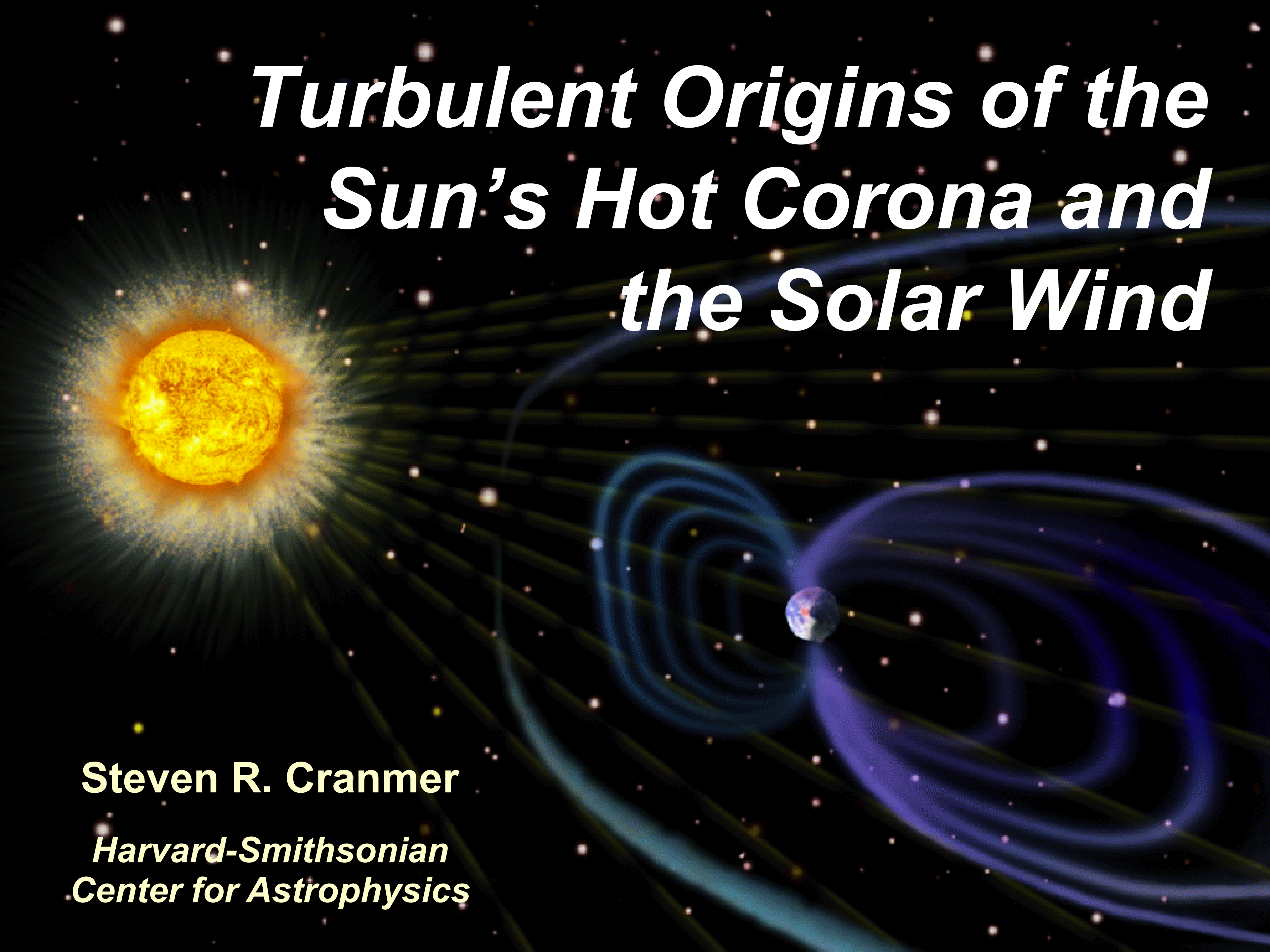

Turbulent Origins of the Sun's Hot Corona and the Solar Wind

Steven R. Cranmer

Harvard-Smithsonian Center for Astrophysics

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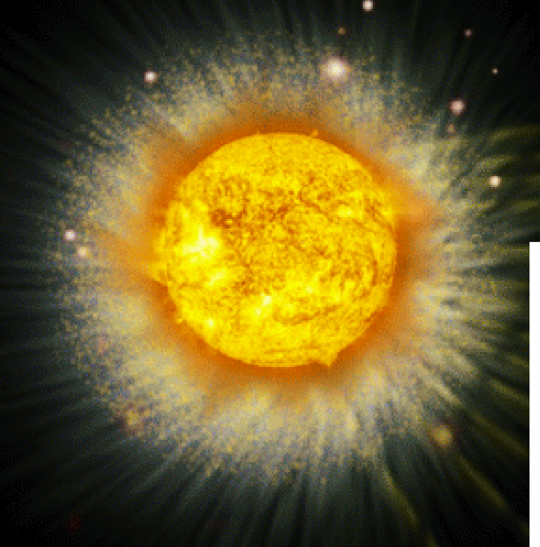

Outline:

1. Solar overview: Our complex "variable star"
2. How do we *measure* waves & turbulence?
3. Coronal heating & solar wind acceleration

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The Sun's overall structure

Core:

- Nuclear reactions fuse hydrogen atoms into helium.

Radiation Zone:

- Photons bounce around in the dense plasma, taking millions of years to escape the Sun.

Convection Zone:

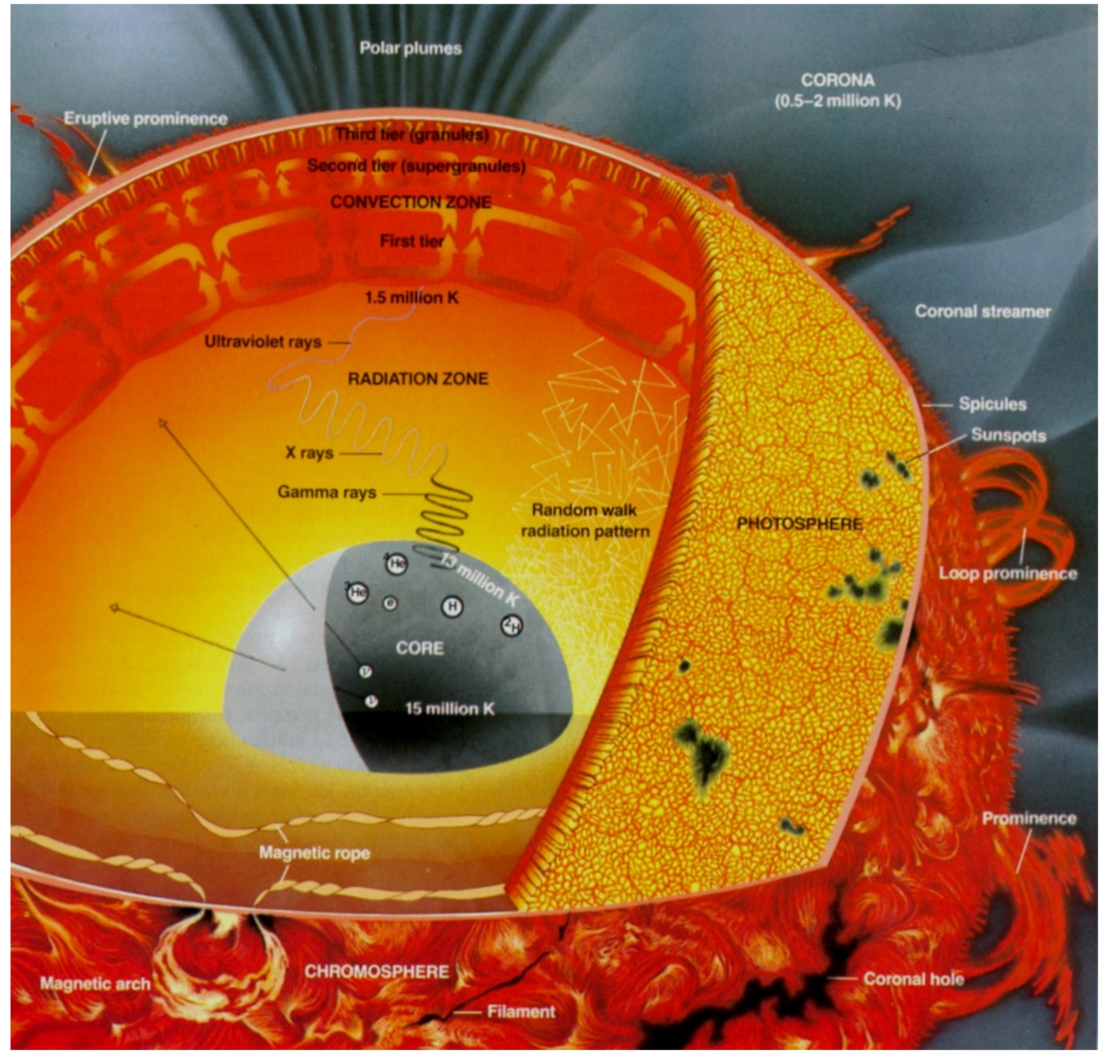
- Energy is transported by boiling, convective motions.

