Waves & Turbulence in the Solar Wind: Disputed Origins & Predictions for PSP

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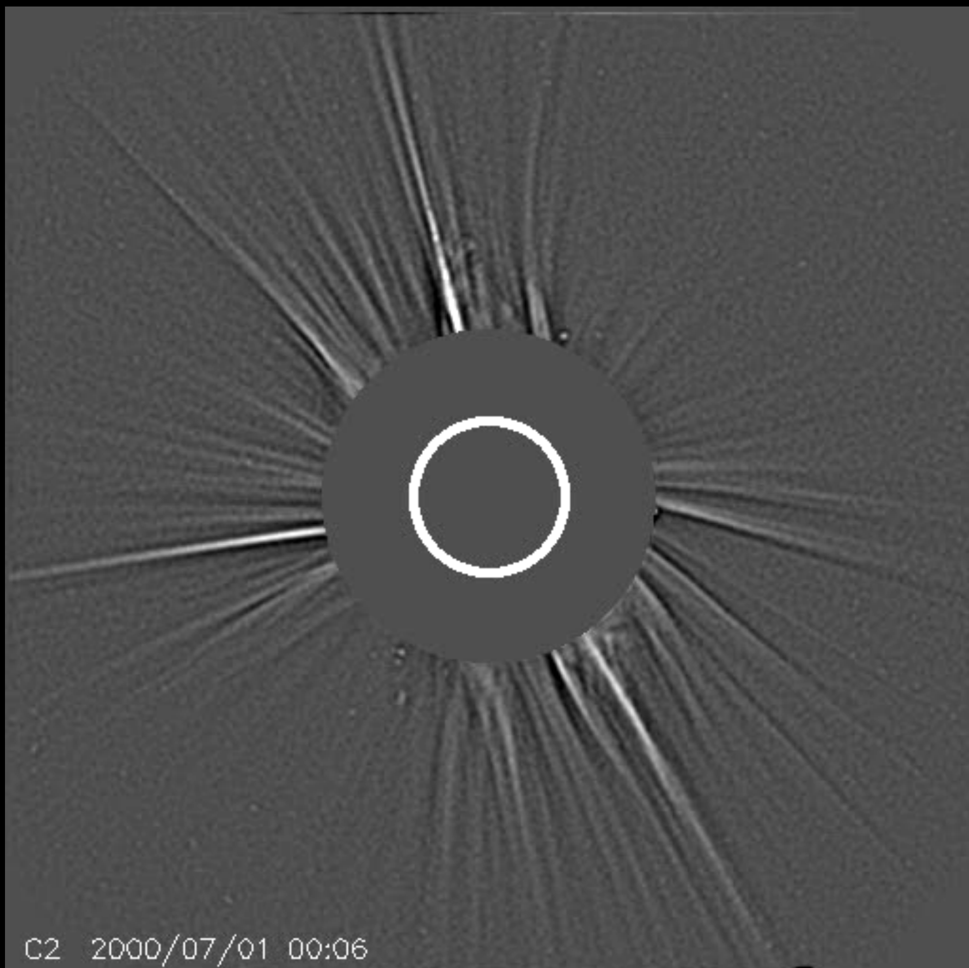
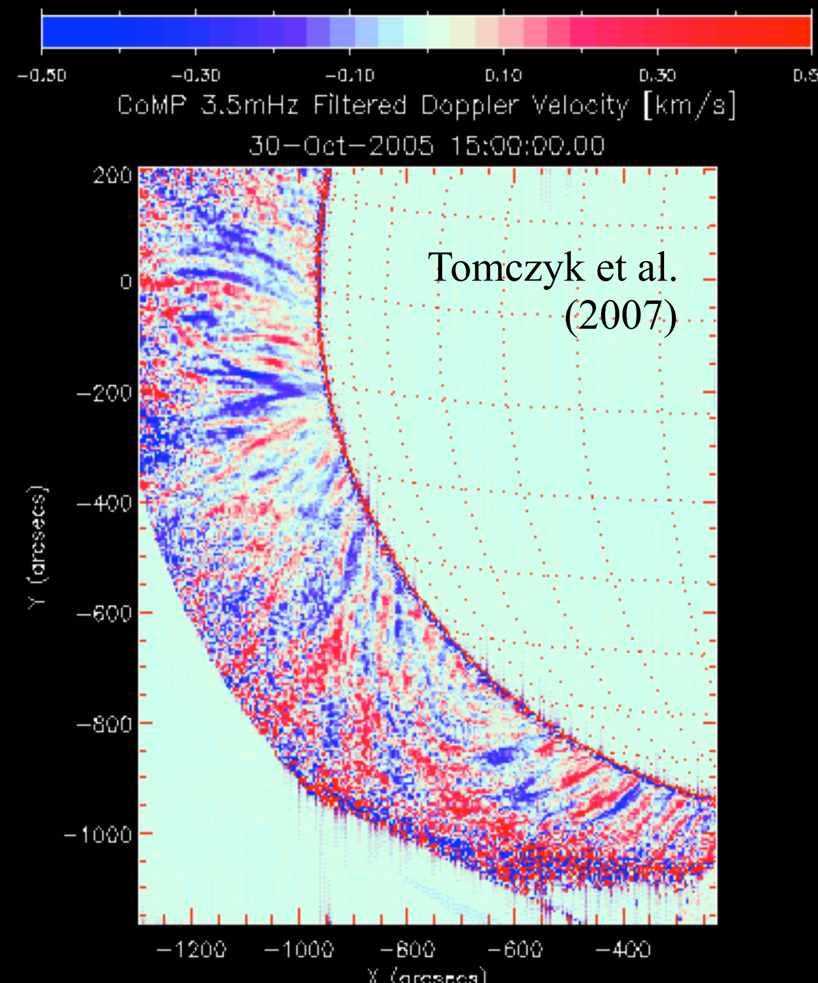
Outline

1. Brief review of observation techniques & what we know so far.
2. Where do solar wind MHD fluctuations come from?
    - Solar photosphere (intergranular flux tubes)
    - Coronal reconnection events
    - Heliospheric stream-stream interactions (CIRs)
    - Kinetic & MHD instabilities?
3. Preliminary PSP predictions: power spectra, variance anisotropies.

