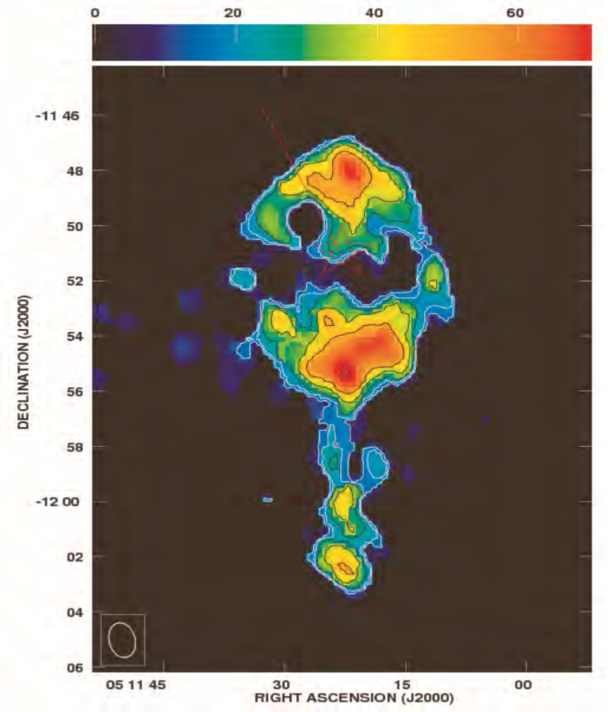
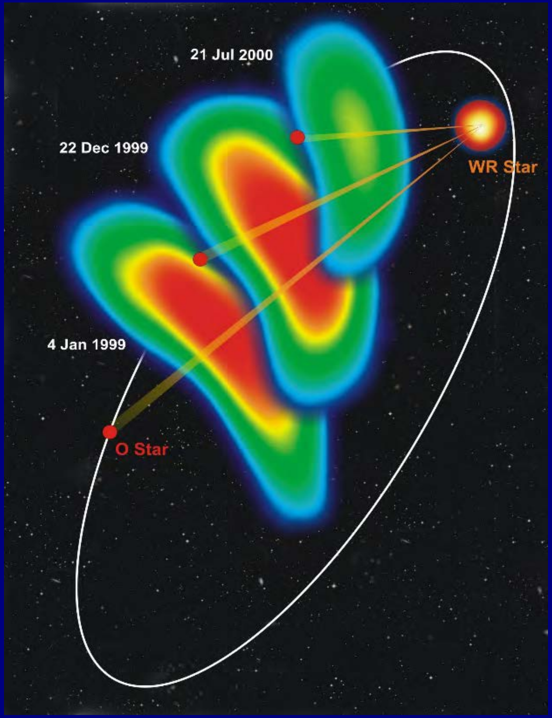
Stellar Winds Across the H-R Diagram



Matthews et al. 2013



Dougherty et al. 2005

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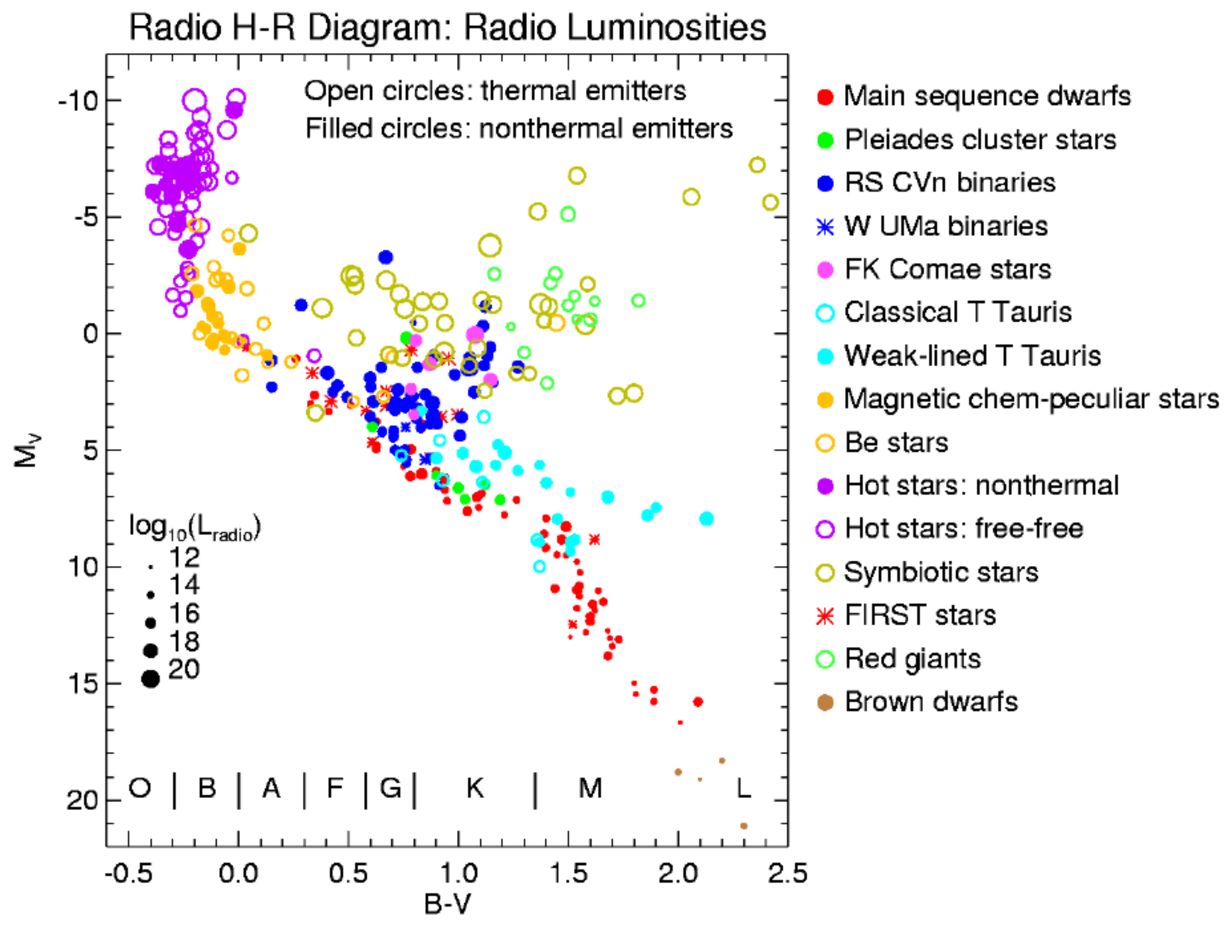
Radio Stars Across the HR Diagram:



Many are from ionized or partially ionized stellar winds.
(S White)

Why Stars Should Not Have Winds

$$\frac{1}{2} m_p \overline{v_p^2} \sim \frac{1}{4} \frac{GMm_p}{R} \sim \frac{1}{4} m_p v_{esc}^2 \rightarrow v_p^2 \sim \frac{1}{4} v_{esc}^2$$

$$\overline{v_p^2} \sim \frac{3k\overline{T}}{m_p} \rightarrow v_{esc}^2 \sim \frac{12k\overline{T}}{m_p}$$

$$\rightarrow \frac{v_s^2}{v_{esc}^2} \sim \frac{T_s}{4\overline{T}}$$

The need to move heat from the interior to the surface should make the T ratio too small to allow escape from the surface.

