TeV cosmic ray anisotropy in the local interstellar medium

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The 10th International Workshop on Air Shower Detection at High Altitudes
14:30-15:00, Jan 9, 2020

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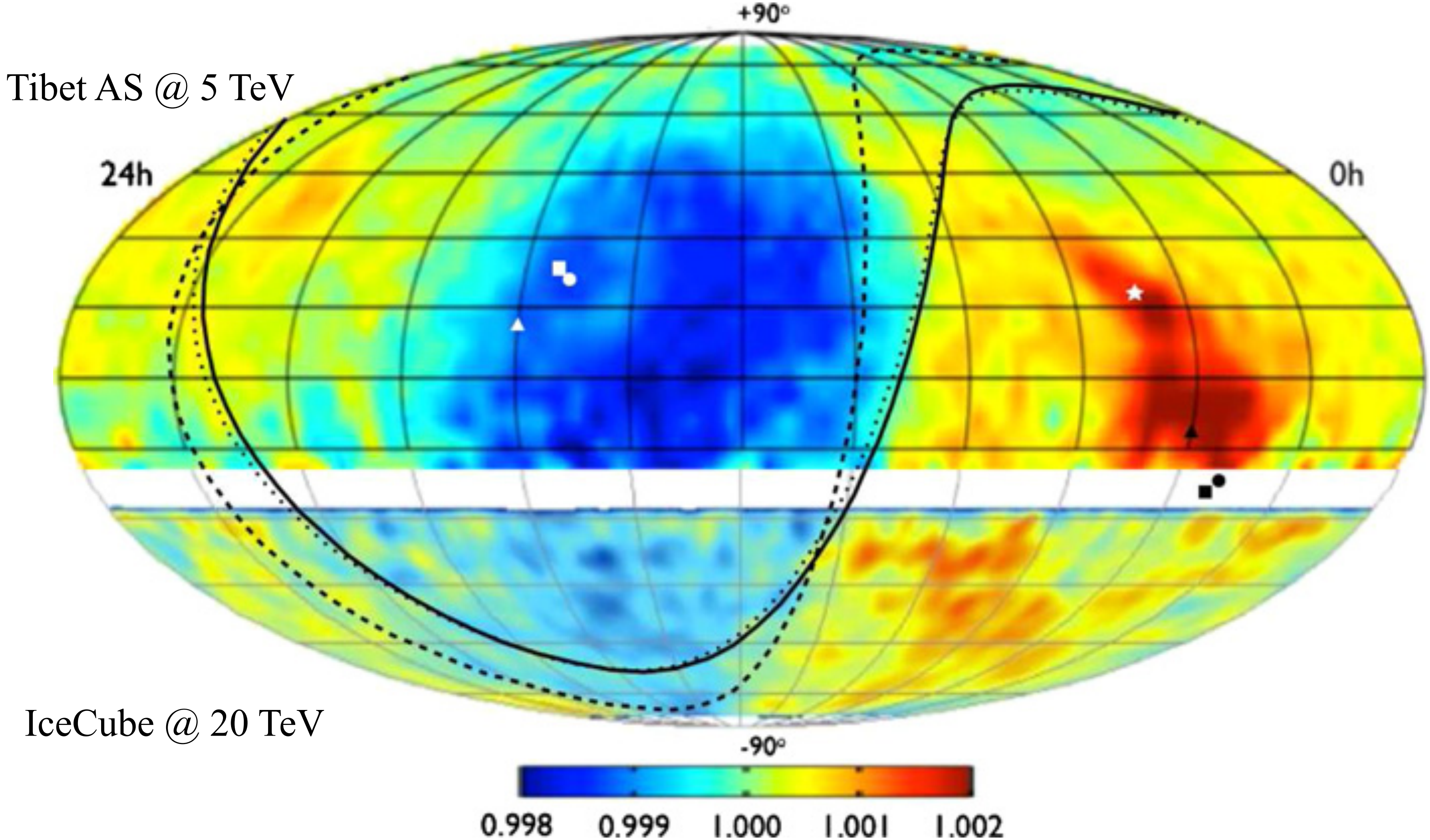
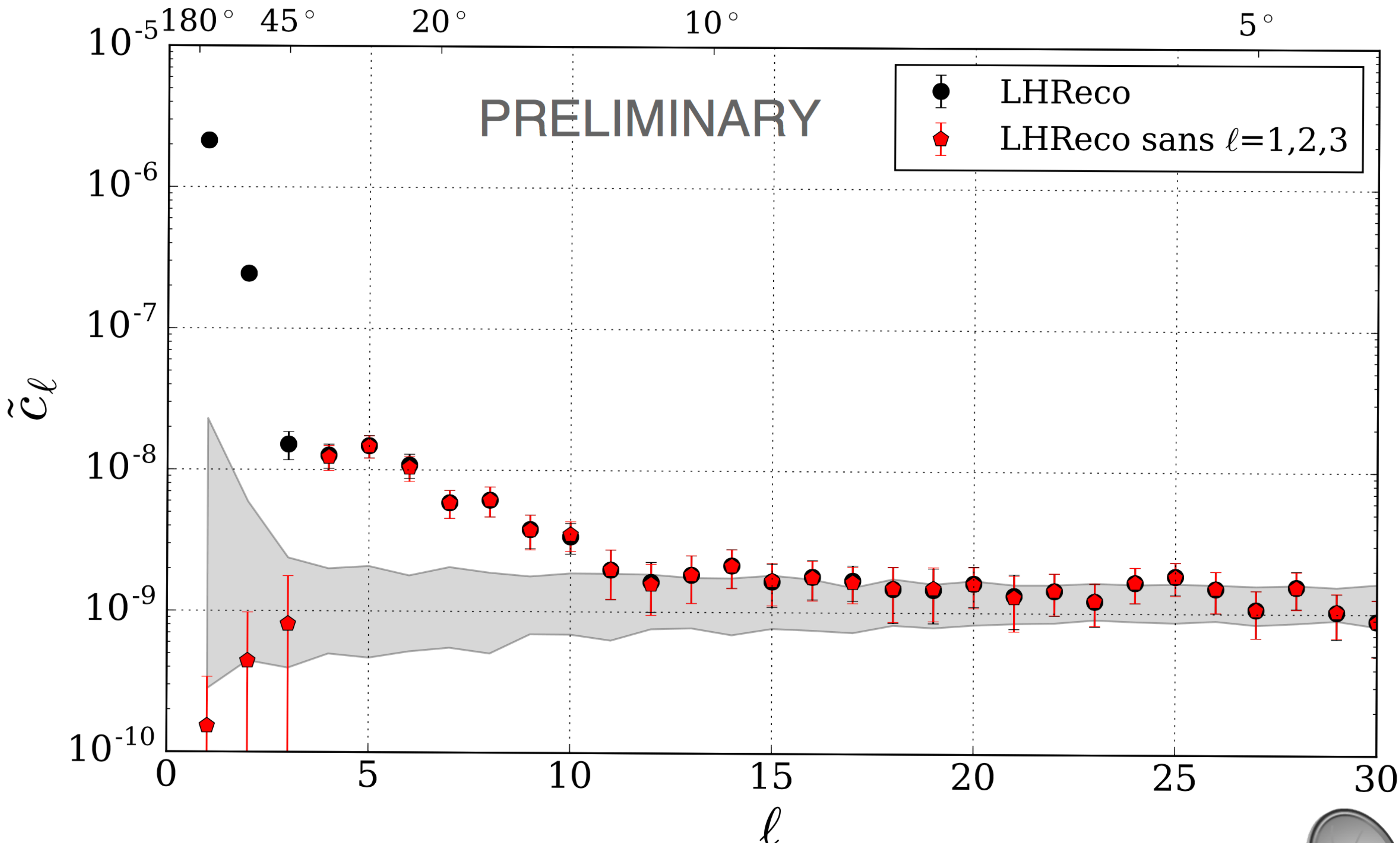
TeV cosmic ray anisotropy observations



