The Evolution and Role of Solar Wind Turbulence in the Inner Heliosphere

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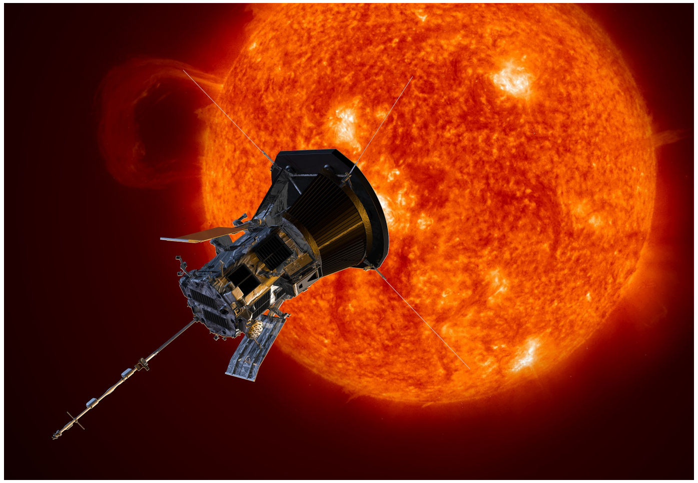
Chen et al. (2020), Astrophysical Journal Supplement, 246, 53

Science Questions

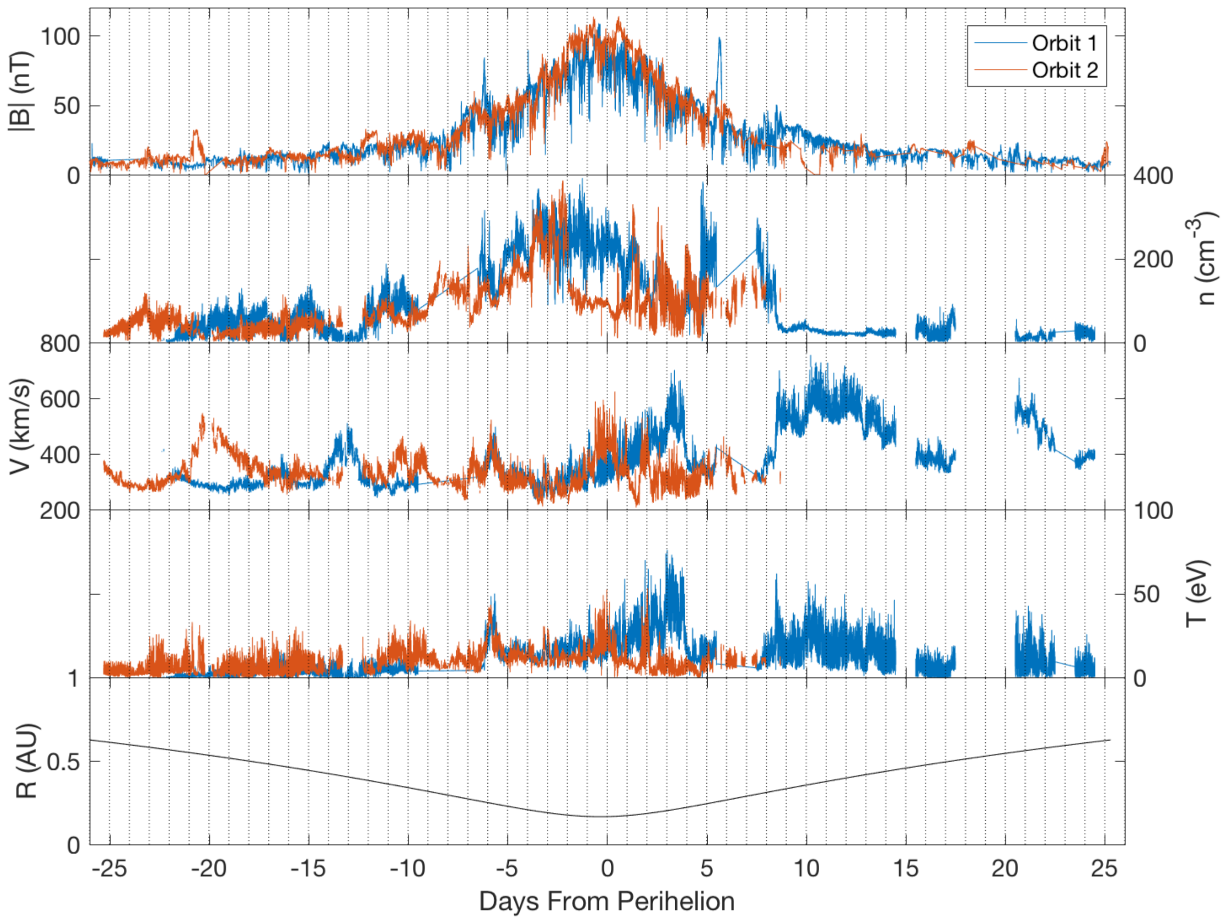
- One objective of Parker Solar Probe:
  “Trace the flow of energy that heats and accelerates the solar corona and solar wind”



