The evolution of massive close binaries:
the effect on overall massive star population synthesis

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Evolution of massive stars
a short history

- Evolution of massive stars started as evolution of massive binaries in the late sixties, and seventies.

  - WR stars have lost most of their hydrogen envelope ➔ RLOF was considered as a most plausible process ➔ binaries

    The massive star conference in 1971 in Buenos Aires:
    Kuhi (1971): all WR stars are binary components

  - The observations of X-ray binaries

  - (Paczynski, van den Heuvel, Iben, Tutukov, Yungelson, Brussels, …)

The rise of stellar winds and the Conti scenario (1976) for WR single stars

Is it possible that WR star form via massive single star evolution, single stars that lose their hydrogen envelope by stellar winds?

Yes: Chiosi et al., 1978 massive single star evolution with stellar winds

But do WR single stars exist (remember Kuhi, 1971)?

Yes: Vanbeveren and Conti, 1980: the Kuhi (1971) statistics is biased, the real WR+OB binary frequency is no more than 30-40%

The rise of massive single star evolution

- Maeder and Meynet (1987) (*overshooting and stellar wind mass loss*)
- Schaller et al. (1992)
- Schaerer et al. (1993)
- Charbonnel et al. (1993)
- Schaerer et al. (1993b)
- Langer et al. (1994)
- Pols et al., (1998)
- Ekstrom et al. (2011) (*rotation*)

Interestingly: overshooting has been introduced in massive star evolution for the first time by Massevitch, Popova, Tutukov, Yungelson (1979): *On the influence of mass loss and convective core overshooting on the evolution of massive stars*

Binary scientists tried to convince the community that massive star population number/spectral synthesis is meaningless without binaries

a. Number synthesis

Meurs and van den Heuvel, 1989: The number of evolved early-type close binaries in the Galaxy,

(Victory after 8 years of trench warfare)

Pols, Hurley, Portegies-Zwart, Verbunt, …

Brussels started with binary population studies in 1998

Vanbeveren et al. (1998):

Population synthesis of O-type stars and WR stars

- Garmany et al. (1980) : 33% are binaries with mass ratio q > 0.2 and period P < 100 days

- The WR+OB binary frequency = 30-40%

  A population of massive stars consists of real single stars, un-evolved (=pre-RLOF) binaries, evolved (= post-RLOF) binaries, post-supernova rejuvenated binary mass gainers (mostly single but with binary origin), binary mergers (singles with a binary origin), etc.

- What must be the primordial massive binary frequency ***f*** in order to explain the two bullets above?

  - Answer: ***f > 0.7*** (H. Sana was still in primary school)

The massive O star population in regions of continuous starformation
(Vanbeveren et al., 1998)

Typical result for O-type stars starting with a primordial binary frequency = 80%:

12% are really single
64% are unevolved binaries
24% are post RLOF O-type stars
- 6% are O+CHeB (O+WR)
- 3% are O+NS (X-ray)
- 1% are O+BH (X-ray)
- 8% are O-type runaway stars
- 15% are single post-SN or mergers

De Mink et al. (2014): 15-40% of massive main sequence stars are the products of binary interaction, 4-17% are mergers

b. Spectral synthesis

Leitherer et al., (1999): Starburst99 (a spectral synthesis tool without binaries) (2000 citations)

Van Bever and Vanbeveren (Brussels, 2003): A detailed study of the effect of massive binaries on the spectral synthesis of starbursts (~100 citations)

Eldridge and Stanway (2009): Similar as was done in Brussels with similar conclusions (~100 citations)

Conclusion

In the sixties and seventies massive stars = massive binaries

but

starting in 1980, for about 3 decades,

HOT BINARIES WERE NOT HOT IN THE HOT STAR COMMUNITY

Fortunately, since a couple of years, more and more people again realize that massive binaries cannot be ignored

H. Sana, S. de Mink, R. Izzard, et al.
N. Langer: if we are lucky all massive stars are born in binaries

Massive single star + binary population codes

Meurs and van den Heuvel (1989)	number code
Pols and Marinus (1994)	number/spectral
Startrack (Belczynski, Ruiter et al.)	number
Seba (Portegies Zwart, Nelemans, Toonen)	number
Binary_c (Claeys et al., 2014)	number
Brussels code (Vanbeveren et al. 1998)	number/spectral
Eldridge and Stanway (2008)	number/spectral
Han and Podsiadlowski (2004)	number/spectral
Yungelson et al. (2000)	number
De Mink et al. (2013)	number
Bonnfires: Lau, Izzard et al. (2014)	number ?

