galactic cosmic ray anisotropy
origin, implications and the role of IceCube

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cosmic rays

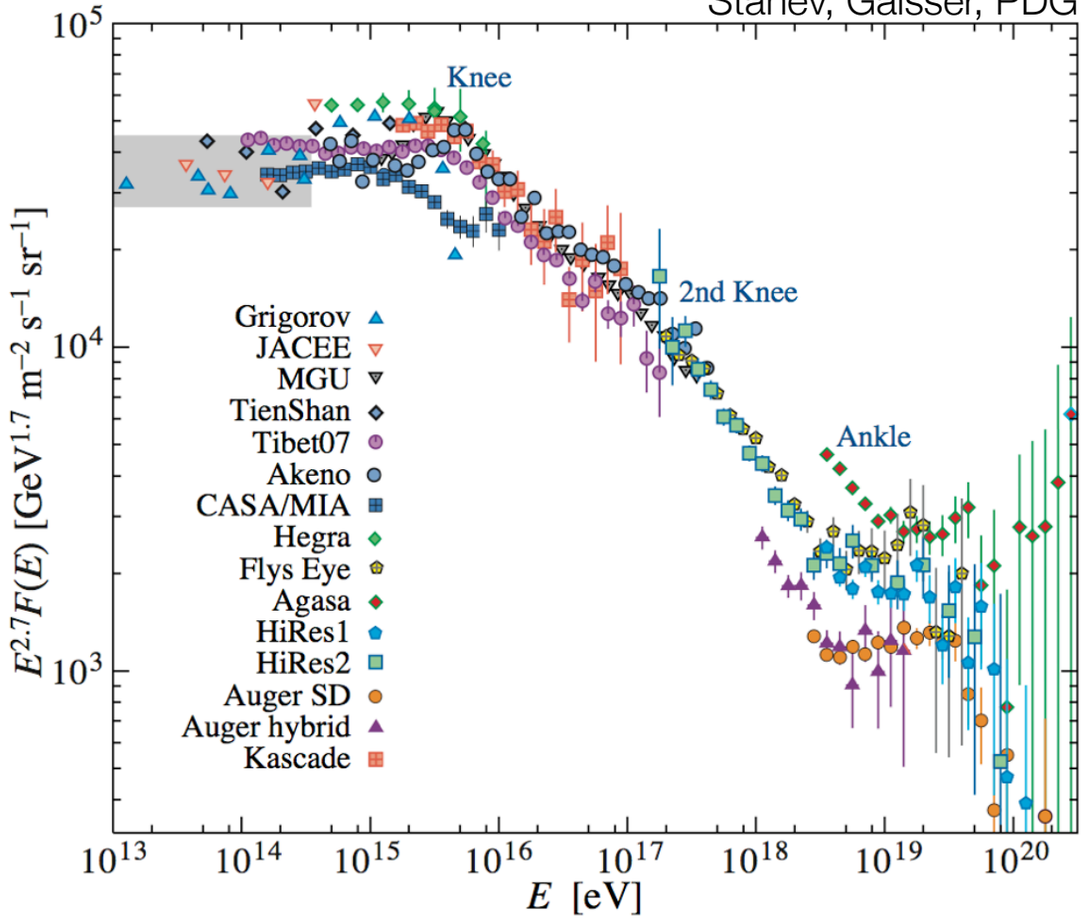
- CR below the knee (~10^6 GeV) believed to be galactic

- CR below ~10^9 GeV believed to be predominantly galactic (transition to extra-galactic @ ~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

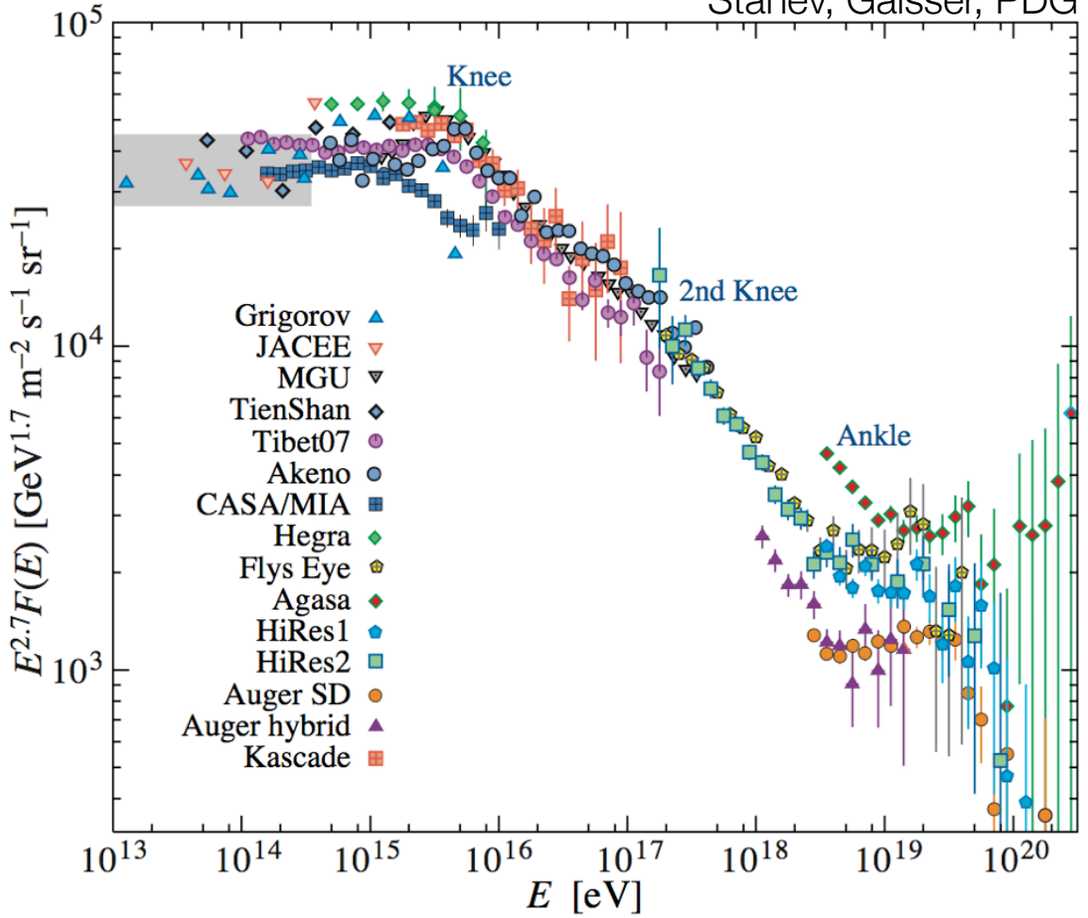


cosmic rays

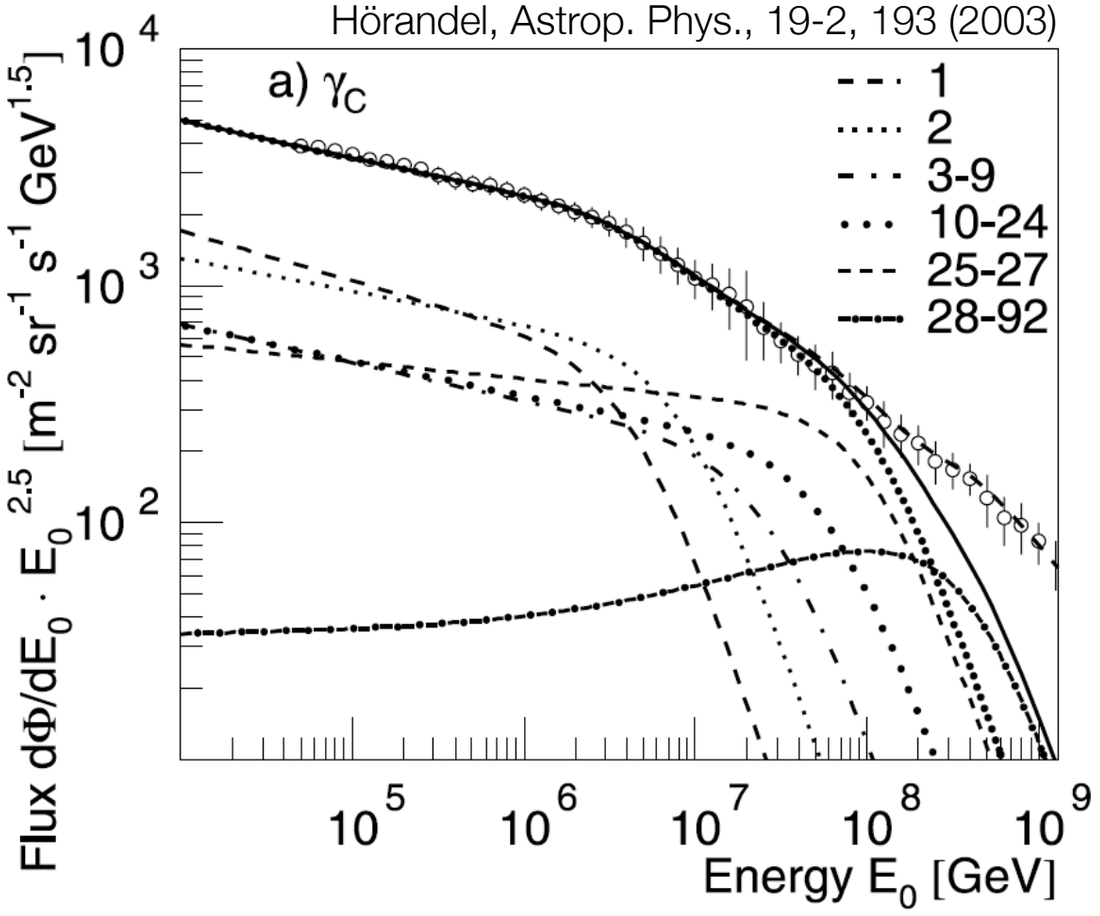
- SNe have enough power to sustain the CR population against escape from the Galaxy and energy losses, if there is a mechanism for channeling ~ O(1)% of the SN mechanical energy release into relativistic particles

- diffuse shock acceleration can accelerate CR up to $3 \cdot 10^{15} \cdot Z$ eV

Stanev, Gaisser, PDG



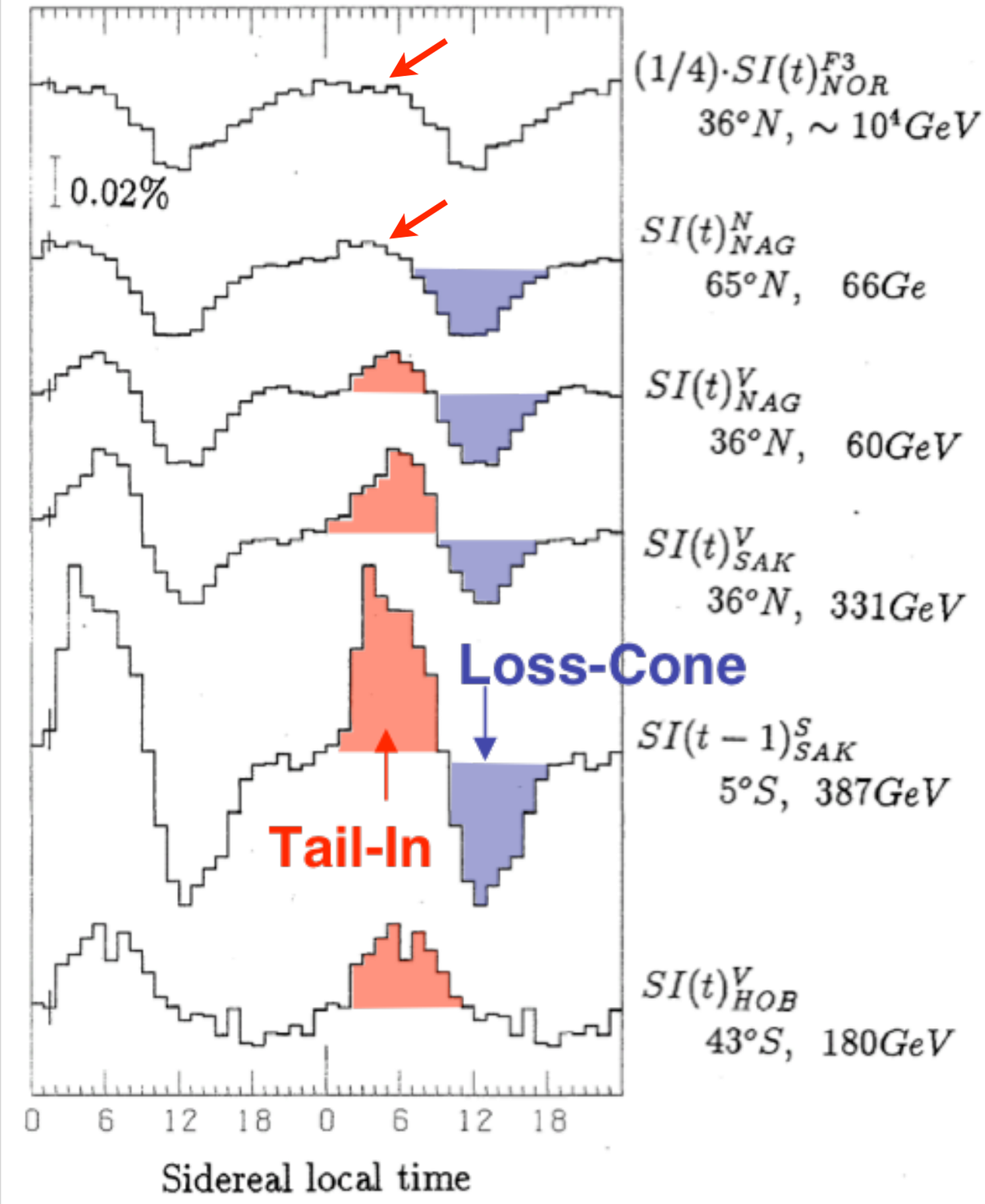
Hörandel, Astrop. Phys., 19-2, 193 (2003)



cosmic ray anisotropy in arrival direction

- Two Hemisphere Network
- anisotropy in arrival direction measured at $10^{-4} \div 10^{-3}$ level
- depends on energy
- depends on declination : north-south asymmetry
- tail-in “excess” modulated in time : max in Dec / min in Jun
- galactic anisotropy + heliosphere

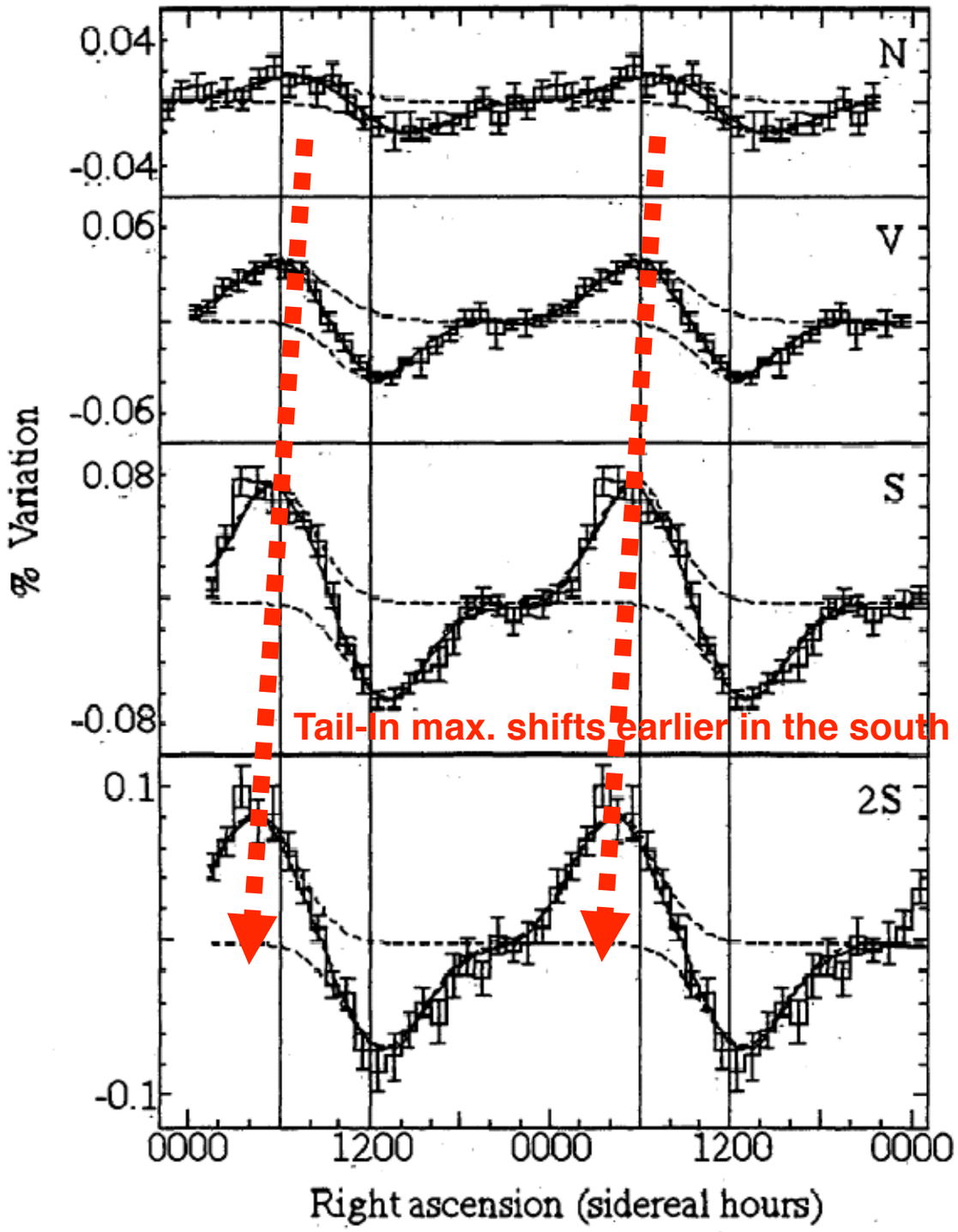
Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)



cosmic ray anisotropy in arrival direction

- Two Hemisphere Network
- anisotropy in arrival direction measured at $10^{-4} \div 10^{-3}$ level
- depends on energy
- depends on declination : north-south asymmetry
- phase of tail-in “excess” shifts with declination

Hall et al., Journ. Geophys. Res., Vol 103, No. A1, Pag. 367 (1998)



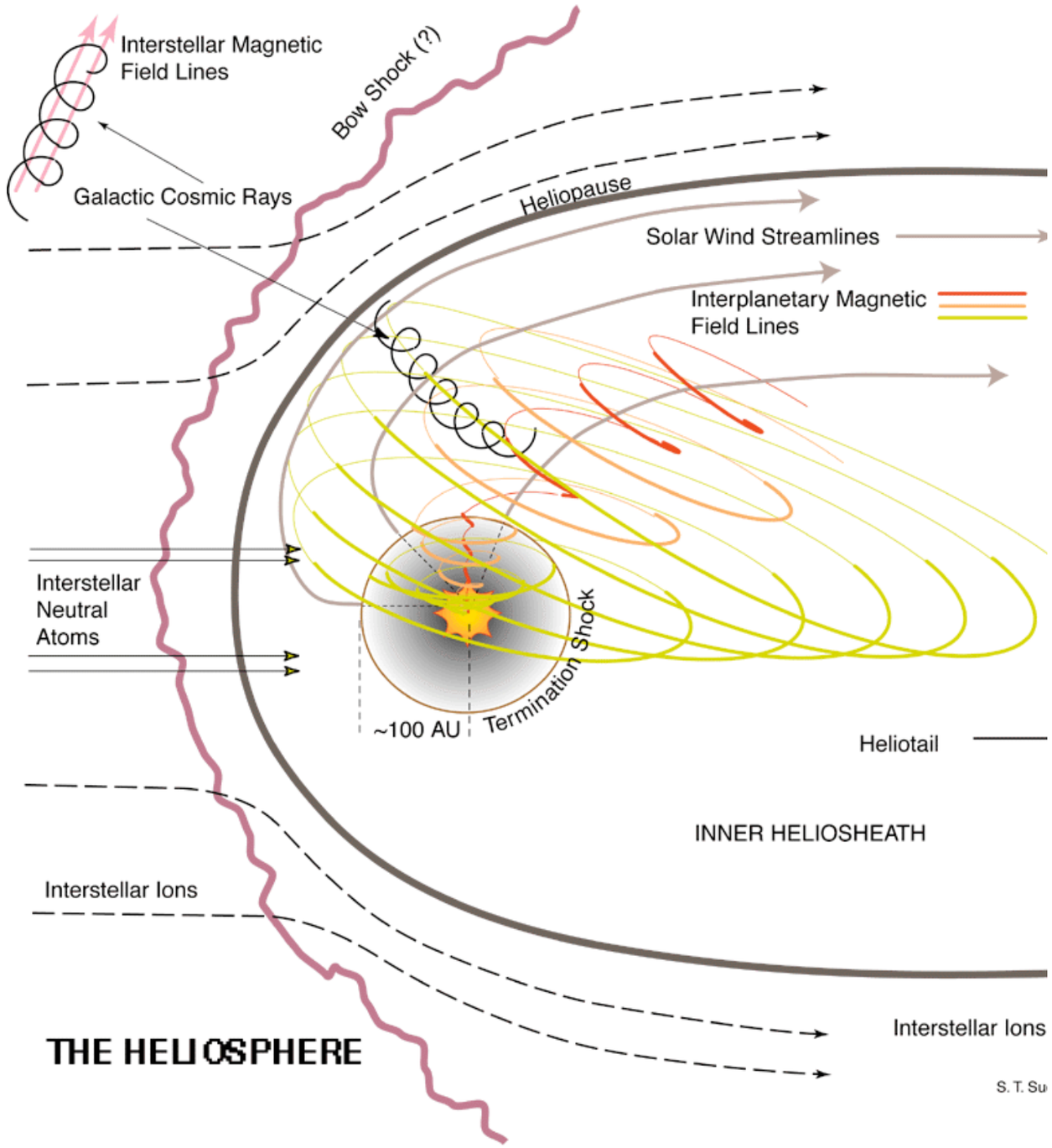
heliosphere

- solar system moves wrt IS medium at 26 km/s

- solar wind diverts interstellar plasma at 400-800 km/s

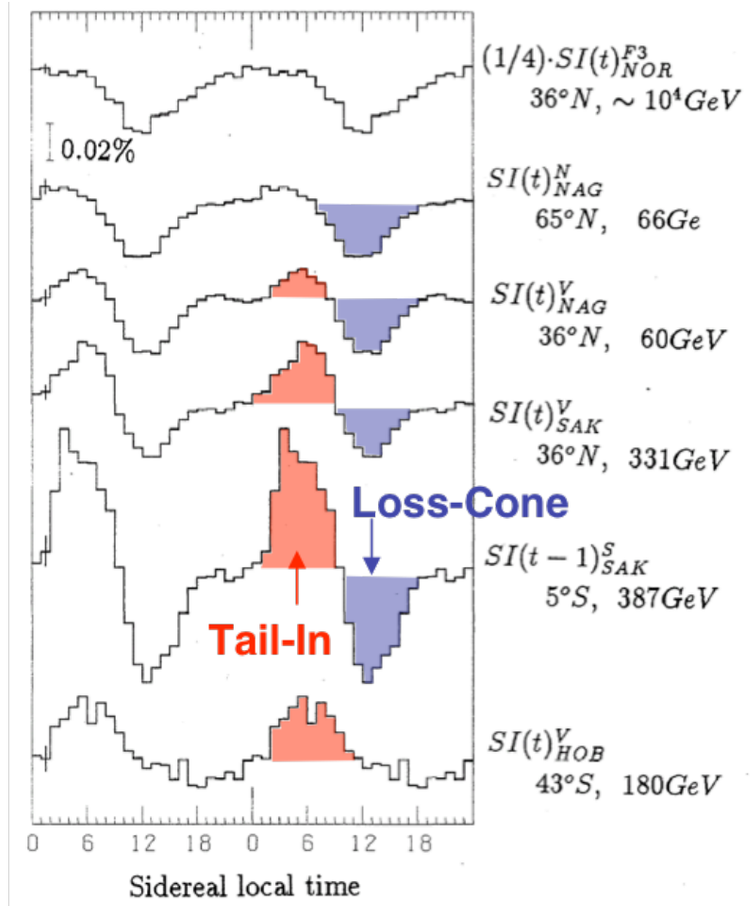
- termination shock @ solar pressure ~ interstellar pressure : ~ 100 AU

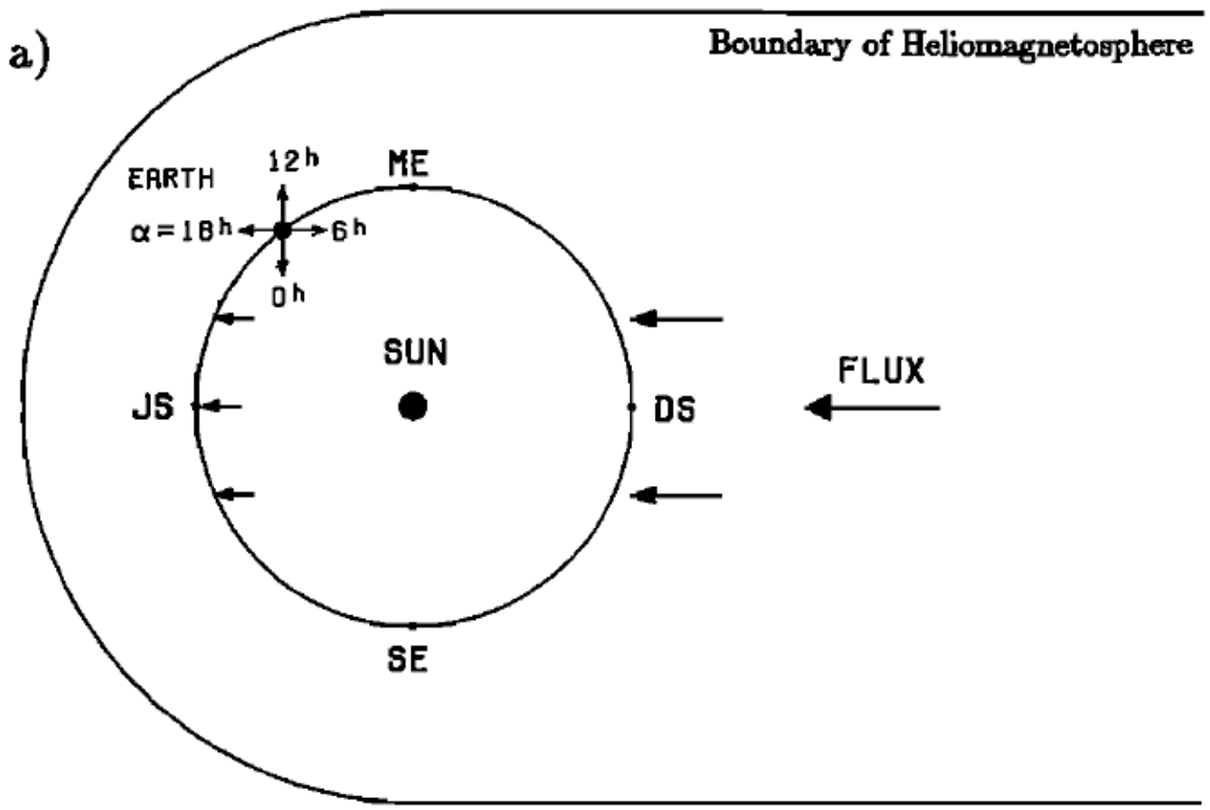
- solar and interstellar medium (& magnetic field) separated by heliopause : ~ 150-200 AU



cosmic ray anisotropy in arrival direction

- Tail-in feature is directed towards the heliospheric tail
- peak located at RA ~ 6h (~ 90°)
- seasonal modulation due to Earth's location wrt heliosphere (< 10 TeV)
- larger effect at Dec solstice
- smaller effect at Jun solstice
- galactic anisotropy + heliosphere





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

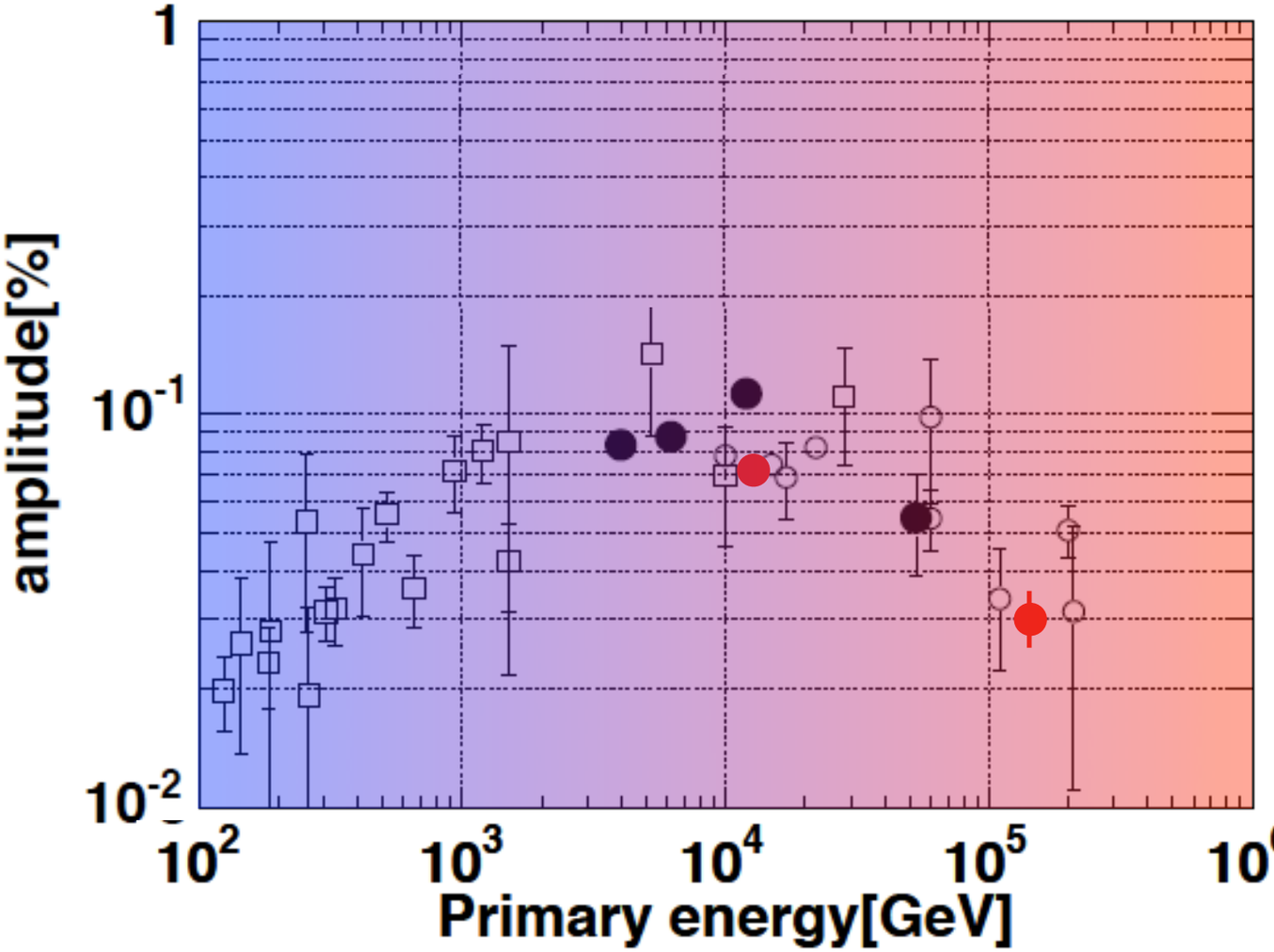
origin of anisotropy ?
a long story

- Compton-Getting effect [Compton & Getting, Phys. Rev. 47, 817 (1935)]
  - apparent ~10^{-3} dipole anisotropy due to relative motion of solar system through ISM
  - motion around galactic center ~ 220 km/s
  - not consistent with observations : relative velocity much smaller ? co-rotation ?

