How Important is Alfvén Wave Heating?

Scene-setting talk (3 of 4) for:
"Outstanding Challenges in Understanding the Heating of the Solar Corona and Solar Wind"

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Session discussion topics

1. Are observational limits on the energy present in Alfvén waves compatible with coronal heating?
2. How is Alfvén wave energy distributed, spectrally and in physical space, from the photosphere to the corona?
3. What heating rates are obtained from the MHD Alfvén wave turbulence heating model for the observational collisions and viscosity?
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Remote sensing of MHD waves

With good instrumentation, **imaging & spectroscopy** can resolve wave-like fluctuations:

- Intensity modulations . . .

$$\delta I \propto (\delta\rho)^{1-2}$$

- Motion tracking in images . . .

$$\delta V_{\rm POS}$$

- Doppler shifts . . .

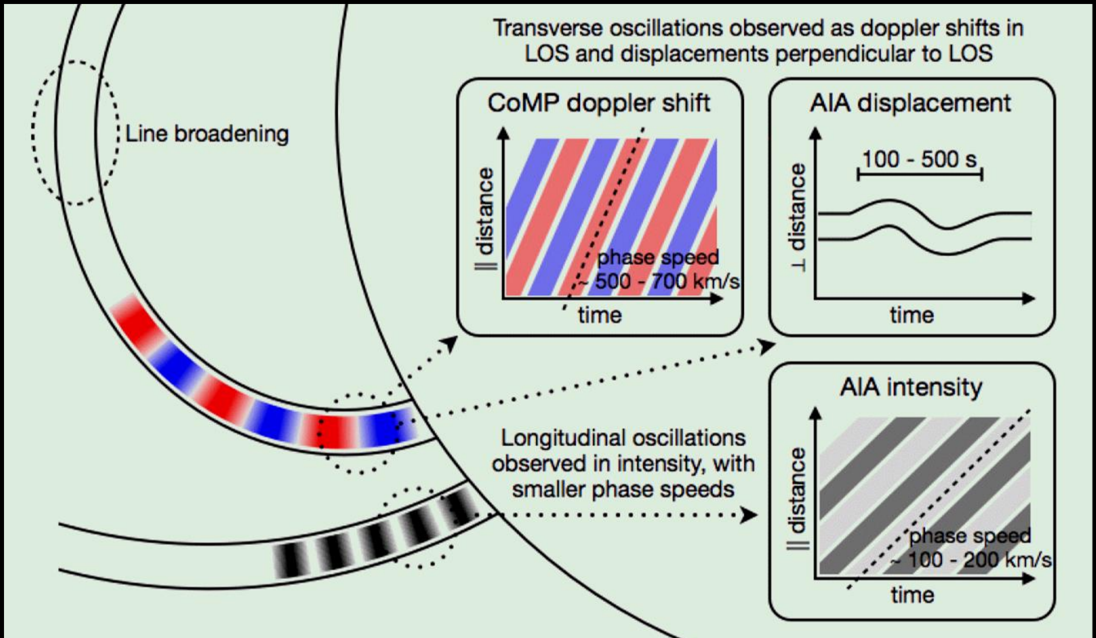
$$\delta\lambda \propto \delta V_{\rm LOS}$$

- Doppler broadening . . .

$$\delta\lambda \rightarrow <\delta V_{\rm LOS}>$$

- Radio sounding . . .

