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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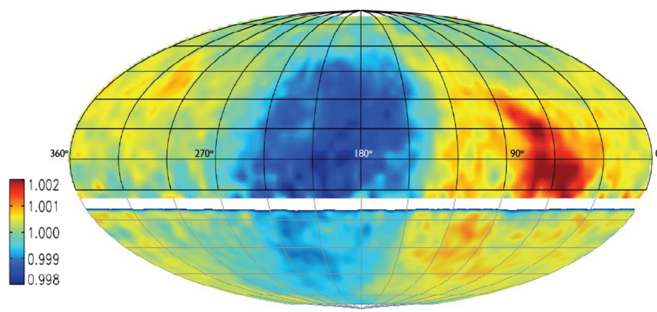
Heliospheric modulation (distortion) in MHD model heliosphere



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

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

Proc of ASTRONUM-2025 (IOP Publishing) accepted (2026)

220千円：消耗品（プリント基板、コネクタ、ケーブル他）、地下観測所用除湿器
ご支援有難うございました。

Analysis method

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

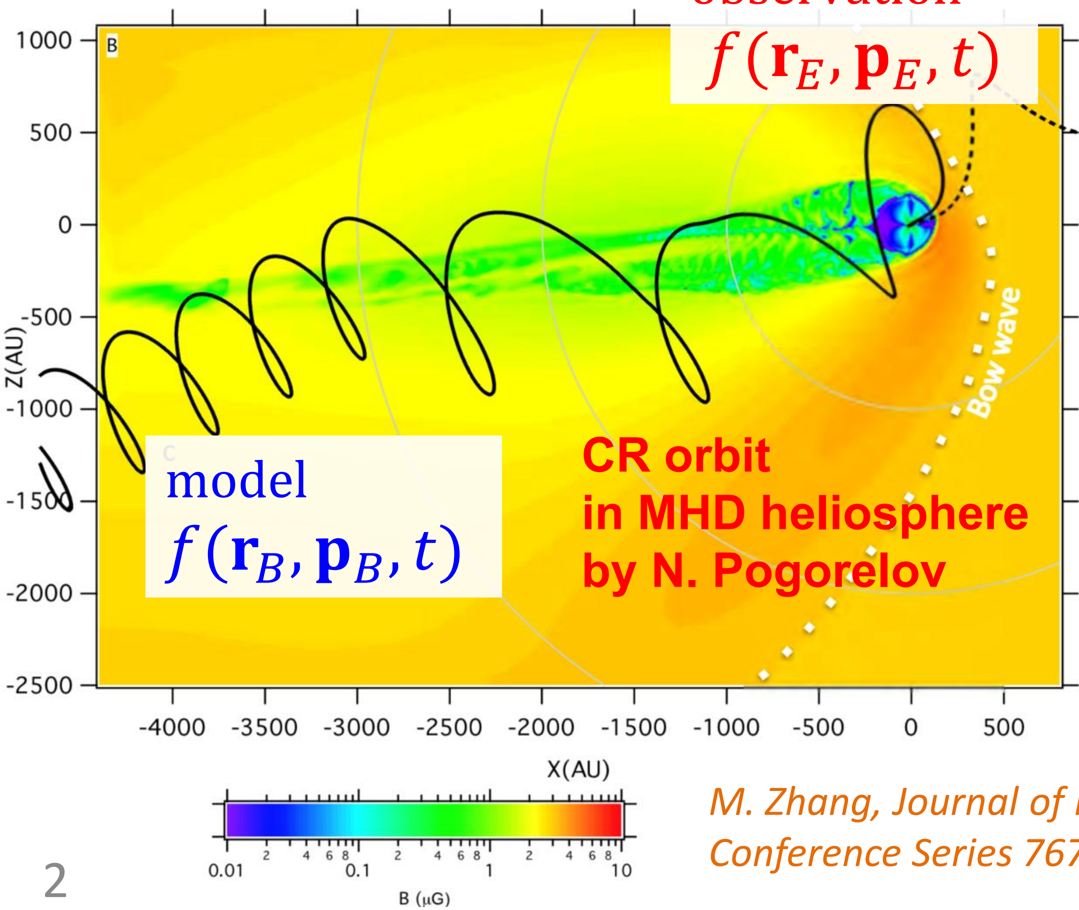
$$Df = \frac{\partial f}{\partial t} + \frac{d\mathbf{r}}{dt}\cdot\frac{\partial f}{\partial \mathbf{r}} + \frac{d\mathbf{p}}{dt}\cdot\frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t}\right)_c \approx 0$$

