OAC, Crete
Escape of Lyman radiation from galactic labyrinths
2018

Ionizing radiation from massive stars

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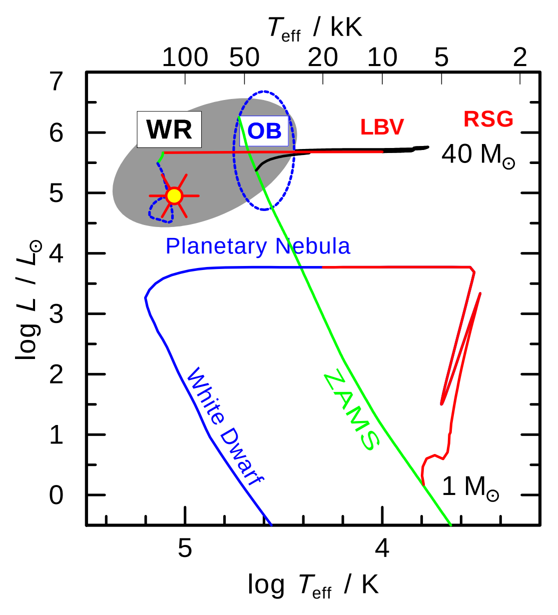
Massive stars

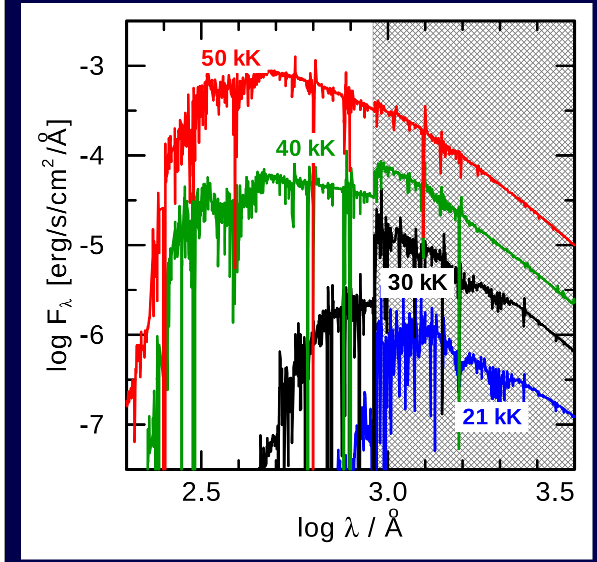


- Large initial mass: $M_{\rm ini}$ = 10 ... 150 $M_\odot$
- O and B stars
- Wolf-Rayet (WR) stars
- LBV (Luminous Blue Variable) ?
- RSG (Red SuperGiant) ?

Possible final fate:
- Supernova (SN)
- Gamma Ray Burst (GRB)
- direct (~silent) collapse

Hot, but less massive: post-AGB stars (after Asymptotic Giant Branch, e.g. Central Stars of Planetary Nebulae)

Spectral Energy Distribution (O stars)



Main sequence model series (log g = 4.0):

$T_{\rm eff}$ [kK]	log L [$L_\odot$]	M_* [$M_\odot$]
50	6.2	112
40	5.3	35
30	4.5	16
21	3.6	8

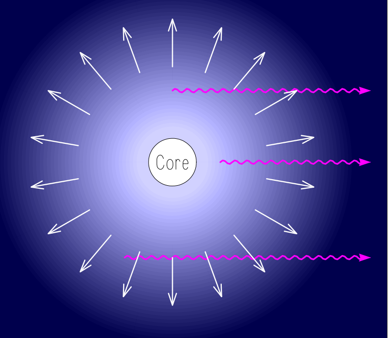
- Lyman continuum (LyC) grows strongly with $T_{\rm eff}$
- Lyman edge less pronounced at higher $T_{\rm eff}$
- *Iron forest* reduces LyC (Galactic metallicity $Z_\odot$)

Hot-star atmospheres with winds: the “standard model”

Basic assumptions

- Spherical symmetry
- Stationarity
- Radiative equilibrium → $T(r)$
- Clumping in the small-scale limit
- Pre-specified wind-velocity law

  i.e. not hydrodynamically self-consistent



Free parameters

T_*	Effective temperature
L	Luminosity (implies R_* via Stefan-Boltzmann)
$\log g$	photospheric gravity (implies stellar mass)
X_i	Chemical composition: mass fractions of H, He, C, N, O, Fe ...

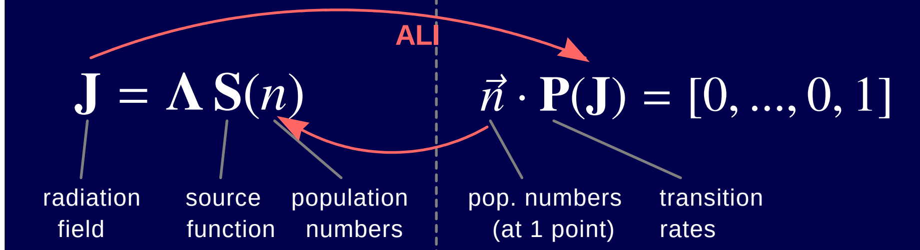
Wind parameters:

$\dot{M}$	Mass-loss rate
v_∞	Terminal wind velocity
D	Clump density contrast = inverse filling factor

Non-LTE (no Local Thermodynamical Equilibrium)

Radiation Transfer
Symbolically: linear mapping Λ

Rate Equations (Statistical Equilibrium)
Set of linear eqns. at each spatial point



$$\mathbf{J} = \Lambda\,\mathbf{S}(n) \qquad \vec{n} \cdot \mathbf{P}(\mathbf{J}) = [0, \ldots, 0, 1]$$

radiation field · source function · population numbers · pop. numbers (at 1 point) · transition rates

