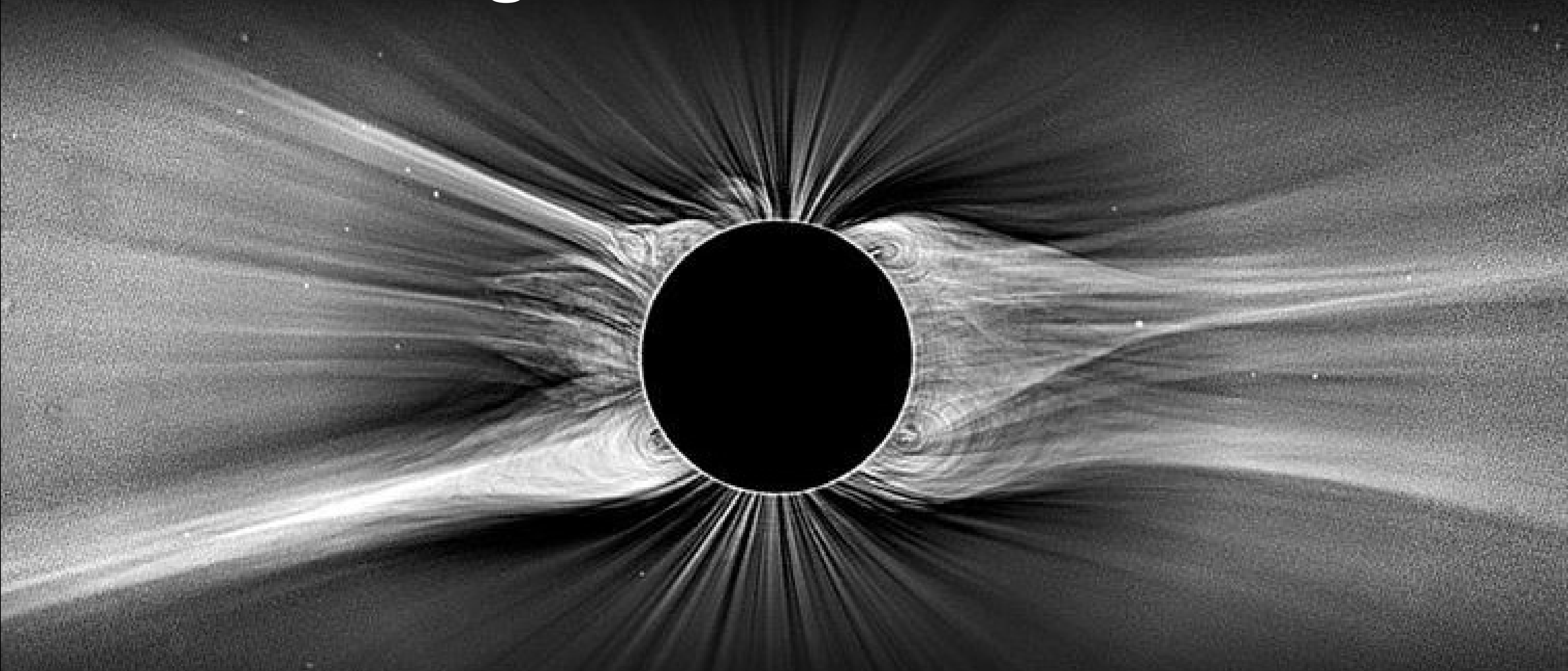
Turbulent Origins of Coronal Heating and the Solar Wind



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Harvard-Smithsonian Center for Astrophysics

A. van Ballegooijen, L. Woolsey, M. Asgari-Targhi, J. Kohl, M. Miralles

Turbulent Origins of Coronal Heating and the Solar Wind

Outline:

1. Turbulence seems to work . . .
2. But how does the dissipation really happen?
3. Can ion cyclotron waves explain what we see?

