Massive stars - binaries, Wolf-Rayets, and the Early Universe connection

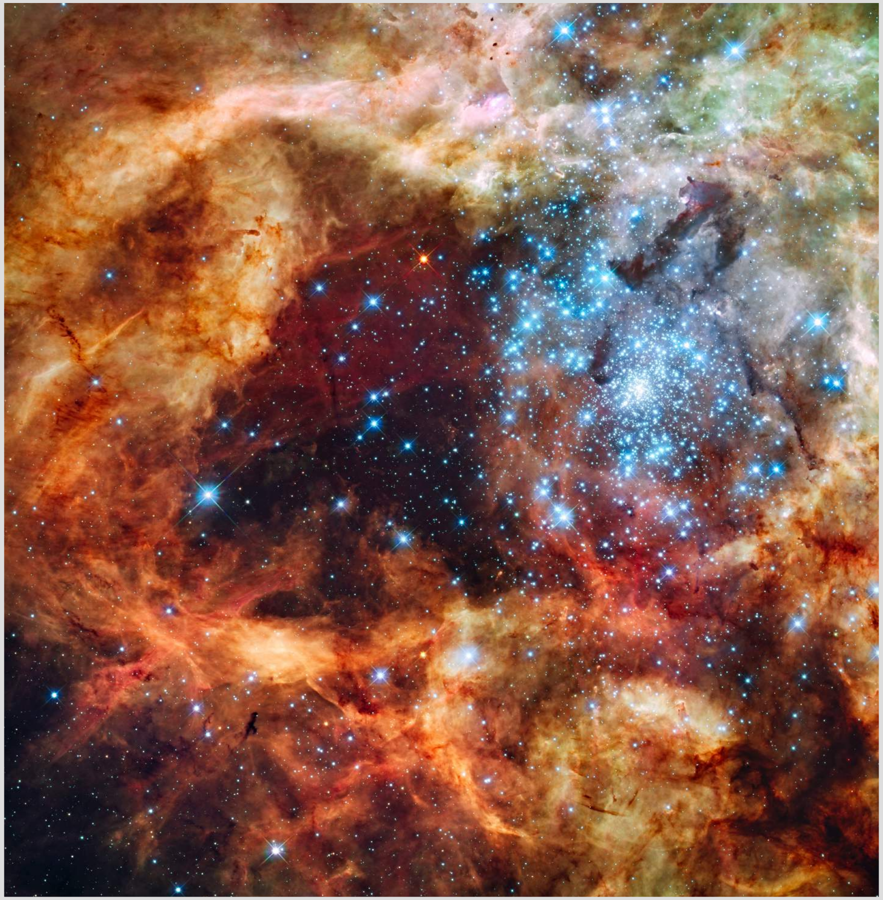
Frank Tramper

European Space Astronomy Centre - Madrid

Introduction - Massive stars

- > ~8 solar masses
- Rare and short-lived, but key players in the Universe

- Strong impact on their surroundings
  - Dominant sources of momentum (stellar winds and SNe)
  - Strong ionizing radiation
  - May halt or start star formation
  - Chemical enrichment: main producers of alpha-elements (C, O, etc.)
  - Re-ionization of the Universe

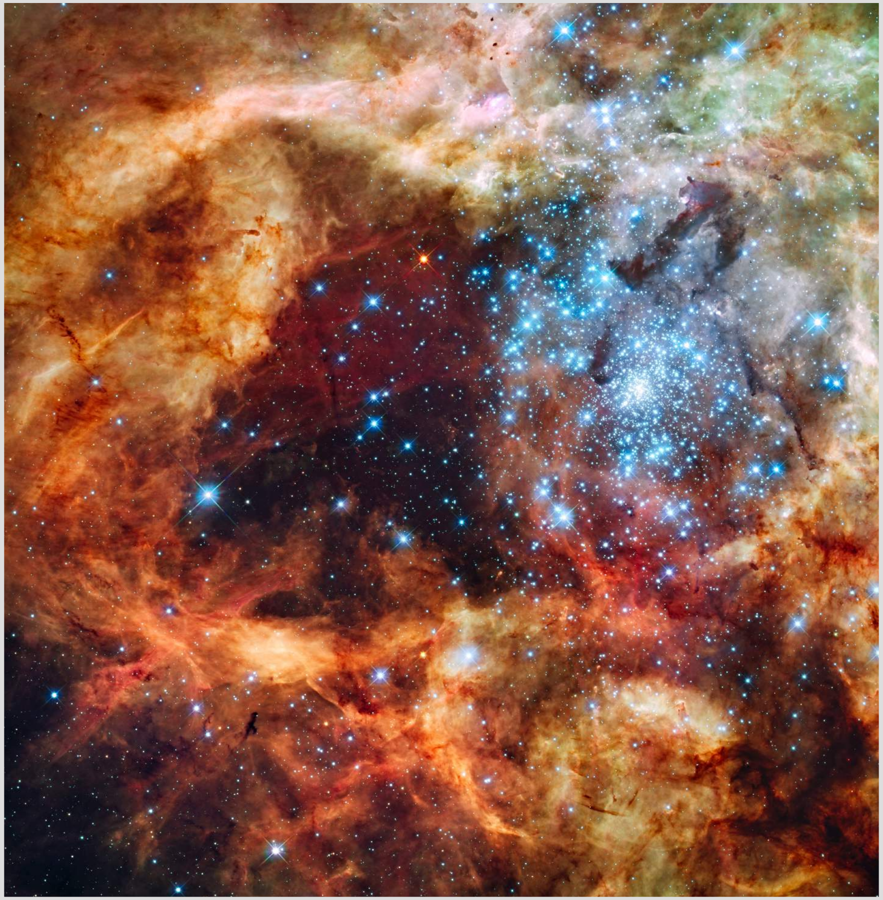


Introduction - Massive stars

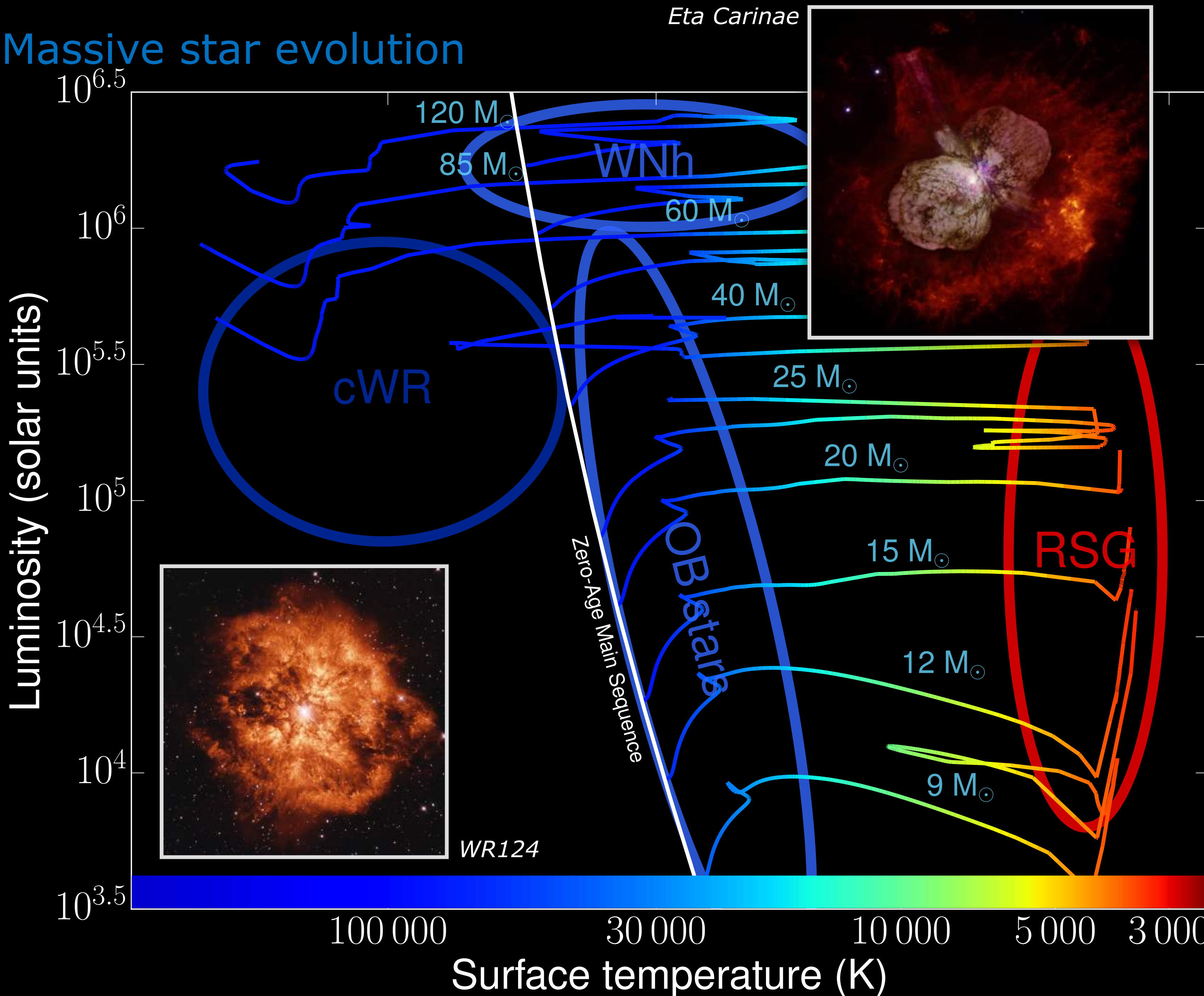
- Progenitors of:
  - Hypernovae
  - (long) Gamma-ray burst
  - X-ray binaries
  - Gravitational wave sources