$$\delta\tilde{n} \rightarrow \delta\rho\,, \delta B \rightarrow \delta V$$

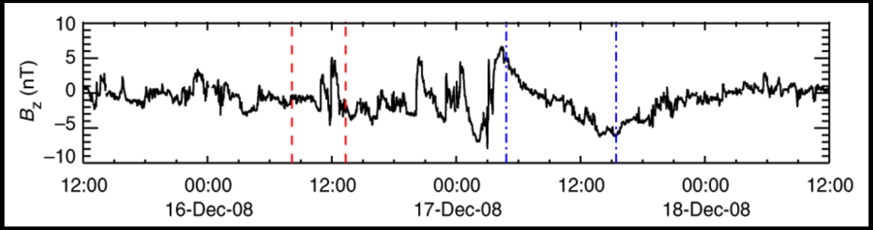


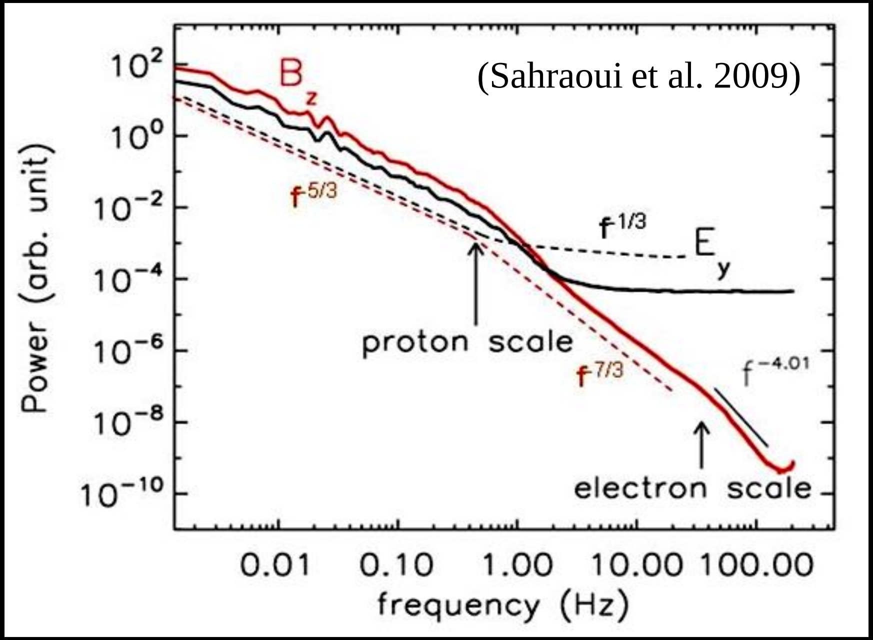
Threlfall et al. (2013)

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

In situ detection in the solar wind

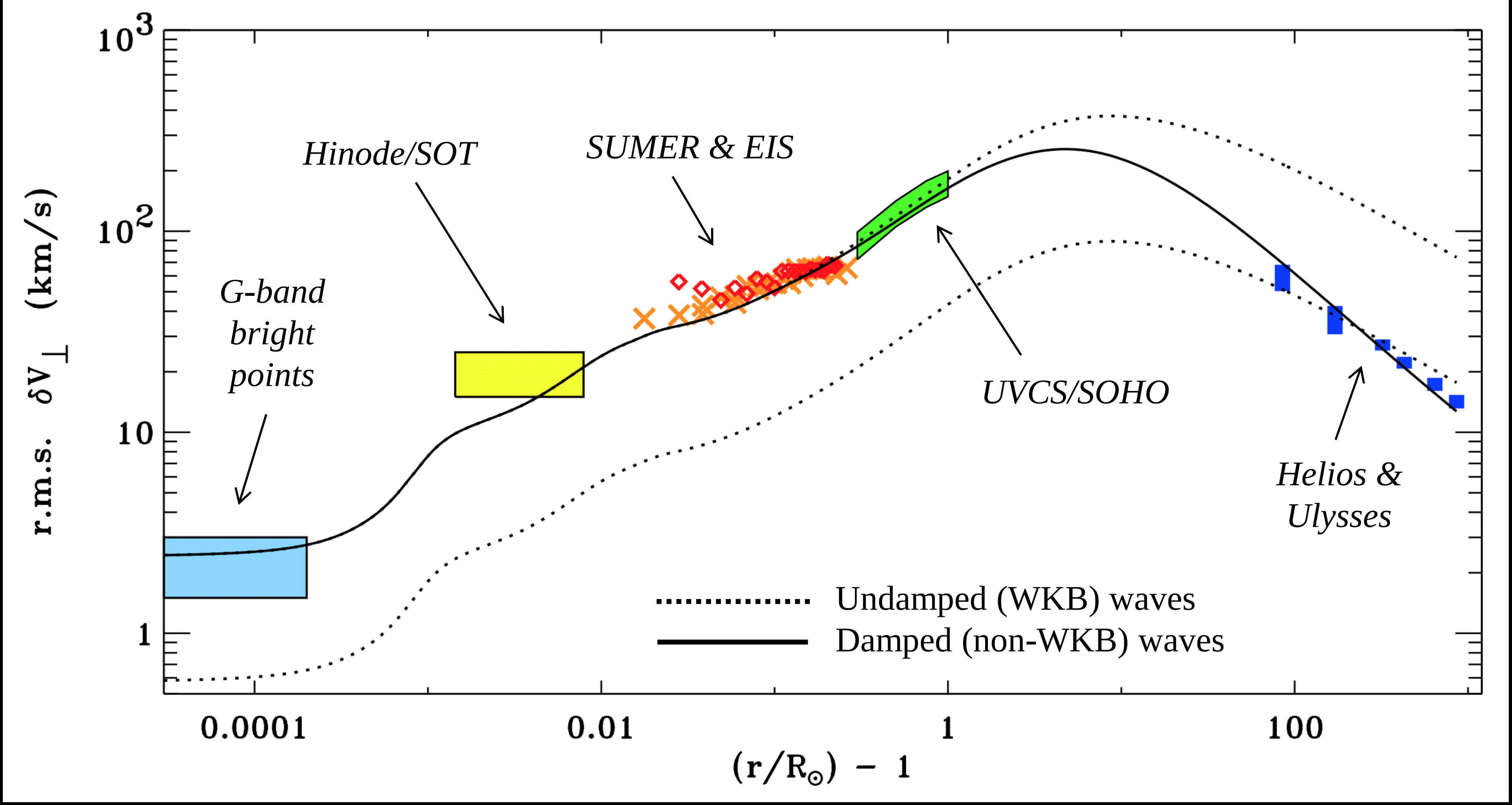
- Direct measurement of E/B fields & particles (speed, density, temperature, etc.)
- So far: $r > 60\ R_s$ (SPP: $r > 9.5\ R_s$)
- ***Challenge:*** how to disentangle spatial & time fluctuations in single-point data?
- **Taylor's hypothesis:** it's often assumed that "eddies" flow past the spacecraft much more rapidly than they evolve (i.e., ~all variation is spatial).
- ***Results:*** Alfvénic fluctuations dominate at large scales, but it's still not clear what they "cascade into" at small scales.





