Outflows from Massive Stars

Artemio Herrero (IAC)
Francisco Najarro (DAMIR)
Miriam García (IAC)

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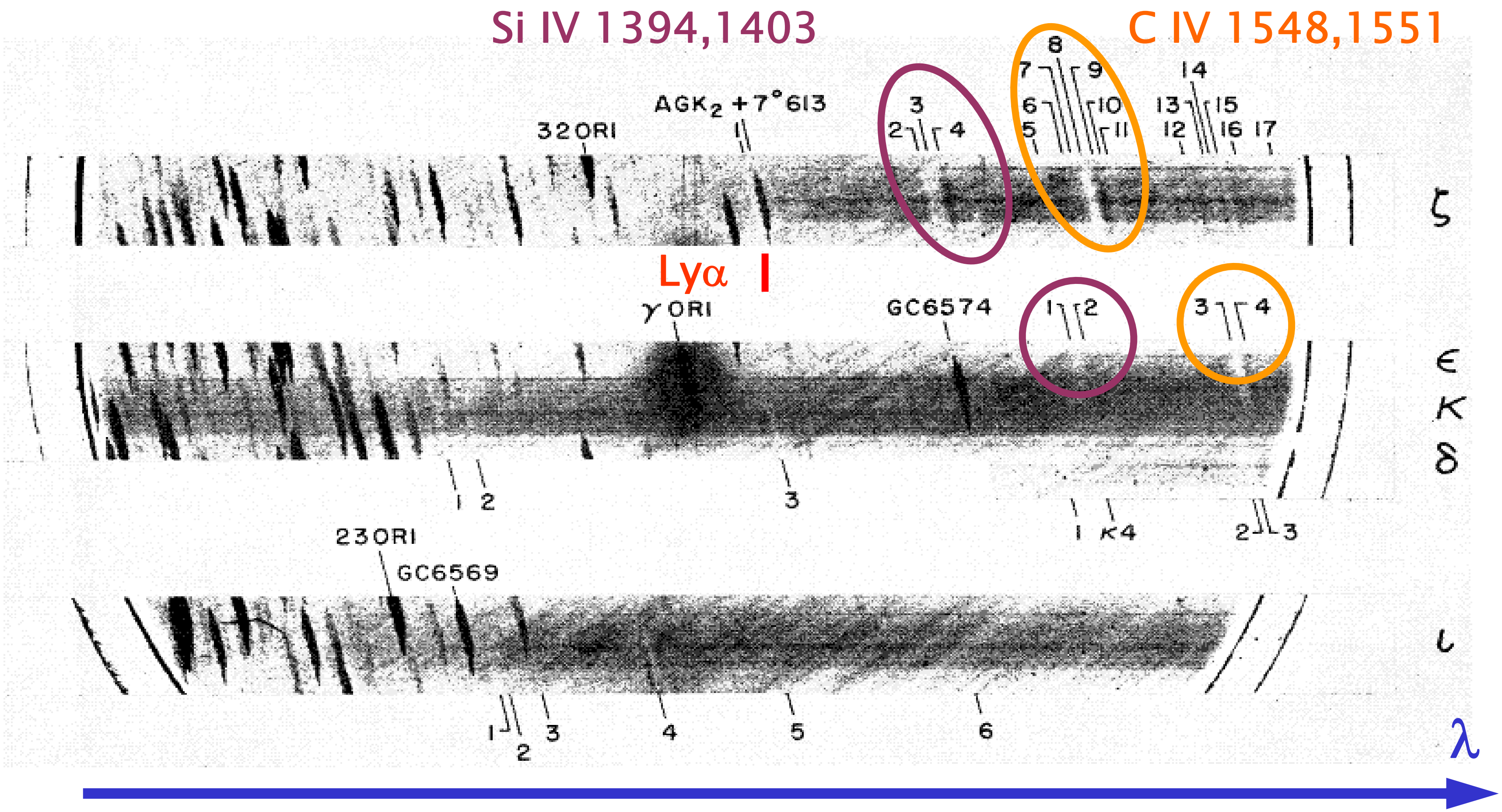
Outline

- **Introducing massive stars and their winds**
  - Evidence
  - UV morphology
  - Link to the early Universe
- **Radiatively driven winds**
  - Origin
  - A bit of theory
- **Determination of stellar parameters**
  - Effects of line-blanketing
  - New Teff scales
  - Parameters from the UV
  - The FLAMES Survey of massive stars
- **Open questions**
- **Conclusions**

Introduction: UV evidence of massive stars outflows



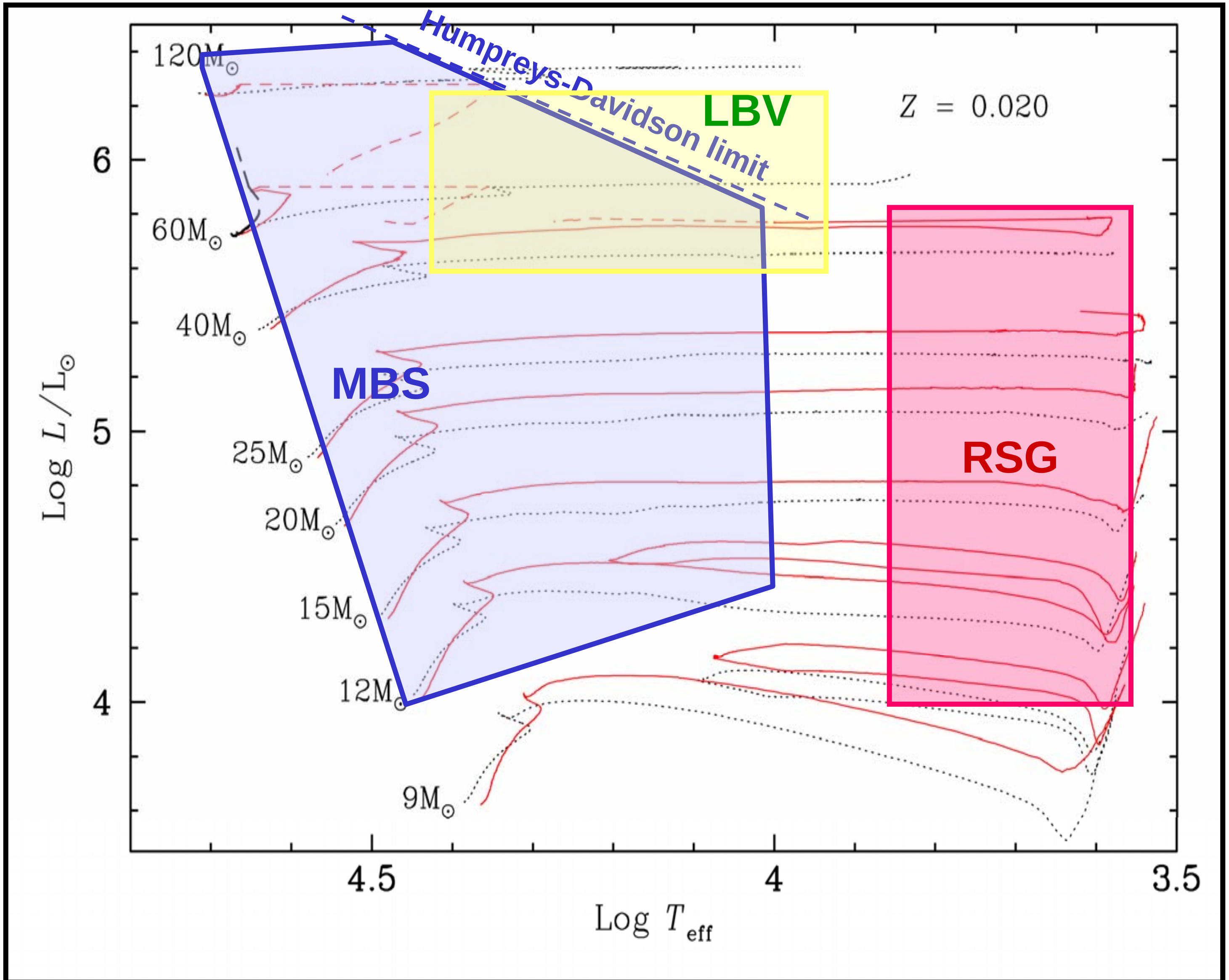
Morton D. C. 1967, ApJ, 147,1017

UV spectrograph (λ>1200Å, Δλ=3 Å) onboard an Aerobee rocket.

Both ζ Ori (O 9.5 Ib) and ε Ori (B0 Ia) display absorption + emission of the SiIV and CIV doublets, with shifts of 1800 – 3800 km/s

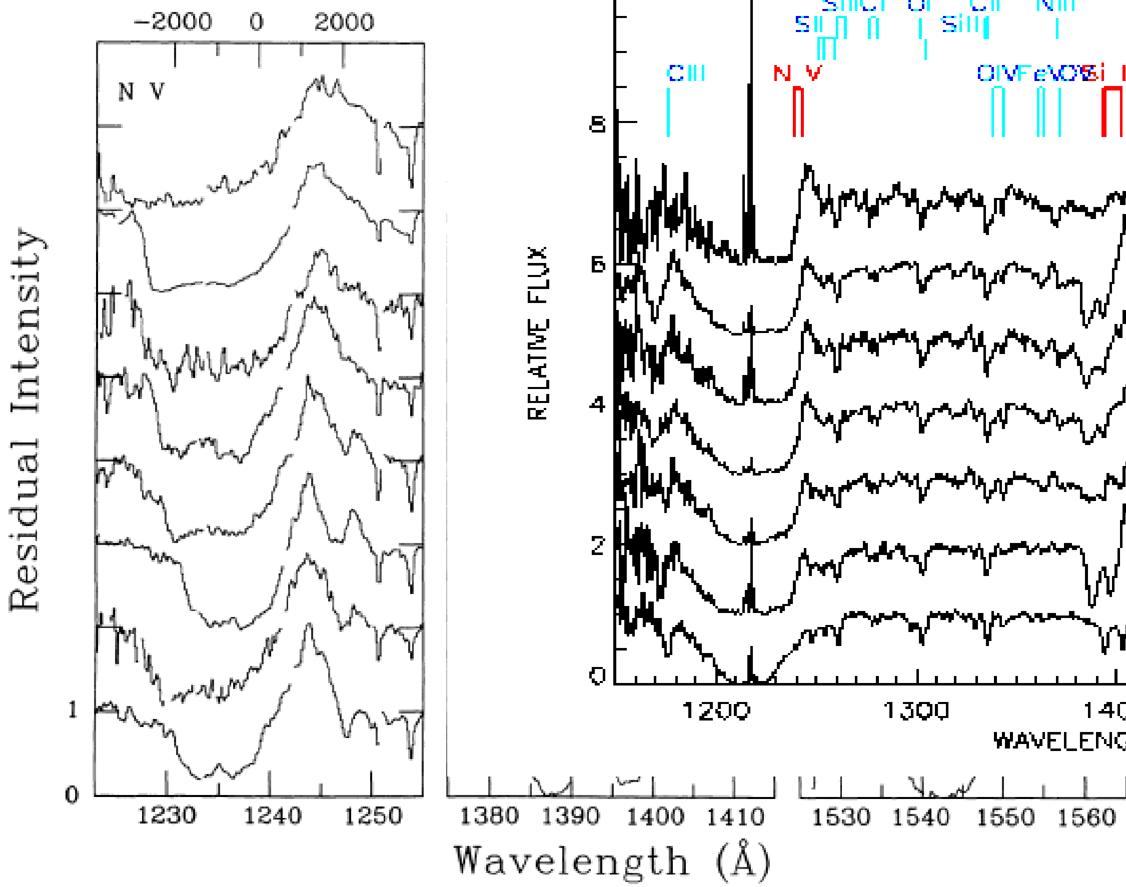
Stars are spectroscopically normal: Outflows shall be common among hot supergiants

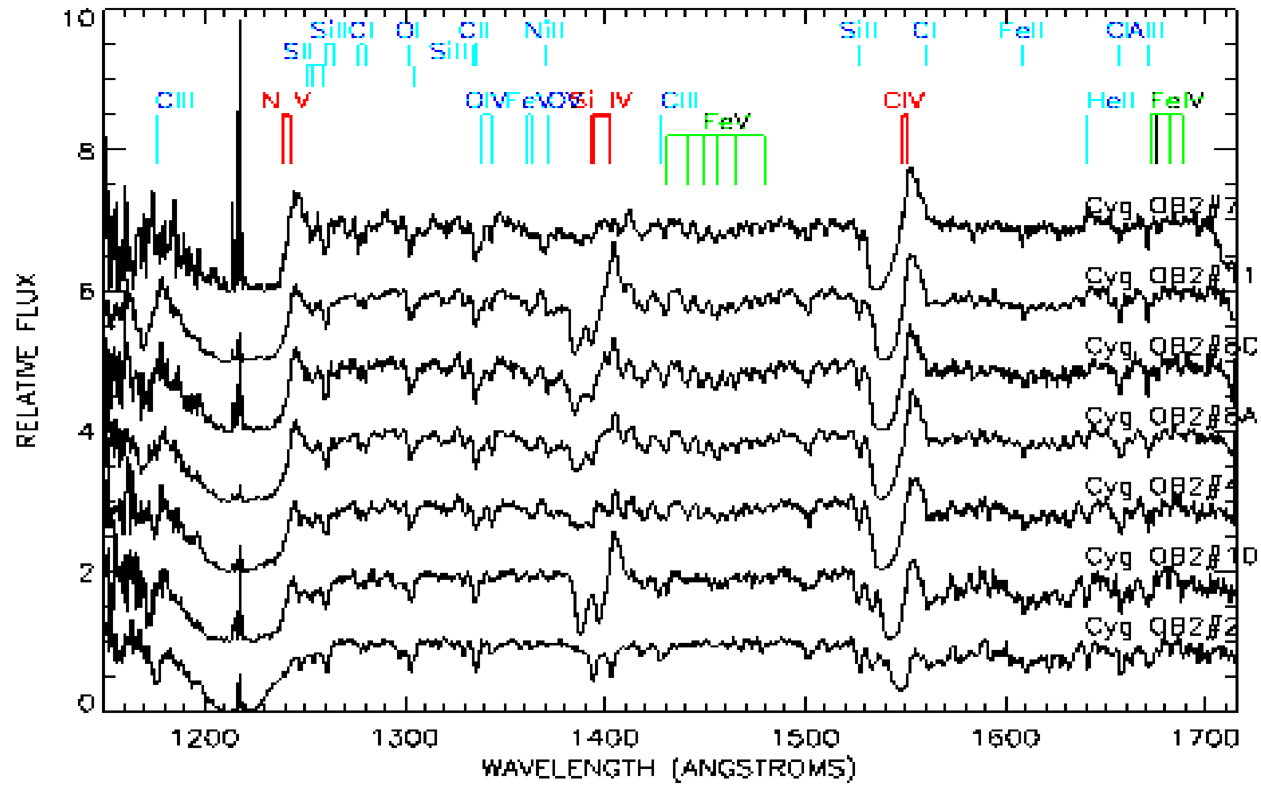
Introduction: massive star winds



Tracks from Meynet & Maeder, paper X

UV Spectral Morphology: O supergiants





Cygnus OB2
Herrero et al. 2001, A&A 366, 623

From Howarth & Prinja, 1989, ApJS 69, 527

Atlas: Walborn & Fitzpatrick, 1996, PASP 108, 477
Walborn et al., 1985, NASA AR 1155

