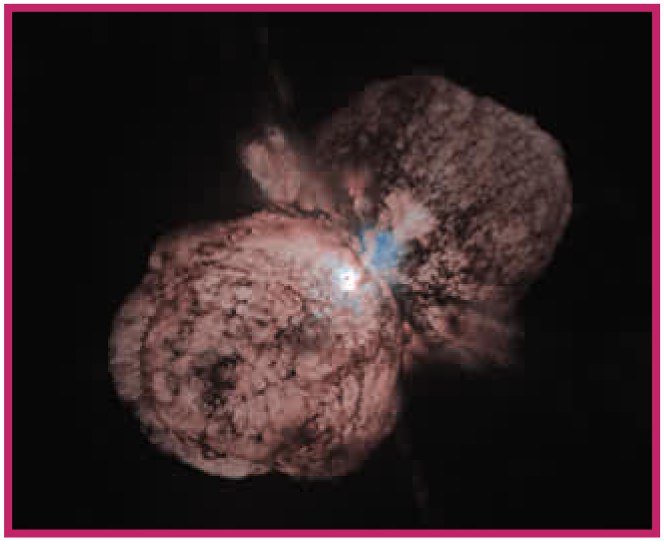
Constraining the evolutionary sequence of very massive stars



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Madrid
Setiembre 2009

Constraining the evolutionary sequence of very massive stars

J. Simon Clark (Open University, UK)
Benedict Ritchie (Open University, UK)
and many others

Madrid
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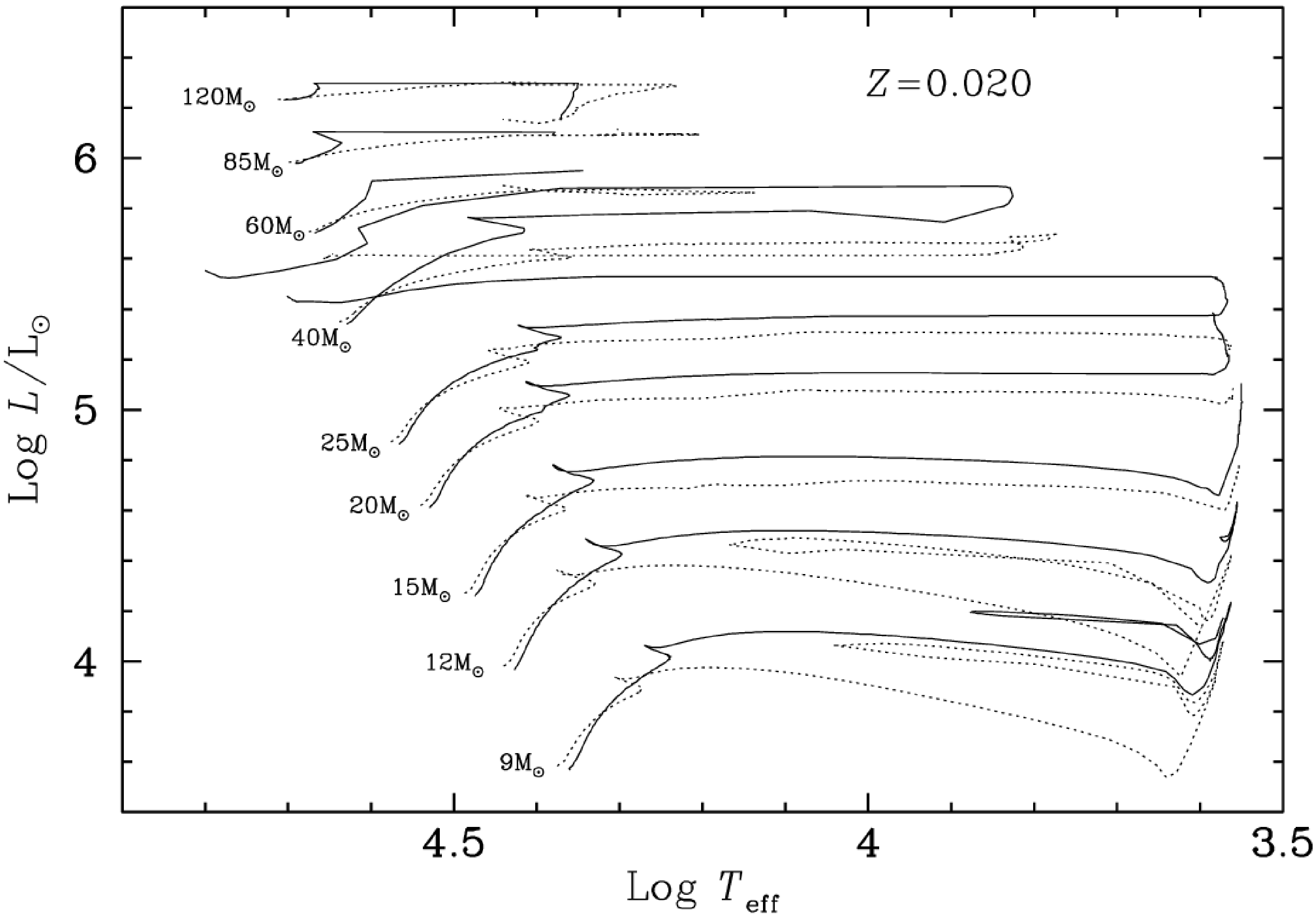
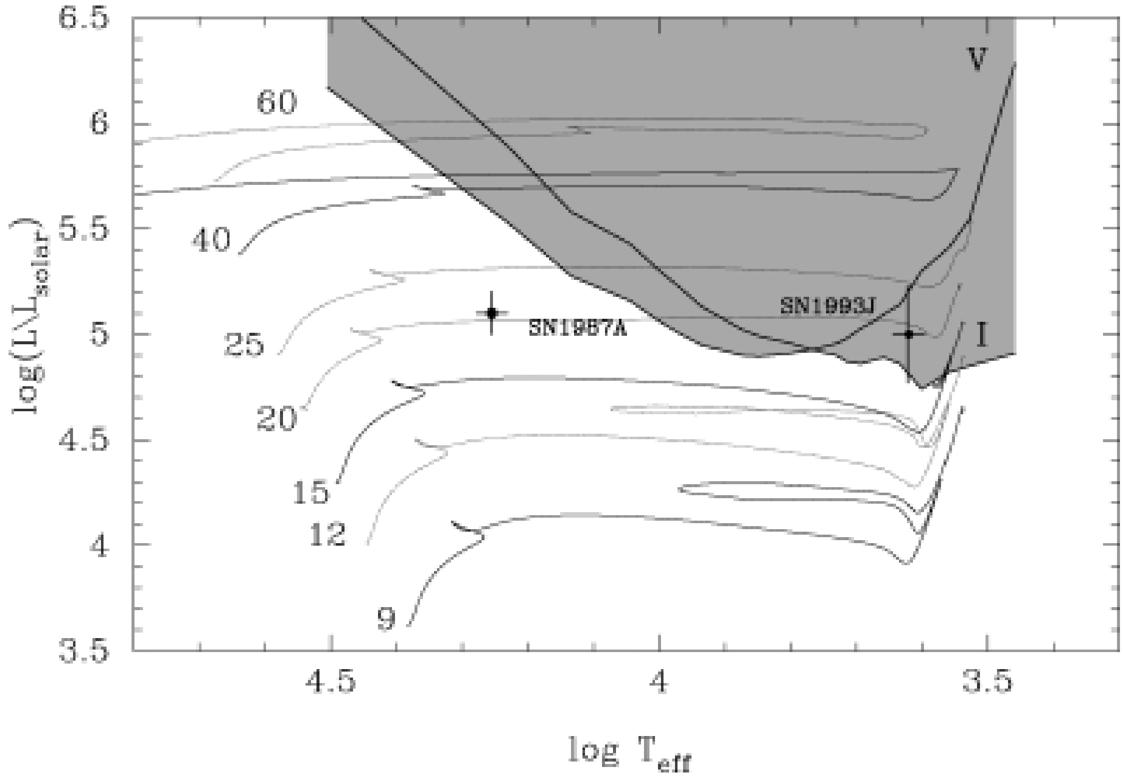
Dotted tracks ...



Rotating models from Meynet & Maeder (2003, A&A 404, 975) **with** v_{rot}**= 300 km/s at ZAMS.**

Which kinds of star explode?

- Red supergiants (Smartt et al. 2004, Science 303, 499)
- Blue supergiants (SN 1987A)
- Wolf-Rayet stars (supernovae Ib)



Permitted region for some supernovae progenitors (Smartt et al. 2003, MNRAS 343, 735)

Where do Wolf-Rayet stars come from?

Cluster	Mass (MS)	Wolf-Rayet
Pismis 24	$105 M_\odot$	WR93 - WC7
Trumpler 27	$50\ M_\odot$	WR25 - WC9
Be 87	$50\ M_\odot$	WR142 - WO2
Wd 1	$40\ M_\odot$	Many - WN5-9, WC8-9
Pismis 20	$40\ M_\odot$	WR67 - WN6
NGC 6871	$40\ M_\odot$	WR133 - WN5
Be 86	$35\ M_\odot$	WR139 - WN5
Bochum 7	$35\ M_\odot$	WR12 - WN8h
Ruprecht 44	$22\ M_\odot$	WR10 - WN5h
Alicante 2	$18\ M_\odot$	WR159 - WN4
Basel 3	$15\ M_\odot$	WR157 - WN5

After Crowther et al. 2006; MNRAS 372, 1407

How do we make Wolf-Rayet stars?

