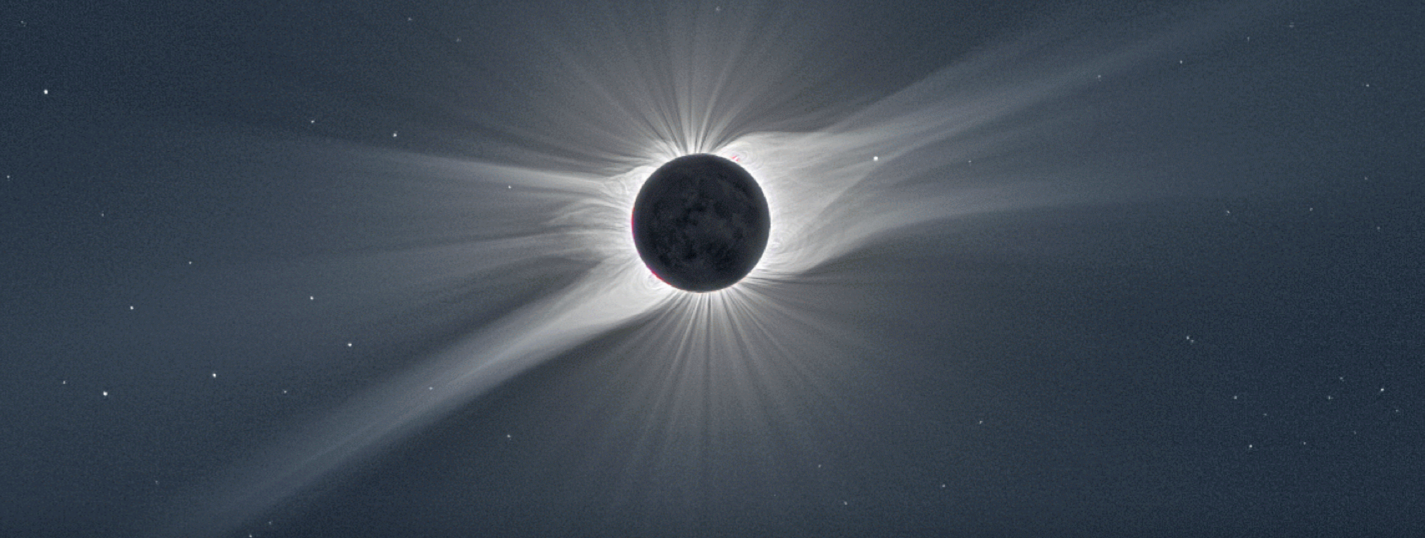
What do we know about the Physics of Energy Transport in Solar/Stellar Winds?



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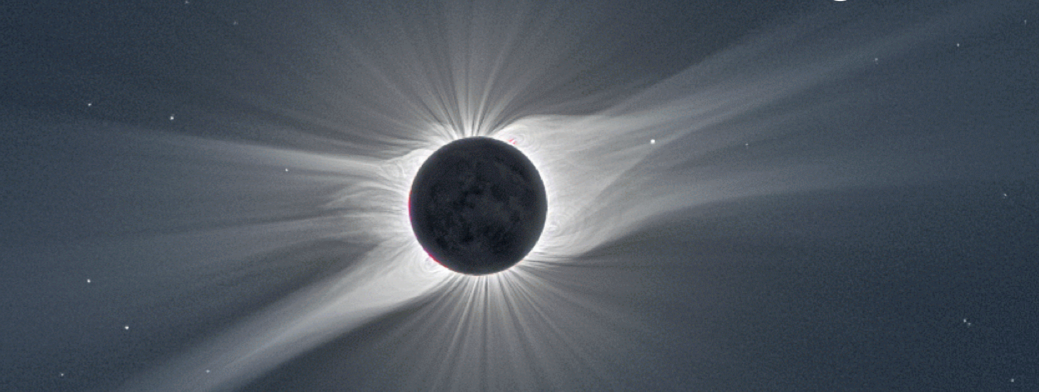
Outline (if I had an hour…)

1. Brief introduction & basic physics of stellar winds

2. **The Sun:** convection → coronal heating?



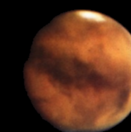
3. **Cool low-mass stars:** mass loss, pulsations, accretion

4. **Hot high-mass stars:** radiation drives "cool" wind!

Why do we care?

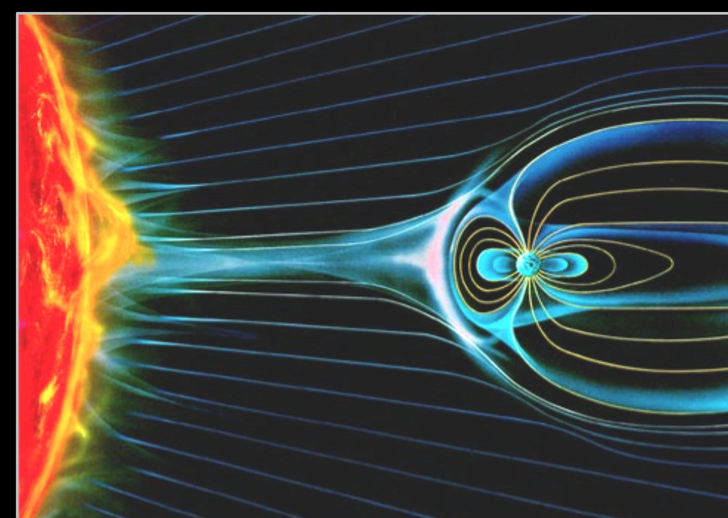
- Stellar winds affect how stars & galaxies evolve… from pre-main-sequence accretion to post-main-sequence "death" & mass recycling.

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

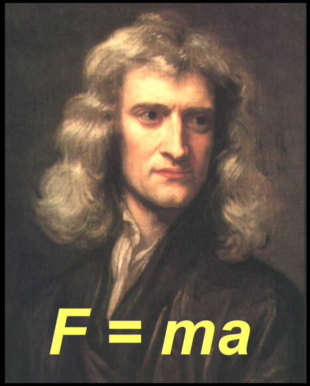


- In our own solar system, "space weather" affects satellites, power grids, pipelines, and safety of astronauts & high-altitude airline crews.

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



Driving a stellar wind



- Gravity must be counteracted above the photosphere *(not below)* by some continuously operating outward force . . .

  - **Gas pressure gradient:** needs $T \sim 10^6$ K ("coronal heating")
  - **Radiation pressure:** possibly important when $L_* > 100\ L_\odot$
    - free electron (Thomson) opacity? (goes as $1/r^2$; needs to be supplemented)
    - ion opacity? ($T_{\rm eff} \gtrsim$ 15,000 K)
    - dust opacity? ($T_{\rm eff} \lesssim$ 3,000 K)
  - **Pulsations / Waves / Shocks:** can produce time-averaged net acceleration.
  - **Magnetic effects:** closed loops of plasma ("plasmoids") can be pinched like melon seeds and carry along some of the surrounding gas.

