# The formation of Wolf-Rayet stars at low metallicity

Tomer Shenar

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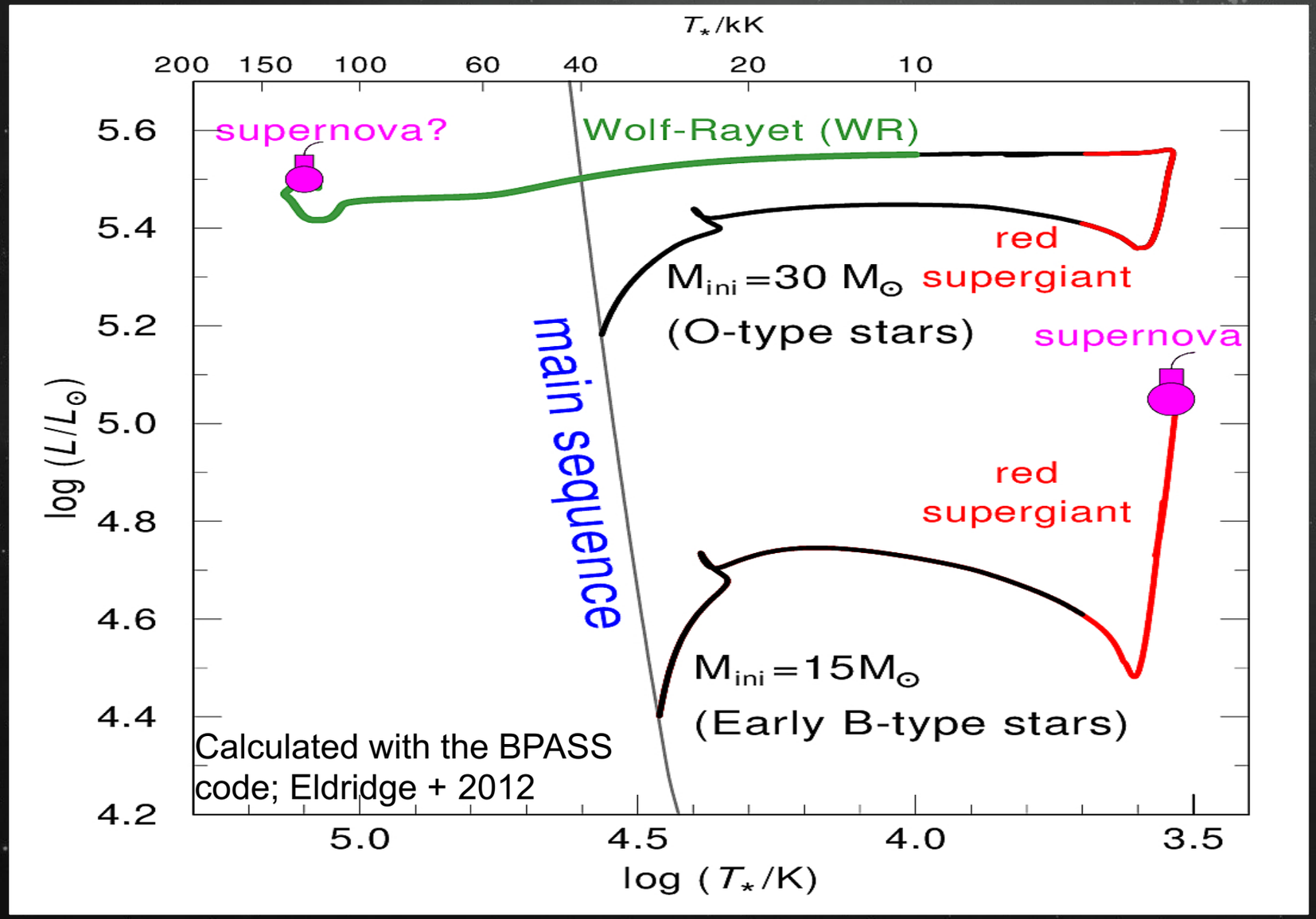
# Massive-star evolution in 30 seconds

- $M_i \lesssim 20 M_\odot$ (in Galaxy):
  RSG → SN II

- $M_i$ ~> 20 $M_\odot$ →
  WR star (→ SN Ib/c?)



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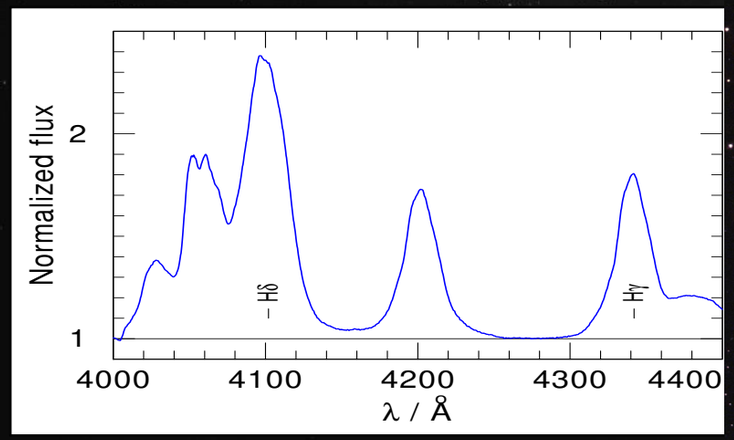


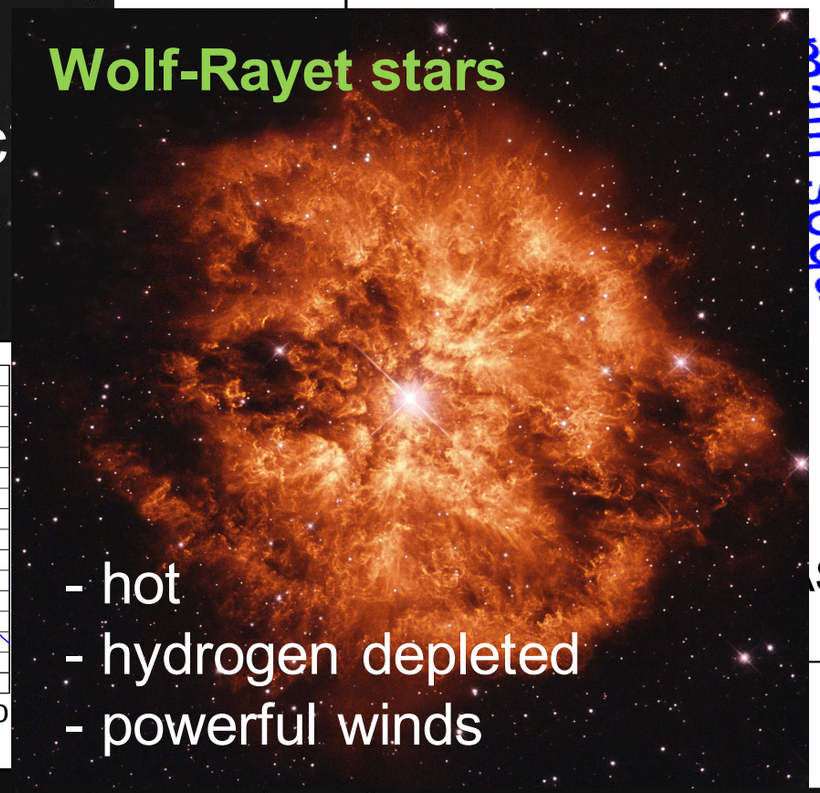

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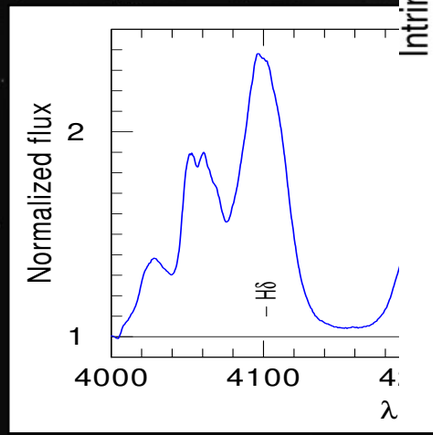
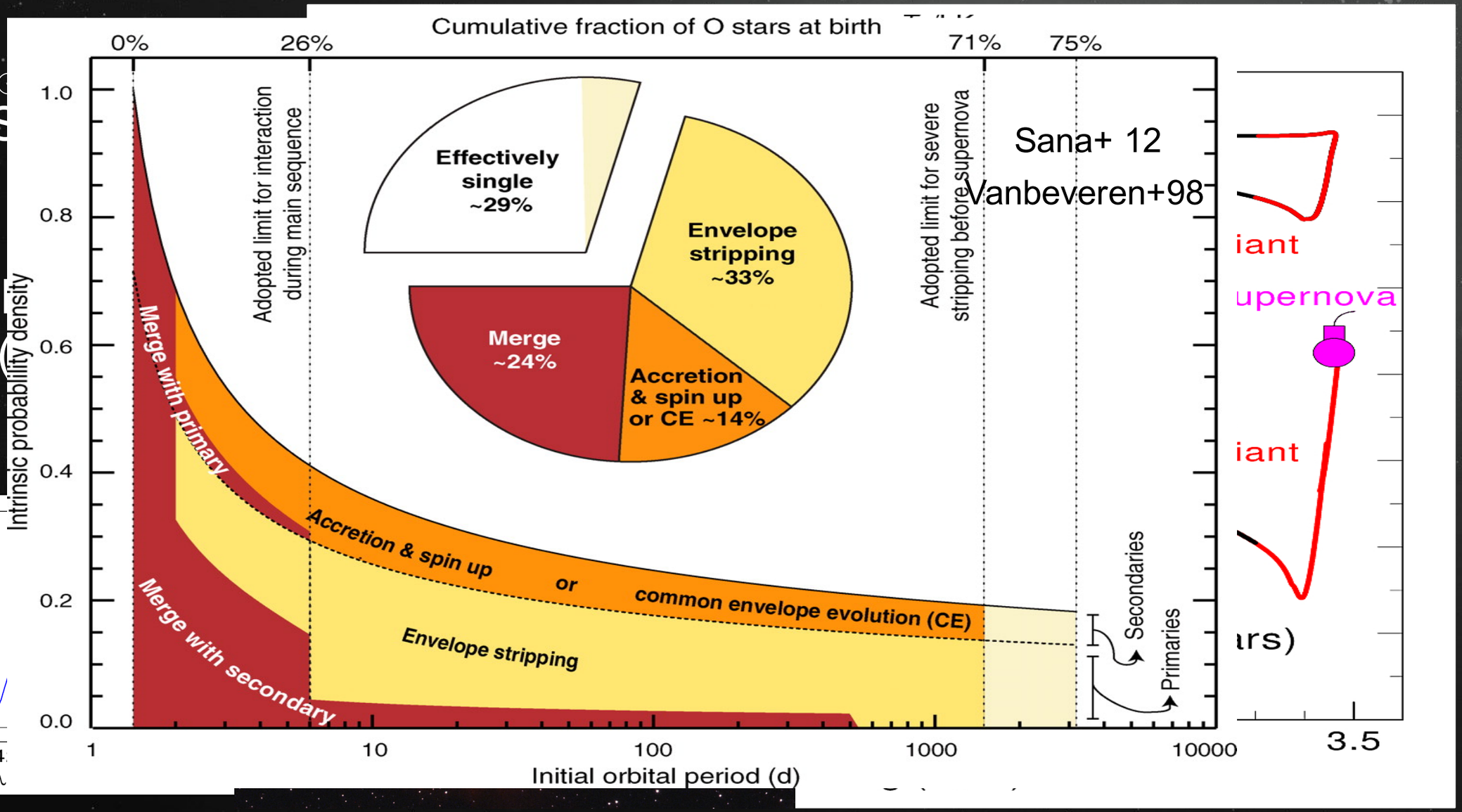
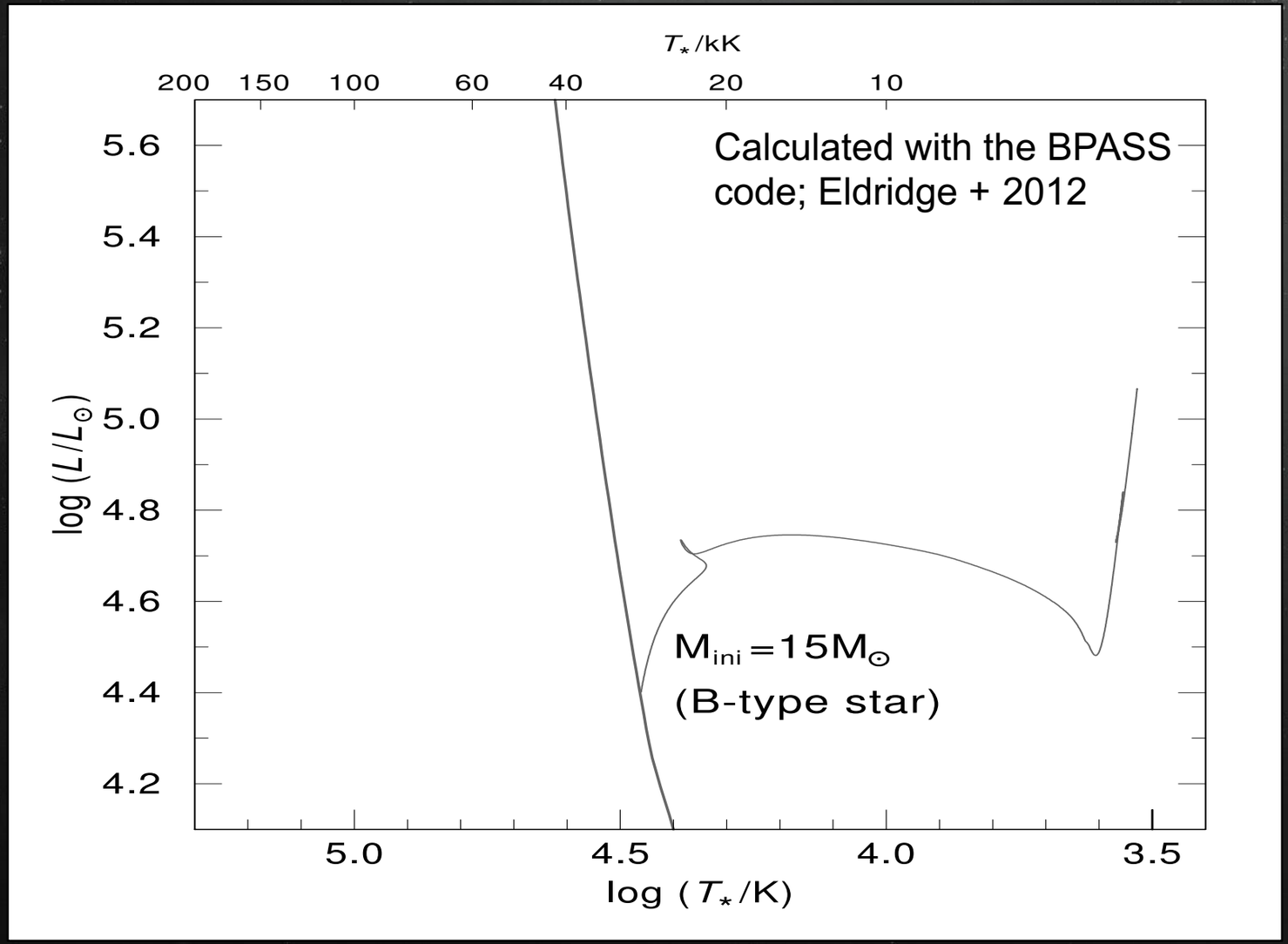