- Evolution dominated by:
  - Mass-loss
  - Rotation
  - Binary interactions

Metallicity

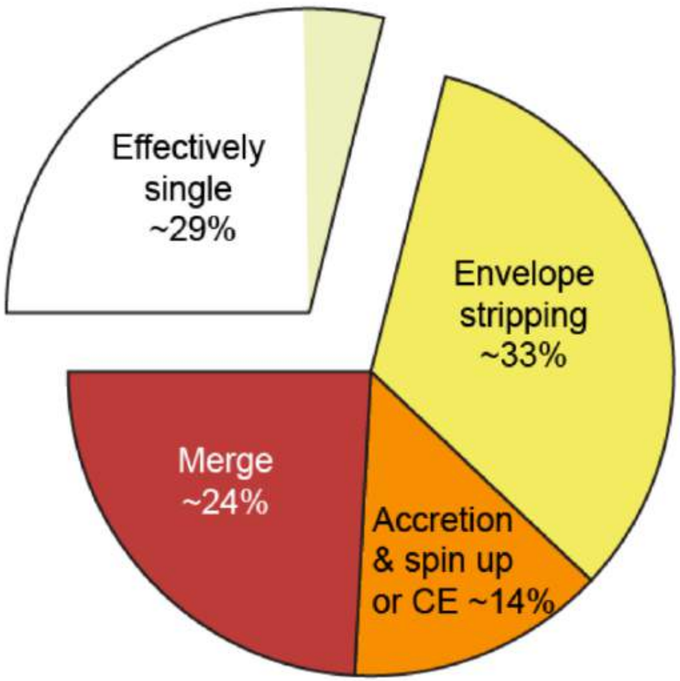


Massive star evolution

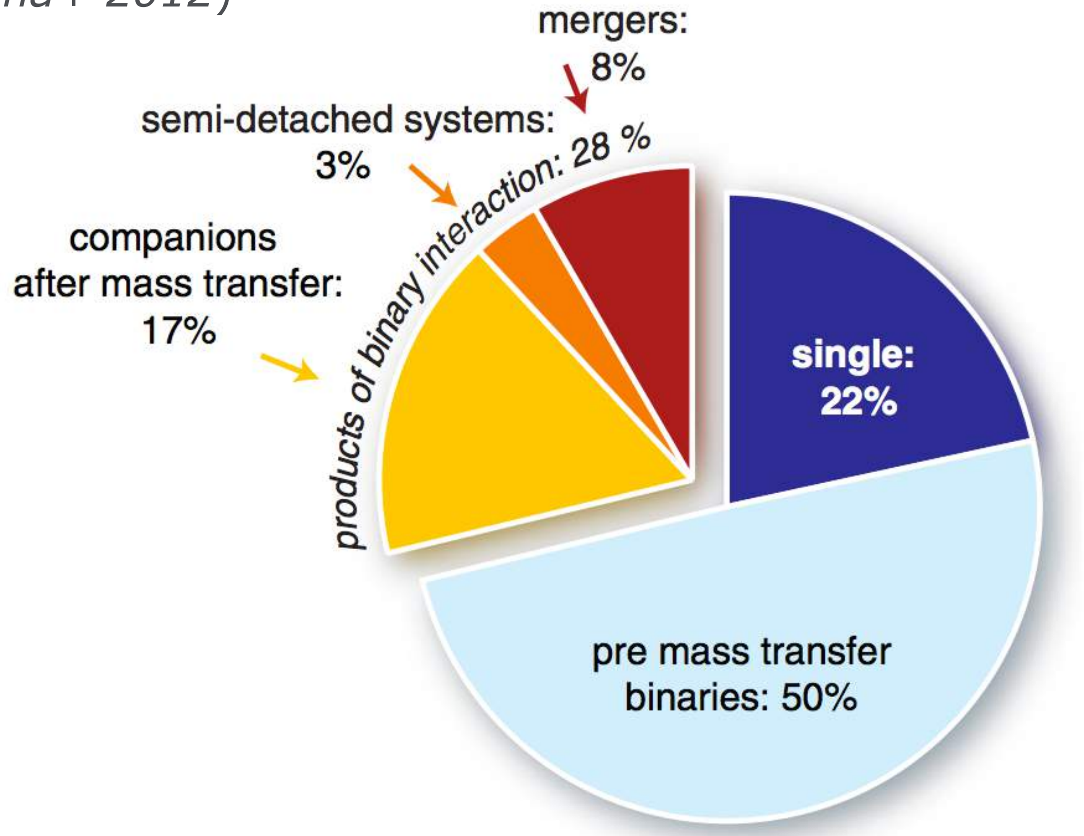


But… binaries!

- Massive stars like company: 91% of nearby O stars has one or more companions (on average 2.1 companions; *Sana+ 2014*)
- Interactions dominate massive star evolution: 71% of all stars born as O-type will interact during their lifetime (*Sana+ 2012*)



Sana+ 2012



de Mink+ 2014

I - Very Massive Binaries

Very massive binaries

- Binaries offer the most accurate determination of stellar mass
  - Radial velocity variations combined with Kepler's laws provide lower limits

$$\frac{M_2^3}{(M_1+M_2)^3}\sin^3 i = \frac{P}{2\pi G} v_1^3 \qquad \frac{M_1}{M_2} = \frac{v_2}{v_1}$$

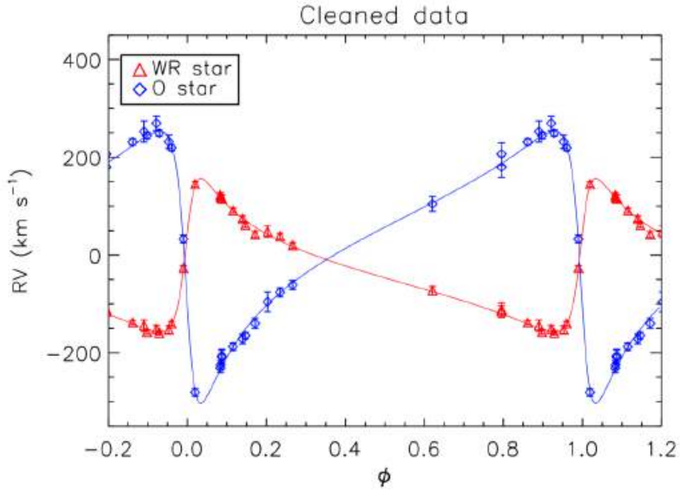
  - If inclination is know then absolute mass
- Orbital solution allow disentangling of spectra: analyse both components individually

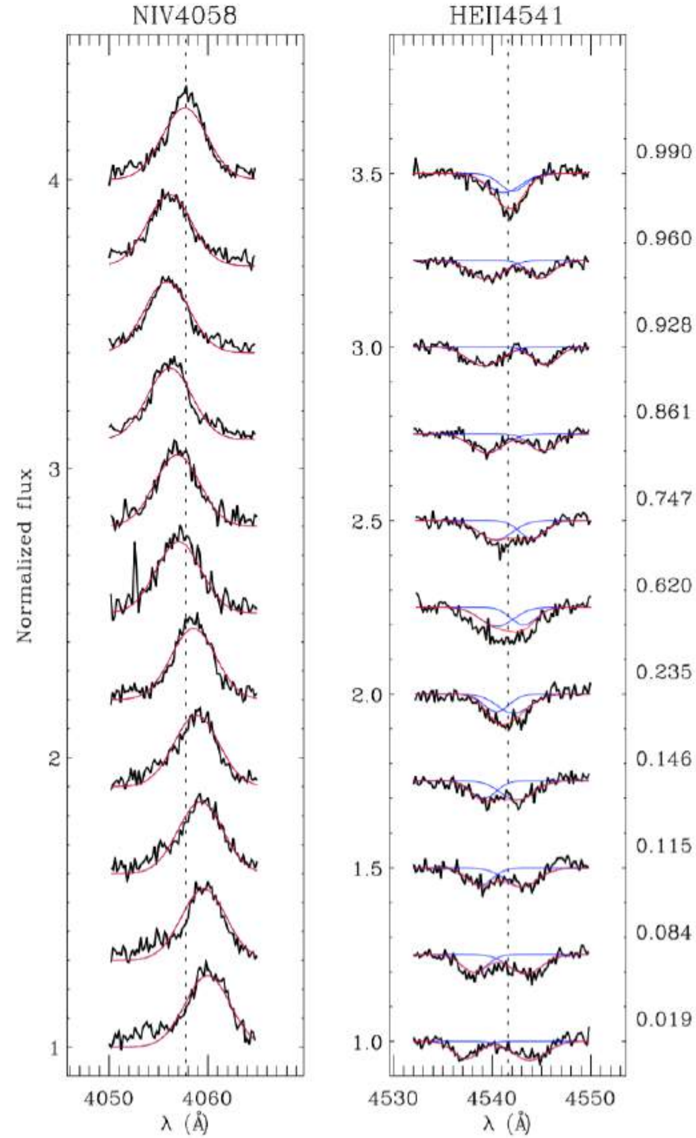
- Most massive stars:
  - NGC 3603-A1: 116(31) $M_\odot$ + 89(16) $M_\odot$ (*Schnurr+ 2008*)
  - R145: 116(33) $M_\odot$ + >48(20) $M_\odot$ (*Schnurr+ 2009*)
  - WR20a: 83(5) $M_\odot$ + 82(5) $M_\odot$ (*Rauw+2004, Bonanos+ 2004*)
  - R139: >78(8) $M_\odot$ + >66(7) $M_\odot$ (*Taylor+ 2011*)

  - R136-a1: 265(+80-35) $M_\odot$ (*Crowther+ 2010*)
  - VFTS 682: ~150 $M_\odot$ (*Bestenlehner+ 2011*)

WR21a

- Likely part of Westerlund 2
  - Distance 8kpc, age 1.5 Myr
- Wolf-Rayet + O-star binary
- Candidate most massive binary in the Milky Way:
  - >87(6) $M_\odot$ + >53(4) $M_\odot$ (*Niemela+ 2008*)
  - Eccentric orbit, no periastron coverage
  - Based on He II 4686
- Observed 26 epochs with X-Shooter
  - Focussed on periastron passage

