Galactic Cosmic-ray Anisotropy with Tibet air shower array

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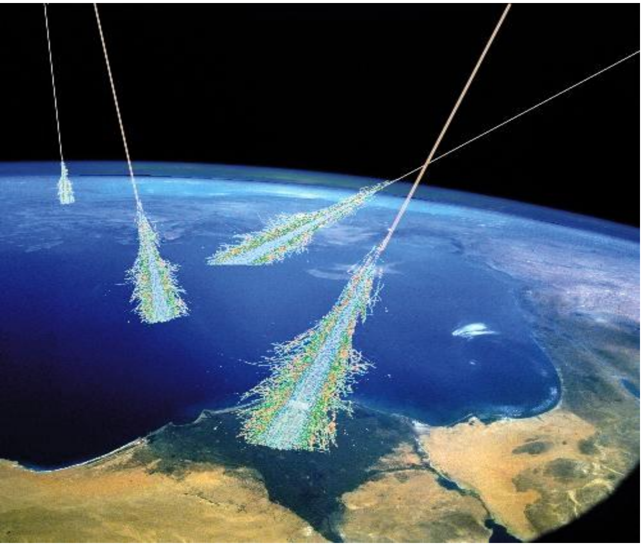
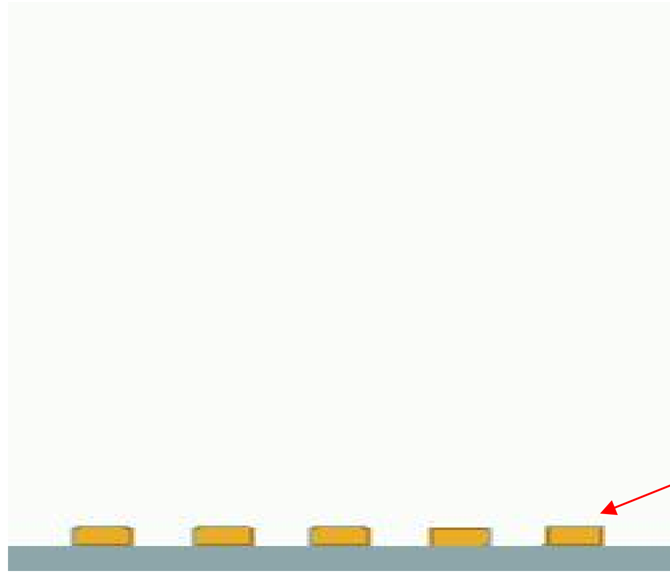
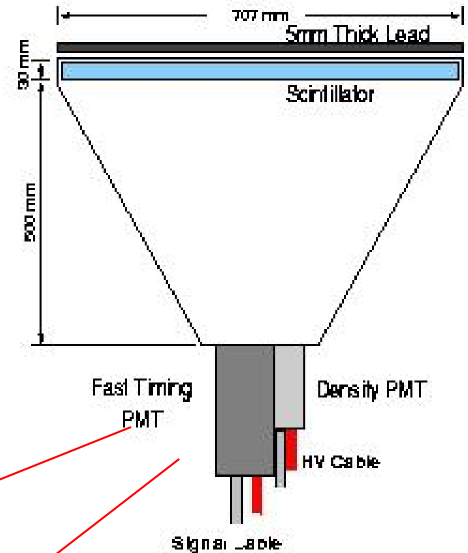
首届LHAASO合作组会议, 2016.8,南开

Yangbajing Observatory

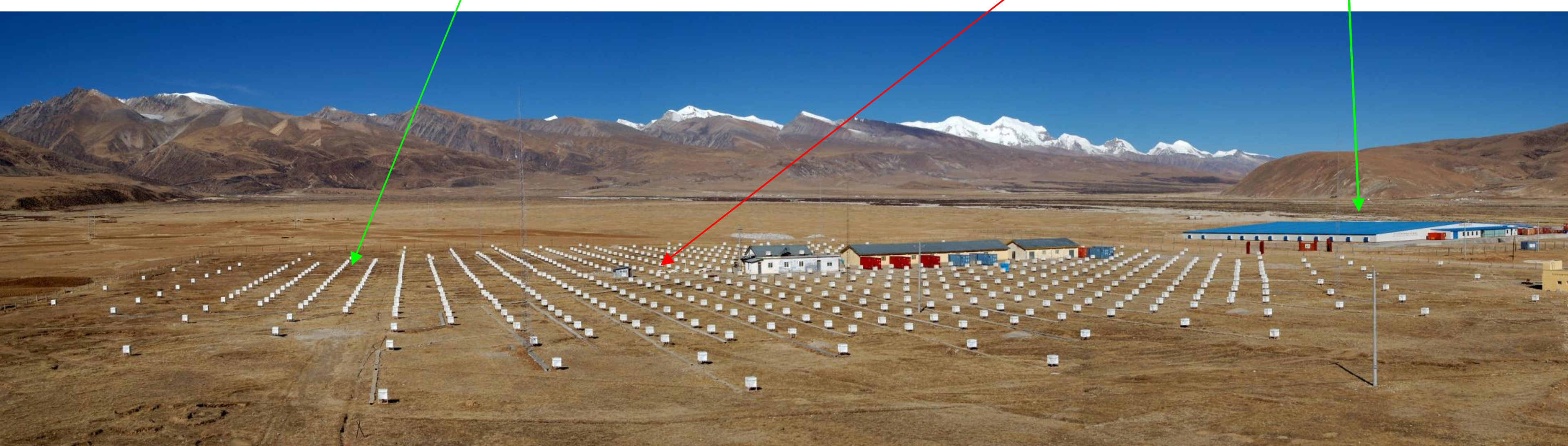






Tibet ASγ array

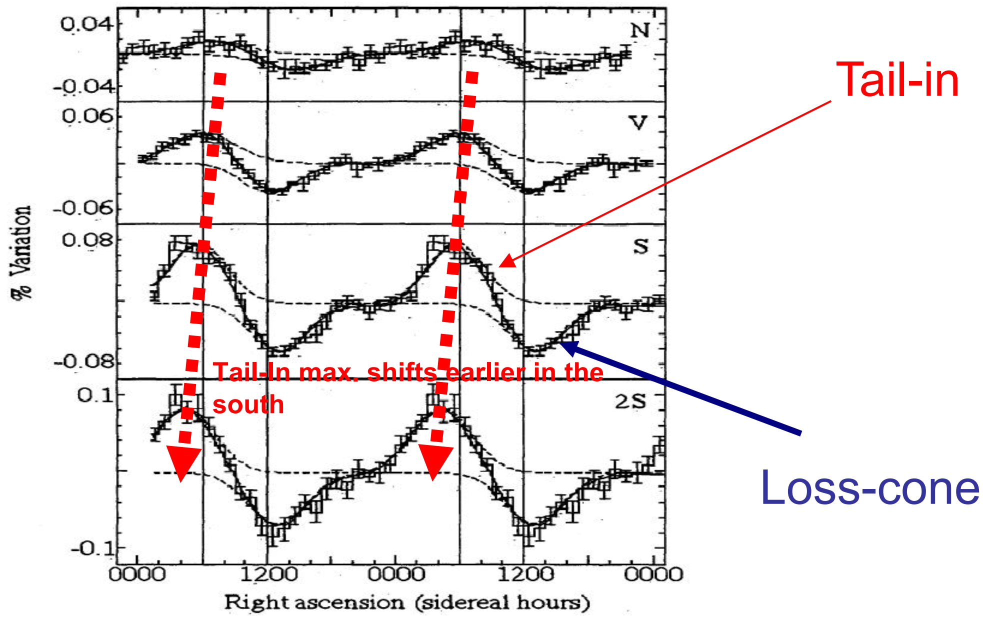
ARGO Hall



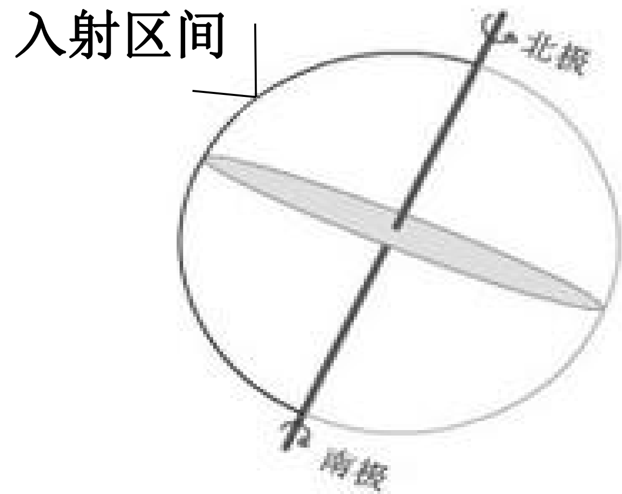
OUTLINE

- 大尺度宇宙线各向异性的观测
  - 各向异性的大尺度结构
  - 各向异性的能量依赖
  - 各向异性的时间演化
- 大尺度宇宙线各向异性的模型
  - **Compton-Getting effect**
  - **Stochastic supernova explosions**
  - **Local Interstellar Magnetic Cloud**
  - 宇宙线各向异性与银晕磁场
- Summary

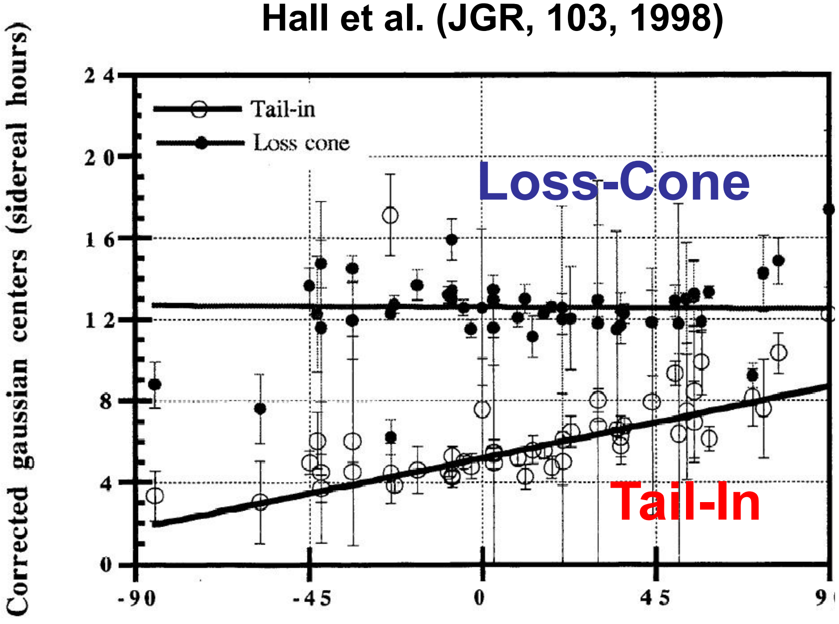
宇宙线各向异性的一维观测



Hall et al. (JGR, 103, 1998)

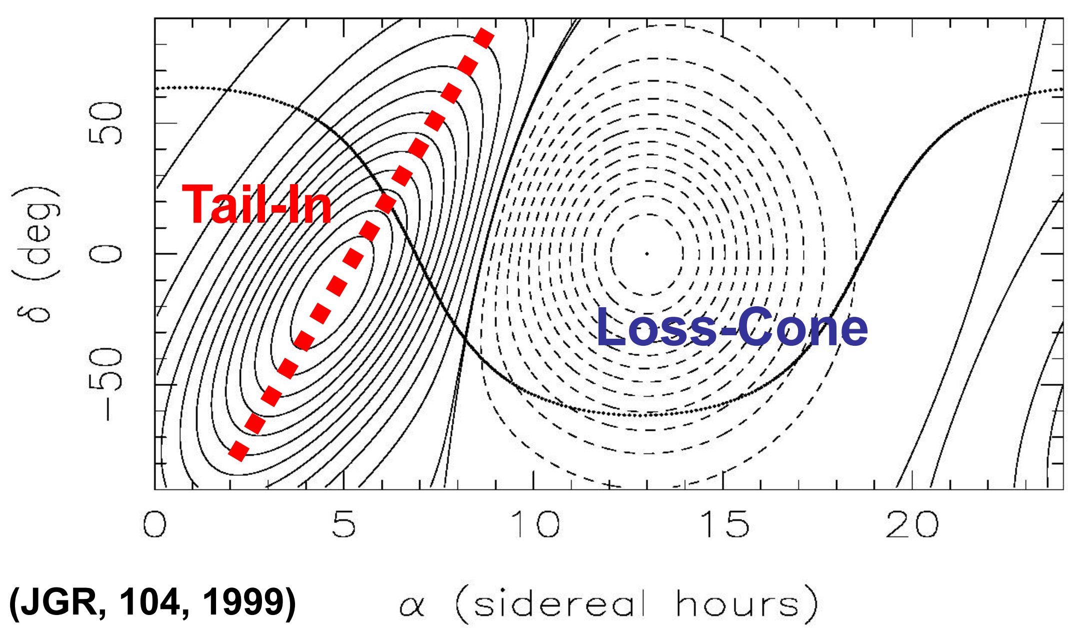


NFJ model

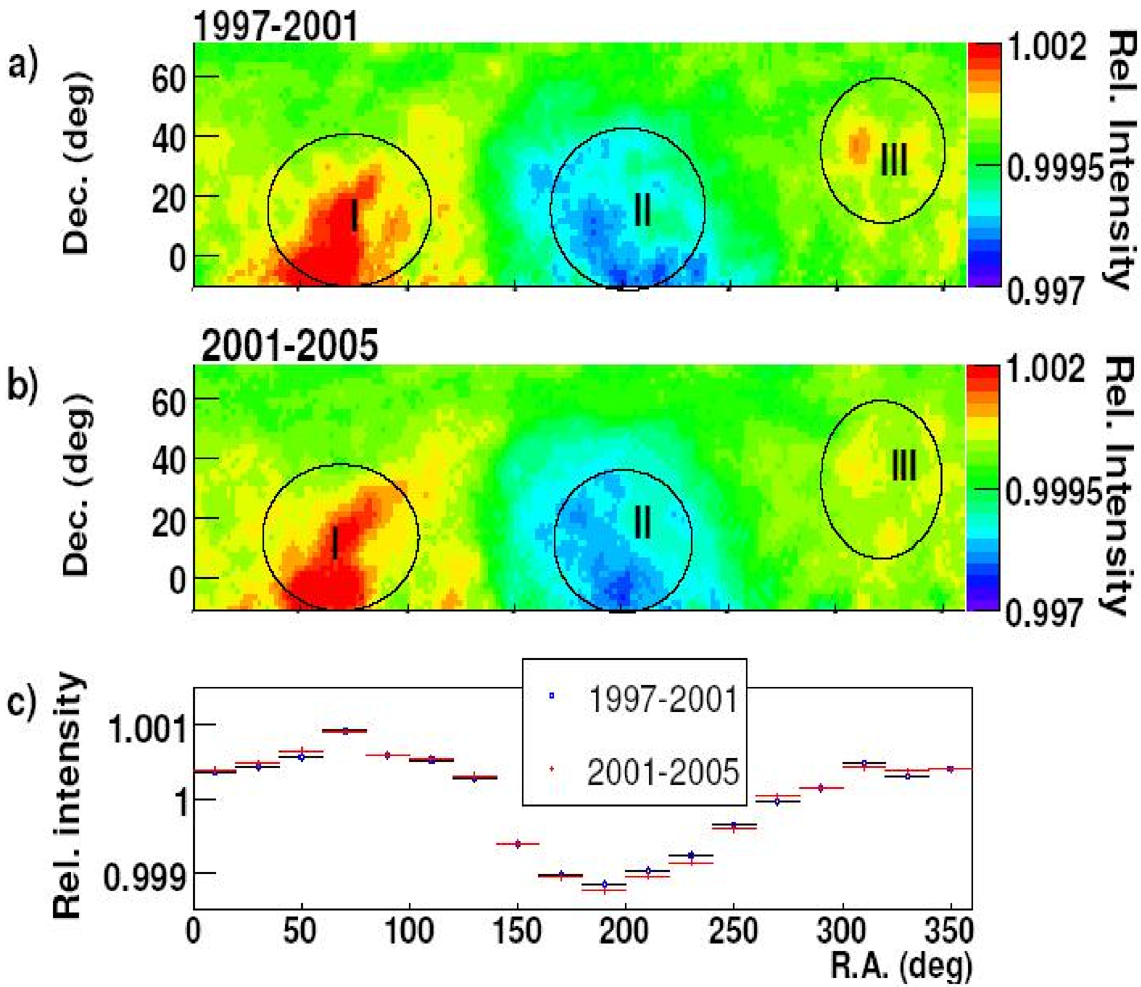


Hall et al. (JGR, 104, 1999)

Percent anisotropy at 500 GV



Tibet measurement in two dimensions



The CR anisotropy is fairly stable in two samples.