Liouville's theorem

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

observation

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



model

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

CR orbit in MHD heliosphere by N. Pogorelov

Intensity of CRs with $\boldsymbol{p}_E$ @ Earth

||

Intensity of CRs with $\boldsymbol{p}_B$ @ Outer Boundary of heliosphere

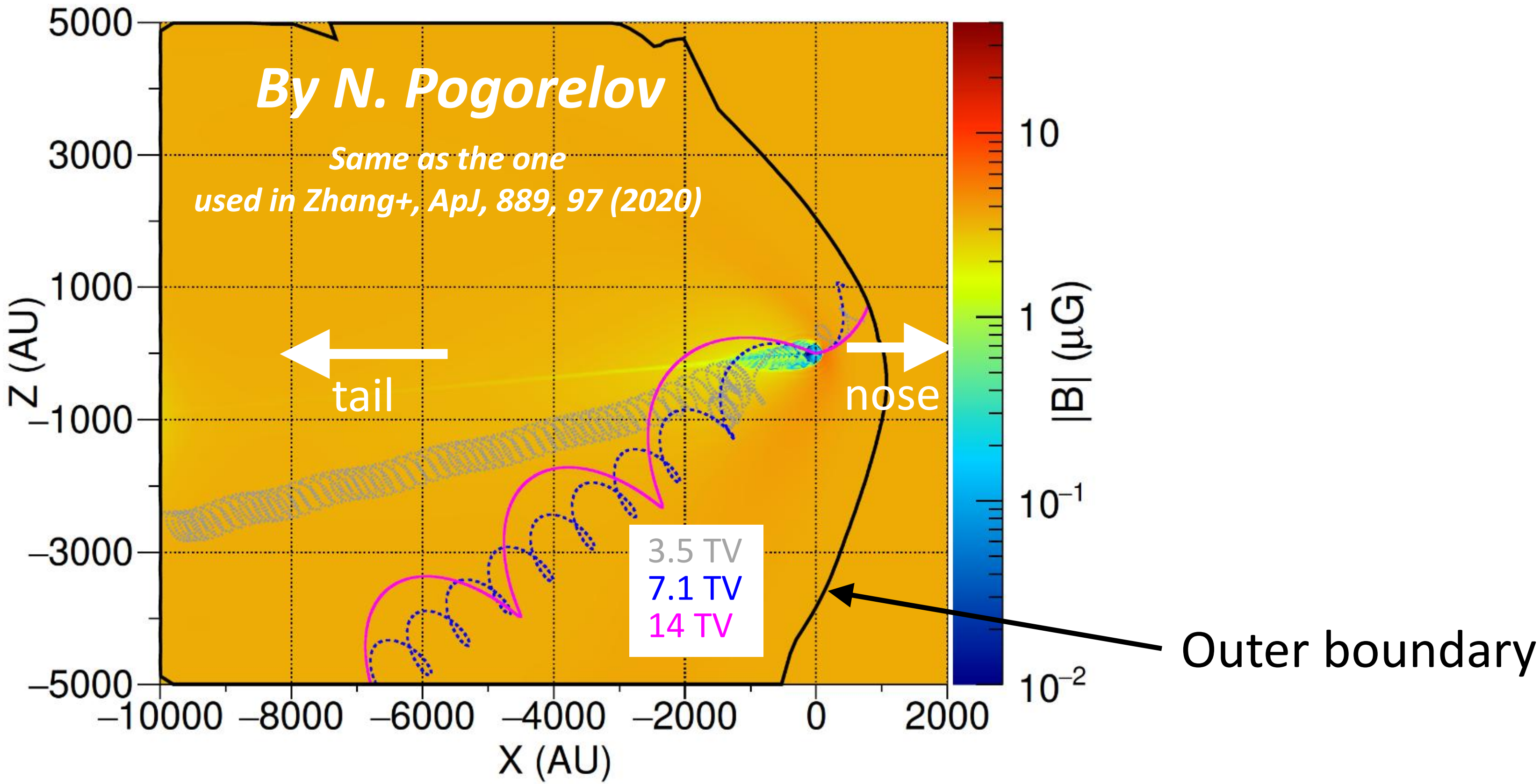
Mapping CR intensity at Earth back to outer boundary

Galactic anisotropy before the heliospheric distortion

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

CR orbits inside the outer boundary of the heliosphere

- Set Earth at 4 positions around Sun (±1AU, 0, 0), (0, ±1 AU, 0)
- Shoot CR particles with reversed charge into MHD model heliosphere
  — initial directions (4 samplings for each data pixel)
  — Observed rigidity distribution taken into account
- Record CR momentum directions @ outer boundary
  — Boundary defined as a surface where:
  Deviation in $\vec{B}_{helio}$ strength from $\vec{B}_{ISM}$ < 0.1%, and
  Deviation in $\vec{B}_{helio}$ direction from $\vec{B}_{ISM}$ < 0.1°

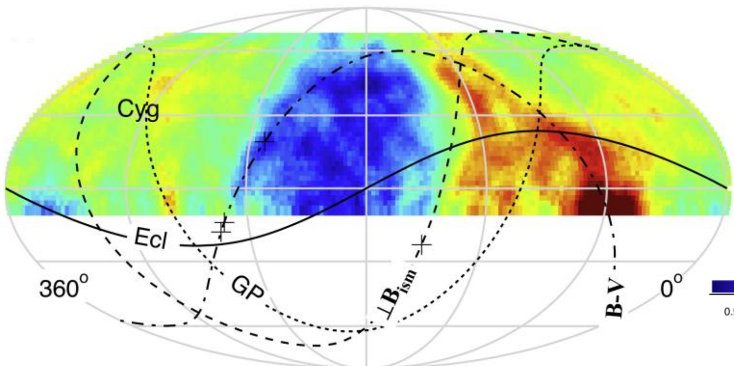


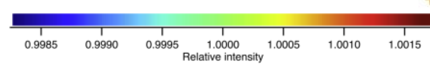
Four parameters fit

$$I_{ISM} = 1 + A_{1\parallel}\cos\mu + A_{2\parallel}\cos^2\mu + A_{1\perp}\cos\mu_\perp + I_{CG}$$

