Stellar evolution of the most massive stars from seismic tuning

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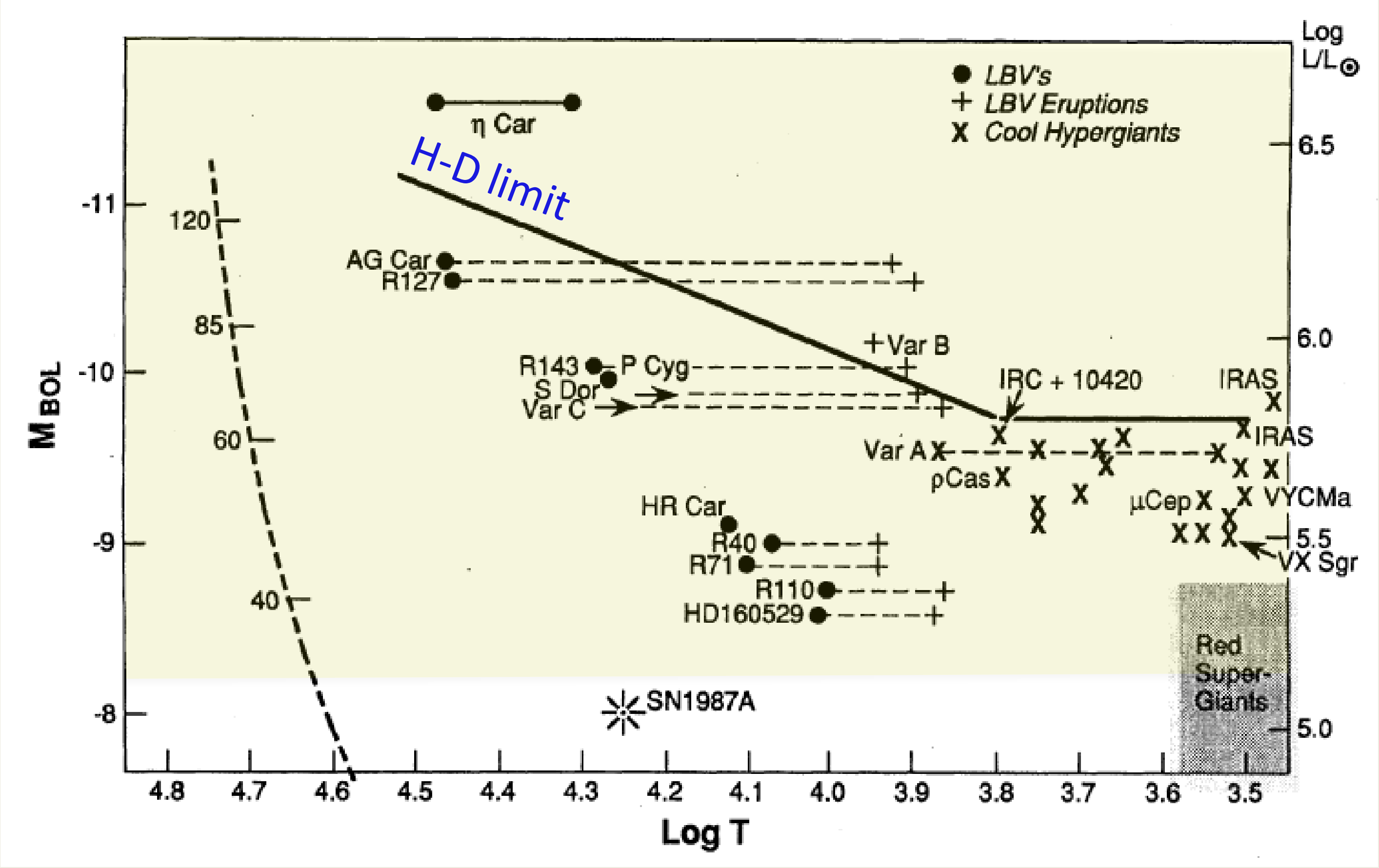
Semi-periodic variations in S Dor and alpha Cygni variables

Radial pulsations excited by Strange-mode instability

Wind mass loss from massive stars ($\geq 25\ M_\odot$)

Semi-periodic light variations in most massive stars

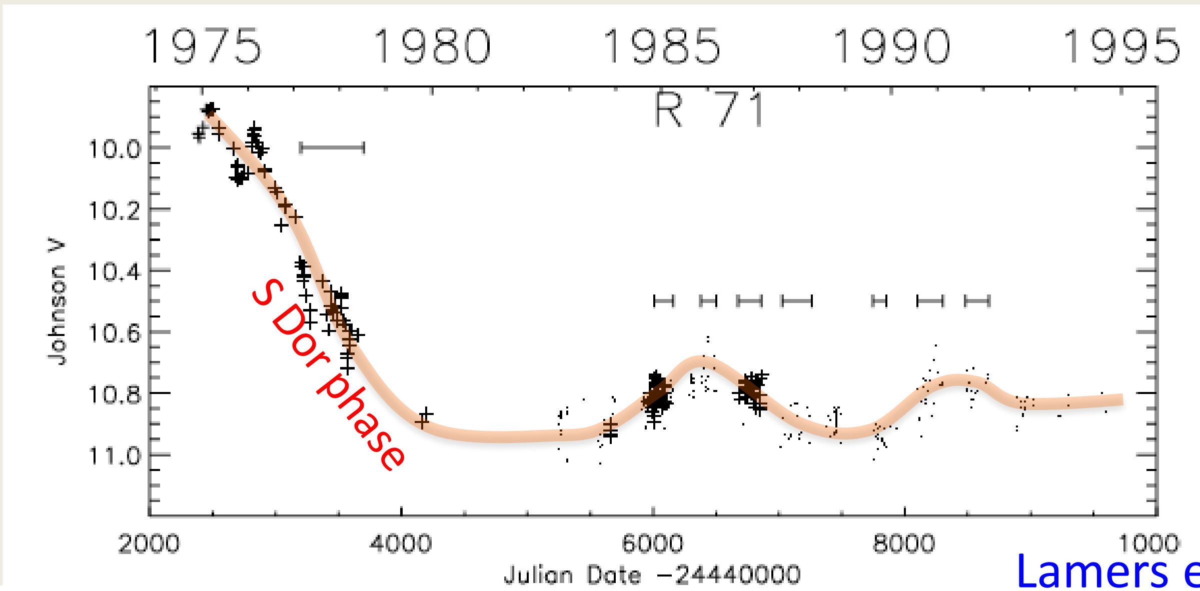
S Dor variables (LBV)
Alpha Cygni variables

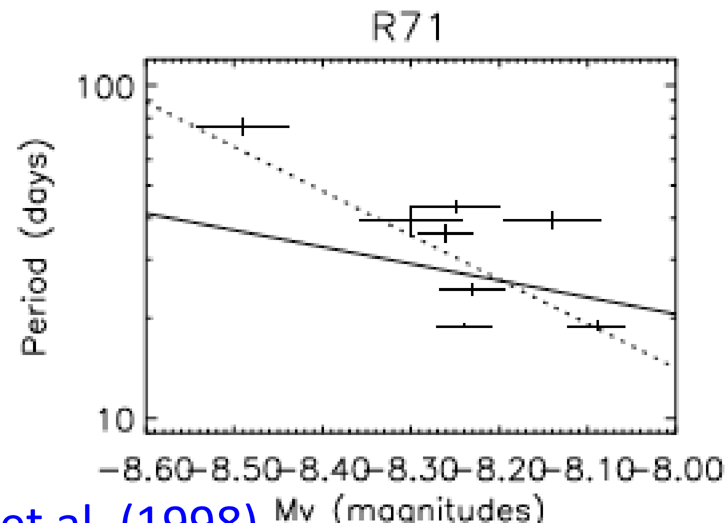


Humphreys and Davidson (1994)

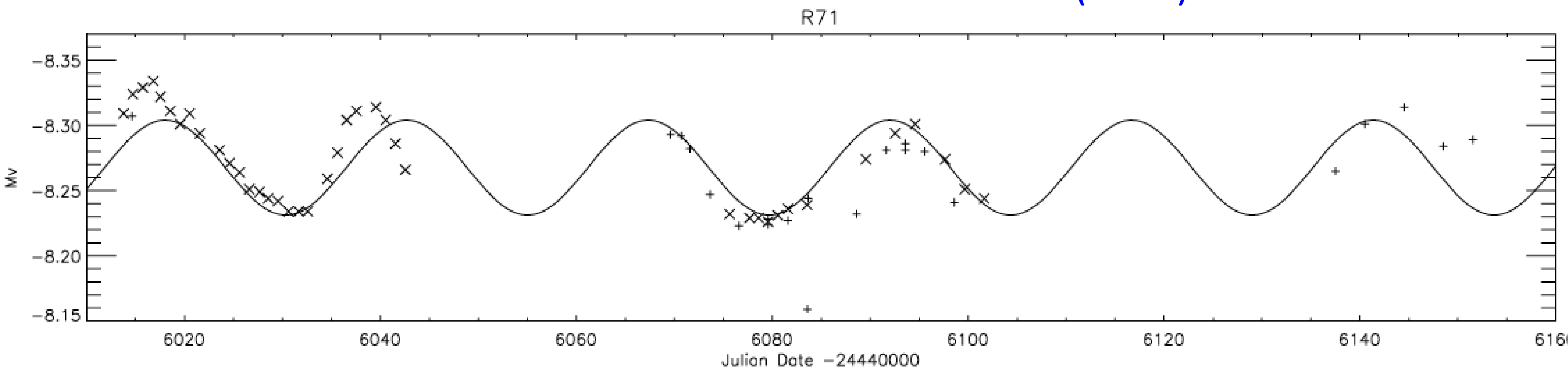
S Dor variables (LBV) show semi-regular variations

