# the origin of galactic cosmic ray anisotropy

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# cosmic rays

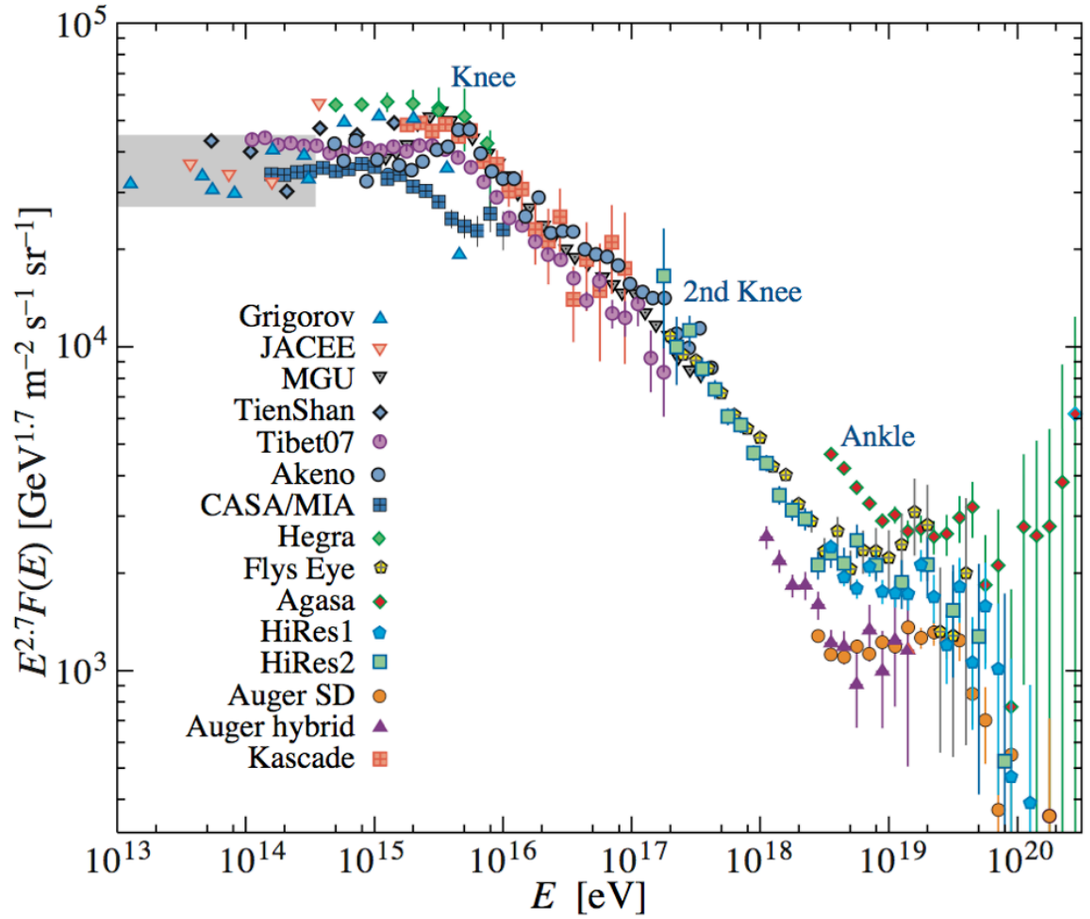
- CR below the knee (~$10^6$ GeV) believed to be galactic

- 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

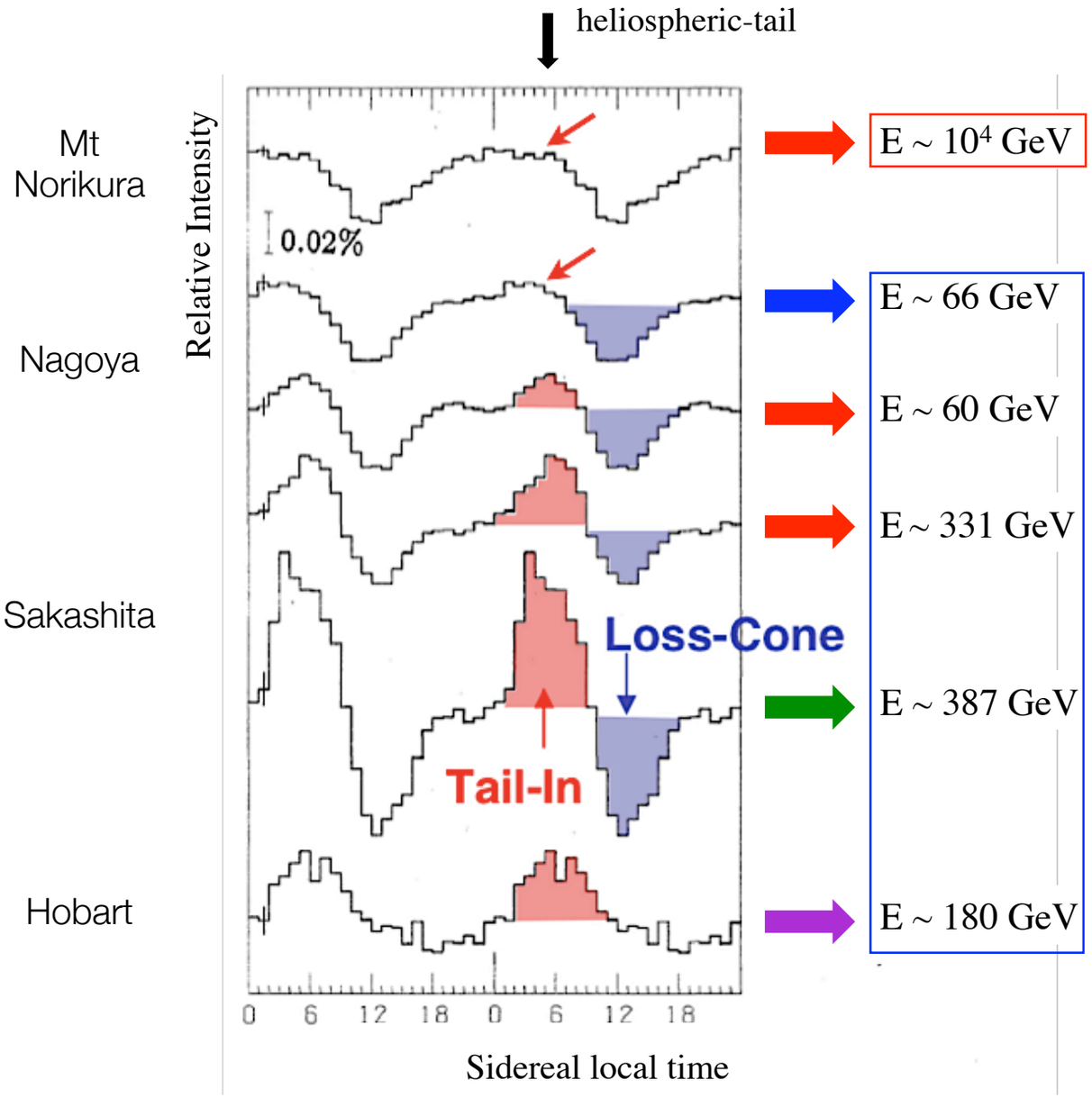
- galactic CR expected to be isotropic : scrambled by galactic magnetic field over very long time

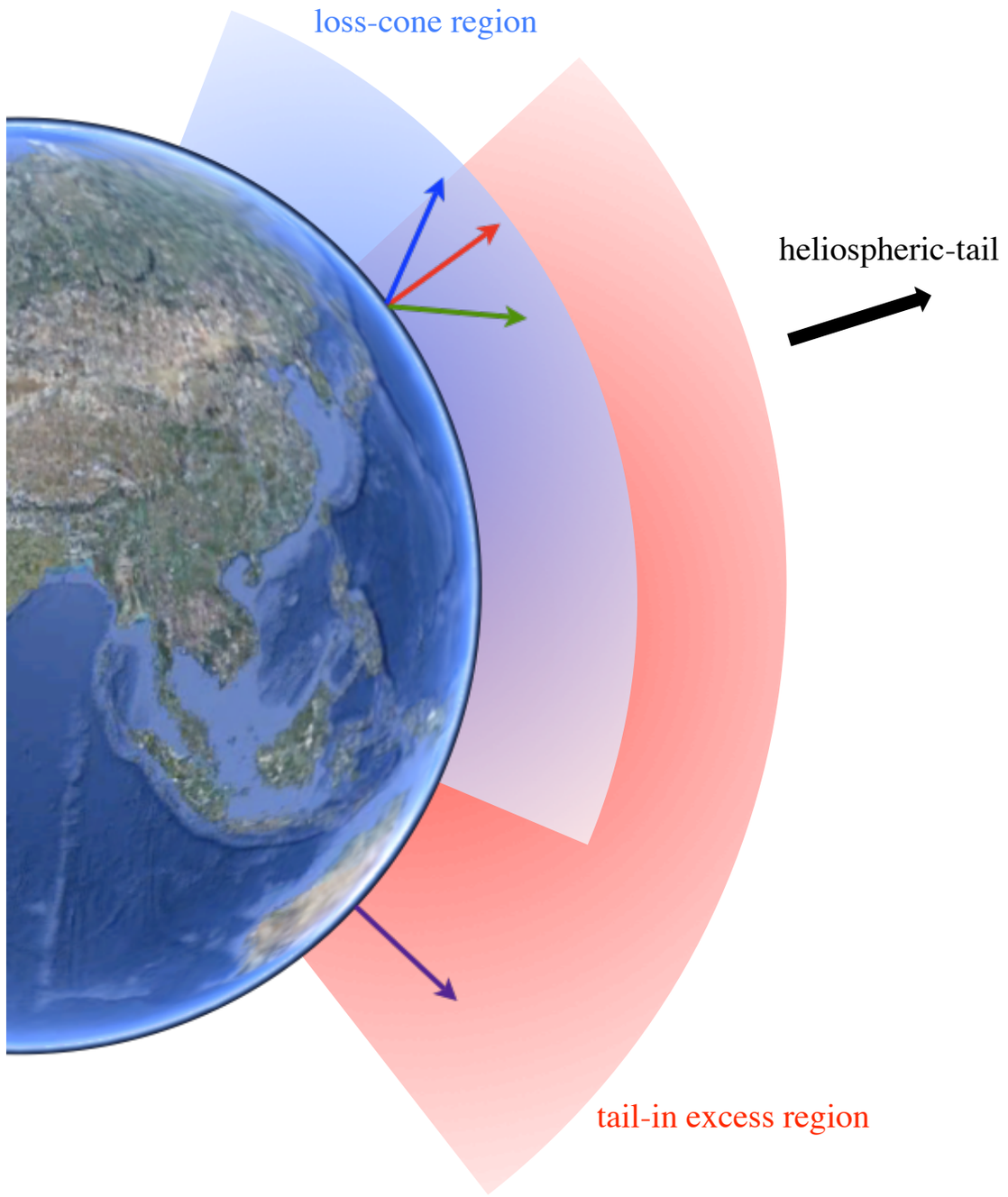
Stanev, Gaisser, PDG



# cosmic ray anisotropy in arrival direction

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



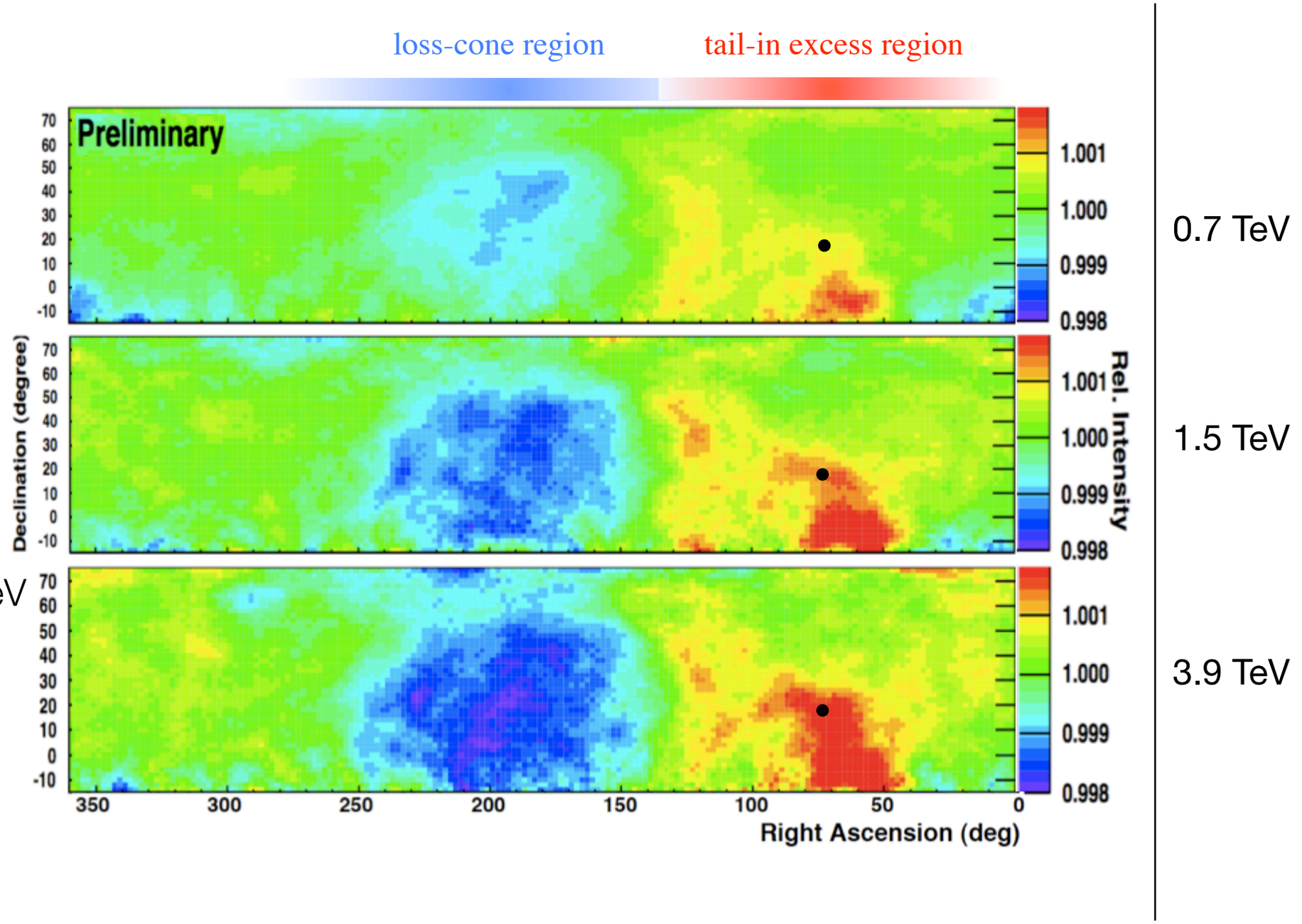



# cosmic ray anisotropy in arrival direction

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

## ARGO-YBJ

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

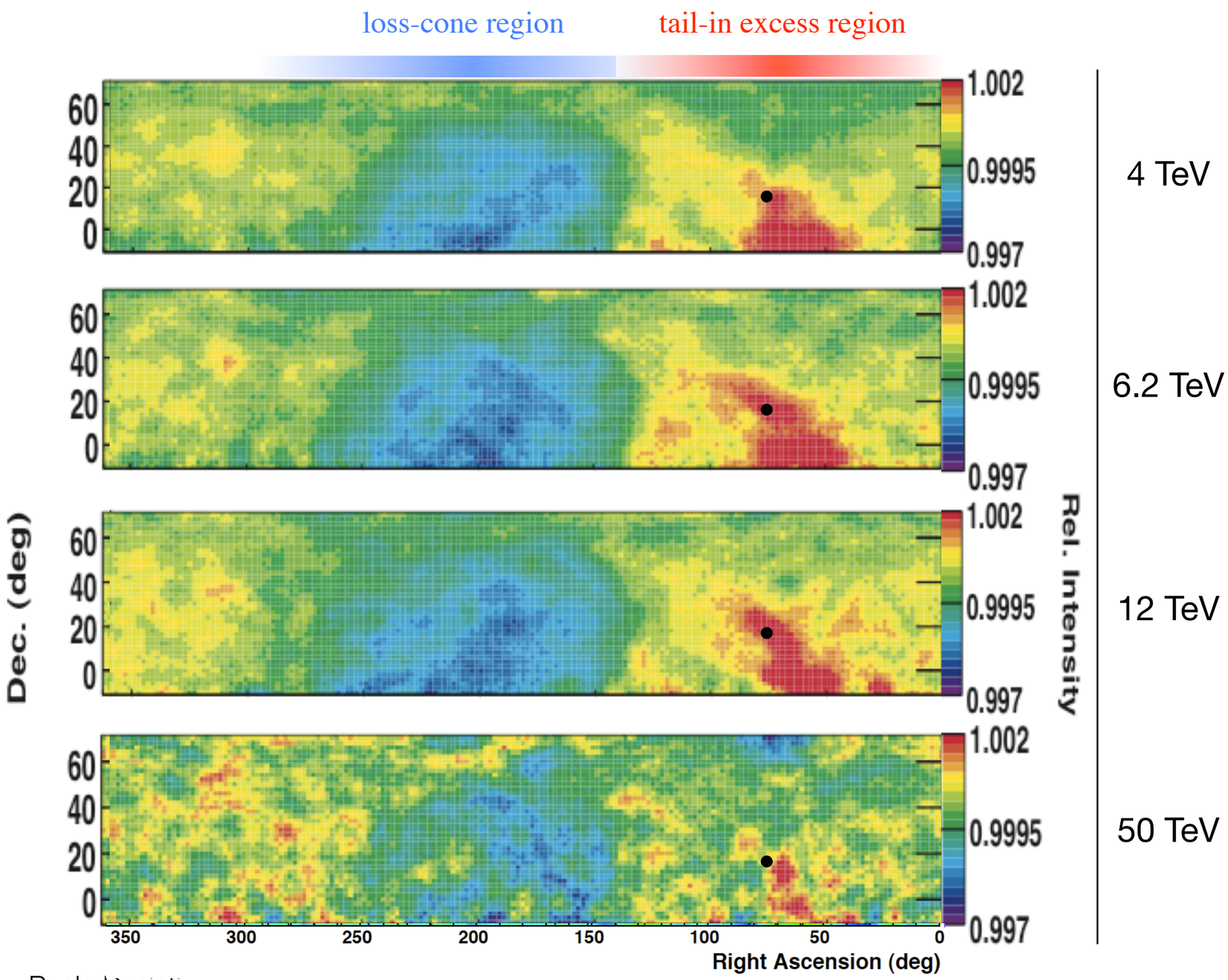


# cosmic ray anisotropy in arrival direction

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

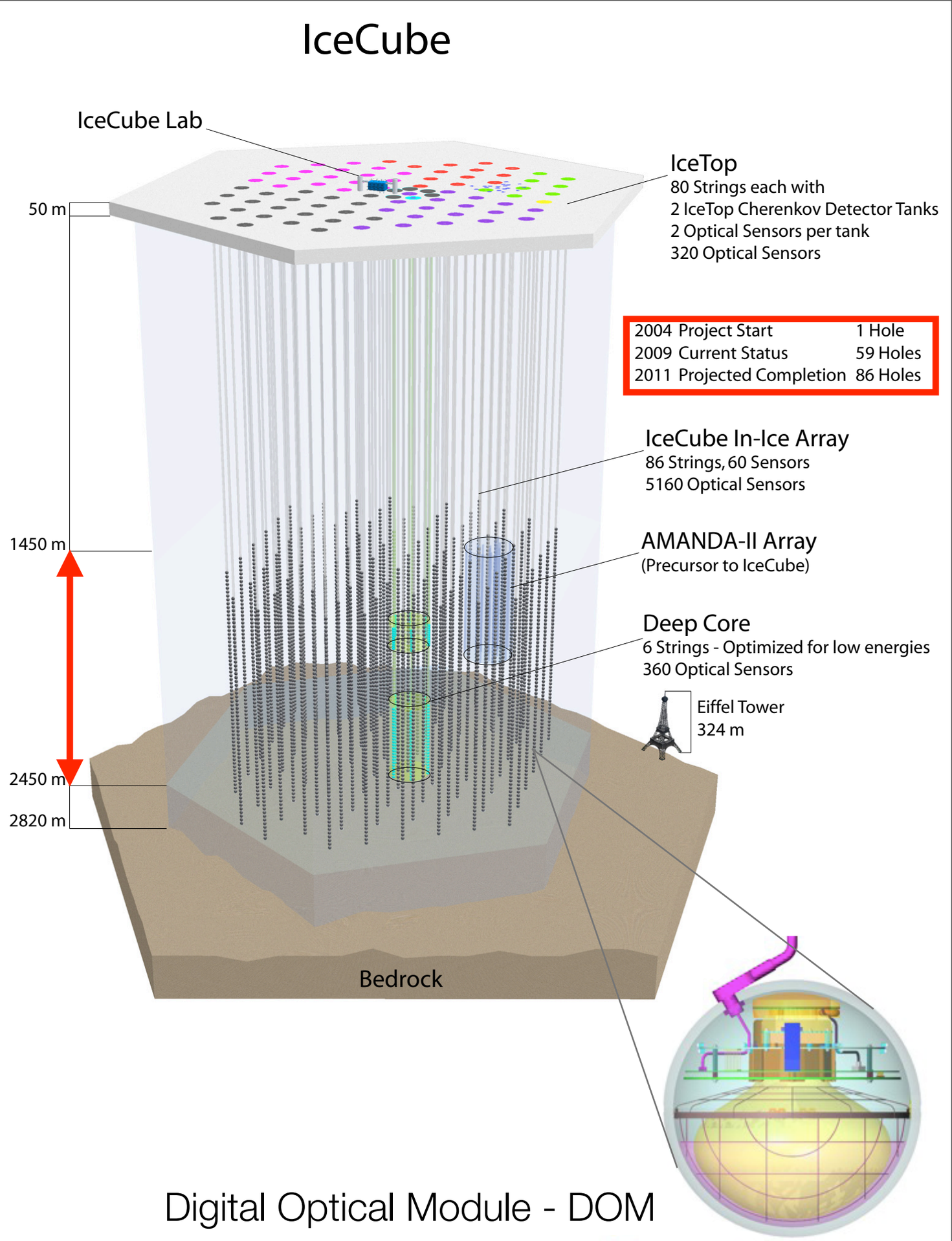
## Tibet-III

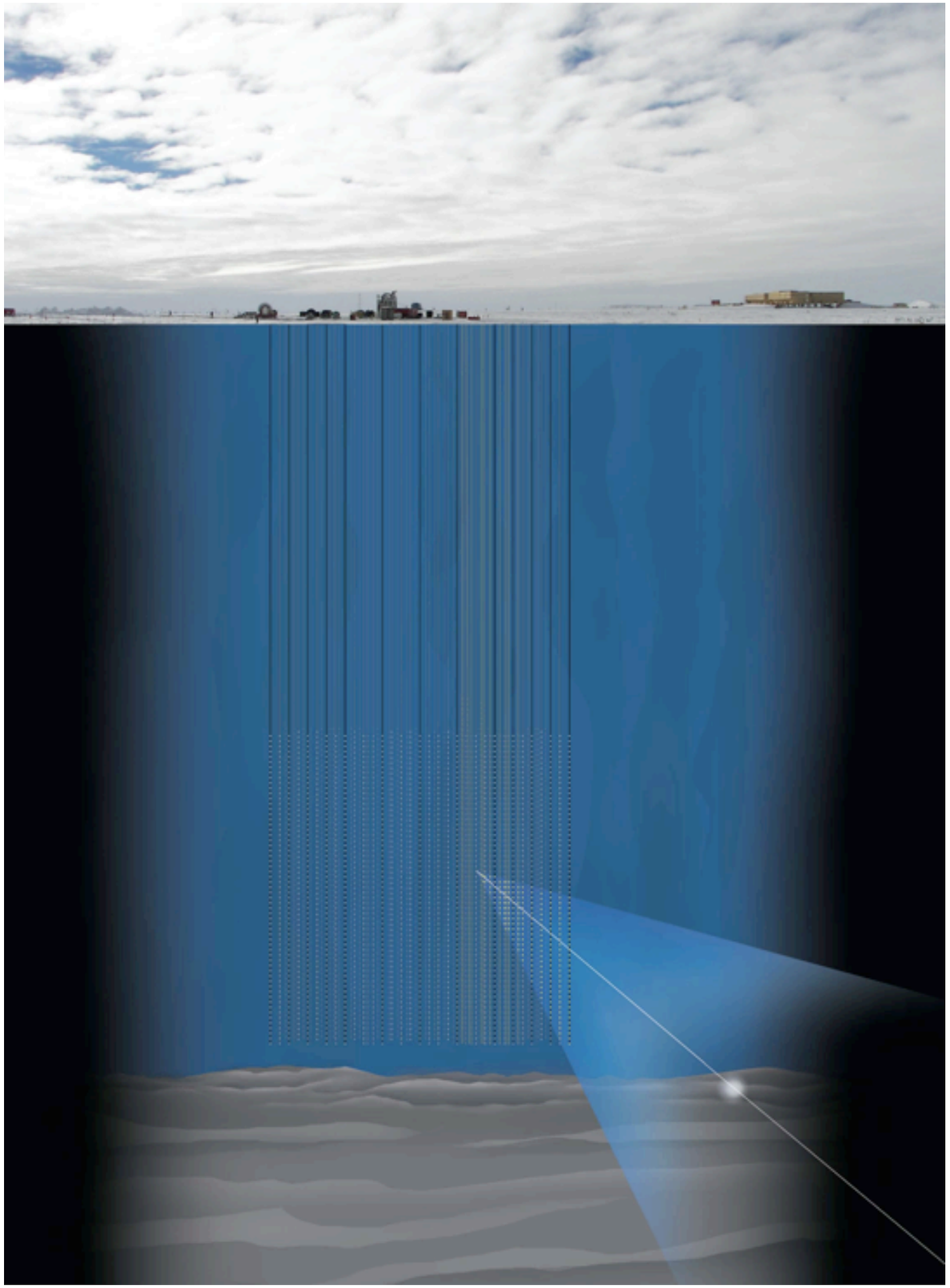
- data from 1997 to 2005
- 1874 days livetime
- $3.7 \cdot 10^{10}$ events
- angular resolution ~ 0.9°
- modal CR energy ~ 3 TeV

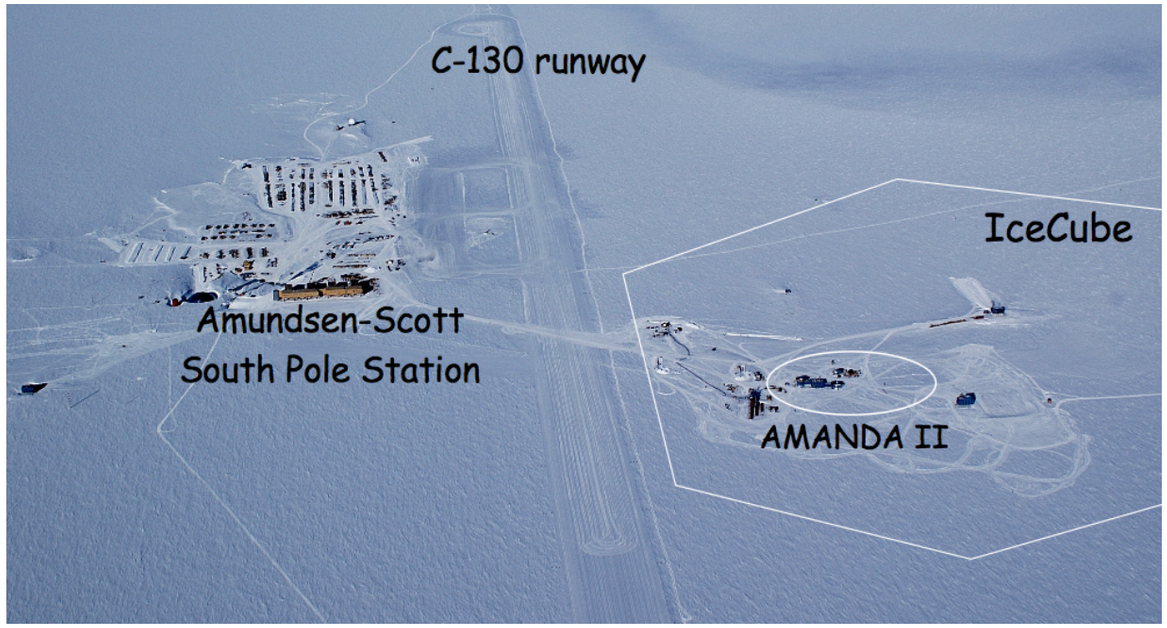


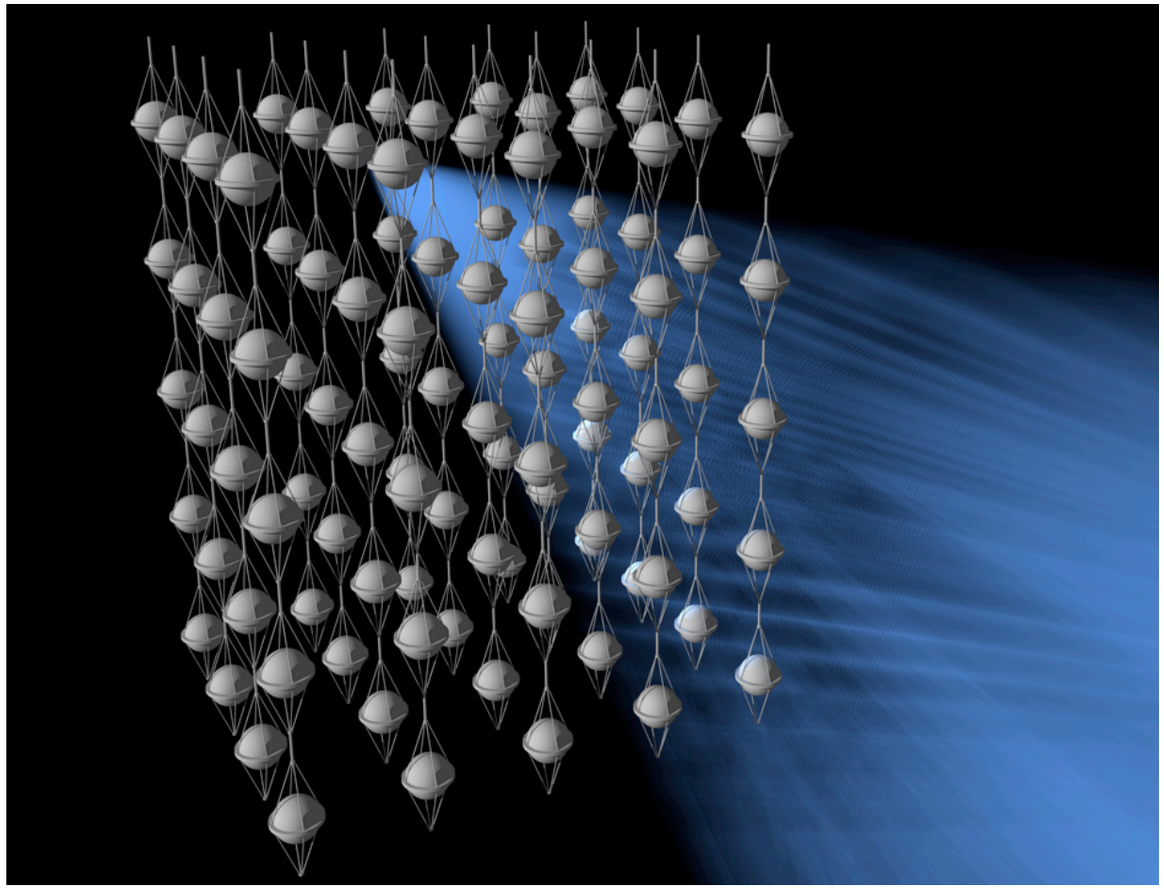
# IceCube Observatory

- 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





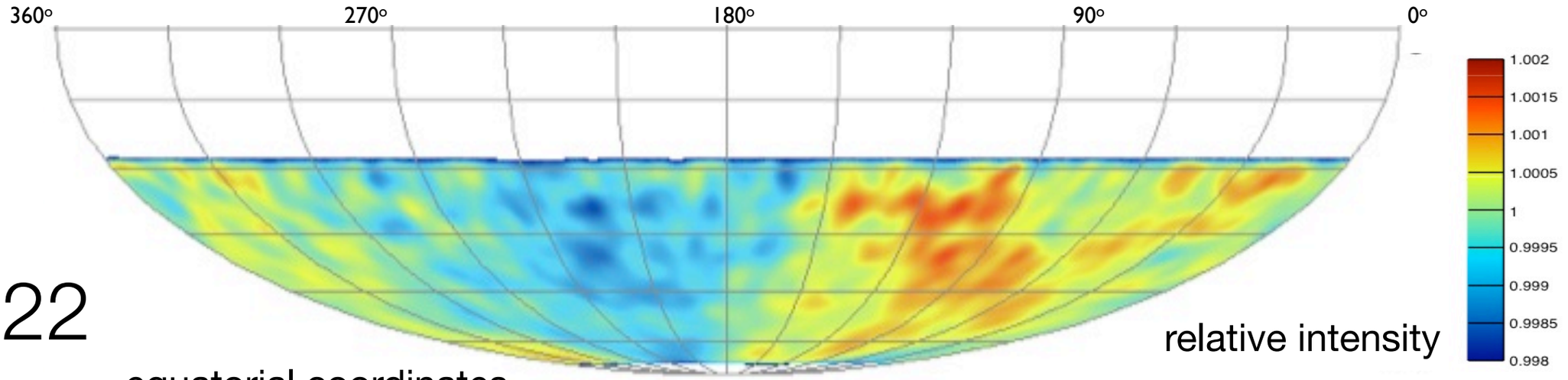


detection technique

# cosmic ray anisotropy in arrival direction

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



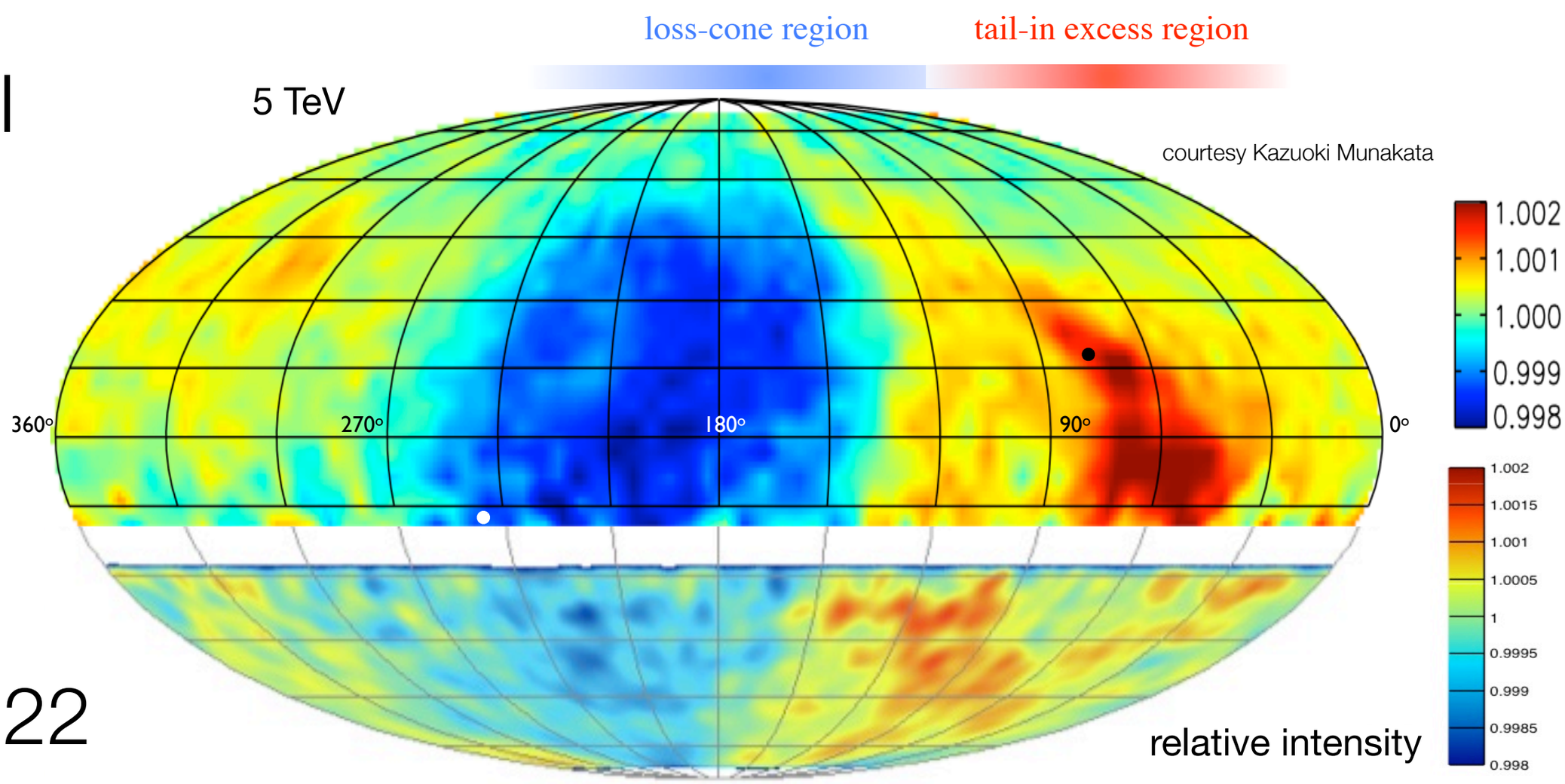

## IceCube-22

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

# cosmic ray anisotropy in arrival direction

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

## Tibet-III




## IceCube-22

20 TeV

equatorial coordinates

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

# cosmic ray anisotropy in arrival direction

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

dipole

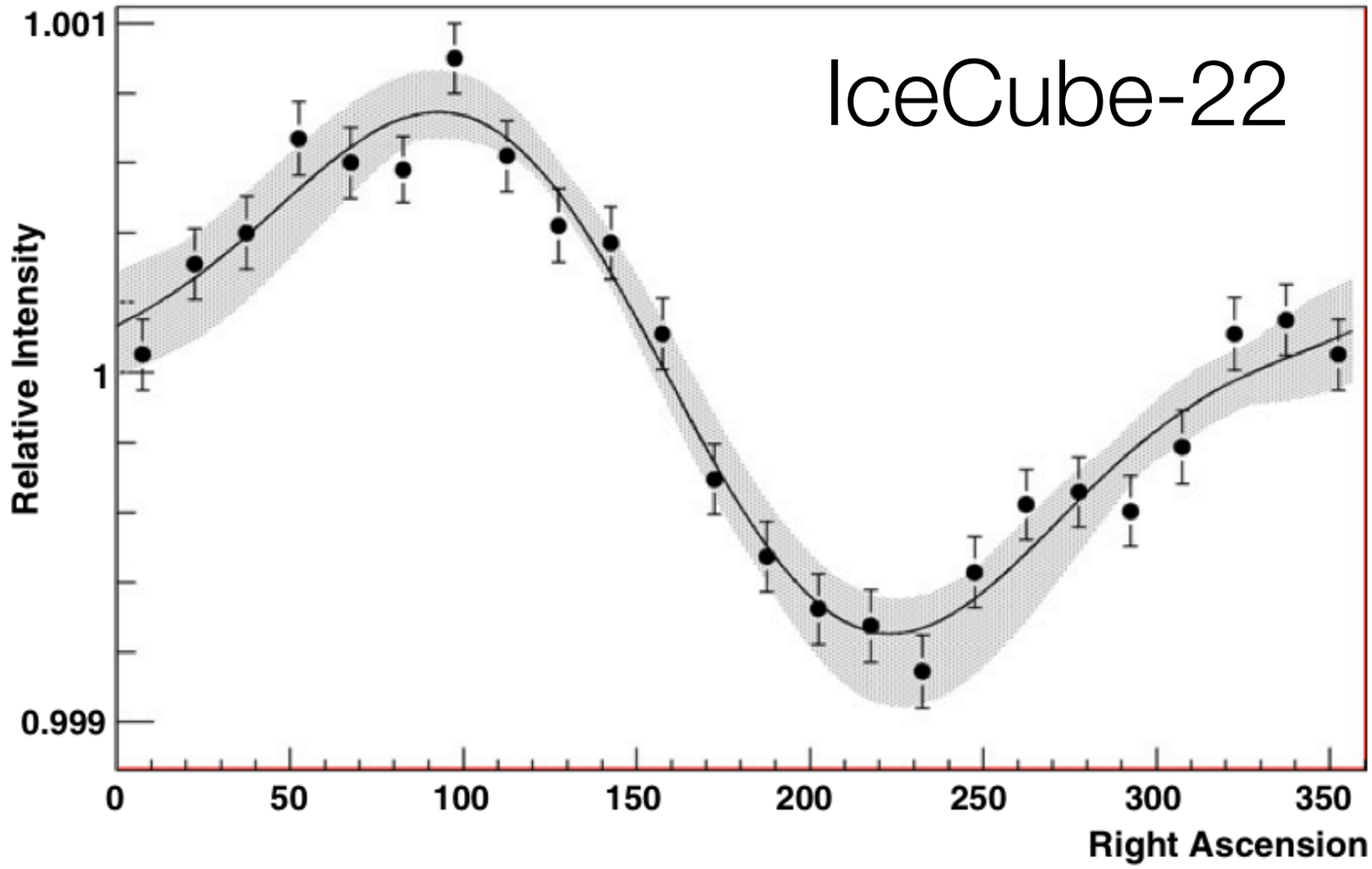
$A_1 = (6.4 \pm 0.2_{stat} \pm 0.8_{syst}) \times 10^{-4}$

$\phi_1 = 66^\circ.4 \pm 2^\circ.6_{stat} \pm 3^\circ.8_{syst}$

quadrupole

$A_2 = (2.1 \pm 0.3_{stat} \pm 0.5_{syst}) \times 10^{-4}$

$\phi_2 = -65^\circ.6 \pm 4^\circ.0_{stat} \pm 7^\circ.5_{syst}$




- data from June 2007 to March 2008
- 226 days livetime
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- median angular resolution ~ 3°
- median CR energy ~ 20 TeV

# cosmic ray anisotropy in arrival direction

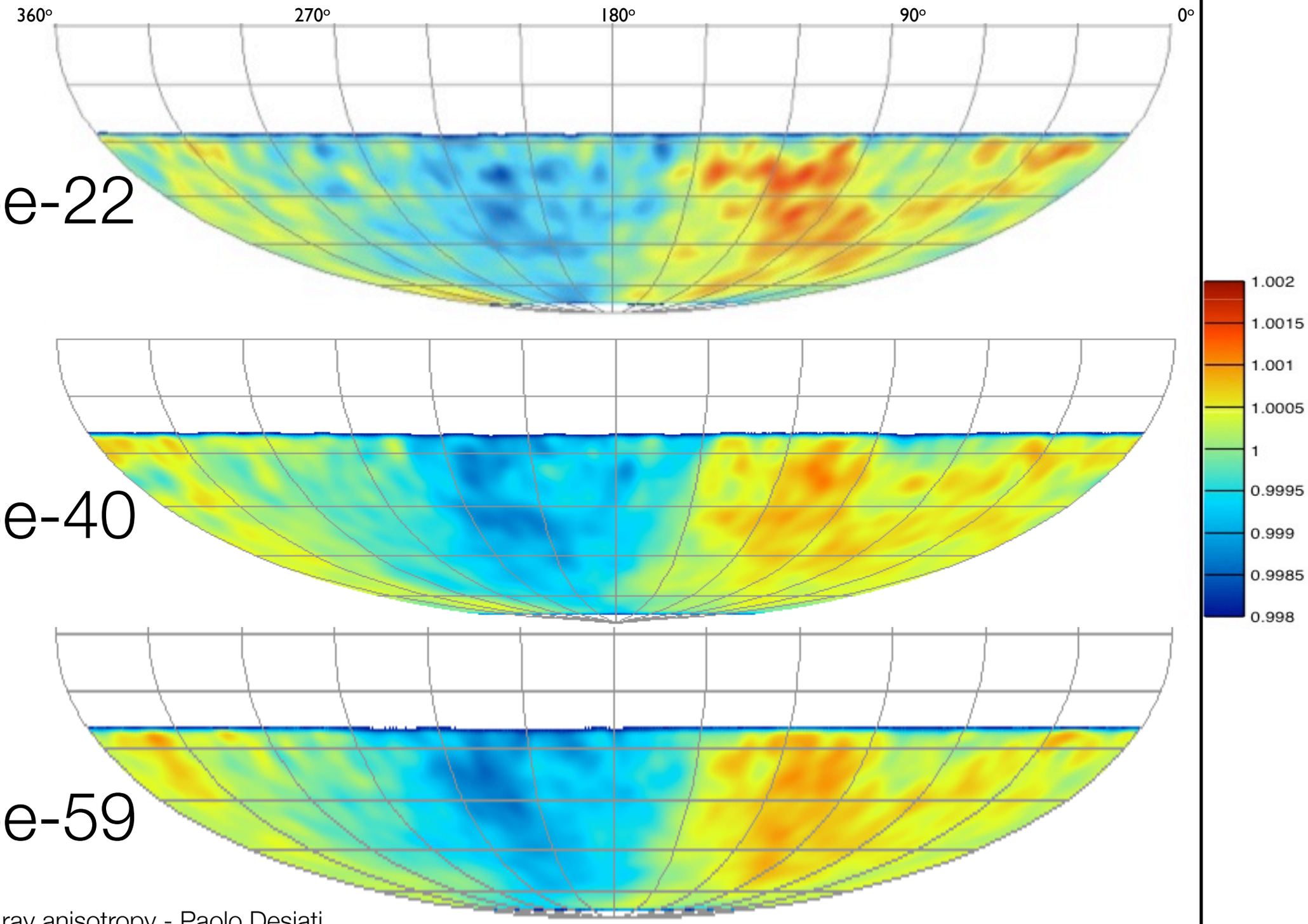
relative intensity

equatorial coordinates

IceCube-22

IceCube-40

IceCube-59

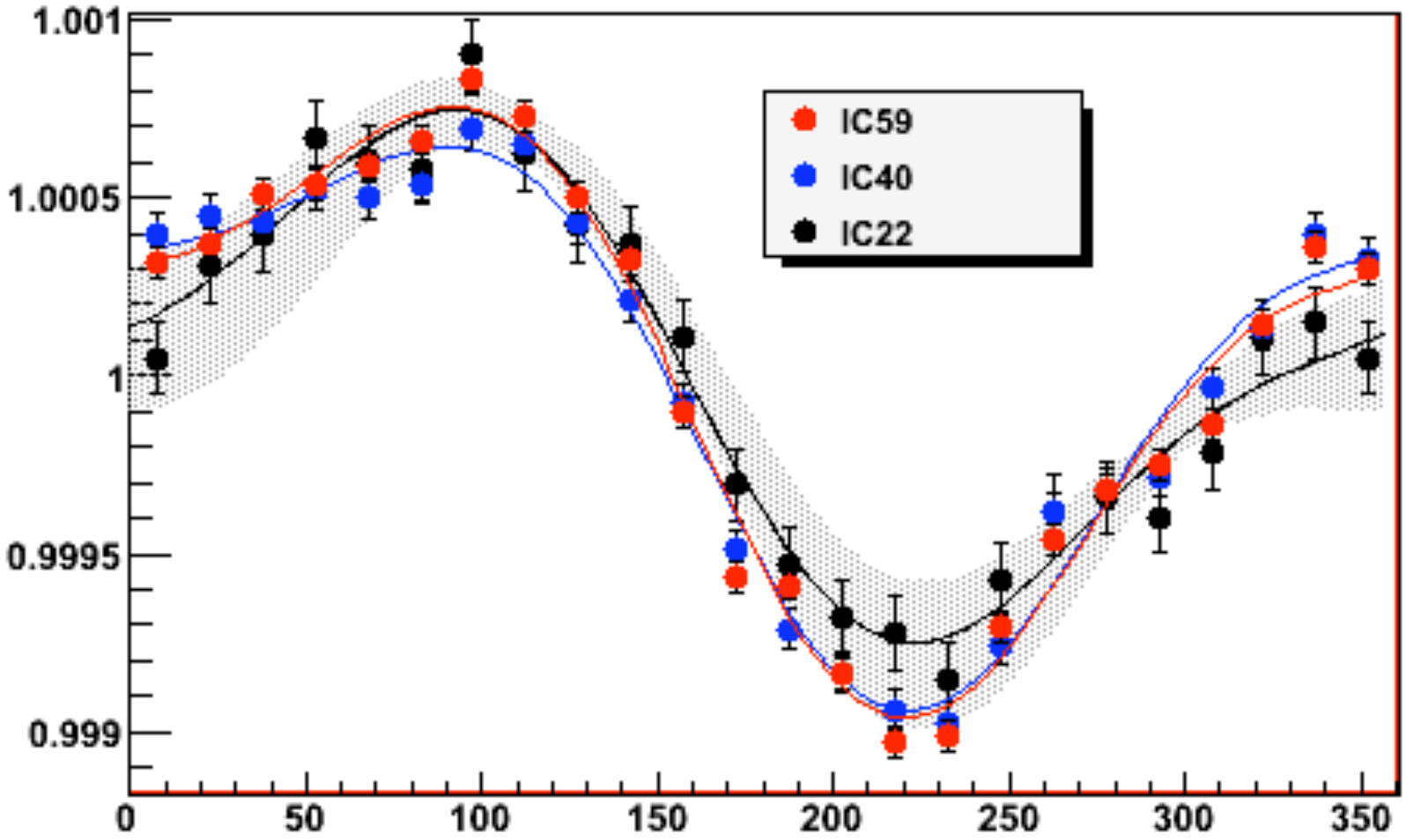


# cosmic ray anisotropy in arrival direction

- June 07 - March 08
- 226 days livetime
- $4.3 \cdot 10^9$ events

- March 08 - May 09
- 324 days livetime
- $19 \cdot 10^9$ events

- May 09 - May 10
- ~360 days livetime
- $\sim 30 \cdot 10^9$ events



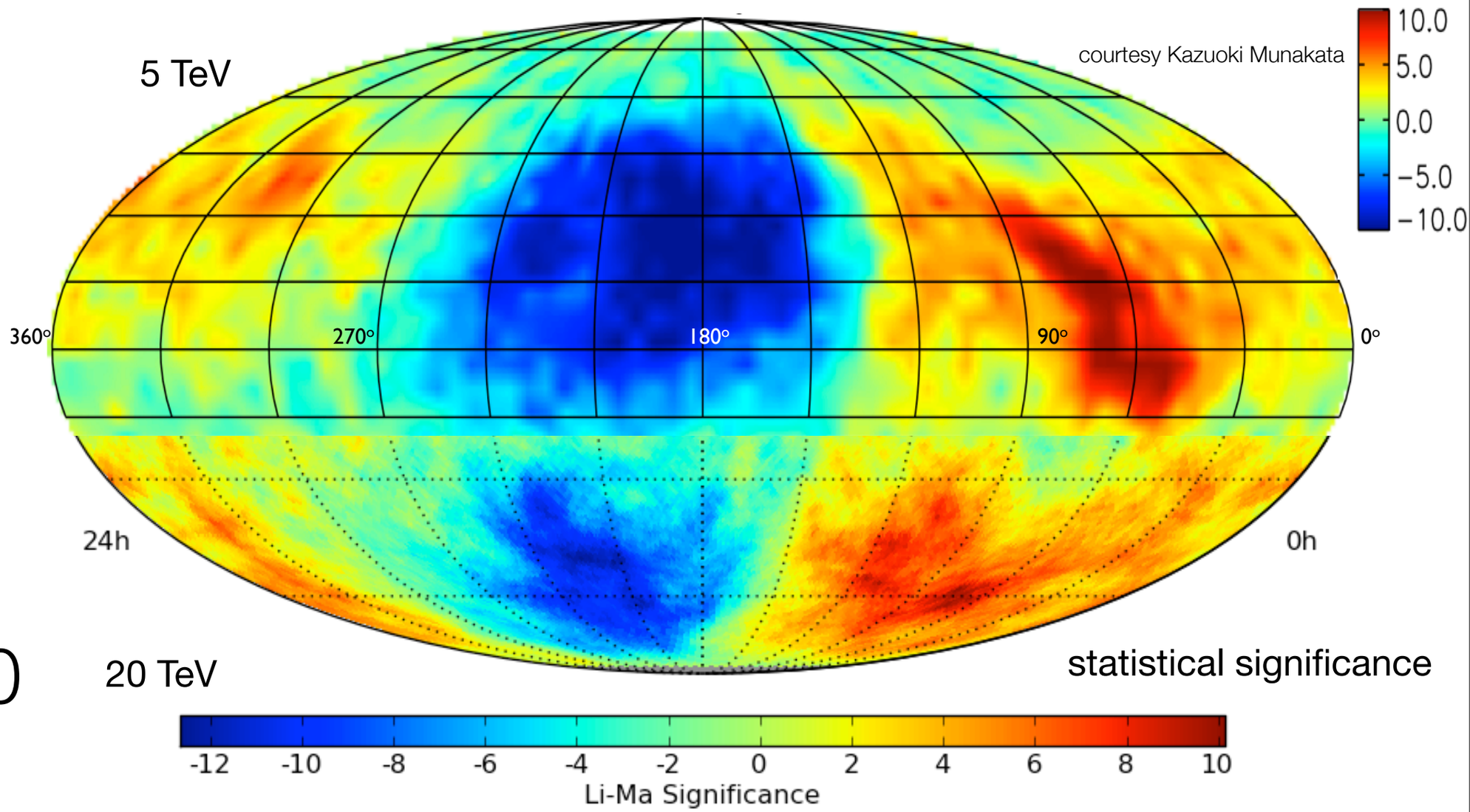

- median angular resolution ~ 3°
- median CR energy ~ 20 TeV

# cosmic ray anisotropy in arrival direction

**PRELIMINARY**

## Tibet-III

**(5° smoothing)**




## IceCube-40

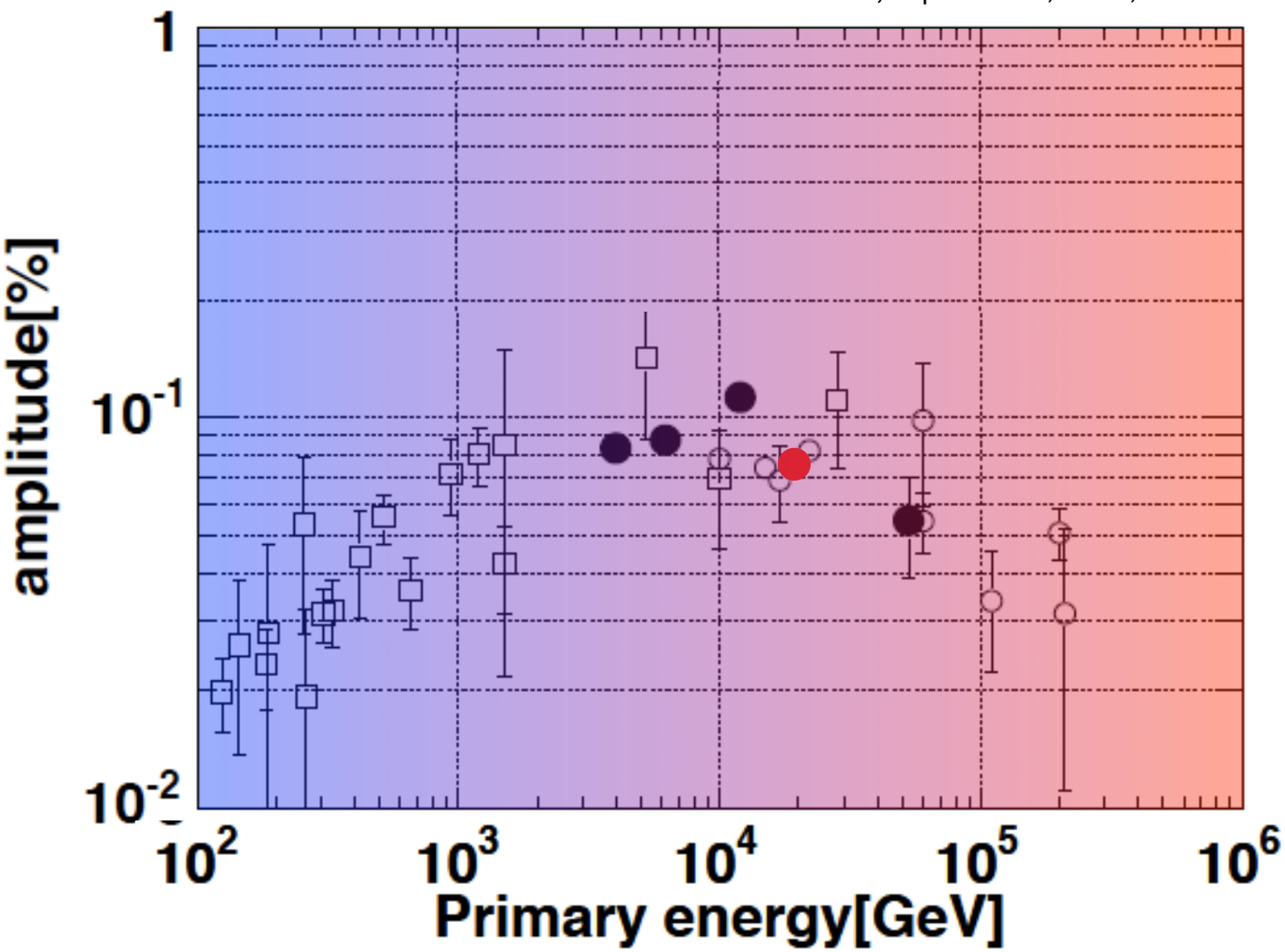
**(3° smoothing)**

equatorial coordinates

- data from March 2008 to May 2009
- 324 days livetime
- $15 \cdot 10^9$ events
- median angular resolution ~ 3°
- median CR energy ~ 20 TeV

# anisotropy vs energy : probing different causes

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

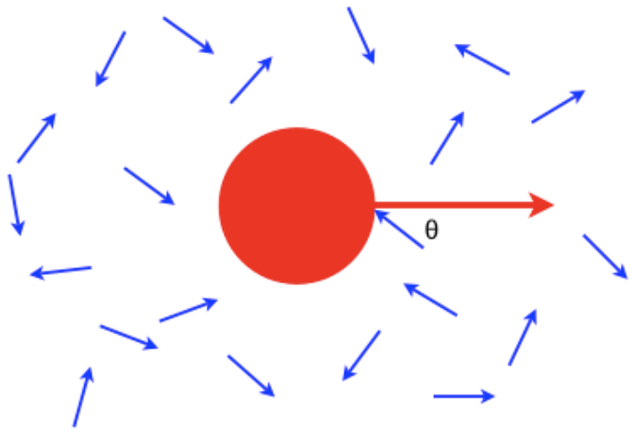



(3 μG)

| | | | | | |
|---|---|---|---|---|---|
| $3 \cdot 10^{-5}$ | $3 \cdot 10^{-4}$ | $3 \cdot 10^{-3}$ | $3 \cdot 10^{-2}$ | 0.3 | gyro-radius (pc) |
| 7 | 70 | 700 | 7,000 | 70,000 | gyro-radius (AU) |

tail-in + galactic ← heliospheric influence | galactic influence →

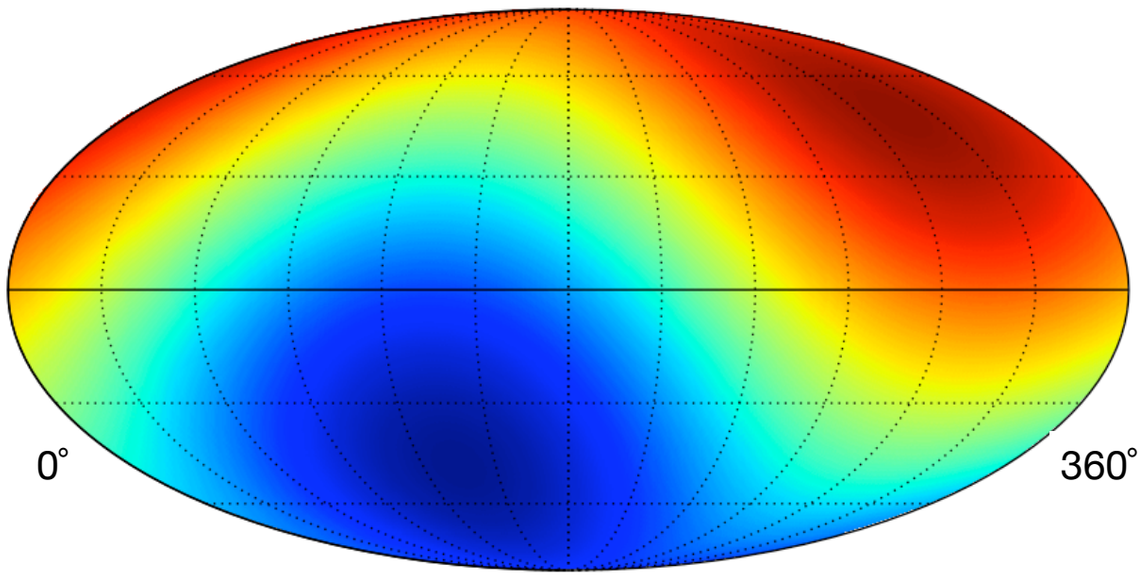
# origin of large scale anisotropy : Compton-Getting Effect ?

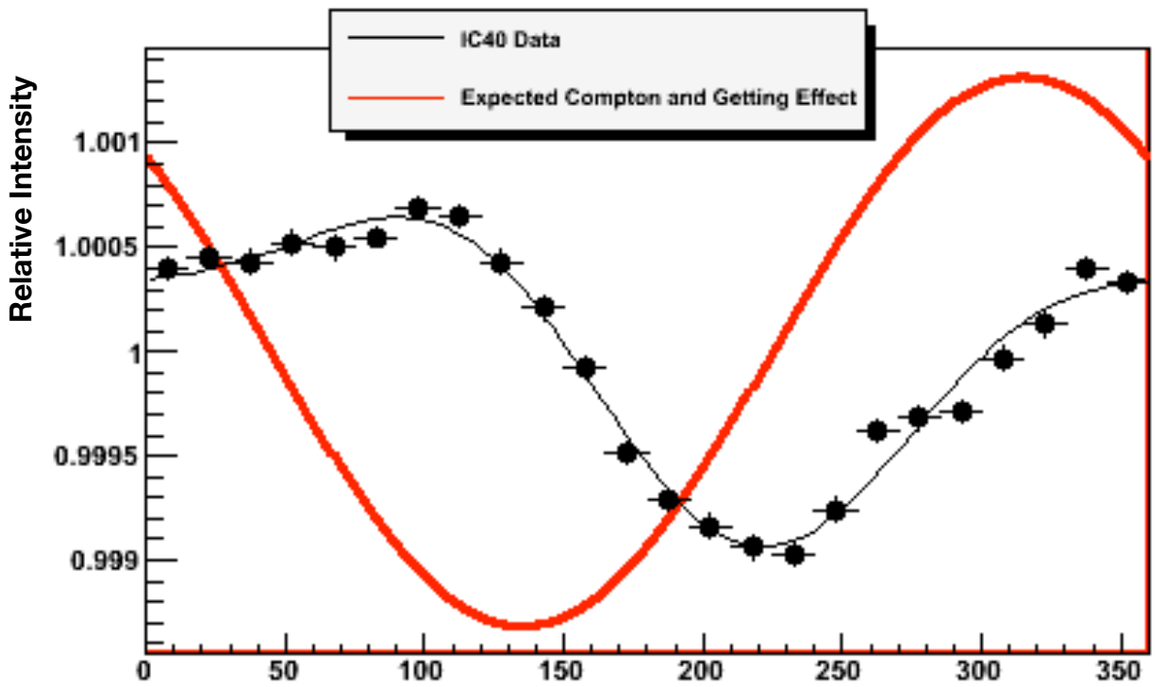



$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

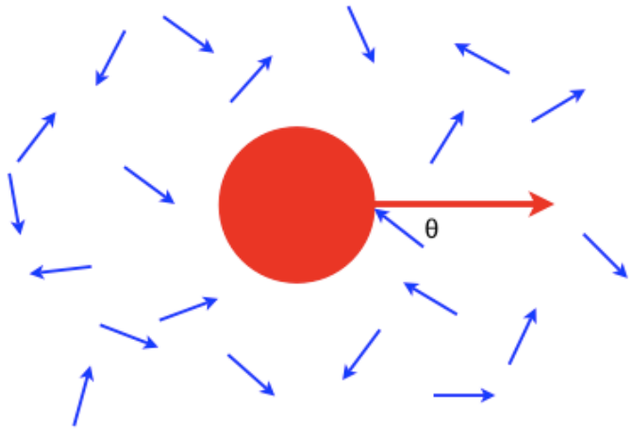
- apparent energy-independent ~$10^{-3}$ dipole anisotropy due to relative motion of solar system through ISM
- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is unknown

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



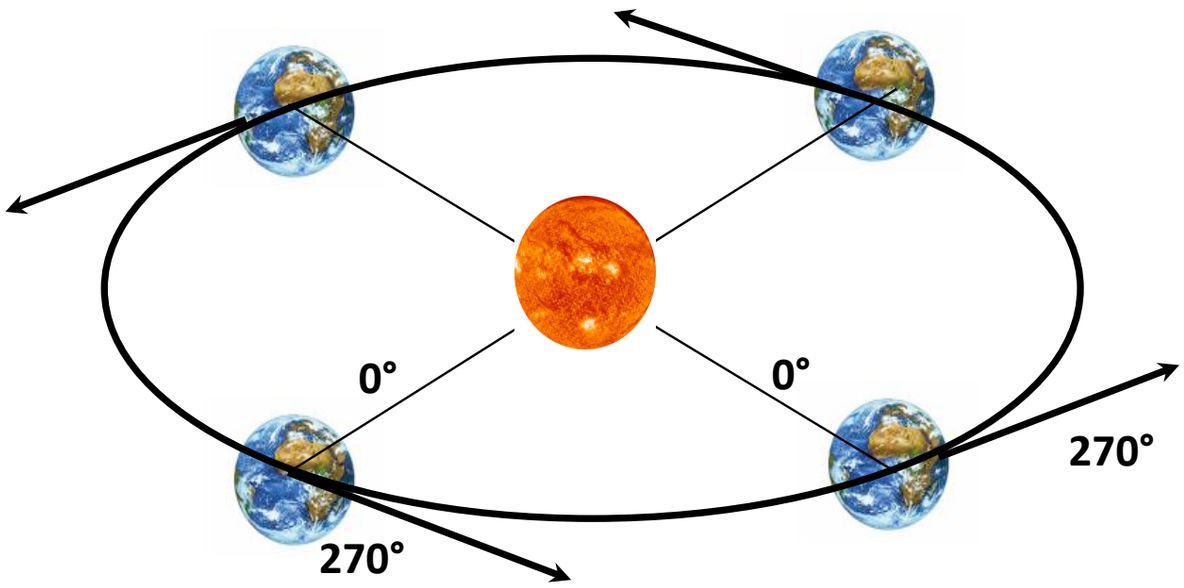



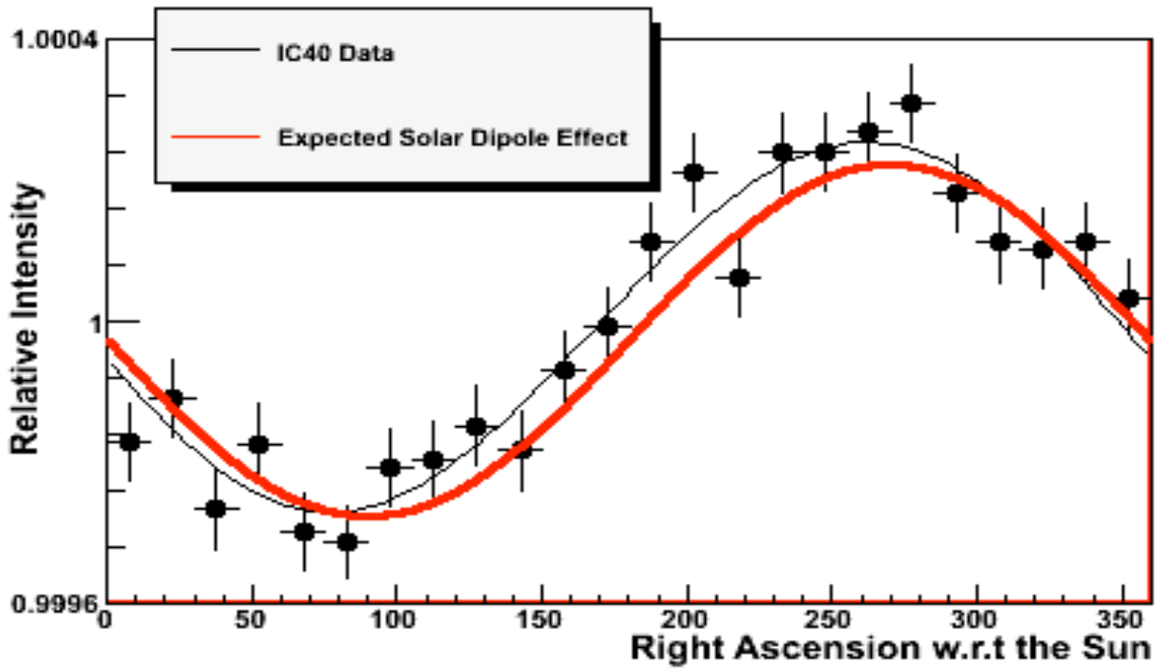
# origin of large scale anisotropy : solar dipole




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

- apparent energy-independent ~$10^{-4}$ 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



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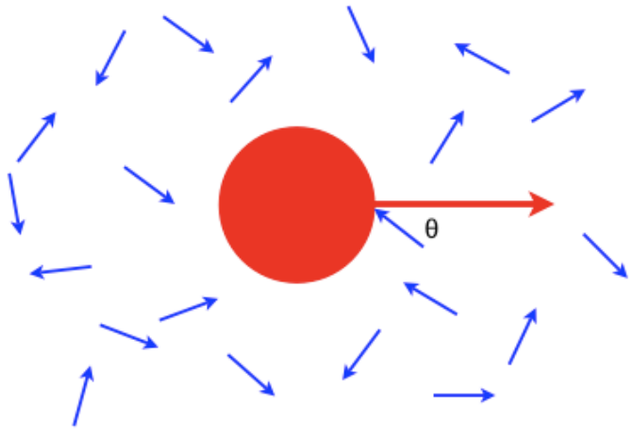


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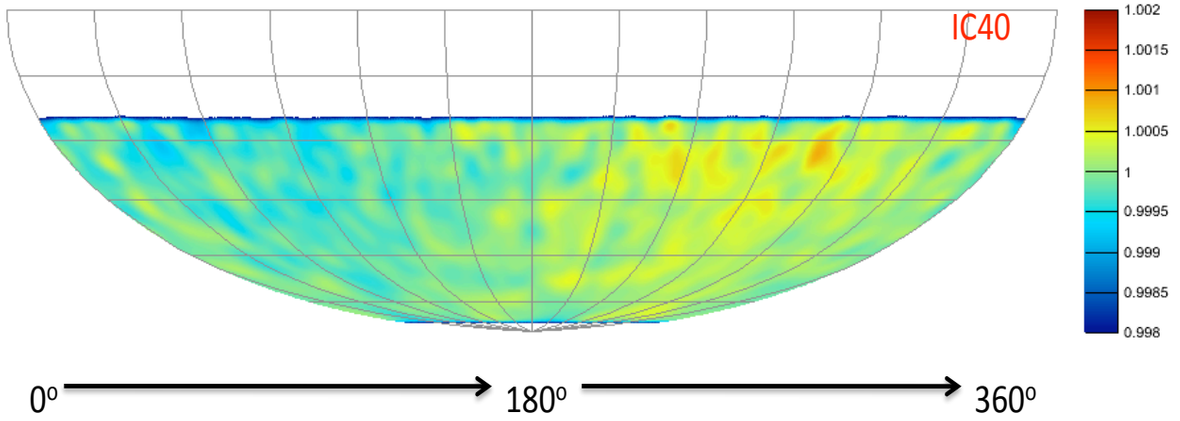
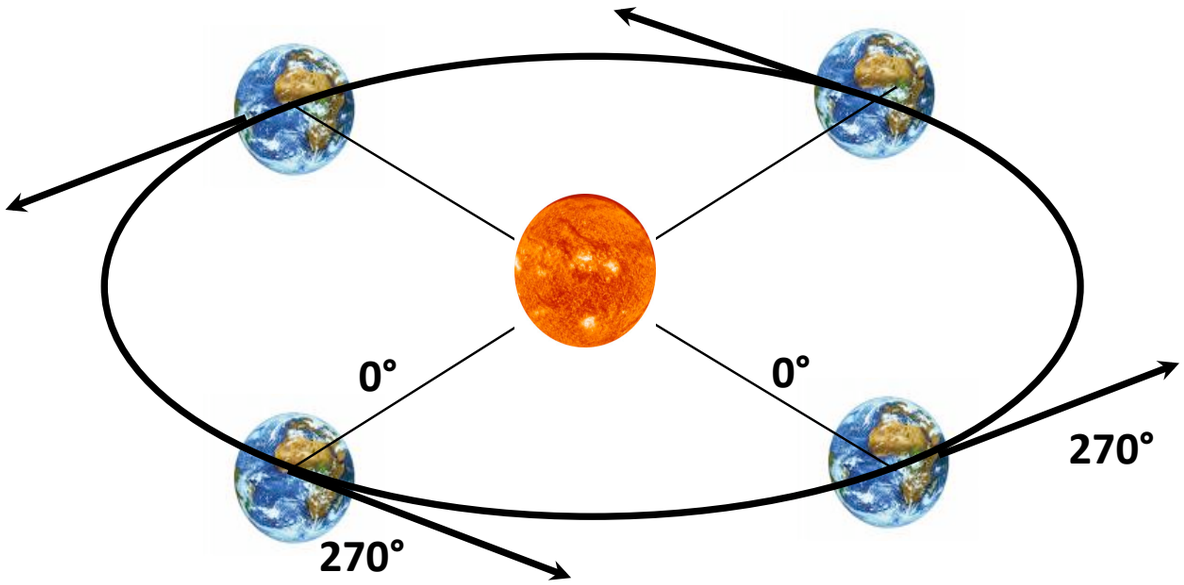
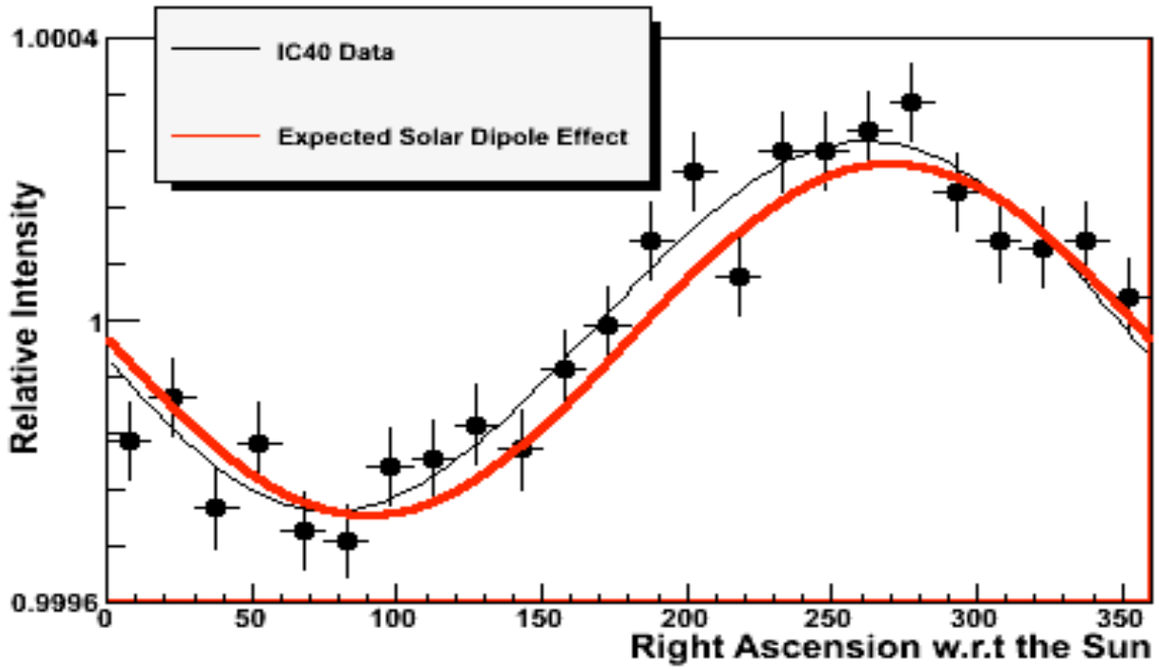
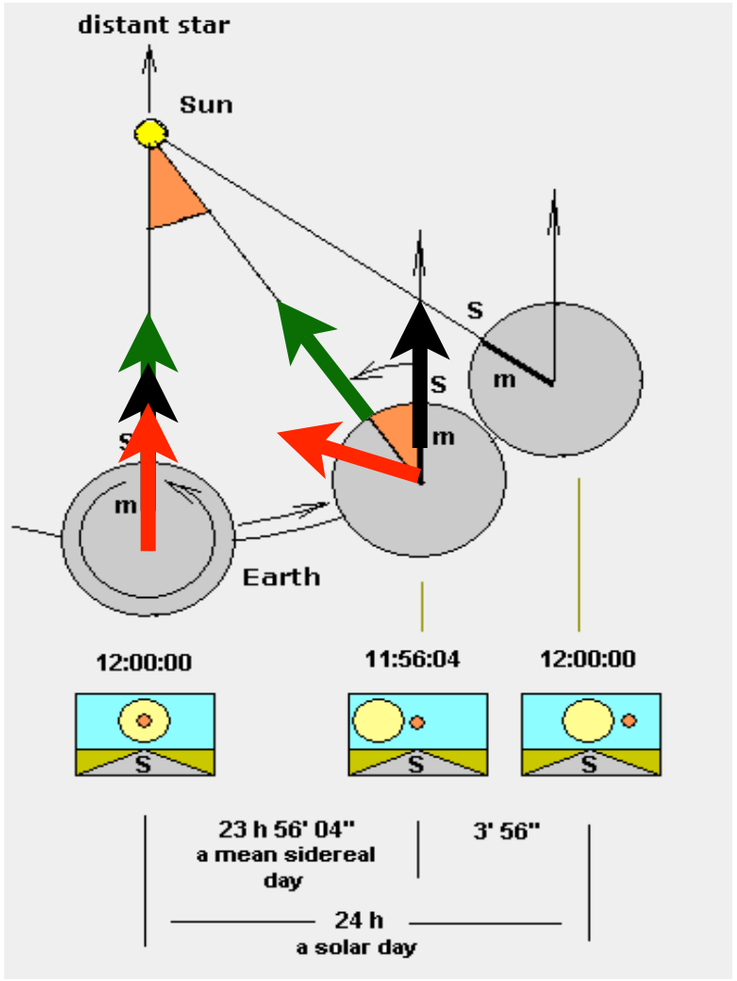


# origin of large scale anisotropy : spurious effects



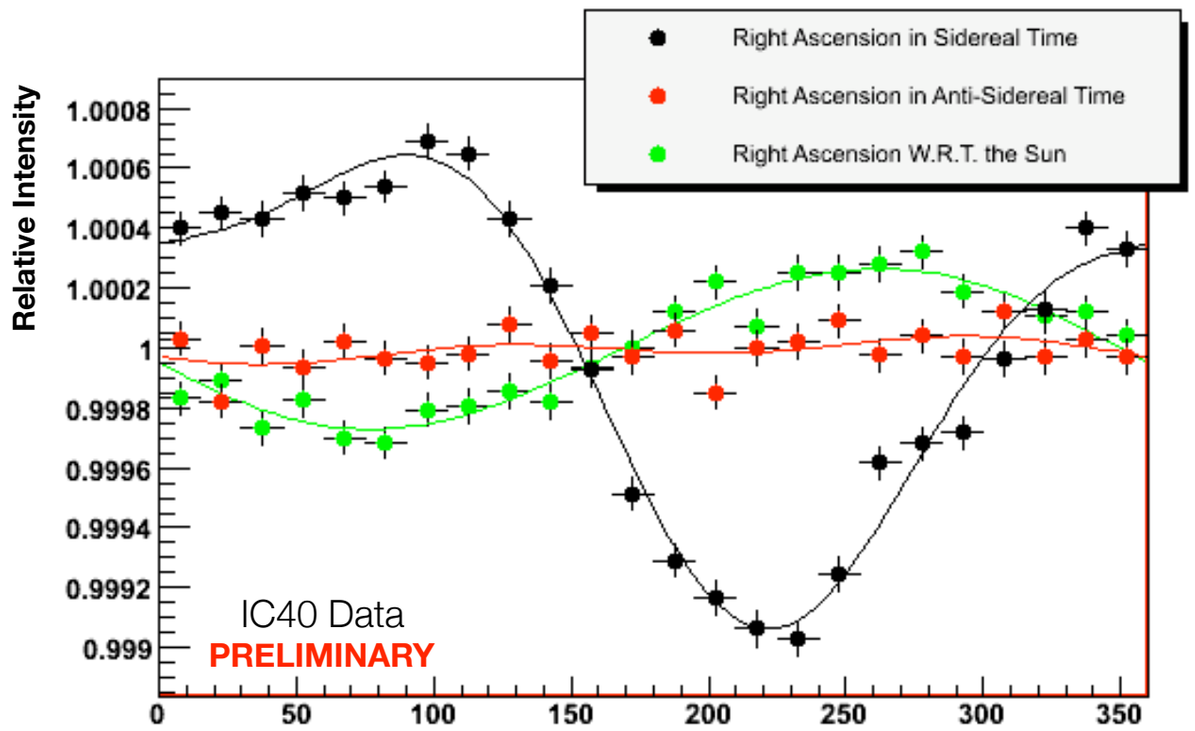

- a yearly-modulated solar diurnal variation induces a spurious sidereal modulation : modulation in anti-sidereal time
- non physical coordinate that results in "*scrambling*" directions
- its modulation measures sidereal spurious effect amplitude

**solar time**

**sidereal time**

**anti-sidereal time**

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



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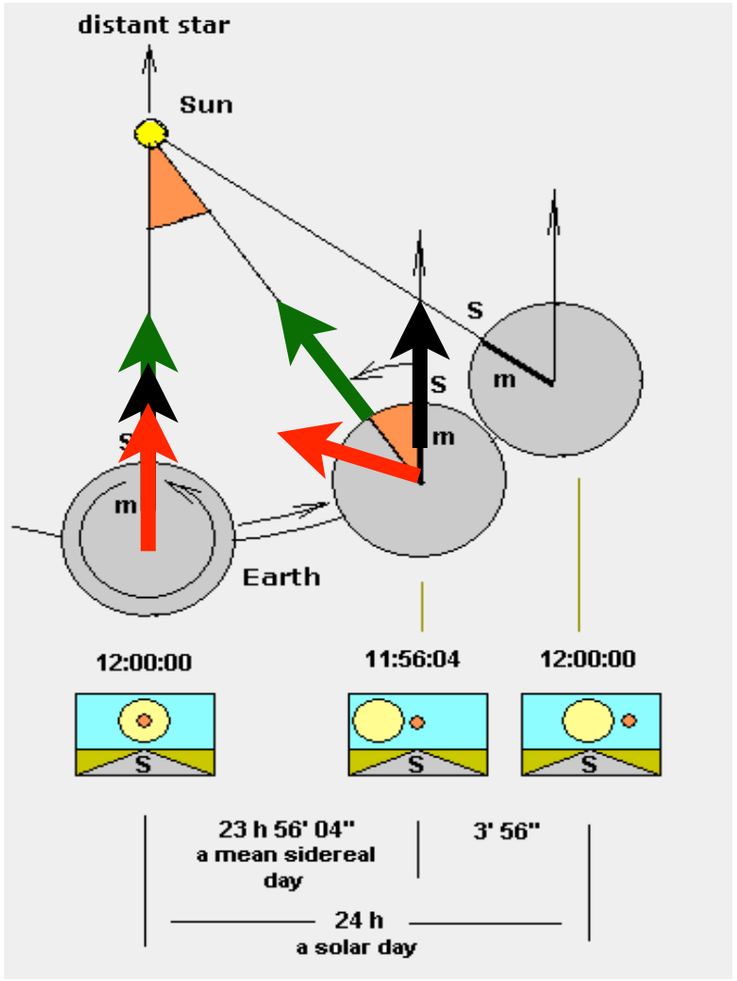
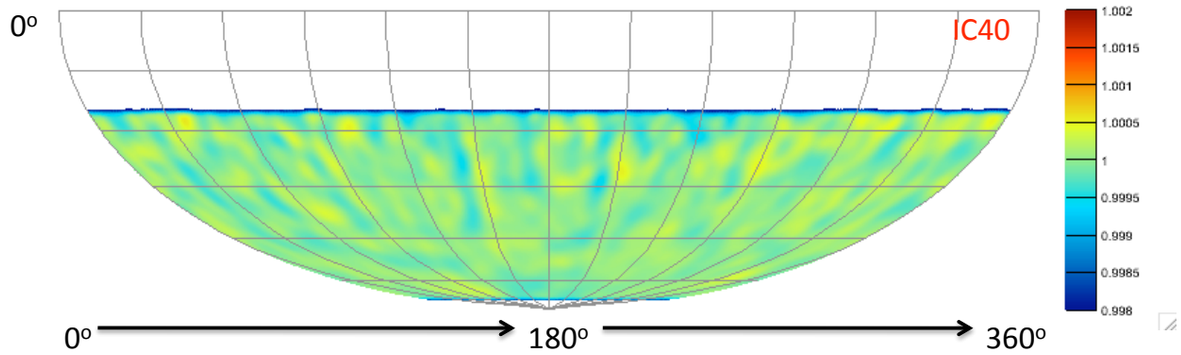



**solar time**

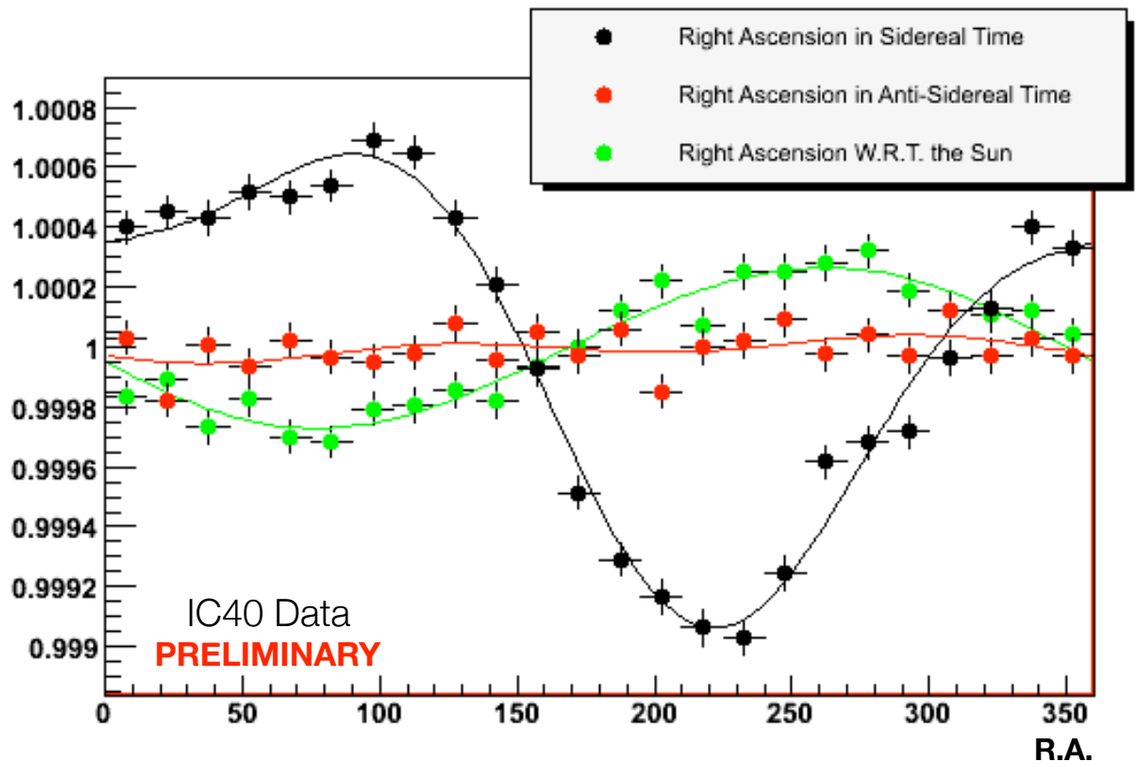
**sidereal time**

**anti-sidereal time**

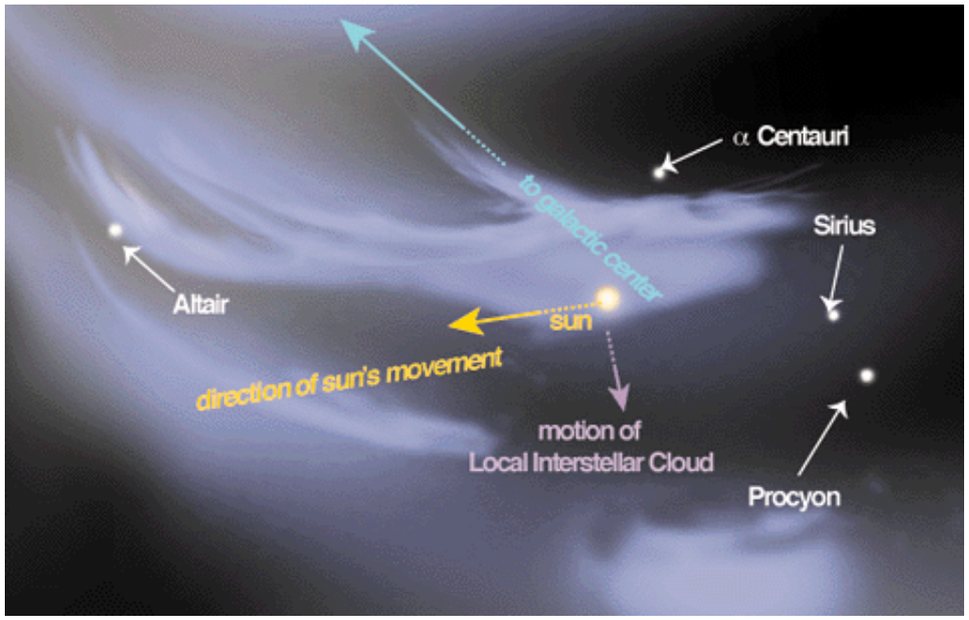
pseudo-equatorial coordinates

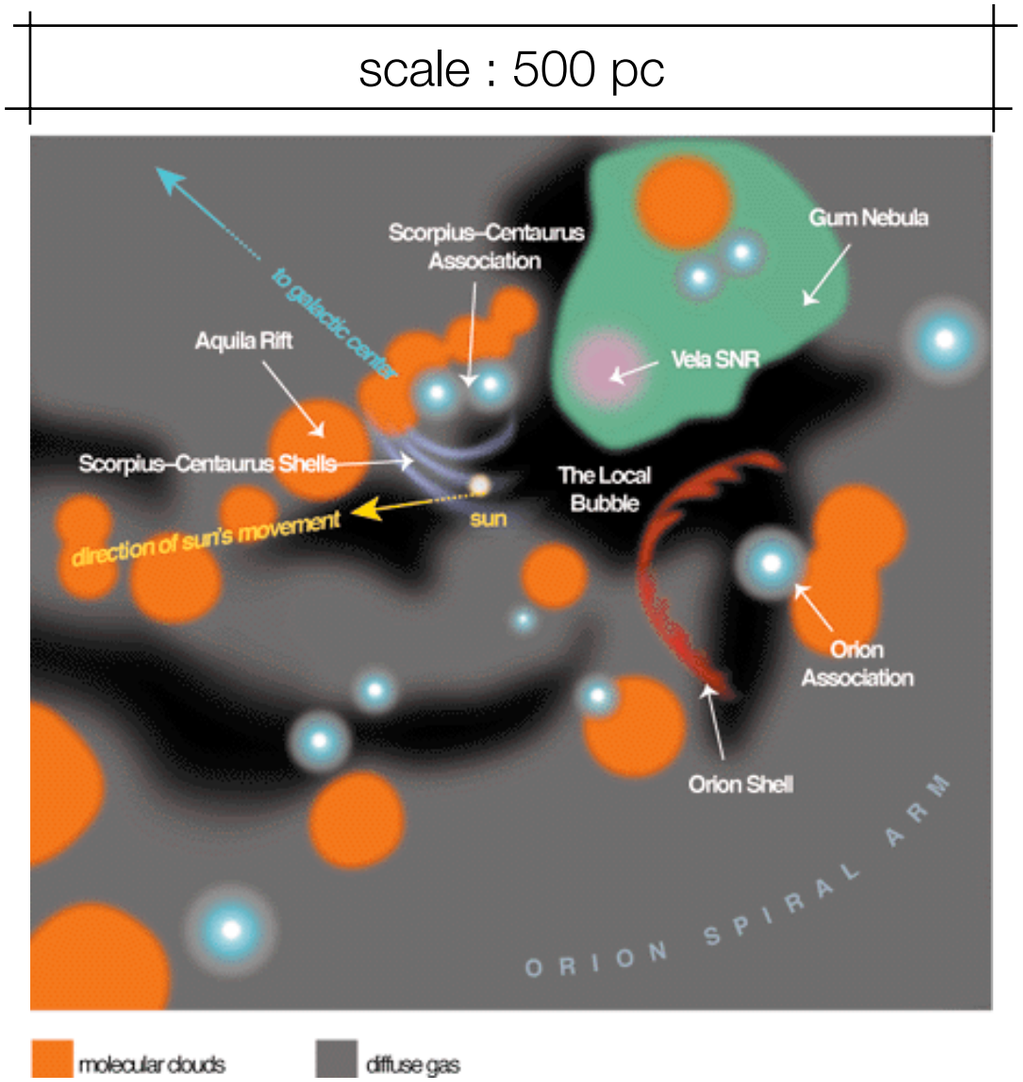



Farley et al., Proc. Phys. Soc., 67, 996 (1954)



# our galactic neighborhood




Priscilla Frisch - University of Chicago

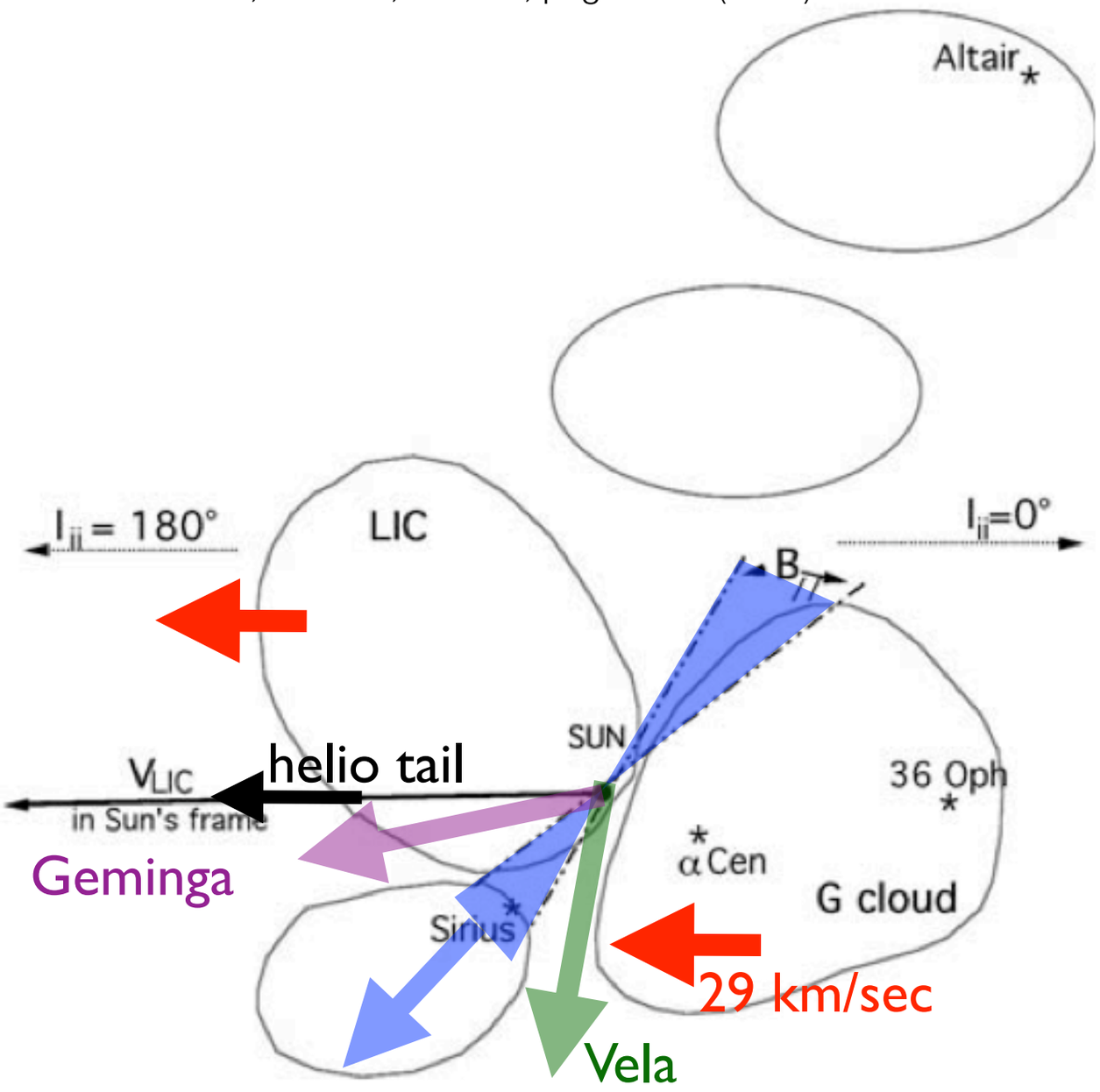
- **Local Bubble** (~300 pc) : cavity of the Orion arm with low density (~1/10 of ISM) of hot neutral H gas that emits X-rays. Produced by ancient SN (perhaps Geminga)

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

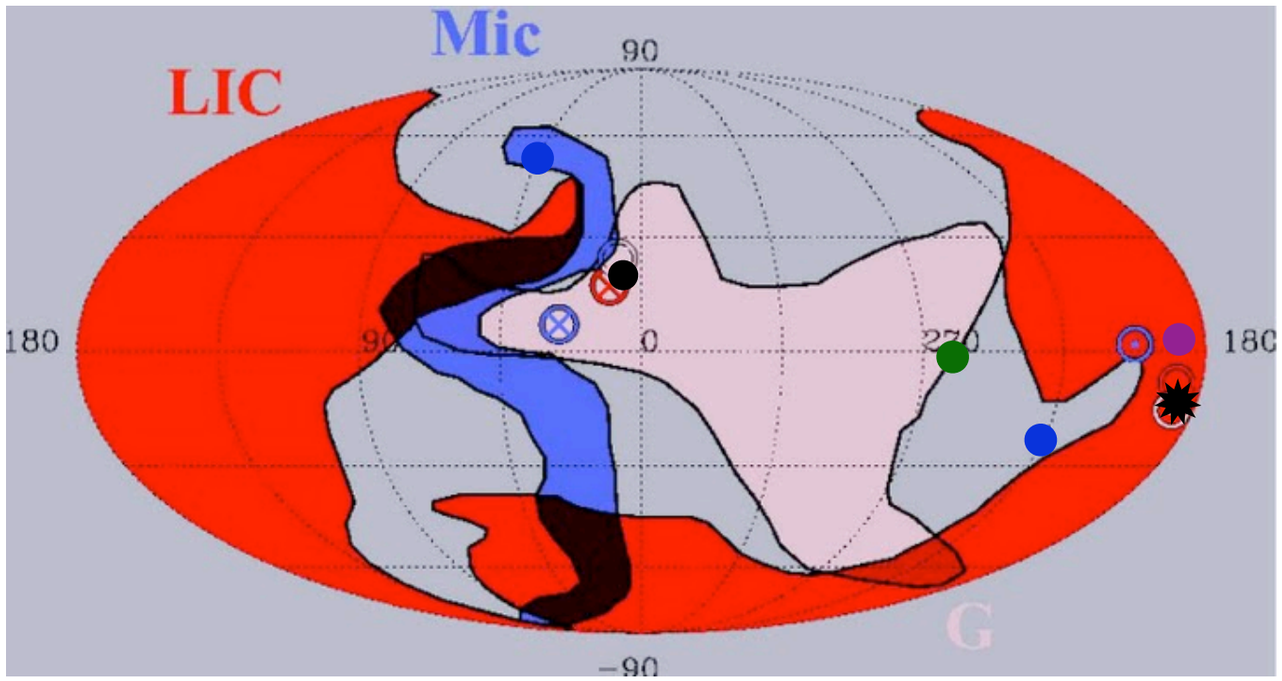
# our galactic neighborhood

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 ISMF is a perturbation of the galactic magnetic field
- the solar system is in transition between the Local Interstellar Cloud and the Cloud G

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

# our galactic neighborhood

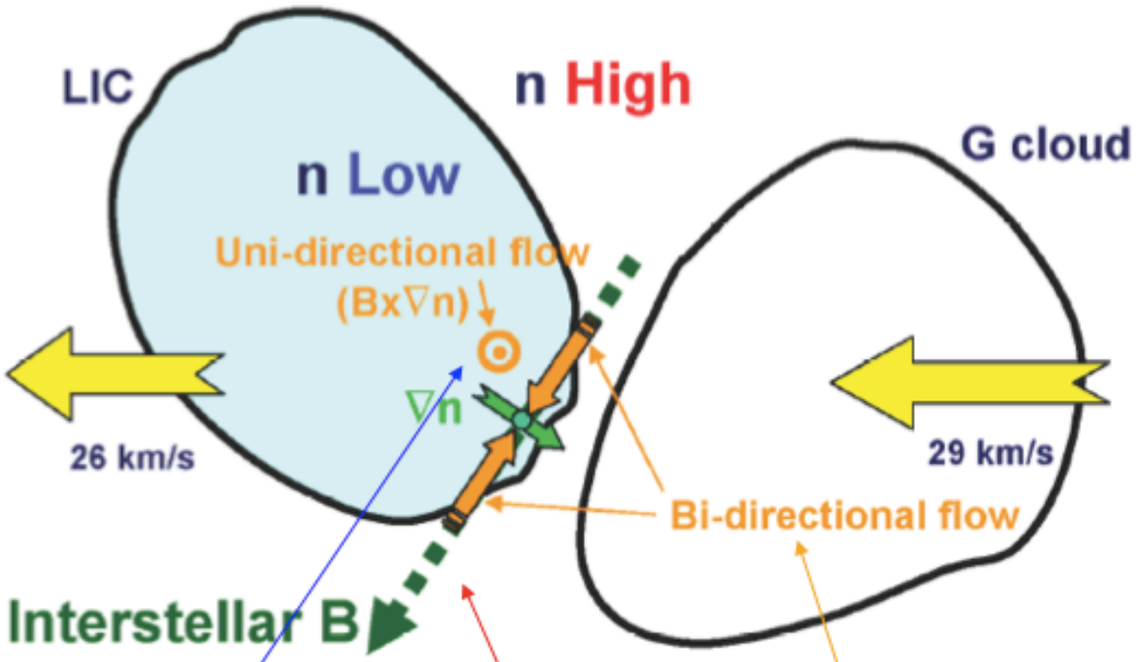
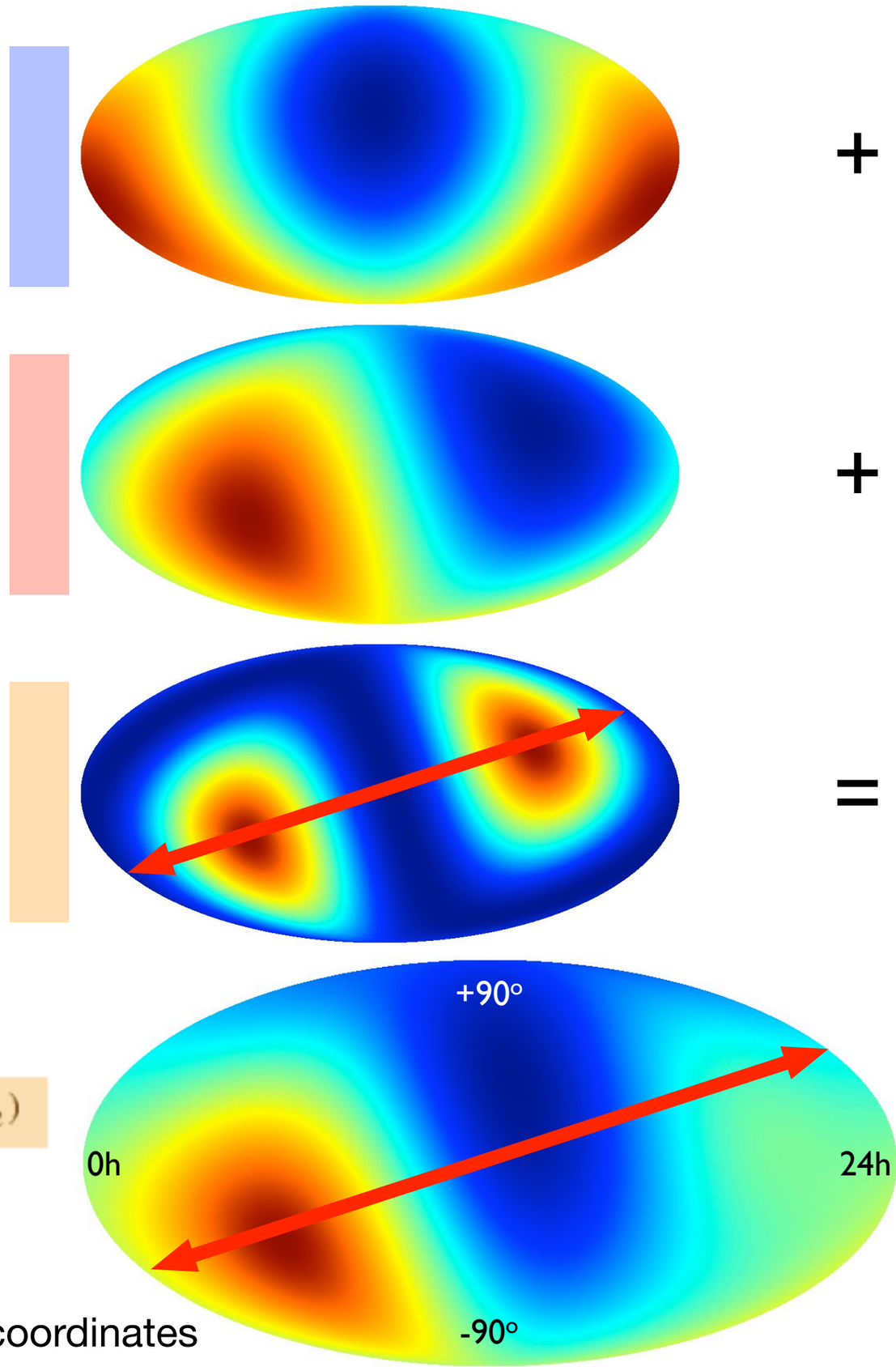



FIGURE 2. A cartoon of the LIC (left) viewed from the galactic north-pole (see [8] for more detail). Another cloud (G cloud) is overtaking the LIC from the Galactic center on the right side. A broken line represents the LISMF line through the heliosphere just inside the LIC boundary. If the GCR density (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).

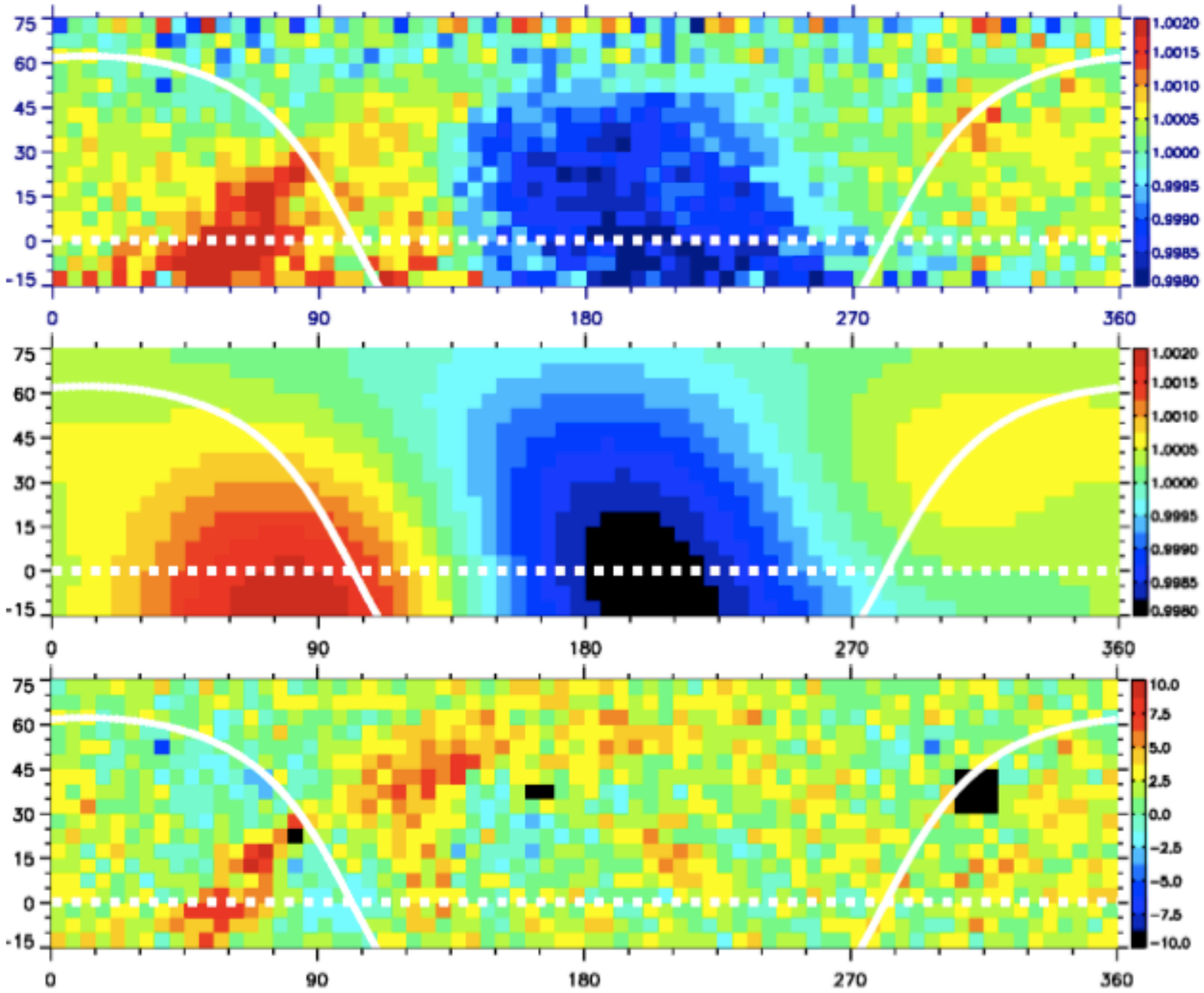
$$I_{n,m} = a_{1\perp}\cos\chi_1(n,m:\alpha_1,\delta_1) + a_{1//}\cos\chi_2(n,m:\alpha_2,\delta_2) + a_2\cos^2\chi_2(n,m:\alpha_2,\delta_2)$$




equatorial coordinates

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

# our galactic neighborhood



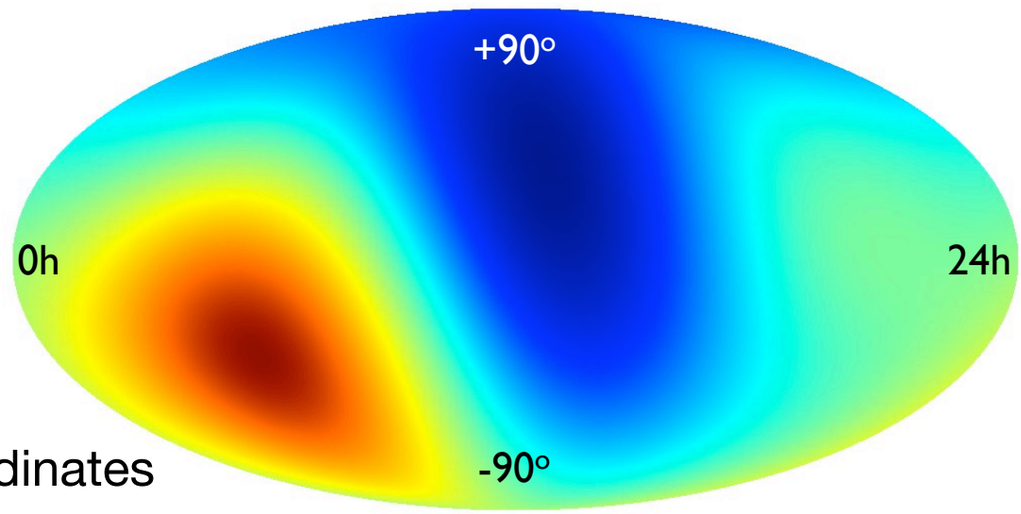

**Tibet-III @ 5 TeV**

anisotropy almost consistent with

uni-directional flow (dipole)

+

bi-directional flow (quadrupole)

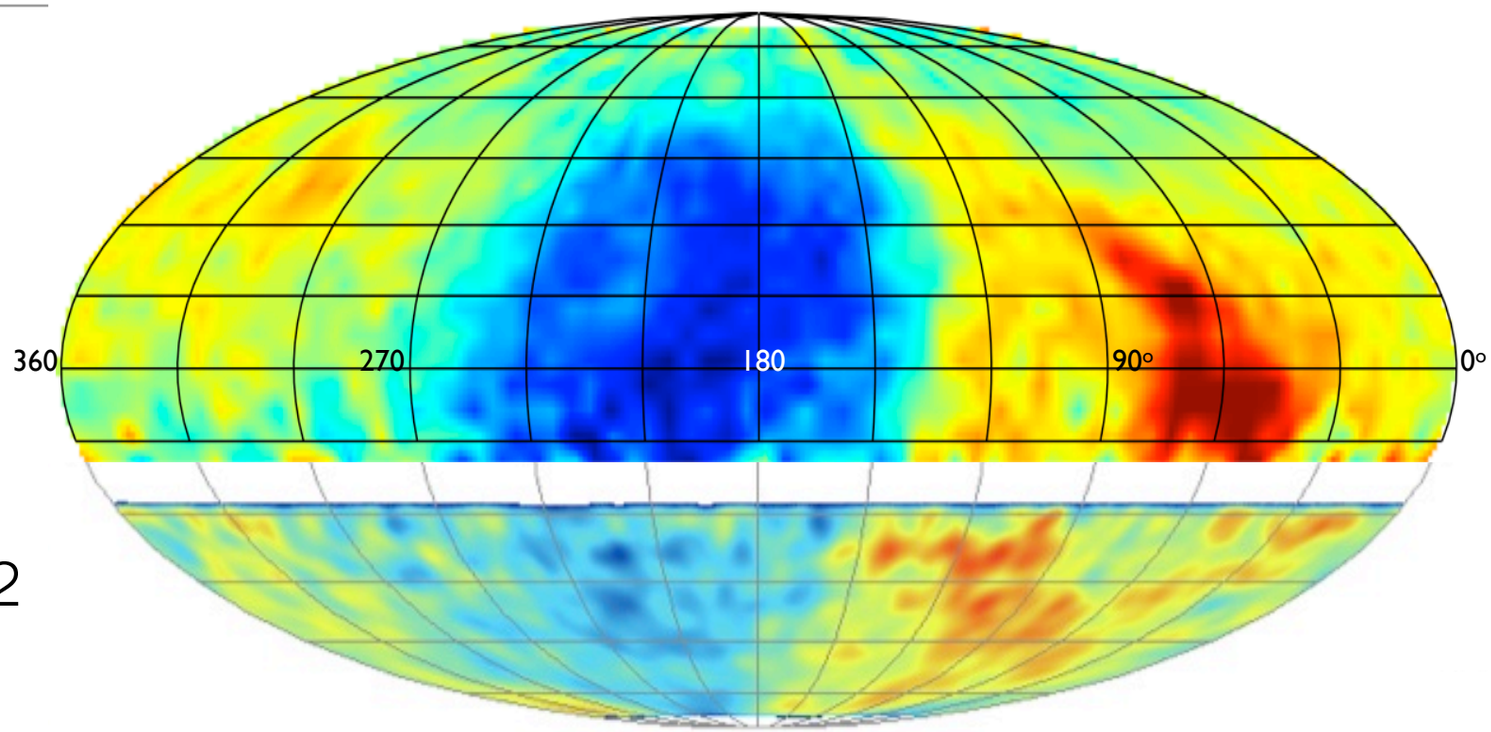



equatorial coordinates

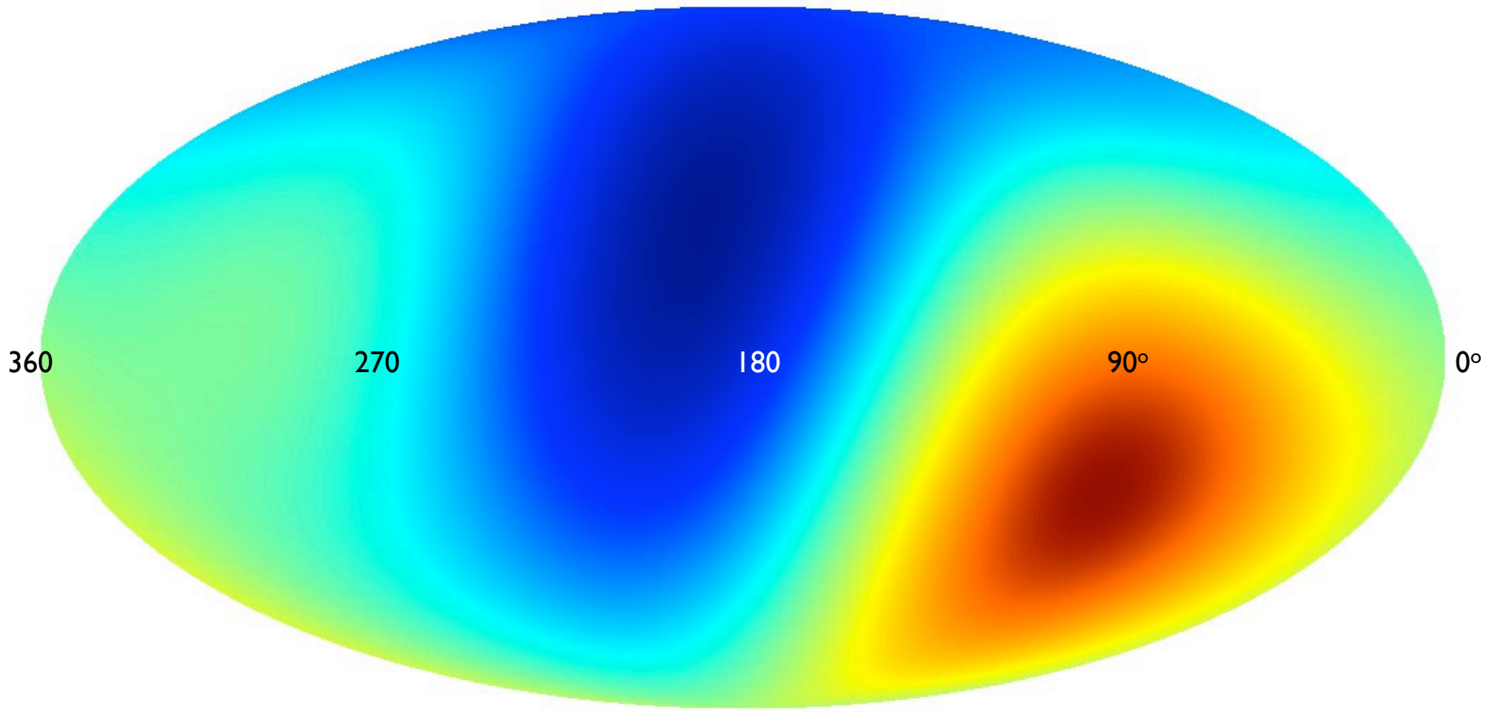
# our galactic neighborhood

relative intensity
equatorial coordinates

Tibet-III




IceCube-22




**IceCube @ 20 TeV**

large scale features qualitatively well described by the global fit

it is the smaller angular features that appear to be interesting

# heliosphere

scale : 100-10,000 AU
0.0005-0.05 pc

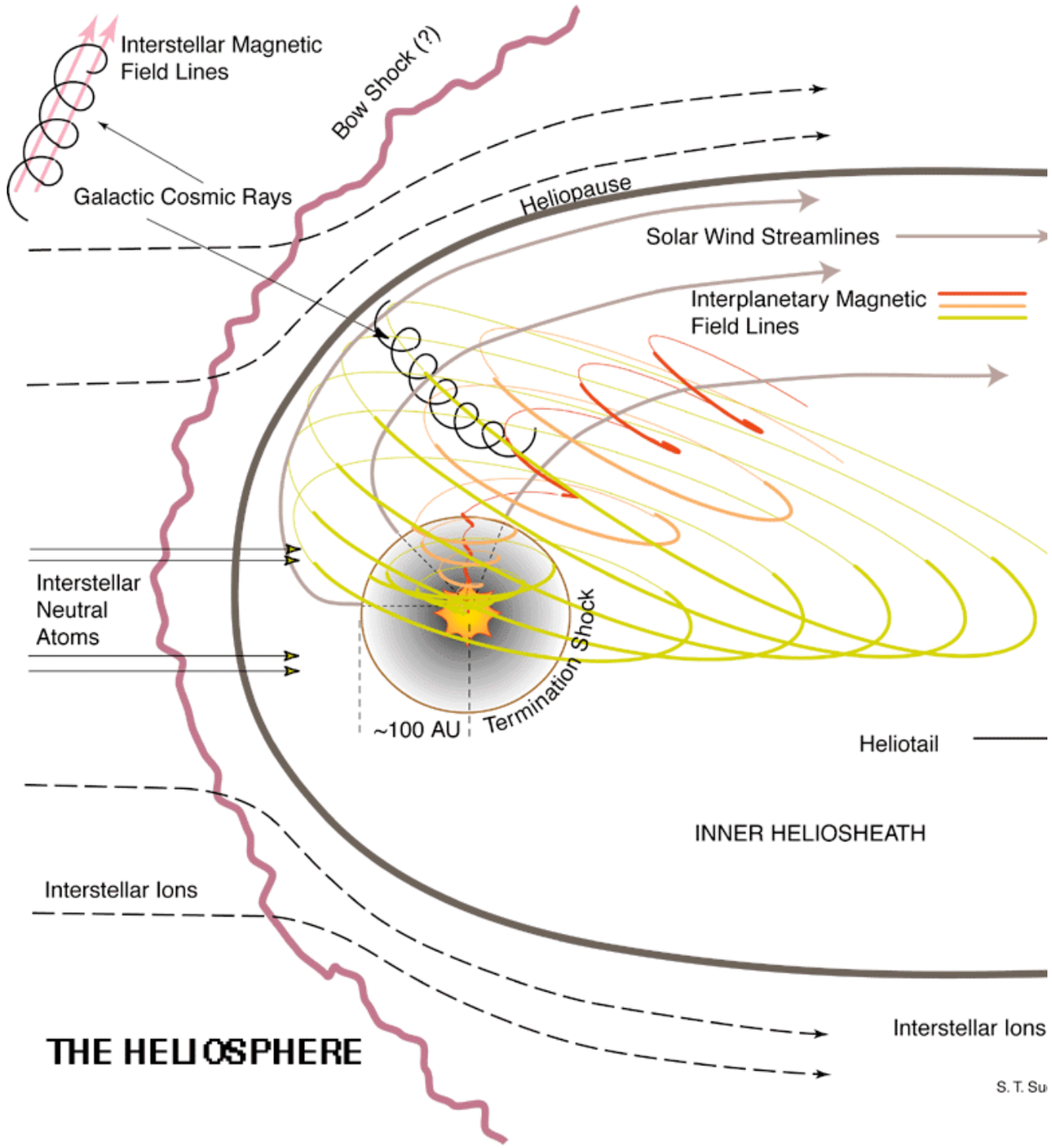
- solar system moves wrt IS medium at 26 km/s

- 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

- heliotail size up to ~ 10,000 AU ?



# investigating on interstellar magnetic field

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

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

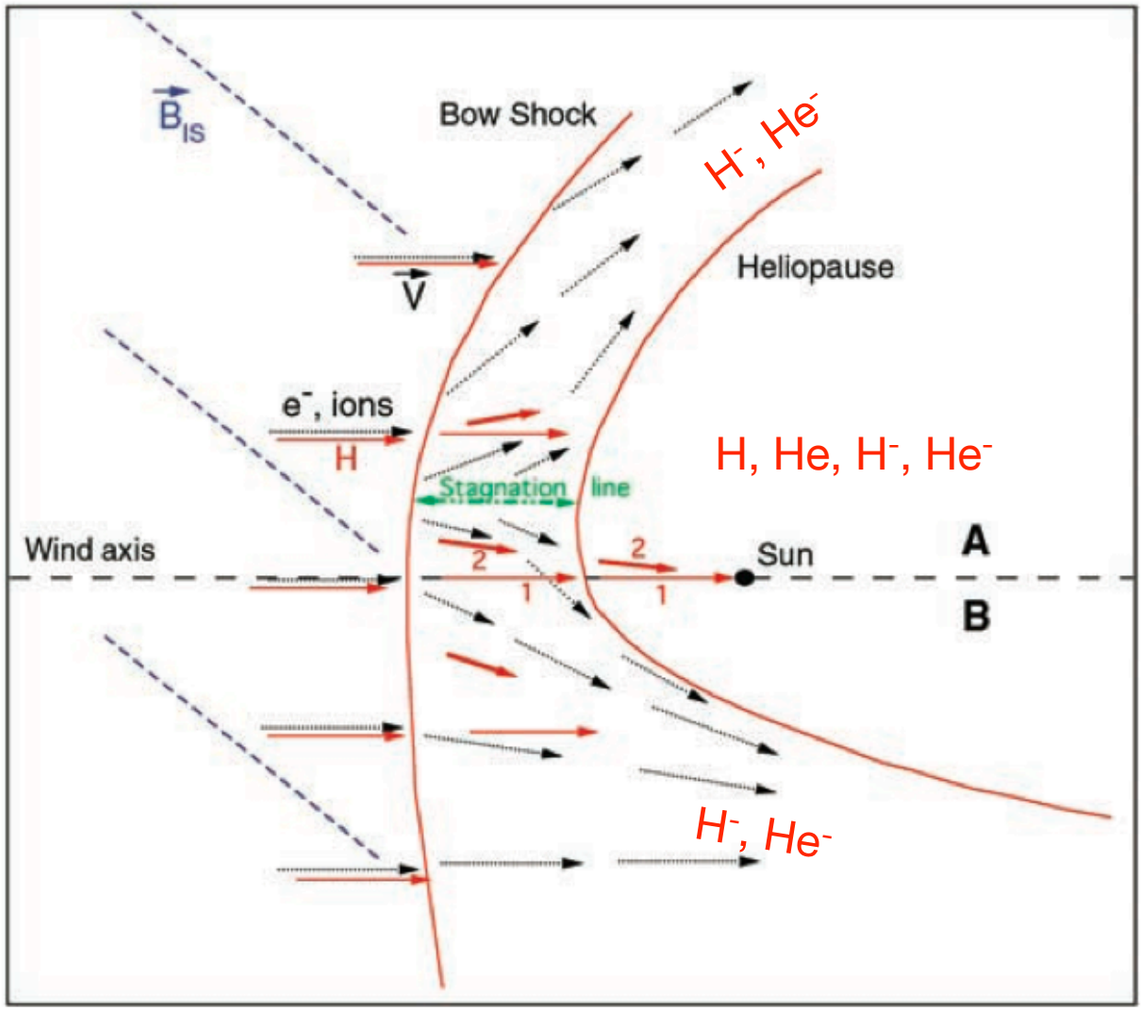
- Energetic Neutral Atoms (ENA) and charged particles ($e^-$ and ions) enters the heliosphere from ISM

- 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)

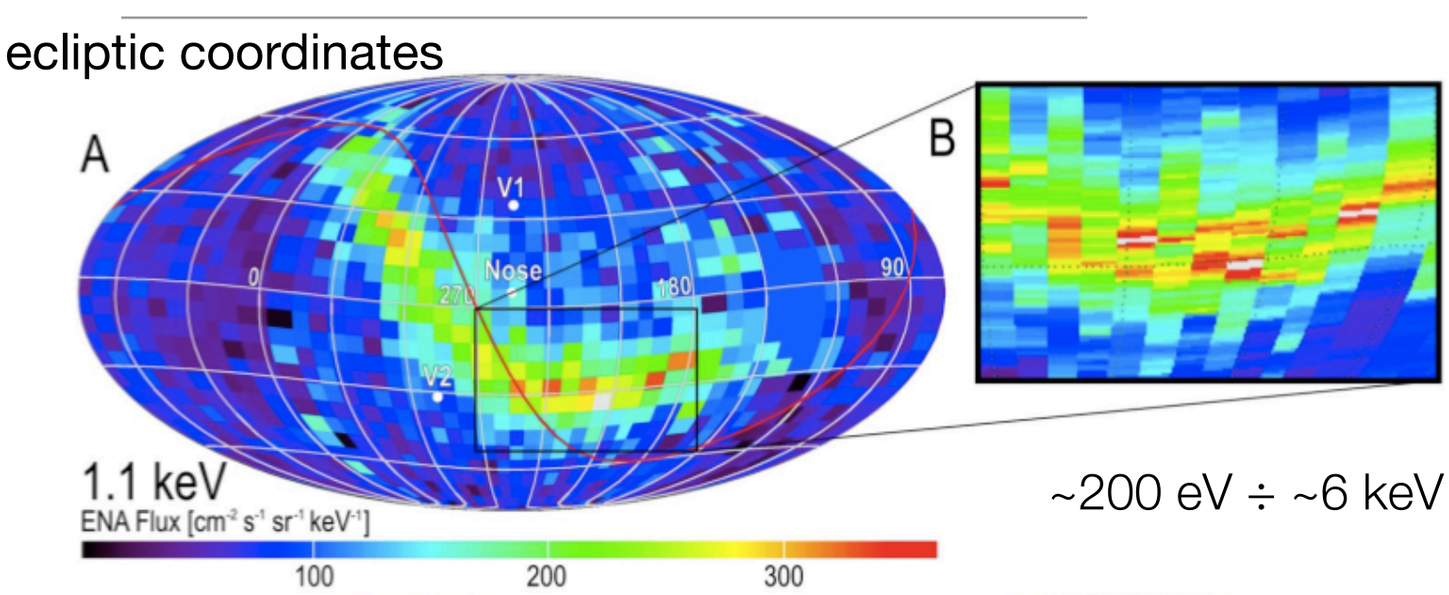



ISMF ~ $(205^\circ \div 240^\circ , -38^\circ \div -60^\circ)_{galactic}$

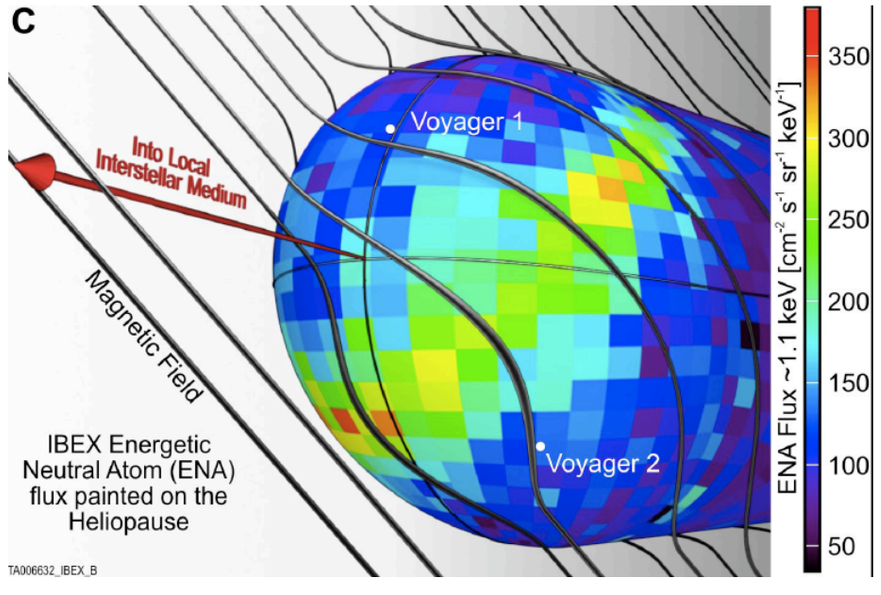
off galactic plane (~ HDP)

# investigating on interstellar magnetic field

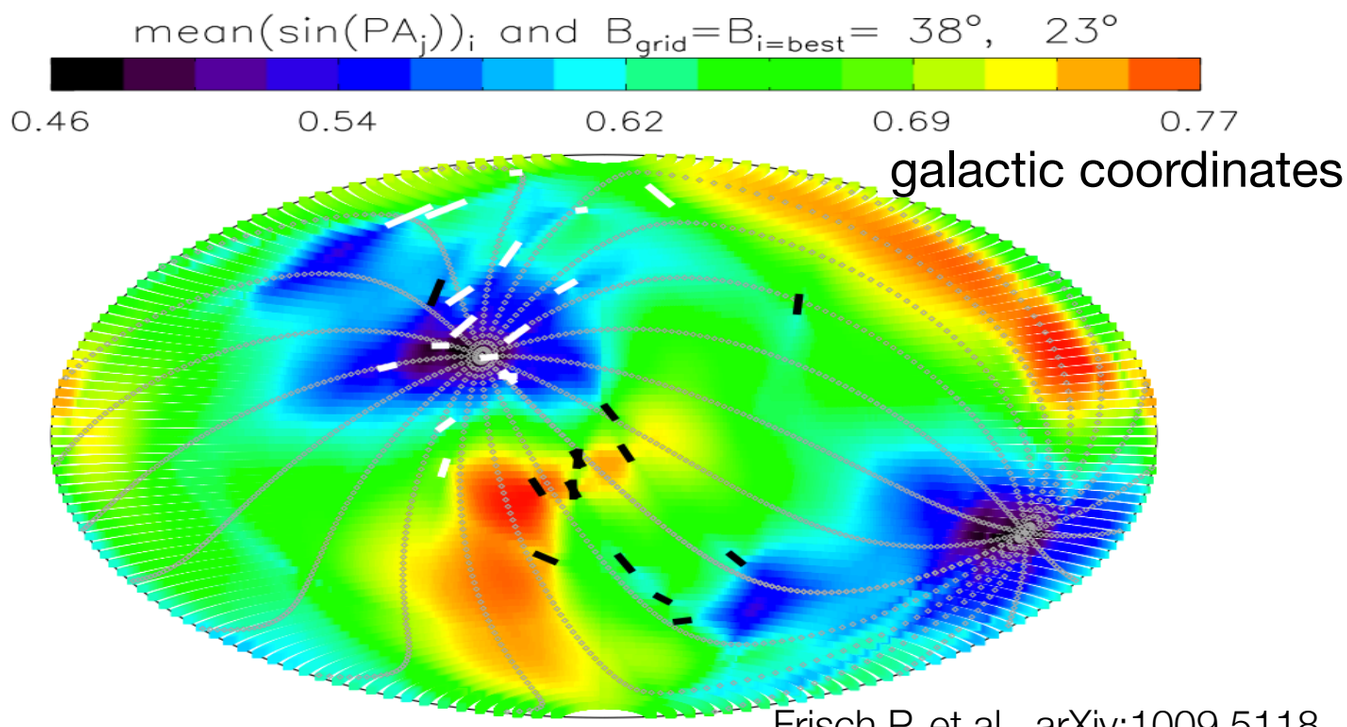
IBEX Collaboration, Science online , October 15, 2009




~200 eV ÷ ~6 keV




- ISMF @ heliosphere from IBEX observation of a ribbon of ENA
- ISMF from optical polarization for stars < 40 pc
- similar directions within ~33°

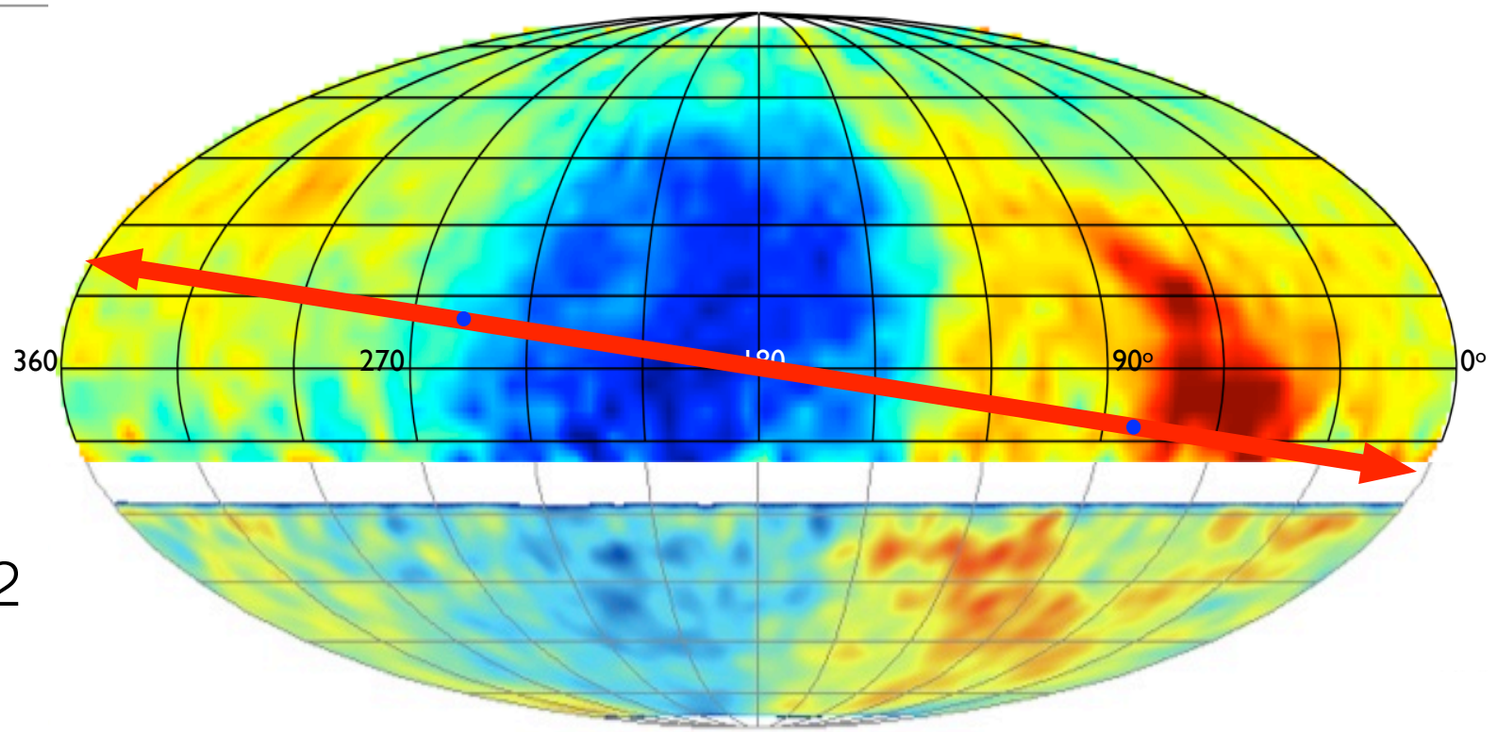



Frisch P. et al., arXiv:1009.5118

# our galactic neighborhood

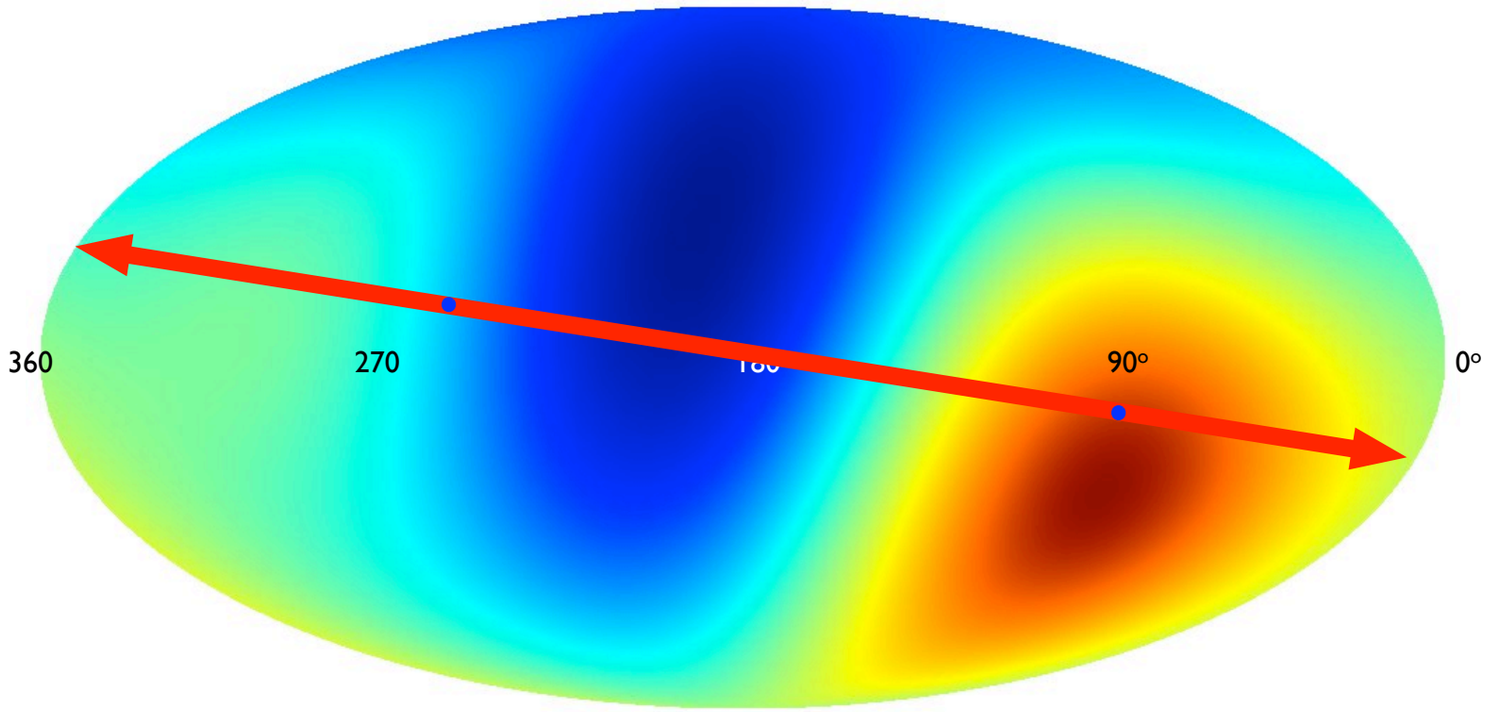
relative intensity
equatorial coordinates

Tibet-III




IceCube-22

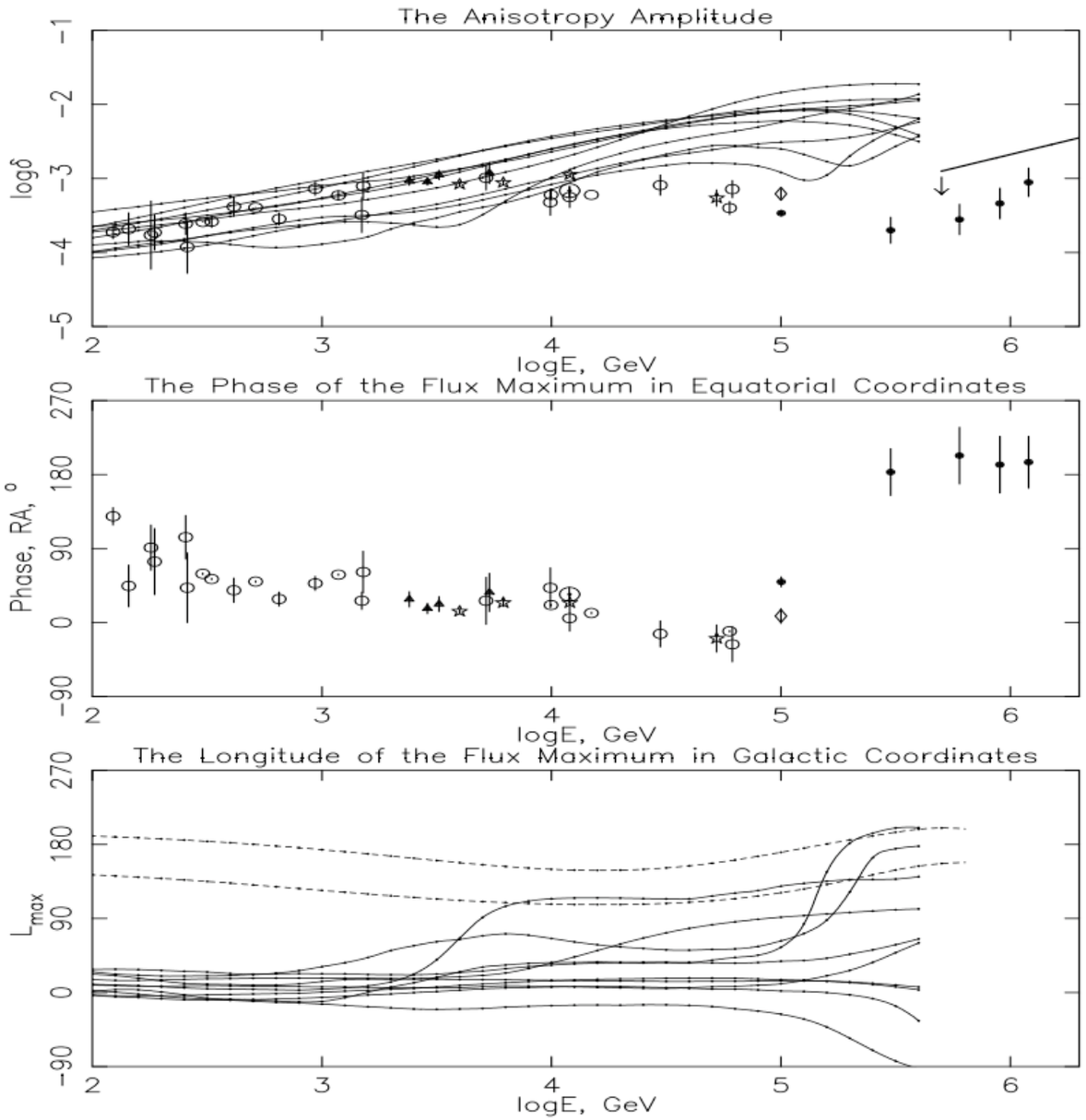
broad excess toward ISMF



# nearby sources of cosmic rays

scale : 100-1,000 pc

Erlykin & Wolfendale Astropart. Phys. 25,183, 2006

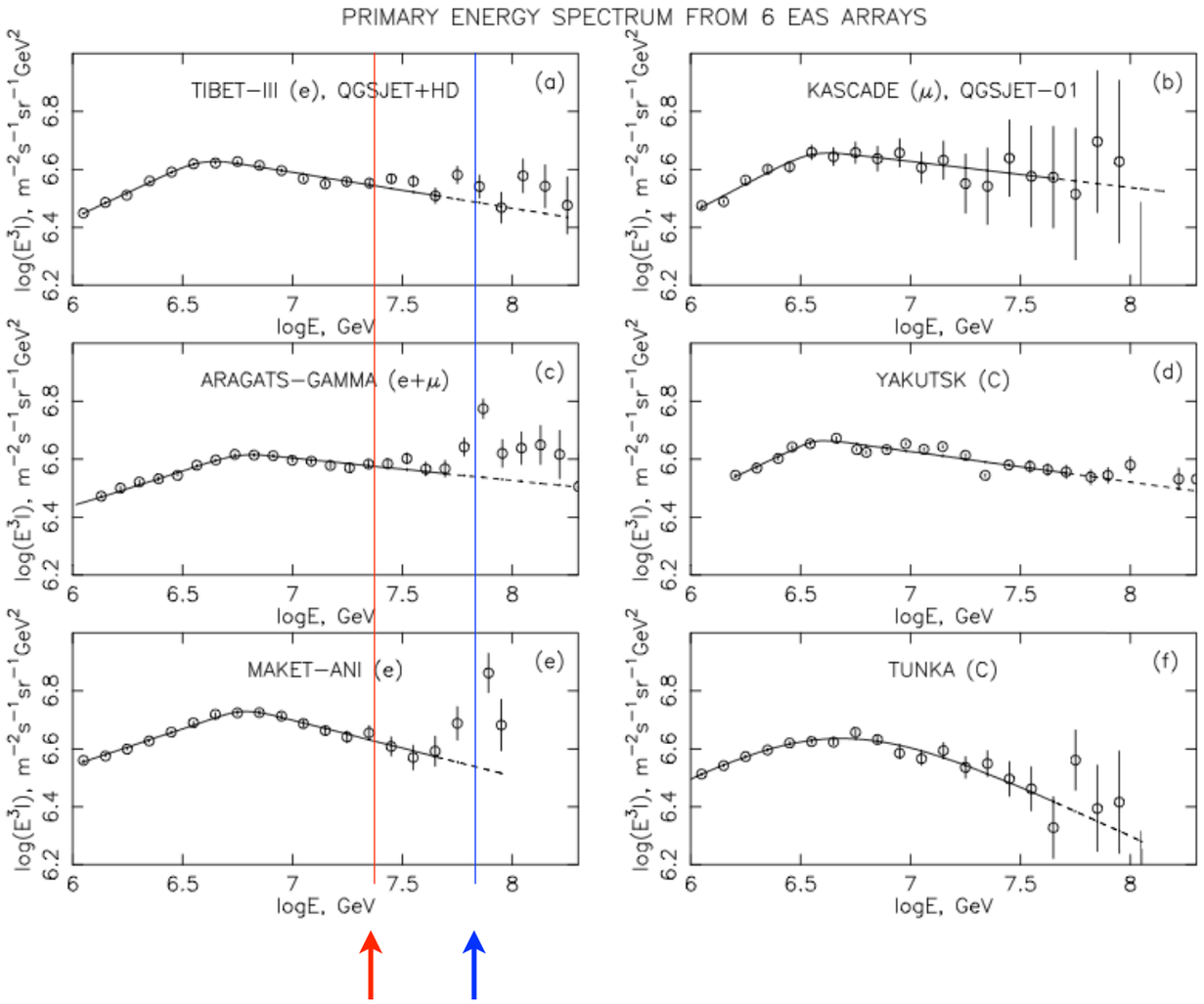



- cosmic rays below the knee from SNR
  - young (<100,000 yr) / nearby (< 1,000's pc) SNR might produce anisotropic random fluctuations
  - anomalous diffusion and mass composition magnifies the stochastic nature of anisotropy
- connection between spectral features and anisotropy
  - the knee of CR from a single source

# nearby sources of cosmic rays

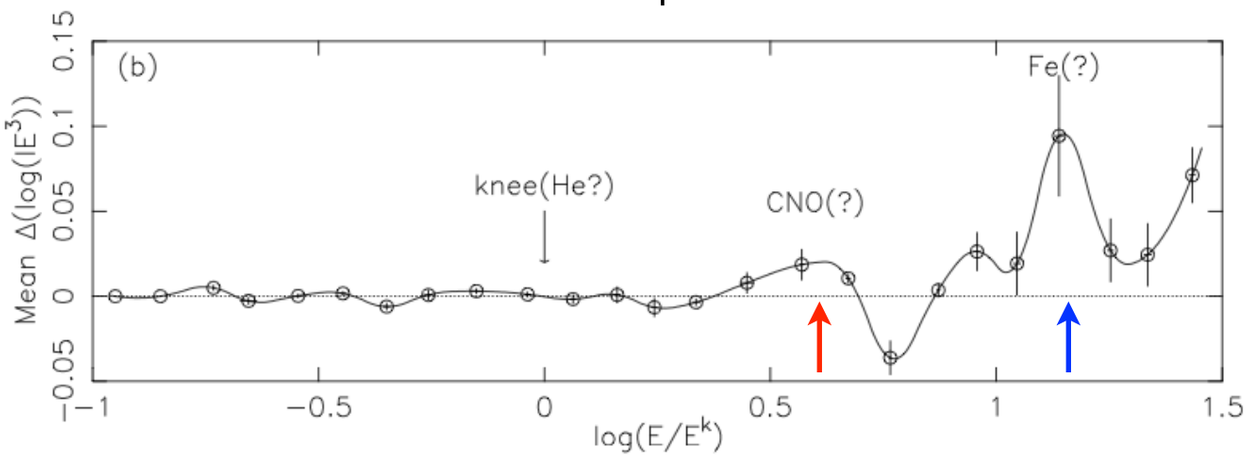
scale : 100-1,000 pc

Erlykin & Wolfendale 31st ICRC Łódź (Poland), 2007




- sharpness of the knee of cosmic ray spectrum
  - from cutoff of maximum acceleration energy
  - single source hypothesis where flatter spectra with cutoffs superimpose to average CR spectrum by adding features
  - Monogem (associated to PSR B0656+14)

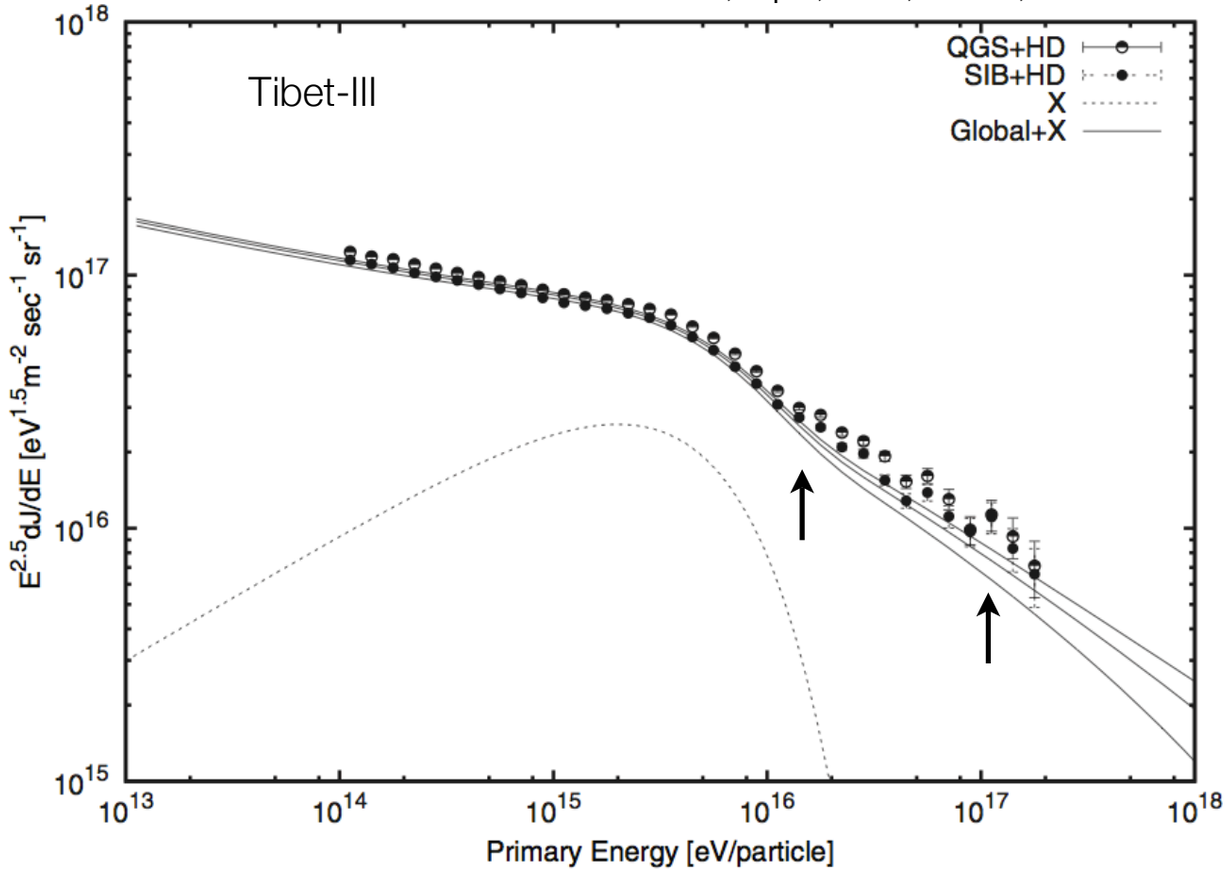
deviation wrt CR spectrum with knee



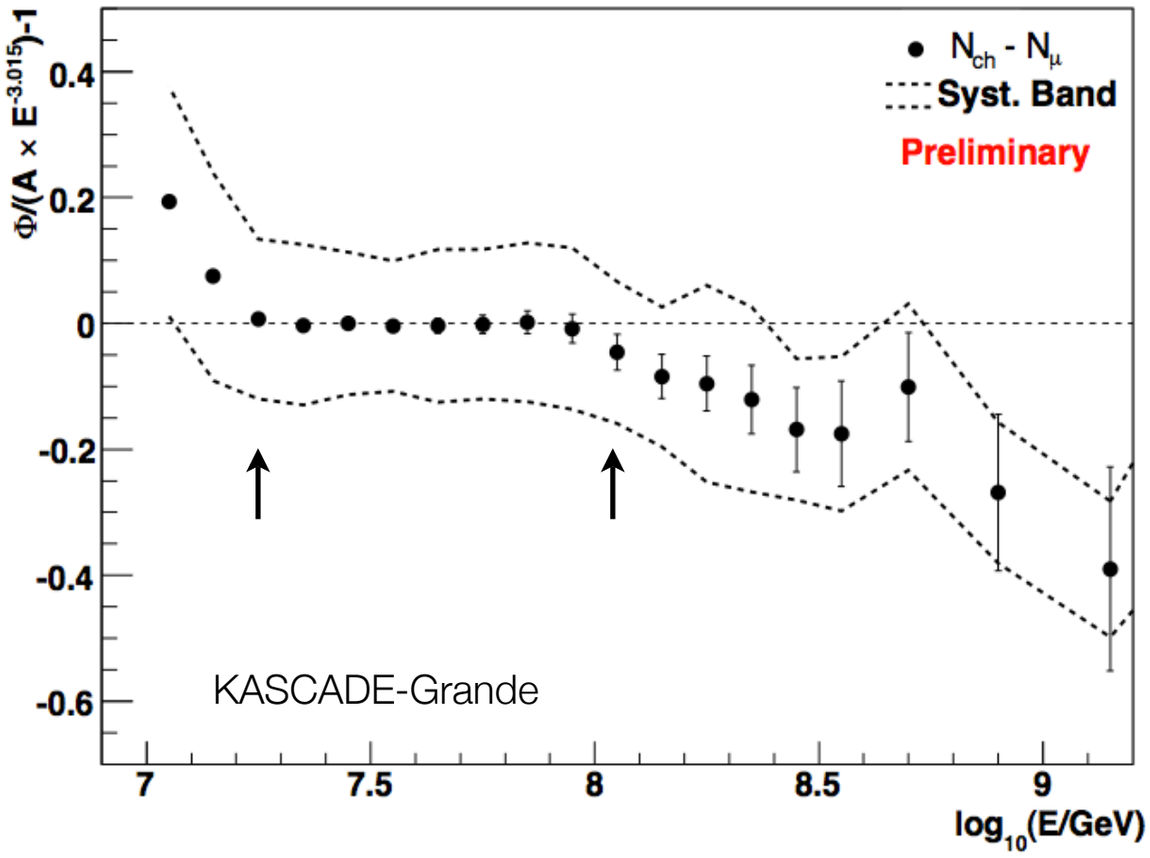
# nearby sources of cosmic rays

scale : 100-1,000 pc

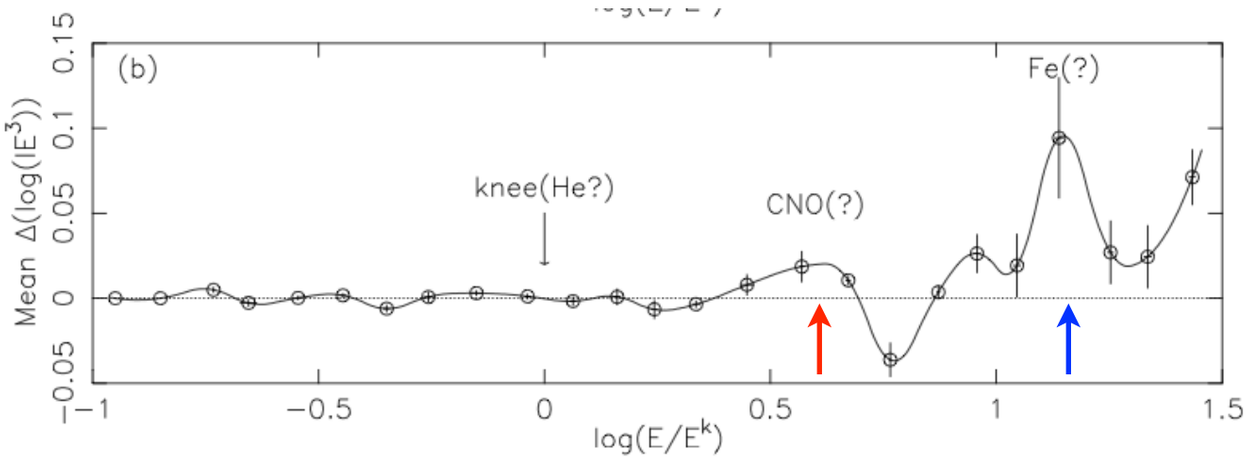
Shibata et al., ApJ, 716, 1076, 2010
Amenomori et al., ApJ, 678, 1165, 2008




Arteaga-Velázquez et al., arXiv:1009.4716



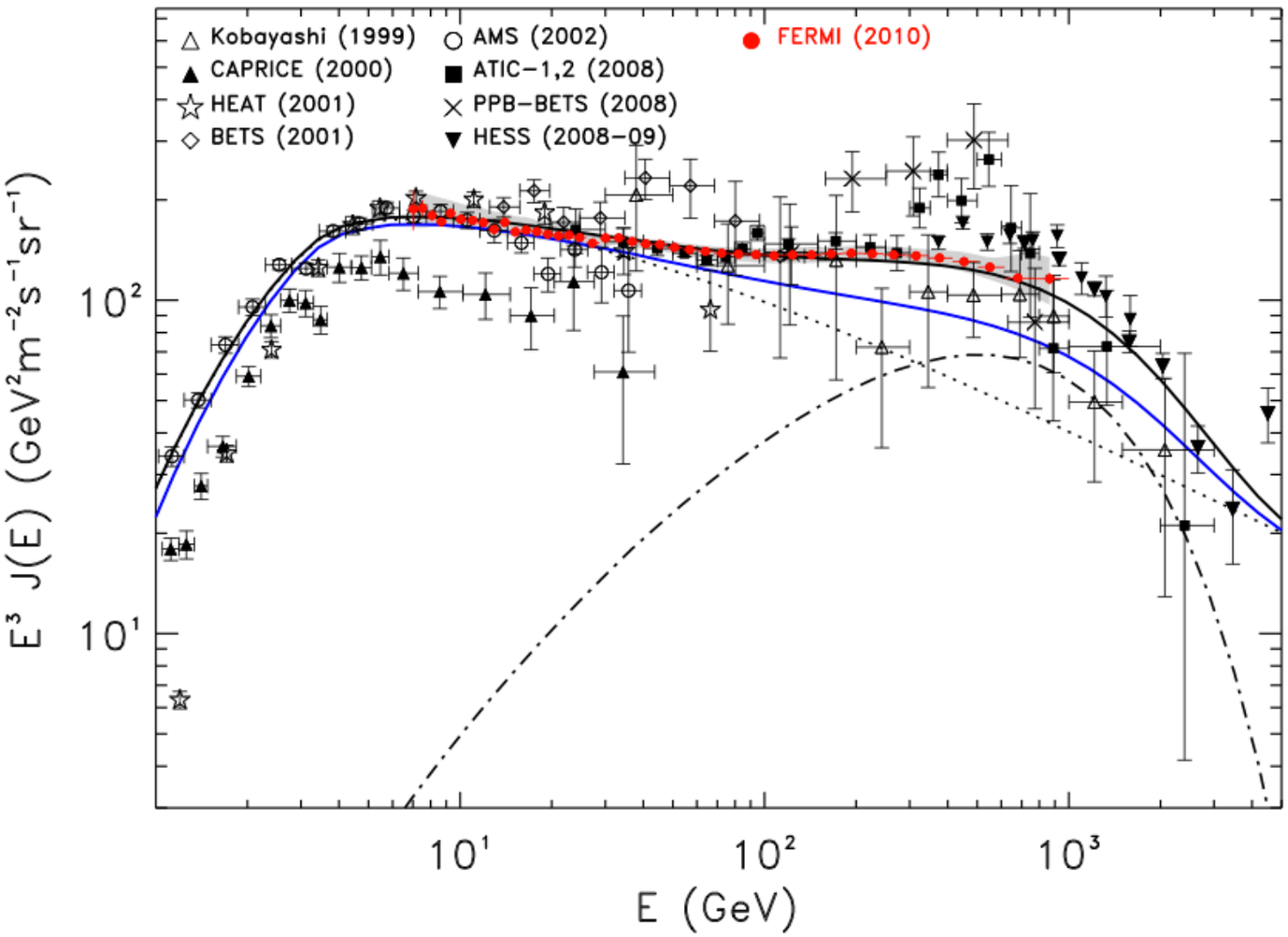

deviation wrt CR spectrum with knee



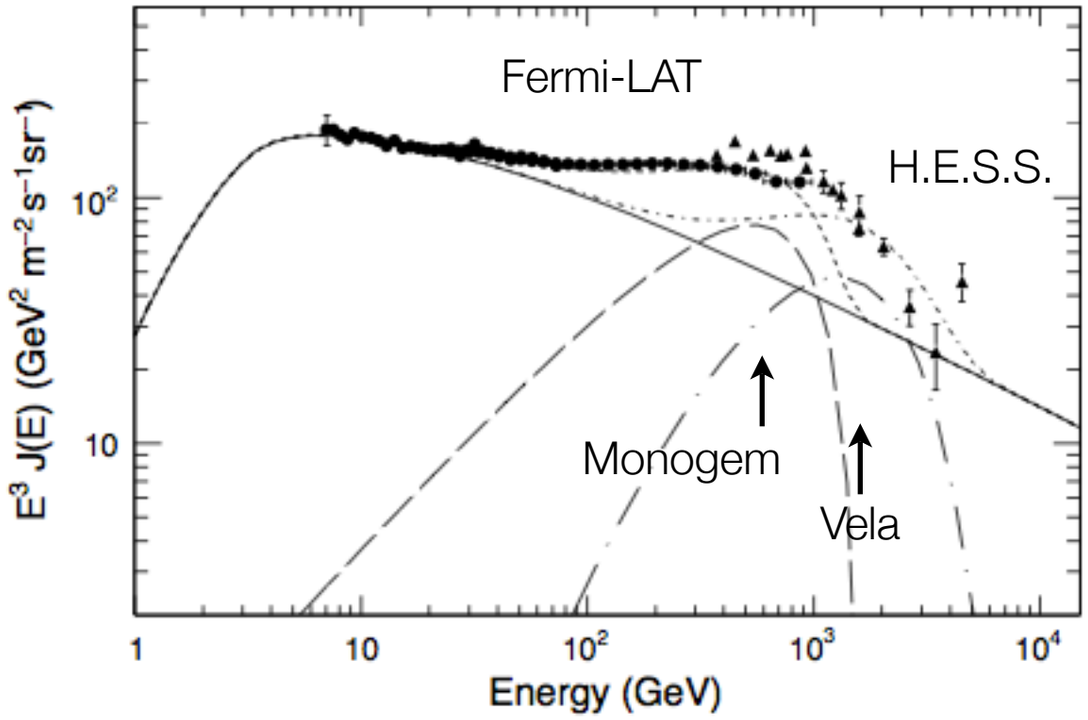
# nearby sources of cosmic rays ($e^+e^-$)

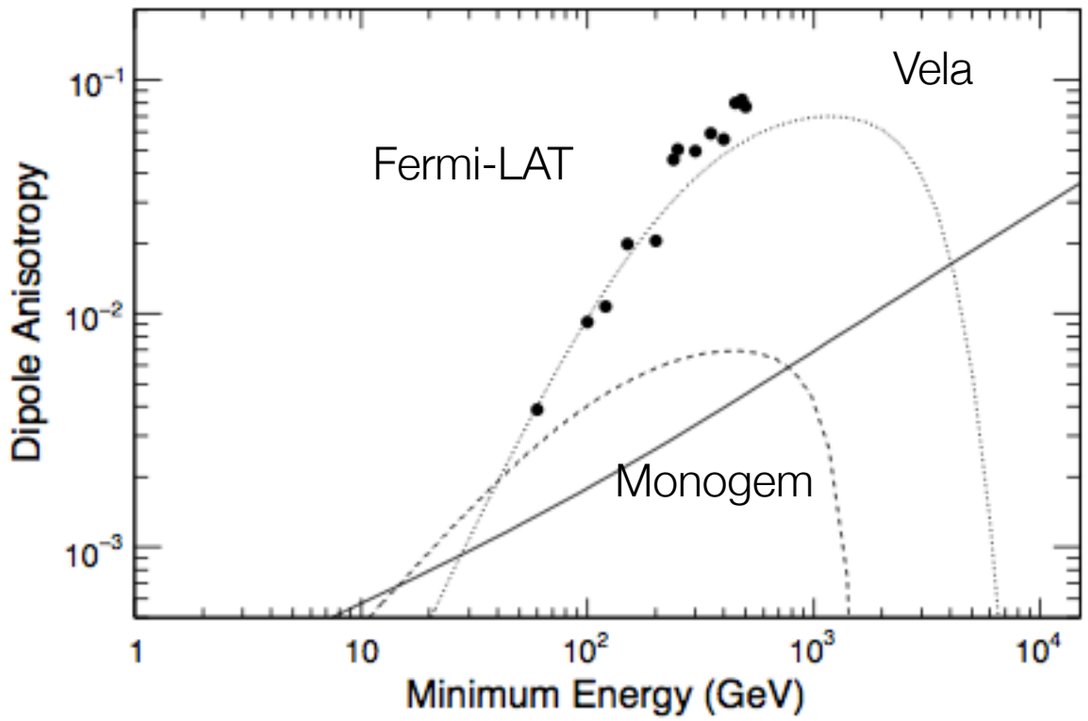
scale : 100-1,000 pc

Ackermann et al., arXiv:1008.3999




Ackermann et al., arXiv:1008.5119

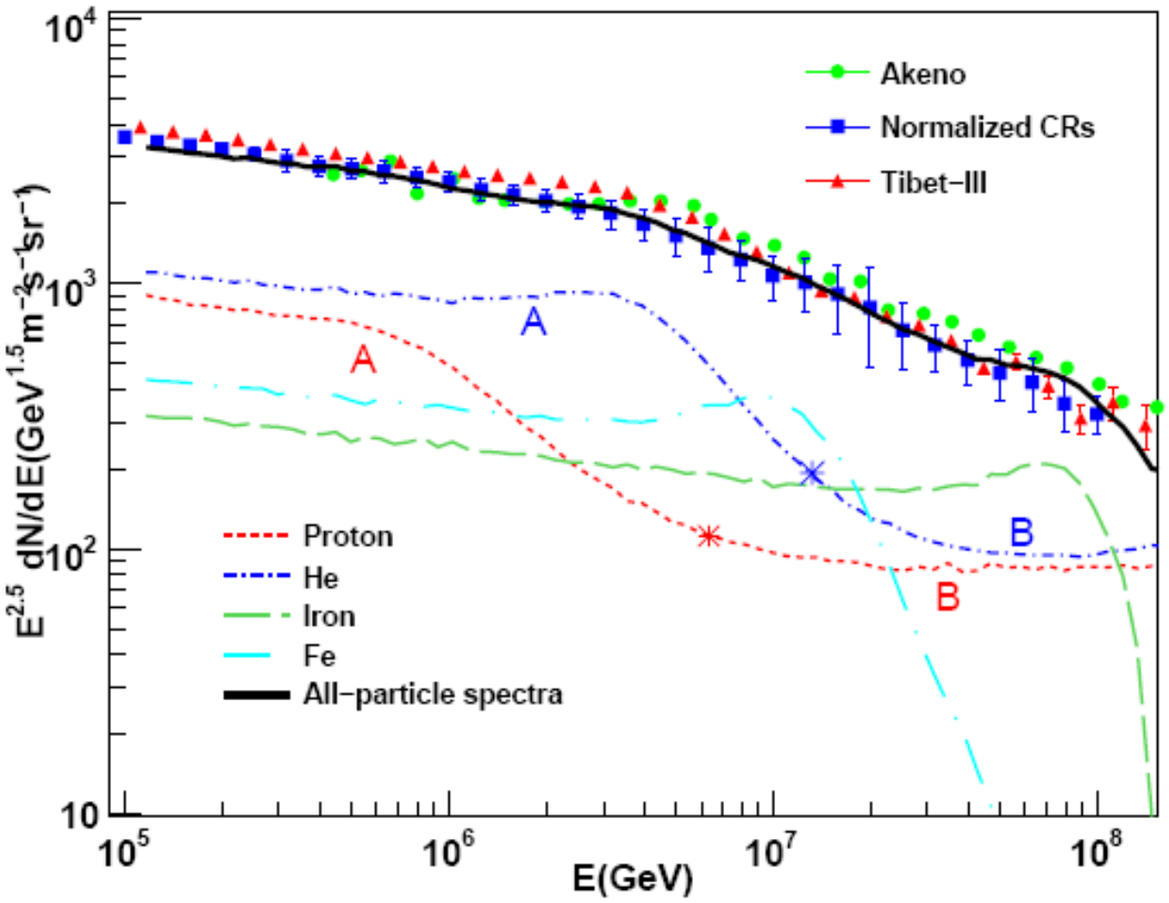


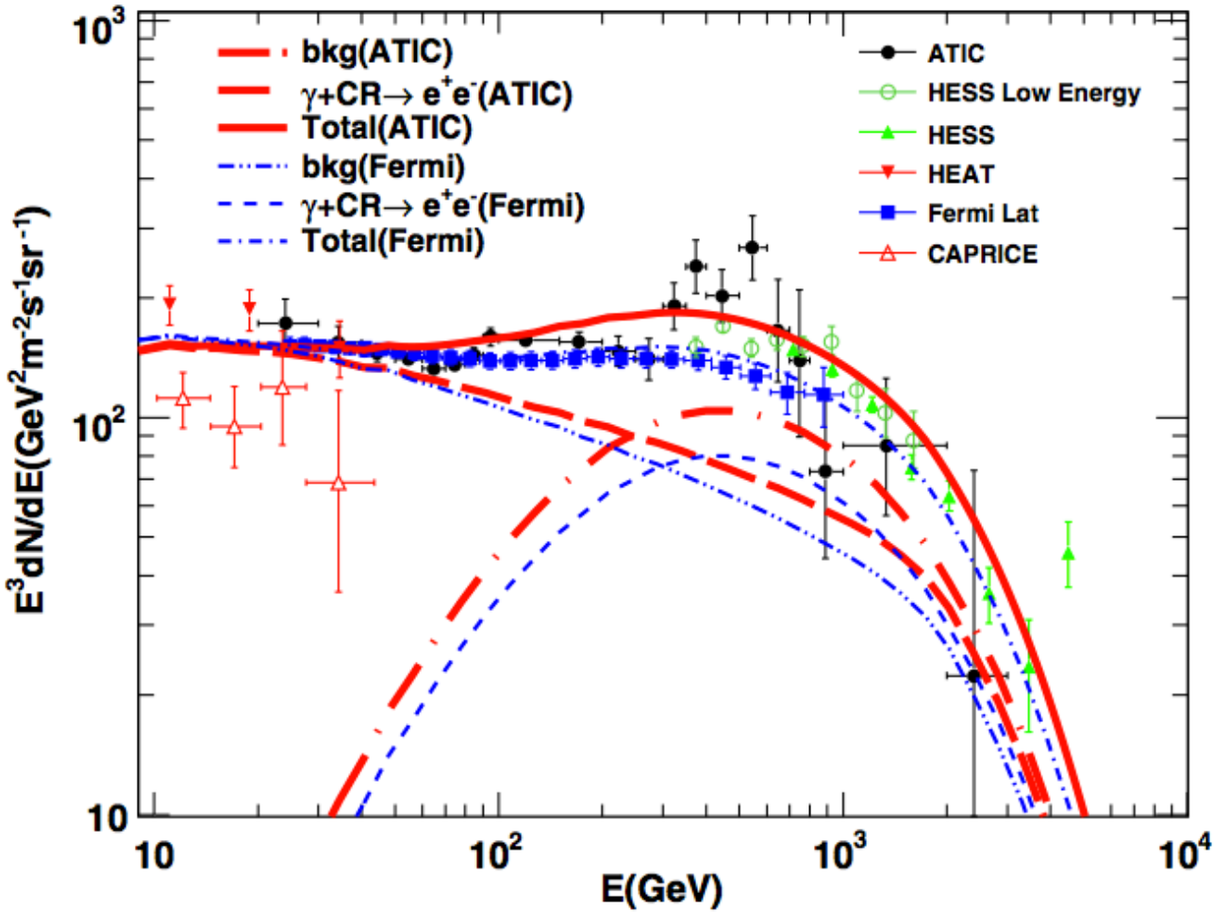



# nearby sources of cosmic rays

scale : 100-1,000 pc

Hong-Bo Hu et al., ApJ, 700, L170, 2009



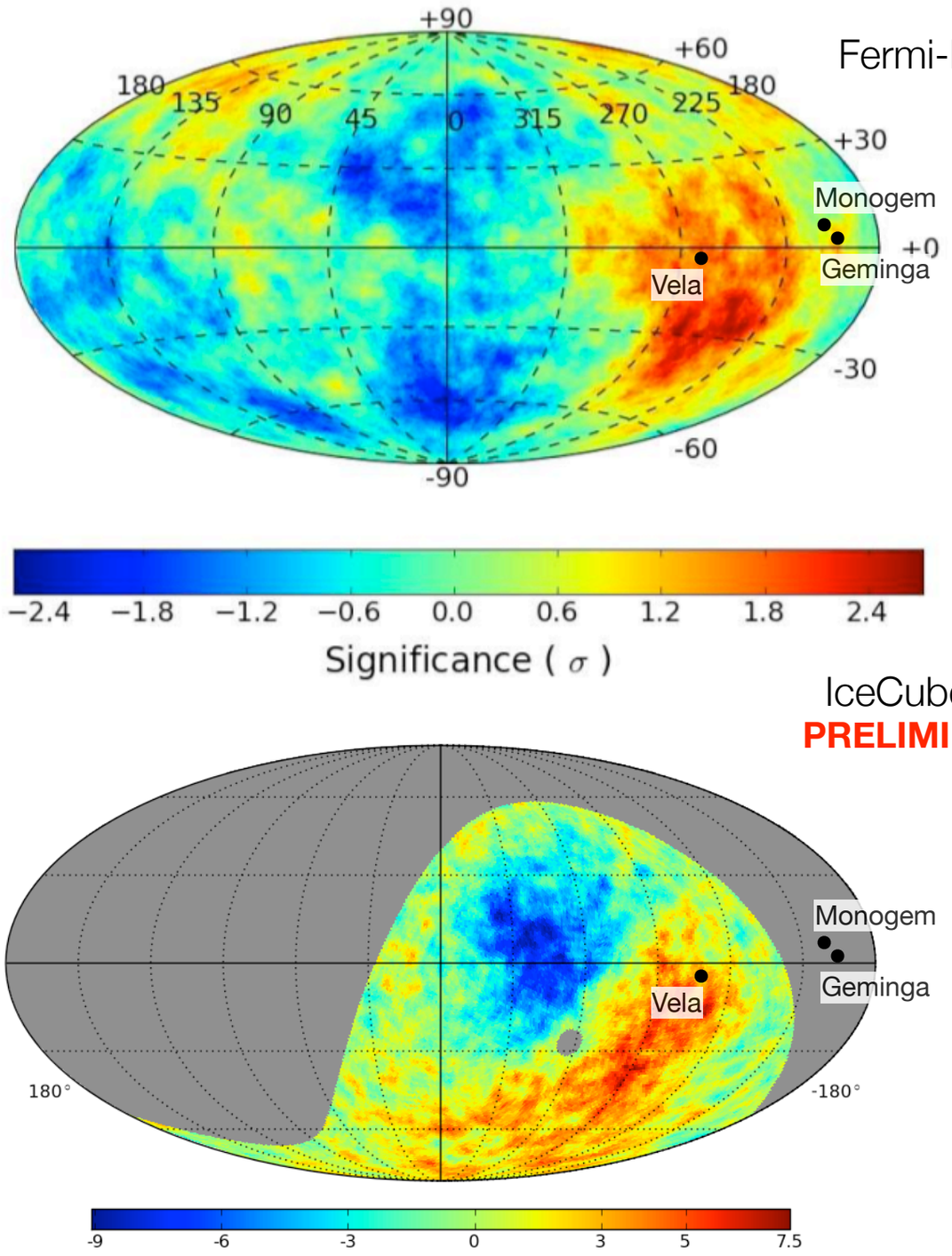




- CR spectral features reproduced in a scenario with $e^+e^-$ pair production by interactions between high-energy CRs and background photons in an environment similar to young SNR

- evidence that at least a portion of CRs might be accelerated in young SNRs ?

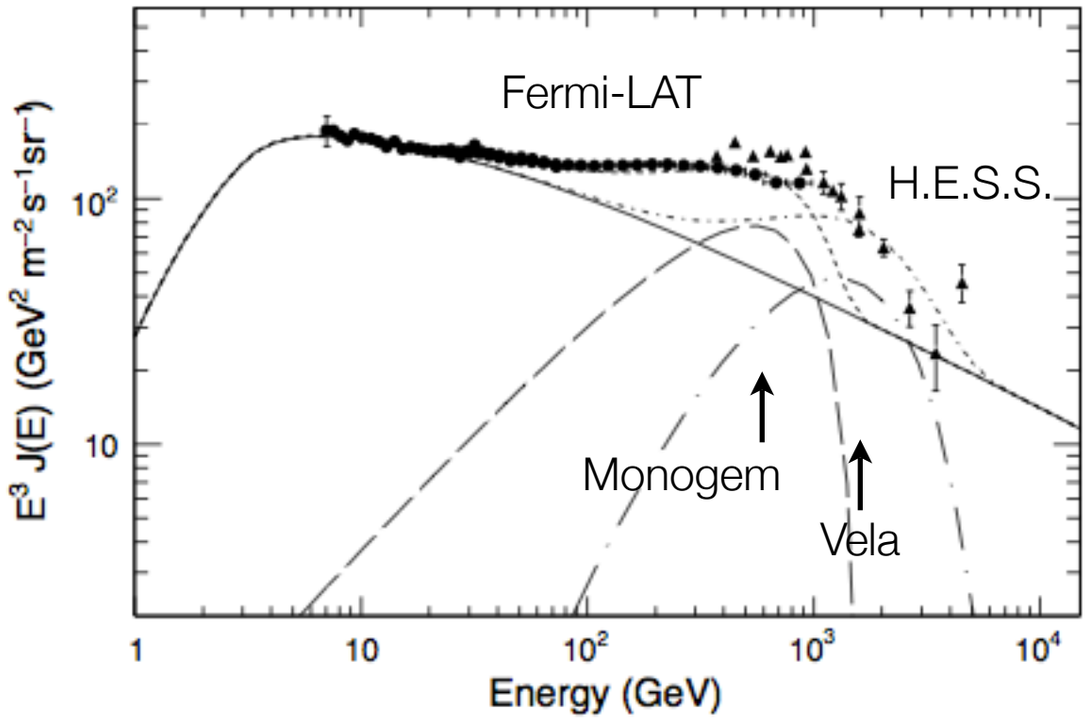
# nearby sources of cosmic rays

scale : 100-1,000 pc

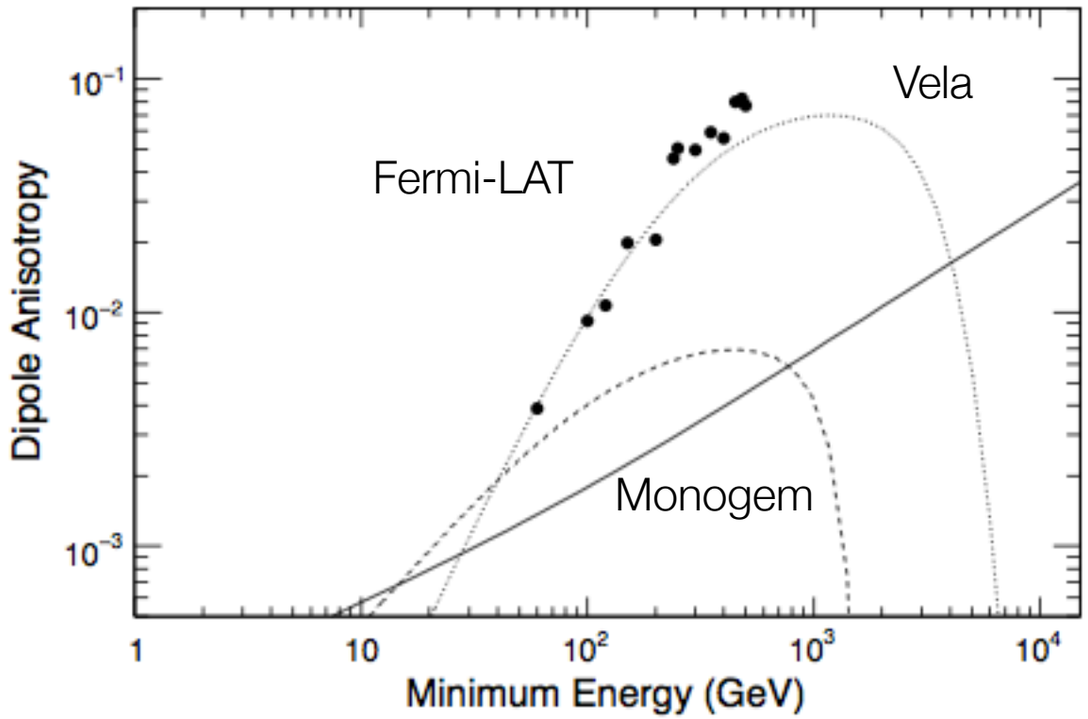



Fermi-LAT

IceCube-40
**PRELIMINARY**



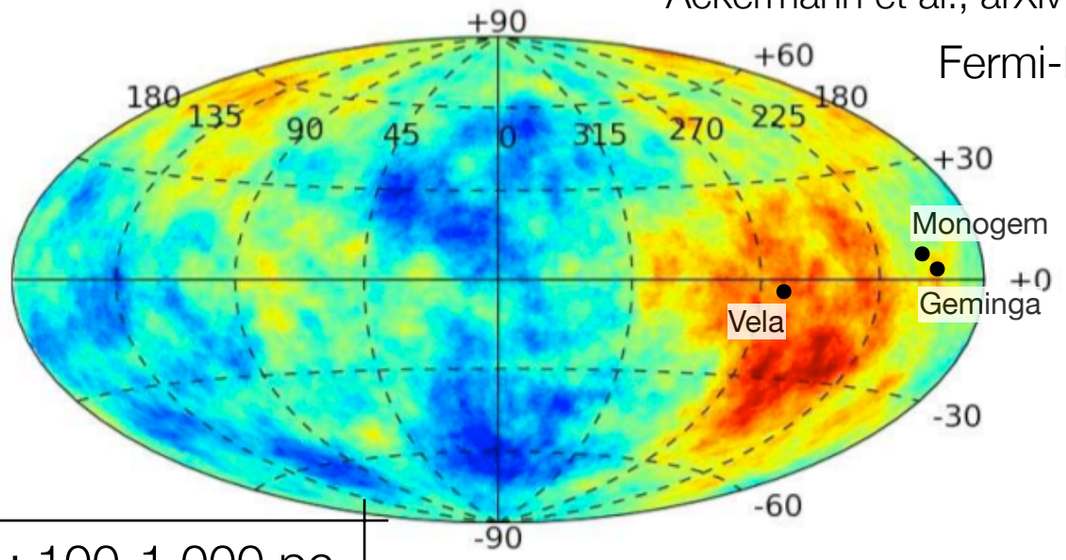

Ackermann et al., arXiv:1008.5119



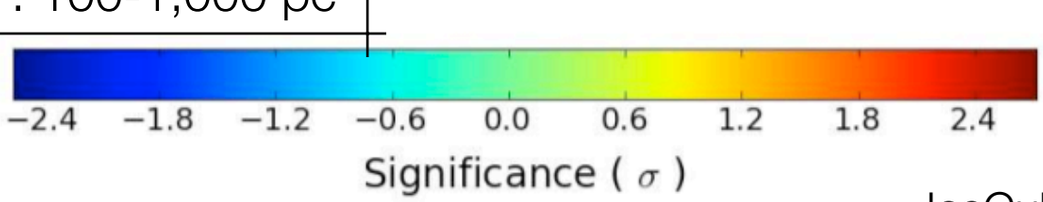
# nearby sources of cosmic rays

Ackermann et al., arXiv:1008.5119

Fermi-LAT

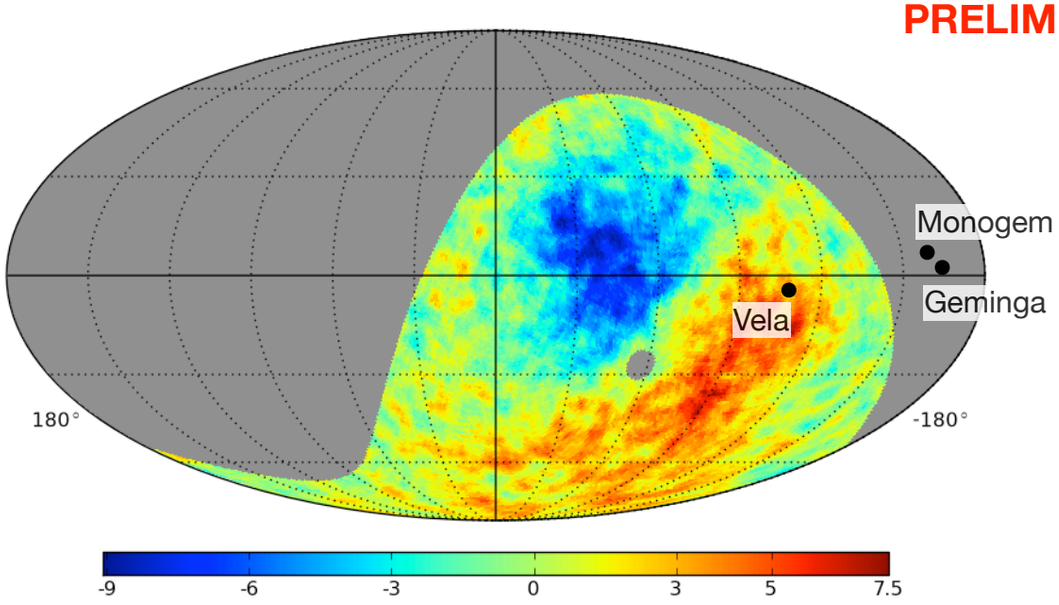



scale : 100-1,000 pc



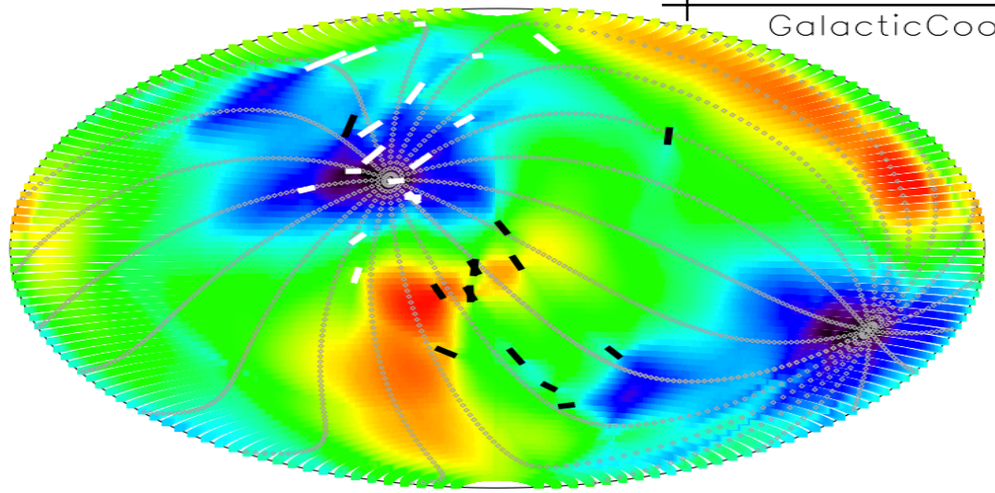

IceCube-40

**PRELIMINARY**



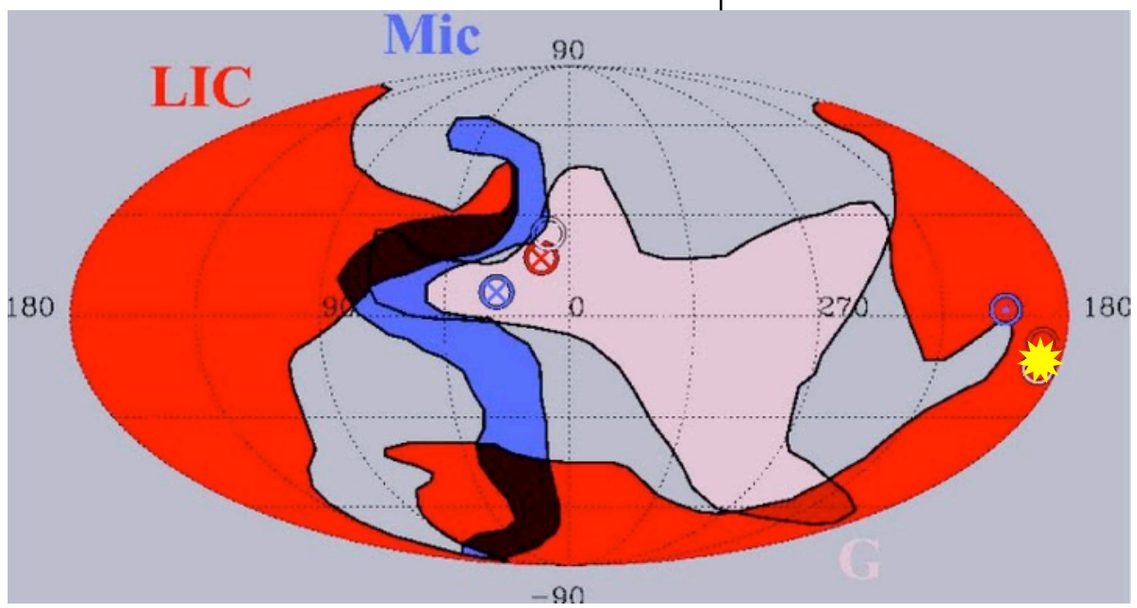

scale : < 40 pc

GalacticCoords



Local Interstellar Magnetic Field

scale : $10^{-3}$-10 pc




Local Interstellar Medium

&

Heliotail

# *large* scale anisotropy

## Tibet-III

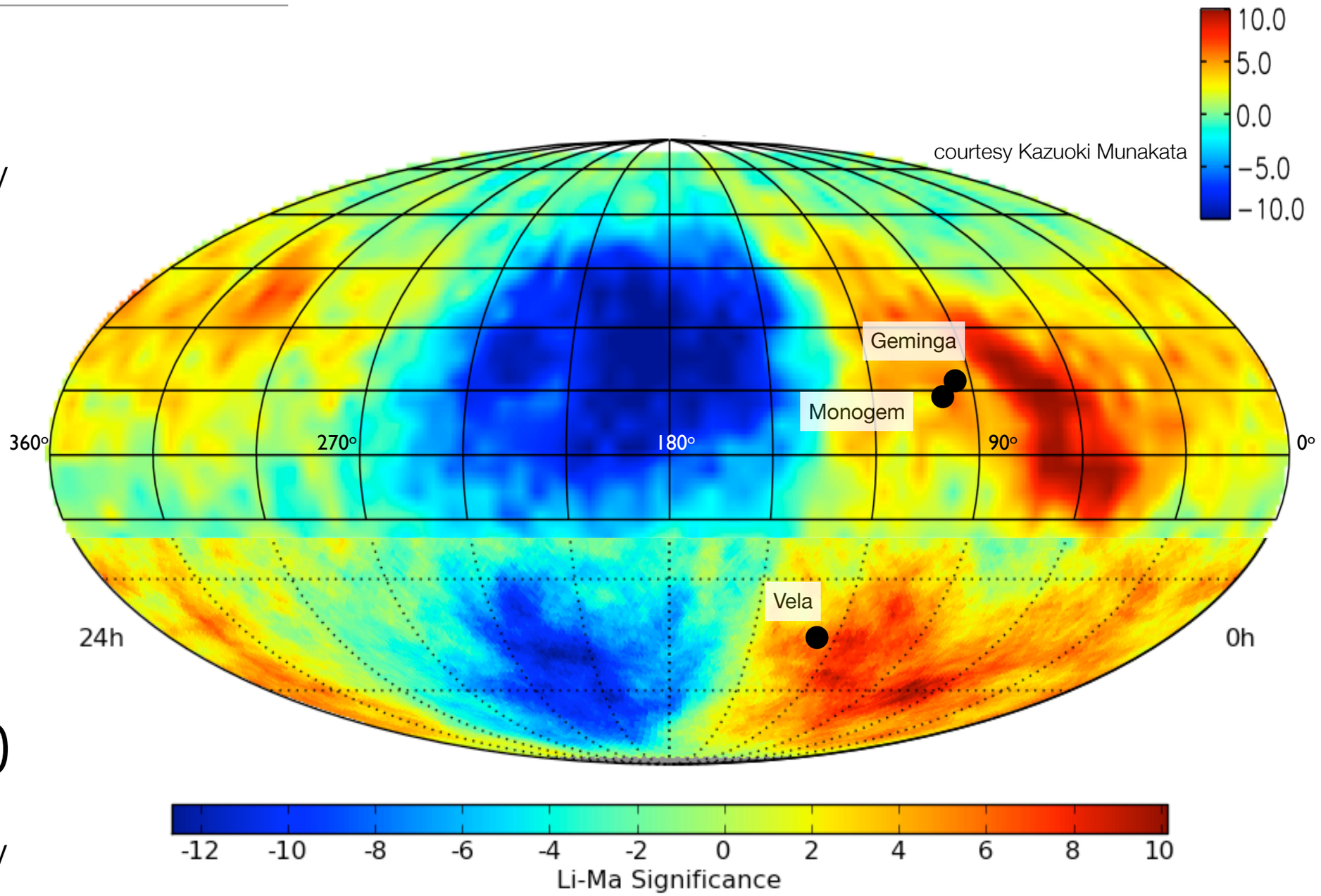
$3.7 \cdot 10^{10}$ events

modal energy ~ 3 TeV

**(5° smoothing)**

PRELIMINARY

courtesy Kazuoki Munakata




## IceCube-40

$12 \cdot 10^{9}$ events

median energy ~ 20 TeV

**(3° smoothing)**

# *medium / small* scale anisotropy

- large scale anisotropy shows smaller angular features, some of which highly significant