Three Componets：
I--------Tail-in;
II-------Loss-cone
III------Cygnus region；

data from 1997 to 2005

1874 days livetime

$3.7 \cdot 10^{10}$ events

angular resolution ~ 0.9°

modal CR energy ~ 3 TeV

一个实验代替多个实验，验证了一维观测的结构。

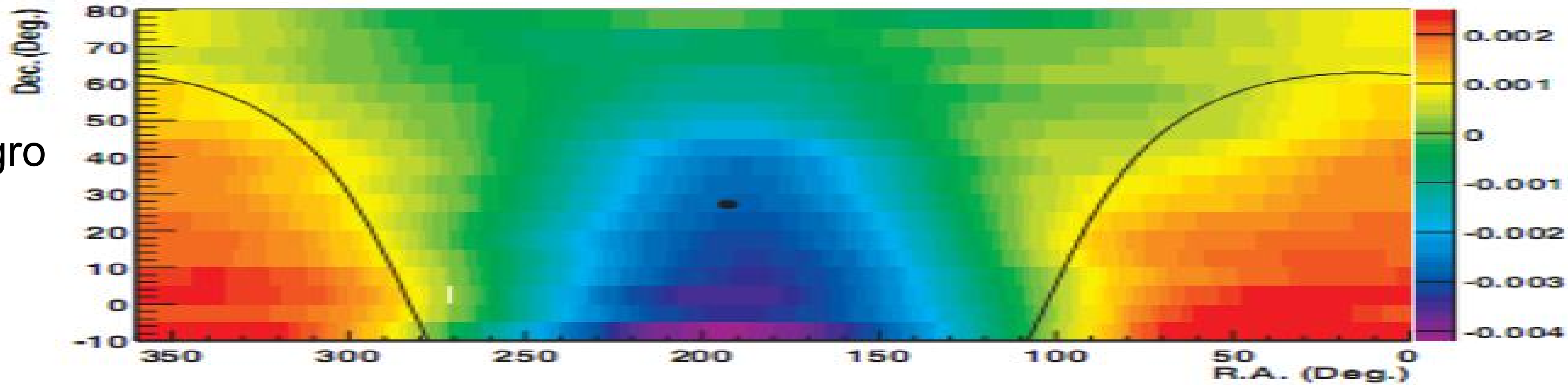
在**Cygnus**区发现新的超出。

宇宙线各向异性的幅度**~0.1%**

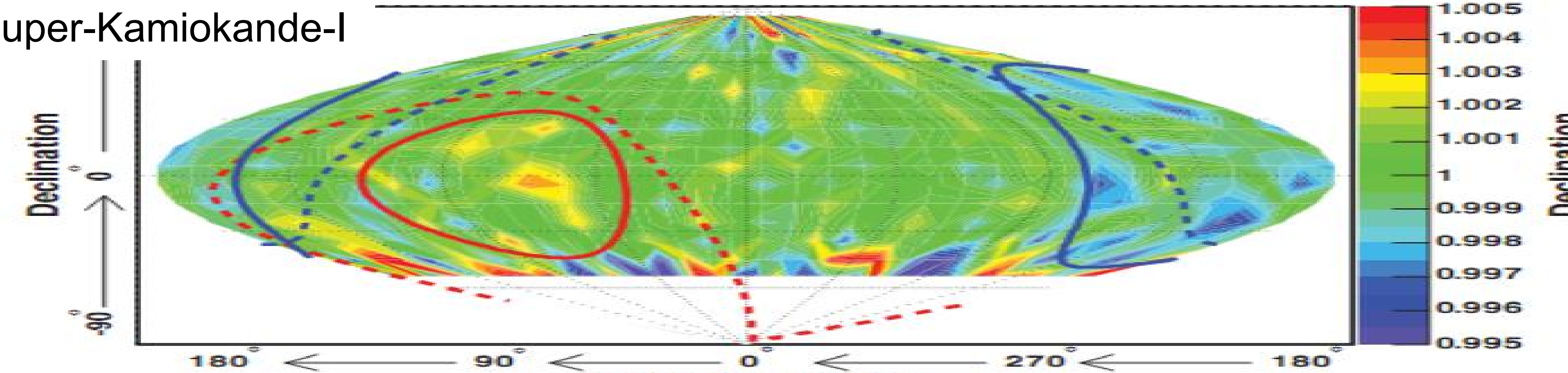
<<Anisotropy and Corotation of Galactic Cosmic Rays >>   M. Amenomori et al., Science, 314 429 (2006)