Periods; 10 -- 100 days



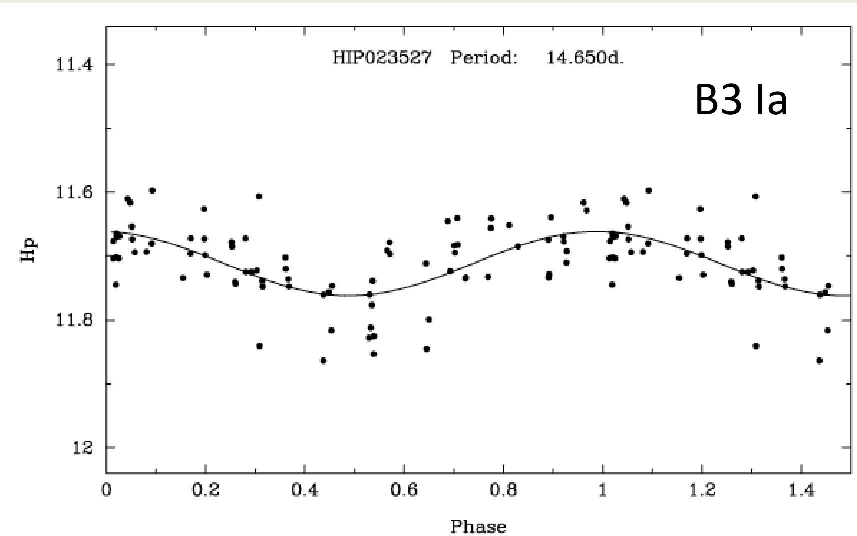


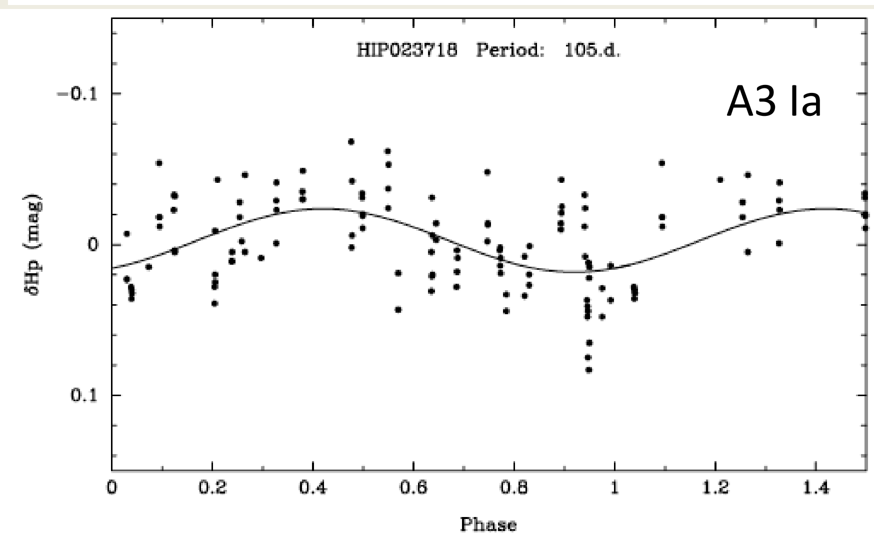
Lamers et al. (1998)



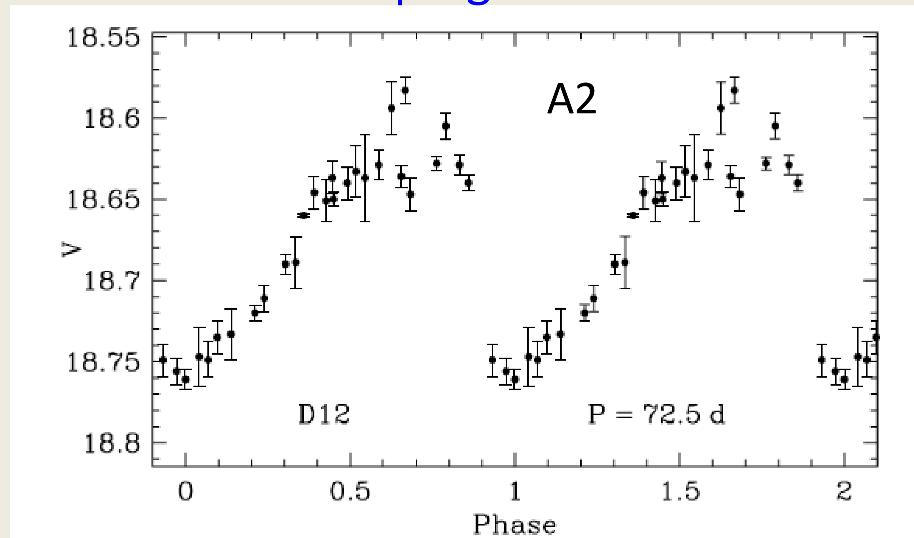
α Cyg variables – Peiods are similar to S Dor stars but no S Dor phases

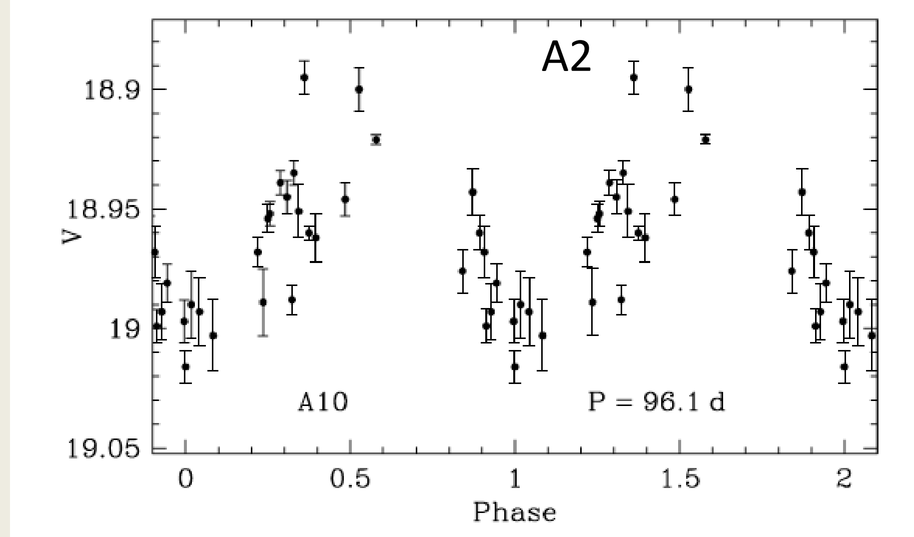
van Leeuwen et al. (1998)
Hipparcos supergiant variables





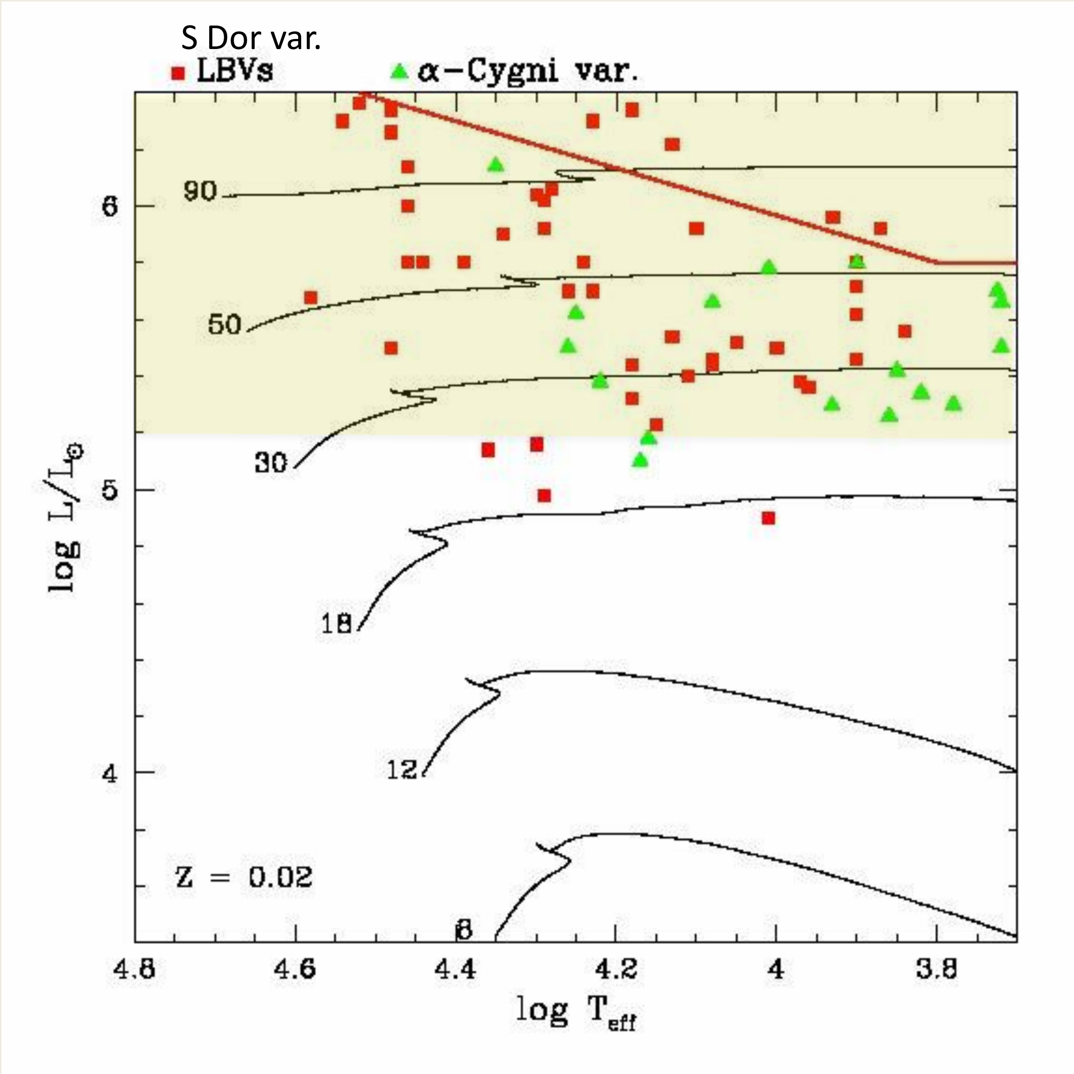
Bresolin et al. (2004)
Variable supergiants in NGC 300





S Dor and α Cygni variables show semi-regular variations with periods;   10 days ---- 10^2 days

