Modeling of the TeV cosmic-ray anisotropy based on intensity mapping in an MHD-simulated heliosphere

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For the Tibet ASγ Collaboration

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The Tibet ASγ Collaboration

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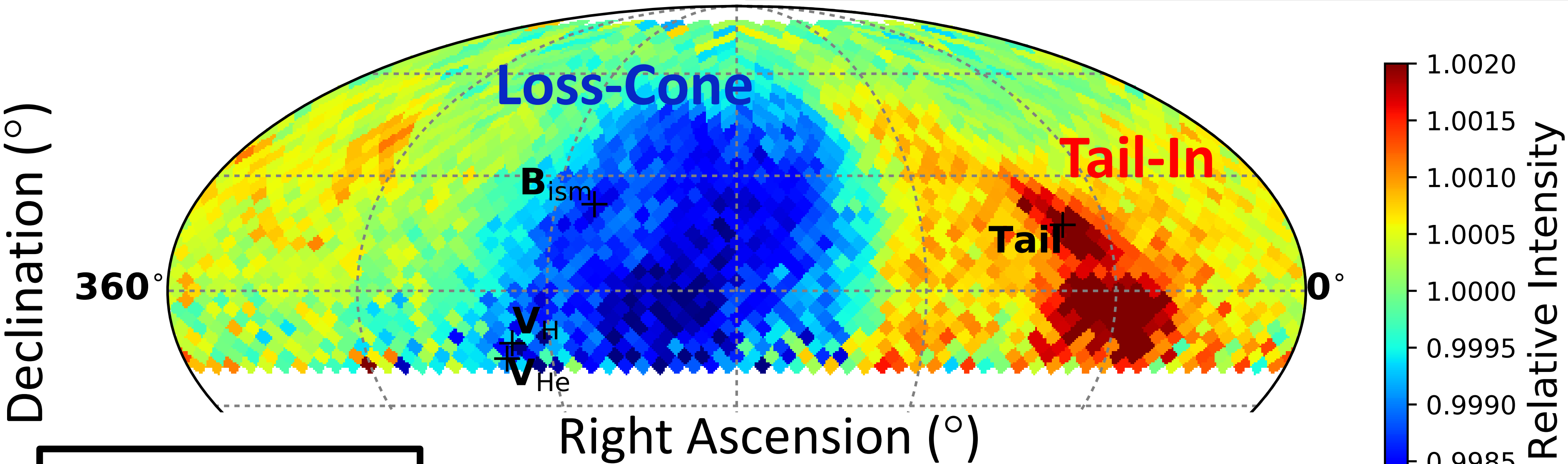
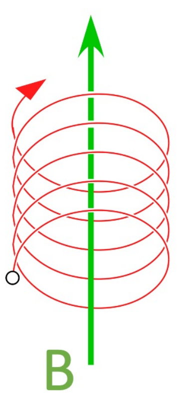
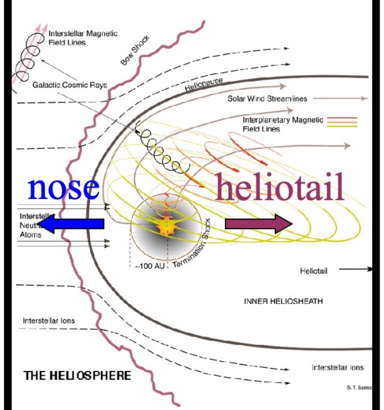
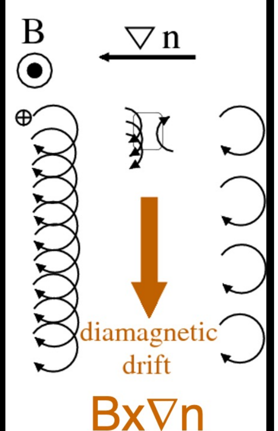
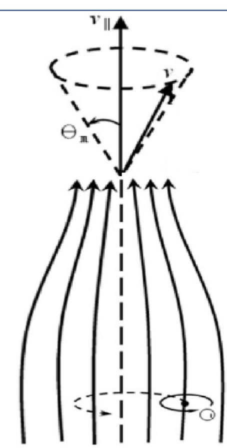
Anisotropy at TeV energies

Tibet ASγ, Nov 1999 - May 2010



(※ with declination bias)

Possible causes

Parallel diffusion	Compton-Getting effect	Diamagnetic drift	Magnetic Mirror Effect
			

+ heliospheric modulation

Recent study based on intensity mapping (1)

