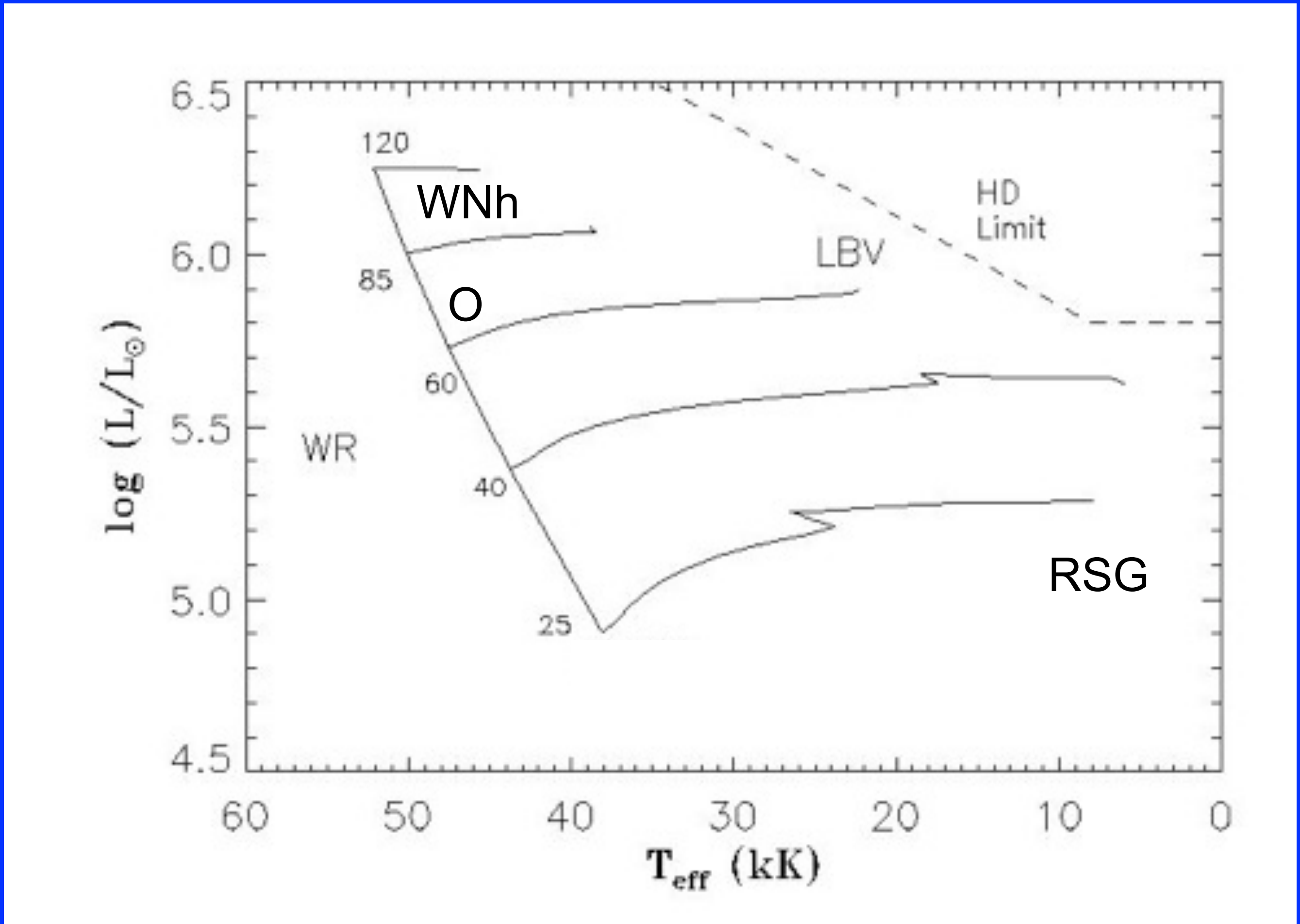
Mass-loss rates ON & OFF the Main Sequence

Jorick S. Vink

(Armagh Observatory & Planetarium)

Upper HRD



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

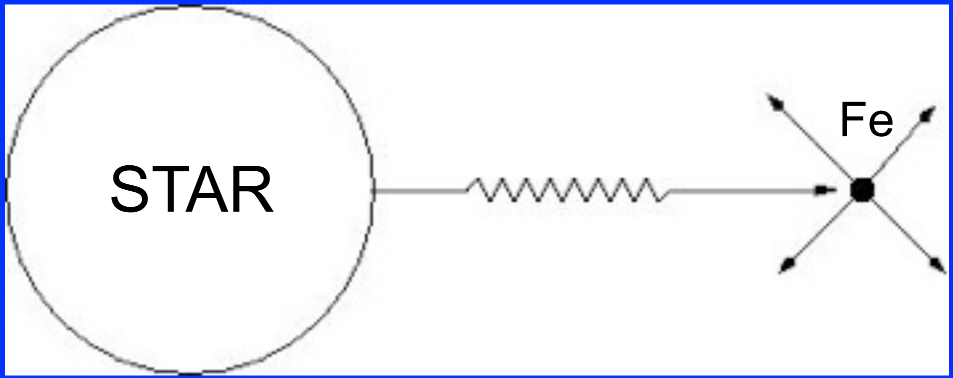
Outline

- O stars and VMS : Theory & Observations
- B supergiants & LBVs: Theory & Observations

Radiation-driven winds

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

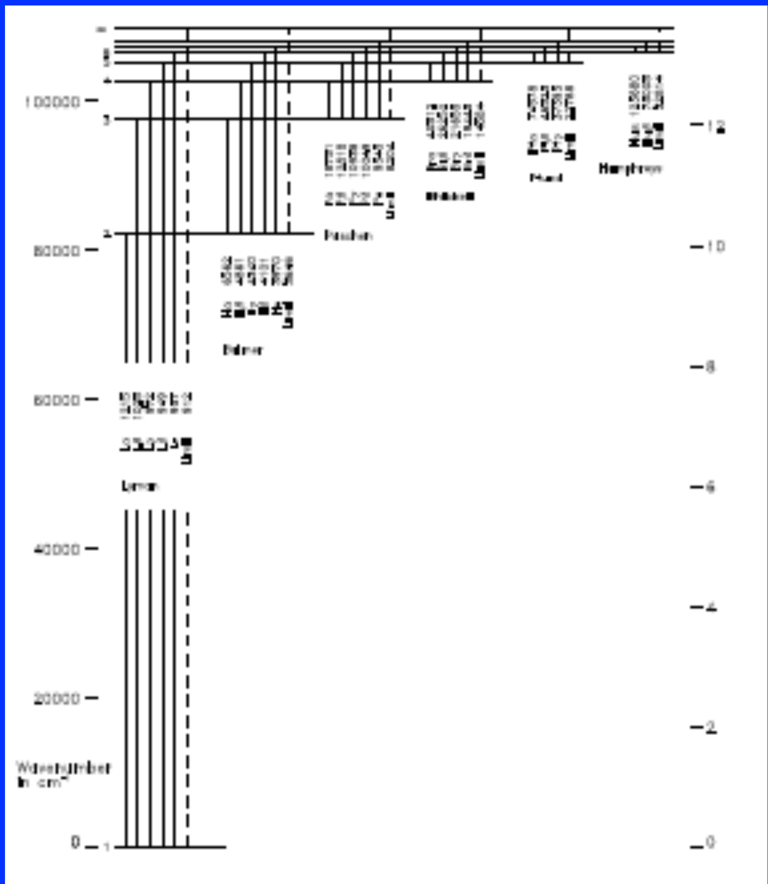
$$\Gamma = \frac{g_{\rm rad}}{g_{\rm grav}} = \frac{\kappa L}{4\pi c G M}$$

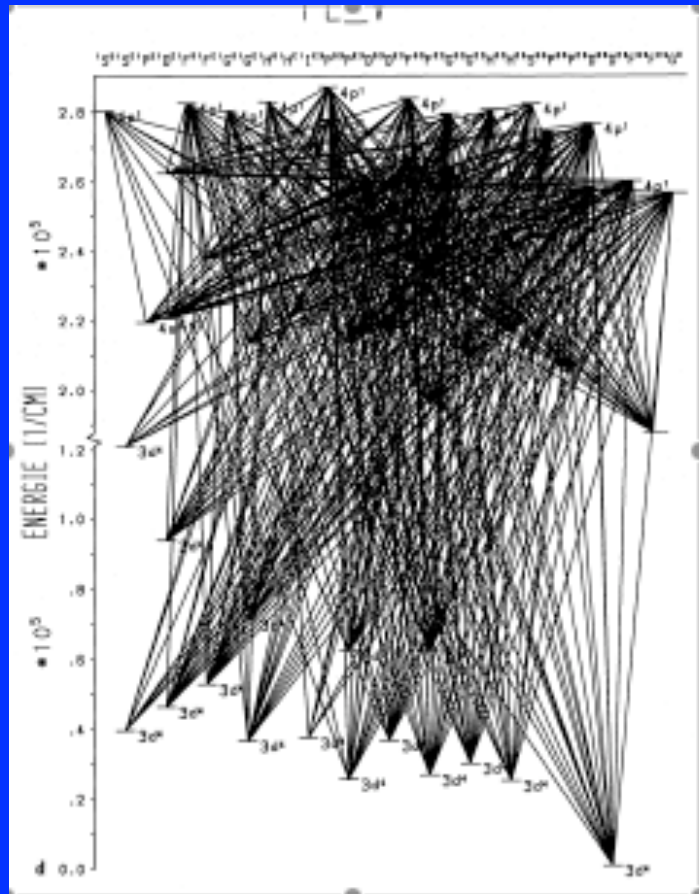


dM/dt = f (L,M,Teff,Z)