Photosphere:

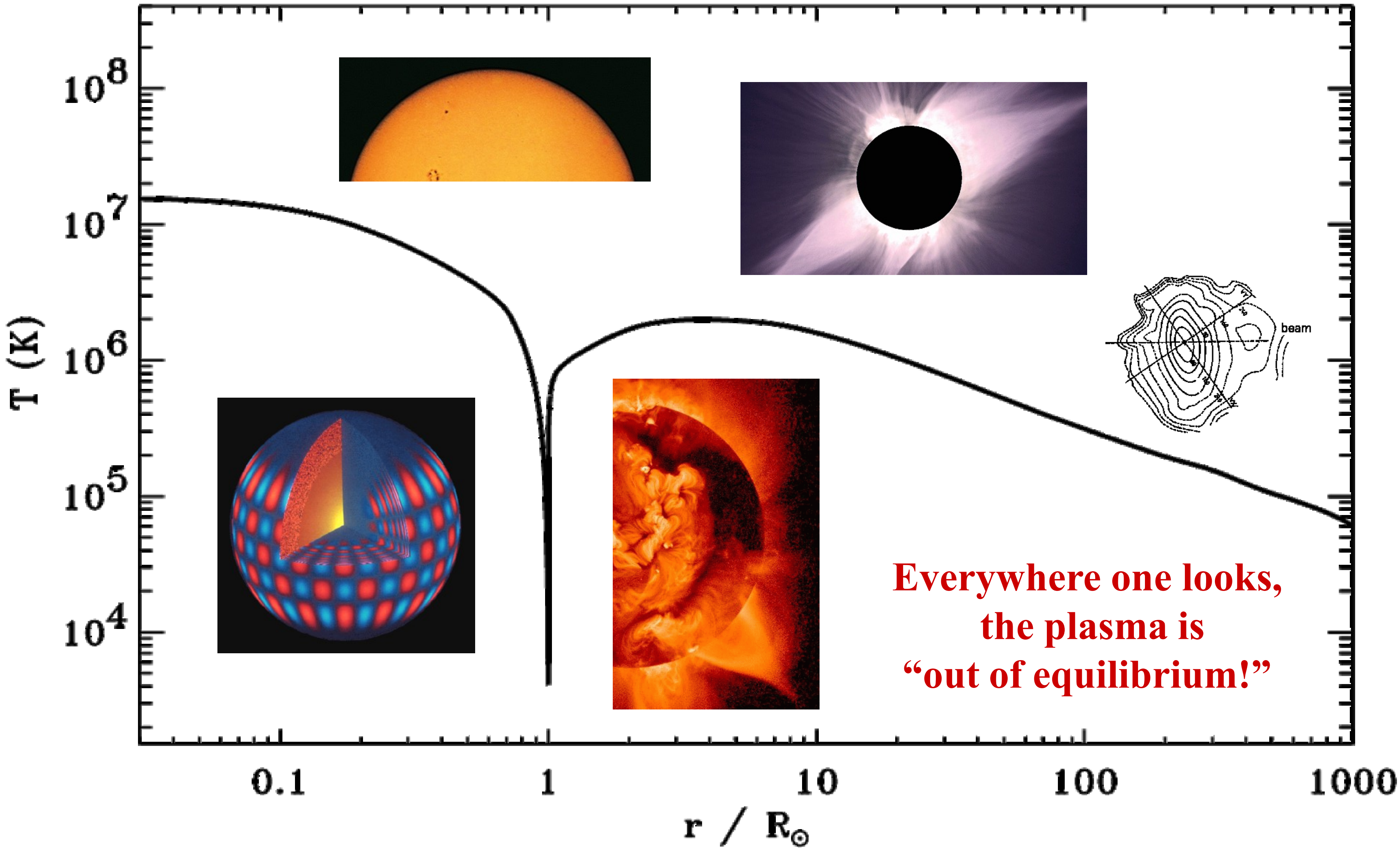
- Photons stop bouncing, and start escaping freely.

Corona:

- Outer atmosphere where gas is heated from ~5800 K to several **million** degrees!