Quantifying a stellar wind

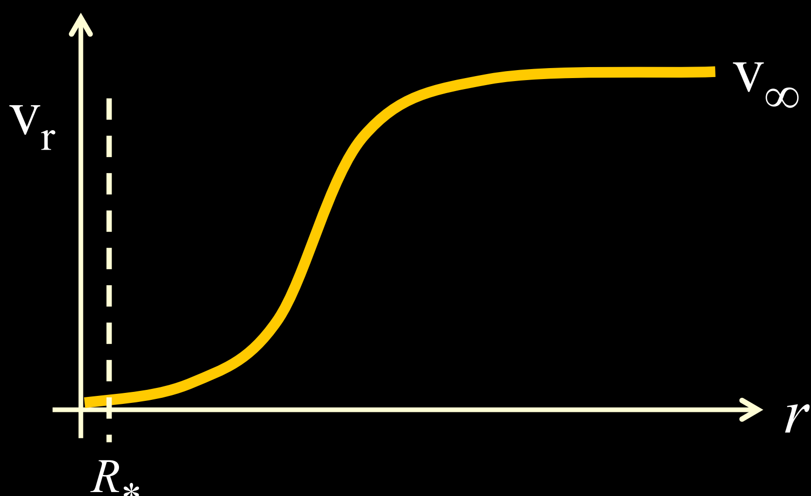
- **Stars** are typically characterized by mass, radius, luminosity
  (…and chemical abundances, rotation rate, magnetic field strength).

- **Winds** need at least 2 more parameters: mass loss rate & "terminal wind speed."

$$\left|\frac{dM_*}{dt}\right| = \dot{M} = \left(4\pi r^2\right)\,\rho\,v_r$$

kg/s   m^2 kg/m^3 m/s

(Typically expressed in units of ***$M_\odot$*/year**)



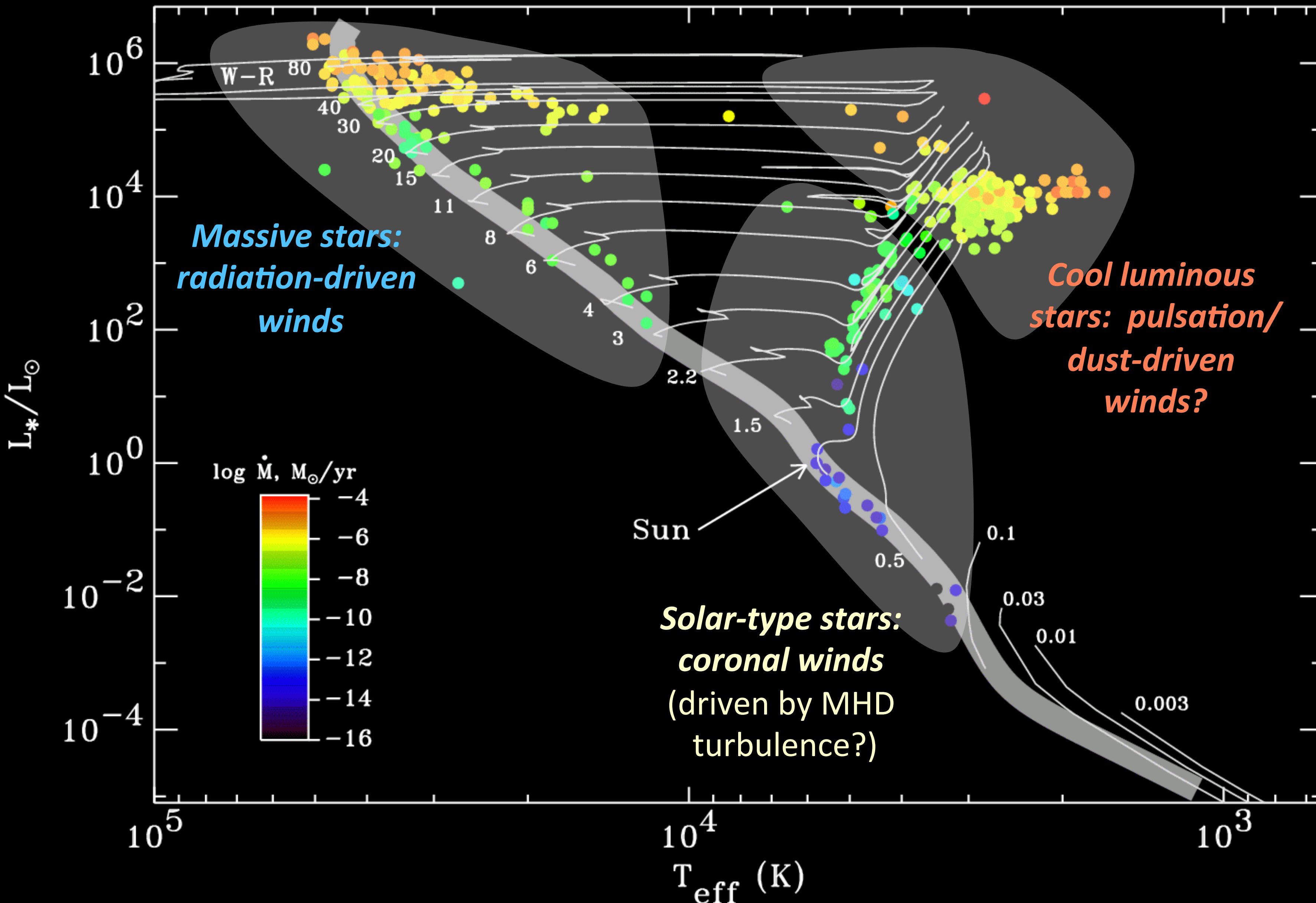
v_∞ is often ≈ surface V_{esc}

(most main-seq. stars)

v_∞ can also be << surface V_{esc} as long as it eventually exceeds the ***local*** V_{esc}