Remote sensing of MHD waves

With good instrumentation, imaging & spectroscopy can resolve fluctuations…

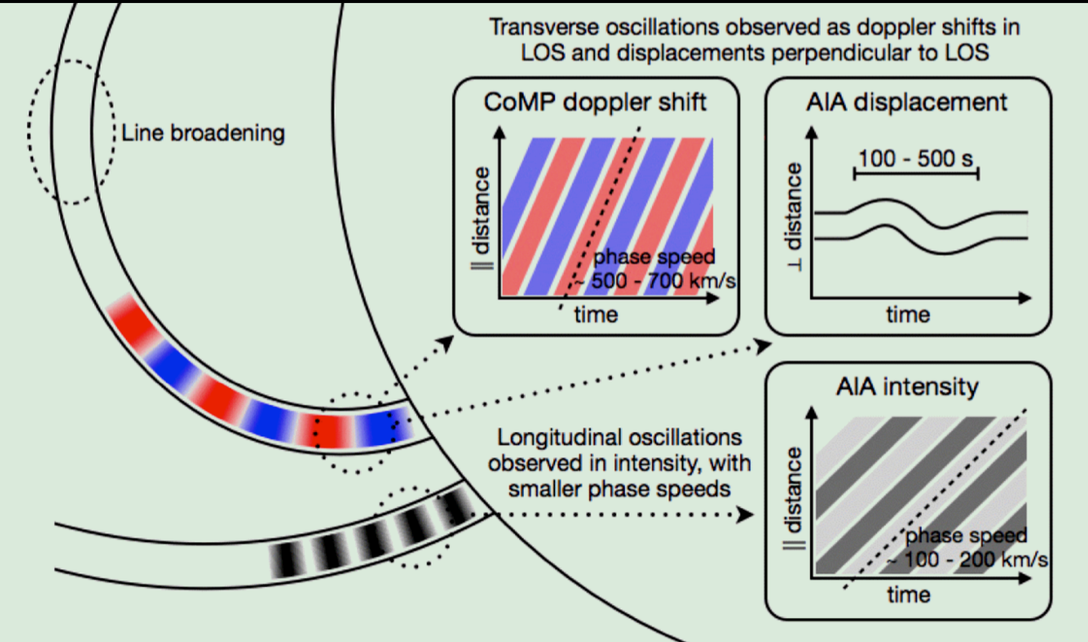




Remote sensing of MHD waves

Multiple diagnostic techniques work well in tandem…

- Intensity modulations . . .
  $$\delta I \propto (\delta\rho)^{1-2}$$
- Motion tracking in images . . .
  $$\delta V_{\rm POS}$$
- Doppler shifts . . .
  $$\delta\lambda \propto \delta V_{\rm LOS}$$
- Doppler broadening . . .
  $$\delta\lambda \rightarrow <\delta V_{\rm LOS}>$$
- Radio sounding . . .
  $$\delta\tilde{n} \rightarrow \delta\rho\,,\delta B \rightarrow \delta V$$

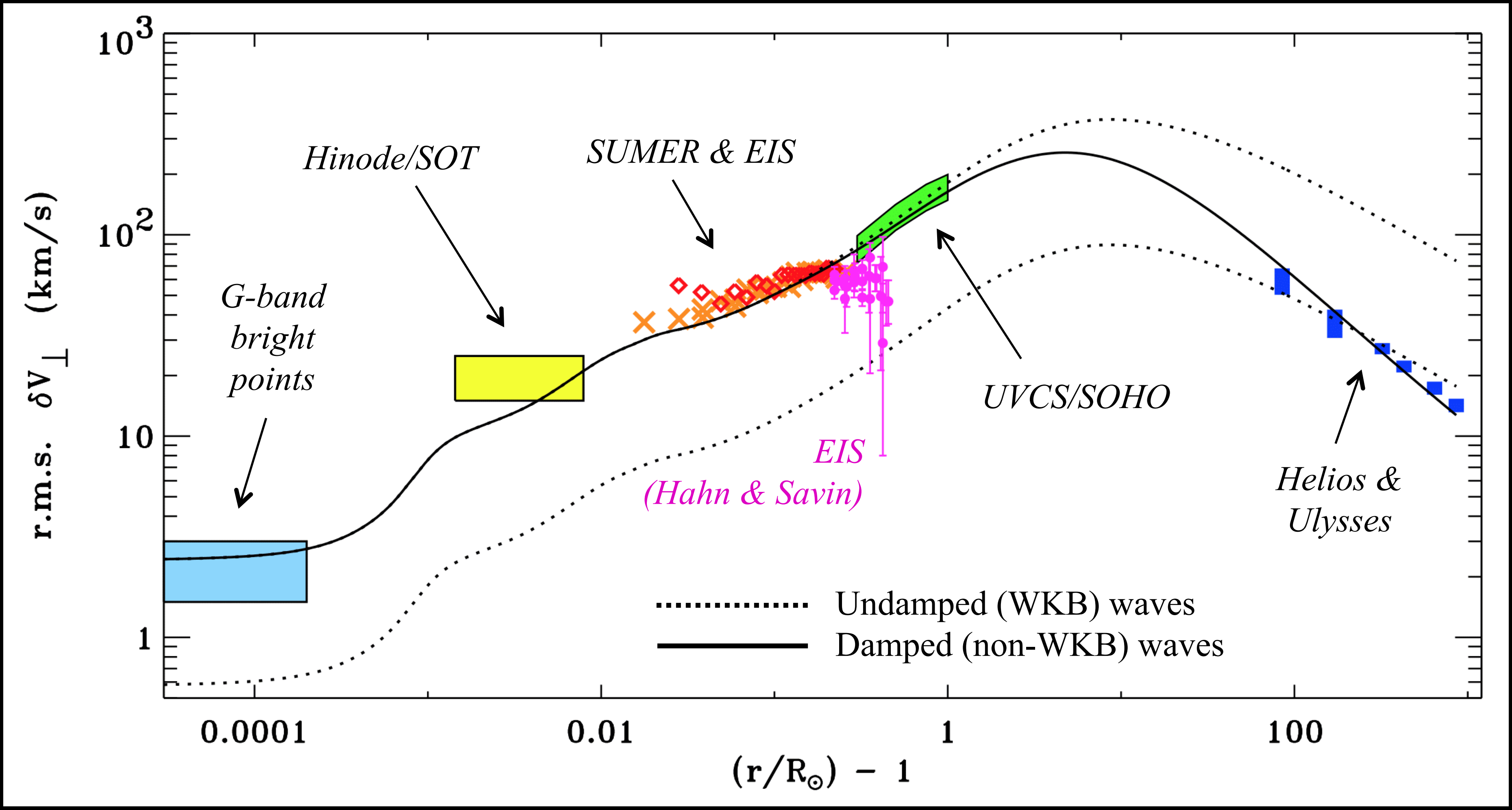


Threlfall et al. (2013)

- ***Results:*** Alfvén-like waves seem to have periods of order 3-5 minutes; compressive waves have periods of order 10-20 minutes.

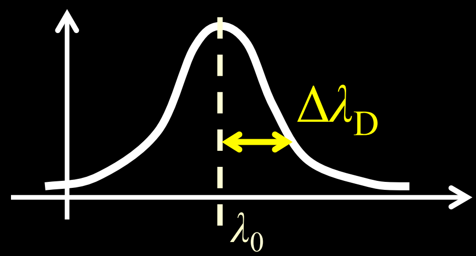
Measured Alfvénic fluctuations

- Cranmer & van Ballegooijen (2005) collected a range of observational data…



Off-limb complications

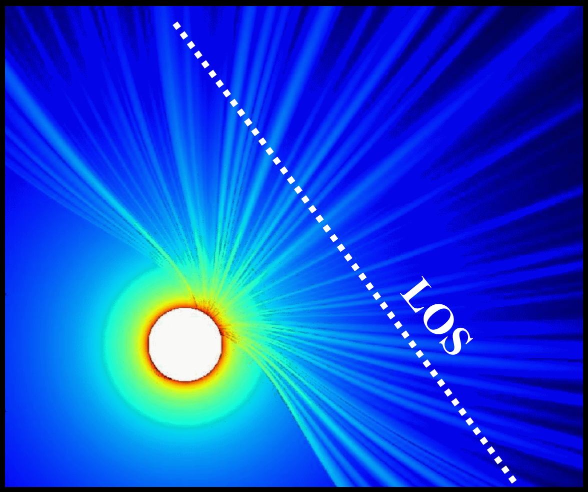
- At large *r*, one must integrate over tens of minutes (hours?) for good profiles.
- Can we separate the 2 components of the **width?**



$$\frac{\Delta\lambda_{\rm D}}{\lambda_0} = \frac{v_{\rm th,eff}}{c} = \frac{1}{c}\sqrt{\frac{2k_{\rm B}T_{\rm ion}}{m_{\rm ion}} + \xi^2}$$

thermal width **nonthermal width (waves?)**

- Observed quantities depend on integration over an optically thin line of sight.
- It's not possible to uniquely "invert" the data.
- Chris Gilbert (CU) is developing new 3D forward models of the corona to better understand the observed trends in emission-line properties. ("frozen-in" ionization is really important!)
- Are *Hinode*/EIS data affected by **"stray light?"**



