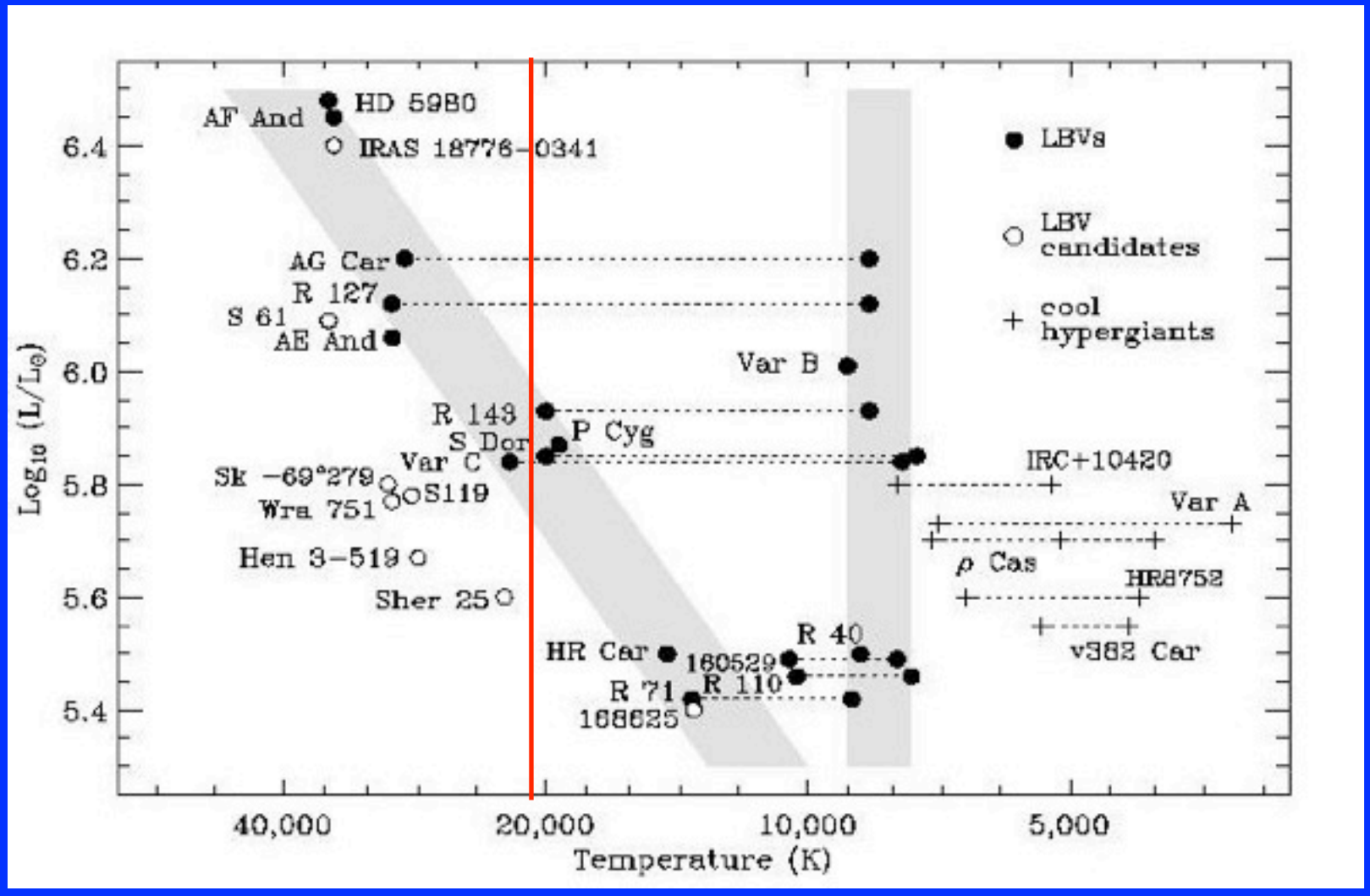
Surface Instabilities

Jorick S. Vink

Armagh Observatory
(Northern Ireland)

+ many

Causes for S Dor cycles

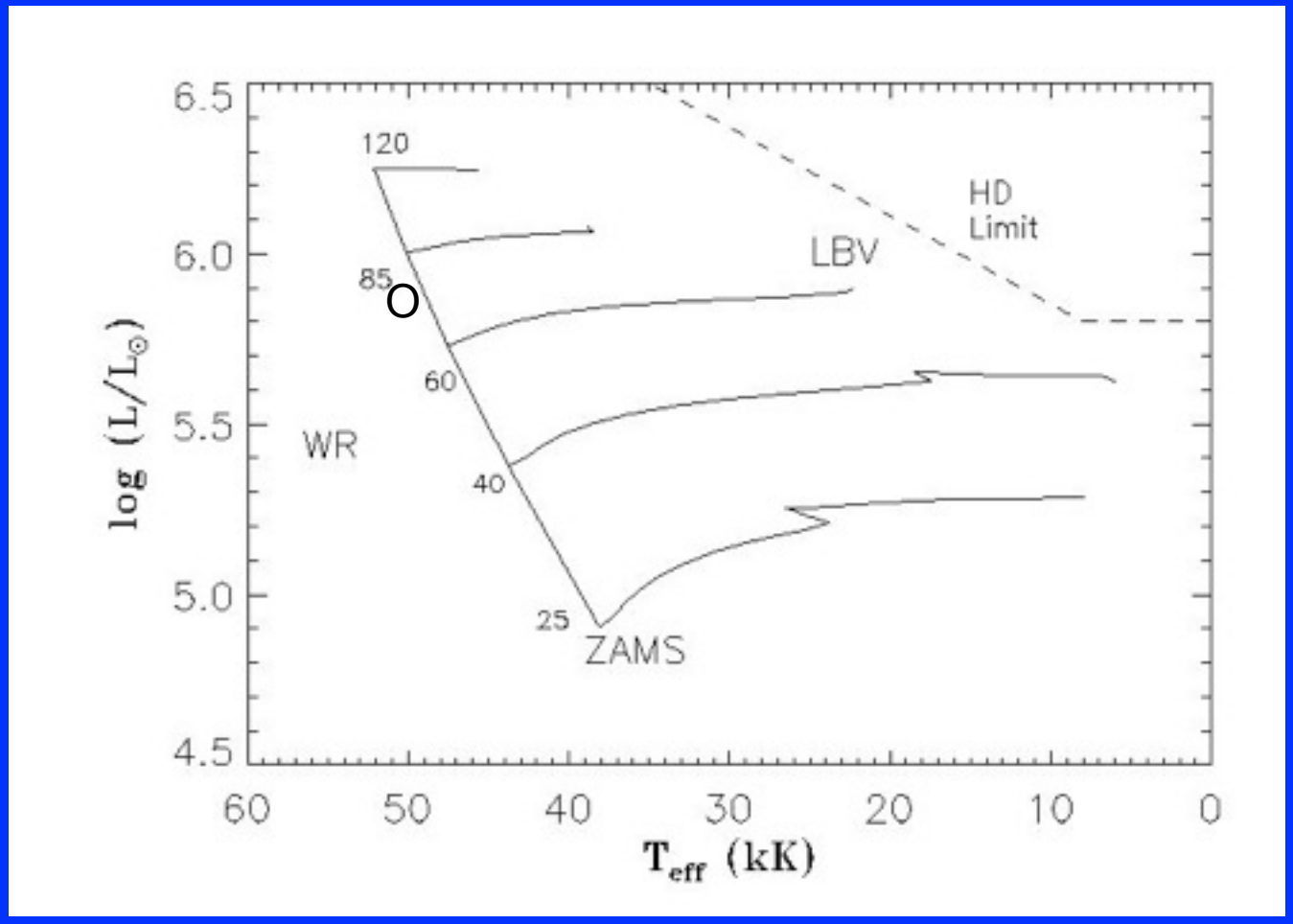


Smith, Vink, de Koter (2004) (after HD 1994)

Outline

- Eddington Limit Mass Loss
- Bi-stability Limit
- Eddington Limit Inflation

Uppermost HRD



Eddington Limit

$$g_{\mathrm{rad}} = \frac{\kappa F}{c} = \frac{\kappa L}{4\pi R^2 c}$$

Eddington Limit

$$g_{\mathrm{rad}} = \frac{\kappa F}{c} = \frac{\kappa L}{4\pi R^2 c}$$

$$g_{\mathrm{grav}} = \frac{GM}{R^2}$$

Eddington Limit

$$g_{\mathrm{rad}} = \frac{\kappa F}{c} = \frac{\kappa L}{4\pi R^2 c}$$

$$g_{\mathrm{grav}} = \frac{GM}{R^2}$$

$$\Gamma = \frac{g_{\mathrm{rad}}}{g_{\mathrm{grav}}} = \frac{\kappa L}{4\pi c G M}$$

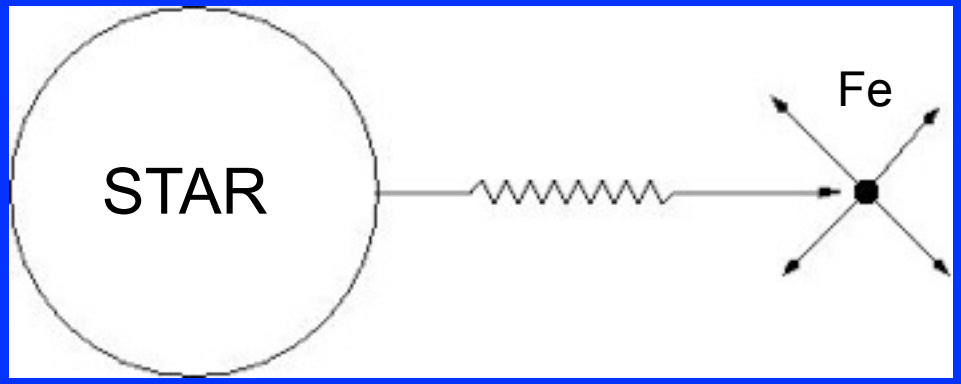
EVOLUTION = MASS LOSS

EVOLUTION = MASS LOSS

VMS evolve ‘Chemically Homogeneously‘

(Graefener et al. 2011)