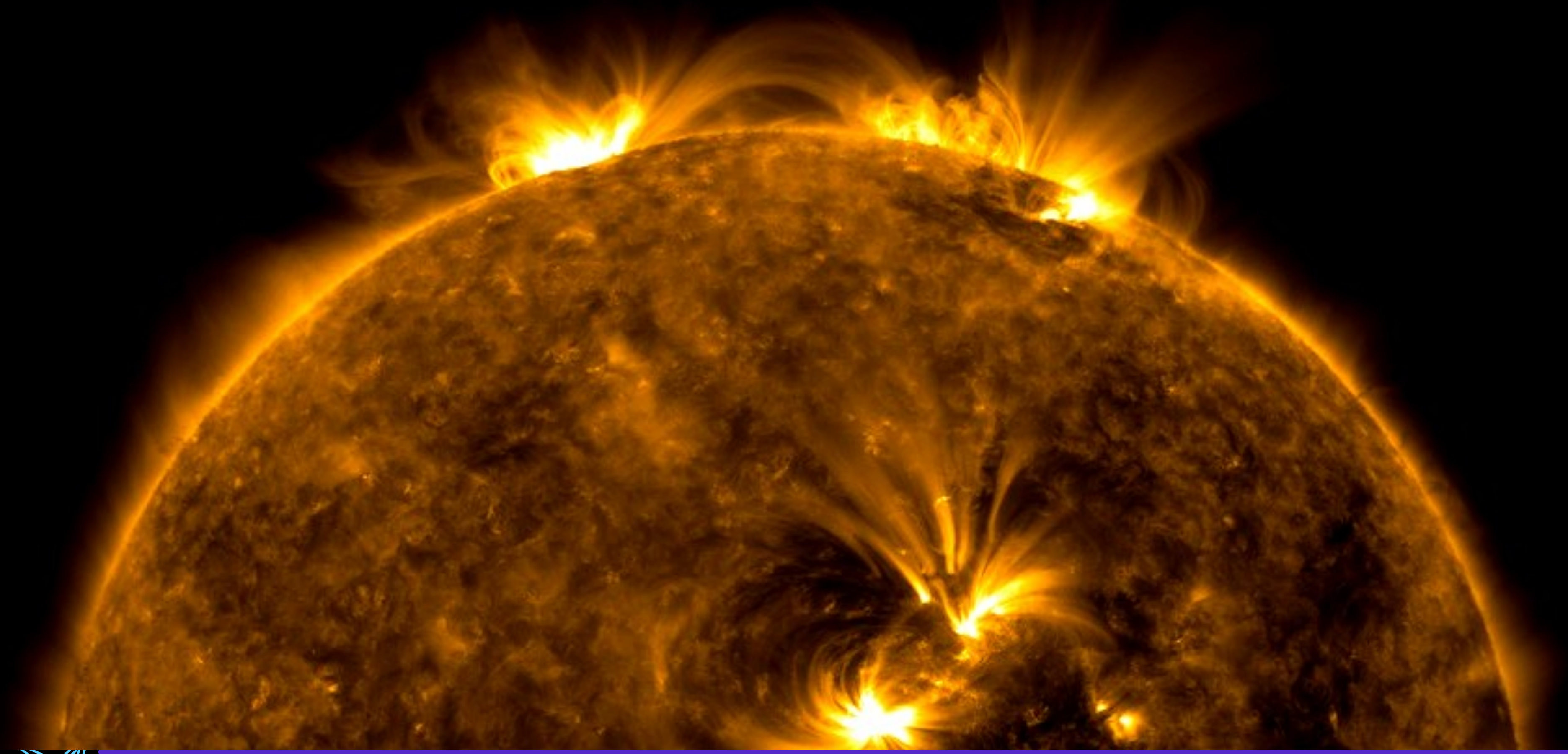
(red supergiants)

Stellar winds across the H-R Diagram



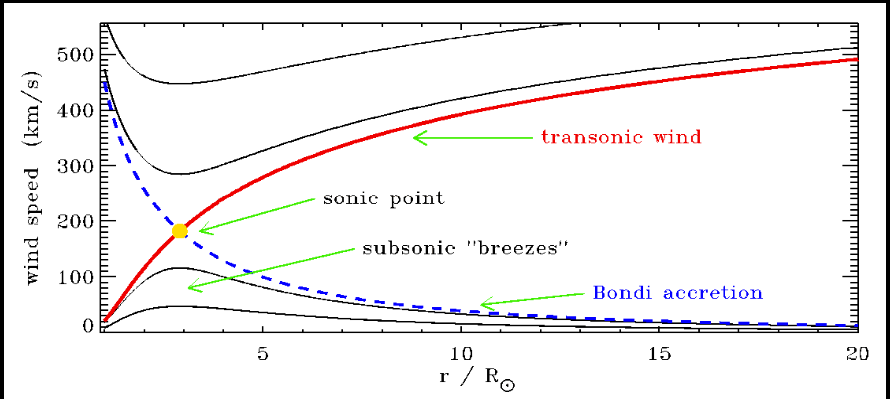
The solar corona

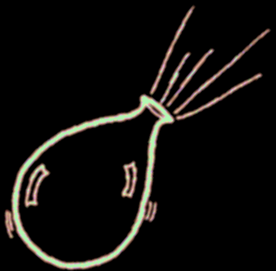
- 1870s: First off-limb solar spectroscopy: unknown emission lines ("coronium?")
- 1930s: Atomic physics identified lines: Fe^{+9}, Fe^{+13} (T needs to be > 1 million K).
- Of course, UV & X-ray observations sealed the deal . . .



The solar wind: prediction & discovery

- 1958: Eugene Parker put pieces together: the million-degree corona has such a high **gas pressure** that it naturally expands!

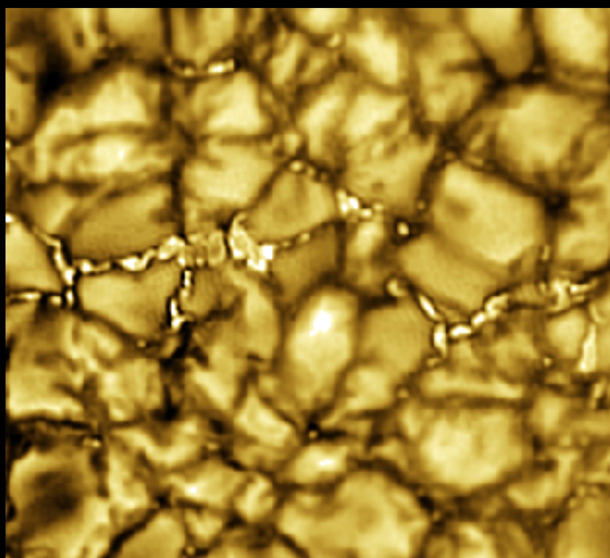


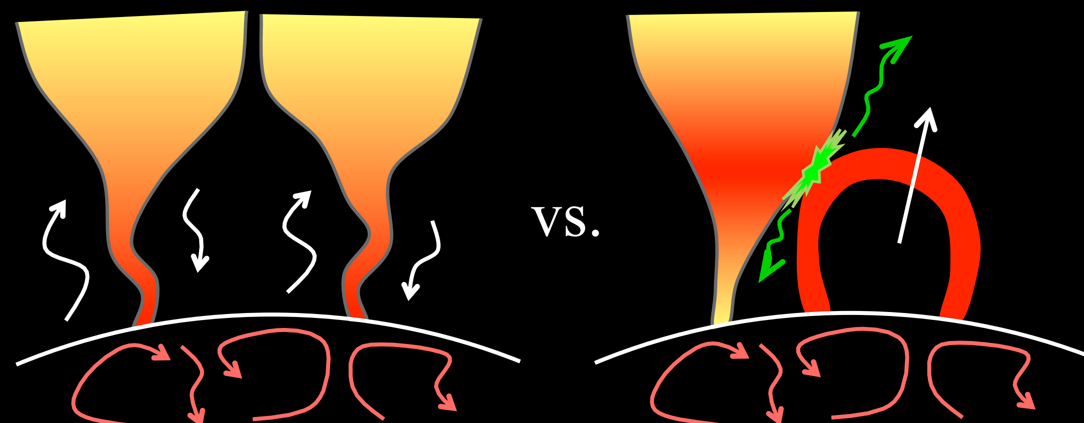


- 1959-1961: Intermittent detections: Russian *Lunik, Venera;* American *Explorer 10*
- 1962: Marcia Neugebauer & colleagues got **continuous** data from *Mariner 2* on its journey to Venus.
- The solar wind fills the solar system!