In situ detection in the solar wind

- PSP will measure E&B fields & particle VDFs closer to the Sun than ever before.
- ***Challenge:*** how to disentangle spatial & time fluctuations in single-point data?
- **Taylor's hypothesis:** it's often assumed that "eddies" flow past the spacecraft much more rapidly than they evolve (i.e., ~all variation is spatial).
- **Klein et al. (2015)** showed that, for outwardly propagating Alfvénic fluctuations, PSP will need to modify the total relative velocity vector $\boldsymbol{U}_{\rm total}$ used in Taylor's hypothesis…

$$\mathcal{P}(\omega) = \int d^3\mathbf{k}\ P_{\rm 3D}(\mathbf{k})\ \delta(\mathbf{k}\cdot\mathbf{U}_{\rm total} - \omega)$$

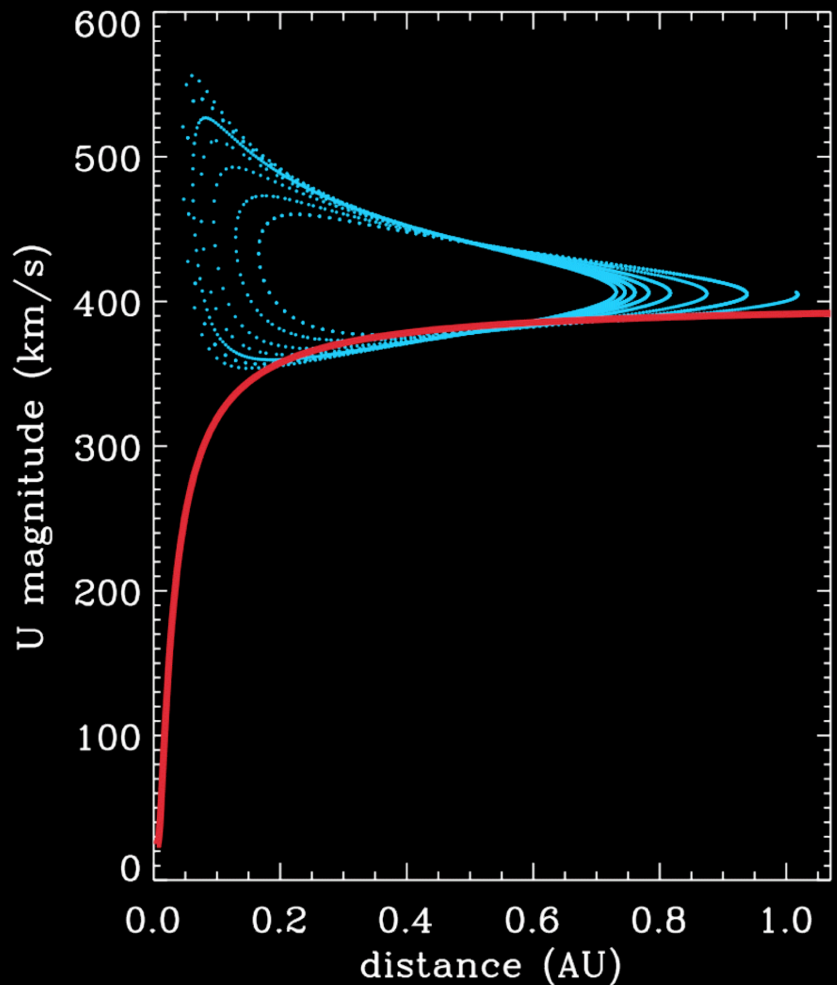
$$\mathbf{U}_{\rm total} = \mathbf{u}_{\rm wind} + \mathbf{V}_{\rm A} - \mathbf{v}_{\rm s/c}$$

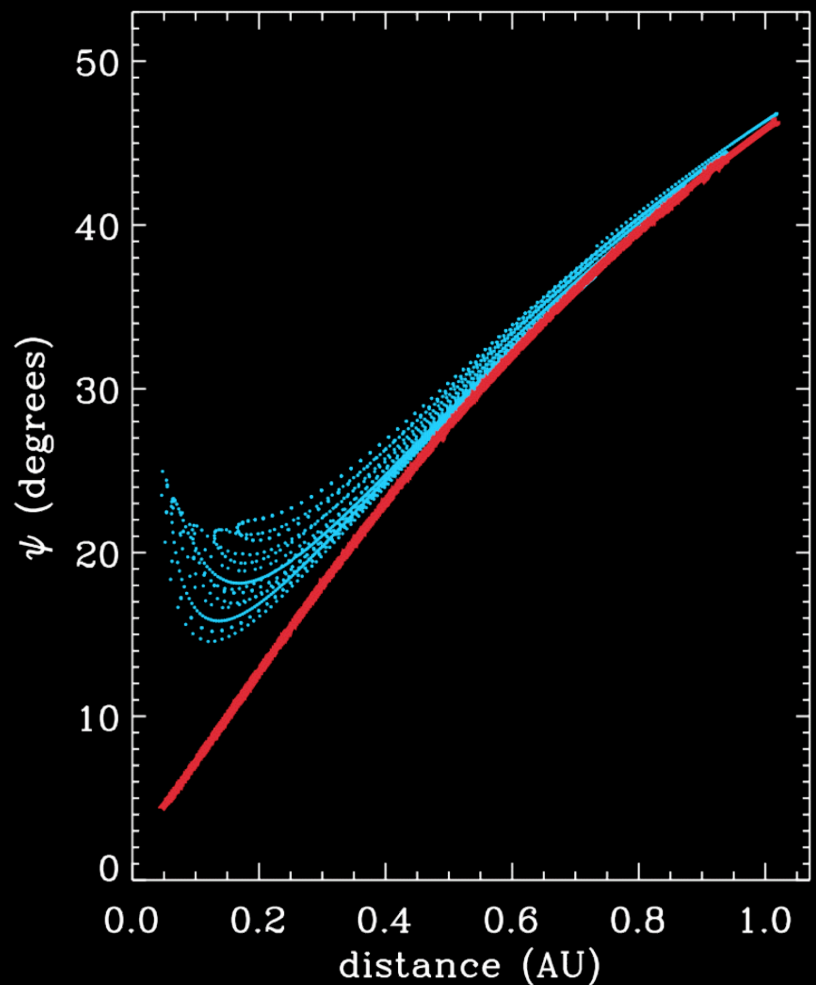
usually largest at 1 AU

need to be included for PSP!

In situ detection in the solar wind

How might $\boldsymbol{U}_{\text{total}}$ (magnitude & "Parker spiral angle") vary over the PSP mission?