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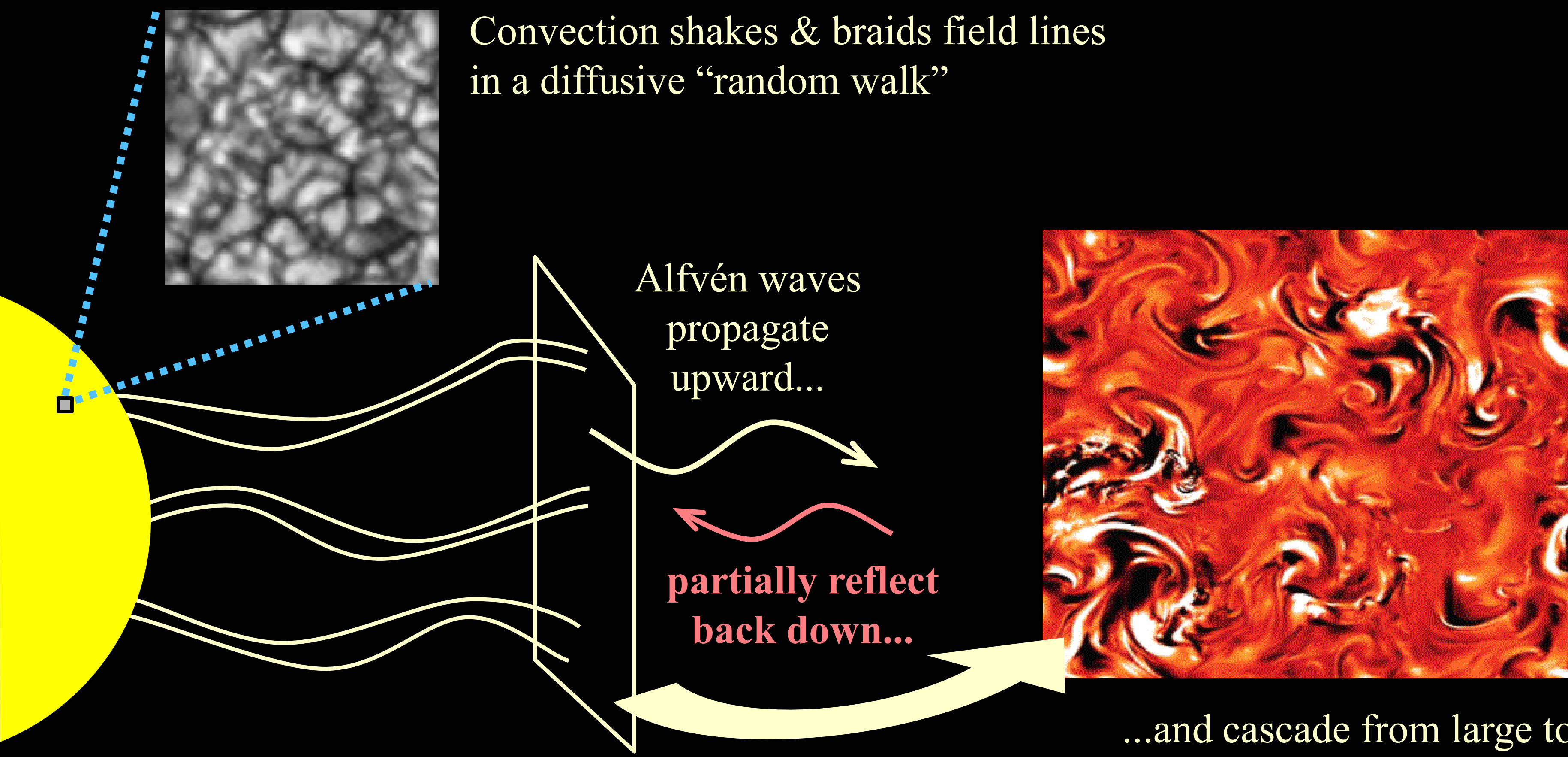
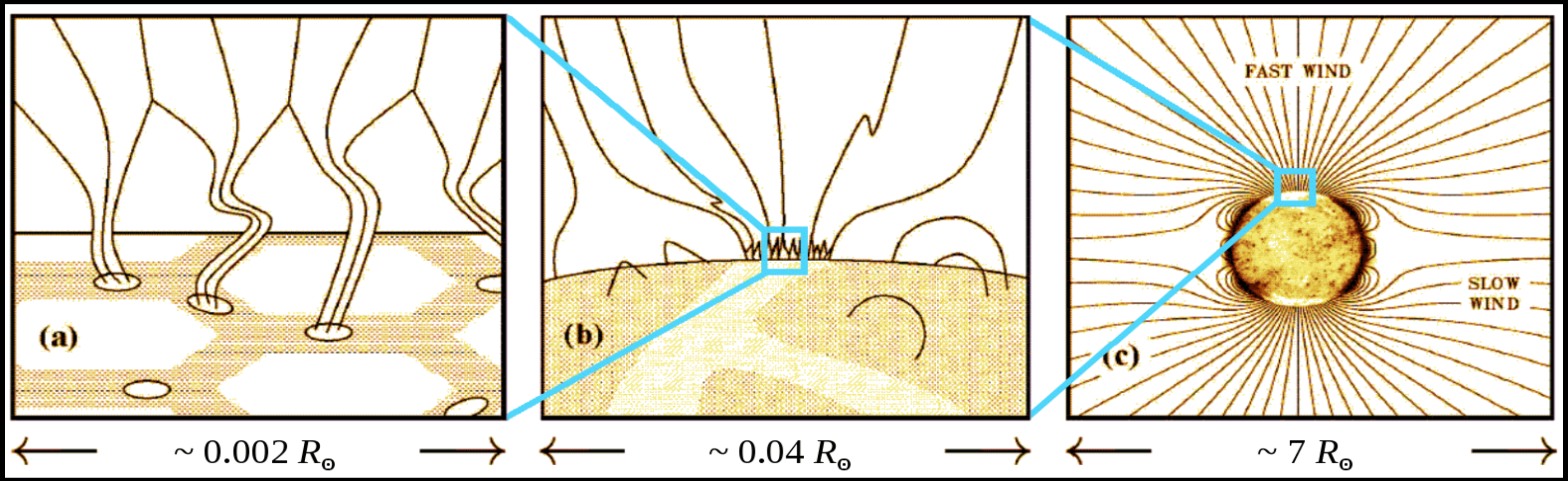
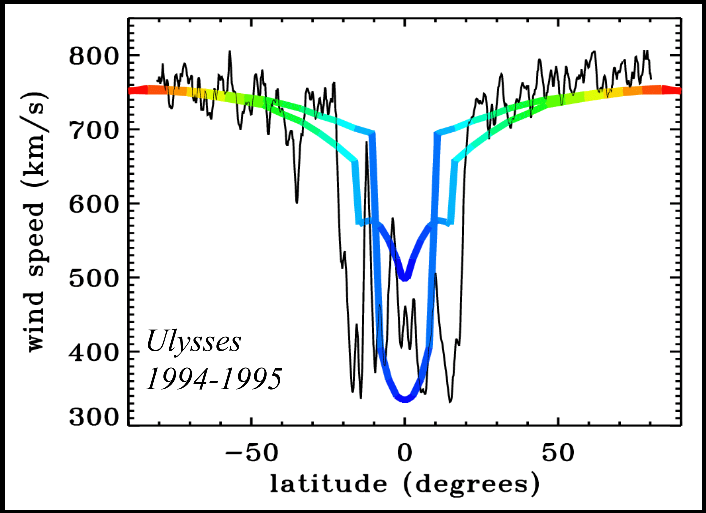
Turbulence: a unifying idea for coronal heating?



Implementing the wave/turbulence idea

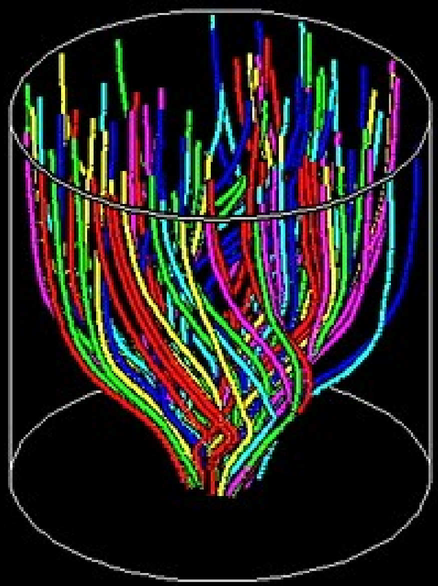
Previous talk discussed self-consistent ZEPHYR models along expanding flux tubes:



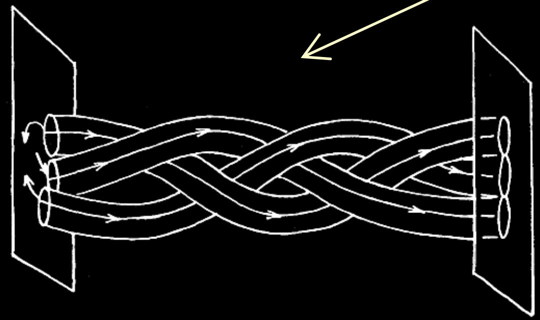


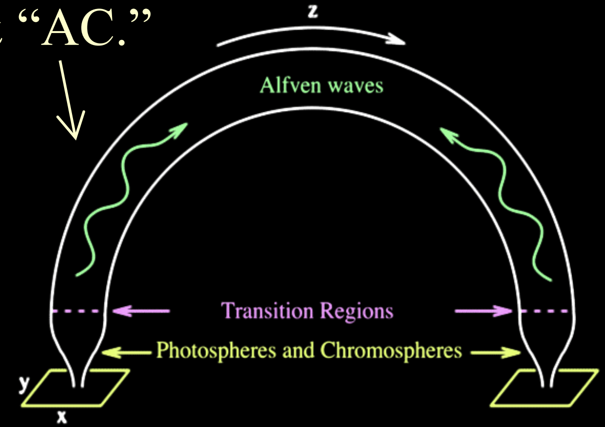
- Models match most observed trends of plasma parameters vs. wind speed at 1 AU.
- See also Suzuki & Inutsuka (2006), Verdini et al. (2010), Chandran et al. (2011).
- **HOWEVER,** models all assumed that turbulent cascade would proceed all the way "down" to small enough scales for dissipation to convert the wave energy into heat.

