Recent results from the Tibet ASγ experiment

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for the Tibet ASγ collaboration

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Contents

1)Tibet ASγ experiment
2)Sun's Shadow (10 TeV)
3)Cosmic-ray Anisotropy (~10—1000 TeV)

The Tibet ASγ Collaboration

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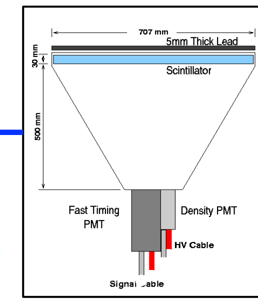
Tibet ASγ Experiment

At Yangbajing in Tibet, China (90.522° E, 30.102° N, 4,300 m a.s.l.)



Scintillation Counter Array : 0.5 m^2 x 789 counters

Effective area : ~ 37,000 m^2

Energy region : ~ TeV - 100 PeV

F.O.V. : ~ 2 sr

Relative timing → **Arrival direction**

Angular Resolution ~0.4° @10TeV

Charge → **Primary cosmic-ray energy**

Energy Resolution ~70% @10TeV

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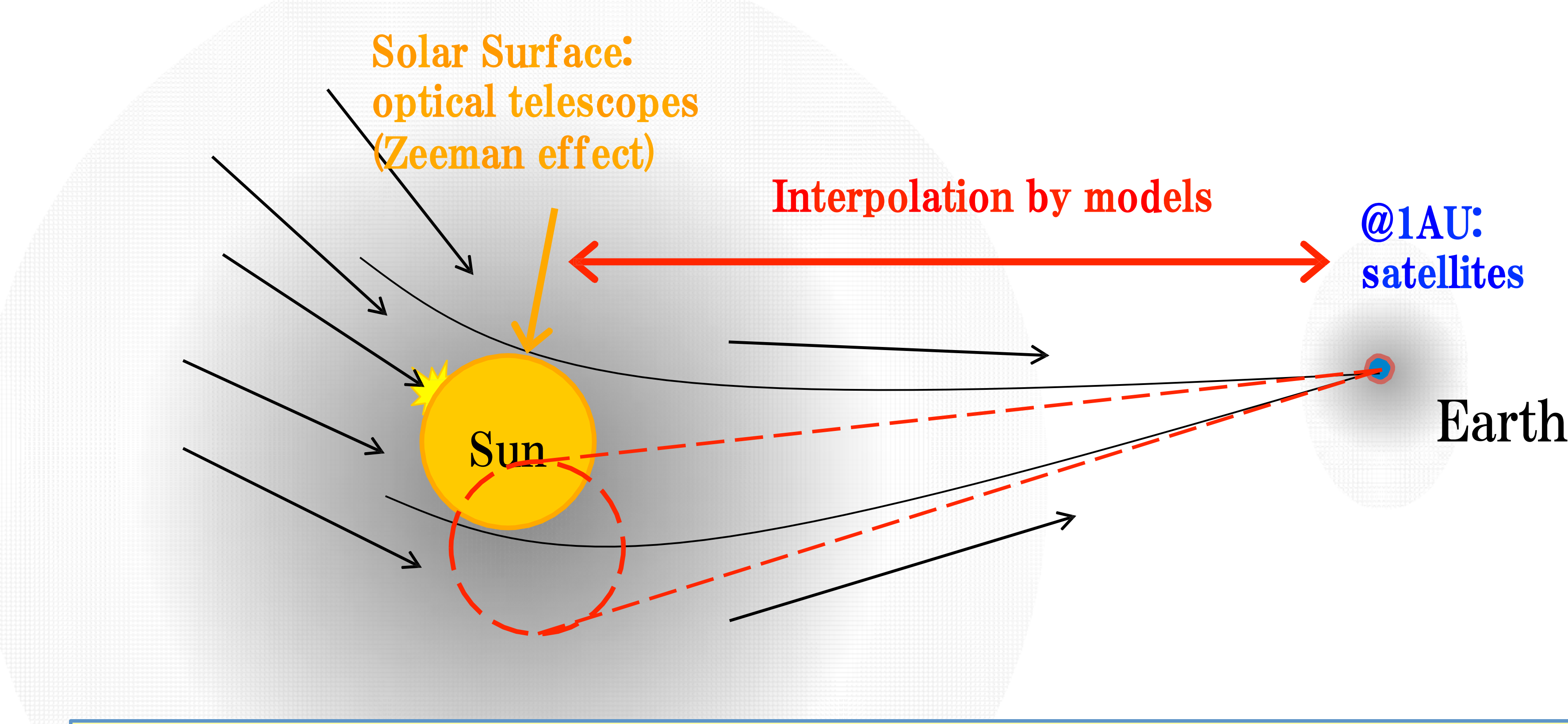
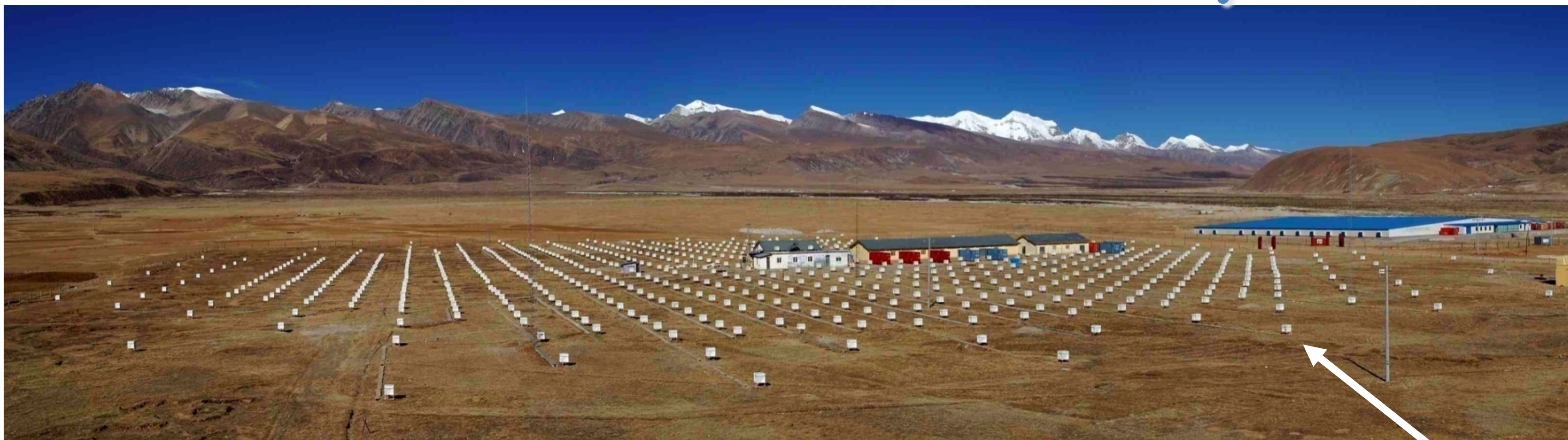
Sun's shadow