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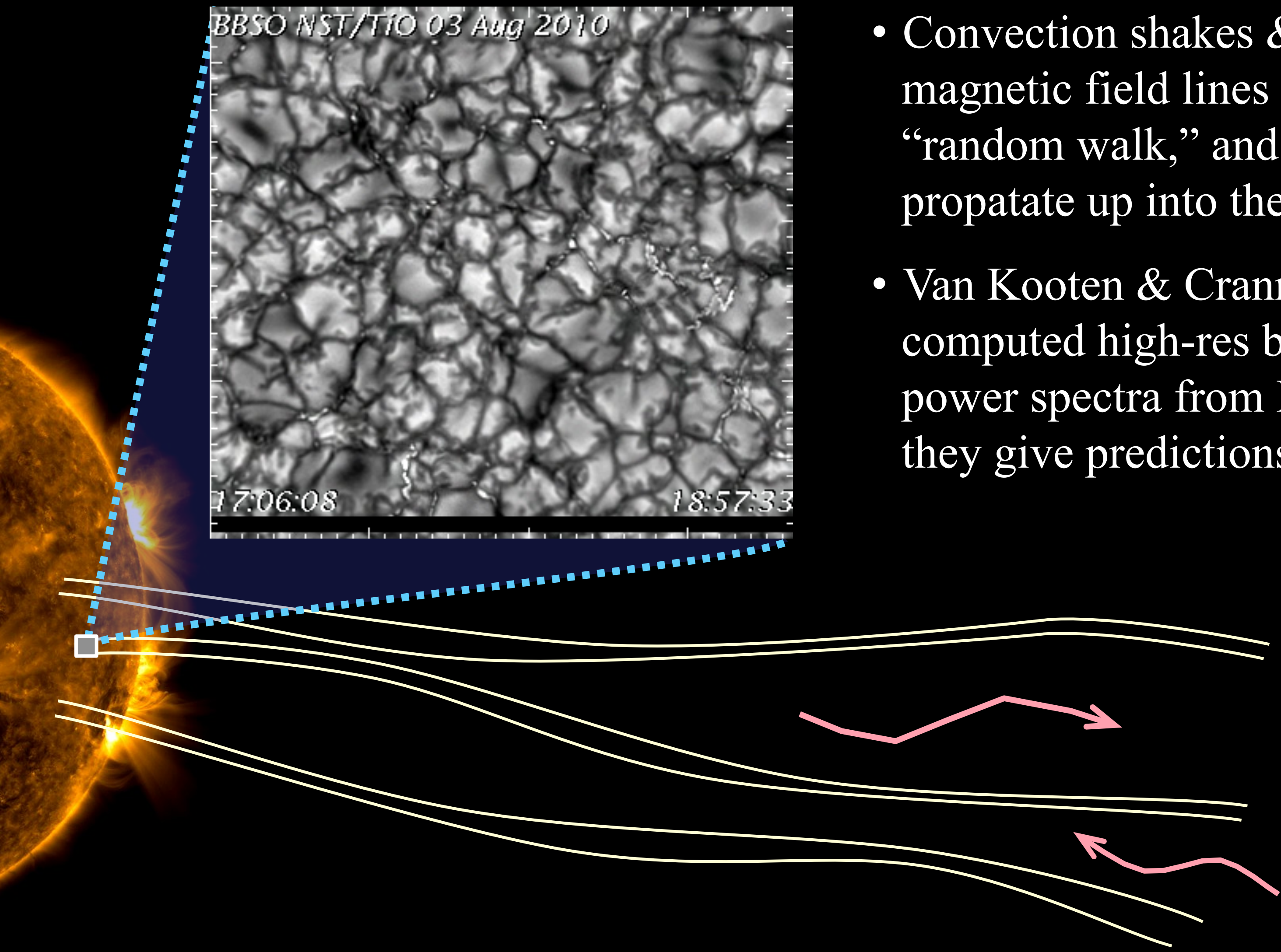
How/where do waves originate? (1 of 3)



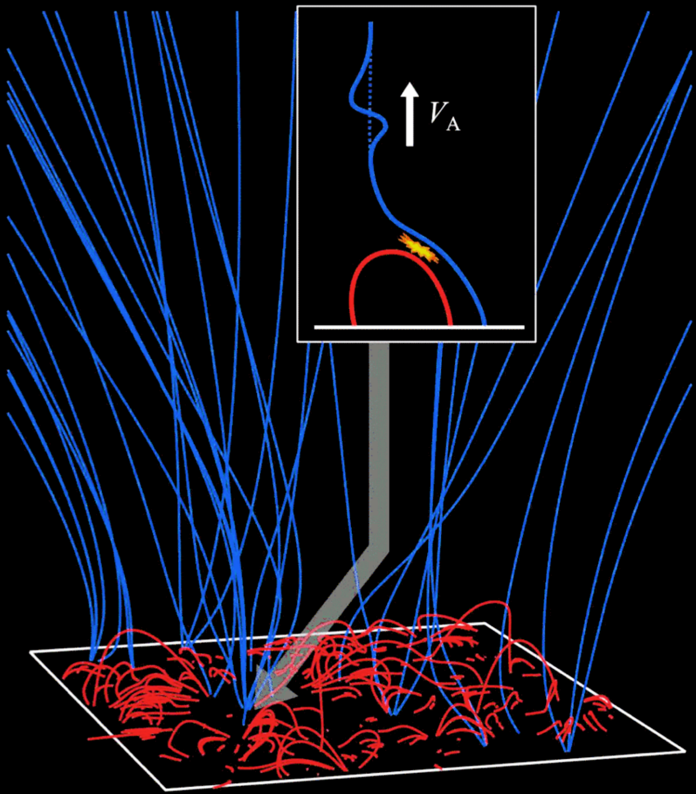
- Convection shakes & braids magnetic field lines in a diffusive "random walk," and MHD waves propatate up into the corona.
- Van Kooten & Cranmer (2017) computed high-res bright-point power spectra from MURaM sims; they give predictions for **DKIST!**

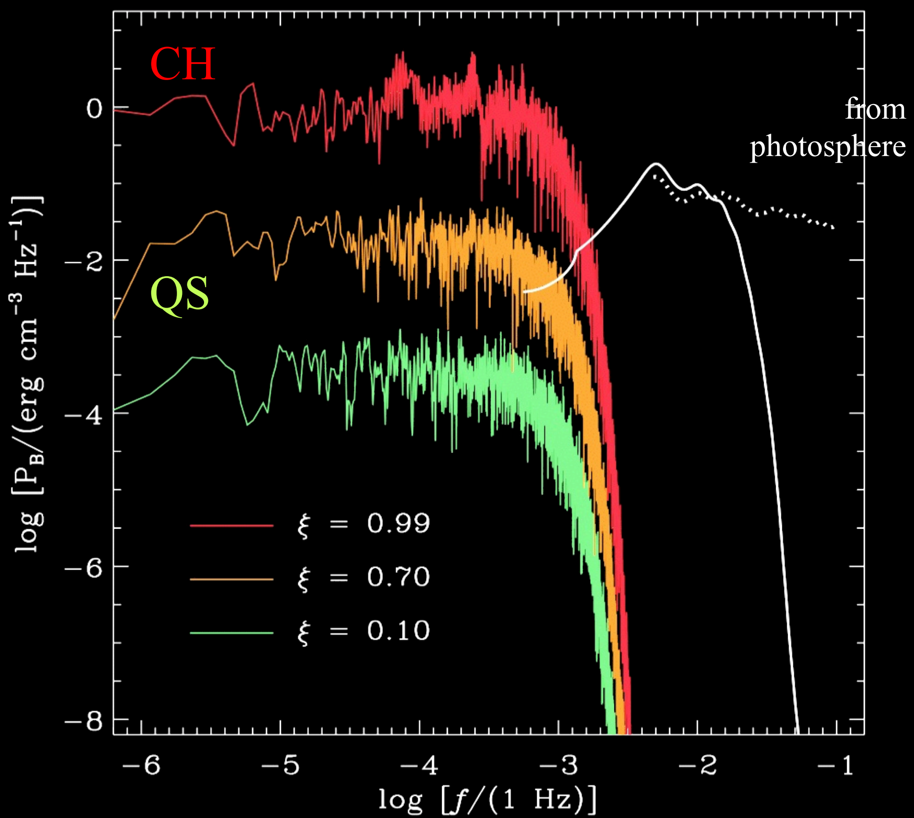
non-WKB reflection seeds turbulence

(Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005)

How/where do waves originate? (2 of 3)

- Magnetic reconnection in the low corona's "magnetic carpet" can drive waves (see, e.g., Hollweg 1990; Lynch et al. 2014; Moore et al. 2015; Tarr et al. 2017).