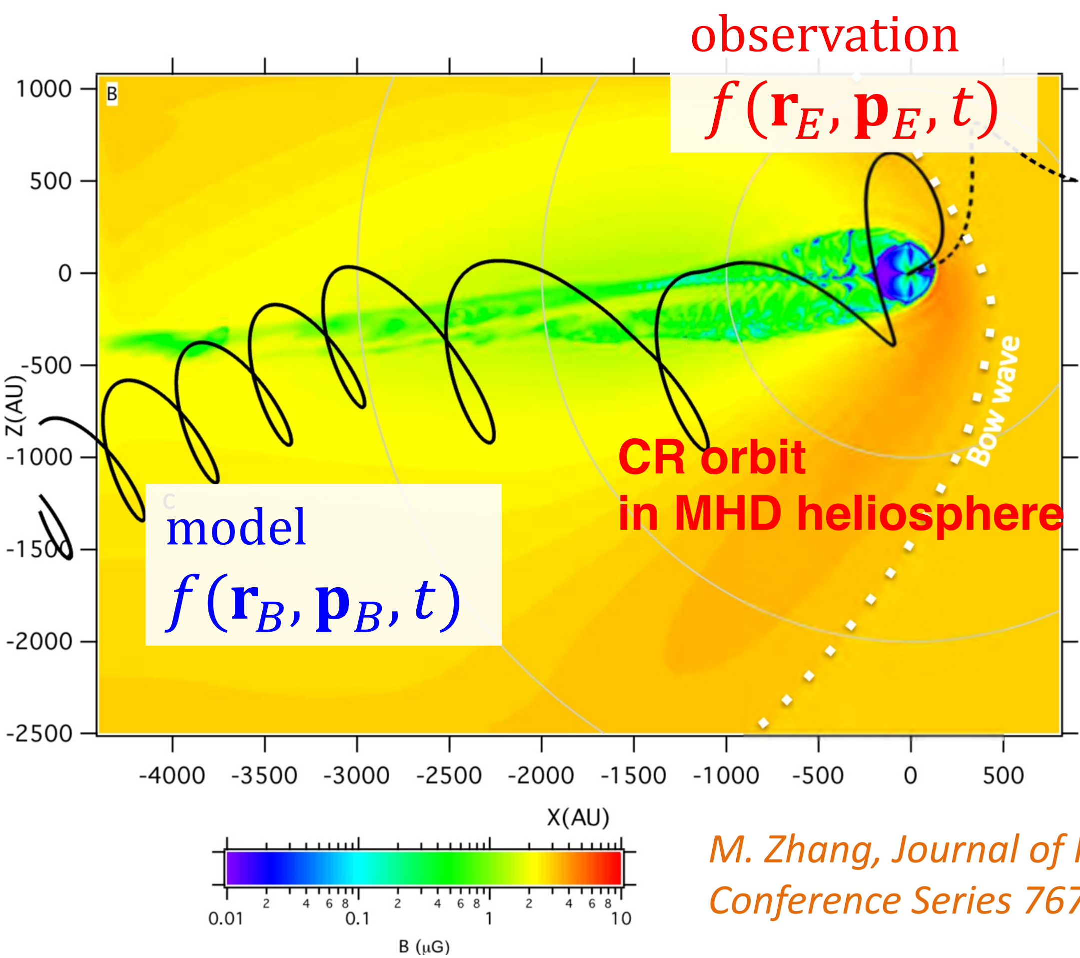
Liouville's theorem

Phase-space density of CRs: $f(\mathbf{r}, \mathbf{p}, t)$

$$Df = \frac{\partial f}{\partial t} + \frac{d\mathbf{r}}{dt} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{d\mathbf{p}}{dt} \cdot \frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t}\right)_c \approx 0$$

$$f(\mathbf{r}_E, \mathbf{p}_E, t) \approx f(\mathbf{r}_B, \mathbf{p}_B, t)$$

Intensity of CRs with $\boldsymbol{p_E}$ @ Earth
||
Intensity of CRs with $\boldsymbol{p_B}$ @ Outer Boundary of heliosphere



Mapping of CR intensity between Earth and outer boundary

⬇

CR anisotropy @ outer boundary

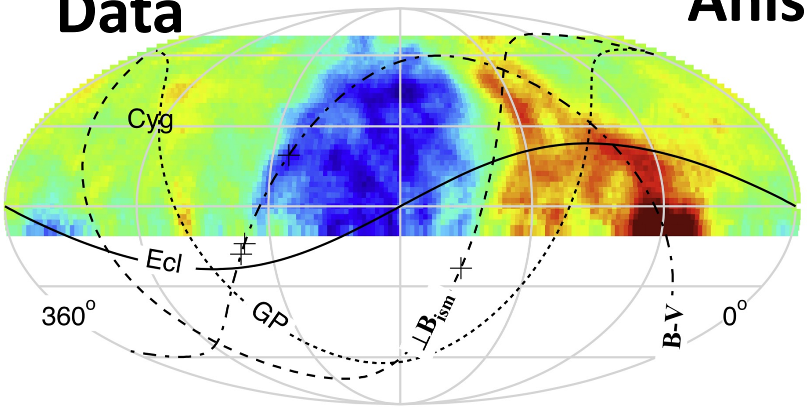
M. Zhang, Journal of Physics, Conference Series 767, 012027 (2016)

Recent study based on intensity mapping (2)

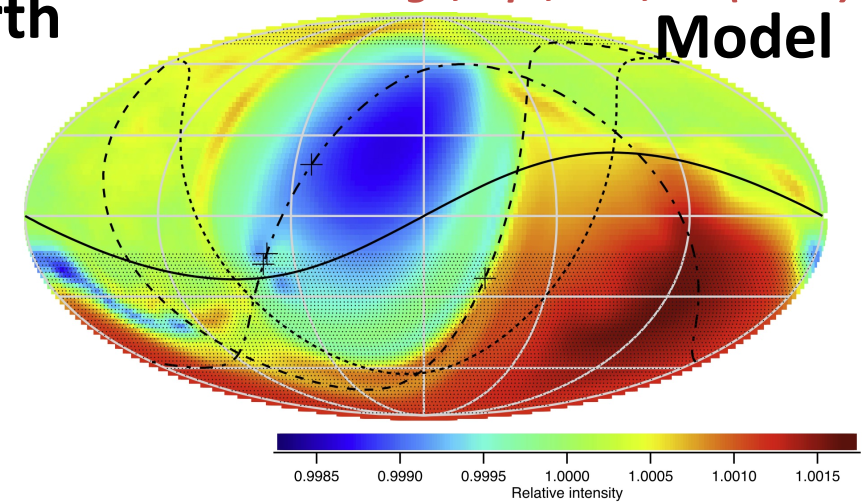
Zhang+, ApJ, 889, 97 (2020)

