Theoretical Wind Models

HST

Jorick S. Vink

Armagh Observatory
(Northern Ireland)

Gotz Grafener
Joachim Bestenlehner
Blagovest Petrov

Outline Winds: dM/dt

- Introduction different stellar winds
- O-star winds
- Very massive star (VMS) winds
- Evolved massive-star winds: LBVs and WRs
- Supernovae

Types of Stellar Winds

- Solar Winds
  - $V_\infty \sim 400\text{-}800$ km/s $\sim= V_{esc}$
  - Low Mdot ($\sim 10^{-14}\ M_{sun}$/yr $<< M_{sun}/t_{life}$)
- Red (super)giant (super)winds
  - Low V_∞ (< Vesc); high Mdot (10^{-4} - $10^{-8}\ M_{sun}$/yr)
- Hot-star Winds
  - High V_∞ ($\sim$3 Vesc = 2000-3000 km/s)
  - High Mdot (10^{-4} - $10^{-8}\ M_{sun}$/yr)

Wind driving mechanisms

- Gas pressure gradient
- Wave pressure gradient
- Radiation pressure gradient

Basic case: Isothermal Wind

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{a^2}{\rho}\frac{d\rho}{dr}$$

$$\frac{d\left(\rho v r^2\right)}{dr} = 0$$

$$\left(1 - \frac{a^2}{v^2}\right)v\frac{dv}{dr} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

Basic case: Isothermal Wind

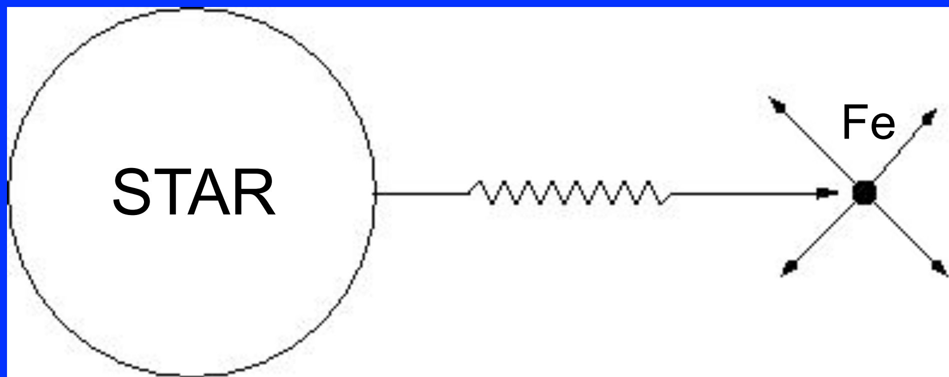
$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{a^2}{\rho}\frac{d\rho}{dr} \qquad \frac{d\left(\rho v r^2\right)}{dr} = 0$$

$$\left(1 - \frac{a^2}{v^2}\right)v\frac{dv}{dr} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{1}{\rho}\frac{dP}{dr} + g_X$$

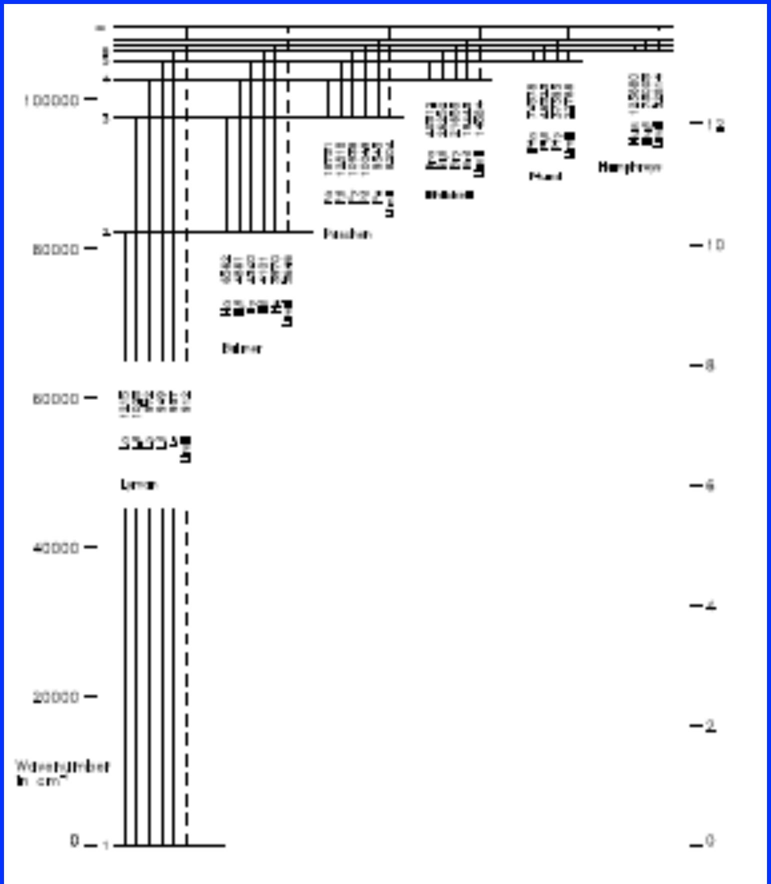
Radiation-driven winds

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

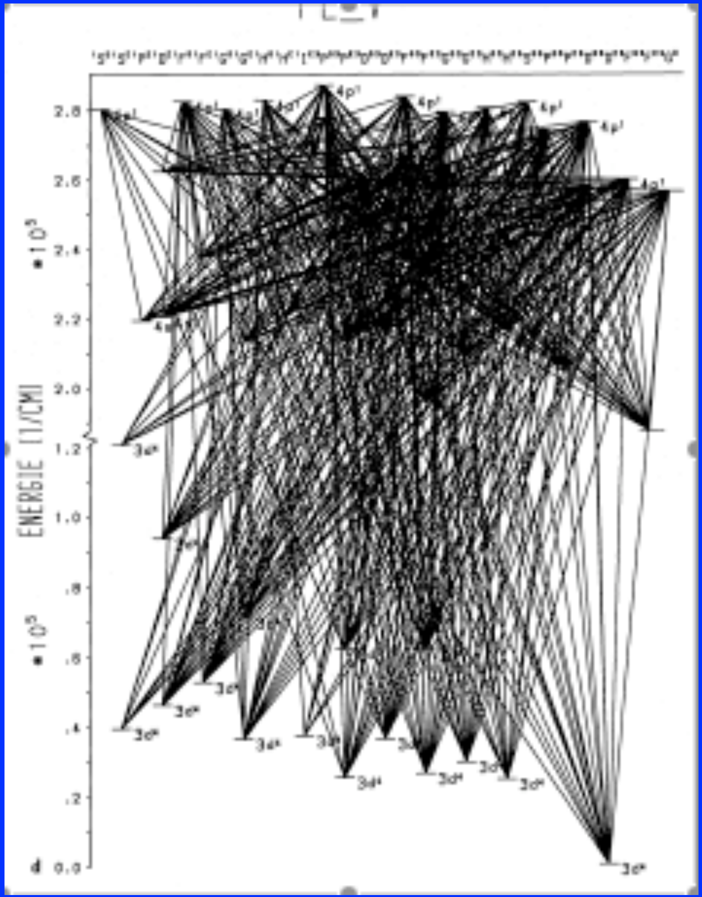


dM/dt = f (L,M,Teff,Z)

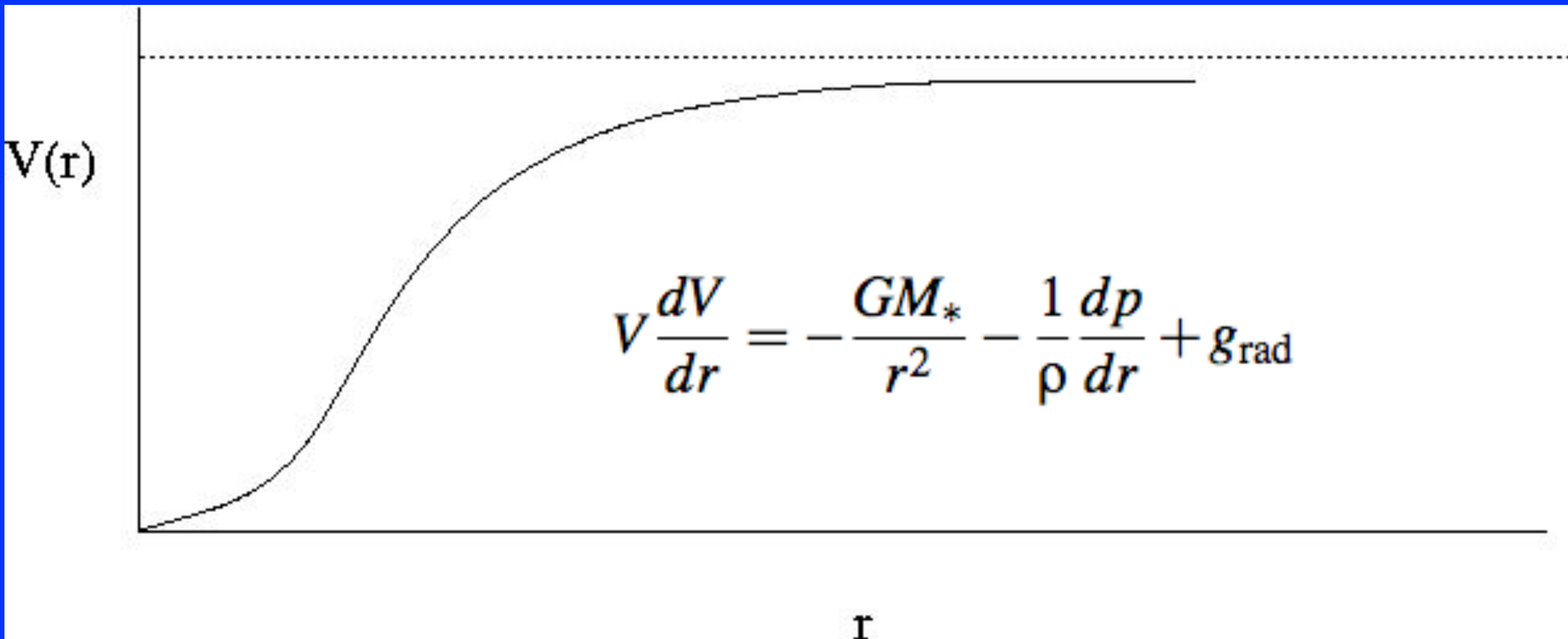
H atom



Fe V atom



Wind dynamics



CAK Wind dynamics

$$g_{\rm L}(r) = g_{\rm e}\, M(t) = \frac{\sigma_e L_*}{4\pi r^2 c} k t^{-\alpha}$$

$$t = \sigma_e v_{\rm th} \rho (dr/dv)$$

CAK Wind dynamics

$$g_{\rm L}(r) \; = \; g_{\rm e}\, M(t) \; = \; \frac{\sigma_e L_*}{4\pi r^2 c} k t^{-\alpha}$$

$$t \; = \; \sigma_e v_{\rm th} \rho (dr/dv)$$

$$V\frac{dV}{dr} = -\frac{GM_{\rm eff}}{r^2} - \frac{1}{\rho}\frac{dp}{dr} + \frac{\sigma_{\rm e}\, L_*}{4\pi r^2 c} K \left(\sigma_{\rm e}\, V_{\rm th}\rho \frac{dr}{dV}\right)^{-\alpha}$$

CAK Wind dynamics

$$g_{\mathrm{L}}(r) = g_{\mathrm{e}}\, M(t) = \frac{\sigma_e L_*}{4\pi r^2 c} k t^{-\alpha}$$

$$t = \sigma_e v_{\mathrm{th}} \rho (dr/dv)$$

$$V\frac{dV}{dr} = -\frac{GM_{\mathrm{eff}}}{r^2} - \frac{1}{\rho}\frac{dp}{dr} + \frac{\sigma_e L_*}{4\pi r^2 c} K \left(\sigma_e V_{\mathrm{th}} \rho \frac{dr}{dV}\right)^{-\alpha}$$

$$\left(\frac{V_\infty}{V_{\mathrm{esc}}}\right) = \sqrt{\frac{\alpha}{1-\alpha}}$$

