Massive Binary Population Synthesis

Dany Vanbeveren

Vrije Universiteit Brussel

Liège 2018

What do we learn from the LIGO observations about the astrophysics of the progenitors of double compact star binaries?

Content

1. LIGO observations and massive star/binary evolution

2. LIGO observations and massive star/binary population synthesis

1. LIGO observations and massive star/binary evolution

The temporal evolution of stars = Plasma-physics not for softies

The hydrostatic pressure equation
Continuity equation
Energy equation
Energy transport
- radiative
- convective

Diffusion equation
Equation of state
Nuclear reaction network
Opacity as function of T and ρ

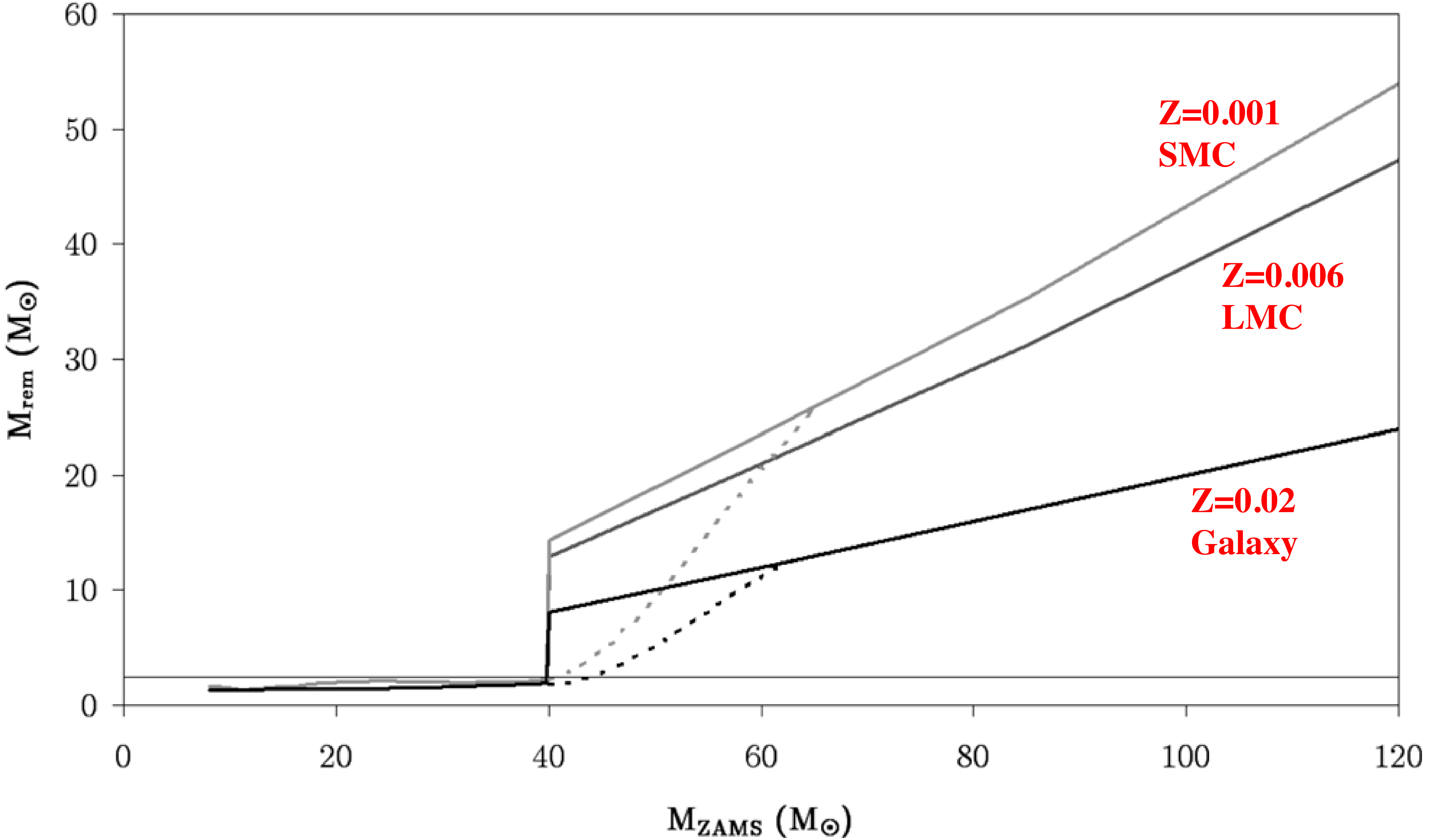
Massive star/binary evolution

Stellar wind mass loss
Rotation
Magnetic fields

Binarity
- Roche lobe overflow
- mass transfer

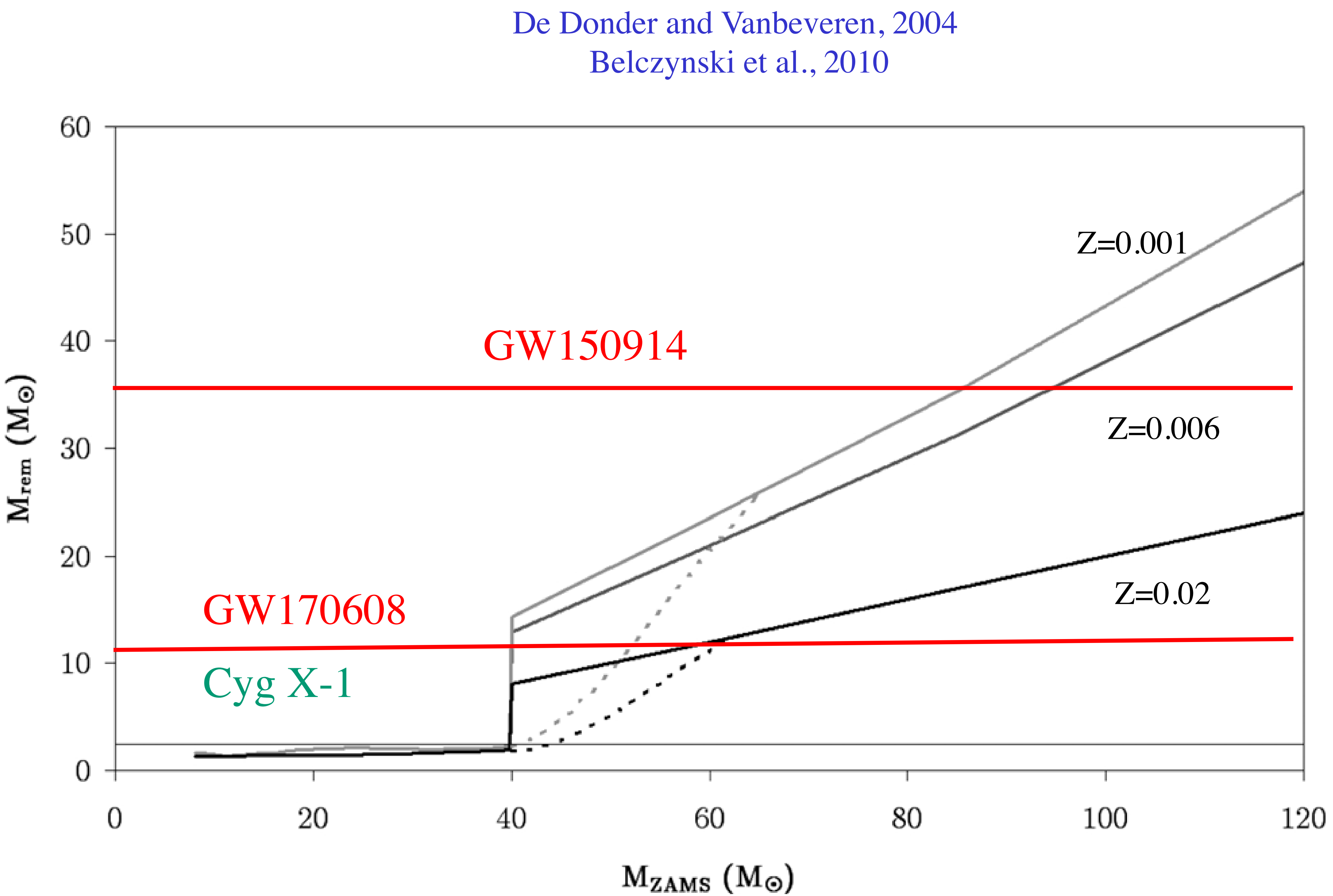
After more than 50 years of intensive research:
strenghts and weaknesses