Massive single star + binary population codes

Differences in the results predicted by population codes depend mainly on

- the treatment of the common envelope phase in binaries
- the treatment of stable Roche lobe overflow in binaries
- the evolutionary results used in these codes

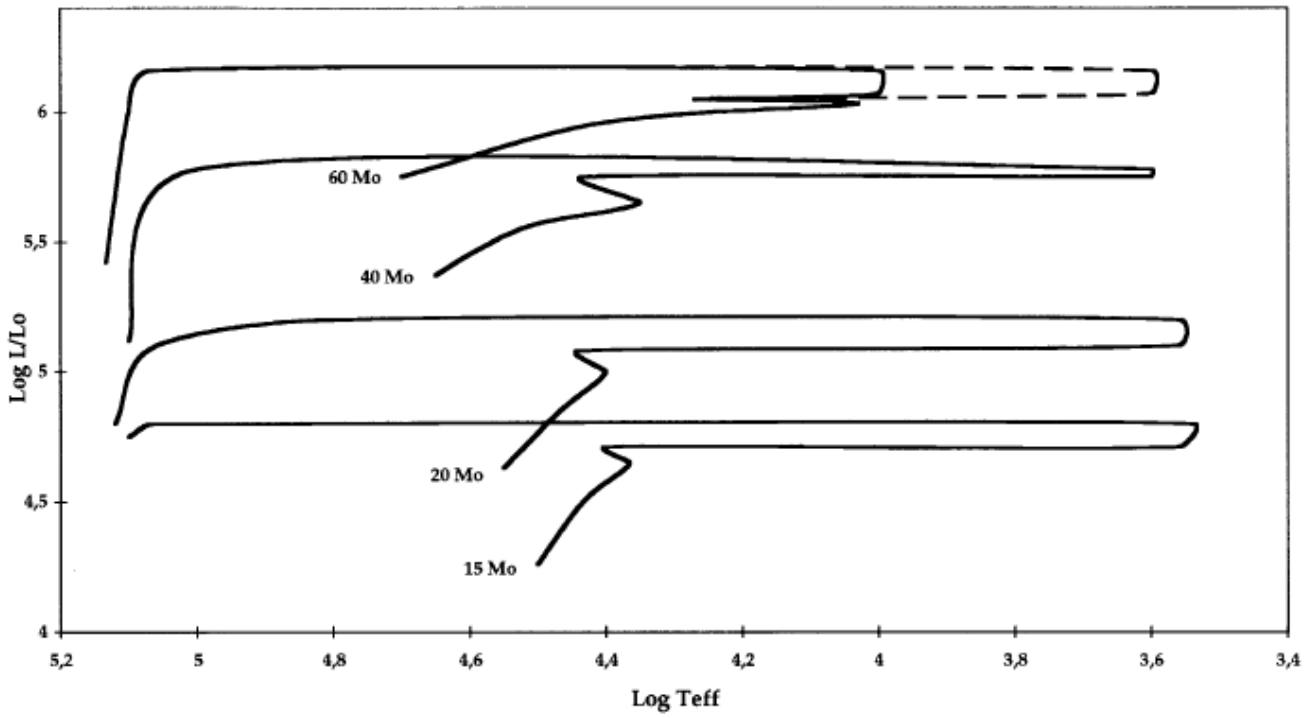
for massive stars this means

- Stellar wind mass loss (OB-phase, LBV phase, RSG phase, WR phase)
- Rotation
- Mass accretion ➔ convection and semi-convection
- Binary merger process

- Hurley et al. (2000, 2002) (or Hurley like) based codes versus non Hurley et al. based codes ➔ interpolation formula versus tables with detailed evolutionary results of single stars and binaries. Some codes are a mixture.

Vanbeveren et al, 1996, 1998

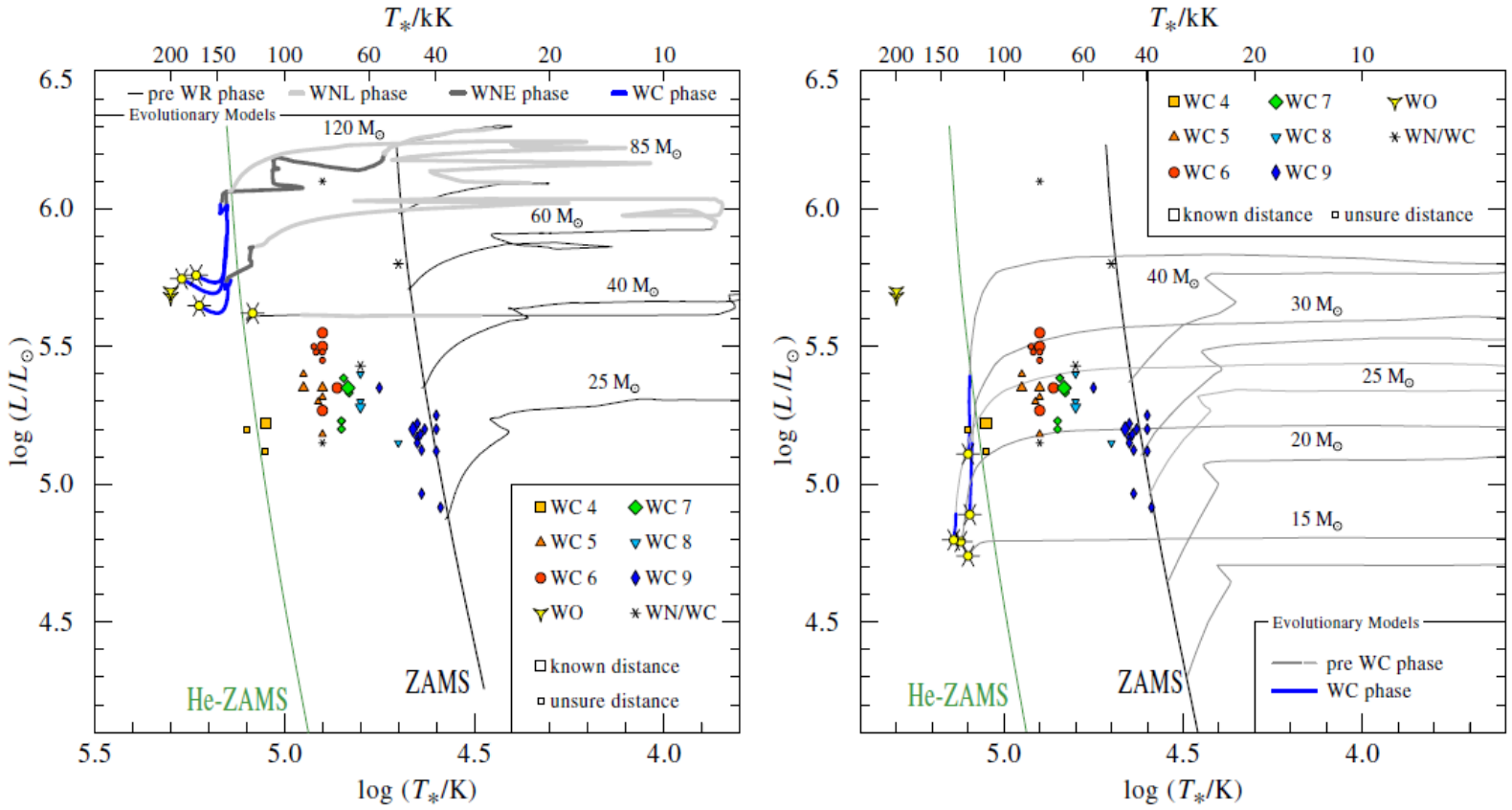
The evolution of single stars with alternative RSG mass loss rates



Recently, also the Geneva team implemented higher RSG mass loss rates in their single star evolution (Ekstrom et al., 2012; Georgy et al., 2012, 2013; however Meynet et al., 2014)

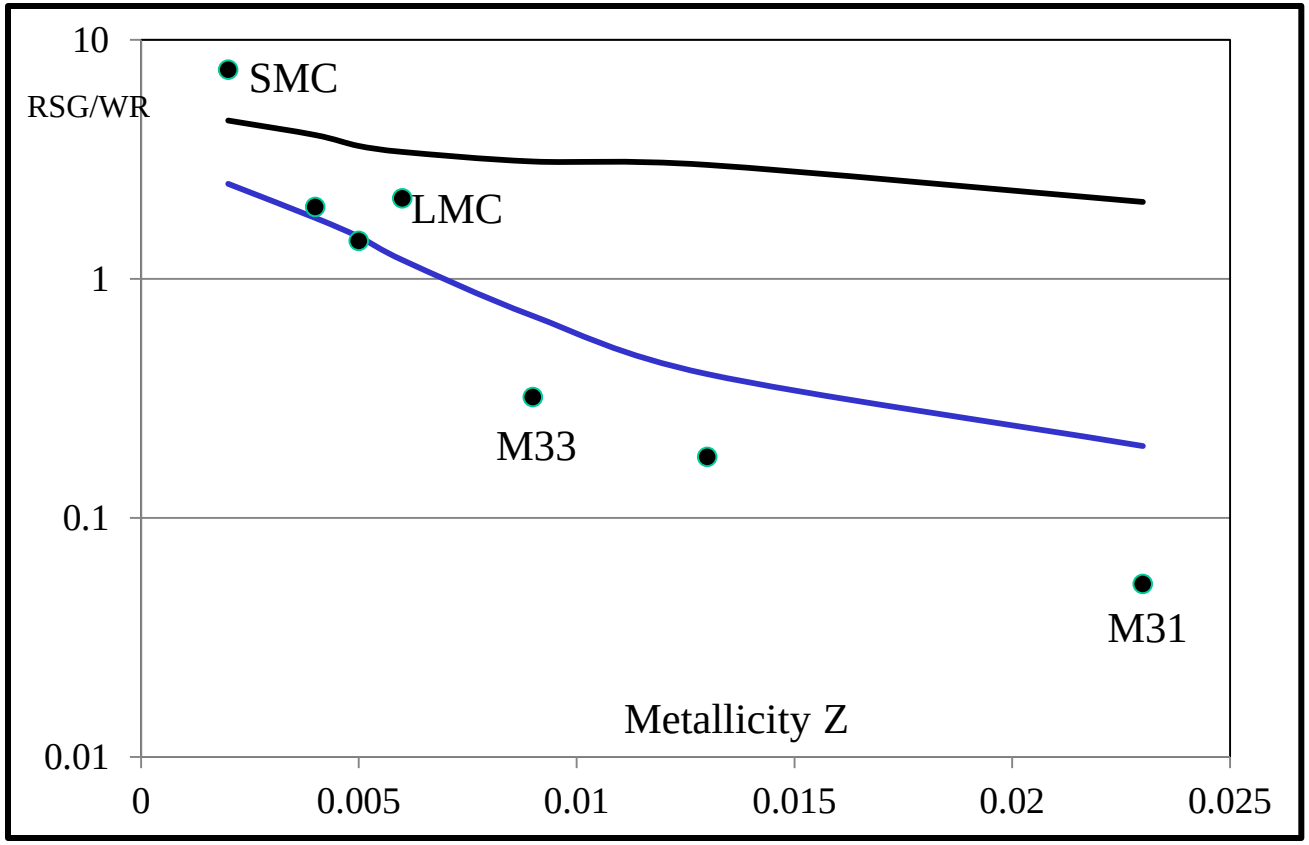
Long period WR binaries may have evolved according to this RSG scenario