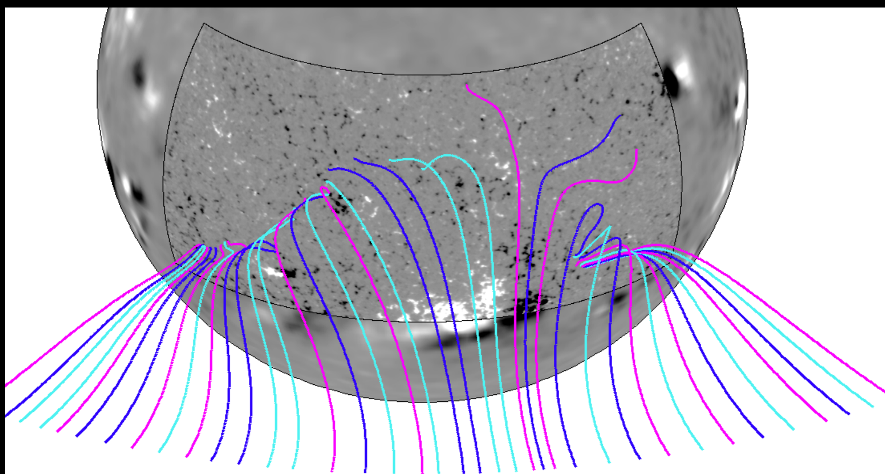


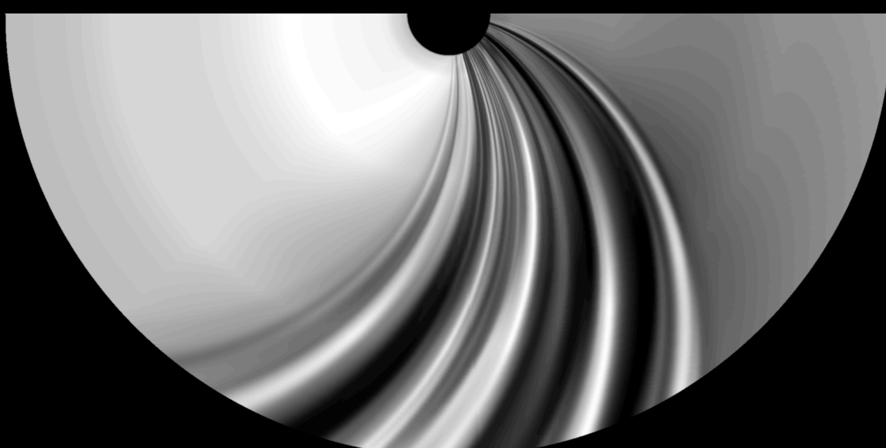


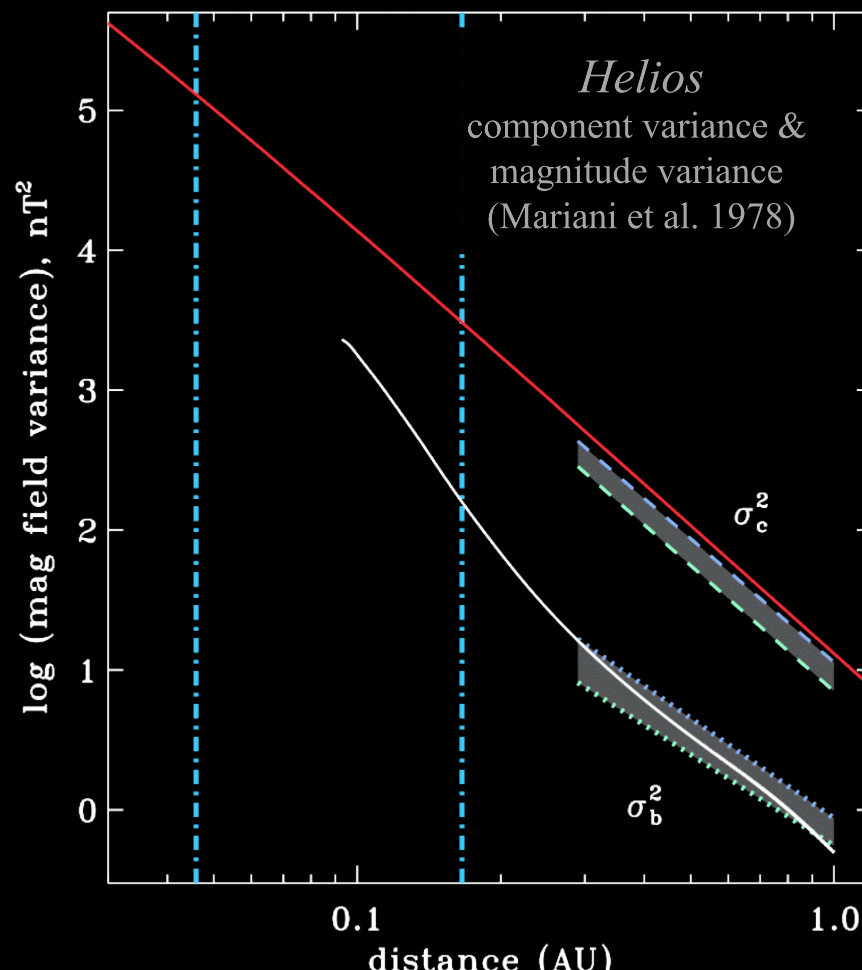
Cranmer (2017) used 2010 Monte Carlo model to estimate wave power from "loop-opening events."

How/where do waves originate? (3 of 3)

- CIR stream interactions start in the corona & get smeared out with increasing distance. Responsible for *B* "magnitude variance?" (Cranmer et al. 2013)







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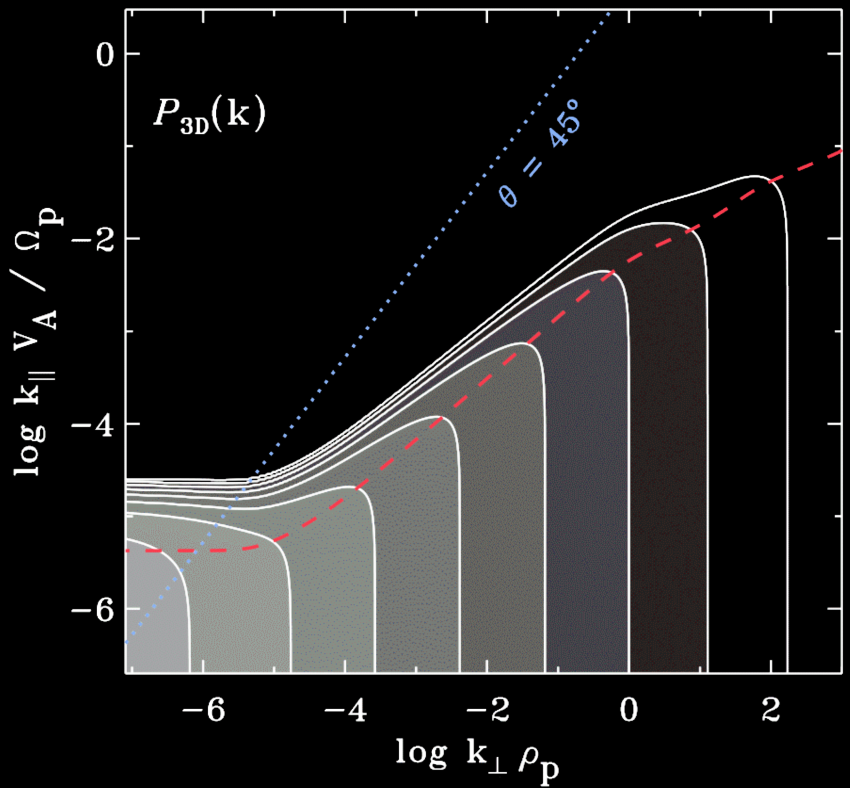
The model

- Cranmer & van Ballegooijen (2012): extremely phenomenological description of Alfvénic & compressive-mode 3D power spectra $P_{3D}(\mathbf{k})$ vs distance.
- For the Alfvén mode, we assume a "filled" region of wavenumber space that follows quasi-2D turbulence theory…



