Magnetic fluctuations and cosmic rays in the Very Local Interstellar Medium (VLISM)

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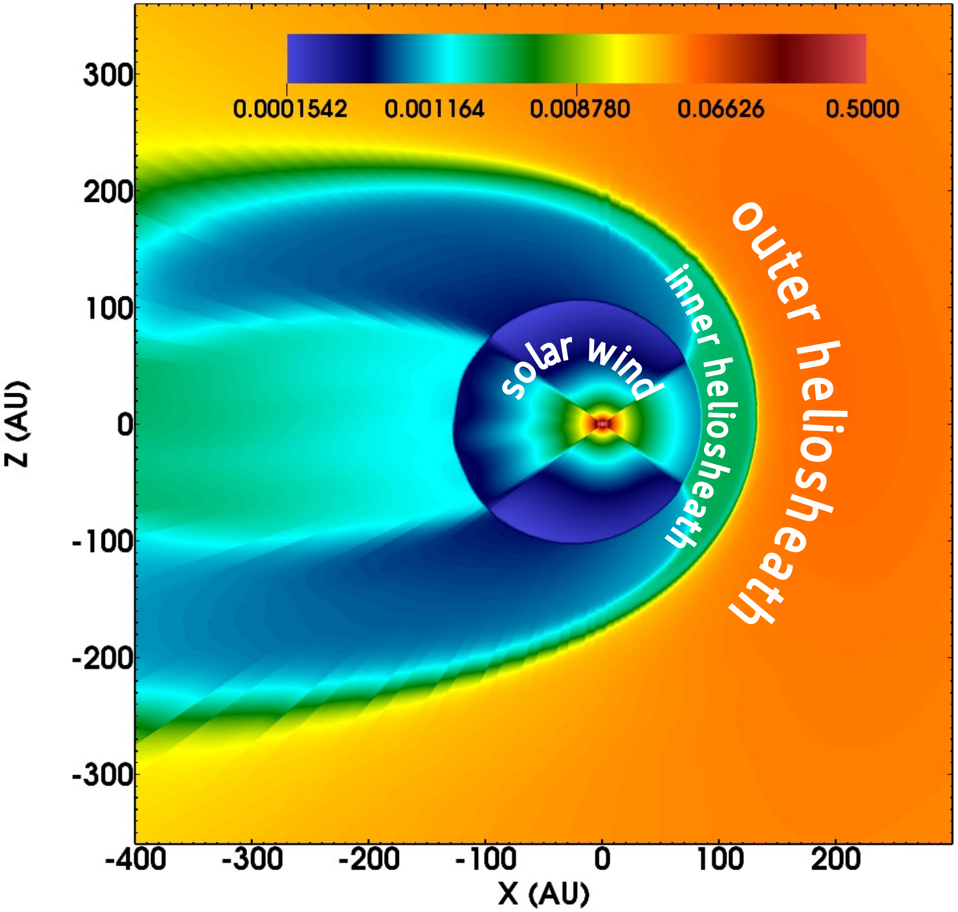
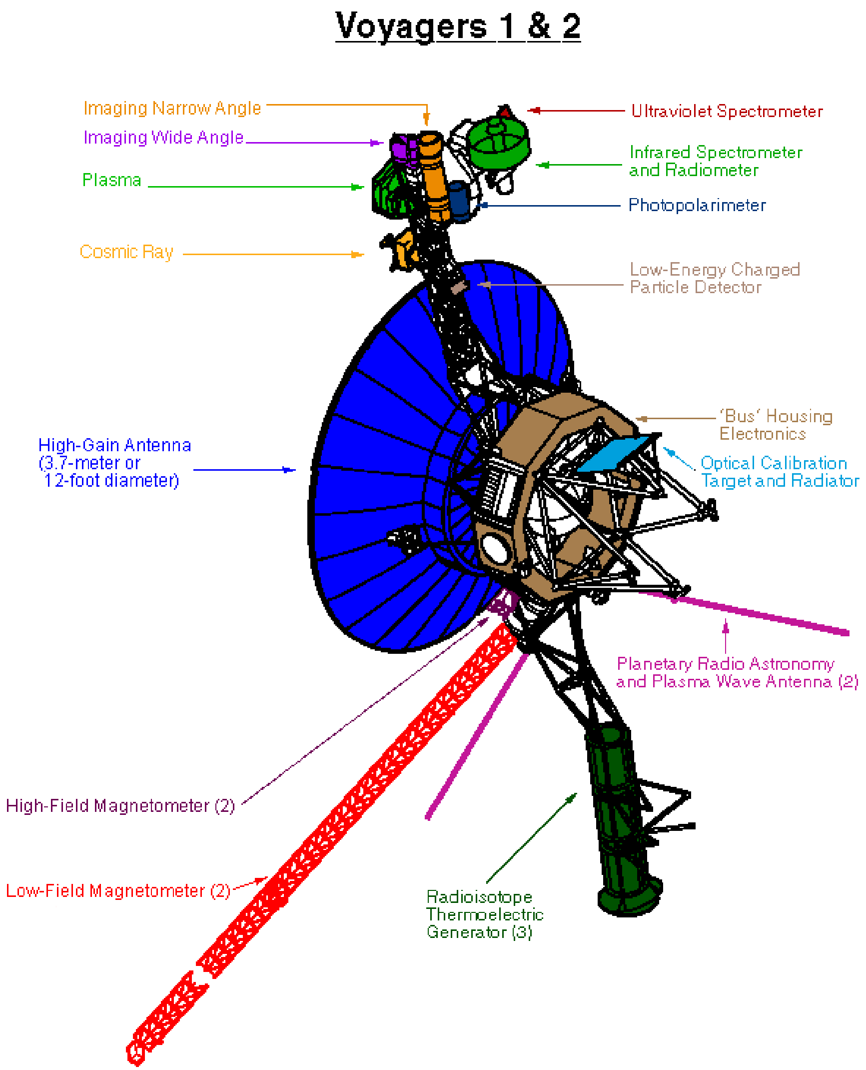
Topics to be discussed

- Observations of magnetic fluctuations in the VLISM
- Possible sources of turbulent fluctuations in the VLISM
- Galactic cosmic ray transport and intensities in the VLISM
- Cosmic-ray anisotropy events

The **Outer Heliosheath** is that region of interstellar space between the bow wave, or the onset of the ISM flow deceleration) and the **Heliopause**, the magnetic boundary of the solar system.
Another term is **Very Local Interstellar Medium** (VLISM), a “disturbed” ISM region affected by the heliosphere.



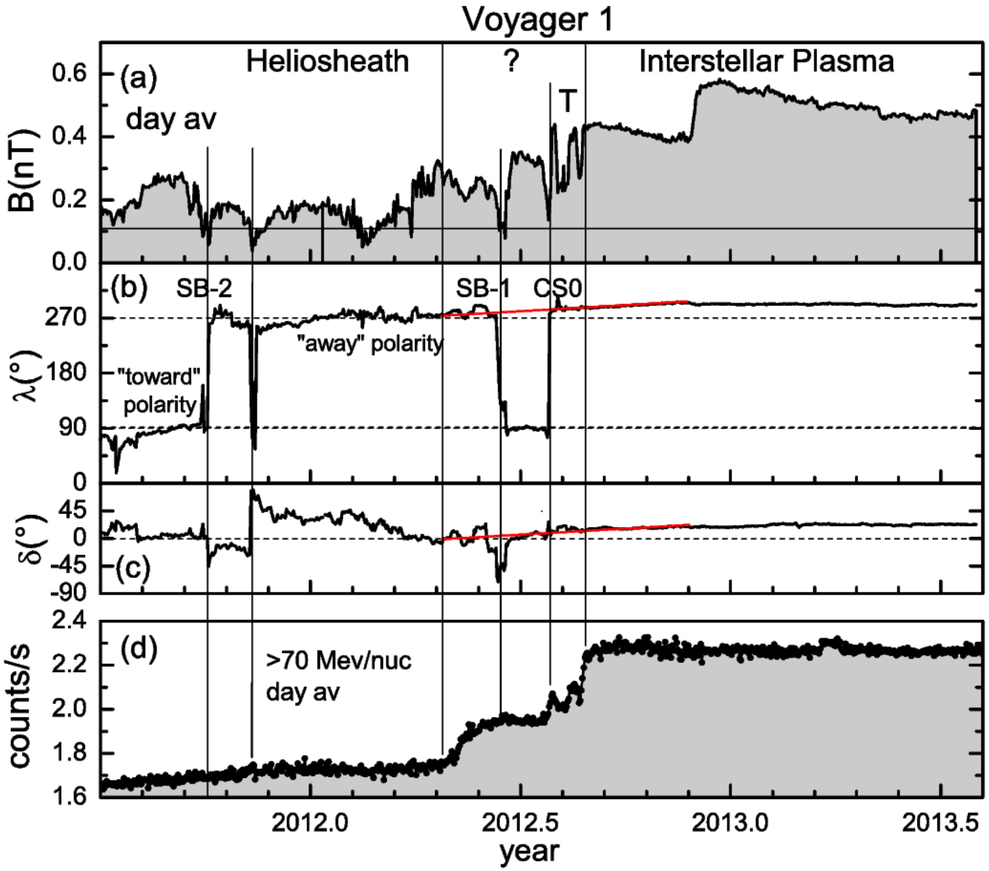
The interstellar Voyagers

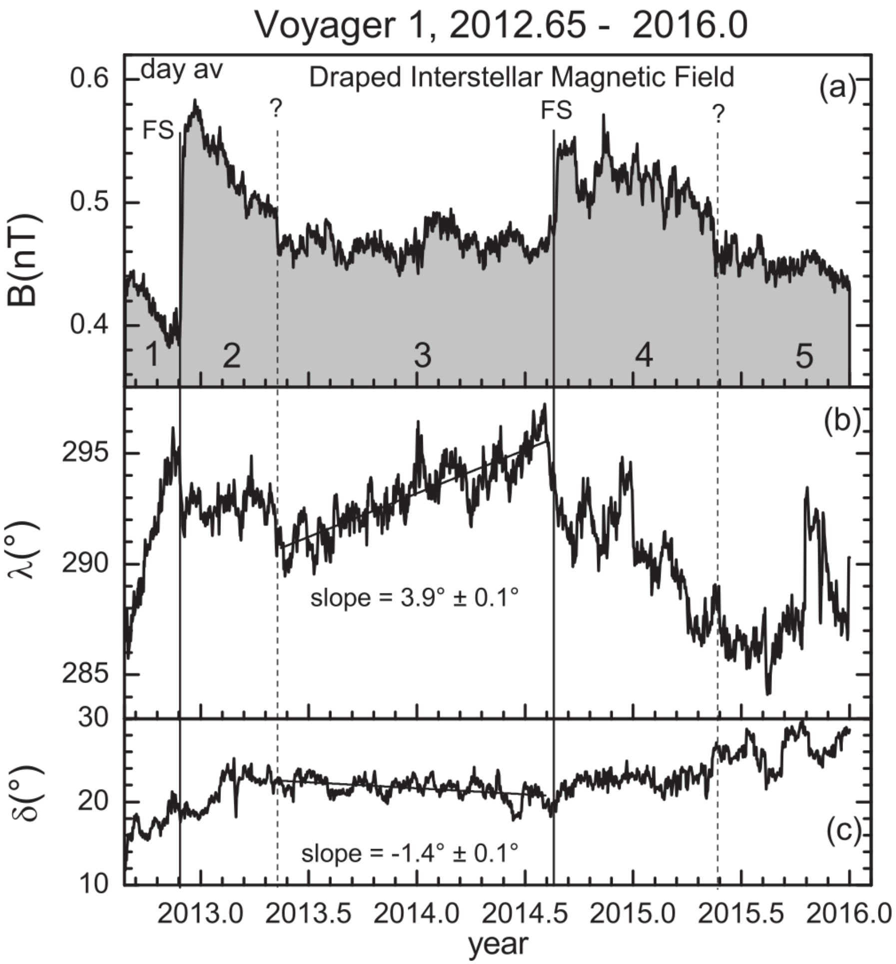


- “Background” plasma ions (E < 6 keV) – instrument failed on Voyager 1
- Magnetic field – measurements difficult because of spacecraft’s magnetic field
- “Low” energy energetic particles from the heliosphere (E =30 keV – hundreds of MeV/n), eight sectors in the RT plane
- Galactic cosmic rays (E = 3 – 1000 MeV/n), 4 telescopes
- EM waves – VLF band (wavelength ~ 100 km)

