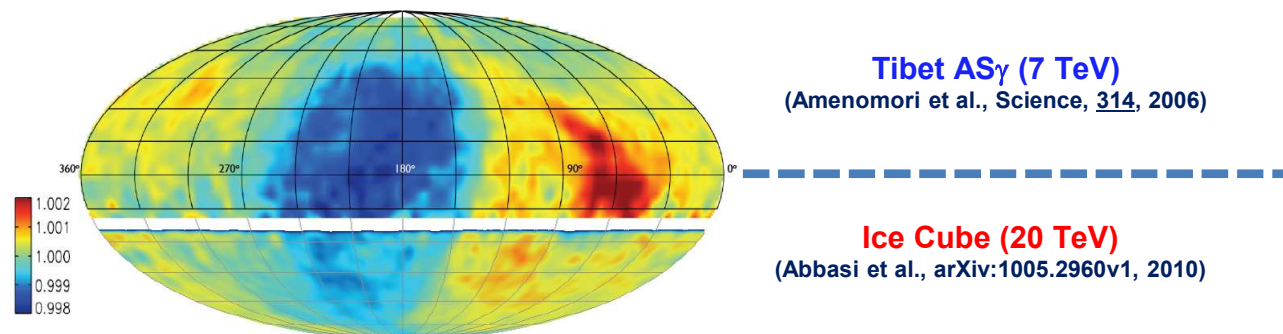


SK/Tibetによる 高エネルギー宇宙線強度の 恒星時異方性の観測

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加藤千尋¹⁾、林優希¹⁾、増田吉起¹⁾、松本瑞生¹⁾、瀧田正人²⁾、鷲見治一³⁾、
¹⁾信州大、²⁾宇宙線研、³⁾九州大

220千円：浜松フォトニクス社製 PMT2本

Heliospheric modulation (distortion) in MHD model heliosphere



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

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

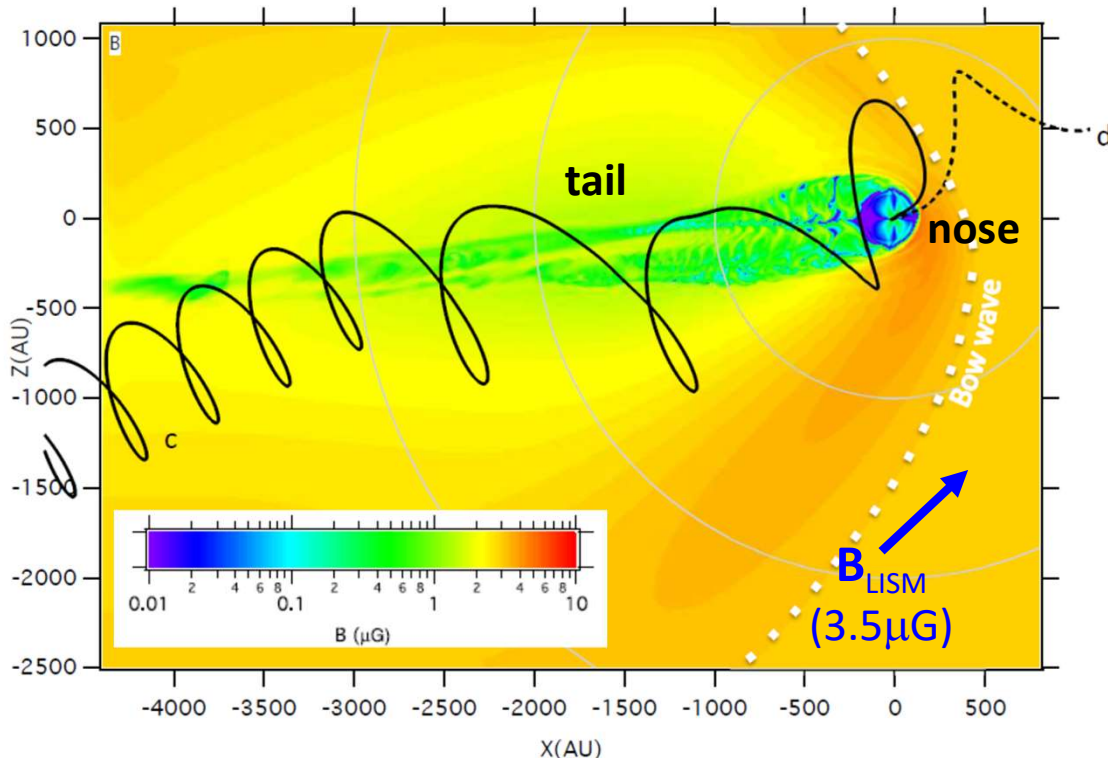
$$\frac{d\mathbf{p}}{dt} = Ze \left(\mathbf{E} + \frac{d\mathbf{r}}{dt} \times \mathbf{B} \right)$$

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

➤ 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* for CR orbit calculation.