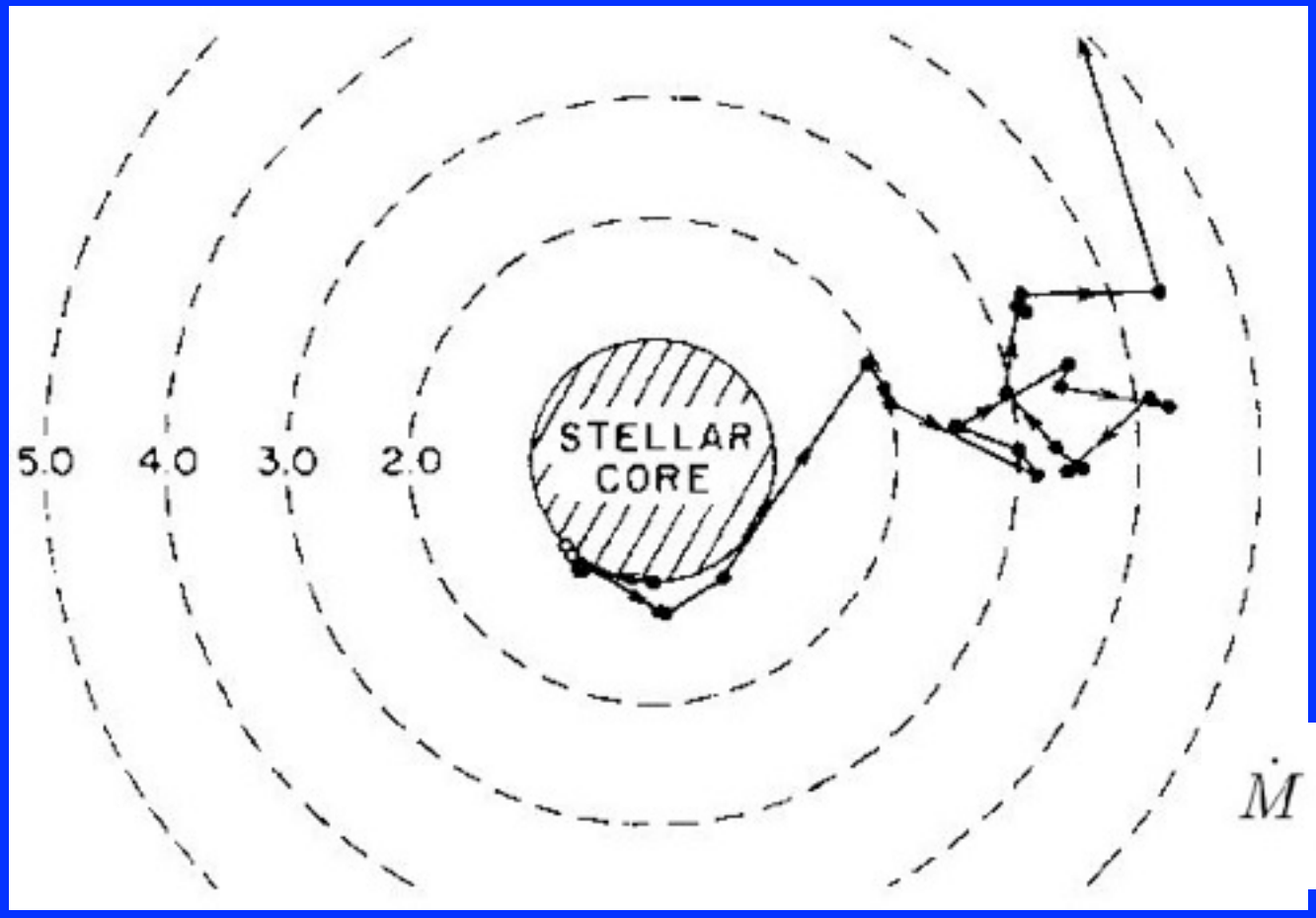
Line-driven winds



Lucy & Solomon (1970)

Castor, Abbott & Klein (1975)

Monte Carlo approach



$$\dot{M}\, v_\infty > \frac{L_*}{c}$$

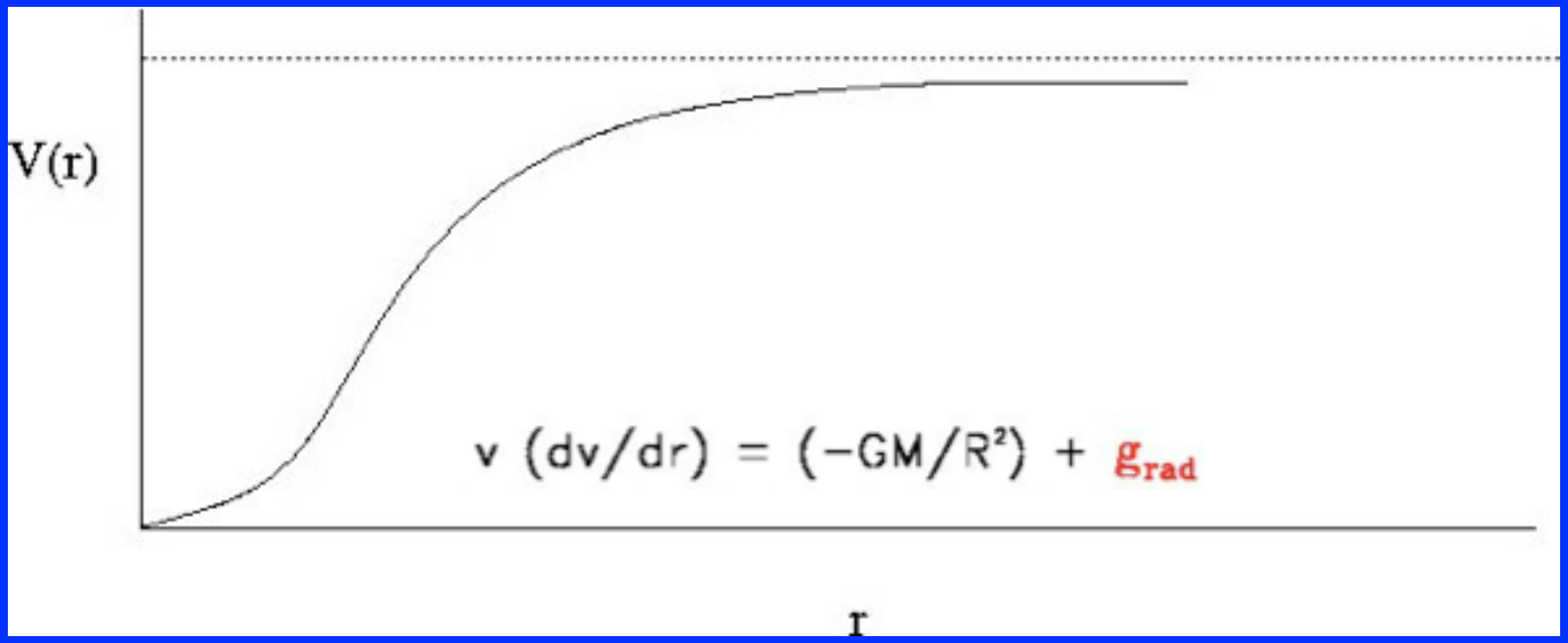
Abbott & Lucy (1985)

Vink, de Koter & Lamers (2000) dM/dt = f (L,M,Z,Teff)

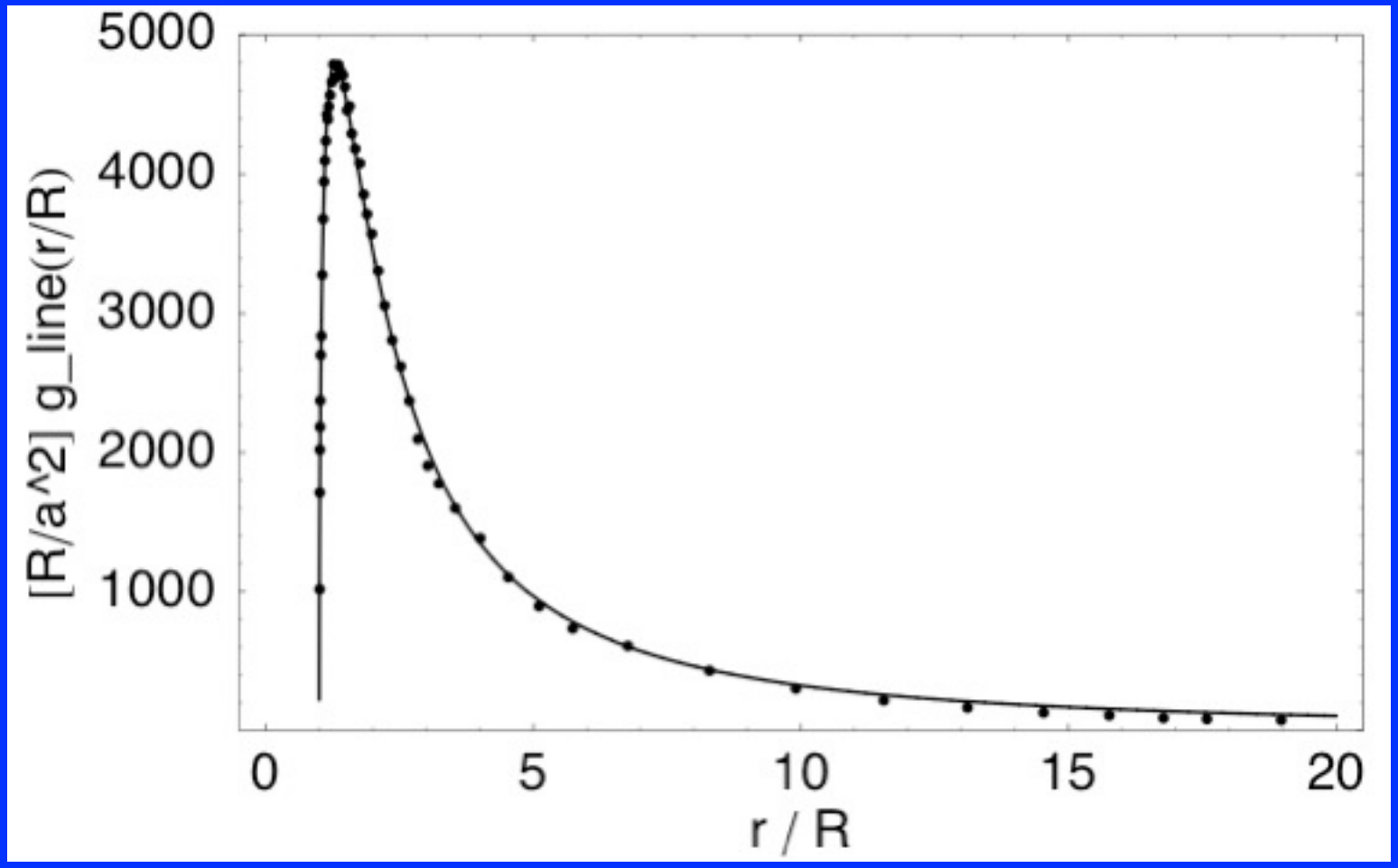
Two new aspects

- Wind dynamics
- New parameter range: Masses 60-300 Msun (high Gamma)

