Cosmic ray propagation in interstellar and interplanetary media

Ming Zhang
Department of Physics and Space Sciences
Florida Institute of Technology
Melbourne, Florida, 32901, USA

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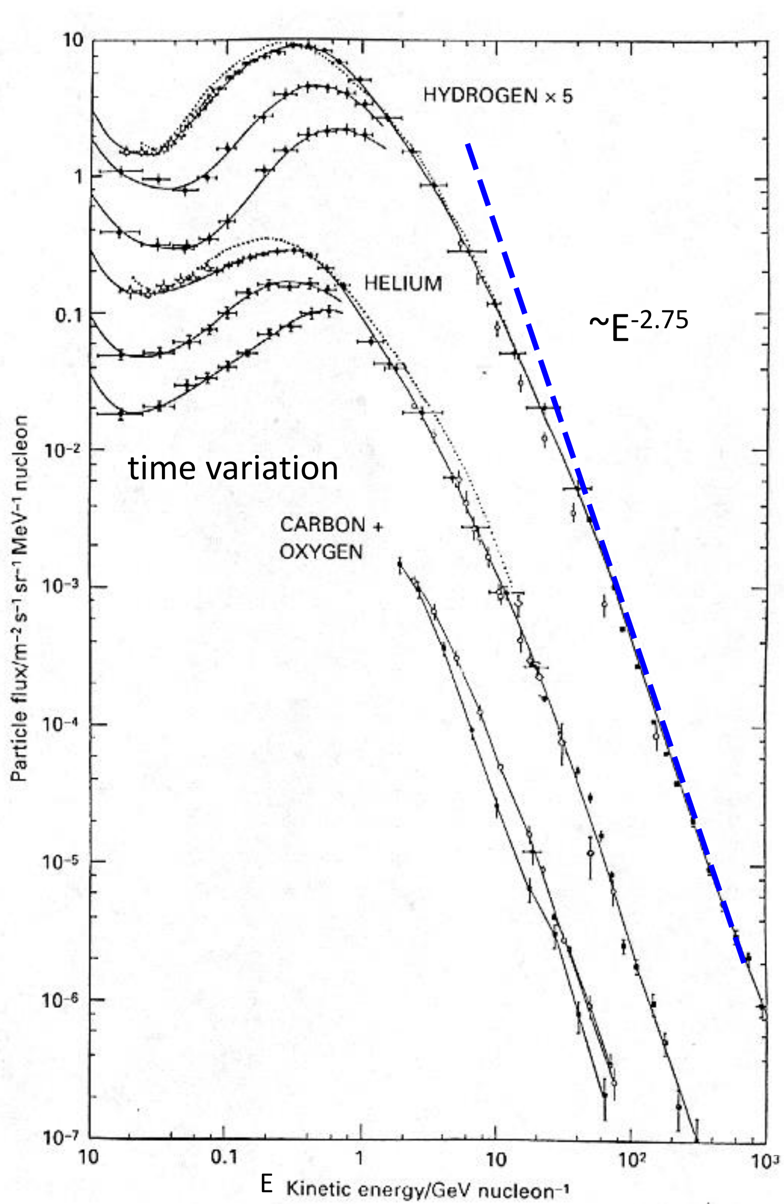
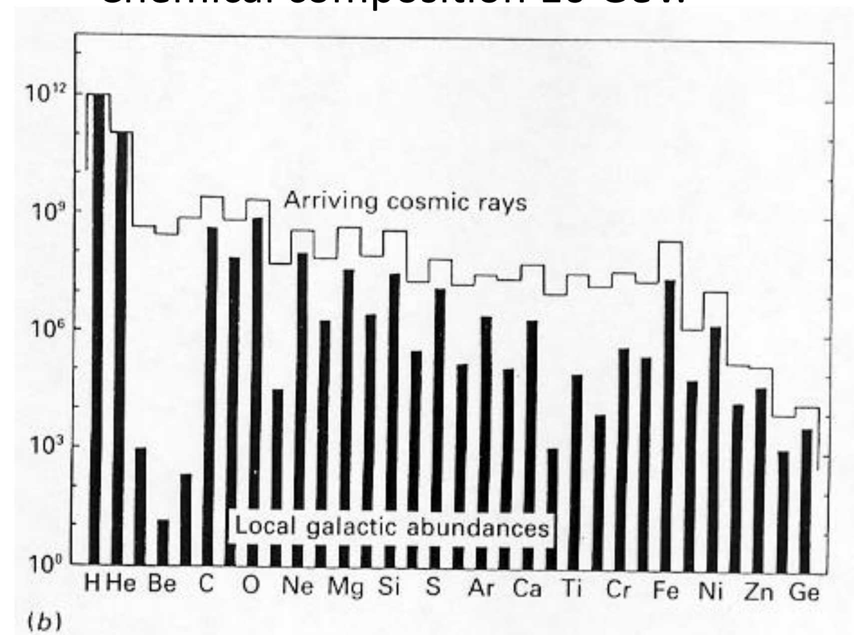
Transport effects in cosmic ray measurements

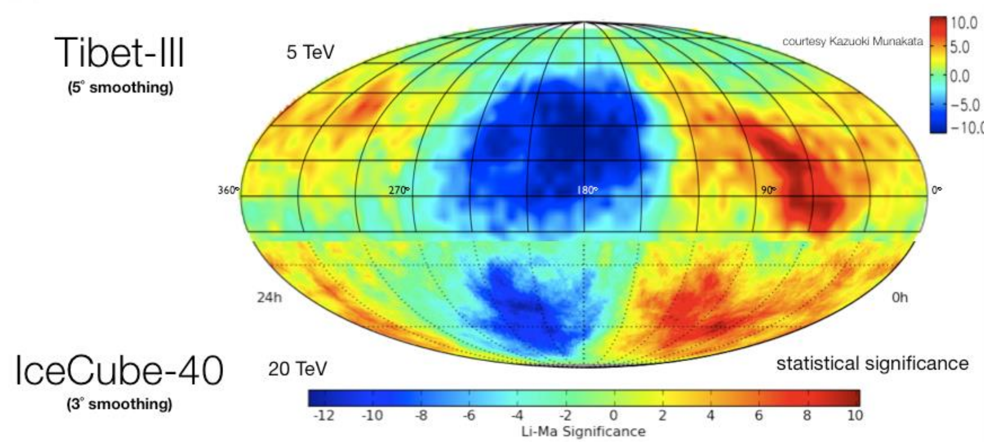
Energy spectrum



Chemical composition 10 GeV.



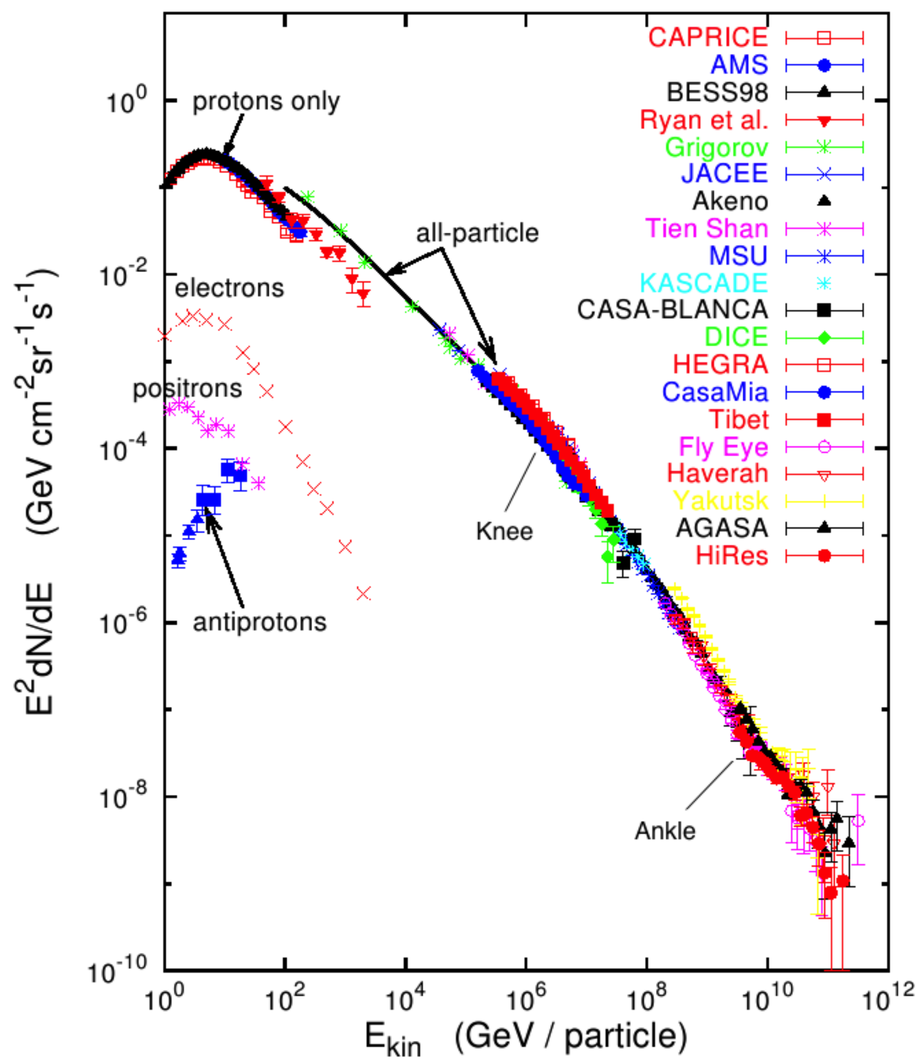
Anisotropy



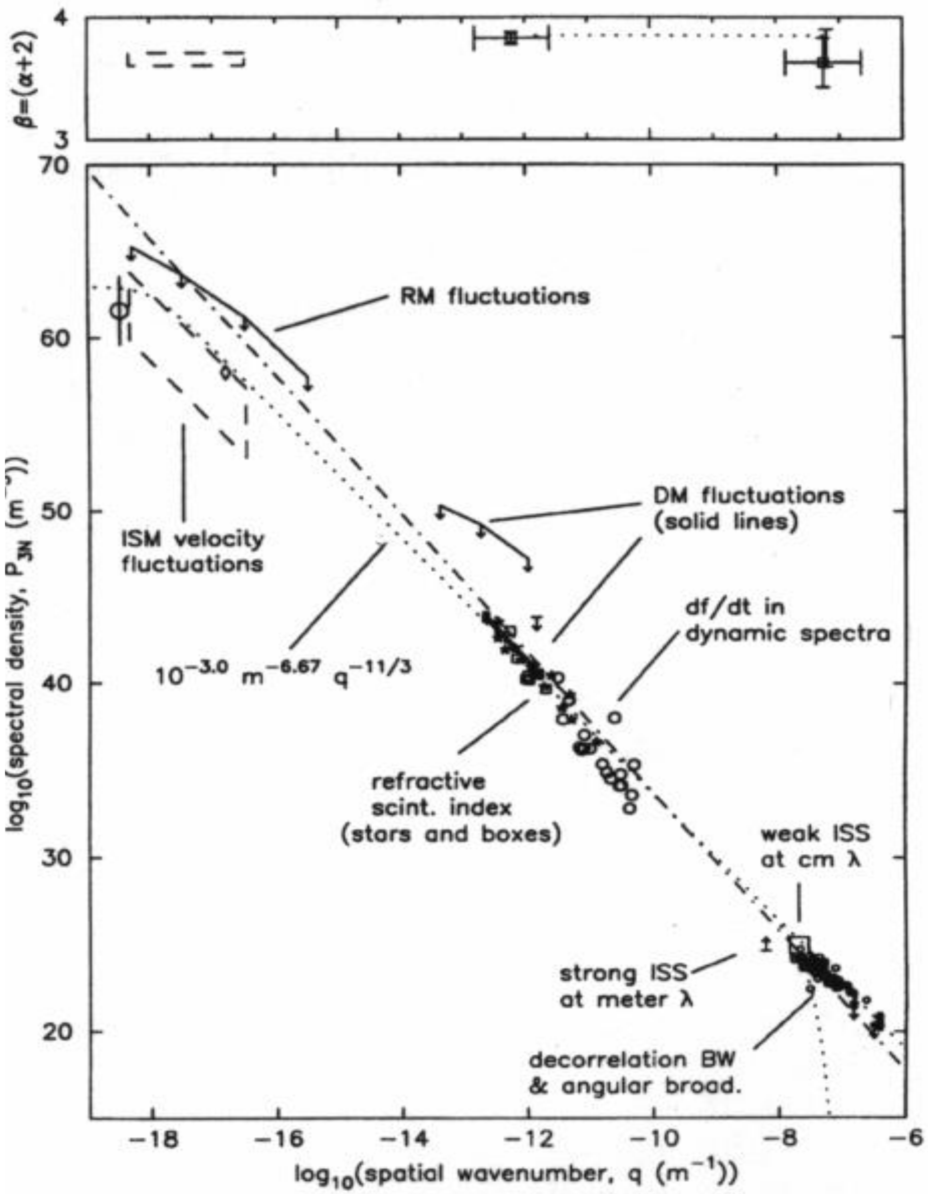
Cosmic ray transport in magnetic field turbulence

Cosmic ray spectrum and interstellar fluctuation spectrum

Energies and rates of the cosmic-ray particles



ISM fluctuations



From Armstrong and Spangler (1995)

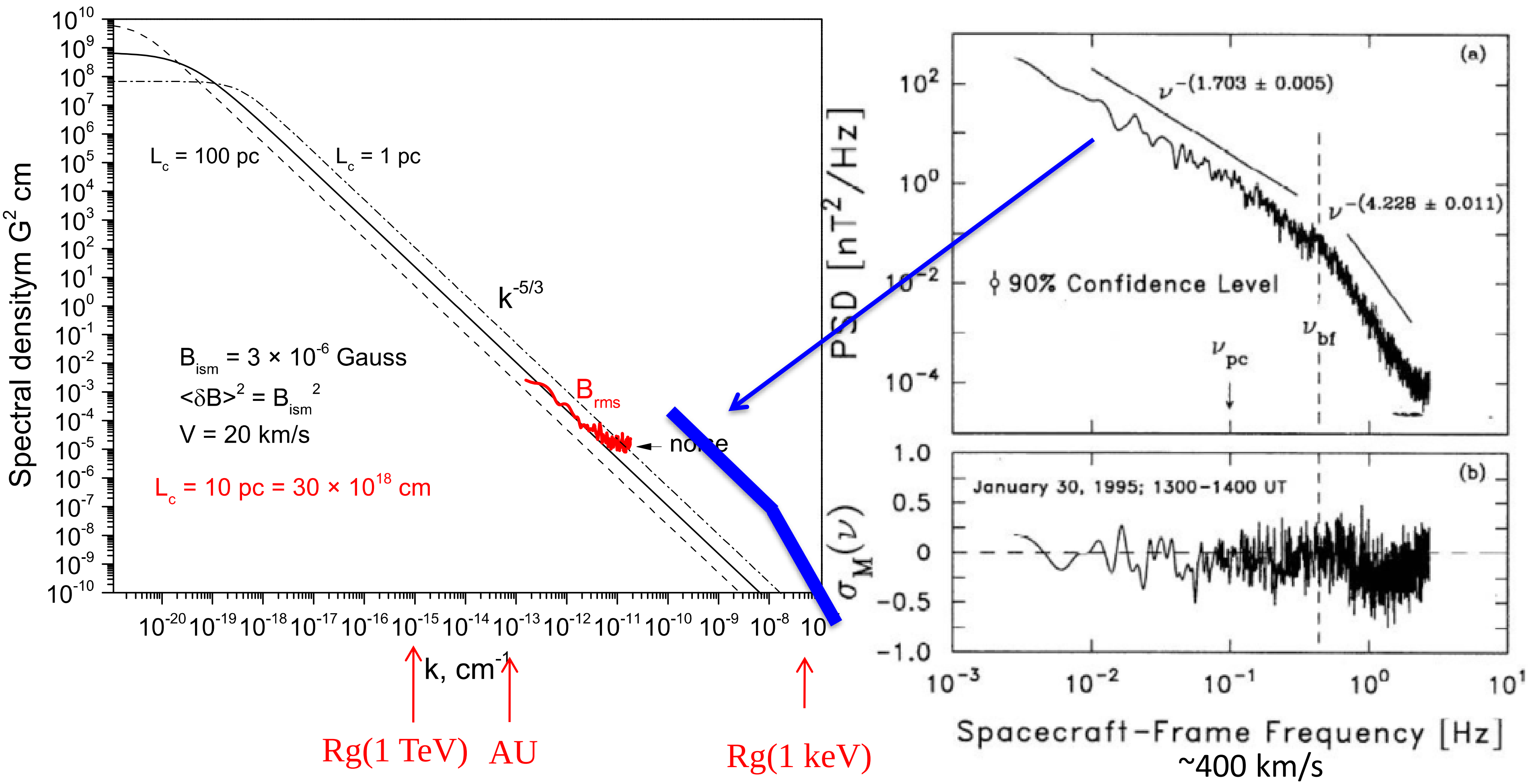
Interstellar and interplanetary magnetic turbulence