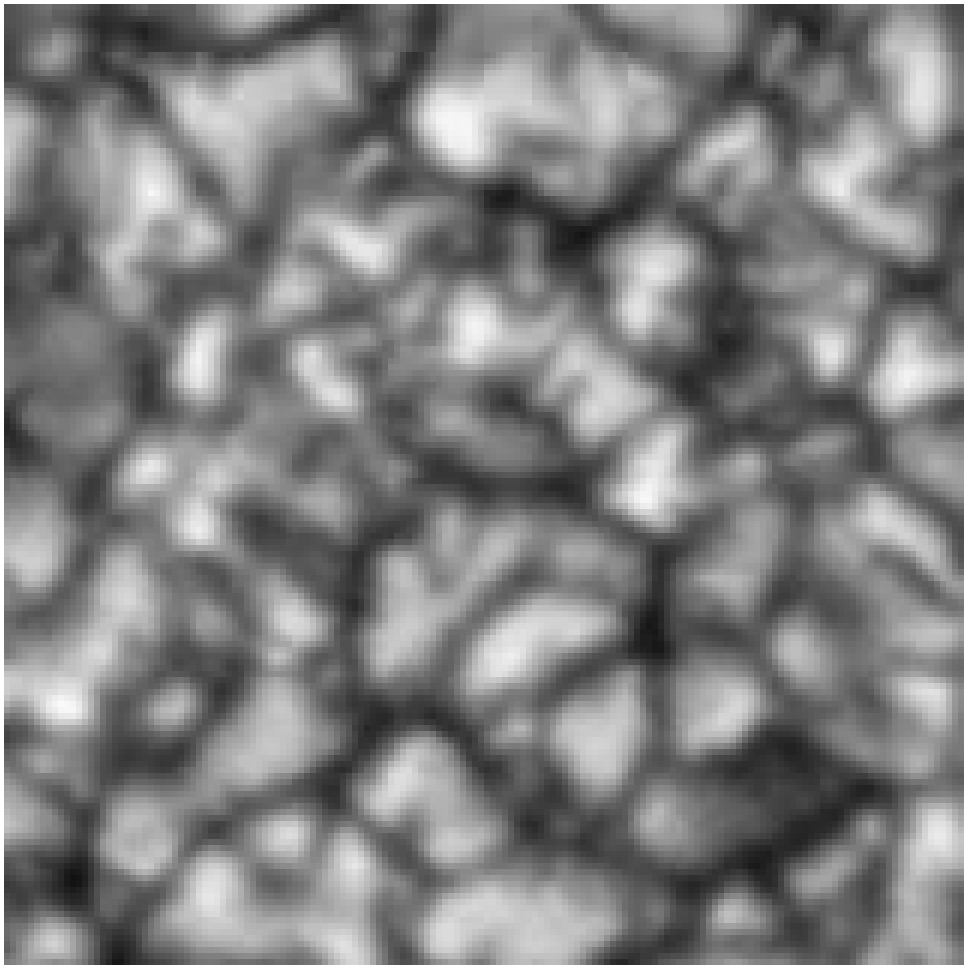


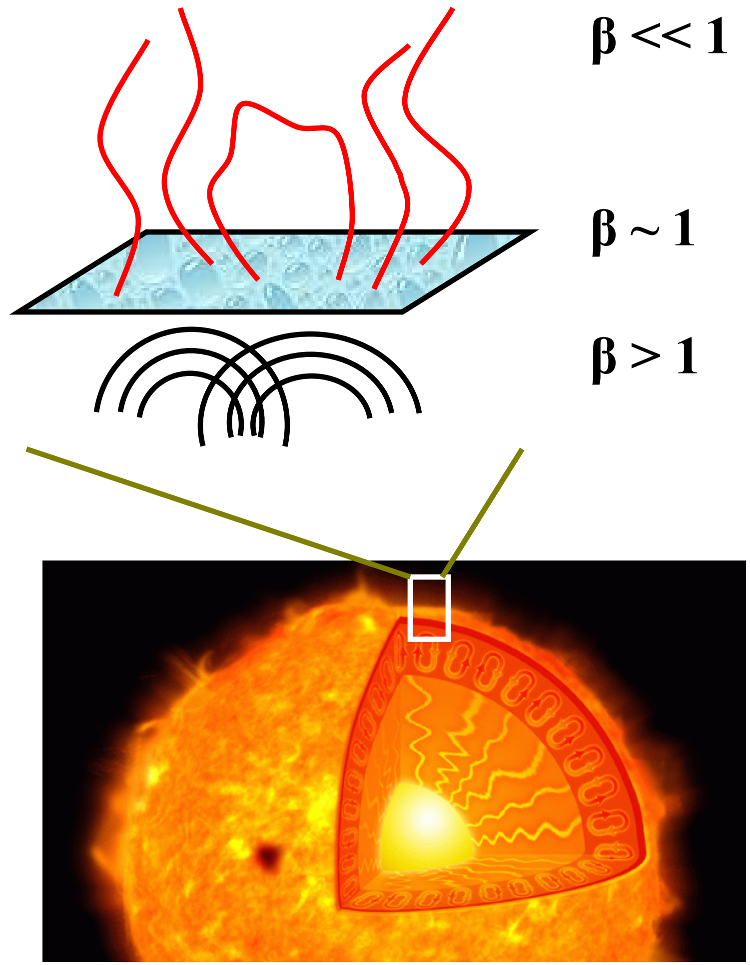
The extended solar atmosphere



The solar photosphere

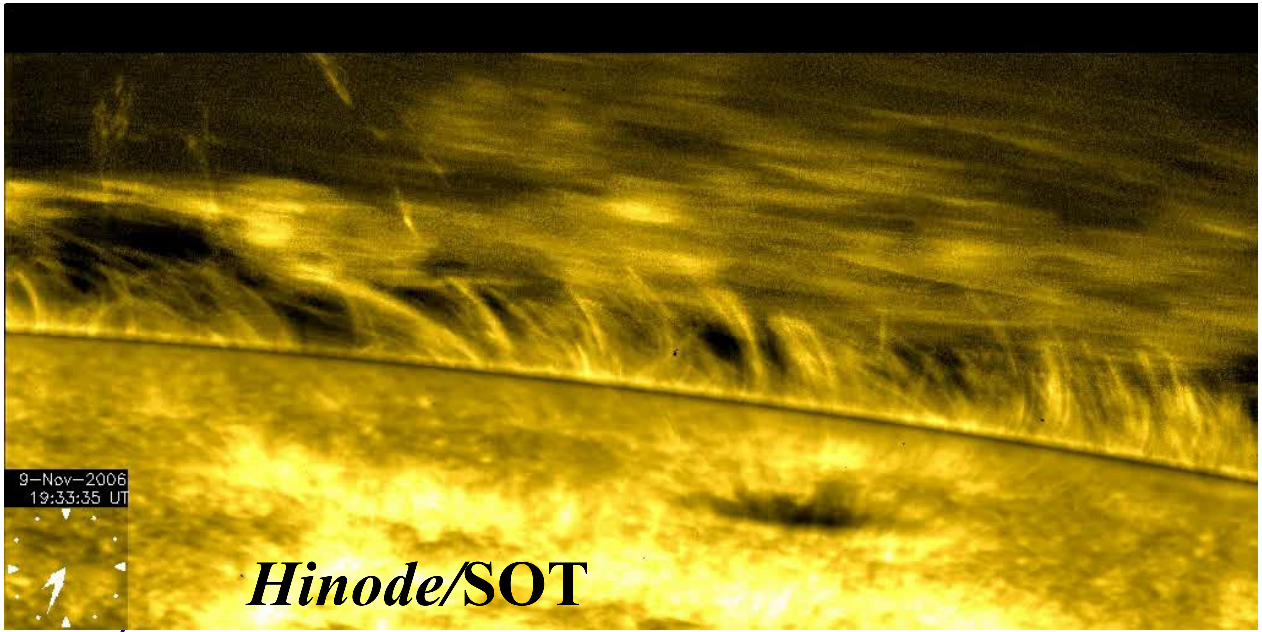
- In visible light, we see top of the convective zone (wide range of time/space scales):

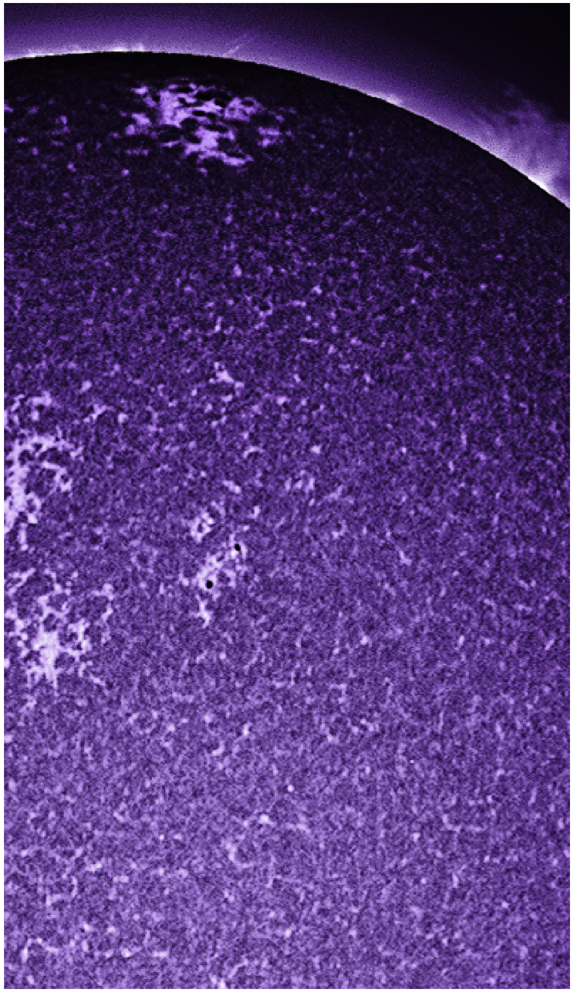




The solar chromosphere

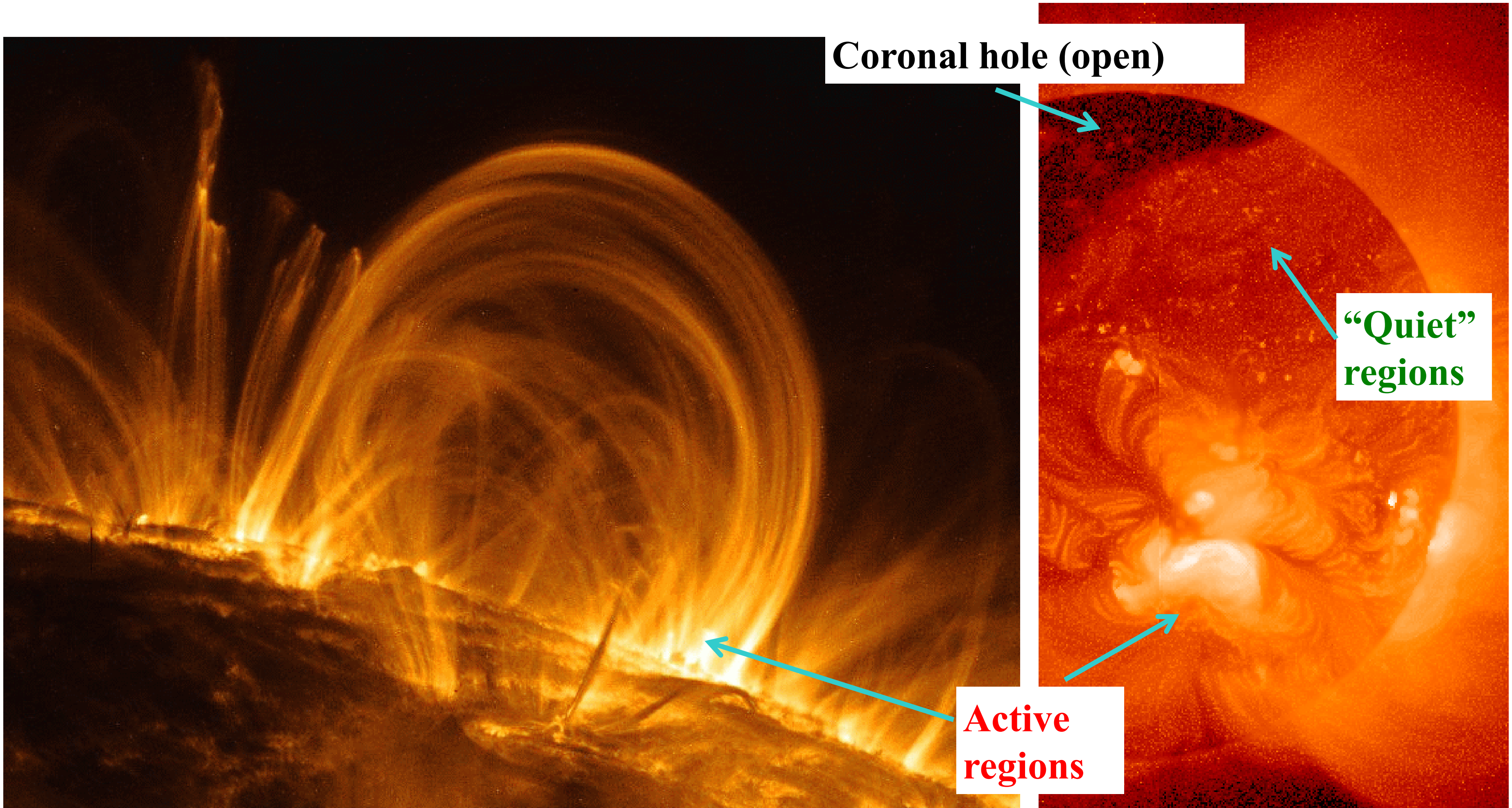
- After T drops to ~4000 K, it rises again to ~20 000 K over 0.002 R_{sun} of height.
- Observations of this region show shocks, thin "spicules," and an apparently larger-scale set of convective cells ("super-granulation").
- Most… but not all… material ejected in spicules appears to fall back down.





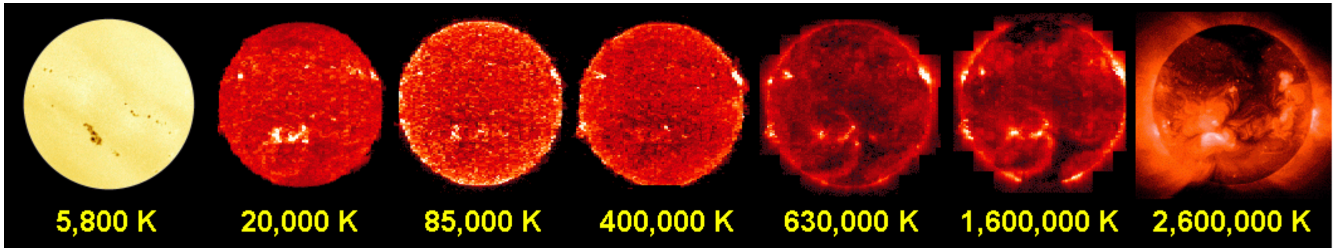
The solar corona

• Plasma at 10^6 K emits most of its spectrum in the UV and X-ray . . .



