



IceCube Observatory & Galactic Cosmic Ray Anisotropy

Paolo Desiati

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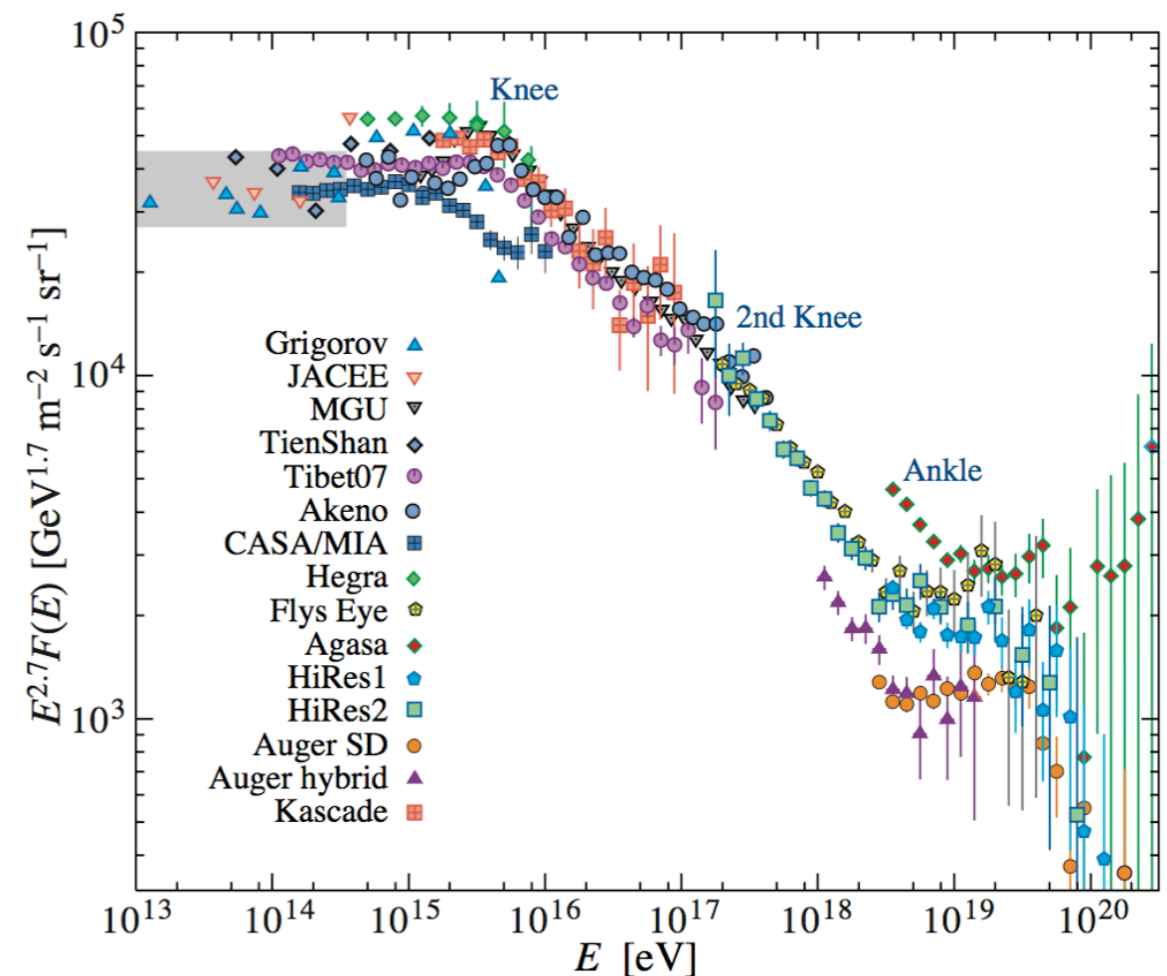
University of Wisconsin - Madison

CCAPP Anisotropy Workshop
Center for Cosmology and AstroParticle Physics
The Ohio State University
June 23th, 2010

cosmic rays

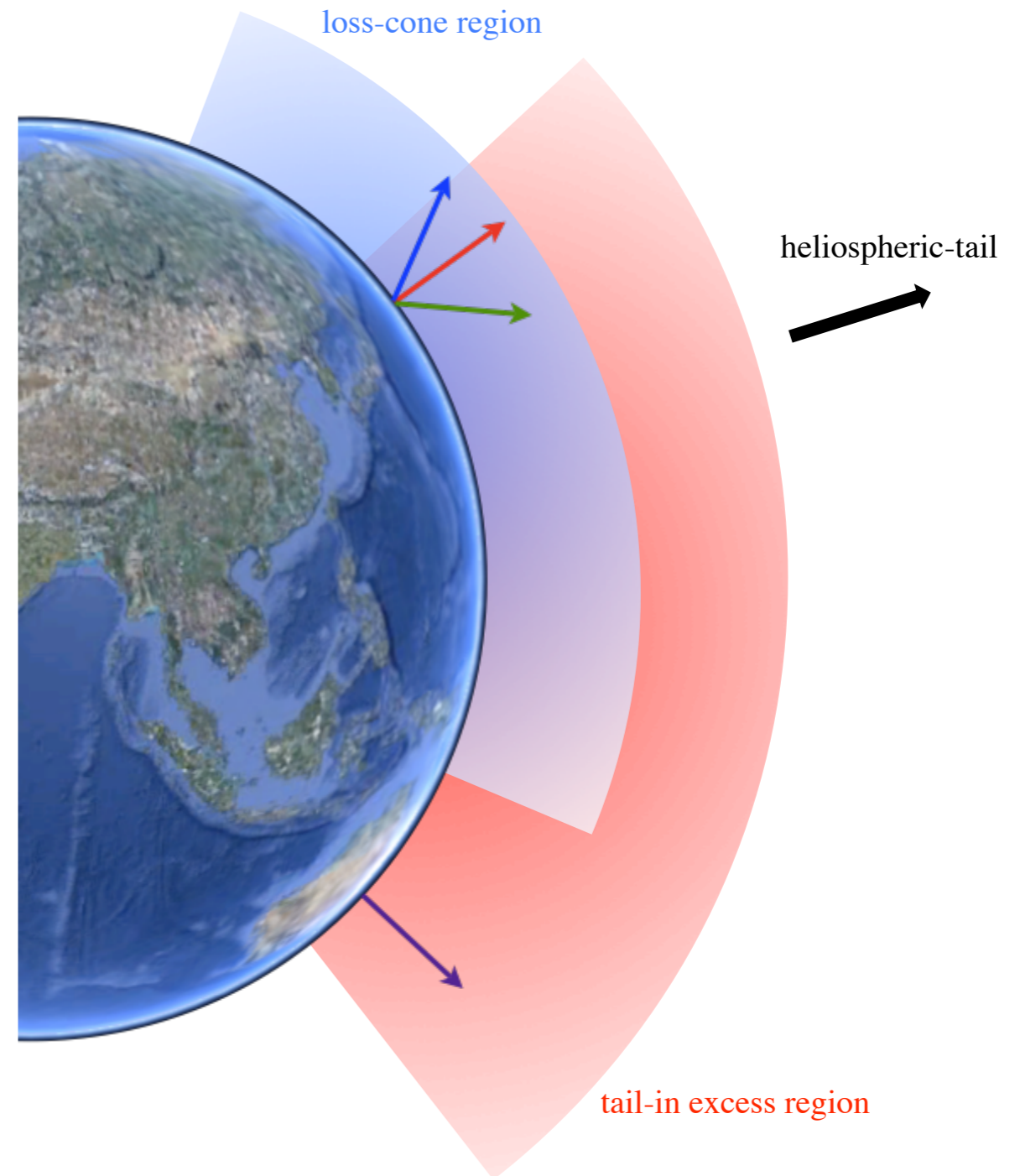
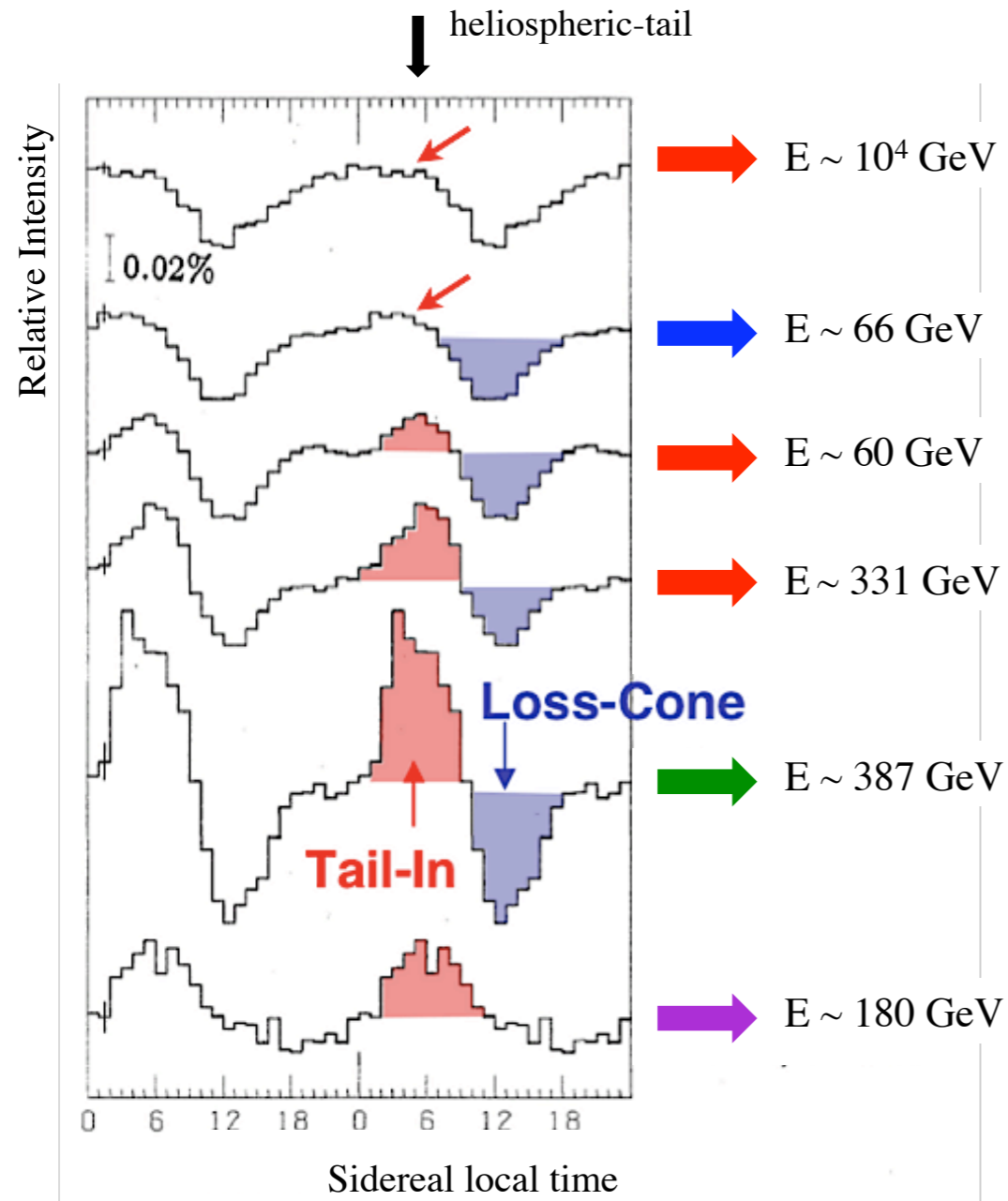
- CR below the knee ($\sim 10^6$ GeV) believed to be galactic
- CR below $\sim 10^9$ GeV believed to be predominantly galactic (transition to extra-galactic @ $\sim 10^9$ - 10^{10} GeV)
- galactic CR believed to be accelerated in expanding shock waves initiated by supernova explosions
- galactic CR expected to be isotropic : scrambled by galactic magnetic field over very long time

Stanev, Gaisser, PDG



cosmic ray anisotropy in arrival direction

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

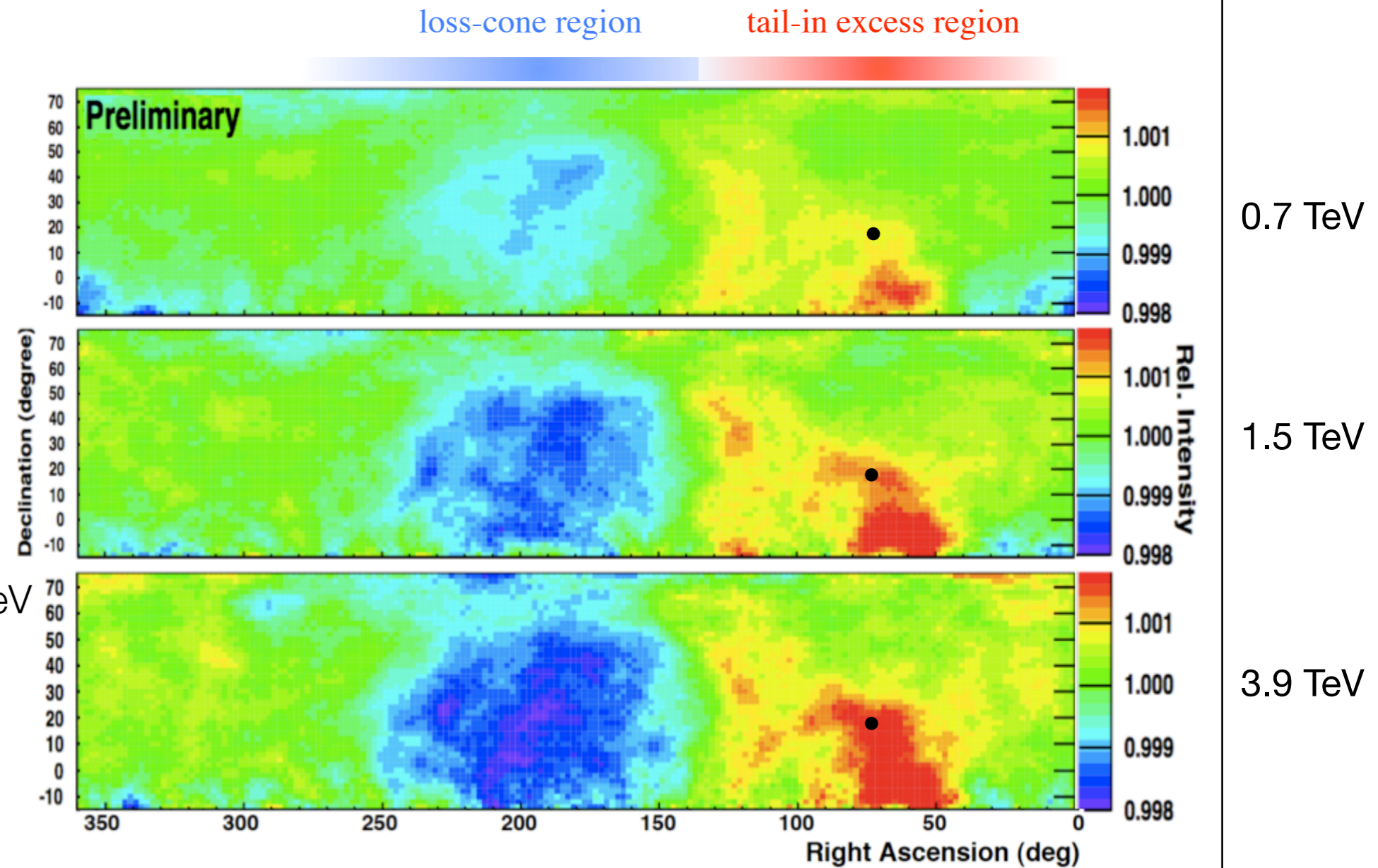


cosmic ray anisotropy in arrival direction

J.L. Zhang et al., ICRC Lodz - Poland (2009)

ARGO-YBJ

- ▶ data from 2008
- ▶ 365 days livetime
- ▶ $6.5 \cdot 10^{10}$ events
- ▶ median CR energy ~ 1.1 TeV