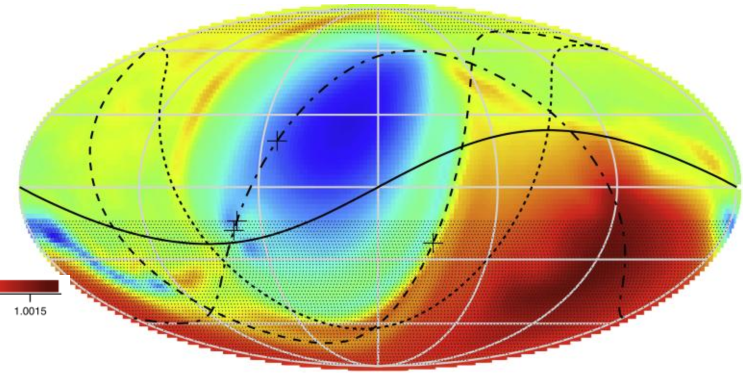
We use $\vec{B}_{ISM}$ (R.A, Dec.)=(232.5°, 19.0°) & $v_{helio} = 23.2$ km/s toward the nose

Observed @ Earth

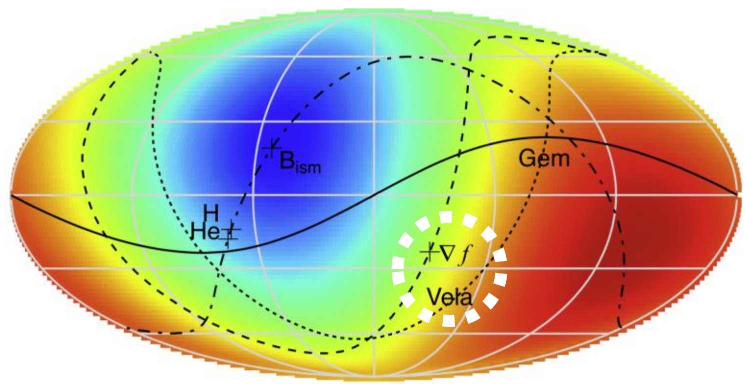




Best-fit Model @ Earth



Anisotropy @ outer boundary (OB)



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	$\|G_\perp\| = (0.021 \pm 0.001)\%/R_g$
Normalization	$f_0 = 1 + (0.024 \pm 0.001)\%$

(Reduced $\chi^2 = 4.5$)

Dipole amplitude along $B_{ISM} \times \nabla f$

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

Zhang+, ApJ, 889, 97 (2020)

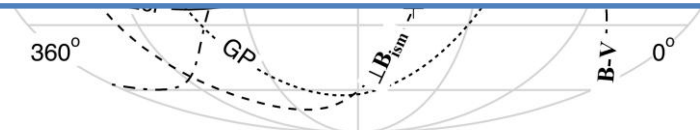
Four parameters fit

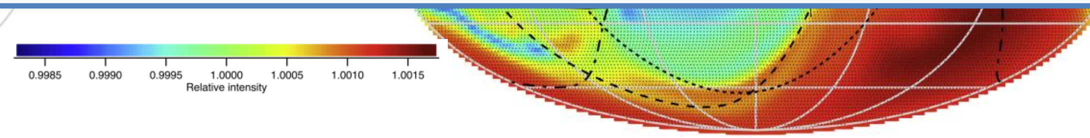
$$I_{ISM} = 1 + A_{1\parallel}\cos\mu + A_{2\parallel}\cos^2\mu + A_{1\perp}\cos\mu_\perp + I_{CG}$$

We use $\vec{B}_{ISM}$ (R.A, Dec.)=(232.5°, 19.0°) & $v_{helio} = 23.2$ km/s toward the nose

Intensity mapping using 4 TeV protons

CR energy spectrum & composition must be considered





OB)

Reduced χ^2 = 4.5

Modeling must be improved

Dipole amplitude along B_{ISM}

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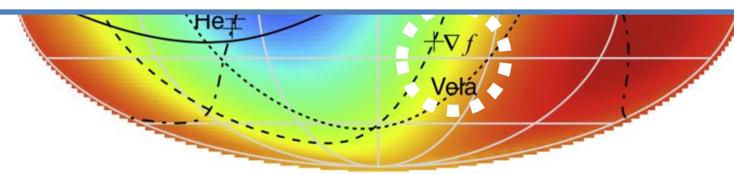
(Reduced χ^2 = 4.5)