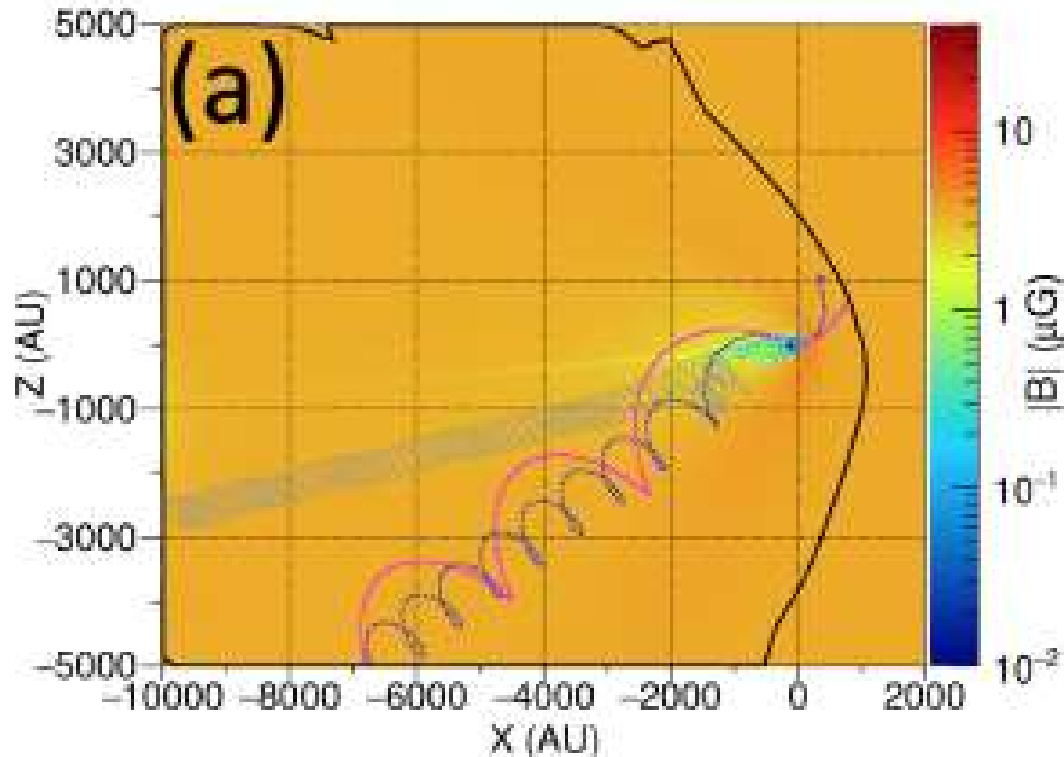
➤ Take accounts of composition, E-spectrum and AS-array performance for quantitative best-fitting.



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

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

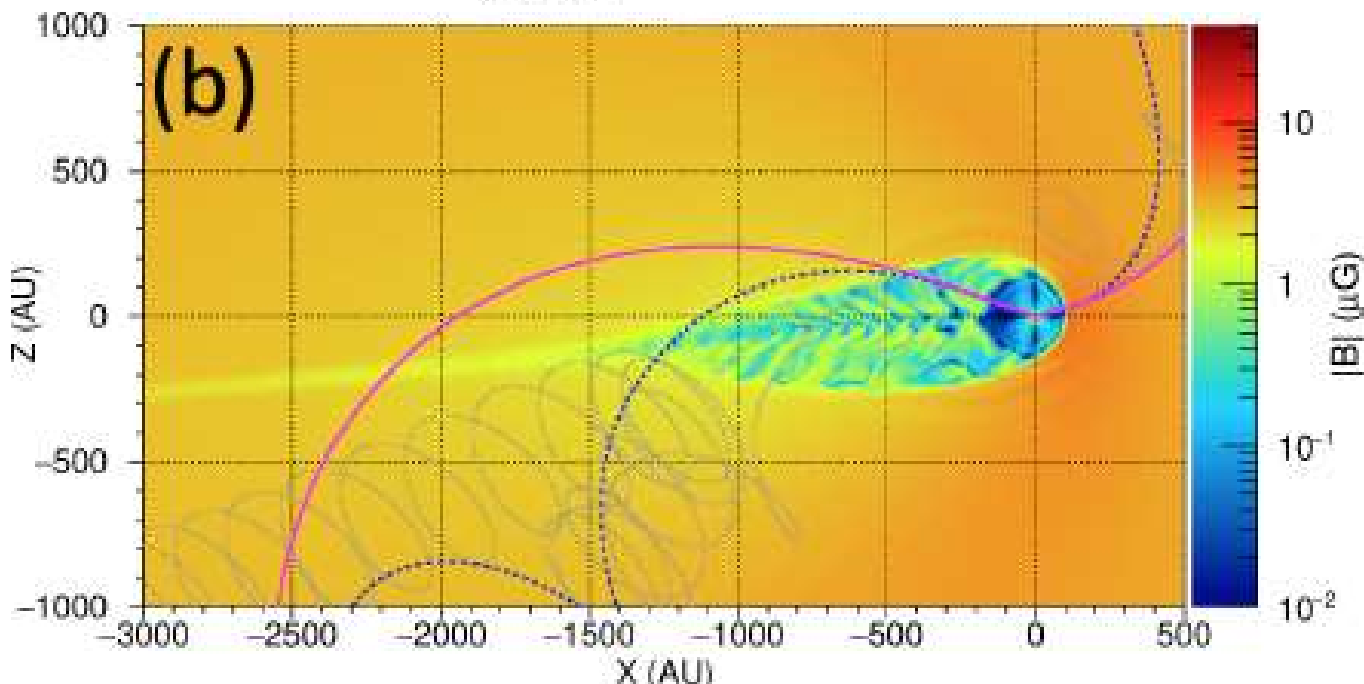
MHD boundary



仮定しているLISMからのズレが...