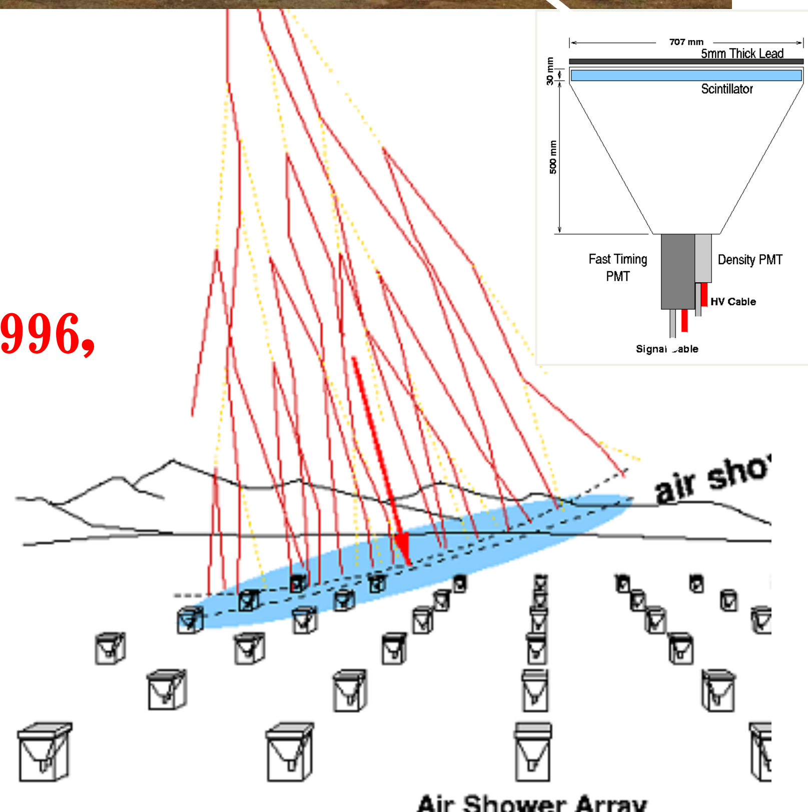
Shielding of cosmic rays by the Sun



TeV charged cosmic rays
Larmor radius
~7.4AU (B=30μ G near Earth)
~0.16$R_\odot$ (B=300mG near the Sun)
Capable of probing the structure of the heliospheric magnetic field

Tibet-III Air Shower Array





- Tibet (90.522°E, 30.102°N) 4300m a.s.l.

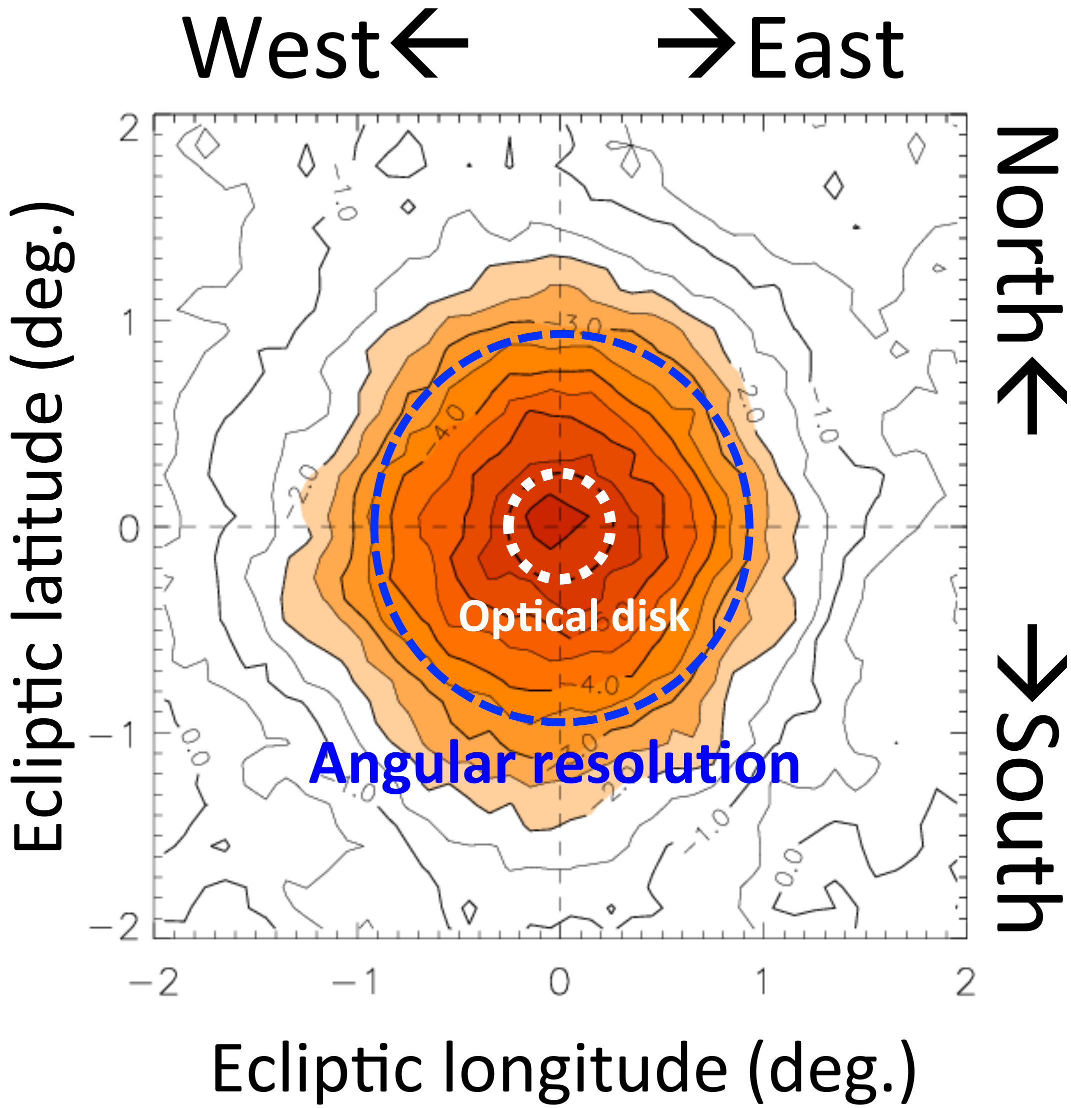
Solar cycle：11-year period
23rd solar cycle starts from 1996
→To keep the AS data consistency from 1996, we use the Tibet-II array configuration (221 detectors, 15m spacing)

- Modal Energy 10 TeV

- Angular Resolution 0.9°

Sun's shadow > 10TeV

Year 1996 (Solar min.)



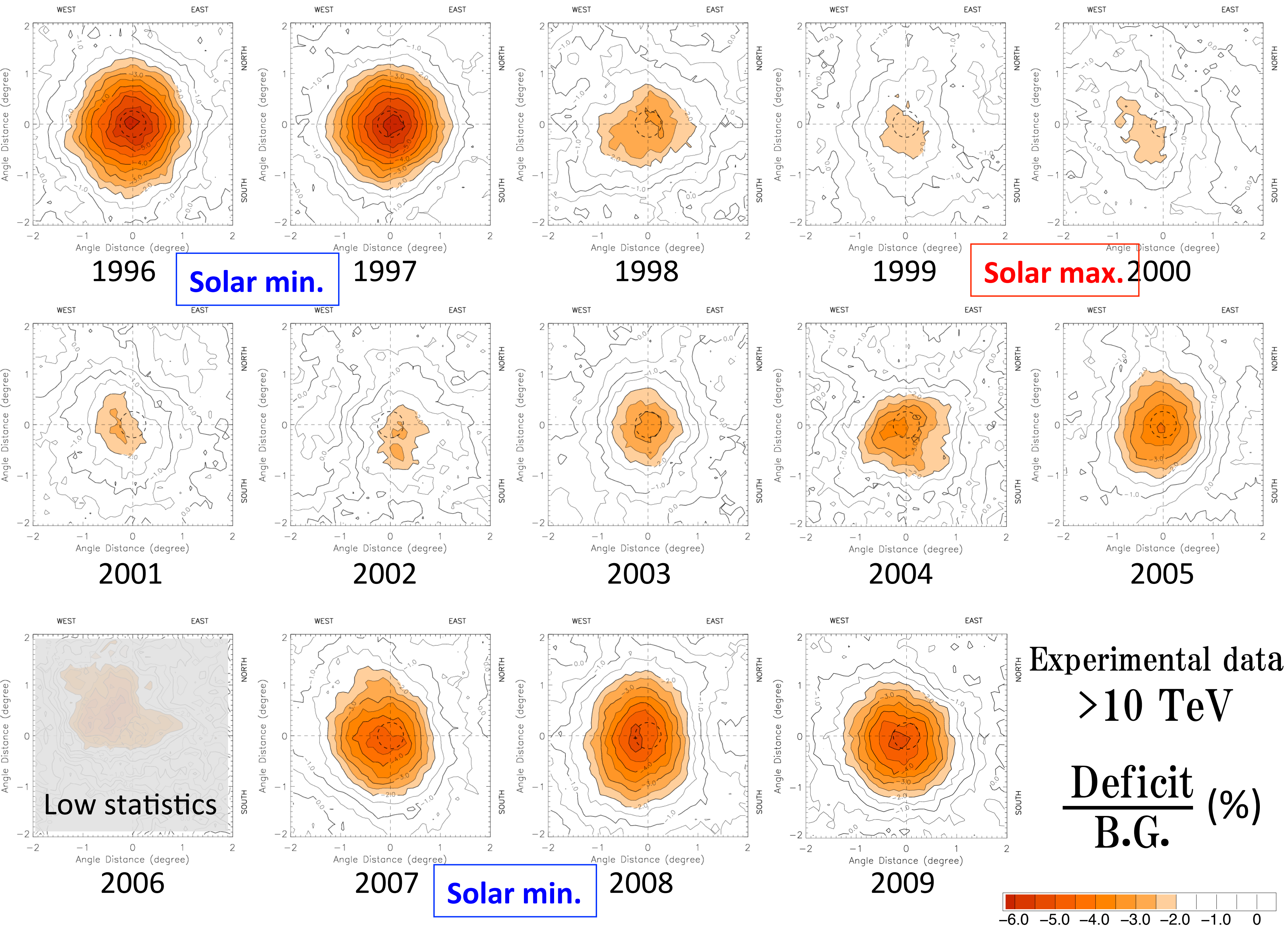
Map of deficit ratio
(= deficit / B.G.(%))

