Topical Overview on Star Cluster Astrophysics
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Wolf-Rayet winds

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SEIT 1386

What are Wolf-Rayet stars?

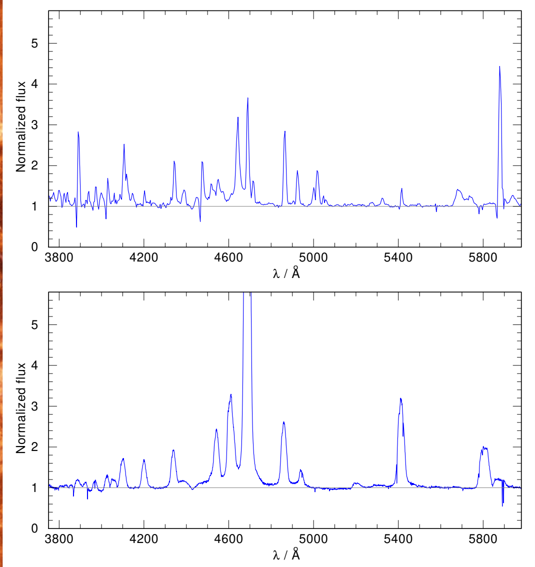
WR 124 (Credit: ESA/Hubble & NASA)

What are Wolf-Rayet stars?

Two Galactic Examples:

WR 124
(WN8h)

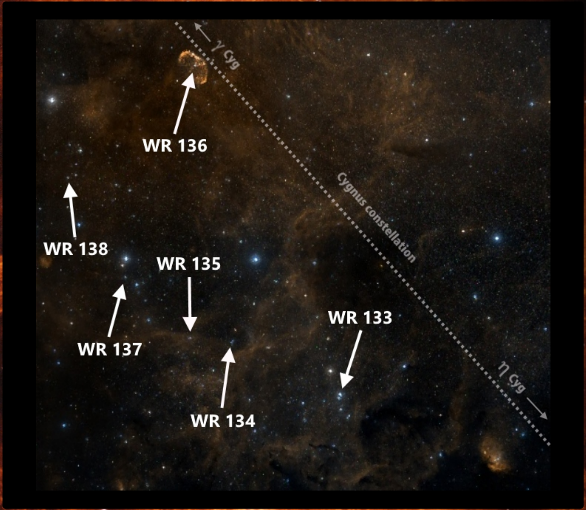
WR 7
(WN4)



WR 124 (Credit: ESA/Hubble & NASA)

WR 7 (Credit: Jschulman555)

What are Wolf-Rayet stars?



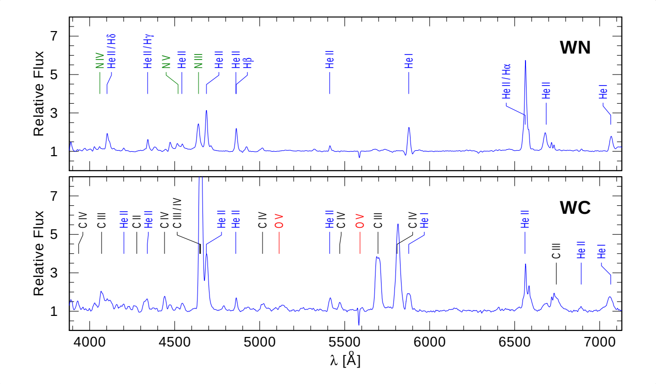
Wolf-Rayet (WR) stars are a *spectroscopic* definition:

- optical spectra with strong and broad emission lines
- named after French astronomers Charles Wolf & George Rayet
- discovered in 1867
- first found in the Cygnus constellation (WR 134, WR 135, WR 137)
- nearest one: γ Vel (WR 11)

WR 124 (Credit: ESA/Hubble & NASA)

WN and WC stars

WR stars are divided into two main spectral subclasses:



WN stars:

- Strong *nitrogen* and *helium* emission lines
- can have hydrogen (SpT notation: WNh)

WC (and WO) stars:

- Strong *carbon*, *oxygen*, and *helium* emission lines
- always hydrogen-free

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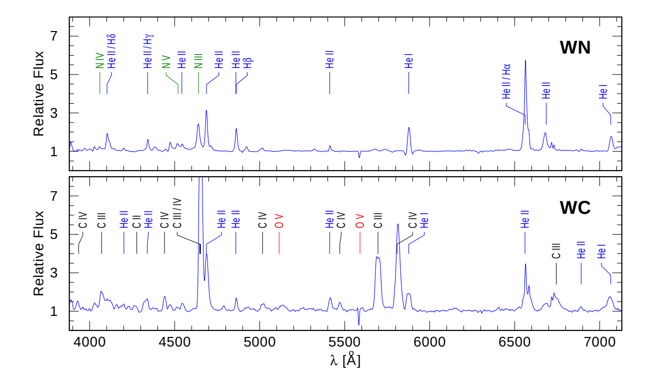

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- Strong *carbon*, *oxygen*, and *helium* emission lines
- always hydrogen-free

- Emission-line spectra often formed completely in the wind, "cloaking" the star
- Analysis of the spectrum needed to uncover WR properties and influence

WR subtypes

early subtypes: (WN2-5, WC4-6)	higher ion stages, broader lines → higher wind velocities
late subtypes: (WN7-11, WC7-9)	lower ion stages, narrower lines → lower wind velocities

Typical values for subtypes at $Z_\odot$:

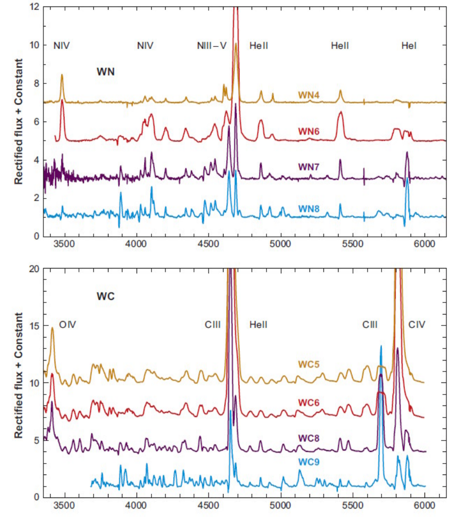
WN2:	3000 km/s	WO2:	5000 km/s
WN5:	1500 km/s	WC5:	3000 km/s
WN10:	500 km/s	WC9:	1200 km/s

subtype occurrence is related to metallicity (Z):

→ distribution shifts to earlier types at lower Z

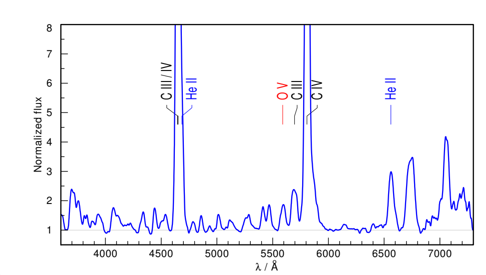
→ WN/WC ratio higher at lower Z

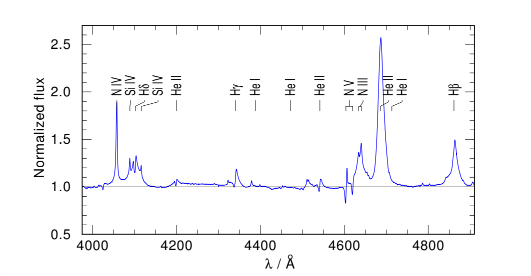
→ WR stars generally more rare at lower Z