Aniso. at Earth

Data



Model



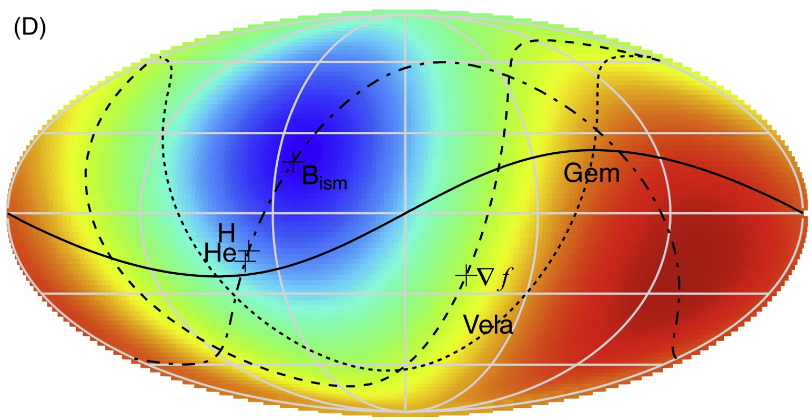
Dipole amplitude along B_{ISM}

Parameter Name	Value
Amplitude of pitch-angle dipole	$A_1 = (0.165 \pm 0.002)\%$
Amplitude of pitch-angle quadrupole	$A_2 = (0.015 \pm 0.002)\%$
CR density gradient	$\lvert G_\perp \rvert = (0.021 \pm 0.001)\%/R_g$
Normalization	$f_0 = 1 + (0.024 \pm 0.001)\%$

(Reduced χ^2 = 4.5)

Dipole amplitude along B_{ISM} x ∇f

Aniso. @ outer boundary



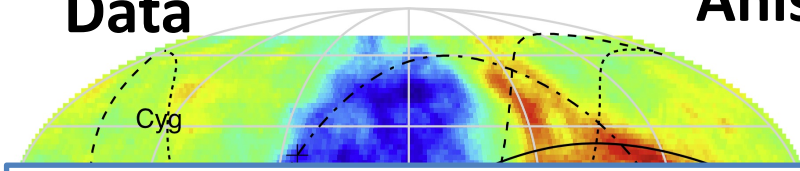
- Dipole amplitude A_1 along B_{ISM} is dominant
- CR density gradient direction (∇f) close to Vela

Recent study based on intensity mapping (2)

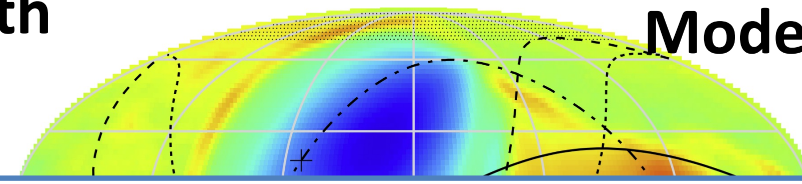
Zhang+, ApJ, 889, 97 (2020)

Aniso. at Earth

Data



Model



Intensity mapping using only 4 TeV monoenergy protons

↓

CR energy spectrum & composition must be considered

Parameter Name	Value
Amplitude of pitch-angle dipole	$A_1 = (0.165 \pm 0.002)\%$
Amplitude of pitch-angle quadrupole	$A_2 = (0.015 \pm 0.002)\%$
CR density gradient	$\lvert G_\perp \rvert = (0.021 \pm 0.001)\%/R_g$
Normalization	$f_0 = 1 +$ [illegible]

