Leaves in the Wind:

The Variety of Radiative & MHD fluctuations in Rotating Solar/Stellar Outflows

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Outline:

1. The Sun: convection → coronal heating?
2. Cool stars: generalizing the solar case; accretion
3. Massive stars: radiation pressure & pulsations

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Why do we care?

- Stellar winds affect how stars & galaxies evolve… from pre-main-sequence accretion to post-main-sequence "death" & mass recycling.

- Consequently, they affect the formation & habitability of **planets,** too.

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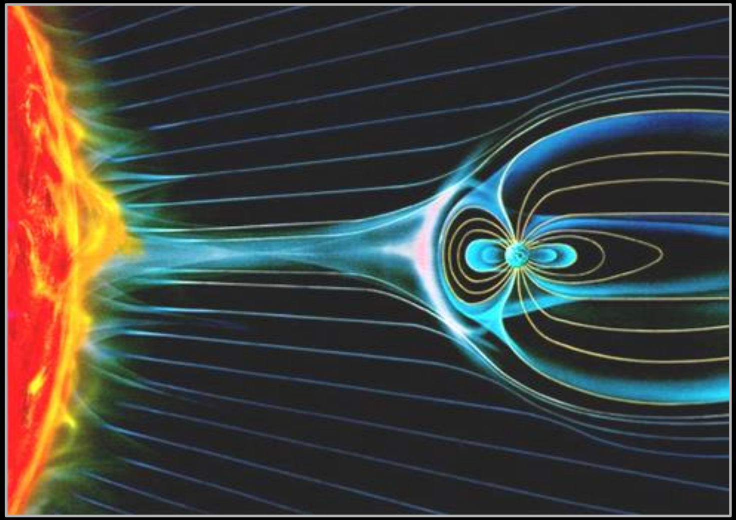
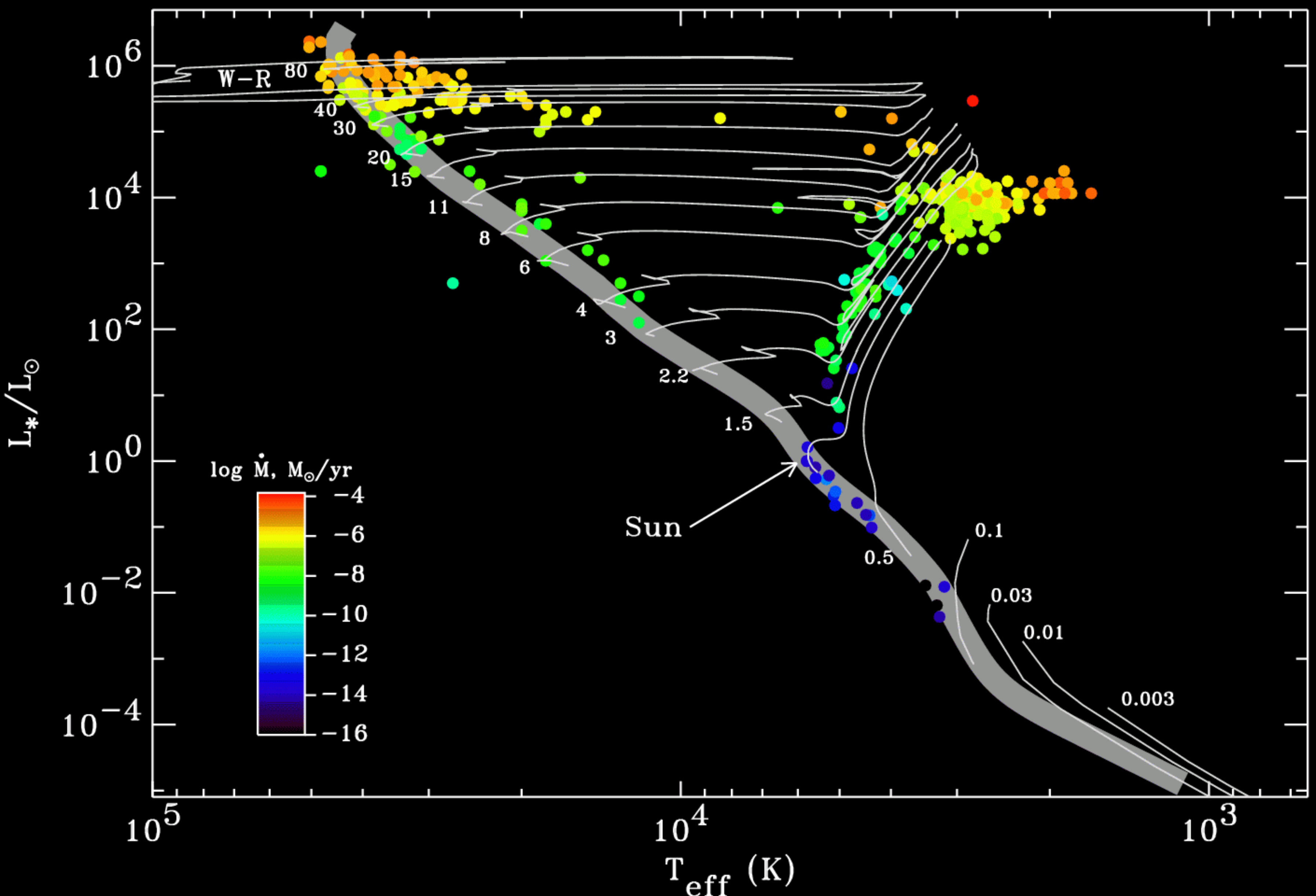
- In our own solar system, “space weather” affects satellites, power grids, pipelines, and safety of astronauts & high-altitude airline crews.

- If you can understand how plasmas behave in turbulent, expanding stellar atmospheres, you’ll have a superb grounding in many fields.



Stellar winds across the H-R Diagram



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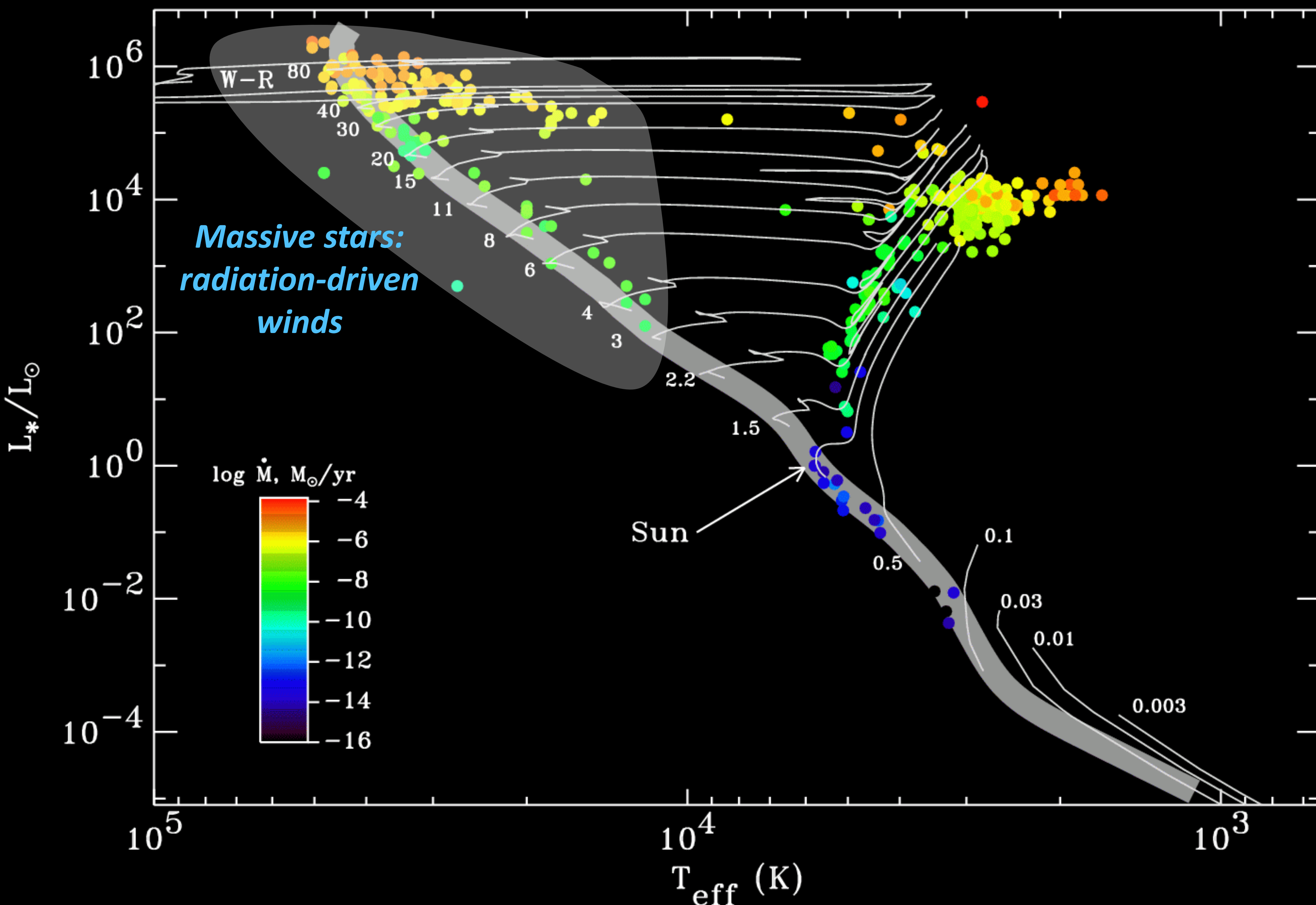