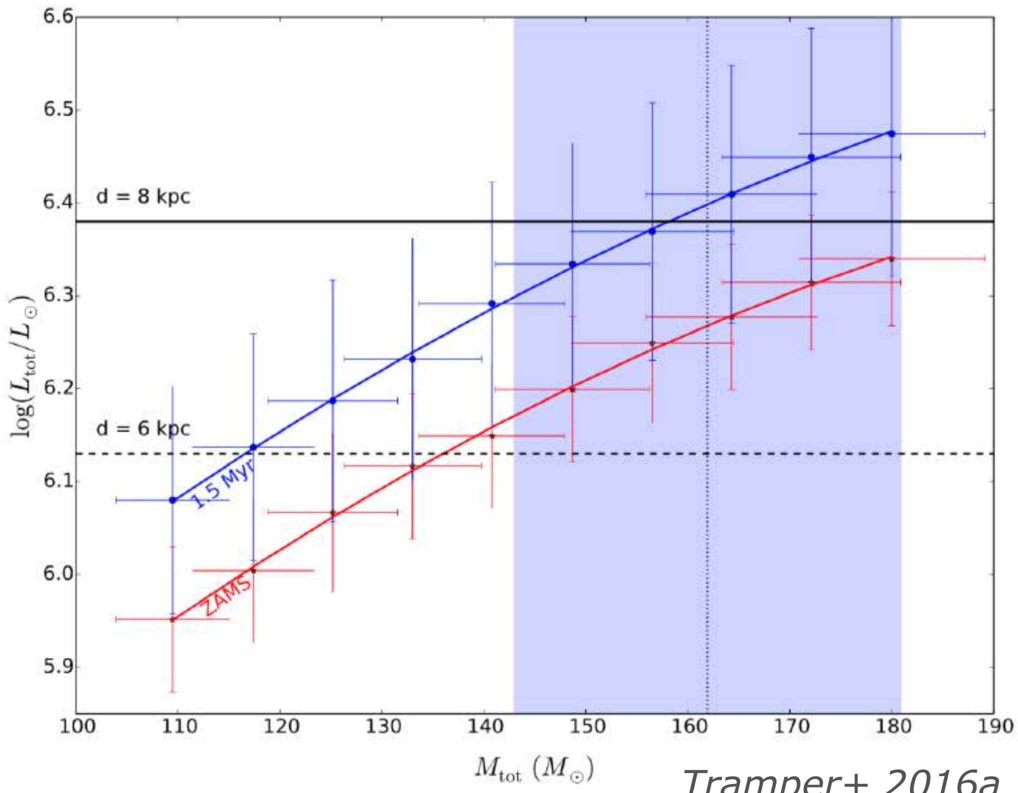




Tramper+ 2016a

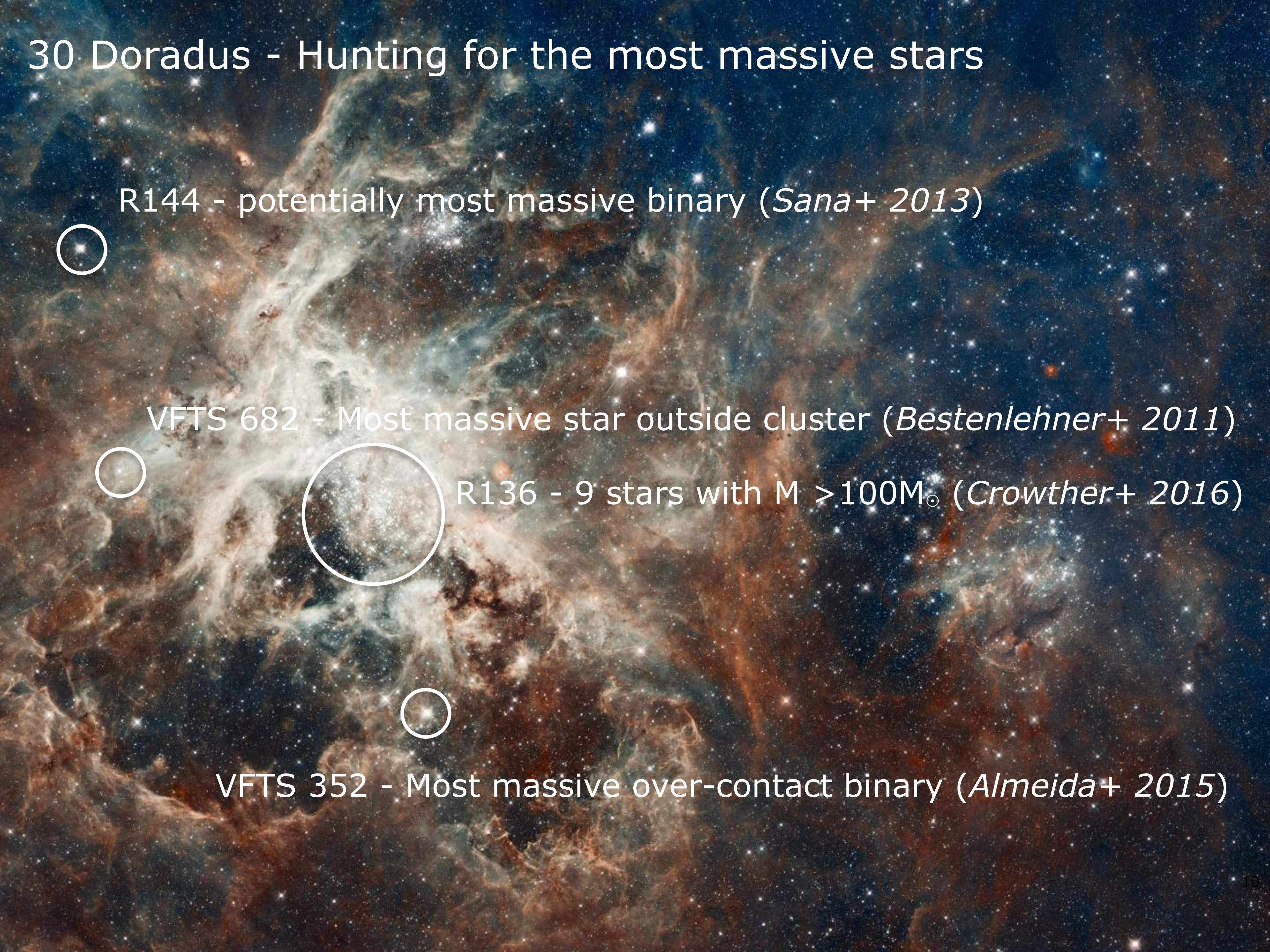
WR21a

- Very accurate lower mass limits: 64.4(4.8) $M_\odot$ + 36.3(1.7) $M_\odot$
    - But inclination unkown, no eclipses
- Mass from spectral type of secondary: 58.3(3.7) $M_\odot$ based on *Martins+ (2005)*
    - Primary mass 103.6(10.2) $M_\odot$, total mass 161.9(19.0) $M_\odot$
- Total mass from luminosity and evolutionary tracks: 150.4(13.7) $M_\odot$



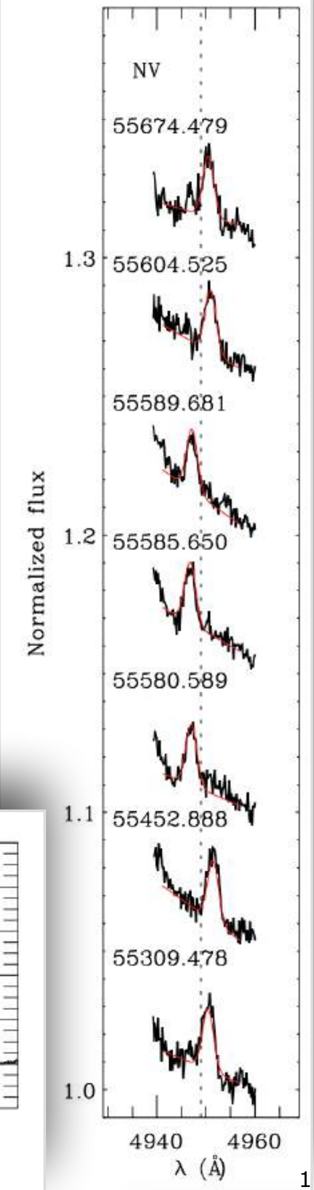
Tramper+ 2016a

30 Doradus - Hunting for the most massive stars

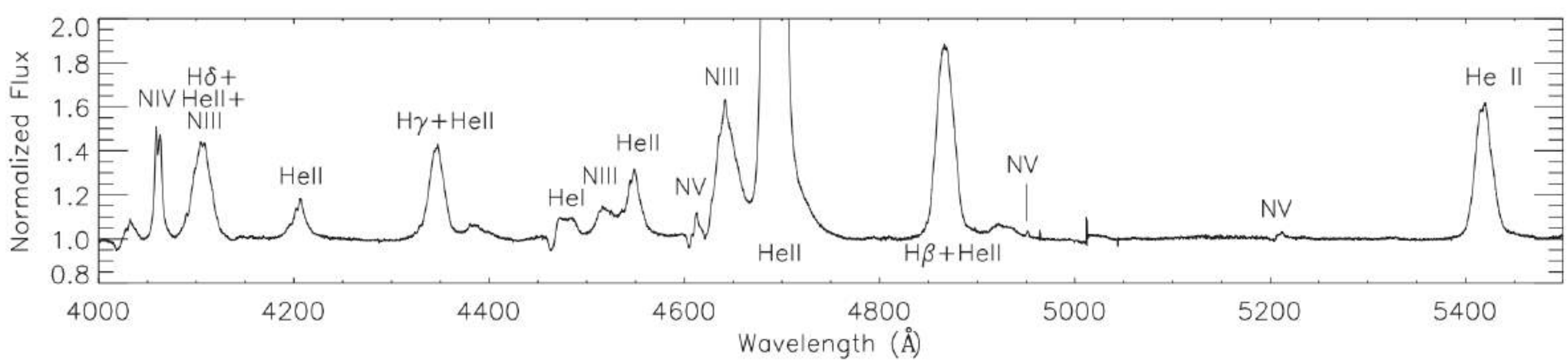


R144 - revealed as very massive binary

- One of the brightest stars in 30 Dor, long suspected to be a binary
  - log $L/L_\odot$ = 6.8
- 7 epochs of X-Shooter observations
- RV of N V anti-correlated with N III -> spectroscopic binary
- Observations too sparse to obtain good orbital solution
  - Additional epochs covering periastron passage obtained
- Based on luminosity: total mass ~200-300 $M_\odot$ (~400$M_\odot$ at birth)

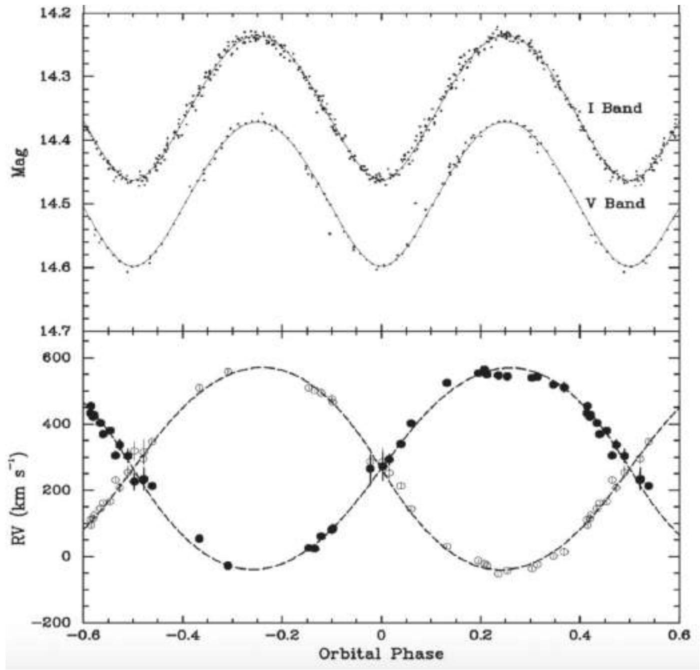


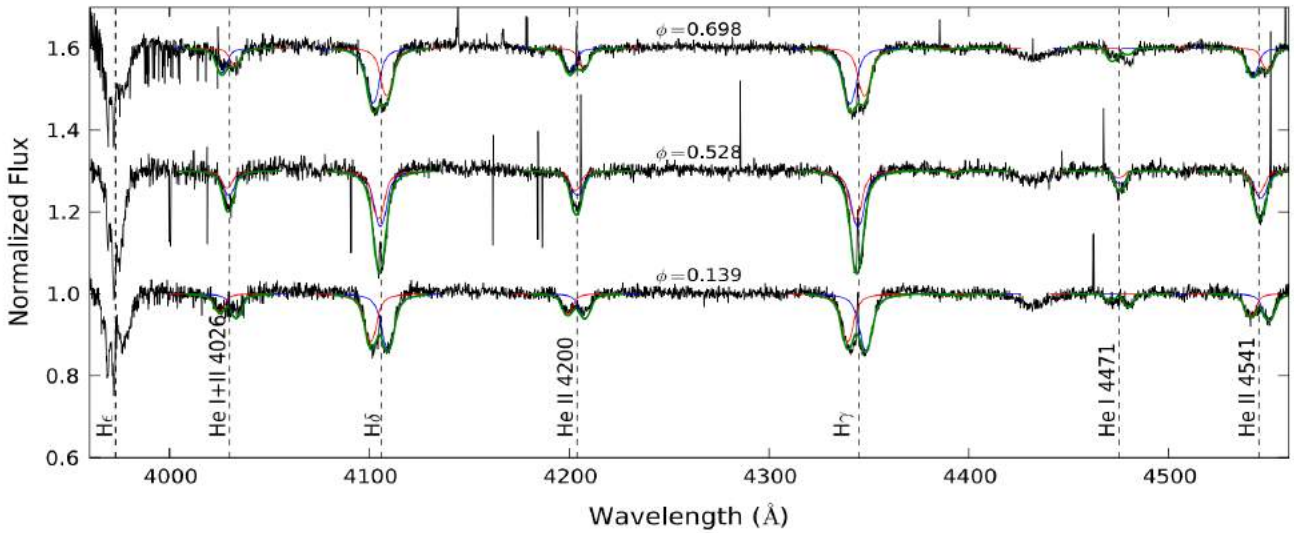
Sana+ 2013



VFTS 352 - the most massive over-contact binary

- Spectroscopic coverage from VFTS + TMBM
    - 38 epochs from 2010 - 2014
- Photometry from OGLE
    - 90 epochs V-band, 760 epochs I-band
- Orbital solution from RV and photometry
- Very short period binary
    - P = 1.12 days
    - Equal mass 28.6 + 28.9 $M_{\odot}$
    - Over-contact configuration
- High temperatures -> enhanced internal mixing