Kolmogorov spectrum

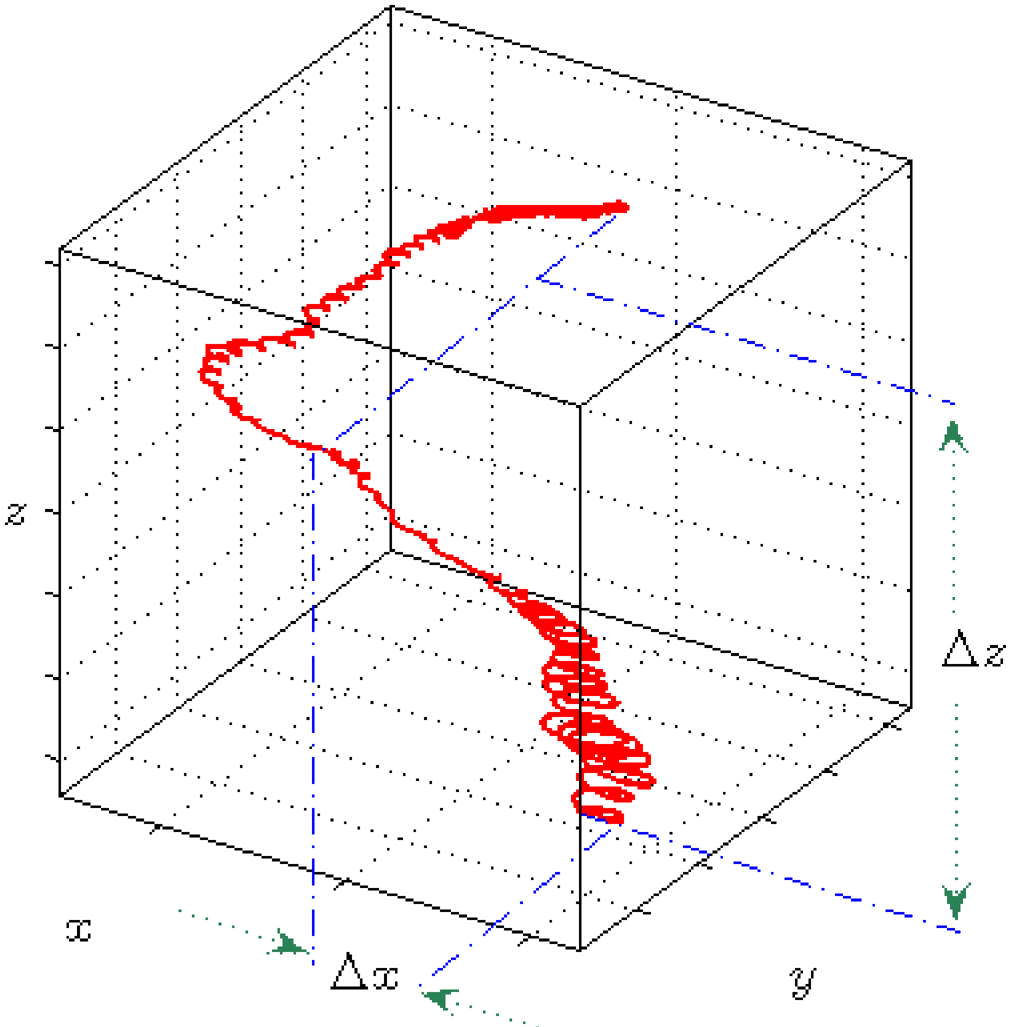
$$< dB^2(k) > \mu\ k^{-5/3}$$

Turbulence on the scale of particle gyroradius should be weak.

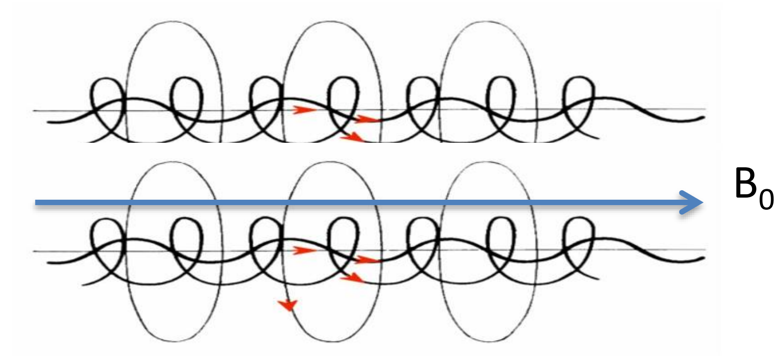
From Burlaga et al. (2015)



Diffusive transport of charged particles in Kolmogorov turbulence

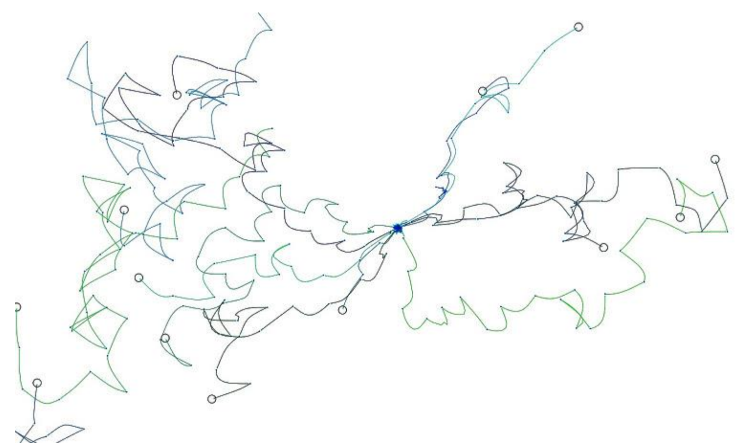


Orderness on small scale



small diffusion $k_{\wedge} / k_{\parallel}$ ratio

Random walk (diffusion) on large scale



large diffusion $k_{\wedge} / k_{\parallel} \sim 1$ ratio

Galactic propagation through interstellar medium

Effects of Galactic propagation

Once released from supernova remnants (after the shock and its magnetic fields weaken), cosmic rays spend tens million years propagating through interstellar medium.

- Propagation is most likely to diffusion ($\kappa \sim 10^{28}(p/\mathrm{GeV})^{0.3}$ cm^2/s) due to a random magnetic field component in the interstellar medium.
- Convection in Galactic wind (~30 km/s).
- Cosmic rays traverse through a significant amount of material (order of 10 g/cm^2) .
  - Energy loss (ionization plus adiabatic cooling)
  - Nuclear reactions are expected to occur. Composition of primary cosmic rays evolves. Production of secondary and tertiary cosmic rays.
  - Electromagnetic radiations, gamma ray, x-ray emissions and radio waves: pion decay from hardronic cosmic rays, inverse-Compton from electrons, synchrotron radiations.
- Escape from the Galaxy through halo boundary (a few kpc).
- Reacceleration during propagation (by Alfven wave V_A=30 km/).

Galprop by Strong and Moskalenko (since 1998), Picard by Kissmann (2014)

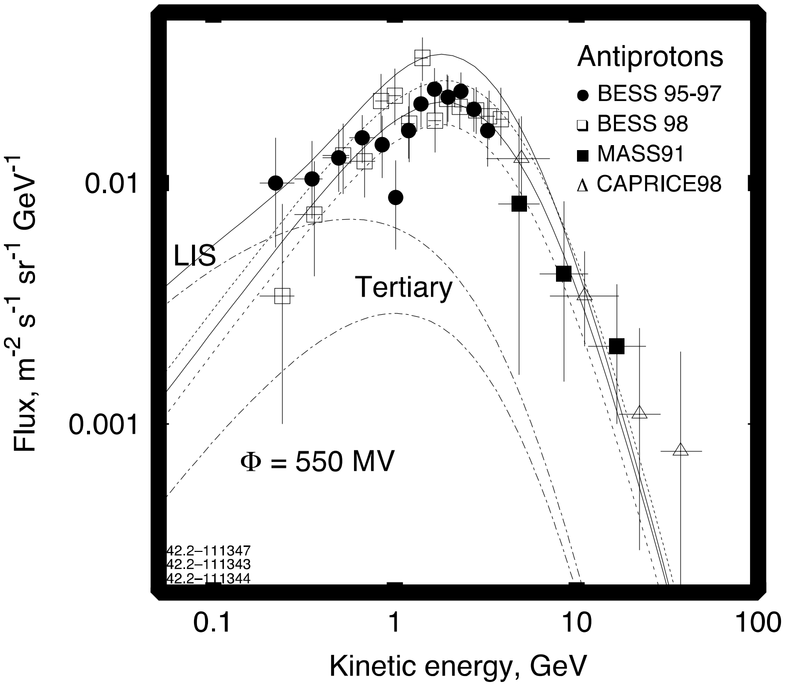
$$\frac{\partial N_i}{\partial t} = \nabla \cdot (\boldsymbol{\kappa}_i \cdot \nabla N_i - \mathbf{V} N_i) + \frac{\partial}{\partial p}[D_i p^2 \frac{\partial}{\partial p}(\frac{N_i}{p^2})] + \frac{\partial}{\partial p}[(\frac{p}{3}\nabla \cdot \mathbf{V} + b_i) N_i]$$

$$- (n v \sigma_i + \frac{1}{\tau_i}) N_i + \sum_{j<i} (n v \sigma_{ij} + \frac{1}{\tau_{ij}}) N_j + S_i$$

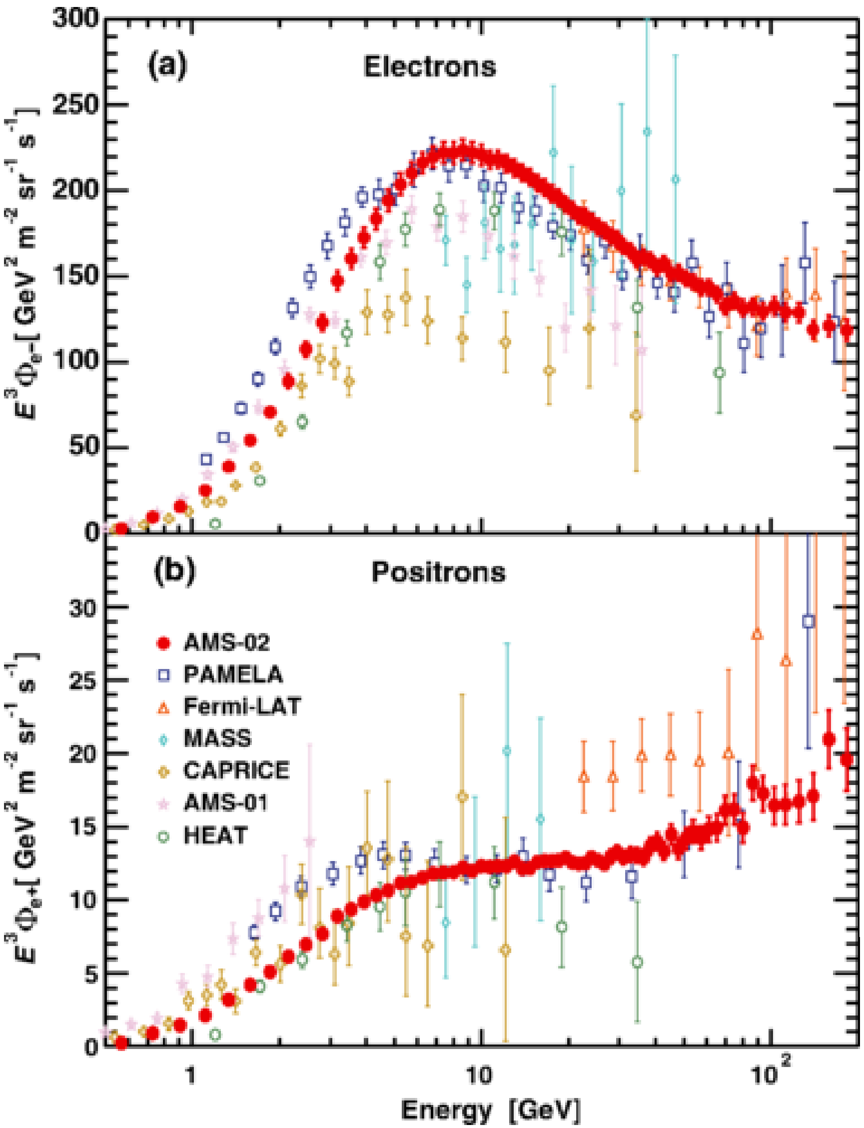
(Array interlinked through nuclear reactions and decays)

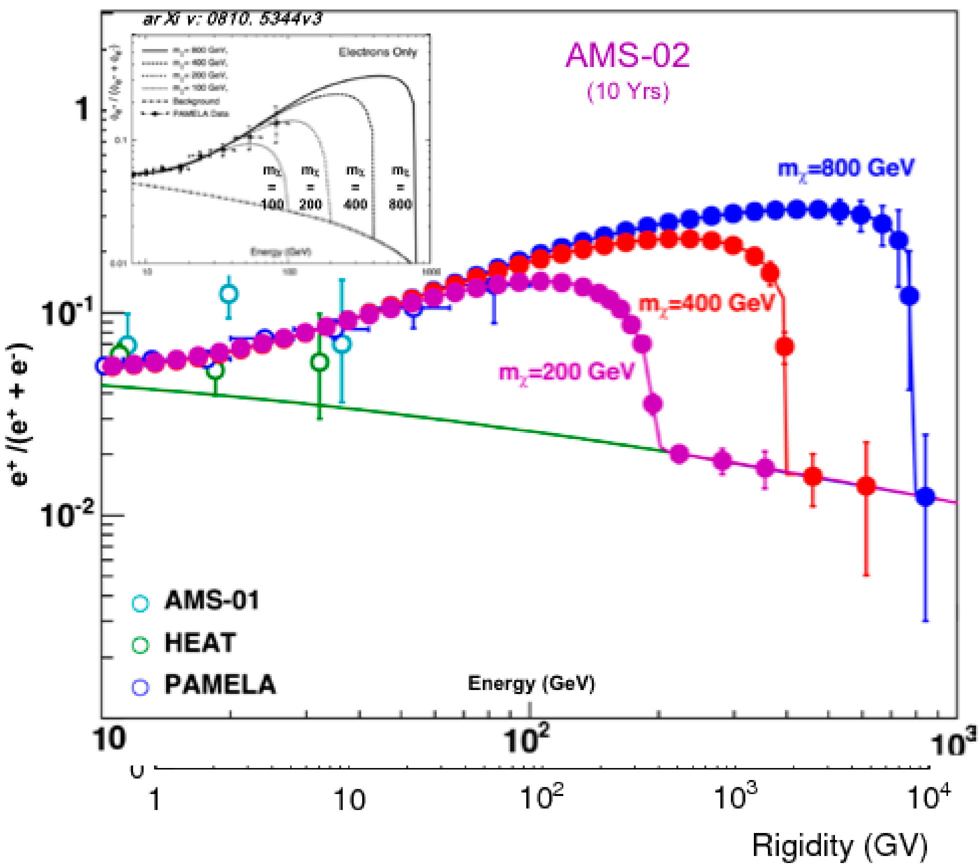
Results from Galactic propagation

- Steepening of energy spectrum due to energy-dependent (diffusive) escape.
- Exponential path-length distribution.
- Stable secondary to “primary” ratio: e.g., B/C, sub-Fe/Fe
- Abundance of radioactive isotope: 14C, 10Be, 26Al, 36Cl, et al. Use these clocks to determine cosmic ray residence time ~ 10 Myr.
- K-capture isotopes, e.g., 59Ni, 57Co, yield information about time of acceleration in interstellar medium.
- Anisotropy of (TeV) cosmic rays put upper limit on cosmic ray diffusion and also put constraints on the slope of cosmic ray source spectrum.
- Diffusive gamma ray emission constrain cosmic ray source spectrum and spatial distribution.
- Antiproton and positron abundance is (at least partly) contributed by secondary cosmic rays.