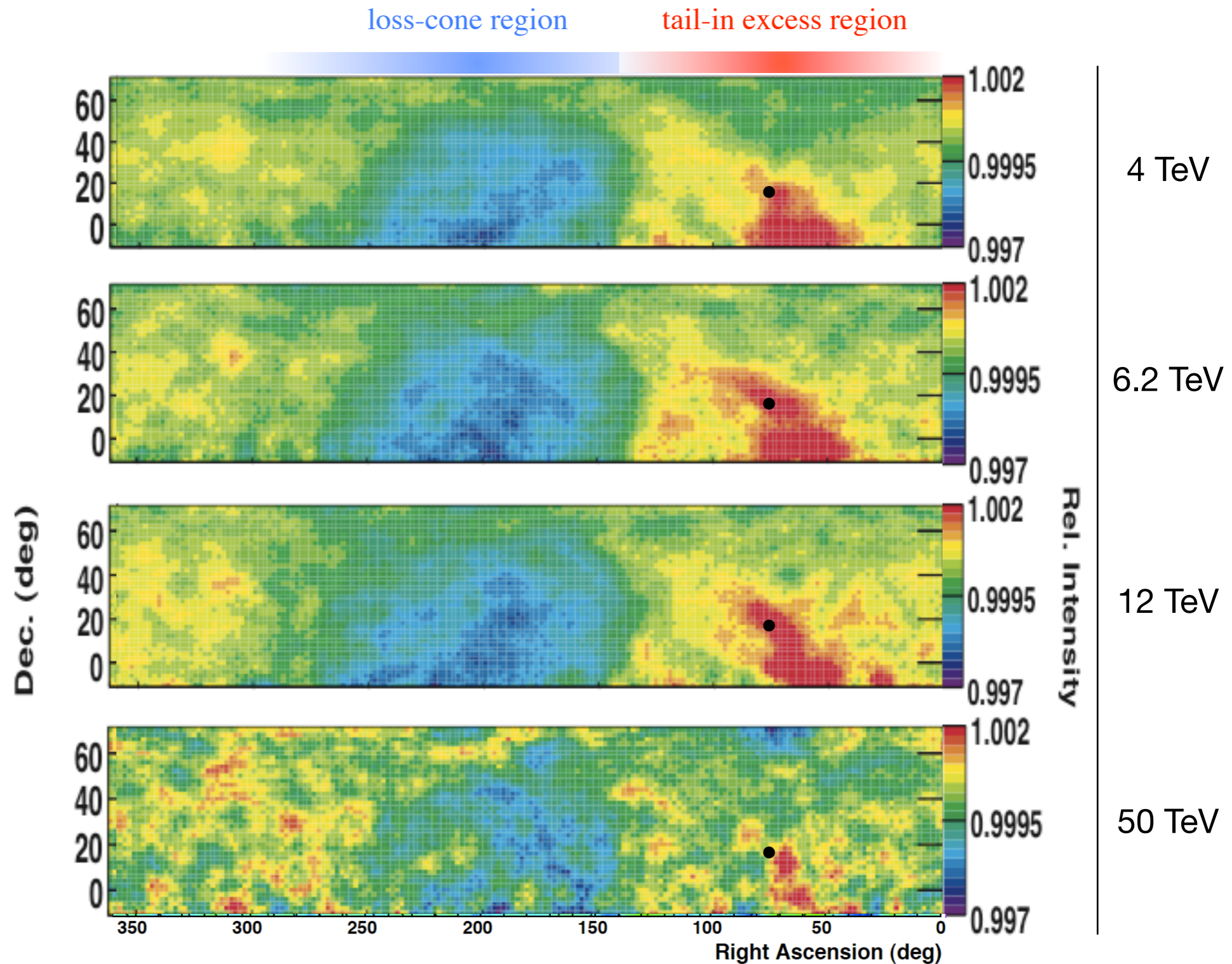


cosmic ray anisotropy in arrival direction

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

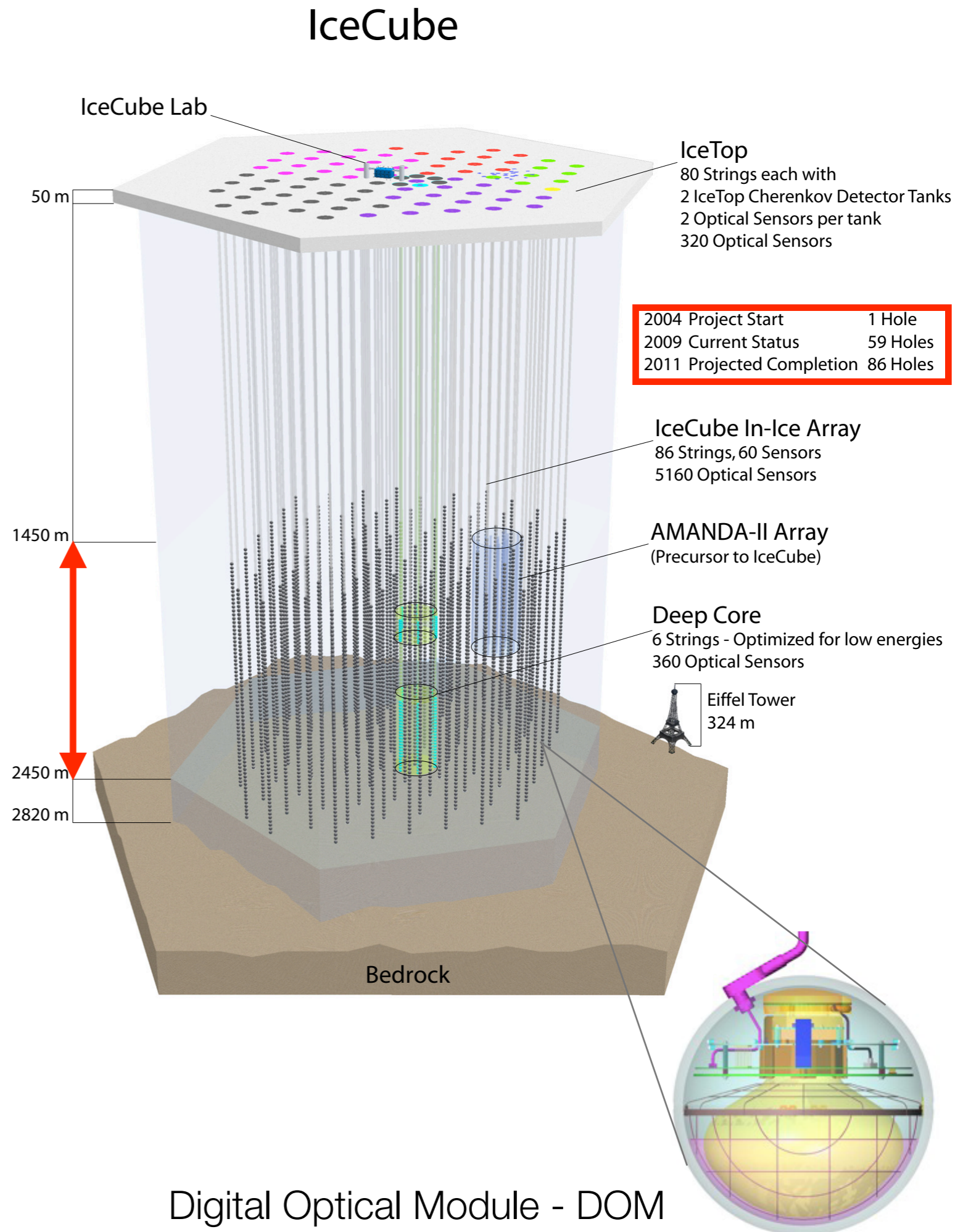
Tibet-III

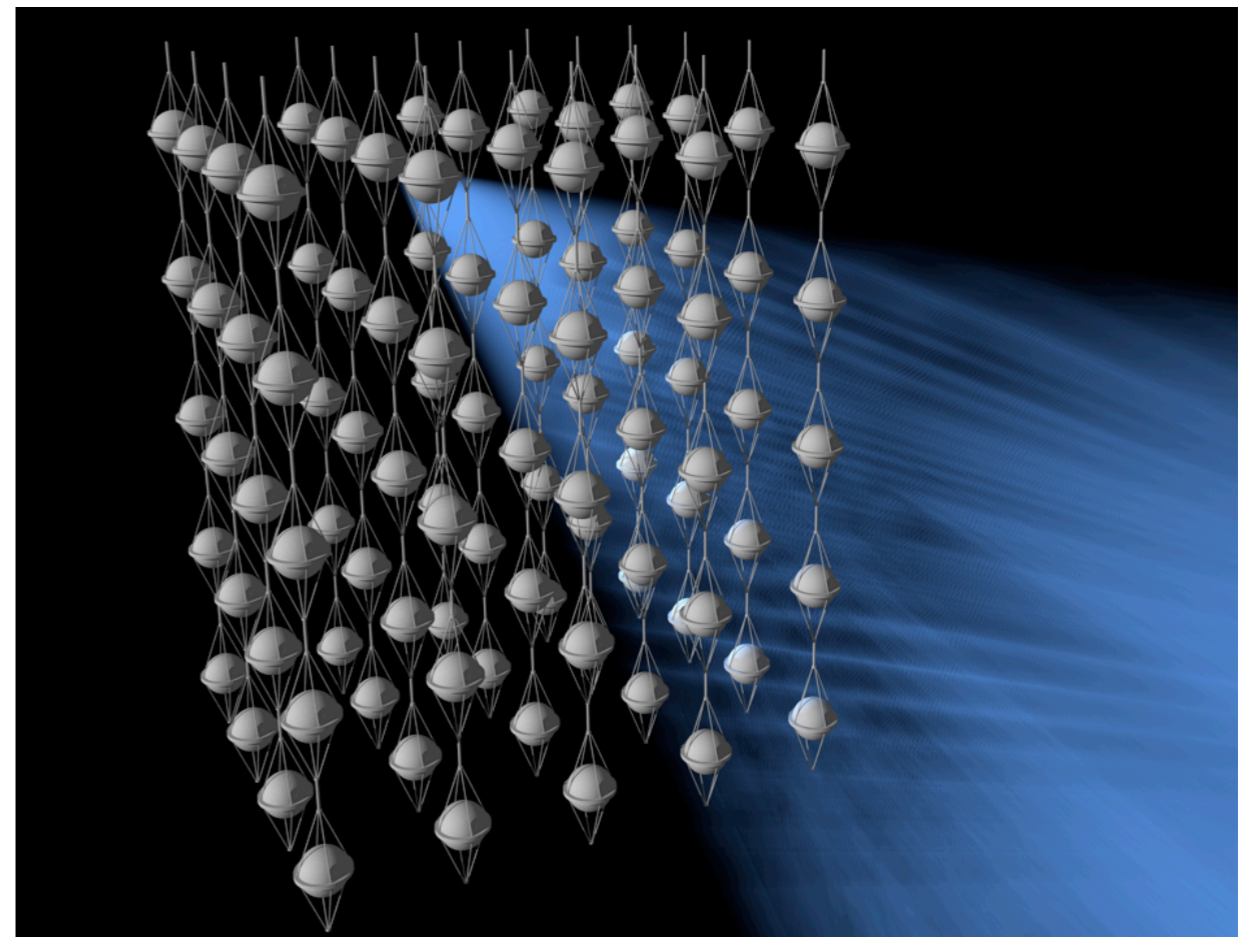
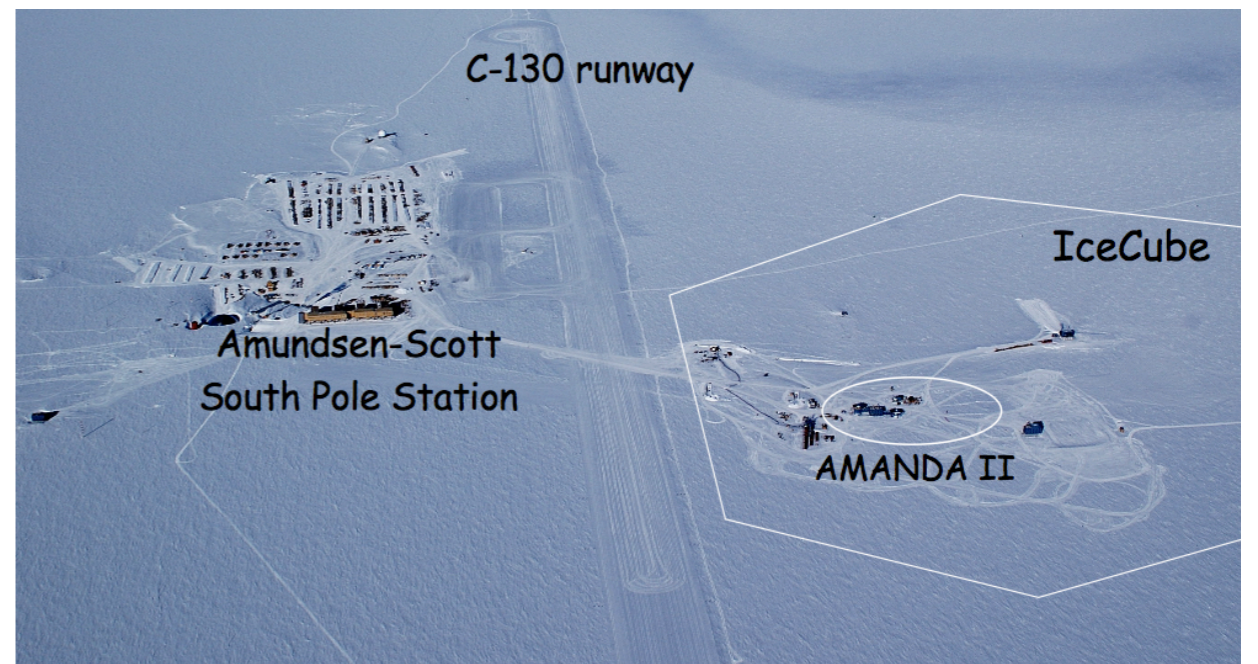
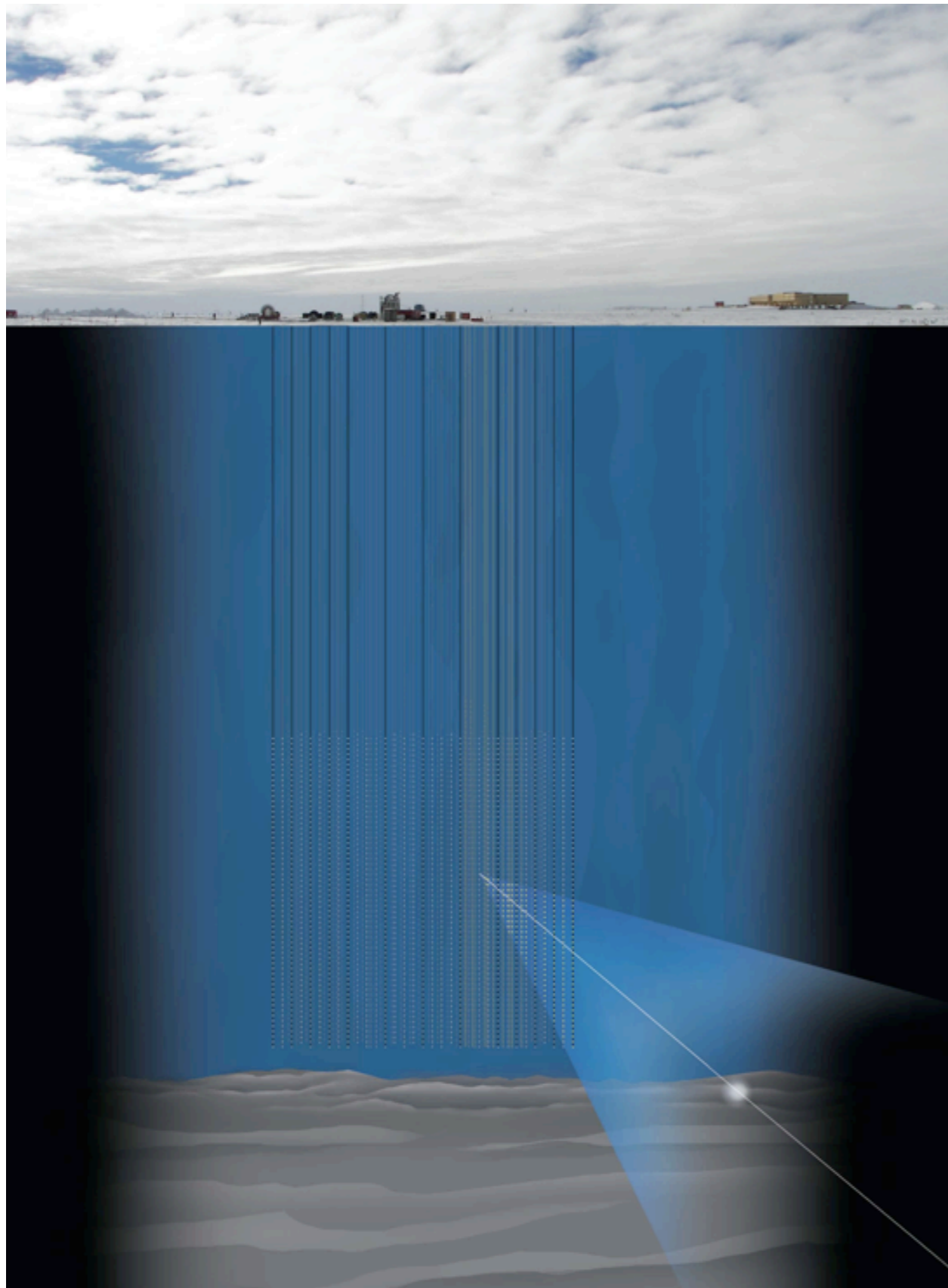
- ▶ data from 1997 to 2005
- ▶ 1874 days livetime
- ▶ $3.7 \cdot 10^{10}$ events
- ▶ angular resolution $\sim 0.9^\circ$
- ▶ modal CR energy ~ 3 TeV



IceCube Observatory

- IceCube
 - currently 79 strings
 - 86 strings in 2011
 - 125 m inter-string spacing
 - 17 m DOM distance
- taking data during construction
- AMANDA decommissioned on May 11, 2009
- Deep Core completed with 6 strings