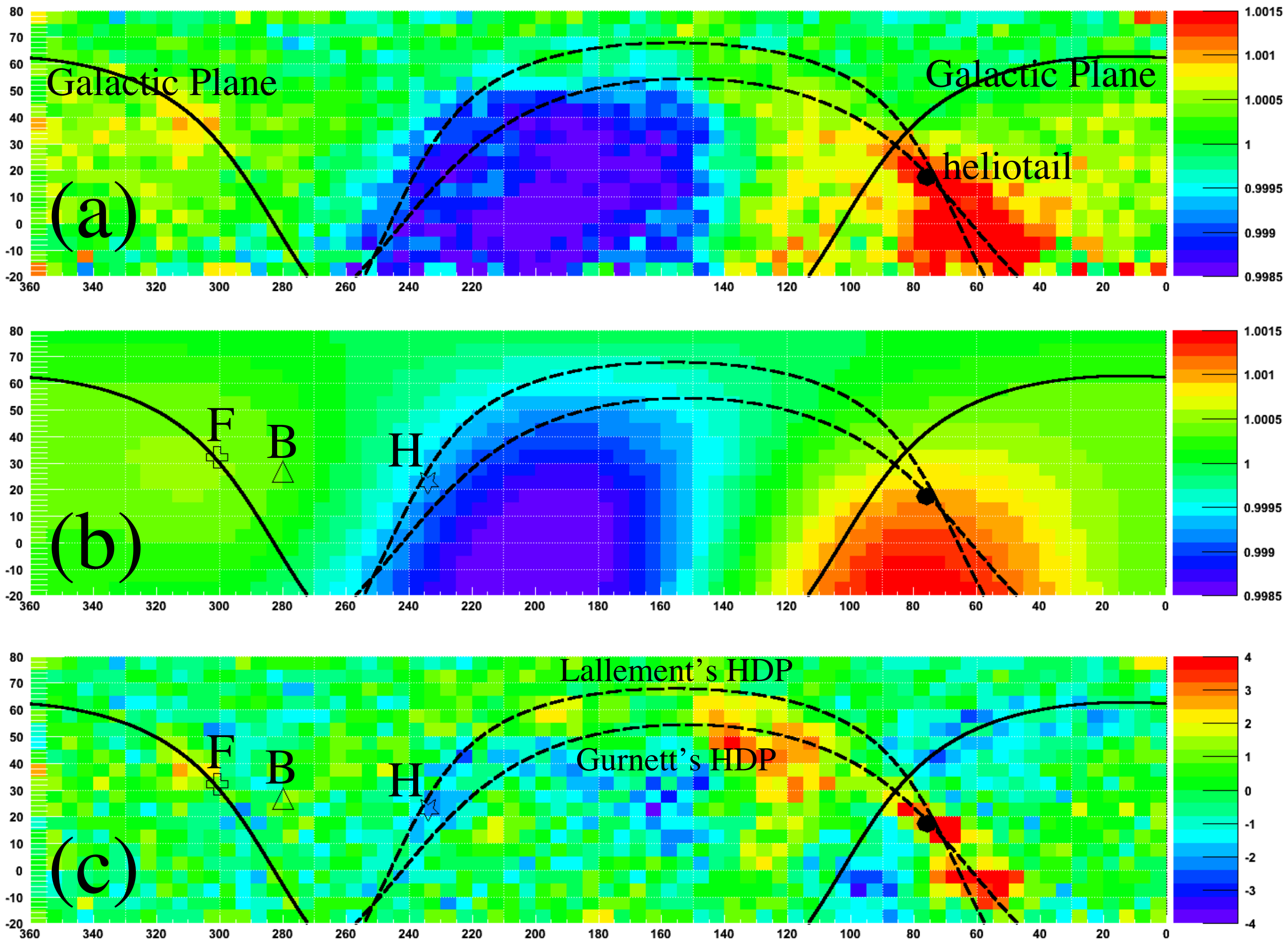
Relative Intensity Map in Equatorial Coordinates
(from Destiati and Lazarian, 2013)

Spherical Harmonic Power Spectrum of TeV CR Anisotropy
IceCube-HAWC construction



Tibet ASγ anisotropy observations

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

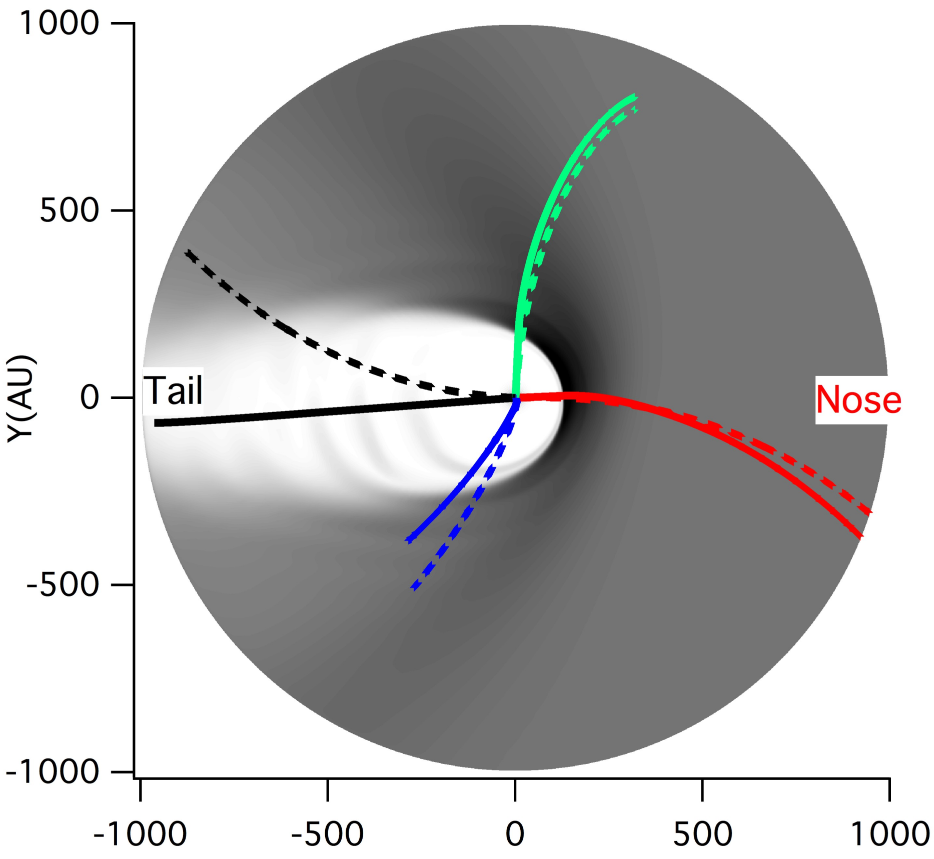


Size of heliosphere (heliopause):
Nose: ~150 AU, Flank ~300 AU
Tail: A few thousand AU

Gyroradius of protons in 3.5 μG LISMF:
1 TeV: 63 AU, 10 TeV: 635 AU
300 TeV: 19 kAU

Heliosphere should affect the anisotropy of TeV cosmic rays

10-TeV proton trajectories
Final arrival directions: Nose, Pole, Flank, Tail



Liouville Mapping of Anisotropy

Anisotropy is a measurement of angular dependence of particle distribution in the observer's reference frame

J observed paricle flux

$$J(\vec{r}_o,\vec{p}_o,t_o) = p_o^2 f(\vec{r}_o,\vec{p}_o,t_o)$$

$\vec{p}_o \Leftarrow$ particle momentum in observer's frame

$f \Leftarrow$ particle distribution function in observer's frame

Liouville's theorem (solution to Boltzmann-Vlasov Eq)

$f(\vec{r}_o,\vec{p}_o,t_o) = f(\vec{r}_{ism},\vec{p}_{ism},t_o - s)$ along a deterministic trajectory

with scattering time (~years) >> propagation time (~days)

f is invariant upon transformation of reference frame

Anisotropy at Earth can be mapped of momentum and particle distribution function from the LISM by finding the relation between $(\vec{r}_o,\vec{p}_o)$ and $(\vec{r}_{ism},\vec{p}_{ism})$ along particle trajectories.

Mapping to Earth from ISM distribution through particle trajectory

$$\frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) = q(-\vec{V} \times \vec{B} + \vec{v} \times \vec{B})$$

with ideal MHD Heliosphere Model where $\vec{E} = -\vec{V} \times \vec{B}$

Cosmic ray distribution in LISM as a magnetized charged particle population

$$f(\vec{r}_o, \vec{p}_o) = f(\vec{r}_{ism}, \vec{p}_{ism}) = f(\vec{R}_g, \vec{p}_{ism})$$

$$= F_0 p_{ism}^{-4.75}[1 + \nabla_\perp \ln F \cdot (\vec{R}_g - \vec{R}_o) + A_{1\|} P_1(\cos\theta_{ism}) + A_{2\|} P_2(\cos\theta_{ism})]$$

↑ Compton-Getting + Acceleration (after Taylor expansion)