- contribution from *local* environment depends on cosmic ray energy
  - heliospheric influence < 10 TeV & *galactic* influence > 10 TeV
  - diffusion and propagation of cosmic rays through local IS medium

anisotropy vs energy : probing different causes

Amenomori et al., astro-ph/0505114



(1 μG)

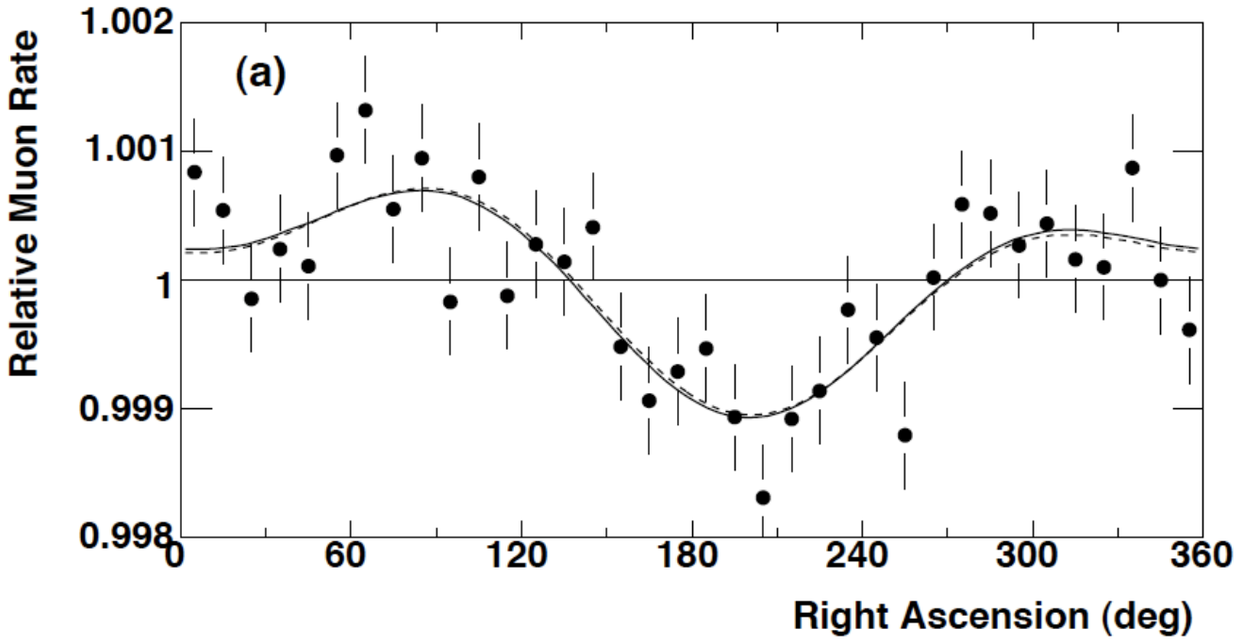
10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	gyro-radius (pc)
20	200	2,000	20,000	200,000	gyro-radius (AU)

tail-in + galactic

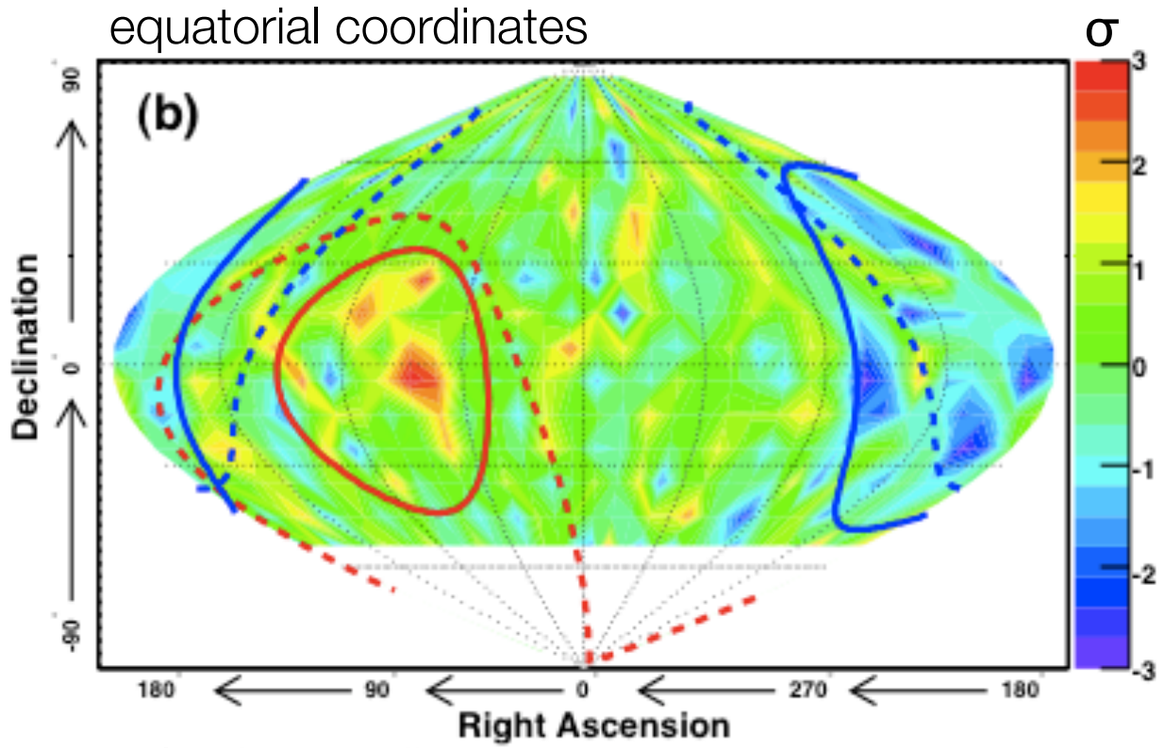
heliospheric influence

galactic influence

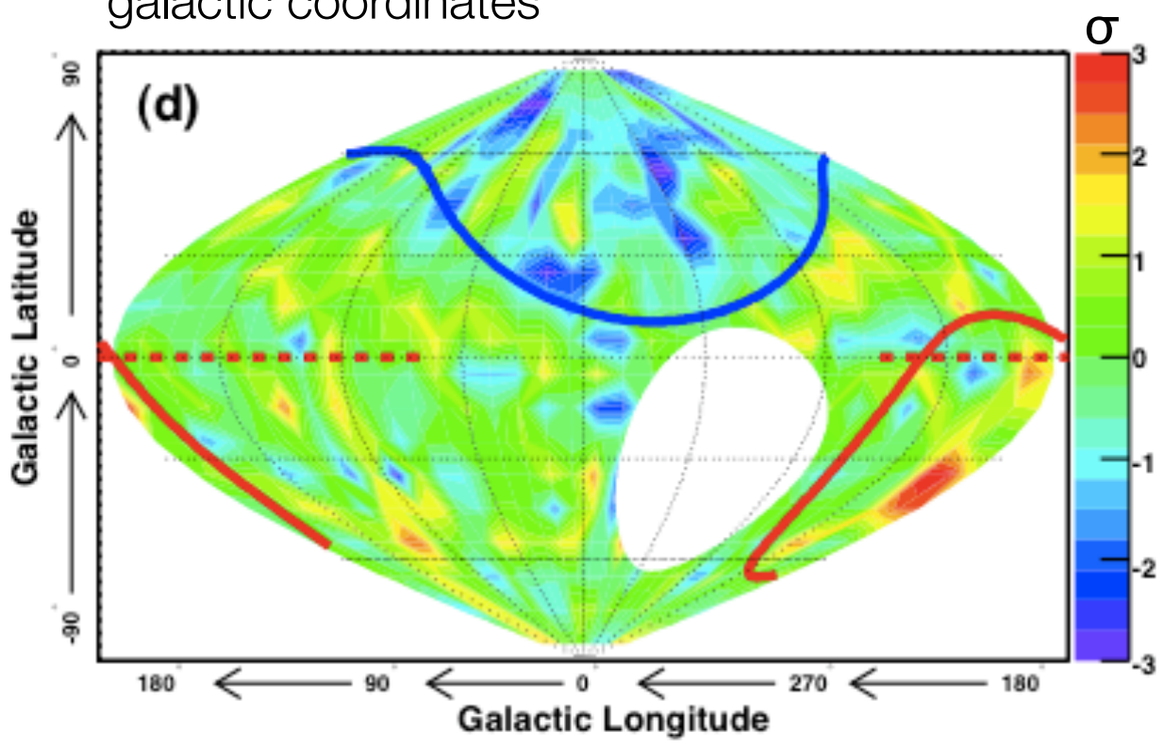
- data from 1996 to 2001
- 1662 days livetime
- $2.1 \cdot 10^8$ events
- angular resolution < 2°
- median CR energy ~ 10 TeV



equatorial coordinates



galactic coordinates

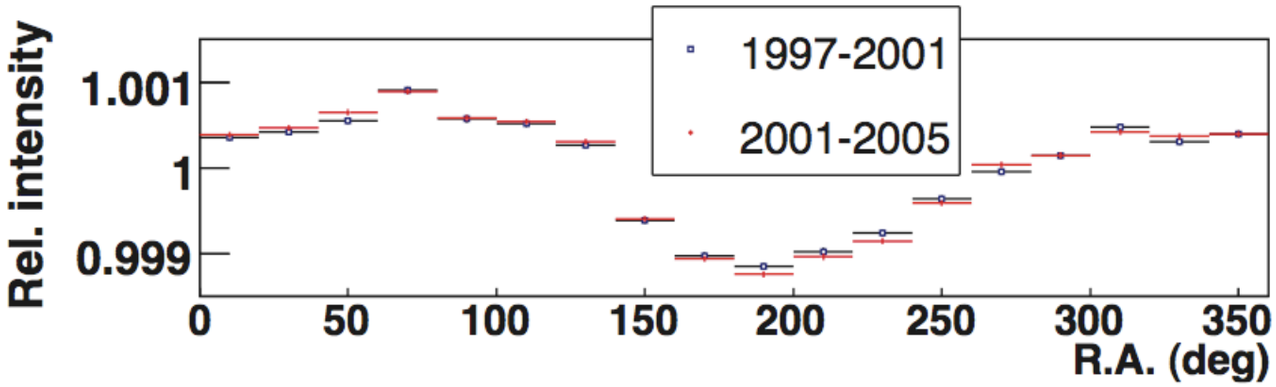


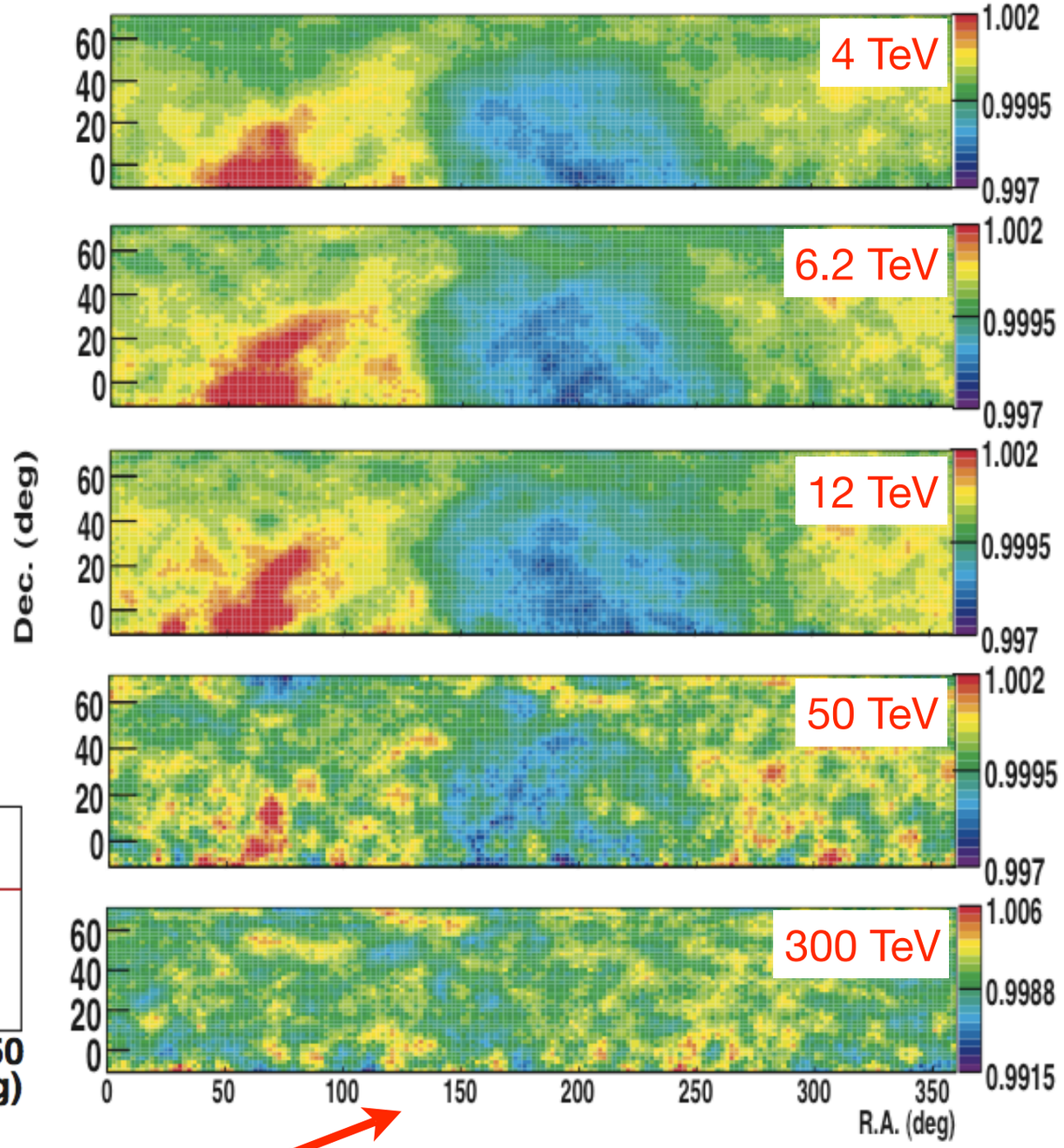
Super-Kamiokande

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

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

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





anisotropy seems to disappear :
co-rotation of cosmic rays ?

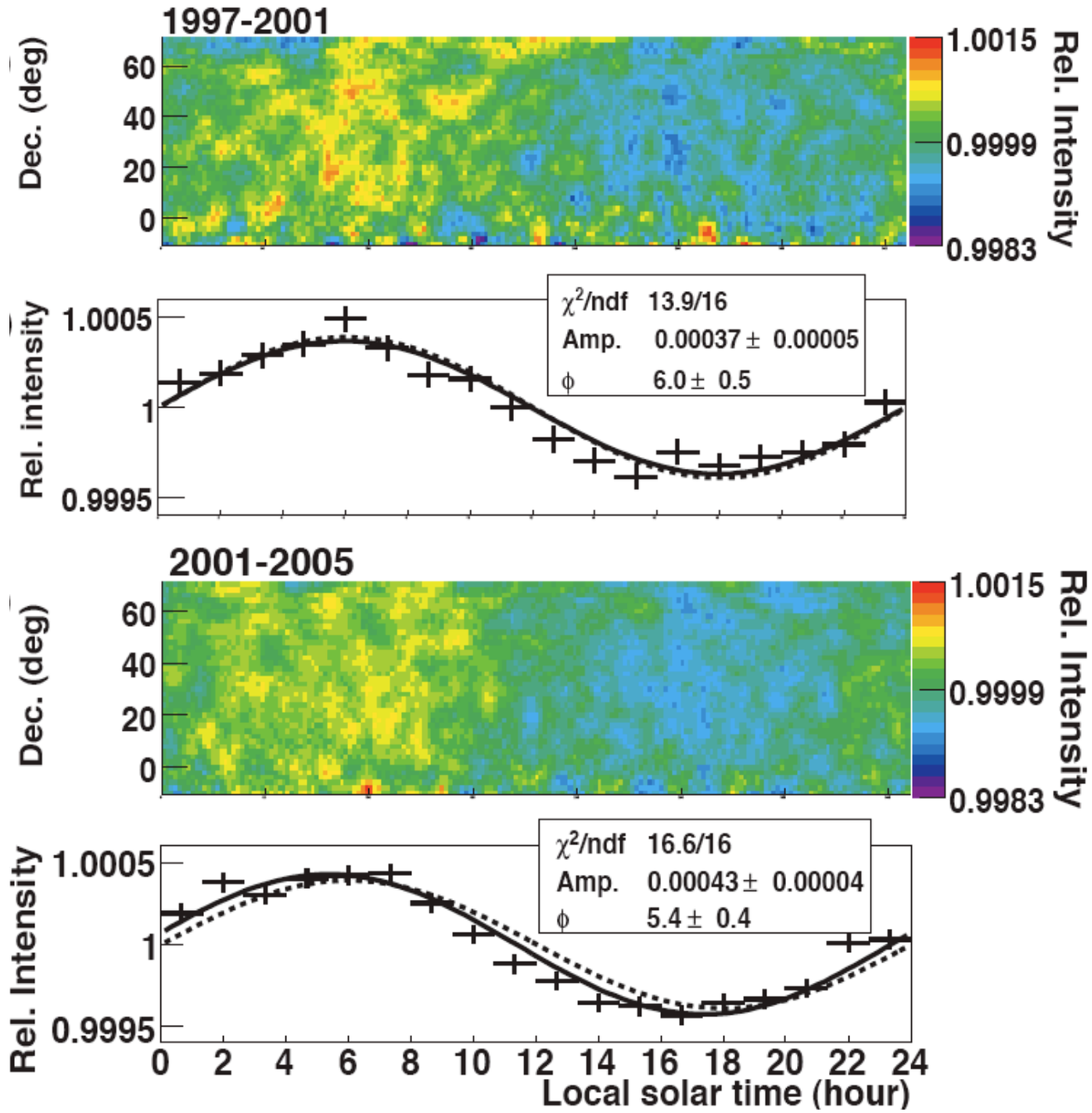
Tibet-III Array

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

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

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

- relative motion of Earth's around the Sun detected in solar time

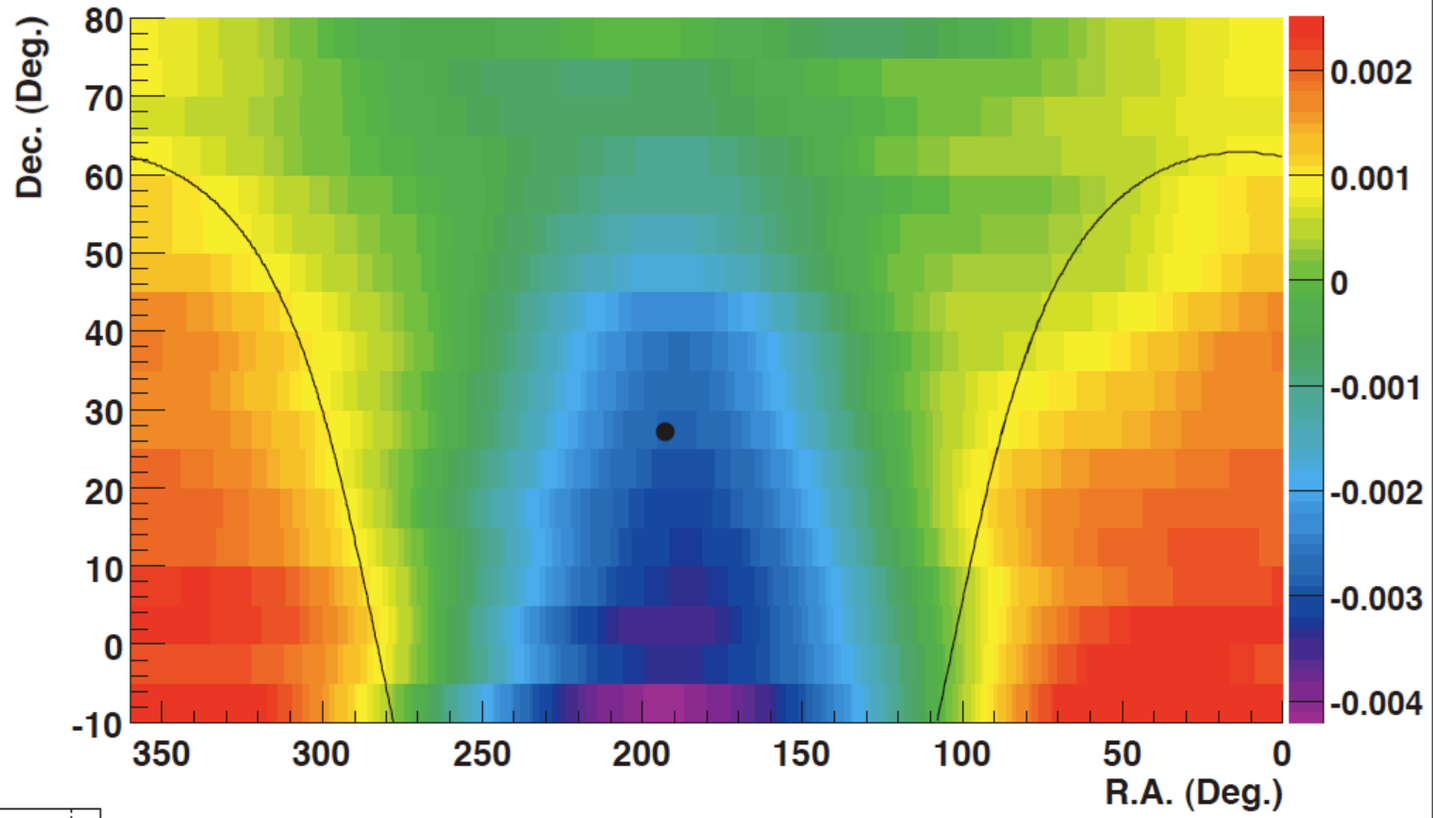


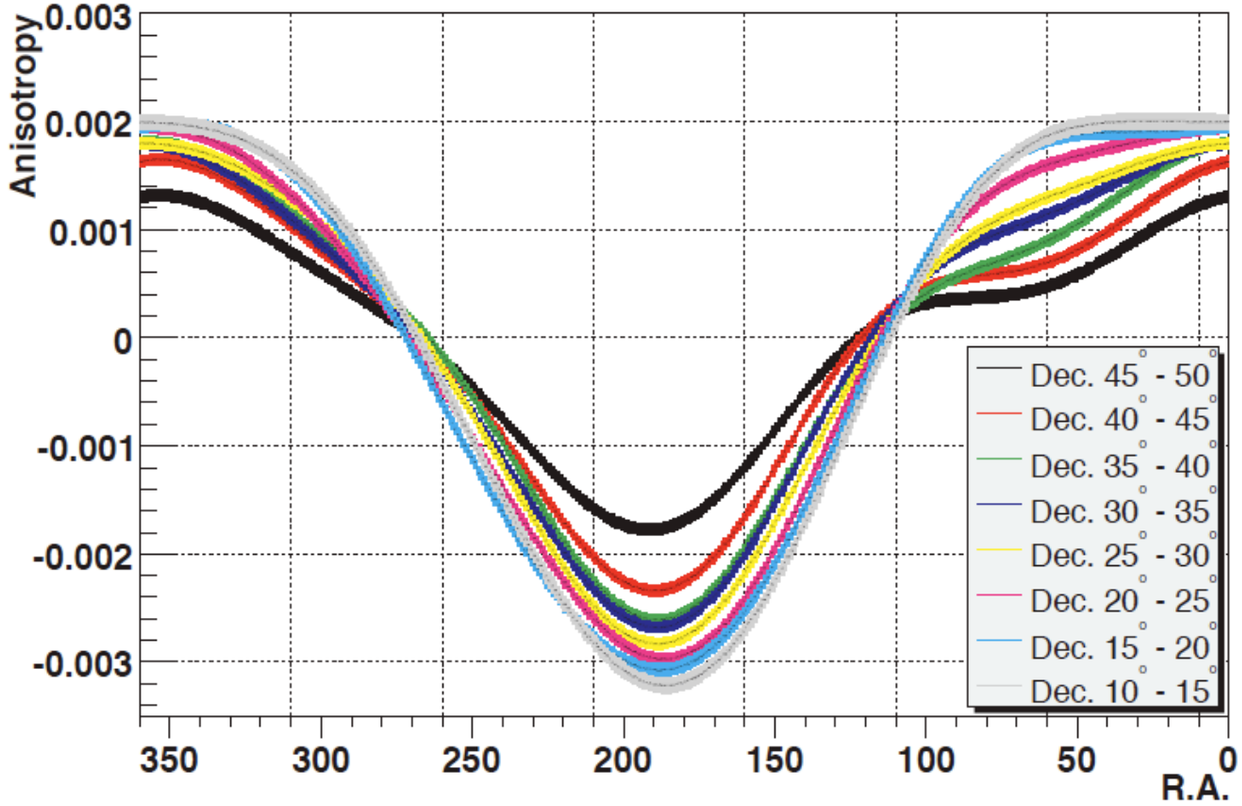
Tibet-III Array

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

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

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





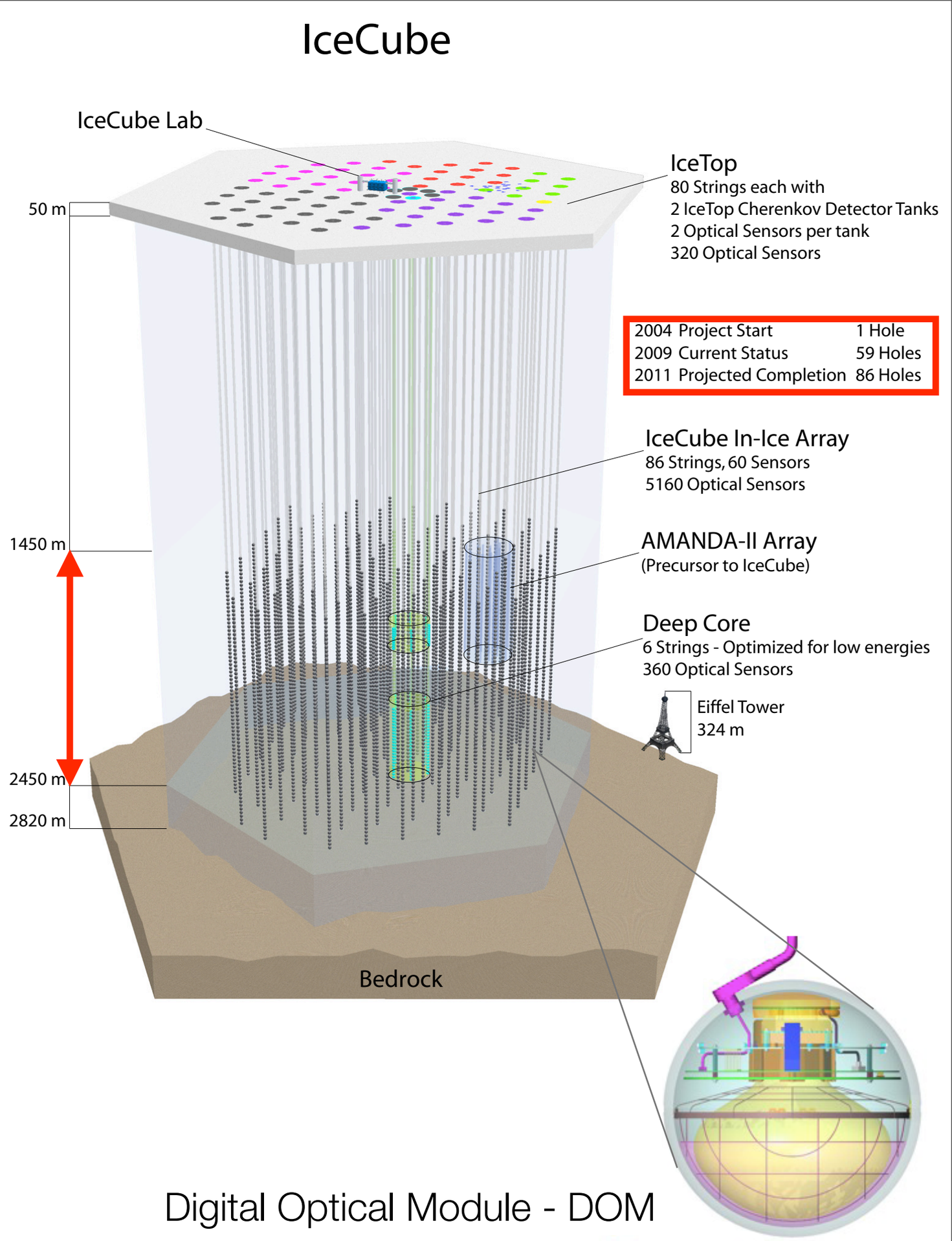
Milagro

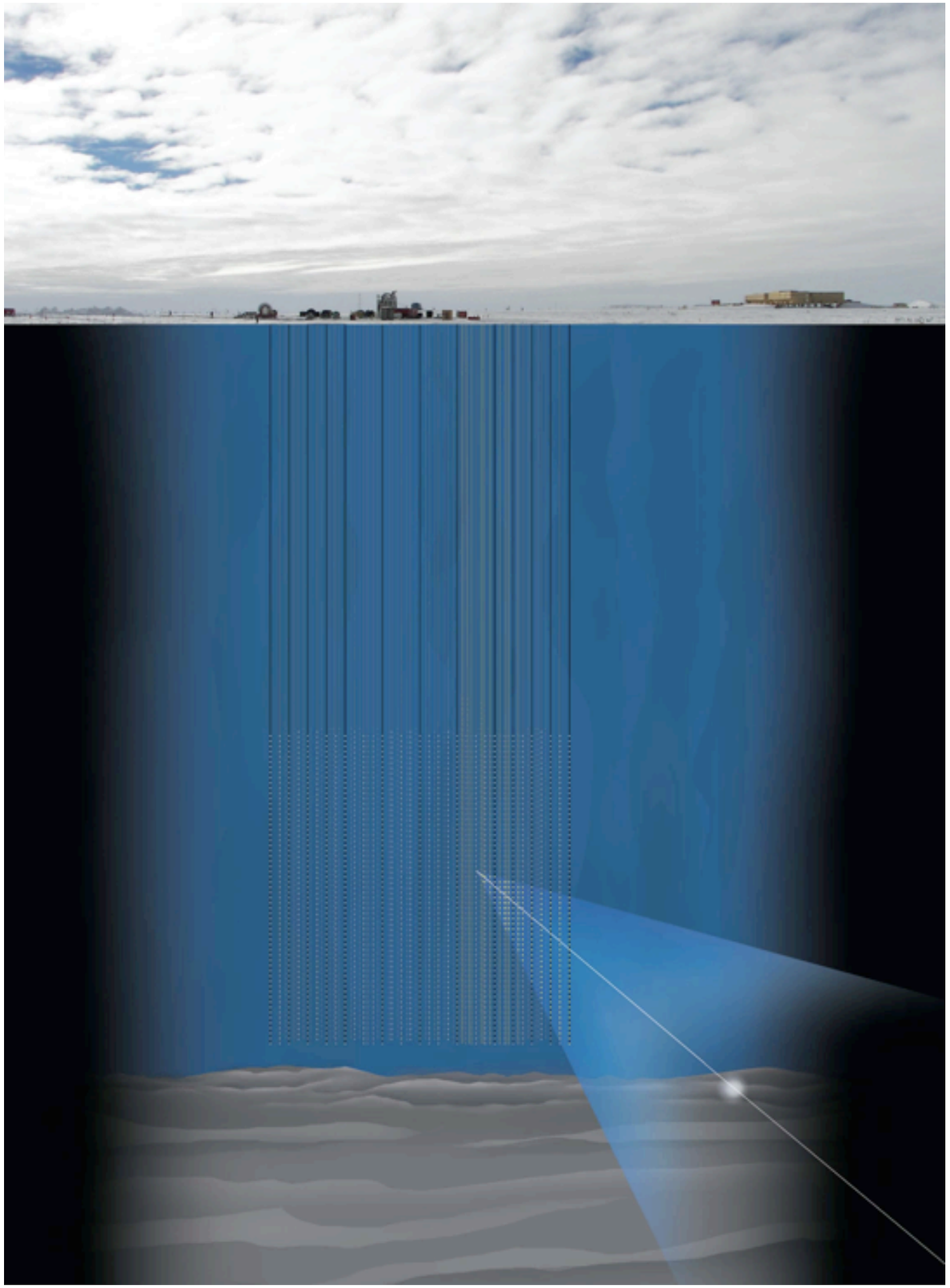
2D skymap of statistical significance (normalized in each declination band)