Almeida+ 2015

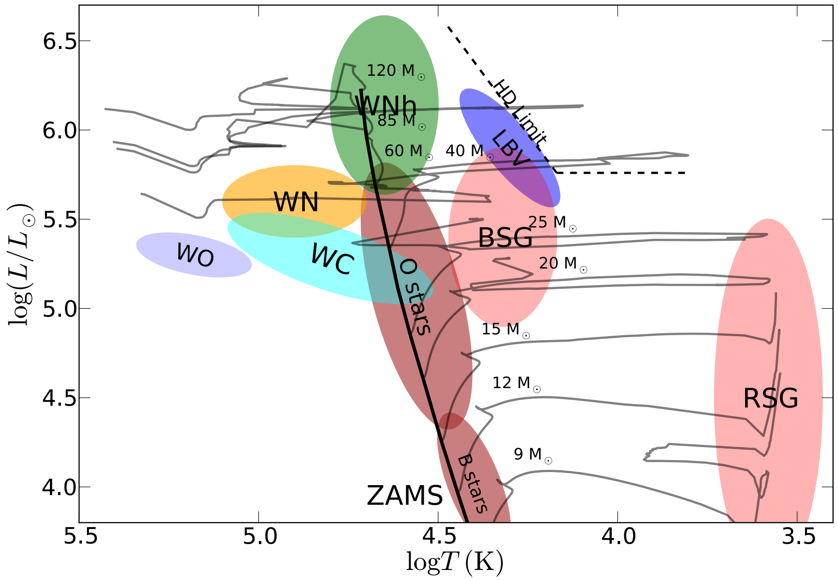
VFTS 352

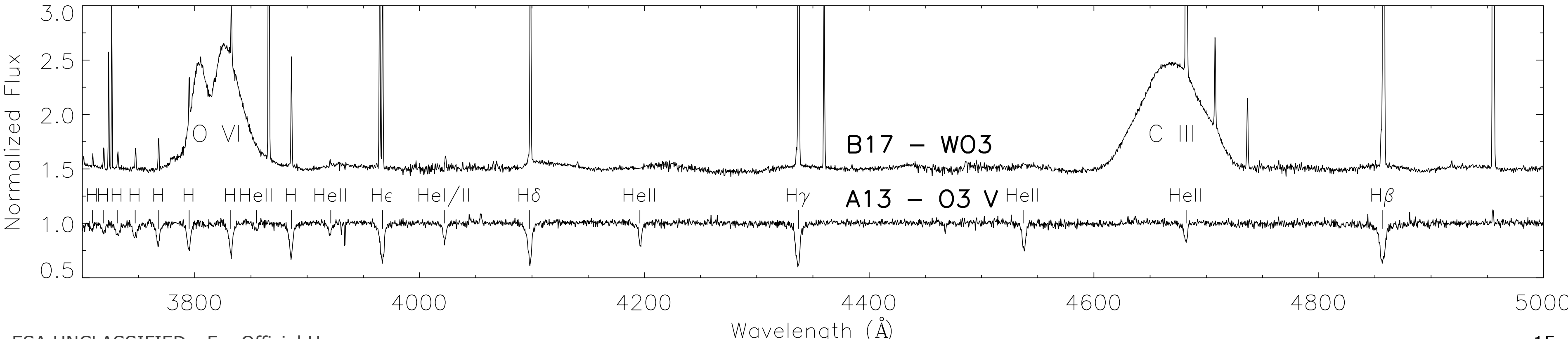
VFTS 352

II - Oxygen Sequence Wolf-Rayet Stars

Wolf-Rayet stars

- Stars with strong, broad emission lines formed in optically thick winds
  - WNh: very massive main-sequence stars
  - Classical Wolf-Rayets: WN, WC, WO
  - (Some CSPN)
- High mass-loss rates: 10^{-4} - 10^{-6} $M_\odot$ /yr

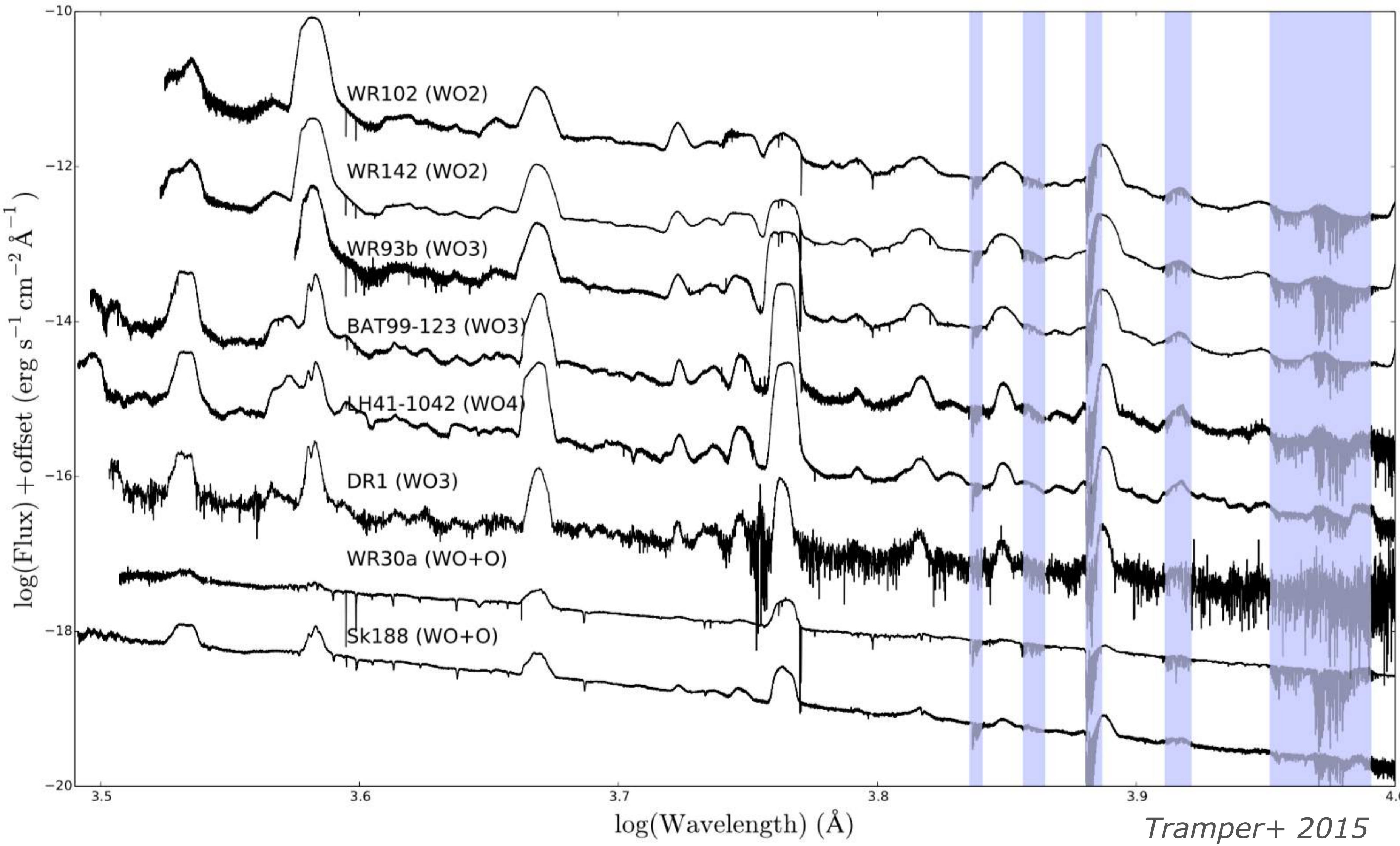




Oxygen sequence Wolf-Rayet (WO) stars

- Very rare stage of massive star evolution
    - 4 in Milky Way (1 binary)
    - 3 in Large Magellanic Cloud
    - 1 in Small Magellanic Cloud (binary)
    - 1 in IC1613 (LG dwarf galaxy)
- Usually interpreted as short stage after WC phase. Spectrum dominated by strong carbon and oxygen emission.
    - possibly the direct pre-SN stage of 40-60 $M_{\odot}$ stars
- All* WOs observed with X-Shooter between Sep. 2011 and Jun. 2014
    - *except 1 in LMC discovered June 2014 (*Massey+ 2014*)

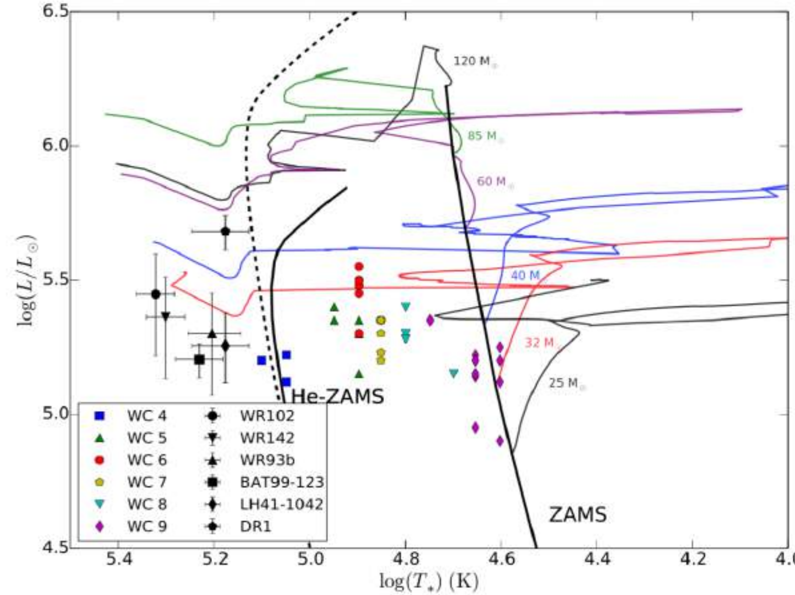
Oxygen sequence Wolf-Rayet stars

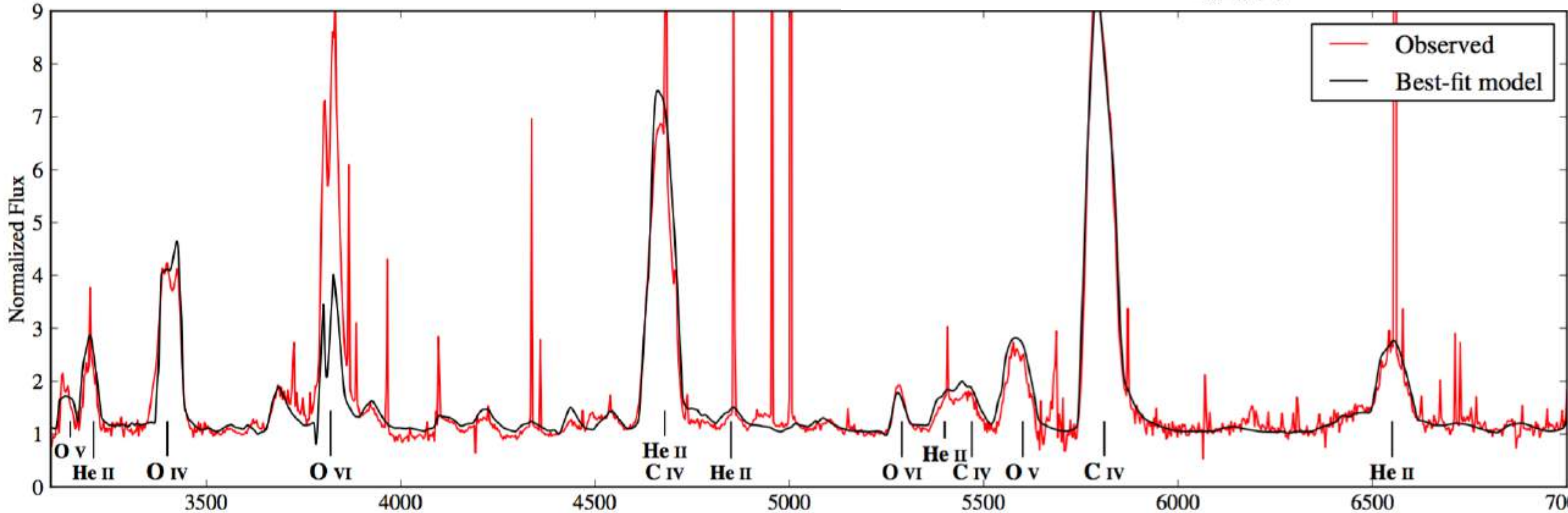


Tramper+ 2015

Properties of WO stars

- Quantitative analysis to derive luminosity, temperature, mass loss, and He, O, and C abundances
- Very high temperatures: 150 kK < T < 220 kK
- Highly evolved: no hydrogen, surface helium abundance 14% < He < 40%
- Properties cannot be reproduced by standard evolutionary models