Total power from RTG: 470 W at launch

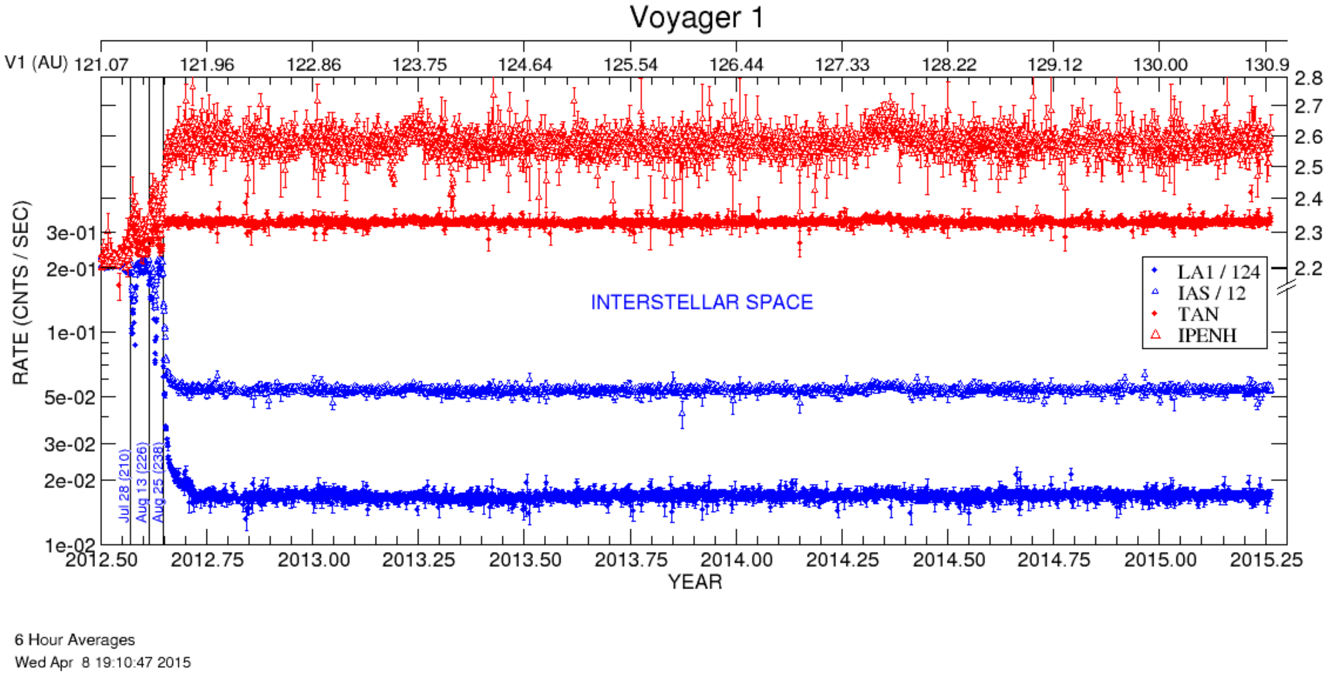
Voyager 1: magnetic fields



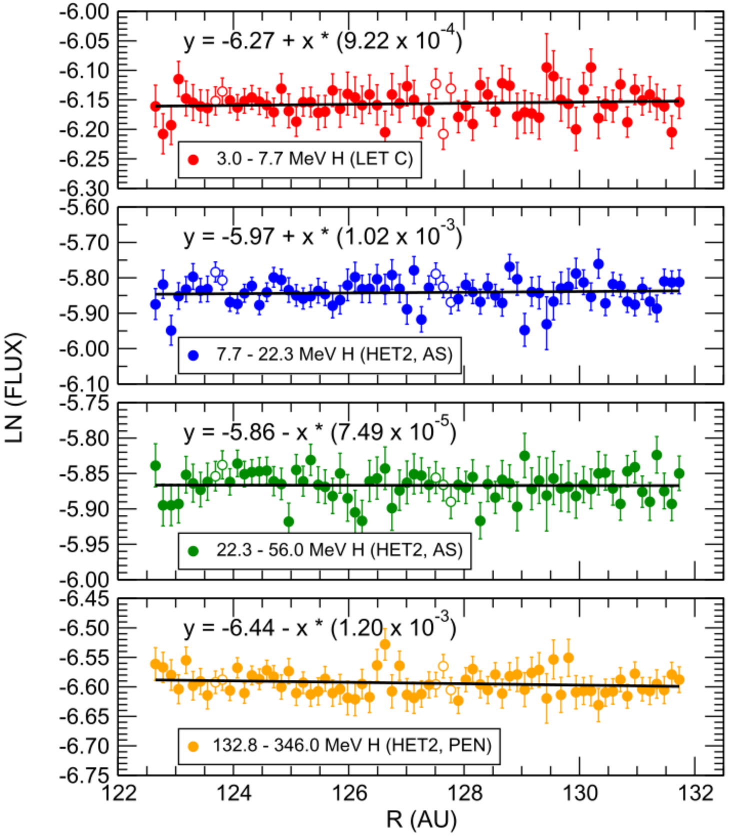


- Voyager 1 is in the region of “disturbed” LISM, affected by the waves produced by the heliopause. Two forward shocks or pressure waves and two unidentified weak structures (Burlaga and Ness, 2016), and electrostatic plasma oscillations (ESO) characteristic of foreshock regions were observed (Gurnett).
- Magnetic field appears, on average, to turn toward the ISM direction defined by the center of the IBEX ribbon (draping): models by Pogorelov, Opher, Izmodenov, ...

Voyager 1: galactic cosmic rays and heliospheric ions



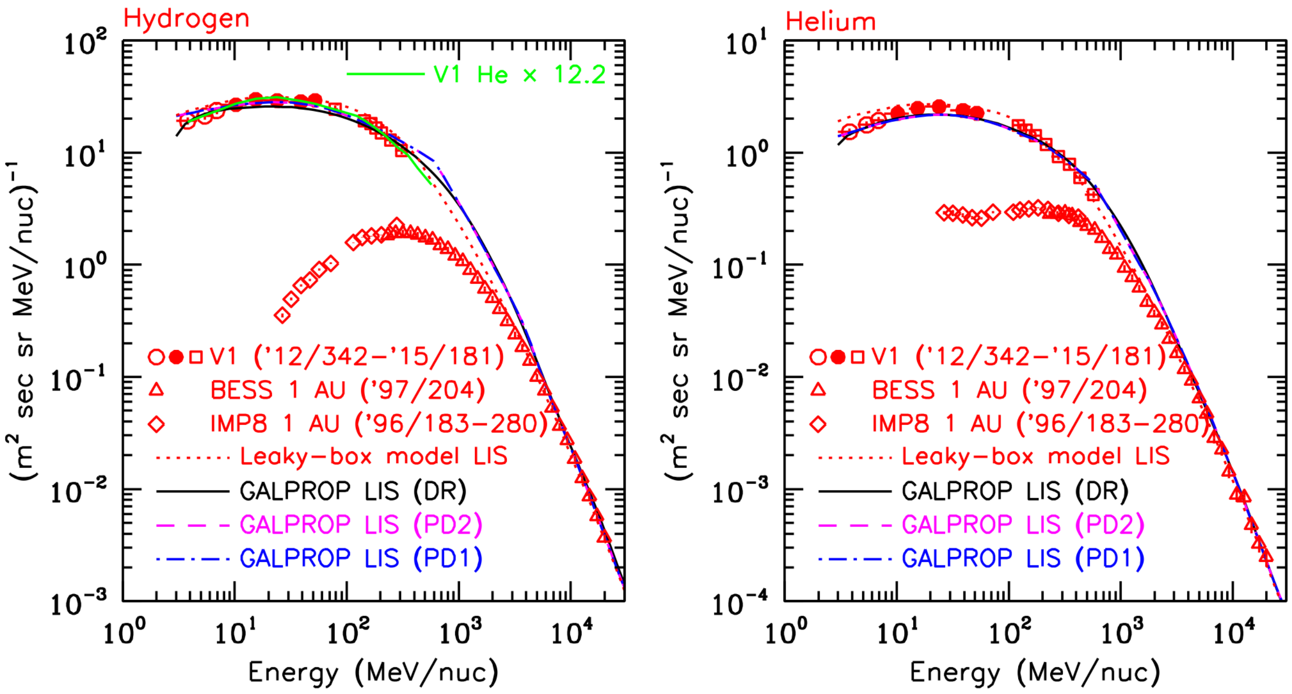
Cummings et al (2016)



- GCR intensities (red) rose significantly in two large steps, one before and one at the heliopause. In the outer heliosheath GCR fluxes were essentially constant for the past four years, showing no large-scale gradient in the VLISM.
- Heliospheric ions (anomalous cosmic rays or accelerated pickup ions, blue) have disappeared shortly after Voyager crossed the heliopause.

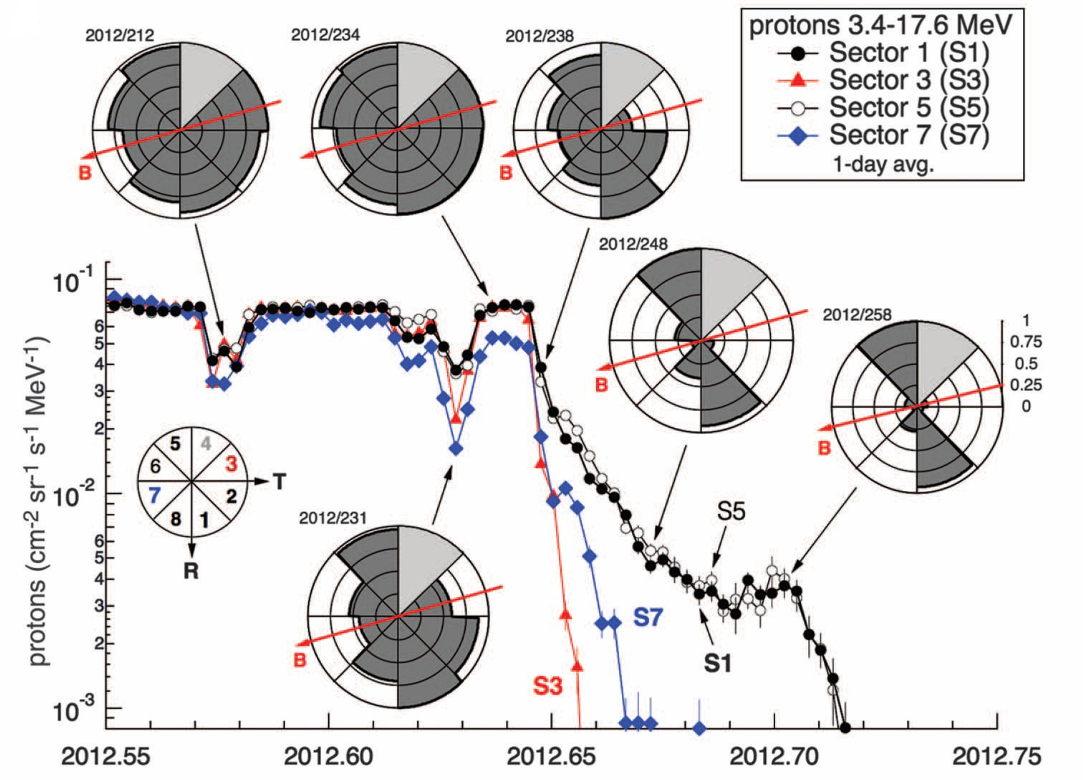
Unmodulated spectra in the VLISM

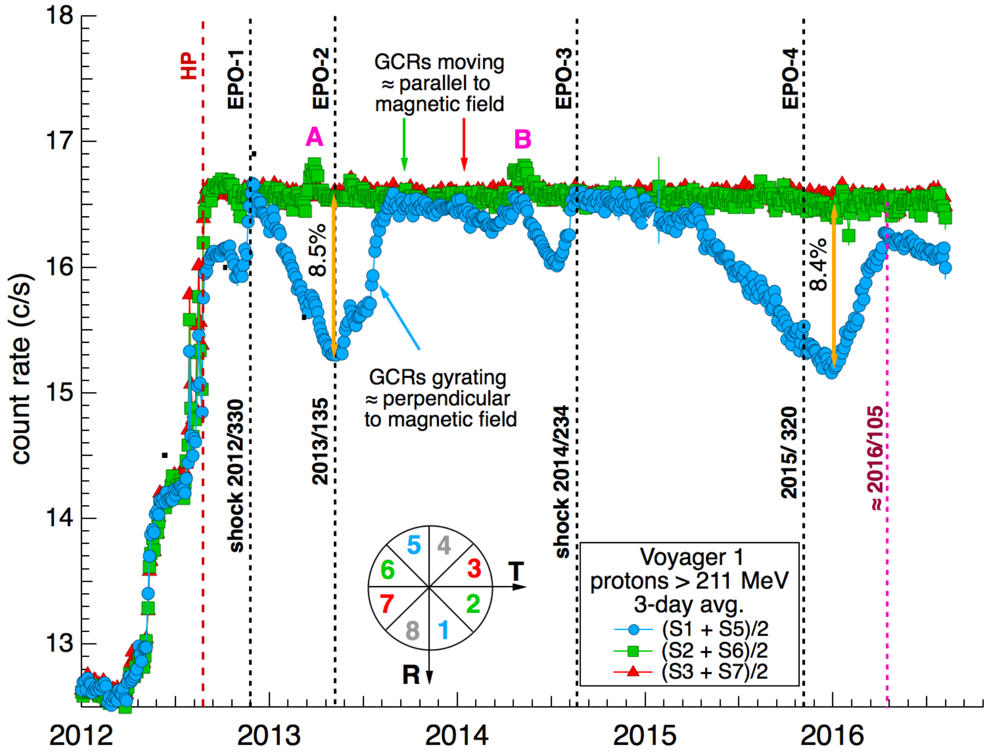
Cummings et al (2016)



Spectral turnover consistent with losses to neutral hydrogen ionization en route from the source.

