OVERVIEW OF MODELING CHALLENGES FOR THE OUTER HELIOSPHERE AND INTERSTELLAR MEDIUM

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OUTLINE:

Current understanding and open questions about the modeling of the

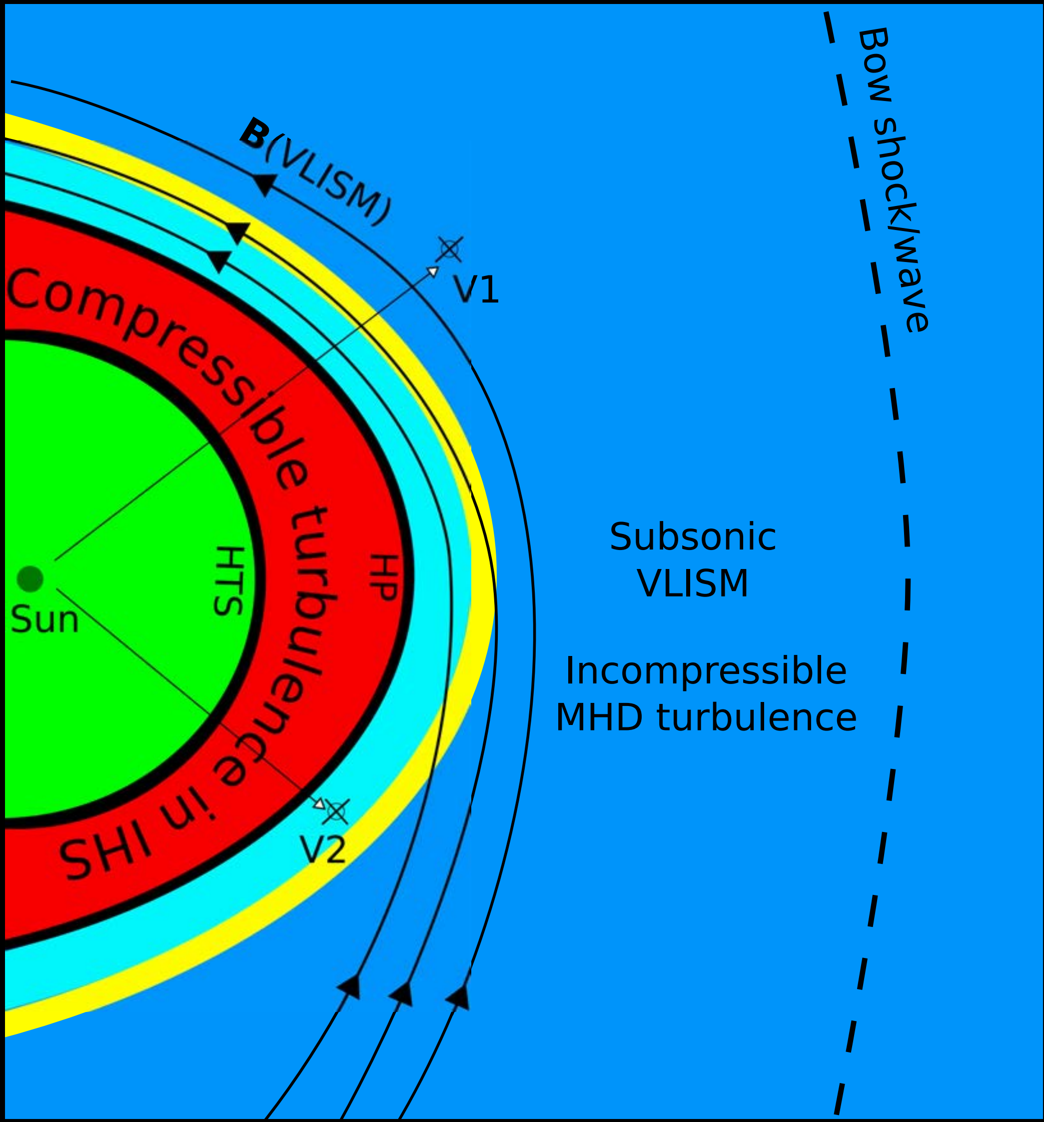
1) Supersonic Solar Wind

2) Heliospheric Termination Shock (HTS)

3) Inner Heliosheath (IHS)

4) Heliopause (HP)

5) Very Local Interstellar Medium (VLISM)



1) SUPERSONIC SOLAR WIND

- **Charge-exchange between solar wind protons and neutral atoms** creates PUIs with a loss of solar wind plasma density, momentum and energy.
- The solar wind includes low-frequency turbulence advected with the solar wind. **The dissipation of the turbulence** contributes to the **heating of the solar wind**
- Newly born PUIs form an unstable ring-beam distribution and are **a source of low-frequency turbulence** The **PUIs are then scattered** to a nearly-isotropic distribution by the turbulence. PUIs are **not** equilibrated with the background solar wind plasma.
- ***The solar wind is mediated by PUIs.***
- Models can be compared with results from the **New Horizon** (NH) Solar Wind Around Pluto (SWAP) instrument and **Voyager 2** measurements for both the **solar wind plasma** and **PUIs** from 1 and 75 au.

How to incorporate PUIs – kinetic, fluid?

General description:

$$\frac{\partial f_p}{\partial t} + \boldsymbol{v}\cdot\nabla f_p + \frac{\boldsymbol{F}}{m}\cdot\nabla_v f_p = \left.\frac{\delta f_p}{\delta t}\right)_{ce} + S_p^{ph} + \left.\frac{\delta f_p}{\delta t}\right)_{wp},$$

$$\begin{aligned}\left.\frac{\delta f_p}{\delta t}\right)_{ce}(\boldsymbol{v}) = &\int \sigma|\boldsymbol{v}-\boldsymbol{v}'| f_{\mathrm{H}}(\boldsymbol{v}) f_s(\boldsymbol{v}')\,d\boldsymbol{v}' \\ &+ \int \sigma|\boldsymbol{v}-\boldsymbol{v}'| f_{\mathrm{H}}(\boldsymbol{v}) f_p(\boldsymbol{v}')\,d\boldsymbol{v}' \\ &- \int \sigma|\boldsymbol{v}-\boldsymbol{v}'| f_p(\boldsymbol{v}) f_{\mathrm{H}}(\boldsymbol{v}')\,d\boldsymbol{v}'.\end{aligned}$$

Simplest description is V-S (bottom right), <u>assuming isotropic PUI distribution</u>;
V-S can fit New Horizons observed PUI distributions but unrealistic parameters;
V-S not good enough!
Critical role of WP-term

Collisional Simplifications: Assume the source and loss terms of CE between pickup protons and H are approximately balanced and that σ is independent of proton and neutral H velocities and that solar wind proton distribution function $f_s(\mathbf{x}, \mathbf{v}, t)$ is Maxwellian.

$$\begin{aligned}\frac{\partial f_p}{\partial t} + \boldsymbol{v}\cdot\nabla f_p + \frac{\boldsymbol{F}}{m}\cdot\nabla_v f_p = &\ \sigma n_s \\ &\times \sqrt{\frac{4}{\pi}v_{Ts}^2 + |\boldsymbol{U}-\boldsymbol{U}_{\mathrm{H}}|^2}\, f_{\mathrm{H}}(\boldsymbol{v}) + S_p^{ph} + \left.\frac{\delta f_p}{\delta t}\right)_{wp},\end{aligned}$$

Further assume (i) a **cold neutral H distribution**, (ii) the **neutral H drift speed U_H = 0**, and (iii) a **cold solar wind plasma**, i.e., $T_s = 0$. CE source term for PUIs becomes

$$S_{ch}(r, v) = \sigma n_s U N(r) \frac{\delta(v-U)}{4\pi v^2}.$$

Wave-Particle Scattering

Gyrophase-averaged Non-relativistic PUI transport equation with wave-particle scattering:

$$\frac{\partial f}{\partial t} + (U_i + c\mu b_i)\frac{\partial f}{\partial x_i} + \frac{1-\mu^2}{2}\left[c\nabla\cdot\mathbf{b} + \mu\nabla\cdot\mathbf{U} - 3b_i b_j \frac{\partial U_j}{\partial x_i} - \frac{2b_i}{c}\frac{DU_i}{Dt}\right]\frac{\partial f}{\partial \mu}$$
$$+\left[\frac{1-3\mu^2}{2}b_i b_j \frac{\partial U_j}{\partial x_i} - \frac{1-\mu^2}{2}\nabla\cdot\mathbf{U} - \frac{\mu b_i}{c}\frac{DU_i}{Dt}\right]c\frac{\partial f}{\partial c} = \boxed{\frac{\partial}{\partial \mu}\left(\nu_s(1-\mu^2)\frac{\partial f}{\partial \mu}\right),}$$

Scattering term:
Lorentz form?
bi-hemispherical?
Ulysses observations?
IMAP?
Role of turbulence?

$$\nu_s f_1 \simeq -\frac{cb_i}{3}\frac{\partial f_0}{\partial x_i} + \frac{DU_i}{Dt}\frac{b_i}{3}\frac{\partial f_0}{\partial c}.$$

➔

$$\frac{\partial f_0}{\partial t} + \mathbf{U}\cdot f_0 - \frac{c}{3}\nabla\cdot\mathbf{U}\frac{\partial f_0}{\partial c} + \nabla\cdot\left(\mathbf{K}\frac{D\mathbf{U}}{Dt}\frac{1}{c}\frac{\partial f_0}{\partial c}\right) = \nabla\cdot(\mathbf{K}\cdot\nabla f_0),$$

$$f_2 \simeq \frac{c\tau_s}{15}\left(b_i b_j \frac{\partial U_j}{\partial x_i} - \frac{1}{3}\frac{\partial U_i}{\partial x_i}\right)\frac{\partial f_0}{\partial c}.$$

➔ Higher order "viscous"-like terms

PUI energization:
Shock waves (interplanetary, HTS)?
Magnetic structures – flux ropes/islands?

Strong scattering?
Modified transport equation?
Gyrophase-averaging appropriate for PUIs?
Role of structures (magnetic flux ropes/islands)?
Role of perp scattering?
Spatial diffusion?
Acceleration terms?

Building a coupled description: Use pitch-angle scattering operator to solve for $f_p(\mathbf{x}, \boldsymbol{v}, t)$ in terms of isotropic leading-order term f_{p0}, plus first- and second-order corrections f_{p1} and f_{p2}. **Expansion of PUI distribution function yields a Chapman–Enskog closure of the pressure tensor and heat flux PUI terms, introducing a first-order heat flux and a second-order viscosity.**

MHD-LIKE MULTI-FLUID EQUATIONS

Conservation form:

Zank et al. (2014, 2016);

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{U}) = -S_c^s$$

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \mathbf{U}) = S_c^s + S_p^{ph}$$

Continuity Eq.

PUI stress tensor

$$\frac{\partial}{\partial t}(\rho \mathbf{U}) + \nabla \cdot \left[\rho \mathbf{U}\mathbf{U} + P_s \mathbf{I} + P_p \mathbf{I} + \mathbf{\Pi}_p + \frac{1}{2\mu_0} B^2 \mathbf{I} - \frac{1}{\mu_0}\mathbf{B}\mathbf{B}\right] = \mathbf{S}_p^m + \mathbf{U}_H S_p^{ph}$$

Momentum Eq.

Turbulent heating

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho U^2 + \frac{P_s}{\gamma_s - 1} + \frac{P_p}{\gamma_p - 1} + \frac{B^2}{2\mu_0}\right) + \nabla \cdot \left[\frac{1}{2}\rho U^2 \mathbf{U} + \frac{\gamma_s}{\gamma_s - 1} P_s \mathbf{U} + \frac{\gamma_p}{\gamma_p - 1} P_p \mathbf{U} + \frac{B^2}{\mu_0}\mathbf{U} + \mathbf{\Pi}_p \cdot \mathbf{U} - \frac{1}{\mu_0}\mathbf{U} \cdot \mathbf{B}\mathbf{B} - \frac{1}{\gamma_p - 1}\frac{1}{3}\mathbf{K}_p \cdot \nabla P_p\right] = S_p^e + \boxed{S_t}$$

Total energy Eq.

PUI heat conduction

$$\frac{\partial P_p}{\partial t} + \mathbf{U} \cdot \nabla P_p + \gamma_p P_p \nabla \cdot \mathbf{U} = \frac{1}{3}\nabla \cdot (\mathbf{K}_p \cdot \nabla P_p) - (\gamma_p - 1)\mathbf{\Pi}_p : (\nabla \mathbf{U}) + (\gamma_p - 1) S_p^e$$

PUI energy Eq.

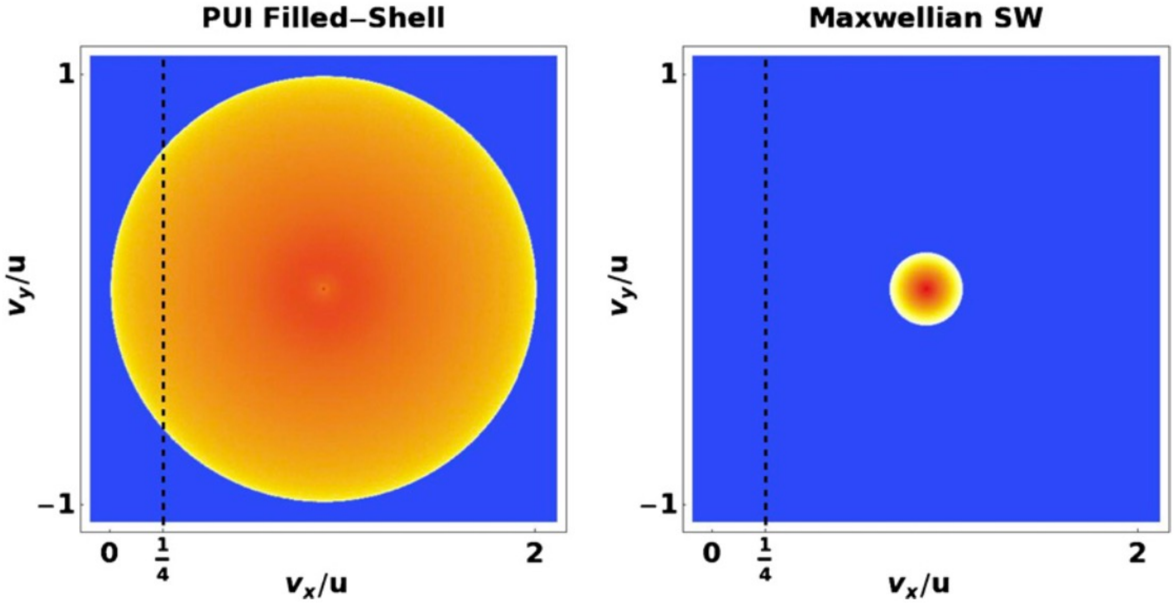
Fluid description of PUI mediated solar wind.

