Modeling of the high-energy galactic cosmic-ray anisotropy

Takashi Sako
on behalf of the Tibet ASγ experiment

The Tibet ASγ Collaboration

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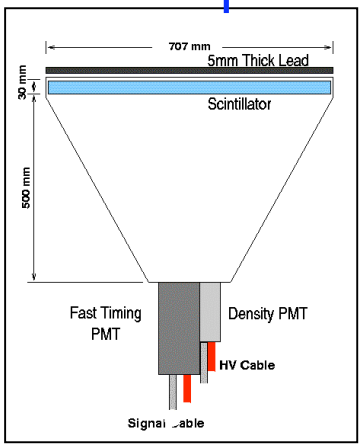
Tibet ASγ Experiment

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 information ➡ **Arrival direction**
Angular Resolution ~0.4° @10TeV
Charge information ➡ **Primary cosmic-ray energy**
Energy Resolution ~70% @10TeV

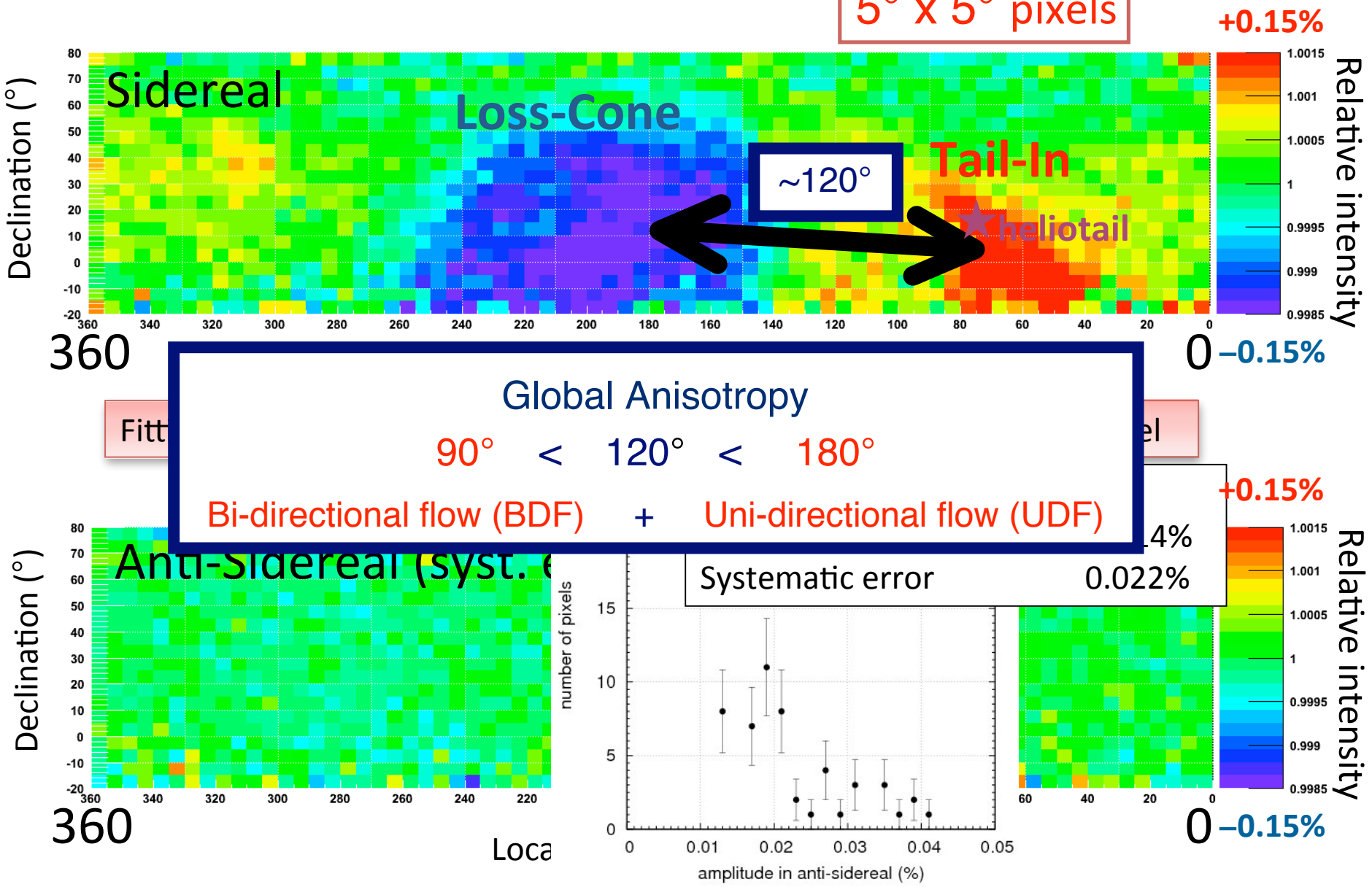


Data used in this talk : 1999 Nov. – 2008 Dec. (1,916 live days)