↑ b × gradient +drift

↑ uni-directional

↑ bi-directional

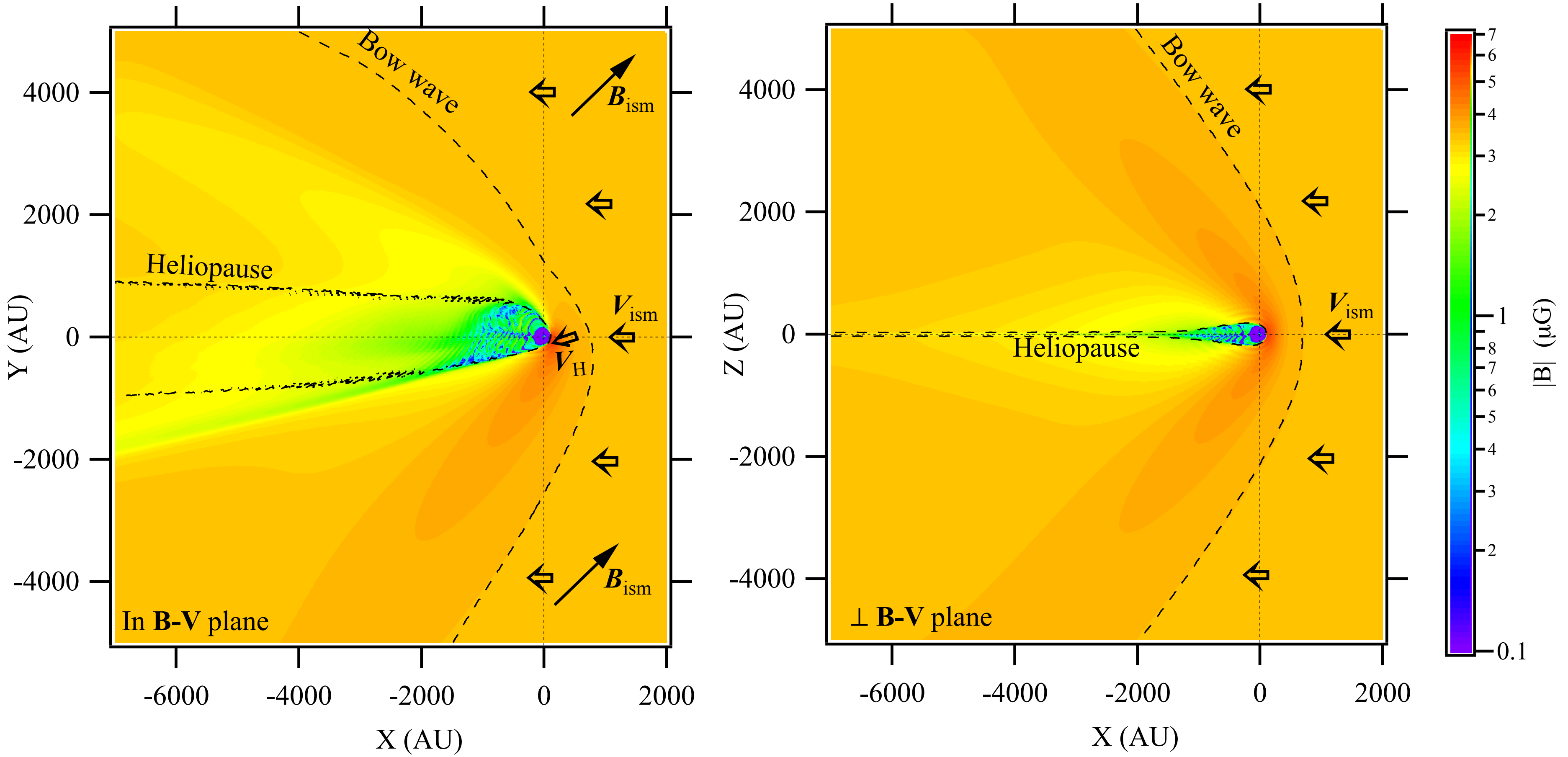
+ Pitch angle change (field-aligned flows)

Total anisotropy is a linear composition of the above 3 types of anisotropies (or 4 maps). Its outcome depends on the magnitude and direction of $A_{1\|}$, $A_{2\|}$, and $\nabla \ln F$ in local interstellar medium.

Shape of heliopause 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=0.185 cm^{-3}



HDP = B-V plane

Shape of heliopause and magnetic field environment

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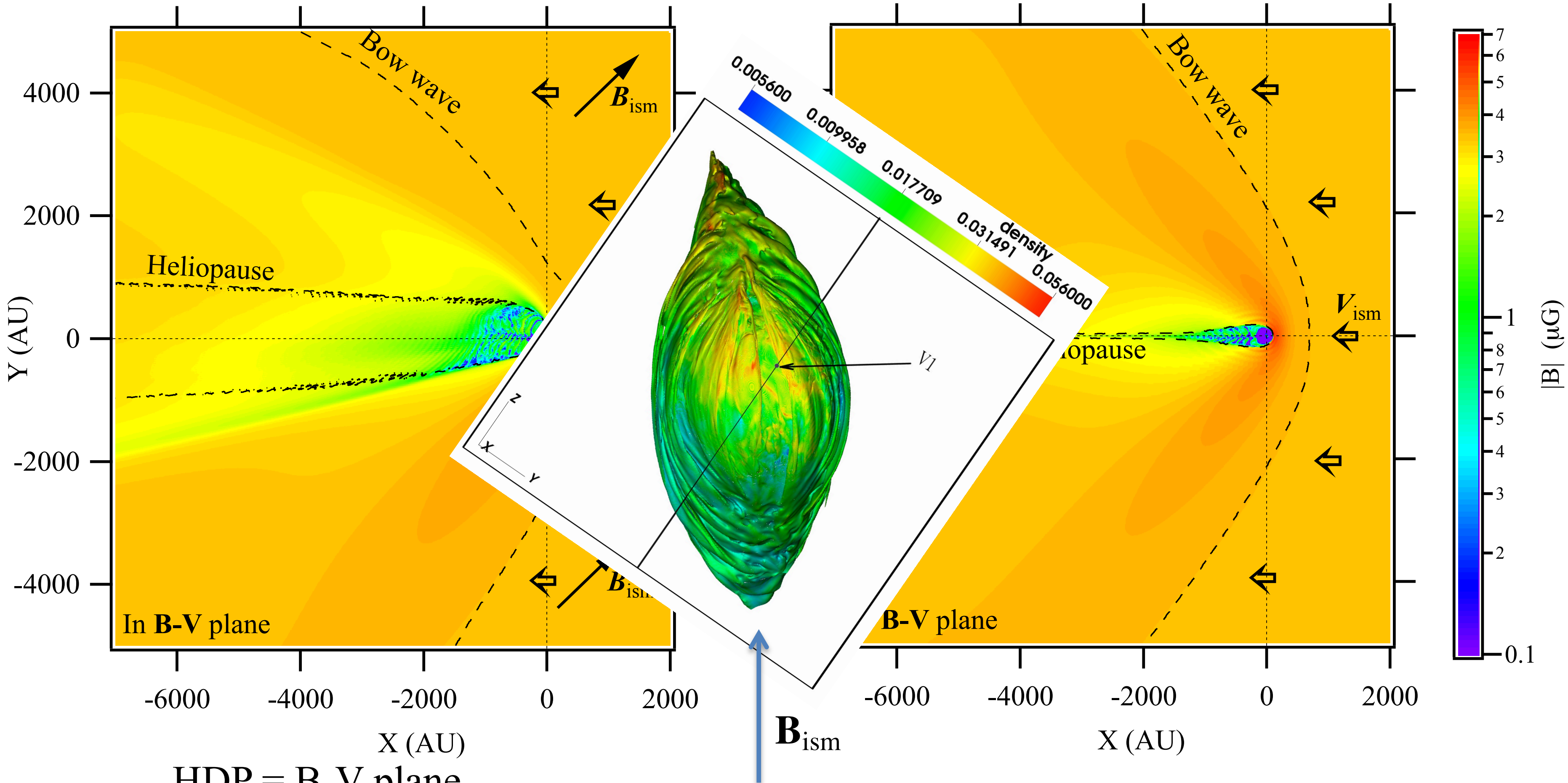
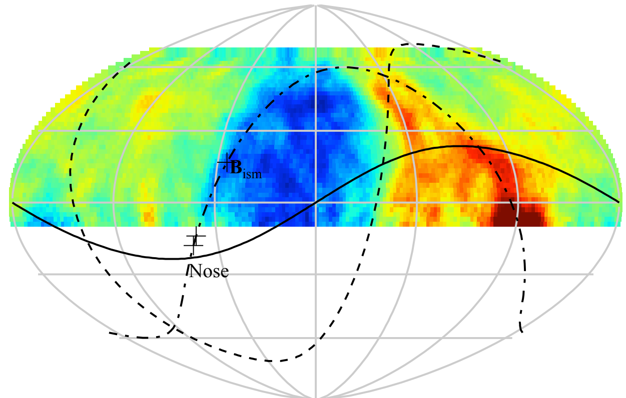
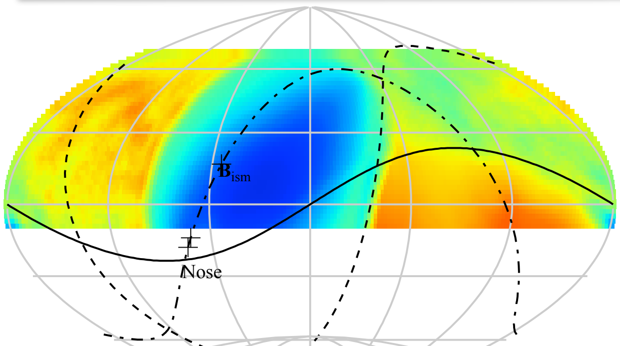