→ Coupling in space

→ Coupling in frequency

Radiative transition rates:
frequency integrals

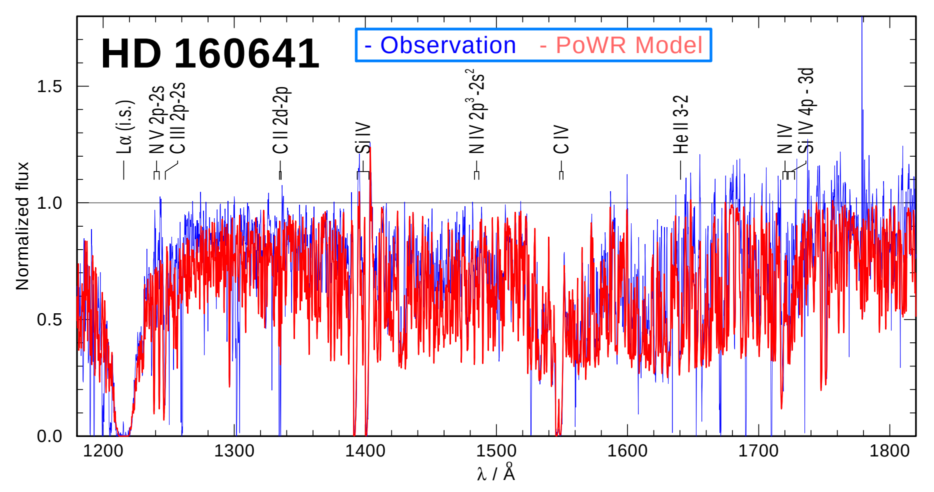
$$R_{lu} = \int \frac{4\pi}{h\nu}\,\sigma_{lu}(\nu)\,J_\nu\,\mathrm{d}\nu$$

→ **Non-linear, fully coupled in space and frequency**

Solution by *Iteration with Approximate Lambda Operators (ALI)*

Iron lines: “blanketing”

- Often form a dense “forest” in the UV
- Strong influence on atmospheric structure (temperature, ionisation)
- Derived effective temperatures significantly modified



Non-LTE model atmospheres for hot stars

TLUSTY (Hubeny & Lanz)

- Plane-parallel, without stellar wind

CMFGEN (Hillier)

- Spherical and with wind, i.e. applicable for any hot stars (WR, O, B, CSPN ...)
- Public code

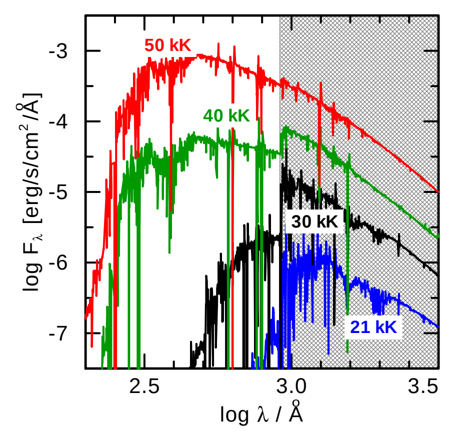
PoWR (Potsdam Wolf-Rayet model atmospheres; Hamann et al.)

- Spherical and with wind, i.e. applicable for any hot stars (WR, O, B, CSPN ...)
- Many models accessible via a web interface: **http://www.astro.physik.uni-potsdam.de/PoWR**
- Non-standard options: macro-clumping; consistent hydrodynamic solution

FASTWIND (Puls)

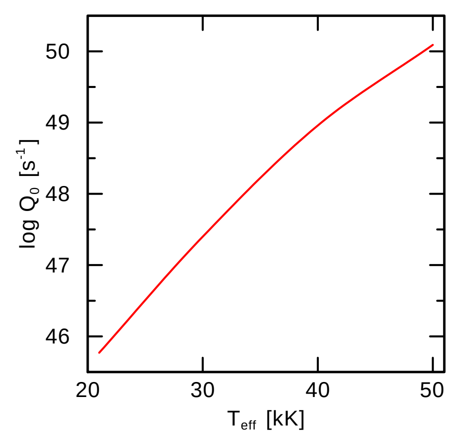
- Approximative; not for UV

Ionizing flux from O stars



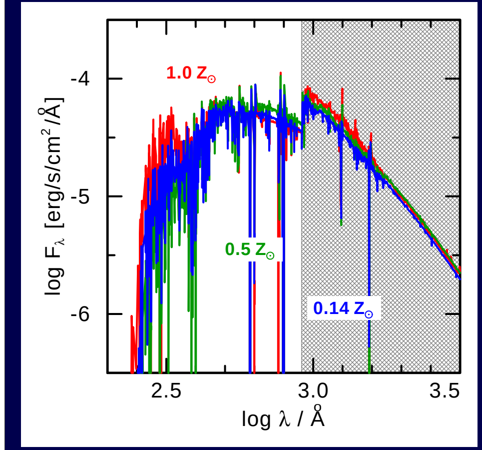
Series of PoWR models at main sequence

→ **Strong dependence on stellar (effective) temperatures**



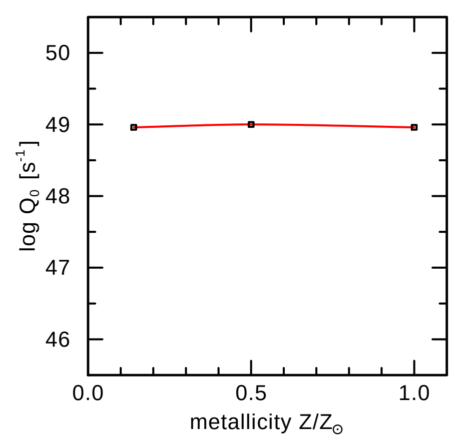
Right: Q_0 = number of photons per second in the Lyman Continuum (LyC), i.e. with $\lambda < 911$ Å