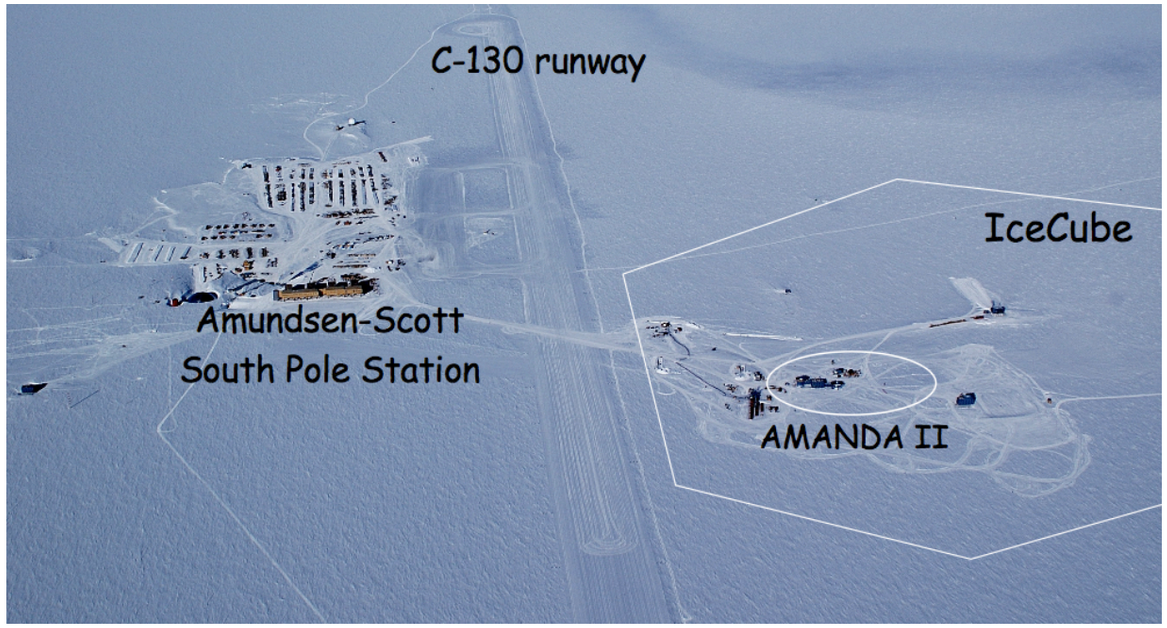
Abdo et al., ApJ, Vol 698-2, pag 2121 (2009)

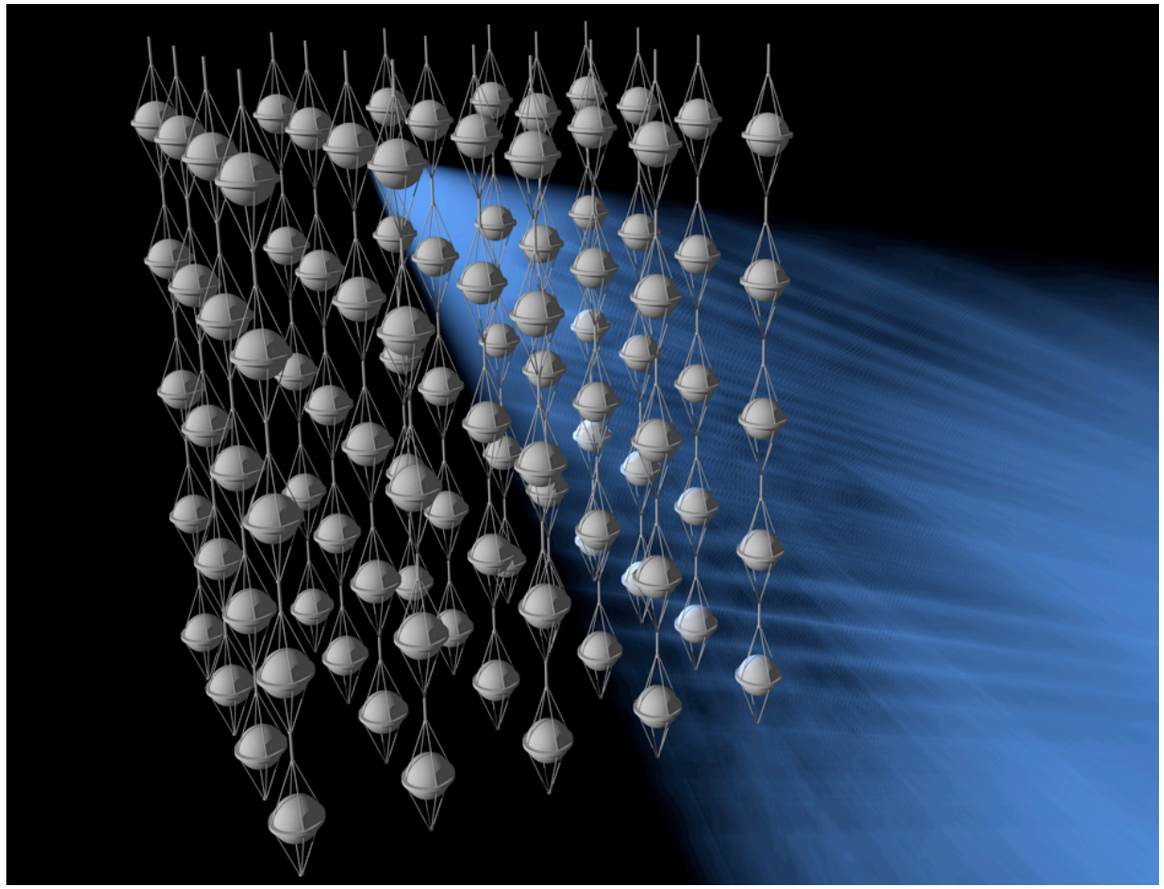
IceCube Observatory

- IceCube
  - currently 59 strings
  - 80 strings in 2011
  - 125m inter-string spacing
  - 17m DOM distance
- taking data during construction
- AMANDA decommissioned on May 11, 2009
- Deep Core currently with 1 string
- Deep Core 6 strings in 2010

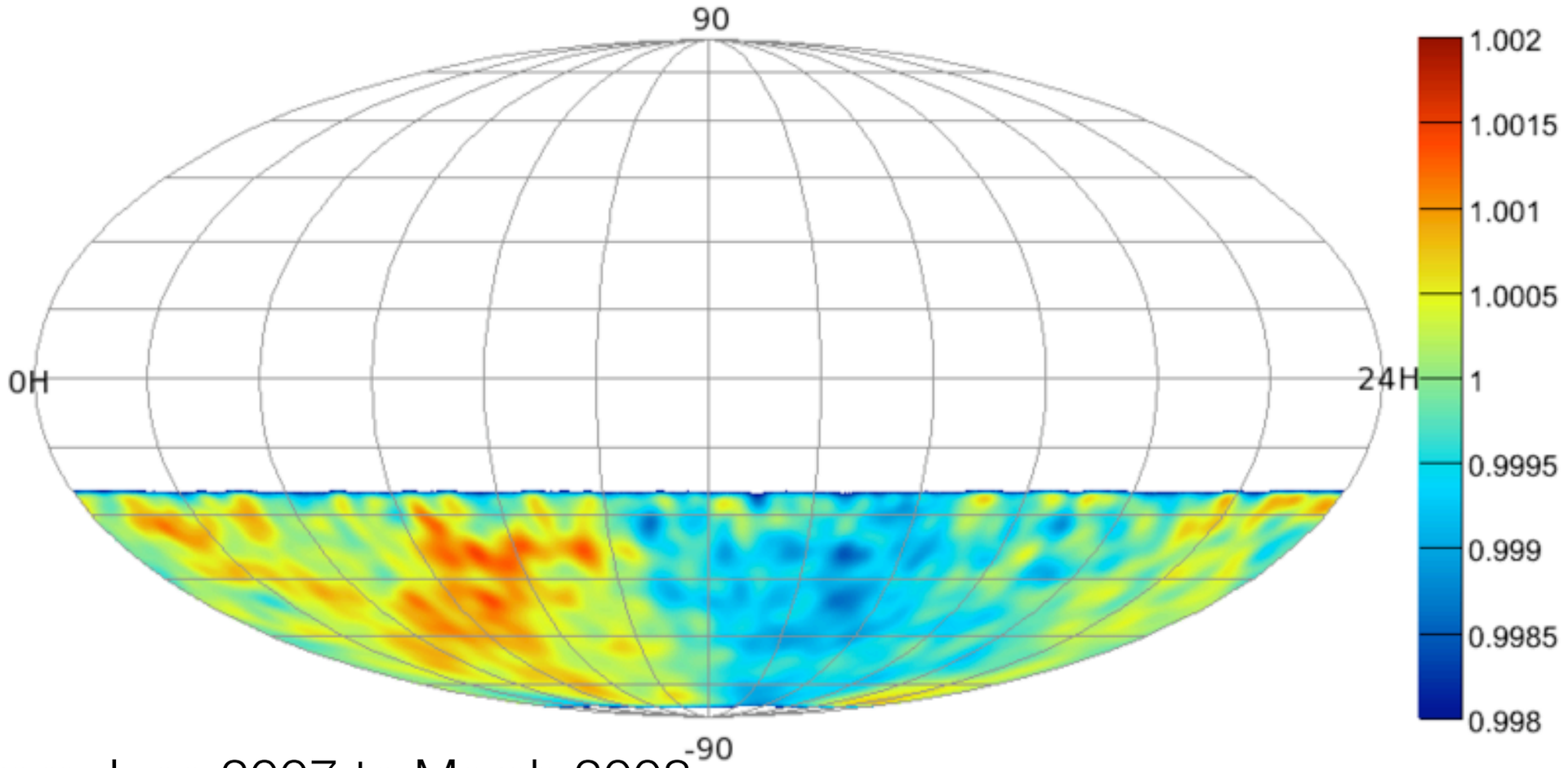




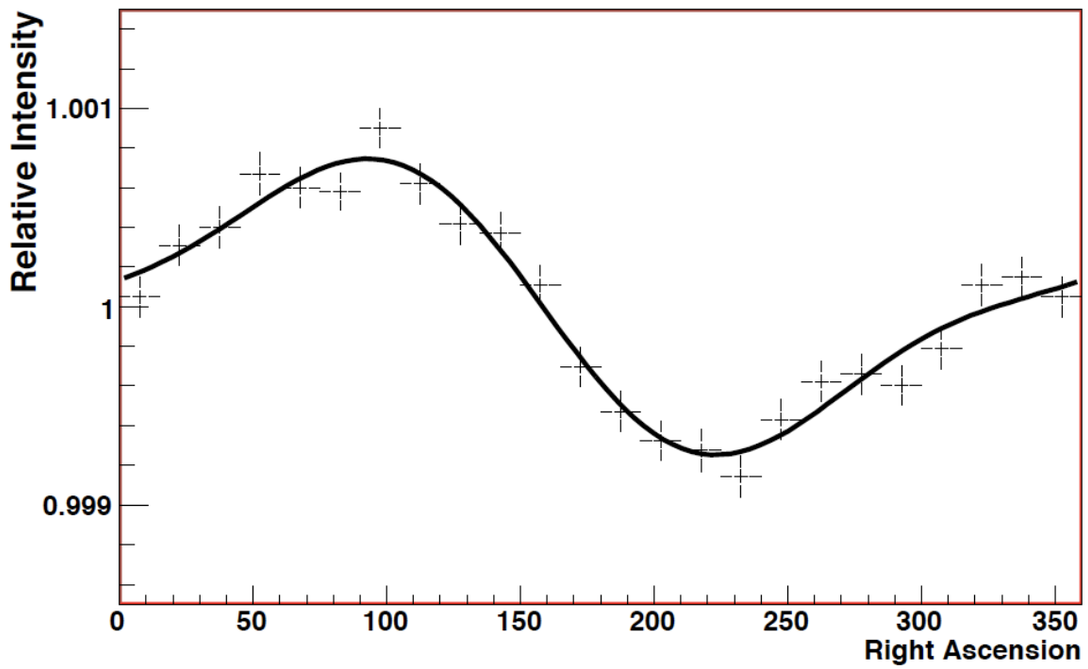




detection technique



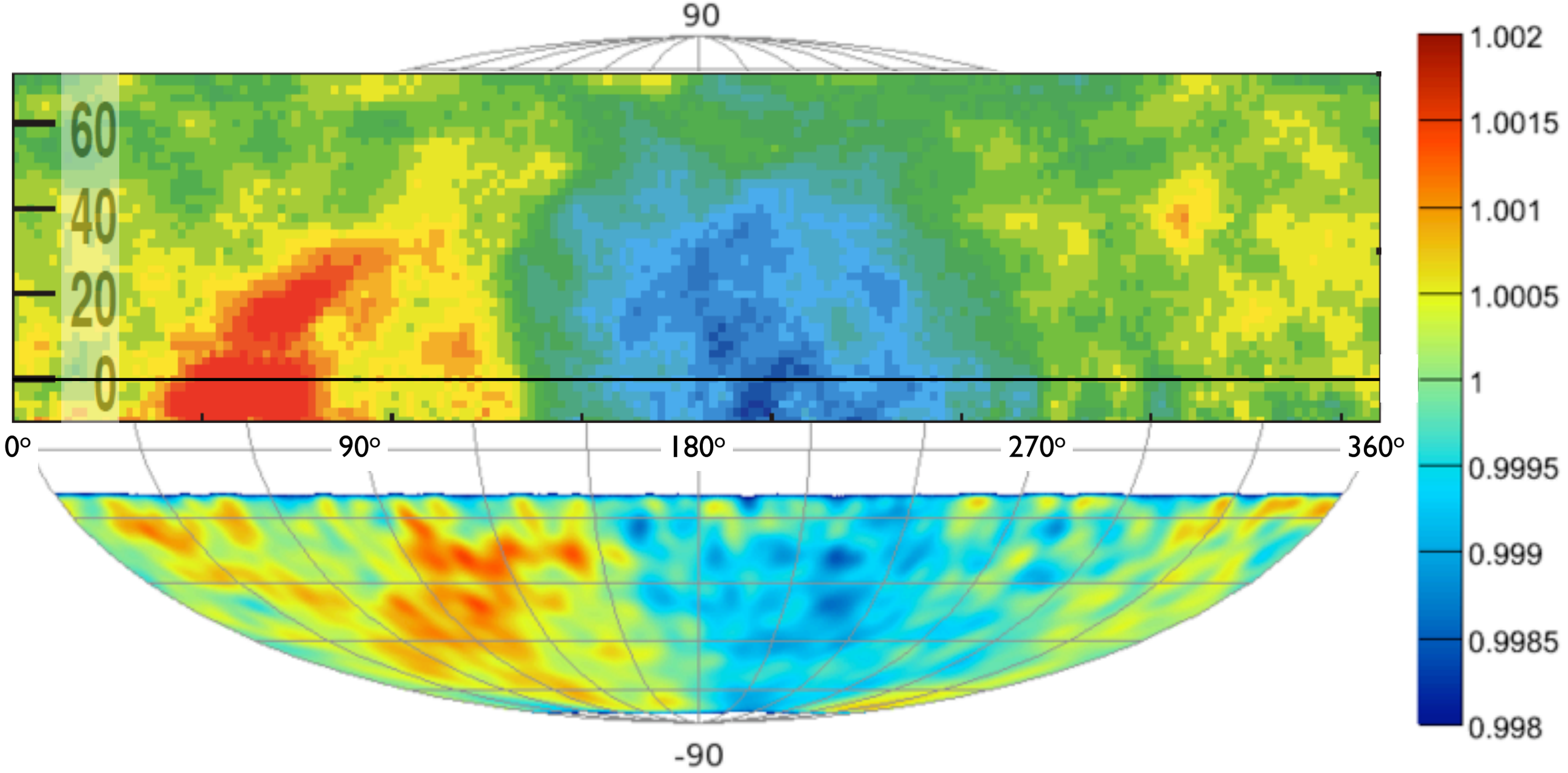
- data from June 2007 to March 2008
- 226 days livetime
- $4.3 \cdot 10^9$ events
- median angular resolution ~ 3°
- median CR energy ~ 14 TeV



IceCube-22

Rasha Abbasi
Juan Carlos Díaz Vélez, PD

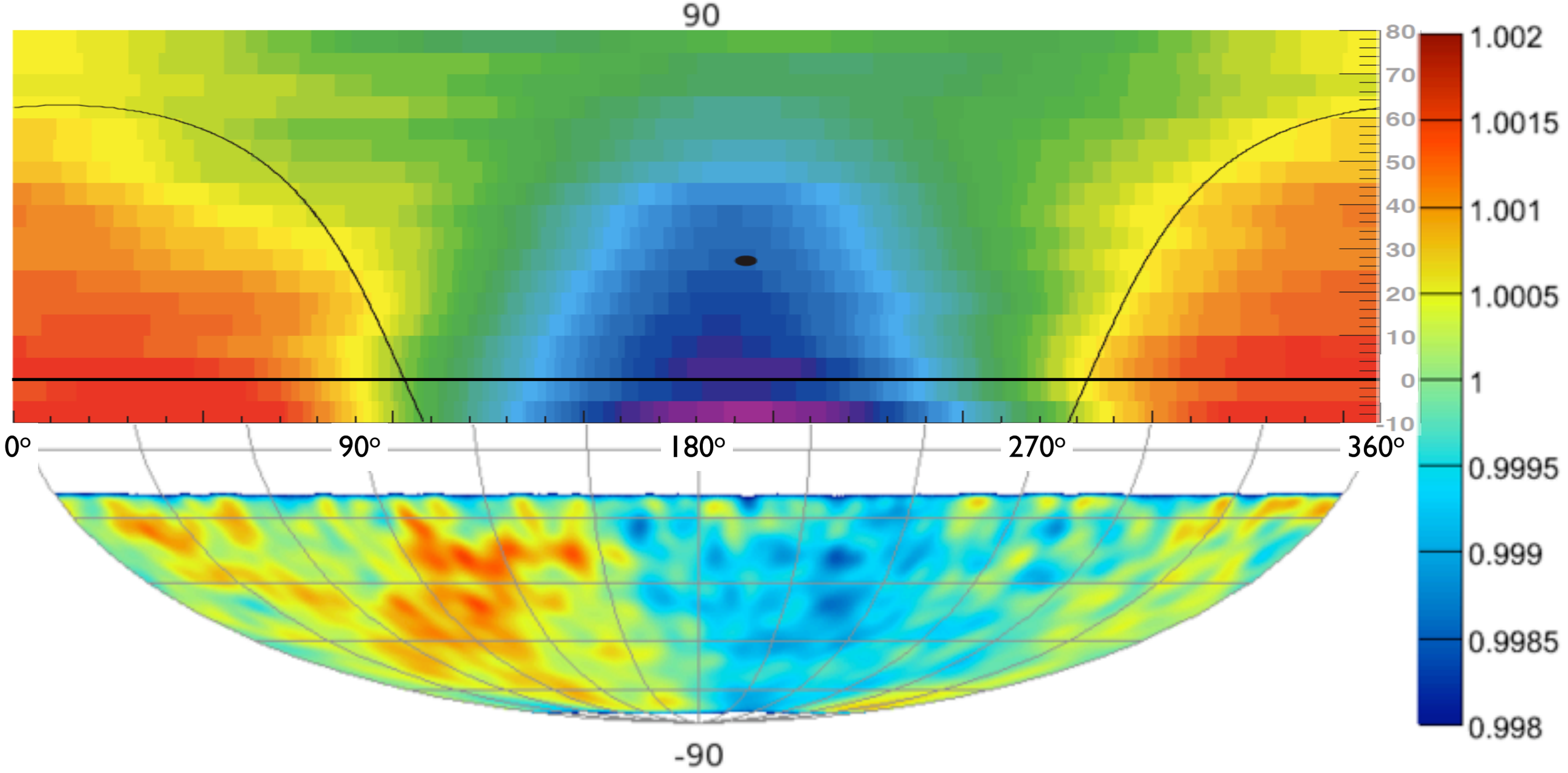
Amenomori et al., Science, Vol 314, pp 439-443 (2006)



IceCube-22

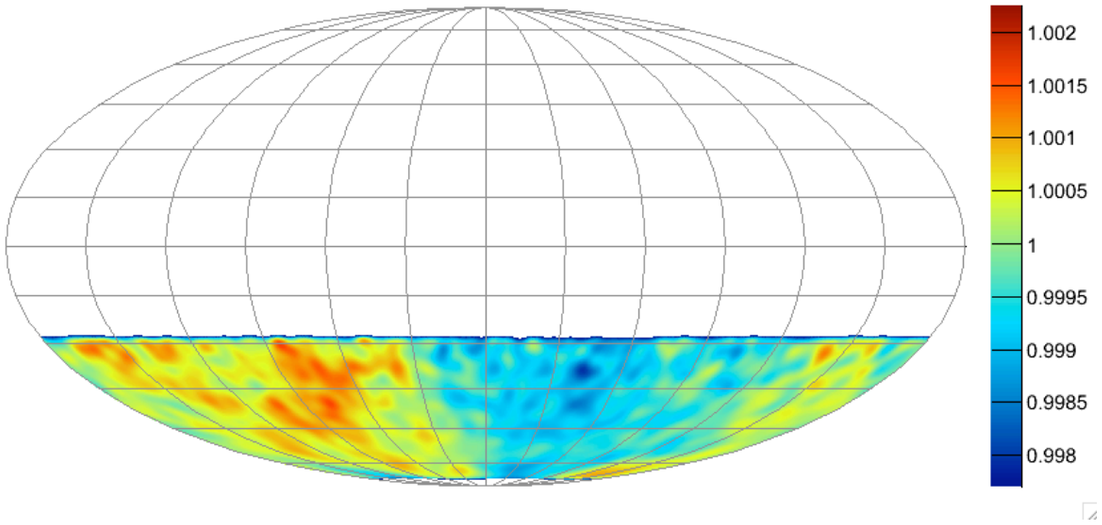
Rasha Abbasi

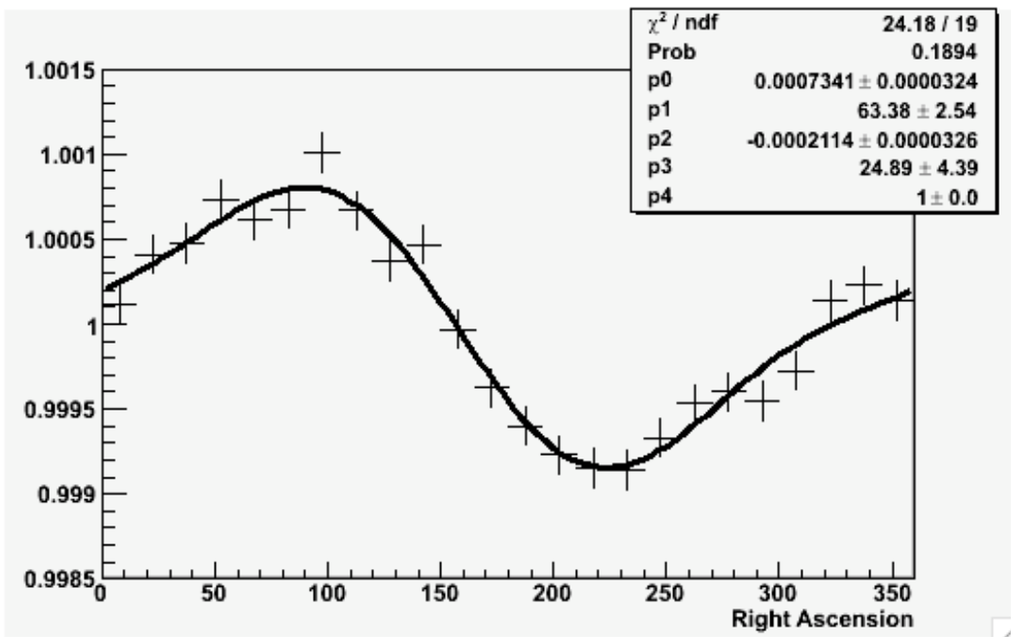
Abdo et al., ApJ, Vol 698, Issue 2, pp 2121-2130 (2009)



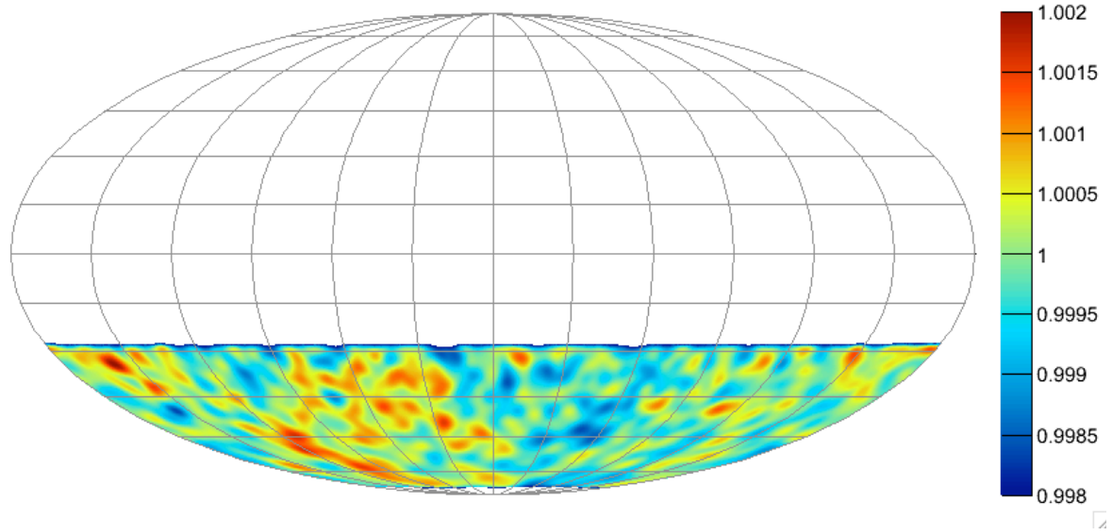
IceCube-22

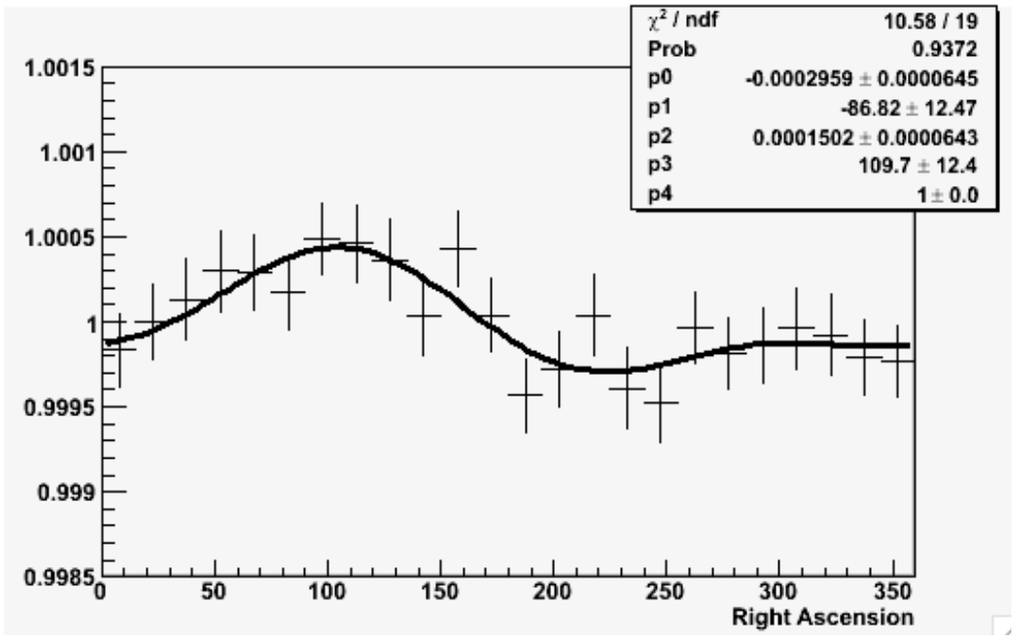
Rasha Abbasi





E_{median} = 12 TeV





E_{median} = 126 TeV

IceCube-22 : anisotropy persists at high energy

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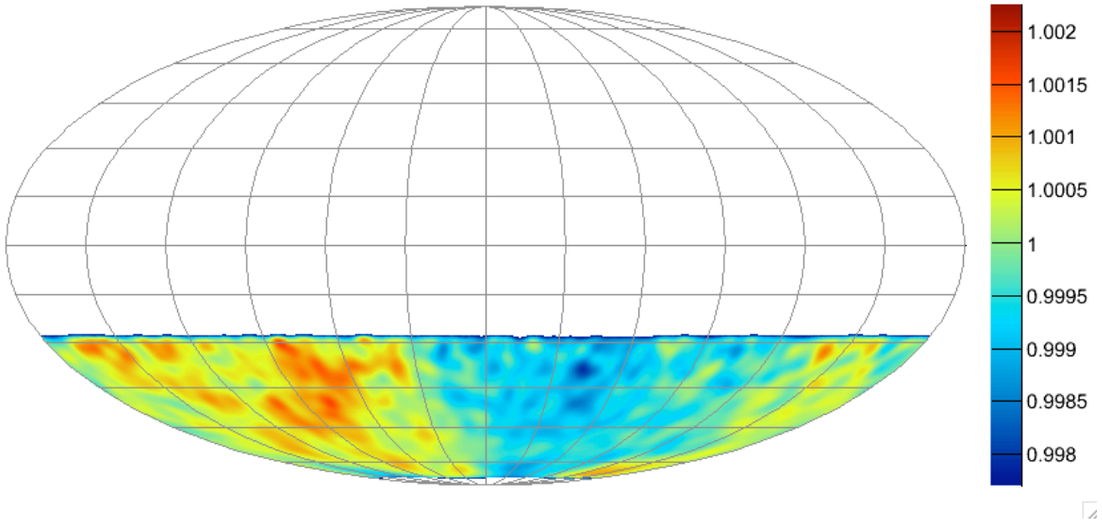