The coronal heating problem

- We still do not understand the physical processes responsible for heating up the coronal plasma. A lot of the heating occurs in a narrow "shell."

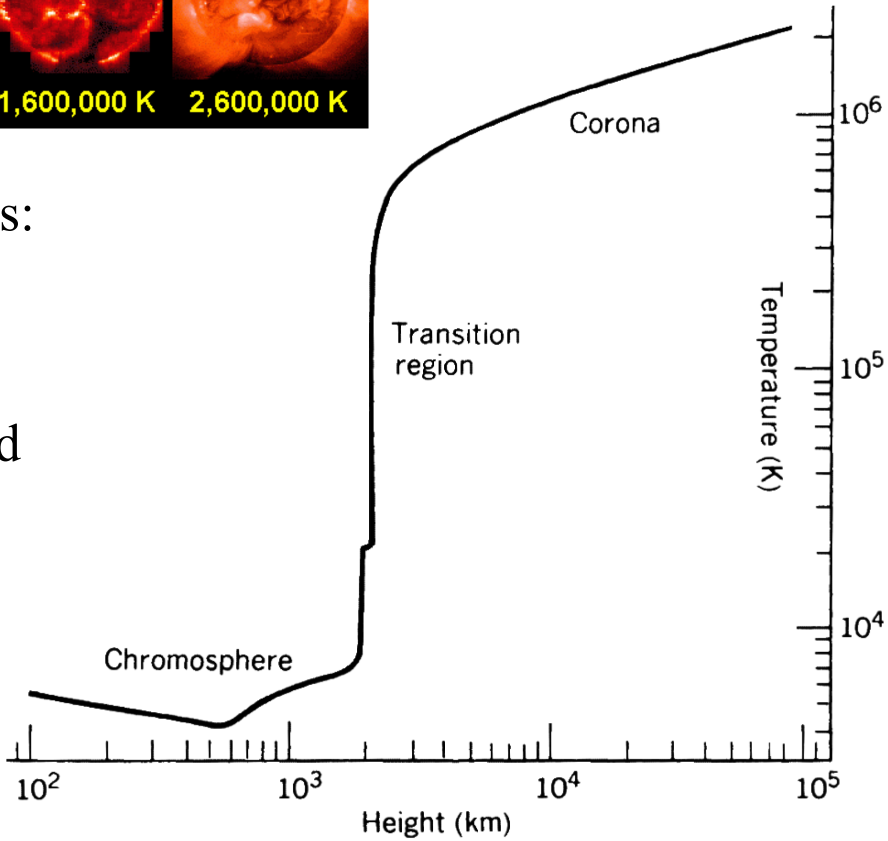


- Most suggested ideas involve 3 general steps:

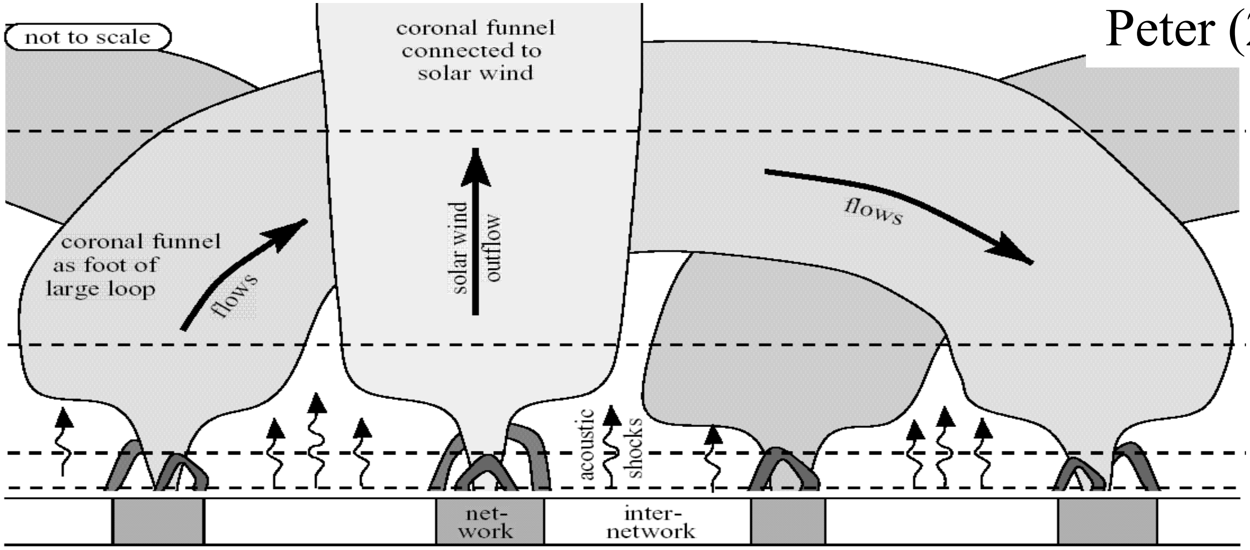
  1. Churning convective motions that tangle up magnetic fields on the surface.
  2. Energy is stored in tiny twisted & braided "magnetic flux tubes."
  3. *Something* releases this energy as heat.

     ➡ Particle-particle collisions?

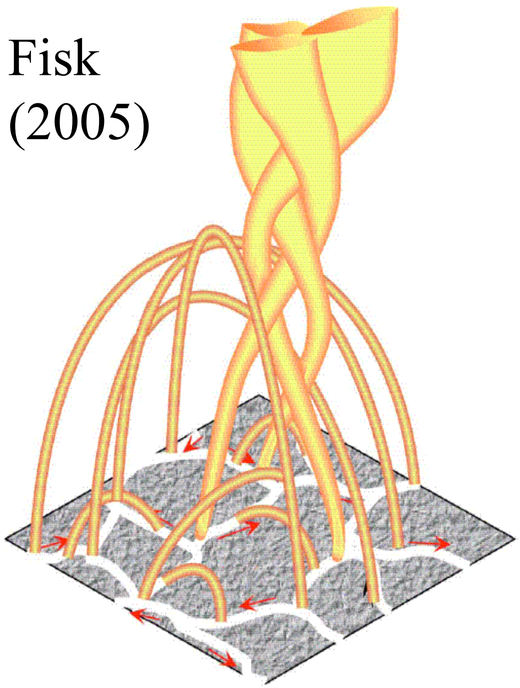
     ➡ Wave-particle interactions?



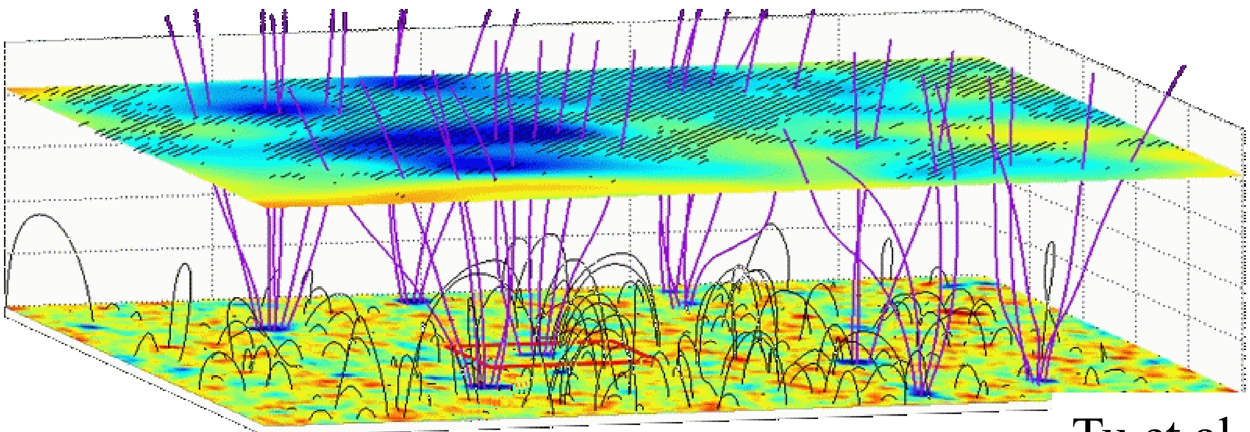
A small fraction of magnetic flux is OPEN



Peter (2001)



Fisk (2005)