Ionizing flux from O stars



Series of main sequence models, T_*=40 kK, different metallizities (Galactic, LMC, SMC)

→ **No significant dependence on metallicity *Z***



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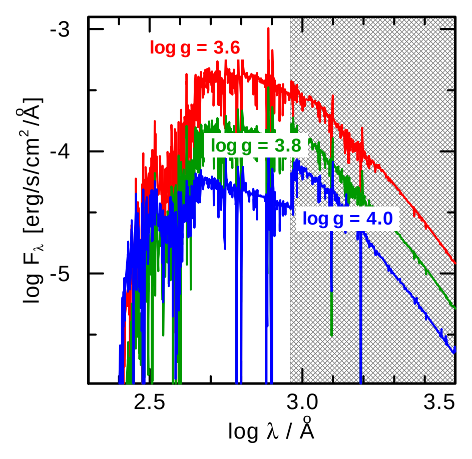
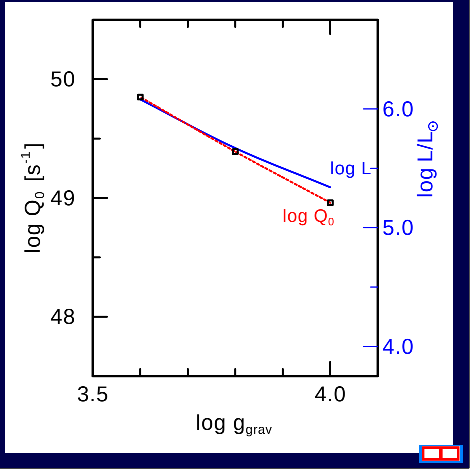
Ionizing flux from O stars



Series of models:

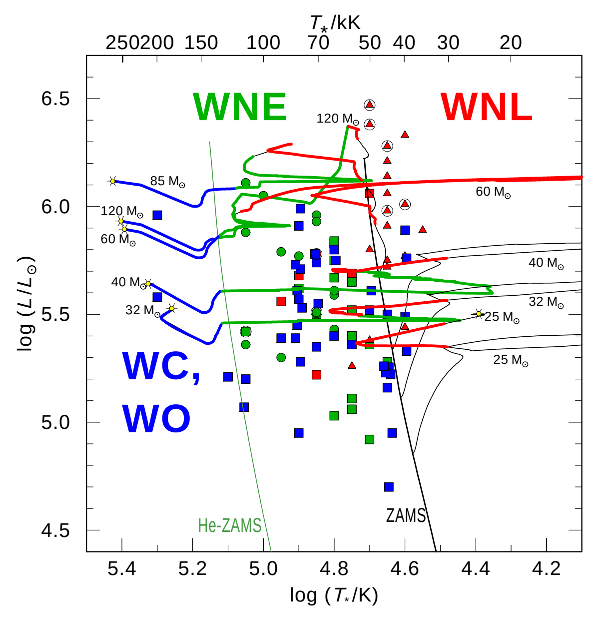
- same T_*=40 kK
- different log g (luminosity class)
- mass from evolutionary tracks



→ **LyC roughly proportional to luminosity**

→ Stronger Lyman jump with higher log g

Wolf-Rayet stars: the really hot things



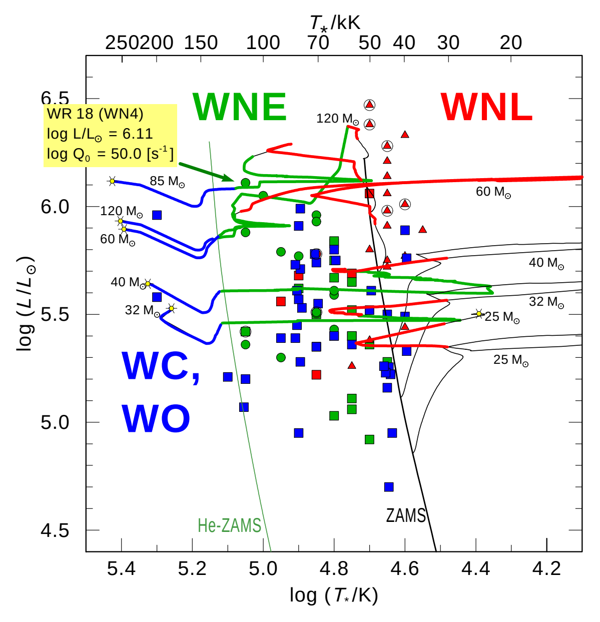
Galactic WR stars

Analyses revised with Gaia distances

- **WNL**: *late* subtypes of nitrogen subclass, hydrogen still present
- **WNE**: *early* subtypes of nitrogen subclass, hydrogen free → between H and He zero age main subclass (ZAMS)
- **WC, WO**: Carbon and oxygen subclasses; hotter than He-ZAMS

Evolutionary tracks with rotation (Ekström et al. 2012)