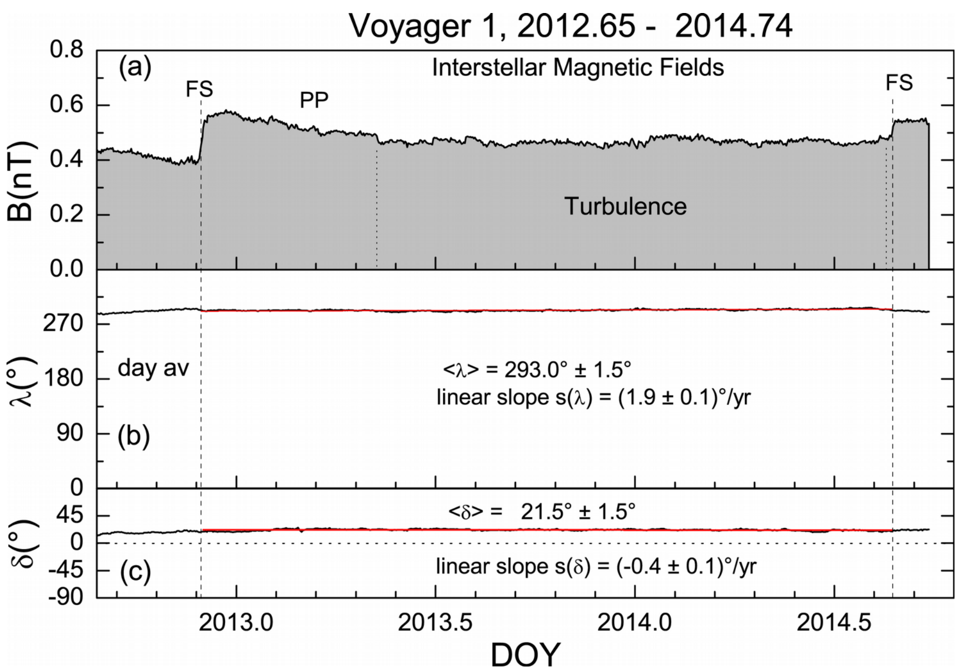
Cosmic ray anisotropies in the VLISM

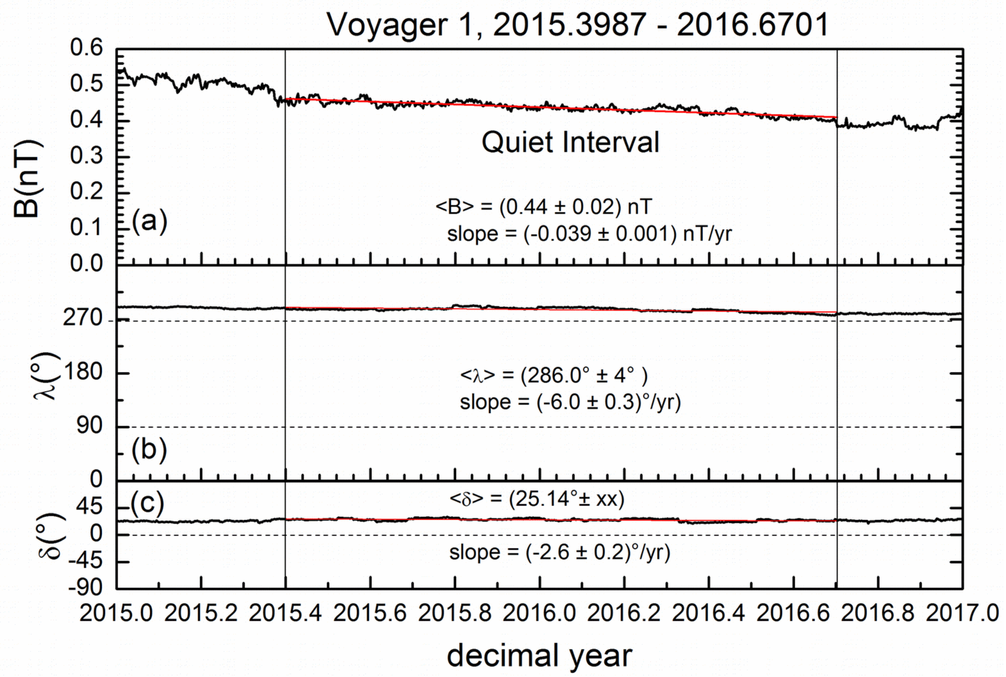




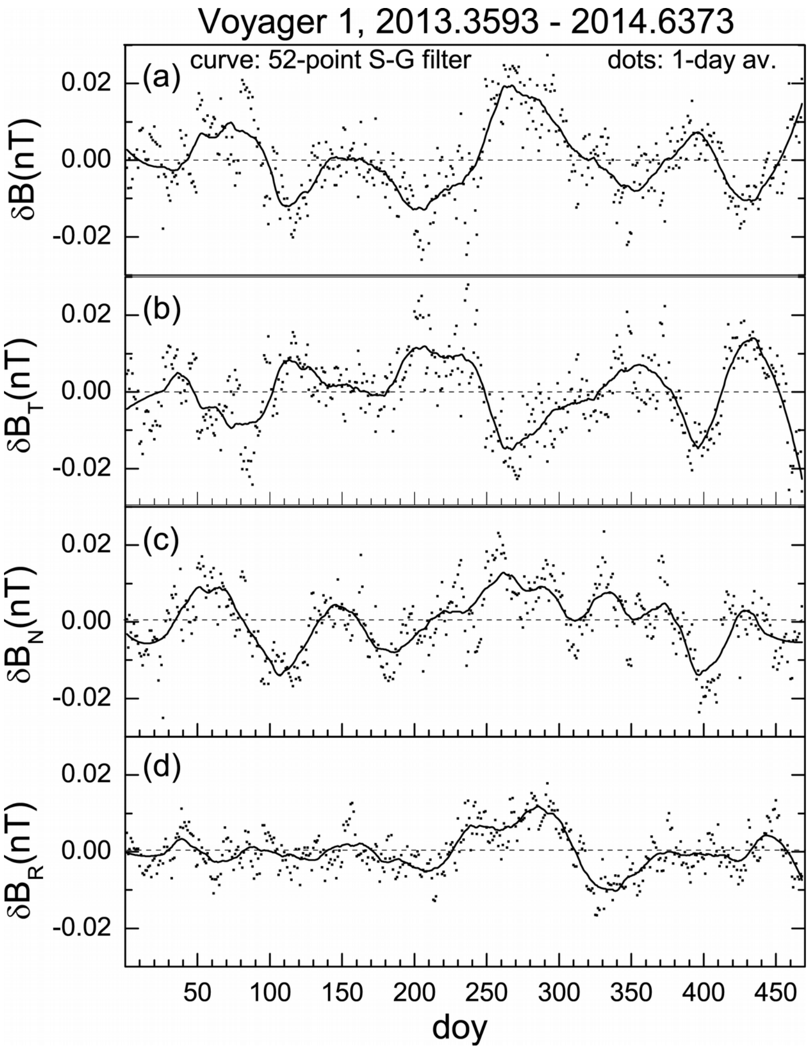
- Heliospheric particles, before disappearing, were predominantly observed near the 90 degree pitch angle (pancake).
- By contrast, galactic cosmic rays showed episodic **depletions near the 90 degree pitch angle** (butterfly) which persisted far beyond the heliopause. The width of the depletions is unknown; some have suggested a very narrow gap near $\mu=0$.

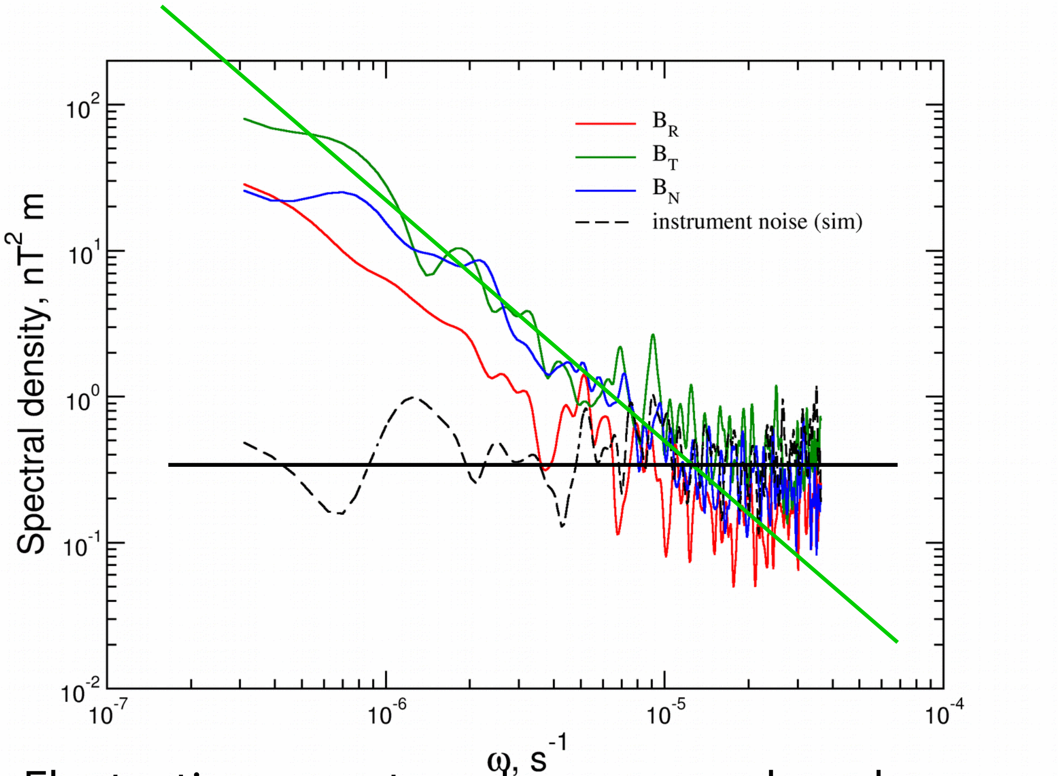
Magnetic fluctuations in the VLISM





- Plasma environment is much quieter in the VLISM than anywhere inside the heliosphere. Magnetic field lines are nearly straight.
- Two 468-day intervals in the VLISM away from shocks and ESO events. Daily averages of magnetic field were used to construct the power spectrum.





Fluctuations spectrum has a power law slope at small frequency

Flattens at high frequency, consistent with white noise with σ=5 pT (instrumental effect).

$\delta B^2/B^2 = 0.023^2 = 0.0005$ for fluctuations in the freq. range 7.38×10^{-5} - 1.57×10^{-7} s^{-1}.

Fluctuations were compressive SD(|B|)=0.88×SD(B) during the first interval

Maximum variance direction was within 4° away from mean B during the first interval

Spectral slopes are -1.74, -1.75, and -1.35 in the R, T, and N directions

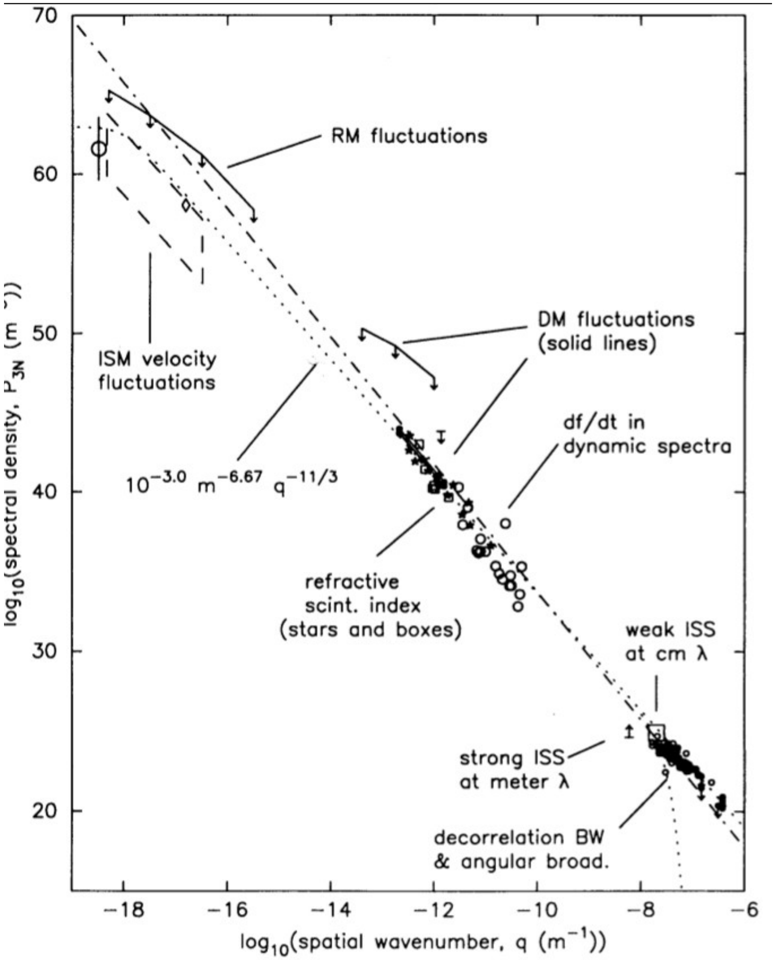
Results are different for the second interval (being analyzed). The fluctuations became primarily transverse.