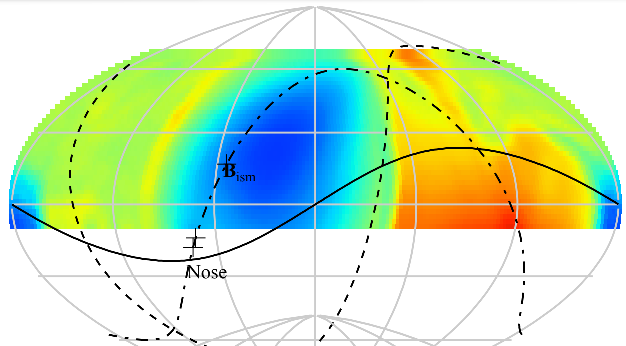
HDP = B-V plane

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



Tibet ASγ Observation 4 TeV

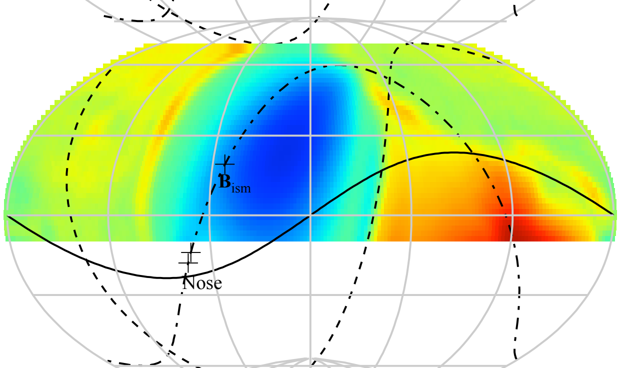


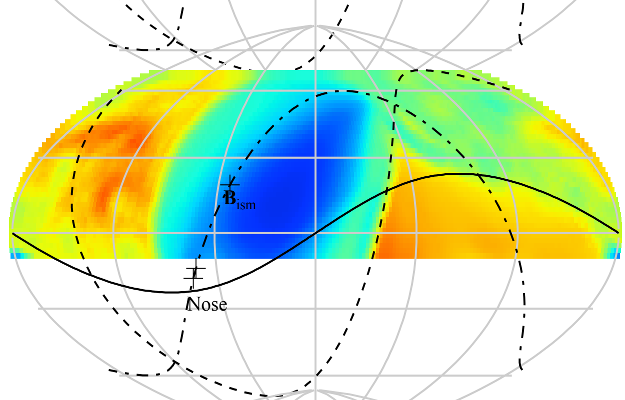


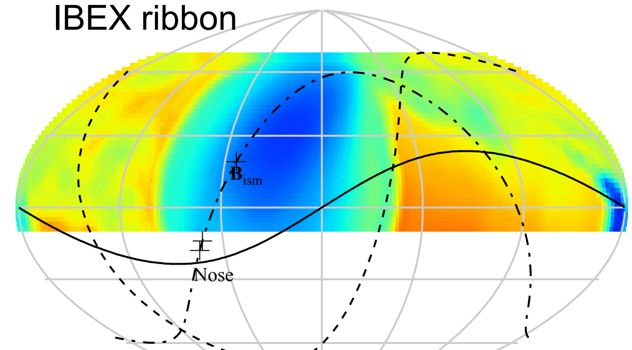
Model calculations

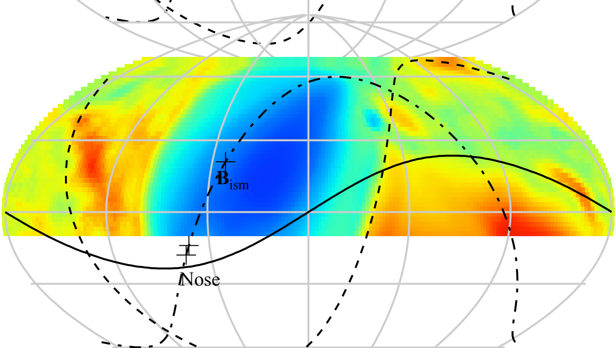
	Low n	Mid n	High n
3.0 mG			
3.5 mG	✓0.065		
4.0 mG			

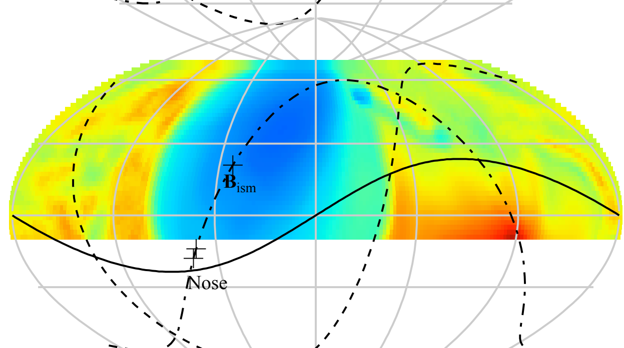
All models constrained by Voyagers IBEX ribbon