(Reduce

Dipole amplitude along B$_{IS}$

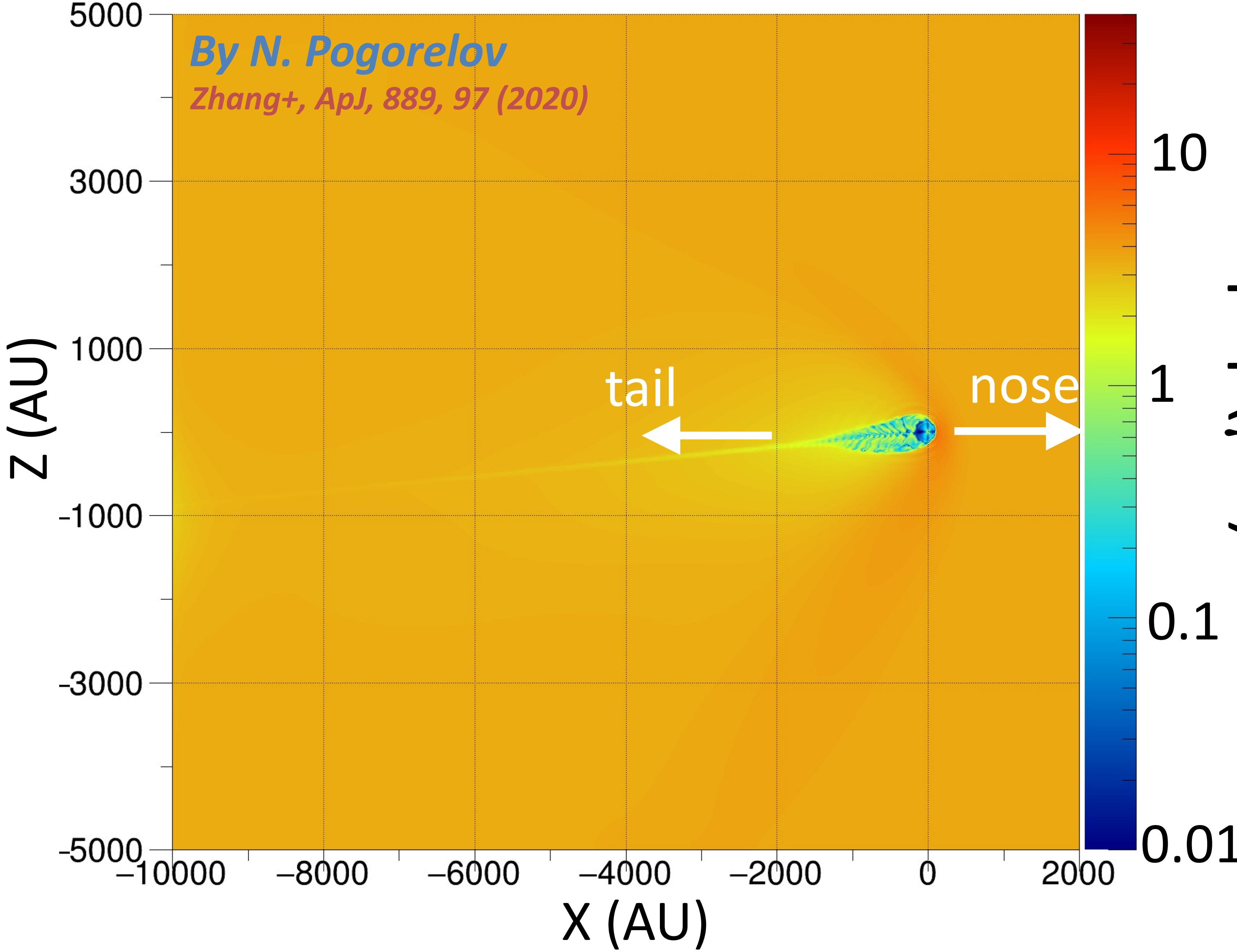
Aniso. @ outer boundary

Reduced $\chi^2 = 4.5$

↓

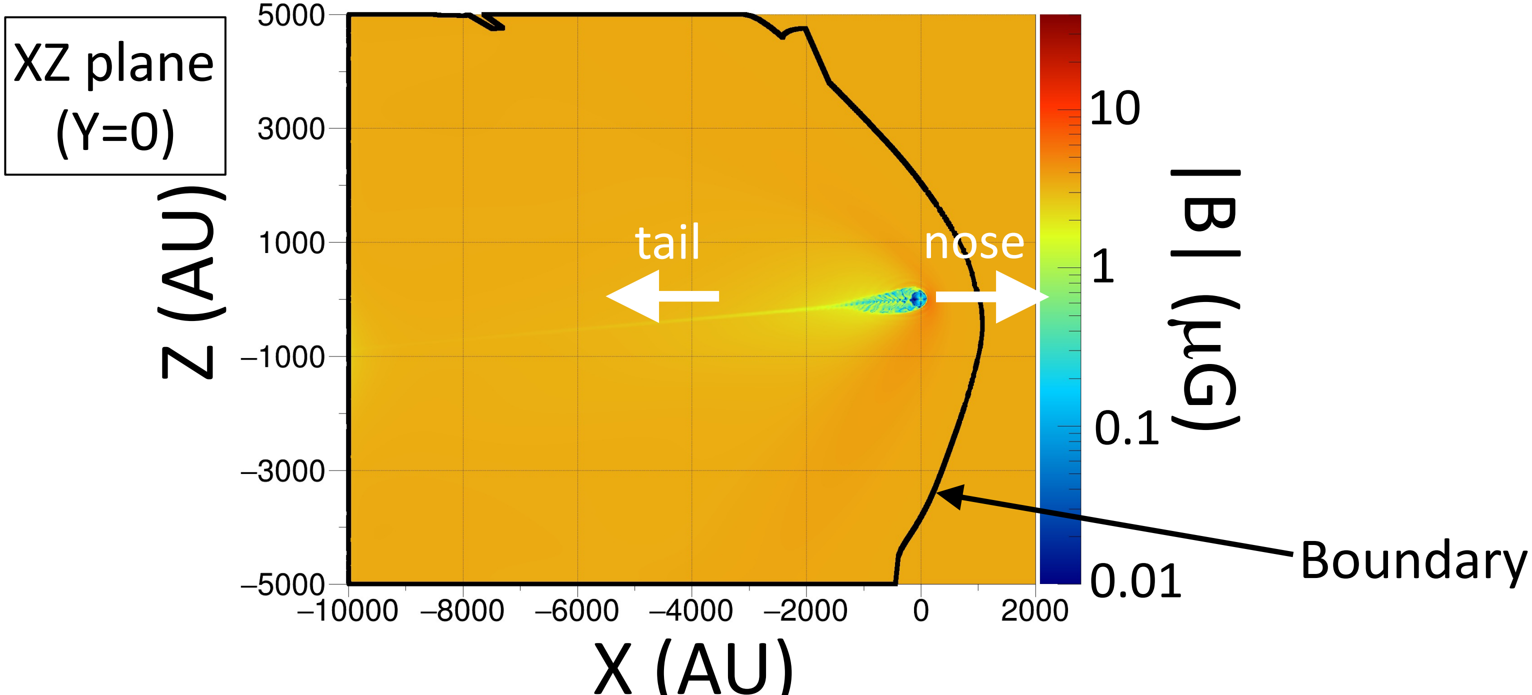
Modeling must be improved

MHD model of heliosphere used in this work



Intensity mapping method

- Set Earth at 4 positions (±1AU, 0, 0), (0, ±1 AU, 0)
- Shoot CR particles with reversed charge into MHD heliosphere
  - — Declination range: –20° < decl. < +80° (our field-of-view)
  - — spectrum & composition taken into account
- Record CR momentum directions at outer boundary
  - — Boundary defined as a surface where:
    Deviation in $\vec{B}_{\rm helio}$ strength from $\vec{B}_{\rm ISM}$ < 0.1%, and
    Deviation in $\vec{B}_{\rm helio}$ direction from $\vec{B}_{\rm ISM}$ < 0.1°