- What role does turbulence play?
  - What is turbulence energy flux near the Sun, is it sufficient to accelerate the wind?
  - How does turbulence heat the solar corona and inner heliosphere?
  - How is inward turbulence component generated to enable the cascade?
  - What is turbulence like closer to the Sun? How does it evolution with distance?
  - What does this tell us about the fundamental nature of MHD turbulence?

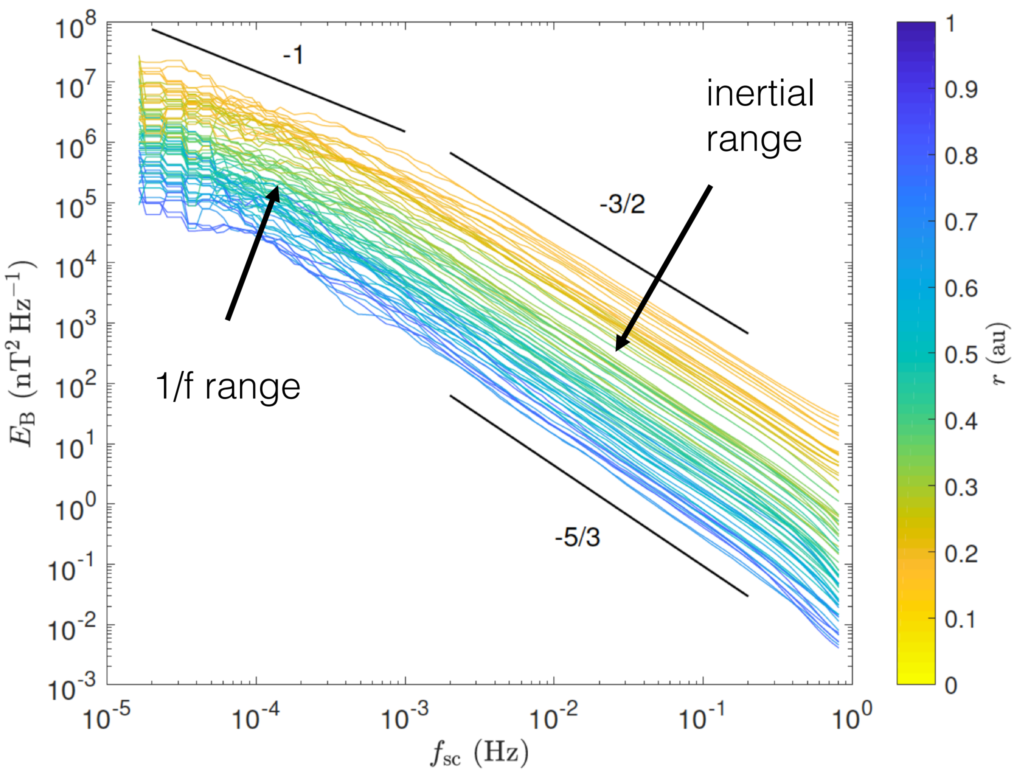
Data Overview

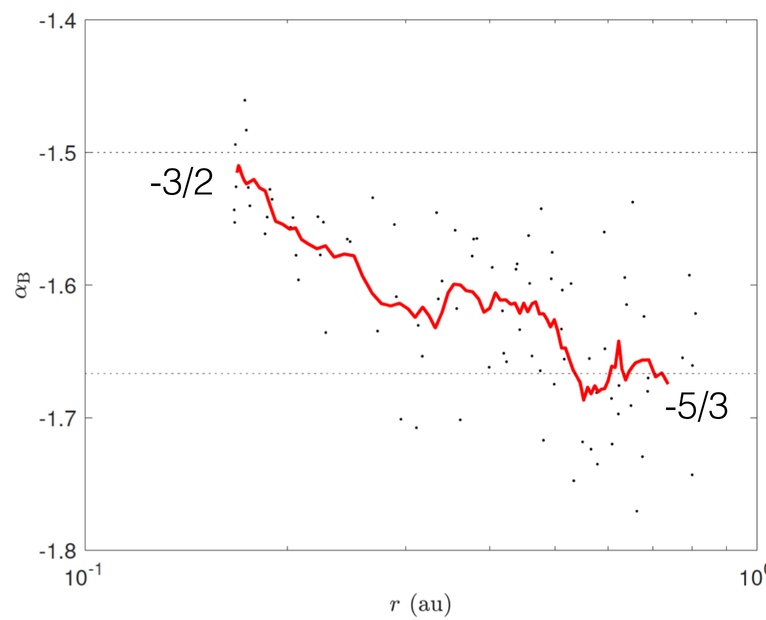
- Time series of data from first two orbits of PSP
- Split into 1-day intervals and calculate turbulence properties