Interstellar turbulence?

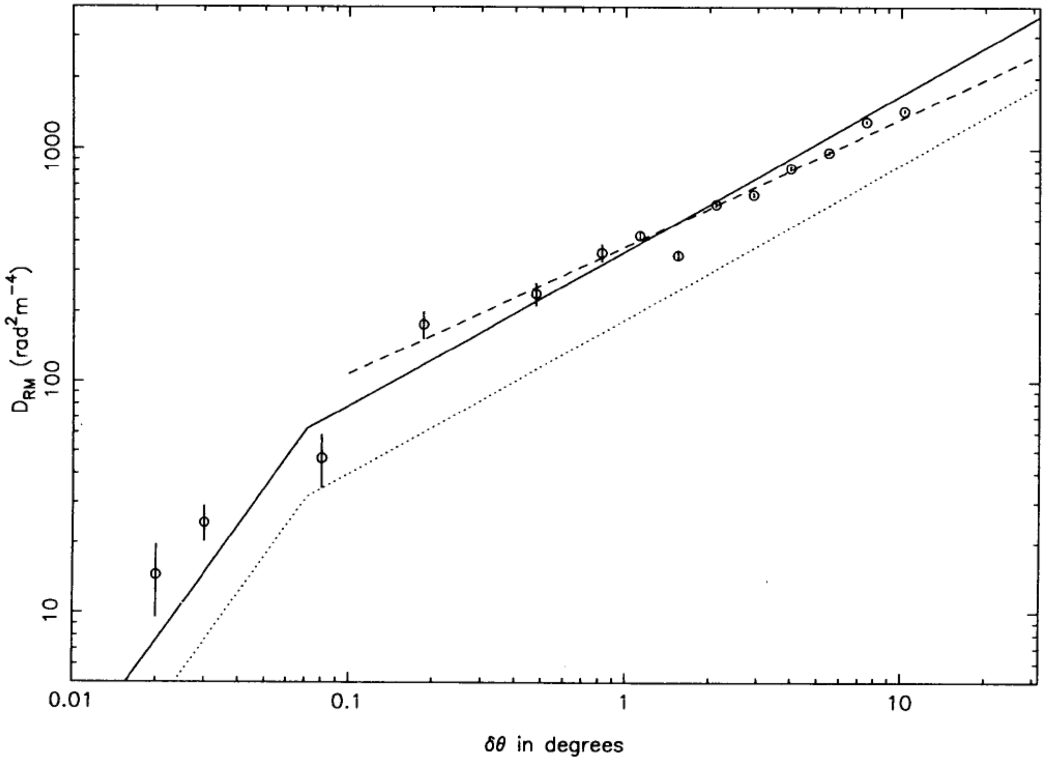
Spectral power density of magnetic fluctuation on very large scales can be measured using Faraday rotation of extragalactic radio sources

$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_0^L n_e \boldsymbol{B} \cdot \boldsymbol{ds}$$

(n_e is the electron density and L is the line of sight integration length)

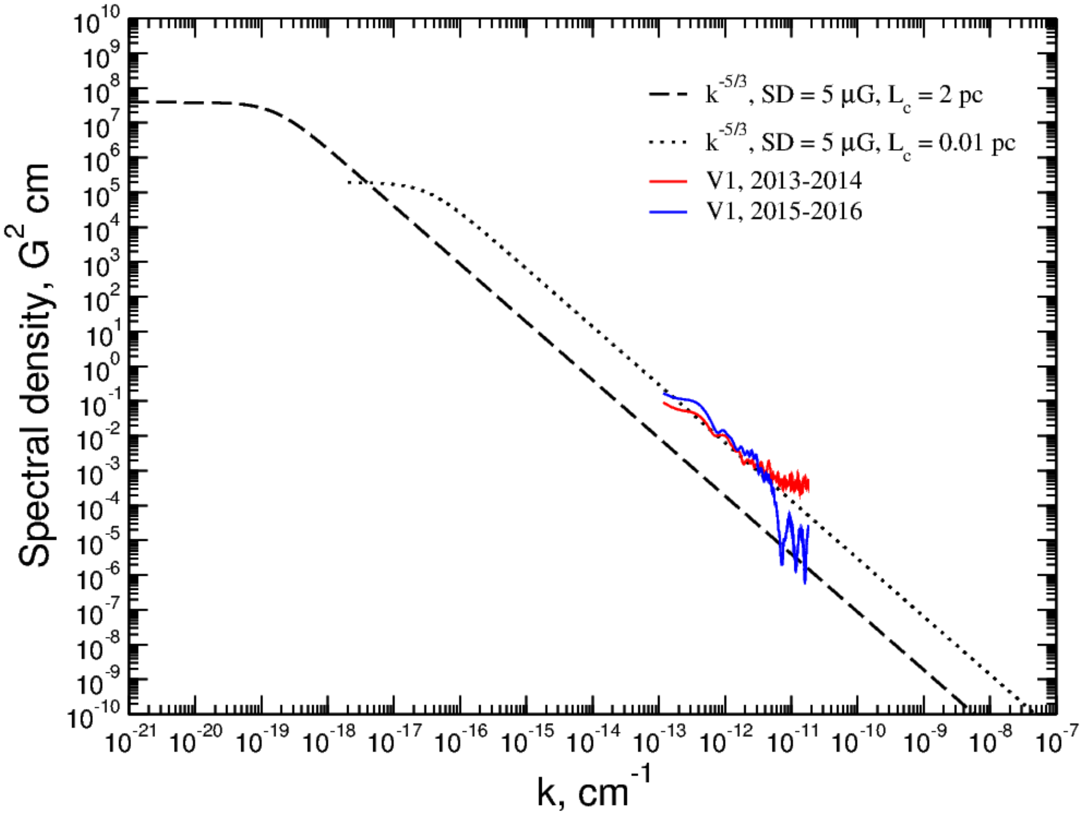


Minter & Spangler (1996)



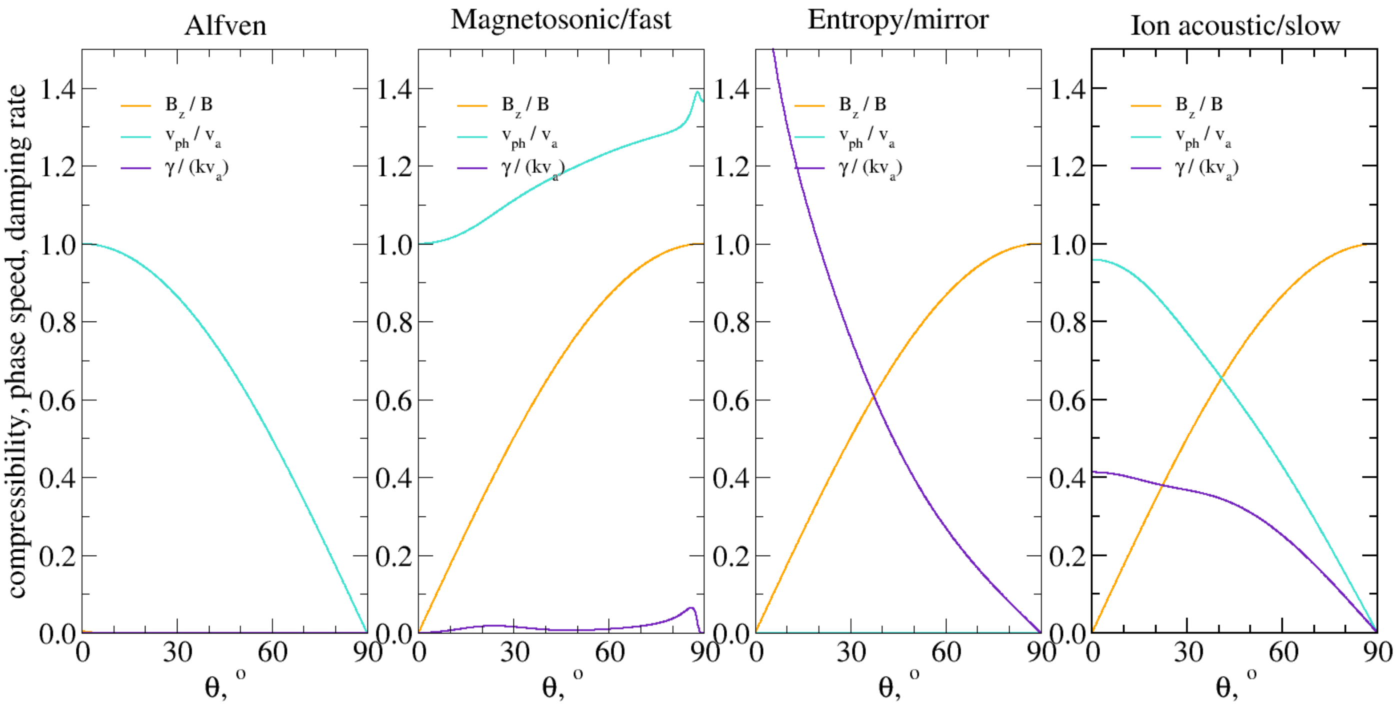
Outer scale for the Kolmogorov ($k^{-5/3}$) range is ~4 pc. At larger scales the power spectrum hardens.

Comparison with interstellar spectrum



- The measured intensity is a factor of ~100 above the "galactic" $k^{-5/3}$ power law spectrum (assuming equipartition $\langle \delta B^2 \rangle / B^2 = 1$)
- Possible local sources of fluctuations: instabilities of the heliopause from charge exchange rate gradient (e.g., Borovikov et al., 2008), magnetic reconnection (e.g., Strumik et al., 2014), magnetic interchange (e.g., Florinski 2015).
- Transmitted across the heliopause from the inner heliosheath (Zank et al., 2017).
- Local Interstellar Cloud effects?

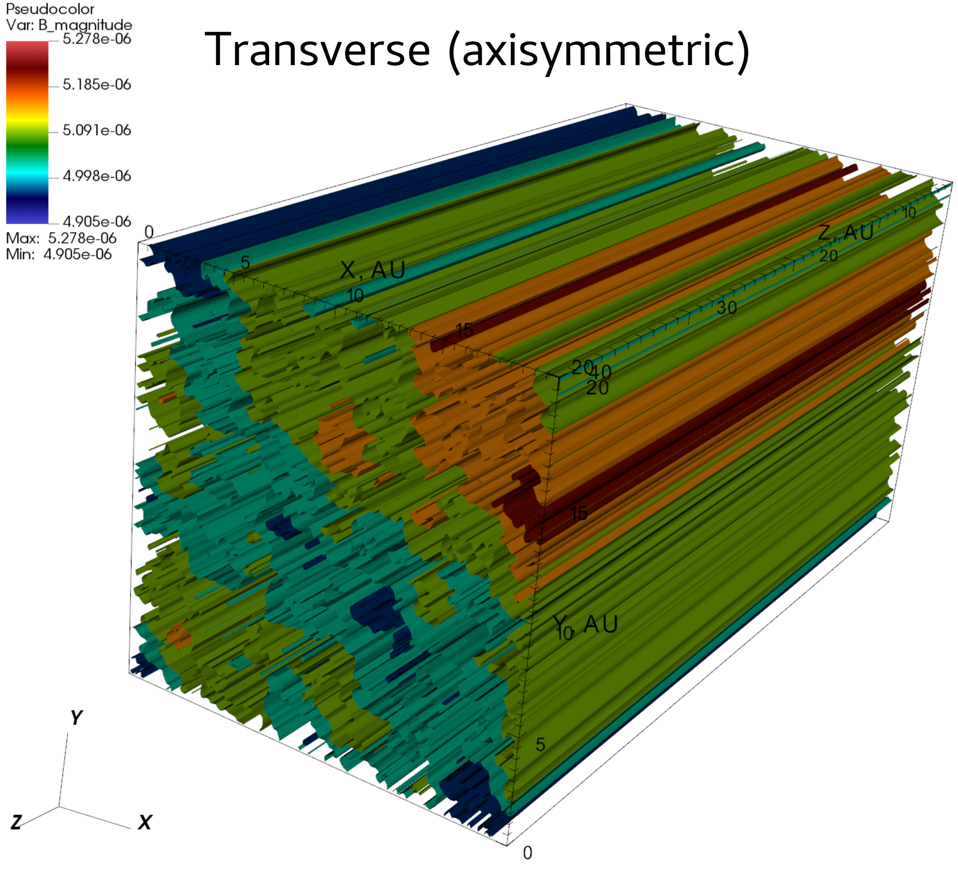
A survey of wave properties



Ion plasma beta $\beta_i \sim 0.4$ – similar to the solar wind inside 1 AU

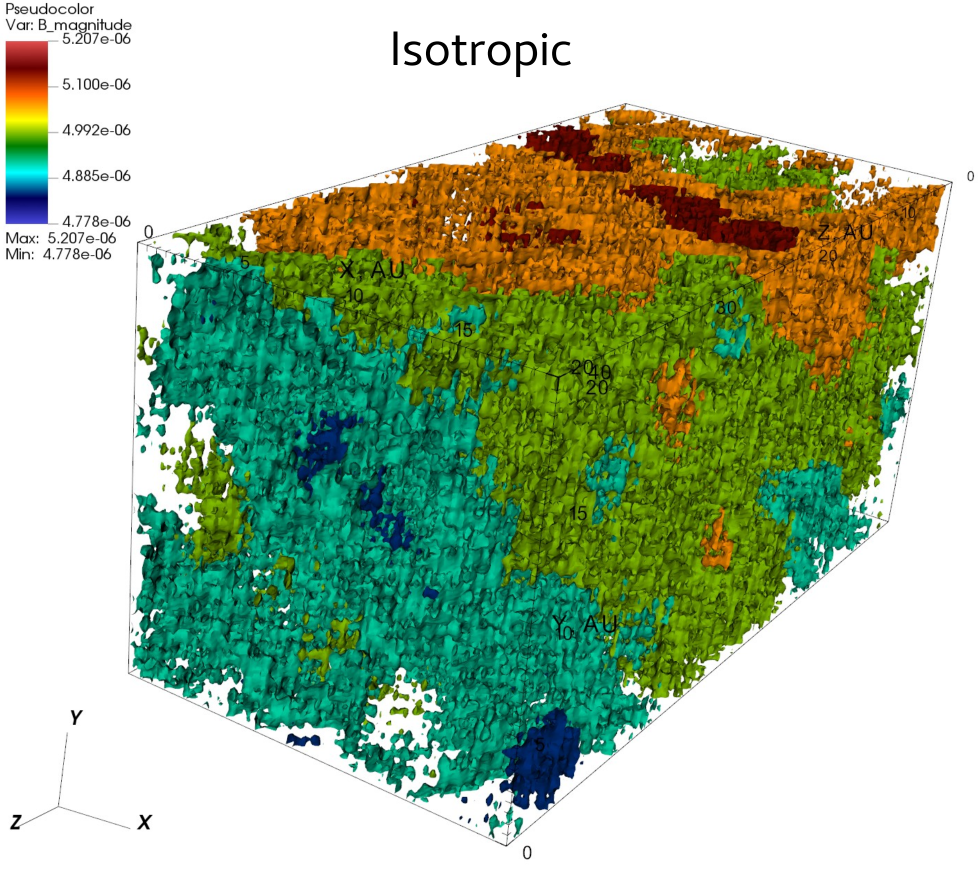
- The Alfven wave is non-compressive at all angles of propagation,
- The magnetosonic (or fast MHD) wave is compressive and weakly damped,
- The entropy mode is compressive, heavily damped and non-propagating
- The ion acoustic (or slow MHD) wave is compressive and damped, except at 90°, where it evolves into a pressure balanced structure (PBS) that is also non-propagating.

Deducing direction of propagation



Transverse (axisymmetric)

$$C_b = \frac{\langle \delta B_{\parallel}^2 \rangle^{1/2}}{\langle \delta B^2 \rangle^{1/2}} = \frac{1}{\sqrt{2}}$$



Isotropic

$$C_b = \frac{\langle \delta B_{\parallel}^2 \rangle^{1/2}}{\langle \delta B^2 \rangle^{1/2}} = \frac{1}{\sqrt{3}}$$

- Magnetic compressibility is the only parameter available – no plasma data
- Voyager 1 measured value was 0.0073 nT : 0.0107 nT = 0.68 – close to the transverse model.

Consequences for cosmic-ray transport

Florinski et al. (2013) modeled turbulence as an isotropic ensemble of fast mode waves. From quasi-linear theory (Schlickeiser and Miller, 1998; Ragot, 1999) we can obtain the parallel mean free path as

$$\lambda_{\parallel} = r_g \frac{B^2}{\langle \delta B^2 \rangle} \left(\frac{2\pi r_g V_a}{l_c v} \right)^{1-q}$$

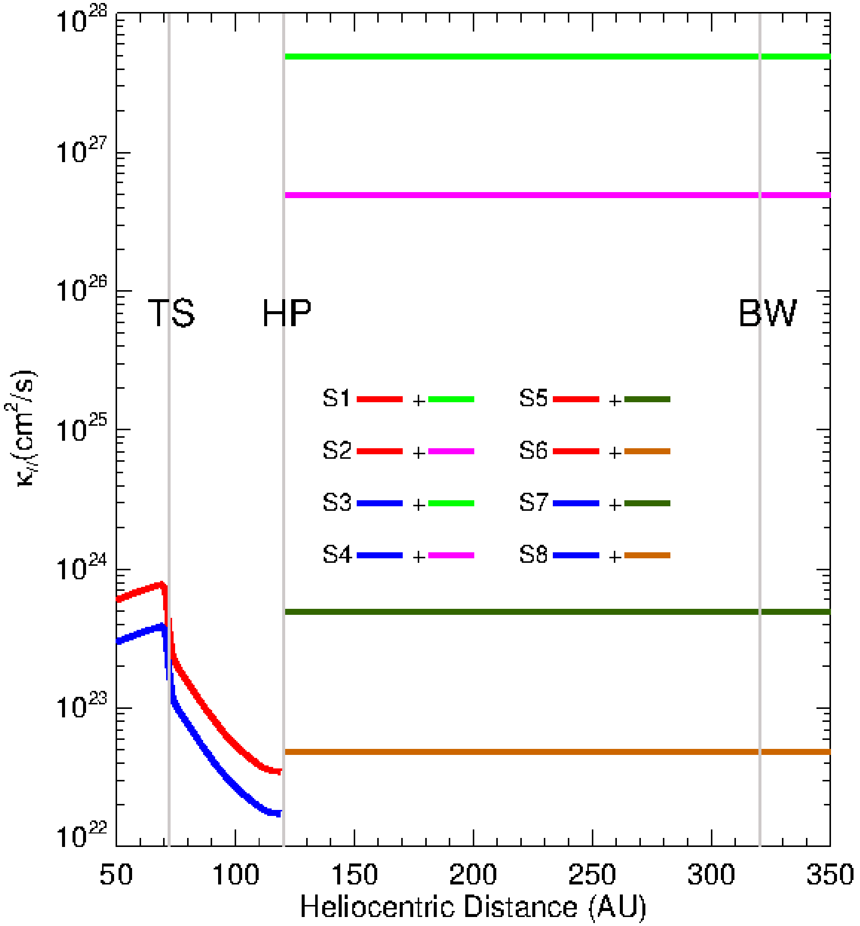
where V_a is the Alfven speed, l_c is the outer scale, and q is the turbulent spectral power law index.

Using V_a = 30 km/s, q = 5/3, l_c = 0.01 pc one obtains $\lambda_{\parallel}$ = 10,000 AU (0.05 pc) for 1 GeV protons. Cosmic-ray transport would appear to be scatter free on the scale of the heliosphere.

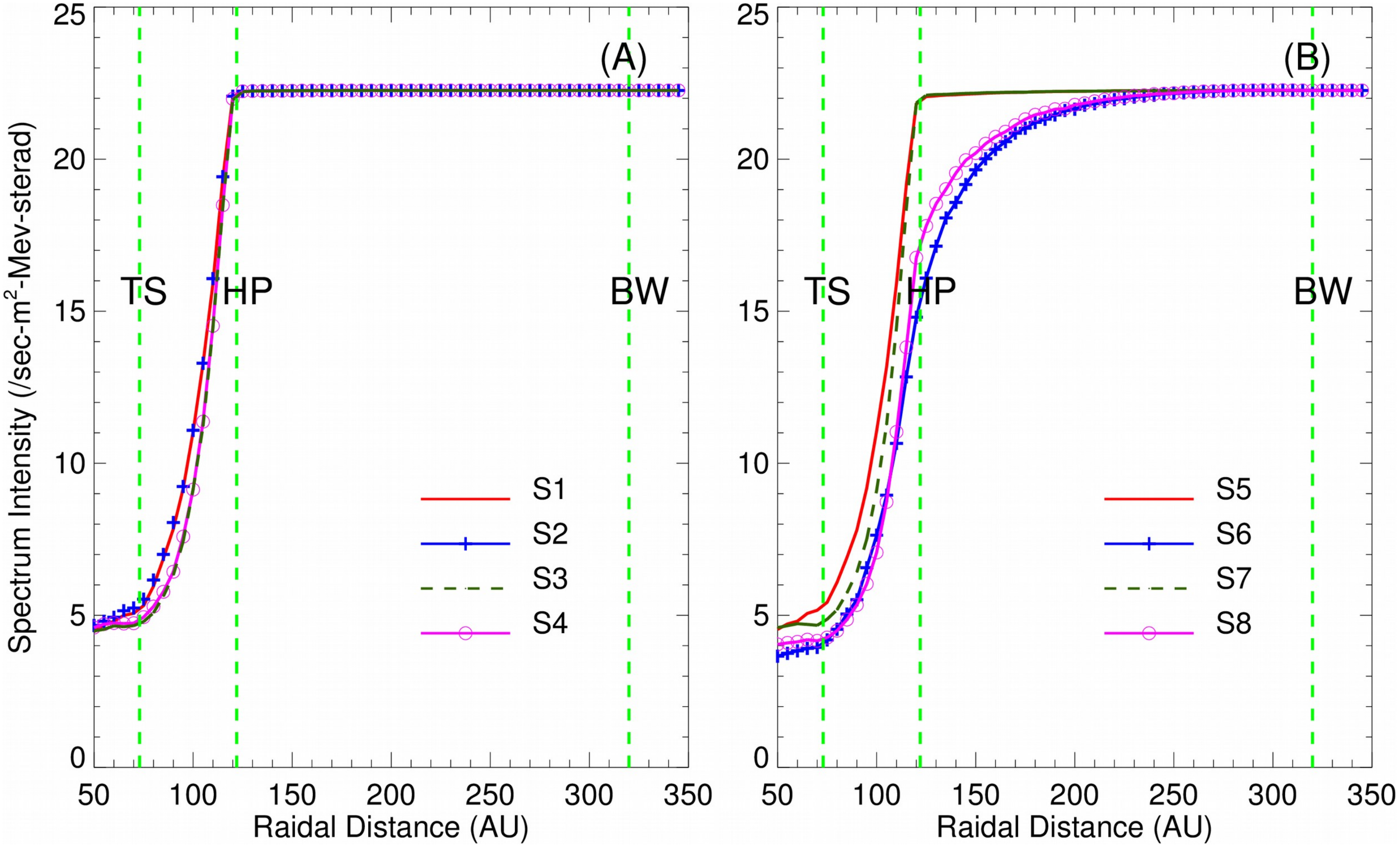
Cosmic-ray modulation in the VLISM

Guo and Florinski (2014)

Scenario	$\lambda_{0,\mathrm{inner}}(\mathrm{AU})$	$\lambda_{0,\mathrm{outer}}(\mathrm{AU})$
1	0.075	1.0×10^5
2	0.075	1.0×10^4
3	0.0385	1.0×10^5
4	0.0385	1.0×10^4
5	0.075	1.0×10^1
6	0.075	1.0×10^0
7	0.0385	1.0×10^1
8	0.0385	1.0×10^0



Testing for modulation: use a global 3D MHD model of the heliosphere and a stochastic transport model for the cosmic rays (see also Strauss et al., 2013, Kota and Jokipii, 2014, Luo et al., 2015).



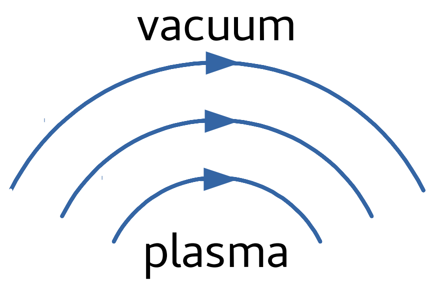
100 MeV protons

- 2 out of 8 models predict non-negligible modulation in the OHS (6, 8)
- Neither of these two model's parameters are realistic (require diffusion coefficient some 10^4 times smaller than expected for the VLISM).

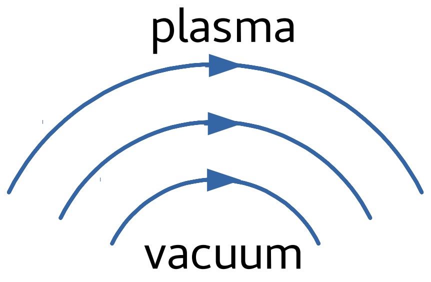
Possible source of fluctuations: interchange at the heliopause

inner heliosheath	outer heliosheath
B_0=2 μG	B_0=4.4 μG
n_0~2×10^{-3} cm^{-3}	n_0~5×10^{-2} cm^{-3}
T_{eff}~1.6×10^{6} K	T_{eff}~2×10^{4} K
β=5.5	β=0.36

The heliopause is convex toward the interstellar medium. The equilibrium state is that of a plasma confined by convex magnetic field lines ("bad curvature"), which is known to be unstable from the studies of fusion plasma confinement. First mentioned in Krimigis et al. (2013) in the context of the heliopause.