CAK Wind dynamics

$$g_L(r) = g_e\, M(t) = \frac{\sigma_e L_*}{4\pi r^2 c} k t^{-\alpha}$$

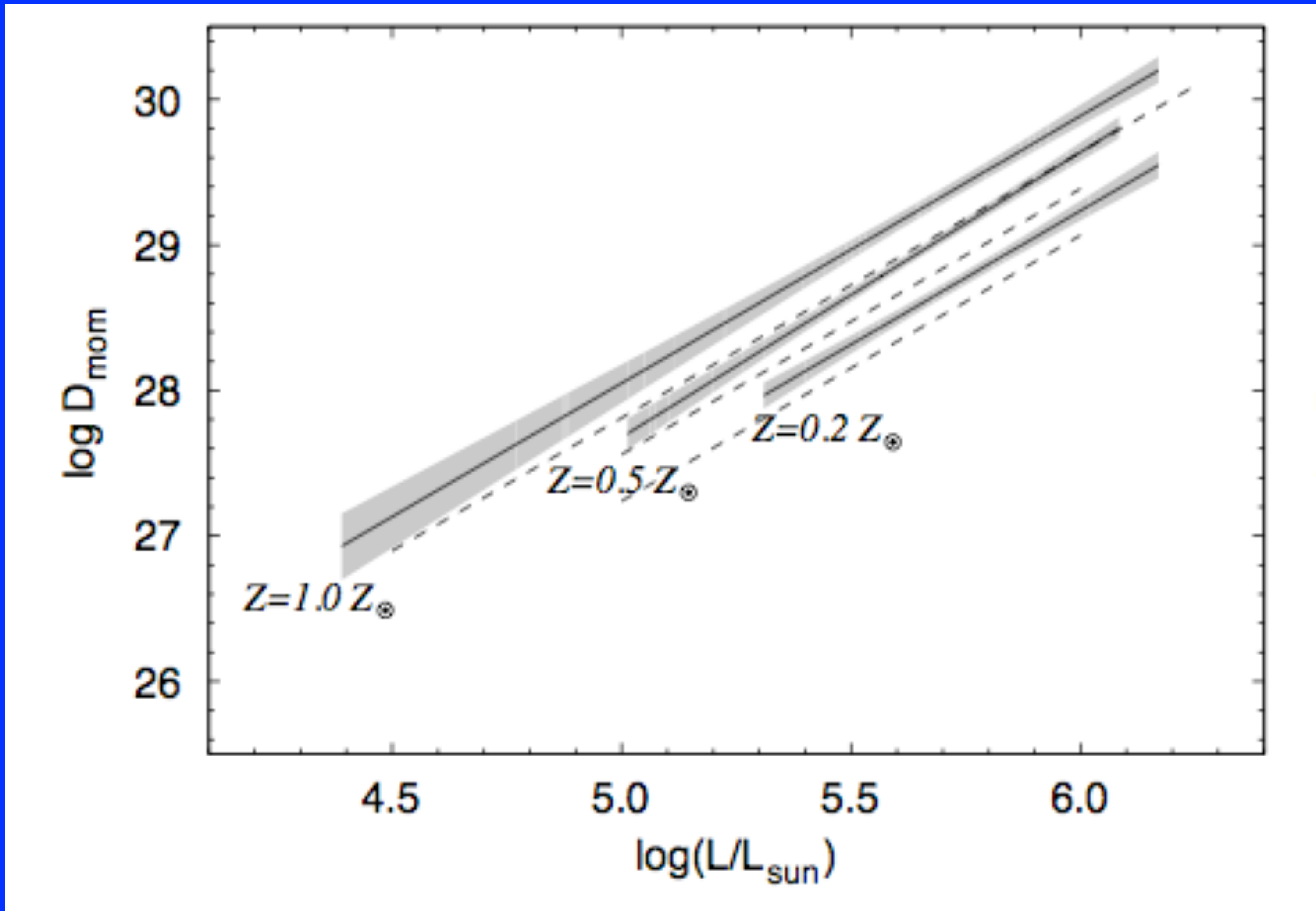
$$t = \sigma_e v_{th} \rho (dr/dv)$$

$$V\frac{dV}{dr} = -\frac{GM_{\rm eff}}{r^2} - \frac{1}{\rho}\frac{dp}{dr} + \frac{\sigma_e L_*}{4\pi r^2 c} K \left(\sigma_e V_{th} \rho \frac{dr}{dV}\right)^{-\alpha}$$

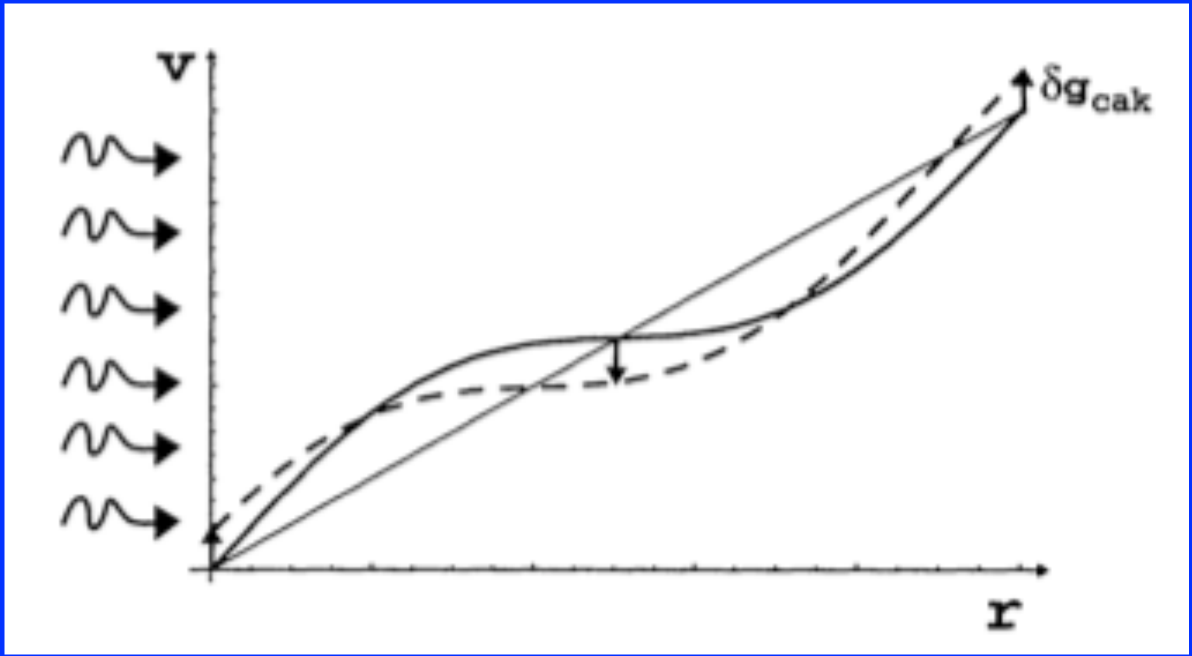
$$\left(\frac{V_\infty}{V_{esc}}\right) = \sqrt{\frac{\alpha}{1-\alpha}}$$

$$\dot{M} = \left(\frac{\sigma_e V_{th}}{4\pi}\right)\left(\frac{\sigma_e}{4\pi}\right)^{1/\alpha}\left(\frac{1-\alpha}{\alpha}\right)^{\frac{1-\alpha}{\alpha}}(\alpha K)^{1/\alpha} \left(\frac{L_*}{c}\right)^{1/\alpha}(GM_*(1-\Gamma_e))^{(\alpha-1)/\alpha}$$

Wind momentum - Luminosity



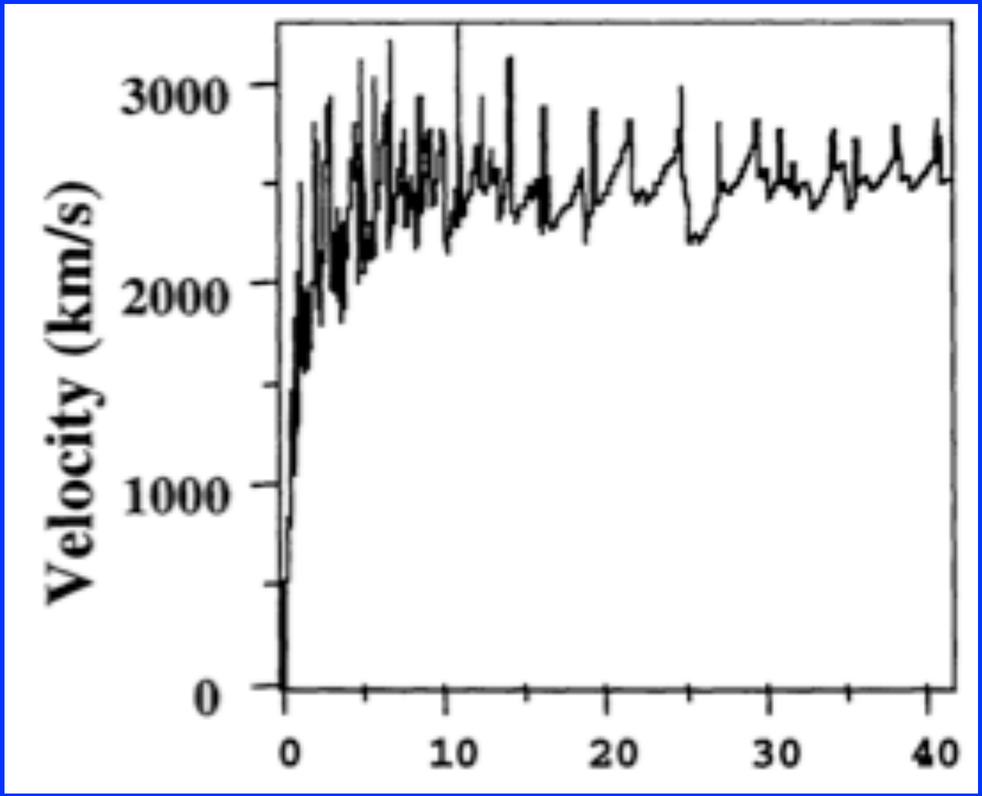
Perturbations: LDI



(Owocki)

Because g = f (dv/dr) delta v --> delta g --> delta v

LDI hydro simulations



(Owocki)

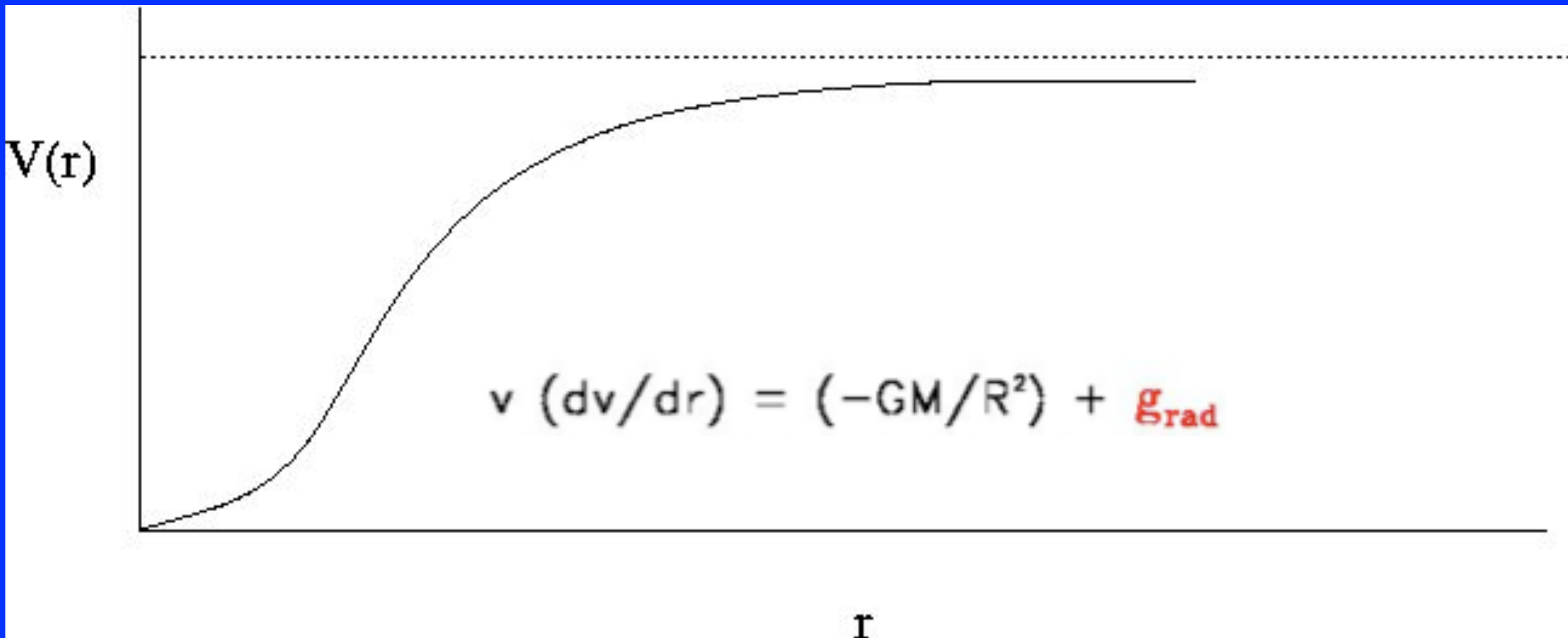
Mdot expected to be preserved

But diagnostics affected!