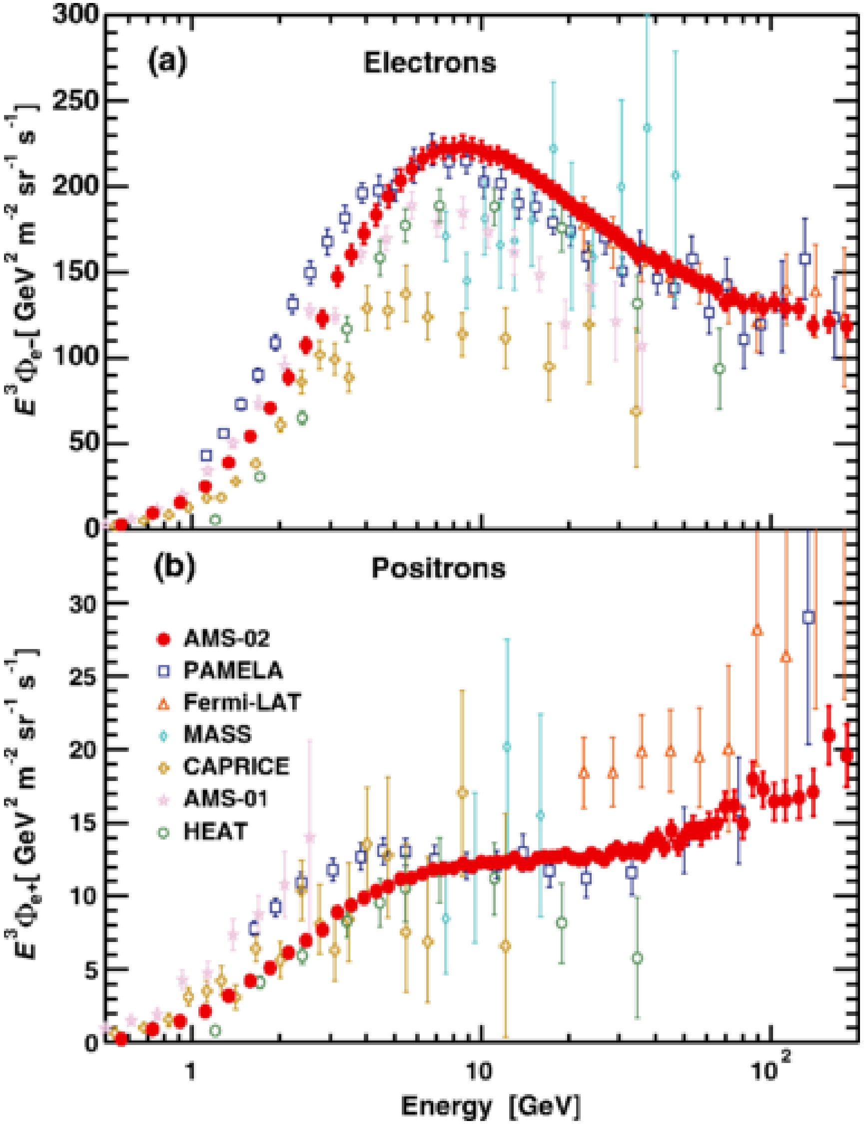


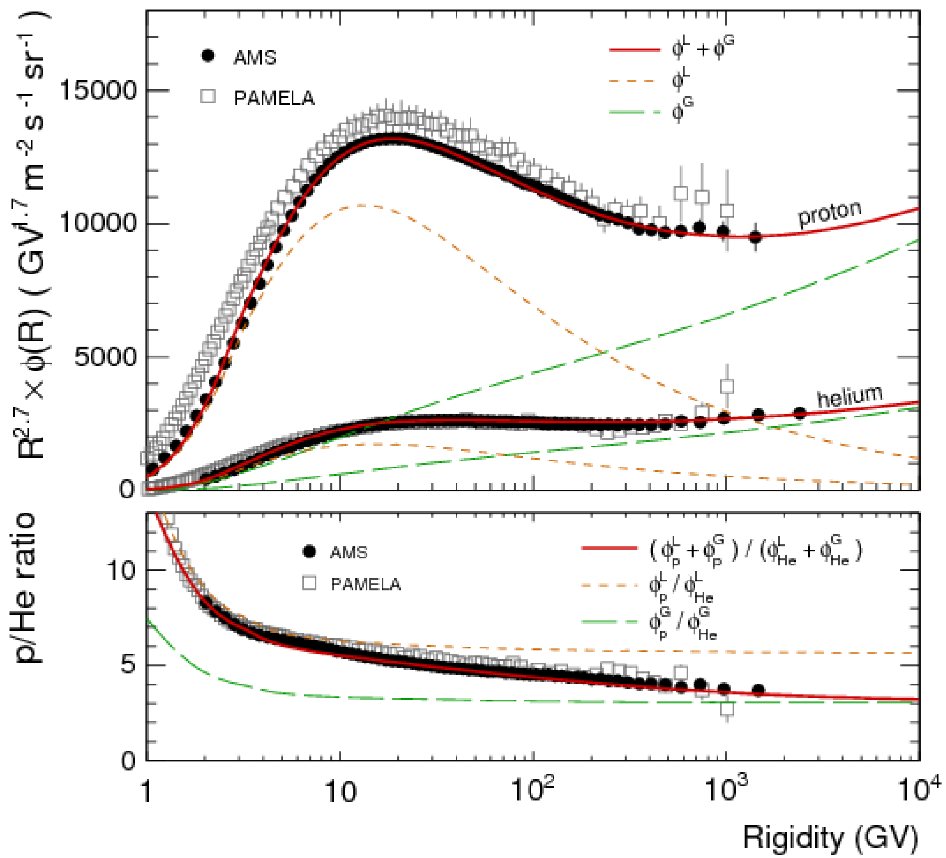
Positron abundance



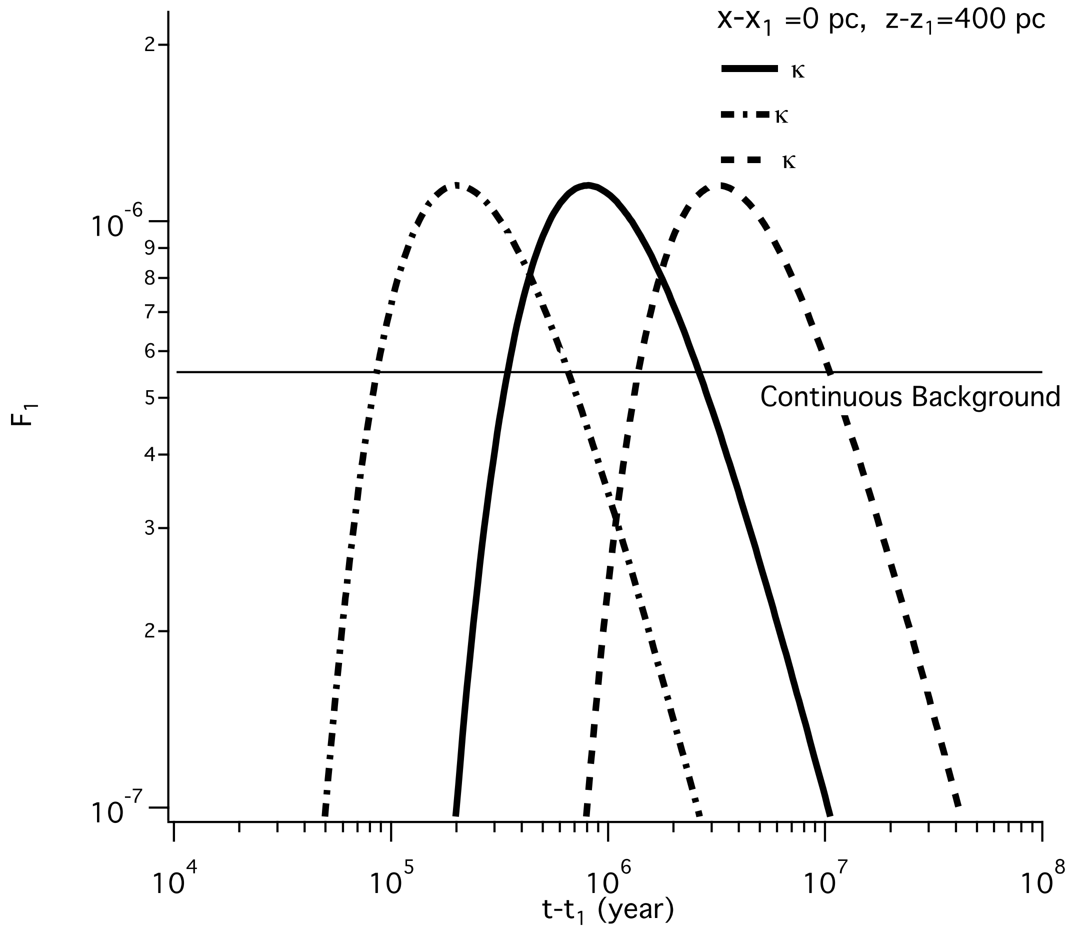


Similarity to He to p ratio



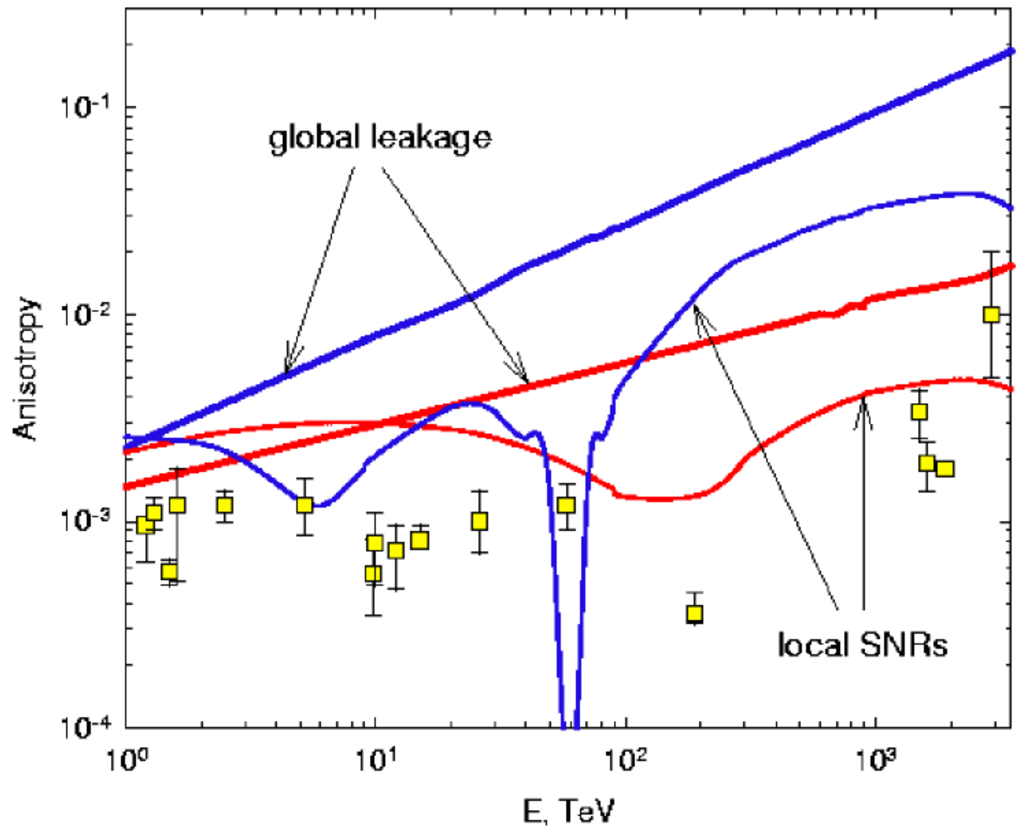


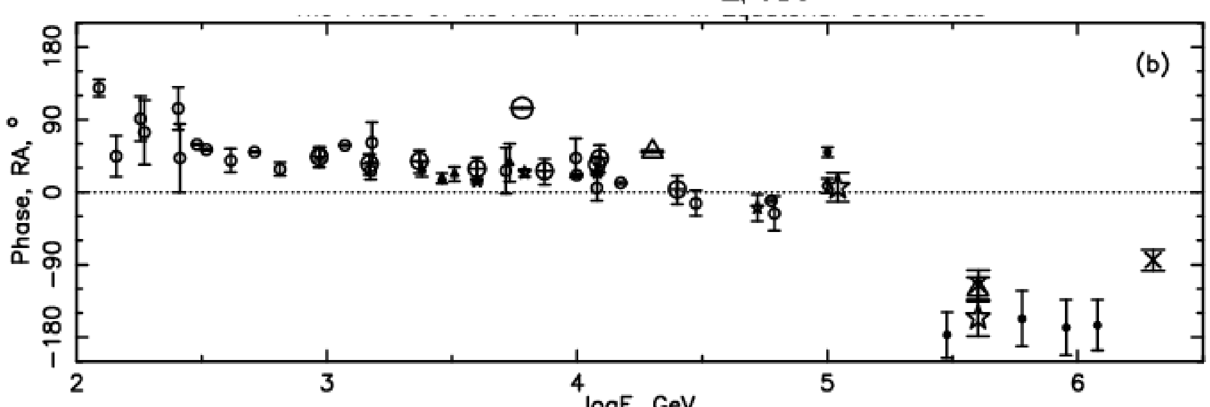
Significant contribution from a few single sources



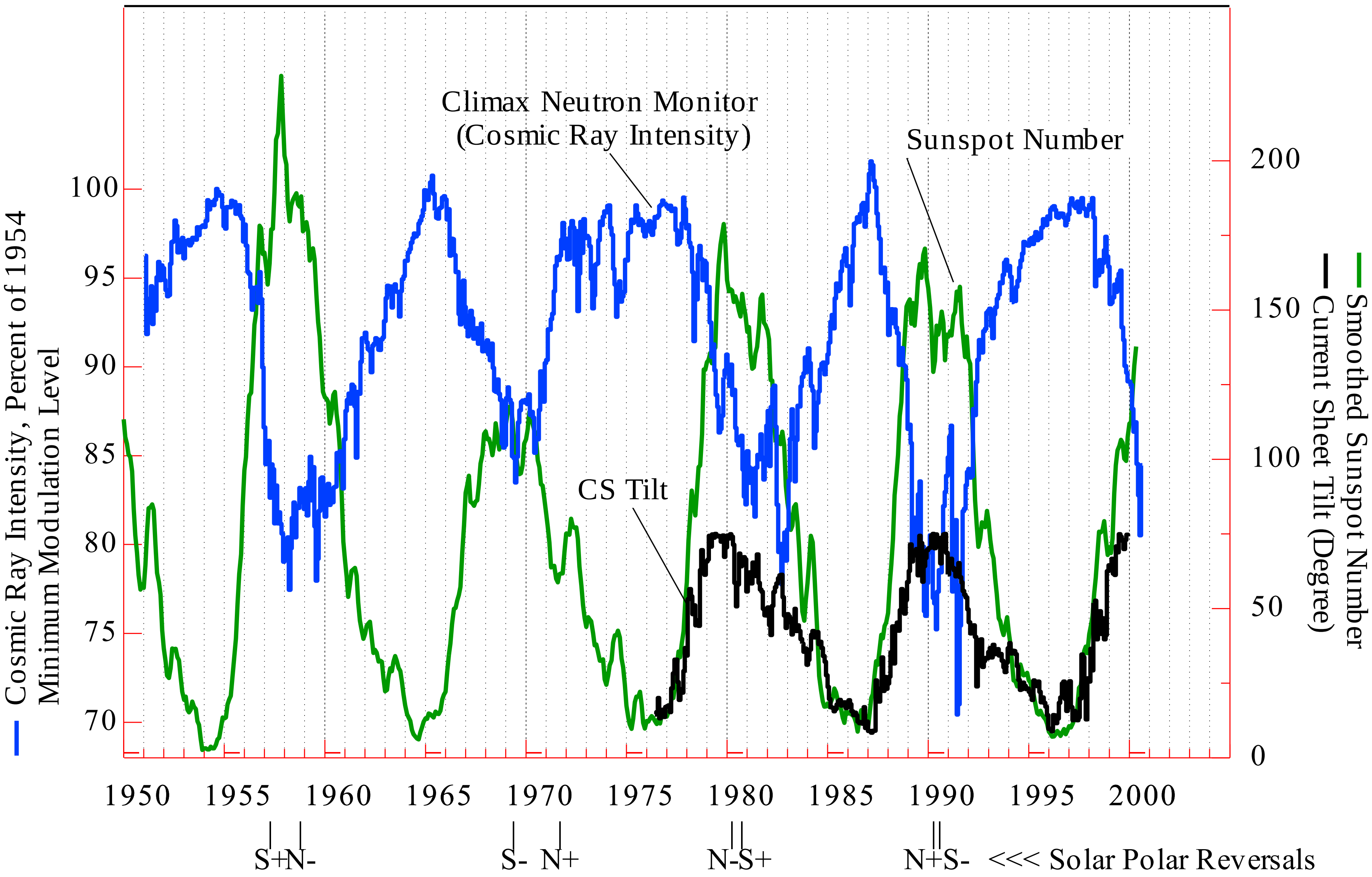
If single source contribute significantly and cosmic ray diffusion is energy dependent, we expect it contributes only to a limited range of energy at a given time.