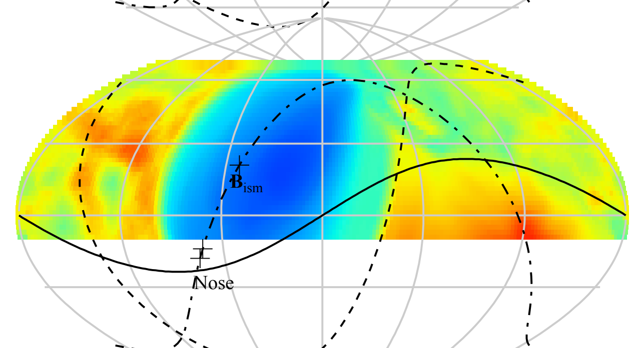




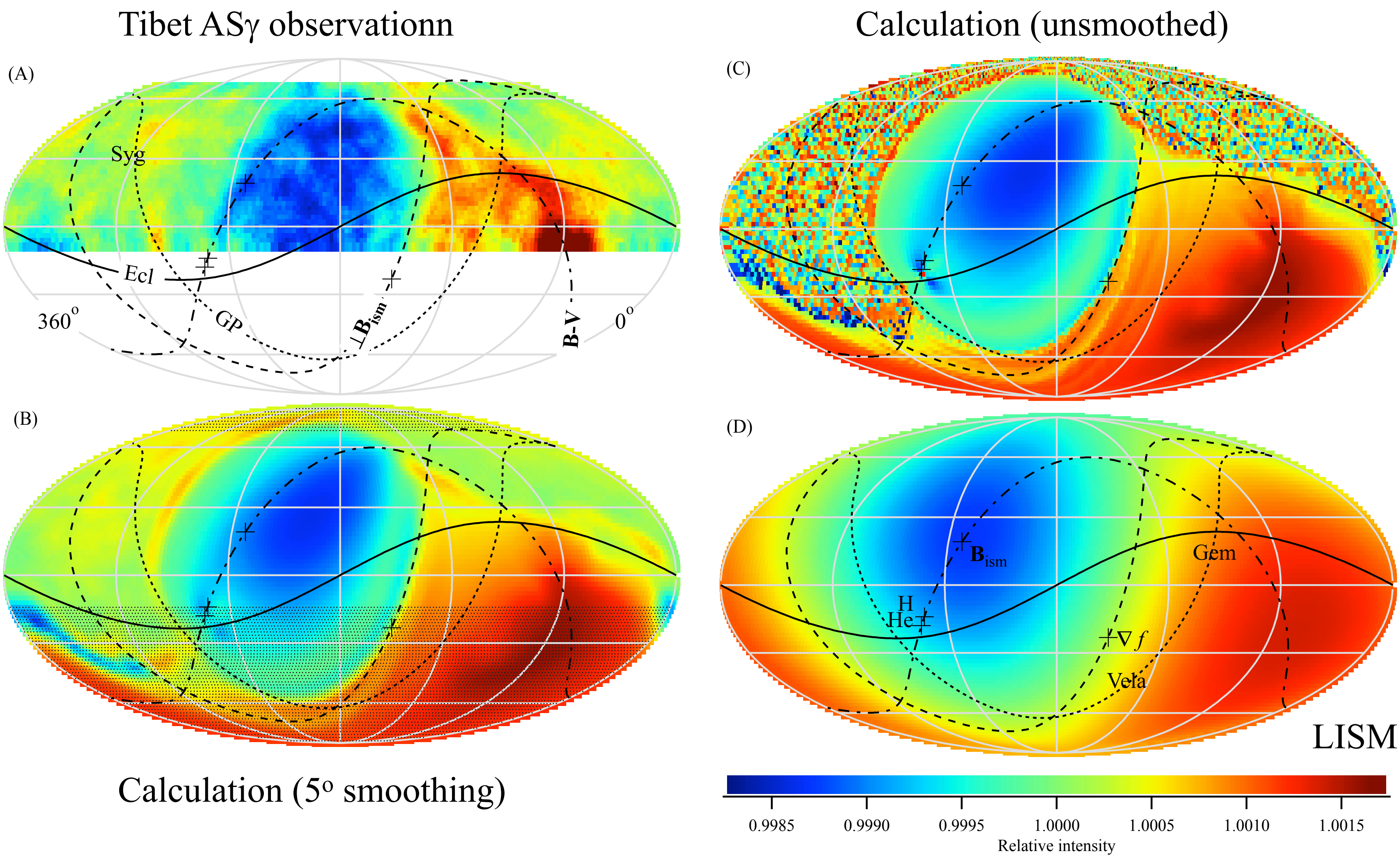




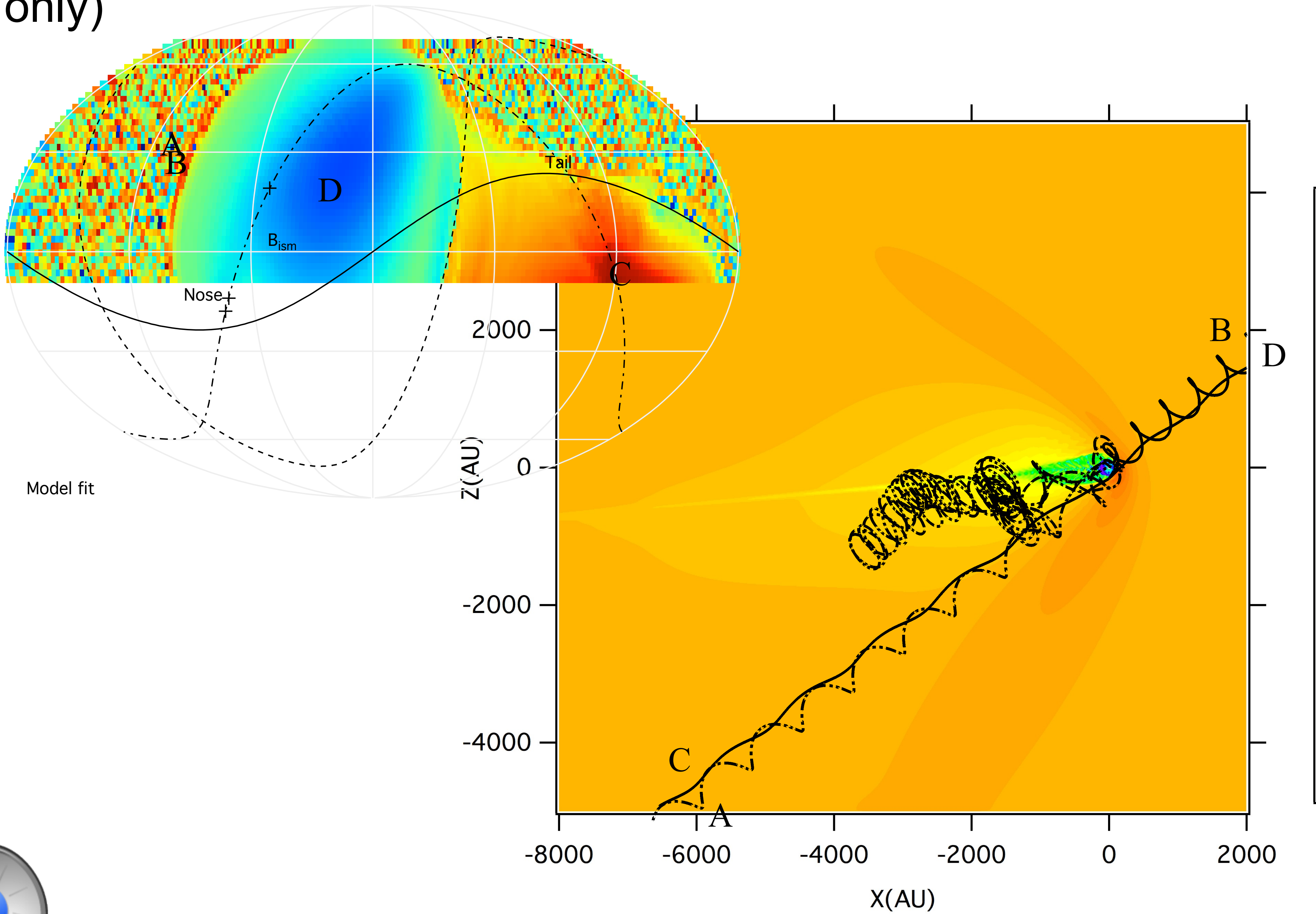




Anisotropy: comparison between observation and calculation



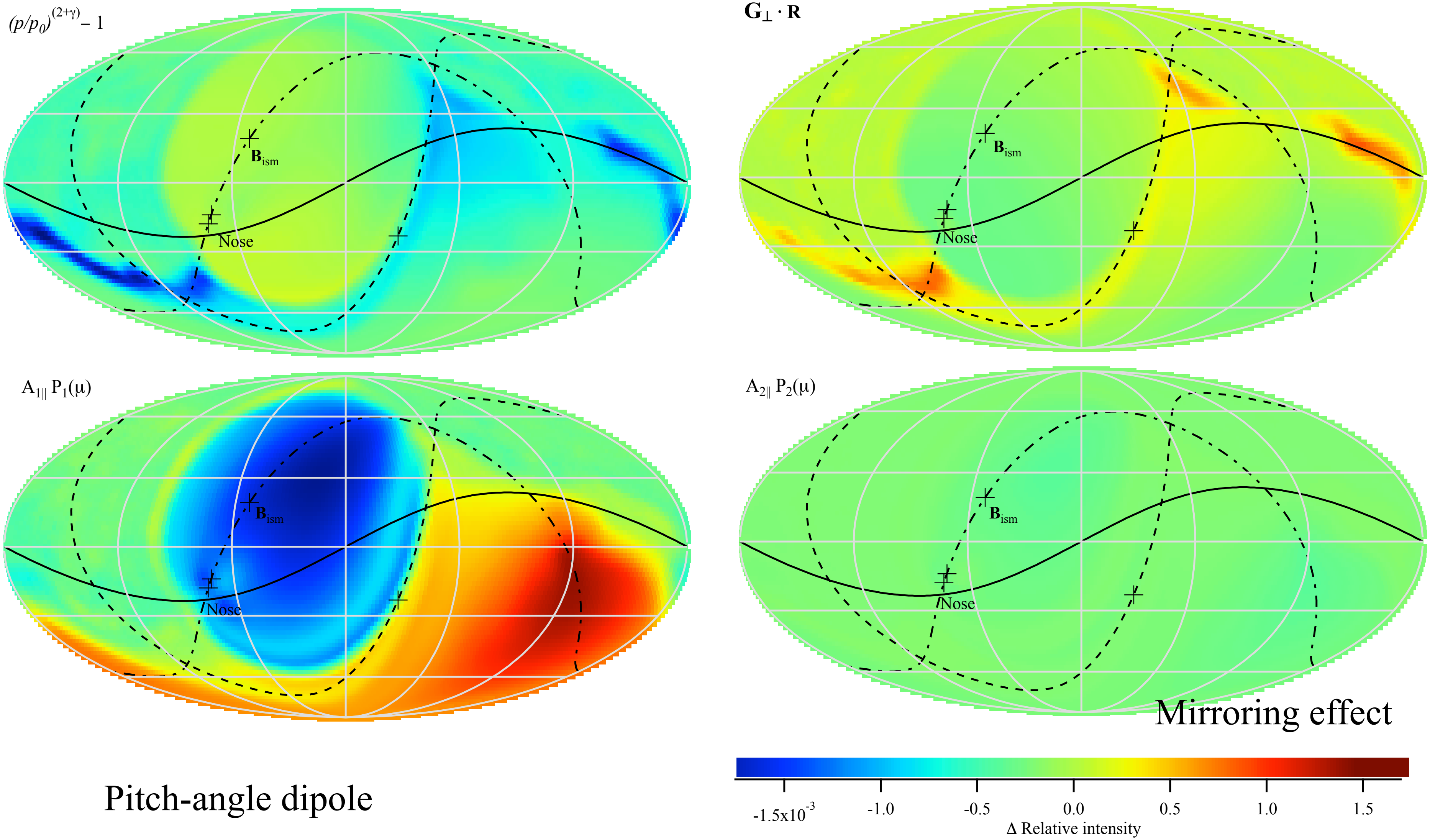
Trajectories arriving in a few sample directions (XZ projection only)