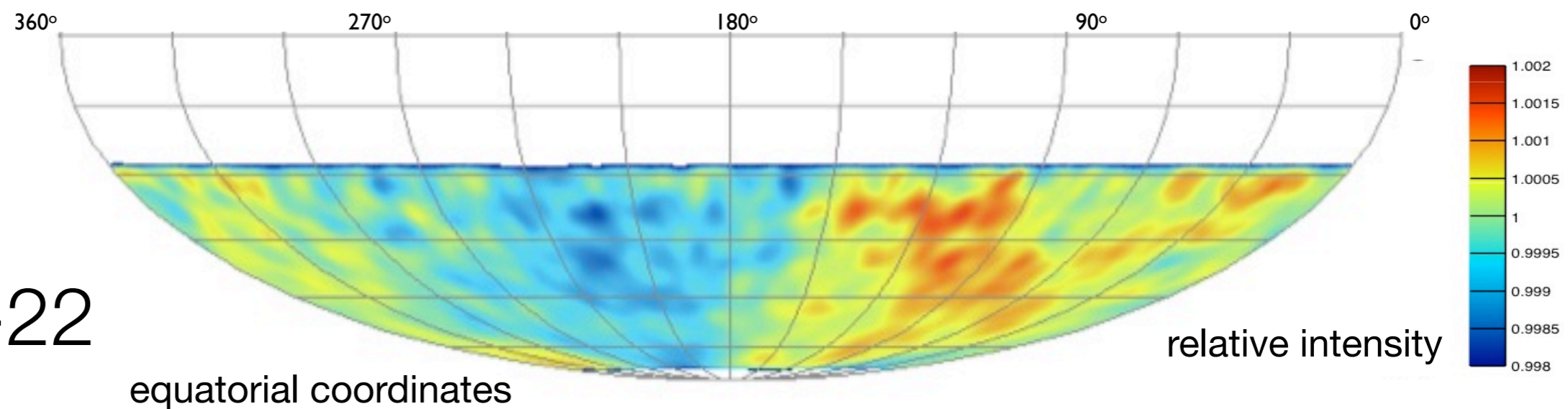




cosmic ray anisotropy in arrival direction

Abbasi et al., submitted to ApJ Letters

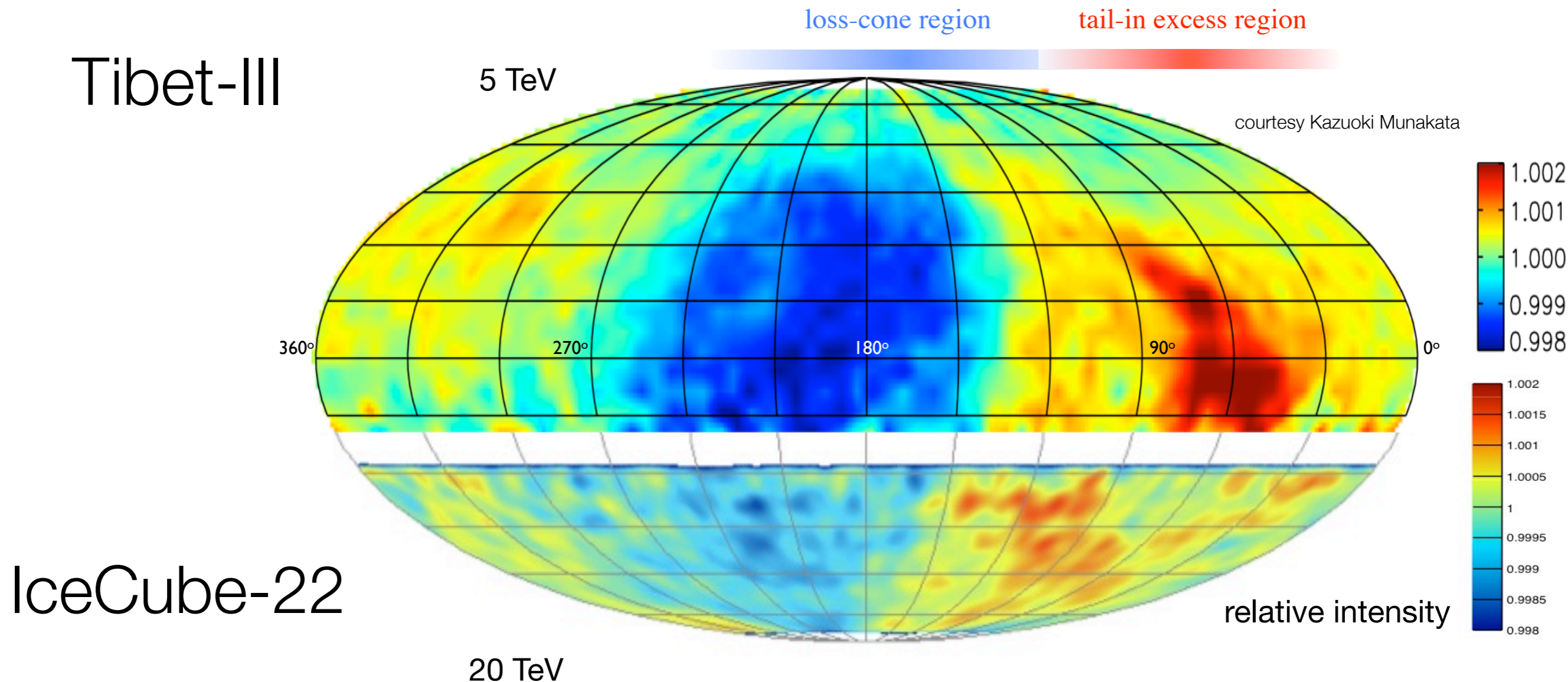
IceCube-22



- ▶ data from June 2007 to March 2008
- ▶ 226 days livetime
- ▶ $4.3 \cdot 10^9$ events
- ▶ median angular resolution $\sim 3^\circ$
- ▶ median CR energy ~ 20 TeV

cosmic ray anisotropy in arrival direction

Abbasi et al., submitted to ApJ Letters



equatorial coordinates

- ▶ data from June 2007 to March 2008
- ▶ 226 days livetime
- ▶ $4.3 \cdot 10^9$ events
- ▶ median angular resolution $\sim 3^\circ$
- ▶ median CR energy ~ 20 TeV

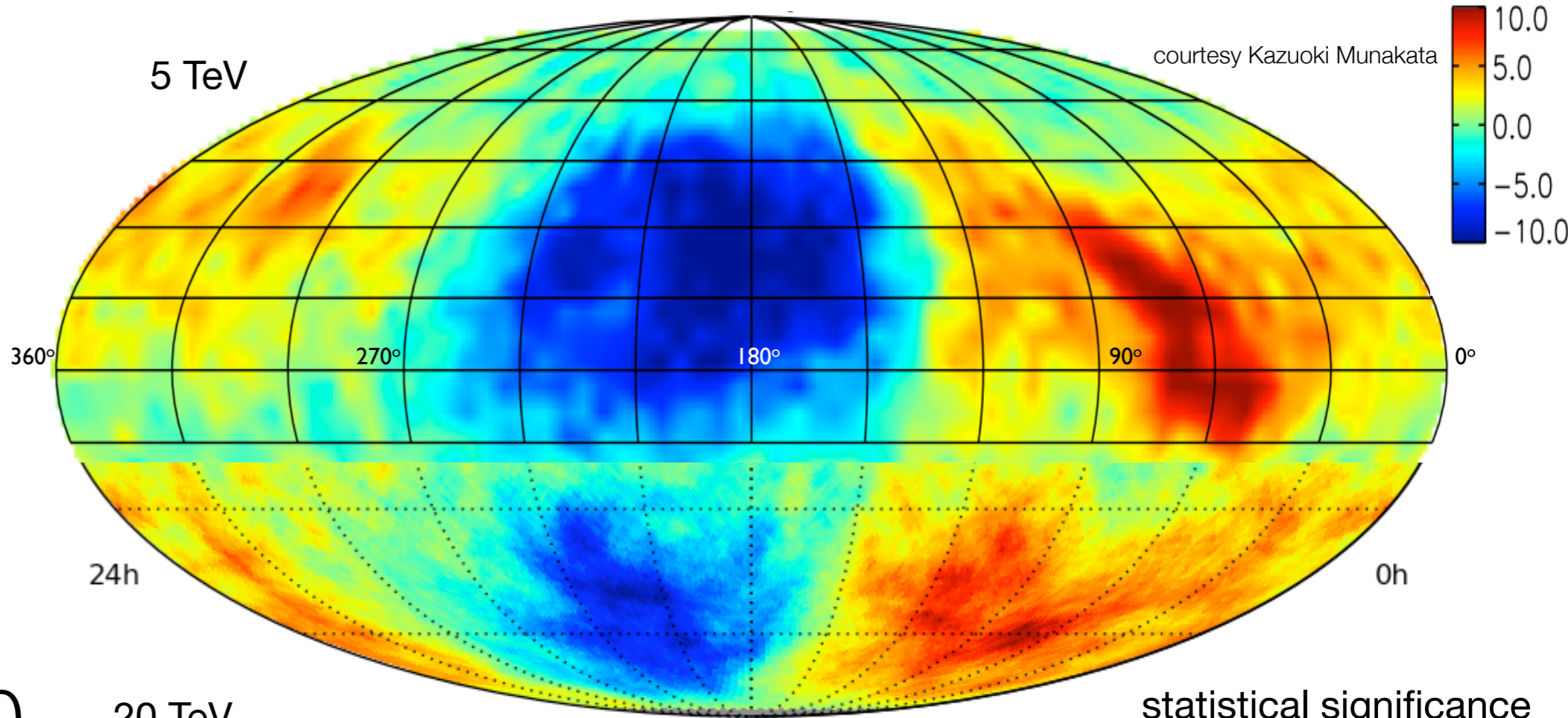
cosmic ray anisotropy in arrival direction

PRELIMINARY

Tibet-III
(5° smoothing)

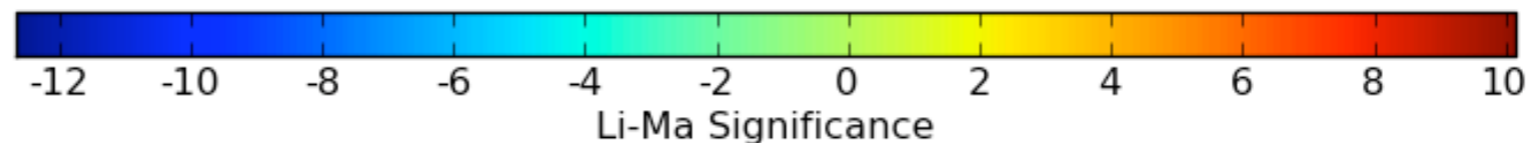
5 TeV

courtesy Kazuoki Munakata



IceCube-40
(3° smoothing)

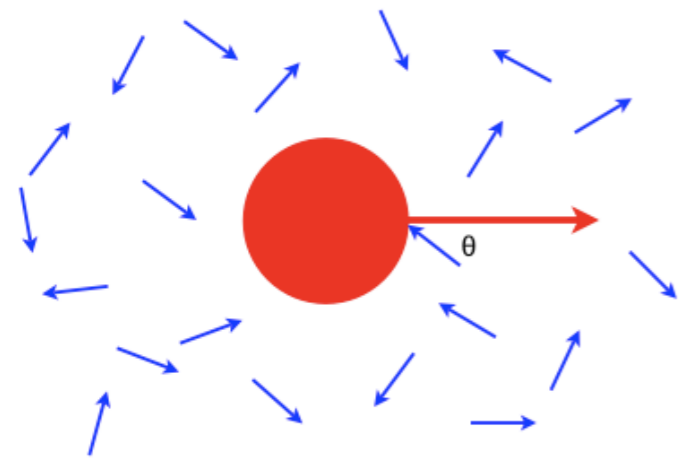
20 TeV



equatorial coordinates

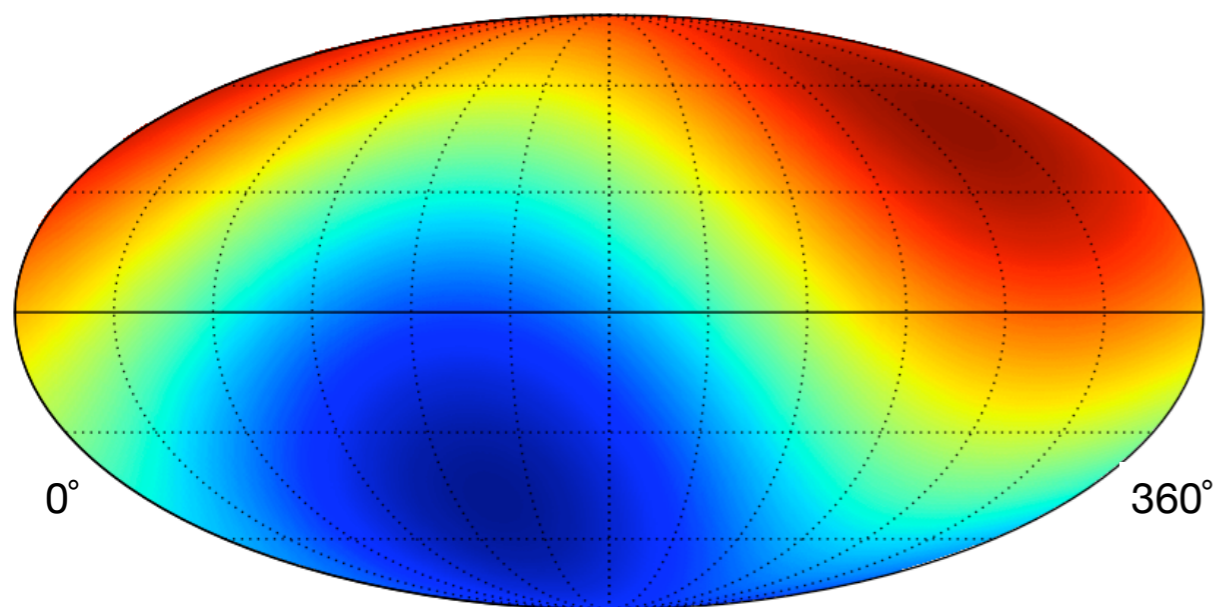
- ▶ data from March 2008 to May 2009
- ▶ ~360 days livetime
- ▶ $\sim 12 \cdot 10^9$ events
- ▶ median angular resolution $\sim 3^\circ$
- ▶ median CR energy ~ 20 TeV

origin of large scale anisotropy : Compton-Getting Effect



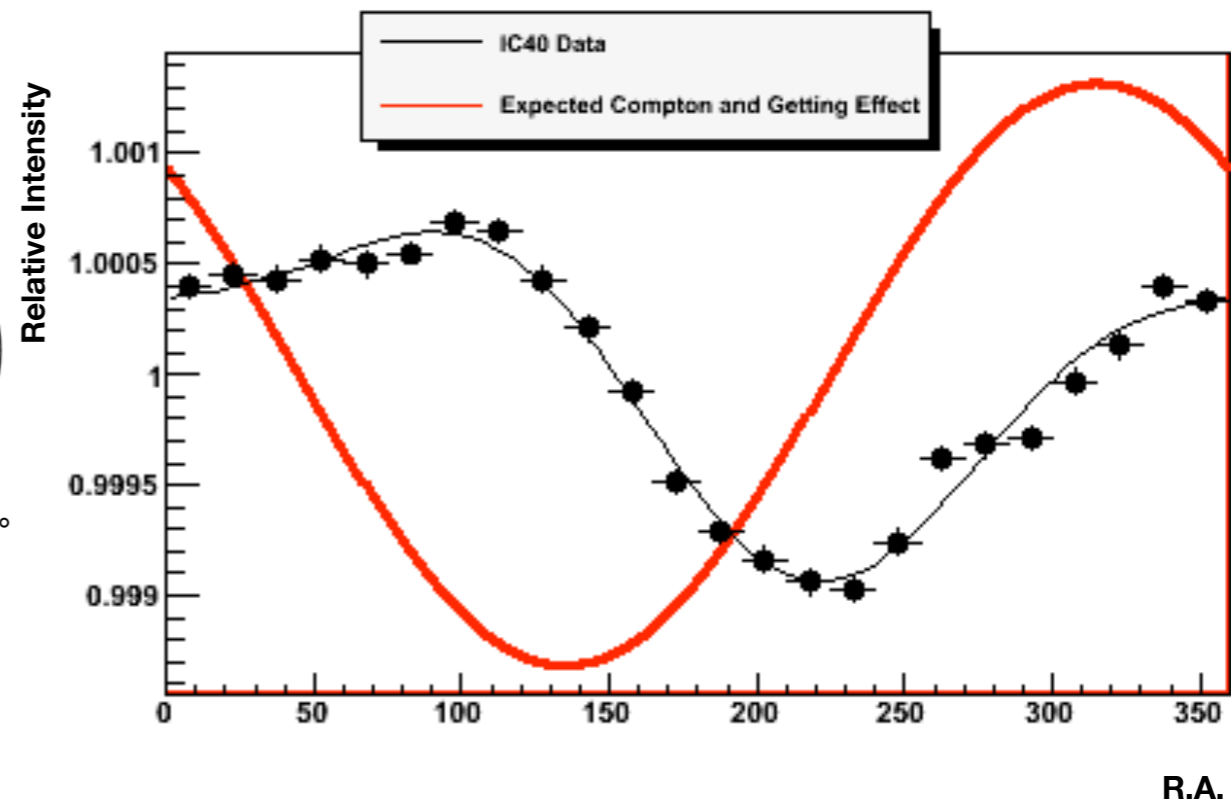
$$\frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta$$

Compton & Getting, Phys. Rev. 47, 817 (1935)

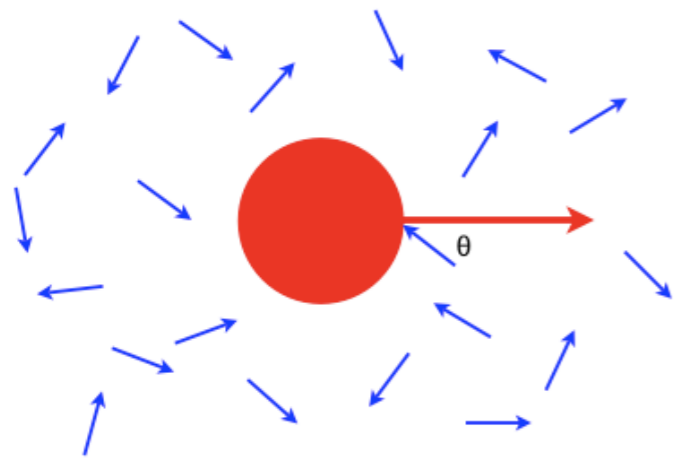


galactic cosmic ray anisotropy - Paolo Desiati

- ▶ apparent energy-independent $\sim 10^{-3}$ dipole anisotropy due to relative motion of solar system through ISM
- ▶ motion of solar system around galactic center ~ 220 km/s
- ▶ reference system of cosmic rays is unknown