Evidence for local source contribution in cosmic ray anisotropy



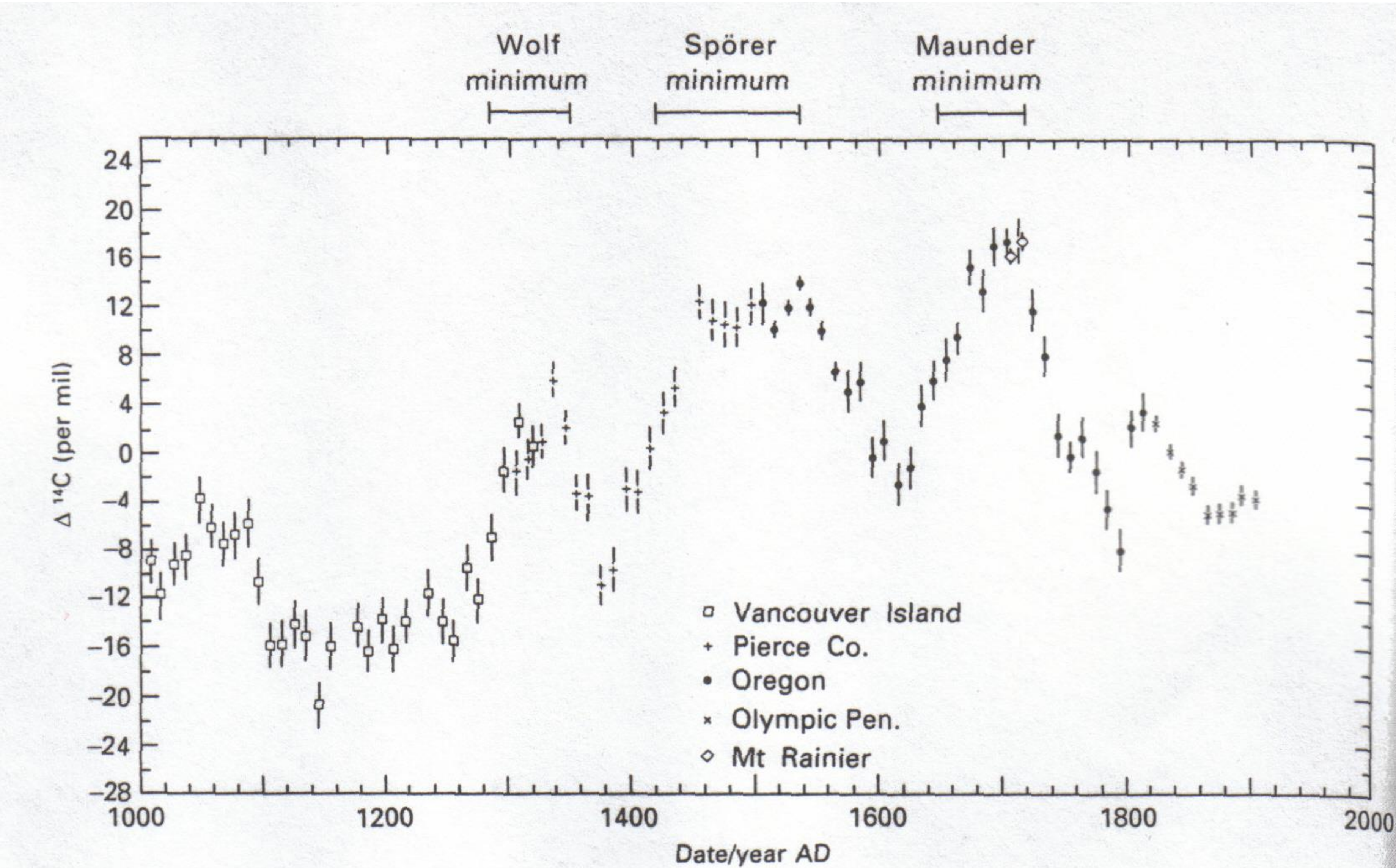


Heliospheric propagation through interplanetary medium

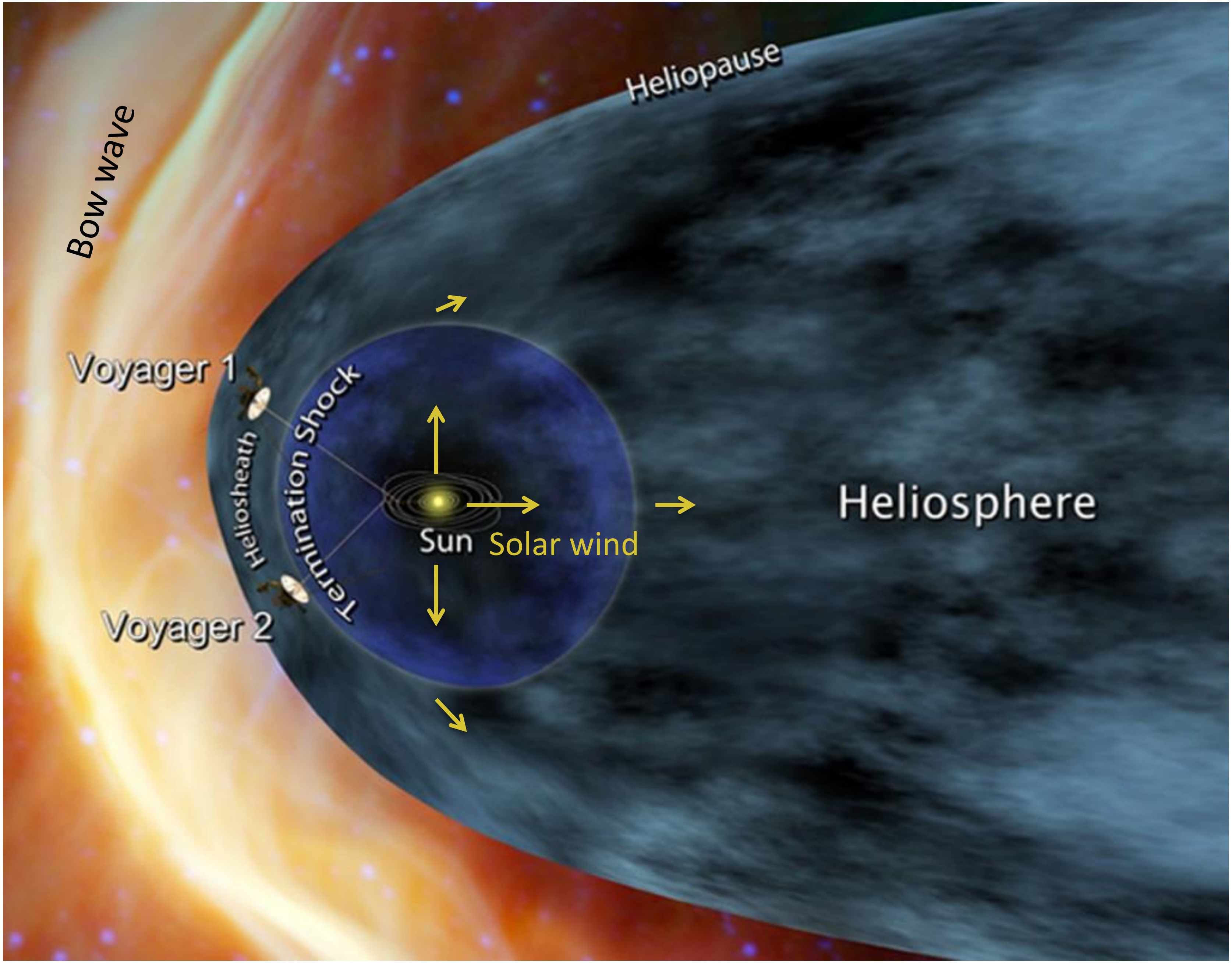


Climax Neutron Monitor
(Cosmic Ray Intensity)
Sunspot Number
CS Tilt
Cosmic Ray Intensity, Percent of 1954
Minimum Modulation Level
Smoothed Sunspot Number
Current Sheet Tilt (Degree)
100
95
90
85
80
75
70
200
150
100
50
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
S+N-
S- N+
N-S+
N+S-
<<< Solar Polar Reversals

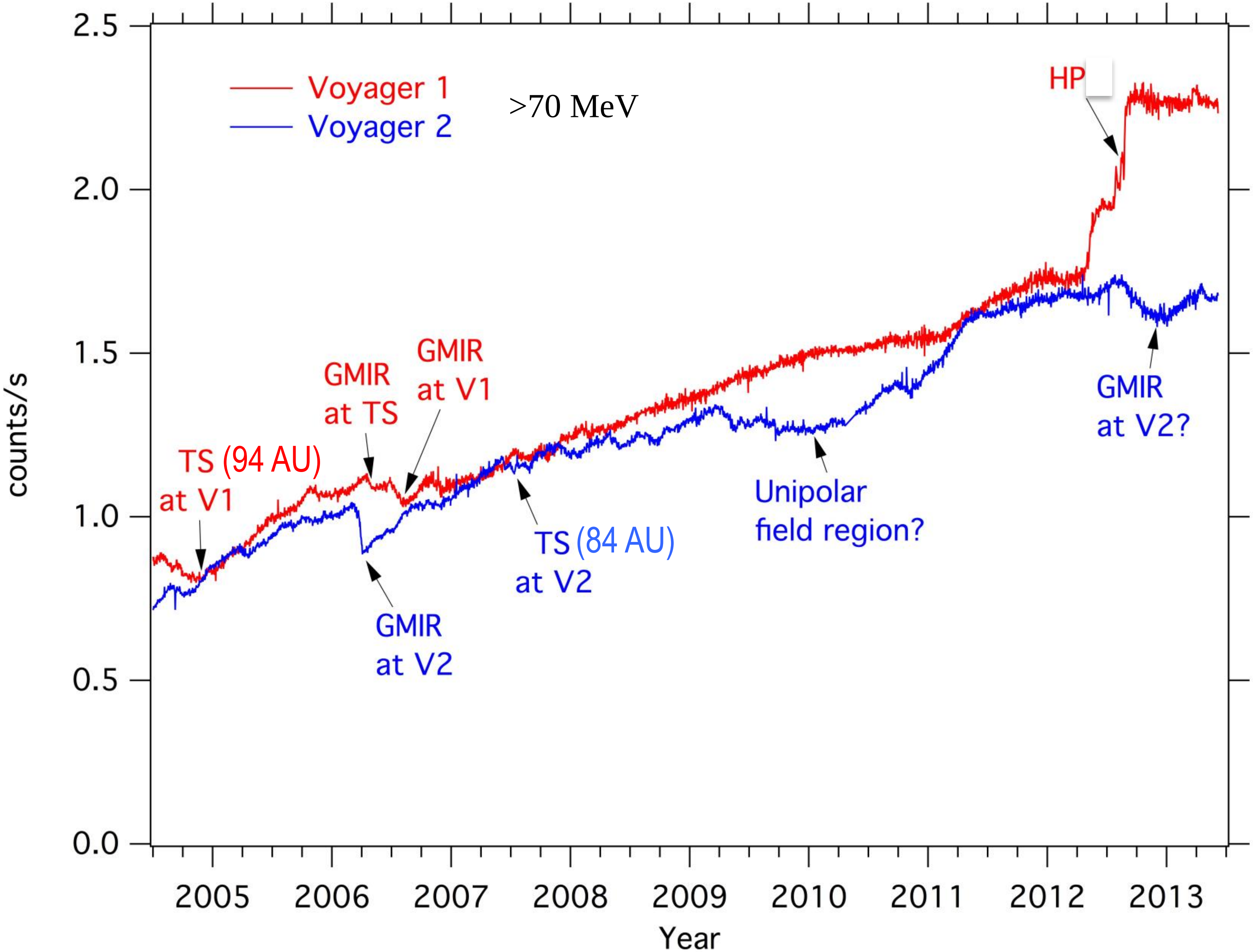
^{14}C in the Atmosphere $\quad {}^{14}N + n \rightarrow {}^{14}C + {}^{1}H$



