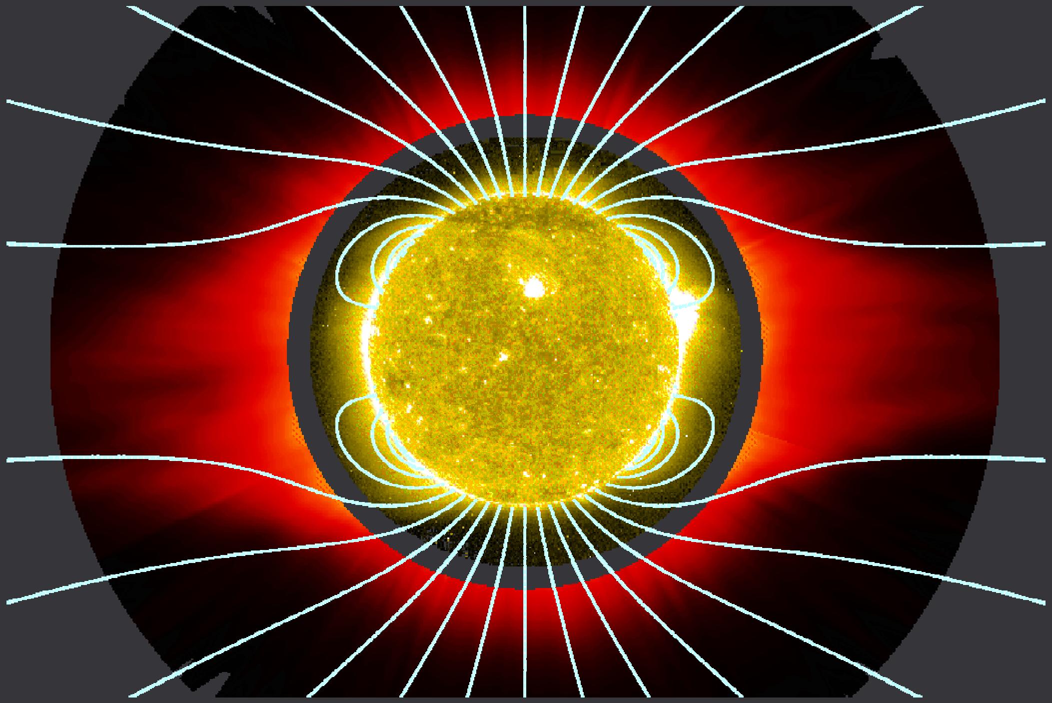
Alfvénic Turbulence in the Fast Solar Wind: from cradle to grave



S. R. Cranmer, A. A. van Ballegooijen, and the UVCS/SOHO Team

Harvard-Smithsonian Center for Astrophysics

Alfvénic Turbulence in the Fast Solar Wind: from cradle to grave

Outline:

- Background
- Alfvén wave generation (thin flux tubes)
- Non-WKB wave reflection
- MHD turbulence
- Collisionless damping ⟶ ion heating

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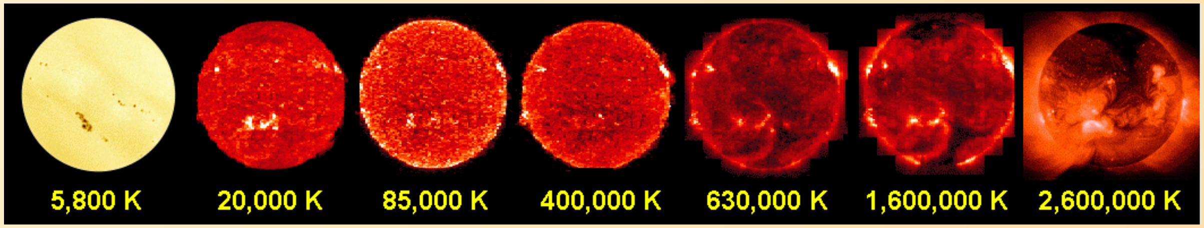
The need for extended coronal heating

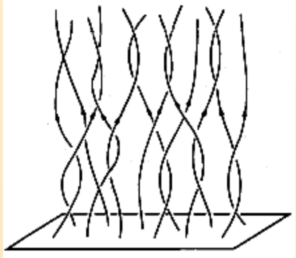
- The **basal** "coronal heating problem" is well known:



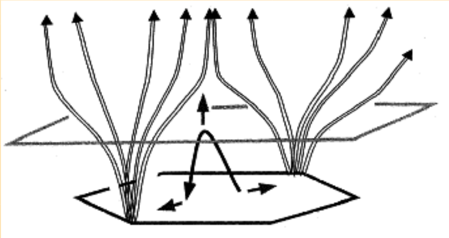
- Above 2 R_s , **additional energy deposition** is required in order to . . .
  - » accelerate the fast solar wind (without artificially boosting mass loss and peak T_e),
  - » produce the proton/electron temperatures seen *in situ* (also magnetic moment!),
  - » produce the strong preferential heating and temperature anisotropy of heavy ions (in the wind's acceleration region) seen with UV spectroscopy.

Coronal heating mechanisms

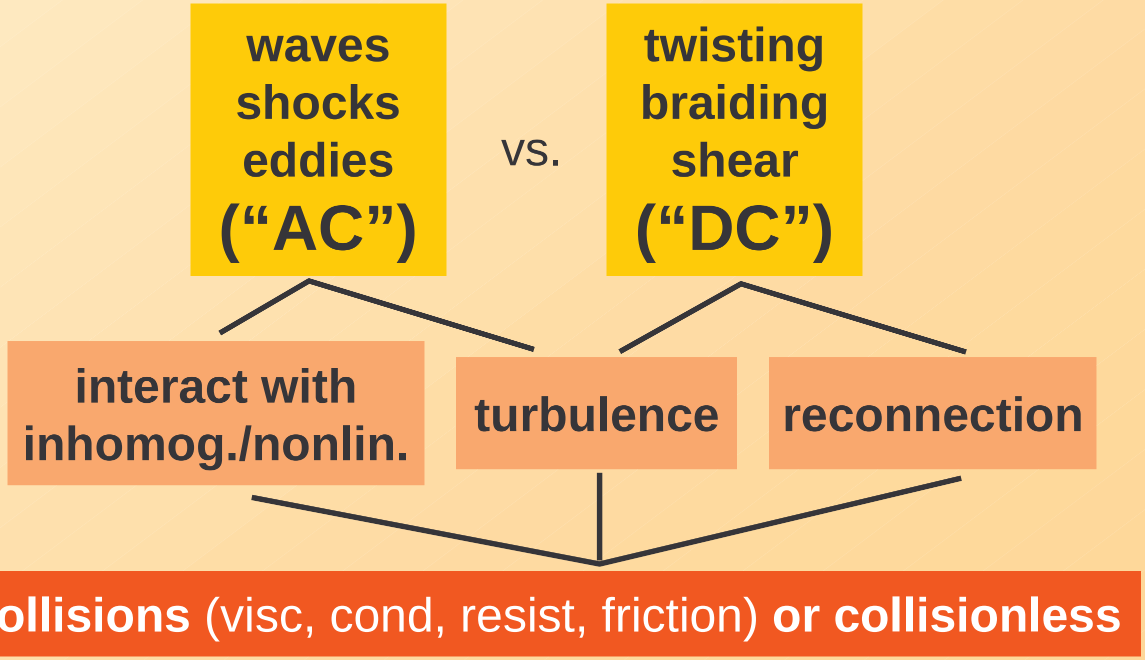
- Surveys of dozens of models: Mandrini et al. (2000), Aschwanden et al. (2001)
- Where does the mechanical energy come from?



vs.



- How is this energy coupled to the coronal plasma?
- How is the energy dissipated and converted to heat?



waves
shocks
eddies
("AC")

vs.

twisting
braiding
shear
("DC")

interact with inhomog./nonlin.