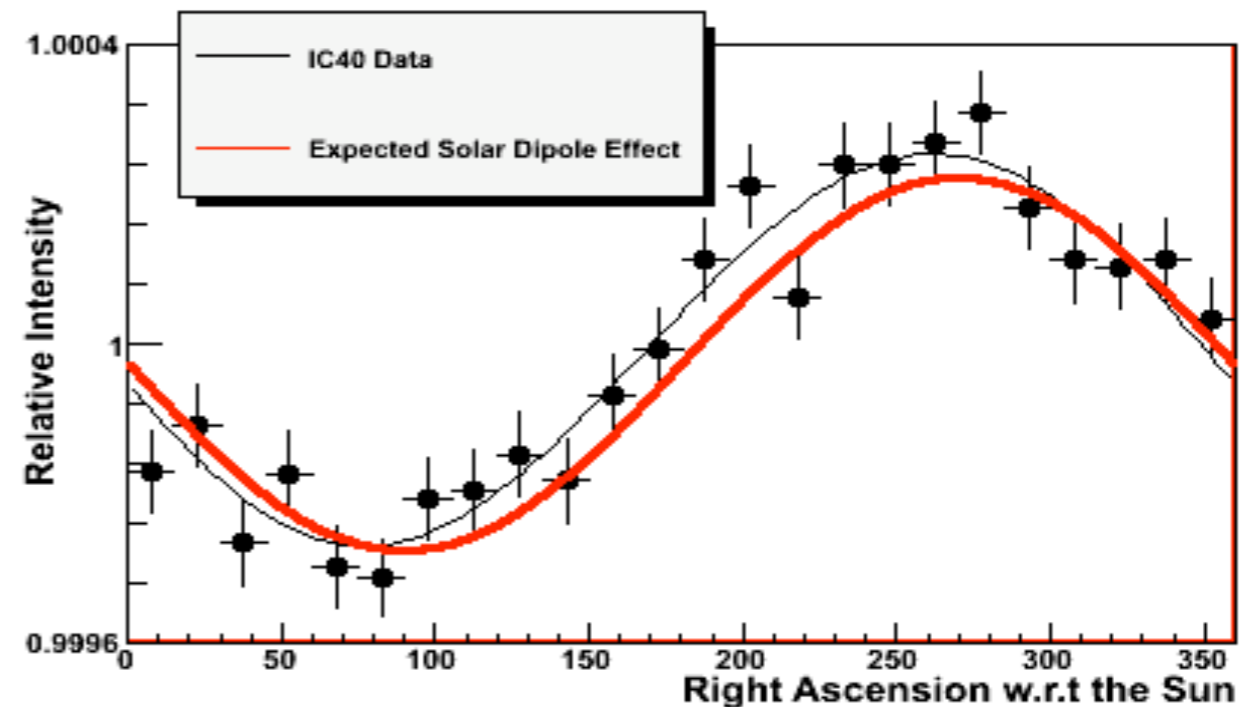
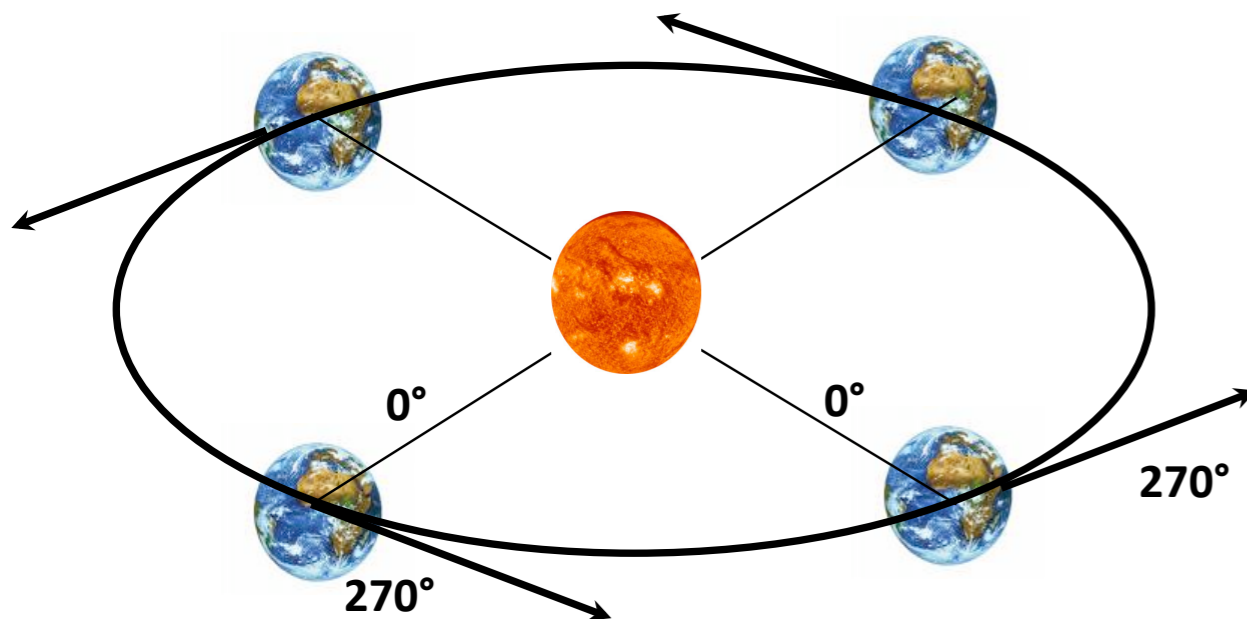


origin of large scale anisotropy : solar dipole

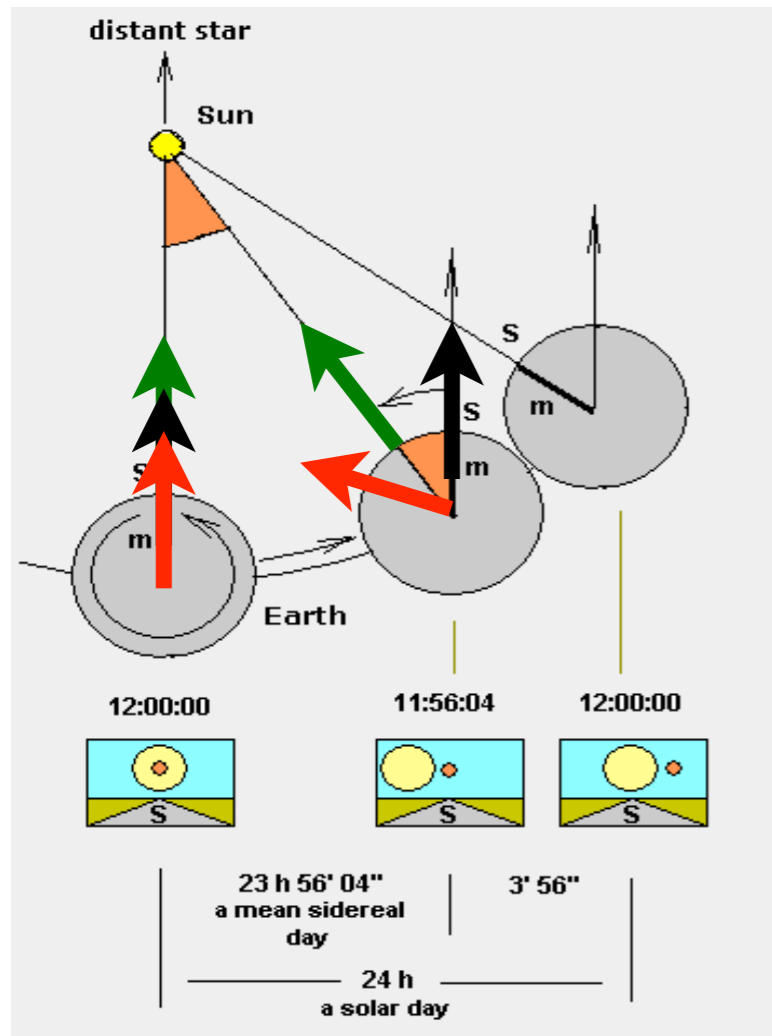


$$\frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta$$

- ▶ apparent energy-independent $\sim 10^{-4}$ dipole anisotropy due to relative motion of Earth around the Sun
- ▶ motion of Earth around the Sun ~ 29 km/s
- ▶ reference system of cosmic rays is well known



origin of large scale anisotropy : spurious effects



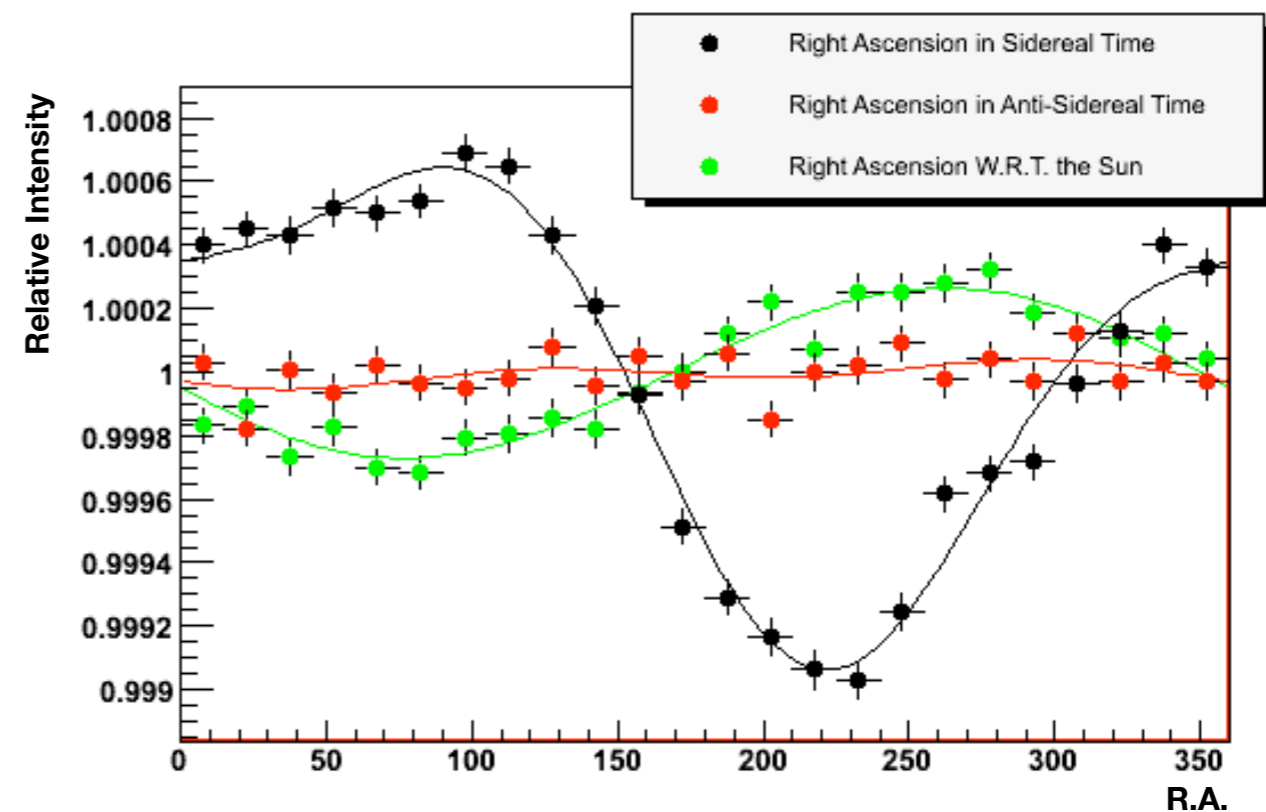
solar time

sidereal time

anti-sidereal time

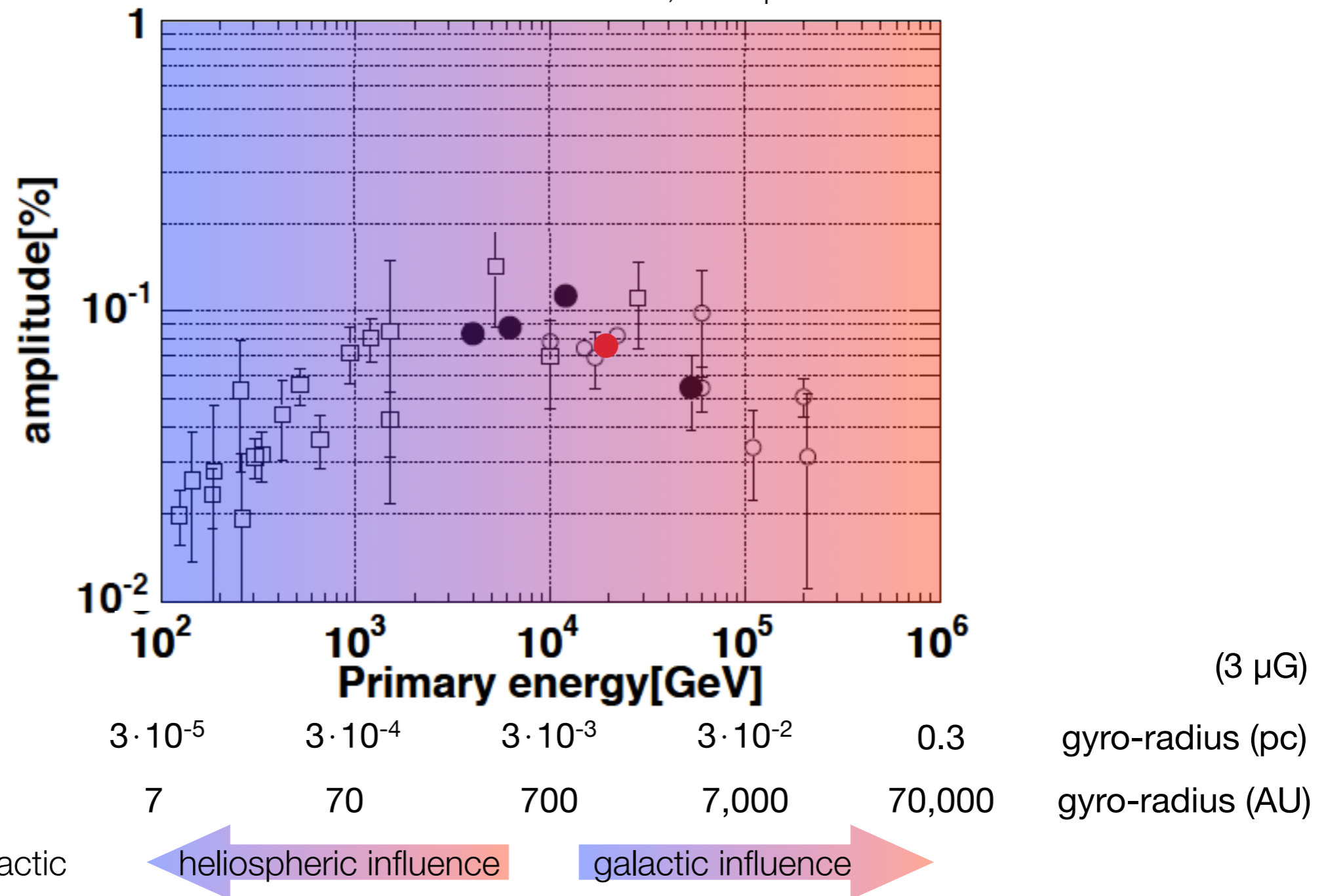
- ▶ a yearly-modulated daily variation induces a spurious sidereal modulation : modulation in anti-sidereal time
- ▶ non physical coordinate that results in scrambling directions
- ▶ its modulation measures sidereal spurious effect amplitude

Farley et al., Proc. Phys. Soc., 67, 996 (1954)



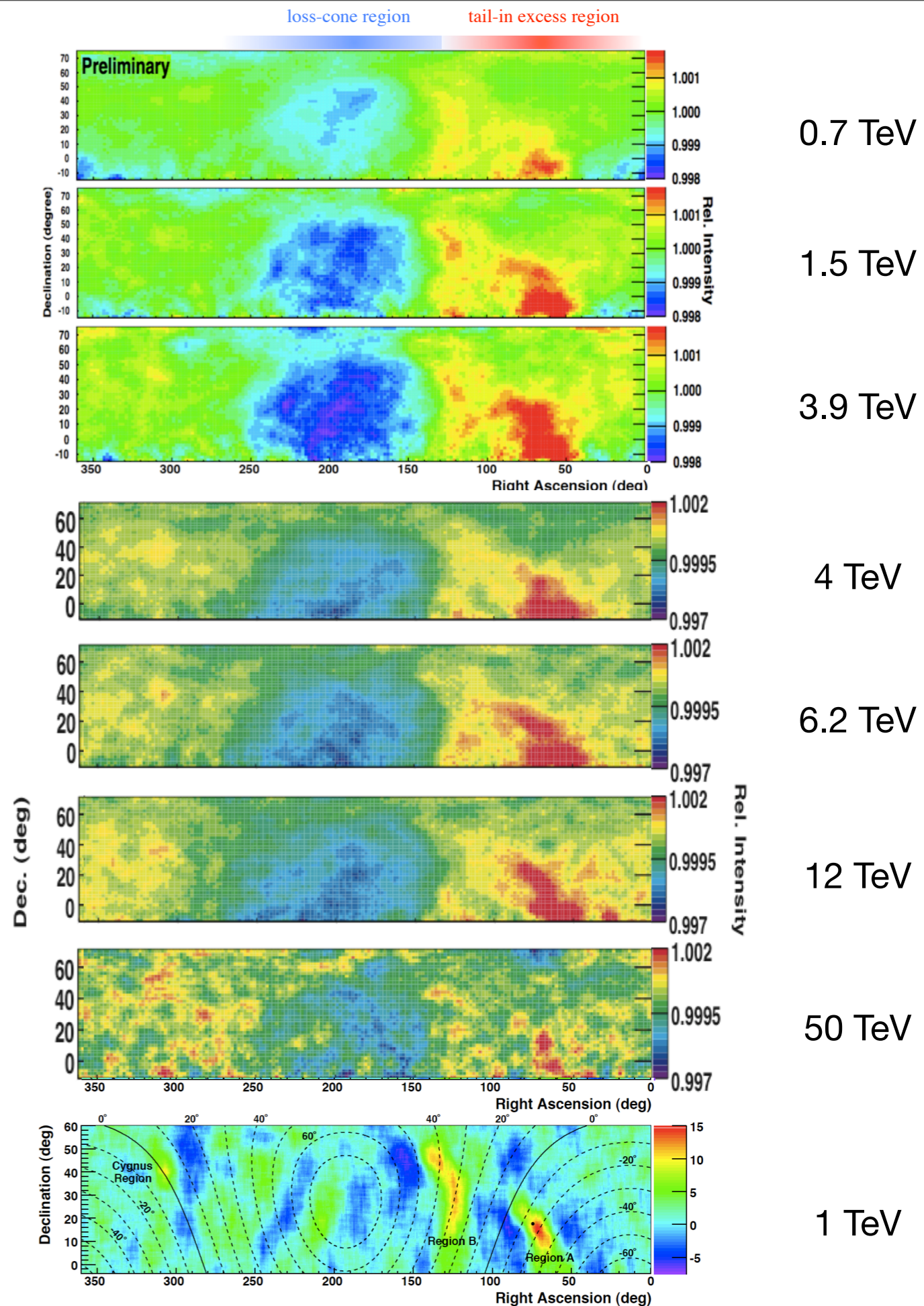
anisotropy vs energy : probing different causes

