The WN population in the Magellanic Clouds

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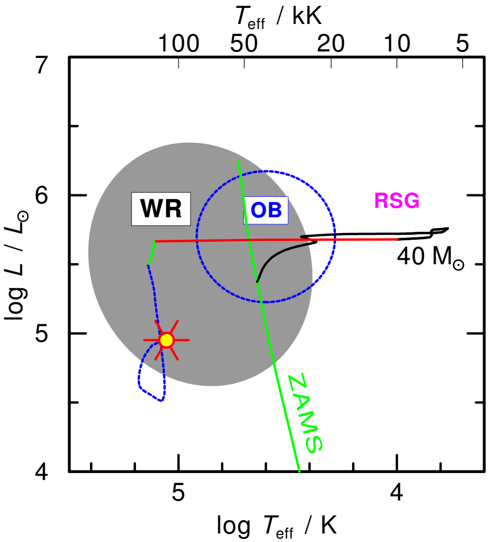
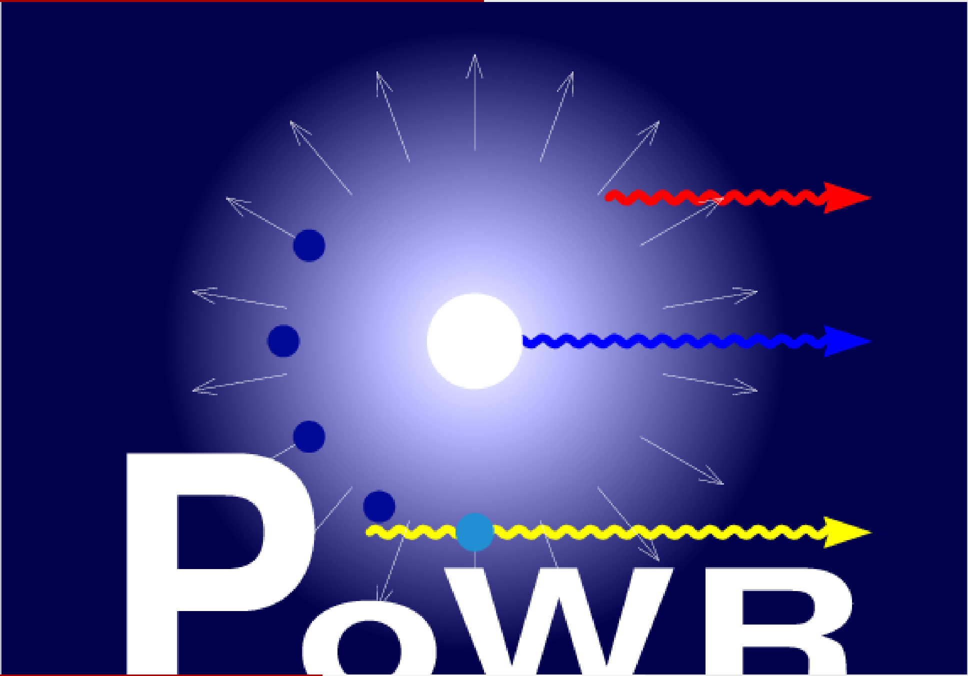
Wolf Rayet Stars (WR)

- evolved massive stars
  ↪ initial masses above $20 M_\odot$
- OB → (BSG/LBV) → WR
- dense and fast stellar winds (up to ≈ 5000 km/s)
- strong mass loss ($10^{-5} M_\odot/\mathrm{yr}$)
- spectra with strong broad emission lines
  - helium and nitrogen
    ↪ WN sequence
  - carbon, helium, and oxygen
    ↪ WC sequence




PoWR

PoWR: Potsdam Wolf-Rayet model code for expanding stellar atmospheres with spherical stellar winds

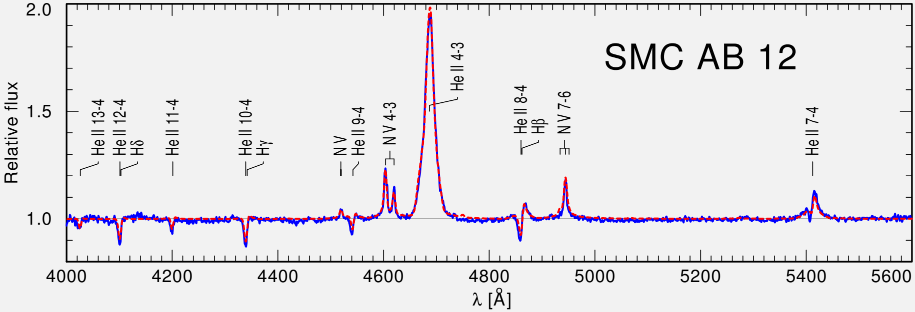
Features:

- full Non-LTE calculation of population numbers
- complex model atoms (H, He, N, C, O, ...)
- radiative transfer in co-moving frame
- pressure broadening in formal integral
- iron-line blanketing (super-level approach)
- wind inhomogeneities (micro-clumping)
- applicable to hot stars (WR, O, B, LBV, CSPN ...)