国际上大型实验的观测

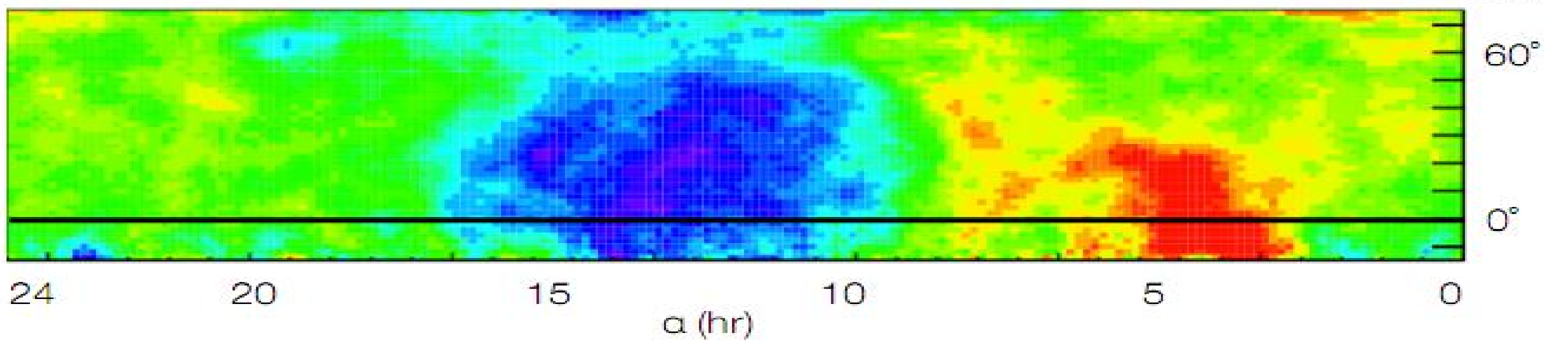
Milagro



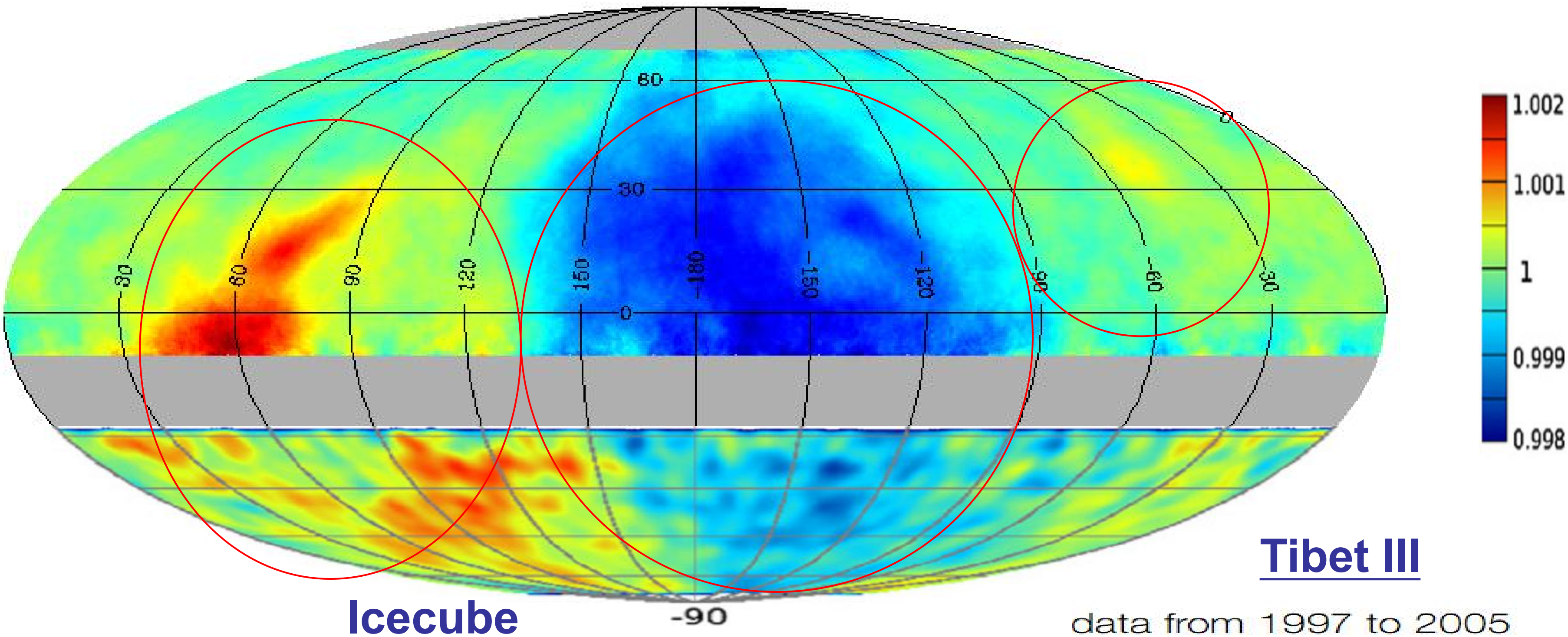
Super-Kamiokande-I



ARGO



Sidereal time anisotropy in two hemisphere



Icecube

- 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

Tibet III

data from 1997 to 2005

1874 days livetime

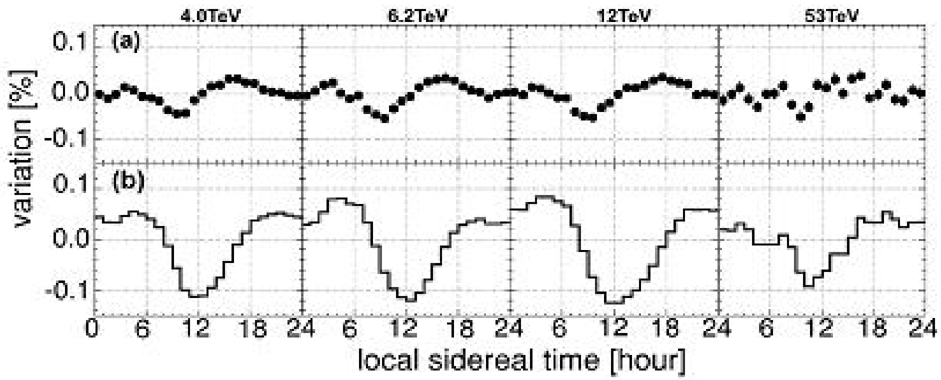
$3.7 \cdot 10^{10}$ events

angular resolution ~ 0.9°

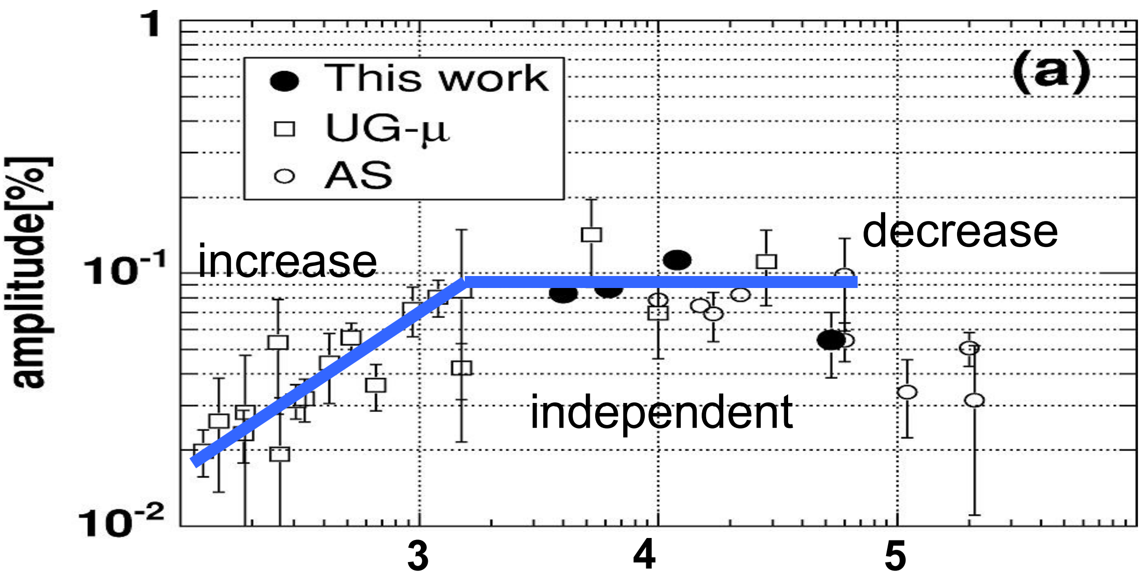
modal CR energy ~ 3 TeV

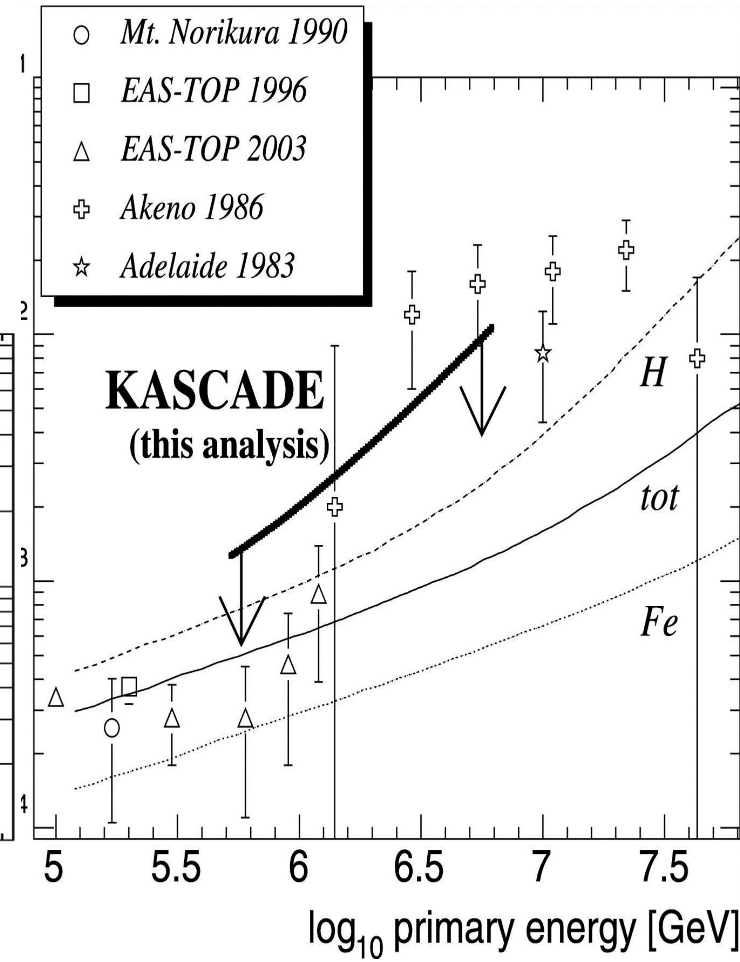
南北半球的观测对大尺度结构新的认识

宇宙线各向异性的能量依赖



Amenomori, APJ, 2005



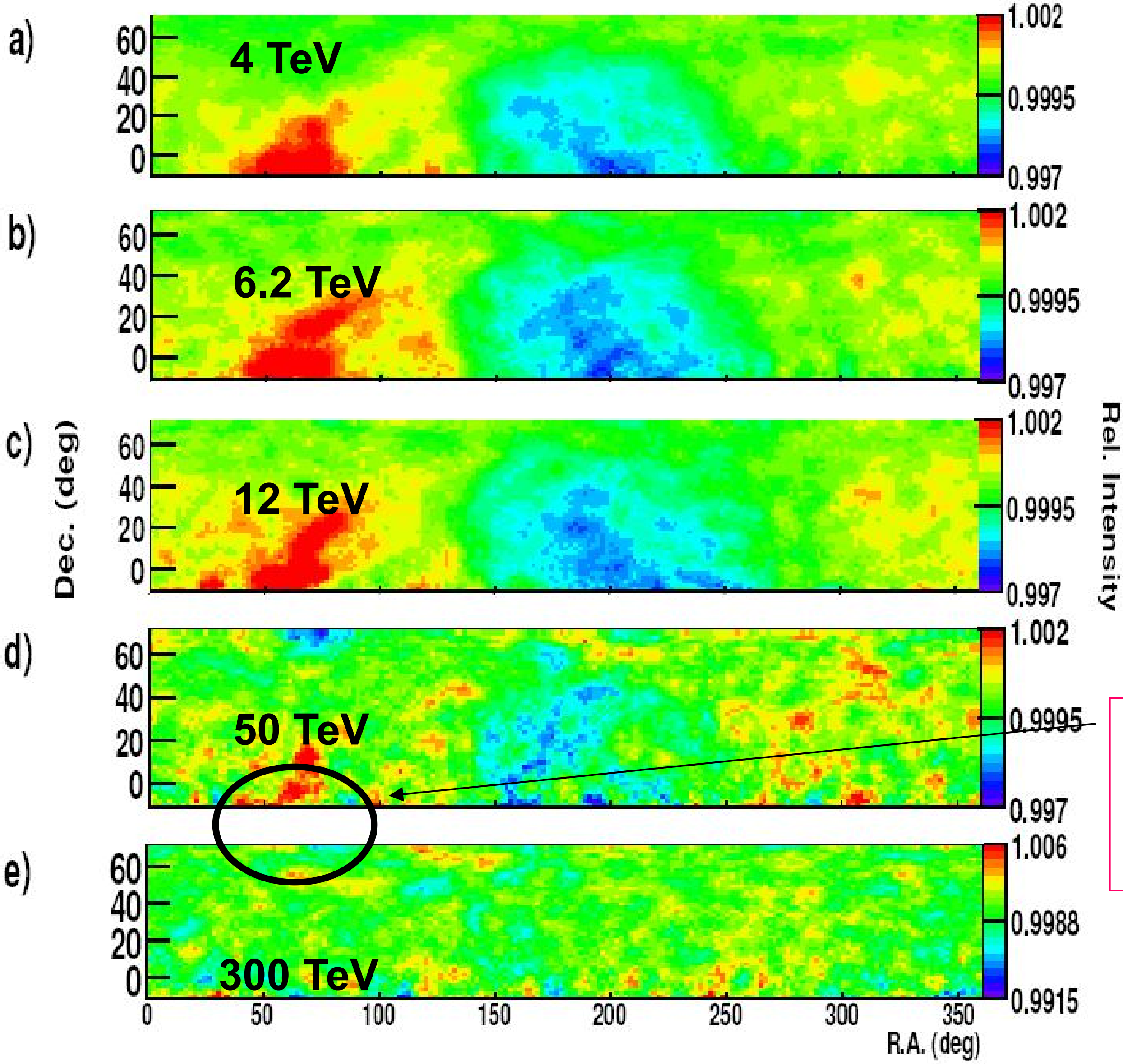


一维分布的谐波分析

宇宙线各向异性，很大的能量区间，有结构

两维观测的能量依赖一

Celestial Cosmic Ray intensity map in five energy range

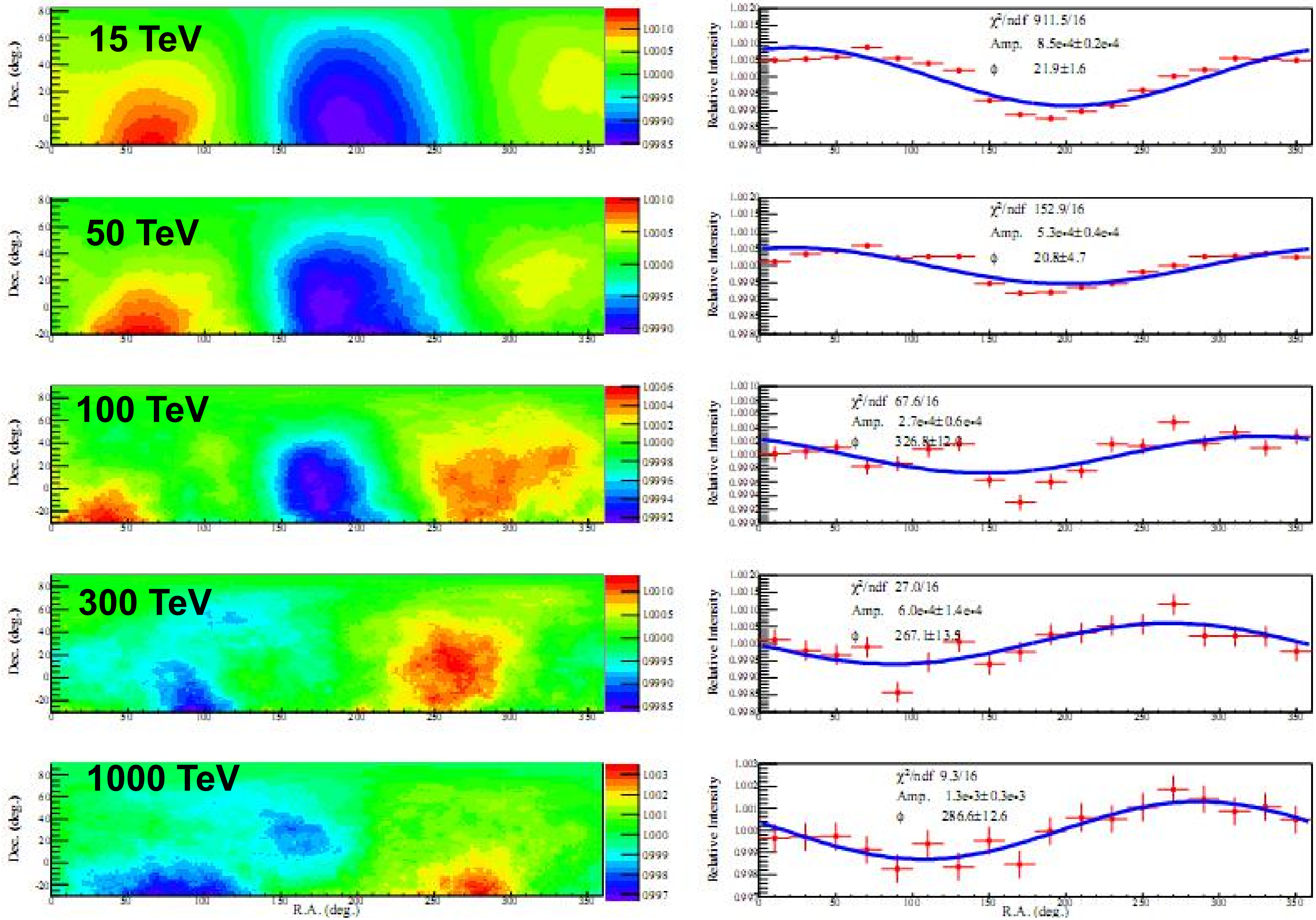


<12TeV Energy independent
>12TeV Fade away

"Tail-in" effect exists in 50TeV, rule out the solar causation.

宇宙线各向异性，结构在高能褪去

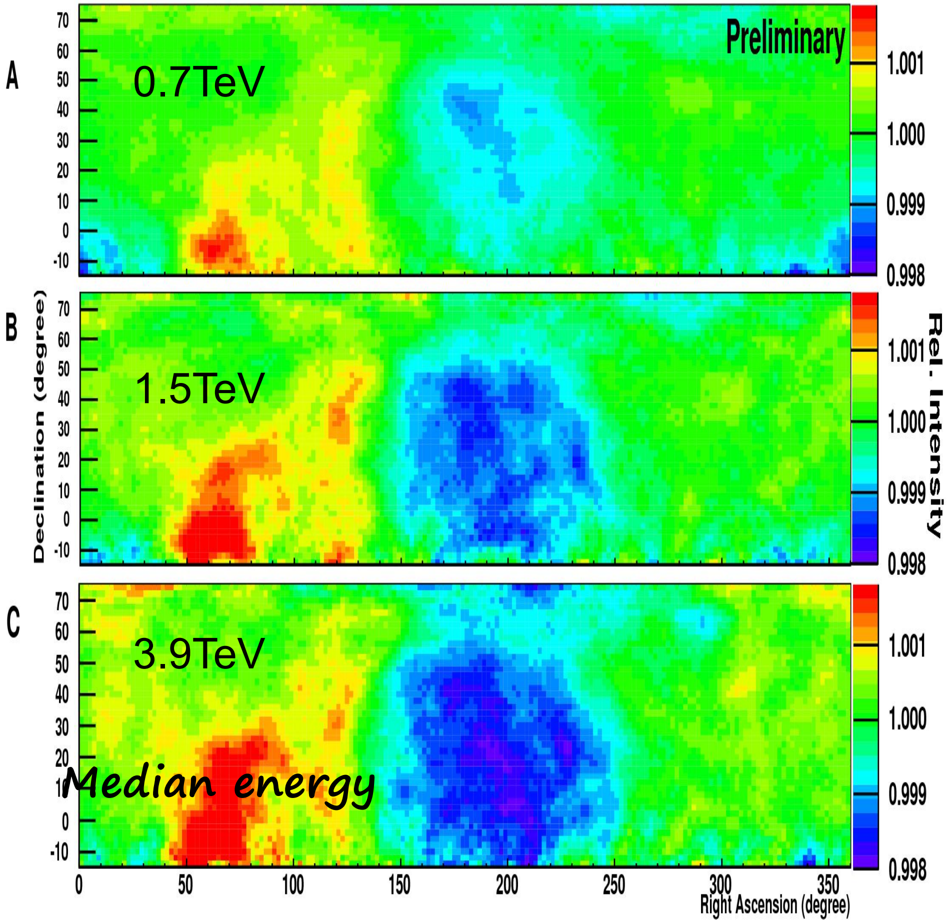
两维观测的能量依赖二

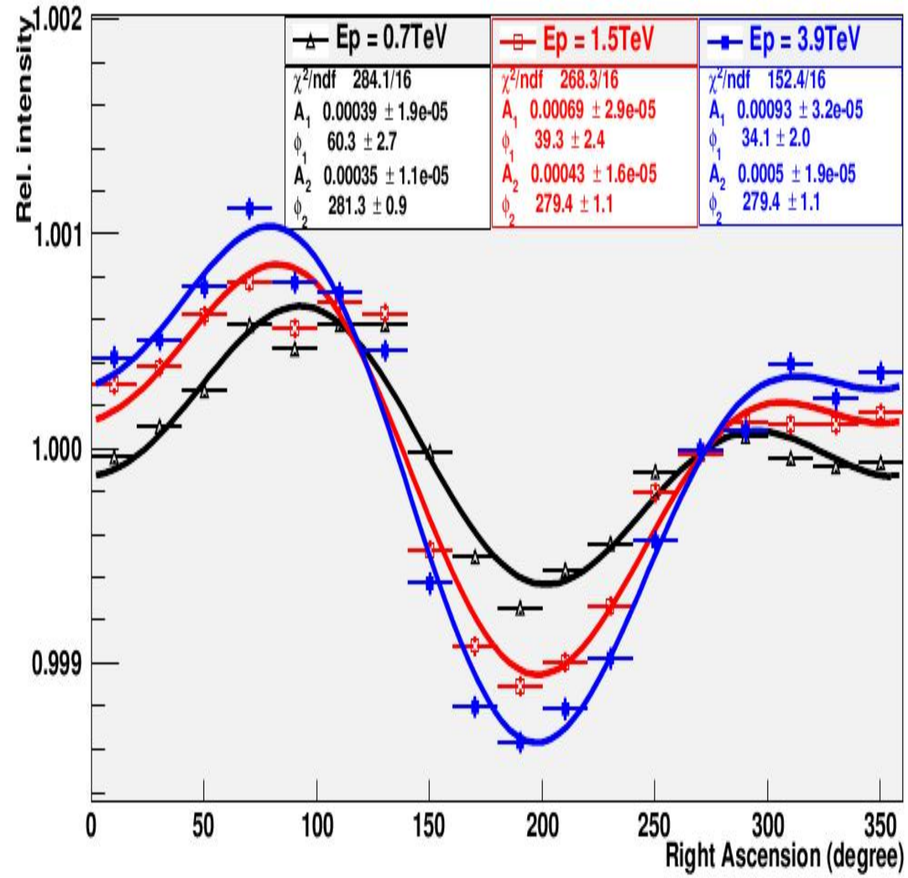


15 TeV
50 TeV
100 TeV
300 TeV
1000 TeV
Dec. (deg.)
R.A. (deg.)
Relative Intensity
χ²/ndf 911.5/16
Amp. 8.5e-4±0.2e-4
ϕ 21.9±1.6
χ²/ndf 152.9/16
Amp. 5.3e-4±0.4e-4
ϕ 20.8±4.7
χ²/ndf 67.6/16
Amp. 2.7e-4±0.6e-4
χ²/ndf 27.0/16
Amp. 6.0e-4±1.4e-4
χ²/ndf 9.3/16
Amp. 1.3e-3±0.3e-3
ϕ 286.6±12.6

两维观测的能量依赖二

Sidereal time anisotropy by ARGO



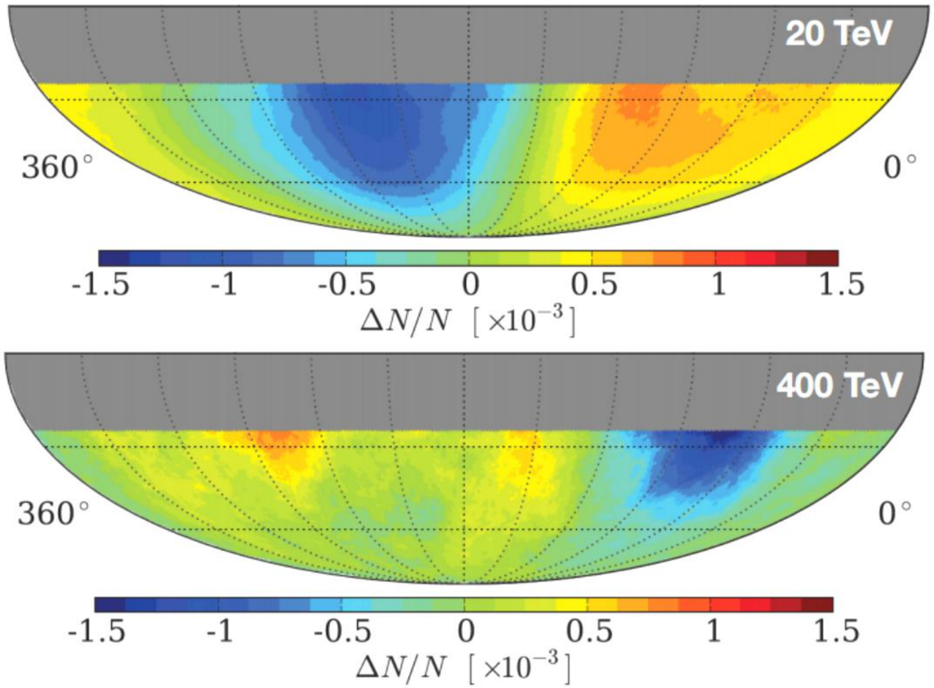


Consistent with the 1D observations, finer structure in 2D

宇宙线各向异性，幅度在低能区变大

<<Observation of TeV cosmic ray anisotropy by the ARGO-YBJ experiment>> ICRC0814,2009

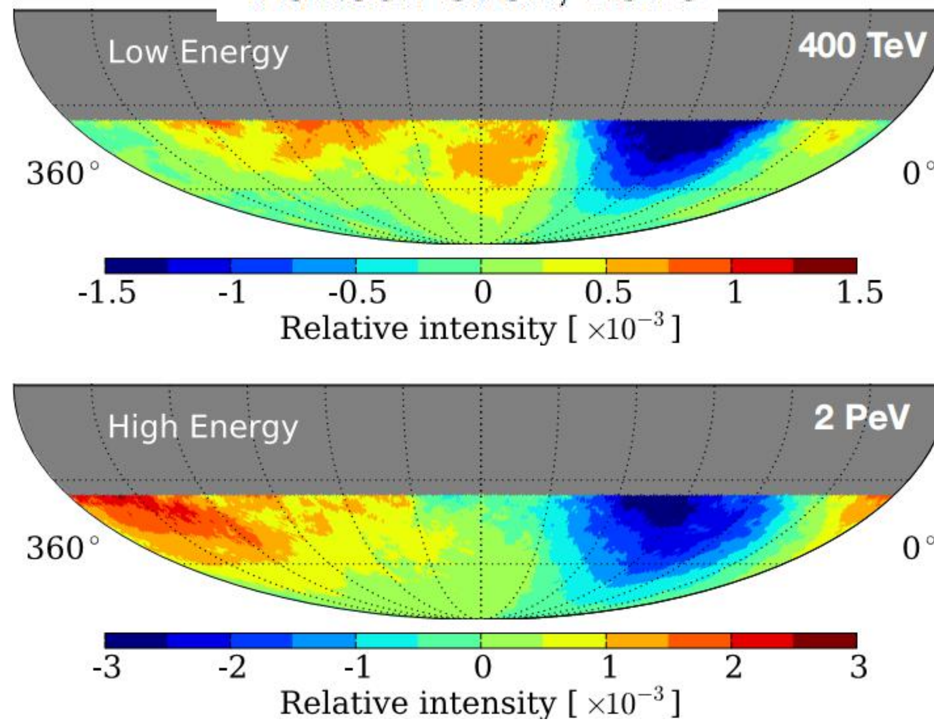
IceCube



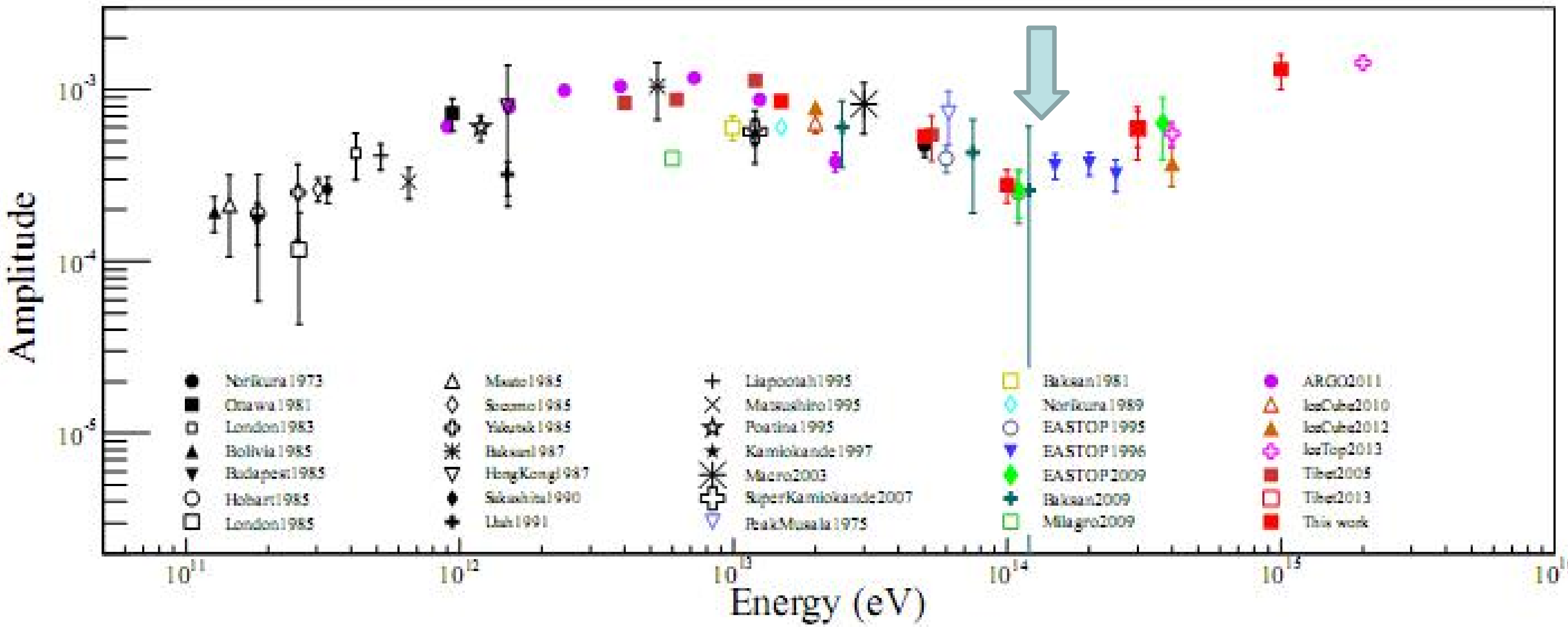
Abbasi et al., 2010, 2012

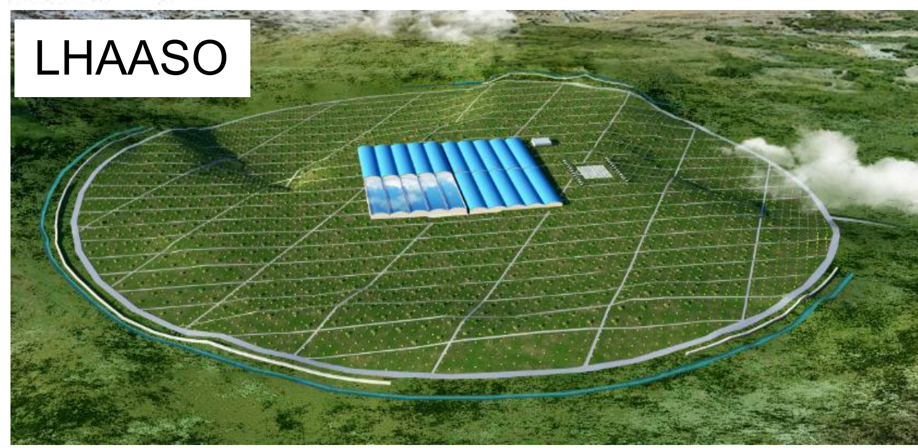
IceTop

Aartsen et al., 2013



研究各向异性在百TeV能区的变化





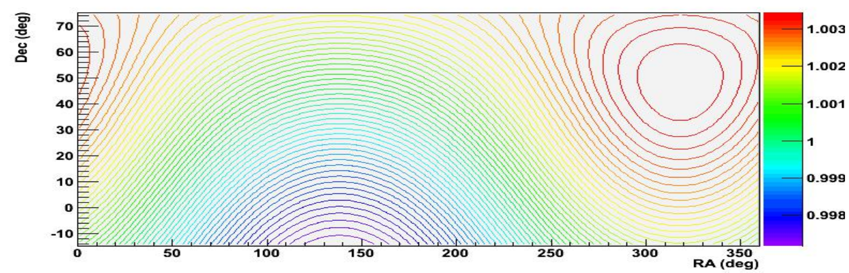
大尺度宇宙线各向异性的理解

—— Compton-Getting Effect

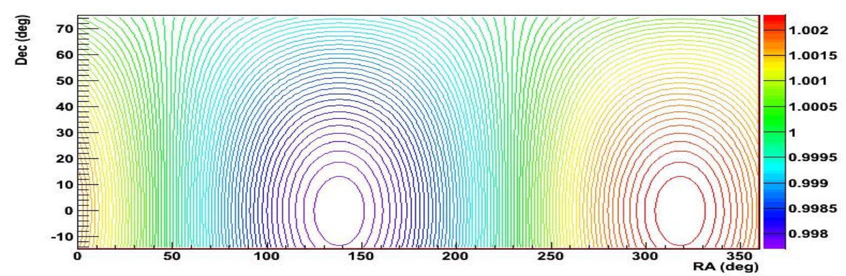
Due to the solar motion around galactic center

