Probing the Local Interstellar Magnetic Field Structure with TeV Cosmic Ray Anisotropy

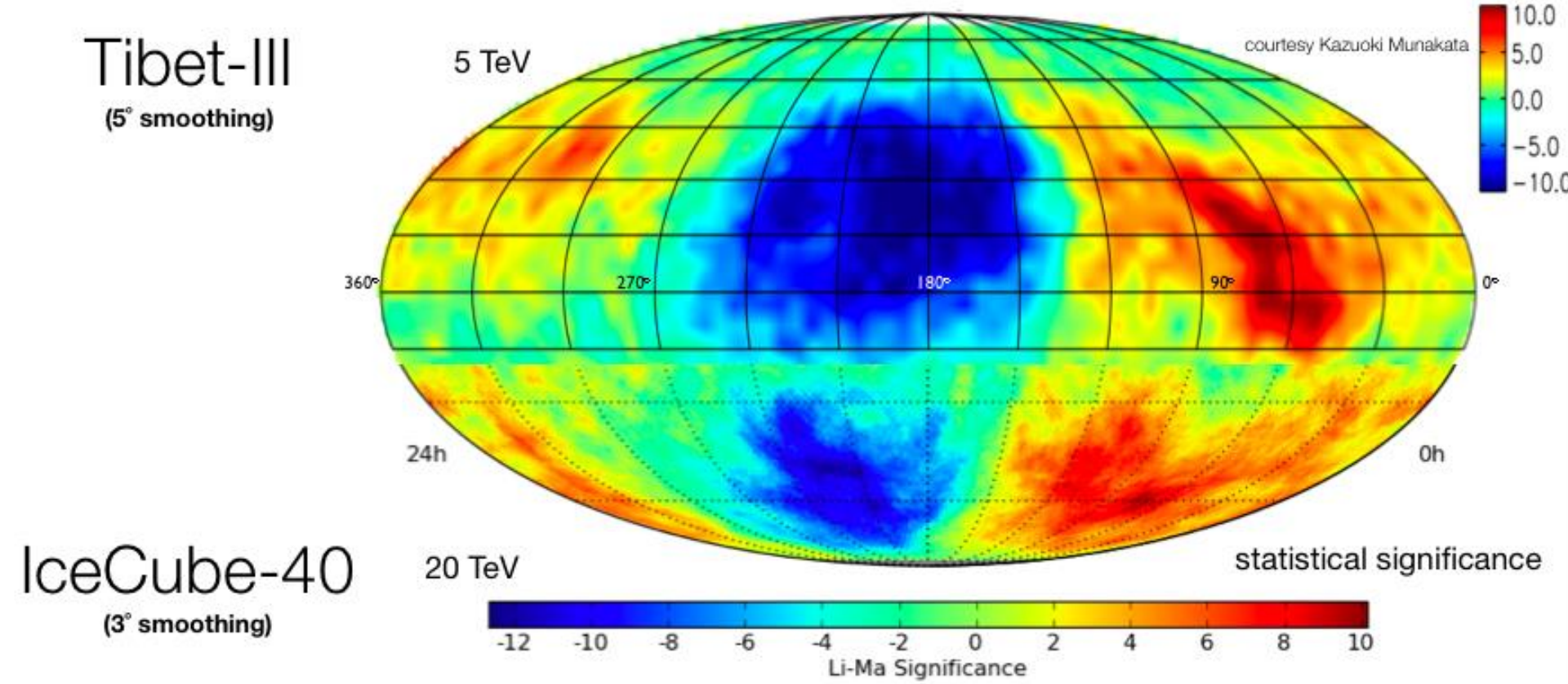
Ming Zhang, Noufel Maalal
Florida Institute of Technology

Nikolai Pogorelov, Federico Fratenale
University of Alabama in Huntsville

Magnetic field, cosmic ray transport and distribution function

- Cosmic rays are scattered by magnetic field fluctuations in pitch angle and guiding center. These lead to diffusion parallel and perpendicular to the magnetic field.
- Random walk of magnetic field lines can bring cosmic rays to diffuse perpendicular to the average direction of the large-scale magnetic field.
- A non-uniform large-scale magnetic field causes cosmic rays to focus or mirror.
- Magnetic focusing and pitch scattering determine the particle pitch angle distribution.
- Pitch angle scattering controls parallel diffusion, which affects particle propagation and nuclear reactions in the ISM, therefore, cosmic ray spectrum, composition, and spatial distribution.
- Anisotropy measurements permit investigations of the above particle transport mechanisms and magnetic field properties.

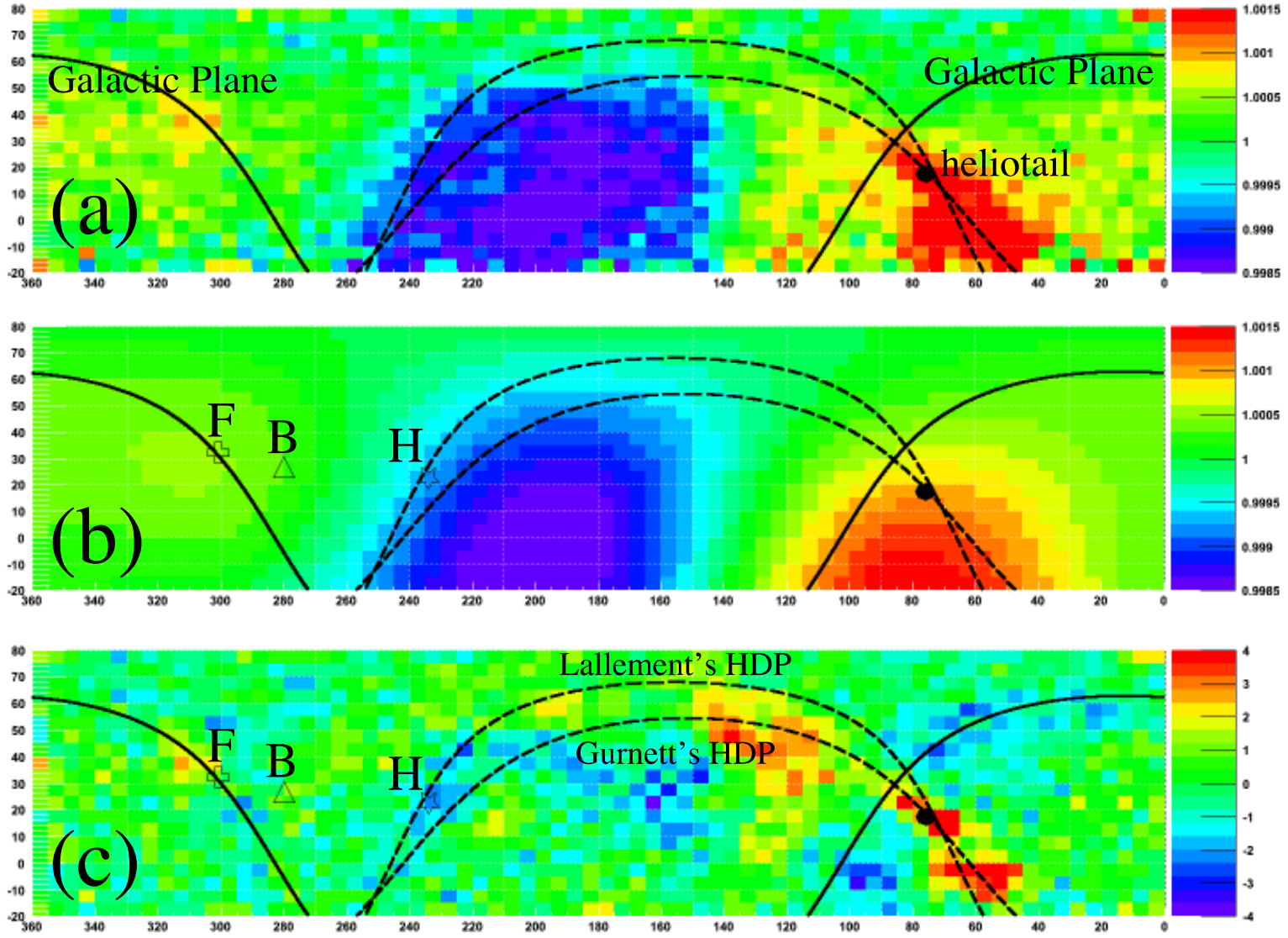
TeV cosmic ray anisotropy observations
In Celestial coordinates



in Equatorial coordinates

Tibet ASγ anisotropy observations (2009)

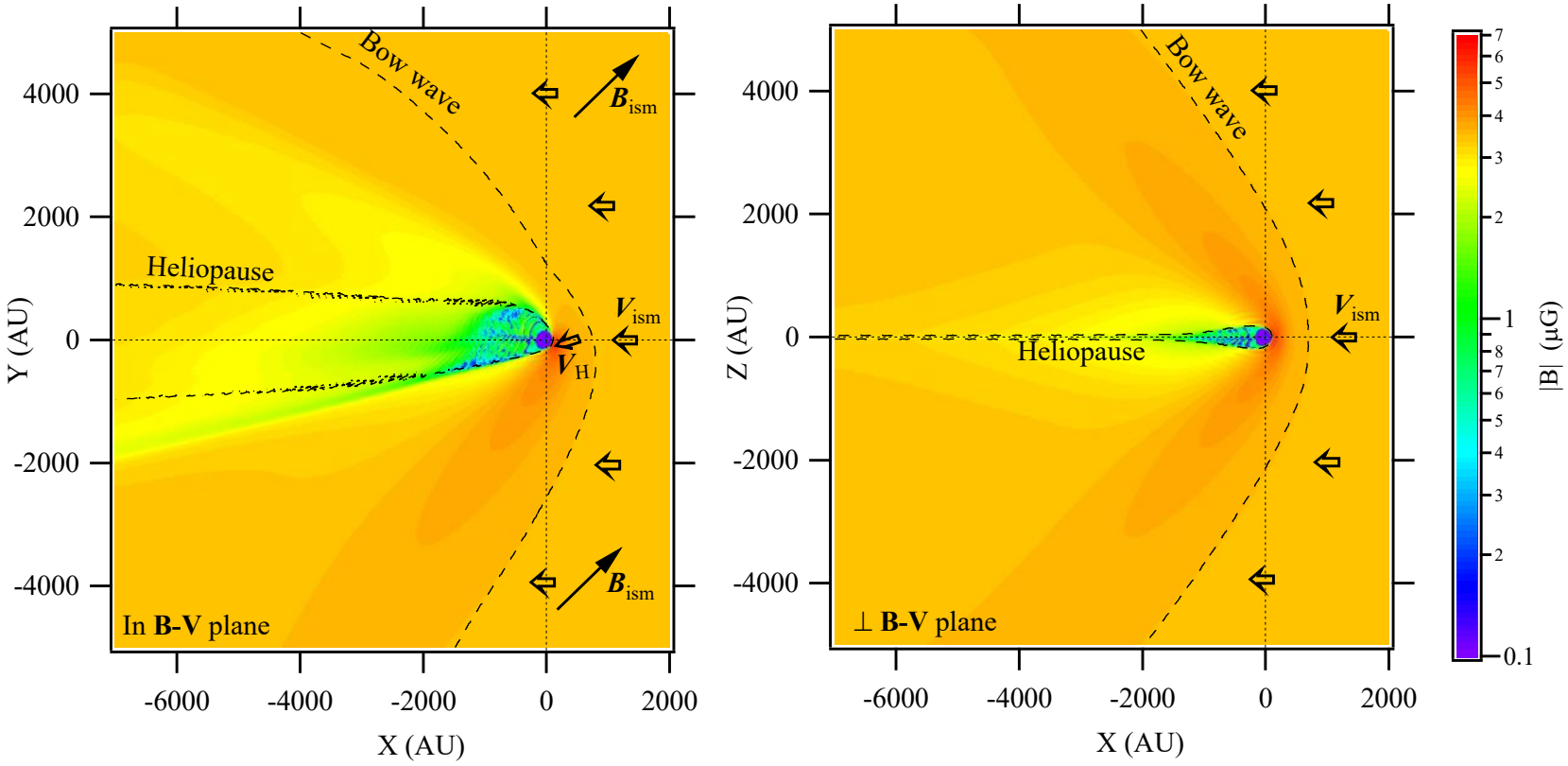
Decomposition into two orthogonal dipoles and one bidirectional anisotropy and plus small features



Shape of heliosphere and magnetic field environment

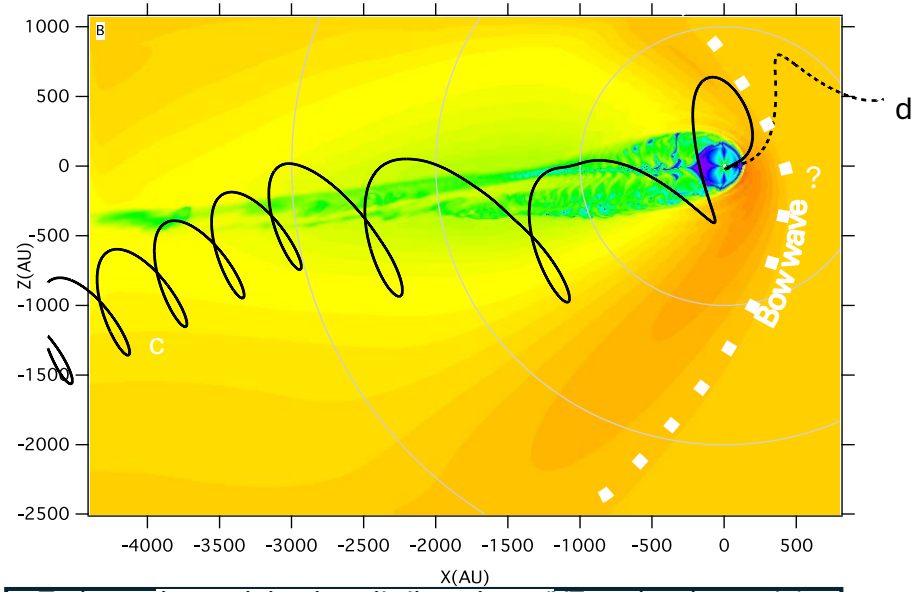
Simulation box 12000x8000x10000 AU for cosmic rays of a few TeV