Velocity of a line-driven wind

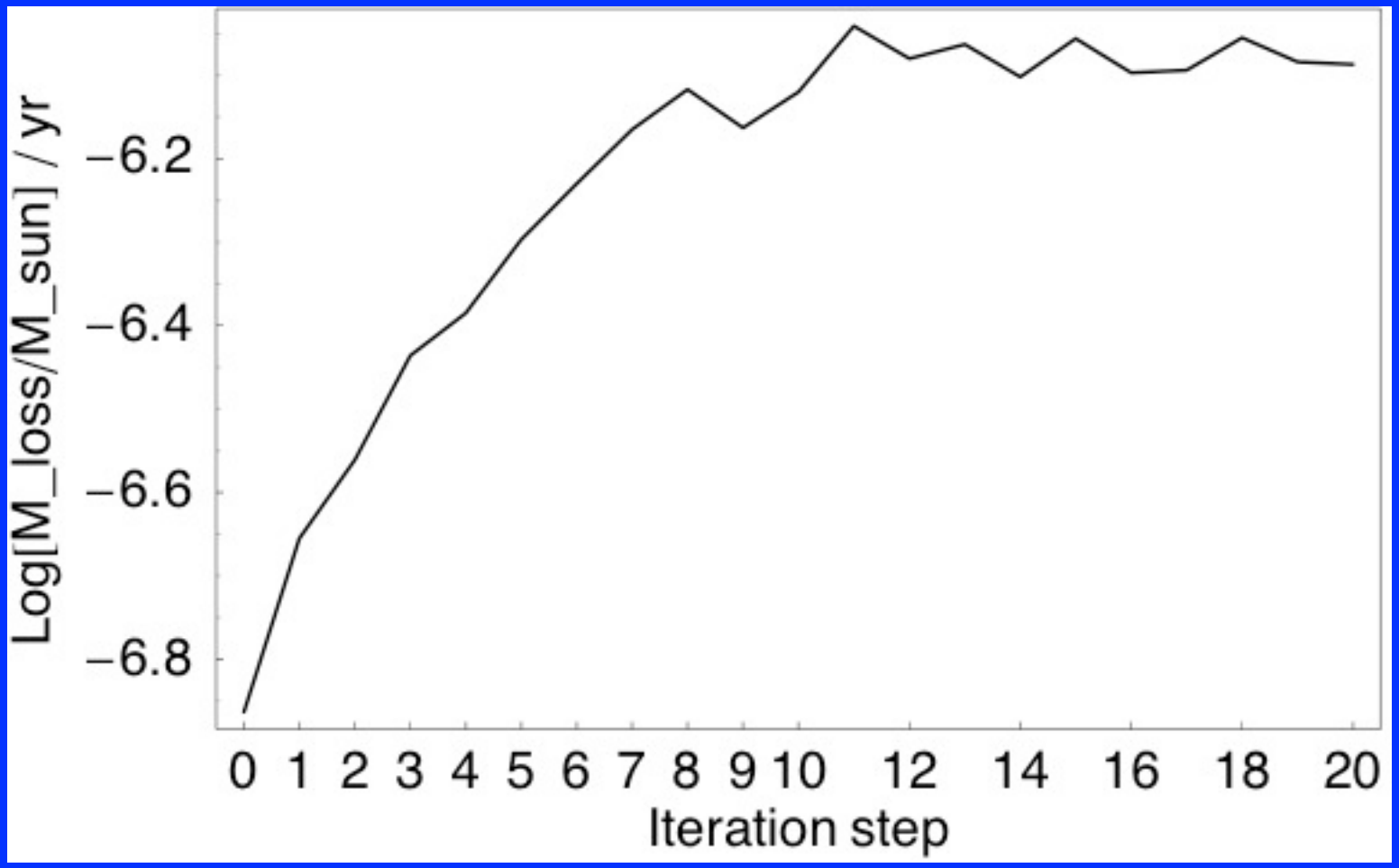


Line acceleration: g(r)



Mueller & Vink (2008)

Mass-loss iteration

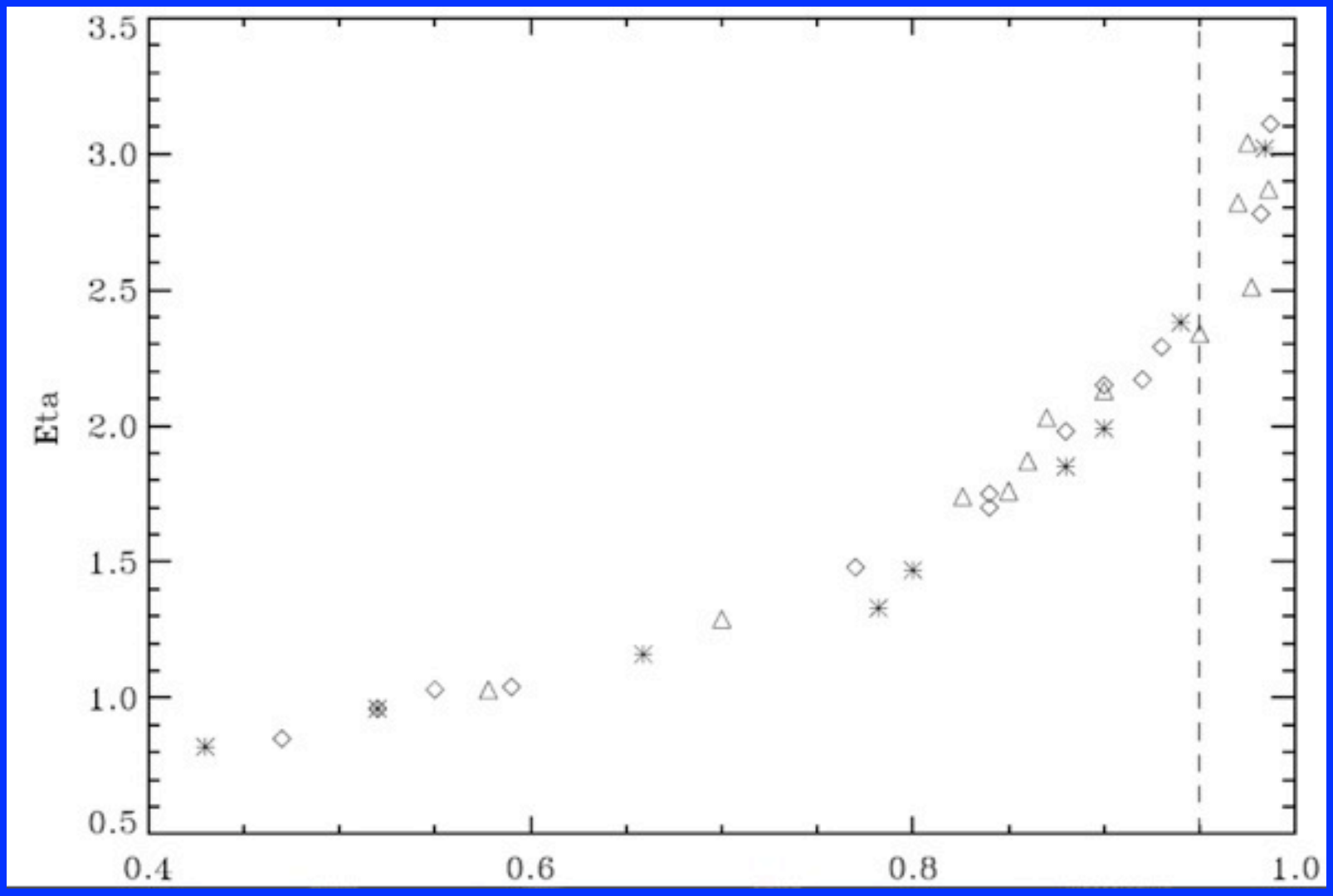


Mueller & Vink (2008) and Muijres et al. (2012)