Clumping

- Observations: evidence for structured winds
- Empirical: dM/dt (new) = dM/dt (old) / sqrt(Cl)

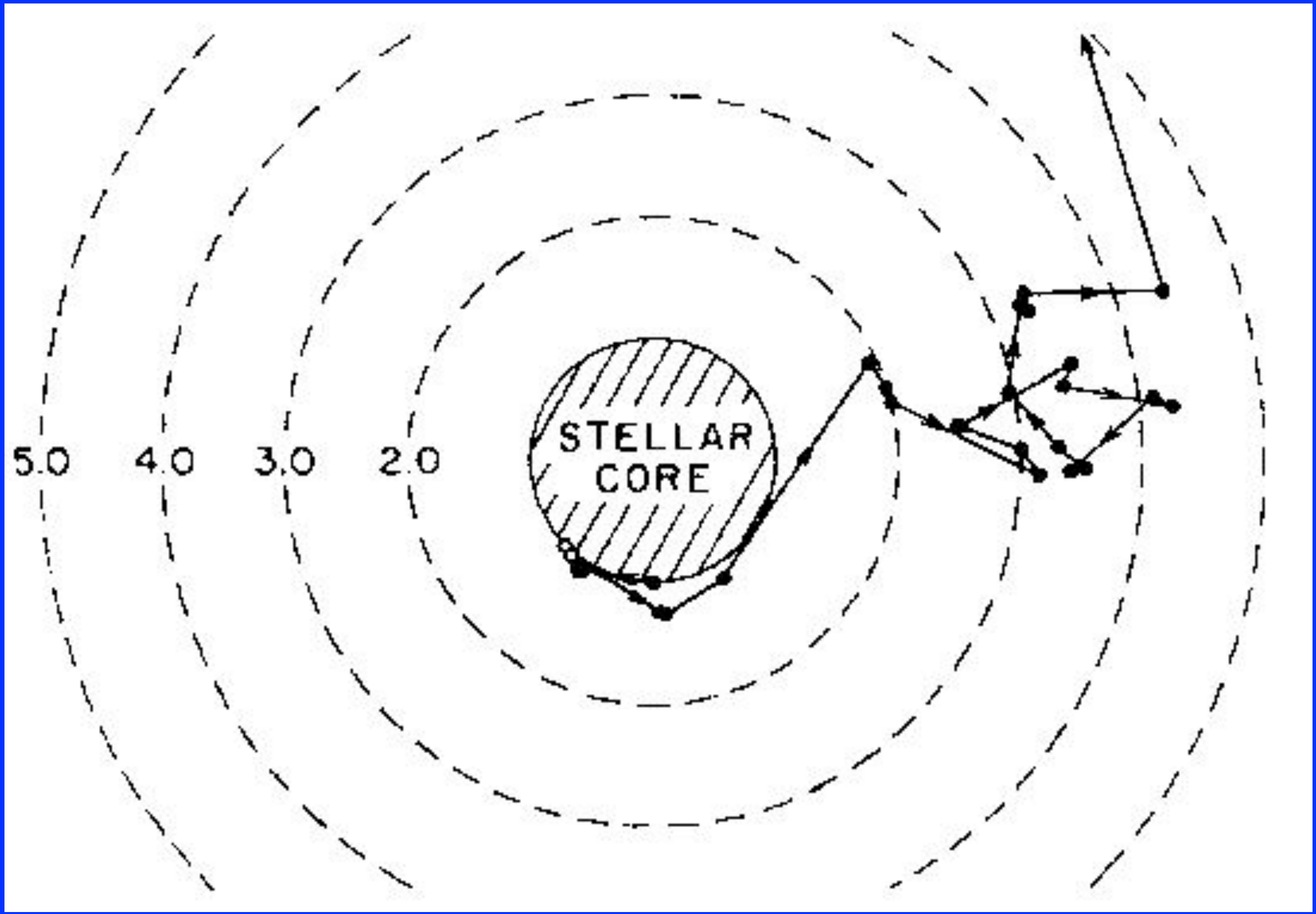
General Wind dynamics



grad= f (dv/dr) — CAK = Castor, Abbott & Klein (1975)
Pauldrach et al. (1986)

grad = f (r) — Mueller & Vink (2008)

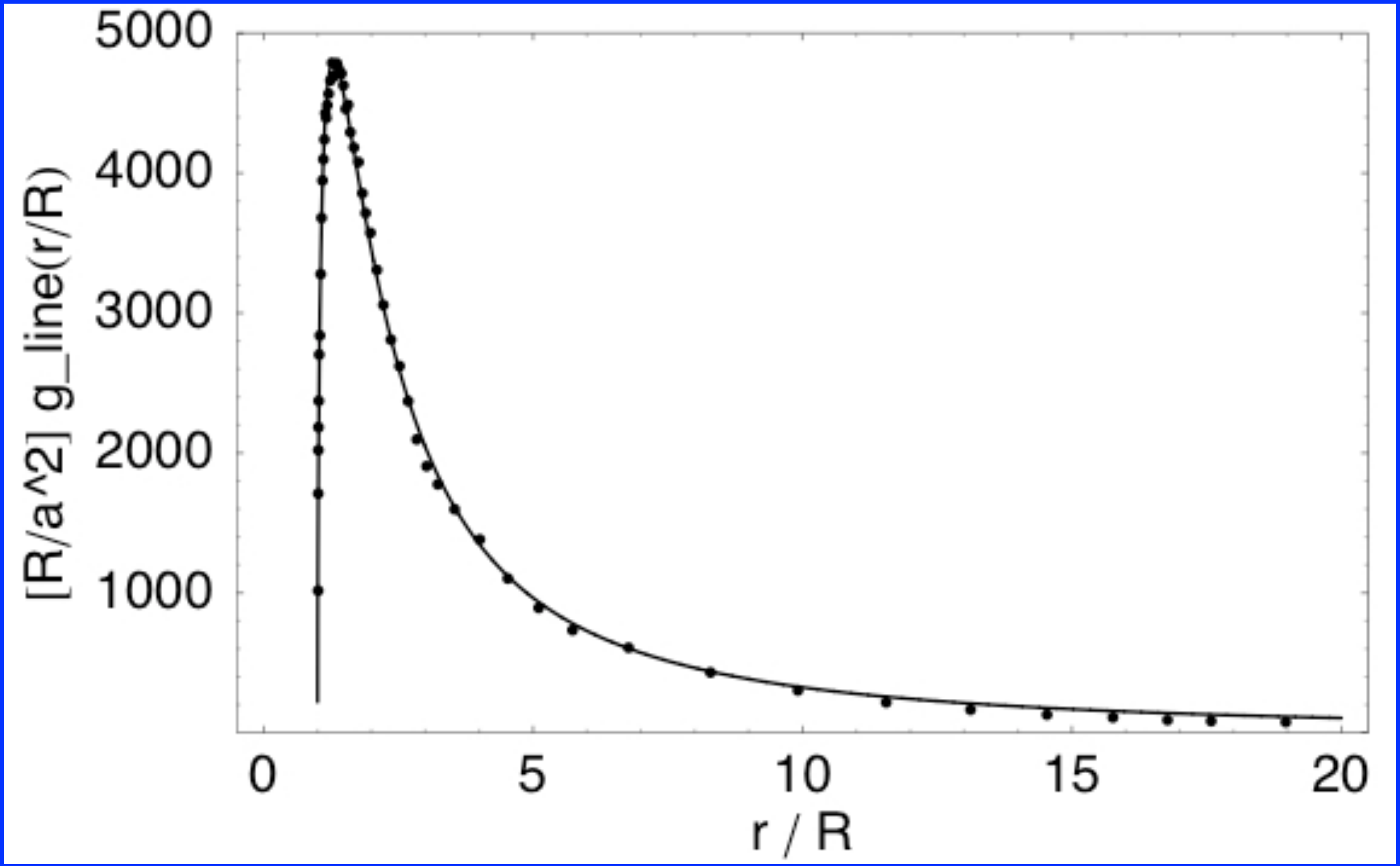
Alternative: Monte Carlo



(Abbott & Lucy 1985; Vink et al. 2000)

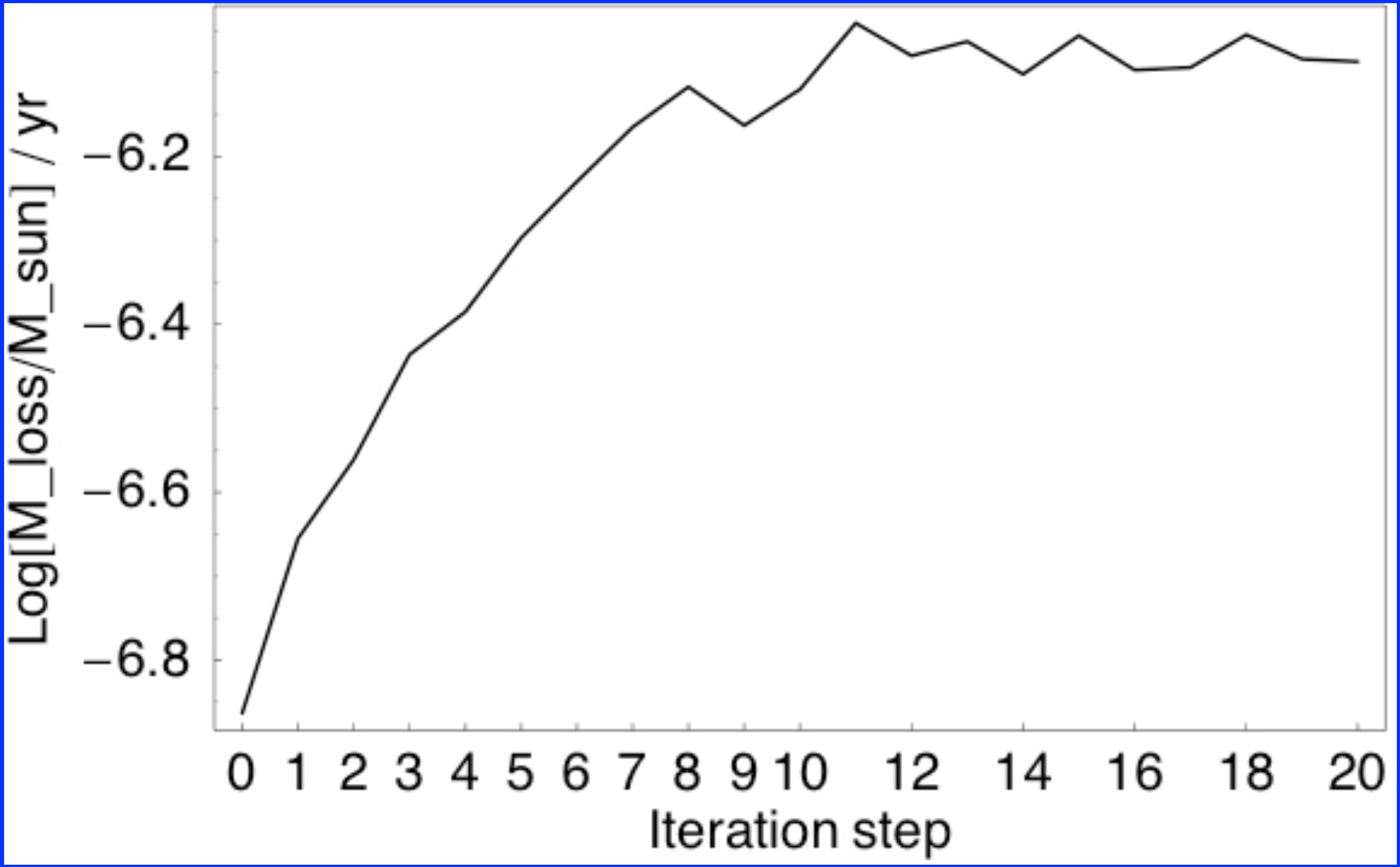
$$\dot{M}\ v_\infty > \frac{L_*}{c}$$

Line acceleration: g(r)



Mueller & Vink (2008)

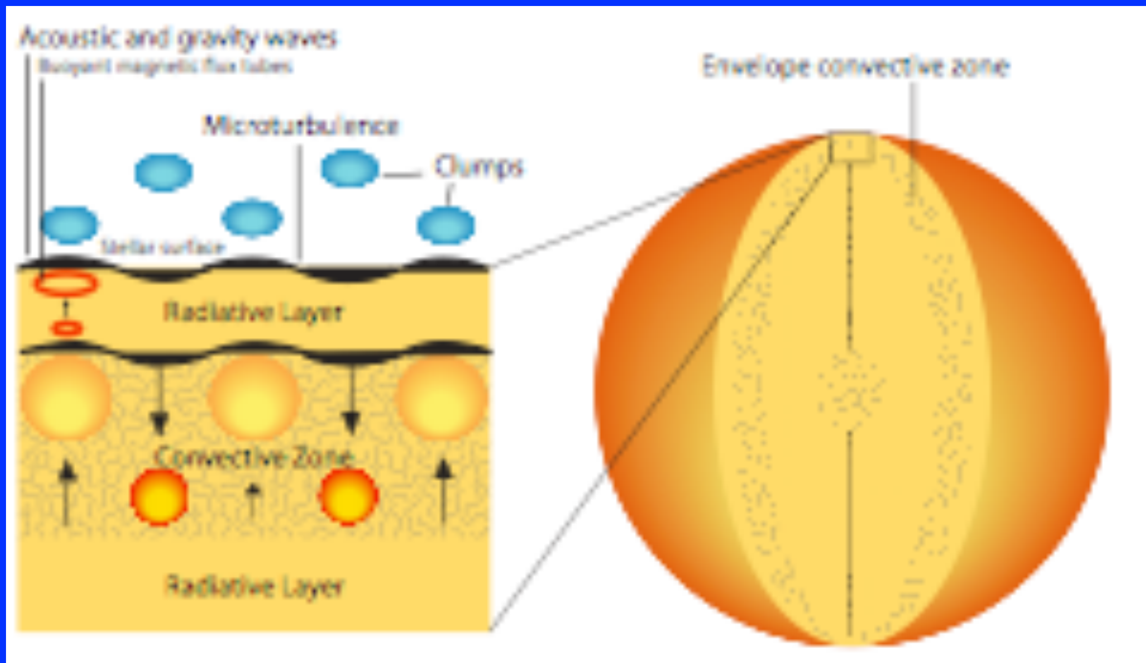
Mass-loss iteration



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

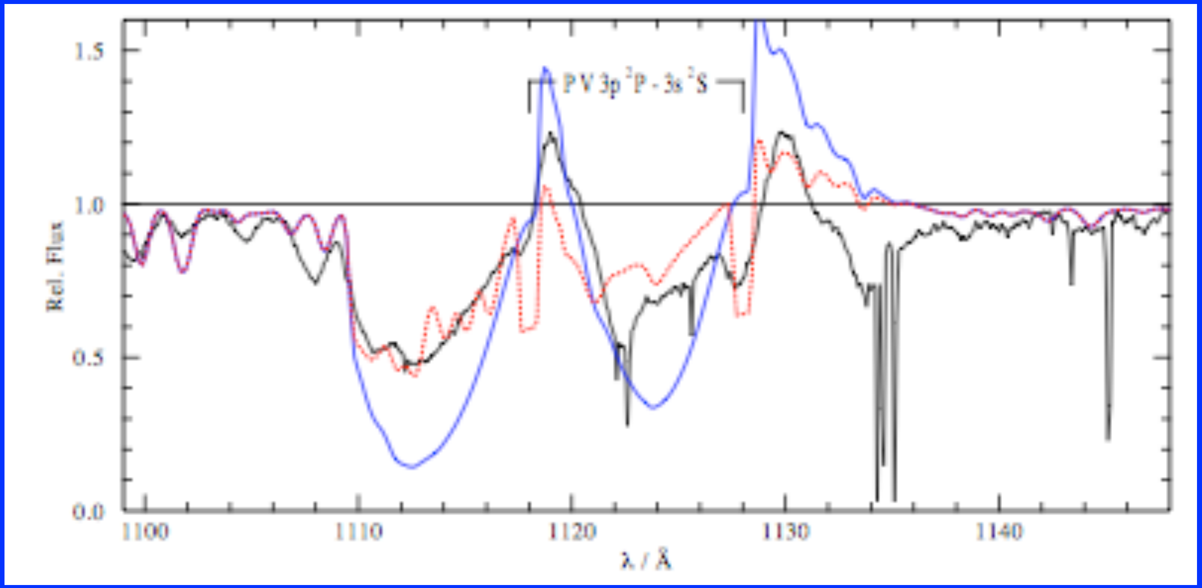
Sub-surface convection

Subphotospheric origin of clumping?