B_{ism}=3.5 mG, n_e=0.065 cm^{-3}, n_H=0.184 cm^{-3}

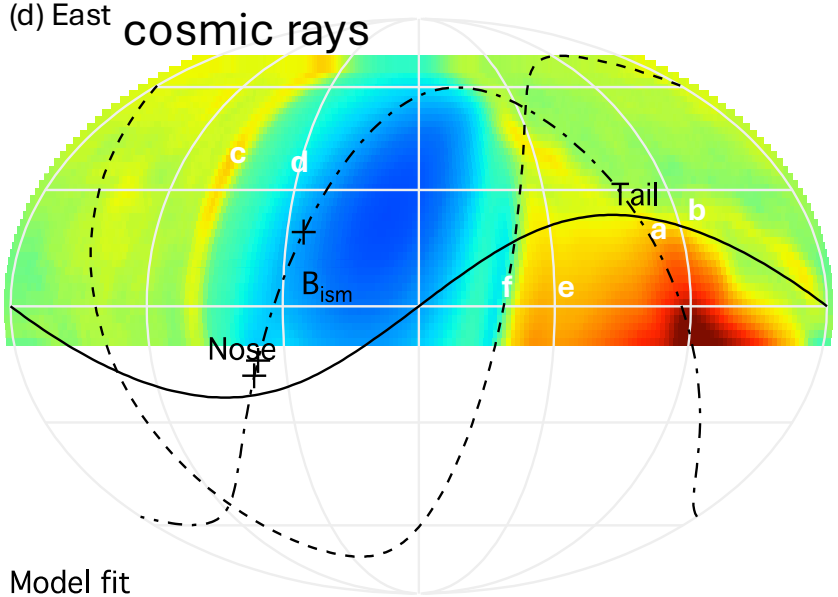


HDP = B-V plane

Trajectories separated by bow wave (XZ projection only): (c) West; (d) East

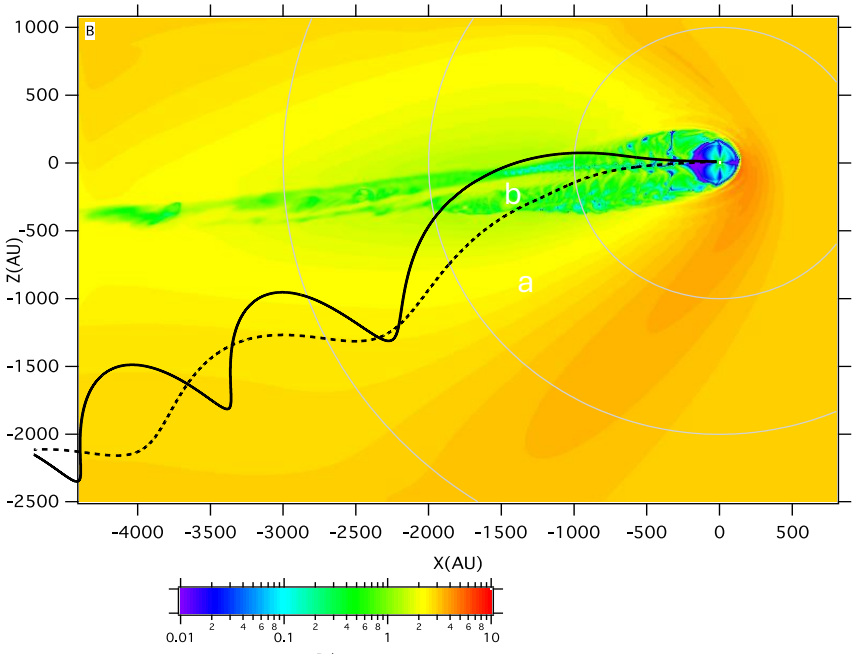


Heliospheric boundary separate cosmic rays

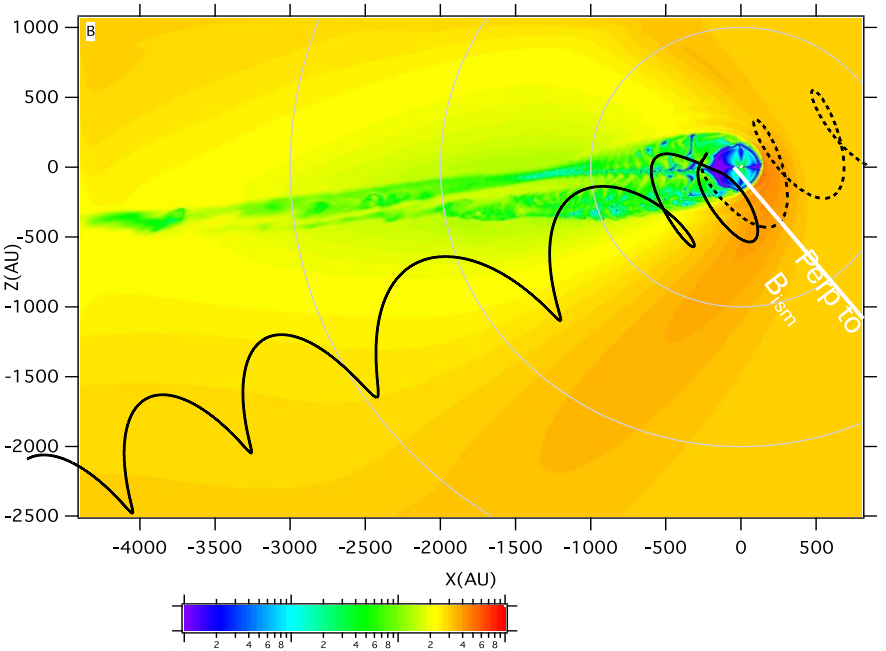


Model fit

Trajectories arriving in tail directions (XZ projection only)
(a) East side of HDP (b) West side of HDP



Trajectories separated by plane perpendicular to B_{ism} (XZ projection only)
(e) West, (f) East



Optical image distortion



Liouville Mapping to Earth from ISM distribution
through calculation of particle trajectory and Lorentz tranformation

$$\dot{p} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) = q(\boldsymbol{v} - \boldsymbol{V}) \times \boldsymbol{B}$$

with ideal MHD Heliosphere Model that supplies $\boldsymbol{V}$ and $\boldsymbol{B}$

Cosmic ray distribution in LISM as a magnetized charged particle population

$$f_o(\boldsymbol{r}_o, \boldsymbol{p}_o) = f_{ism}(\boldsymbol{r}, \boldsymbol{p}) = f_{ism}(\boldsymbol{R}_g, \boldsymbol{p})$$
$$= f_0(p/p_o)^{-4.75}\left[1 + \boldsymbol{G}_\perp \cdot (\boldsymbol{R}_g - \boldsymbol{r}_o) + Pad(\mu)\right]$$

↑ Compton-Getting + Acceleration

↑ B x gradient

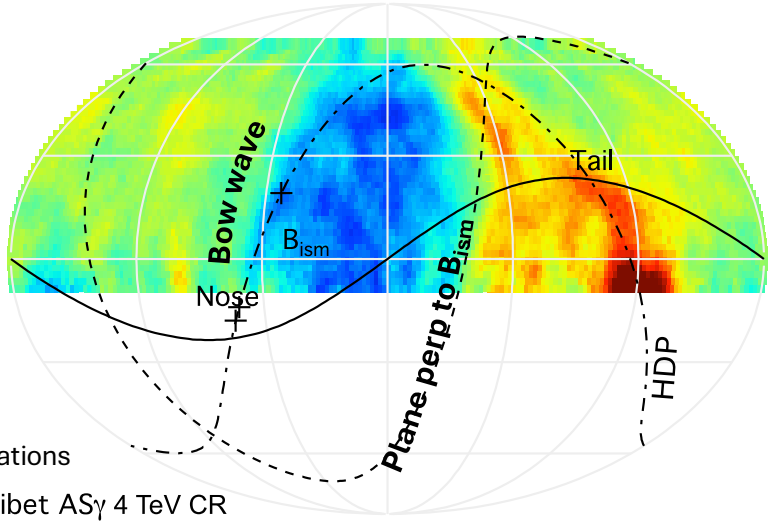
↑ ISM Pitch angle distribution

Total anisotropy is a linear composition of the above 3 types of anisotropies.

$$Pad(\mu) - 1 = (A_1P_1(\mu) + A_2P_2(\mu) + \ldots)$$

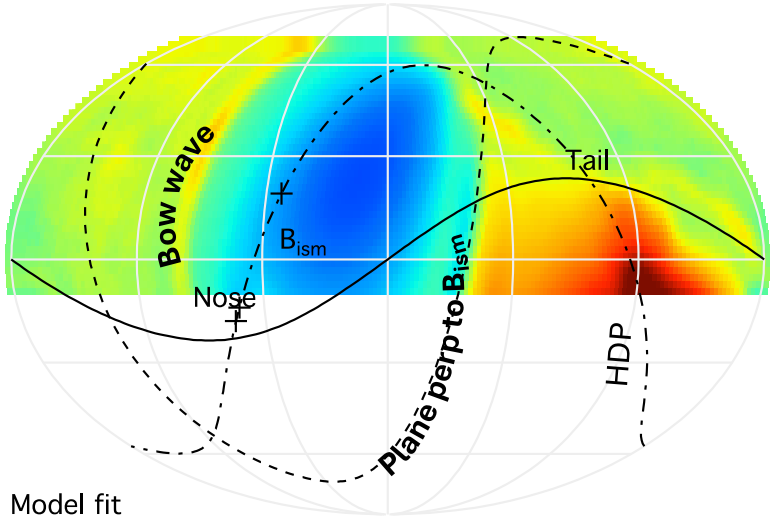
Fitting function $I(\theta, \varphi) = \dfrac{f(\boldsymbol{r}(\theta,\varphi), \boldsymbol{p}(\theta,\varphi))}{\frac{1}{2\pi}\int_0^{2\pi} f(\boldsymbol{r}(\theta,\varphi), \boldsymbol{p}(\theta,\varphi))d\varphi}$

