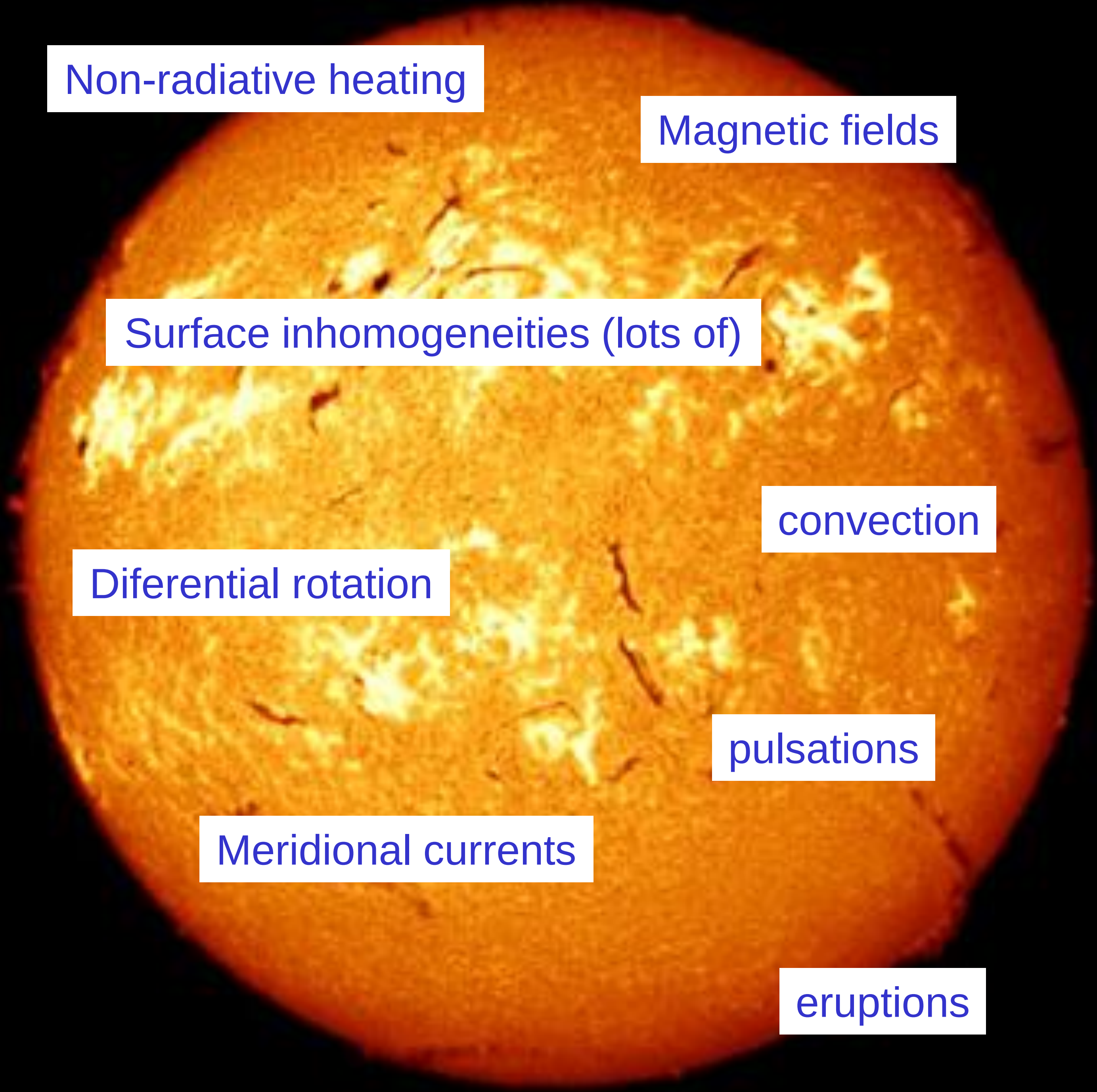


Non-radiative heating

Magnetic fields

Surface inhomogeneities (lots of)

convection

Diferential rotation

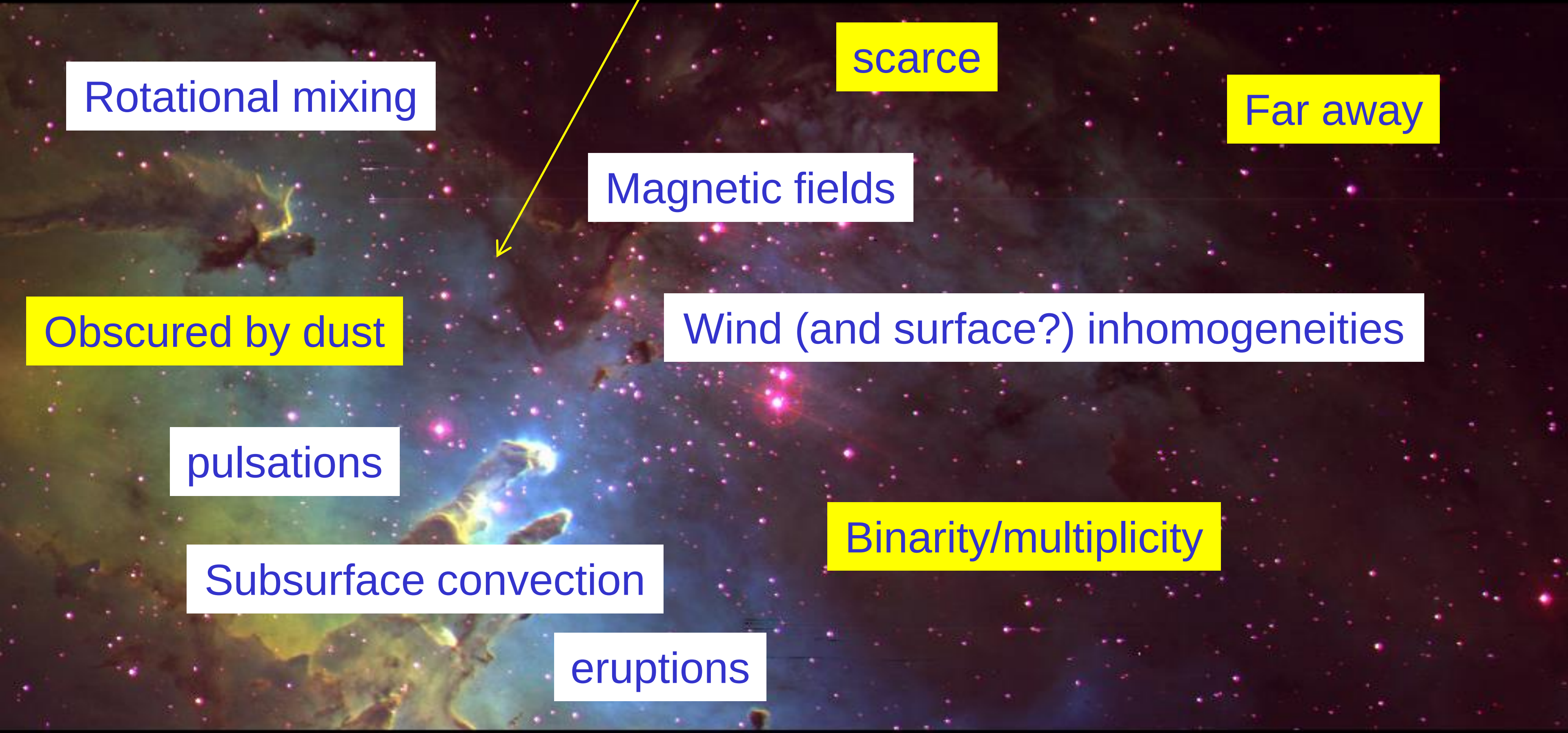
pulsations

Meridional currents

eruptions

NLTE

winds



scarce

Rotational mixing

Far away

Magnetic fields

Obscured by dust

Wind (and surface?) inhomogeneities

pulsations

Binarity/multiplicity

Subsurface convection

eruptions

Massive stars: open questions and MOS

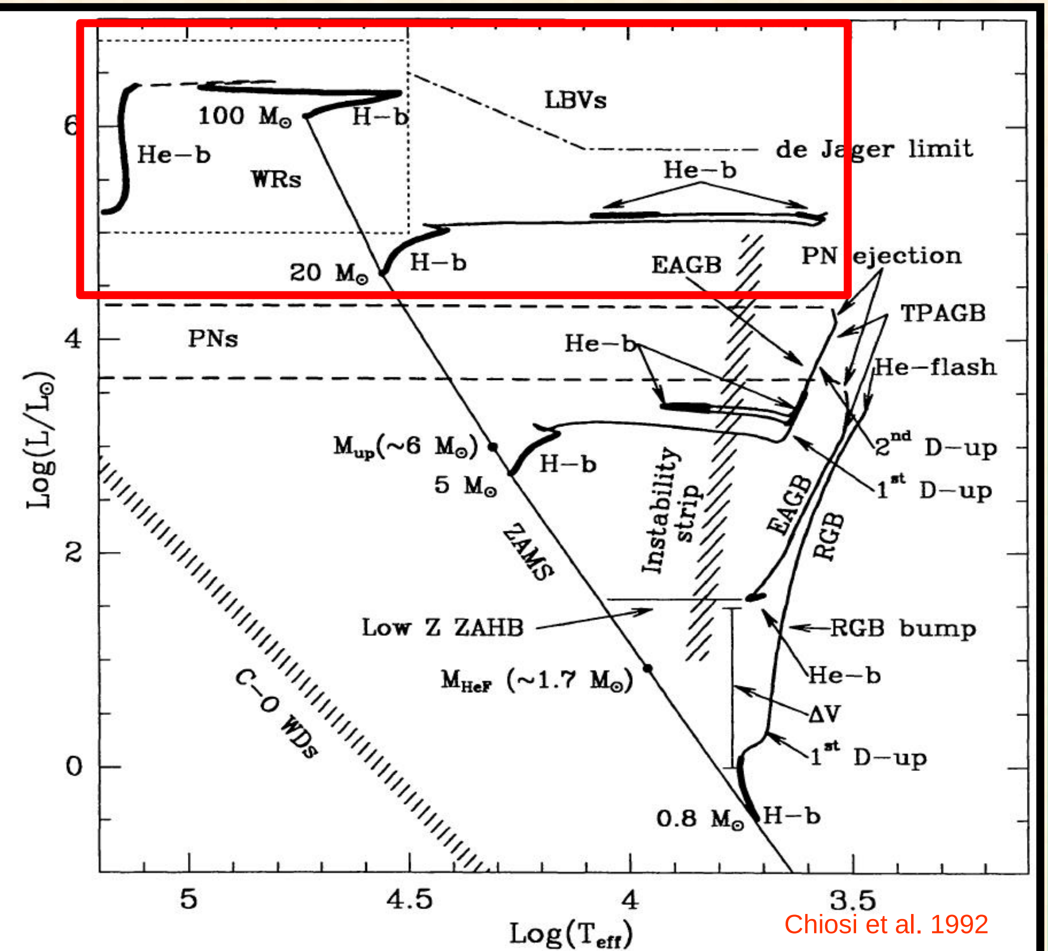
some

Thanks to
Sergio Simón-Díaz (IAC)
Miriam Garcia (CAB)
Jo Puls (USM)
The VFTS collaboration

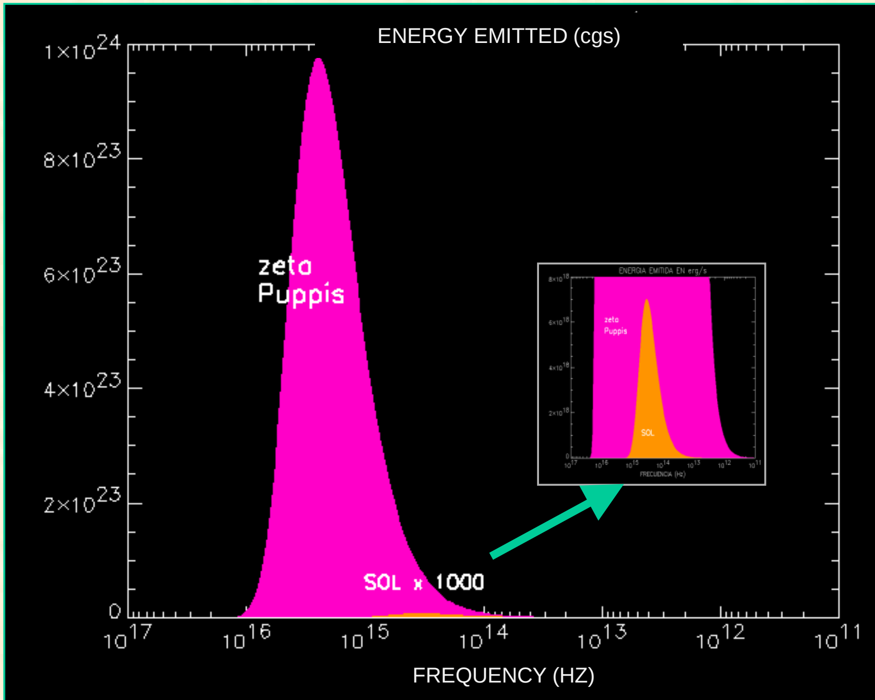
Artemio Herrero
La Palma, march 3th, 2015