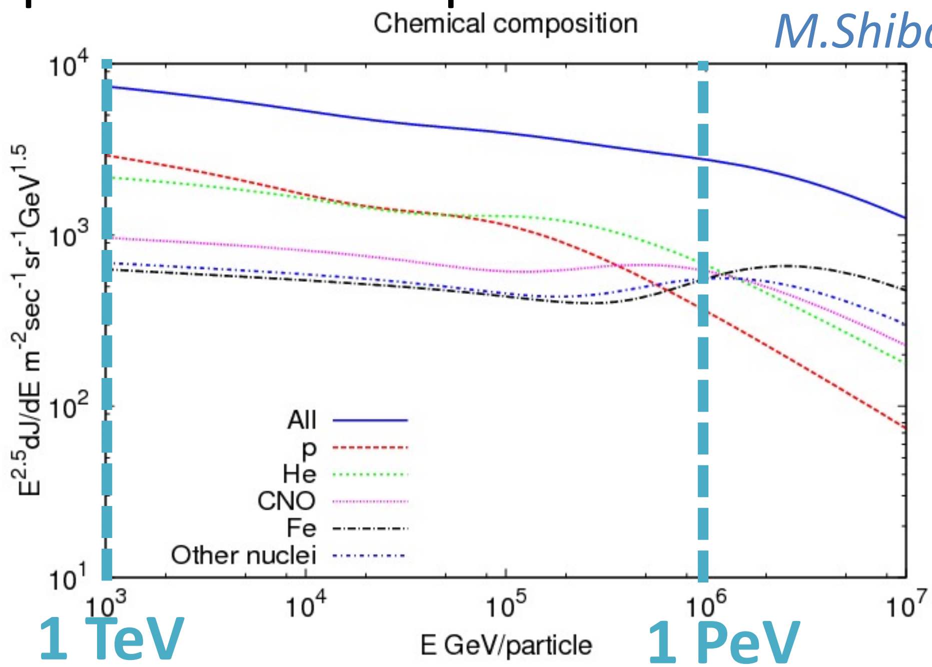


Energy spectrum & composition

Evaluate how different CR species with different energies contribute to the observed anisotropy using MC sim.

- CR energy spectrum & composition based on direct measurements

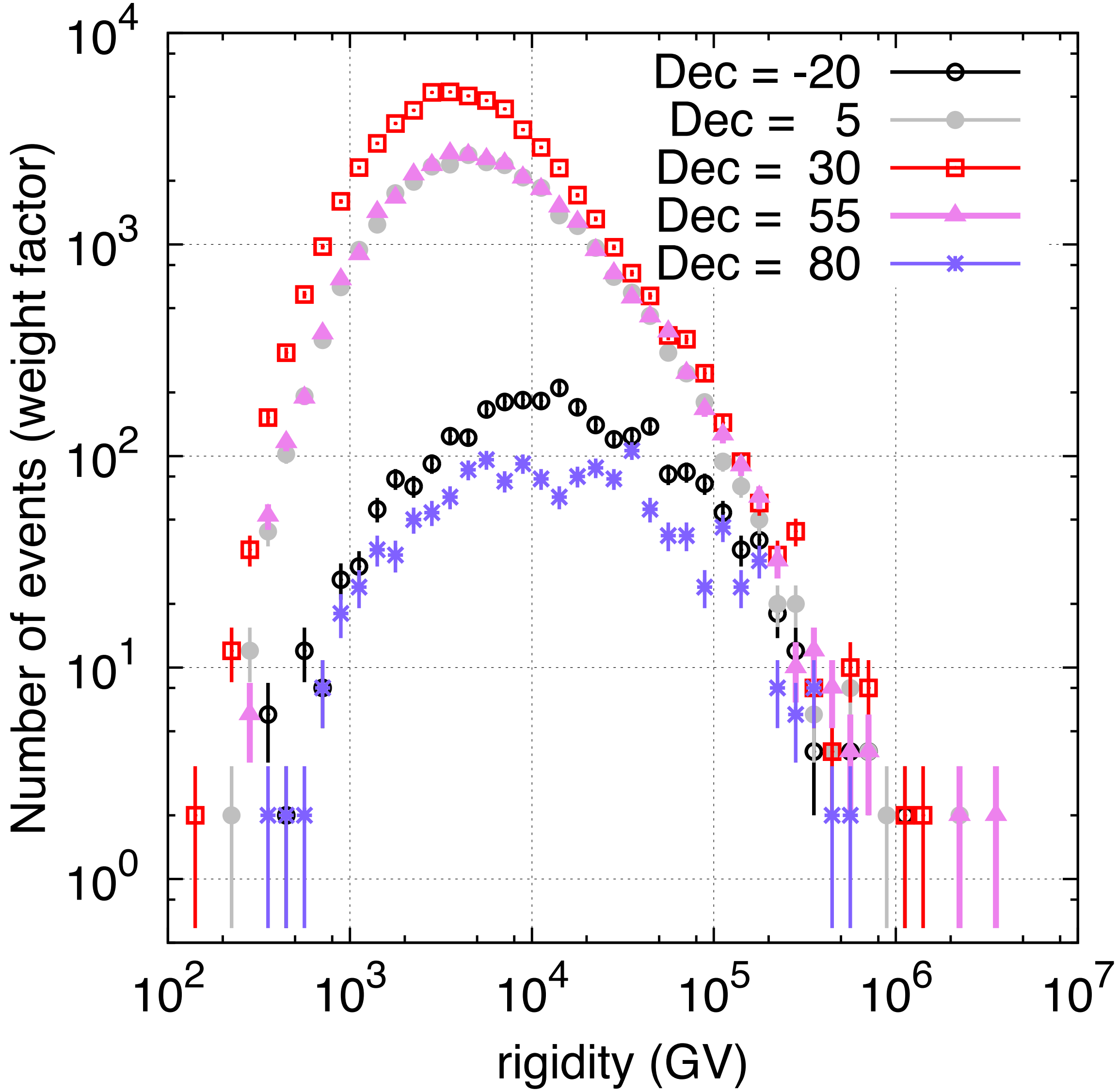
M.Shibata+, ApJ, 716, 1076 (2010)