The "coronal heating problem"

- Why is the corona's $T \sim 1$ million K, when underlying atmosphere is ~6000 K ?
- (Nearly!) everyone agrees that there is more than enough "mechanical energy" in the sub-surface convection zone to do the job…

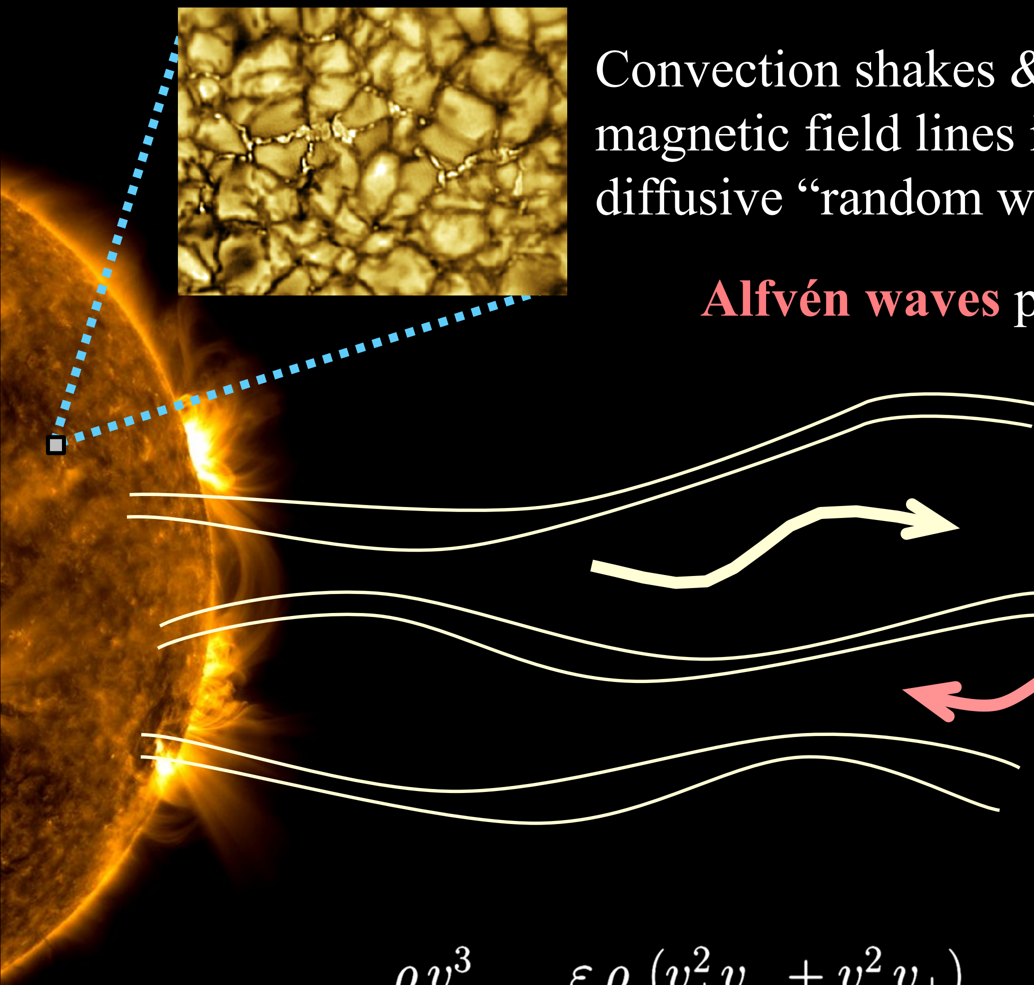




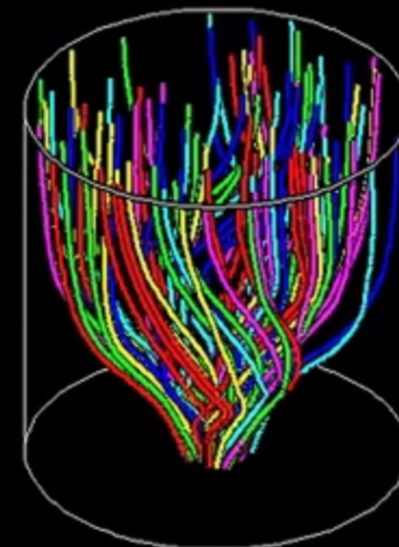
How does a fraction (~1%) of available energy get:

1. transported up to the corona,
2. converted to magnetic energy,
3. dissipated as heat

Turbulence: Recent models are converging…



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

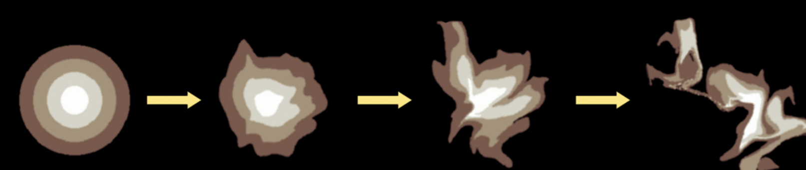


Alfvén waves propagate up...

partially reflect back down...

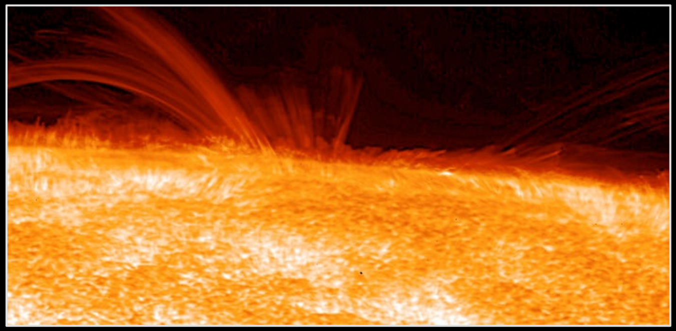
...and they undergo an MHD turbulent cascade, from large to small eddies, eventually dissipating in intermittent stochastic **"nanoflares"**

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



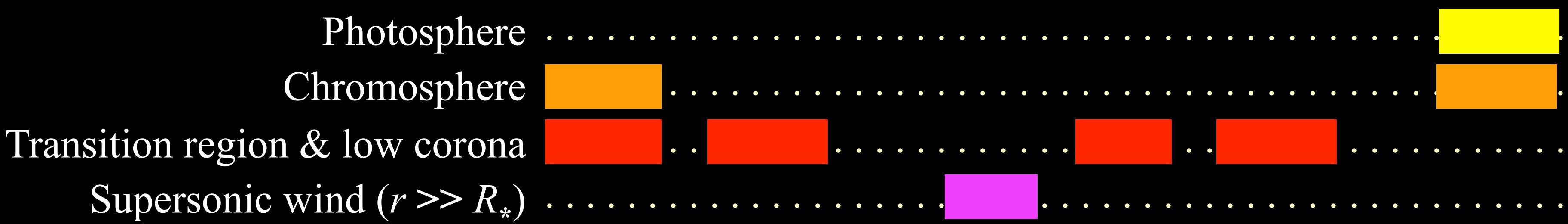
Solar wind physics

- Parker (1958) is generally still valid.
- If we solve the heating problem, we're ~90% of the way to understanding **$v_r(r)$.**



- However, what sets the mass loss rate?
- Not Parker!
- It's a thermal energy balance… set in the upper chromosphere / lower transition region.