4 TeV CR anisotropy in relation to heliospheric structures

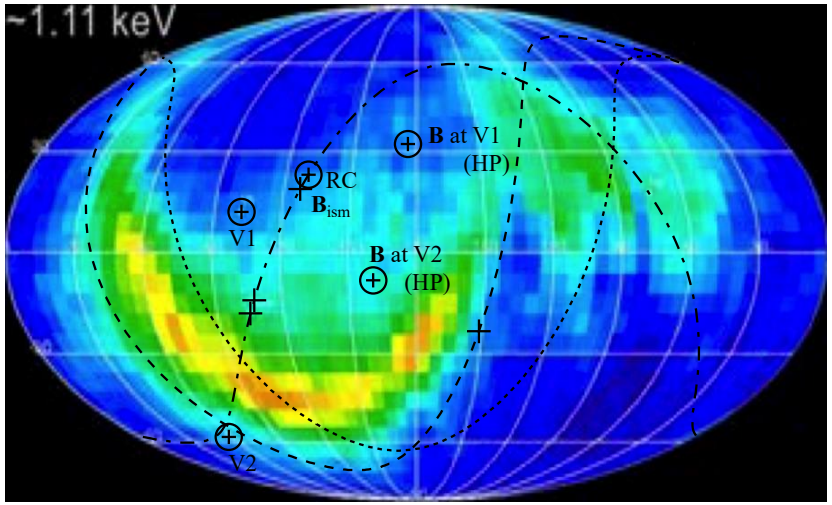


Observations

Tibet ASγ 4 TeV CR
Anisotropy measurement

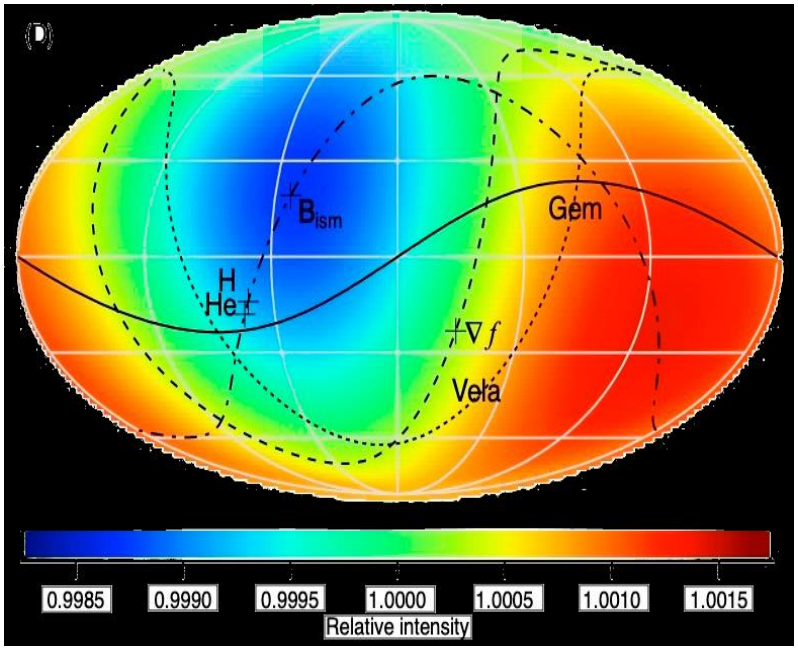


Model fit

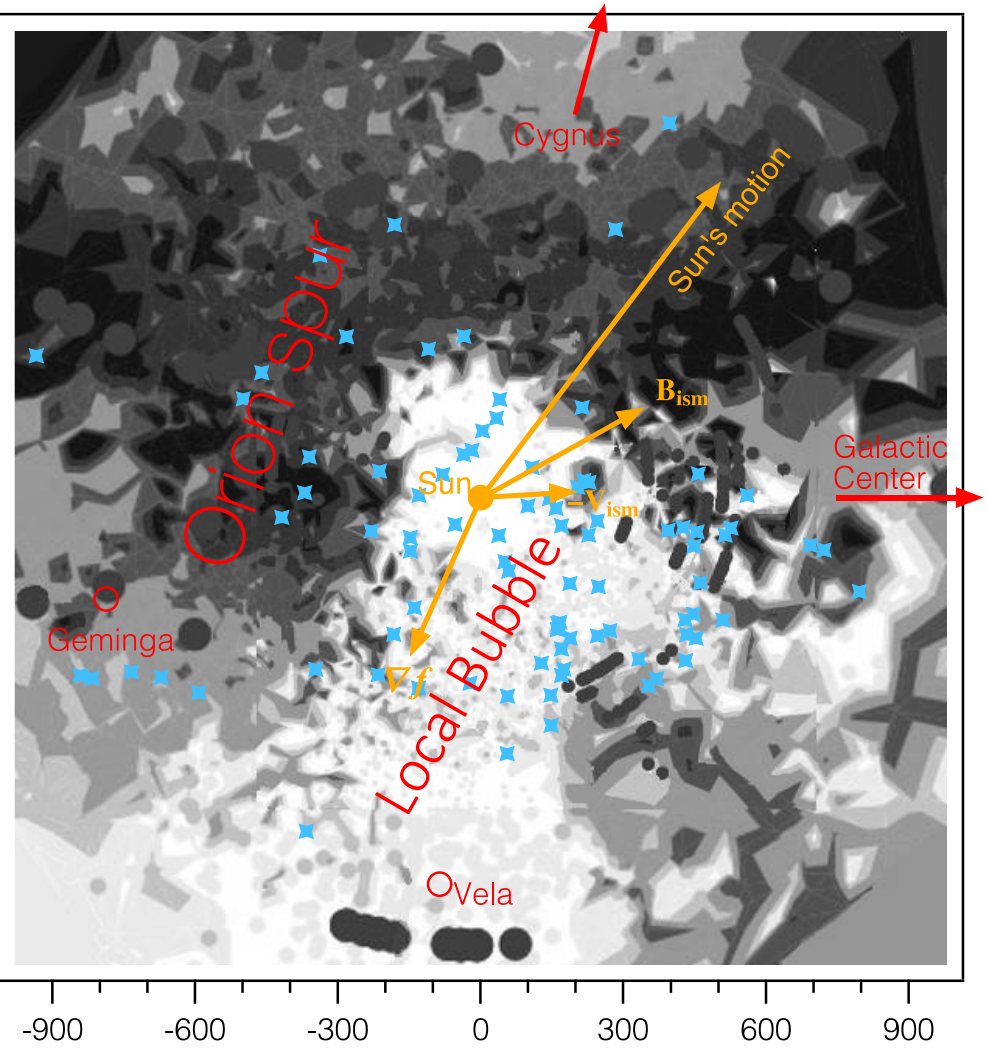


IBEX ENA Emissions

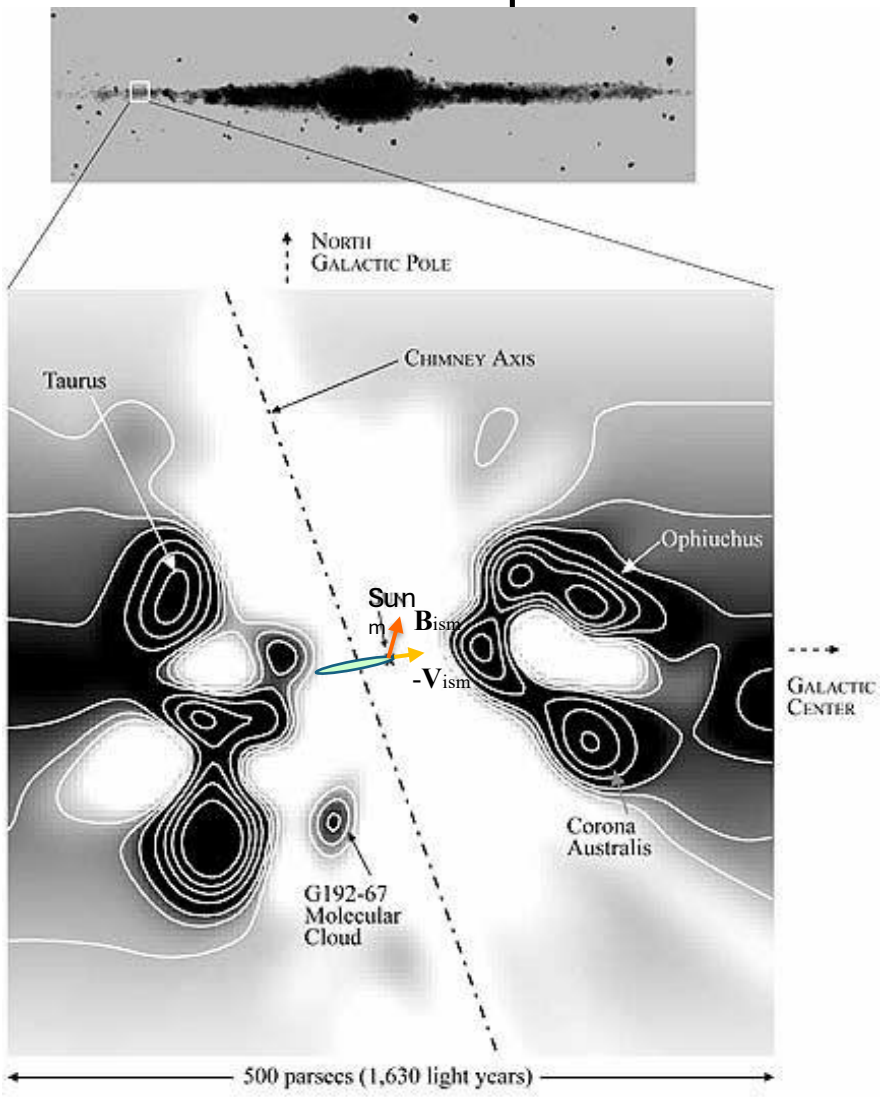
IBEX image from
McComas et al.



Solar system neighbor environment in the Galactic plane

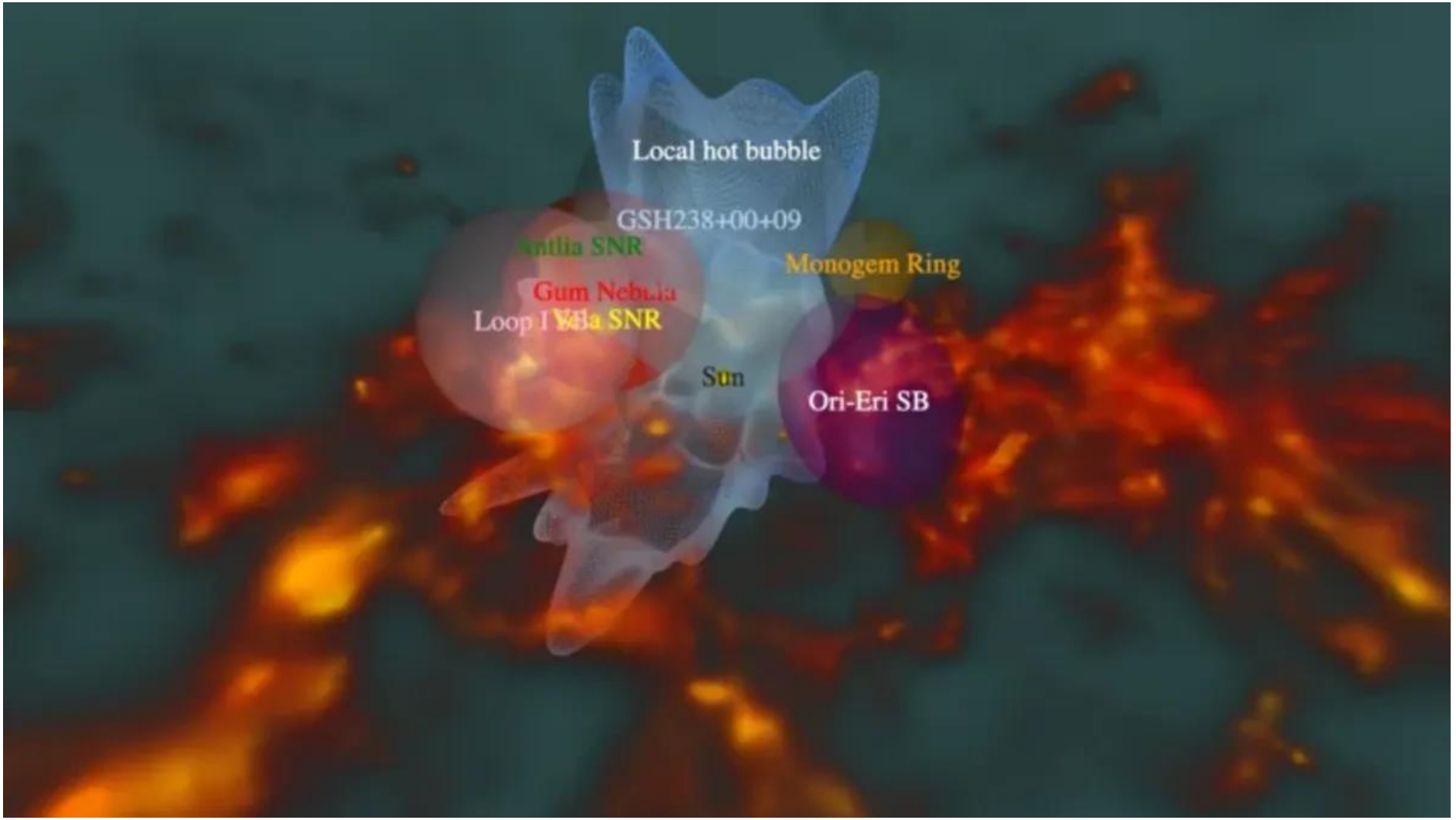


ISM based on Frisch (2017)



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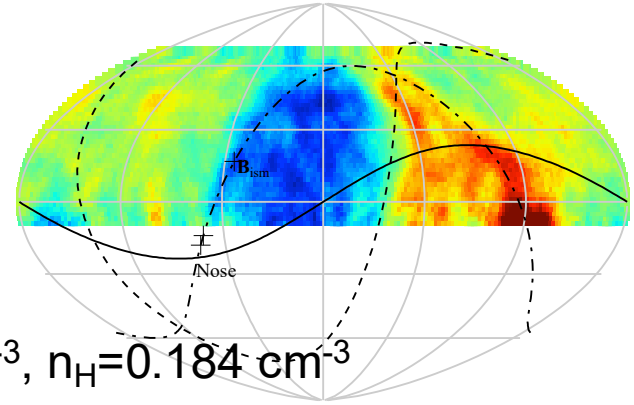
Local bubble



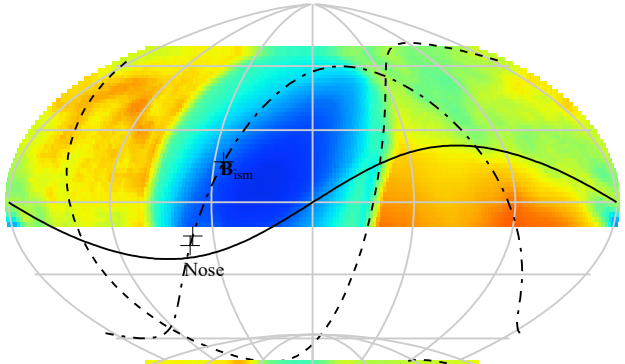
A 3D model of the Milky Way's "local bubble" created using data from eROSITA (Michael Yeung of MPE)

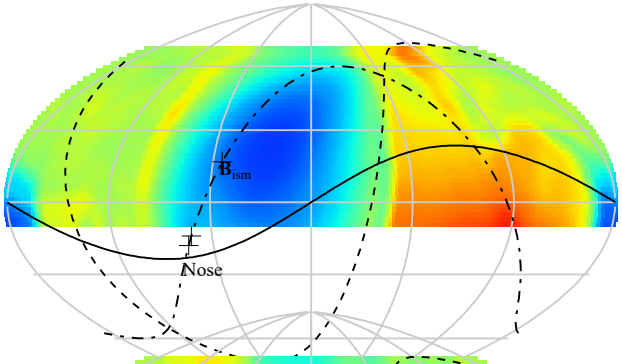
Search for the best Heliosphere and LISM magnetic field and ion density.