Measured Alfvénic fluctuations

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



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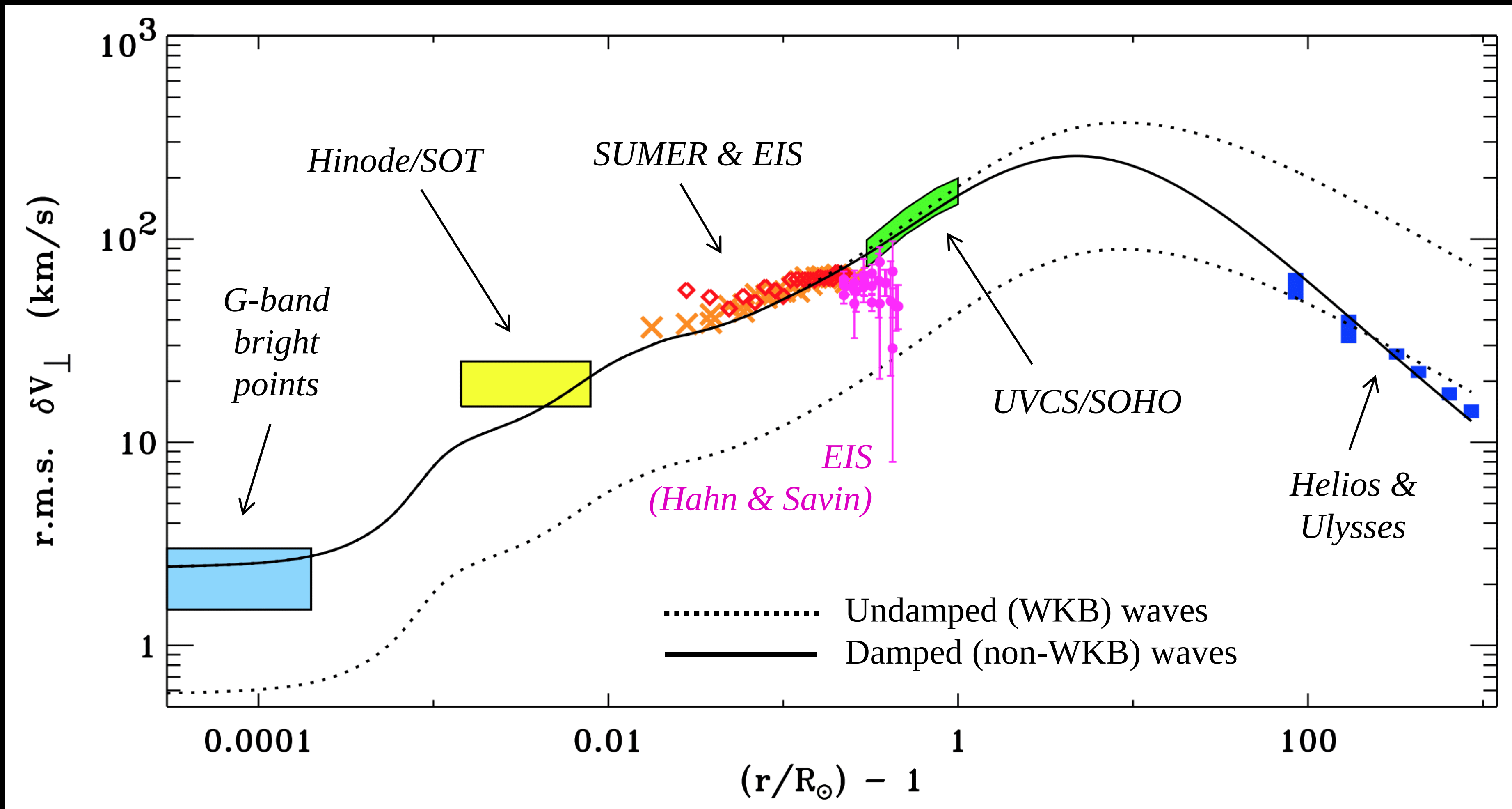


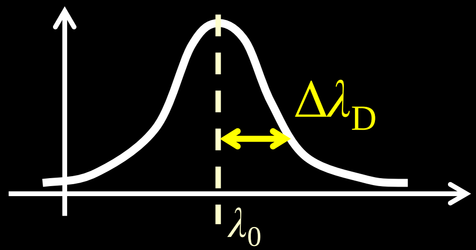
Off-limb complications

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

$$\frac{\Delta\lambda_D}{\lambda_0} = \frac{v_{\rm th,eff}}{c} = \frac{1}{c}\sqrt{\frac{2k_B T_{\rm ion}}{m_{\rm ion}} + \xi^2}$$

thermal width

nonthermal width (waves?)