Turbulence in the Outer Heliosphere

Turbulence source terms:

$$+ 2C^{*\pm}_{\rm sh}\frac{r_0|\Delta U|V_A^2}{r^2} + \frac{f_D n_{\rm H}^{\infty} U V_A}{n_{SW}^{0}\tau_{\rm ion}^{0}}\exp\left(\frac{-L}{r}\right);$$

Shear source + PUI-driven source

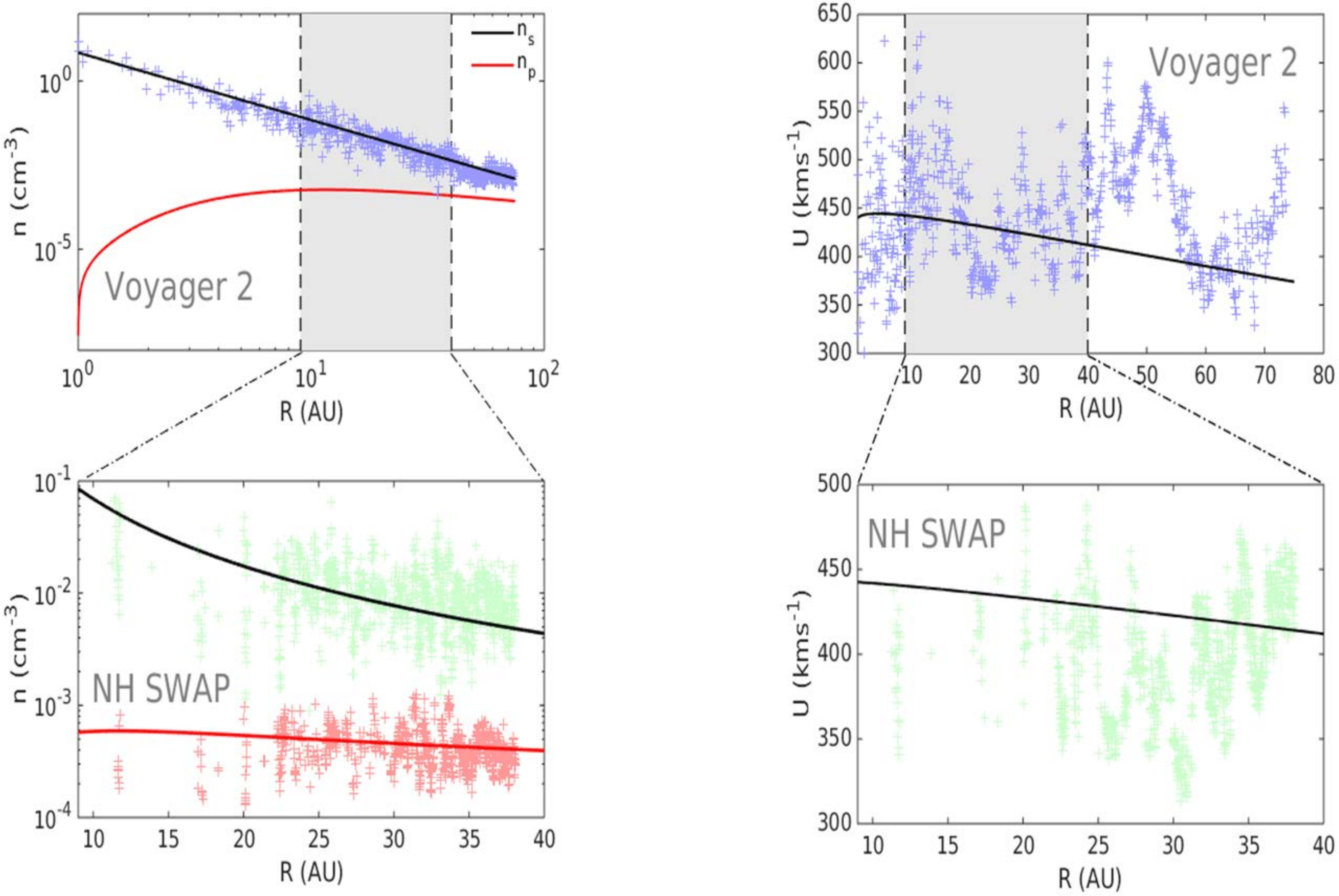


Non-equilibrated proton distribution function in distant SW

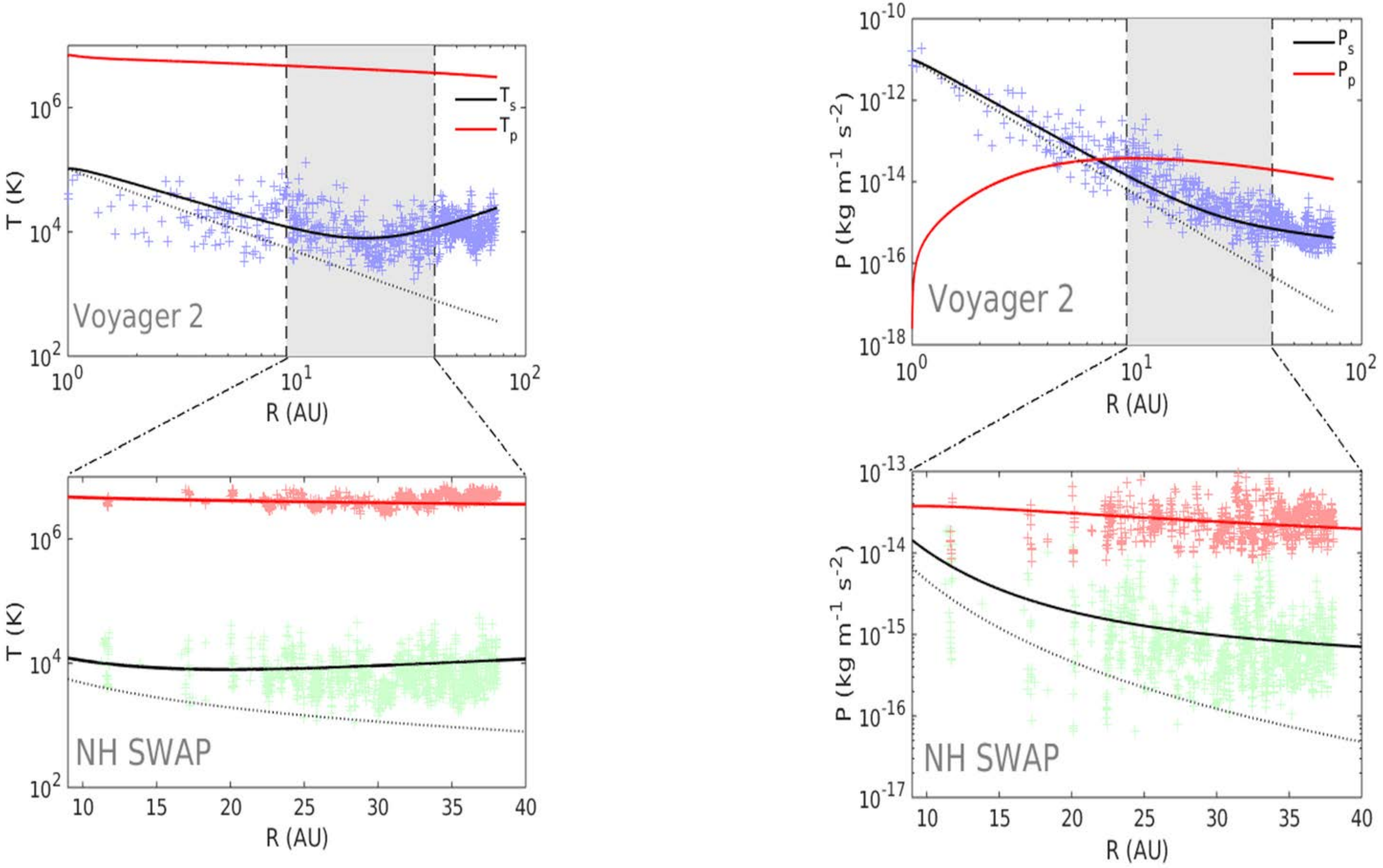
Nature of turbulence:

- Does turbulence change in the outer heliosphere from the inner heliosphere?
- Inner heliosphere description appears to be superposition of dominant quasi-2D-minority slab component – is this still true of distant SW?
- Turbulence transport models
- What is nature of dissipation process in plasma comprised of distinct suprathermal PUI and cold Maxwellian SW distribution?
- Is the PUI source term for turbulence fully correct (ring-beam instability, QLT scattering onto bispherical shell)?
- Should the full system be treated as a closed system?