$$\frac{\partial}{\partial t}\left(\frac{\rho v^2}{2} + \frac{3P}{2}\right) + \nabla \cdot \left[\mathbf{F}_{\rm heat} + \mathbf{F}_{\rm cond} + \rho \mathbf{v}\left(\frac{v^2}{2} + \frac{5P}{2\rho} - \frac{GM_*}{r}\right)\right] = Q_{\rm rad}$$



Applying it to other stars

- Basal energy balance gives a good approximation for the **mass loss rate** (Leer & Holzer 1980; Hammer 1982; Hansteen et al. 1995).
- Stellar wind power: $$L_{\text{wind}} = \dot{M}\left(V_{\text{esc}}^2 + v_\infty^2 + \left\{ \begin{array}{c} \text{heat?} \\ \text{waves?} \end{array} \right\}\right) \sim \frac{GM_* \dot{M}}{R_*}$$
- Reimers (1975) proposed a useful scaling…

$$L_{\text{wind}}/L_* \sim \text{const.} \quad \longrightarrow \quad \dot{M} \propto L_* R_* / M_* \propto L_*^{1.5}\, M_*^{-1}\, T_{\text{eff}}^{-2}$$

- Schröder & Cuntz (2005) and Suzuki (2018) modified it…

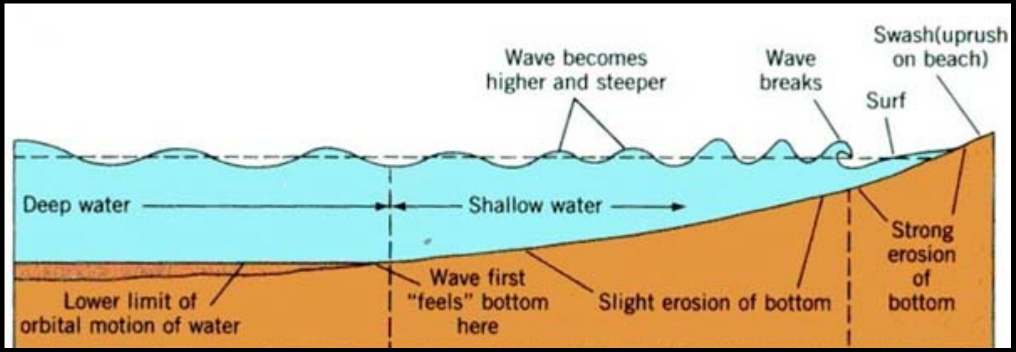
$$\dot{M} \propto L_*^{1.5}\, M_*^{-1}\, T_{\text{eff}}^{p-6} \quad (p \approx 6 \text{ to } 10) \qquad \dot{M} \propto L_*^{1.61}\, M_*^{-1.11}\, T_{\text{eff}}^{3.06}$$

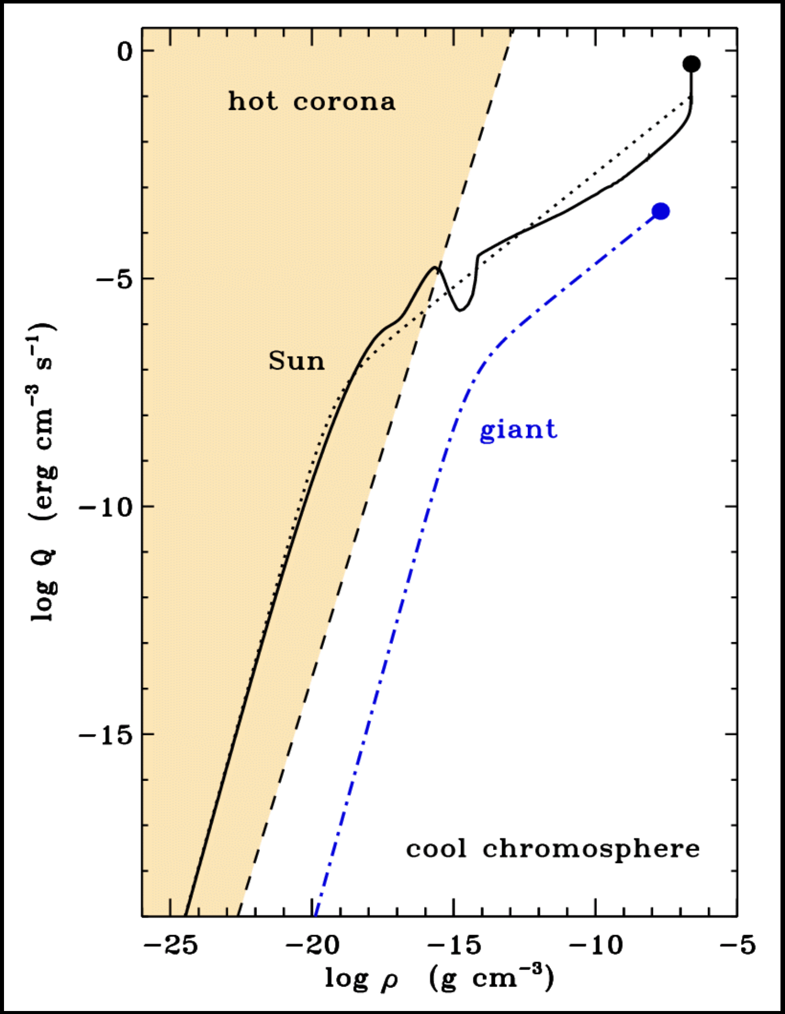
- The Cranmer & Saar (2011) version is my favorite…