(Cantiello et al. 2009)

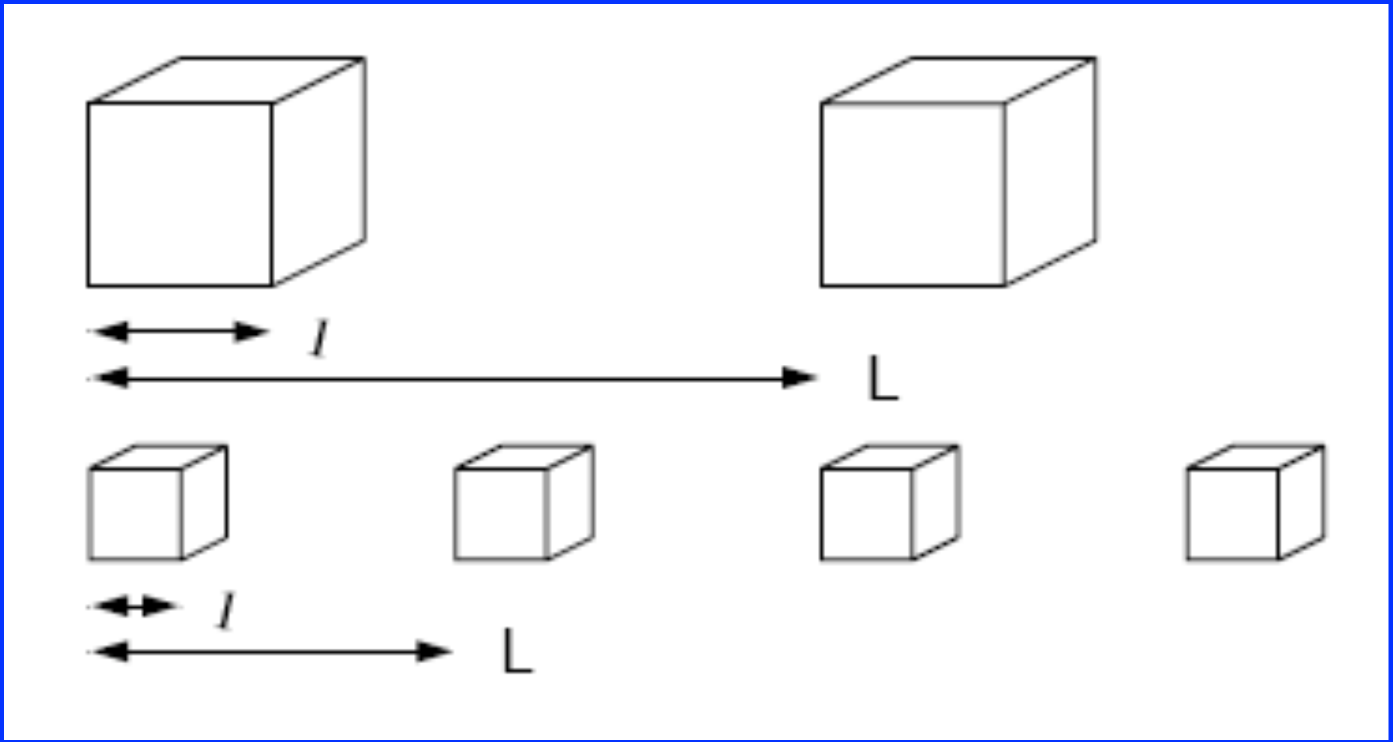
Phosphorus V problem



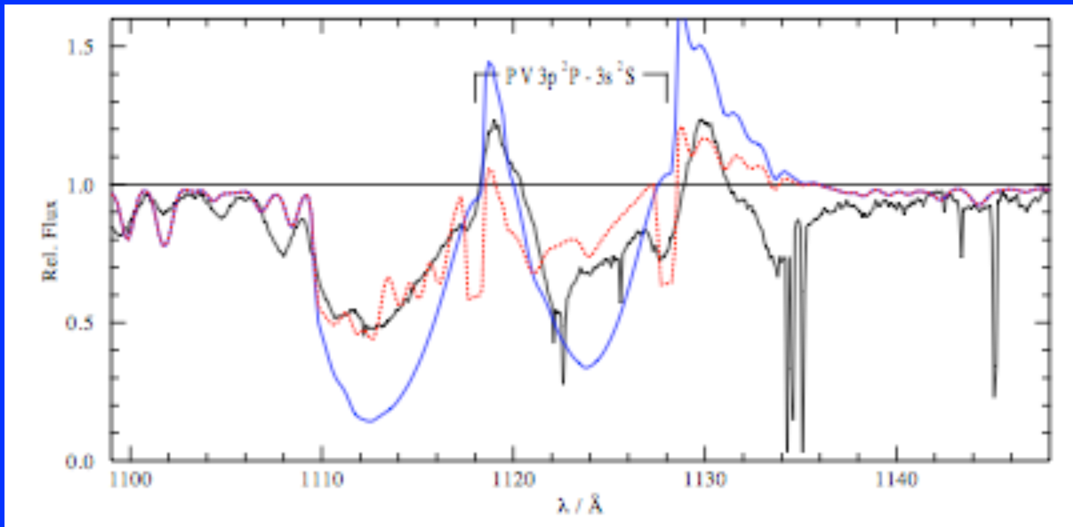
Empirical dM/dt reduced ?

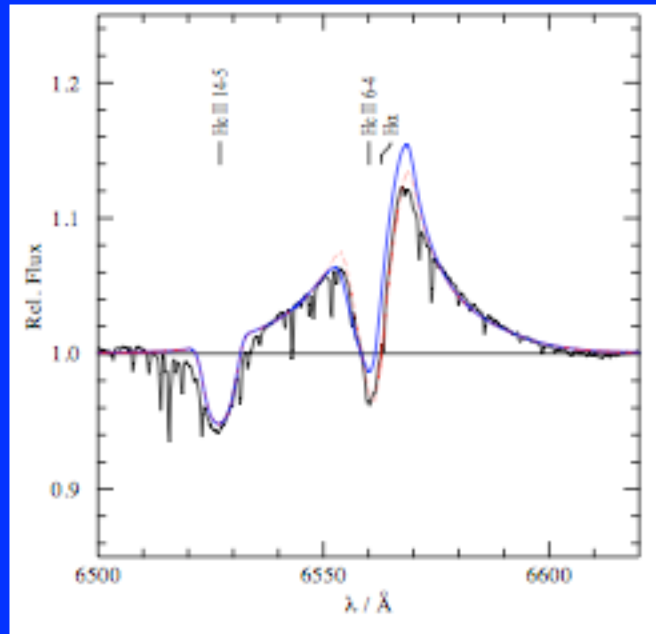
(e.g. Fullerton et al. 2006)

Clumping: Porosity

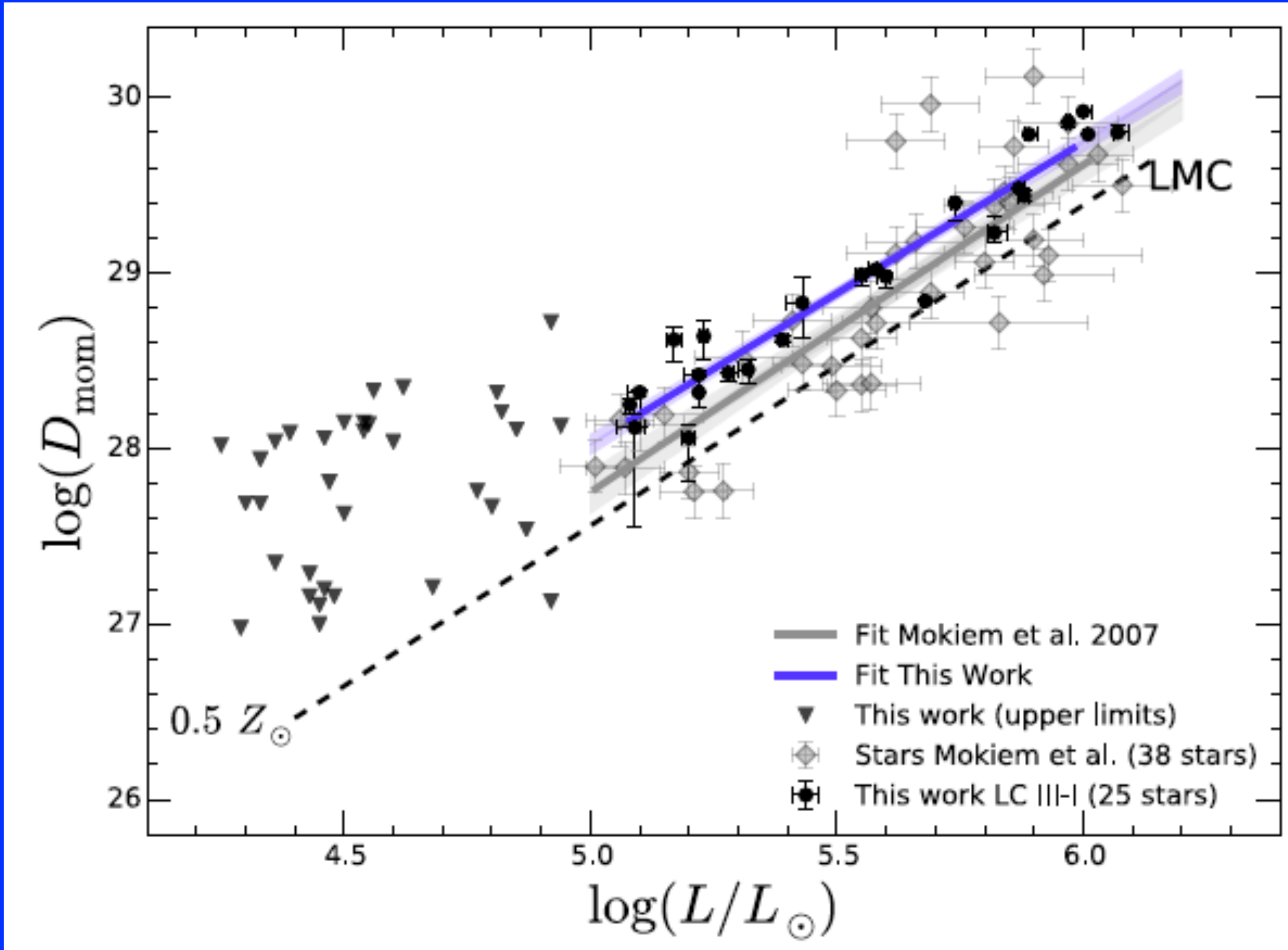


Observations: UV + optical Ha





(Oskinova et al. 2007. See also Sunqvist et al. 2010, Surlan et al. 2013)



(Oscar Ramirez + VFTS)

Empirical dM/dt down by factor of 3 - with Cl 6-8
If theory OK

VMS: High Gamma

What is Gamma?

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

What is Gamma?

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

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

What is Gamma?