Light-curves are simple --- probably radial pulsations

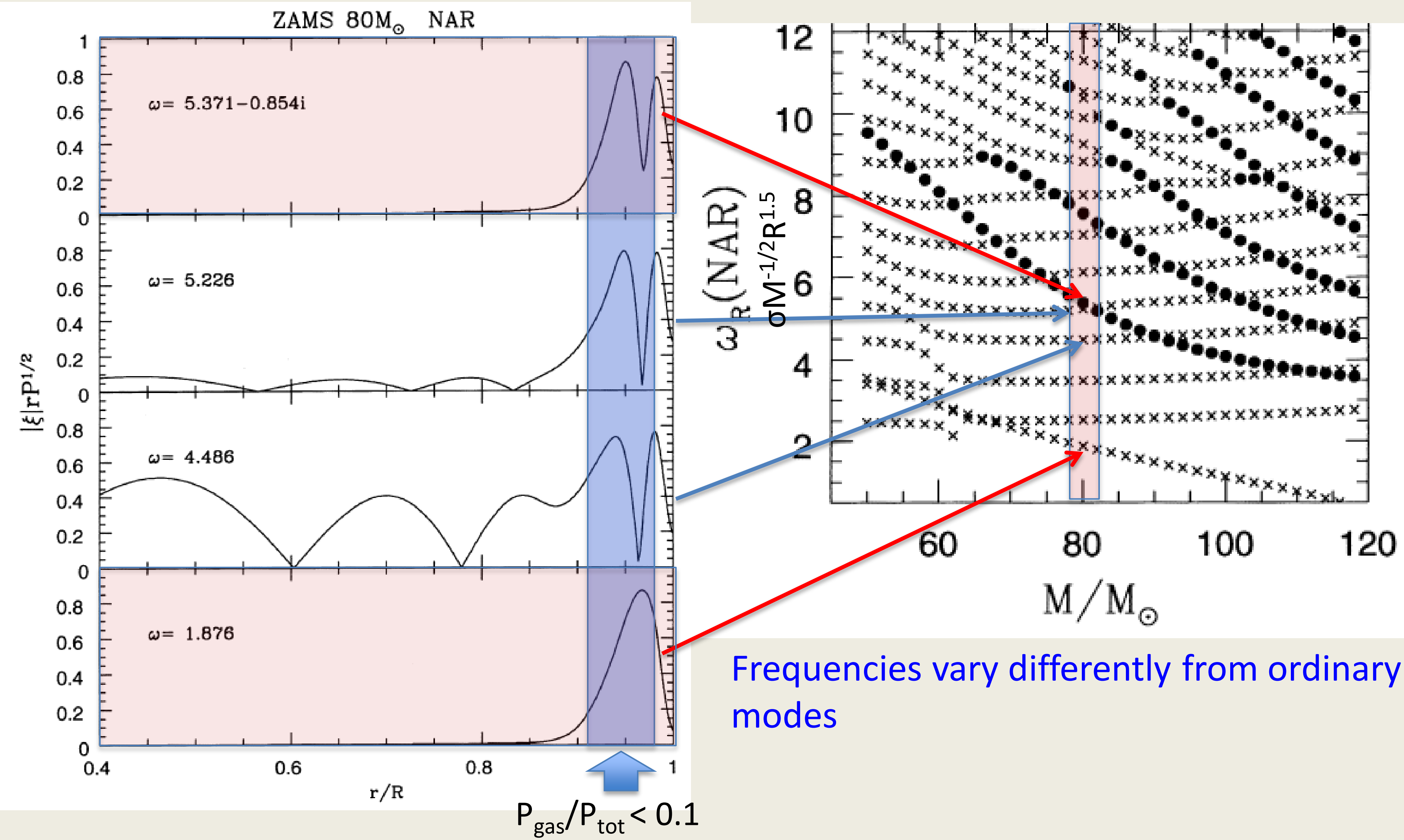


Both groups similarly distributed in HRD

Bounded by luminosity
log L > 5.2   (M_i > 25)
but no color boundary

They are excited by
strange-mode instability

Strange modes in very luminous stars ($L/M > 10^4$)



Frequencies vary differently from ordinary modes

Strange modes are trapped in a cavity where $P_{rad}/P_{gas} >> 1$ ($L/M > \sim 10^4$)

Strange mode instability (L/M > 10^4)

In extremely nonadiabaric limit; $t_{th} \to 0$

$$ist_{th}\frac{Ds}{C_p} = De_n - \frac{dDL_r}{dM_r} \to 0; \quad i.e., \quad \frac{dDL_r}{dM_r} \approx 0$$ in the envelope

Plane-parallel approximation (for strange modes trapped in outer layers)

$$\frac{\Delta F}{F} = -\frac{\kappa_T}{4}\frac{\Delta P_R}{P_R} - \kappa_\rho \frac{\Delta\rho}{\rho} - \frac{c}{\kappa F}\frac{\partial \Delta P_R}{\partial m} = 0$$

Assume $k_T = 0$ for simplicity

$$\frac{\partial \Delta P_R}{\partial m} = -\frac{\kappa_\rho \kappa F}{c}\frac{\Delta\rho}{\rho}$$

$P_R >> P_{gas};$

$$\frac{\partial \Delta P}{\partial m} = -\frac{\kappa_\rho \kappa F}{c}\frac{\Delta\rho}{\rho}$$

(cf. adiabatic relation; $\frac{\Delta P}{P} = \Gamma_1 \frac{\Delta\rho}{\rho}$)

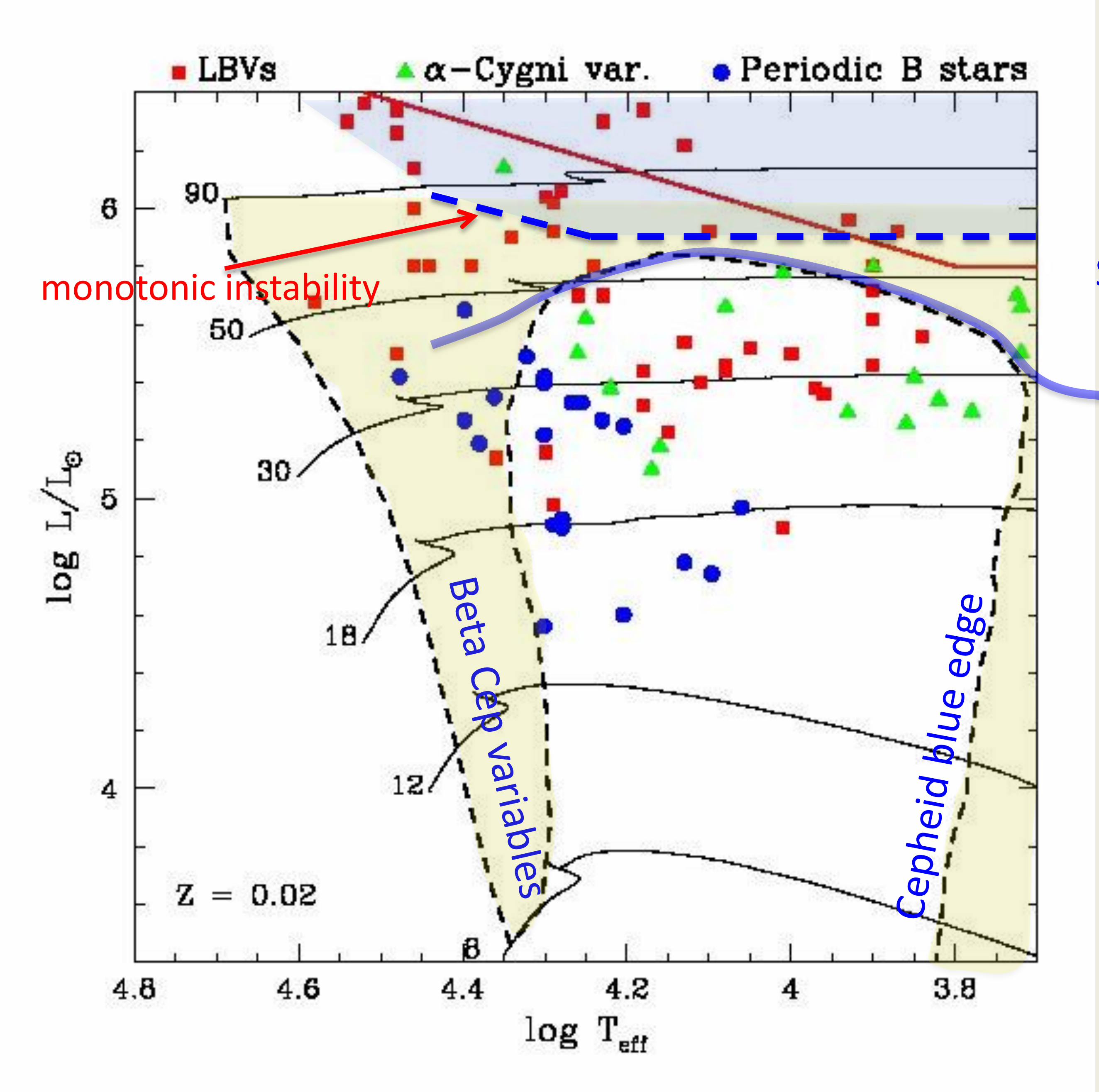
$$\Delta P \propto \exp(i\sigma - ik_z)$$

$$\Delta P = i\frac{\kappa_\rho \kappa F}{k_z c}\Delta\rho$$

Large phase difference between ΔP *and* $\Delta\rho$

---→ Strong instability

Instability boundary for low-order radial-modes



Extremely nonadiabatic

$$P_{rad} >> P_{gas}$$

$$\frac{\partial \Delta P}{\partial m} \approx -\frac{\kappa_\rho \kappa F}{c}\frac{\Delta\rho}{\rho}$$