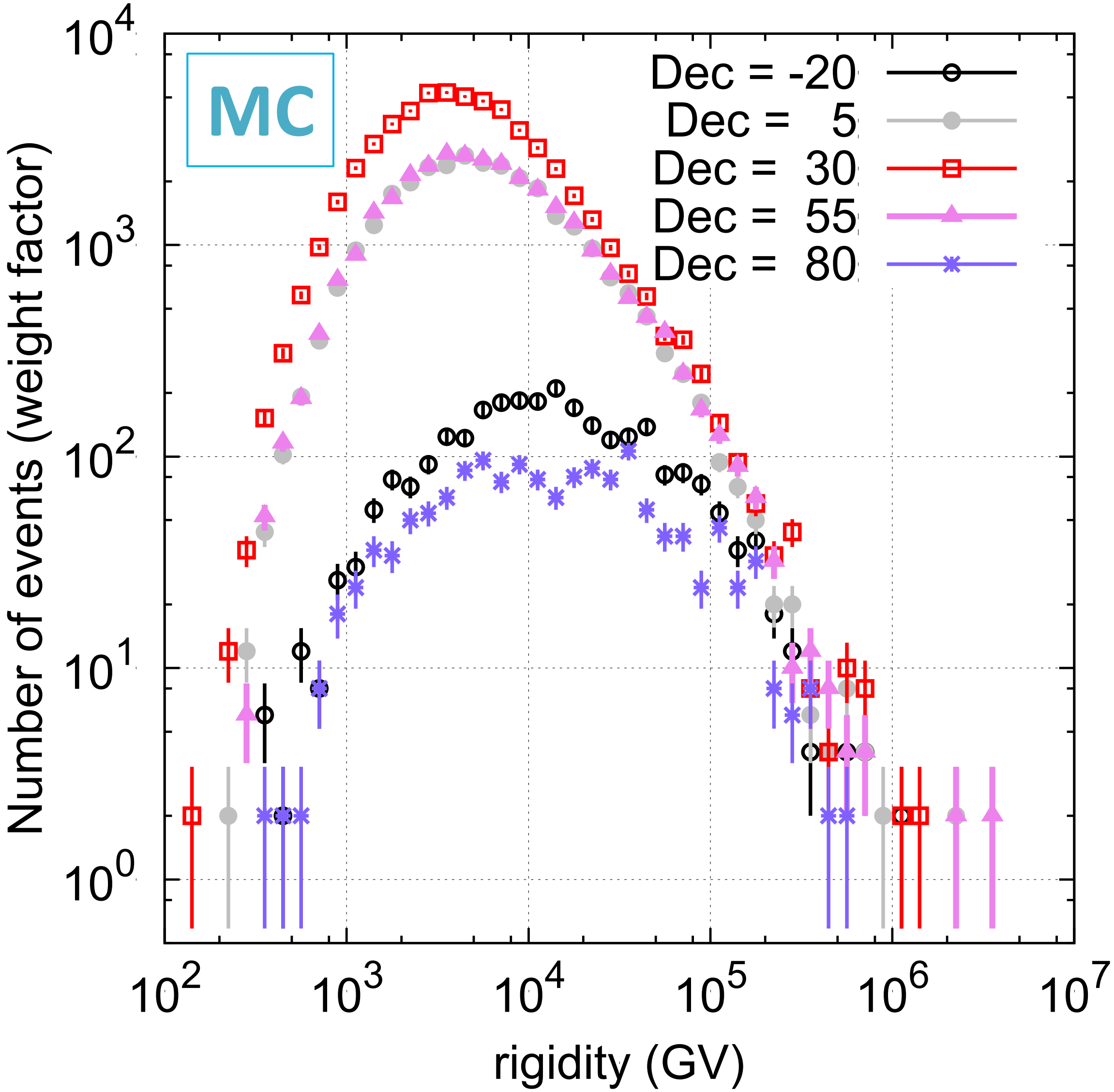
Dipole amplitude along B_{ISM} x ∇f



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

Zhang+, ApJ, 889, 97 (2020)