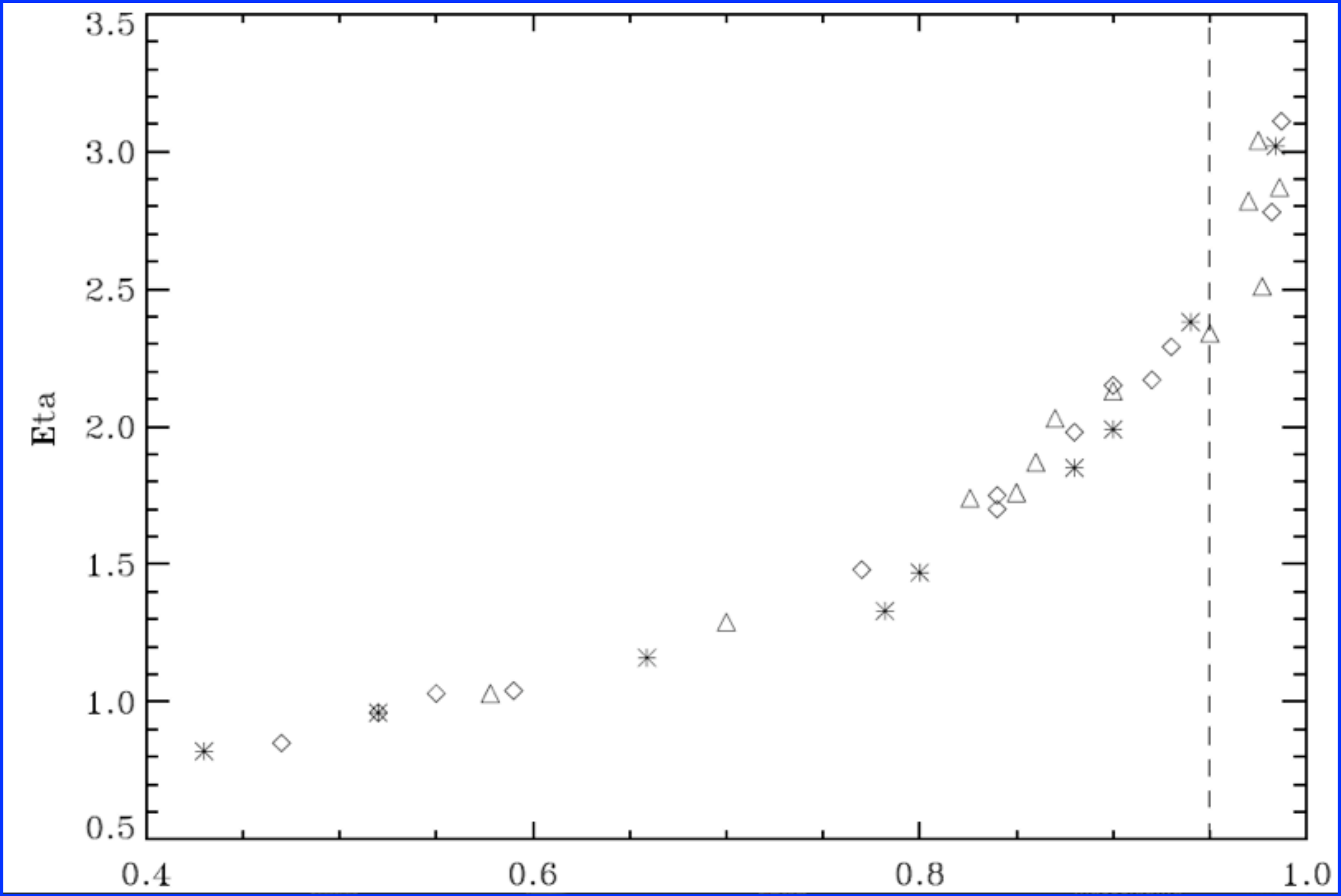
$$g_{\rm rad} = \frac{\kappa F}{c} = \frac{\kappa L}{4\pi R^2 c}$$

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

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

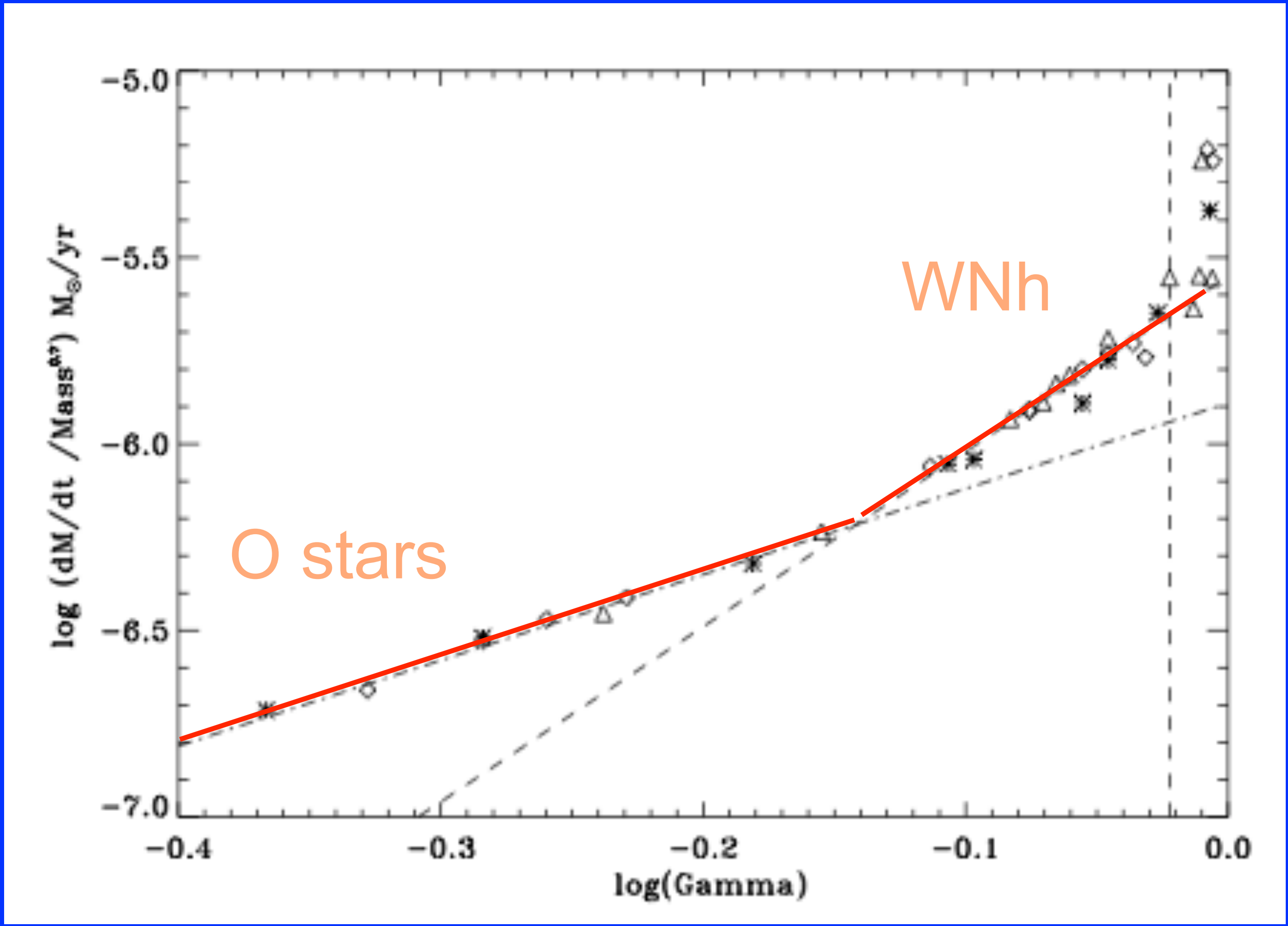
Wind efficiency

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



Vink et al. (2011)

KINK in Mass loss - Gamma Dependence



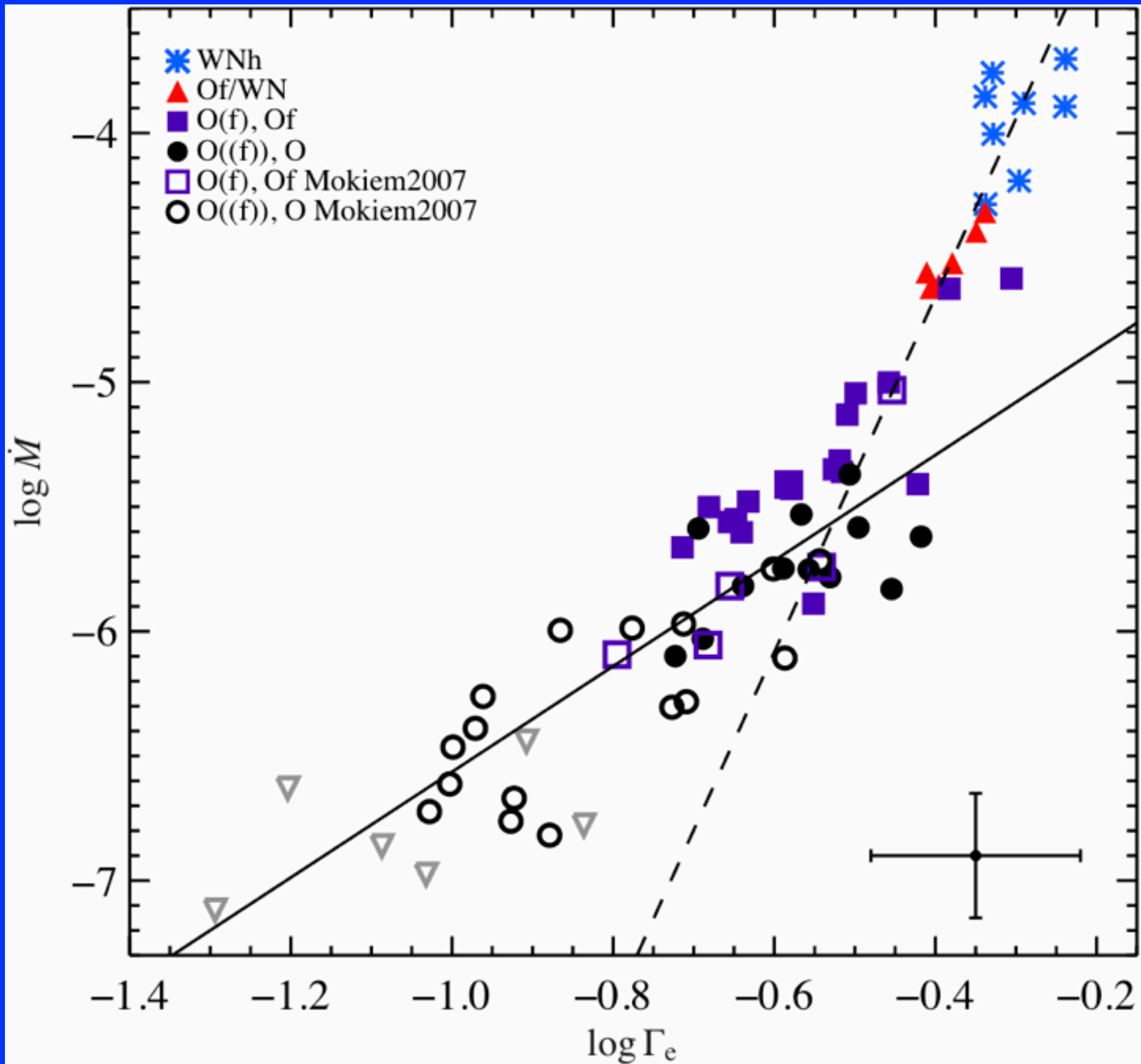
Vink et al. (2011)

Mass loss calibration

- ETA = TAU = 1
- dM/dt = L/cv

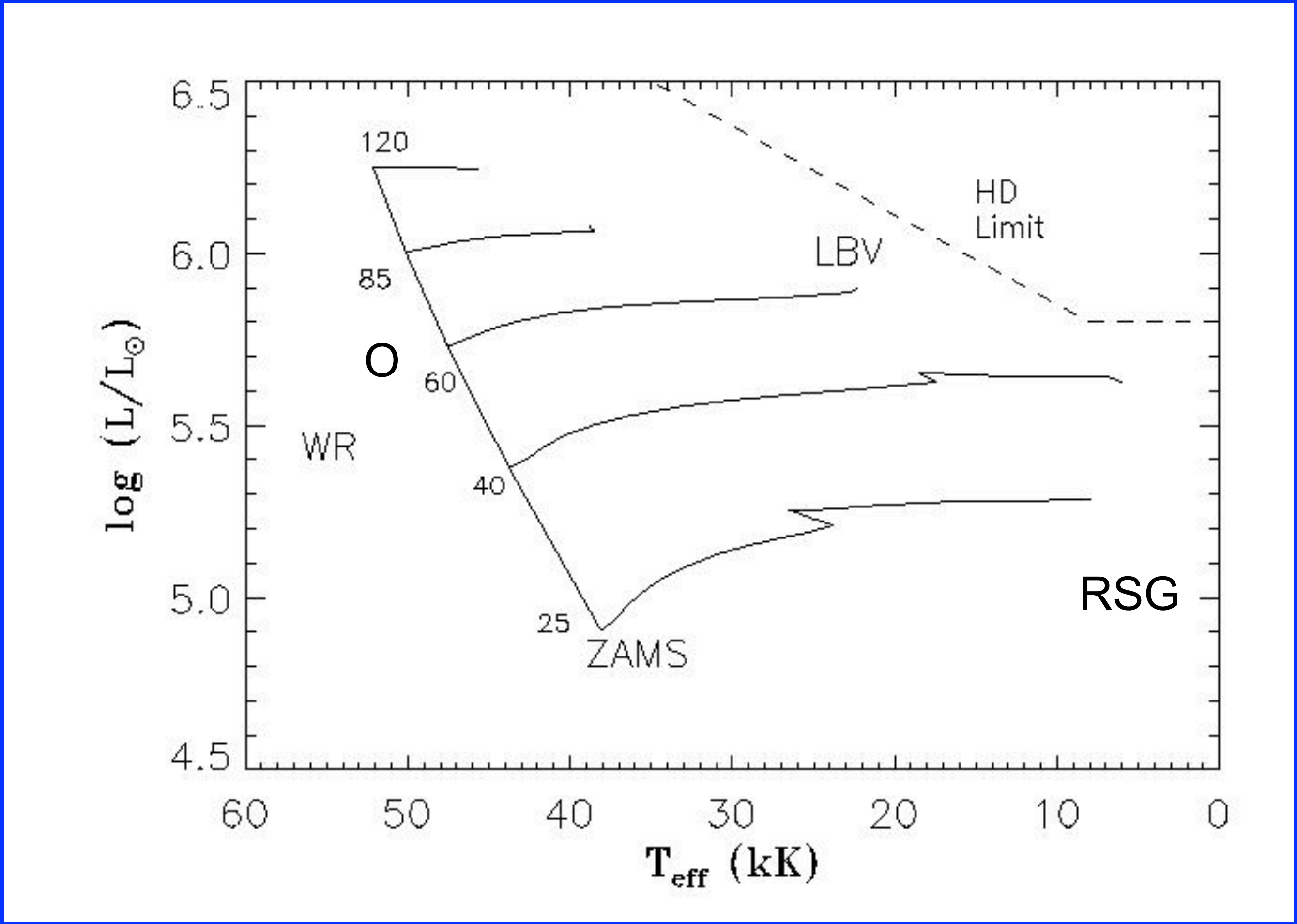
Vink & Grafener (2012)