# Binary evolution in 30 seconds

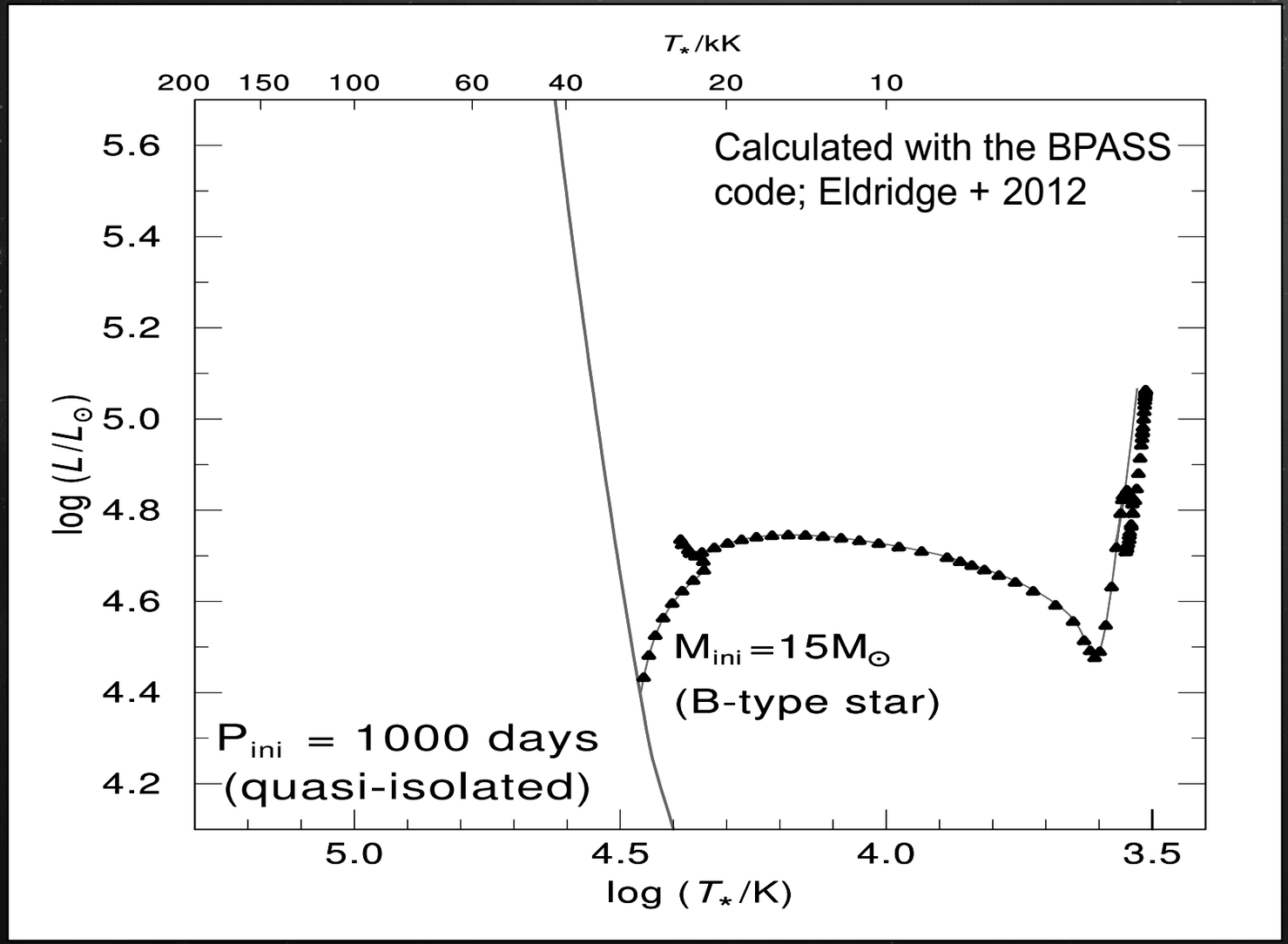
- 15Msun: RSG → SN II



# Binary evolution in 30 seconds

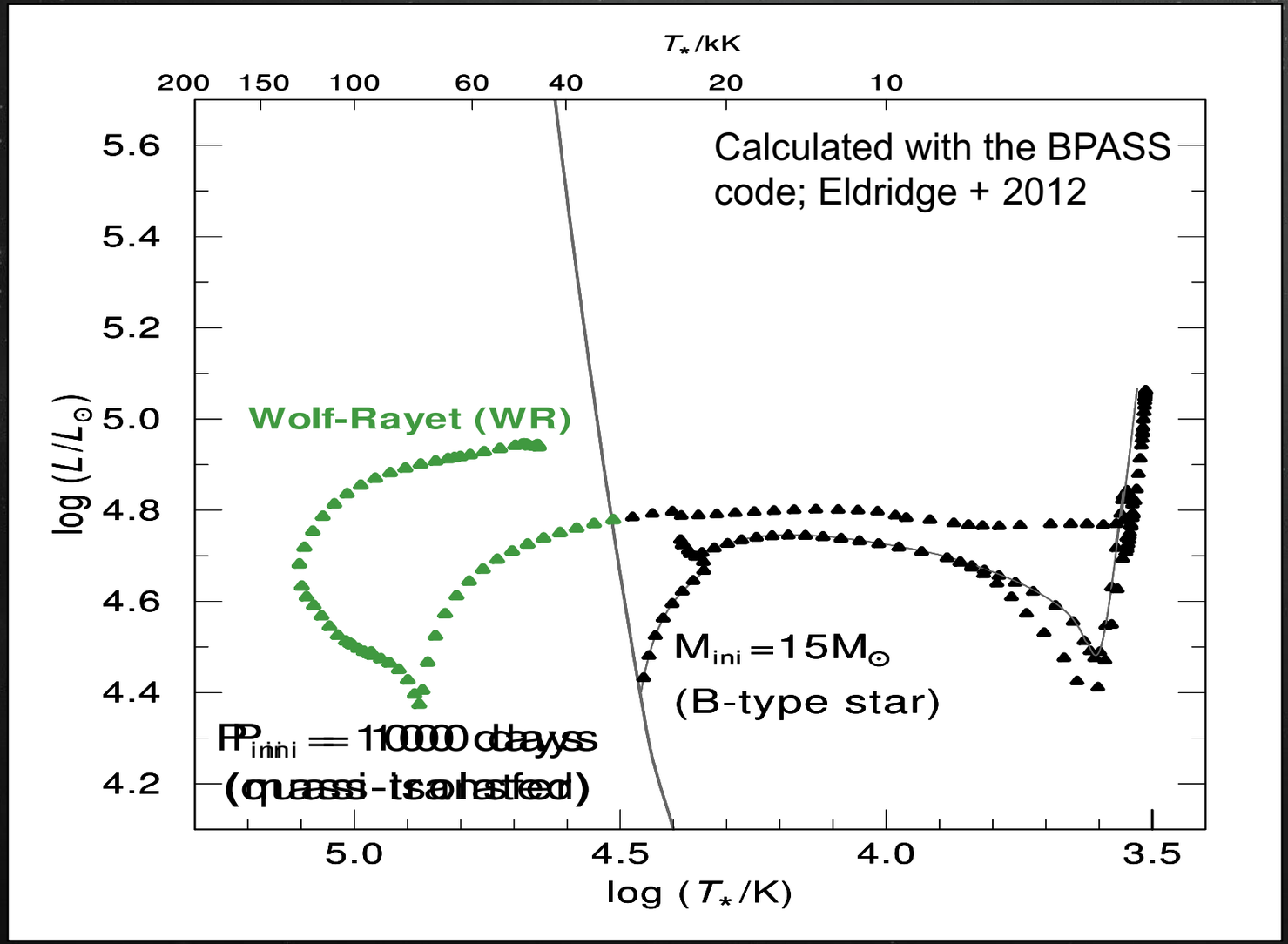
- 15Msun: RSG → SN II

- P=1000d → quasi single



# Binary evolution in 30 seconds

- 15Msun: RSG → SN II
- P=1000d → quasi single
- P=100d → WR-like



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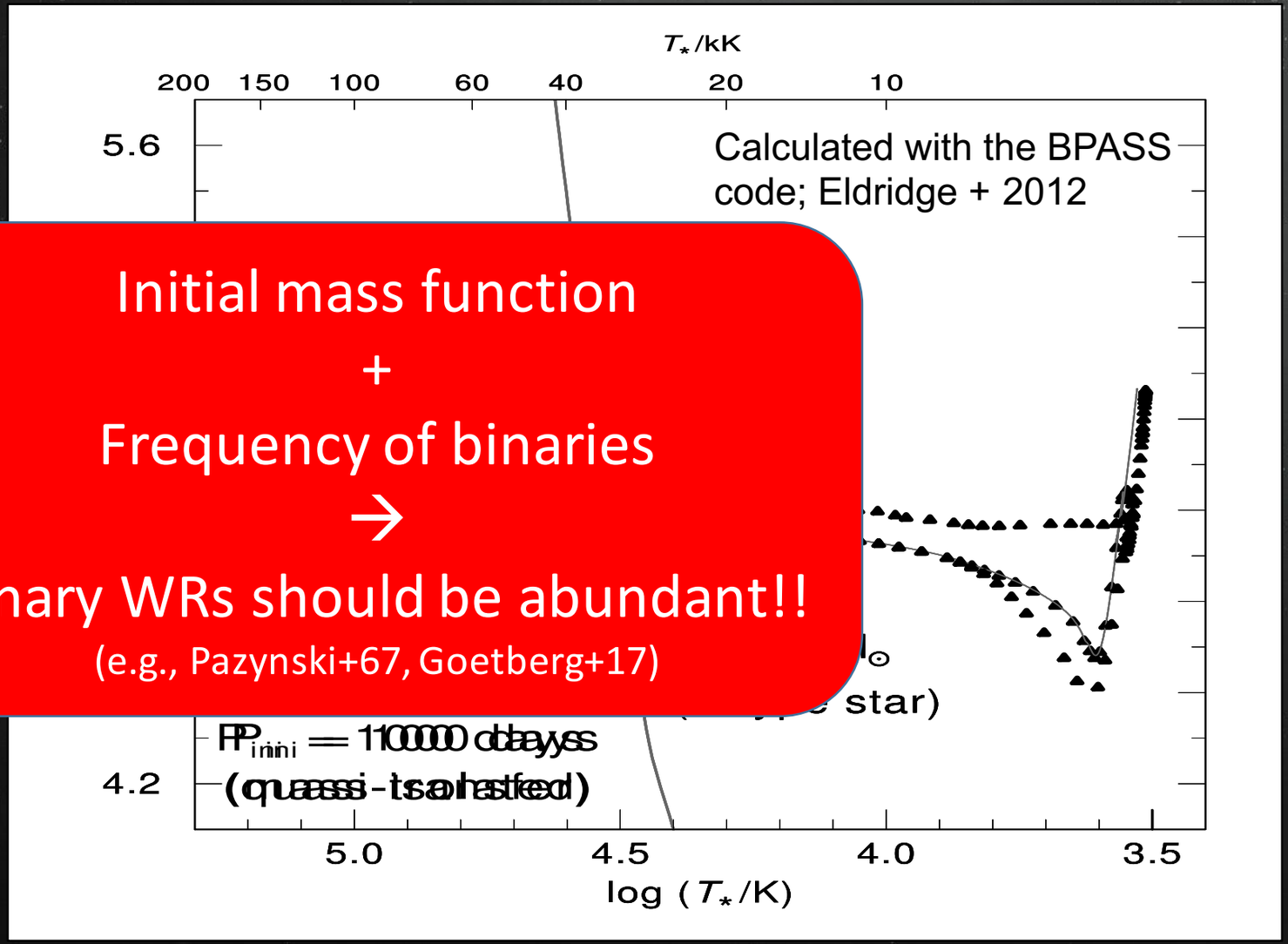
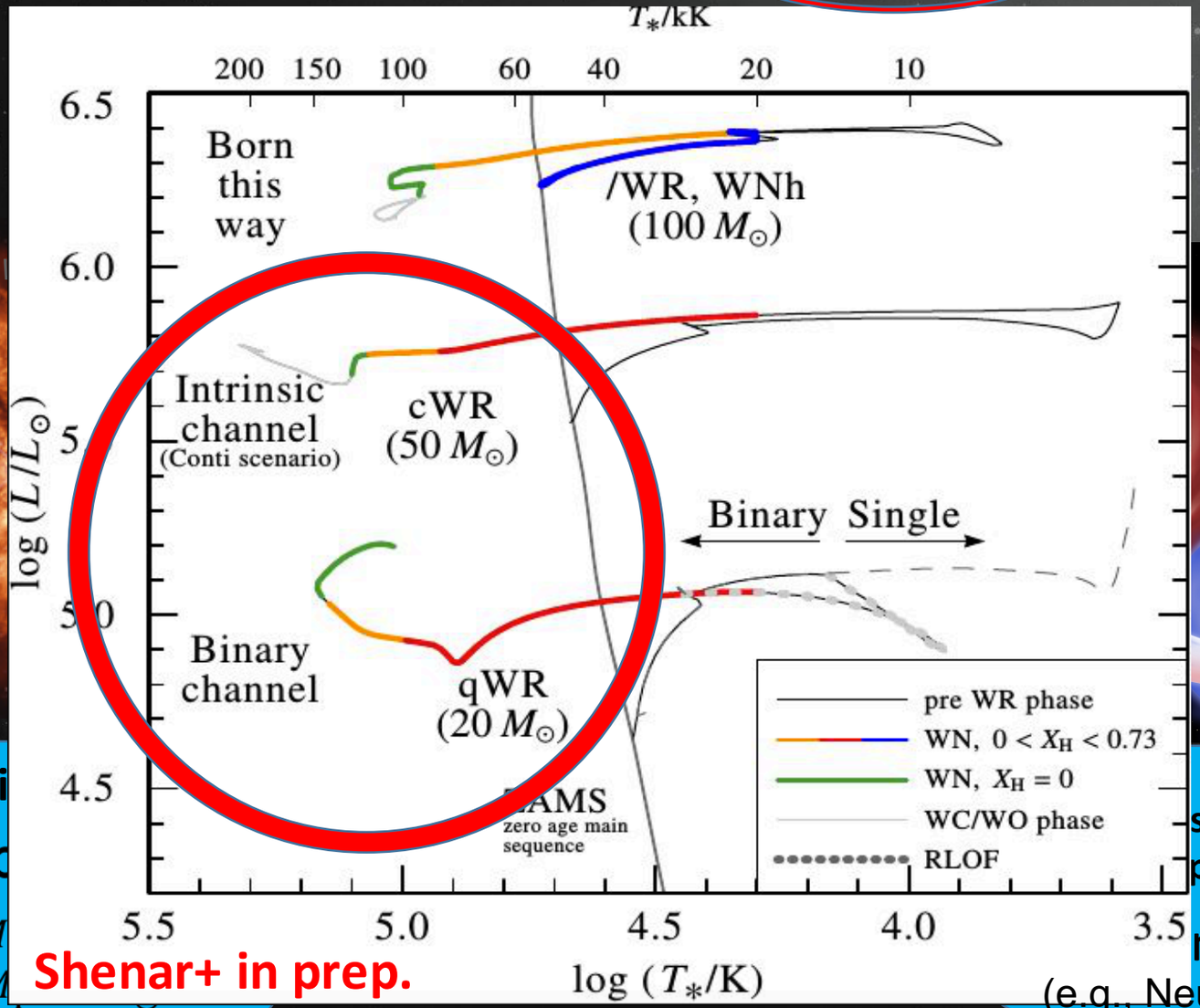
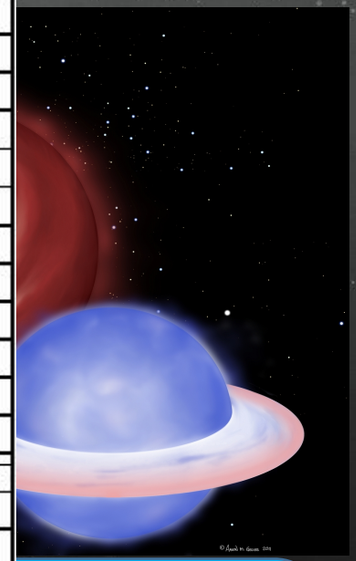



Initial mass function
+
Frequency of binaries
→
Binary WRs should be abundant!!
(e.g., Pazynski+67, Goetberg+17)

# Formation channels of classical WR stars




Shenar+ in prep.