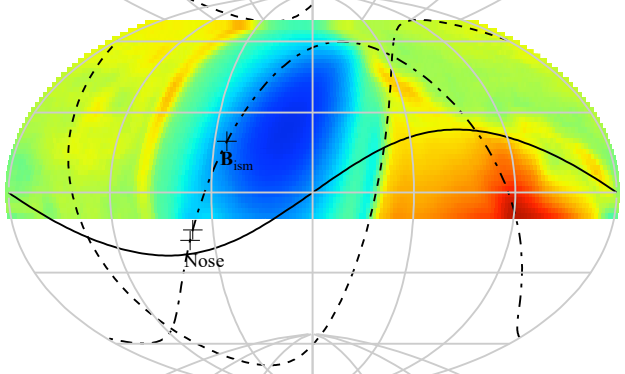
B_{ism}=3.5 μG, n_{ion}=0.065 cm^{-3}, n_H=0.184 cm^{-3}

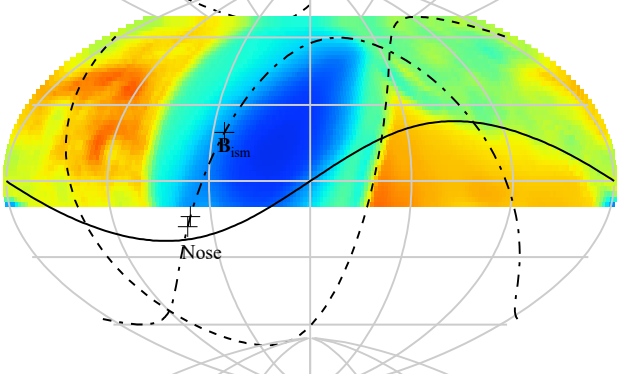


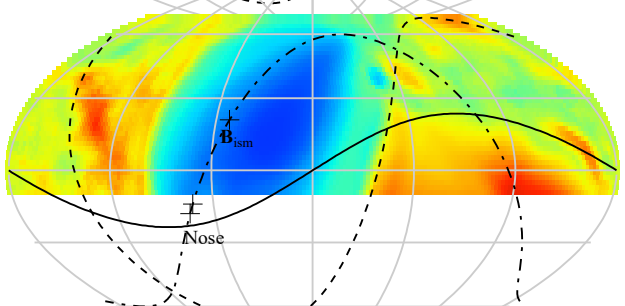
Tibet ASγ
Observation
4 TeV

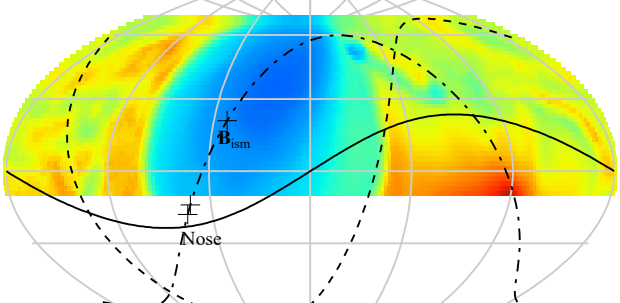








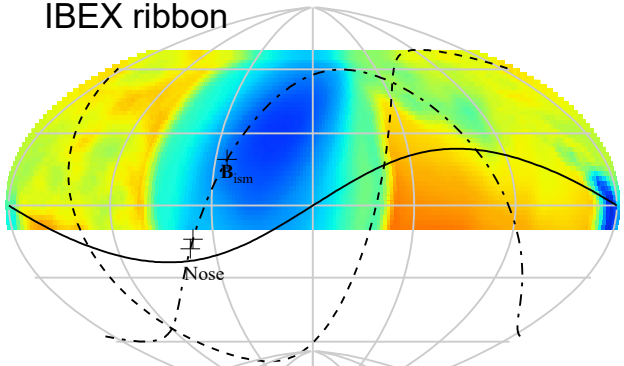


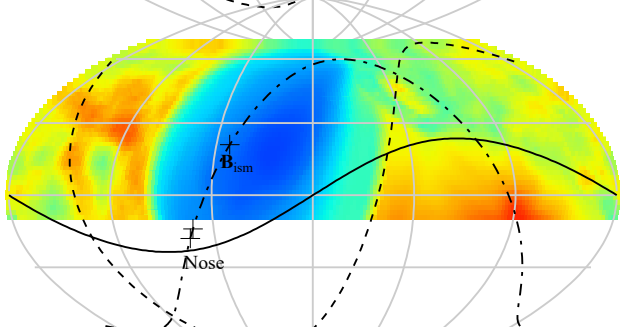


Model calculations

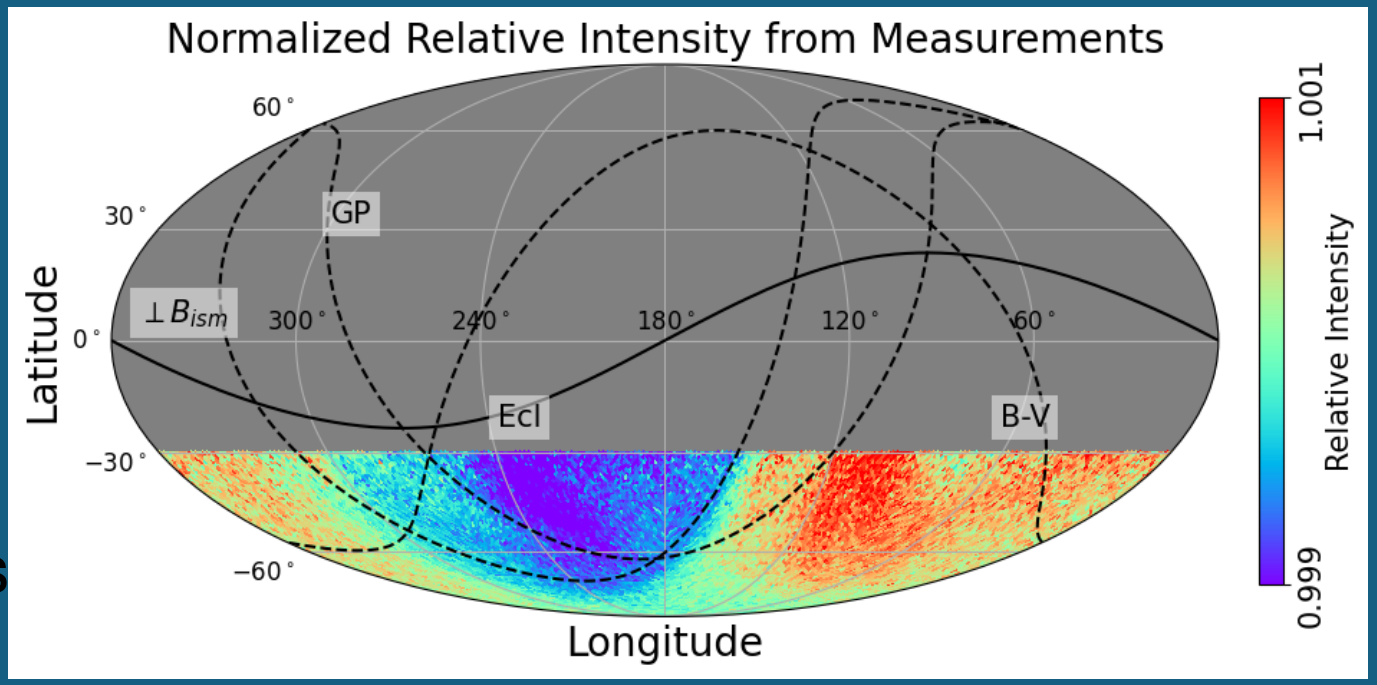
B field	Low n_{ion}	Mid n_{ion}	High n_{ion}
3.0 μG			
3.5 μG	0.065 cm^{-3}		
4.0 μG			

All models constrained by Voyagers IBEX ribbon

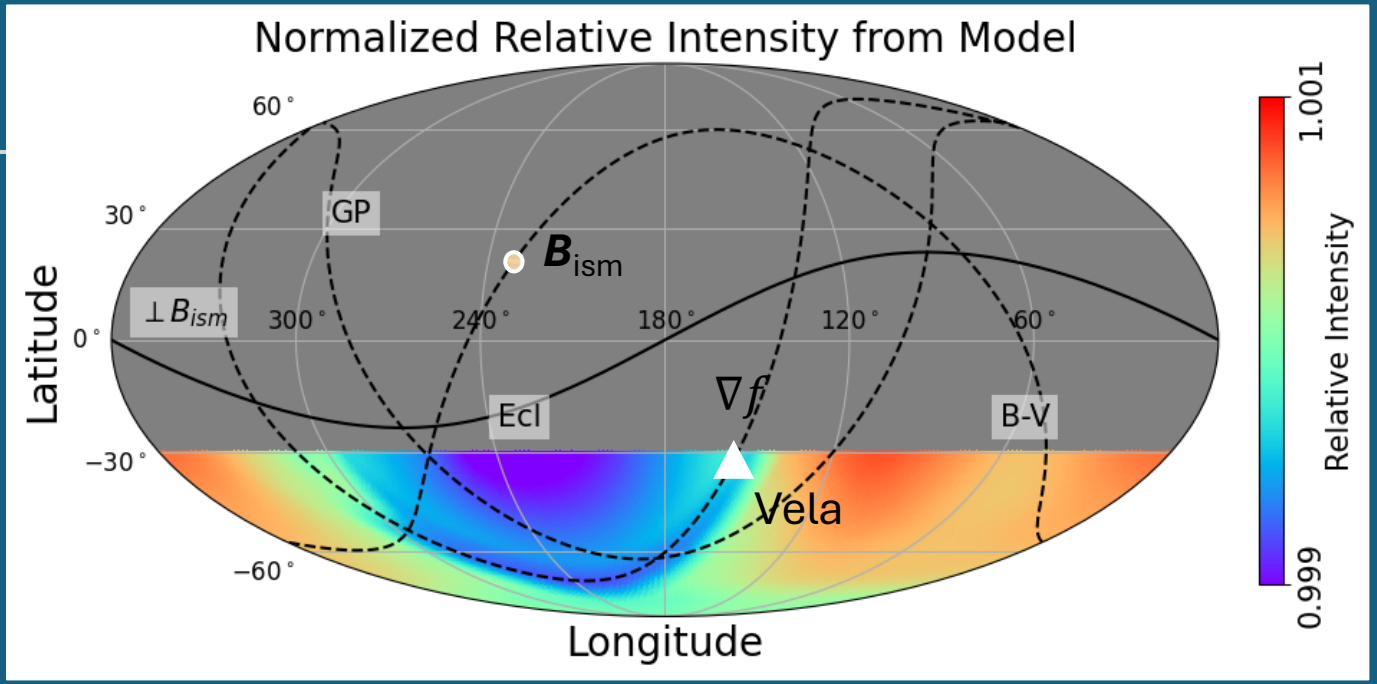




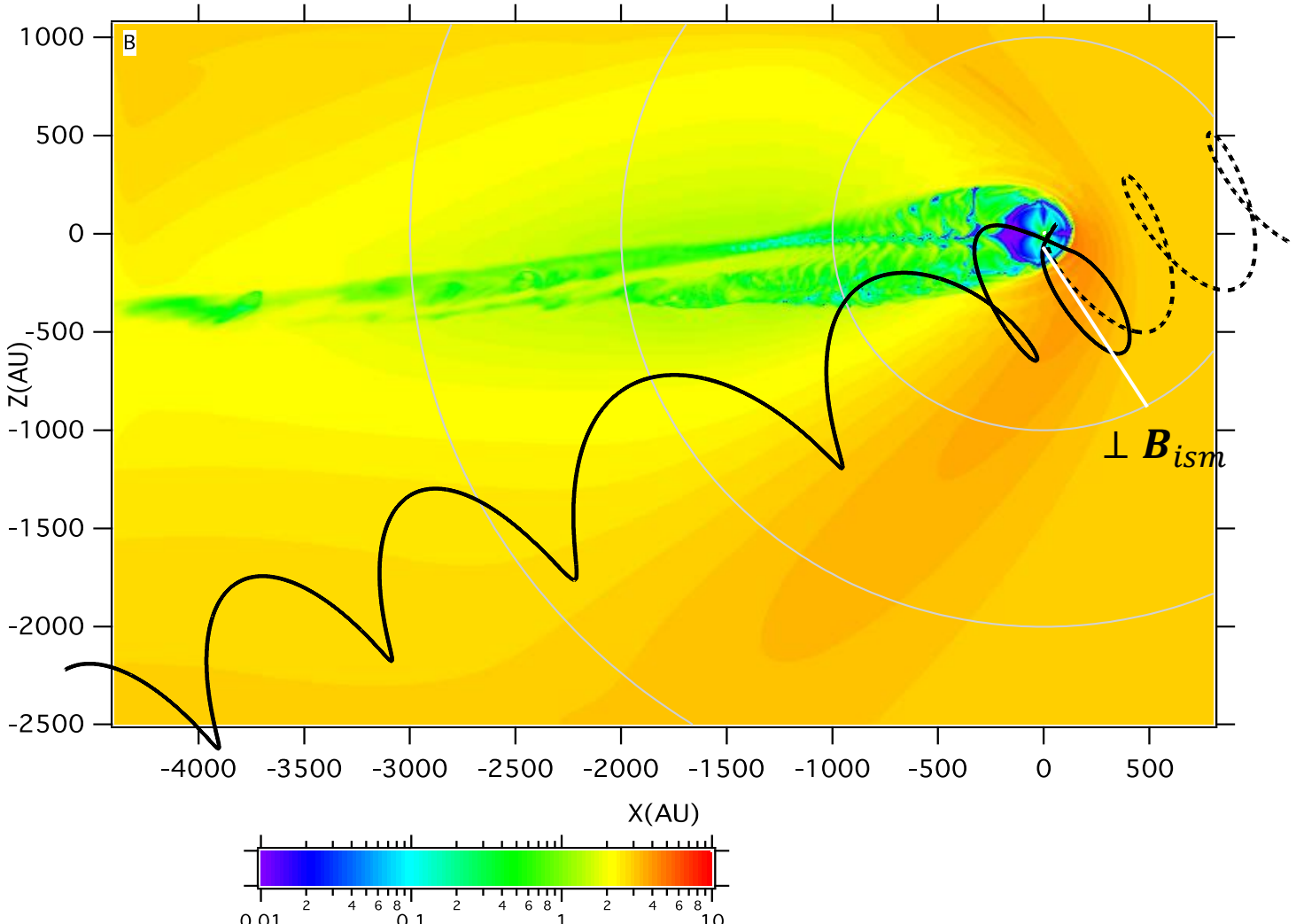
13 TeV cosmic-ray anisotropy IceCube measurements in the south