Rigidity dependent weight factor for each declination band



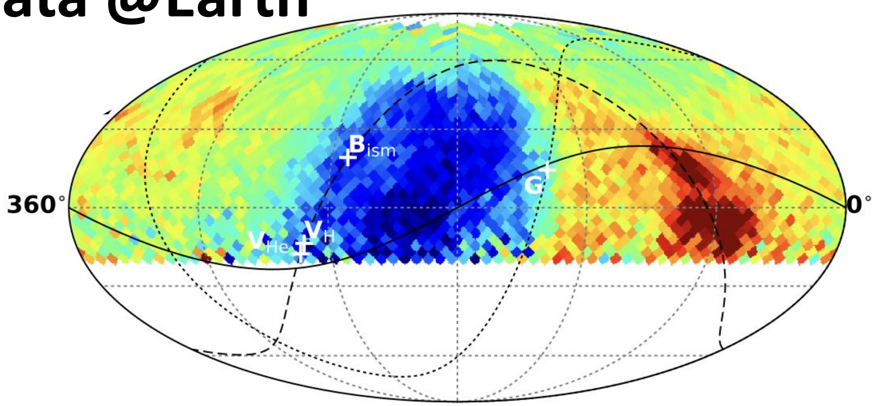
Results

4 parameters fit

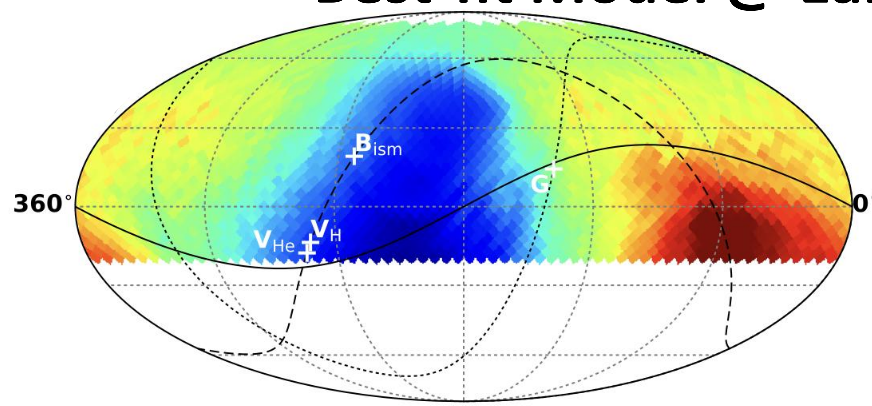
Dipole amplitude along B_{ISM} — Dipole amplitude along $B_{ISM} \times \nabla n$ — χ^2 / ndf = 3320 / 2052 = **1.62**

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

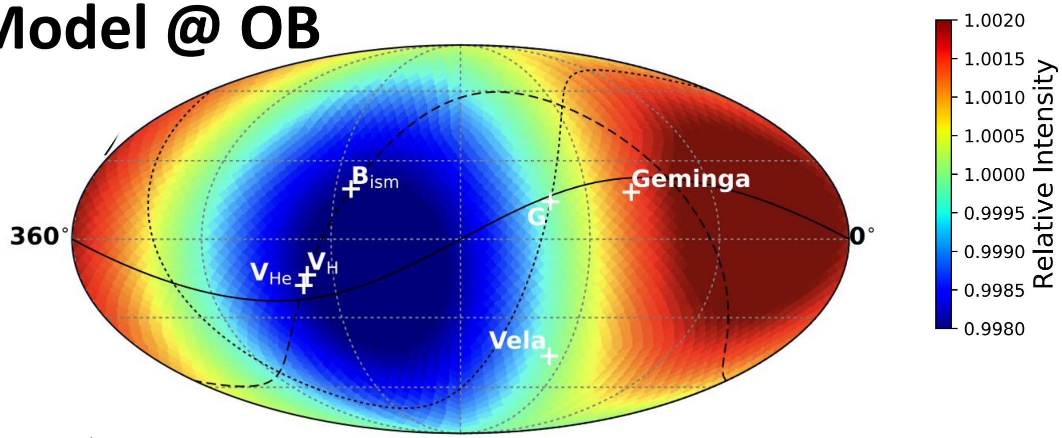
Data @Earth

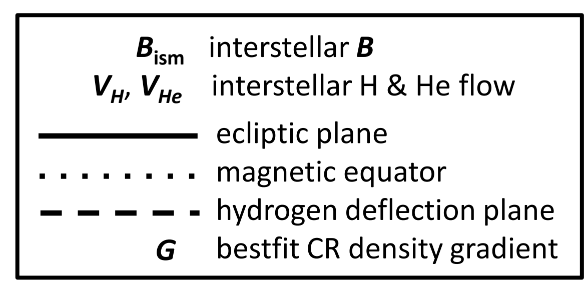


Best-fit Model @ Earth



Model @ OB





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

Results

4 parameters fit

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

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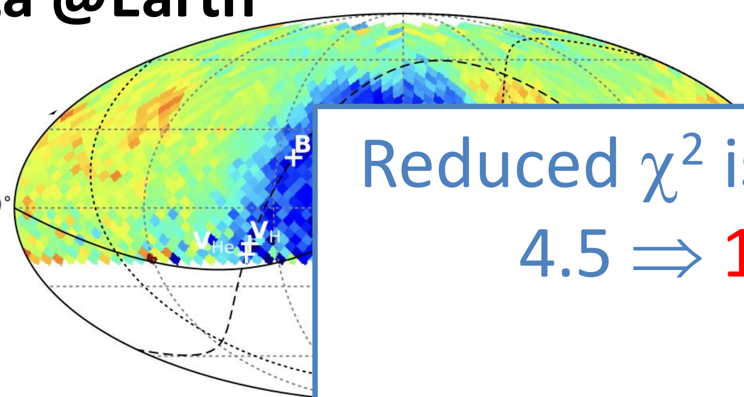
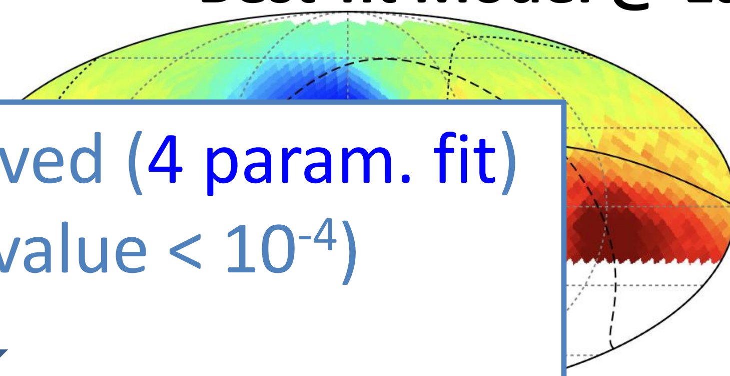