Amenomori et al., astro-ph/0505114



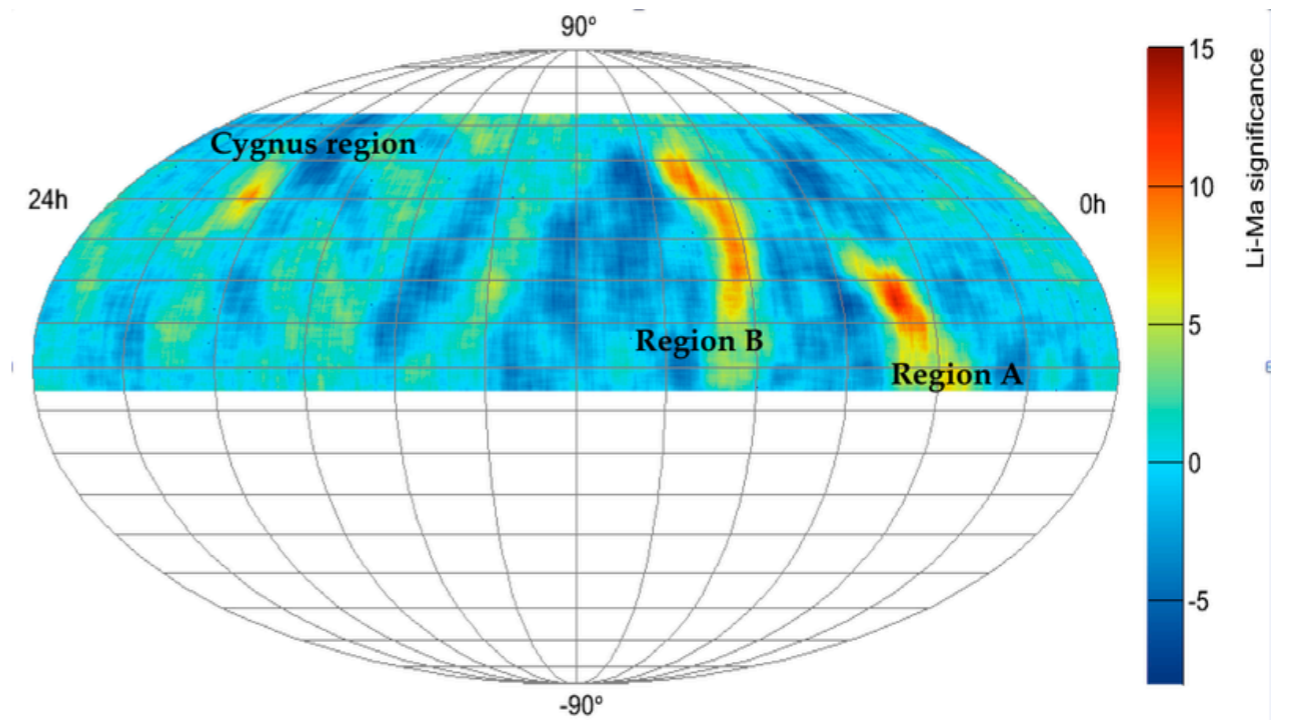
medium / small scale anisotropy

- ▶ large scale anisotropy shows smaller angular features, some of which highly significant
- ▶ their origin is unknown
- ▶ discovery : if eliminating all angular features $> 30^\circ$ MILAGRO discovered two highly significant localized excess regions
- ▶ MILAGRO sky map of statistical significance
- ▶ technique used in gamma ray searches
- ▶ CR spectrum harder than diffuse < 10 TeV

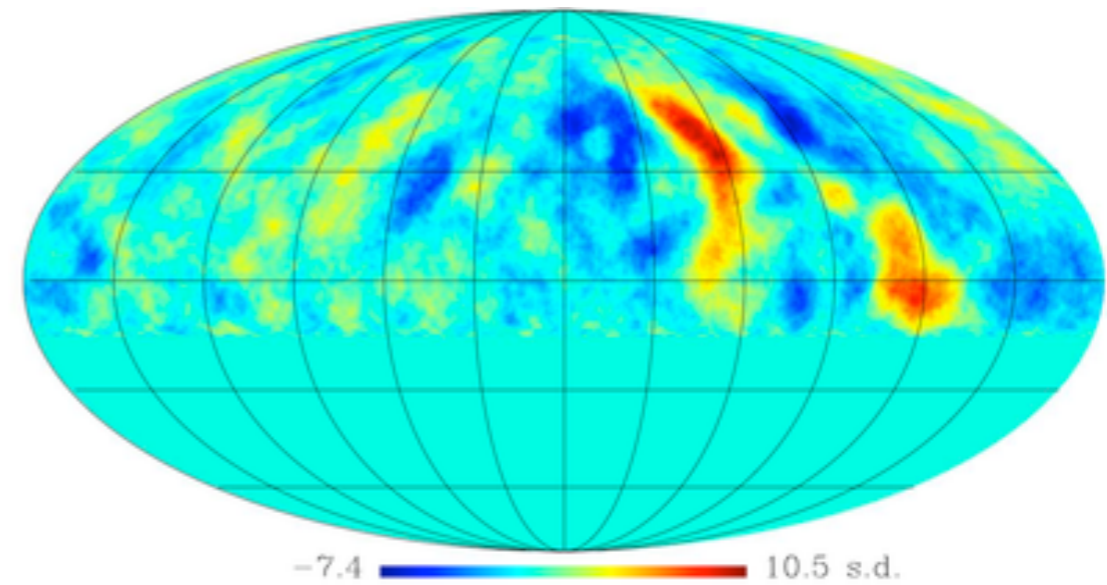


medium / small scale
anisotropy

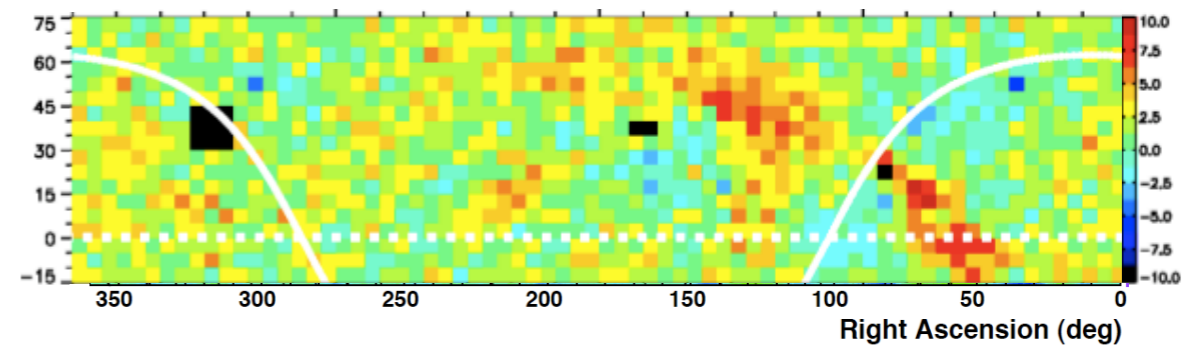
Milagro



ARGO-YBJ



Tibet-III



medium / small scale anisotropy

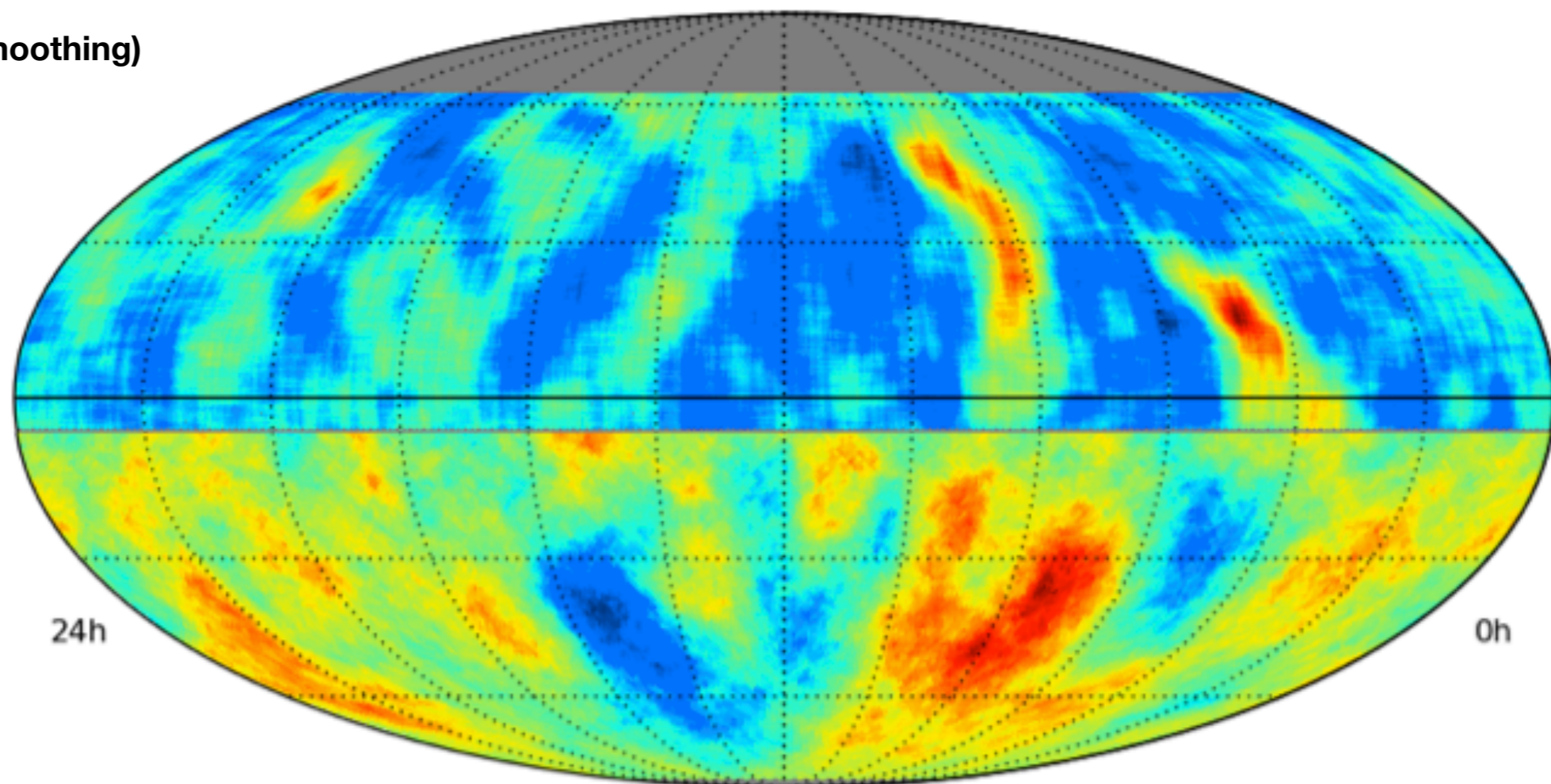
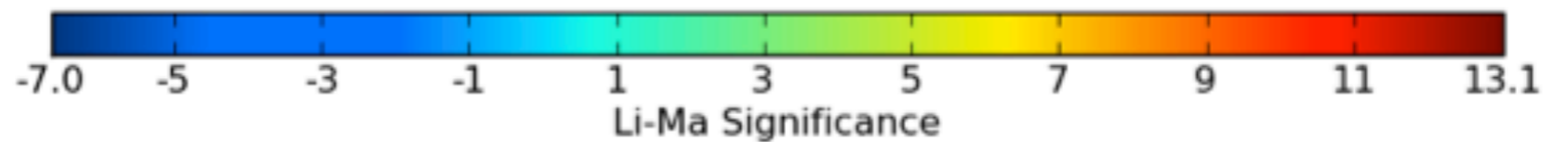
PRELIMINARY

Milagro

$2.2 \cdot 10^{11}$ events

median energy ~ 1 TeV

(2 hr integration $\sim 30^\circ$ cut-off, 10° smoothing)

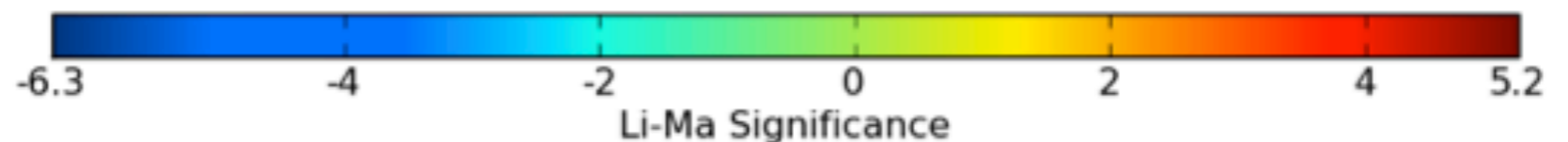


IceCube-40

$12 \cdot 10^9$ events

median energy ~ 20 TeV

(4 hr integration $\sim 60^\circ$ cut-off, 10° smoothing)



medium / small scale anisotropy

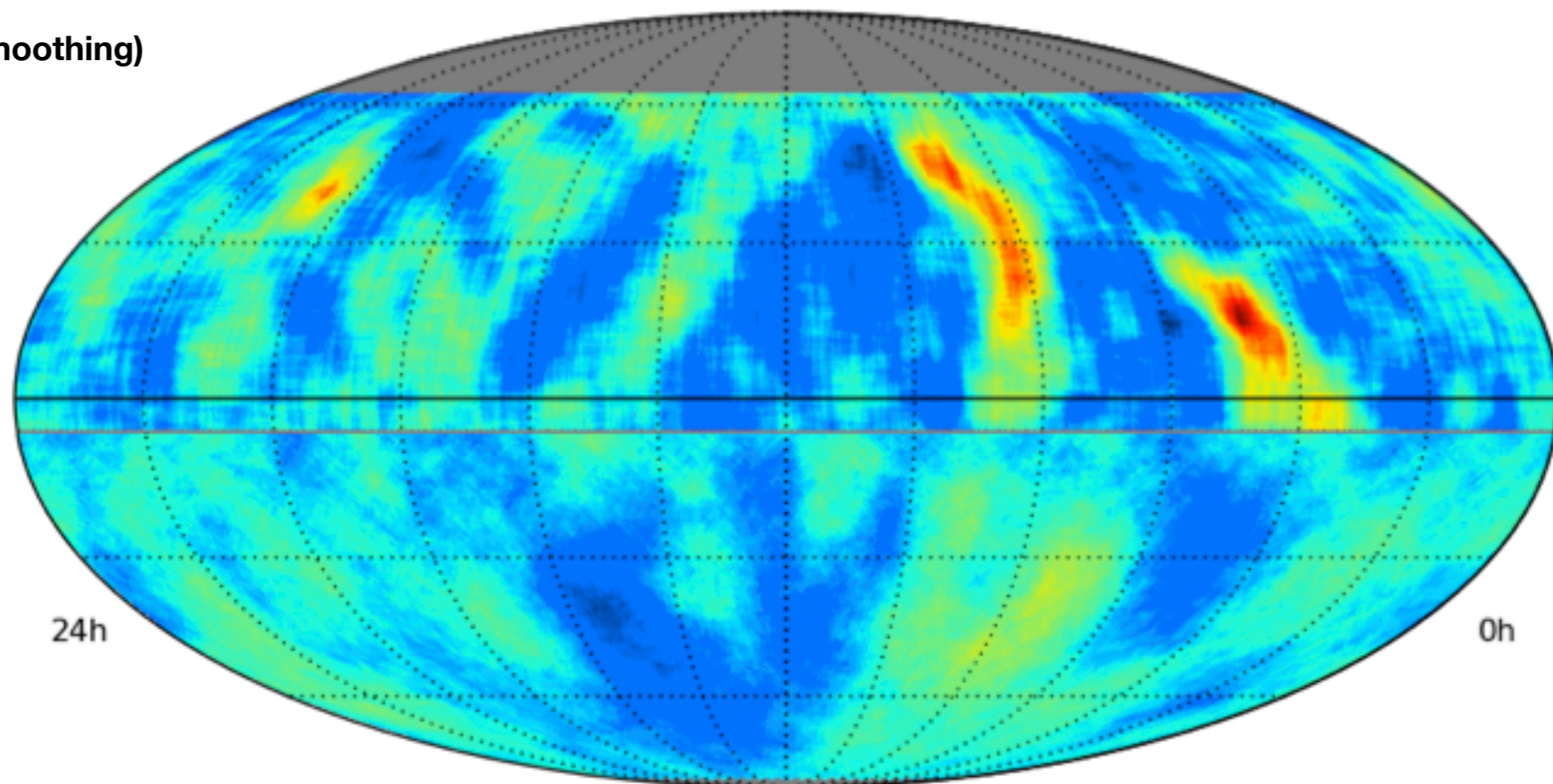
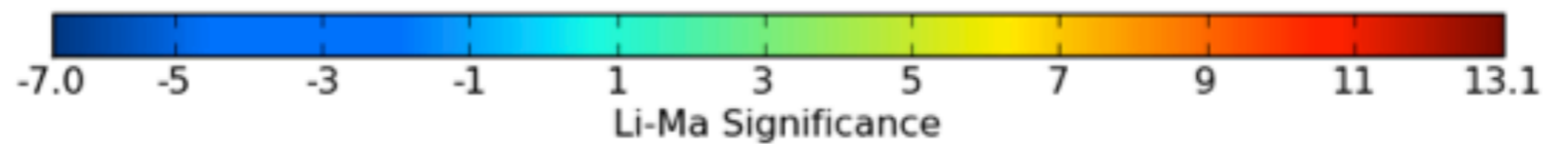
PRELIMINARY