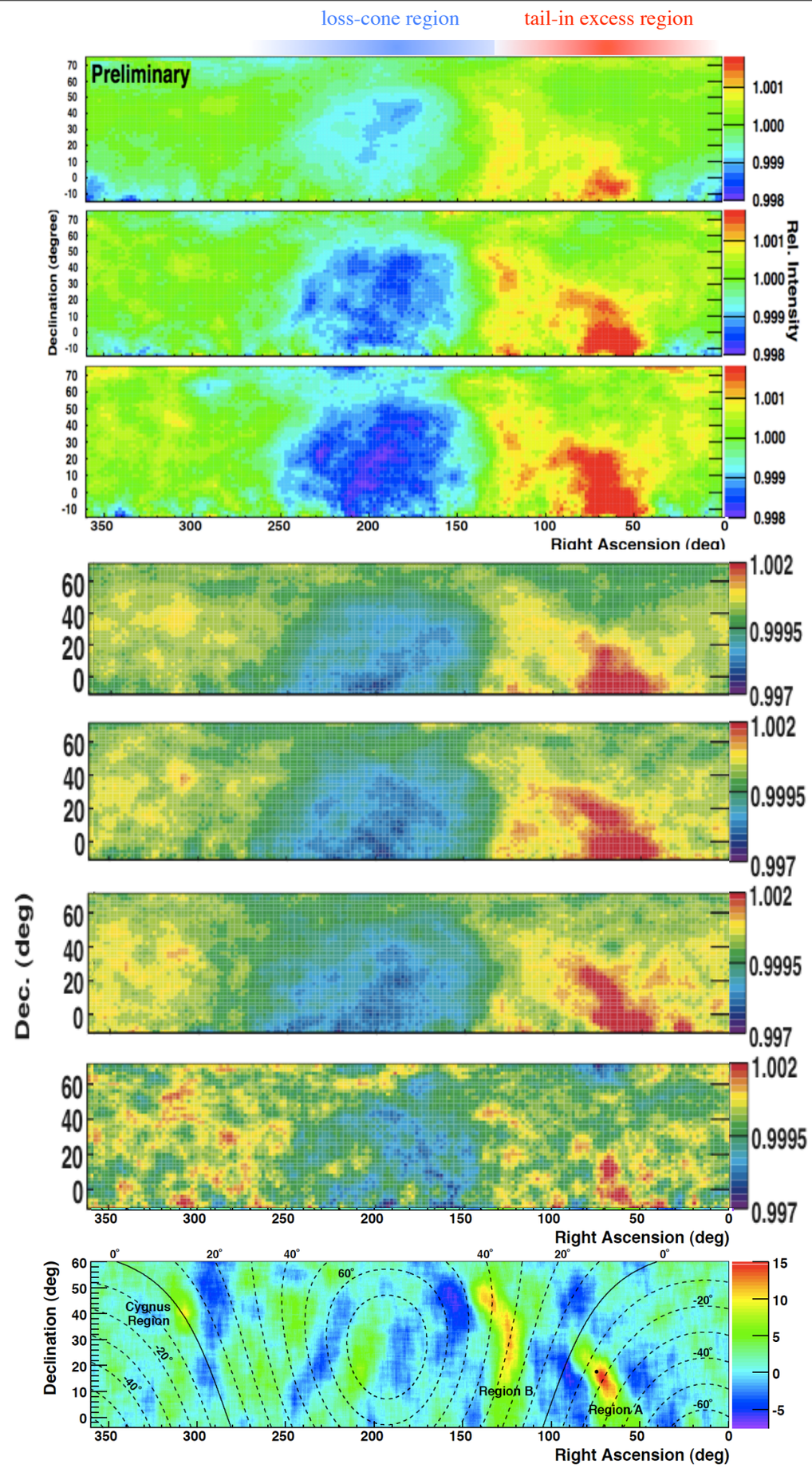
- their origin is unknown

- discovery : if eliminating all angular features > 30° MILAGRO discovered two highly significant localized excess regions

- MILAGRO sky map of statistical significance

- technique used in gamma ray searches

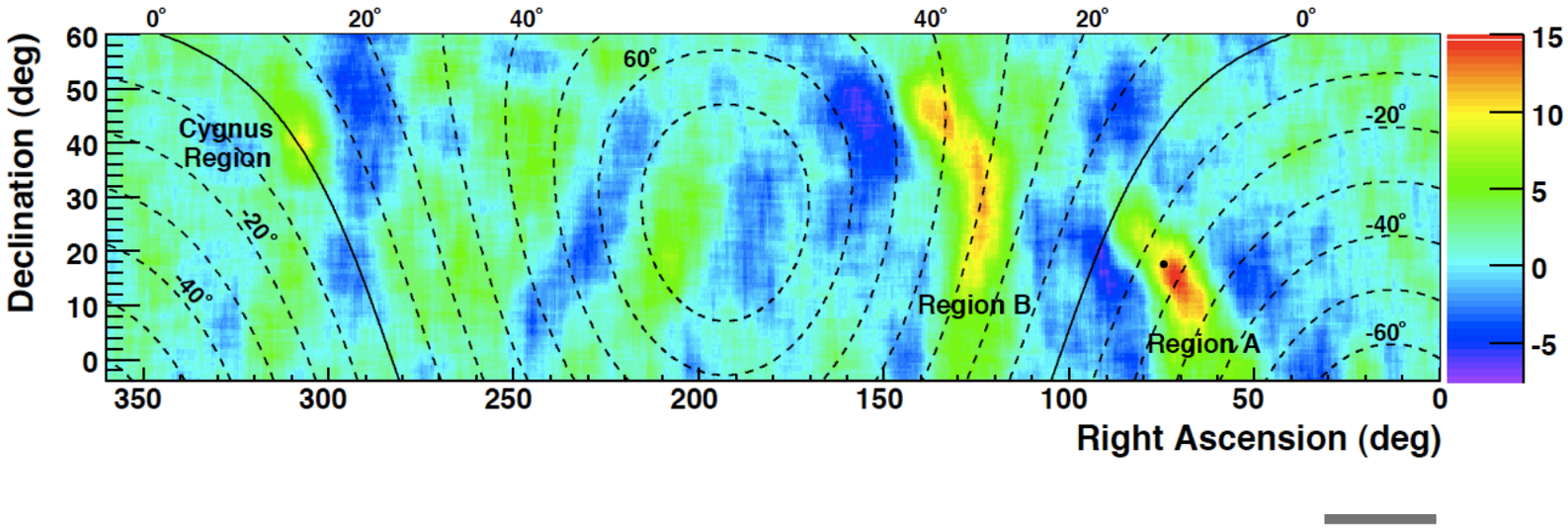
- CR spectrum harder than diffuse < 10 TeV

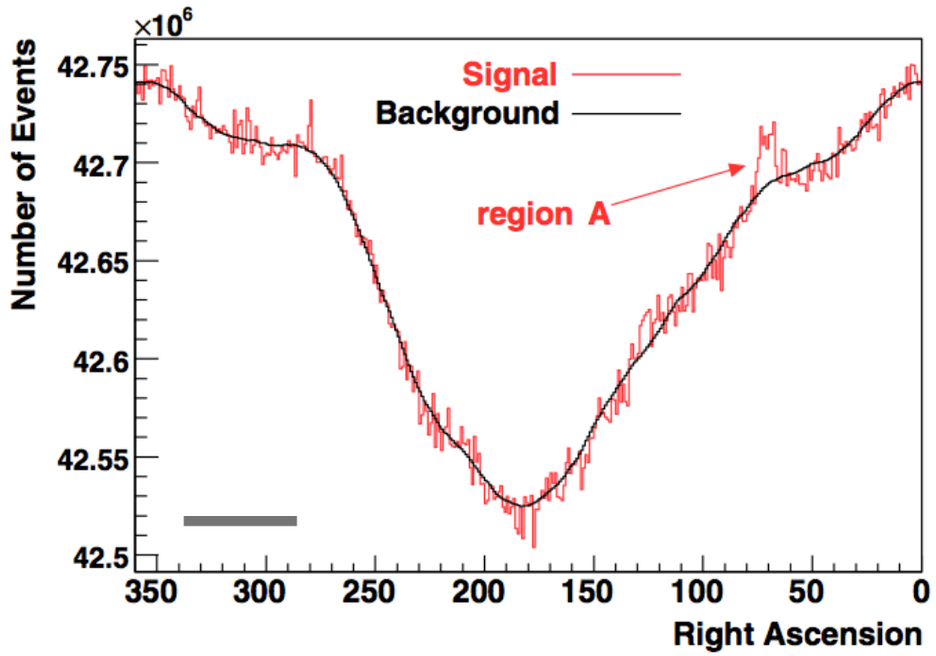



Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

# *medium / small* scale anisotropy

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



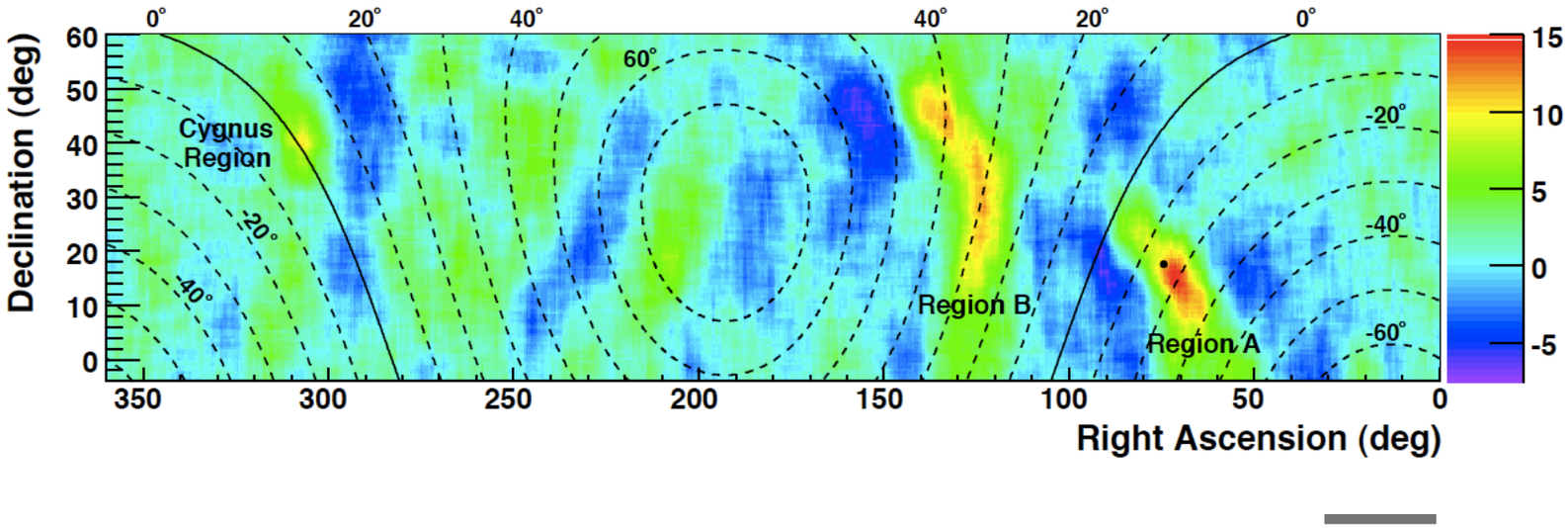

# Milagro

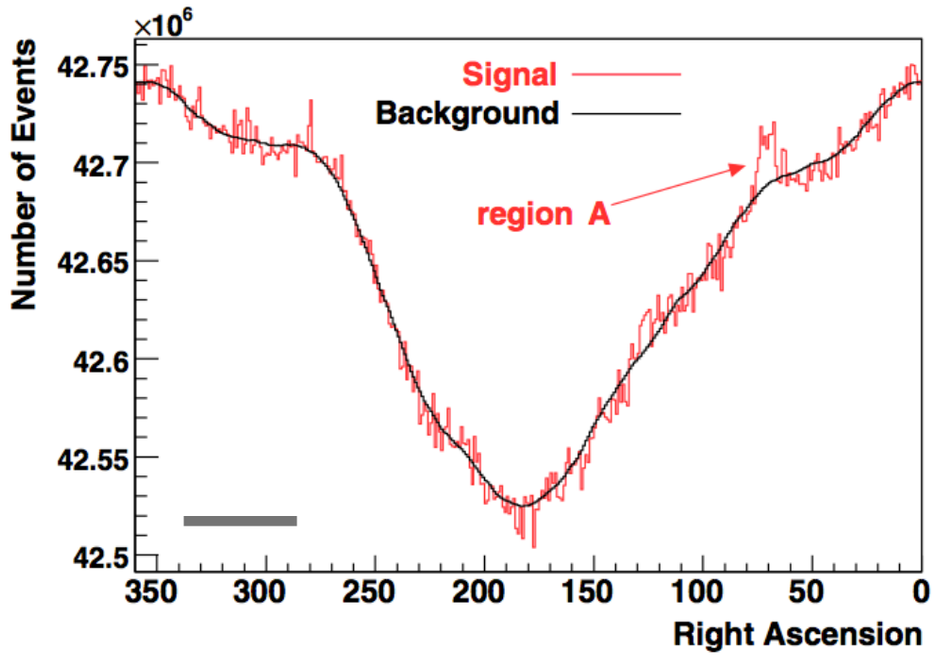
$2.2 \cdot 10^{11}$ events
median CR energy ~ 1 TeV
average angular resolution < 1°

2hr time window
10° smoothing

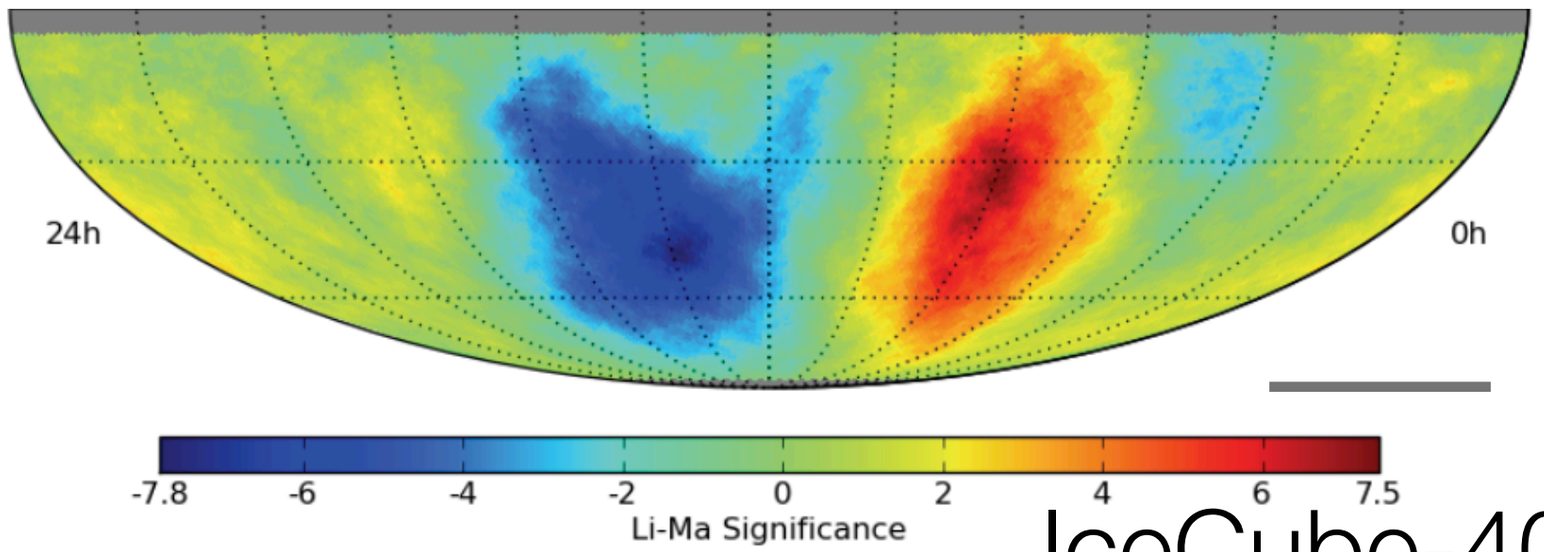
# *medium / small* scale anisotropy

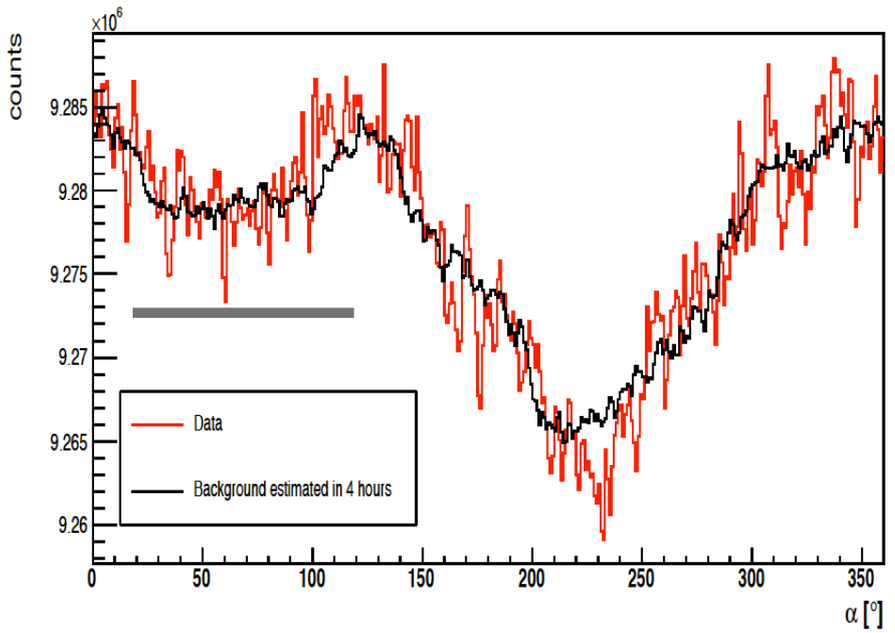
Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101




**PRELIMINARY**



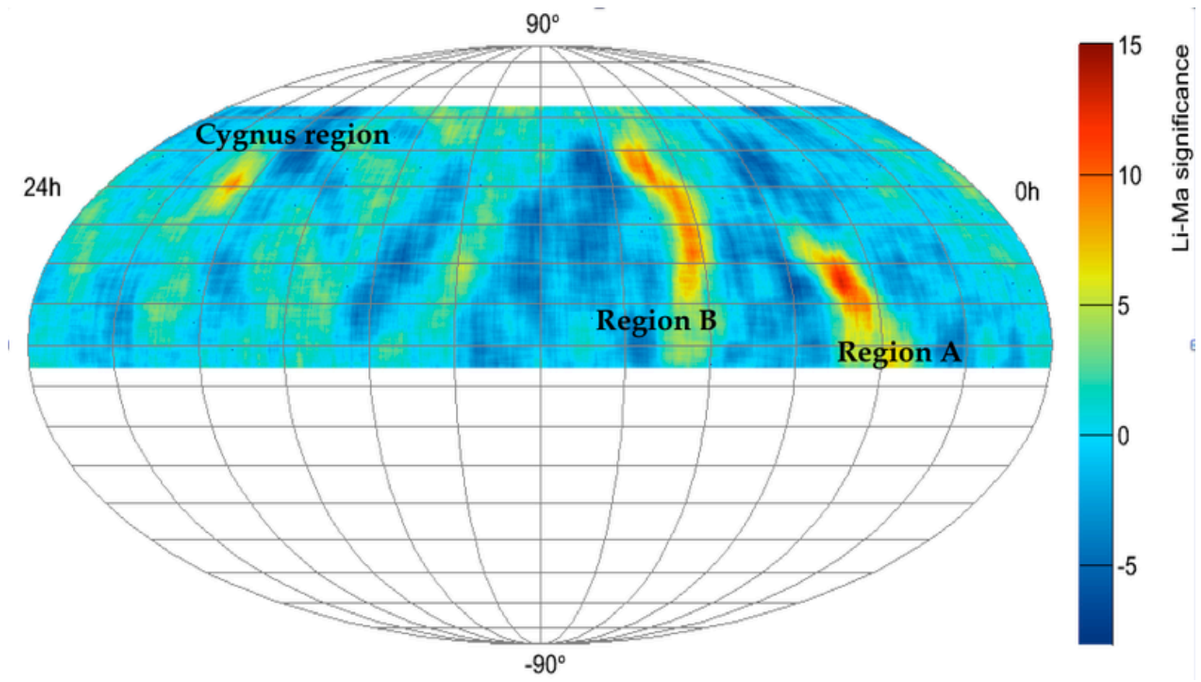




IceCube-40

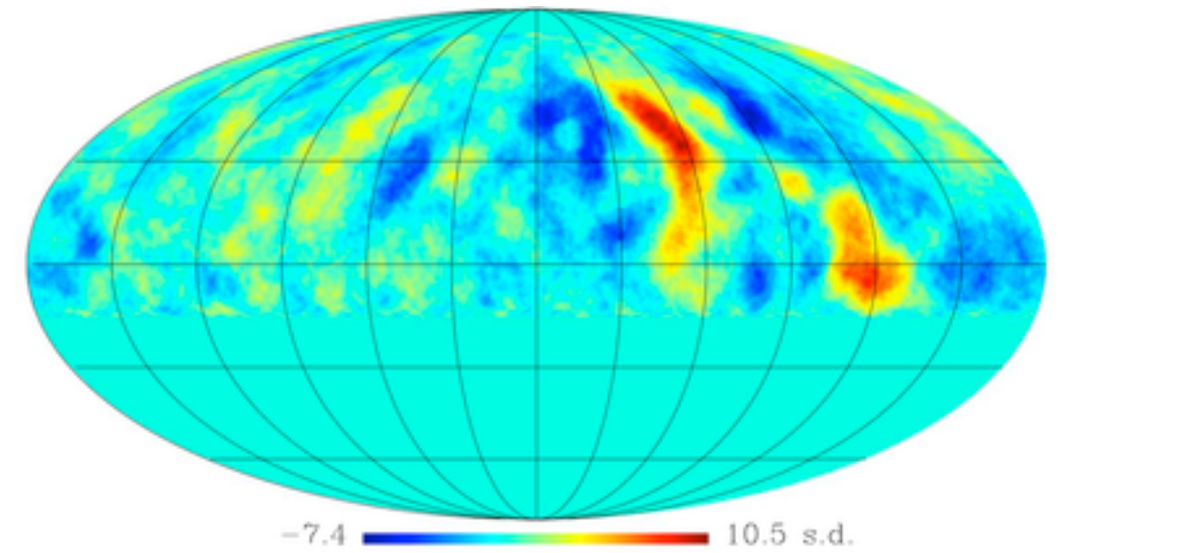
$19 \cdot 10^9$ events
4hr time window
25° smoothing

# *medium / small* scale anisotropy

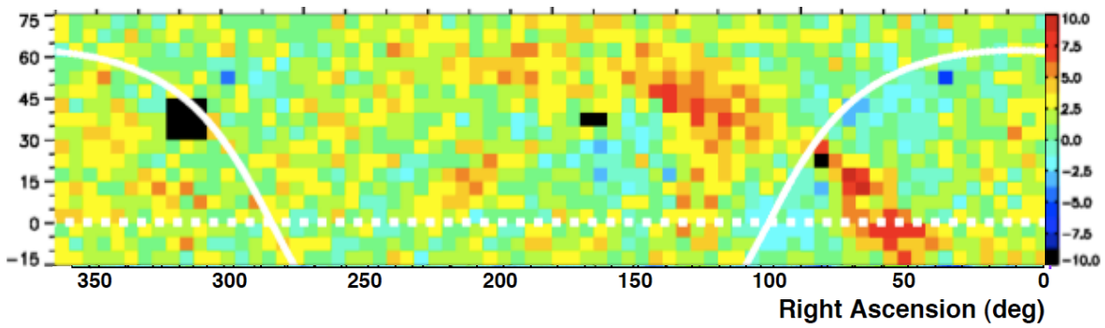
Milagro




ARGO-YBJ




Tibet-III



# *medium / small* scale anisotropy

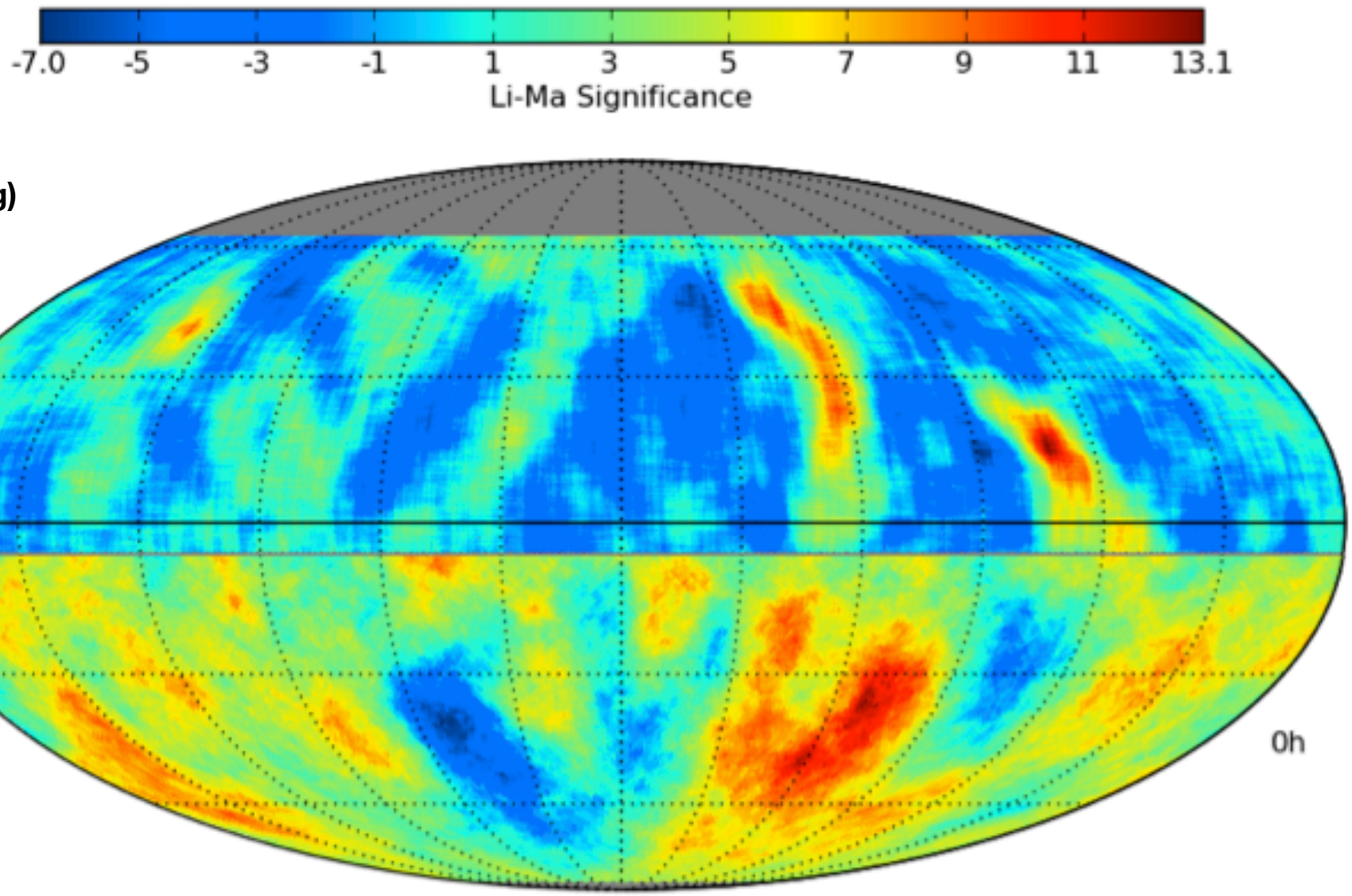
PRELIMINARY

## Milagro

$2.2 \cdot 10^{11}$ events

median energy ~ 1 TeV

**(2 hr integration ~ 30° cut-off,10° smoothing)**




## IceCube-40

$19 \cdot 10^{9}$ events

median energy ~ 20 TeV

**(4 hr integration ~ 60° cut-off,10° smoothing)**

equatorial coordinates

# *medium / small* scale anisotropy

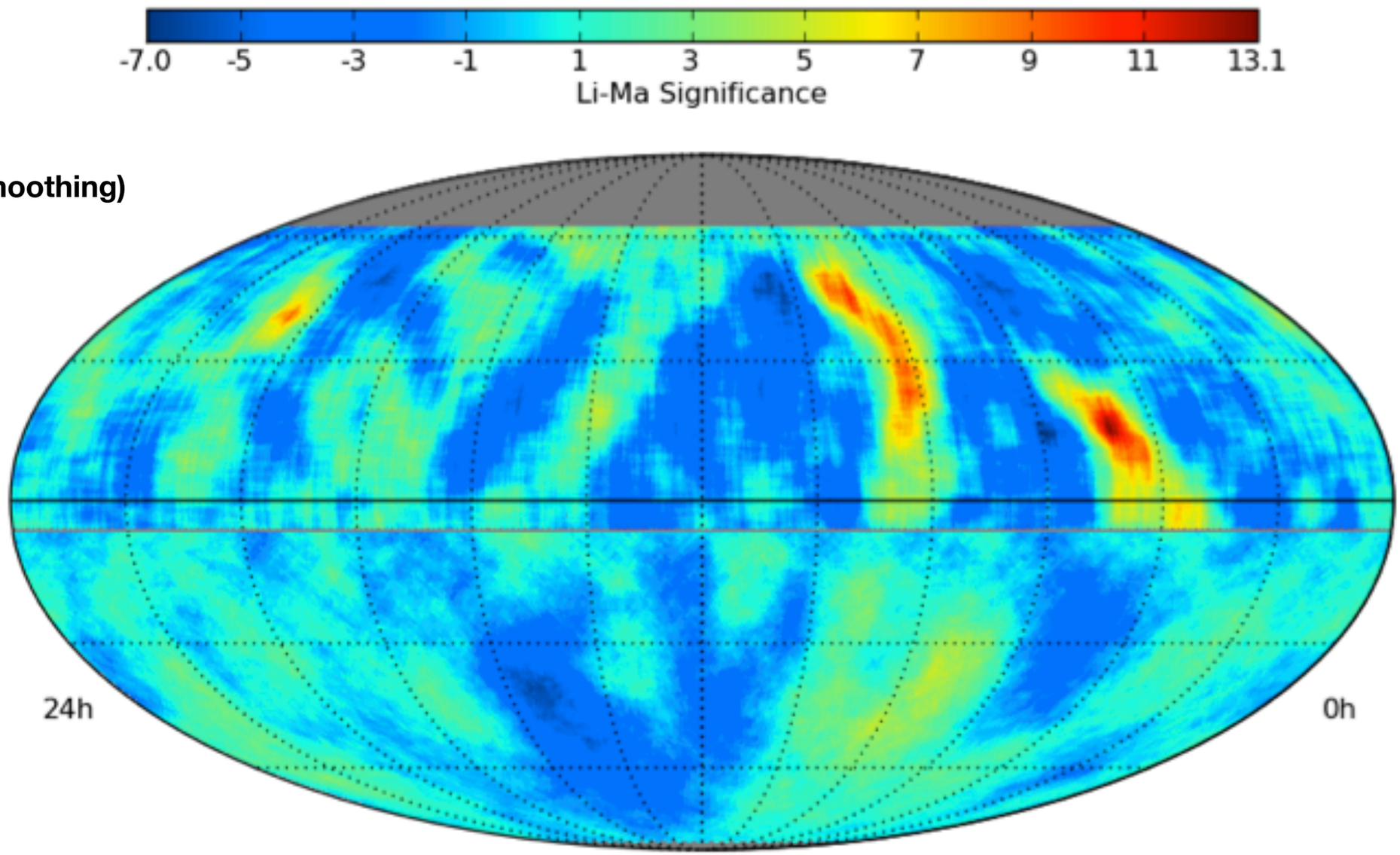
PRELIMINARY

## Milagro

$2.2 \cdot 10^{11}$ events

median energy ~ 1 TeV

**(2 hr integration ~ 30° cut-off,10° smoothing)**

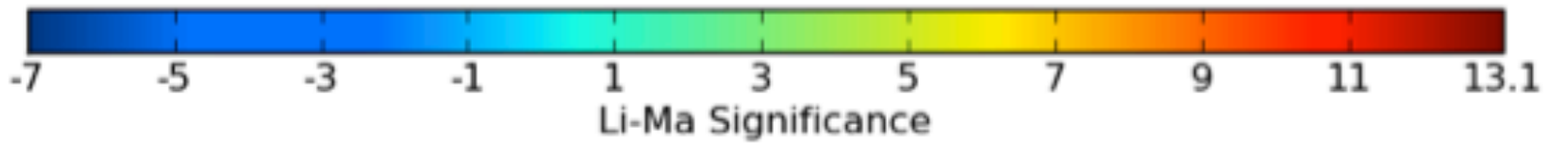



## IceCube-40

$12 \cdot 10^{9}$ events

median energy ~ 20 TeV

**(4 hr integration ~ 60° cut-off,10° smoothing)**




equatorial coordinates

# origin of small scale anisotropy : CR source

Salvati & Sacco, arXiv:0802.2181

Drury & Aharonian, Astropart. Phys. 29, 420, arXiv:0802.4403

Salvati, Astron. & Astrophys. arXiv:1001.4947

- galactic cosmic ray accelerator (Salvati & Sacco)
  - Geminga (~155 pc) was closer 340,000 yr ago : ~90 pc
  - Bohm diffusion of 10 TeV ~ 65 pc
  - if turbulence frac. excess compatible with $\sim 1.5 \cdot 10^{49}$ erg
  - energy passband (cutoff HE, delays LE) ~ hard spectrum
- magnetic nozzle (Drury & Aharonian)
  - to avoid large angular scale of excess
  - CR freely propagating through magnetic nozzle
  - but direction to Geminga is $\perp$ galactic magnetic field