De Donder and Vanbeveren, 2004; Belczynski et al., 2010



List of compact star binary merger events

GW event	Detection date Merger Type	Primary mass ($M_\odot$)	Secondary mass ($M_\odot$)	Notes
GW150914	2015-09-14 BH+BH	35.4	29.8	First detection; largest BH masses
LVT151012	2015-10-12 BH+BH	23	13	13% chance of being noise
GW151226	2015-12-26 BH+BH	14.2	7.5	
GW170104	2017-01-04 BH+BH	31.2	19.4	
GW170608	2017-06-08 BH+BH	12	7	Smallest BH masses
GW170814	2017-08-14 BH+BH	30.5	25.3	Detection by three observatories
GW170817	2017-08-17 NS+NS	1.36-1.6	1.17-1.36	GRB170817A



De Donder and Vanbeveren, 2004
Belczynski et al., 2010
60
50
40
30
20
10
0
Z=0.001
GW150914
Z=0.006
Z=0.02
GW170608
Cyg X-1
0
20
40
60
80
100
120
M_{rem} ($M_\odot$)
M_{ZAMS} ($M_\odot$)

2. Ligo observations and massive star/binary population synthesis

Combine all we know about

> the formation of stars and binaries
> the evolution of stars and binaries
> the effect of an SN explosion in a binary