4^ox4^o around the Sun's optical position

Angular resolution (~0.9^o)

Optical disk radius (~0.26^o)

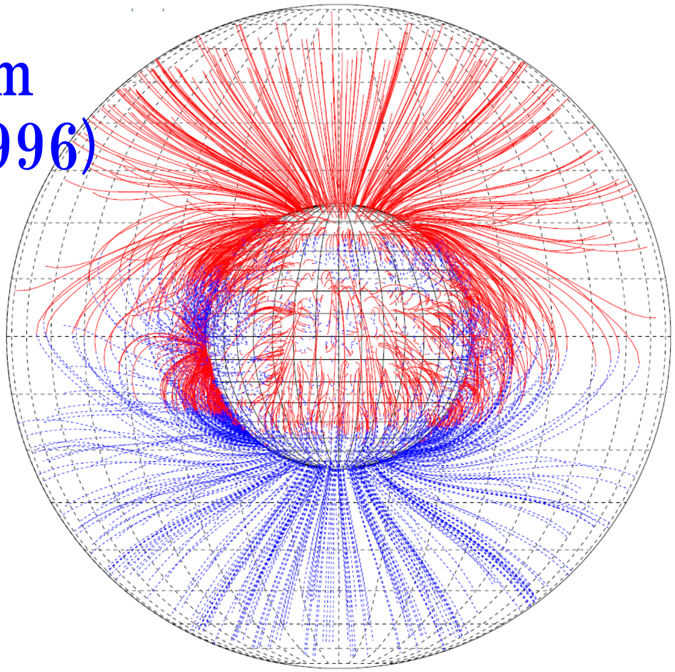
~6% deficit ratio

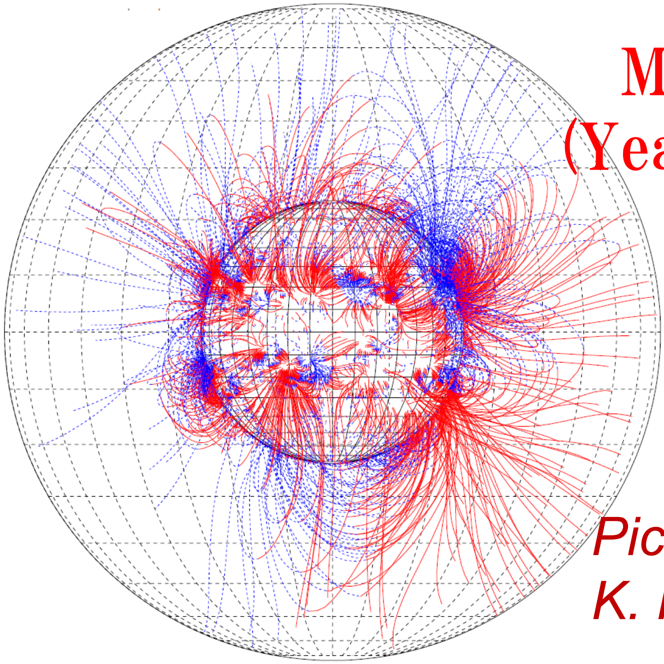

WEST
EAST
NORTH
SOUTH
Angle Distance (degree)
1996
Solar min.
1997
1998
1999
Solar max.
2000
2001
2002
2003
2004
2005
2006
Low statistics
2007
Solar min.
2008
2009
Experimental data
>10 TeV
Deficit / B.G. (%)
−6.0 −5.0 −4.0 −3.0 −2.0 −1.0 0

Magnetic fields (MC)

Geomag. -> Dipole model
IMF -> Parker Spiral Model
including latitudinal dependence of solar wind
Coronal -> Source Surface models (PFSS / CSSS)
derived from photospheric MF observation
for each Sun rotation (~27 days)

Minimum
(year 1996)
PFSS





Maximum
(Year 2000)
PFSS

Pictures from K. Hakamada

Source Surface models (MC)

1. PFSS (Potential Field Source Surface) [widely used]

   assumes electric currents are negligible in the corona

$$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = -\nabla\Psi$$

$$\nabla \cdot \mathbf{B} = 0$$

→ Laplace Equation

$$\nabla^2 \Psi = 0$$

Hakamada, Solar Physics (1995)

2. CSSS (Current Sheet Source Surface)

   includes large-scale horizontal currents

$$\frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla \mathbf{p} - \rho \frac{GM}{r^2}\hat{\mathbf{r}} = 0$$

Magnetostatic force balance equation

→

$$\mathbf{J} = \frac{1}{\mu_0 r}[1-\eta(r)]\left[\frac{1}{\sin\theta}\frac{\partial^2\Psi}{\partial\phi\partial r}\hat{\theta} - \frac{\partial^2\Psi}{\partial\phi\partial r}\hat{\phi}\right]$$