UV Spectral morphology:O supergiants

SIV 1062,1073 Å

CIII+CIV 1176 Å

SiIV 1394, 1403 Å

NV 1239,1243 Å

CIV 1548,1551 Å

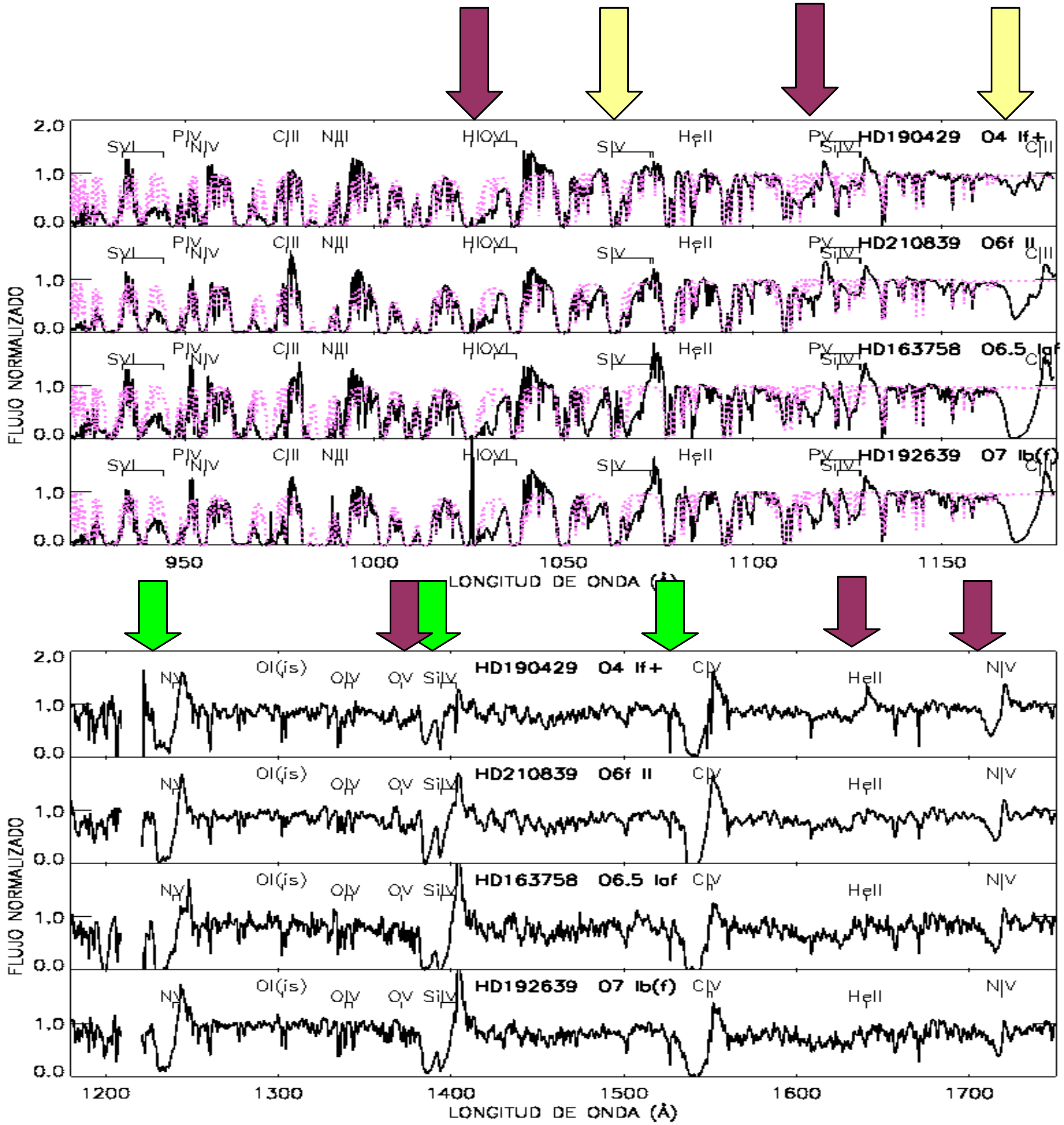
OV 1371 Å

OVI 1032, 1038 Å

NIV 1718 Å

PV 1118,1128 Å

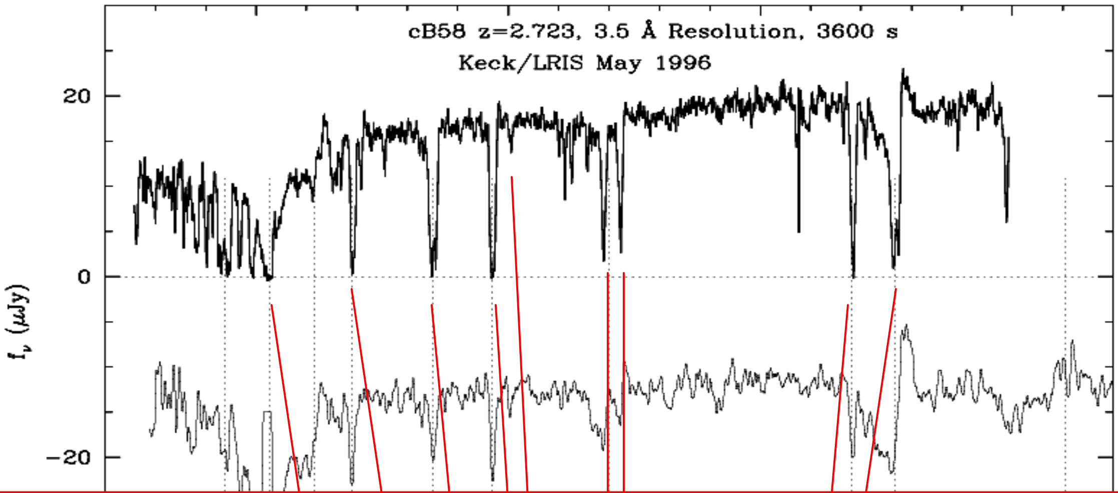
HeII 1640 Å



Bianchi & Garcia 2002

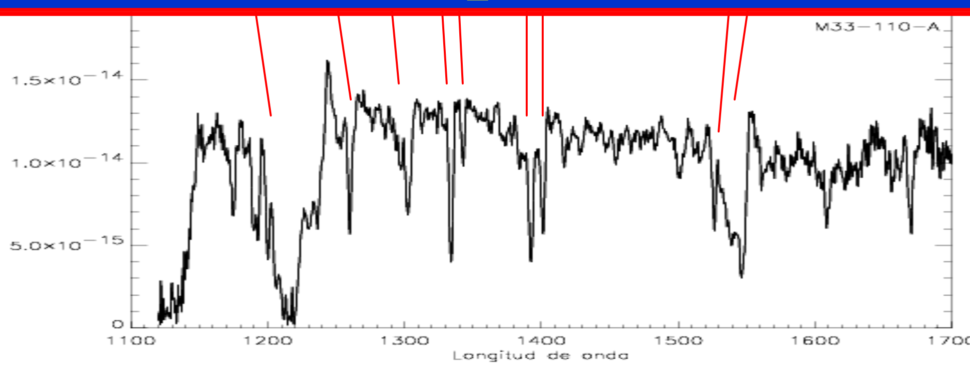
Garcia & Bianchi 2004

massive stars winds: link to the early Universe



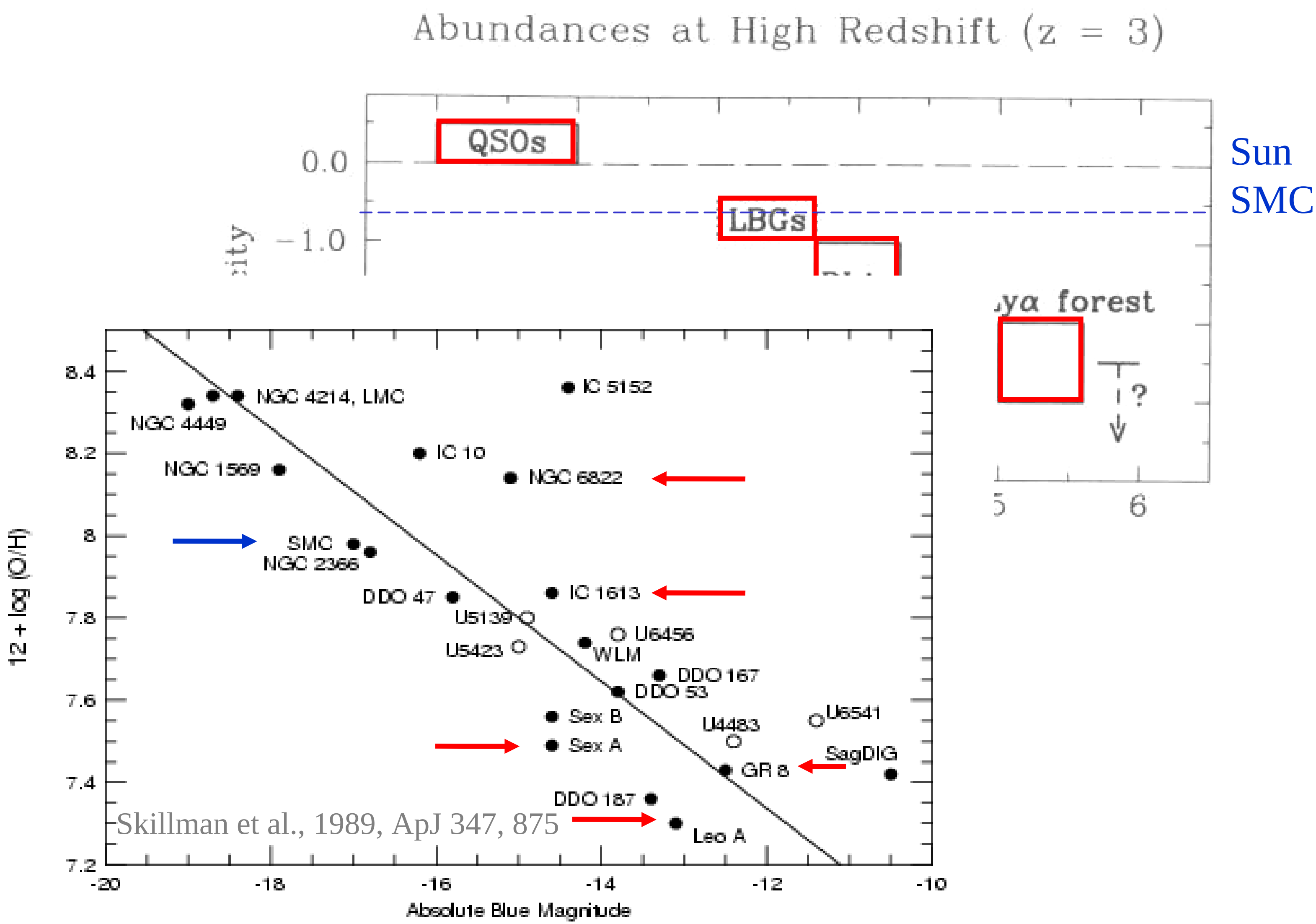
Comparison of UV spectra of NGC 4214, a local star-forming galaxy and cB58 at z= 2.723
(Steidel et al., 1996)

The UV spectrum of massive stars is a key tool in our interpretation of the early Universe

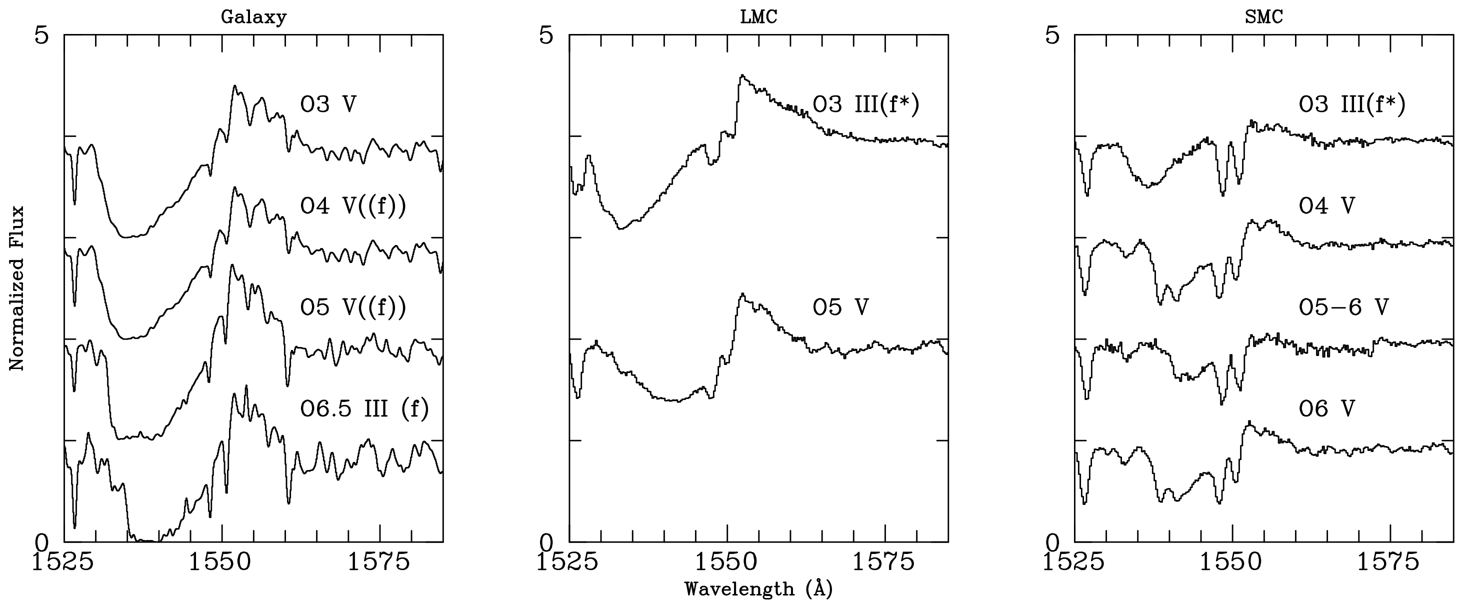


Wind dominated UV spectrum of a B supergiant in M33
(Urbaneja et al., 2002)

massive star winds: link to the early Universe

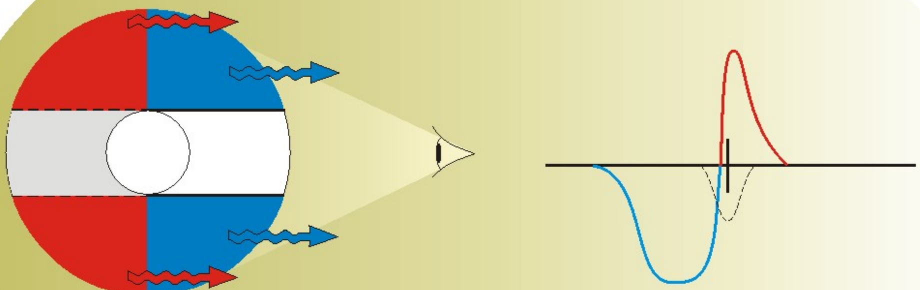


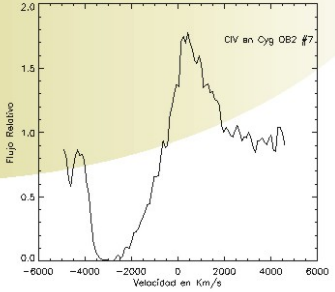
UV spectral morphology: metallicity effects