$j \propto E^{-\alpha}$ **V=220km/s,** $\alpha = 2.7$

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



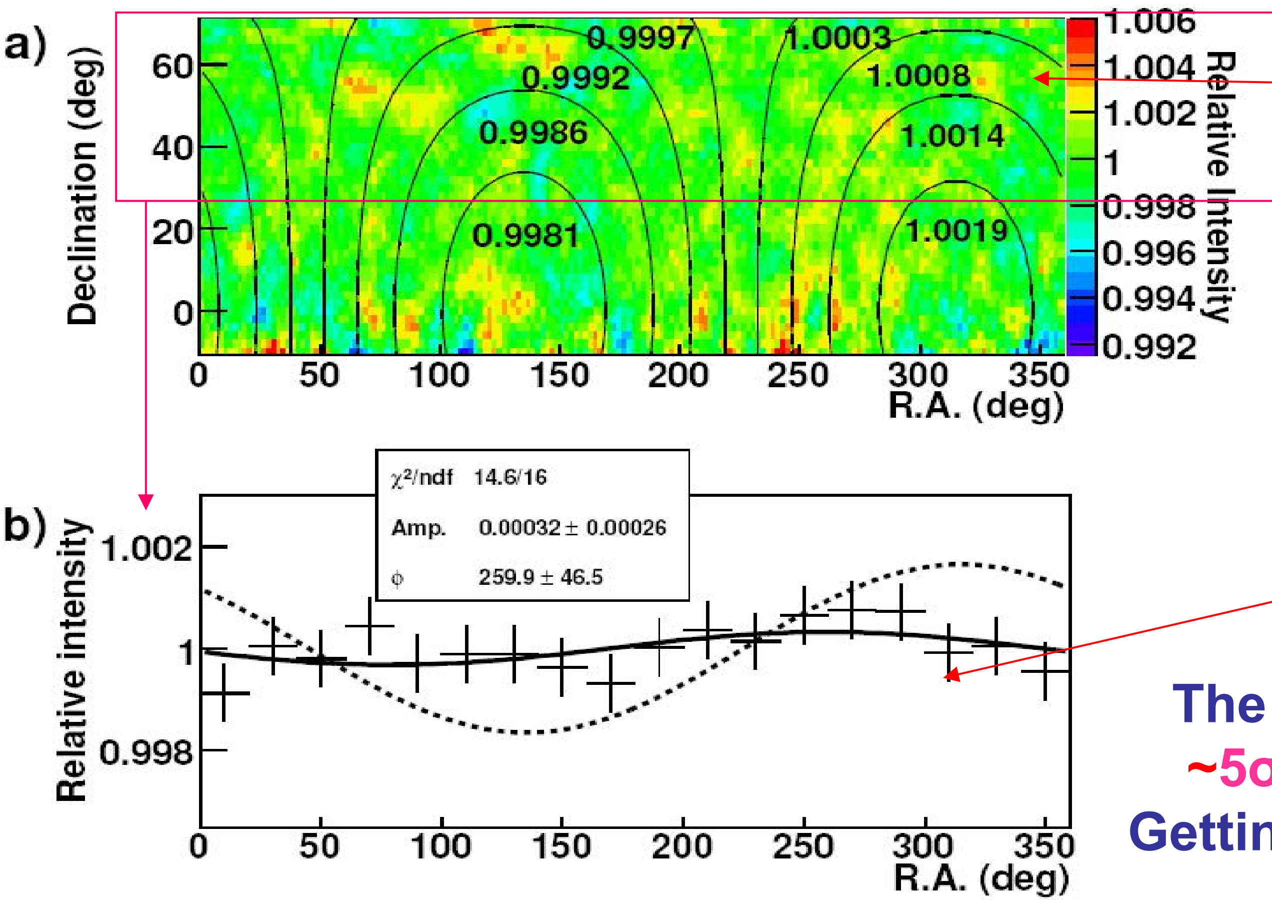
Expected dipole effect



We could observe

A.H. Compton and I.A. Getting, Phys. Rev. **47**, 817(1935)

Celestial Cosmic Ray intensity map for 300 TeV



Expected

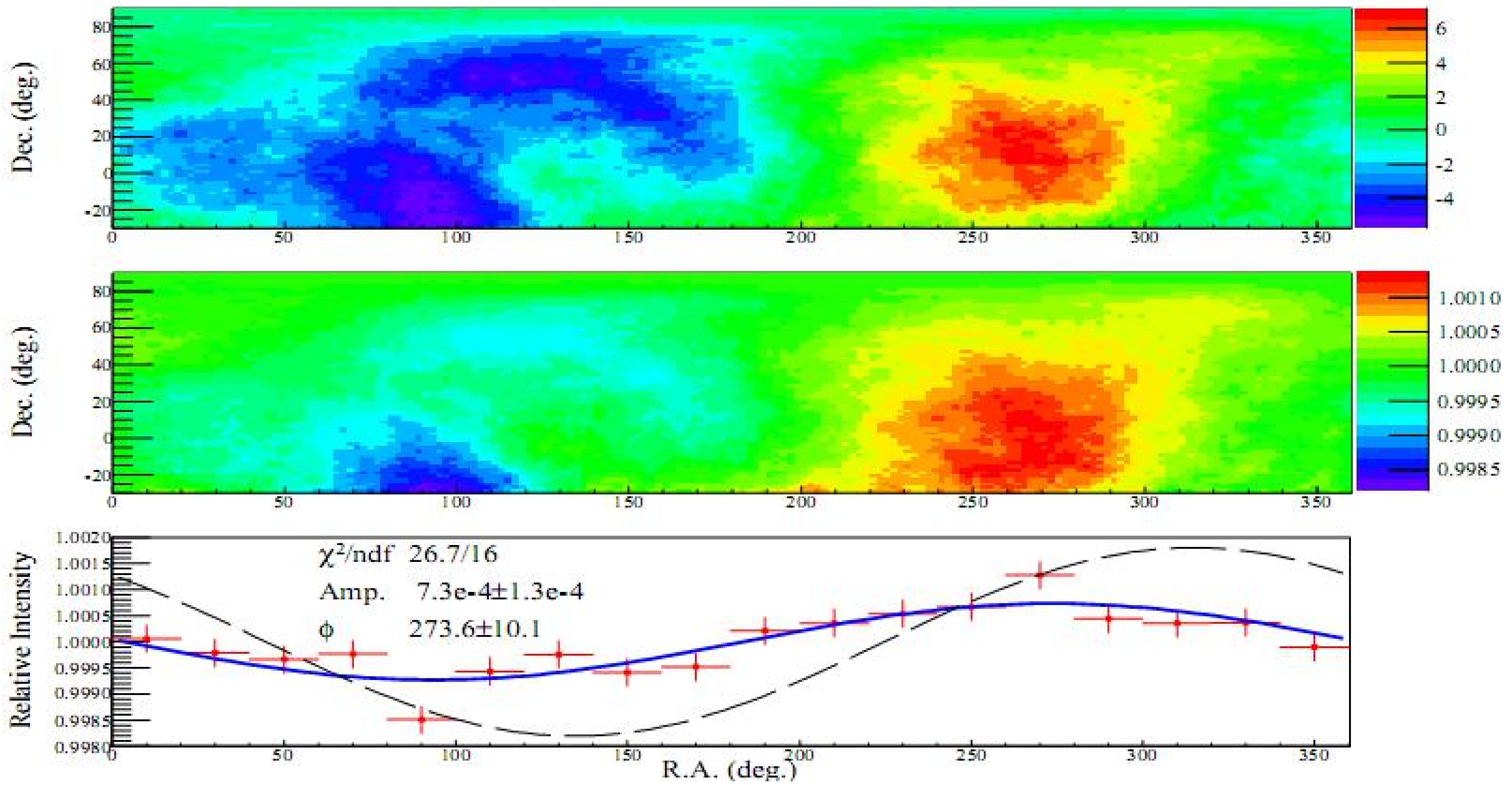
Expected

Amp= 0. 16%

The statistic error 0. 026%, ~5σ rule out the Compton-Getting effect.

These results have an implication that cosmic rays in this energy range is still strongly deflected and randomized by the Galactic magnetic field in the local environment.

Celestial Cosmic Ray intensity map for 300 TeV



宇宙线各向异性的时间演化一

Sidereal time anisotropy in 9 Phases (1999-2008)

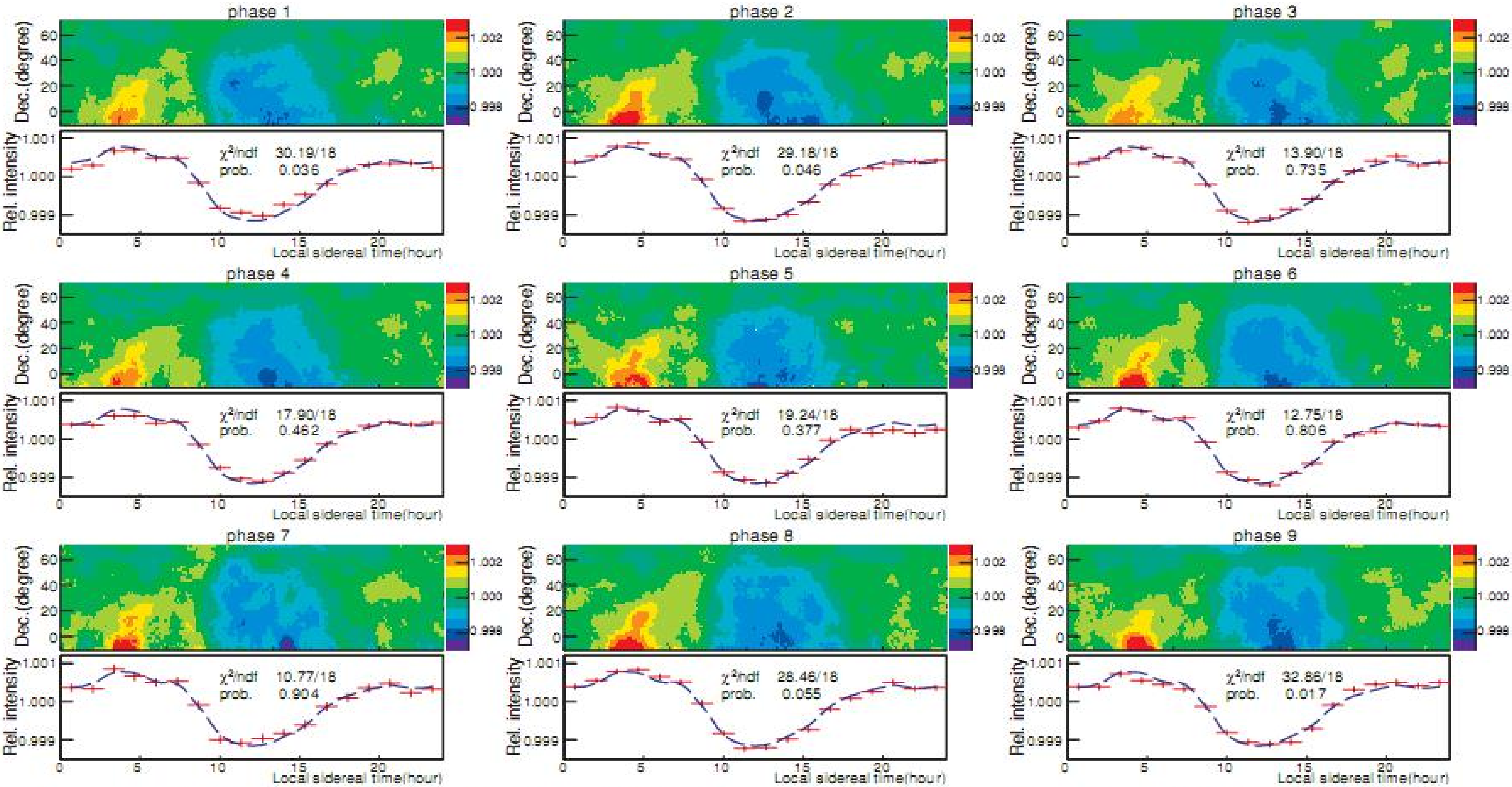


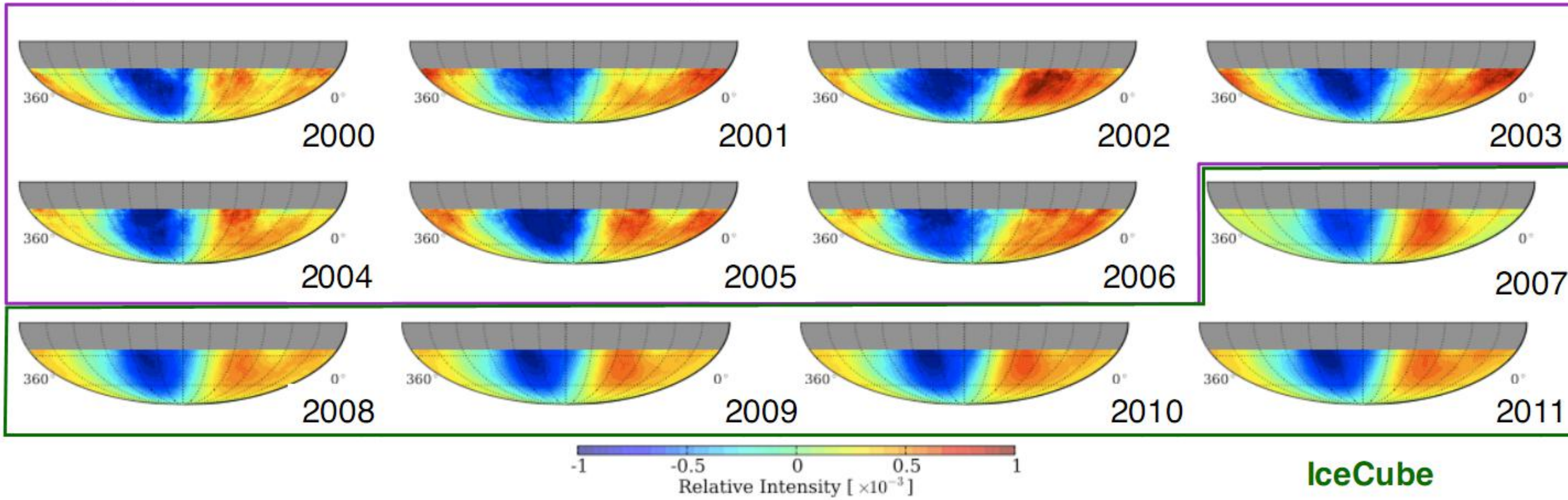
Figure 2. CR intensity variation in the local sidereal time frame for CRs with the modal energy around 5 TeV in the nine phases of Tibet III array. Top: two-dimensional intensity map of each phase; Bottom: one-dimensional projection averaged over all declinations. In bottom plots of each panel, the red crosses in each plot show the intensity variation over each phase respectively, while the dashed blue lines represent the intensity averaged over all nine phases of Tibet III array.