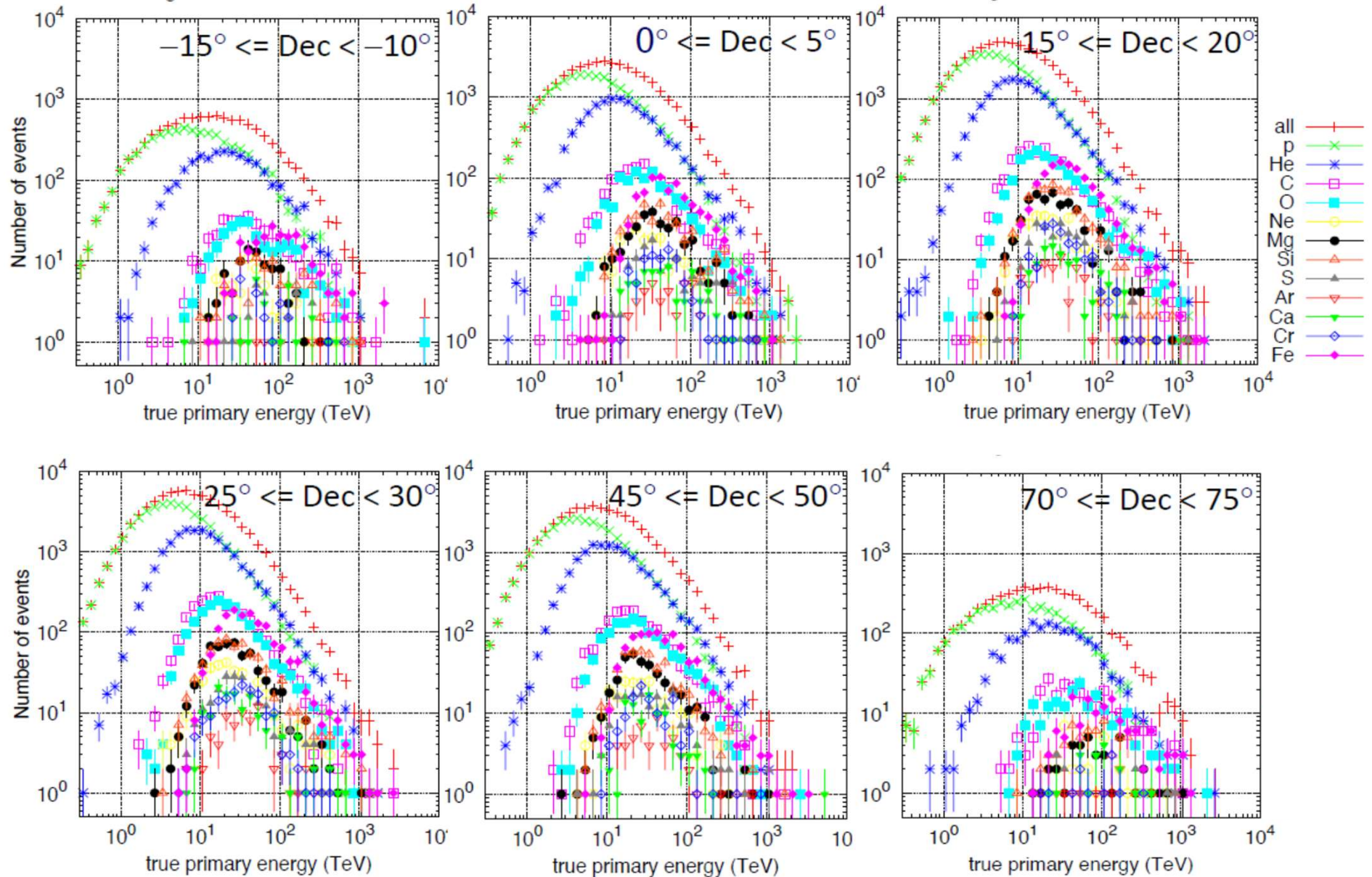
- 磁力線の向きで 1° 以内
- 磁場強度の絶対値で1%以下

...に収まる最も内側の面としてOuter boundary (黒線)を定義している。

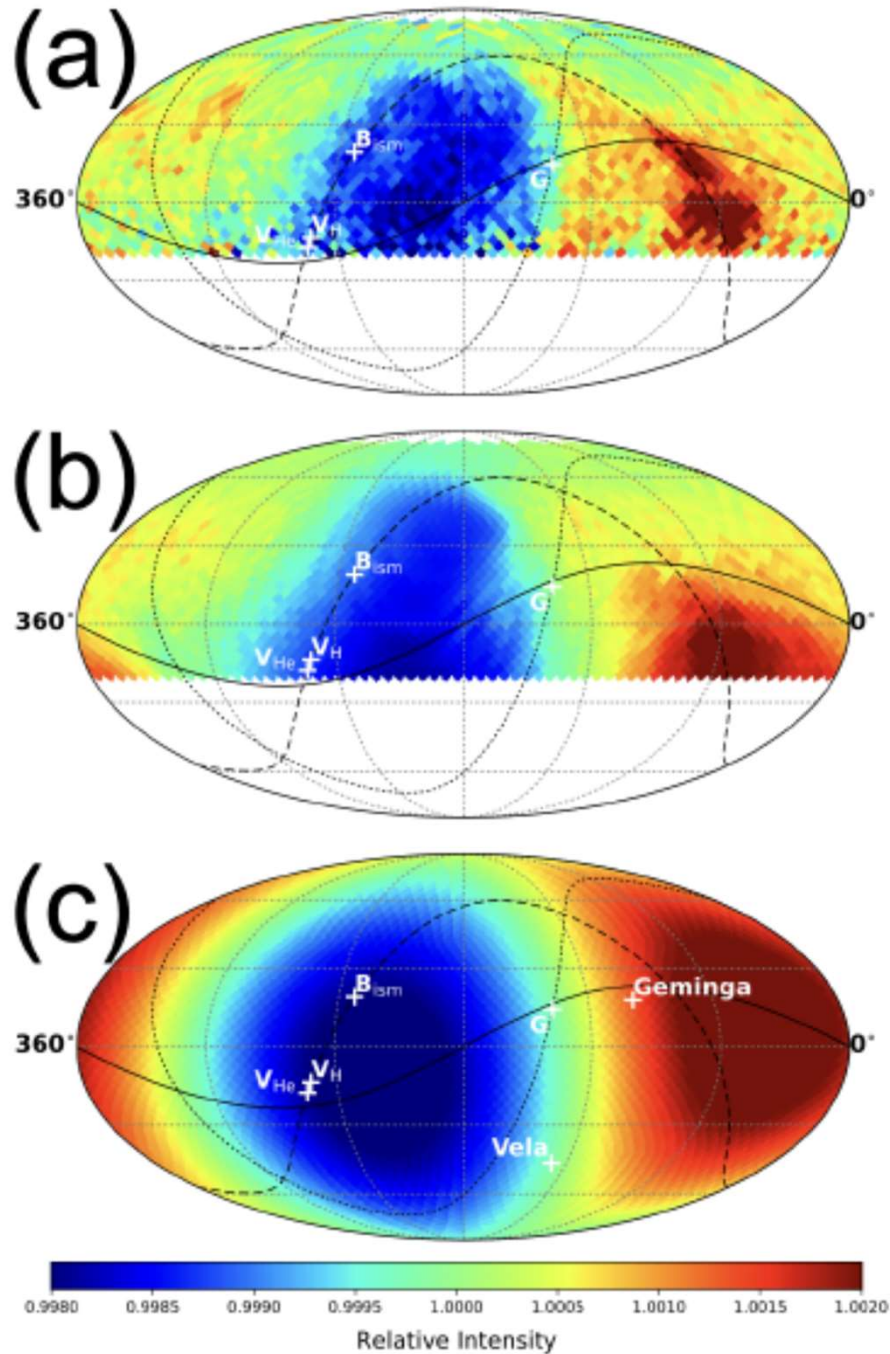


例として、地球からnose方向とtail方向に打ち出された、3.5 TV、7.1 TV、14 TVの反粒子の軌道がプロットしてある。

Weighting with composition & E-spectra by MC (instead of using monochromatic protons)