PoWR models: www.astro.physik.uni-potsdam.de/PoWR.html

Spectral analysis

Aim: reproduce the complete spectra instead of individual lines



Observation vs. PoWR-model

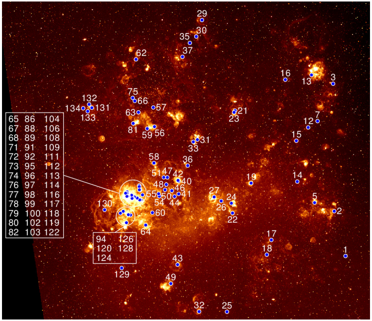
Results:

- obtain consistent set of stellar parameters
  $\Rightarrow T_*, L, \dot{M}, v_\infty, \ldots.$

Magellanic Cloud sample

Large Magellanic Cloud

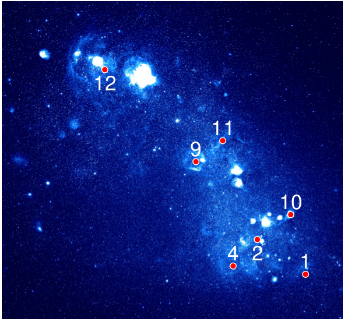
- nearly complete WN population (101 of 117 WN stars) ↪ Hainich et al. (2014)
- 31 binaries/binary suspects (Foellmi et al. 2003b)



Magellanic Cloud Emission-Line Survey (Smith et al. 2005)

Small Magellanic Cloud

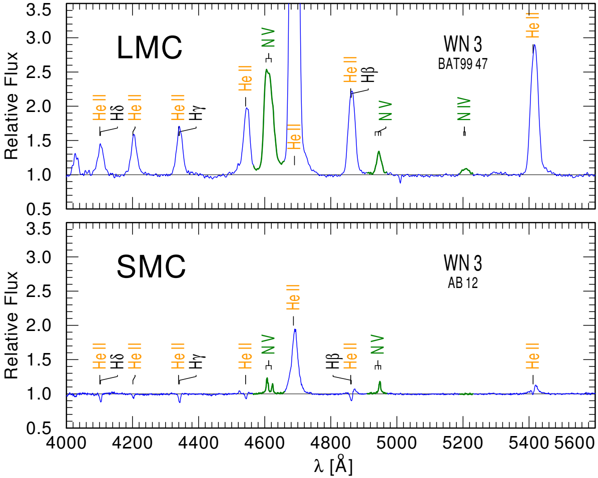
- complete WN population
- 7 single stars + 4 binaries (Foellmi et al. 2003a)
- single: Hainich et al. (in prep.) binary: Shenar et al. (in prep.)



Magellanic Cloud Emission-Line Survey (Smith et al. 2005)

WN spectra: comparison between LMC and SMC

WN stars: helium & nitrogen emission lines



WNE: WN 2 - WN 5
WNL: WN 6 - WN 11

SMC:

- considerably weaker emission lines
- inherent absorption lines
- photosphere might be partly visible
- weaker winds

↪ metallicity effect

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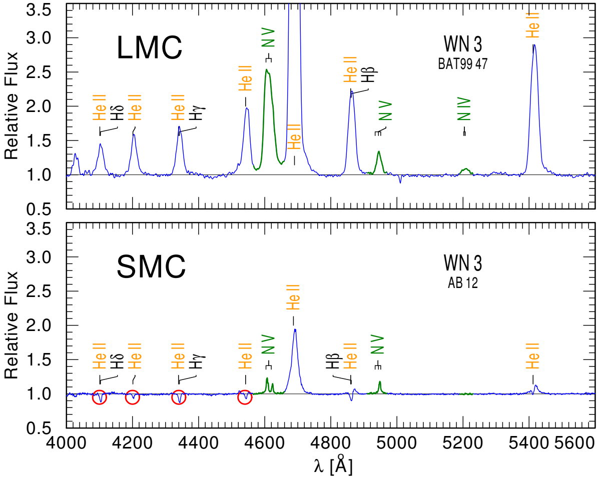