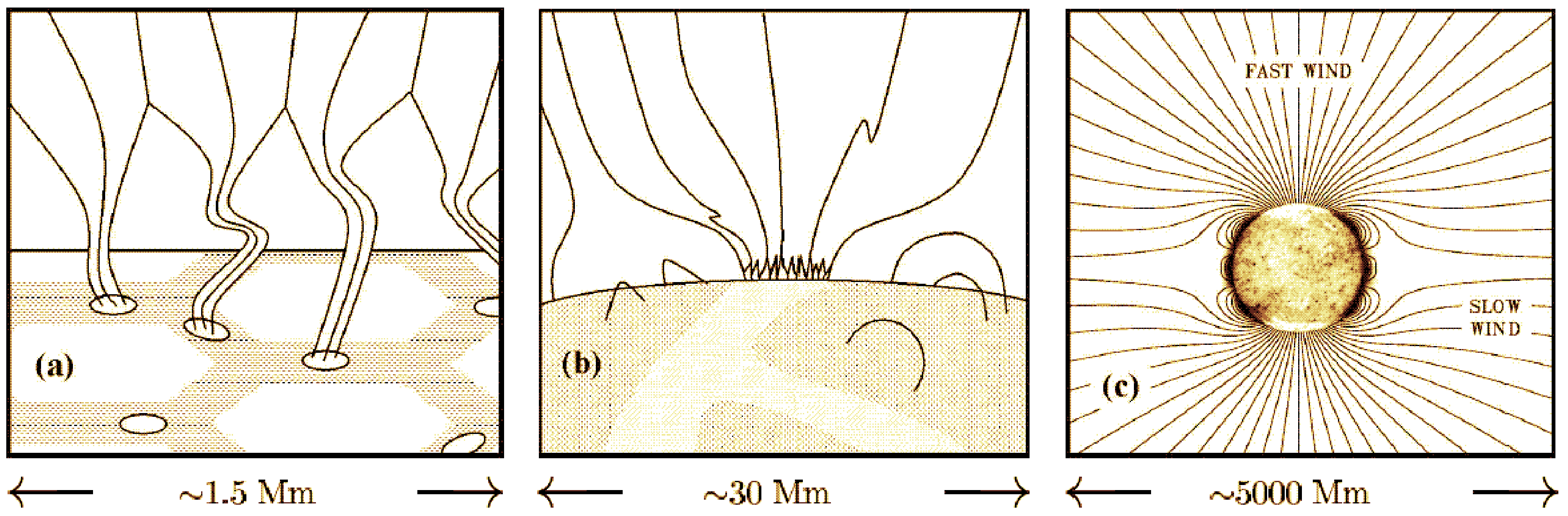
turbulence

reconnection

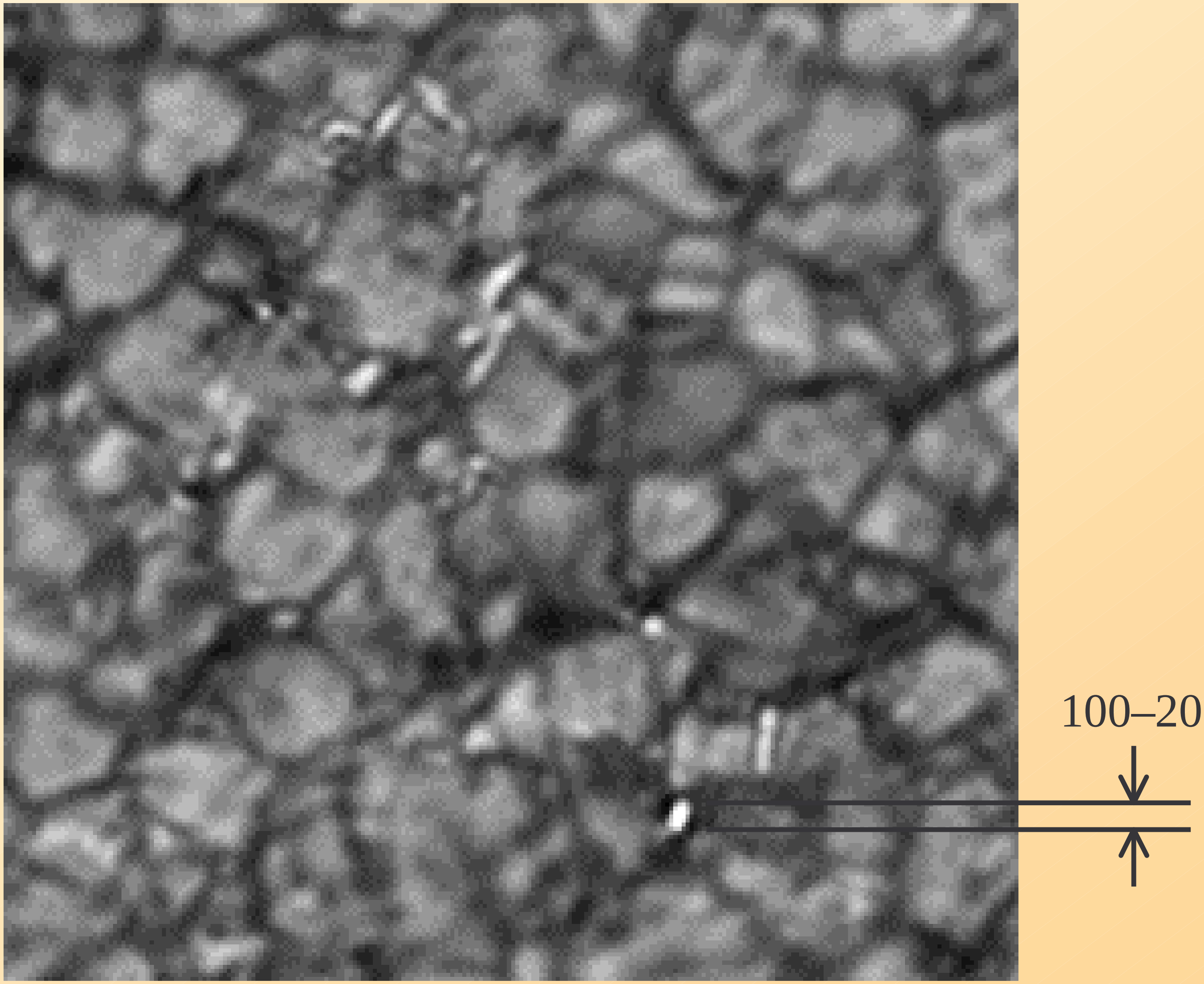
collisions (visc, cond, resist, friction) **or collisionless**

Alfvén waves in open flux tubes

- Cranmer & van Ballegooijen (2005) built a model of the global properties of **incompressible** Alfven waves in an open coronal-hole flux tube.
- Background plasma properties (density, flow speed, B-field strength) are fixed empirically; wave properties are modeled with virtually no “free” parameters.
- Note successive **merging** of flux tubes on granular & supergranular scales:



G-band bright points (close-up)



Photospheric power spectrum

- The basal transverse fluctuation spectrum is specified from observed BP motions.
- The “ideal” data analysis of these motions:

$$x(t)\ ,\ \ y(t)$$

$$\Downarrow$$

$$v_x(t)\ ,\ \ v_y(t)$$

$$\Downarrow$$

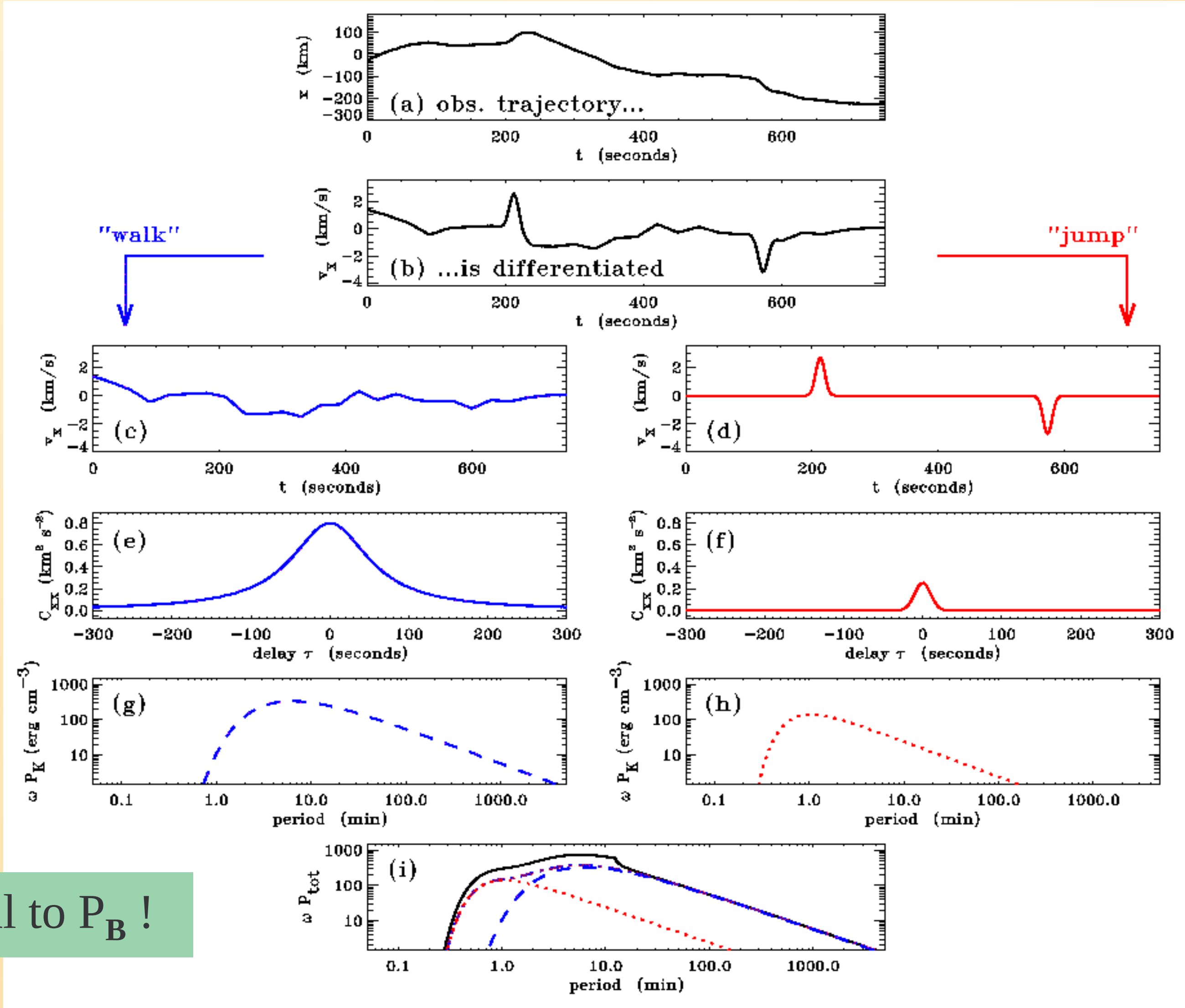
$$C_{xx}(\tau) \;=\; \lim_{\Delta t \rightarrow \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{+\Delta t/2} dt\ v_x(t)\, v_x(t+\tau)\ \ , \quad \text{also for } C_{yy}$$

$$\Downarrow$$

$$P_x(\omega) \;\equiv\; \frac{1}{2\pi} \int_{-\infty}^{+\infty} d\tau\, C_{xx}(\tau)\, e^{i\omega\tau}\ \ , \quad \text{also for } P_y$$

Photospheric power spectrum

- In practice, there are two phases of observed BP motion:
- **“random walks”** of isolated BPs (e.g., Nisenson et al. 2003);
- **“intermittent jumps”** representing mergers, fragmenting, reconnection? (Berger et al. 1998).



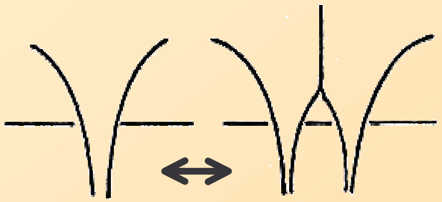
P_K not necessarily equal to P_B !

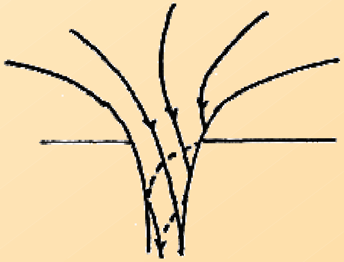
Kink-mode waves in thin flux tubes

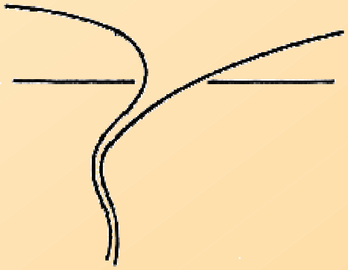
- Below a 600 km **“merging height”** we follow Lagrangian perturbations of a ~vertical flux tube (Spruit 1981):

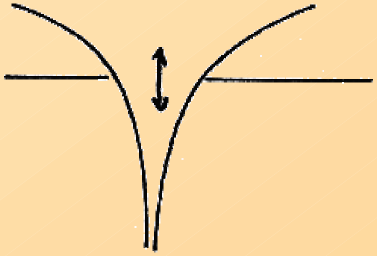
$$\frac{\partial^2 v_\perp}{\partial t^2} = \frac{g\,\Delta\rho}{\rho_{\rm tot}}\frac{\partial v_\perp}{\partial r} + V_{\rm ph}^2\,\frac{\partial^2 v_\perp}{\partial r^2}$$

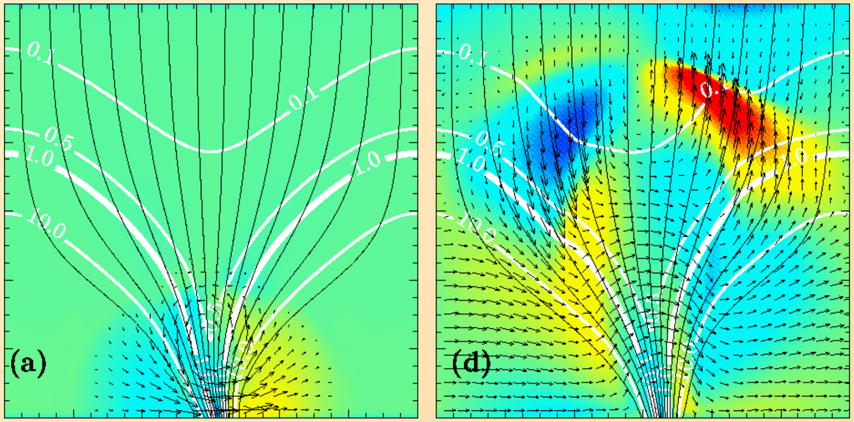
↑
buoyancy term
(cutoff period: 9 to 12 min.)


splitting/merging


torsion

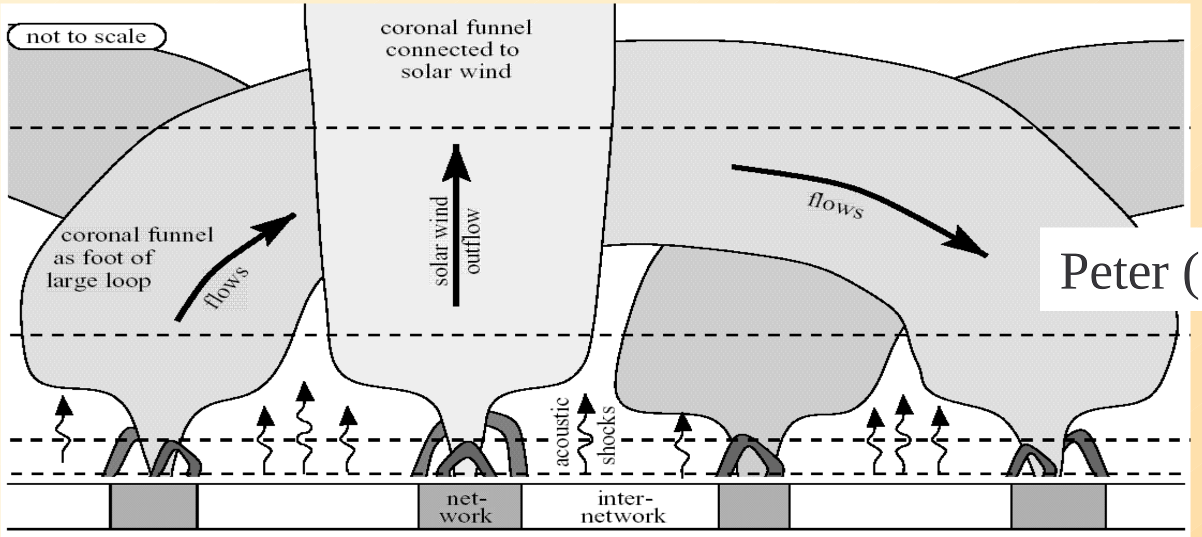

bending
(transversal wave)