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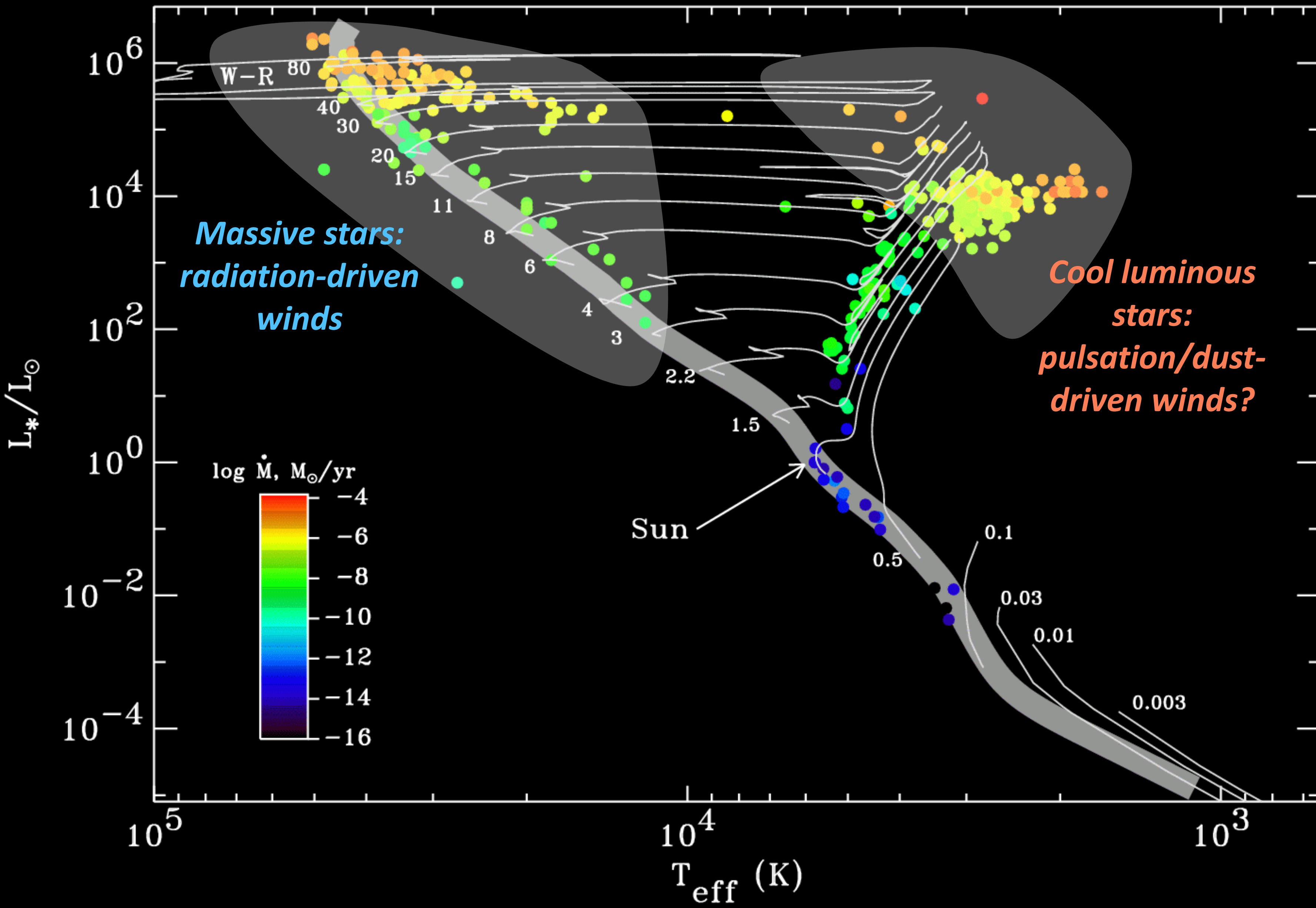

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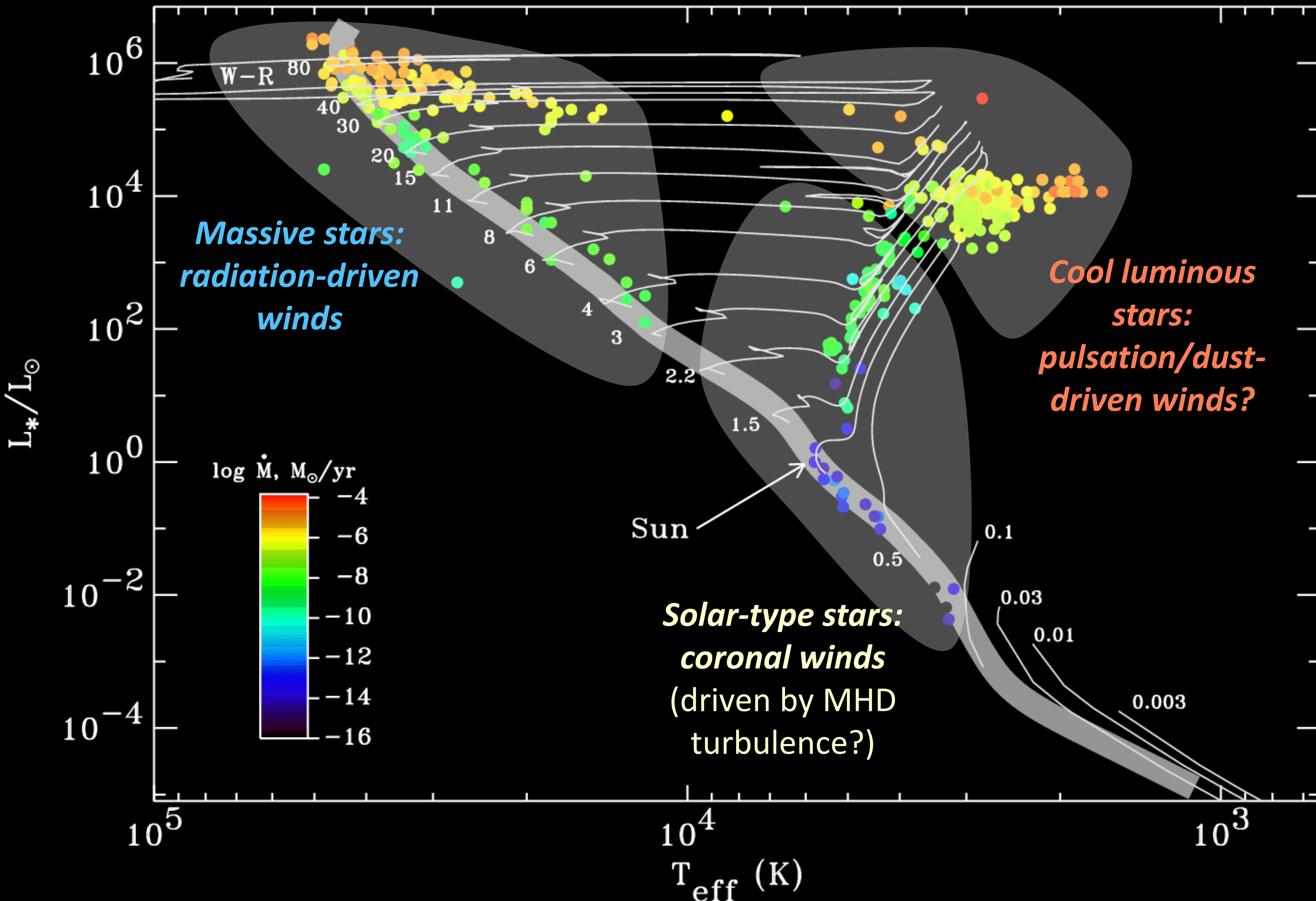

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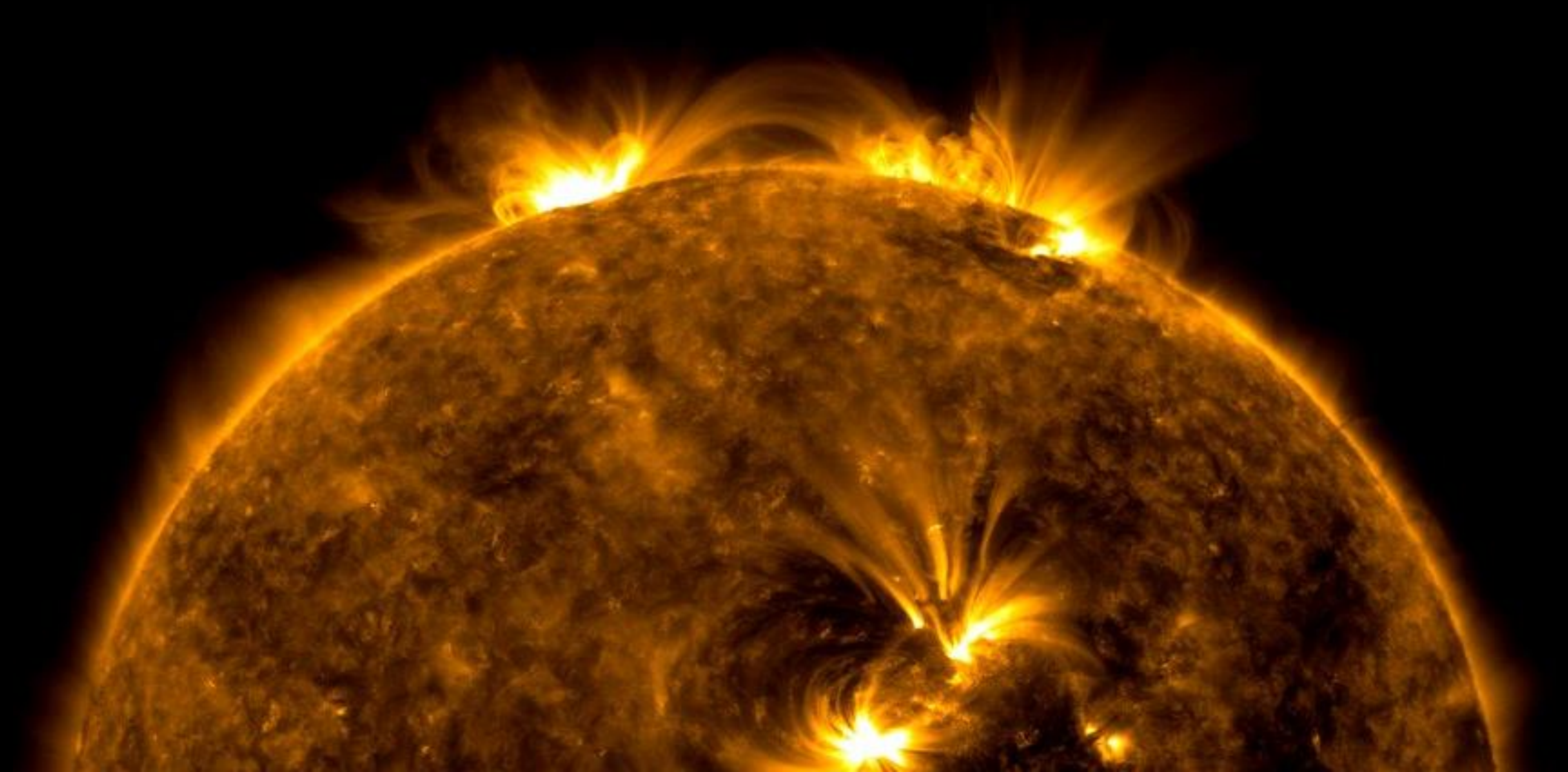
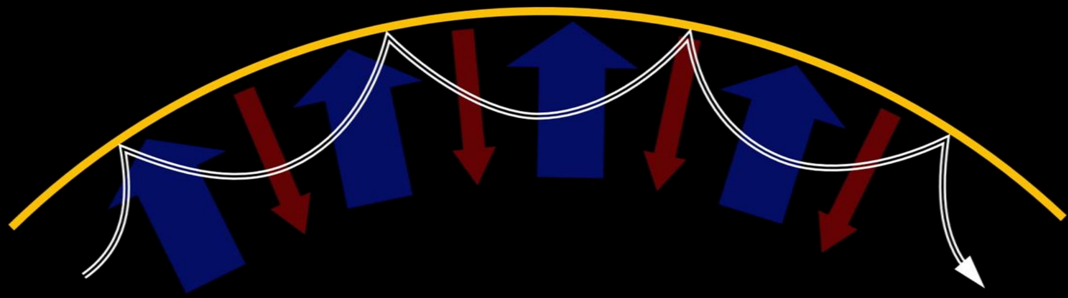
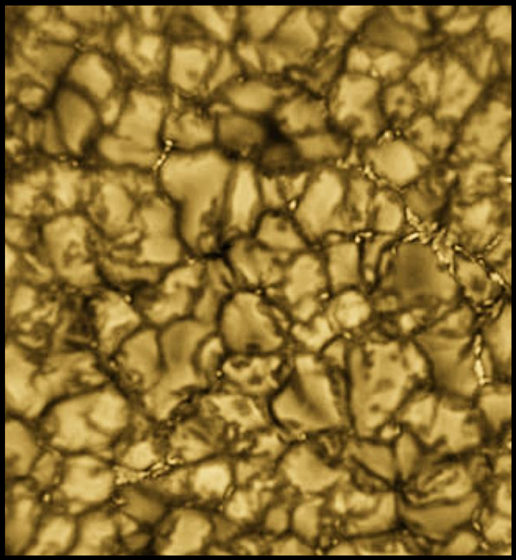