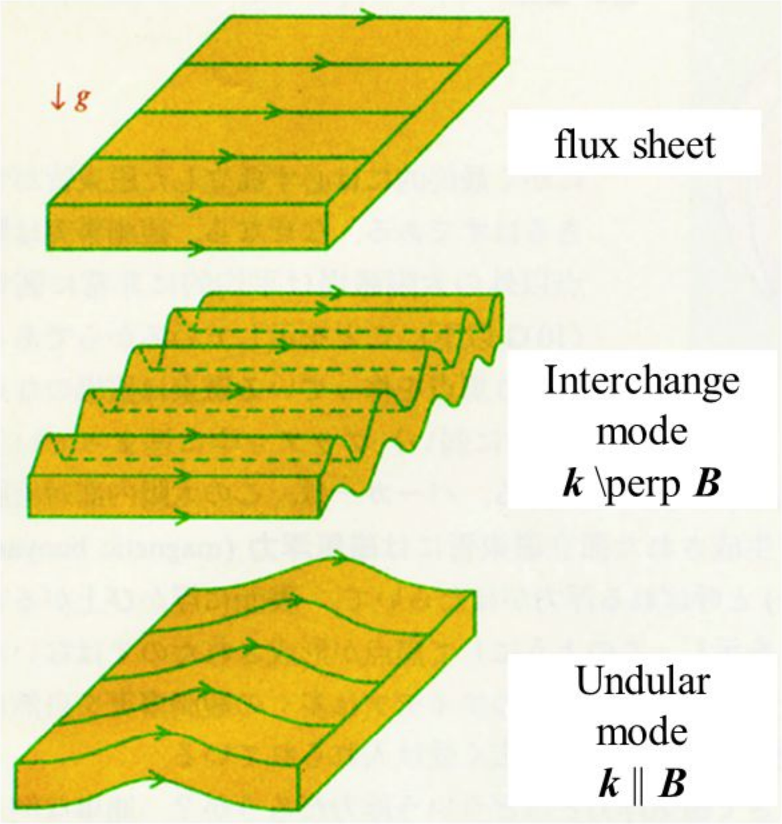
"bad"



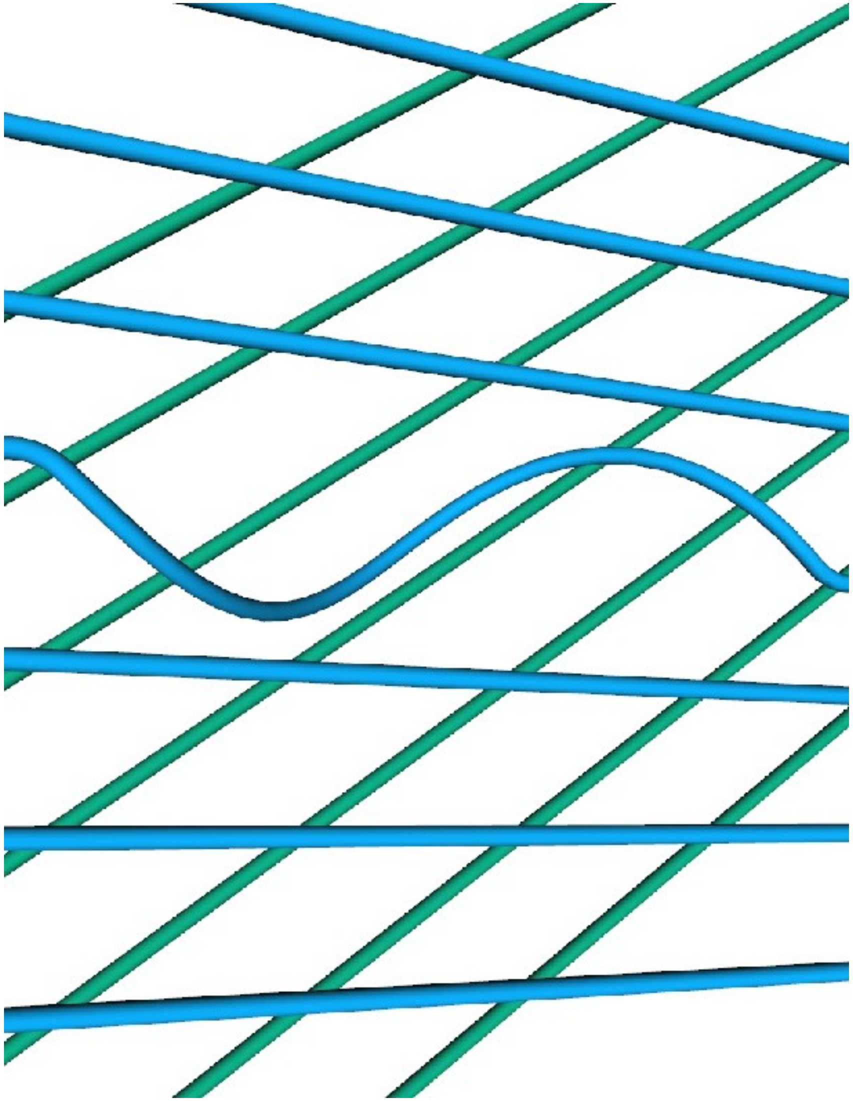
"good"

Centrifugal force from guiding center motion along curved field lines

Instability threshold: $$\frac{d\ln p_0}{d\ln r} < -\frac{4\gamma}{2+\gamma\beta}$$ always satisfied for the HP

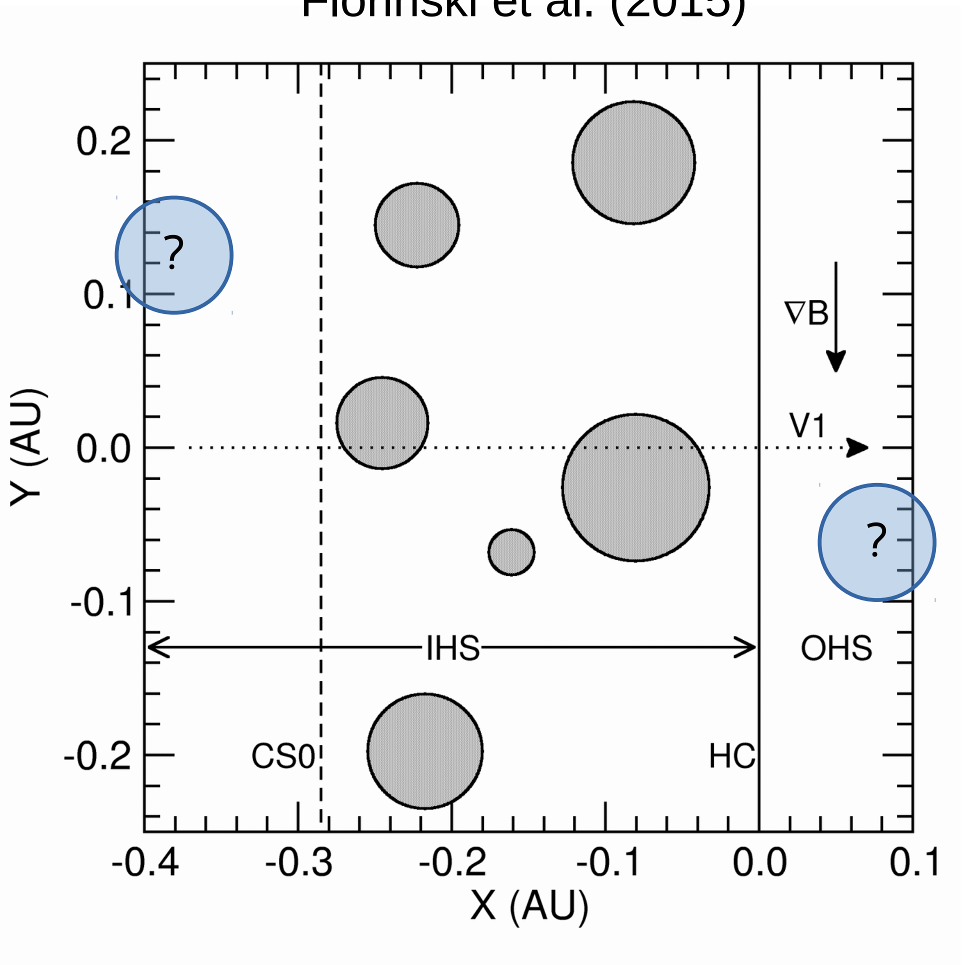


The fastest growing mode has **k•B**=0 (interchange) because it involves no bending of magnetic field lines



Magnetic flux tube mixing

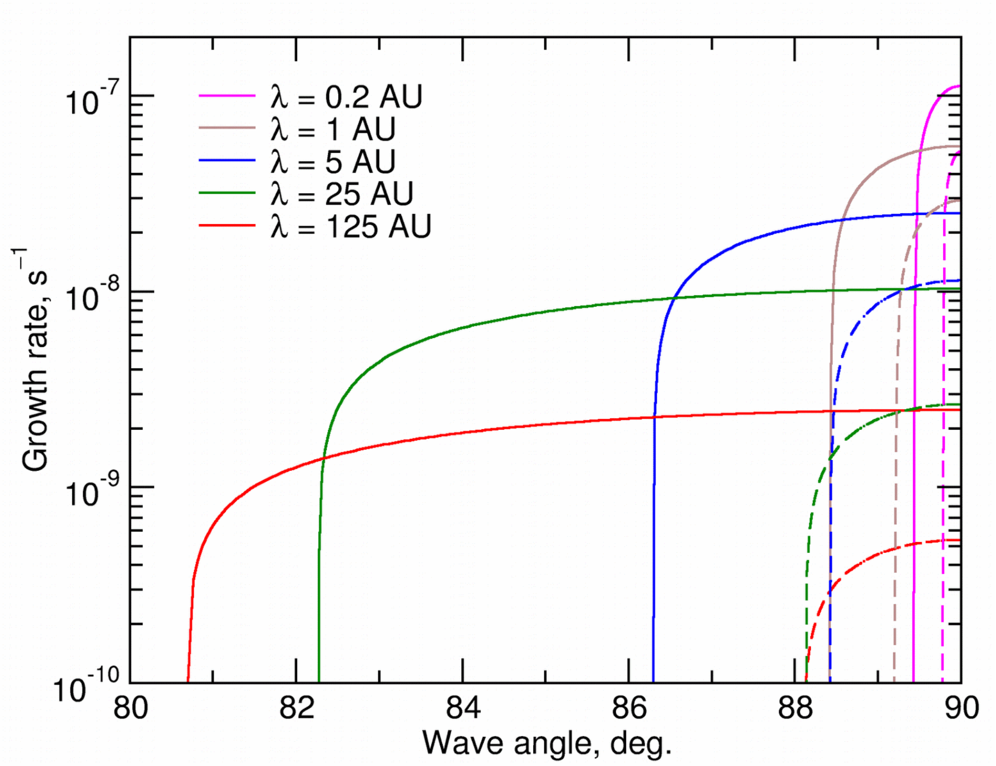
Florinski et al. (2015)



- Heliopause transition region becomes permeated by interchanged flux tubes.
- Flux tubes connected to LISM at both ends, ACRs can readily escape both ways.
- Magnetic field rotates gradually over the width of the flux tube region, as observed.
- The first step increase in GCRs might be the inner edge of the flux-tube permeated region.