Why They Do: Push ‘em or Heat ‘em


Radiation Pressure (pushed, by opacity from UV lines or dust)

high luminosity stars

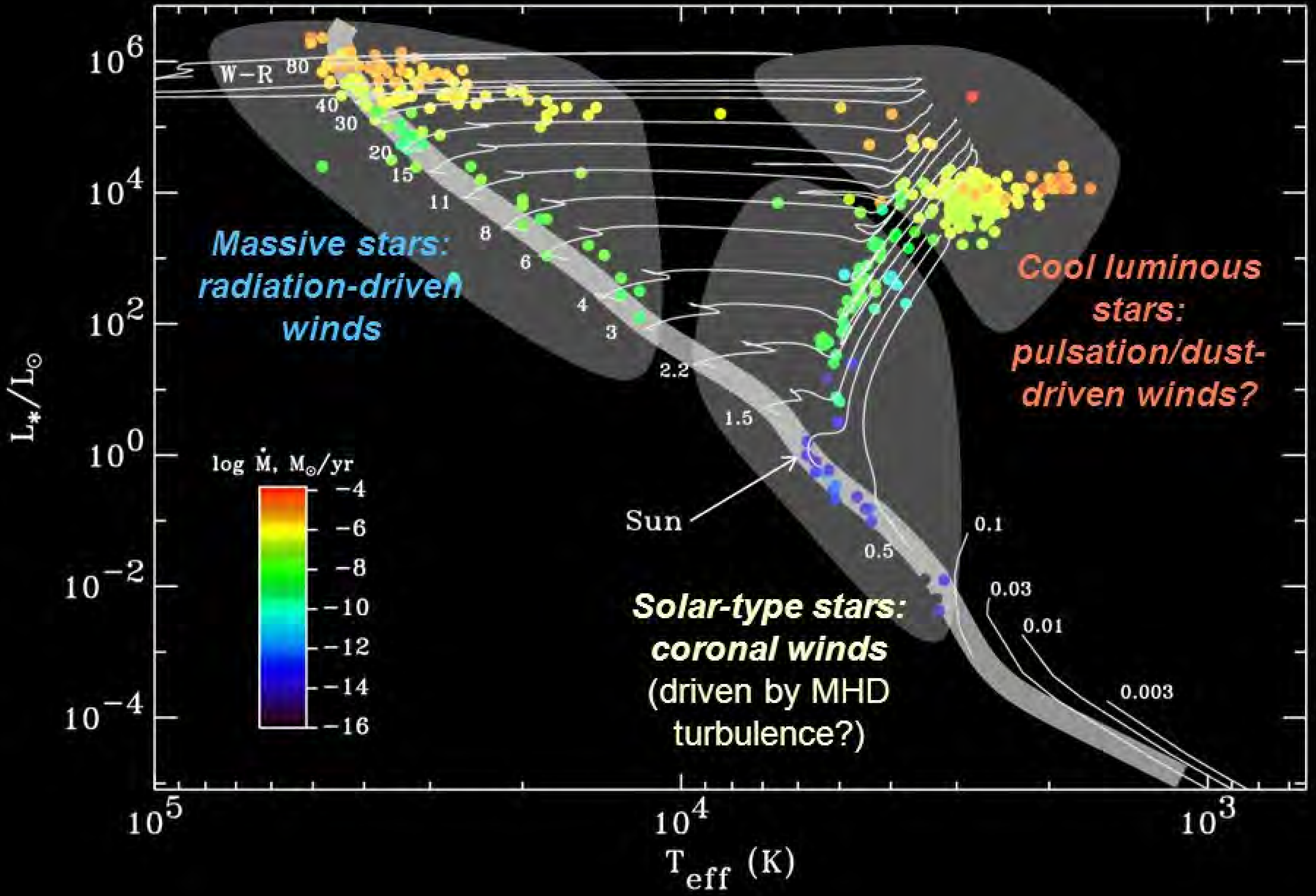

Magnetic Pressure (pushed, by MHD waves or field stresses)

rapid rotators or bloated radii


Gas Pressure (heated, by waves or reconnection or ?)

high temperature winds

Stellar winds across the H-R Diagram



Massive stars: radiation-driven winds

Cool luminous stars: pulsation/dust-driven winds?

Solar-type stars: coronal winds
(driven by MHD turbulence?)

If You Can’t Push ‘em with Light:

If $\kappa_{\max} < \kappa_{Edd} = \frac{4\pi GcM}{L}$ then push with waves if

$$v_{th} \ll v_{esc}$$

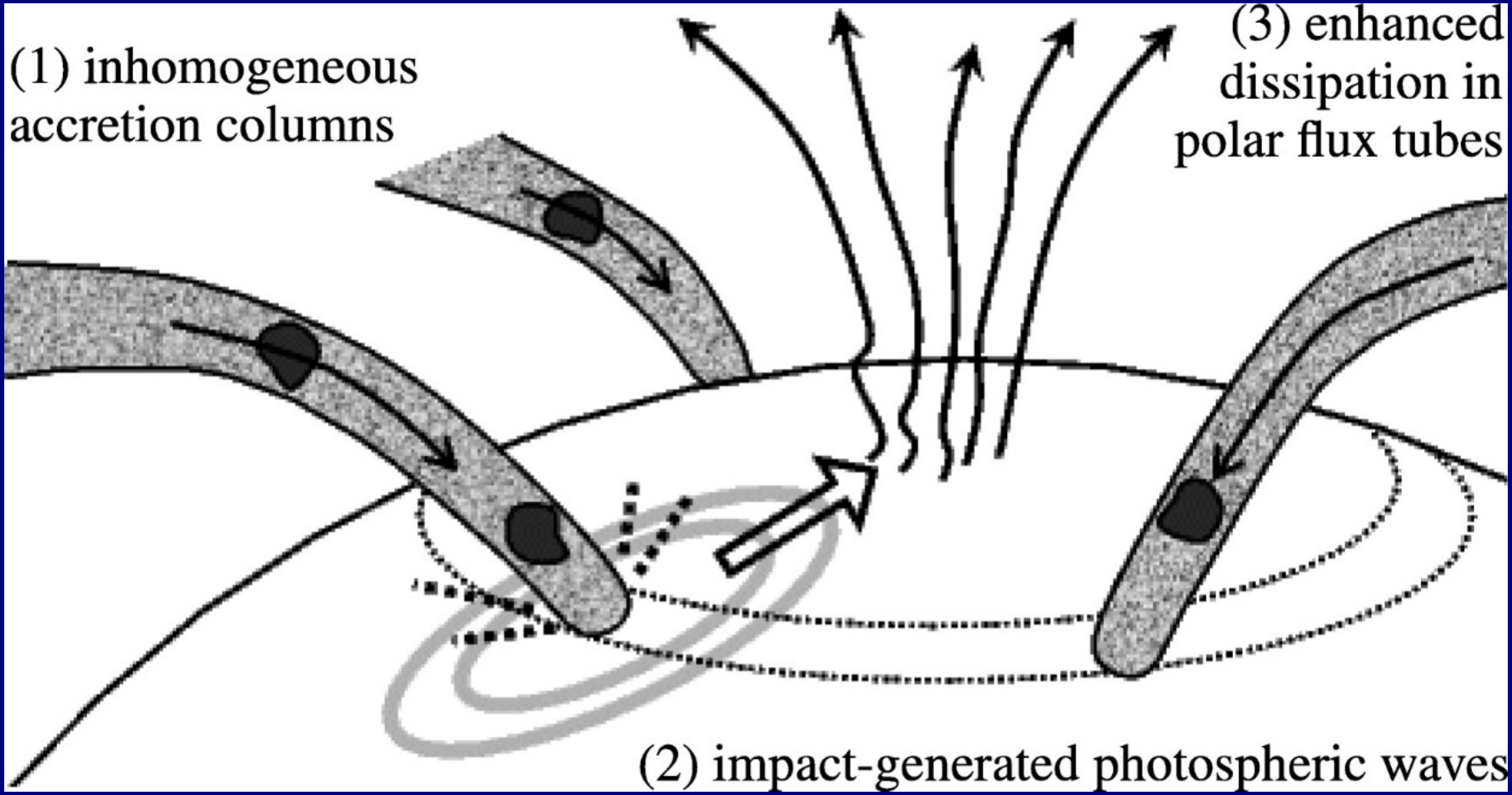
(T Tauri stars? RSGs?)

Or, dump heat into them if you can get $v_{th} \sim v_{esc}$

(Coronal winds)

But watch out for the hump at T~100,000 K, where the radiative line cooling is highly efficient. That corresponds to $v_{esc} \sim 40\, {}^{km}\!/\!{}_{s}$

T Tauri Accretion Driven Winds



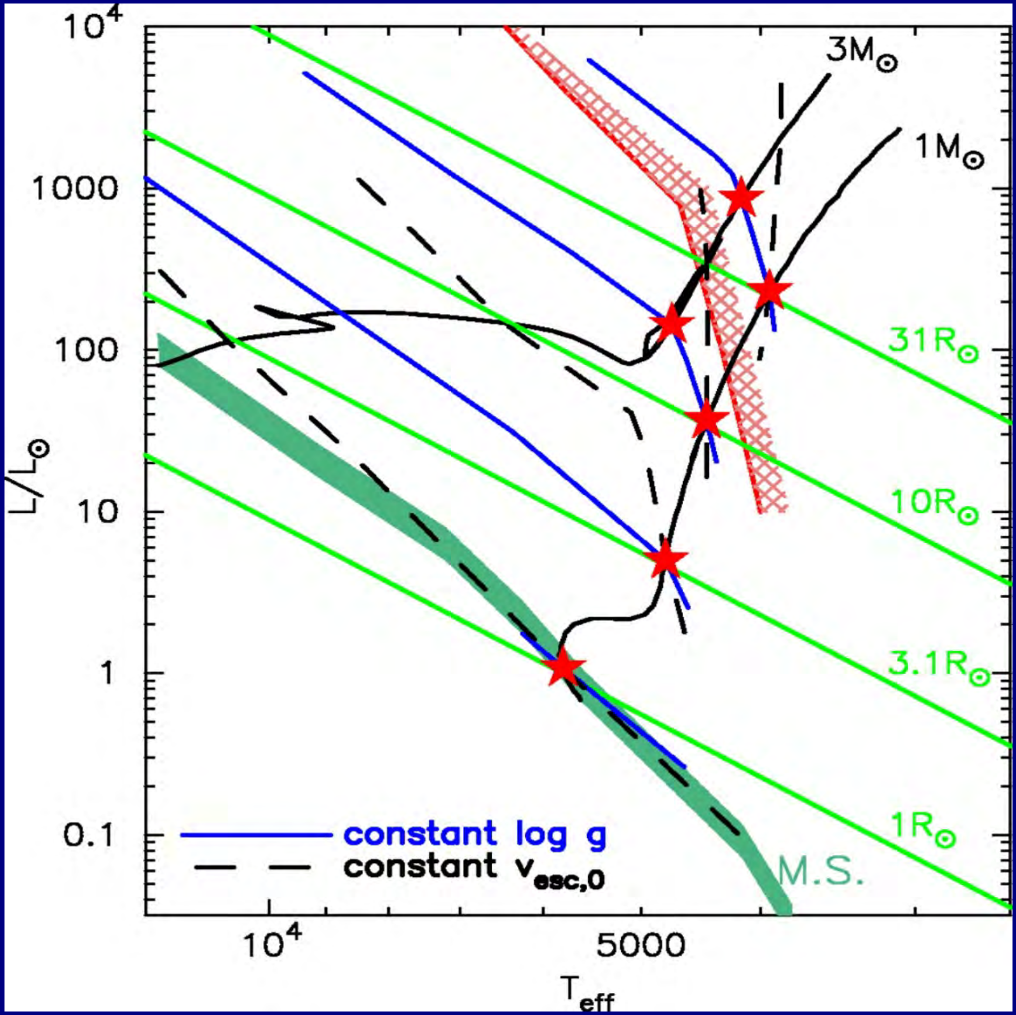
Cranmer 2008

When the escape speed ~ 100 km/s:

Protons can achieve thermal or microturbulent speeds whose tails exceed escape speed without climbing the radiative cooling hump, allowing “chromospheric” winds without a strong momentum source.

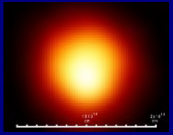
These cool dense winds swamp coronal gas, burying it in the “coronal graveyard” of Linsky, Haisch, and Ayres. This may also be the source of “superwinds” from AGB and RSG stars.