Milagro

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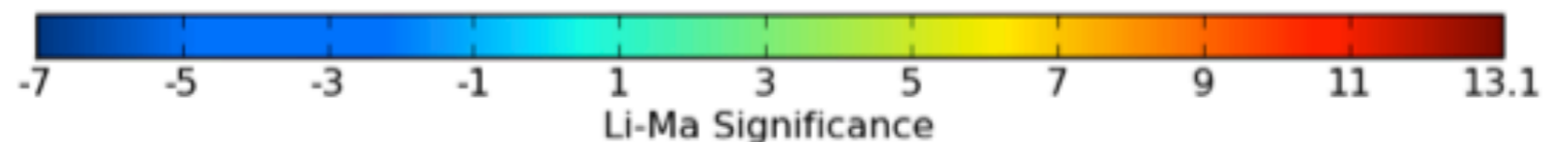


IceCube-40

$12 \cdot 10^9$ events

median energy ~ 20 TeV

(4 hr integration $\sim 60^\circ$ cut-off, 10° smoothing)



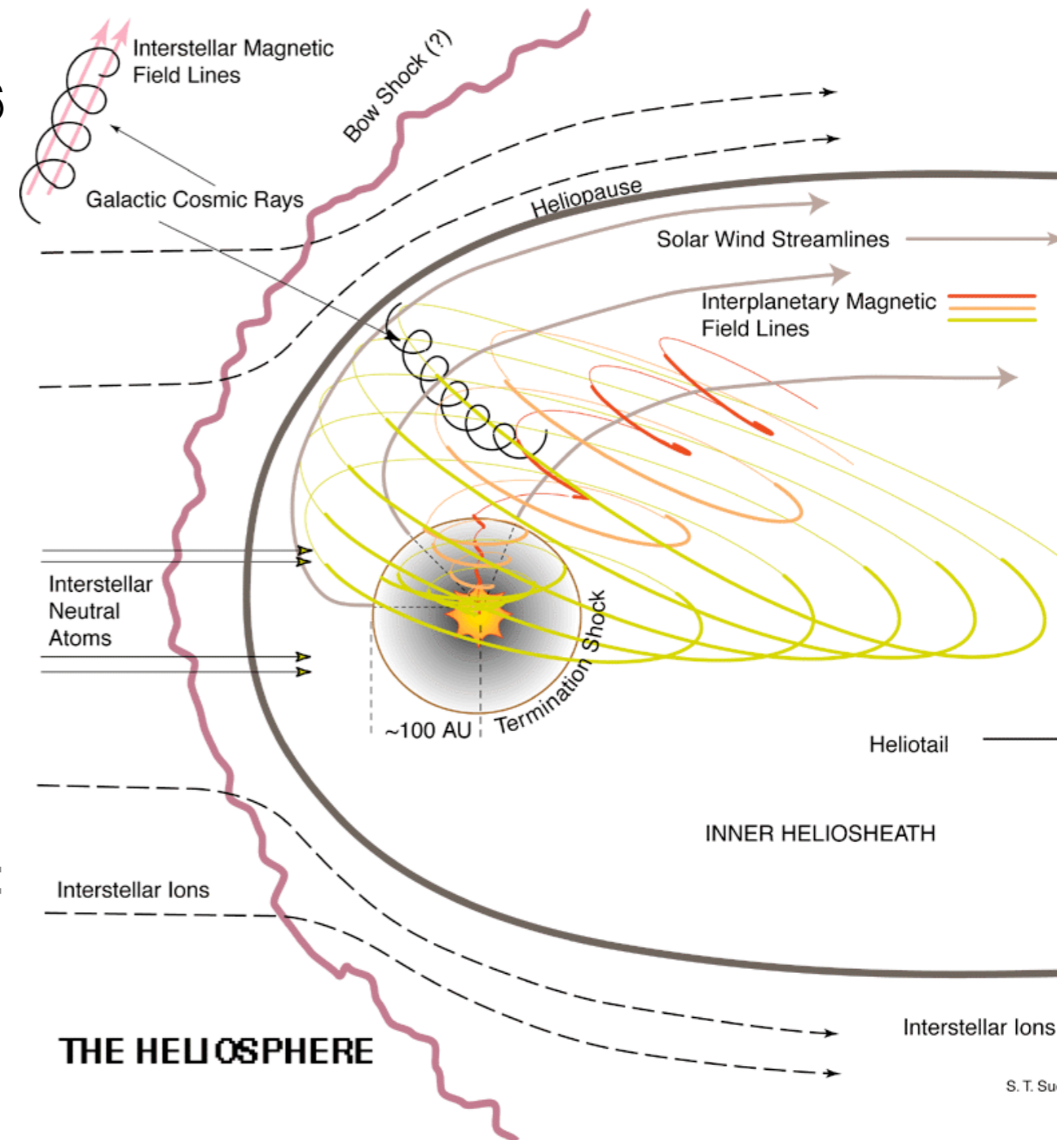
conclusions

- anisotropy in arrival direction of cosmic rays observed in GeV - 100 TeV range
- anisotropy as probe of Heliosphere, LISM and LIMF
- anisotropy and astrophysical sources of cosmic rays
- diffusion properties of cosmic rays
- connection spectral features / anisotropy
- angular & energy scale of anisotropy and their connection to distance scale

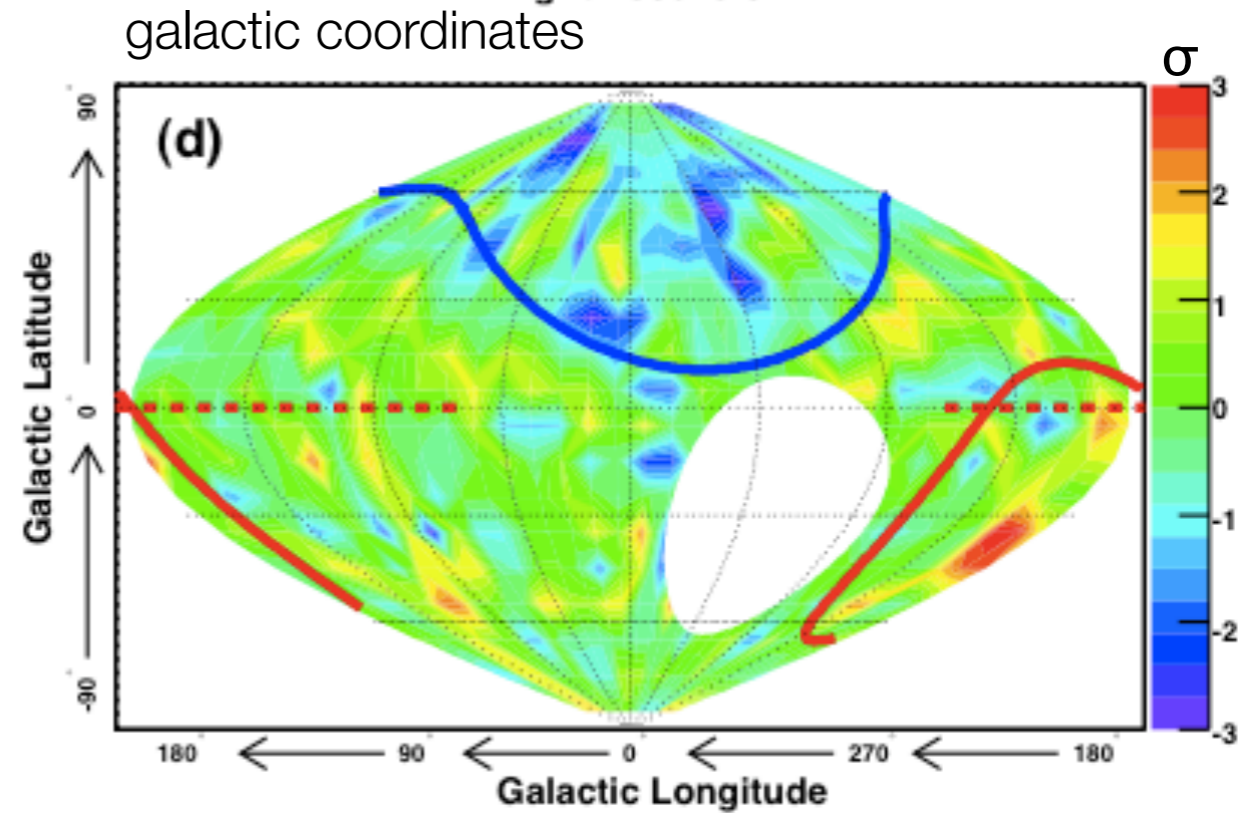
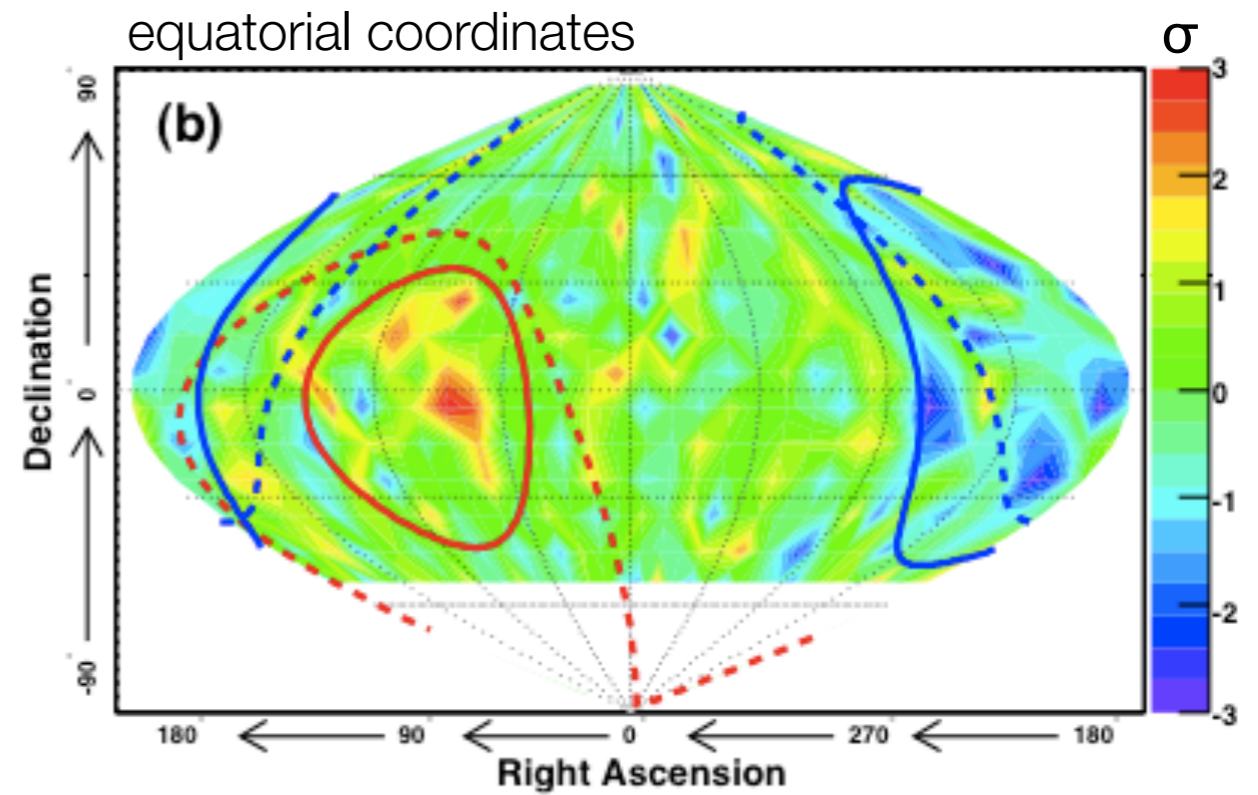
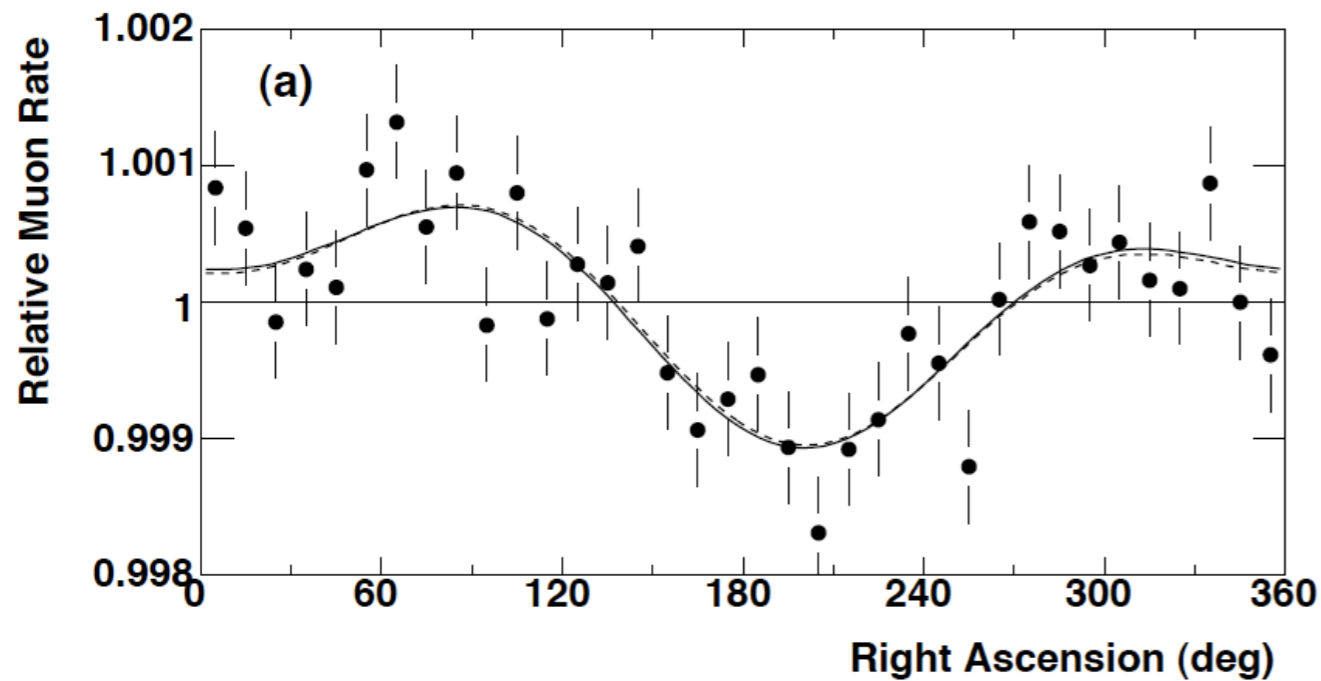
extra slides

heliosphere

- solar system moves wrt IS medium at 26 km/s
- solar wind diverts interstellar plasma at 400-800 km/s
- termination shock @ solar pressure ~ interstellar pressure : ~ 100 AU
- solar and interstellar medium (& magnetic field) separated by heliopause : ~ 150-200 AU
- helio-tail size up to ~ 10,000 AU ?