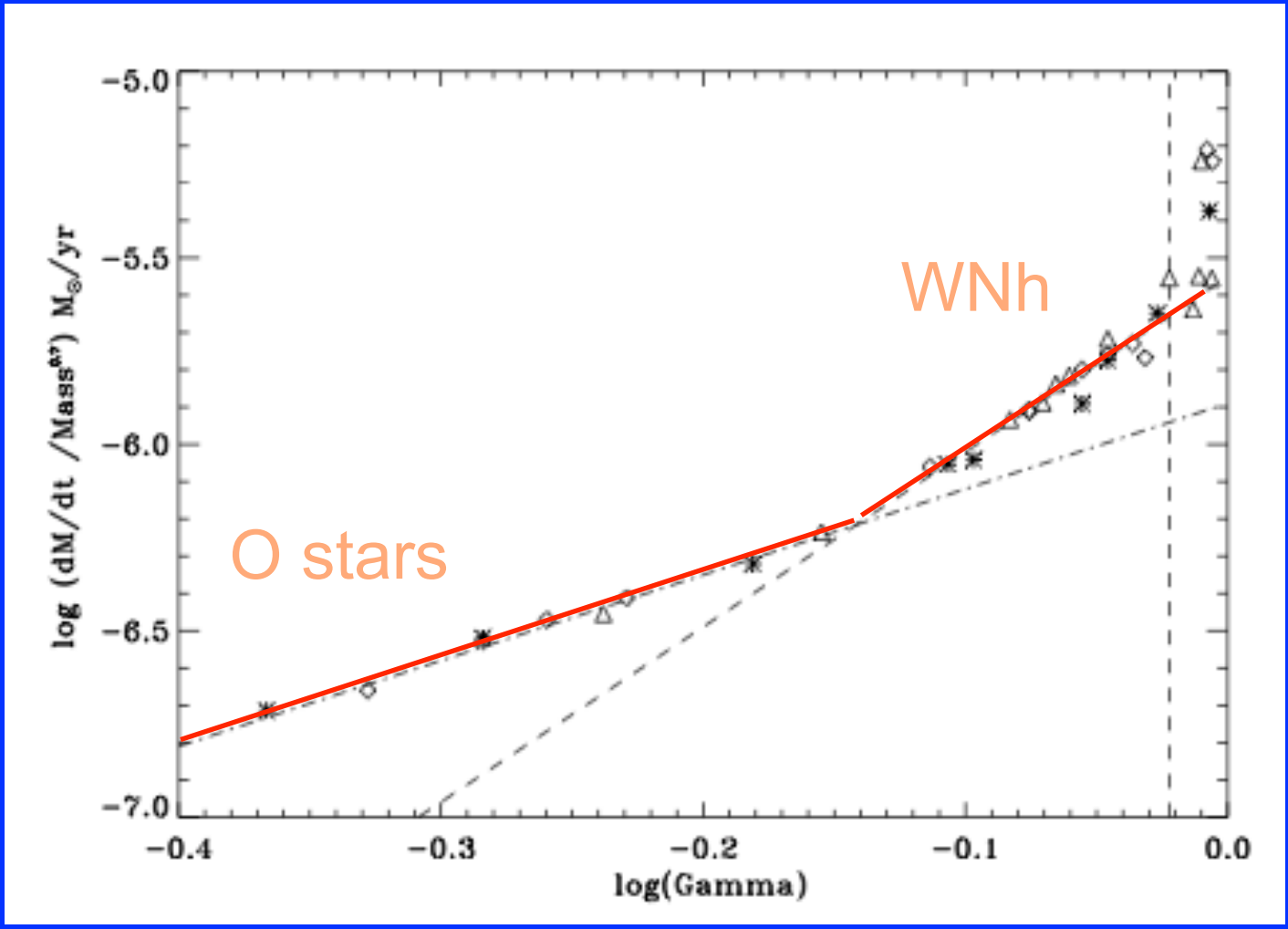
Gamma-dependence

Wind efficiency

$$\eta = \frac{\dot{M} v_\infty}{L/c}$$



KINK in Mass loss - Gamma Dependence



Vink et al. (2011)

Transition Point Of/WN

- Below KINK Gamma: dM/dt = Gamma^2

Transition Point Of/WN

- Below KINK Gamma: dM/dt = Gamma^2
- Above KINK Gamma: dM/dt = Gamma^5

Transition Point Of/WN

- Below KINK Gamma: dM/dt = Gamma^2
- Above KINK Gamma: dM/dt = Gamma^5

Vink et al. (2011) (Vink 2006) .

See also co-moving frame computations by Graefener & Hamann (2008)

Empirical Evidence: Graefener et al. (2011)

?

Transition Point Of/WN

- ETA = TAU = 1

Vink & Graefener (2012) ; see Abbott (1980) - Lamers & Cassinelli (1999)

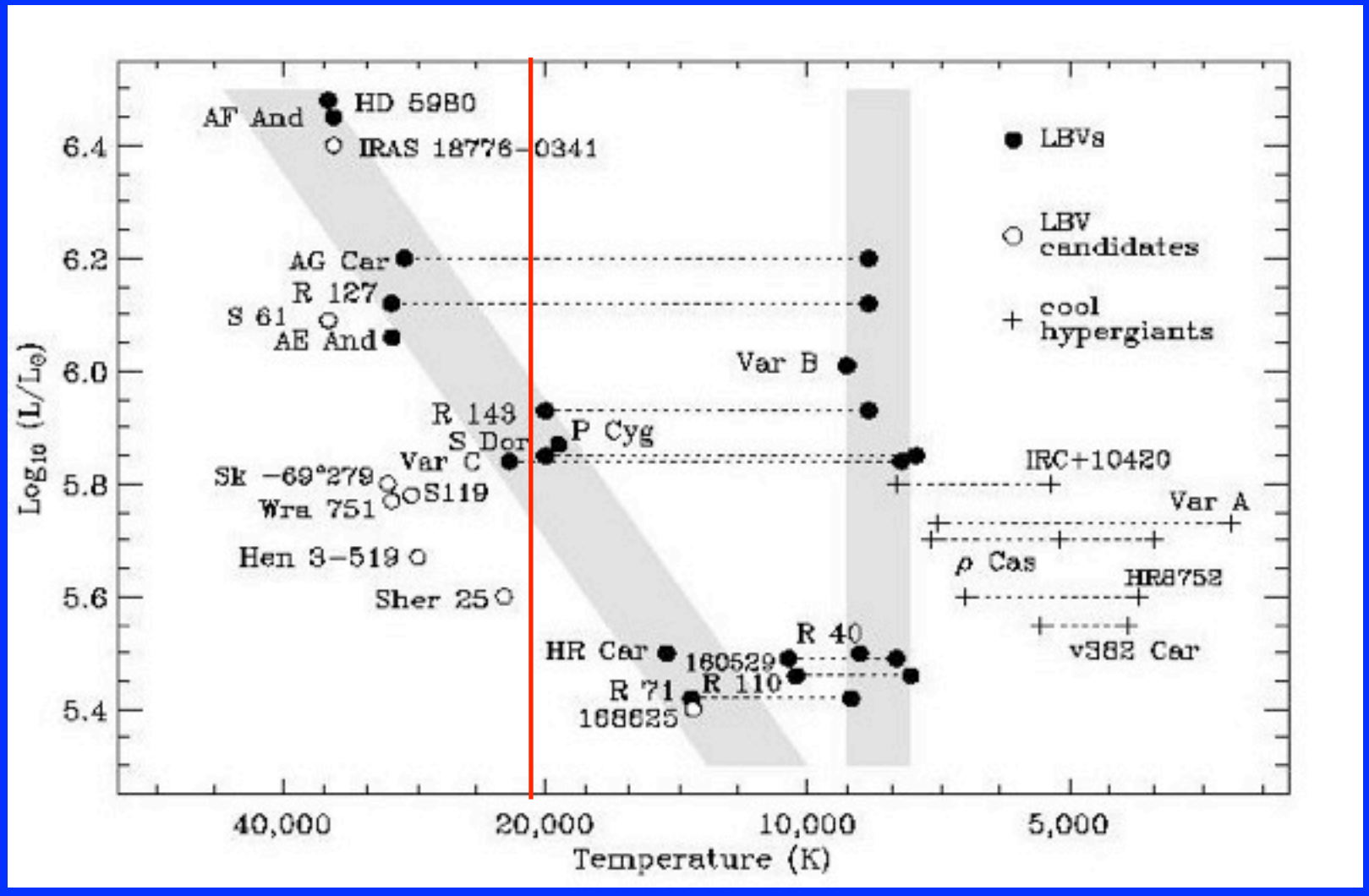
- dM/dt = L/vc

Vink & Graefener (2012) .

