SK/Tibetによる 高エネルギー宇宙線強度の 恒星時異方性の観測

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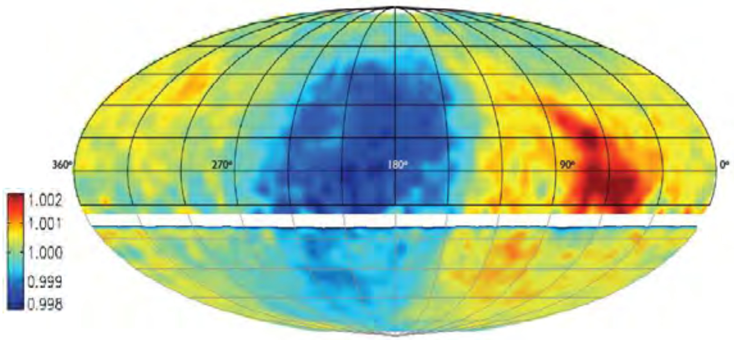
220千円：直流安定化電源、同軸ケーブル、無停電電源

Heliospheric modulation (distortion) in MHD model heliosphere



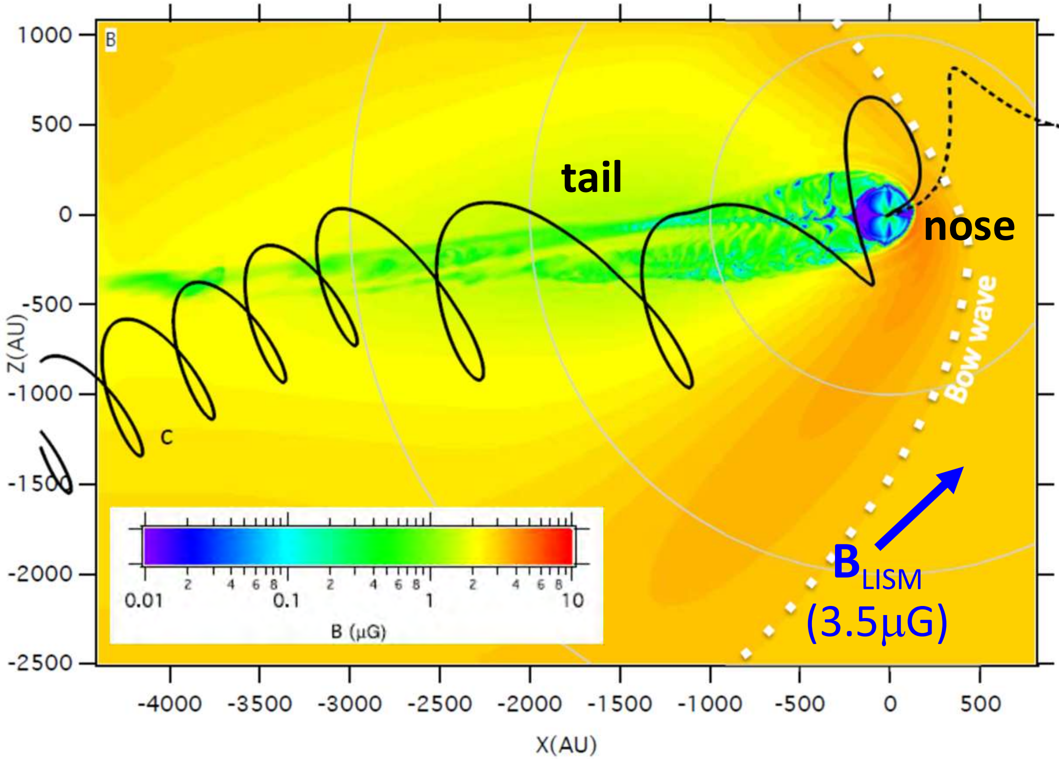
Tibet ASγ (7 TeV)
(Amenomori et al., Science, 314, 2006)

Ice Cube (20 TeV)
(Abbasi et al., arXiv:1005.2960v1, 2010)

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

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

$$\frac{d\mathbf{p}}{dt} = Ze\left(\mathbf{E} + \frac{d\mathbf{r}}{dt} \times \mathbf{B}\right)$$



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

- Obtain model $f(\mathbf{r}_B, \mathbf{p}_B, t)$ best-fit to the observed $f(\mathbf{r}_E, \mathbf{p}_E, t)$.
- We use MHD heliosphere by *N. Pogorelov+ (ApJL 812 L6 2015)* for CR orbit calculation.
- Take accounts of composition, E-spectrum and AS-array performance for quantitative best-fitting.

Model 1 (four parameters fit):

$$f(\mathbf{r}_B, \mathbf{p}_B, t) = 1 + f^{CG} + A_{1\parallel}\cos(\mu_2) + A_{2\parallel}\cos^2(\mu_2) + A_{1\perp}\cos(\mu_1)$$

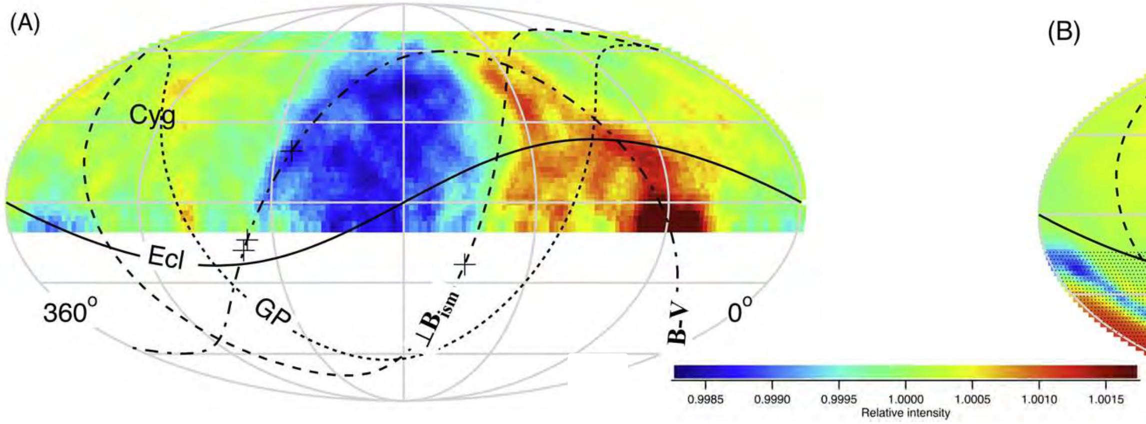
orientation of $A_{1\perp}$ $(\alpha_{1\perp}, \delta_{1\perp})$