Intrinsi

$\dot{M}$ c

MW: $M$

SMC: $M$

sfer in binaries

ped stars")

ndent of Z

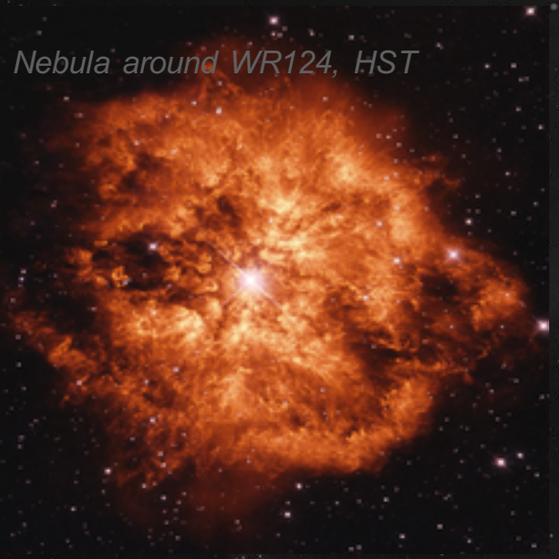
(e.g., Neugent+ 2014)

1. Paczynski 1967, Acta Astron, 17, 355 2. Vanbeveren et al. 1998, A&A Rev, 9, 63

# Formation channels of classical WR stars

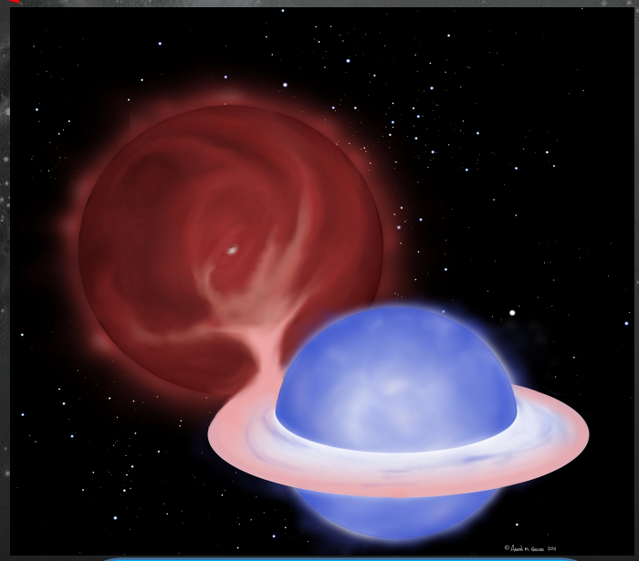
Single-star channel

Binary Channel[1,2]



Nebula around WR124, HST

**The binary channel should become important at low-Z environments**



**Intrinsic mass-loss**

$$\dot{M} \propto Z^{\alpha}$$

MW: $M_{\rm i} > 20 M_{\odot}$

SMC: $M_{\rm i} > 60 M_{\odot}$

**Mass-transfer in binaries ("stripped stars")**

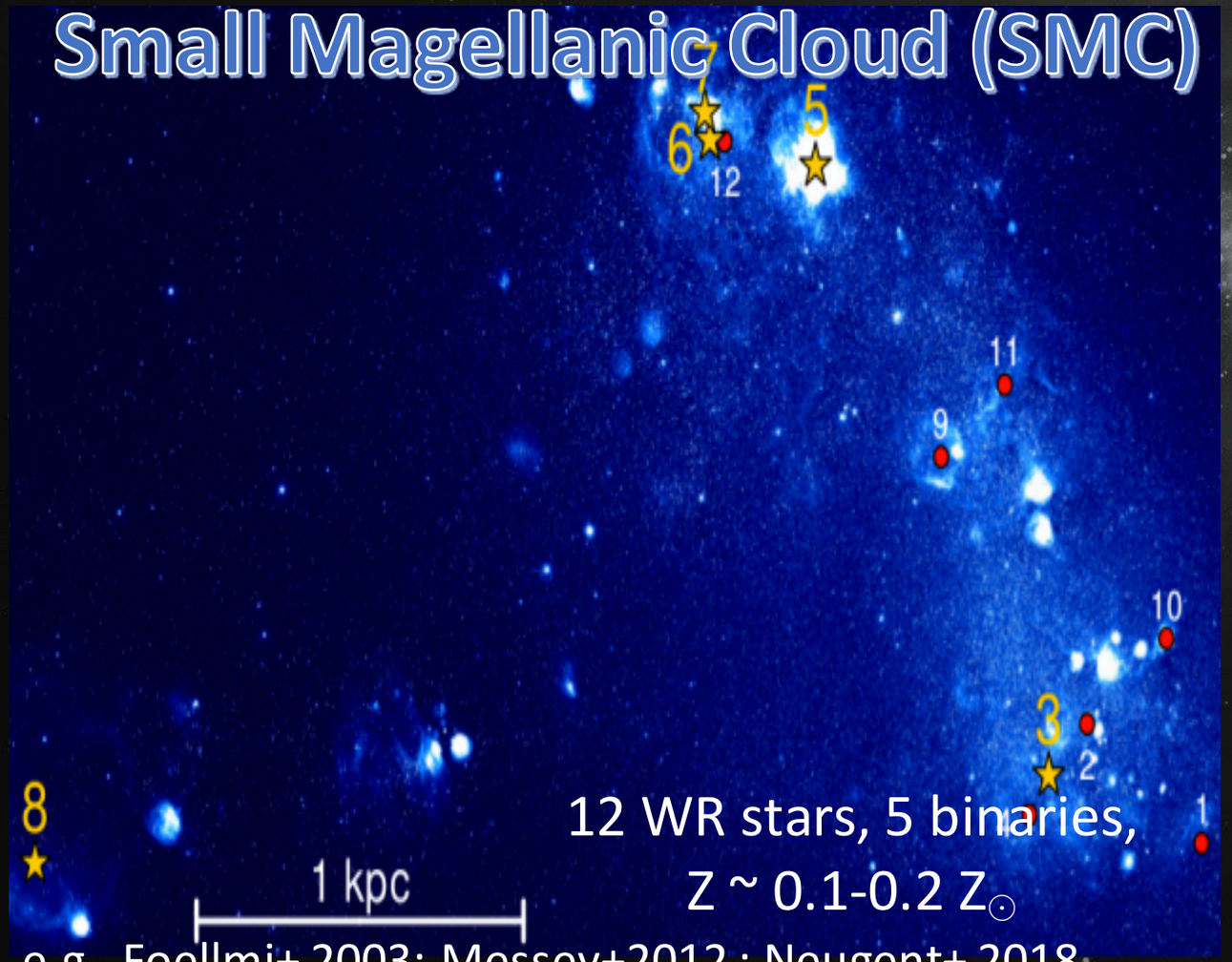
independent of Z

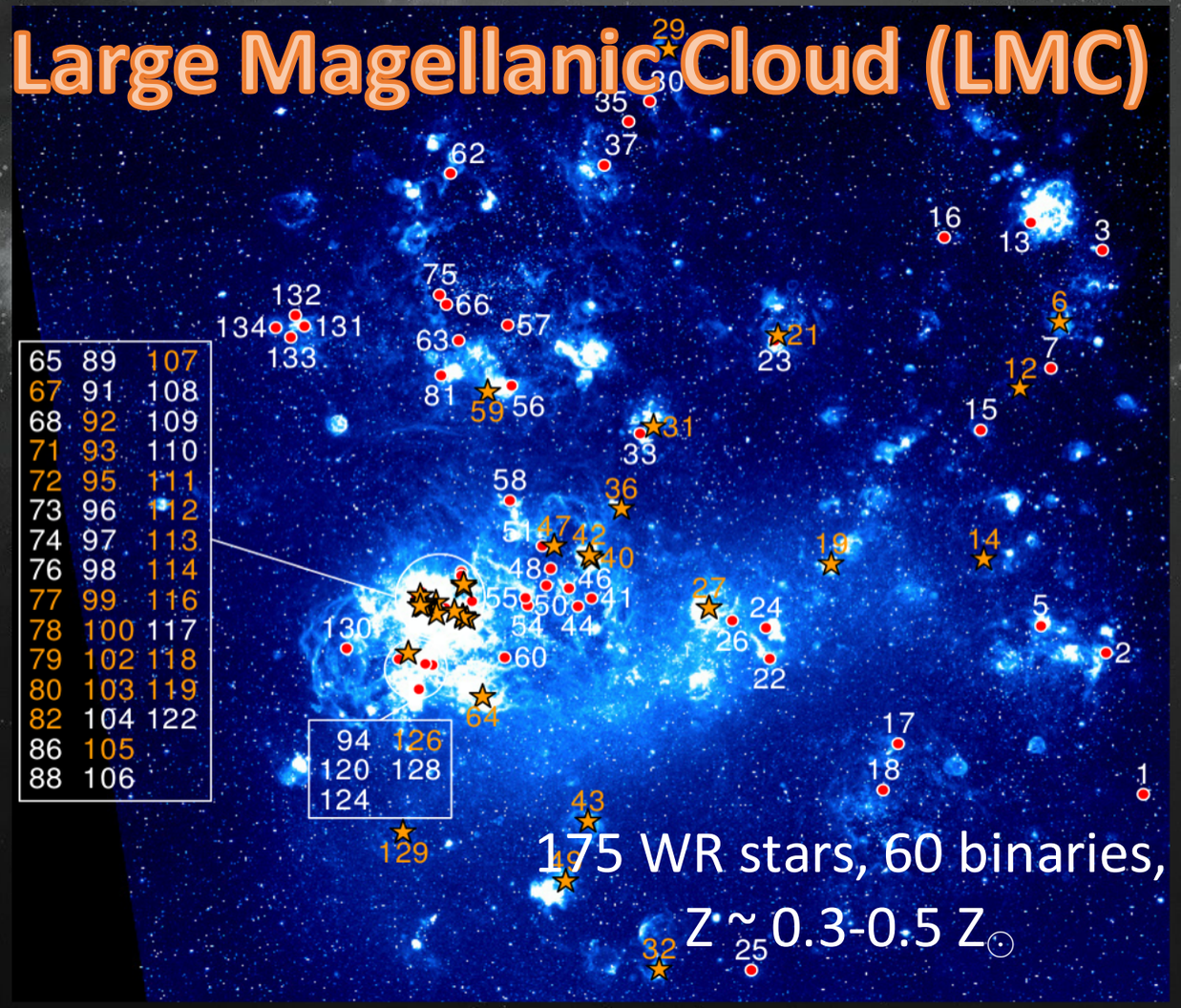
(e.g., Neugent+ 2014)

1. Paczynski 1967, Acta Astron, 17, 355 2. Vanbeveren et al. 1998, A&A Rev, 9, 63

# The Magellanic Clouds:

G. Wade, yesterday: “Phil Massey, today: ‘The MCs are ideal laboratories….’ “




e.g., Foellmi+ 2003; Messey+2012 ; Neugent+ 2018

# The Magellanic Clouds:

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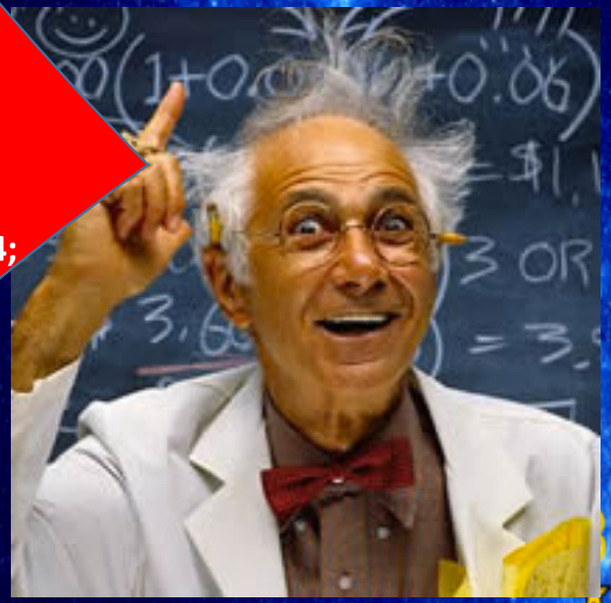
## Small Magellanic Cloud (SMC)

**Theory:**
**All WR stars in the SMC form via binarity**
**(e.g. Maeder & Meynet 94; Georgy et al. 2015)**



12 WR stars, 5 binaries,
$Z \sim 0.1\text{-}0.2\ Z_{\odot}$

1 kpc

e.g., Foellmi+ 2003; Messey+2012 ; Neugent+ 2018

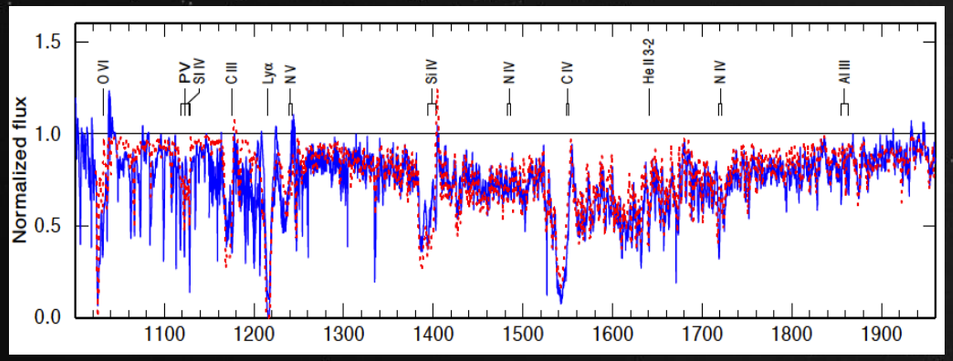
## Large Magellanic Cloud (LMC)