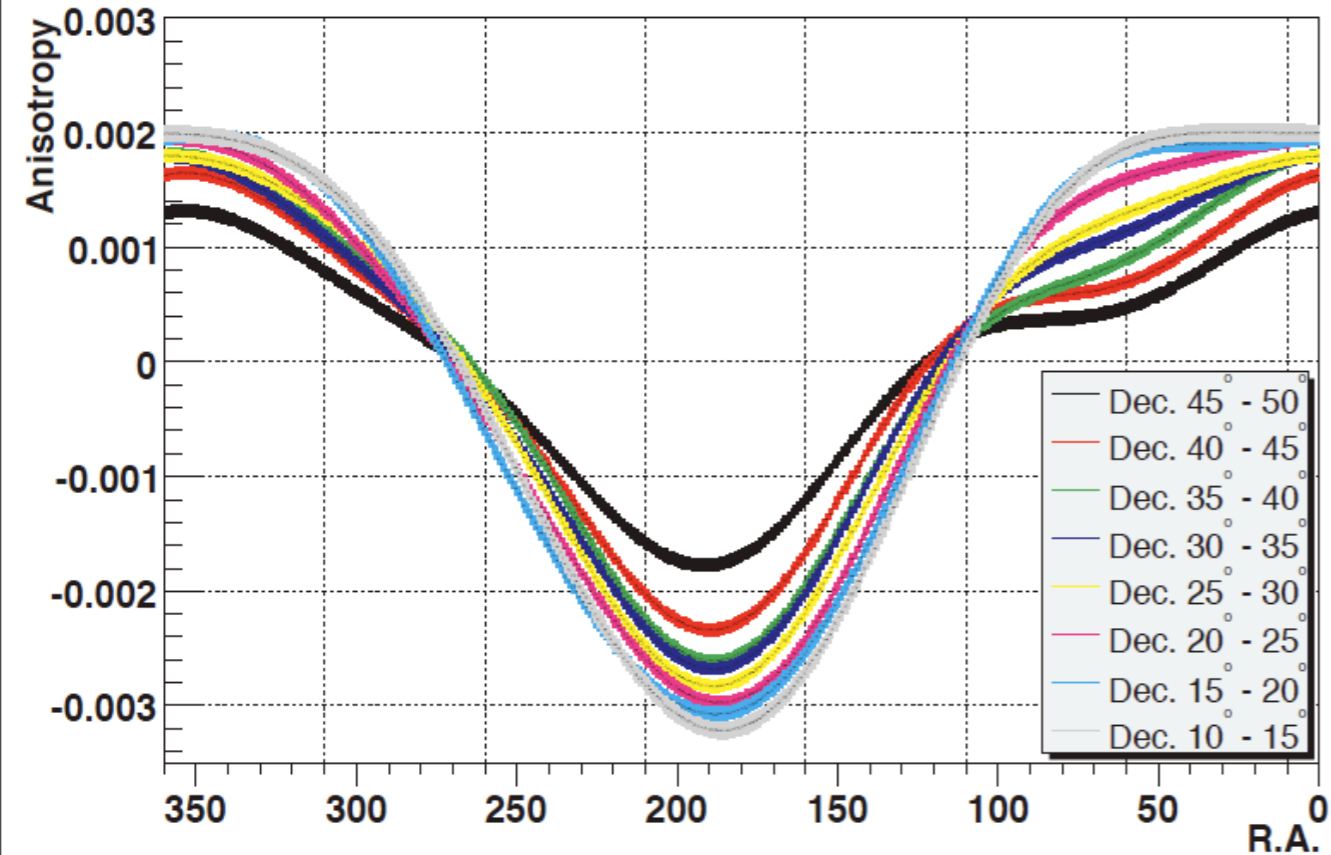
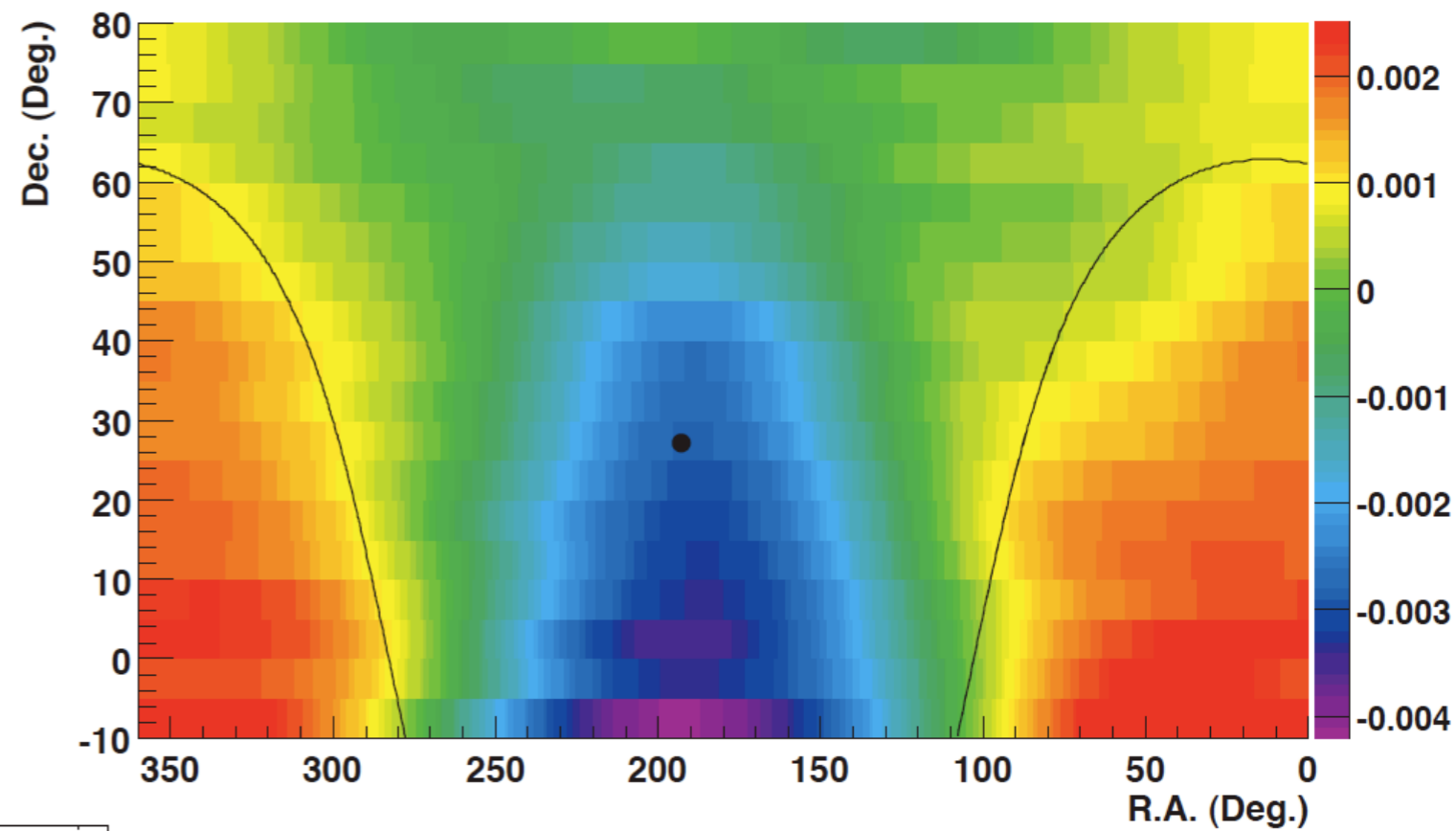
- ▶ data from 1996 to 2001
- ▶ 1662 days livetime
- ▶ $2.1 \cdot 10^8$ events
- ▶ angular resolution $< 2^\circ$
- ▶ median CR energy ~ 10 TeV



Super-Kamiokande

2D skymap of statistical significance (normalized in each declination band)

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



Milagro

2D skymap of relative intensity
(normalized in each declination band)

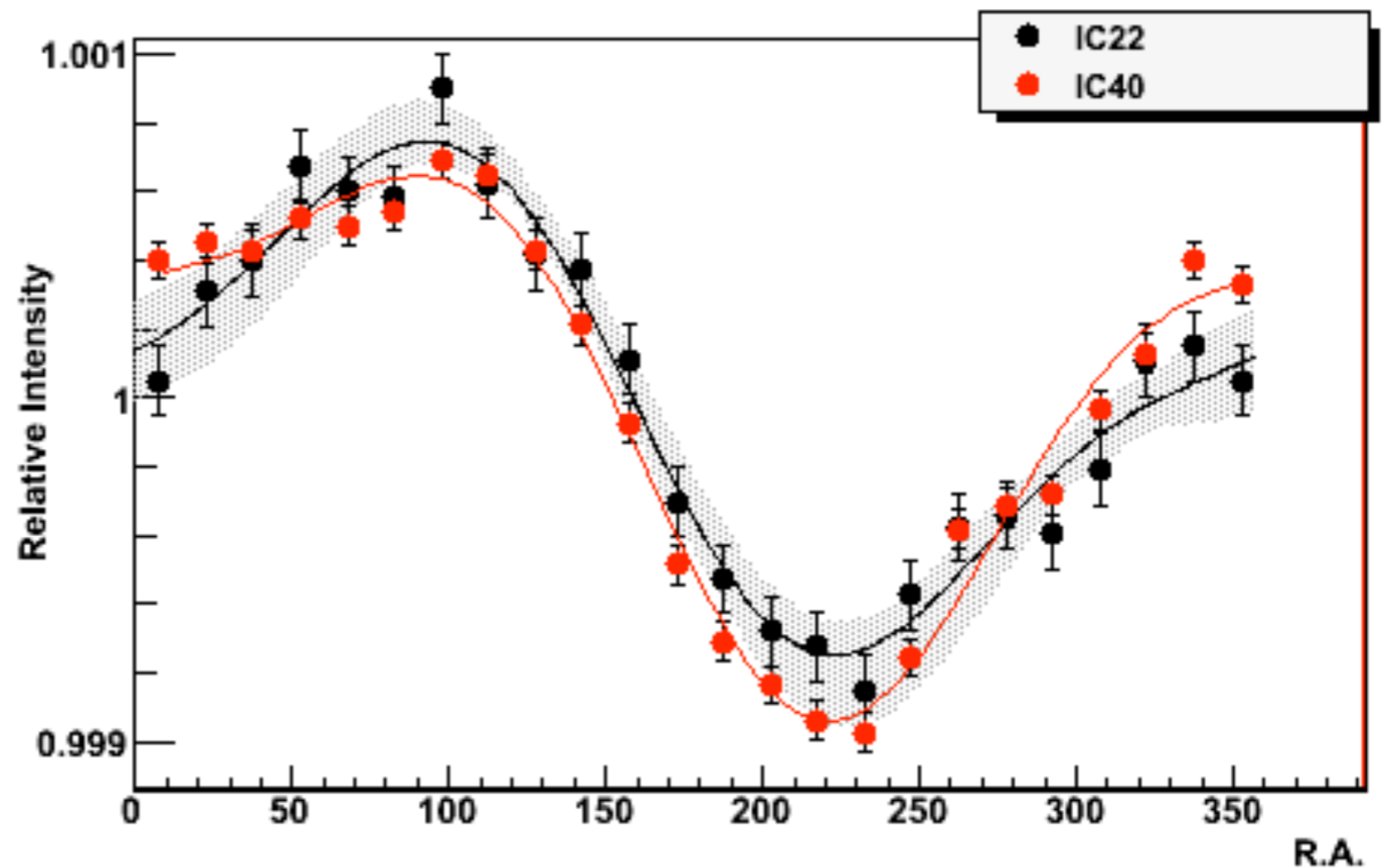
cosmic ray anisotropy in arrival direction

Abbasi et al., submitted to ApJ Letters

- ▶ data stability (gray band) :
 - ▶ seasonal variations
 - ▶ data time coverage
 - ▶ event rates

IceCube-22

IceCube-40

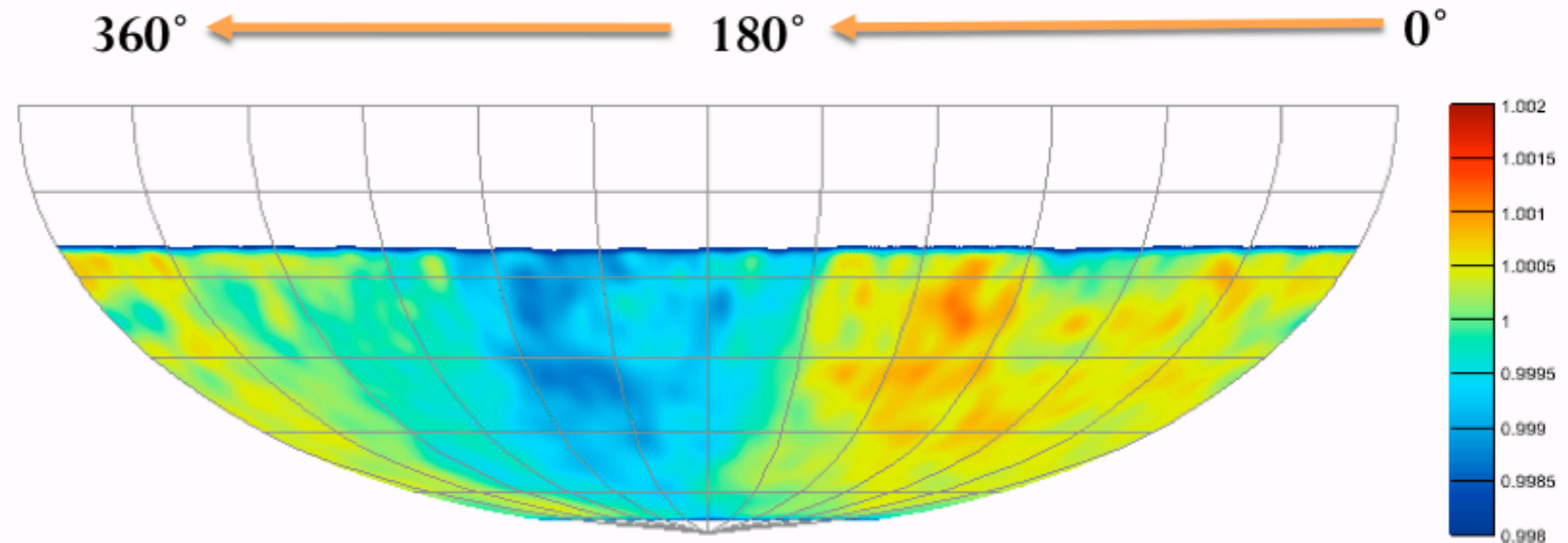


cosmic ray anisotropy in arrival direction

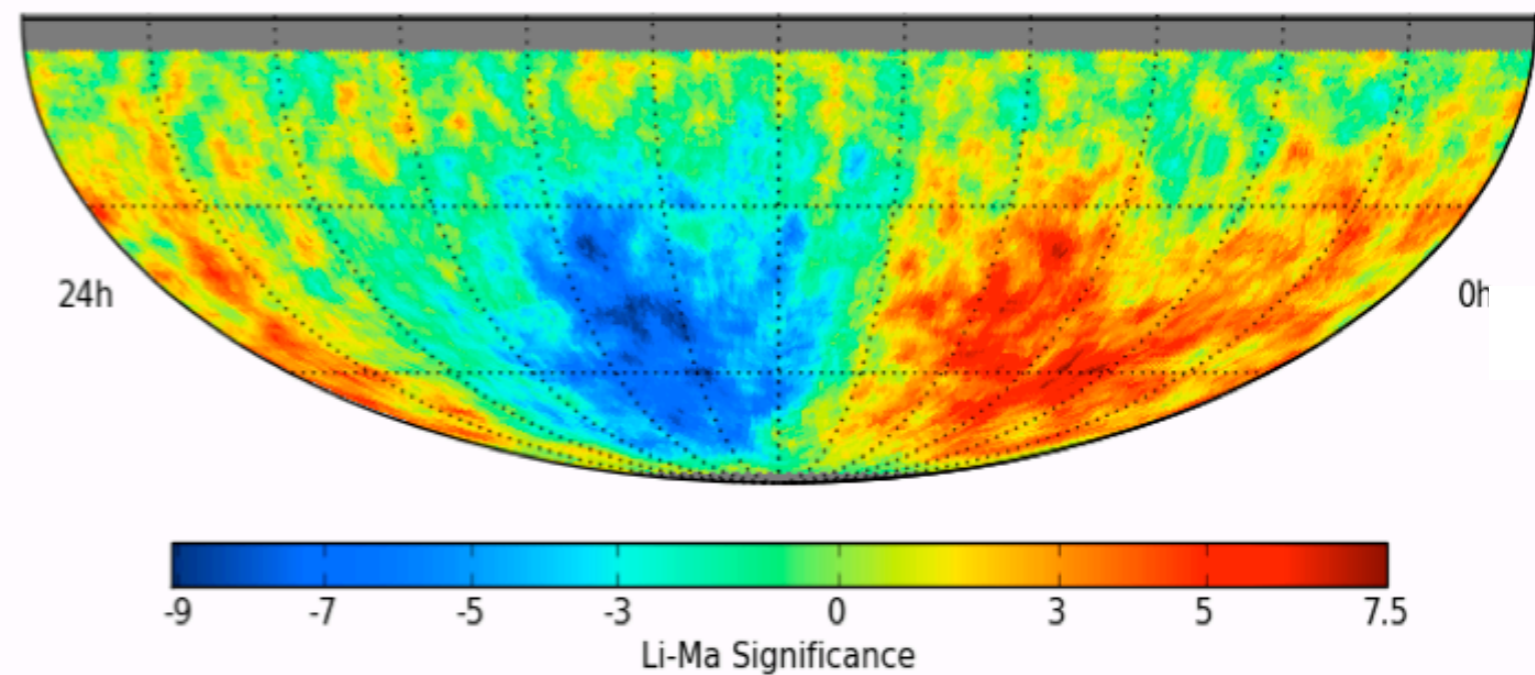
IceCube-40

PRELIMINARY

relative intensity
(declination bands independently
normalized)

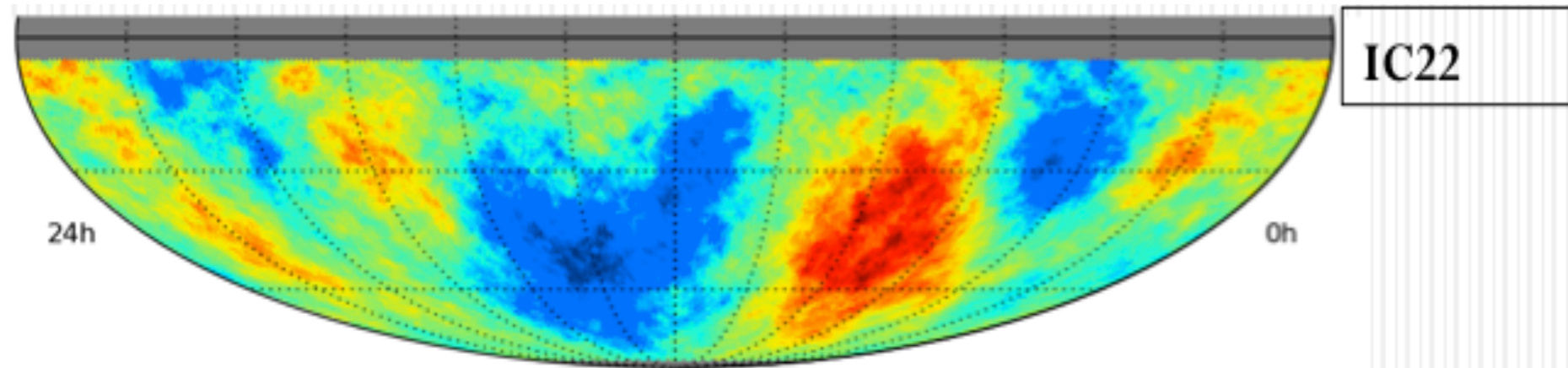


statistical significance
(4 hr integration, 3° smoothing)

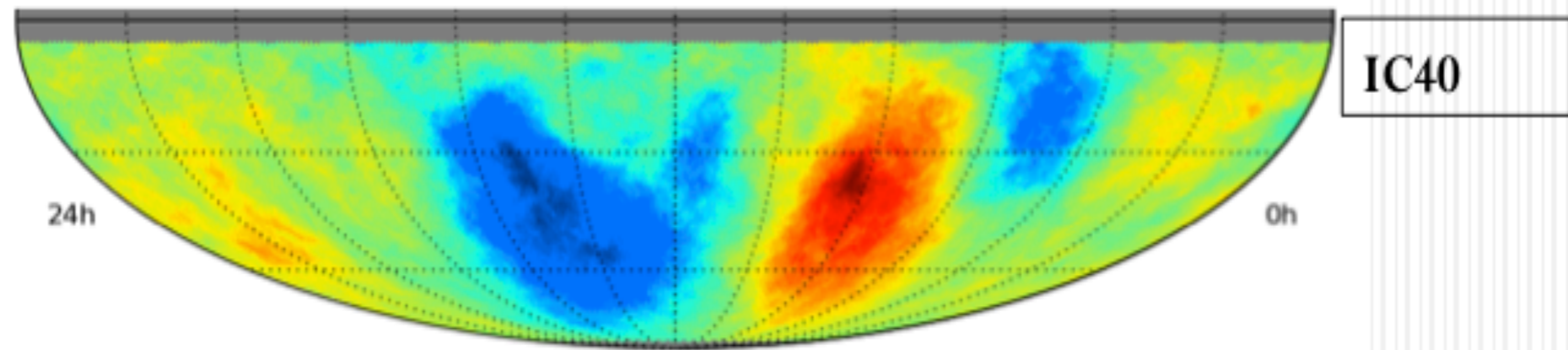


medium / small scale anisotropy

PRELIMINARY



statistical significance
(4 hr integration, 20° smoothing)