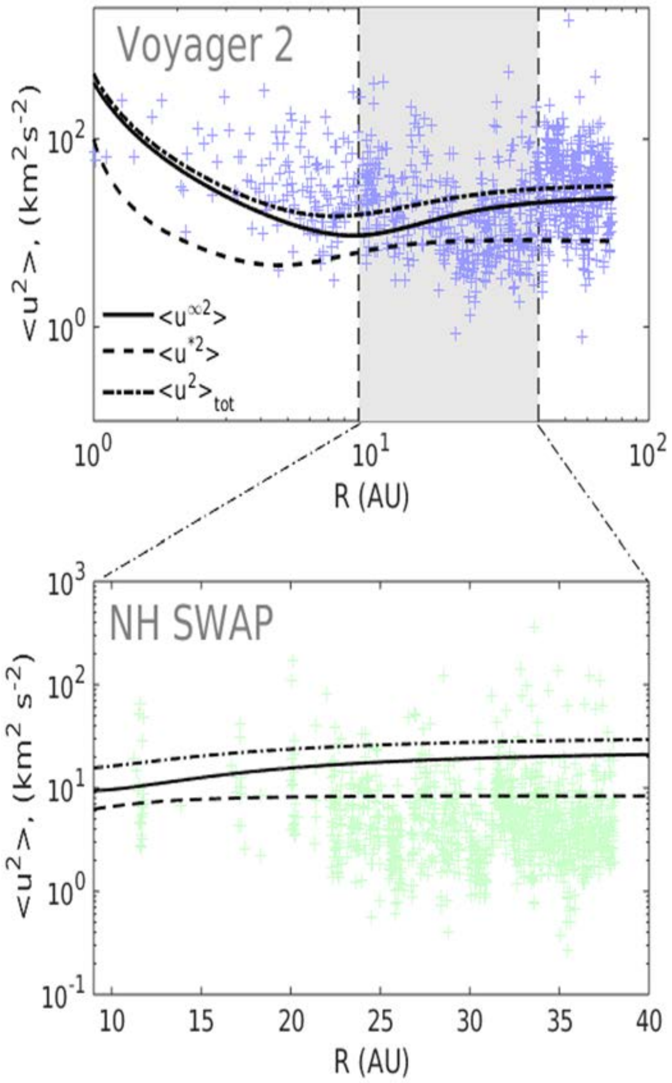
BULK SW PLASMA AND PUI RESULTS

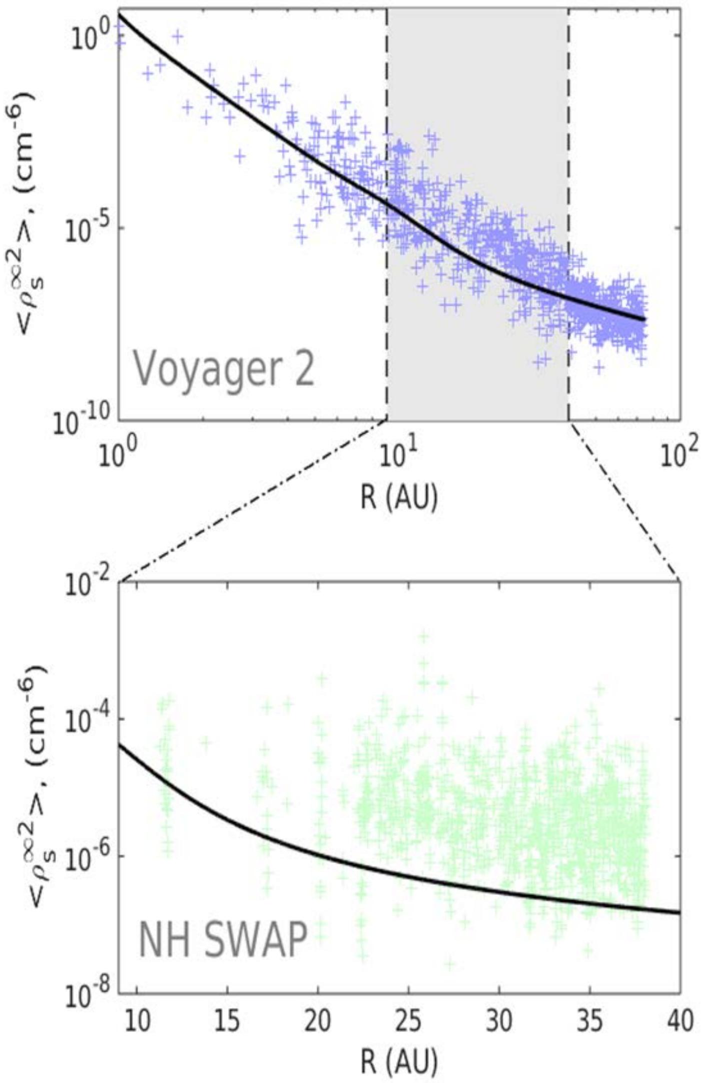


EFFECTS OF TURBULENCE HEATING

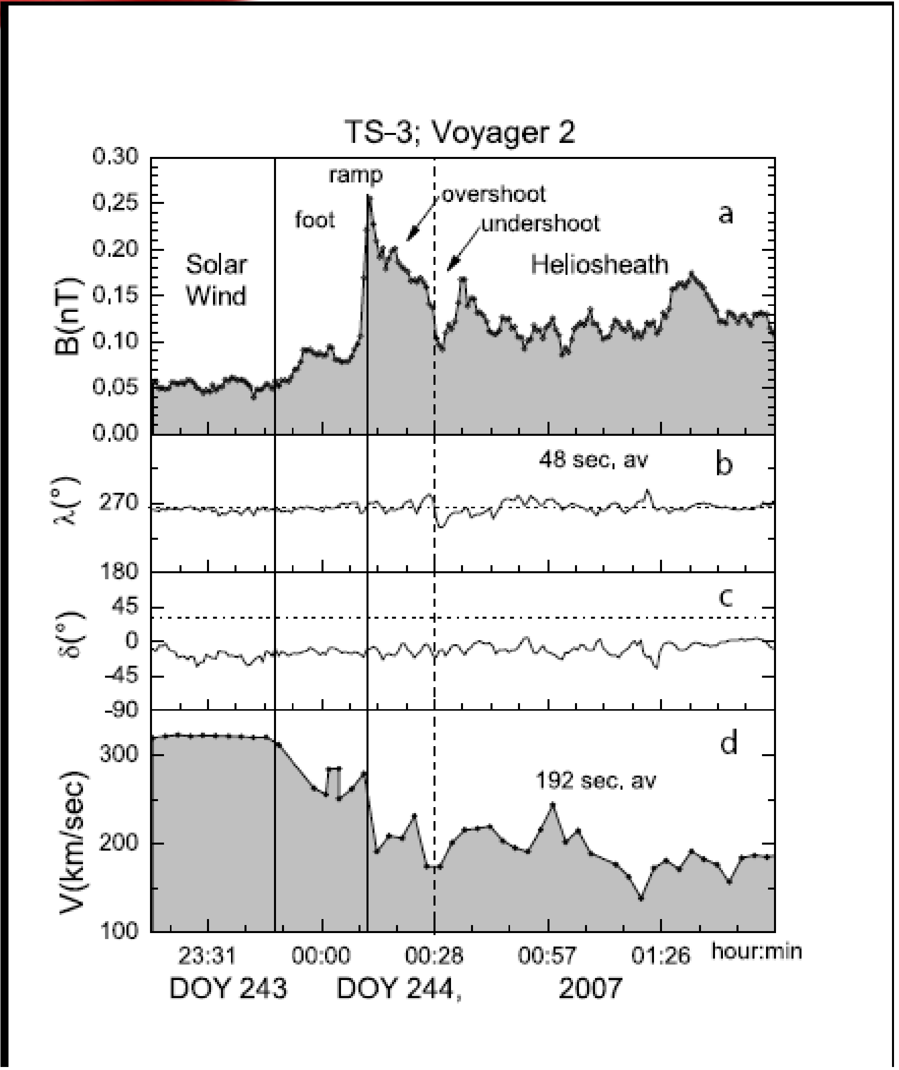


TURBULENCE QUANTITIES

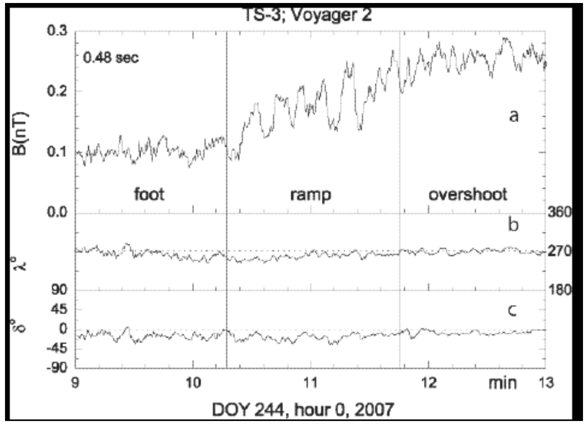




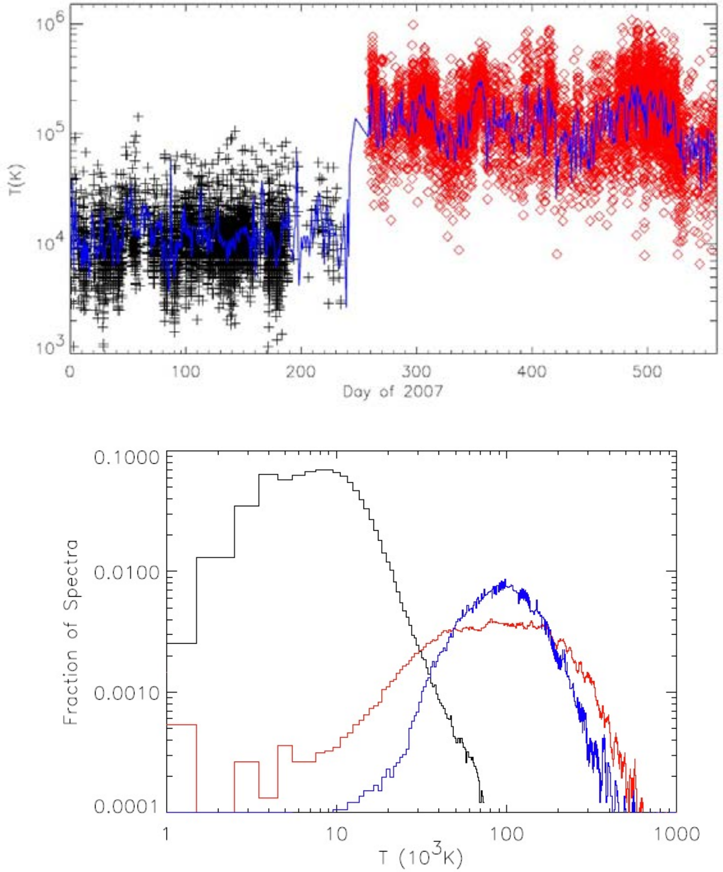
2) PHYSICS OF THE HELIOSPHERIC TERMINATION SHOCK (and outer heliospheric shocks)



Burlaga et al. 2008



TS-3 is a supercritical quasi-perpendicular shock. The magnetic field strength profile shows the classical features of a supercritical quasi-perpendicular shock: a “foot”, “ramp”, “overshoot”, “undershoot”, and smaller oscillations. (Right) The internal structure of the ramp of TS-3.

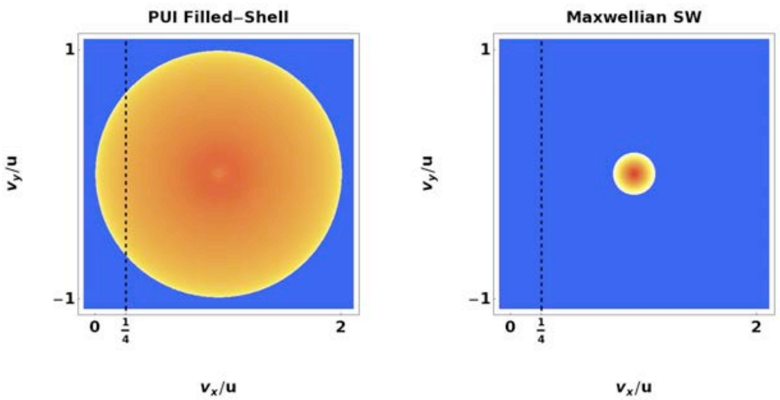


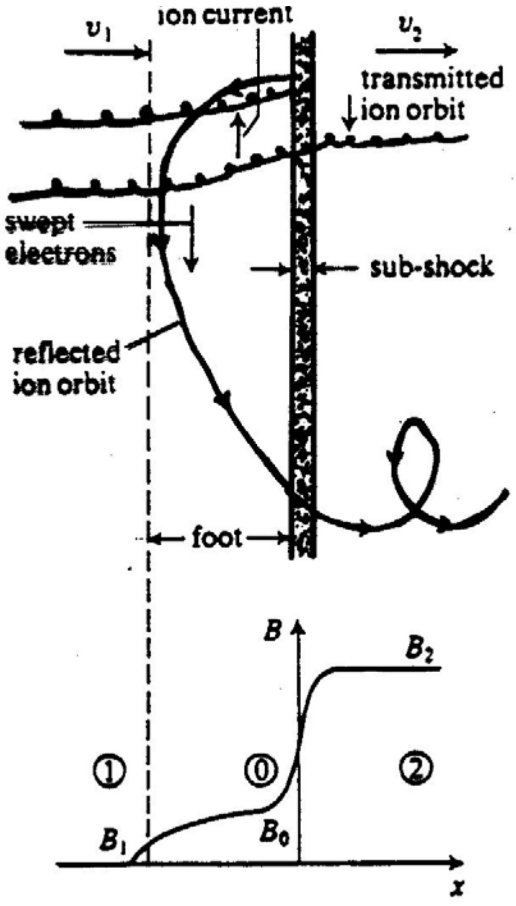
Upstream and downstream SW temperatures and distribution function observed by V2.

Richardson et al., 2008

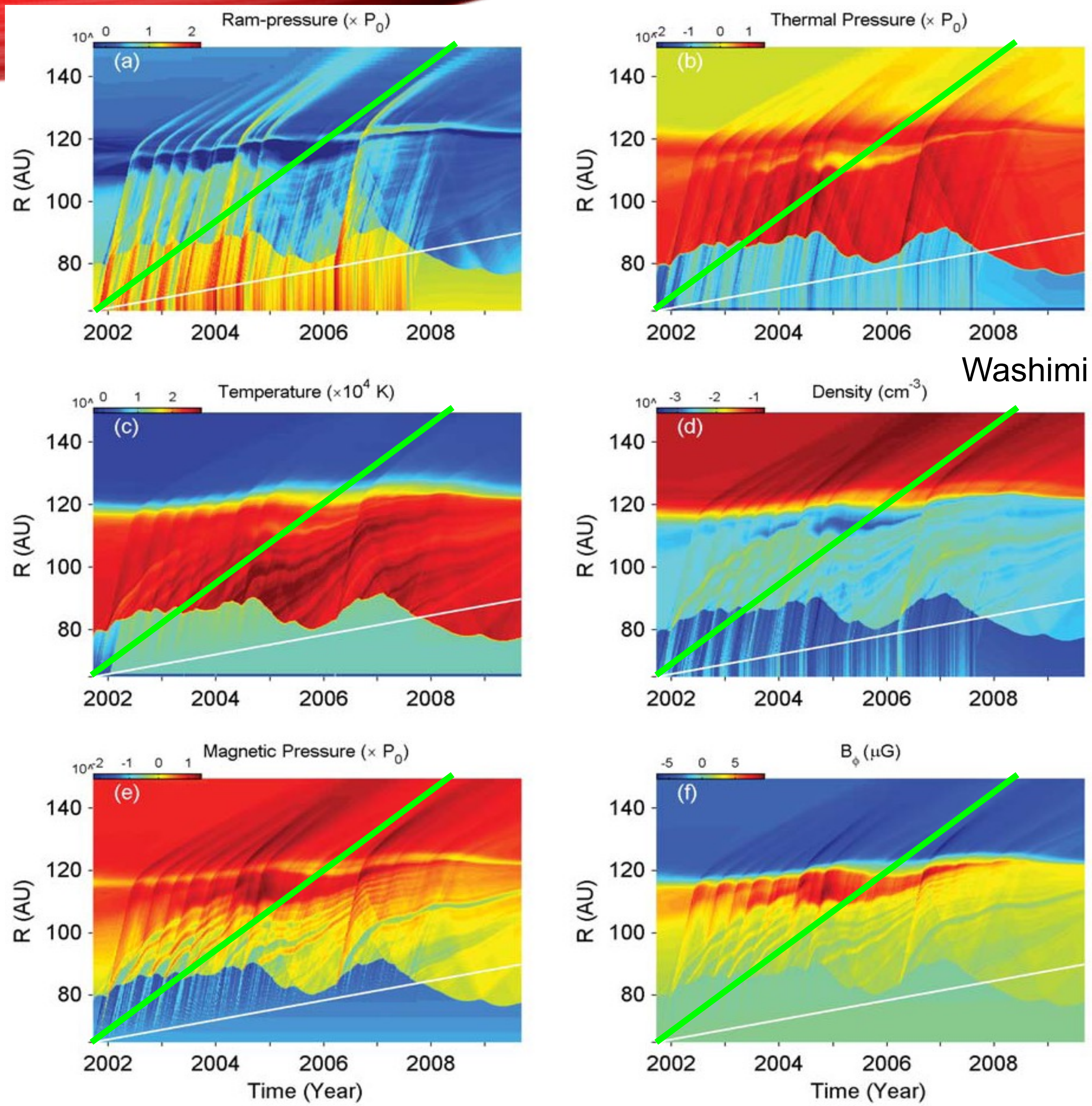
- Basic understanding of role of PUIs at shocks predicted in 1996, well before V2 observations and subsequently New Horizons confirmed basic ideas.
- Filled shell character of PUI distribution function ensures PUIs preferentially reflected by cross-shock potential at quasi-perpendicular shocks, and hence PUI reflection is primary dissipation mechanism for the HTS and interplanetary shocks in outer heliosphere (Zank et al 1996).
- Hence quasi-perpendicular shocks in distant solar wind are PUI-mediated
- Theory forms foundation of ENA generation by PUIs in inner heliosheath
- Extensively tested against simulations

- **THIS REQUIRES THAT A HOT DOWNSTREAM PUI (POSSIBLY MULTIPLE) POPULATION(S) BE MODELED DISTINCTLY FROM THE COLD THERMAL SW PLASMA IF THE DYNAMICS AND ENA CHARACTERISTICS ARE TO BE CAPTURED IN GLOBAL MODELS.**

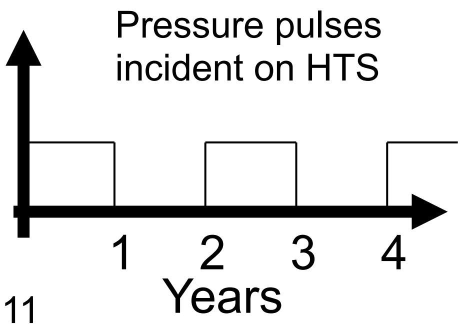


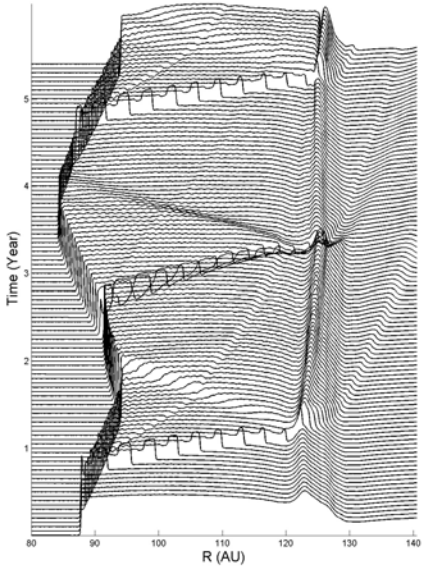


Inner Heliosheath (IHS): Transmission of interplanetary disturbances, structures, and turbulence