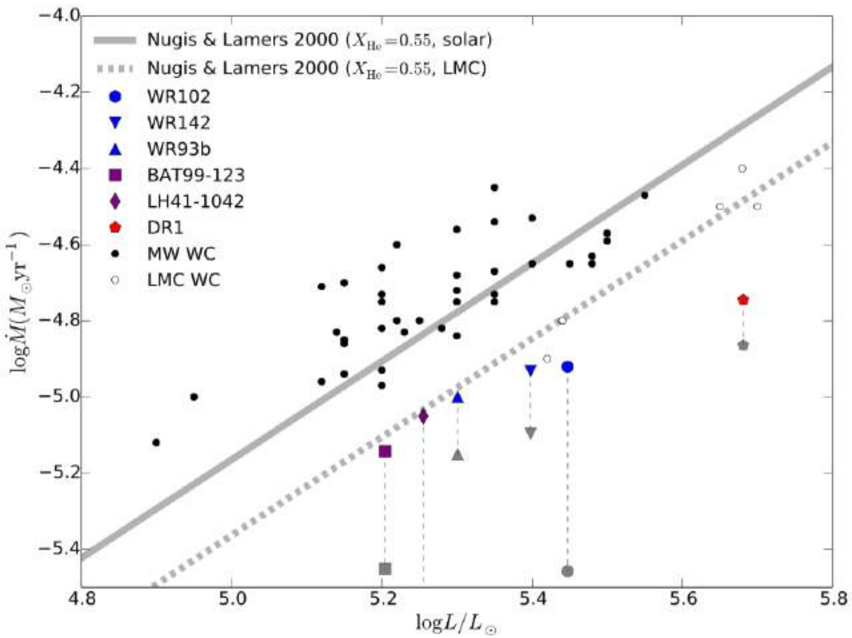


Tramper+ 2013, 2015

Evolutionary state of WO stars - I

- Evolutionary models use mass-loss prescription from *Nugis & Lamers (2000)*
  - Mass-loss as function of luminosity and surface abundance
  - Does not reproduce the mass-loss of WO stars: fails for low helium abundance

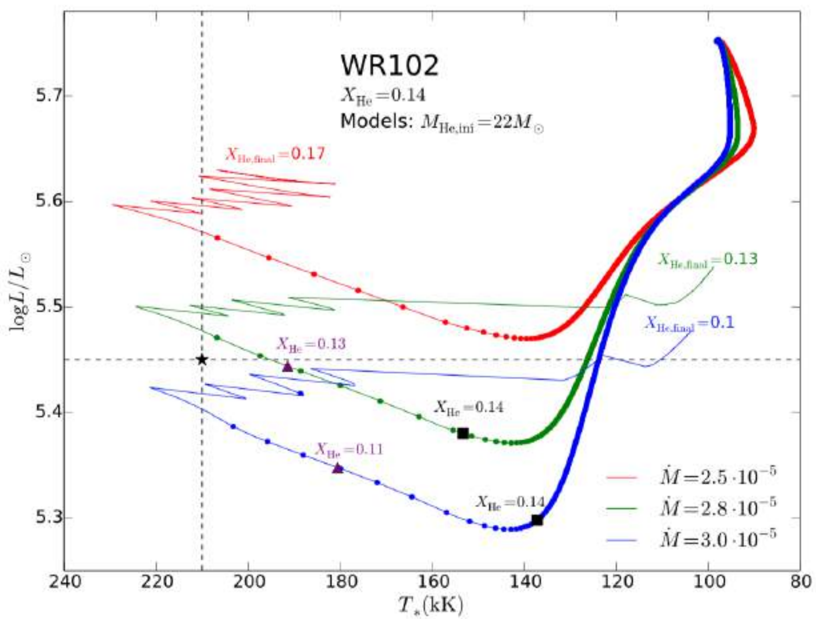
- Calculate evolutionary models for the WO stars
  - Use several fixed mass-loss rates, start at He-ZAMS
  - Determine evolutionary state
  - Determine time to SN

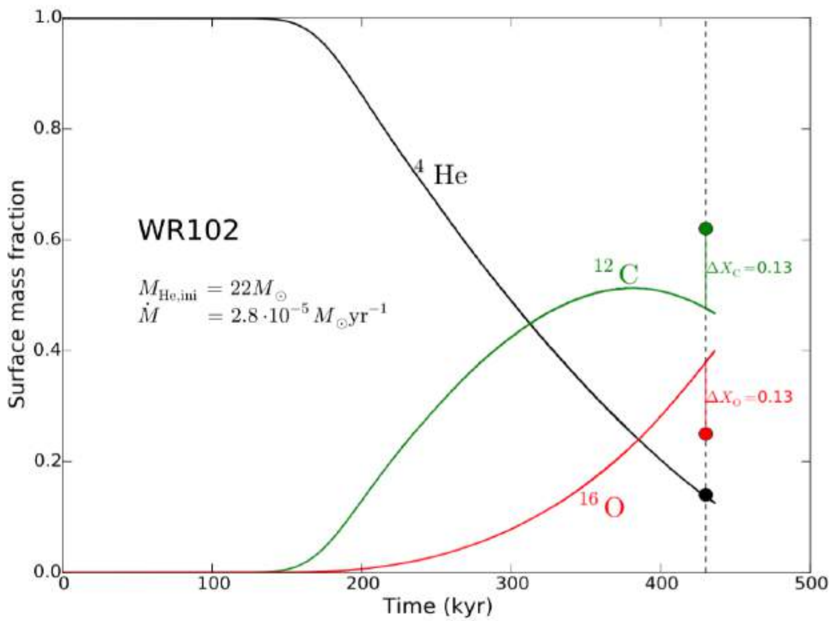


Tramper+ 2015

Evolutionary state of WO stars - II

- Evolutionary models can reproduce luminosity, temperature and helium abundance when using constant high mass loss
- All WO stars are post-helium burning, explode within 10000 yr
- Most extreme: WR102 with t_{SN} < 1500 yr

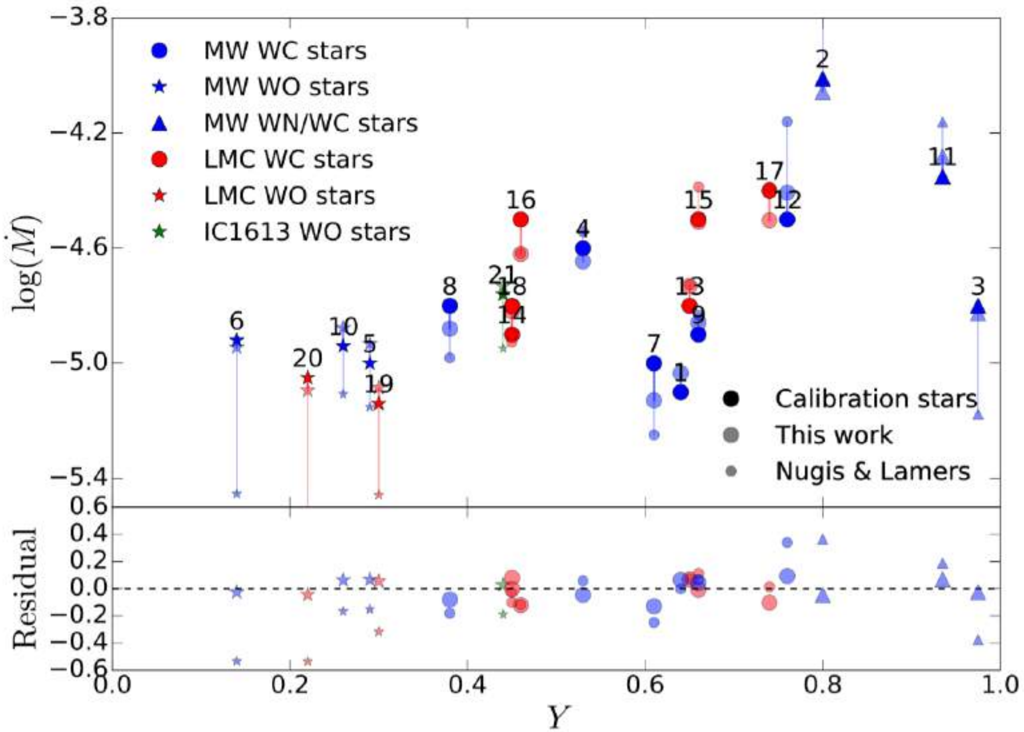




Tramper+ 2015

Mass-loss of WO and WC stars

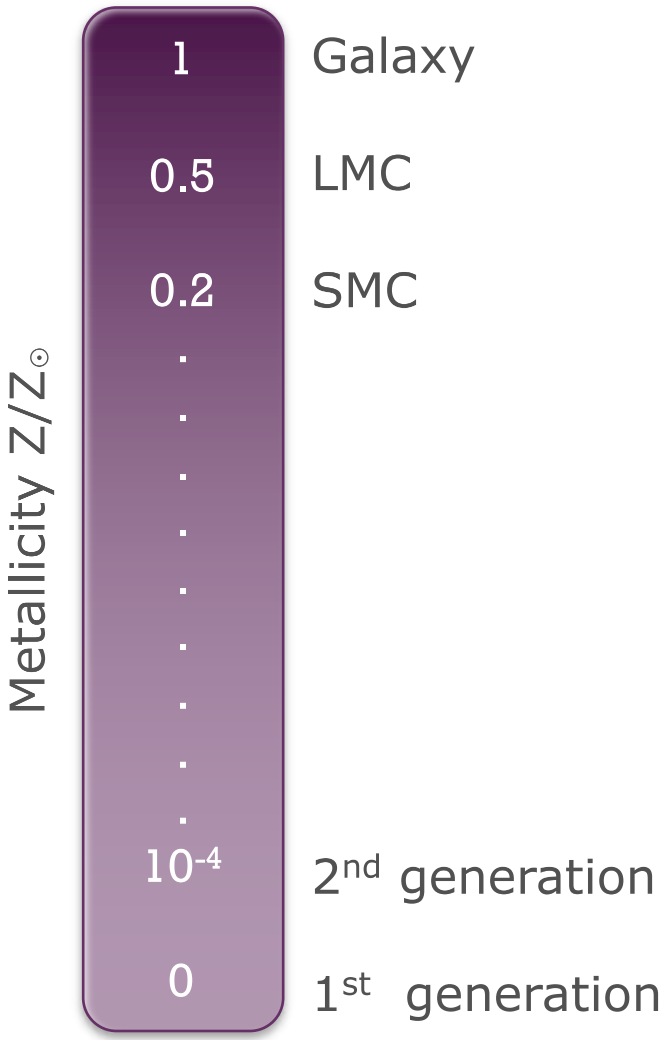
- New prescription that works for all WC and WO stars
  - Mass-loss function of luminosity, helium abundance, and metallicity
  - WC parameters from literature, using detailed spectroscopic analyses
- Ongoing: evolutionary models for WO stars using new mass-loss prescription
  - Trainee Carlos Viscasillas



Tramper+ 2016b

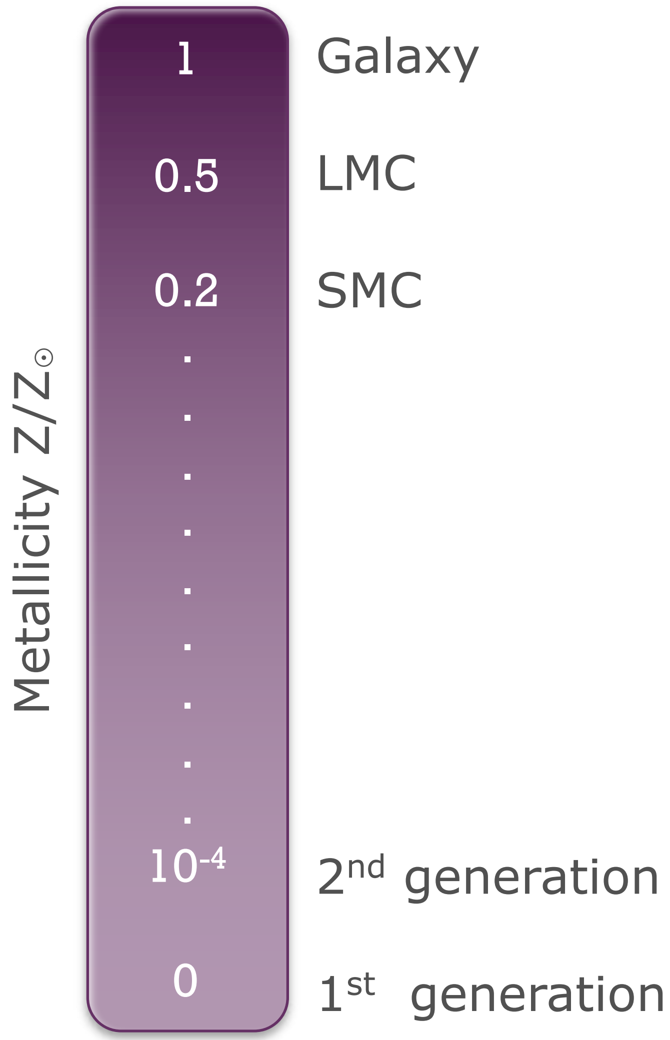
III - The quest towards low metallicities