Massive stars – tools to understand the Universe

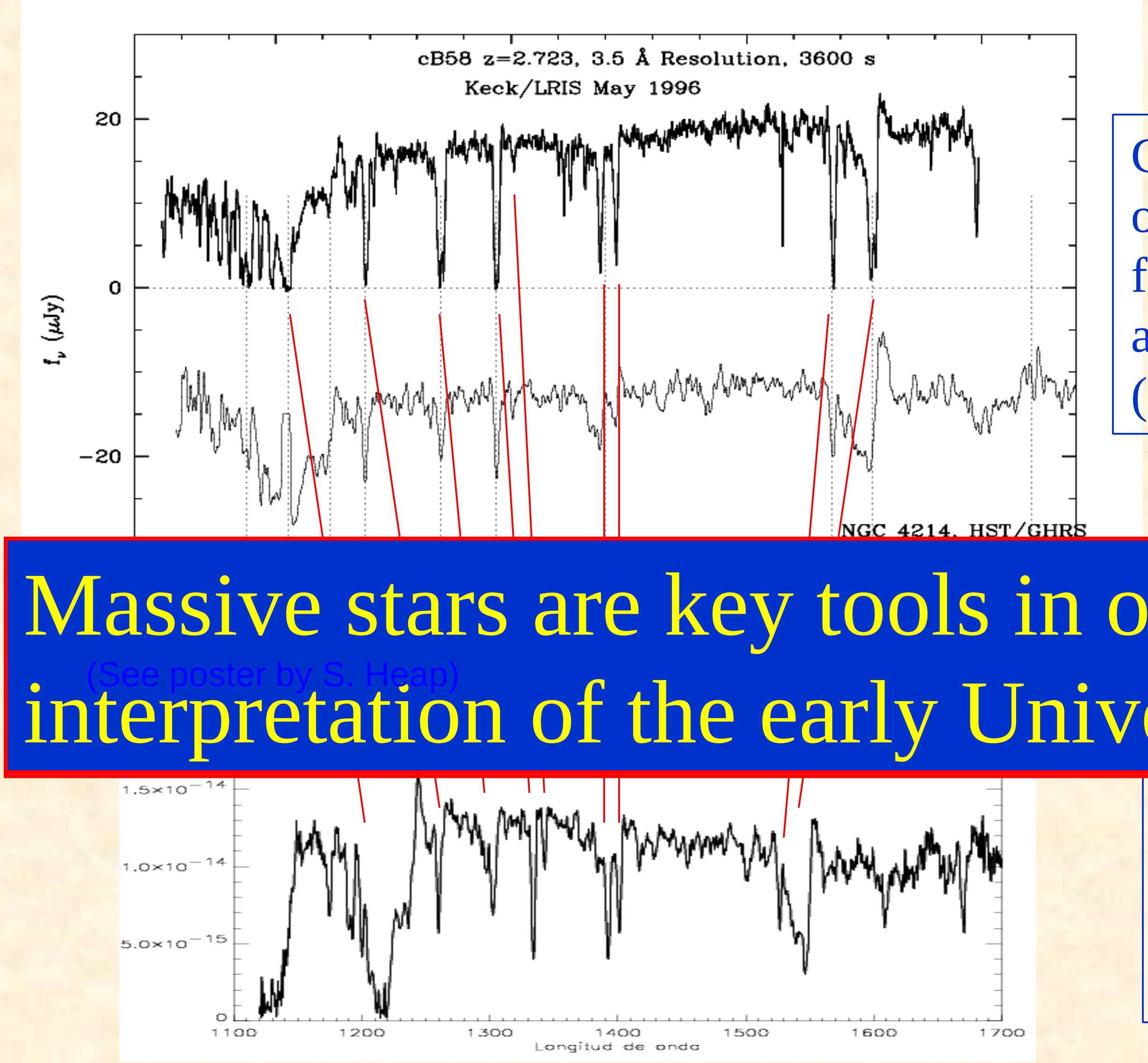
Massive stars have M> 8 $M_\odot$ and explode as SNe
A unique property:
its extreme luminosity, that makes them observable at large distances individually (up to 10Mpc) or through their effects (large z: LBG, LAEs)



Chiosi et al. 1992



Massive stars – tools to understand the Universe



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

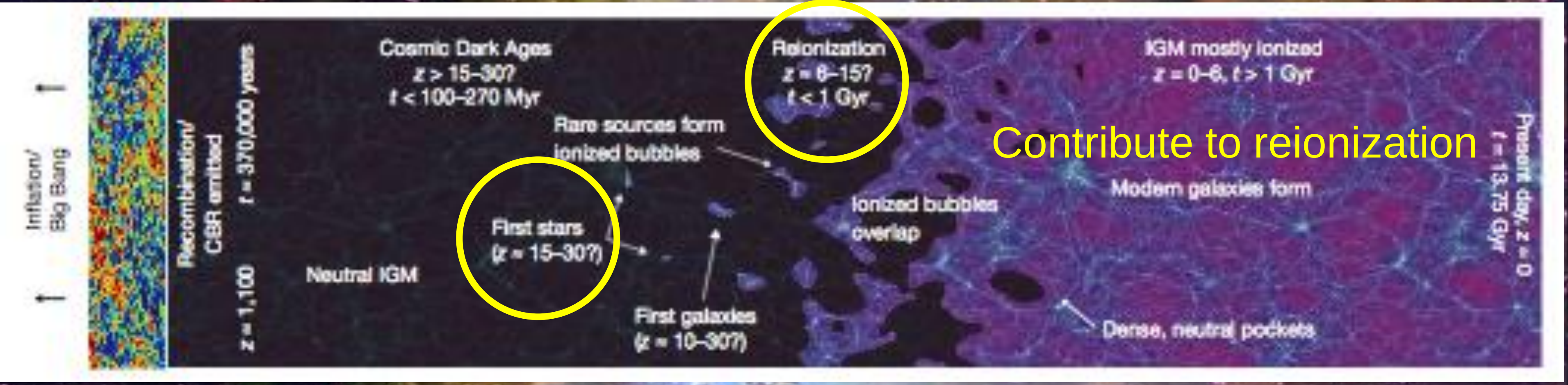
Massive stars are key tools in our interpretation of the early Universe

(See poster by S. Heap)

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

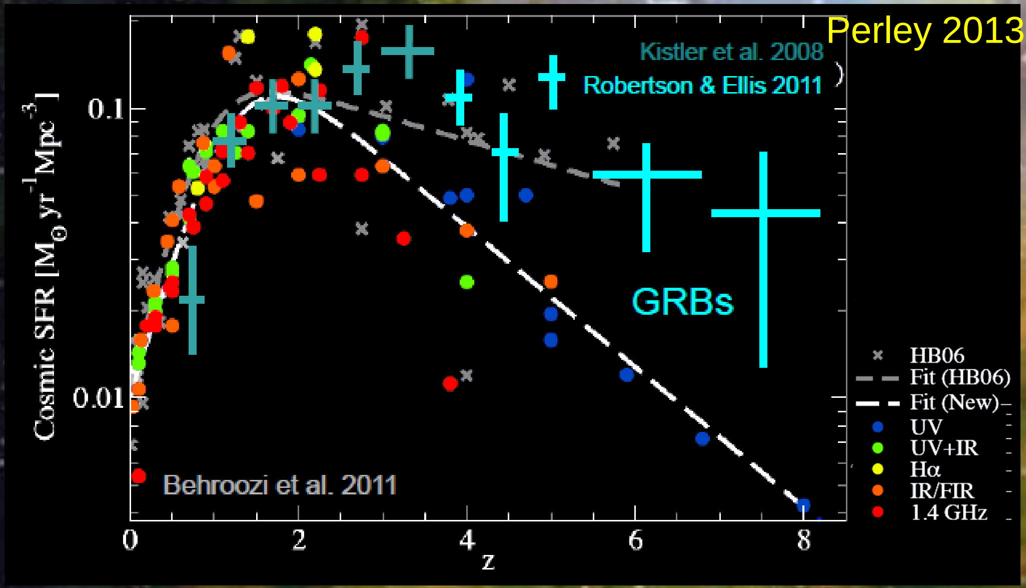
Massive stars – tools to understand the Universe

Massive stars are used to…



Contribute to reionization

Determine SFRs



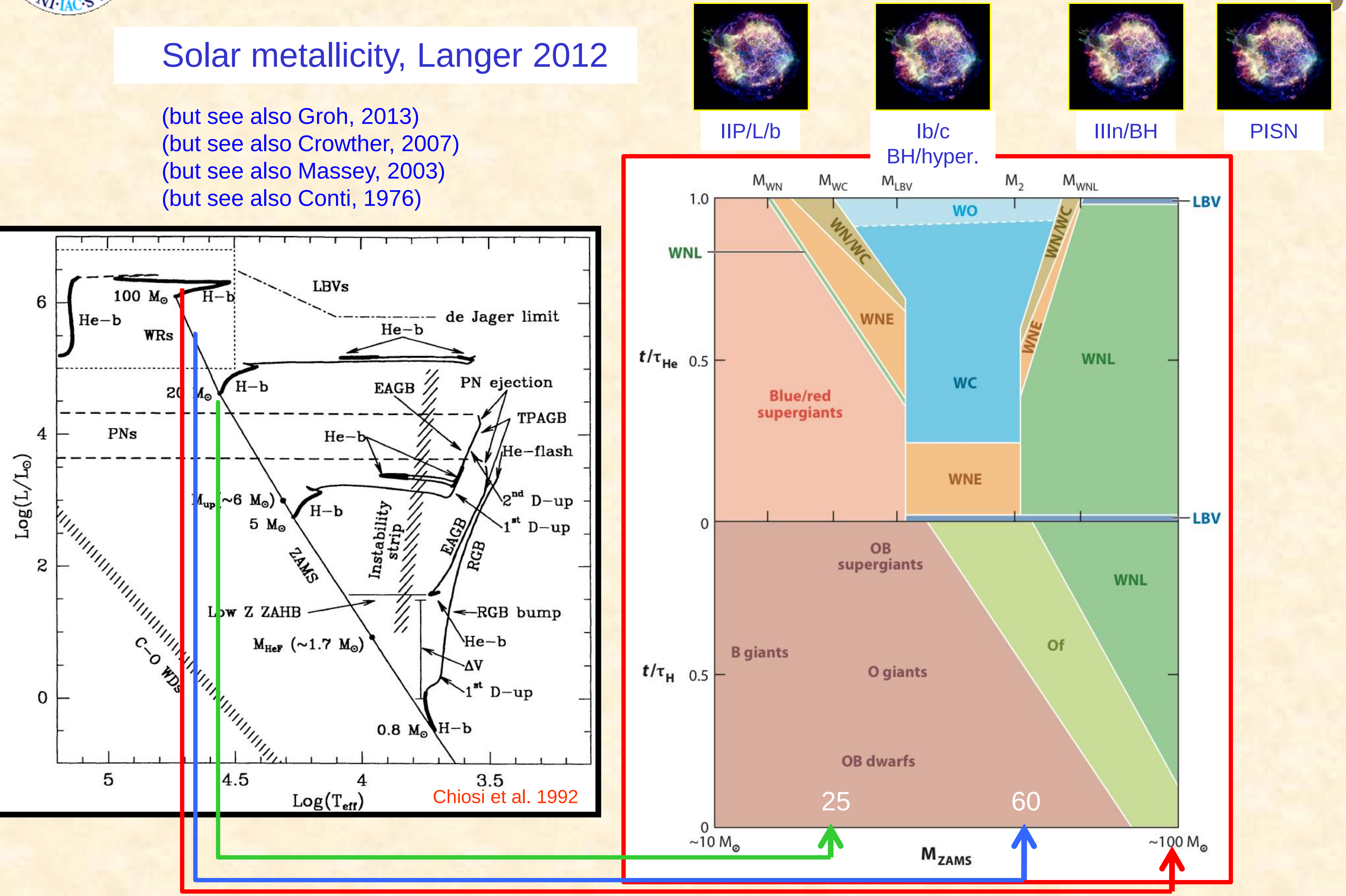
Perley 2013

Chemical footprint in early epoch stars

Massive stars – tools to understand the Universe

Solar metallicity, Langer 2012

(but see also Groh, 2013)
(but see also Crowther, 2007)
(but see also Massey, 2003)
(but see also Conti, 1976)



Chiosi et al. 1992

Massive stars – tools to understand the Universe

Thus we are interested in:

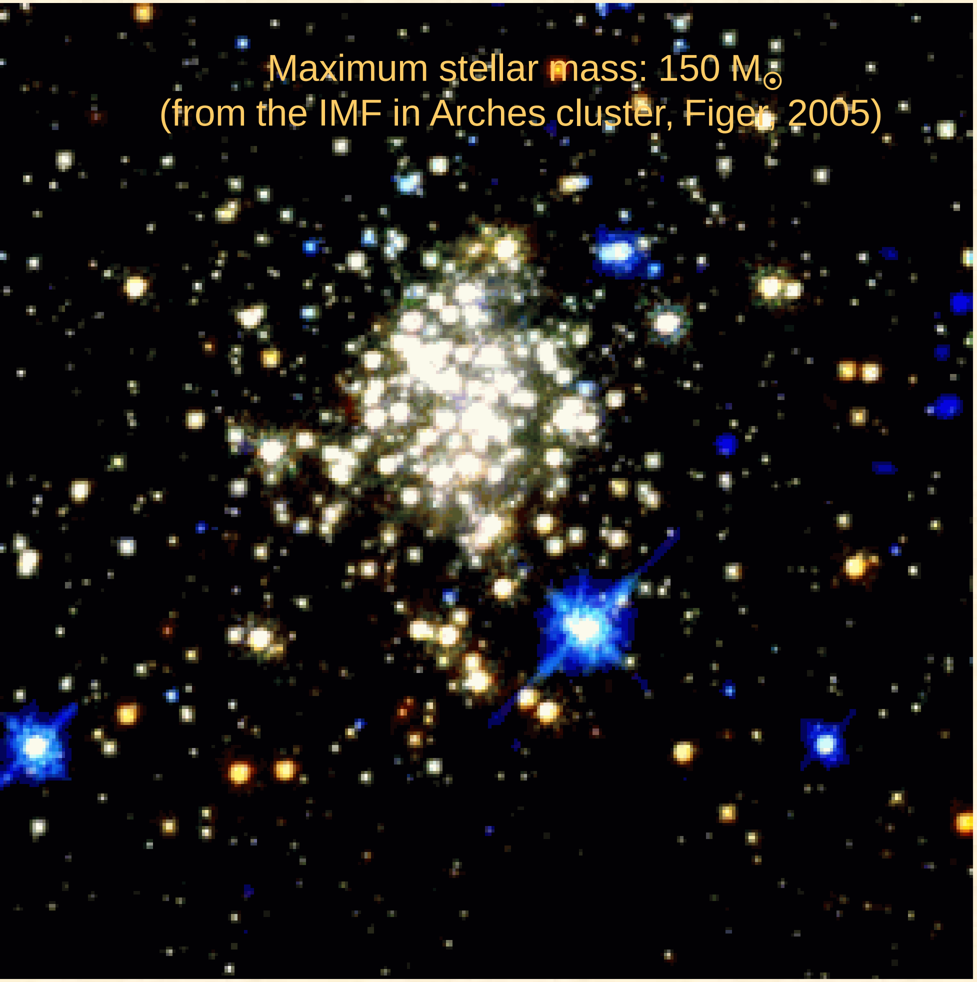
- Mass
- Angular momentum
- Initial composition
- Mass-loss

Determine the structure and evolution

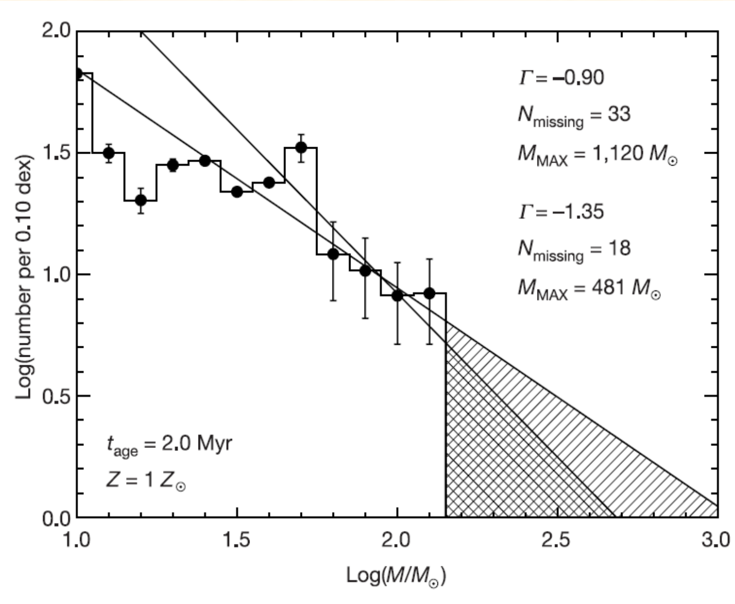
- Teff

Gives L, R together with M_V

Massive stars – masses



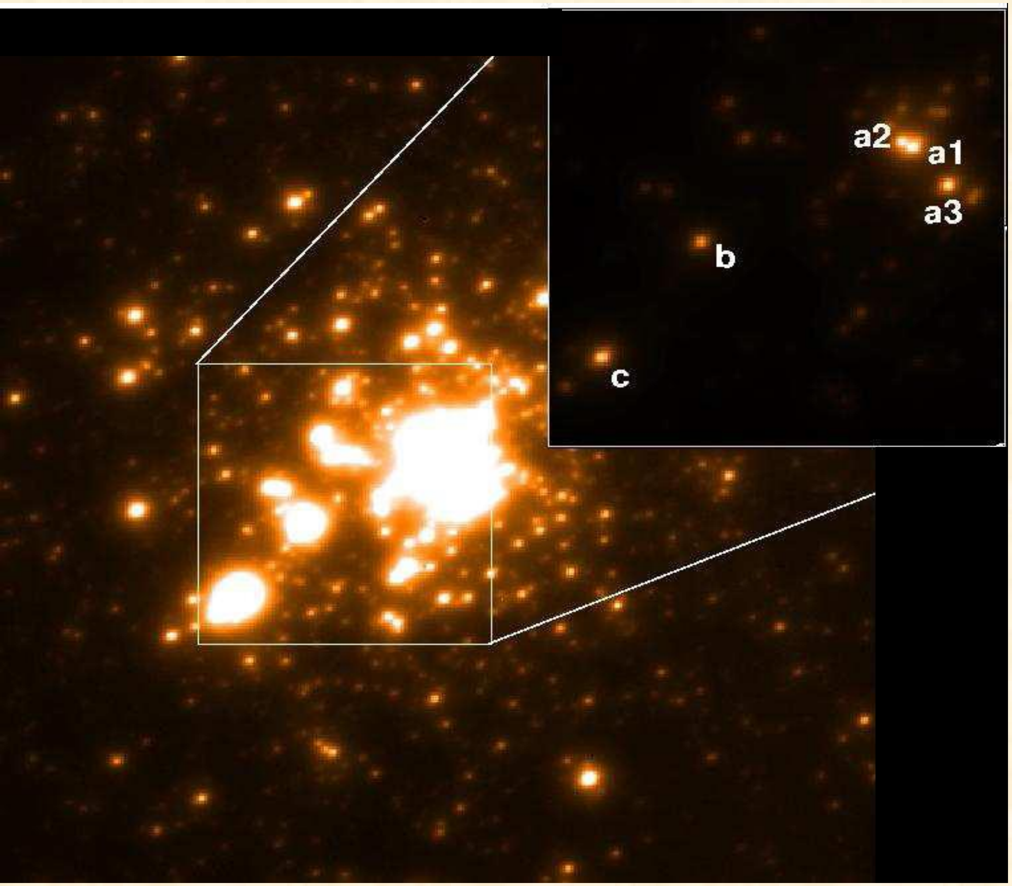
Maximum stellar mass: 150 $M_\odot$
(from the IMF in Arches cluster, Figer, 2005)



MOST MASSIVE BINARIES

Star	Sp Types	Mass	
R144	WN5-6h WN6-7h	200-300 (total)	Initial total mass: 400 $M_\odot$ (Sana et al., 2013, 432, L26)
NGC3603-A1	WN6h+O	116±31 89±16	Schnurr et al., 2008, MNRAS 389, L38
R145	WN6h+O	116±33 48±20	Minimum masses Schnurr et al., 2009, MNRAS 395,823
WR21a	WN+O	87 87	Gamen et al., 2007, BAAA 50; 2008, arXiv 0803.0681
WR20a	WN6h WN6h	82.7 81.9	Rauw et al., 2005, A&A 432, 985

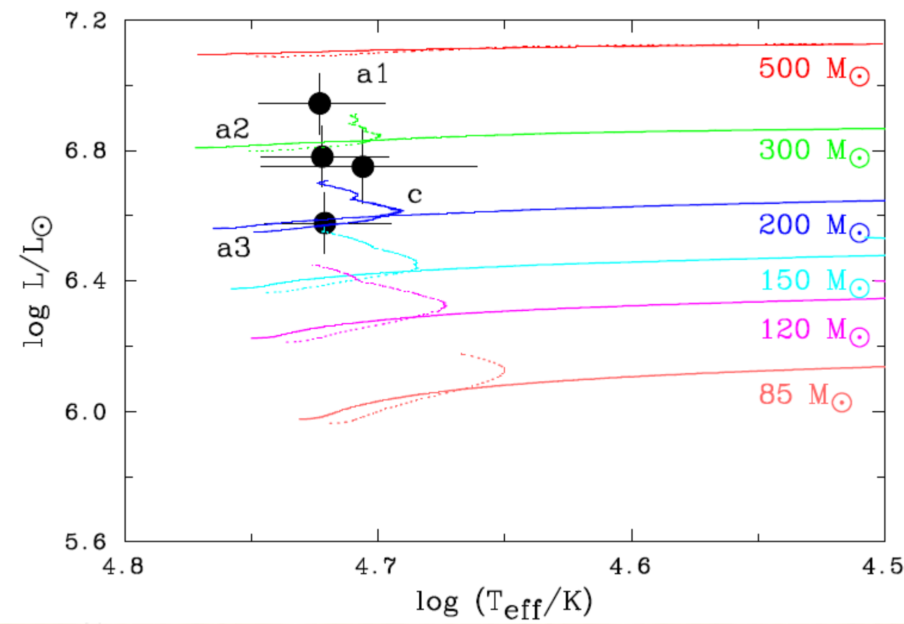
Massive stars – masses



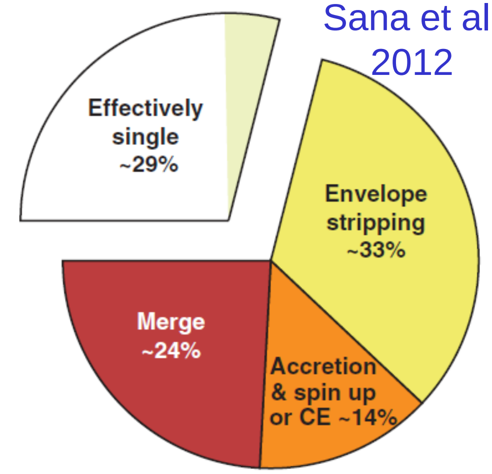
Very massive stars in 30 Dor

(160-320 $M_\odot$)

Crowther et al., 2010, MNRAS 408, 731



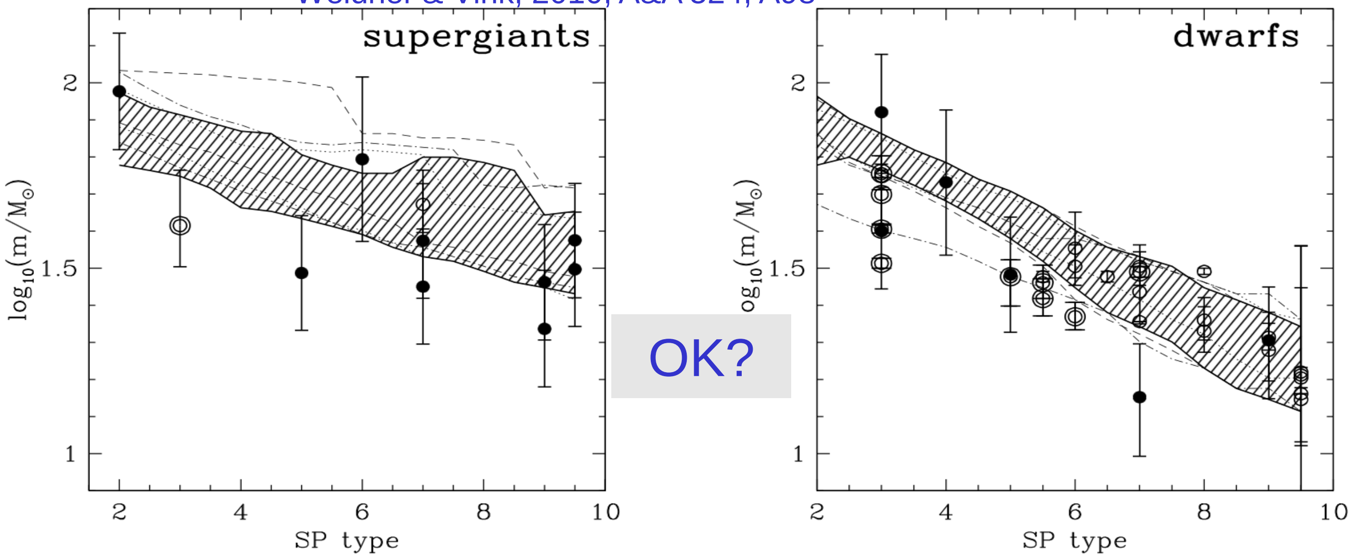
Sana et al. 2012



Massive stars – masses

Our determination of massive stars masses have been plagued by the so-called mass-discrepancy: evolutionary masses larger than spectroscopic masses (Herrero et al., 1992, A&A 261, 209)