Wolf-Rayet stars: the really hot things



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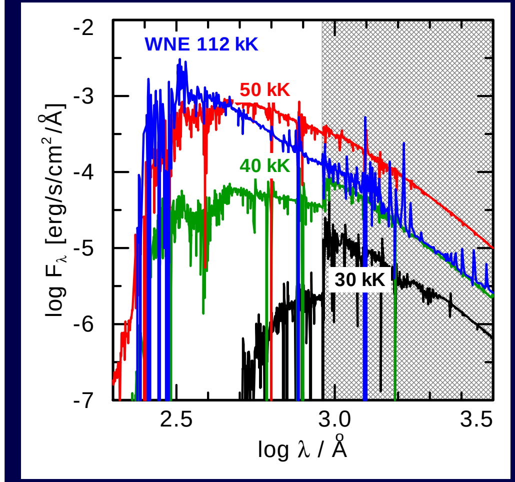
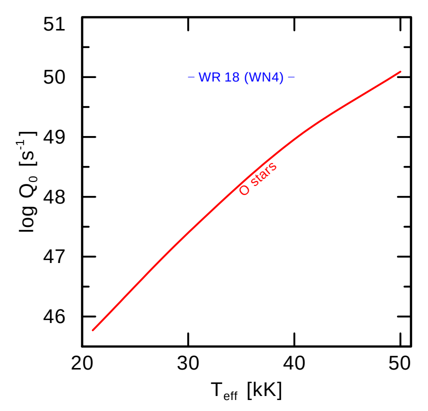
Ionizing flux from WN stars



SED for the very luminous Galactic WNE star WR 18

- $T_* = 112$ kK ($T_{2/3} = 69$ kK)
- $\log L/L_\odot = 6.11$
- $\log \dot M$ [$M_\odot$/yr] = -4.1

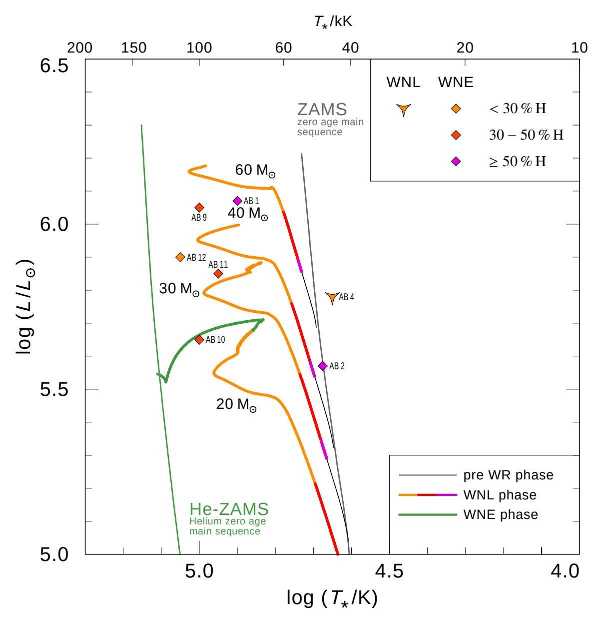


→ Nearly all flux in the LyC

→ No Lyman edge (H-free!)

→ $\log Q_0$ [s^{-1}] = 50.0

Wolf-Rayet stars at low metallicity



Small Magellanic Cloud (SMC)

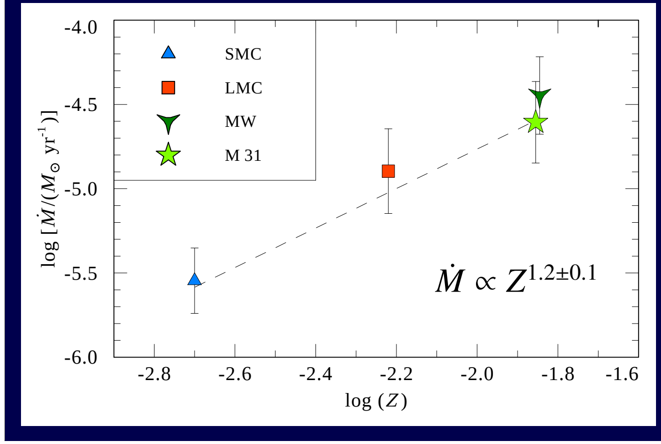
- Discrete symbols: analyzed WR stars (Hainich et al. 2015)
  → *ALL* WN stars in the SMC contain hydrogen (like Galactic WNL), but are hot and compact (like Galactic WNE)
- **Evolutionary tracks** (very strong rotational mixing, $Z=0.14\,Z_\odot$) (Brott et al. 2011) → **nearly homogeneous !**

Metallicity dependence of WR mass-loss rates

Large samples of WN stars from

- Small Magellanic Cloud (SMC)
- Large Magellanic Cloud (LMC)
- Milky Way
- Andromeda Galaxy (M31)

$$\boxed{\dot M_{\rm WR} = f(L, T_*, X_{\rm He}, Z)}$$



$$\dot M_{\rm WR} \propto Z^{1.2}$$

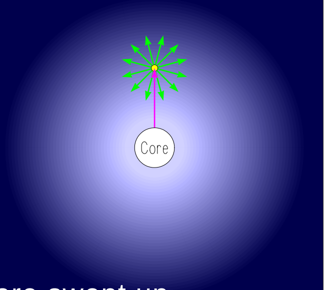
For O stars (Mokiem et al. 2007):

$$\dot M_{\rm O} \propto Z^{0.8}$$

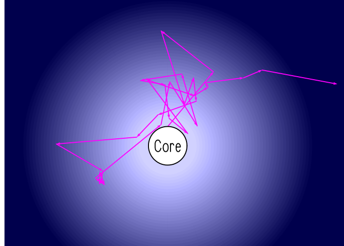
→ Z-dependence for WR even steeper than for O stars

← Hainich et al. (2015)