longitudinal
flow/wave

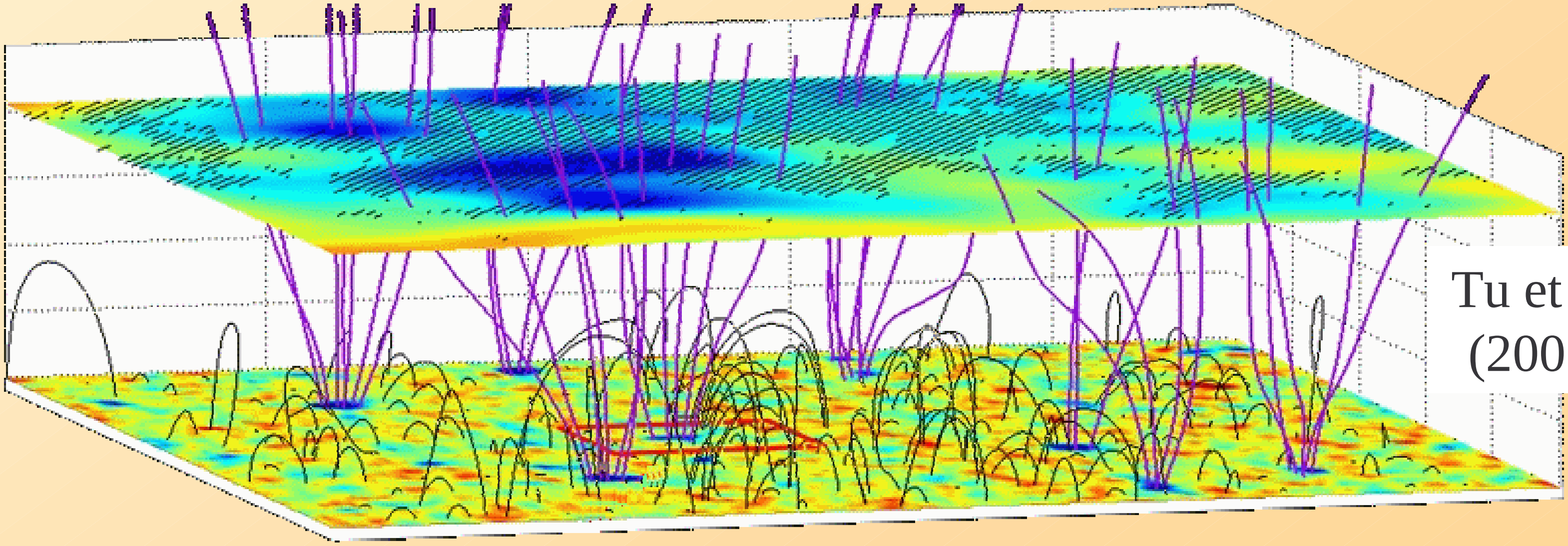


In reality, it’s not incompressible . . .
(Hasan et al. 2005; astro-ph/0503525)

Supergranular “funnel” cartoons



Peter (2001)



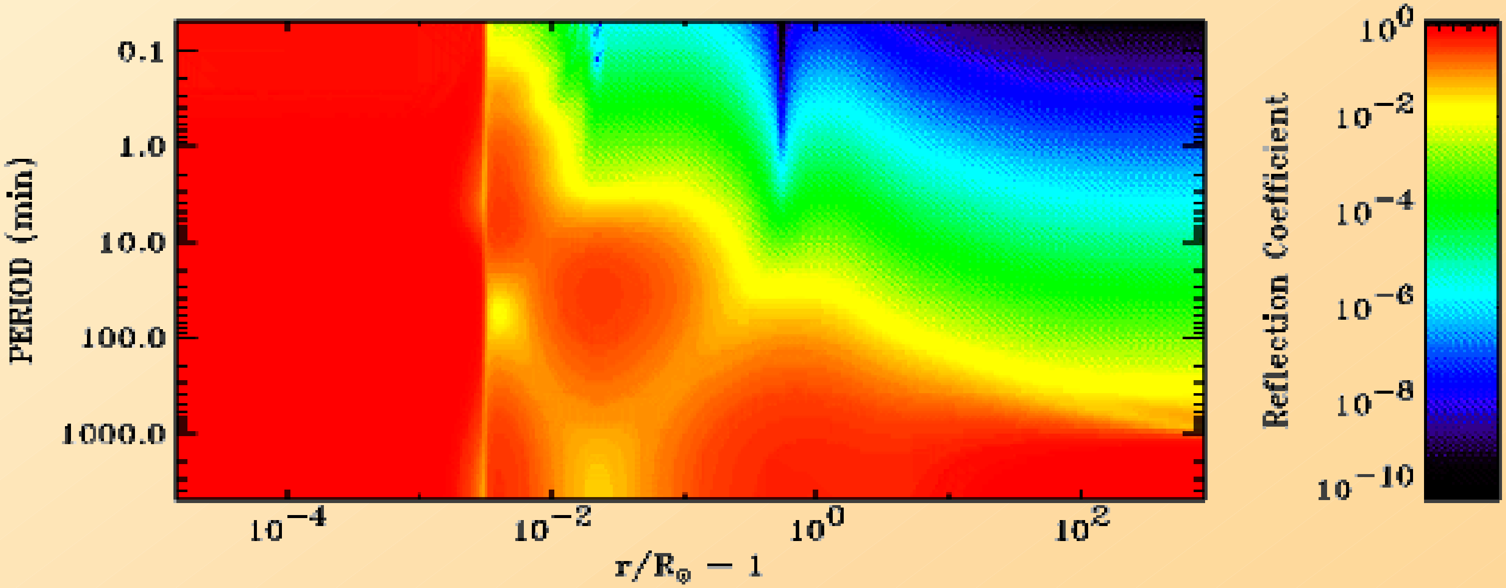
Tu et al.
(2005)

Non-WKB Alfvén wave reflection

- Above the 600 km merging height, we follow Eulerian perturbations along the axis of the superradial flux tube, with wind (Heinemann & Olbert 1980; Velli 1993):

