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THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

# How measurements of solar wind plasma inform models of turbulence and transports

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SHINE 2022 Workshop

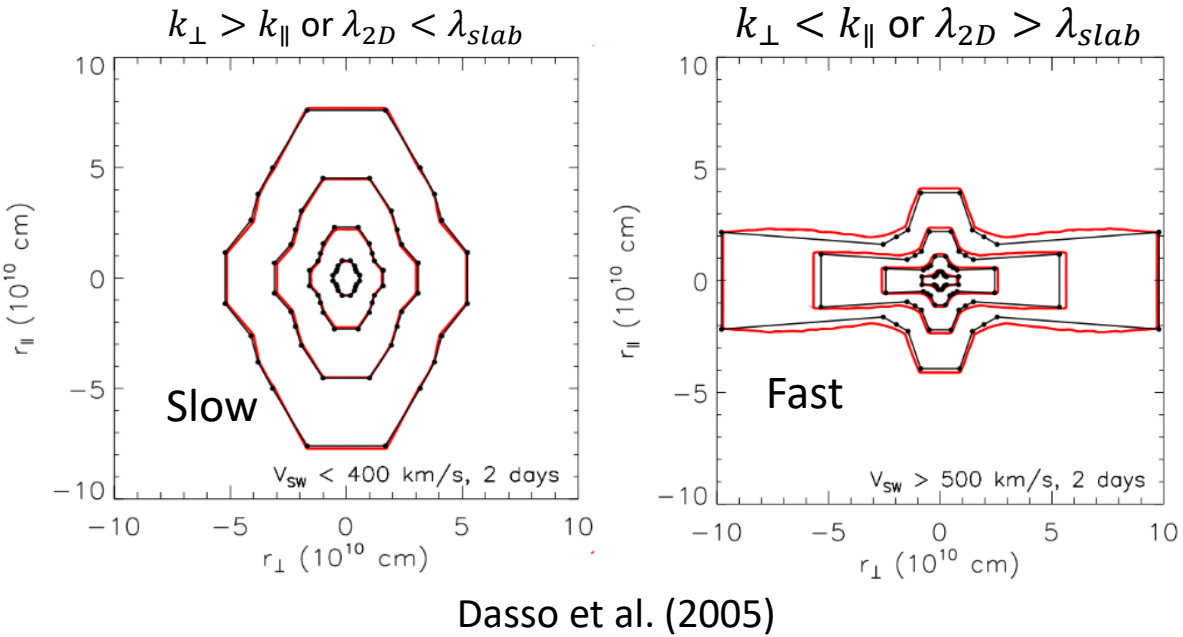
June 29, 2022

# OUTLINE

- Models and observations of anisotropy in solar wind turbulence measured by Parker Solar Probe and implications for particle transport.
- Coupled solar wind plasma-turbulence-energetic particle models and shock structures.