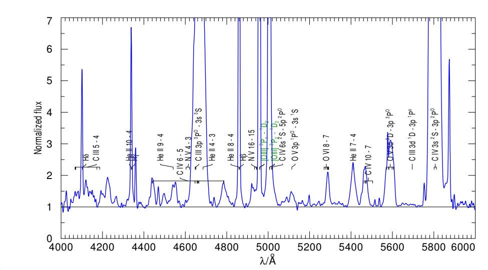


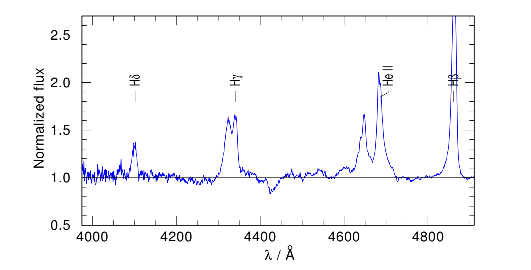
Crowther (2007)

The Wolf-Rayet phenomenon









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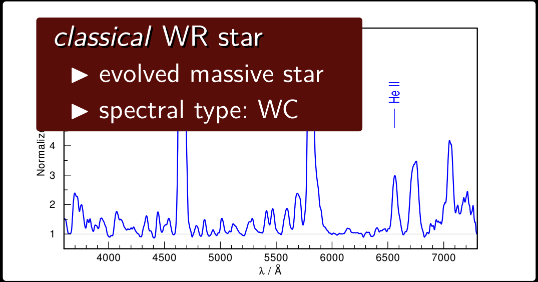
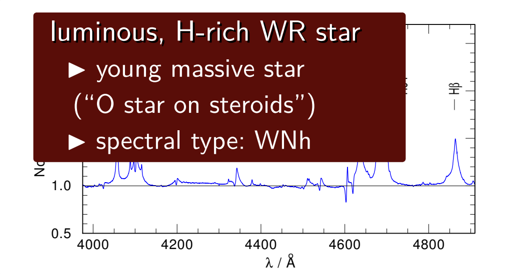


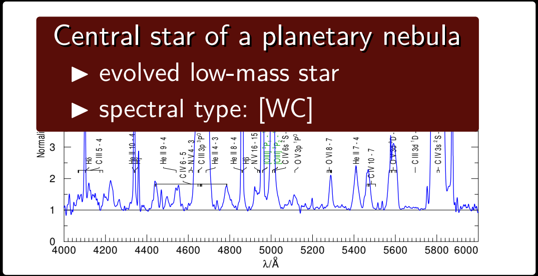
classical WR star

- evolved massive star
- spectral type: WC



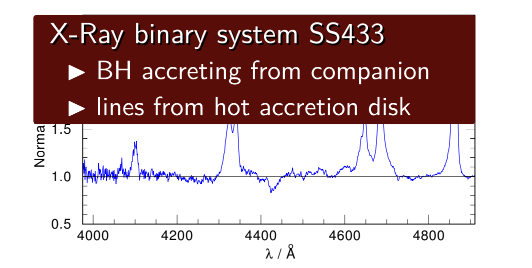
luminous, H-rich WR star

- young massive star ("O star on steroids")
- spectral type: WNh



Central star of a planetary nebula

- evolved low-mass star
- spectral type: [WC]

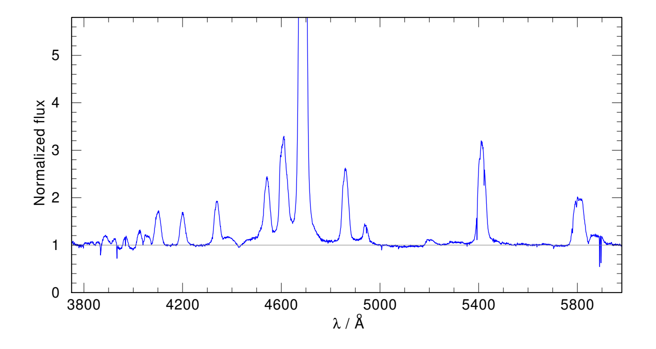


X-Ray binary system SS433

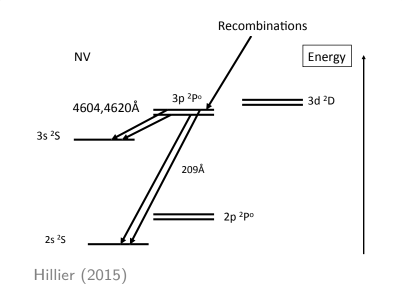
- BH accreting from companion
- lines from hot accretion disk

Why do we get emission-line spectra?