In a galactic context

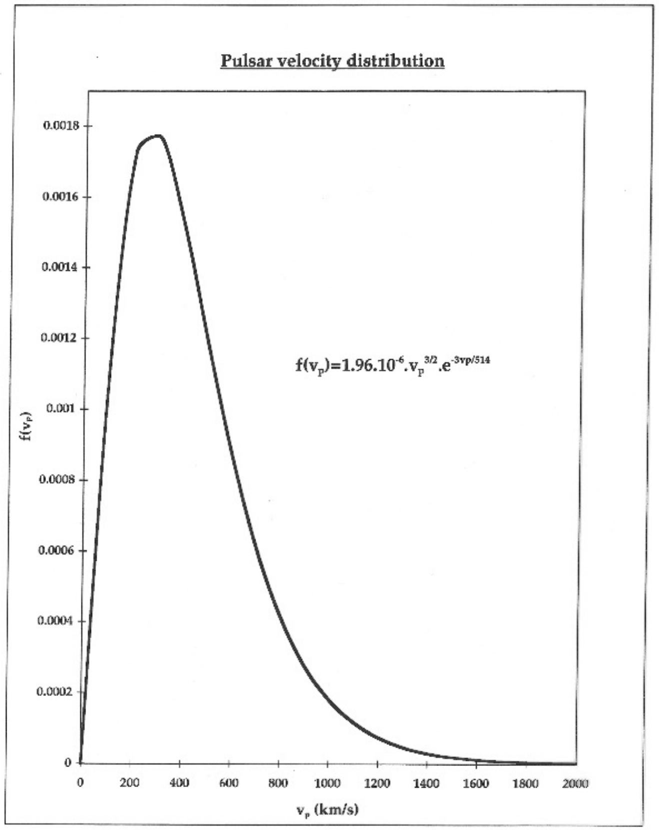
> the formation of stars and binaries as function of time
> the temporal evolution of the metallicity of a galaxy

Comparison with ALL available observations of populations

- OB stars
- WR stars
- High mass X-ray binaries
- Supernovae
- Double compact star binaries
- Etc.

The NS sample in the Galaxy

- The (pecular) space velocity distribution of more than 1000 pulsars



The NS sample in the Galaxy

- The (pecular) space velocity distribution of more than 1000 pulsars

- 12 NS+NS binaries

  Kim et al., 2015: based on the orbital parameters the NS+NS binaries, the merger rate in the Galaxy is estimated to be 7-50 events/Myr (average is 20 ; could be a factor 2 larger)

- A NS+BH binary has not been observed (yet)

The baryonic mass of the Galaxy = 6.10^{10} Mo (McMillan, 2011)

R-process elements with A > 140 in Sun = 3.1 10^{-8} Mo

Galactic content at the moment the Sun was born = 1860 Mo

Suppose only NSNS merger events
Suppose only NSBH merger events

Bauswein et al. (2014): 0.01 Mo per event, 75% R-process elements with A > 140
0.04

1860/(0.75*0.01) = 248000 events
1860/(0.75*0.04) = 62000 events

Sun was born 8.5 Gyr ➔ 28 events/Myr
7 events/Myr

Massive star/binary population codes
the study of double compact star binaries and mergers

Belczynski et al., 2008 (StarTrack)
Dominik et al., 2012, 2015 (StarTrack)
Portegies Zwart et al., 1996 (SeBa)
Eldridge & Stanway, 2008 (BPAS)
Voss & Tauris, 2003
Bogomazov et al., 2007

The Brussels population code (in a galactic context)

Vanbeveren et al. 1998

4 PhDs: De Donder 2004
Van Bever, 2004
Belkus, 2007
Mennekens, 2014

The formation channels of binary black holes (BBH) that merge within Hubble time in general, the progenitor of GW150914 in particular