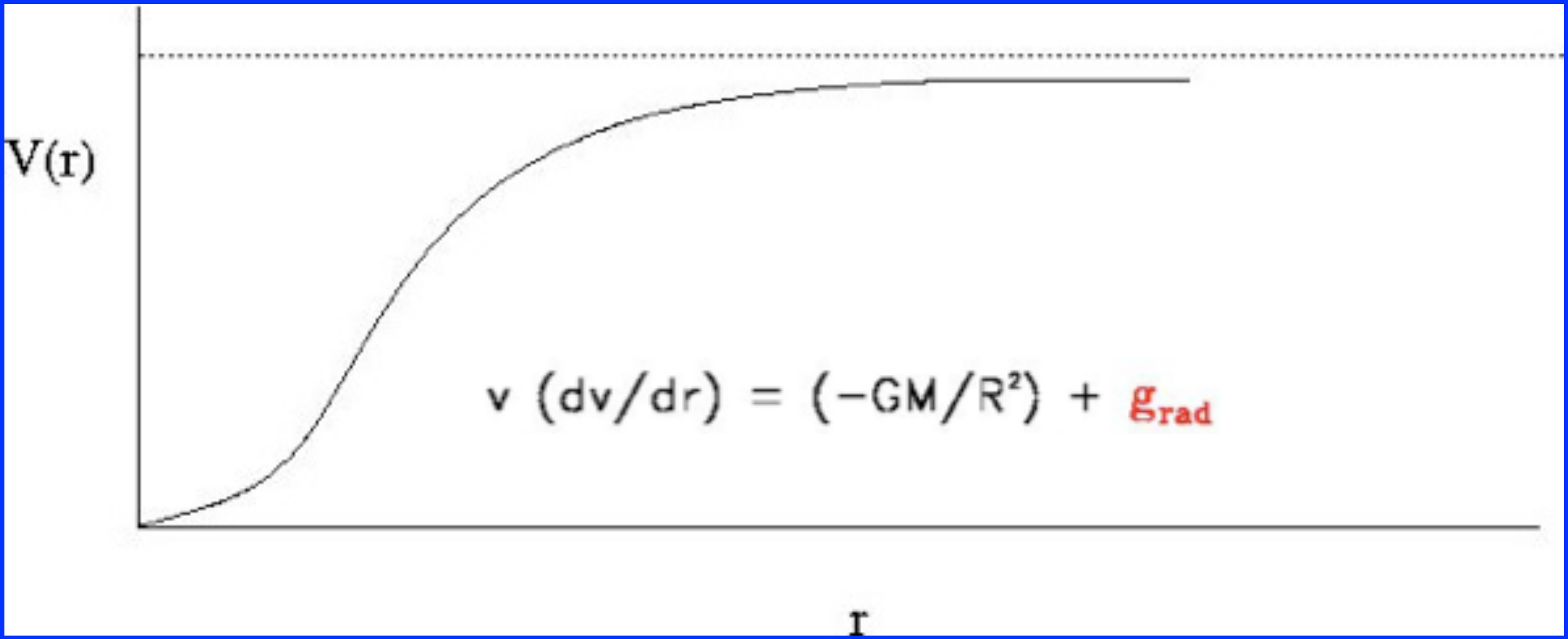
H atom

Fe V atom

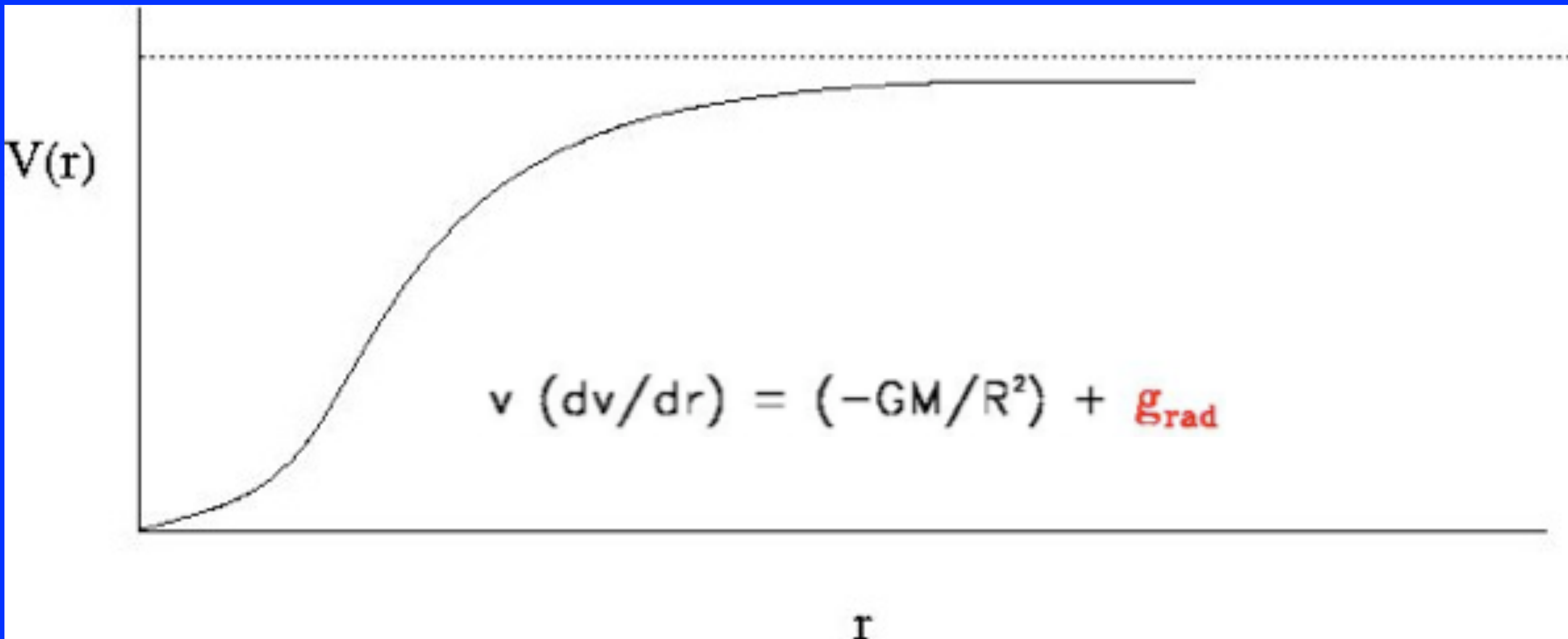




Wind dynamics



Wind dynamics



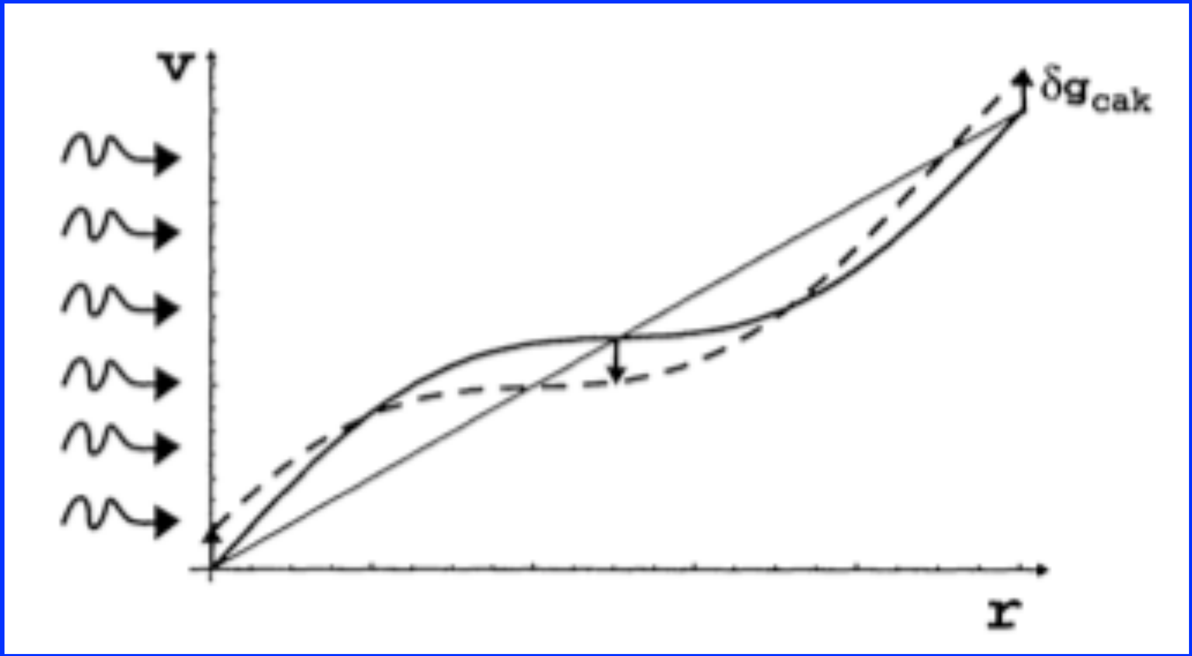
grad= f (dv/dr)

CAK = Castor, Abbott & Klein (1975)
Pauldrach et al. (1986)

grad = f (r)

Mueller & Vink (2008)