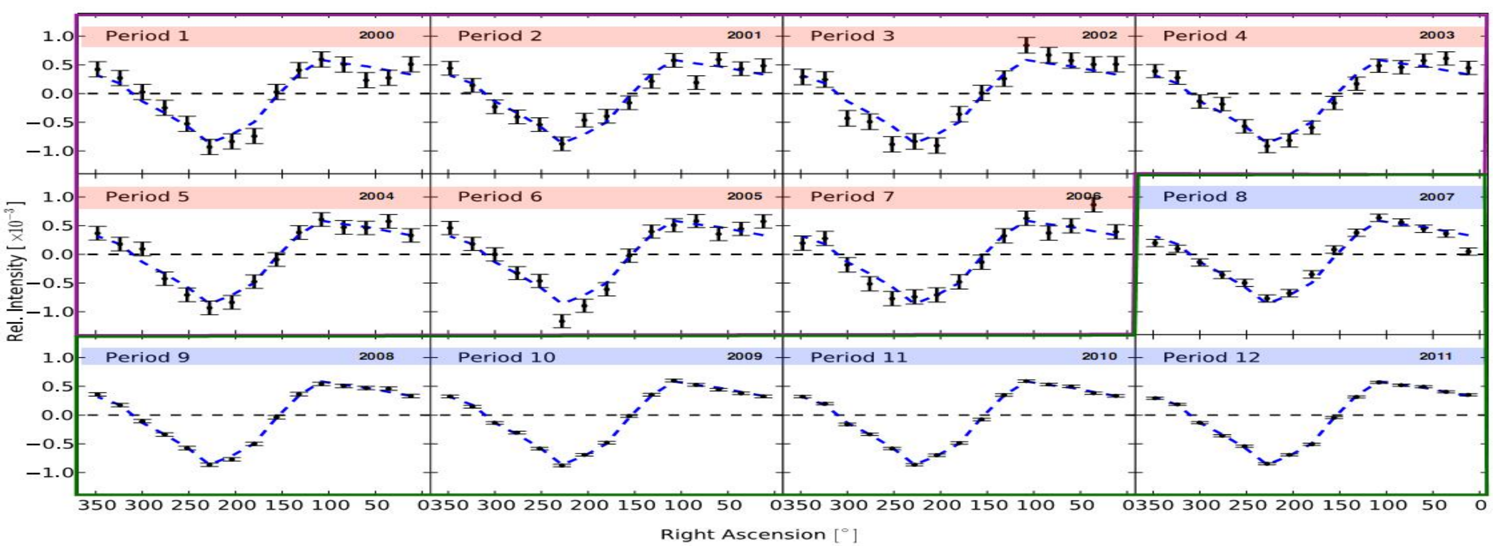
Improved analysis method, more statistic. **Stable Insensitive to solar activities**

<<On Temporal Variations of the Multi-TeV Cosmic Ray Anisotropy Using the Tibet III Air Shower Array >>, M. Amenomori et al., ApJ 711, 119 (2010)

AMANDA and **IceCube** yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties

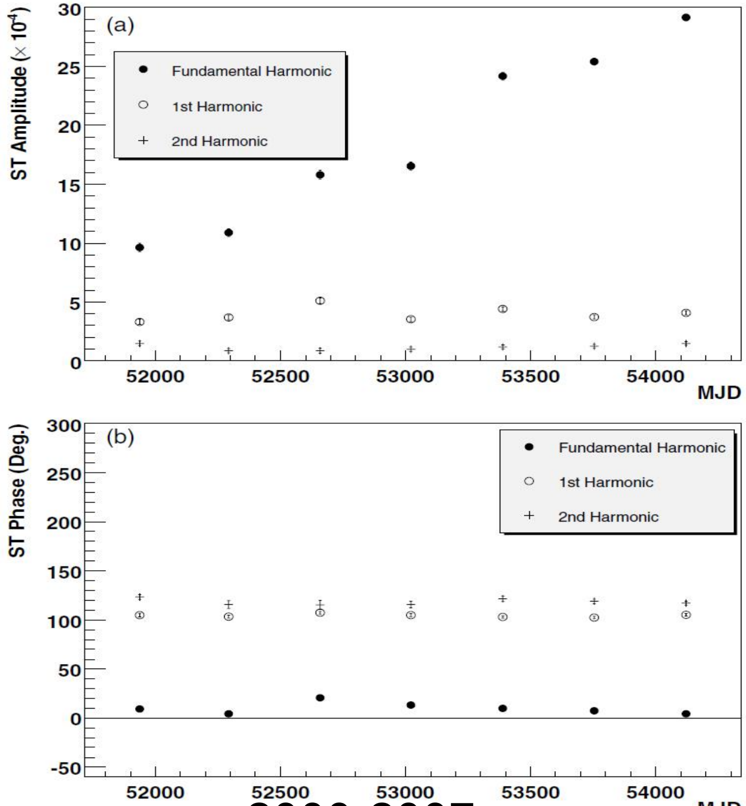
no apparent effect correlated to solar cycles





宇宙线各向异性的时间演化二

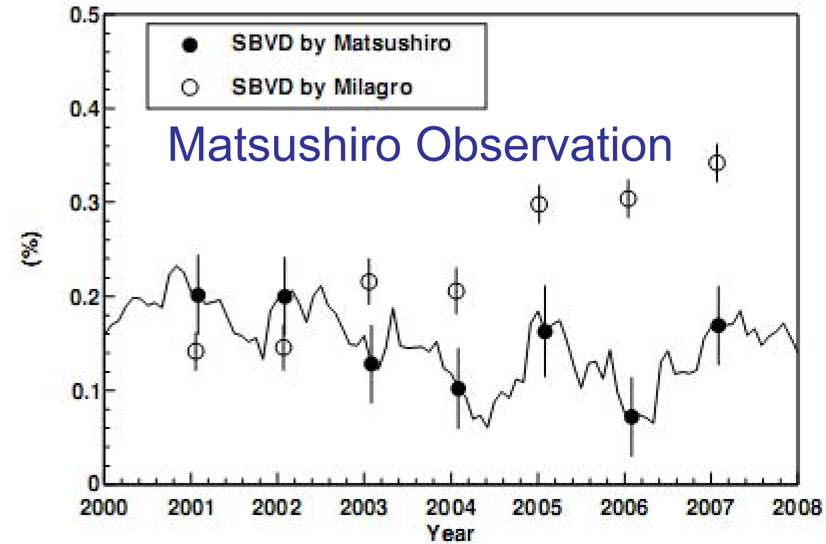
Time Evolution of the Sidereal Anisotropy



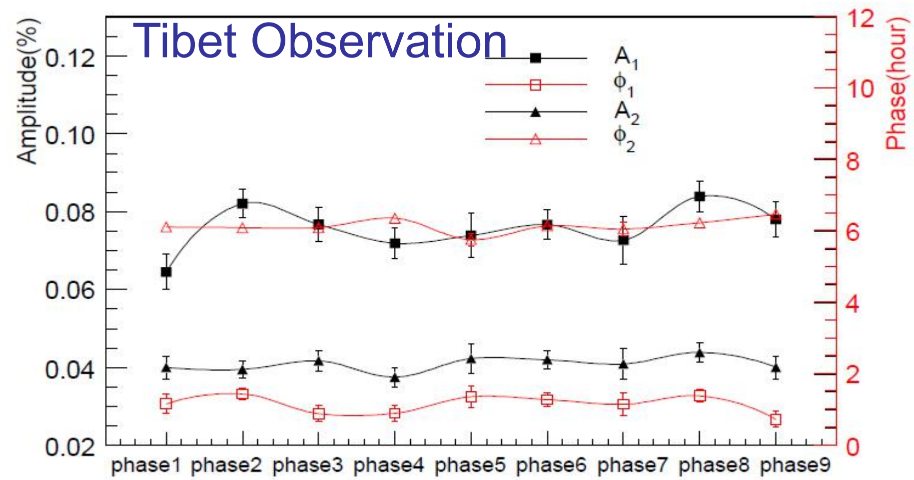
2000-2007

Milagro observation

The fundamental harmonic increase in amplitude with time.



No steady increase

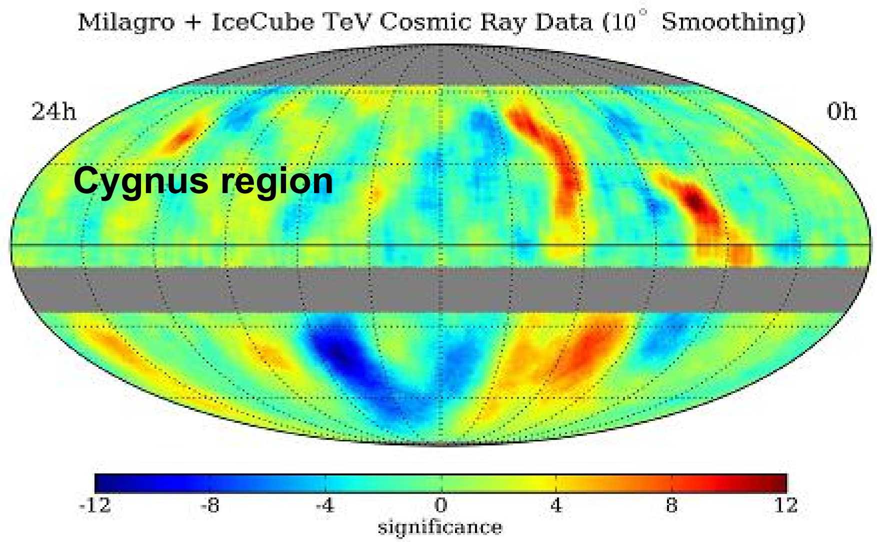


1999-2008

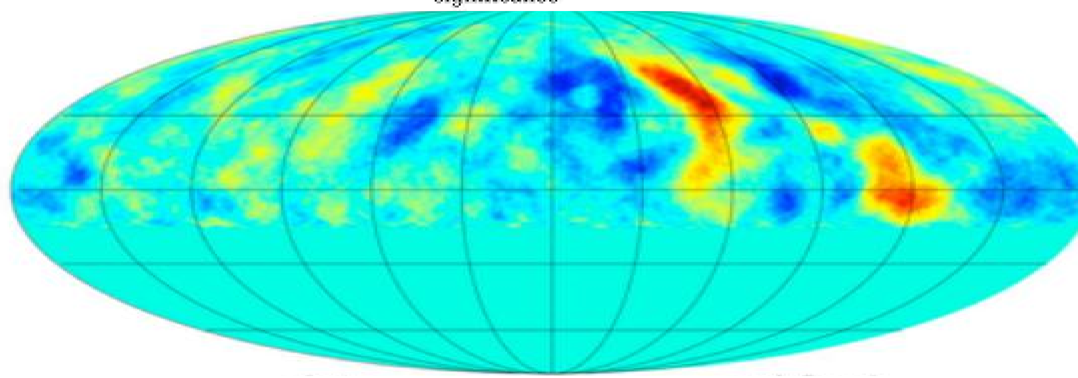
Loss-cone, Insensitive to solar activities

中尺度的宇宙线各向异性

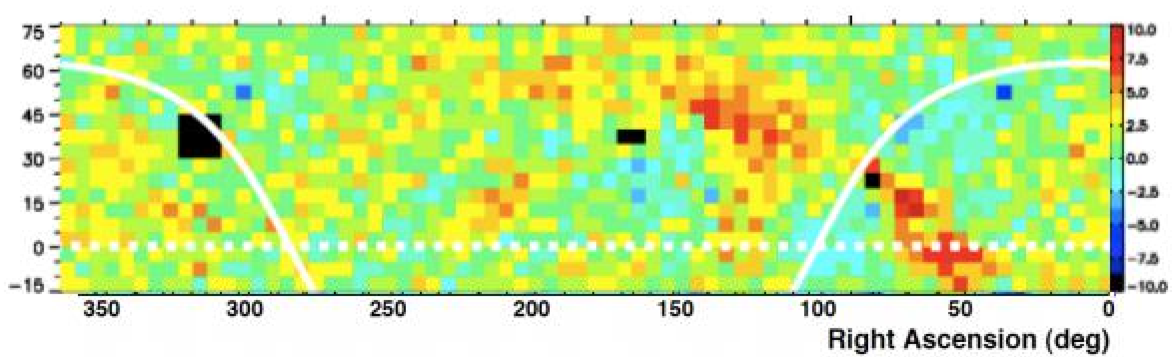
Milagro+Ice cube



ARGO



Tibet-III



Anisotropy product of stochastic supernova explosions

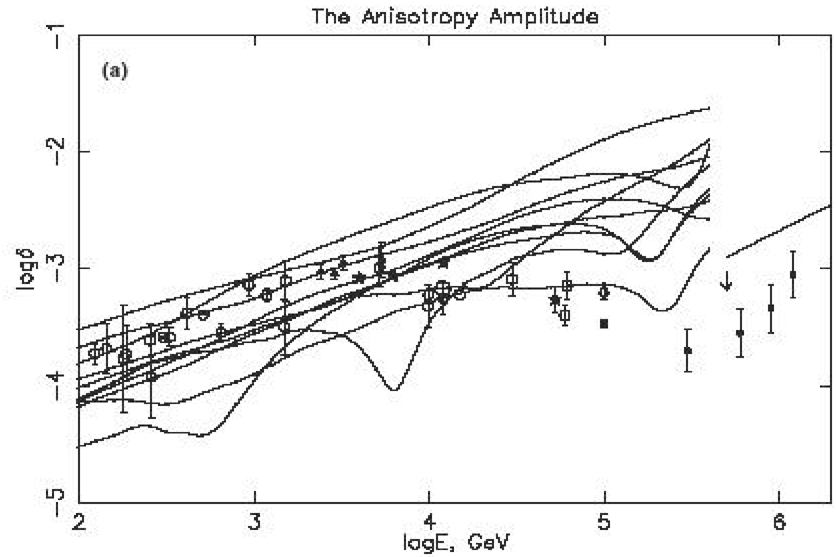
Diffusion model:

The amplitude of anisotropy

$$A = \frac{3D(R)\nabla N}{cN}$$

$D(R) \sim R^{\delta}$ (R – rigidity)
(δ ~ 0.3-0.6)

increase with the energy!



A. D. Erlykin, A. W. Wolfendale, Astropart. Phys. 25, 183(2006)

Random character of SN explosions：

1. Mixed primary mass composition;

3. Possible eff ect of the single source;
   Monogem Ring SNR and associated pulsar B0656 + 14

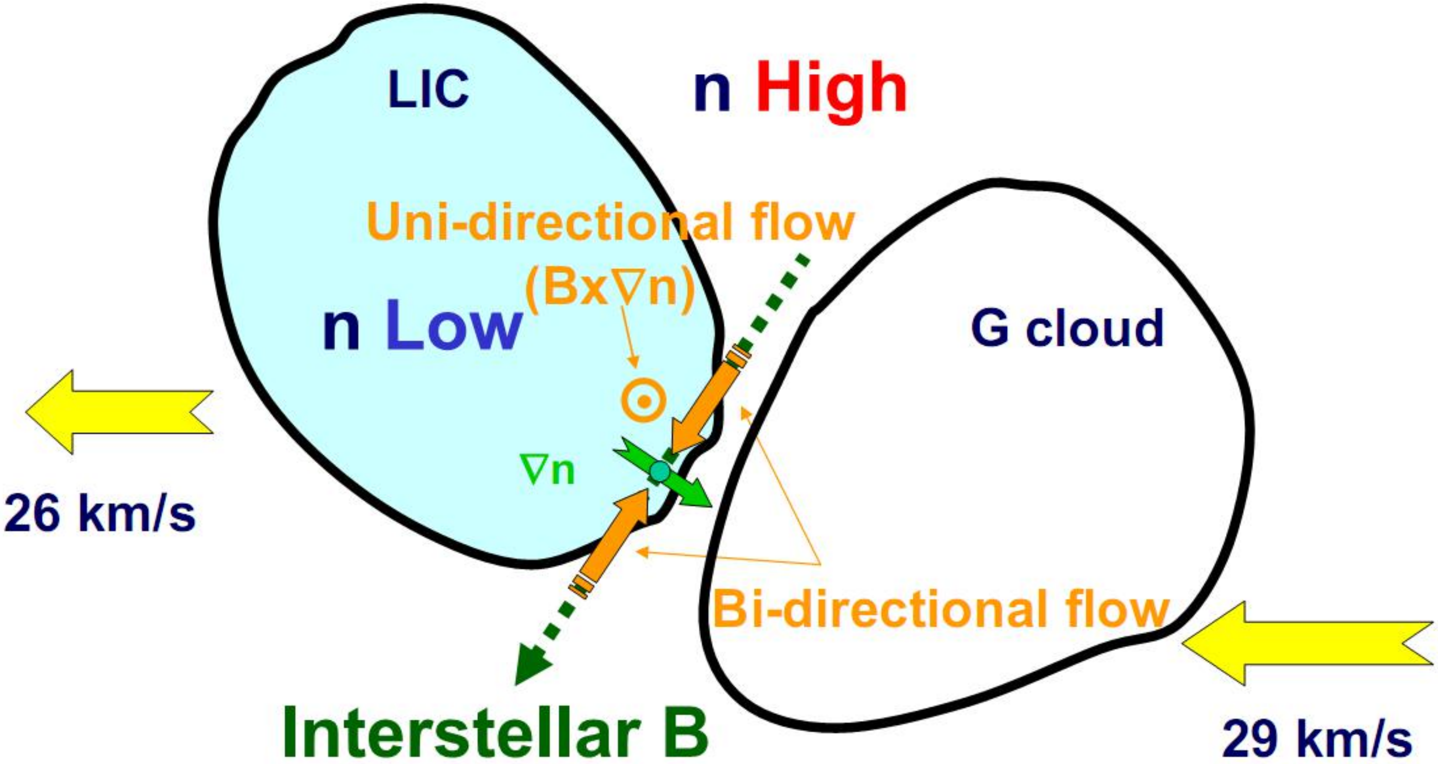
4. The Galactic Halo;

Important probe, discover CR origin, study CR propagation.

LIMC (Local Interstellar Magnetic Cloud) model

Local Interstellar Cloud, egg-shaped cloud, 93 pc^3.