Time-dependent turbulence models

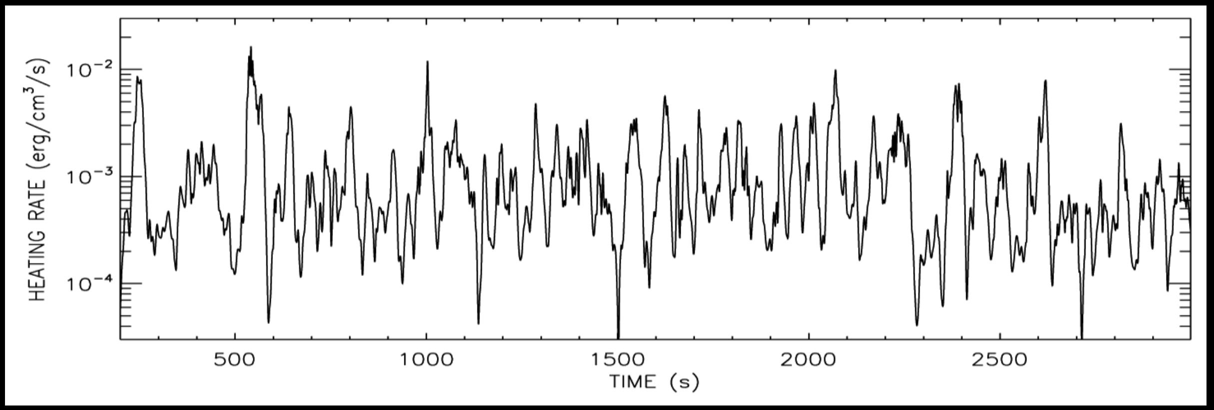


- van Ballegooijen et al. (2011) & Asgari-Targhi et al. (2012, 2013) simulated reduced MHD turbulence in expanding flux tubes.
- Bridged the gap between "DC" & "AC."



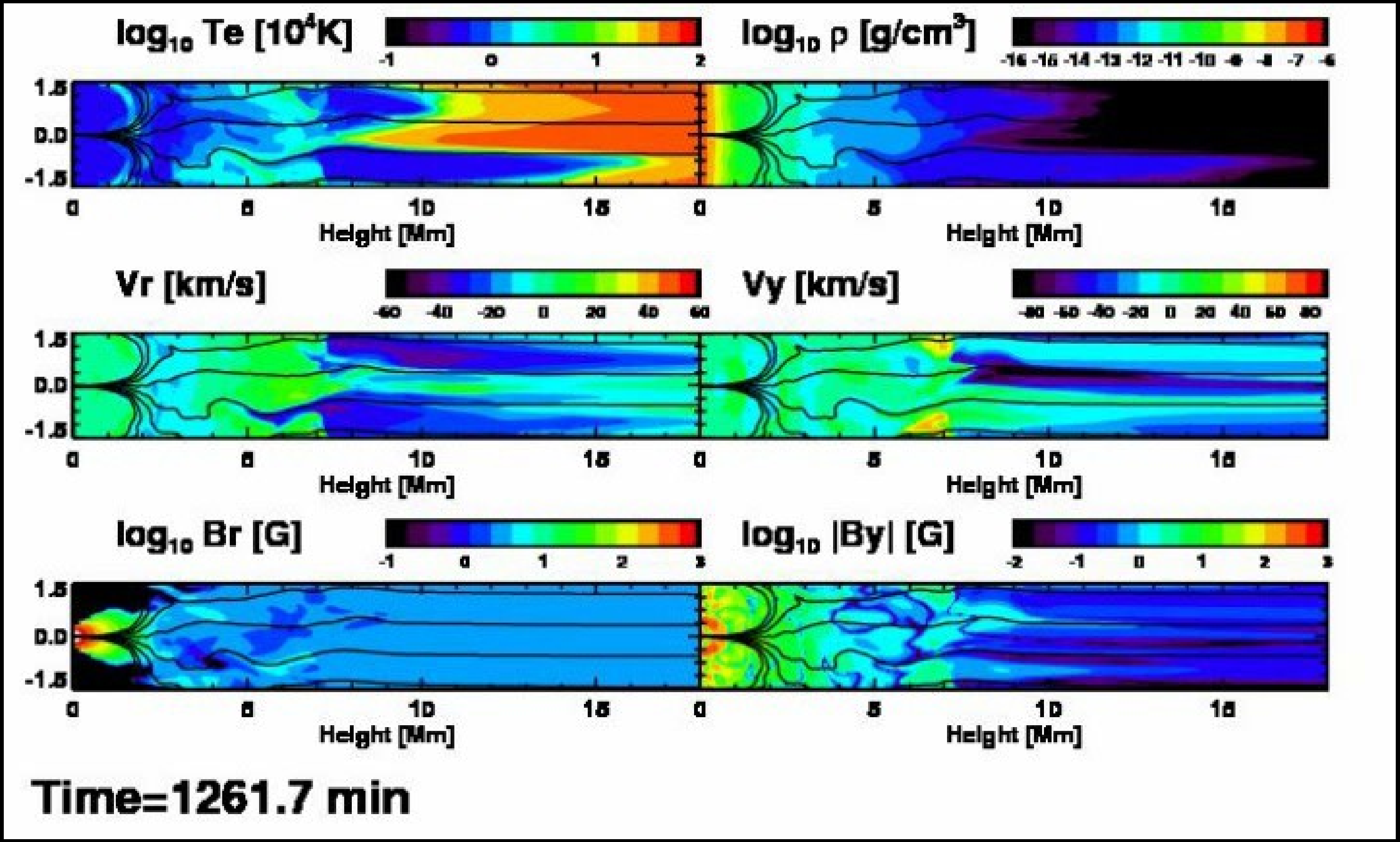


- Chromospheric and coronal heating is of the right magnitude, and is **highly intermittent** ("nanoflare-like").



Moving beyond just Alfvén waves

- Matsumoto & Suzuki (2012, 2013) drive the system like we do, but they include compressibility effects.... "spicules" and flows *along* the field occur.
- They get coronal heating & wind acceleration, but **without** much traditional cascade.