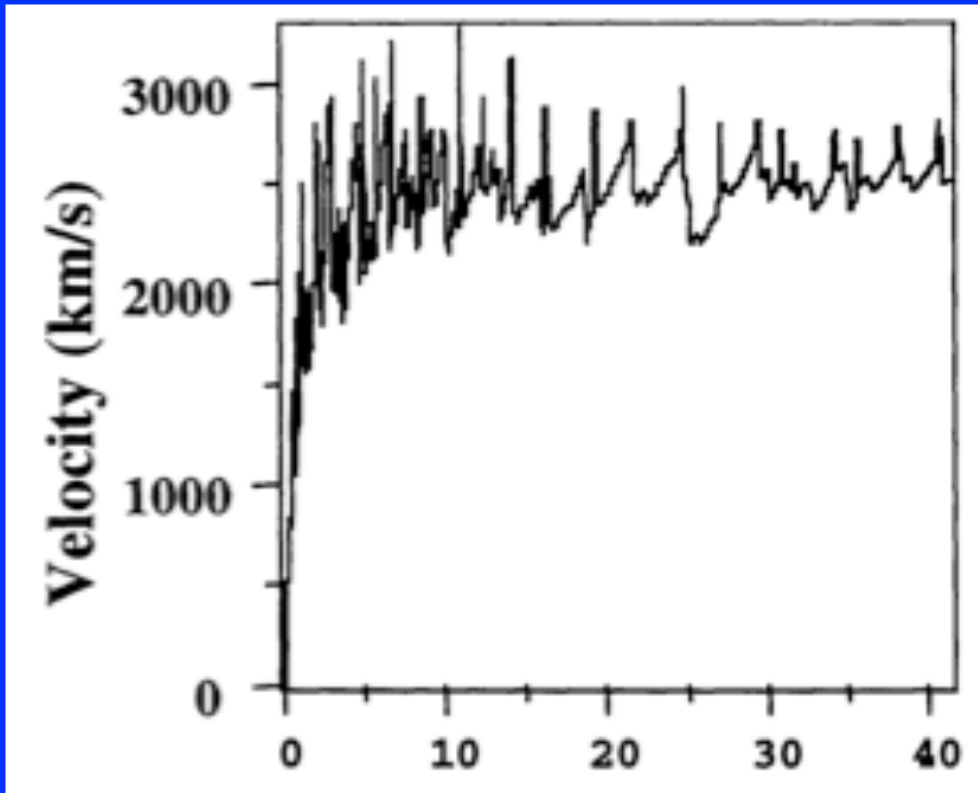
Perturbations: LDI



(Owocki)

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

LDI hydro simulations

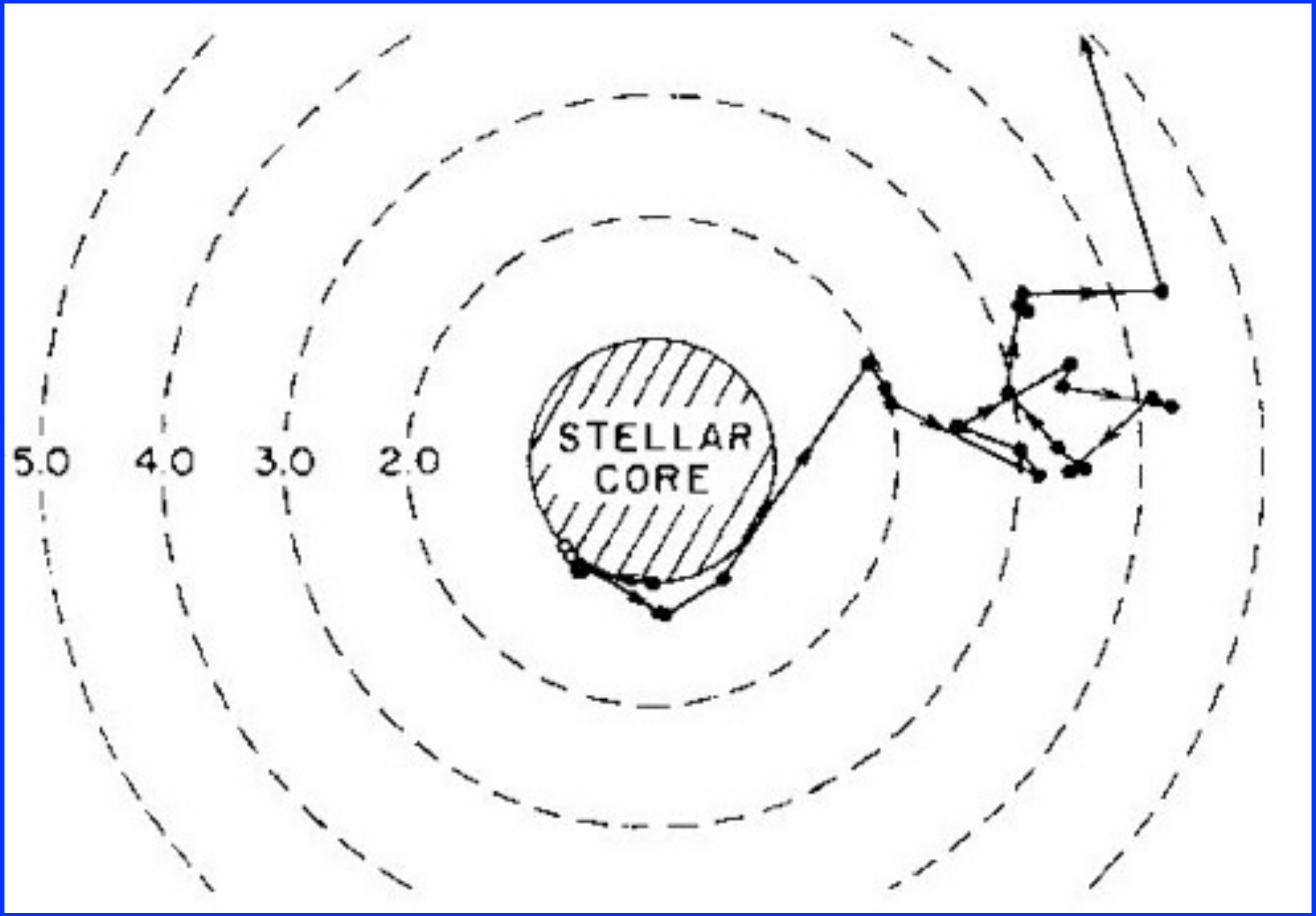


(Owocki)

dM/dt expected to be preserved

But diagnostics affected!

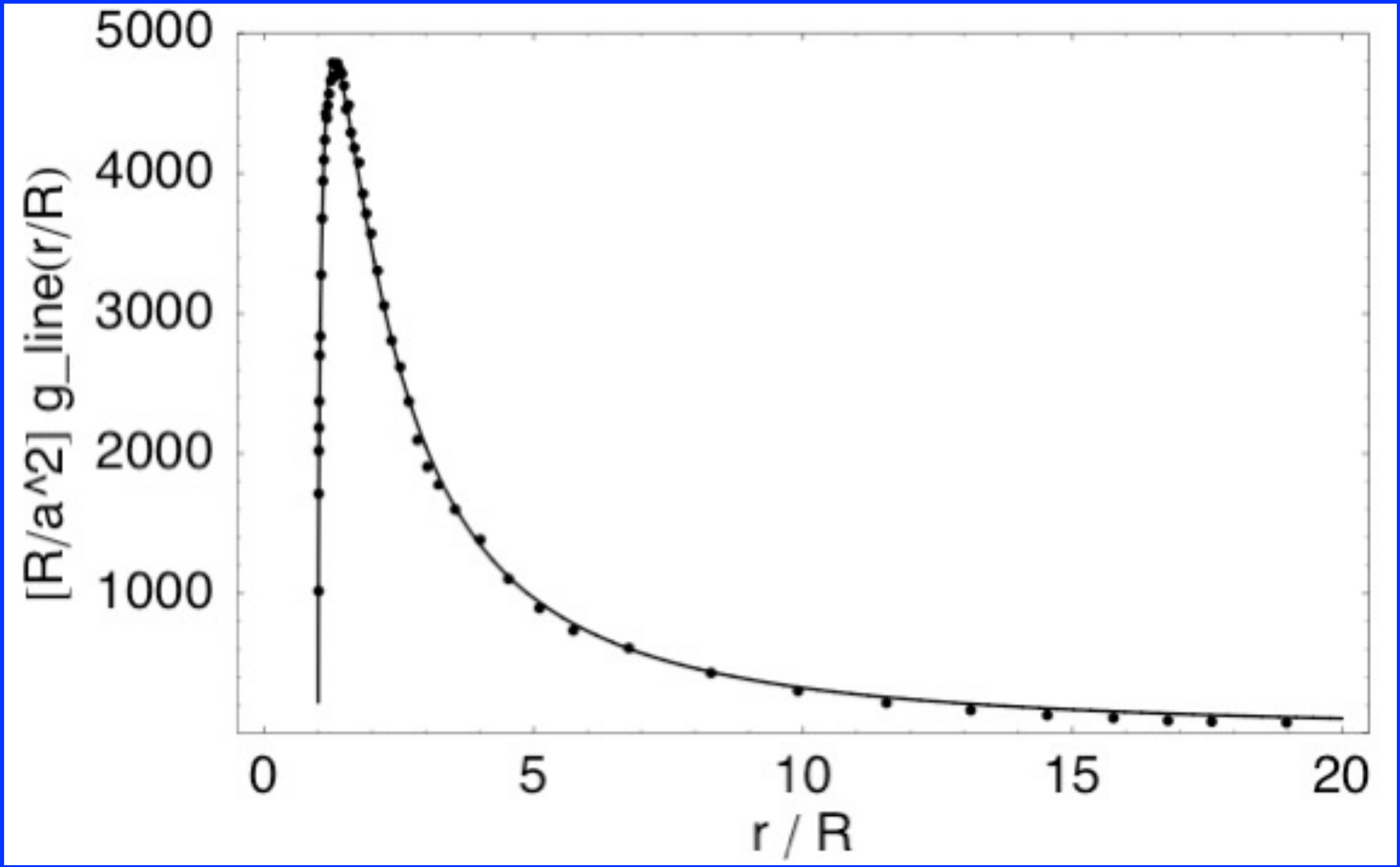
Monte Carlo approach



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

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

Line acceleration: g(r)



Mueller & Vink (2008)

Clumping

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

- Theory: extra parameters: C & C(r)