9.1 x 10^{10} events, modal energy 7TeV

Anisotropy map @ 7 TeV

5° x 5° pixels

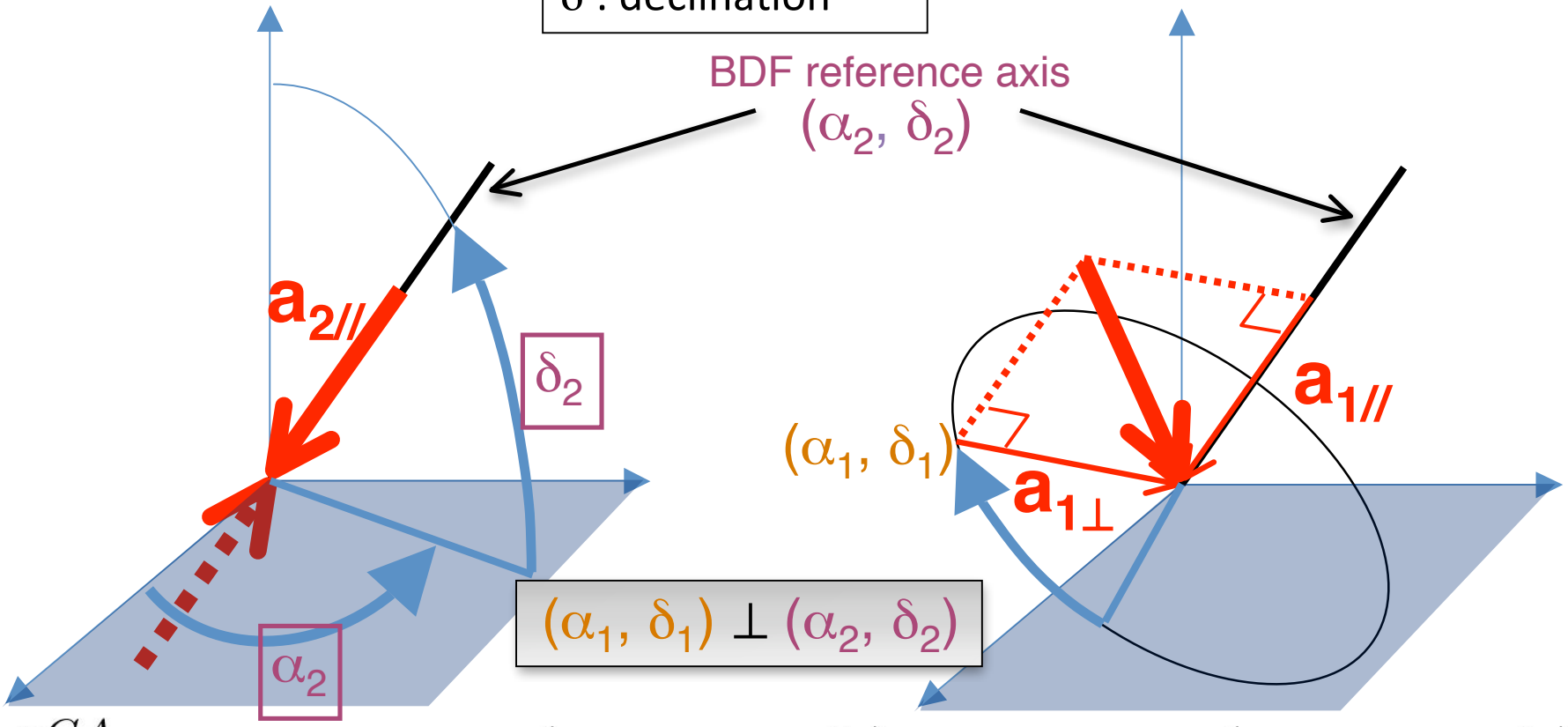


Global Anisotropy (GA) in GA+AE model

Bi-Directional Flow (BDF)

Uni-Directional Flow (UDF)