Best-fit results



Assuming a **free dipole anisotropy** plus **bidirectional flow** along the LISM

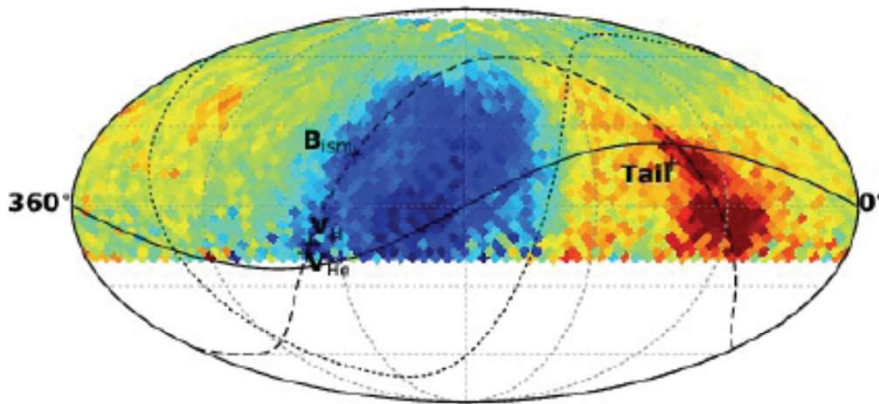
		Best-fit values	
		this work	Paper 1
	$A_{1\parallel}$	$(0.234 \pm 0.002)\%$	$(0.165 \pm 0.002)\%$
	$A_{2\parallel}$	$(0.011 \pm 0.005)\%$	$(0.015 \pm 0.002)\%$
	$A_{1\perp}$	$(0.131 \pm 0.006)\%$	$(0.021 \pm 0.001)\%$
Parameters	α_{\perp}	$193.1^{\circ} \pm 7.9^{\circ}$	$287^{\circ\ddagger}$
	δ_{\perp}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

Results: fitting by spherical harmonics

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

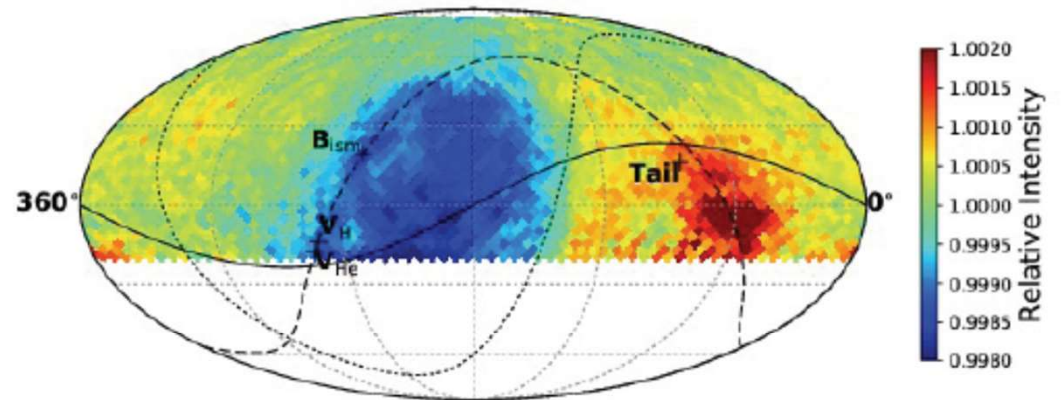
$L_{\max} = 24$ (624 parameters)

Data @ Earth

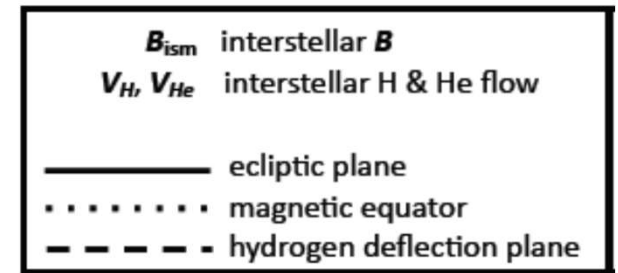
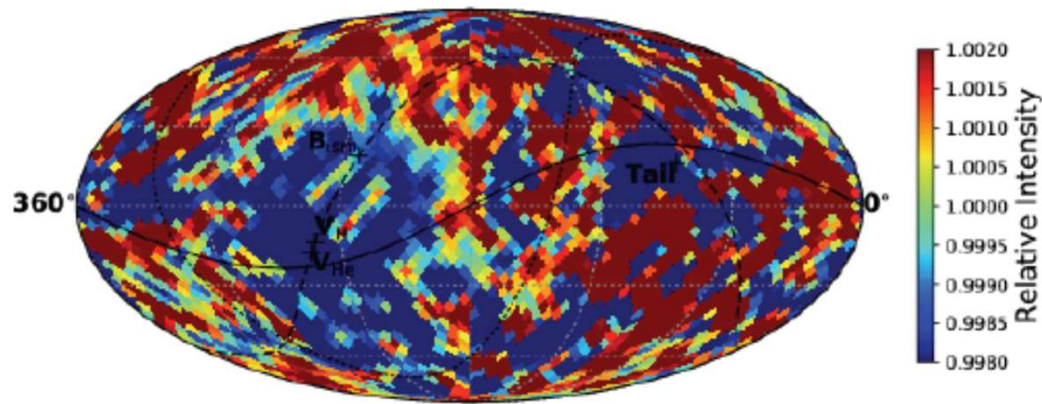