Magnetic Spectrum

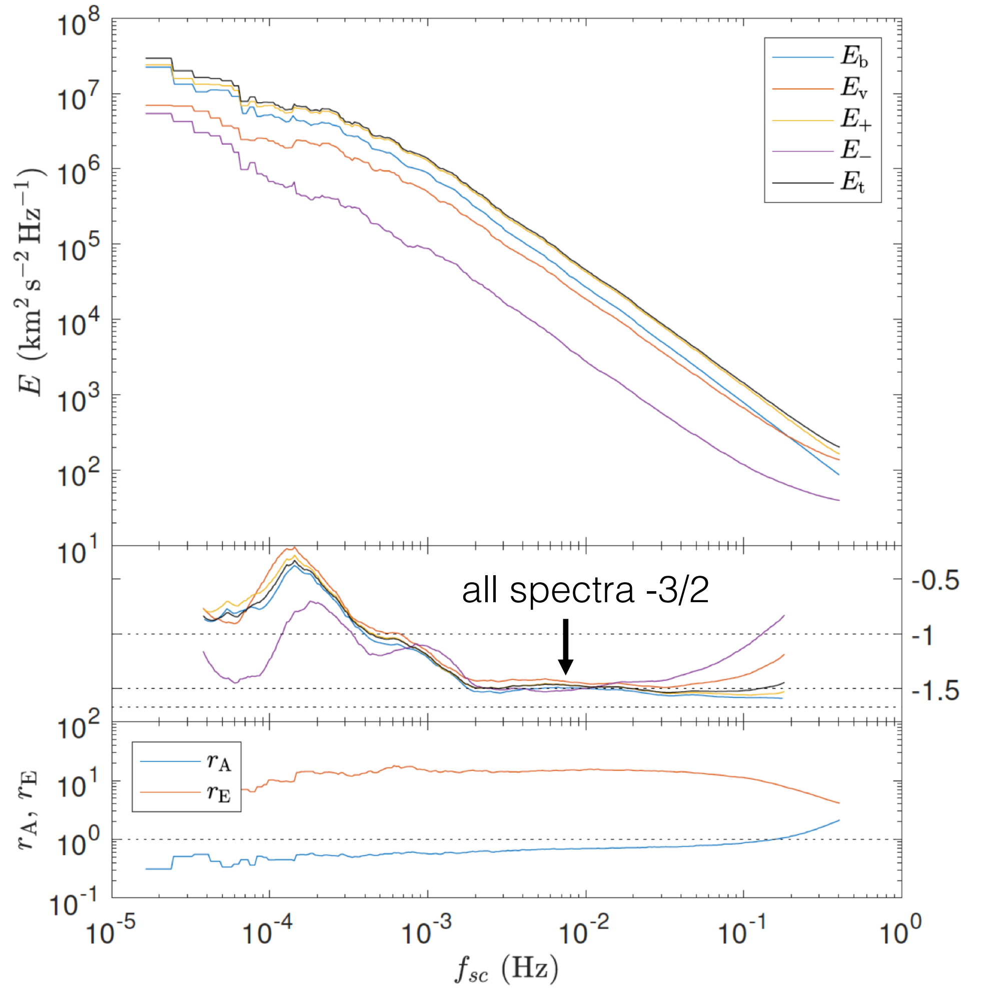
- Magnetic spectra are power law (inertial range), with low frequency flattening
- Power increases towards Sun (~10^3 times)
- Shallower inertial range spectrum closer in, from -5/3 to -3/2
- These are the two main predictions from MHD turbulence models
  -5/3 from critical balance model (Goldreich & Sridhar 1995)
  -3/2 from scale-dependent alignment (Boldyrev 2006)