Best-fit Model @ Earth



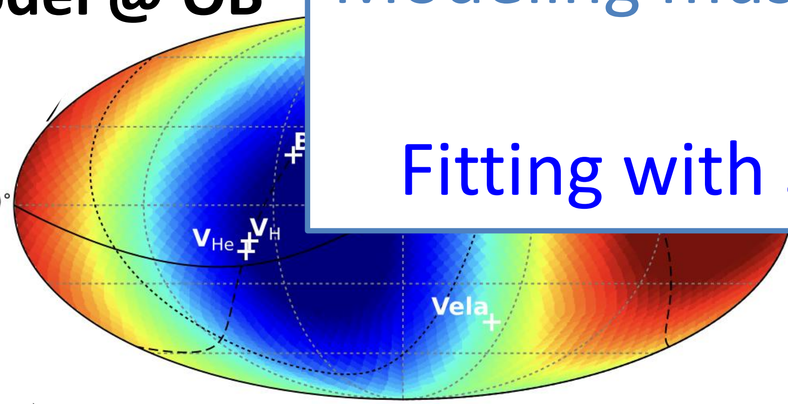
Reduced χ^2 is improved (4 param. fit)

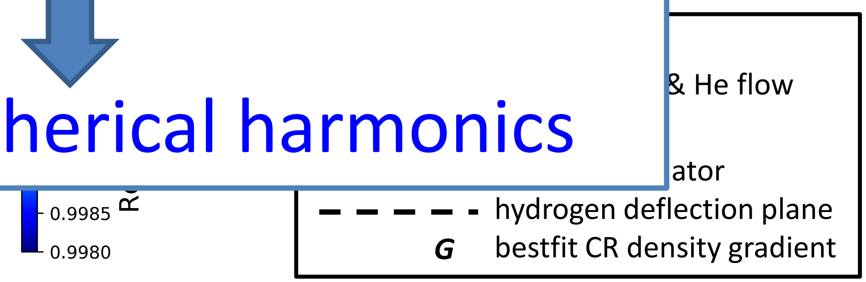
4.5 ⇒ 1.62 (p-value < 10^{-4})

Modeling must be improved further

Fitting with spherical harmonics

Model @ OB





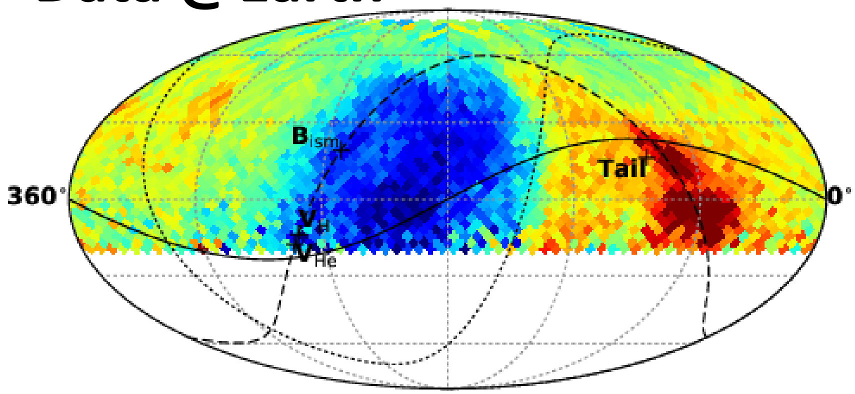
- $A_{1\perp}$ is also significant; about half of $A_{1||}$
- CR density gradient direction (G) not close to Vela

Fitting with spherical harmonics

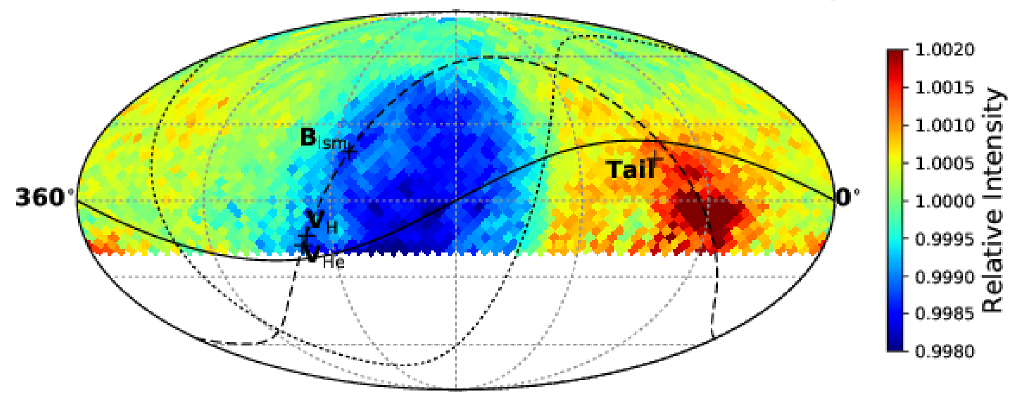
$$I_{\mathrm{ISM}}(\theta,\phi) = 1 + \sum_{l=1}^{l_{\max}} \sum_{m=-l}^{l} f_{lm} Y_{lm}(\theta,\phi) + I_{\mathrm{CG}}$$