# origin of small scale anisotropy : IS magnetic field turbulence

Malkov et al., arXiv:1005.1312

- anisotropic MHD turbulence in the ISM

  - pitch angle scattering peaked near the direction of magnetic field ( $k_\perp R_g(p_\perp) \lesssim 1$ )

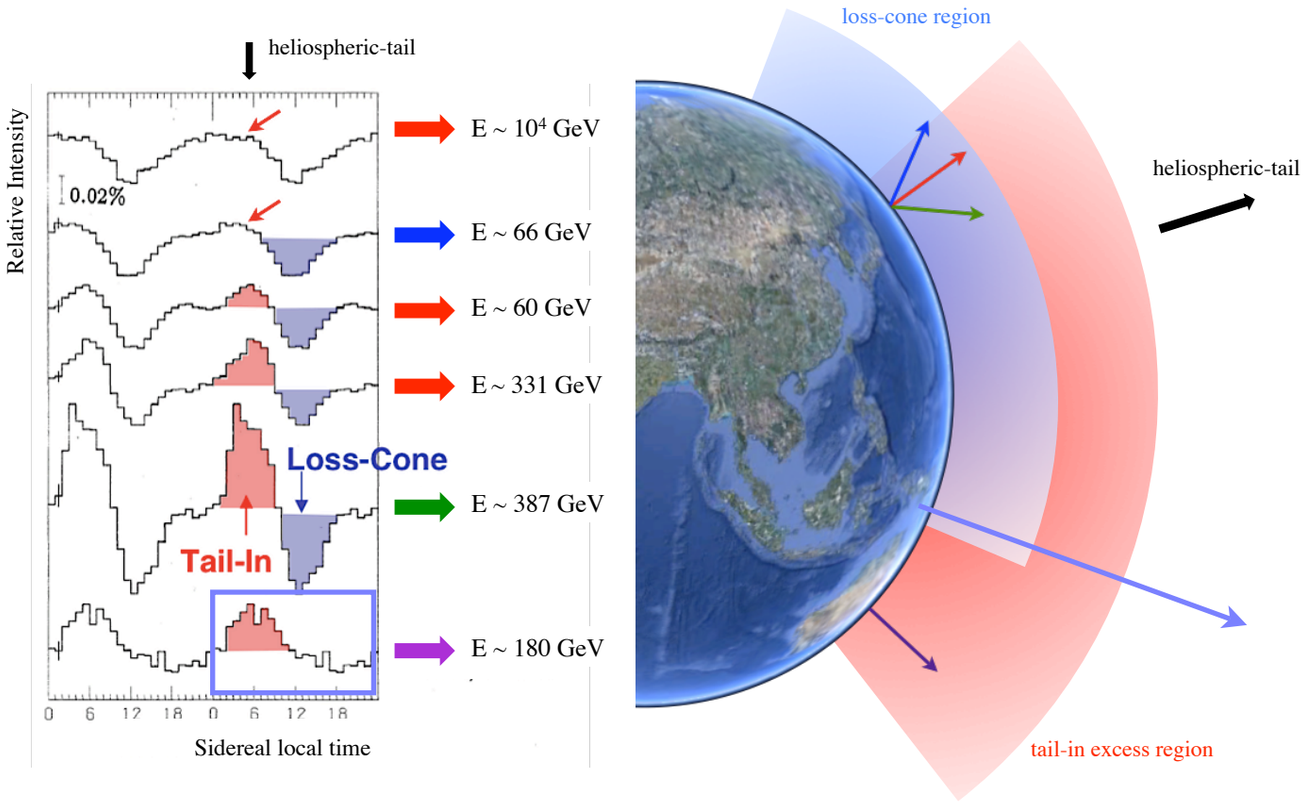
  - the large scale anisotropy is “perturbed” by faint beam of collimated particles along the “magnetic” tube that connects to the source

  - outer scale of perturbation determines beam angular width and strength ( $\propto R_g(p)/l_{scale}$ )

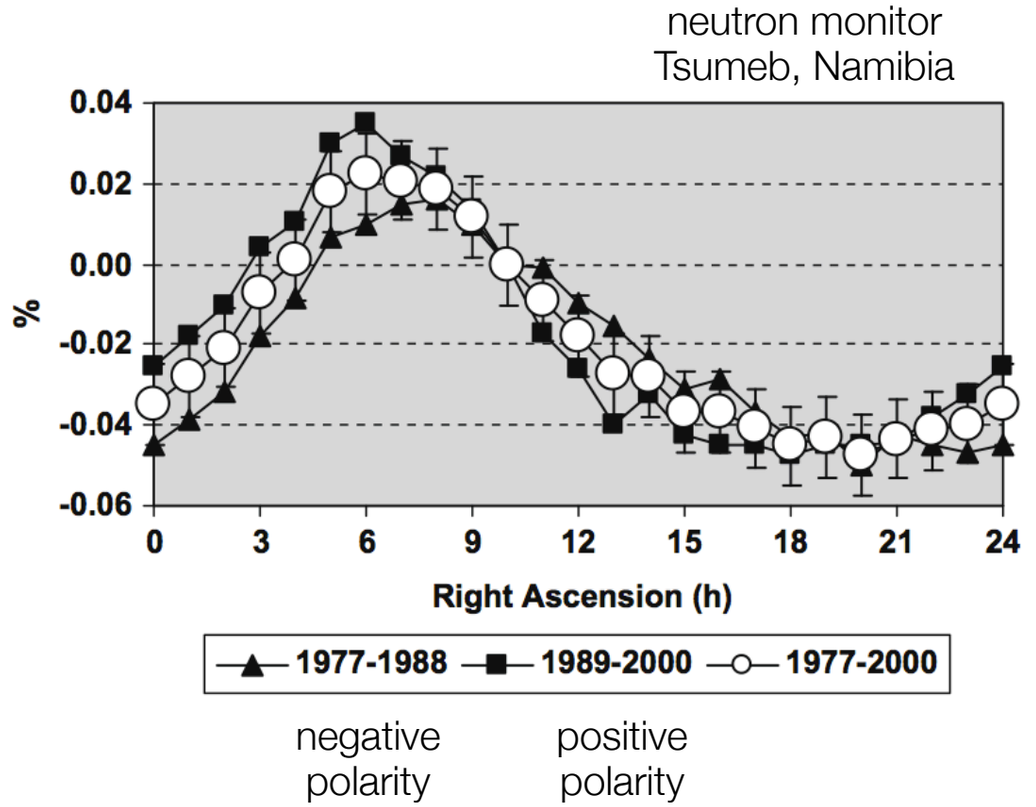
  - $l_{scale}$ ~ 1 pc/B(μG) : consistent with MILAGRO angular width, excess and max energy of region A

  - sources responsible of the beam must be within a few 100’s pc

# origin of small scale anisotropy : heliospheric tail



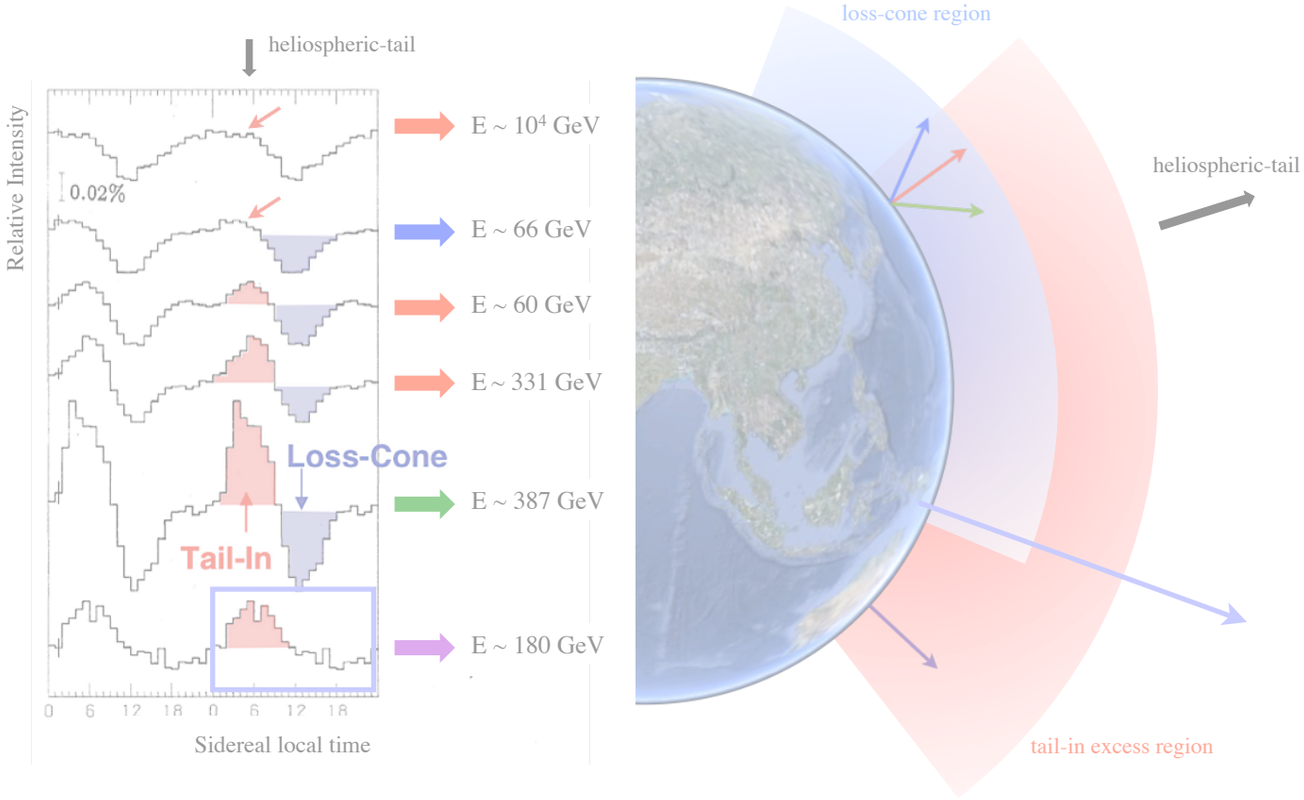

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)



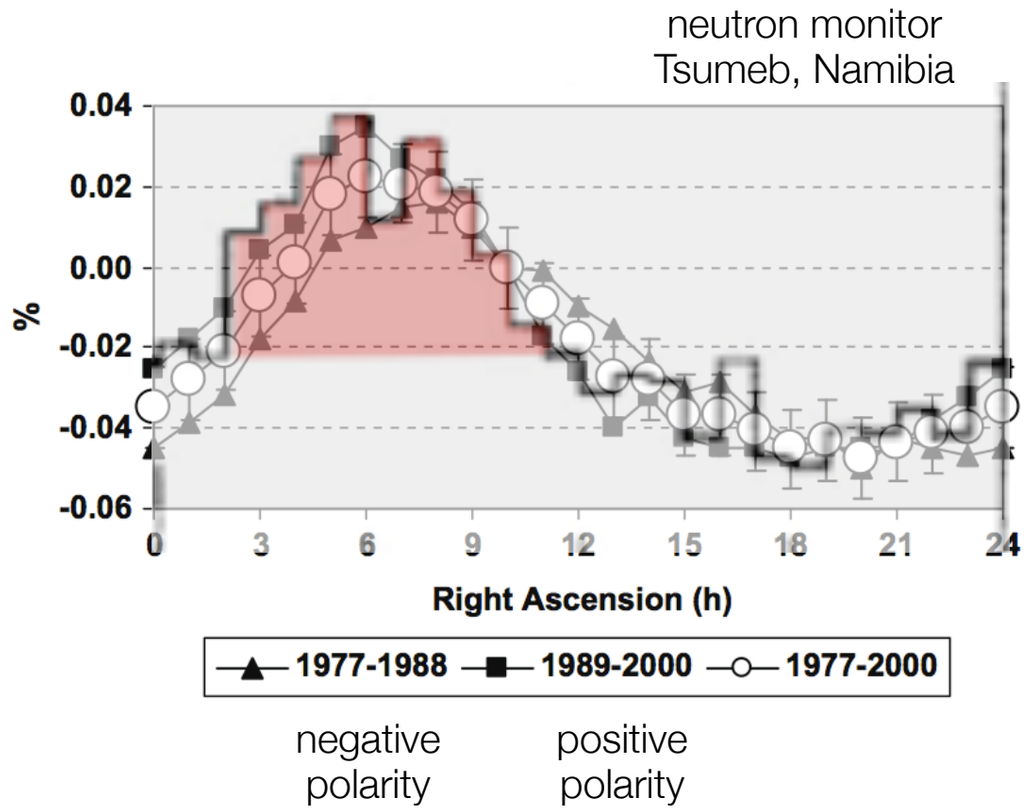

Karapetyan, Astrop. Phys., 33, 146, 2010

- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail

# origin of small scale anisotropy : heliospheric tail



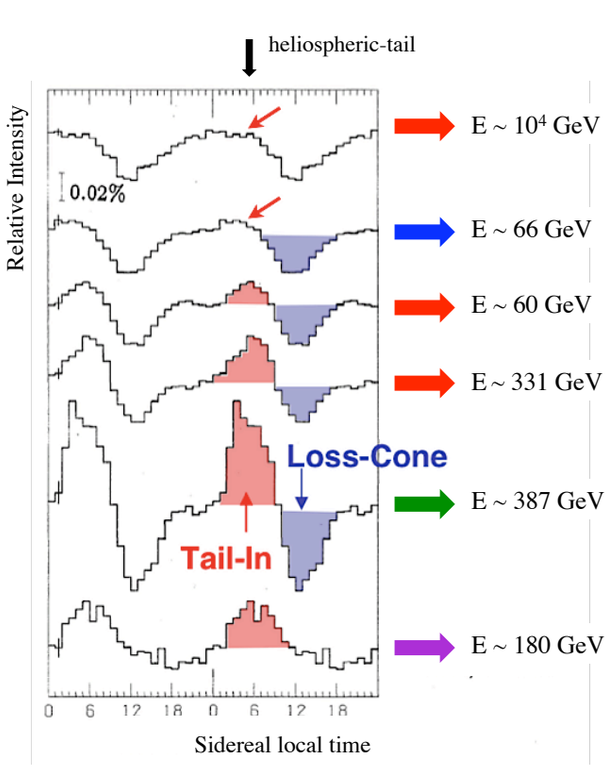

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)

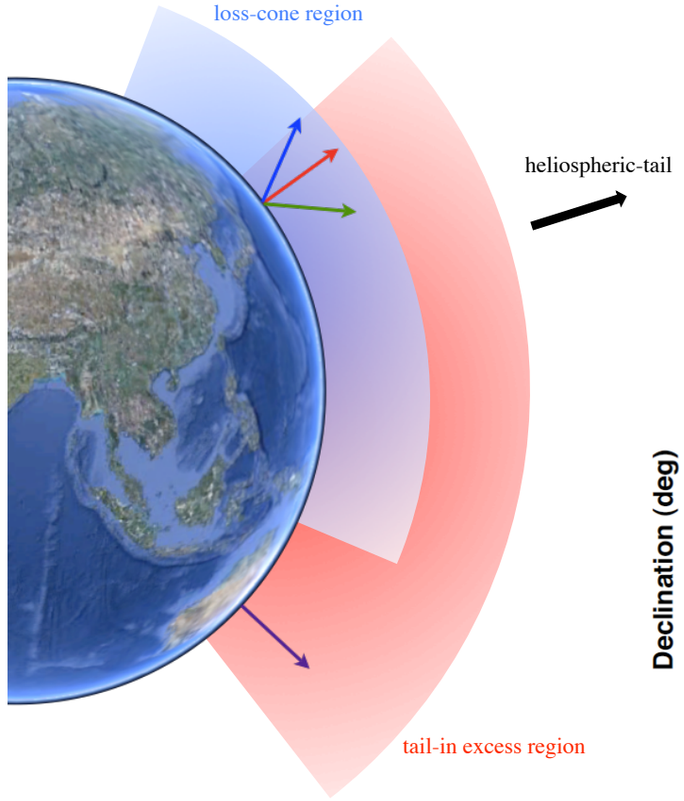


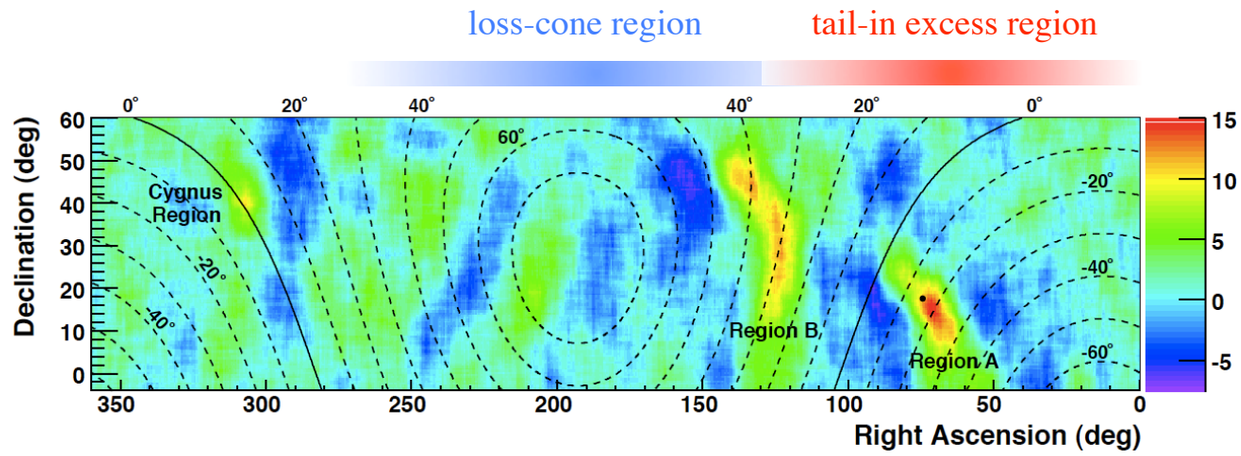

Karapetyan, Astrop. Phys., 33, 146, 2010

- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail
- solar magnetic field reversal should affect galactic anisotropy
- origin of excess is “heliospheric”

# origin of small scale anisotropy : heliospheric tail




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

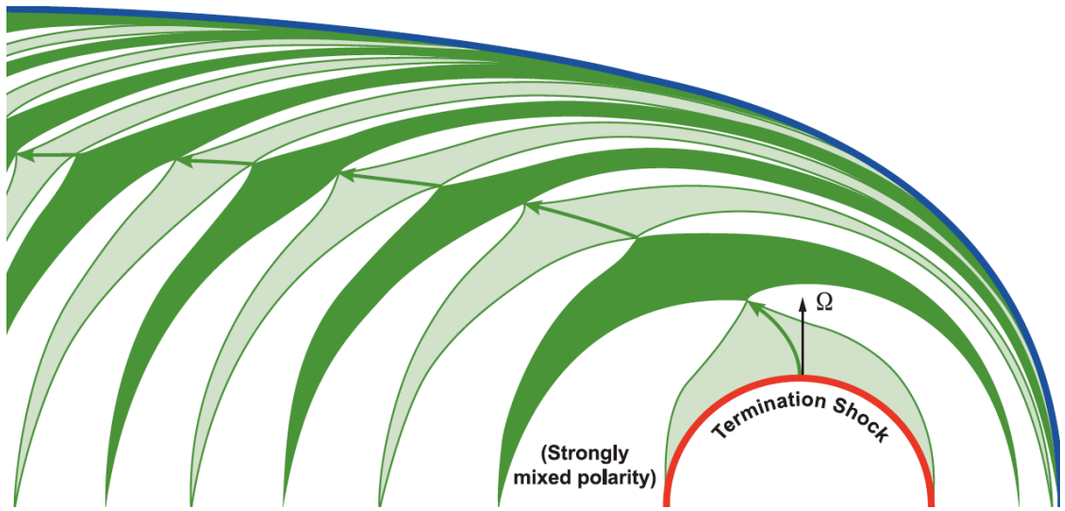
Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

- localized excess of multi-TeV cosmic trays from the direction of the heliotail
- medium/small scale modulation to be connected to nearby perturbations
- first-order acceleration in magnetic reconnection regions in the heliotail

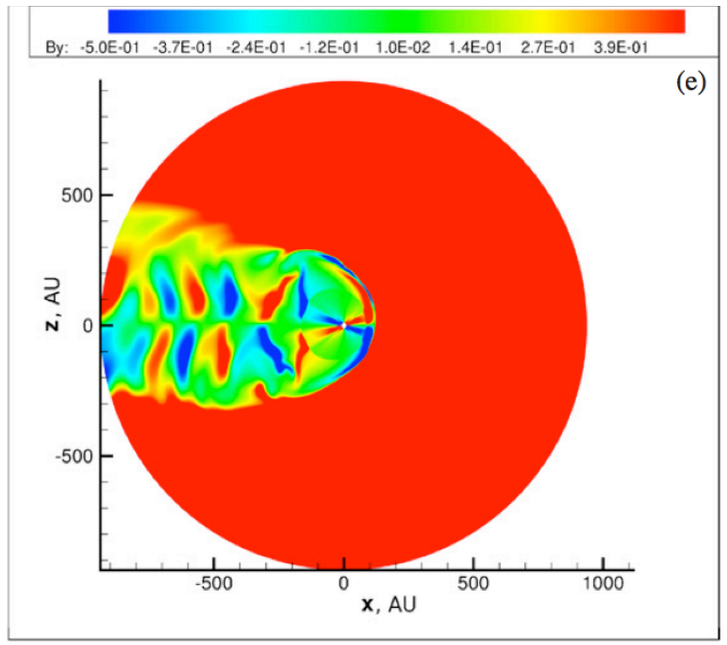
# origin of small scale anisotropy : heliospheric tail

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

Lazarian & Desiati, ApJ, 722, 188, 2010




Pogorelov et al., ApJ, 696, 1478, 2009

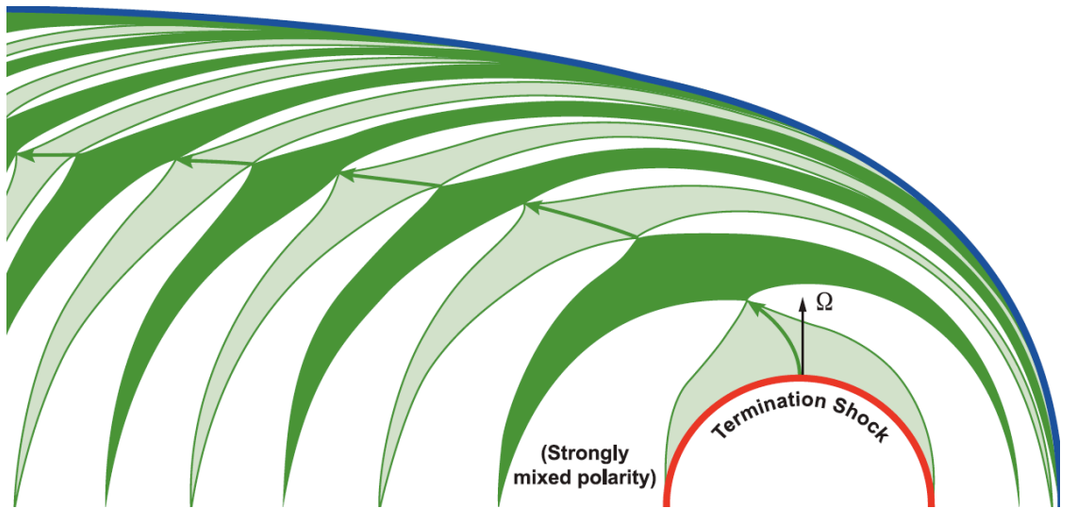


# origin of small scale anisotropy : heliospheric tail

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

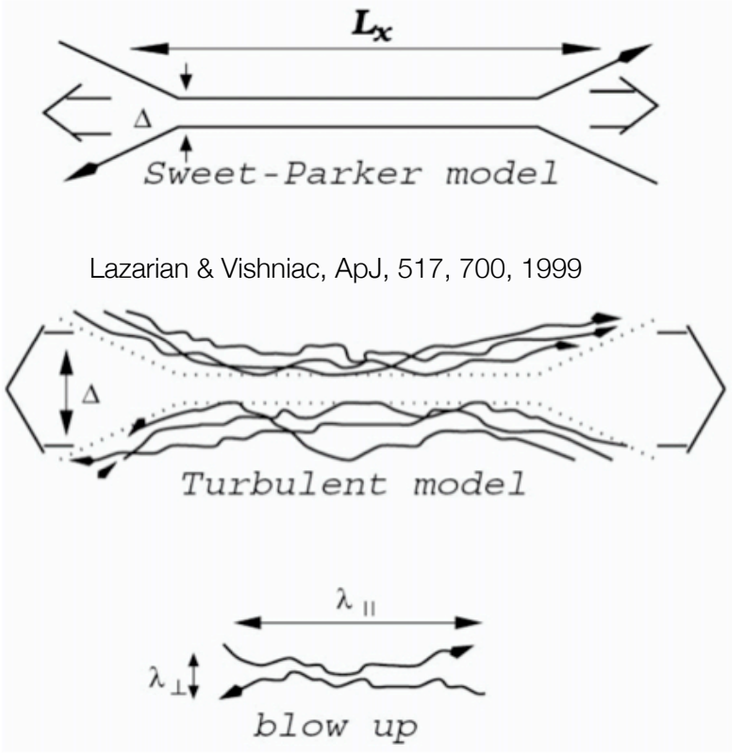
- turbulence makes reconnection fast and not affected by ohmic dissipation

Lazarian & Desiati, ApJ, 722, 188, 2010




Sweet, IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics, 123, 1959.

Parker , J. Geophys. Rev., 62, 509, 1957



# origin of small scale anisotropy : heliospheric tail

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

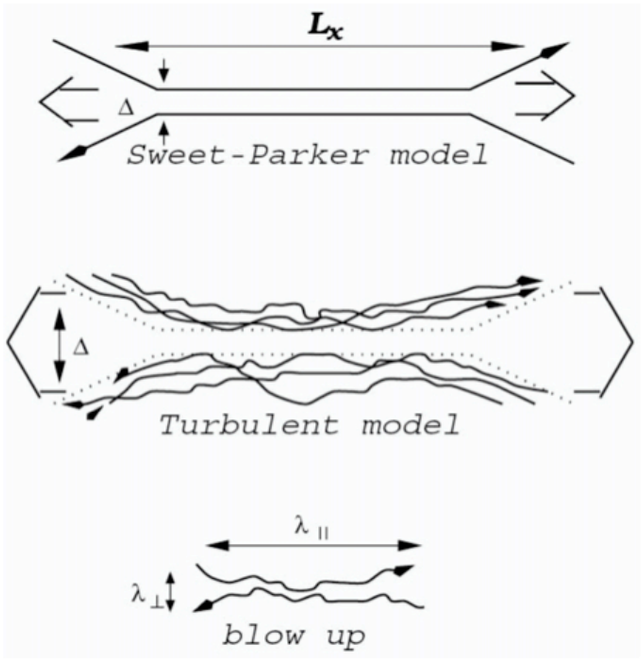
- turbulence makes reconnection fast and not affected by ohmic dissipation

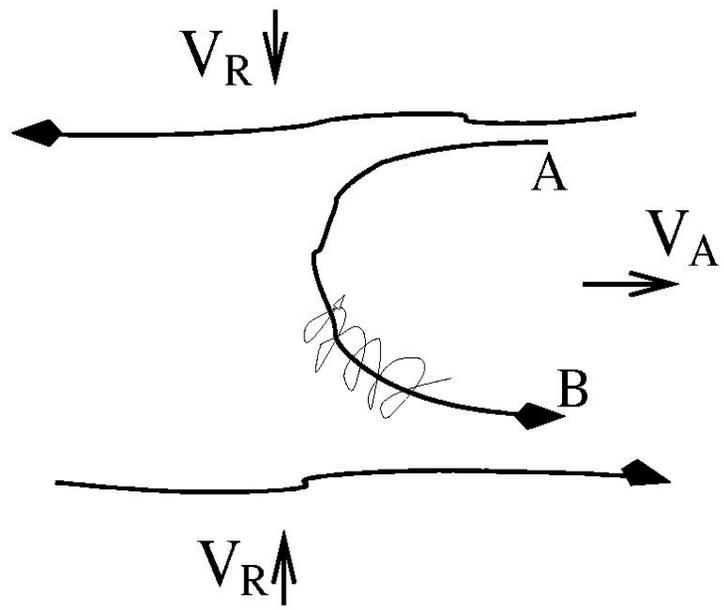
- magnetic mirror @ reconnection as site of acceleration

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

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

Lazarian & Desiati, ApJ, 722, 188, 2010



# conclusions … to start with

- cosmic ray anisotropy has been observed from ~10 GeV to ~100 TeV
  - large scale structure with fine structures at high energy
- origin unknown: probably related to our local galactic environment
- a nearby SRN may induce a large scale anisotropy: spectral features ?
- small/medium scale anisotropy to be sensitive to distance scale of the effect
- IceCube performing :
  - *energy dependence of anisotropy: magnetic fields, interstellar medium*
  - *angular power spectrum of anisotropy: distance scale*