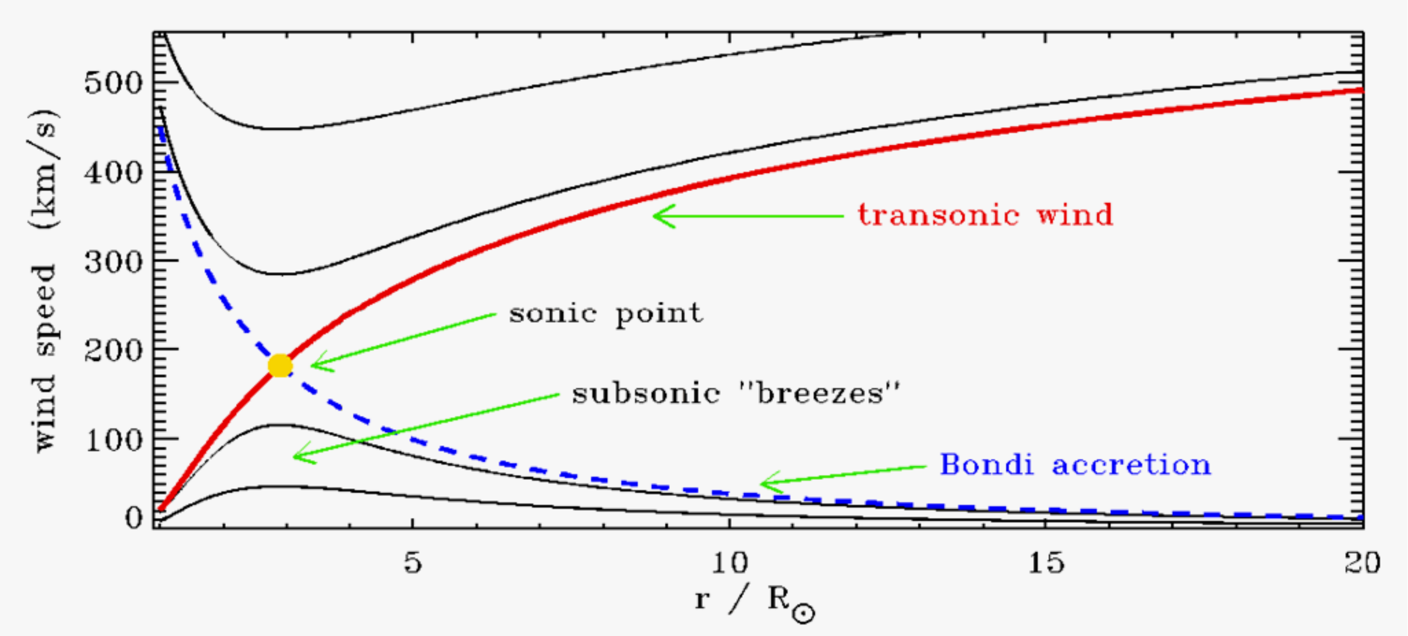


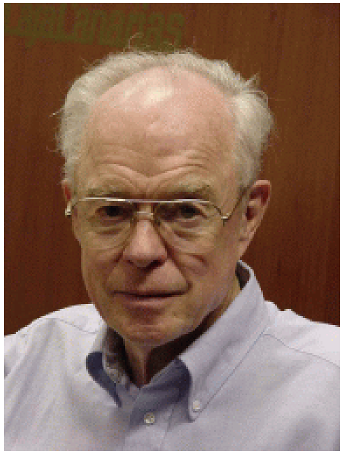
Tu et al. (2005)

The solar wind: discovery

- 1860–1950: Evidence slowly builds for **outflowing magnetized plasma** in the solar system:
  - solar flares → aurora, telegraph snafus, geomagnetic "storms"
  - comet ion tails point anti-sunward (no matter comet's motion)
- 1958: Eugene Parker proposed that the **hot corona** provides enough gas pressure to counteract gravity and accelerate a "solar wind."

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} = \frac{\nabla P}{\rho} - \mathbf{g} + \mathbf{a}_{\rm other}$$

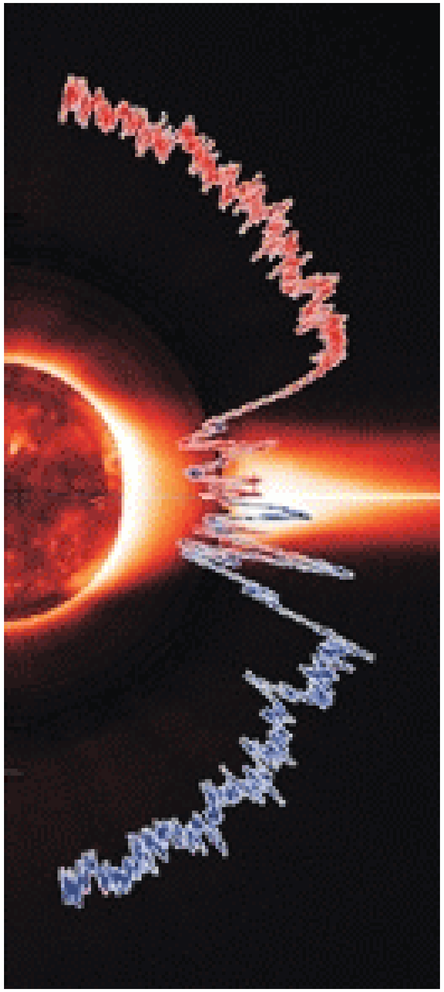




In situ solar wind: properties

- *Mariner 2* (1962): first direct confirmation of continuous **fast** & **slow** solar wind.
- Uncertainties about which type is "ambient" persisted because measurements were limited to the ecliptic plane …
- 1990s: *Ulysses* left the ecliptic; provided first 3D view of the wind's source regions.
- 1970s: *Helios* (0.3–1 AU). 2007: *Voyagers* @ term. shock!

	fast	**slow**
speed (km/s)	**600–800**	**300–500**
density	**low**	**high**
variability	**smooth + waves**	**chaotic**
temperatures	$T_{ion} >> T_p > T_e$	**all ~equal**
abundances	**photospheric**	**more low-FIP**



Outline:

1. Solar overview: Our complex "variable star"
2. **How do we *measure* solar waves & turbulence?**
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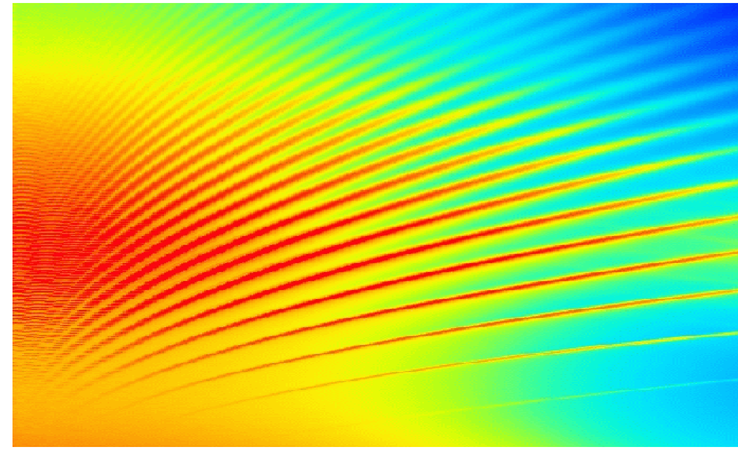
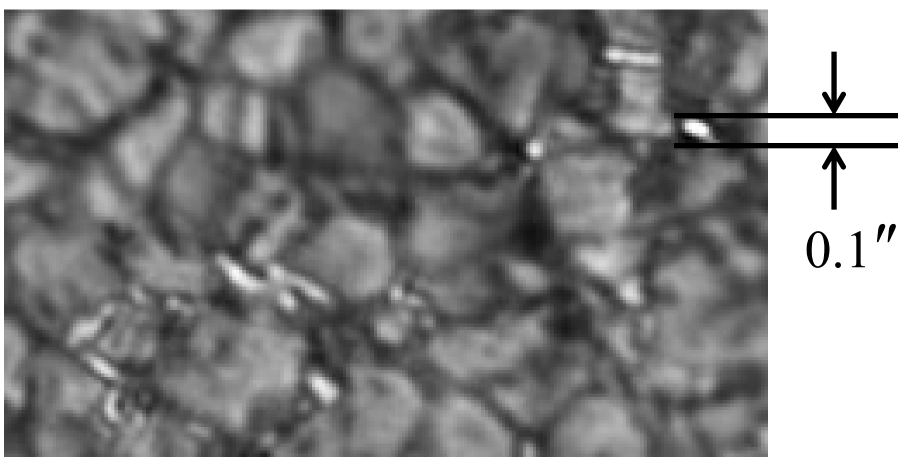
Waves & turbulence in the photosphere

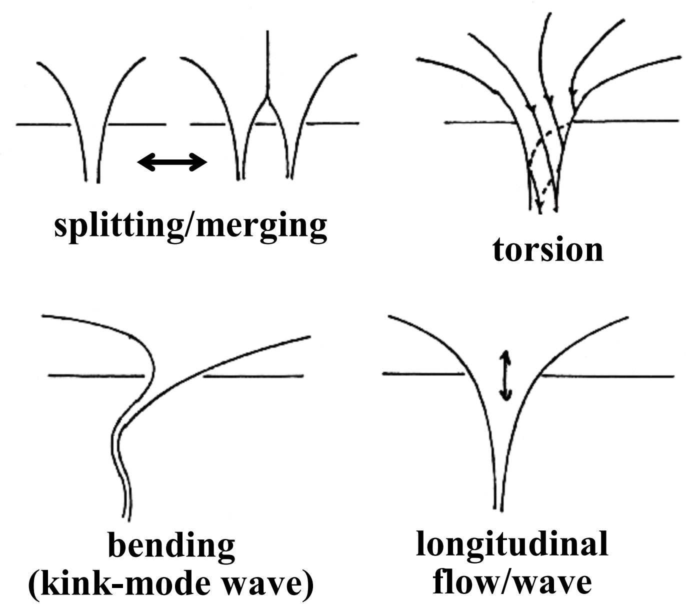
- **Helioseismology:** direct probe of wave oscillations below the photosphere (via modulations in intensity & Doppler velocity)
- How much of that wave energy "leaks" up into the corona & solar wind?

  → Still a topic of vigorous debate!



- Measuring **horizontal** motions of magnetic flux tubes is more difficult . . . but may be more important?





Waves in the corona

- Remote sensing provides several direct (and **indirect**) detection techniques:

- Intensity modulations . . .

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

- Motion tracking in images . . .

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

- Doppler shifts . . .