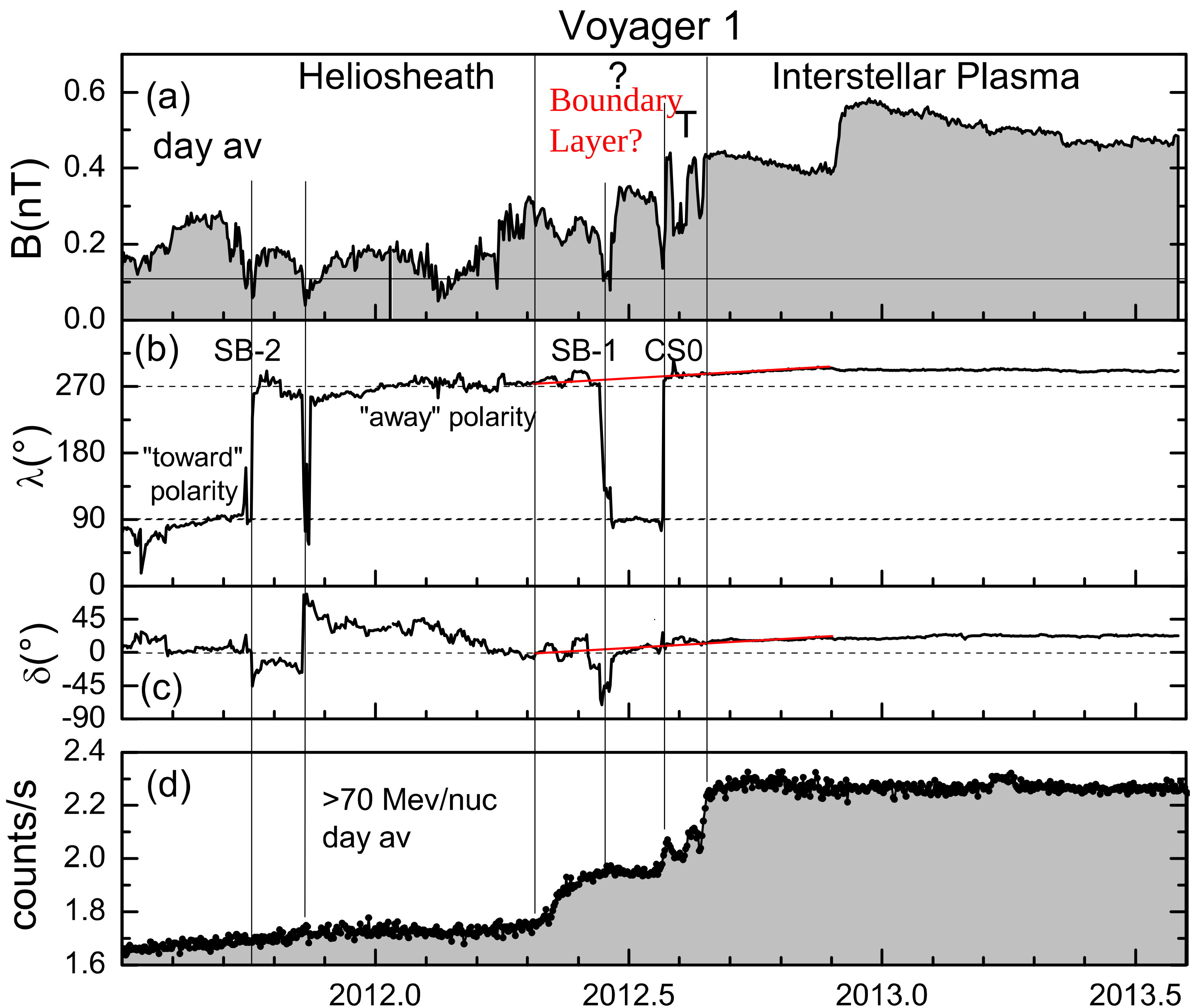
Voyager 1 & 2 in Heliosheath



Cosmic-ray Modulation Boundary

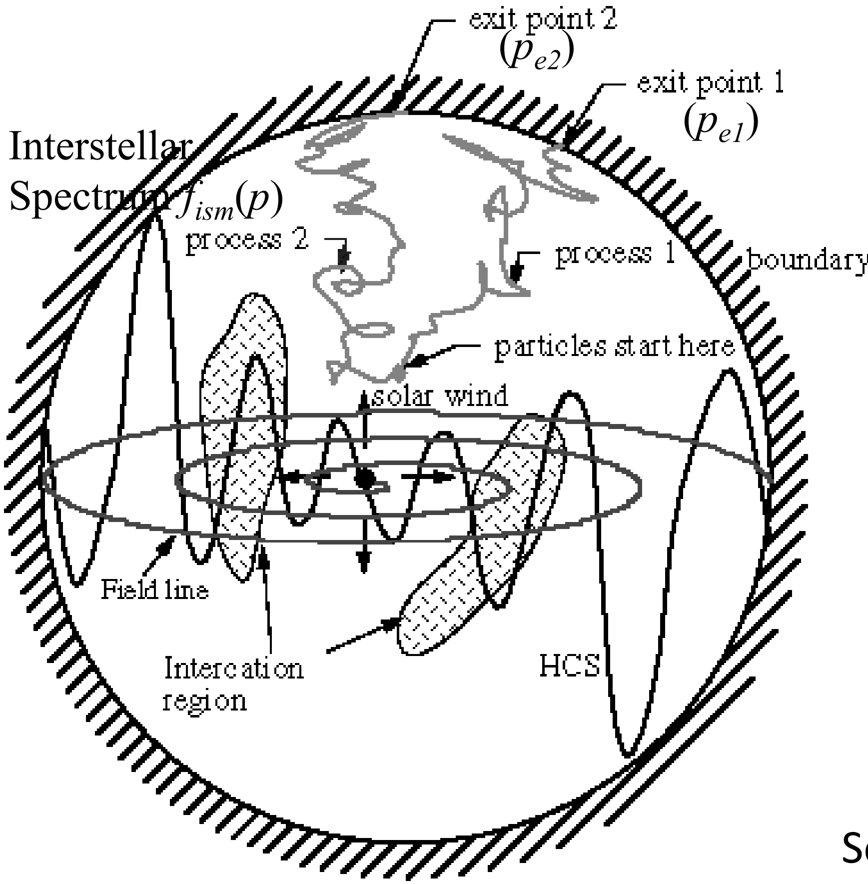


Magnetic field and cosmic ray at the heliopause (from Burlaga and Ness, 2014)



Cosmic ray step increase at HP

Stochastic method to Parker cosmic ray transport equation low-energy cosmic rays



$$\frac{\partial f(x,p,t)}{\partial t} = \nabla\cdot(k\nabla f) \quad \leftarrow \text{Diffusion}$$

$$- V_{sw}\cdot\nabla f \quad \leftarrow \text{Convection}$$

$$- V_d\cdot\nabla f \quad \leftarrow \text{Drift}$$

$$+\frac{1}{3}(\nabla\cdot V_{sw})p\frac{\partial}{\partial p}f \quad \neg \text{ Adiabatic energy change}$$

with $f = f_{ism}(p)$ at outer boundary

and $f = 0$ at inner boundary

Backward stochastic trajectories of particles

$$d\mathbf{x}(s) = \sum_{i=1}^{3} s_i dw_i(s) + (\nabla k - \mathbf{V} - \mathbf{V}_d)ds$$

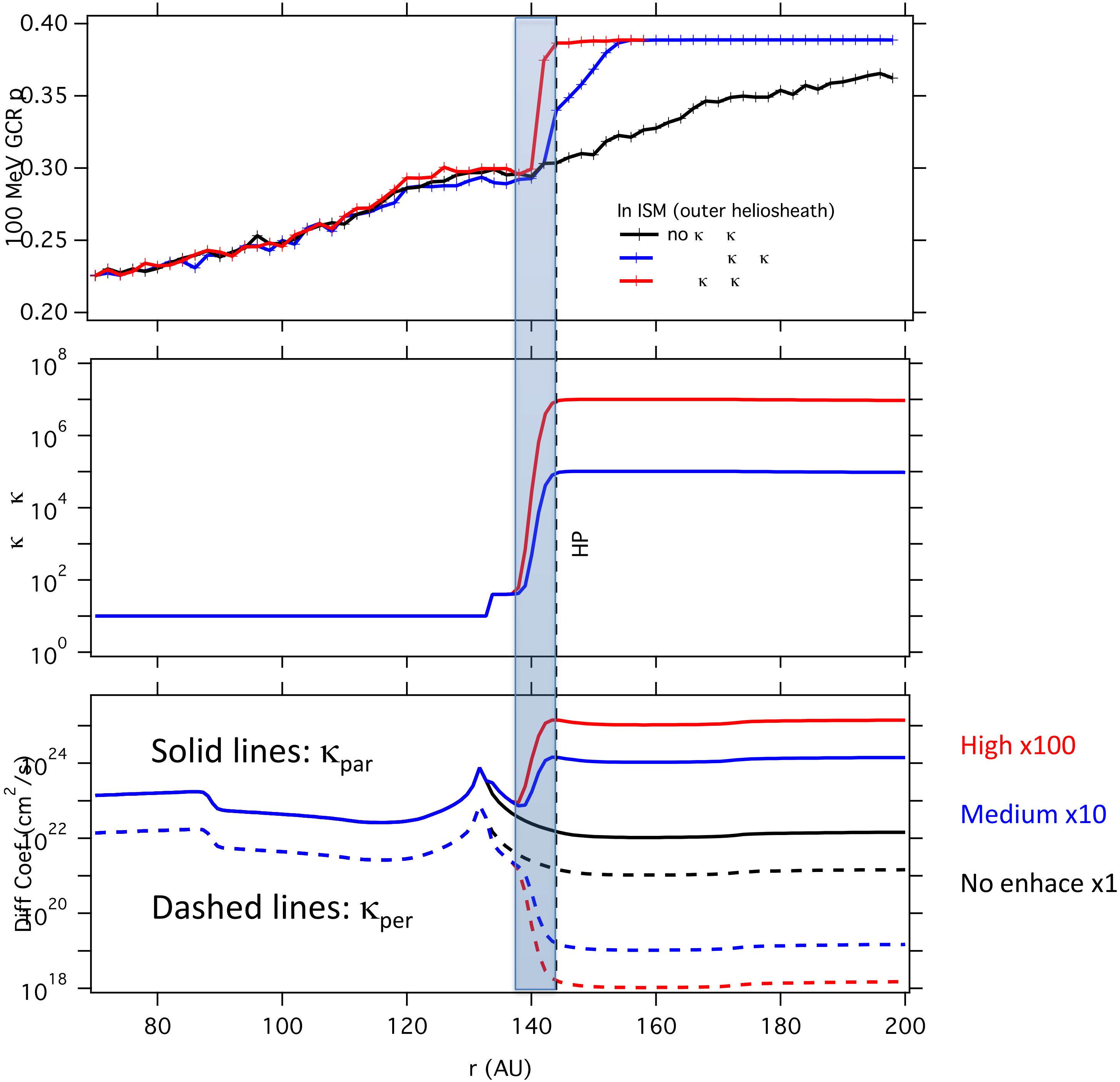
$$dp(s) = \frac{1}{3}(\nabla\cdot V)pds$$

All trajectories start at observer ($\mathbf{x}, p, t$)

Solution of modulated spectrum:

$$f(x,p,t) = \langle f_b\rangle \text{ » } \langle f_{ism}(p_{exit})\rangle$$

Model input: MHD model of plasma velocity and magnetic field, energy- and location-dependent diffusion coefficient $k \mu bp^{0.5}B^{-1}$



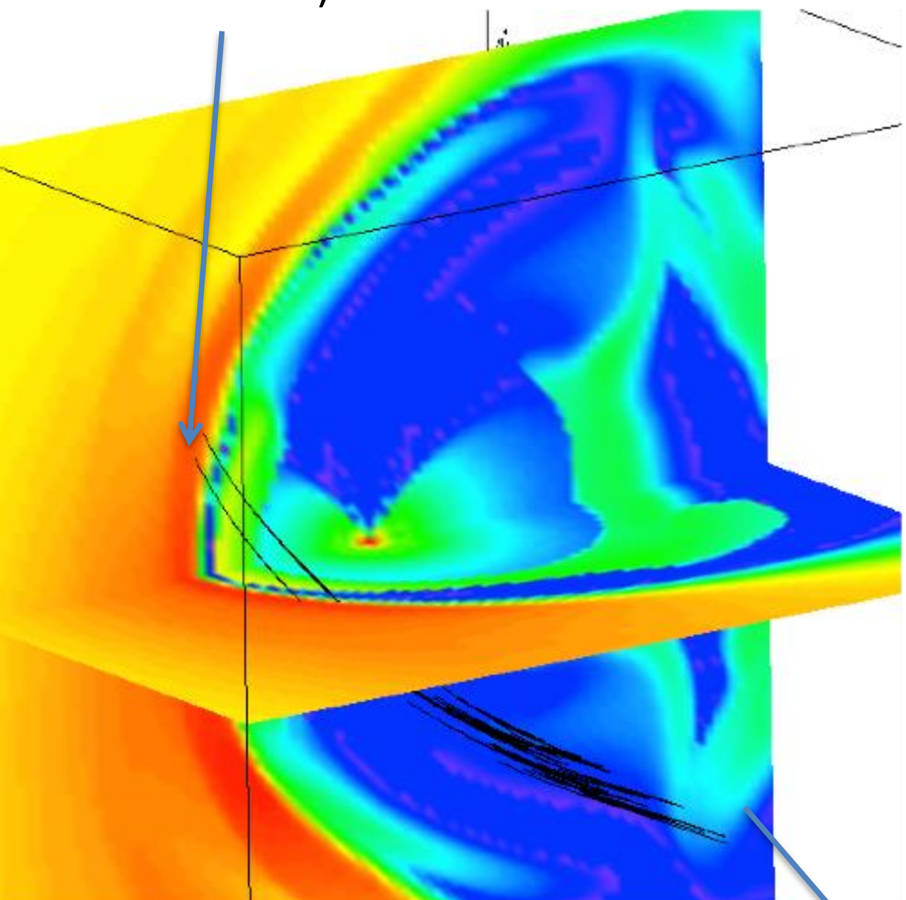
100 MeV GCR ρ
In ISM (outer heliosheath)
no κ κ
κ κ
κ κ
κ κ
HP
Diff Coef (cm^2/s)
Solid lines: κ_par
Dashed lines: κ_per
High x100
Medium x10
No enhace x1
r (AU)

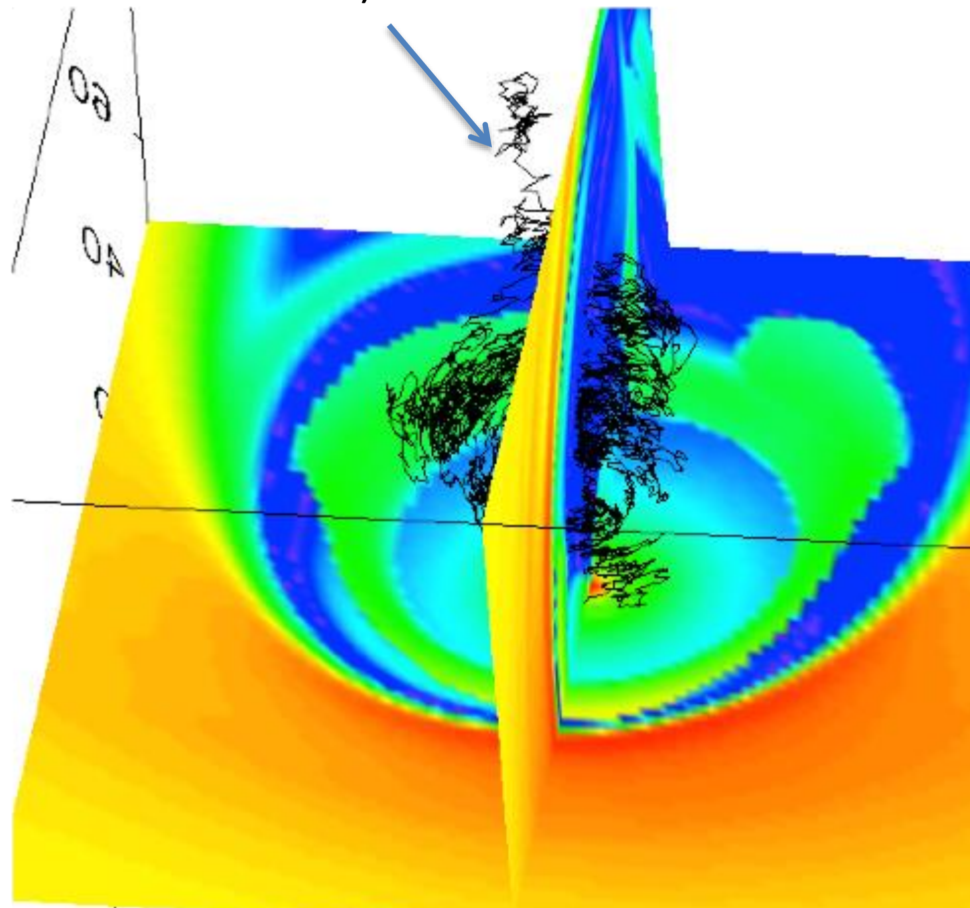
Sample cosmic ray trajectories with reduced turbulence in LISM

$$\frac{l_{\parallel} \text{ in ISM}}{l_{\parallel} \text{ in SW}} \sim 10^2 - 10^4; \qquad \frac{l_{\parallel}}{l_{\perp}} = 1 + (l_{\parallel} / R_g)^2$$ (quasilinear behavior)

A Galactic cosmic ray proton arriving at 160 AU V1 direction (outer heliosheath) with 100 MeV