# Anisotropy in Solar Wind Turbulence

## ◆ Wavevector anisotropy:

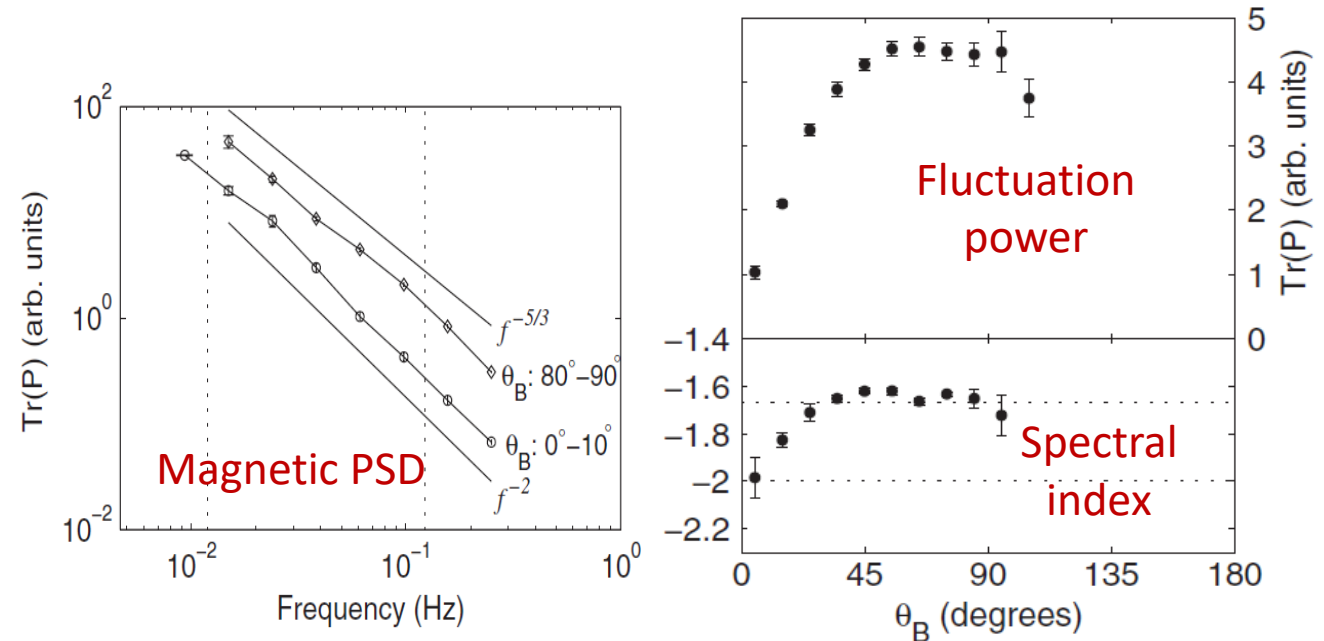


## ◆ Power anisotropy:

$$\text{i.e., } P(k_{\parallel}) \leq P(k_{\perp})$$

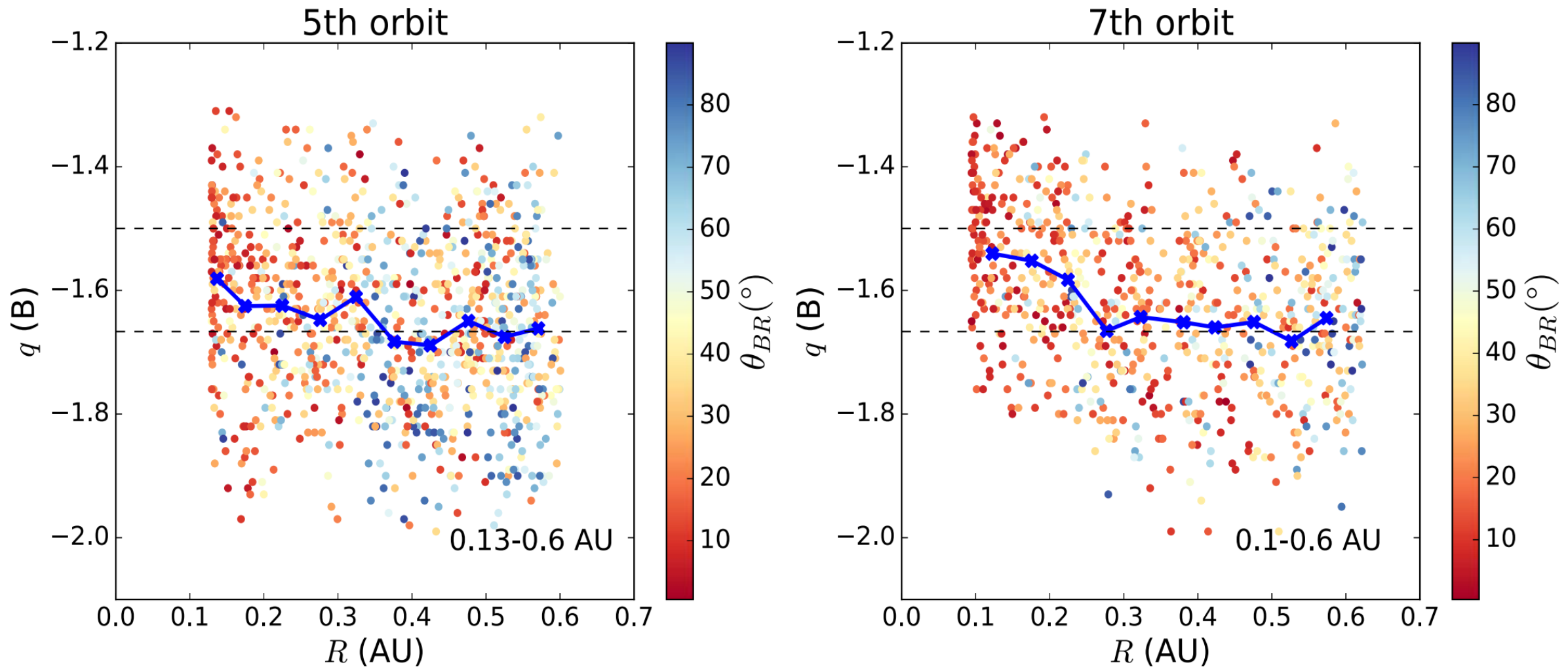
## ◆ Spectral index anisotropy:

Different spectral indices in parallel and perpendicular wavevector.



Horbury et al. (2008)

# The power-law index of the magnetic trace PSD



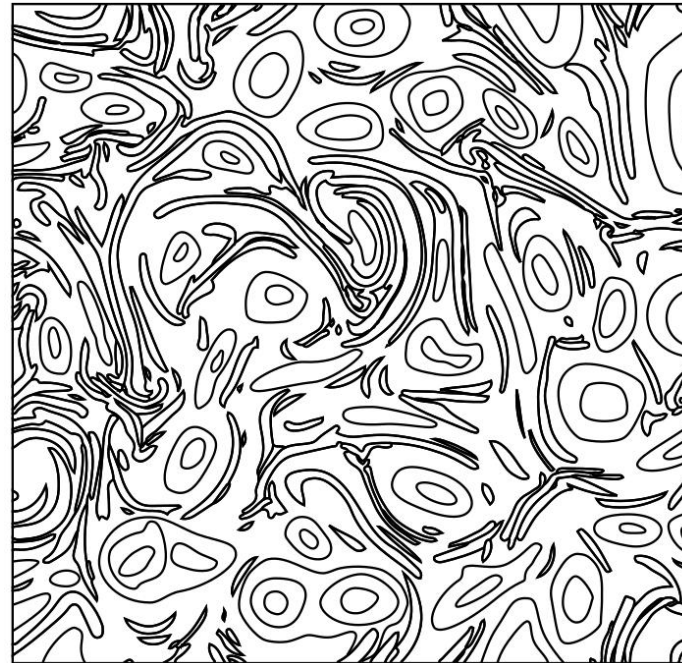
Zhao et al., ApJL, 2022a

Observations by Parker Solar Probe (PSP)