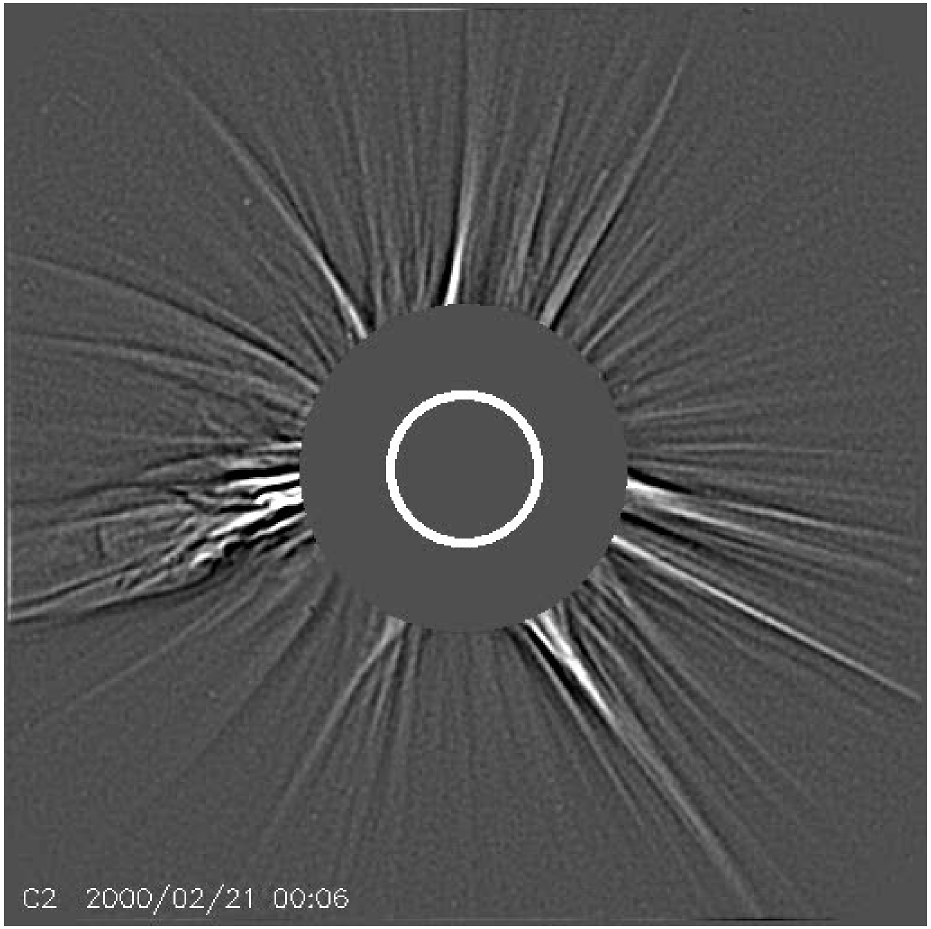
$$\delta\lambda \propto \delta V_{\rm LOS}$$

- Doppler broadening . . .

$$\delta\lambda \rightarrow \langle \delta V_{\rm LOS} \rangle$$

- Radio sounding . . .

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



SOHO/LASCO (Stenborg & Cobelli 2003)

Wavelike motions in the corona

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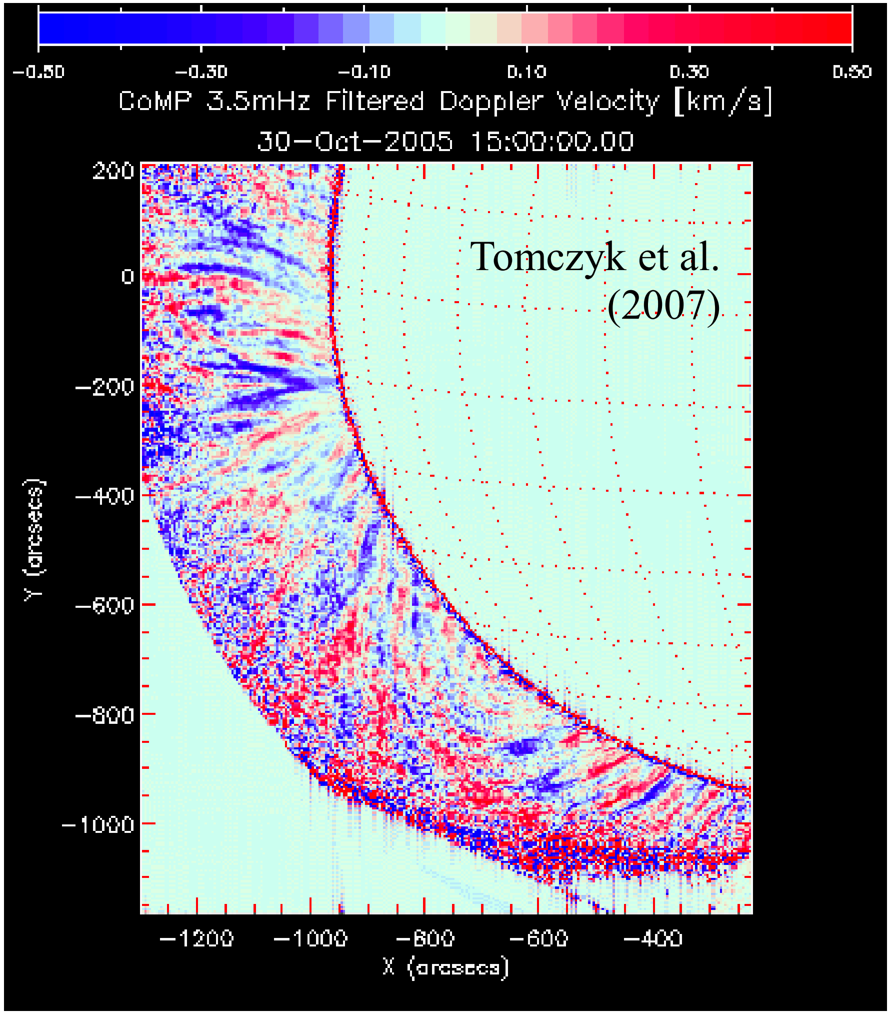

Wavelike motions in the corona

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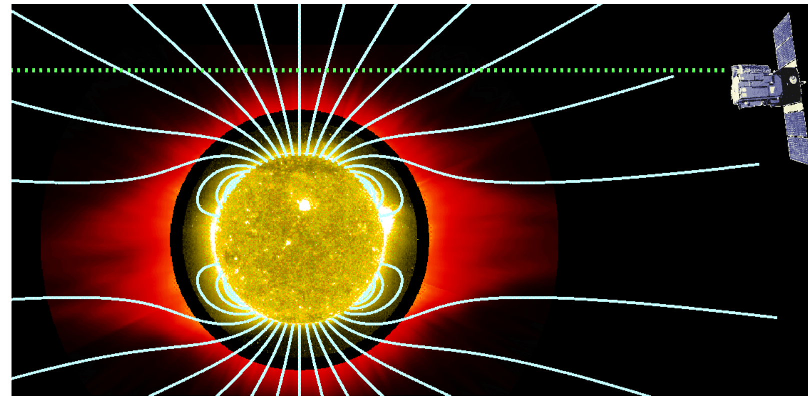
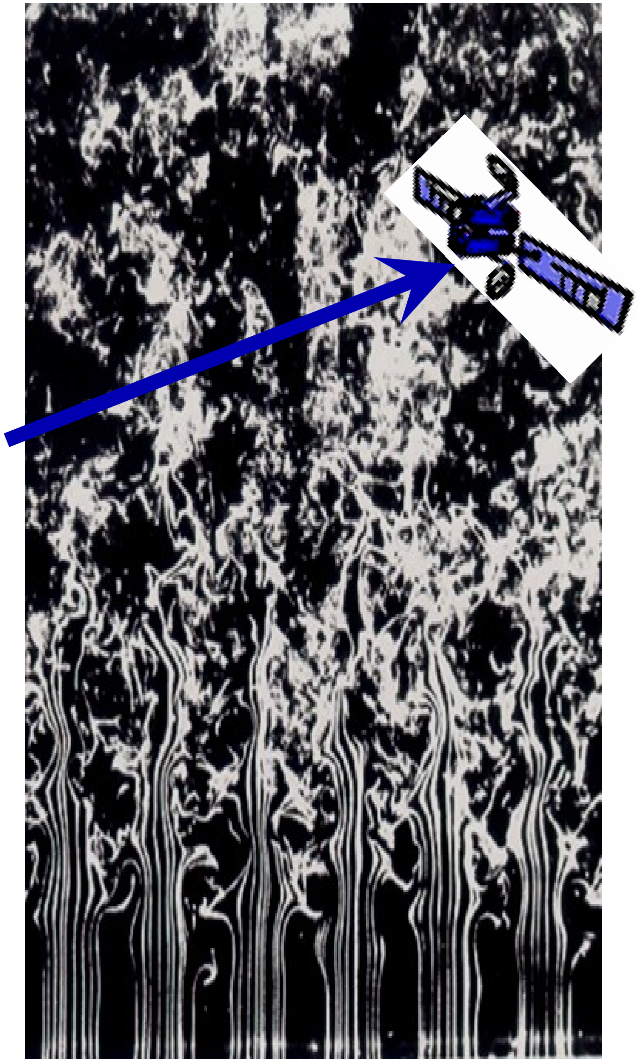


- The Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO has measured plasma properties of protons, ions, and electrons in low-density **collisionless** regions of the corona (1.5 to 10 solar radii).