$$\chi^2 / \text{ndf} = 1393 / 1432 = 0.973 \text{ (76.4 \%)}$$

Model Fitting @ Earth



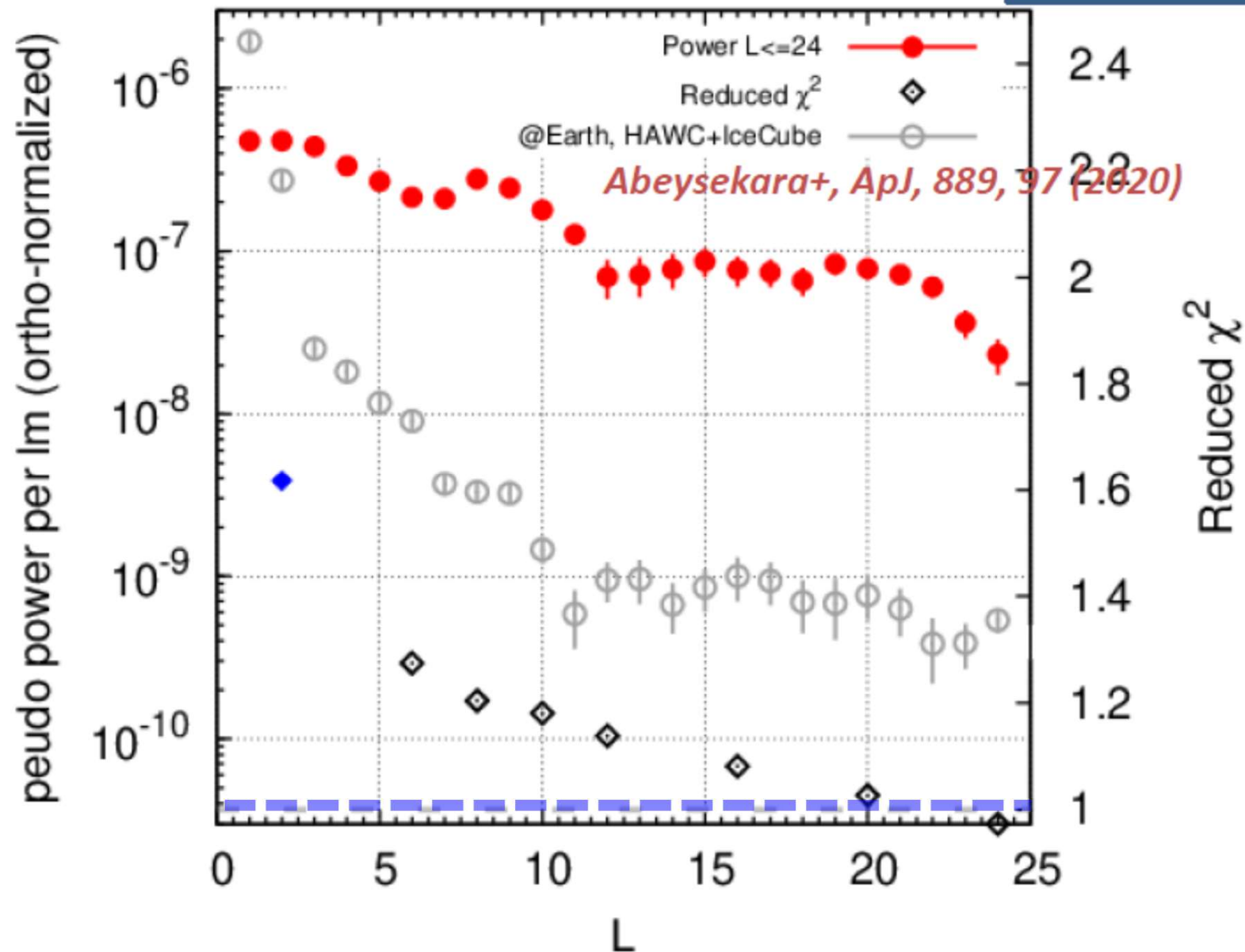
Model @ Boundary



➤ Unrealistic small-scale anisotropy appears @ outer boundary

Results: Power spectrum

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

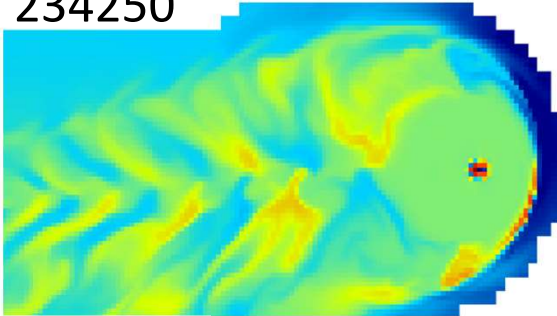


- $L \geq 20$ terms are needed @ outer boundary to get reasonable χ^2
- Spectrum flatter @ outer boundary than @ Earth

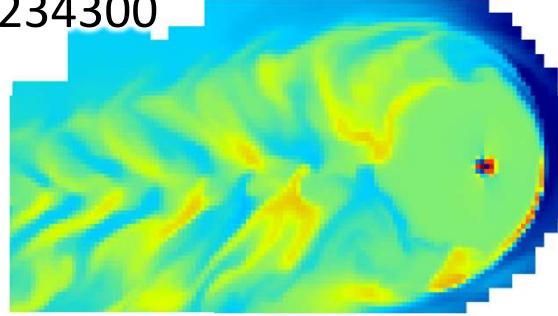
Using 12 MHD snap shots

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

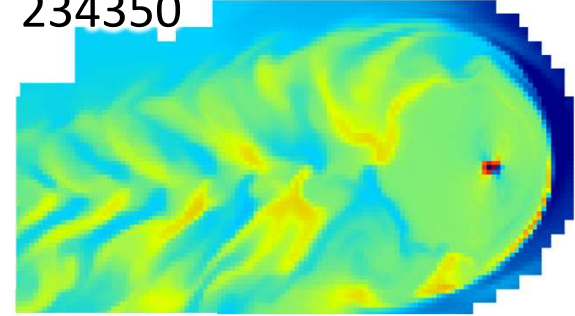
234250



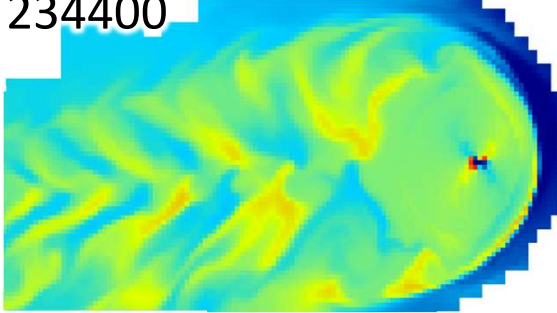
234300



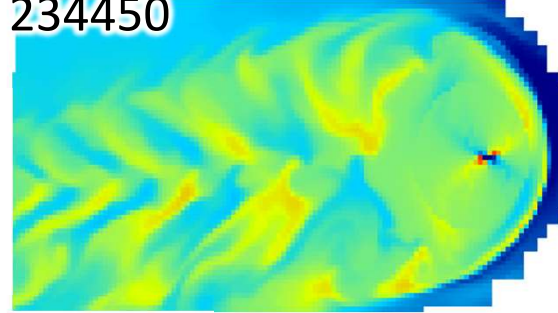
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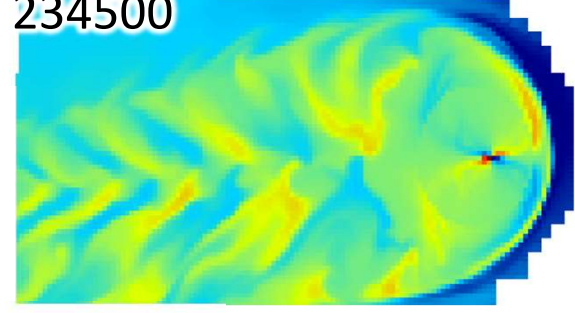
234400



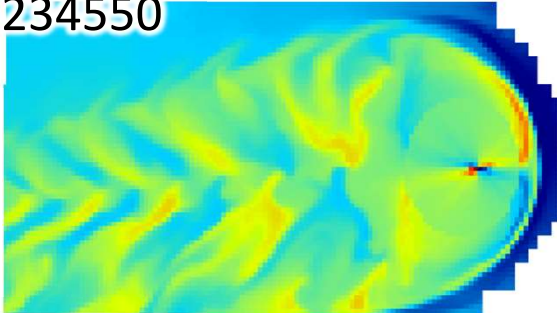
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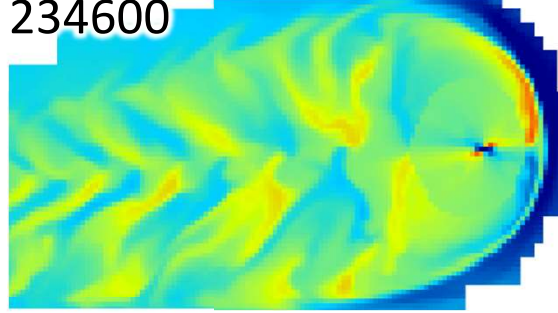
234500



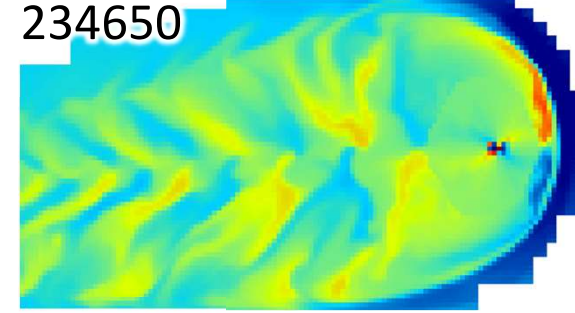
234550



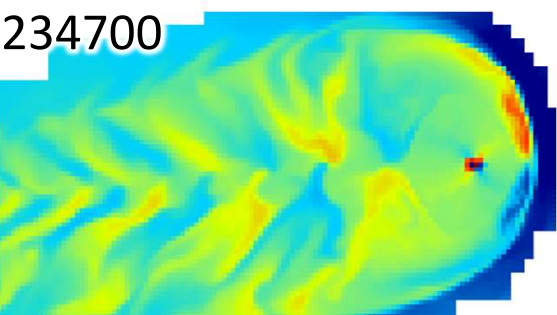
234600



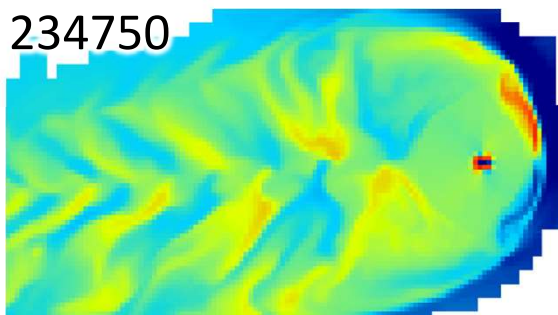
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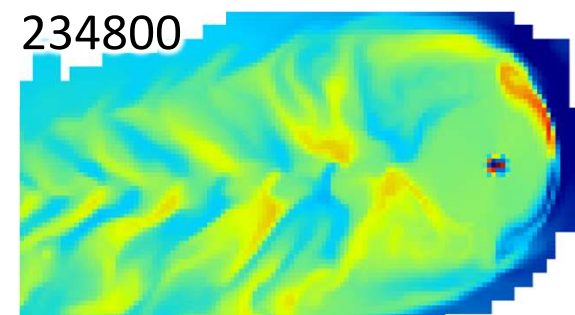
234700



234750



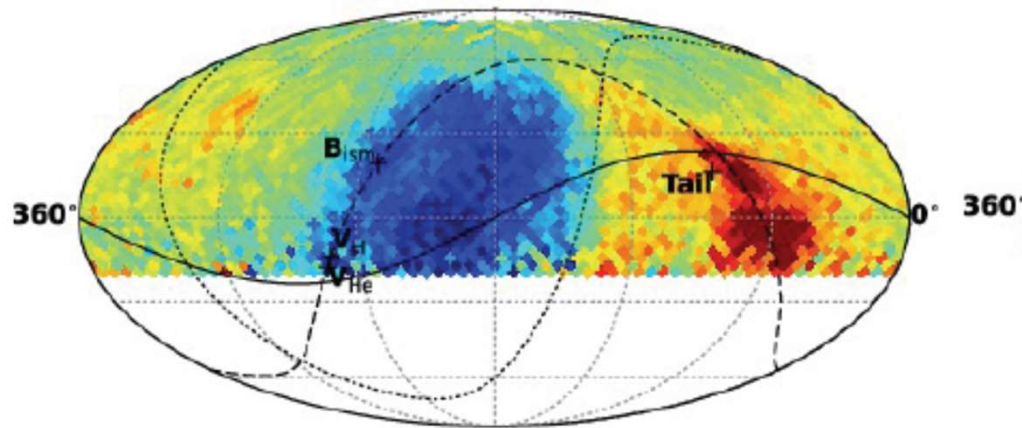
234800



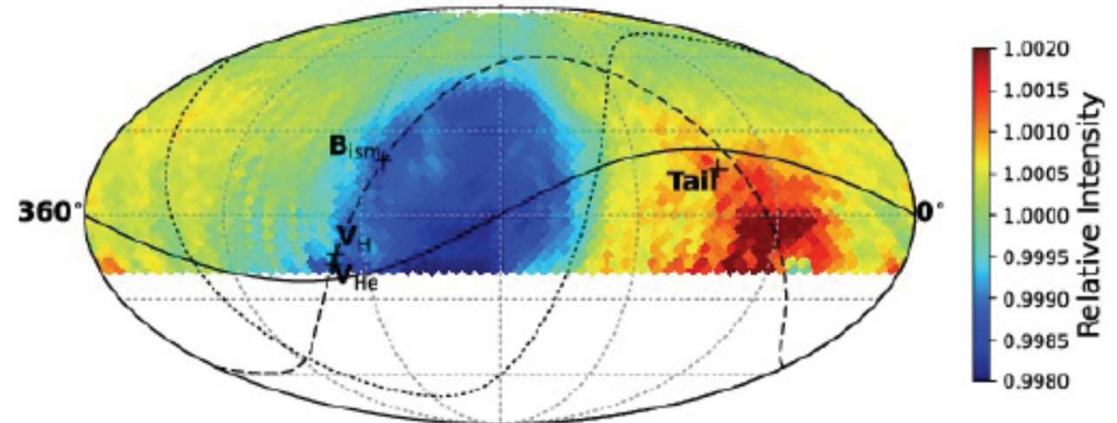
$L_{\max} = 12$ (168 parameters)

$\chi^2 / \text{ndf} = 1869 / 1888 = 0.990$ (61.8 %)

Data@Earth normalized

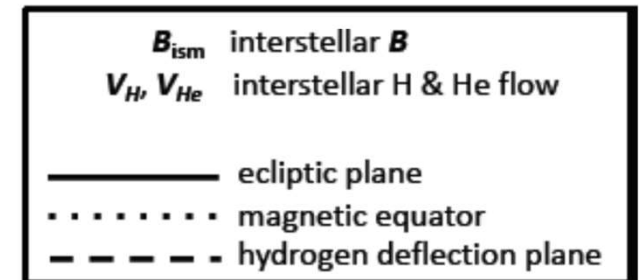
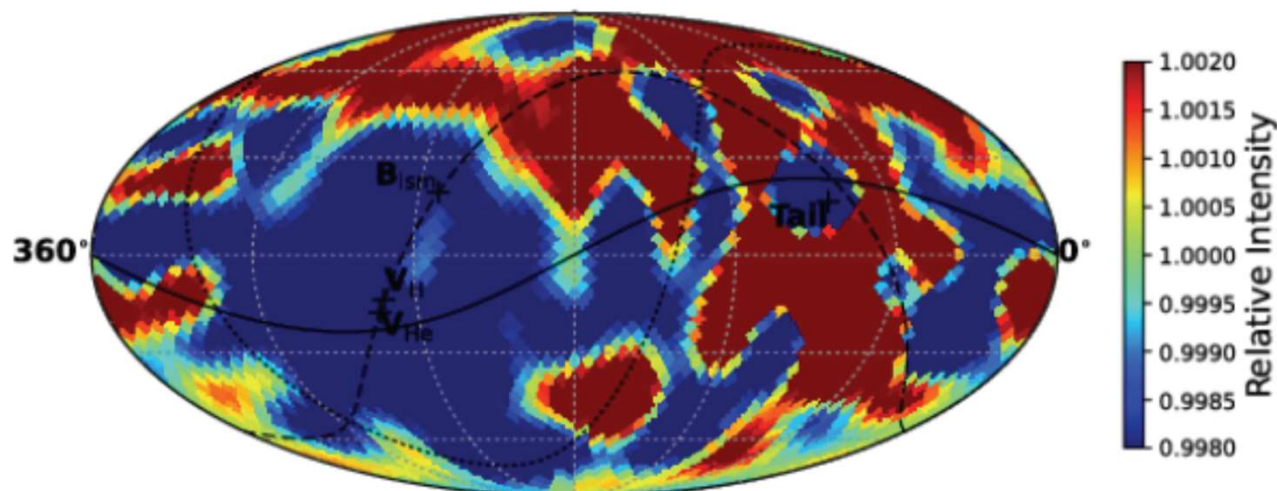