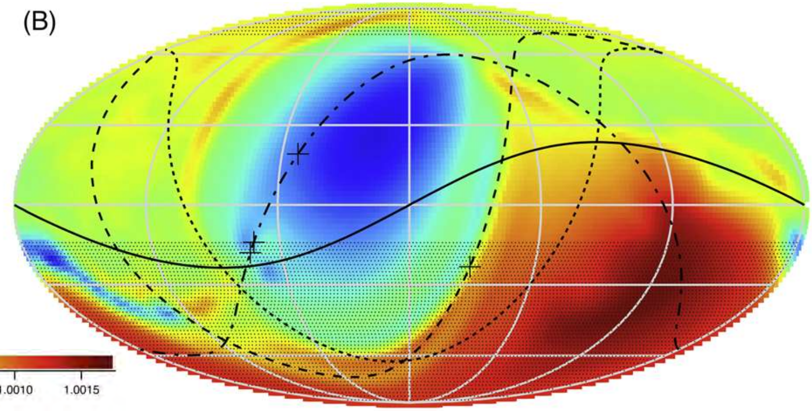
Recent study based on intensity mapping

Zhang+, ApJ, 889, 97 (2020)

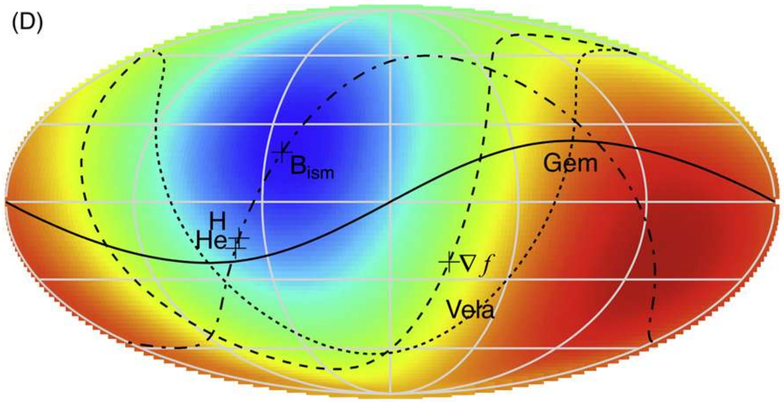
Using orbits of monochromatic 5 TV protons

(a) Data **Anisotropy @ Earth** **(b) Best-fit**





(c) Anisotropy @ outer boundary



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	$f_0 = 1 + (0.024 \pm 0.001)\%$

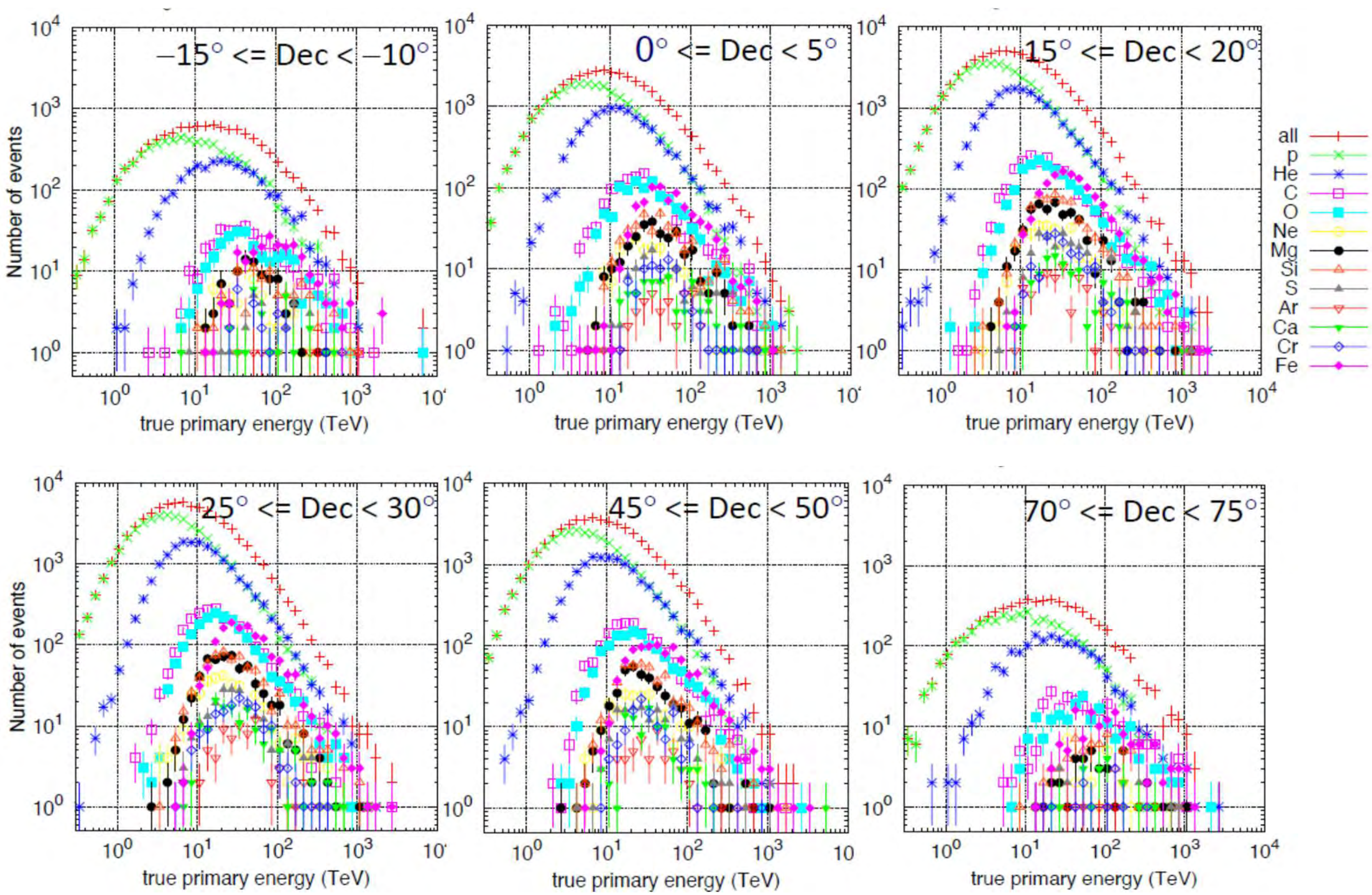
(Reduced χ^2 = 4.5)