65 89 107
67 91 108
68 92 109
71 93 110
72 95 111
73 96 112
74 97 113
76 98 114
77 99 116
78 100 117
79 102 118
80 103 119
82 104 122
86 105
88 106

94 126
120 128
124

175 WR stars, 60 binaries,
$Z \sim 0.3\text{-}0.5\ Z_{\odot}$

# Working plan




**Spectral analyses (PoWR, Hamann+ 2002)**

Data: Foellmi+ 2003, Schnurr+ 2008, ESO / MAST archives, Torres+Massey…

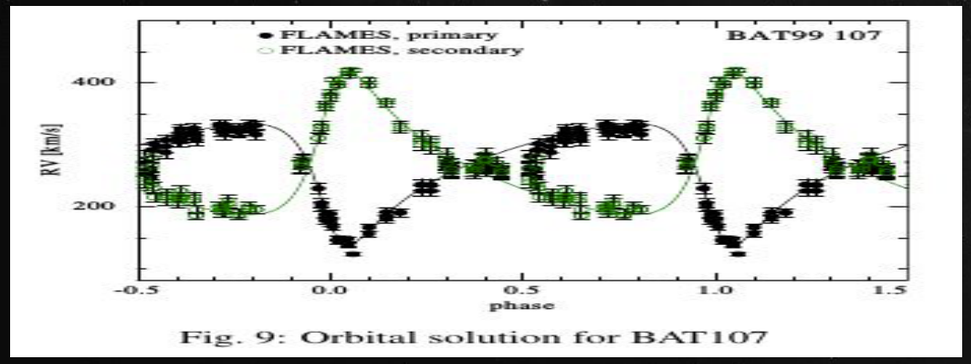



Fig. 9: Orbital solution for BAT107

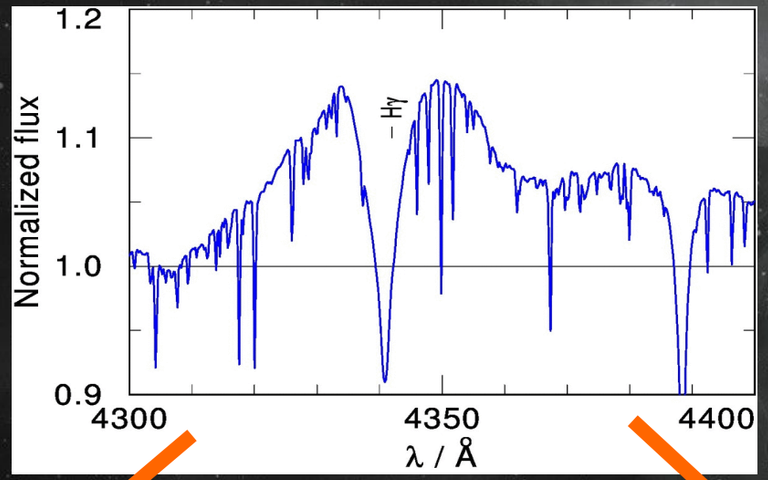
**Orbital analyses**

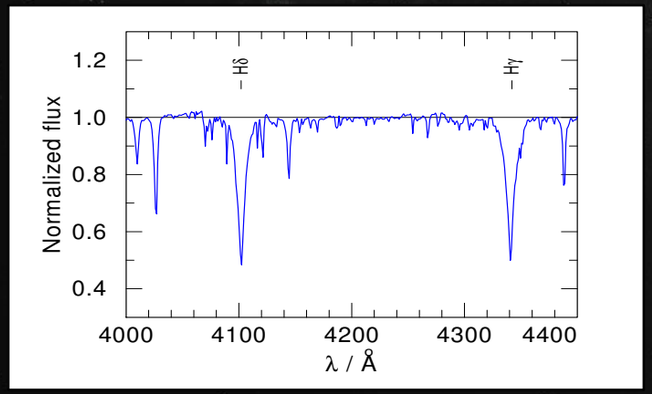
Physical + orbital parameters:

- Luminosity
- Effective temperature
- Abundances
- Masses
- Mass-loss rates
- …

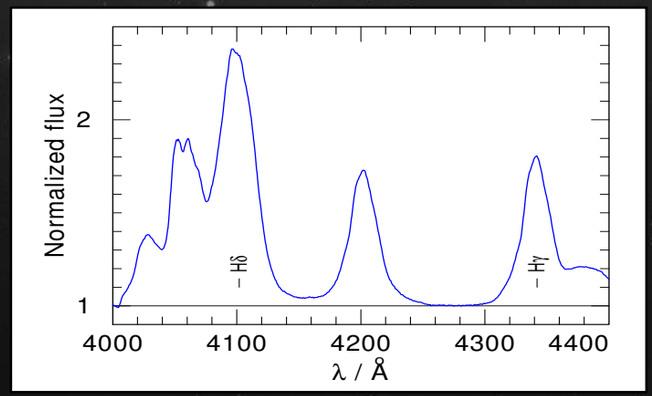
Comparison to evolution models

# Spectral disentanglement




Requires phase coverage resolved in Doppler space



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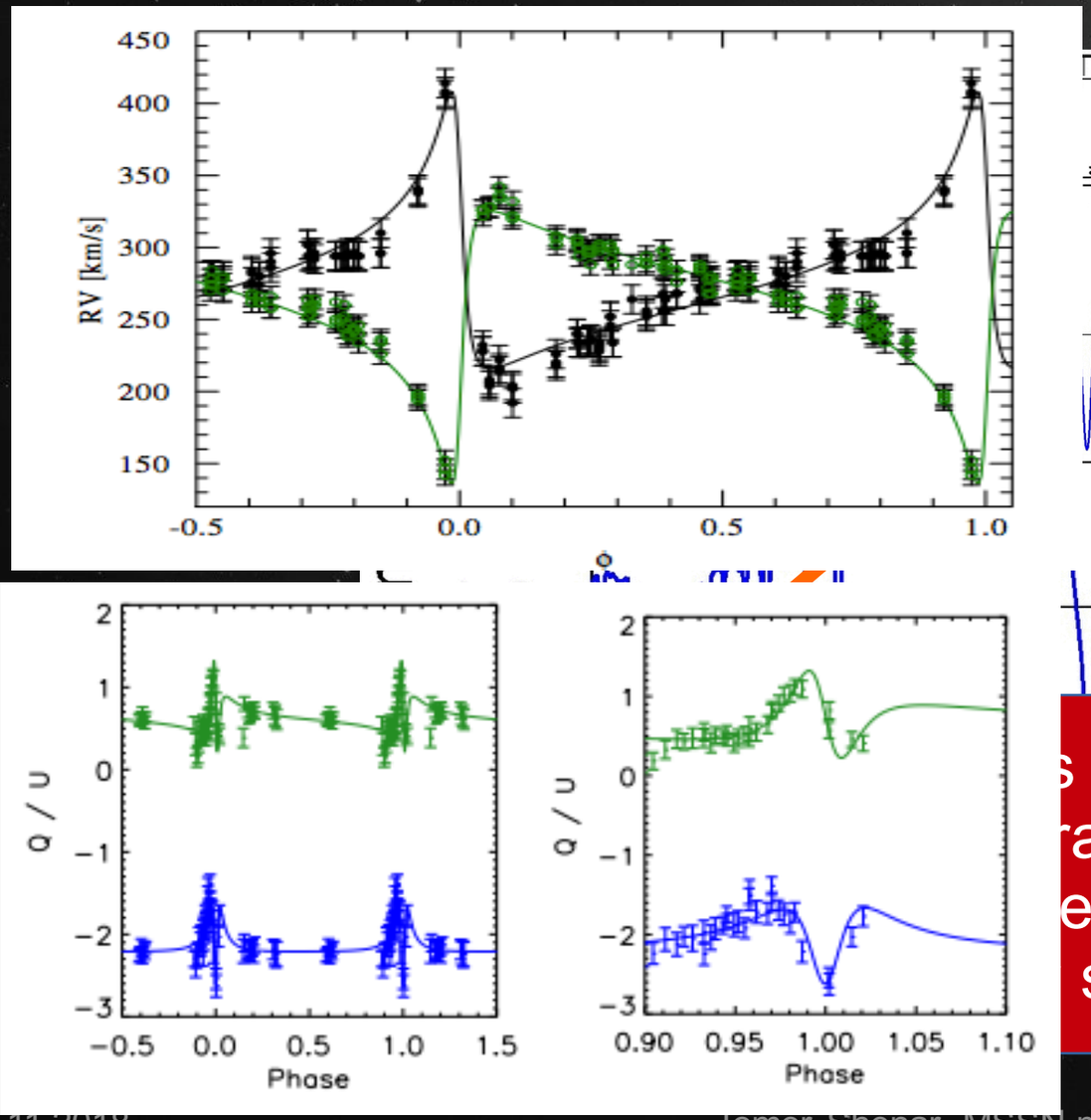