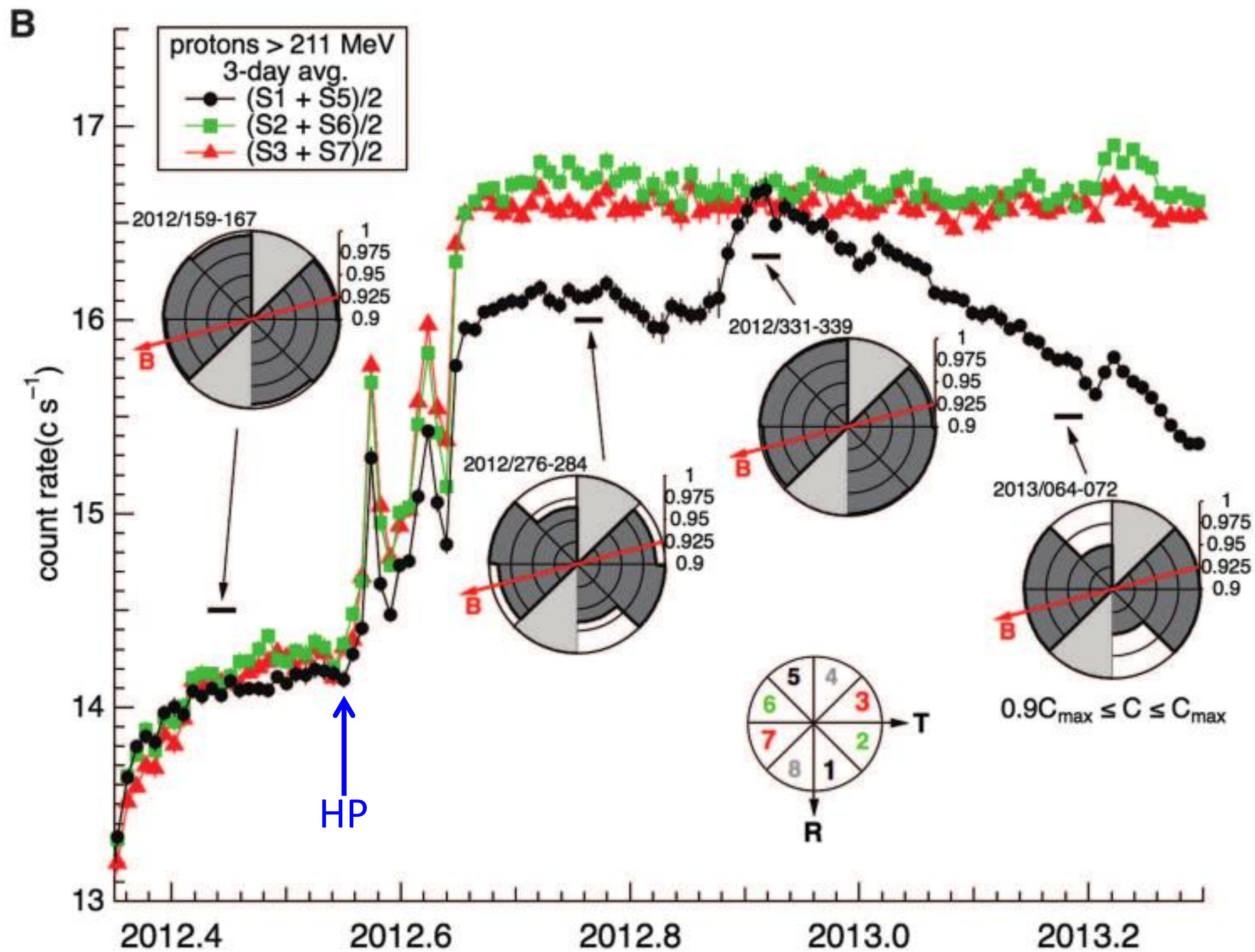
A Galactic cosmic ray proton arriving at 100 AU V1 direction (inner heliosheath) with 100 MeV





Color map of MHD model of magnetic field strength (Pogorelov et al)

- Observed bi-directional anisotropy of GCR by Voyager 1 LECP instrument is consistent with direct fast access to the undisturbed LISM along magnetic field lines.
- Correct modeling of GCR at the heliopause should use 3d focused transport equation instead of Parker equation.



from Krimigis et al. 2013

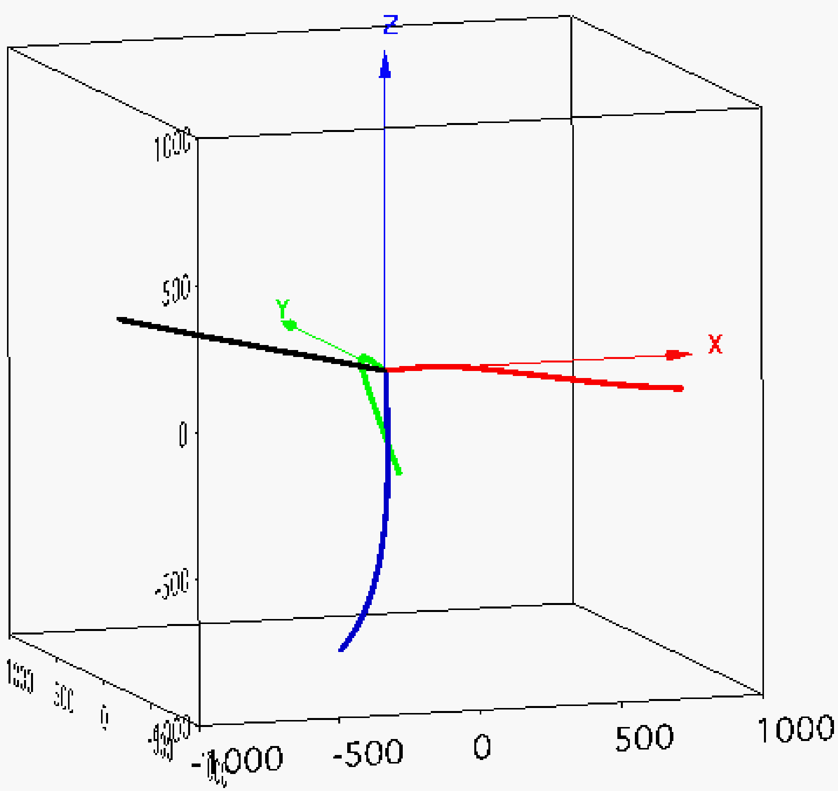
Anisotropy of TeV cosmic rays in LISM

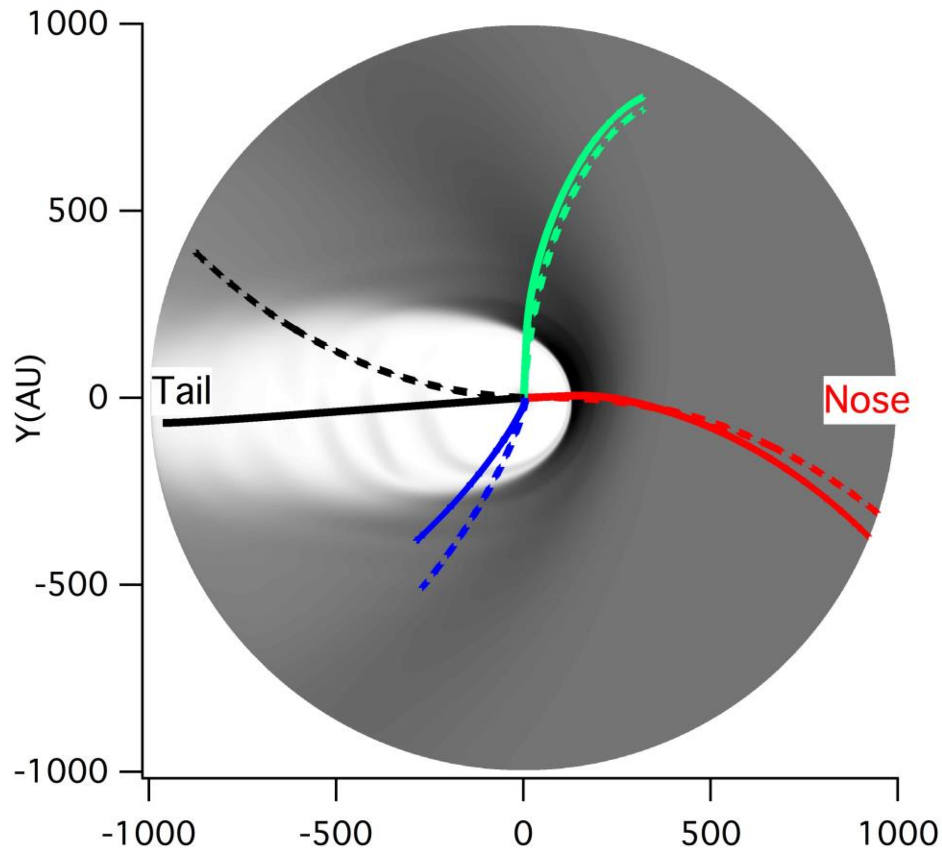
Size of heliosphere:
Nose: ~150 AU, Flank ~300 AU
Tail: A few thousand AU

Gyroradius of protons in 3 μG LISMF:
1 TeV: 74 AU, 10 TeV: 740 AU
300 TeV: 22 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)

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

Deterministic propagation

$$f(\vec{r}_o, \vec{p}_o, t_o) = \left\langle f(\vec{r}_{ism}, \vec{p}_{ism}, t_o - s) \right\rangle$$

Stochastic propagation

f is invariant upon transformation of reference frame

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

Liouville mapping of cosmic ray anisotropy from LISM to Earth

Scatter-free propagation through the heliosphere and surrounding before arrival: diffusion coefficient $k = 10^{29}$ cm^2/s, mean free path l = 3 pc

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

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

$$f(\vec{r}_o, \vec{p}_o) = f(\vec{r}_{ism}, \vec{p}_{ism}) = F_0 p_o^{-4.75}$$

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

↑ Compton-Getting + Acceleration

↑ b × gradient +drift

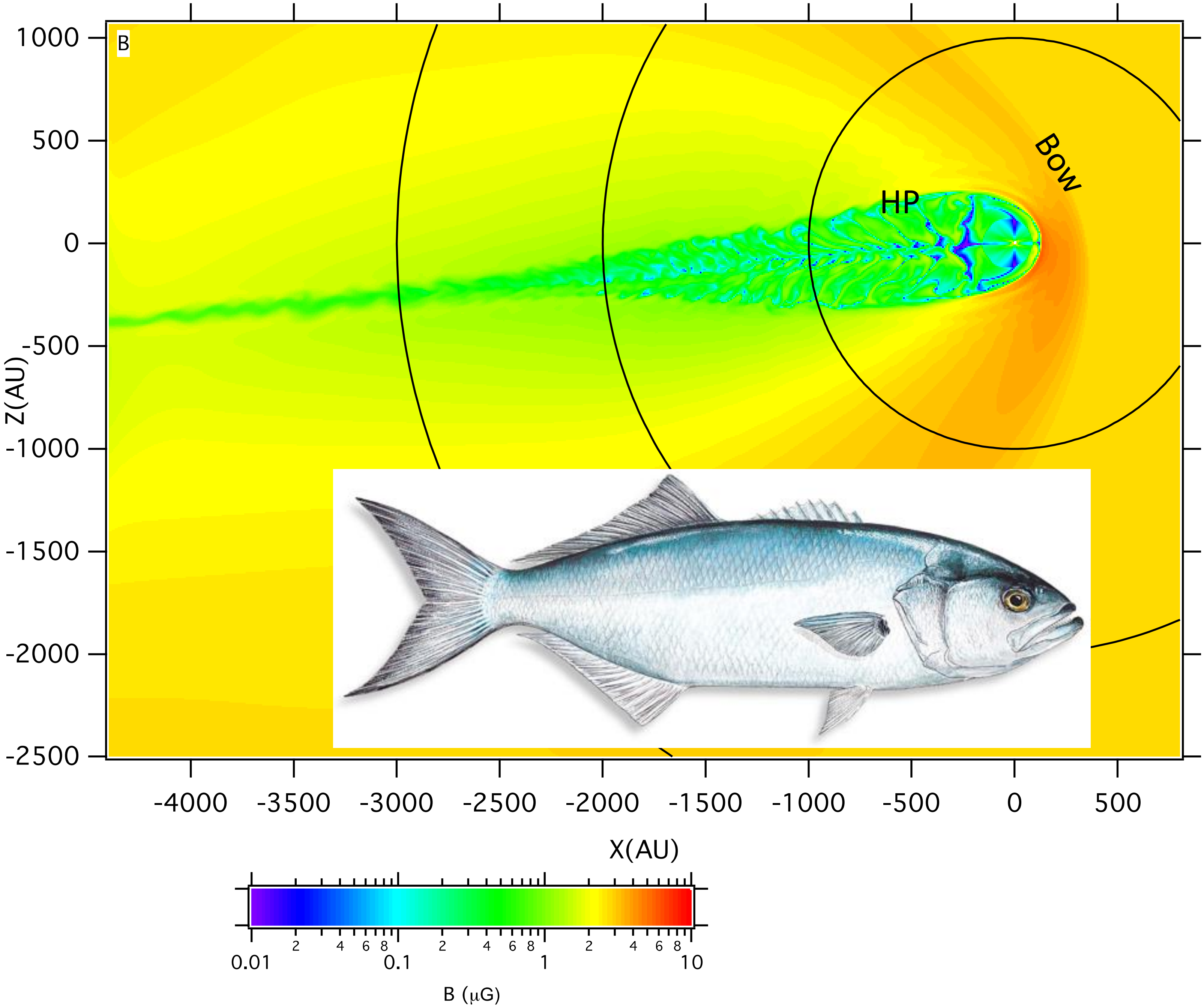
↑ uni-directional

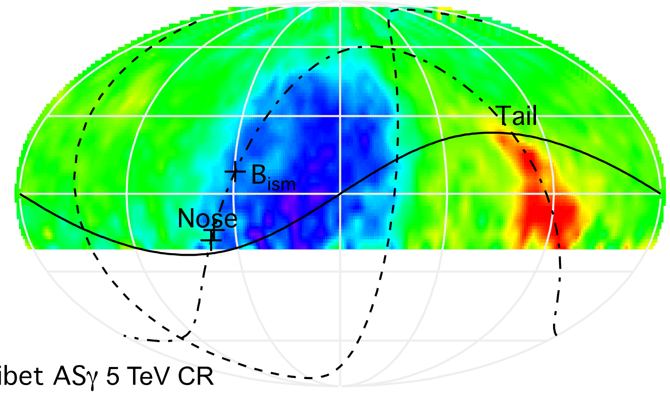
↑ by-directional

+ Pitch angle changes

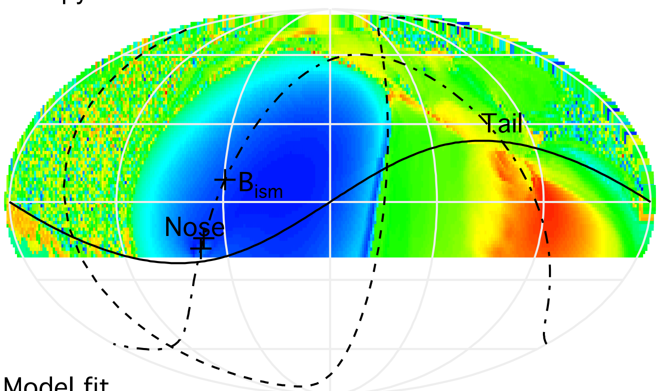
Total anisotropy is a linear composition of the above 3 types of anisotropies (or 5 maps). Its outcome depends on the magnitude and direction of $A_{1||}$, $A_{2||}$, and $\nabla \ln F$ in local interstellar medium.