Strange-mode instability

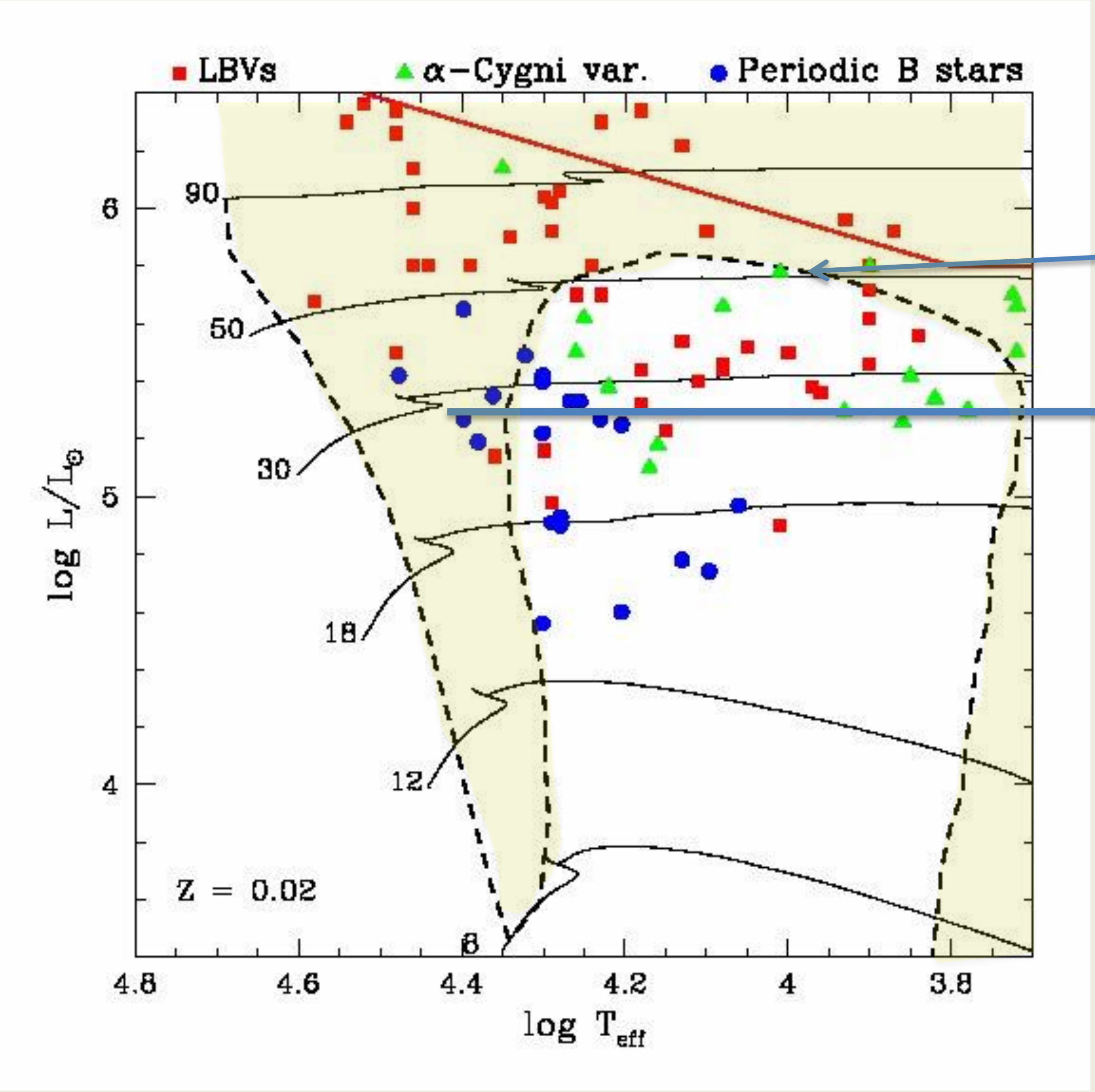
$$L/M \gg 10^4$$

Kappa-mechanism excitation

(Vertical boundaries)

Nearly adiabatic

$$(\Delta P / P = \Gamma_1 \Delta\rho/\rho)$$

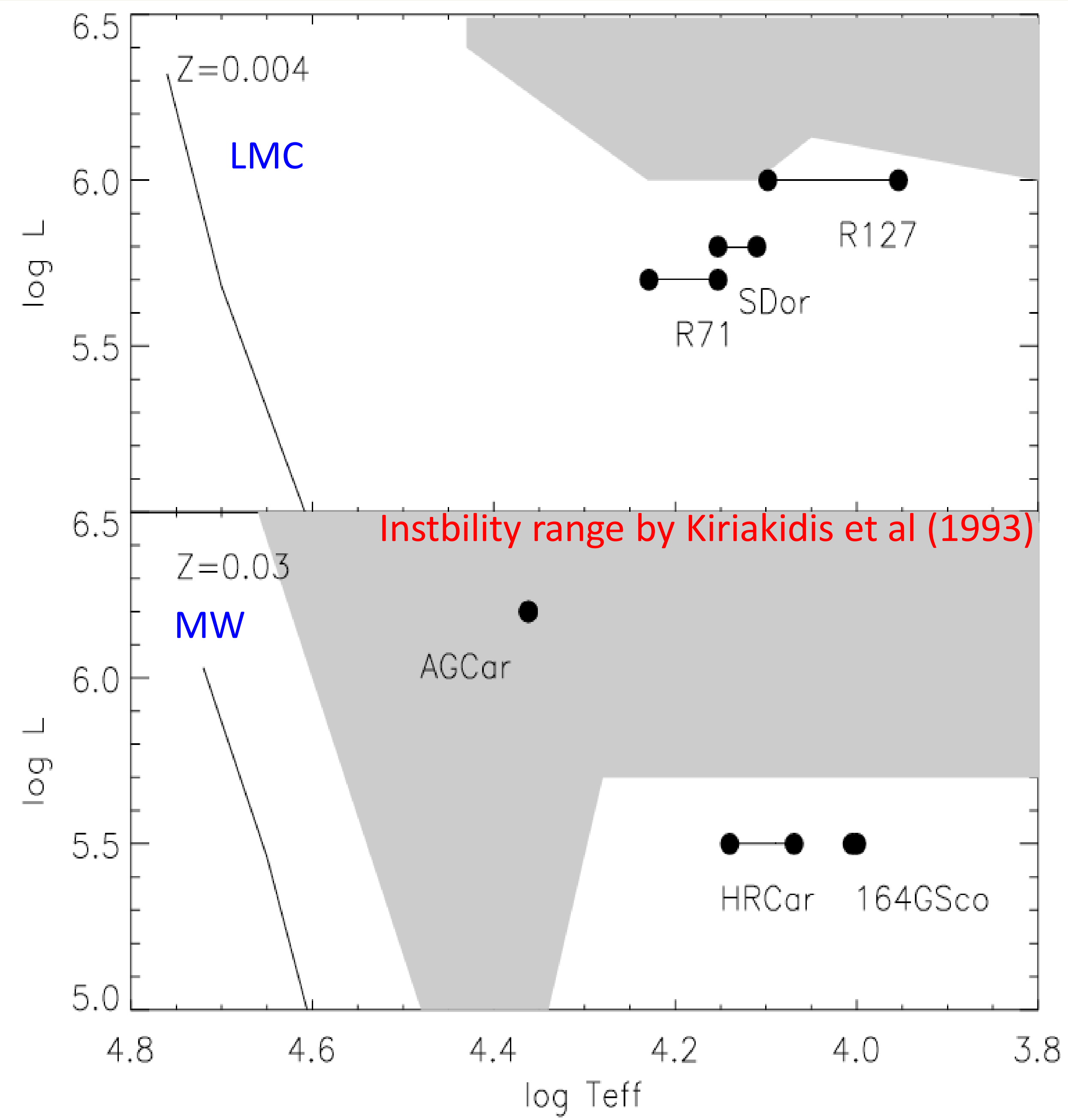


However,
Luminosity at the boundary of the strange mode instability determined by L/M

is higher than

Lower boundary of the distribution of S Dor and α Cyg variables.

S Dor variables (Lamers, Astiaanse, Aerts, Spoon 1998)



Lamers et al. (1998) rejected the explanation by strange mode instability for the semi-periodic variations in S Dor variables because they are outside of the instability range

But enhanced wind mass loss might solve the problem

Models with enhanced mass loss rates:

$$\dot{M}_{evol} = f_{wind} \times \dot{M}$$

$$\begin{aligned}\log \dot{M} = &- 6.697\ (\pm 0.061) \\ &+ 2.194\ (\pm 0.021)\ \log(L_*/10^5) \\ &- 1.313\ (\pm 0.046)\ \log(M_*/30) \\ &- 1.226\ (\pm 0.037)\ \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\ &+ 0.933\ (\pm 0.064)\ \log(T_{\rm eff}/40\,000) \\ &- 10.92\ (\pm 0.90)\ \{\log(T_{\rm eff}/40\,000)\}^2 \\ &+ 0.85\ (\pm 0.10)\ \log(Z/Z_\odot)\end{aligned}$$

for $27\,500 < T_{\rm eff} \leq 50\,000$ K

$$\begin{aligned}\log \dot{M} = &- 6.688\ (\pm 0.080) \\ &+ 2.210\ (\pm 0.031)\ \log(L_*/10^5) \\ &- 1.339\ (\pm 0.068)\ \log(M_*/30) \\ &- 1.601\ (\pm 0.055)\ \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\ &+ 1.07\ (\pm 0.10)\ \log(T_{\rm eff}/20\,000) \\ &+ 0.85\ (\pm 0.10)\ \log(Z/Z_\odot)\end{aligned}$$

for $12\,500 \leq T_{\rm eff} \leq 22\,500$ K

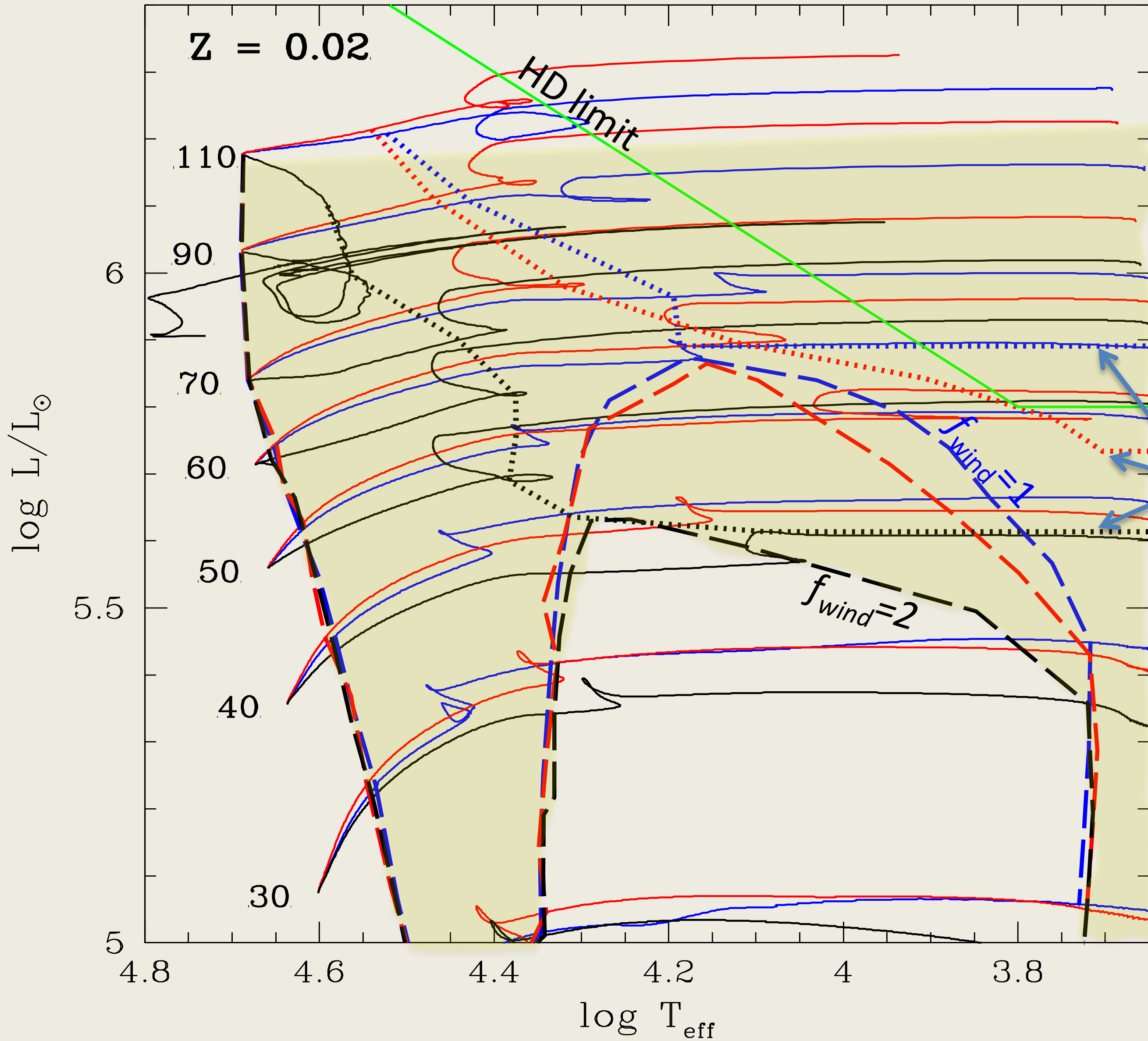
Vink et al. (2001)