- Air shower generation (CORSIKA) & AS array response simulation (Geant4)
- Analyze MC events in the same way as experimental data

➡ **Evaluate weight factor**

Weight factor for each declination band



How to derive anisotropy @ outer boundary

1) Assume relative intensity @ outer boundary as:

$$I_{\mathrm{ISM}} = 1 + A_{1||}\cos(\mu_2) + A_{2||}\cos^2(\mu_2) + A_{1\perp}\cos(\mu_1) + I_{\mathrm{CG}}$$

- μ_2: pitch angle
- μ_1: angle between particle's $\vec{p}$ and $\vec{B}_{\mathrm{ISM}} \times \nabla n$
- $A_{1||}$: dipole amplitude parallel to $\vec{B}_{\mathrm{ISM}}$
- $A_{2||}$: quadrupole amplitude parallel to $\vec{B}_{\mathrm{ISM}}$
- $A_{1\perp}$: dipole amplitude perpendicular to $\vec{B}_{\mathrm{ISM}}$
- I_{CG}: Compton-Getting anisotropy due to heliospheric motion relative to ISM ($v = 23.2$ km/s ➡ amplitude 0.03%)

* $\vec{B}_{\mathrm{ISM}}$: (R.A., Dec) = (232.5°, 19.0°)

2) Map I_{ISM} to Earth

3) Normalize relative intensity @ Earth to 1 for each declination band

4) Calculate χ^2 with experimental data

➡ Repeat 1) – 4) and obtain best-fit parameter values that minimize χ^2

4 free parameters: $A_{1||}$, $A_{2||}$, $A_{1\perp}$, α_1

(α_1, δ_1): direction of ∇n (CR density gradient perpendicular to $\vec{B}_{\mathrm{ISM}}$)

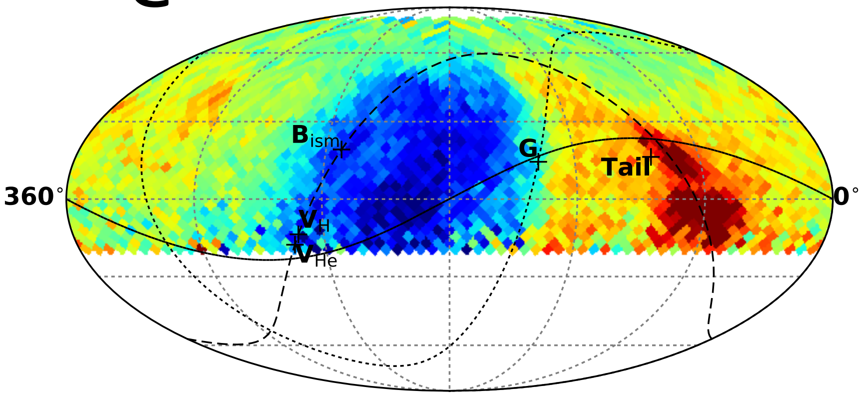
Results 1 (fitting by dipole & quadrupole flows)

$I_{\rm ISM} = 1 + A_{1\|}\cos(\mu_2) + A_{2\|}\cos^2(\mu_2) + A_{1\perp}\cos(\mu_1) + I_{\rm CG}$ (α_1, δ_1) : direction of ∇n

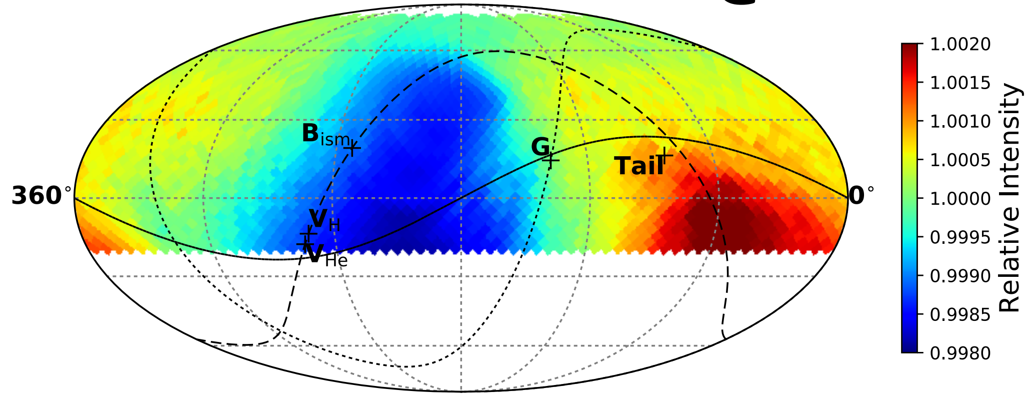
Dipole amplitude along B_{ISM} **Dipole amplitude along $B_{ISM} \times \nabla n$** χ^2 / ndf = 3320 / 2052 = **1.62**

$A_{1\|}$ (%)	$A_{2\|}$ (%)	$A_{1\perp}$ (%)	α_1 (°)	δ_1 (°)
0.234 ± 0.002	0.011 ± 0.004	0.131 ± 0.006	137.5 ± 1.4	14.2 ± 3.8