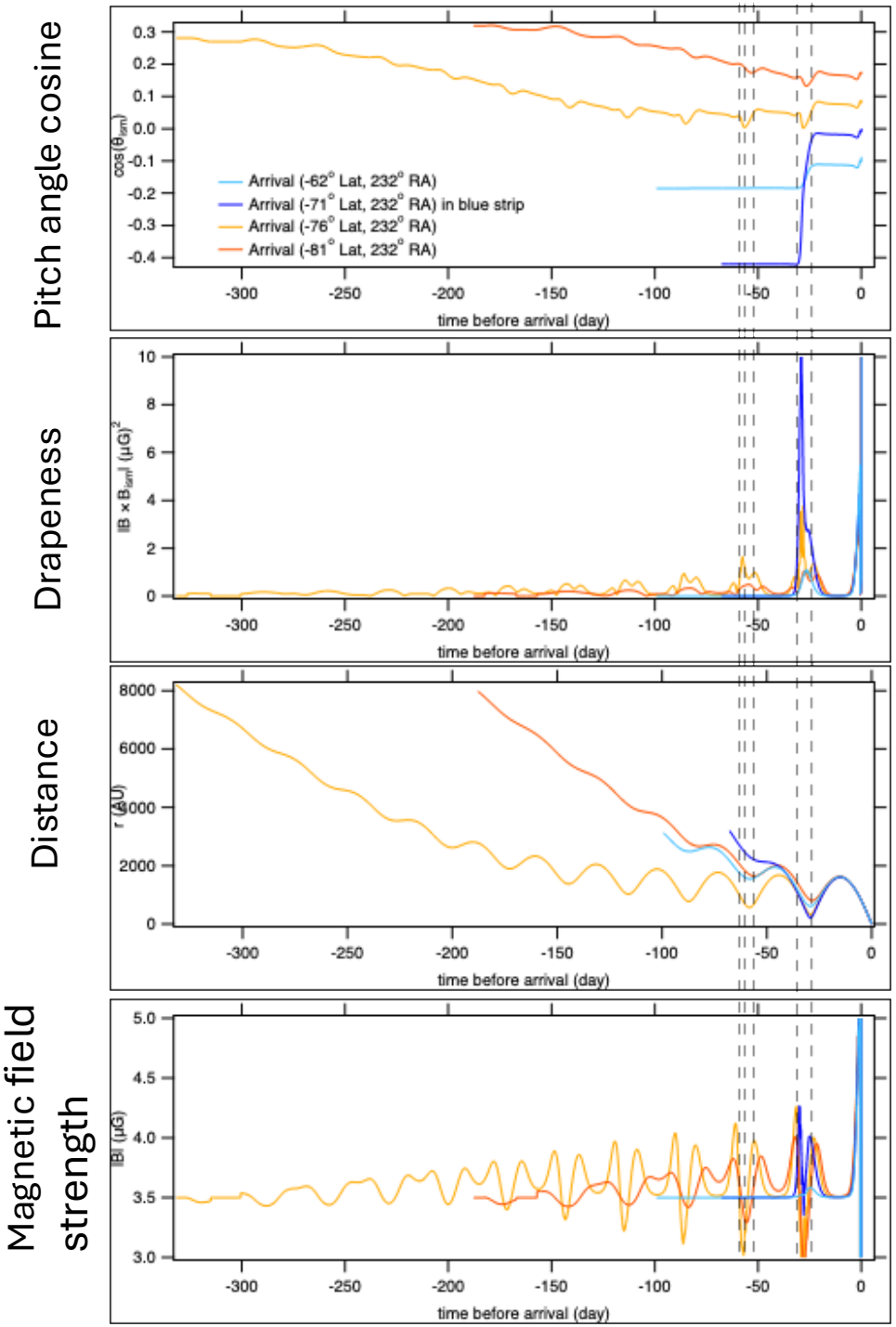


Model



Trajectories of cosmic rays from two ends of the magnetic field lines



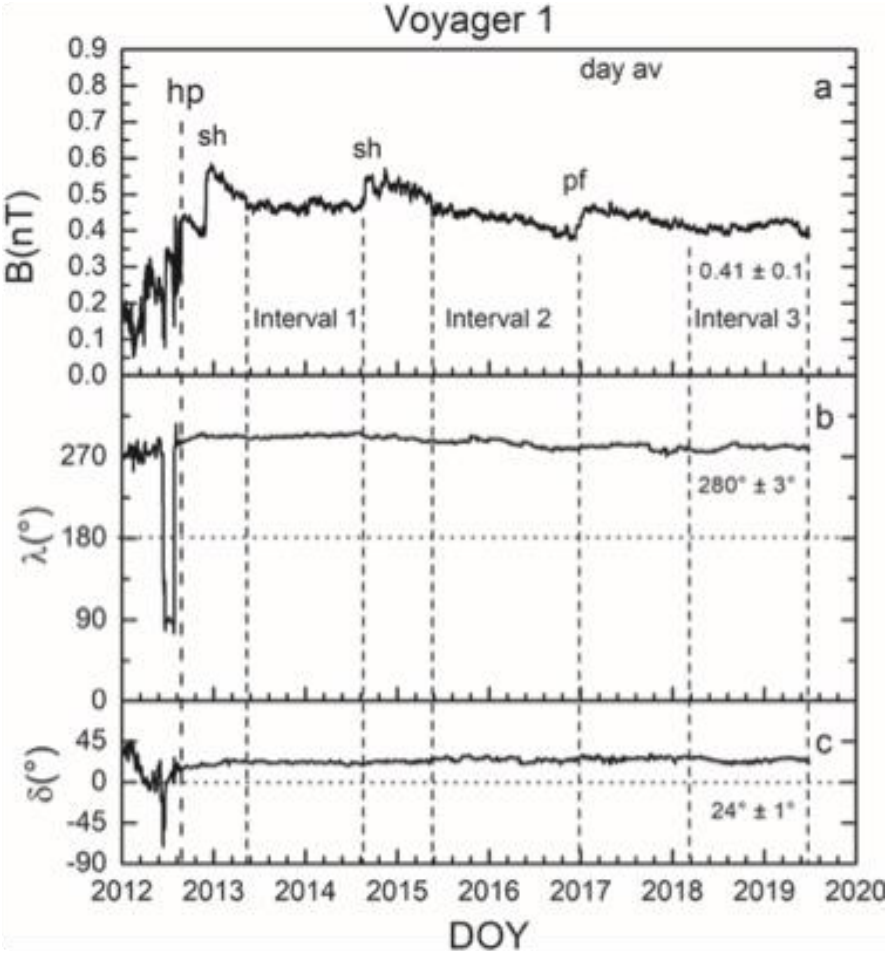


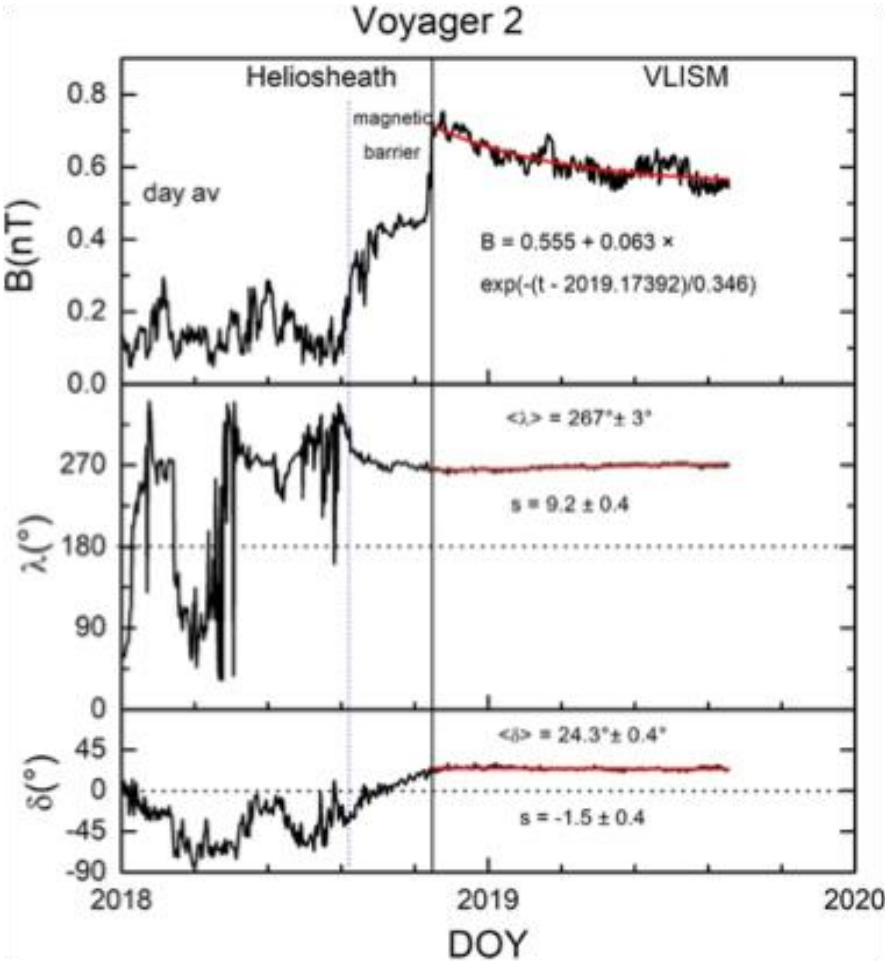
Lines color coded with cosmic ray intensity.

Mechanism that produced the low-intensity stripe in ICECUBE measurement near the plane perpendicular to the interstellar magnetic field direction:
Especially stronger pitch angle change cause the draped interstellar magnetic field magnetic field in the outer heliosheath, particularly near the heliopause.

In-situ measurement of the very local interstellar magnetic field in the outer heliosheath

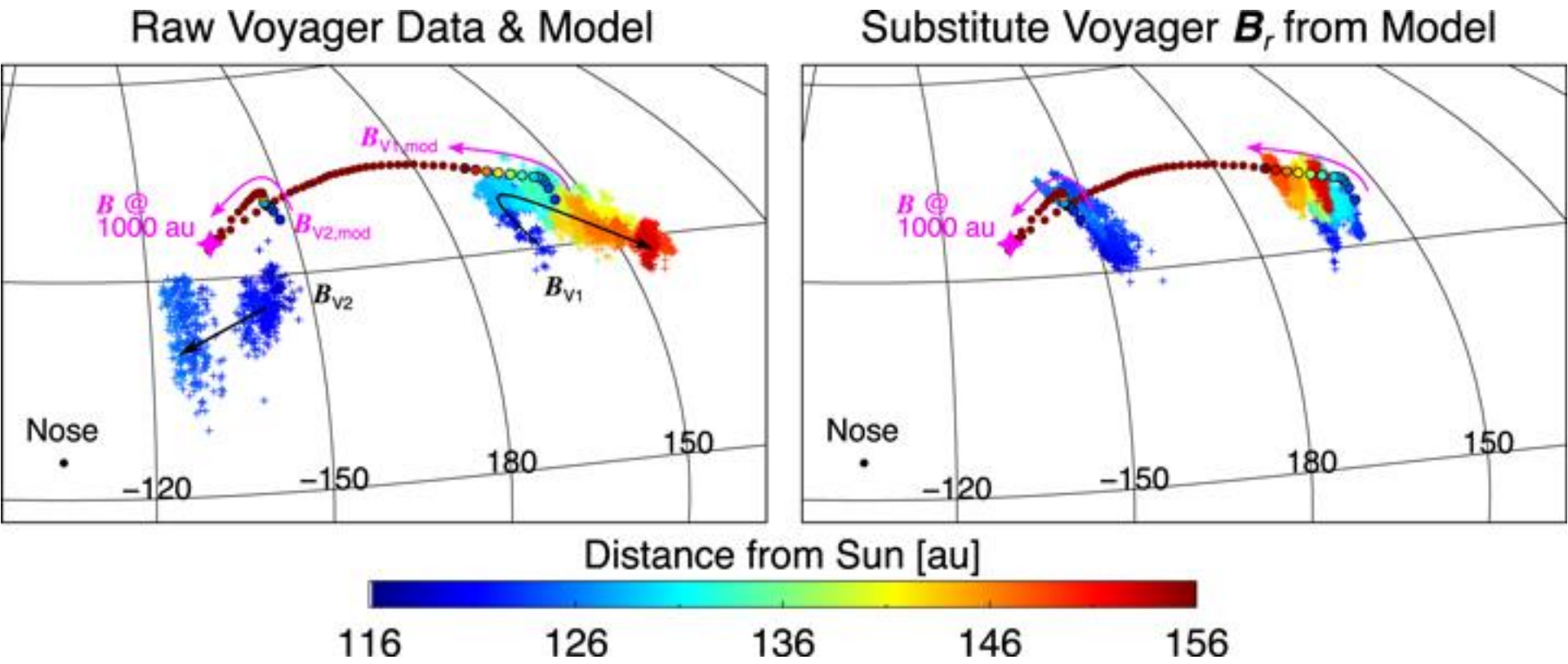
The magnetic field has been modified by the heliosphere:
Draping and solar activities