The HR-Diagram of WC stars



Galactic WC stars: Sander et al., 2012

The number ratio Red Supergiants/WR

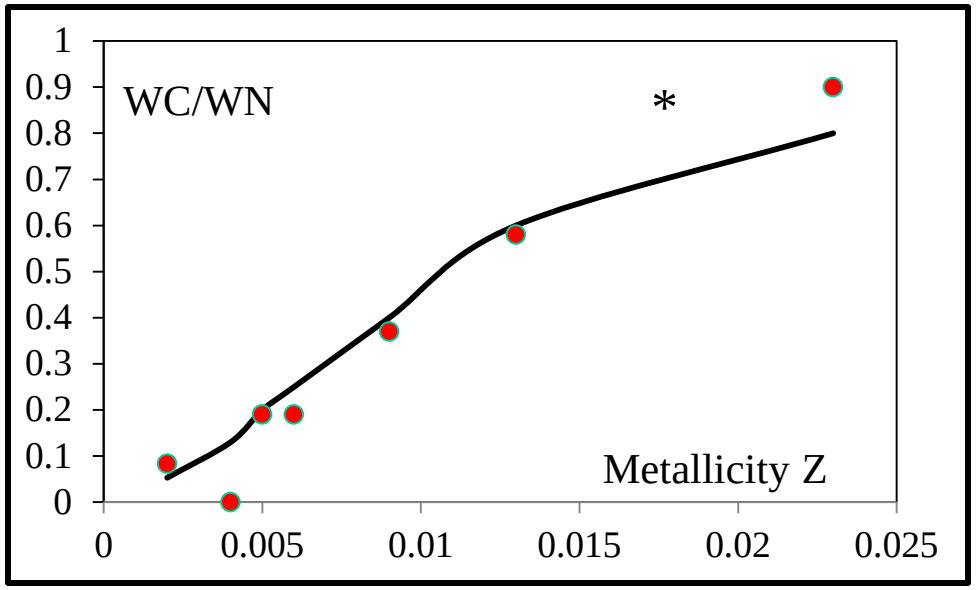


Data: Massey (2003)
Mbol < -7.5

Black line: prediction Eldridge et al. (2008)
Blue line: prediction with Brussels tracks (1998)
40% single stars, 60% binaries

The WC/WN number ratio

(Vanbeveren et al., 2007)



The WC/WN ratio as a function of Z

L. Smith (1973): argued that metallicity might be responsible for the relative absence of WCs in the Magellanic Clouds, but without understanding the physical mechanism

Vanbeveren and Conti (1980): argued that it is the effect of Z on stellar wind mass loss that causes the differences in WC/WN number ratio

The figure compares observations (Massey, 2003) with theoretical prediction (Vanbeveren et al., 2007; see also Eldridge et al., 2008); 60% binaries, 40% single stars, using our 1998 single star tracks with alternative RSG stellar wind mass loss rates ➔ correspondence is rather satisfactory.

Population synthesis of SN II and SN Ib/c: the effect of binaries

Tutukov et al. (1992)
Podsiadlowski et al. (1992)
Joss et al. (1992)
De Donder & Vanbeveren (1998, 2003, 2004)
Belczynski et al. (2002)

... some more recent studies essentially confirm the earlier ones

Conclusions:

1. The ratio SNII rate/SNIbc rate depends critically on the massive interacting binary frequency; differences between different types of galaxies may reflect differences in the population of these massive binaries

2. By comparing the overall (cosmological) observed ratio with PNS predictions we concluded that the overall cosmological massive interacting binary frequency ~50 %

The effect of LBV mass loss on the population of double compact binaries, double compact binary mergers and detection rates of future GW detectors (aLIGO, 2015)

Dominik et al. (2012, 2013, etc)

LBV mass loss is not large enough to suppress the RLOF in case B/C binaries M > 40 Mo

Mennekens and Vanbeveren (2014)

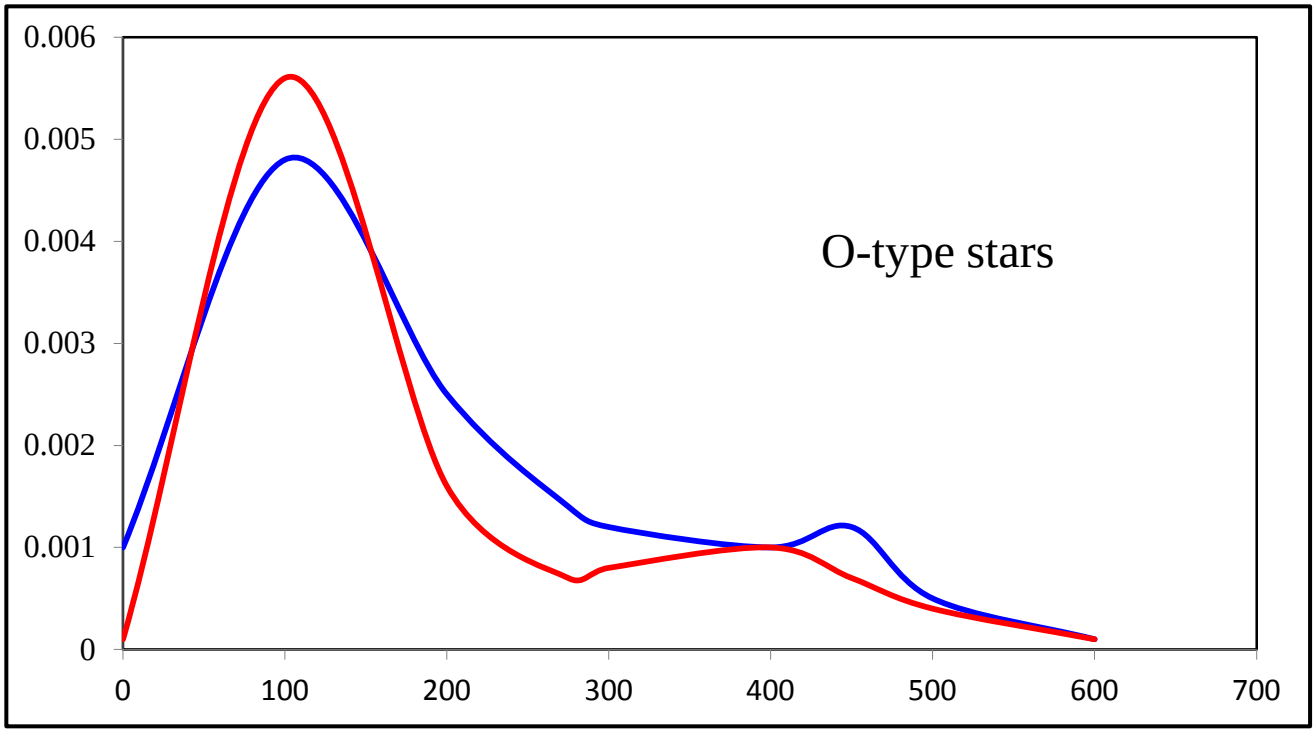
LBV mass loss is large enough to suppress the RLOF in case B/C binaries M > 40 Mo (The LBV scenario of massive binaries, Brussels, 1992)

The effect of LBV mass loss on the detection rates is enormous (about a factor 1000); primarily the BH-BH merger rate is affected.

Warning: initial final mass relation; Hurley versus non-Hurley

(Ilka Petermann)

Rotation, evolution and population synthesis



Penny, 1996; Vanbeveren et al., 1998; Ramirez-Agudelo et al., 2013;

Red: Galaxy Blue: VLT-Flames Tarantula

Could it be that a significant fraction of stars in the high velocity tail may be binary products ? (confirmed by detailed population simulations of De Mink et al., 2013) or products of cluster dynamics (where binaries are involved, ζ Pup, Pauldrach et al., 2012)

The massive Be star population in starburst regions

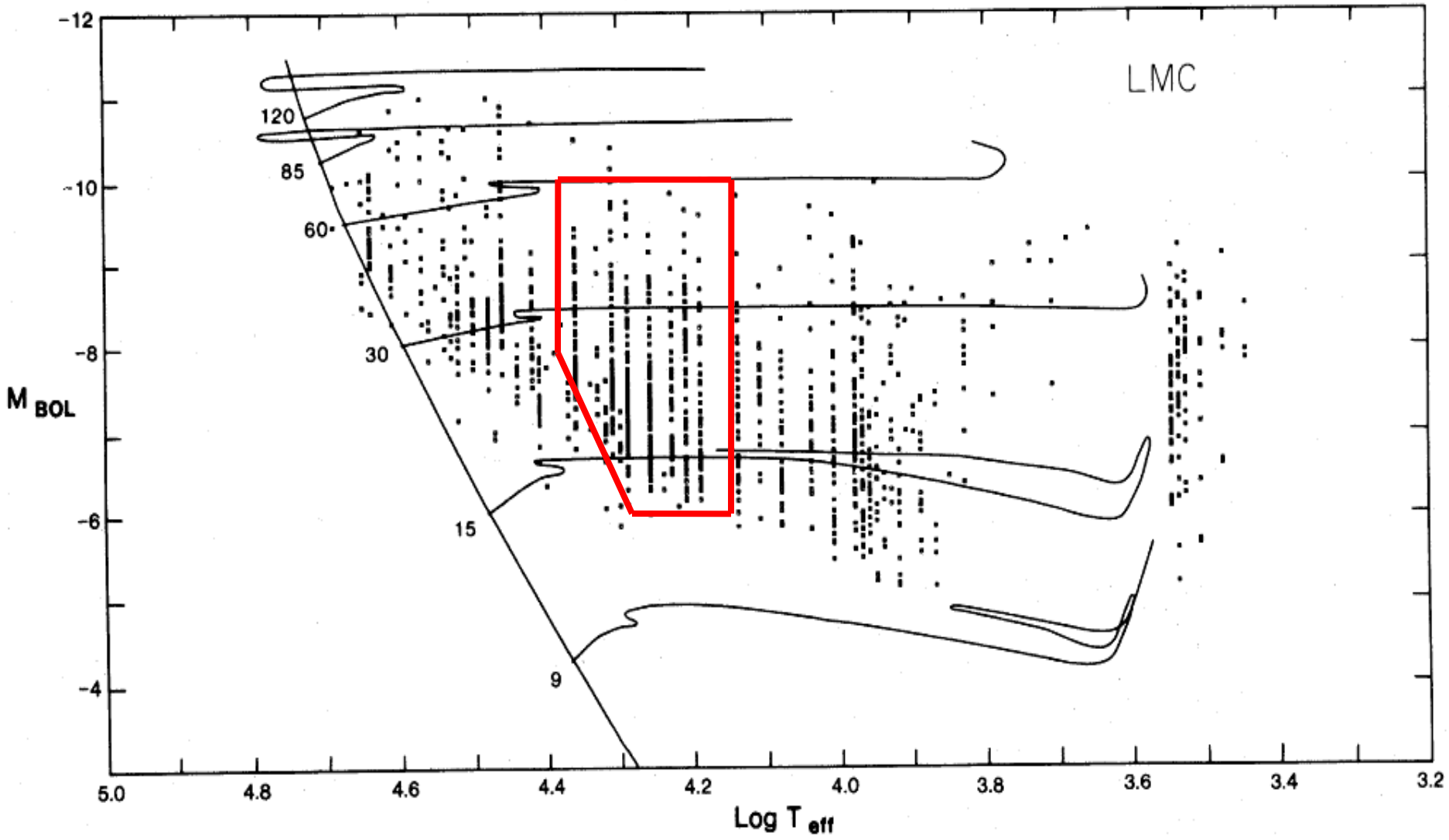
(Pols and Marinus, 1994; Van Bever and Vanbeveren, 1997, 1998; Vanbeveren et al. 2015)