# Anisotropic turbulence model

## Majority 2D Turbulence or $k_{\perp}$ fluctuations

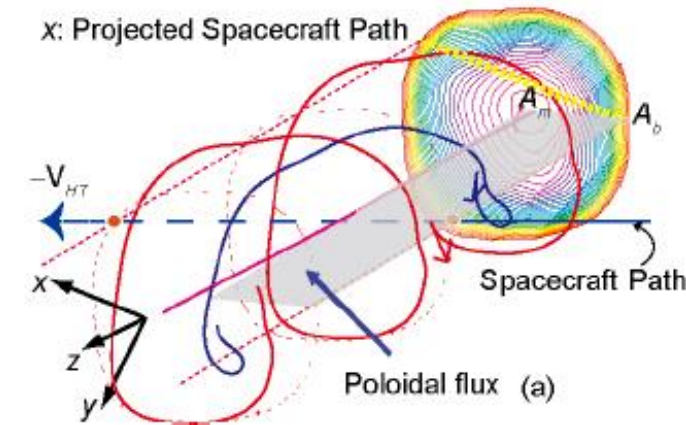
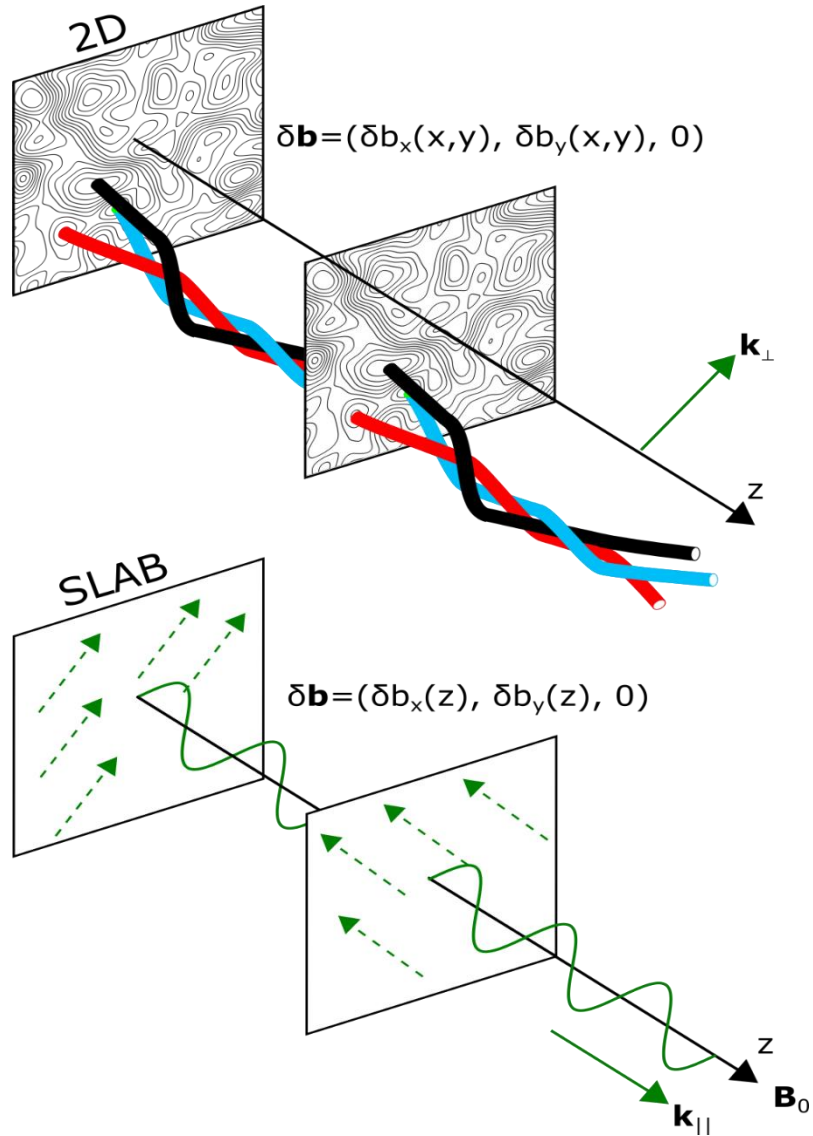
--- Advected structures/magnetic islands/flux tubes



A "sea" of magnetic islands

Zank et al. (2014)