$$\dot{M} \propto L_*^{1.43}\, M_*^{0.14}\, f_*^{0.27}$$

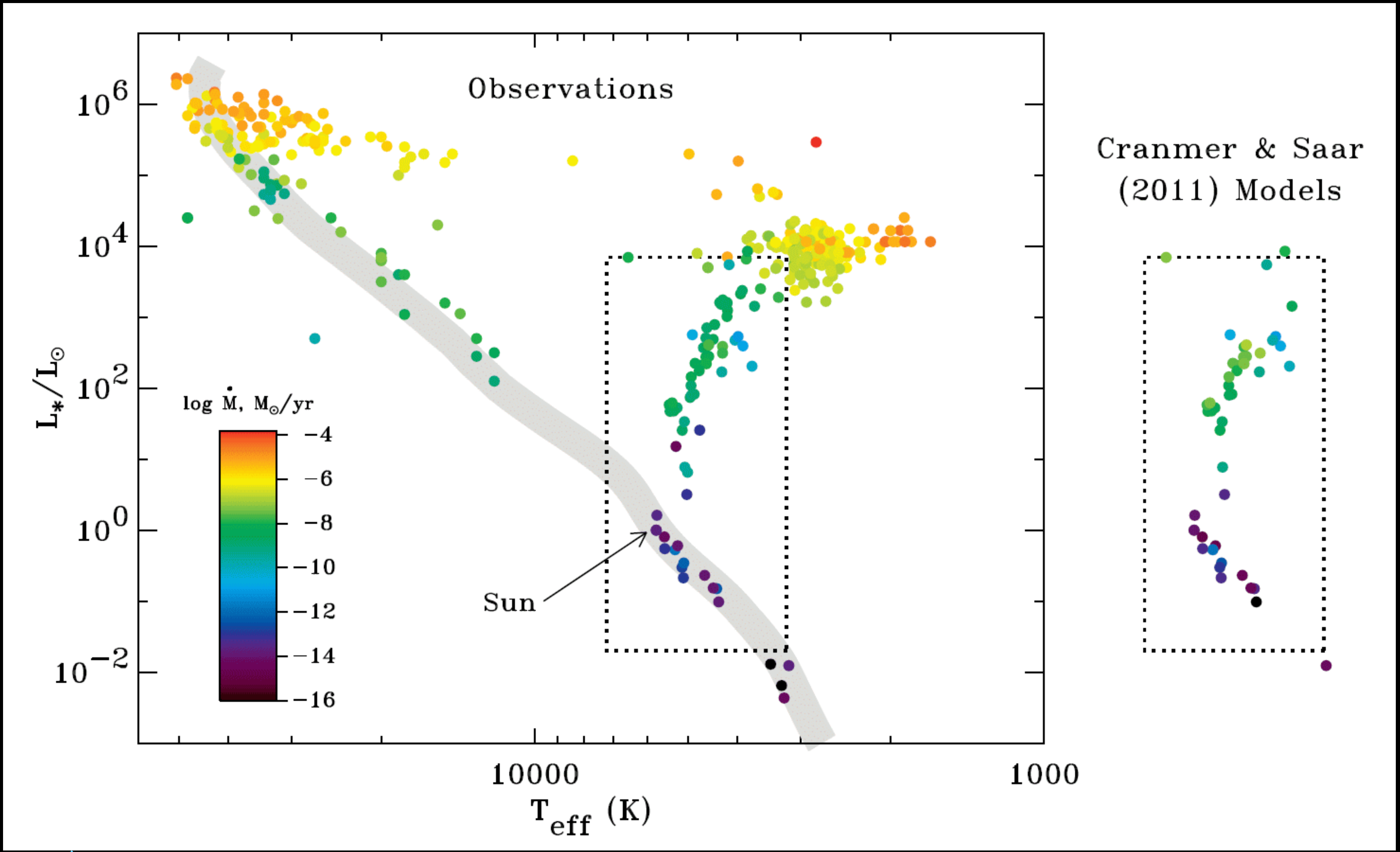
One last complication…

- Does Alfvénic turbulence *always* produce coronal heating? No!
- If the mass loss rate is large, the wind density is >> solar wind's density, and **radiative cooling** remains strong far above the stellar surface!
- In those "cold" cases (usually for luminous giants), gas pressure can't accelerate wind.
- **Alfvén wave pressure** may take the place of gas pressure (Holzer et al. 1983).

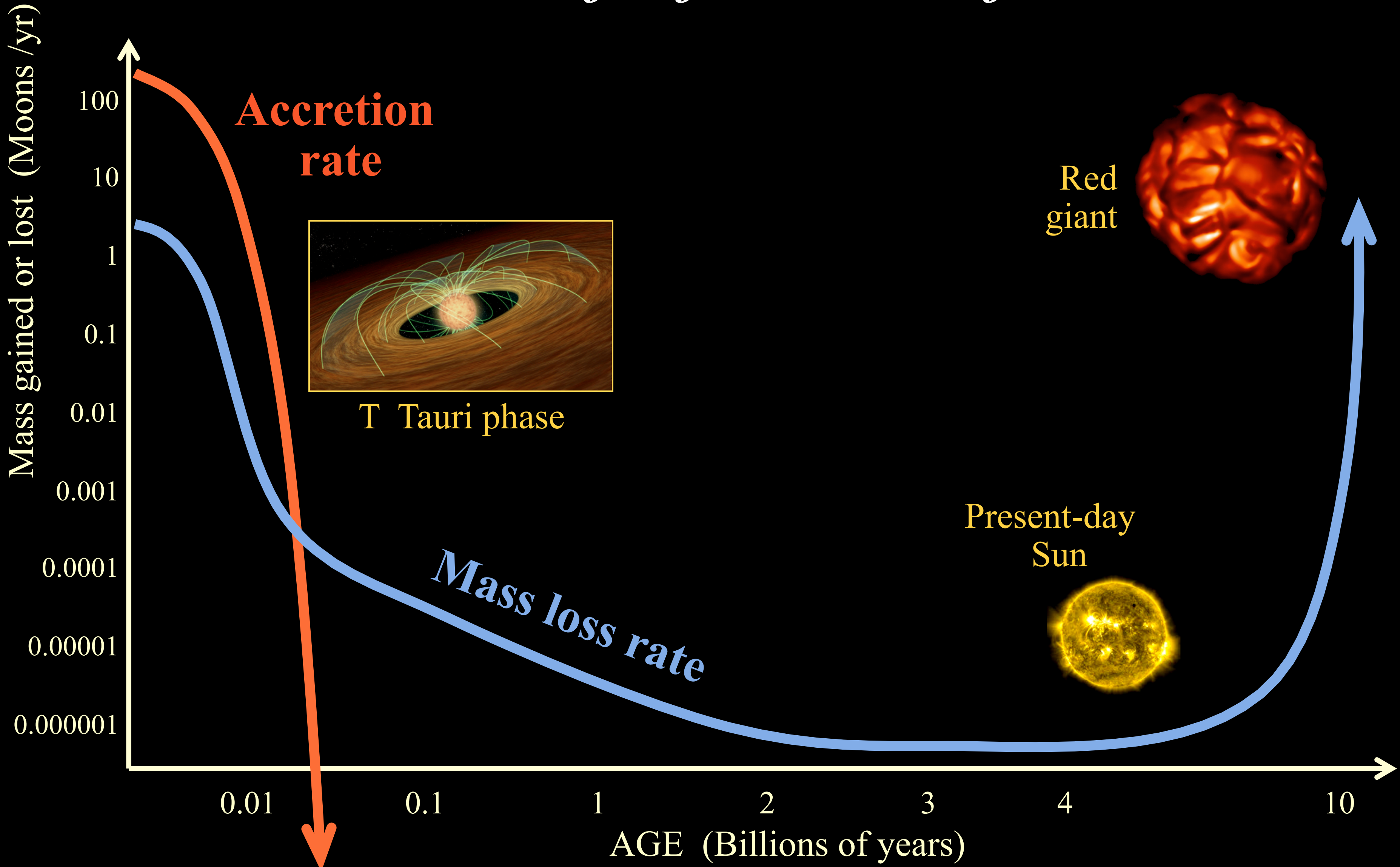




Applying turbulence theory to cool stars

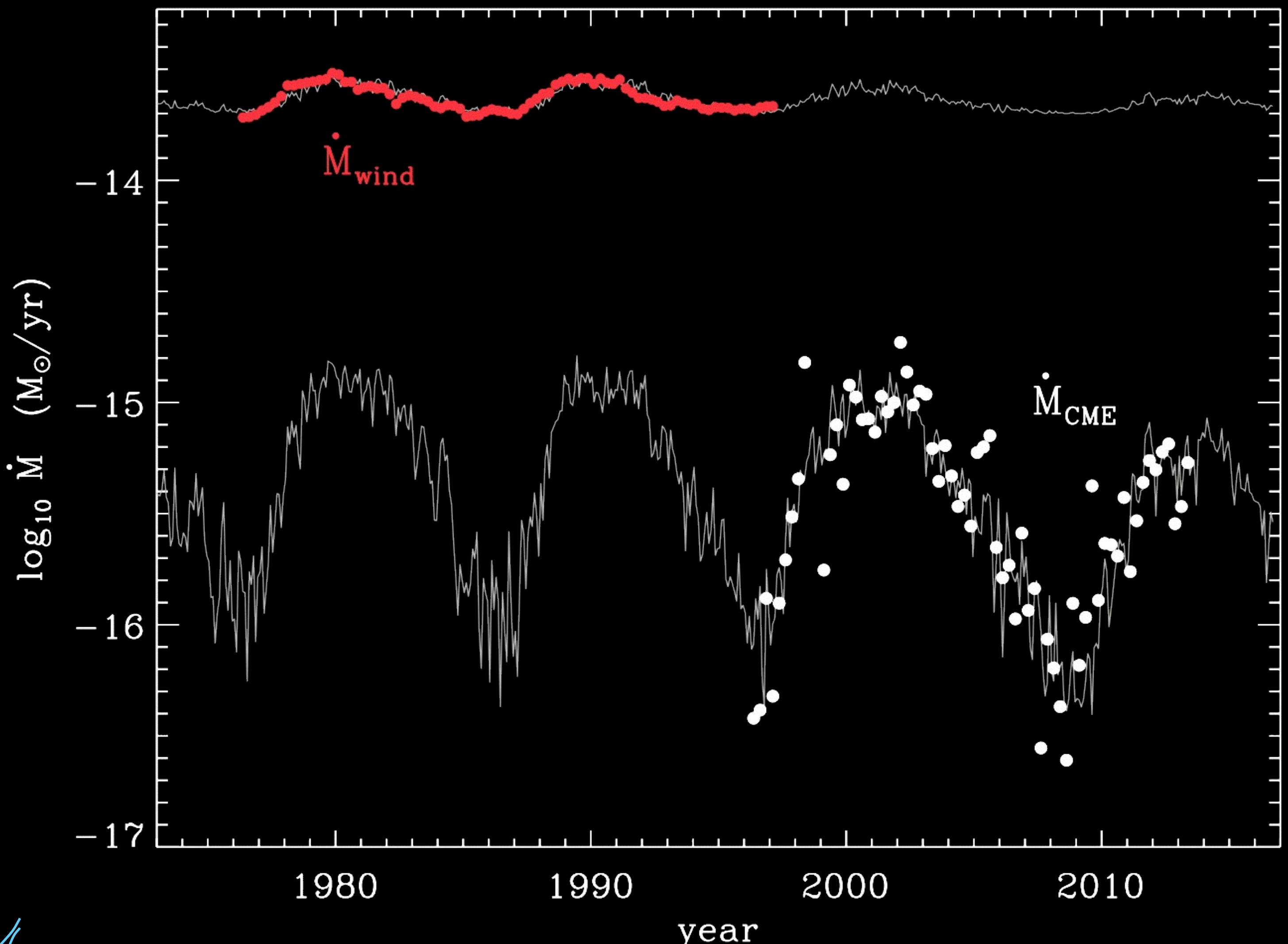


Evolution of inflows & outflows



What about CMEs?

- For present-day Sun, the steady wind beats CMEs by > an order of magnitude.

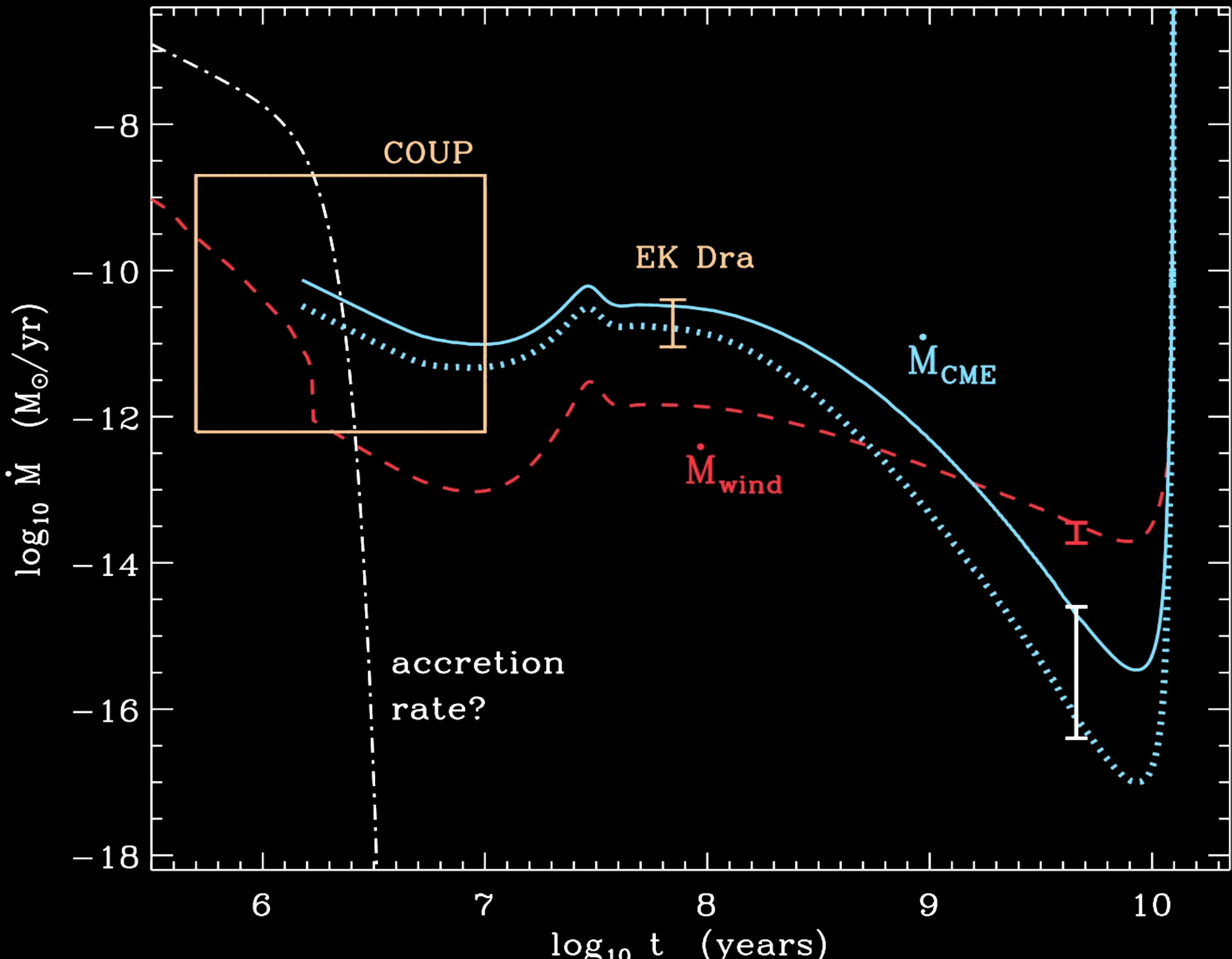


$\sim f_*^{0.27}$

$\sim f_*^{2.51}$

What about CMEs?

- Cranmer (2017): going back in time, CME mass loss "wins!"