Spectra of MHD Variables at 0.17 au

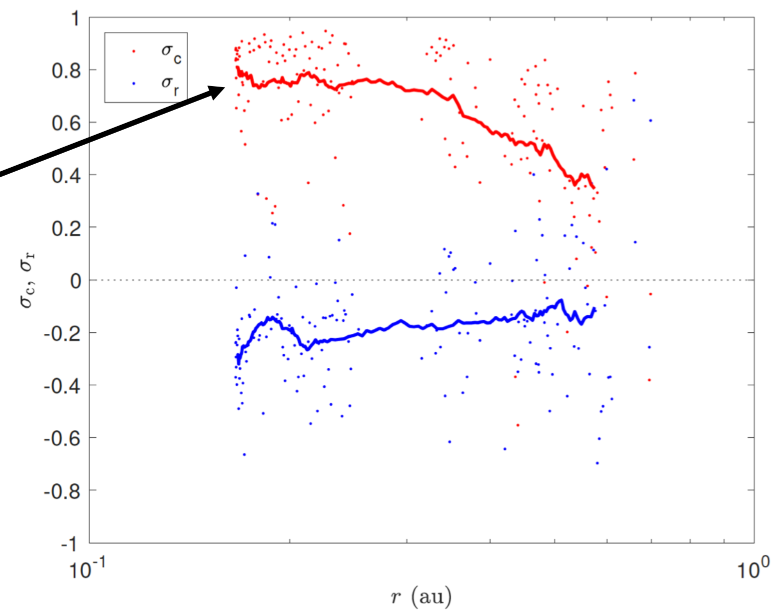
- Highly imbalanced ($E_+ >> E_-$), with small amount of residual energy ($E_b >\sim E_v$)
- All spectra have -3/2 inertial range (until noise level)
- Matches turbulence models with scale-dependent alignment (Boldyrev 2006, Perez & Boldyrev 2009, Chandran et al. 2015, Mallet & Schekochihin 2017)
- Elsasser spectra scale the same, rules out other classes of imbalanced turbulence models
- Similar to imbalanced turbulence at 1 AU



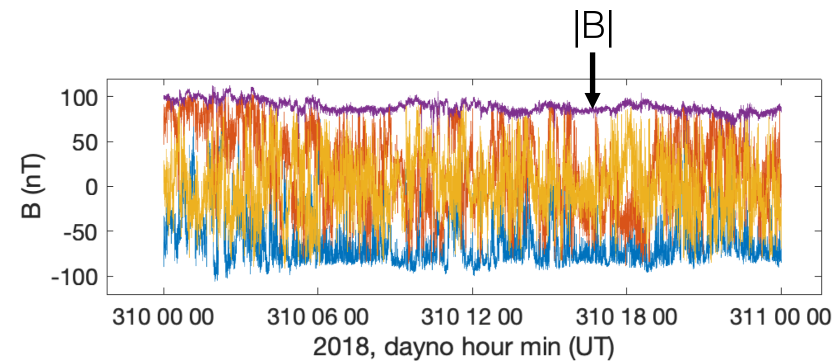
Spectral Index & Cross-Helicity

- Is radial trend in magnetic spectrum index due to to cross-helicity?
- σ_C evolves radially, consistent with 1 au data showing index depends on σ_C
- Other possible interpretations for -3/2 at perihelion:
  - Transitory evolution towards -5/3 spectrum (but many nonlinear times)
  - Transition from k^{-1} spectrum of reflection driven cascade (Velli et al. 1989)?
  - Closer to Sun turbulence is in forced rather than decaying state
  - Effects of driving sources from Sun are affecting inertial range
- Want to see how trends continue as we get in closer to distinguish these