α : right ascension
δ : declination

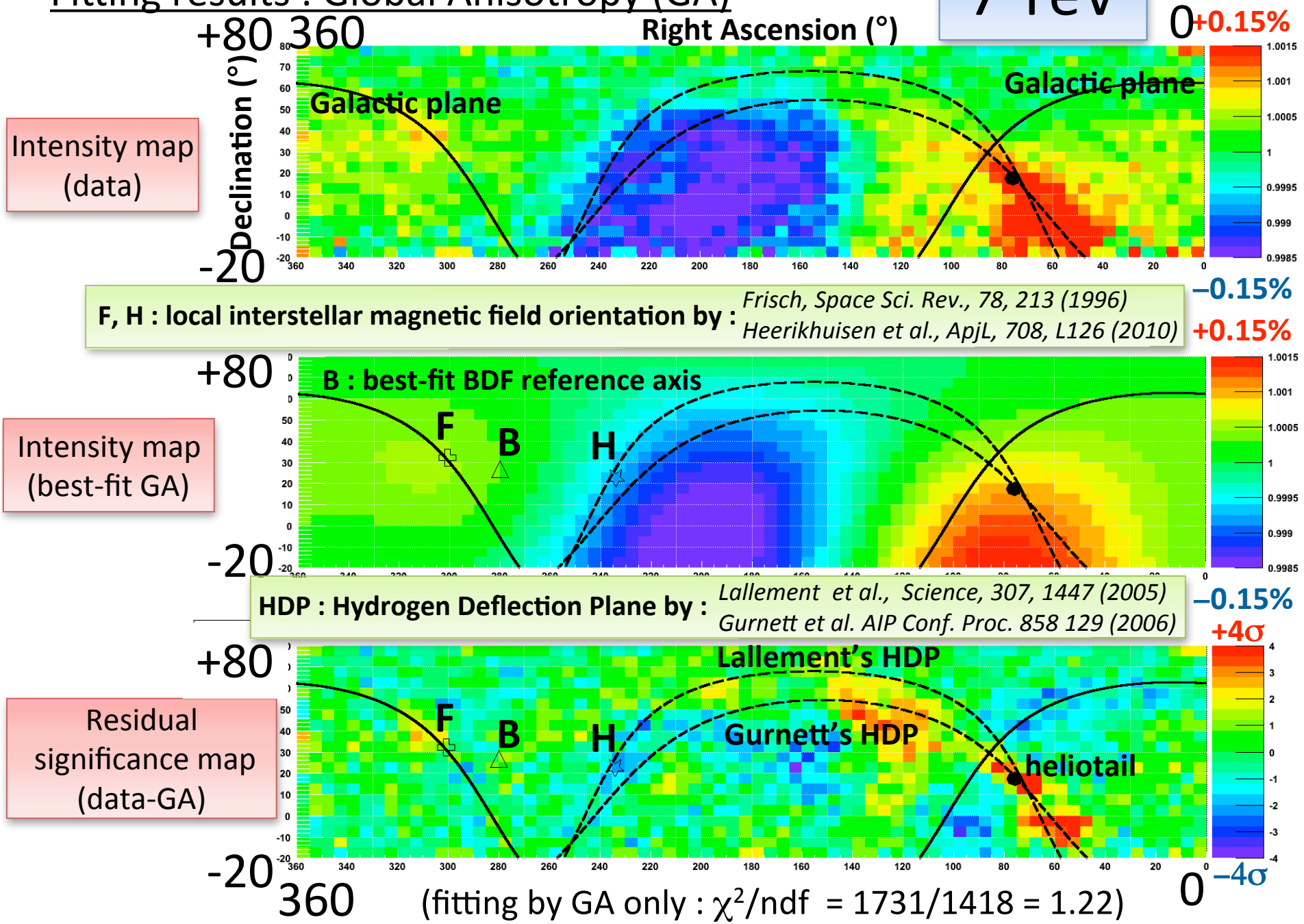


$$I^{GA}_{n,m} = \underbrace{a_{1\perp} \cos\chi_1(n,m:\alpha_1,\delta_1) + a_{1\parallel} \cos\chi_2(n,m:\alpha_2,\delta_2)}_{\text{UDF}} + \underbrace{a_{2\parallel