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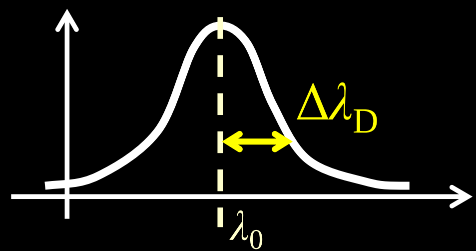

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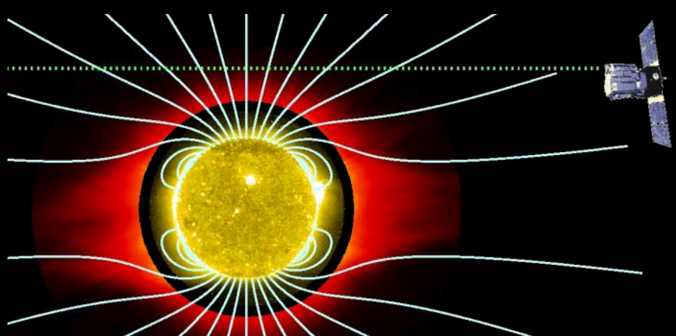
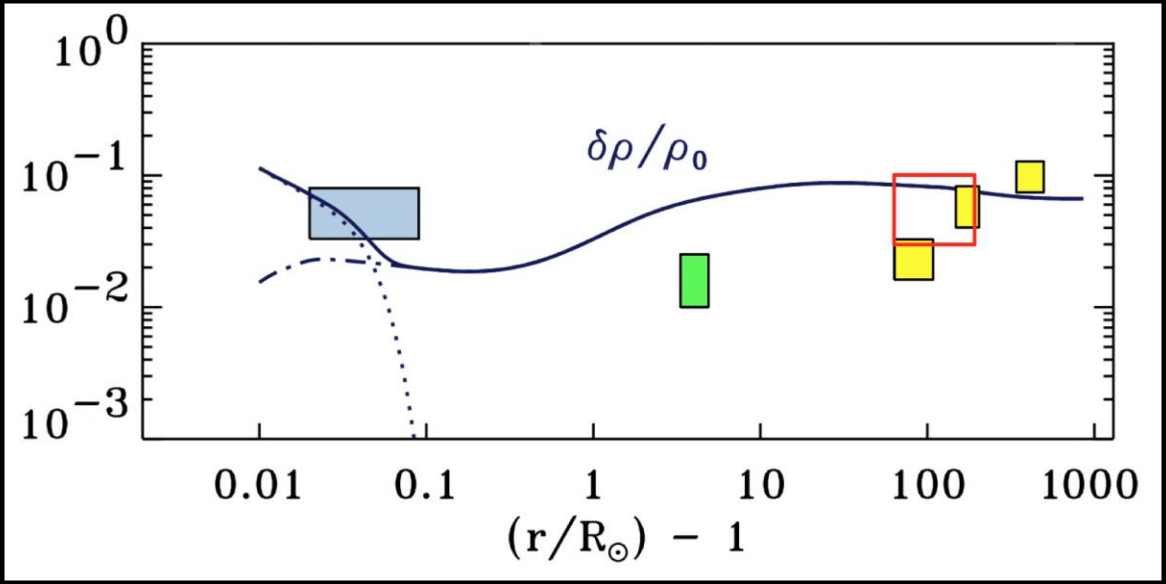


Observing even higher up (e.g., UVCS/SOHO) reveals indirect information about waves, via how their dissipation heats the particles . . .

$$T_{\rm ion} \gg T_{\rm p} \gtrsim T_{\rm e}\ , \quad T_{\perp} > T_{\parallel}\ , \quad \mathbf{v}_{\rm ion} > \mathbf{v}_{\rm p}$$

Measured compressive fluctuations

- Cranmer & van Ballegooijen (2012) extended models to all 3 MHD wave modes:



- **Intensity oscillations** along polar plumes (Ofman et al. 1999; Krishna Prasad et al. 2012)
- **Radio scintillations** (Coles & Harmon 1989; Spangler 2002; Chandran et al. 2009)
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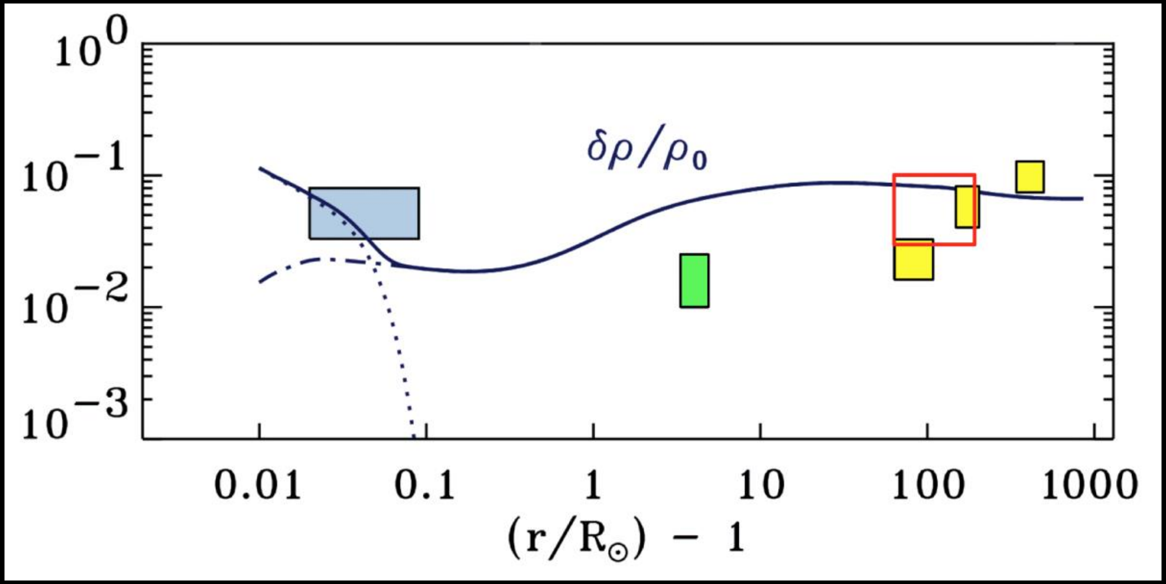

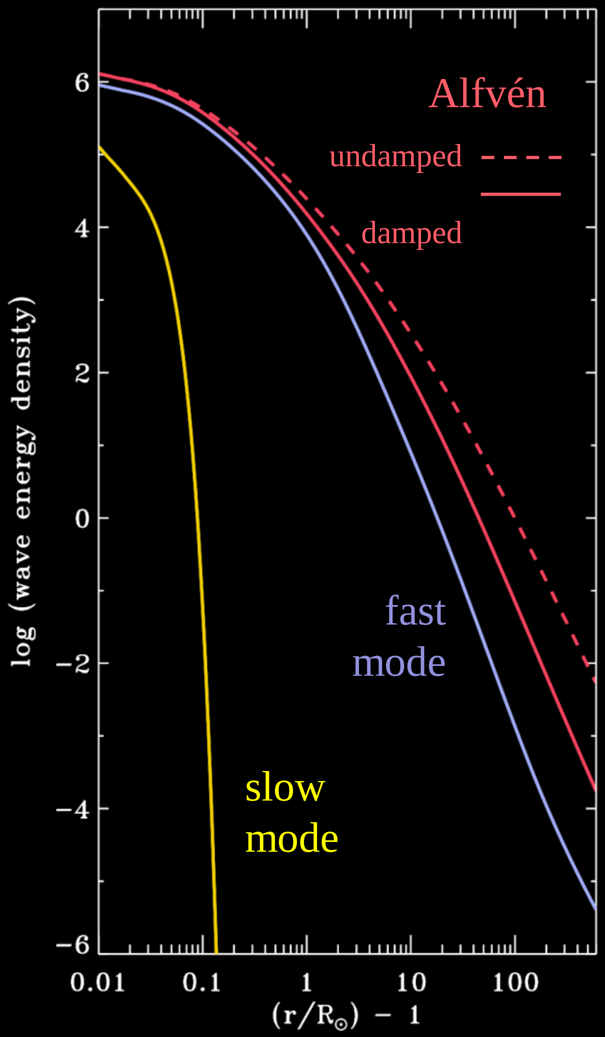

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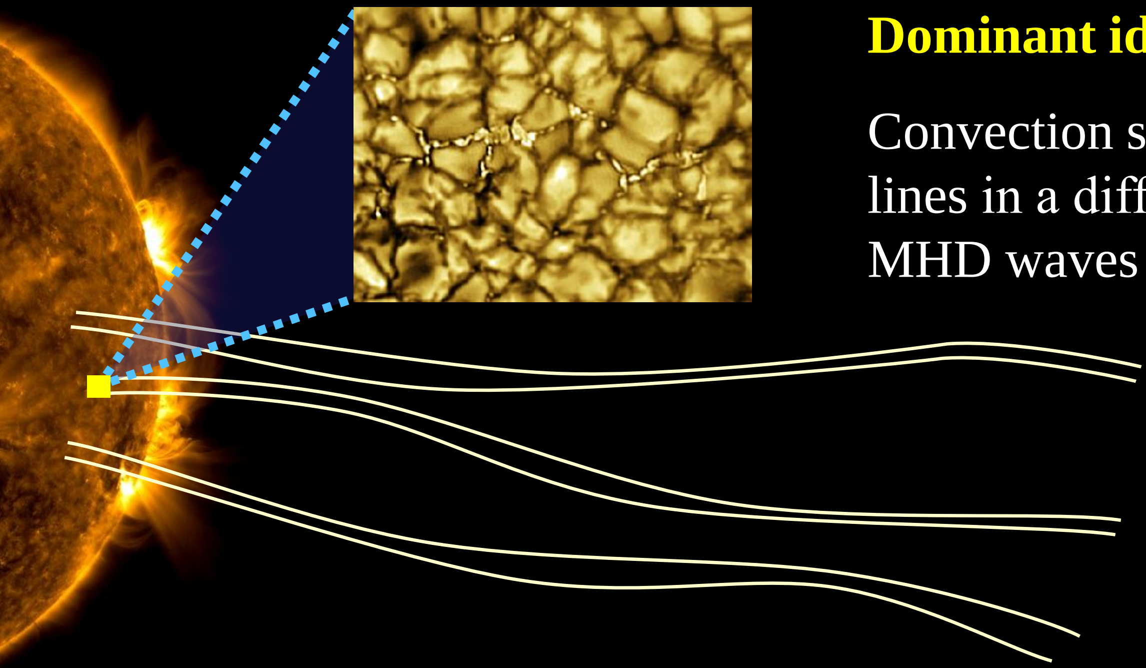
How/where do waves originate?