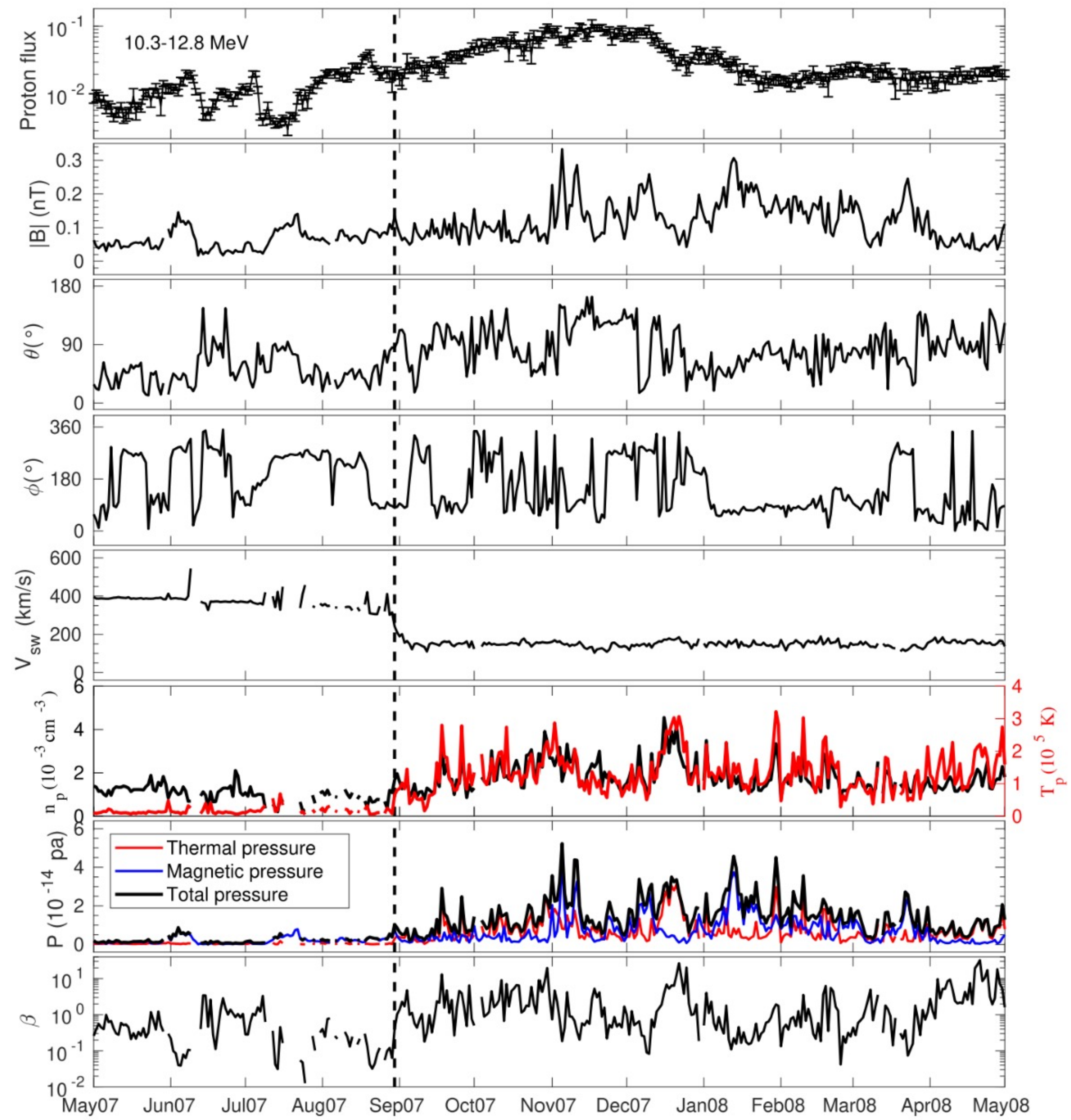
Washimi et al., 2011

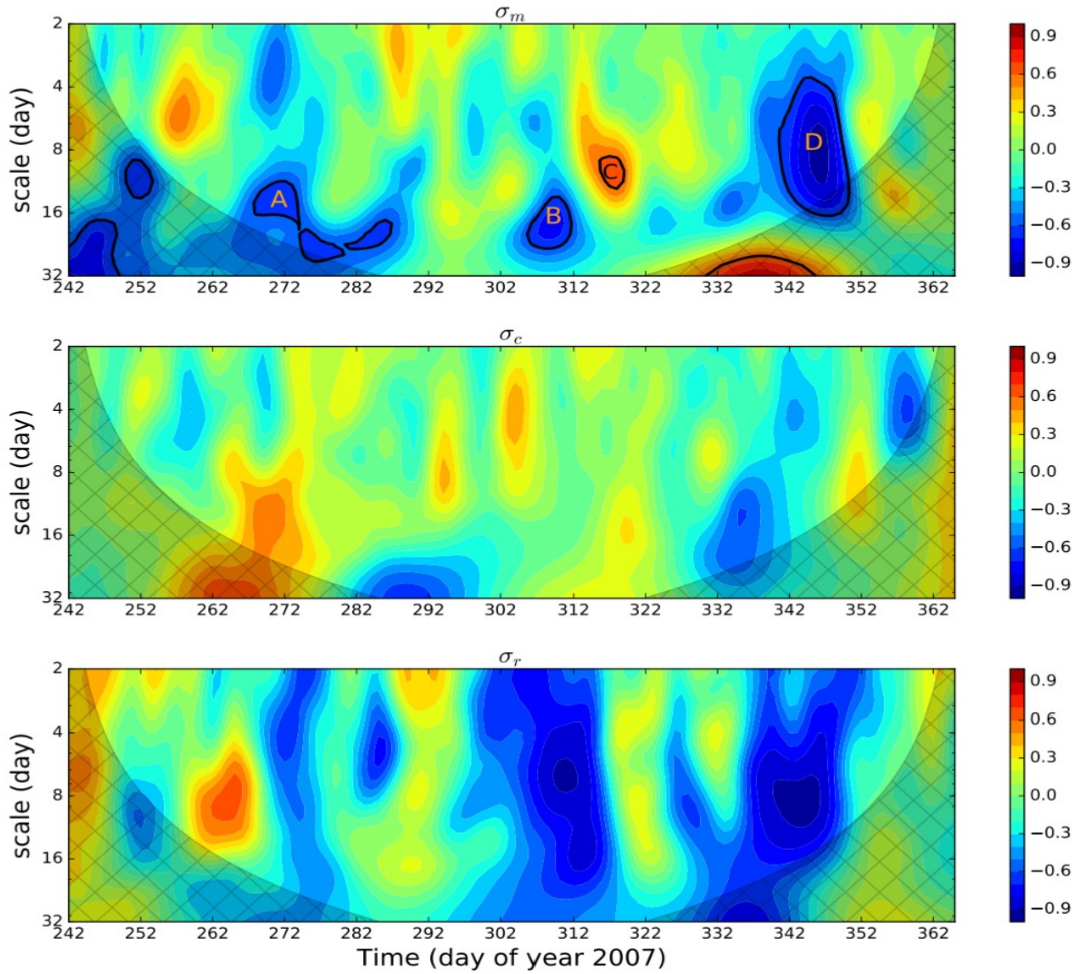


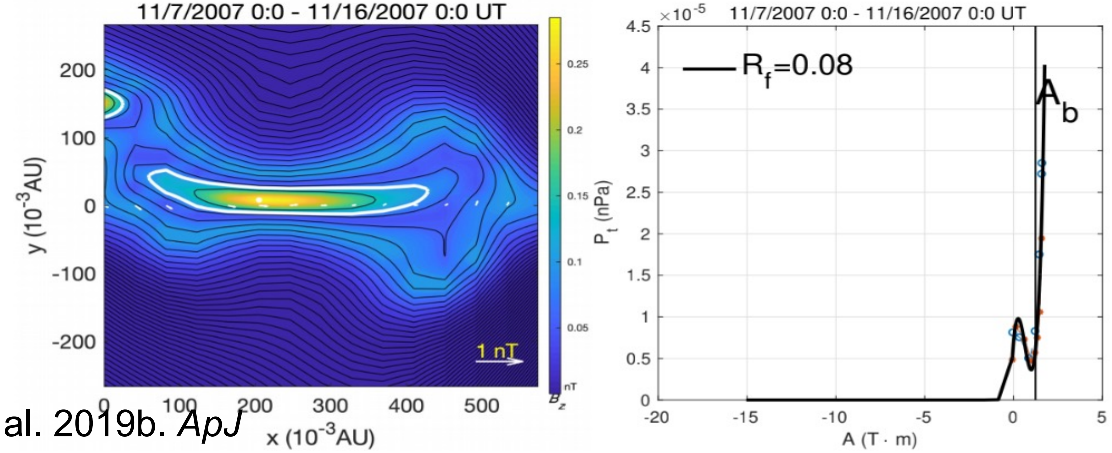


- ➢ **Transmission of disturbances from upstream SW determines temporal characteristics of inner heliosheath on large, meso, and small-scales**
- ➢ Response of HTS (and HP) to incident large-scale disturbances reasonably well explored in MHD description – however, role of energetic particles (PUIs, ACRs) remains largely unexplored, especially wrt response to disturbances from downstream

Voyager 2 observations of downstream flux ropes (~10 day)