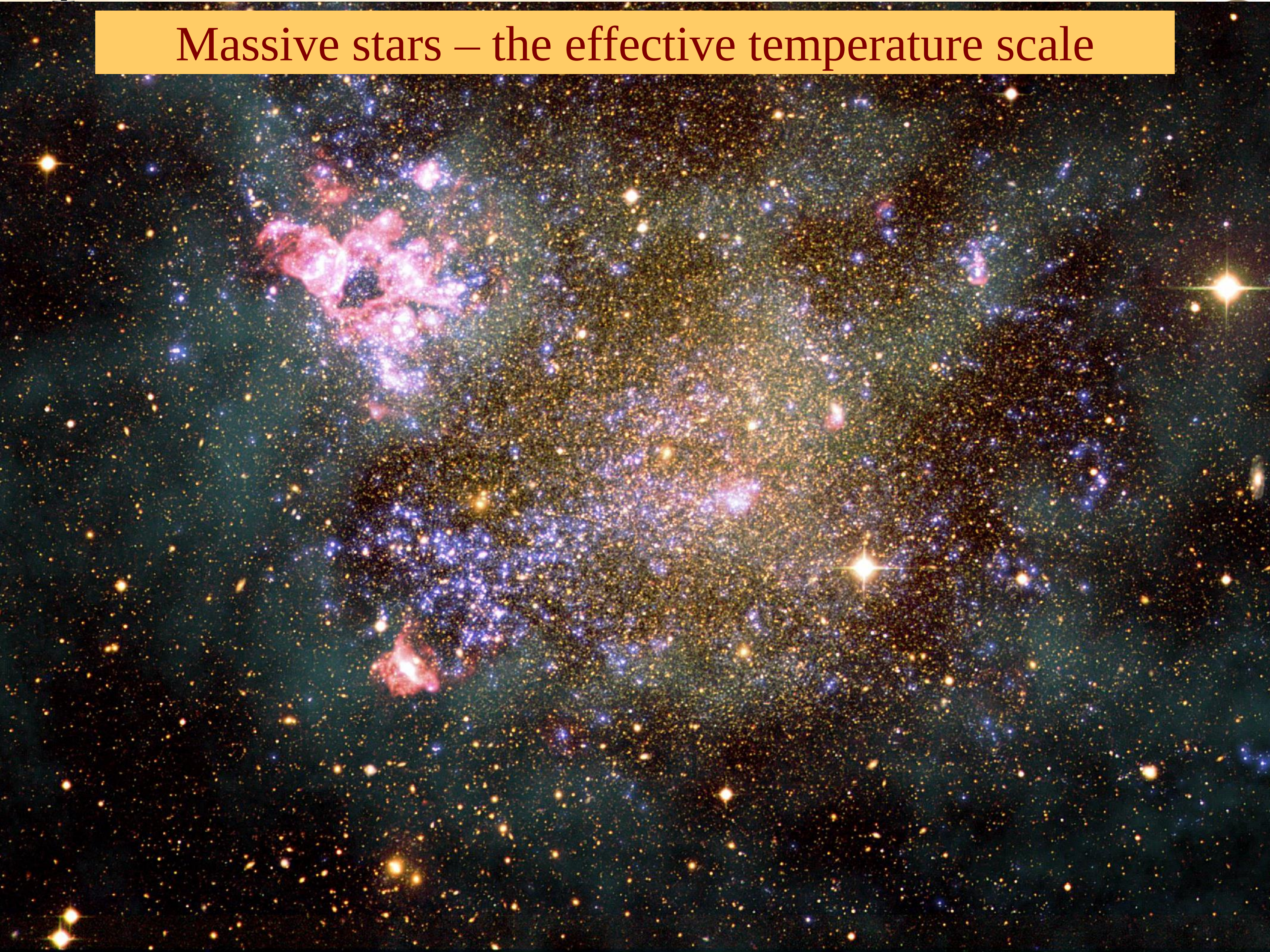
Weidner & Vink, 2010, A&A 524, A98



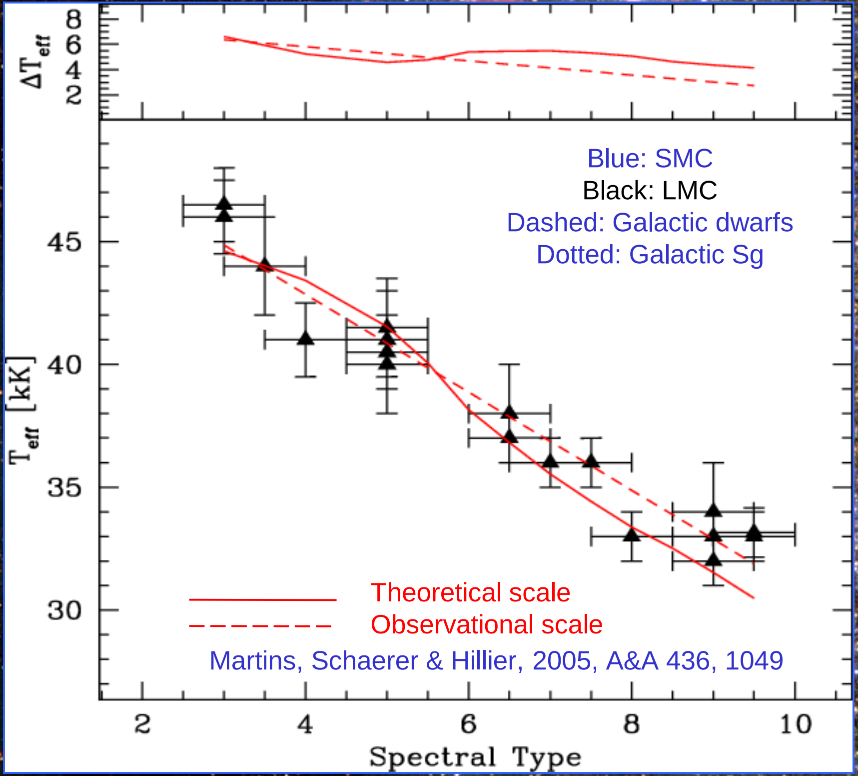
OK?

Recent results: much better, but not completely clear (Martins et al., 2012; Morell et al., 2014)

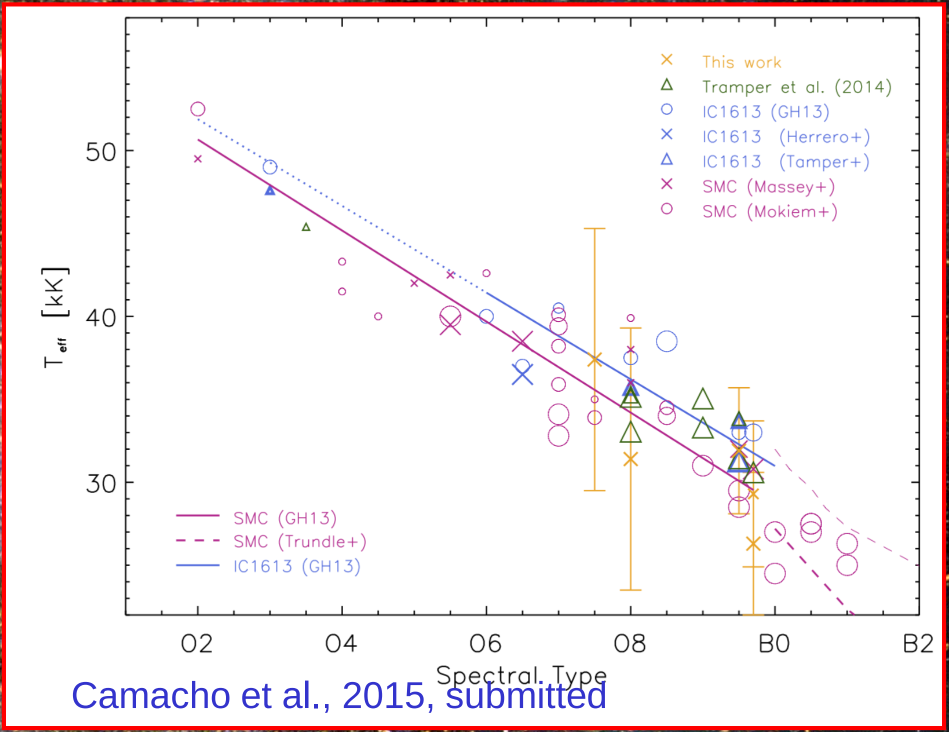
Massive stars – the effective temperature scale



Massive stars – the effective temperature scale



Martins, Schaerer & Hillier, 2005, A&A 436, 1049

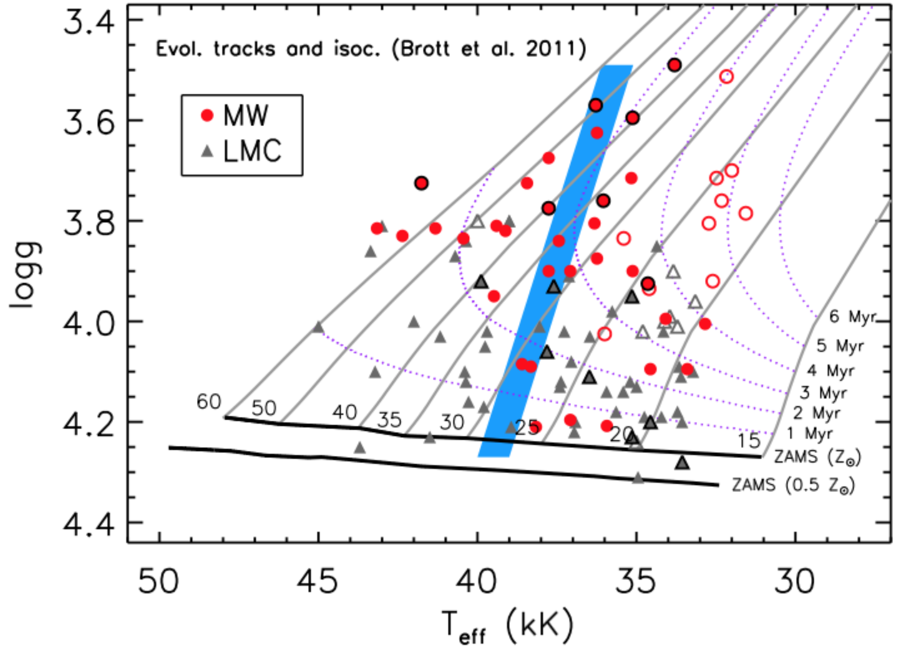


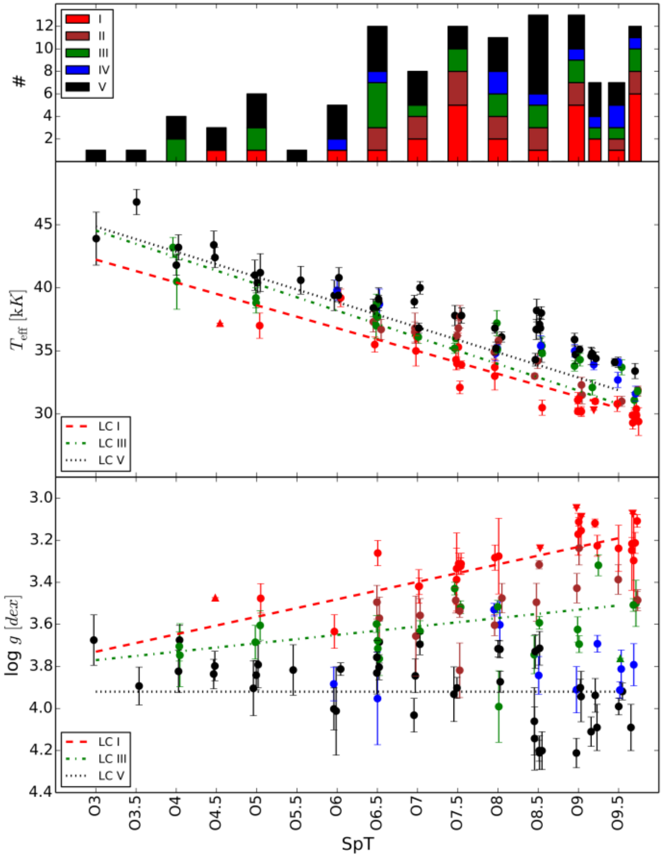
Camacho et al., 2015, submitted

There seems to be a pattern towards hotter stars at lower metallicities but samples are still too small → MOS is the only way to significantly increase it

Massive stars – the effective temperature scale

Simón-Díaz et al., 2014, A&A 570, L6

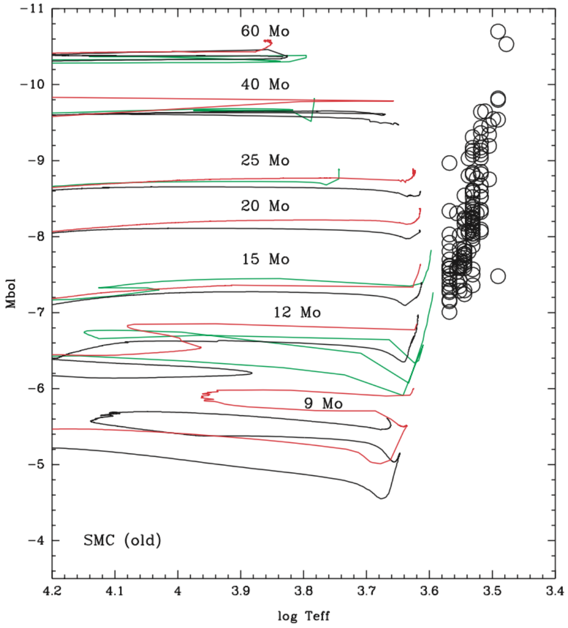




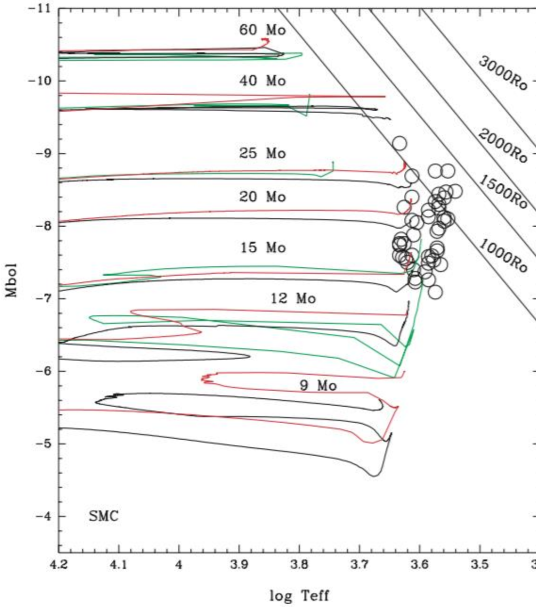
SPECTRAL CLASSIFICATION IS NOT SUFFICIENT