VLT Flames Tarantula Survey



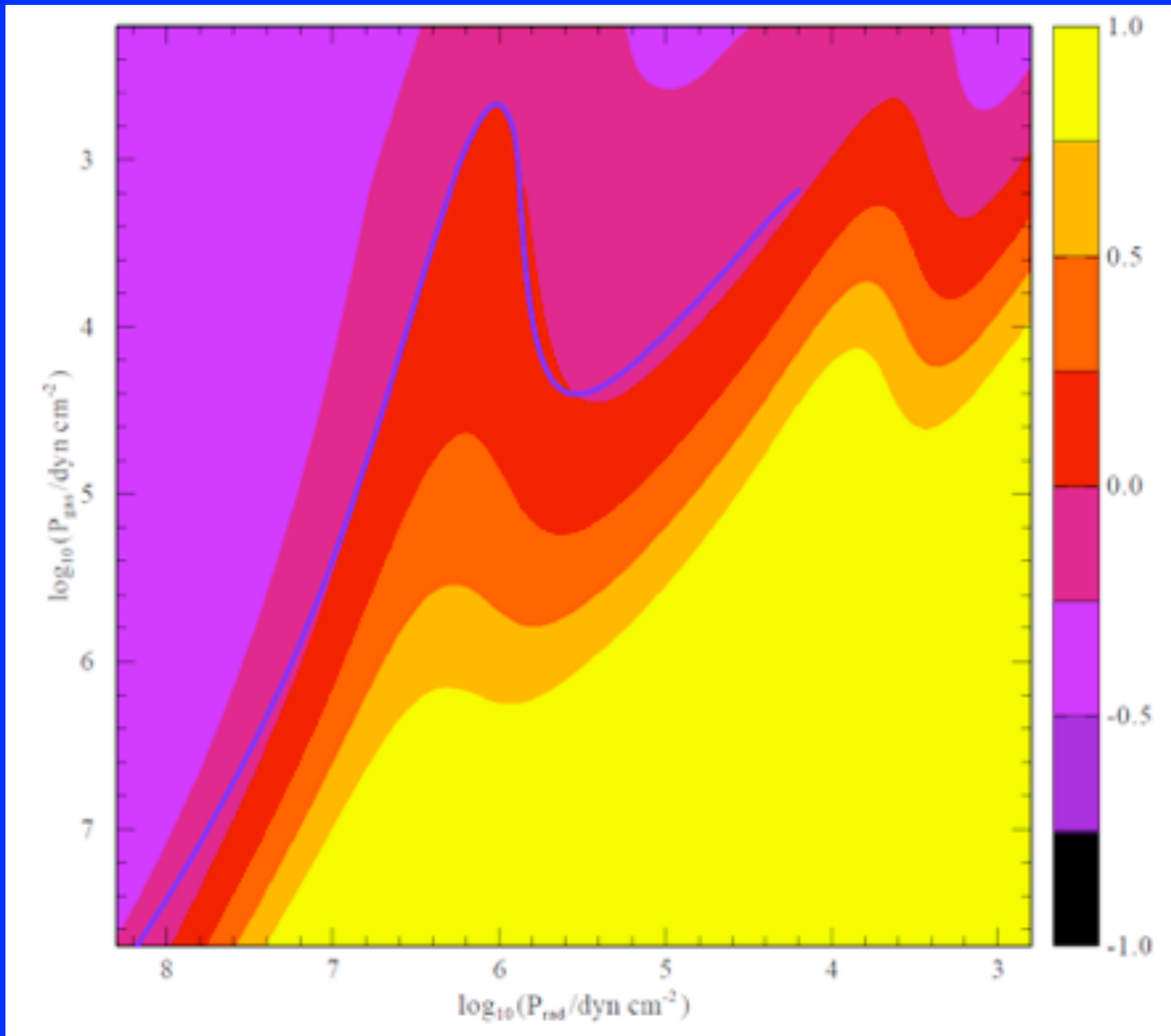
Bestenlehner et al. (2014)

Upper HRD



6.5
6.0
5.5
5.0
4.5
log (L/L☉)
120
85
60
40
25
O
WR
ZAMS
LBV
HD
Limit
RSG
60
50
40
30
20
10
0
Teff (kK)

Radius Inflation

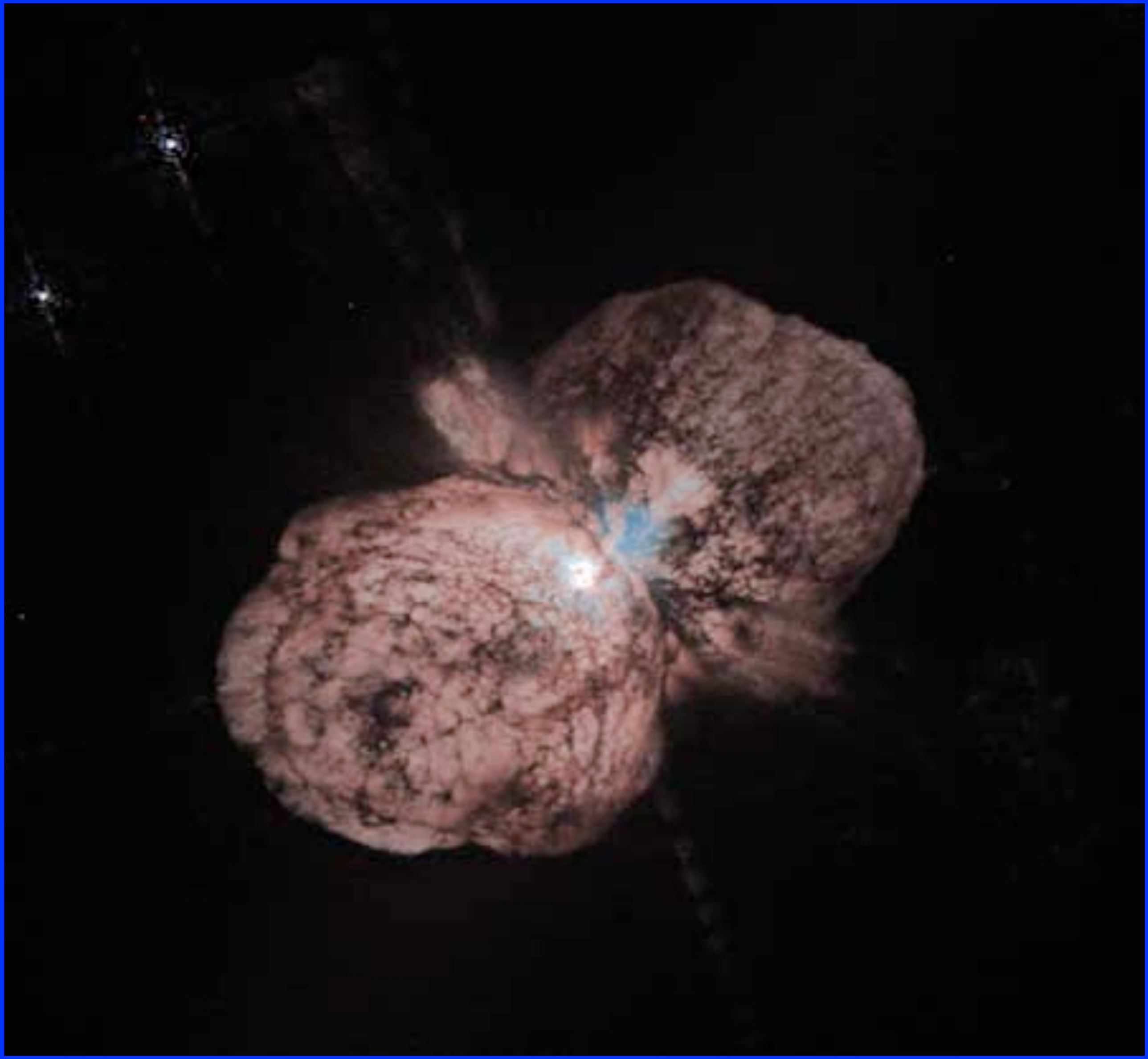


Ishii et al. (1999), Petrovic et al. (2006), Grafener et al. (2012)

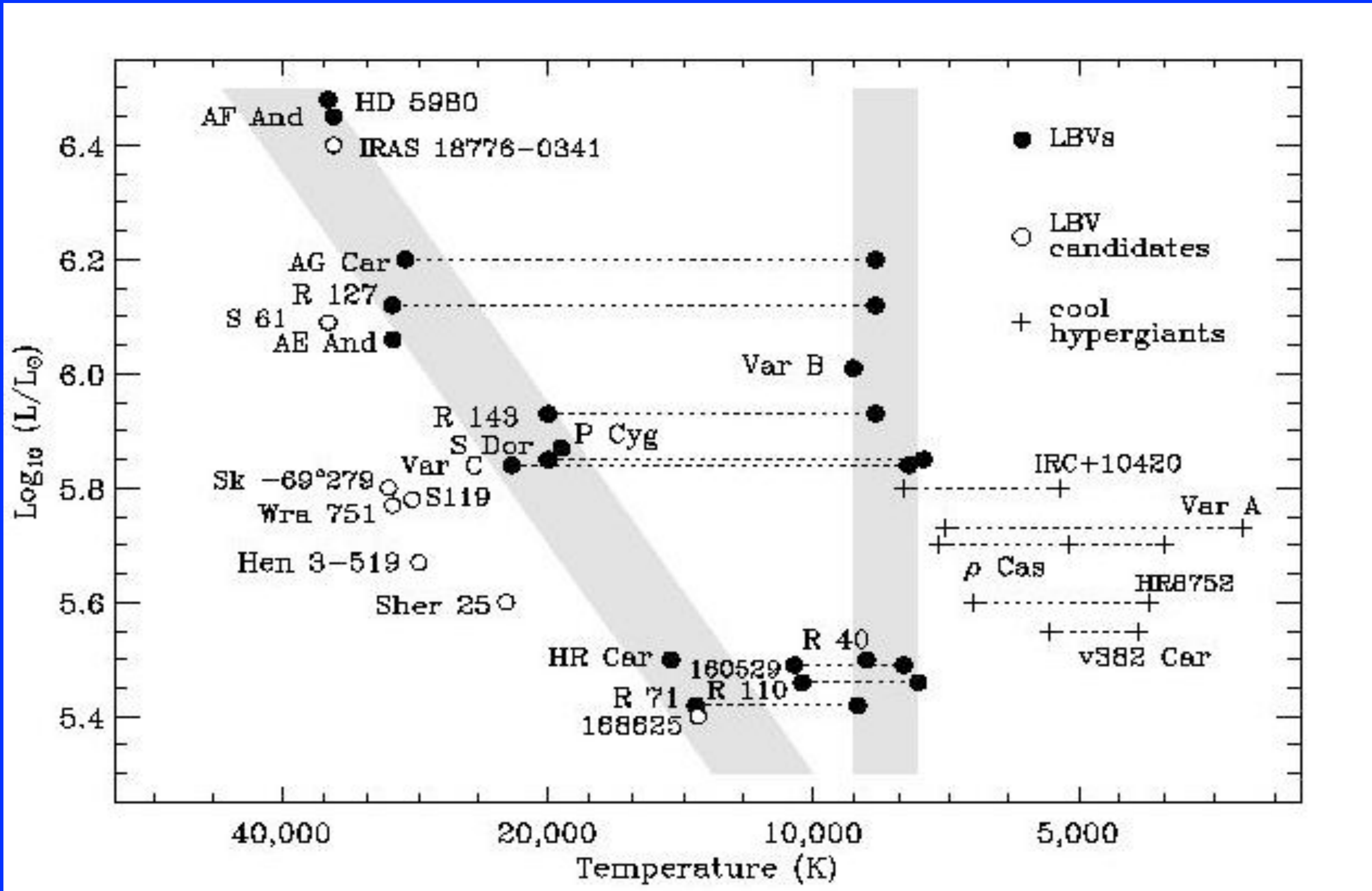
Radius Inflation

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

Grafener, Owocki & Vink (2012)