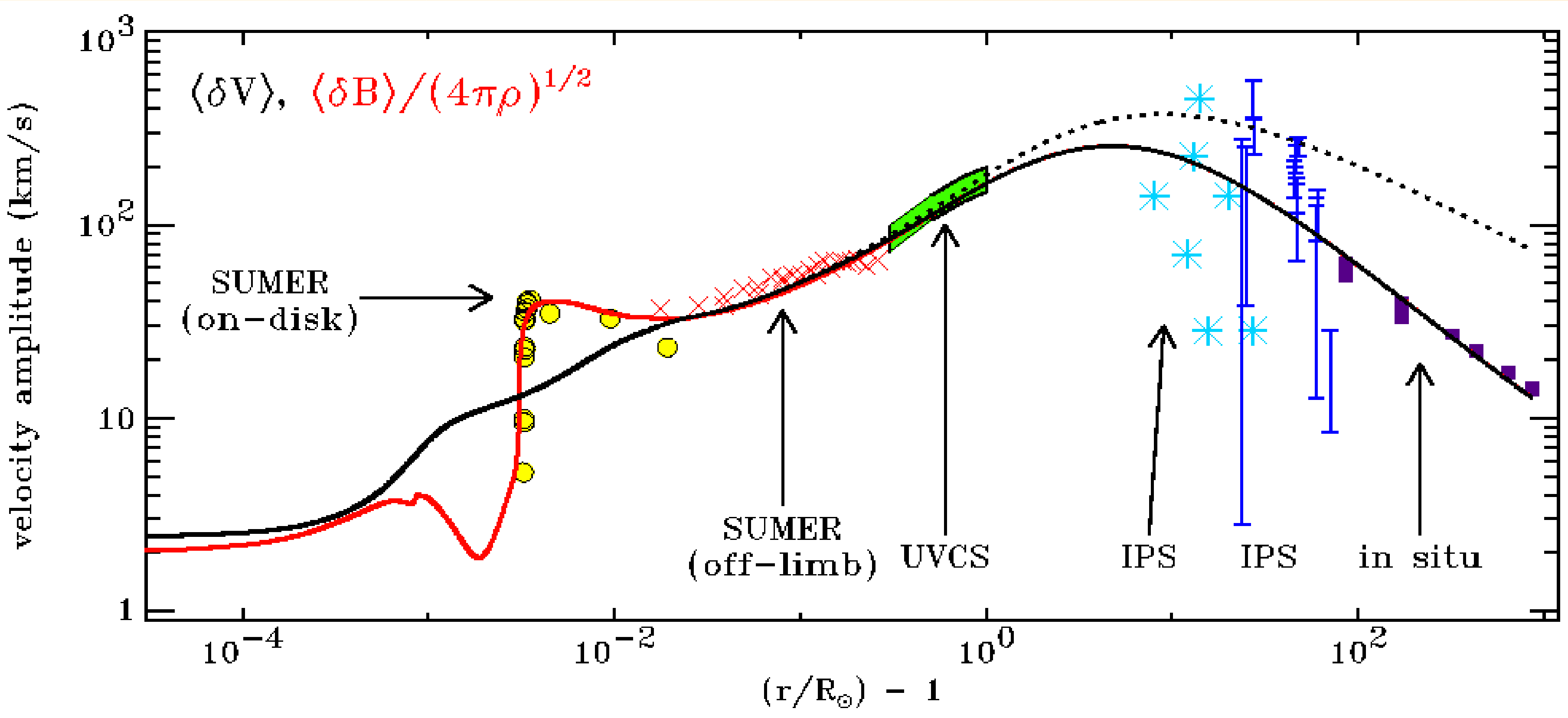
$$\frac{\partial Z_\pm}{\partial t} + (u \mp V_A)\frac{\partial Z_\pm}{\partial r} = (u \pm V_A)\left(\frac{Z_\pm}{4H_D} + \frac{Z_\mp}{2H_A}\right) - \frac{Z_\pm |Z_\mp|}{2L_\perp}$$

$$\text{where } Z_\pm \equiv v_\perp \pm B_\perp / \sqrt{4\pi\rho}$$



Resulting wave amplitude (with damping)

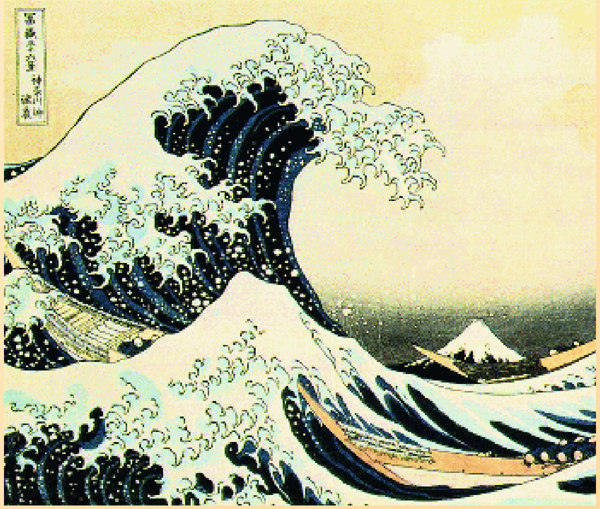
- Transport equations solved for 300 “monochromatic” periods **(3 sec to 3 days)**, then renormalized using photospheric power spectrum.
- One free parameter: base “jump amplitude” (0 to 5 km/s allowed; 3 km/s is best)



MHD turbulence

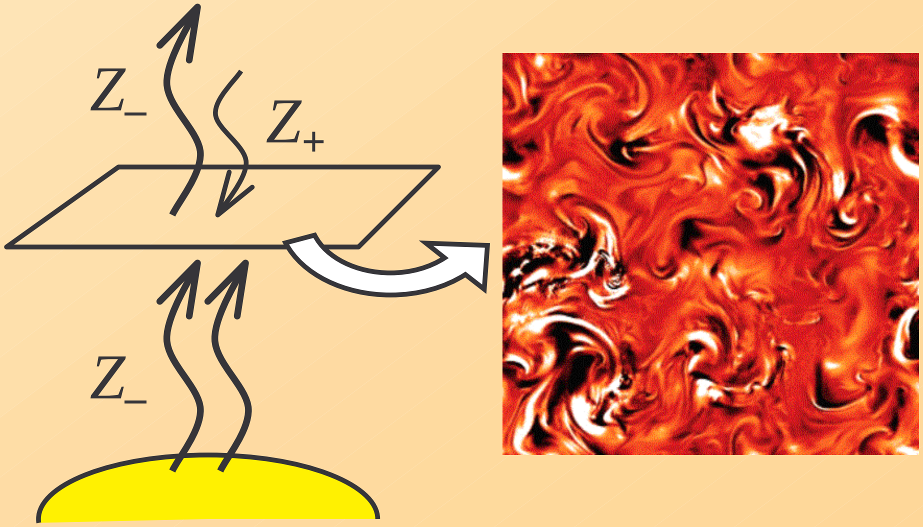
- It is highly likely that somewhere in the outer solar atmosphere the fluctuations become turbulent and **cascade** from large to small scales:

$$\mathcal{E}_{\rm out} = \frac{\rho\, v_{\rm eddy}^{3}}{\ell_{\rm eddy}} \quad \rightsquigarrow \rightsquigarrow \rightsquigarrow \quad Q_{\rm heat} \approx \mathcal{E}_{\rm out}$$