Dipole amplitude along B_{ISM} x ∇f

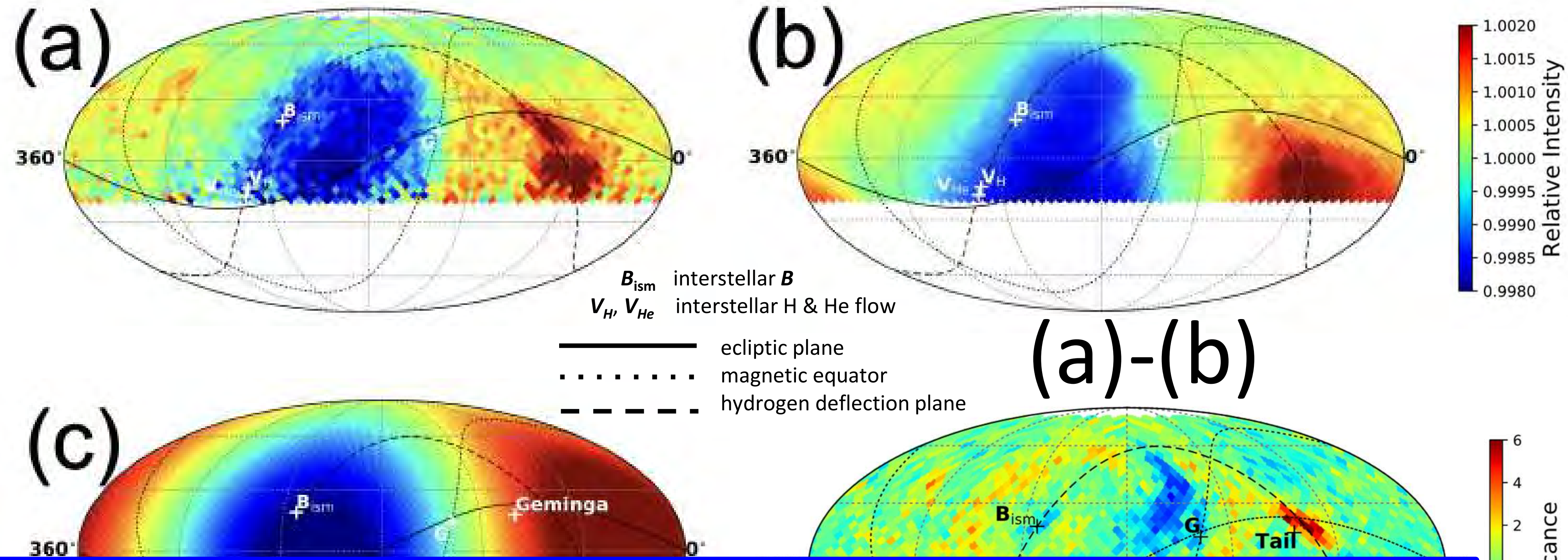
- Dipole amplitude A_1 along B_{ISM} is dominant
- CR density gradient direction (∇f) close to Vela
- But fitness is too poor (χ^2 = 4.5)

Weighting with composition & E-spectra by MC

(instead of using monochromatic protons)



Best-fit results with Model 1



Model 2: $f(\mathbf{r}_B, \mathbf{p}_B, t) = f^{CG} + \sum_{l=1}^{L_{max}} \sum_{m=-l}^{l} f_l^m Y_l^m(\theta, \phi)$ θ, ϕ: Dec, R.A.

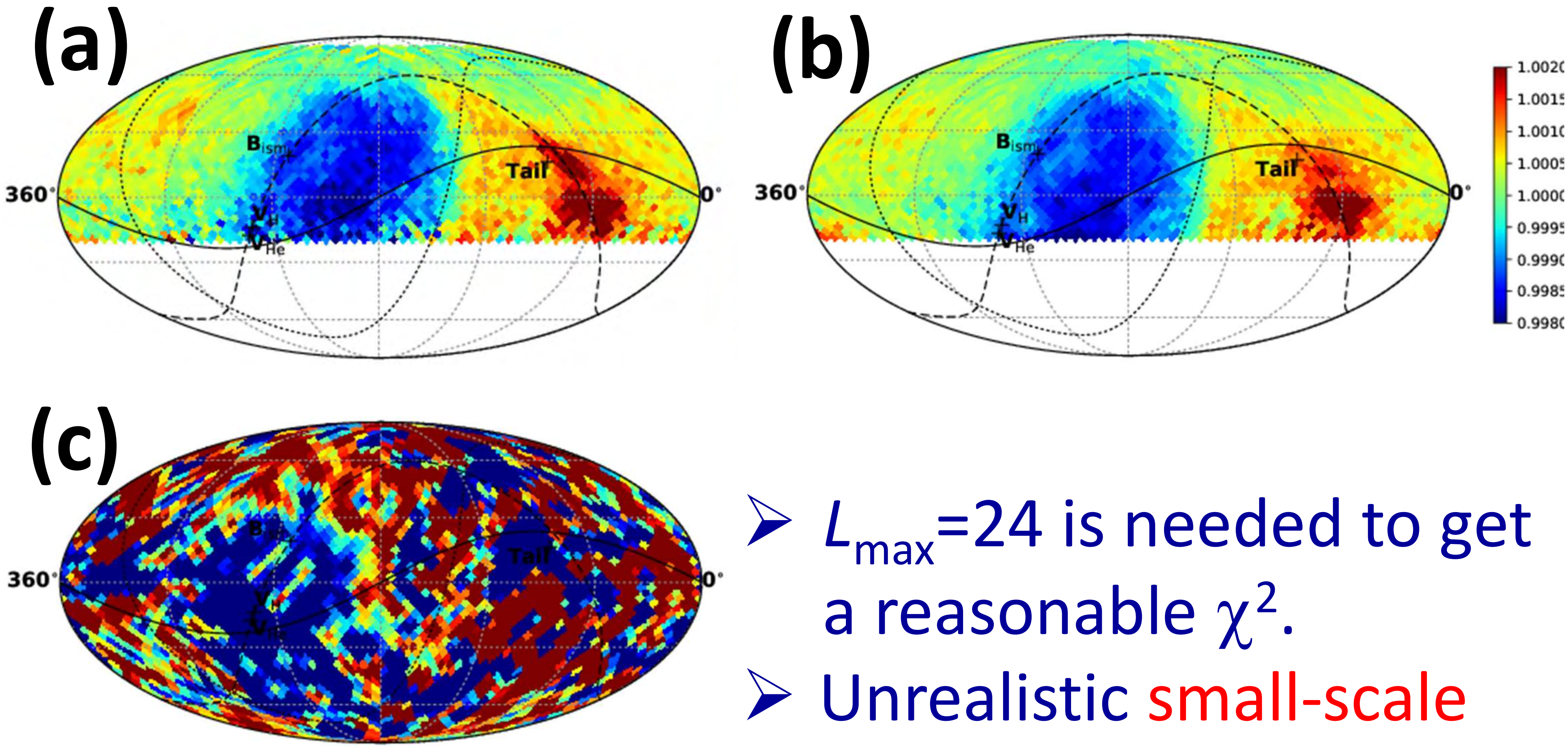
$N_{param.} = (L_{max} + 1)^2 - 1$ (= **440** for $L_{max} = 20$)

		Best-fit values	
		this work	Paper 1
Parameters	$A_{1\parallel}$	$(0.234 \pm 0.002)\%$	$(0.165 \pm 0.002)\%$
	$A_{2\parallel}$	$(0.011 \pm 0.005)\%$	$(0.015 \pm 0.002)\%$
	$A_{1\perp}$	$(0.131 \pm 0.006)\%$	$(0.021 \pm 0.001)\%$
	$\alpha_\perp$	$193.1° \pm 7.9°$	$287°^{\ddagger}$
	$\delta_\perp$	$-66.0° \pm 2.4°$	$-59°^{\ddagger}$
	α_G	$137.5° \pm 1.4°$	$151°^{\dagger}$
	δ_G	$14.2° \pm 3.8°$	$-23°^{\dagger}$
χ^2/d.o.f.		1.62	4.5

- $A_{\perp 1}$ is also significant with $\nabla_\perp f$ apart from Vela (closer to Geminga).
- χ^2 is reduced to 1.62 from 4.5, but fitness is still poor.
- Best-fit with Model 2 is examined.