Dominant idea: (?)

Convection shakes & braids magnetic field lines in a diffusive “random walk,” and MHD waves propatate up into the corona.

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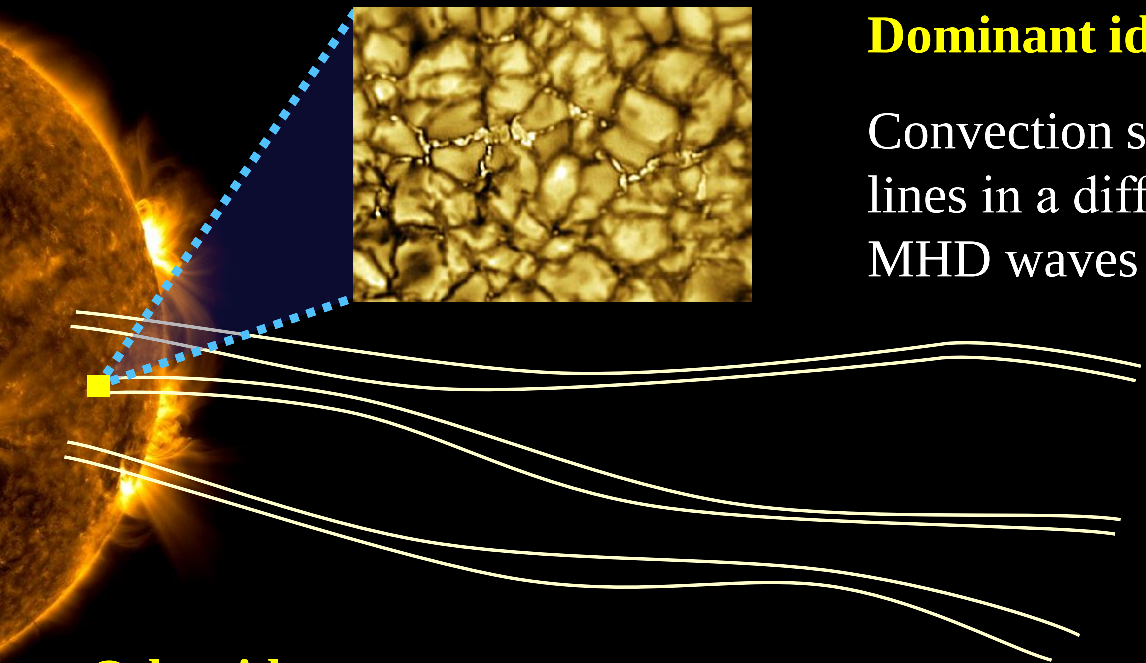

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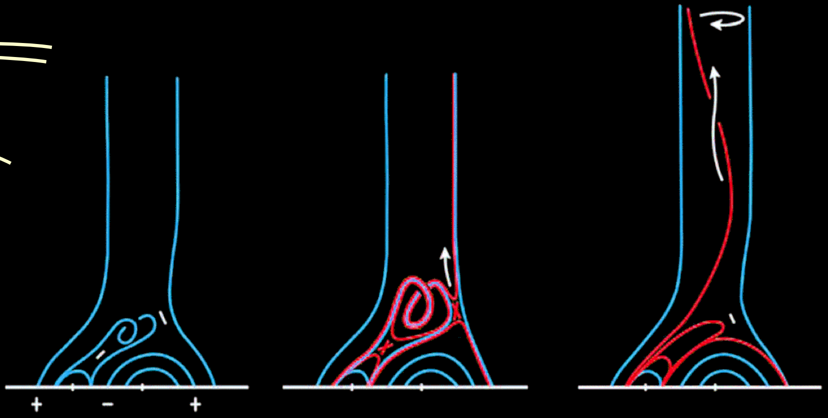

Other ideas:

- Magnetic reconnection in the low corona's "magnetic carpet" (Hollweg 1990; Lynch et al. 2014; Moore et al. 2015).
- K-H instabilities along streamer or CIR shear flows.

Mode conversion?