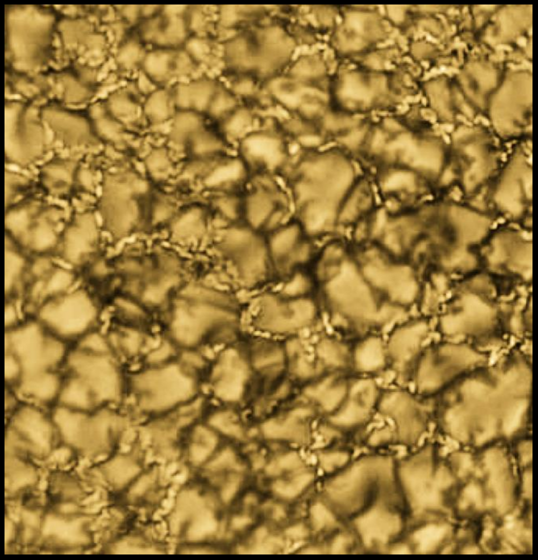
Convection produces granulation

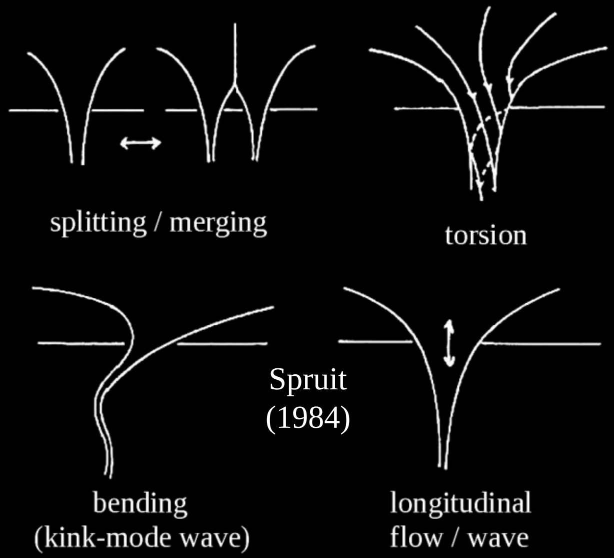
- Unstable convective overturning drives **p-mode** internal pulsation modes: largely evanescent at surface.



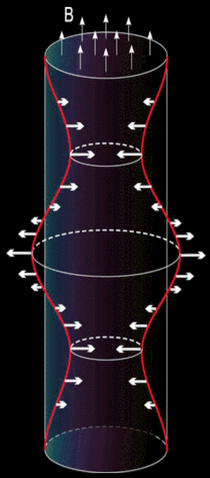
- The uppermost convection cells are visible as “granules,” and strong-field **magnetic flux tubes** are jostled (mostly) horizontally…



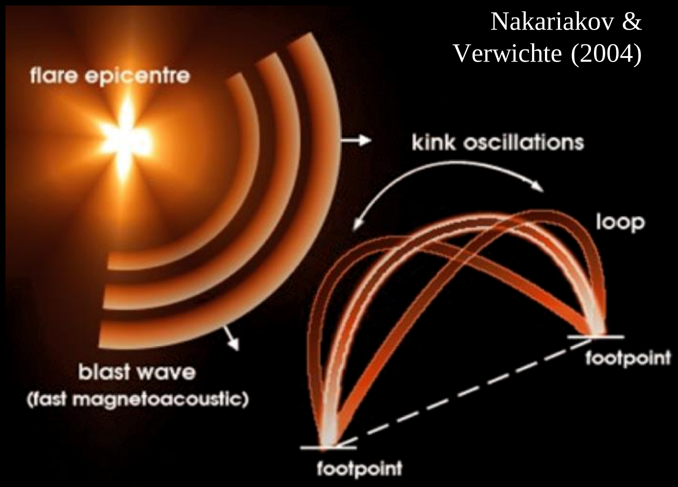




Flux tubes (eventually) fill the corona



Analyzing some individual thin-tube oscillations has led to novel ways to measure the magnetic field **(“coronal seismology”).**



Nakariakov & Verwichte (2004)

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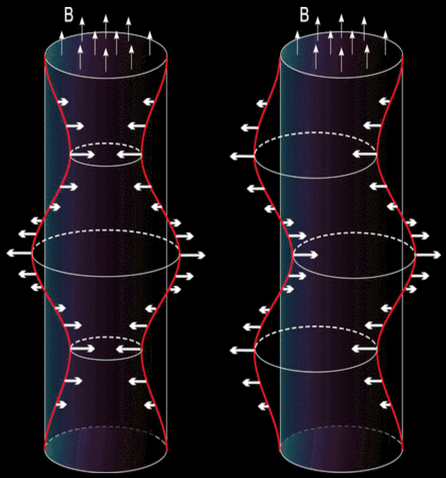

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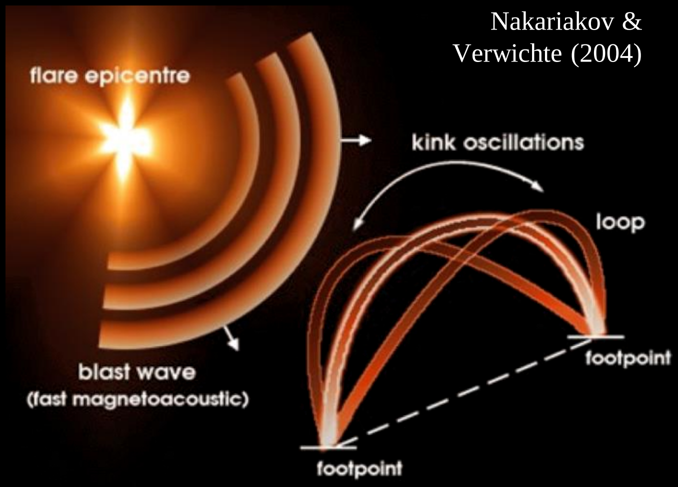
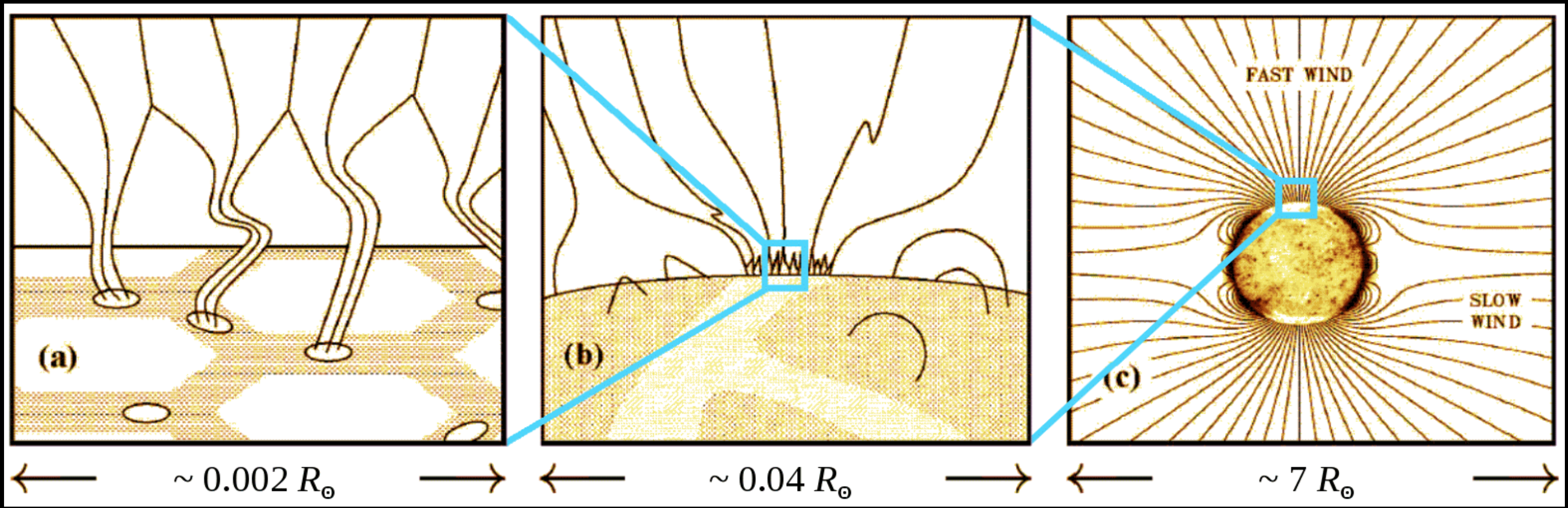




MHD waves expand out into the corona

With good instrumentation, imaging & spectroscopy can resolve plasma fluctuations in multiple ways…

- Intensity modulations . . .

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

- Motion tracking in images . . .

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

- Doppler shifts . . .

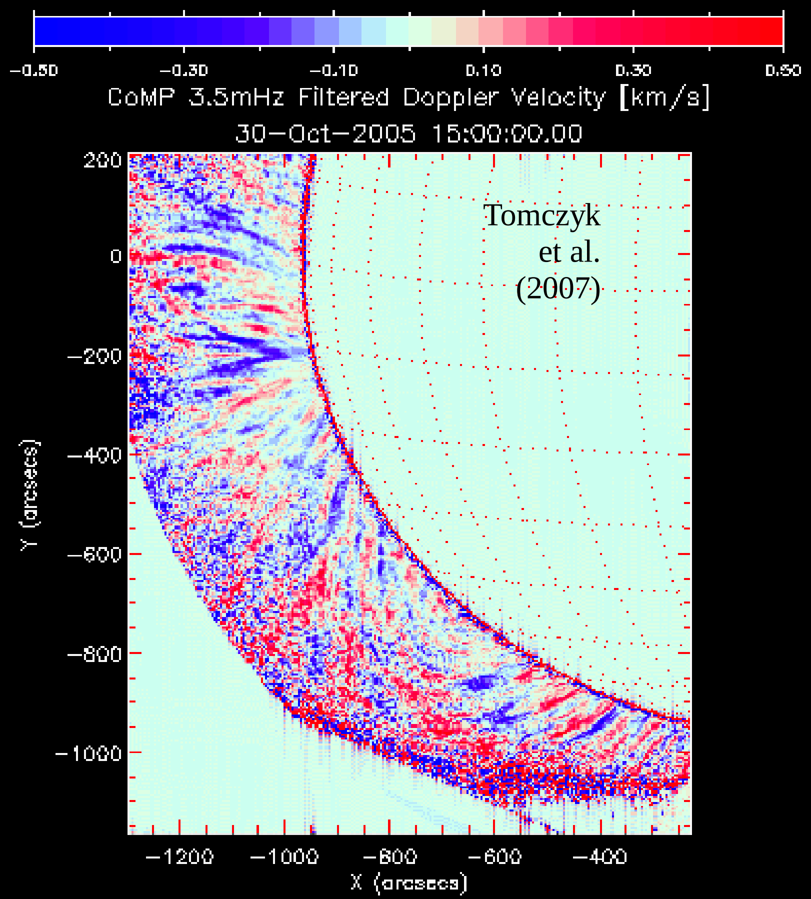
$$\delta\lambda \propto \delta V_{\rm LOS}$$

- Doppler broadening . . .