cross-helicity larger closer to Sun

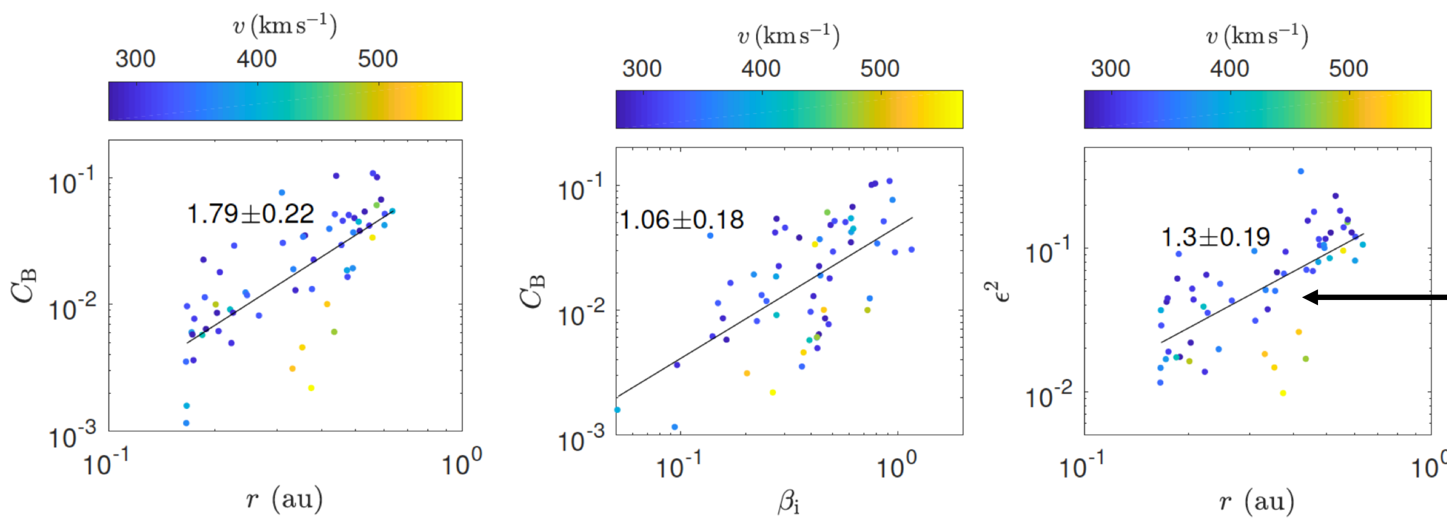


Magnetic Compressibility & Slow Modes



- SW has low magnetic compressibility
- This decreases further at smaller r
- Assume mix of Alfvén/slow modes
- Compressibility:
  - is proportional to β as expected
  - decreasing slow mode KE fraction ϵ at smaller r
- Slow mode generation with r? PDI?
- Process reducing δ|B|? Magnetic pressure force?

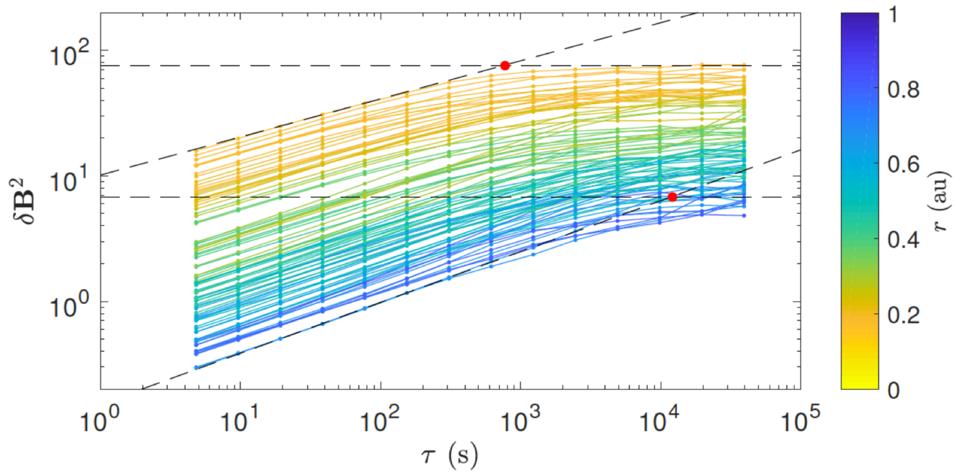
$$\left(\frac{\delta|\mathbf{B}|}{|\delta\mathbf{B}|}\right)^2 = \frac{\beta\gamma\epsilon^2\sin^4(\theta_{kB})}{2}$$