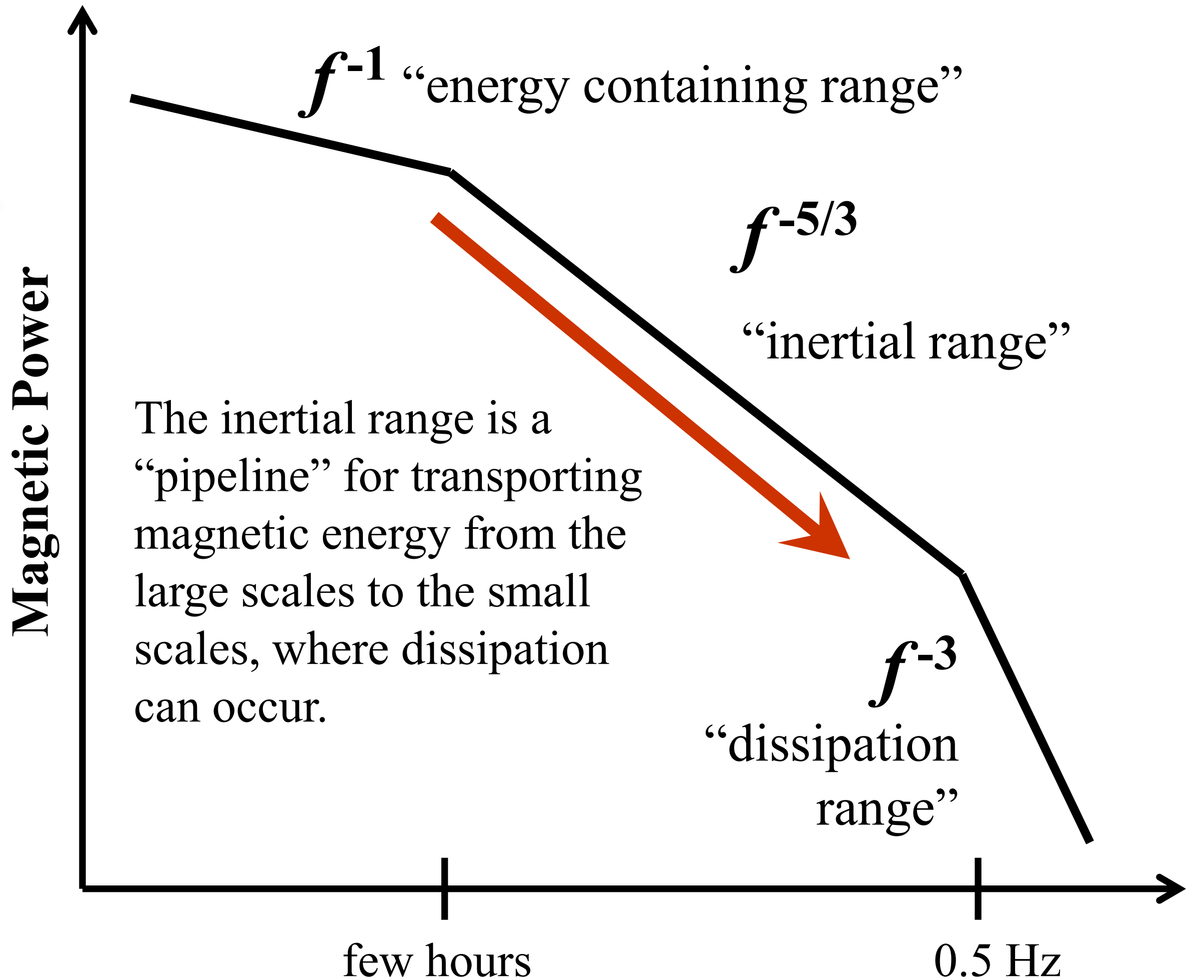
$$\left\{ \begin{array}{ccc} T_{\rm ion} & \gg & T_p > T_e \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ T_{\perp} & \gg & T_{\parallel} \\ u_{\rm ion} & > & u_p \end{array} \right\}$$

- Ion cyclotron waves (10–10,000 Hz) have been suggested as a "natural" energy source that can be tapped to preferentially heat & accelerate the heavy ions, as observed.

In situ fluctuations & turbulence



- Fourier transform of *B(t), v(t),* etc., into frequency:



Outline:

1. Solar overview: Our complex “variable star”
2. How do we *measure* solar waves & turbulence?
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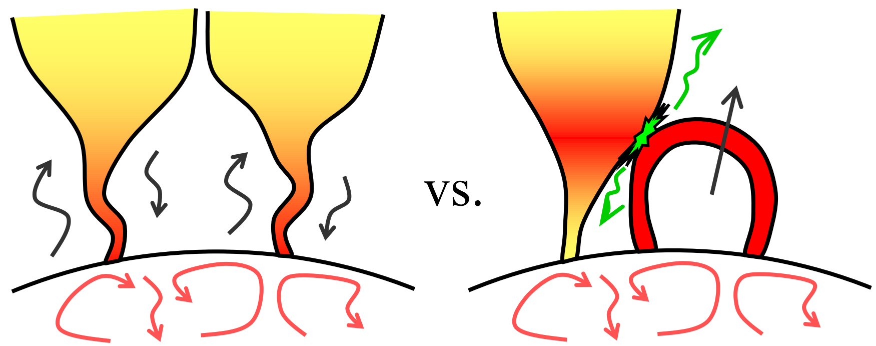
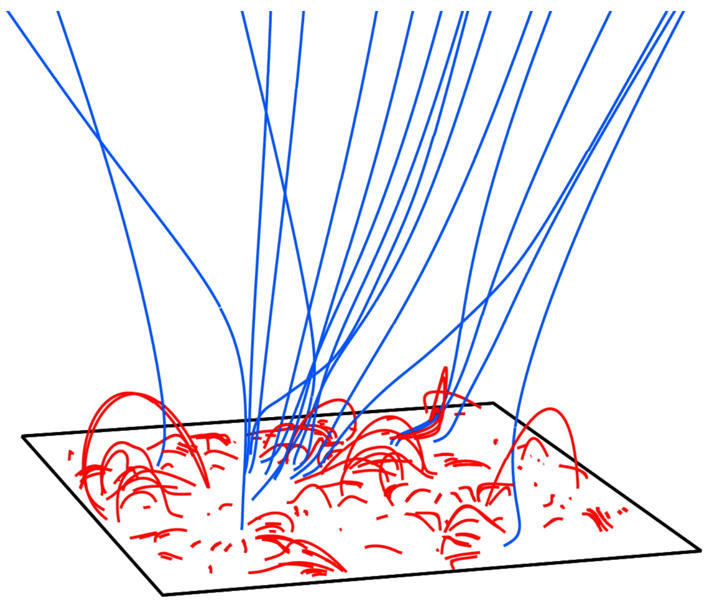
What processes drive solar wind acceleration?

Two broad paradigms have emerged . . .

- Wave/Turbulence-Driven (**WTD**) models, in which flux tubes "stay open"
- Reconnection/Loop-Opening (**RLO**) models, in which mass/energy is injected from closed-field regions.

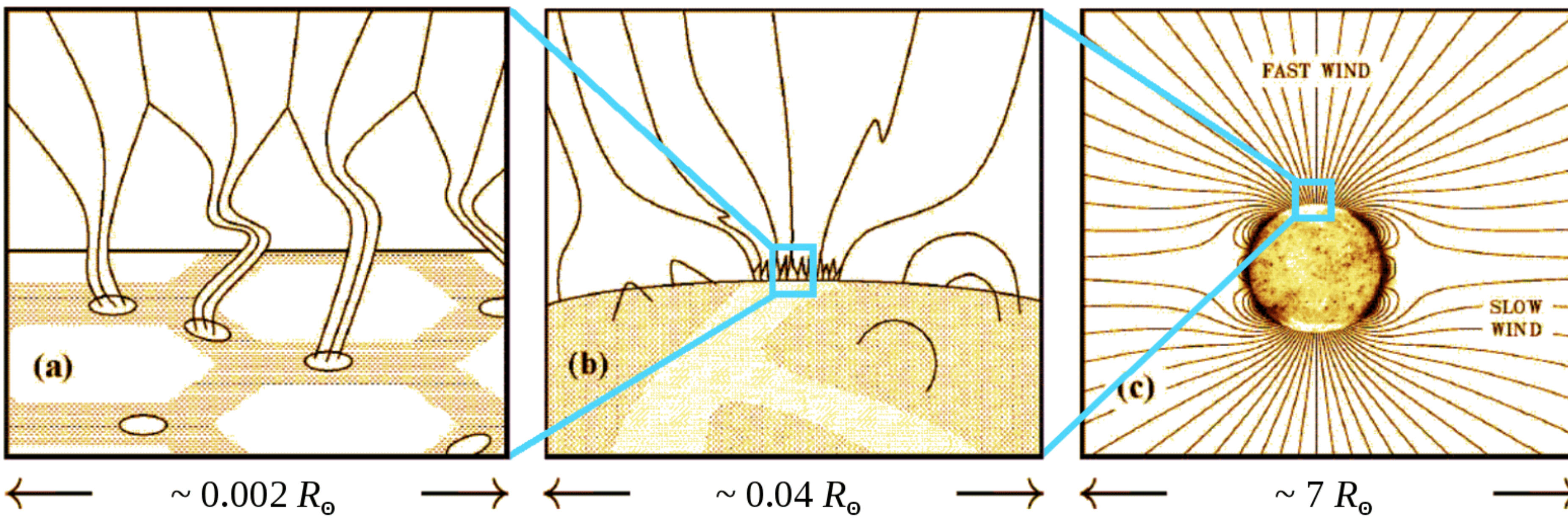




- There's a natural appeal to the RLO idea, since only a small fraction of the Sun's magnetic flux is open. Open flux tubes are always **near closed loops!**
- The "magnetic carpet" is continuously churning.
- Open-field regions show frequent **coronal jets** (SOHO, Hinode/XRT).