Radiatively driven winds: origin of massive stars outflows

In the wind, photons are absorbed and reemitted by matter moving towards or away from the observer



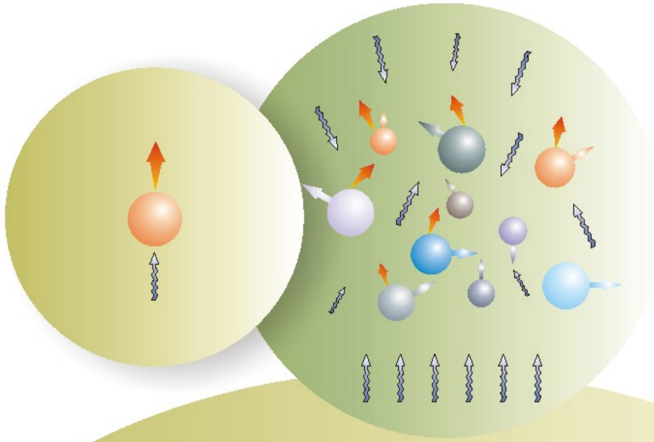


Final result:

- Blue absorption and red emission: P-Cygni profile
- λmin corresponds to the maximum wind velocity
- The emission peak is slightly red shifted

Radiatively driven winds: origin of massive stars outflows

- When photons are absorbed, both energy and momentum are gained by atoms
- No impact in an isotropic radiation field
- In a strongly directional radiation field, this means a net force
- In the stellar atmosphere, matter is accelerated outwards



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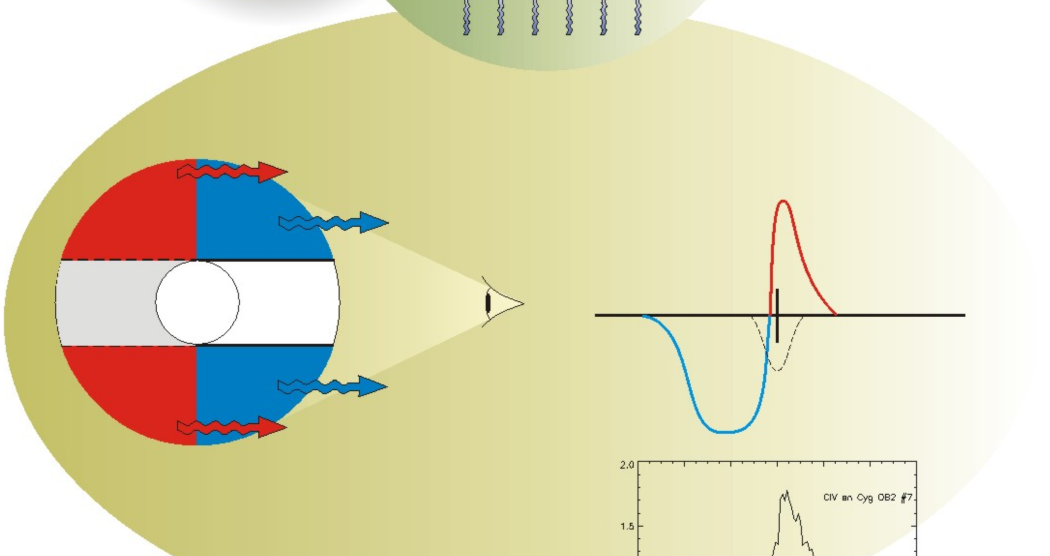

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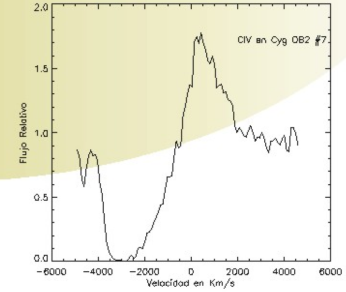
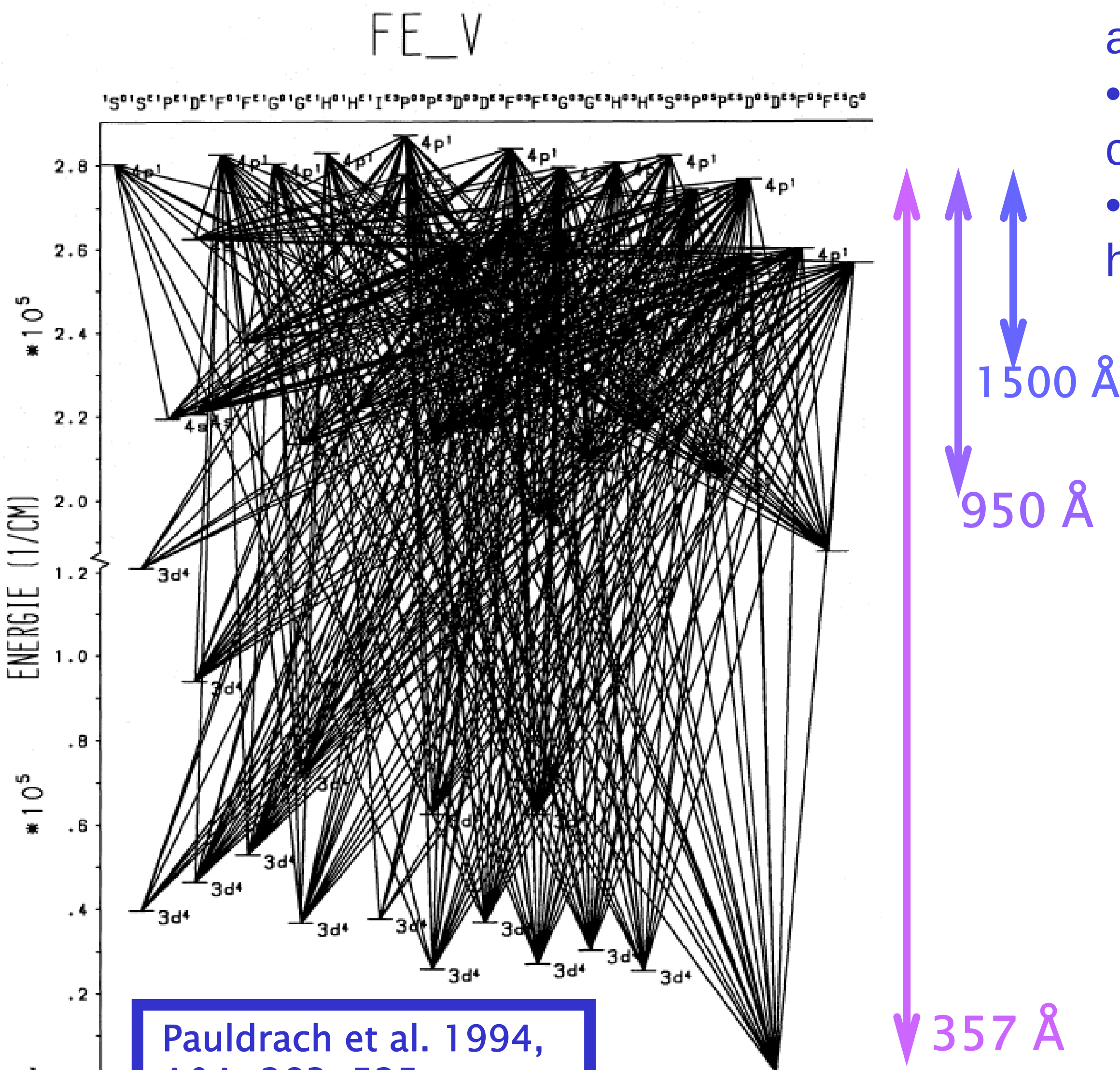
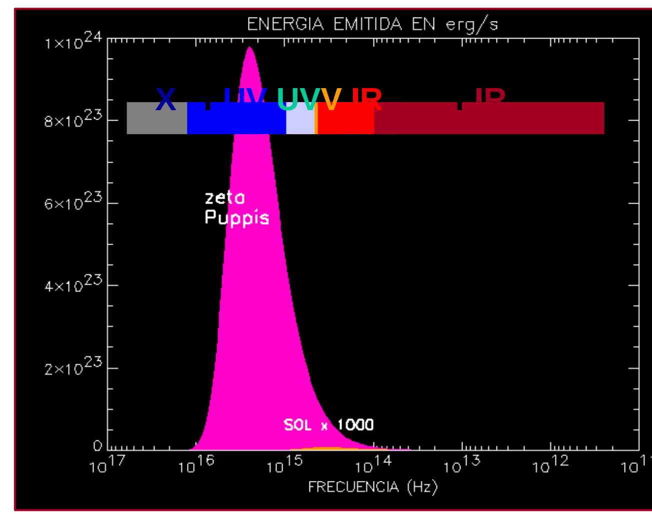


Radiatively driven winds: origin & importance of UV



Pauldrach et al. 1994, A&A, 283, 525

- Winds are initiated by photon absorption in spectral lines
- In hot stars, radiative energy concentrates in the UV
- High ionization stages of metals have many spectral lines



ζ Pup: 42000 K

Radiatively driven winds: basic theory

A simple estimation of the acceleration in one line:

$$g_R^L = \underbrace{\frac{\pi e^2}{mc} f_L}_{} \underbrace{\frac{\pi B_\nu(T_{ef})}{c}}_{} \underbrace{\frac{n_{ijk}}{N_{jk}} \frac{N_{jk}}{N_k} \frac{\alpha_k X}{m_H}}_{}$$

atomic absorption coefficient	line momentum	density of absorbing atoms

A more sophisticated calculation gives (Castor, Abbott & Klein, 1975, CAK theory):

$$g_R^L = \frac{L}{c^2} \frac{v}{4\pi r^2} v_{th} S_E N_0 \left(\frac{dv/dr}{S_E \rho v_{th}} \right)^\alpha \Gamma(\alpha)$$

$S_E = \frac{n_e \sigma_e}{\rho}$

N_0: number of lines with $k \geq S_E$

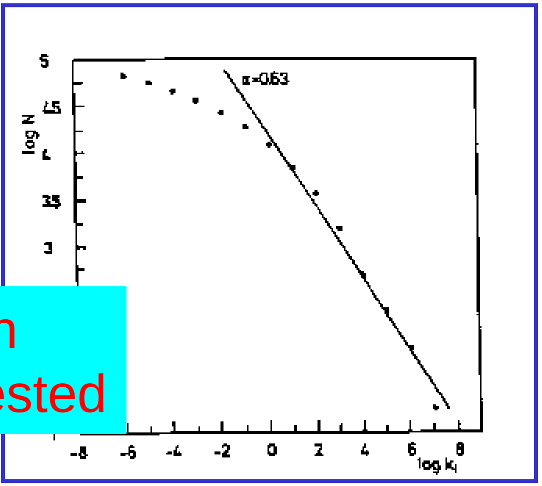
α: exponent of the cumulative function

Γ: special function

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

$$\dot{M} \propto L^{1/\alpha} \left(\frac{1}{M(1-\Gamma)} \right)^{\frac{1-\alpha}{\alpha}}$$

It can be tested



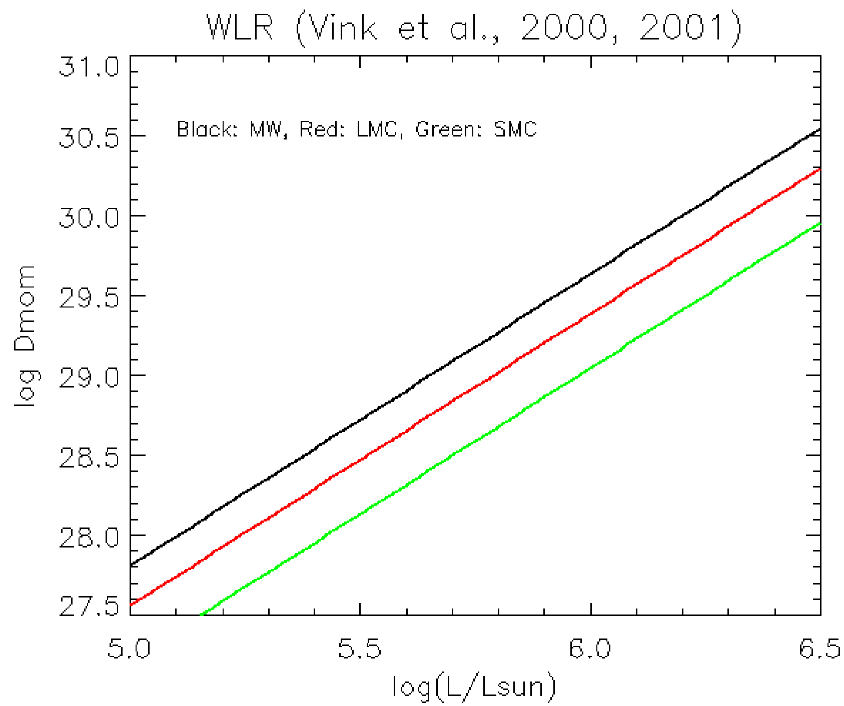
α and N_0 will be a function of:

- element abundance
- ionization fractions
- atomic properties

Radiatively driven winds:

The WLR, a strong test of the radiatively driven wind theory

- Radiatively driven wind theory predicts a relation between (Mdot, V∞, R) and L



WLR

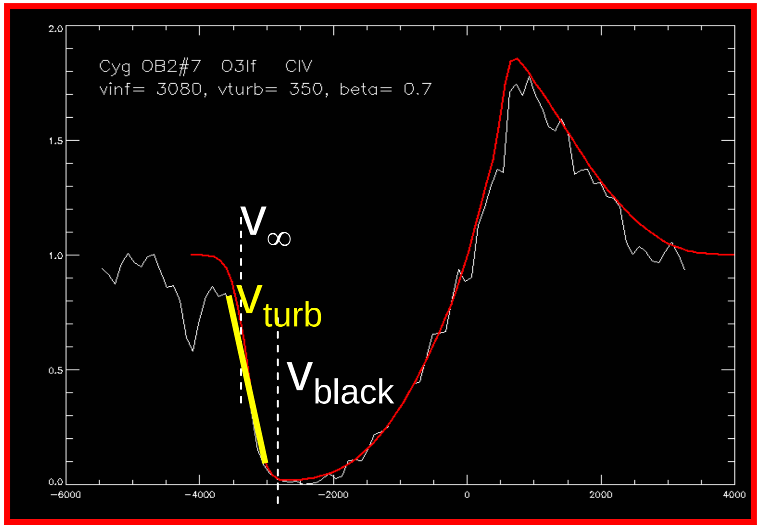
Wind momentum-Luminosity Relation

$$D_{mom} = \dot{M}\ V_{\infty}\ R^{0.5} \propto L^{1/\alpha}$$

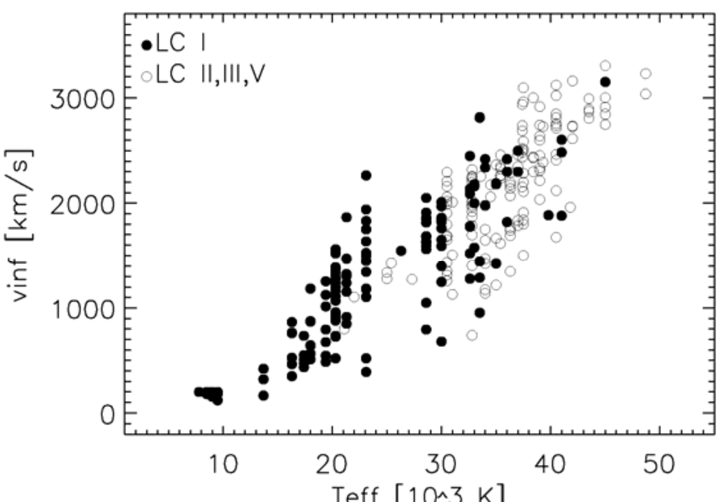
← **line force, metallicity**

Derivable **Distance ?**

Radiatively driven winds: derivation of v_∞

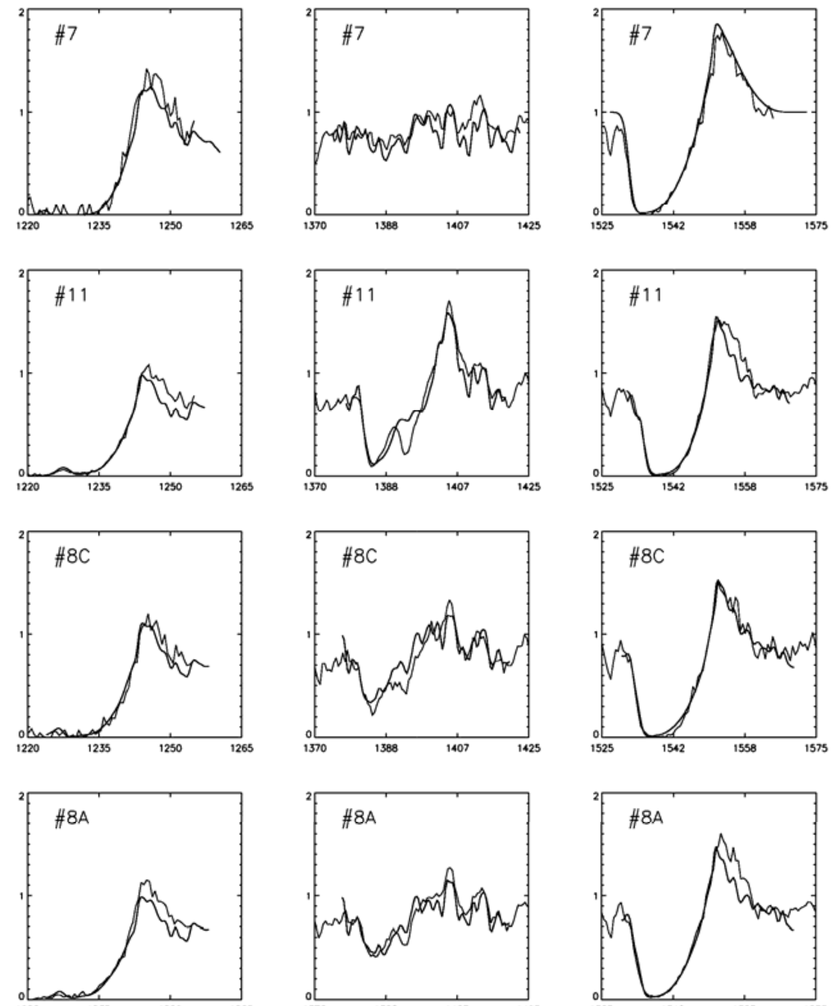


Terminal wind velocity from the UV



Kudritzki & Puls, 2000

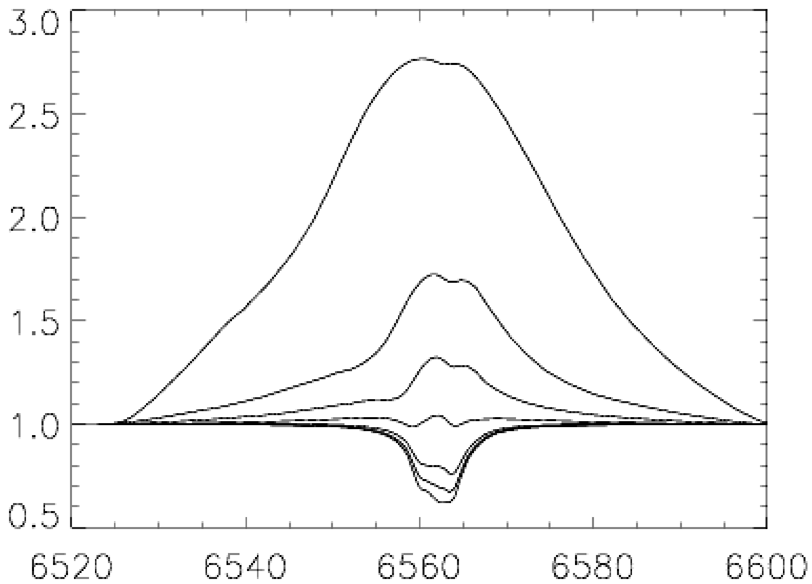
$$V(r) = V_\infty \; (1.- bR/r)^\beta$$



Herrero et al., 2001

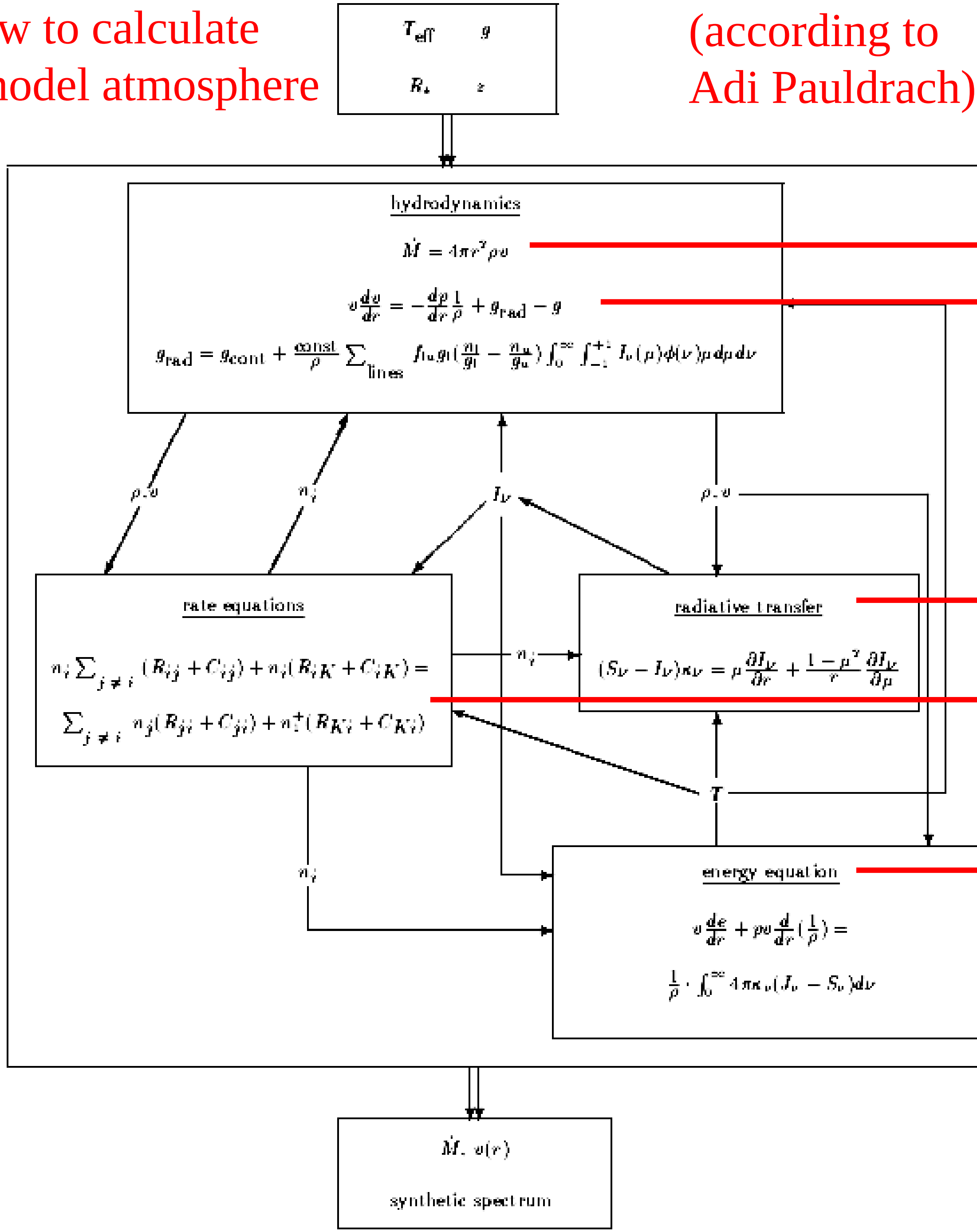
Radiatively driven winds: derivation of $\dot{M}$

Mass-loss rate from Hα
(also from UV, IR or radio)



$\dot{M}$= 30, 10, 5, 2.5, 0.01 x 10^{-6} $M_{\odot}$ /yr

How to calculate a model atmosphere (according to Adi Pauldrach)



Model Atmosphere Equations

mass-loss (radiatively driven winds)

Mass conservation

Momentum conservation

NLTE (Statistical Equilibrium)