The effective temperature scale is not a univocal function of spectral classif. There is a variation of surface gravity (because of evolution) with spectral type that affects the effective temperature

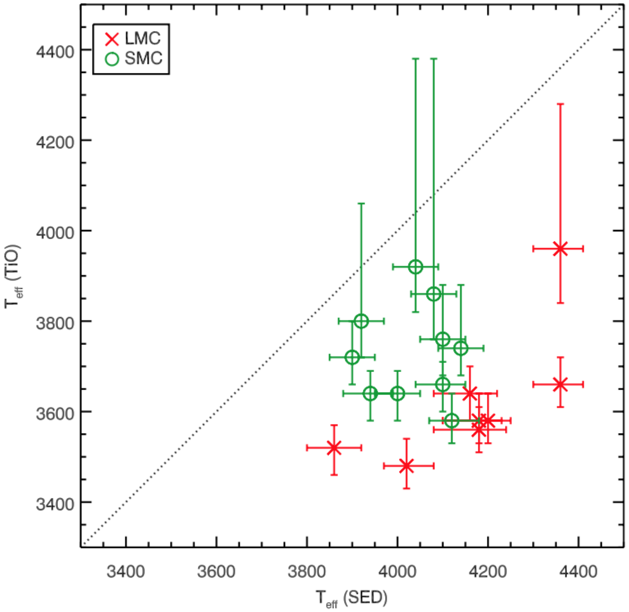
Massive stars – the effective temperature scale
The temperature scale of RSGs



OLD situation



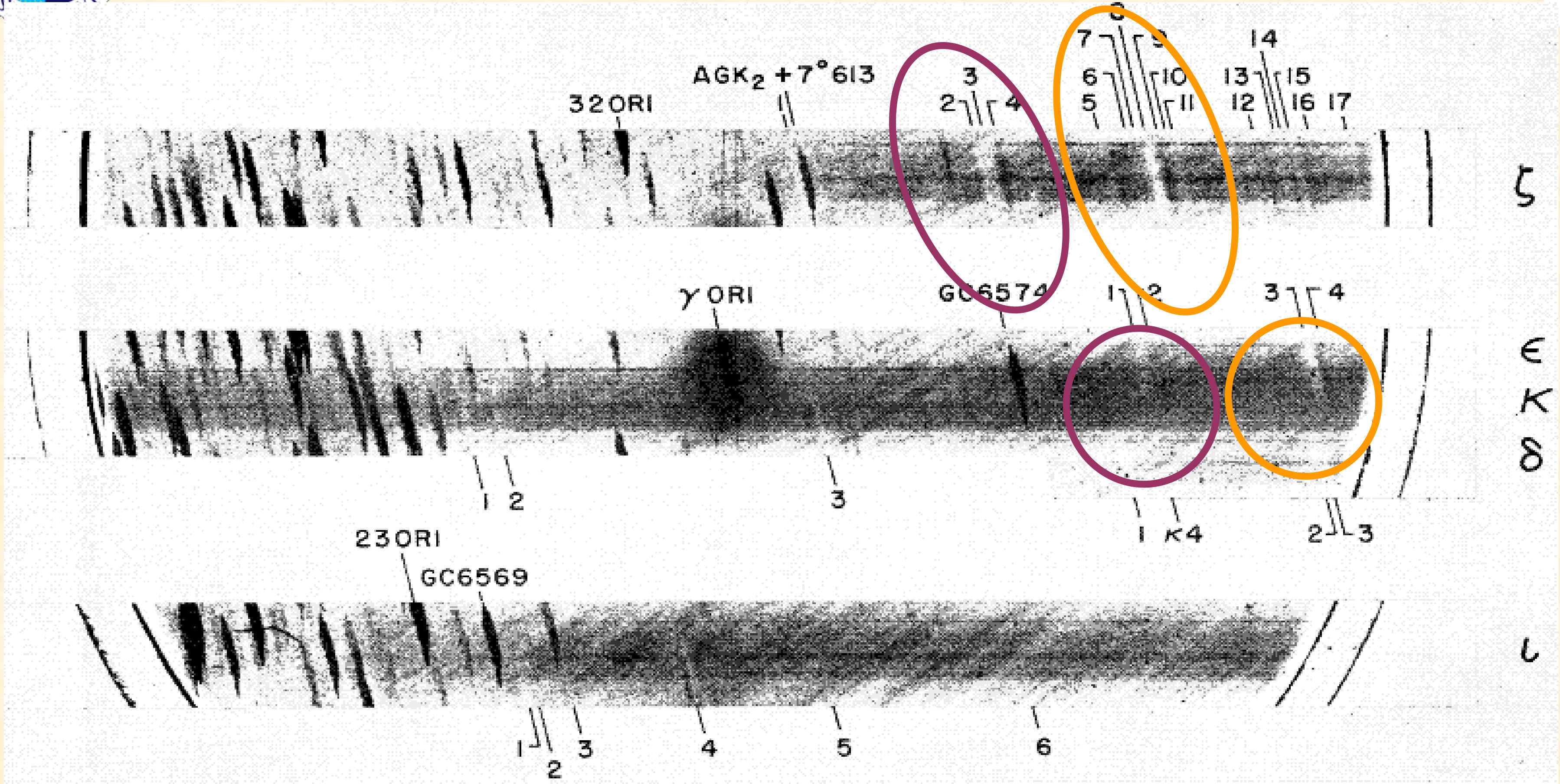
Levesque et al., 2005
TiO bands



Davies et al., 2013
SED
(also FIR method, TiO)

TiO bands form in the upper layers of RSGs, where opacity, structure and 3D effects are large
The masses and luminosities derived by Davies et al. for SN progenitors are a 30% larger
This may help to solve the question of the lack of high-mass SN progenitors from RSG (Smartt et al., 2009)
But: effect smaller at Galactic metallicities

Massive stars – the mass-loss



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

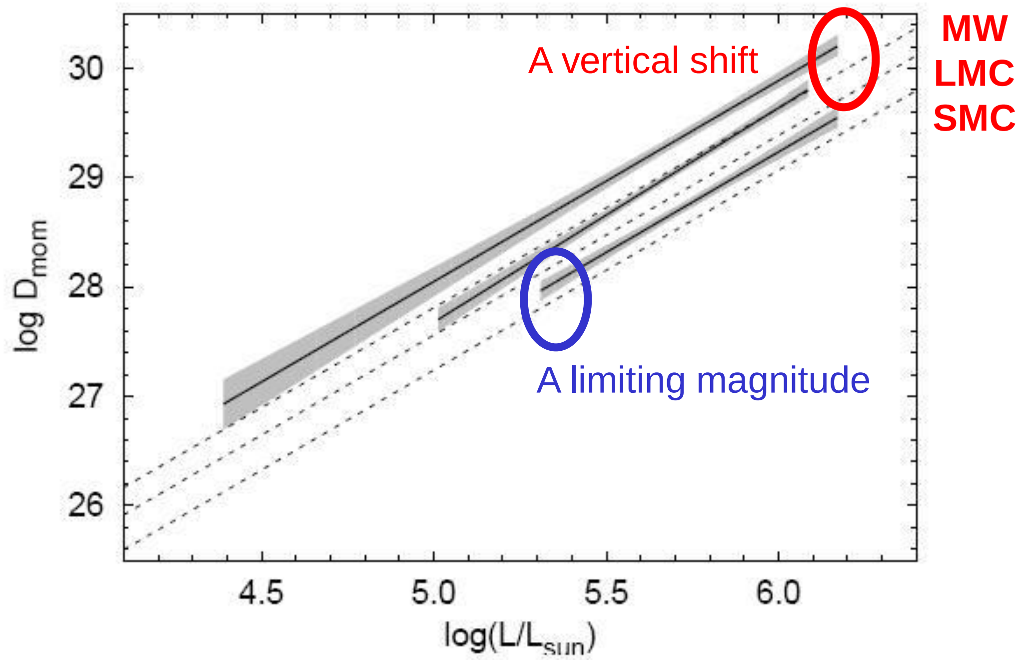
Stars are spectroscopically normal: Outflows shall be common among hot supergiants

Massive stars – the mass-loss

The fundamental prediction from radiatively driven wind (RDW) theory is a relation between the wind momentum gained by the wind and the stellar luminosity (The so-called Wind Momentum – Luminosity Relationship, Kudritzki et al., 1995)

$$\log D_{mom} = \log(\dot{M} v_\infty R_*^{1/2}) \approx \frac{1}{\alpha'} \log L + const(z,\ \text{sp.type})$$

D_{mom} does not directly depend on M



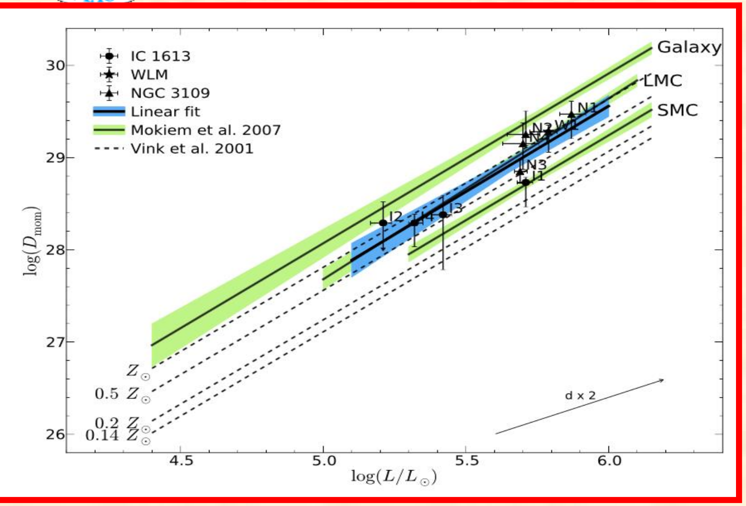
WLR for the MW (top), LMC (middle and SMC (bottom) from Mokiem thesis. No clumping. Shaded areas are 1 sigma uncertainties, dashed lines are theoretical predictions by Vink et al.

Theory has been confirmed for the range of metallicities between the MW and the SMC (Mokiem et al., 2007, FLAMES-I)

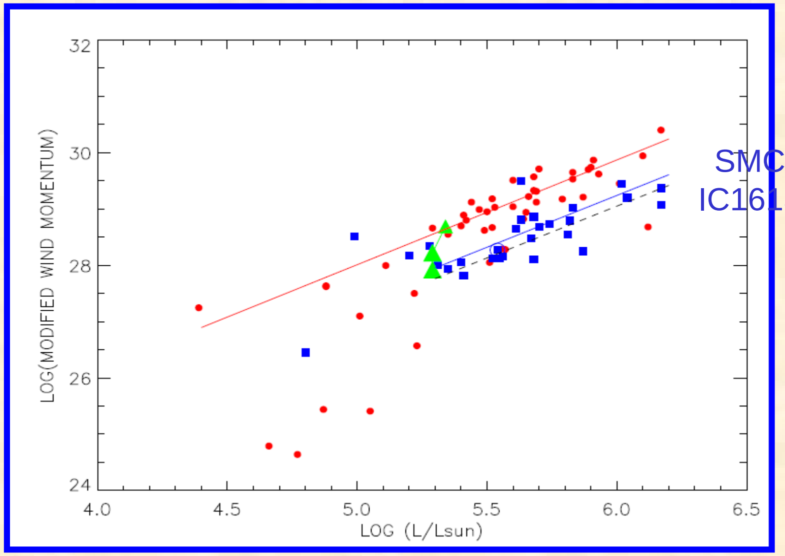
$$\dot{M} \propto (Z/Z_\odot)^{0.72\pm0.15}$$

Consistent with theoretical predictions

Massive stars – the mass-loss
The Z-dependence



Tramper et al., 2014



Herrero et al. (2011,2012) ; MW and SMC data from Mokiem et al. (2007)

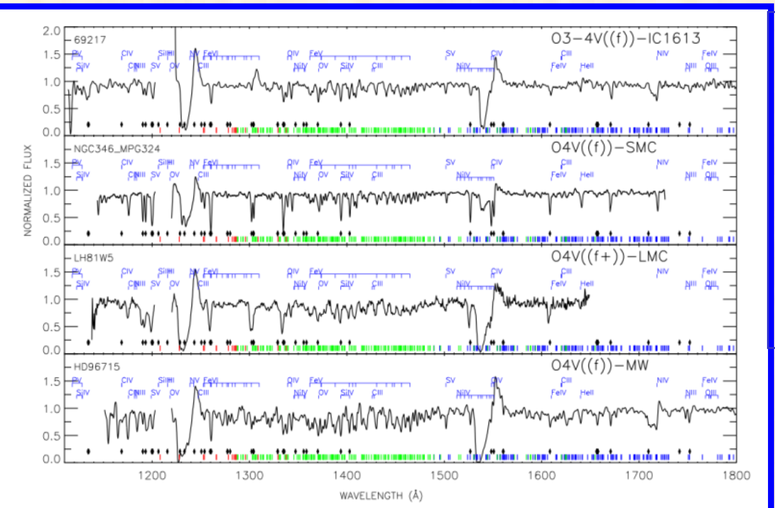
An error of 30% in the terminal wind velocity translates into a factor of 2 in the WLR

→ We need UV data

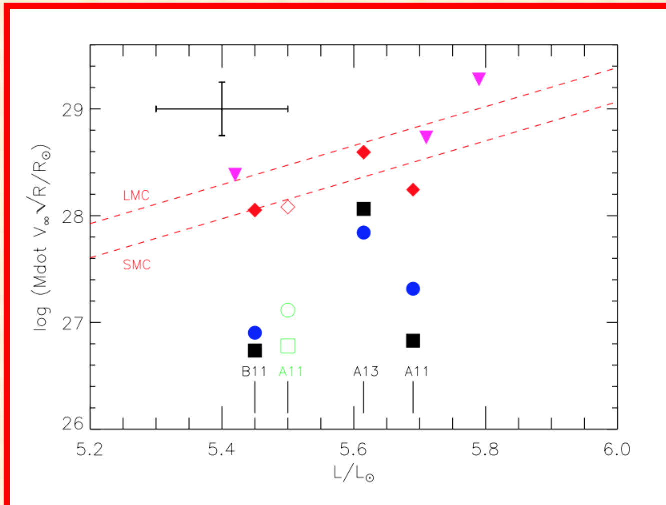
Bouret et al., 2015

No theory breakdown ?