1. The field binary evolution model via common envelope evolution (Dominic et al., 2012)

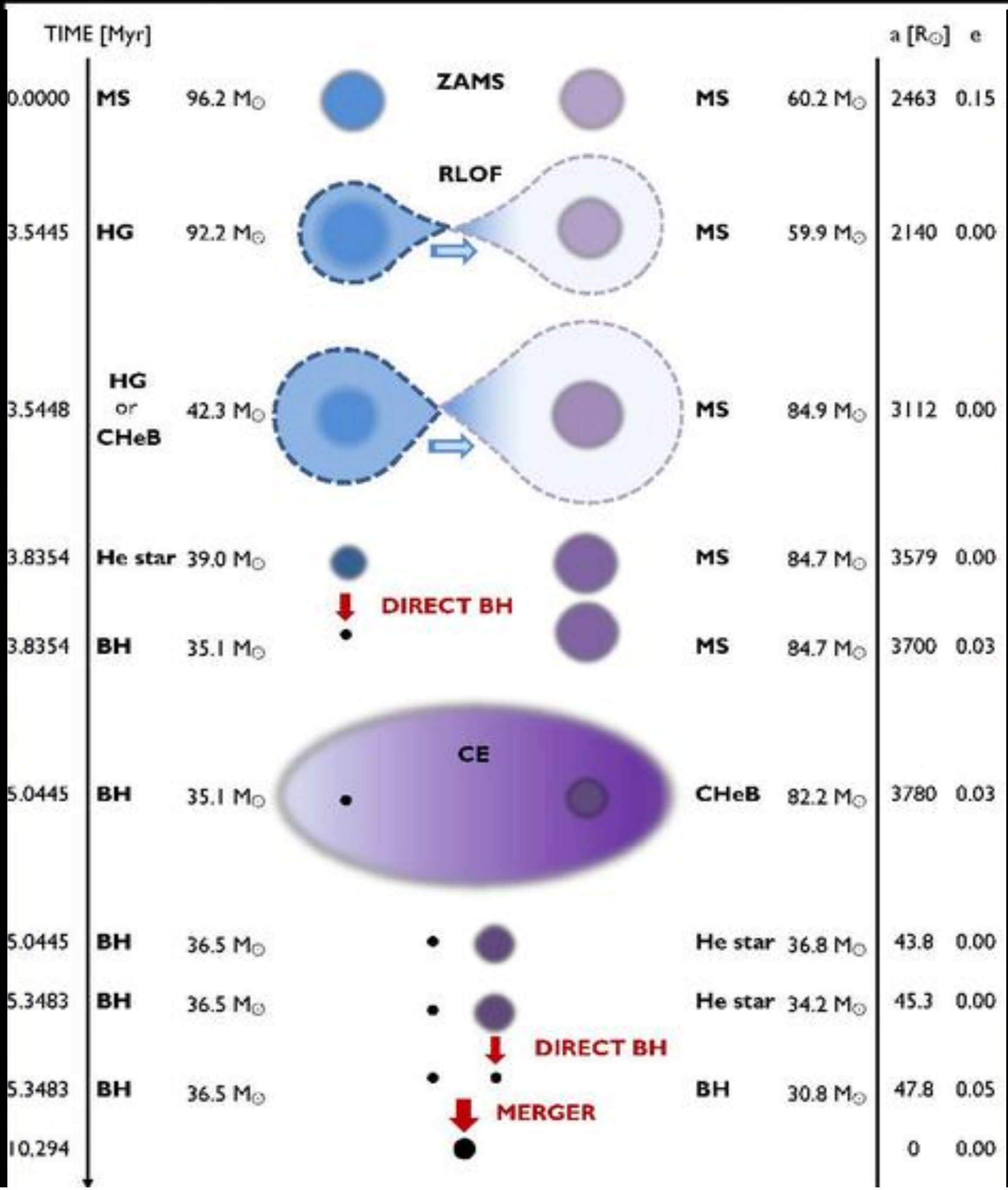
2. Chemically homogeneous evolution of tight massive binaries (De Mink & Mandel, 2016; Marchant et al., 2016)

3. Merger rates of BBH formed by stellar dynamics in Globular Clusters (Rodriguez et al., 2016) ➔ **GW170104 a 32Mo+19Mo double BH-binary where the BHs may have misaligned spins**

4. More exotic or may be not so exotic: primordial double black holes (Bird et al., 2016)

BBH Formation from Isolated Binaries

Dominik et al., 2012
Belczynski et al., 2016

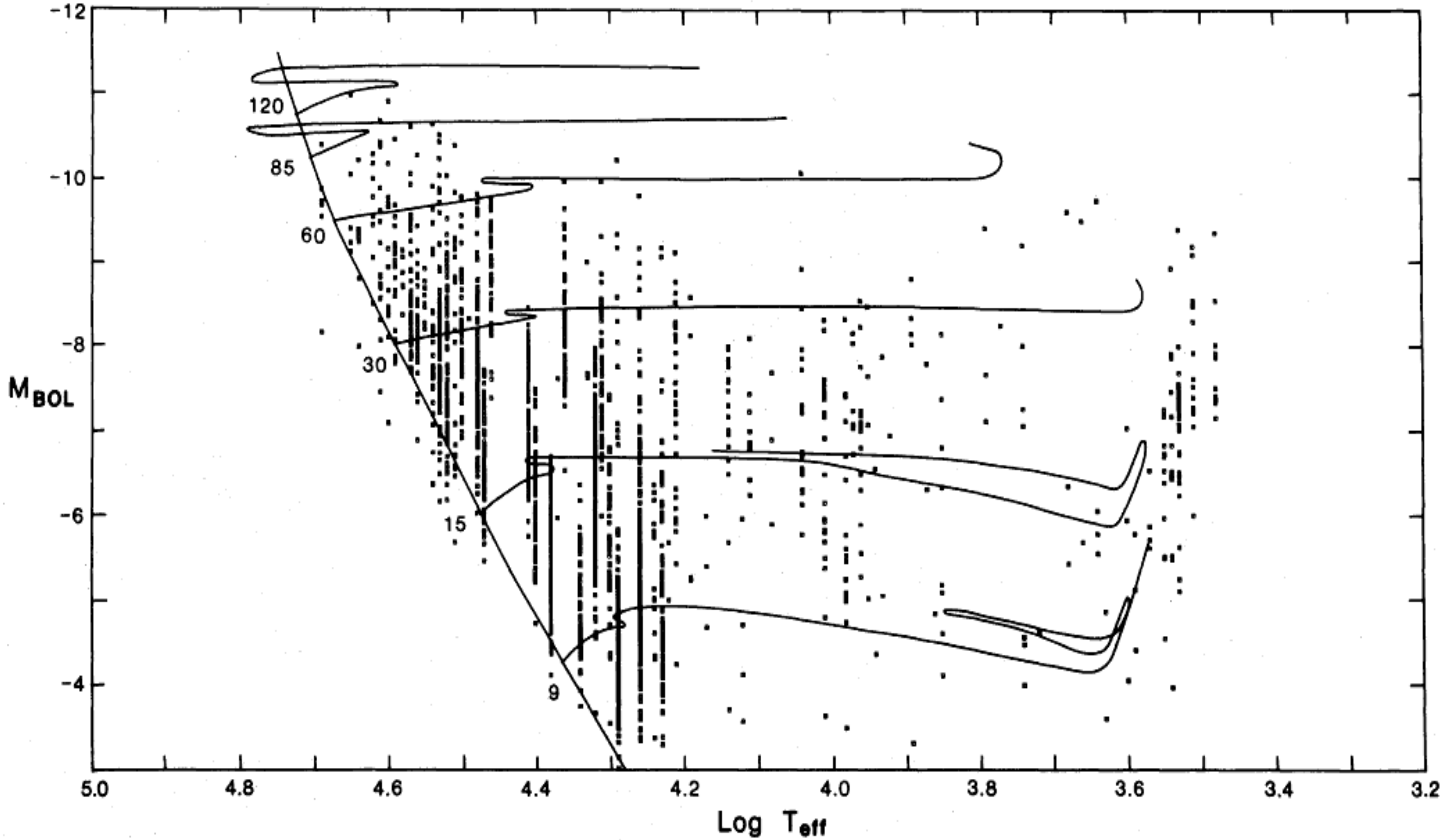


Results

- Population models that meet as much as possible the constrains imposed by ALL available observations predict that Advanced LIGO with the design sensitivity should detect at least 5-10 times more NSBH mergers than NSNS mergers

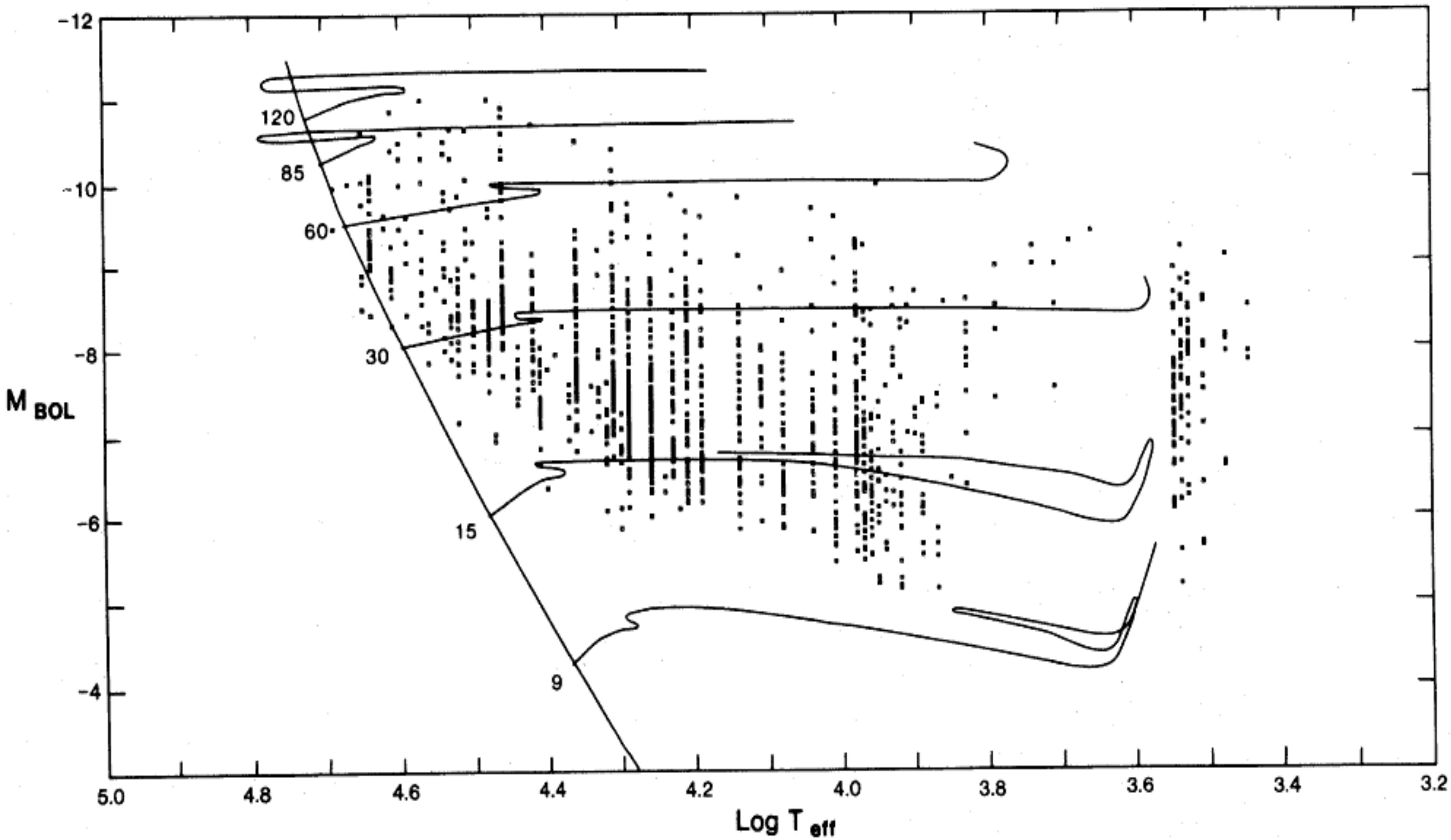
- However, the population models that use the BHBH formation scenario outlined on the previous slide predict that Advanced LIGO with the design sensitivity should detect at least 5-10 BHBH mergers PER DAY

Observational data of Galactic Association stars in the Solar neighborhood
from Humphreys & McElroy, 1984



2500 stars

Observational data of LMC stars from Humphreys & McElroy, 1984



1300 stars

The effect of LBV/RSG mass loss on the population of double compact binaries, double compact binary mergers and GW-detection rates

(the case GW150914)

Mennekens and Vanbeveren (2014)

Stellar wind mass loss during the LBV/RSG phases is large enough to reduce significantly the importance of the RLOF/common envelope process in case B/C binaries with initial mass > 40 Mo

If this is true also for small Z the effect on the detection rates is enormous (up to a factor 1000); primarily the BH-BH merger rate is affected.

If this is true also for small Z it is possible that a double BH leading to GW150914 cannot be formed via the CE of a field massive binary

Conclusion

GW observations will play a decisive role in our understanding of the physics of stars and stellar systems, the building blocks of the universe.

SMC AB8 in the SMC

(Shenar et al., 2016)

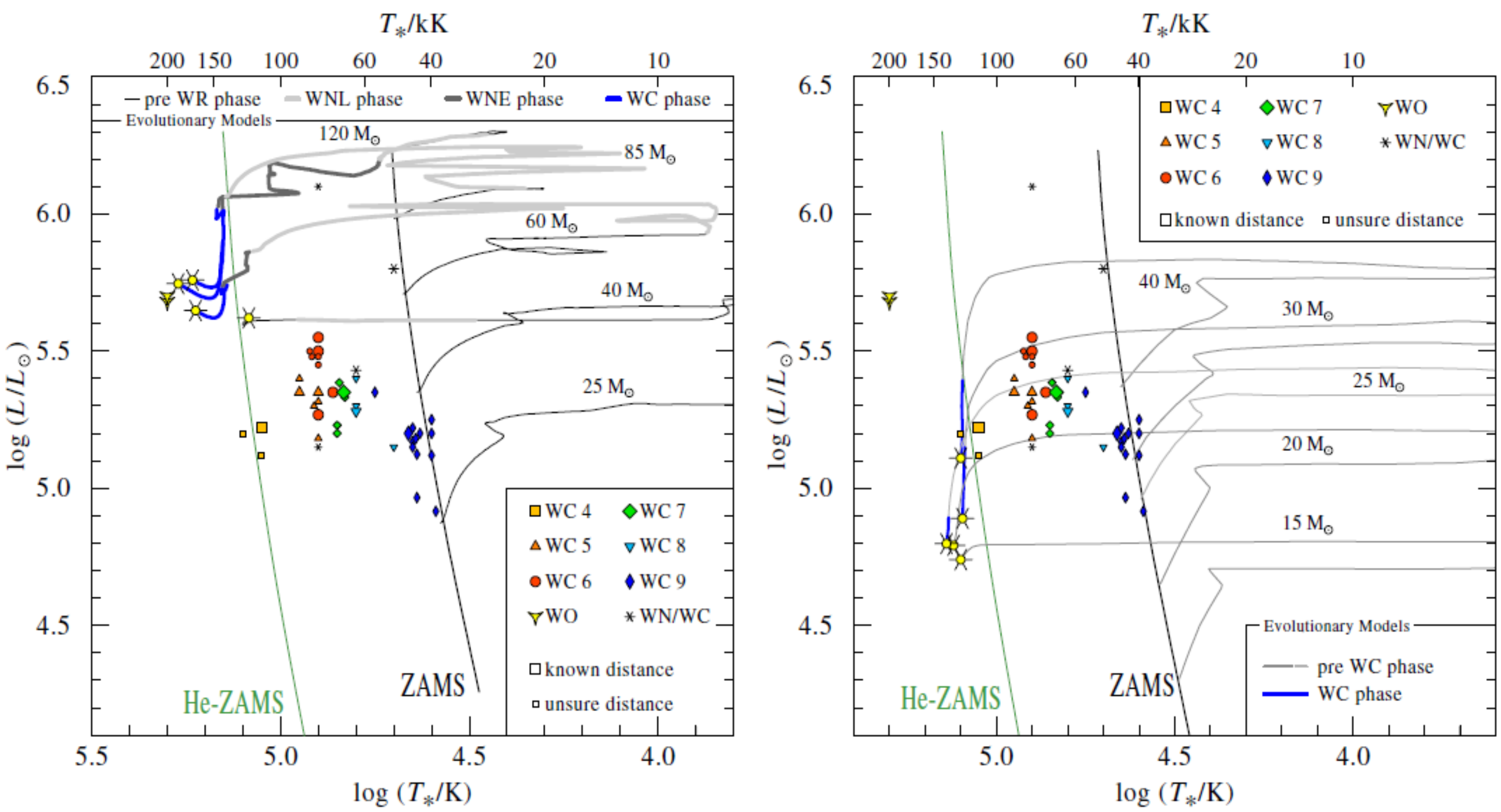
WO4 + O4V

Period P = 16.6 days

19 $M_{\odot}$ + 61 $M_{\odot}$

V_{rot} ~190 km/s

The HR-Diagram of WC stars



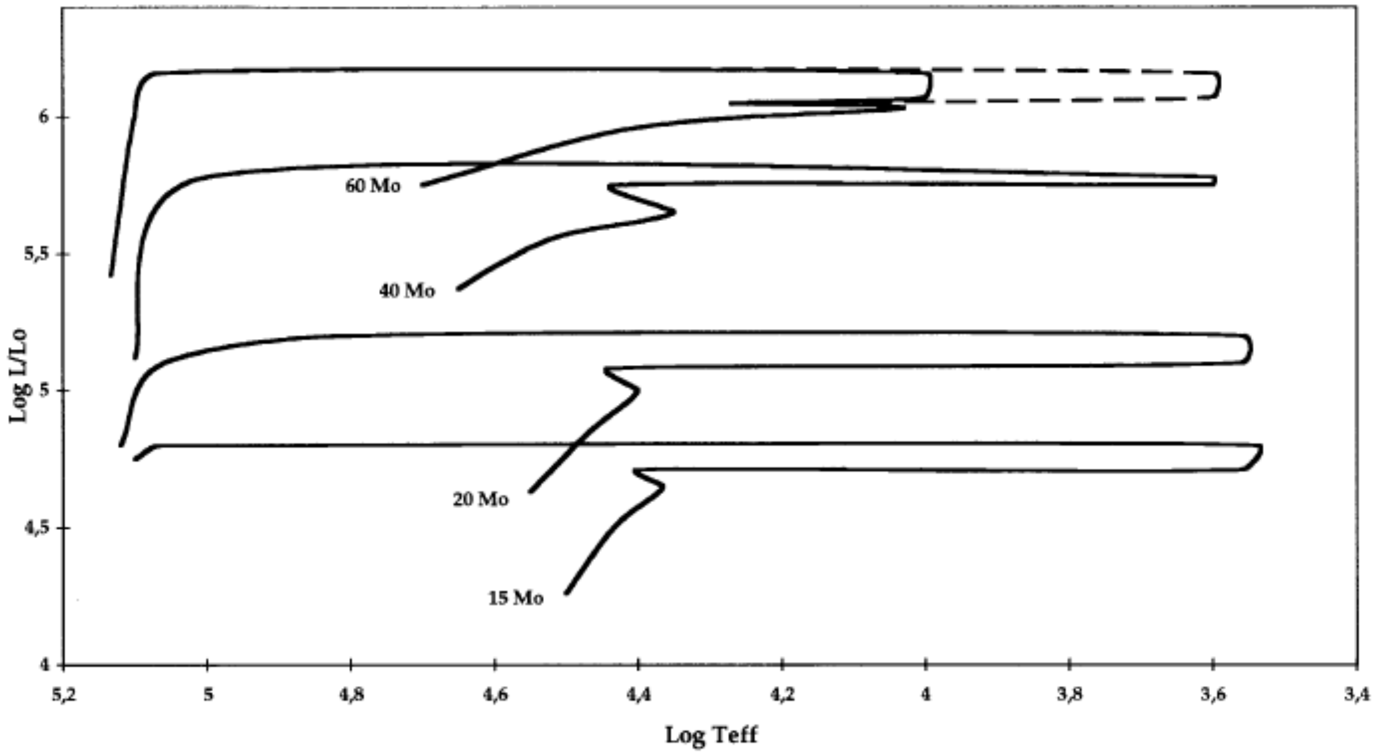
Galactic WC stars: Sander et al., 2012

Due to mass and angular momentum transfer during RLOF spin-up of the gainer implying differential rotation ➔ formation of a magnetic field due to the dynamo process (Spruit, 2002) ➔ the magnetic field provides the mechanical energy that drives mass out of the binary and this mass loss may be of the order of the mass accretion rate (Tout & Pringle, 1992) ➔ mass loss corotating up to the Alfvén surface causes efficient spin-down ➔ if magnetic fields are generated of the order of a kiloGauss, then the spin-down rate is of the same order as the spin-up rate

➔ the process explains why mass gainers may not reach the critical rotation despite significant mass accretion.