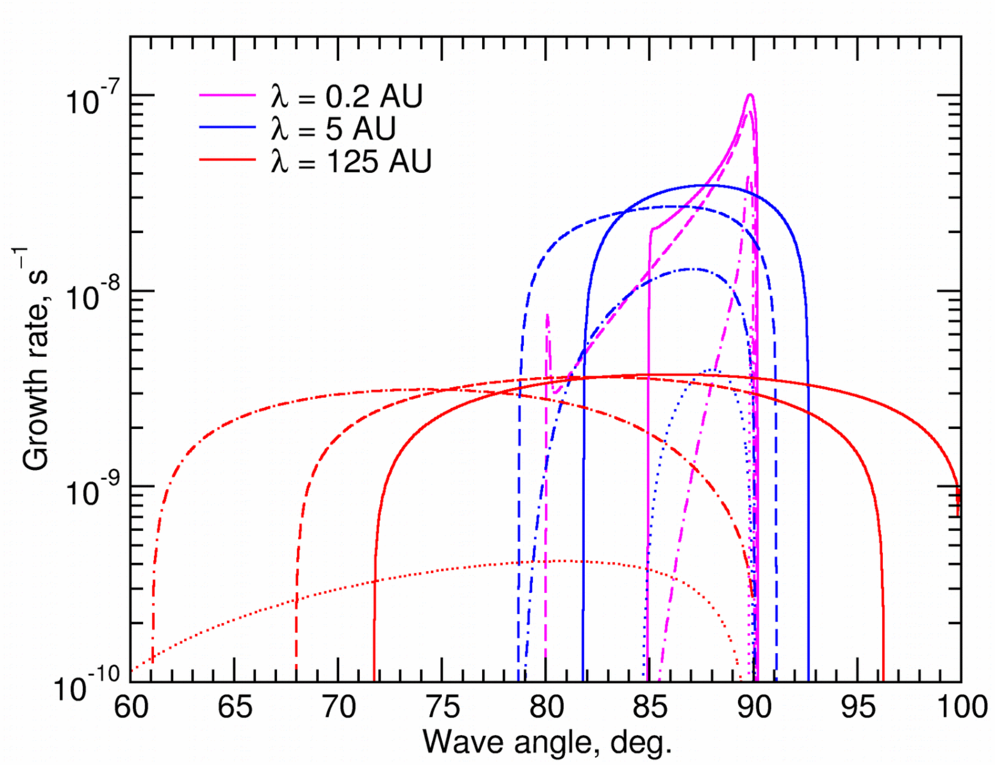
Interchange instability growth rates

zero shear



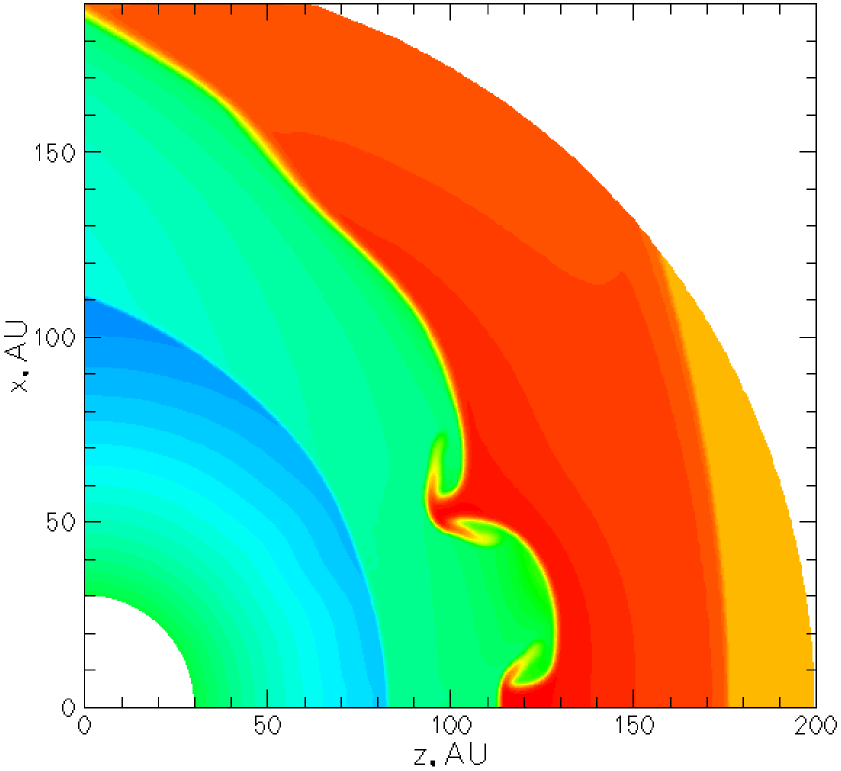
Florinski (2015)

14° shear

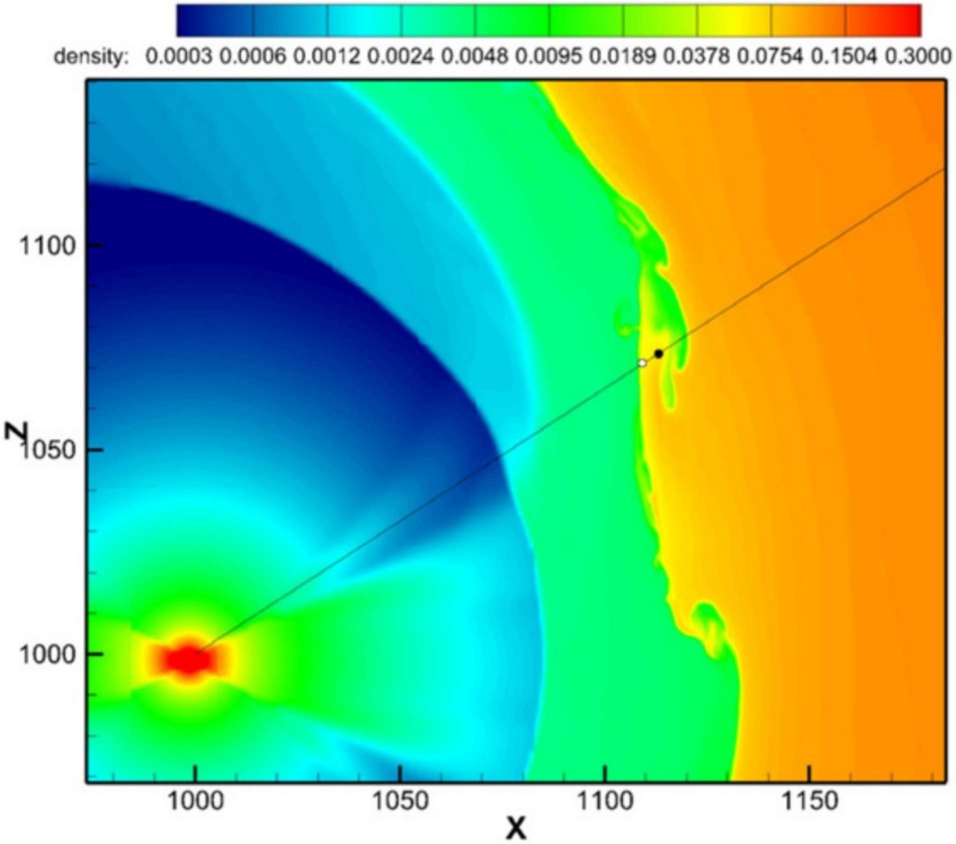


- Shear angles smaller than 20° are unstable – V1 (14° change in elevation angle), but probably not V2.
- Long (tens of AU), thin filaments – consistent with the properties of the flux tubes. Growth time 2 months to several years.
- Flux tubes from the OHS may intrude the IHS, rotating to adapt to the dominant field in the IHS, interchange becomes possible.

Charge-exchange driven instabilities of the heliopause (Liewer et al., 1996, Zank 2001). Rayleigh-Taylor like, driven by the difference in charge-exchange rates on the two sides of the HP (higher in the OHS). Stabilized by a magnetic field (?)



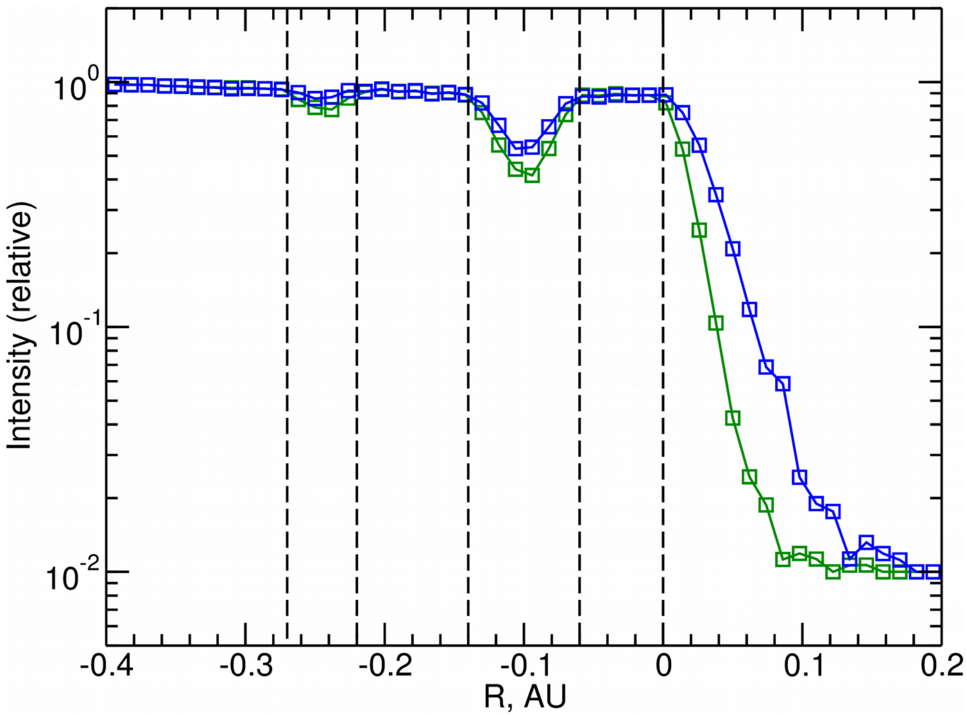
Florinski et al. (2005): theory + GD, 2D model



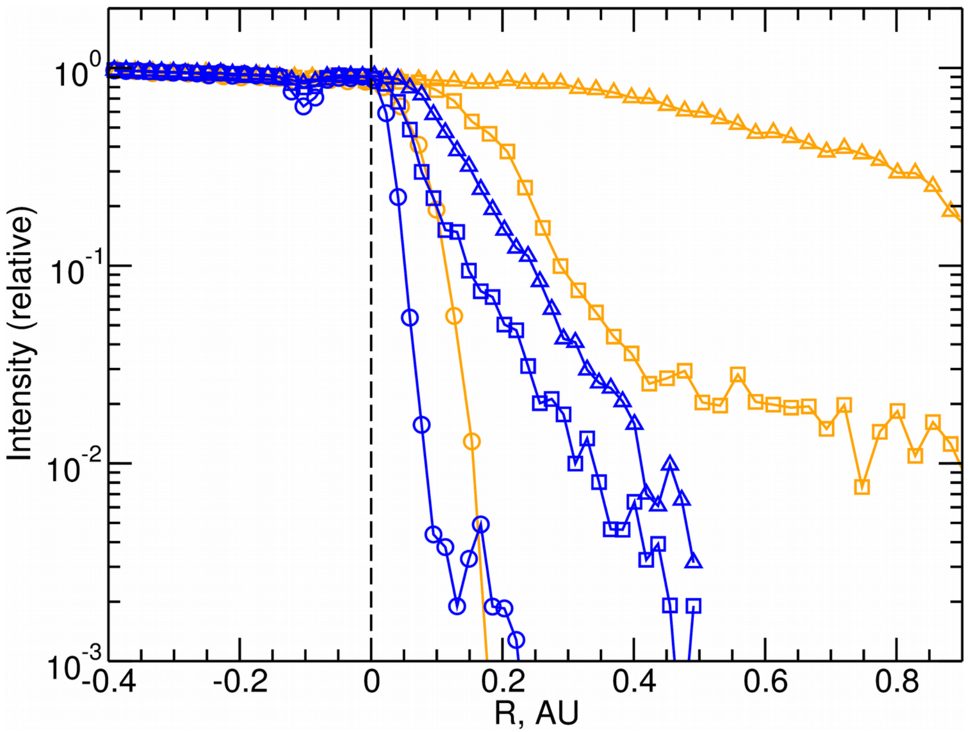
Borovikov & Pogorelov (2014): MHD, 3D model, solar cycle

Pancake anisotropies of heliospheric ions

H: gyrating vs. streaming



He^{+1} vs O^{+1}



- The heliopause is a tangential discontinuity possessing a magnetic shear layer.
- Alternative: near reconnection site (Swizdak et al. 2013) creating direct path into the VLISM. However, field aligned anisotropies were not observed.
- The gyrating particles are able to overcome the shear layer owing to their large Larmor radius, whereas streaming particles are stopped by the barrier.
- Cross field transport may be provided by drift (Florinski et al., 2015) or perpendicular diffusion (Strauss et al., 2015).

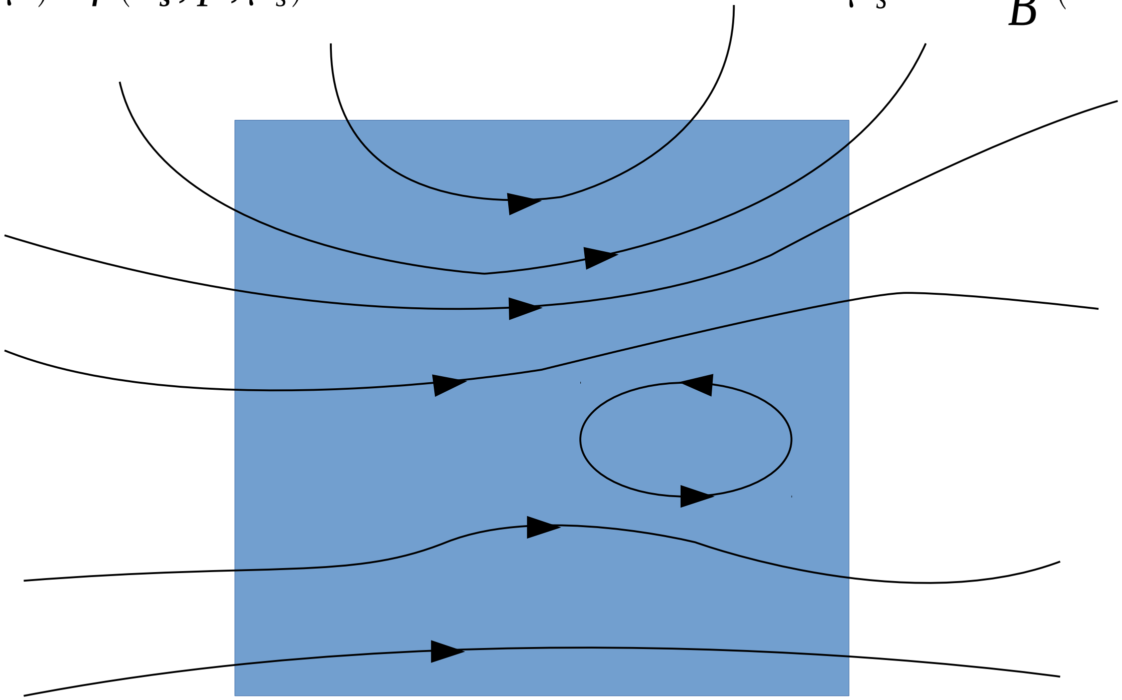
GCR 90° anisotropy puzzle

Generating anisotropies from an existing isotropic population is difficult!