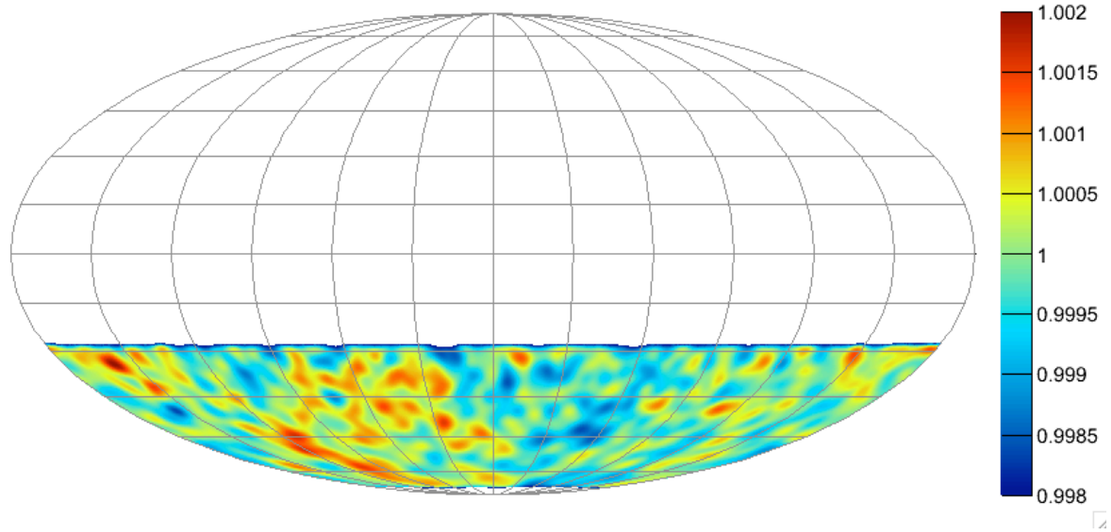

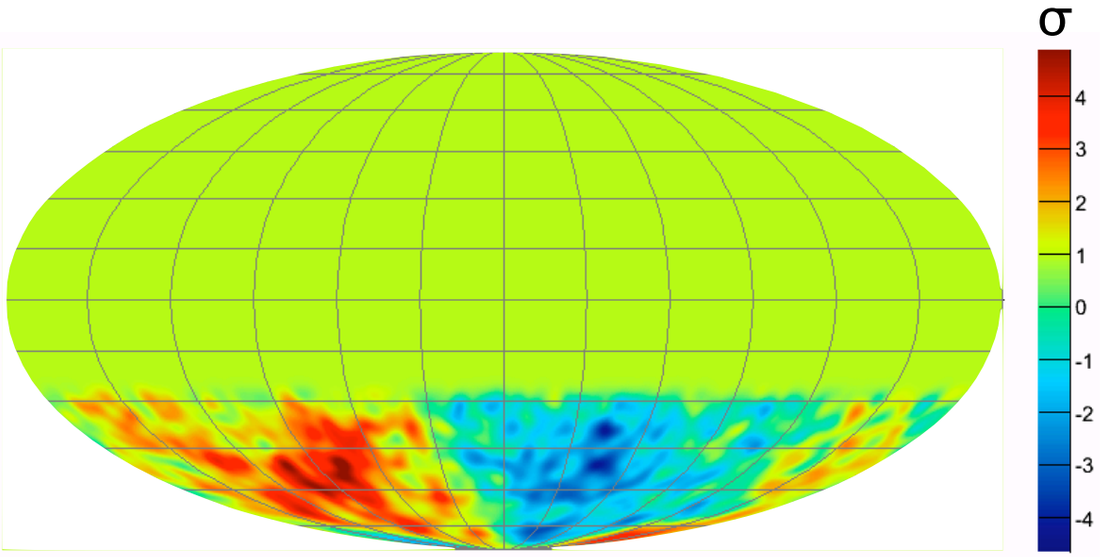

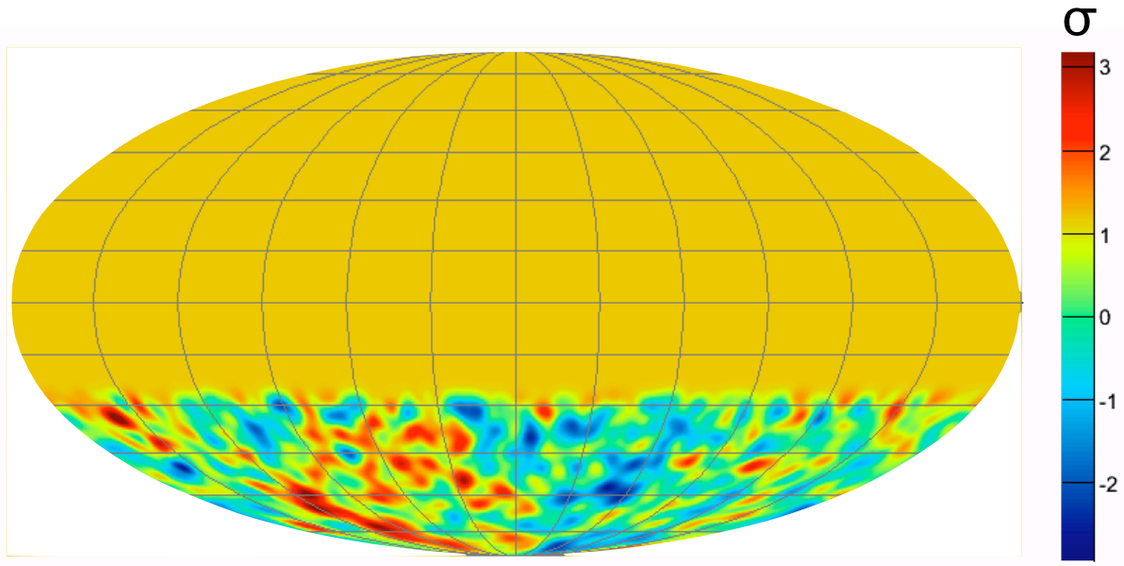

E_{median} = 12 TeV

E_{median} = 126 TeV

IceCube-22 : significance

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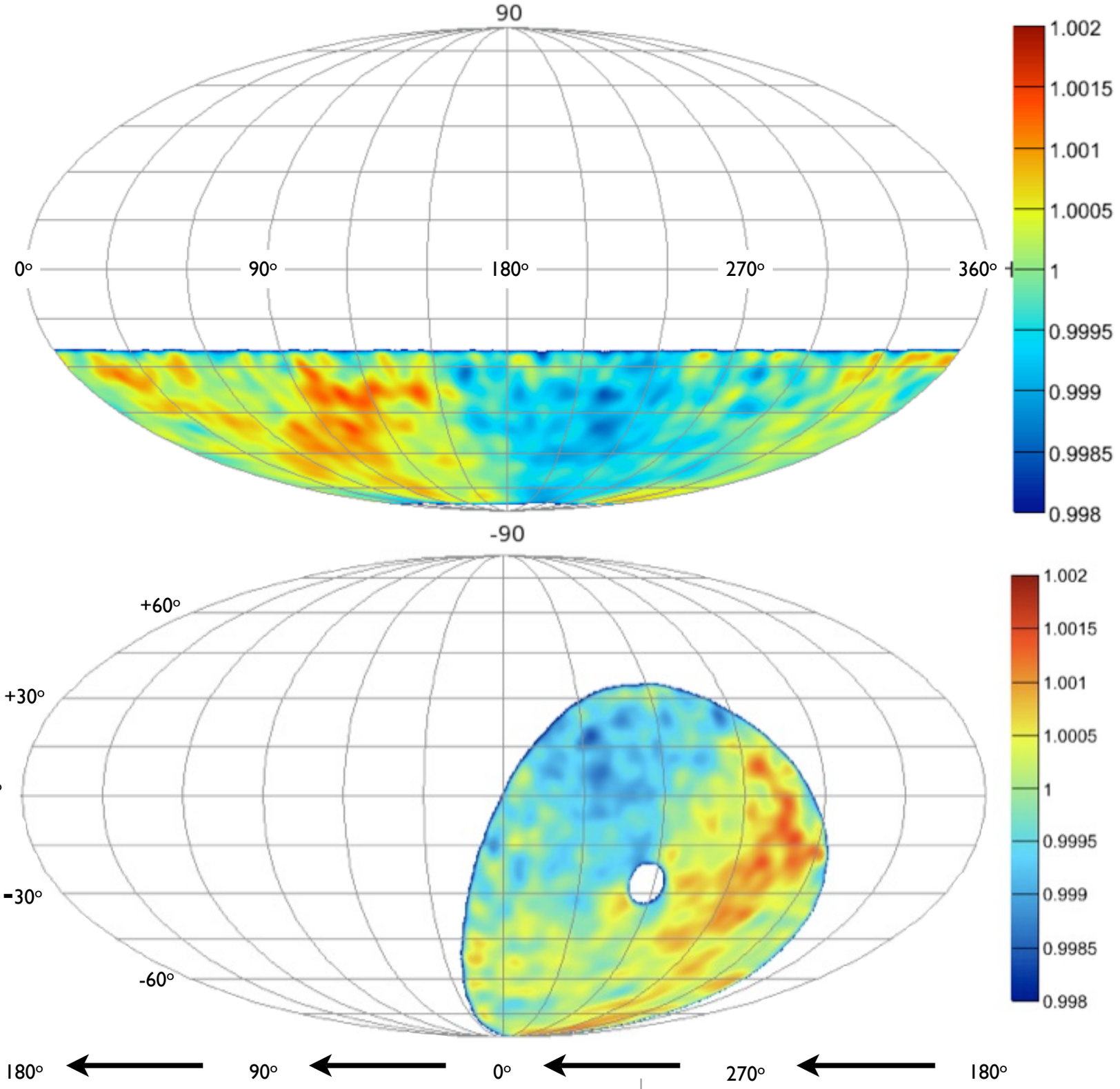
equatorial coordinates



galactic coordinates

IceCube-22

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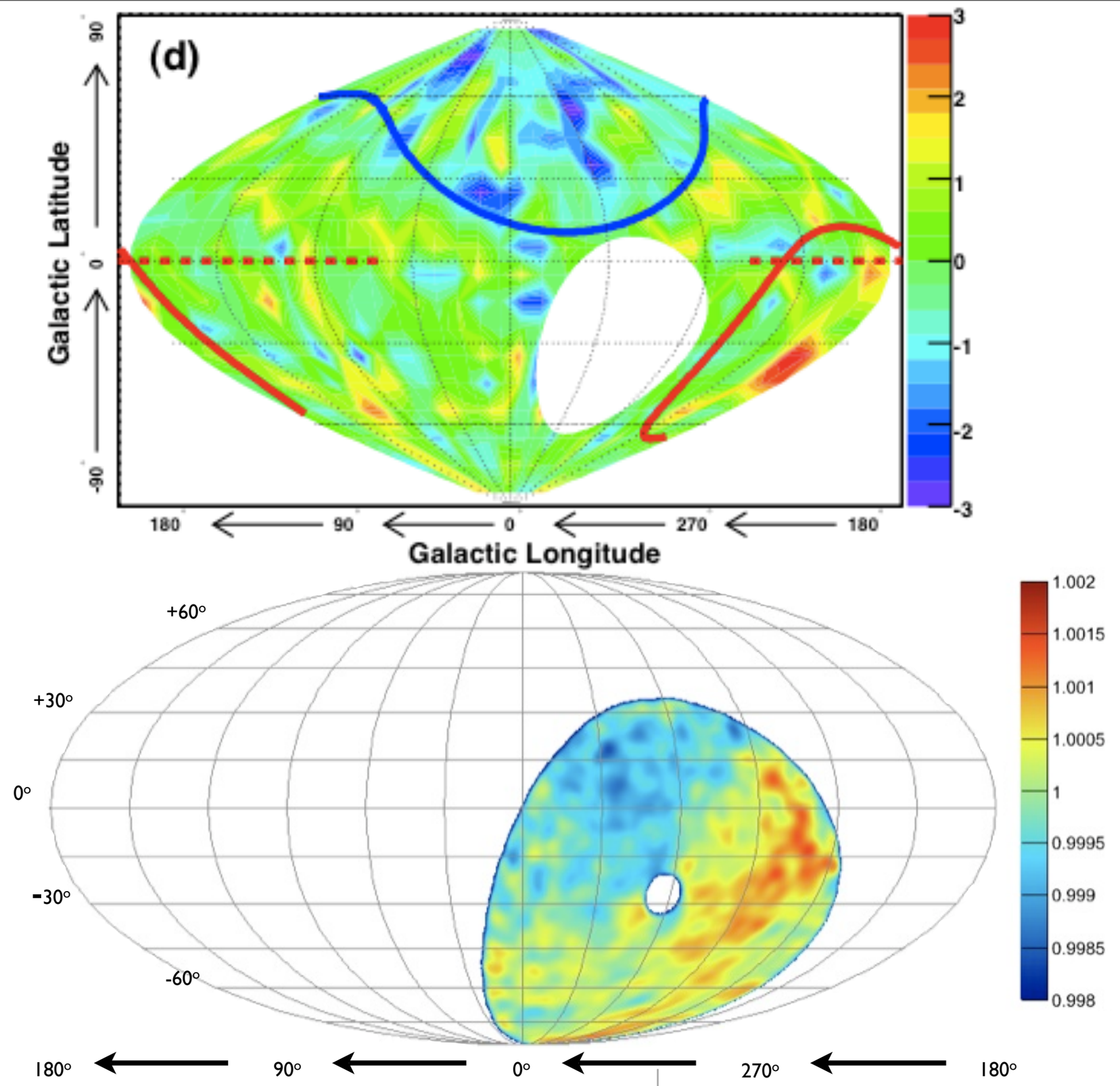
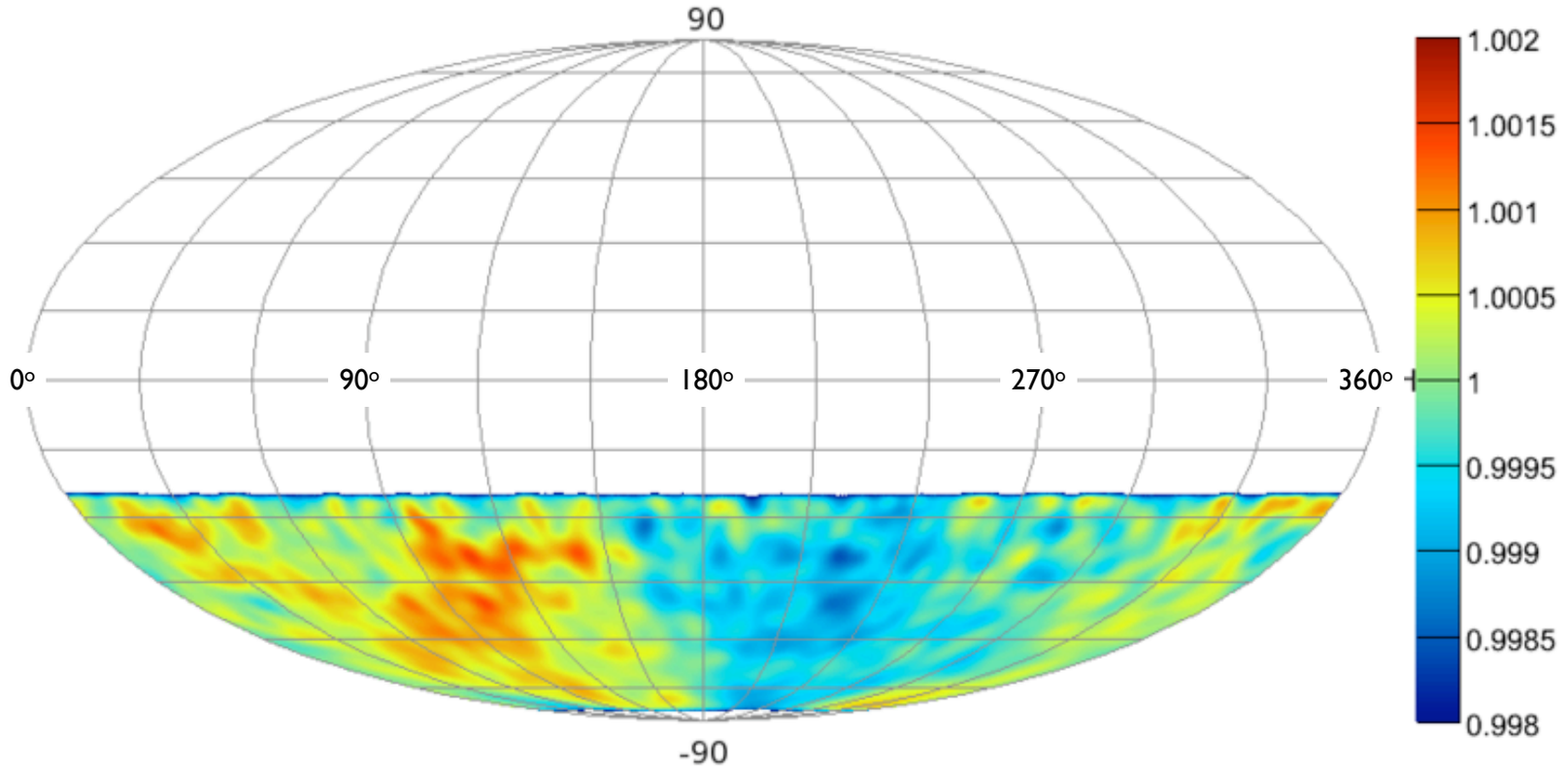
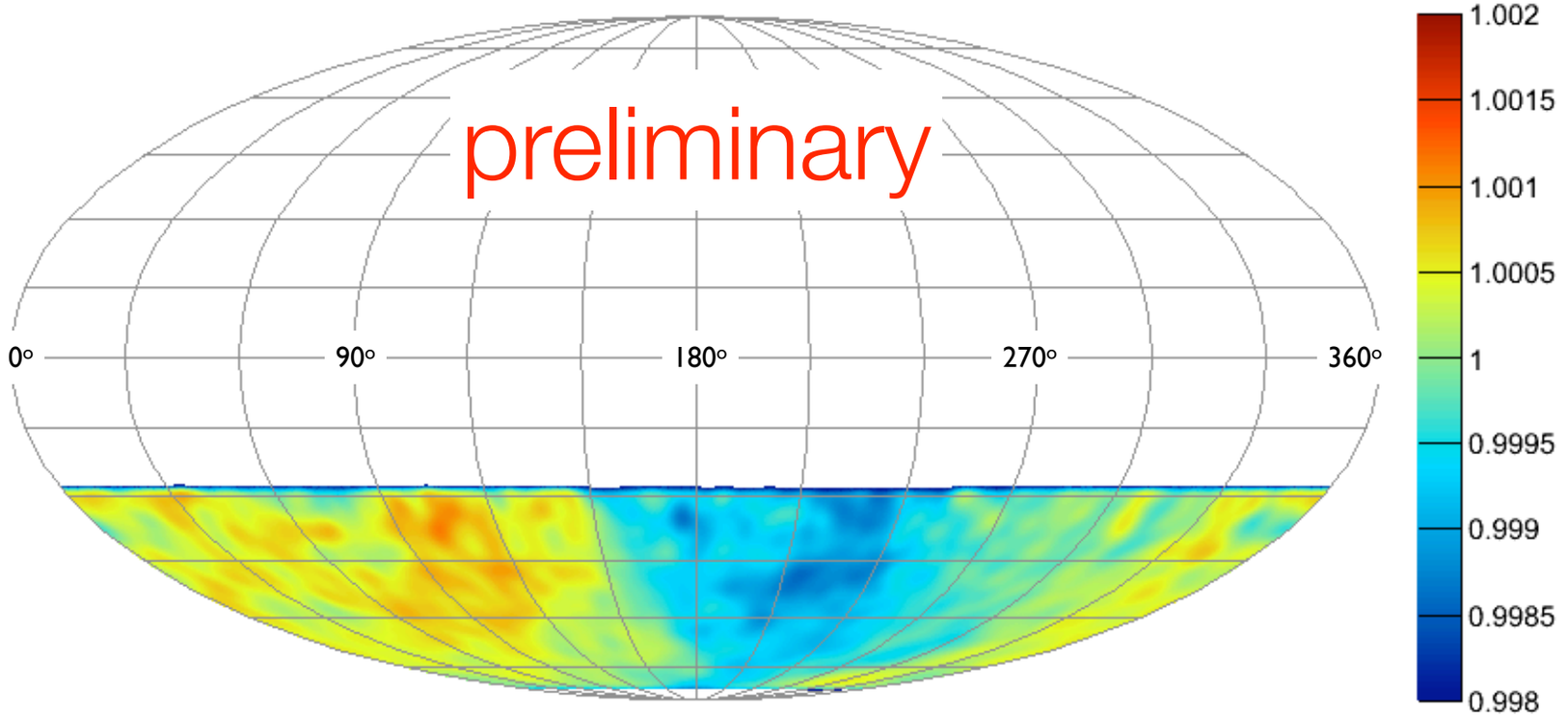


Super-K & IceCube-22

IceCube-22



IceCube-40



IceCube-22 & IceCube-40

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origin of anisotropy ?
a long story

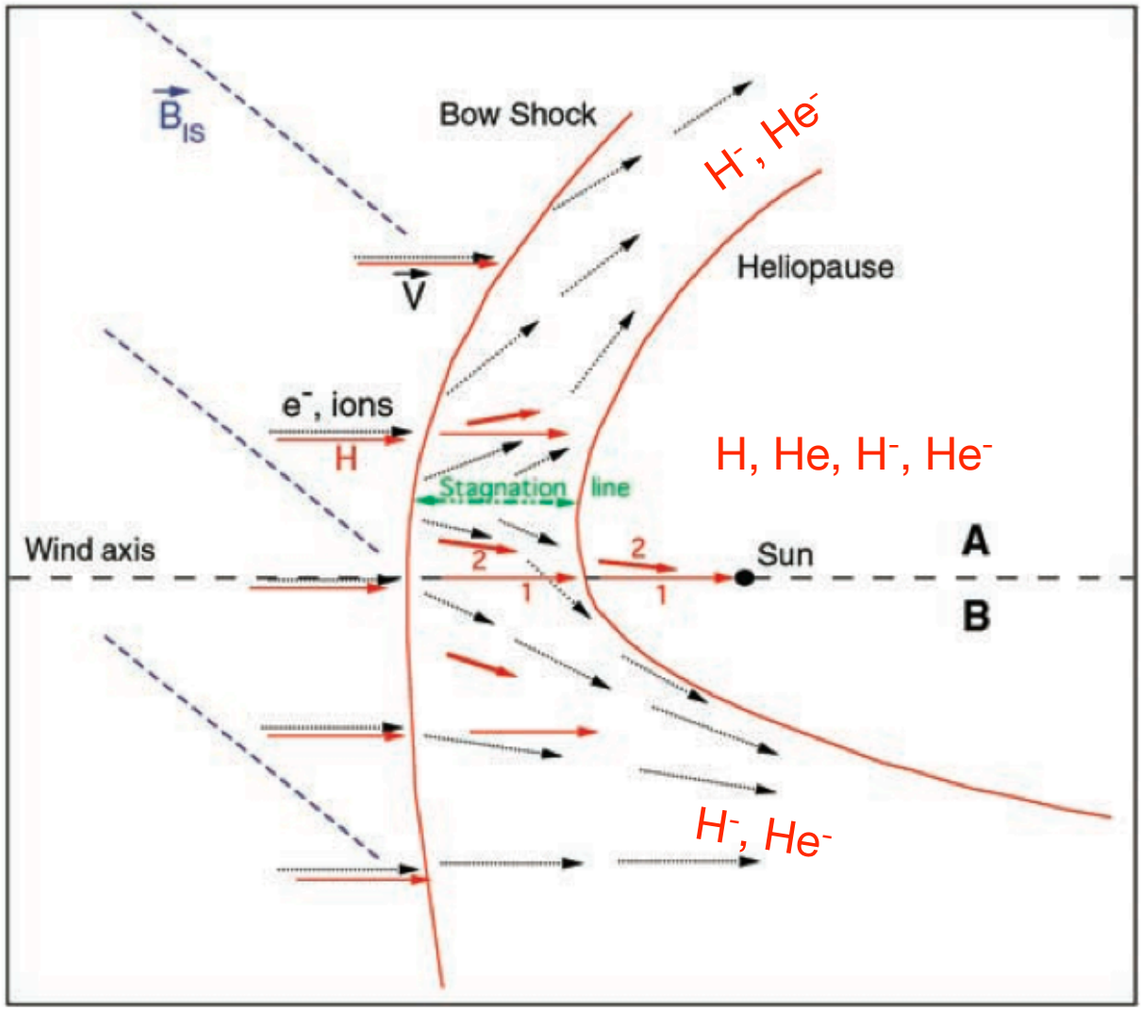
- anisotropy might be connected to the local interstellar magnetic field
  - isotropy of $< 10^6$ GeV cosmic rays is broken within 0.1 - 1 pc
    - ➡ how much do we know about our galactic neighborhood ?
    - ➡ the more we know the more we can understand its influence
  - not clear if an already anisotropic flux is needed to explain the observations

investigating on interstellar magnetic field

scale : 100 AU ~ $5 \cdot 10^{-4}$ pc

- Sun moving through a tenuous 20-30% ionized interstellar cloud
- Energetic Neutral Atoms (ENA) and charged particles (e^- and ions) enters the heliosphere from ISM
- charge exchange between ENA and ions
- angle between H and He flow (~4°) due to distortion of heliosphere : Hydrogen Deflection Plane (HDP)
- ISMF deforms heliospheric shape

Lallement et al., Science, Vol 307, page 1447 (2005)



$B_{IS} \sim (205^\circ \div 240^\circ , -38^\circ \div -60^\circ)_{galactic}$

off galactic plane (~ HDP)

investigating on interstellar magnetic field

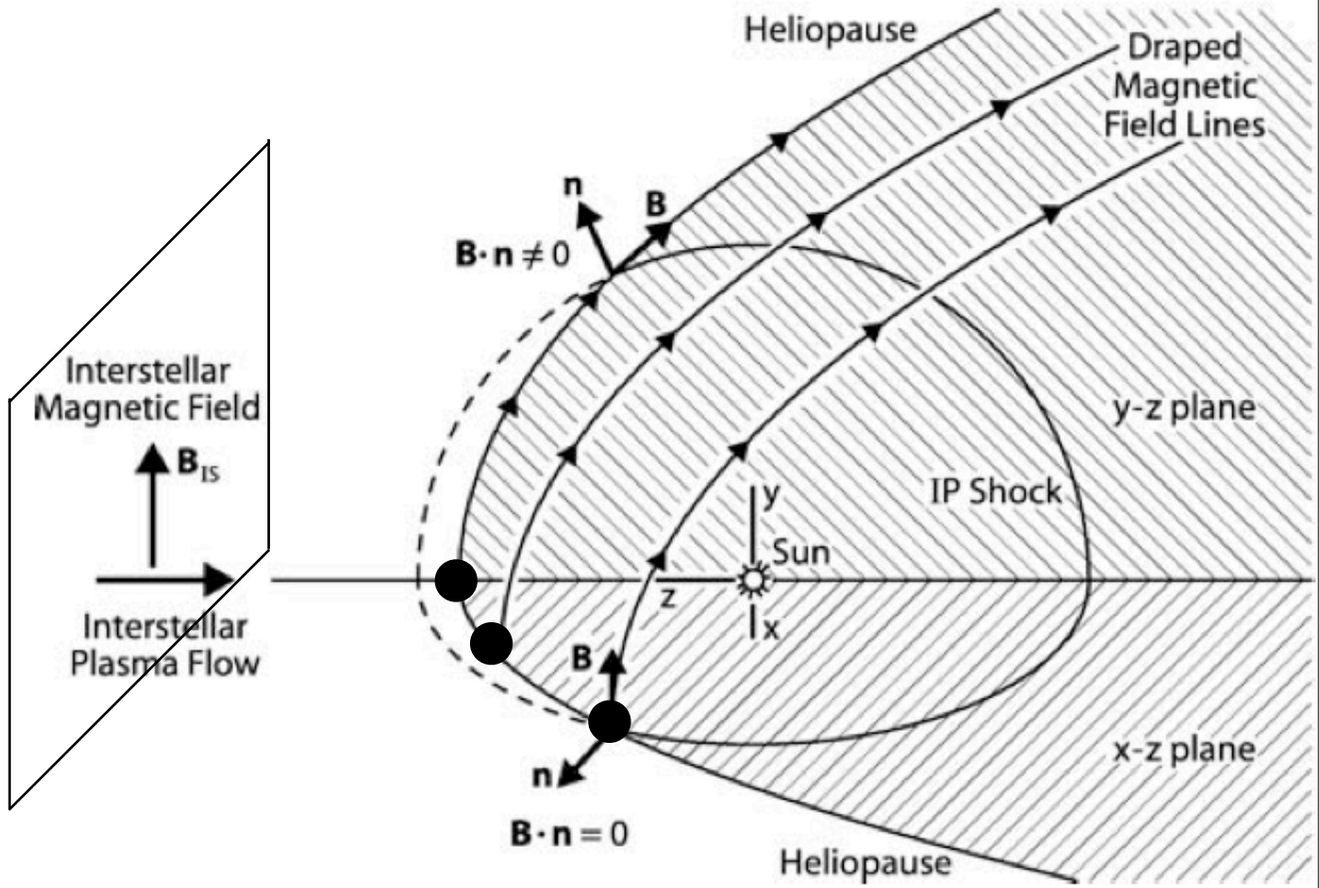
- Sun moving through a tenuous 20-30% ionized interstellar cloud

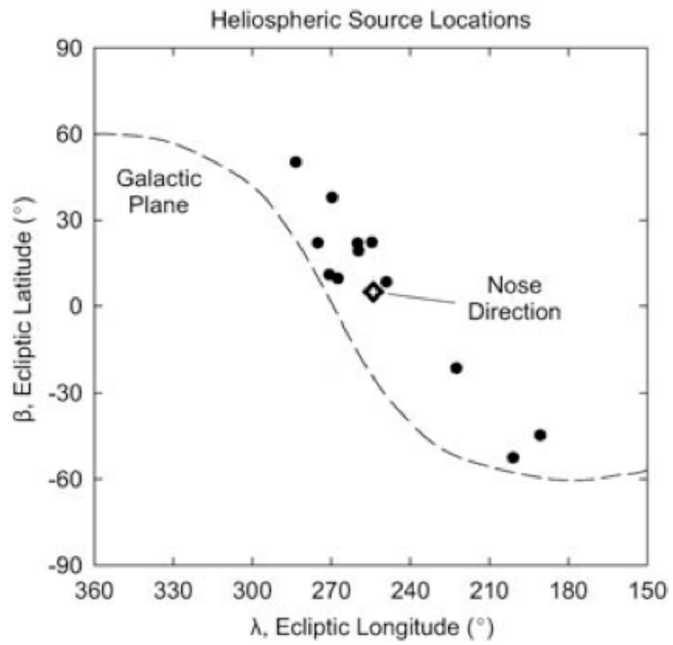
- direction finding of heliospheric radio emissions with Voyager 1/2

- sun shock wave accelerated electrons interacting with heliopause produces radio emission (2-3 kHz) @ $B \cdot n = 0$ ~ galactic plane

- B_{IS} almost perpendicular to galactic plane (~ HDP) : < 20° of previous determination

Gurnett et al., AIP Conf. Proc., 858, page 129 (2006)