Line-driven stellar winds



- Wind transparent in continuum, opaque in many lines
- Absorption from ~ radial direction; re-emmission isotropic
- Acceleration → velocity → Doppler shift of the line
- Photons from a whole frequency band $\Delta\nu$ are swept up
- Driving by > 100 lines → mass-loss dominates evolution



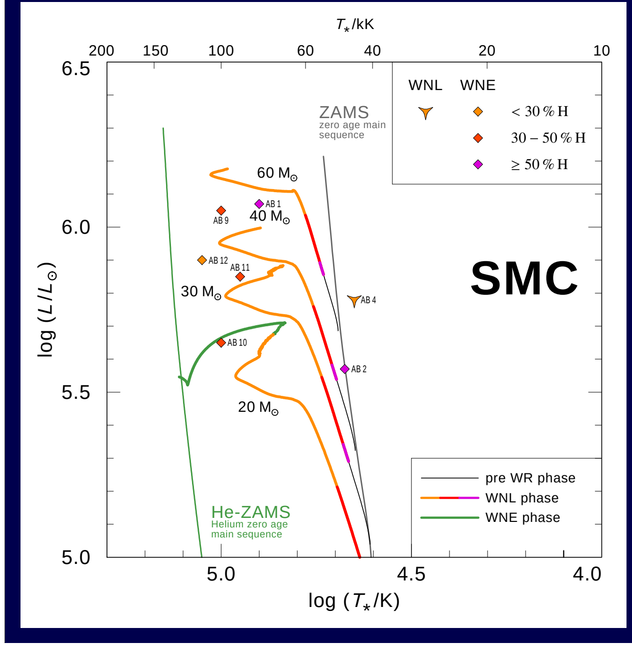
How are Wolf-Rayet winds driven ?

Often: $L/c < \dot M v_\infty$

→ mass loss exceeds *single-scattering limit*

→ *Multiple scattering* can drive WR winds Gräfener & Hamann (2005, 2008)

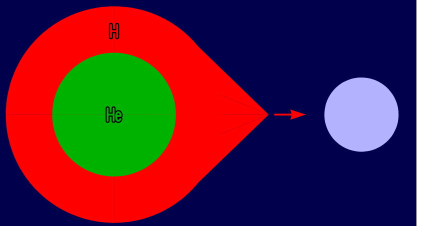
Wolf-Rayet stars at low metallicity



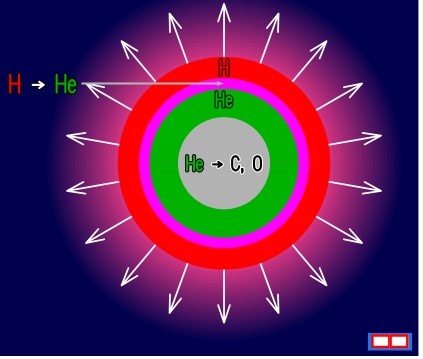
- Low mass loss → low angular momentum loss
- Rapid rotation → strong mixing → homogeneous evolution
- All WN in the SMC are very hot and compact → strong LyC emission !

Star	log Q_0
AB 1	49.94
AB 2	49.40
AB 4	49.61
AB 9	49.90
AB 10	49.50
AB 11	49.72
AB 12	49.73

How can a star get rid of its hydrogen-rich envelope ?

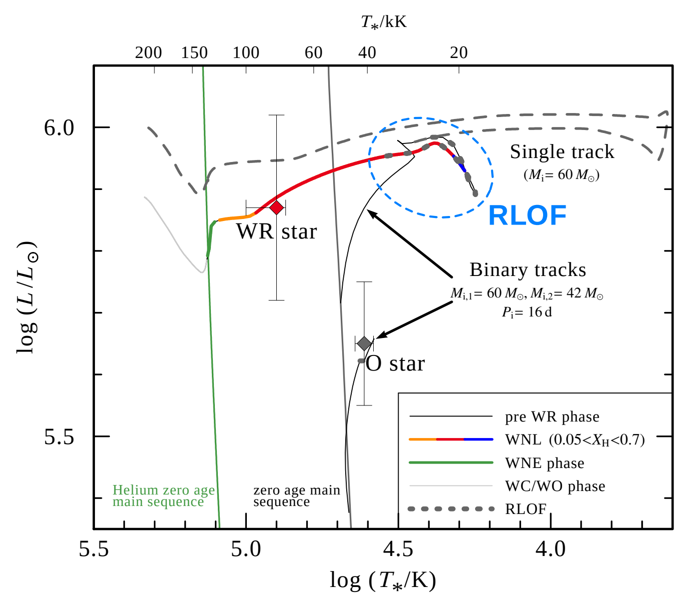


- by Roche-lobe overflow in a close binary system (original idea, e.g. Paczynski 1967)



- by stellar-wind mass loss (the *Conti scenario*, Conti 1975)

Massive stars in binaries (e.g. WR+O)



Example:
SMC AB6
(WN3+O5+O5+O7)
(Shenar et al. 2018)

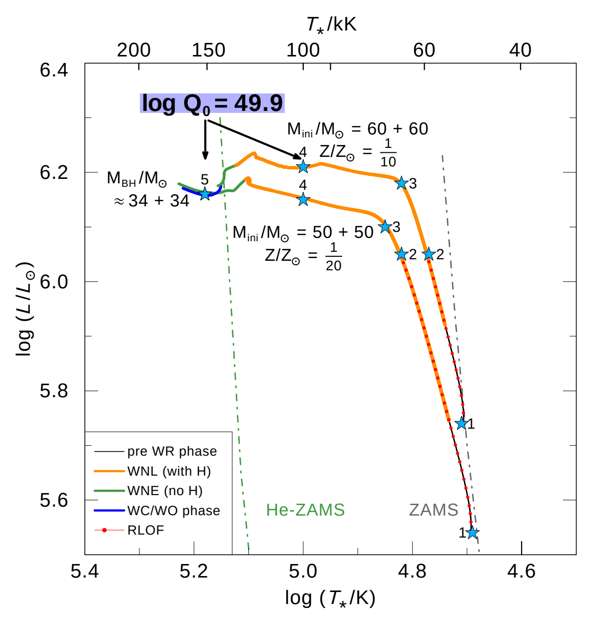
5 such systems known in SMC

Binary evol. modeled with BPASS (Eldridge)