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Homogeneous background:

- Linearly polarized Alfvén waves can excite 2nd order **ponderomotive oscillations** (period: shorter)
- Circularly polarized Alfvén waves can undergo **parametric instabilities** (period: longer)
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Structured background:

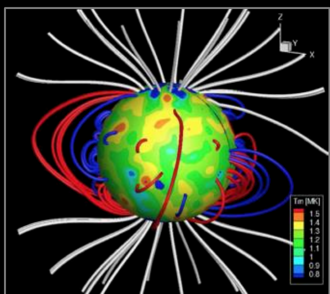
$\nabla_{\perp} V_A$: phase mixing, surface-wave generation, filamentation instability, “S-web” (?)

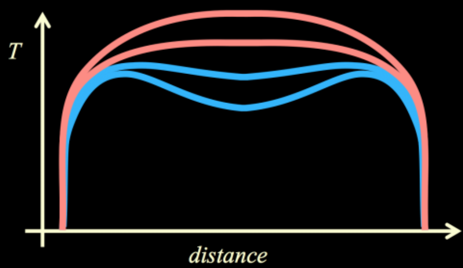
$\nabla_{\perp} \rho$: drift-wave instability, radio IPS “inner scale?”

$\nabla_{\perp} v_{\text{flow}}$: shear-driven wave mode transformation

Mode conversion: examples **(poster advertisements)**

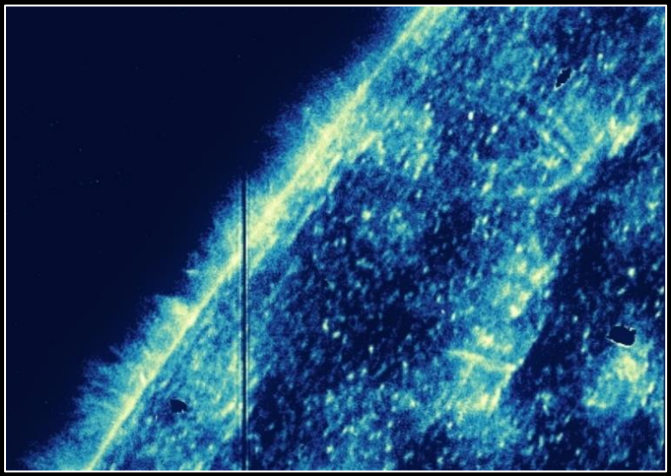
- AIA DEM tomography has shown some large quiescent coronal loops to have "inverted" temperature profiles (Huang et al. 2012; Nuevo et al. 2013):





Schiff & Cranmer (2016) show that conventional (Alfvénic) turbulence cannot make stable "down-loop" profiles, but if 99% of the Alfvén wave power was **converted to compressive modes,** it can!

- Can IRIS network jets (= Type II spicules?) be explained with mode conversion from "bursty" Alfvénic turbulence to $\delta\rho$ pressure pulses?
- Woolsey & Cranmer (2016) shows their footpoints are unipolar -- i.e., *not* due to reconnection!?



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Wave dissipation mechanisms

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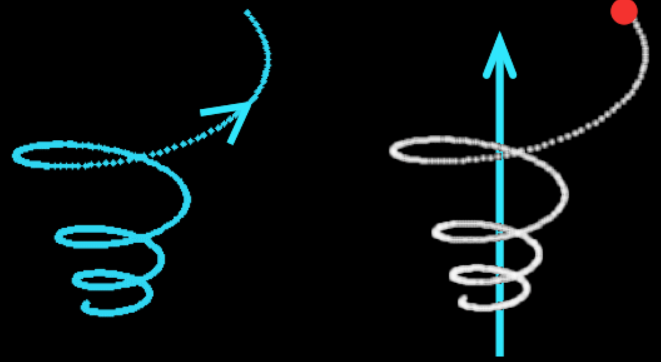
strong for fast & slow modes (→ thermal conduction)

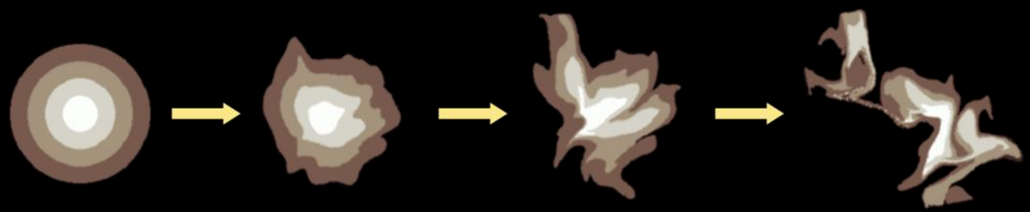
dominant for Alfvén mode (but ~weak in corona) (→ viscosity)

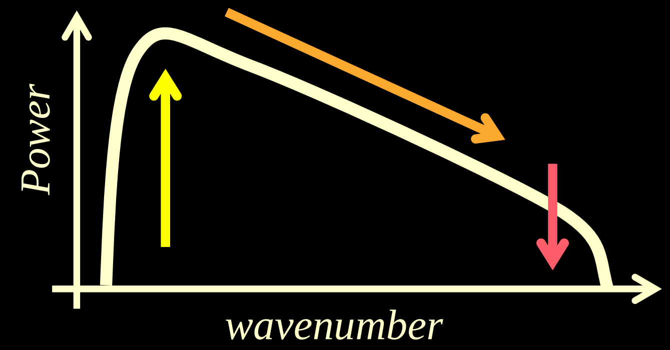
- With increasing *r*, the corona becomes collisionless: **wave-particle resonances** can act like quasi-collisions to provide a (statistically averaged) transfer from wave energy to "thermal" particle energy.