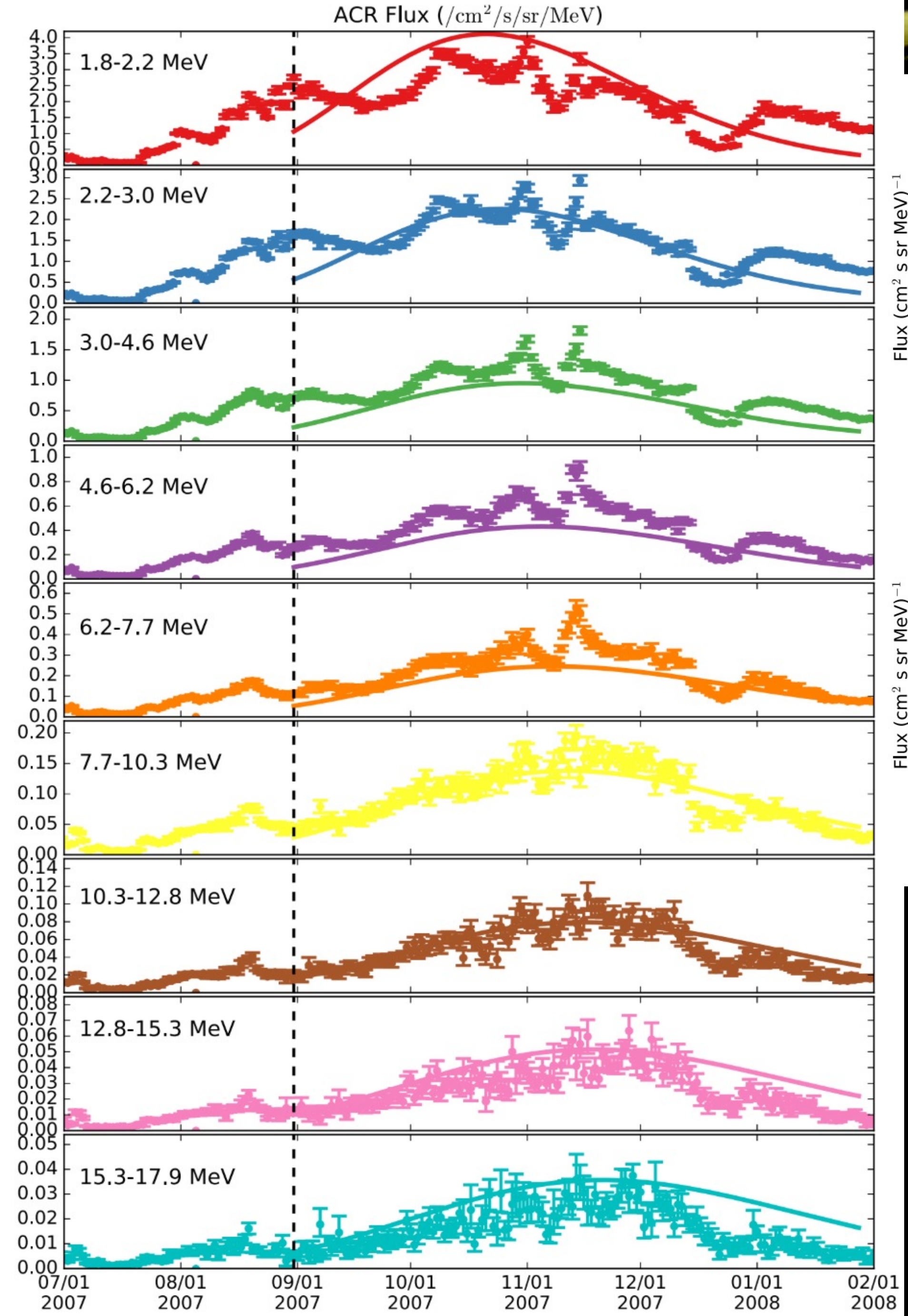


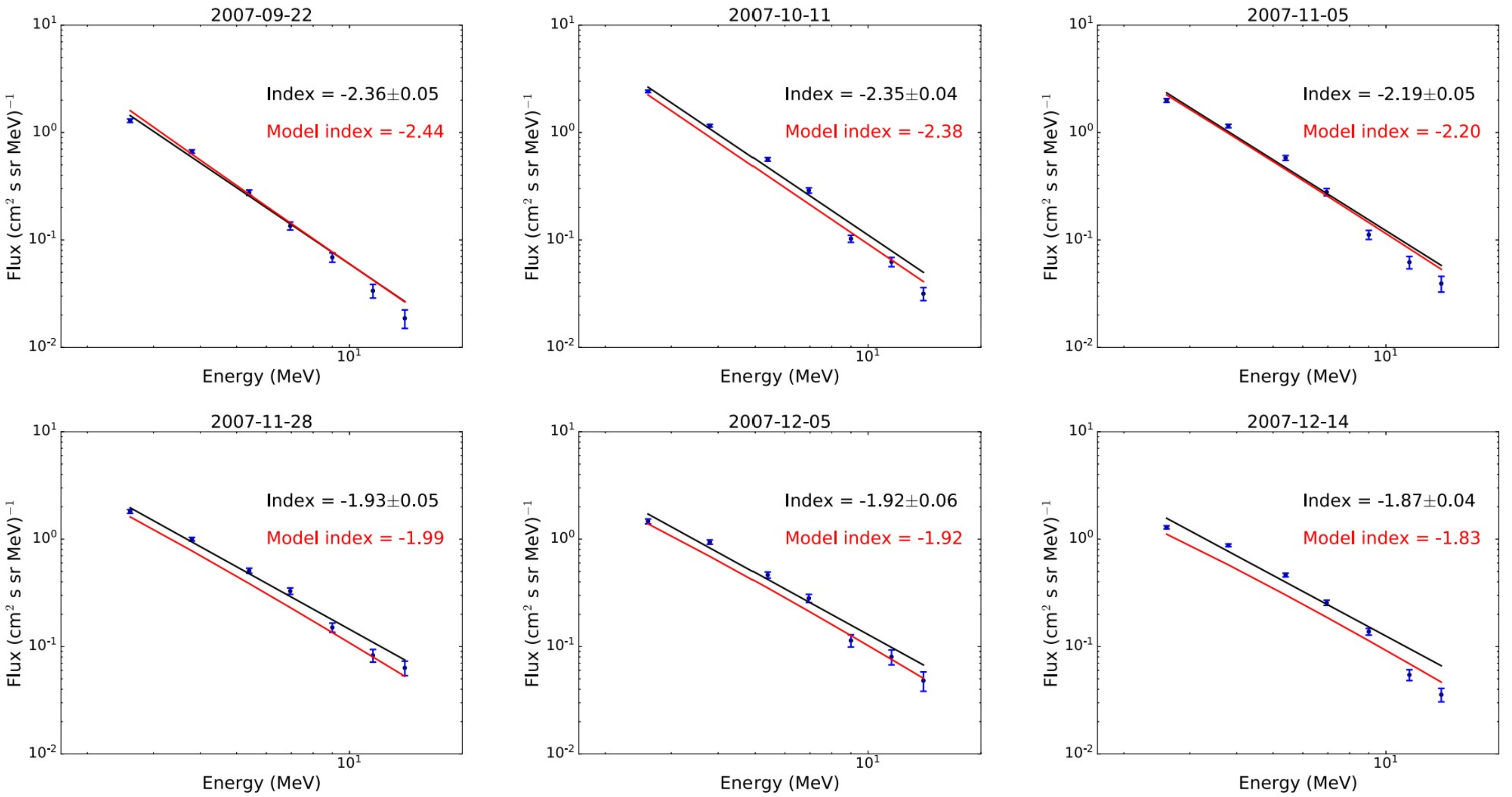




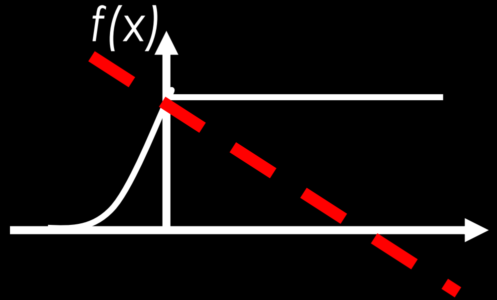
Zhao et al. 2019b. *ApJ*

Structures such as flux ropes may be important for particle acceleration



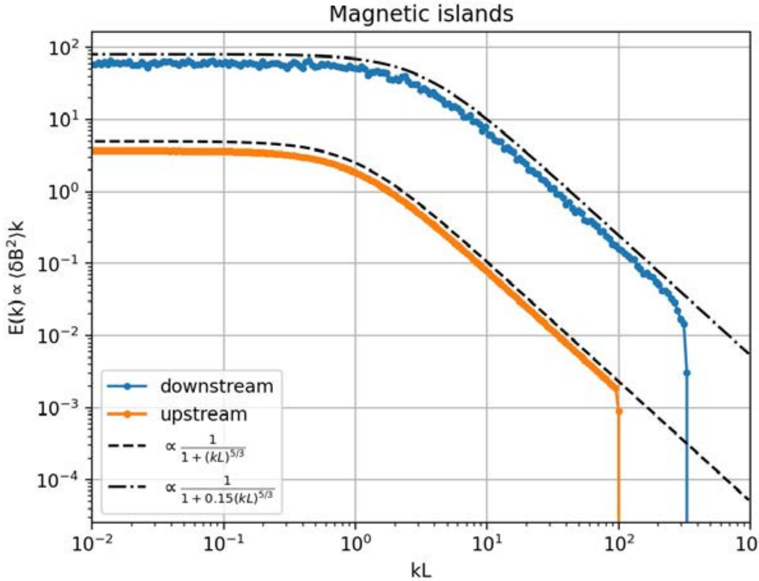


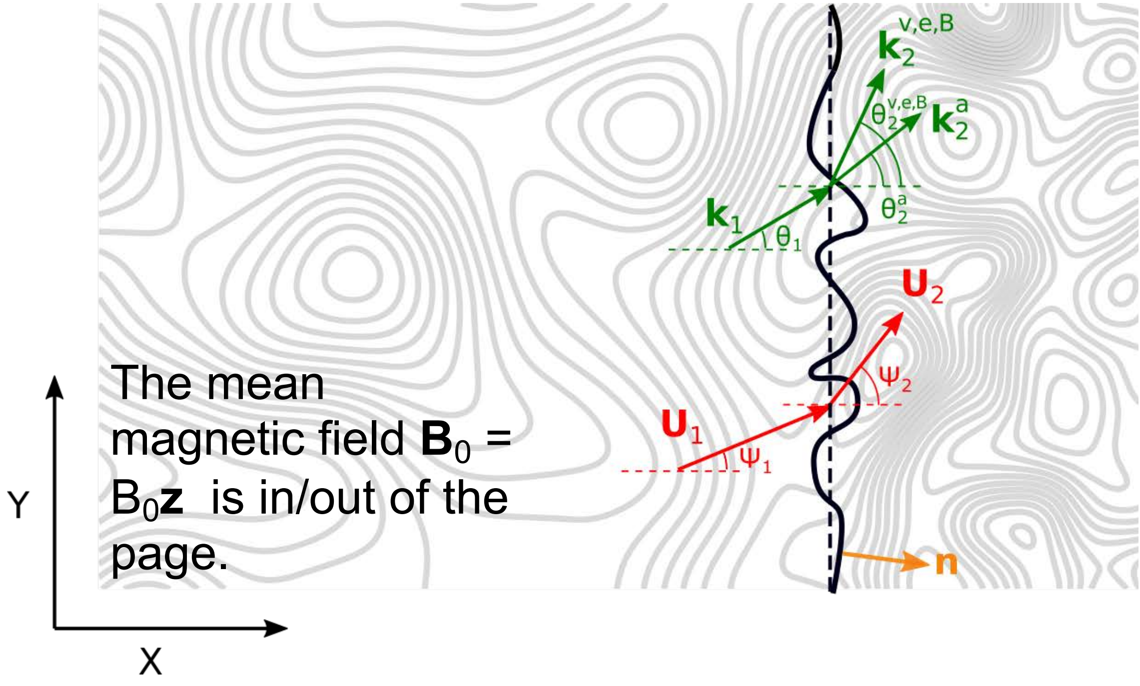
- Observed ACR energetic particle spectrum ~ days after the HTS crossing shows agreement with reconnection-based diffusive particle acceleration model (Zank et al. 2014, 2015; Zhao et al. 2019b) – largely unexplored in context of ACR acceleration



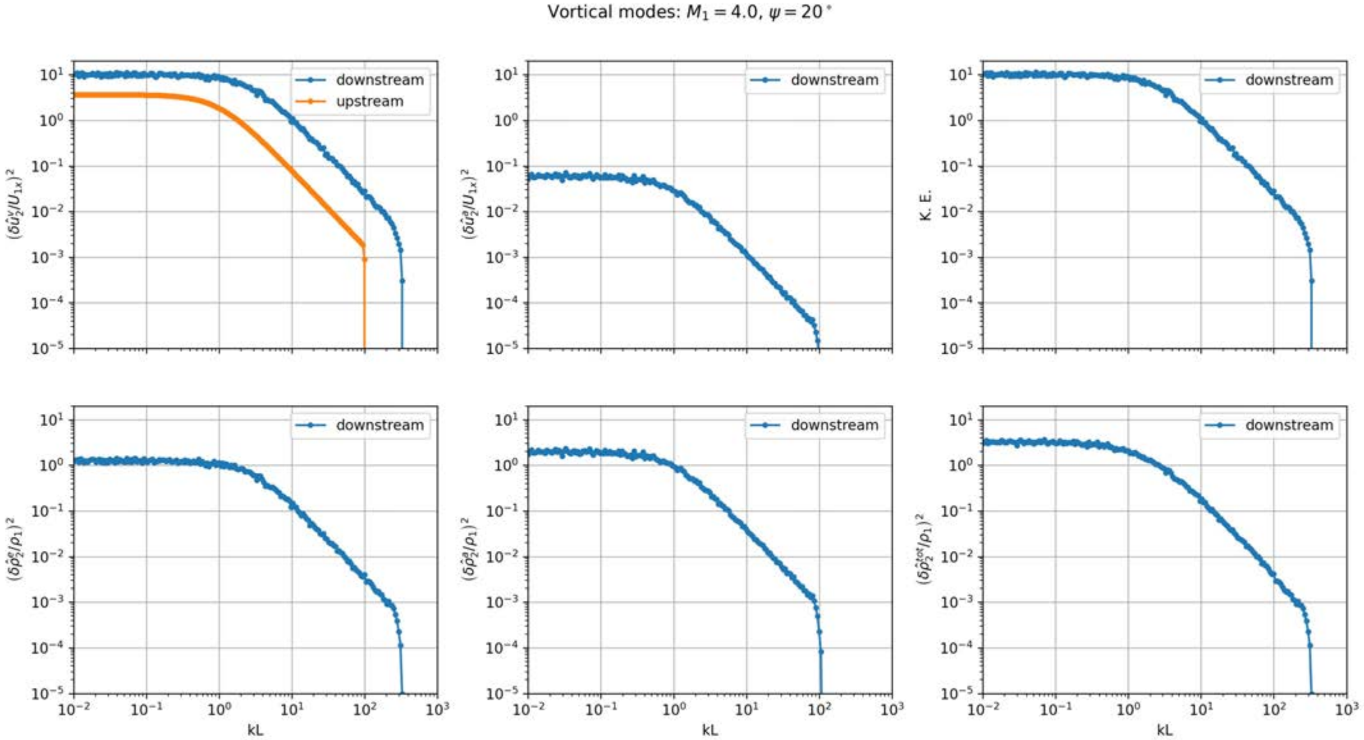
Transmission of structures and turbulence across HTS

- Consider an upstream weak mean magnetic field $\mathbf{B}_0 = B_0\mathbf{z}$ oriented perpendicularly to the flow vector $\mathbf{U}_0 = (U_x, U_y, 0)$, such that transverse magnetic fluctuations $(dB_x, dB_y, 0)$ are of the same order of magnitude as B_0 and thus fluctuations $dB_z << B_0$.
- Can be interpreted as strong perpendicular magnetic turbulence despite the large plasma beta.
- Such an orientation yields magnetic islands in the plane of the flow velocity.



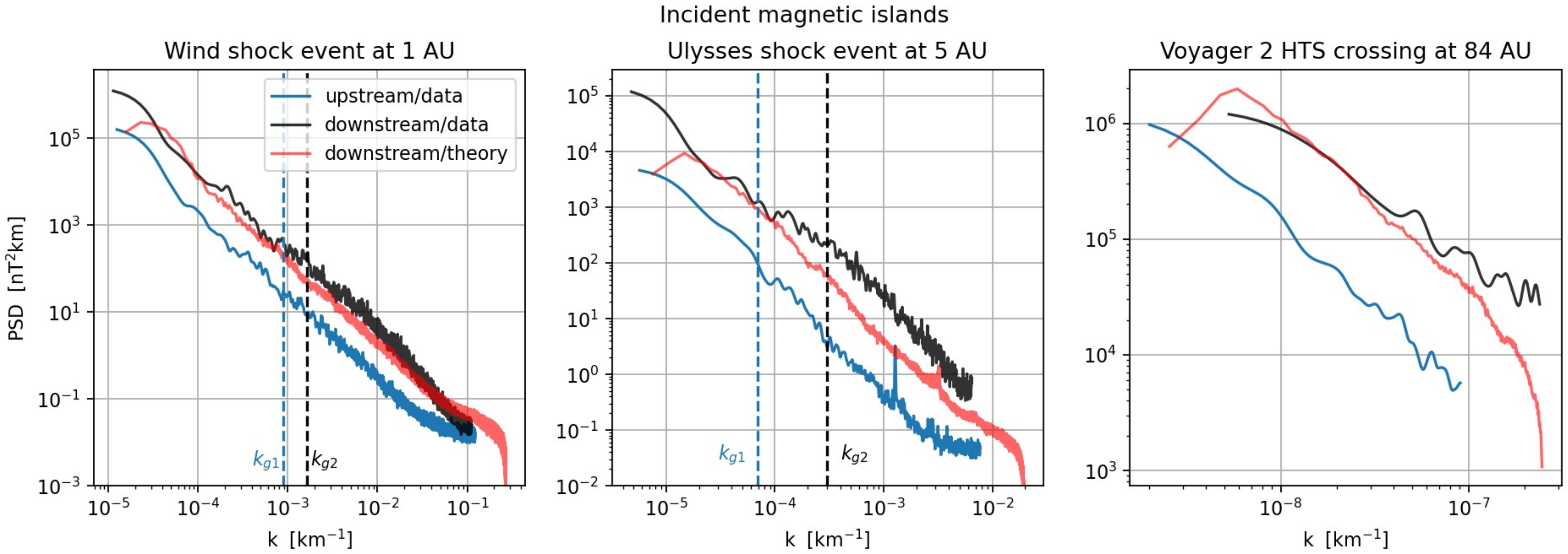


The mean magnetic field $\mathbf{B}_0 = B_0\mathbf{z}$ is in/out of the page.