For Teff < 12500 K

$$\log(-\dot{M}) = -7.93 + 1.64 \log\left(\frac{L}{L_\odot}\right) + 0.16 \log\left(\frac{M}{M_\odot}\right) - 1.61 \log T_{\rm eff}.$$

Nieuwenhuijzen & de Jager (1990)

Effects of f_{wind} and α_{OV}



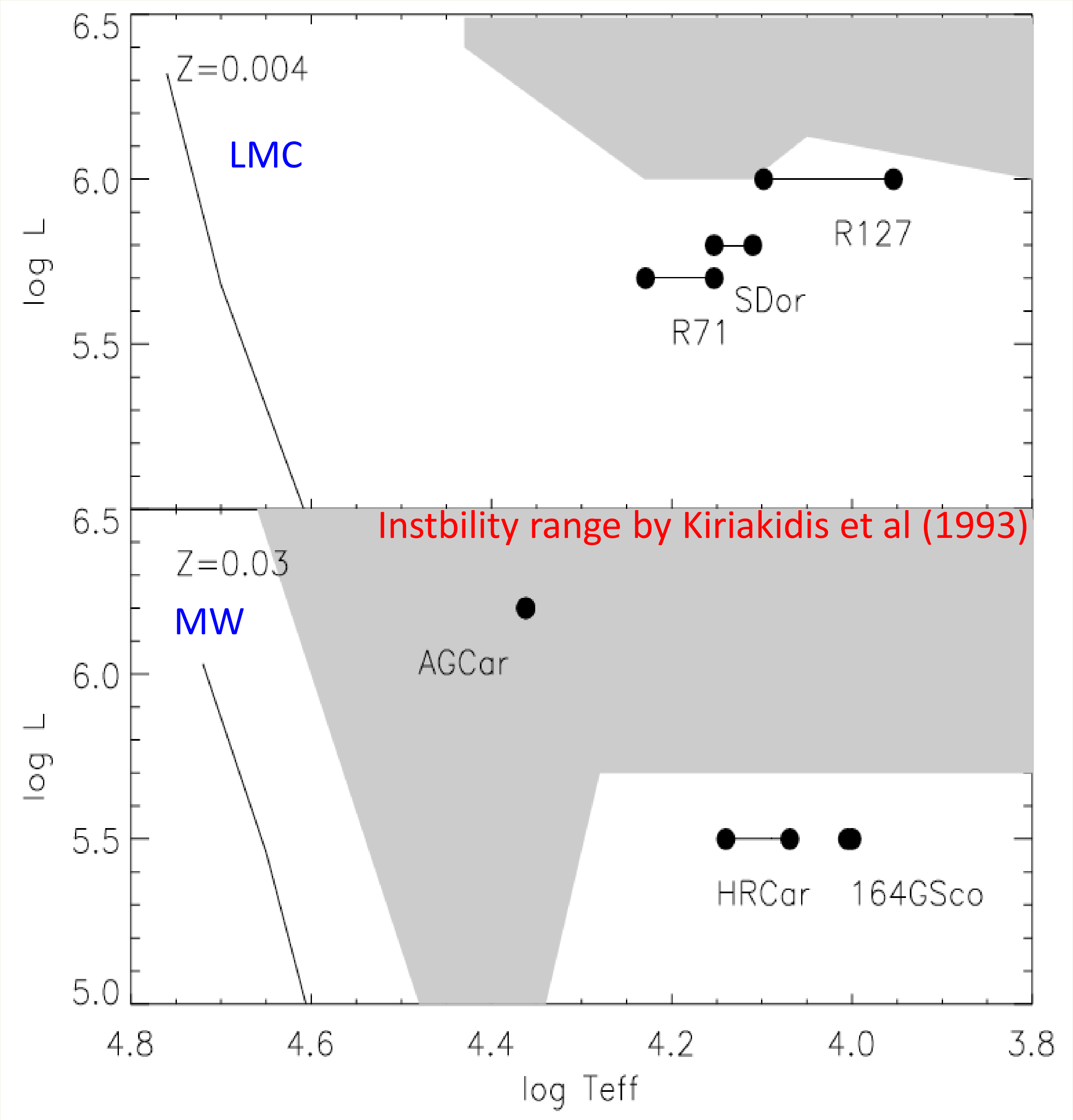
α_{OV}=0, f_{wind}=1

α_{OV}=0.2, f_{wind}=1

α_{OV}=0.2, f_{wind}=2

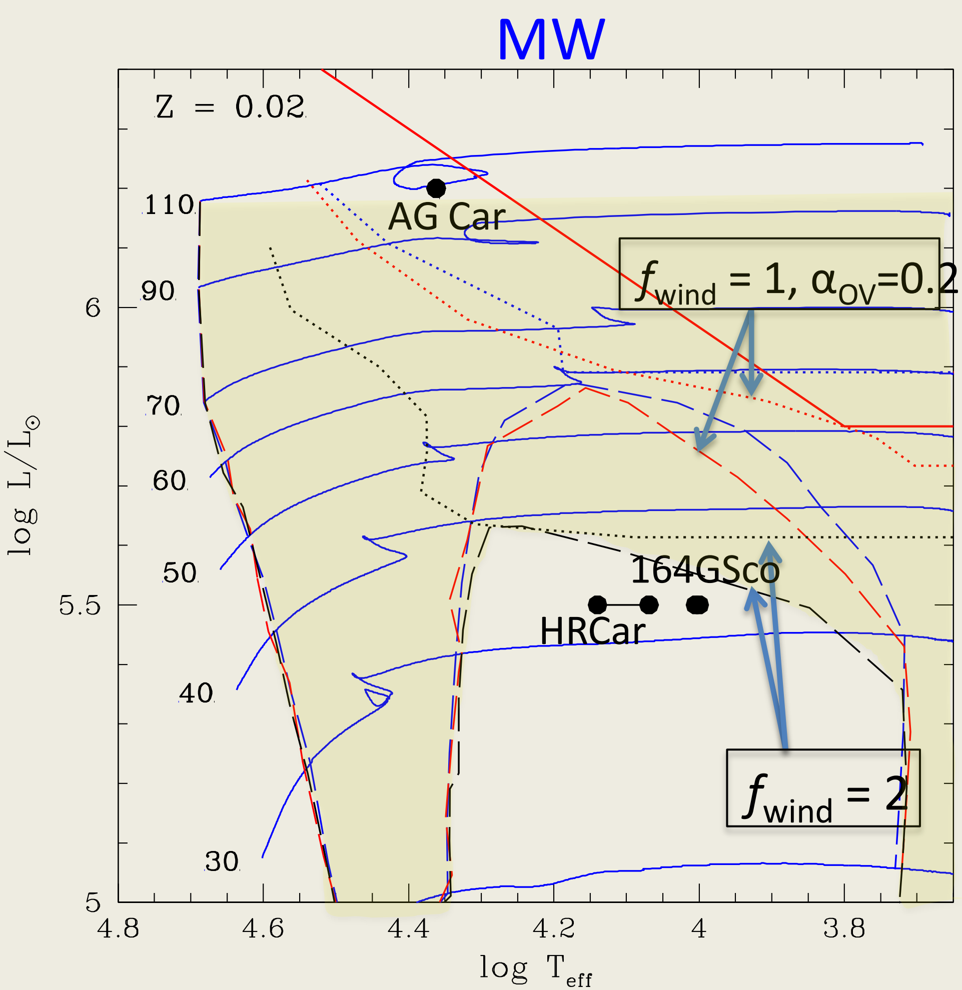
Monotonic instability boundaries

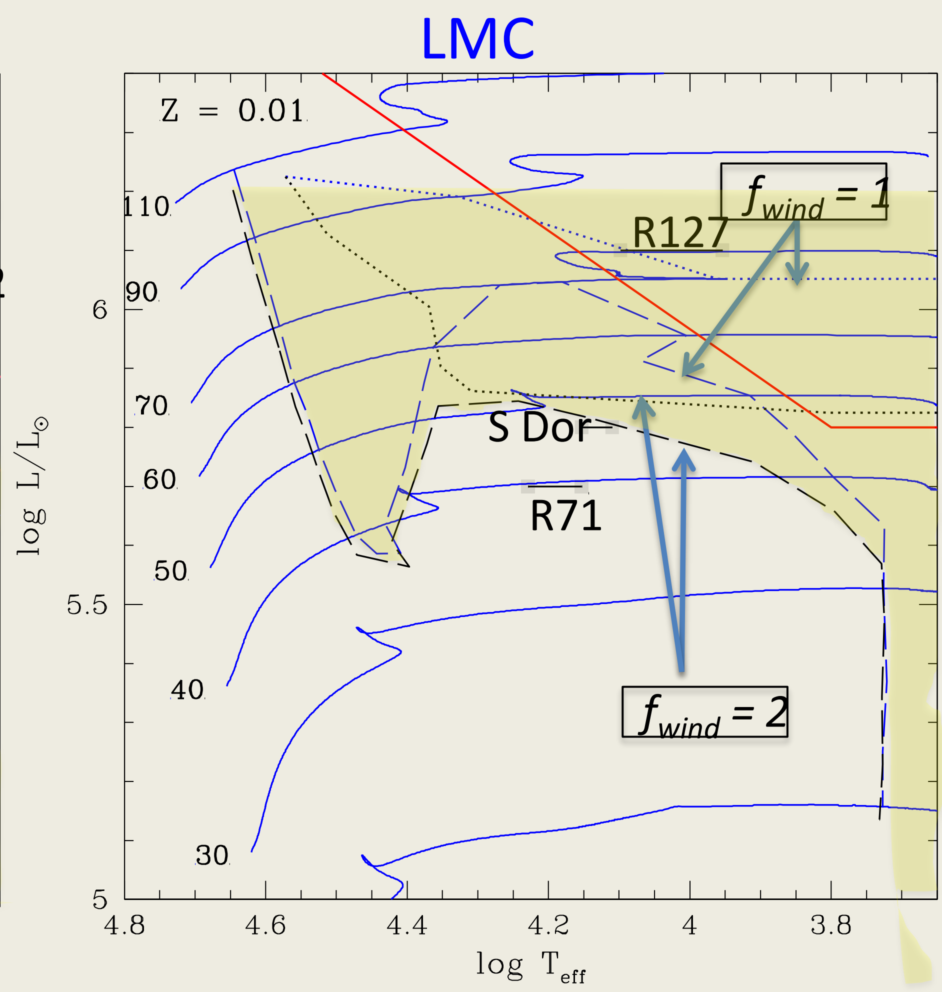
S Dor variables (Lamers, Astiaanse, Aerts, Spoon 1998)