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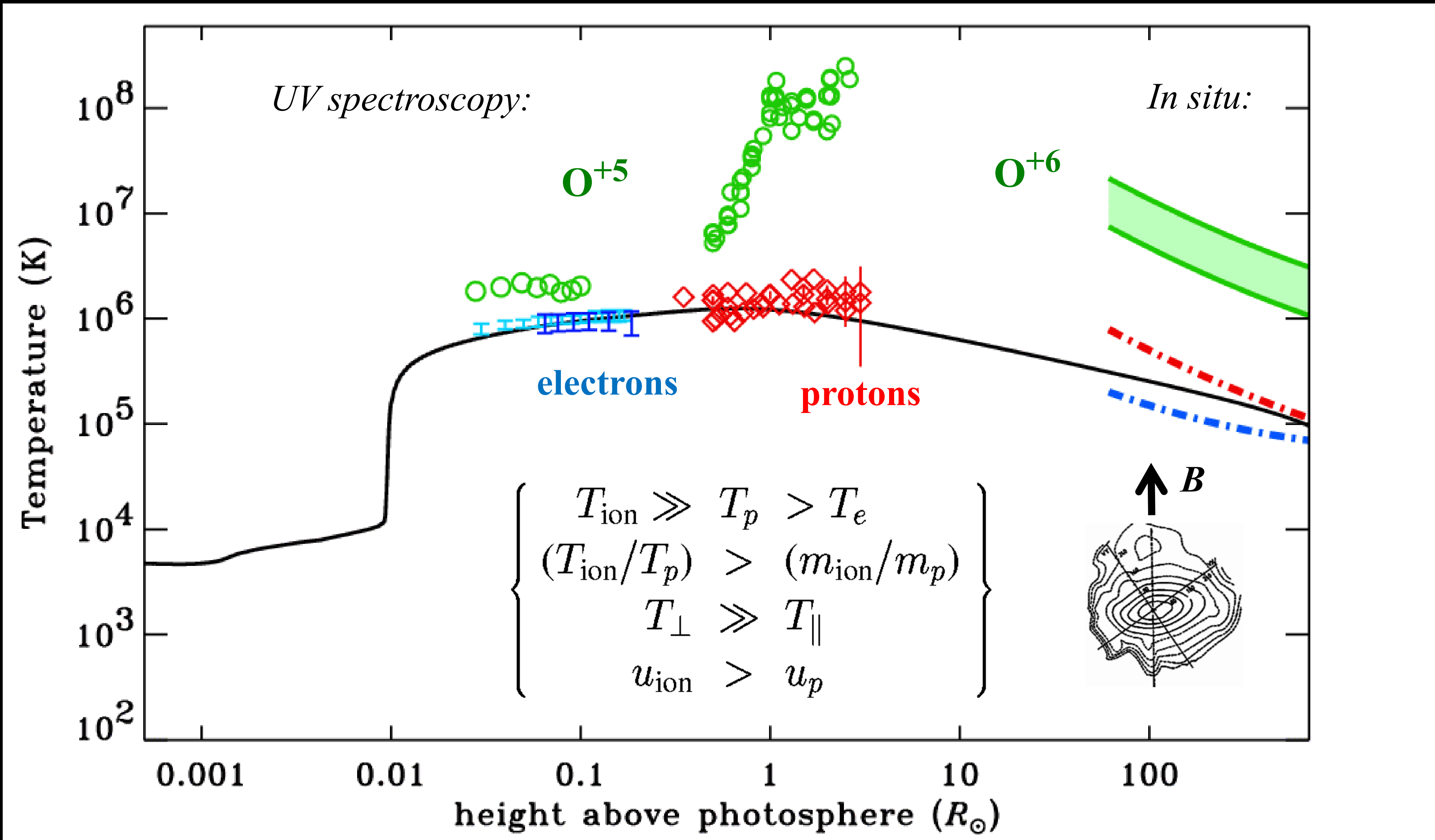
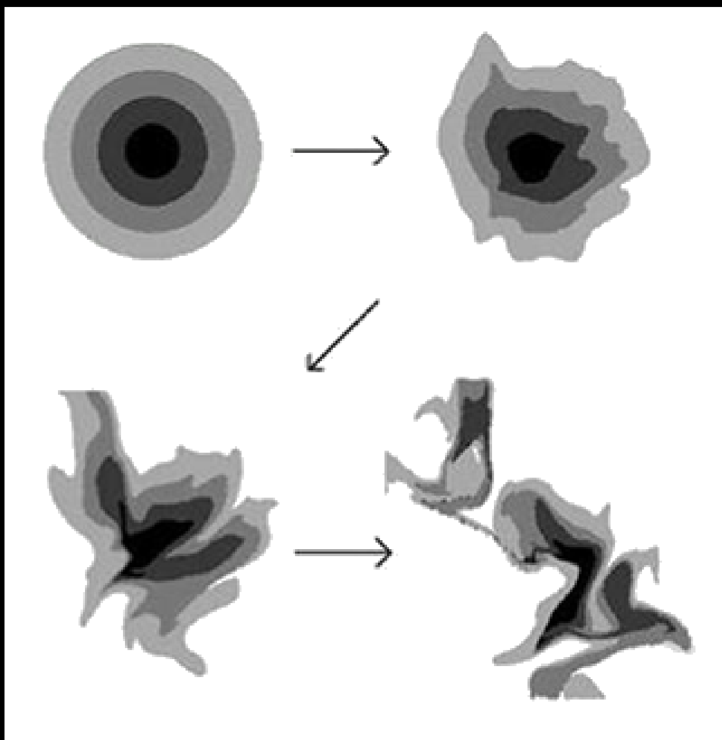
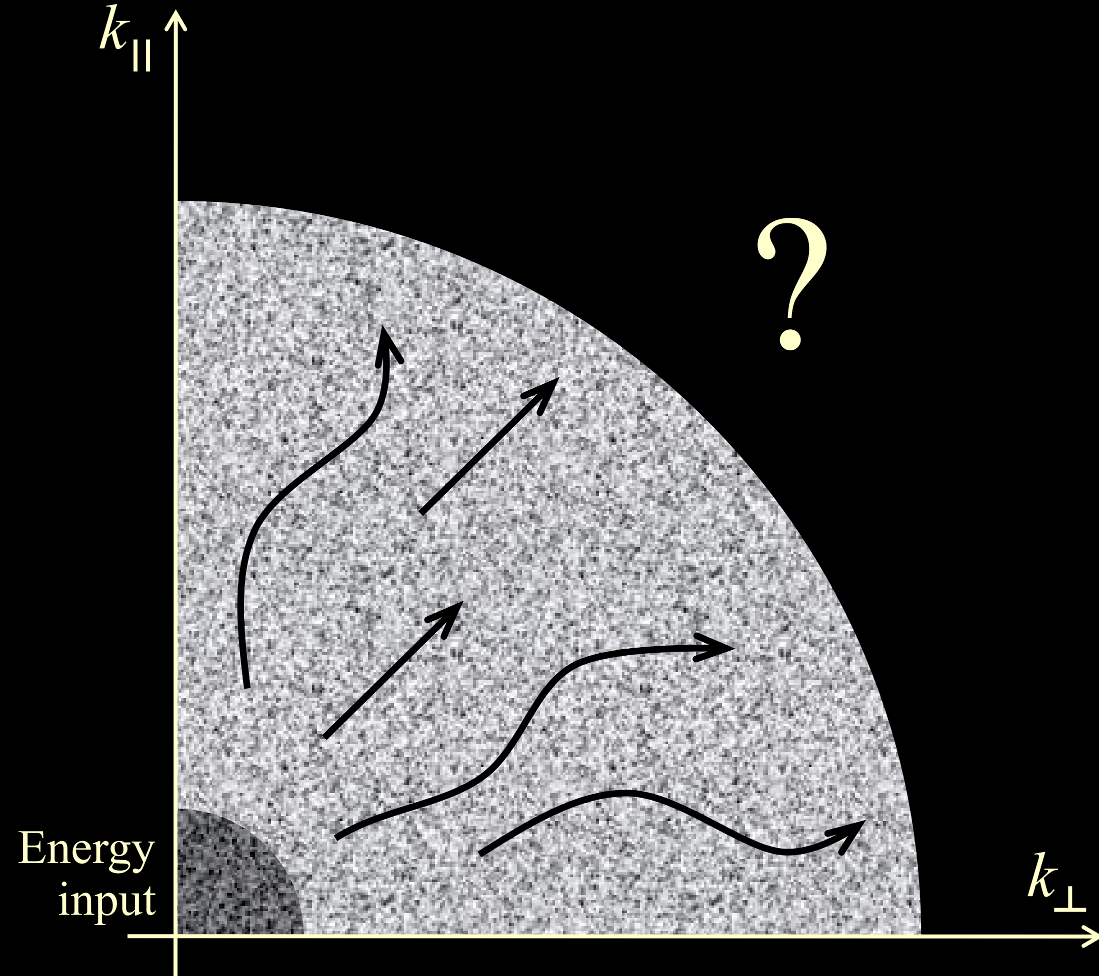
Aside: observable effects of dissipation