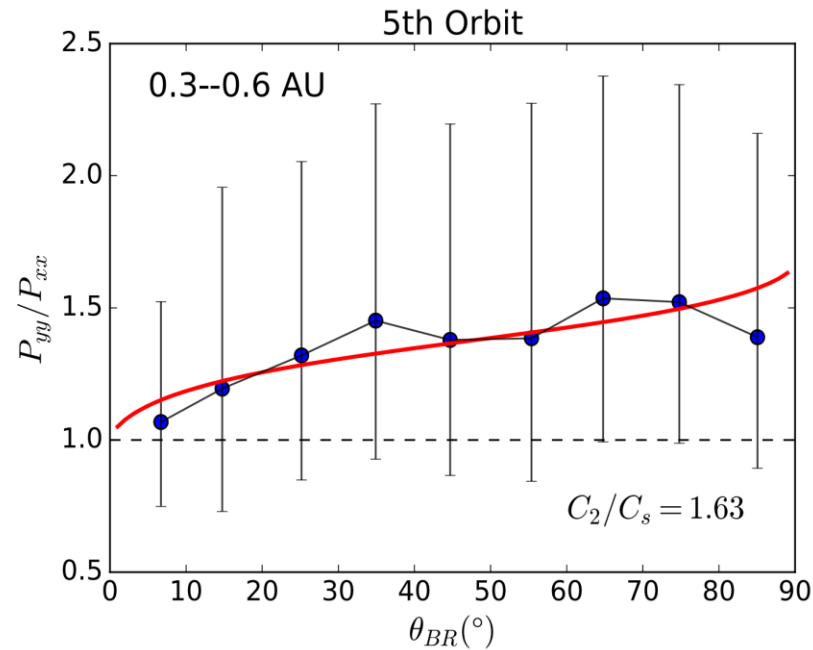
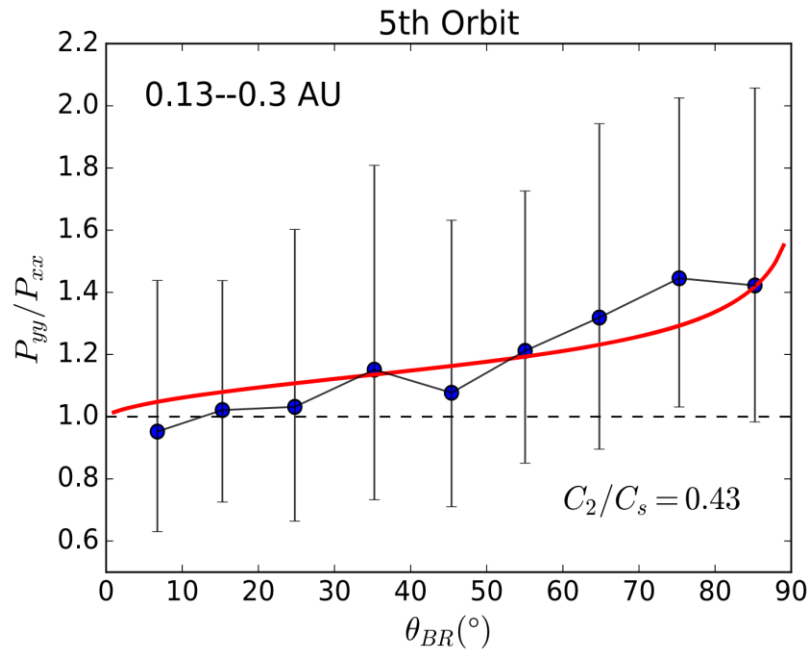
2D turbulence emerges as a "sea" of magnetic islands/flux tubes.



Small-scale magnetic flux rope (SFR)

Hu (2017)

# Radial evolution of solar wind turbulence anisotropy



- The fraction of power in **2D fluctuations is smaller** closer to the Sun during all *PSP* orbits

➤ Statistics of the transverse power anisotropy as a function of the sampling angle. The data are split into two groups by radial distance from the Sun.

Wave-vector Anisotropy in Different PSP Orbits

Orbit	$C_2/C_s$ ( $\leq 0.3$ au) $q = -5/3$	$C_2/C_s$ ( $\leq 0.3$ au) $q = -3/2$	$C_2/C_s$ (0.3–0.6 au) $q = -5/3$
# 1	0.47 (32% : 68%)	0.75 (43% : 57%)	1.70 (63% : 37%)
# 2	0.11 (10% : 90%)	0.20 (17% : 83%)	1.63 (62% : 38%)
# 4	0.28 (22% : 78%)	0.47 (32% : 68%)	1.56 (61% : 39%)
# 5	0.43 (30% : 70%)	0.72 (42% : 58%)	1.63 (62% : 38%)
# 6	0.40 (29% : 71%)	0.52 (34% : 66%)	1.50 (60% : 40%)
# 7	0.25 (20% : 80%)	0.49 (33% : 57%)	0.67 (40% : 60%)

**Note.** The perihelion distance to the Sun is different for different PSP orbits. The exact radial distance range in the second column also varies with orbit, which we list as follows: 0.17–0.3 au (Orbits 1 and 2); 0.13–0.3 au (Orbits 4 and 5); 0.10–0.3 au (Orbits 6 and 7).