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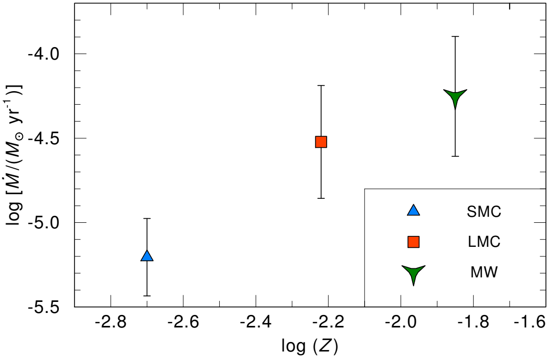
$\dot{M}$-Z-relation



$\dot{M}$-Z-relation:

- averaged $\dot{M}$ for each galaxy
- $Z_{\mathrm{MW}} = 0.014$
- $Z_{\mathrm{LMC}} = 0.006$
- $Z_{\mathrm{SMC}} = 0.002$

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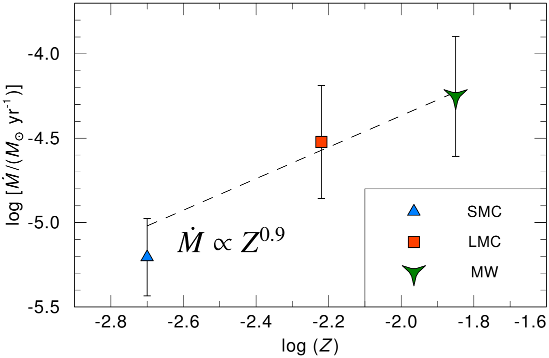

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weighted fit:

$$\dot{M} \propto Z^{0.9}$$

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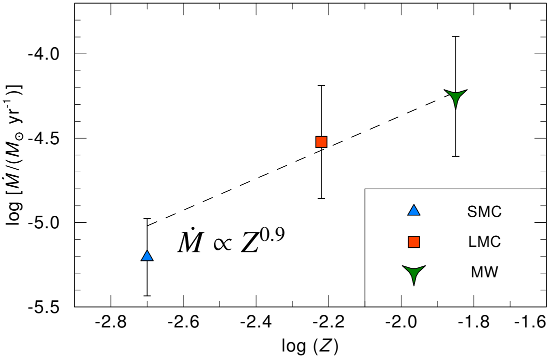

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Mass-loss prescription for WN stars:

(χ^2-fit to the whole dataset)

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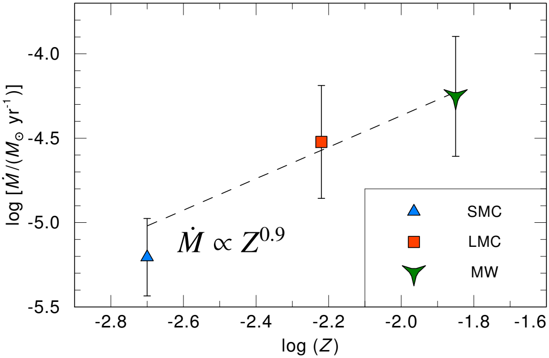

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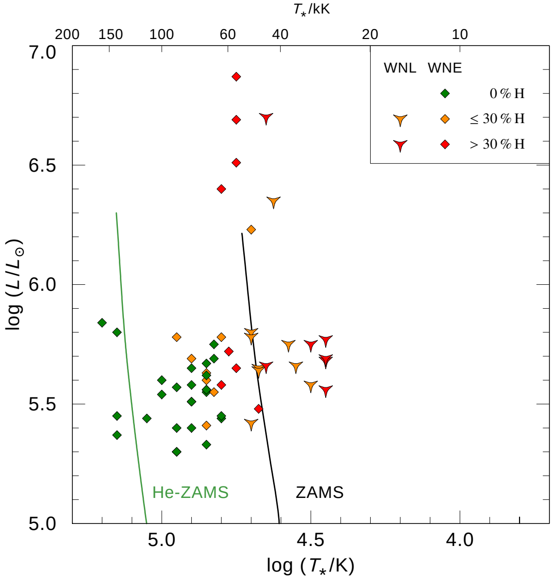
$$\dot{M} = -12.6 + 2\log(1 + X_H) + 2.3\log(L/L_\odot) - 2.5\log(M/M_\odot) + 0.7\log(Z)$$