Composition the anisotropy: various contribution

Compton-Getting and Acceleration effects

Drift in density gradient

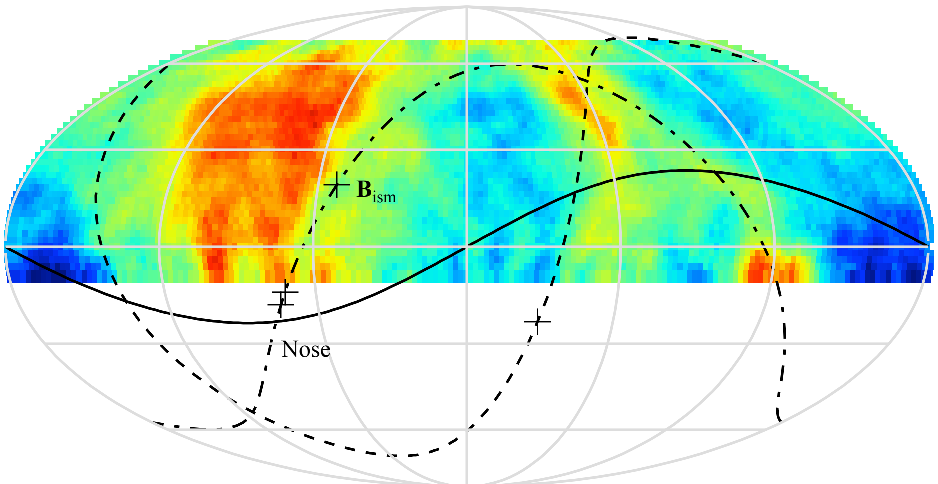


Mirroring effect

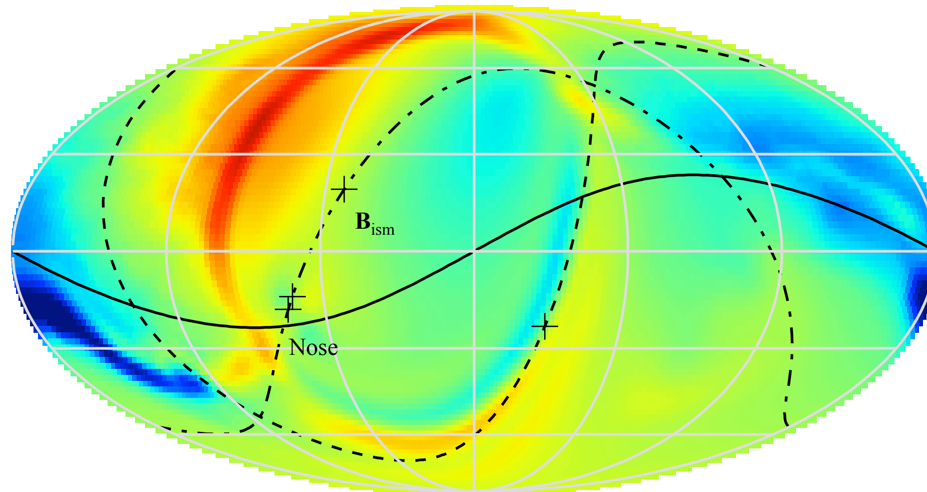
Pitch-angle dipole

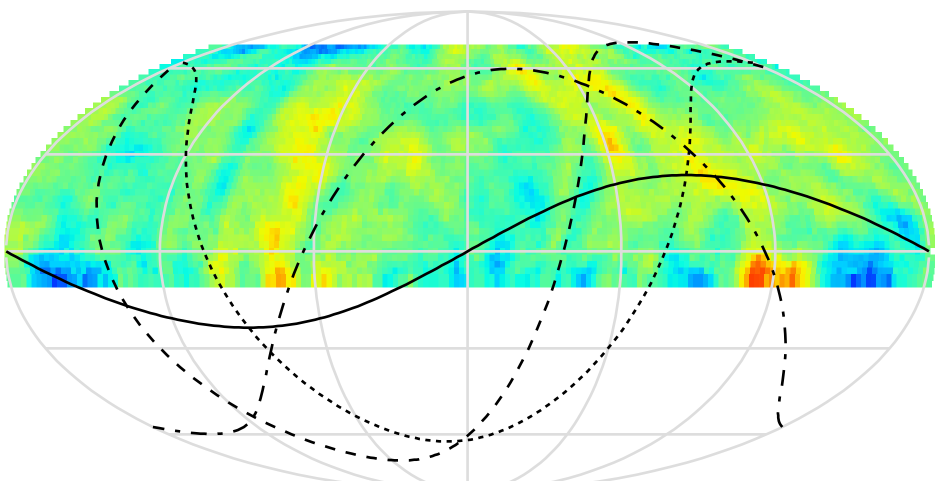
Heliospheric Distortion and Residue

Observed heliospheric distortion



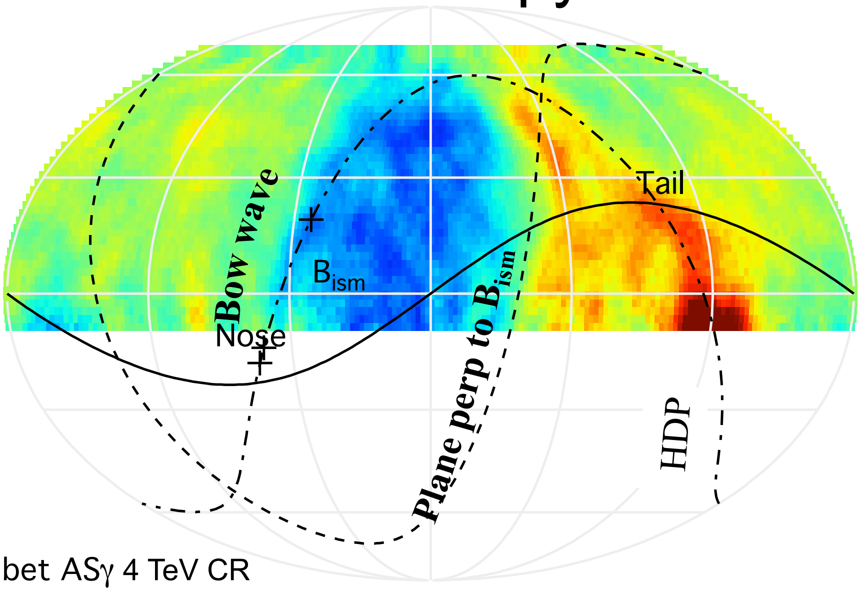
Calculated heliospheric distortion



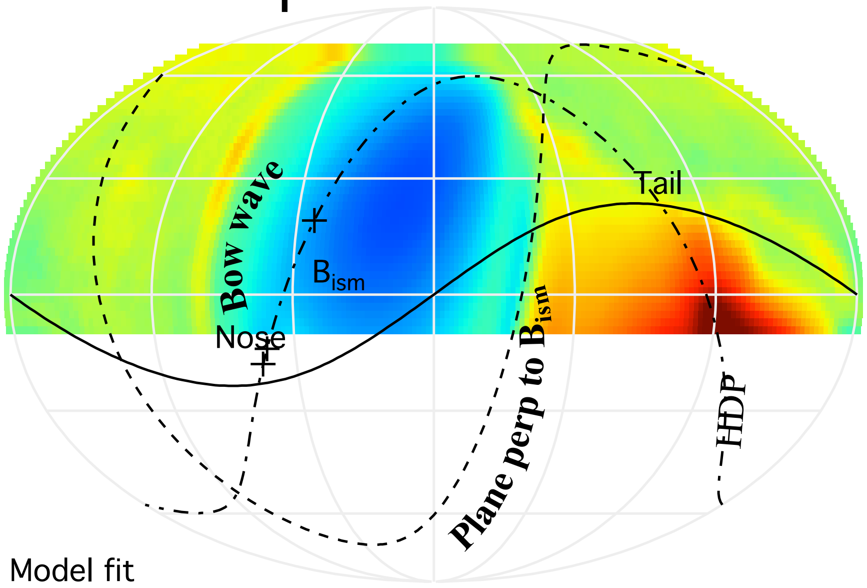


Residue

TeV CR anisotropy in relation to heliospheric structures

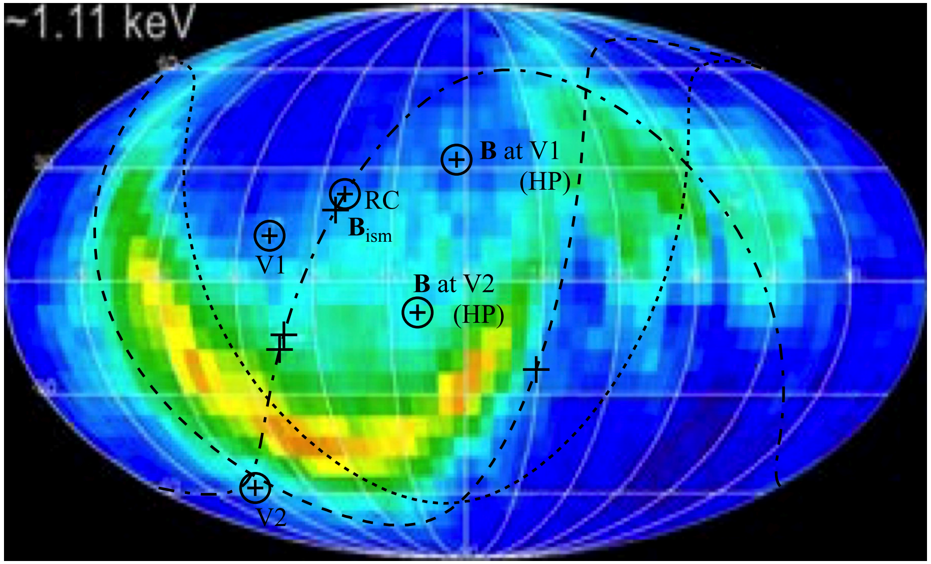


Tibet ASγ 4 TeV CR
Anisotropy measurement



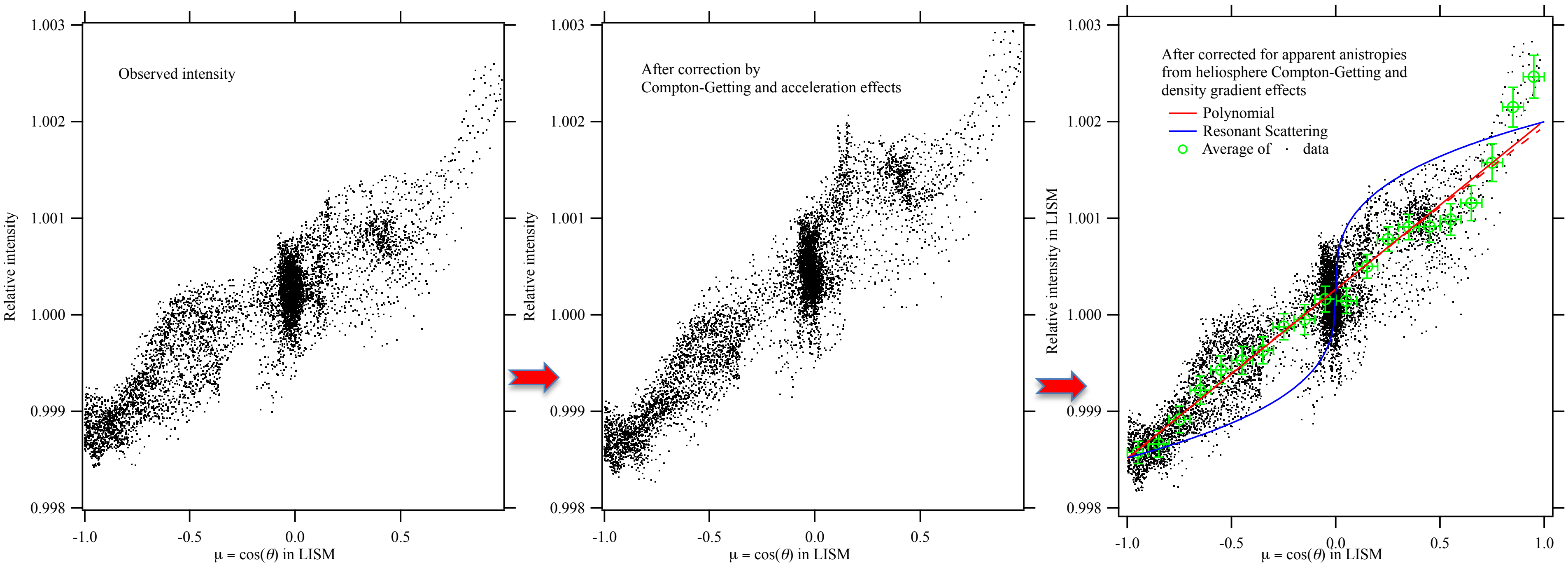
Model fit

IBEX ENA Emissions



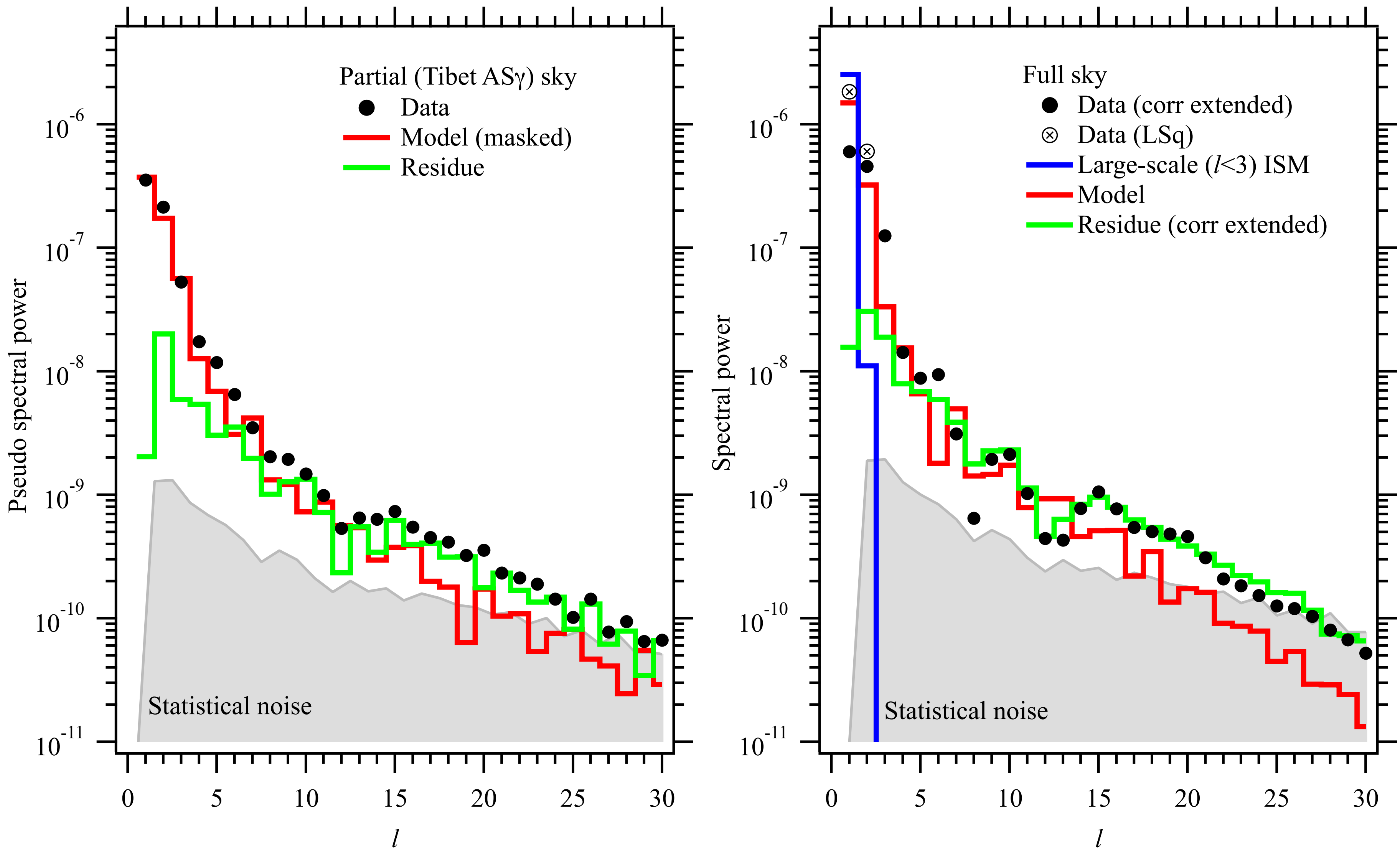
IBEX image from McComas et al.

4 TeV Cosmic ray pitch angle distribution in LSIM



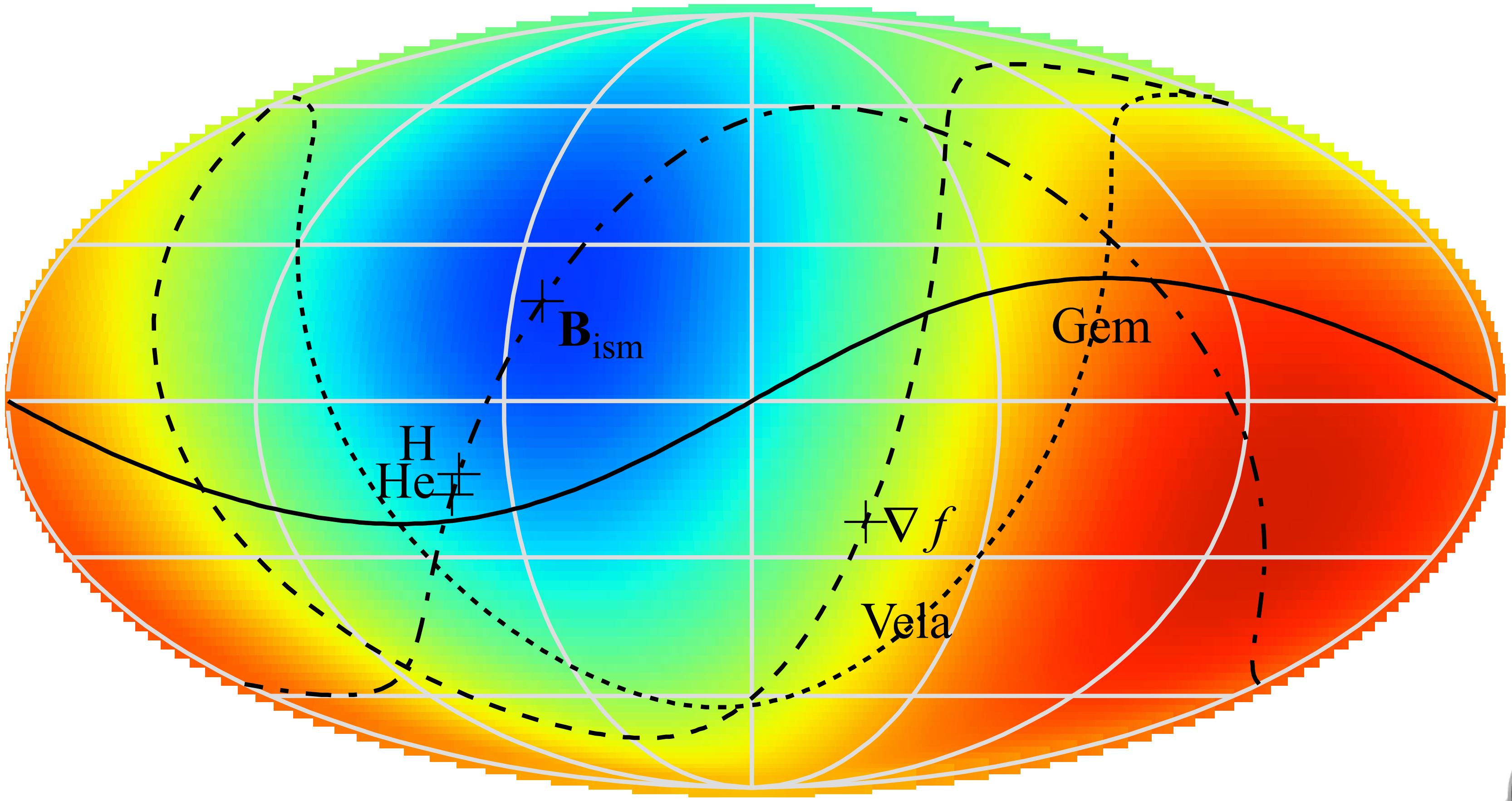
- Pitch-angle distribution is a pure dipole.
- It indicates that scattering of ISM turbulence is isotropic, or $D_{\mu\mu}$ is proportional to $(1-\mu^2)$
- Resonant scattering by Aflvenic turbulence with a Kolmogorov spectrum does not work