Phase of Roche lobe overflow (RLOF)

	log Q [s^{-1}]
WN3	49.8
All 4	50.0

Massive overcontact binary (MOB) evolution



New scenario (Marchant et al. 2016):

- Two massive stars born as tight binary
- Evolve fully mixed due to tidally induced fast spin
- Swap mass several times, leading to about equal masses
- Can avoid early merging
- At low metallicity, can produce a close pair of BHs

← Hainich et al. (2017)

Hot massive stars: their possible natures

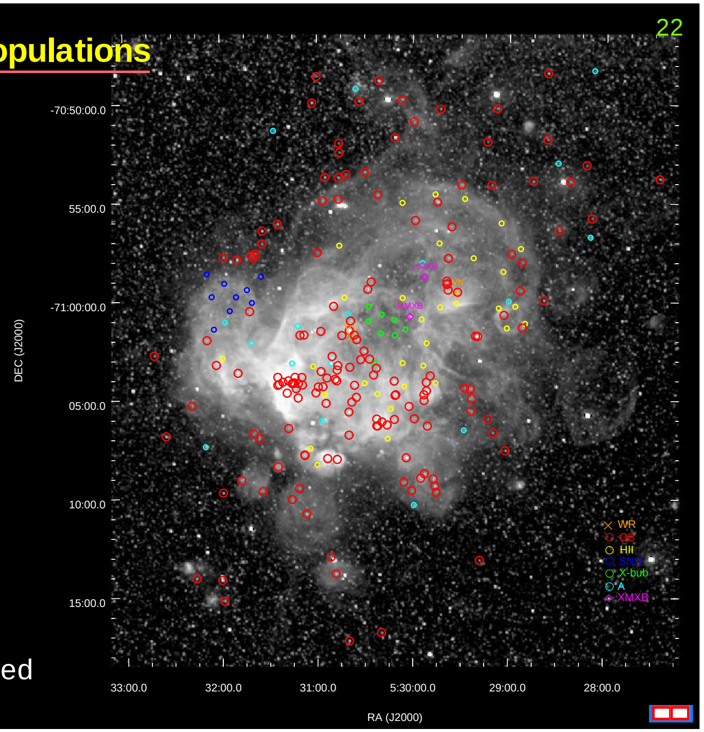
- Massive main-sequence stars
- Very massive supergiants avoiding Red Super Giant (RGS) phases
- Post-RSG stars having lost their envelope by winds (works best at high metallicities)
- Very massive stars at low Z undergoing homogeneous evolution (works best at low metallicities)
- Massive stars in close binaries which lost their envelope by Roche Lobe Overflow (all metallicities)
- Very tight binaries: “Massive Overcontac Binary (MOB) evolution” (theoretical suggestion, not yet observed)

Young stellar populations

Example 1: star-forming complex **LMC-N206**

Spectral analysis of the massive-star population (Ramachandran et al. 2018a,b)

- 1 WN+O
- 1 WC+O
- 9 Of
- 31 O (other)
- 125 B
- 18 Oe/Be
- 17 A
- 2 HMXB: disproved