Red Giant Winds

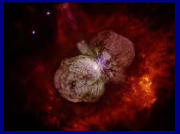


Suzuki 2007

But high-L stars have Eddington opacity below the maximum available opacity: Push 'em with Light



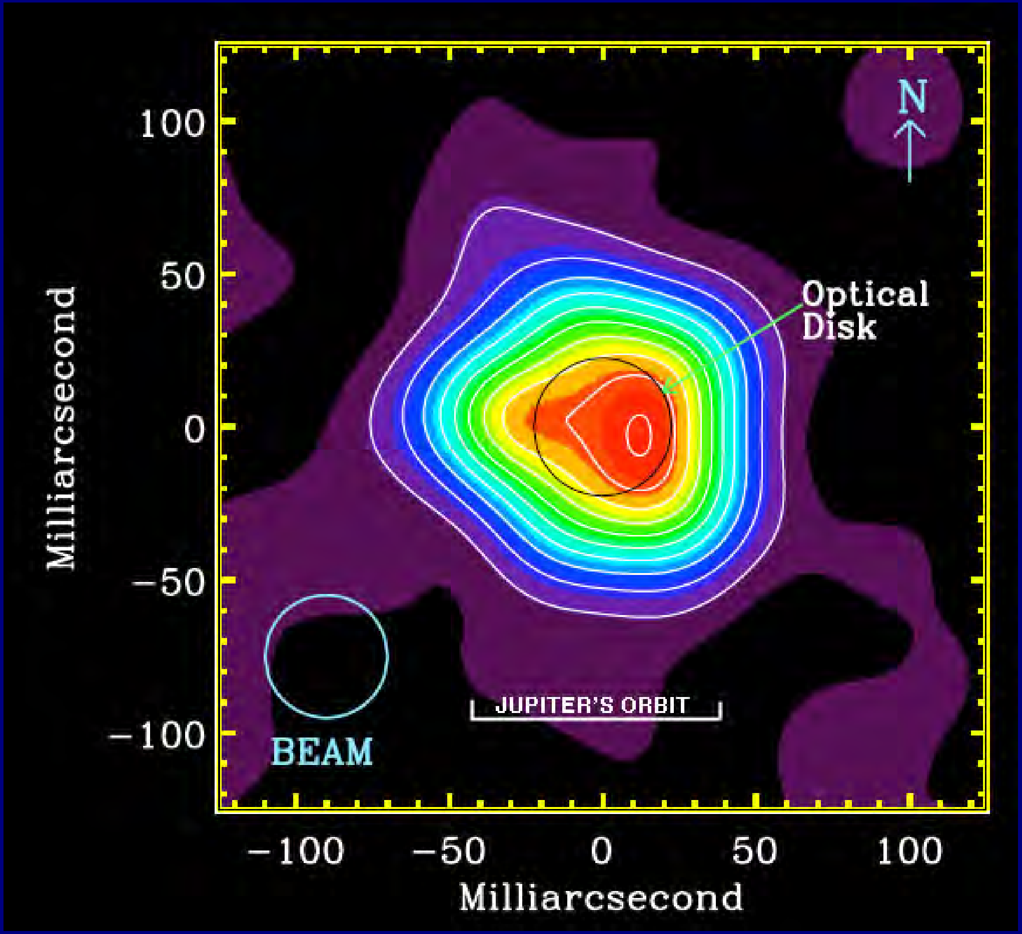
Dust-driven (RSGs, AGBs)



Continuum-driven (LBVs)

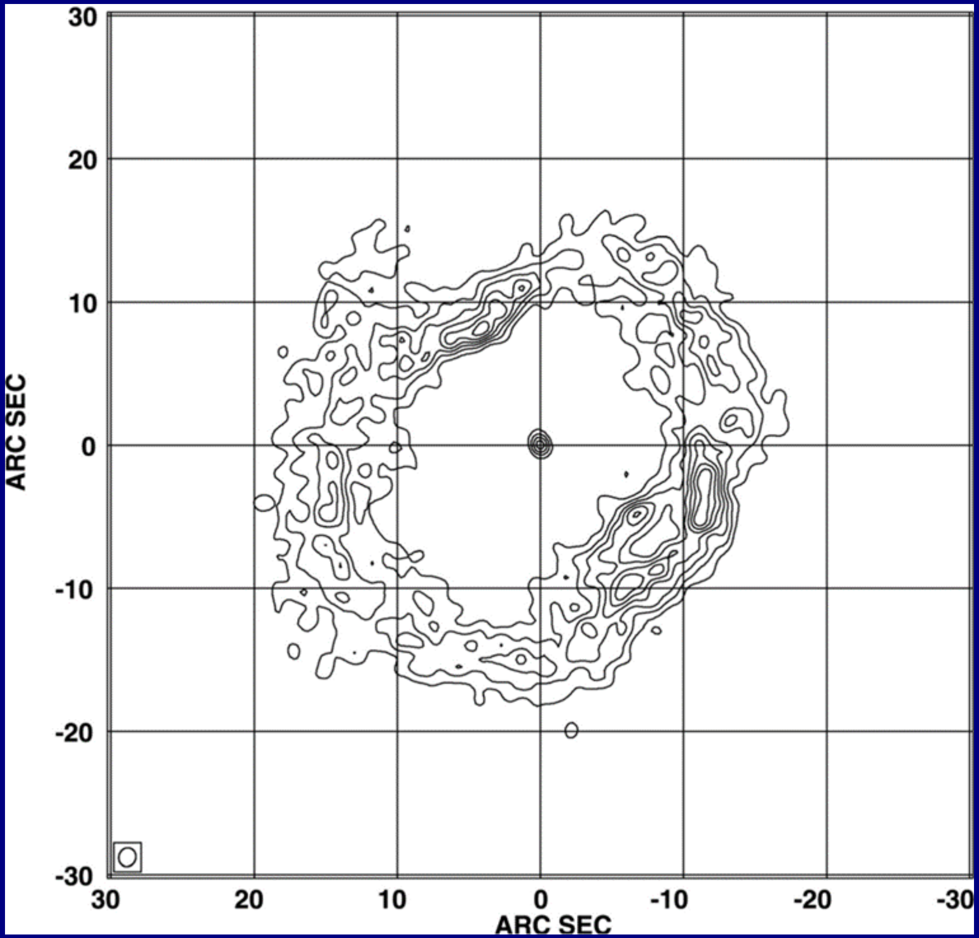
UV line-driven (W-R, BSG,CSPN, hot MS)

Betelgeuse at 7 mm (RSG)