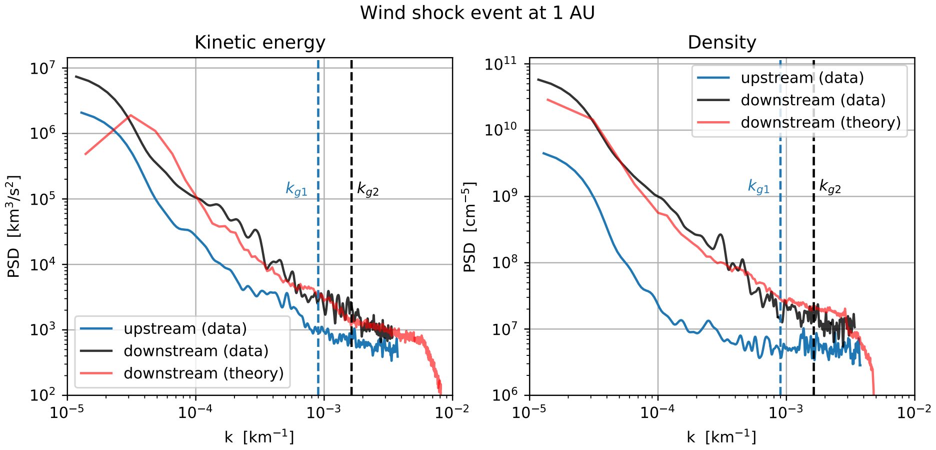


Observed and predicted magnetic, kinetic, and density spectra

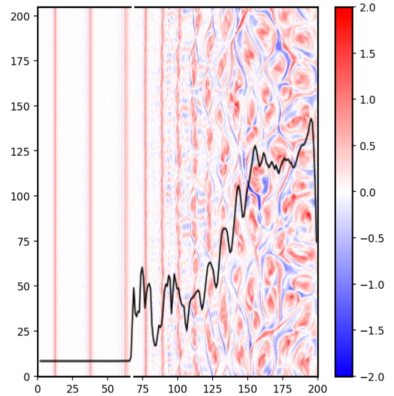
Are these results consistent with the Burlaga & Ness results discussed above – compressibility, lognormal vs Gaussian distributions? Promising start but much remains to be elucidated

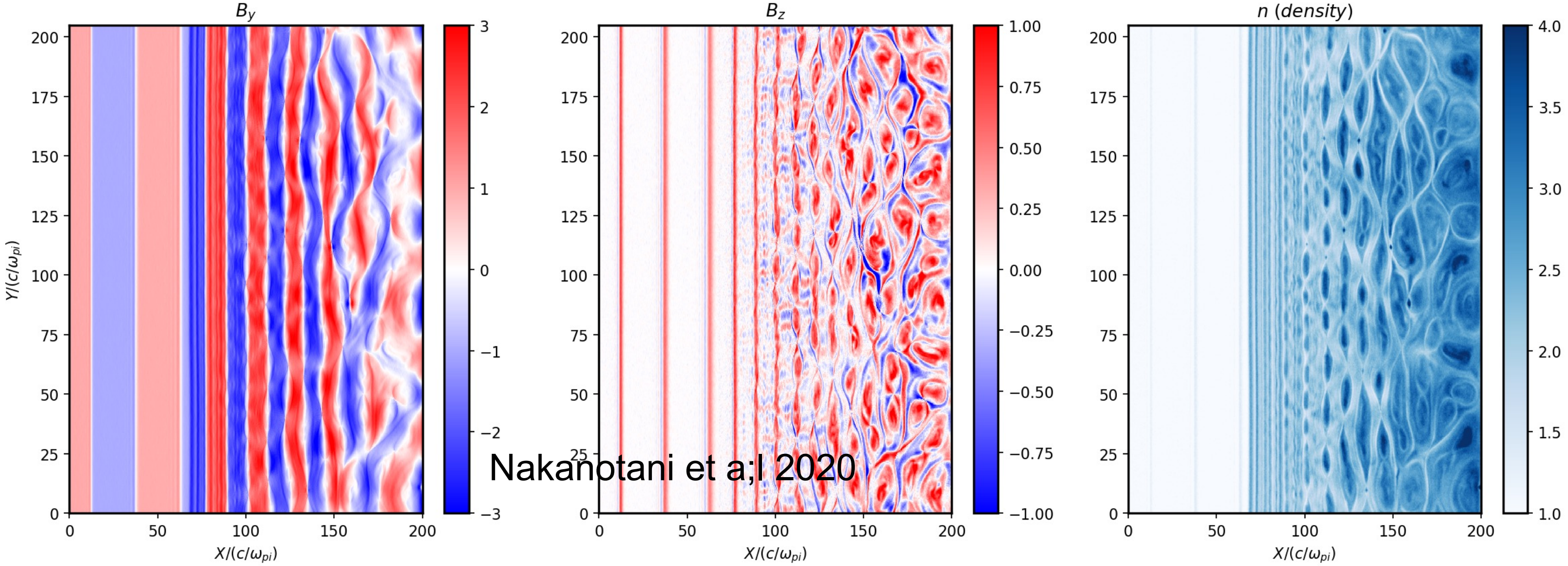

Incident magnetic islands

Zank et al 2021


Wind shock event at 1 AU

Black line shows the number of particles satisfying $|v|>5V_A$.

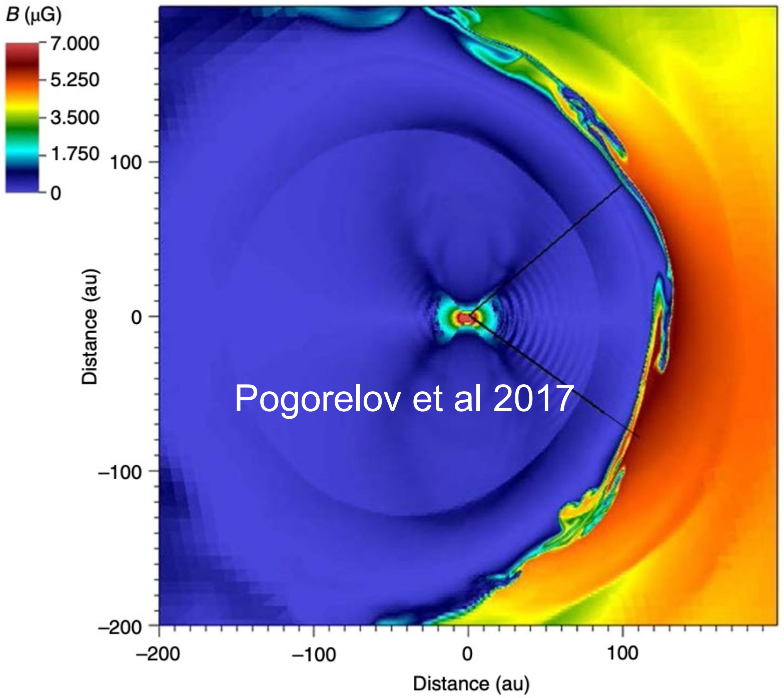




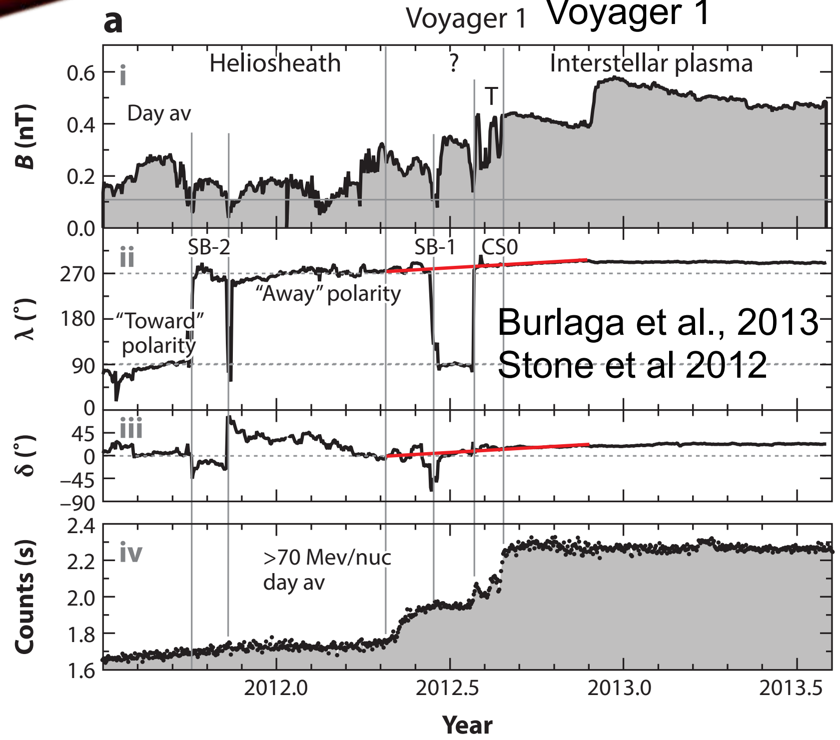
Nakanotani et a;l 2020

- ➢ Current sheets are compressed by the shock wave and become unstable downstream.
- ➢ Magnetic fields become turbulent because of reconnection and the merging of islands

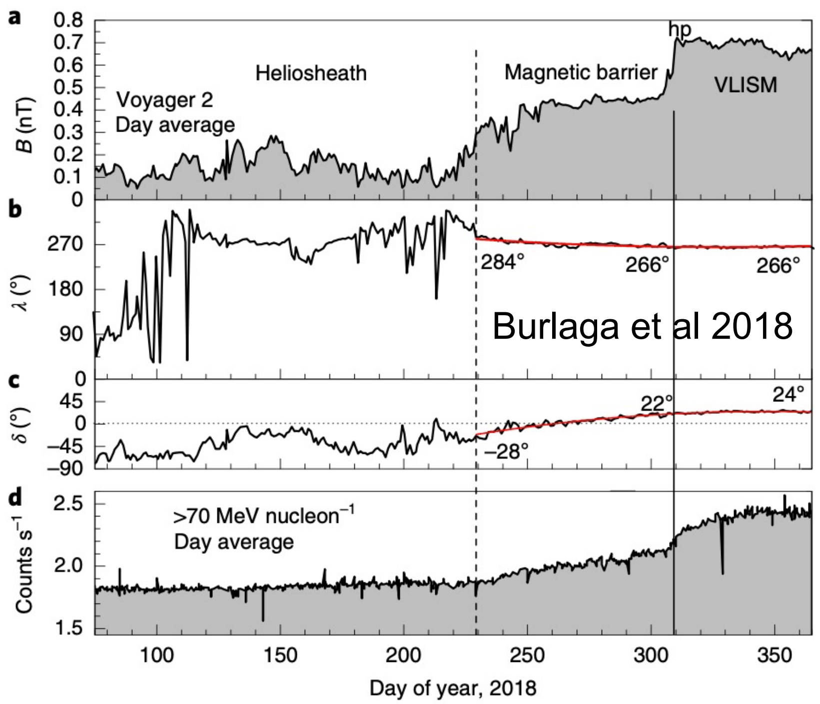
4) Heliopause


Pogorelov et al 2017

Voyager 1


Burlaga et al., 2013
Stone et al 2012

Voyager 2


Burlaga et al 2018

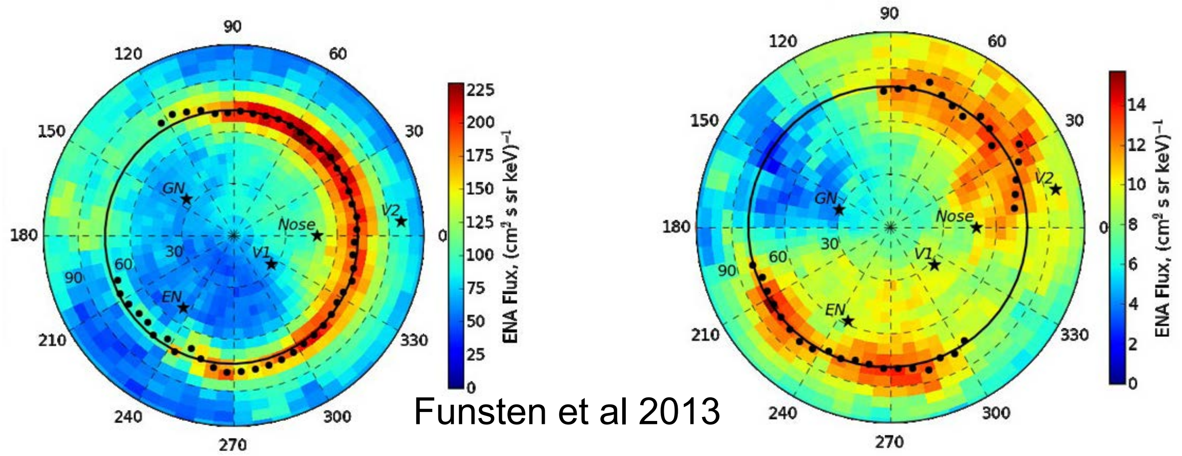
Very little understood about the structure of the HP – figures summarizes basic complications

1) Structure is complex unlike discontinuity of theory – what are the fundamental scales?
2) What is the role, if any, of PUIs, ACR, and GCRs in determining HP structure?
3) How do various HP instabilities, including neutral H-driven instabilities, interchange instabilities, … contribute to HP structure?
4) What to the magnetic field reversals signify? Vicinity of the HCS? Reconnection-related effects of solar and interstellar field?
5) How does the interaction and transmission of interplanetary shocks into VLISM modify/mediate/restructure HP?
6) Critical need for a viable theory of HP structure!

Very Local Interstellar Medium (VLISM)

Zank 2015 definition: the VLISM is “that region of the interstellar medium surrounding the Sun that is modified or mediated by heliospheric processes or material.”