Radiative transfer

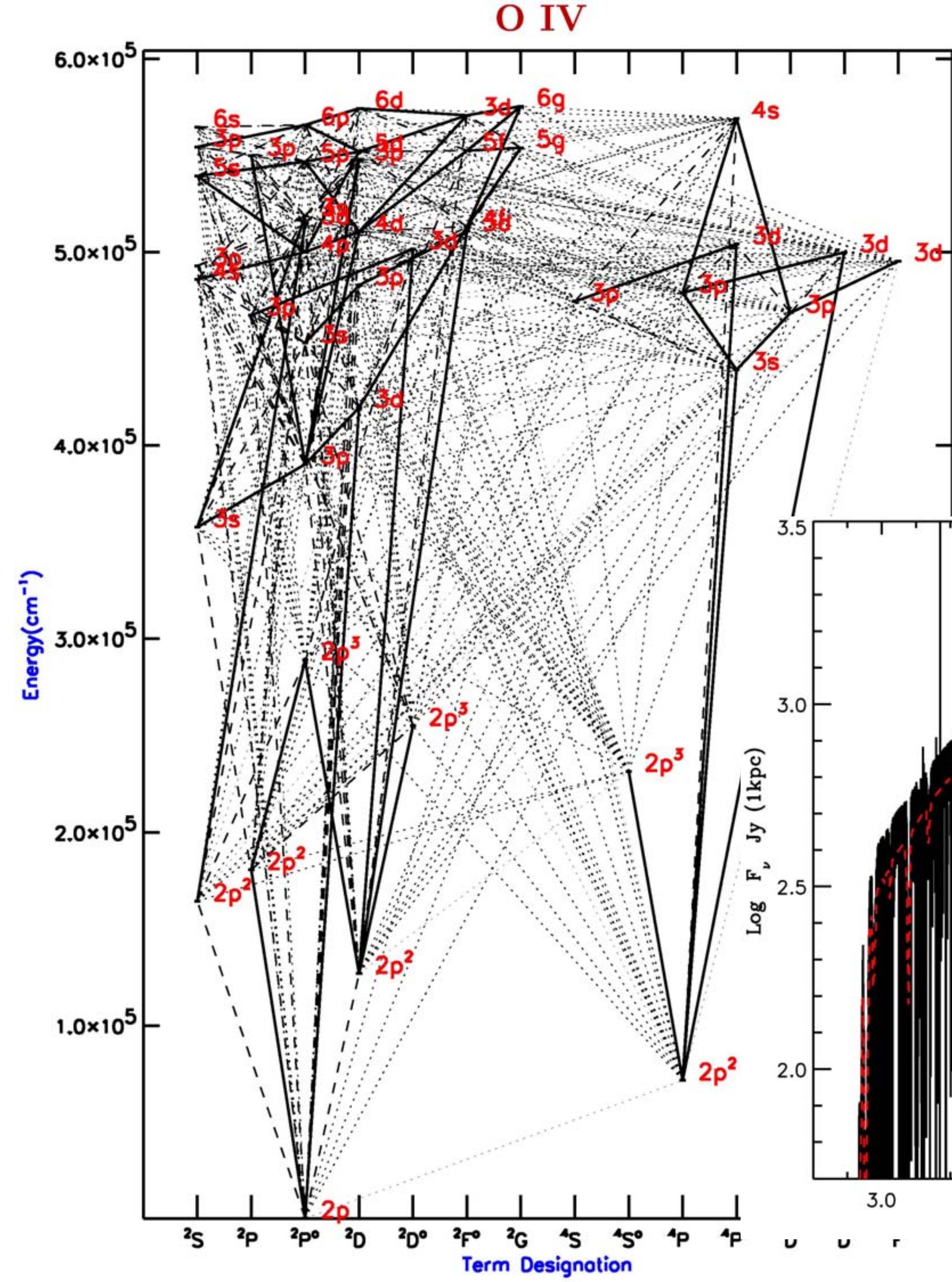
Statistical Equilibrium

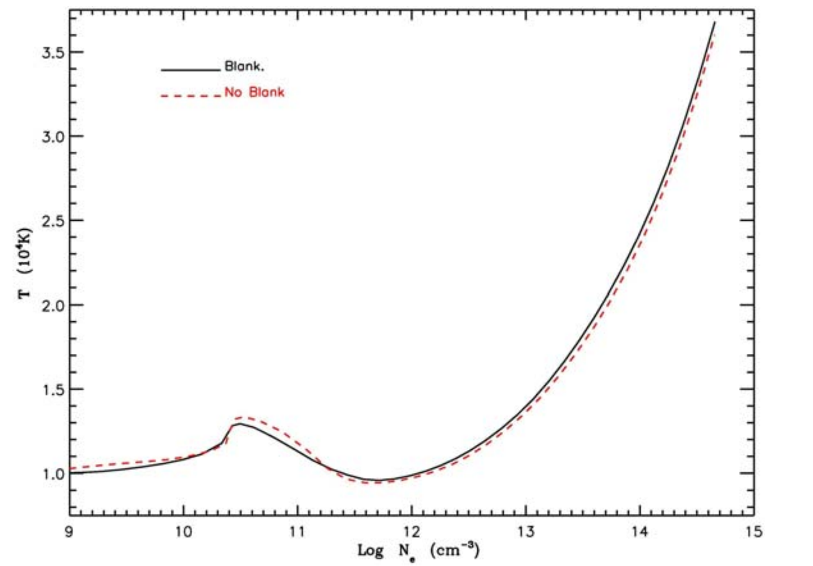
Energy conservation

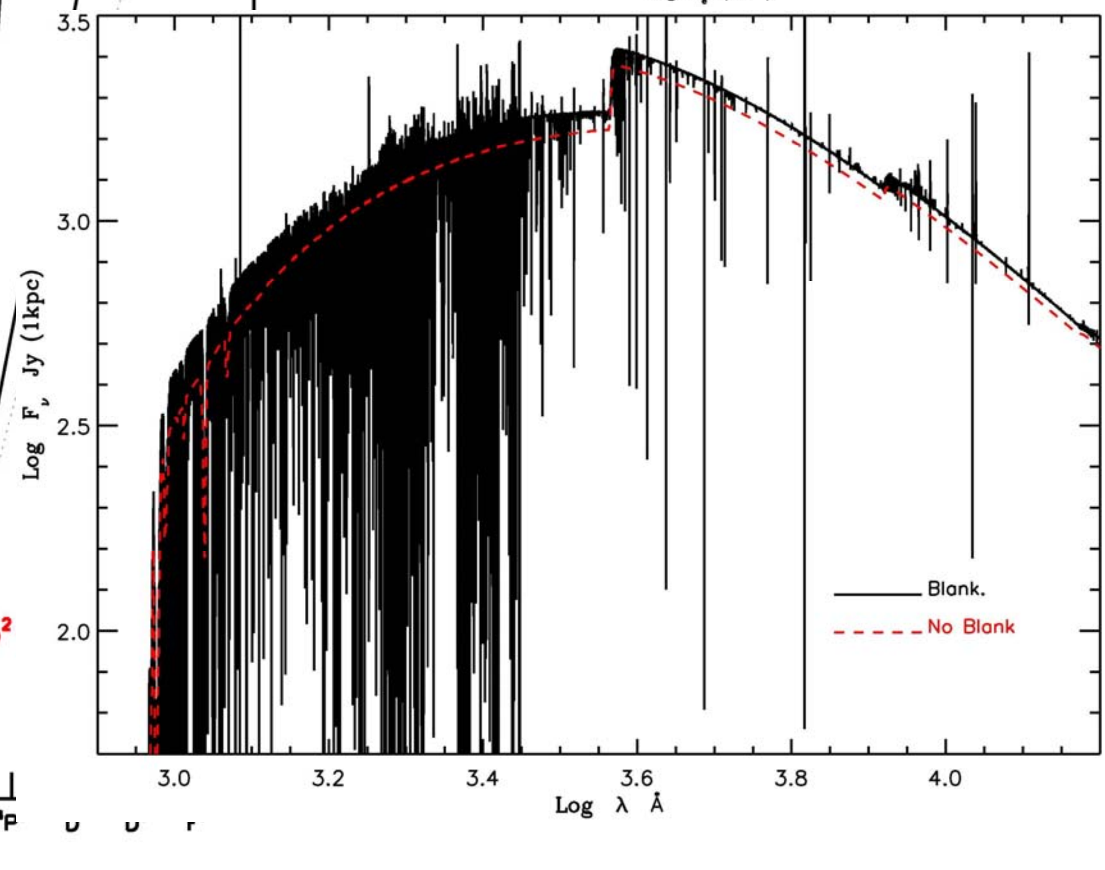
Interaction

κ n I v

Atomic description


O IV
Energy(cm^{-1})
Term Designation
6.0×10^5
5.0×10^5
4.0×10^5
3.0×10^5
2.0×10^5
1.0×10^5
^{2}S
^{2}P
^{2}P^o
^{2}D
^{2}D^o
^{2}F^o
^{2}G
^{4}S
^{4}S^o
^{4}P
6s
6p
6d
3d
6g
4s
5s
5p
5g
3p
3s
4d
4p
2p^3
2p^2
2p

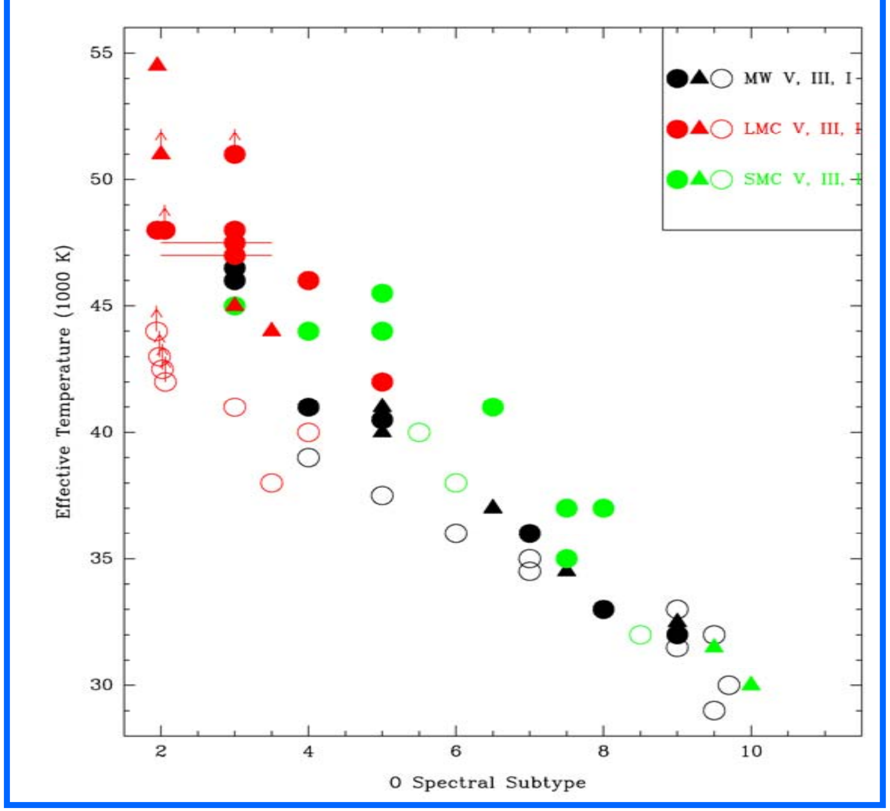

Blank.
No Blank
T (10^{4}K)
Log N$_e$ (cm^{-3})
3.5
3.0
2.5
2.0
1.5
1.0
9
10
11
12
13
14
15


Log F$_\nu$ Jy (1kpc)
Log λ Å
Blank.
No Blank
3.5
3.0
2.5
2.0
3.0
3.2
3.4
3.6
3.8
4.0

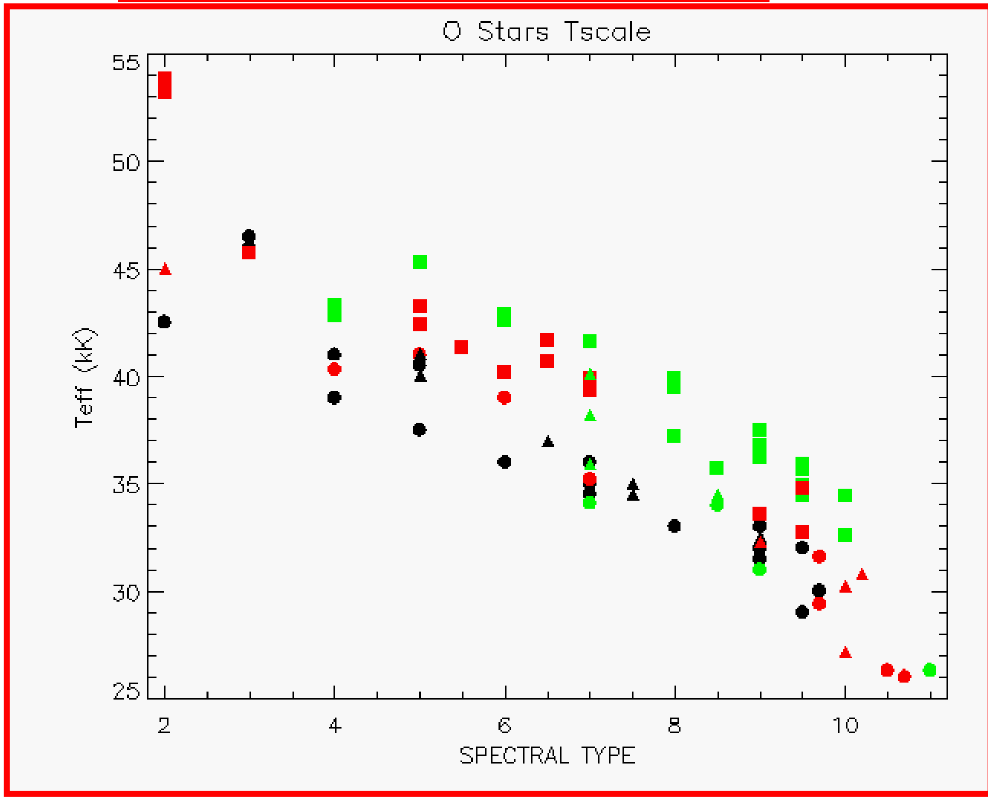
Parameters of massive blue stars:

A new Teff scale for O stars in the Magellanic Clouds

Massey et al., 2004, 2005



Mokiem et al., 2006, 2007



Black symbols: Repolust et al., 2004 in both figures

Comparison of metallicities

SMC stars hotter than MW counterparts

same results for SG and dwarfs

BUT: intrinsic scatter very large

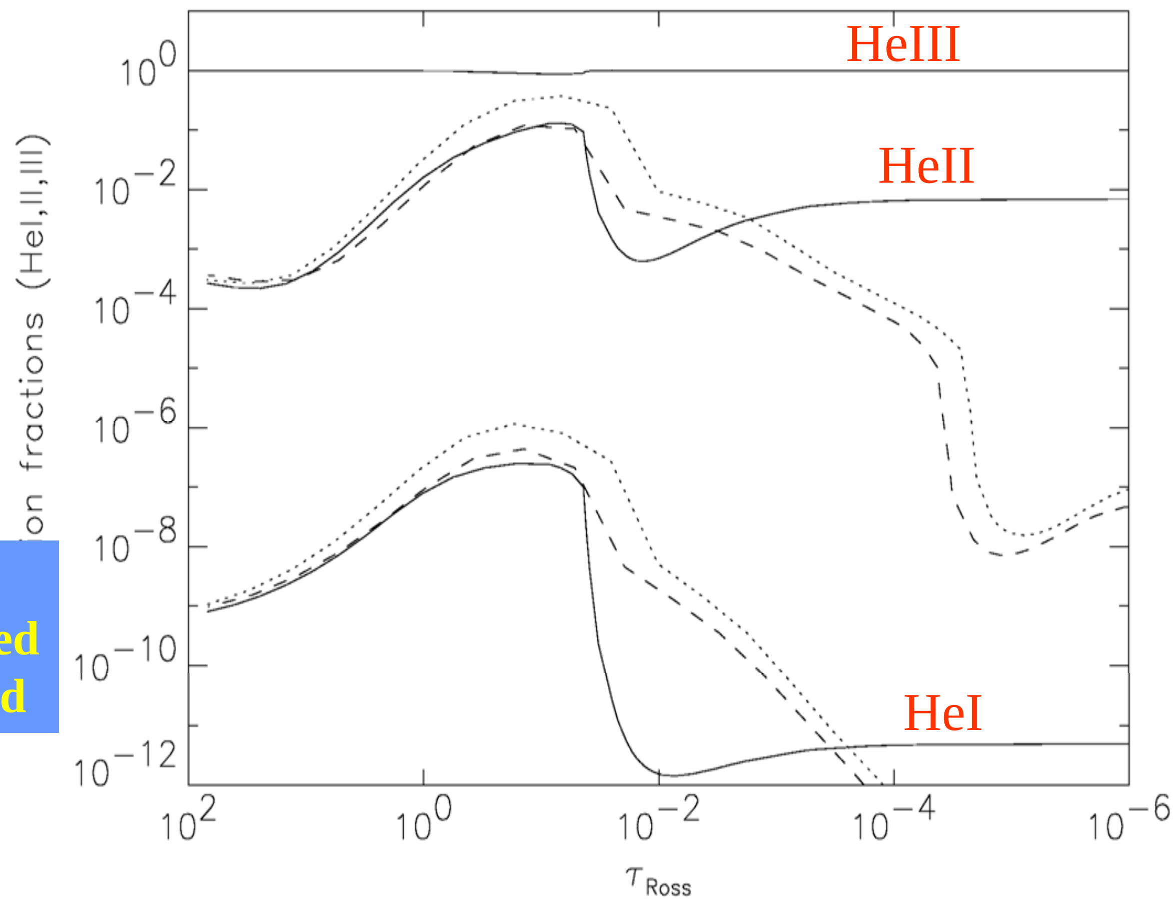
LMC not clearly intermediate SMC/MW

Model atmospheres: effects of line-blanketing

- Why do we obtain lower temperatures when including sphericity, mass loss and metal line opacities?

higher (lower) ionization degree of key ionization stages at the line formation depth (Repolust, Puls, Herrero, 2004)