Anisotropic MHD turbulence

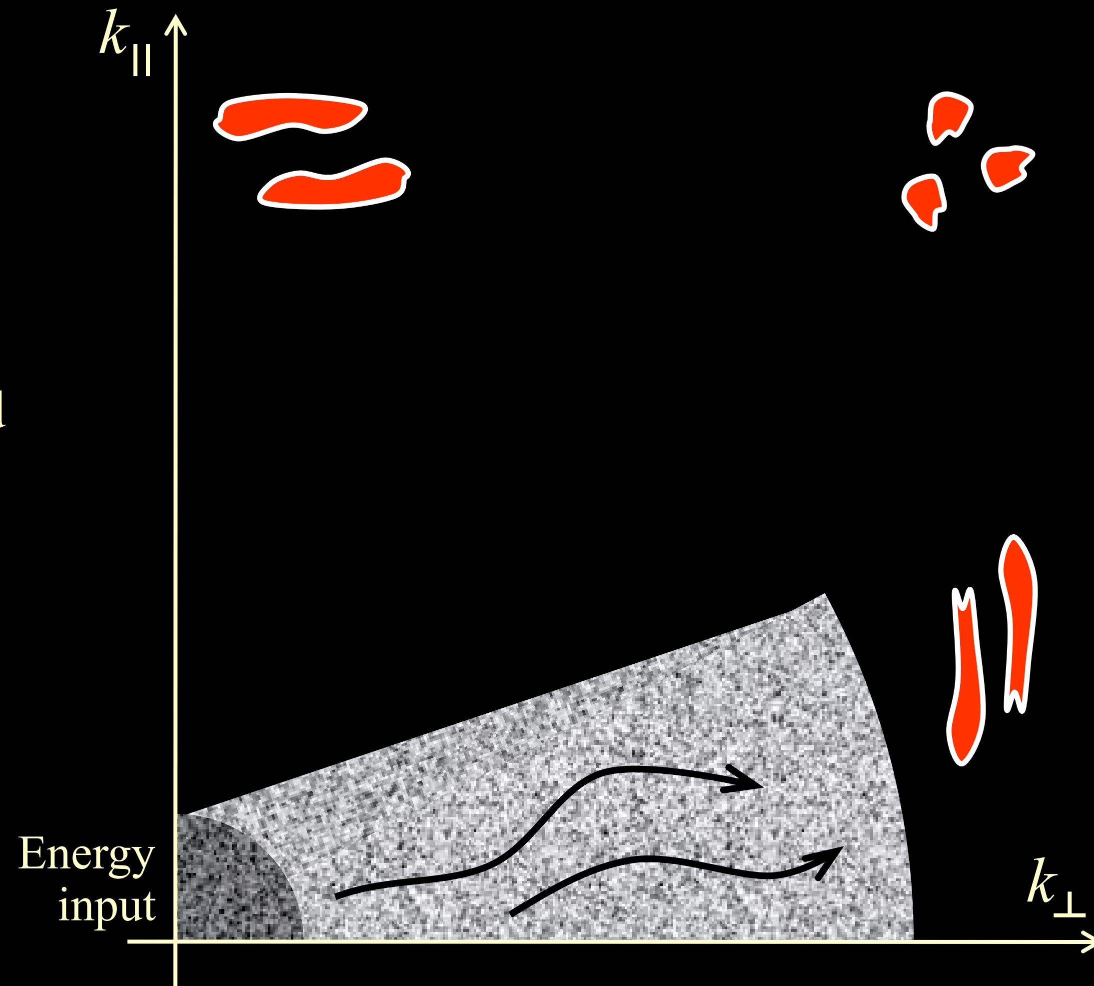
- Can MHD turbulence explain the presence of perpendicular ion heating? Maybe not!





Anisotropic MHD turbulence

- Can MHD turbulence explain the presence of perpendicular ion heating? Maybe not!
- Alfvén waves propagate ~freely in the **parallel** direction (and don't interact easily with one another), but field lines can "shuffle" in the **perpendicular** direction.
- Thus, when the background field is strong, cascade proceeds mainly in the plane perpendicular to field (Strauss 1976; Montgomery 1982).



Anisotropic MHD turbulence

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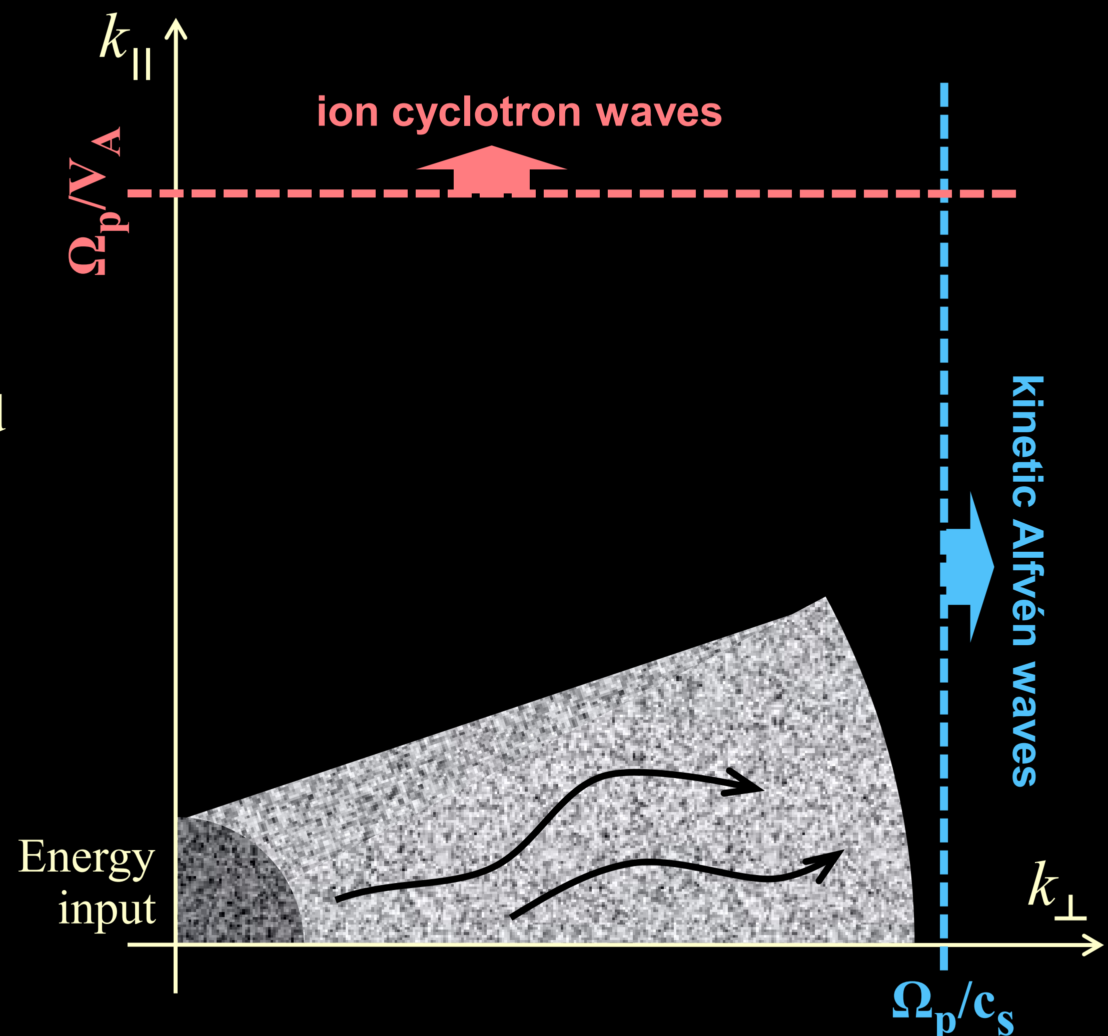
- Thus, when the background field is strong, cascade proceeds mainly in the plane perpendicular to field (Strauss 1976; Montgomery 1982).
- In a low-β plasma, cyclotron waves heat **ions & protons** when they damp, but kinetic Alfvén waves are Landau-damped, heating **electrons.**



How are the ions preferentially heated?