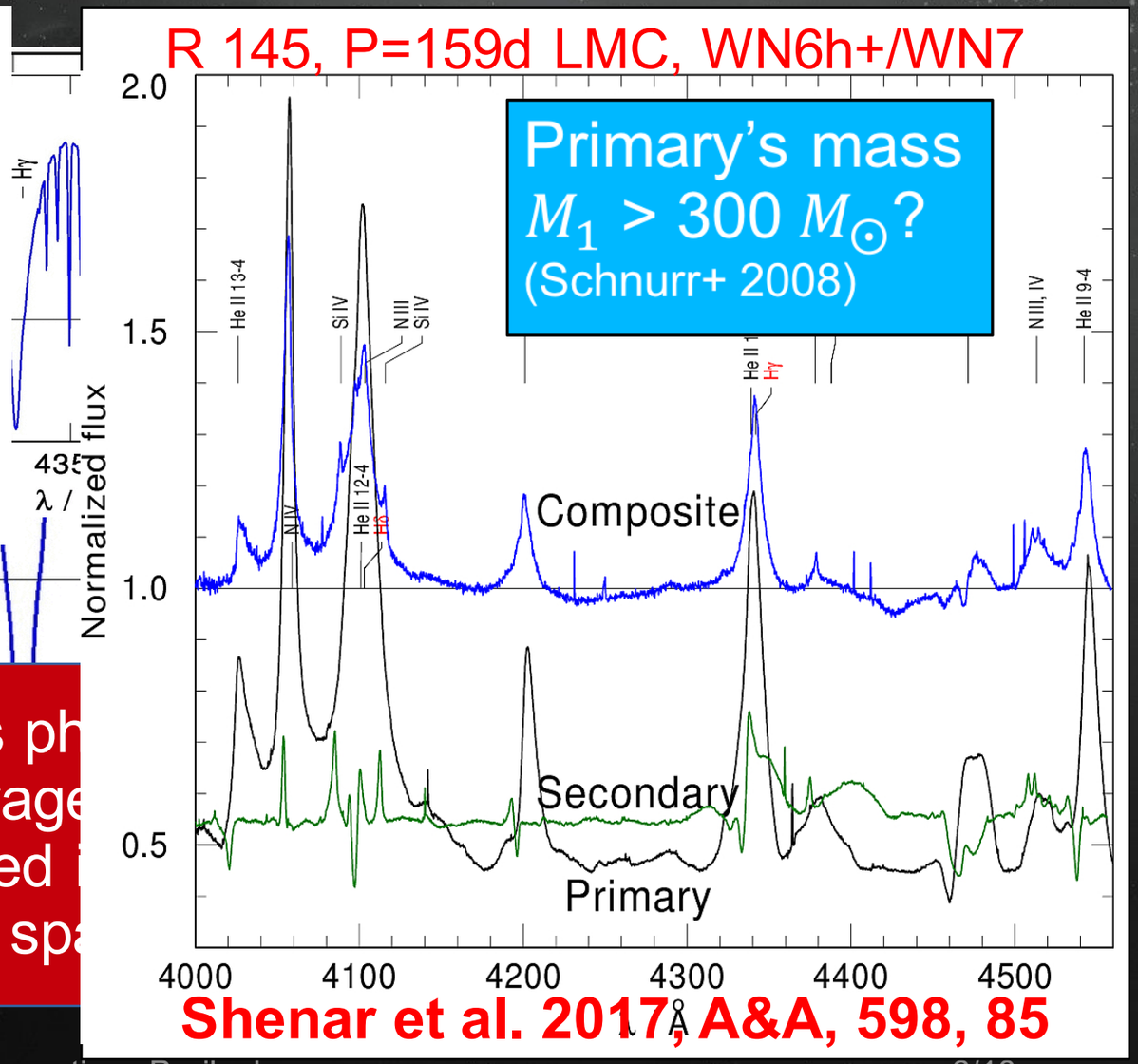

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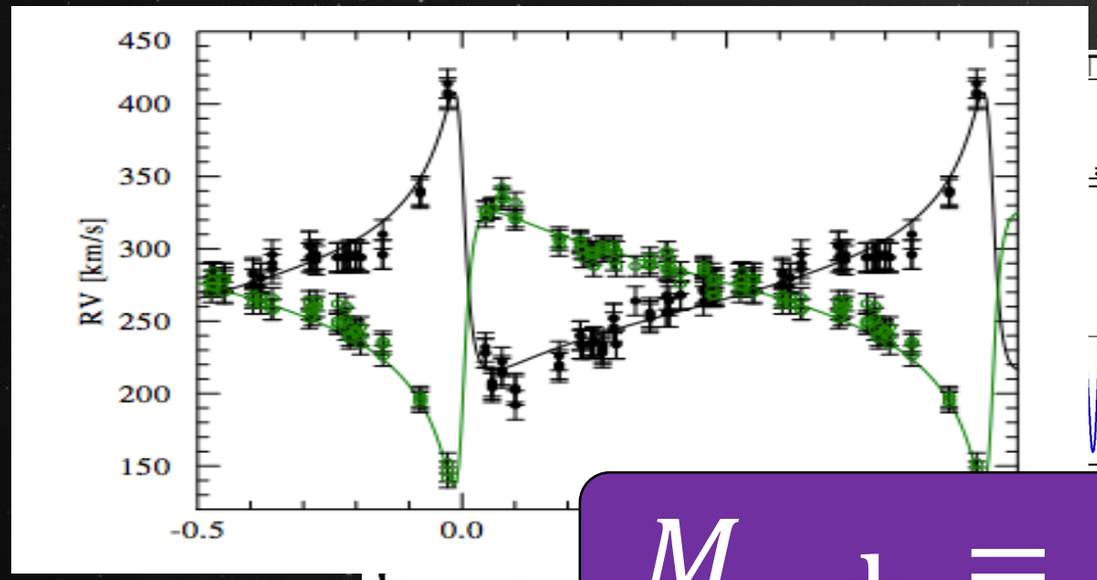
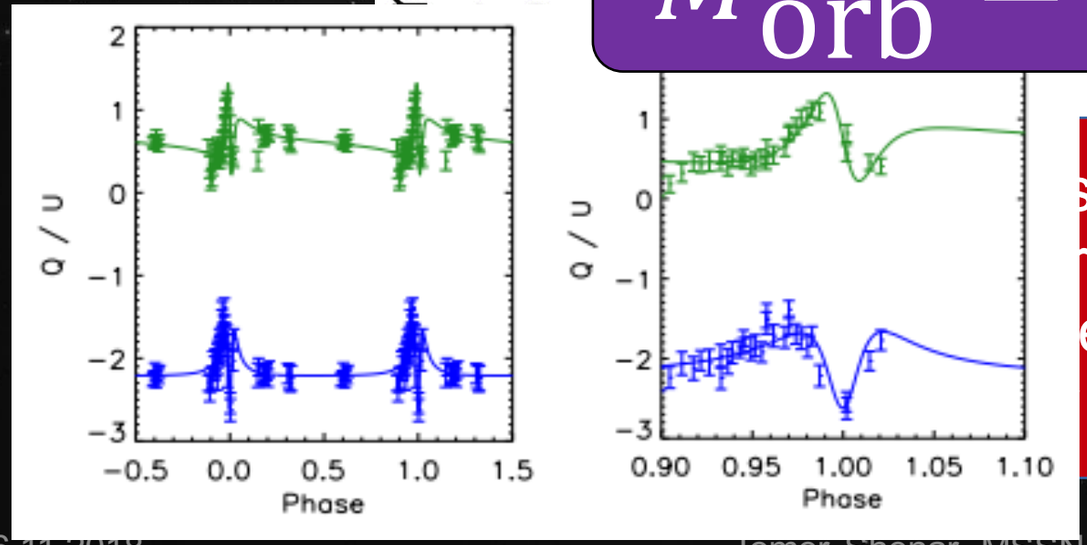
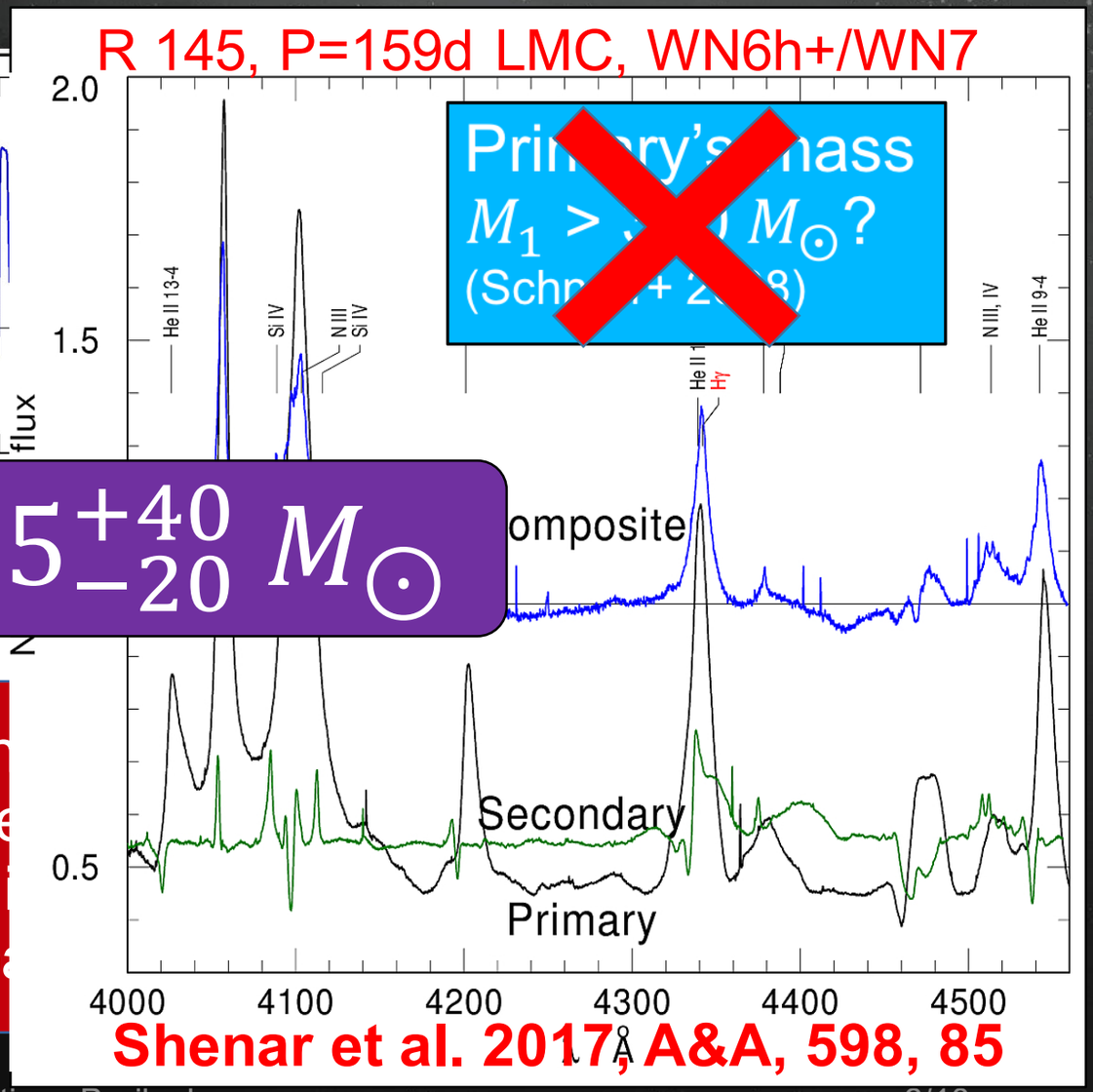


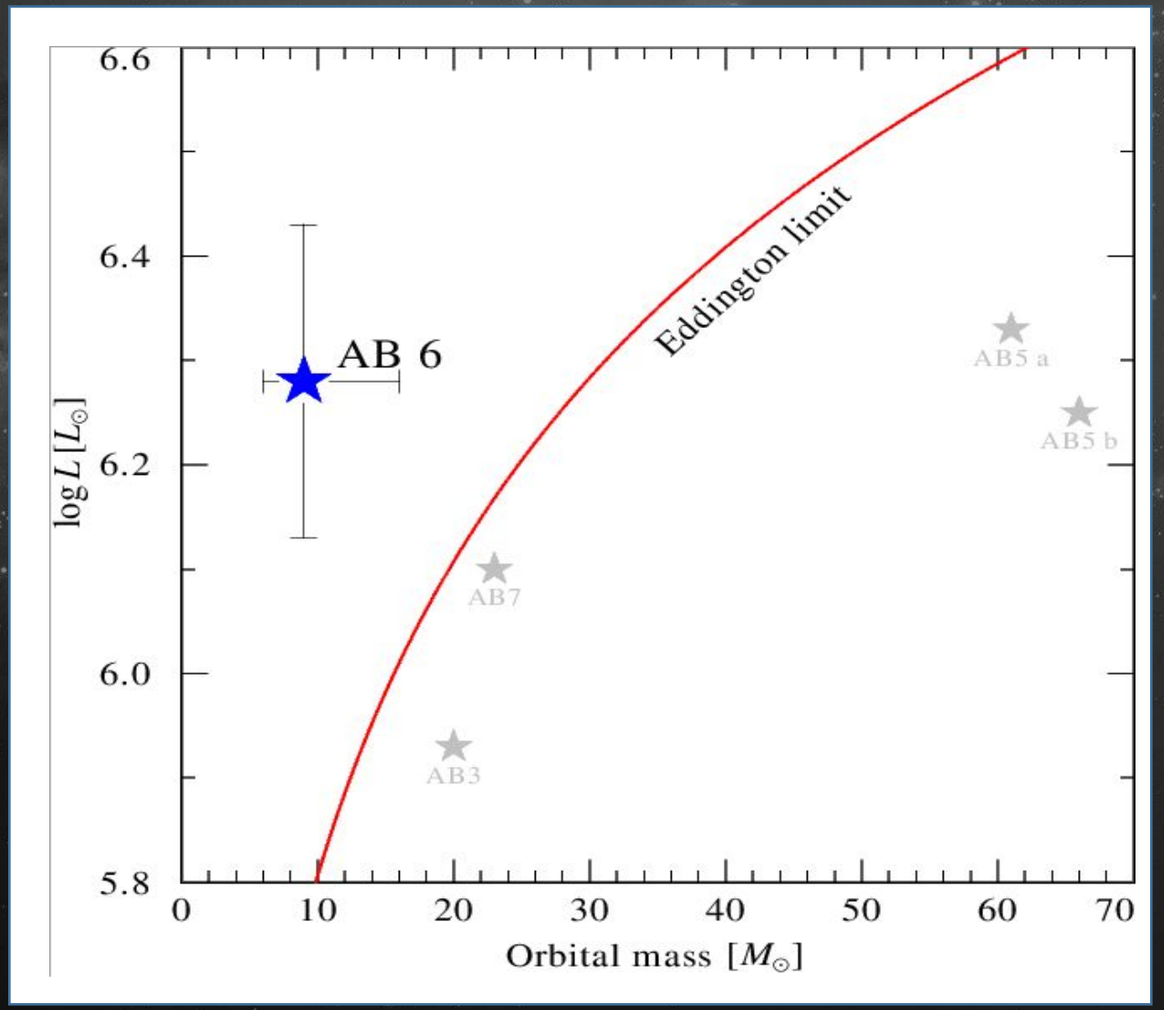




$$M_{\rm orb} = 55^{+40}_{-20}\ M_\odot$$



# And it doesn't end with binaries!

SMC AB 6 = a "standard" WR+O binary?
(P=6d, WN4 + O5I f, Foellmi+ 2003)



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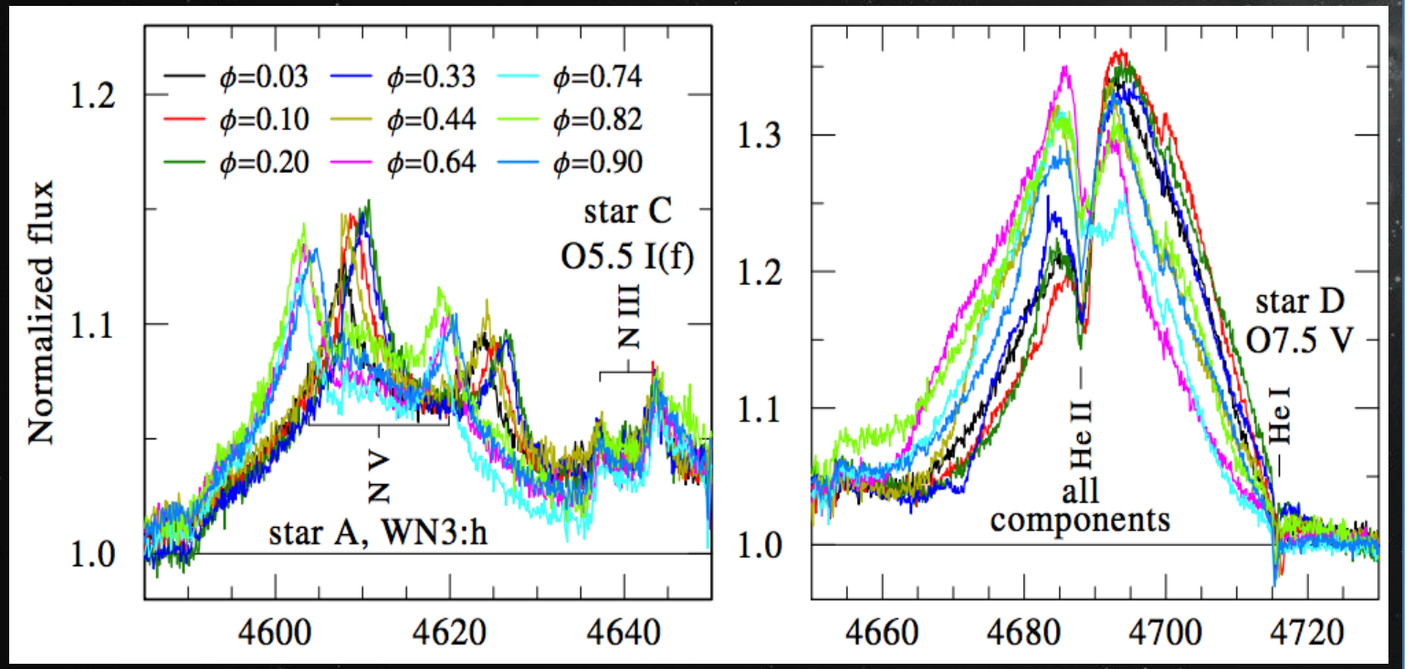