HD 15629 O5 V

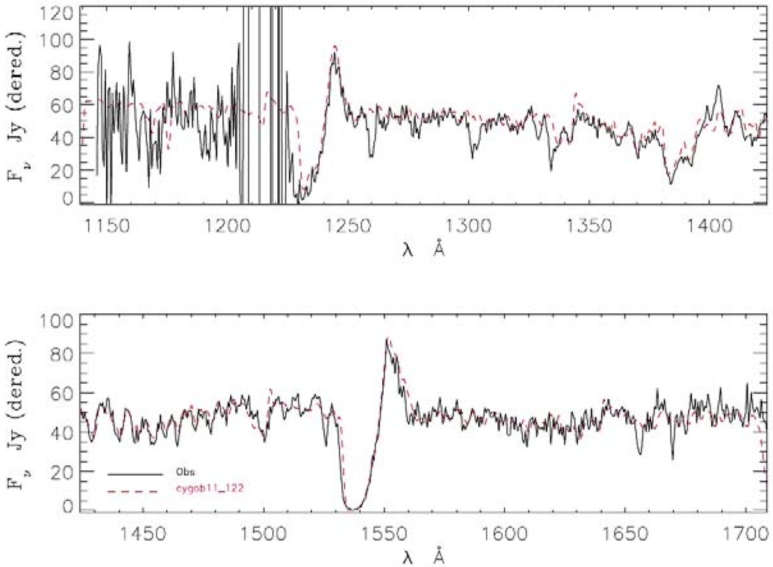


Solid: cooler, blanketed
Dashed: hotter, unblanketed
Dotted: cooler, unblanketed

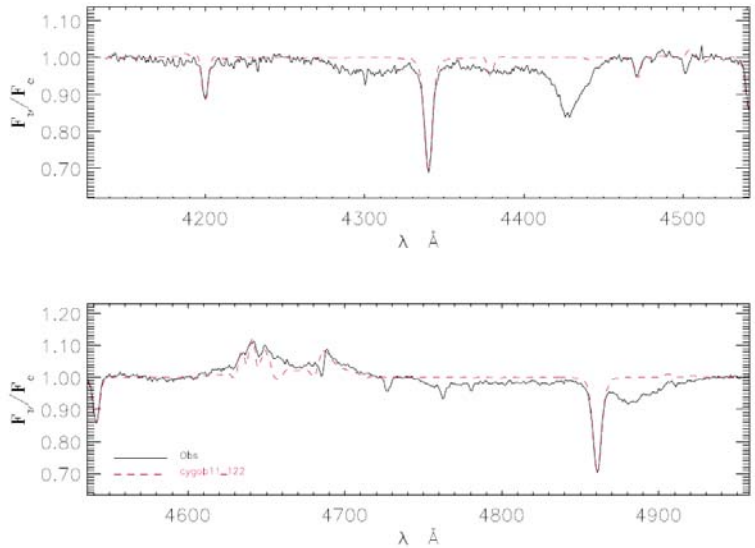
Model atmospheres: from UV to IR

Cyg OB2 8C

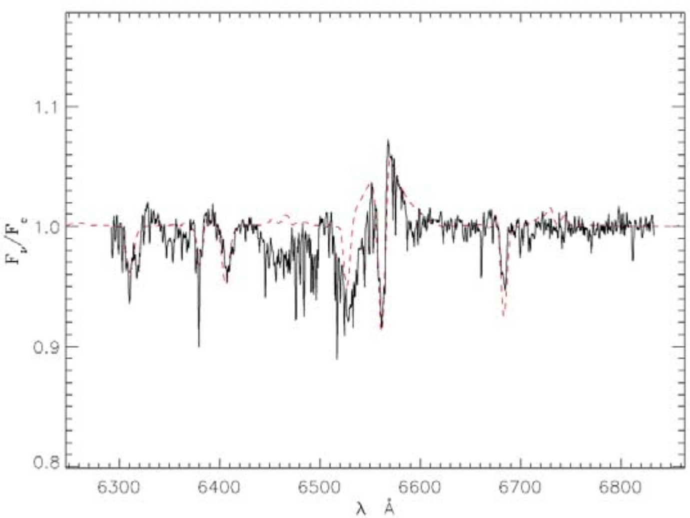
UV



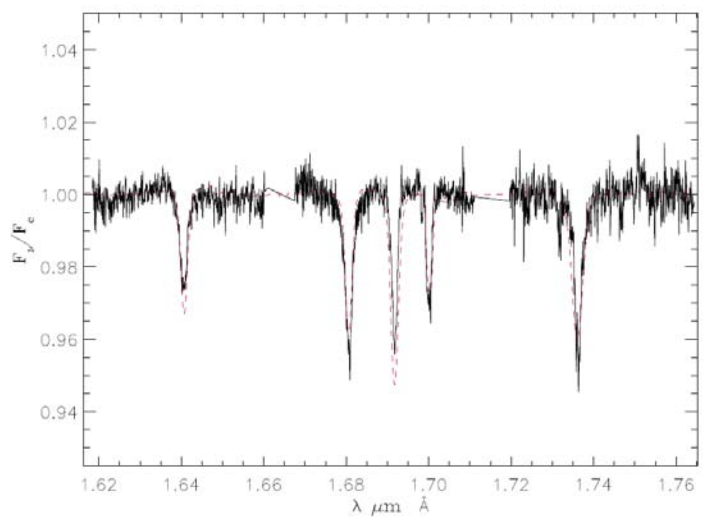
blue



red



H band



N11
(LH9/10)

Massive blue stars in nearby galaxies:
The FLAMES survey of masive stars

P.I.: S.J. Smartt

Observe massive OB stars in the MW and MC with FLAMES (R≈ 25000) (some with FEROS)

Main goals

- -Test the WLR
- -Test evolutionary models
- -Test the Vrot – metallicity dependence

Co-I: D.J. Lennon
P. Dufton
C. Evans
C. Trundle
A. de Koter
R. Mokiem
J. Puls
F. Najarro
S. Simón-Díaz
A. Herrero

Observations in:

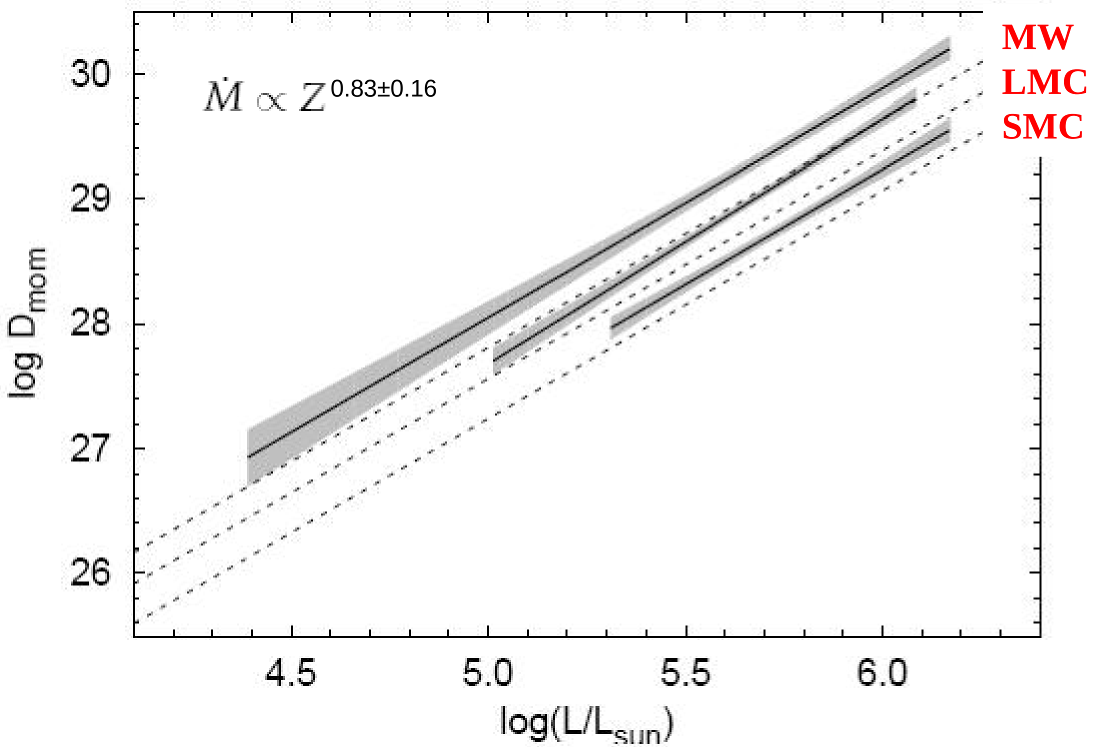
NGC 3293 (99 B stars)
NGC 4755 (98 B)
NGC 6611 (13 O, 40 B)
NGC 2004 (1 WR, 4 O, 107 B)
LH 9/10 (44 O, 76 B)
NGC 330 (6 O, 109 B)
NGC 346 (19 O, 86 B)

Total: 1 WR, 86 O, 615 B, 101 AFG

N11

The FLAMES survey of massive stars

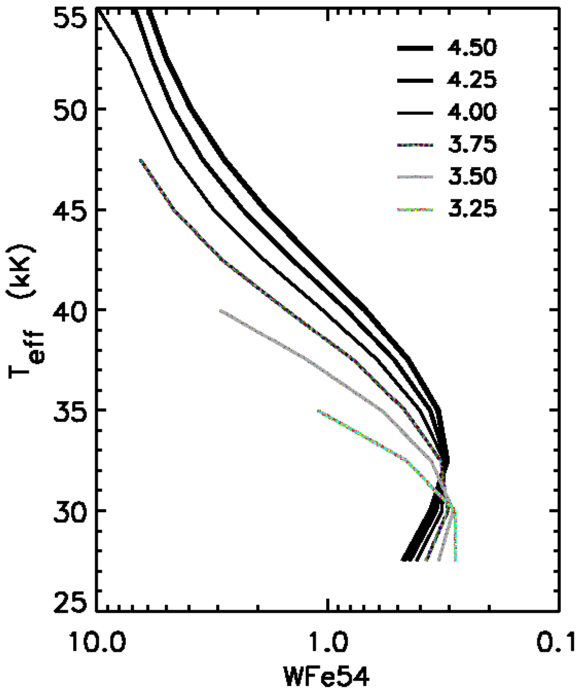
P.I. S. Smartt

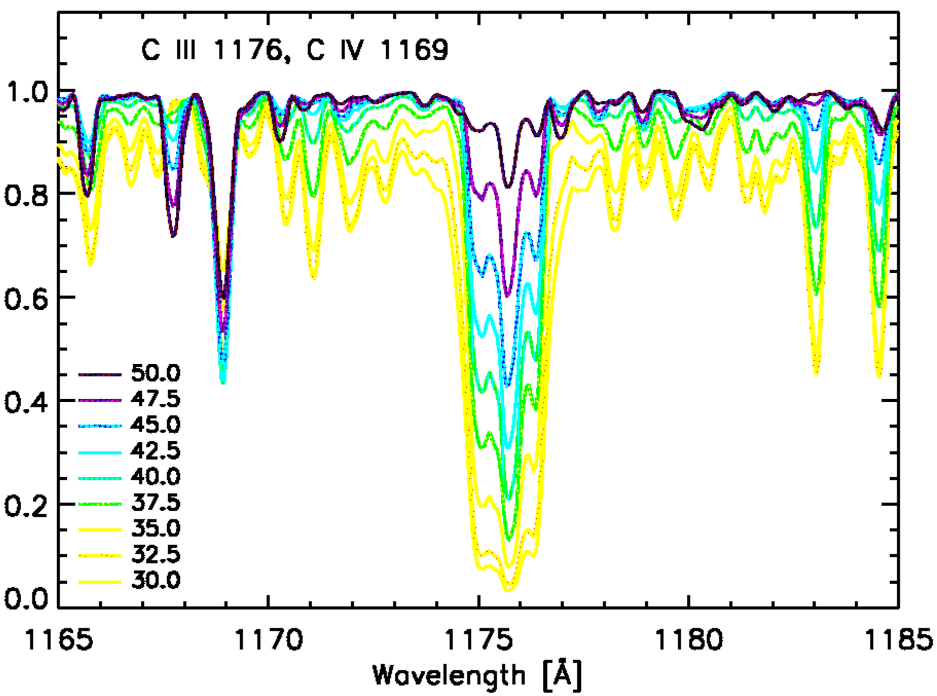


WLR for the MW (top), LMC (middle and SMC (bottom) from Mokiem thesis. No clumping. Shaded areas are 1 sigma uncertainties, dashed lines are theoretical predictions by Vink et al.

Dotted lines: Vink et al., 2001, A&A 369, 574
Shaded: Mokiem et al., 2007 (submitted)

Parameters of massive blue stars: Teff from UV



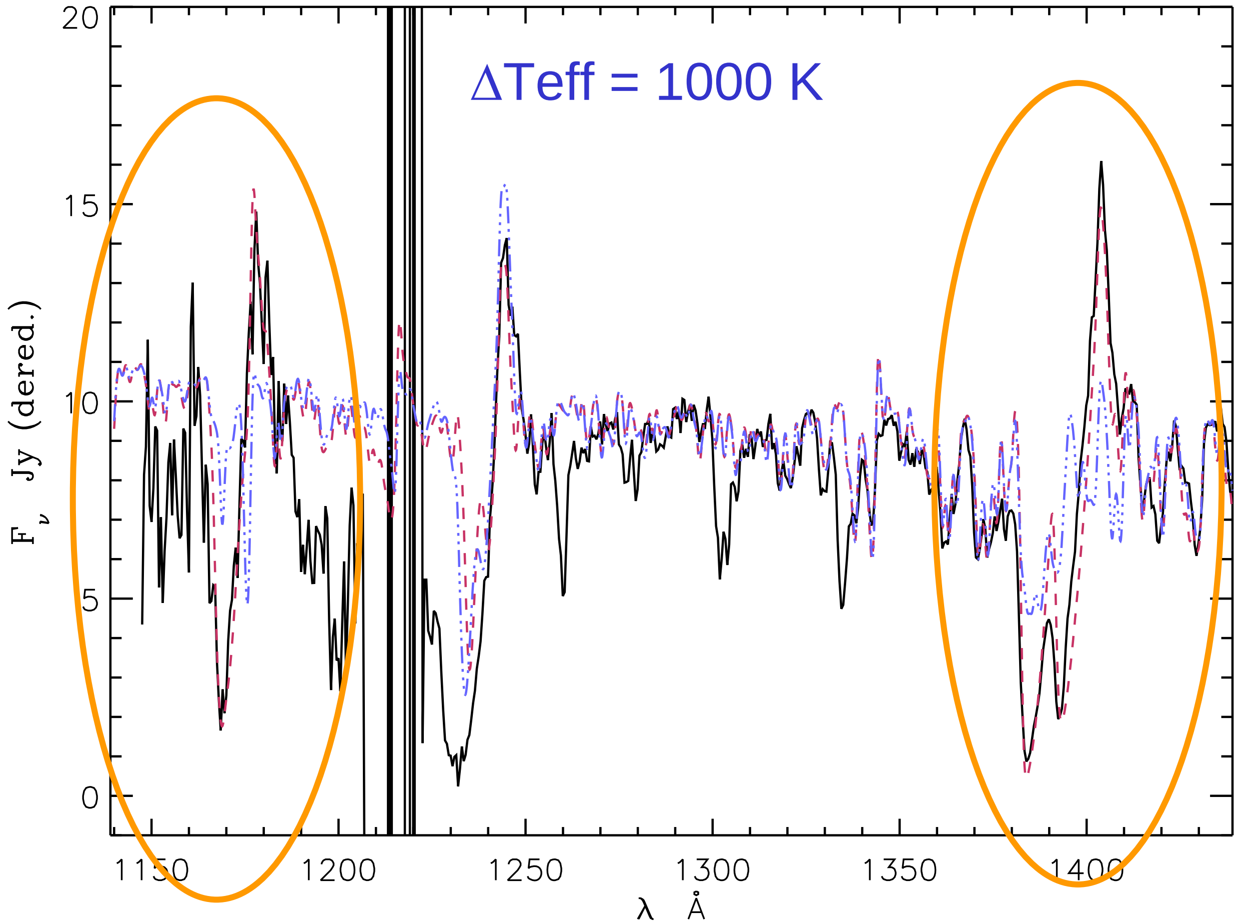


FeV lines around 1370 Å
FeIV lines around 1620 Å
Note: gravity has to be determined independently