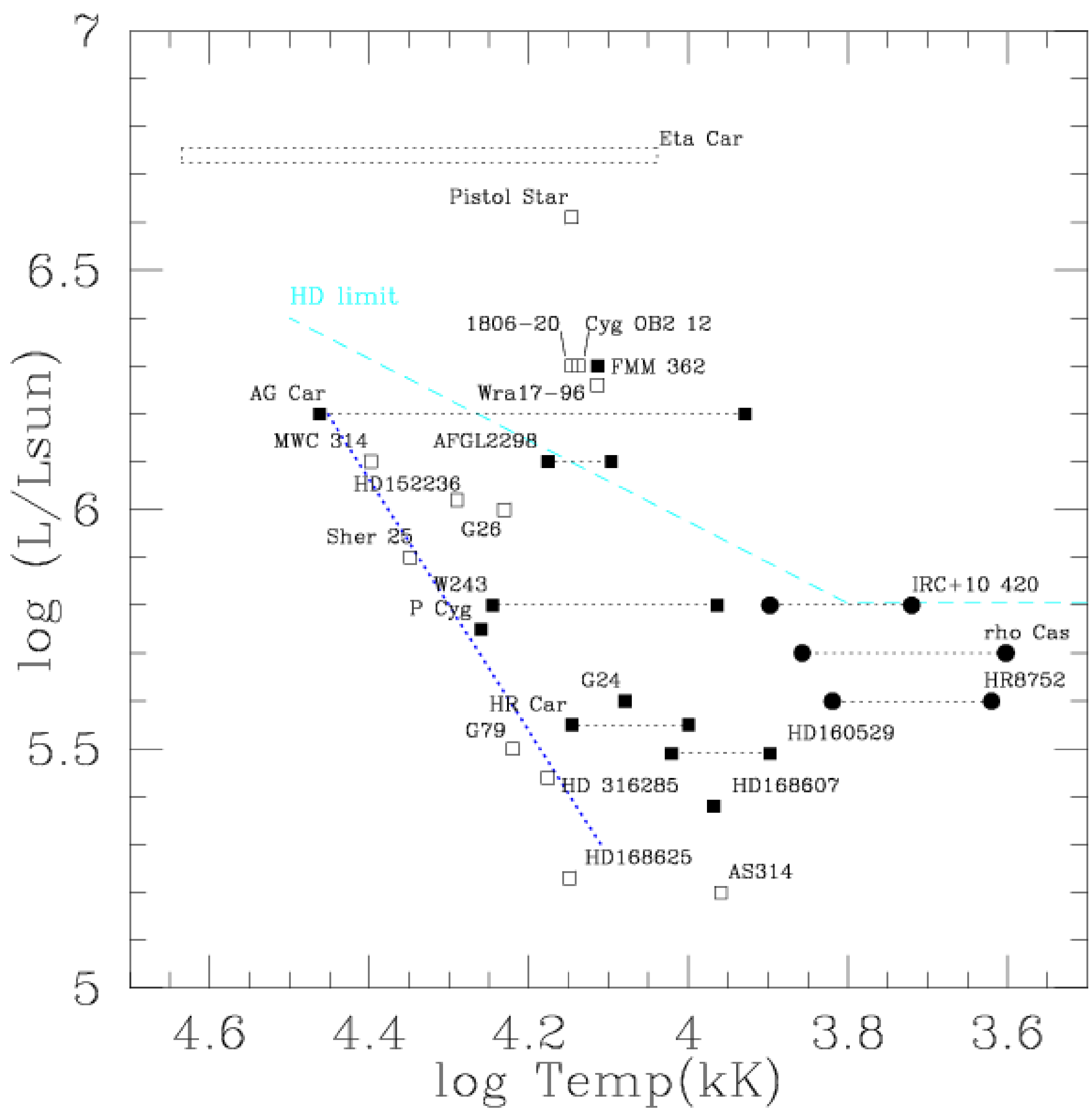
- Main-sequence O-type stars have

  $\dot{M} < 10^{-6}$ $M_{\odot}$/year (García & Bianchi 2004, ApJ 606, 497)

- O-type supergiants have

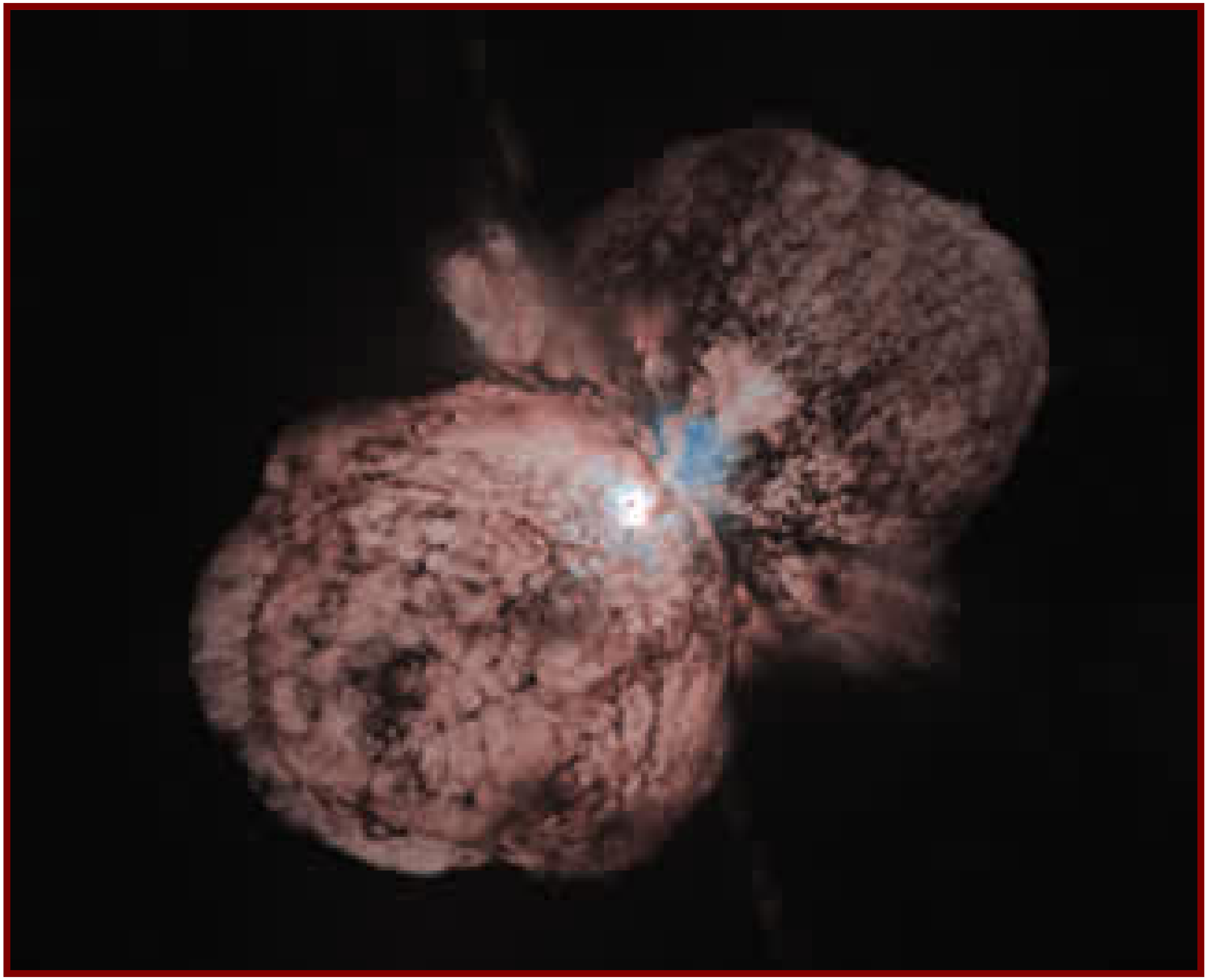
  $\dot{M} = 2 - 4 \times 10^{-6}$ $M_{\odot}$/year, reaching ~10^{-5} $M_{\odot}$ in the earliest and more luminous cases.

The zoo of massive weirdoes



Very luminous evolved massive stars in the Galaxy, from **Clark et al. (2005, A&A 435, 239).**

Losing the mass …



Losing the mass …

- **Amount of mass lost:**
  - How much is left in the nucleus?
  - What sort of remnant will be left?
  - Will there be a supernova explosion?
  - How much goes to the medium?
- **When is it lost?**
  - Processed or unprocessed material?