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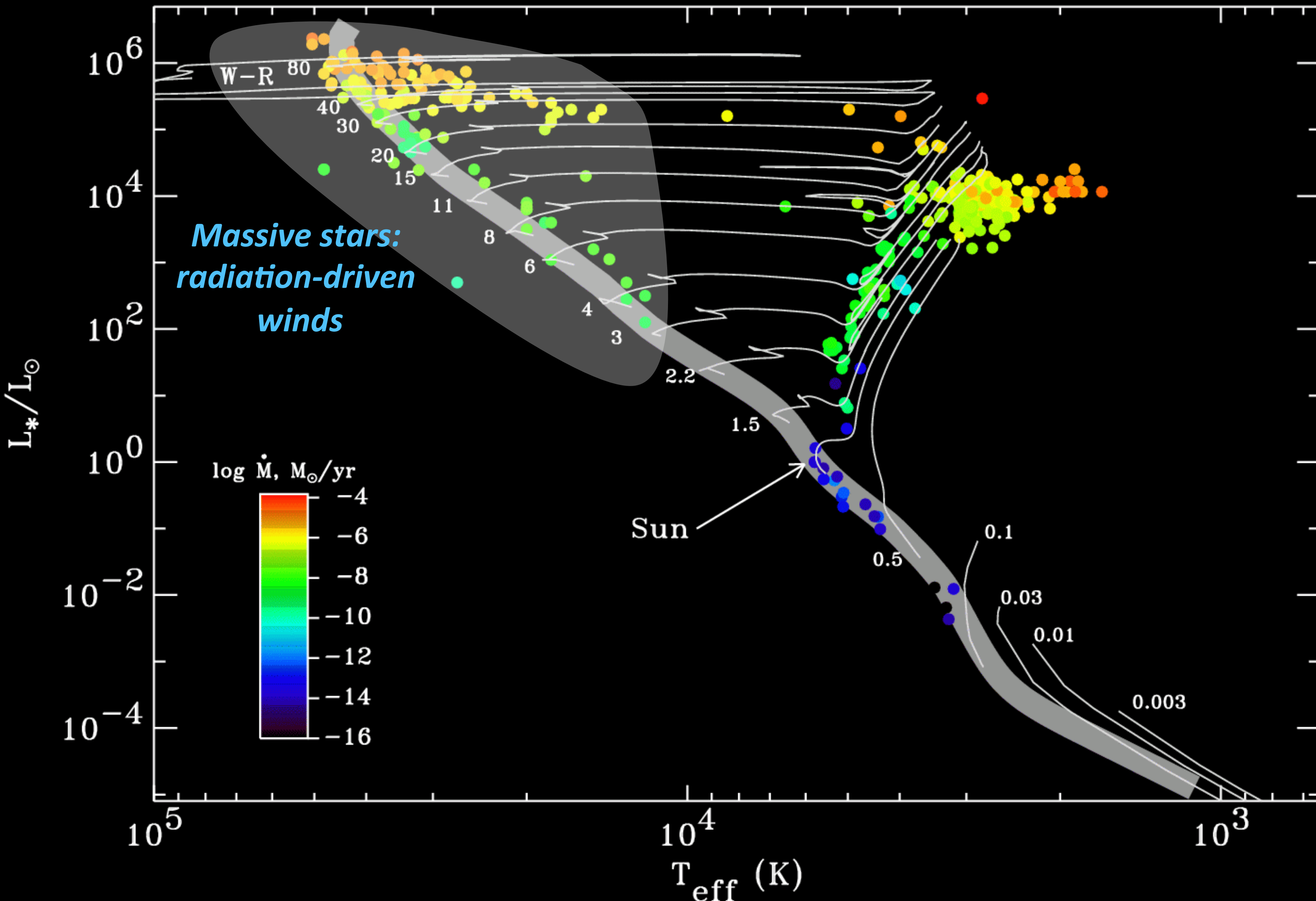
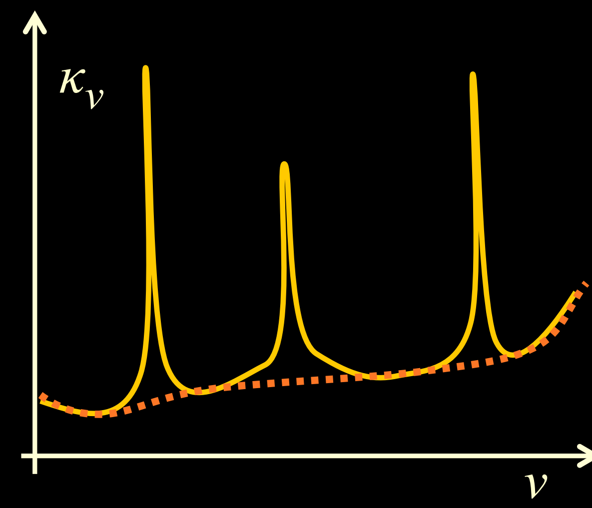


Massive star winds: radiative driving

- Castor, Abbott, & Klein (1975) worked out how a hot star's radiation can accelerate a time-steady wind, even if gravity >> continuum radiation force.

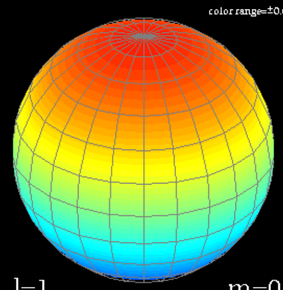


- Spectral lines are the key! $$\mathbf{a}_{\rm rad} = \int d\nu \, \frac{\kappa_\nu \mathbf{F}_\nu}{c}$$

- CAK-type theory works well for spherical stars… but massive stars are…

Rapidly rotating

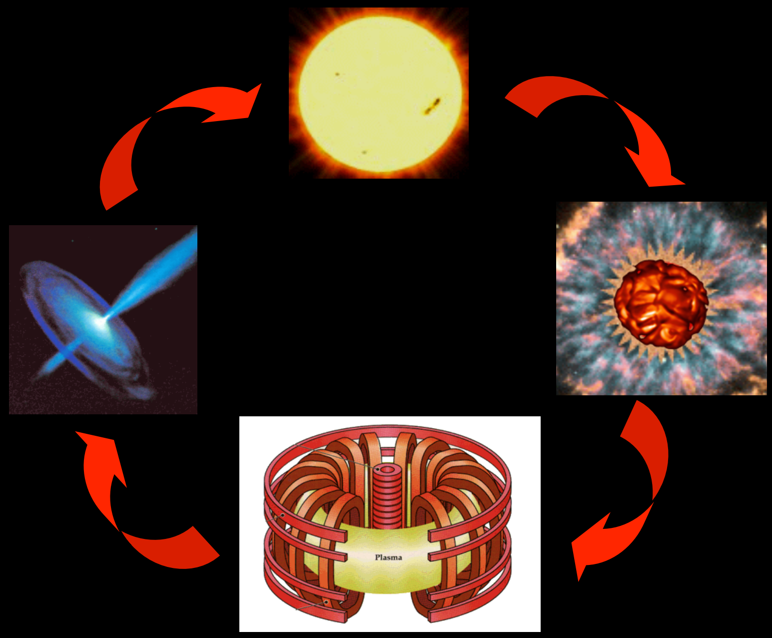
Strongly pulsating



- Most pulsational energy is trapped below the surface.
- But can some of the variability "leak out" into the wind?

Conclusions

- 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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