Garcia et al., 2014

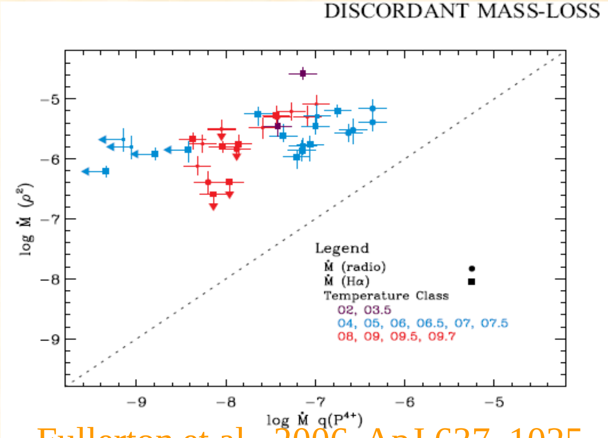


The ***Fe content*** in IC 1613 seems closer to 0.2 Fe(☉) (SMC value) than to 0.13 (as derived from oxygen)



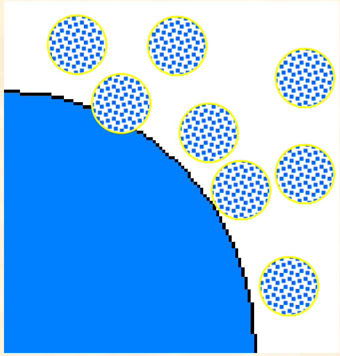
Massive stars – the mass-loss clumping

10 years ago, evidences for mass-loss discrepancies from different diagnostics…



Fullerton et al., 2006, ApJ 637, 1025

Radiation driven winds are intrinsically unstable, leading to wind inhomogeneities



Micro-clumping hypothesis:
Wind is described as small-scale optically thin random clumps over an almost-void inter-clump medium

But also:
Macro-clumping (opticallt thick clumps)
Porosity (photons avoid regions of enhanced density)
Vorosity (photons avoid regions of enhanced opacity in frequency domain)

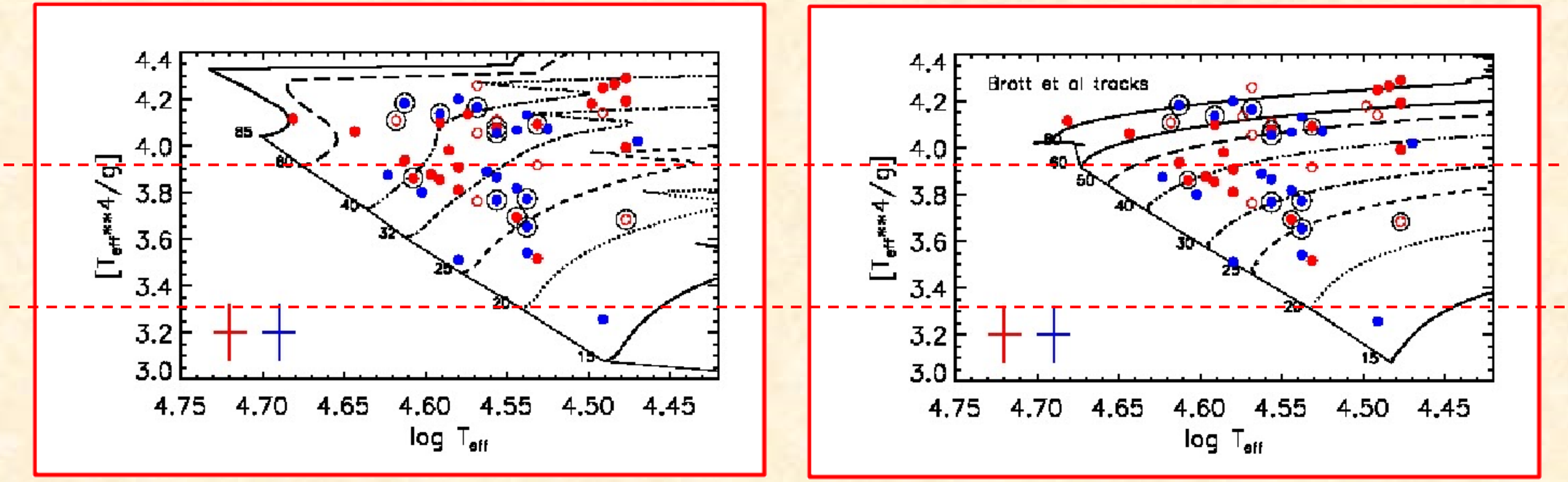
Recombination lines (Hα) → micro-clumping → mass-loss overestimated
(UV) resonance lines → macro-clumping and porosity → mass-loss underestimated

Best diagnostics from X-ray lines → factor 3 below the usual recipe (Vink et al., 2001)

Massive stars – mass-loss

Vink, de Koter & Lamers, 2001

$$\overset{g}{M}_{Vink} = f\left(L_*, M_*, \upsilon_\infty/\upsilon_{esc}, T_{eff,}Z\right)$$



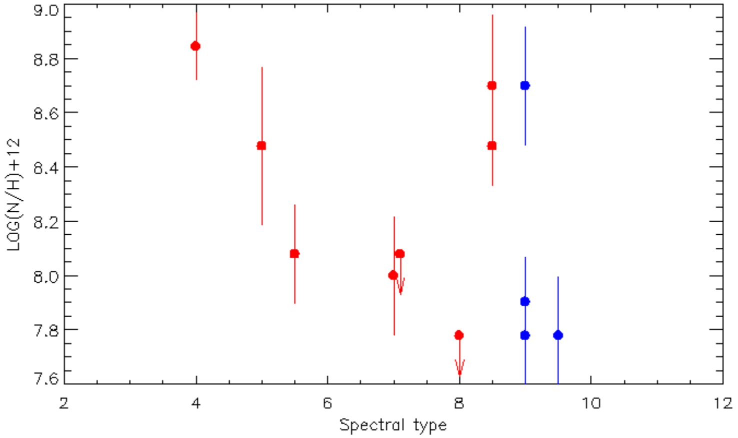
Geneva (left) vs.Bonn (right) rotating tracks.

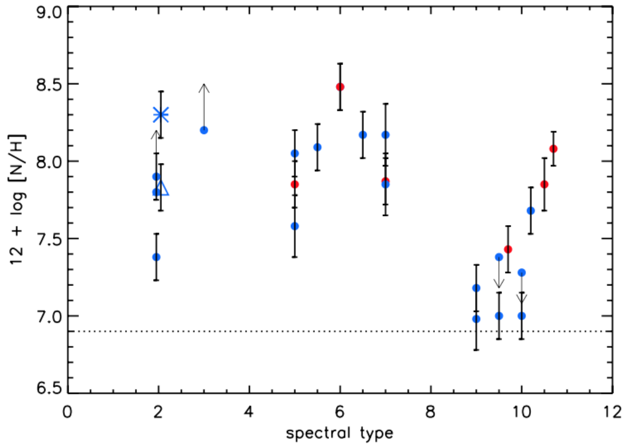
V_{rot} (ini) = 0.4 v_{crit} (Geneva) or 300 km/s (Bonn)

From Markova & Puls, Poster-paper IAUS 307 (Geneva)

Massive stars – rotation

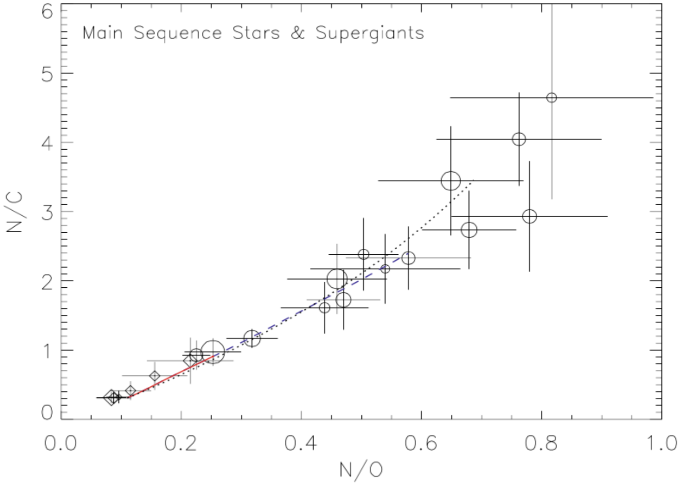
Some recent evidences of mixing in massive stars
Martins et al., 2012, A&A 538, A39
Rivero-González et al., 2012,
Przybilla et al., 2010, A&A 517, A3

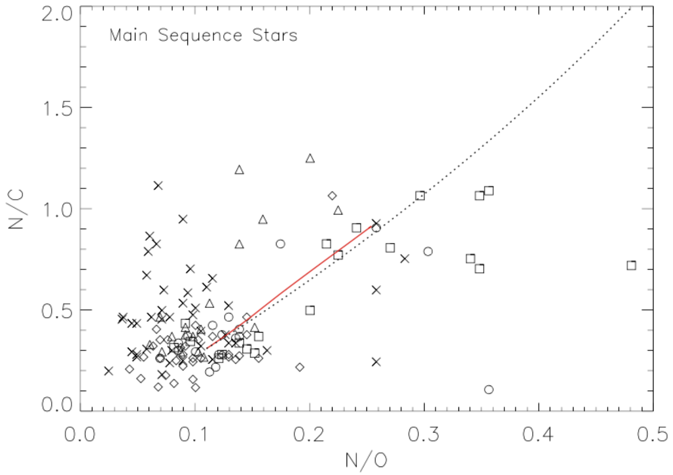




Evidences have been known since more than 20 years

(see references in Maeder & Meynet, 2000, ARAA 38, 143

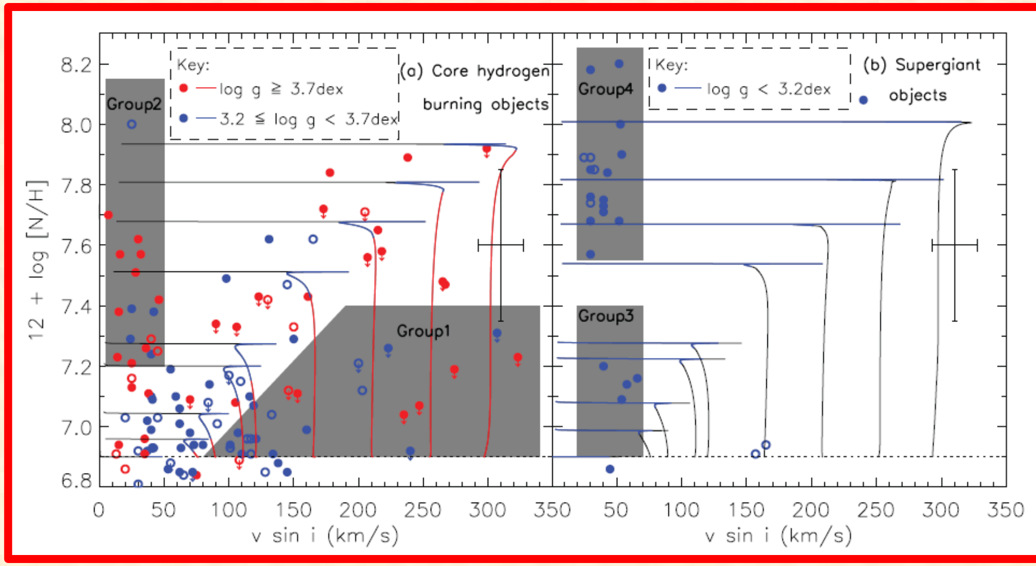


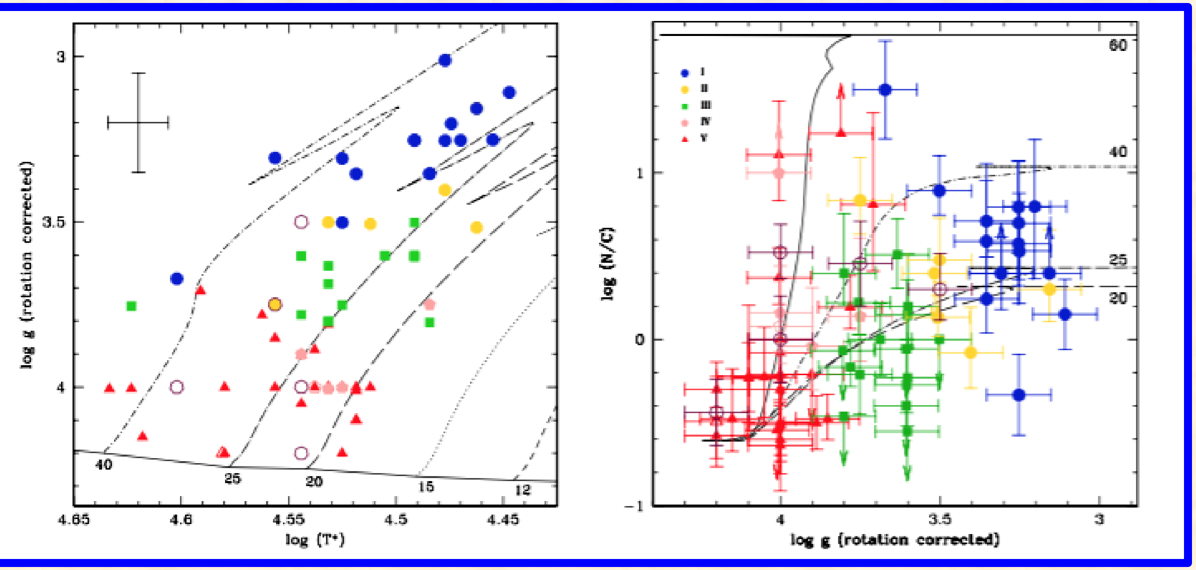


Rotational mixing introduced in evolutionary calculations

Massive stars – rotation

Hunter et al., 2008
135 early **B-type** stars in the LMC
Groups 1 and 2 not consistent with rotational mixing