# Particle Diffusion

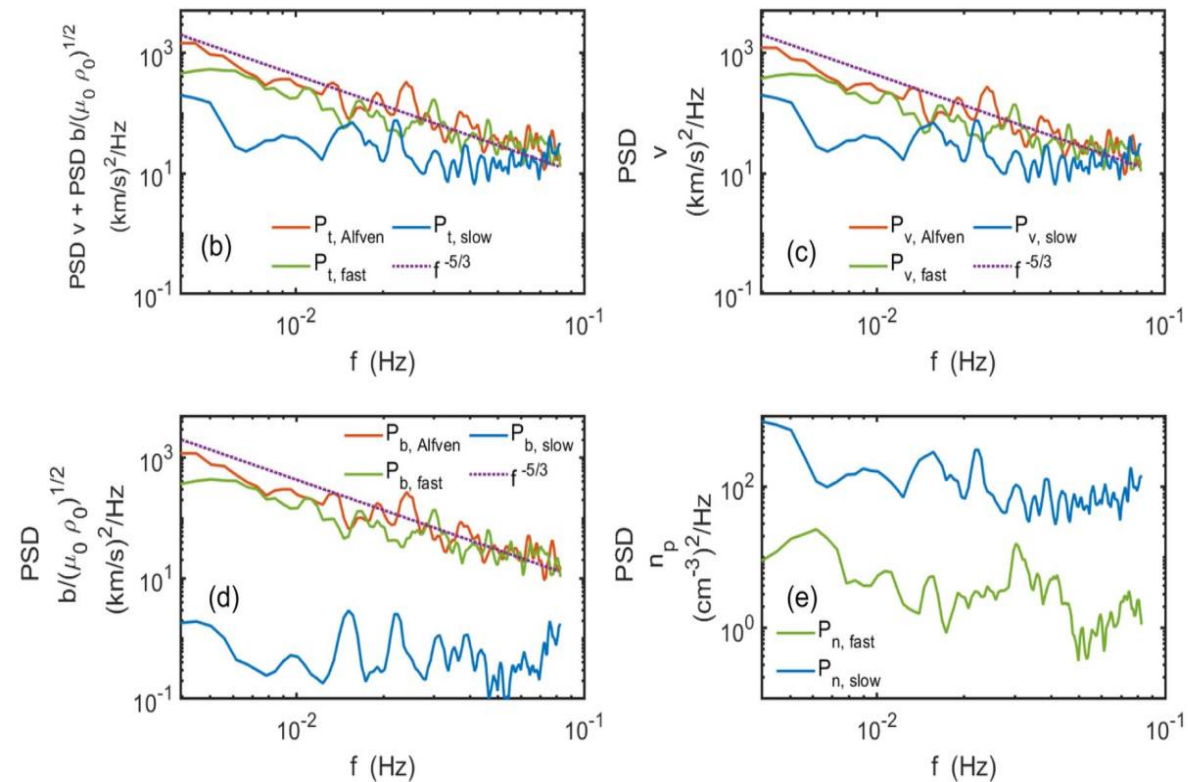
- Pitch-angle scattering rate (quasi-linear theory, QLT)

$$D_{\mu\mu} = \frac{2\pi v^2 (1 - \mu^2)}{B_0^2 R_L^2} \int_0^\infty dk_{\parallel} g(k_{\parallel}) [R_-(k_{\parallel}) + R_+(k_{\parallel})]$$

- Resonance function  $R_{\pm} = \pi \delta(k_{\parallel} v_{\parallel} \pm \Omega)$
- Resonance occurs when  $v_{\parallel}/\Omega = \mp 1/k_{\parallel}$
- Power spectrum  $g(k_{\parallel})$
- Parallel diffusion coefficient

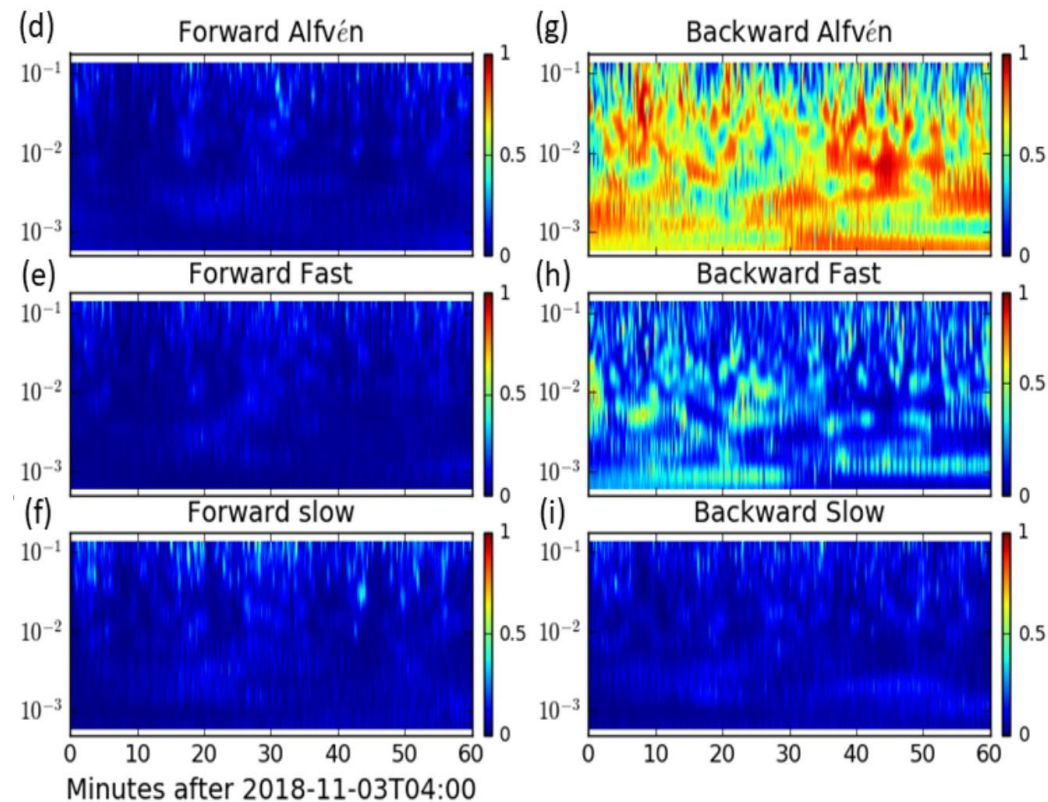
$$\kappa_{\parallel} = \frac{v^2}{8} \int_{-1}^1 d\mu \frac{(1 - \mu^2)^2}{D_{\mu\mu}}$$