Weakly dependent on gravity

Najarro, Herrero, Verdugo (2006)

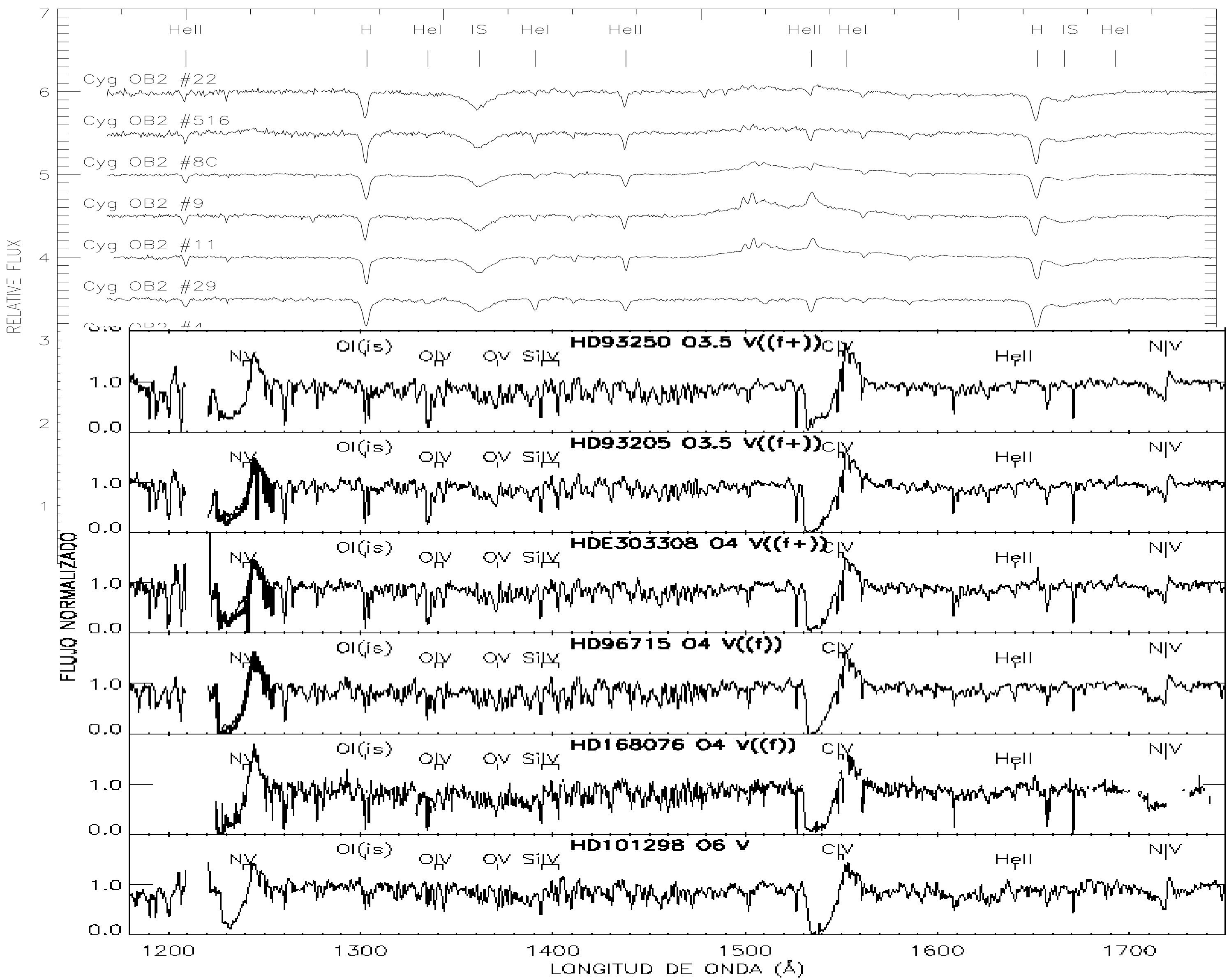
Parameters of massive blue stars: Teff from UV



CMFGEN fits to HST spectrum of Cyg OB2 #11

Najarro, Herrero, Verdugo (2006)

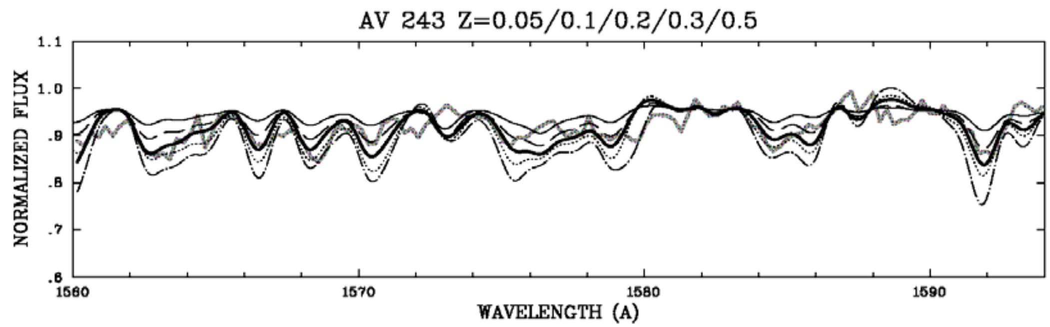
Parameters of massive blue stars: abundances

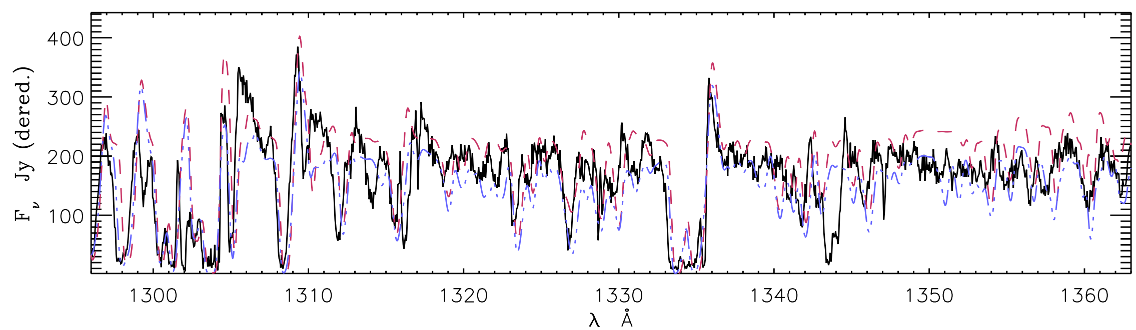


Parameters of massive blue stars: abundances

Taresch et al., 1997

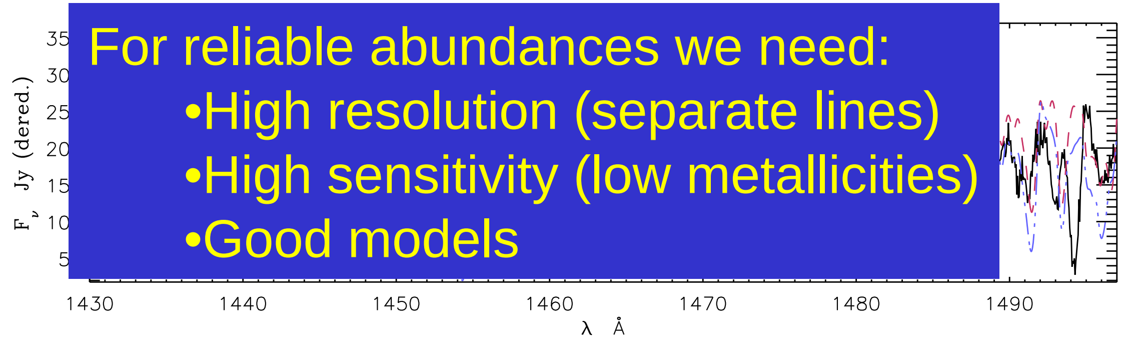
Z determination in the SMC





P-Cygni (IUE)

(Najarro, 2001)



For reliable abundances we need:

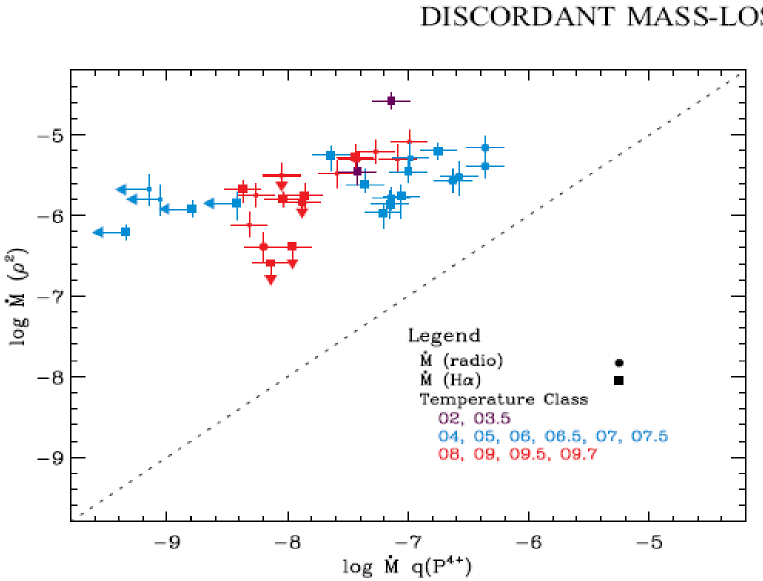
- High resolution (separate lines)
- High sensitivity (low metallicities)
- Good models

Blue: iron blanketing

Red: + Ni, Co

Winds of massive stars: open questions- clumping

Increasing evidence for clumping



Fullerton et al., 2006, ApJ 637, 1025

- Discrepancies with predicted WLR (Herrero et al., 2002; Repolust et al., 2004; Massey et al., 2005)
- P v abundances in the O stars (Crowther et al., 2002; Hillier et al. 2003; Massa et al., 2003, 2004; Fullerton et al., 2006)
- Wind ionization fractions for B-supergiants by Prinja et al., 2005
- Radio observations

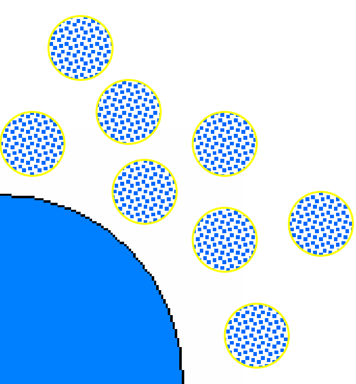
UV lines $\propto \rho$

Hα, radio $\propto \rho^2$

$$<\rho>^2 \neq <\rho^2>$$

$$f_{cl} = \frac{<\rho^2>}{<\rho>^2} \geq 1$$

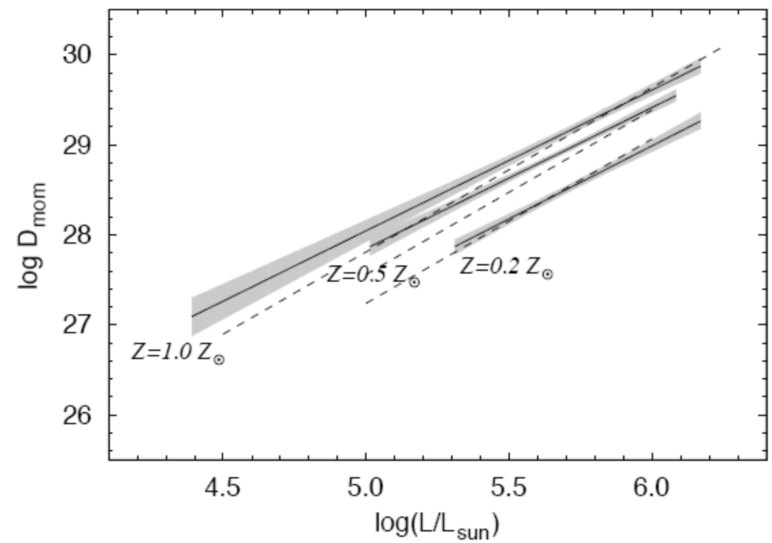
$$\dot{M}(\rho^2)_c = (1/\sqrt{f})\,\dot{M}(\rho^2)_s$$



Puls et al., 2006

f ≈ 1-10, with radial dependence

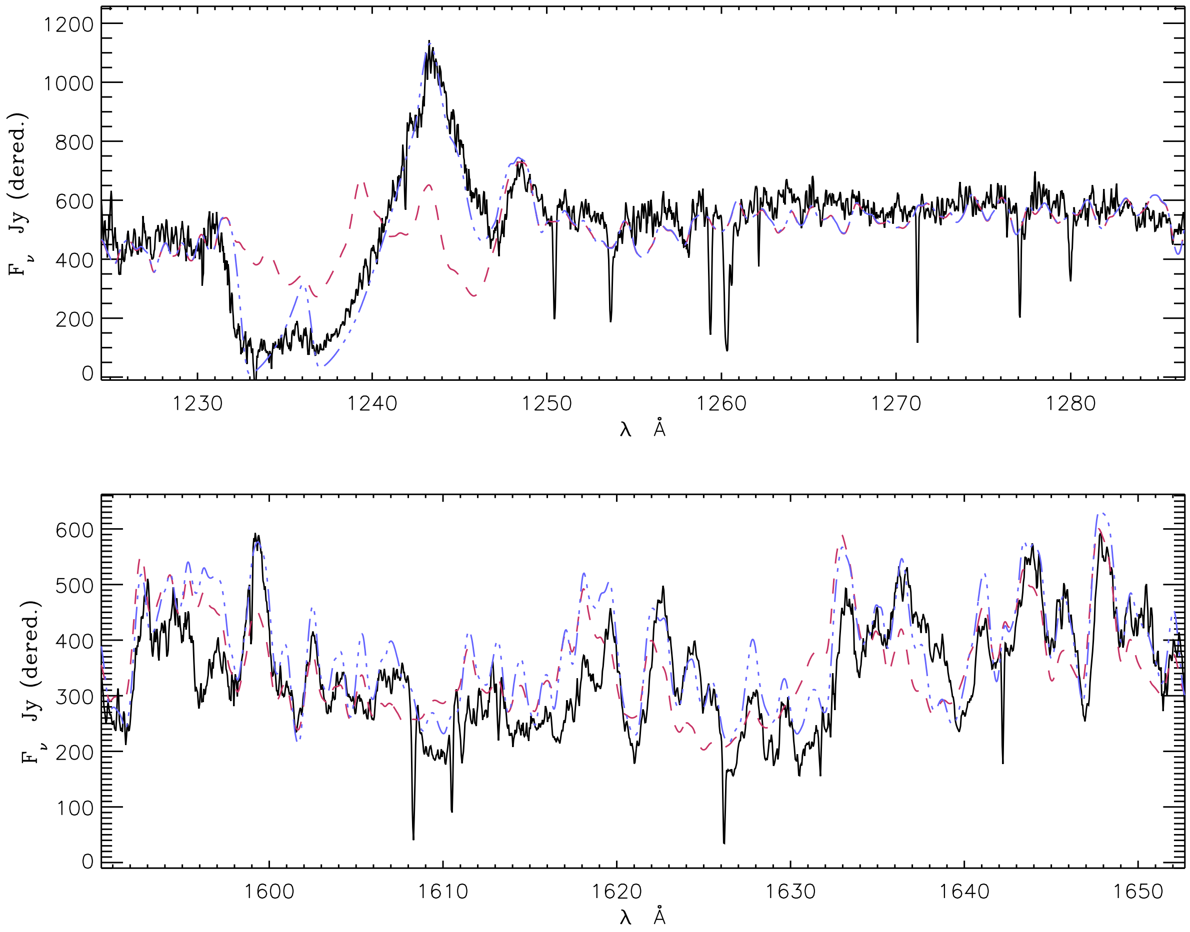
Hα mass-loss lower by 1 – 3



Dotted lines: Vink et al., 2001, A&A 369, 574

Shaded: Mokiem et al., 2007 (submitted)