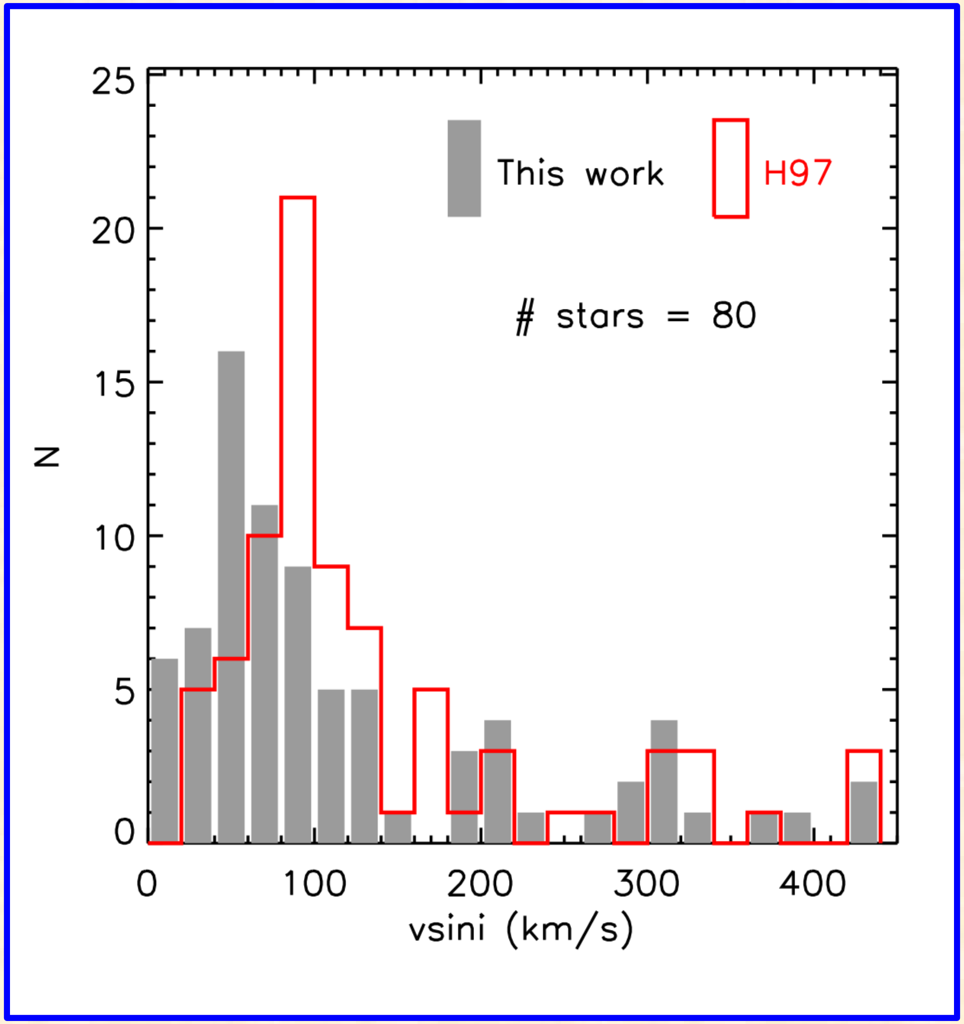




Martins et al., 2015 (**O stars**)
Comparison with Geneva tracks with rotation
They conclude that **80% of the targets can be explained by rotational mixing**

But: Aerts et al. (2014, O+B stars) find that the rotational velocity has no predictive power for the N abundance

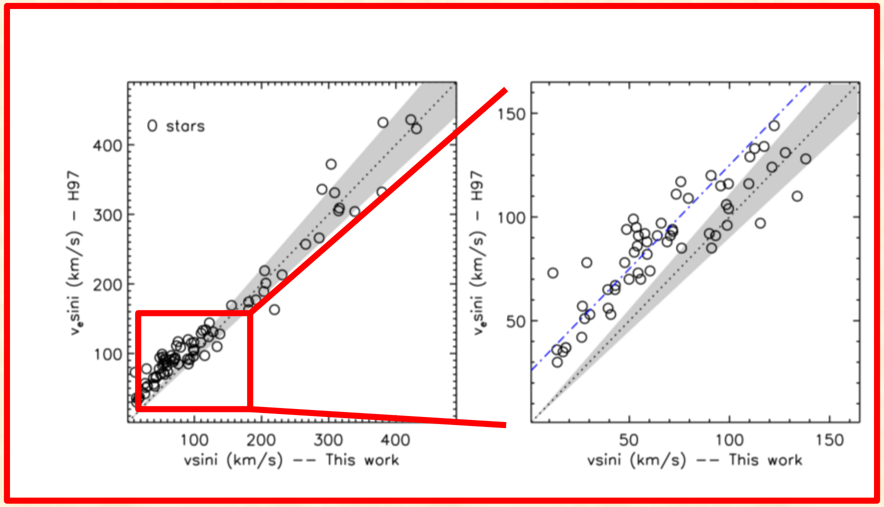
Massive stars – rotation and broadening



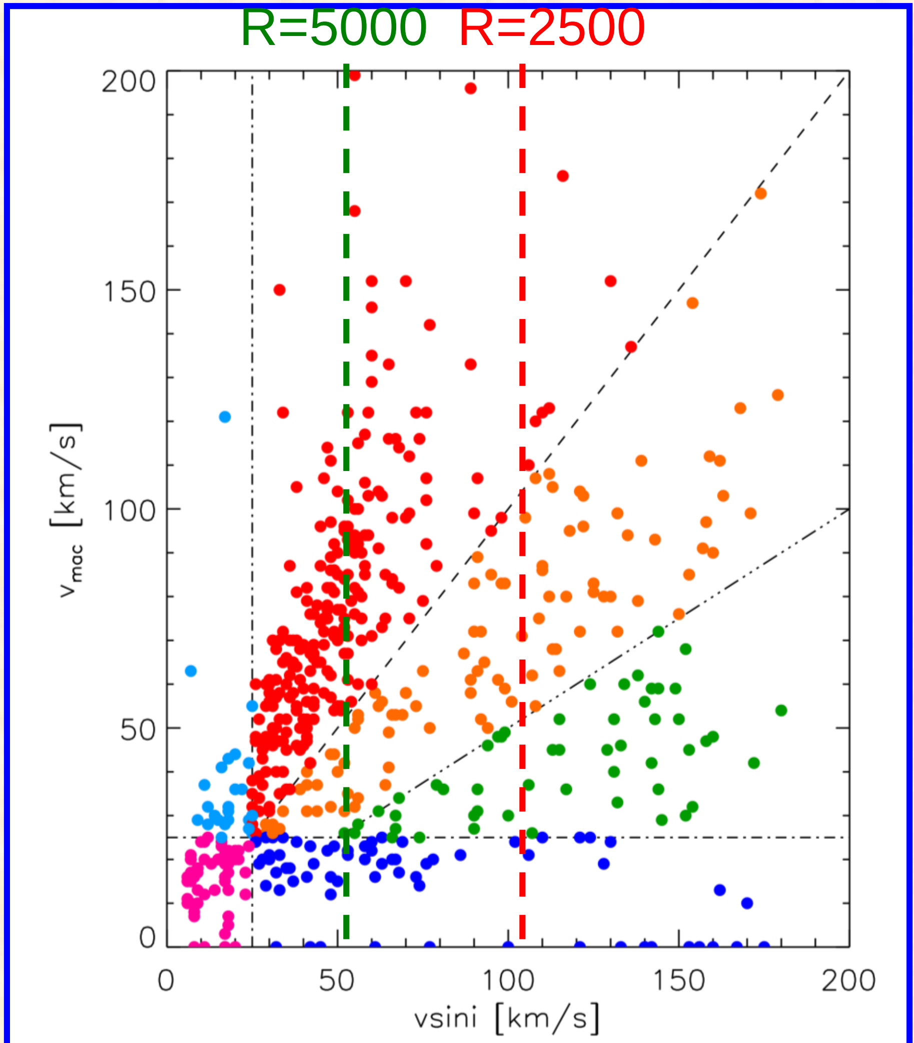
Simón-Díaz & Herrero, 2014, MW

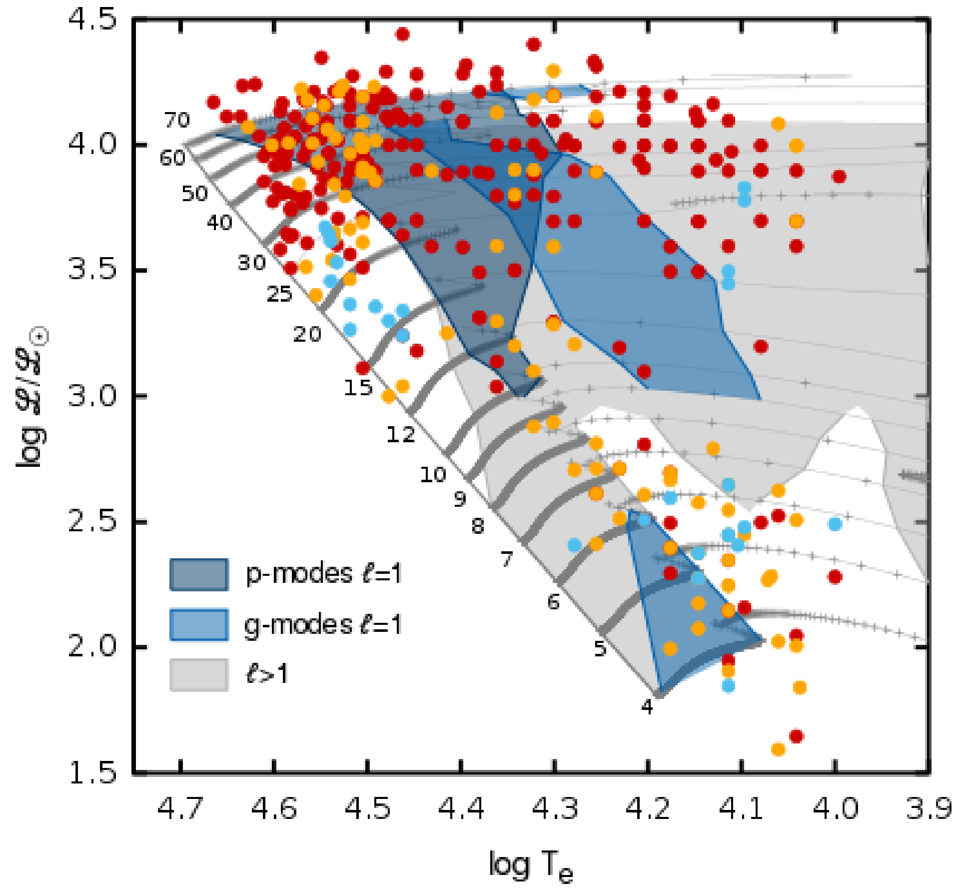
(H97= Howarth, 1997)