} \cos^2\chi_2(n,m:\alpha_2,\delta_2)}_{\text{BDF}}$$

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

Fitting results : Global Anisotropy (GA)

7 TeV



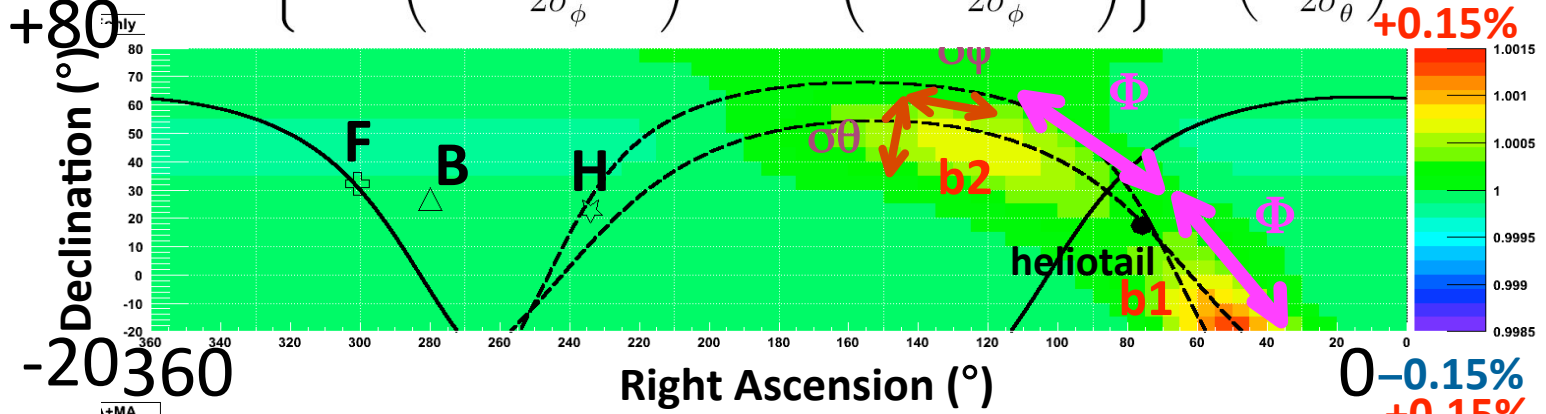
Fitting results : Midscale Anisotropy (MA)