The massive star laboratory

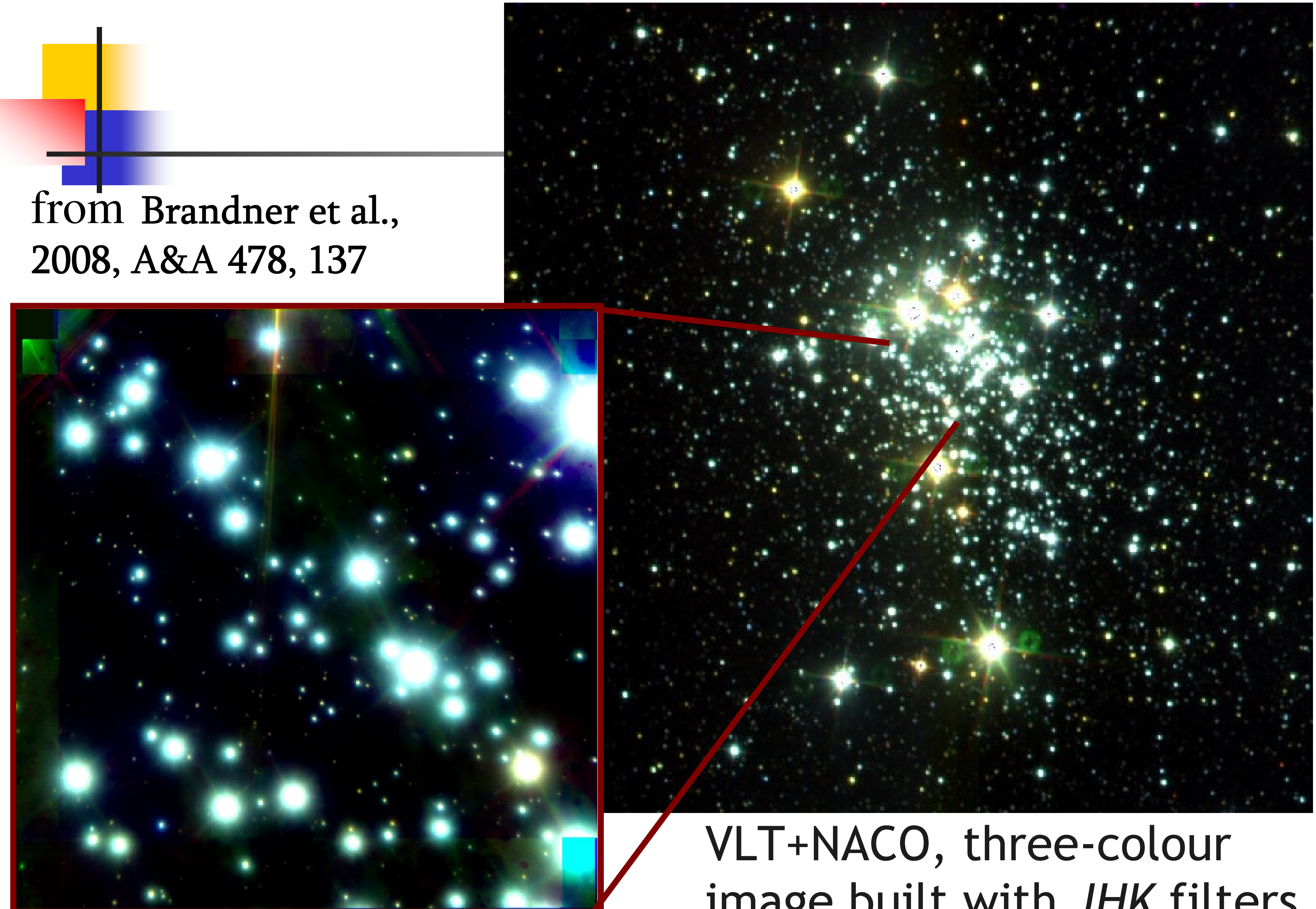
Westerlund 1

NTT+SOFI
Three-colour image
built with *JHK* filters

from Brandner et al., 2008,
A&A 478, 137

The massive star laboratory

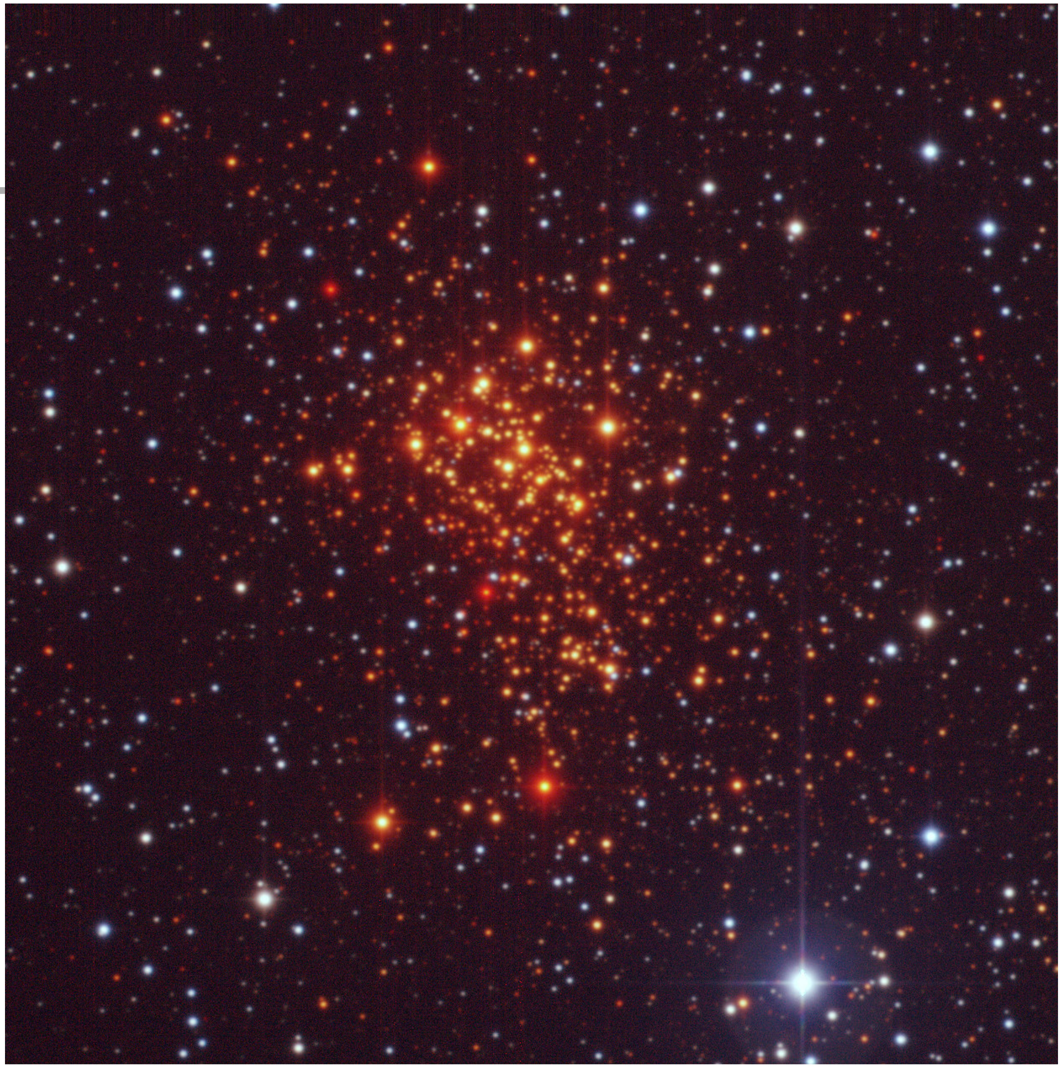
from Brandner et al., 2008, A&A 478, 137



VLT+NACO, three-colour image built with *JHK* filters

Westerlund 1 is the most massive young open cluster known in the Milky Way.

- At least 150 evolved massive ($M > 30\ M_{\odot}$) stars observed imply $M > 10^5 M_{\odot}$ (Clark et al. 2005, A&A 434, 949)
- Star counts in the IR imply $M > 5\mathrm{x}10^4 M_{\odot}$ (Brandner et al. 2008, A&A 478, 137)
- Radial velocity dispersion of 10 stars gives $M \sim 1.3\mathrm{x}10^5 M_{\odot}$ (Mengel & Taconi-Garman 2007, arXiv:0711.1779)



The Super Star Cluster Westerlund 1
(2.2m MPG/ESO + WFI)

ESO PR Photo 09a/05 (22 March 2005)

Using the laboratory …

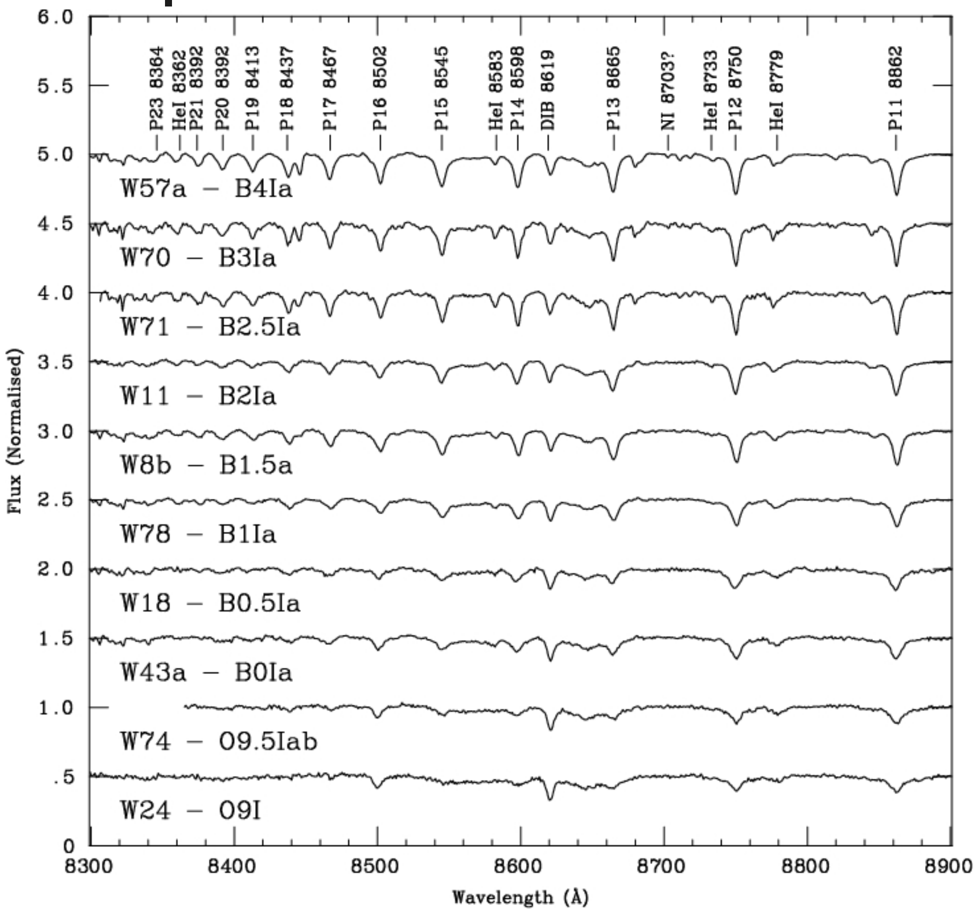
- Monitoring programmes running for some time to:
  - Survey its content
    - FORS2 073.D-0327 (A,B)
    - ISAAC 69.D-0497(A), 073.D-0327(C), 075.D-0469
  - Understand transitional massive stars (super & hypergiants and their kind)