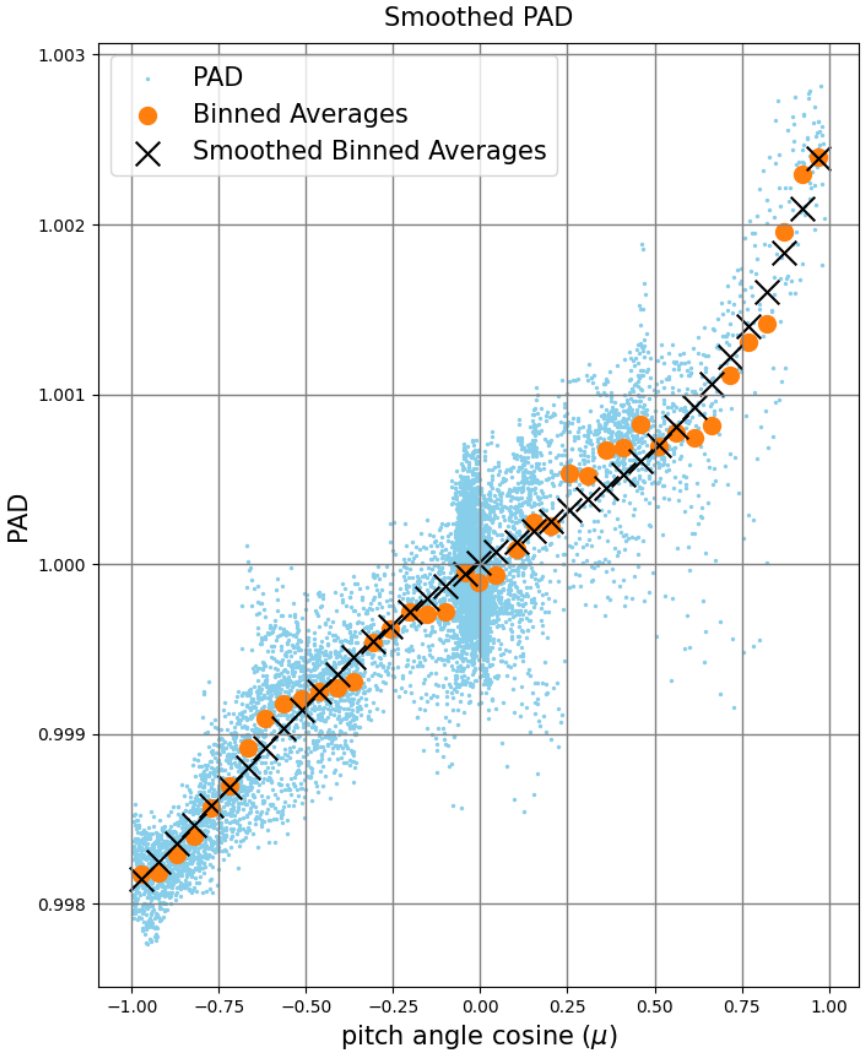
Burlaga et al. 2020

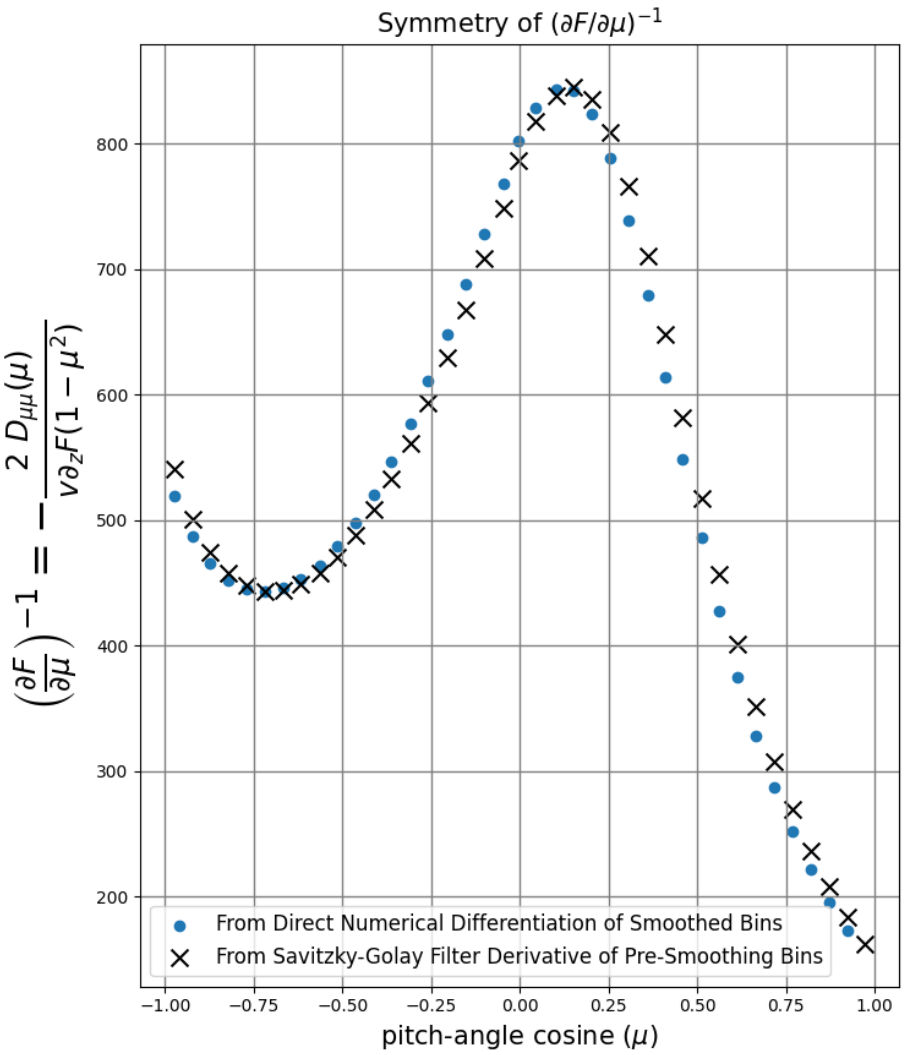
Proposed correction to Br of Voyager measurements in ecliptic coordinates



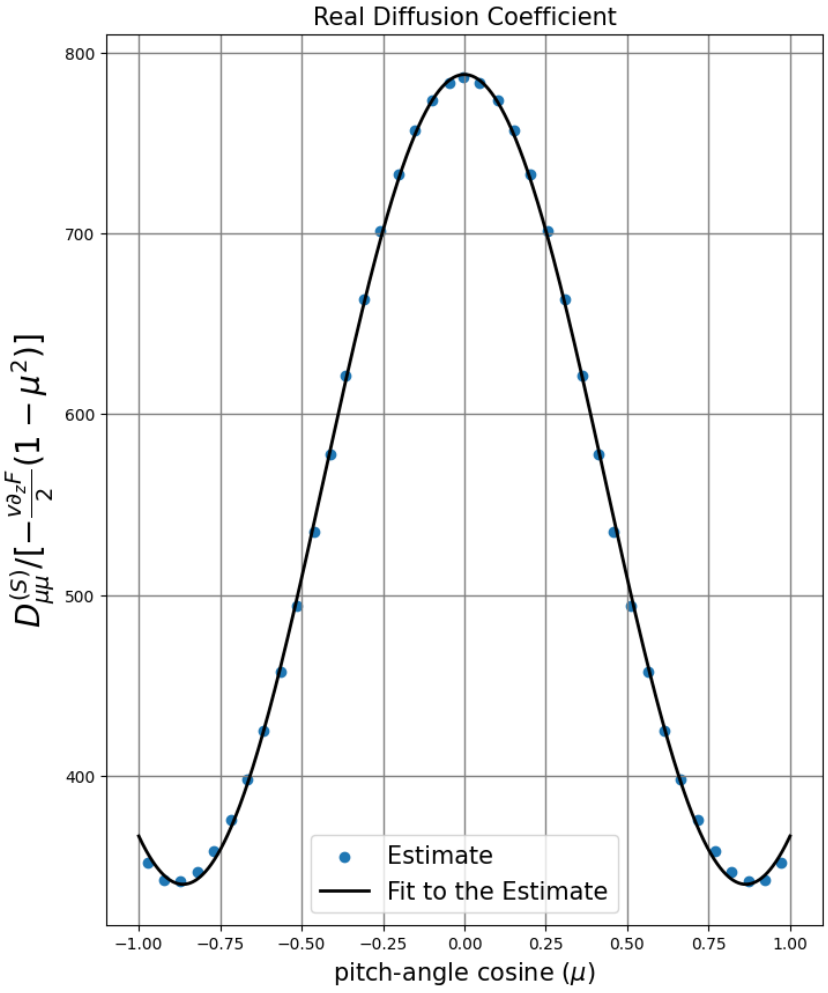
Rankin et al. 2023

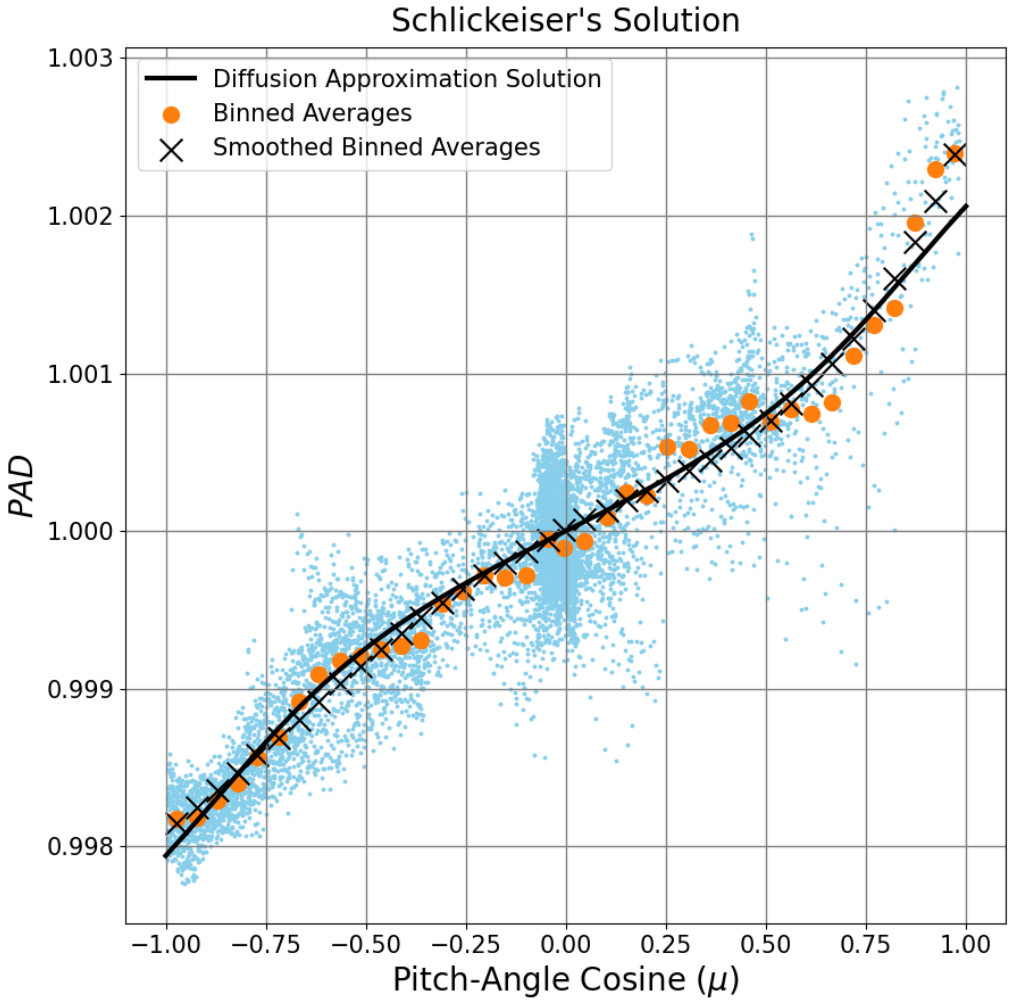
Pitch-angle diffusion coefficient determined from Pitch –angle distribution under diffusion approximation