Cosmic ray density (n) lower inside LIC than outside, adiabatic expansion



$$I^{GA}_{n,m} = a_{1\perp} \cos\chi_1(n,m:\alpha_1,\delta_1) + a_{1\parallel}\cos\chi_2(n,m:\alpha_2,\delta_2) + a_{2\parallel}\cos^2\chi_2(n,m:\alpha_2,\delta_2).$$

$(\alpha = 300.9° \text{ and } \delta = 32.2°)$

⊥Perpendicular
// Parallel

LISMF

uni-directional flow (UDF) ⊥
bi-directional flow (BDF) //

LIMC (Local Interstellar Magnetic Cloud) model

$$I_{n,m} = I_{n,m}^{GA} + I_{n,m}^{MA},$$

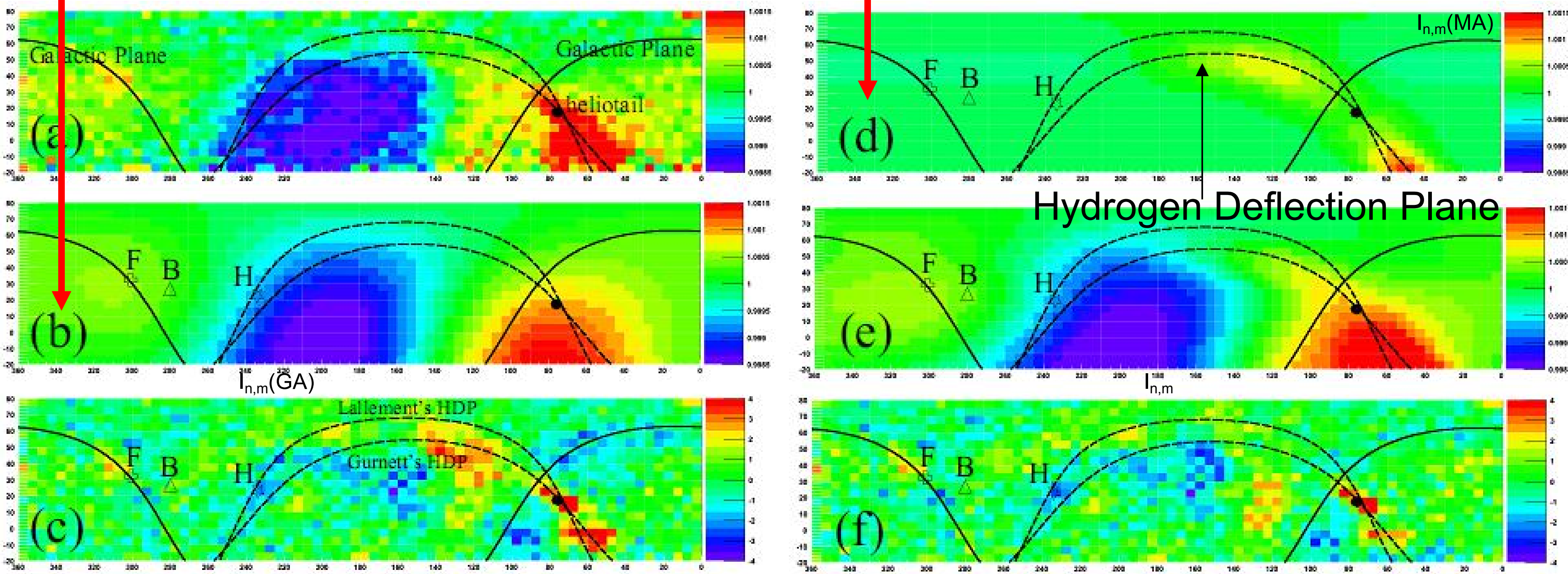
Global +Midscale Anisotropy

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

uni-directional flow +bi-directional flow
Local interstellar magnetic field

$$I_{n,m}^{MA} = \left\{ b_1 \exp\left(-\frac{(\phi_{n,m}-\Phi)^2}{2\sigma_\phi^2}\right) + b_2 \exp\left(-\frac{(\phi_{n,m}+\Phi)^2}{2\sigma_\phi^2}\right)\right\} \times \exp\left(-\frac{\theta_{n,m}^2}{2\sigma_\theta^2}\right),$$

Two intensity enhancements along a
Hydrogen Deflection Plane

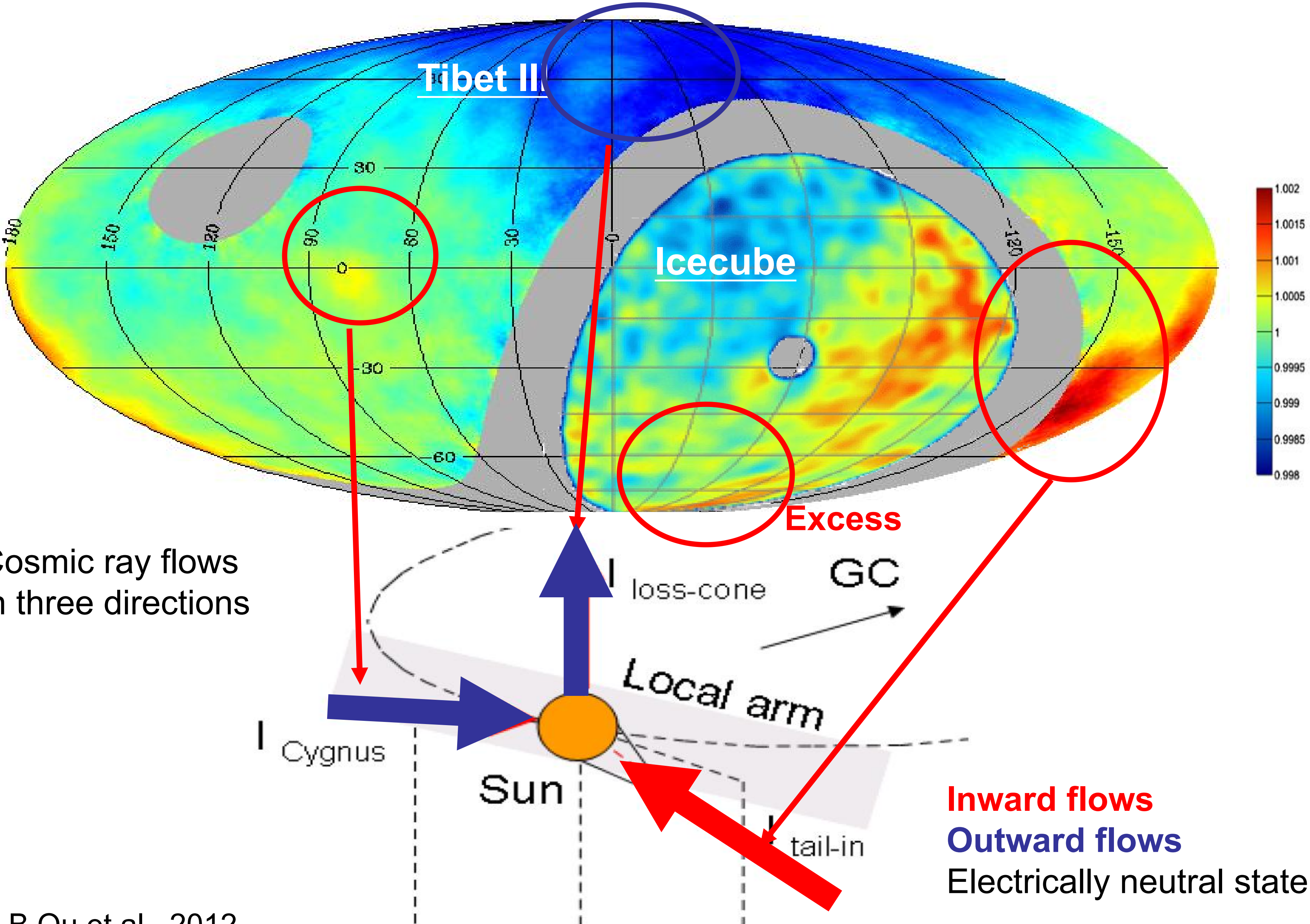


Residual anisotropy after subtracting $I_{n,m}$(GA)

Residual anisotropy after subtracting $I_{n,m}$

Amenomori, M., et al. 2010, Astrophys. Space Sci. Trans., 6, 49

Sidereal time anisotropy in Galactic coordinate



Cosmic ray flows in three directions

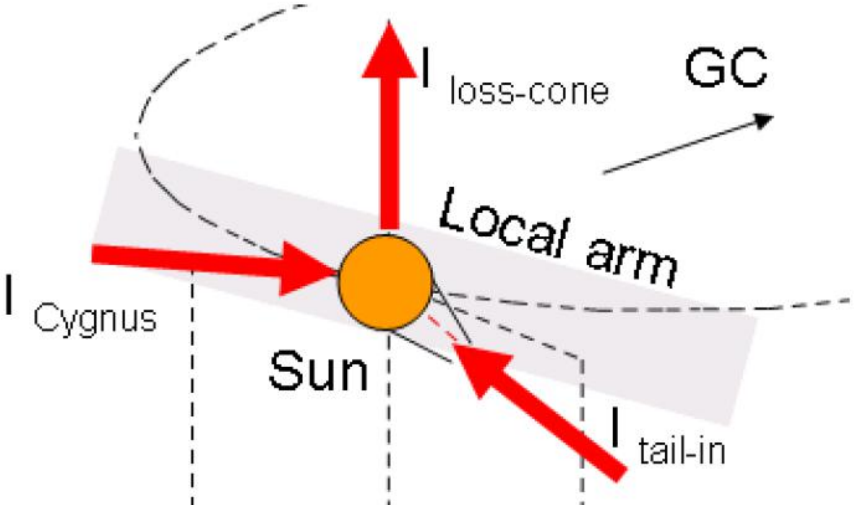
Inward flows

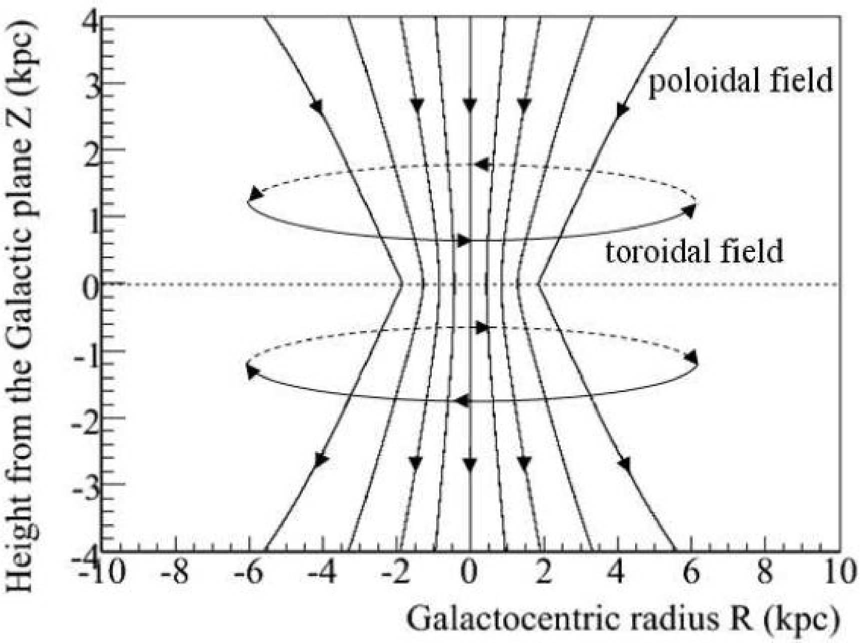
Outward flows

Electrically neutral state

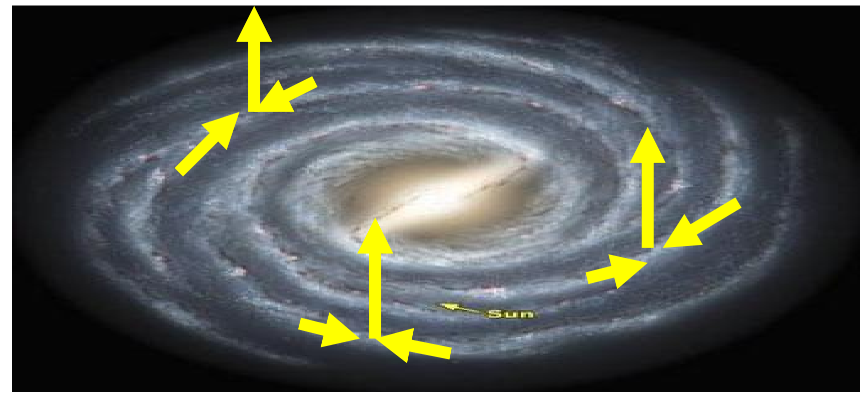
X.B.Qu et al., 2012

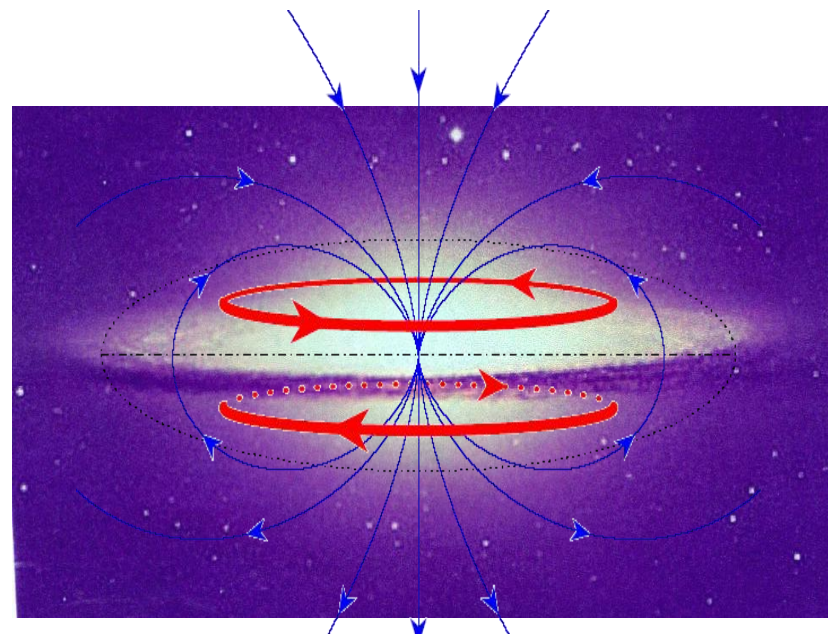
宇宙线各向异性与银晕磁场





模型计算出的磁场(X.B.Qu et al., APJ L750 L17 2012)



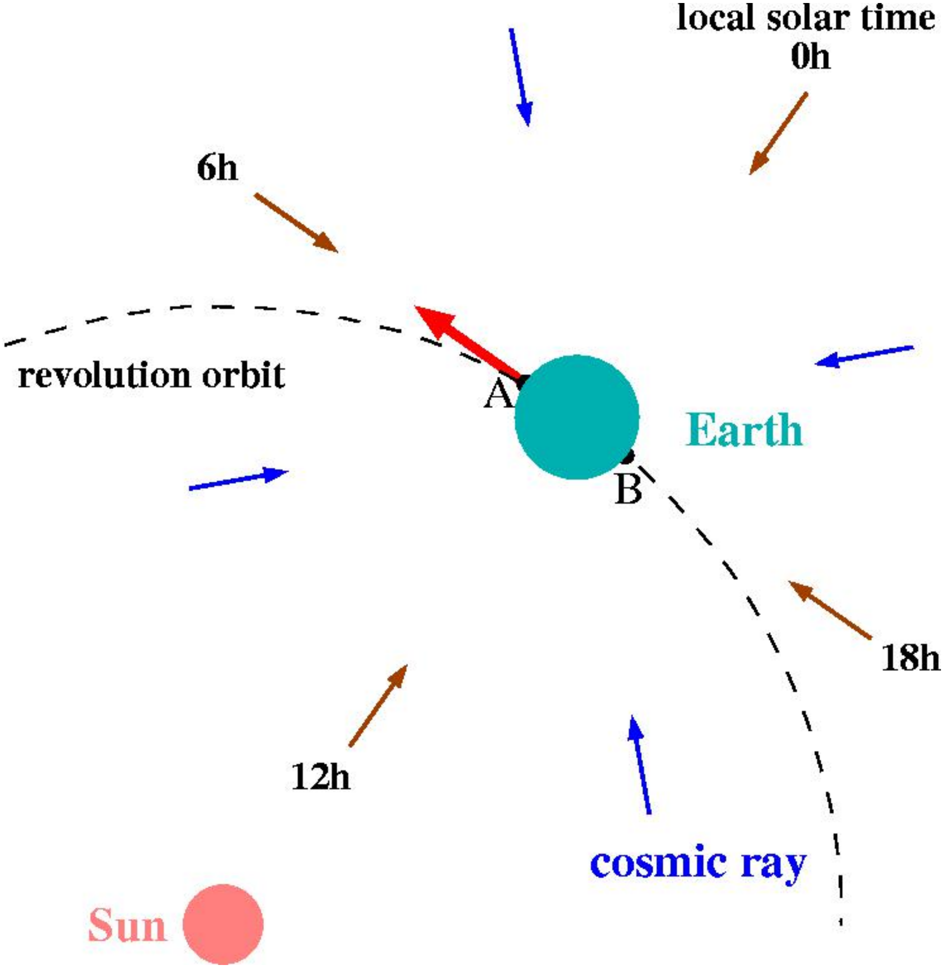


与韩金林组的观测结论一致

Known origin of large scale anisotropy

—— Compton-Getting effect

Due to terrestrial orbital motion around the Sun

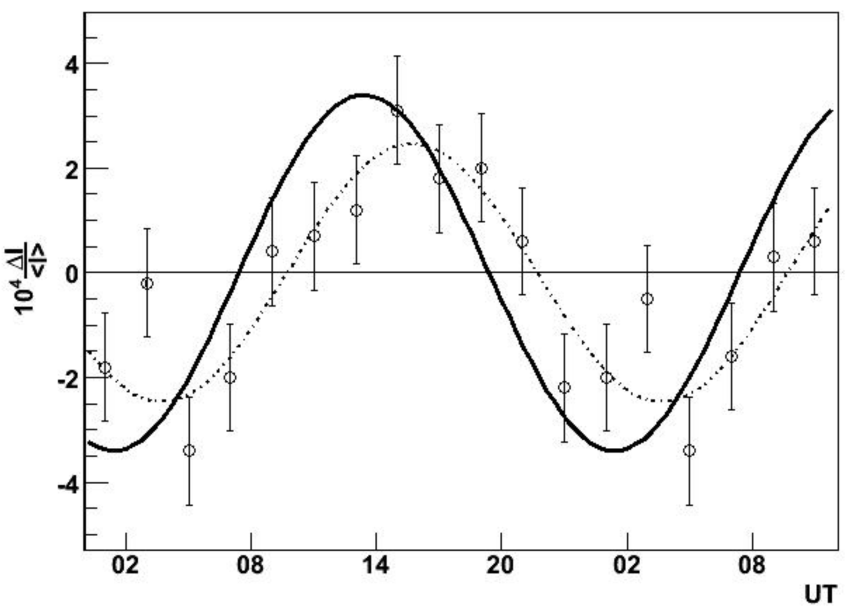


D.J. Cutler, D.E. Groom, Nature 322, L434 (1986)