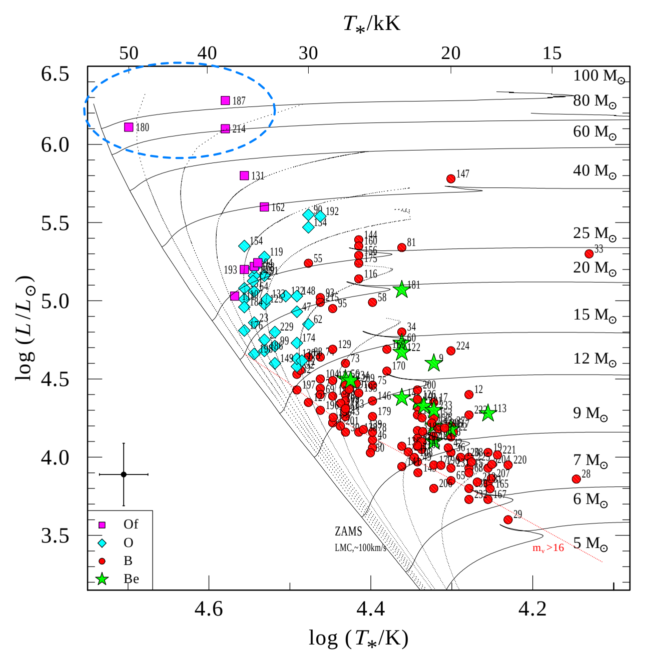


LMC-N206

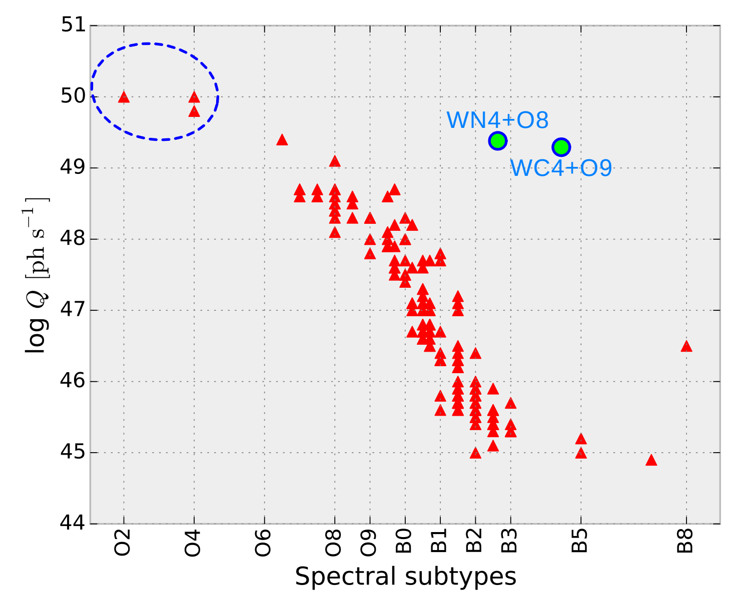
HRD of the massive-star population (V < 16 mag)

Tracks and isochrones: Brott et al. 2011, Köhler et al. 2015

- Massive stars are *not* co-eval
- Ages spread from 0 - 30 Myr
- 3 stars with log L > 6 are the youngest (<5 Myr) and most massive (60 - 80 $M_\odot$)



LMC-N206: sources of ionizing radiation



65% of ionizing radiation stem from 3 stars of earliest O-subtype

Young stellar populations

Example 2: Massive stars in the **Tarantula Nebula (LMC)**

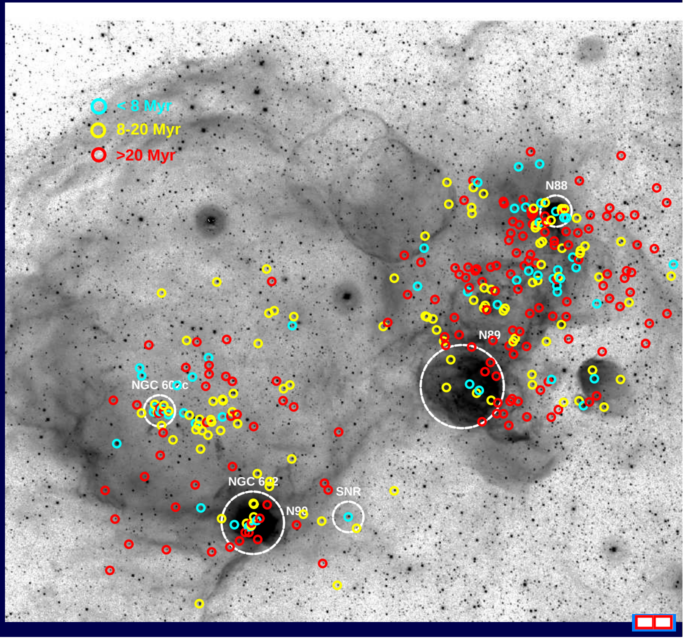
Census of ~1000 massive stars (Doran et al. 2013)

→ 40% of LyC from 31 WR and early O-type stars

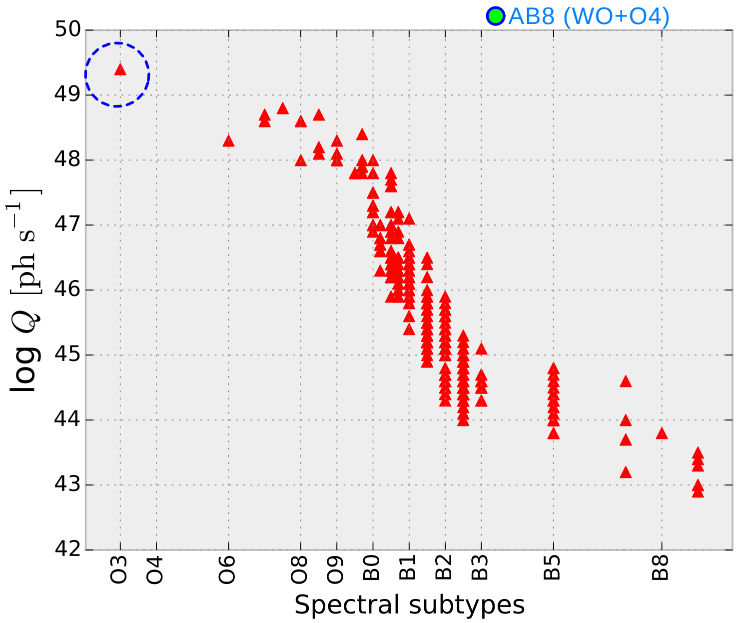
Young stellar populations

Example 3: Supergiant shell **SMC-SGS 1** (Ramachandran et al. in prep.)