# MHD wave decomposition



*S. Q. Zhao et al., ApJ, 2021*

- (b) total power spectra; (c) kinetic power spectra; (d) magnetic power spectra; (e) proton density power spectra.



*L.-L. Zhao et al., ApJ, 2021*

- The relative fraction of spectral energy density in each MHD wave mode.

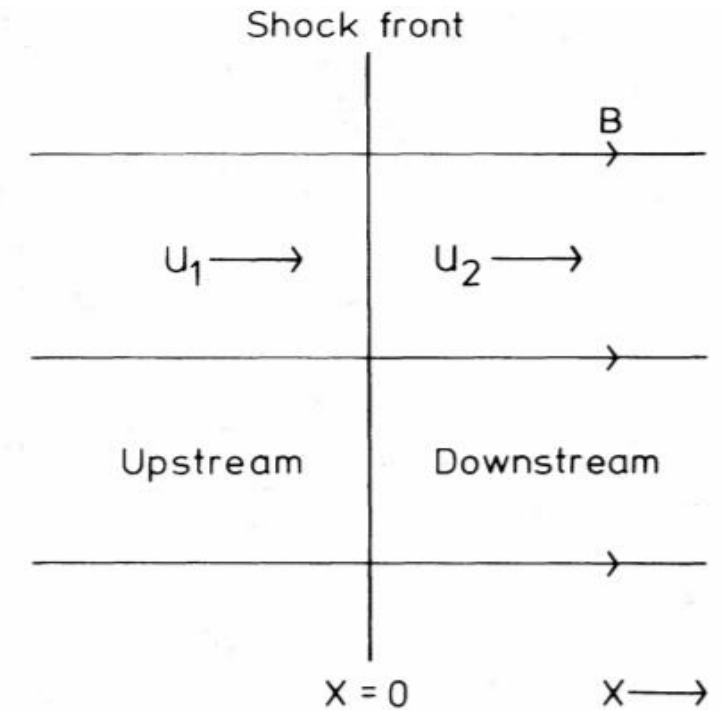
Coupled solar wind plasma-turbulence-energetic  
particle models and shock structures

- **Test particle model**

- Simple shock structure with discontinuity
- Power law particle spectrum

- **Nonlinear diffusive shock acceleration**

- Energetic particles pressure
- Turbulence generated by Energetic particles
- Heating gas resulted from dissipation of turbulence
- Turbulence pressure
- Modified shock structure, complex particle spectrum



(Bell, 1978)

## Two-fluid model

Drury & Völk (1981), Axford (1982), McKenzie & Völk (1982)

$$\rho \left( \frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) U = - \frac{\partial}{\partial x} (P_c + P_g + P_w)$$

$$\left( \frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) P_g + \gamma_g P_g \frac{\partial U}{\partial x} = 0$$

$$\frac{\partial P_c}{\partial t} + (U - V_A) \frac{\partial P_c}{\partial x} + \gamma_c P_c \frac{\partial}{\partial x} (U - V_A) = \frac{\partial}{\partial x} \left( K \frac{\partial P_c}{\partial x} \right)$$

$$\frac{\partial}{\partial t} \frac{(\delta B)^2}{4\pi} + \frac{\partial}{\partial x} \left[ \frac{(\delta B)^2}{4\pi} \frac{3}{2} (U - V_A) \right] = U \frac{\partial}{\partial x} \left( \frac{(\delta B)^2}{8\pi} \right) + V_A \frac{\partial P_c}{\partial x}$$

Cosmic ray particles and the thermal gas are both treated as the fluid.