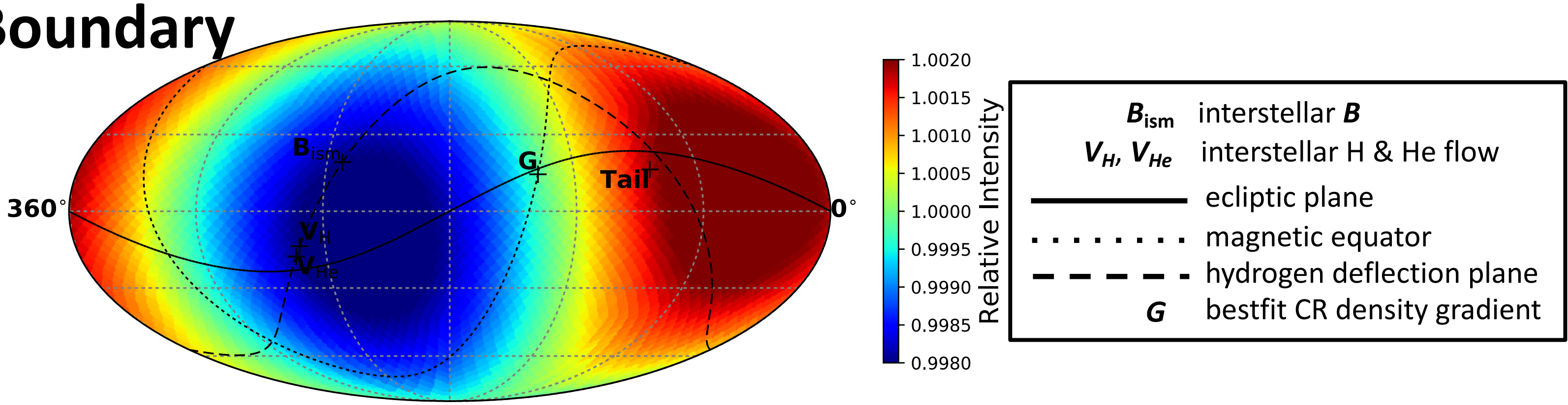
Data@Earth



Model@Earth



Model @ Boundary



- $A_{1\perp}$ is not so small; about half of $A_{1||}$
- CR density gradient direction (G) not close to Vela

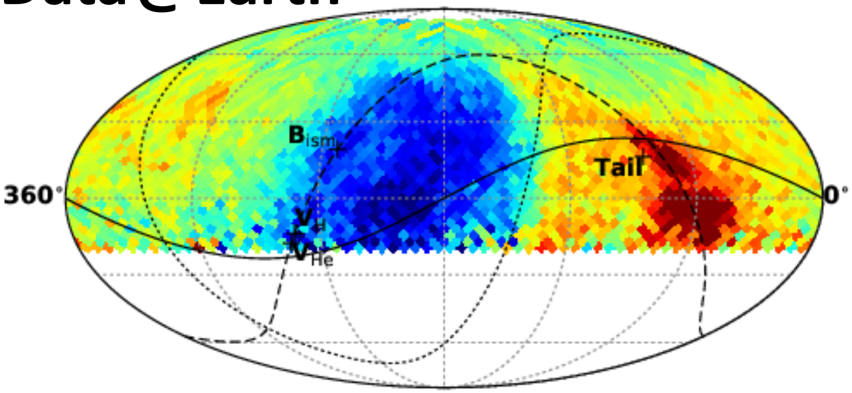
Results 2 (fitting by spherical harmonics)

l_{max} = 20 (440 parameters)

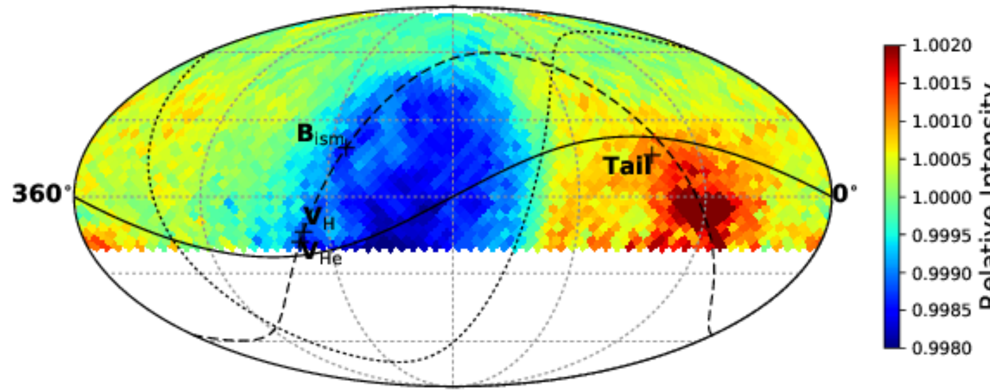
$$I_{\mathrm{ISM}}(\theta,\phi) = 1 + \sum_{l=1}^{l_{\max}} \sum_{m=-l}^{l} f_{lm} Y_{lm}(\theta,\phi) + I_{\mathrm{CG}}$$