Waves & turbulence in open flux tubes

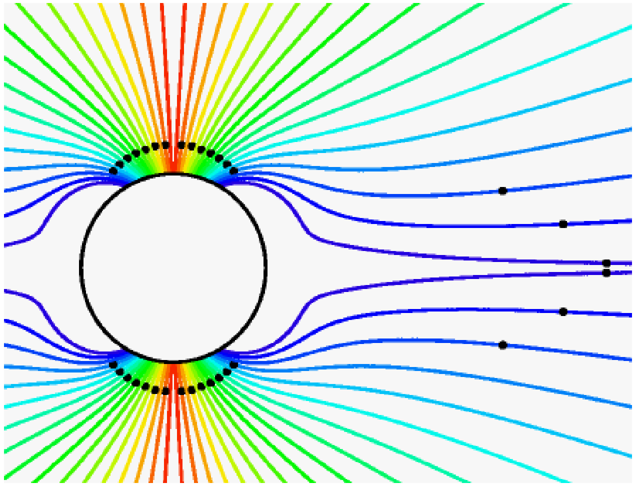
- Photospheric flux tubes are **shaken** by an observed spectrum of horizontal motions.
- Alfvén waves propagate along the field, and partly **reflect** back down (non-WKB).
- Nonlinear couplings allow a (mainly perpendicular) **cascade**, terminated by damping.

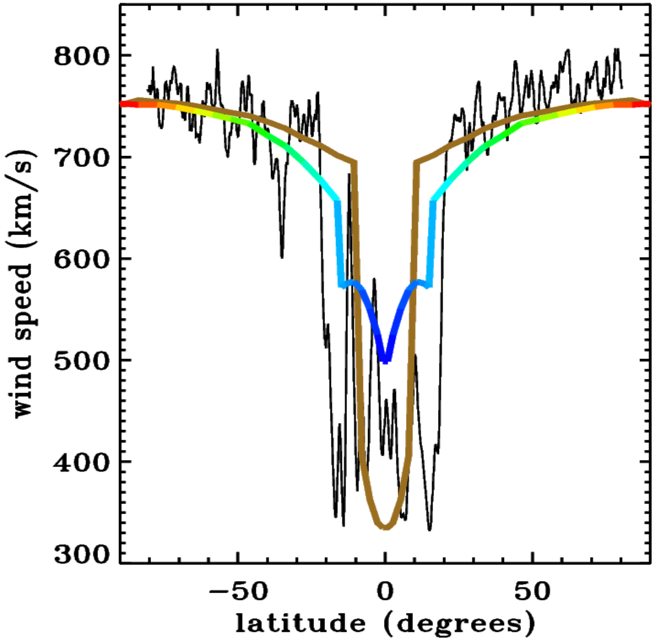


(Heinemann & Olbert 1980; Hollweg 1981, 1986; Velli 1993; Matthaeus et al. 1999; Dmitruk et al. 2001, 2002; Cranmer & van Ballegooijen 2003, 2005; Verdini et al. 2005; Oughton et al. 2006; many others)

Results of wave/turbulence models

- Cranmer et al. (2007) computed self-consistent solutions for waves & background plasma along flux tubes going from the photosphere to the heliosphere.
- **Only free parameters:** radial magnetic field & photospheric wave properties. (No arbitrary "coronal heating functions" were used.)

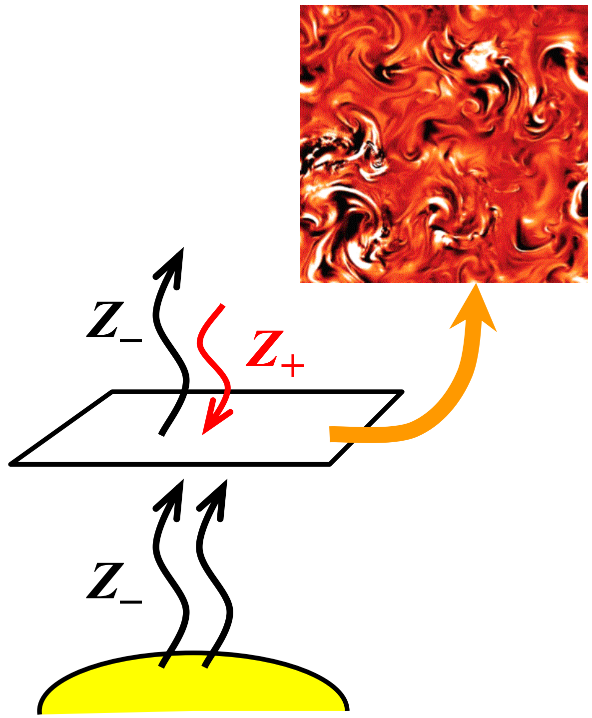




- Self-consistent coronal heating comes from gradual Alfvén wave reflection & turbulent dissipation.
- Is Parker's **"critical point"** above or below where most of the heating occurs?
- Models match most observed trends of plasma parameters vs. wind speed at 1 AU.

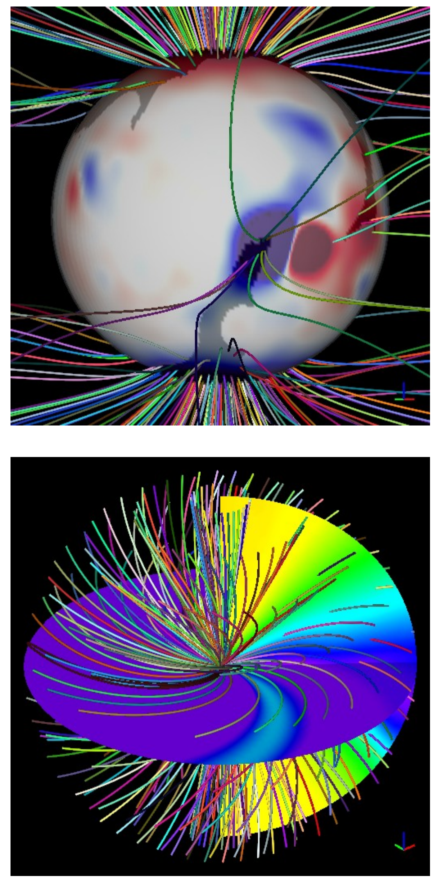
Understanding physics reaps practical benefits

Self-consistent WTD models



$$Q_{\rm heat} = |\nabla \cdot \mathbf{F}_{\rm heat}| = \rho \mathcal{F} \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4 L_\perp}$$

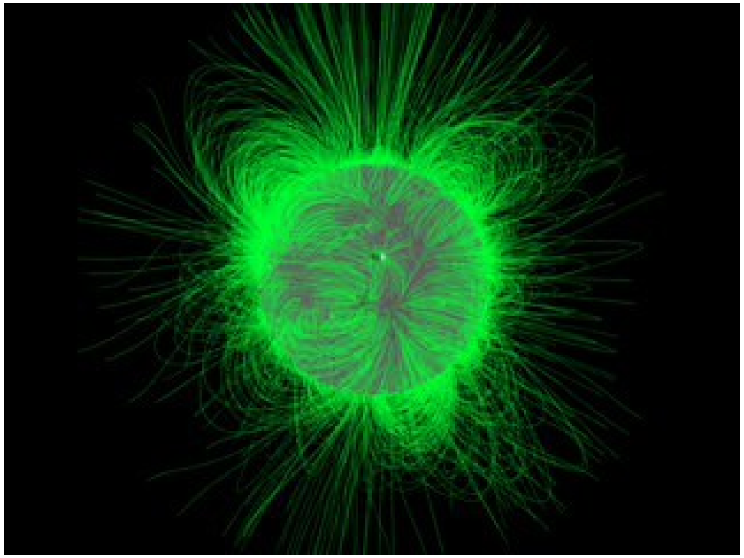
3D global MHD models

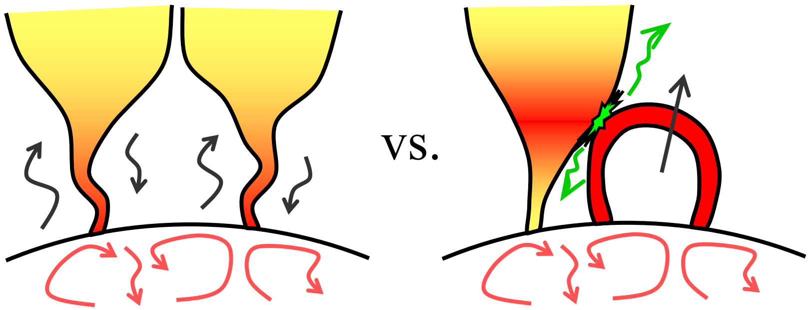


Real-time "space weather" predictions?

Conclusions

- It is becoming easier to include "real physics" in 1D → 2D → 3D models of the complex Sun-heliosphere system.
- Theoretical advances in MHD turbulence continue to help improve our understanding about coronal heating and solar wind acceleration.





- 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/