# Multi-fluid model equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho U)}{\partial x} = 0;$$

$$\rho \left( \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} \right) = -\frac{\partial P_g}{\partial x} - \frac{\partial P_c}{\partial x} - \frac{\partial \Pi}{\partial x} - \frac{\partial P_w}{\partial x};$$

$$\frac{\partial P_g}{\partial t} + U \frac{\partial P_g}{\partial x} + \gamma_g P_g \frac{\partial U}{\partial x} = (\gamma_g - 1) \frac{\rho}{2\lambda} \left[ (E_T + E_C)(E_T - E_C)^{1/2} + (E_T - E_C)(E_T + E_C)^{1/2} \right];$$

$$\frac{\partial P_c}{\partial t} + (U - \sigma_C V_A) \frac{\partial P_c}{\partial x} + \gamma_c P_c \frac{\partial}{\partial x} (U - \sigma_C V_A) = \frac{1}{3} \frac{\partial}{\partial x} \left( K \frac{\partial P_c}{\partial x} \right) - (\gamma_c - 1) \Pi \frac{\partial}{\partial x} (U - \sigma_C V_A);$$

$$\begin{aligned} \frac{\partial}{\partial t} \left( \frac{1}{2} \rho U^2 + \frac{\gamma_c P_c}{\gamma_c - 1} + \frac{\gamma_g P_g}{\gamma_g - 1} + E_w \right) + \frac{\partial}{\partial x} \left( \frac{1}{2} \rho U^2 U + \frac{\gamma_c}{\gamma_c - 1} P_c (U - \sigma_C V_A) + \frac{\gamma_g P_g}{\gamma_g - 1} U \right. \\ \left. + \Pi (U - \sigma_C V_A) - \frac{1}{\gamma_c - 1} \frac{K}{3} \frac{dP_c}{dx} + (U - \sigma_C V_A) E_w + U P_w \right) = 0, \end{aligned}$$

Wang et al., ApJ, 2022

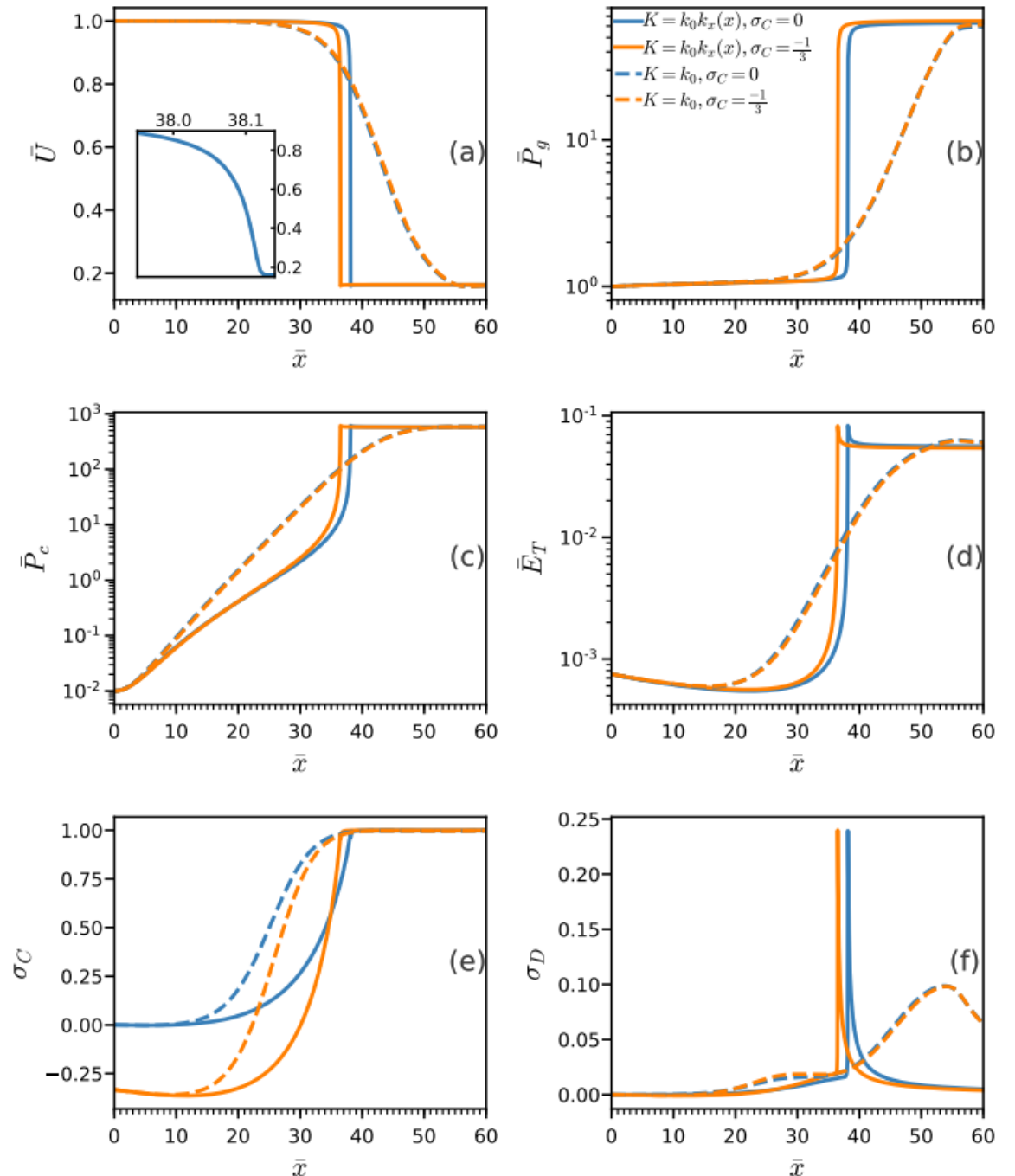
- ❖ CR pressure and viscous stress; Turbulence heating; CR diffusion coefficient