L_{max} = 24 (624 parameters) χ^2 / ndf = 1393 / 1432 = **0.97 (76 %)**

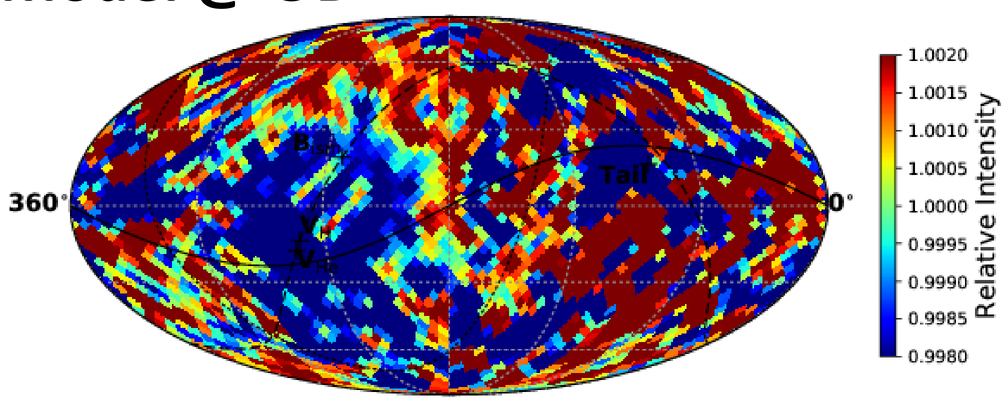
Data @Earth



Best-fit Model @ Earth



Model @ OB

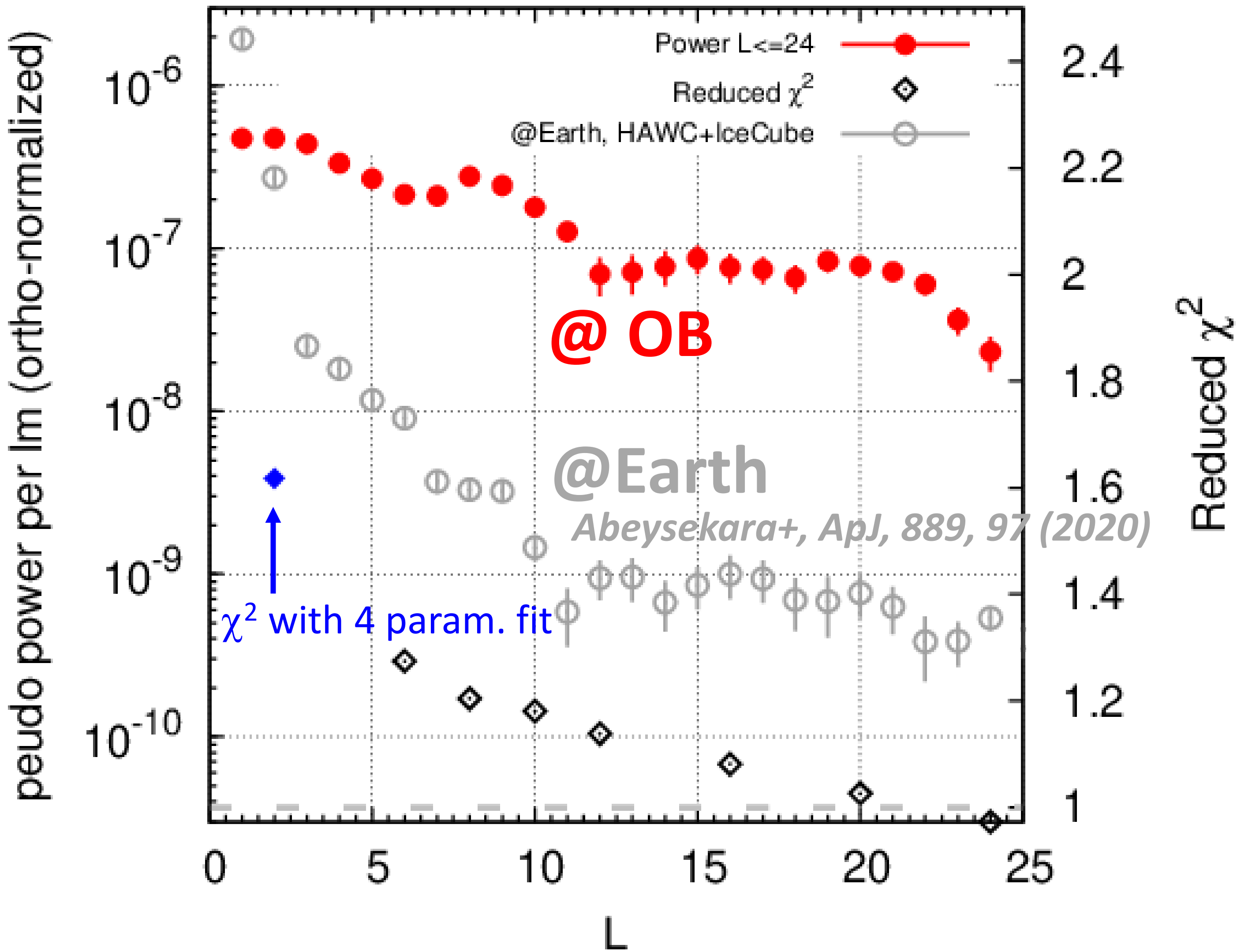


B_{ism}	interstellar B
V_H, V_{He}	interstellar H & He flow
———	ecliptic plane
· · · · · · · ·	magnetic equator
— — — —	hydrogen deflection plane

Unrealistic small-scale anisotropy appears @ outer boundary

Power spectrum by spherical harmonics fit

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



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

Discussions on small-scale anisotropy

- Using the average of 12 MHD snapshots over ~10-years

  L_{max}=12 for χ^2 / ndf = 0.99

- Fitting with P > 3TV alone