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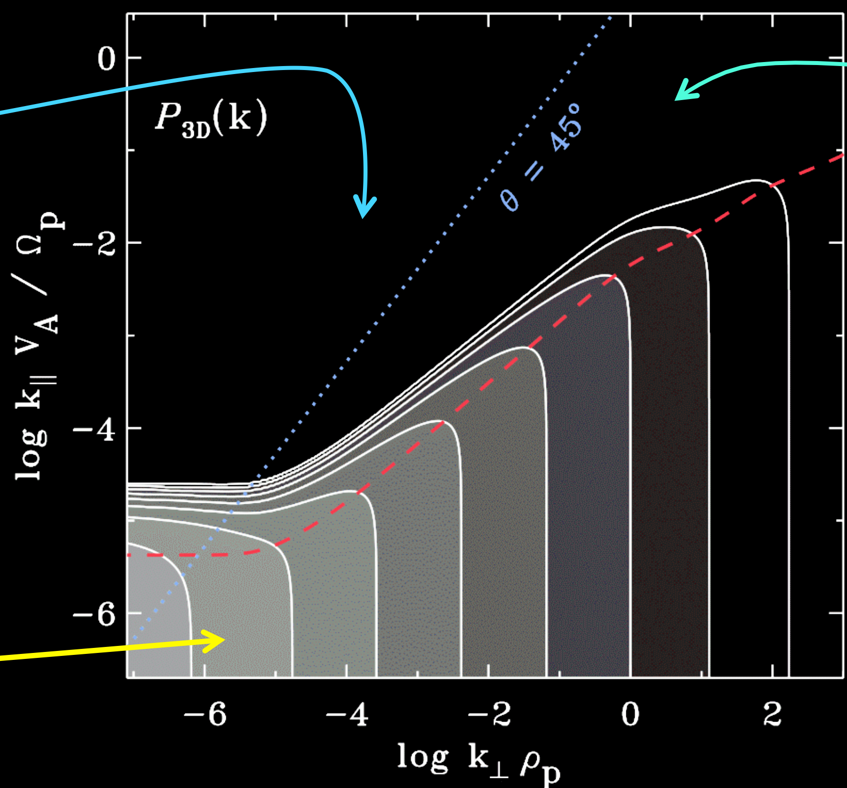
High-$k_{\parallel}$ part of spectrum determined by analytic solution of wavenumber diffusion in $k_{\perp}$

Normalization set by choice of **"outer scale"** $k_{0\parallel}$ and $k_{0\perp}$



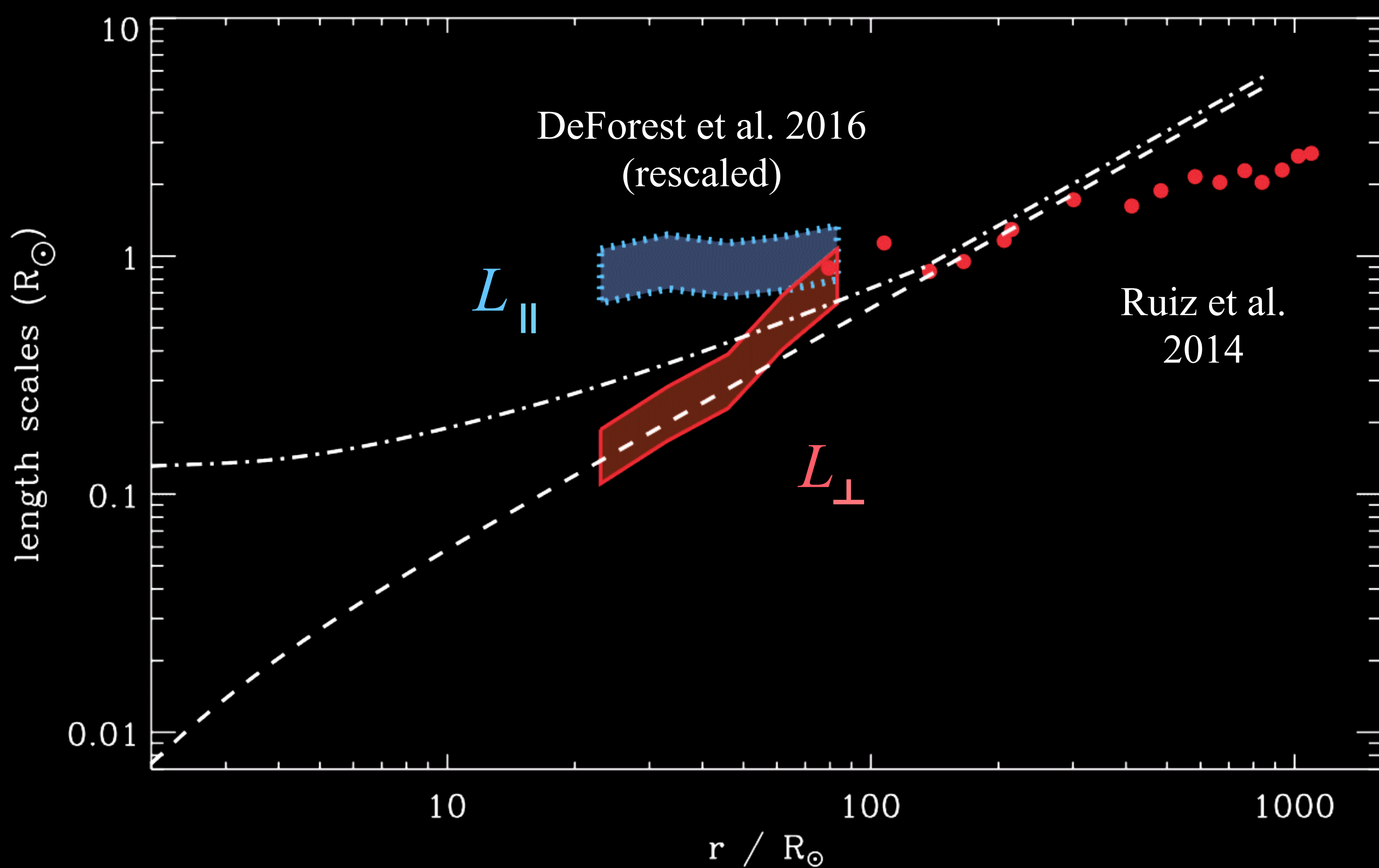
KAW & ICR dispersion & damping included

Spectrum "filled" for $\tau_{NL} < \tau_{wave}$

(e.g., Matthaeus et al. 1998; Maron & Goldreich 2001)