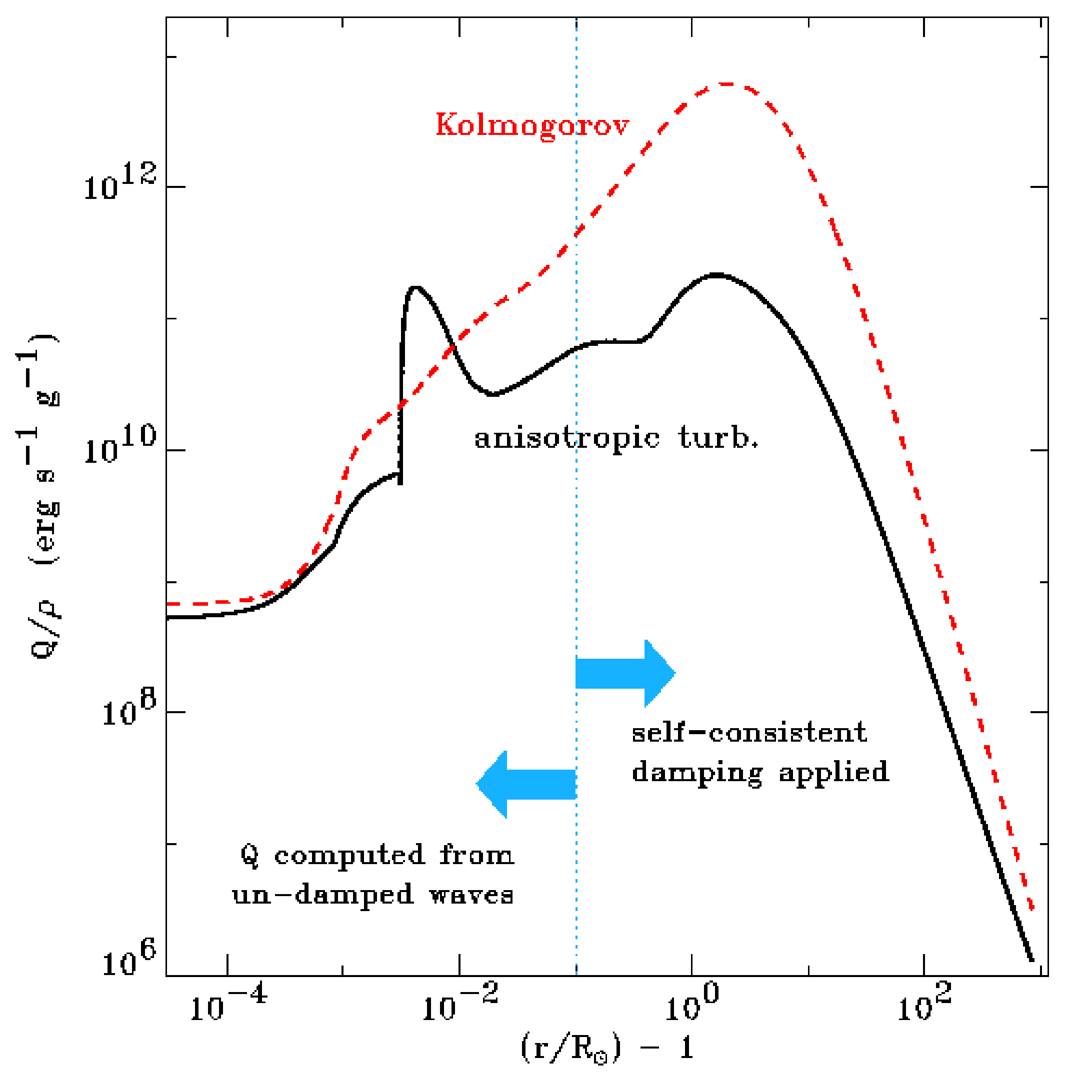
- With a strong background field, it is easier to **mix** field lines (perp. to ***B***) than it is to **bend** them (parallel to ***B***).
- Also, the energy transport along the field is far from isotropic:

$$Q_{\rm heat} = \rho\, \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4 L_\perp}$$



Turbulent heating rate

- Anisotropic heating and damping was applied to the model; $L_\perp$ = 1100 km at the merging height; scales with transverse flux-tube dimension.
- The isotropic Kolmogorov law **overestimates** the heating in regions where $Z_- >> Z_+$



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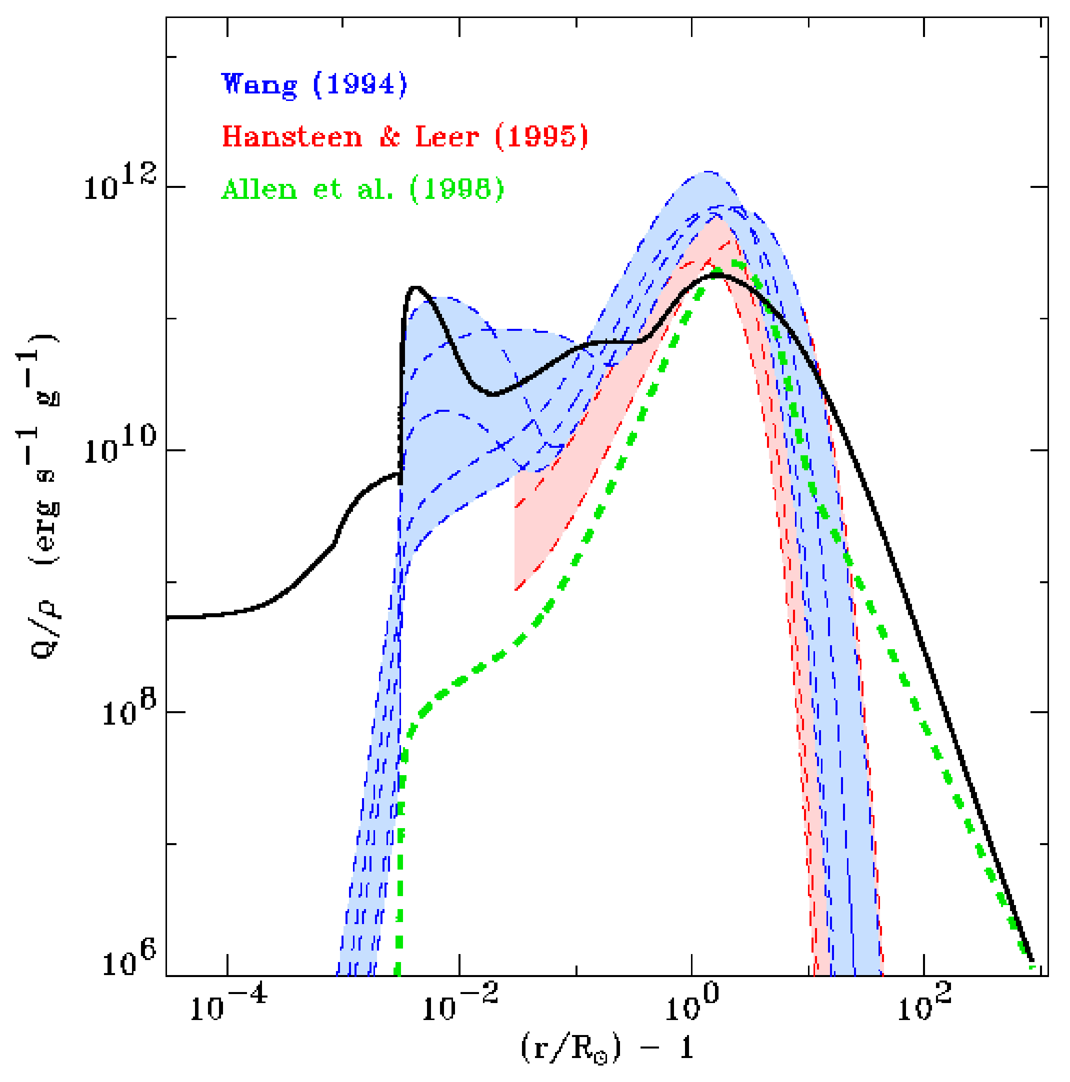
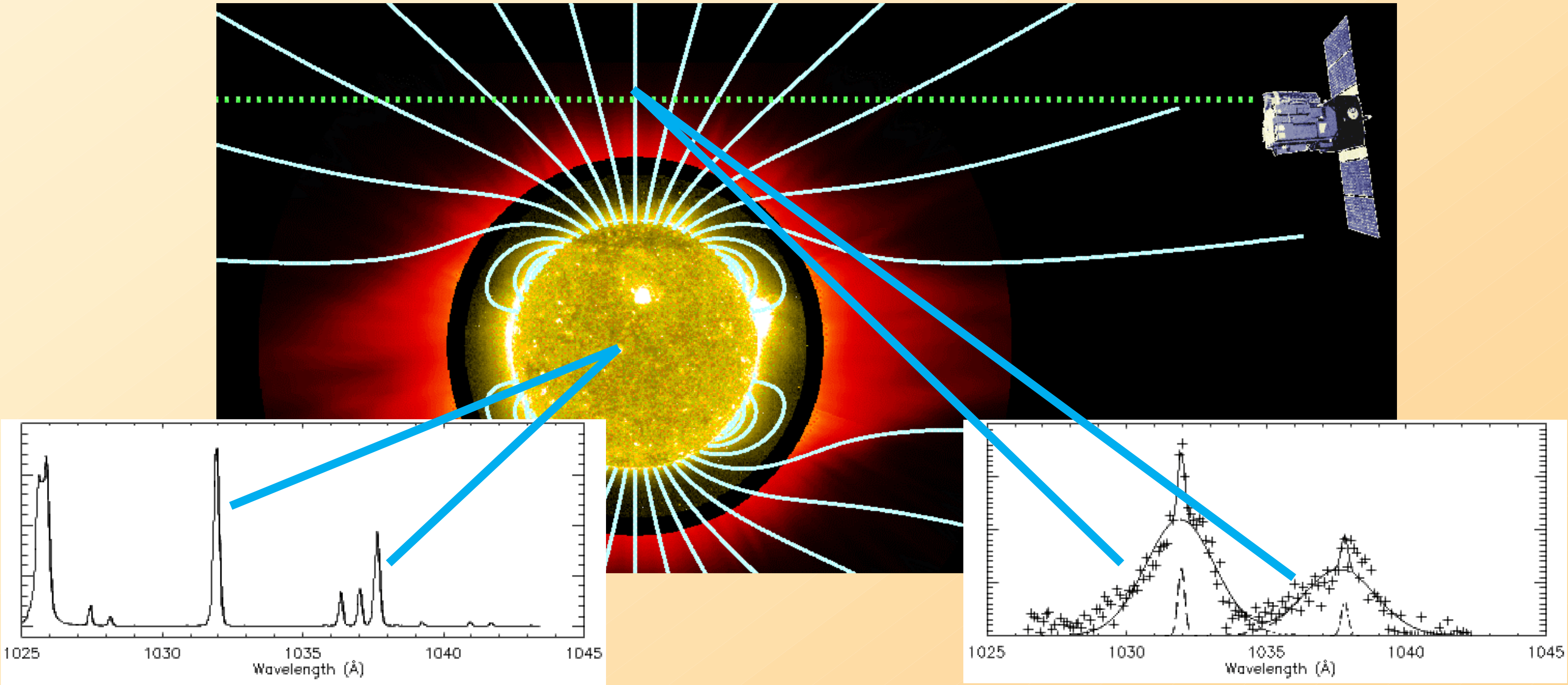
- The isotropic Kolmogorov law **overestimates** the heating in regions where $Z_- >> Z_+$
- Dmitruk et al. (2002) predicted that this anisotropic heating may account for much of the expected (i.e., empirically constrained) coronal heating in open magnetic regions . . .