Angular power spectrum



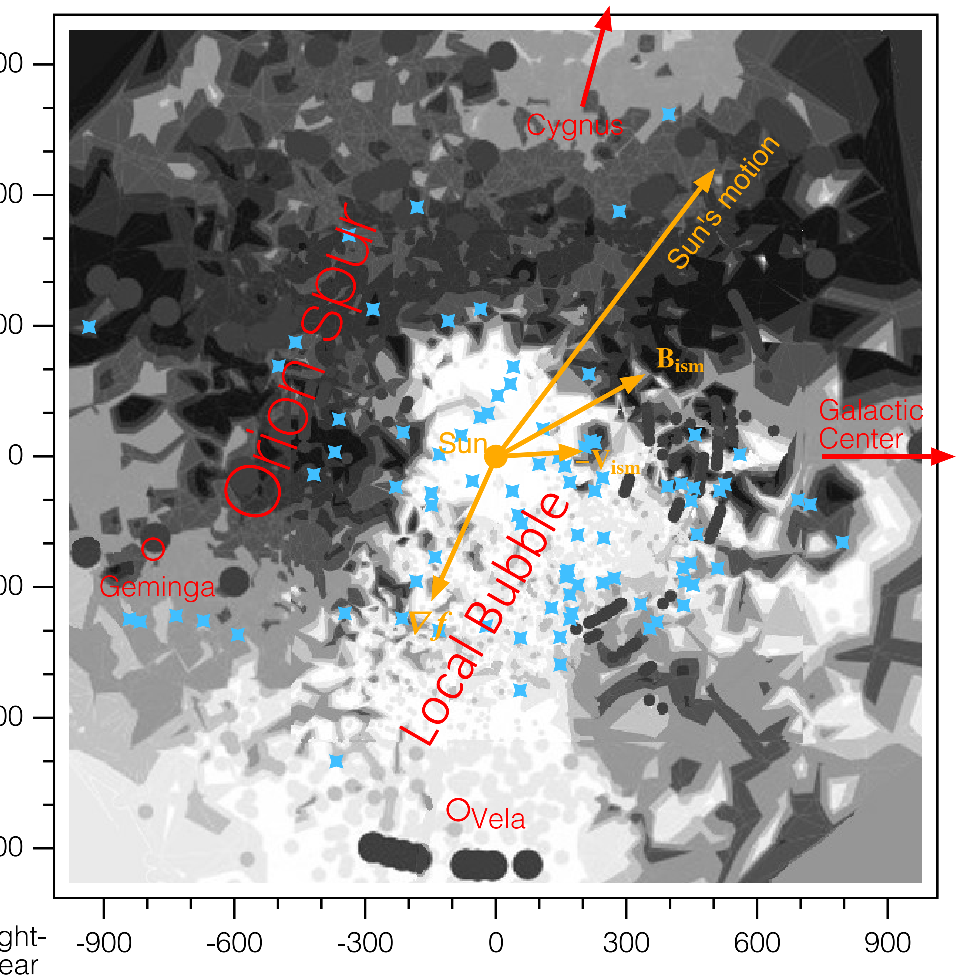
- 98% of spectral power is in the dipole
- Heliosphere generates the majority of medium-scale anisotropy between l=2, and l=13

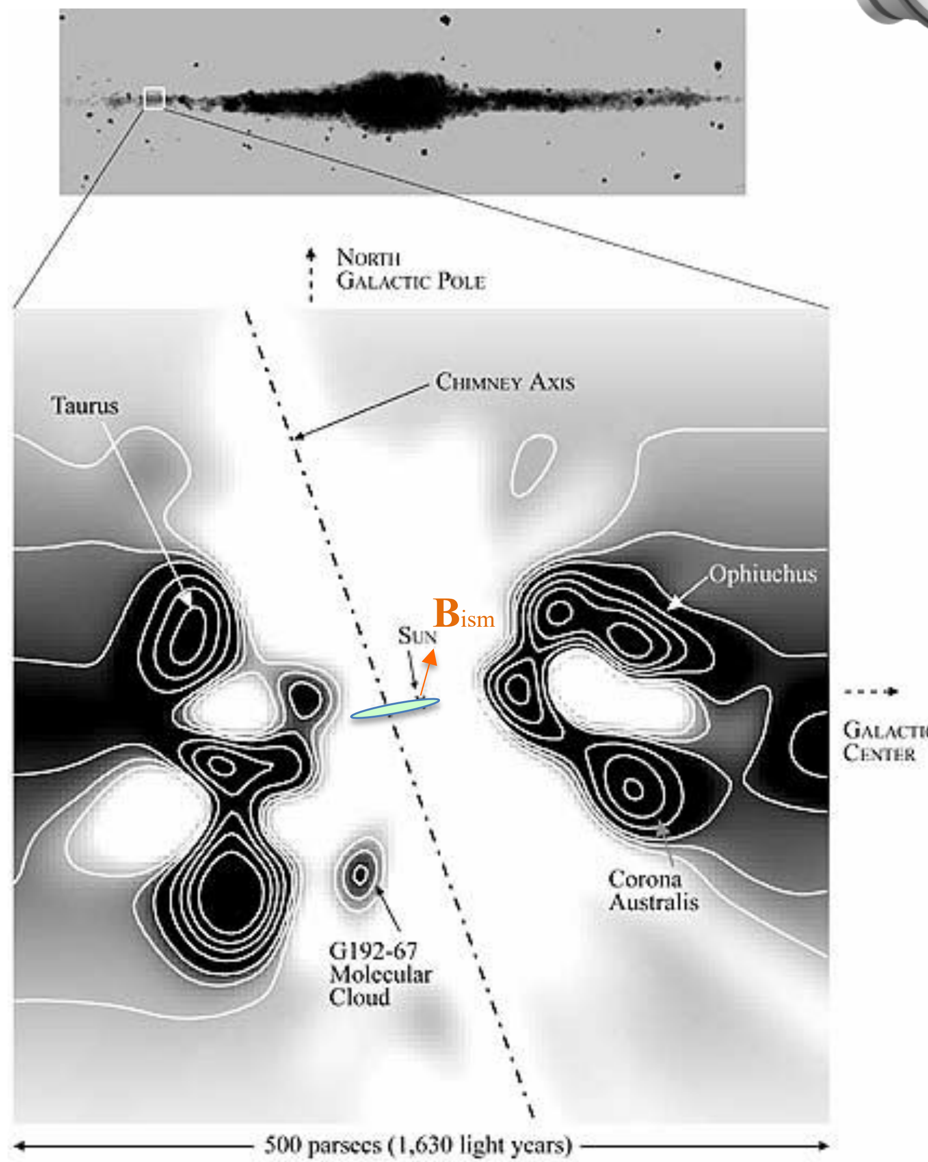
TeV CR anisotropy in LISM up to *l* = 2
(High orders are negligible)



Solar system neighbor environment in the Galactic plane

ISM based on Frisch (2017)





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TeV cosmic ray transport in LISM

Parameters of cosmic ray distribution inferred to anisotropy

$$A_{1\|} = 0.165 \pm 0.002\%; \;\; A_{2\|} = 0.015 \pm 0.002\%;$$

$$|\nabla_{\perp} \ln f| = 0.021 \pm 0.001\% / \mathrm{R_g}(254\mathrm{AU}) = 8.3 \times 10^{-7} /\mathrm{AU} = 0.017/\mathrm{pc}$$

Parallel to magnetic field

$$\frac{j_{\|}}{f} = \frac{\kappa_{\|}\partial f}{f\,\partial z} = 3A_{1\|}c = 4.95 \times 10^{-3} c \approx 1500 \text{ km/s}$$

$$\text{if } \kappa_{\|} = \kappa_{\|29} 10^{29} \text{ cm}^2/\text{s} \quad \text{then} \quad \nabla_{\|} \ln f = 2.23 \times 10^{-8} / \kappa_{\|29} \text{ AU}^{-1} = 4.51 \times 10^{-3} / \kappa_{\|29} \text{ pc}^{-1}$$

$$A_{1\|} >> A_{2\|} \quad \rightarrow \quad \text{Weak or no mirroring}$$

Perpendicular to magnetic field

$$|\nabla_{\perp} \ln f| = 8.2 \times 10^{-7} \text{ AU}^{-1} = 1.7 \times 10^{-1} \text{ pc}^{-1} >> \nabla_{\|} \ln f$$

$$\text{Since } \kappa_{\perp} << \frac{cR_g}{3}, \quad \frac{j_{\perp}}{f} = \kappa_{\perp} \nabla_{\perp} \ln f << 9.3 \times 10^{-5} c = 28 \text{ km/s}$$

TeV cosmic ray transport in LISM is dominated by parallel diffusion along magnetic field into northern Galactic Halo. The density gradient is mainly perpendicular to the magnetic field. This requires a very anisotropic diffusion.

Global source distribution Or recent local SN source?

- The density gradient cannot be supported by a global continuous source distribution:
  - Large density gradient of 0.17/pc perpendicular to the LIS magnetic field. It cannot persist over too large distance; otherwise, we will in diffuse γ-ray emission.
  - Halo height of H=221$\kappa_{||29}$ pc results in short cosmic ray lifetime of $\tau=H^2/(2\kappa)=7.3\text{x}10^4\ \kappa_{||29}$ years if it persist globally.
- Recent local source: Is it Vela, 250 pc away 11 kyr old?
  - Density gradient points approximately towards Vela in the Local Bubble.
  - Require highly anisotropic transport, because

$$j_{||} >> j_{\perp} \text{ and } \nabla_{||} f << \nabla_{\perp} f$$

Summary

- The CR anisotropy in the LISM is almost a pure pitch-angle dipole opposite the magnetic field. It indicates that cosmic ray transport is mainly through parallel diffusion into the northern Galactic halo.
- Pitch angle anisotropy of a few TeV cosmic rays have been determined. Particle pitch-angle scattering is isotropic.
- CR density gradient is perpendicular to the LISM magnetic field. It is large, indicating local SN source is making a special contribution. Its direction is consistent with a source in the local bubble, possibly Vela.
- The LISM magnetic field and hydrogen ionization ratio are now more tightly constrained.
- Large-scale magnetic field structures of the heliosphere are seen in TeV cosmic ray anisotropy. TeV cosmic ray anisotropy images contain features related to
    - Hydrogen deflection plane (HDP) in the heliotail
    - Plane perpendicular to B_{ism}
    - Bow wave
- Heliospheric magnetic field distort LISM dipole anisotropy to form many small features (l = 2-12) in the anisotropy images seen at Earth. A part of sky is completely smeared by chaotic CR trajectory.