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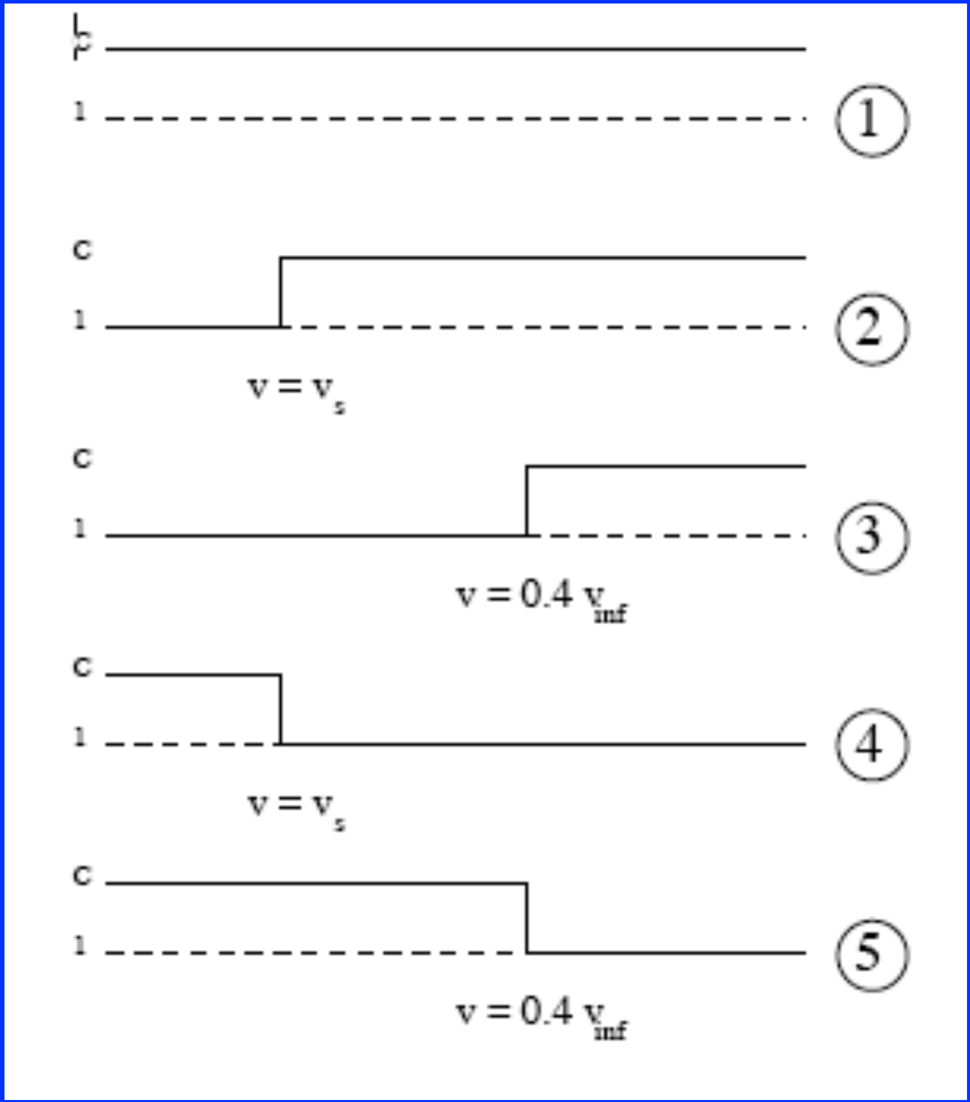
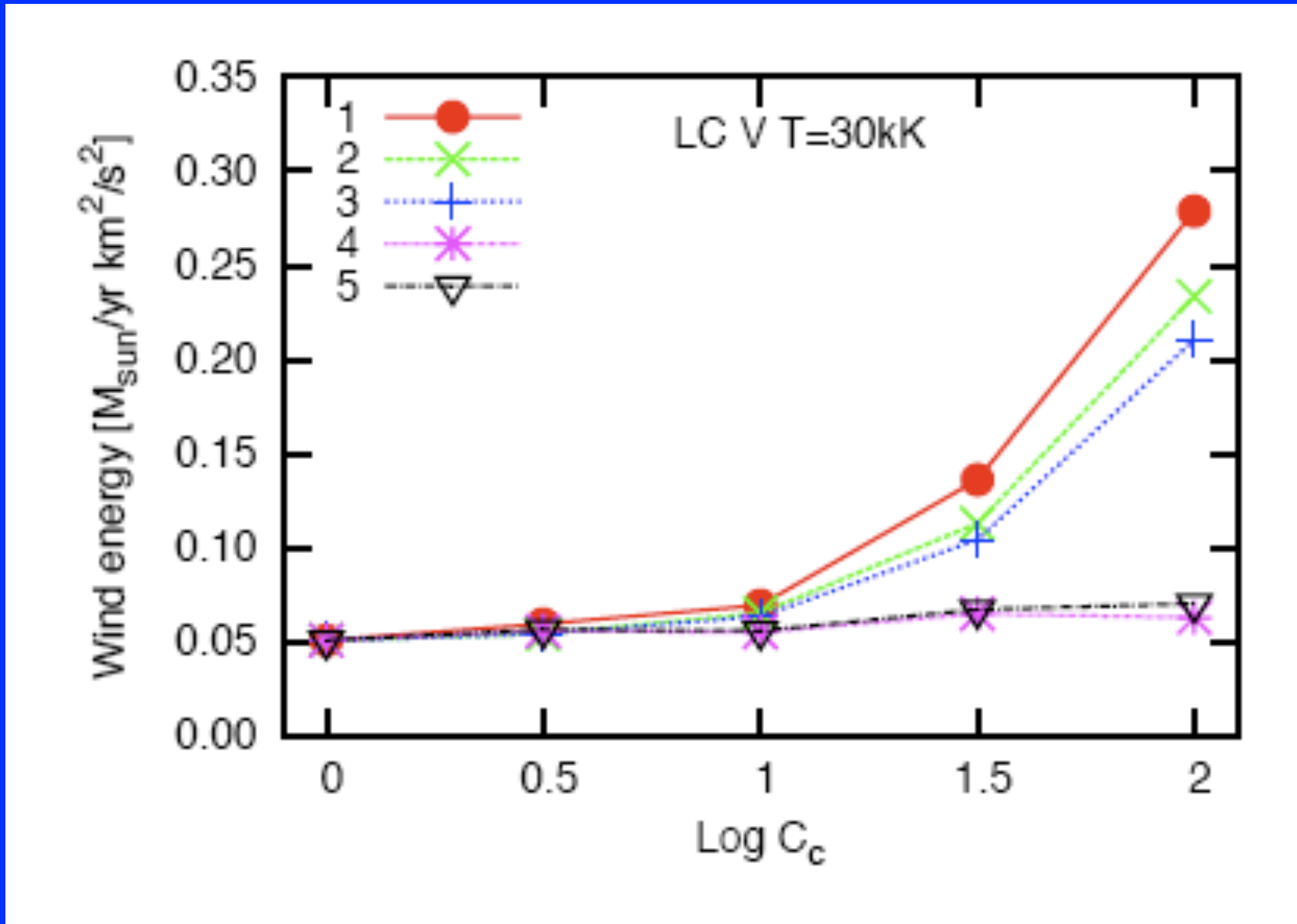
- Theory: extra parameters: C & C(r) + Porosity
- Is clumping L,M,Teff,Z dependent?

Clumping: C (r)

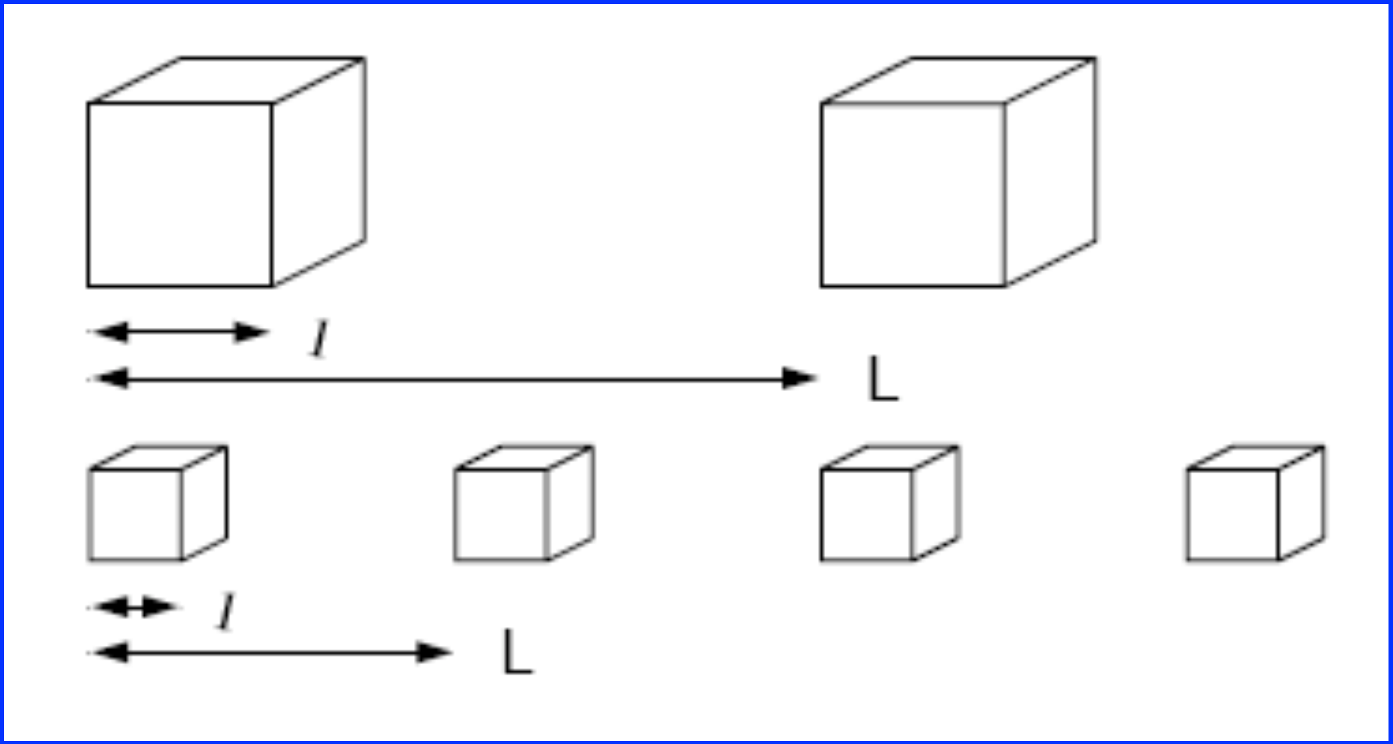


Clumping: dM/dt up!