# Applied to CR modified shock

- Fluid equations
- Turbulence transport equations (Zank et al., 2012)
- CR diffusion coefficient (QLT)

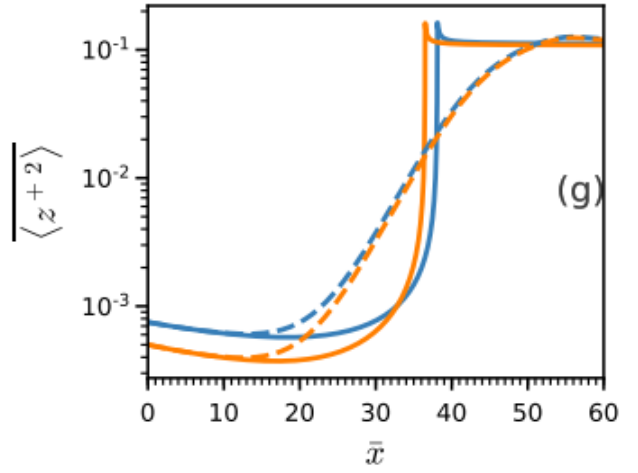
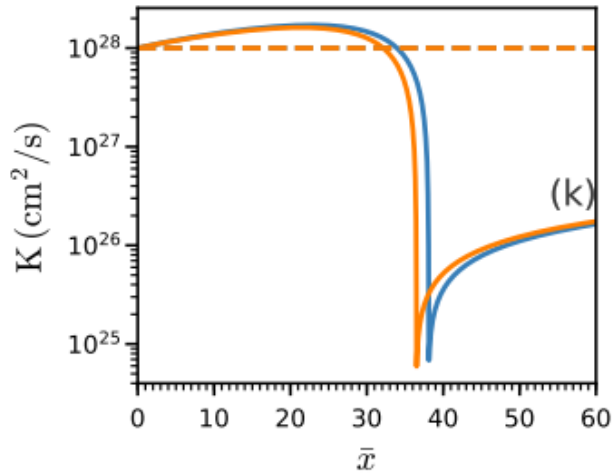
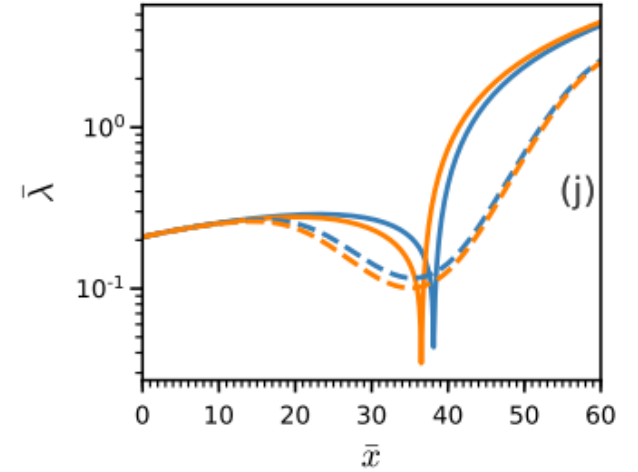
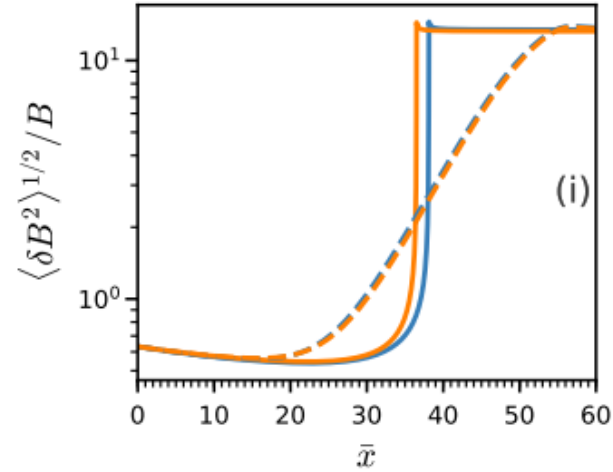
The gradient force of CR pressure, gas pressure, and the viscous stress decelerate the incoming gas.

Wang et al., ApJ, 2022



# Turbulence quantities

- The turbulence level is indicated by the ratio of turbulent magnetic field amplitude and mean magnetic field amplitude.
- The turbulent magnetic field could be about 10 times larger than the mean field.
- The diffusion coefficient is more than 3 orders smaller than that of far upstream.



(Wang et al., ApJ, 2022)

## Summary

- Measurements of solar wind plasma can **inform** models of turbulence and transport. Vice versa, better models of turbulence and transport will be helpful for **interpreting** solar wind measurements.
- **Coupled solar wind plasma-turbulence-energetic particle models** are needed to understand shocks and other processes in the heliosphere.