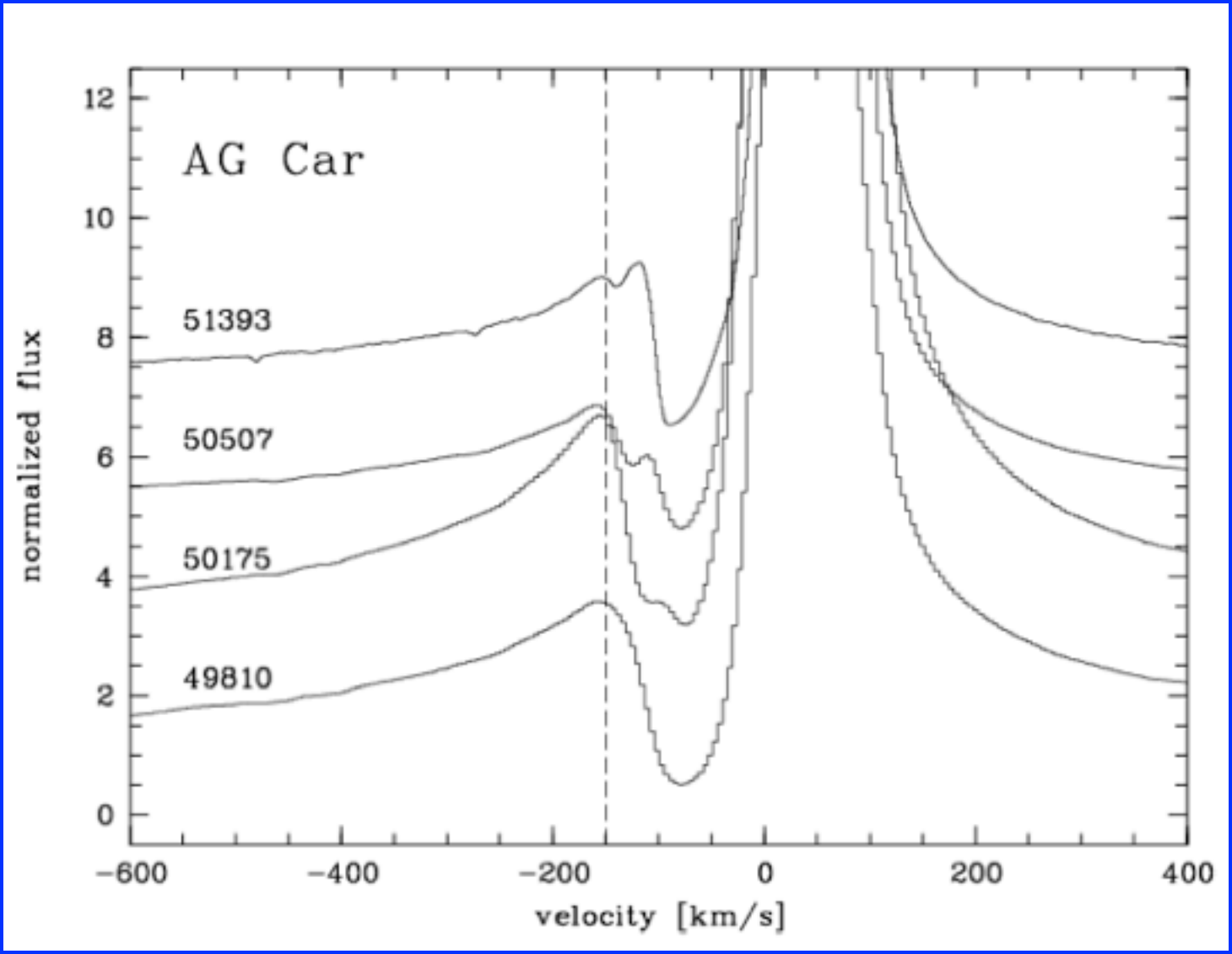
BISTABILITY

Pauldrach & Puls (1990) for P Cygni

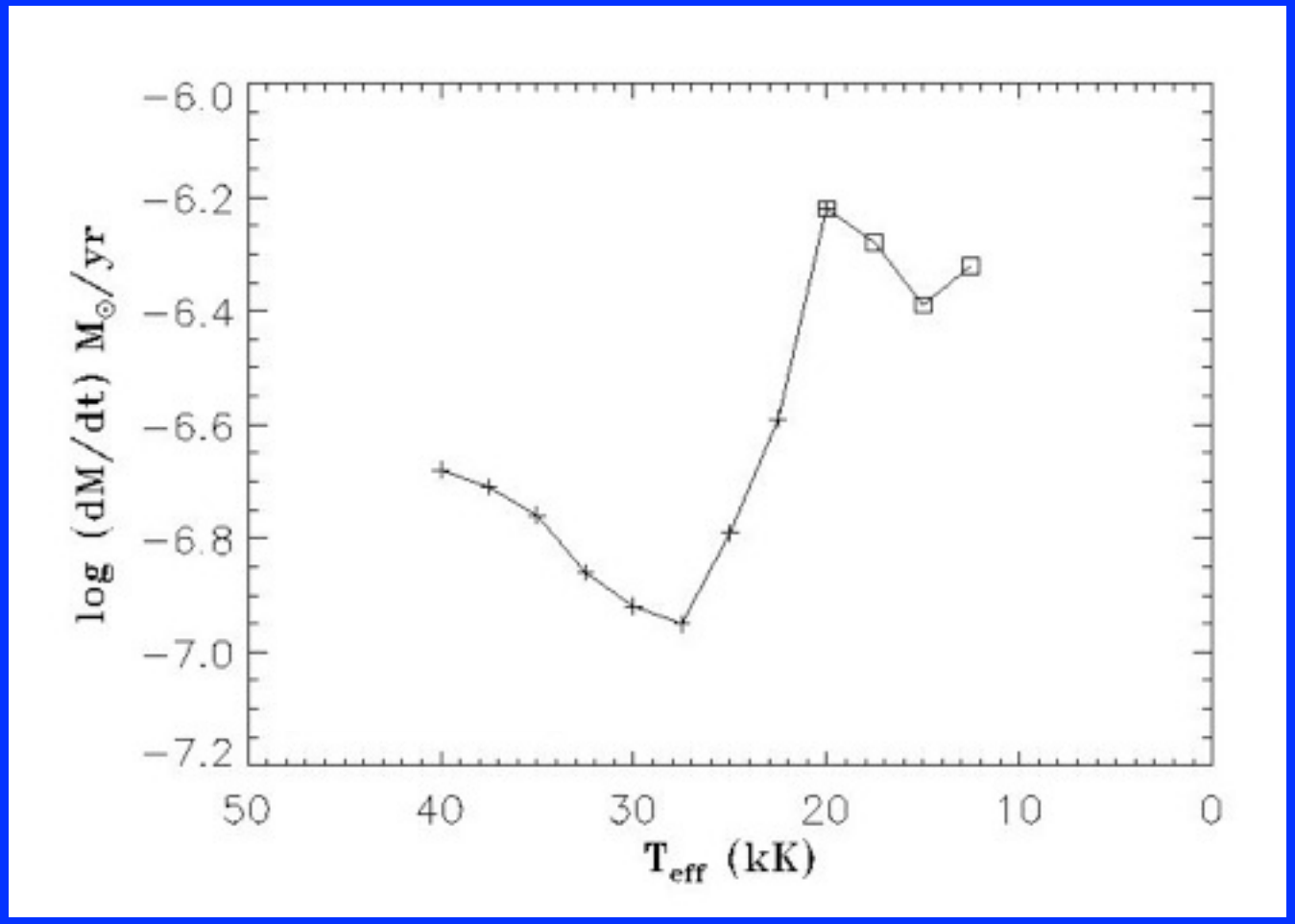
LBVs in the HRD



Slow and dense LBV winds



Change in mass loss



→ dM/dt jumps up by factor 5

(Vink et al. 1999)

Bi-stability Jump

HOT (O stars)	COOL (B supergiants)
modest dM/dt	large dM/dt
fast wind	slow wind
Fe IV	Fe III

Does bi-stability Jump exist?

Against:

Halpha (dM/dt) in
B supergiants too low

(Vink et al. 2000;
Trundle et al. 2004;
Markova & Puls 2008)

FOR:

Vinf drops by factor 2
(Lamers et al. 1995;
Crowther et al. 2006)

(dM/dt) local maximum
(Benaglia et al. 2007)

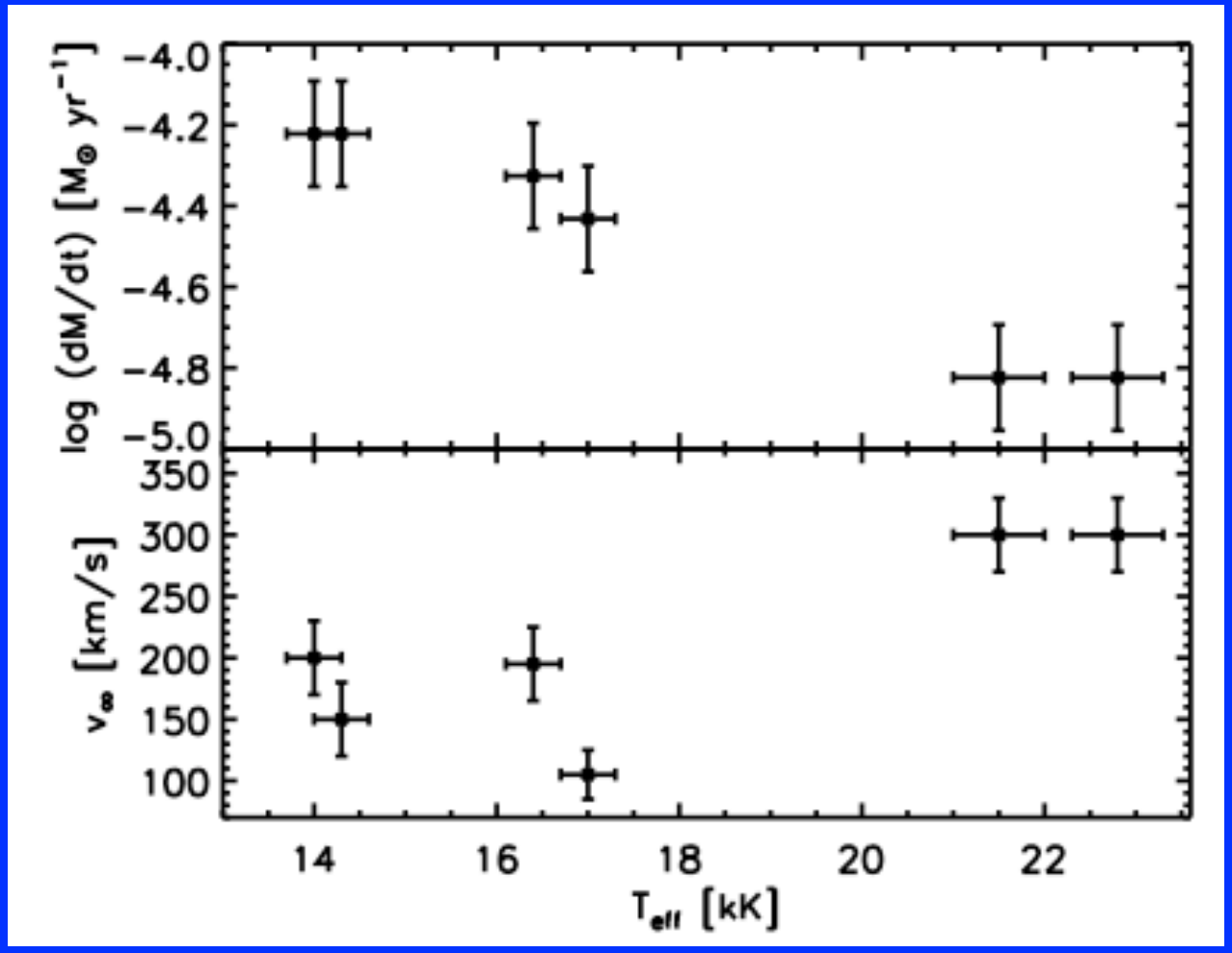
The reason for the word *jump*

- Temperature drops

→ Fe recombines from Fe IV to Fe III
→ Line force increases
→ dM/dt up
→ density up
→ V(inf) drops