Towards very low metallicities - I



- First stars were very massive
  - Provided the first elements other than hydrogen & helium
  - Reionized the Universe
  - Dominate galaxy evolution
- Winds driven by radiation pressure on metals: weaker winds at low Z
  - More massive end products (GW progenitors)
  - More rapidly rotating end products (GRB progenitors)
- *We need to understand low-Z massive stars*

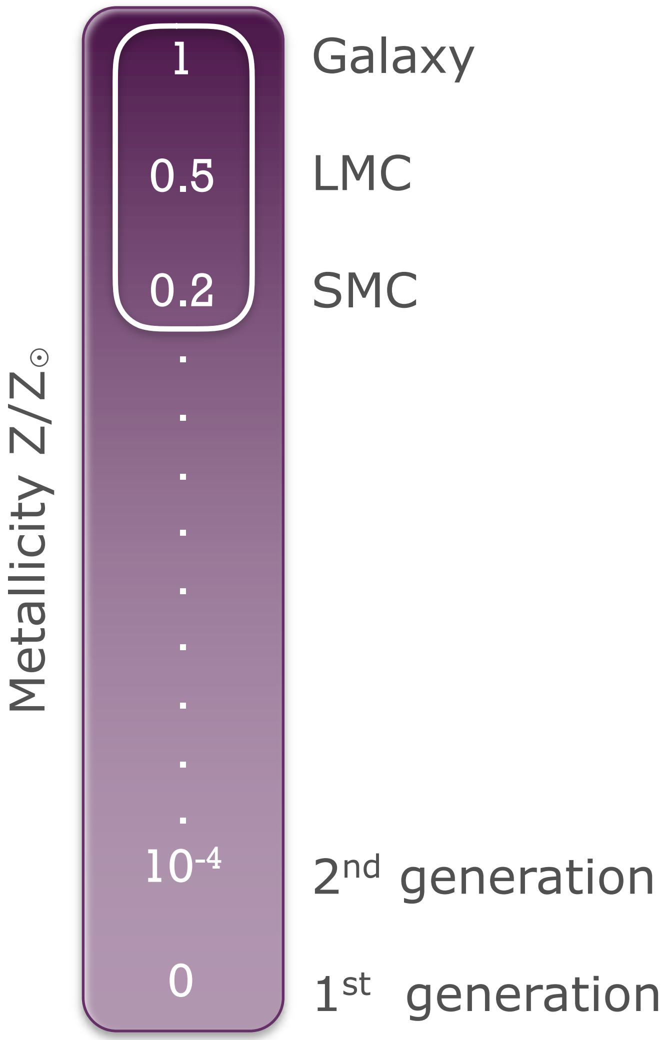
Towards very low metallicities - II



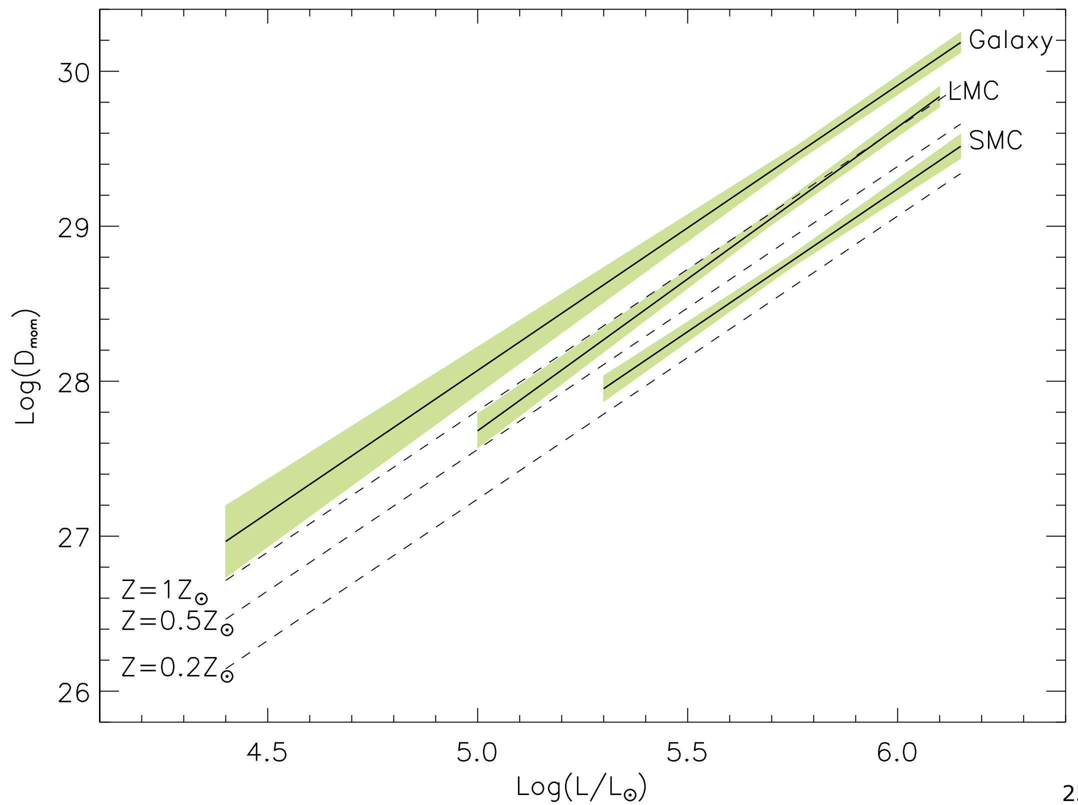
- The problem: we cannot observe individual stars in high redshift galaxies
- The solution: nearby dwarf galaxies with low SFR
  - Provide conditions similar to those in the early Universe

- current 8-10m class telescopes can resolve massive stars up to 2 Mpc*
  - *pitfalls: clustering, multiplicity

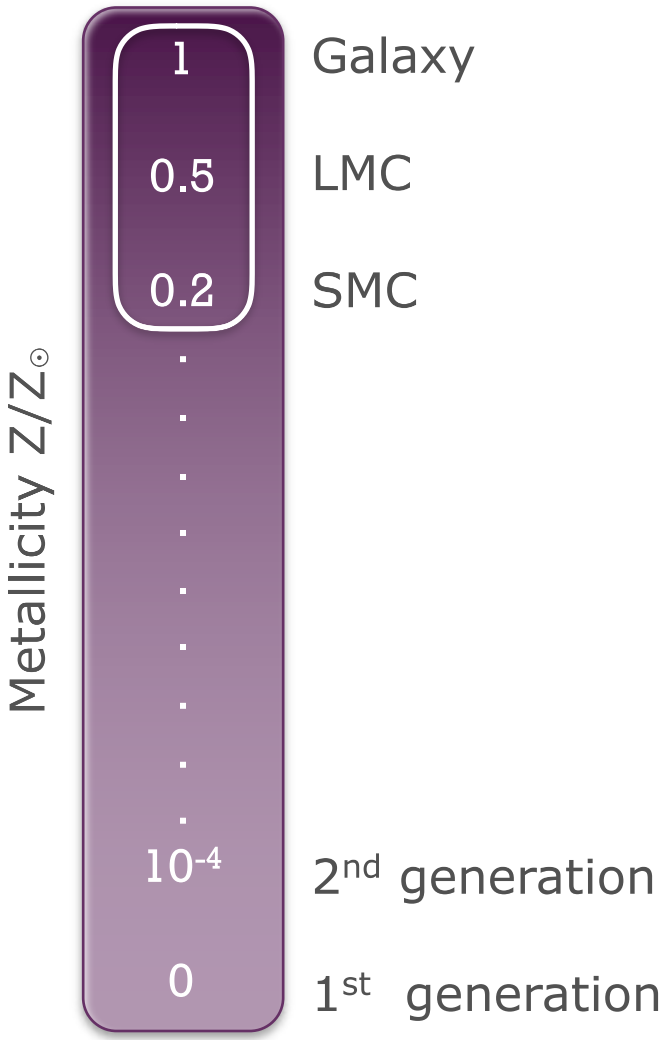
Stellar winds at low metallicity



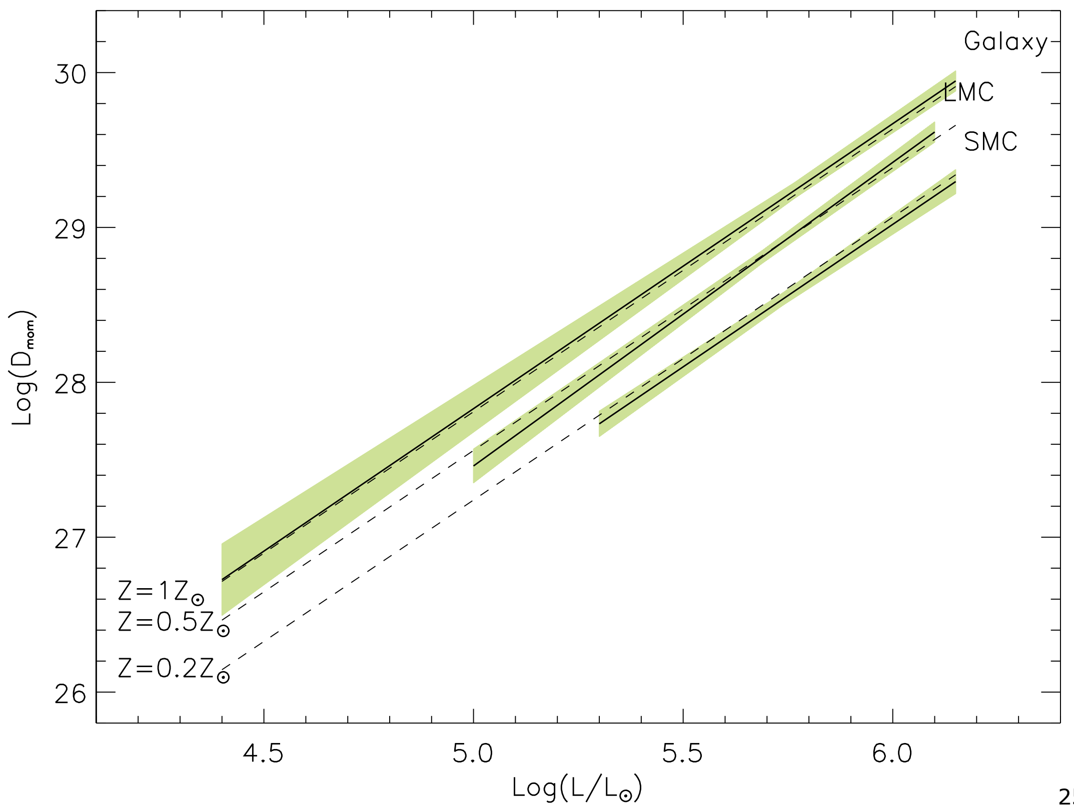
- Theory: $\dot{M} \propto Z^{0.69}$ (*Vink+ 2001*)
- VLT/Flames Survey of Massive Stars (Evans+ 2005): MW, LMC, SMC
  - $\dot{M} \propto Z^{0.83\pm0.16}$ (*Mokiem+2007*)



Stellar winds at low metallicity



- Theory: $\dot{M} \propto Z^{0.69}$ (*Vink+ 2001*)
- VLT/Flames Survey of Massive Stars (Evans+ 2005): MW, LMC, SMC
  - $\dot{M} \propto Z^{0.83 \pm 0.16}$ (*Mokiem+2007*)



Going beyond the SMC - I

Metallicity $Z/Z_\odot$

1 Galaxy

0.5 LMC

0.2 SMC

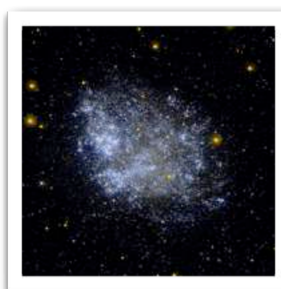
0.15 IC1613, WLM, NGC3109

.
.
.
.
.
.
.
.