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

- Radio sounding . . .

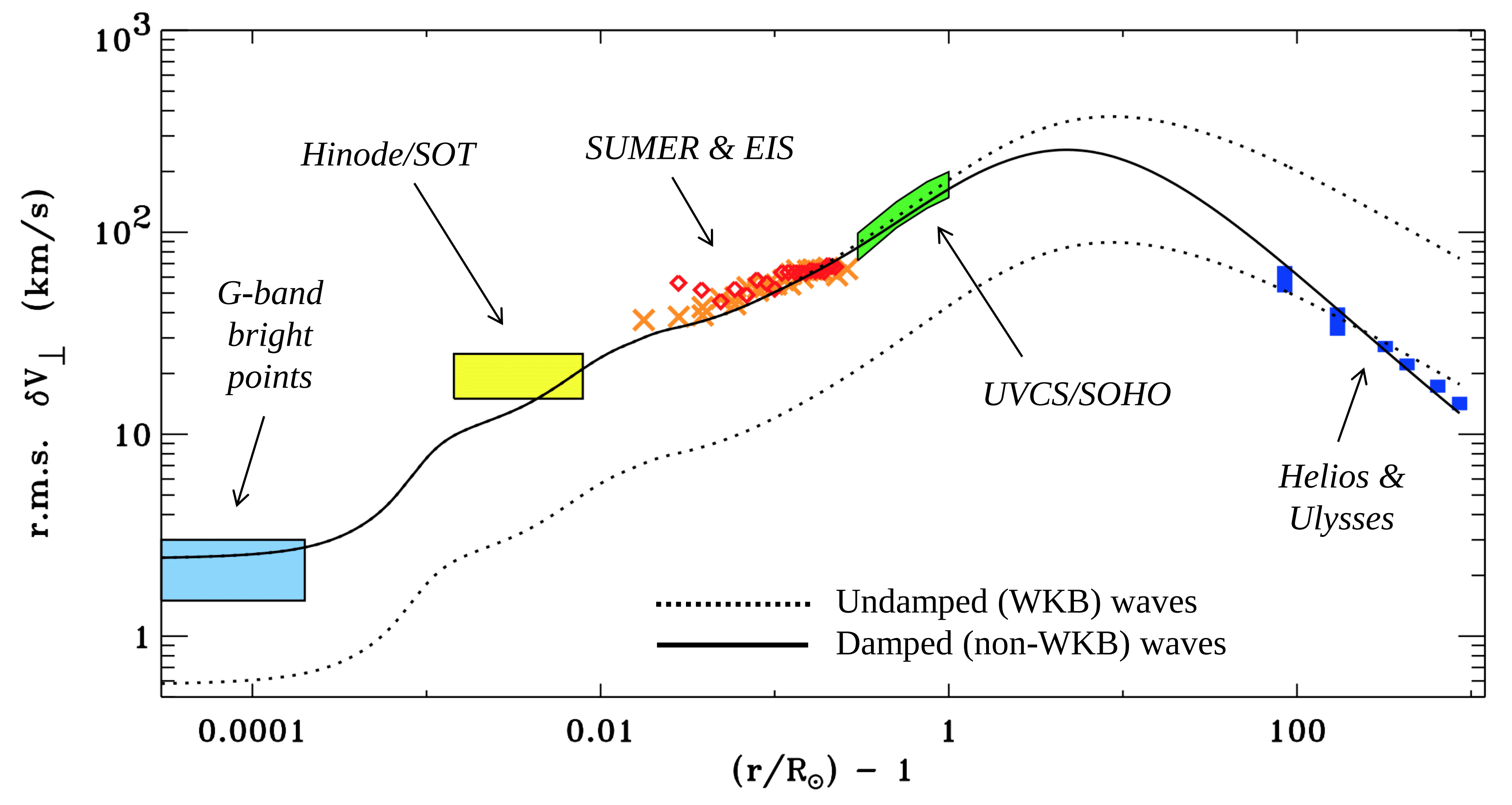
$$\delta\tilde{n} \rightarrow \delta\rho\,,\delta B \rightarrow \delta V$$



- Transverse **Alfvén waves** dominate, with periods of order 3-5 minutes.

Measured Alfvénic fluctuations

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



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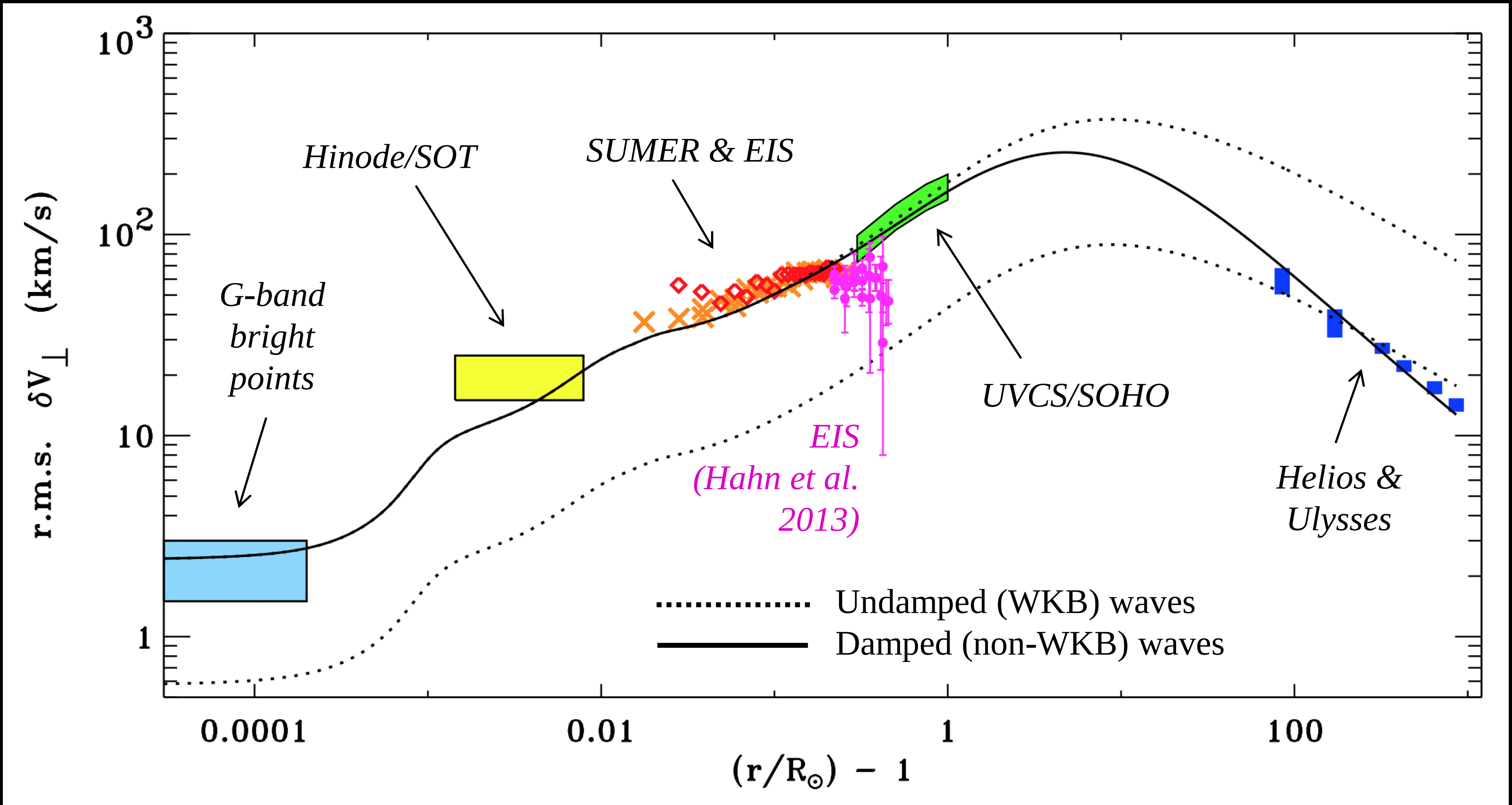
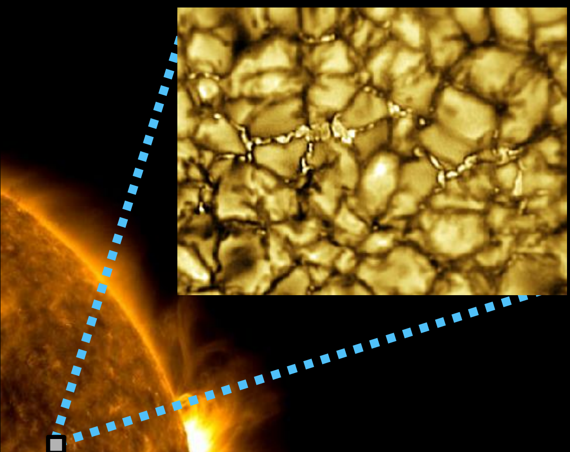
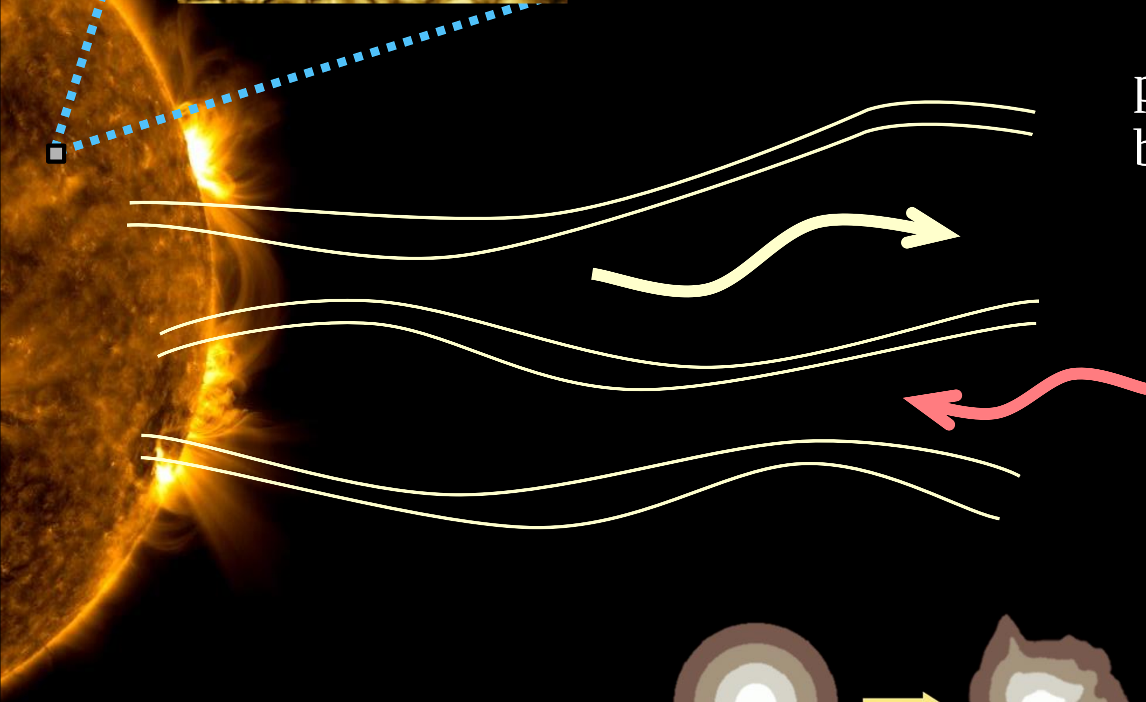


Can turbulence explain coronal heating?