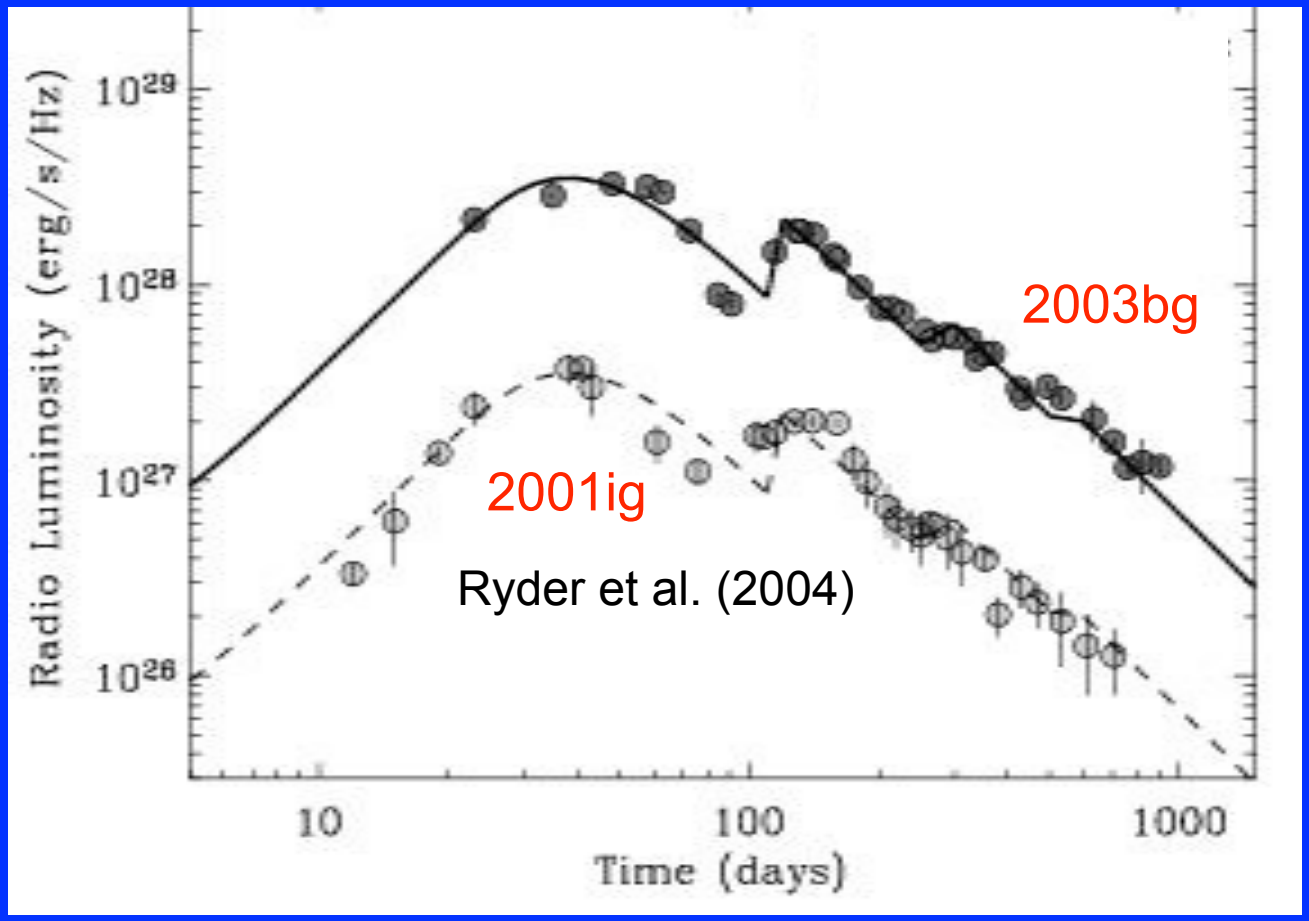
→ "Runaway"

The mass loss of AG CAR



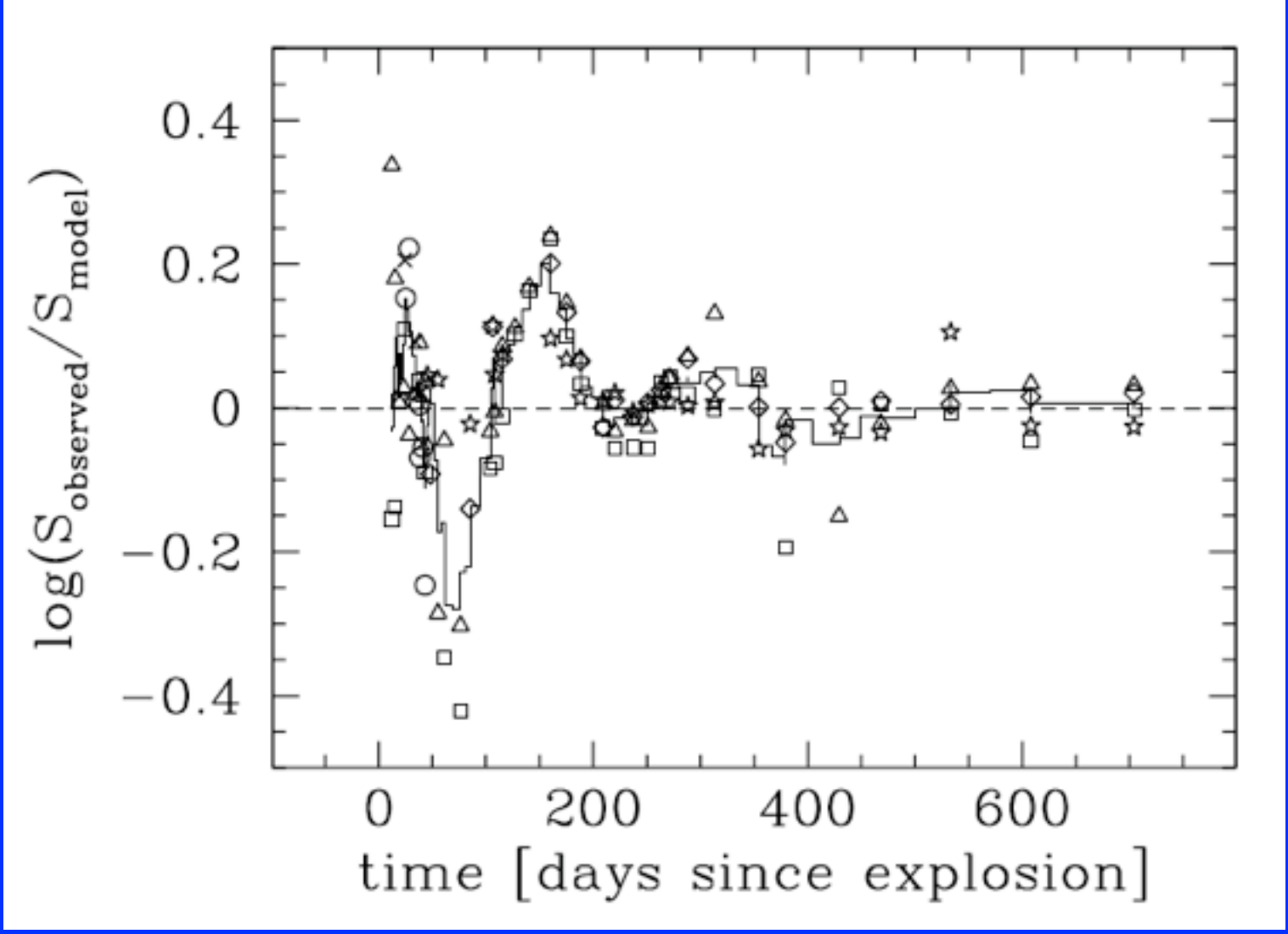
Groh et al. (2011) also: Vink & de Koter (2002)

Radio supernova lightcurves



Soderberg et al. (2006)

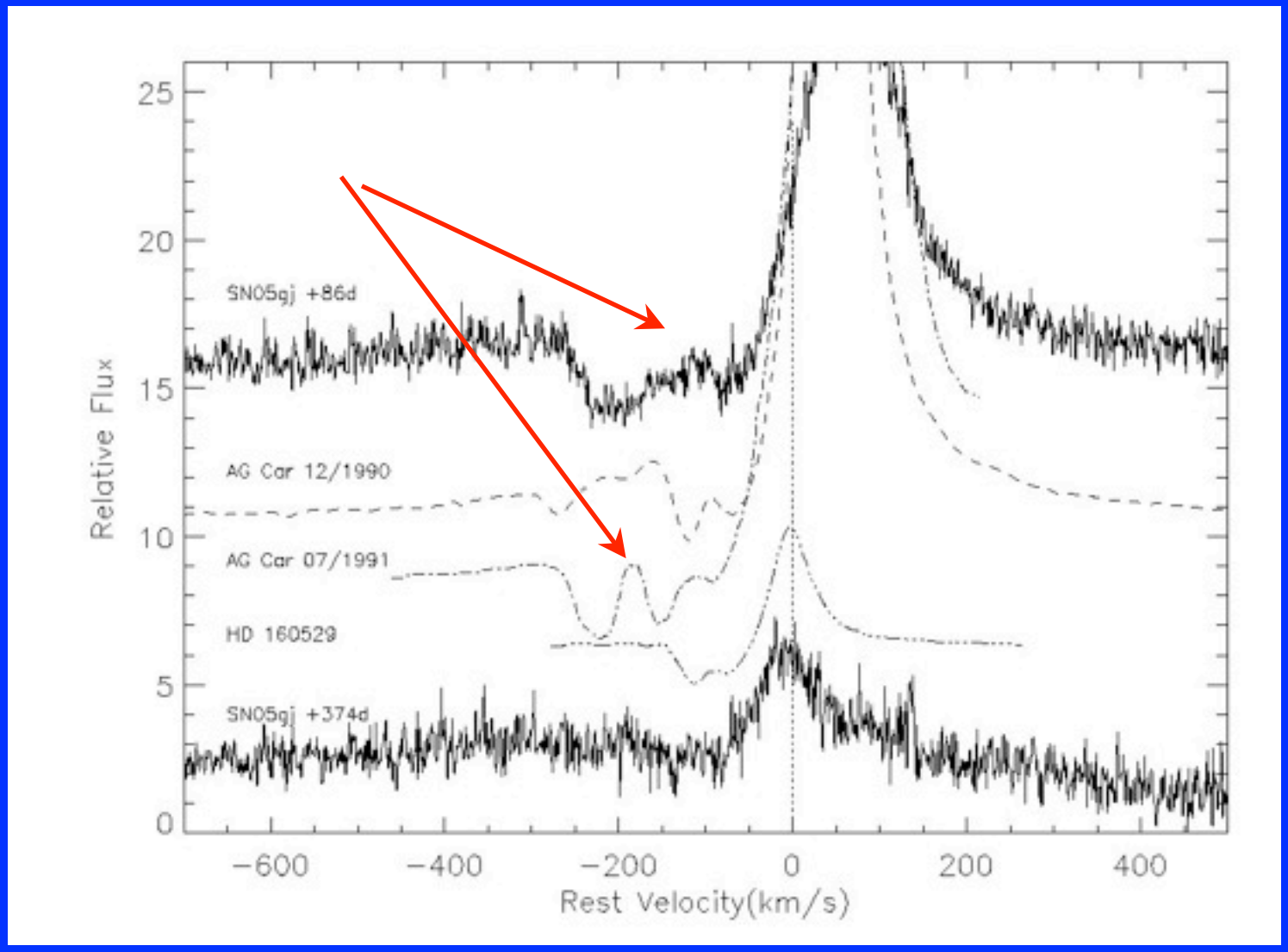
Radio supernova lightcurves



LBV !?