How is the turbulent heating “partitioned” between protons, electrons, and heavy ions?

UVCS results: solar minimum (1996-1997)

- Ultraviolet spectroscopy probes properties of ions in the wind’s acceleration region.
- In June 1996, the first measurements of heavy ion (e.g., O^{+5}) line emission in the extended corona revealed **surprisingly wide** line profiles . . .



On-disk profiles: T = 1–3 million K

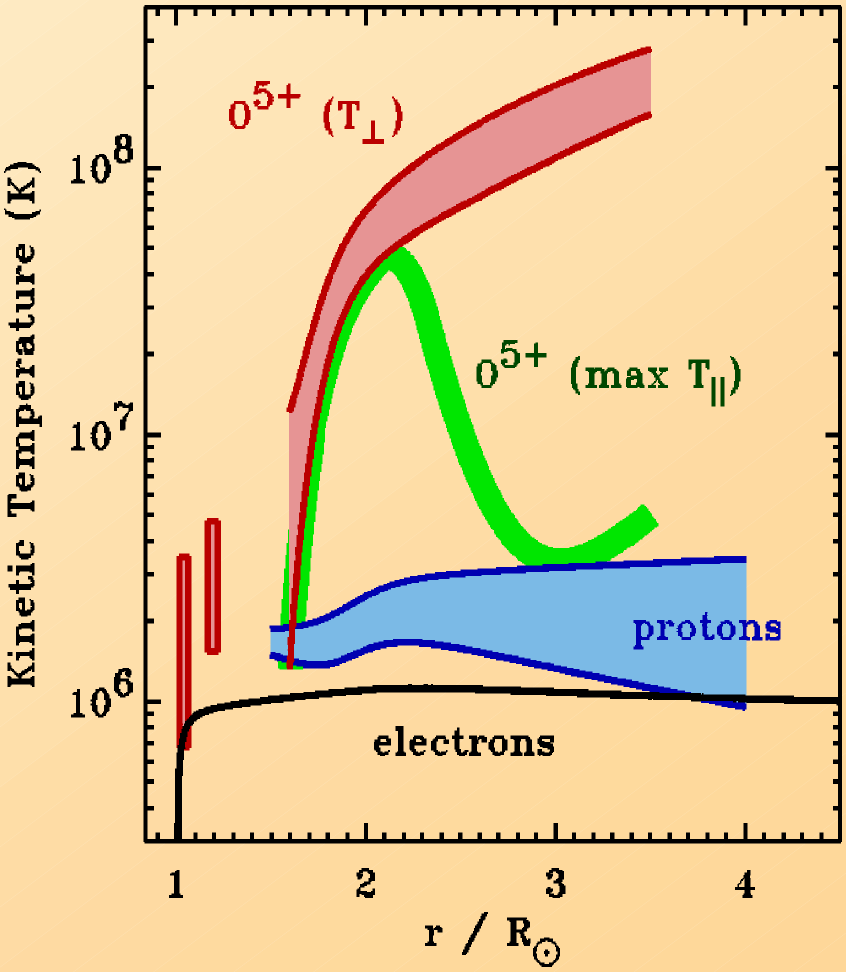
Off-limb profiles: **T > 200 million K !**

Solar Wind: The Impact of UVCS

UVCS/SOHO has led to new views of the acceleration regions of the solar wind. Key results include:

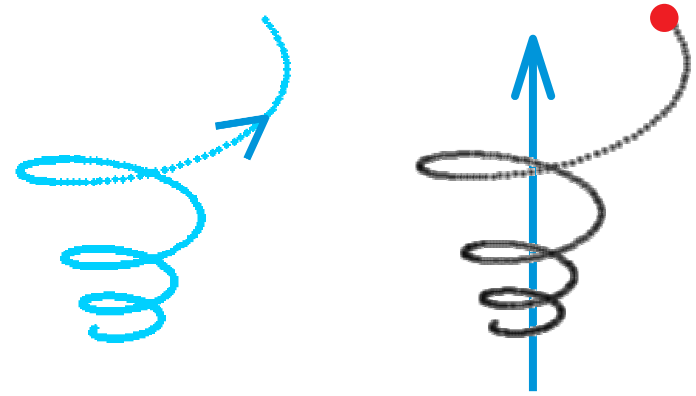
- The fast solar wind becomes **supersonic** much closer to the Sun (~2 R_s) than previously believed.
- In coronal holes, heavy ions (e.g., O^{+5}) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**.

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



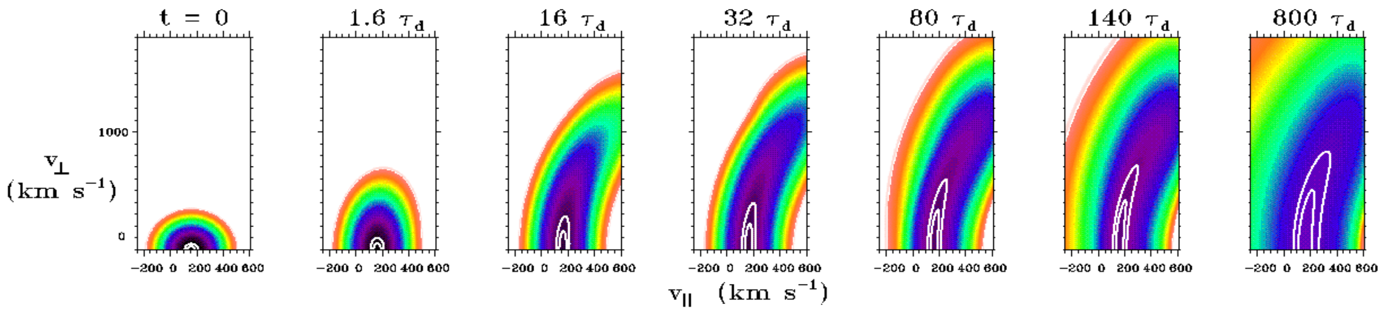
Ion cyclotron waves in the corona?

- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.
  - Ion cyclotron waves (10 to 10,000 Hz) suggested as a natural energy source that can be tapped to preferentially heat & accelerate heavy ions.
  - Dissipation of these waves produces **diffusion** in velocity space along contours of ~constant energy in the frame moving with wave phase speed:



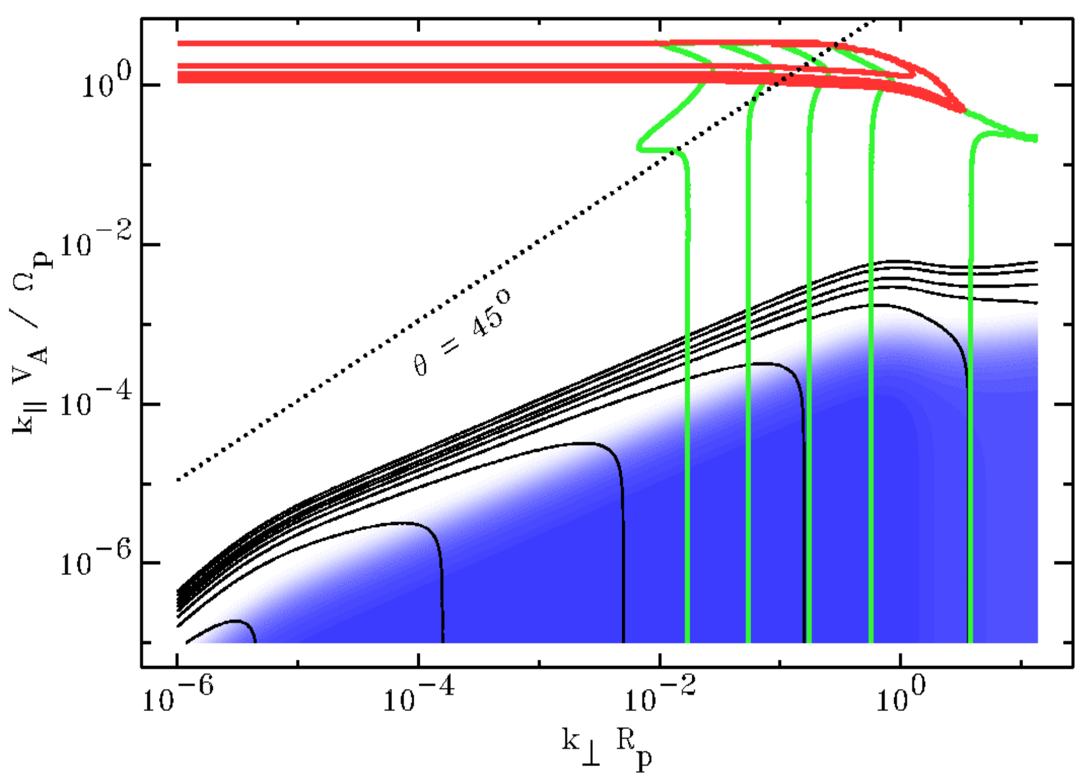
Alfven wave's oscillating E and B fields

ion's Larmor motion around radial B-field



Anisotropic MHD cascade

- Can MHD turbulence generate ion cyclotron waves? Many models say no!
- Simulations & analytic models predict cascade from small to large $k_\perp$,leaving $k_\parallel$ ~unchanged. **"Kinetic Alfven waves"** with large $k_\perp$ do not necessarily have high frequencies.
- In a low-beta plasma, KAWs are Landau-damped, heating **electrons** preferentially!



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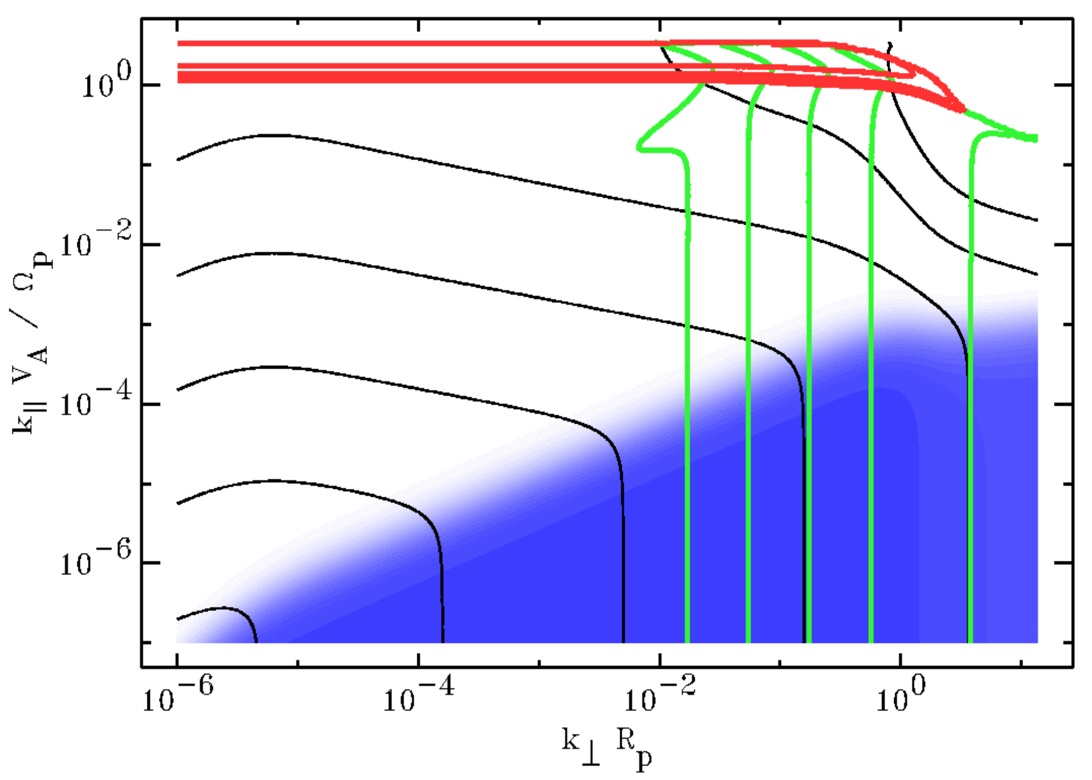
- In a low-beta plasma, KAWs are Landau-damped, heating **electrons** preferentially!
- Cranmer & van Ballegooijen (2003) modeled the anisotropic cascade with advection & diffusion in k-space and found ***some*** $k_\parallel$ “leakage” . . .



How are ions heated preferentially?

Variations on "Ion cyclotron resonance:"

- Additional unanticipated **frequency cascades** (e.g., Gomberoff et al. 2004)
- Fermi-like **random walks** in velocity space when inward/outward waves coexist (heavy ions: Isenberg 2001; protons: Gary & Saito 2003)
- Impulsive plasma **micro-instabilities** that locally generate high-freq. waves (Markovskii 2004)
- **Non-linear/non-adiabatic** KAW-particle effects (Voitenko & Goossens 2004)
- Larmor "spinup" in dissipation-scale **current sheets** (Dmitruk et al. 2004)

Other ideas:

- KAW damping leads to electron beams, further (Langmuir) turbulence, and Debye-scale **electron phase space holes**, which heat ions perpendicularly via "collisions" (Ergun et al. 1999; Cranmer & van Ballegooijen 2003)
- Collisionless **velocity filtration** of suprathermal tails (Pierrard et al. 2004)

Conclusions

- Our understanding of the dominant physics in the acceleration region of the solar wind is growing rapidly . . . But so is the complexity!
- **Preliminary**: It does seem possible to heat & accelerate the high-speed wind via mainly incompressible Alfvenic turbulence.
- We still don’t know several key plasma parameters (e.g., T_e and T_p) with sufficient accuracy, as a function of r, θ, and solar cycle.
- Upcoming missions (SDO, STEREO, Solar-B) will help build a more complete picture, but we really need **next-generation UVCS and LASCO,** as well as **Solar Probe!**
- Lines of communication between {solar/stellar/plasma/astro} physicists must be kept open.

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