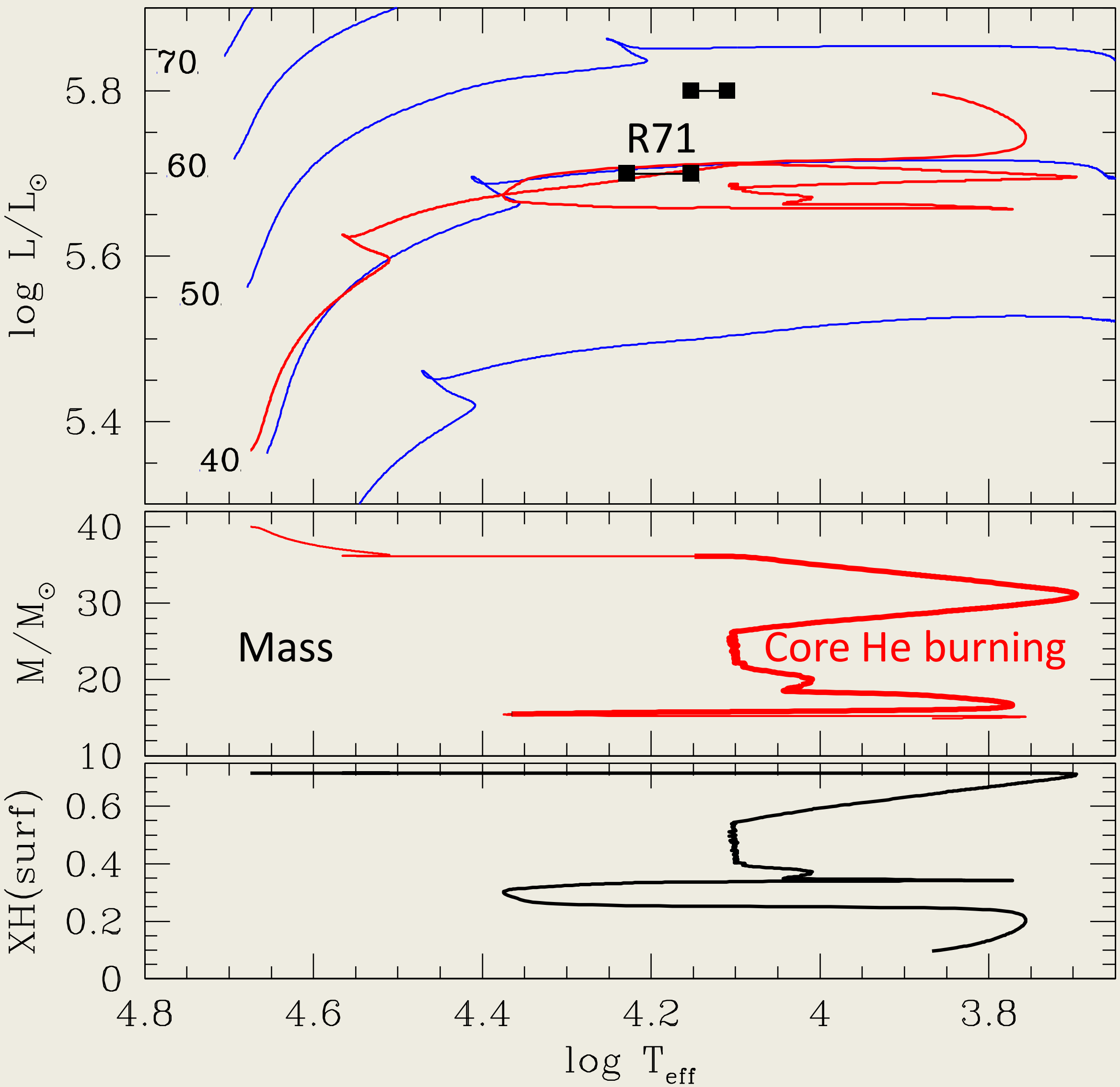
Comparison with S Dor variables

Some S Dor variables are still outside of the instability range for f_{wind}=2





Evolution with f_{wind}= 3

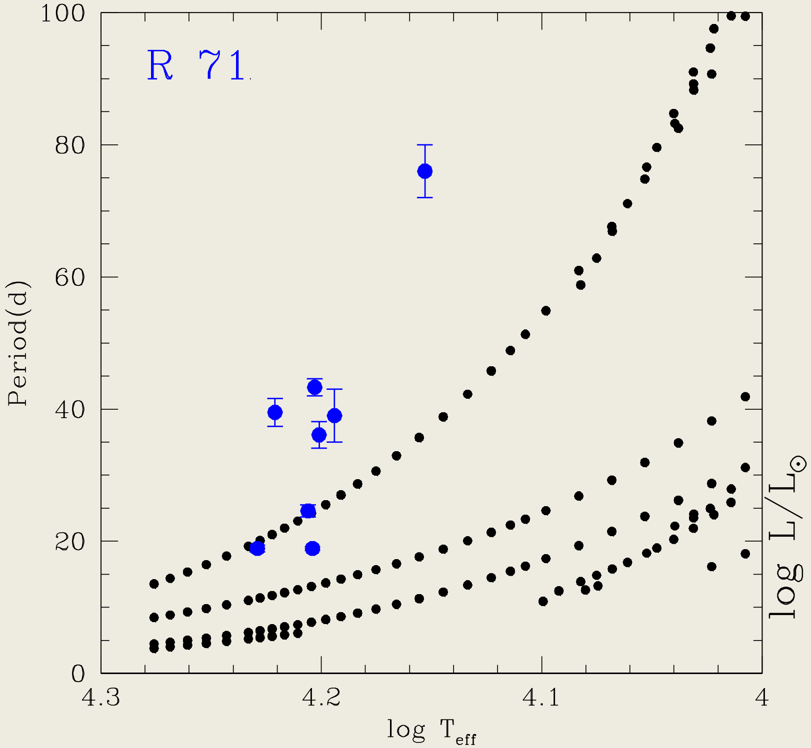


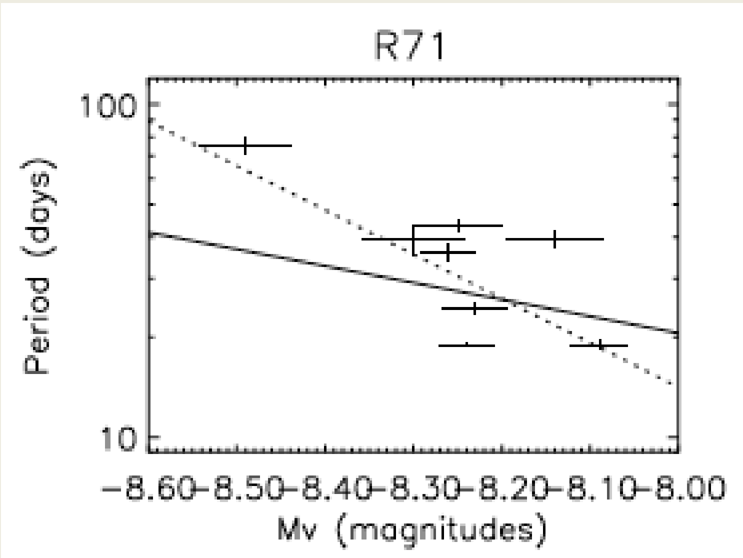
Latter half of the core He burning stage occurs in an extended blue loop after a significant mass was lost in a cooler region