Evolutionary status of the WN stars

Stellar evolution: LMC



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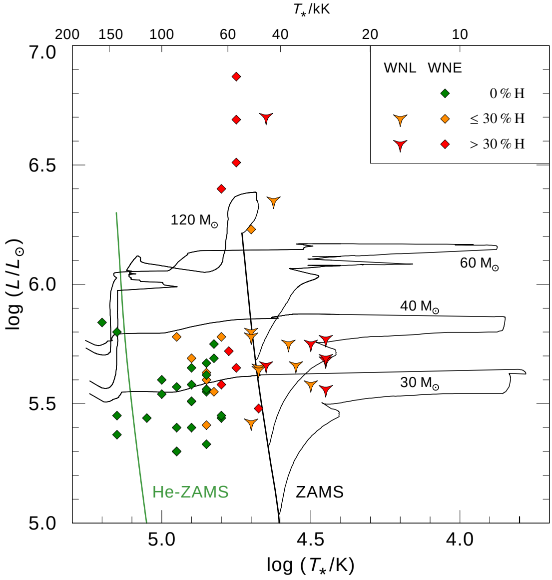
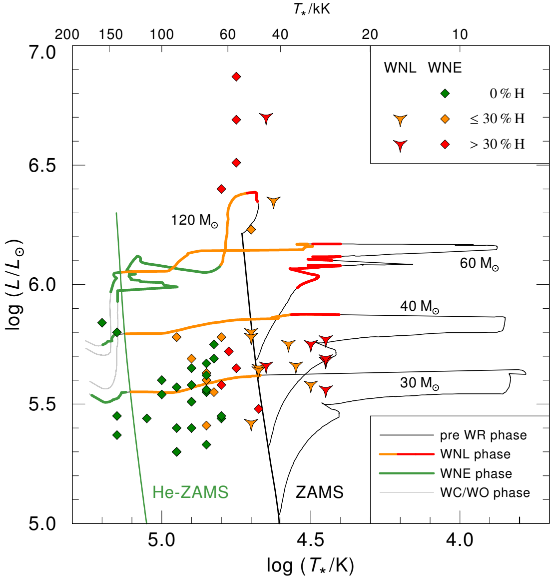


Geneva evolution tracks: Meynet & Maeder (2005)

- $Z = 0.008$
- with rotation
- $M_{\mathrm{WR,ini}} \approx 30\,M_{\odot}$

Stellar evolution: LMC



Geneva evolution tracks:
Meynet & Maeder (2005)

- $Z = 0.008$
- with rotation
- $M_{\mathrm{WR,ini}} \approx 30\,M_\odot$

deduced initial WR mass:

$\approx 20\,M_\odot$

SMC WN stars: comparison with LMC and MW sample

MW sample:

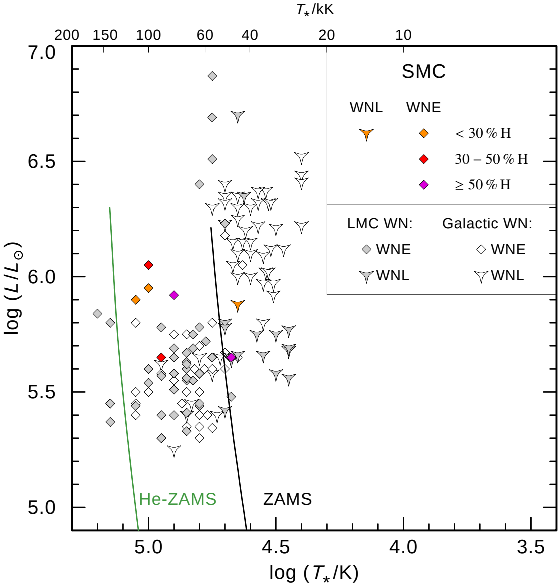
- Hamann et al. (2006)
- Martins et al. (2008)
- Liermann et al. (2010)
- Oskinova et al. (2013)

LMC sample:

- Hainich et al. (2014)

SMC sample:

- considerably more luminous



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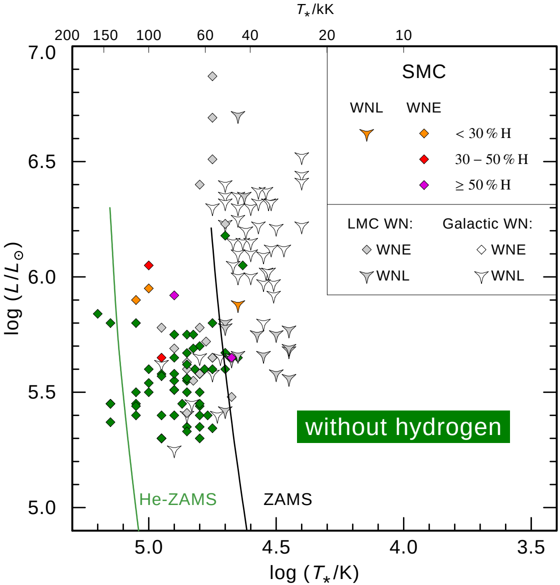
- Oskinova et al. (2013)

LMC sample:

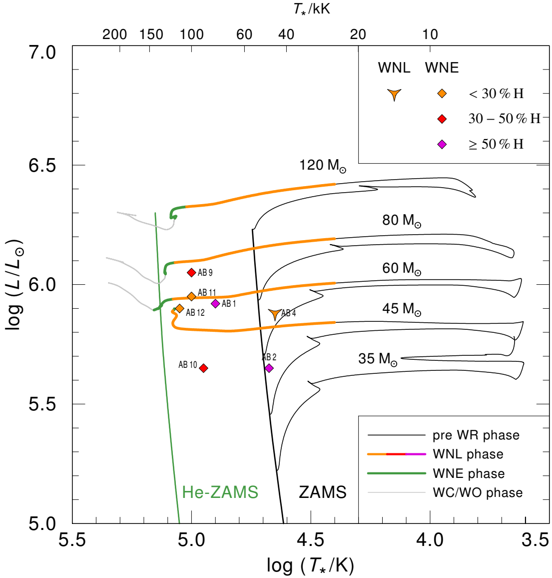
- Hainich et al. (2014)

SMC sample:

- considerably more luminous
- all with hydrogen



Stellar evolution: SMC



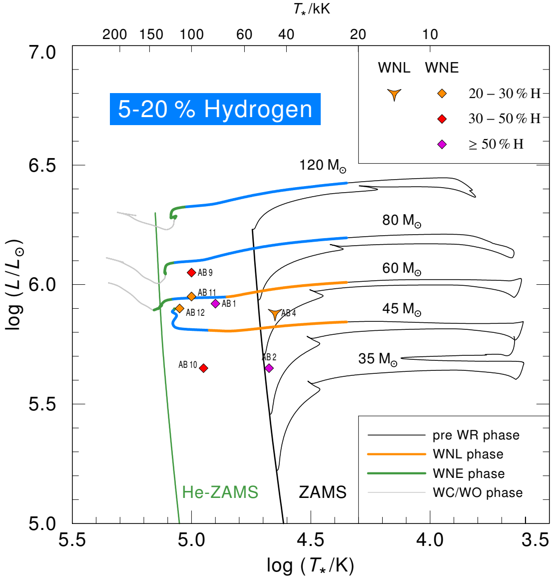
Evolution tracks from Eldridge & Vink (2006)

- $Z = 0.004$
- without rotation
- $M_{\mathrm{WR,ini}} \approx 45\,M_\odot$

deduced initial WR mass:

$\approx 30 - 35\,M_\odot$

Stellar evolution: SMC



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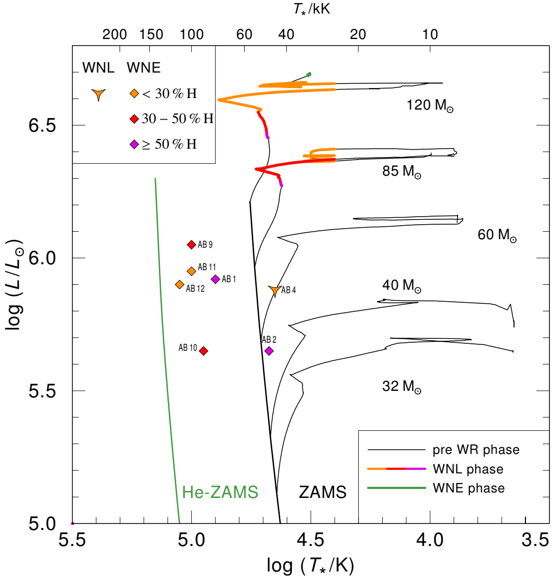