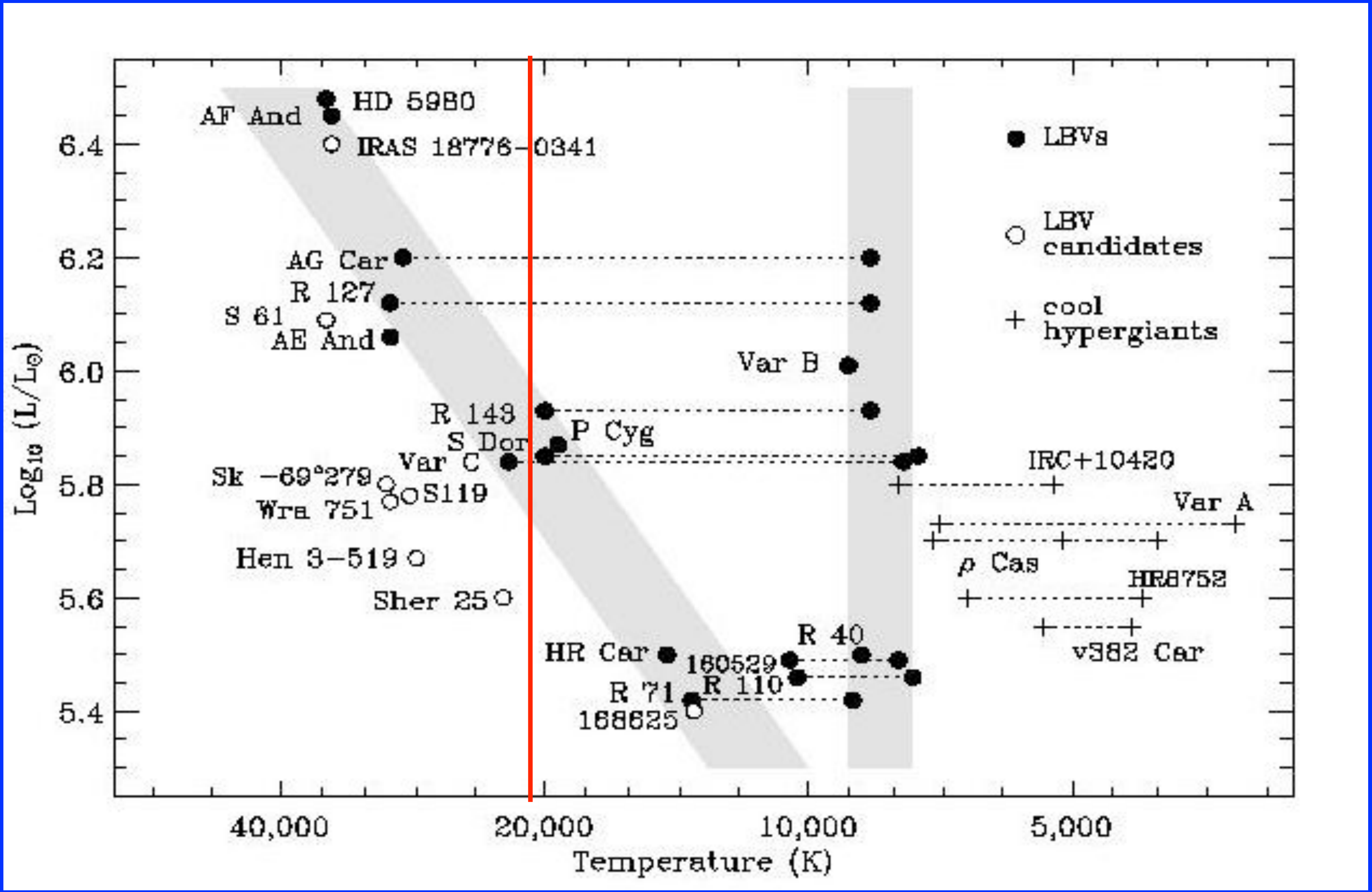


LBVs in the HRD



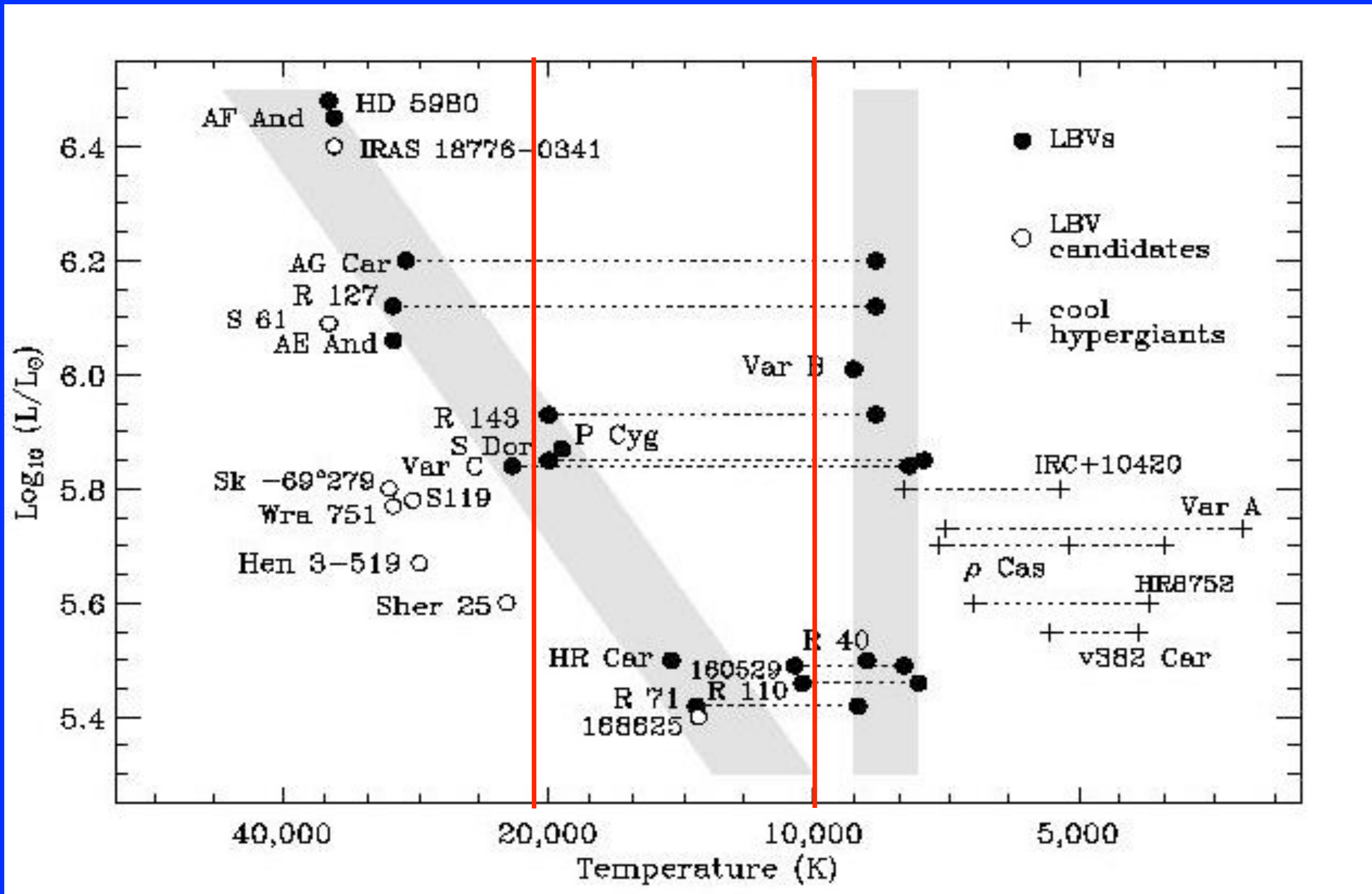
Smith, Vink & de Koter (2004)

LBVs in the HRD



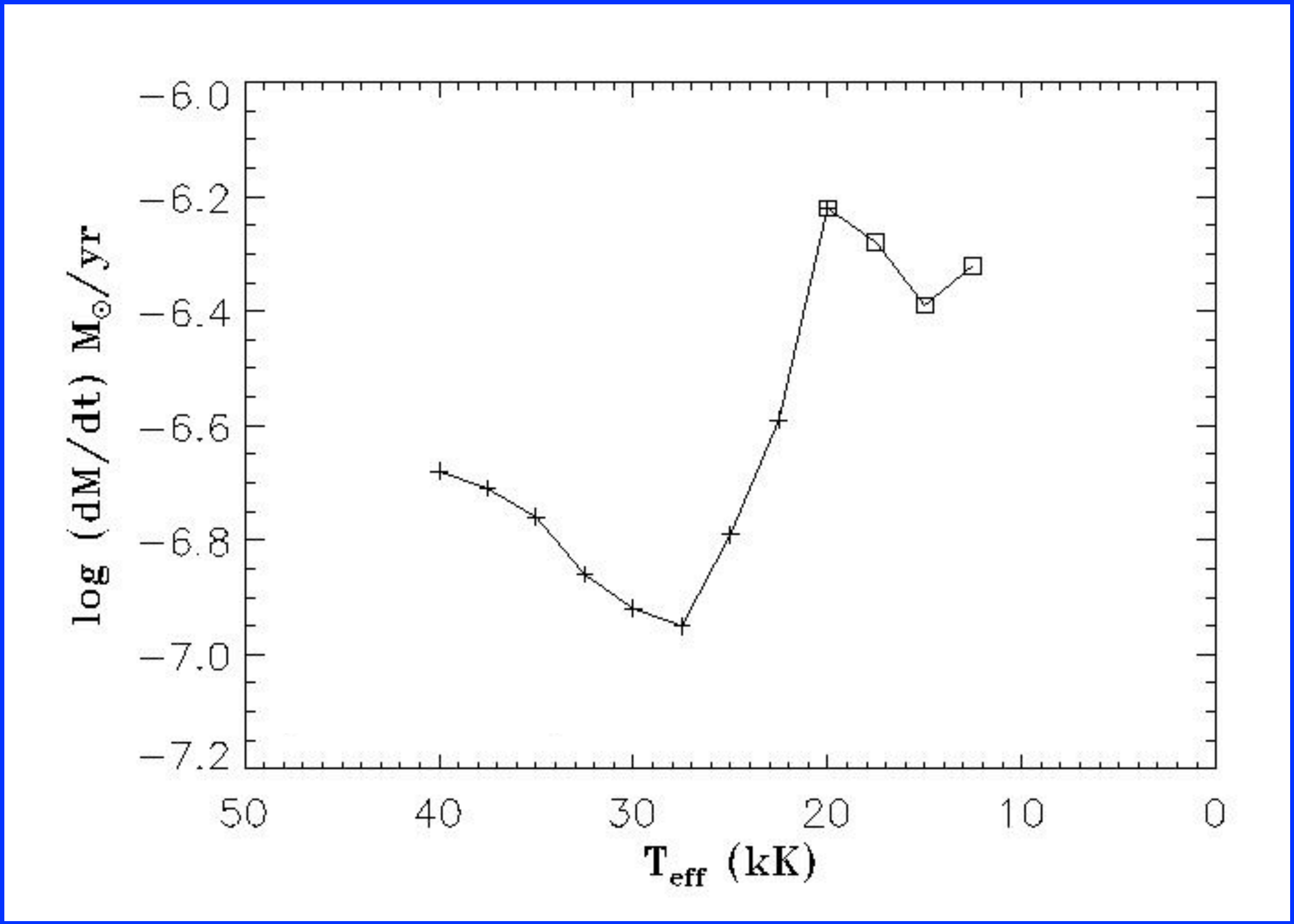
Smith, Vink & de Koter (2004) Vink (2012)

LBVs in the HRD



Vink et al. (1999) Petrov et al. (2016)

Change in mass loss



→ dM/dt jumps up by factor 5

Bi-stability Jump

HOT (O stars)

modest dM/dt
fast wind

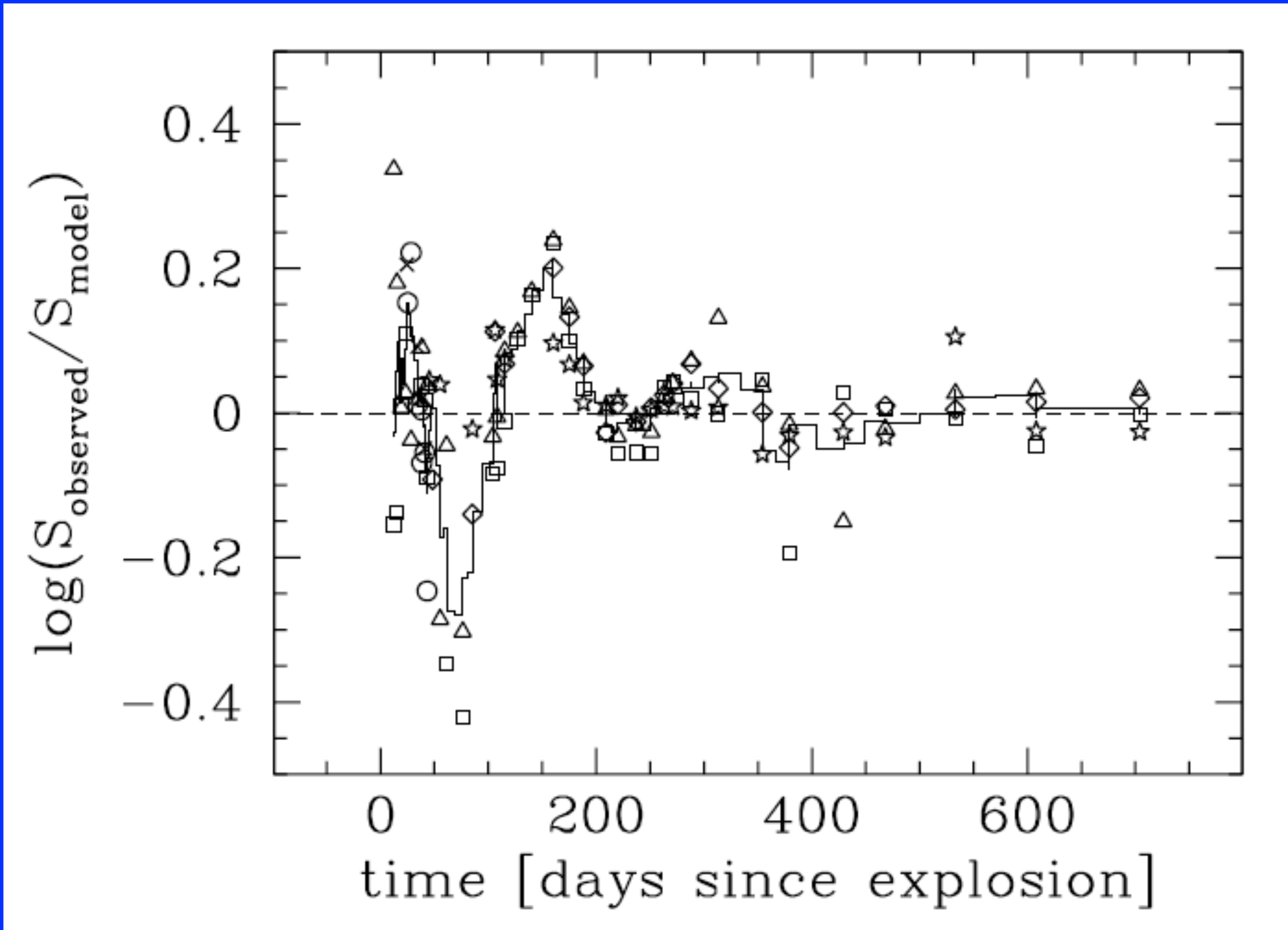
Fe IV

COOL (B supergiants)