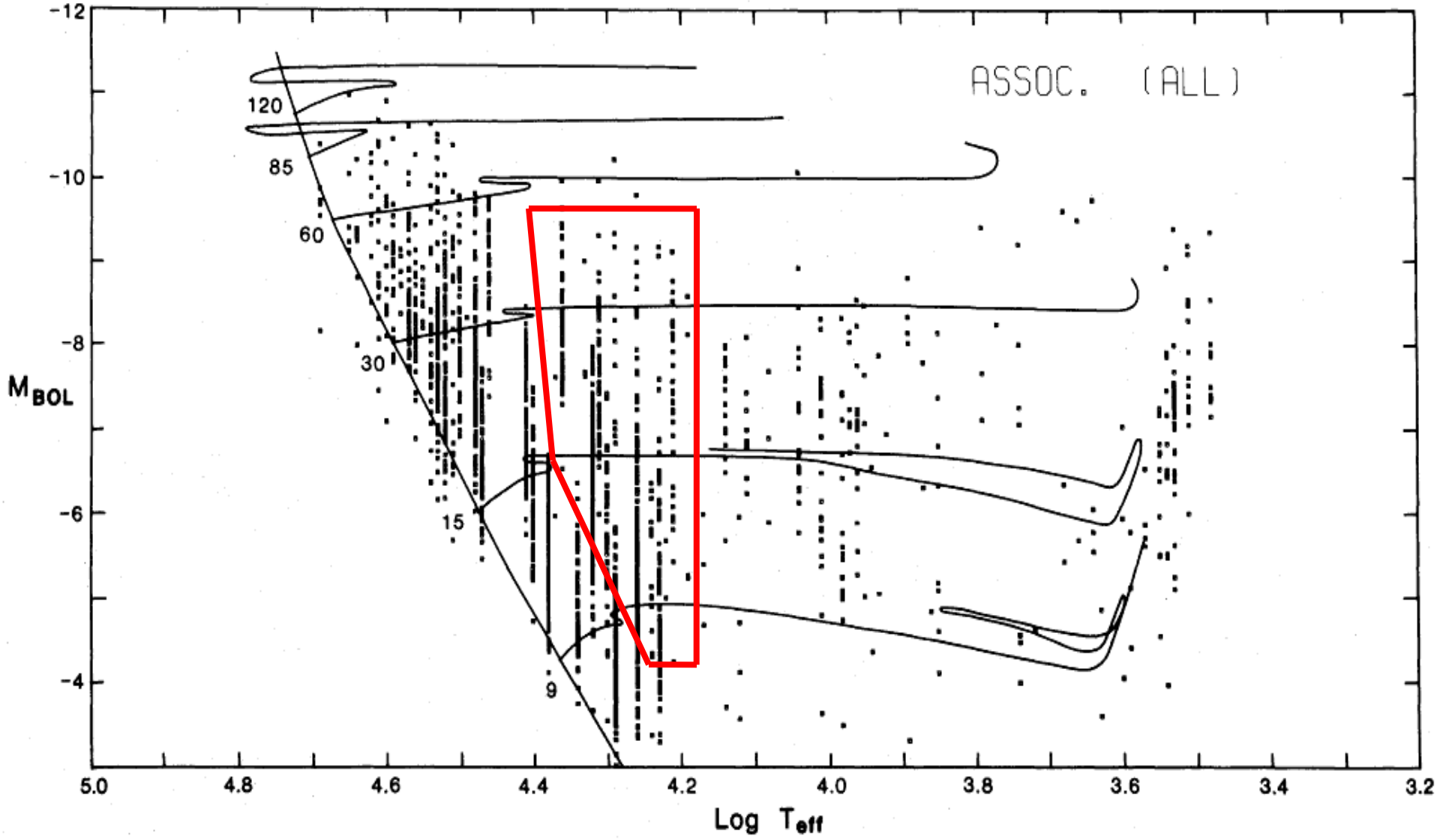
The post-RLOF binary hypothesis to explain a significant fraction of rapid rotators does not explain the very large Be-fraction in clusters with age around 20 Myr