- There are dozens of suggested mechanisms. For now, discuss two popular ideas:

Ion cyclotron waves
(they must be present at some level)

- *In situ* measurements see them all over the place!
- If there are also compressible magnetosonic waves in the system, ***they*** cascade more isotropically than Alfvén waves.
- Nonlinear couplings could bring energy back to the Alfvén waves once they reach high-$k_\parallel$ in other forms.

Nonlinear structures in
low-frequency, high-$k_\perp$ turbulence

- If the velocity perturbation amplitudes are large enough, the ions undergo nonlinear **stochastic motions,** and can be heated strongly.
- KAW turbulence isn't just made of incoherent wave packets, but is organized into small dissipative **current sheets.** (Test particle models show preferential ion heating.)
- KAWs undergo strong perpendicular shear motions, which may be unstable to spontaneous growth of high-freq. waves.

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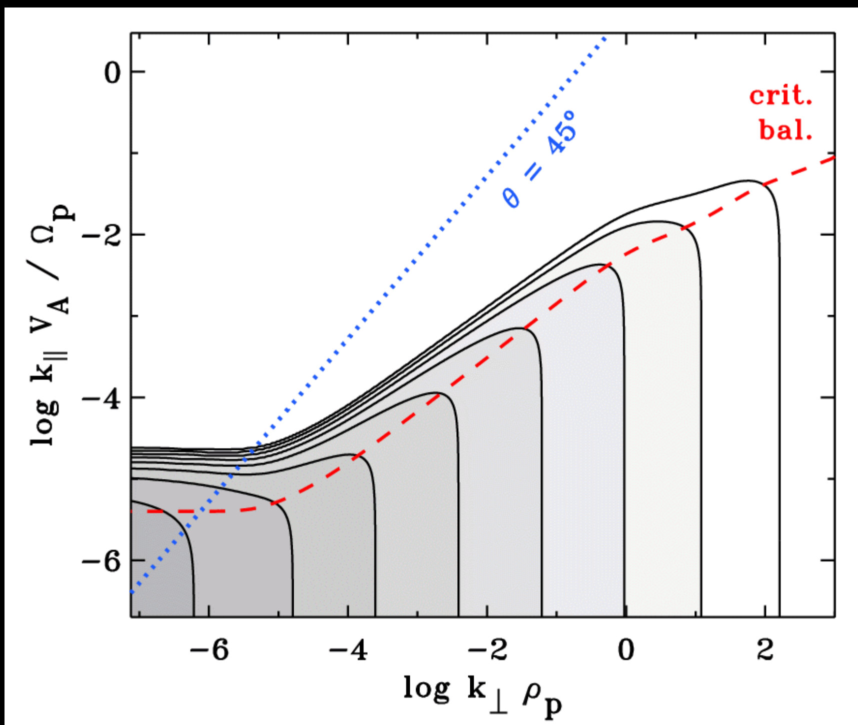
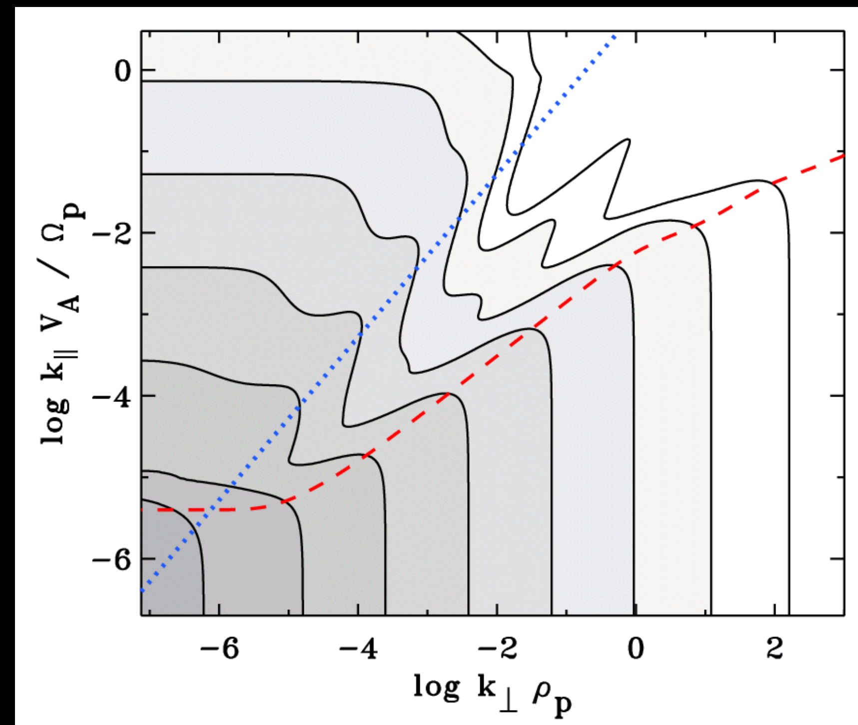
Model cascade + Alfvén/fast-mode coupling

- Cranmer & van Ballegooijen (2012) modeled cascade as diffusion in ($k_\parallel$, $k_\perp$) space.
- **Dissipation** from ion cyclotron & Landau resonances (A); transit-time damping (F).
- **Coupling** between A & F modes treated with Chandran (2005) weak turb. timescale.

Pure Alfvén mode:

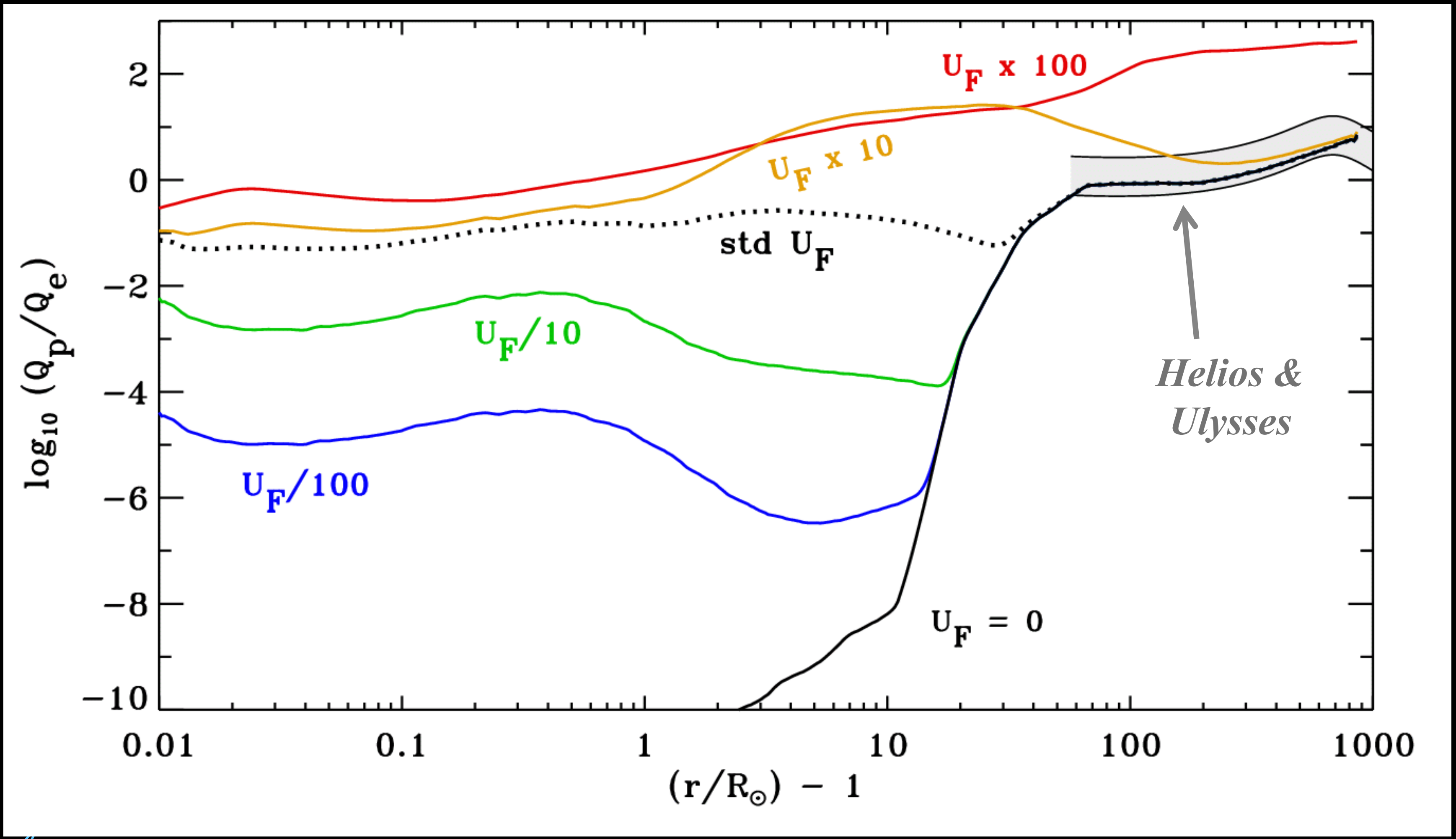


Alfvén mode with AAF/AFF coupling:



Results for proton/electron heating ratio

- Cranmer & van Ballegooijen (2012) computed heating rates for protons & electrons for the "known" Alfvén wave power, plus a variable fast-mode wave component.



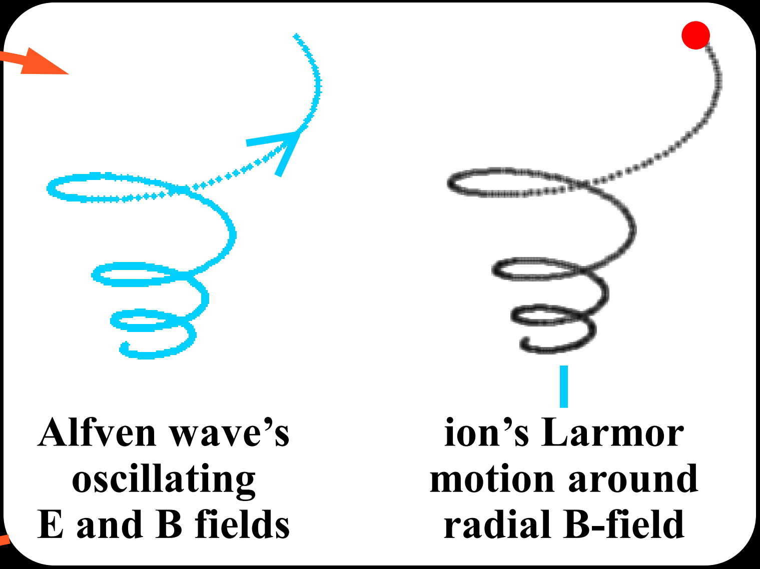
How does cyclotron resonance work?

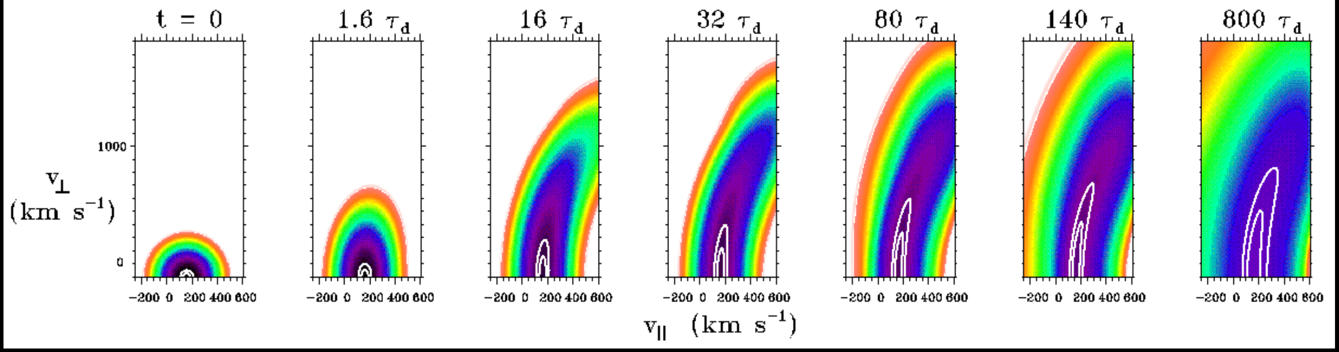
- Parallel-propagating **ion cyclotron waves** (10–10,000 Hz in the corona) interact with positive ions in a resonant way . . .

$$
\left\{ \begin{array}{ccc} T_{\rm ion} \gg & T_p & > T_e \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\rm ion} & > & u_p \end{array} \right\}
$$