7 TeV

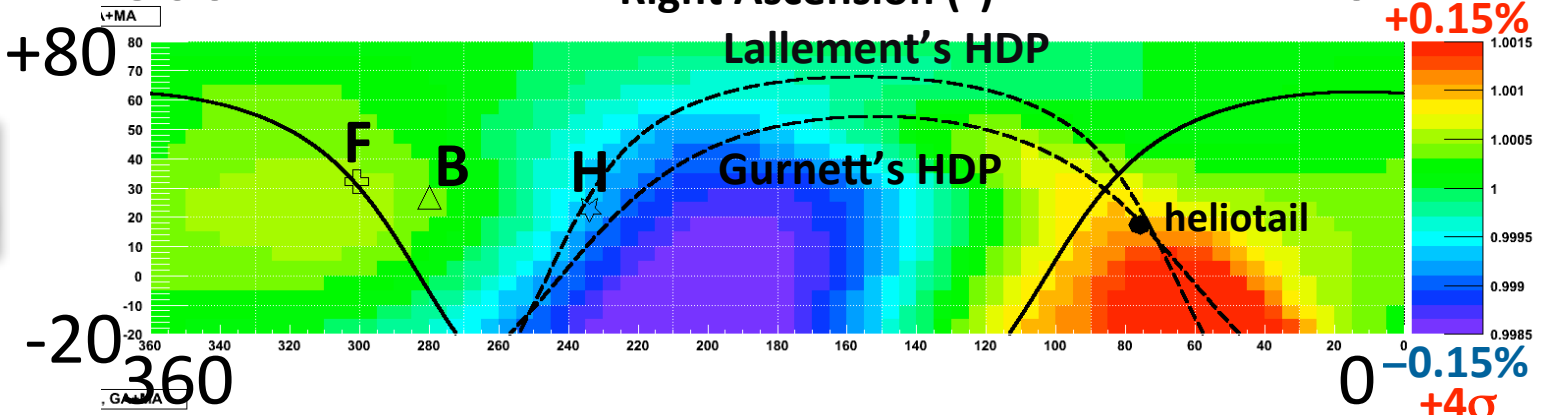
φn,m : longitude from heliotail direction on HDP
θn,m : latitude from HDP

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

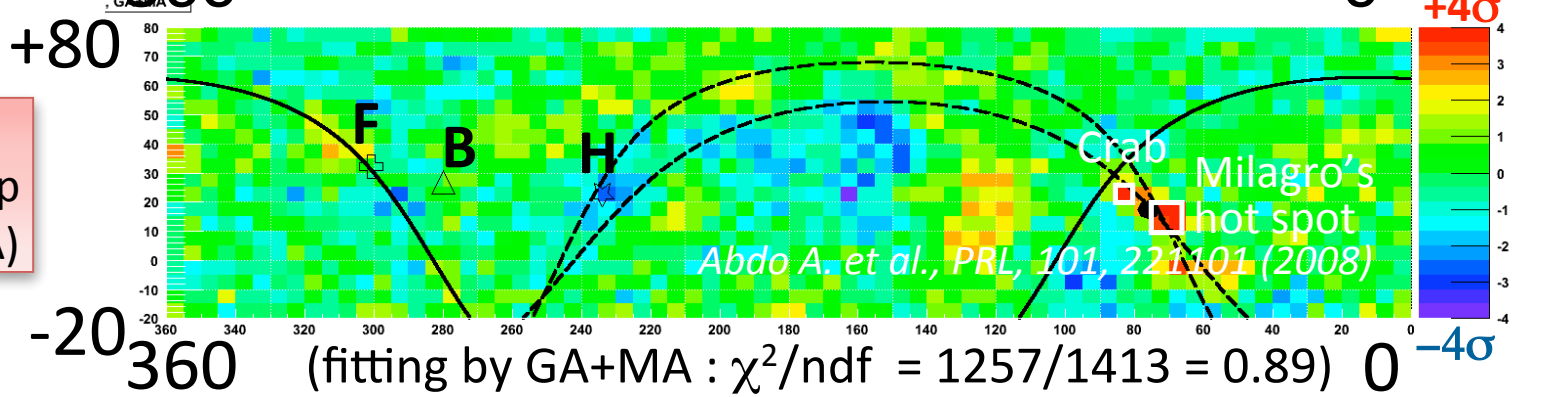
Intensity map (best-fit MA)



Intensity map (best-fit GA+MA)



Residual significance map (data – GA – MA)



(fitting by GA+MA : χ^2/ndf = 1257/1413 = 0.89)

Discussion : Global Anisotropy (GA)

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 ~ 0.002pc (in 3μG)

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

Bohm factor λ// ÷ R_L ~ 1500 >> 1 ∴ perpendicular diffusion is negligible.