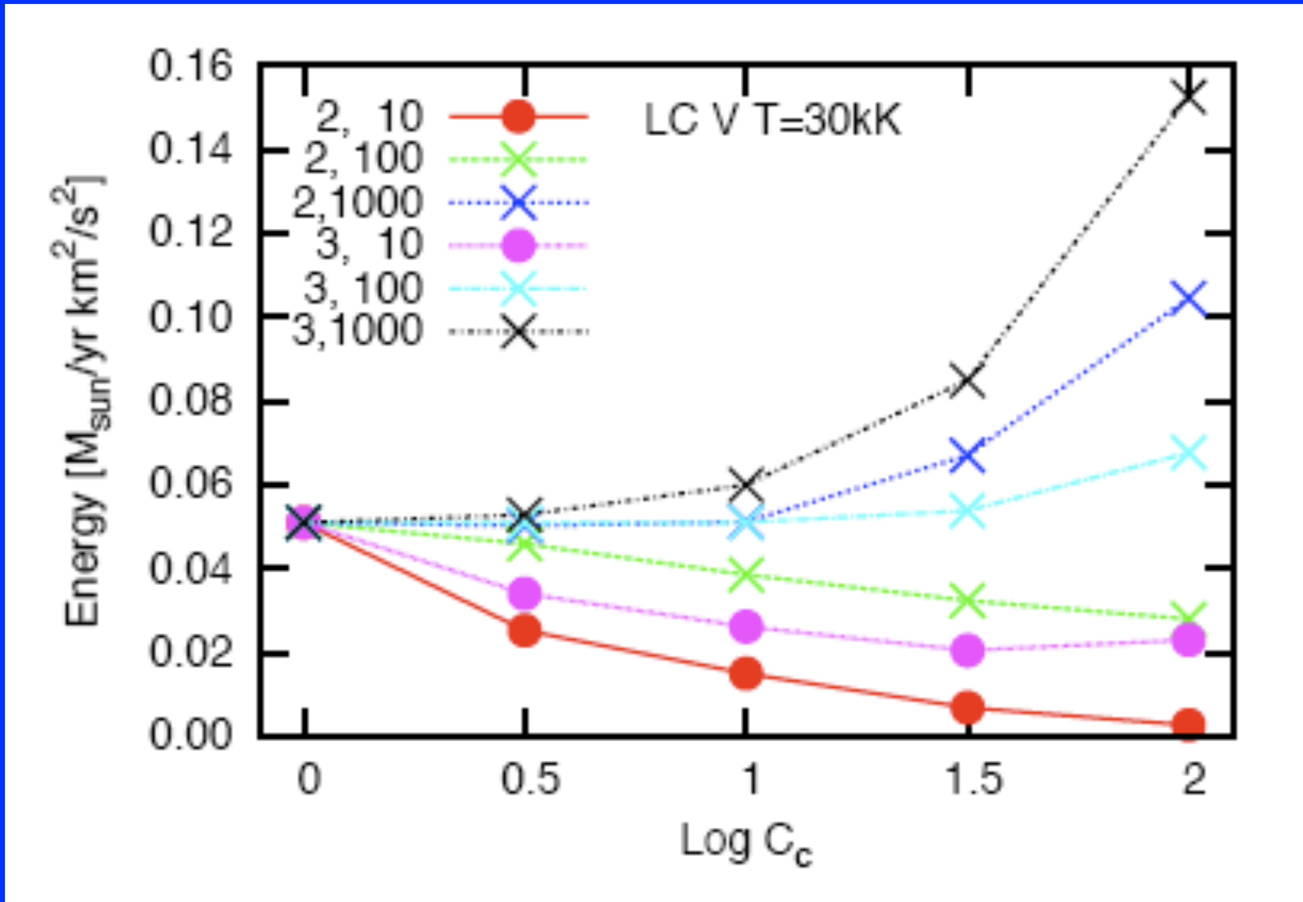


(Muijres et al. 2011)