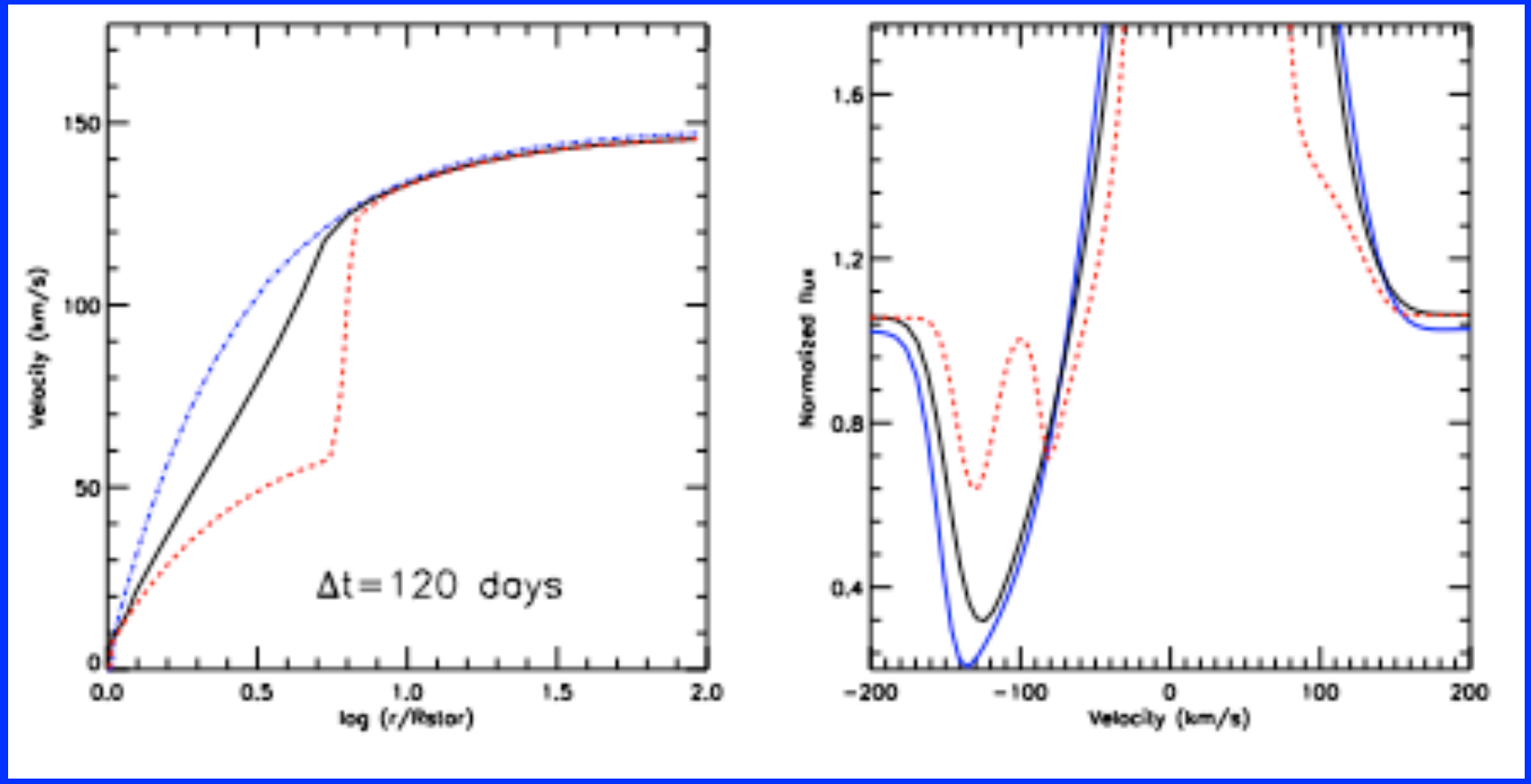
Kotak & Vink (2006)

Do LBVs explode?



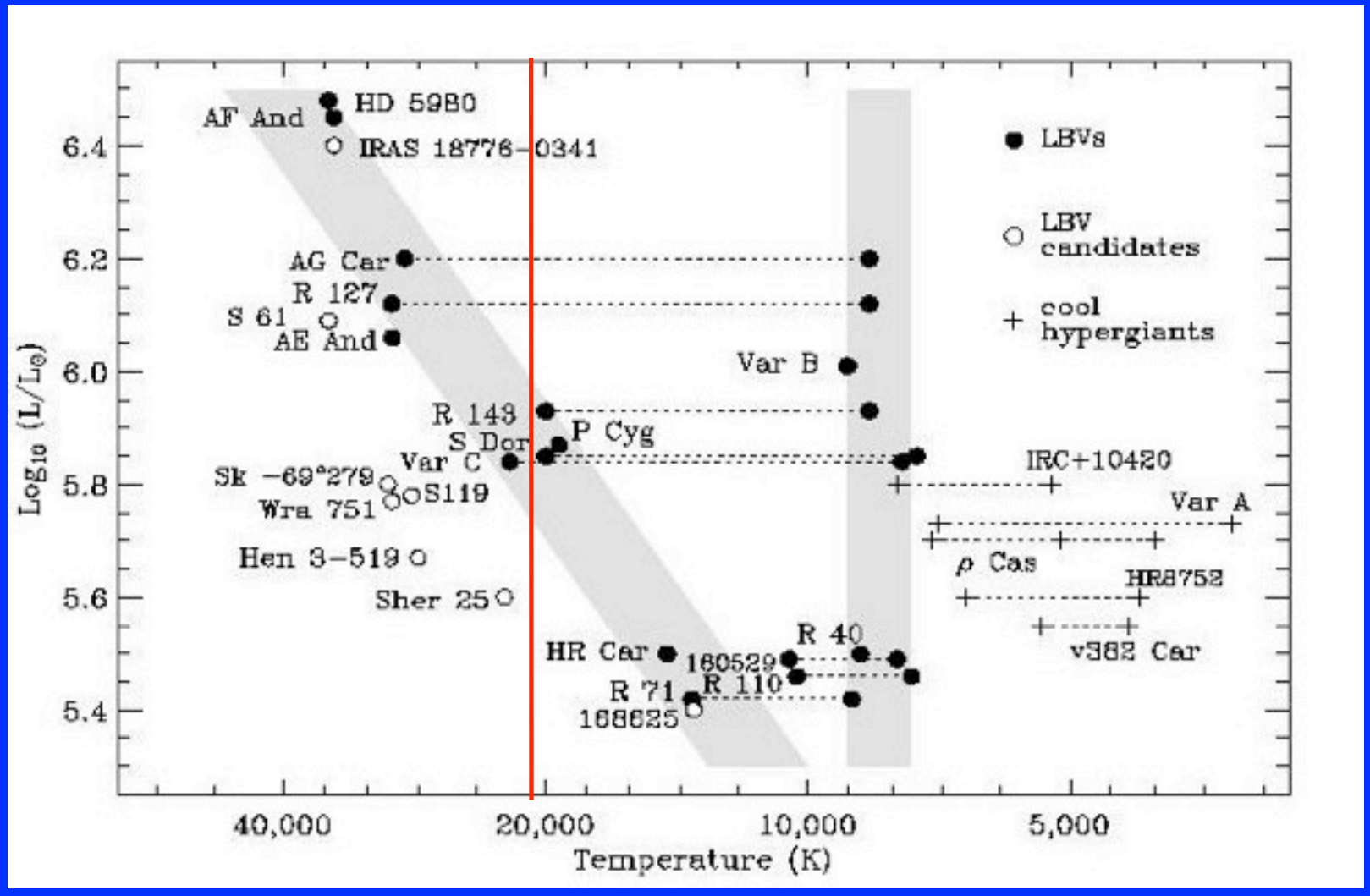
Trundle et al. (2008)

Changing mass loss!

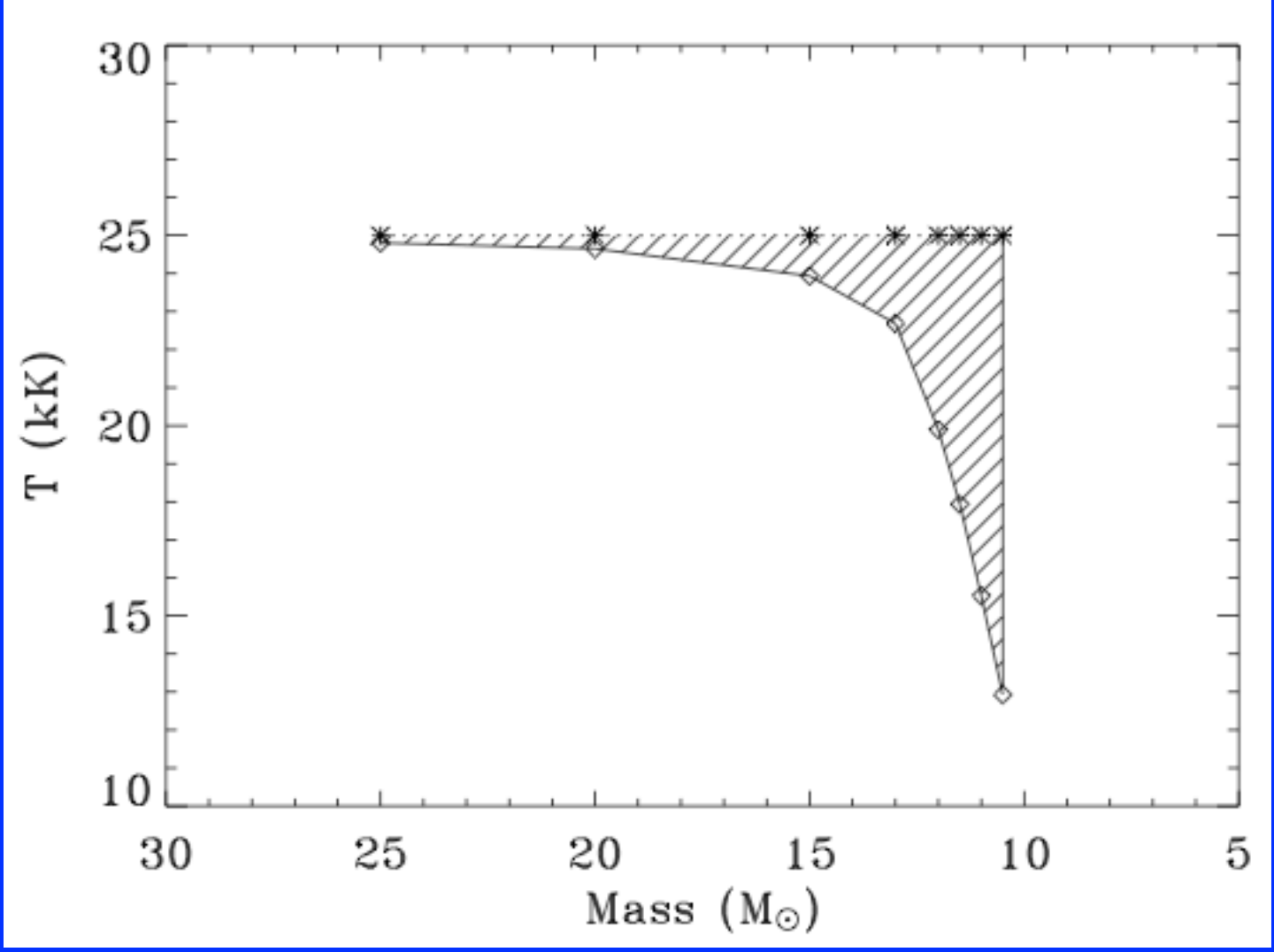


Groh & Vink (2011)

Causes for S Dor cycles



Do LBVs make pseudo-photospheres?