In a static magnetic field, if the distribution function is uniform and isotropic on the boundary of some volume, then it is also isotropic inside, provided there are no local minima in the magnetic field along any field line and no closed field line loops.

$$f(\boldsymbol{r}, p, \mu) = f(\boldsymbol{r}_s, p, \mu_s)$$

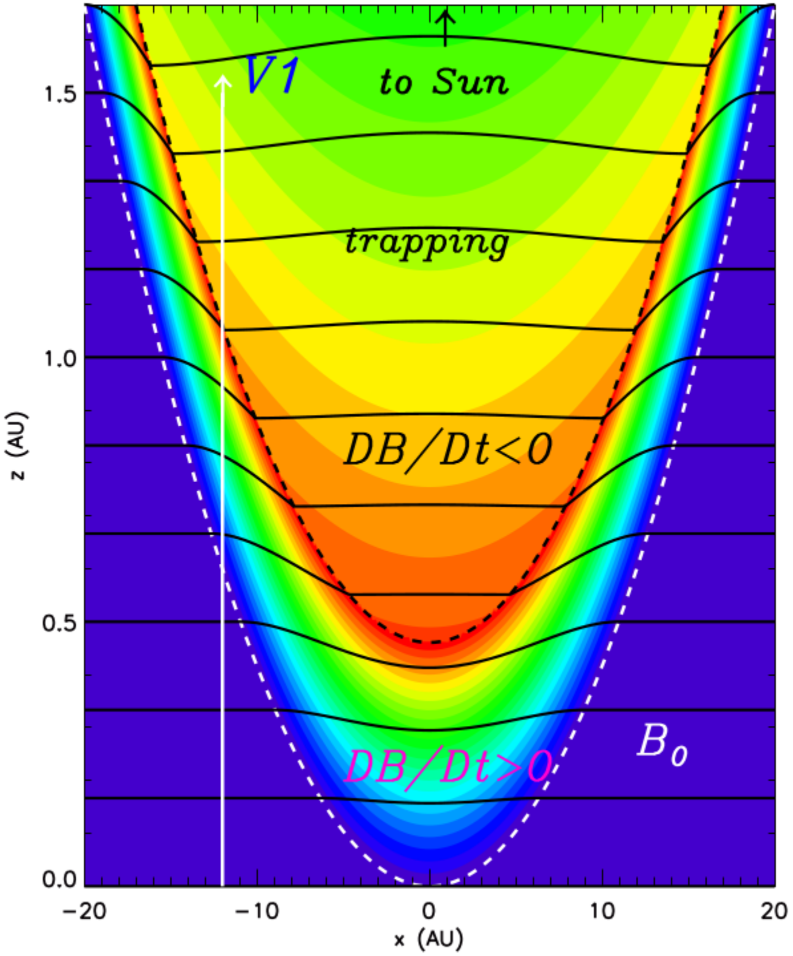
$$\mu_s^2 = 1 - \frac{B_s}{B}(1-\mu^2)$$



Possible escape from “Louiville curse”:

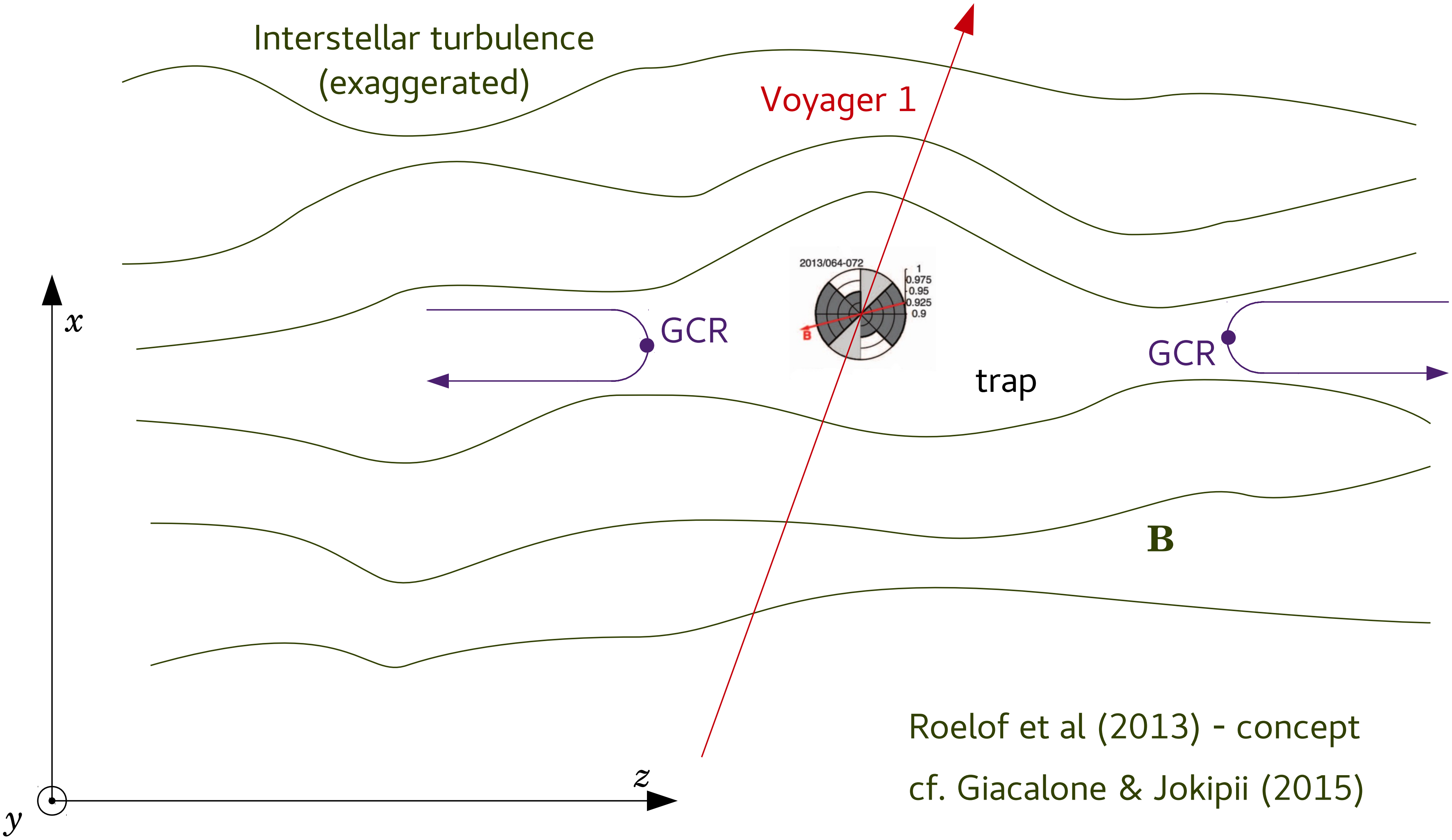
“Steady state”: Remap the $\mu=0$ region into higher momentum p at the source
”Time dependent”: Source variation, gradients – not observed

Possible explanations of GCR anisotropy



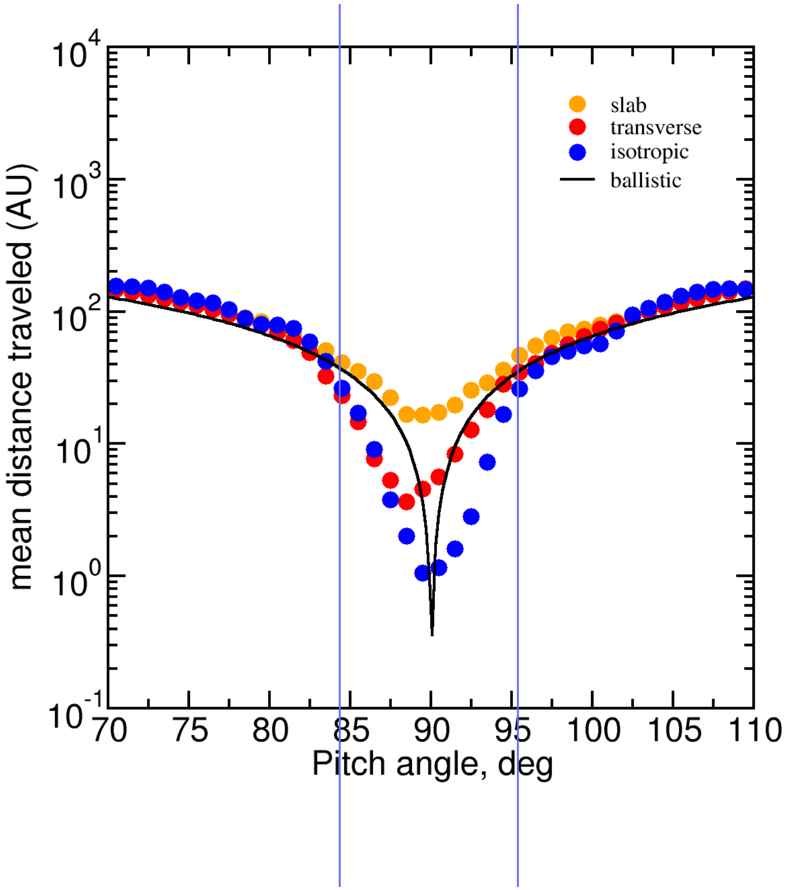
- Roelof (2013, unpublished) suggested focusing / reflection creates a narrow gap in the distribution at 90 degrees. This appears to to be in contradiction with the Liouville’s theorem.
- Cairns and Fuselier (2017) suggested a relationship with the plasma depletion layer, but did not identify the mechanism.
- Kota and Jokipii (2017) proposed that the gyrating CRs cool off in the expansion region behind a shock. This would map them into a less dense region of the velocity space.

Compressive magnetic fluctuations?

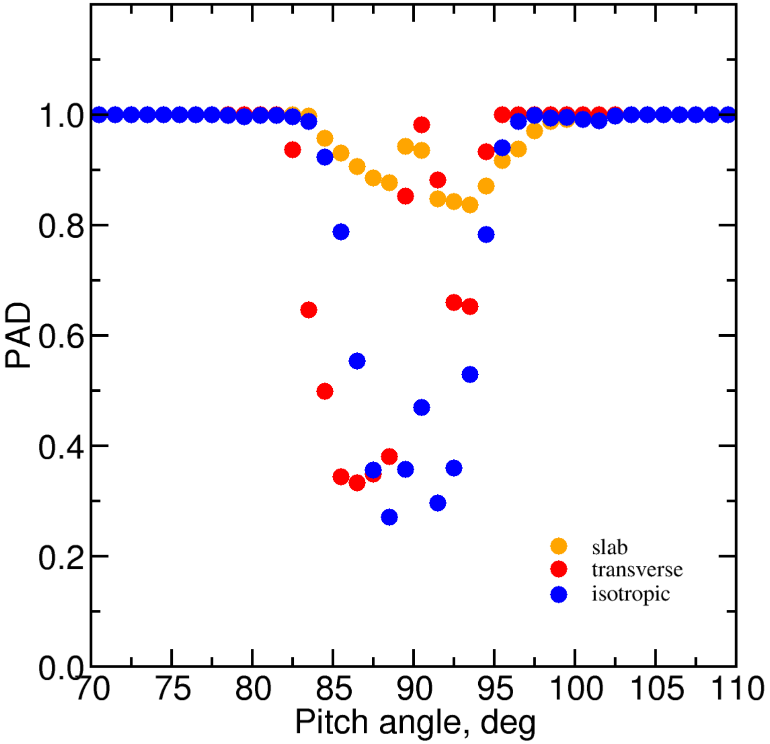


Roelof et al (2013) - concept

cf. Giacalone & Jokipii (2015)



partial rejection range



Transport is non-diffusive, no $\Delta z \sim \Delta t^{1/2}$ behavior observed.

Trapped particles in this backward simulations correspond to inaccessible phase space in a forward simulation (complimentary to a loss cone).

Pitch angle distribution might develop a gap near $\mu = 0$.

Magnetic trap empty initially – not realistic. Louiville’s curse still applies!

Summary

- Magnetic field continues to evolve slowly in the VLISM, as a result of draping around the heliopause,
- Low frequency magnetic fluctuations are observed throughout Voyager 1 journey through the VLISM. Their amplitude is well above the hypothetical spectrum of galactic fluctiations.
- Galactic cosmic ray intensities are essentially constant in the VLISM,
- The 90 degree gyrating anisotropy of the heliospheric particles can be understood in terms of cross field transport at the heliopause,
- The 90 degree gyrating anisotropy of GCRs is still not understood at the present, but the shock model appears promising.