Symmetrized Pitch angle diffusion coefficient

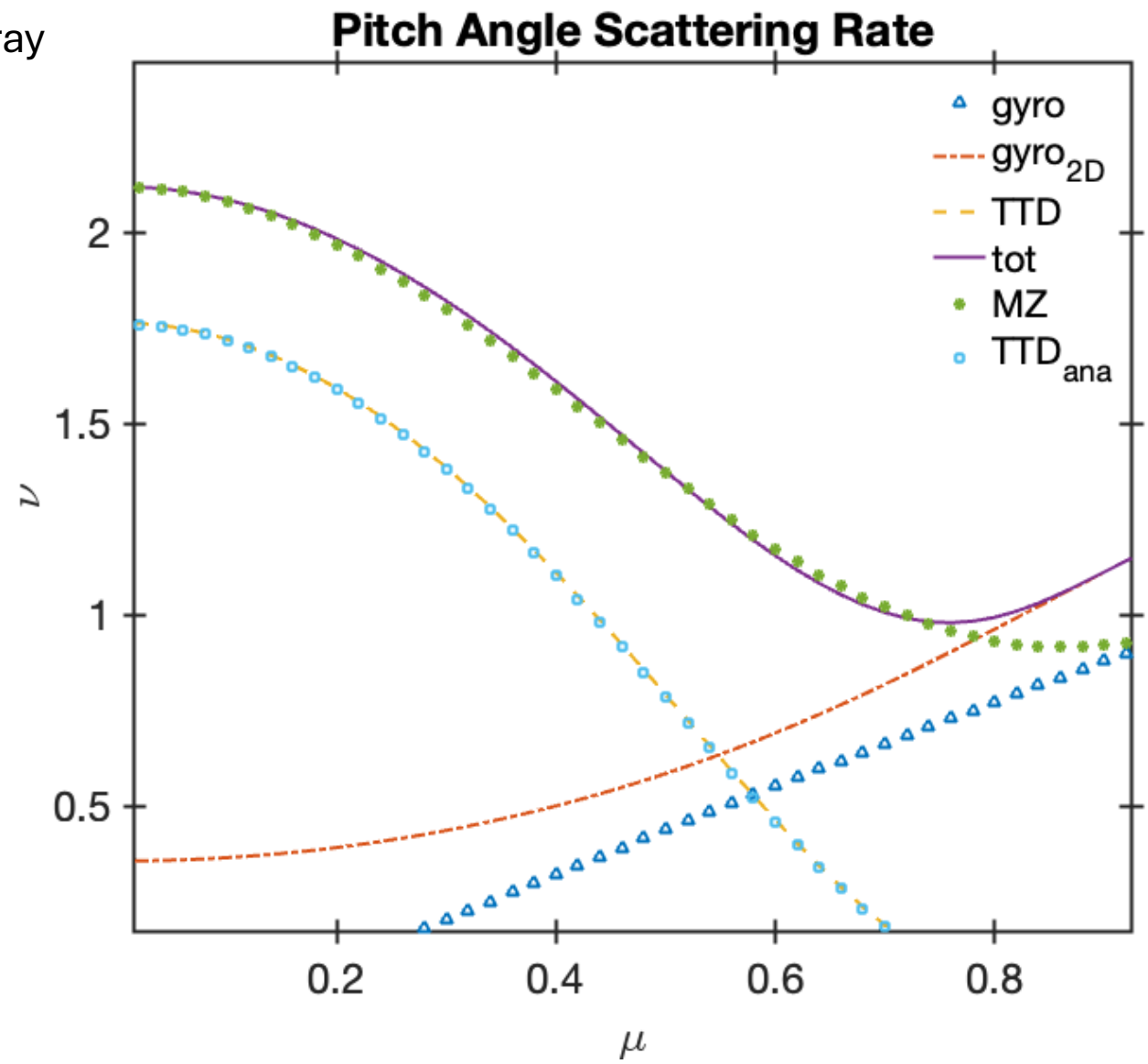




Pitch angle scattering rate $\nu = D_{\mu\mu}/(1-\mu^2)$

Properties of LISM turbulence that produces TeV cosmic-ray pitch angle scattering

- Compressible mode
- Iroshnikov–Kraichnan spectrum $k^{-3/2}$.
- Damping of small-scale quasi-perpendicular mode due to TTD interaction with particles.
- Evolve toward large-scale quasi-parallel modes
- $M_A = 0.5$
- $\beta = 0.1$
- T=8710 K
- $N_{gas} = 0.1$ cm^{-3}



Same result as predicted by Yan and Lazarian (2008)

Pitch angle diffusion and physical model fit

Pitch angle diffusion with focusing

$$\frac{\partial}{\partial \mu} D_{\mu\mu} \frac{\partial f}{\partial \mu} - B_\mu \frac{\partial f}{\partial \mu} = \frac{\partial f}{\partial t} + v\mu \frac{\partial f}{\partial z} - \frac{\partial}{\partial \mu} D_{\mu p} \frac{\partial f}{\partial p}$$

$$B_\mu = \frac{v(1-\mu^2)}{2L_B} \quad \text{with} \quad L_B = \left[\frac{\partial \ln B}{\partial z} \right]^{-1}$$

~~Kolmolgorov scattering $D_{\mu\mu} = D_0(1-\mu^2)|\mu|^{2/3}$~~

Isotropic scattering $D_{\mu\mu} = D_0(1-\mu^2)$

Perturbative solution: $f = F_0 + f_1$ with $F_0 \gg f_1$

with focusing:

$$f_1 = -\frac{v}{2D_0 L_f}\mu, \quad L_f = \left[\frac{\partial F_0}{F_0 \, \partial z} \right]^{-1}$$

$$\text{with } \frac{v}{2D_0 L_f} = \frac{\lambda_\parallel}{L_f} = -0.00183 \pm 0.00006$$

with focusing:

$$f_1 = \frac{\partial F_0}{2B_0^2 D_0 F_0 \, \partial z}[(1+B_0)ln(1-\mu) - (1-B_0)ln(1+\mu)]$$

$$+ \frac{C_1}{2}[e^{B_0} ei(-B_0 + B_0\mu) e^{-B_0} ei(B_0 + B_0\mu)] + C_0$$

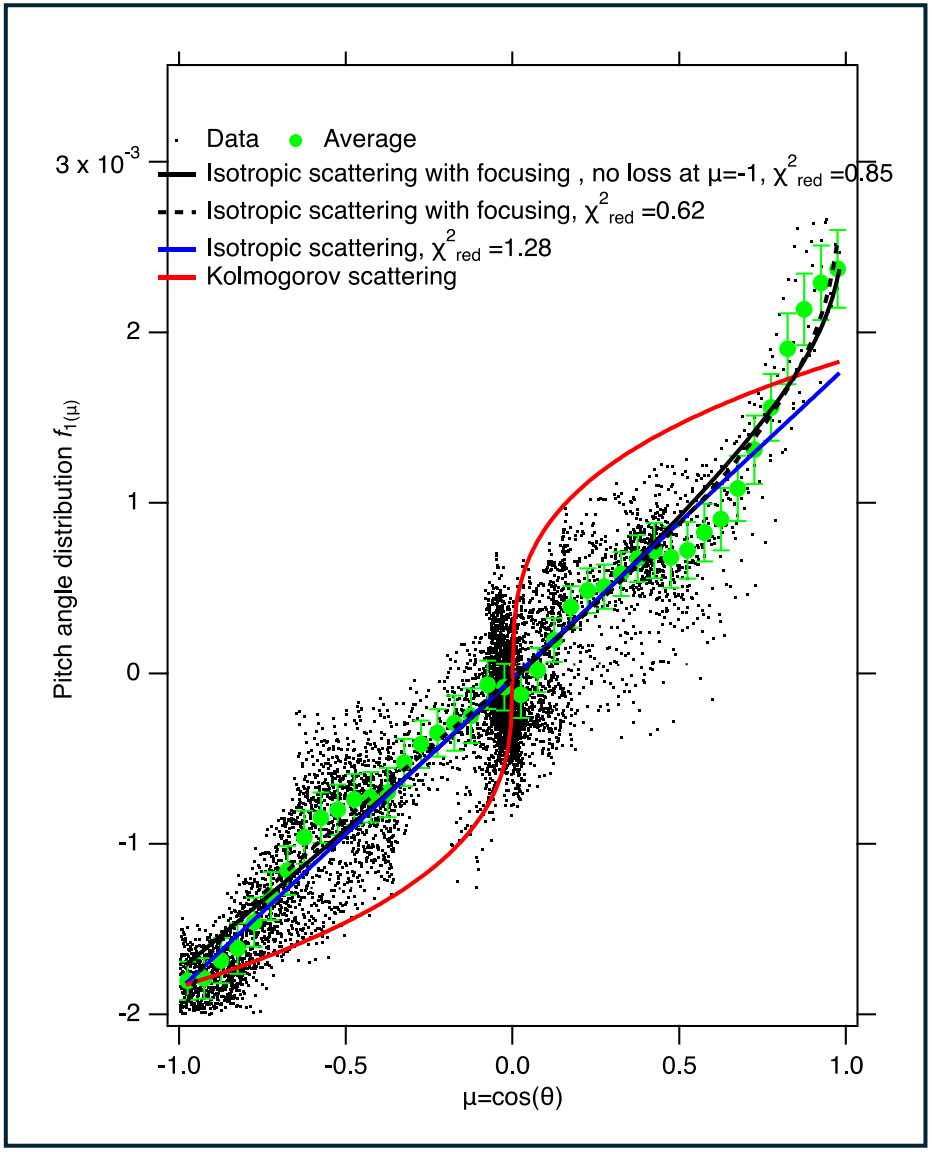
$$B_0 = -\frac{\lambda_\parallel}{L_B} = 0.16 \pm 0.05$$

$$\frac{\lambda_\parallel}{L_f} = -0.0024 \pm 0.0004$$

If $\kappa_{||} = \kappa_{29} \times 10^{29}$ cm^2/s, $\lambda_\parallel = 3.2\,\kappa_{29}$ pc

$$L_B = \left(\frac{\partial \, lnB}{\partial z}\right)^{-1} = 20\,\kappa_{29} \text{ pc}$$

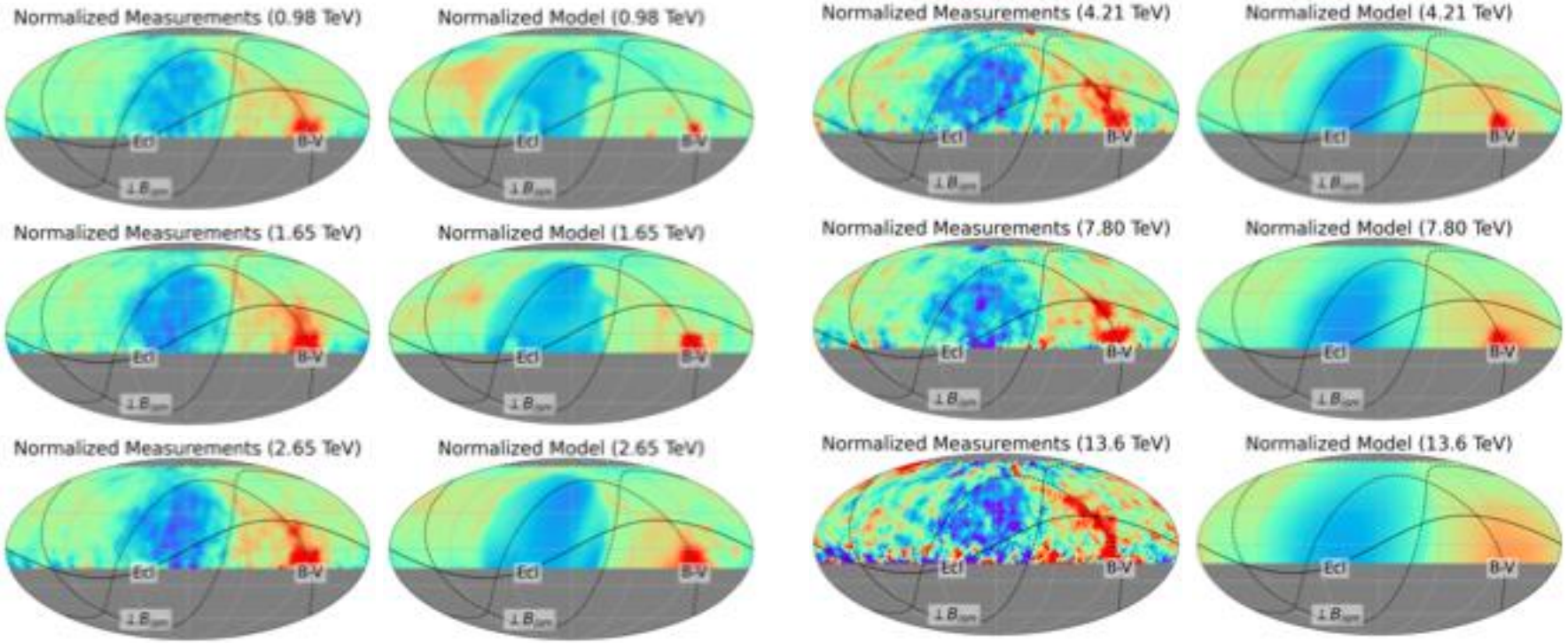
$$L_f = \left(\frac{\partial \, lnf}{\partial z}\right)^{-1} = 1.72\,\kappa_{29} \text{ kpc}$$