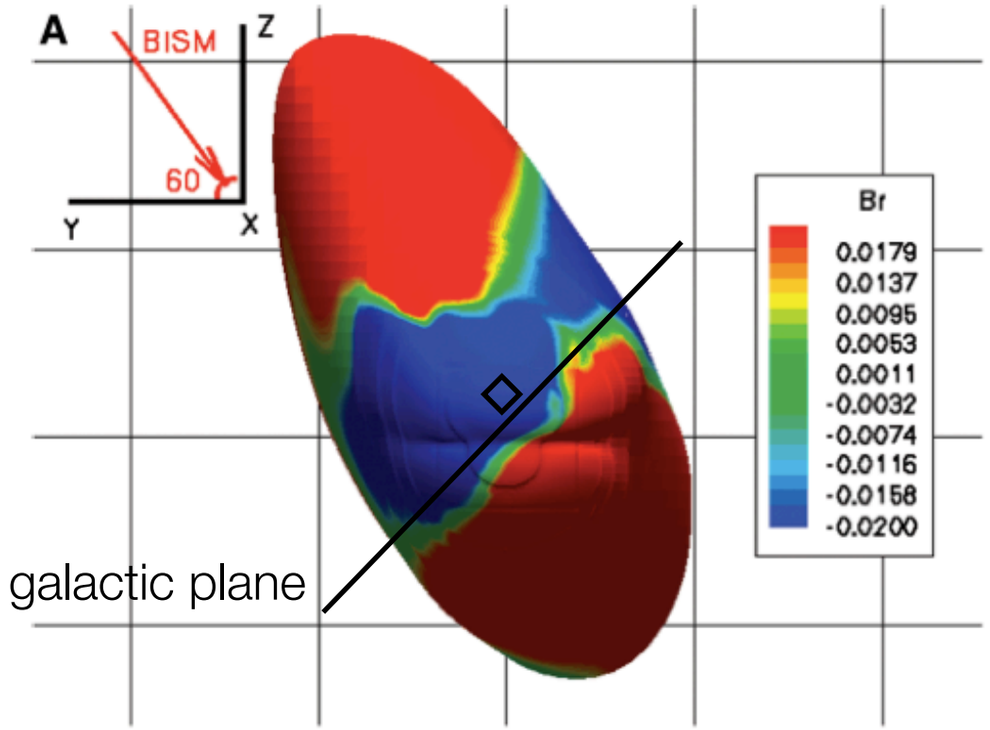


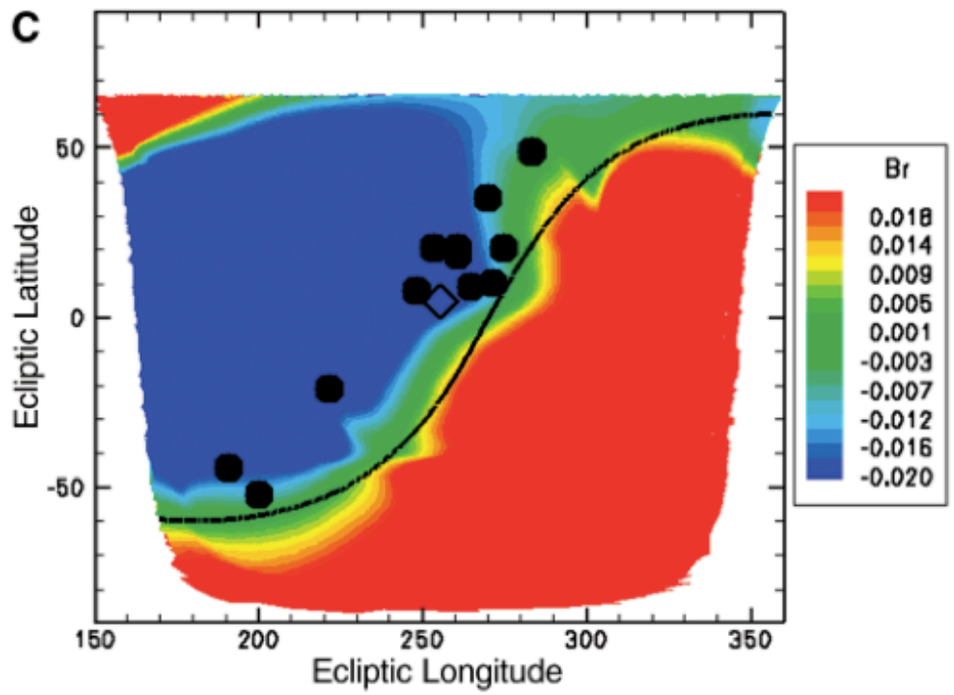


investigating on interstellar magnetic field

- direction finding of heliospheric radio emissions with Voyager 1/2
- streaming of ENA's
- heliopause deformed by B_{IS} : MHD simulations
- consistent with other observations

Opher et al., Science, Vol 316, pag 875 (2007)





investigating on interstellar magnetic field

- in the meantime V1/V2 both passed the termination shock (2004, 2007) @ (95 AU, 85 AU)

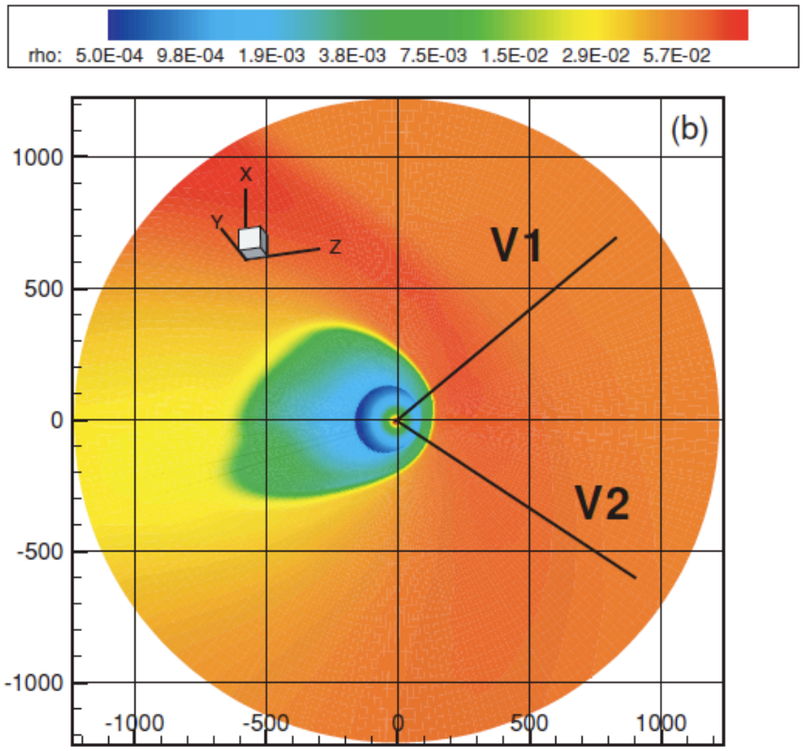
- B_{IS} ~ 4 μG compatible with such an asymmetry

- IBEX measures streaming of ENA

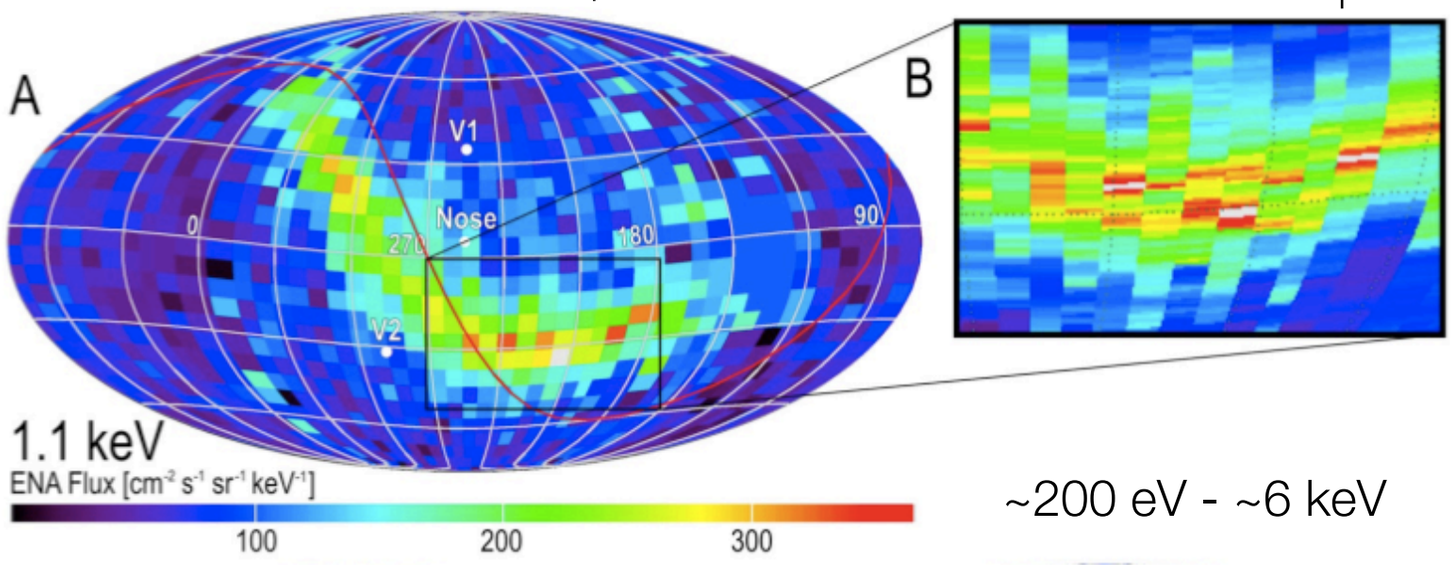
- H ENA from charge exchange in solar wind ions and interstellar pickup ions (~ keV)

- H, He & O from local IS medium

Pogorelov et al., ApJ Vol 695, L31-L34 (2009)



new unexpected results

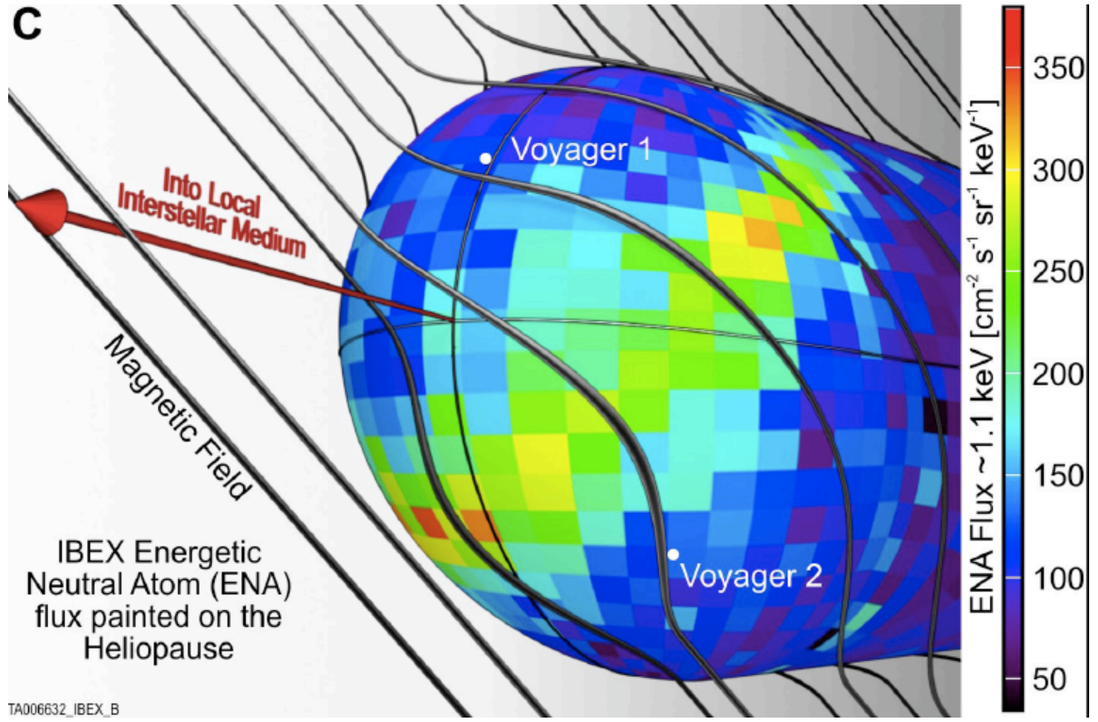


~200 eV - ~6 keV

IBEX Collaboration, Science online , October 15, 2009

investigating on interstellar magnetic field

IBEX Collaboration, Science online , October 15, 2009



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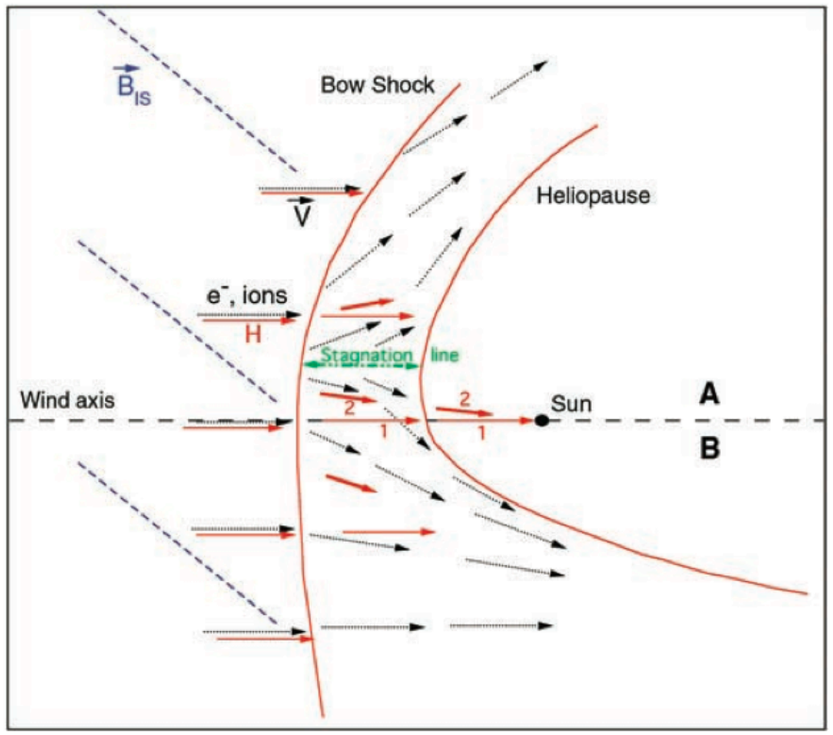
- H ENA from charge exchange in solar wind ions and interstellar pickup ions (~ keV)

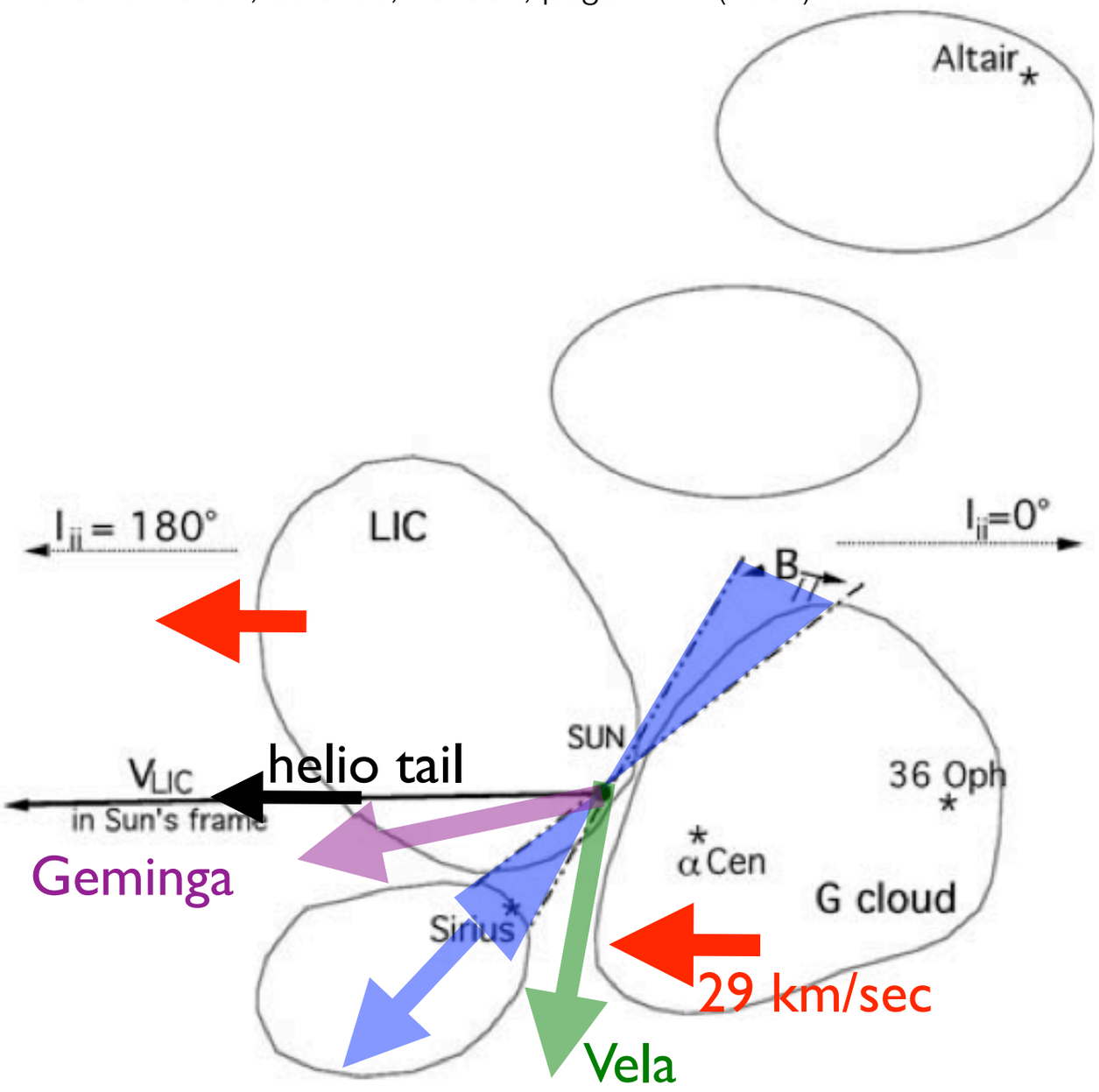
- H, He & O from local IS medium



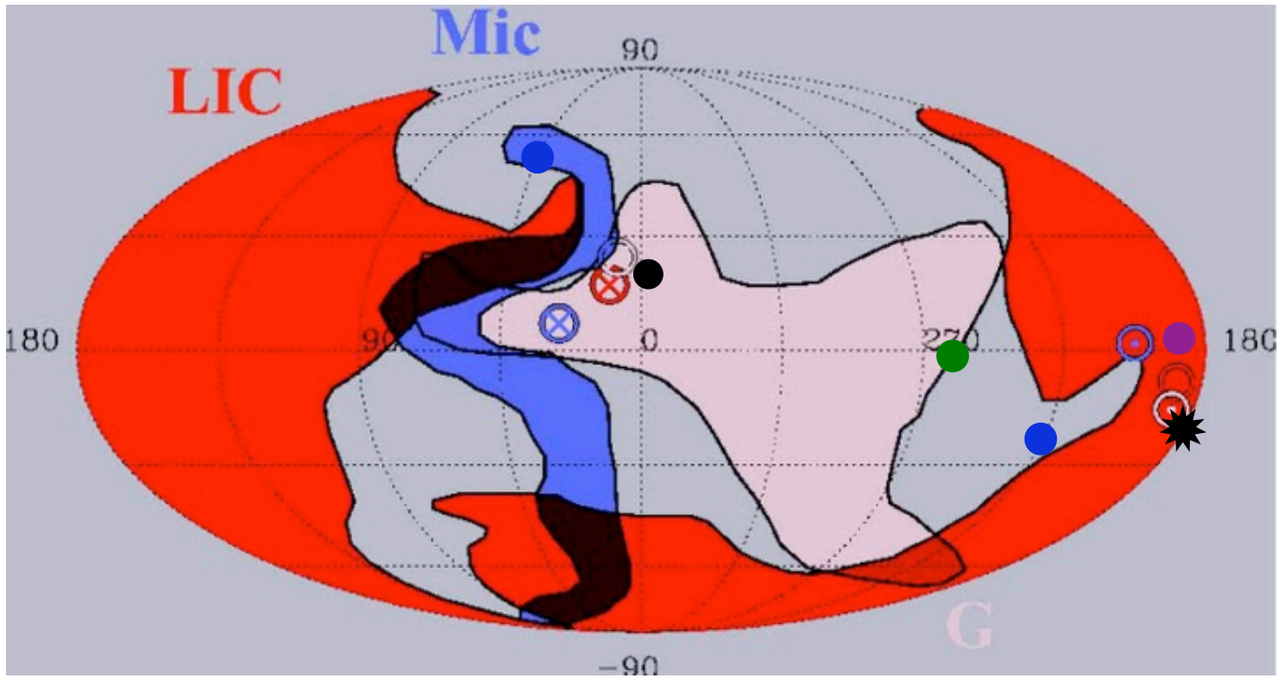
our galactic neighborhood

scale : O(1-10) pc

Lallement et al., Science, Vol 307, page 1447 (2005)



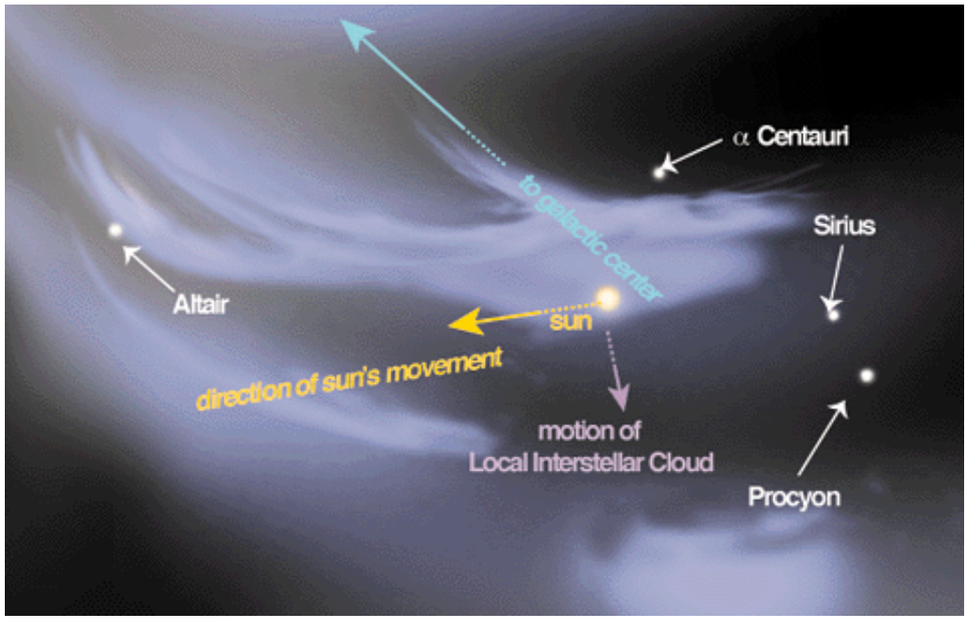
Redfield & Linsky, ApJ, Vol 673, pag 283 (2008)

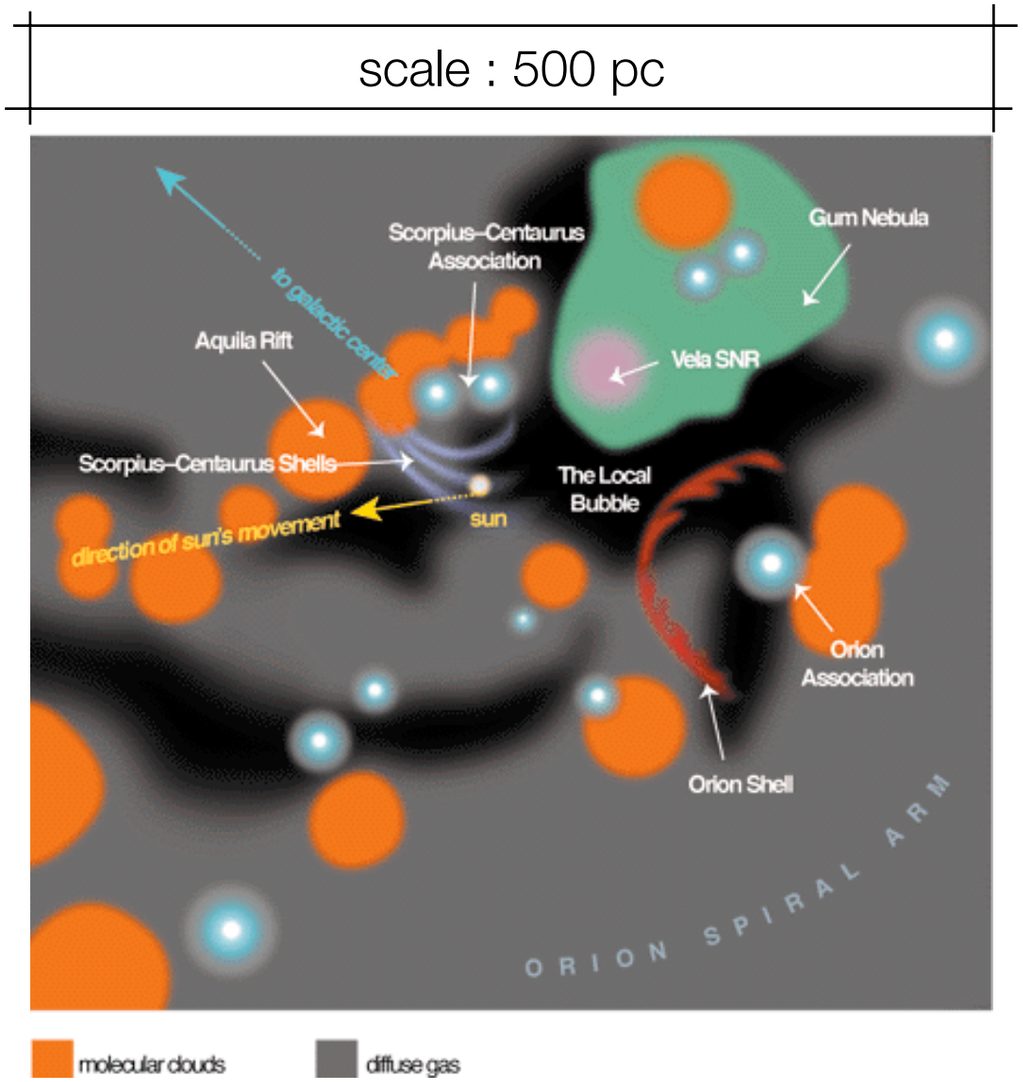


- our neighborhood is highly non-homogeneous and the B_{IS} is a perturbation of the galactic magnetic field

- the solar system is in transition between the Local Interstellar Cloud and the Cloud G

our galactic neighborhood





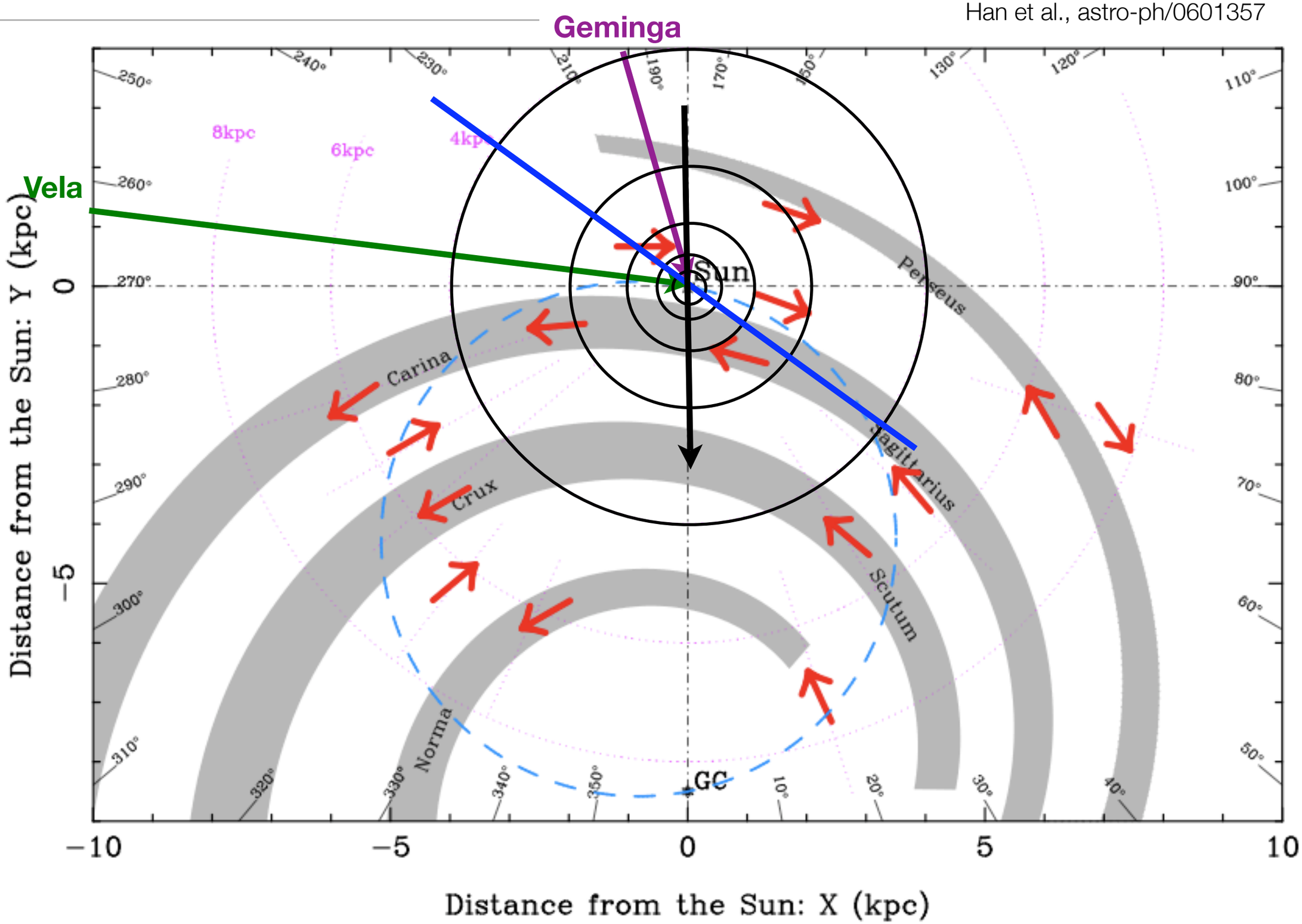
Priscilla Frisch - University of Chicago

- **Local Bubble** (~300 pc) : cavity of the Orion arm with low density (~1/10 of ISM) of hot neutral H gas that emits X-rays. Produced by ancient SN (perhaps Geminga)

- **Local Interstellar Cloud** (~10 pc) : thin cloud (~1/5 of ISM) is flowing from the Scorpius-Centaurus Association, a star forming region

our galactic neighborhood

Han et al., astro-ph/0601357



origin of anisotropy ?
a long story

- anisotropy might be connected to the origin of galactic cosmic rays
  - major features due to *local* environment (< 1 kpc) and its history : SN & magnetic field
  - local IS medium (< 1 kpc) is non-uniform, nearby SN might give a significant contribution

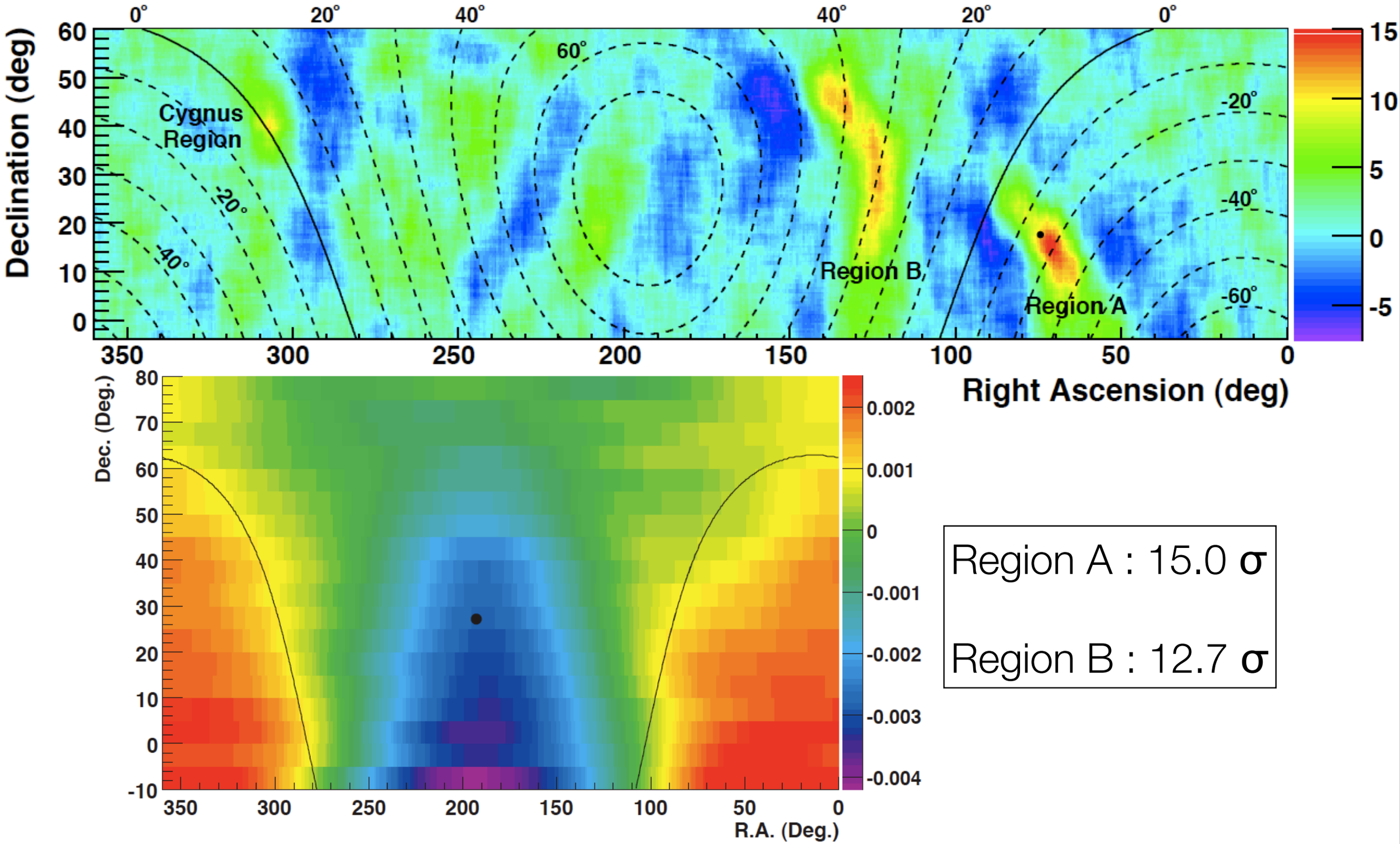
    ➡ is angular scale of the anisotropy related to the distance where it originates ?