		Age(Myr)	Observed Be fraction	Predicted rapid rotator fraction
Galaxy	h&χ Per	<20	0.2-0.5	0.02
	NGC 663	22	0.4	0.03
	NGC 3760	22	0.33	0.03
MCs	NGC 330	19	0.27	0.02
	NGC 2004	20	0.11	0.02
	NGC 1818	25	0.2	0.04

A problem that exists already 3-4 decades

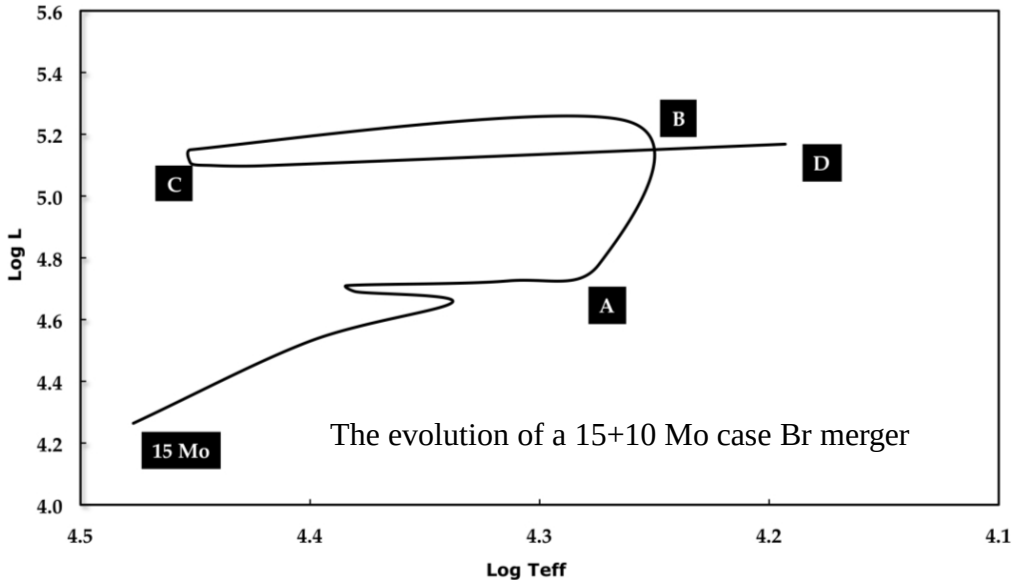
Observational data from Humphreys & McElroy, 1984




ASSOC. (ALL)
120
85
60
30
15
9
-12
-10
-8
-6
-4
M_{BOL}
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
Log T_{eff}

The answer could be case Br binary mergers …

Vanbeveren & Mennekens, 2013, Justham et al., 2014



... but binary mergers are expected to be rapid rotators and the observations tell us that most B-type supergiants are not rapid rotators

The answer could also be larger convective core overshooting in massive stars

the study of Claude Doom (1985) and the Roxburgh criterion for convection

Larger overshooting and the DTD of SNIa

Advice (not only for young scientists)

Before starting a research topic try to get a literature overview that is as complete as possible and do not forget that also in the previous millenium interesting studies have been published.

Conclusion

A theoretical population study of massive stars where binaries are ignored may have an academic value but may be far from reality.