  L_{max}=12 for χ^2 / ndf = 0.98

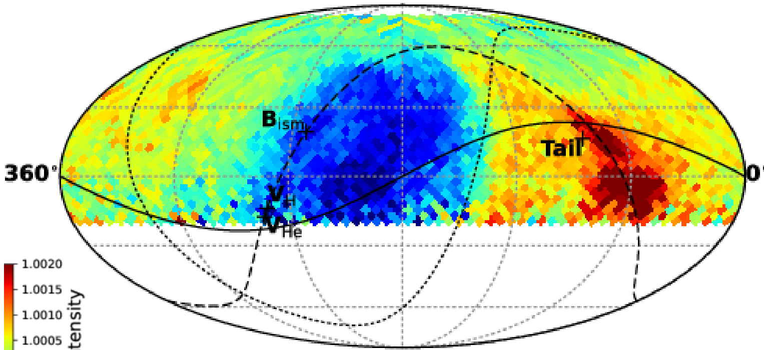
- Reducing r_B in tail-region

  r_B=3980 AU: L_{max} = 20 for χ^2 / ndf = 0.94

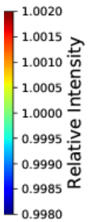
  r_B=1580 AU: L_{max} = 8 for χ^2 / ndf = 0.98

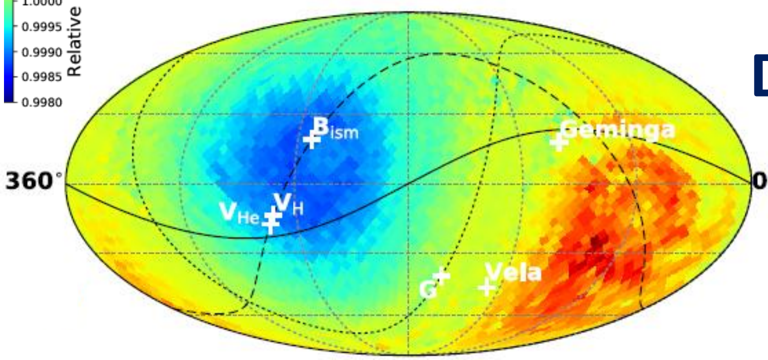
  r_B=630 AU: L_{max} = 4 for χ^2 / ndf = 0.96

Possible over-fitting due to One-hemisphere observation at Tibet

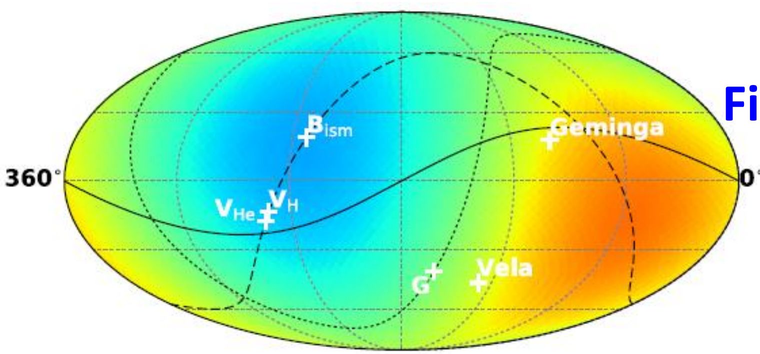


Data @Earth





Data mapped back to OB



Model @ OB

Fitting with uniform average error

χ^2 / ndf = 2995 / 3048 = **0.98**

$A_{1\parallel}$ (%)	$A_{2\parallel}$ (%)	$A_{1\perp}$ (%)	α_1 (°)	δ_1 (°)
0.124 ± 0.0009	0.017 ± 0.001	0.029 ± 0.0008	159.5 ± 0.9	-40.4 ± 1.5