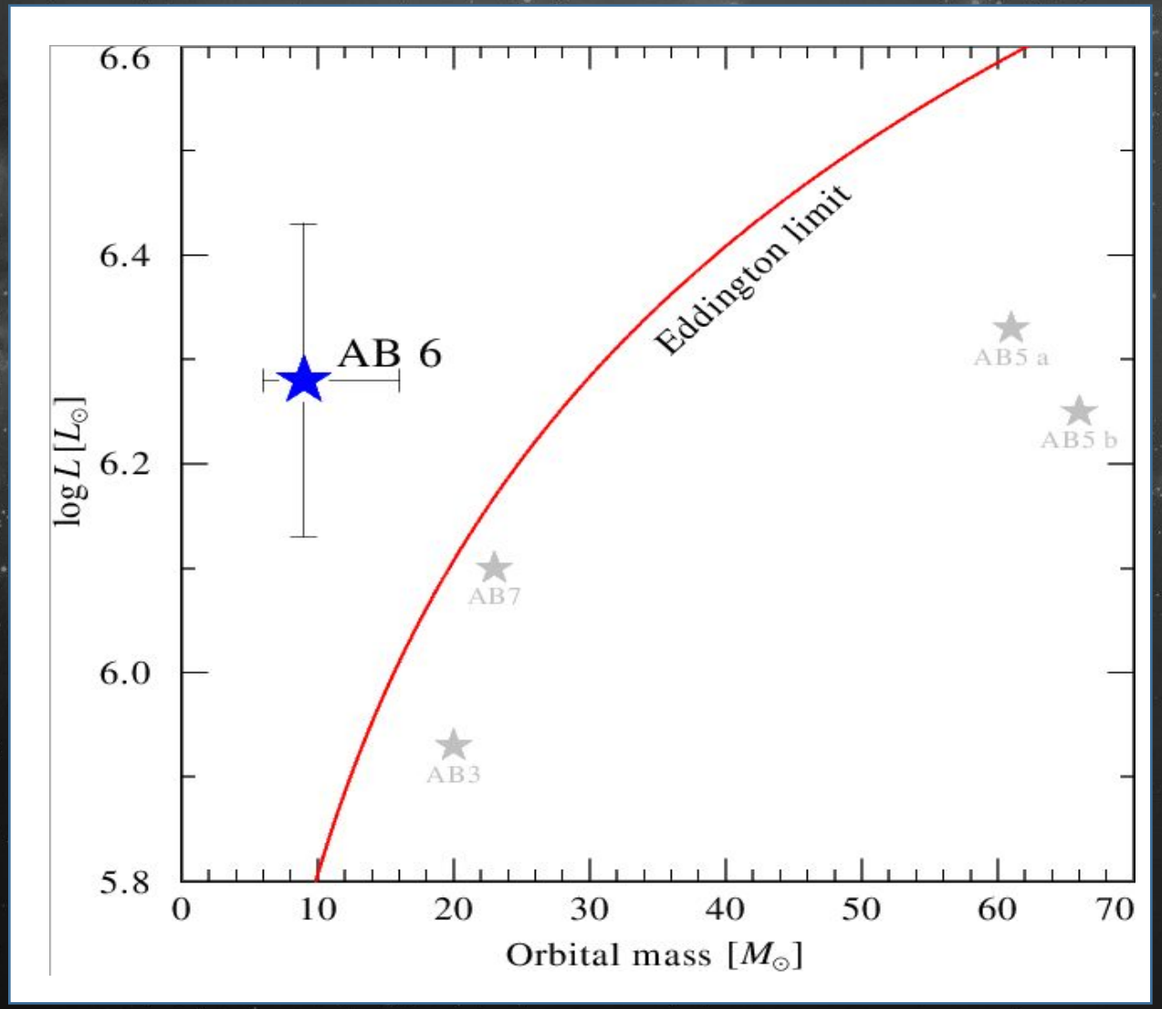


**Shenar et al. 2018, A&A, 616, 103**

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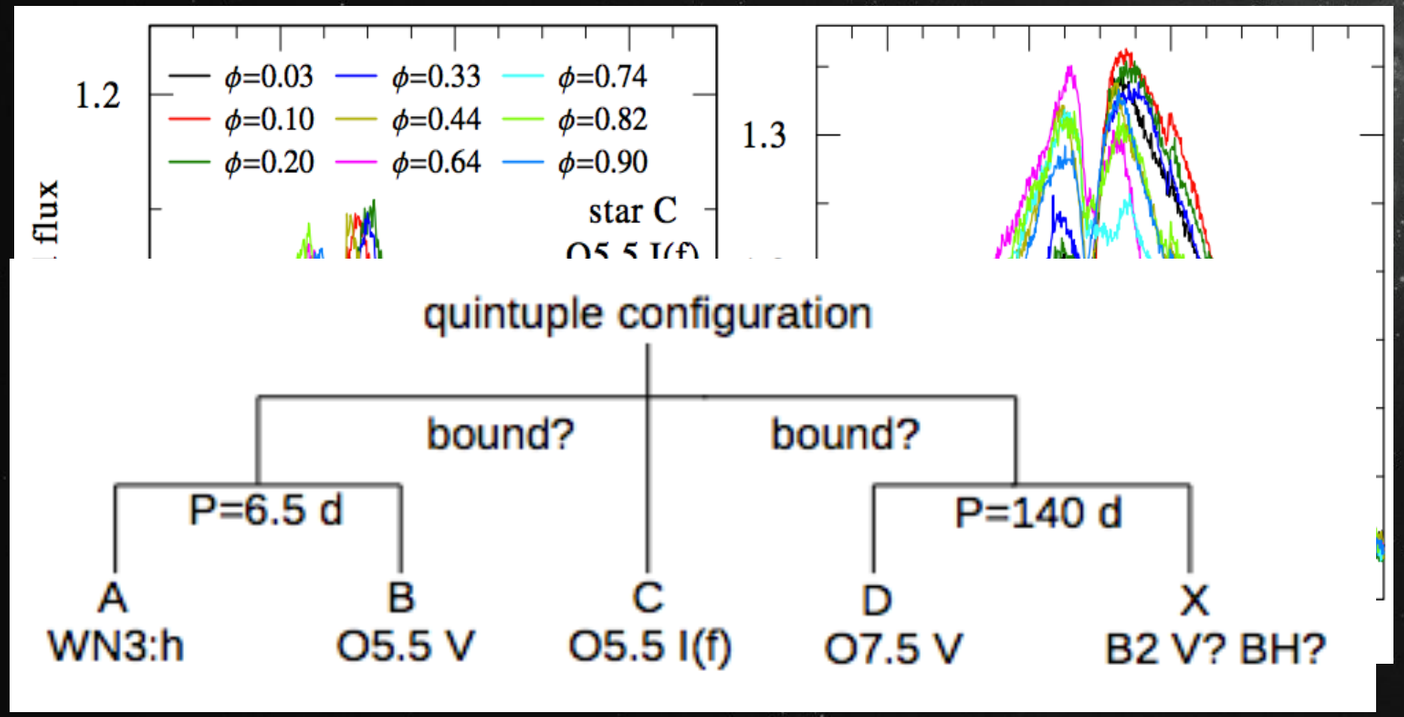


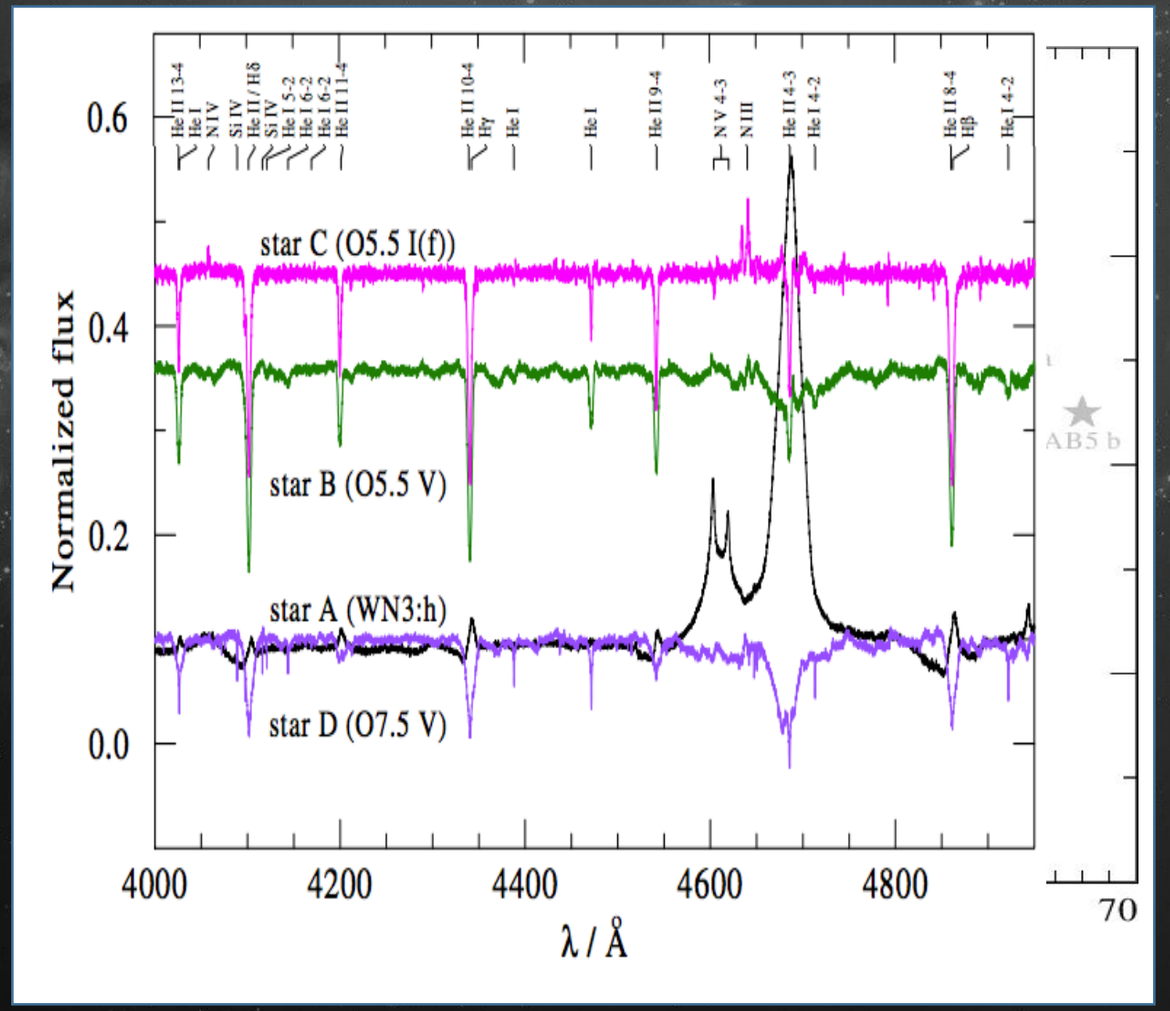


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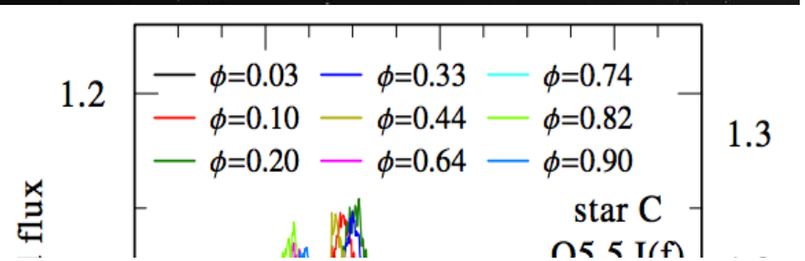


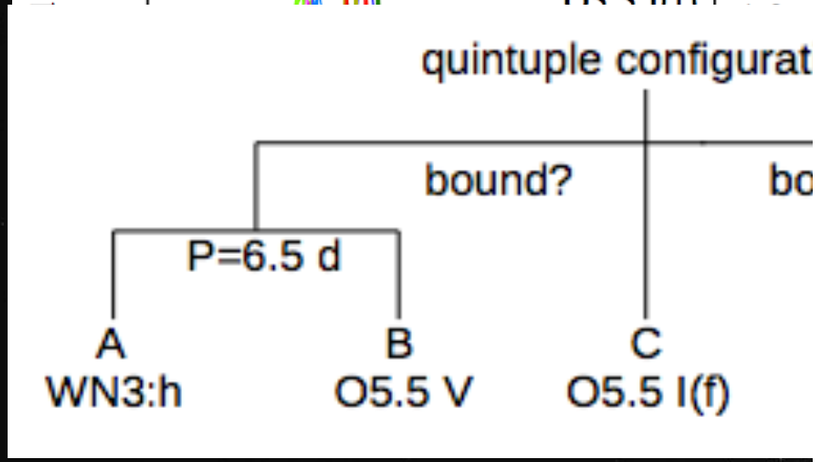


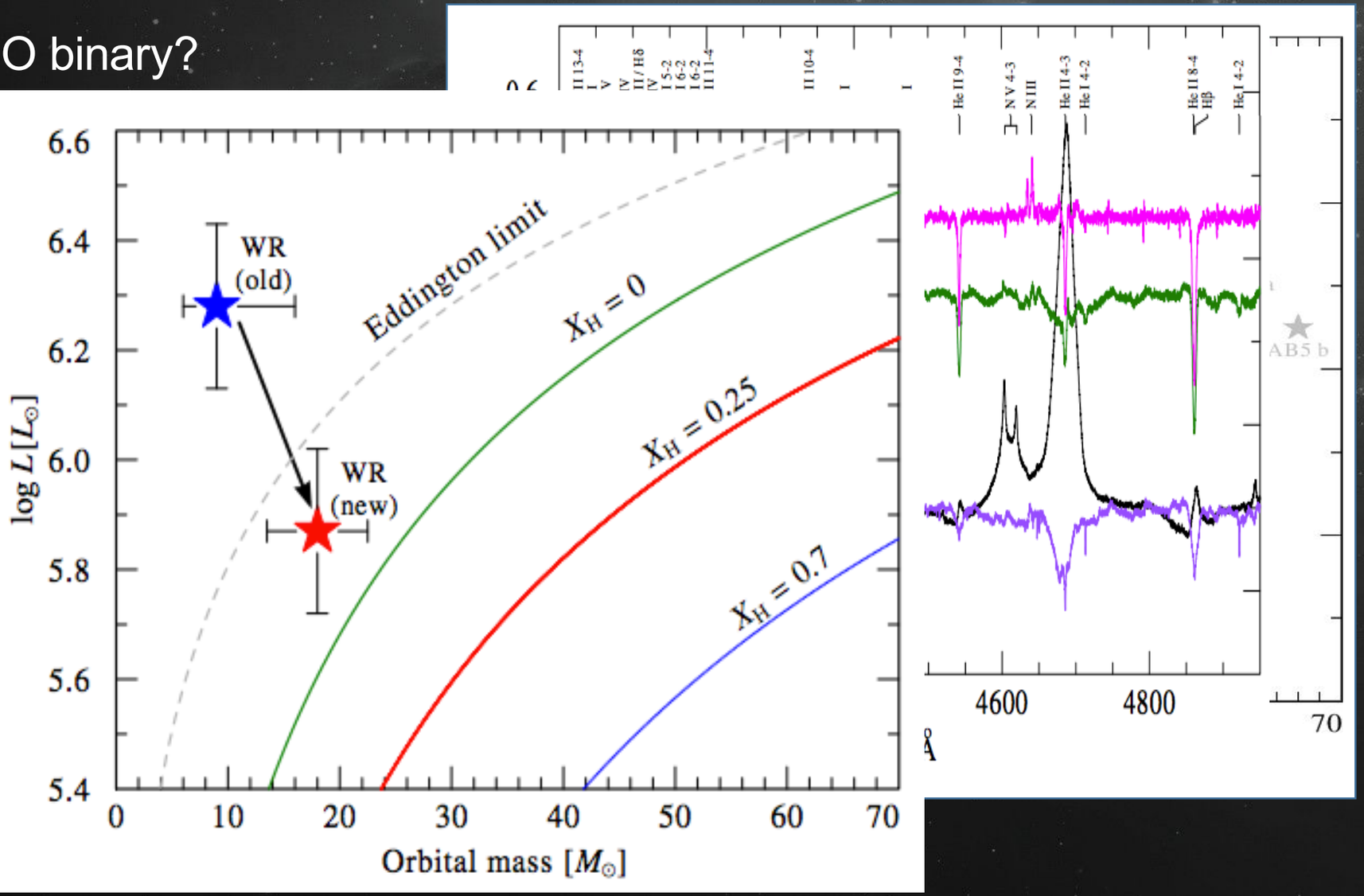


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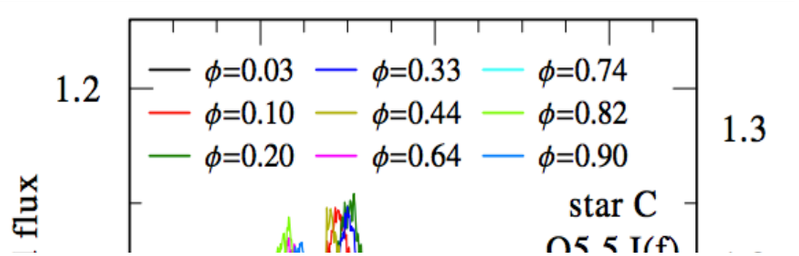