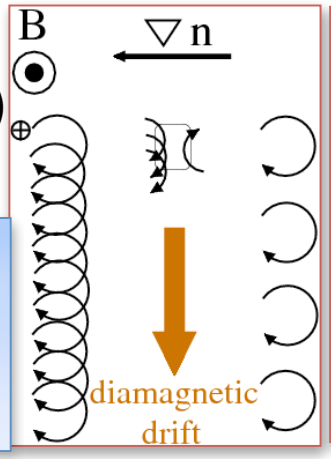
➡ Diamagnetic drift caused by the cosmic-ray density gradient in LISMF

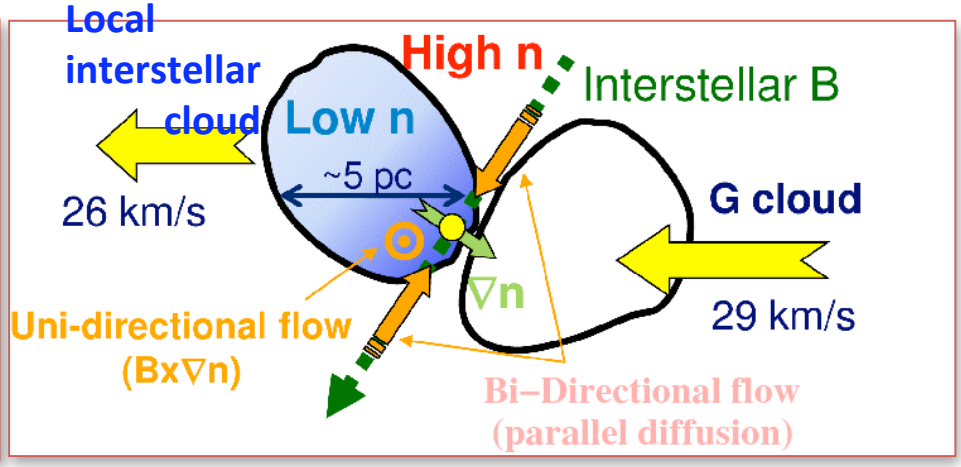
$$a_{1\perp} = \left|\frac{\nabla n}{n}\right| r_L \sim \frac{1}{n}\frac{n}{L} r_L = \frac{r_L}{L}$$

(L : scale of density gradient ∇n)

L = R_L /a1⊥ ~ 2pc

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

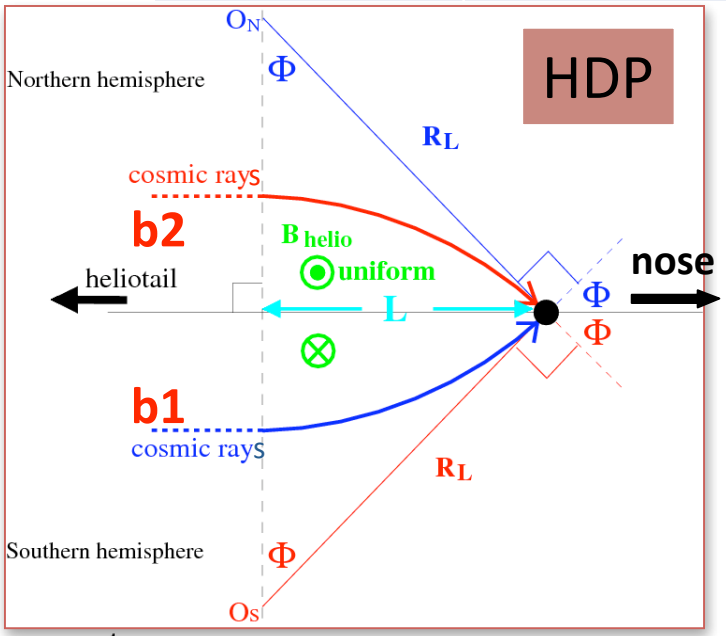




Discussion : Midscale Anisotropy (MA)

7 TeV

b1 (%)	b2(%)	σϕ (°)	σθ (°)	Φ (°)
0.154±0.018	0.092±0.006	24.5±1.1	10.7±0.8	49.2±1.4



$$L\ [\mathrm{pc}] = R_L\ [\mathrm{pc}]\ \sin\Phi \approx \frac{E\ [\mathrm{TeV}]}{B_{\mathrm{helio}}\ [\mu\mathrm{G}]}\ 10^{-3}\ \sin\Phi$$