Best-fit results with Model 2

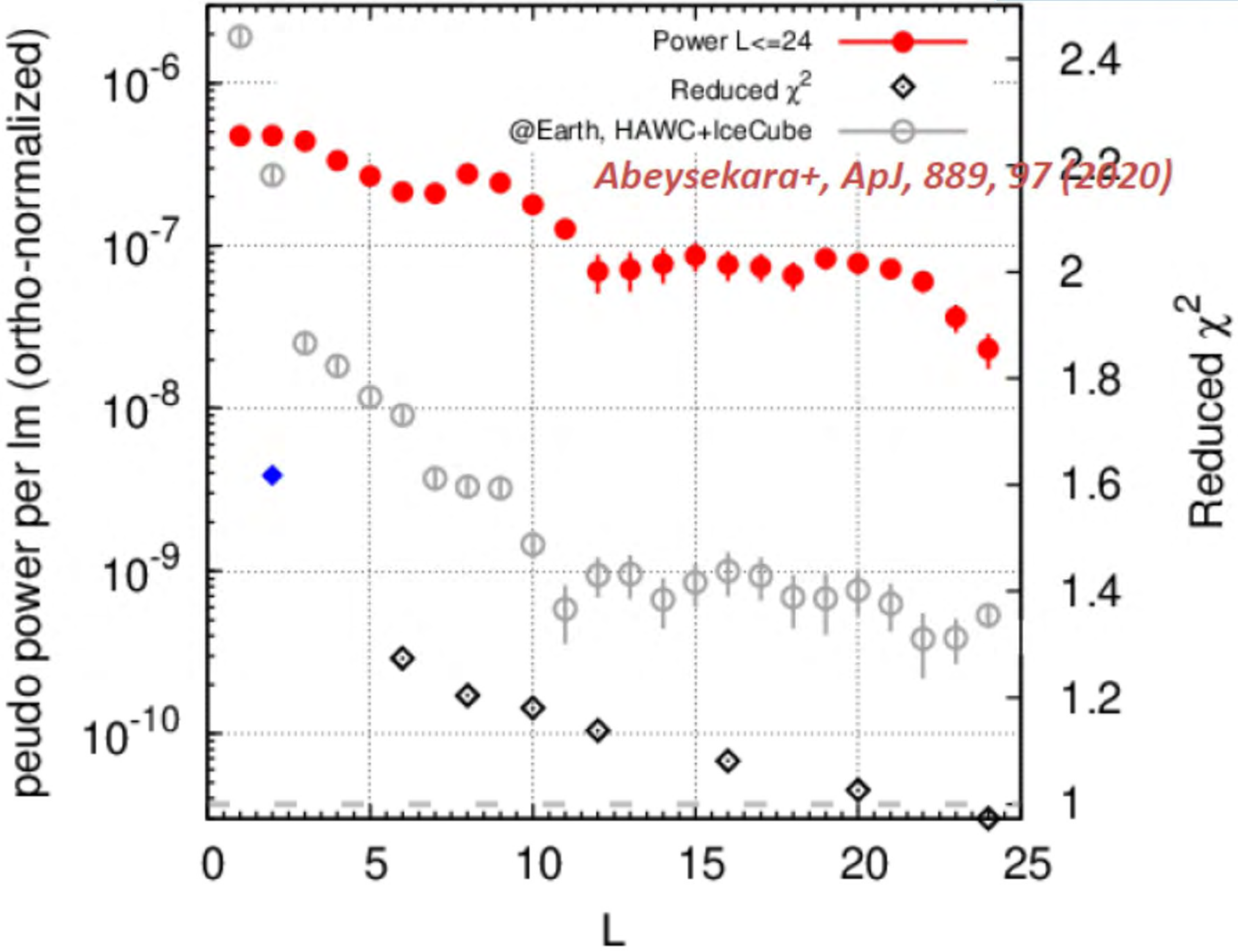
L_{max} = 24 (624 parameters) χ^2 / ndf = 1393 / 1432 = **0.973 (76.4 %)**



- L_{max}=24 is needed to get a reasonable χ^2.
- Unrealistic small-scale anisotropy appears @ outer boundary.