UAH model of the Heliosphere



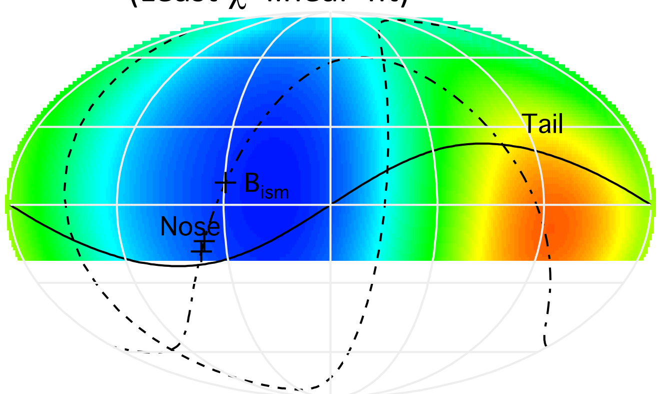


Map A: Tibet ASγ 5 TeV CR Anisotropy measurement

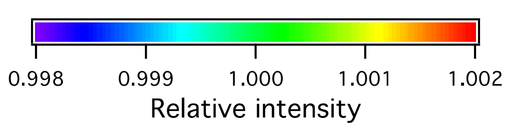


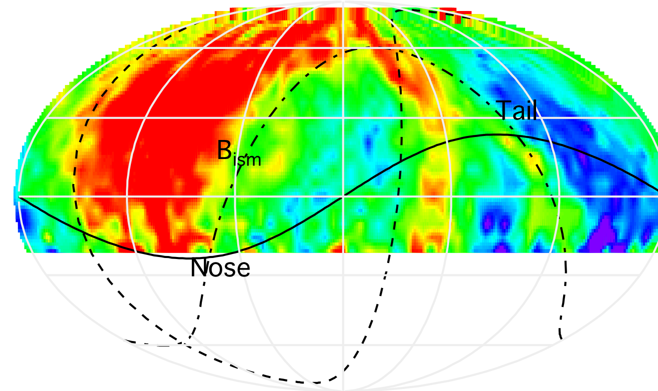
Map B: Model fit

(Least χ^2 linear fit)



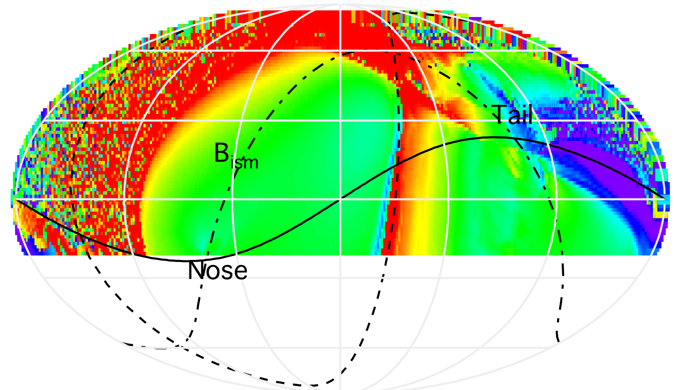
Map C: Inferred anisotropy in ISM





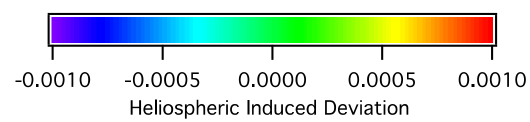
Measurement - inferred ISM

Map A - Map C



Model - Inferred ISM

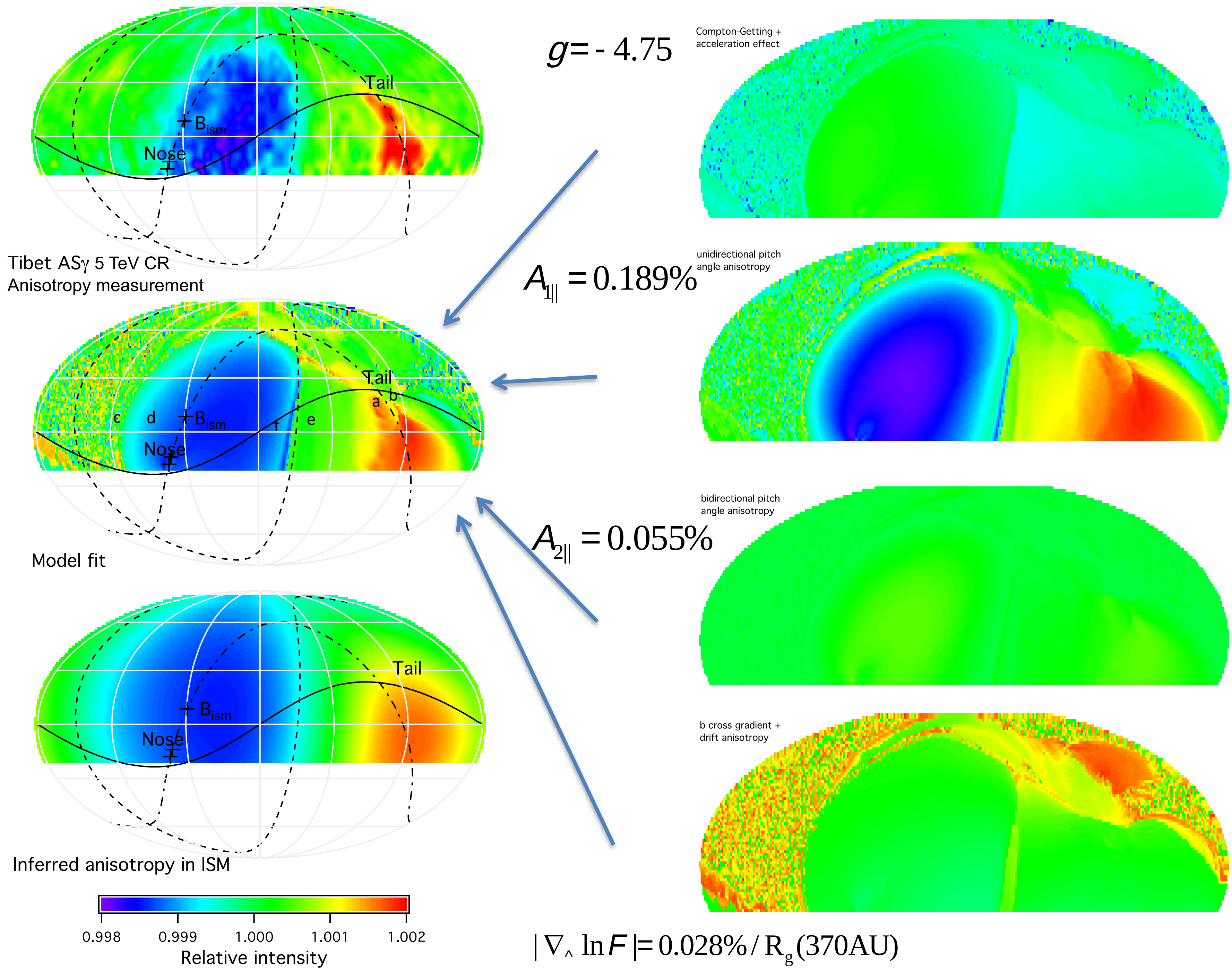
Map B - Map C



$$A_{1\|} = 0.189\%;$$

$$A_{2\|} = 0.055\%;$$

$$|\nabla_{\wedge} \ln F| = 0.028\% / \mathrm{R_g}\,(370\ \mathrm{AU})$$



Tail
B_ism
Nose
Tibet ASγ 5 TeV CR
Anisotropy measurement
Tail
a
b
c
d
B_ism
e
f
Nose
Model fit
Tail
B_ism
Nose
Inferred anisotropy in ISM
0.998
0.999
1.000
1.001
1.002
Relative intensity
g= - 4.75
Compton-Getting +
acceleration effect
A_1|| = 0.189%
unidirectional pitch
angle anisotropy
A_2|| = 0.055%
bidirectional pitch
angle anisotropy
b cross gradient +
drift anisotropy
| ∇_∧ ln F |= 0.028% / R_g(370AU)

TeV cosmic ray transport in LISM

$A_{1\|} = 0.189\%$ $\quad A_{2\|} = 0.055\%$ $\quad |\nabla_\perp \ln f| = 0.028\% / \mathrm{R_g}(370\mathrm{AU})$

Little mirroring of TeV cosmic rays by large-scale ISM magnetic field

Parallel to magnetic field

$$\frac{j_\|}{f} = \frac{k_\| \partial f}{f \partial z} = 3A_{1\|}c = 5.67 \times 10^{-3} c$$

$$\text{if } k_\| = 10^{29}\ \mathrm{cm^2/s} \quad \text{then} \quad \frac{\partial \ln f}{\partial z} = 2.55 \times 10^{-8}\ \mathrm{AU^{-1}} = 5.25 \times 10^{-3}\ \mathrm{pc^{-1}}$$

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

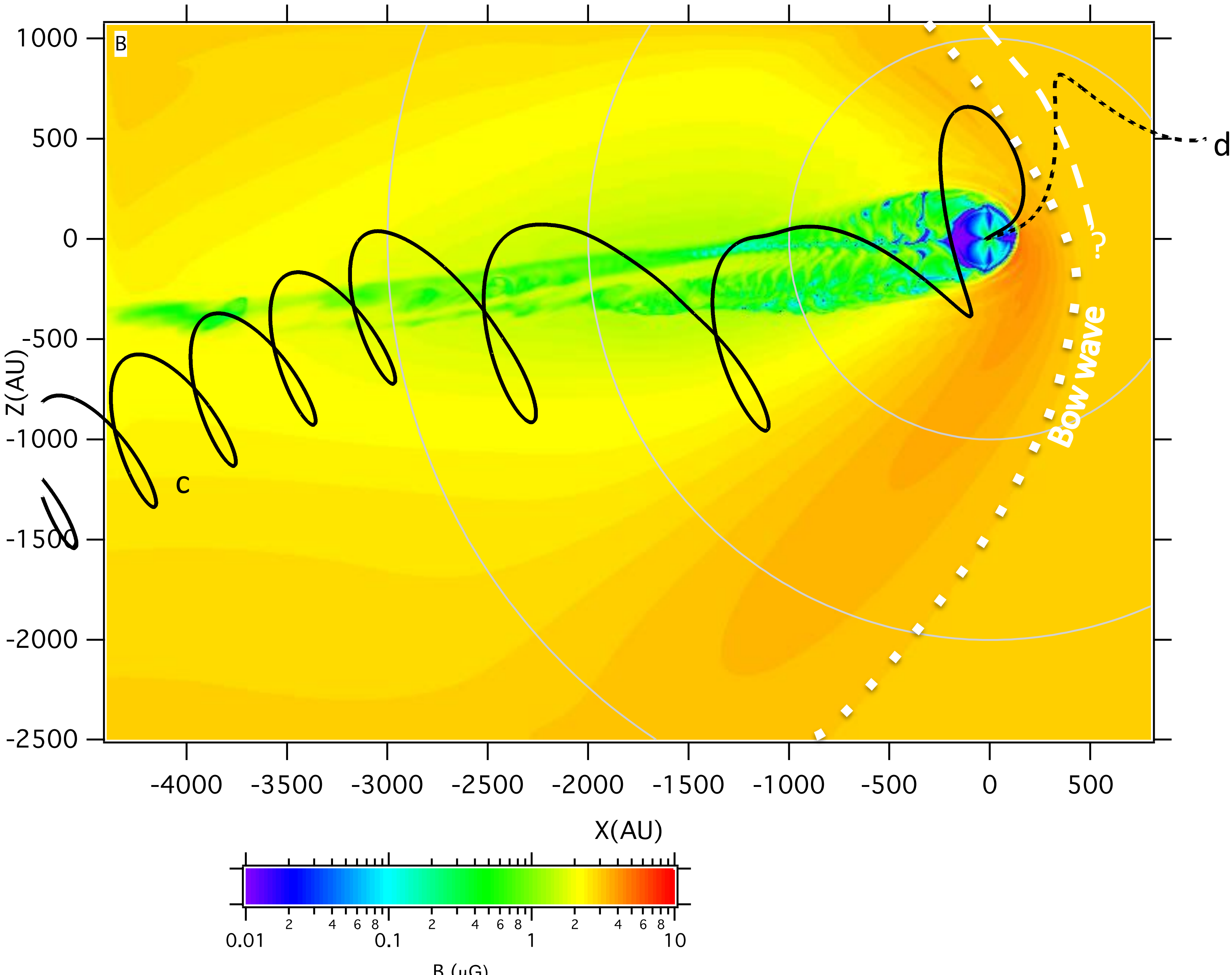
Perpendicular to magnetic field

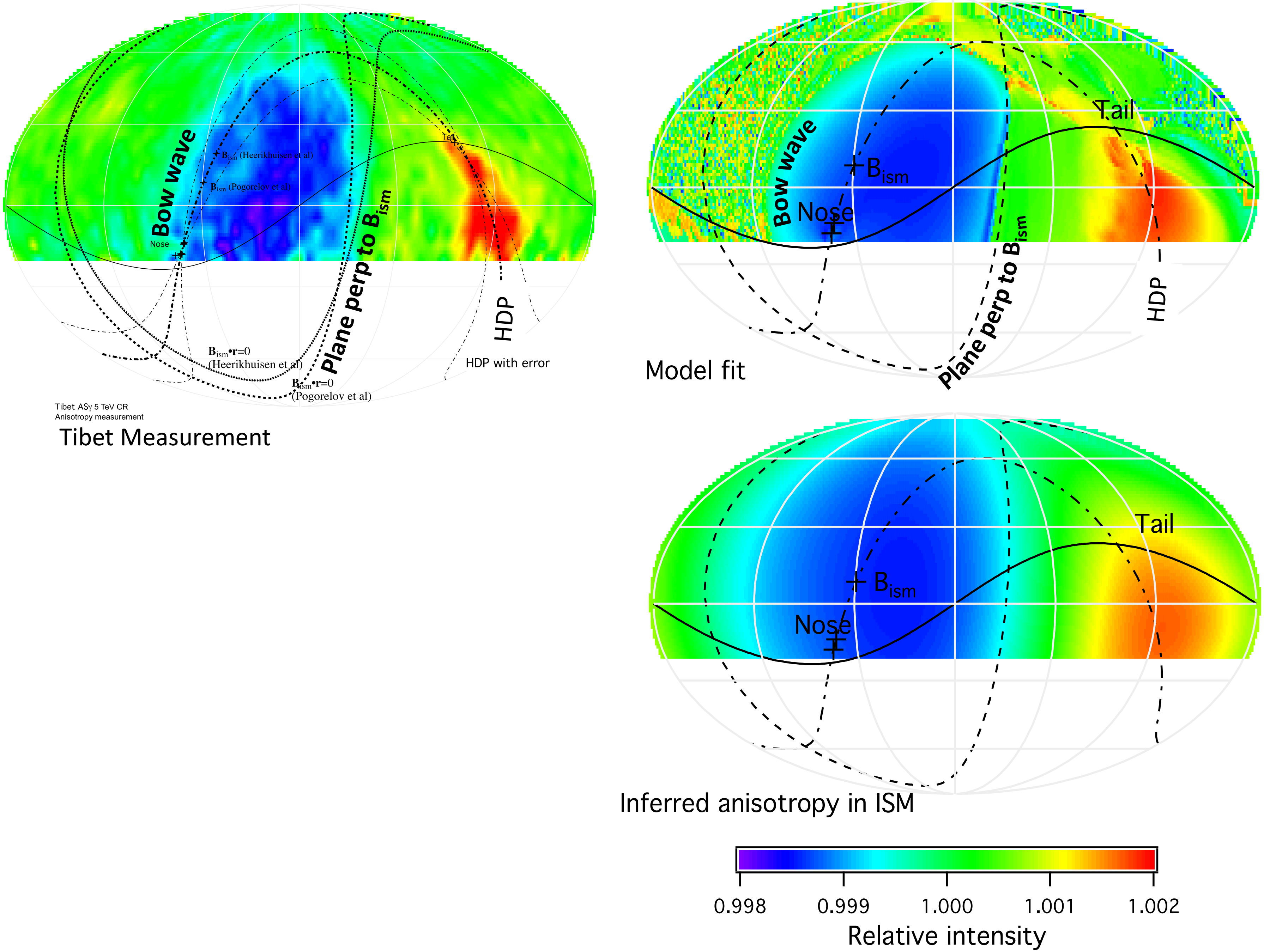
$$|\nabla_\perp \ln f| = 7.6 \times 10^{-7}\ \mathrm{AU^{-1}} = 1.6 \times 10^{-1}\ \mathrm{pc^{-1}}$$

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

TeV cosmic ray transport in LISM is dominated by parallel diffusion

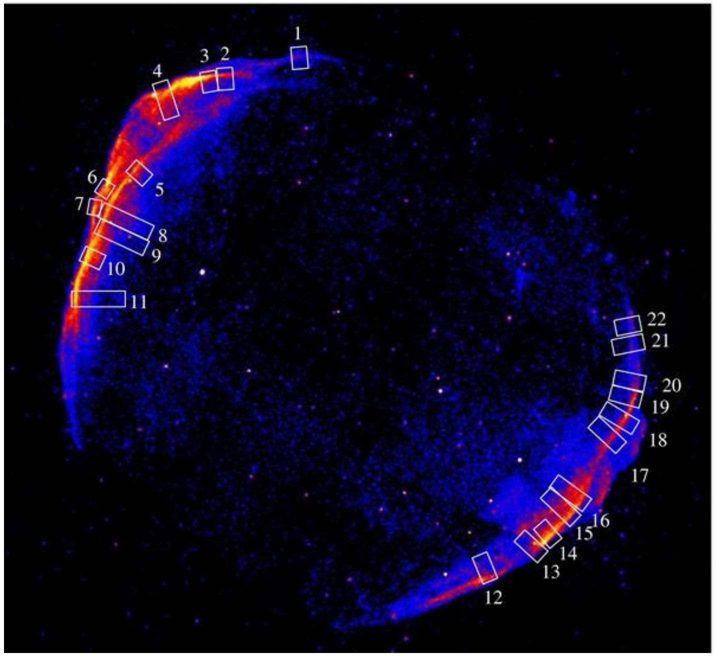
Trajectories separated by bow wave (XZ projection only): (c) West; (d) East



