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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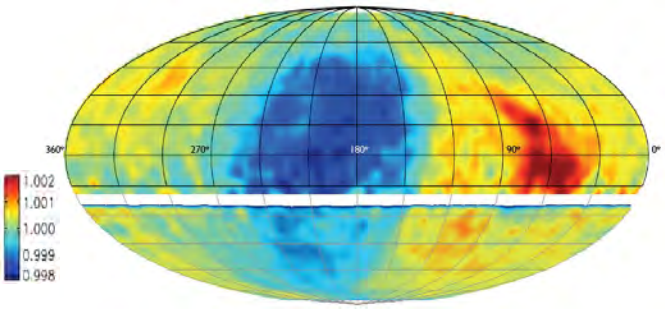
638千円（2020-2022繰越総額）：PMT出力用増幅器設計・製作、PC

Heliospheric modulation (distortion) in MHD model heliosphere



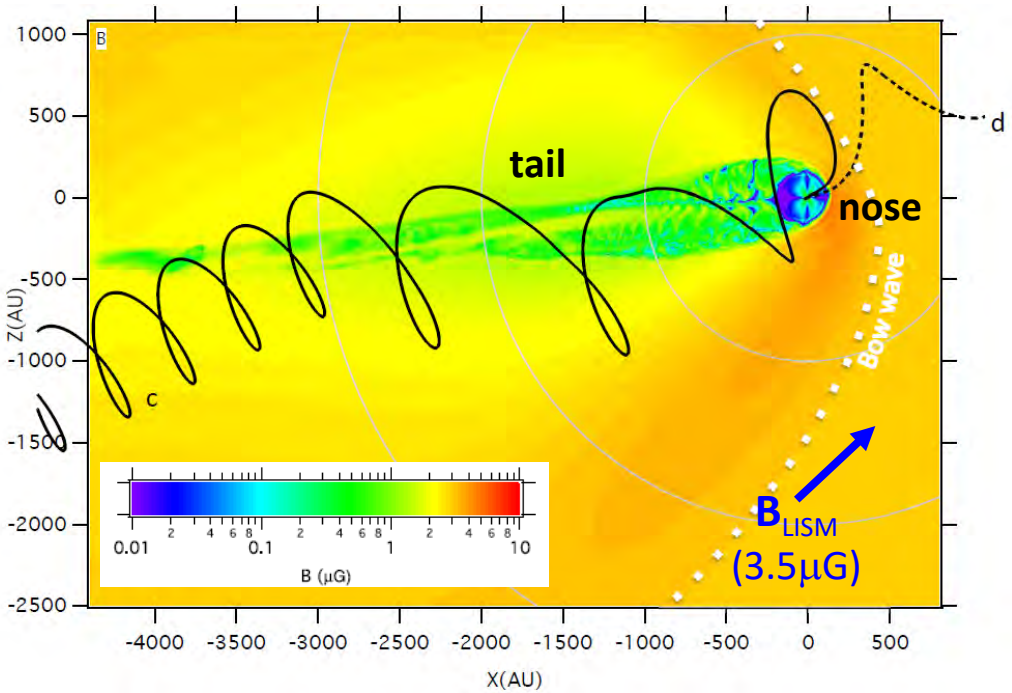
Tibet ASγ (7 TeV)
(Amenomori et al., Science, 314, 2006)