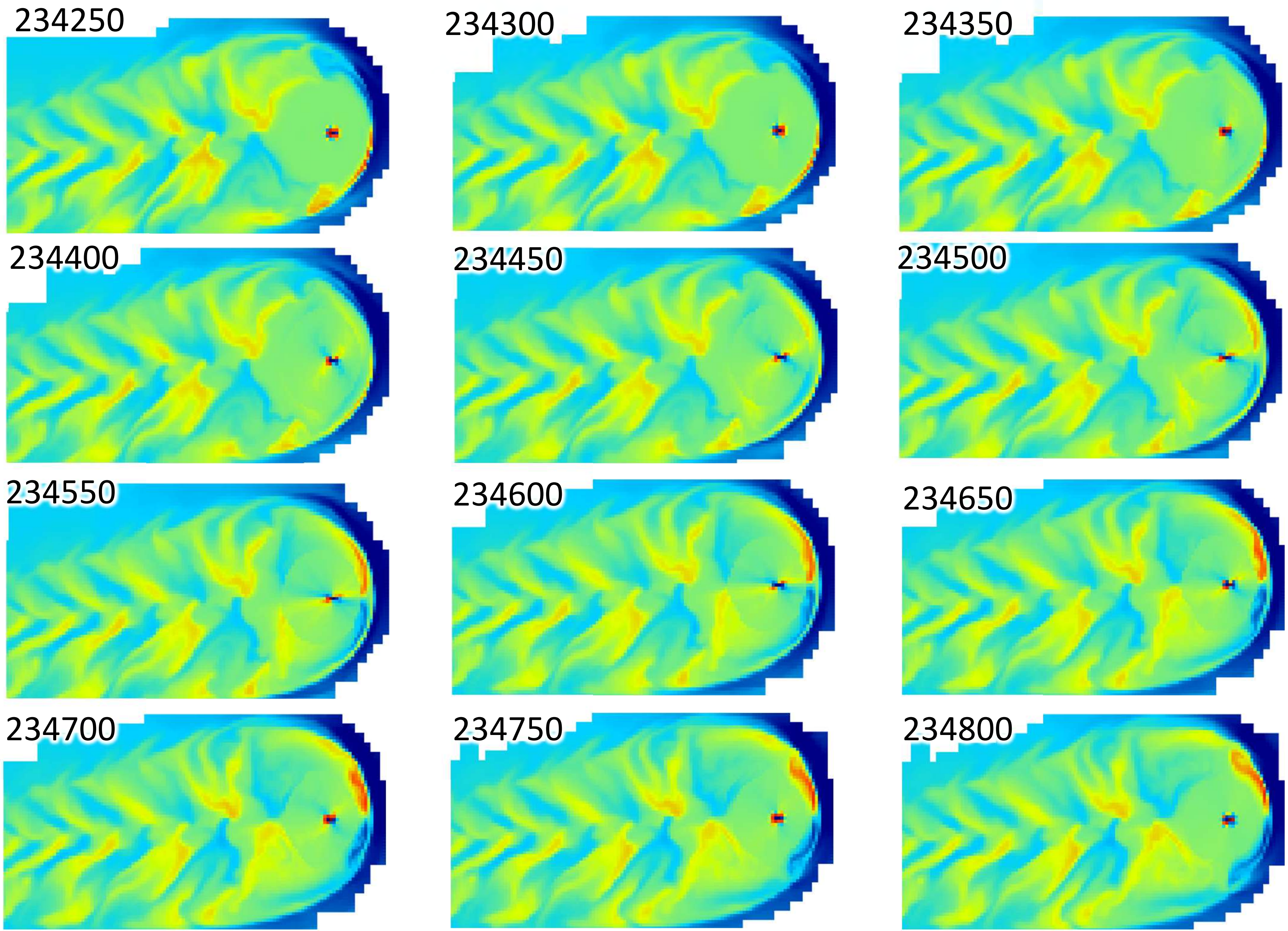
Results: Power spectrum

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

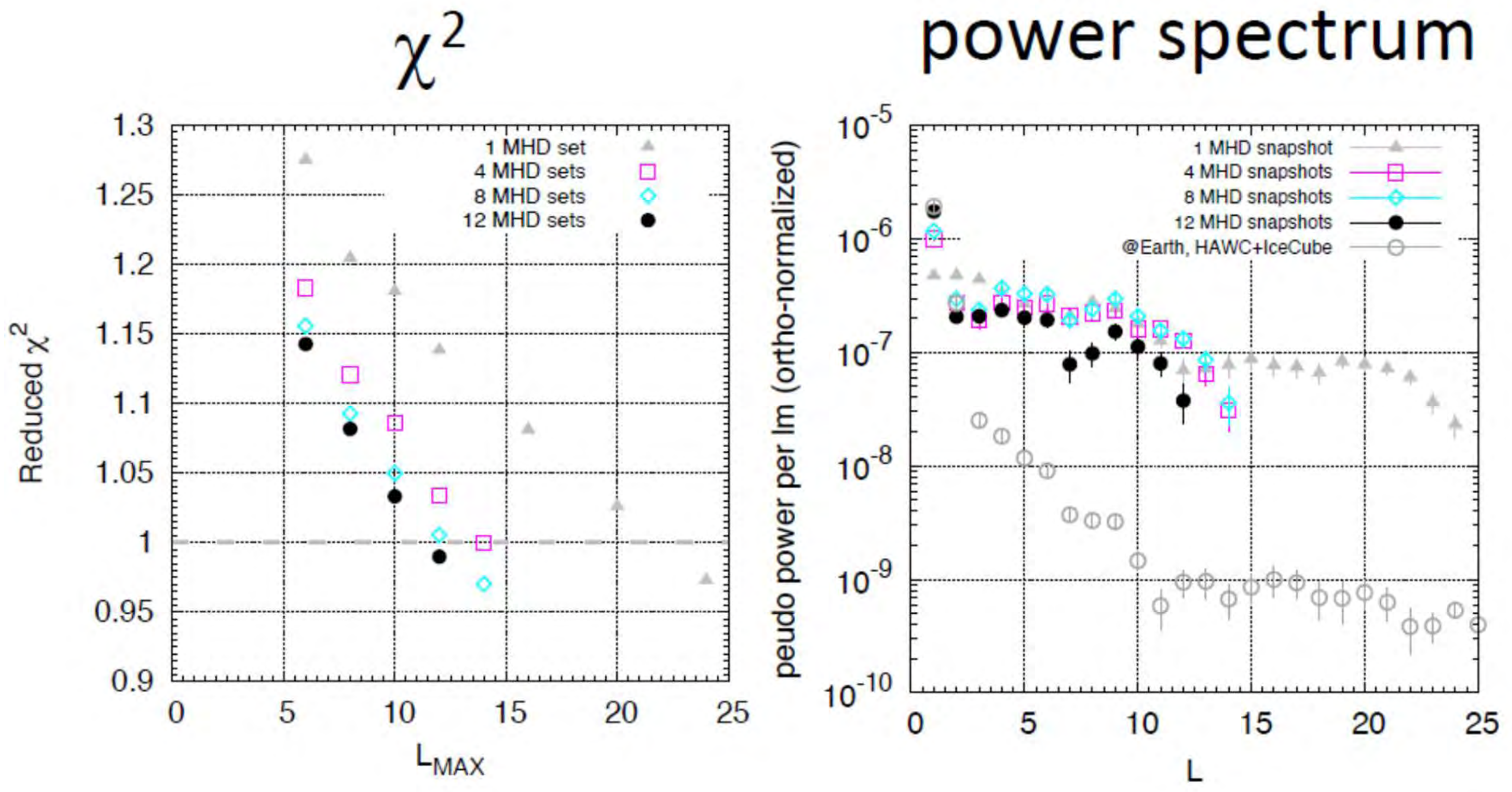


Using 12 MHD snap shots

Corresponding to 10-year observation by Tibet in A<0 epoch

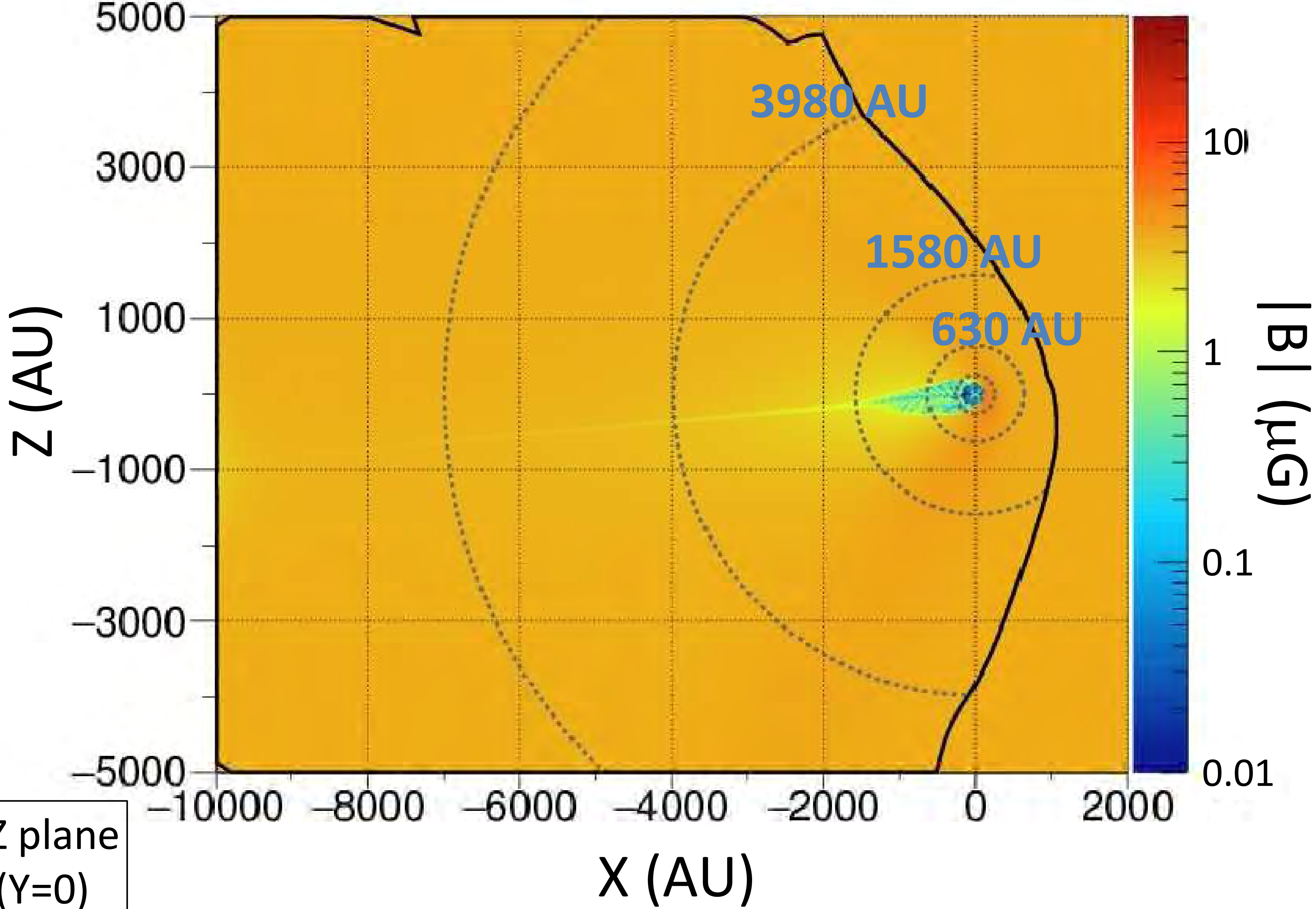


Power spectrum using average orbits in 12 MHD snap shots



- *L*max~10 is still needed to get a reasonable χ^2.
- Unrealistic small-scale anisotropy (L ≥3) still appears @ outer boundary.