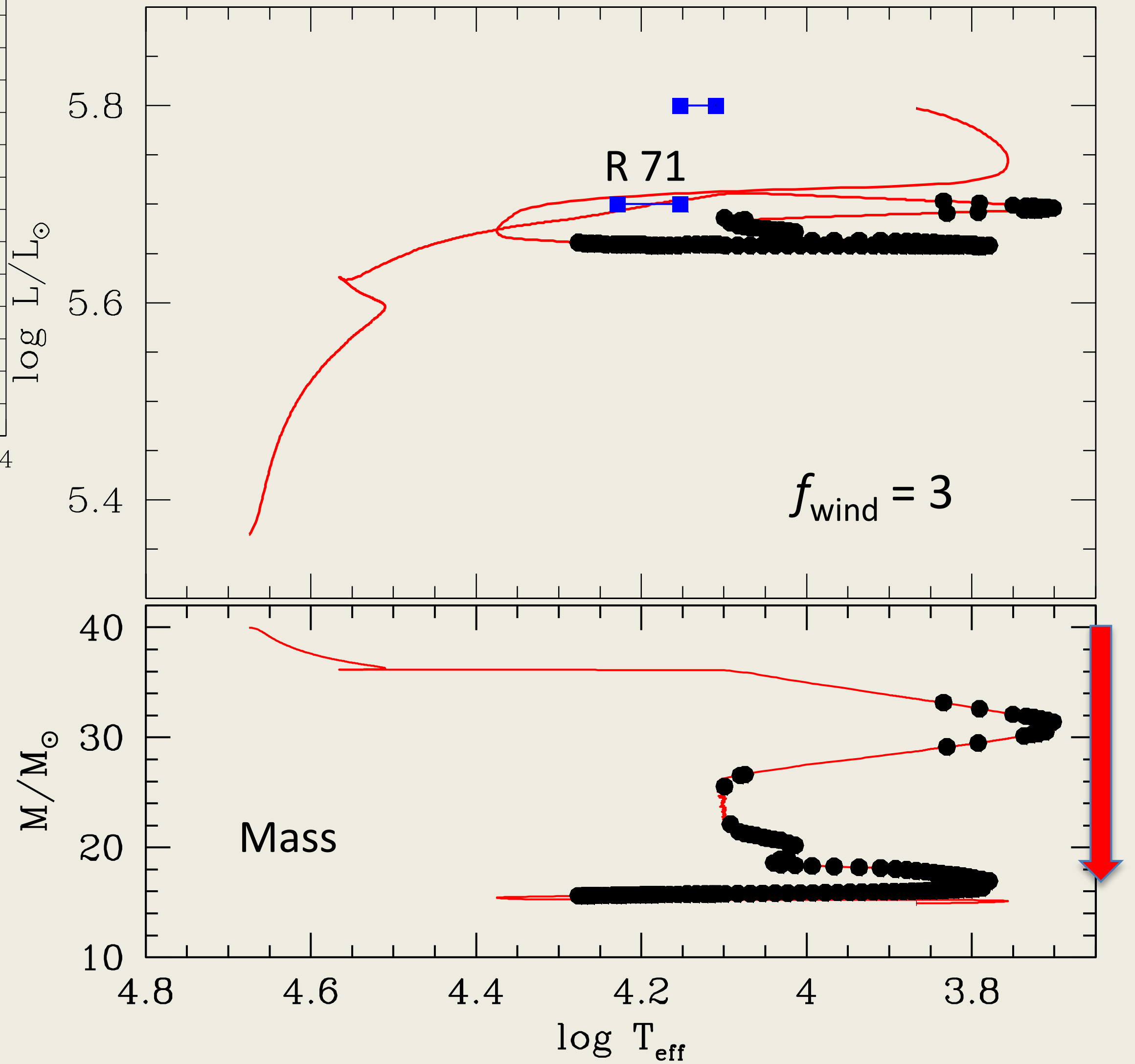
$L/M > 10^4$

Strange mode instability works

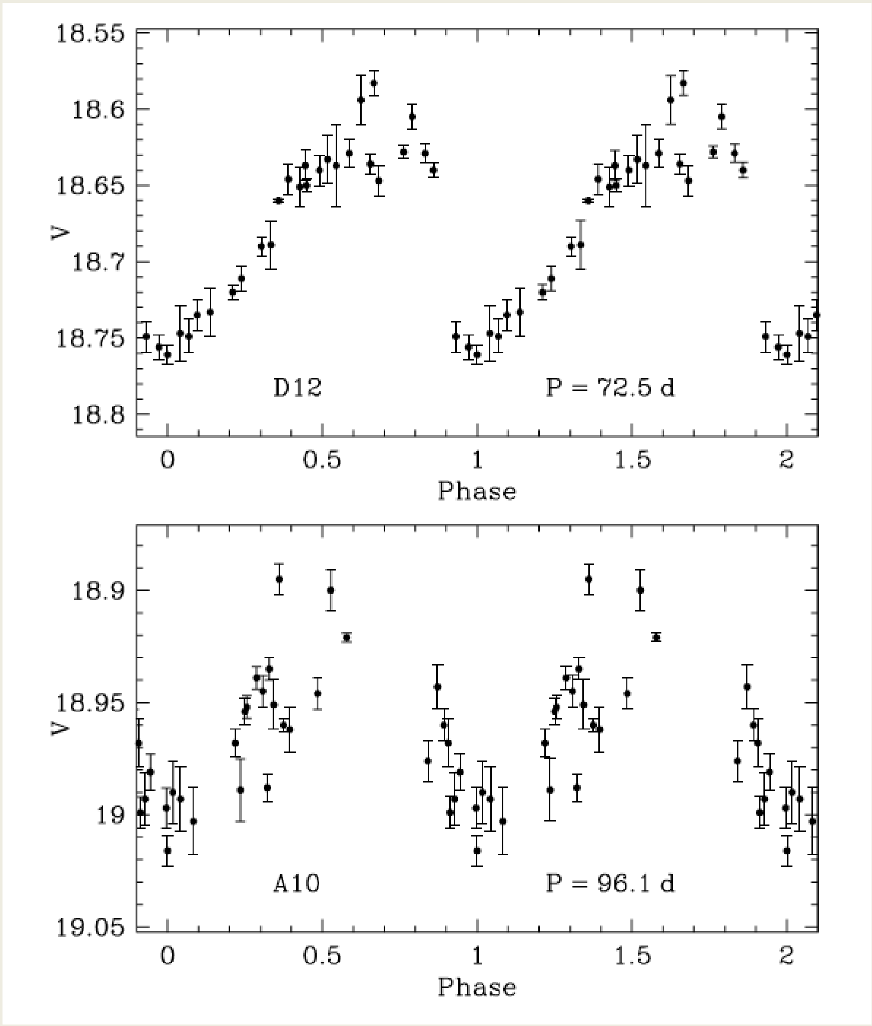
Excited radial pulsations have periods comparable to those of the S Dor variable R71 in LMC