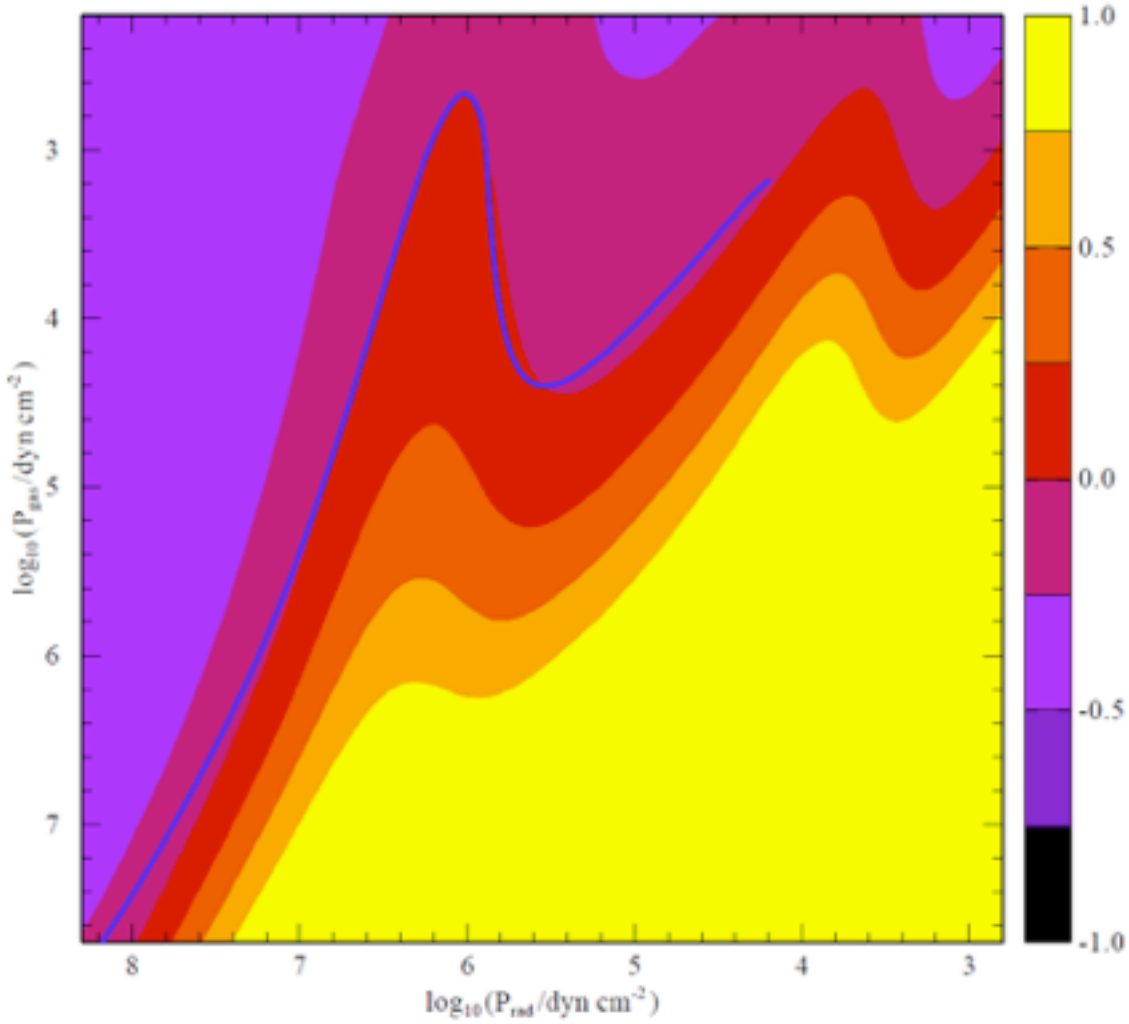


Smith, Vink, de Koter (2004)

INFLATION

Ishii et al. (1999) Petrovic et al. (2006)

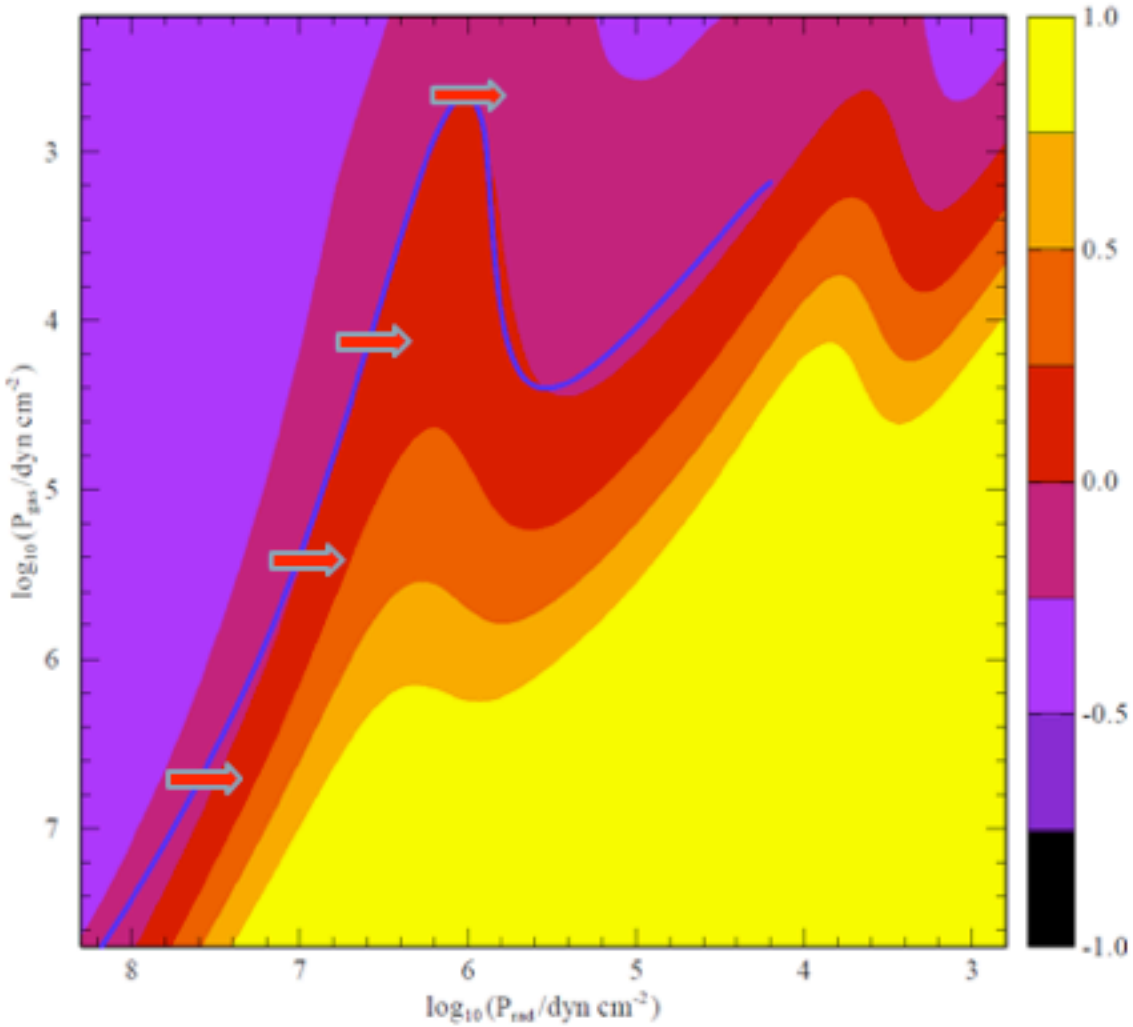
Radius Inflation



$$\frac{\partial P_{\mathrm{gas}}}{\partial P_{\mathrm{rad}}} = \frac{1}{\Gamma} - 1$$

Graefener, Owocki & Vink (2012)

Radius Inflation



$$\frac{\partial P_{\mathrm{gas}}}{\partial P_{\mathrm{rad}}} = \frac{1}{\Gamma} - 1$$

$$\Gamma = 1:$$

$$\frac{\partial P_{\mathrm{gas}}}{\partial P_{\mathrm{rad}}} = 0$$

Graefener, Owocki & Vink (2012)

Radius Inflation

$$\frac{R_{\text{out}}}{R_{\text{in}}} = \frac{1}{1-W}, \qquad W = \frac{\Delta P_{\text{rad}} R_{\text{in}}}{GM\rho_{\text{mean}}}$$

Summary

- Mass-loss rate = f (Gamma (L/M),T, Z)

Summary

- Mass-loss rate = f (Gamma (L/M),T, Z)
- ETA = TAU = 1
- Used to calibrate wind dM/dt

Summary

- Mass-loss rate = f (Gamma (L/M),T, Z)
- ETA = TAU = 1
- Used to calibrate wind dM/dt

- Close to Gamma = 1 “Inflation”
- Formula for Envelope Inflation

Summary

- Mass-loss rate = f (Gamma (L/M),T, Z)
- ETA = TAU = 1
- Used to calibrate wind dM/dt

- Close to Gamma = 1 “Inflation”
- Formula for Envelope Inflation
- W - Instability