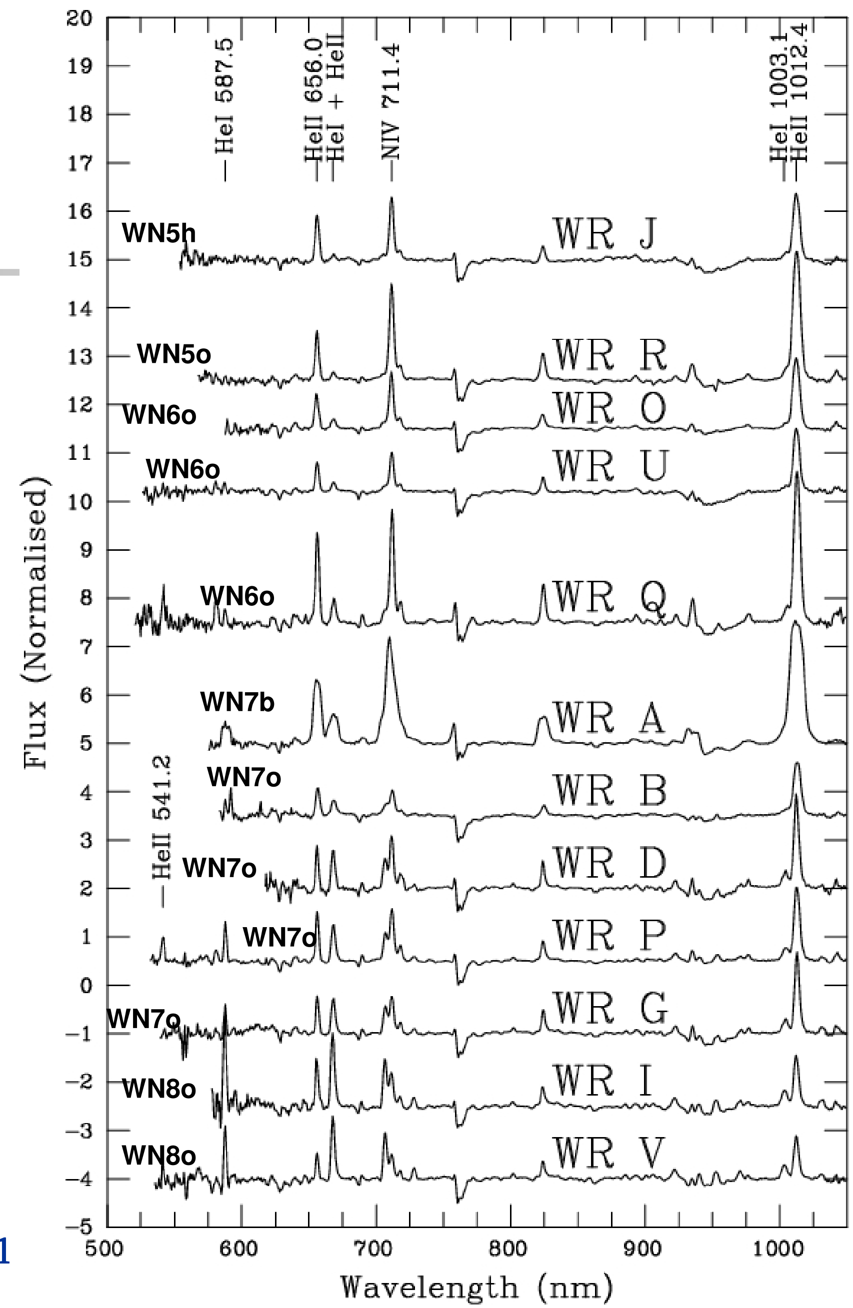
    UVES & FLAMES (ESO 271.D-5045, 073.D-0025, 075.D-0388)
  - Determine binary fraction

    FLAMES (ESO 081.D-0324, 083.D-0633)

Work with Simon Clark, Benedict Ritichie, Paul Crowther, et al.

A rich variety of everything …





Negueruela et al. 2008, in Proceeding IAU Symp 250, CUP, p. 301

Negueruela et al. 2009, A&A, about to be submitted

A rich variety of everything …

- The IMF looks compatible with Salpeter down to ~$1 M_{\odot}$ (Brandner et al. 2008, A&A 478, 137)
- The population seems (mostly) co-eval:
  - 57 evolved OB stars with accurate spectral types (Negueruela et al.; about to be submitted), covering O9 II-B8 Ia^{+}
  - Presence of a magnetar shows that all stars more massive than 20 $M_{\odot}$ do not leave black holes (Muno et al. 2006; ApJ 636, L41)
  - Presence of red supergiants somewhat unexpected
  - Absence of HMXBs suggests that they fly away from natal environment very quickly (Clark et al. 2008; A&A 477, 147)

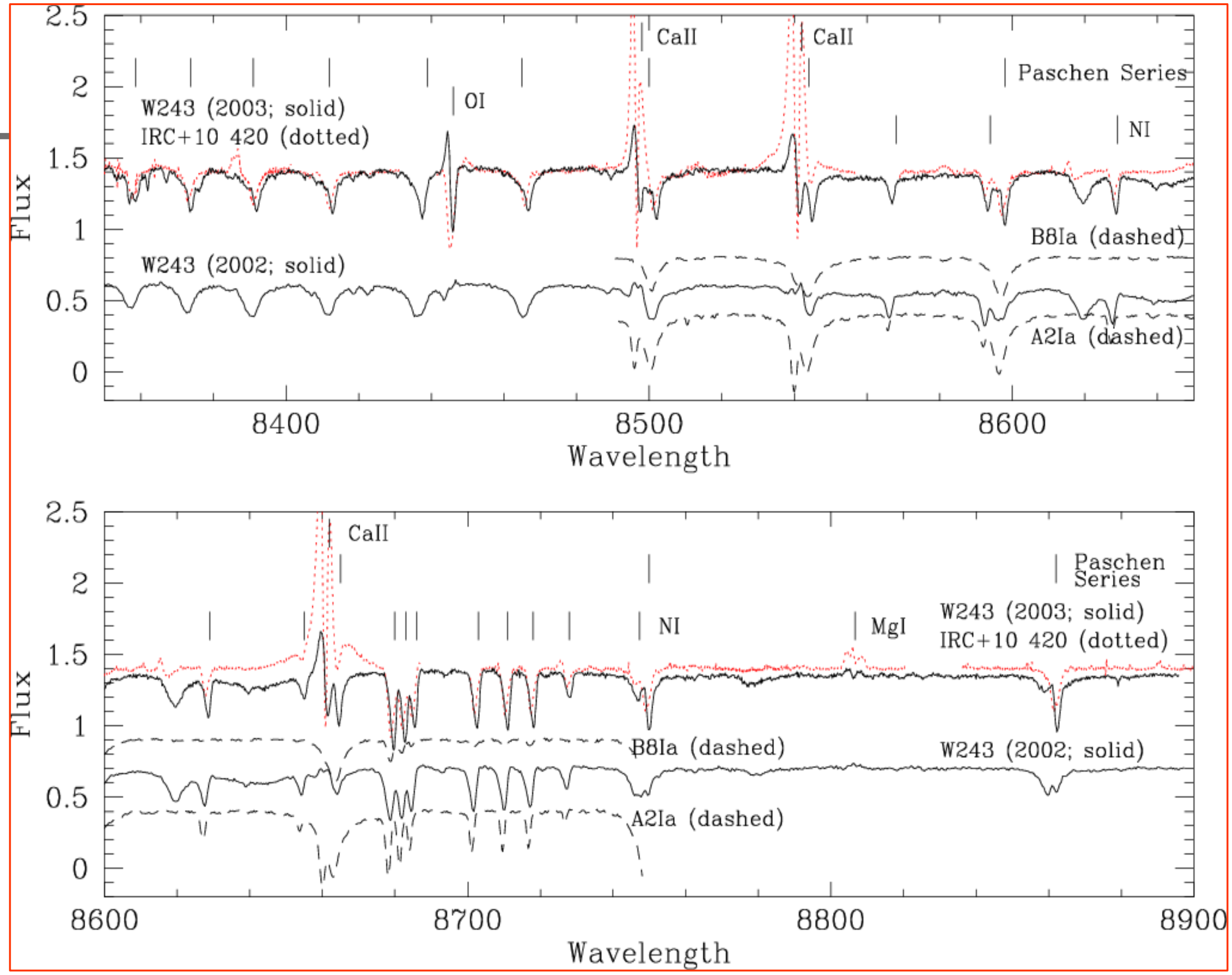
Negueruela et al. 2008, in Proceeding IAU Symp 250, CUP, p. 301