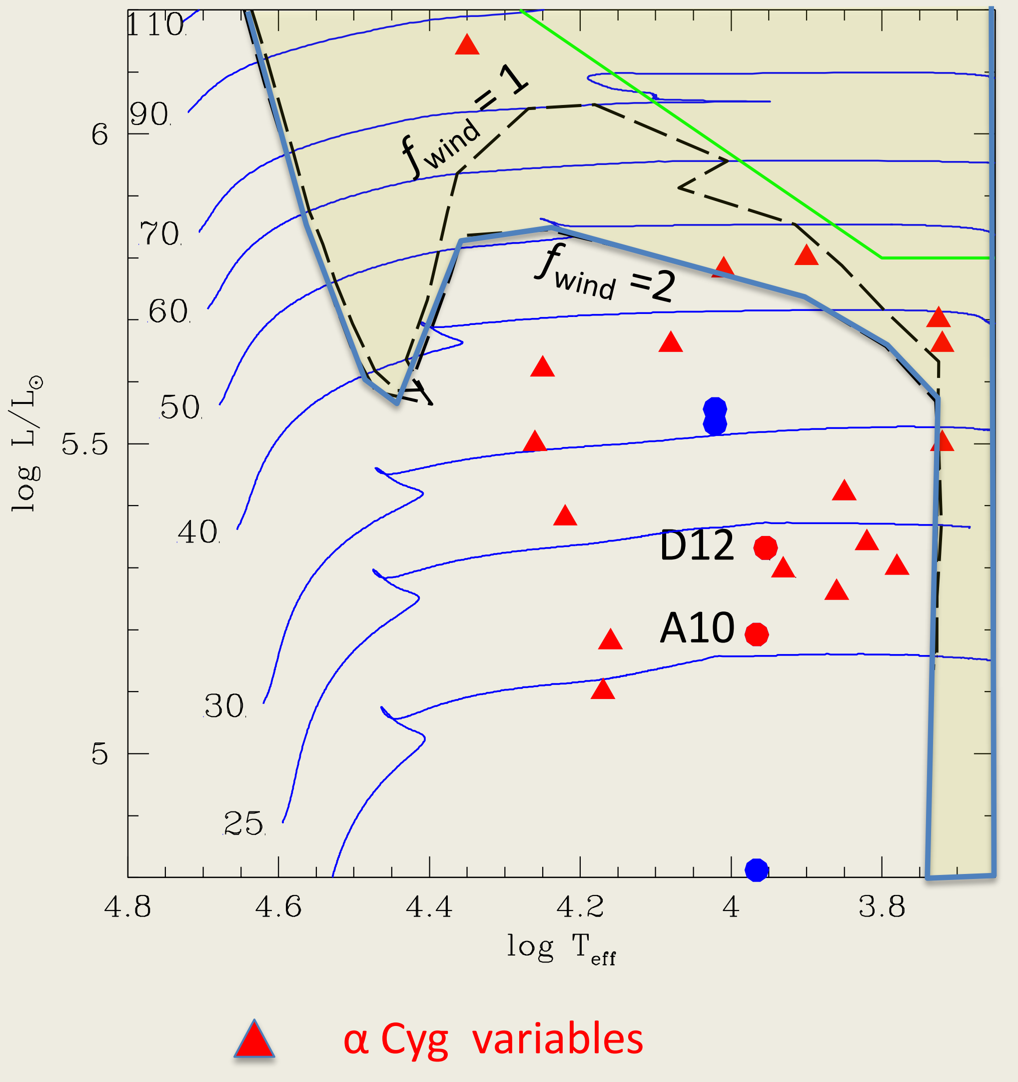






D12 & A10 – α Cyg variables in NGC 300



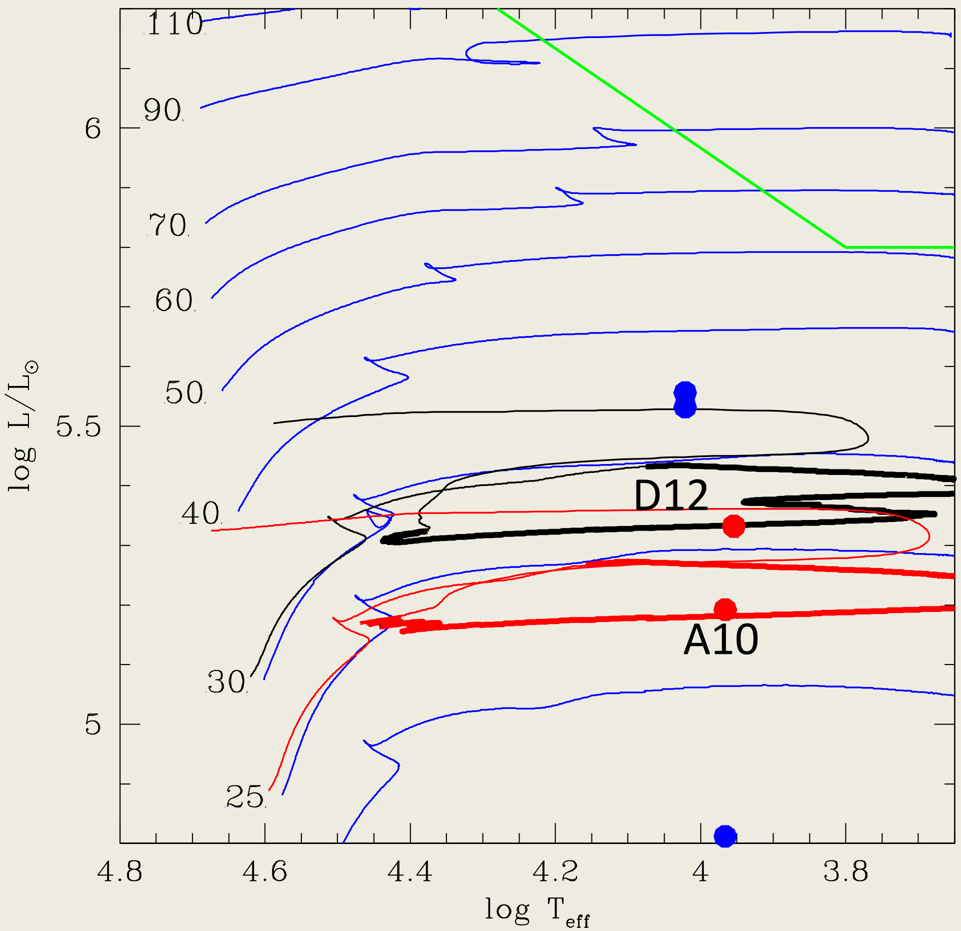


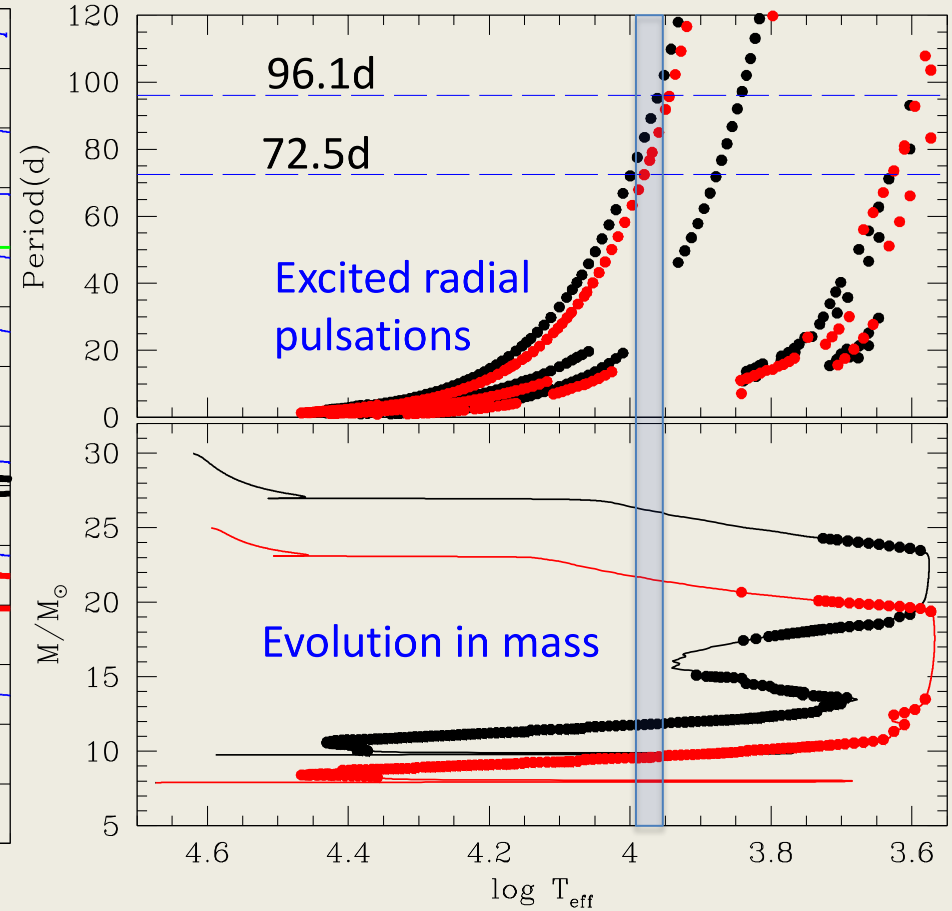
Evolution models with $f_{wind}=3$

D12 & A10 in NGC 300

pass the position of D12 and A10 during core He burning stage, after significant mass was lost in RG stage

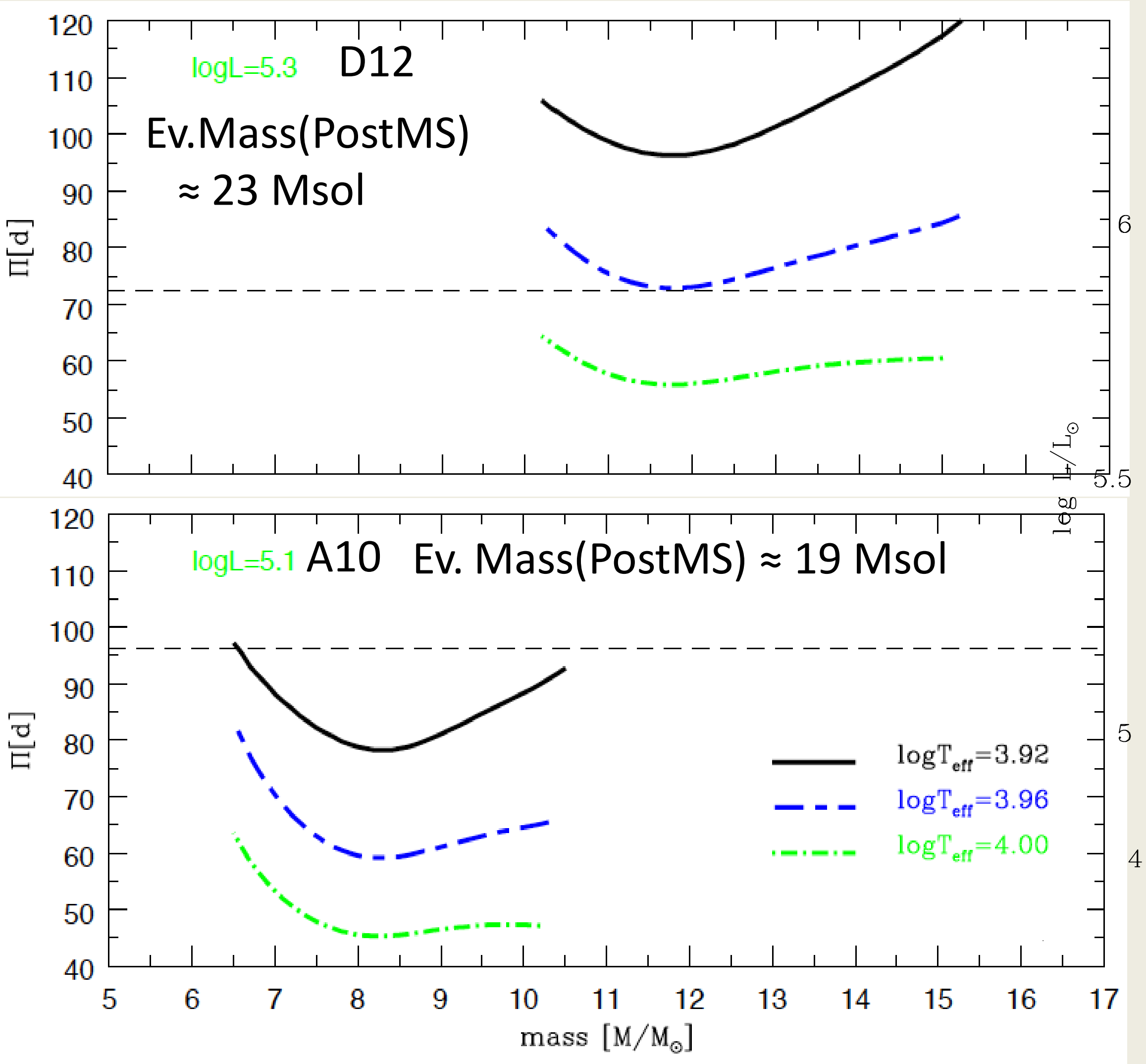
Radial pulsations with periods comparable to the observed ones are excited by strange mode instability

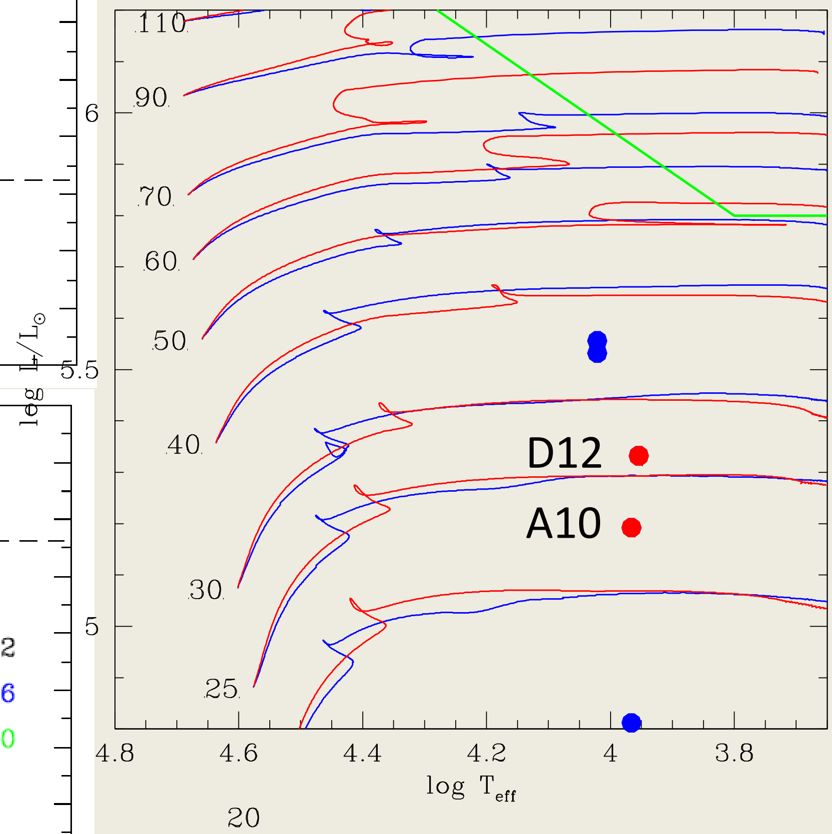




Dziembowski and Slawinska (2005) concluded

Significantly low masses are needed to explain pulsations in D12 and A10





Envelope models with various masses

Conclusion

Semi-periodic variations of S Dor and α Cyg variables are radial pulsations excited by the strange mode instability.

Wind mass loss must be enhanced by

$$f_{\text{wind}} \approx 3$$