    ➡ is it the nearby medium that determines small angular scale ?

    ➡ diffusion of galactic cosmic rays is the key

  - if cosmic ray knee generated by a single nearby source [Erlykin & Wolfendale, ICRC 2009] this source might induce an anisotropy

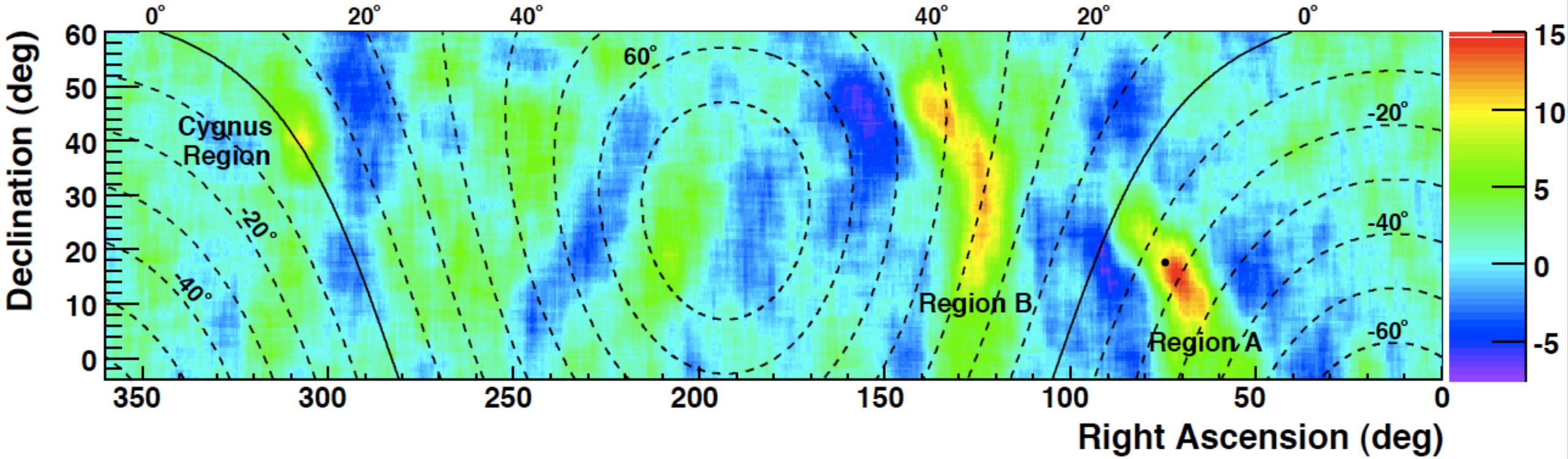
    ➡ our observations might be accidental



Region A : 15.0 σ

Region B : 12.7 σ

MILAGRO | arXiv:0801.3827



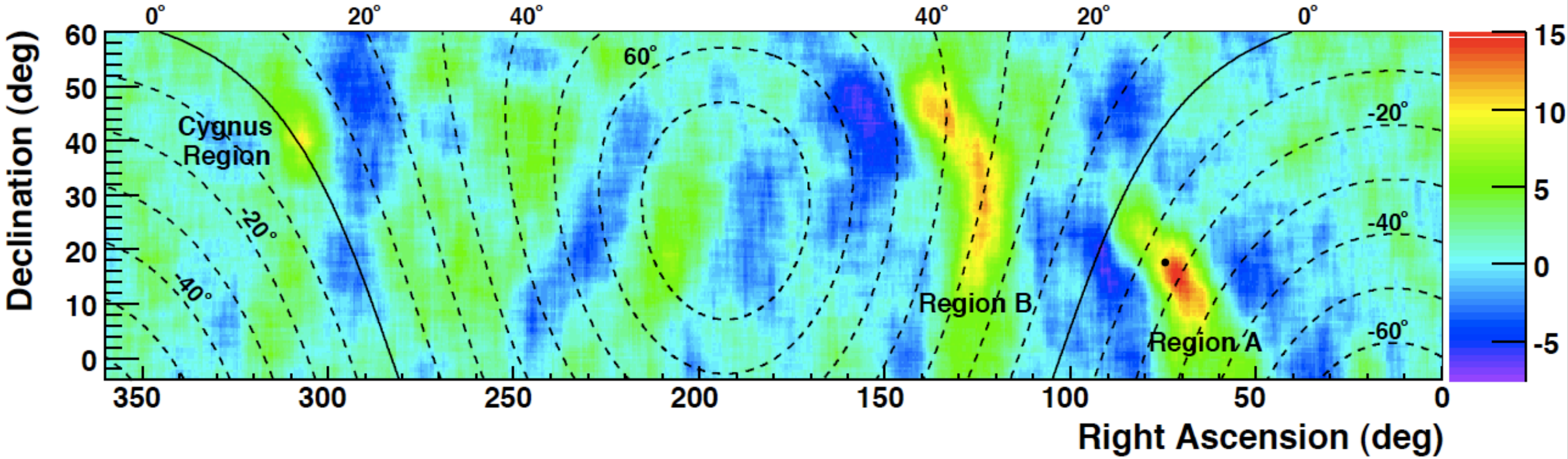
- data between June 2000 and August 2007
- $2.2 \cdot 10^{11}$ events
- median CR energy ~ 1 TeV
- average angular resolution < 1°

Region A : 15.0 **σ**

Region B : 12.7 **σ**

MILAGRO

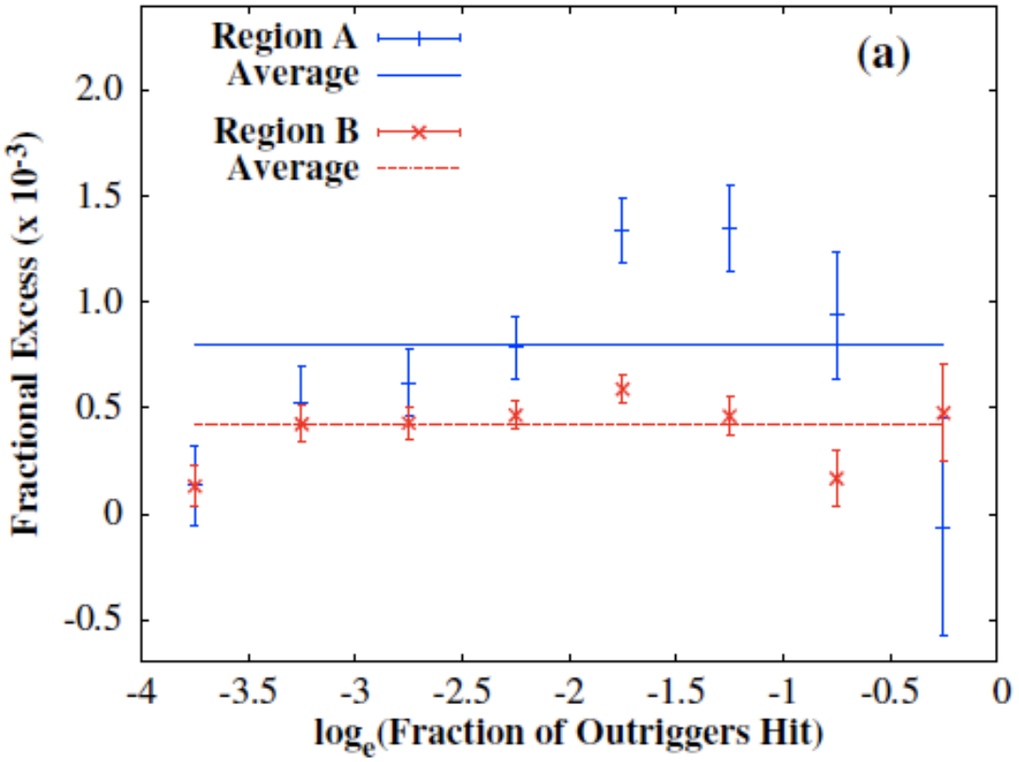
arXiv:0801.3827

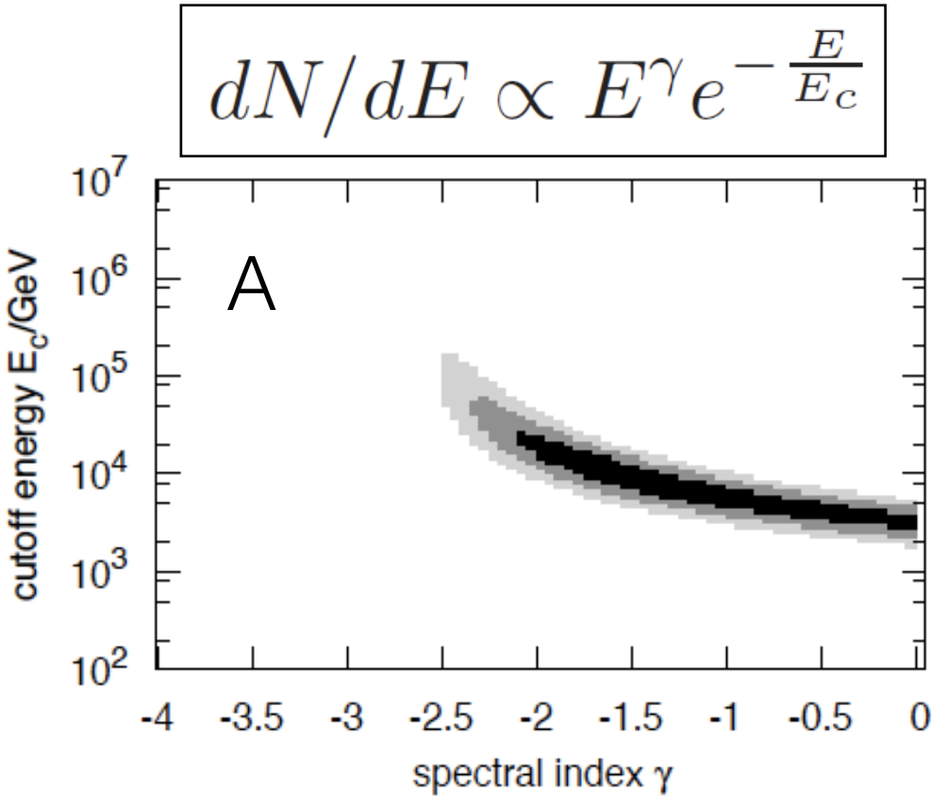


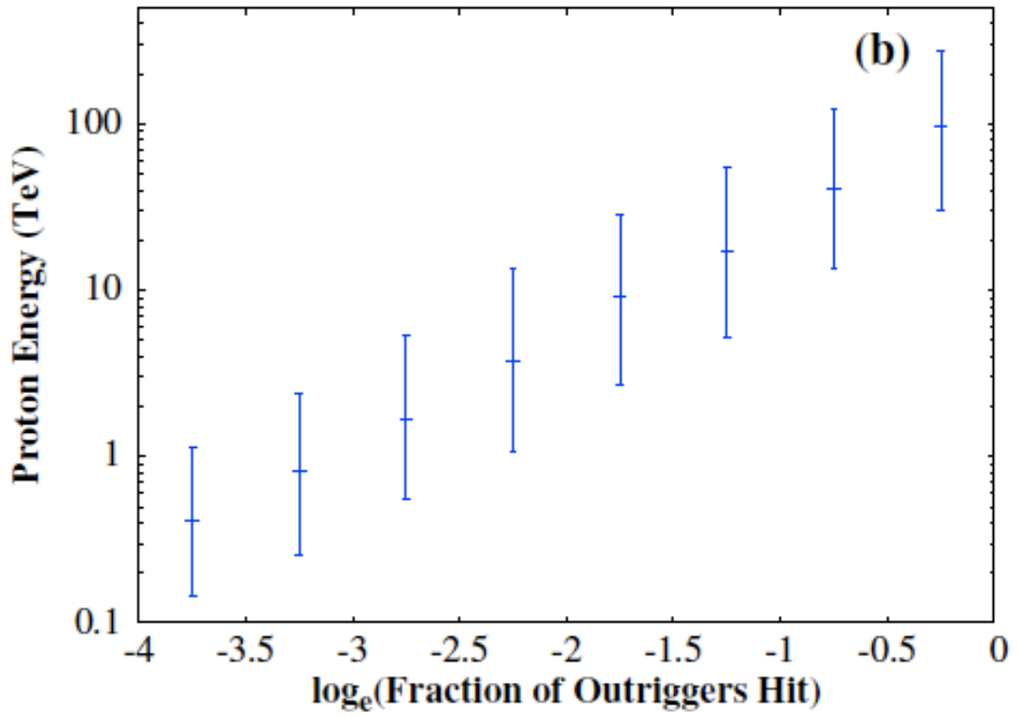
- fractional excess lowest in summer
- highest in winter

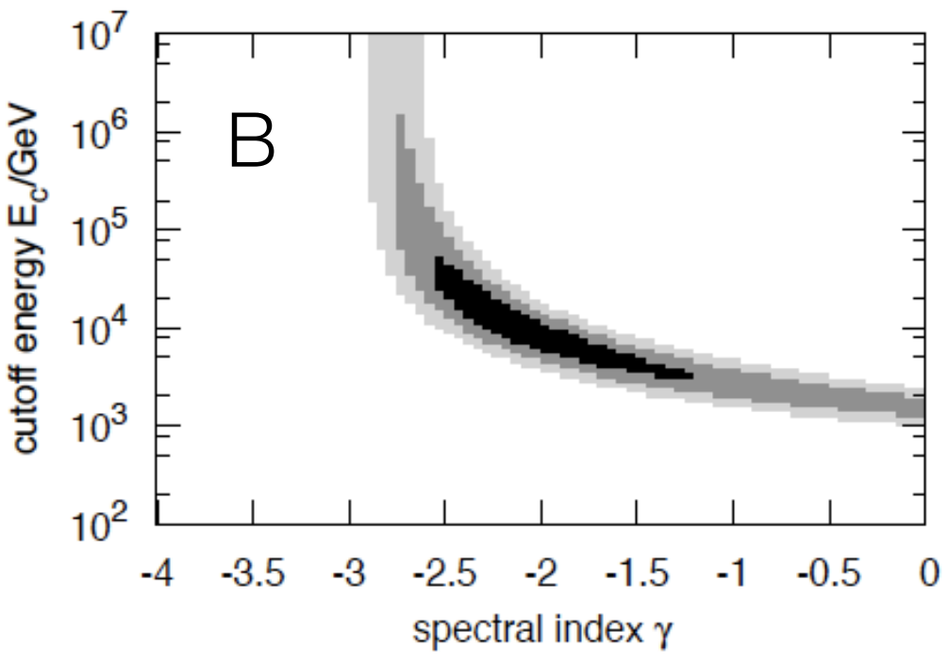
- χ^2 probability for constant excess ~ 5%
  - suggestive of heliospheric connection (< 10 TeV)
  - or detector systematics

MILAGRO | arXiv:0801.3827







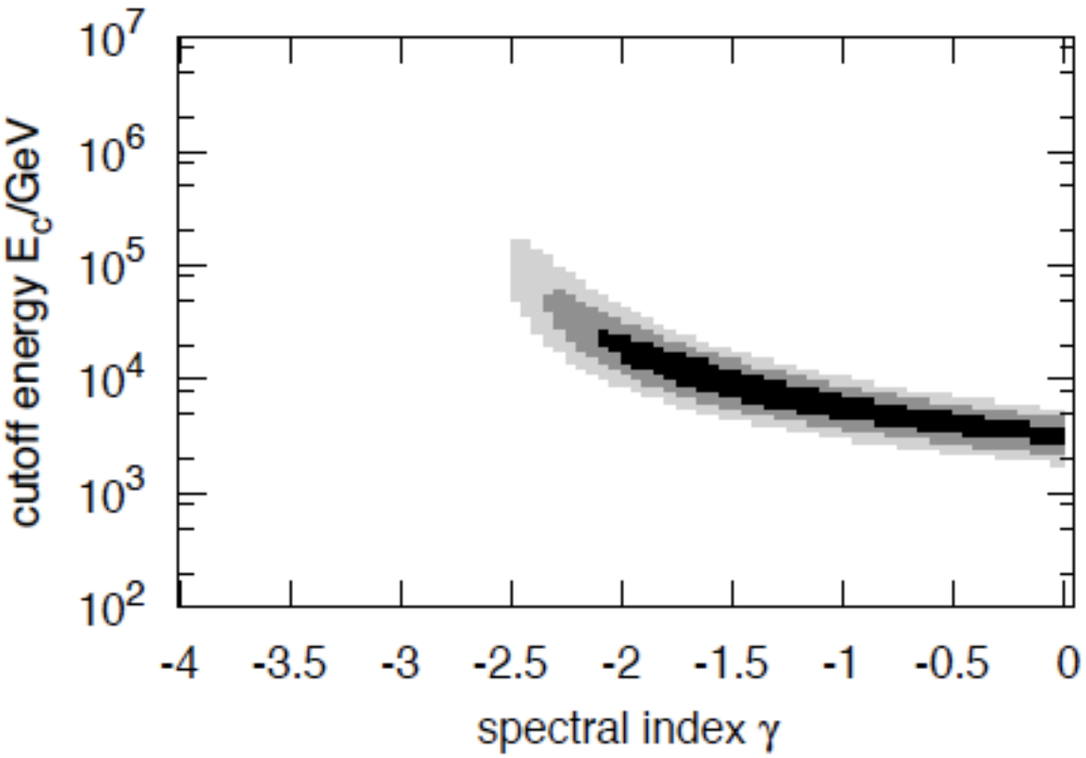


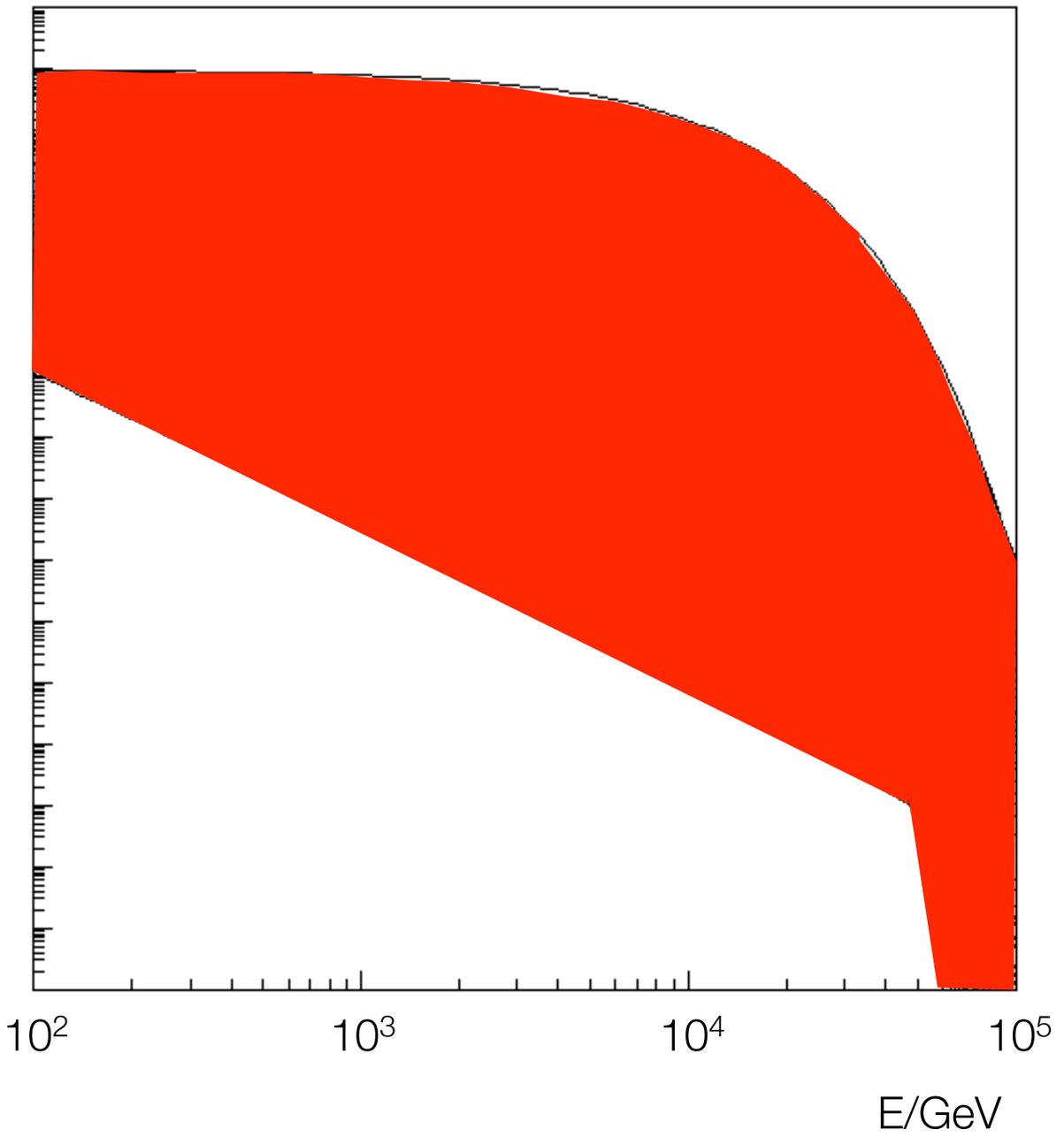
pure gamma ray hypothesis
strongly disfavored

MILAGRO

arXiv:0801.3827

$$dN/dE \propto E^{\gamma} e^{-\frac{E}{E_c}}$$

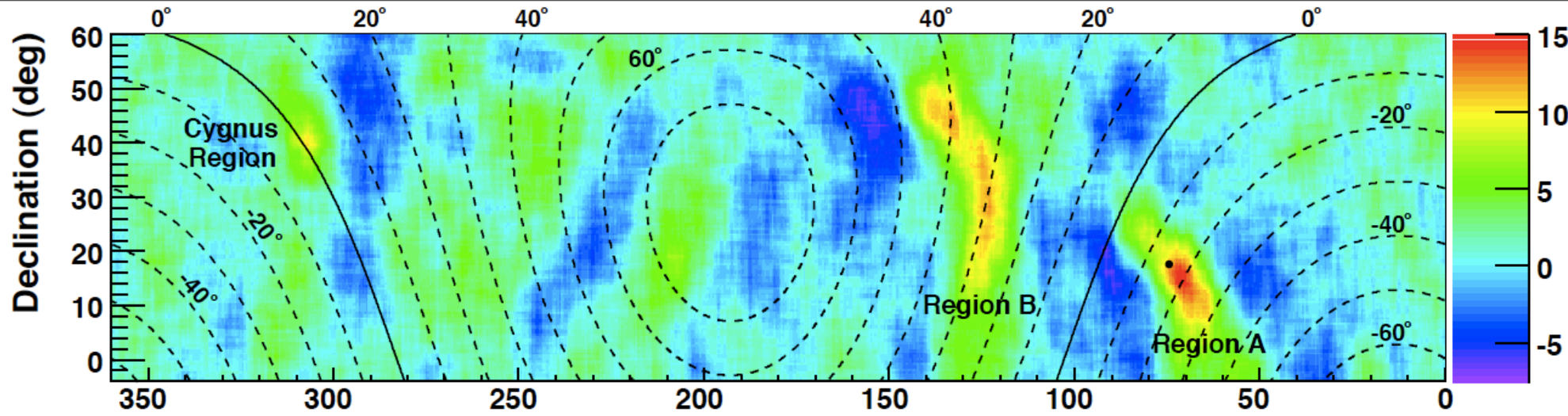




pure gamma ray hypothesis
strongly disfavored

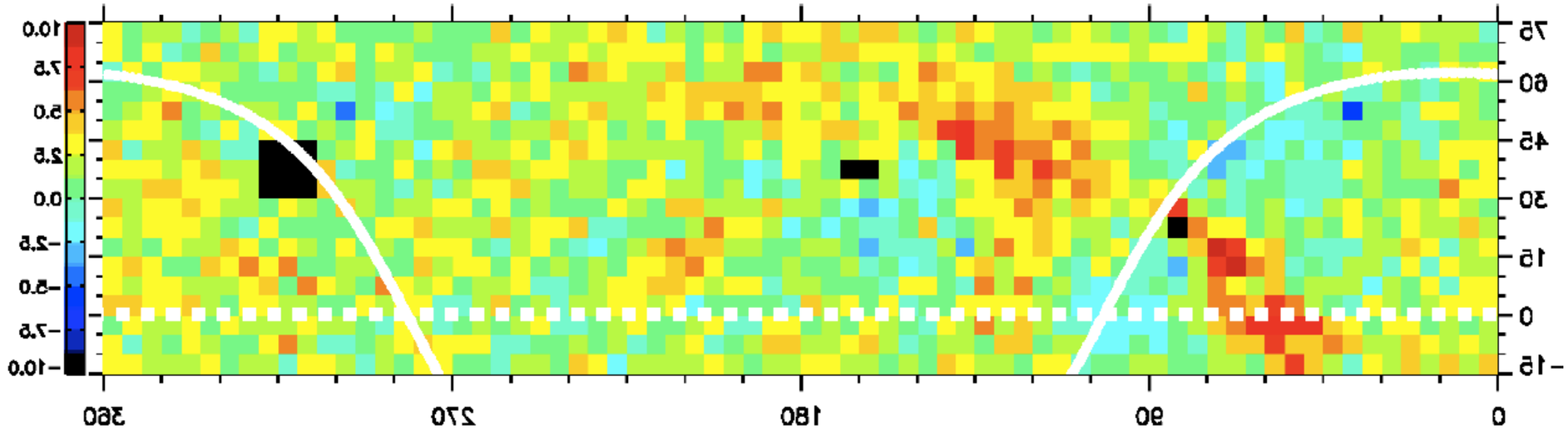
MILAGRO

arXiv:0801.3827



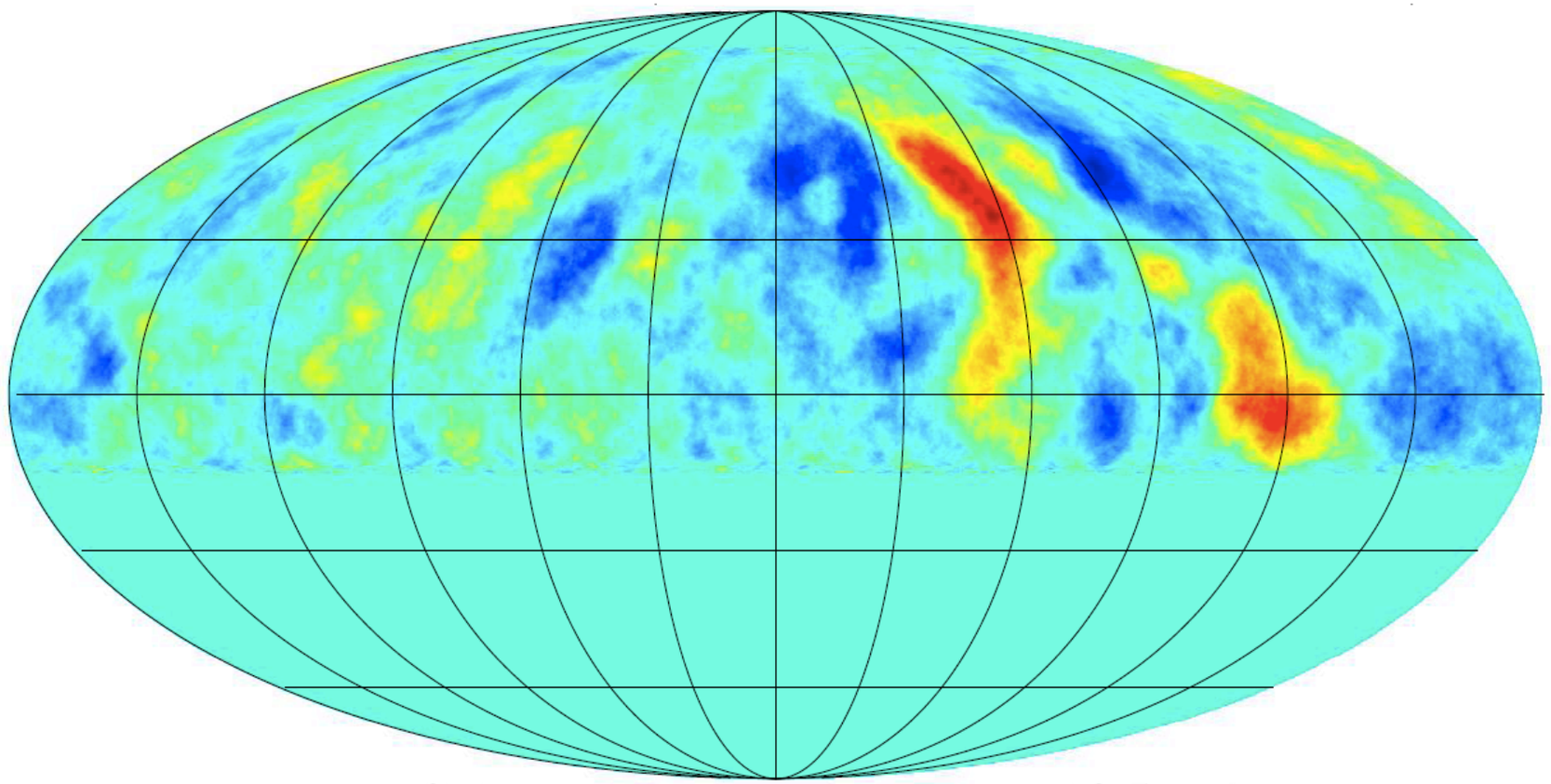
Milagro

direct integration



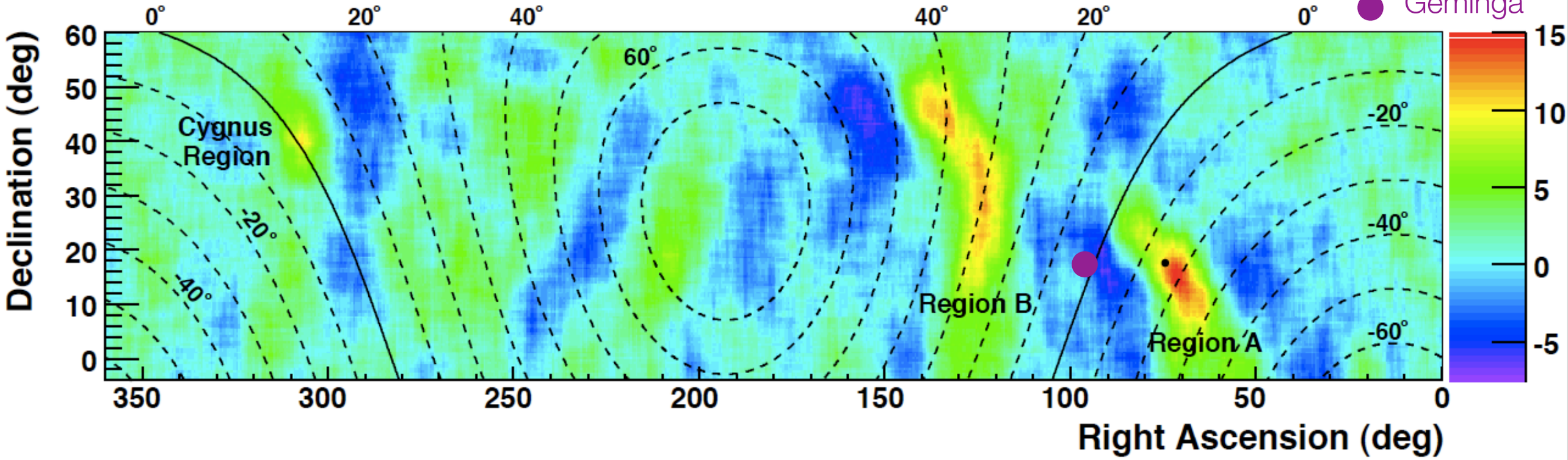
Tibet-III

global fit



ARGO-YBJ

time scrambling



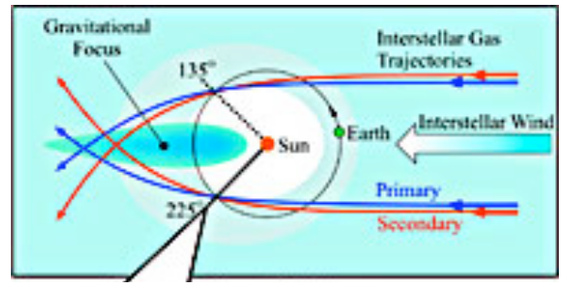
- region A & B might have different origins
- region A is ~ 10° wide with cosmic rays in the 1-10 TeV range
- small structure suggests a nearby origin
- region A associated to Geminga ?