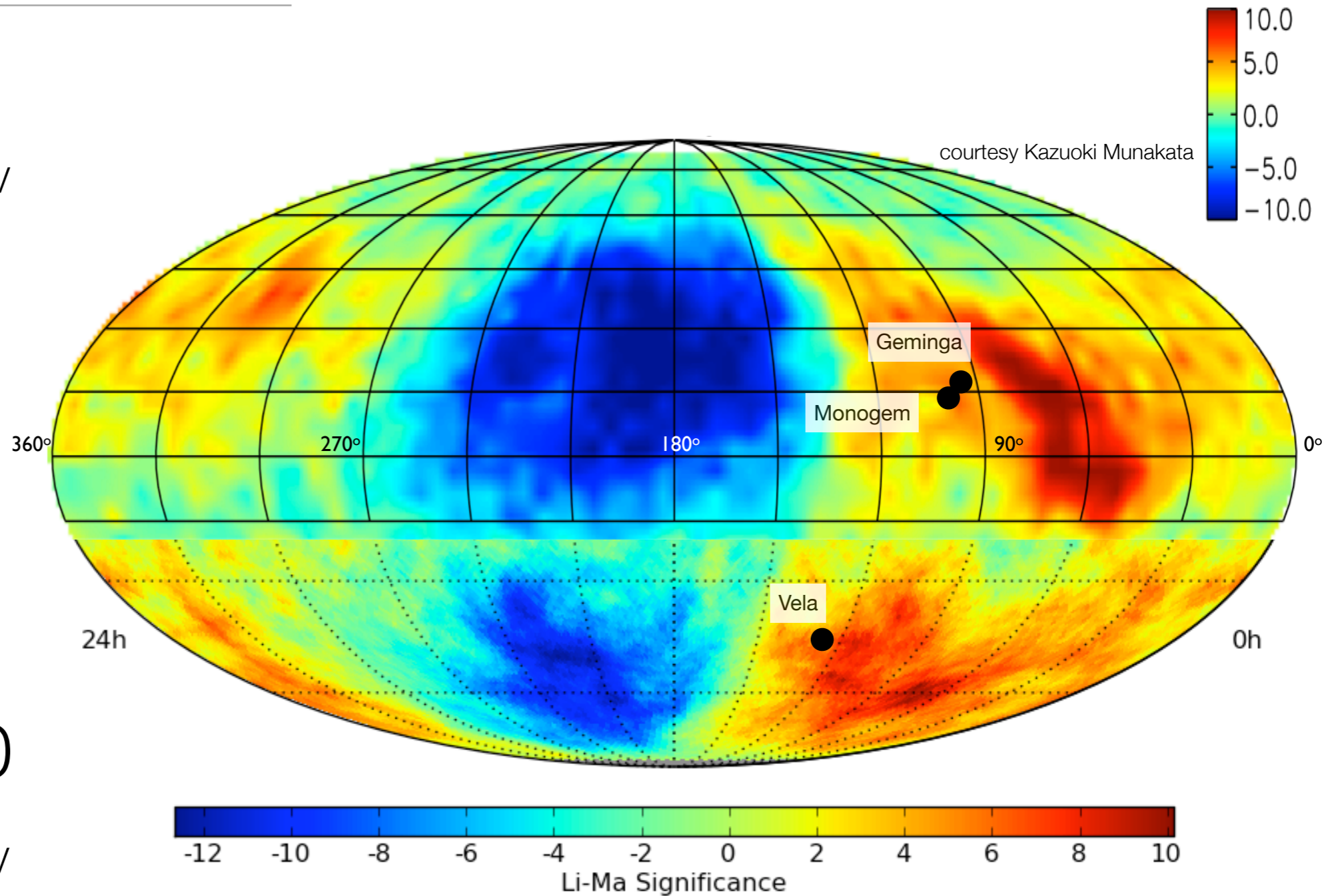
large scale anisotropy

Tibet-III

$3.7 \cdot 10^{10}$ events
modal energy ~ 3 TeV
(5° smoothing)

PRELIMINARY

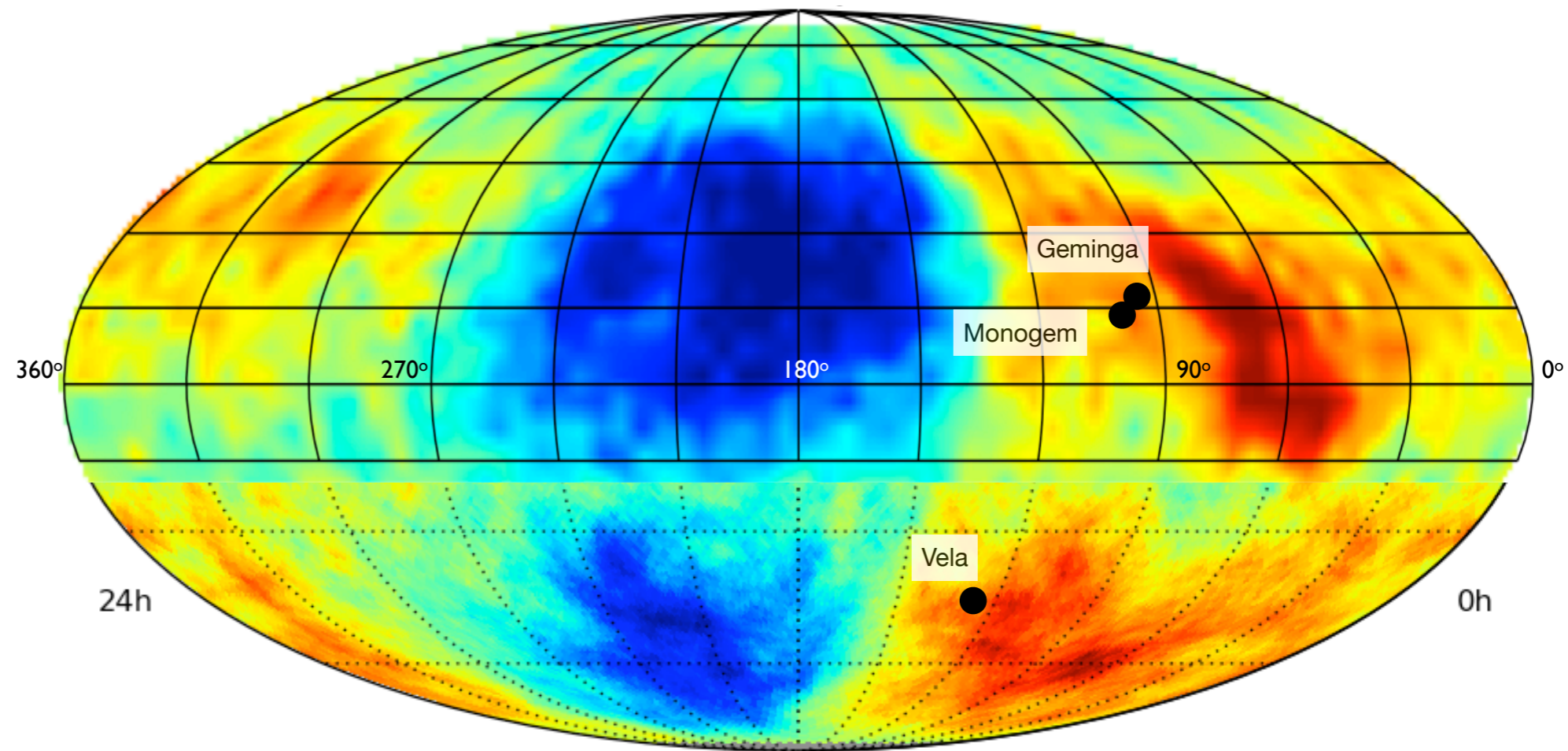
courtesy Kazuoki Munakata



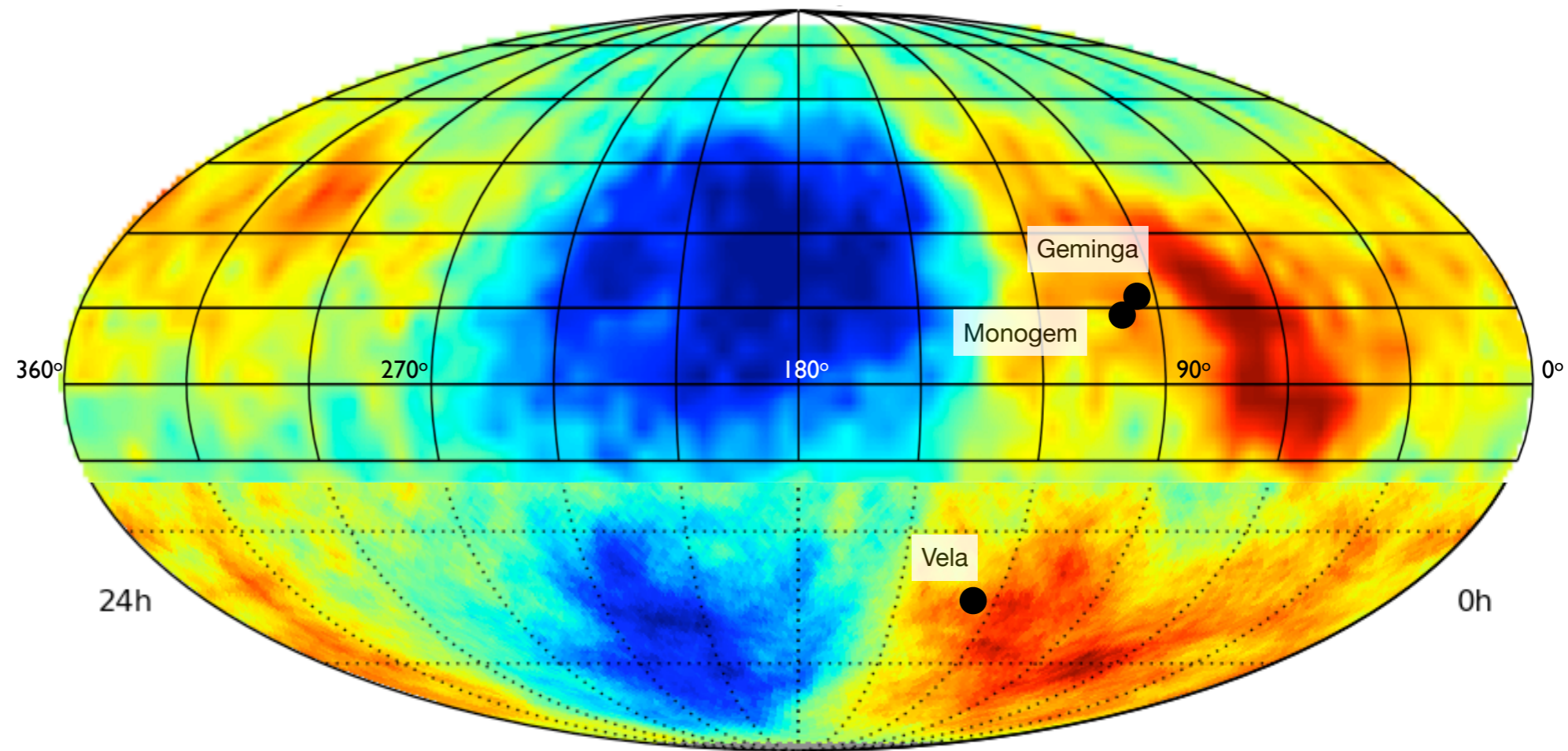
IceCube-40

$12 \cdot 10^9$ events
median energy ~ 20 TeV
(3° smoothing)

large scale anisotropy



large scale anisotropy



medium / small scale anisotropy

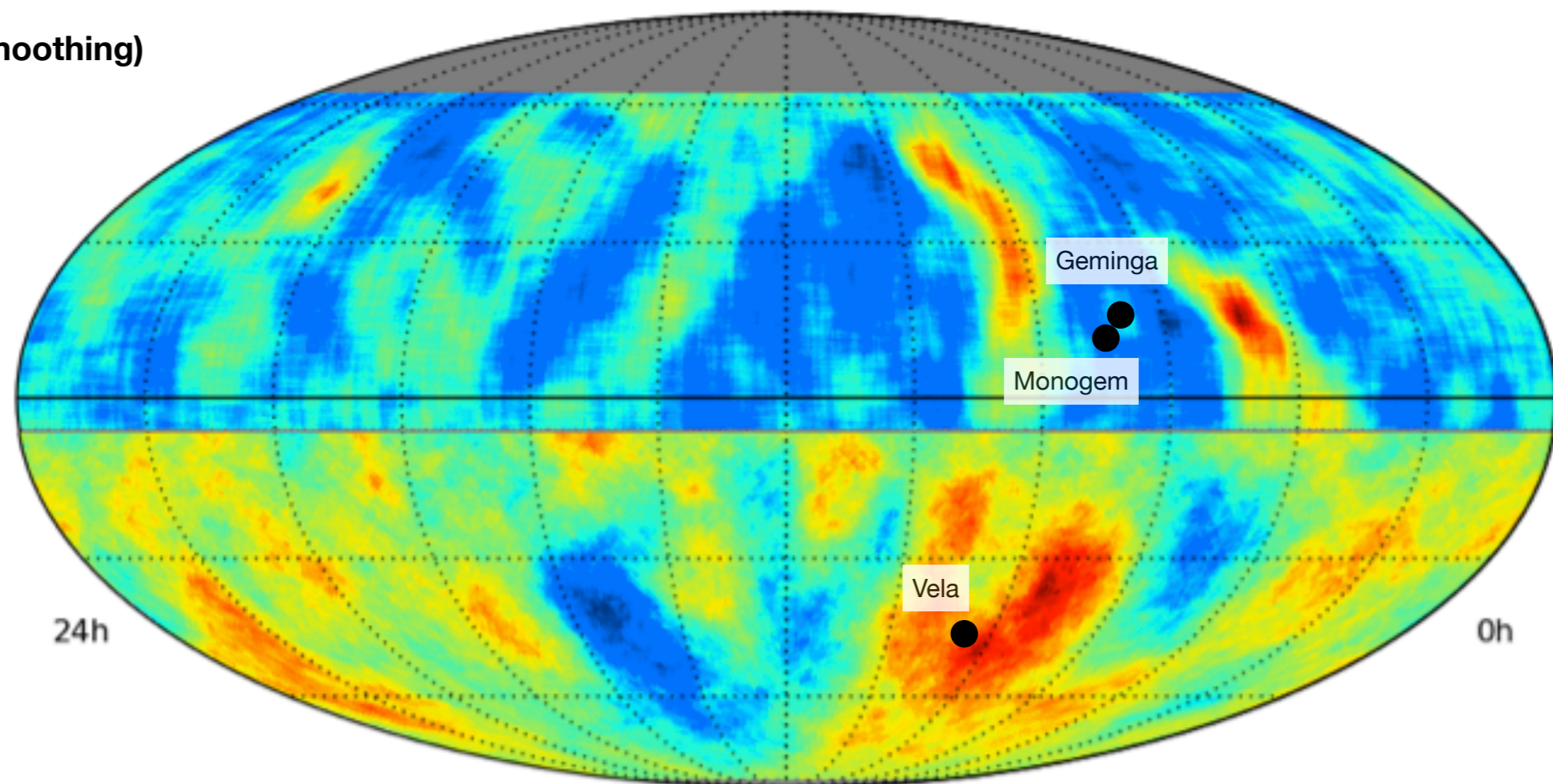
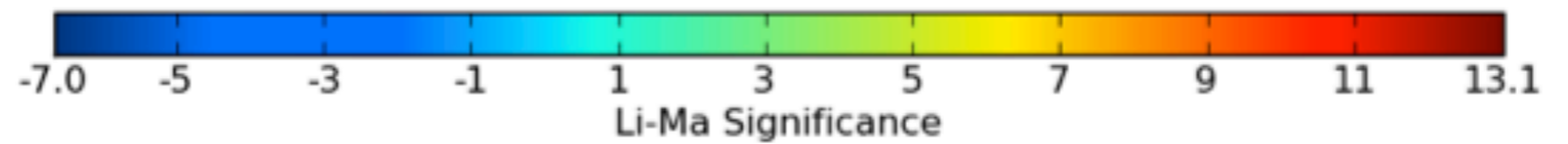
PRELIMINARY

Milagro

$2.2 \cdot 10^{11}$ events

median energy ~ 1 TeV

(2 hr integration $\sim 30^\circ$ cut-off, 10° smoothing)

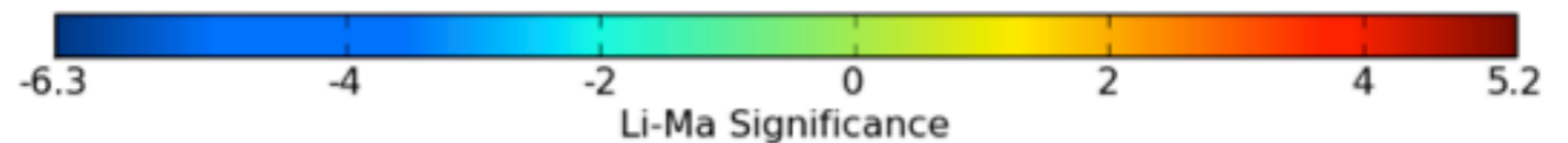


IceCube-40

$12 \cdot 10^9$ events

median energy ~ 20 TeV

(4 hr integration $\sim 60^\circ$ cut-off, 10° smoothing)



harmonic analysis

- ▶ large scale anisotropy pseudo-power spectrum shows smaller angular features, some of which highly significant

- ▶ in small scale analysis $> 60^\circ$ features are cancelled out

PRELIMINARY