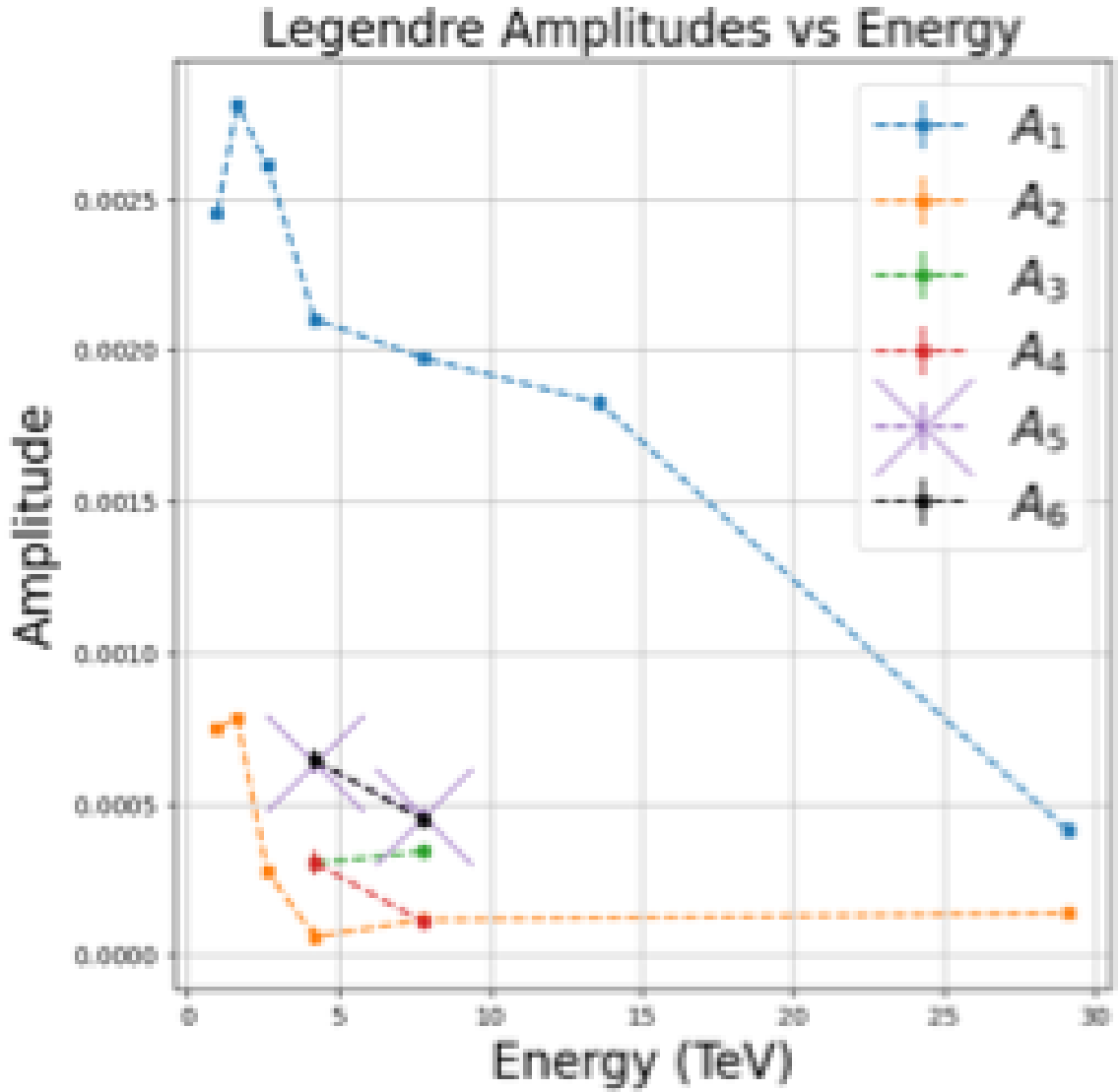


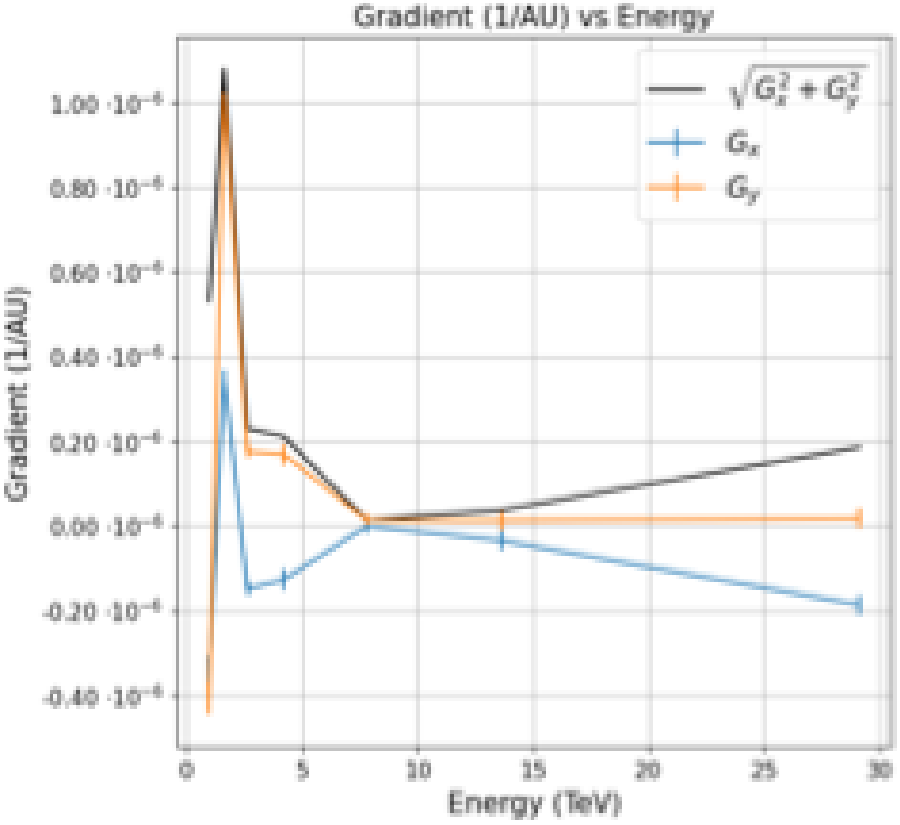
Summery

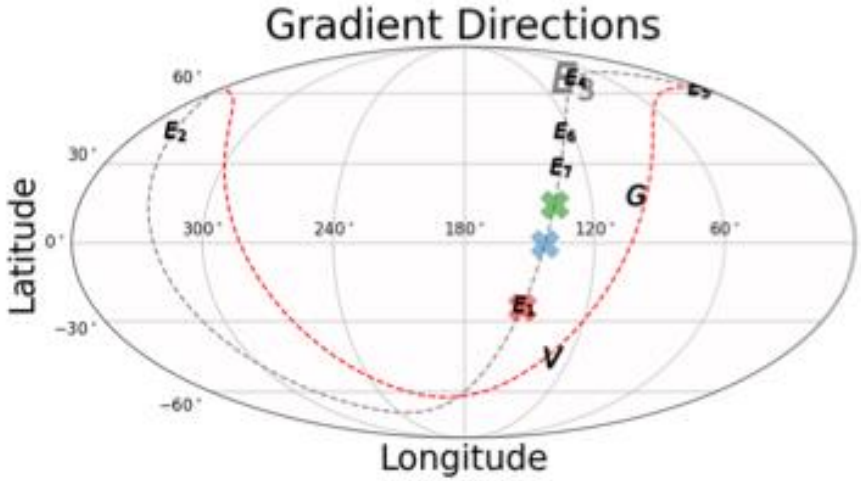
- In the last ~15 years Major progress has been made in determining the local interstellar magnetic field and turbulence properties.
- With the help of physics-based heliosphere model, the combination of IBEX, Voyager (partially), and TeV cosmic-ray observations can determine the direction of local interstellar magnetic field quite accurately, probably within an error bar of less than 5 degrees. The strength of local interstellar magnetic field should be with 3.5 +- 1 μG.
- The gradient scale of interstellar magnetic field is ~20 pc, consistent with the outer scale of turbulence.
- Interstellar turbulence is much weaker than heliospheric turbulence, resulting in much slow pitch-angle scattering and perpendicular diffusion in interstellar medium. The turbulence inferred from TeV cosmic-ray is mostly scattered by compressible turbulence, with M_A ~0.5.

Energy dependent measurements of TeV cosmic ray anisotropy by ARGO experiment




Legendre Amplitudes vs Energy
Amplitude
Energy (TeV)
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
30
A_1
A_2
A_3
A_4
A_5
A_6

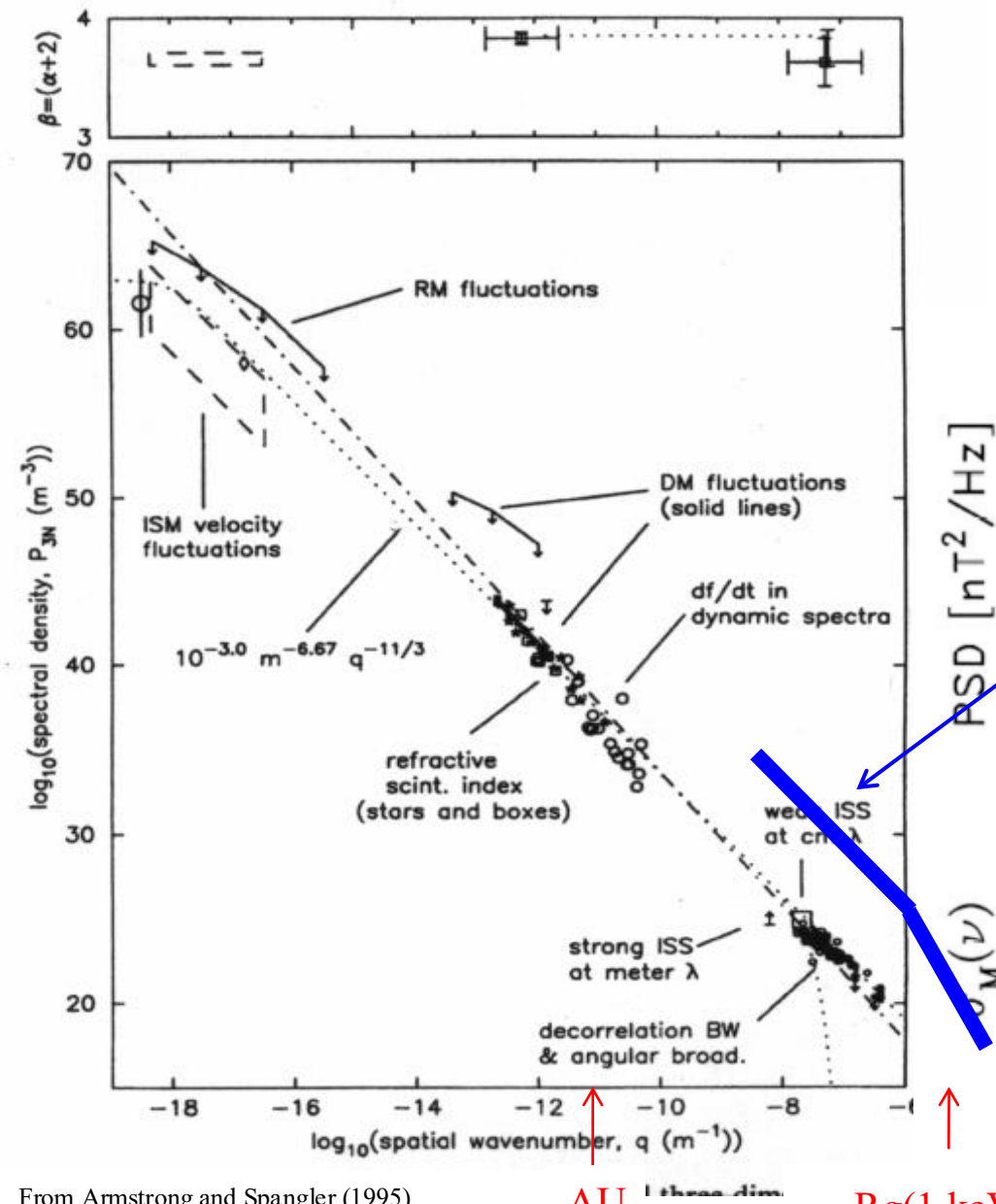

Gradient (1/AU) vs Energy
$\sqrt{G_x^2 + G_y^2}$
G_x
G_y
1.00 ·10⁻⁶
0.80 ·10⁻⁶
0.60 ·10⁻⁶
0.40 ·10⁻⁶
0.20 ·10⁻⁶
0.00 ·10⁻⁶
-0.20 ·10⁻⁶
-0.40 ·10⁻⁶
Gradient (1/AU)
0
5
10
15
20
25
30
Energy (TeV)

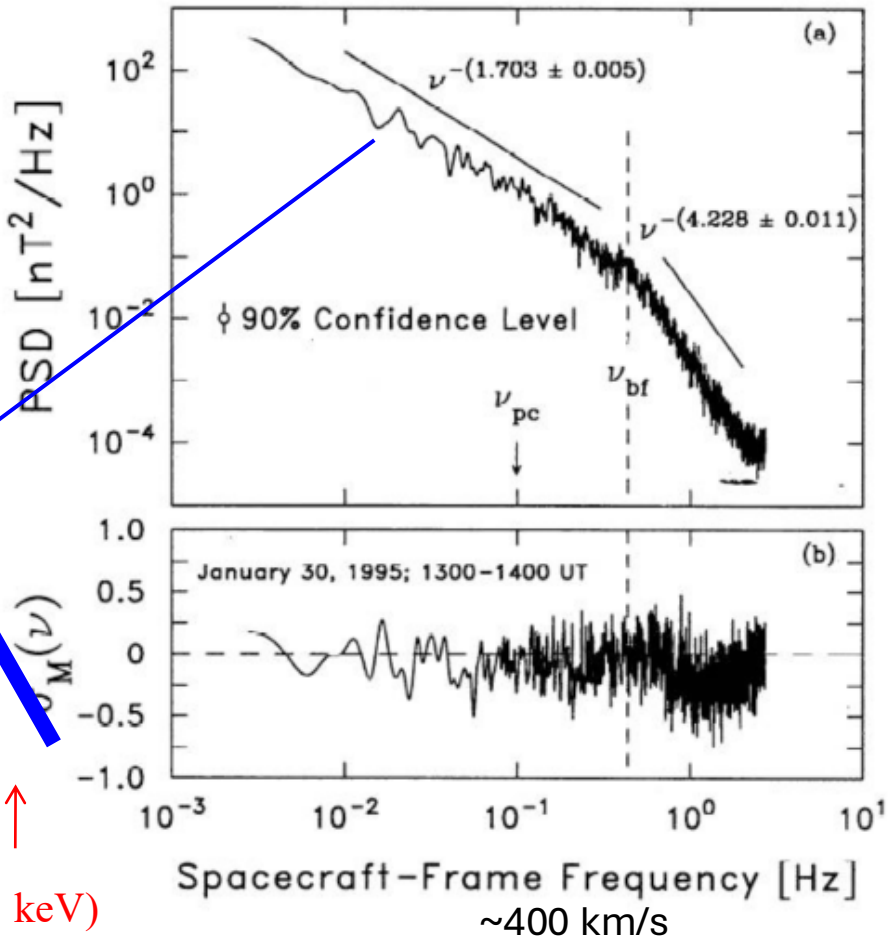

Gradient Directions
60°
30°
0°
−30°
−60°
300°
240°
180°
120°
60°
Latitude
Longitude
E_2
E_6
E_7
E_1
G
V

Interstellar and interplanetary magnetic turbulence

On the scale of ribbon (tens AU), $\Delta B/B < \sin(20^o) = 0.34$.

Turbulence on the scale of





From Armstrong and Spangler (1995)

AU

Rg(1 keV)