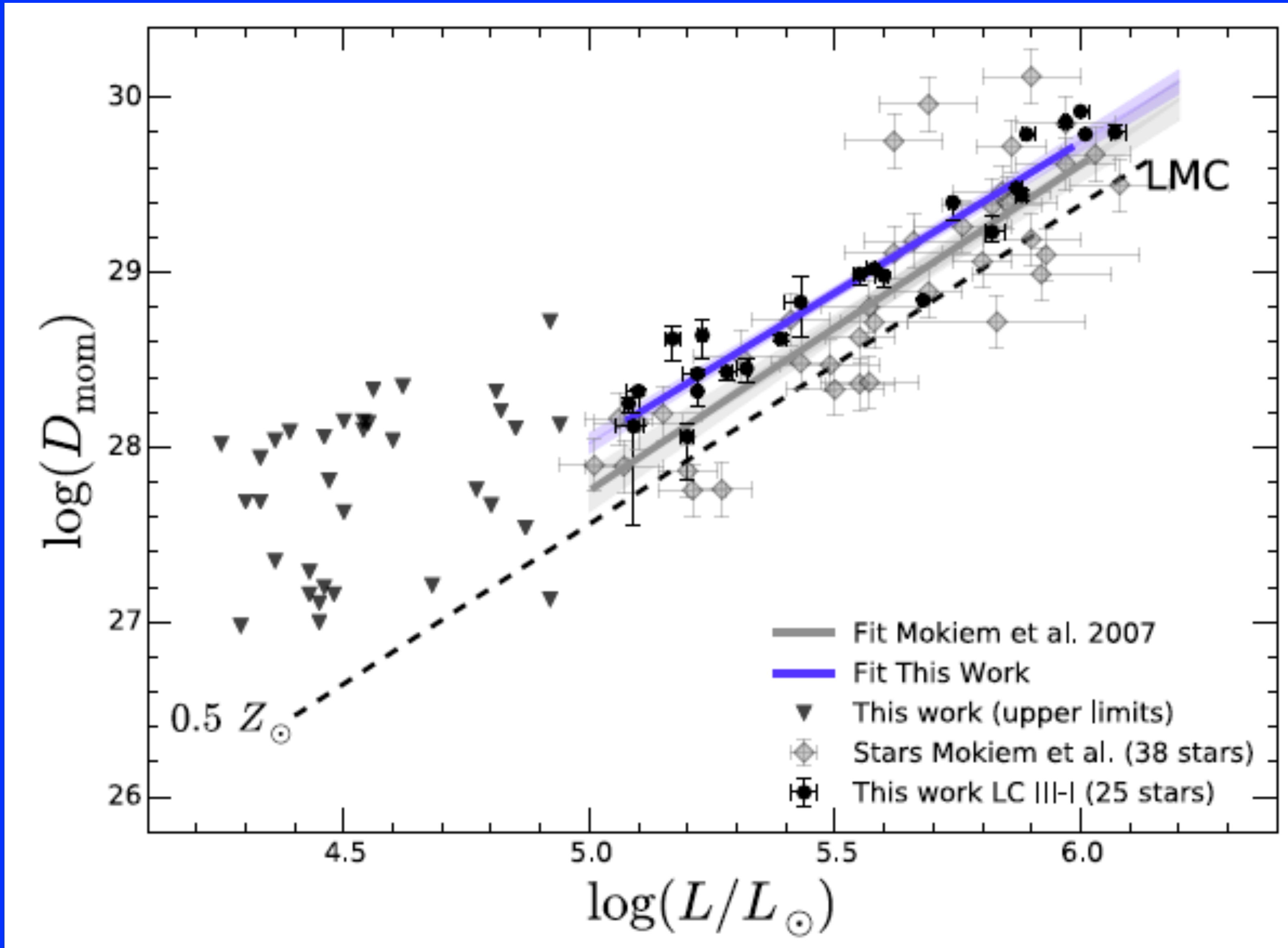
Clumping: Porosity



Clumping & Porosity



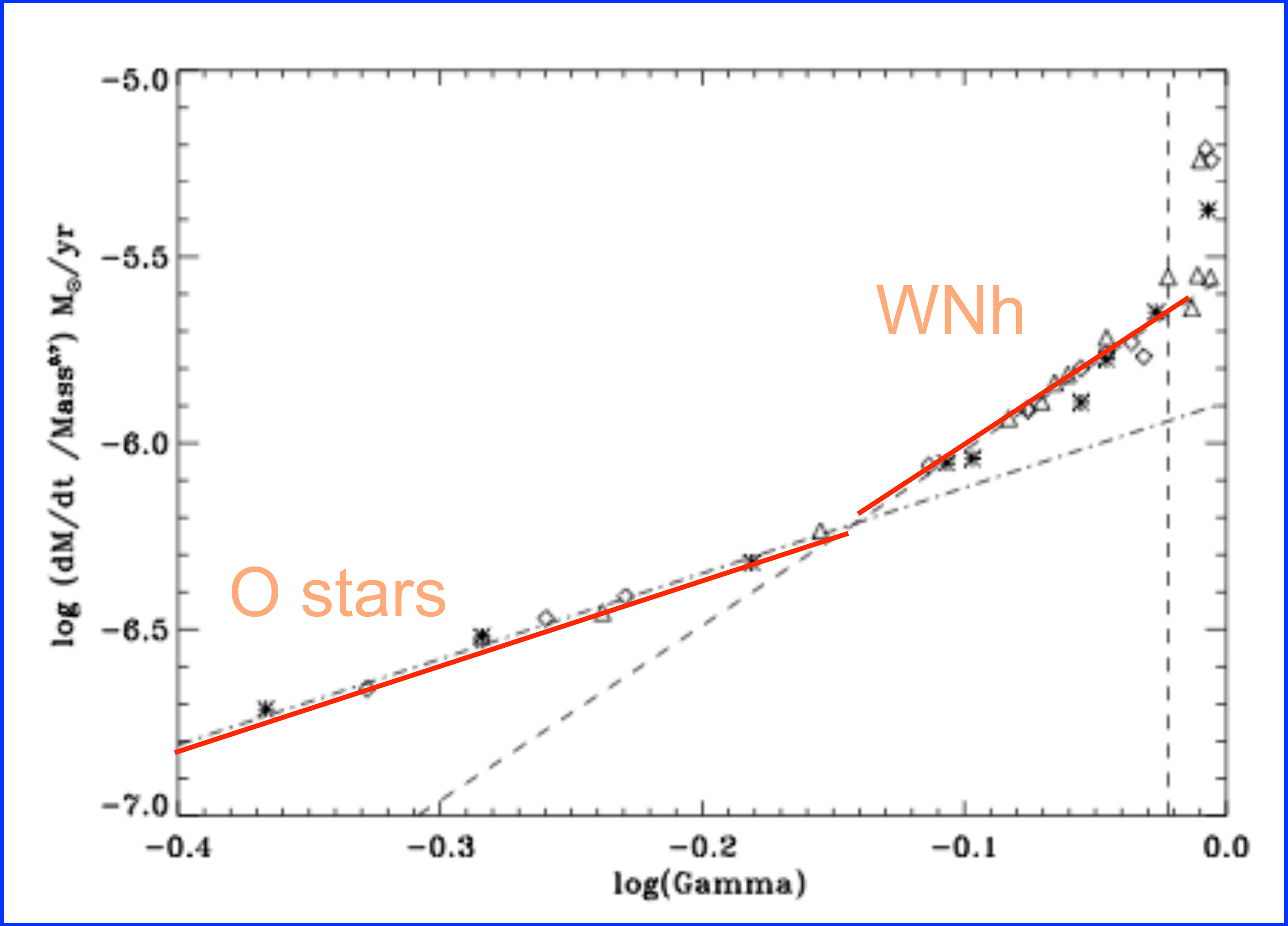
(Muijres et al. 2011)



(Ramirez+17 VFTS) Empirical dM/dt down by factor of 3 - with Cl 6-8
If theory OK

?

KINK in dM/dt = f (Gamma)



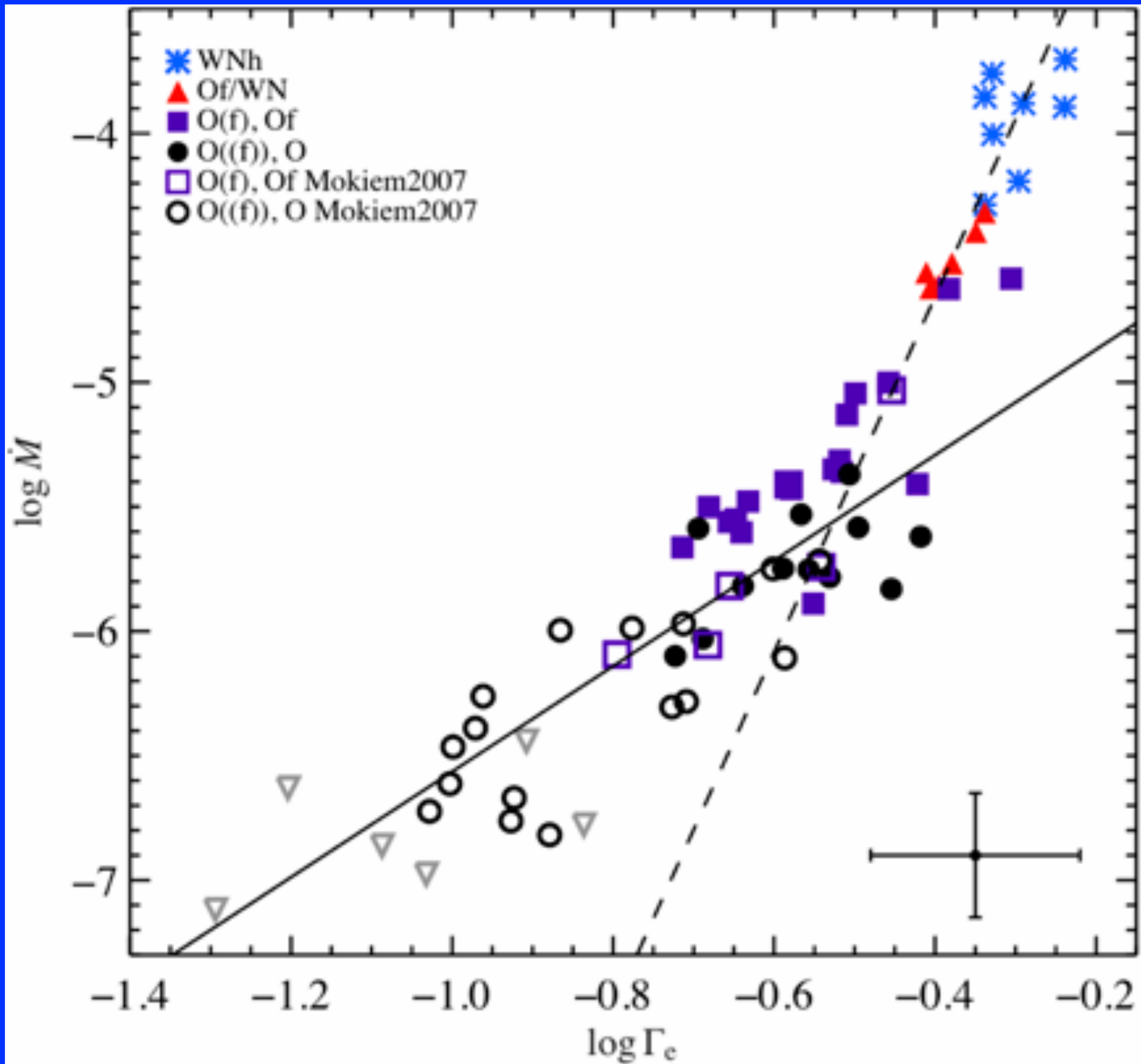
Vink et al. (2011) with g(r) Mueller & Vink (2008)

Transition Point Of/WN

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

Vink & Graefener (2012)

VLT Flames Tarantula Survey



Bestenlehner et al. (2014)

2) B supergiants

- Current Recipe Vink et al. (2000) dM/dt = f(Teff)

- Physics: Bistability Vink et al. (1999), Benaglia et al. (2007)
  Pauldrach & Puls (1990)
  Najarro et al. (1997)

Bi-stability Jump

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

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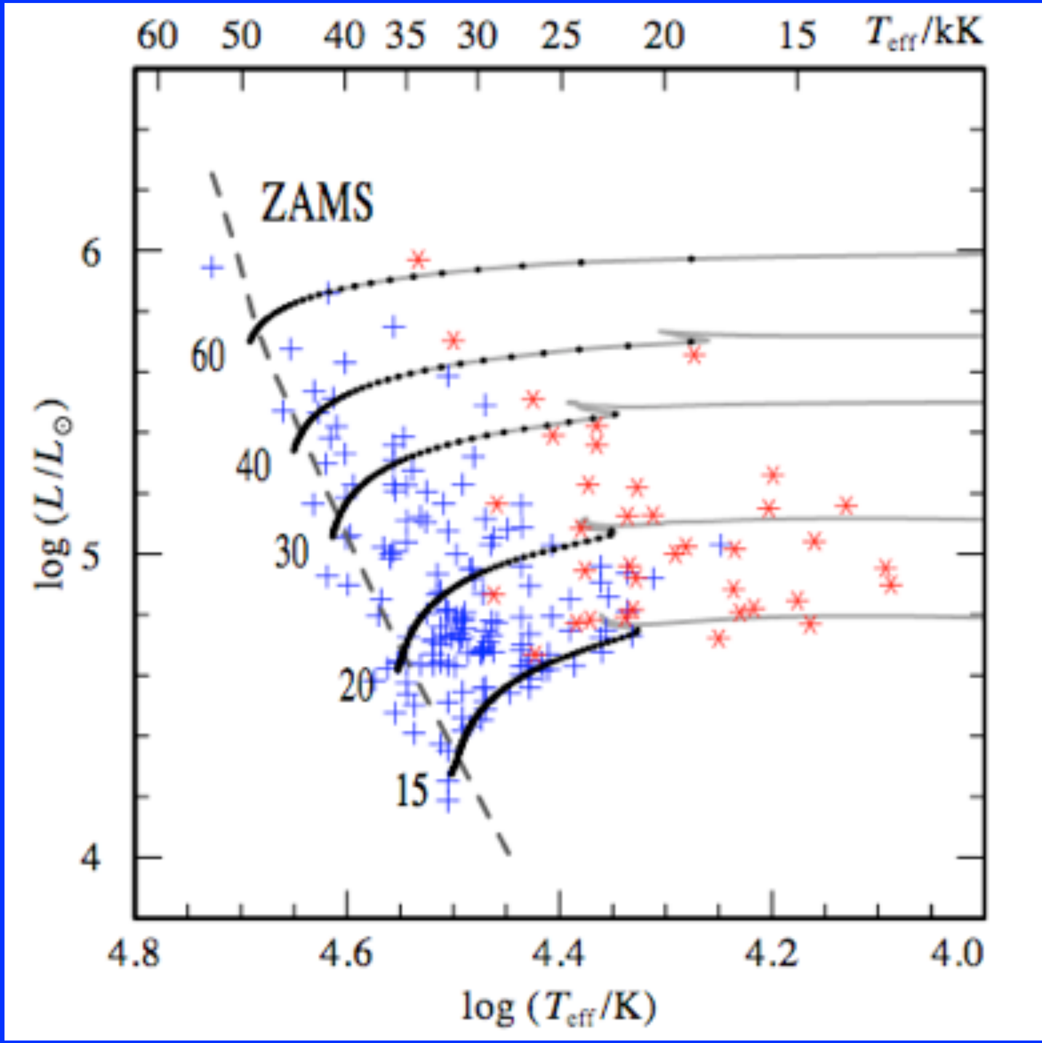
- Najarro et al. (1997)