instabilities

dissipation

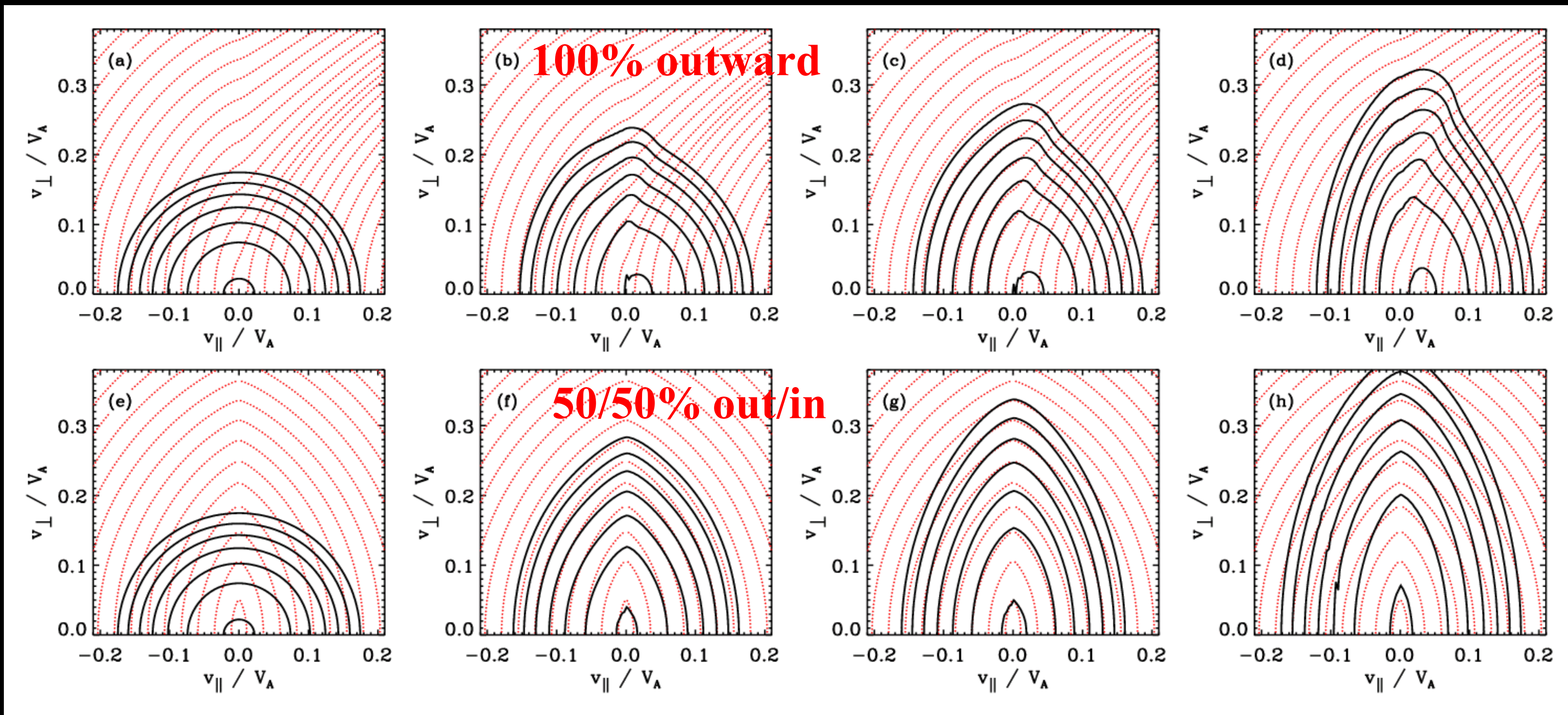




For a turbulent power spectrum, ion cyclotron resonance produces **diffusion** in velocity space.

Proton cyclotron diffusion

- Protons diffuse in velocity space, with evolution details determined by the relative amounts of power in outward vs. inward propagating cyclotron waves (Cranmer 2014).

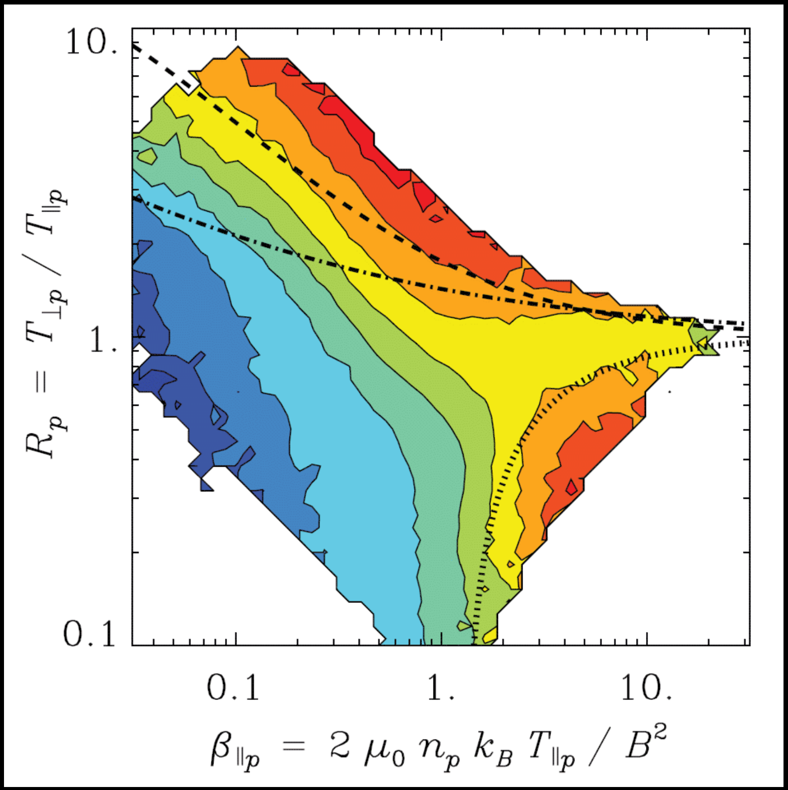


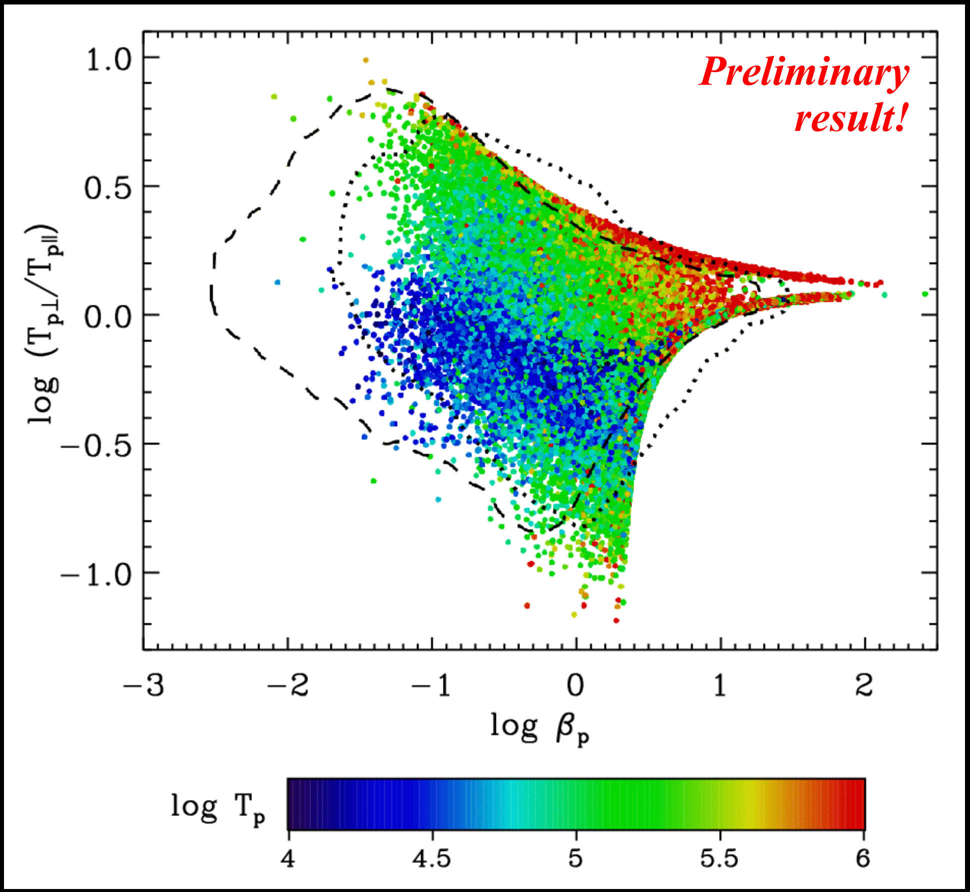
→ *time* →

Proton cyclotron heating out to 1 AU

- Cranmer (2014) treated the diffusion with bi-Maxwellian proton velocity distributions and a Monte Carlo sampling of solar wind parameters (with probability distributions constrained by measurements) to derive an ensemble of kinetic properties at 1 AU.

measurements from Wind spacecraft (Maruca et al. 2011)





Conclusions

- Advances in MHD turbulence theory and kinetic plasma physics continue to help improve our understanding about how the Sun produces its hot corona & solar wind.
- However, we still do not have complete enough **observational constraints** to be able to choose between competing theories.

For more information:
http://www.cfa.harvard.edu/~scranmer/