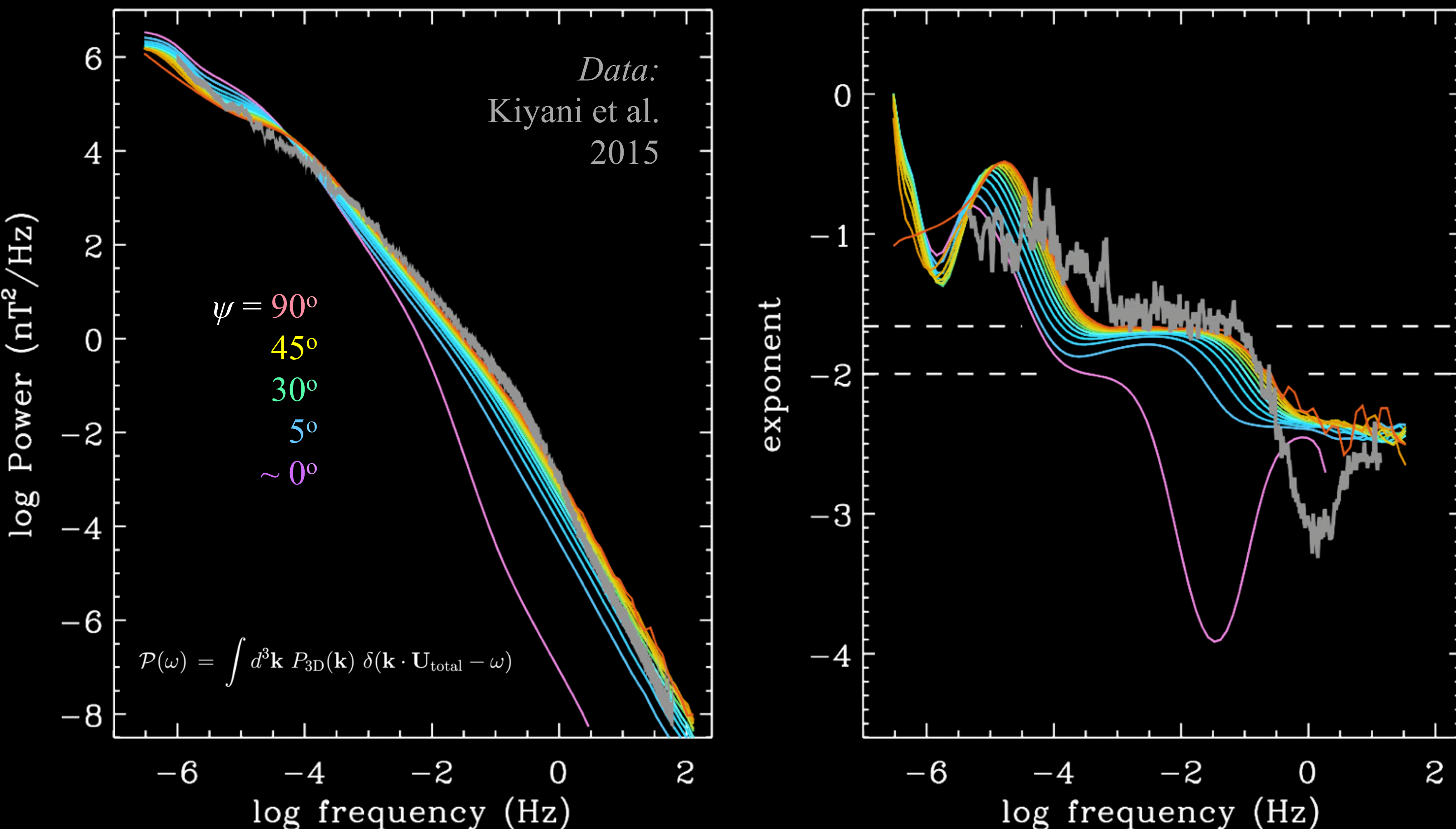
Outer-scale correlation lengths

- Observations are limited… and definitions vary…



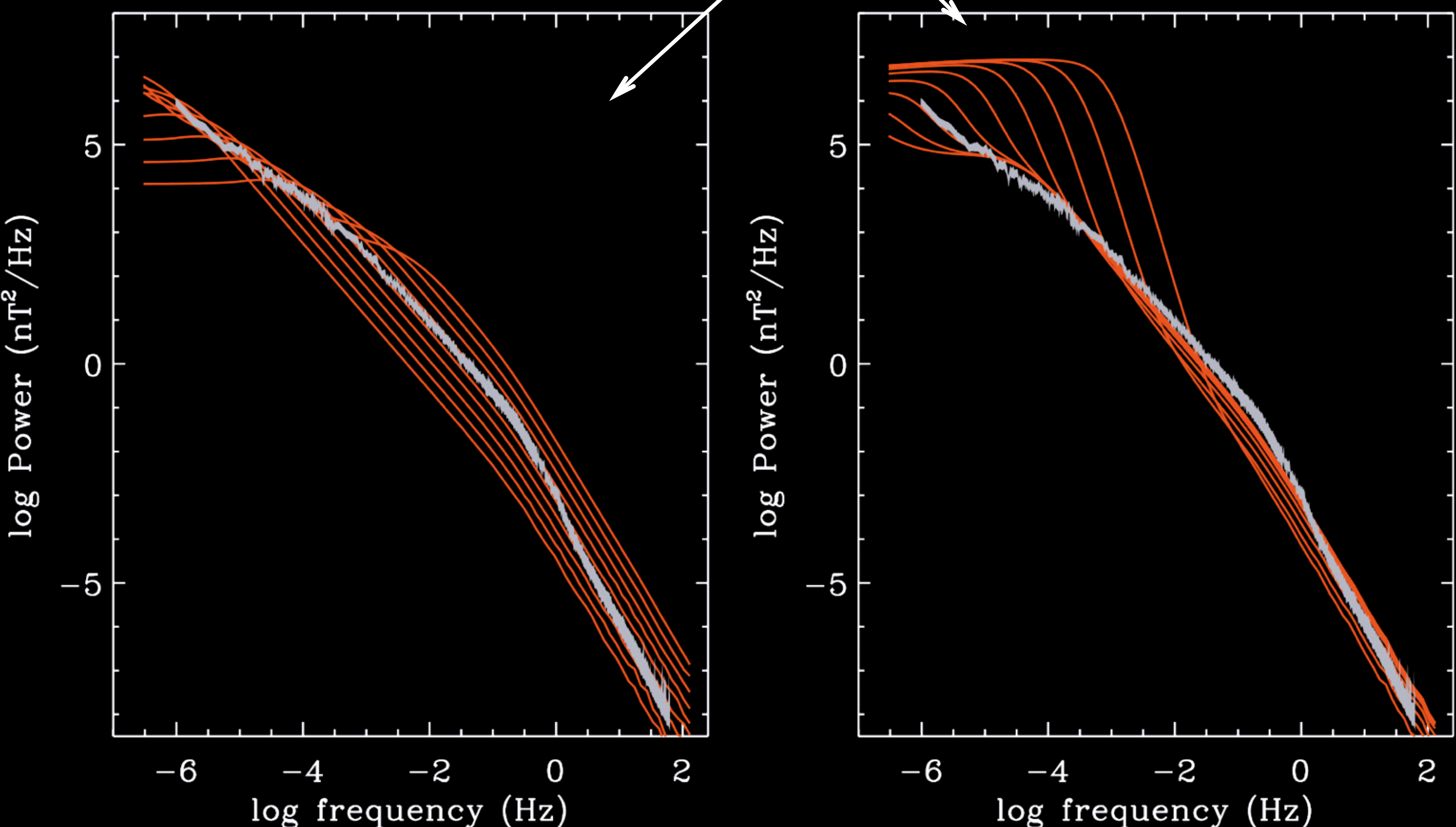
Preliminary power spectra (1 of 4)

- Take a "standard" set of parameters at 1 AU; vary ψ_{rB} (e.g., Forman et al. 2011)



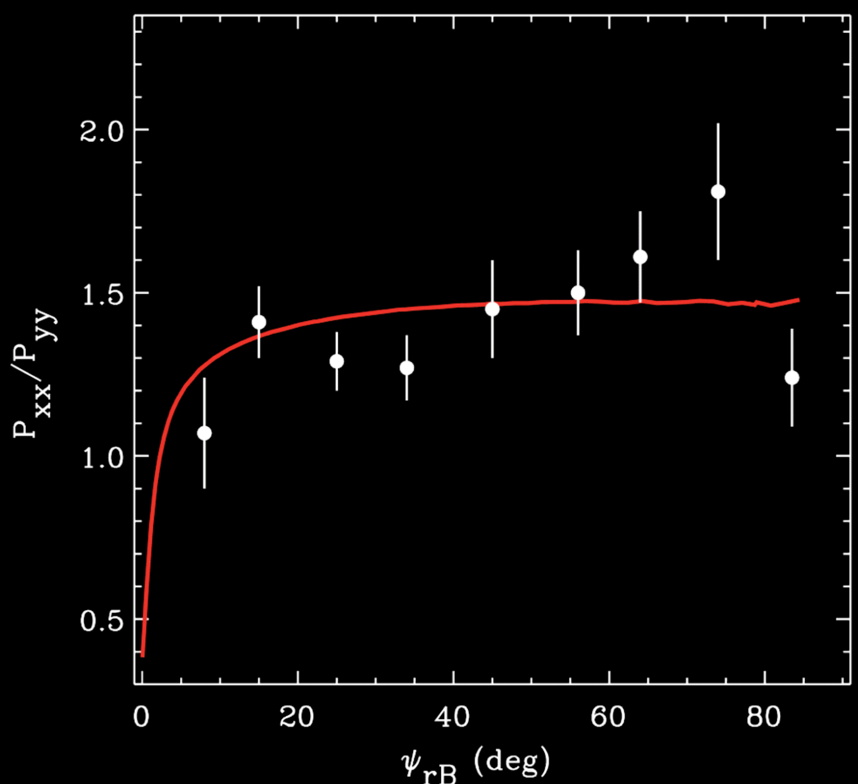
Preliminary power spectra (2 of 4)