- BUT alternative: lower dM/dt Kudritzki et al. (1999)
  Trundle & Lennon (2005)
  Crowther et al. (2006)
  Markova & Puls (2008)

- BSG *Problem*

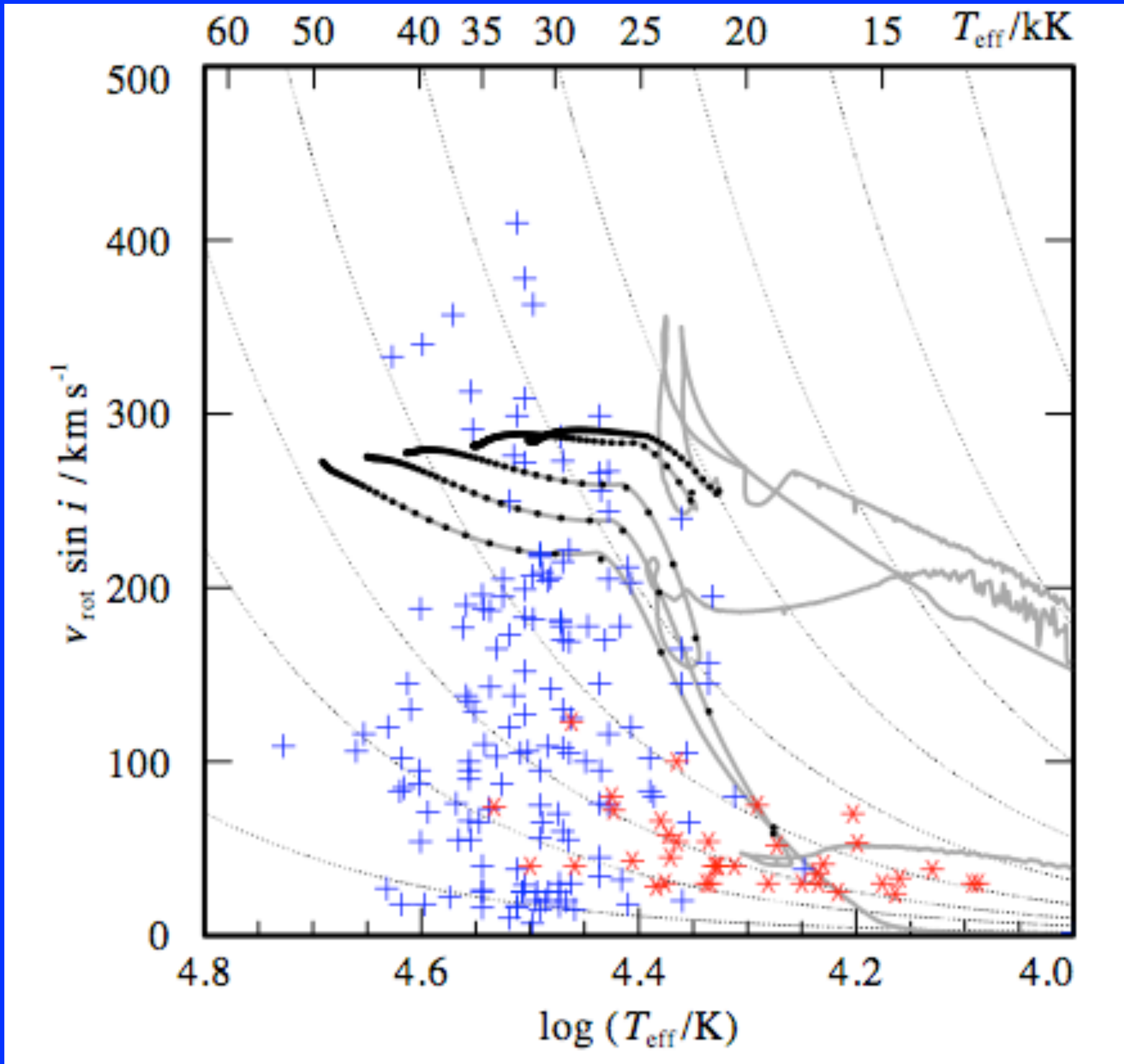
Bsg PROBLEM



Vink et al (2010)

Hunter et al. (2008)
Brott et al. (2011)

BSgs all Braked !!!



Vink et al (2010)

Implication:

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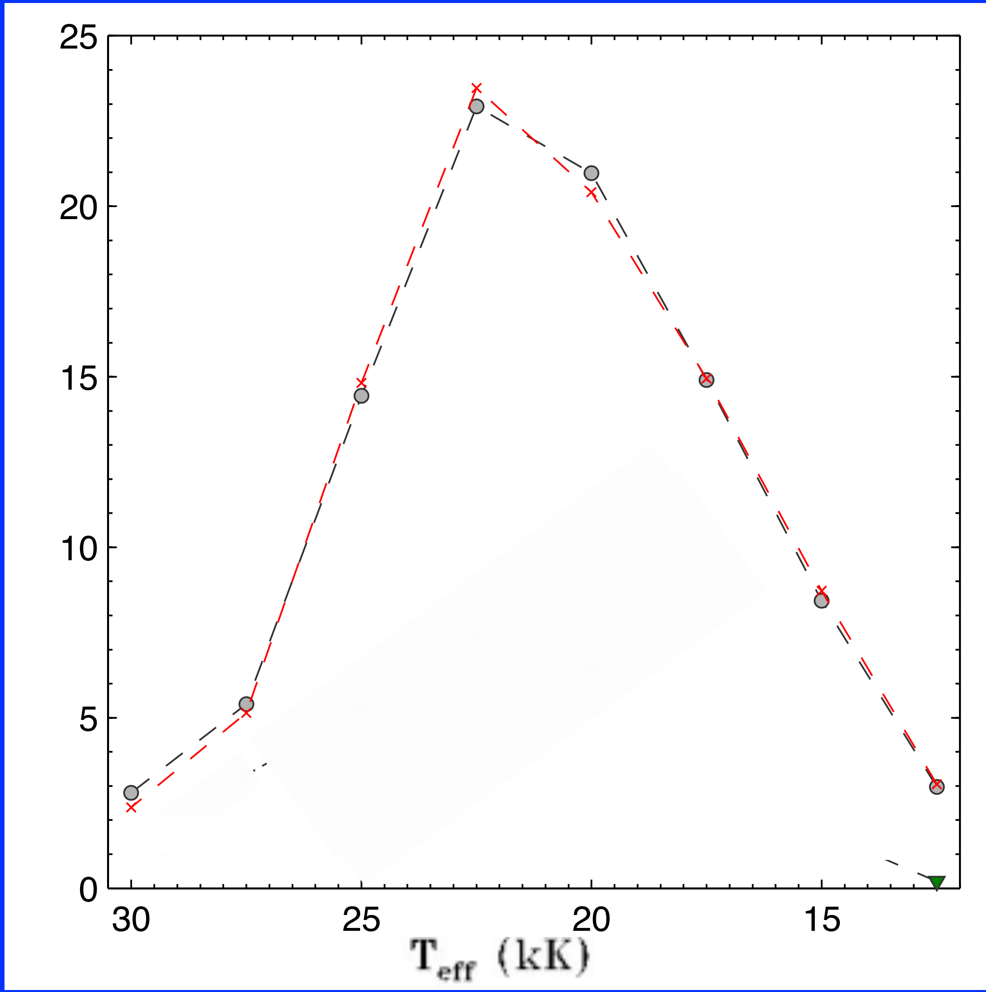
- Study Halpha line physics in detail!

Rise and Fall of Halpha EW



- PEAK at Jump!

Petrov et al. (2014)