large dM/dt
slow wind

Fe III

Radio supernova lightcurves



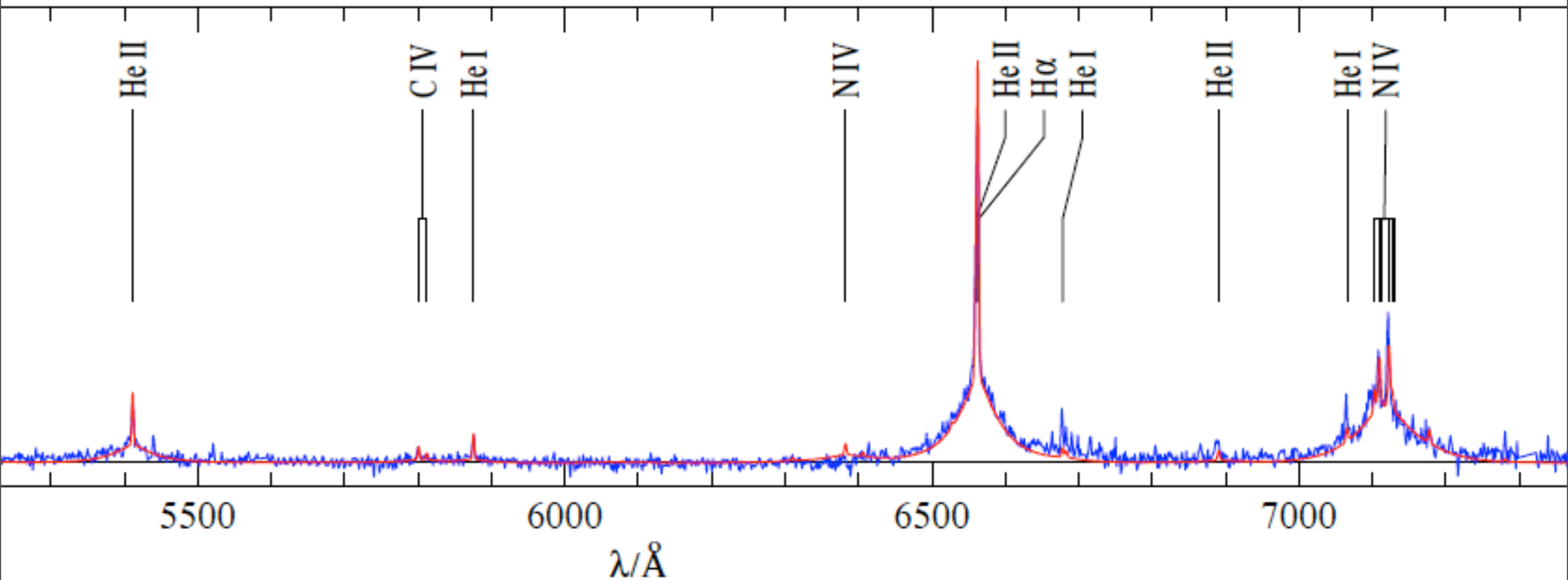
Ryder et al. (2004)

Soderberg et al. (2006)

LBV !?

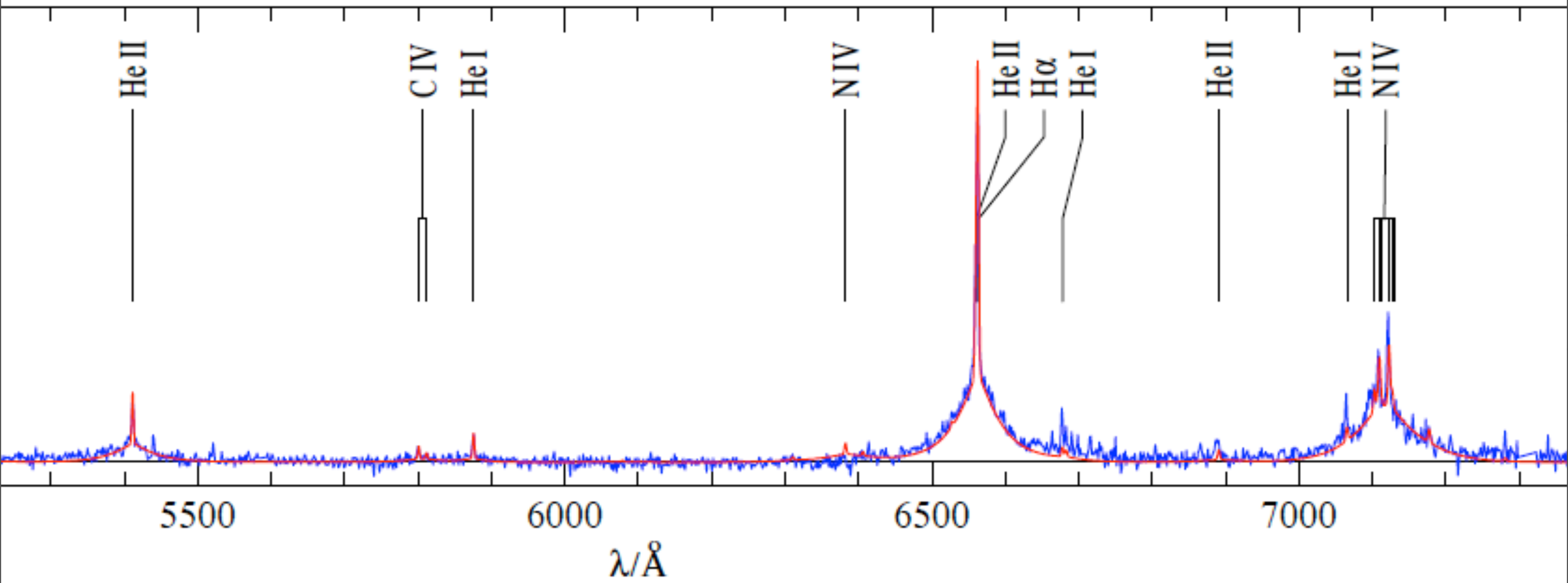
Kotak & Vink (2006)

The IIb SN 2013cu



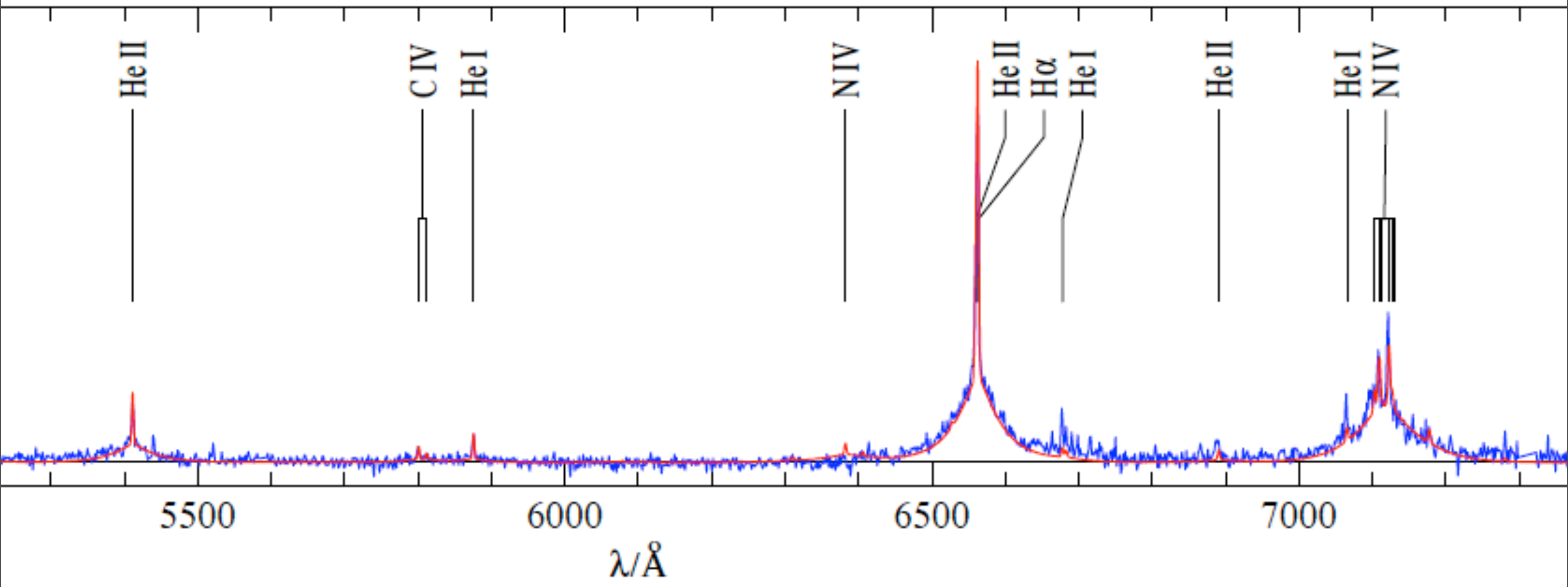
Gal-Yam et al. (2014): WR progenitor..

The IIb SN 2013cu



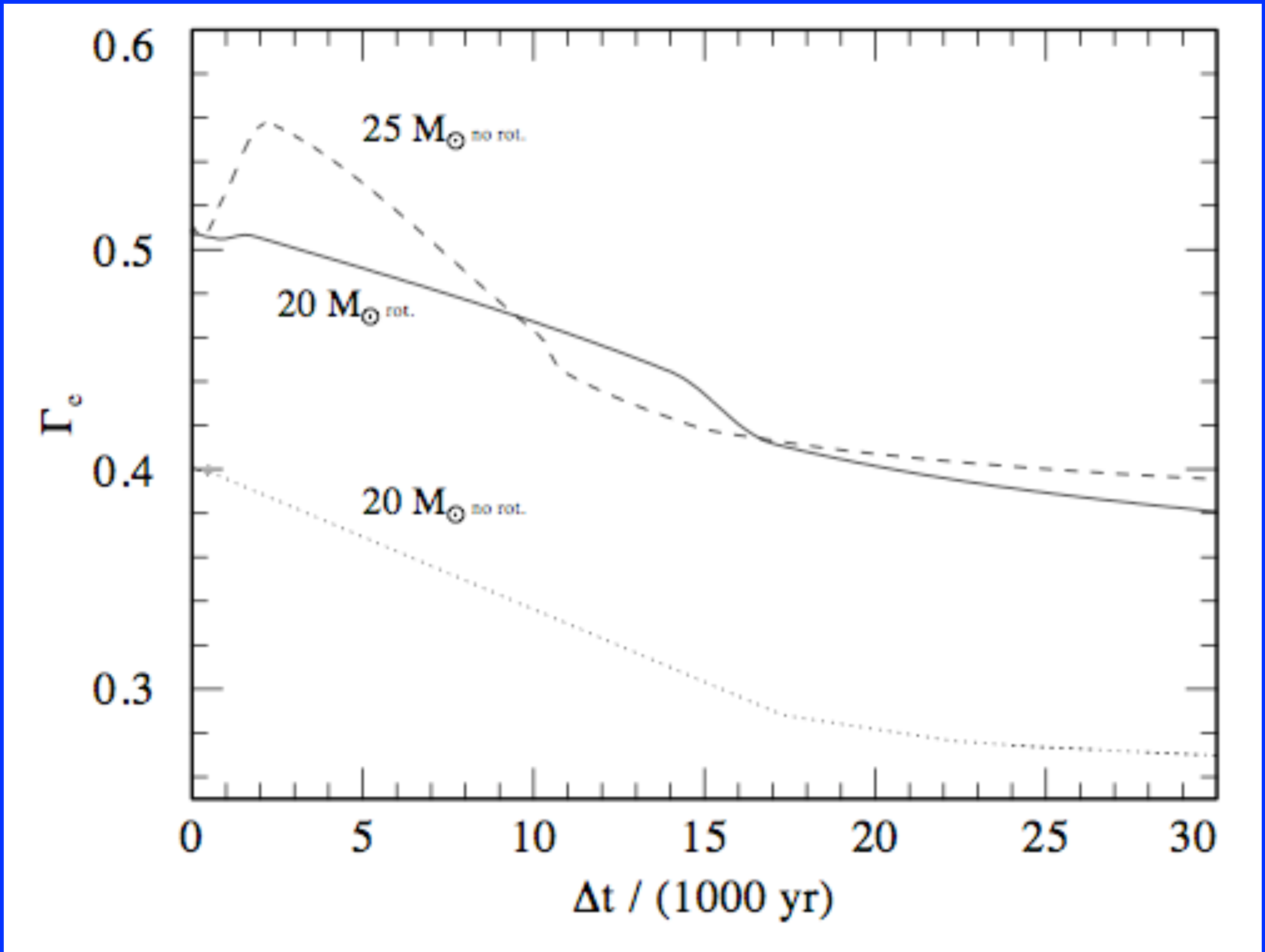
Gal-Yam et al. (2014): WR progenitor..
Groh (2014) LBV/YHG

The IIb SN 2013cu



Gal-Yam et al. (2014): WR progenitor..
Groh (2014) LBV/YHG
Graefener & Vink (2016) LBV/YHG/p-RSG

Eddington Factor at end of Life



Grafener & Vink (2016) - numbers from Ekstrom et al. (2012)

Summary

$dM/dt = f(L, M, T_{eff}, Z)$

- $dM/dt = f$ (Gamma) (VMS, WRs & LBVs, SNe)
- $dM/dt = f$ (T) (LBV-SNe IIb, IIn)
- $dM/dt = f$ (Z) (GRBs, PISNe, SLSNe)

- Feedback as a function of metallicity