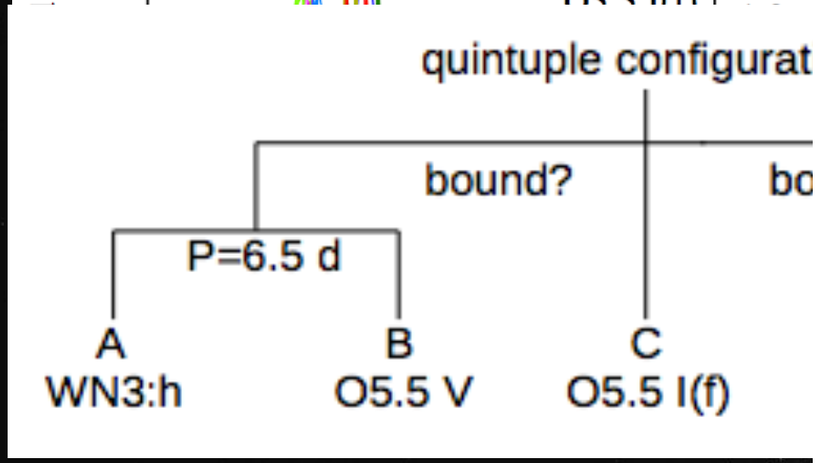


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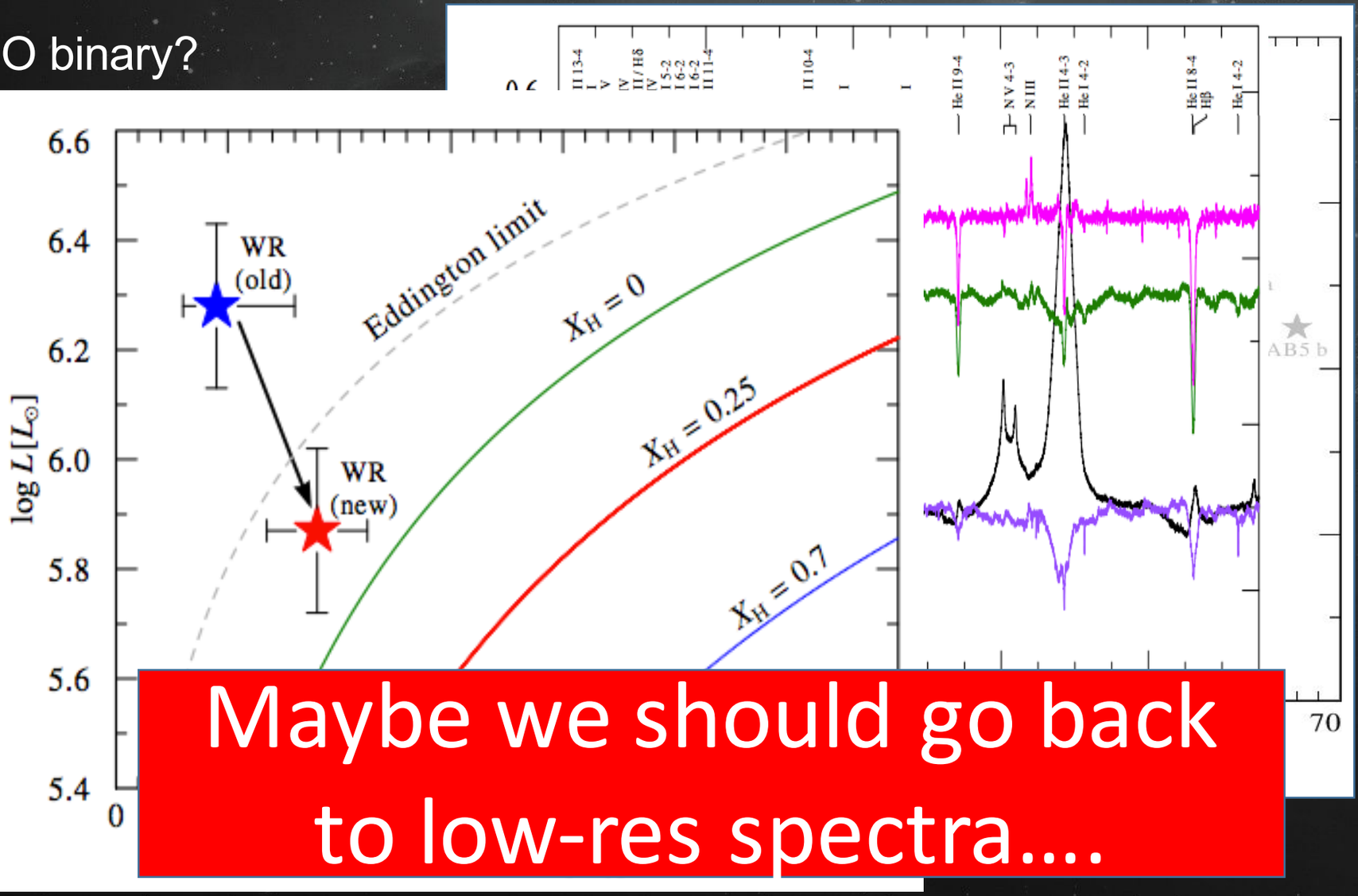
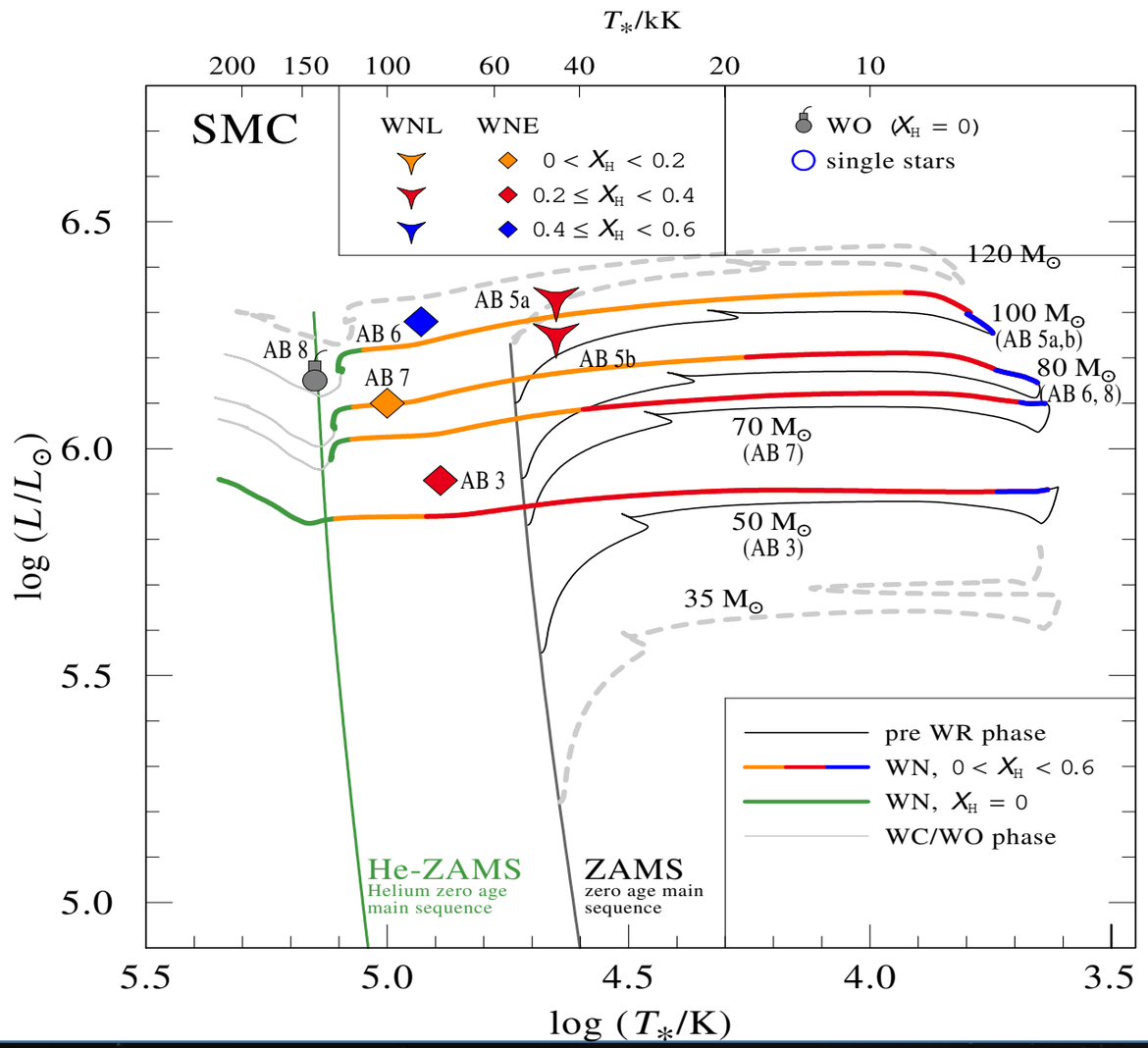


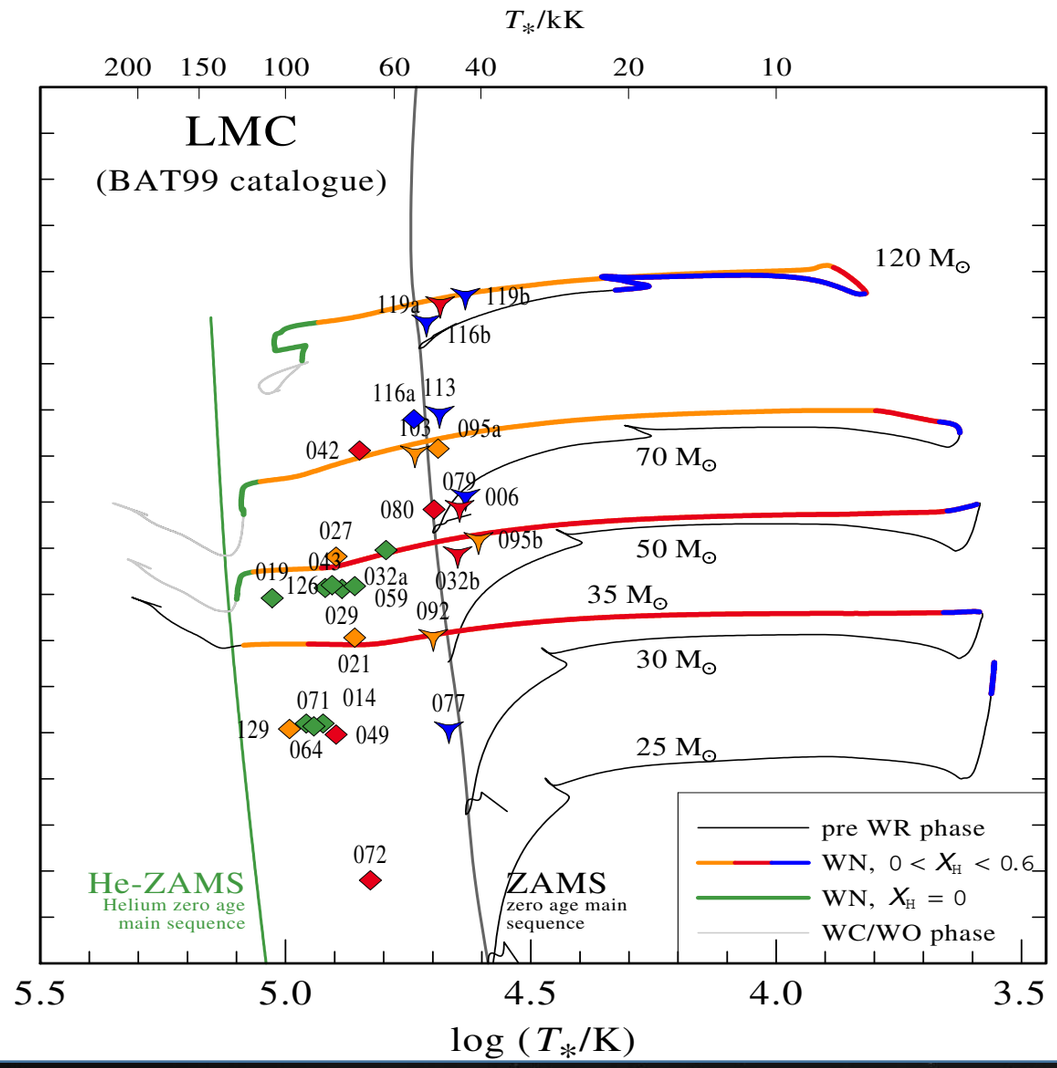

**Maybe we should go back to low-res spectra….**

# Complete analysis of SMC+LMC WN binaries

Shenar+ 2016, A&A, 591, 22




Shenar+ in prep.