A candidate LBV

Wd1-243

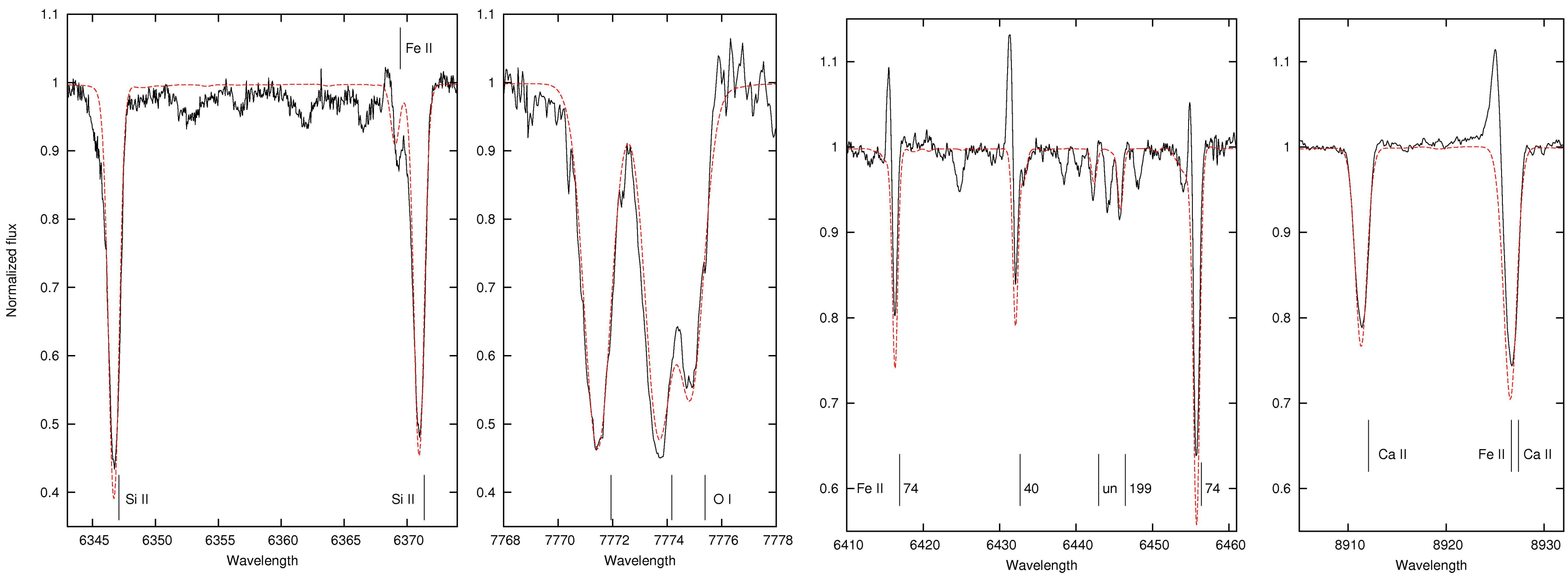
Variable spectrum around A0 Ia

(Clark & Negueruela 2004, A&A 413, L15)



A candidate LBV

We fit a CMFGEN atmospheric model (developed by Paco Najarro, CAB)



(Ritchie et al., A&A, almost accepted)

A candidate LBV

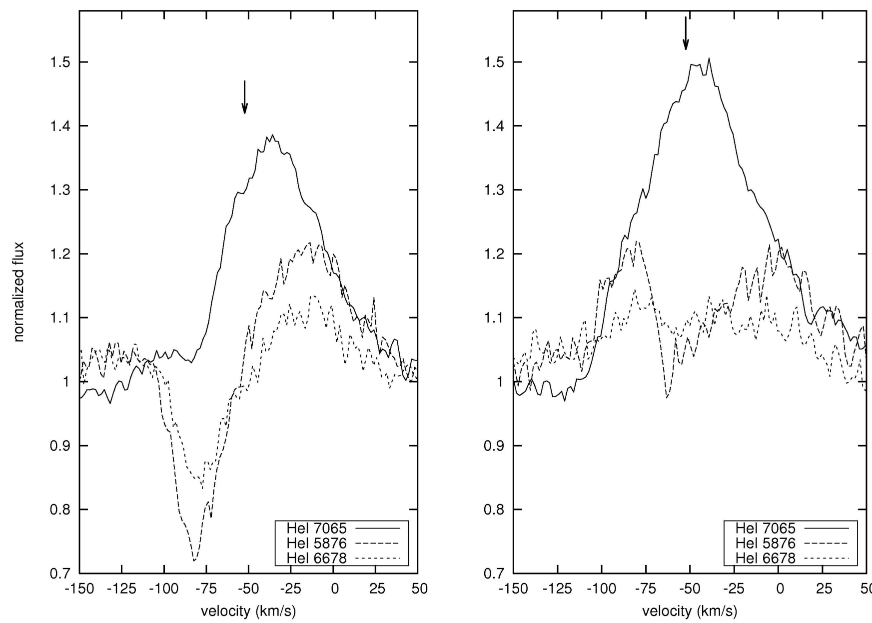
Our current model for Wd1-243

A3 Ia$^+$ + hot companion

$T_{eff} \sim 8500K$

$R_* = 377\, R_\odot$

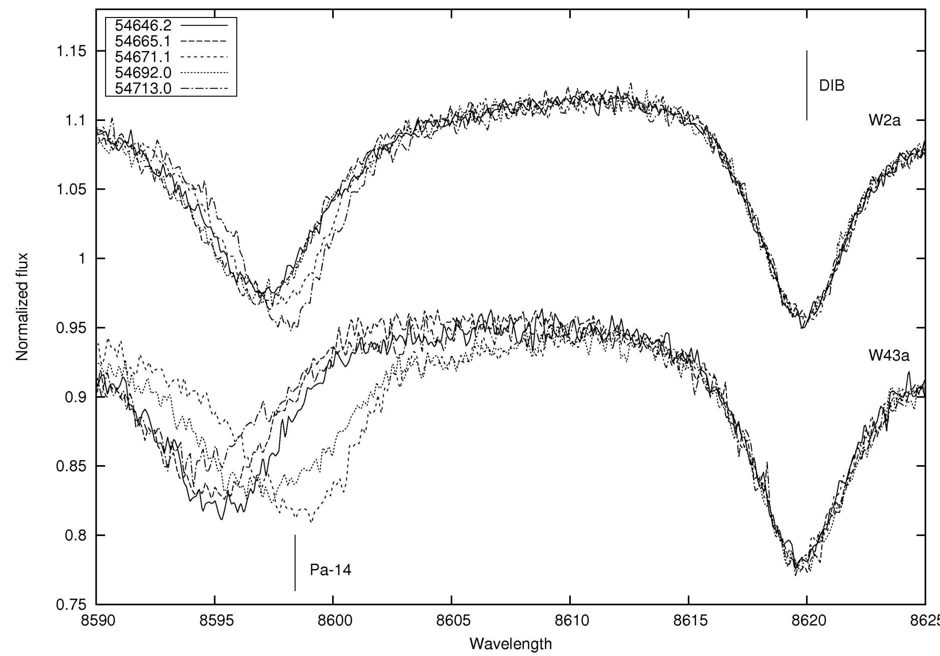
$L_* = 7x10^5\, L_\odot$



(Ritchie et al., A&A, almost accepted)

Radial velocity survey

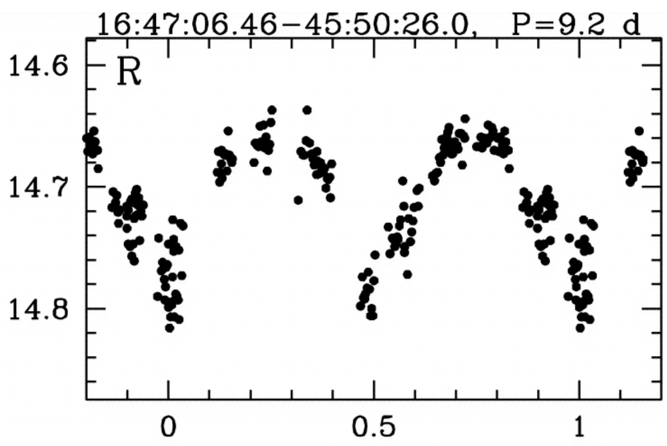
At present, we have between 5 and 9 epochs for a sample of ~50 stars.