normalized Model Fitting @Earth

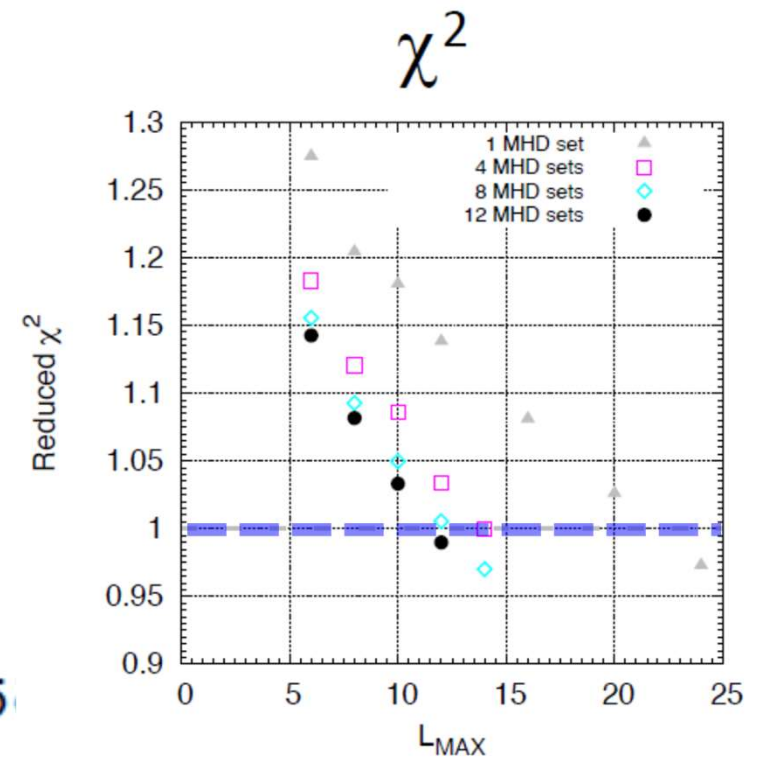
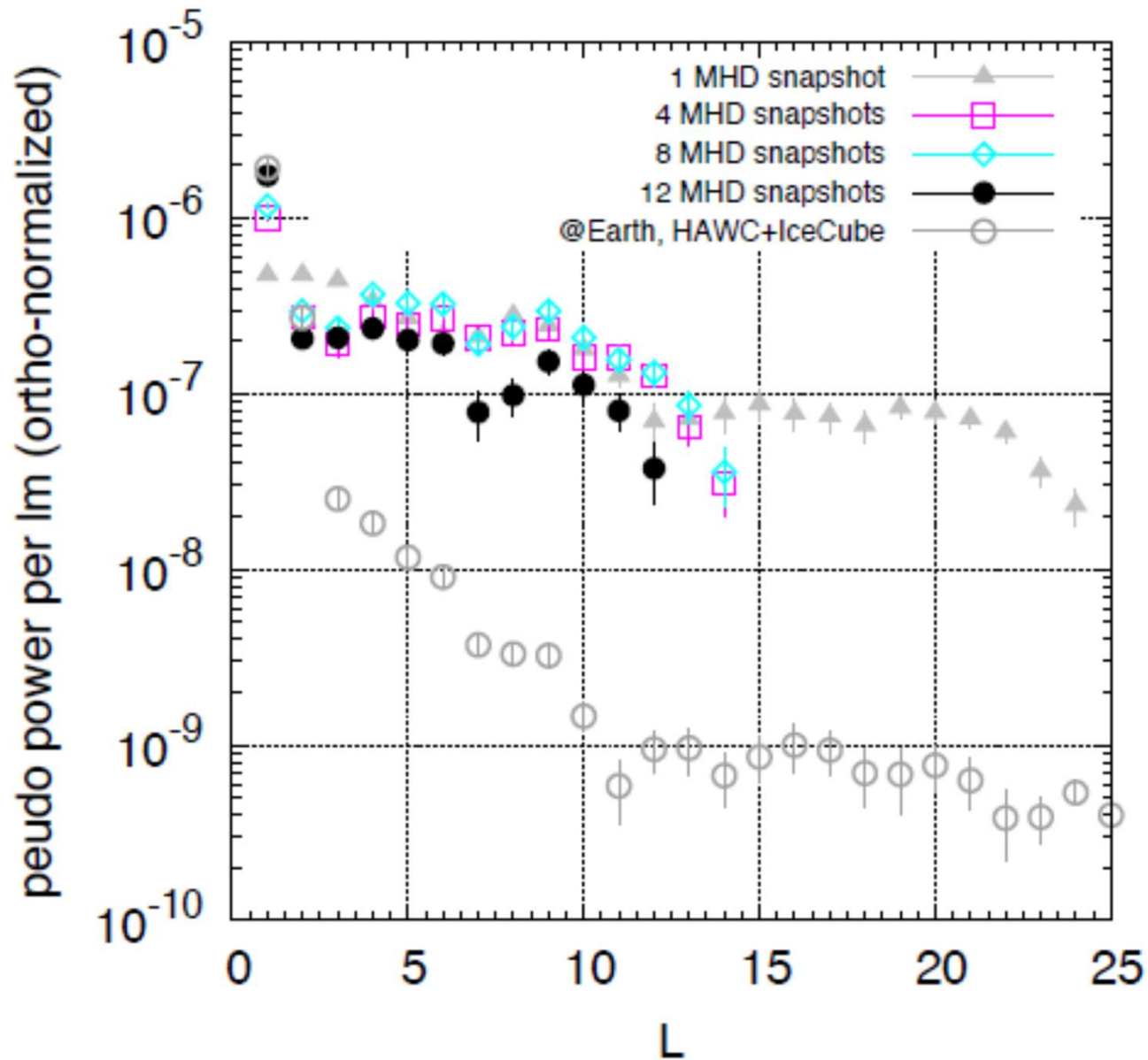


Model @ Boundary

unnormalized



power spectrum



Summary

- 観測される宇宙線のリジディティ・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)。
- Outer boundary上の異方性のpower spectrumでは微細な異方性が卓越しており、reduced χ^2 を1程度にまで下げるためには、 $L \sim 20$ 程度までの高次の異方性が必要であった。
- 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 $L \geq 3$ の高次異方性が卓越している。
- 今後、ここまでの結果を論文にまとめて公表したい。

成果発表等

- [Poster] AGU23, San Francisco, California USA (hybrid (on site + online)), 11-15 December 2023 "Modeling of TeV cosmic-ray anisotropy using intensity-mapping method in an MHD model heliosphere"
- [Oral] ASTRONUM2023, Pasadena, California USA, 25-30 June 2023 "Modeling of TeV Galactic Cosmic-ray Anisotropy based on Intensity Mapping in an MHD Model Heliosphere"
- [Oral] CRA2023, Loyola University, Chicago, USA, 16-19 May 2023 "Modeling of cosmic-ray anisotropy at TeV energies in an MHD model heliosphere"
- [Oral] ICRC2023, Nagoya University, Japan, 26 July - 3 August 2023 "Modeling of the galactic cosmic-ray anisotropy at TeV energies using an intensity-mapping method in an MHD model heliosphere"
- [Oral] AIAC2023, Turin, Italy, 25-29 March 2024 "Modeling of the sidereal anisotropy of TeV galactic cosmic rays with the Tibet ASgamma experiment"
- 物理学会、東北大学、9/16 - 9/19, 2023 "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)"