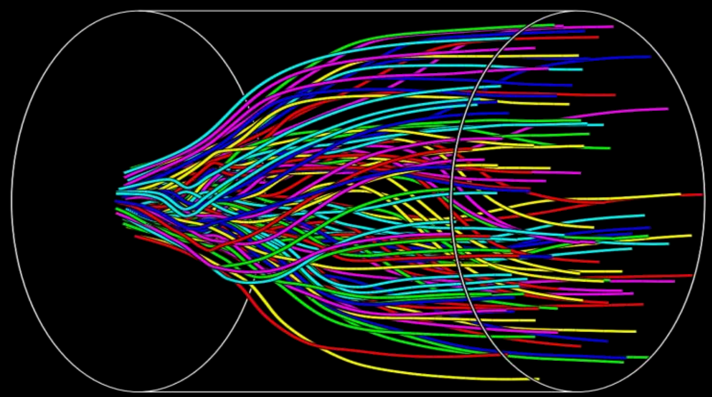
MHD turbulence

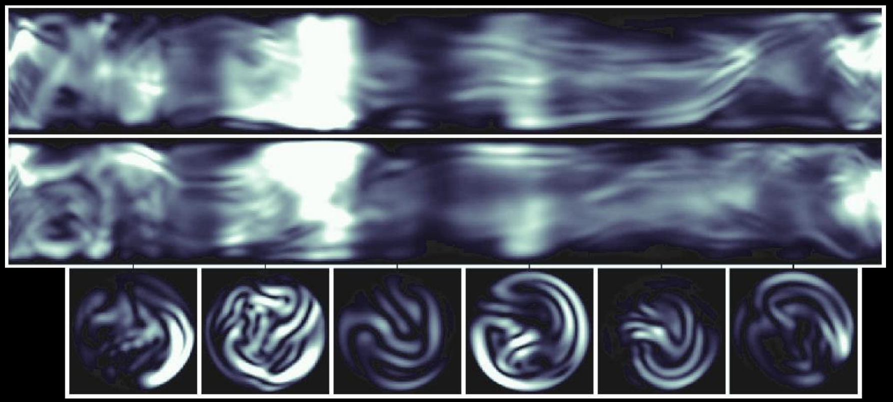
- Small scales in the corona & wind seem to be easy to obtain via strong turbulent cascade…





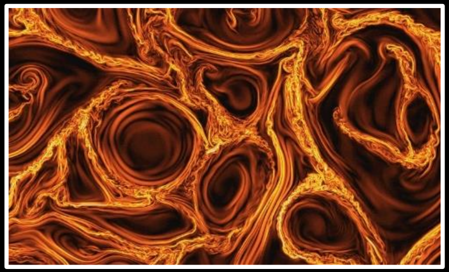
- The process is intermittent and "nanoflare-like!" (see Asgari-Targhi poster)





- What actually happens at the "dissipation scale?" (see sessions 9, 10, 11)

Can turbulence account for the kinetic data?



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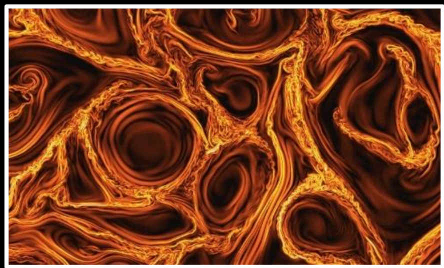

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- If **ion cyclotron waves** somehow propagate up into the corona & solar wind (e.g., parallel cascade?) they can efficiently heat ions (Hollweg & Isenberg 2002; Marsch 2006; Cranmer 2001, 2014; Isenberg & Vasquez 2015).
- When MHD turbulence cascades to small perpendicular scales, the small-scale **shearing motions** may be unstable to generation of cyclotron waves (Markovskii et al. 2006).
- Dissipation-scale **current sheets** may preferentially spin up ions (Dmitruk et al. 2004; Servidio et al. 2015).
- If MHD turbulence exists for both Alfvén and fast-mode waves, the two types of waves can **nonlinearly couple** with one another to produce high-frequency ion cyclotron waves (Chandran 2005; Cranmer & van Ballegooijen 2012).
- If **nanoflare-like reconnection events** in the low corona are frequent, they may fill the extended corona with electron beams that become unstable and produce other modes that heat ions (Markovskii 2007; Che et al. 2014).
- If kinetic Alfvén waves reach large enough amplitudes, they can damp via **stochastic heating** to energize ions (Voitenko & Goossens 2006; Wu & Yang 2007; Chandran 2010).
- Kinetic Alfvén wave damping in the extended corona could lead to electron beams, Langmuir turbulence, and Debye-scale **electron phase space holes** which could heat ions perpendicularly (Matthaeus et al. 2003; Cranmer & van Ballegooijen 2003).

I'll shut up now . . . back to discussion topics

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