Vanbeveren et al, 1996, 1998

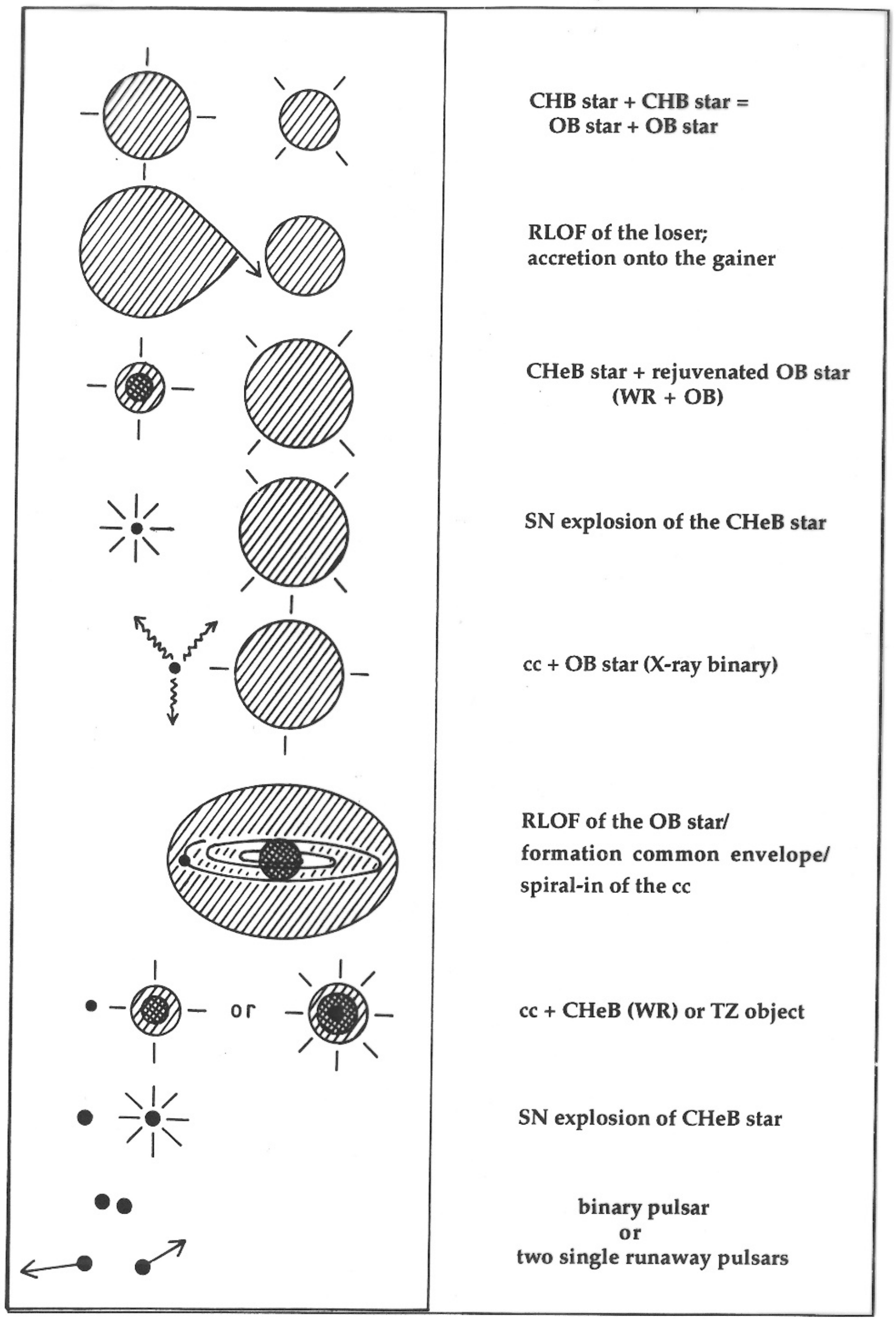
The evolution of single stars with alternative (compared to De Jager et al., 1988)
RSG mass loss rates



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; Meynet et al., 2014)

The evolution of a massive binary

Van den Heuvel & Heise, 1972



WR binaries in the Solar Neighbourhood
SALT observations of vrot

Shara, Crawford, Vanbeveren, Moffat, Zurek, Crause, 2016

System	Sp. Type	Period (d)	WR mass	OB mass	vrot
WR21	WN5 + O4-6	8,3	19,0	36,9	355 (440)
WR30	WC6 + O6-8	18,8	16,4	34,0	497 (520)
WR31	WN4 + O8V	4,8	7,6	17,8	312 (493)
WR42	WC7 + O7V	7,9	13,7	22,9	496 (574)
WR79	WC7 + O5-8	8,9	10,6	28,9	224 (290)
WR97	WN5 + O7	12,6	12,2	21,7	474 (502)
WR113	WC8 + O8-9IV	29,7	12,7	26,7	354 (360)
WR11	WC8 + O7.5III-V	78,5	9,6	30,5	225 (232)
WR127	WN3 + 09.5V	9,5	16,9	36,4	305 (365)
WR139	WN5 + O6III-V	4,2	9,3	27,9	219 (365)