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

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

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

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



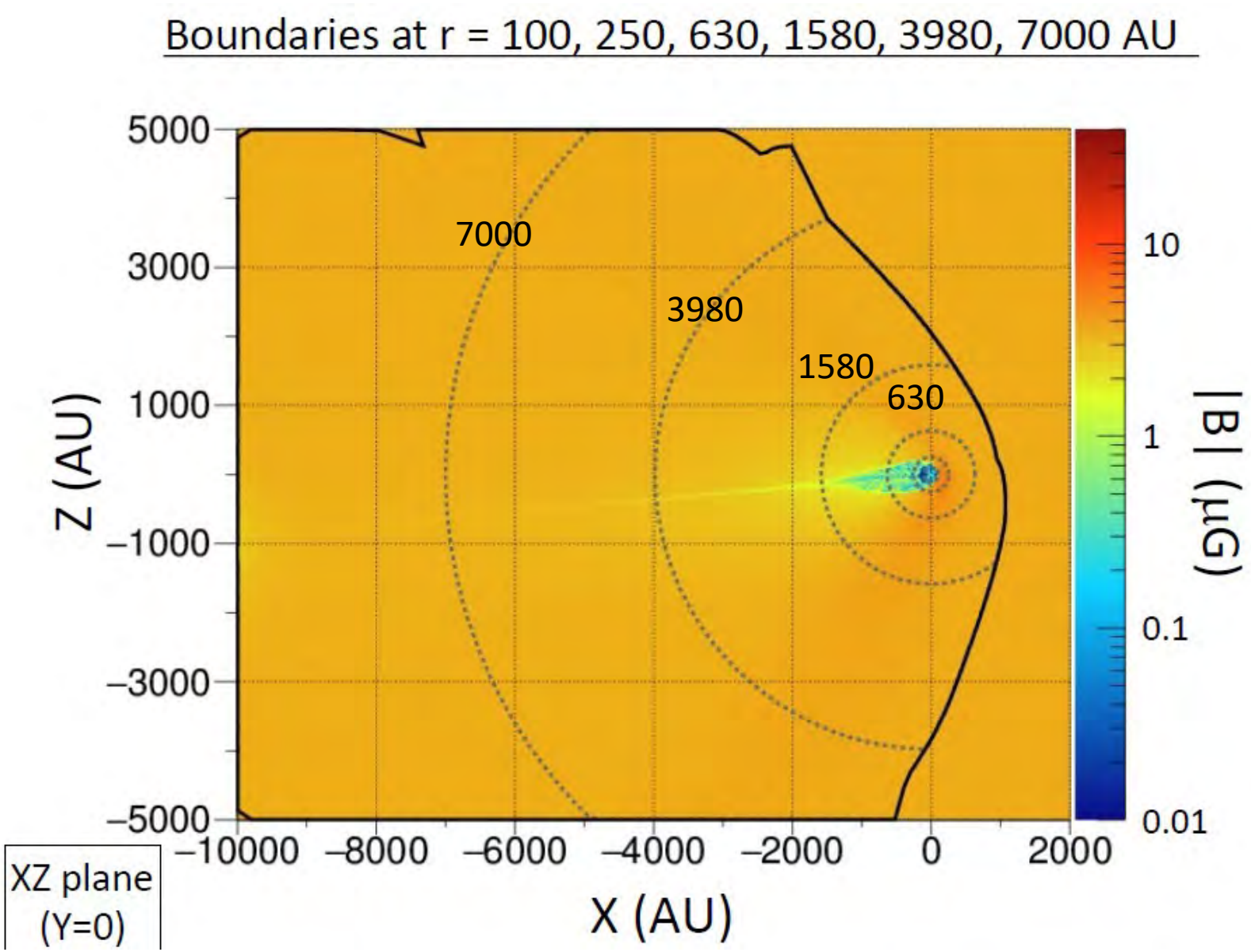
$$f(\mathbf{r}_E, \mathbf{p}_E, t) \approx f(\mathbf{r}_B, \mathbf{p}_B, t)$$

- 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*** for CR orbit calculation.
- Take accounts of composition, E-spectrum and AS-array performance for quantitative best-fitting.

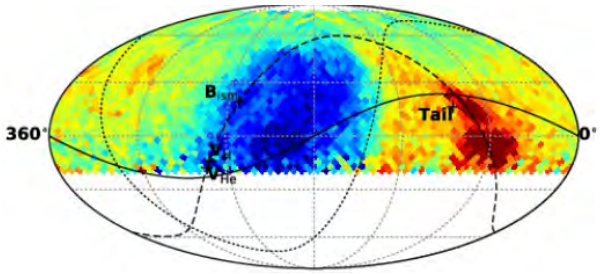
Model: $f(\mathbf{r}_B, \mathbf{p}_B, t) = f^{CG} + \sum_{l=1}^{L_{max}} \sum_{m=-l}^{l} f_l^m Y_l^m(\theta, \phi)$ θ, ϕ: Dec, R.A.