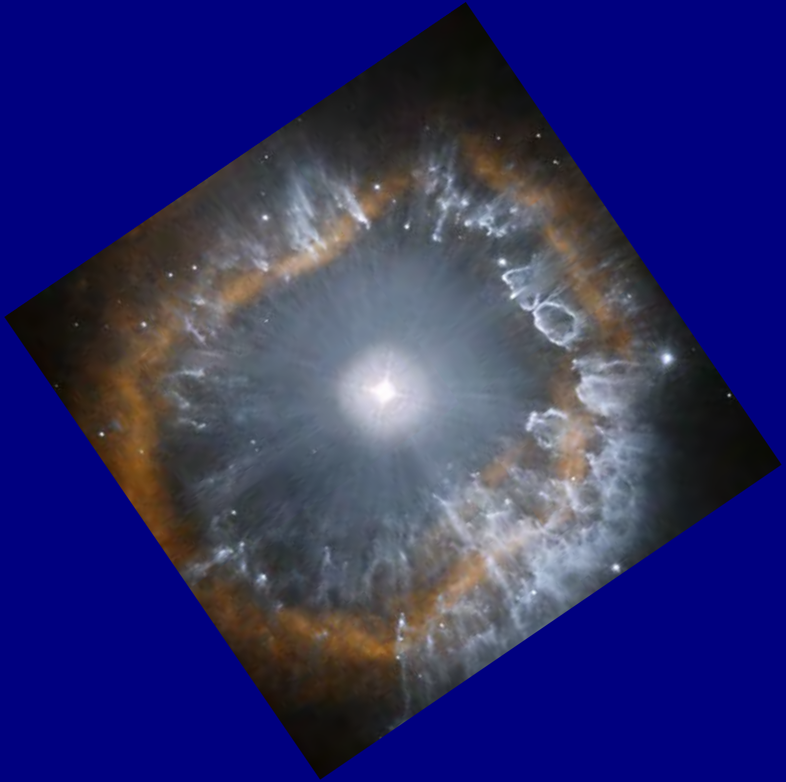


Jeremy Lim, Chris Carilli, Stephen White, Anthony Beasley, and Ralph Marson VLA, NRAO, NSF, NASA.

AG Car (LBV)

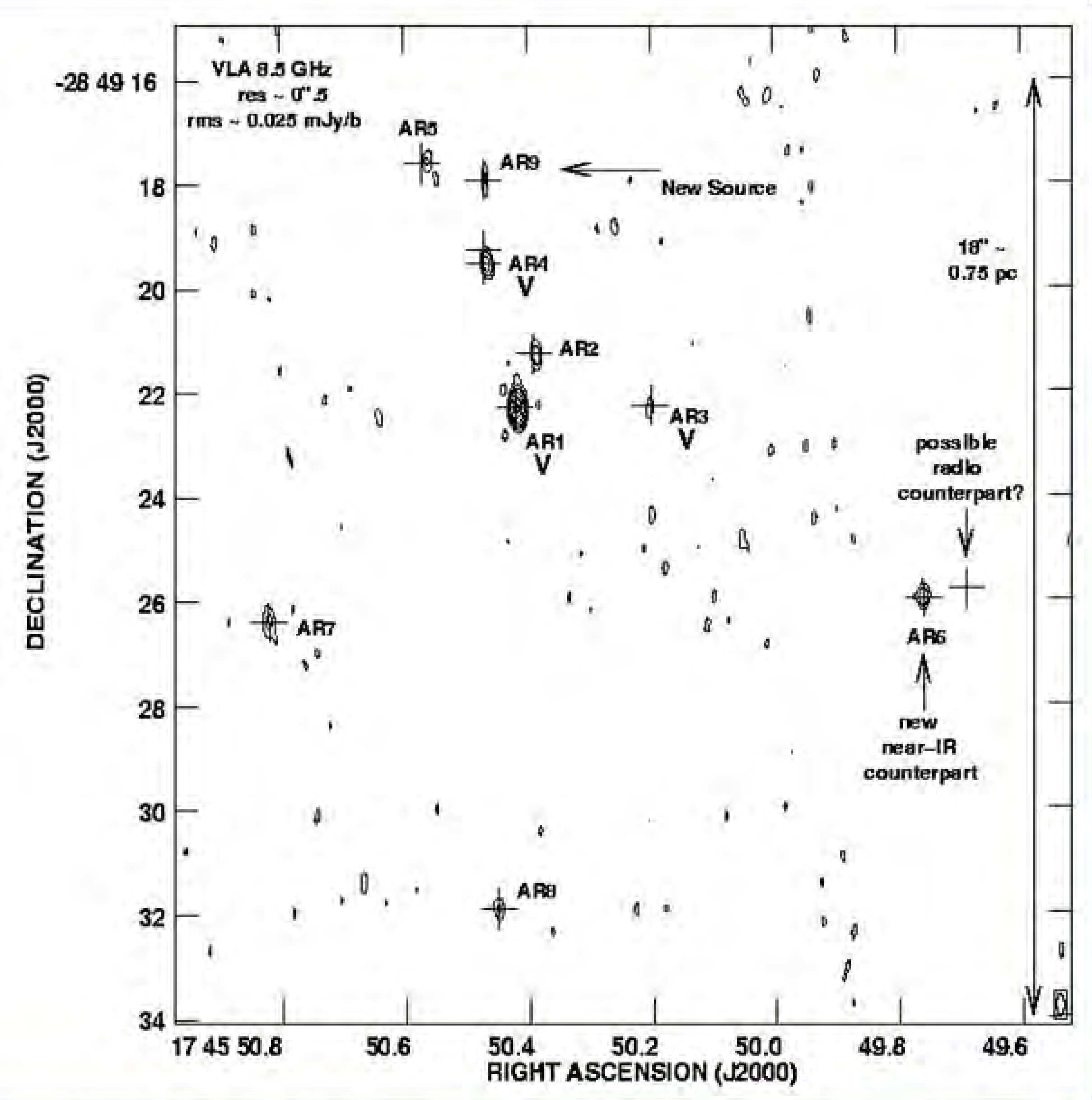


3 cm (Duncan & White 2002)



optical

Radio: Stellar Winds in the Arches Cluster



- 9 sources detected at 4.9, 8.3, 22, 43 GHz

  $\alpha \sim +0.3$ to $+0.9$

  $\alpha \sim -0.7$ (AR6)

- + represent near-IR mass-losing sources

  (Nagata et al. 95; Cotera et al. 96)

- "V" sources show 10-30% variability between epochs

- high mass loss rates $\sim 3 - 17 \times 10^{-5}\ M_{o}\ yr^{-1}$ (no clumping corrections)

combination of 1999 (Lang et al. 2001b) and 2002 observations

CAK Theory of Hot-star Winds

- Wind speed is pegged to the escape speed by the action of thick and thin UV lines:

$$g_{thin} \sim \frac{v_{esc}^2}{R} \qquad g_{thick} \sim \frac{v_\infty^2}{R} \qquad g_{thin} \sim g_{thick} \quad \longrightarrow \quad v_\infty \sim v_{esc}$$

- Mass-loss rises until the line self-shadowing reduces the effective opacity to Eddington level:

$$\kappa_{\max} \cdot f(\dot{M}) = \kappa_{Edd} = \frac{\kappa_{es}}{\Gamma} \longrightarrow \kappa_{\max} \text{ must be } > \frac{\kappa_{es}}{\Gamma}$$