Line broadening in massive stars is not only due to rotation



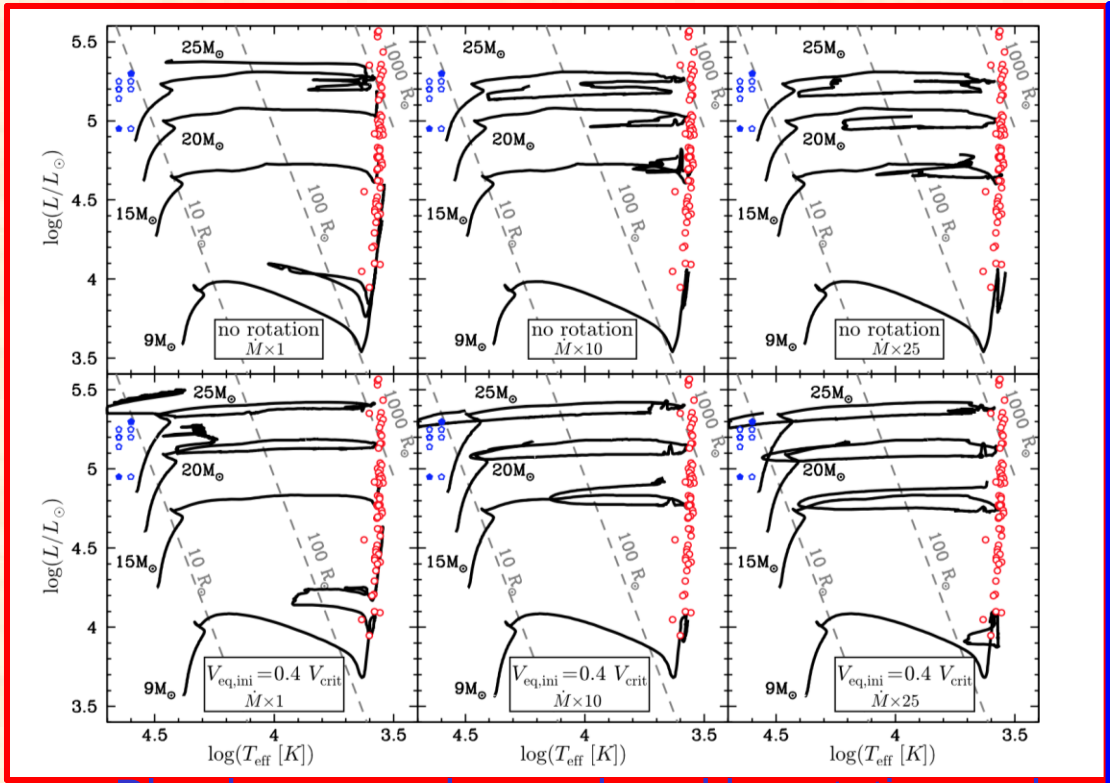
Massive stars – rotation and broadening





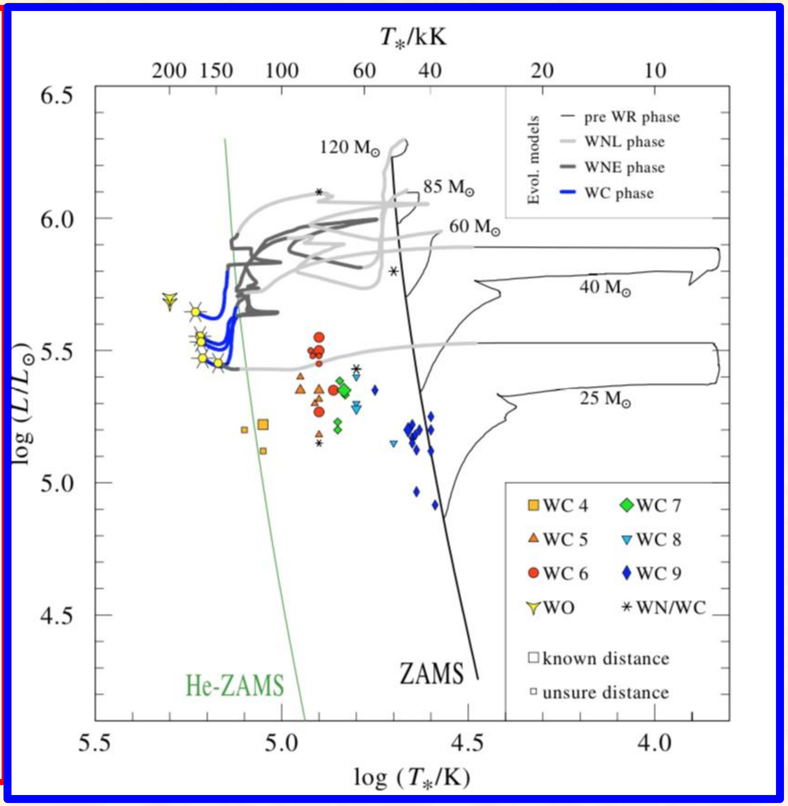
See poster by Simón-Díaz et al.

Massive stars – rotation and broadening



Blue-loops can be produced by rotation and enhanced mass-loss.

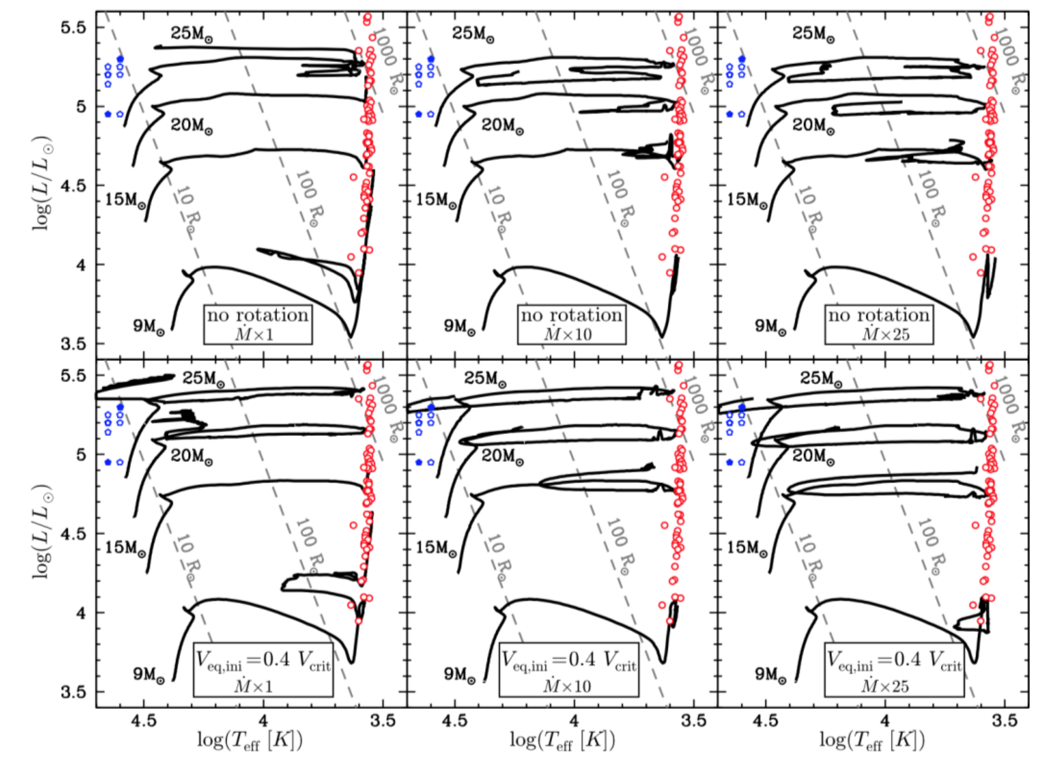
(Meynet et al., 2015)



Sander et al., 2012

Massive stars – rotation and broadening

Model/star	N/C	N/O	$X_{\rm He}$
‘Schwarzschild’ (model)	57.86	4.17	0.635
‘Ledoux’ (model)	6.97	1.61	0.458
Rigel (observation)	2.0	0.46	0.32
Deneb (observation)	3.4	0.65	0.37



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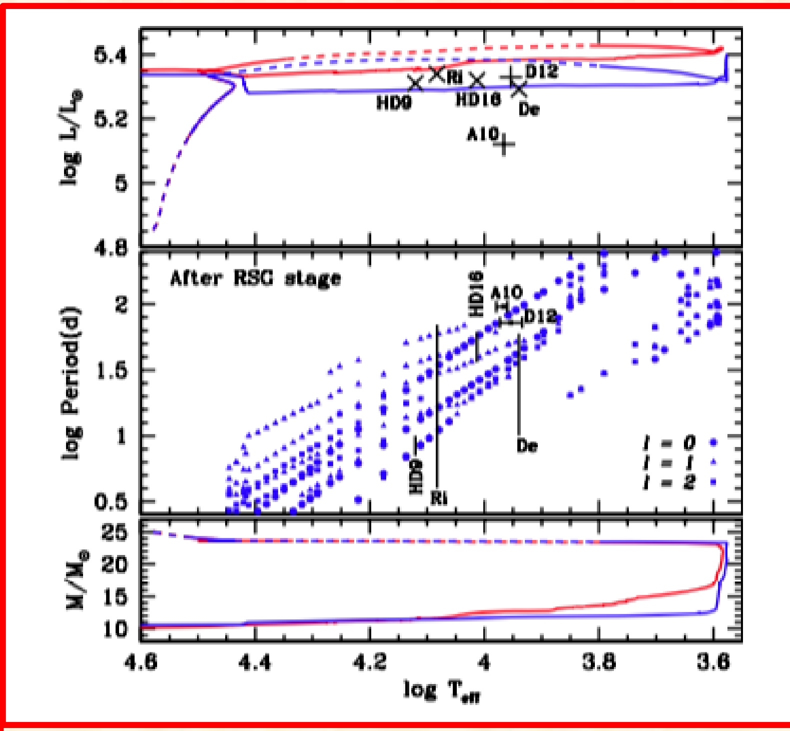


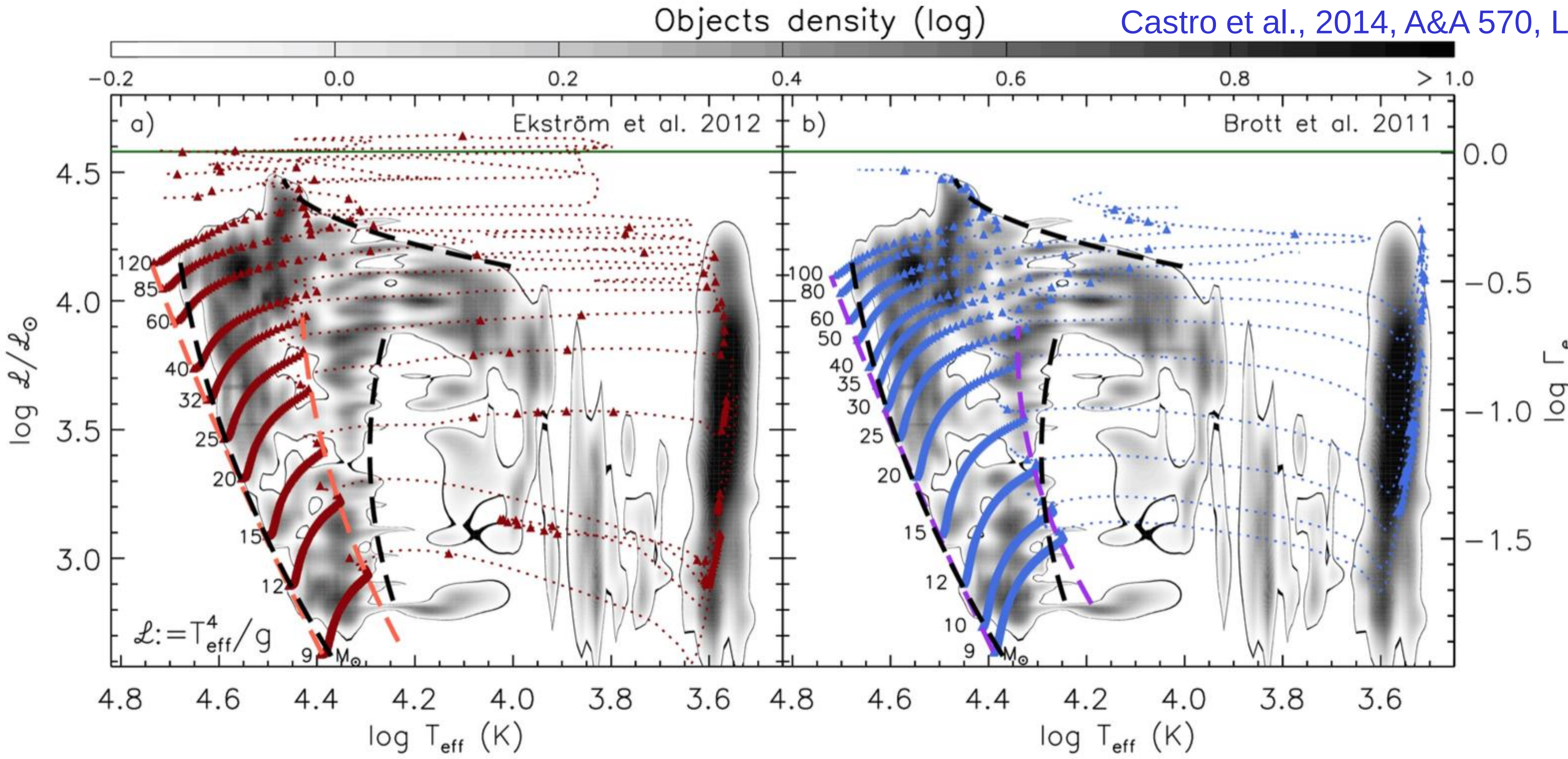
Properties of α Cyg variables can be reproduced by models in the post-RSG phase

Georgy, Saio & Meynet, 2014, MNRAS 439, L6
Saio, Georgy & Meynet, 2013, MNRAS 433,1246

Massive stars – MOS and WEAVE

- The structure and evolution of massive stars depends on many physical processes and their associated parameters
  - Mass, luminosity, effective temperature, mass-loss, rotation, multiplicity, magnetic fields…
- These processes often interact with each other, opening new possibilities
- The feedback of massive stars and their impact in the environment also depends on these processes and its interplay
- To dissentangle the role of each process/parameters we require
  - large samples, statistically meaningful, under different conditions
  - Adequate resolution and wavelength coverage
  - Good SNR
- This can only be achieved with MOS
  - Which also implies automatic & accurate analysis methods

Massive stars – MOS and WEAVE



Castro et al., 2014, A&A 570, L13

WEAVE will help us to construct a complete Galactic HRD for OB stars in an homogeneous way

- census as complete as possible thanks to present surveys (IPHAS…, see poster by I. Negueruela)
- Accurate distances thanks to Gaia
- Grouping the stars according to different conditions (age, evolutionary phase, stellar parameters…) making easier to determine their connections
- High resolution survey for a subsample