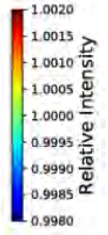
$N_{param.} = (L_{max} + 1)^2 - 1$ ($= \mathbf{440}$ for $L_{max} = 20$)

MHD boundary



Observed at Earth (Nov. 1999 to Dec. 2008 corresponding to A<0 period)

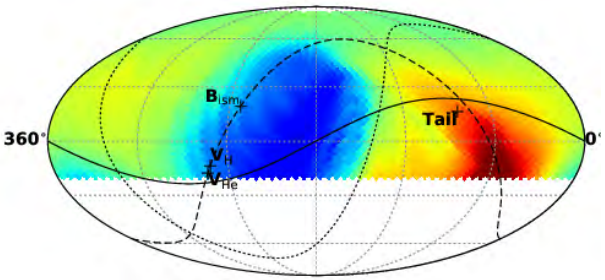




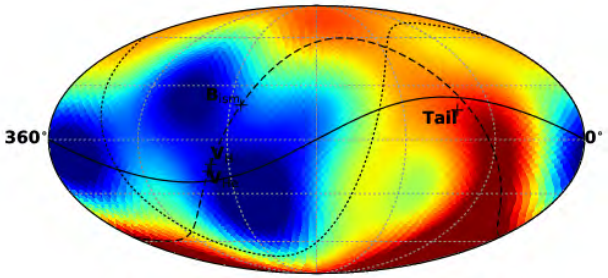
B_{ism}	interstellar B
V_H, V_{He}	interstellar H & He flow
———	ecliptic plane
· · · · · · · ·	magnetic equator
– – – – –	hydrogen deflection plane
G	bestfit CR density gradient

Reproduced at Earth

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

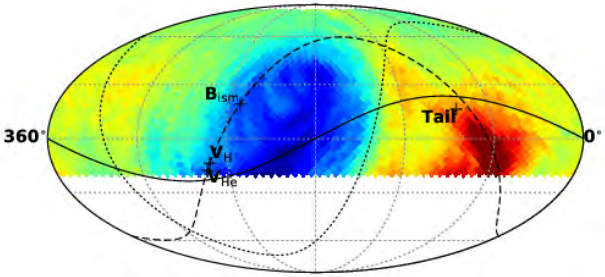


r_B= 630 AU

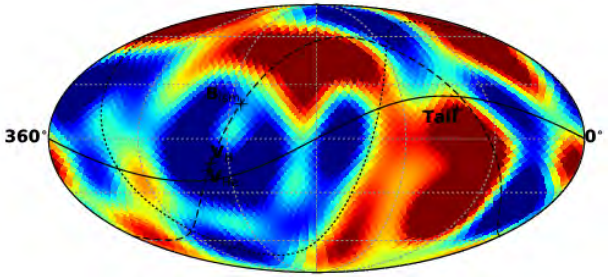


L_{max} = 4 ($N_{param.}$=26)

χ^2 / ndf = 0.962

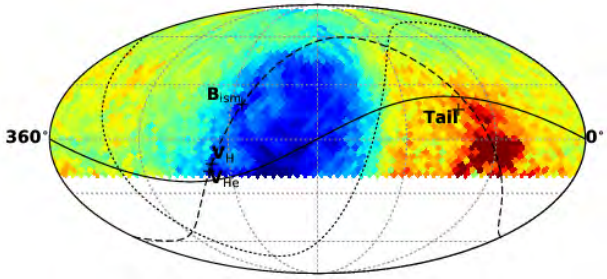


1580 AU

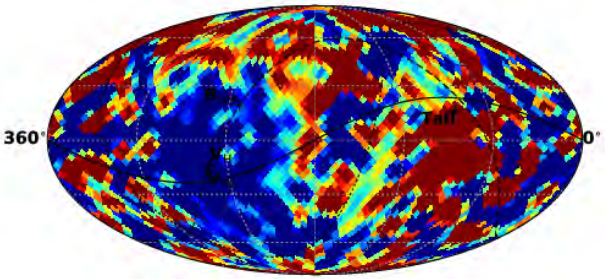


L_{max} = 8 ($N_{param.}$=80)