MILAGRO

arXiv:0801.3827

possible explanations : *neutrons, heliosphere*

- **neutrons** [Drury & Aharonian, arXiv:0802.4403]
  - decay length ~ 0.1 pc (~ 20,000 AU) @ 10 TeV
  - secondary n production in gravitationally focused heliotail
  - density too small to explain the fractional excess in region A

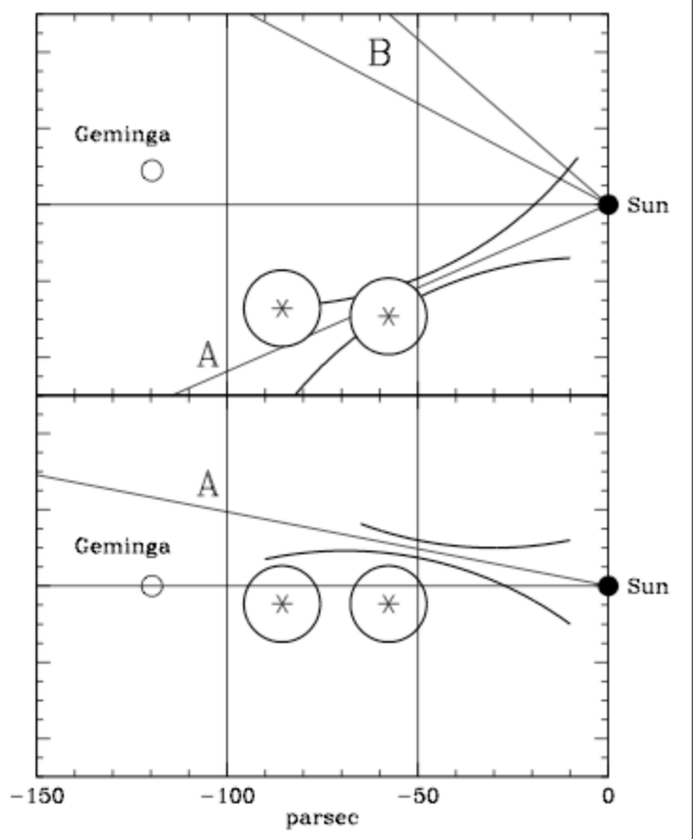


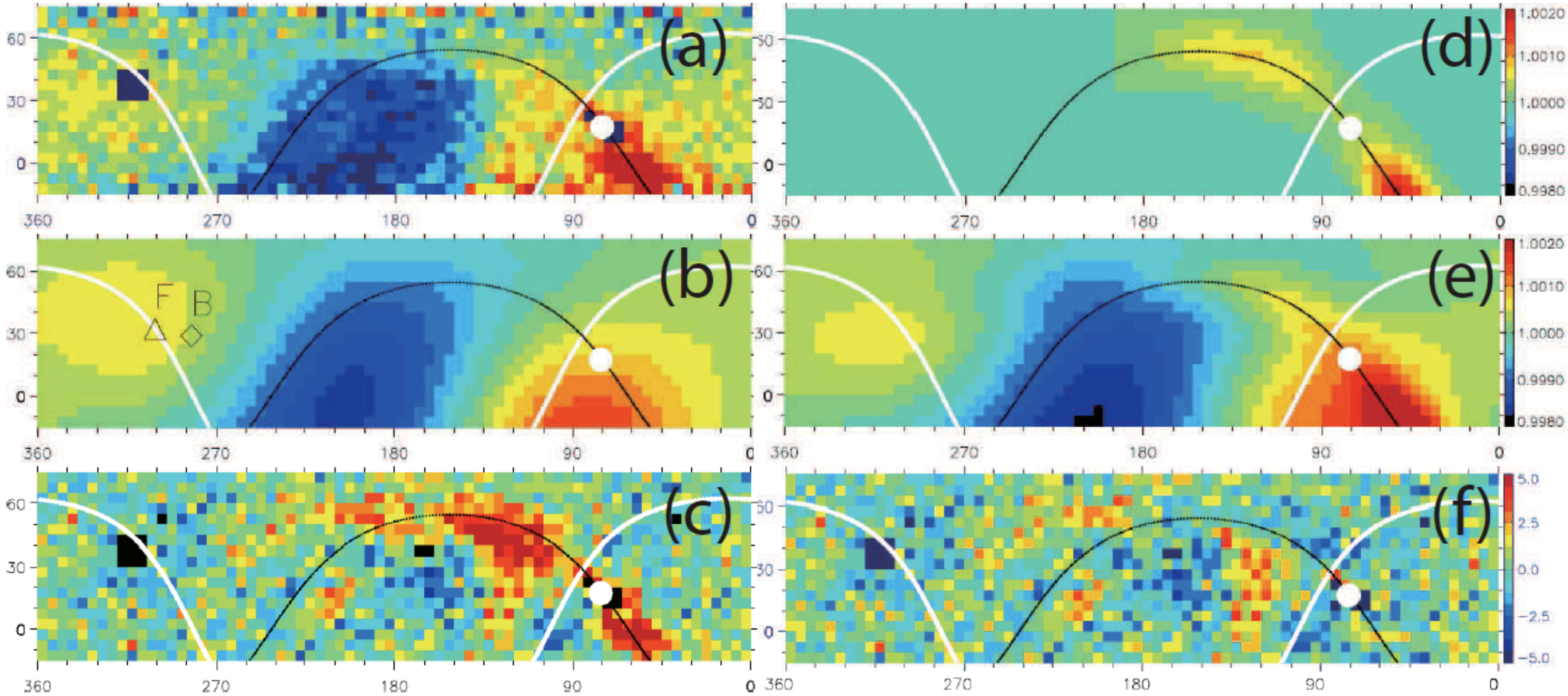
- gyro-radius @ 10 TeV, 1μG ~ 0.01 pc (~ 2,000 AU ~ 20x size of heliopause)
  - acceleration @ heliosphere does not explain observation [Salvati & Sacco, arXiv:0802.2181]

possible explanations : *nearby source*

- galactic cosmic ray accelerator (Salvati & Sacco)
  - Geminga (~155 pc) was closer 340,000 yr ago : ~90 pc
  - Bohm diffusion of 10 TeV ~ 65 pc
  - fractional excess compatible with $\sim 1.5 \cdot 10^{49}$ erg
  - energy passband (cutoff HE, delays LE) ~ hard spectrum

- slow diffusion + magnetic nozzle
  - to avoid large angular scale of excess
  - CR *freely* propagating through magnetic nozzle

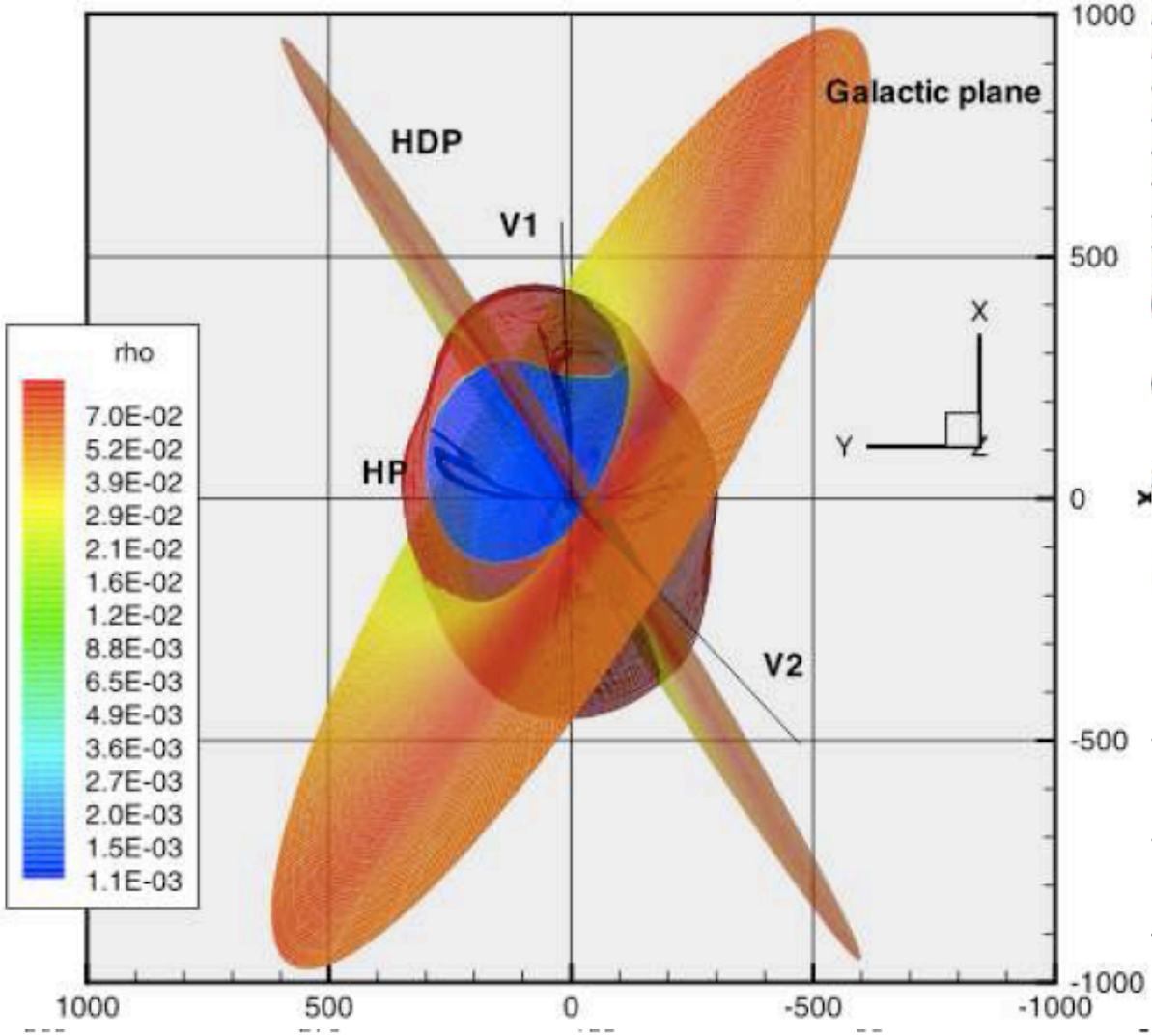


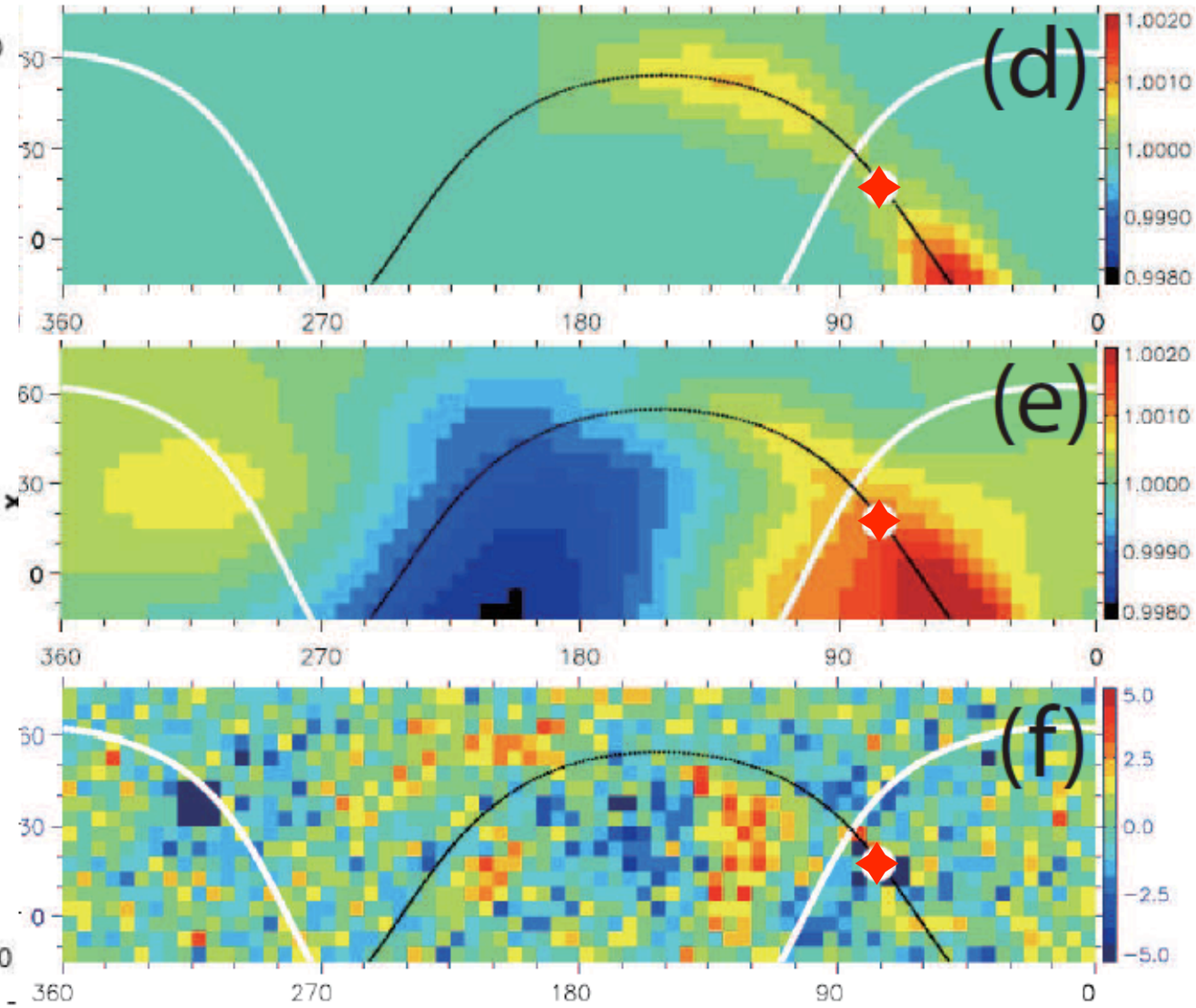


- Hydrogen Deflection Plane contains LIMF and interstellar wind velocity vector

- the excesses are on the HDP and may be caused by the north-south heliospheric asymmetry induced by the LINMF

Tibet-III | ICRC 2009





- Hydrogen Deflection Plane contains LIMF and interstellar wind velocity vector

- the excesses are on the HDP and may be caused by the north-south heliospheric asymmetry induced by the LINMF

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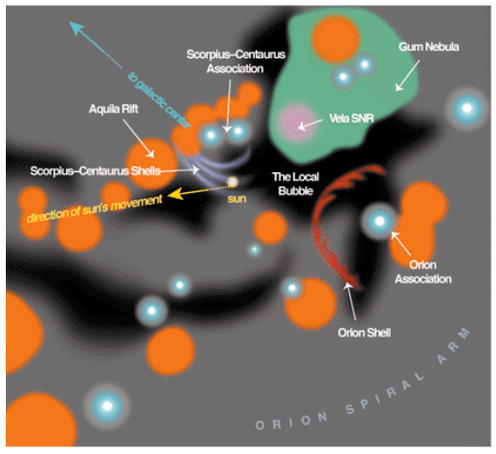
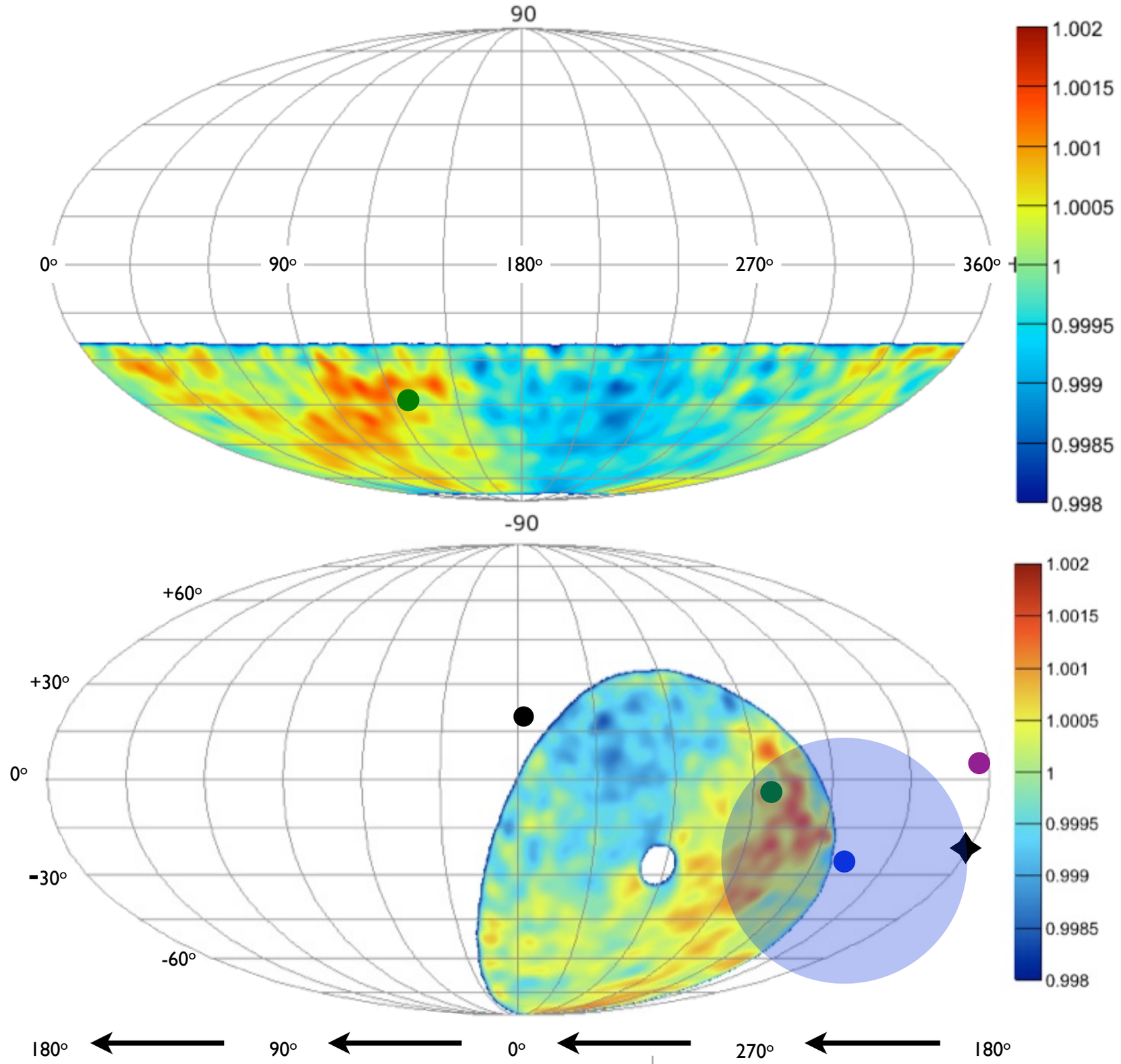
equatorial coordinates



galactic coordinates



IceCube-22

IceCube working on determination of small angular scale anisotropy

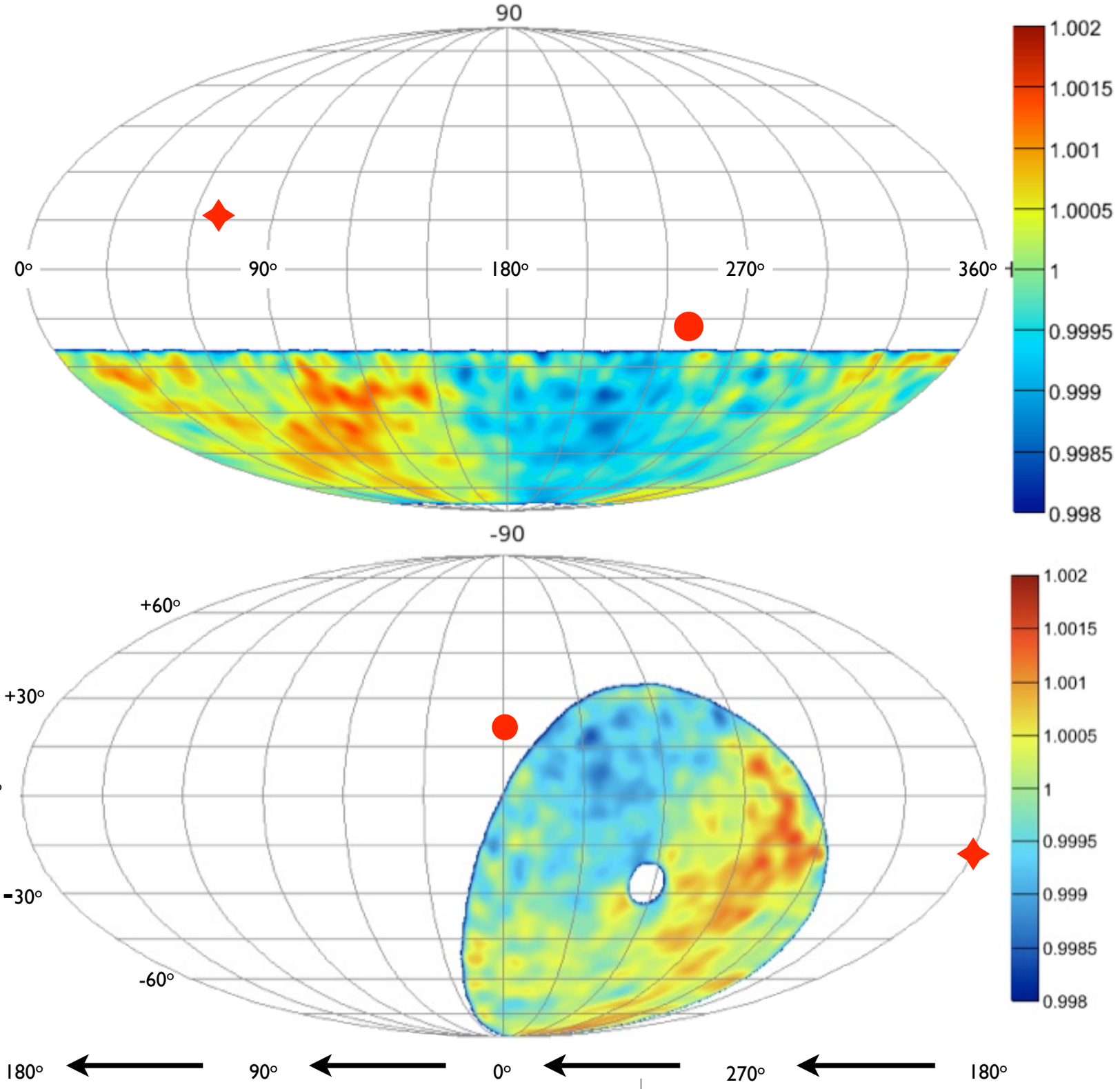
conclusions
or starting points

- anisotropy in arrival direction of galactic cosmic rays exists
  - below 10 TeV likely heliospheric / heliosphere tail contribution
  - above 10 TeV some sort of *galactic contribution*
- need to understand IS medium structure and magnetic field
- possible connection to nearby sources of cosmic rays
  - might contribute to large angular scale anisotropy
  - small angular scale modulated by *nearby* environment

➡ cosmic ray measurement can give us precious information on magnetic field and origin of cosmic rays