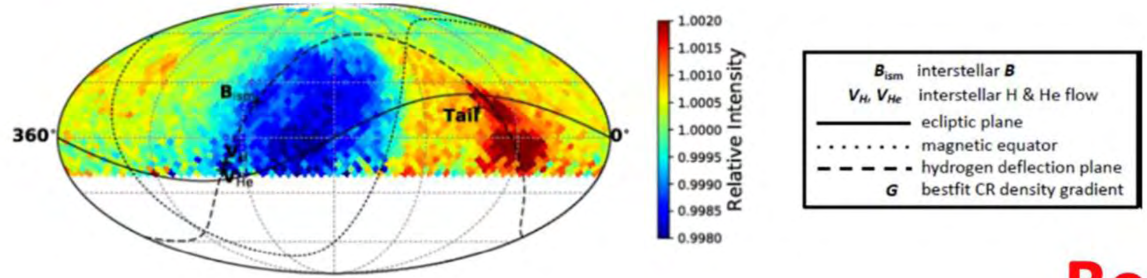
CR intensity distributions at different boundaries?



XZ plane
(Y=0)

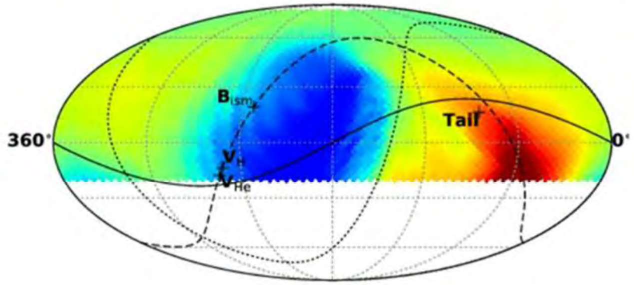
Results: intensity distributions @ different outer boundaries

Observed at Earth

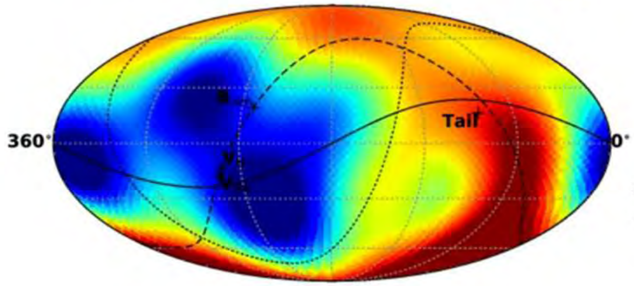


Reproduced at Earth

Best-fit at boundary ($r=r_B$)

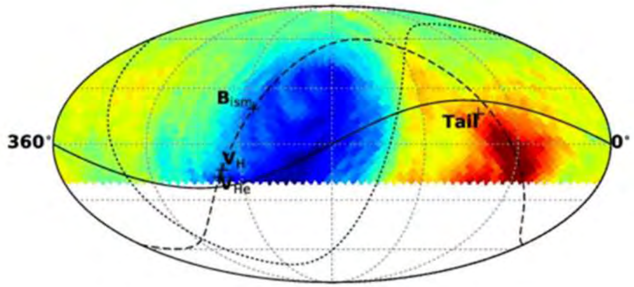


r_B= 630 AU

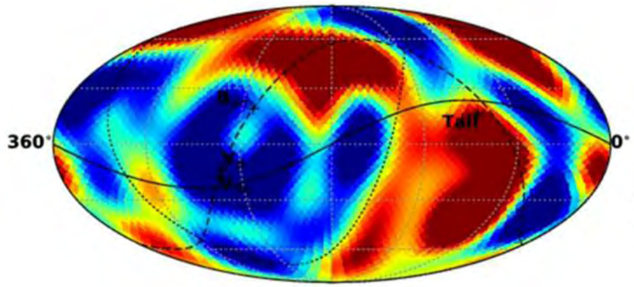


L_{max} = 4 ($N_{param.}$=26)