χ^2 / ndf = 0.982



3980 AU

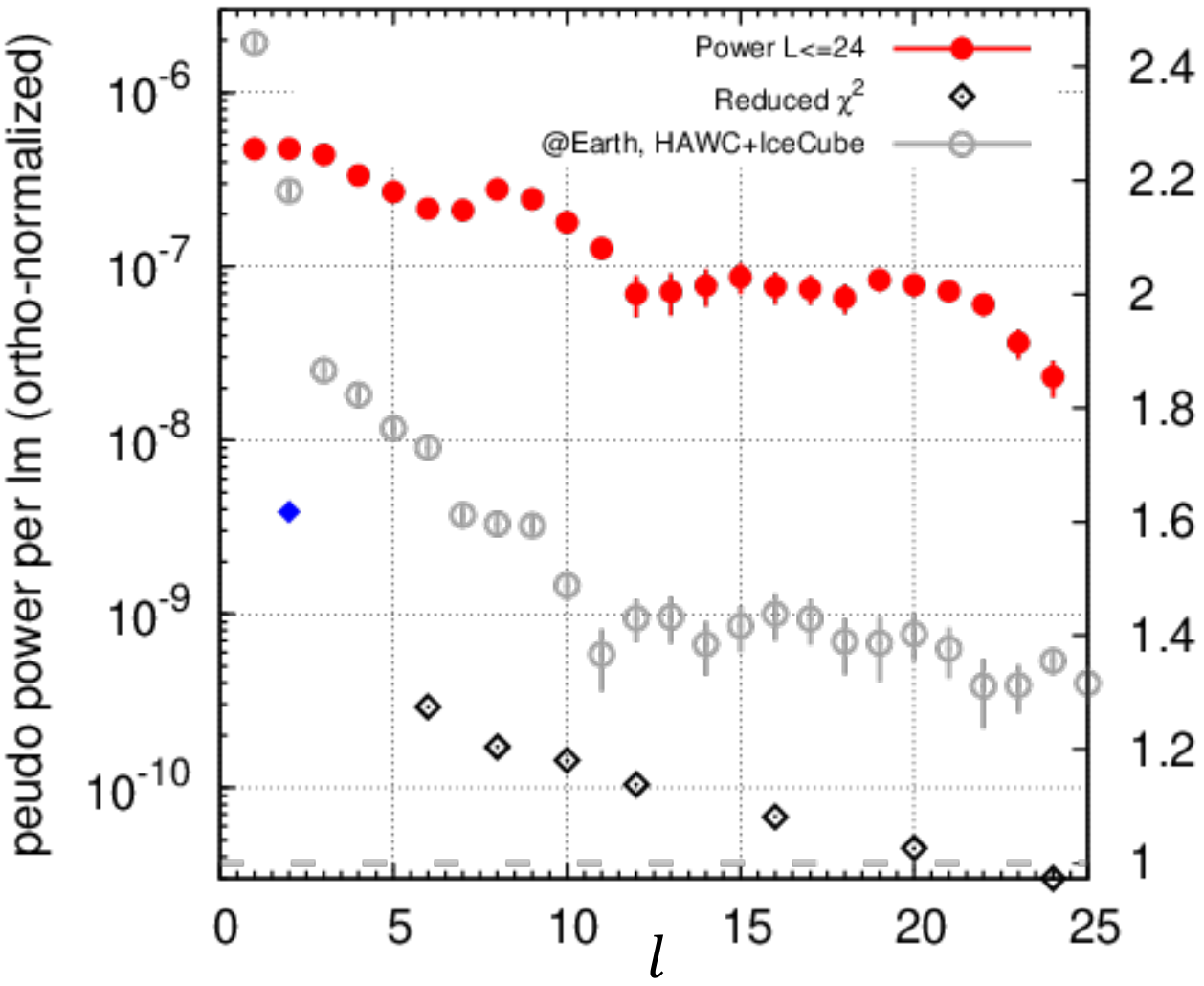


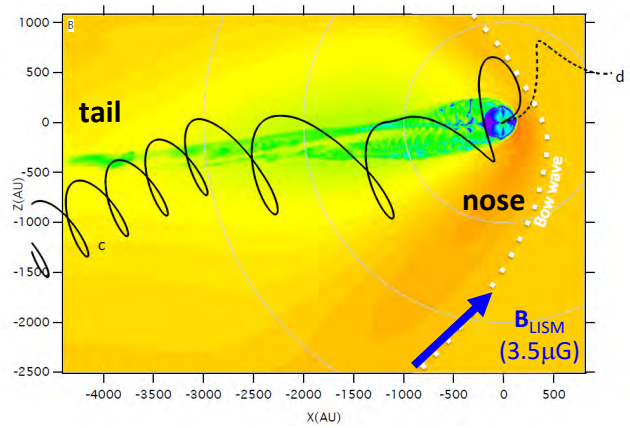
L_{max} = 20 ($N_{param.}$=440)

χ^2 / ndf = 0.942

Power spectrum

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





Introduce the multiple pitch angle scattering

Multiple scattering theory (Rossi, 1952)

The projected angle Θ is defined as the angle between **V** and the projection of the scattered velocity on one of the planes, and has the following probability distribution:

$$\Phi(\Theta) = \frac{1}{\sqrt{2\pi\langle\Theta^2\rangle}} \exp\left(-\frac{\Theta^2}{2\langle\Theta^2\rangle}\right), \quad (1)$$

where $\langle\Theta^2\rangle$ is the mean square angle of Θ for dl and is related with the scattering mean free path L as

$$\langle\Theta^2\rangle = \left(\frac{\pi}{2}\right)^2 \left(\frac{dl}{L}\right), \quad (2)$$

Yasue+
Planet Space Sci. 33, 1057 (1985)

Diffusion coefficient

Moskalenko+, ApJ, 565, 280 (2002)

$$D = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^{\delta} \quad (\beta \approx 1)$$

$D_0 = 6.1 \times 10^{28}$ [cm^{2}s^{-1}]

$\rho_0 = 4$ [GV]

$\delta = \frac{1}{3}$

Mean free path

$$D = \frac{1}{3} v L \quad (v \approx c)$$

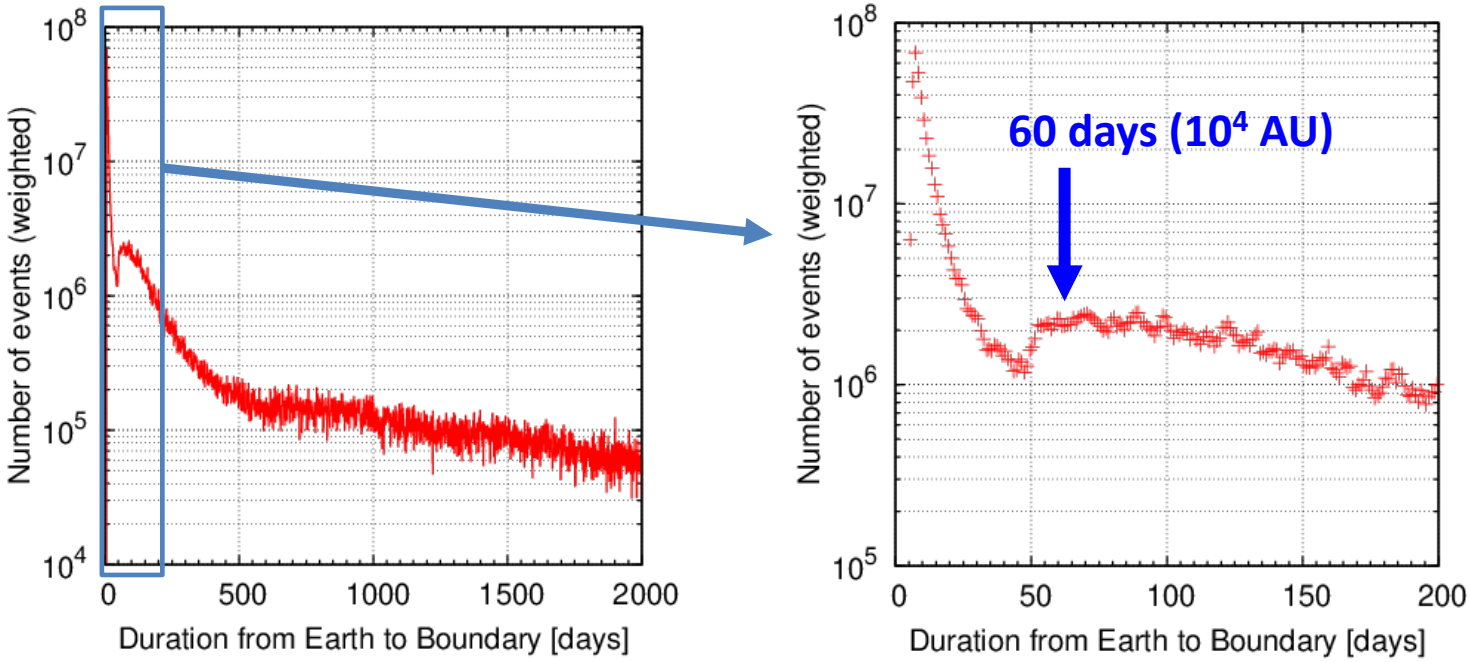
$L \sim 5 * 10^6$ AU for 7 TeV p

Assuming $T \sim 60$ days to Earth from r_B

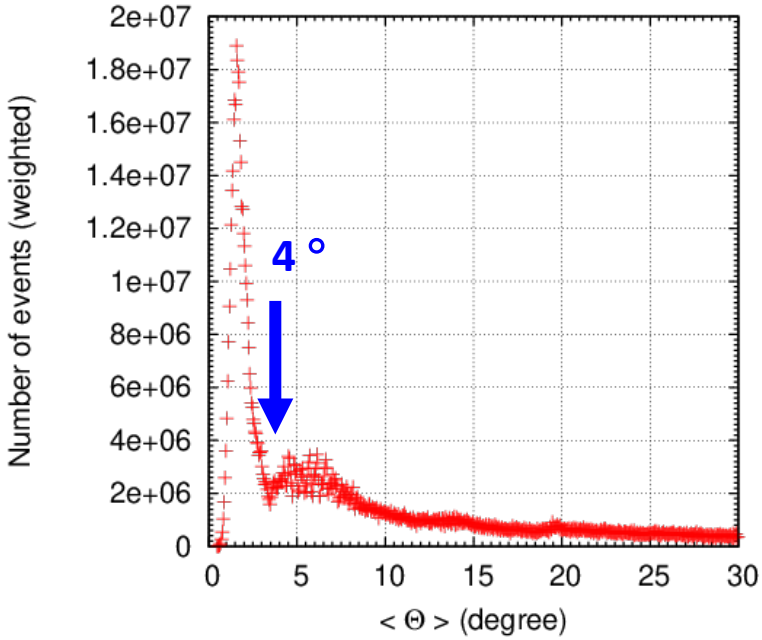
➡ $dl = 10^4$ AU

➡ $\sqrt{\langle\Theta^2\rangle} \sim 4°$ for 7 TeV p

Distribution of the time from Earth to Boundary



Scattering angle distribution

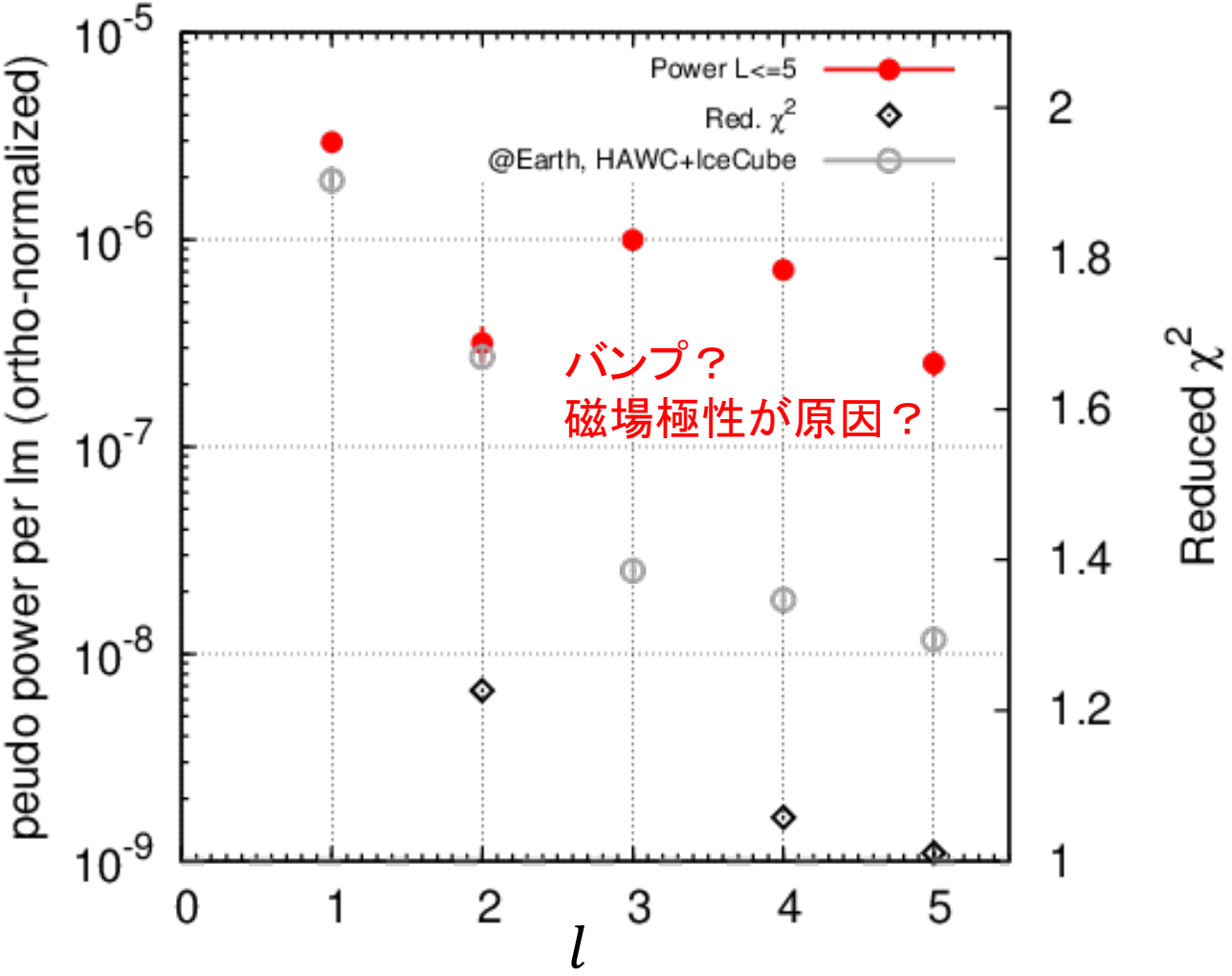


Power spectrum

Pogorelov MHD model

A>0

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



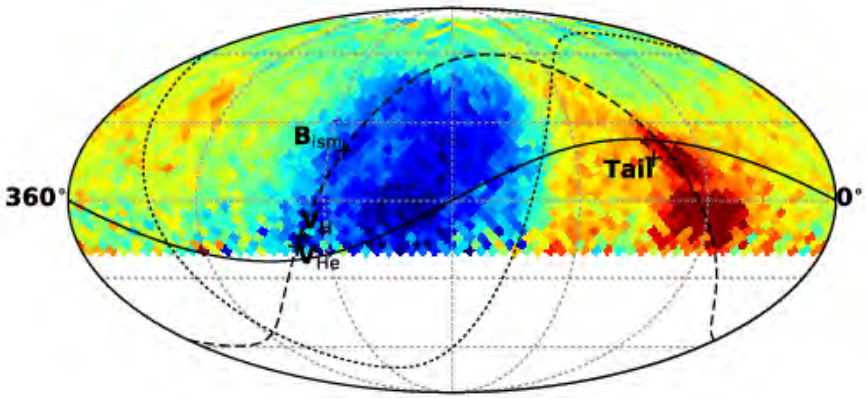
D0 * 1.0

L_{max} = 5 (35 parameters)