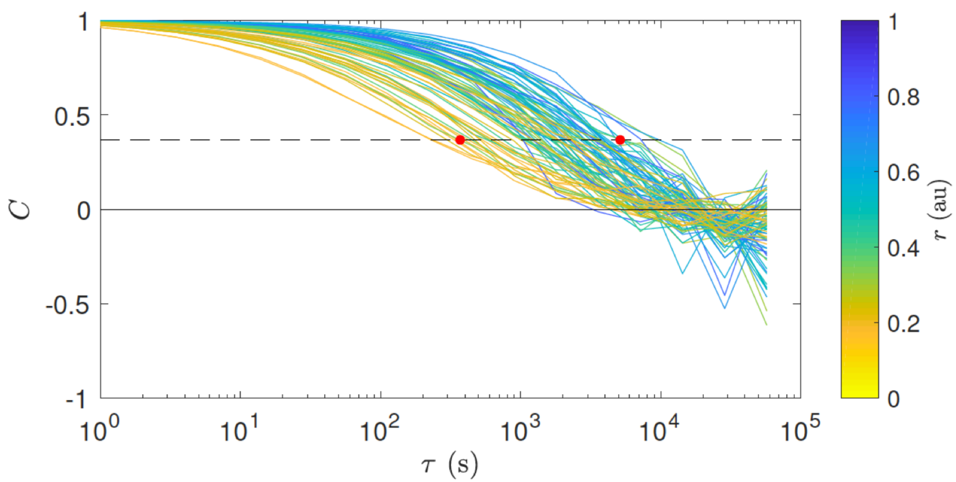


slow mode kinetic energy fraction increases with distance

Turbulence Outer Scale

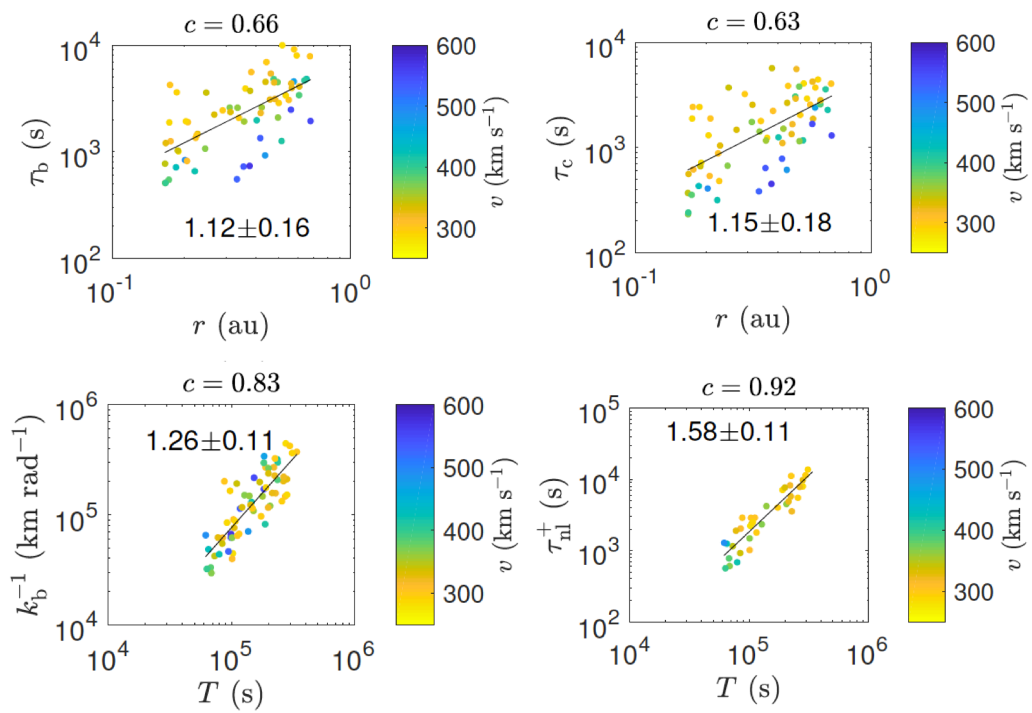
- Break to 1/f range found from structure functions
- Correlation time determined as when C=1/e
- Outer scale is larger at larger distances
- Use to test different 1/f models (Matthaeus & Goldstein 1986, Velli et al. 1989, Verdini et al. 2012, Perez & Chandran 2013, Chandran 2018, Matteini et al. 2018)
- “Classic” interpretation of break is the largest scale at which eddies have had time to decay





Turbulence Outer Scale

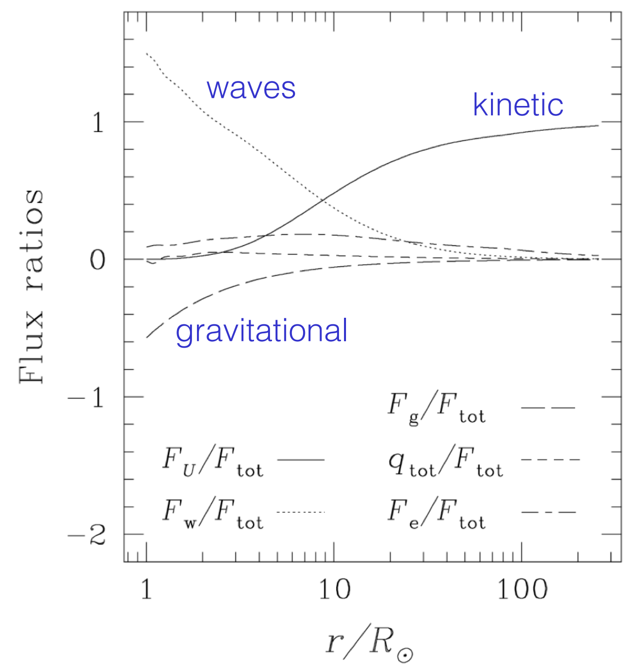
- Approximately linear with r (with scatter) - same as ion break scale (Duan et al. 2020)
- 1/f break scale and correlation scale behave similarly
- Better correlation as k vs T
- Good correlation between outer scale nonlinear time and travel time
- But τ << T, 1/f range has time for nonlinear processing
- As for recent ideas for 1/f range (Velli et al. 1989, Verdini et al. 2012, Perez & Chandran 2013, Chandran 2018, Matteini et al. 2018)