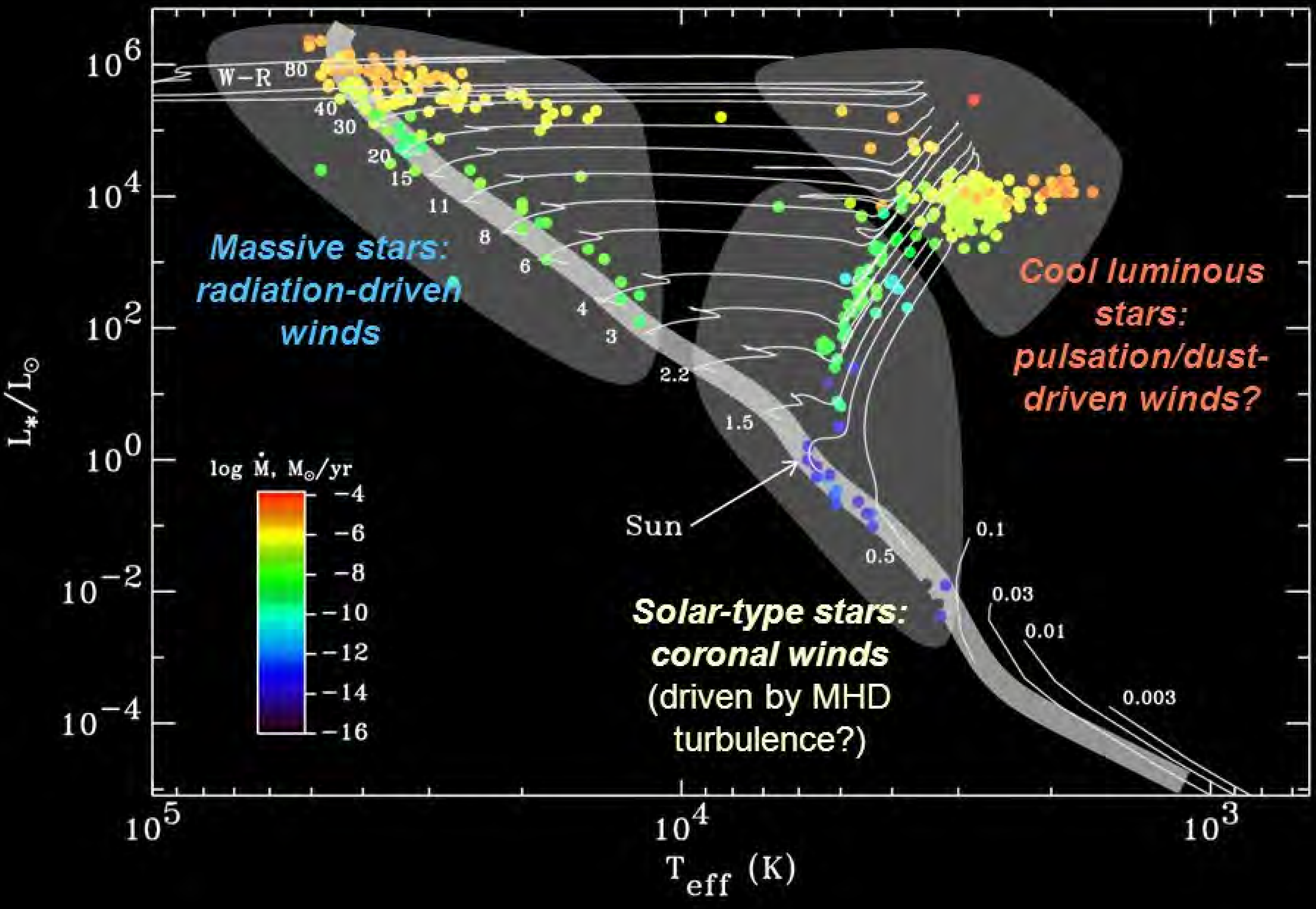
- Max opacity from bound electron resonance multiplier:

$$\kappa_{\max} \sim \kappa_{es} \cdot \bar{Q} \qquad \bar{Q} \sim \frac{3}{8}\frac{\lambda}{r_e} A_Z \sim 10^3 \qquad A_Z \sim 10^{-4}$$

- So the requirement for UV-line driven winds is:

$$\Gamma\bar{Q} > 1 \quad \to \Gamma \sim 10^{-4} M^2 > 10^{-3} \to M > 3$$

Stellar winds across the H-R Diagram



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Hot-star Winds

- So the mass-loss rate is set by the self-shadowing:

$$f(\dot{M})\Gamma\overline{Q} \sim 1 \quad \rightarrow f(\dot{M}) \sim \frac{1}{\Gamma\overline{Q}} \sim \frac{10}{M^2}$$

- Where the self-shadowing reduction is given by:

$$f(\dot{M}) \sim \left(\frac{\kappa_1}{\kappa_*}\right)^{\alpha} \qquad \alpha = \frac{g_{thick}}{(g_{thick} + g_{thin})} \approx \frac{2}{3}$$

- And the barely-thick and strongest line opacities are:

$$\kappa_1 v_{th} \sim \frac{4\pi v_{esc}^2 R}{\dot{M}} \qquad \kappa_* v_{th} \sim \frac{\pi e^2 A_Z}{m_p m_e \nu}$$

- Which leads to:

$$f(\dot{M}) \sim \left(\frac{8Gm_p m_e M}{e^2 A_Z \nu \dot{M}}\right)^{2/3} \sim \frac{10}{M^2} \quad \rightarrow \dot{M} \sim 10^{-13} M^4$$

Hot-star Winds

- This gives the fraction of its mass that a UV star loses in each cycle of a driving UV photon, from basic constants:

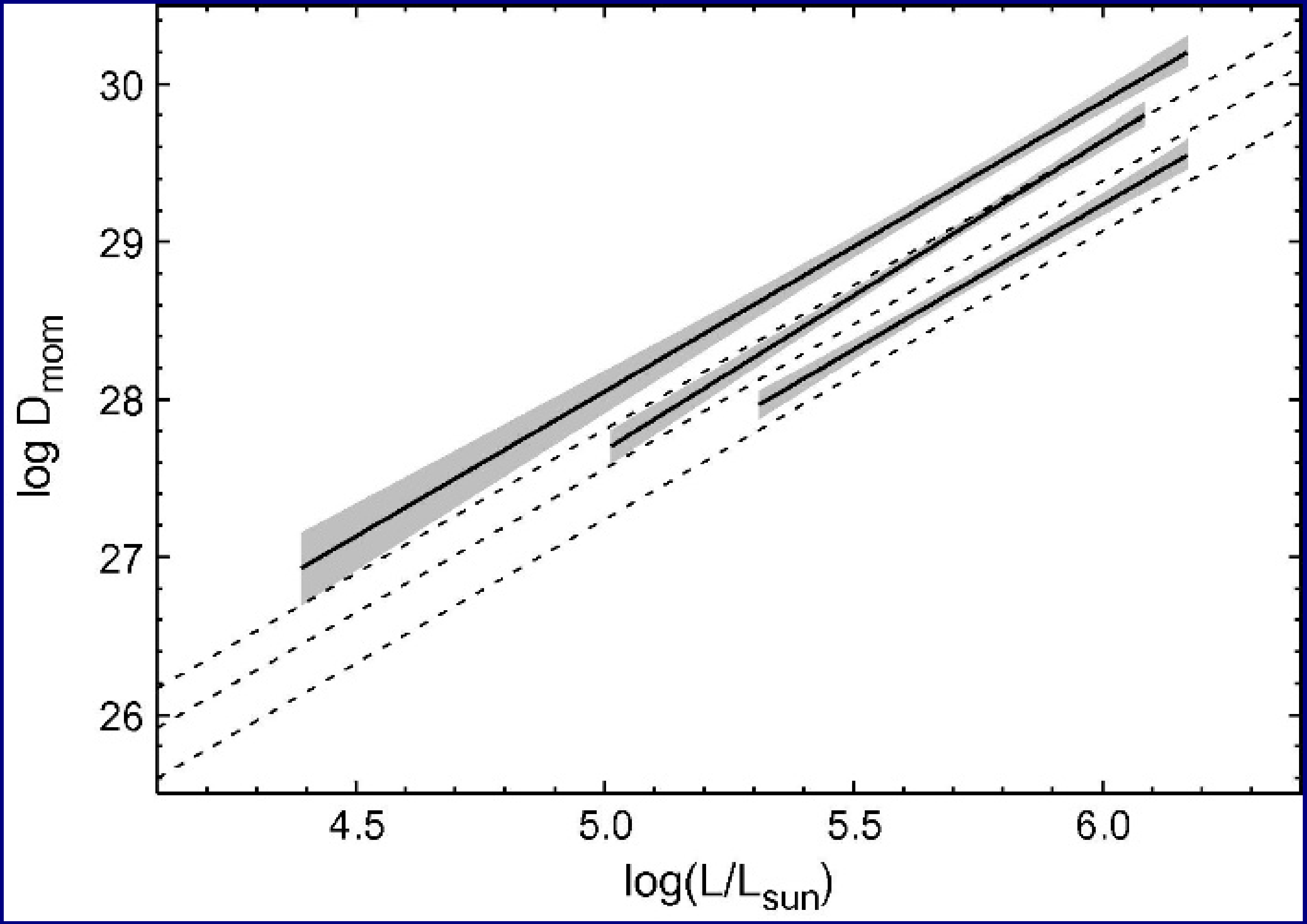
$$\frac{\dot{M}}{\nu M} \sim \left(\frac{2\pi\lambda}{\lambda_C}\right)^{3/2} \frac{m_p m_e}{m_o^2} \alpha_e^{-5/2}\Gamma^{3/2}\sqrt{A_Z}$$

$$\sim 10^{-28}\Gamma^{3/2}\sqrt{A_Z}$$

- Here λ_C is the electron Compton wavelength, and

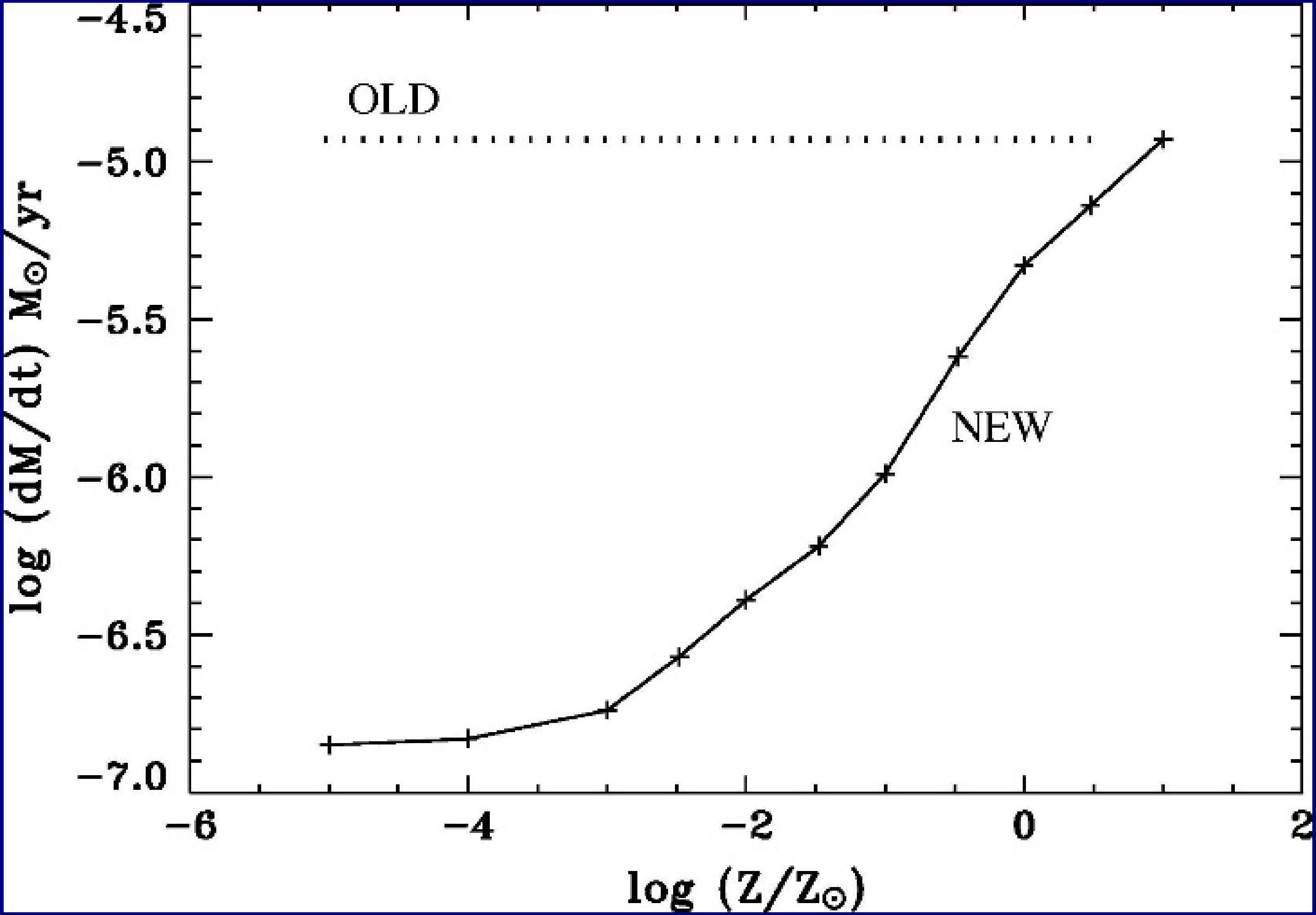
  m_o is the Planck mass.