χ^2 / ndf = 2042/2021 = **1.01 (36 %)**

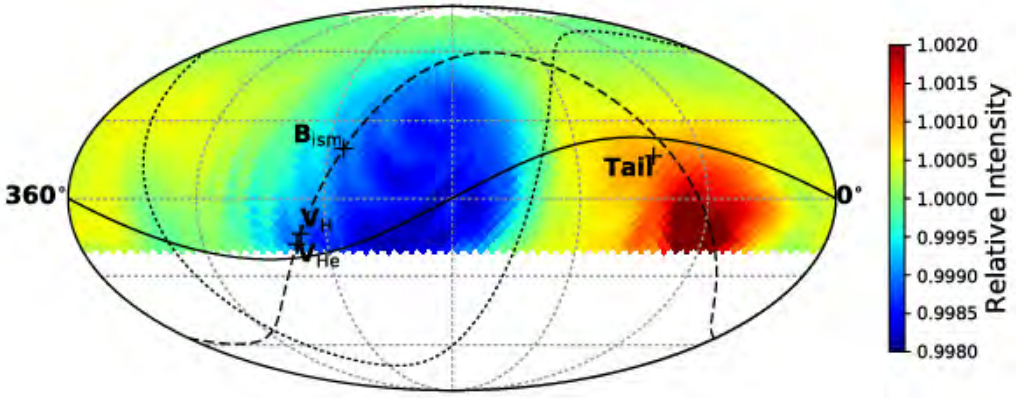
Data@Earth

normalized



normalized

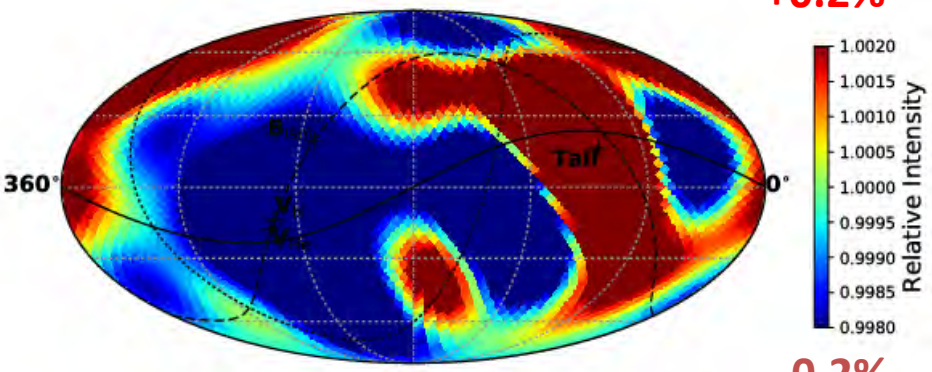
Model Fitting@Earth



Model @ Boundary

unnormalized

+0.2%

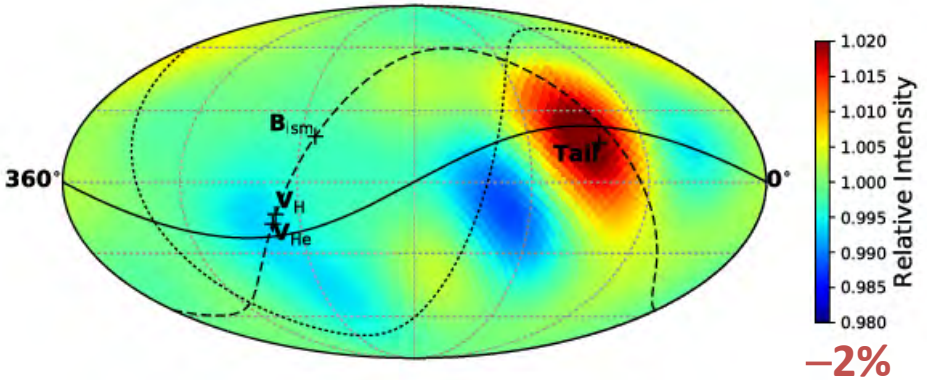


–0.2%

Max: +2.3%

Min: –1.2%

+2%



–2%

“To do” list.

- Suppress apparent small-scale anisotropy seen in $f(\mathbf{r}_B, \mathbf{p}_B, t)$.
- Discuss the solar modulation of $f(\mathbf{r}_B, \mathbf{p}_B, t)$.
- Analyses with other MHD heliosphere models (e.g. models by Washimi+ & Opher+).
- Examine the observed E-dependence of $f(\mathbf{r}_B, \mathbf{p}_B, t)$ (below/above 100 TeV?).