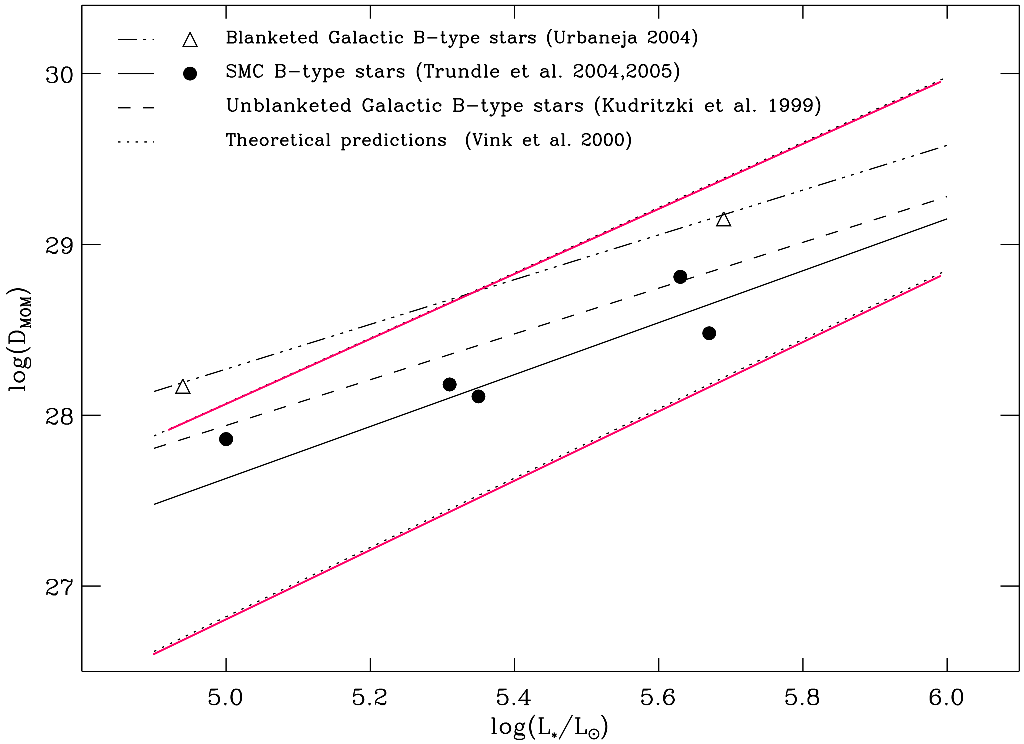
Winds of massive stars: open questions- X-rays



Effect of X-rays on α Cam

Winds of massive stars: open questions

The WLR of mid B supergiants

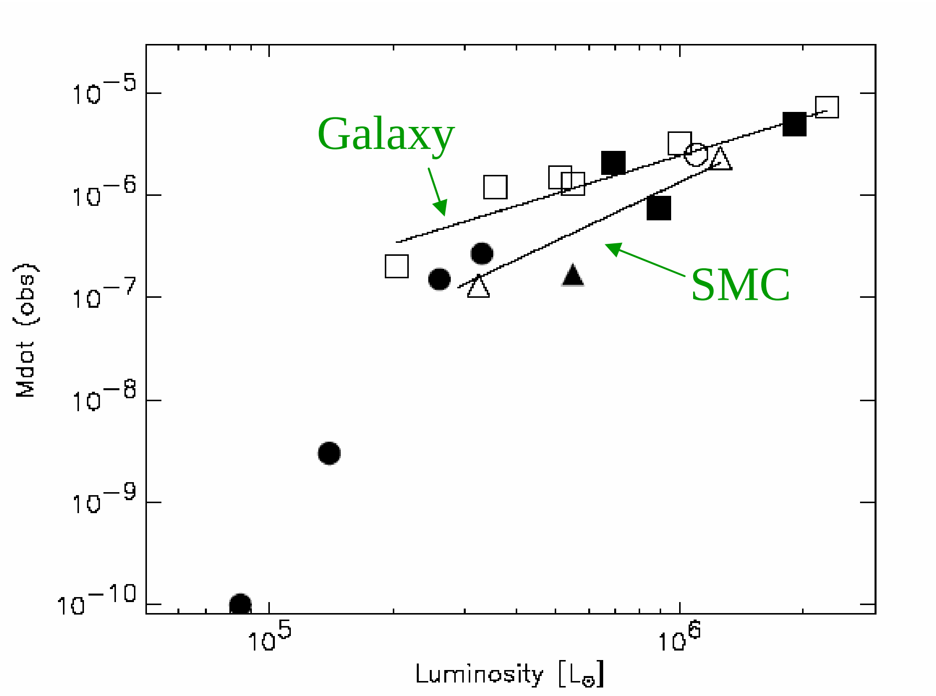


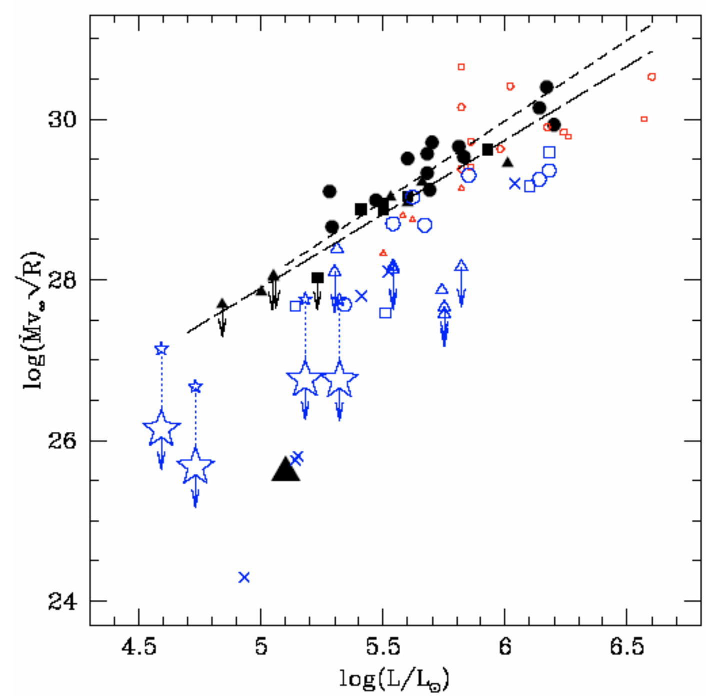
Trundle et al., 2005

- DACs
- Rotation ?
- Magnetic fields?

Winds of massive stars: open questions- thin winds

- Herrero, Puls, Najarro (2002) obtain a very low value for the mass-loss rate of 10 Lac (O9.5V)
- Bouret et al. (2003) and Martins et al. (2004) show that this is more general





Solid circles: Bouret et al. objects in NGC 346

Blue stars: Martins et al. objects in N81

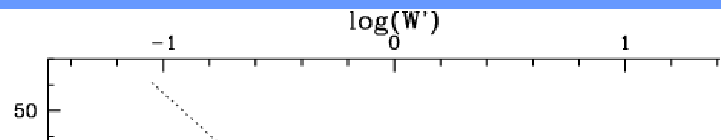
See also poster by M. García et al.

Conclusions

- Present model atmospheres for blue massive stars are able to reproduce the observations
- Open questions are probably linked to our understanding of the UV radiation
- The UV plays a central role in such models and offers a large number of possibilities for the study of these stars in the Milky Way and nearby galaxies
- Massive stars offer a key tool for research in Astrophysics, particularly if we understand them at all metallicities

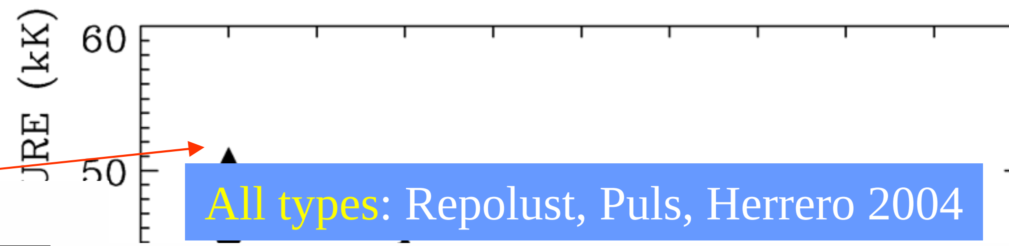
Parameters of massive blue stars:
A new Teff scale for O stars in the MW

Dwarfs: Martins, Schaerer, Hillier 2002

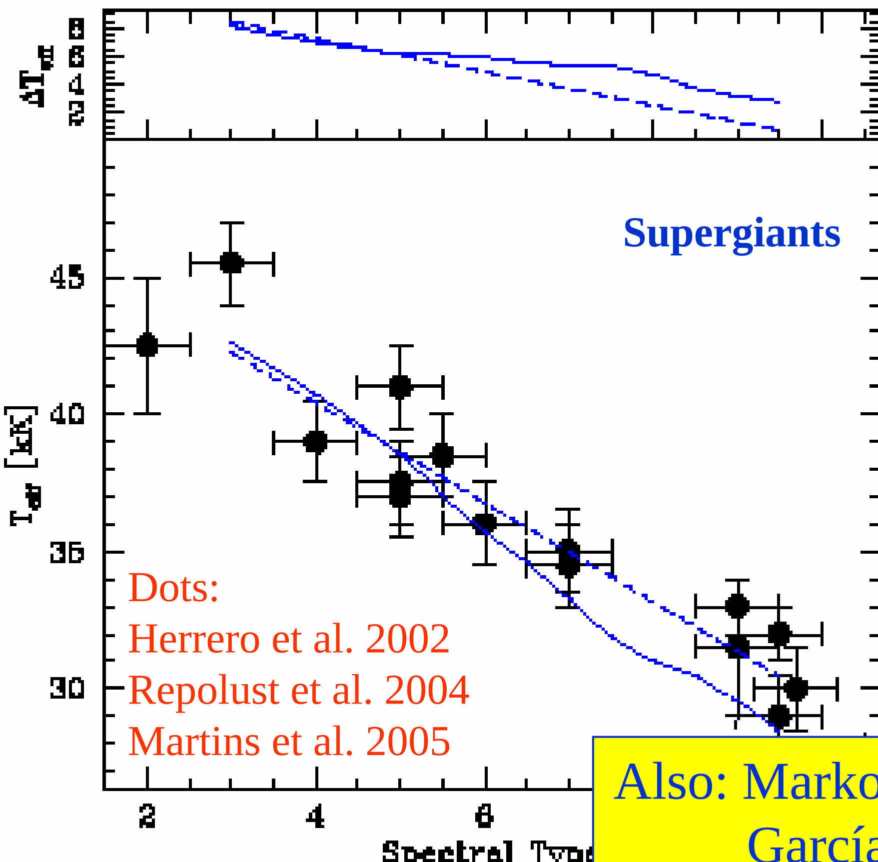


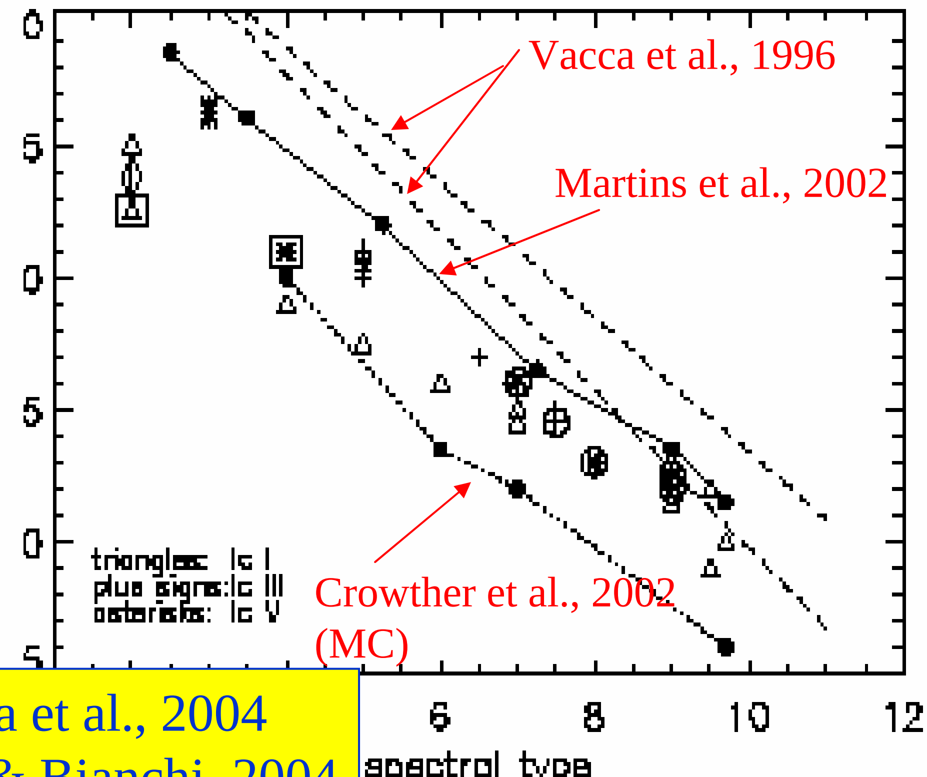
All types: Martins, Schaerer, Hillier 2005

CygOB2 SG: Herrero, Puls, Najarro 2002



All types: Repolust, Puls, Herrero 2004





Also: Markova et al., 2004
García & Bianchi, 2004