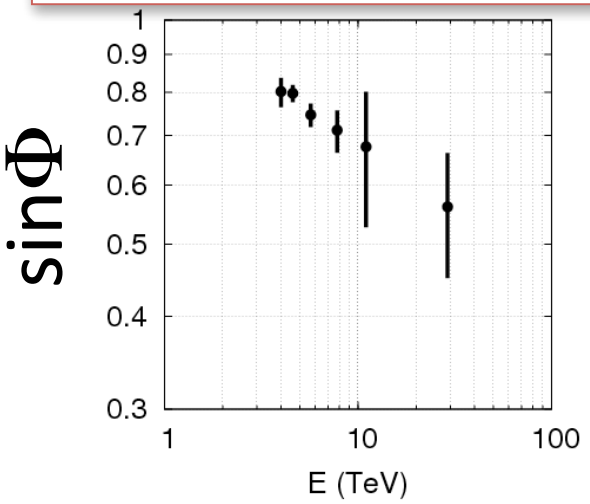
R_L : Larmor radius

B_{helio} : Magnetic field in the heliotail

L : scale of B_{helio} responsible for MA

Assuming B_{helio} = 10 μG, L ~ 5 x 10^{-4} pc = 100 AU

In contrast to GA (~2pc = 4x10^5 AU), MA would be caused by B_{helio} near the Sun (<~100 AU).



Energy dependence of L

$\sin\Phi = (0.68\pm0.04)\ (E/10\mathrm{TeV})^{-0.20\pm0.08}$

$L = (140\pm8)\ (E/10\mathrm{TeV})^{0.80\pm0.08}$

$L \propto E^{0.80}$ (not $\propto E^{1.0}$) might result from actual complex spatial structures of B_{helio}.

B_{helio} within ~70AU to ~340AU from the sun would be responsible for MA in 4TeV—30 TeV.

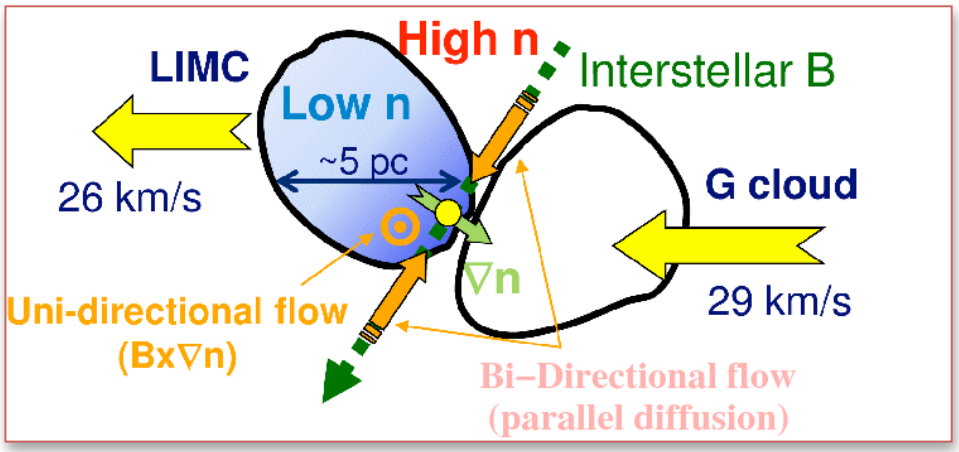
Summary

We discussed the origin of the galactic cosmic-ray anisotropy at TeV energies
by means of the data taken by the Tibet ASγ experiment
from 1998 Nov. through 2008 Dec. (live time 1916 days).

Global Anisotropy

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.



Midscale Anisotropy

In the heliotail (<~100AU for 7TeV cosmic rays)

Additional cosmic-ray inflows on Hydrogen Deflection Plane (HDP) from two directions, each centered away from the heliotail by Φ ~50° @7TeV.

Φ monotonously decreases with increasing energy.

END

Thank you for your attention!