extra slides

equatorial coordinates

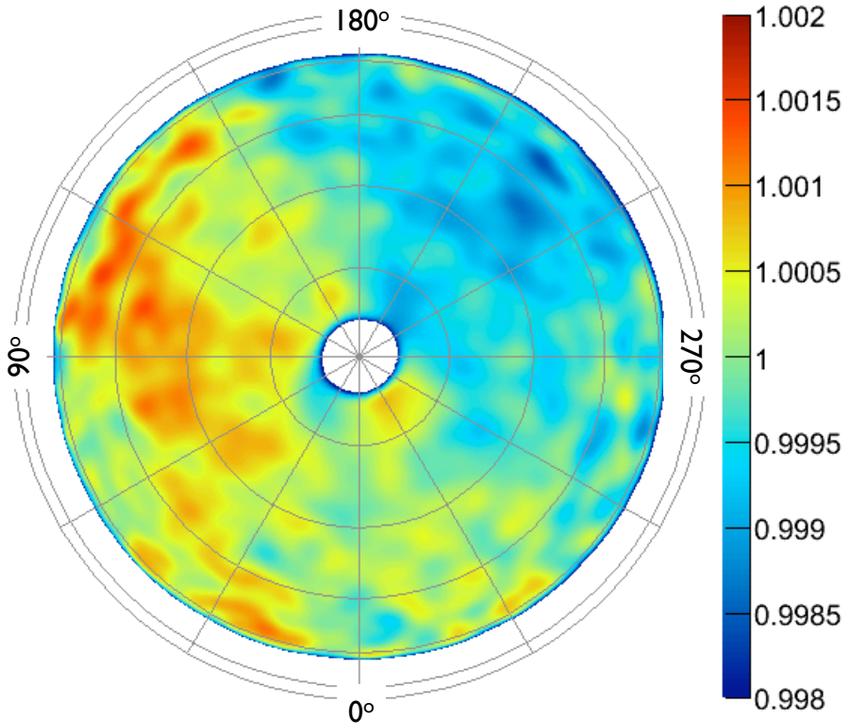


galactic coordinates

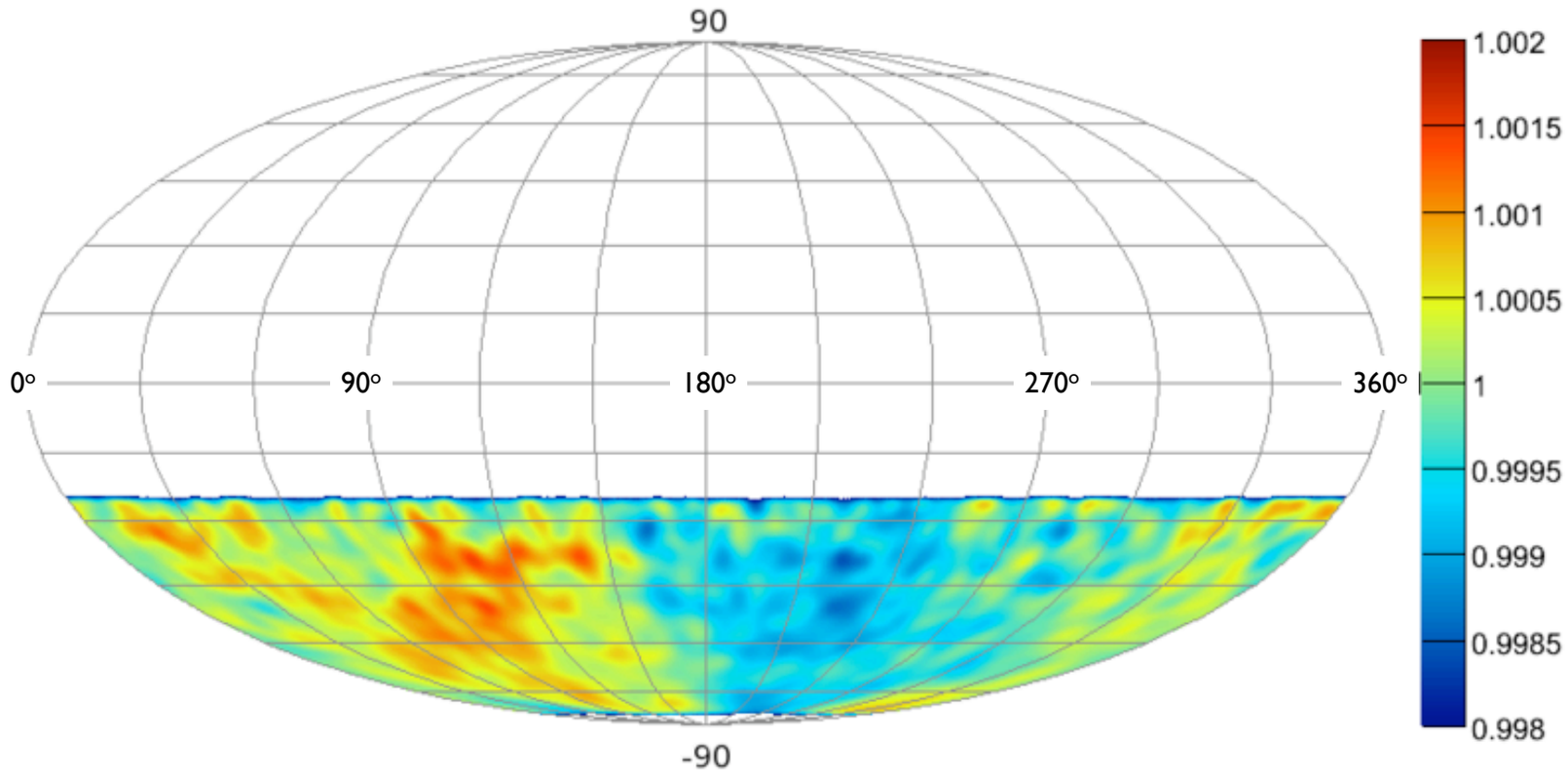
IceCube-22

Rasha Abbasi

polar coordinates

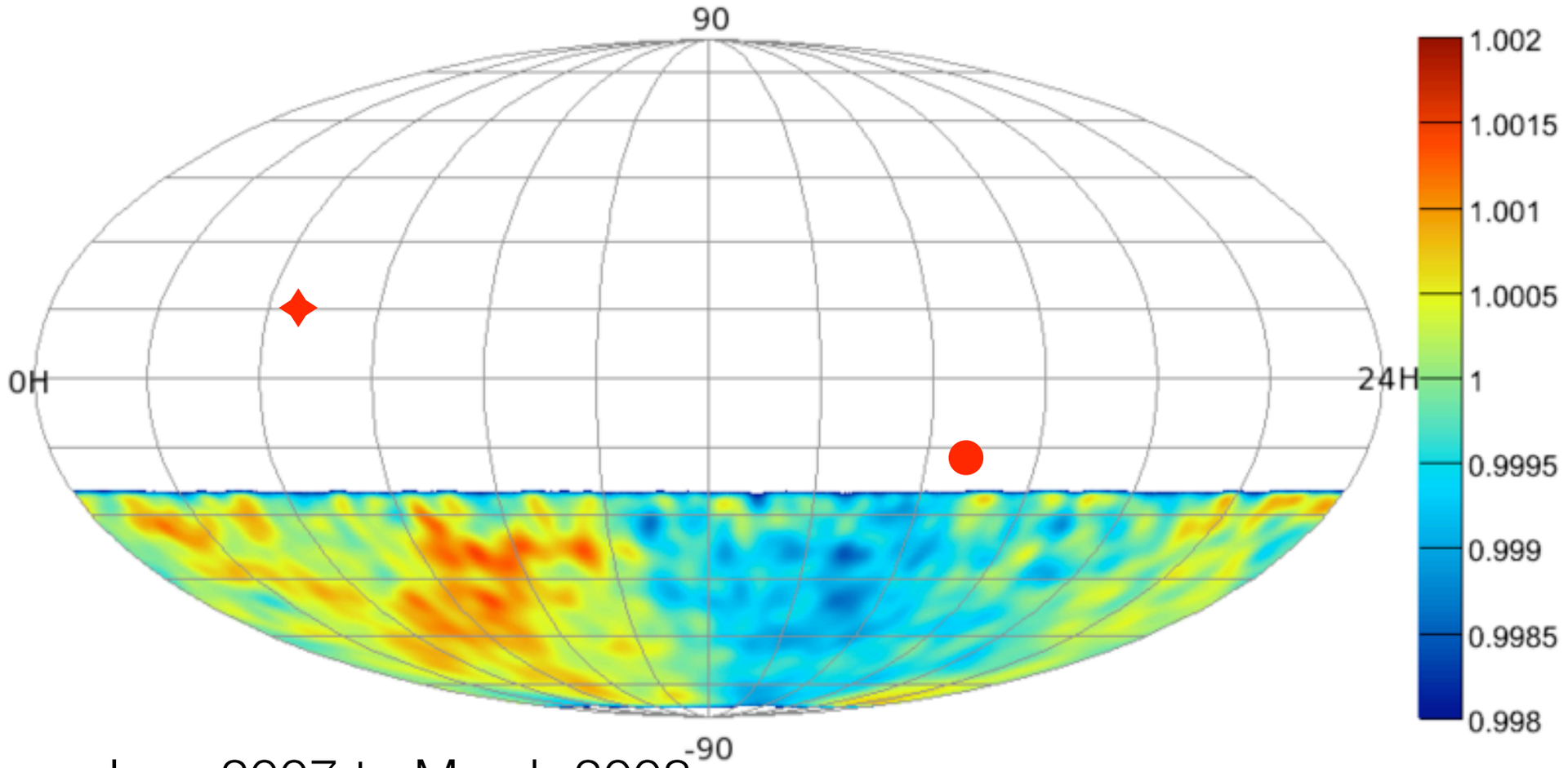


equatorial coordinates

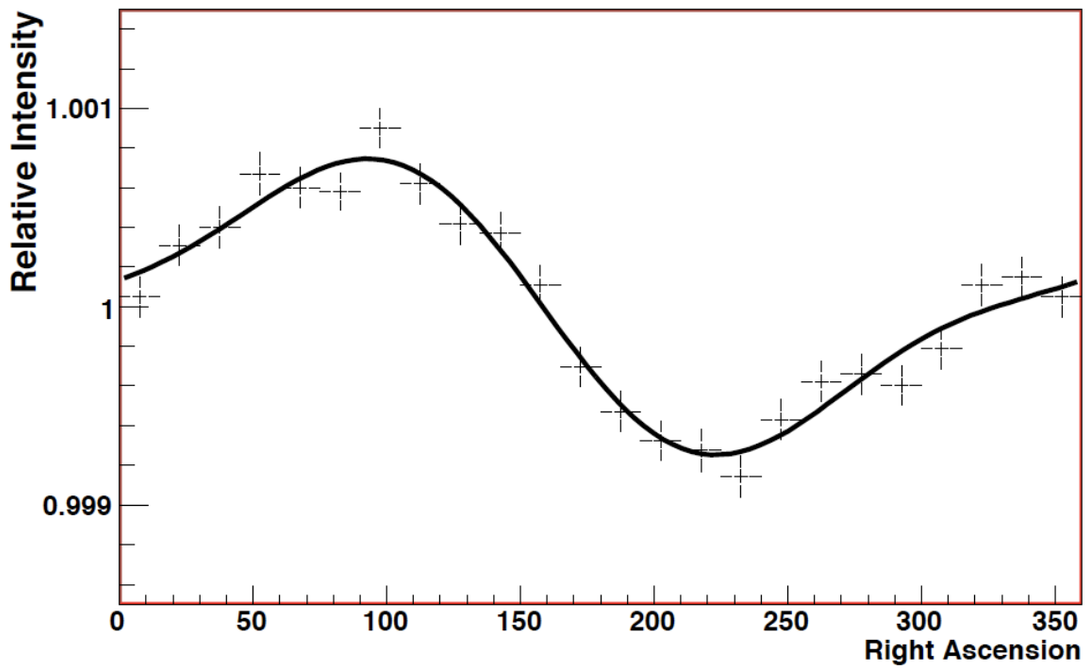


IceCube-22

Rasha Abbasi

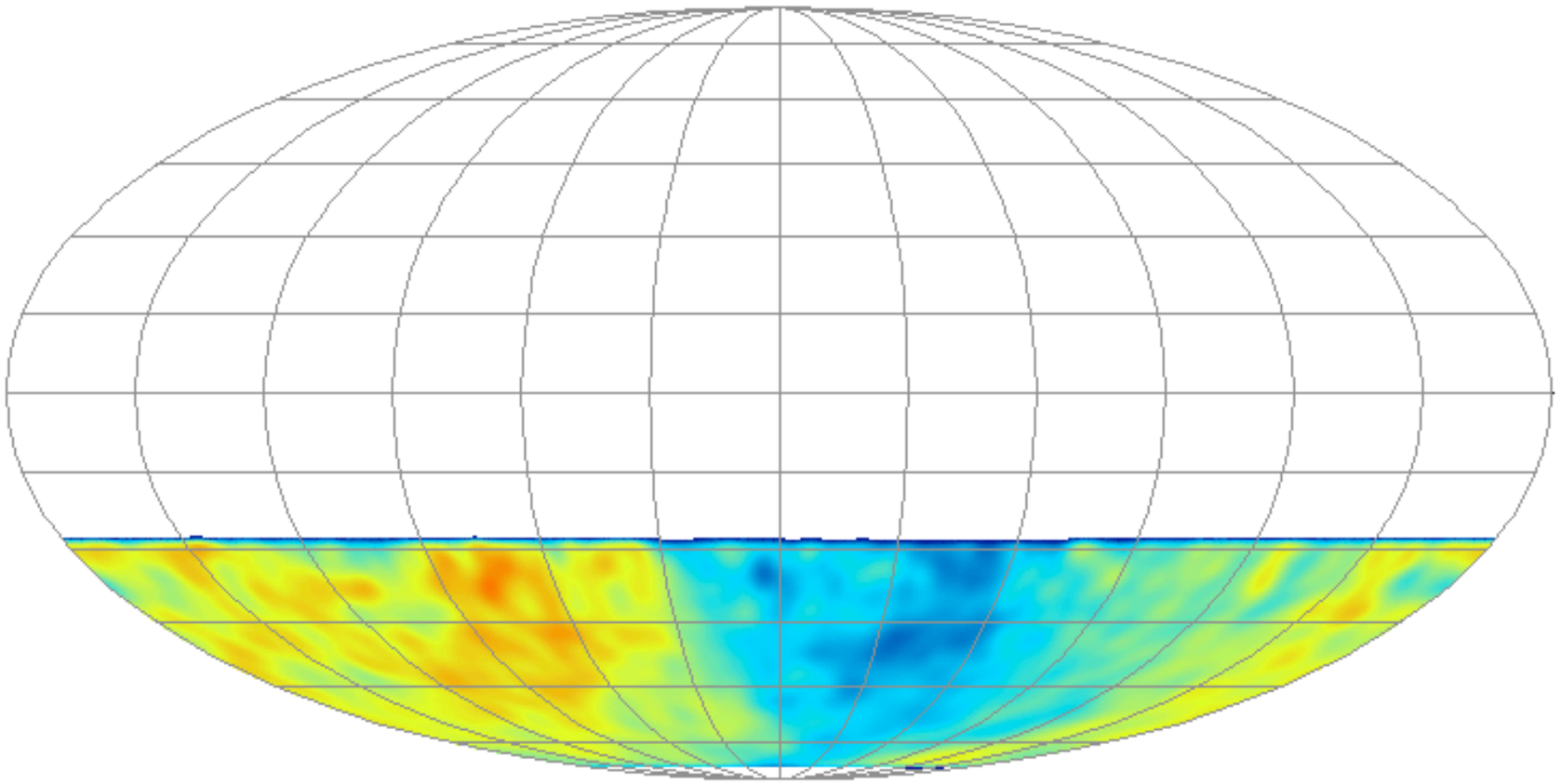


- data from June 2007 to March 2008
- 226 days livetime
- $4.3 \cdot 10^9$ events
- median angular resolution ~ 3°
- median CR energy ~ 14 TeV

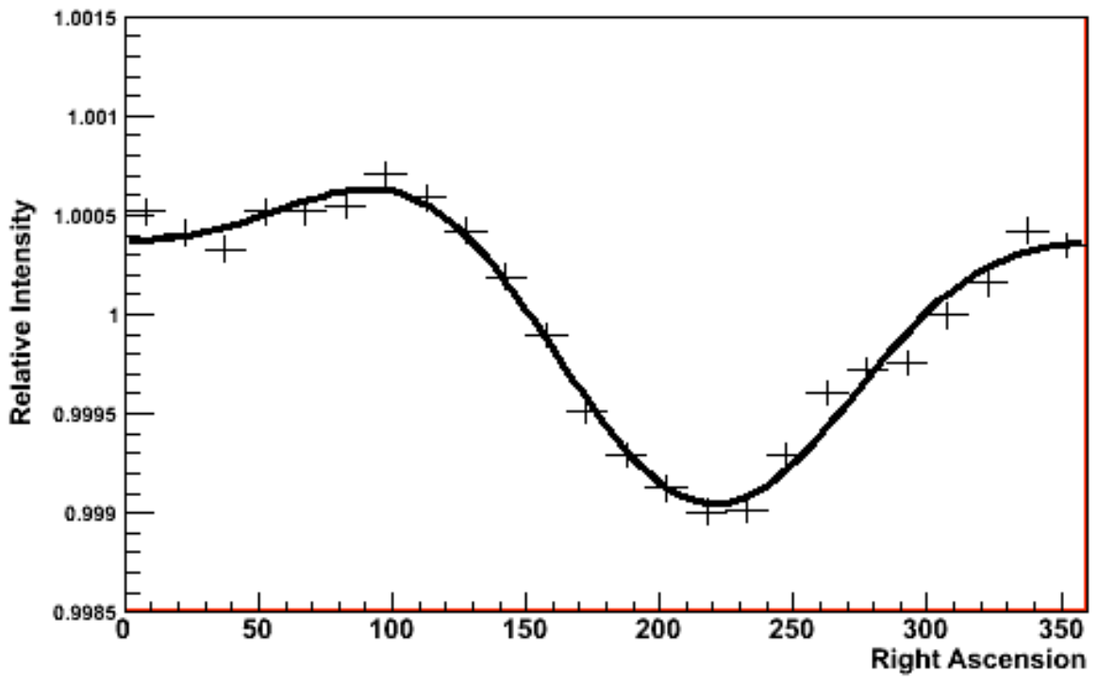


IceCube-22

Rasha Abbasi
Juan Carlos Díaz Vélez, PD

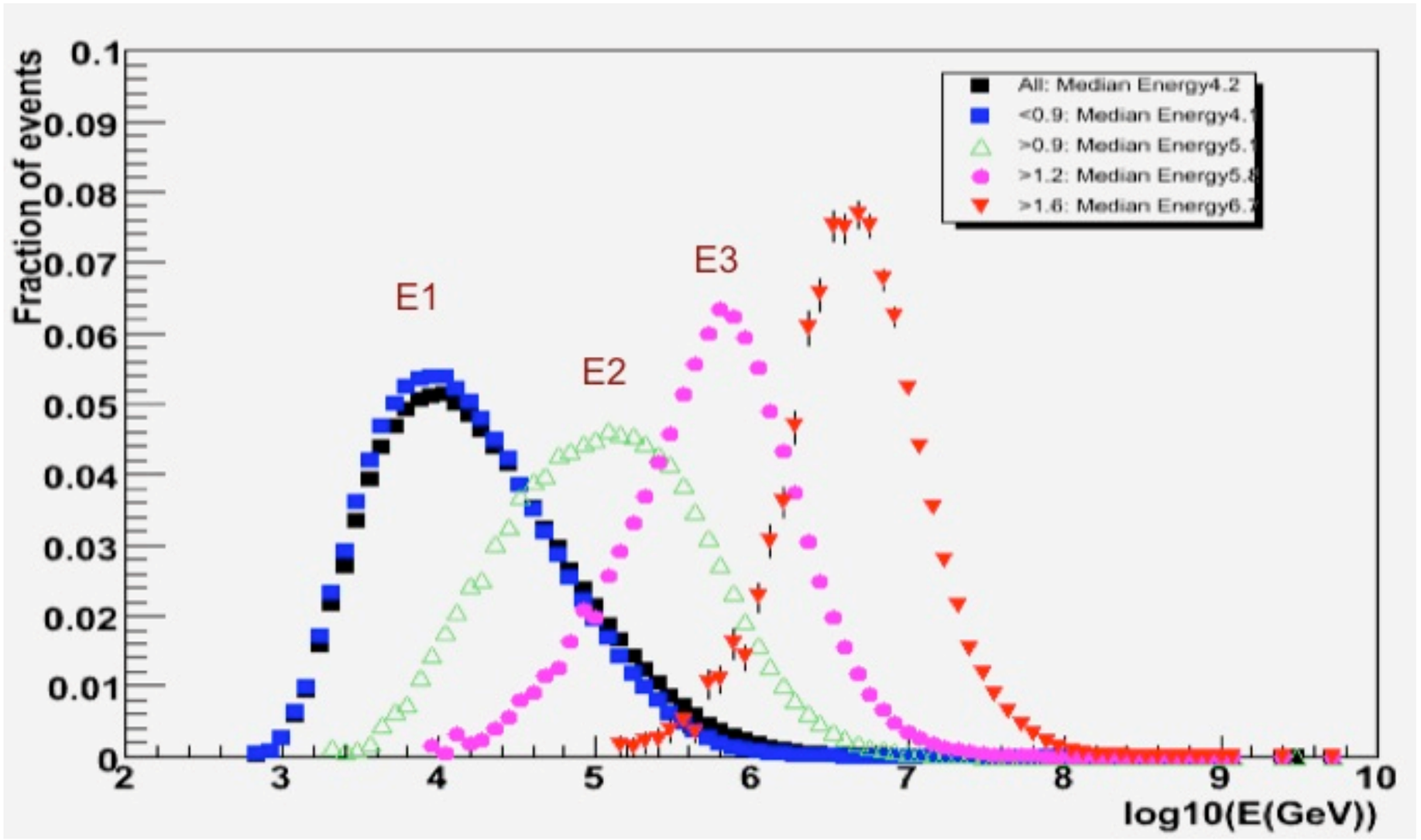


- ~$12 \cdot 10^9$ events
- median angular resolution ~ 3˚
- median CR energy ~ 14 TeV



IceCube-40 preliminary

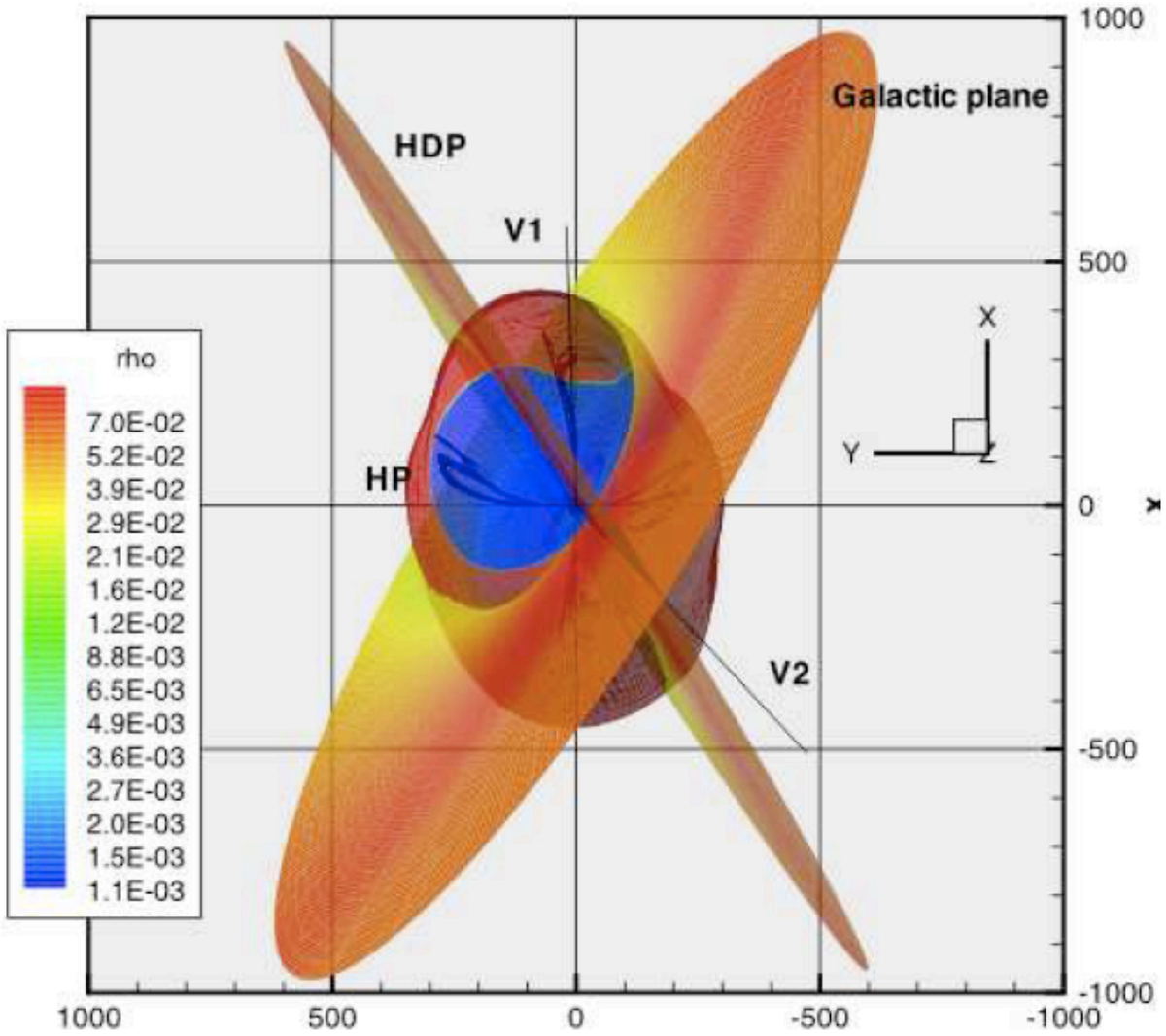
Rasha Abbasi



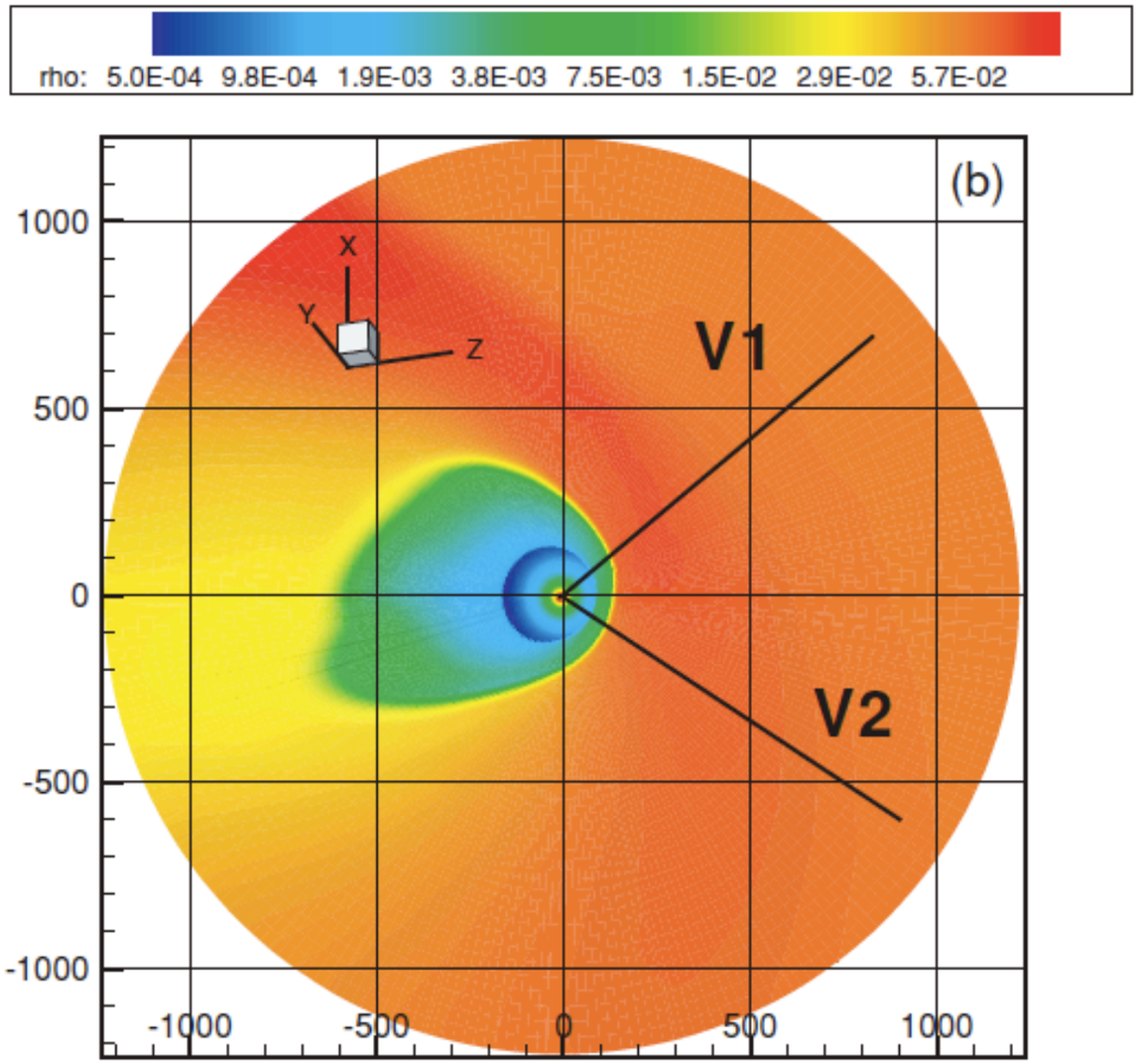
IceCube-22

energy bands

investigating on interstellar magnetic field



Pogorelov et al., ApJ, arXiv:0801.4167



Pogorelov et al., ApJ Vol 695, L31-L34 (2009)

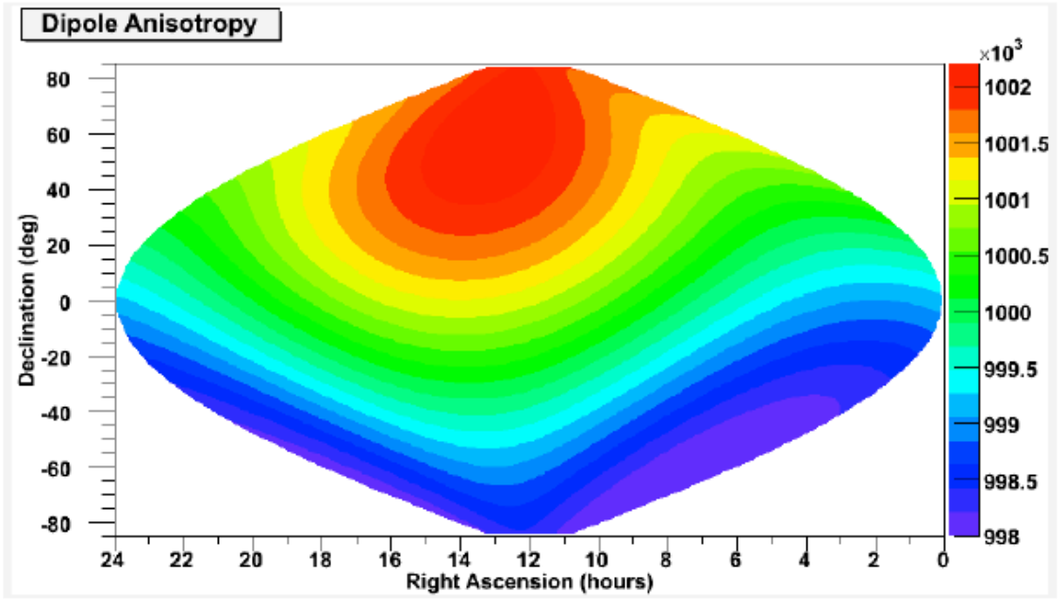


Fig. 9. The original dipole anisotropy (ideal) used for demonstration in the Monte Carlo analysis. Its distribution has maximum at point $\alpha_0 = 14$ h RA, $\delta_0 = 60°$. The degree of anisotropy is $\xi = 0.2\%$.

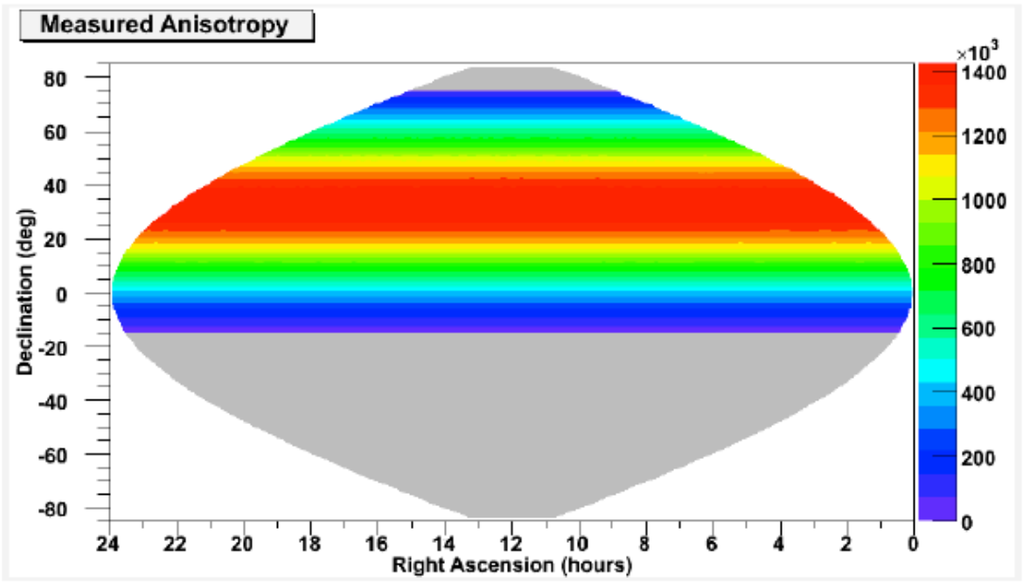


Fig. 11. The map of events detected by an EAS array on the Earth's surface. Anisotropy is included, but is not seen due to a large range of the modulating factor (see Fig. 4). The celestial region unobservable by the array is shown in gray color.

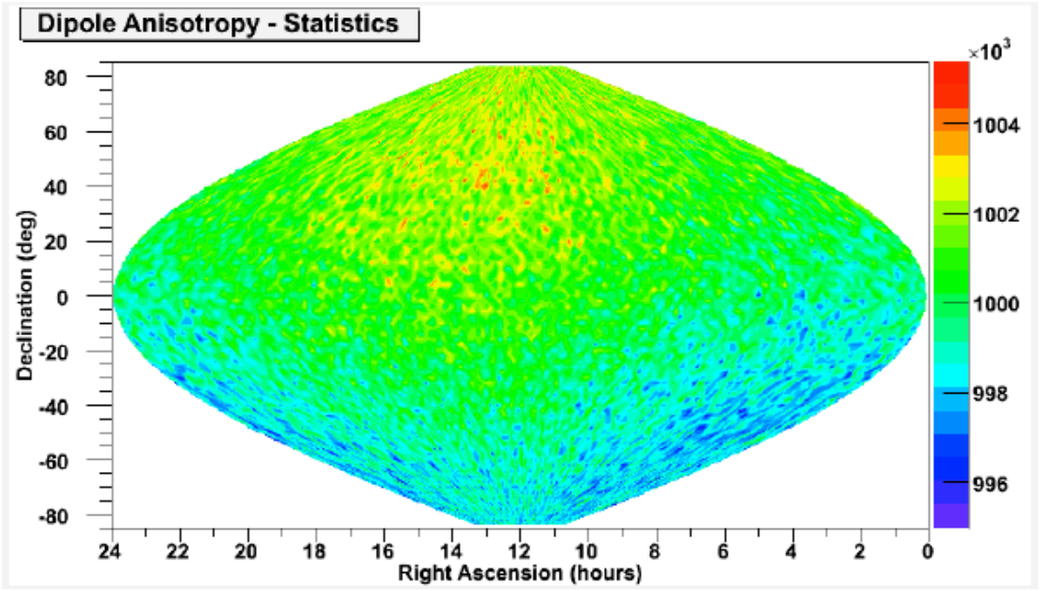


Fig. 10. The real dipole anisotropy (statistics is taken into account) detected without terrestrial effects. Simulation is made according to the normal law in each cell with dimensions 2°x2° with a mean value of 10^6 and variance 10^3.

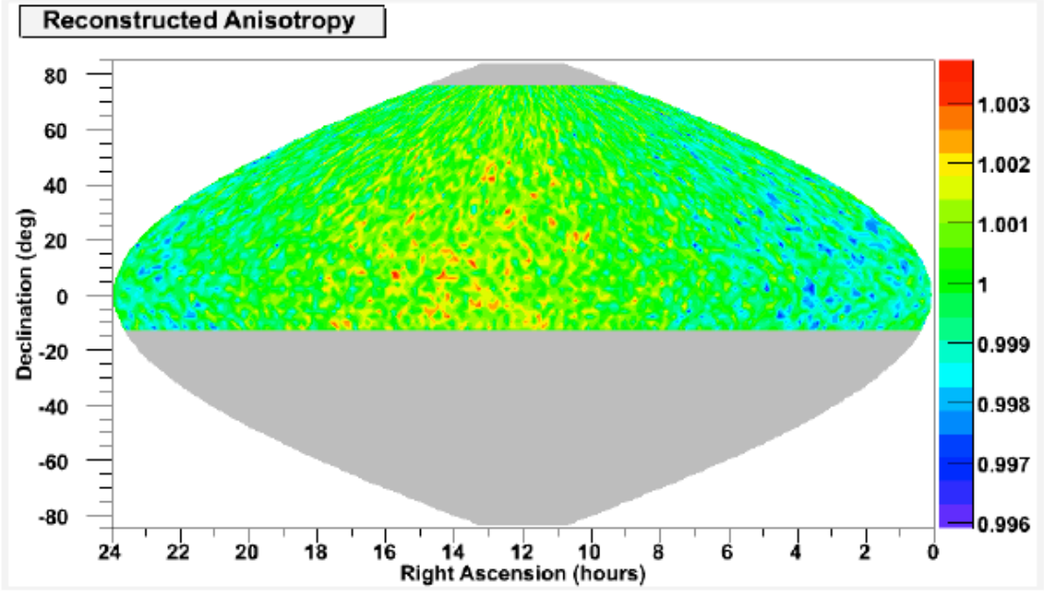


Fig. 12. The difference map after averaging in narrow declination bands and subtraction of the averaged value in every cell (this procedure reproduces the method used by Super-K and Tibet ASγ collaborations). One can see that both maximum and minimum on this map lie near the equator (though original anisotropy was quite different, see Figs. 9 and 10).