- Neutral gas of SW origin – fast and hot H – and the creation of solar PUIs in the ISM – manifest most obviously in the discovery of the IBEX Ribbon
- Observations of compressible turbulence near the HP and possible conversion to incompressible turbulence
- Propagation of interplanetary shocks in the VLISM



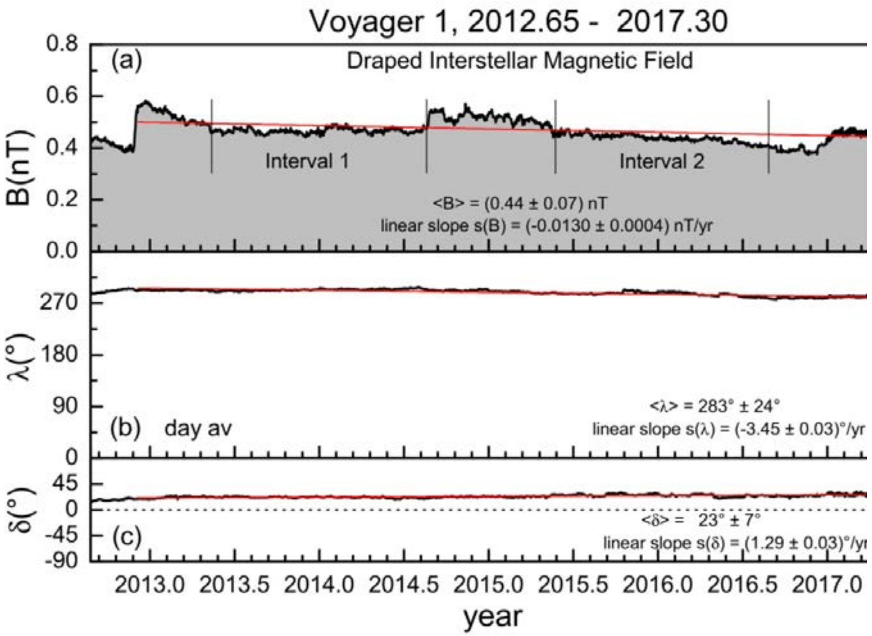
Funsten et al 2013

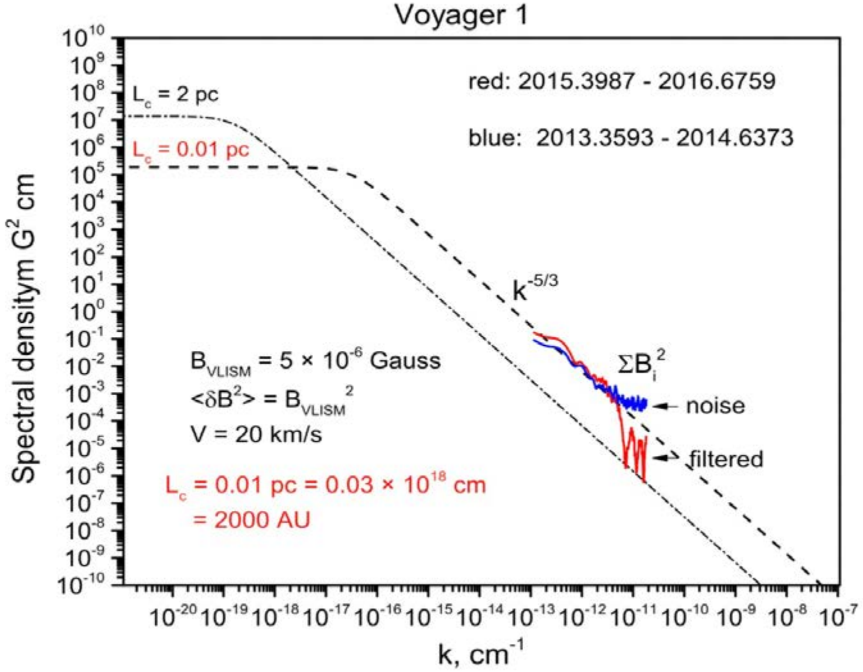
- VLISM neutral H temporal on solar cycle, and hence so to PUI creation.
- Good progress on Ribbon plasma physics but details remain. Reconcile IBEX Ribbon and Cassini observations, potential source(s), interpretation.

VLISM plasma characteristics

- VLISM plasma appears to be collisional for both thermal protons and electrons. However, CE of hot and fast neutral H of SW origin creates minority hot non-equilibrated collisionless PUI population in VLISM ~75 – 100 au upwind of HP. Basic plasma model of weakly collisionless non-equilibrated plasma needed?
- Dissipation, heating, and instabilities in collisional/ collisionless non-equilibrated VLISM plasma e.g., shock wave structure, pressure waves, at which point is collisionality insufficient to balance nonlinearity?
- Will basic plasma model introduce fundamentally new physics into current global MHD models?

Turbulence in the VLISM





Power primarily in the || component during Interval 1, and primarily in the transverse components during Interval 2.

Theory based on IHS fast- and slow-mode waves incident on the HP generating only fast-mode waves propagating into VLISM, adding to preexisting VLISM magnetic field power spectral density. Thereafter, mode conversion in low beta plasma converts compressible modes to incompressible Alfven and zero-frequency fluctuations, i.e., manifestation of heliospheric processes. Detailed theory remains to be developed, including simulations (see Matsukiyo et al 2020).

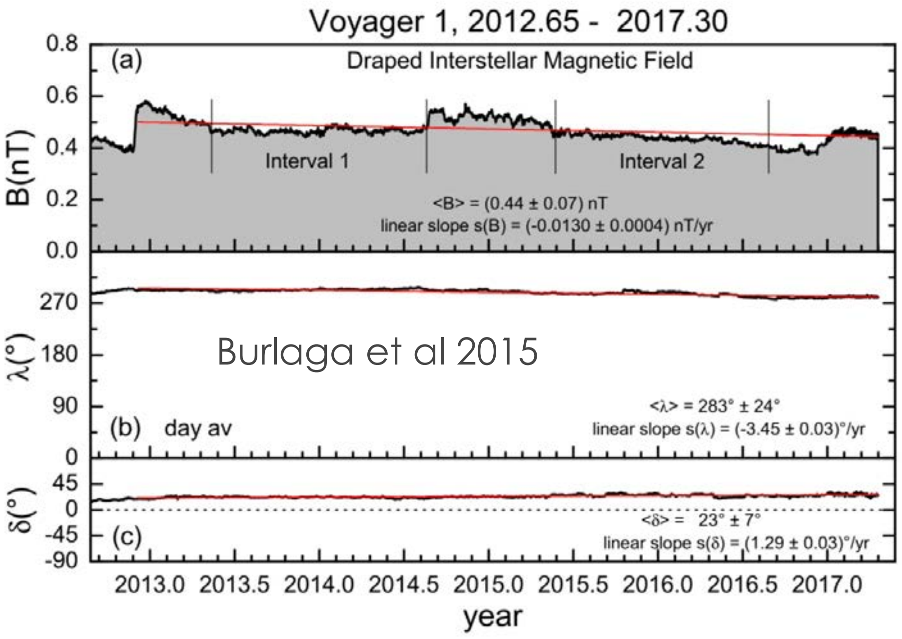
Turbulence observed in Interval 1 is curious;

i) the fluctuating magnetic field is almost entirely parallel to VLISM mean magnetic field, implying turbulence is essentially compressive, and
ii) despite being predominantly compressive, power spectrum has a ~ $k^{-5/3}$ Kolmogorov-like spectrum.

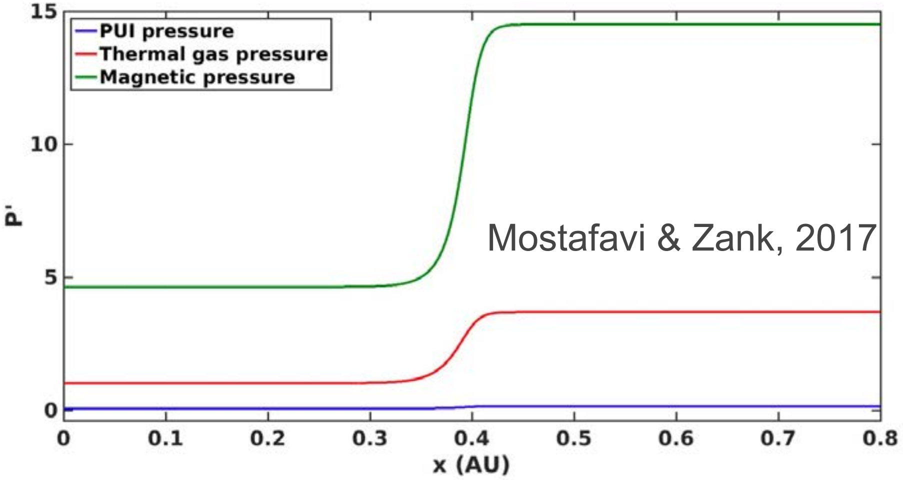
Raises two important questions:

i) What is the origin of the compressible fluctuations in the VLISM? and
ii) is observed magnetic turbulence spectrum representative of interstellar turbulence in a partially ionized interstellar plasma, or a manifestation of mediation by heliospheric processes?