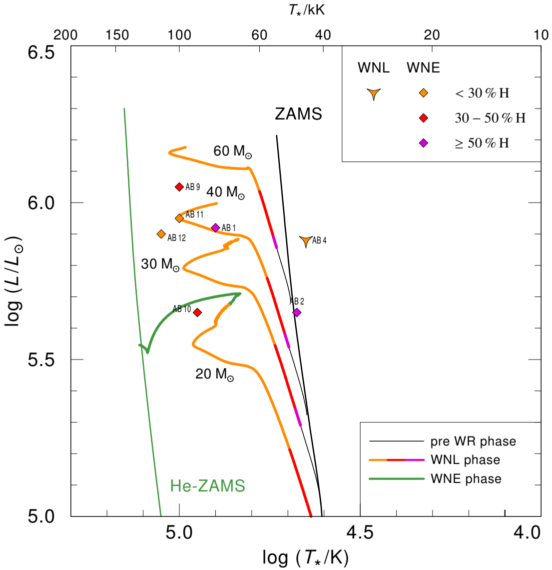
Geneva evolution tracks: Georgy et al. (2013)

- $Z = 0.002$
- with rotation
- $M_{\mathrm{WR,ini}} \approx 85\,M_\odot$

deduced initial WR mass:

$\approx 30 - 35\,M_\odot$

Stellar evolution: SMC – quasi homogeneous evolution



Homogeneous evolution:

- proposed by Martins et al. (2005)

Evolution tracks from Brott et al. (2011)

- $Z = 0.002$
- $v_{\rm rot,ini} \approx 500\,\rm km/s$

- fail to reproduce the observed surface abundances

Conclusions

Open question:

How to explain the observed hydrogen abundance for SMC WN stars simultaneously with their individual HRD positions?

Stellar evolution models:

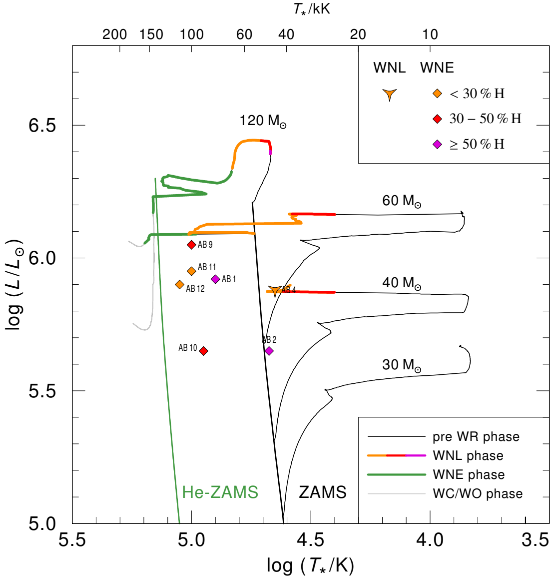
- still partly fail to reproduce the observed WN parameter range
  - predicted initial WR mass to high
  - SMC: observed hydrogen abundances cannot be reproduced

Stellar wind mass loss:

- winds of SMC WN stars weaker than their MW and LMC counterparts
- mass-loss prescription for WN stars:

$\hookrightarrow \dot{M} = -12.6 + 2\log(1 + X_H) + 2.3\log(L/L_\odot) - 2.5\log(M/M_\odot) + 0.7\log(Z)$

Stellar evolution: SMC – old generation of Geneva models



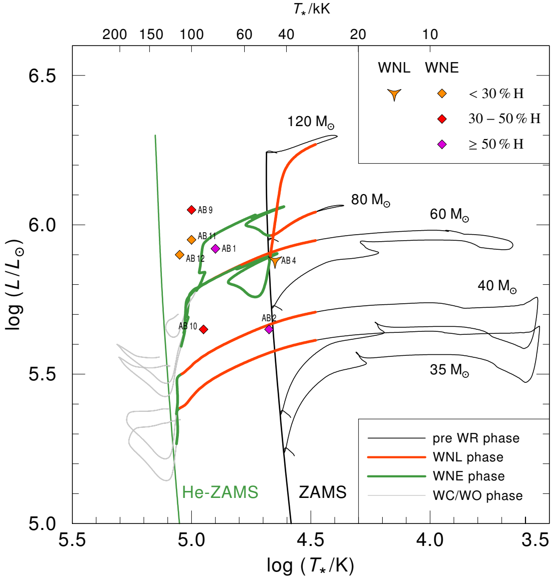
Geneva evolution tracks: Meynet & Maeder (2005)