χ^2 / ndf = 0.962

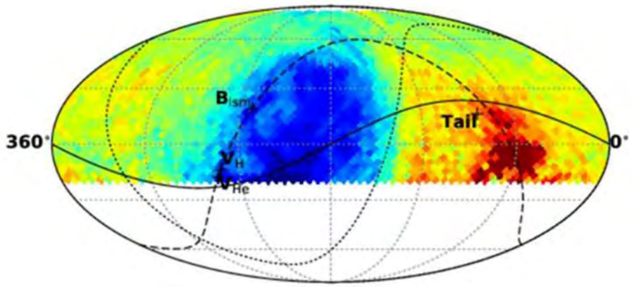


1580 AU

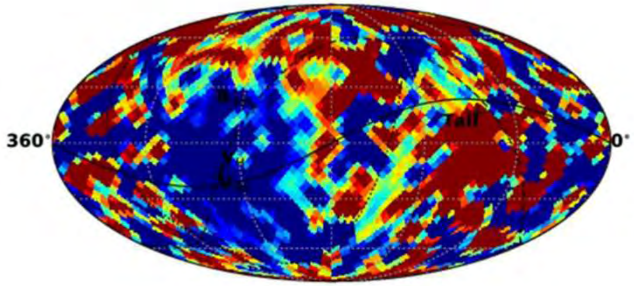


L_{max} = 8 ($N_{param.}$=80)

χ^2 / ndf = 0.982



3980 AU

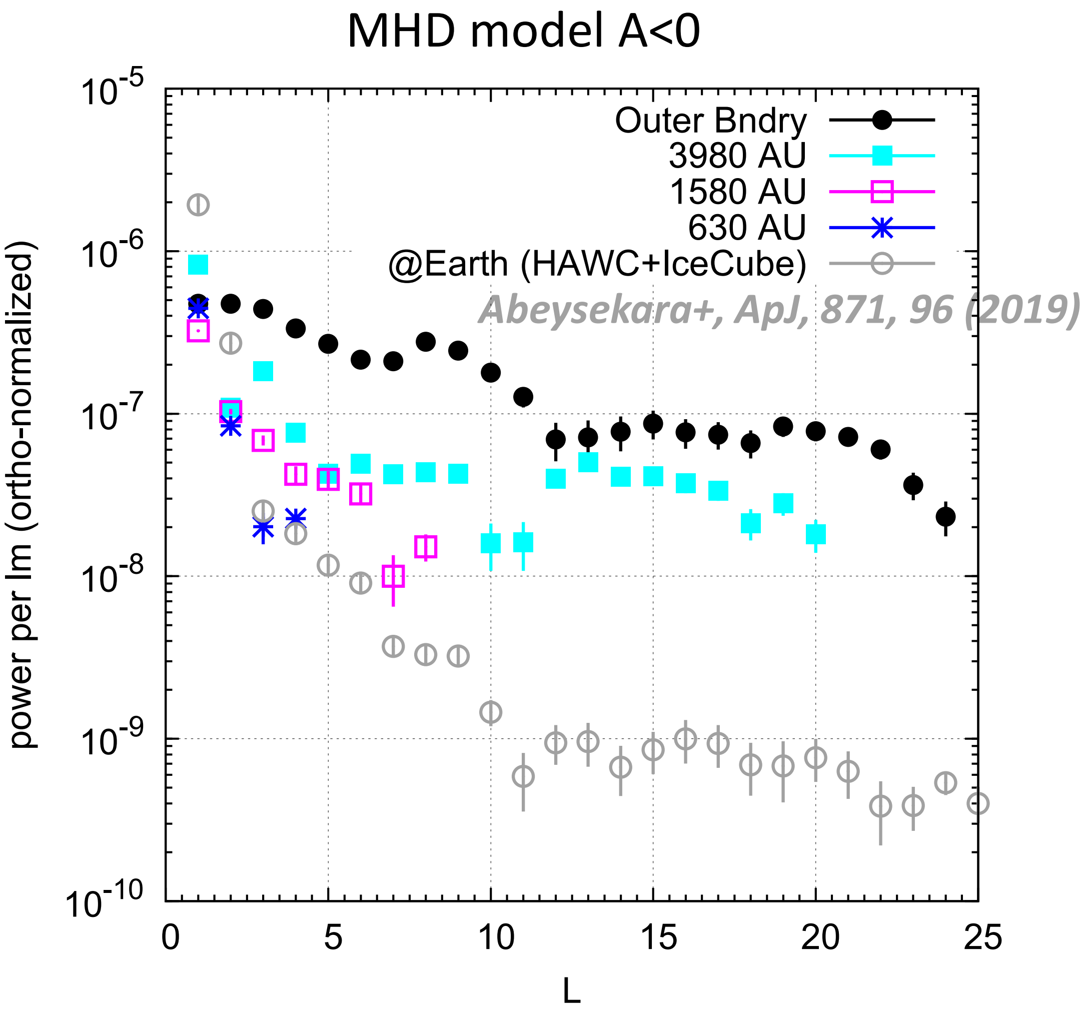


L_{max} = 20 ($N_{param.}$=440)