χ^2 / ndf = 1658 / 1616 = **1.03 (22.8 %)**

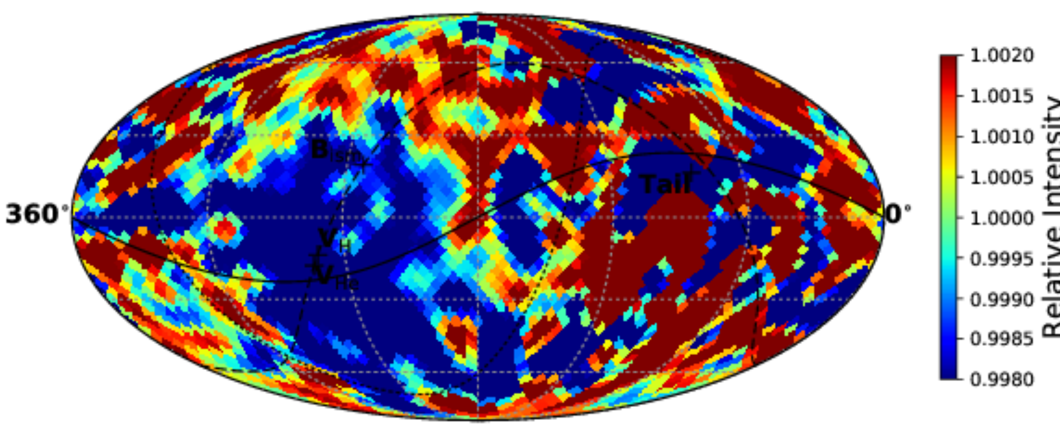
Data @Earth



Model Fitting @Earth



Model @ Boundary



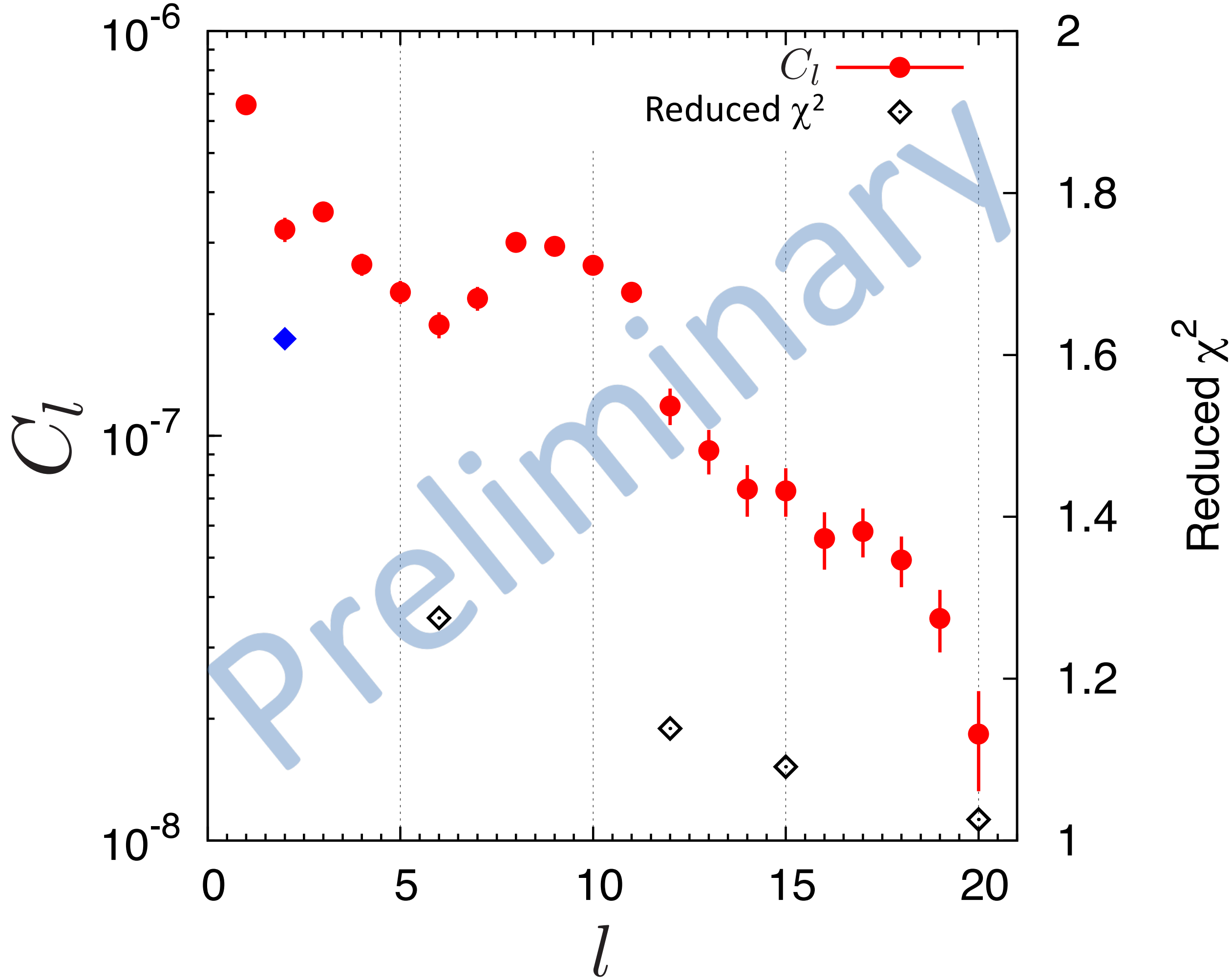
B_{ism}	interstellar ***B***
V_H, V_{He}	interstellar H & He flow
———	ecliptic plane
· · · · · · · ·	magnetic equator
— — — —	hydrogen deflection plane

➢ Small-scale structures appear @ Boundary

Results 2 (fitting by spherical harmonics)

$$C_l = \left(\frac{1}{4\pi}\right)\left(\frac{1}{2l+1}\right)\sum_{m=-l}^{l} f_{lm}^2$$

Power spectrum



Summary

Quantitative study on the origin of TeV CR anisotropy
based on intensity mapping

- ✓ CR energy spectrum & composition taken into account
- ✓ Modeling@boundary improved using spherical harmonics

- ☐ Power spectrum@boundary has a bump at L=7-11

Future prospects

- ➢ Study the cause of the bump L=7-11
- ➢ Adjust MHD model heliosphere to observation period A<0 (2000 — 2009)
- ➢ Observe CR anisotropy in the southern sky by ALPAQUITA/ALPACA for better modelling ➡ Please refer to talks #777 by T. Sako
  #857 by S. Kato
  #947 by Y. Yokoe