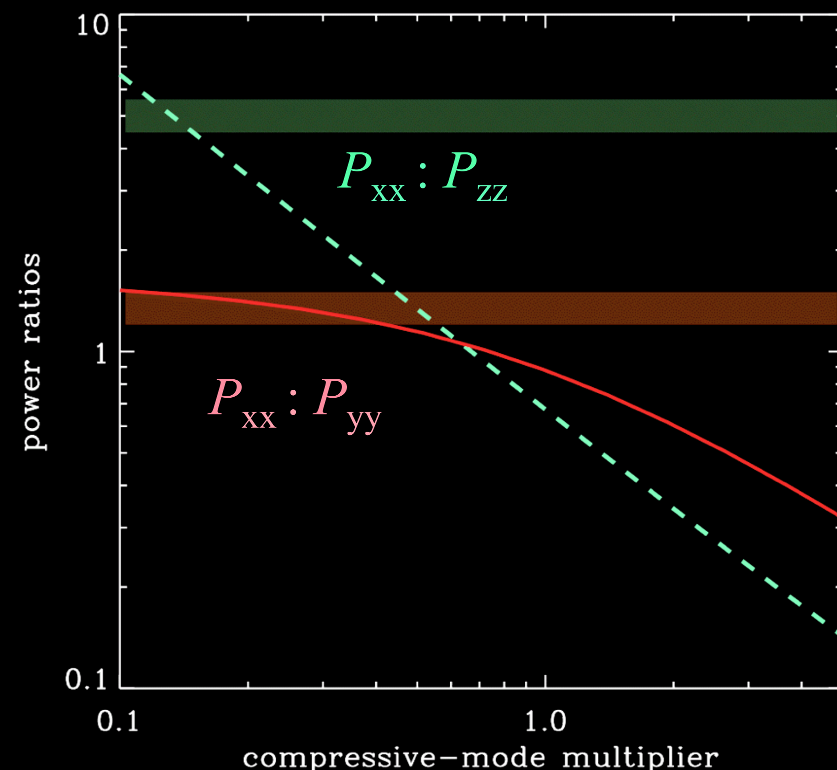
- Vary "outer scale" wavenumbers (both perp & parallel) by 4 orders of magnitude:



Preliminary power spectra (3 of 4)

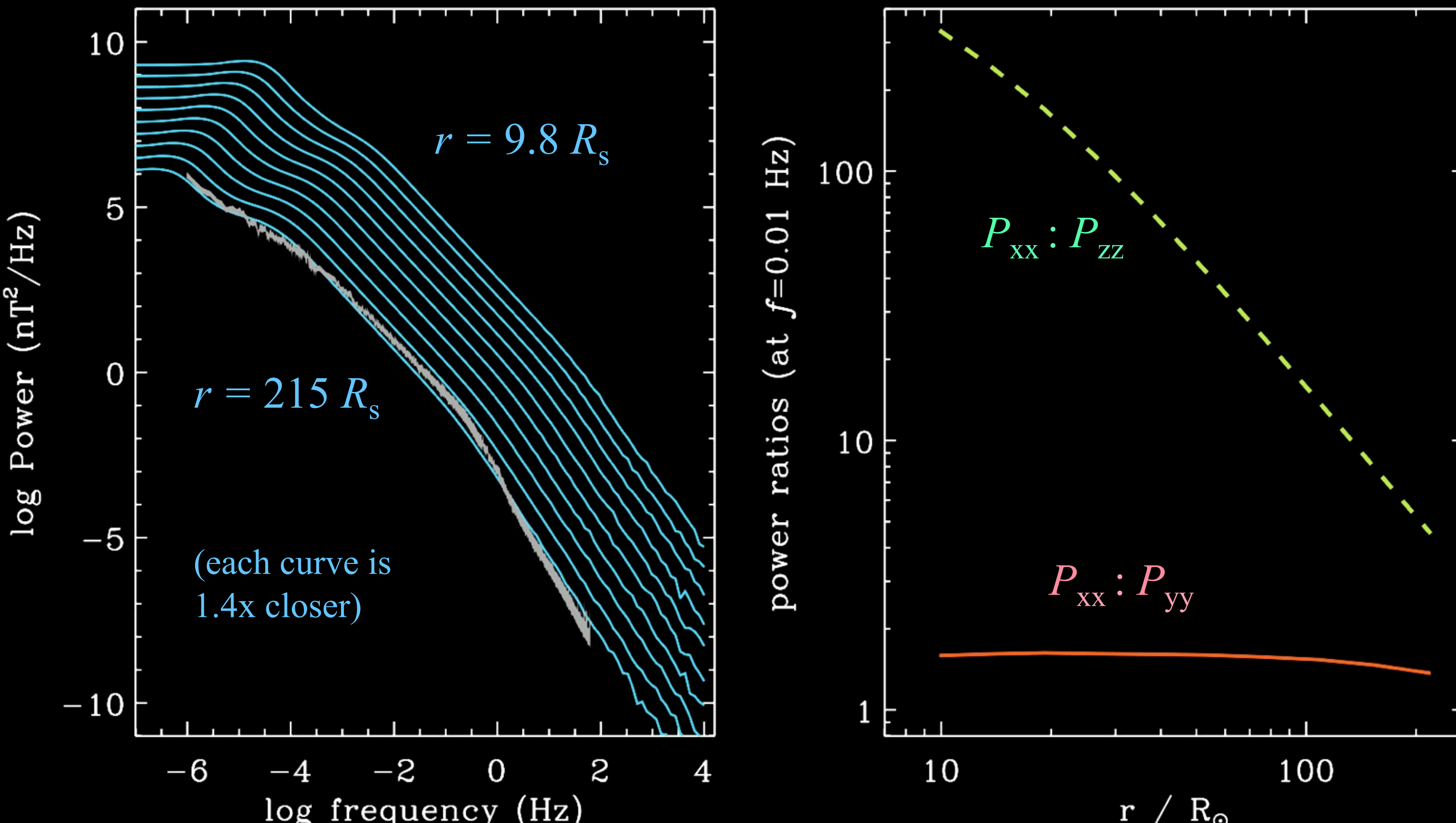
- "The" power spectrum is really a 2nd rank spectral tensor (e.g., Wicks et al 2012)
- Belcher & Davis (1971) found $\{P_{xx} : P_{yy} : P_{zz}\}$ power ratios of ~ **5:4:1**
- Bieber et al. (1996) found one could reproduce the 5:4 by "slab+2D" turbulence
- Cranmer & van Ballegooijen (2012) model reproduces full 5:4:1 (more or less):





Preliminary power spectra (4 of 4)

- Why we're all here… predictions for smaller heliocentric distances…



Conclusions

- PSP is poised to "constrain" theorists like never before!
- Specifically, extending inward the *in situ* fluctuation measurements tells us:

    how/where MHD fluctuations come from

    how/where they undergo turbulent cascade & other nonlinear interactions

    how/where they damp to heat the plasma

- Don't forget synergy with other (mostly remote-sensing) missions coming soon: