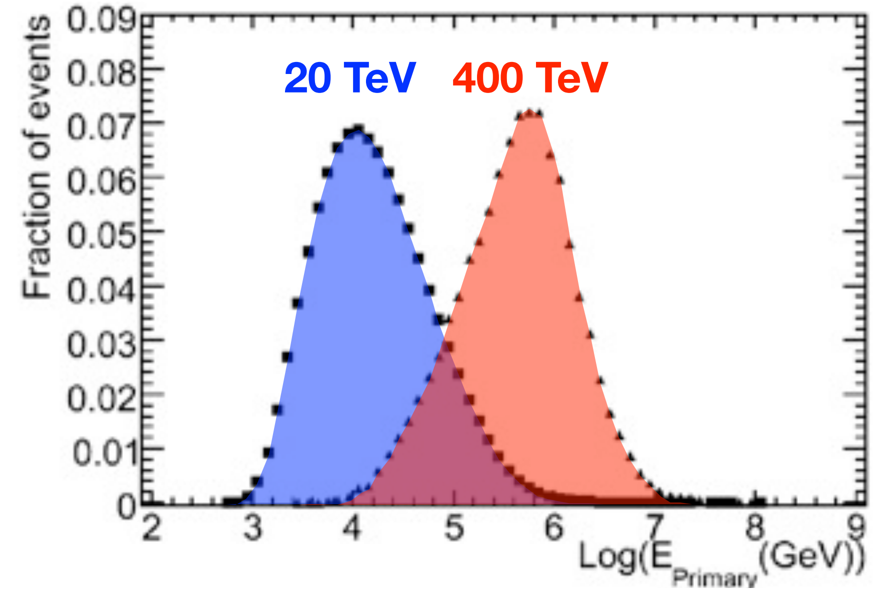
cosmic ray anisotropy vs energy in IceCube-59

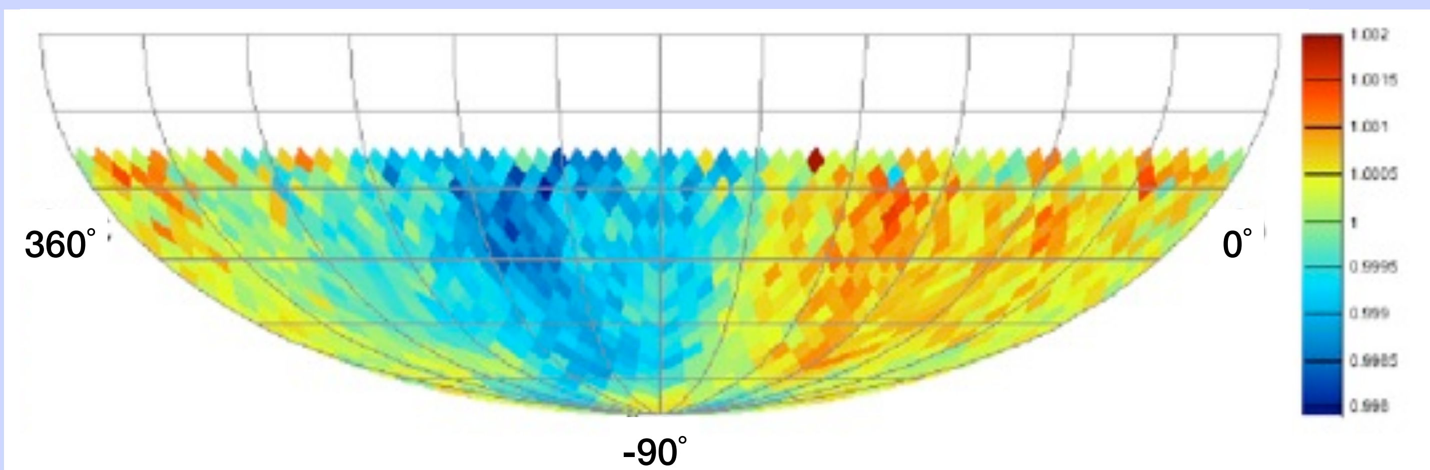
energy

relative intensity equatorial coordinates

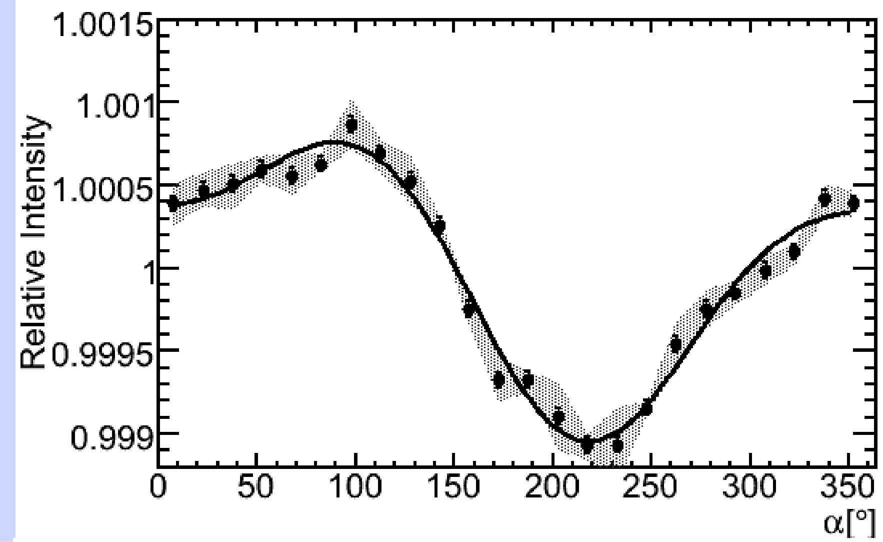


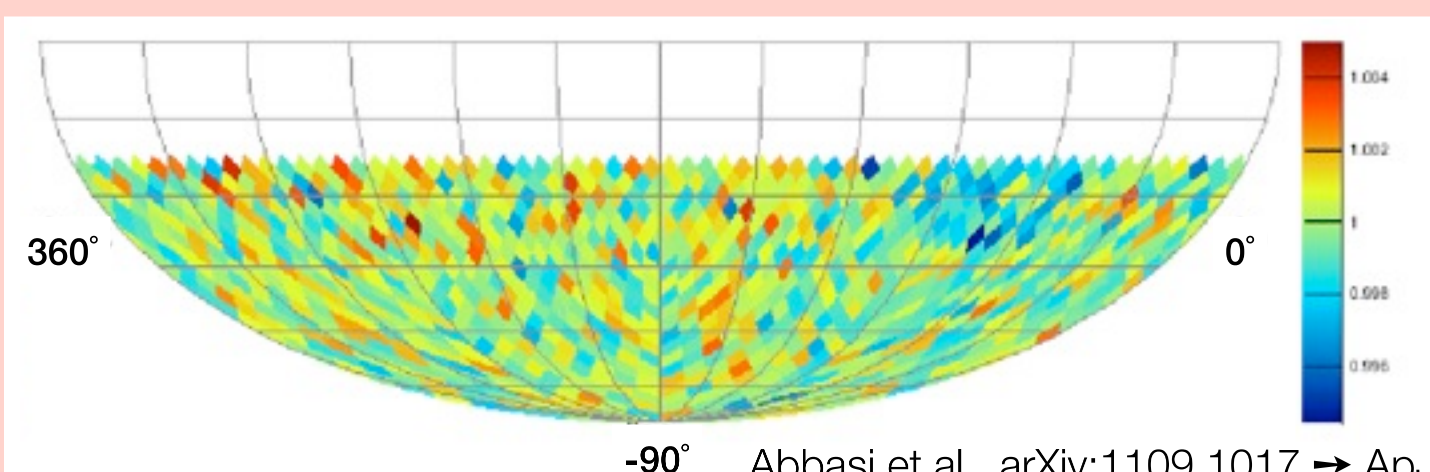
no energy selection



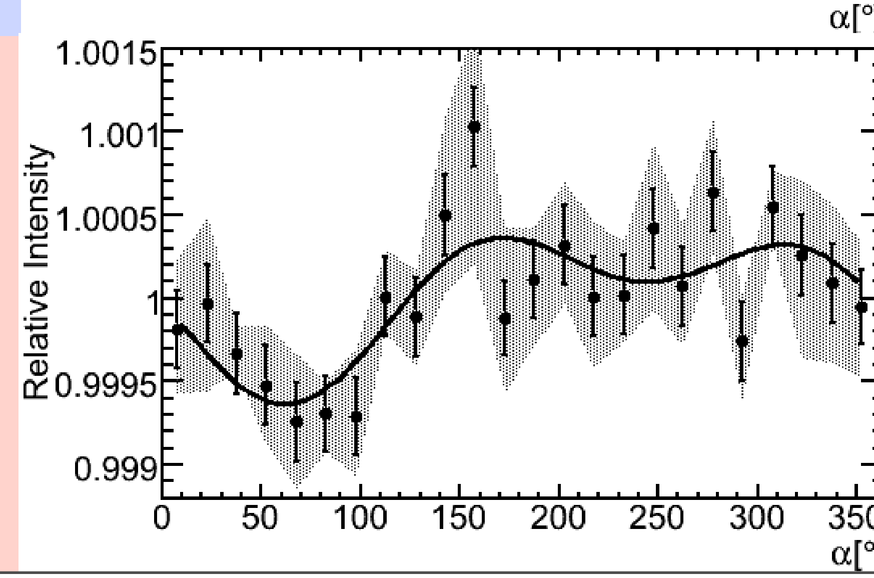


20 TeV





400 TeV



Abbasi et al., arXiv:1109.1017 → ApJ

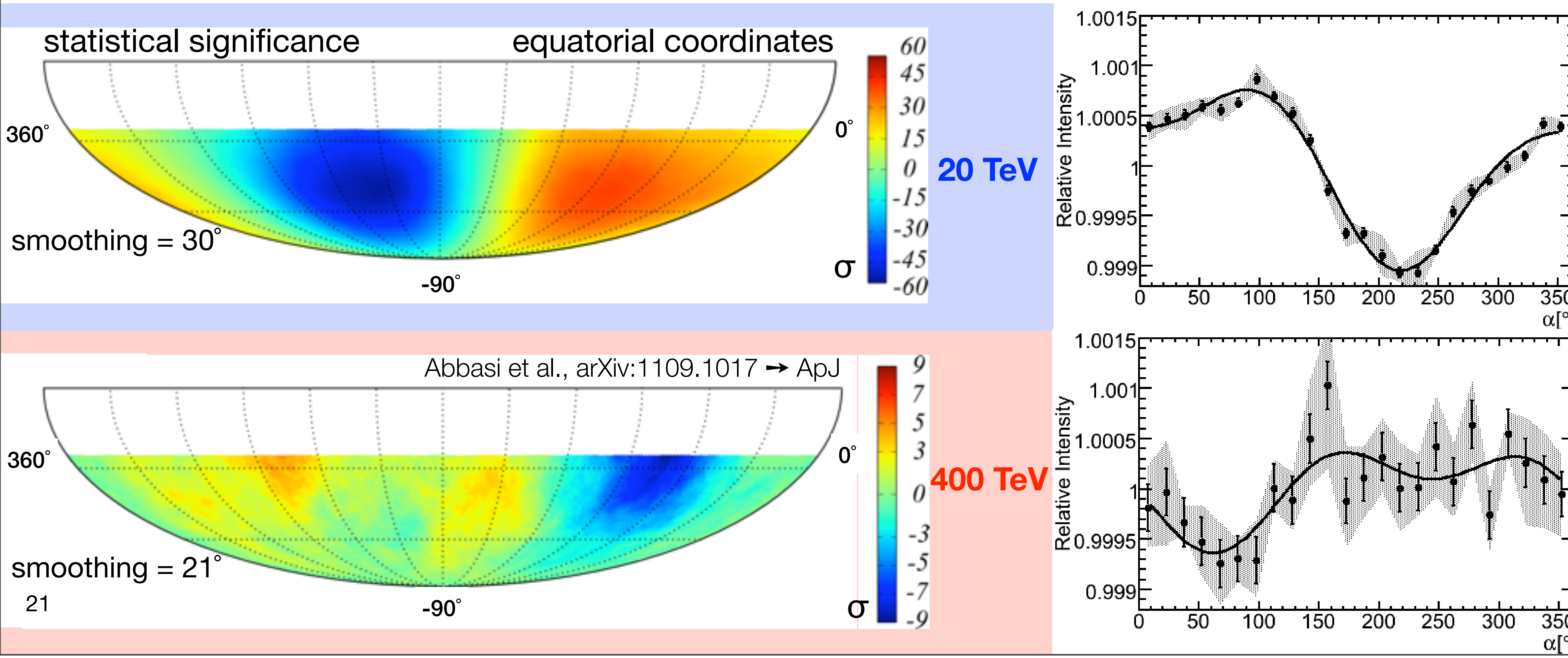
cosmic ray anisotropy vs energy in IceCube-59

energy

- reference map derived from data with time scrambling
- smoothing radius optimized on highest significance in excess/deficit region

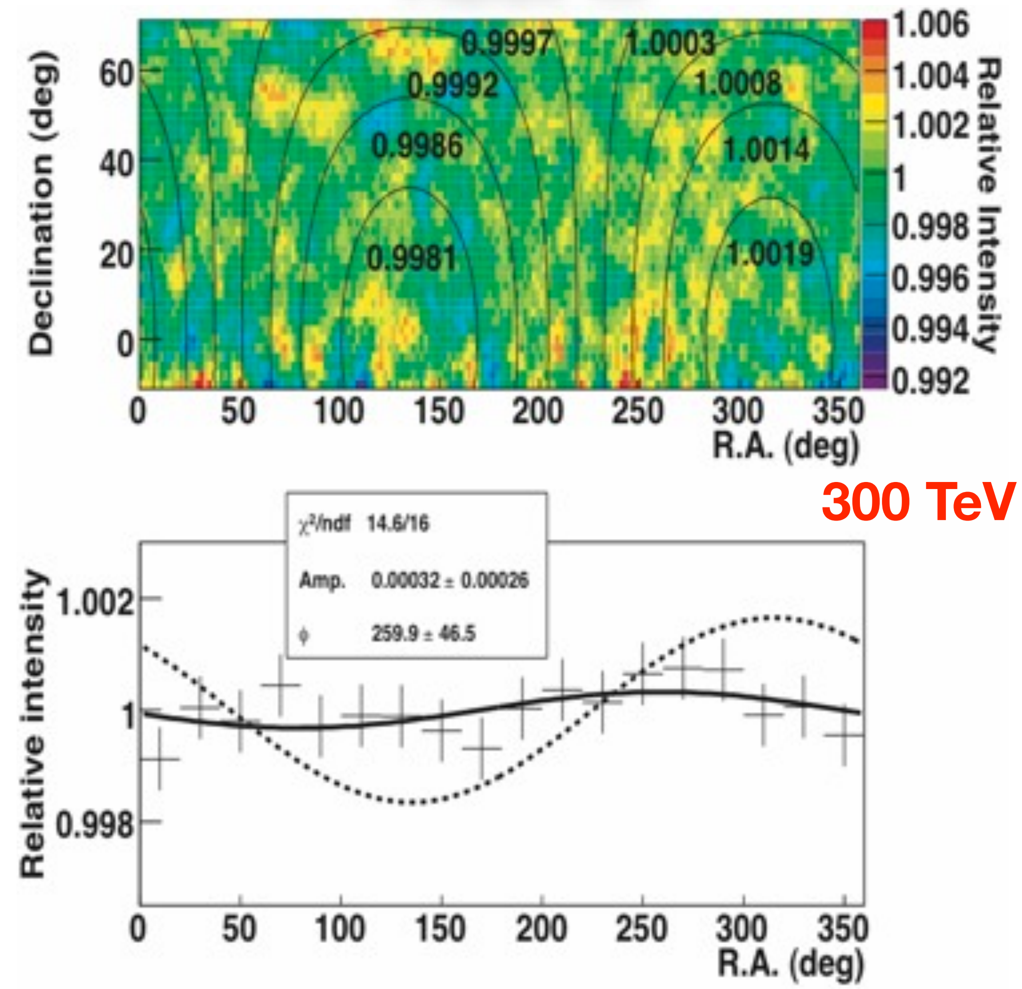
$$s = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

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



cosmic ray anisotropy vs energy in IceCube-59

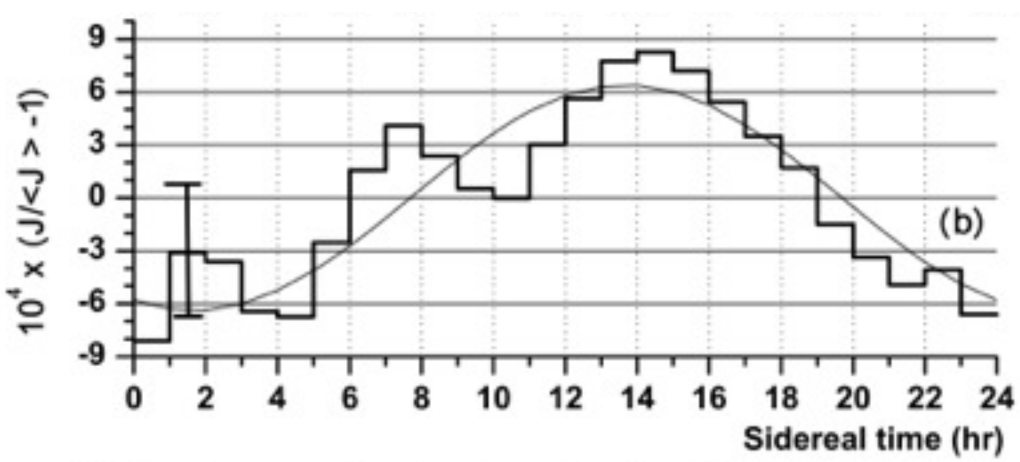
Tibet-III

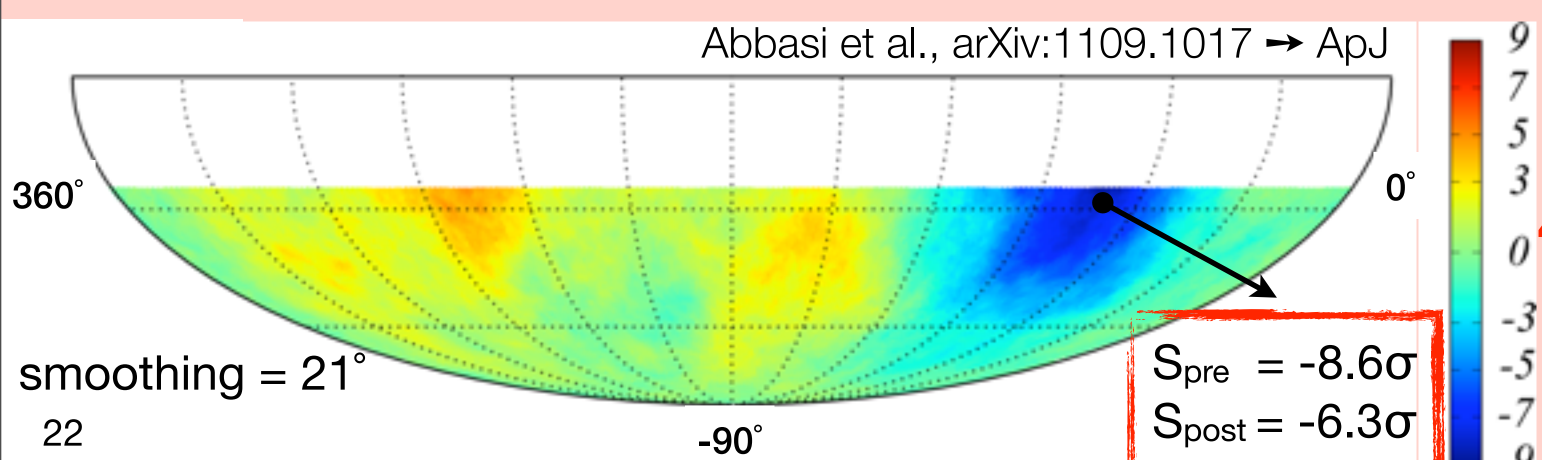


300 TeV

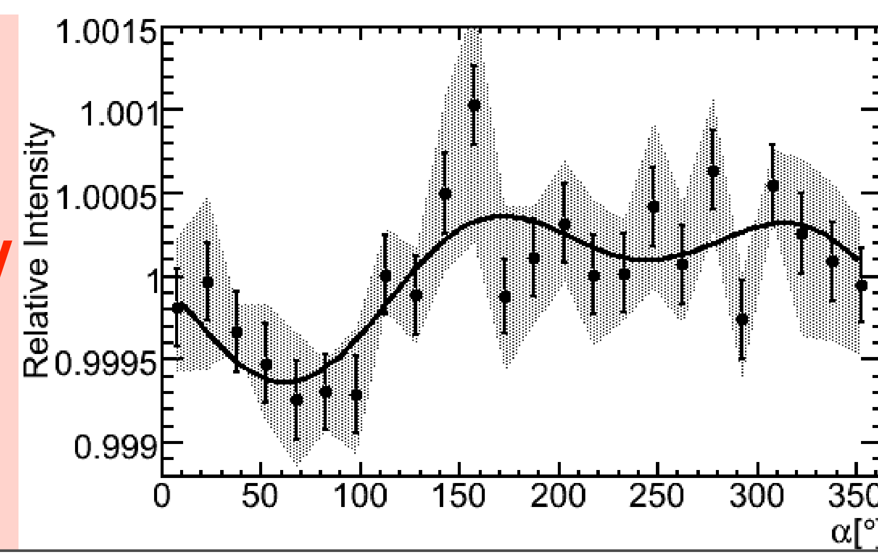
EAS-TOP

370 TeV



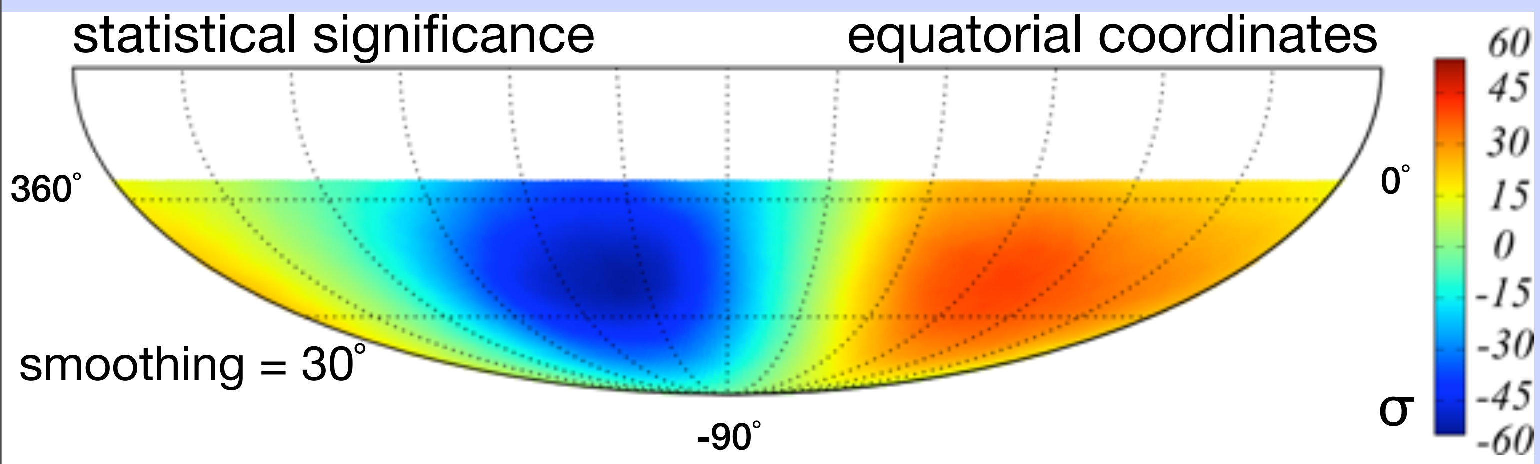


400 TeV

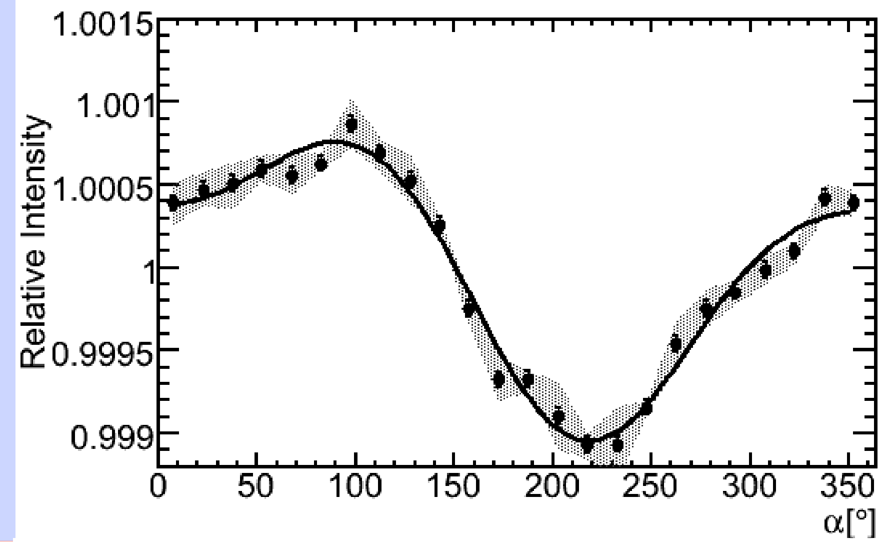


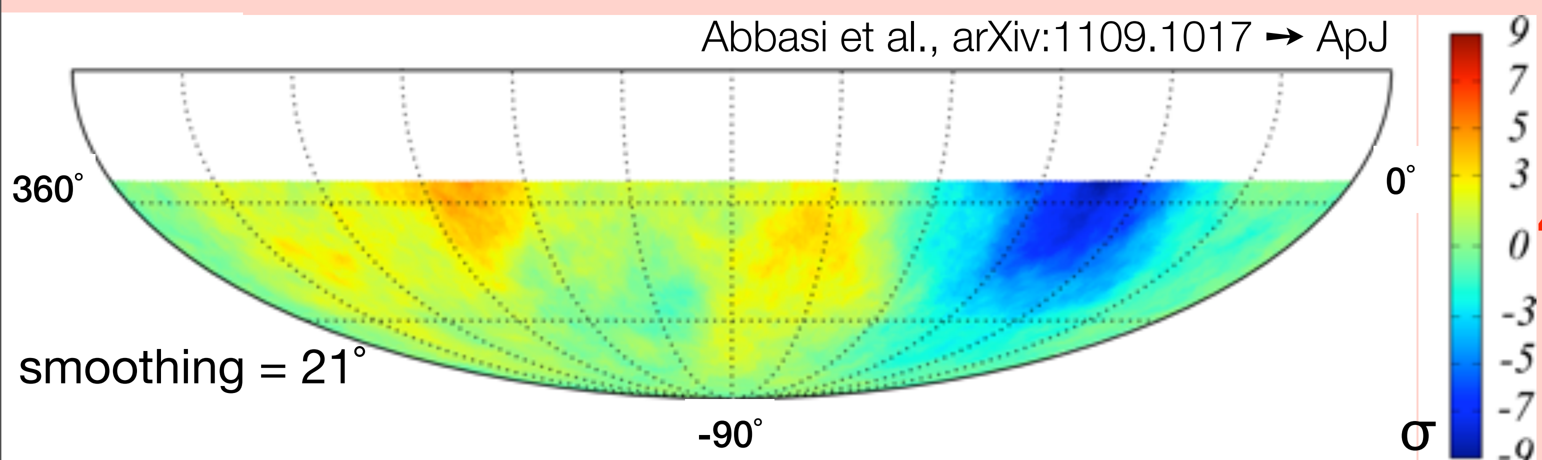
cosmic ray anisotropy vs energy in IceCube-59

energy

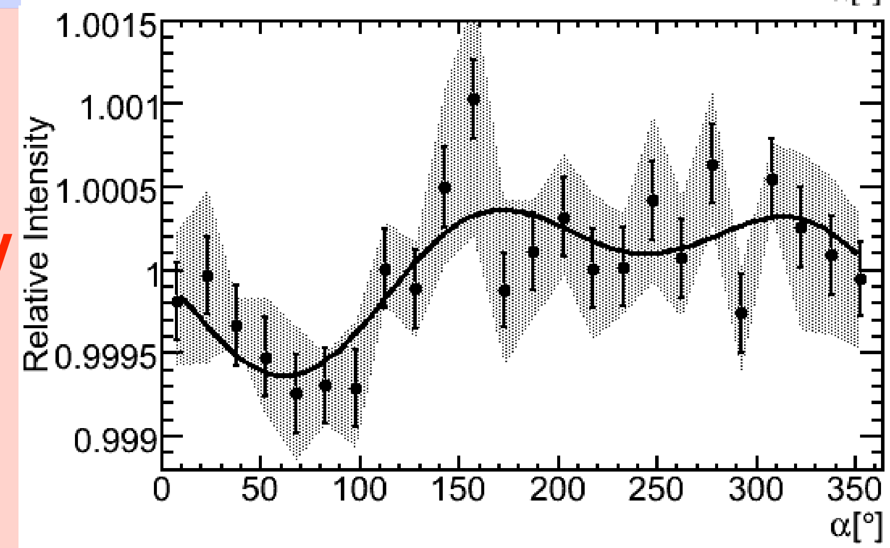


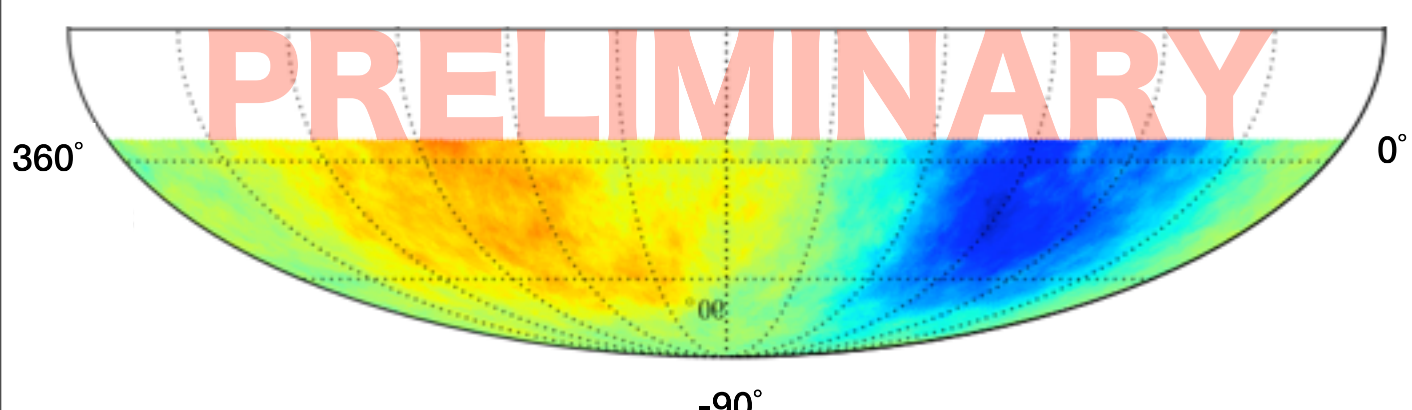
20 TeV





400 TeV





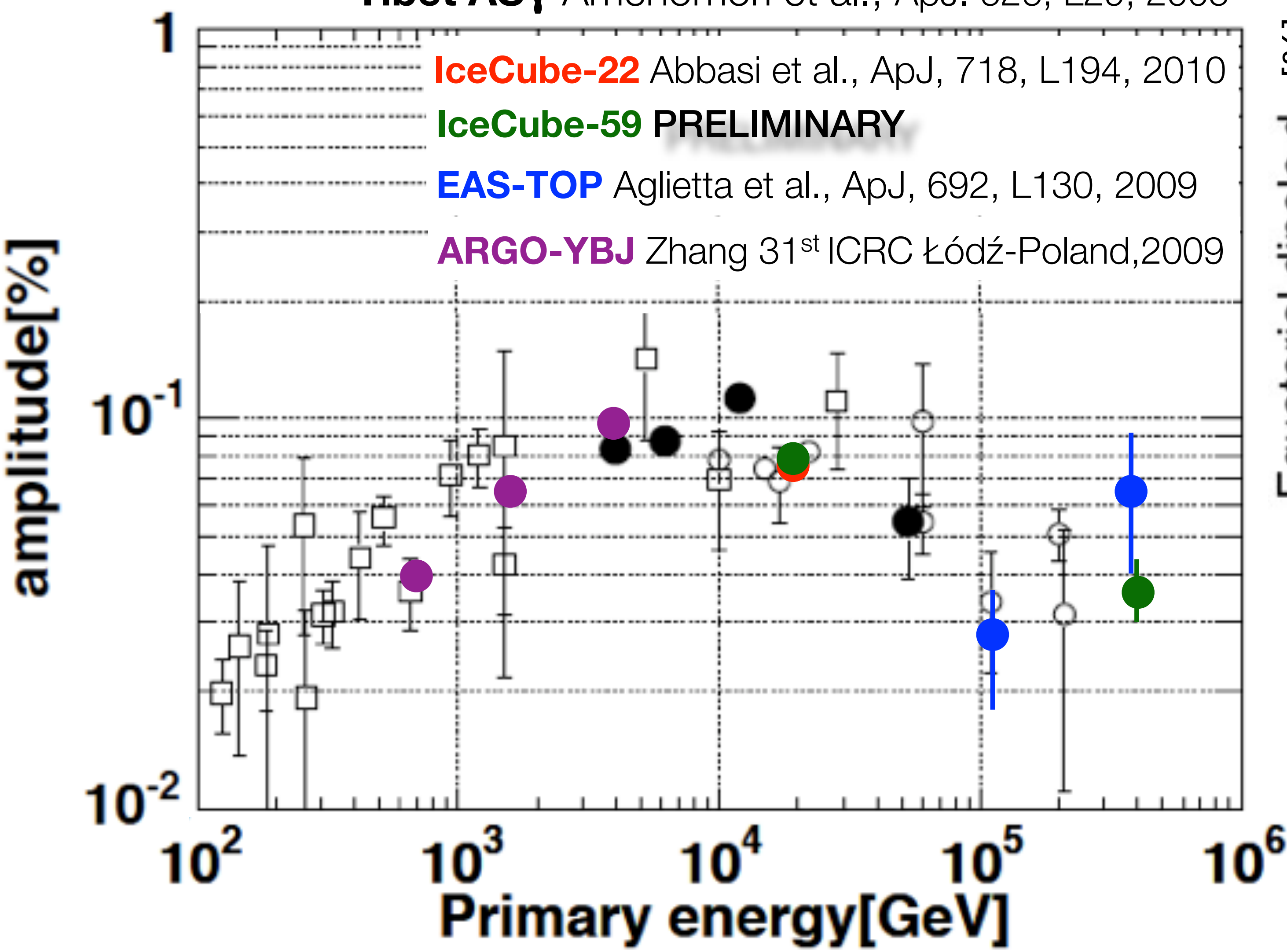
~1 PeV

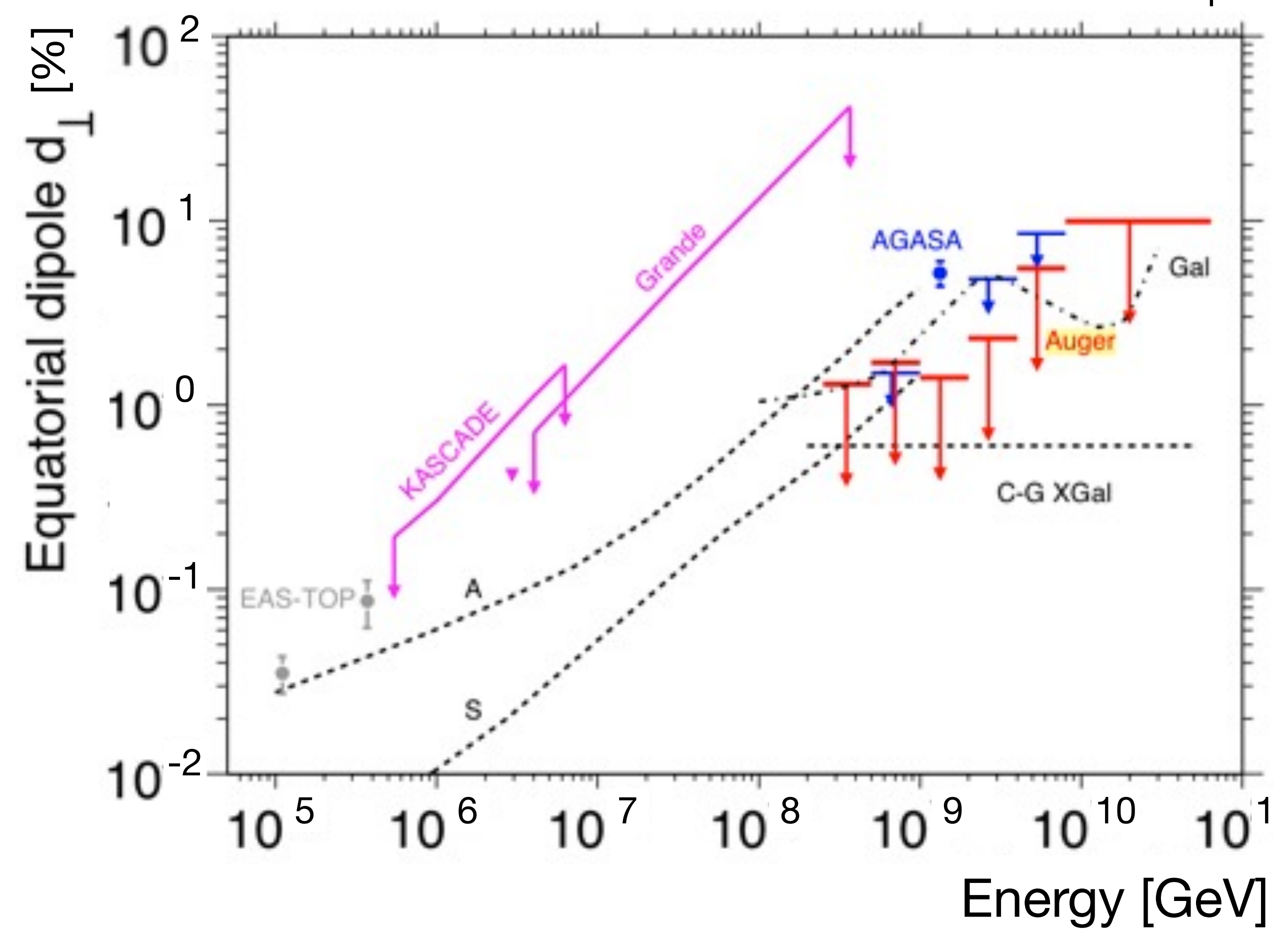
anisotropy vs energy

(3 μG)
(~0.01 μG)

$3\cdot10^{-2}$	0.3	3	30	300	3,000	pc
10	100	10^3	10^4	10^5	10^6	pc

Tibet ASγ Amenomori et al., ApJ. 626, L29, 2005





Abreu et al., Astrop. Phys., 34, 627, 2011

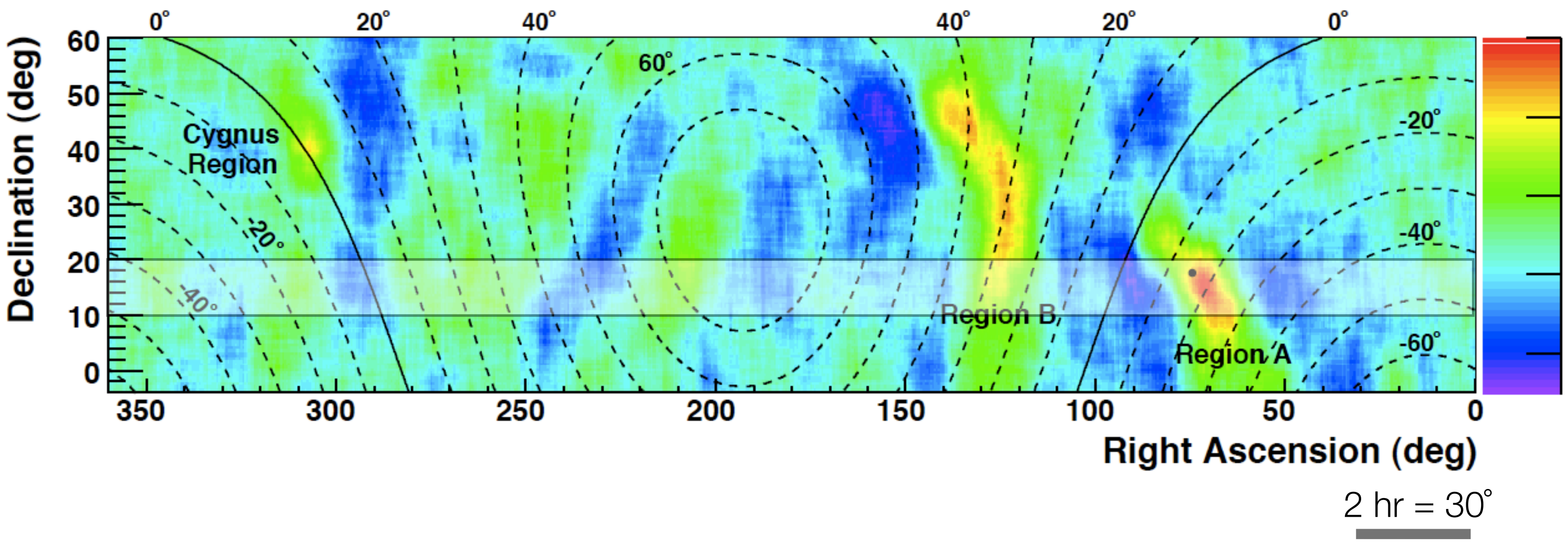
(3 μG)

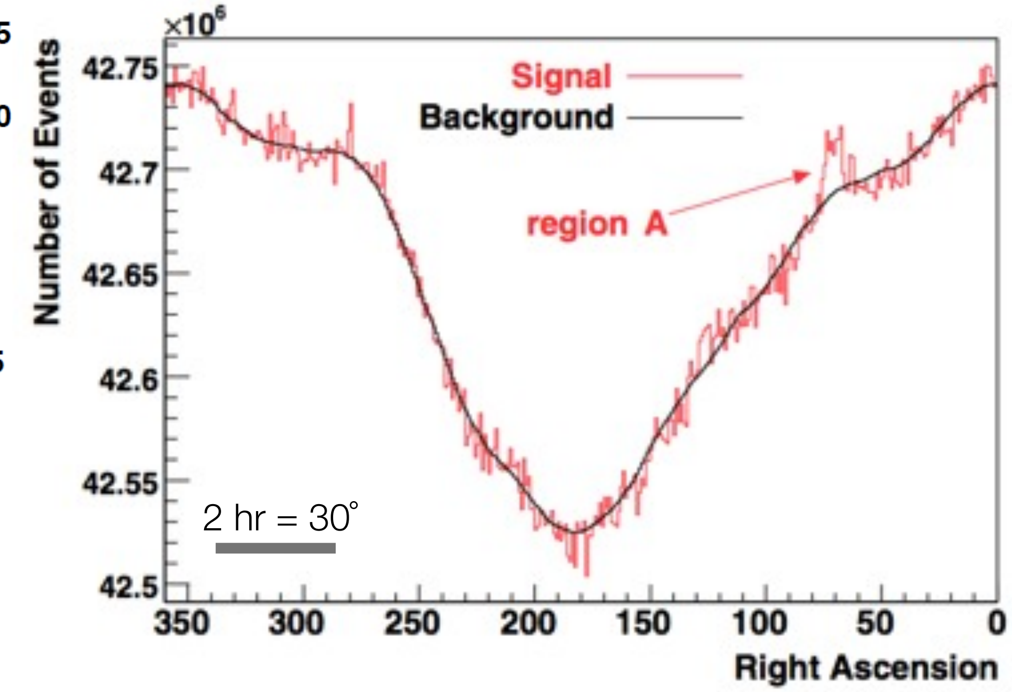
$3\cdot10^{-5}$	$3\cdot10^{-4}$	$3\cdot10^{-3}$	$3\cdot10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)

heliospheric influence galactic influence

cosmic ray anisotropy vs angular scale

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



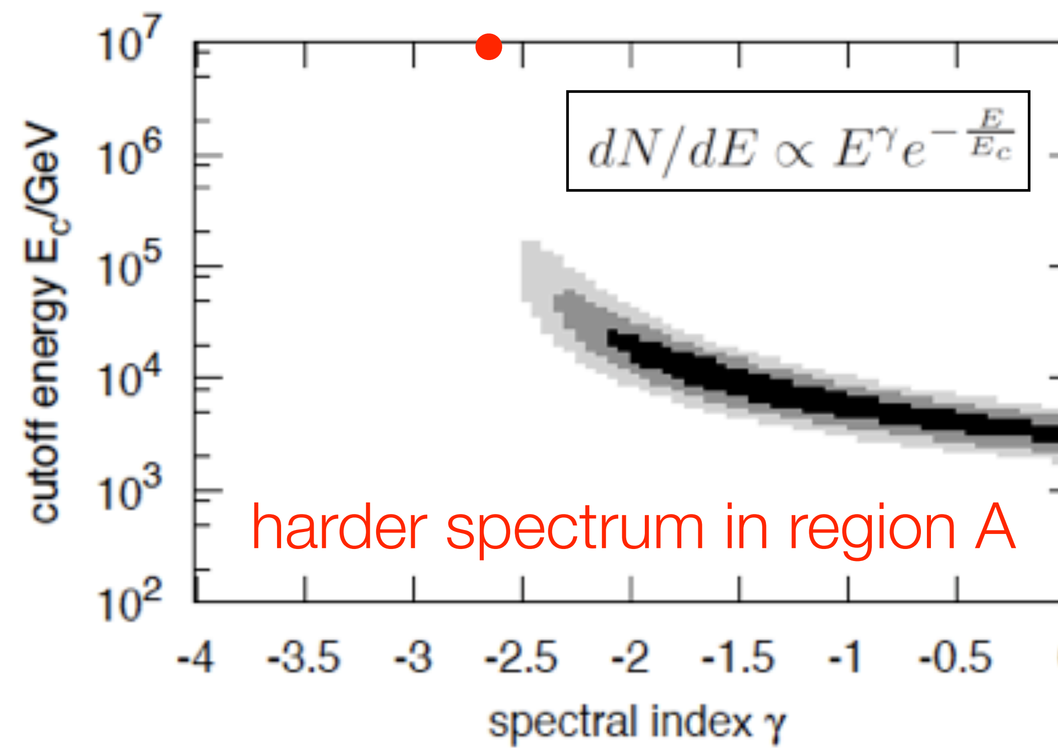


Milagro

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

2hr time window
10° smoothing

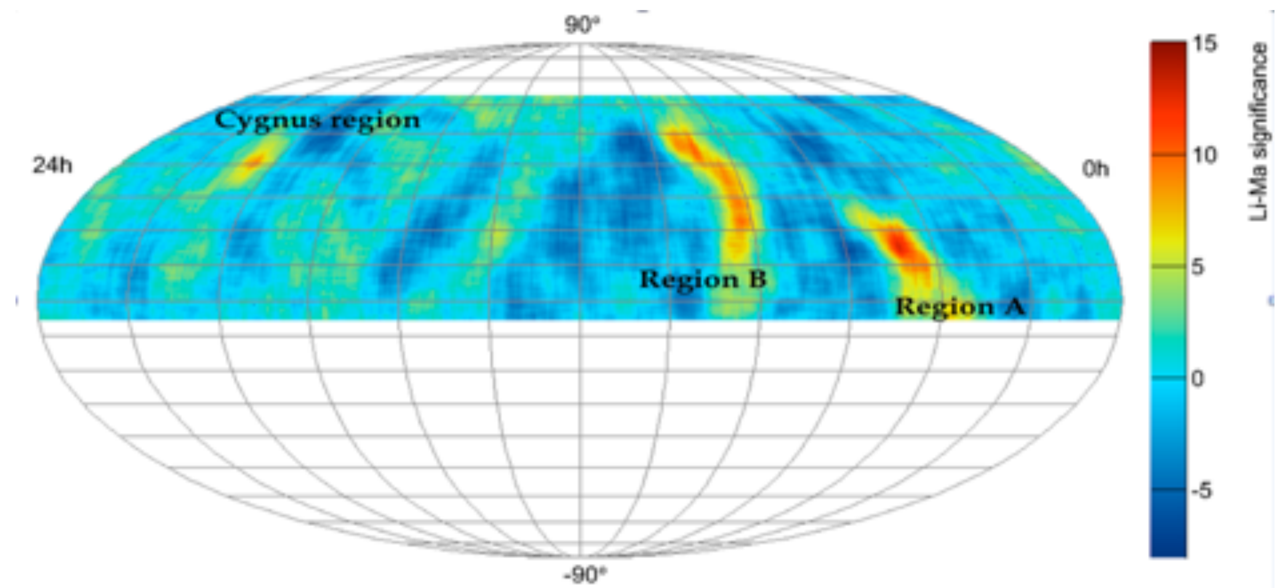
- filter all angular features > 30°
- technique used in gamma ray searches



medium / small scale anisotropy for different experiments

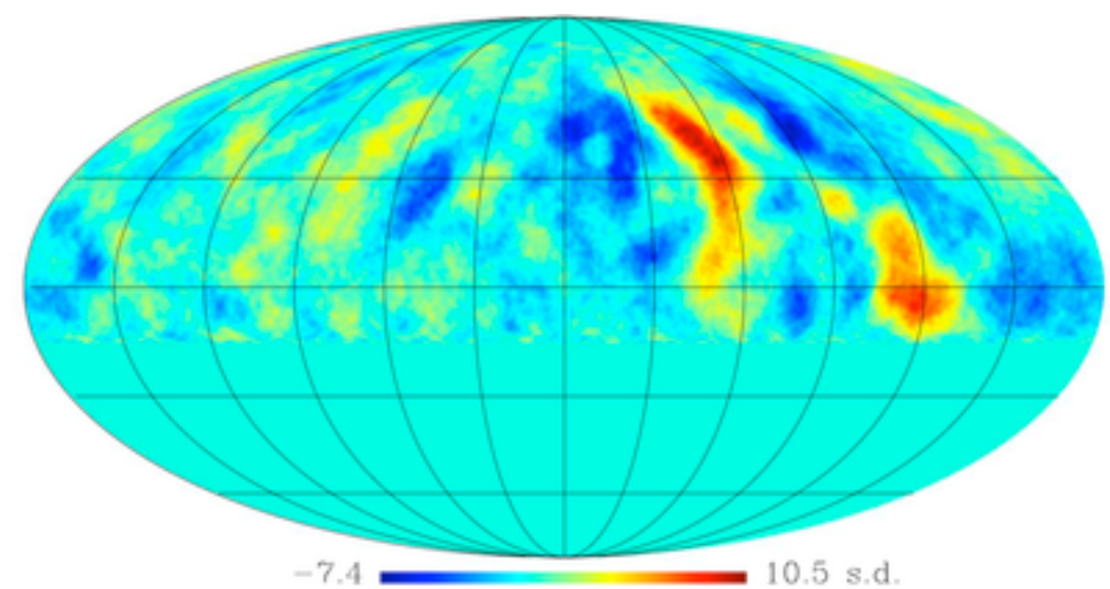
Milagro

(direct integration)



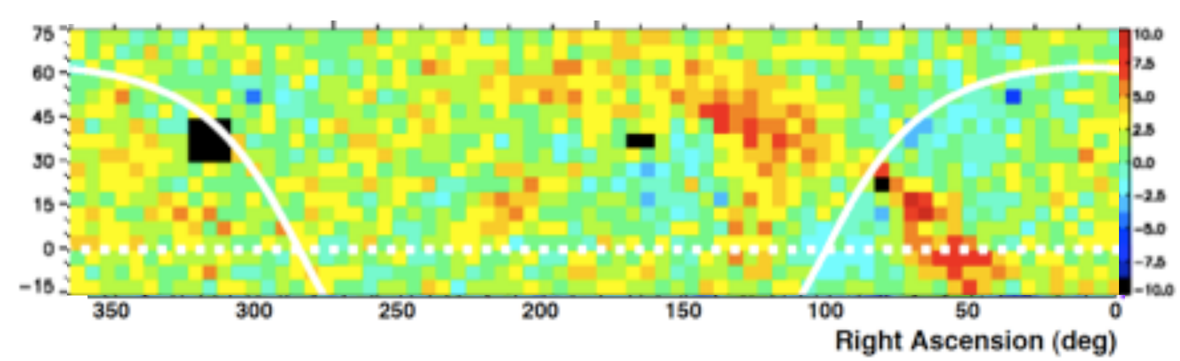
ARGO-YBJ

(time scrambling)

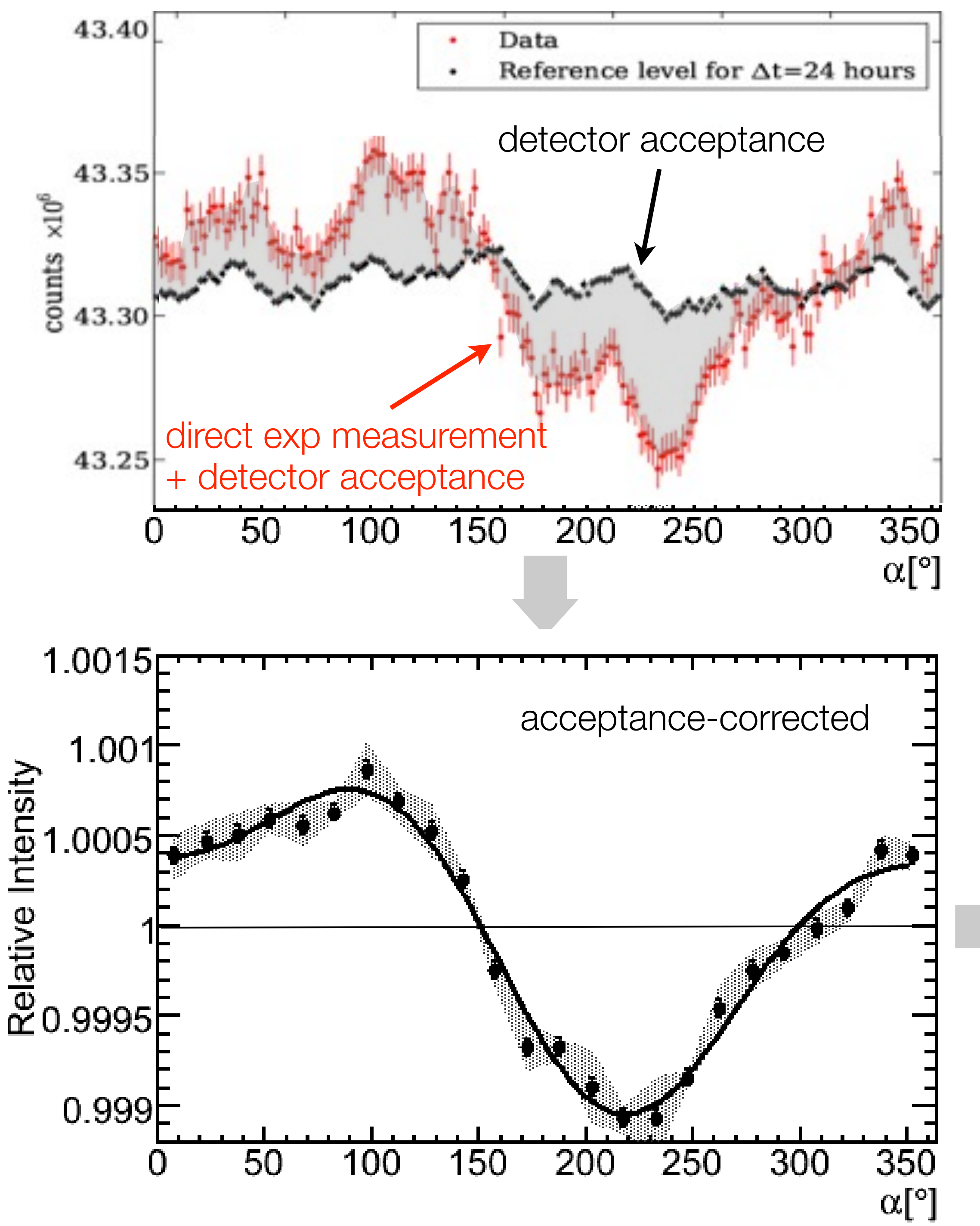


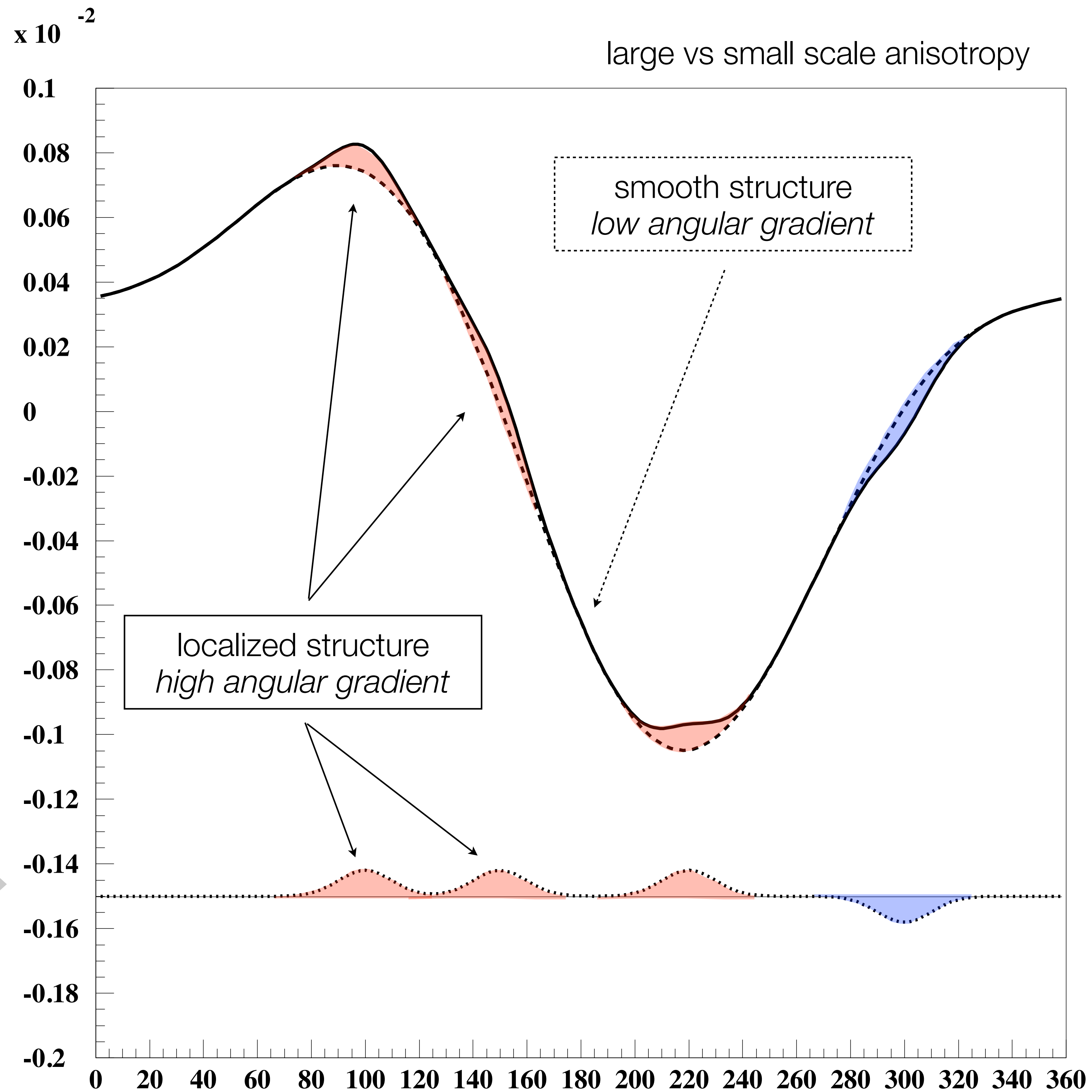
Tibet-ASγ

(global fit)



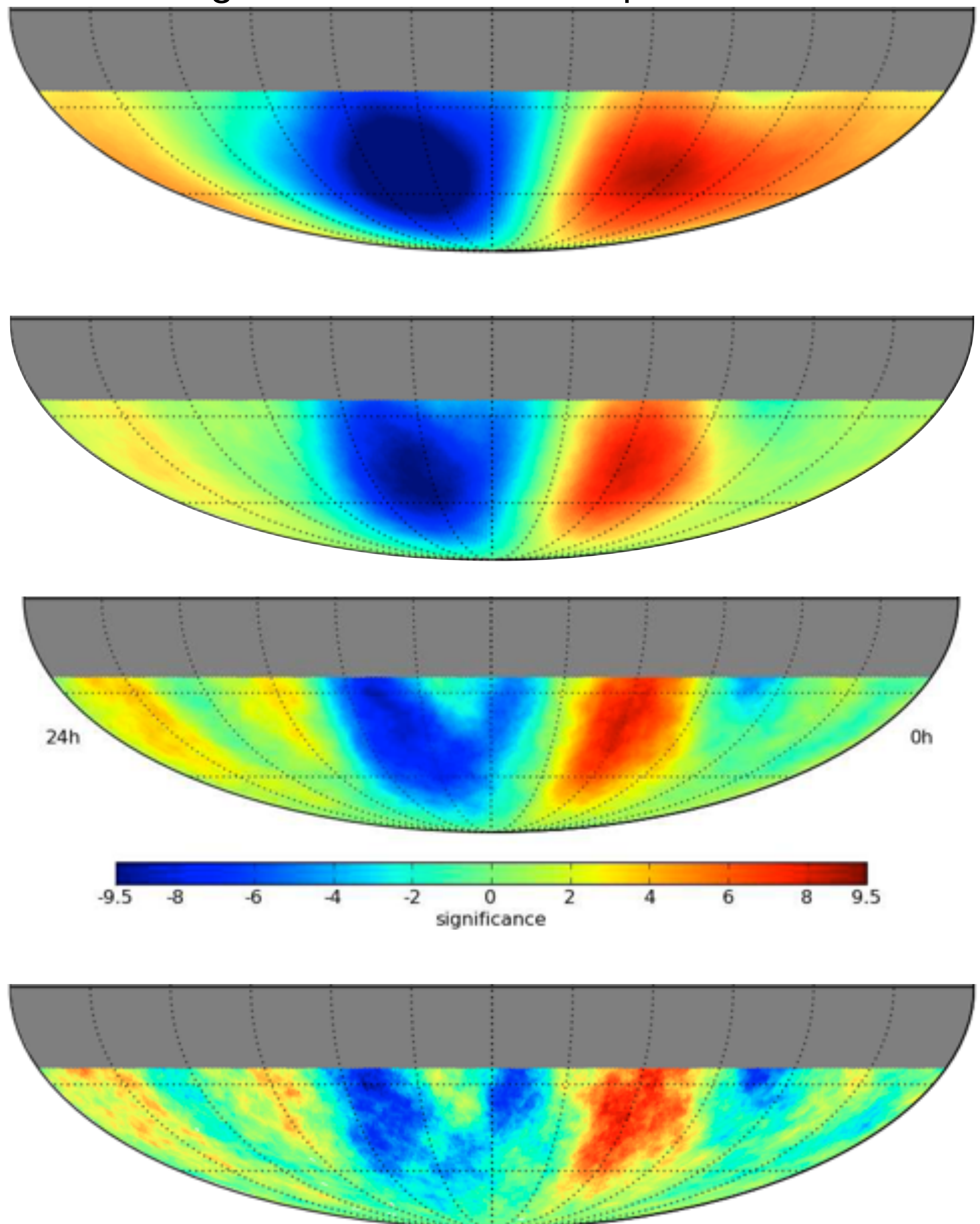
fine structure in the anisotropy





cosmic ray anisotropy vs angular scale

statistical significance equatorial coordinates

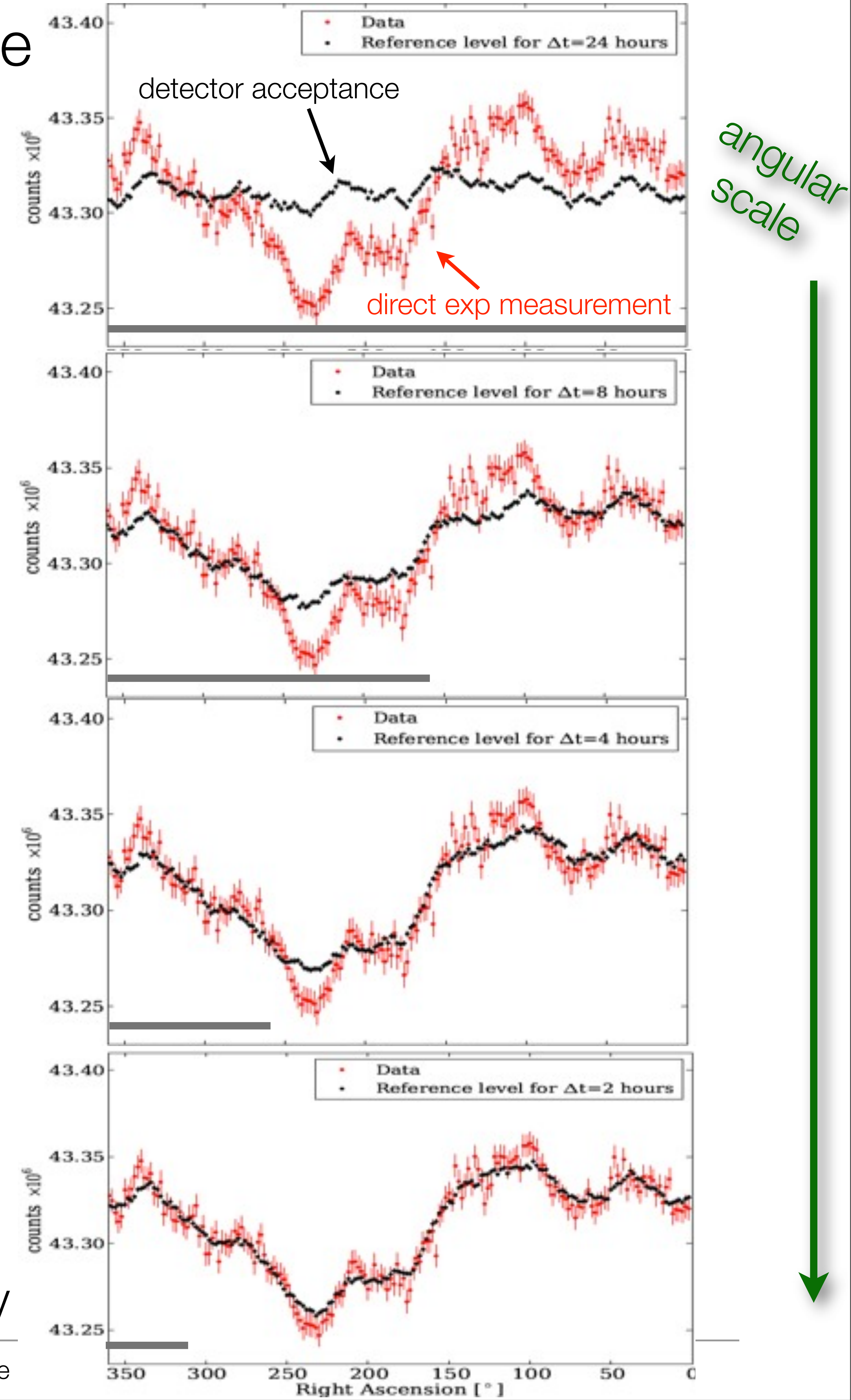


24 hr

8 hr

4 hr

2 hr



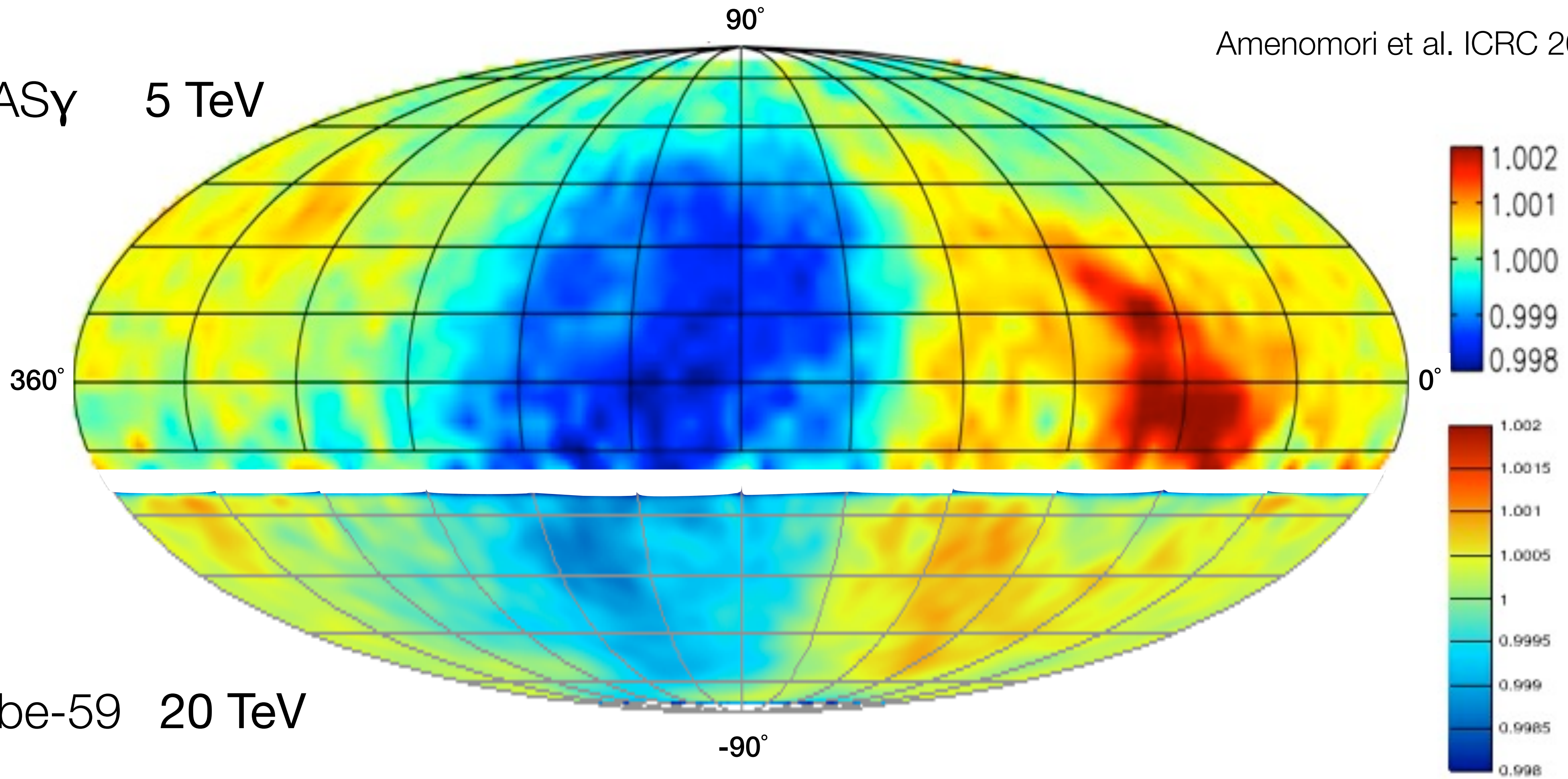
IceCube-59 - 20 TeV

cosmic ray anisotropy in arrival direction

equatorial coordinates   relative intensity

Tibet-ASγ   5 TeV

Amenomori et al. ICRC 2011, #0379

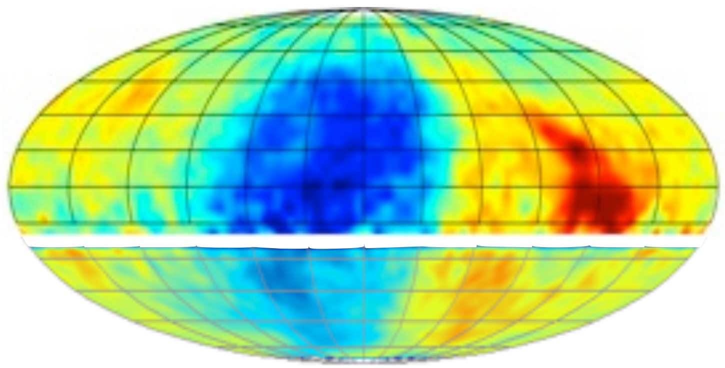


IceCube-59   20 TeV

Abbasi et al., arXiv:1109.1017 ➙ ApJ

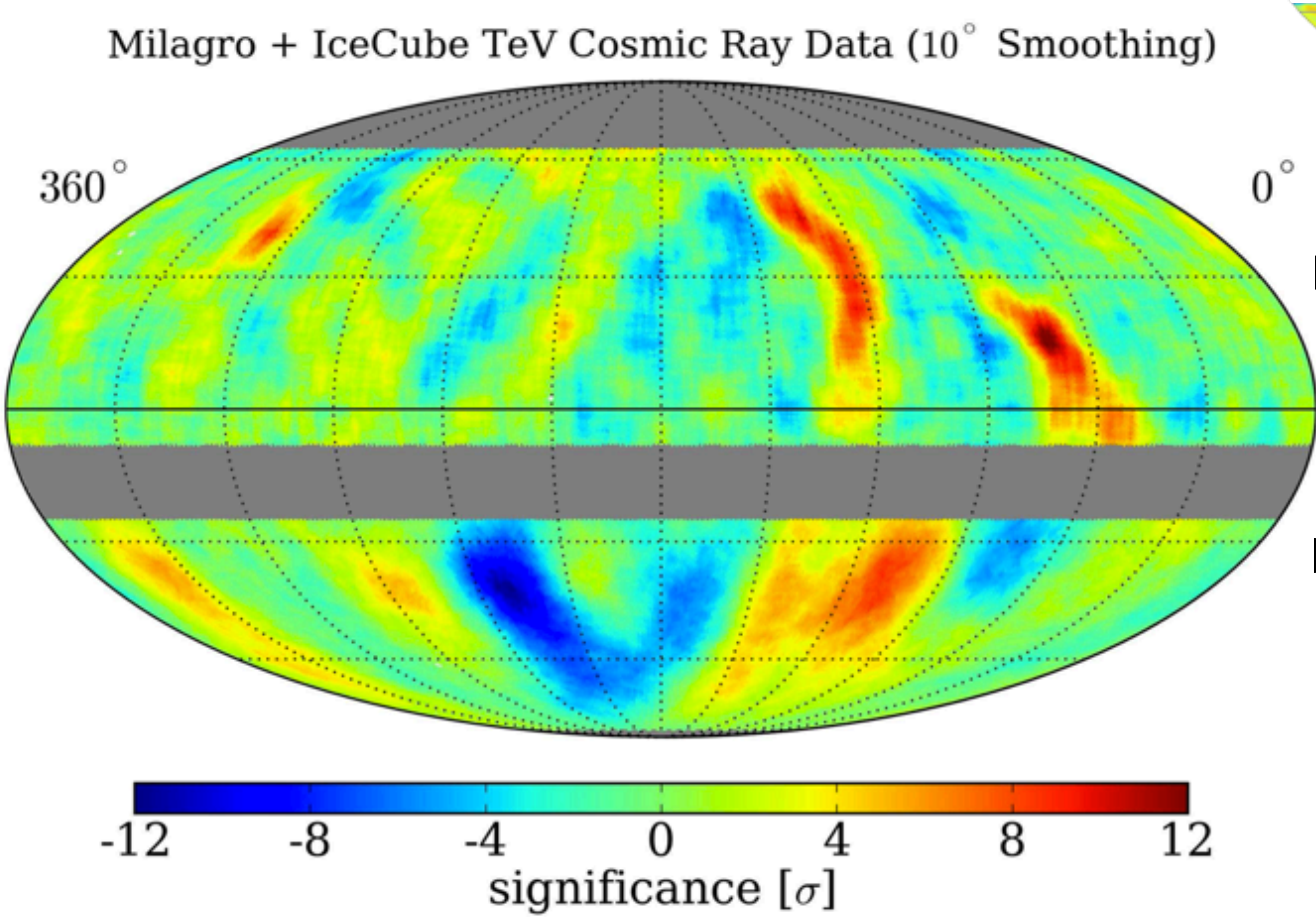
cosmic ray anisotropy in arrival direction

equatorial coordinates   statistical significance



2 hr = 30°

4 hr = 60°



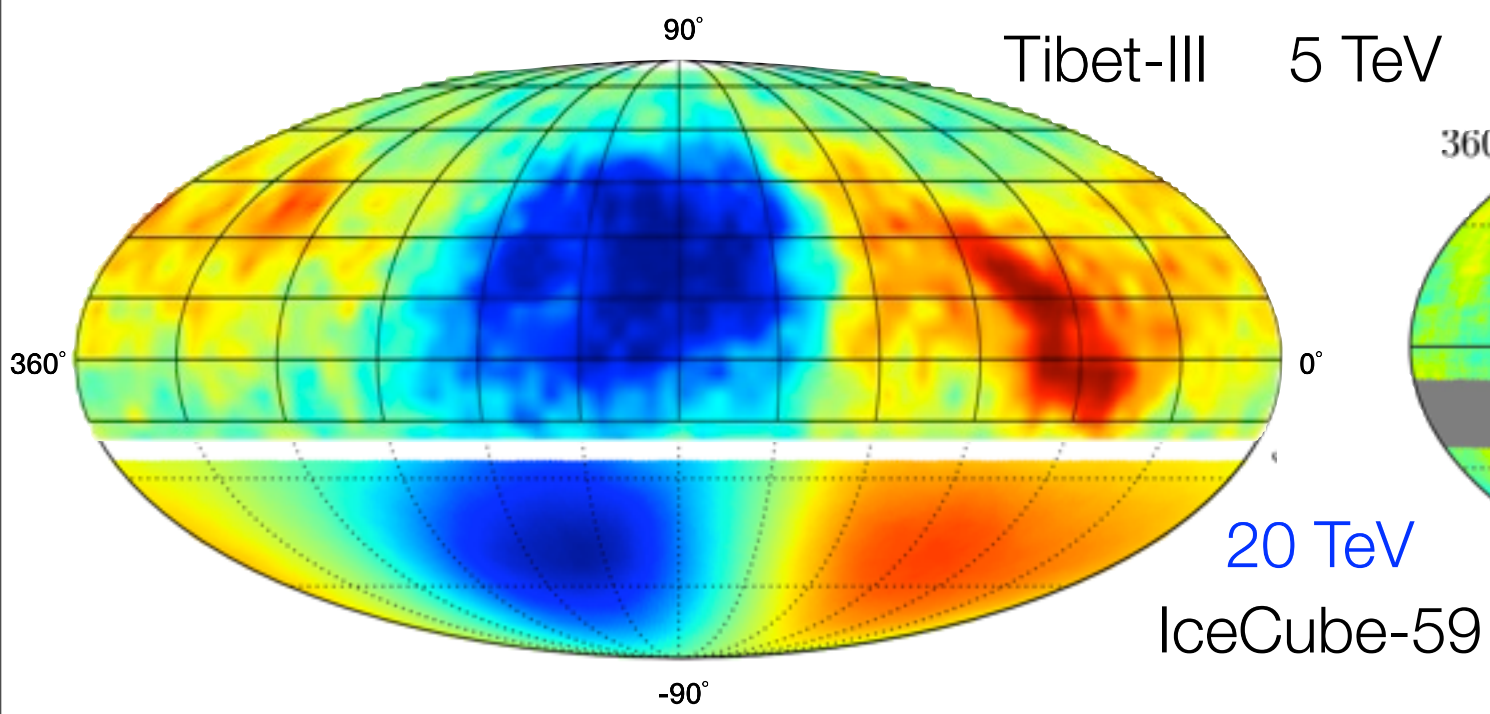
Milagro 1 TeV

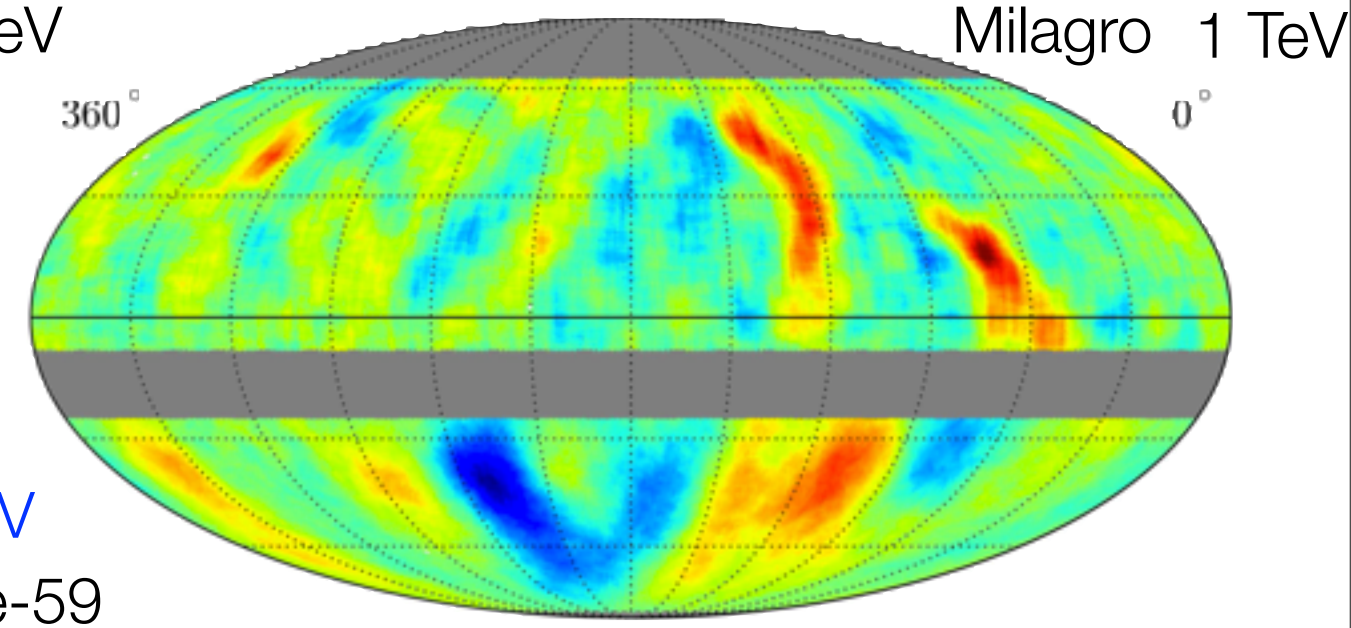
IceCube-59 20 TeV

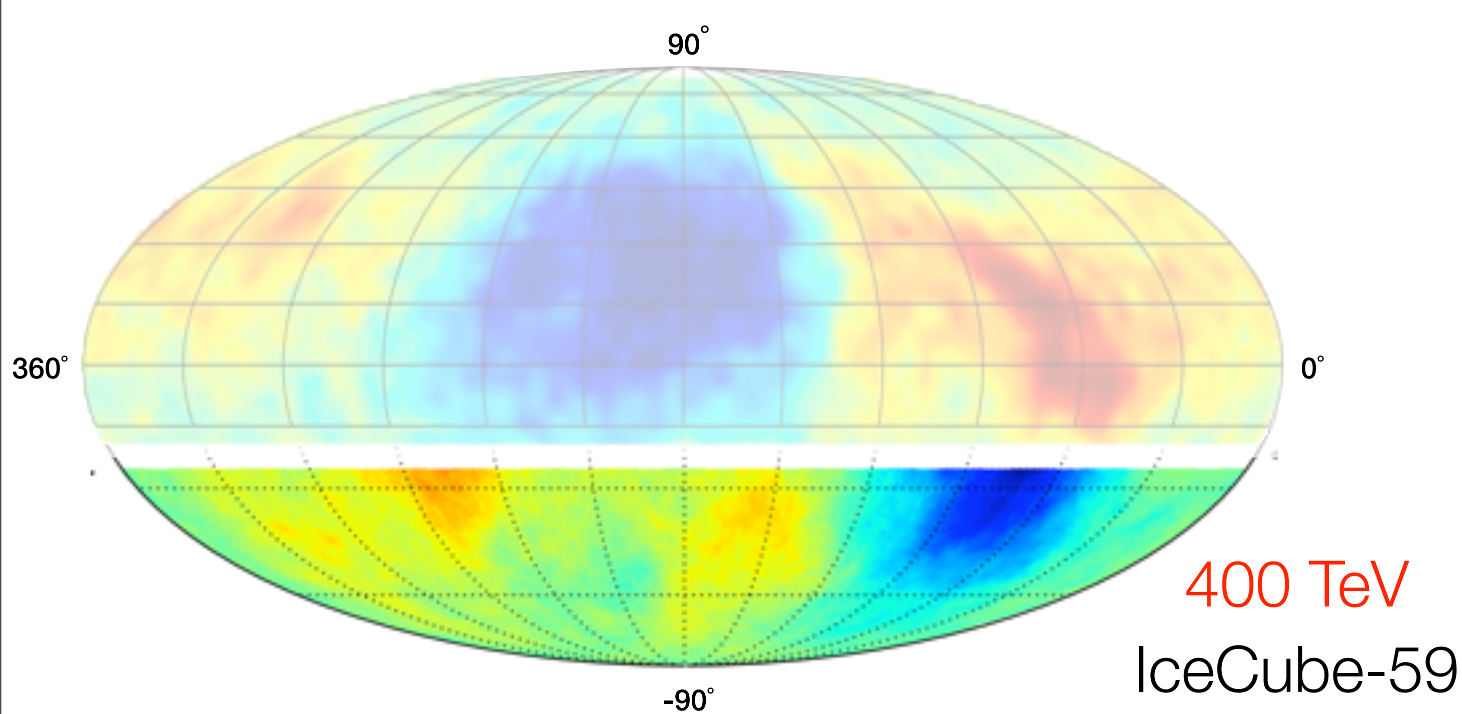
Abbasi et al., ApJ (2011) 740 16, arXiv:1105.2326

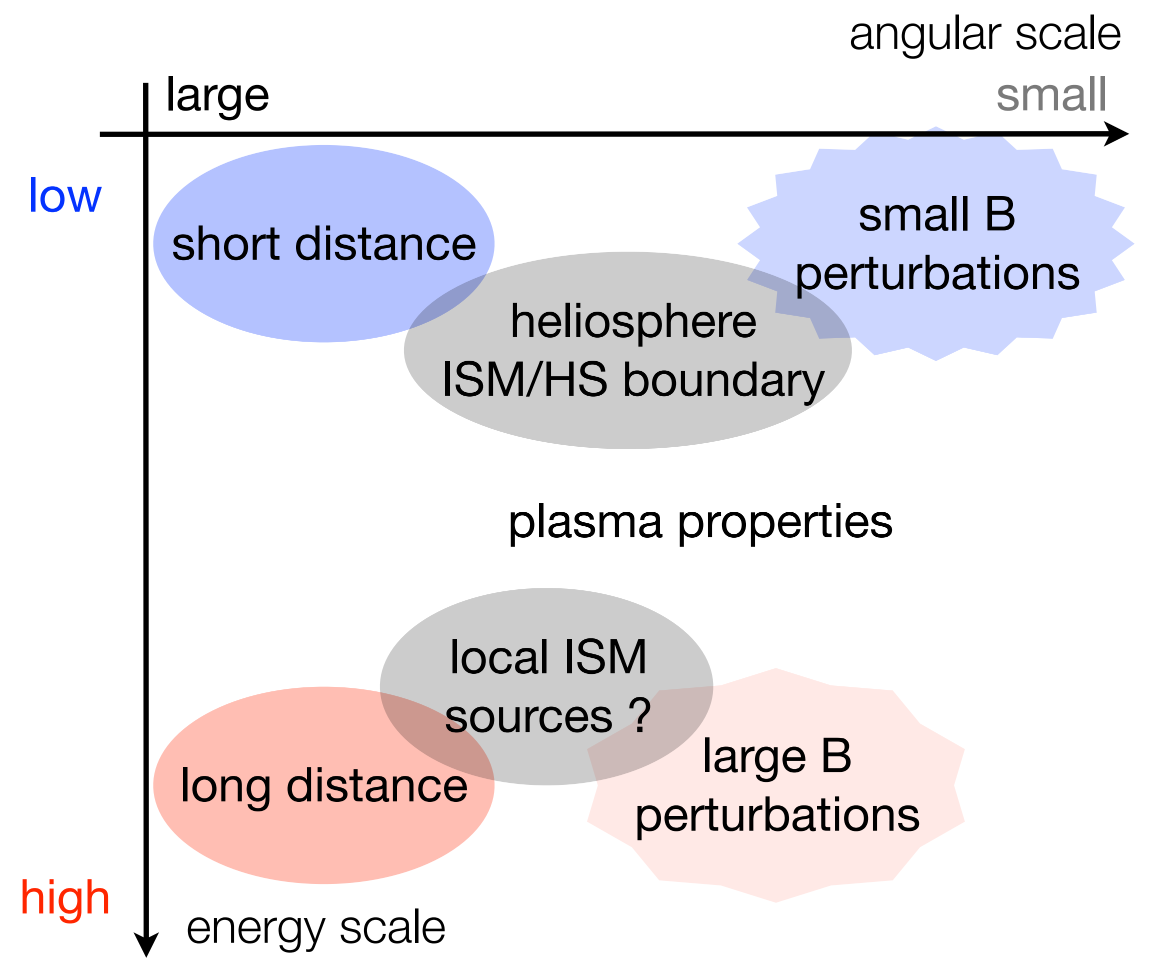
cosmic ray anisotropy

equatorial coordinates   statistical significance









Tuesday, December 6, 2011

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
- escape from galaxy — Butt, Nature, 460, 701 (2009)
- galactic magnetic field induced by cosmic ray flow along the arms — X.B.Qu et al., arXiv:1101.5273
- 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)
- effect from Local Interstellar Cloud (LIC) and local IS magnetic field < 1 pc — Amenomori et al., ICRC 2007, Mérida, México (2007)
- Heliosphere and the sub-GeV cosmic rays — Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)

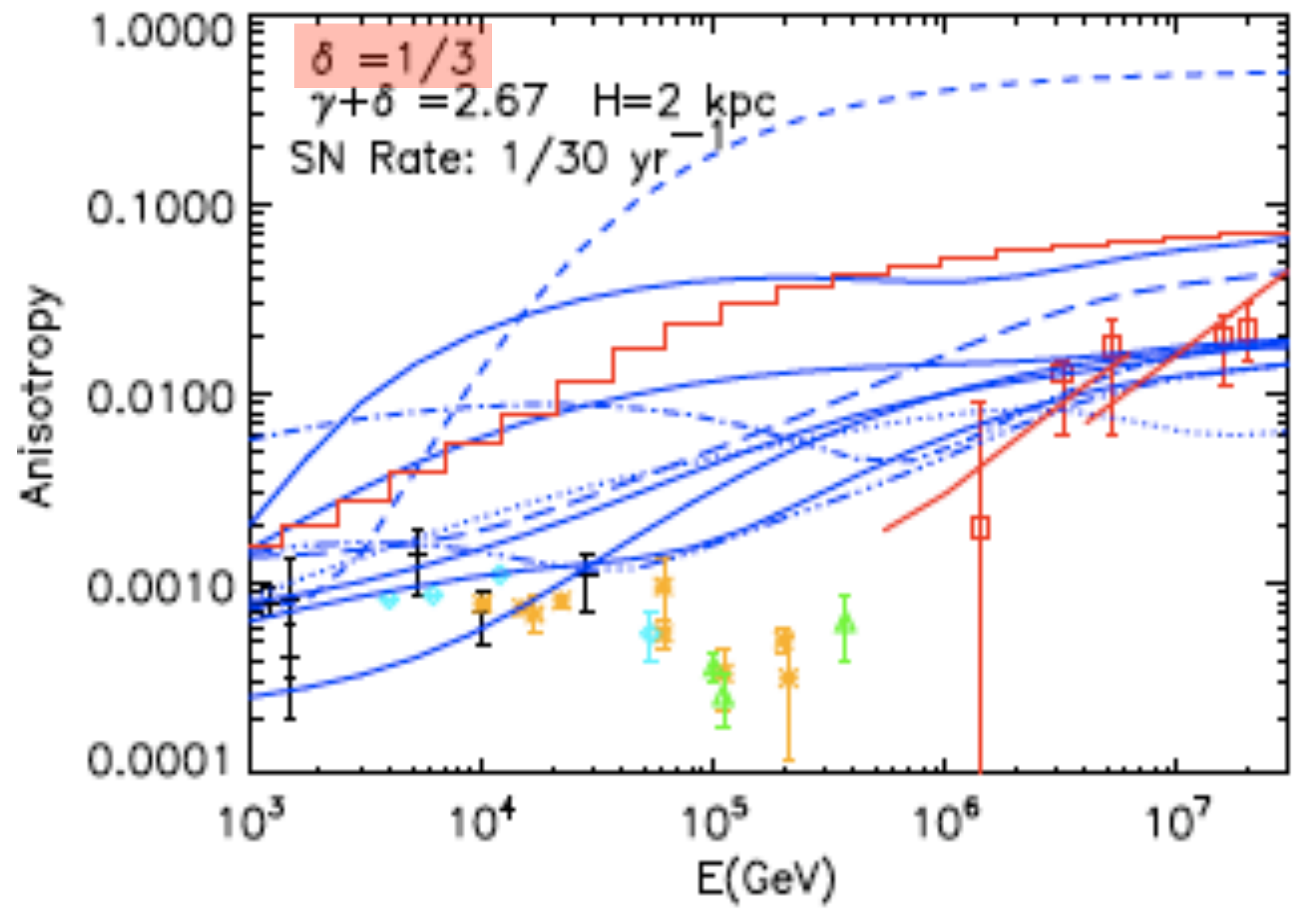
origin of *large scale* anisotropy ?

Blasi & Amato, arXiv:1105.4529

- *diffuse* dipole anisotropy from the galactic center (stationary)
- superposition of dipole anisotropy contributions from nearby sources of cosmic rays
- each source contributes at different energy from a different direction

$$\phi_{CR} \approx 2.4 \cdot \left(\frac{E_{SN}}{10^{51} erg}\right) \cdot \epsilon_{CR} \cdot \left(\frac{15kpc}{R_d}\right)^2 \cdot \left(\frac{R_{SN}}{30yr}\right) \cdot (\gamma - 2) \cdot 3^{-\delta} \cdot \left(\frac{E}{1TeV}\right)^{-\gamma-\delta} \quad [TeV^{-1} m^{-2} s^{-1} sr^{-1}]$$

$$\delta_A = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{Hc}$$



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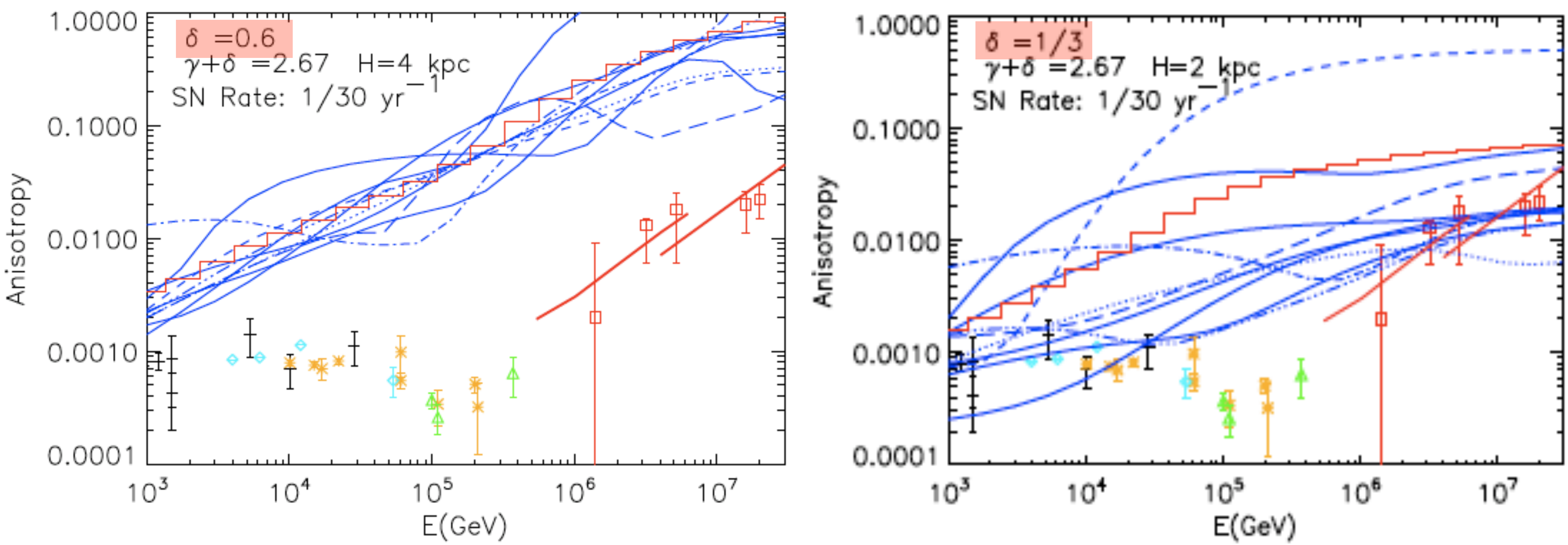

Tuesday, December 6, 2011

origin of *large scale* anisotropy ?

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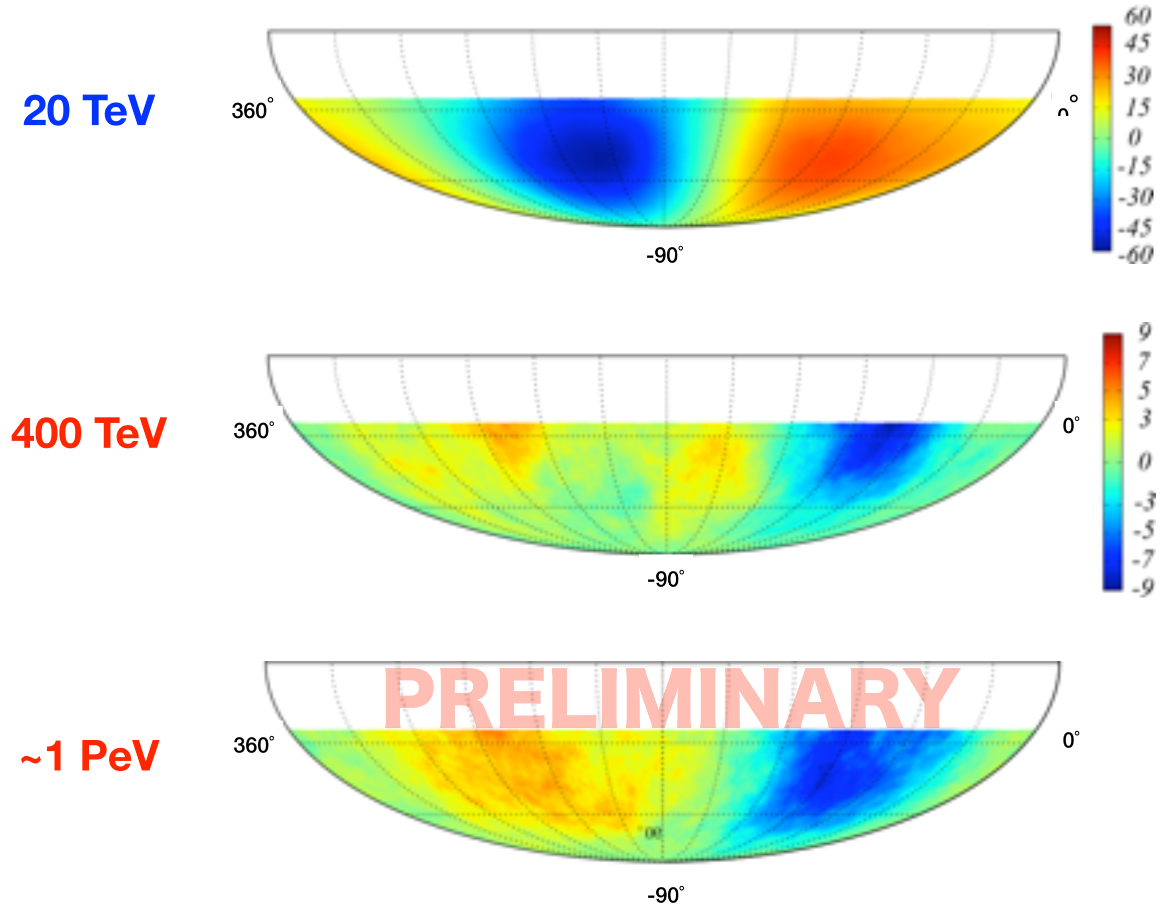
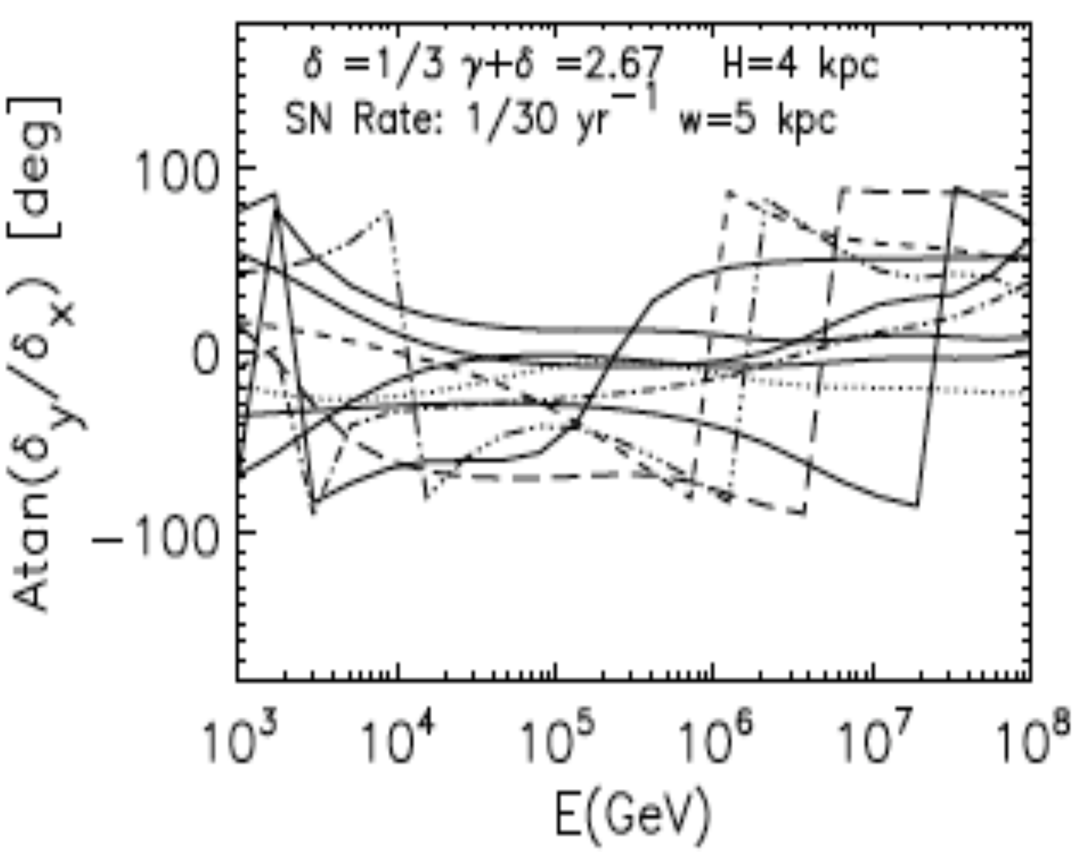


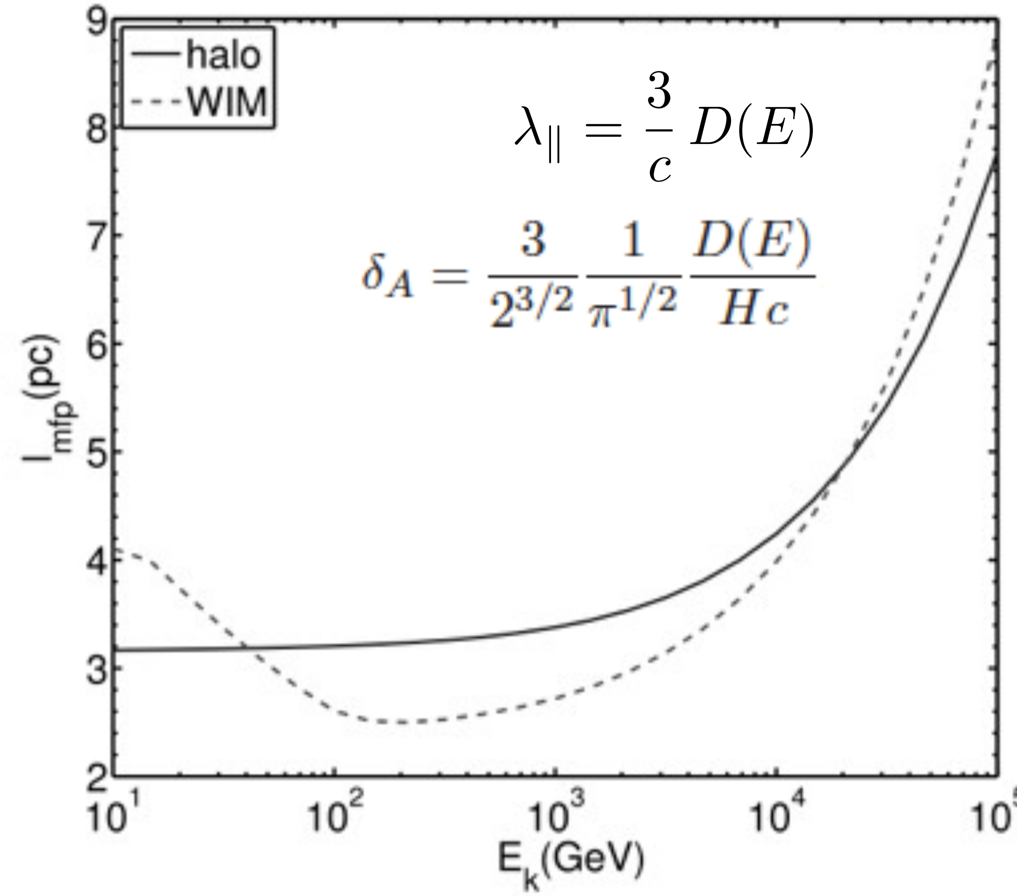


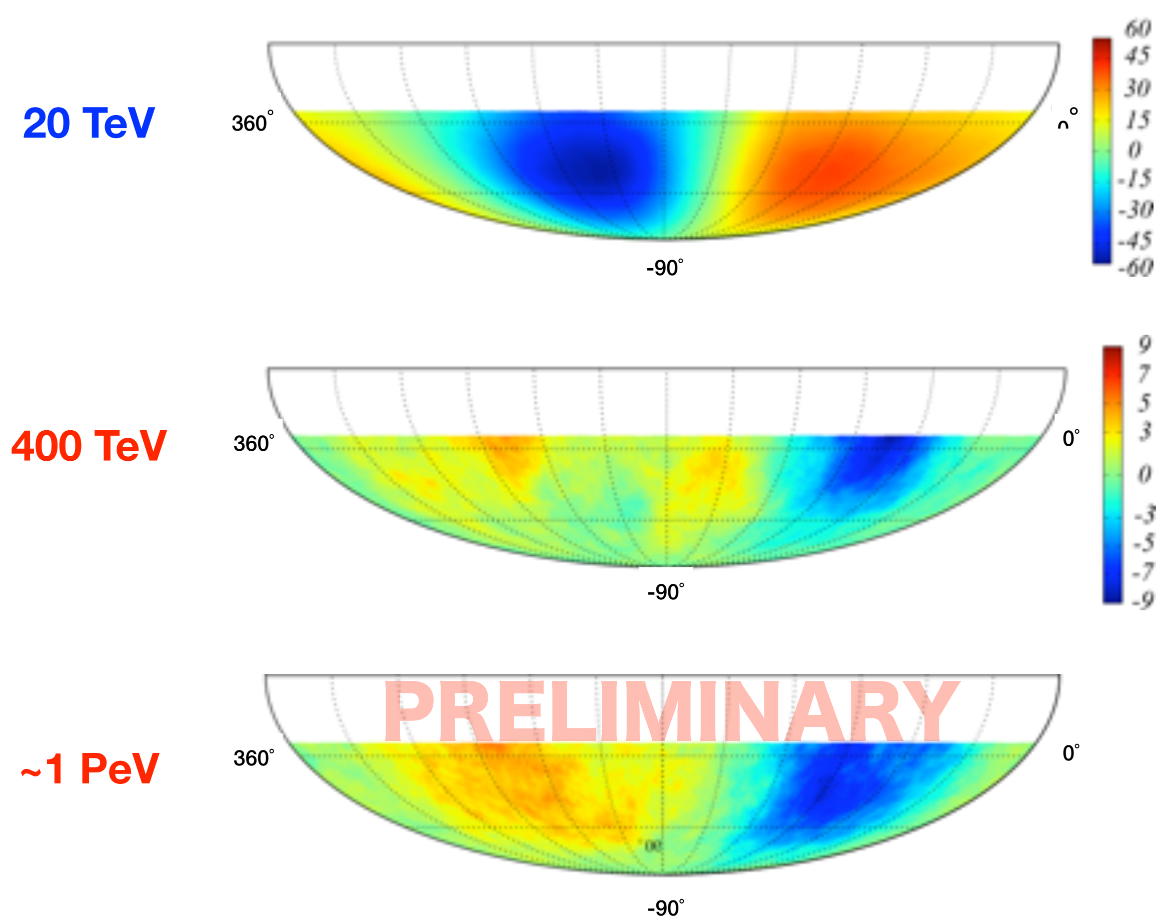
Tuesday, December 6, 2011

origin of *large scale* anisotropy ?

- anisotropic diffusion does not affect the stationary diffuse dipole anisotropy
- propagation from nearby sources might be non-dipolar

Yan & Lazarian, ApJ, 2008, 673, 942





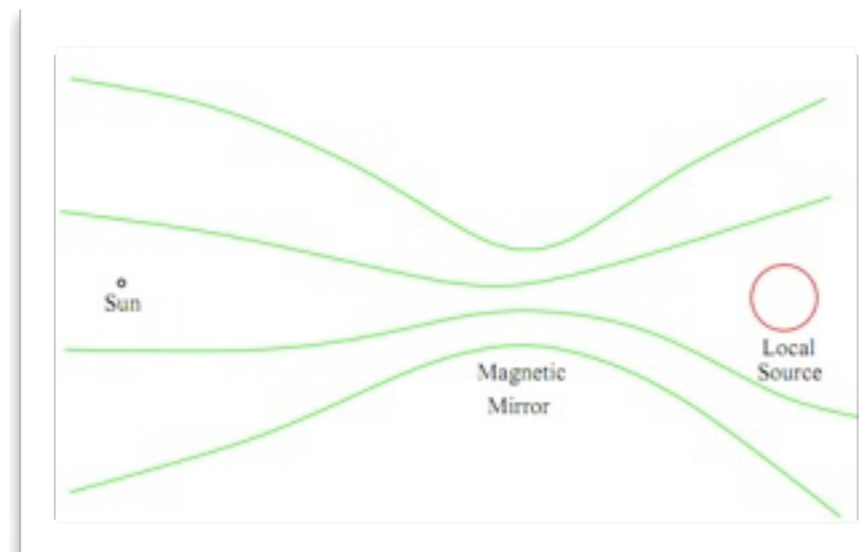
- cascading MHD turbulence + turbulence induced by CR
- scattering by fast modes (depends on medium)
- anisotropic CR distribution is essential

origin of *small scale* anisotropy ?

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

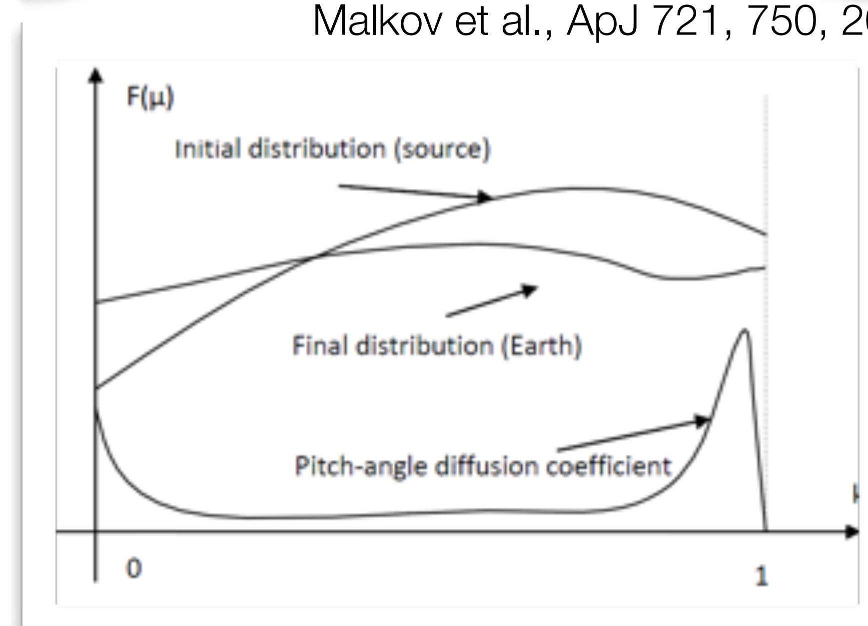
- **CR from Geminga:** ~90-200 pc, 340,000 yr ago
  - energy passband (cutoff HE, delays LE) ~ hard spectrum

Salvati, Astron. & Astrophys. arXiv:1001.4947



- **magnetic connection & propagation in turbulent LIMF**

Malkov et al., ApJ 721, 750, 2010

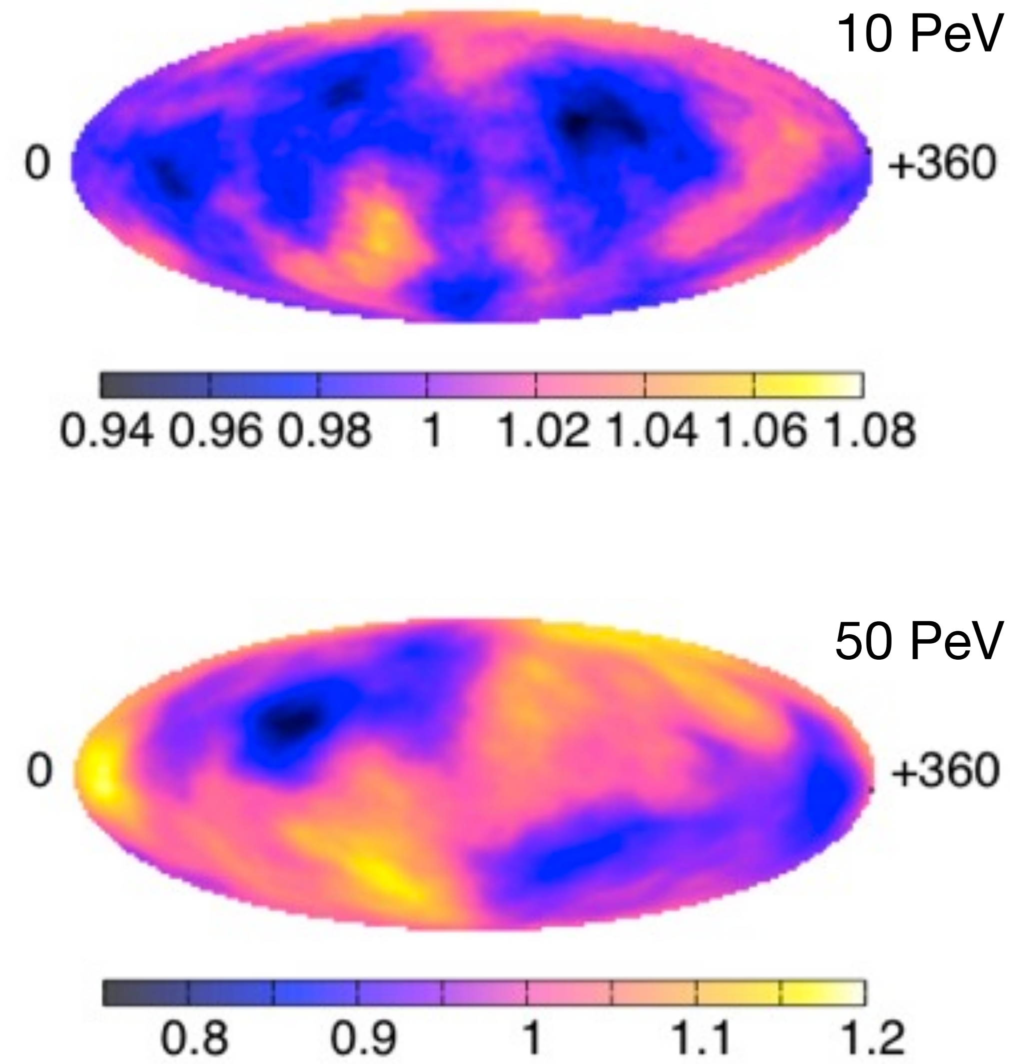


- **anisotropic MHD turbulence in the ISM**
  - large scale anisotropy is “perturbed” by faint beam of collimated particles along the “magnetic” lines connecting to a source (~100 pc)
  - pitch angle scattering peaked near the direction of LIMF
  - outer scale of perturbation ~1 pc determines beam angular width and strength

origin of small scale anisotropy ?

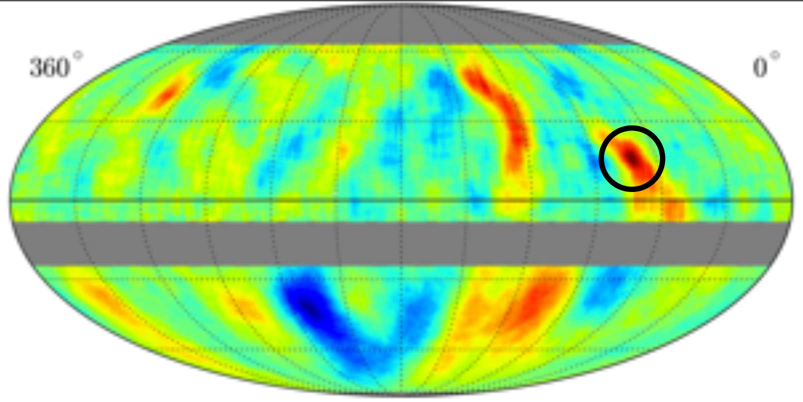
Giacinti & Sigl, arXiv:1111.2536

- 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



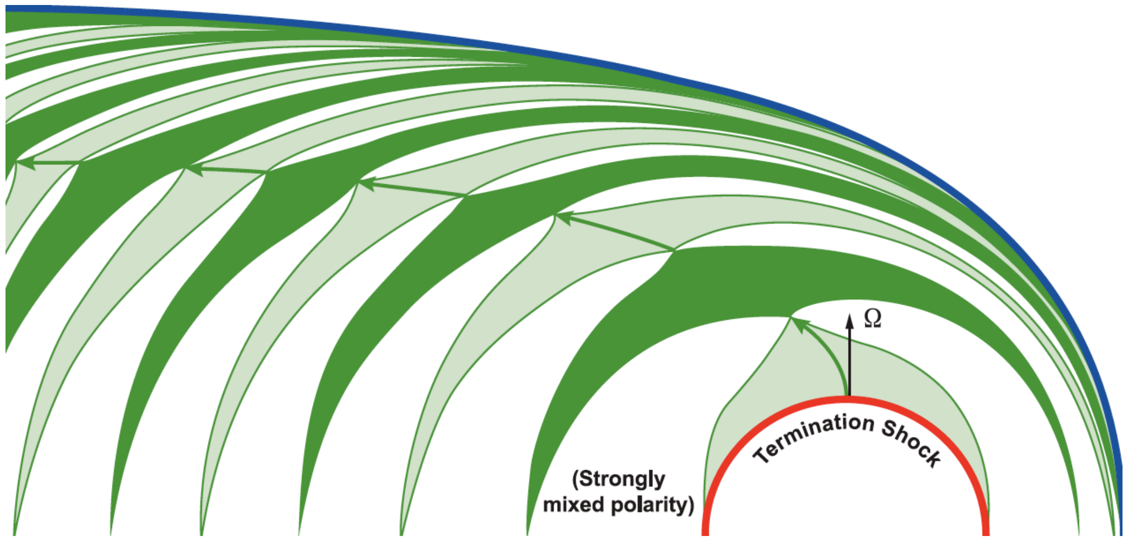
20° smoothing

origin of small scale anisotropy ?



Lazarian & PD, ApJ, 722, 188, 2010

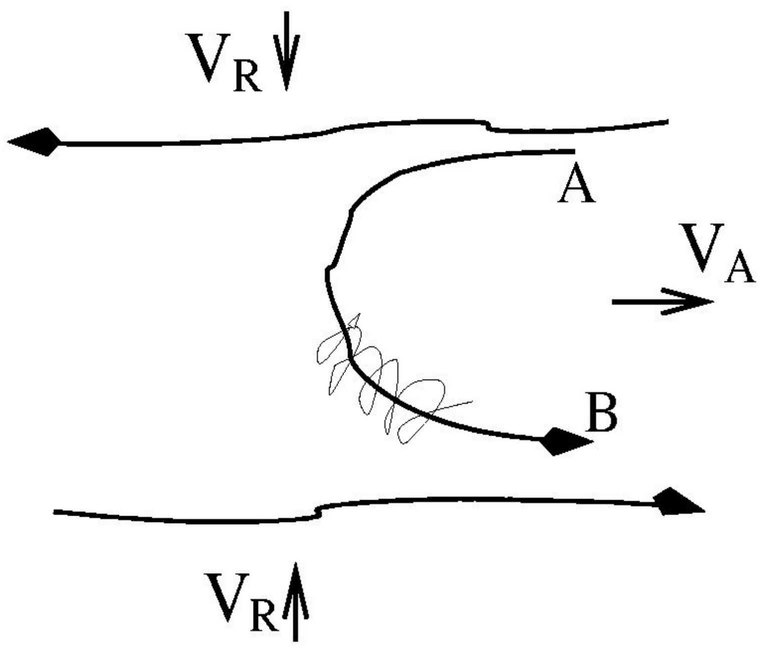
- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail



- turbulence makes reconnection fast and not affected by ohmic dissipation
- magnetic mirror @ single reconnection as site of acceleration

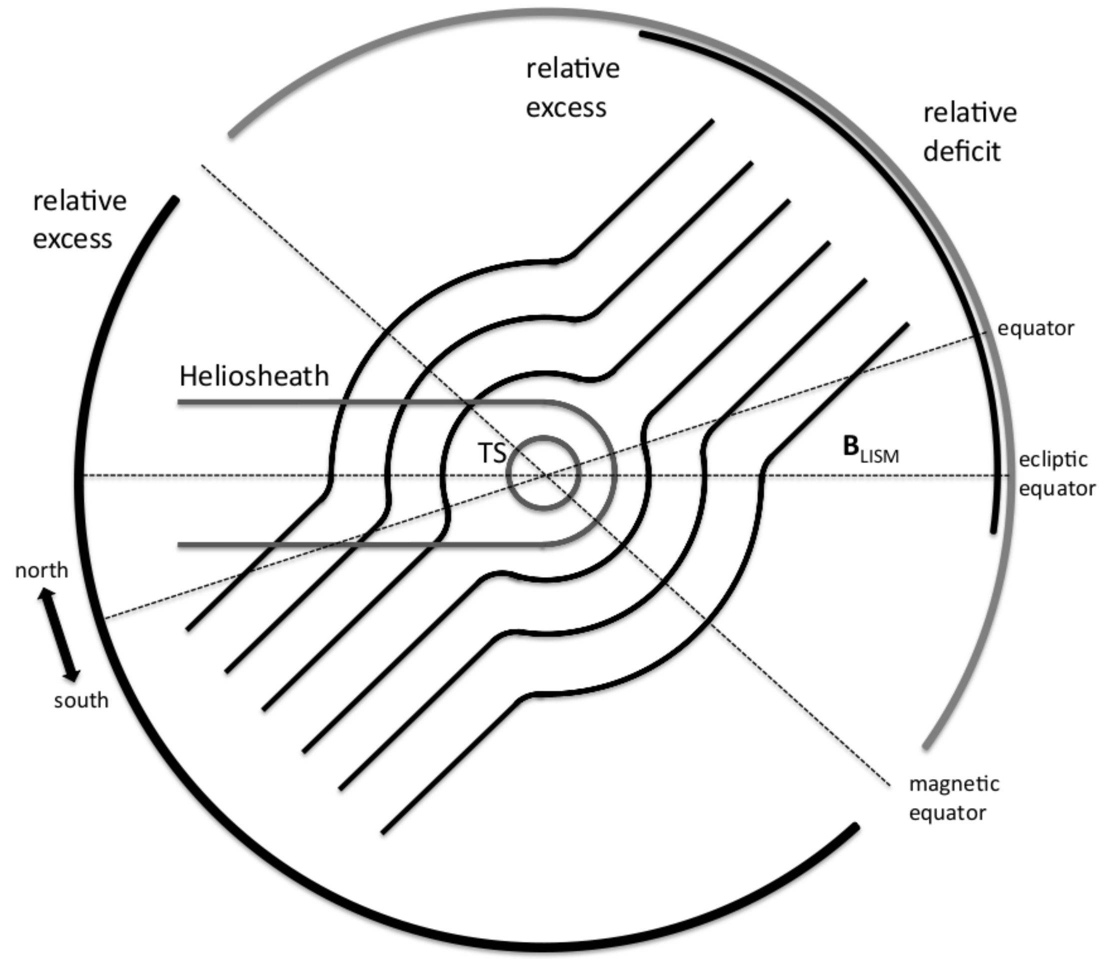
$$N(E)dE \sim E^{-5/2}dE$$

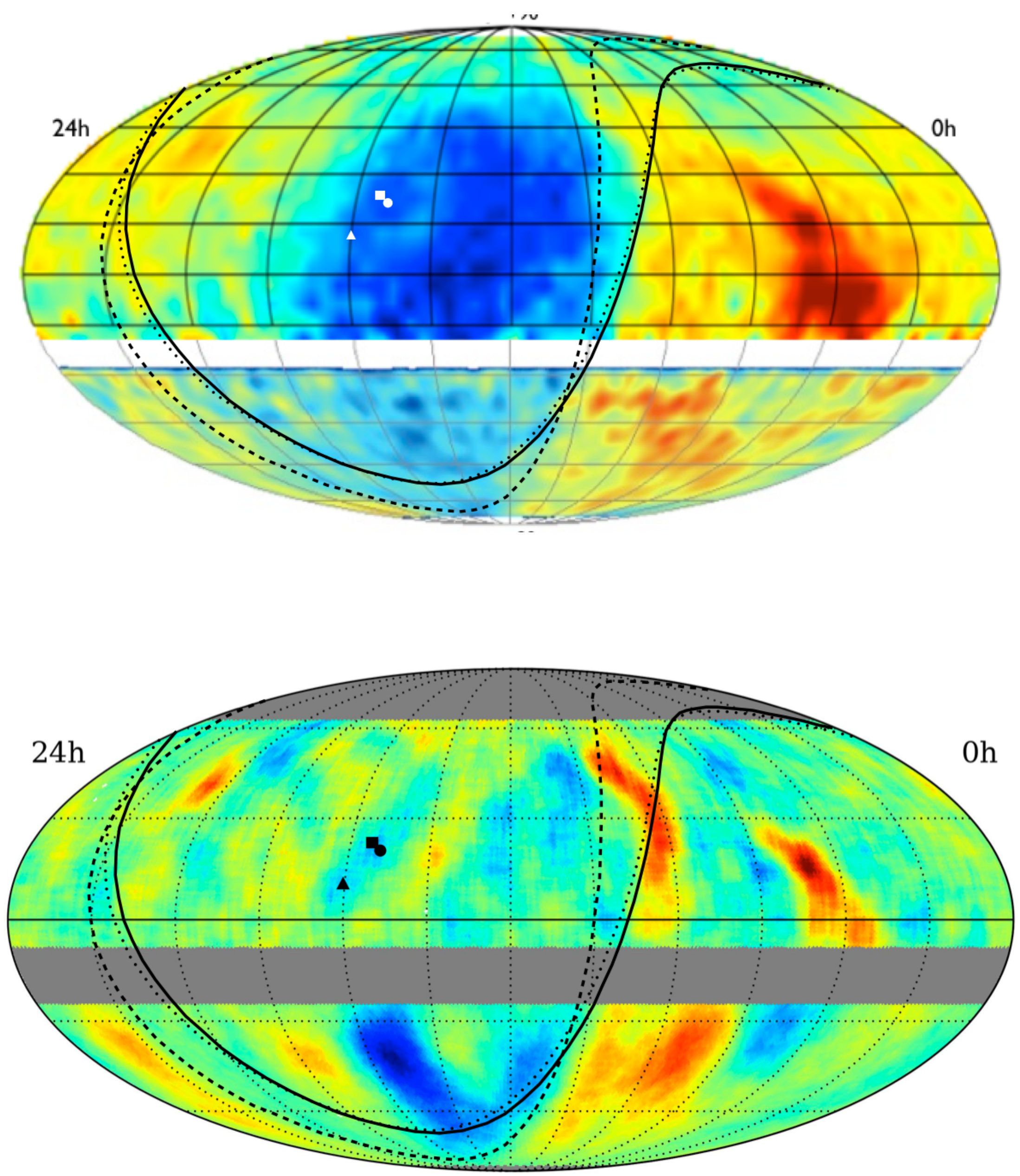
$$E_{max} \approx 10^{13}\ eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right)$$ ~ 10 TeV



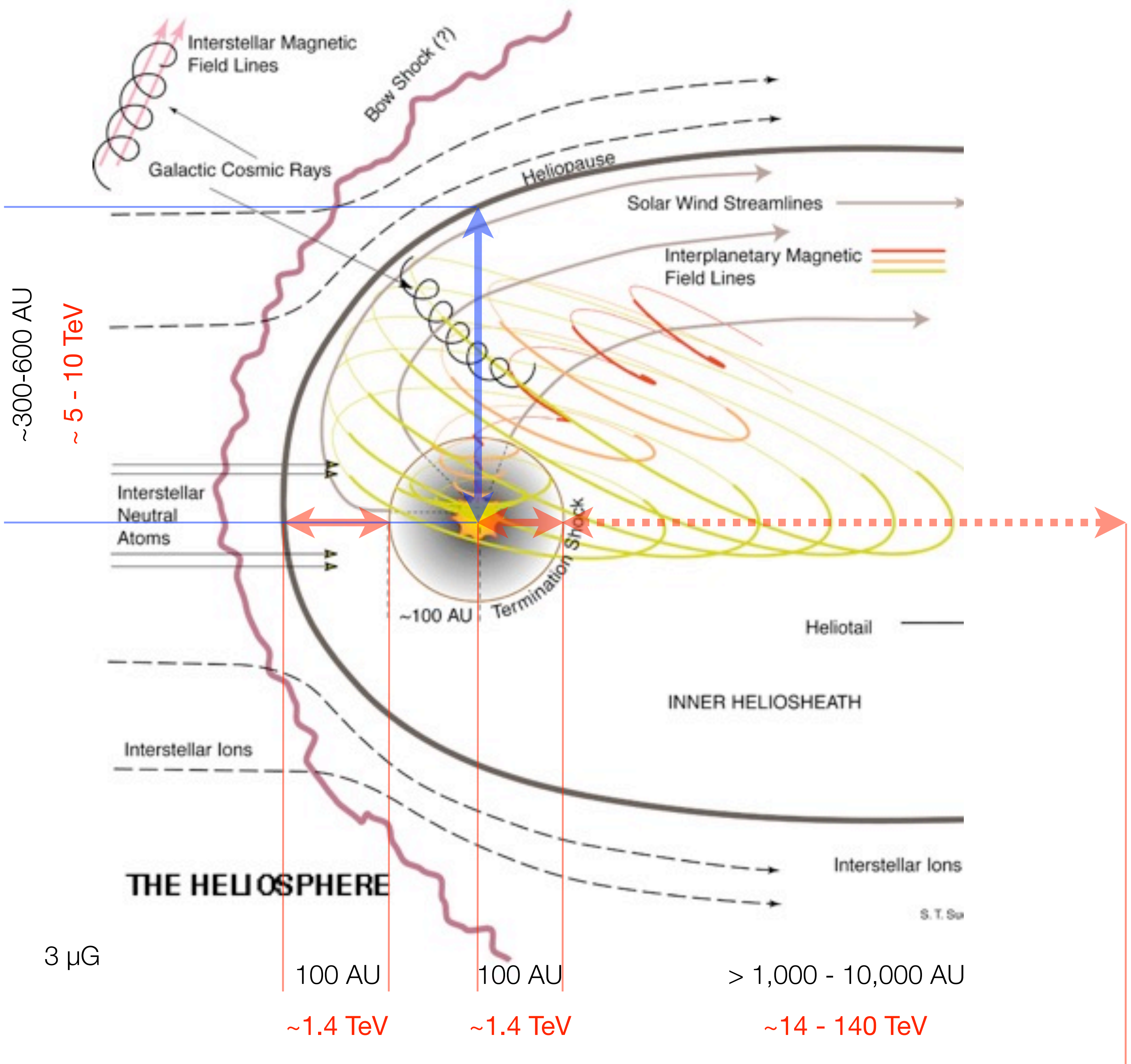
origin of small scale anisotropy ?

PD & Lazarian, arXiv:1111.3075

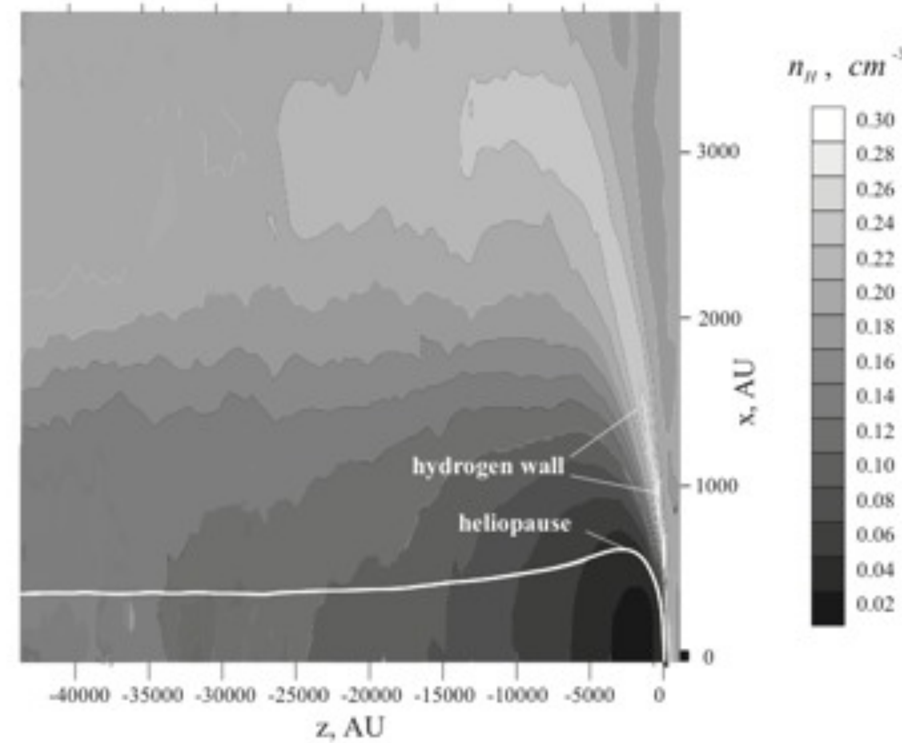




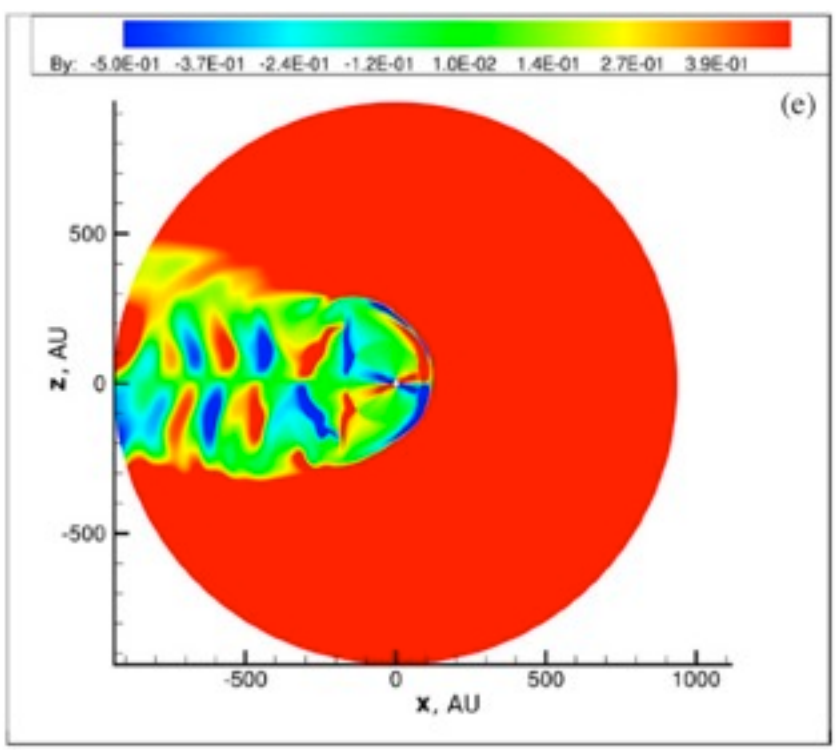
the heliosphere



Izmodenov et al., Astron. Lett., 29, 1, 58 (2003)



3D simulation of heliosphere/heliotail
Pogorelov et al., ApJ, 696, 1478 (2009)

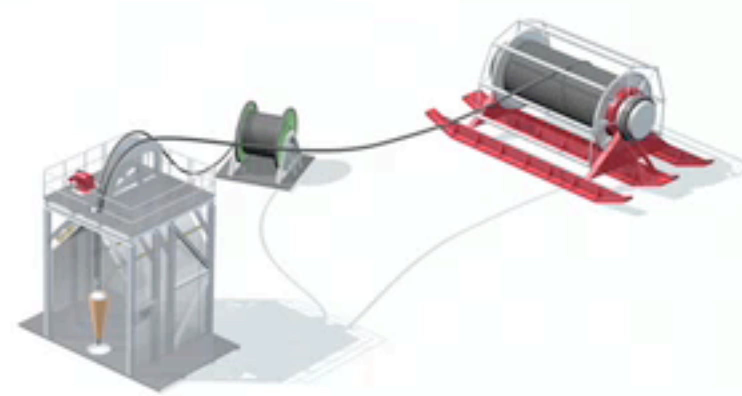


summary

- cosmic ray anisotropy **evolution** observed from 20 TeV to 400 TeV- 1 PeV with high significance in the southern hemisphere
- the origin of scale anisotropy might be related to effects within mean free path, or resulting from propagation
- understanding of baseline large scale anisotropy from stochastic sources (which would make it an accident) and from propagation in (heterogeneous) ISM through turbulent magnetic field
- take into account micro-physics of turbulence, 3D magnetic field and propagation
- use GALPROP to determine neutrino emission from galactic plane

backup slides

drilling in the ice



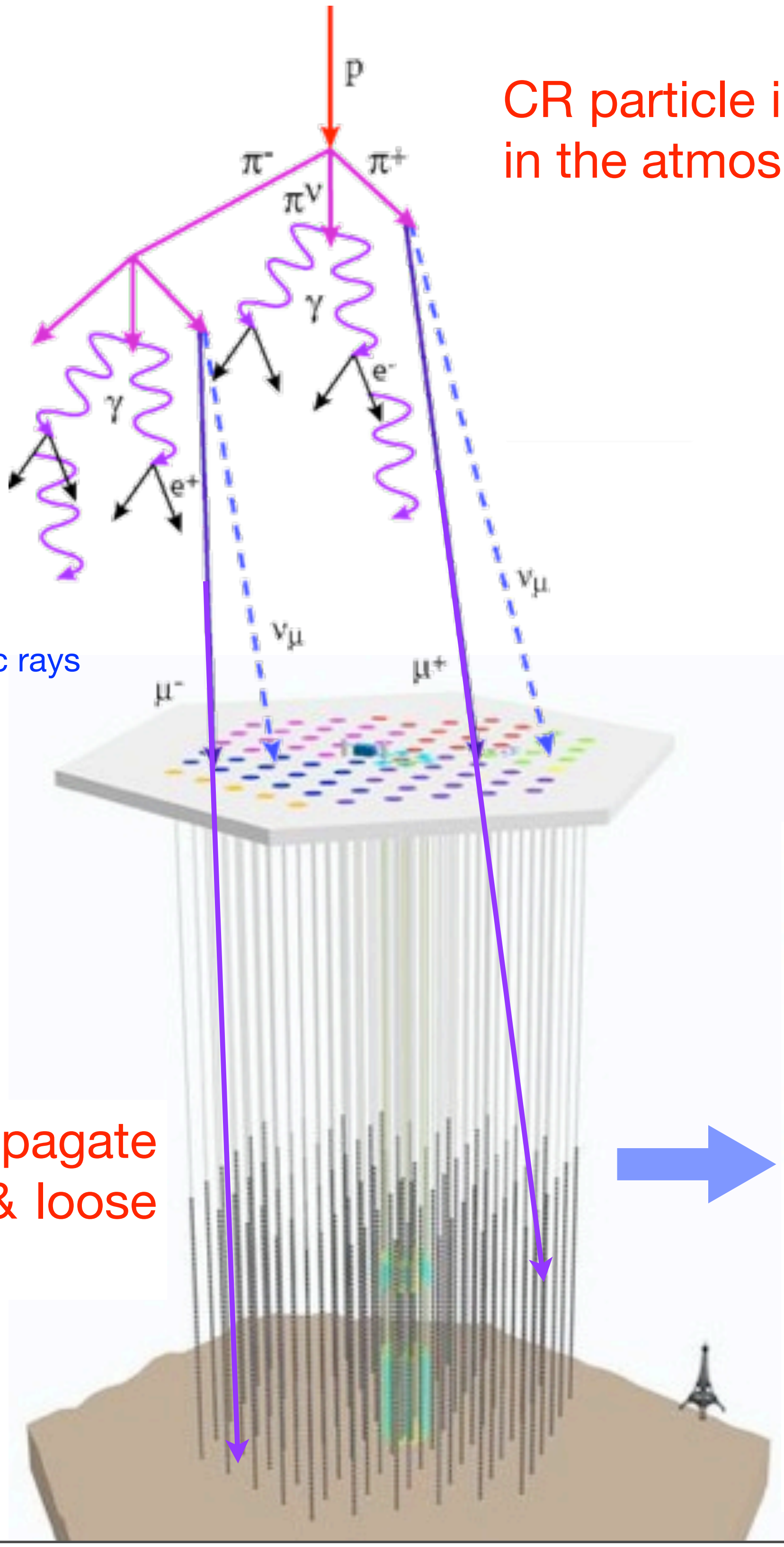
summary of measurement for IceCube-59

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

	$E_{primary}$ (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

cosmic ray energy estimation with muons

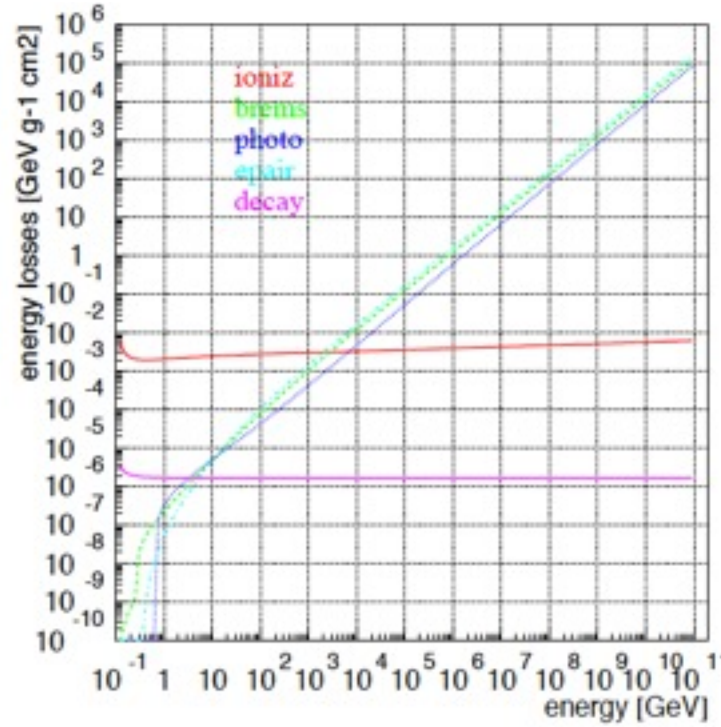
CR particle interacts in the atmosphere



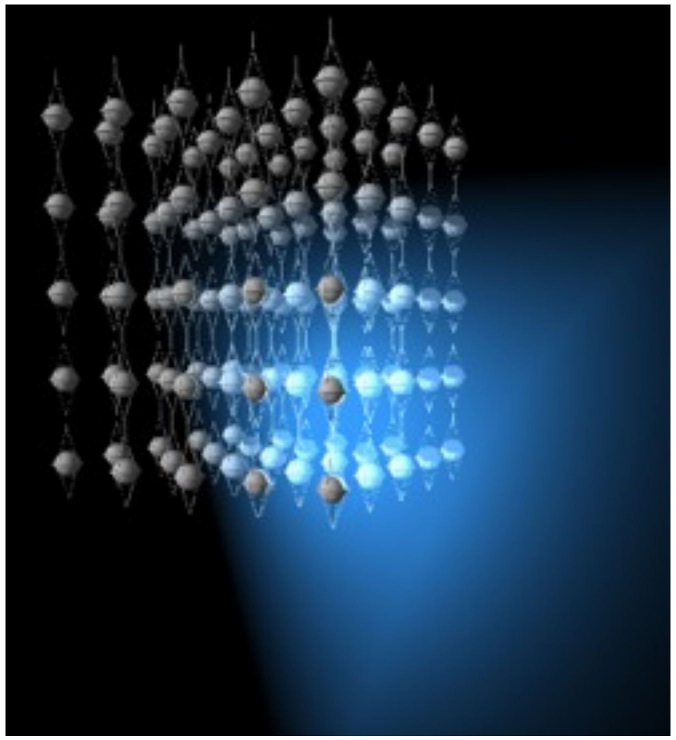
$E_\mu \propto E_{cosmic\ rays}$

muons propagate in the ice & loose energy

energy of secondaries $\propto E_\mu$



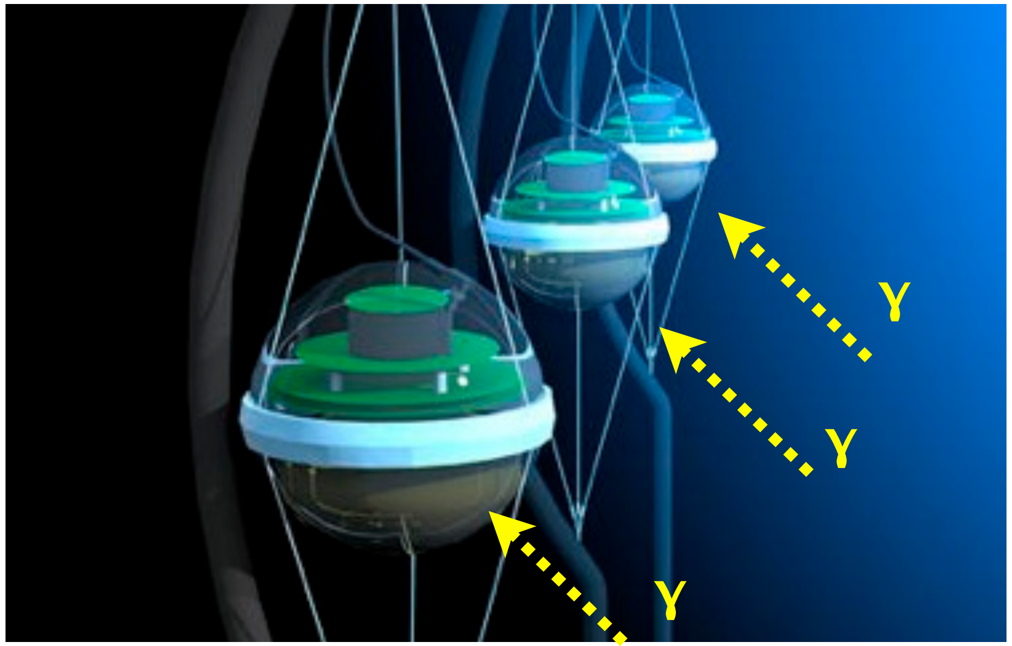
Cherenkov photons from μ and secondaries



counts number of photons

$\propto$ energy of secondaries $\propto E_\mu$

$\propto E_{cosmic\ rays}$



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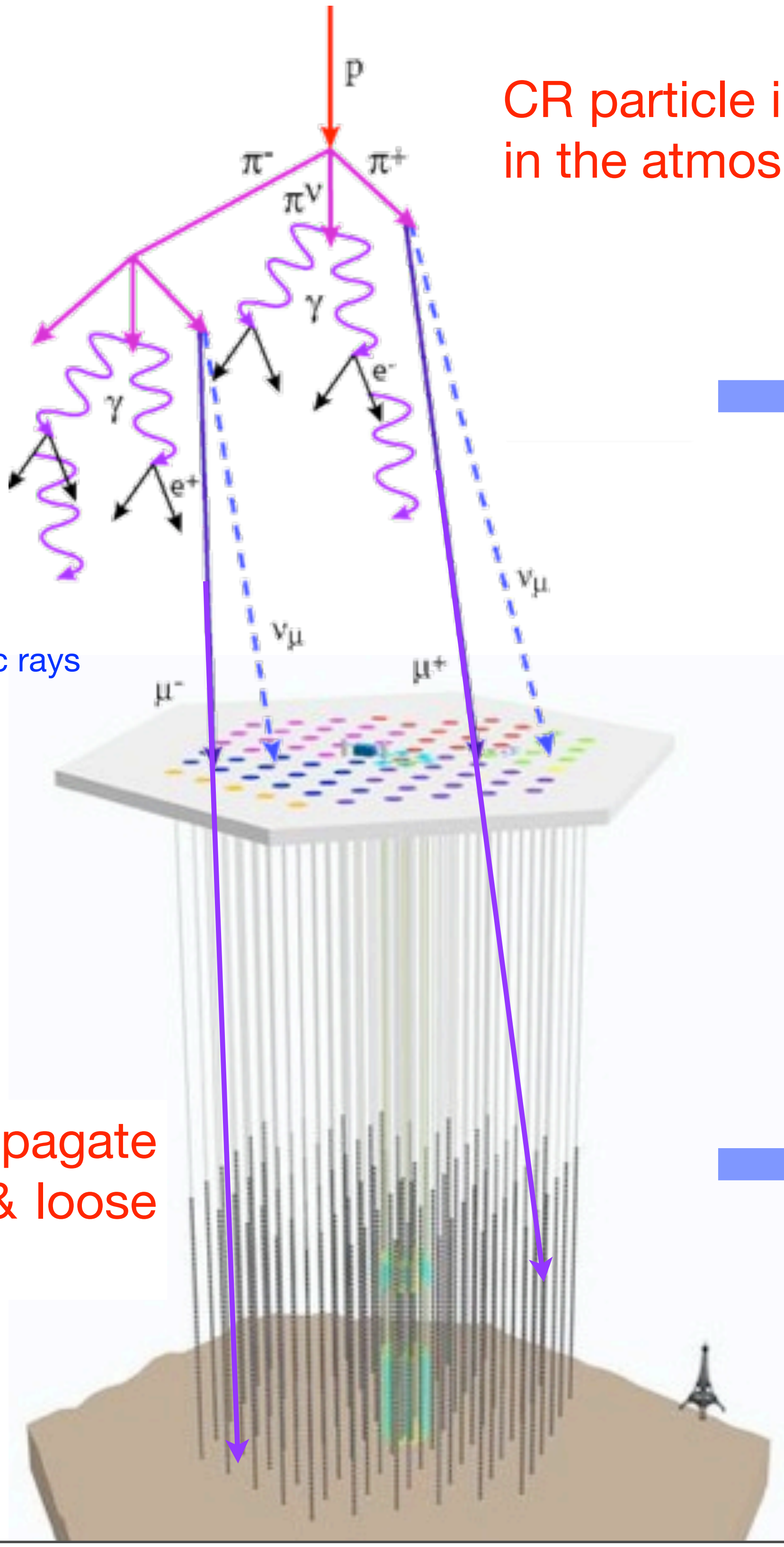
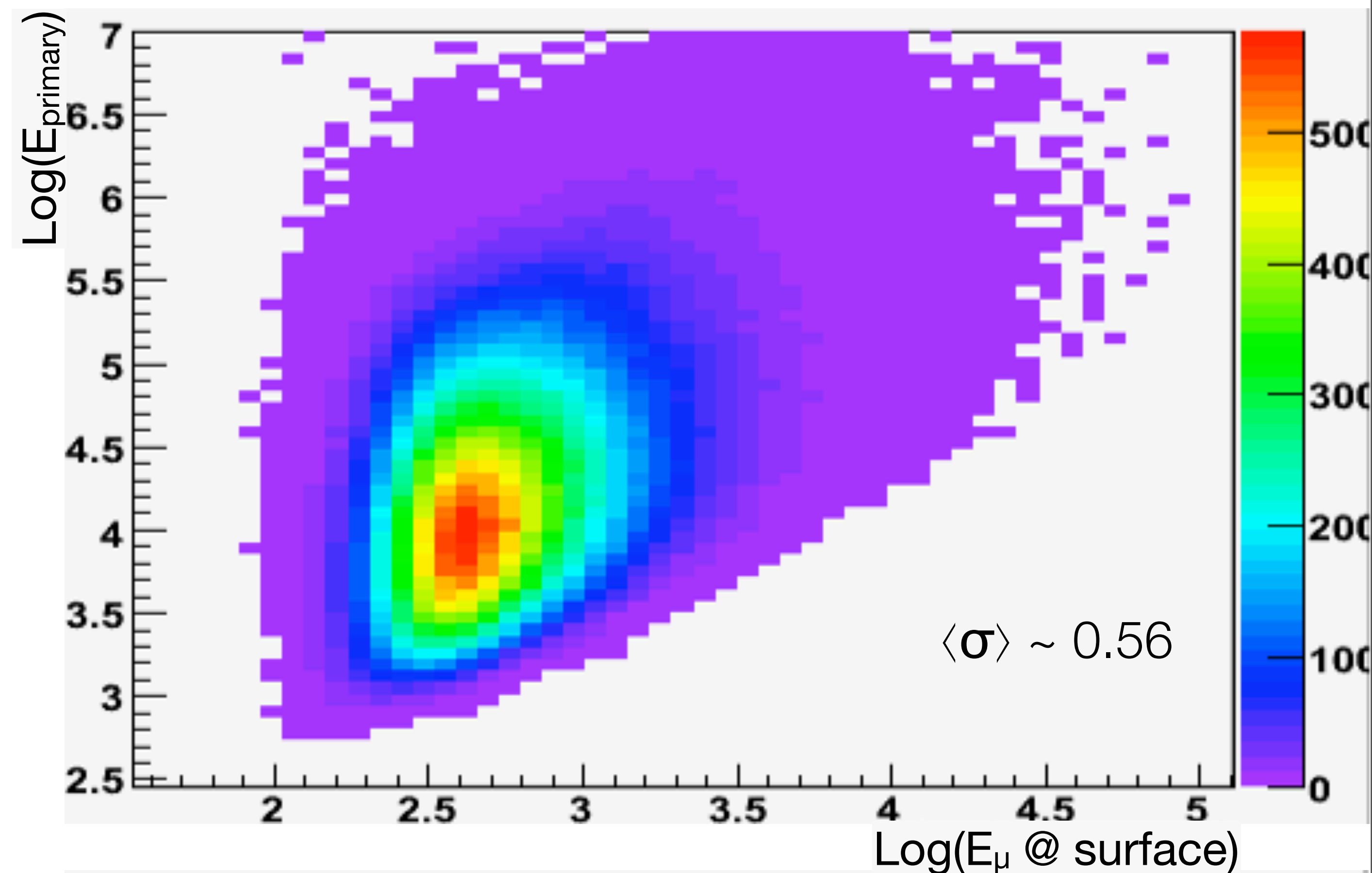
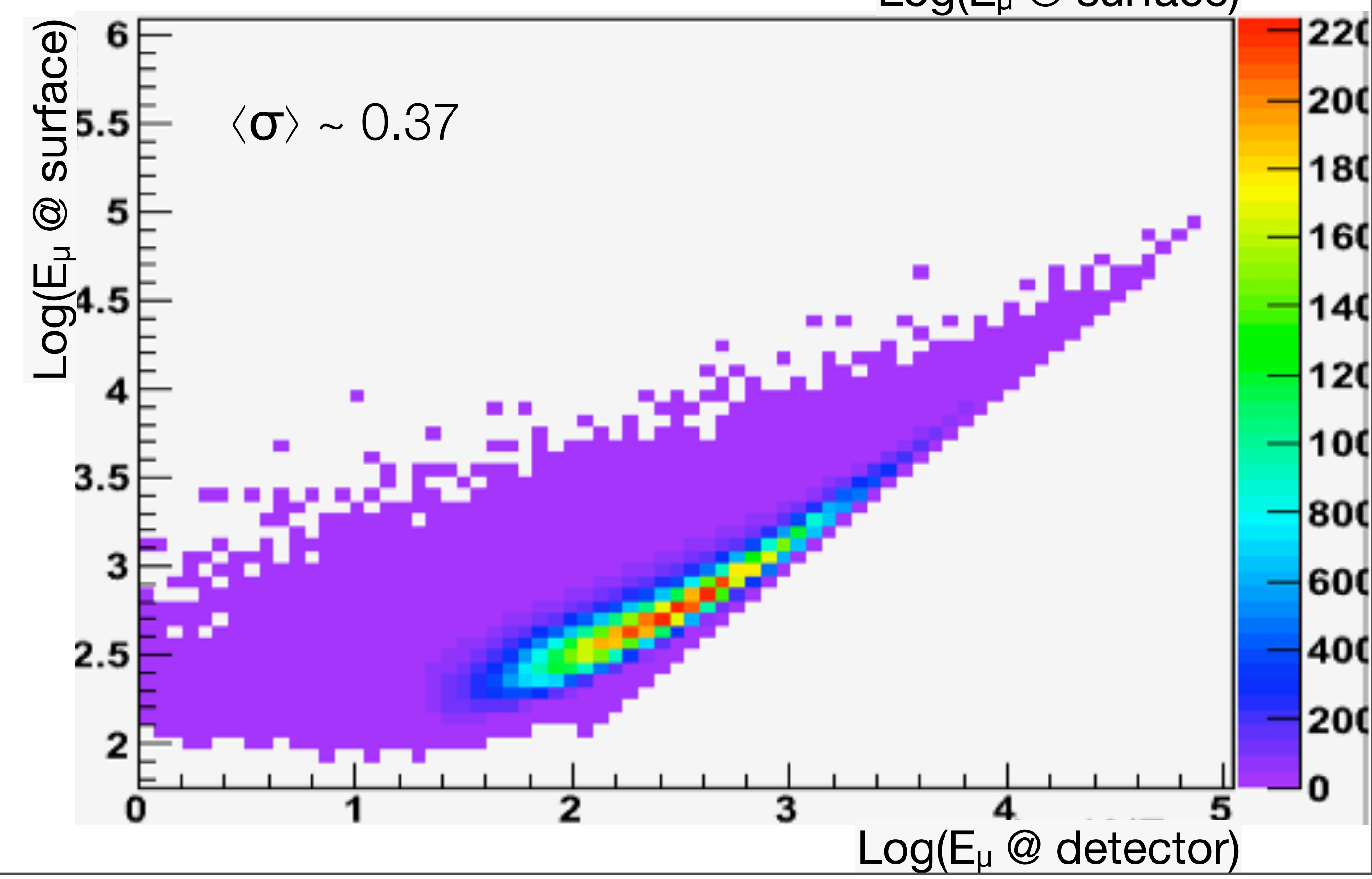
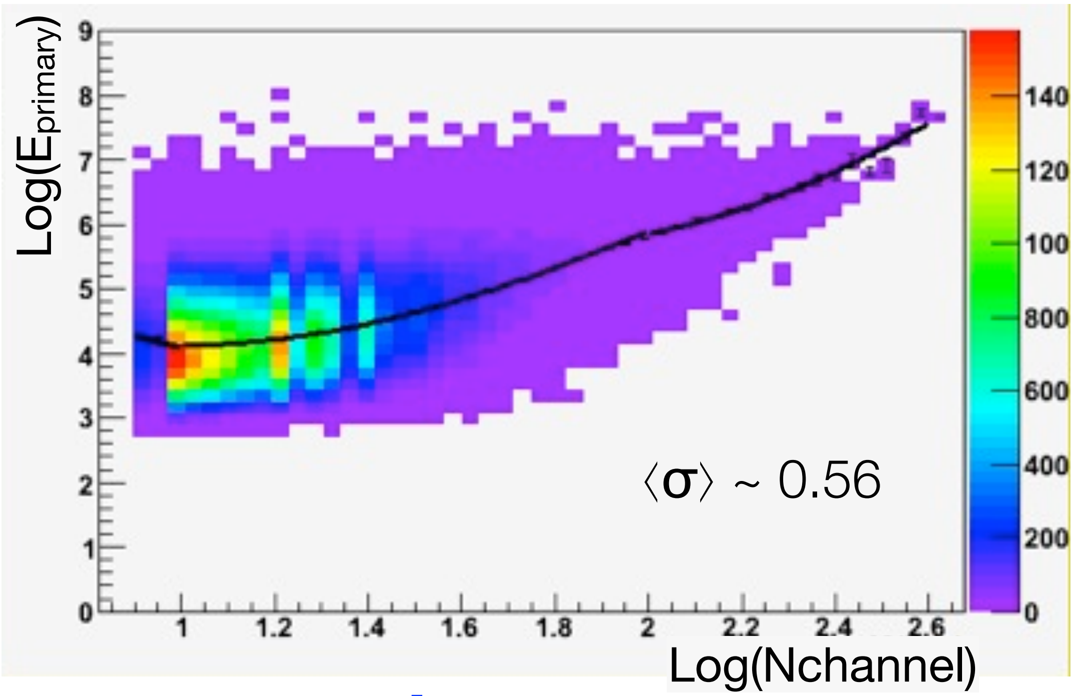


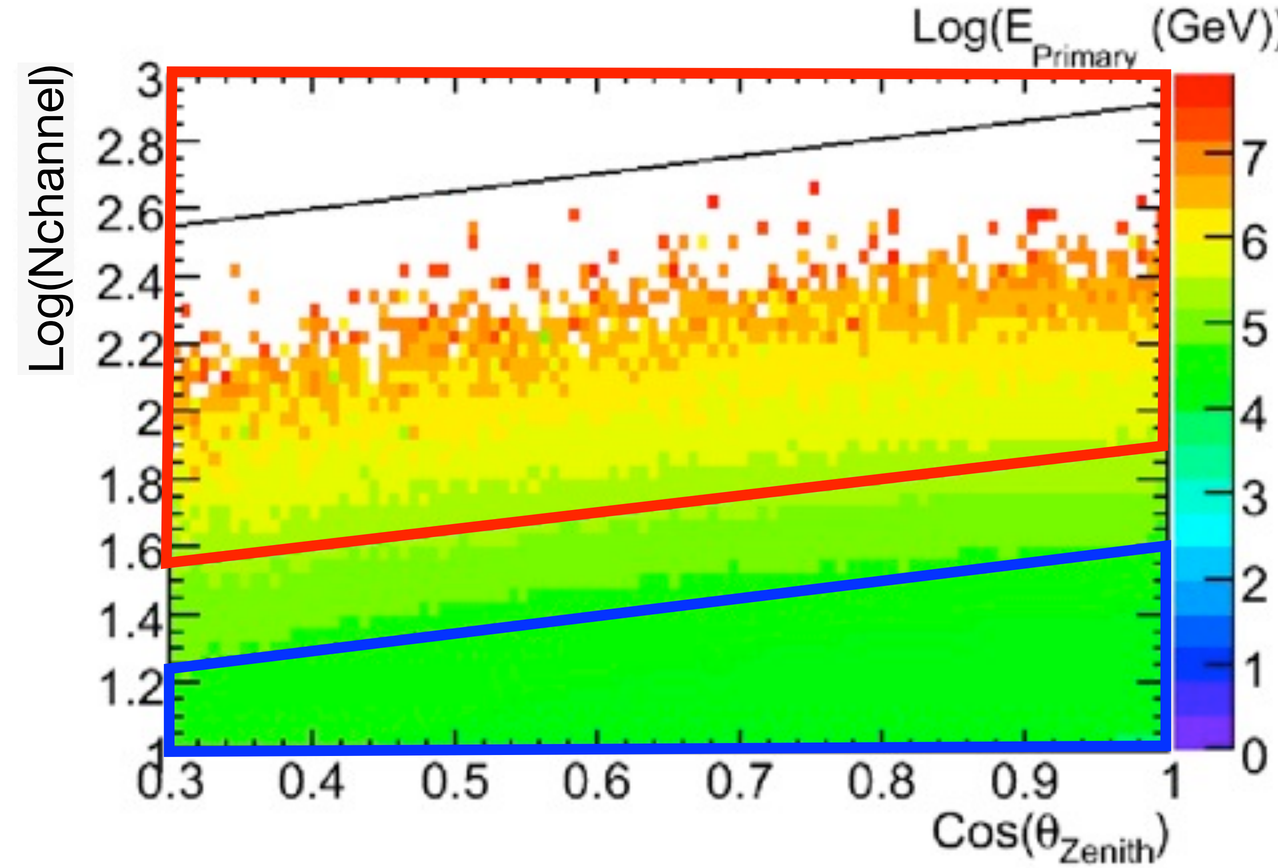
Monte Carlo simulations

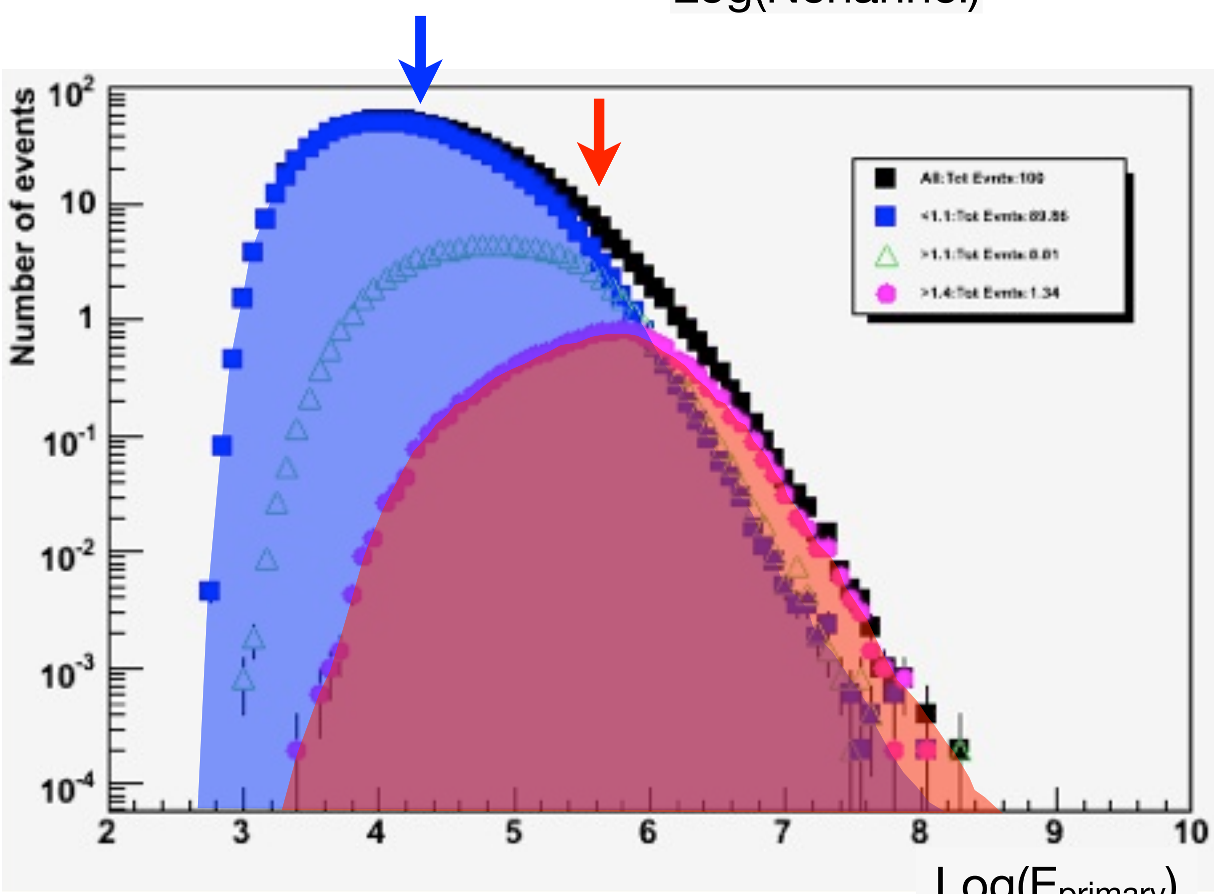


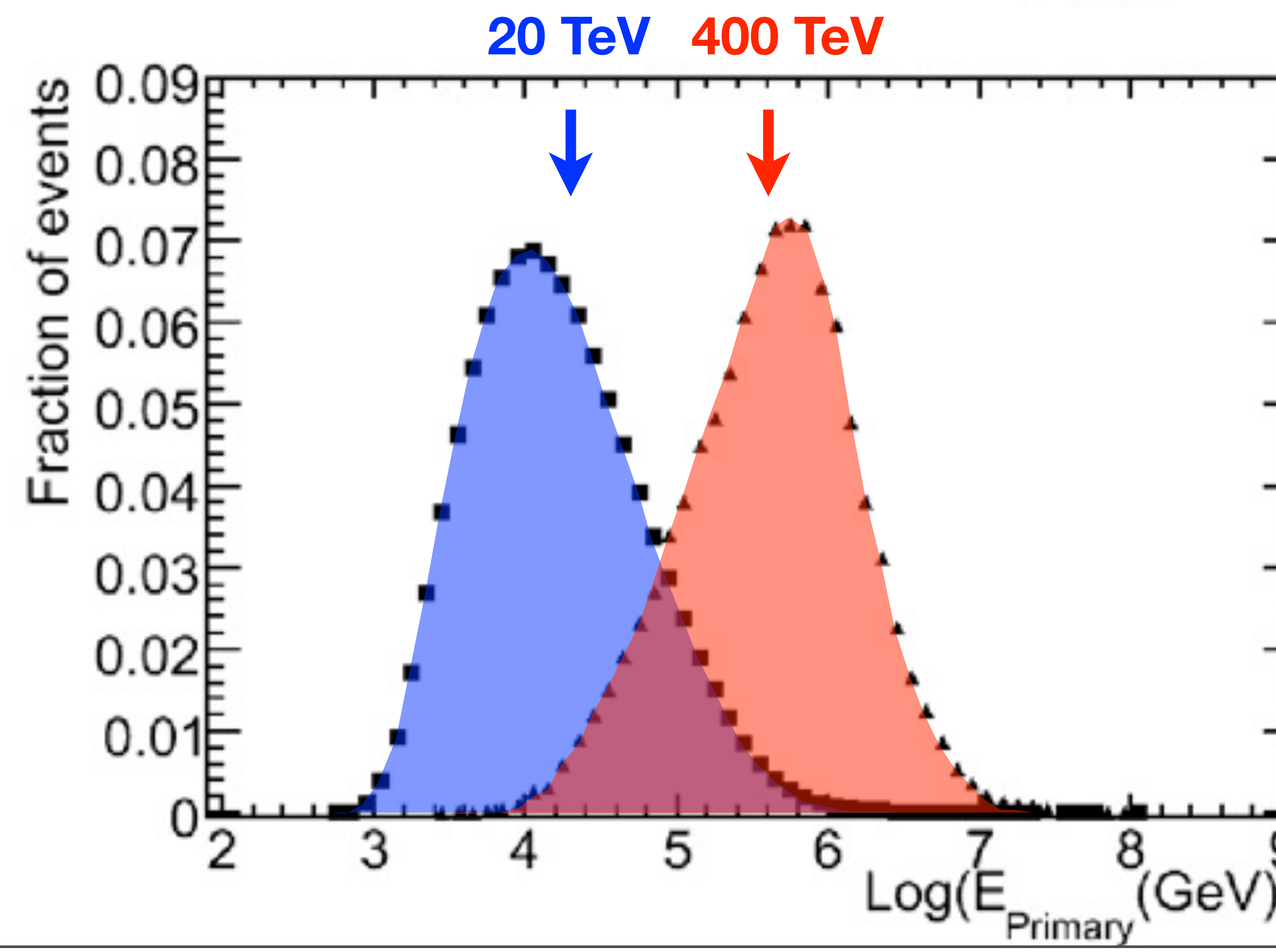


cosmic ray energy estimation with IceCube



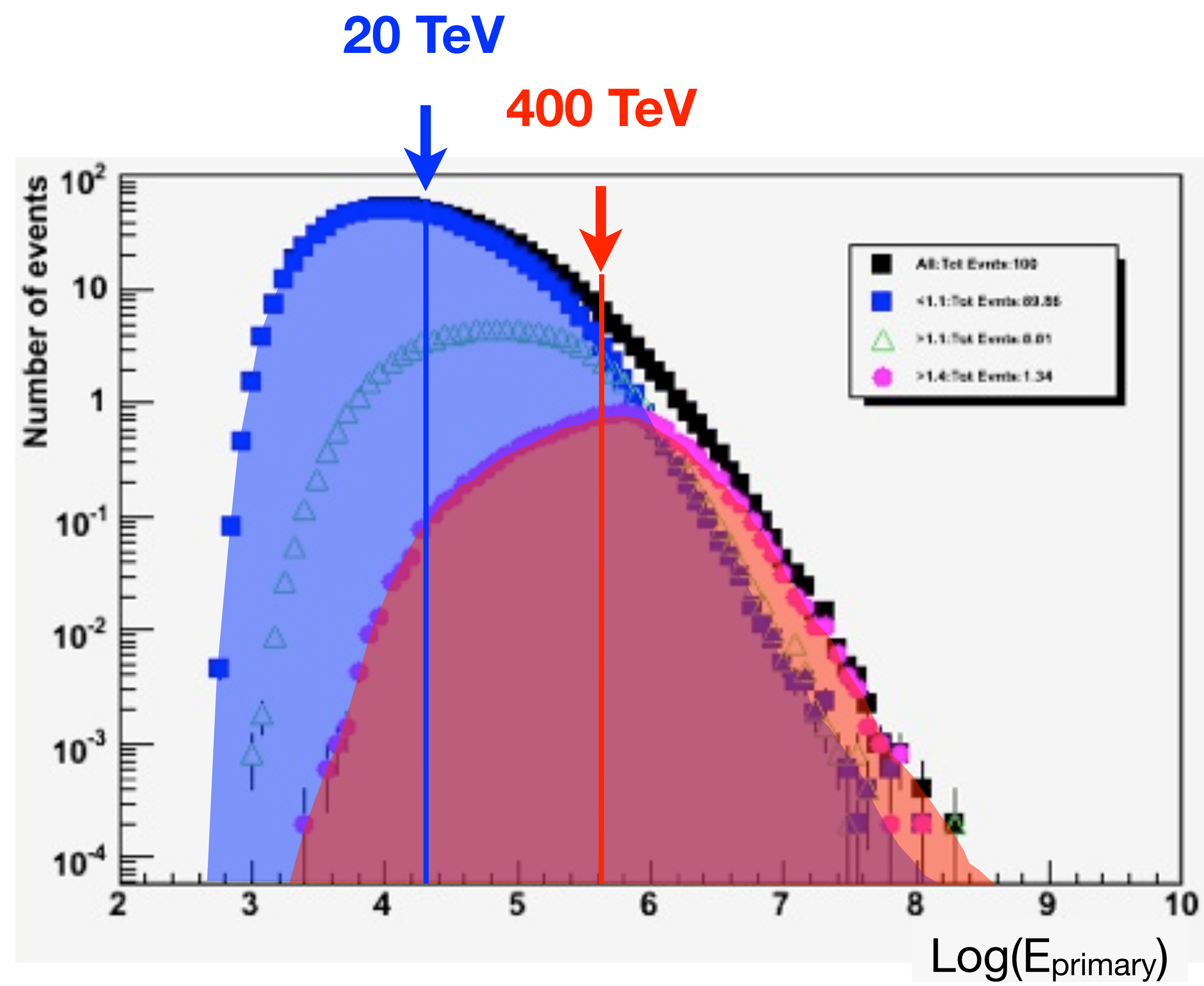






cosmic ray energy estimation with IceCube

$E_{primary}$ (TeV)	$N_{HE}(<E_{primary})$ / $N_{LE}(<E_{primary})$	$N_{HE}(>E_{primary})$ / $N_{LE}(>E_{primary})$
20	0.02%	4%
40	0.1%	6%
100	0.3%	14%
400	0.7%	64%

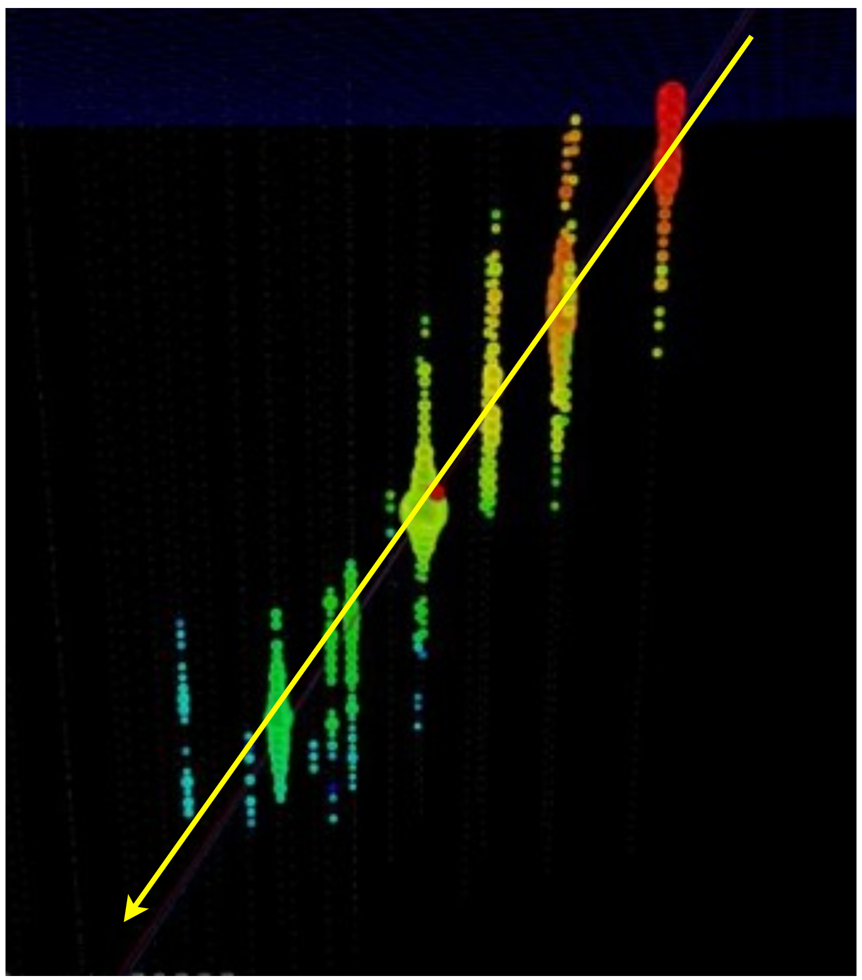


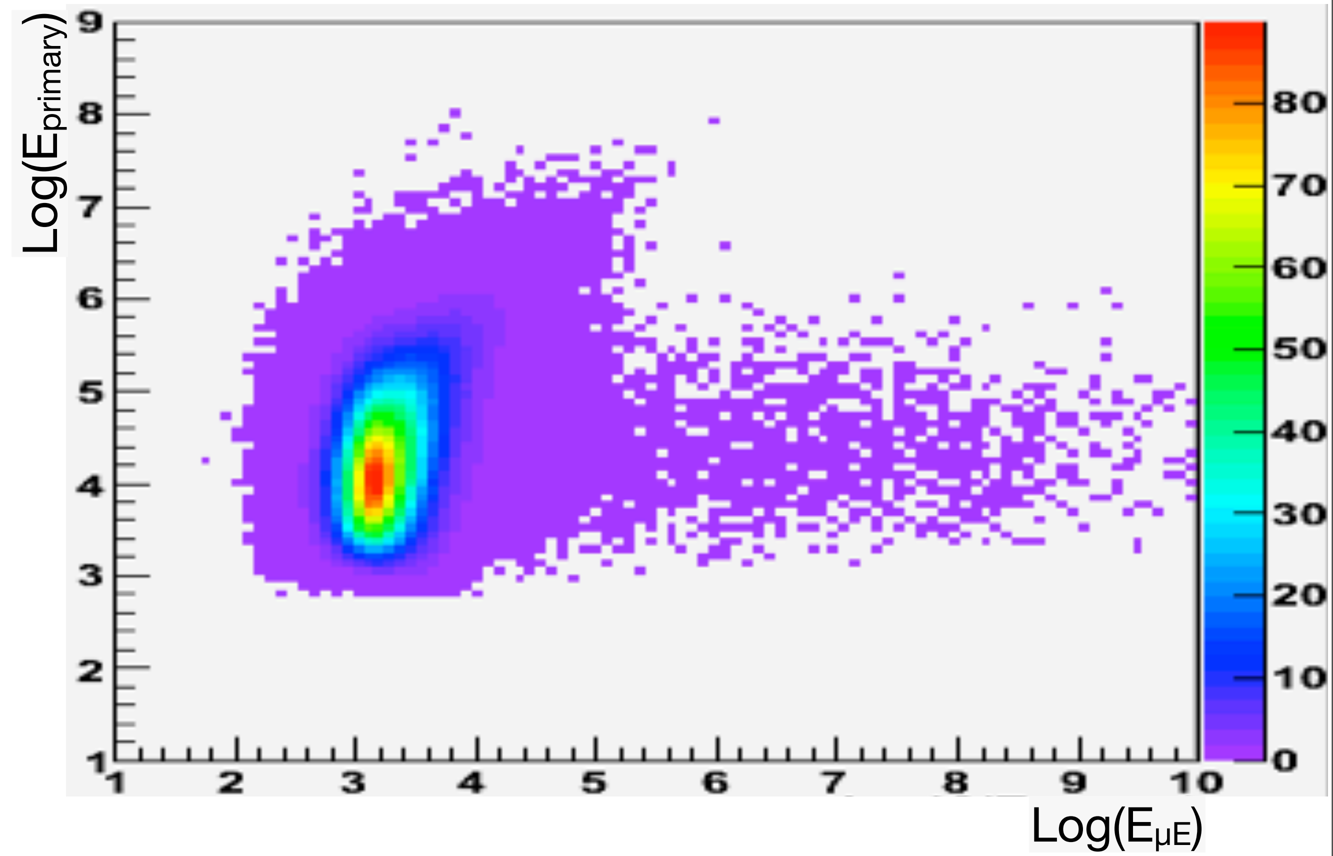
How much of the anisotropy observed @ 400 TeV is influenced by that @ 20 TeV ?

Does the anisotropy observation @ 20 TeV contain features from 400 TeV scale ?

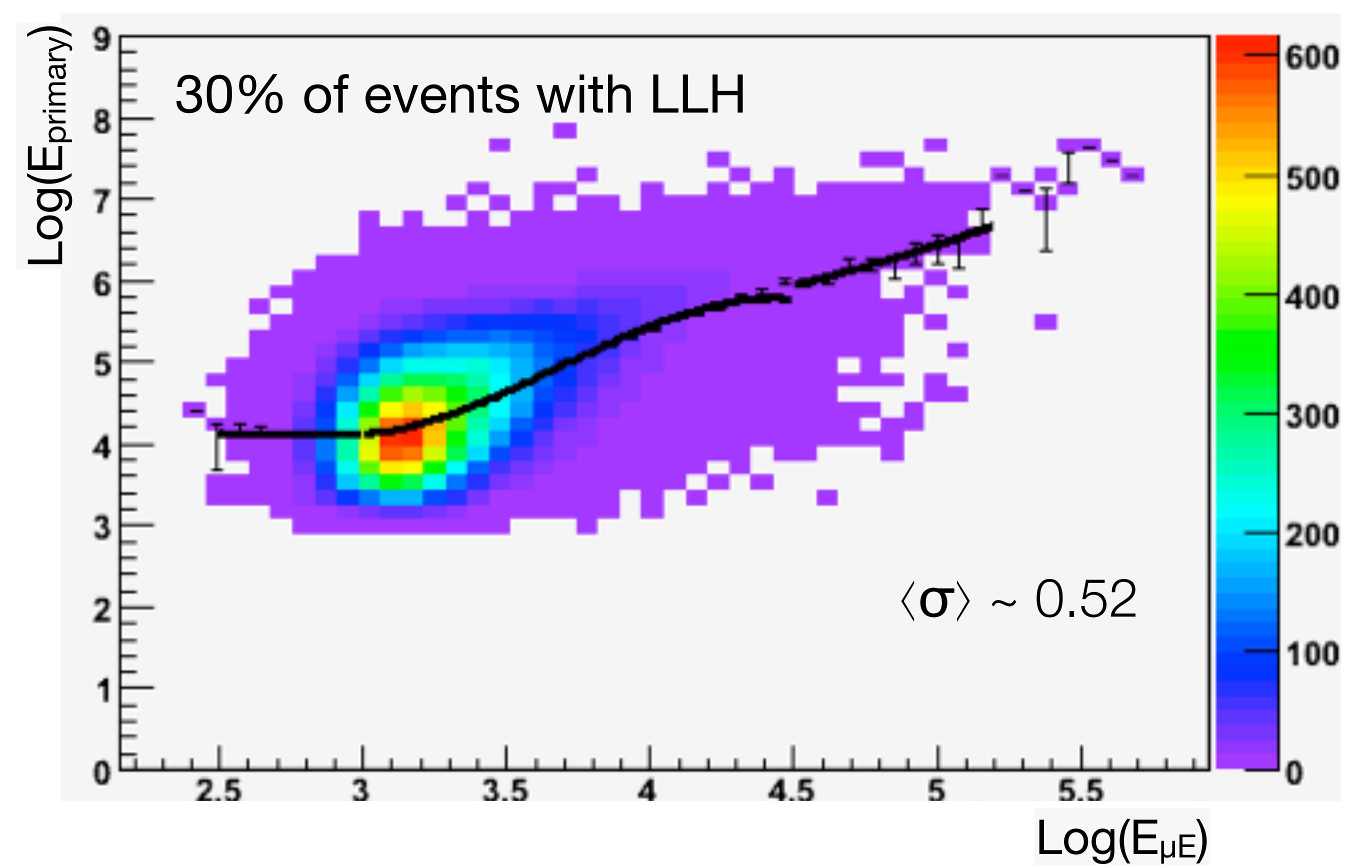
MuE vs Nchannel

$$\mu E = \frac{\langle N_\gamma \rangle}{L_{track}} \cdot A_{eff}^{PMT}$$

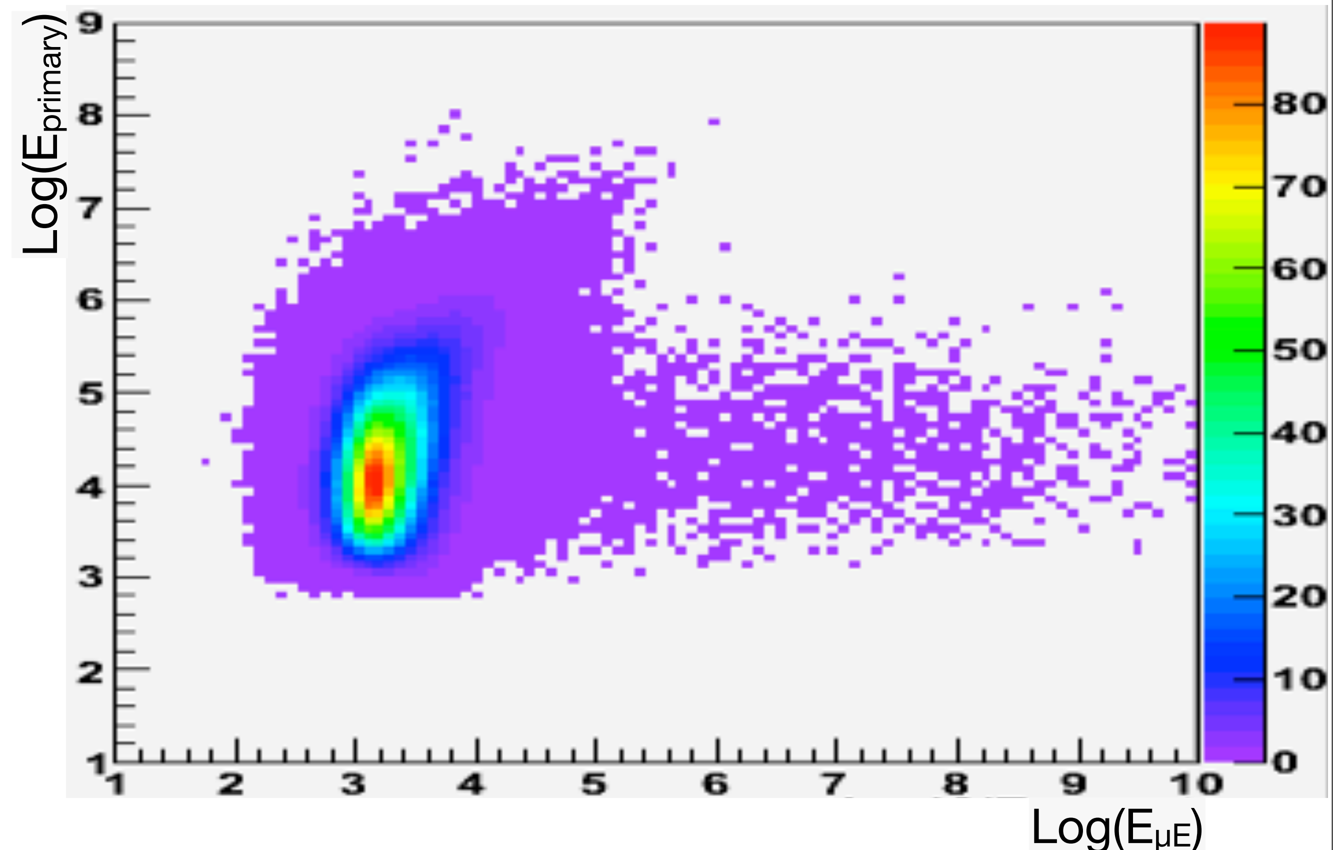




Optimized Cut Values on Angular Resolution					
NString	Opening Angle	LDirC	NChan	Rlogl	Distance to the COG
> 2	< 5 degrees	> 468	> 9	< 10	< 740



MuE vs Nchannel



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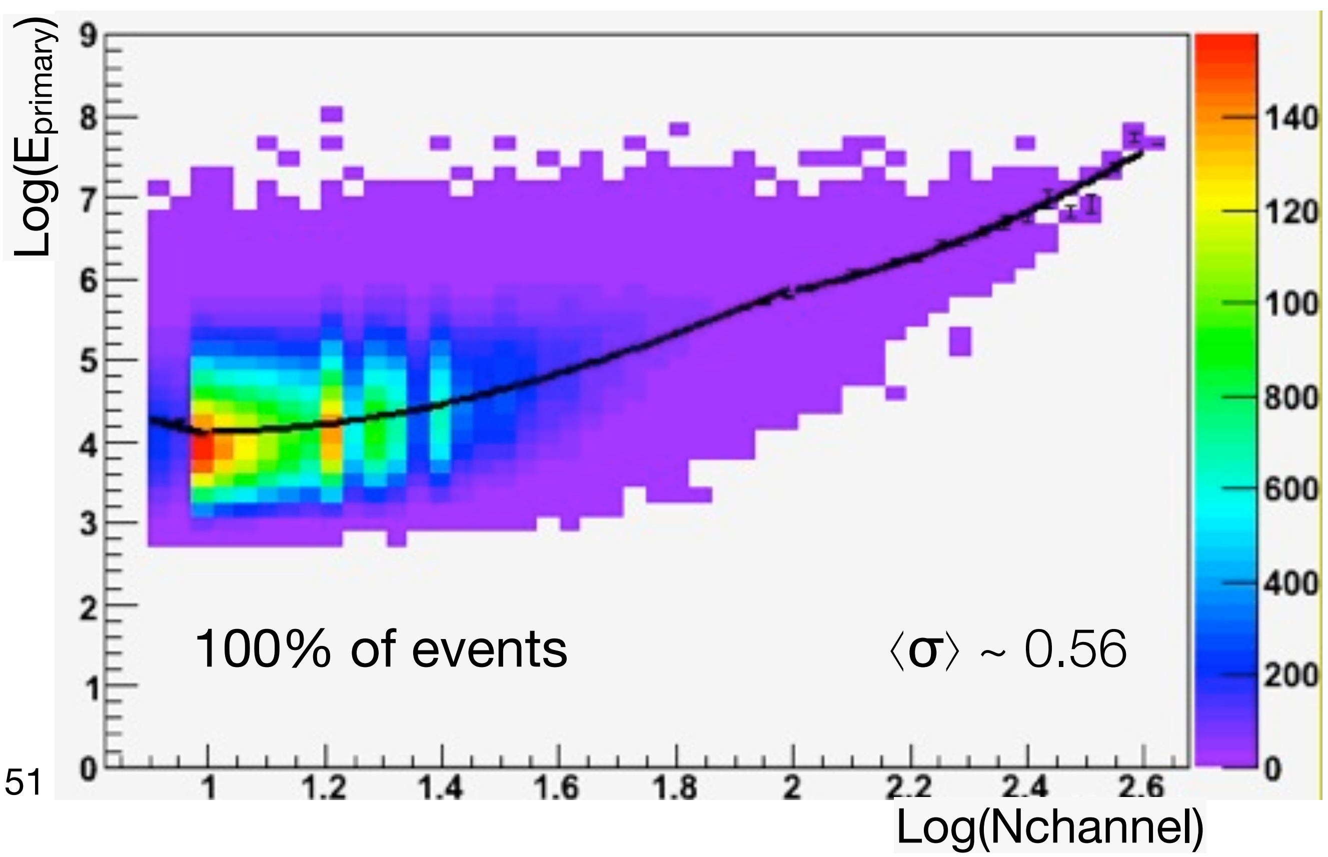
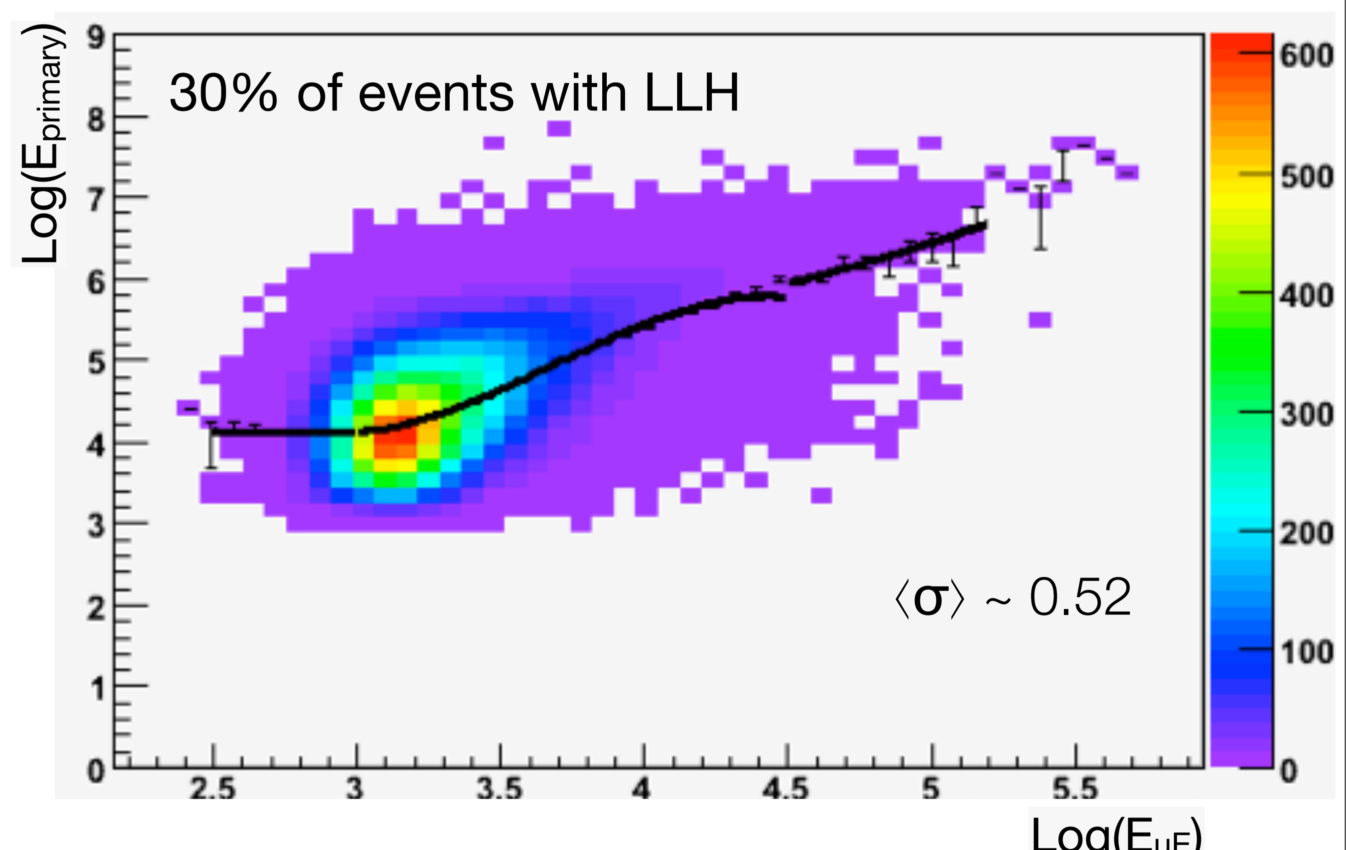




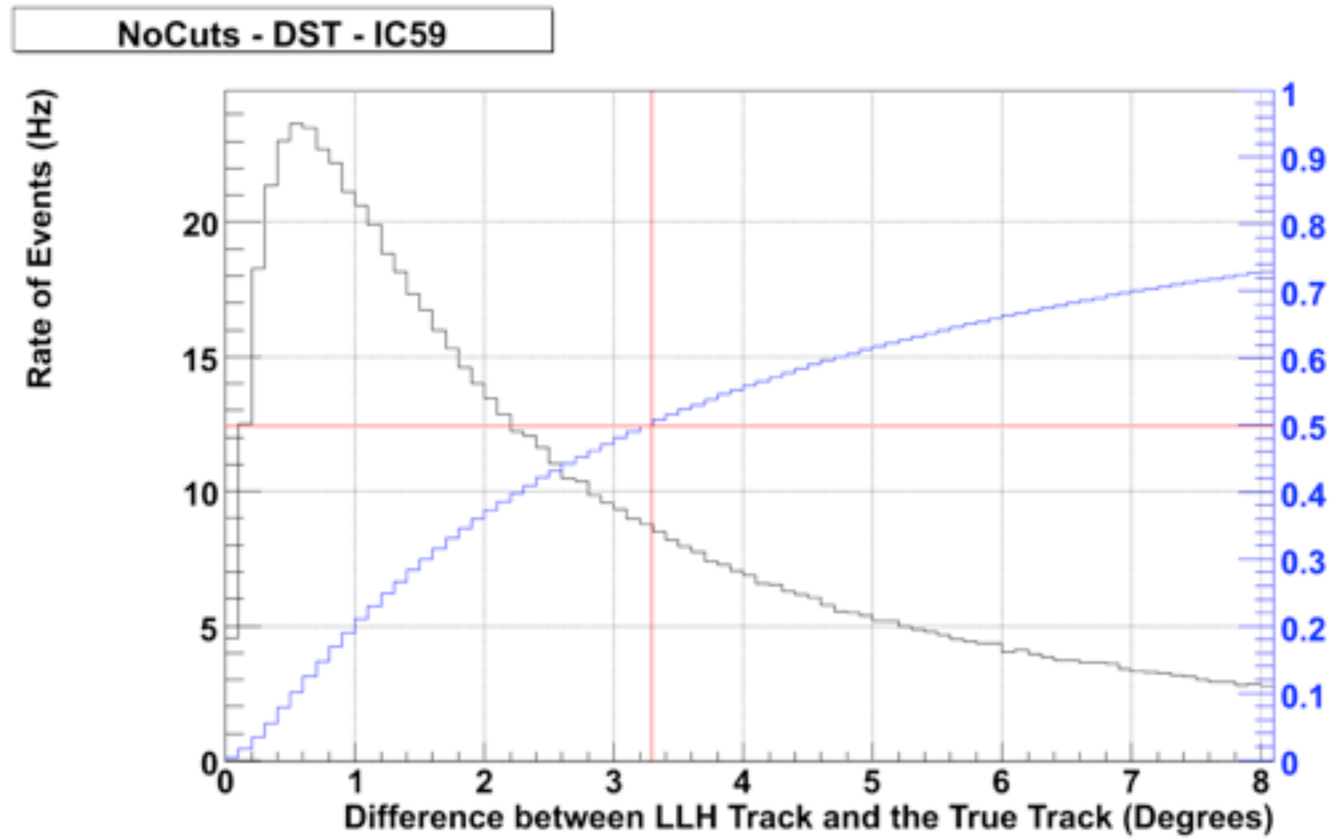
Craig Price

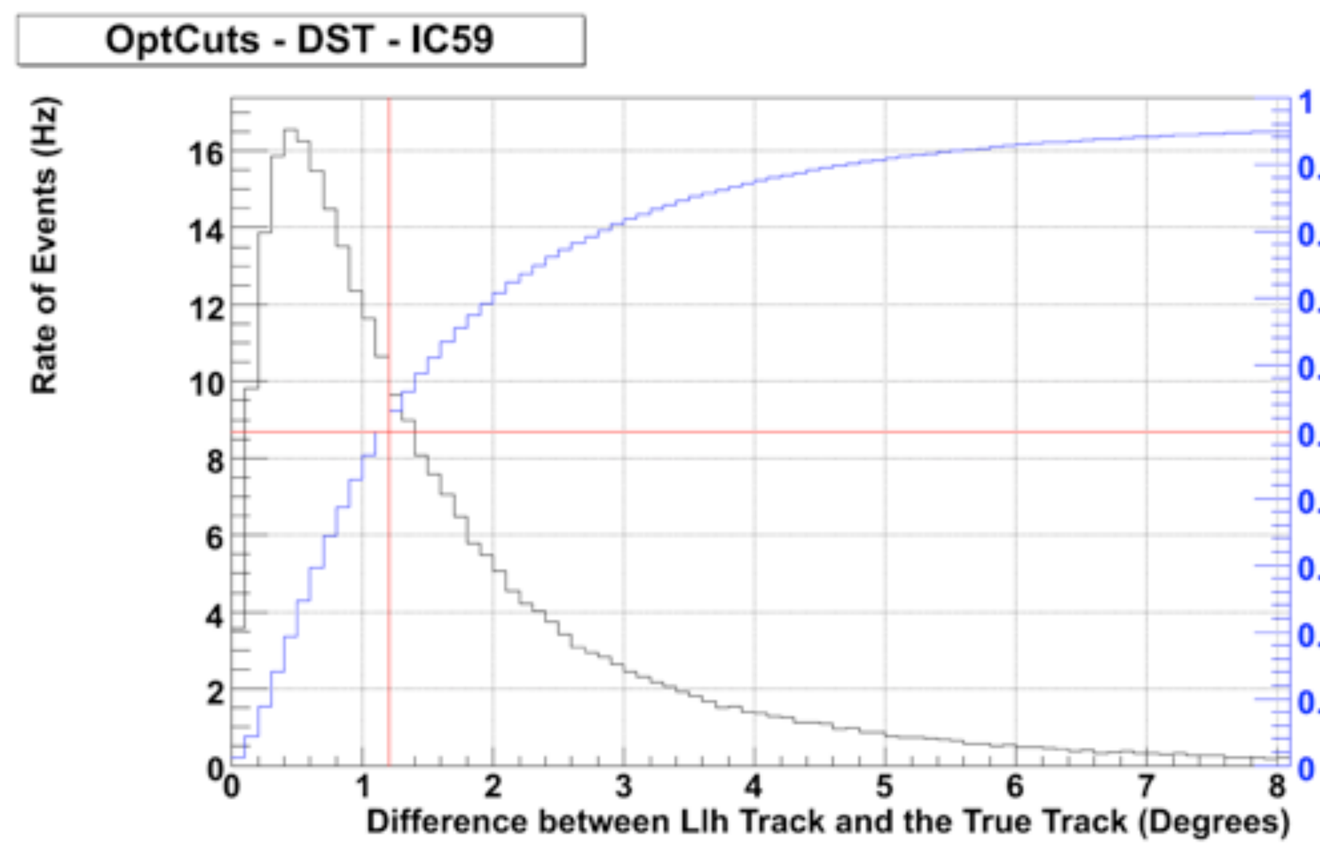
cut optimization

$$\epsilon = \frac{\Phi_{LLH,MC}}{\sqrt{\frac{N_{selected}}{N_{total}}}}$$

Optimized Cut Values on Angular Resolution					
NString	Opening Angle	LDirC	NChan	Rlogl	Distance to the COG
> 2	< 5 degrees	> 468	> 9	< 10	< 740

selection efficiency ~ 30%



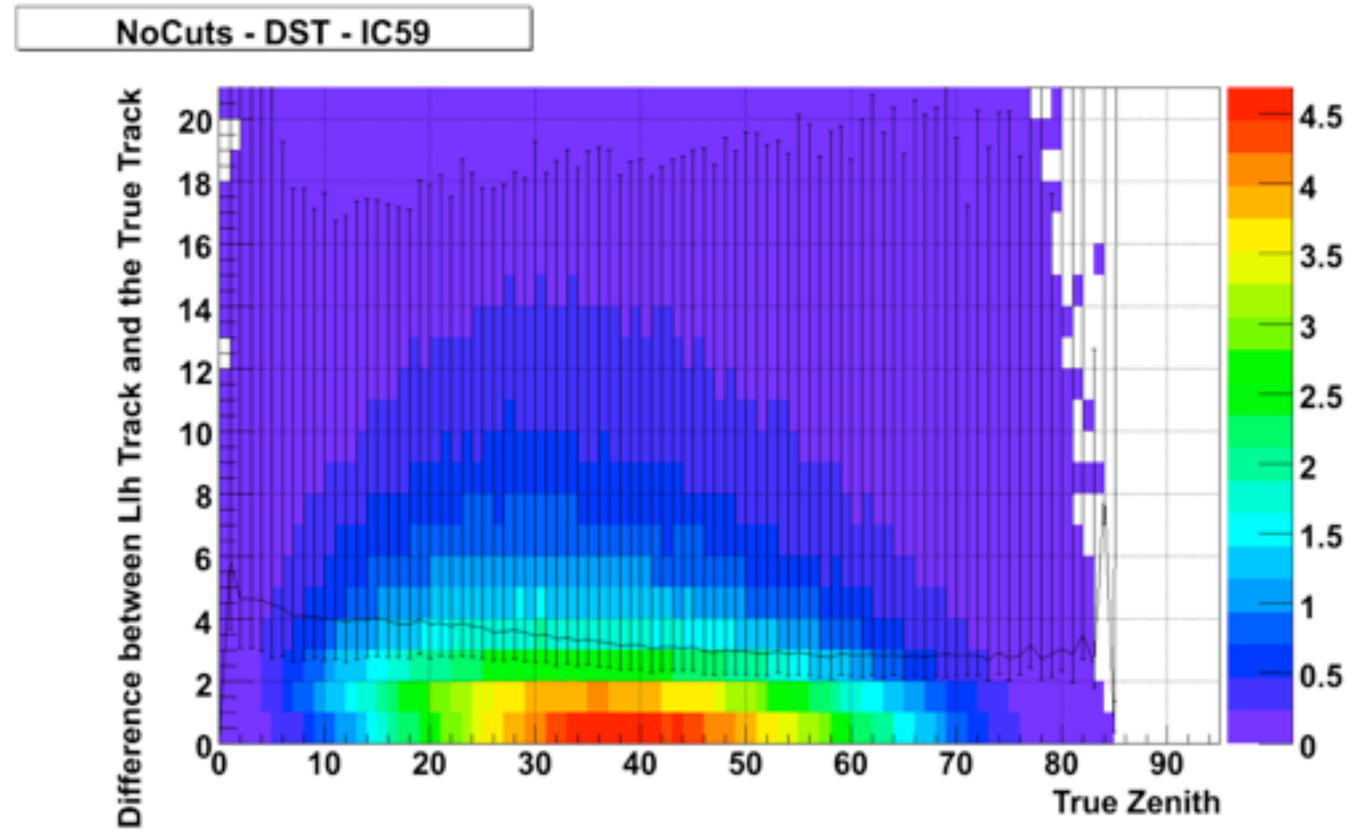


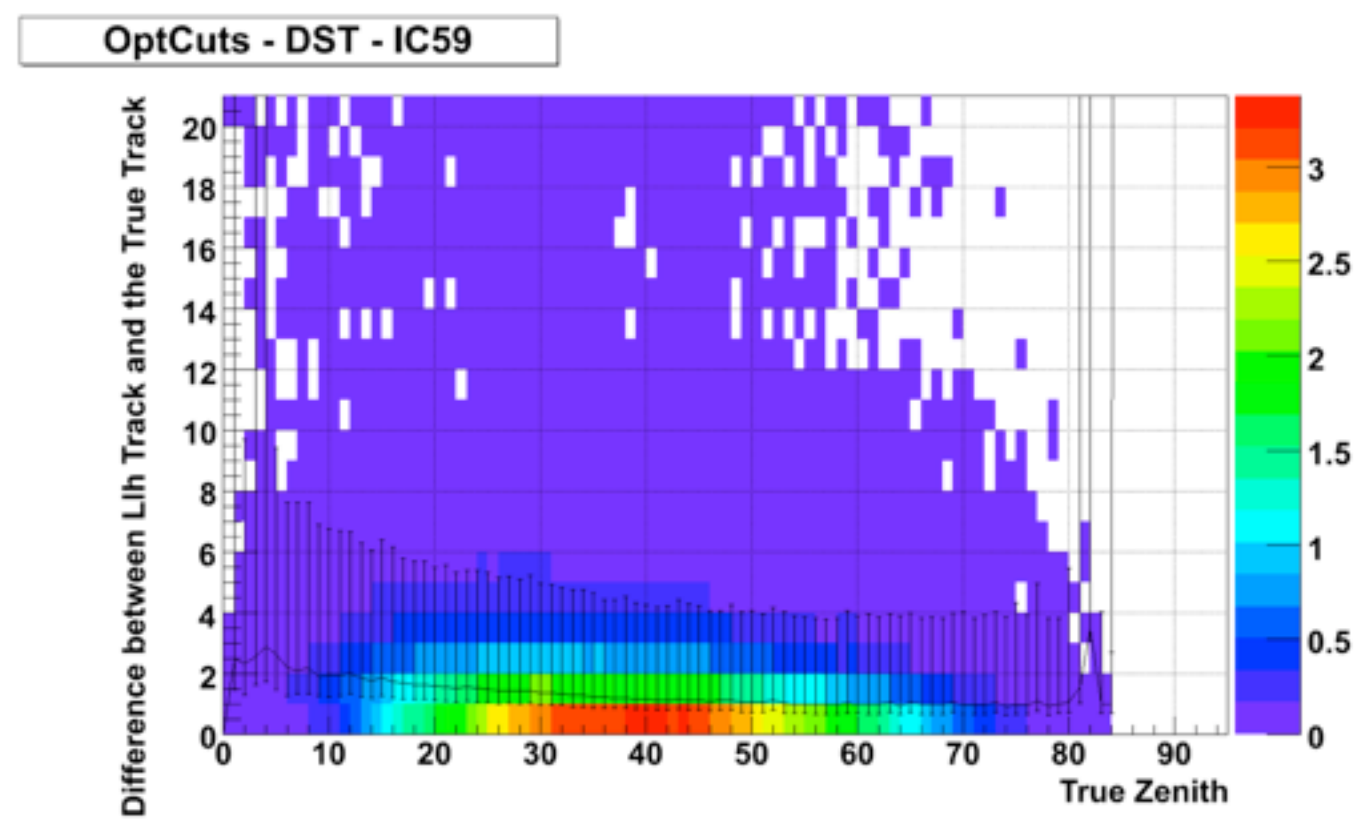
Craig Price

cut optimization

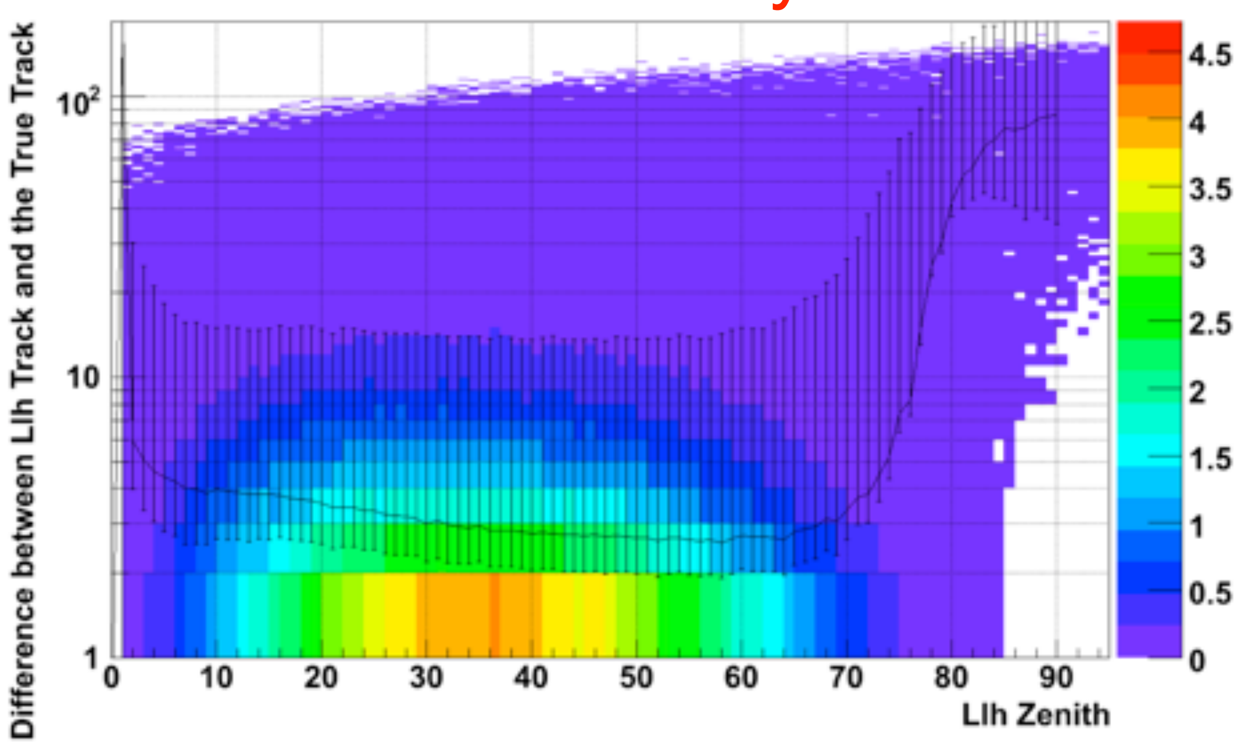
$$\epsilon = \frac{\Phi_{LLH,MC}}{\sqrt{\frac{N_{selected}}{N_{total}}}}$$

Optimized Cut Values on Angular Resolution					
NString	Opening Angle	LDirC	NChan	Rlogl	Distance to the COG
> 2	< 5 degrees	> 468	> 9	< 10	< 740

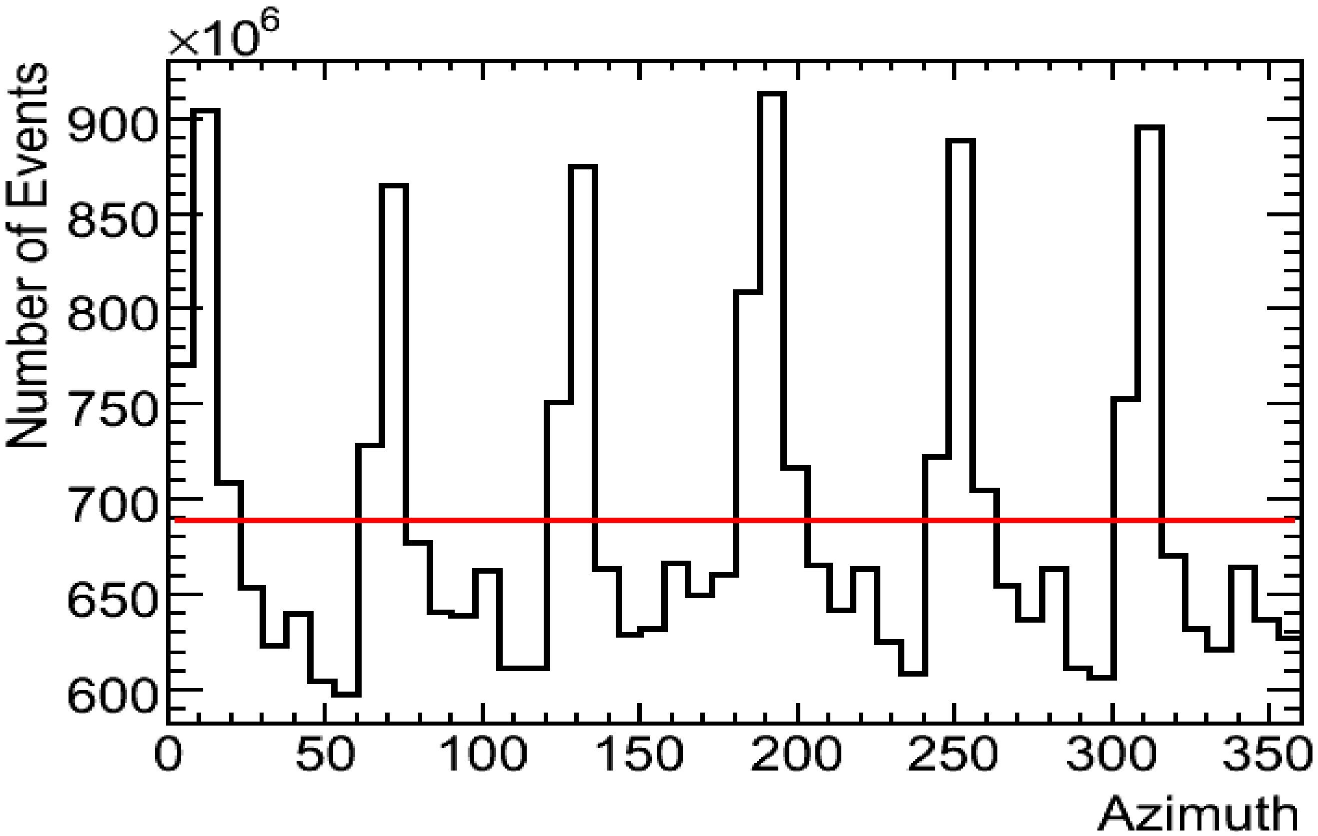




selection efficiency ~ 30%



detector acceptance correction



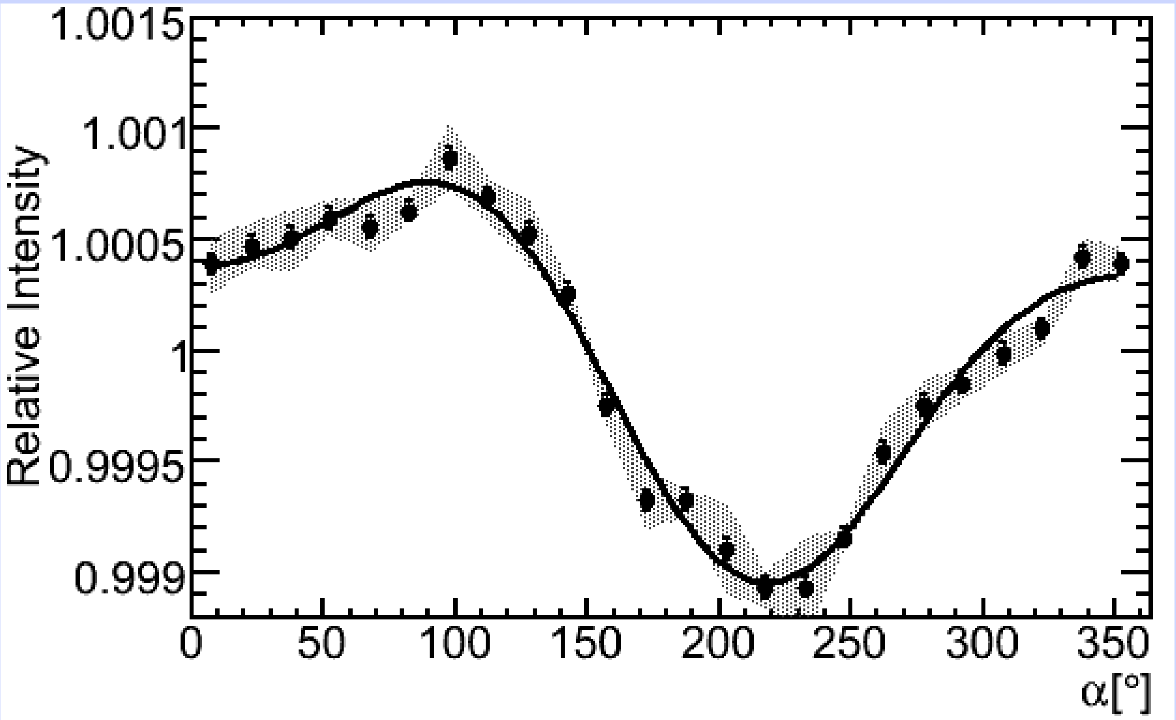
$$w_i(\delta) = \frac{\bar{n}(\delta)}{n_i(\delta)} = \frac{mean\ \#\ events\ in\ \delta}{number\ of\ events\ in\ bin}$$

local azimuth angle distribution stable over time ($<10^{-5}$)

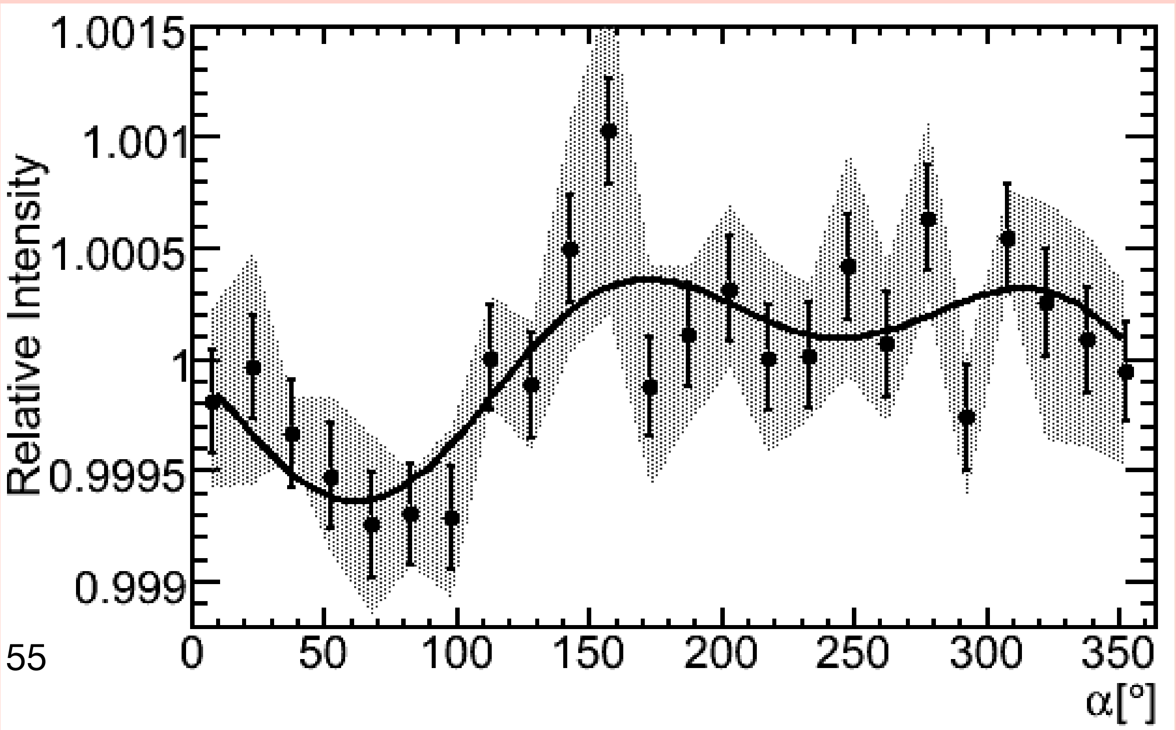
acceptance correction better than 10^{-5}

systematic uncertainties IceCube-59

statistical stability tests + anti-sidereal effect



20 TeV

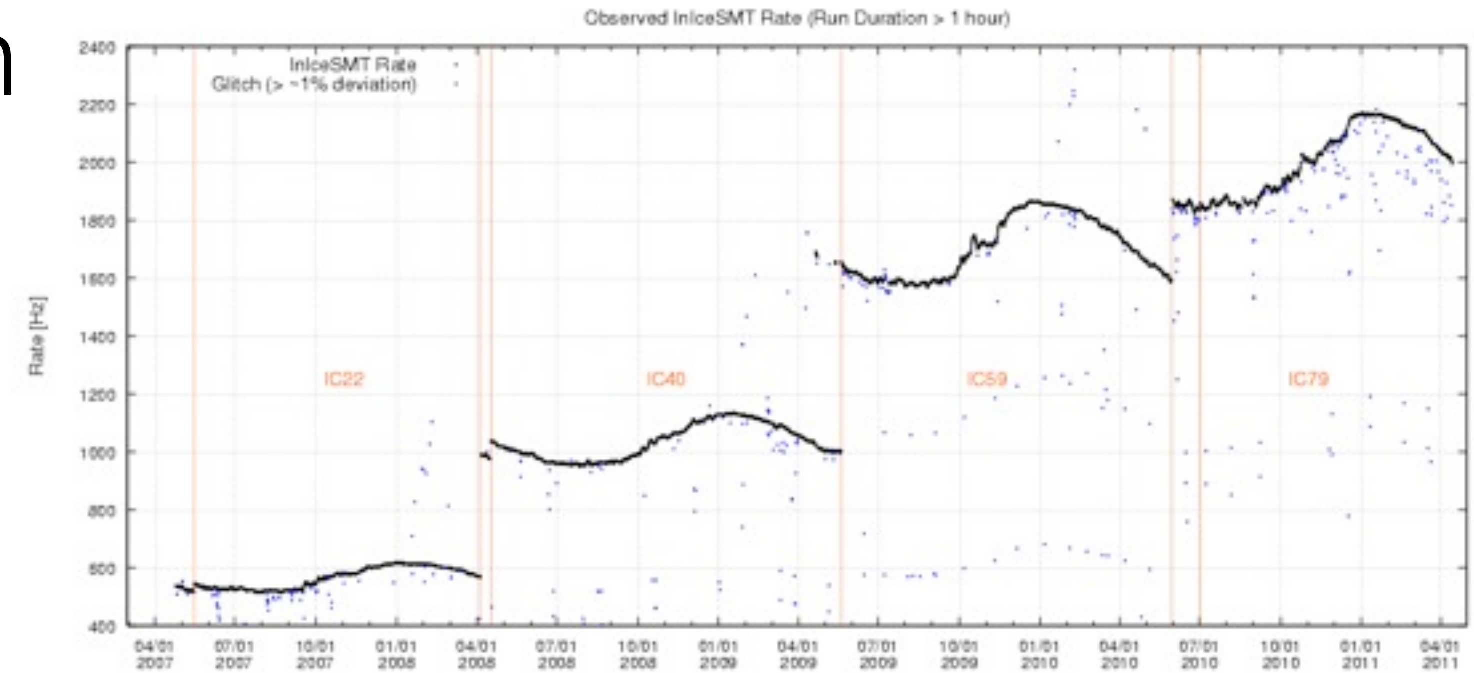


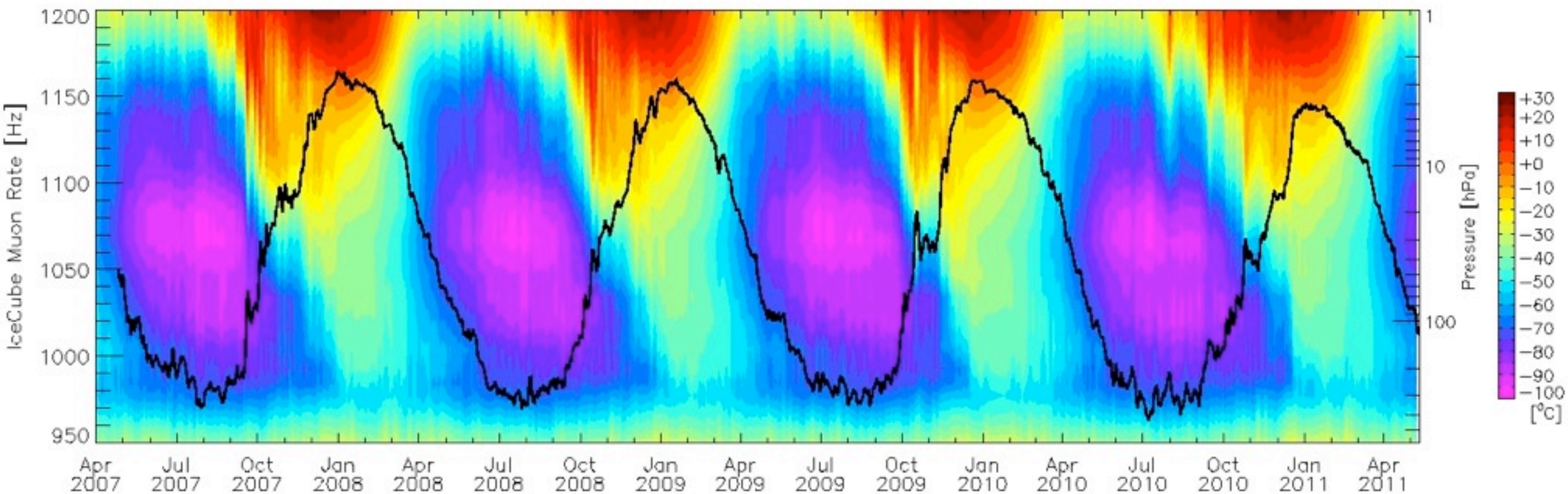
400 TeV

statistical stability tests:

- summer/winter season datasets
- rate ≳ median daily rate
- even/odd sub-runs (2 mins data)
- random sub-run selection
- use ~24 hr full days (214/324 d)

growing IceCube & temperature correlation





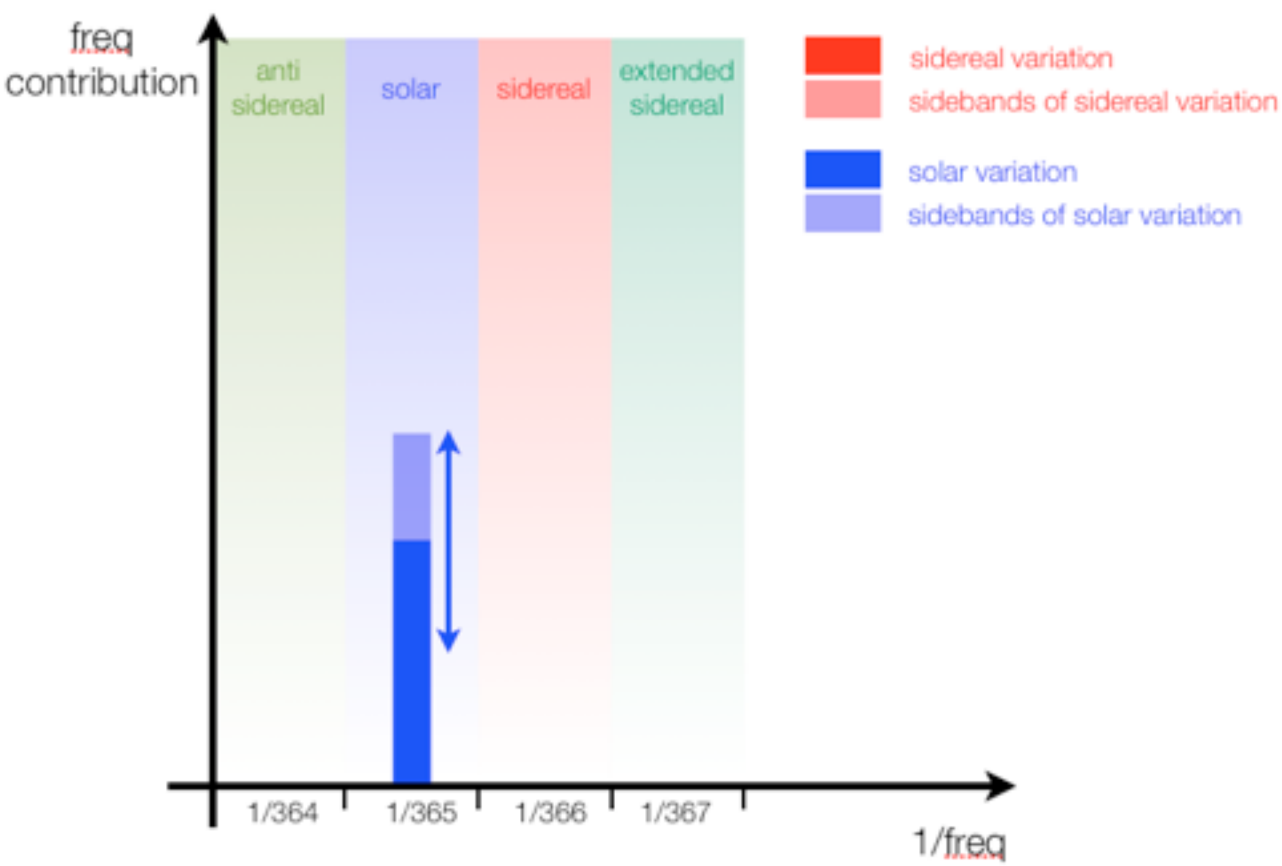
Farley, & Storey, Proc. Phys. Soc., 67, 996, 1954

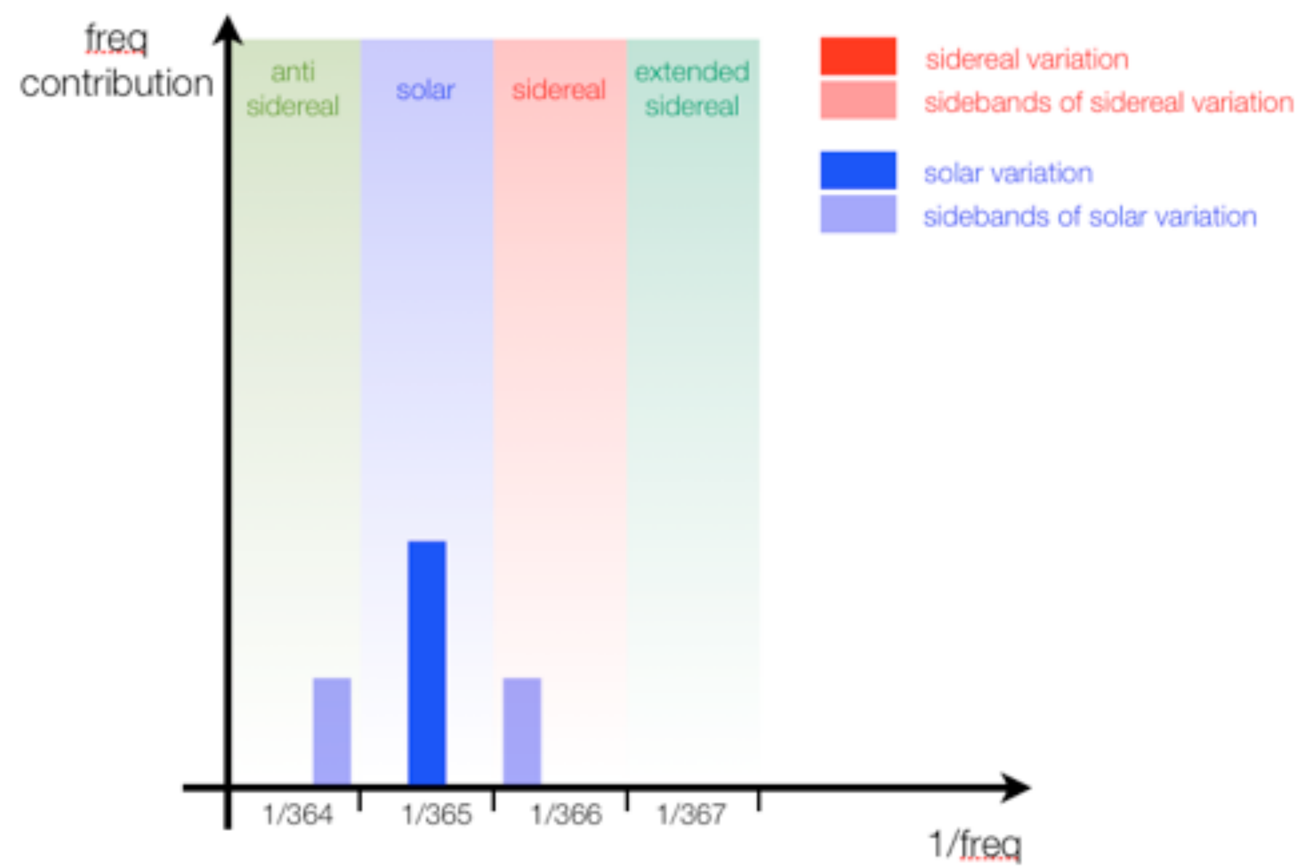
Nagashima, et al., Nuovo 907 Cimento C, 6, 550, 1983

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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anti- / extended-sidereal reference frames

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

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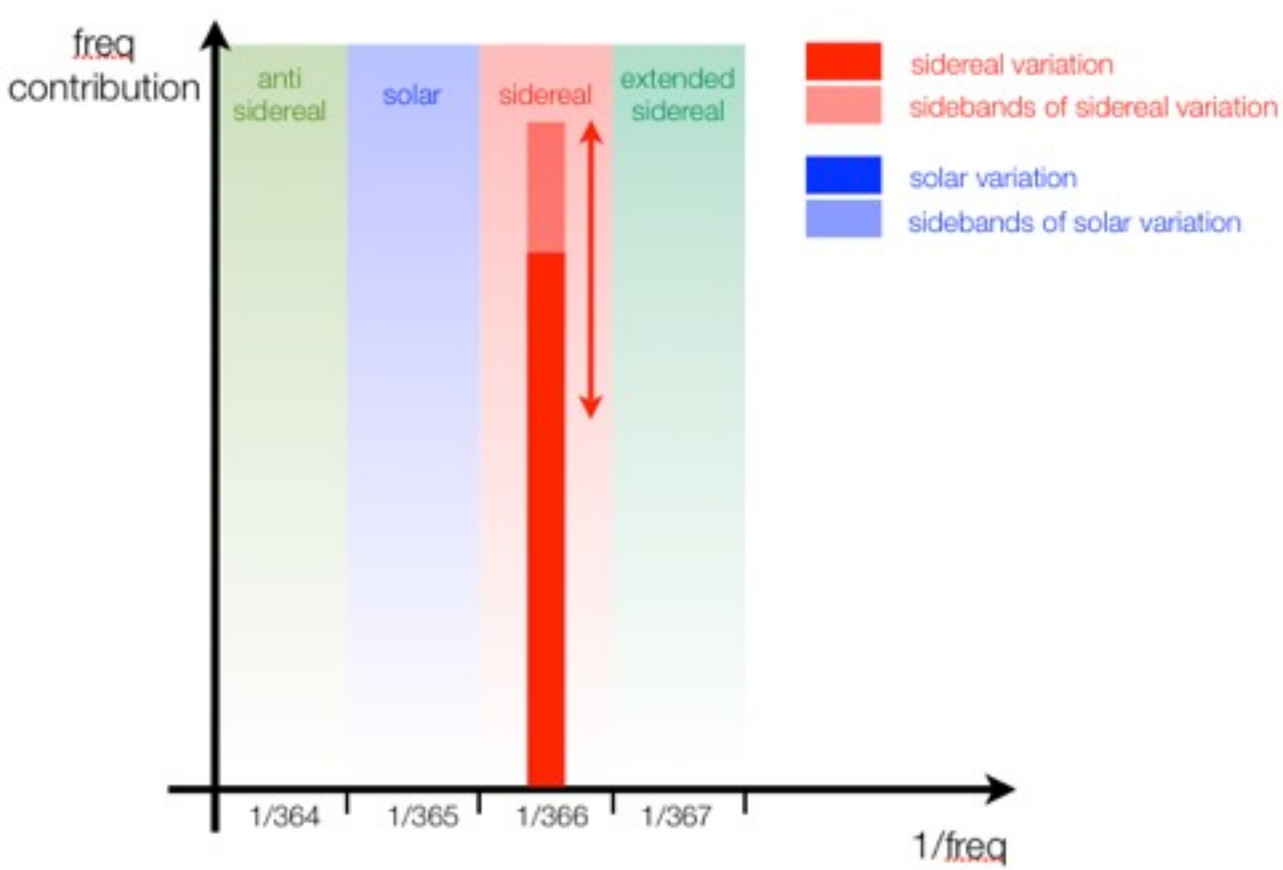
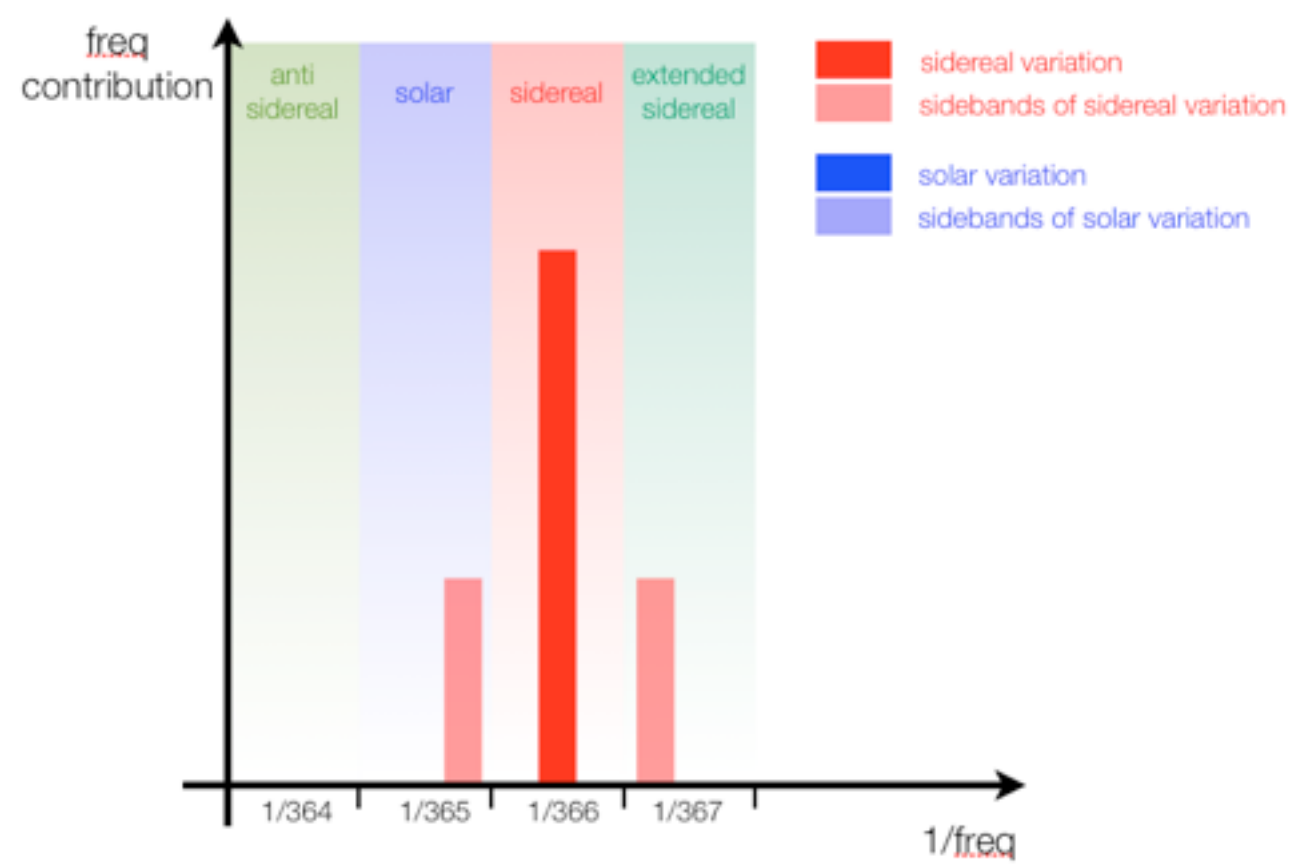
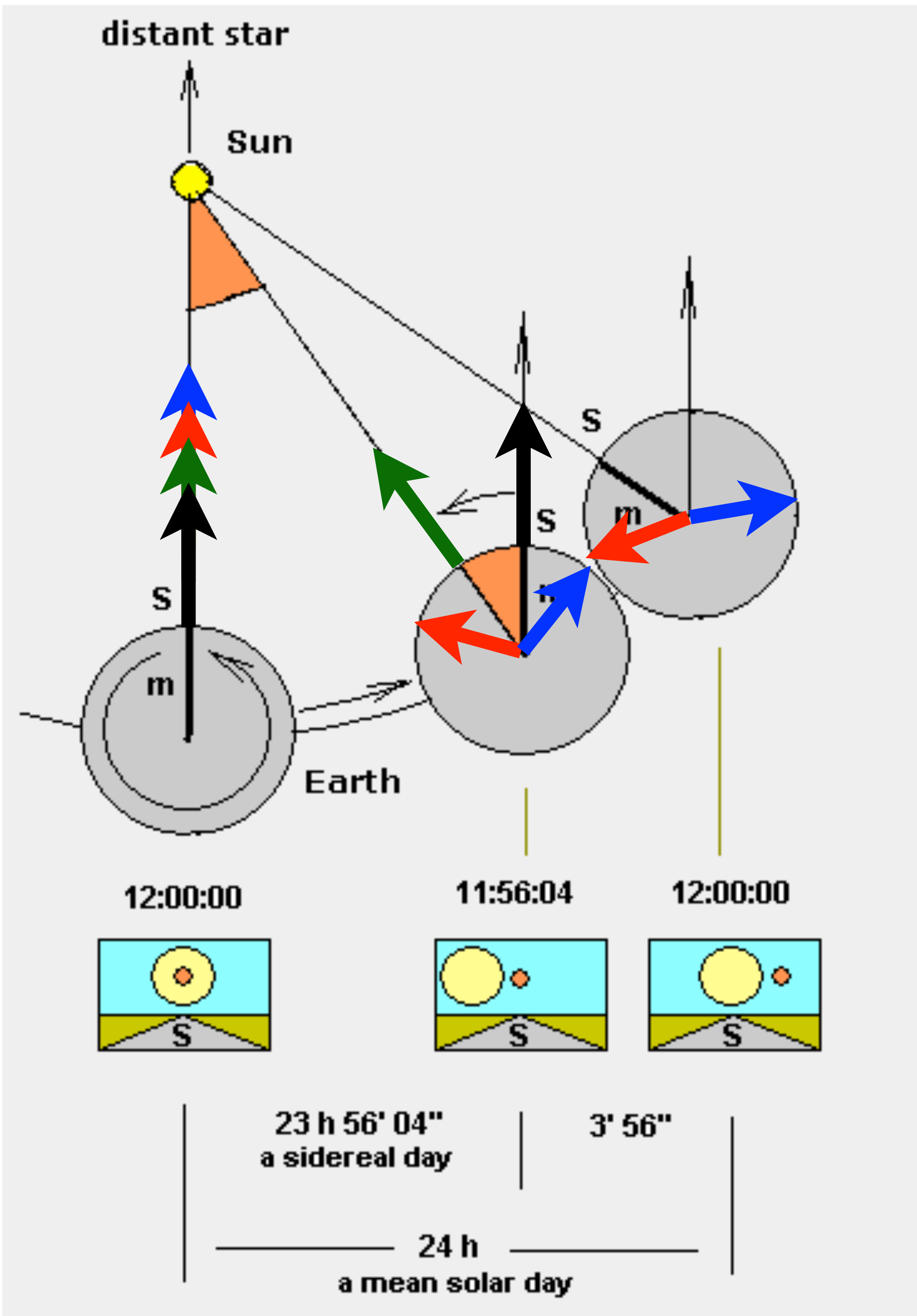




anti- / extended-sidereal reference frames



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

the interstellar magnetic field

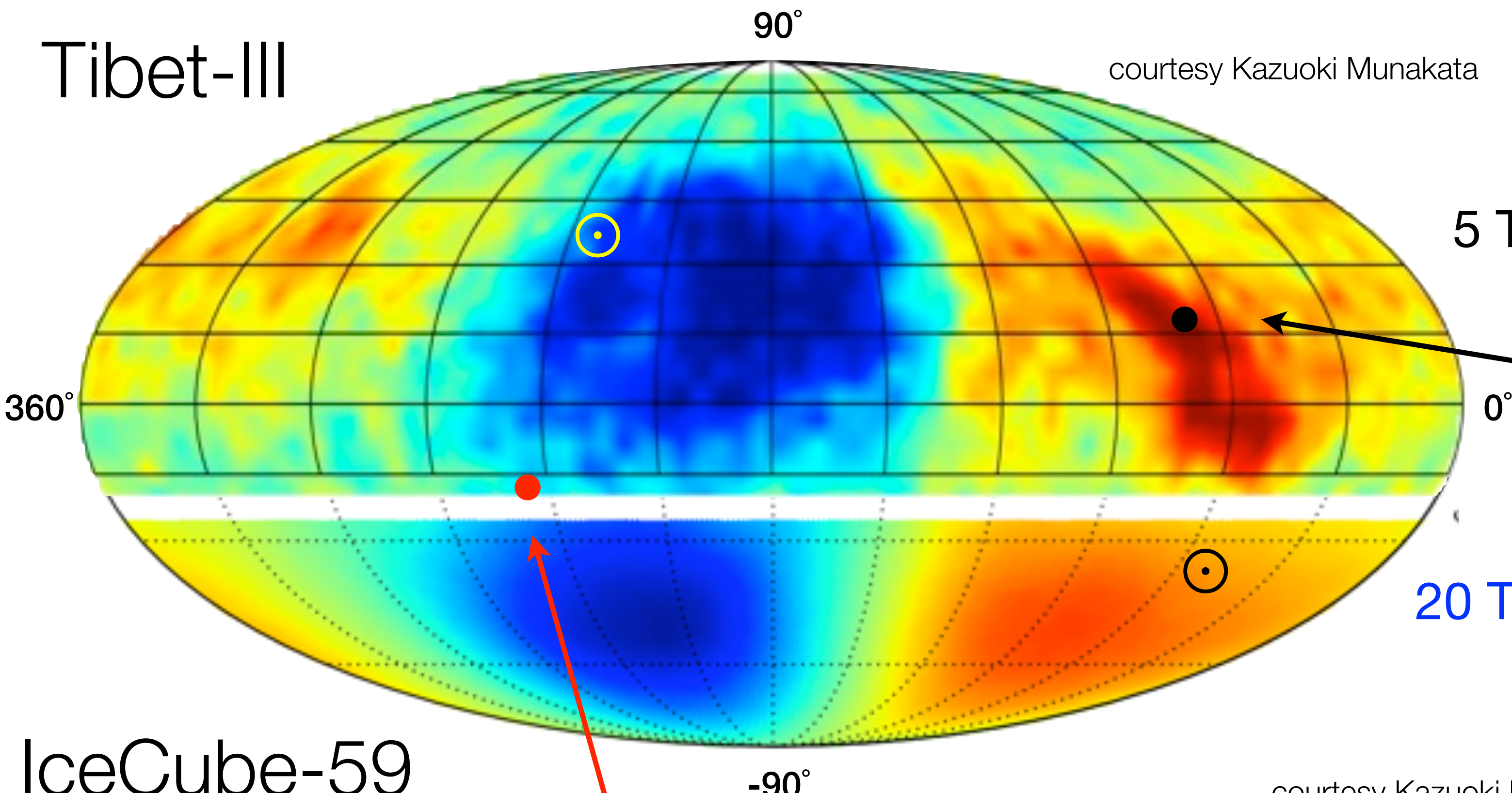
scale : < 40 pc

visual comparison only

statistical significance

equatorial coordinates

Tibet-III



5 TeV

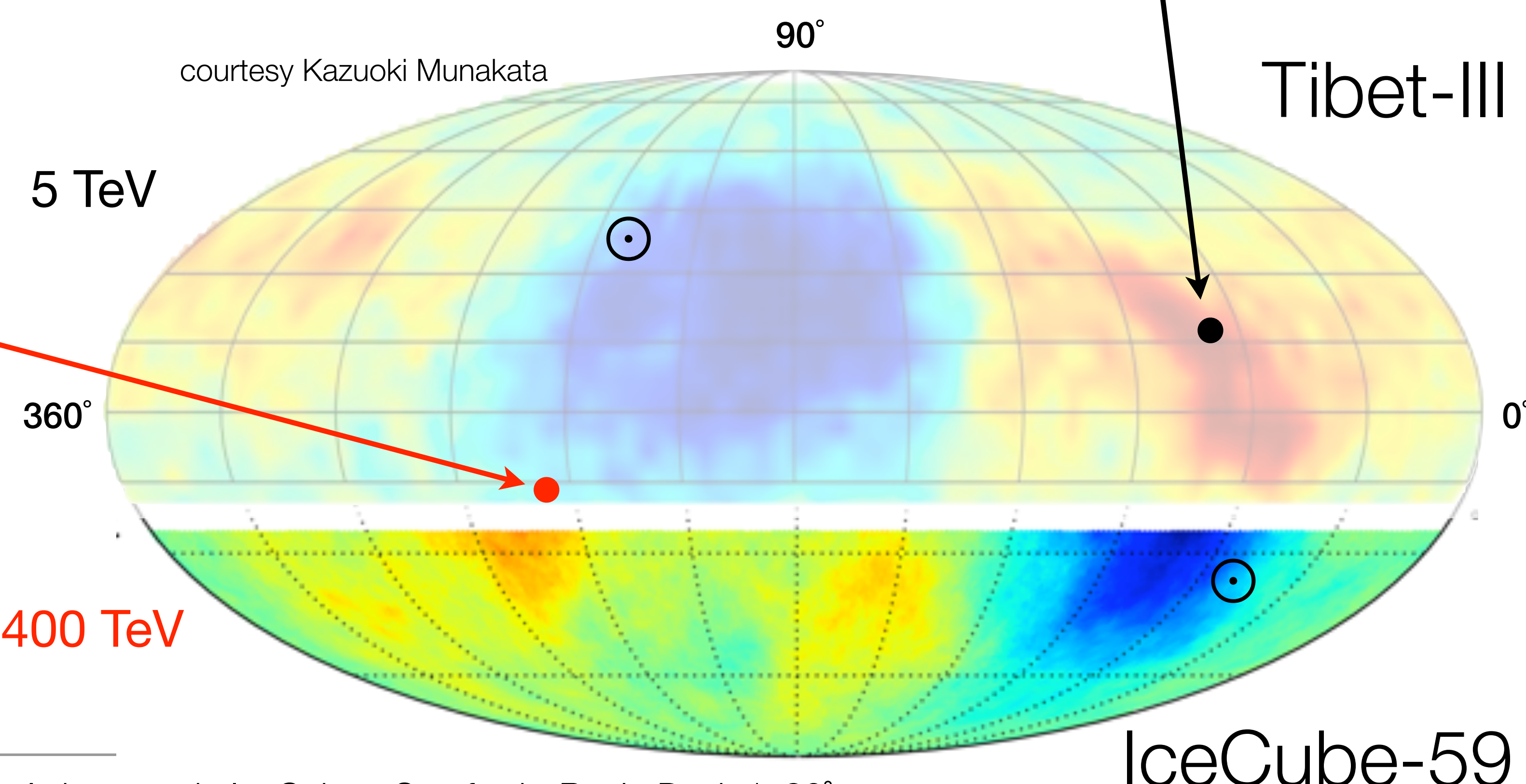
20 TeV

IceCube-59

heliospheric tail

heliospheric nose

Tibet-III



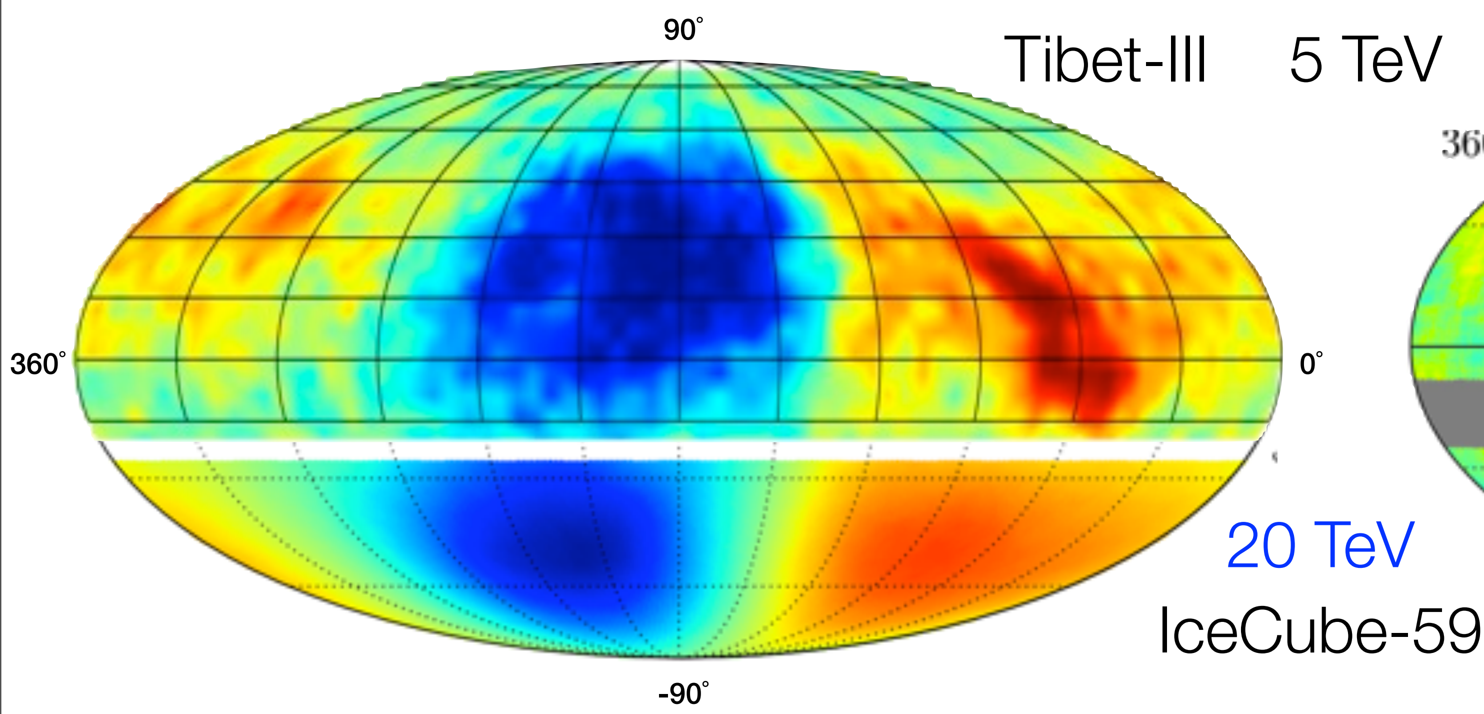
5 TeV

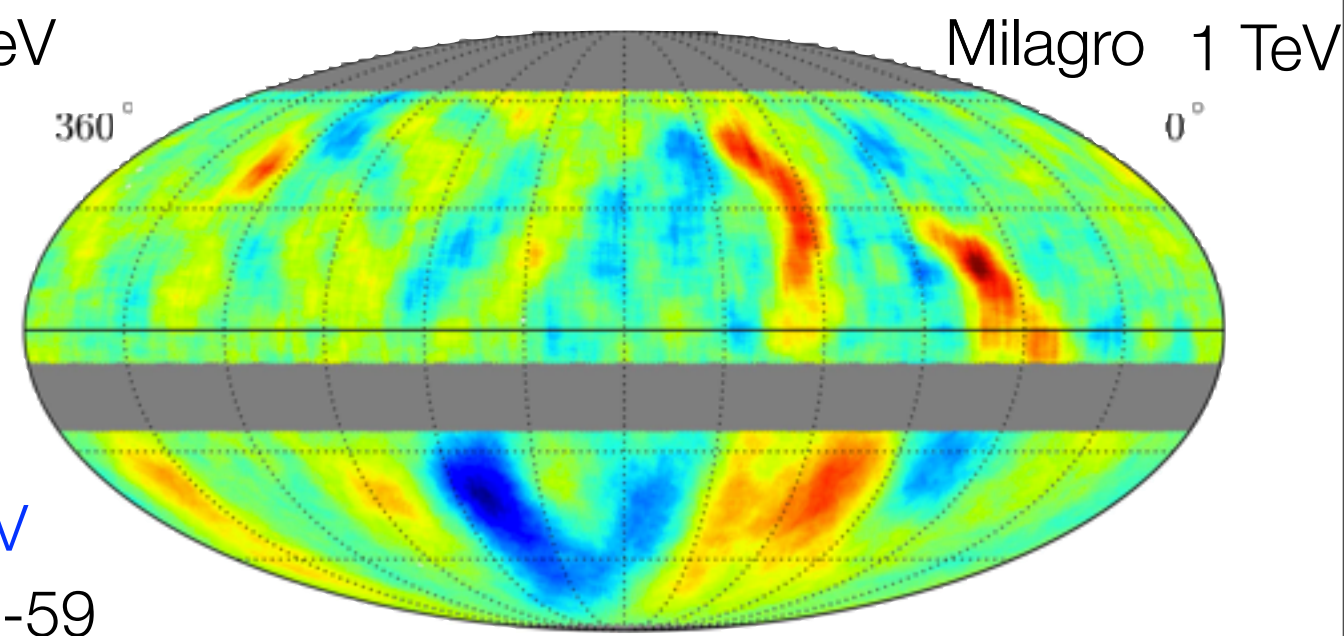
400 TeV

IceCube-59

⊙ local interstellar magnetic field

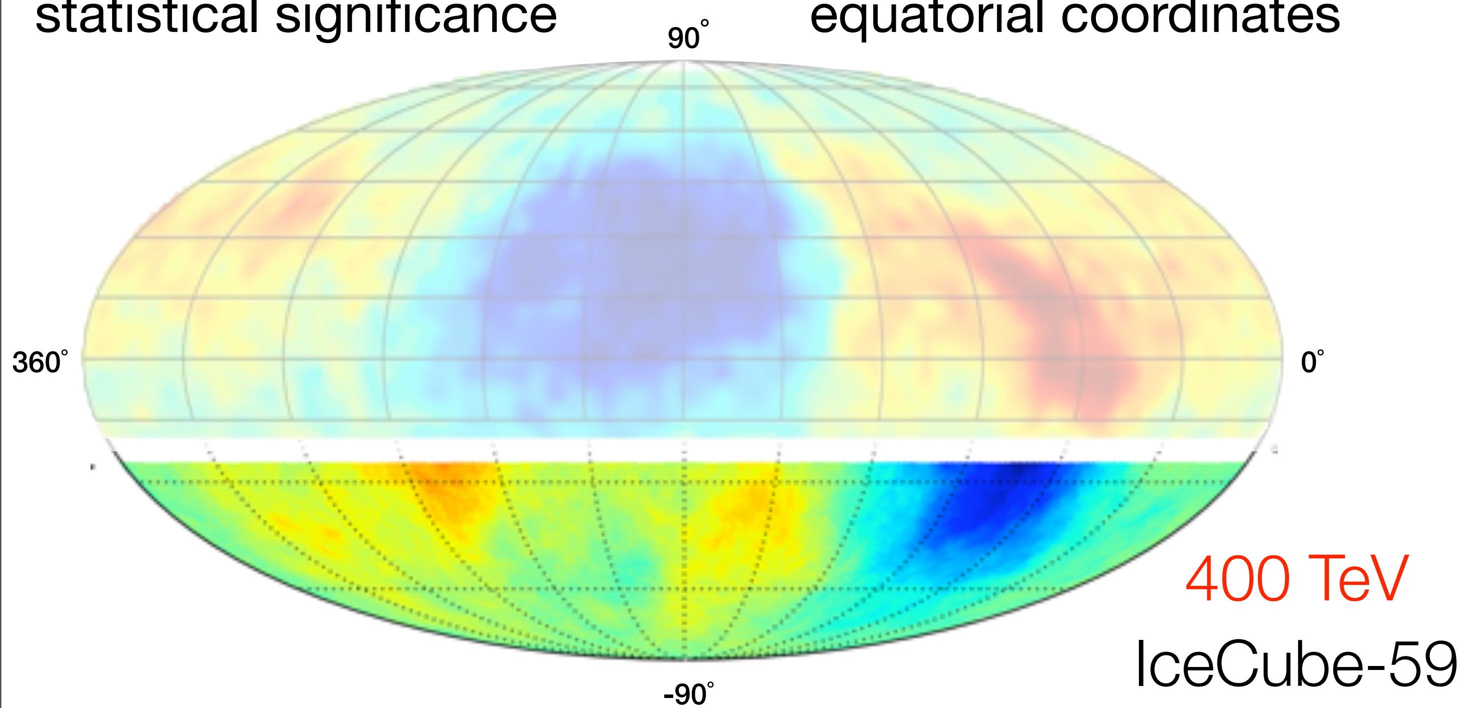
cosmic ray anisotropy

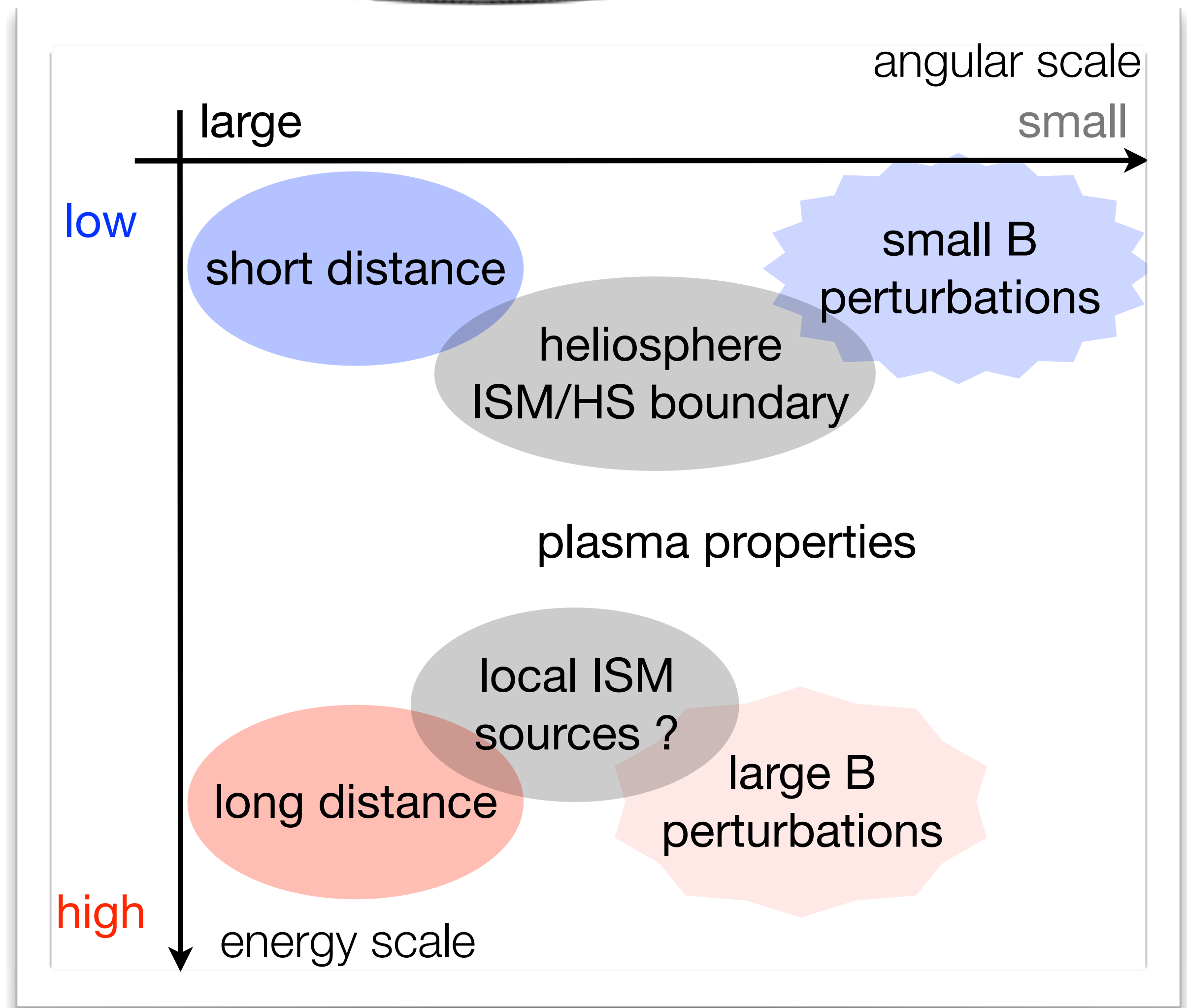




statistical significance

equatorial coordinates

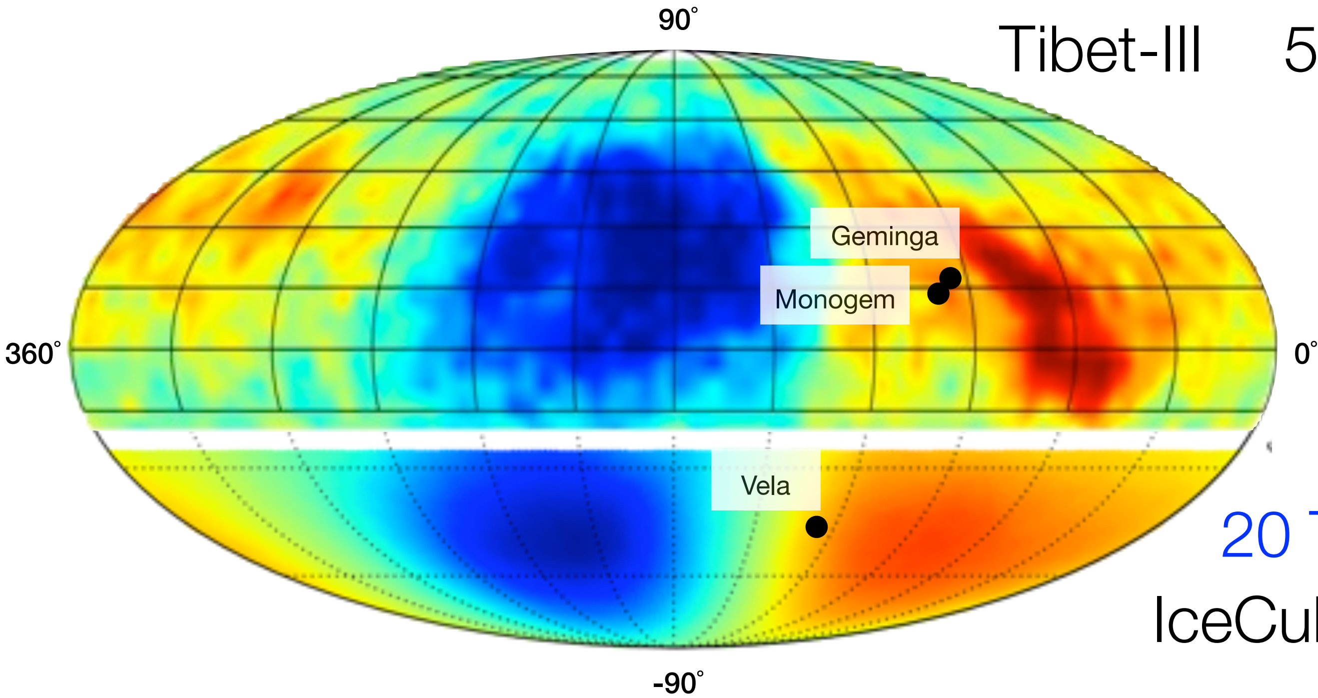




equatorial coordinates   statistical significance

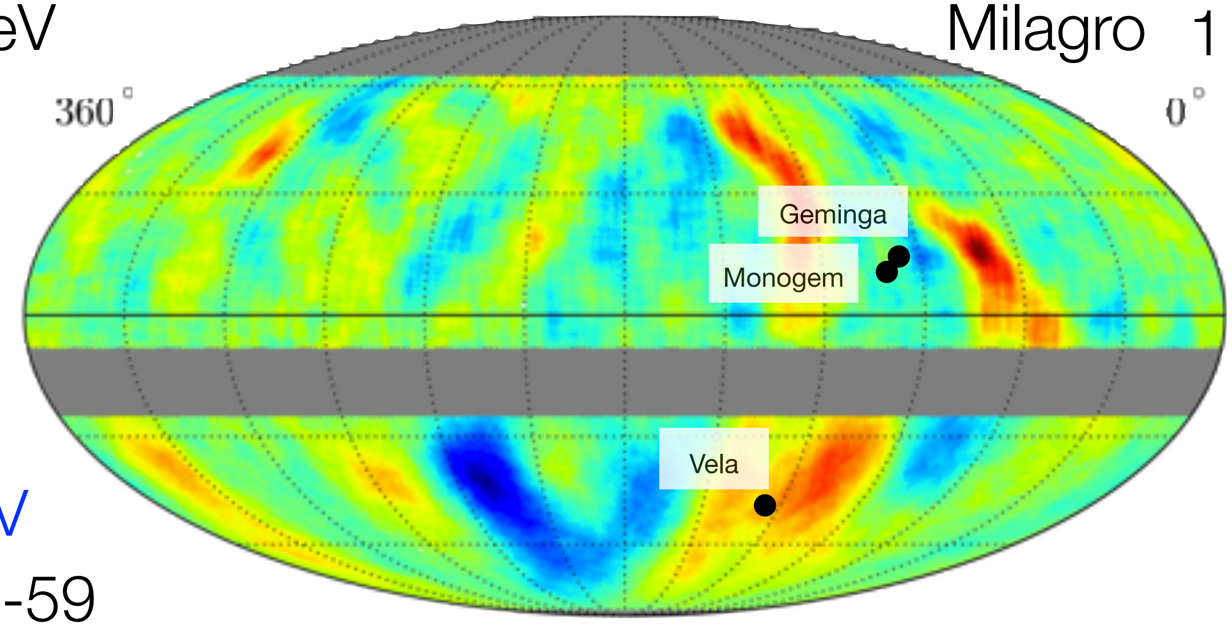
cosmic ray anisotropy

Tibet-III 5 TeV

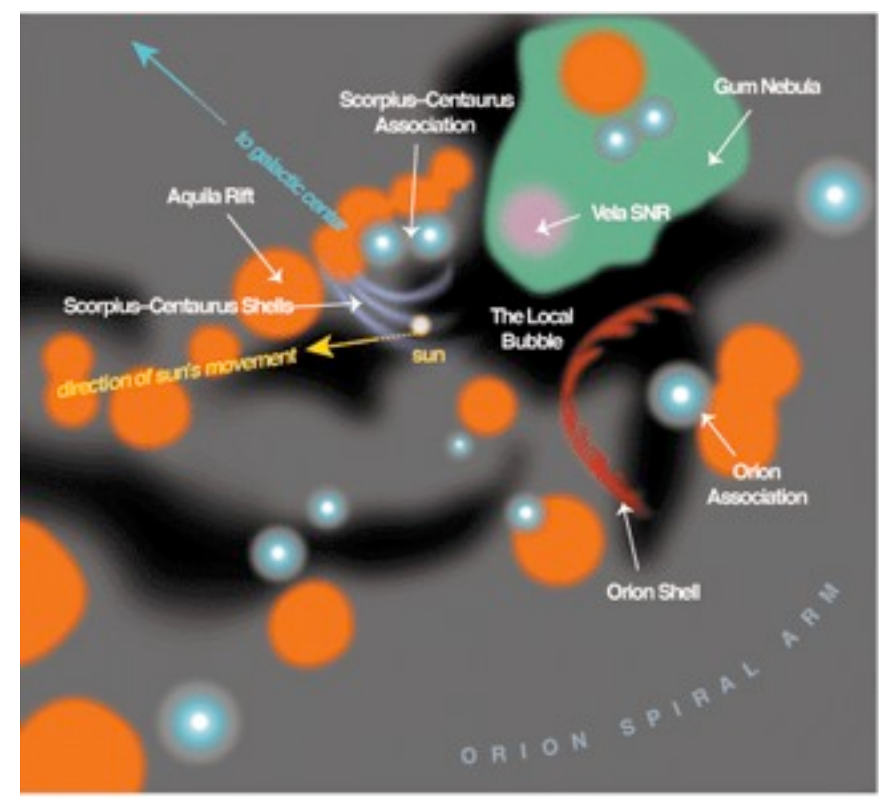


20 TeV
IceCube-59

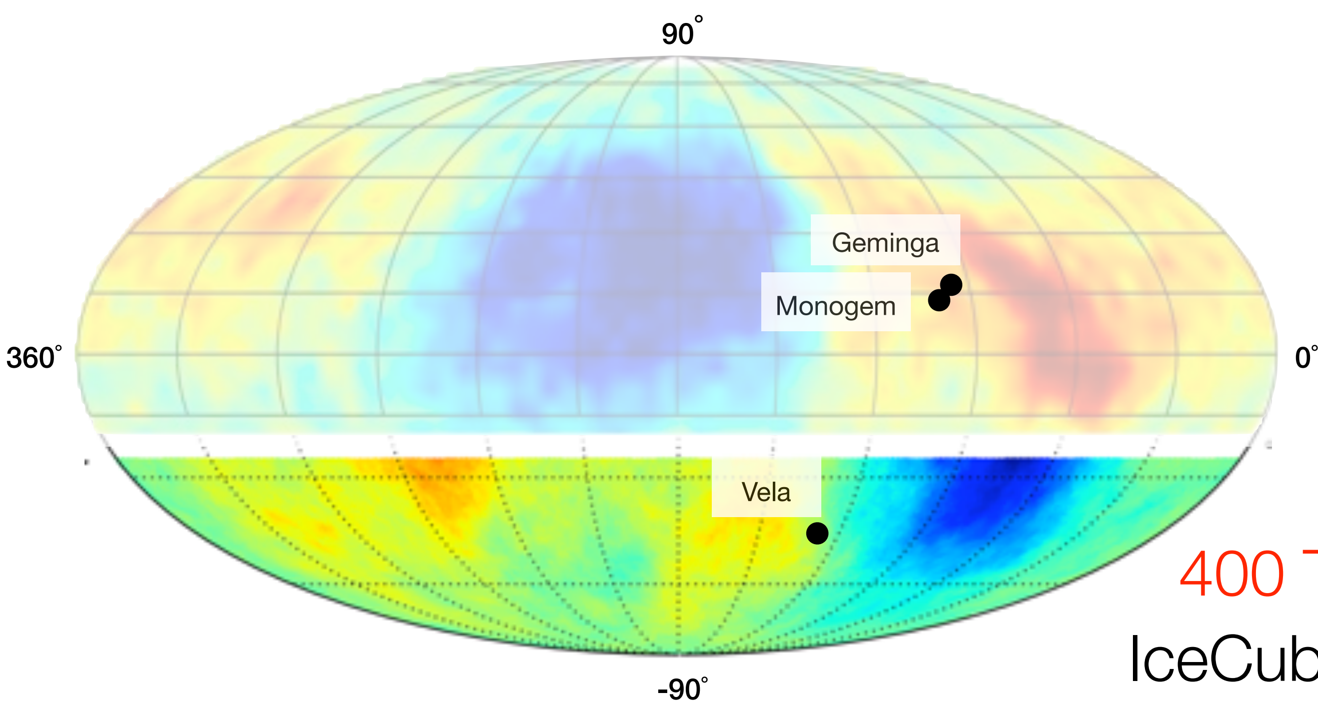
Milagro 1 TeV



scale : 500 pc



molecular clouds   diffuse gas   Priscilla Frisch - University of Chicago



400 TeV
IceCube-59

our galactic neighborhood

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

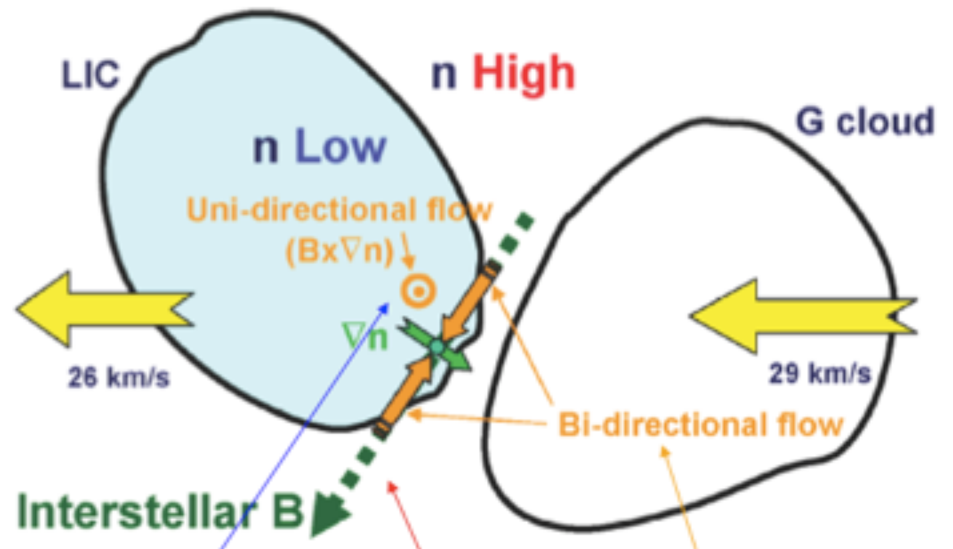
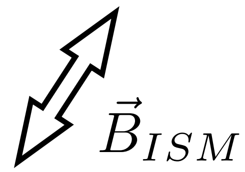
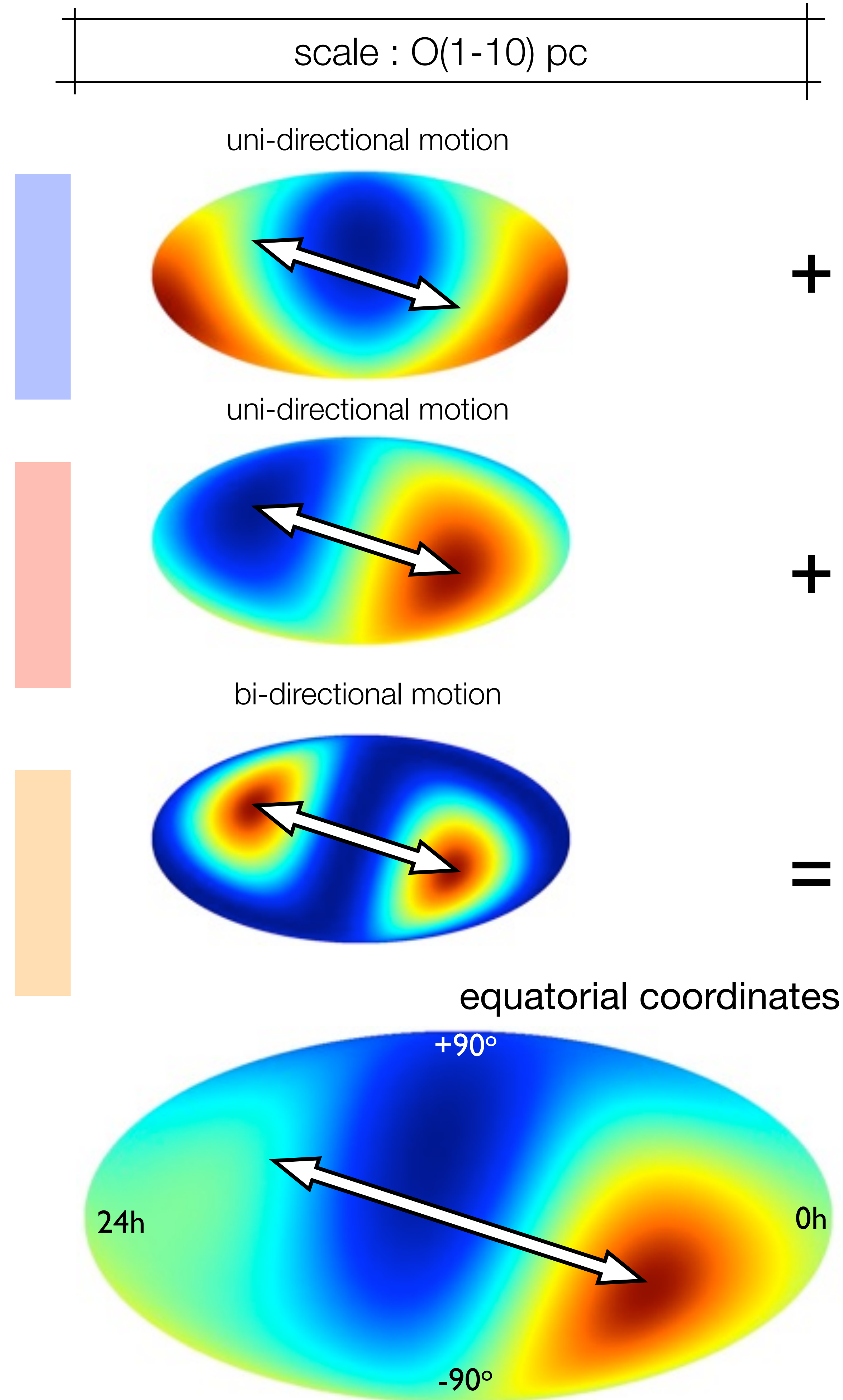


FIGURE 2. A cartoon of the LIC (left) viewed from the galactic north-pole (see [8] for more detail). Another cloud (G cloud) is overtaking the LIC from the Galactic center on the right side. A broken line represents the LISMF line through the heliosphere just inside the LIC boundary. If the GCR density (n) is lower inside the LIC than outside, the BDF is expected from the pitch angle diffusion of GCRs into LIC along the LISMF line. The UDF is also expected from B×G drift anisotropy (see text).

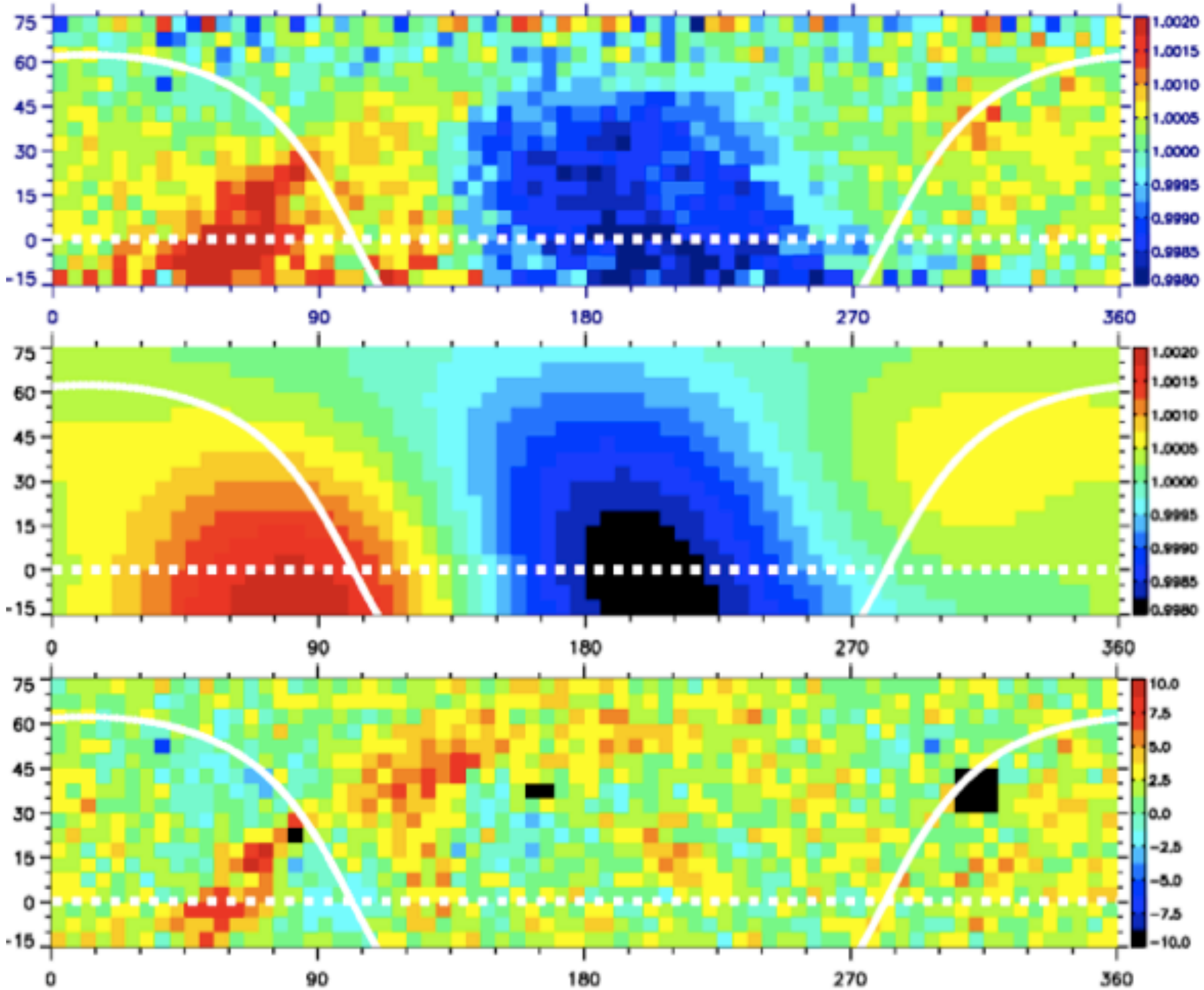
$$I_{n,m} = a_{1\perp}\cos\chi_1(n,m:\alpha_1,\delta_1) + a_{1/\!/}\cos\chi_2(n,m:\alpha_2,\delta_2) + a_2\cos^2\chi_2(n,m:\alpha_2,\delta_2)$$





- magnetic field compression between cloudlets
- can produce anisotropy from isotropic flux
- or enhance existing anisotropy

our galactic neighborhood

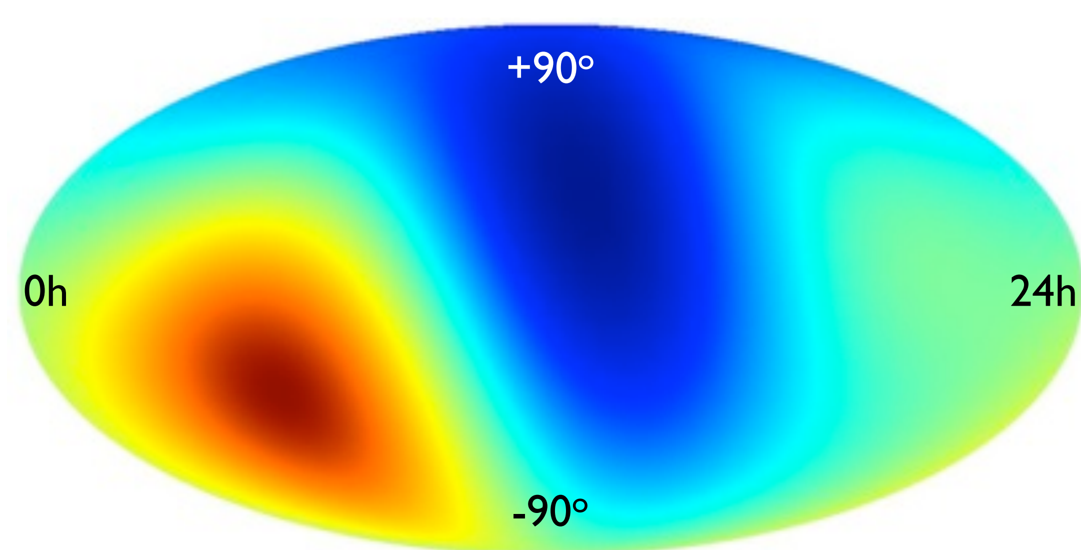


Tibet-III @ 5 TeV

anisotropy almost consistent with

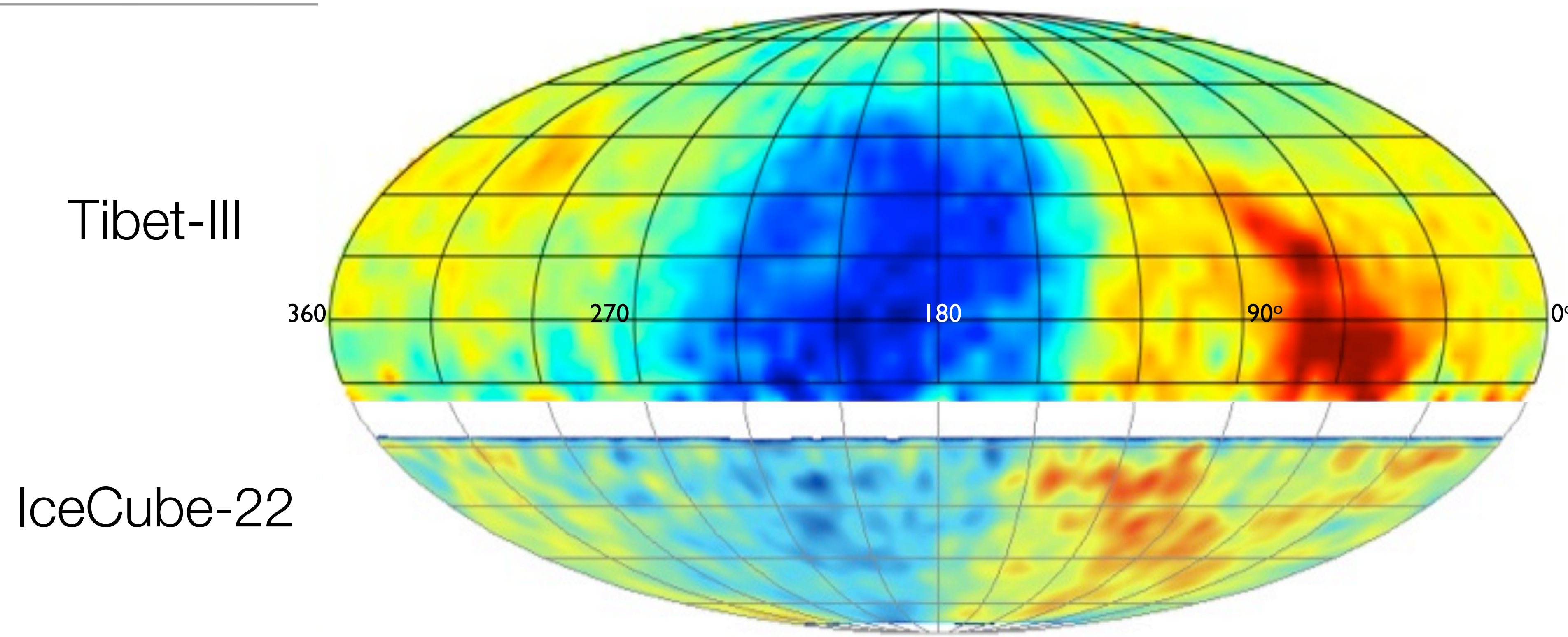
uni-directional flow (dipole)
+
bi-directional flow (quadrupole)

equatorial coordinates

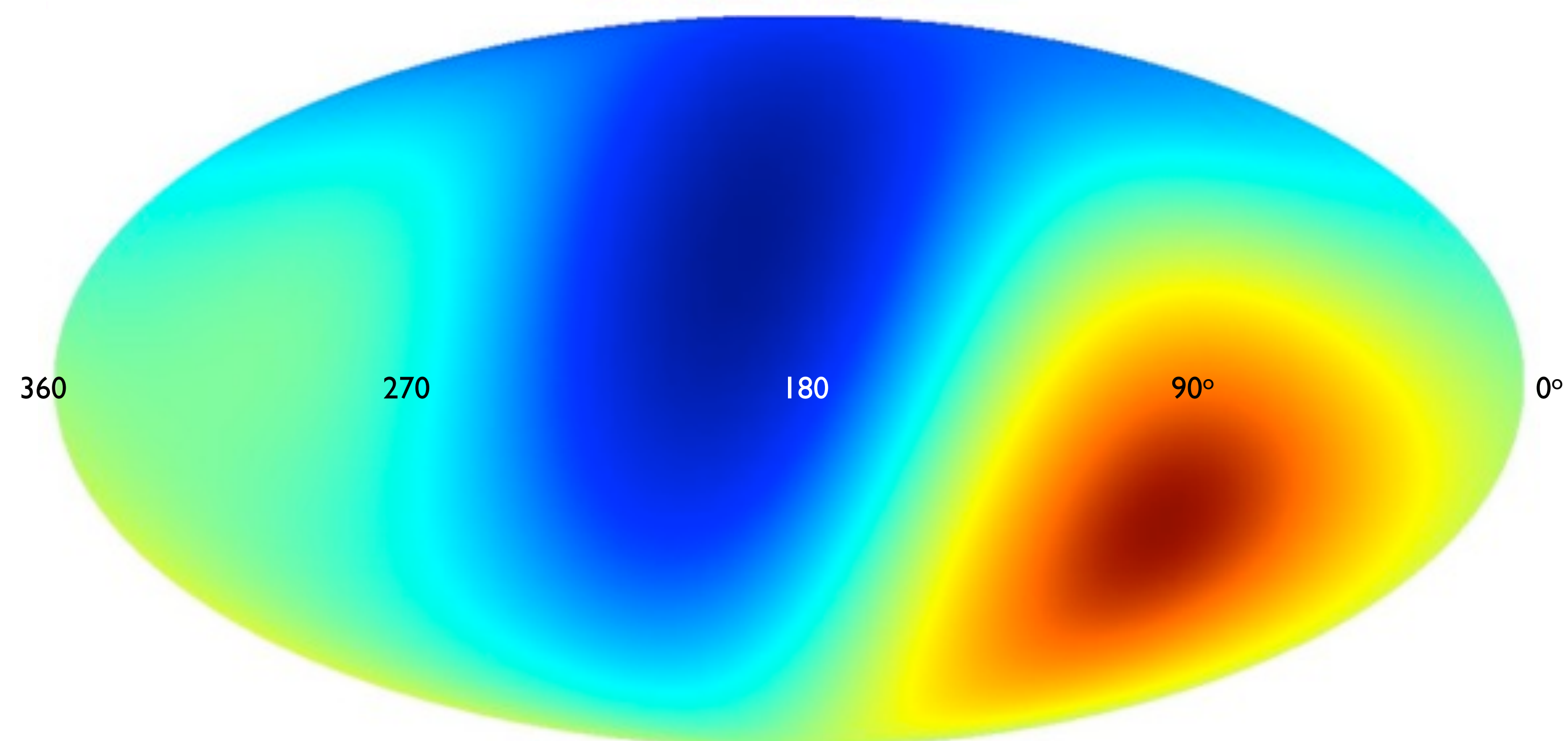


our galactic neighborhood

relative intensity
equatorial coordinates



IceCube @ 20 TeV



large scale features qualitatively well described by the global fit

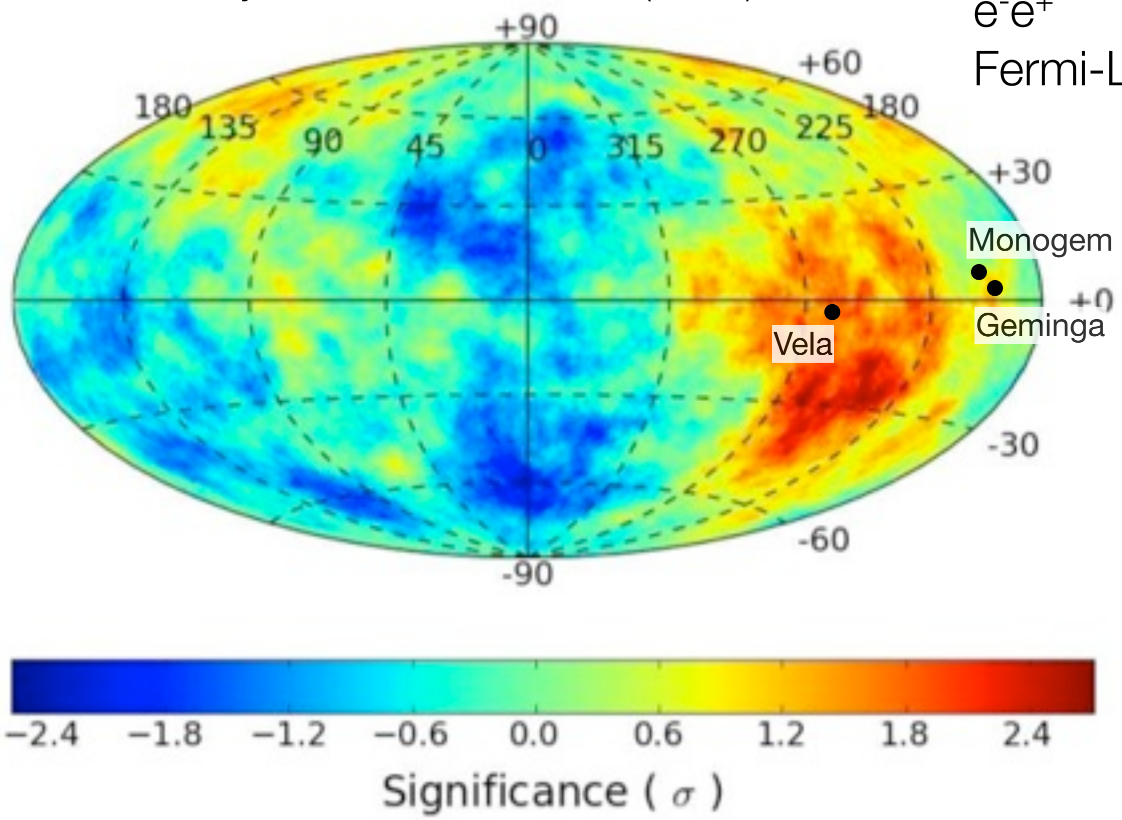
it is the smaller angular features that appear to be interesting

anisotropy and local interstellar medium

scale : 100-1,000 pc

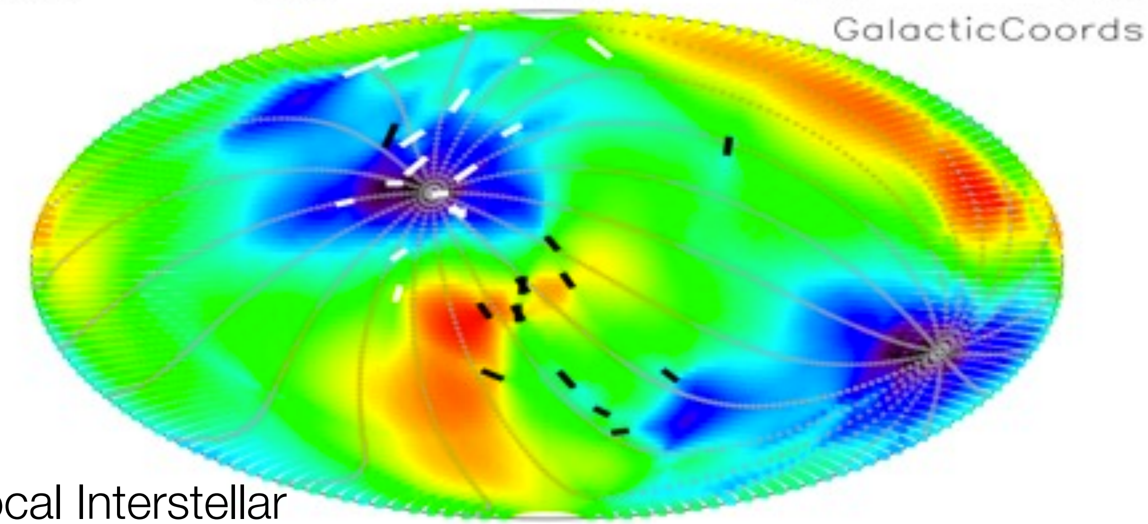
Ackermann et al., Phys. Rev D82, 092003 (2010)

e^-e^+
Fermi-LAT



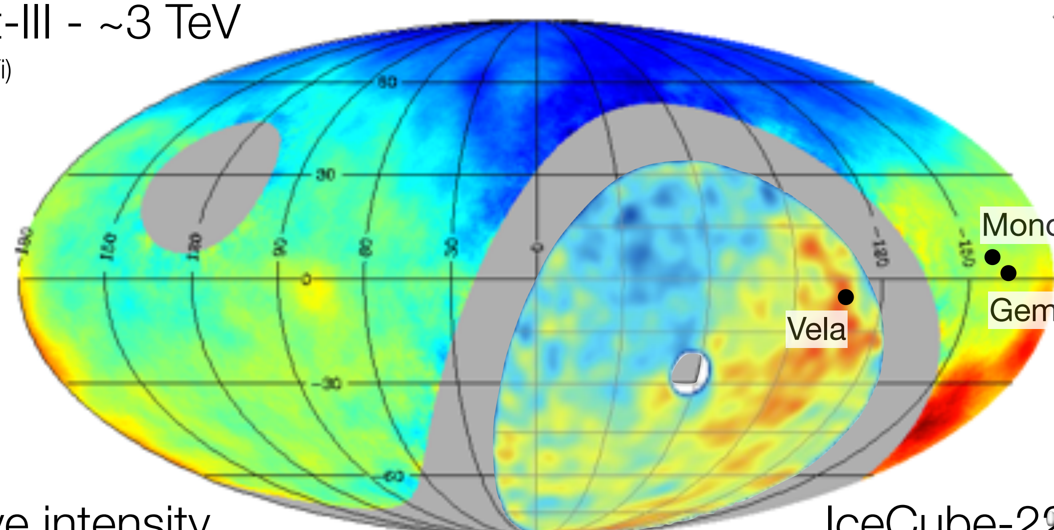
scale : < 40 pc

Frisch P. et al., ApJ, 724, 1473 (2010)



Local Interstellar Magnetic Field

Tibet-III - ~3 TeV
(Zhang Yi)



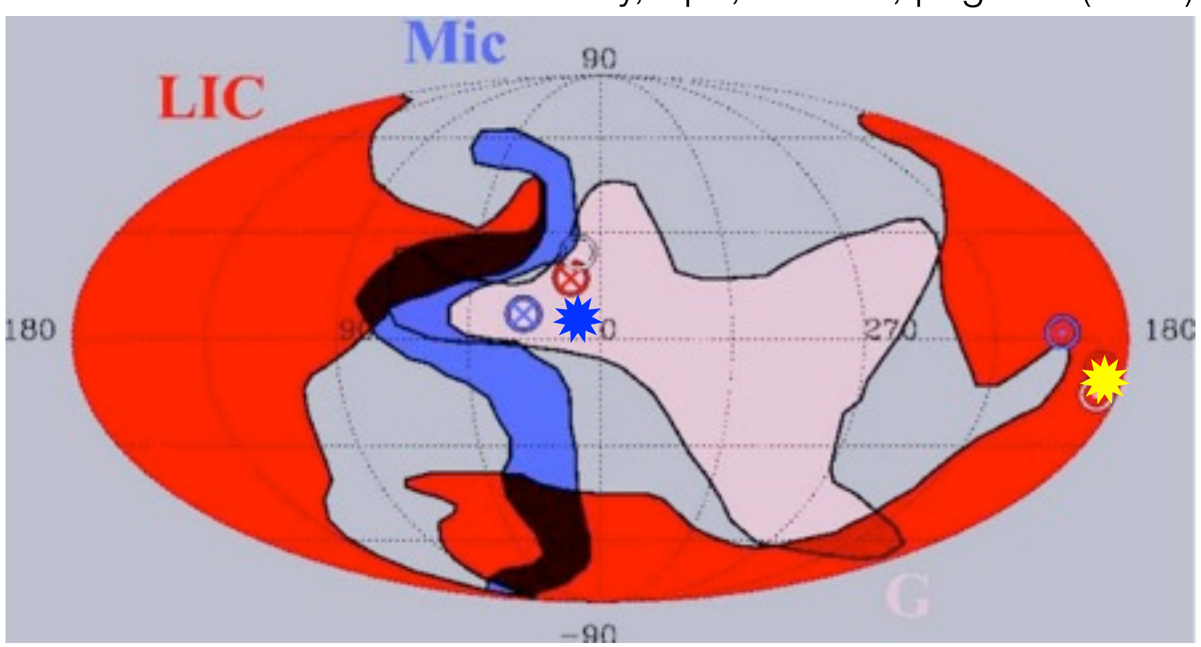
relative intensity

IceCube-22 - ~20 TeV

Abbasi et al., ApJ, 718, L194 (2010)

scale : 10^{-3}-100 pc

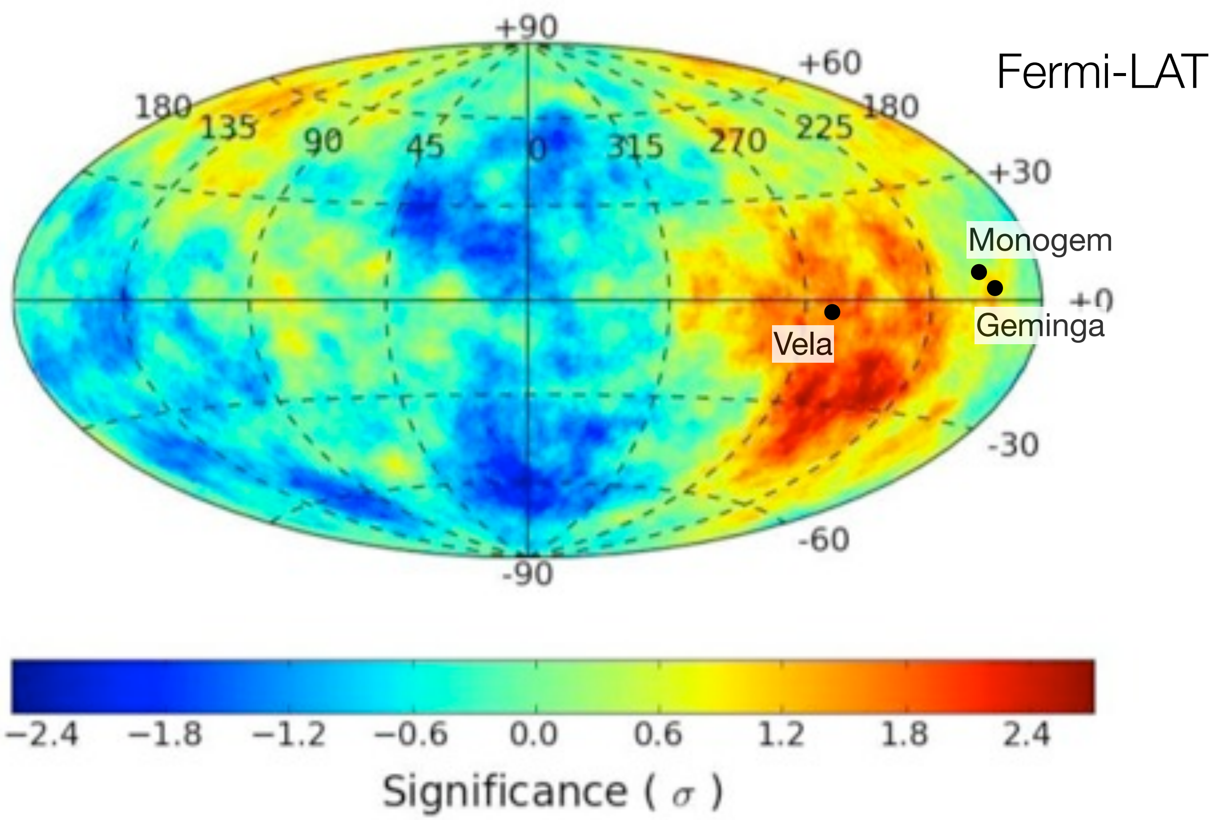
Redfield & Linsky, ApJ, Vol 673, pag 283 (2008)

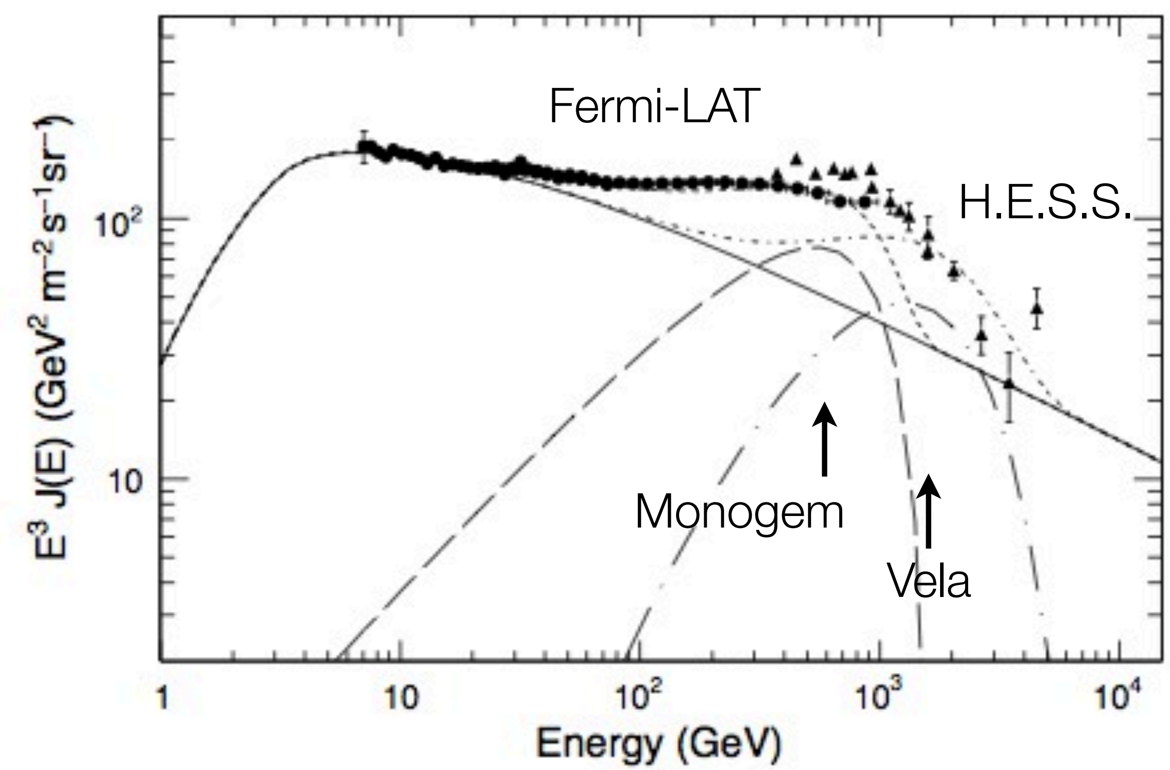


Local Interstellar Medium & Heliosphere

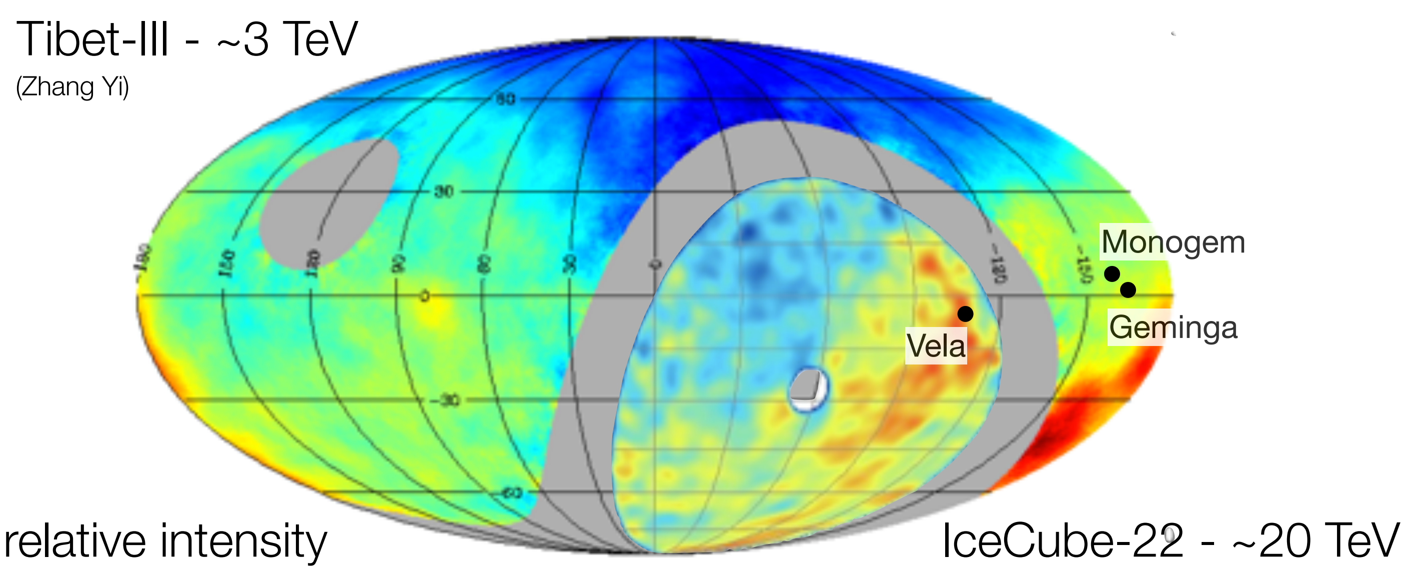
nearby sources of cosmic rays

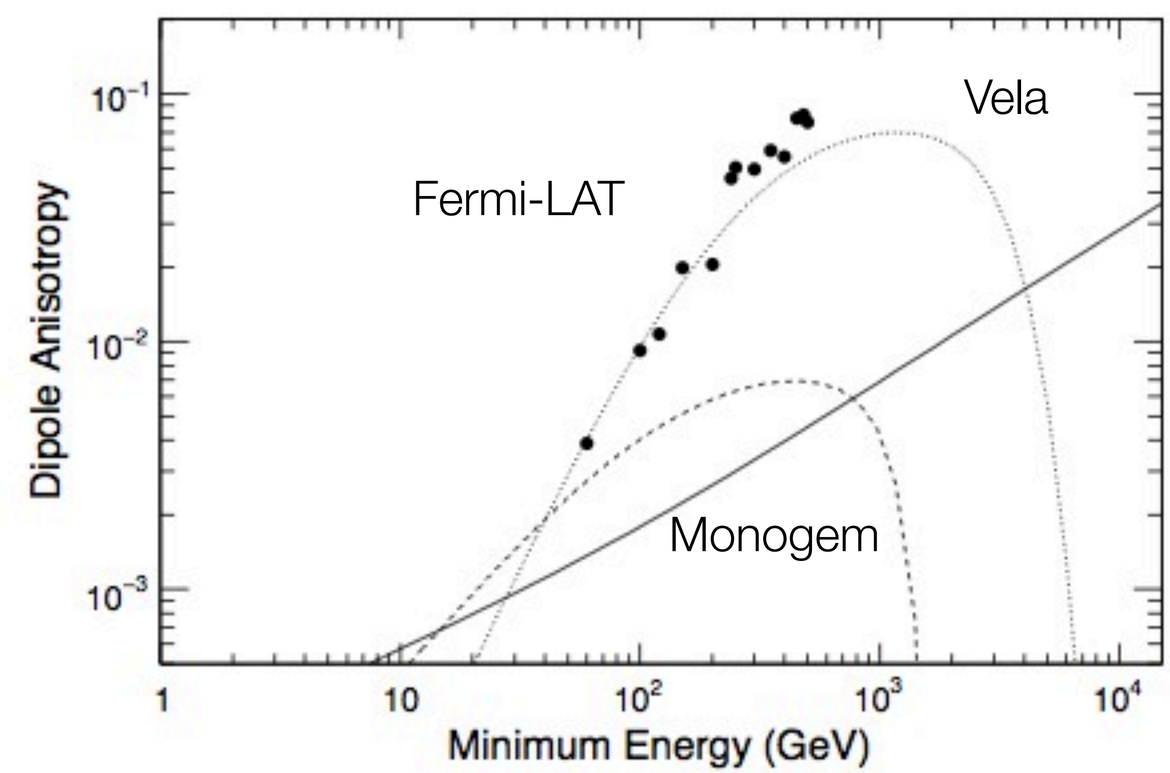
scale : 100-1,000's pc





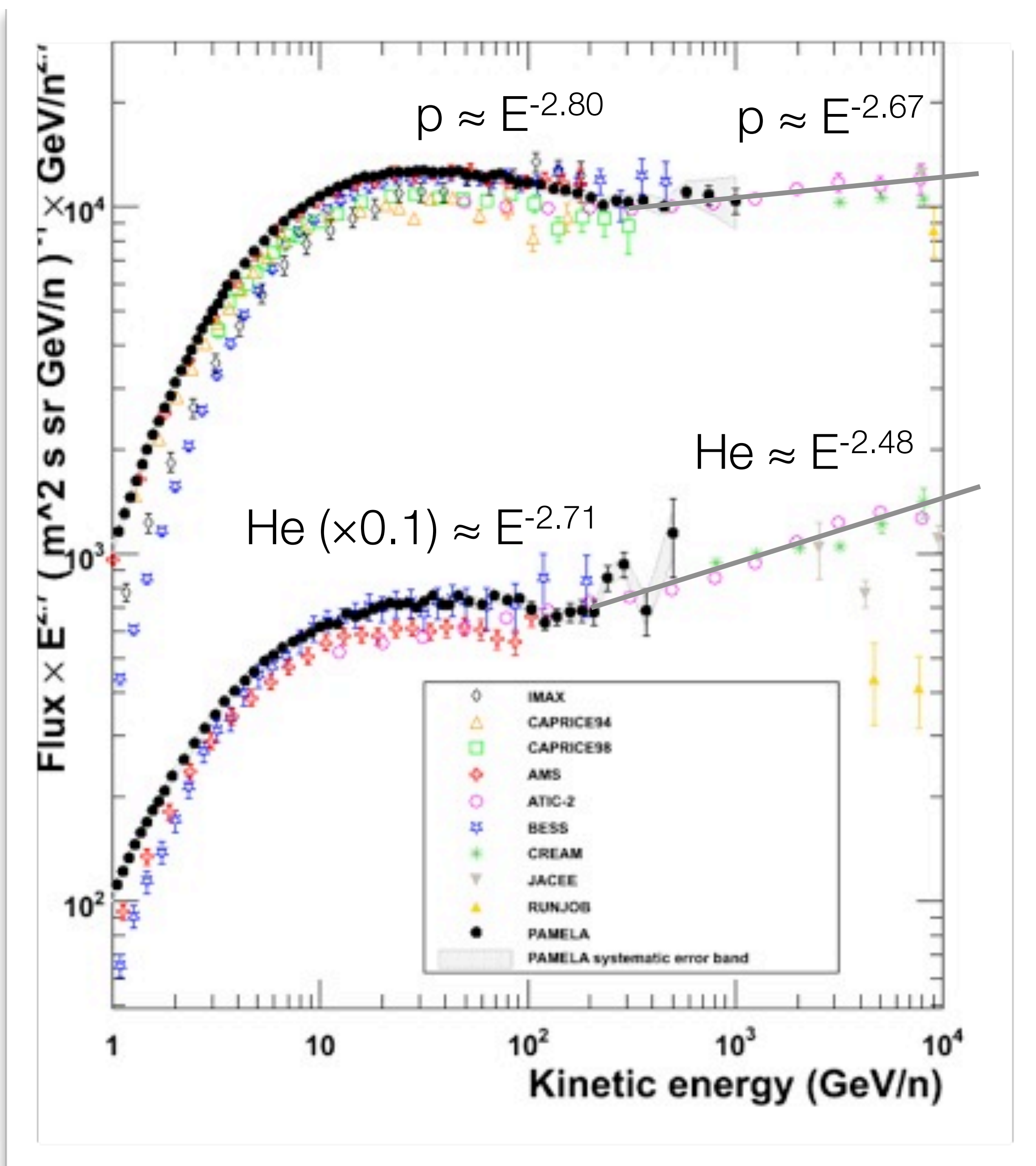
Fermi-LAT - Ackermann et al., Phys. Rev. D82, 092003, 2010



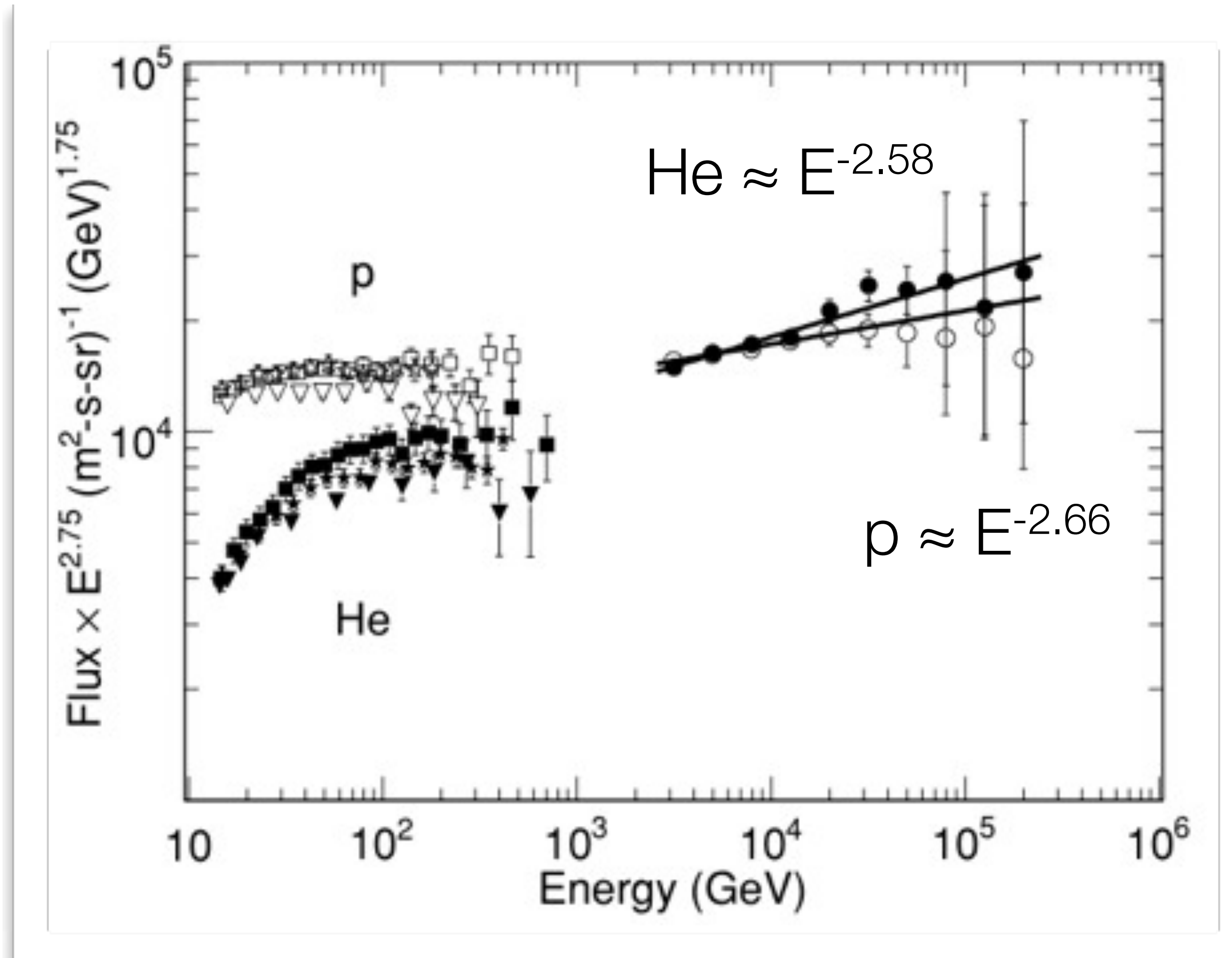


structures in galactic cosmic ray spectrum

PAMELA - Adriani et al., Science, 332, 69, 2011



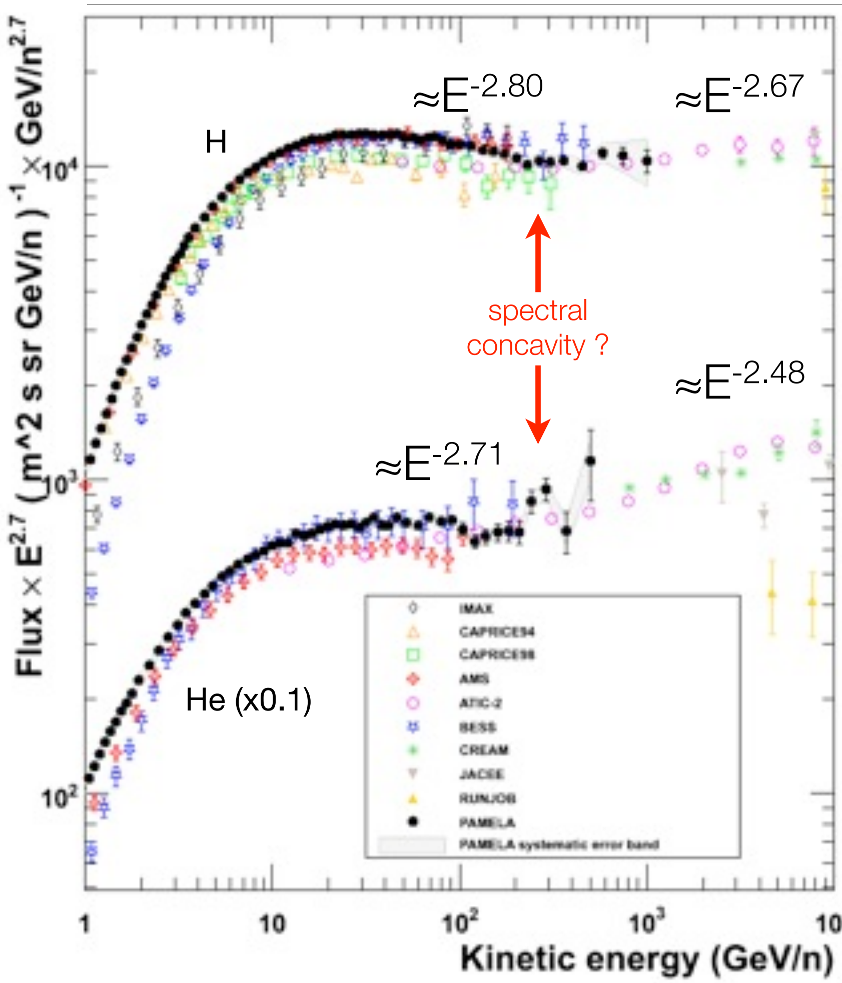
CREAM - Ahn et al., ApJ, 714, L89, 2010



- **spectral concavity** from non-linear acceleration or propagation processes
- **nearby source** of cosmic rays ?

spectral concavity / hardening

PAMELA
Adriani et al., Science, 332, 69, 2011



KASCADE-Grande
Arteaga-Velázquez et al., arXiv:1009.4716