10^{-4} 2^{nd} generation

0 1^{st} generation

- Local Group dwarf galaxies with $Z{\sim}1/7\ Z_\odot$
  - Low line of sight extinction
  - Young stellar population
- 10 brightest O stars observed with X-Shooter

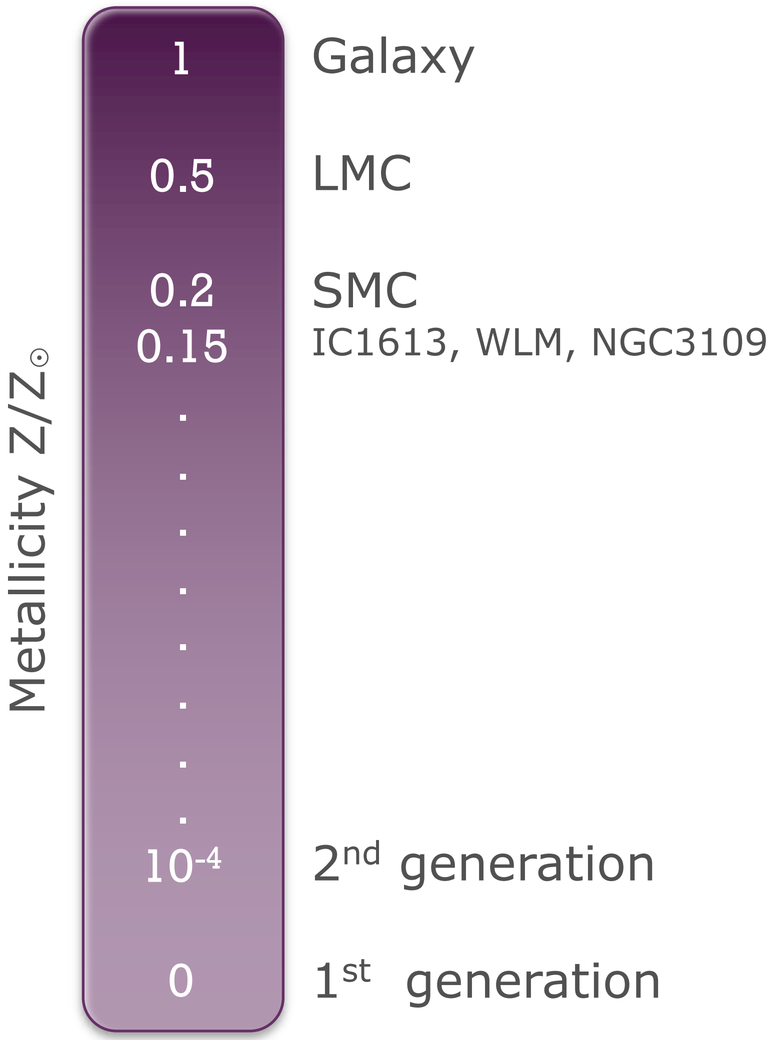


IC 1613 @ 720 kpc

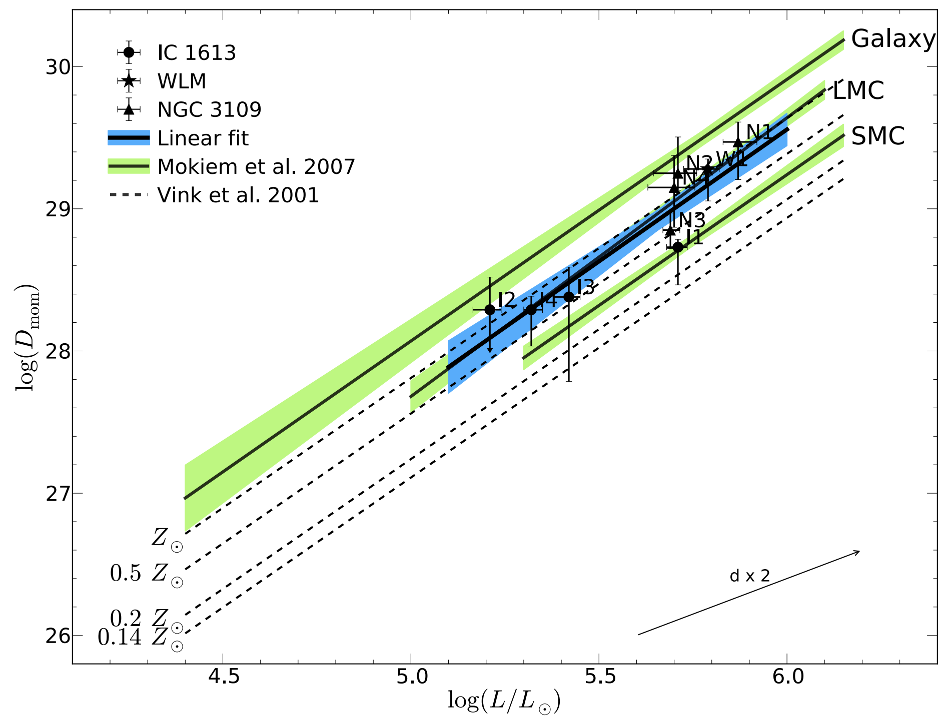
WLM @ 995 kpc

NGC 3109 @ 1.3 Mpc

Going beyond the SMC - II



- Stellar winds appear to be too strong for their metallicity (*Tramper+ 2011, 2014*; see also *Herrero+ 2010, 2012*)
  - HST UV spectroscopy needed to confirm (see *Bouret+ 2014*)

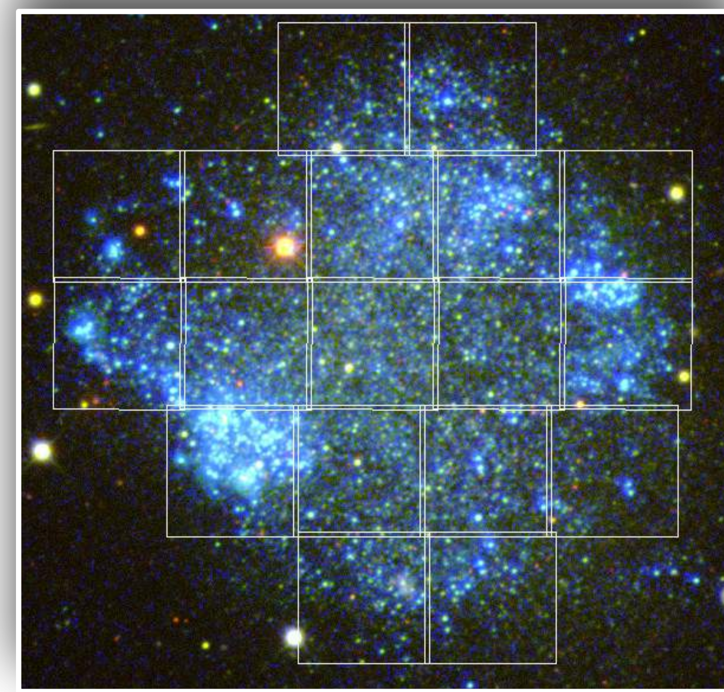


Going beyond the SMC - Upcoming

Metallicity $Z/Z_\odot$

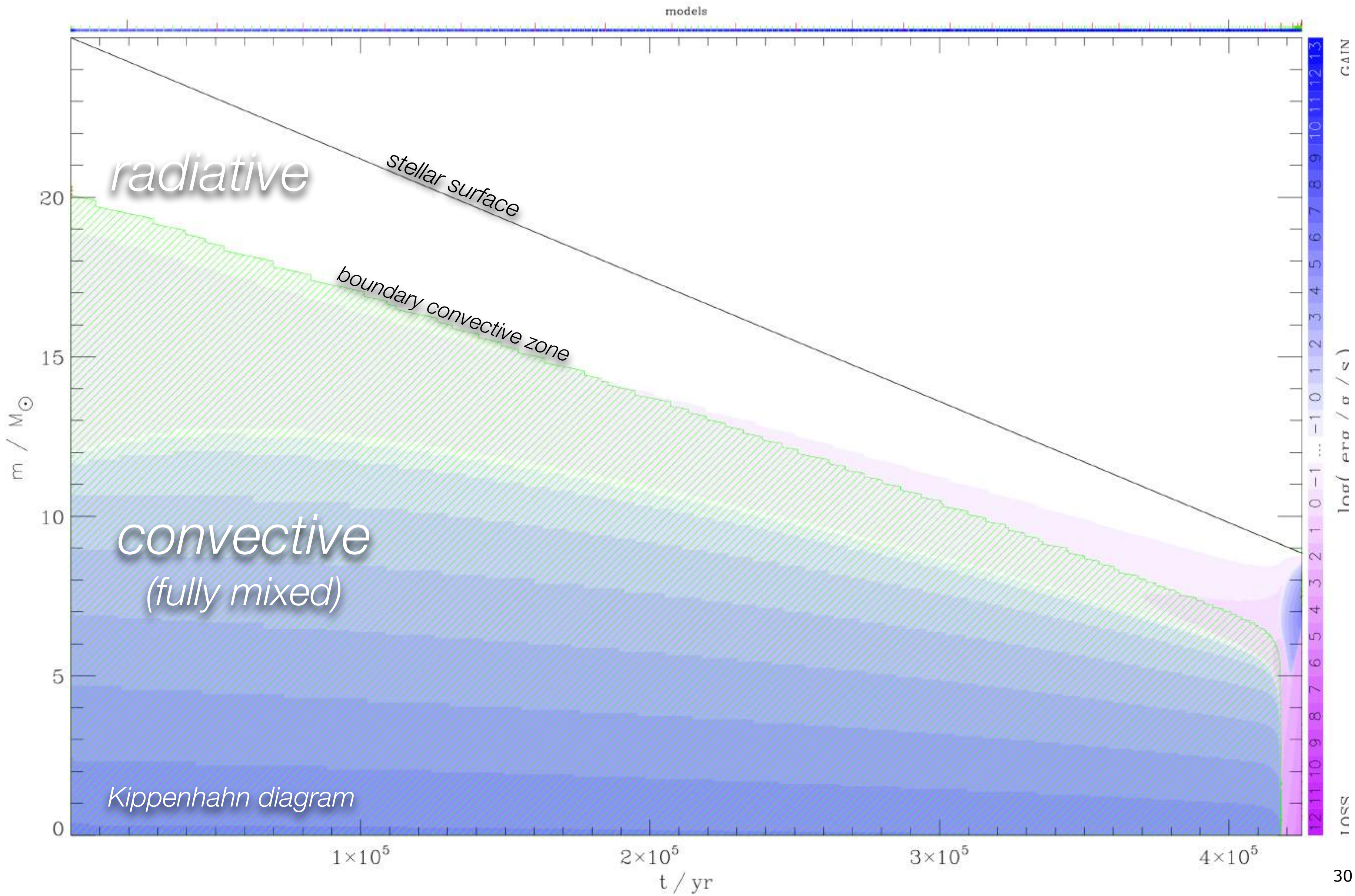
$Z/Z_\odot$	
1	Galaxy
0.5	LMC
0.2	SMC
0.15	IC1613, WLM, NGC3109
0.06	Sextans A
0.01	SAGDIG
.	
.	
.	
.	
.	
.	
10^{-4}	2^{nd} generation
0	1^{st} generation

- The next step: Sextans A & Sagittarius Dwarf irregular galaxy
  - Far enough to be small on the sky
  - Close enough to resolve the stellar population