χ^2 / ndf = 0.942

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

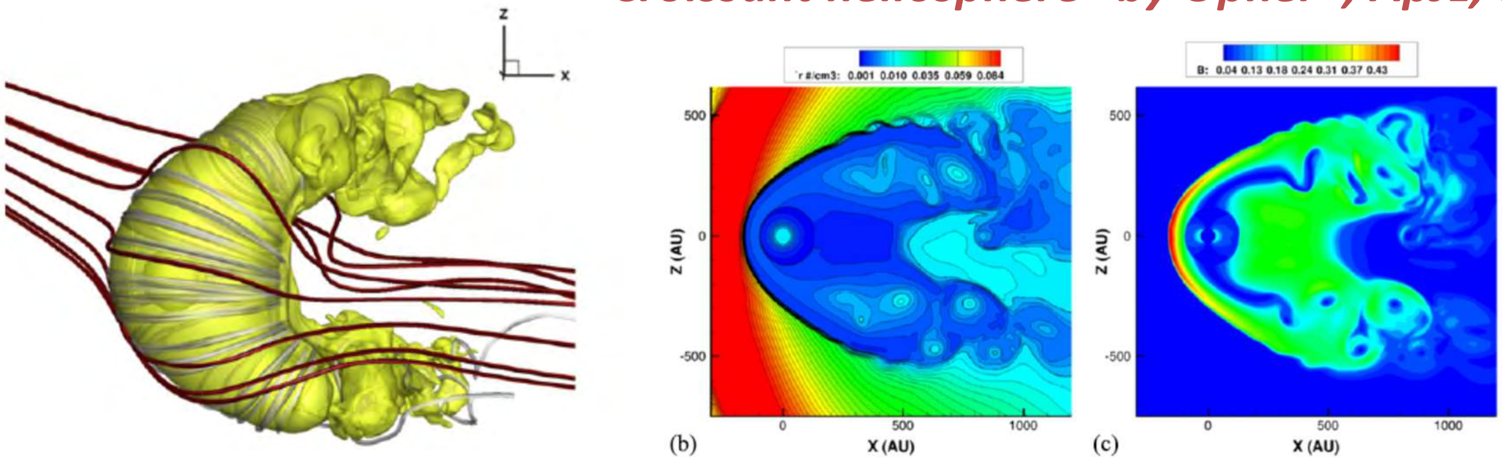
Power spectrum



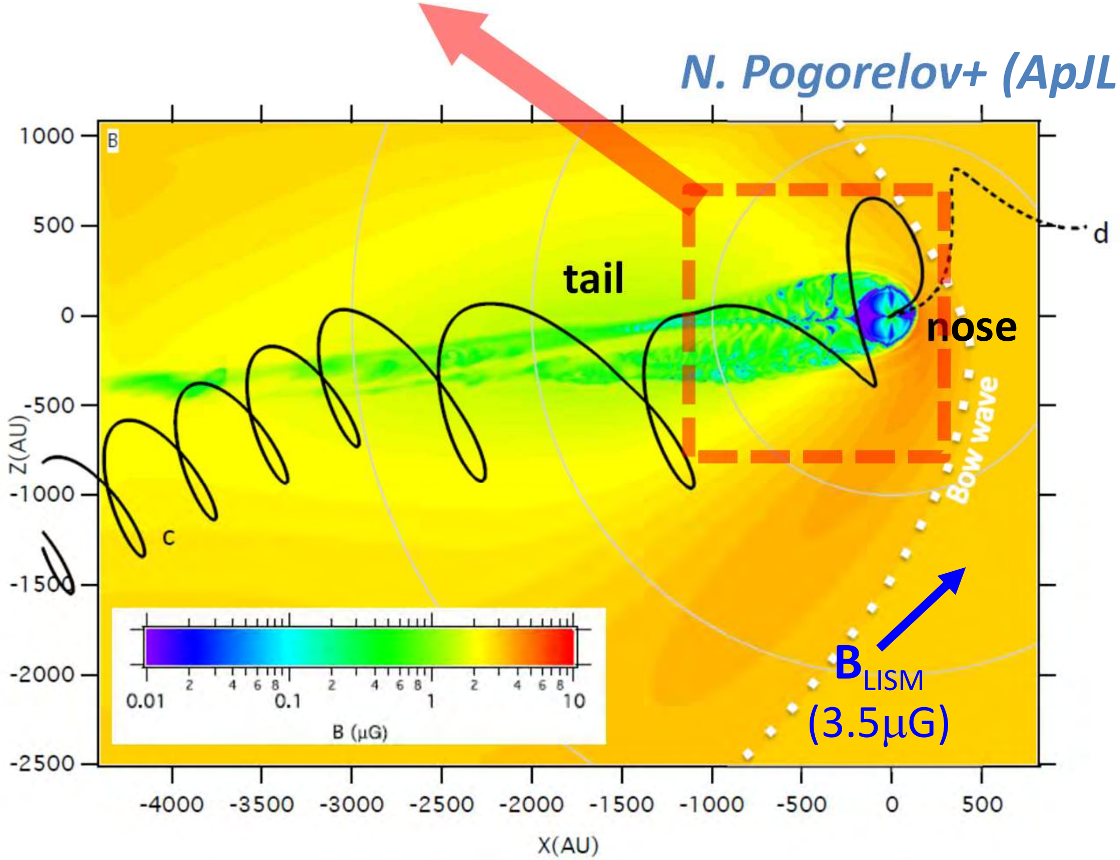
Alternative MHD heliosphere?

Polar jets confined in Parker field.

"Croissant heliosphere" by Opher+, ApJL, 800, L28 (2015)



N. Pogorelov+ (ApJL 812 L6 2015)



Summary

- 観測される宇宙線のリジディティー･スペクトラムを考慮することにより、reduced χ^2を大幅に下げることが出来た（4 parameter-fitで、4.5→1.6　d.o.f.=2052）が、依然不十分。
- Best-fitで得られたOuter boundary上の異方性には微細な構造が含まれており、reduced χ^2を1程度にまで下げるためには、L~20程度までの高次異方性が必要。
- 観測期間（約10年間）に対応する12個のMHD-snap shotを軌道計算に用いると、上の問題に一部改善が見られたが、依然としてL ≧ 3の高次異方性が必要。
- Outer boundary上に必要な高次異方性は、太陽圏外部境界を近づけることで減少する。

⇒ “comet-like”なheliosphereの描像に修正を迫る結果かも知れない。

成果発表等

- T. K. Sako et al., “Modeling of cosmic-ray anisotropy at TeV energies in an MHD Model Heliosphere”, **CRA 2023**, May 16-19, Loyola University (Chicago), USA (oral).
- T. K. Sako et al., “Modeling of TeV galactic cosmic-ray anisotropy based on Intensity Mapping in an MHD model heliosphere”, **ASTRONUM 2023**, June 26-30, Pasadena, USA (oral).
- T. K. Sako et al., “Modeling of the galactic cosmic-ray anisotropy at TeV energies using an intensity-mapping method in an MHD model heliosphere”, **ICRC2023**, July 26 - August 3, Nagoya, Japan (oral).
- T. K. Sako et al., “Modeling of TeV cosmic-ray anisotropy using intensity-mapping method in an MHD model heliosphere”, **AGU fall meeting 2023**, December 11-15, San Francisco, USA, (poster).
- T. K. Sako et al., “Modeling of the sidereal anisotropy of TeV galactic cosmic rays with the Tibet ASg experiment”, **AIAC 2024**, March 25-29, Turin, Italy (oral).
- K. Kawata, "Recent Observation and Modeling of the Sidereal Cosmic-ray Anisotropy at TeV Energies with the Tibet ASgamma Experiment“, **AOGS 2024**, June 23-28, Pyeongchang, Korea (oral).
- M. Takita, "Modeling of the sidereal cosmic-ray anisotropy at TeV energies with data from the Tibet ASgamma experiment” **ASTRONUM 2024**, July 1-5, La Rochelle, France (oral).

- **物理学会第78回年次大会**、2023年 9/16 – 19、**東北大学、佐古崇志ほか、「チベット実験で観測された宇宙線異方性の太陽圏磁場による変調(4)」**
- **ISEE 研究集会「太陽地球環境と宇宙線モジュレーション」**2024年 3/4-3/7、**名古屋大学/オンライン、佐古崇志ほか、**「TeV **領域宇宙線異方性の太陽磁場による変調」**