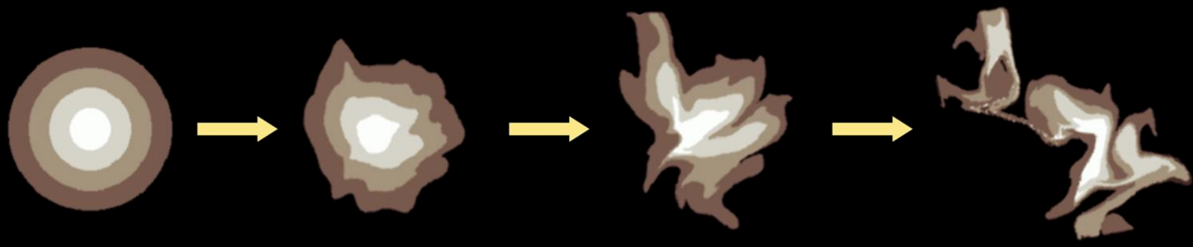
Convection shakes & braids magnetic field lines in a diffusive “random walk”

Alfvén waves propagate up...



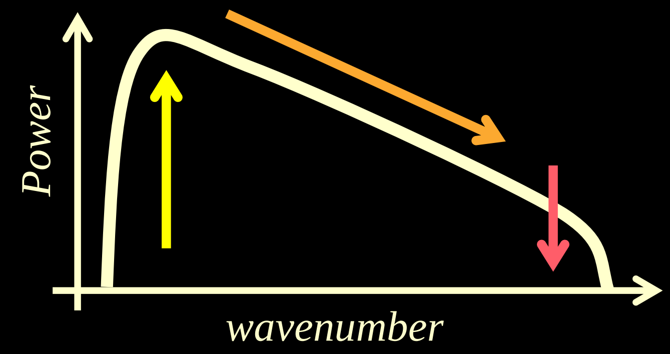
partially reflect back down...

...and they undergo an MHD **turbulent cascade,** from large to small eddies, eventually dissipating in intermittent stochastic “nanoflares”



Can turbulence explain coronal heating?

- If the cascade is driven & time-steady, the rate of **stirring** should = rate of **cascade** = rate of **dissipation & heating.**
- MHD simulations inspire phenomenological scalings for the stirring/cascade rate:



$$Q_{\text{heat}} \approx \frac{\rho\, v^3}{\ell} \approx \frac{\varepsilon\, \rho\, (v_+^2 v_- + v_-^2 v_+)}{\ell_\perp}$$

(e.g., Iroshnikov 1963; Kraichnan 1965; Strauss 1976; Shebalin et al. 1983; Hossain et al. 1995; Goldreich & Sridhar 1995; Matthaeus et al. 1999; Dmitruk et al. 2002; Chandran 2008)

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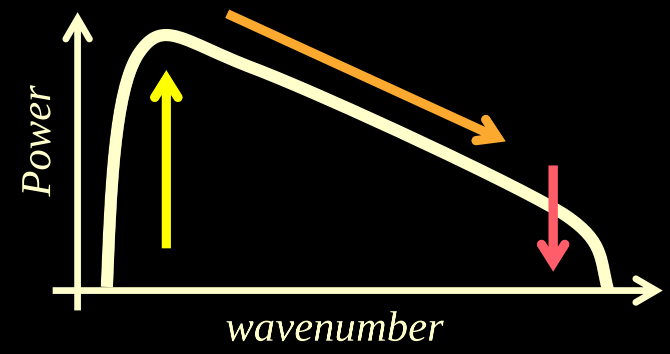

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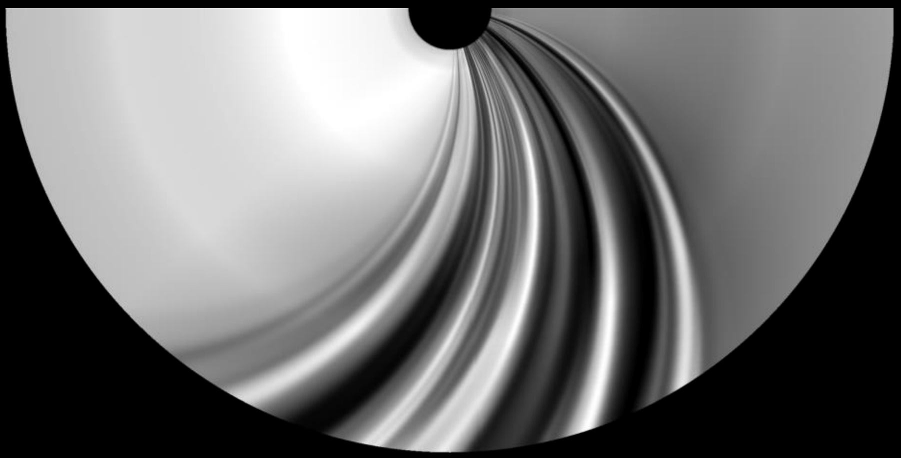
- When plugged into self-consistent solutions for coronal heating & solar wind acceleration, it seems to work! (Cranmer et al. 2007).
- Including rotation produces realistic 3D structure (Cranmer et al. 2013).



Kinetic consequences…

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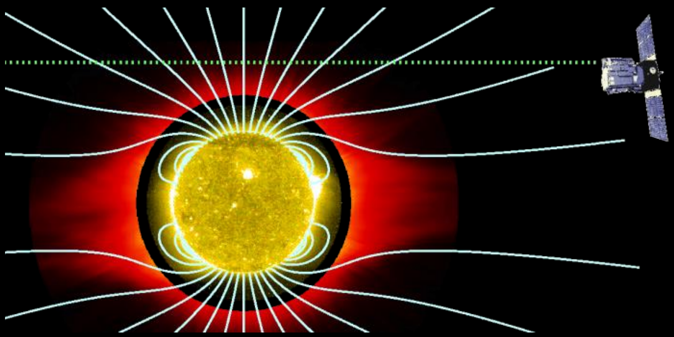
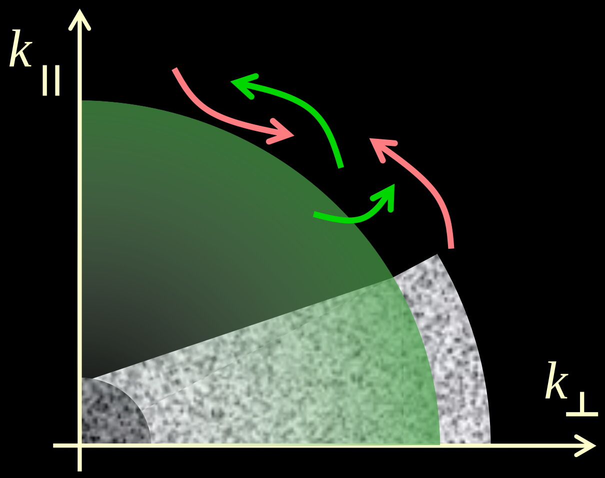


Observing **collisionless** heating rates high up (e.g., UVCS/SOHO) reveals indirect information about how wave dissipation heats particles . . .

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

- When eddies reach gyroradius scales, does the anisotropic cascade prefer:
  - ion cyclotron waves?
  - kinetic Alfvén waves?
  - magnetosonic whistlers?



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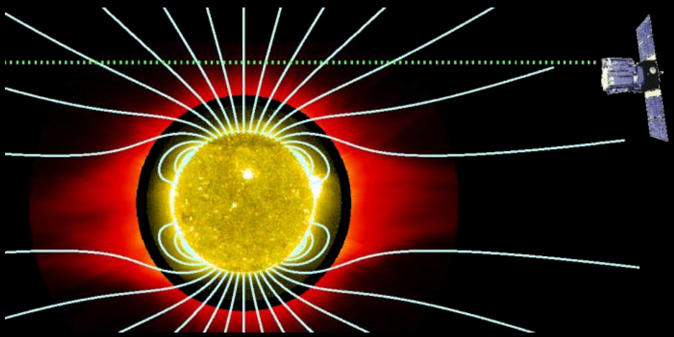

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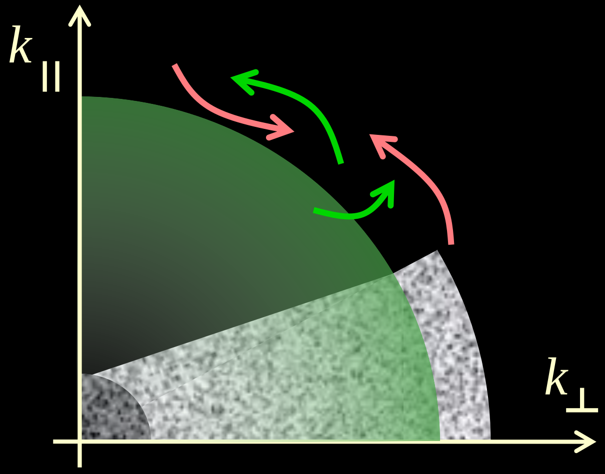
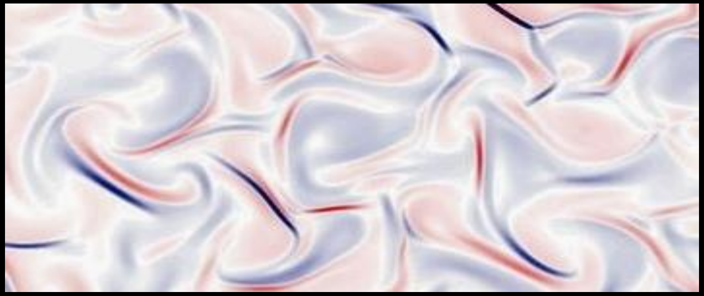




Does the "wave" picture break down altogether when the turbulence is organized into coherent **current sheets?**

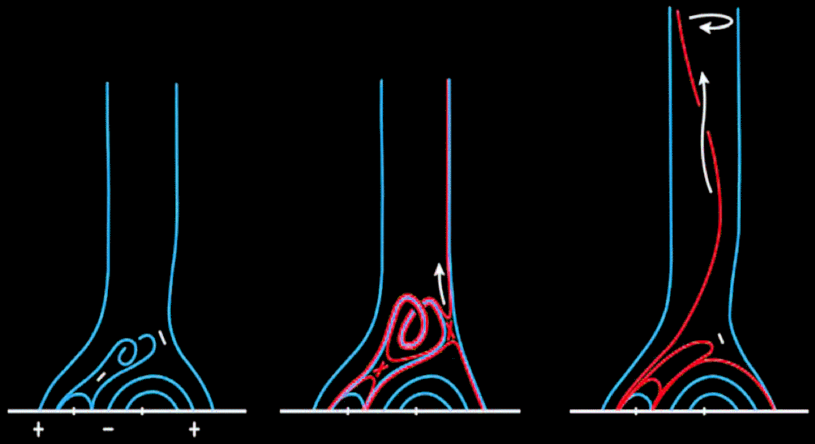
MHD waves generated "higher up?"

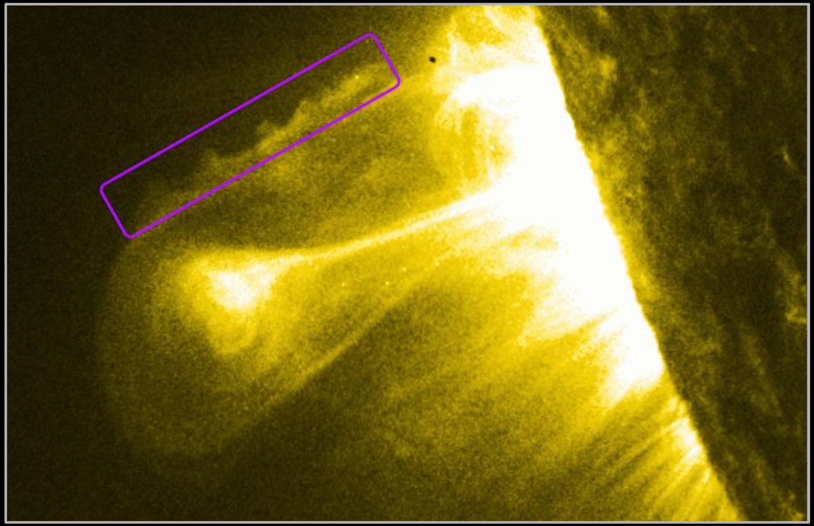
Not all coronal & solar wind fluctuations come directly from the solar surface…

MHD waves generated "higher up?"

Not all coronal & solar wind fluctuations come directly from the solar surface…

- The coronal magnetic field evolves via **magnetic reconnection** between ever-changing magnetic flux systems.
- Some forms of reconnection can launch MHD waves (Lynch et al. 2014; Moore et al. 2015).





- Strong shears between fast & slow solar wind (and CMEs!) can be unstable to wave growth via **Kelvin-Helmholtz instabilities** (Foullon et al. 2011; Ofman & Thompson 2011).

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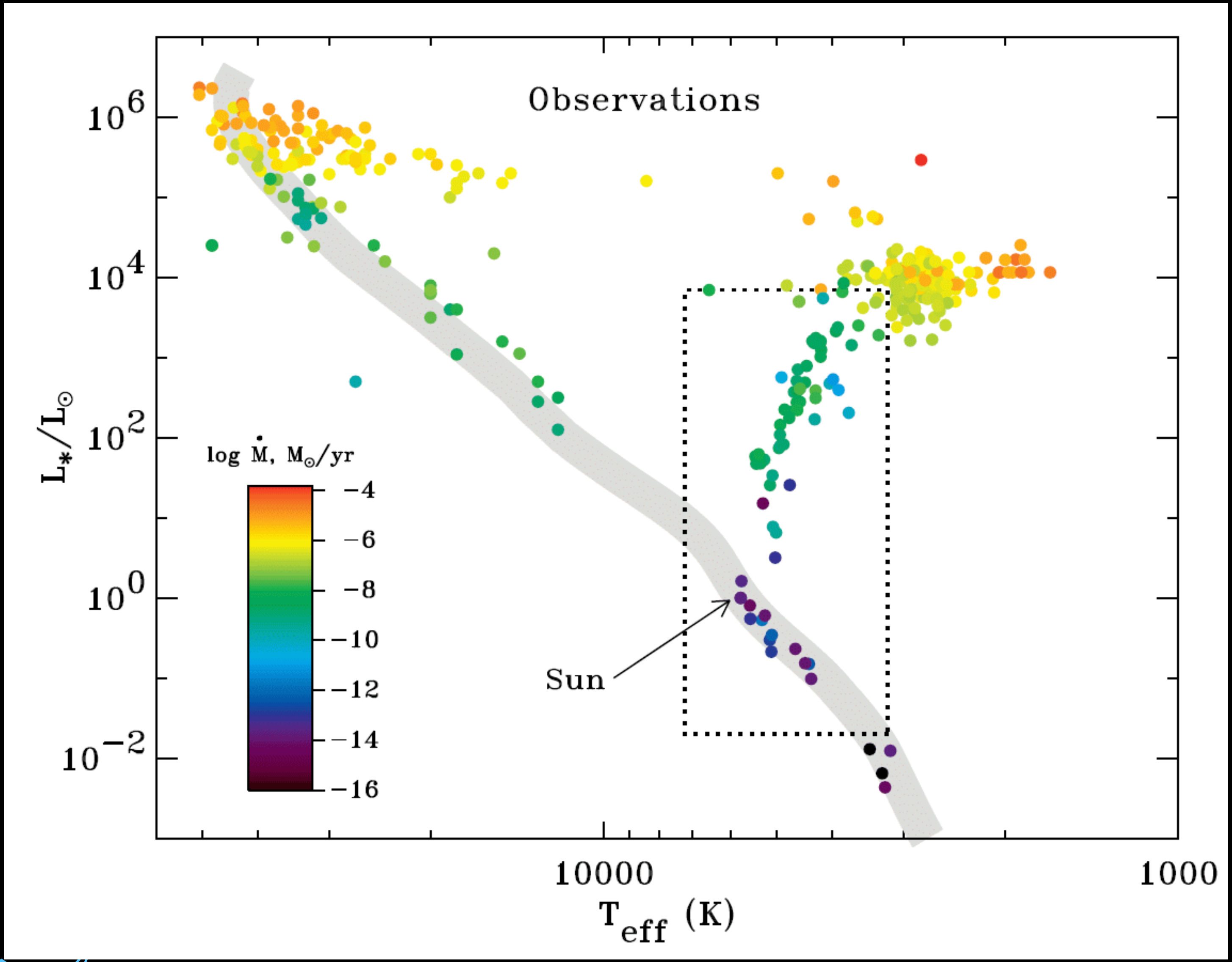
Applying turbulence theory to solar-type stars



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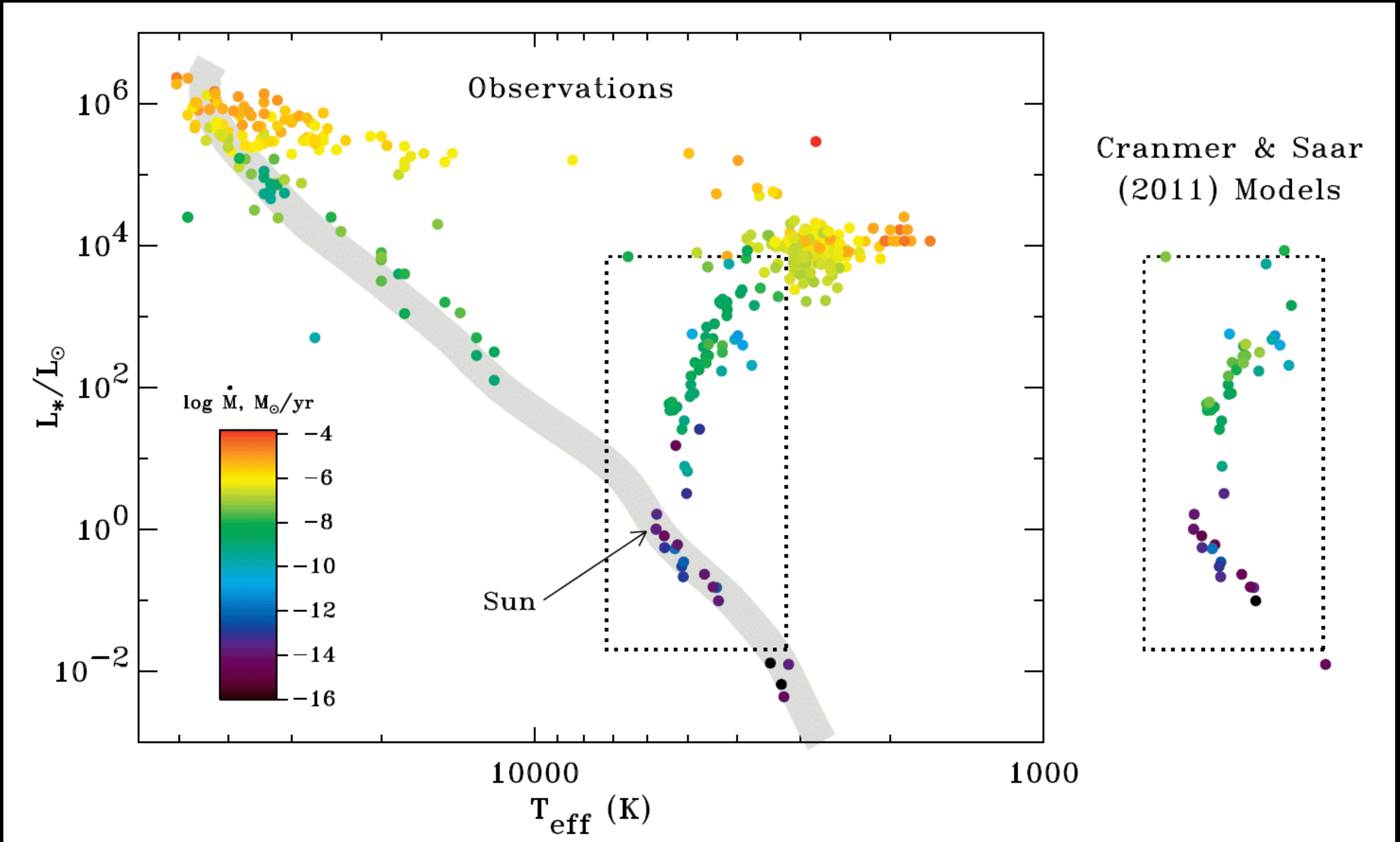
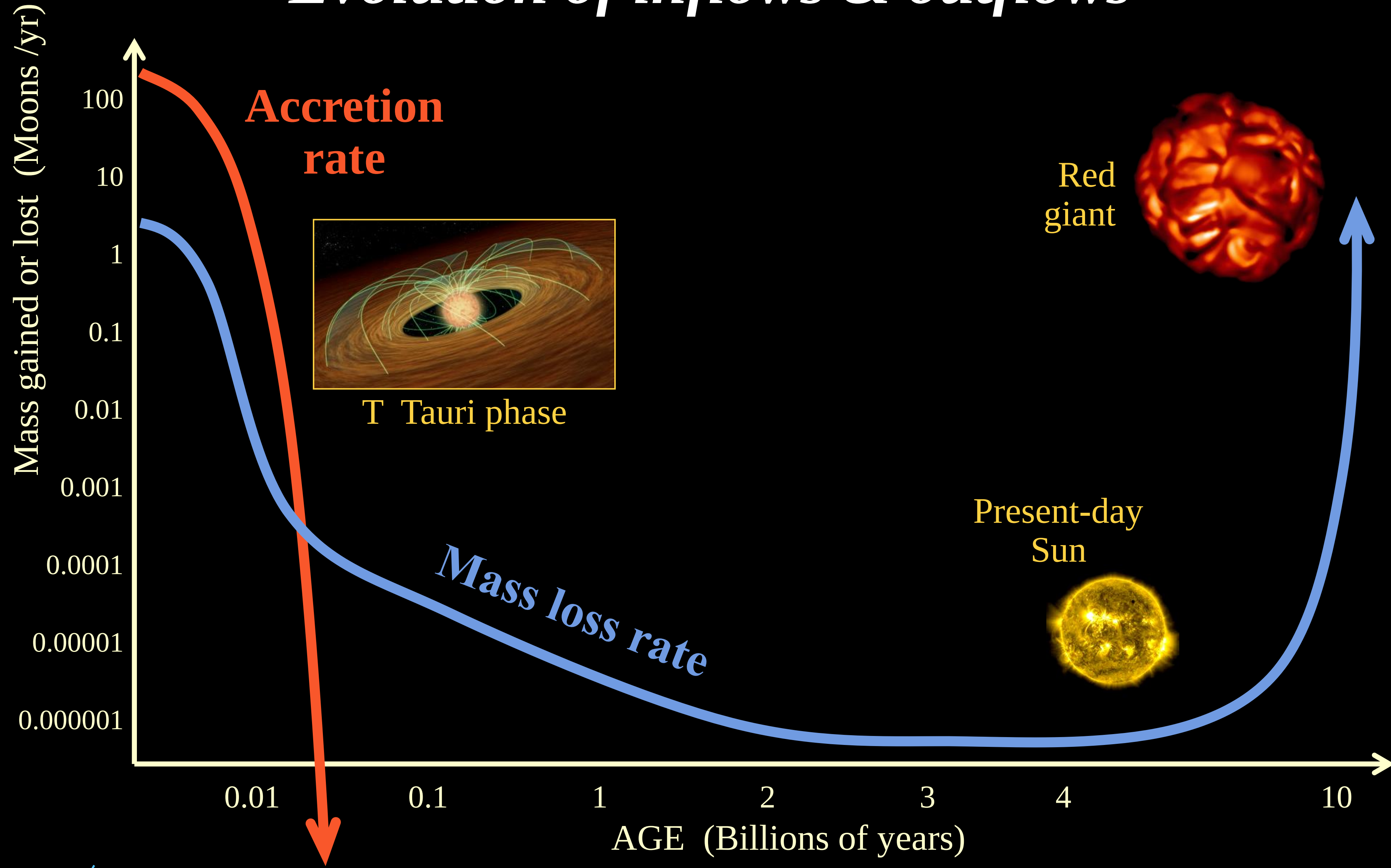
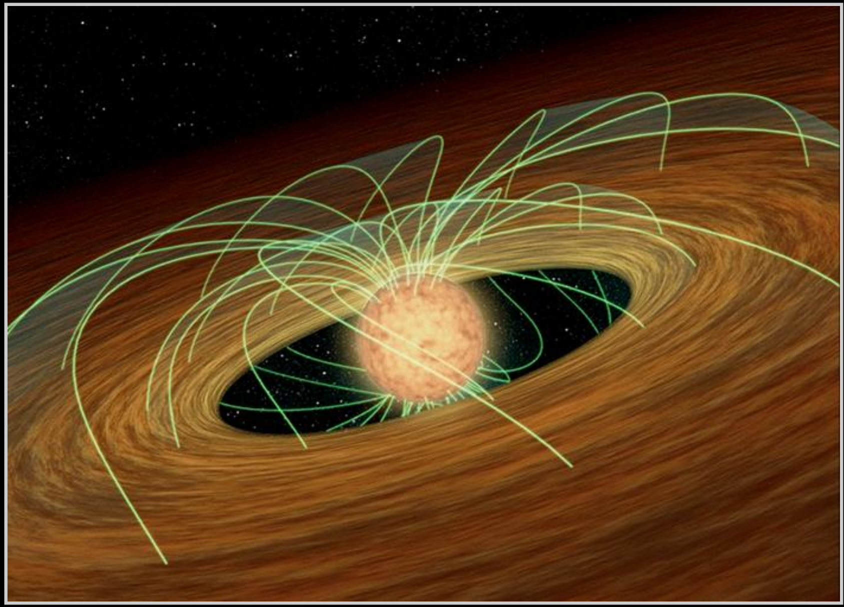


Evolution of inflows & outflows

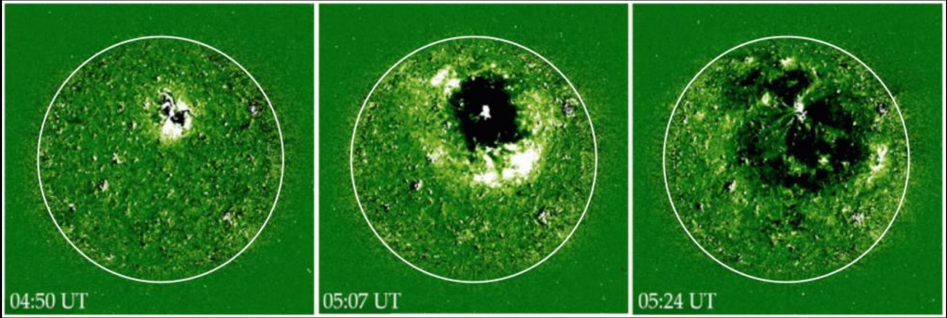


Young stars: 2 sources of turbulence

- T Tauri protostars are convectively unstable… they generate their own waves.
- But the accretion is variable! Clumps of plasma impact the star… and induce “externally driven” surface turbulence.
- Cranmer (2008, 2009) modeled the resulting winds & X-ray emission.



Impact-generated “ripples” are similar to **EUV waves** observed on the Sun after strong flares…



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Massive star winds: radiative driving

- Castor, Abbott, & Klein (1975) worked out how a hot star's radiation can accelerate a time-steady wind, even if gravity >> continuum radiation force.
- Spectral lines are the key! $$\mathbf{a}_{\rm rad} = \int d\nu \, \frac{\kappa_\nu \mathbf{F}_\nu}{c}$$
- Bound electron resonances have higher cross-sections than free electrons (i.e., **spectral lines** dominate the opacity $\boldsymbol{\kappa}_\nu$)

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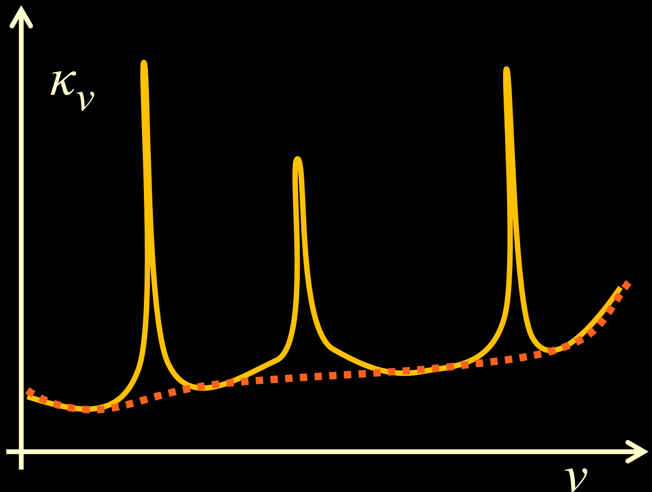
- Bound electron resonances have higher cross-sections than free electrons (i.e., **spectral lines** dominate the opacity $\boldsymbol{\kappa_\nu}$)
- In the accelerating wind, narrow opacity sources become **Doppler shifted** with respect to star's photospheric spectrum.
- Acceleration thus depends on velocity & velocity gradient! This turns "*F=ma*" on its head! (Nonlinear feedback...)



New forces → new wave modes

- Radiative acceleration is proportional to *(dv/dr)* and wind density…

$$g_{\rm CAK} = g_{\rm CAK,0} + g_{\rm CAK,1} = g_{\rm CAK,0} + \frac{\partial v_1}{\partial r}\left[\frac{\partial g_{\rm CAK}}{\partial(dv/dr)}\right]_0 + \rho_1\left[\frac{\partial g_{\rm CAK}}{\partial \rho}\right]_0$$

Steeper gradients → stronger line forces.
The Abbott (1980) speed U_A can be supersonic