- $Z = 0.004$
- with rotation
- $M_{\mathrm{WR,ini}} \approx 40\,M_\odot$

deduced initial WR mass:

$\approx 30 - 35\,M_\odot$

Binary evolution



Radial velocity study:

Foellmi et al. (2003a)

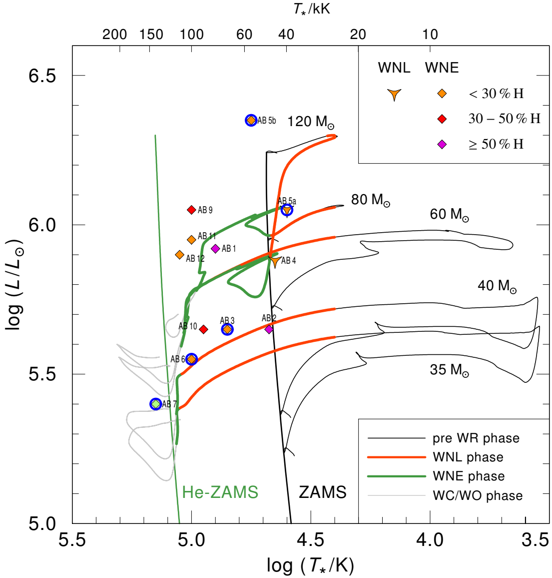
Binary evolution:

Evolution tracks from Eldridge et al. (2013)

- $Z = 0.02$
- evolution tracks for the primary

- also fail to reproduce the observed surface abundances

Binary evolution



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Binary evolution:

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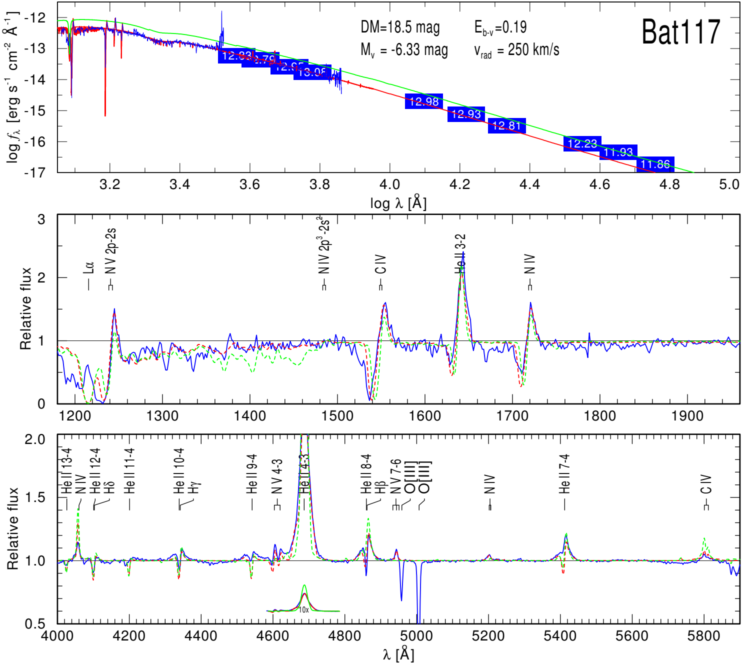


Bat117
DM=18.5 mag
M_v = -6.33 mag
E_{b-v}=0.19
v_{rad} = 250 km/s
12.98
12.93
12.81
12.23
11.93
11.86
log f_λ [erg s^{-1} cm^{-2} Å^{-1}]
log λ [Å]
Relative flux
Lα
N V 2p-2s
N IV 2p^3-2s^2
C IV
He II 3-2
N IV
He II 13-4
He II 12-4
Hδ
He II 11-4
He II 10-4
Hγ
He II 9-4
N V 4-3
He II 4-3
He II 8-4
Hβ
N V 7-6
O[III]
He II 7-4
10x
λ [Å]