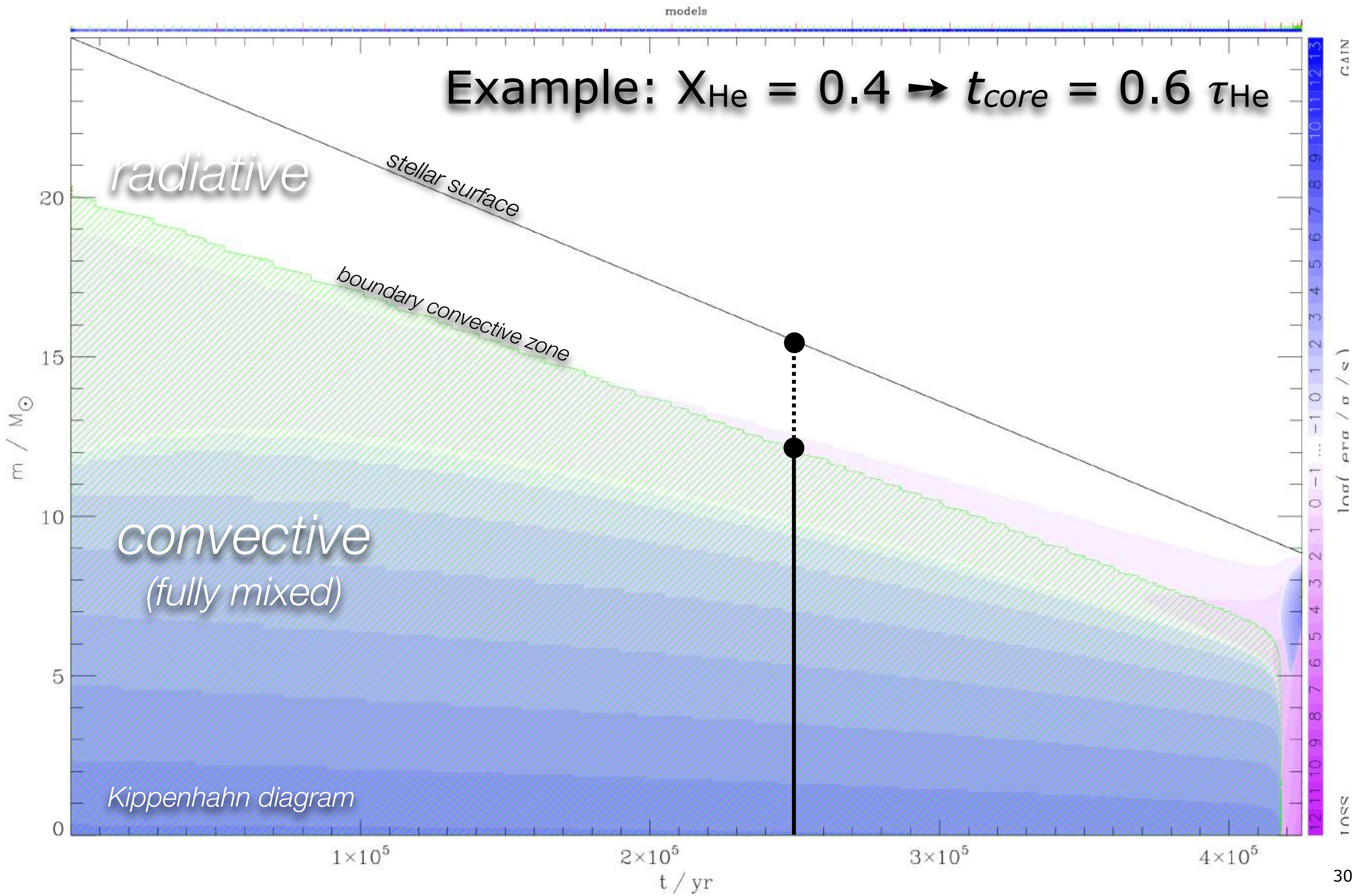
Take-home messages

- Binaries play an important role in massive star evolution
- Getting the mass loss right is key to accurately predict stellar evolution
- WO stars offer a rare glimpse in the life of massive stars just before the supernova
- Strength of stellar winds at low metallicities remains uncertain
- Nearby low-metallicity galaxies offer a unique doorway to the early Universe

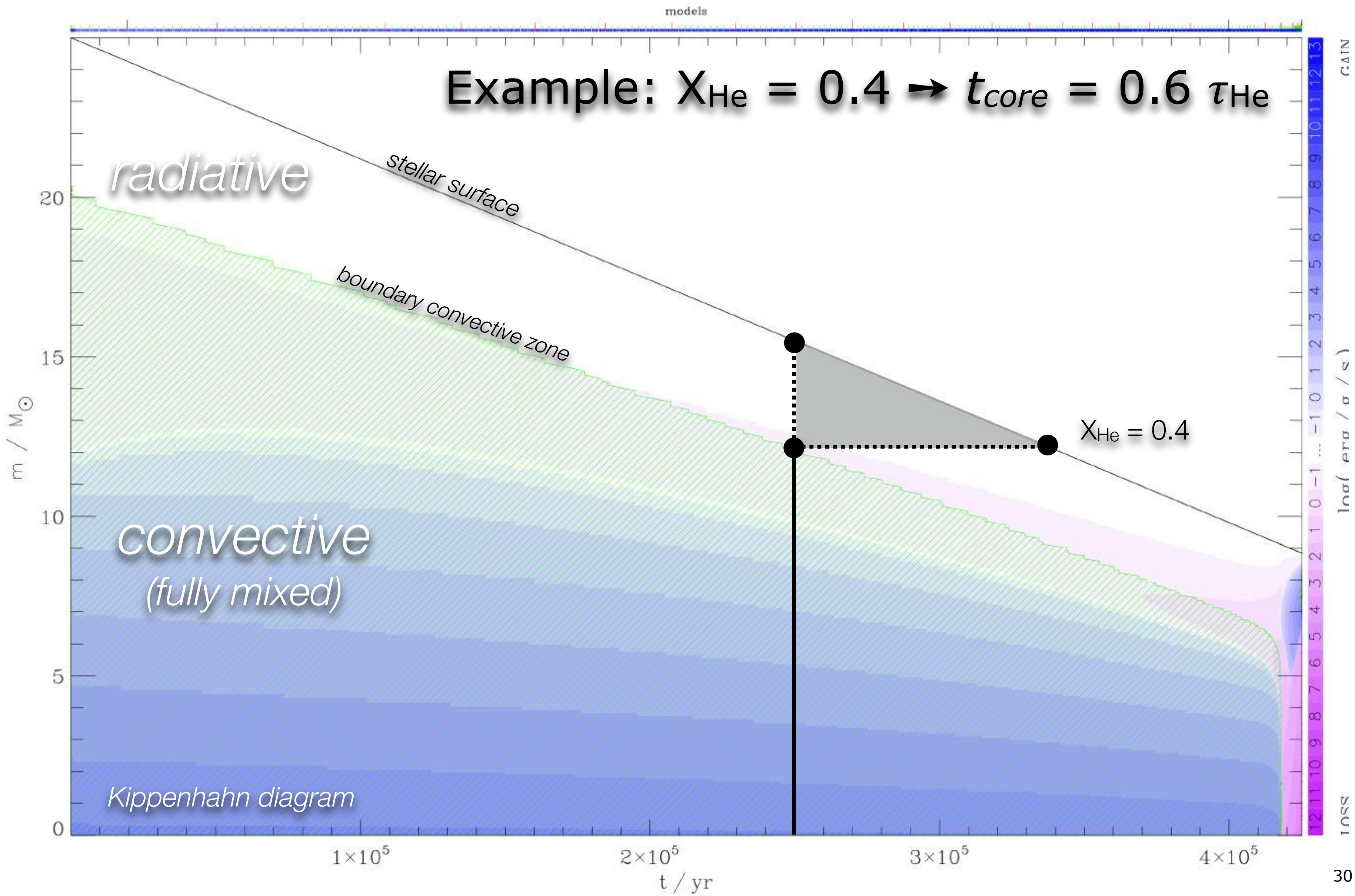


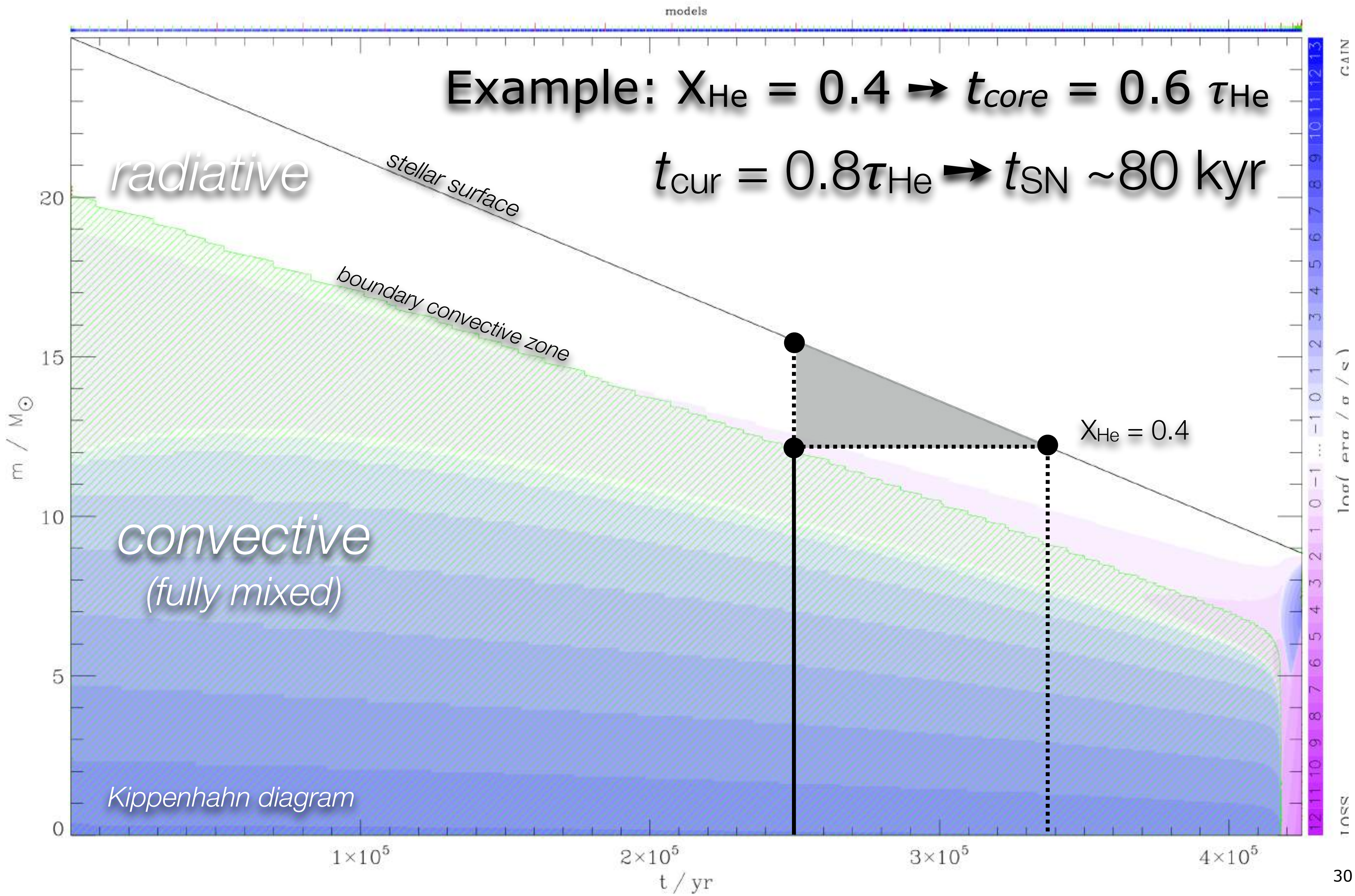
European Space Agency

Example: $X_{He} = 0.4 \rightarrow t_{core} = 0.6\ \tau_{He}$



Example: $X_{He} = 0.4 \rightarrow t_{core} = 0.6\ \tau_{He}$





Example: X_{He} = 0.4 → t_{core} = 0.6 τ_{He}
t_{cur} = 0.8τ_{He} → t_{SN} ~80 kyr
models
radiative
stellar surface
boundary convective zone
convective
(fully mixed)
Kippenhahn diagram
X_{He} = 0.4
m / M$_\odot$
t / yr
1×10^5
2×10^5
3×10^5
4×10^5
0
5
10
15
20
GAIN
LOSS
log(erg / g / s)