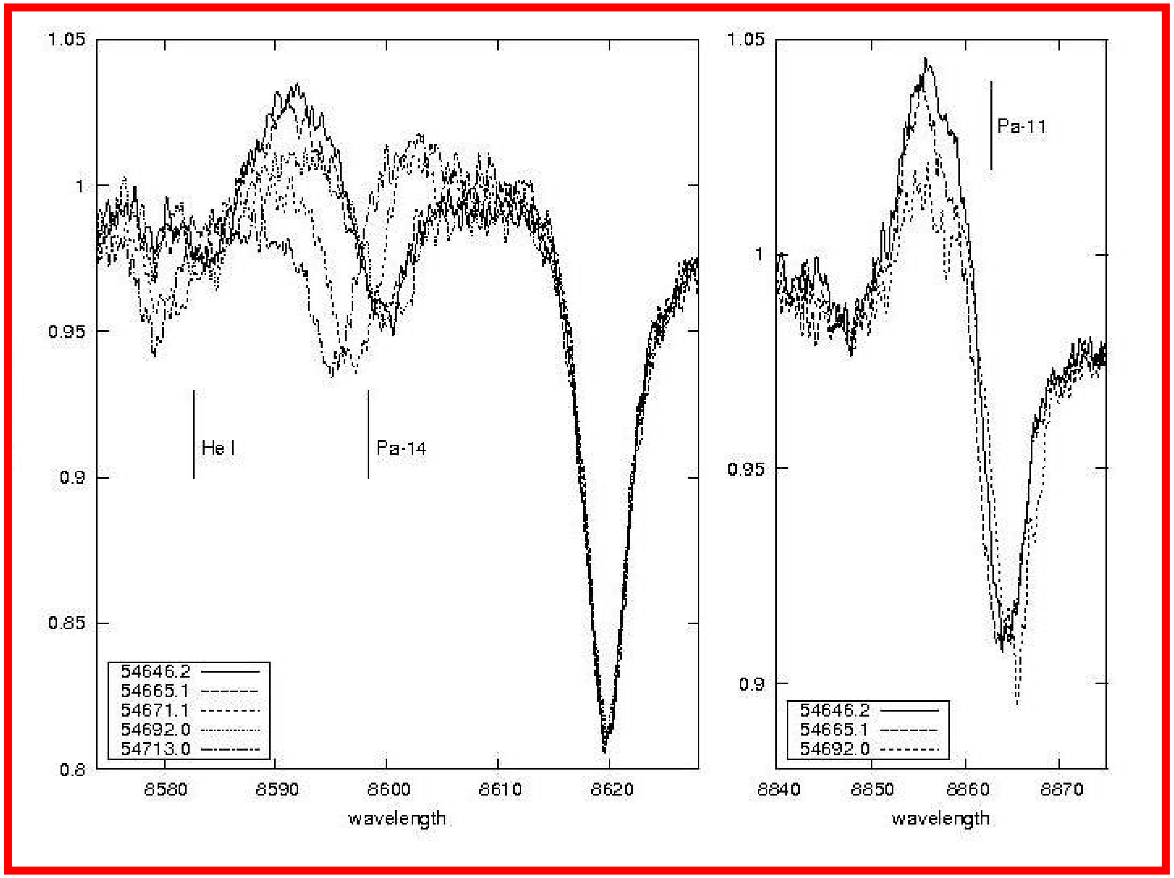
Many hints pointing to very high massive binary fraction (>80%?)

(Ritchie et al., A&A, accepted; `arXiv:0909.3815`)

Radial velocity survey



This is a 9.2-d (detached?) eclipsing binary
(Bonanos 2007, AJ 133, 2696)

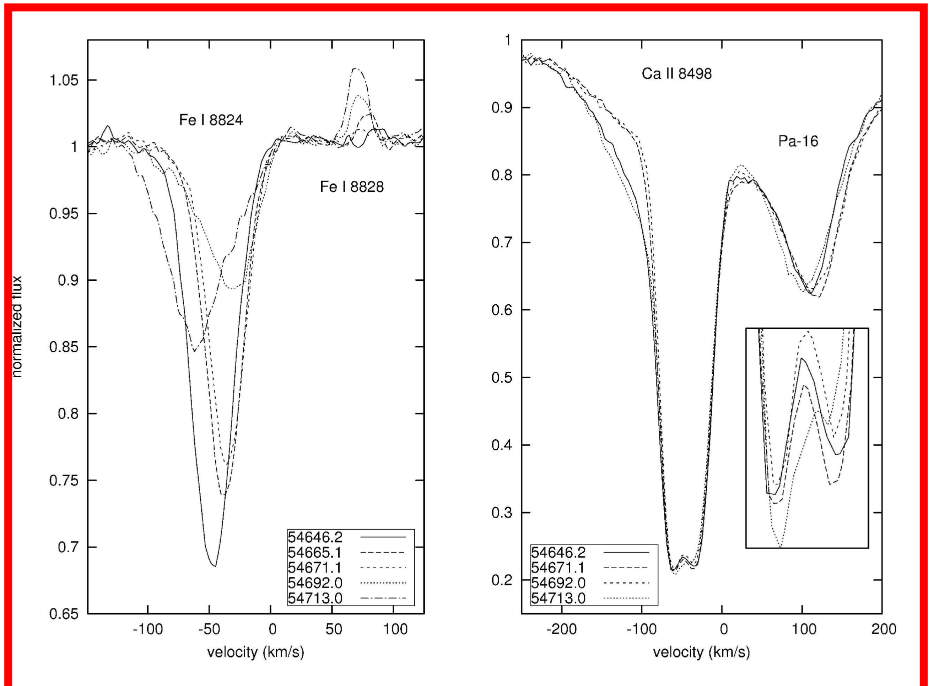


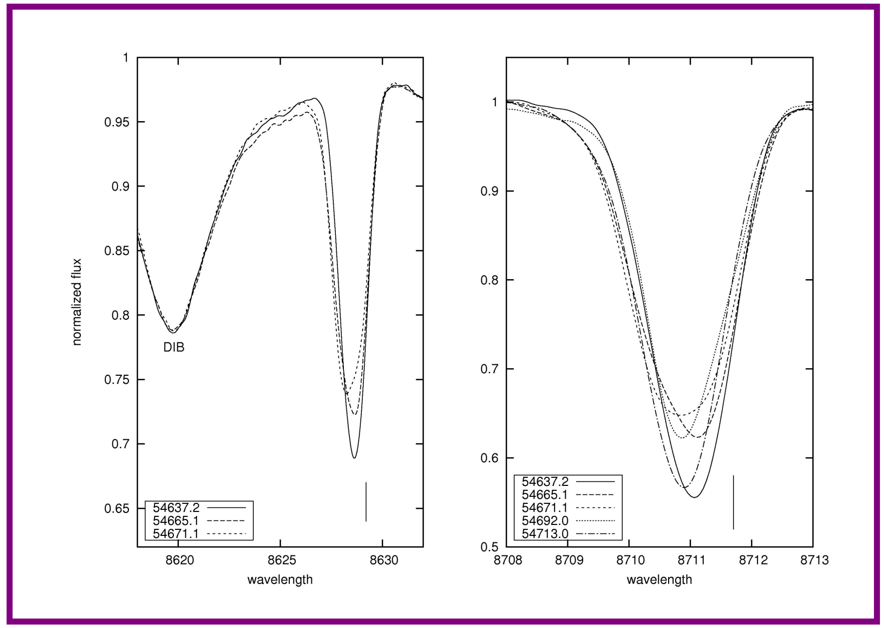
(Ritchie et al., A&A, accepted;
arXiv:0909.3815)

Radial velocity survey

G hypergiant pulsating

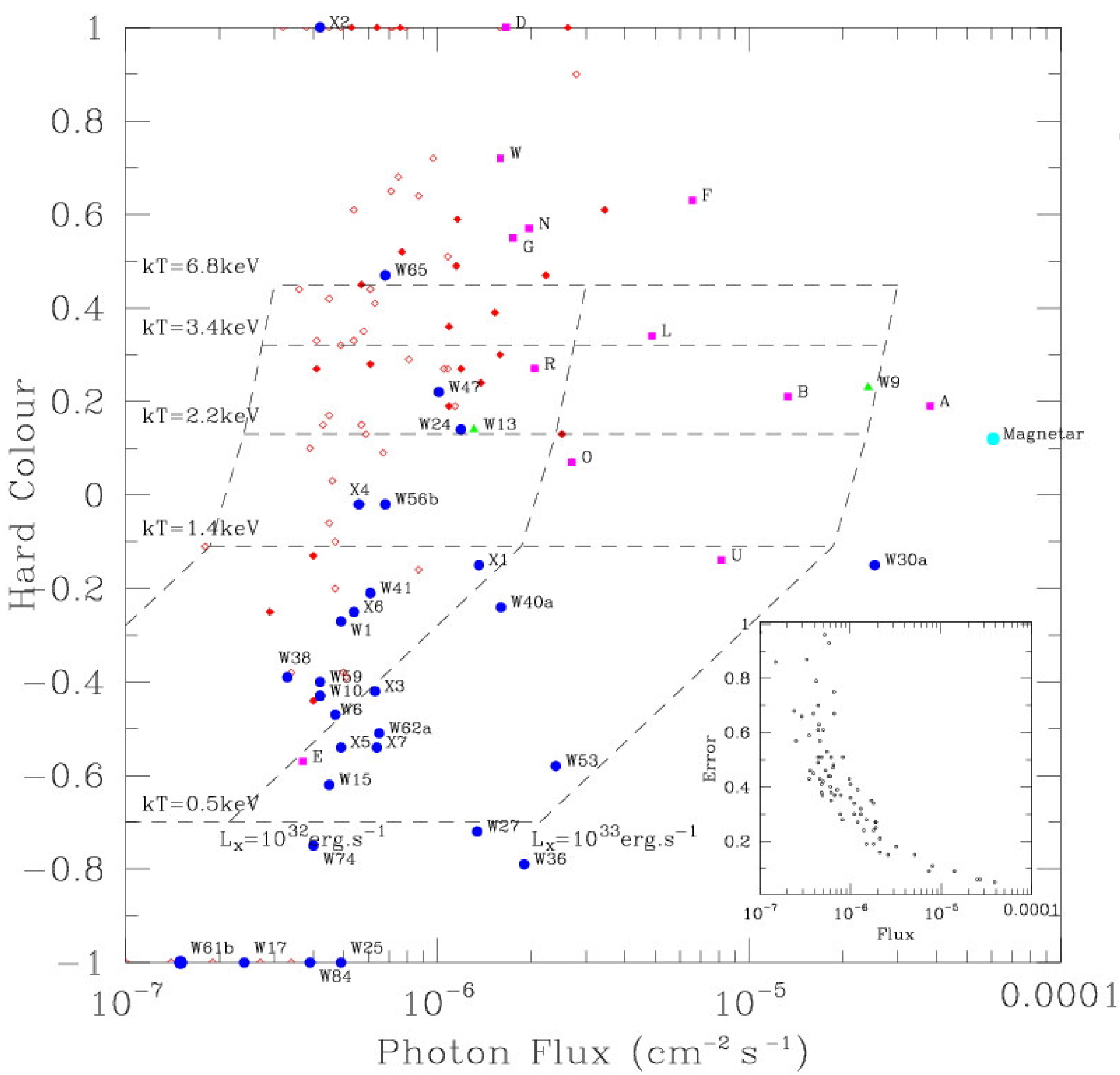
B supergiant pulsating



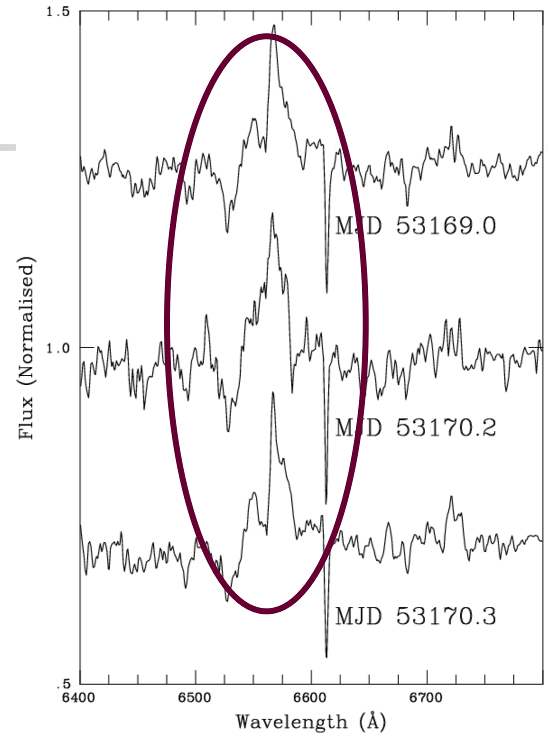


(Ritchie et al., A&A, accepted; arXiv:0909.3815)

A population of interacting wind binaries?



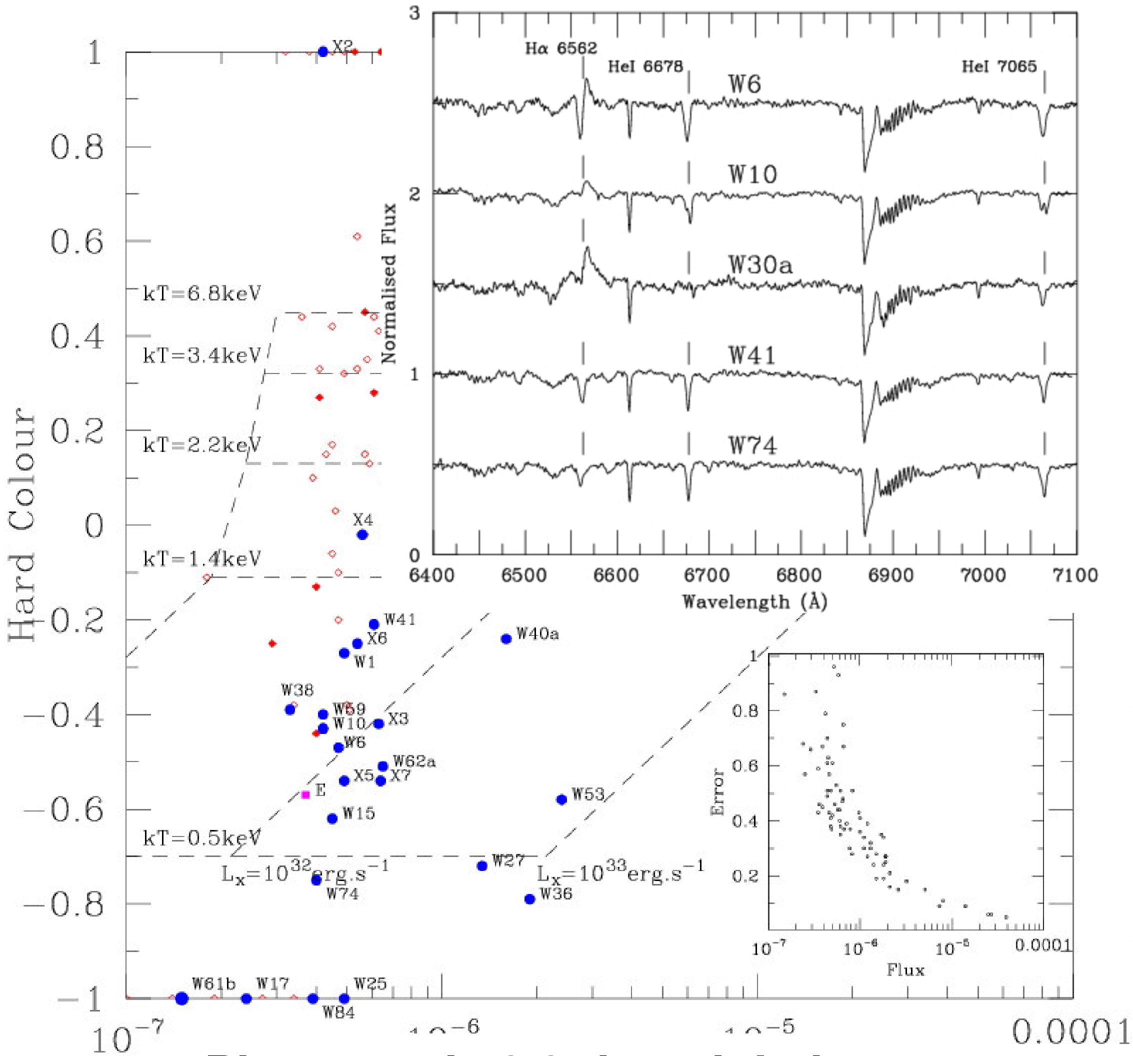
Clark et al. 2008; A&A 477, 147

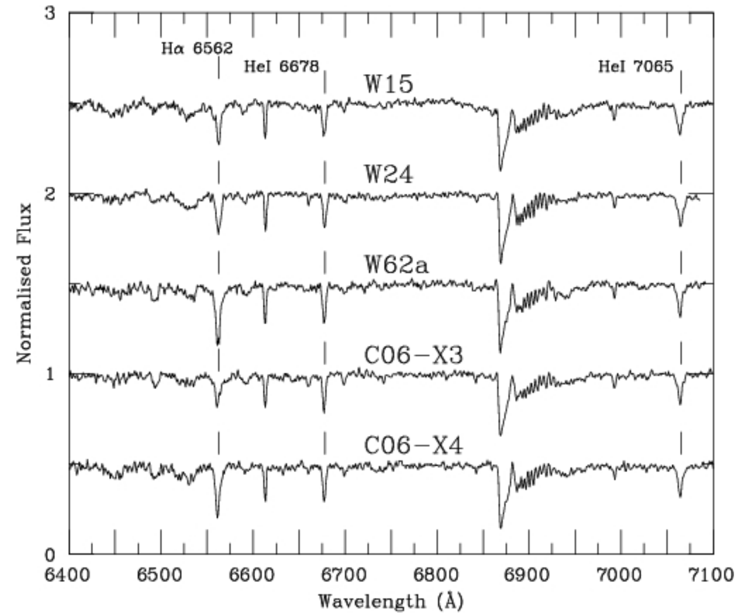


W30, interacting binary of some kind.