Differential E spectrum : $j \propto E^{-\alpha}$

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

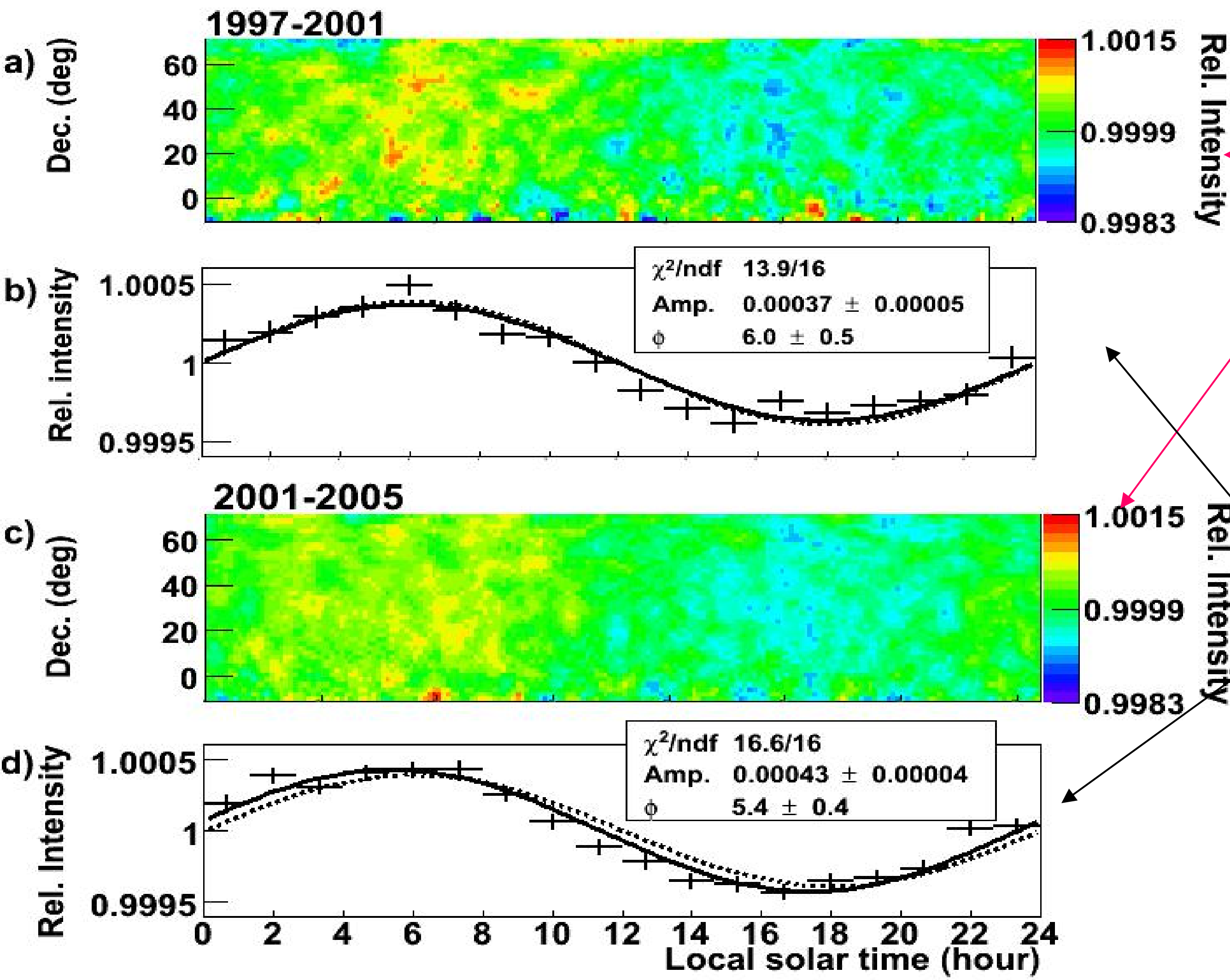
V=30km/s, $\alpha = 2.7$



The amplitude is ~0.04%

Tibet measurement in solar time I

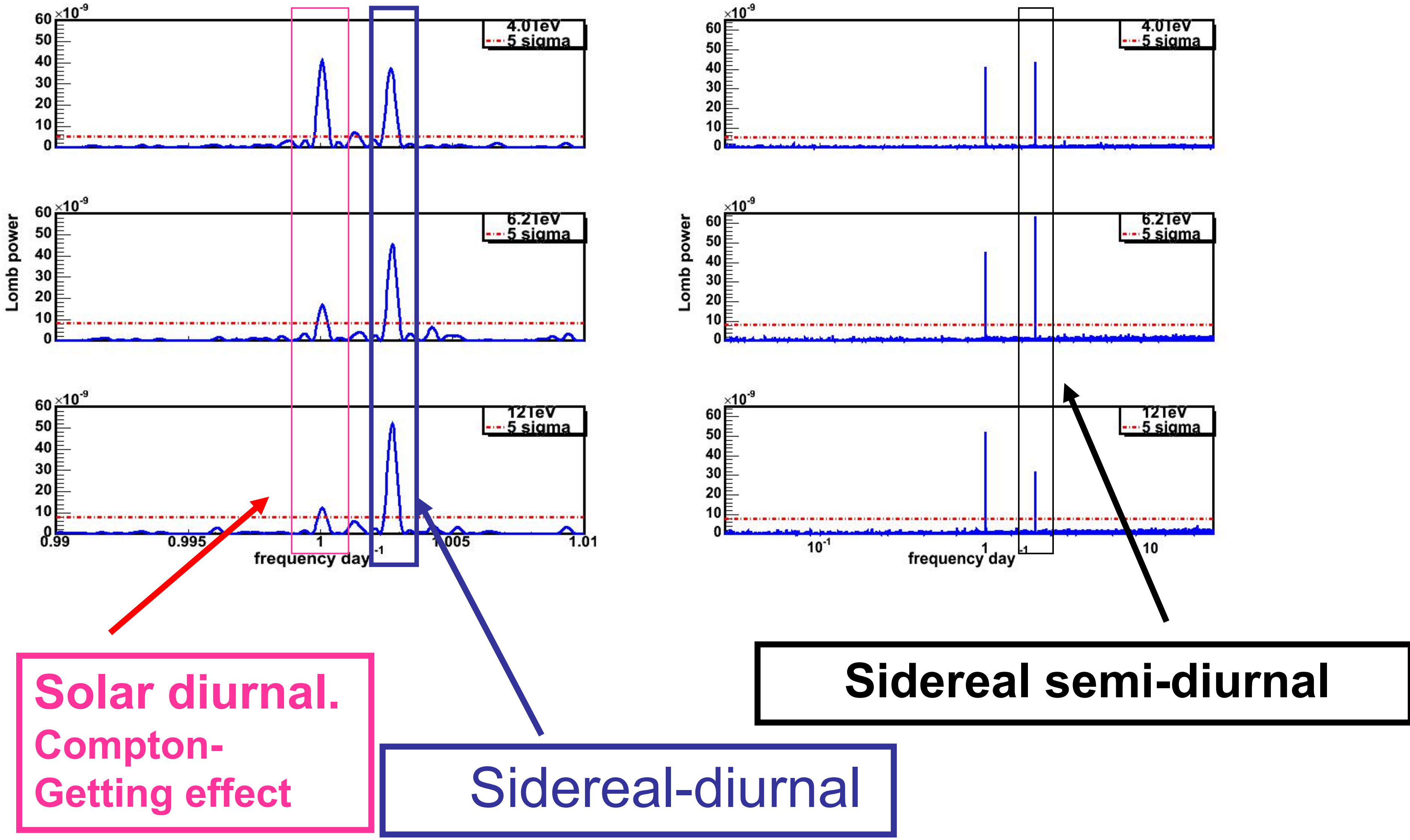
——Compton-Getting effect （12TeV）



The solar time anisotropy is table in two intervals with different solar activity

The 1D modulation (solid line) is consitent with the expected one (dash line)。

Periodicity search in 3 energy ranges



<<Observation of Periodic Variation of Cosmic Ray intensity with the Tibet III Air Shower Array>>, A.-F. Li Nuclear Physics B,, 529, 2008.

Summary

•对宇宙线各向异性也有了大量的研究，能量依赖，时间演化，周期性，大尺度，中尺度等等。

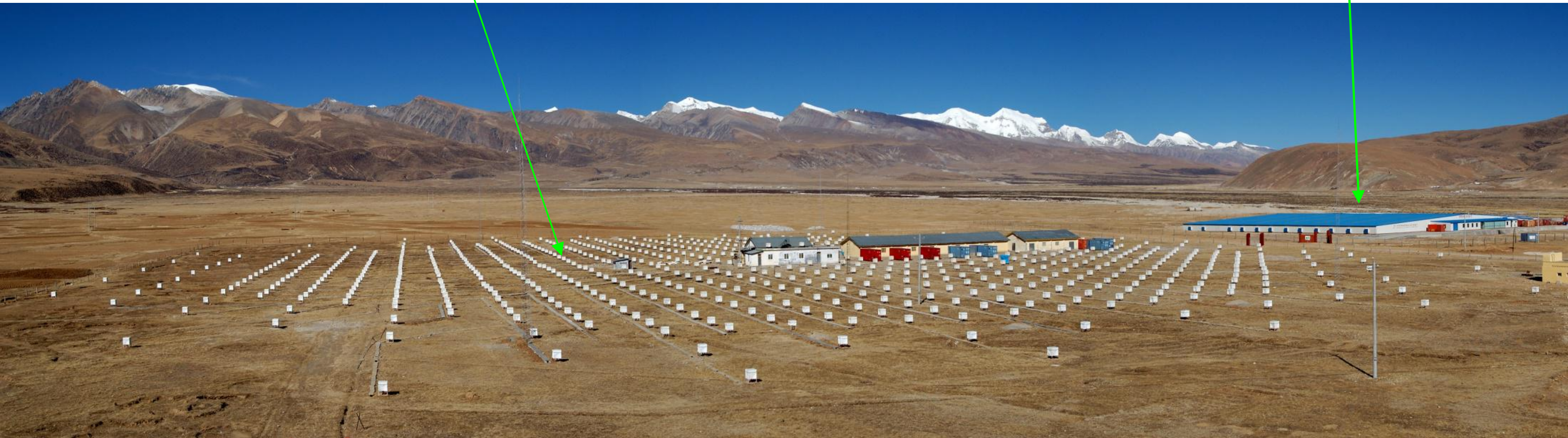
•宇宙线各向异性可能与加速源分布，传播过程或太阳系附近环境都有关系。涌现出一批唯像模型，但目前没有一个普遍接受的模型。

•各向异性在百TeV能区，结构发生变化，LHHASO在北半球实现高精度的观测。

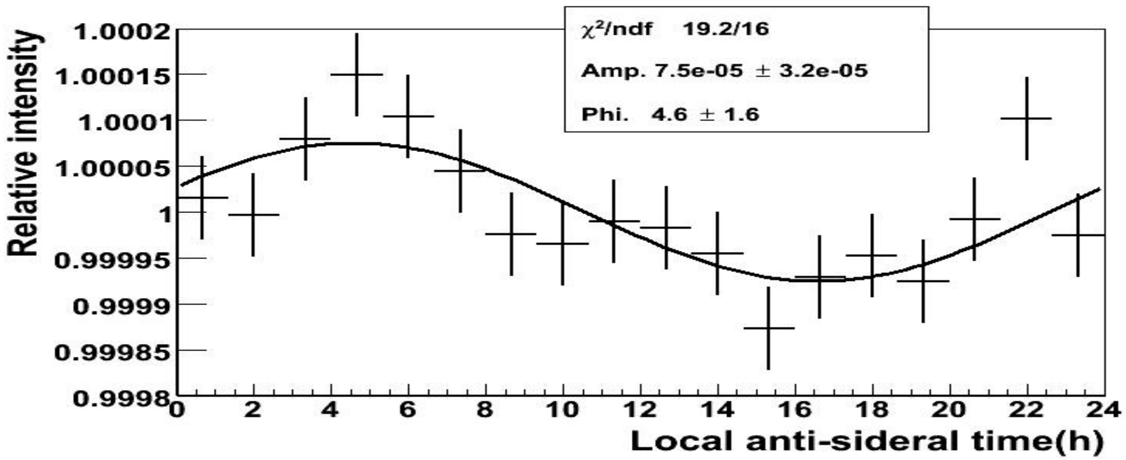
Thanks for your attention！

中日ASγ探测阵列

中意ARGO实验大厅

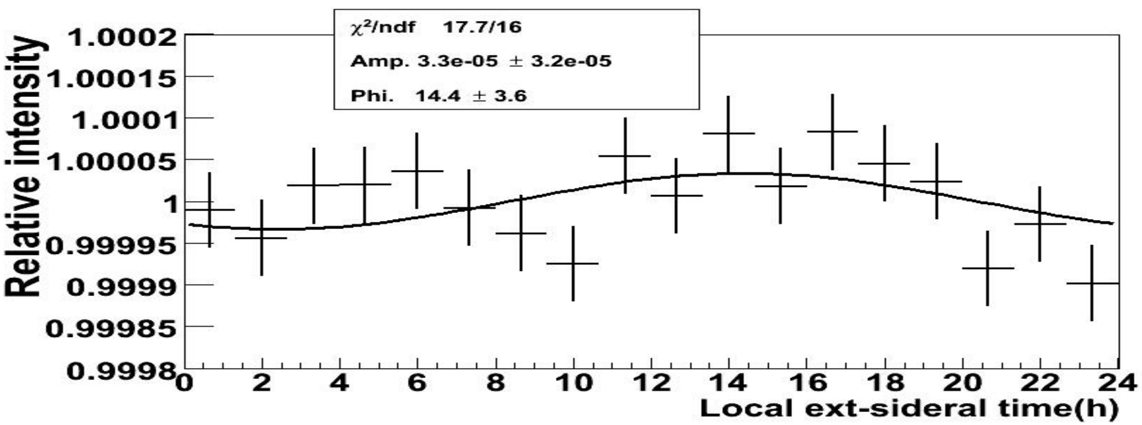


Anisotropy Observations in other periods



$$T = \frac{365.2422}{364.2422} \text{ Solar day}$$

Anti sidereal time

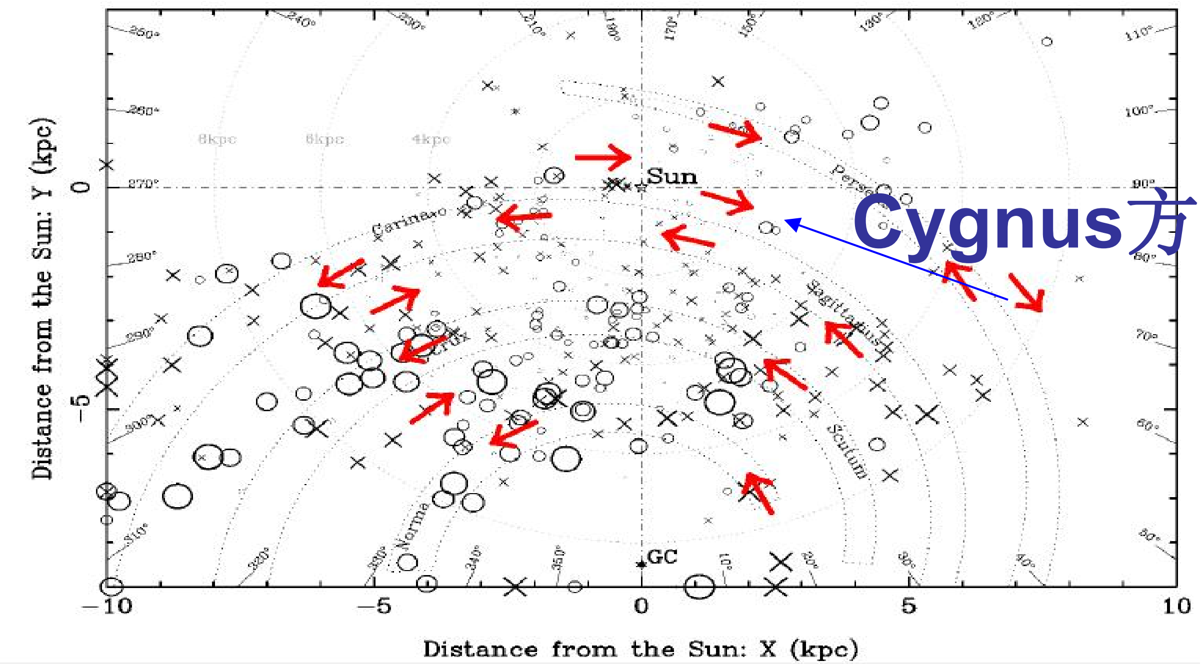


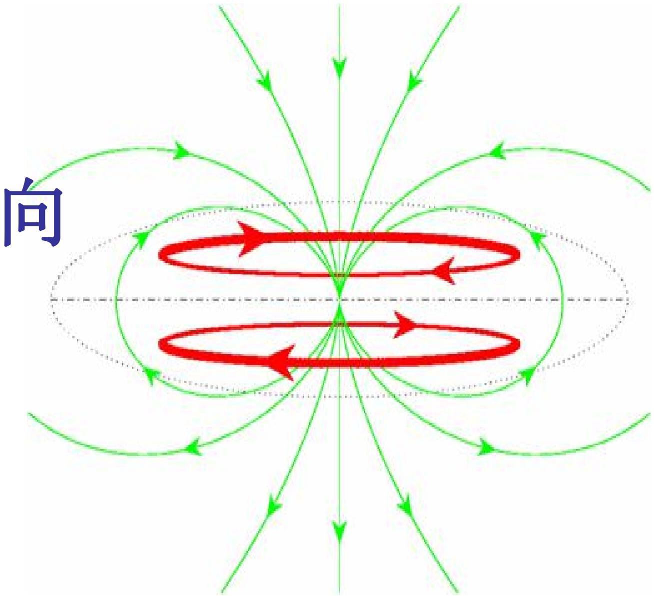
$$T = \frac{365.2422}{367.2422} \text{ Solar day}$$

Ext-sidereal time

No signal is expected, the amplitude observed is within statistic error.