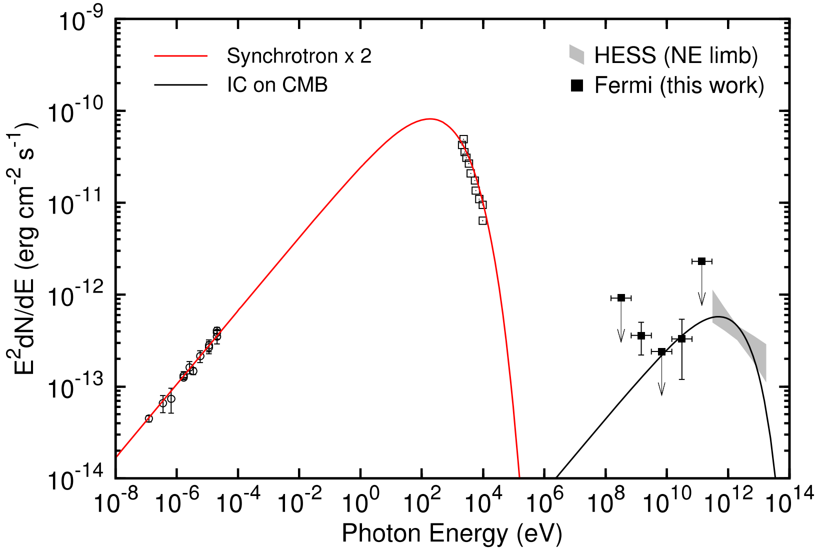

Bow wave
Nose
B_ism (Heerikhuisen et al)
B_ism (Pogorelov et al)
Plane perp to B_ism
Tail
HDP
B_ism•r=0
(Heerikhuisen et al)
B_ism•r=0
(Pogorelov et al)
HDP with error
Tibet ASγ 5 TeV CR
Anisotropy measurement
Tibet Measurement
Tail
B_ism
Bow wave
Nose
Plane perp to B_ism
HDP
Model fit
Tail
B_ism
Nose
Inferred anisotropy in ISM
0.998
0.999
1.000
1.001
1.002
Relative intensity

Summary

- Observed cosmic ray distribution function at Earth as a function of energy, spatial position, direction, and composition is severely affected by cosmic ray transport through interstellar and interplanetary magnetic fields with embedded turbulence. Understanding of cosmic ray source requires us to separate out the transport effects.
- The behavior of cosmic ray transport on small scales could be very different from that on the large scale. Cosmic ray observations may contain local transport effects. Structure of magnetic field and anisotropy of cosmic ray transport could become important.



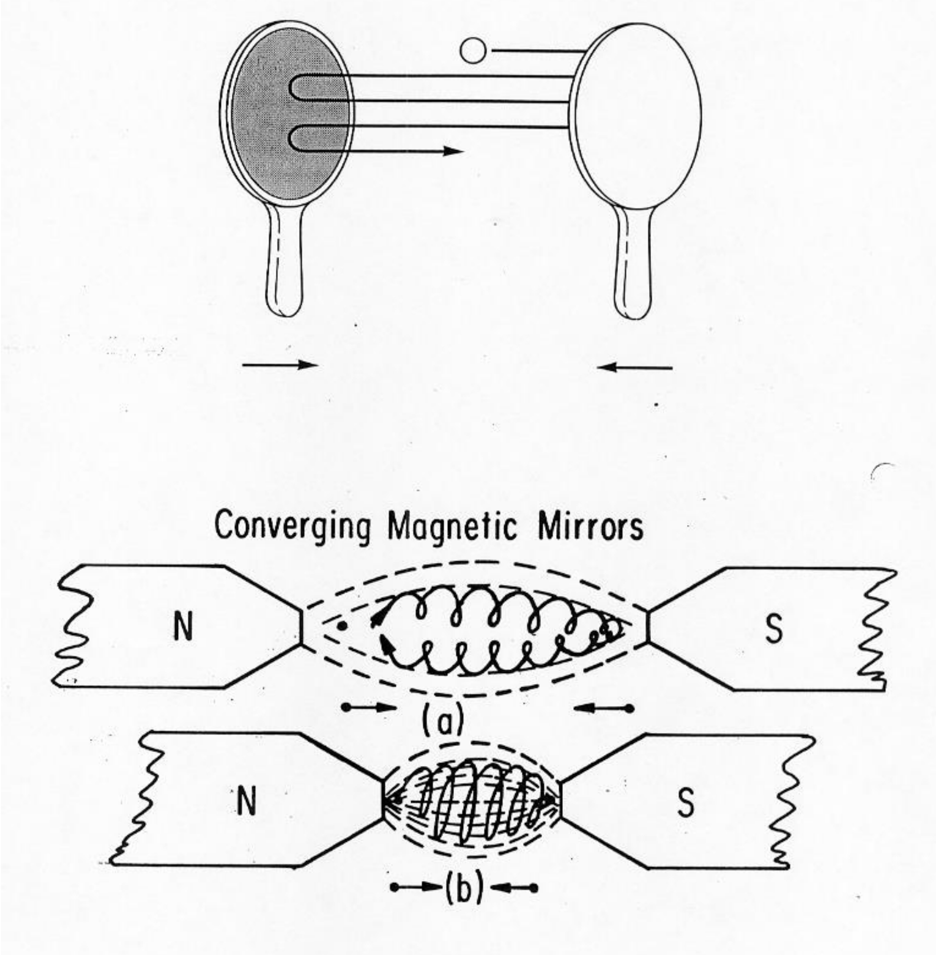
SN1006 Chandra image 2-7 keV

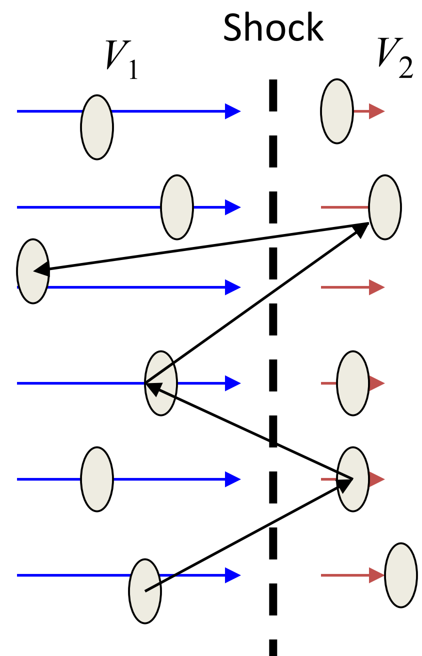


- Spectrum and radial variation of x-ray emission is consistent with synchrotron radiation in an magnetic field amplified by the shock to ~100 μG (Ressler et al. 2014).
- TeV gamma ray emission is detected by HESS. The spectrum is consistent with inverse-Compton scattering from electrons. (e.g., Xing et al. 2016)

Cosmic ray acceleration by supernova remnants

Fermi theory of particle acceleration

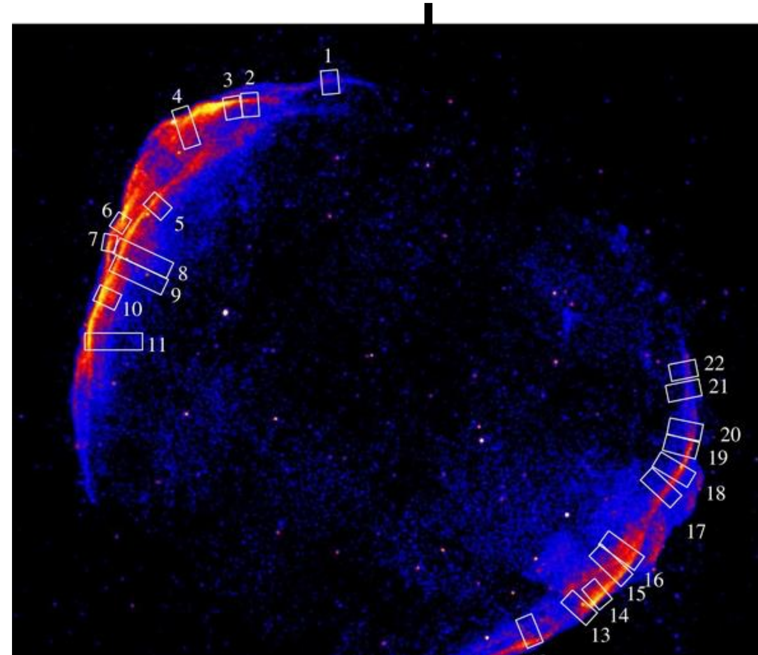




Shock Compression:

$R = V_1 / V_2$

$1 < R \leq 4$



SN1006 Chandra image 2-7 keV

Diffusive acceleration by supernova shock waves

Standard theory:

Energy spectrum: $J = p^2 f(p) \propto p^{-s}$ where power-law spectral slope $s = \dfrac{R+2}{R-1}$

For a strong (supernova) shock, $R = 4$, $s = 2$

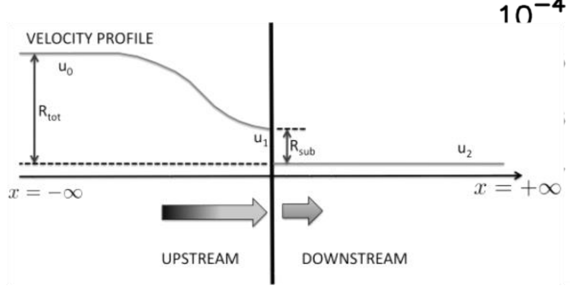
Maximum energy or momentum p_m is determined from time of acceleratoion $t = \int_0^{p_m} \dfrac{3\kappa_1}{(U_1 - U_2)U_1} \dfrac{dp}{p}$

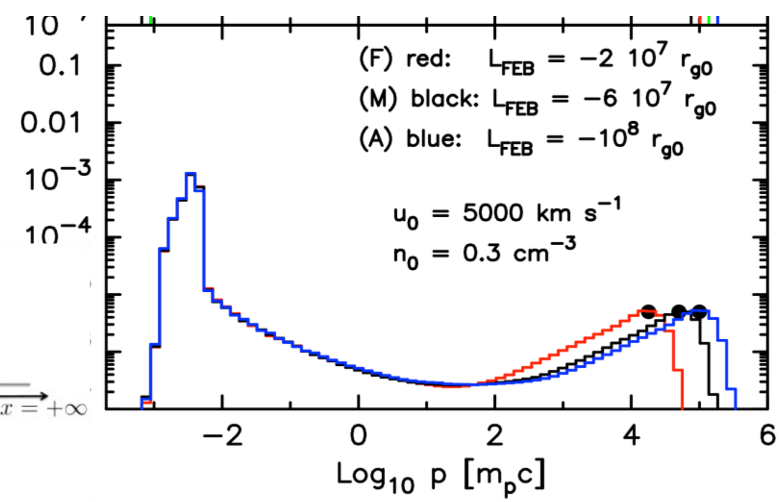
Given the typical lifetime, shock speed, and particle diffusion in upstream interstellar magnetic field, supernova shocks can only accelerate cosmic rays to 10^{14} eV at best.

Composition of cosmic rays: Interstellar medium, or progenitor stellar wind material

Nonlinear shock acceleration theory:

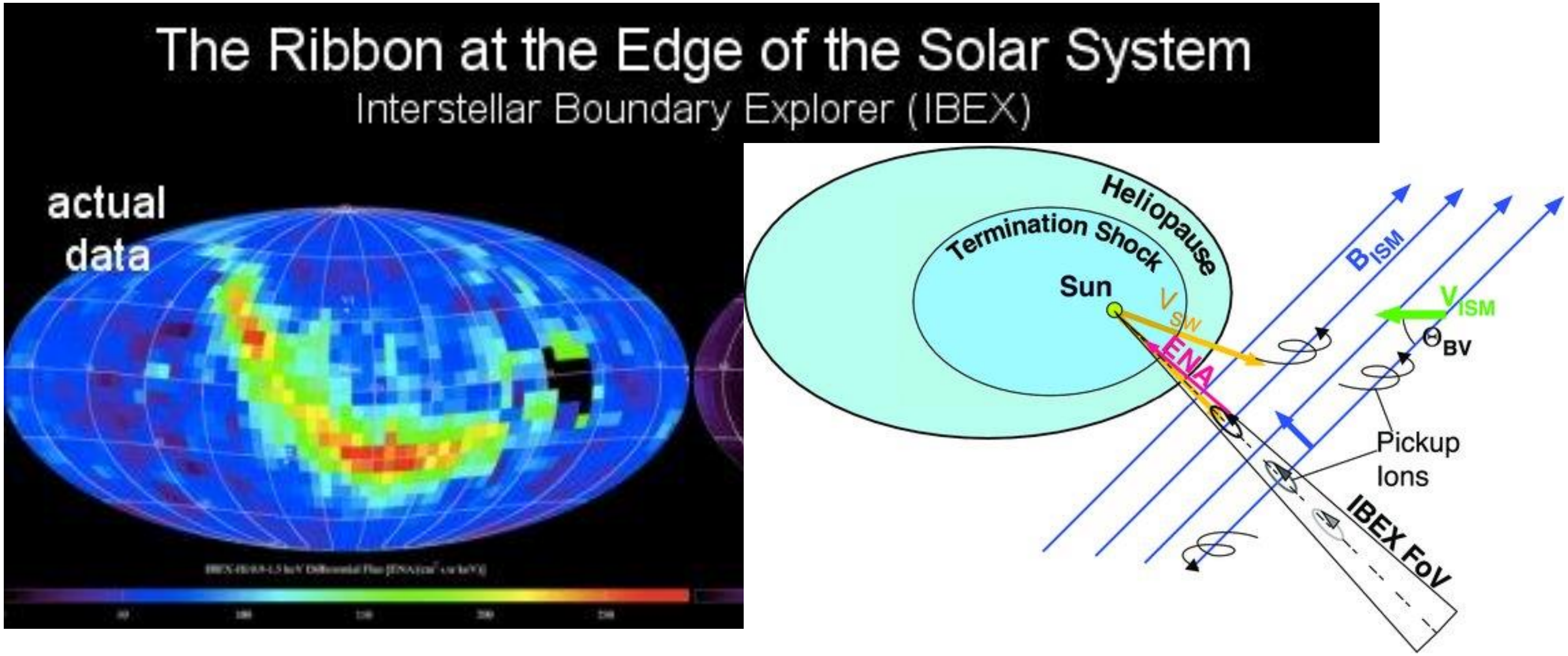
- Waves are generated by cosmic rays streaming away from the shock.
- Magnetic field is amplified
- Pressure of cosmic rays modifies shock structure.





- Cosmic ray source spectrum is harder than p^{-2} and maximum energy is closer to the knee energy 3×10^{15} eV.

Magnetic field in LISM



Turbulence in Heliosphere: $(dB/B)^2 \sim 1, \quad l_{\parallel} = 10 r_g = 100 l_{\wedge}$ $\qquad r_g^2 = \frac{l_{\wedge} l_{\parallel}}{1 - l_{\wedge}/l_{!!}}$

Turbulence of local ISM magnetic field is likely to be low:

$$(dB/B)^2 \sim 0.1, \quad l_{\parallel} = 33 r_g = 1000 l_{\wedge} \qquad \text{so: } A_{d\wedge} = \frac{l_{\wedge}}{L_{\wedge}} << A_{b' g} = \frac{r_g}{L_{\wedge}} \quad \text{and } A_{d\parallel} = \frac{l_{\parallel}}{L_{\parallel}}$$

Scatter-free propagation through the heliosphere and surrounding before arrival:

$$\text{diffusion coefficient } k = 10^{29} \text{ cm}^2/\text{s}, \ \text{mean free path } l = 3 \text{ pc}$$