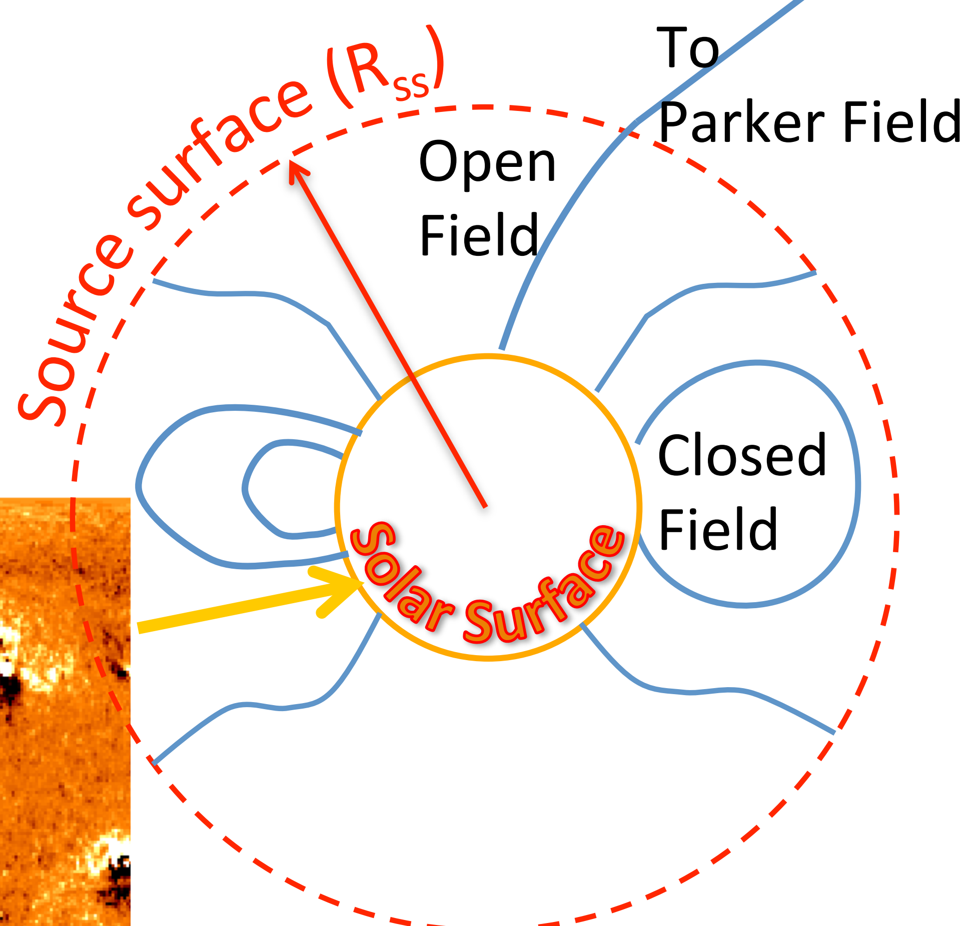
$$\mathbf{B} = -\eta(r)\frac{\partial\Psi}{\partial r}\hat{r} - \frac{1}{r}\frac{\partial\Psi}{\partial\theta}\hat{\theta} - \frac{1}{r\sin\theta}\frac{\partial\Psi}{\partial\phi}\hat{\phi}$$

Zhao & Hoeksema, JGR (1995)

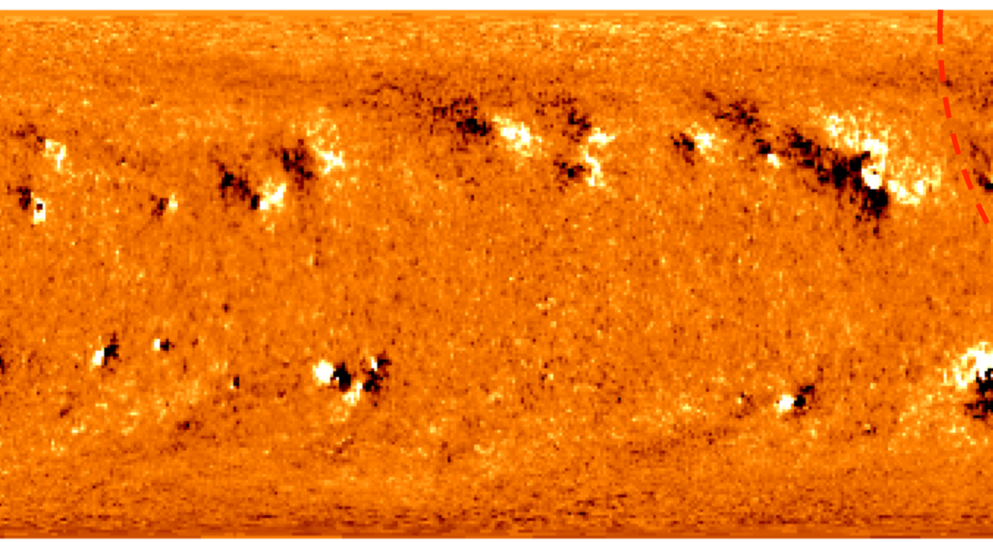
Source Surface

B is calculated from measured photospheric magnetic fields using Maxwell equation. The source surface is defined as a boundary spherical surface where magnetic field lines become purely radial.

Standard R_{ss}=～$2.5R_{\odot}$

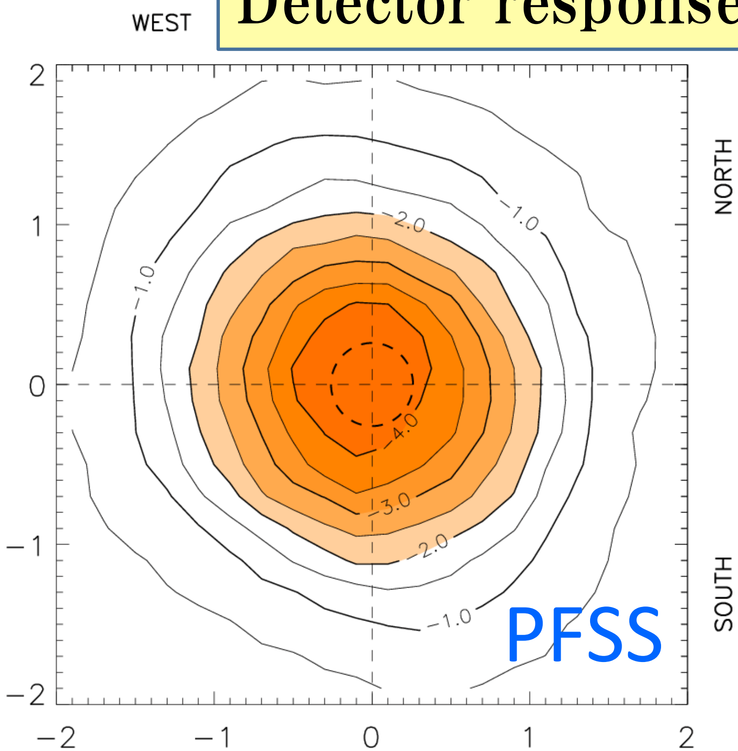


Magnetograph (Zeeman Effect)
Kitt Peak Vacuum Telescope
(FeI 868.8, 630.1 and 630.2nm)

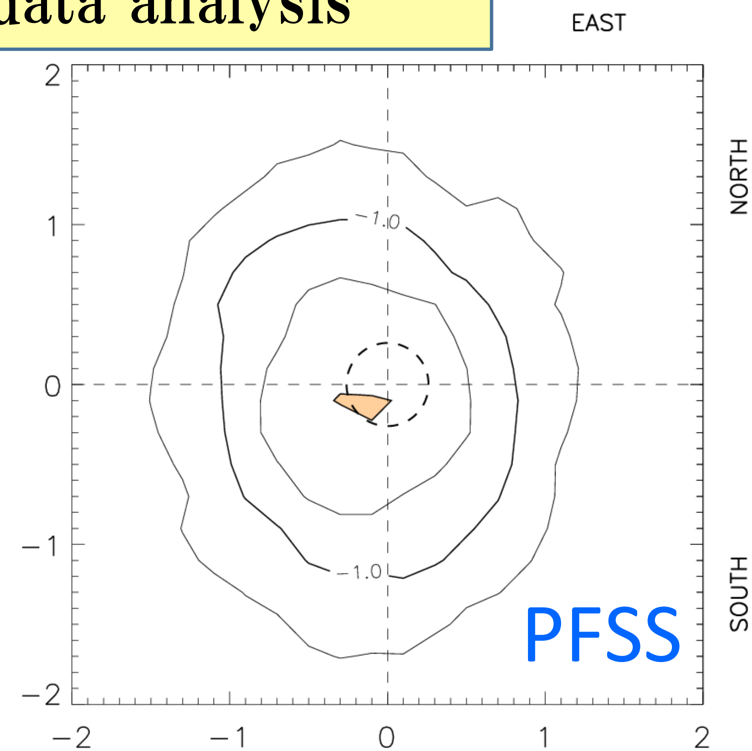


Examples of MC Results

Density map of events hitting the Sun
MC takes into account
CR composition & spectra
Detector response & data analysis

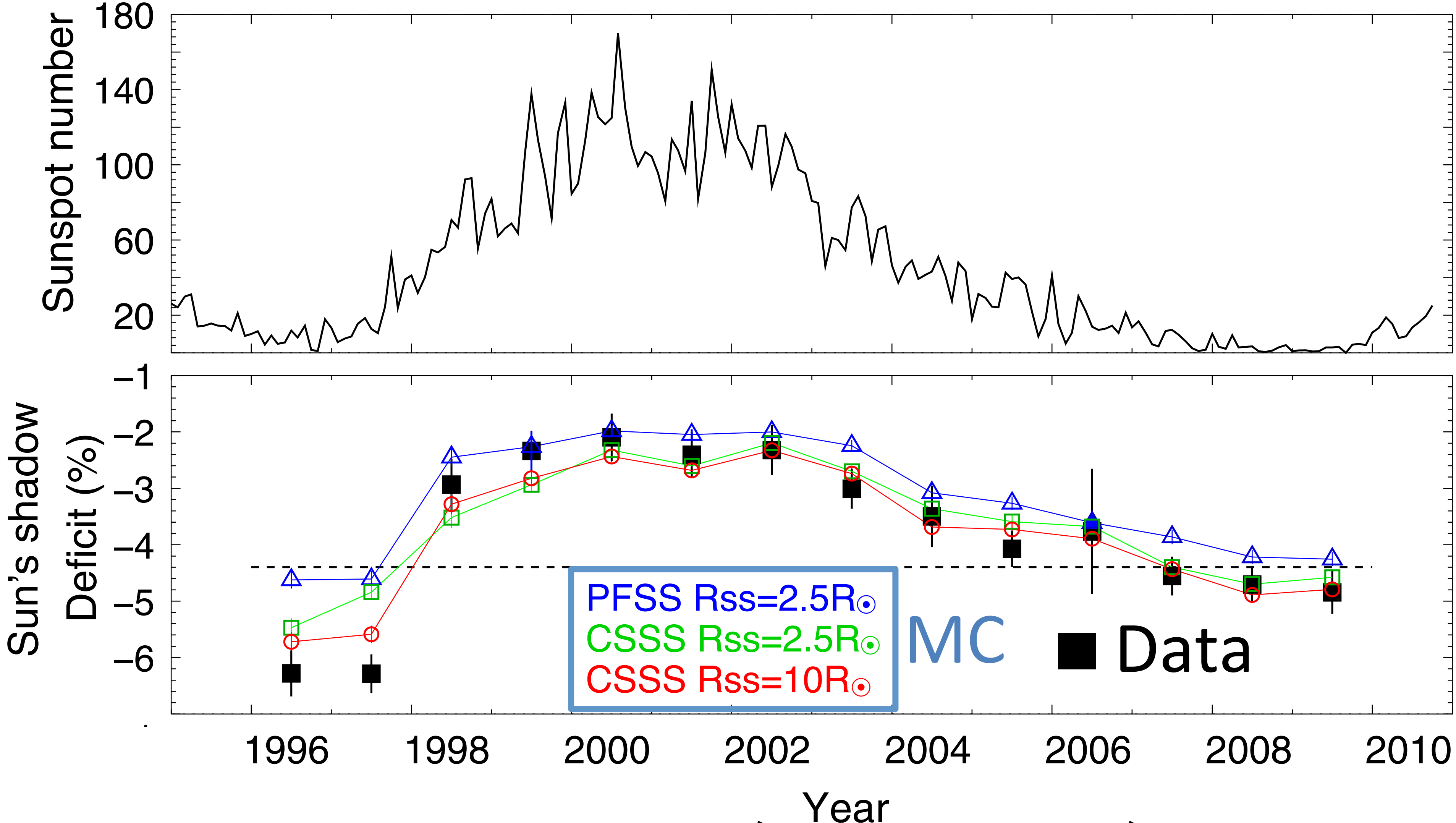


Soalr Minimum
in 1996



Solar Maximum
In 2001

Sun's Shadow : yearly variation >10TeV



PFSS : unrealistic ($\chi 2$/d.o.f. = 55.2/14)

CSSS : OK ($\chi 2$/d.o.f. = 10.3/14)

Sun's Shadow : Summary

- Observed Sun's shadow from 1996 to 2009 @ 10 TeV (23rd cycle of solar activity)

- Found that Sun's shadow is sensitive to solar coronal magnetic field structures

- Found that the CSSS (Current Sheet Source Surface) model well reproduces the yearly variation of the Sun's shadow

First successful attempt to evaluate the Sun's coronal MF models using the Sun's shadow

*Reference: M. Amenomori et al., Phys. Rev. Lett., **111**, 011101 (5pp) (2013)*

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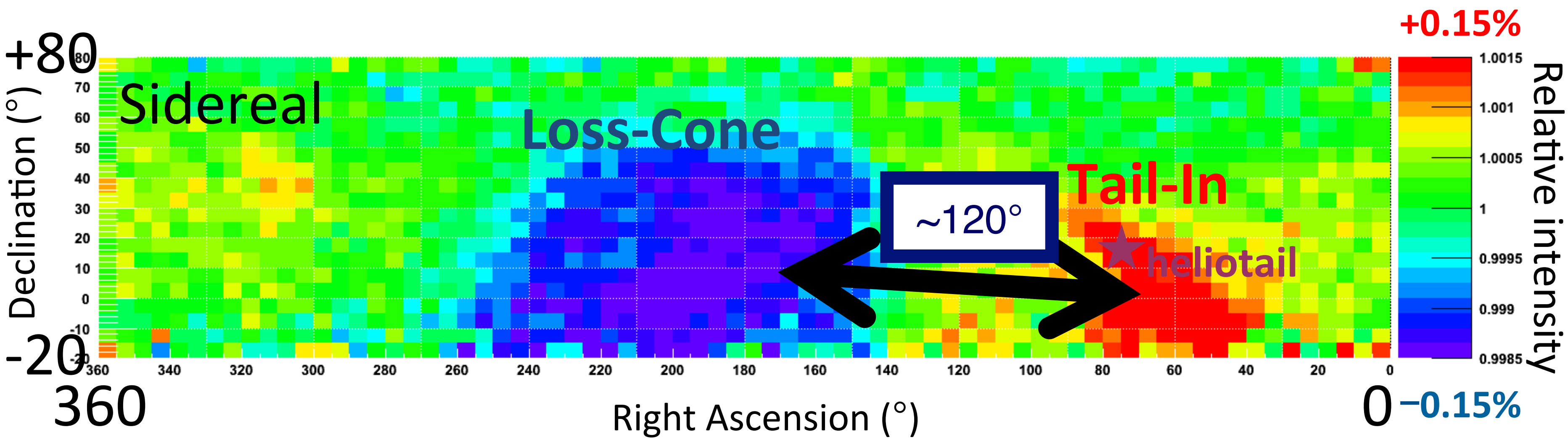
Large-scale sidereal anisotropy map (> 7 TeV)



Possible models :

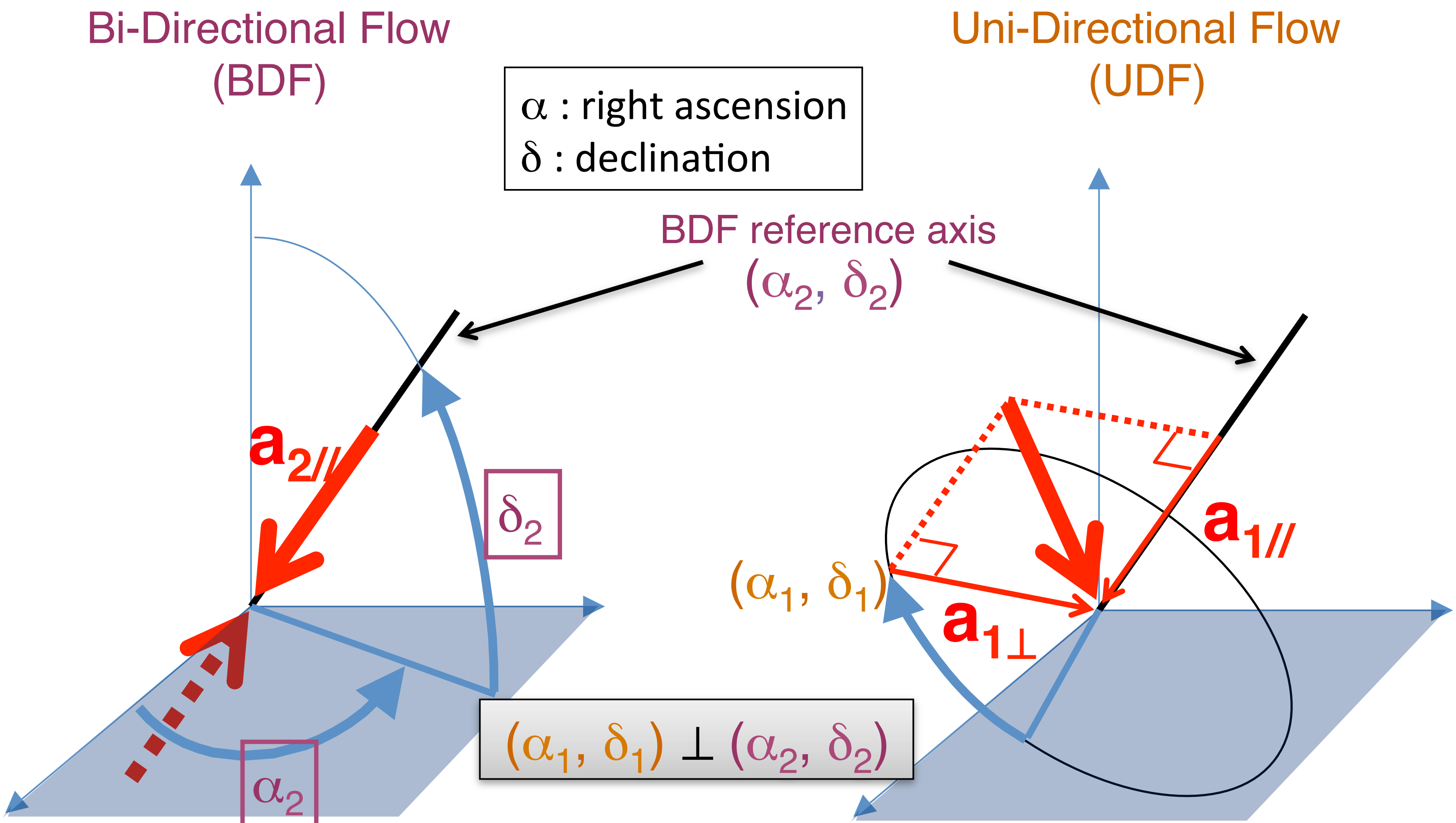
M. Amenomori et al., Astrophys. Space Sci. Trans., 6, 49 (2010)
M. Zhang et al., ApJ, 790, 5 (2014)
N. A. Schwadron et al., Science, 343, 988 (2014)
X. B. Qu et al., ApJL, 750, L1 (2012)

Global Anisotropy Model

90° < 120° < 180°

Bi-directional flow (BDF) + Uni-directional flow (UDF)

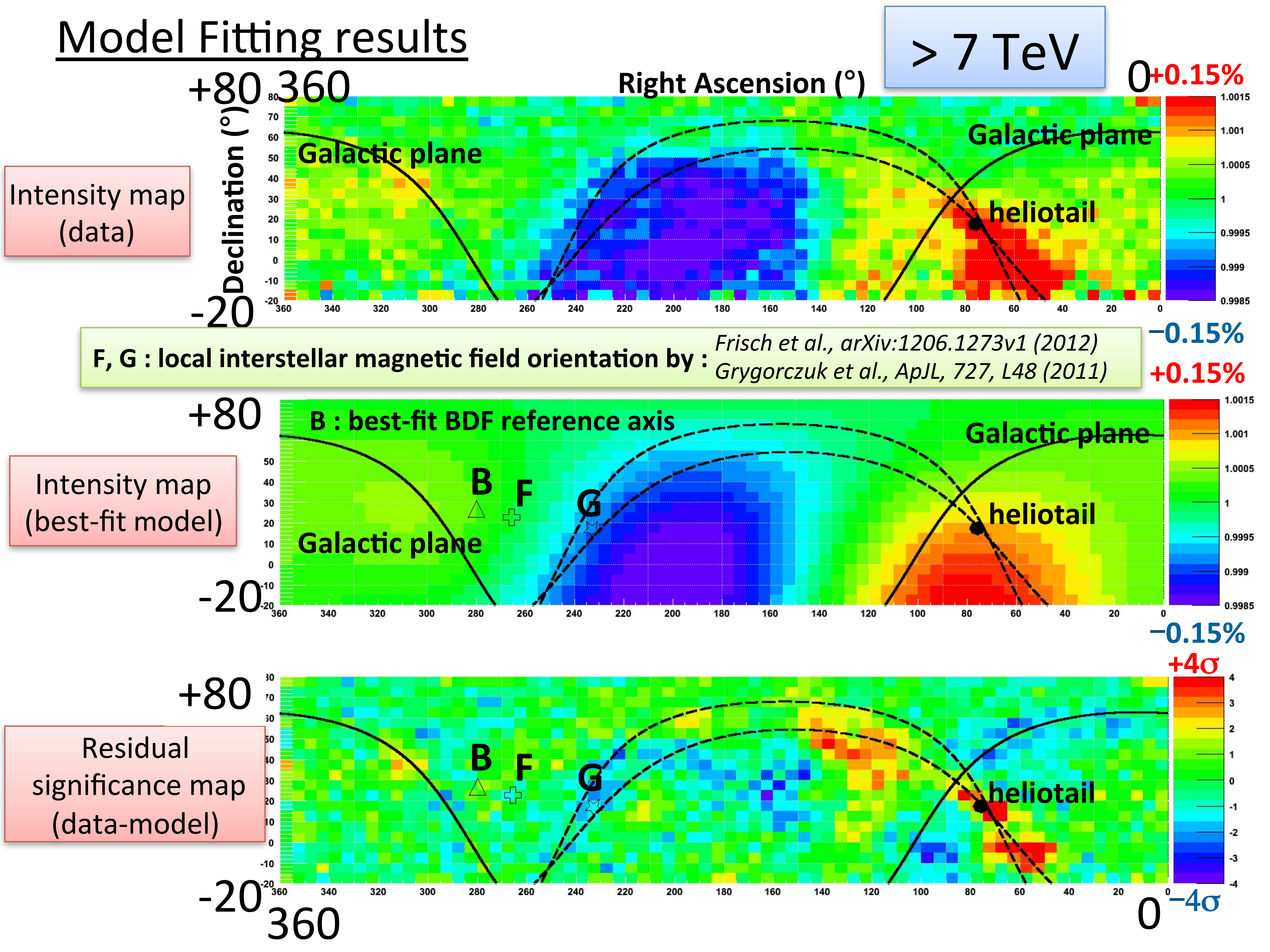
Global Anisotropy Model



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

$$+ \underbrace{a_{2\parallel}\cos^2\chi_2(n,m:\alpha_2,\delta_2)}_{\text{BDF}}$$

$\chi_{1,2}$: angular distance
from the axis (α_1, δ_1) or (α_2, δ_2)



Model Fitting results
> 7 TeV
Right Ascension (°)
Declination (°)
Intensity map (data)
Galactic plane
heliotail
+0.15%
−0.15%
F, G : local interstellar magnetic field orientation by : Frisch et al., arXiv:1206.1273v1 (2012) Grygorczuk et al., ApJL, 727, L48 (2011)
Intensity map (best-fit model)
B : best-fit BDF reference axis
B
F
G
Residual significance map (data-model)
+4σ
−4σ
+80
−20
360
0

Discussion : Global Anisotropy (1)

> 7 TeV

a1⊥ (%)	a1// (%)	a2// (%)	α1 (°)	δ1 (°)	α2 (°)	δ2 (°)
0.139±0.002	0.007±0.002	0.131±0.004	33.3±1.1	38.4±1.2	279.9±0.9	26.7±2.0

◆BDF (Bi-Directional Flow) : cosmic-ray inflow along the local interstellar magnetic field (LISMF)

◆UDF (Uni-Directional Flow)

a1// << a1⊥ ➡ **UDF ⊥ BDF, thus ⊥ LISMF**

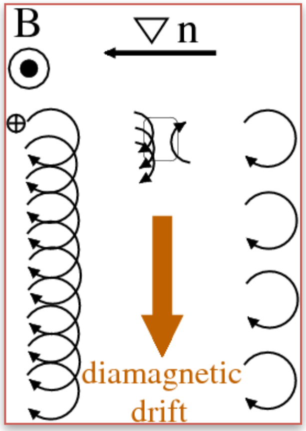
a1⊥ ~ a2// ➡ **UDF ~ BDF in amplitude**

For 7TeV cosmic rays, Larmor radius $R_L \sim 0.002$pc (in 3μG)

scattering m.f.p. λ// ~ 3pc *(Moskalenko V. et al, ApJ, 534, 825 (2000))*

Bohm factor λ// ÷ $R_L \sim 1500 >> 1$ ∴ perpendicular diffusion is negligible.

➡ Diamagnetic drift caused by the cosmic-ray density gradient in LISMF



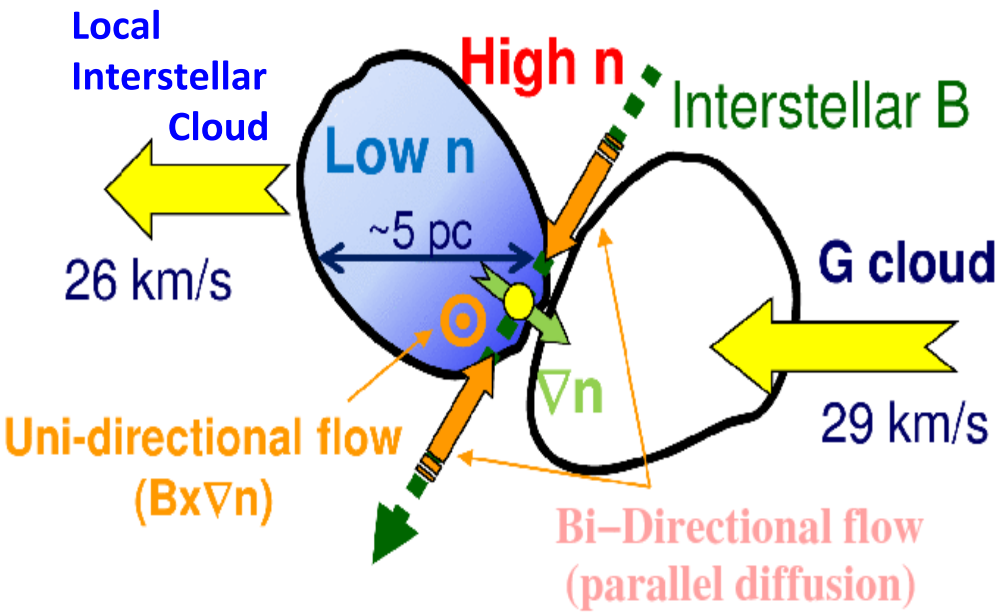
$$a_{1\perp} = \left|\frac{\nabla n}{n}\right| r_L \sim \frac{1}{n}\frac{n}{L} r_L = \frac{r_L}{L}$$

(L : scale of density gradient ∇n)

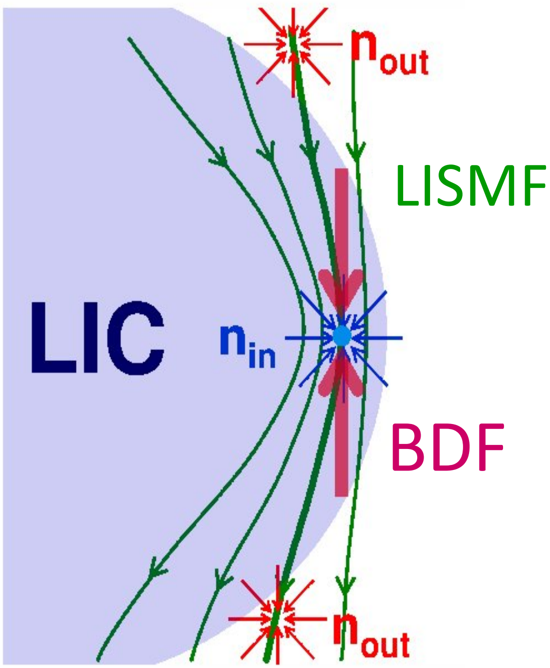
$$L = R_L / a1\perp \sim 2\text{pc}$$

Local interstellar space (~2pc) surrounding the heliosphere would be responsible for Global Anisotropy.

Discussion : Global Anisotropy (2)



Lallement et al., Science, 307, 1447 (2005)
Redfield & Linsky, ApJ, 534, 825 (2000)



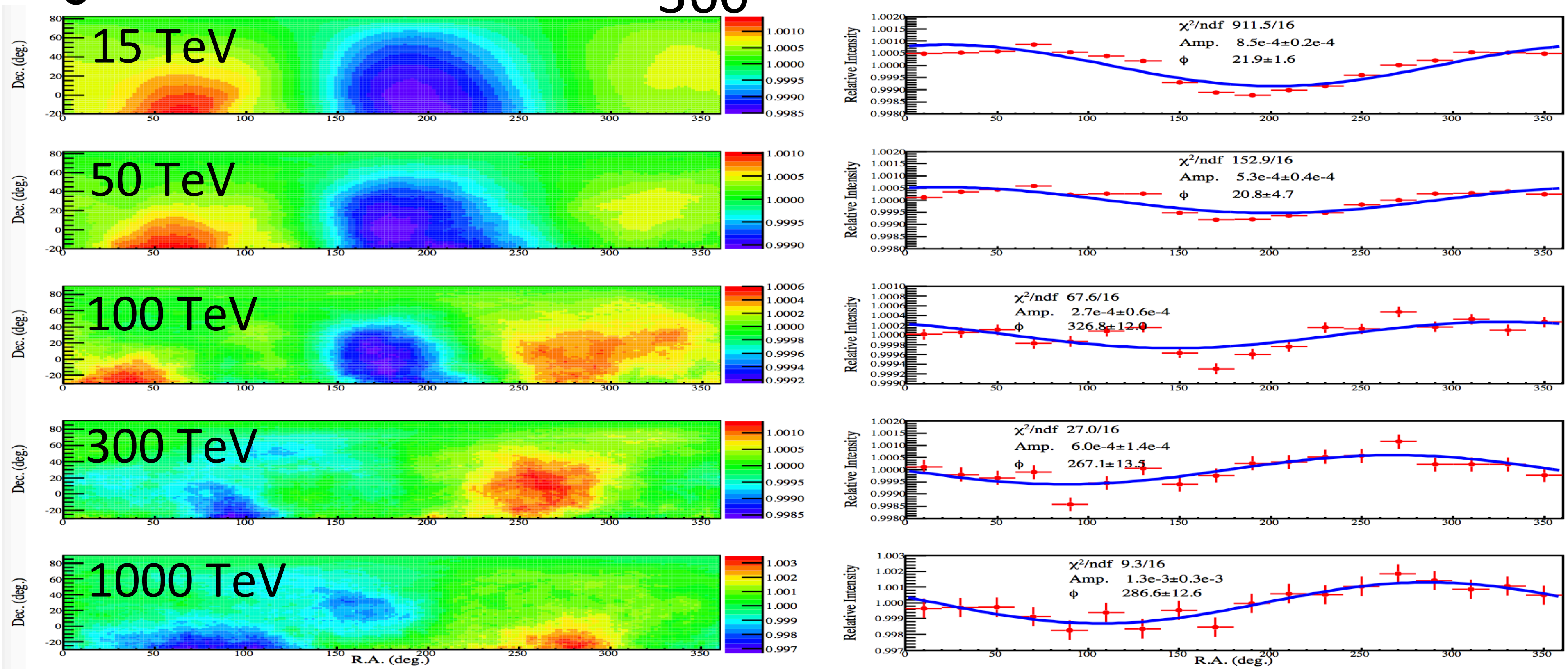
Hypotheses

- LISMF is compressed in the region between LIC and G cloud, causing magnetic-mirror effect that generates BDF.
- Adiabatic expansion of LIC makes CR number density within LIC smaller than outside, creating a steady ∇n.
- Diamagnetic drift by CR density gradient in LISMF creates UDF.

Transition of the large-scale sidereal anisotropy (10 TeV —1000 TeV)

M. Amenomori et al., ICRC2015 (id355)

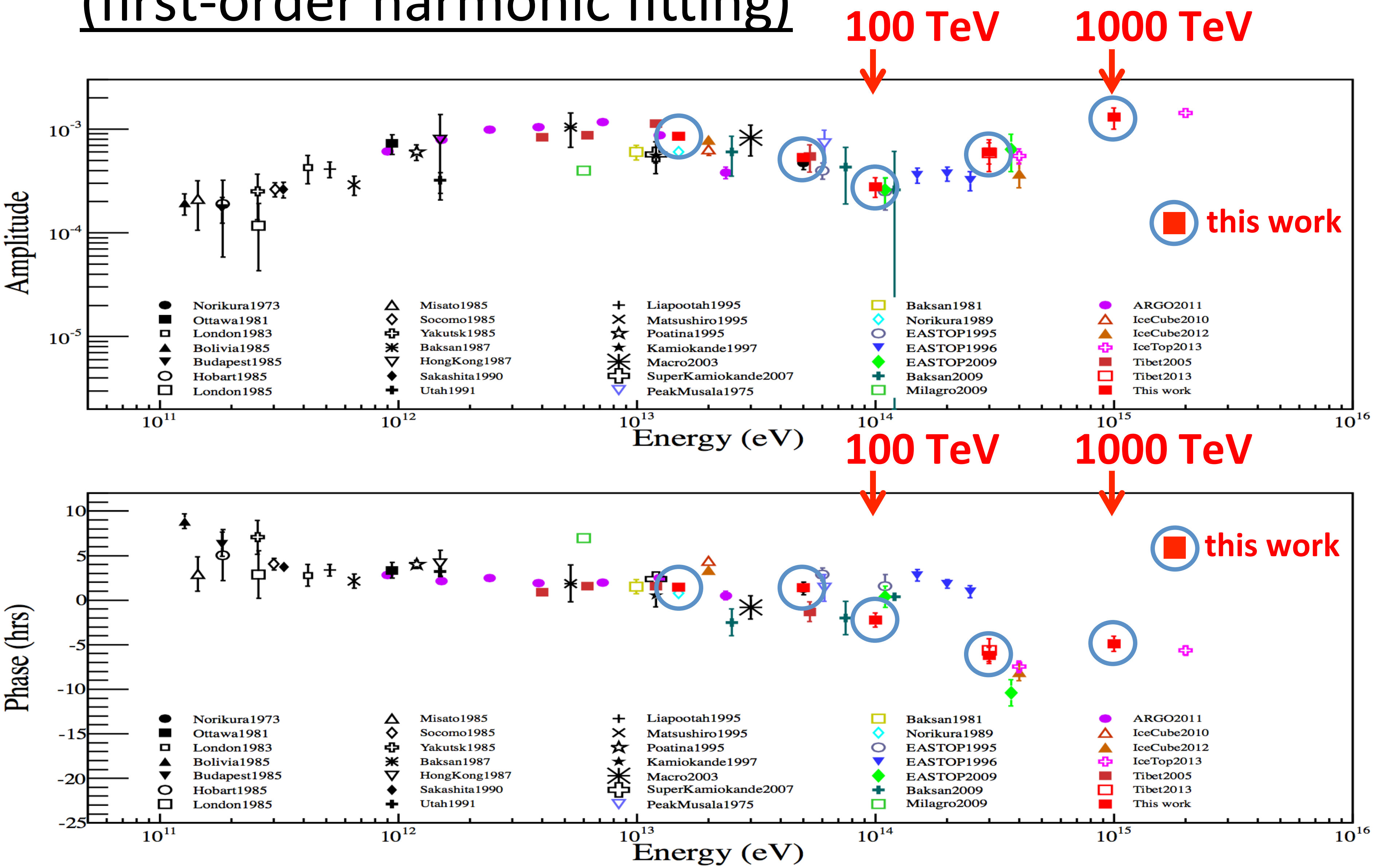
0 360



Above ~300 TeV

- Global Anistropy Model no longer applicable
- Anisotropy originating in **space farther than a few parsecs** surrounding heliosphere

Energy Dependence of Amplitude & Phase (first-order harmonic fitting)



Large-scale sidereal anisotropy : Summary

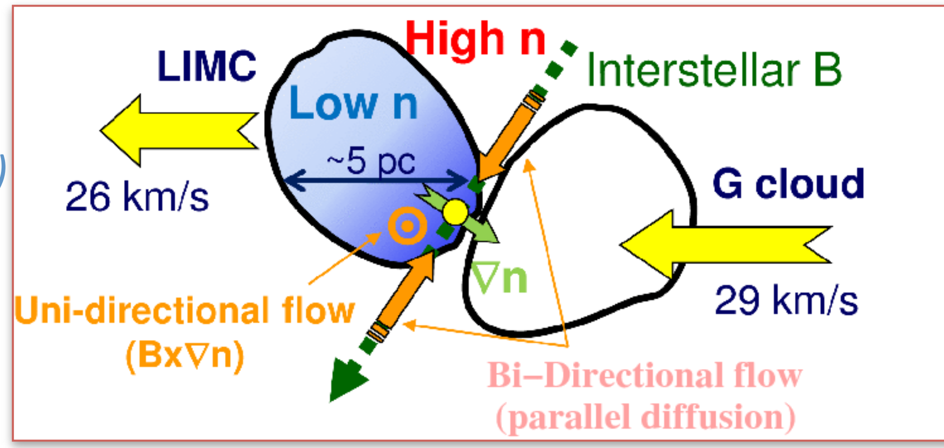
Origin of the galactic cosmic-ray anisotropy

◆ TeV energies

Our model **In the local interstellar space (~2pc for 7TeV cosmic rays)**

Combination of **the bi-directional inflow** along the local interstellar magnetic field and **the uni-directional flow** of the diamagnetic drift caused by the cosmic-ray density gradient in it.

*M. Amenomori et al., Astrophys. Space Sci. Trans., **6**, 49–52, (2010)*



◆ Above ~300 TeV

— Model in **space farther than a few parsecs surrounding heliosphere** must be considered