银河宇宙线在磁场中传播



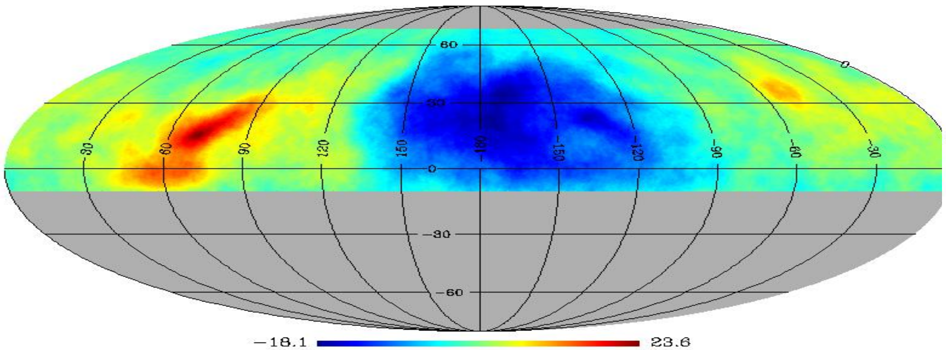


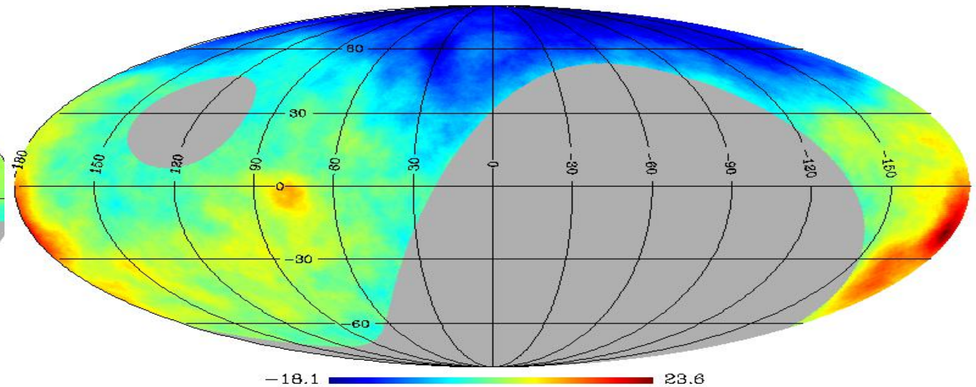
银河系磁场强度为3uG时

回旋半径 $r_L[pc] \approx \frac{E}{3 \times 10^{15} eV}$

3TeV对应0.001pc (200AU)

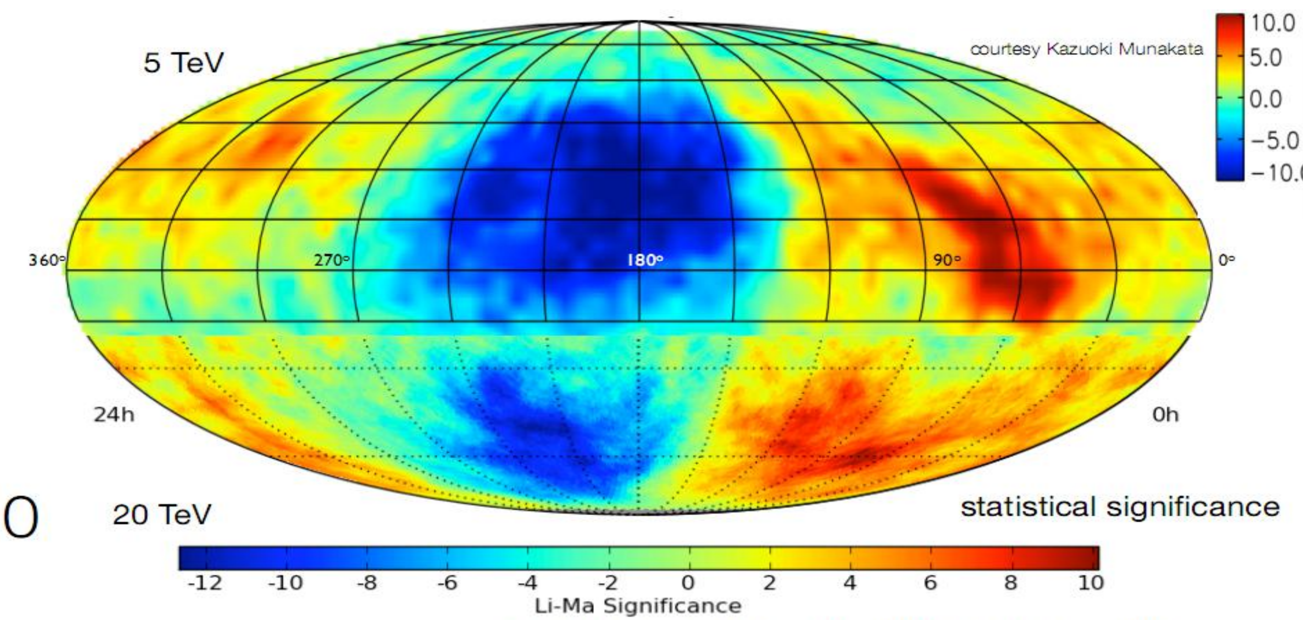
带电粒子在传播过程中受磁场影响而偏离其原本方向．星际磁场就像一个搅拌机，将宇宙线粒子搅拌得各向同性．





Tibet-III

(5° smoothing)

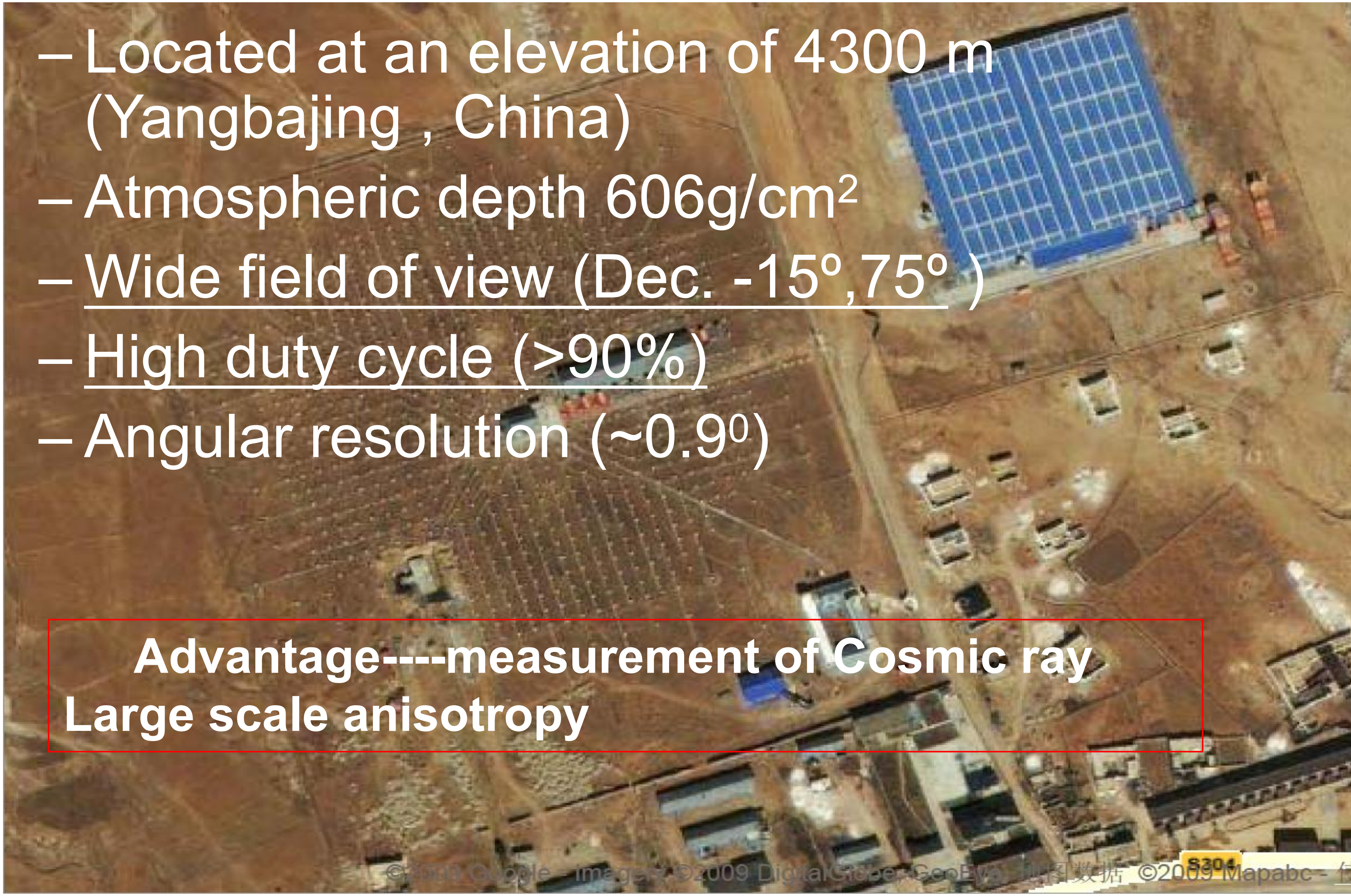


IceCube-40

(3° smoothing)

- data from March 2008 to May 2009

The Tibet Air shower Array

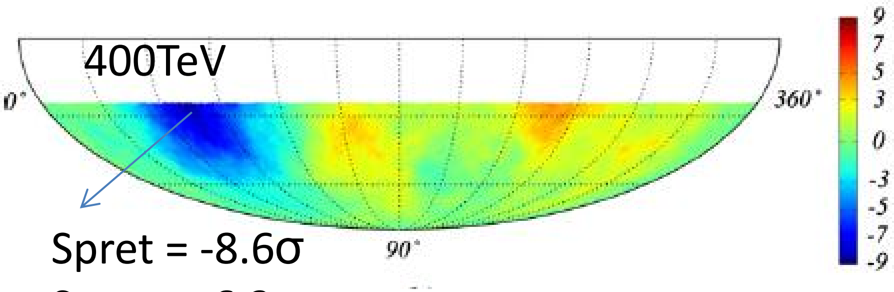


- Located at an elevation of 4300 m (Yangbajing , China)
- Atmospheric depth 606g/cm^2
- Wide field of view (Dec. -15º,75º)
- High duty cycle (>90%)
- Angular resolution (~0.9^0)

Advantage----measurement of Cosmic ray Large scale anisotropy

400 TeV anisotropy observations in Southern hemisphere

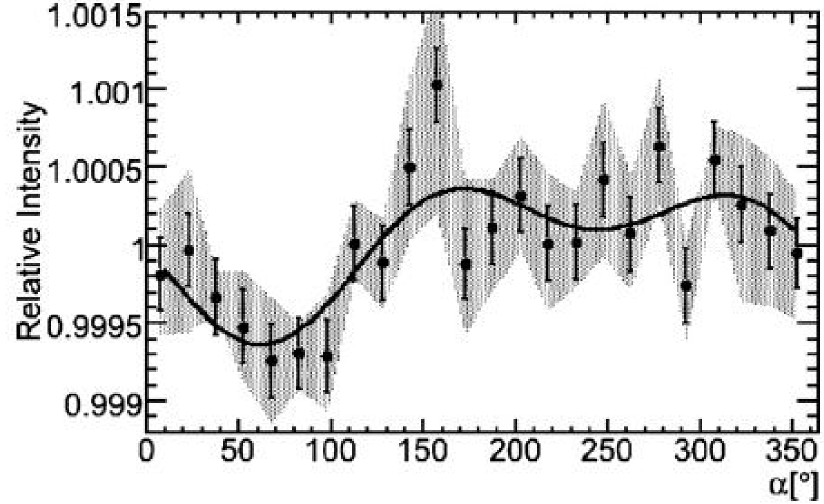
IceCube: new anisotropy structure



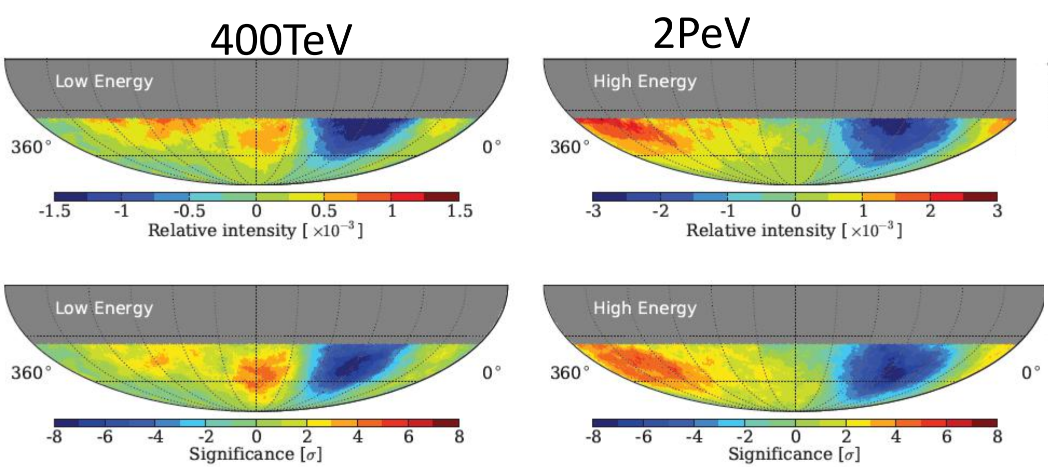
Spret = -8.6σ

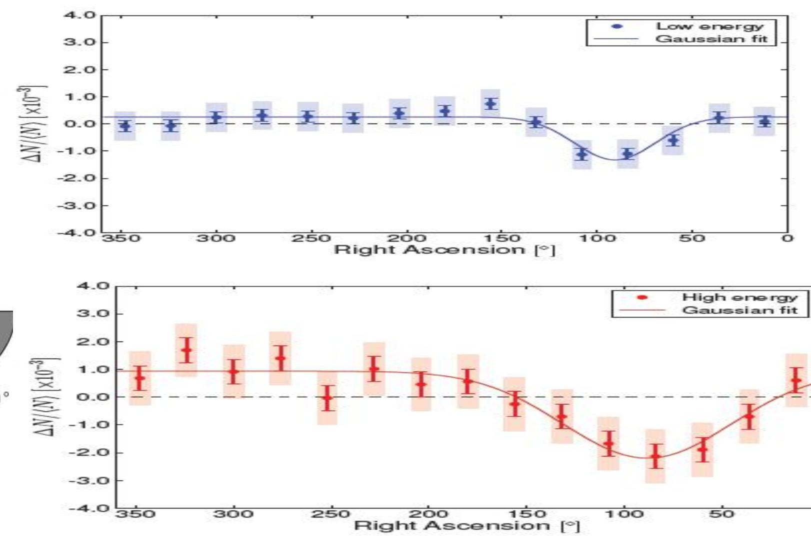
Spostt=-6.3σ

ApJ, 746, 33,,2012



IceTop: consist with IceCube results, persists to PeV energies



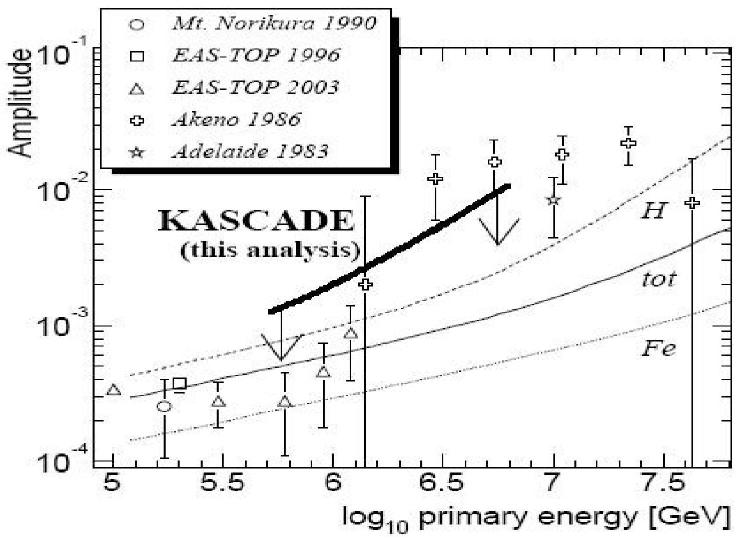


ApJ, 765, 55, 2013

Experiments results in Northern hemisphere

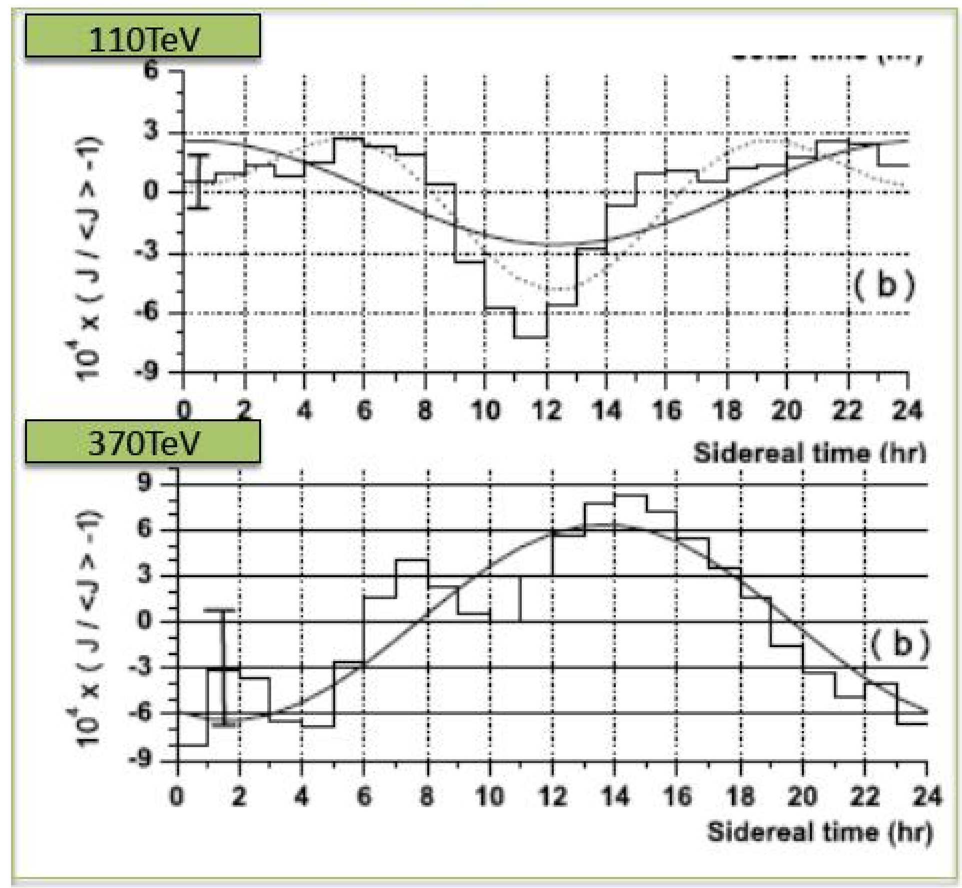
KASCADE: No anisotropy from 0.7-6PeV

EAS-TOP: sharp increase in the anisotropy for primary energies of ~370 TeV



2004, ApJ, 604,687

EAS-TOP



2009, ApJ, 692, L130