- Low star-formation density
- Stellar ages: 0 ... 100 Myr
- Star formation peaked 25 Myr ago

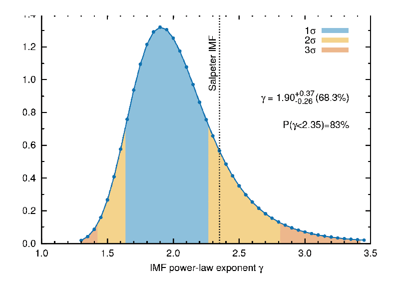


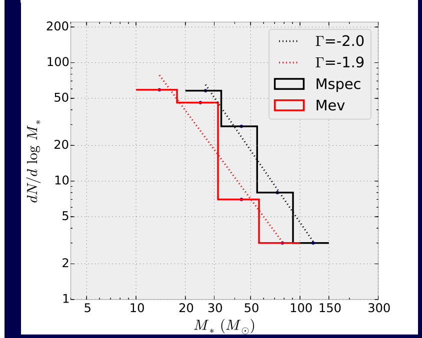
SMC-SSG 1: sources of ionizing radiation



- $Q_0 = 2\ 10^{50}\ s^{-1}$ in total
- 60% from one WO binary
- 4% from the youngest, most massive O star

How many high-Q stars exist? The initial mass function (IMF)

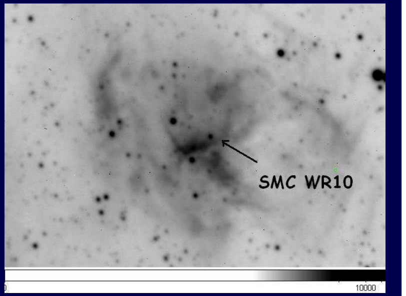




- Standard assumption: Saplpeter-IMF with slope 2.35
- Top-heavy IMF found in 30 Dor (Schneider et al. 2018)
- Similar result found for LMC-N206 (Ramachandran et al. 2018)
- Not much known about IMF at really low metallicities

He III regions and the sources of their ionization

Project with M. Pakull



Observation:

Nebula with diffuse He II 4686Å (narrow) line emission

Question:

Which stars produce large amounts of photons λ < 228 Å ?

He III regions found around Wolf-Rayet stars:

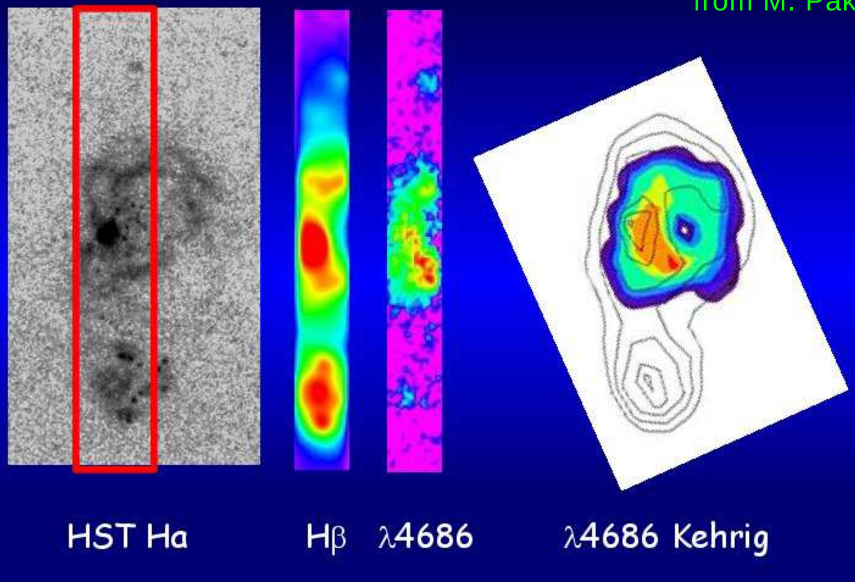
Galaxy	# of He III neb.	# of all WRs
MW	1	300
LMC	2	150
SMC	3	12

→ Fraction seems to increase with decreasing metallicity

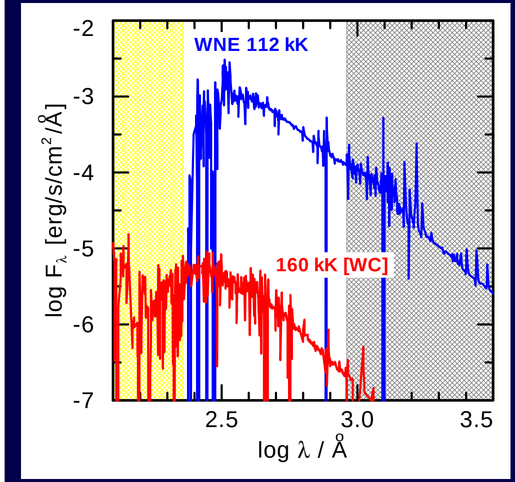
He II 4686Å emission from I Zw 18 ($Z/Z_\odot$ = 0.02)

Broad-slit spectra:

from M. Pakull



Ionizing flux from old stellar populations



e.g.: hydrogen-deficient post-AGB stars: central stars of planetary nebulae of type [WC]

Example: SED for the central star of **NGC 5189** (red)

- T_* = 160 kK
- log $L/L_\odot$ = 3.7
- log $\dot{M}$ [$M_\odot$/yr] = -7.2
- Compared to the very luminous Galactic WNE star WR 18 (blue)

→ Nearly all flux in the LyC

→ No Lyman edge (H-free!)

→ log Q_0 [s^{-1}] = 47.5

→ Many He II ionizing photons: log $Q_{\rm He\,II}$ [s^{-1}] = 46.5

Conclusions

- The hottest and most luminous massive stars emit per second up to 10^{50} hydrogen ionizing photons
- In a young stellar population, ~1 out of 100 massive stars might fall into that category; this ~1% typically produce more than half of all LyC photons
- The fraction of very LyC-bright stars might increase at low metallicities due to quasi-homogeneous evolution of high-mass stars
- Very rare stars with T_* > 100 kK can emit up to $10^{48.5}$ photons at λ < 228 Å (He II ionizing)
- Post-AGB stars can become very hot and emit up to log Q_0 [s^{-1}] ~ 47.5 in LyC, and up to $10^{46.5}$ He II ionizing photons/s, especially if hydrogen-deficient