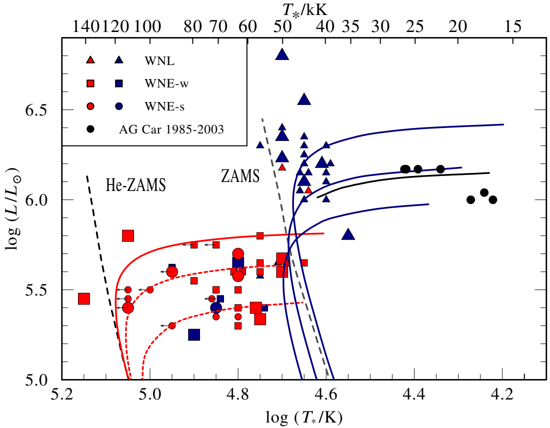
Radius problem of WR stars

- Observed T_* of H-free WR stars much lower than predicted

Stellar envelope inflation

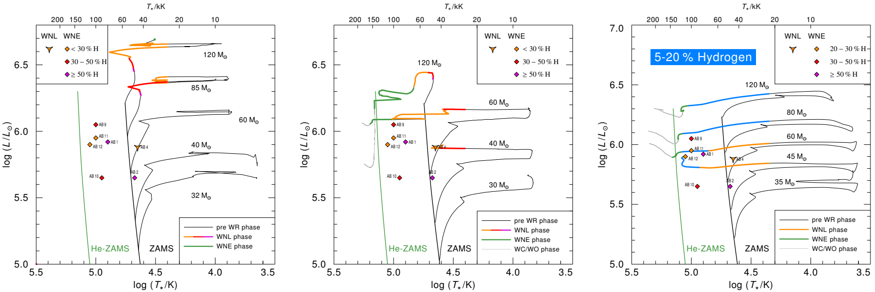
- Extended sub-photospheric layers
- Taking the effect of clumping into account (Gräfener et al. 2012)
- Solving the temperature discrepancy

HRD of the Galactic WN stars



Credit: Gräfener et al. (2012)

Single star evolution: SMC



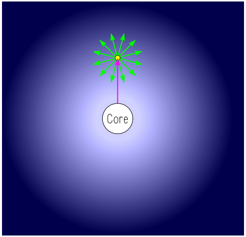
Stellar evolution models vs. observation:

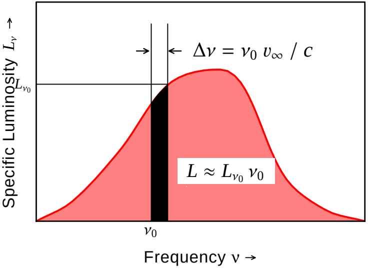
- hydrogen abundances are lower than observed
- in general the agreement seems to be better at higher metallicities
  - initial metallicity of SMC WN stars higher than $Z = 0.002$
    $\hookrightarrow$ Piatti (2011): strongly age dependent Z_{SMC}
  - mass-loss rates higher than prescribed in stellar evolution models
  - missing physical ingredient

Line-driven stellar winds

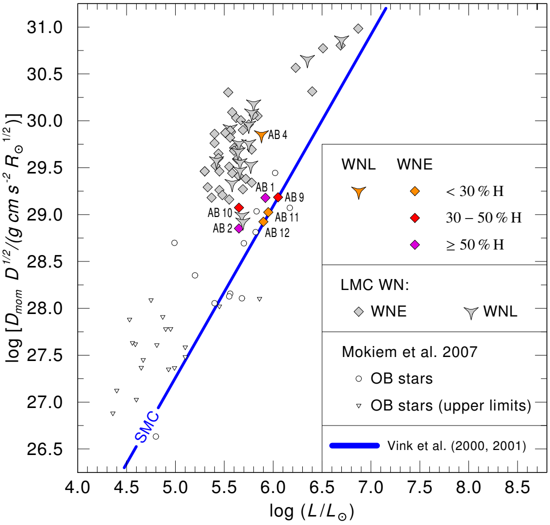
(Castor, Abbott & Klein 1975, "CAK")

- absorption mainly from radial directions but isotropic re-emmission
  $\Rightarrow$ acceleration $\Rightarrow$ velocity $\uparrow$
  $\Rightarrow$ Doppler shift of the line
- photons from whole frequency band $\Delta\nu$ are swept up
- intercepted momentum per time and line: $L_{\nu_0}\Delta\nu/c = L v_\infty/c^2 = \dot{M} v_\infty$
- mass loss by each thick line: $\dot{M} = L/c^2 \mathrel{\widehat{=}} \dot{M}$ by nuclear burning
- fails for WR stars
  $\hookrightarrow$ WR mass loss exceeds the single scattering limit





Modified wind momentum-luminosity relation



D_{mom}-L-relation:

compared to the results for LMC OB stars (Vink et al. 2000, 2001; Mokiem et al. 2007)

- Wind momentum:

$$D_{\text{mom}} = \dot{M} v_\infty R_*^{1/2}$$

winds of SMC WR stars
$\approx$
winds of O stars