usually neglected;
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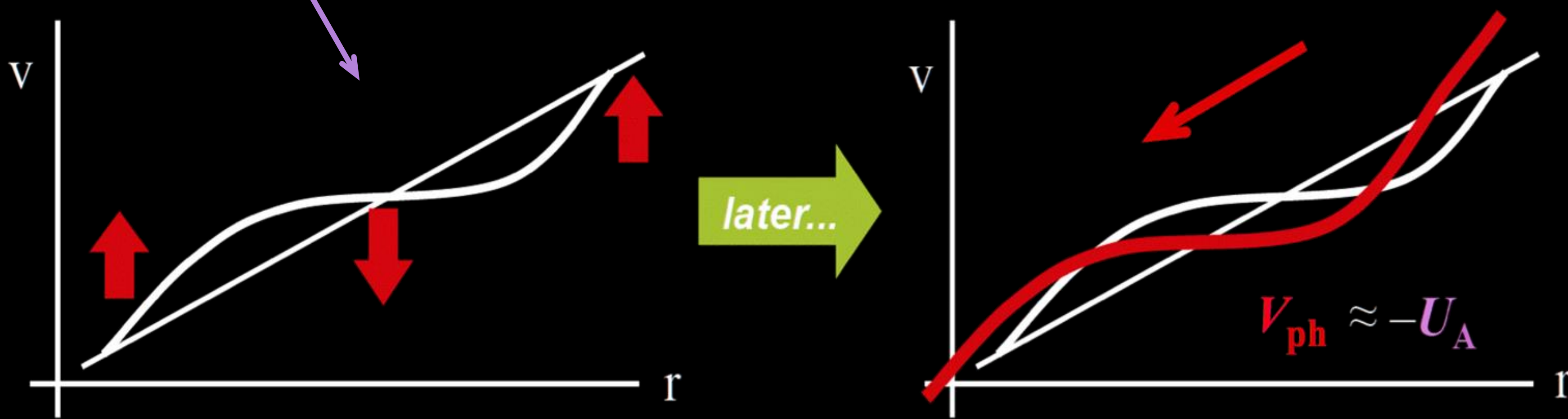
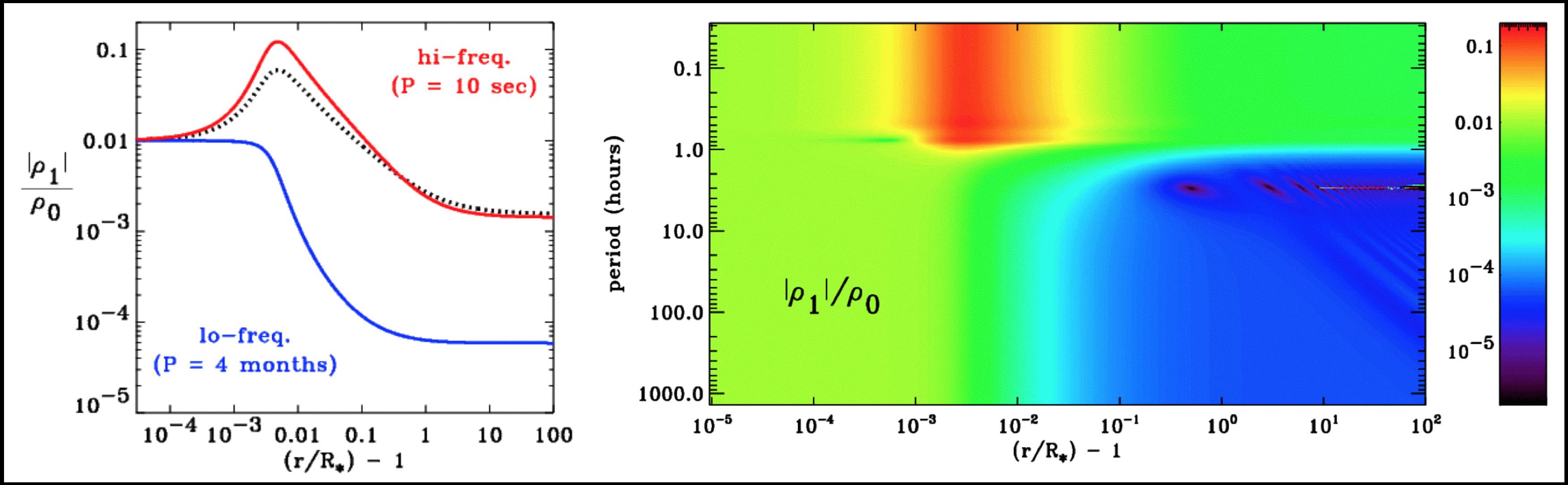
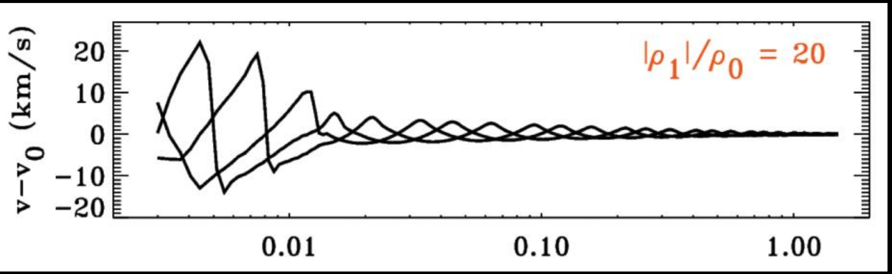


New forces → new wave modes

- Massive stars undergo low-frequency **pulsations.** Do waves "leak out?"
- Proper treatment requires a non-WKB model of Abbott waves (Cranmer 2007).



Strongly **nonlinear** pulsations saturate; radiation forces produce "kinks" in *v(r)*



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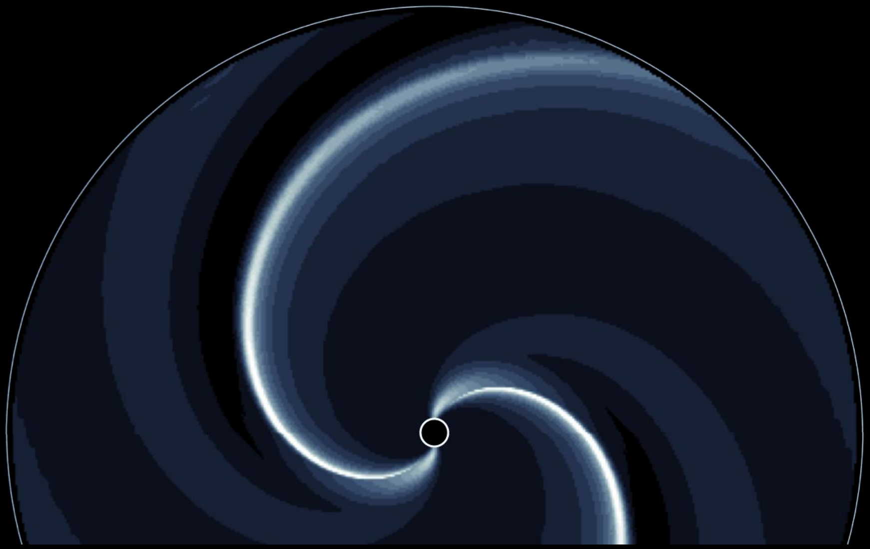

- For a rotating star with "spots," the nonlinear kinks produce **corotating interaction regions (CIRs).**
- CIRs appear to be visible in spectral lines formed in rotating winds (Cranmer & Owocki 1996).

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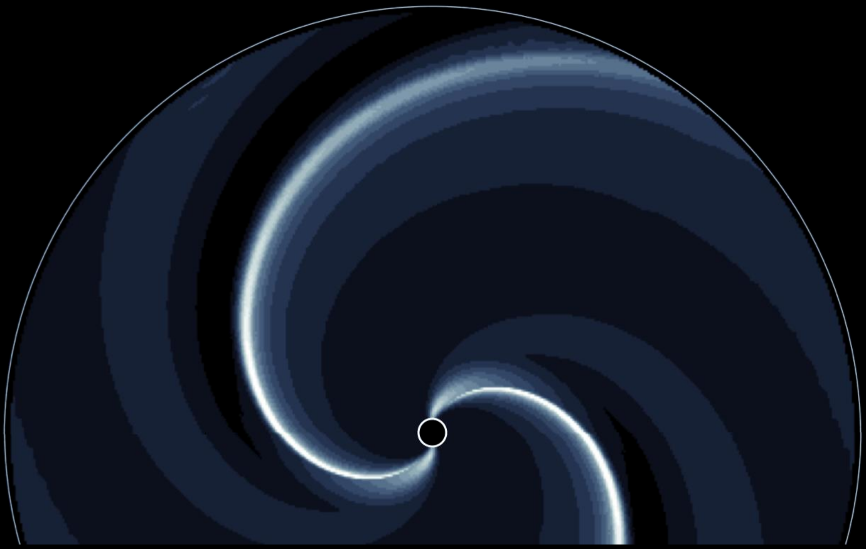

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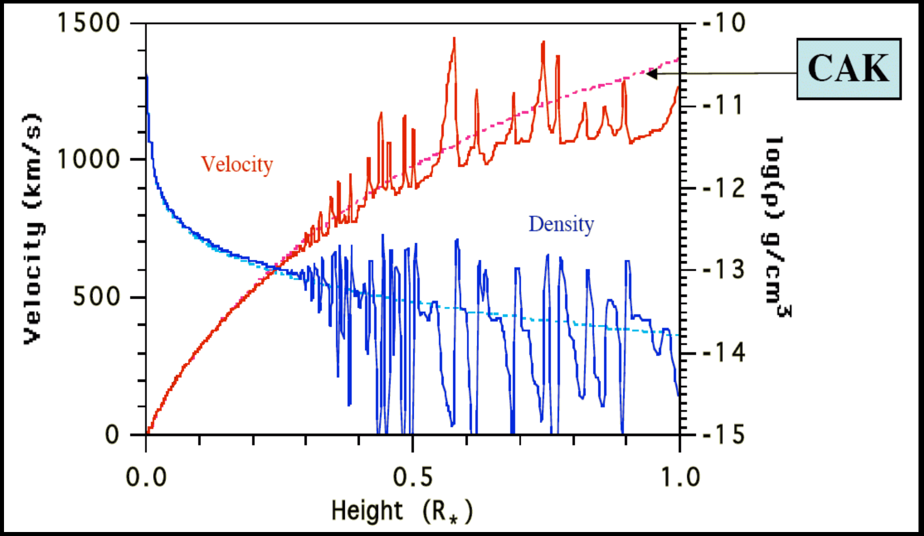
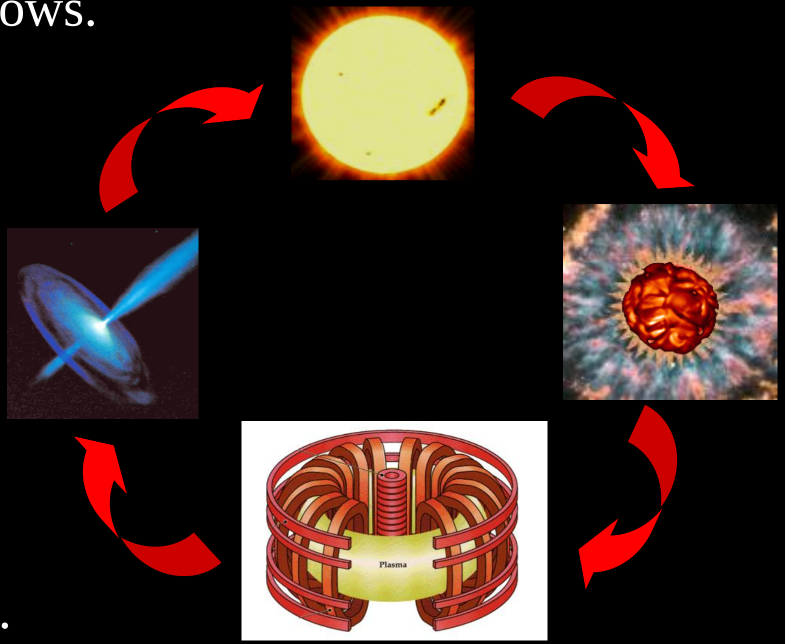
- A more accurate treatment of the radiation force shows that small wavelengths are **strongly unstable** to rapid growth (Owocki & Rybicki 1984, 1985, 1986, …)
- The resulting shocks appear to explain **X-rays** seen around most O stars.



Conclusions

- Waves are excellent diagnostics of stellar outflows.
- Within an order of magnitude, theories aren't doing *too* badly in predicting observed properties of solar & stellar winds.
- However, there's still much to do . . .
- Understanding is greatly aided by ongoing collaboration between the solar physics, plasma physics, and astrophysics communities.



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