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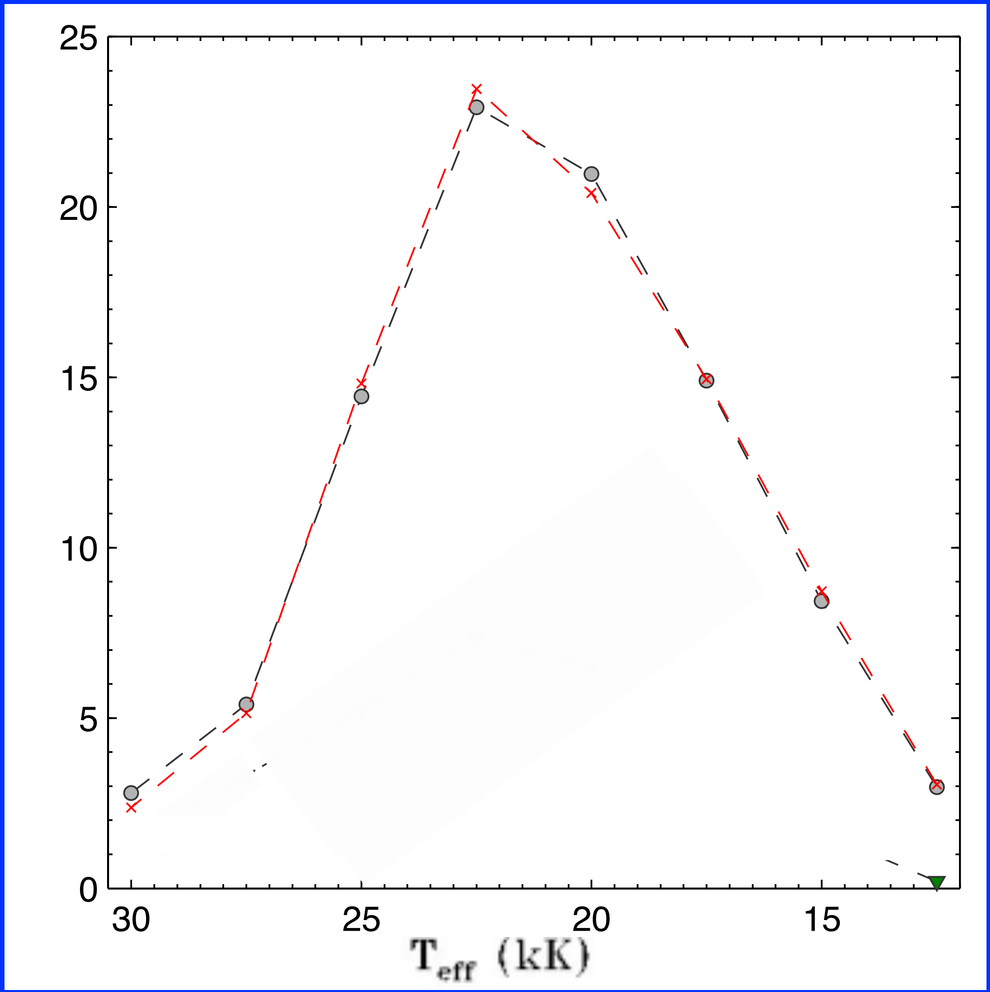
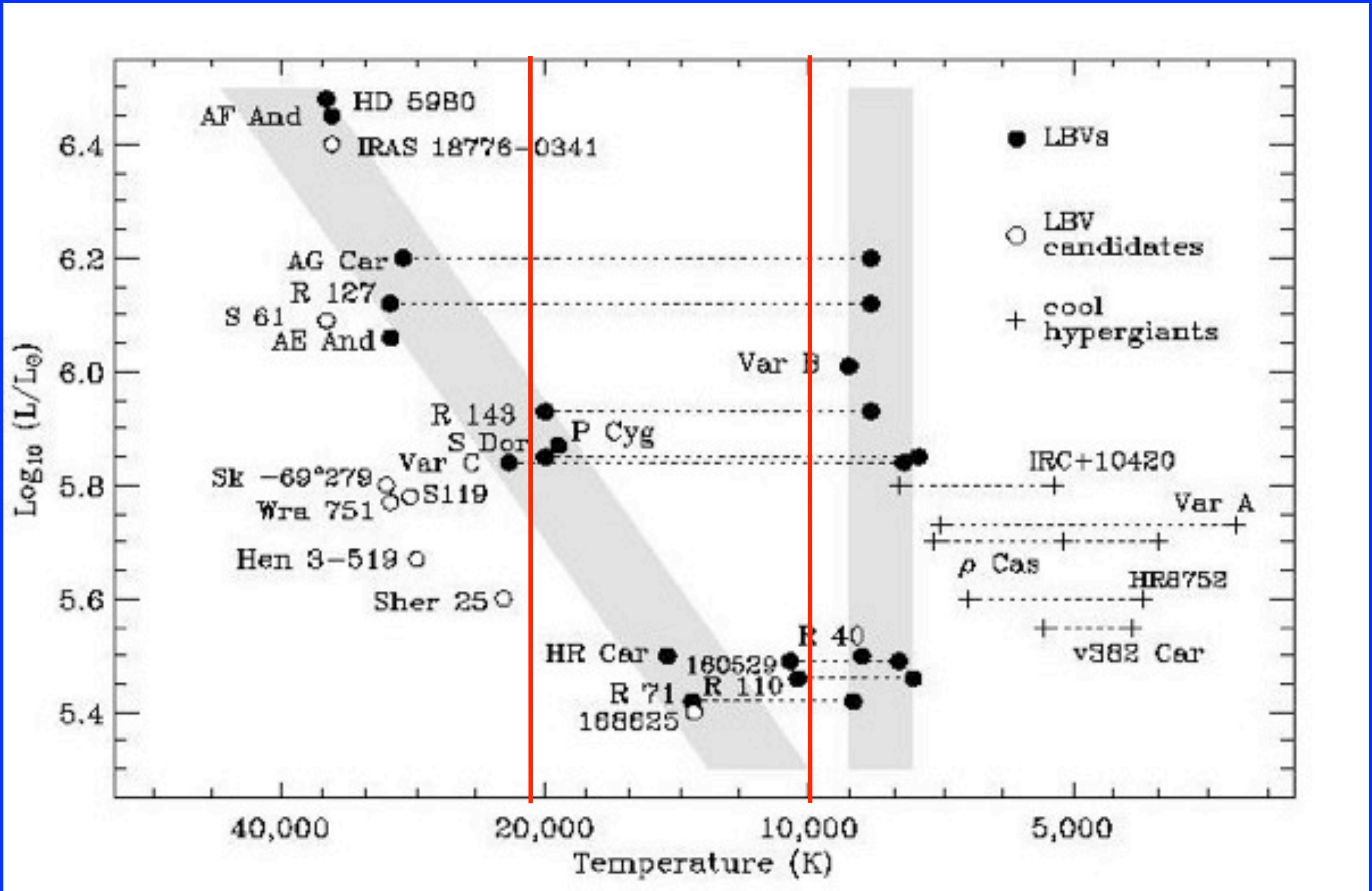


- PEAK at Jump!
- Line profile changes!

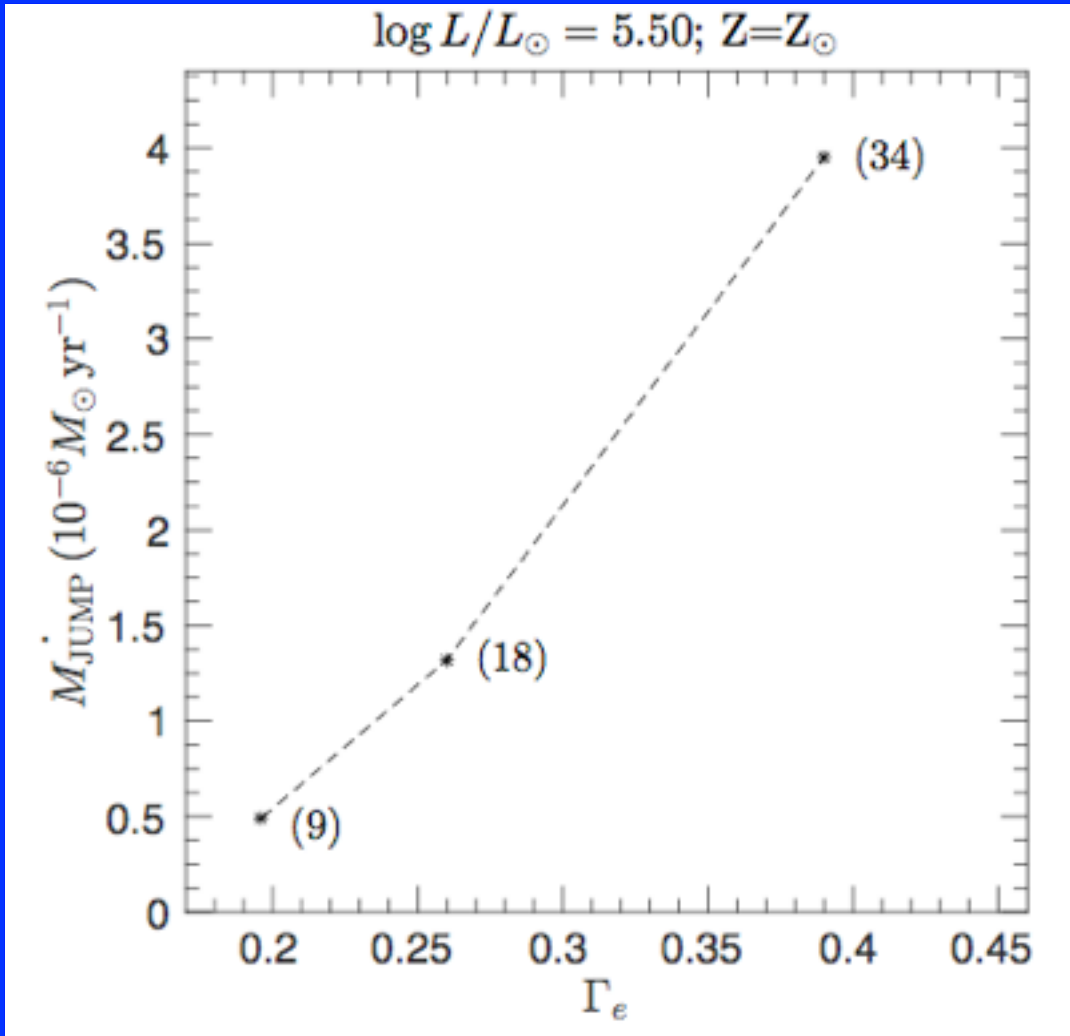
Petrov et al. (2014)

LBVs in the HRD



Smith, Vink & de Koter (2004) - Vink (2012) in HD

The Second BS Jump



Petrov, Vink & Grafener (2016) (also Vink et al. 1999)

Summary

- dM/dt depends on Gamma (L/M & Teff & Z)
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- Clumping might affect predictions
- Search for Origin and Implications of Clumping should continue!

Progress

- Large Samples! (e.g. VFTS; Massa et al. 2017)

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- non-Sobolev transfer
- Complete opacities

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 reason for the Halpha EW drop

- T drops
- H recombines
- n1,n2,n3 up
- Halpha emission up

→ at critical level: Lyman continuum optically thick

→ n_2 up

→ Lyman alpha optically thick