Shock propagation in the VLISM

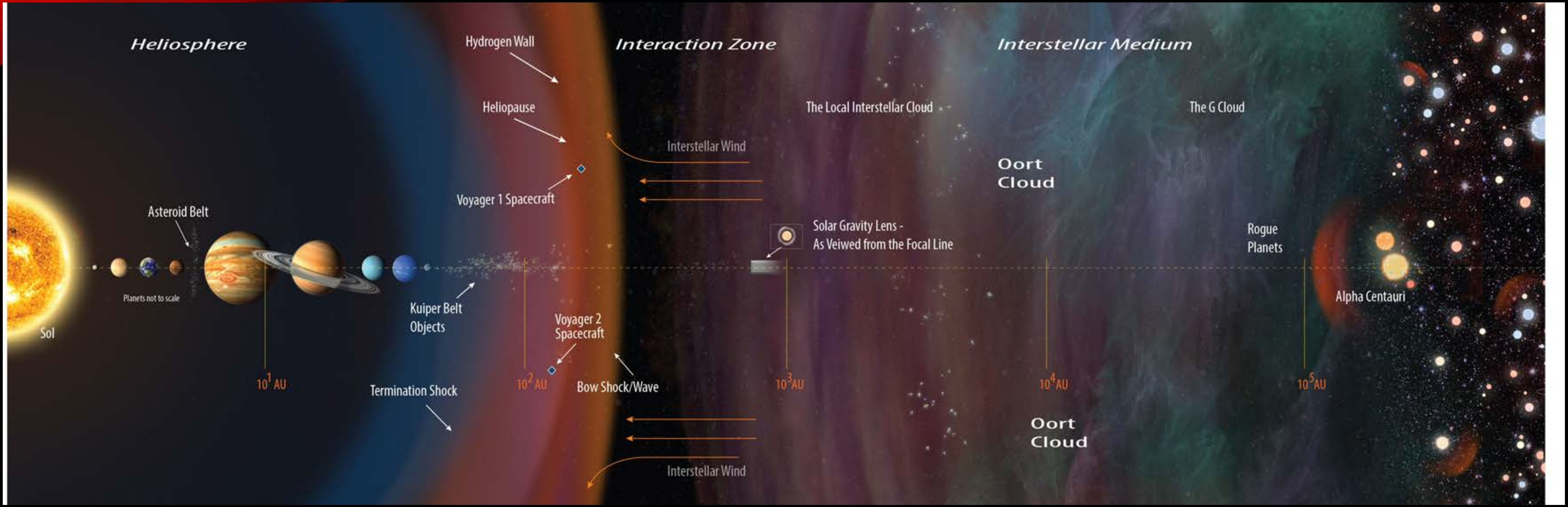


Burlaga et al 2015

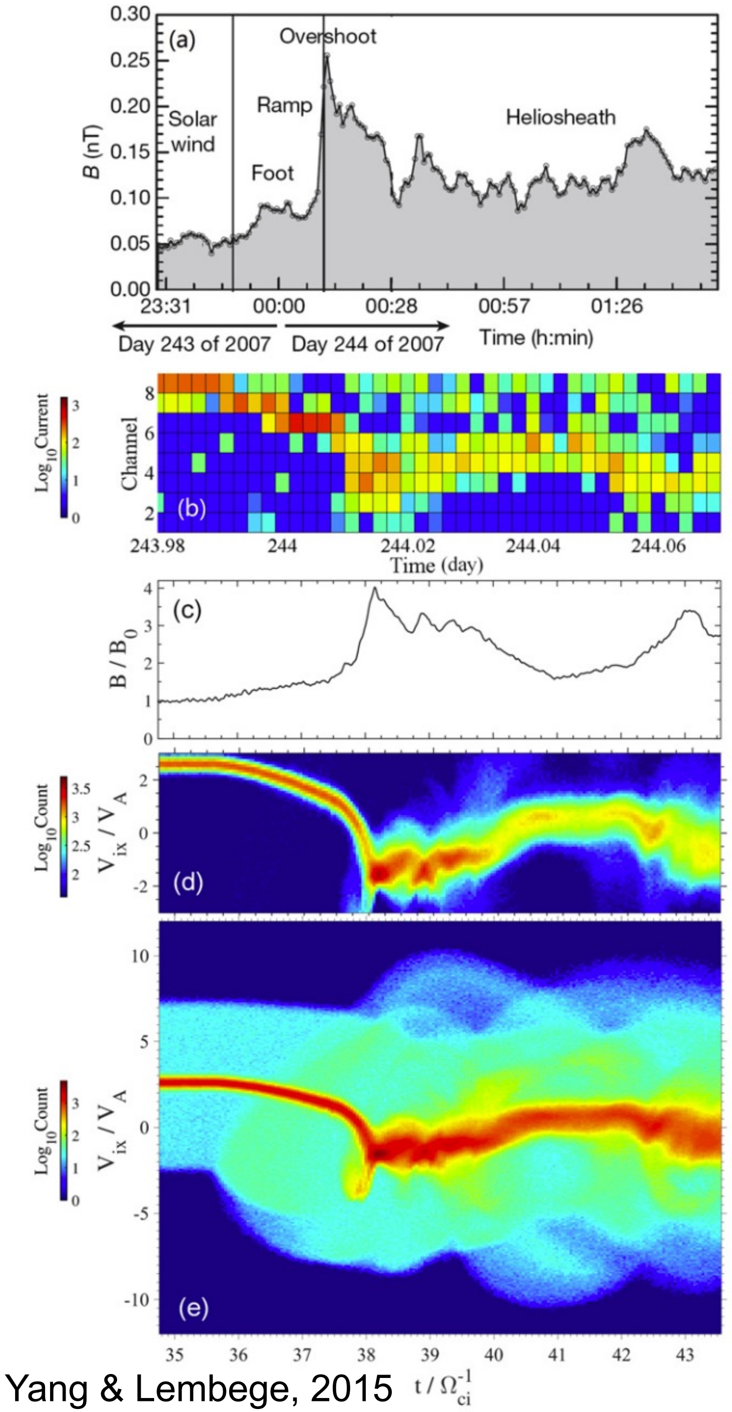


Mostafavi & Zank, 2017

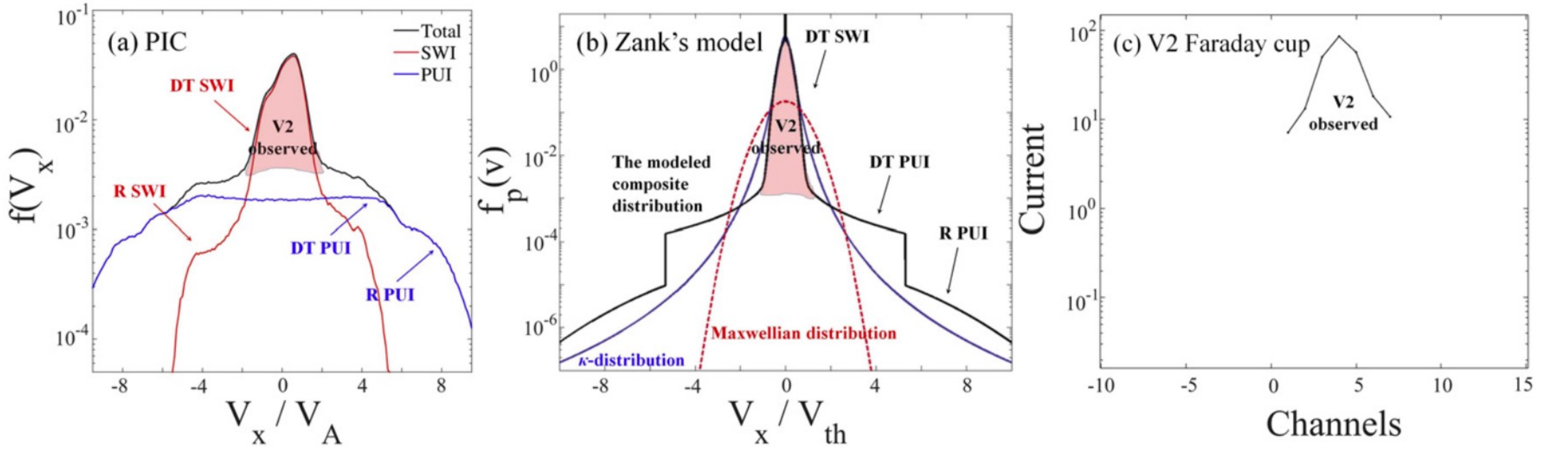
- VLISM is collisional for thermal plasma (e.g., L^{pp} ~ 0.3 au)
- Unusually broad structures observed that are interpreted as shocks and frequently are observed to excite Langmuir waves observed by PWS (and sometimes radio emission)
- Nonlinearity of weak shocks propagating in VLISM can be balanced by dissipation associated with collisions, introducing shock scaling associated with collisional heat conduction and/or collisional viscosity.
- Strong shocks likely to require collisionless dissipation – is this a distinction between radio emitting shocks and radio-quiet shocks?
- Excitation of plasma waves typically assumes generation of electron beam – for weak broad shocks, what is process for generating electron beams since mirroring unlikely to be effective?
- Is this related to reflection of GCRs and development of locally anisotropic CR distributions?
- Do shocks in VLISM generate significant levels of turbulence?



The fascinating coupling of complex plasma physical processes that makes up the Outer Heliosphere has been insufficiently probed in situ at a level needed to properly clarify the physics. Numerous open questions remain. This presentation provides an incomplete overview of the foundations of our current understanding of the basic physical processes governing the Outer Heliosphere and presents a few of the many open questions that need to be resolved.

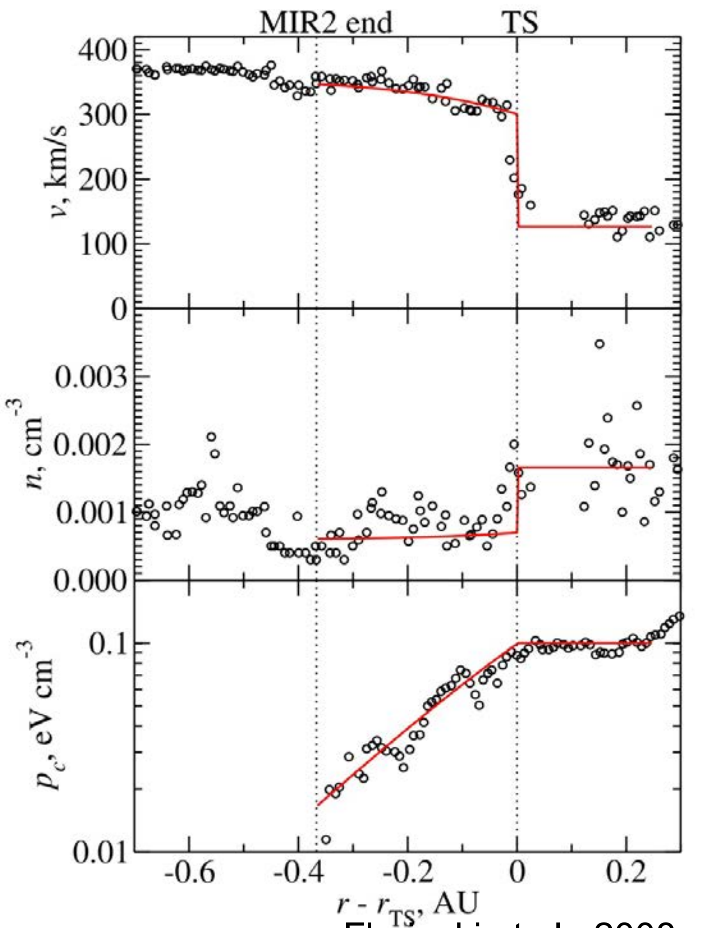


Yang & Lembege, 2015



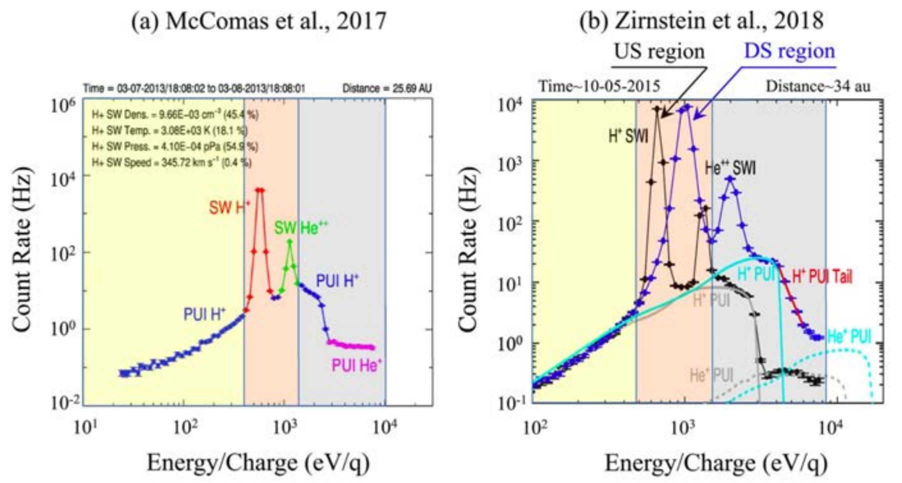
- Microstructure of HTS beginning to be understood but primarily for TS-3 example –role of different obliquities, backstreaming ions, time dependence, response to turbulence and other incident disturbances, downstream disturbances incident on HTS?

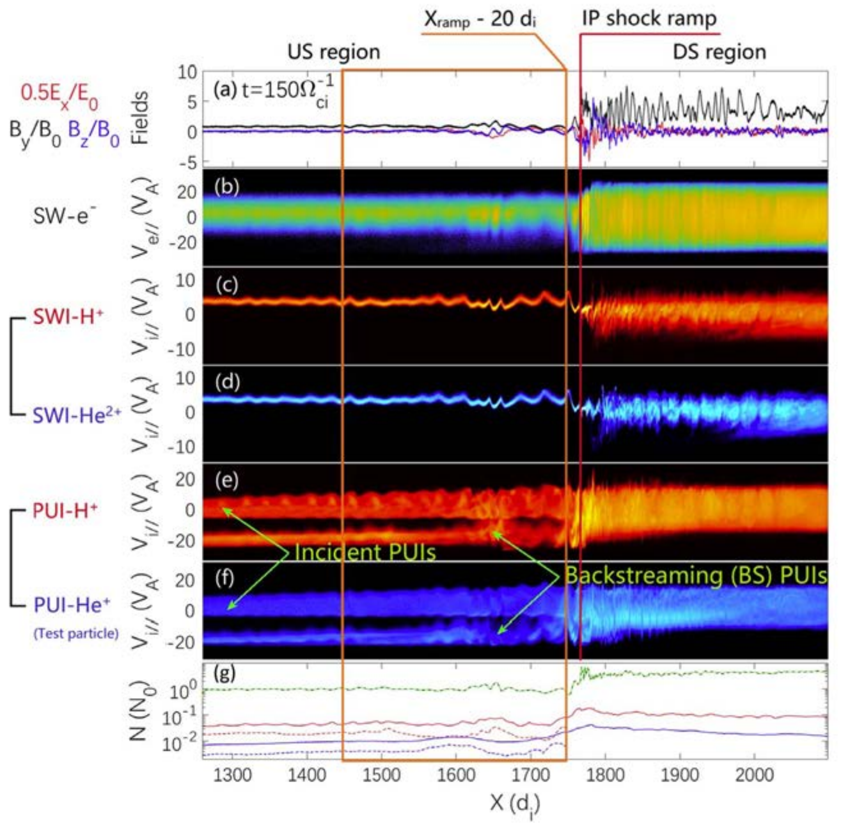
- Incorporation of energetic particle and back-reaction, turbulence, structures, …



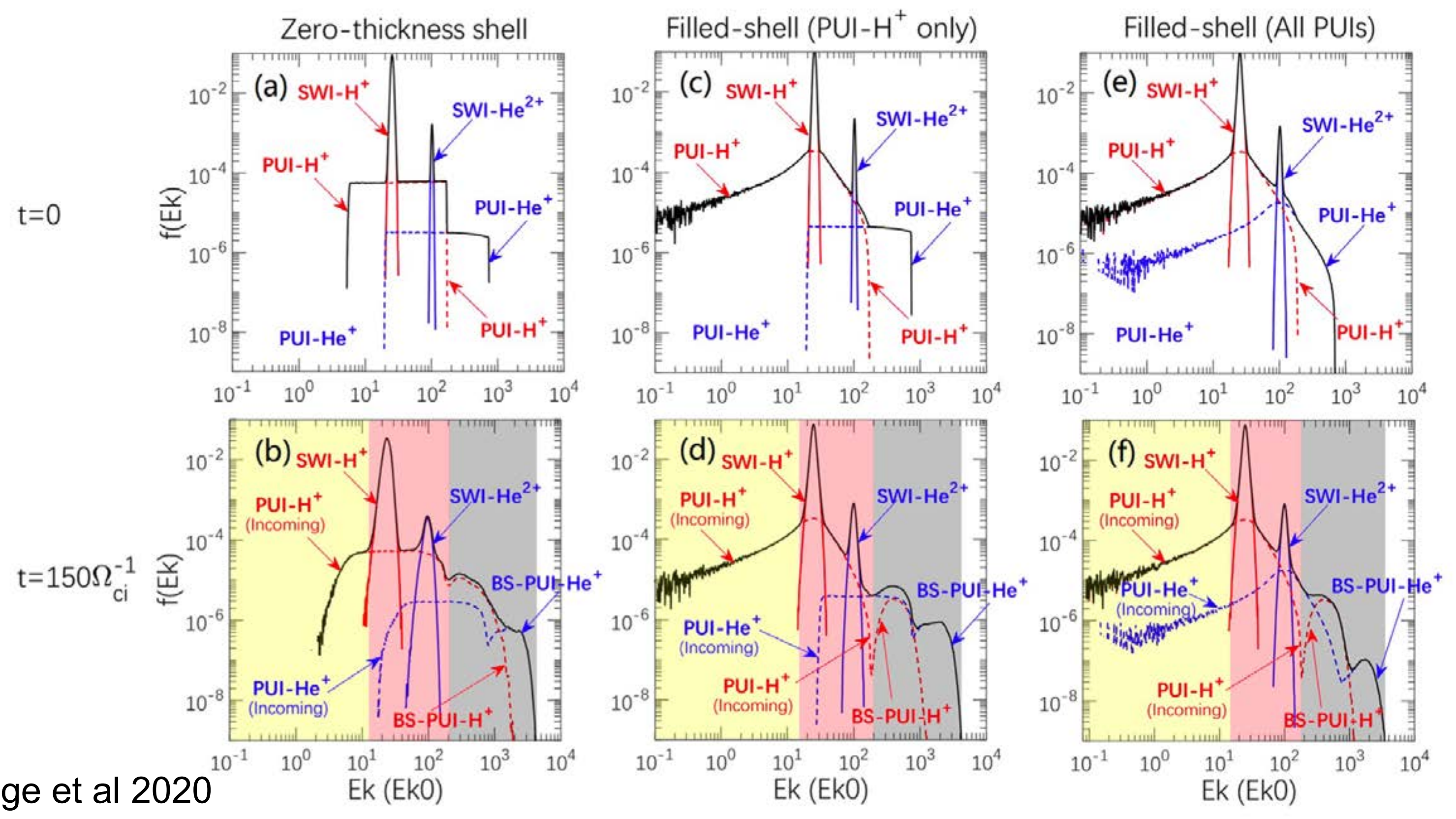
Florinski et al., 2008

Insights from interplanetary shocks – New Horizons





- Can be understood on basis of preferential PUI reflection described above – example shows 55^{o} obliquity



ge et al 2020

- Several detailed studies of the fluctuating fields observed in the IHS have been published (Burlaga et al 2006, Burlaga & Ness 2009)
- Intriguing hints at the nature of linear waves, “compressible” turbulence, and structures have emerged.
- ***Virtually no supporting theoretical analysis exists yet.***

- Burlaga et al 2006 study investigates short period in the post-HTS region, when V1 in a sector of positive polarity for 125 days.
- Throughout the sector, the distribution functions of each of the component fluctuations of hour averages of ***B*** were essentially Gaussian with similar widths, indicating that the fluctuations were nearly isotropic relative to the mean magnetic field. Distribution of hourly averages *B* was Gaussian. The Gaussian distribution of *B* in heliosheath (in contrast to the lognormal distributions of B in the supersonic solar wind) suggests that some process tends to equilibrate the plasma in the heliosheath.

- Burlaga & Ness 2009 compared turbulence in a region of constant magnetic field direction (``unipolar region'') with that observed in the post-HTS region. Daily and 48 s averages of *B* were found to be lognormal in the post-HTS region and Gaussian in the unipolar region.

- Time series of the magnitude and direction of ***B*** show that the **fluctuations are highly compressive**.
- The turbulence includes ``kinetic-scale'' features (with sizes ~10 - 100 gyroradii), such as isolated **magnetic holes** and **humps**, and **trains of magnetic holes and humps** (Burlaga et al 2006). The turbulence also includes “microscale” features (> 100 proton gyroradii) on fluid-like scales.