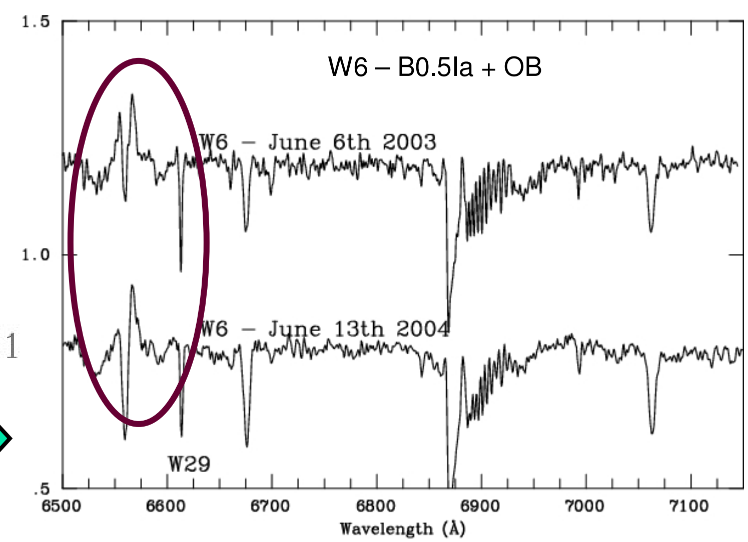
Work with Mike Muno

A population of interacting wind binaries?

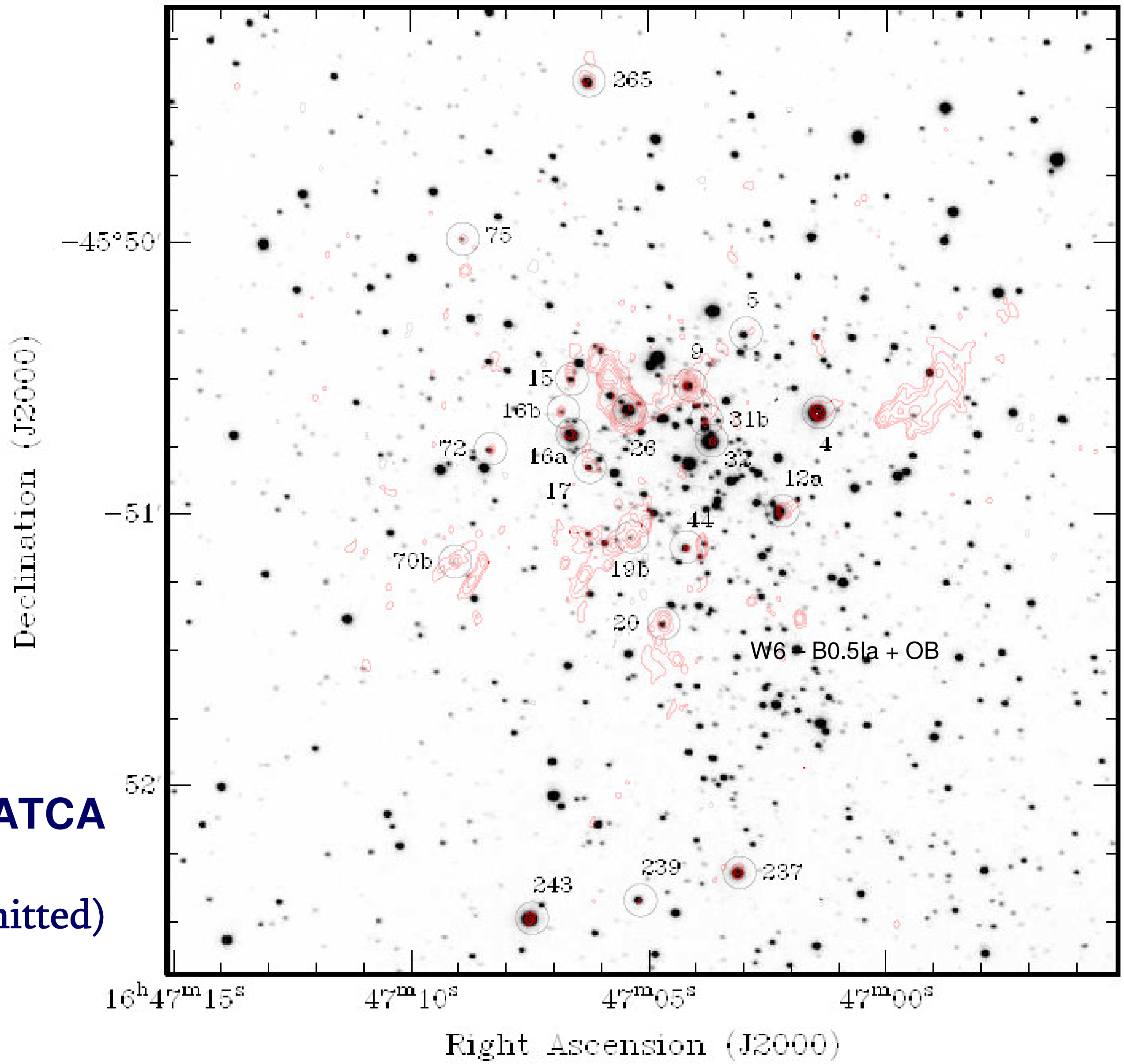




Photometric 2.2-d modulation
(Bonanos 2007, AJ 133, 2696)



A direct handle on the mass loss



Combining our data with ATCA radio observations

(Dougherty et al., A&A, submitted)

Results are coming in …

Directly related to our scientific aims:

• Very high binary fraction amongst massive stars $\Rightarrow$ further epochs to constrain orbital parameters

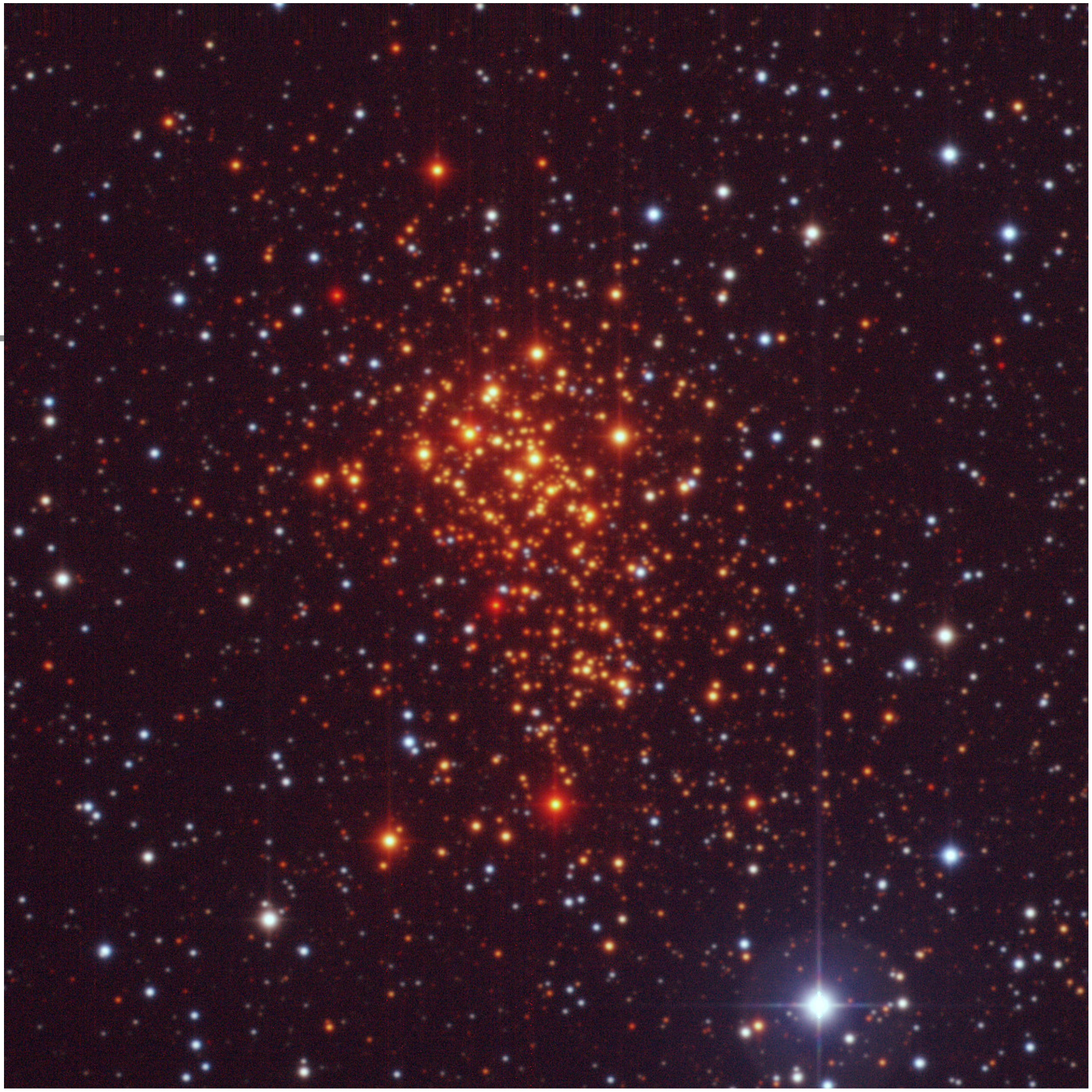
• We are starting to get a handle on instability and mass loss rates in post-MS objects $\Rightarrow$ high-resolution spectra for modelling

• IMF not strongly affected by starburst environment $\Rightarrow$ low-mass component outside our domain

Other important issues:

• Integrated spectrum of a cluster can be dominated by a few very bright members (e.g., yellow hypergiants)

• Radial velocity dispersion of a very young cluster can be dominated by binary motion; radial velocity dispersion of a slightly older cluster can be dominated by supergiants pulsating.



The Super Star Cluster Westerlund 1
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ESO PR Photo 09a/05 (22 March 2005)