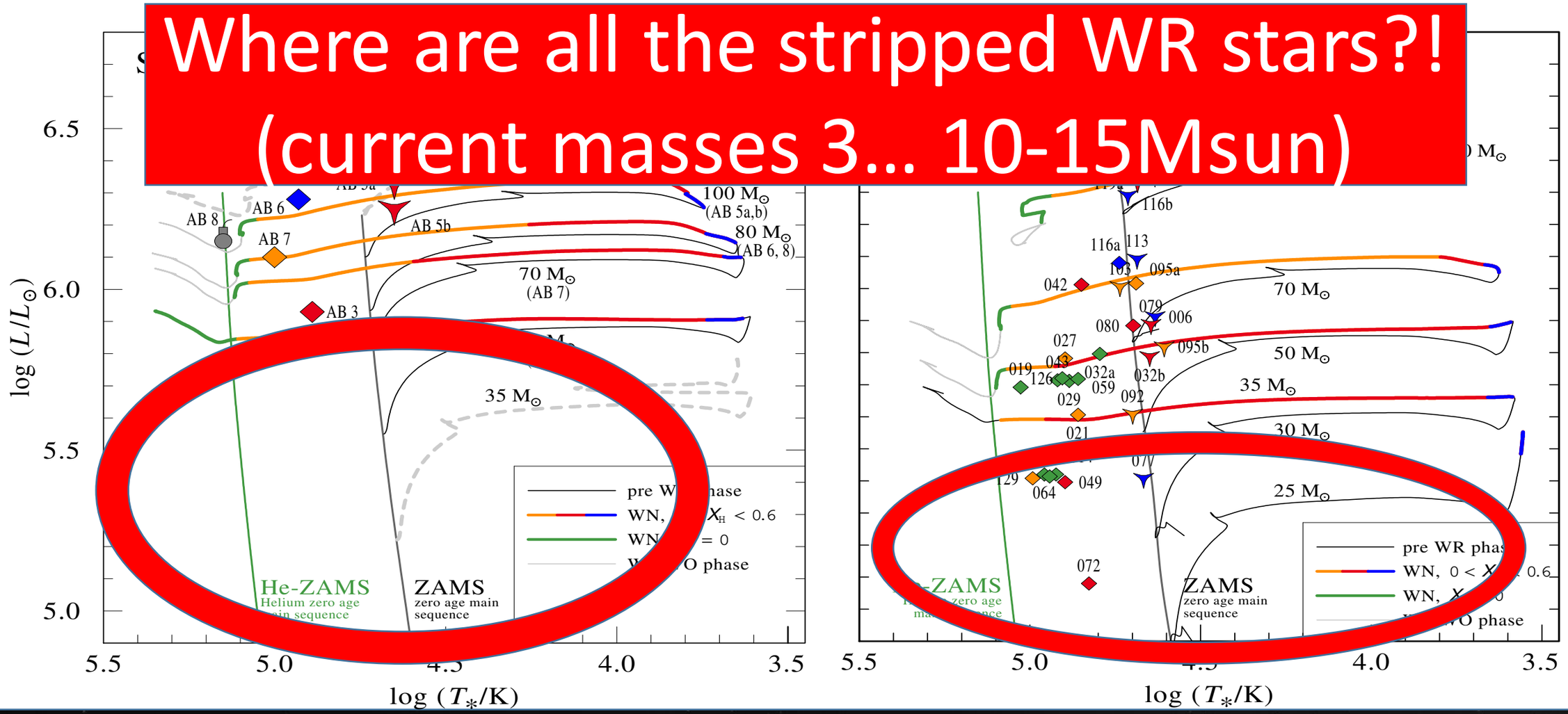


# Complete analysis of SMC+LMC WN binaries

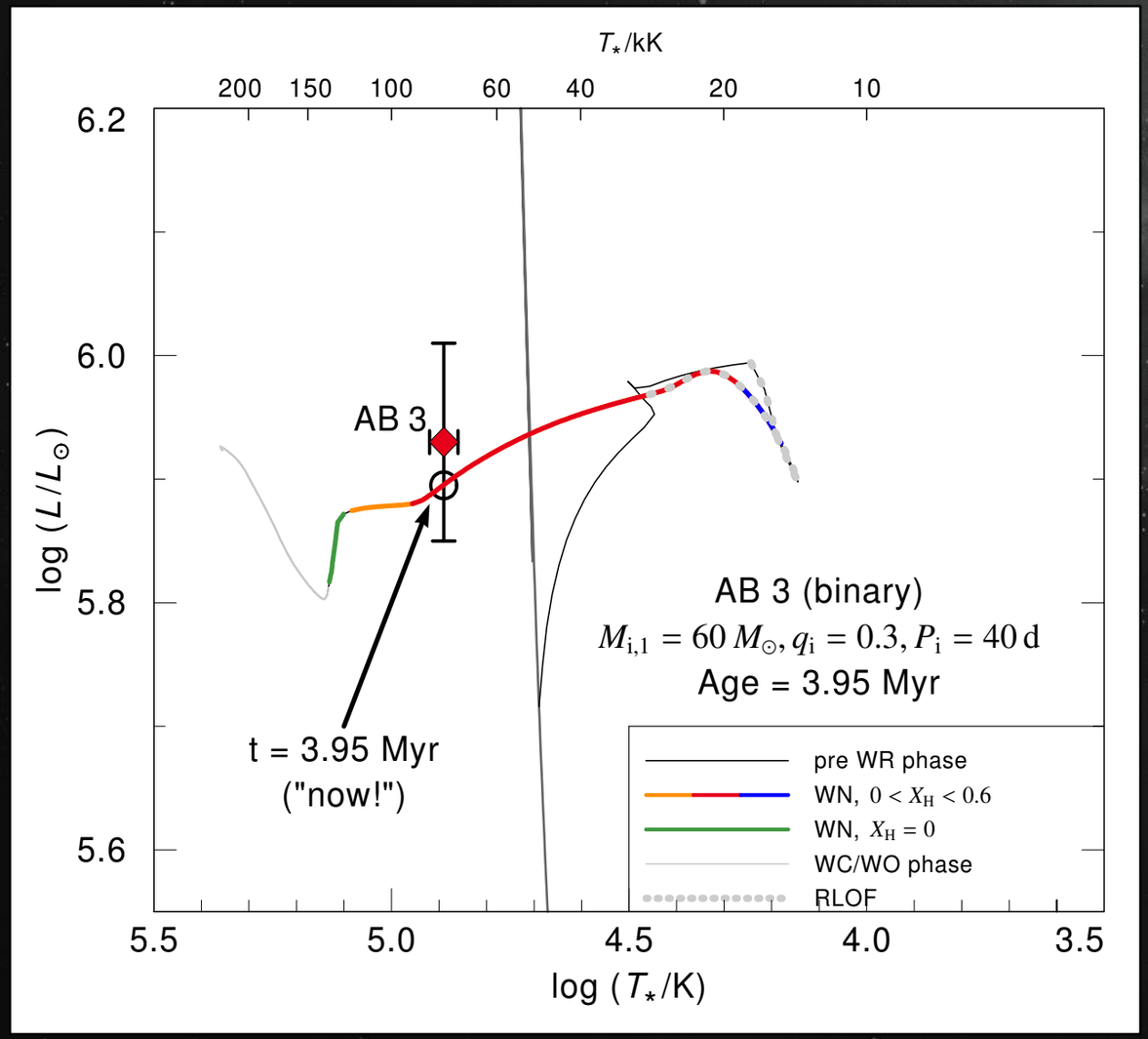
Shenar+ 2016, A&A, 591, 22

Shenar+ in prep.

**Where are all the stripped WR stars?!**
**(current masses 3… 10-15Msun)**



# Does binarity dominate WR formation?




- $\chi^2$ fitting with **binary evolution tracks** (Eldridge+ 2012), accounting for all observables:

  $P, X_H, M_1, M_2, L_1, L_2, T_1, T_2$

- derived set of initial parameters (period, masses)

Shenar+ 2016, A&A, 591, 22;

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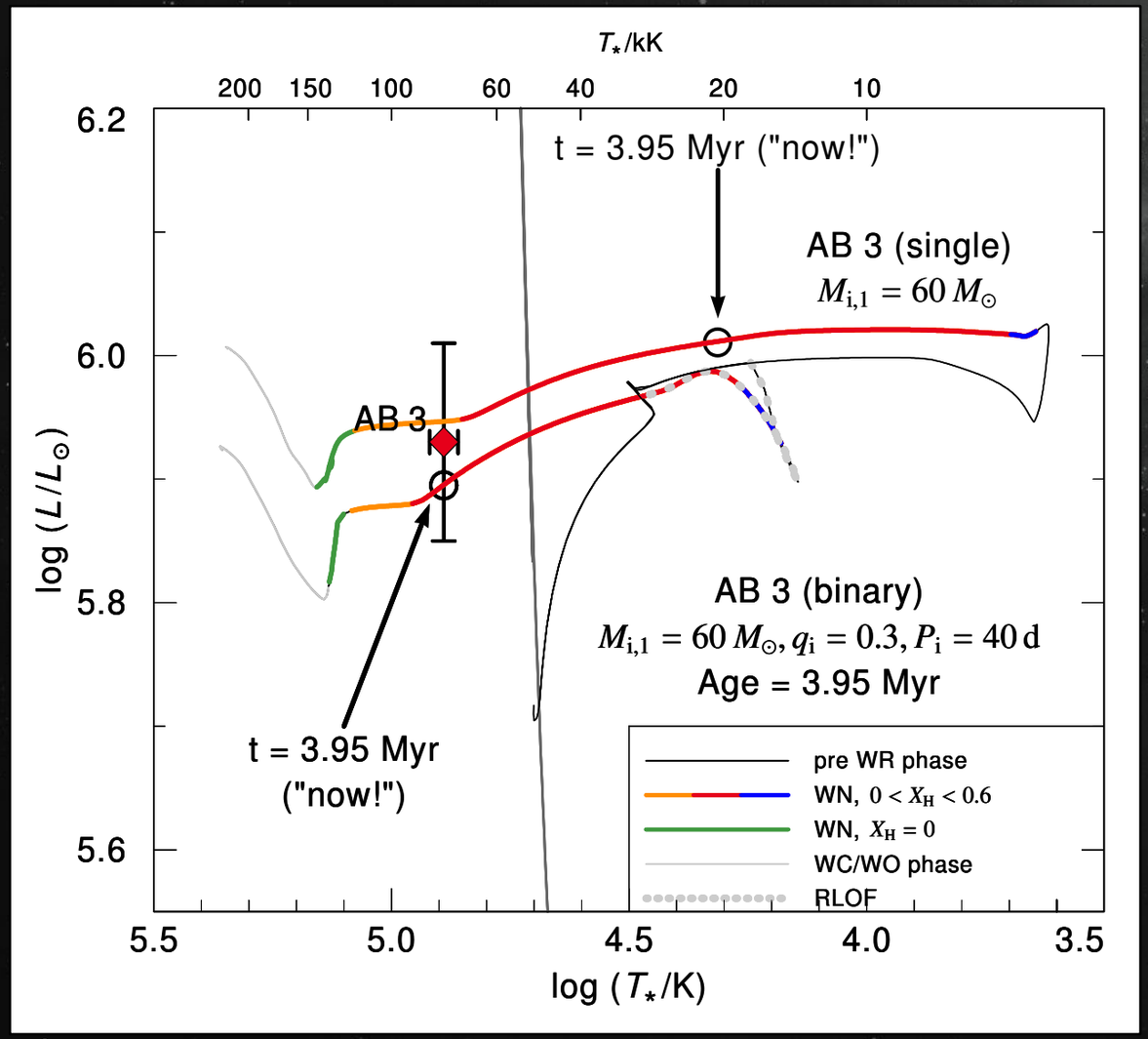


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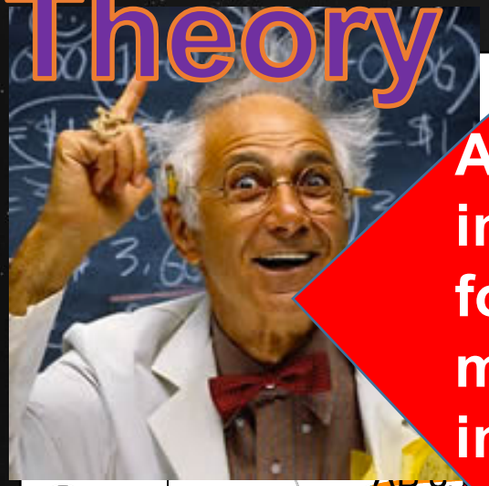
  $P, X_H, M_1, M_2, L_1, L_2, T_1, T_2$
- derived set of initial parameters (period, masses)
- **WR stars are massive enough to enter the WR phase as single stars!**

Shenar+ 2016, A&A, 591, 22;

# Does binarity dominate WR formation?

## Theory



**All WR stars in the SMC form via mass-transfer in binaries!**



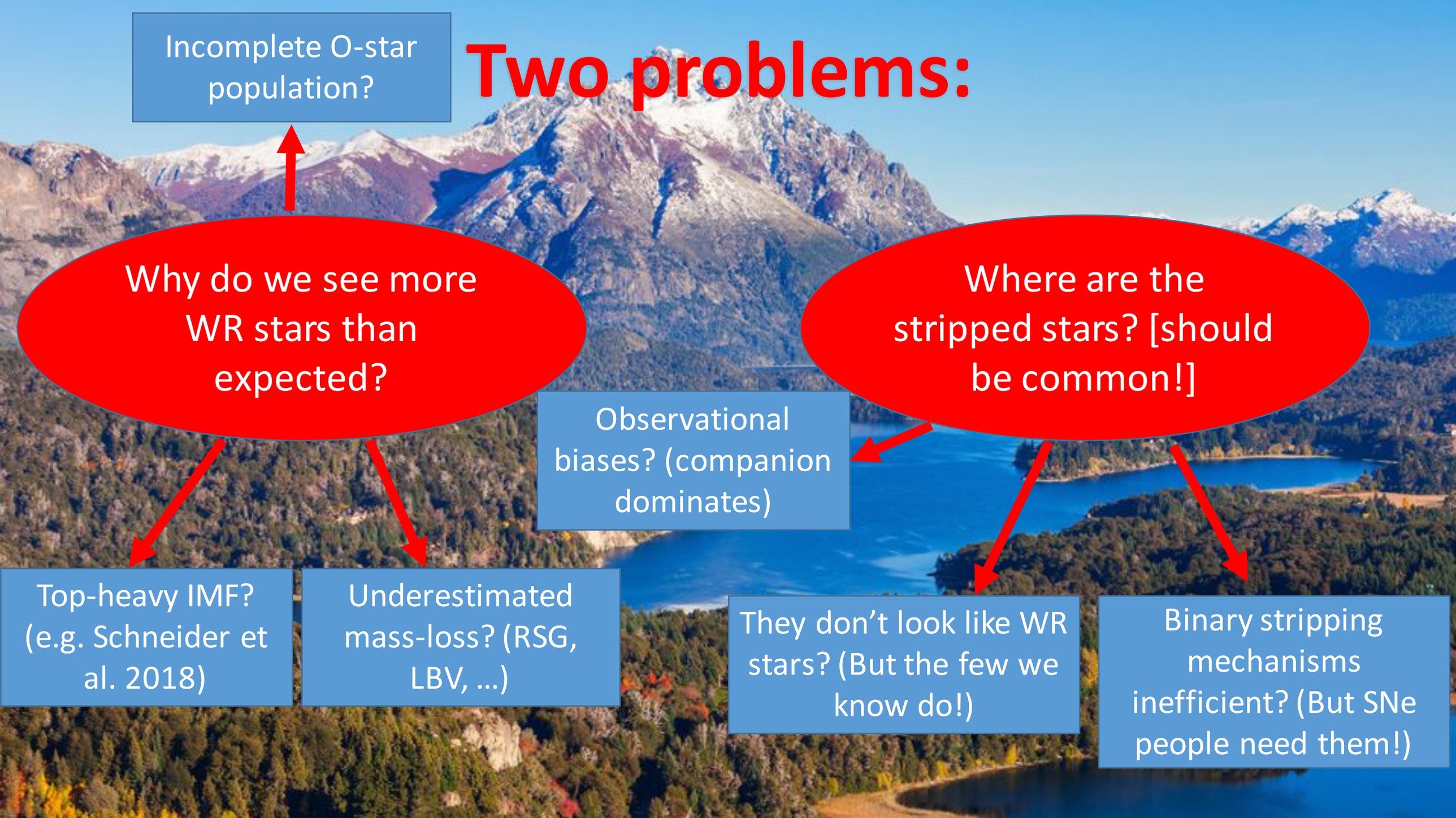

- $\chi^2$ fitting with **binary evolution tracks** (Eldridge+ 2012), accounting for all observables:

$P, X_{\rm H}, M_1, M_2, L_1, L_2, T_1, T_2$

## observation

**#WR in SMC not dependent on binary evolution (Shenar et al.2016)**

Shenar+ 2016, A&A, 591, 22;


Incomplete O-star population?
Two problems:
Why do we see more WR stars than expected?
Where are the stripped stars? [should be common!]
Observational biases? (companion dominates)
Top-heavy IMF? (e.g. Schneider et al. 2018)
Underestimated mass-loss? (RSG, LBV, …)
They don’t look like WR stars? (But the few we know do!)
Binary stripping mechanisms inefficient? (But SNe people need them!)