Hot-star Winds



Mokiem et al. 2007

Hot-star Winds



Vink & de Koter 2005

Dust-Driven AGB Winds

- Eddington opacity from dust when:

$$\kappa_{Edd} = \frac{\kappa_{es}}{\Gamma} < \kappa_{dust} < \frac{Z\sigma}{m} \sim \frac{Z}{\sqrt{\sigma}}$$

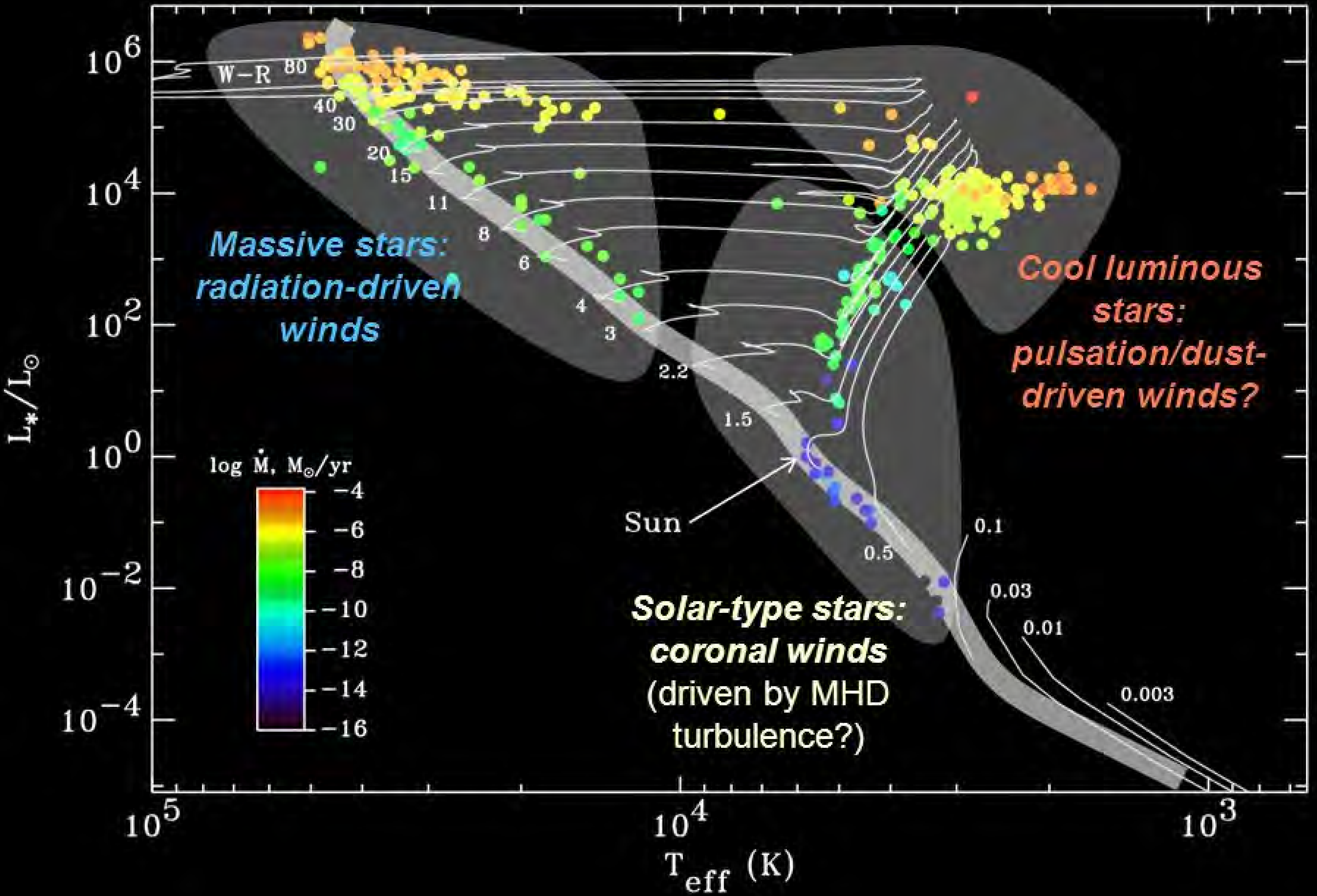
is at peak efficiency when the cross section matches the micron driving radiation:

$$\sigma \sim 1\mu^2$$

which implies

$$\Gamma > \frac{\sqrt{\sigma}\kappa_{es}}{Z} \sim 10^{-2} \qquad \rightarrow \frac{L}{M} > 10^2$$ in solar units

Stellar winds across the H-R Diagram



But Can the Wind Achieve It?

- The wind cannot self-regulate to achieve both optical cross sections and complete dust creation on exactly the wind timescale
- The wind might self-regulate its mass flux to achieve one or the other, but which?
- Dust-driven wind speeds tend to be well below escape speeds
- Perhaps this is because dust must be created, and wind initiates as soon as it levitates against gravity, with little inertial term

Coronal Winds

Dwarfs: Parker winds explain how adding heat to low-density gas invokes the thermal instability above T~100,000 K, allowing

$$v_{th} \sim v_{esc}$$

Giants: Lower escape speeds induce chromospheric winds before the gas can get to coronal temperatures, although pockets of hot gas may be “buried in the coronal graveyard”

Conclusions

- Significant progress has been made in understanding line-driven, dust-driven, chromospheric, and coronal winds
- Many important questions remain, and can be addressed in the radio regime

Questions for RG and AGB Winds

- Can pulsations alone drive weaker winds?
- What causes the transition to superwinds?
- Is optimal micron-sized dust achieved?
- How are winds driven when C/O~1?
- Does the thermal instability play a role when the escape speed is low enough?
- Are dust-free winds driven by adding heat, or by pushing with waves?

Questions for Hot-Star Winds

- What provides the extra opacity needed to explain the high momentum of WR winds?
- How strong is wind clumping and what are the implications of lower mass-loss rates?
- Is wind clumping due to the LDI, or variable mass loading at the base of the wind?
- How do rapid rotation or strong magnetic fields affect wind geometry?

Questions for Coronal Winds

- How is the corona heated?
- What is causing the “afterburner” effect in the fast solar wind?
- What aspects of the star alter the balance between steady mass loss and episodic CME-type mass loss?

Questions for Winds of All Types

- What is the history and future of a wind?
- Is it continuous or episodic, and increasing or decreasing with age?
- How is mass loss affected by rapid rotation or strong magnetic fields?
- When is a wind an outside-in surface phenomenon, and when an inside-out consequence of interior processes?