$$\tau_{\rm nl}^{+} = (k_{\rm b}\delta z_{\rm rms}^{-})^{-1}$$

Waves/Turbulence Driven Solar Wind

- Energy in waves/turbulence:
  - Dissipates to heat corona
  - Fluctuation pressure accelerates solar wind
  - Rest becomes solar wind turbulence
- Non-linear simulations suggest ~1/3 energy to each (Perez & Chandran 2013 ApJ)
- Advanced wave-driven models can produce realistic fast solar wind
  - Chandran et al. 2011: two-species, ion anisotropy, collisional/collisionless heat flux, reflection-driven turbulence



Chandran et al. 2011 ApJ

Parker wind Wave/turbulence flux

$$F = 4\pi r^2 \left\{ V\left[\tfrac{1}{2}\rho V^2 + \frac{\alpha}{(\alpha-1)}p + \rho\Phi\right] + \tfrac{1}{2}(\tfrac{1}{2}\rho\delta V^2)V + \tfrac{1}{2}\frac{\delta B^2}{4\pi}(V + V_A)\right\}$$

Belcher 1971 JGR

Turbulence Energy Flux

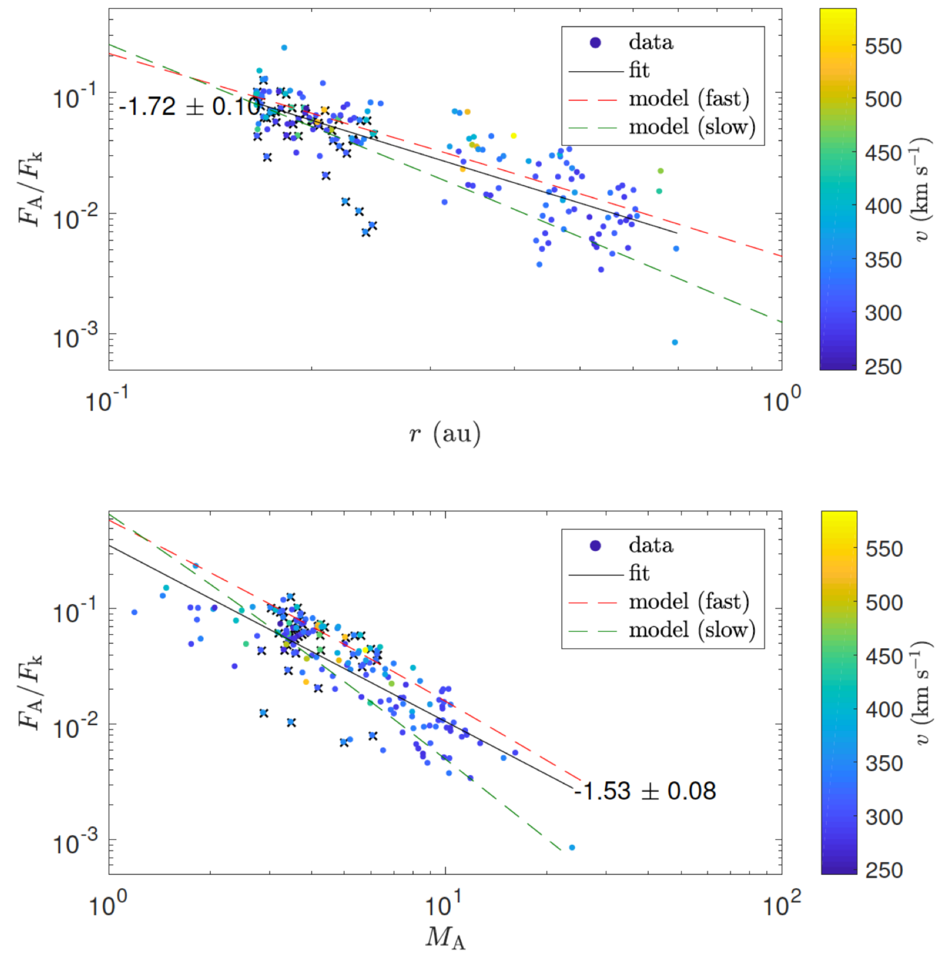
- Ratio of wave/turbulence to bulk kinetic flux

$$F_{\mathrm{AW}} = \frac{\rho|\delta \mathbf{z}^{+}|^{2}}{4}\left(v_A + \frac{3}{2}v_R\right)$$

$$F_{\mathrm{kinetic}} = \frac{1}{2}\rho v_R^3$$

- Increases to significant levels
  - ~ 10% at perihelion
  - ~ 40% extrapolated to r_A
  - consistent with a turbulence-driven solar wind

- Coronal hole wind in E1 marked with x, mostly fits models, apart from periods of radial quiet wind

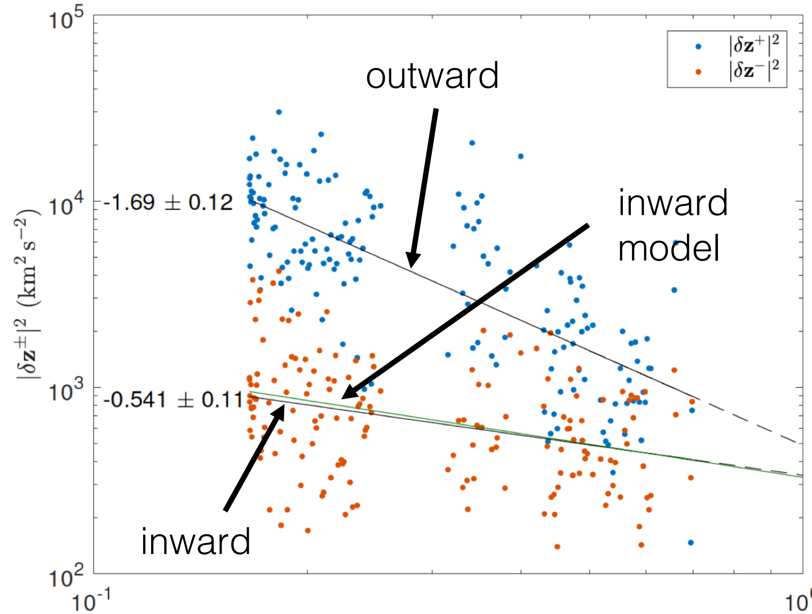


Origin of Inward Component

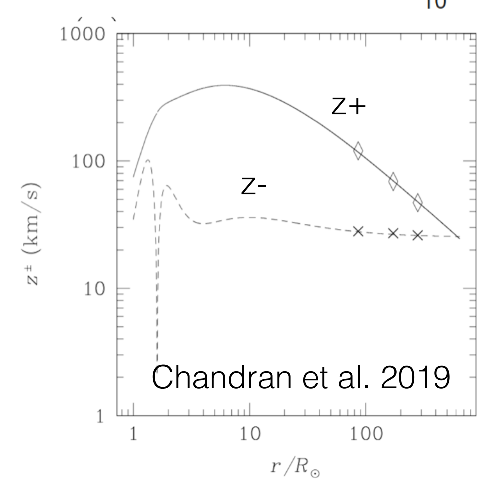
- Sun produces outward Alfvén waves but need inward for non-linearity (turbulence)
- Can arise from reflection, shear driving, parametric decay,…
- Model balancing reflection and cascade gives (Chandran et al. 2011)

$$\delta z^- = L_{\perp\odot}\sqrt{\frac{B_\odot}{B}}\left(\frac{v_\mathrm{r}+v_\mathrm{A}}{v_\mathrm{A}}\right)\left|\frac{\partial v_\mathrm{A}}{\partial r}\right|$$

- Assuming $L_{\perp s}$ = 1.4x10^4 km and B_s = 1.18 mT this gives $(z^-)^2 \sim r^{-0.58}$ consistent with observations
- Inward component consistent with reflection generation
- Also correlation time of z- much longer, consistent with reflection (low-pass filter)



Field	τ_c
$\mathbf{B}$	417 s
$\mathbf{v}$	419 s
$\mathbf{z}^+$	407 s
$\mathbf{z}^-$	3,300 s



Summary

- Turbulence different in some ways at 0.17 au
  - Power levels much higher
  - B spectral index -3/2 to match all fields
  - Lower compressibility (less slow modes)
  - Smaller outer scale, nonlinear processing of 1/f range
- Role of turbulence in solar wind generation
  - Turbulence energy flux fraction increases (to ~10% of sw energy flux)
  - Consistent with turbulence-driven solar wind models
  - Inward component consistent with reflection generation
- Open questions & future work
  - What happens to the spectrum closer in? Driving?
  - Origin of compressive fluctuations and 1/f range
  - Energy fluxes within corona vs turbulence-driven models
  - Kinetic range turbulence and heating mechanisms