WR emission lines: Emitting surface area larger than the adjacent continuum



→ Detailed atomic physics are crucial



Hillier (2015)

In detail, various origins for the different lines:

- resonance scattering
- collisional excitation
- recombination
- continuum fluorescence
- dielectronic recombination
- line overlap/interactions

The WR mass-loss enigma

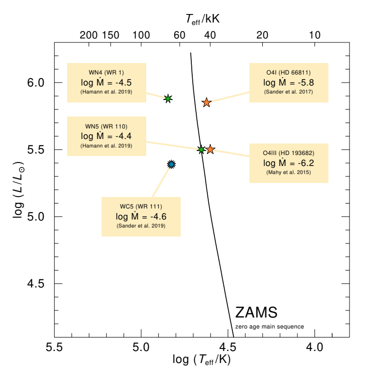
Historical *momentum problem*:

$L_{\mathrm{WR}} \approx L_{\mathrm{OB}}$, but $\dot{M}_{\mathrm{WR}} \gg \dot{M}_{\mathrm{OB}}$

→ higher *wind efficiency* $\eta = \frac{\dot{M} v_\infty}{L/c}$

→ mCAK wind theory cannot explain this ($\eta \lesssim 1$)

⇒ is radiative driving alone sufficient to explain WR winds?



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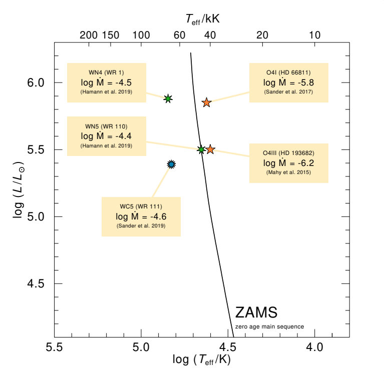


Possible alternative WR driving forces:

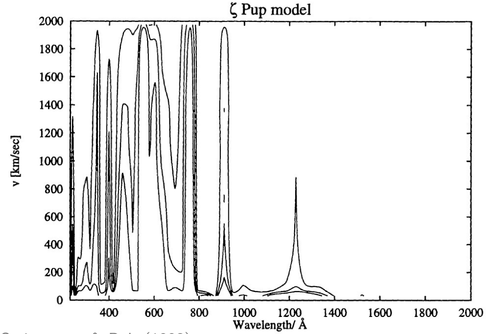
- strange-mode instabilities (e.g., Gautschy and Glatzel 1990, Wende et al. 2008)
  $\hookrightarrow$ but no coherent oscillations found in long-term monitoring (Moffat et al. 2008)
- convection close to or at the wind onset (Cantiello et al. 2009)
- super-chromosphere with $T_{\mathrm{e}} > T_{\mathrm{rad}}$ ("Dick Thomas force" after Richard N. Thomas, 1949)

The WR mass-loss enigma

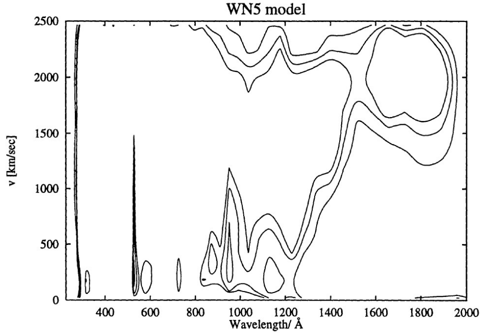
Monte Carlo Calculations: $\eta > 1$ as such is not a problem

- de Koter et al. (1997): R136 WNh winds have changing Fe/Ni ionization
- Springmann & Puls (1998): “frozen-in” (OB) vs. changing ionization (WR)
  → closure of “radial gaps” that would otherwise lead to photon “leakage”

⇒ *opacity problem* rather than momentum problem (Gayley et al. 1995)



Springmann & Puls (1998)



Springmann & Puls (1998)

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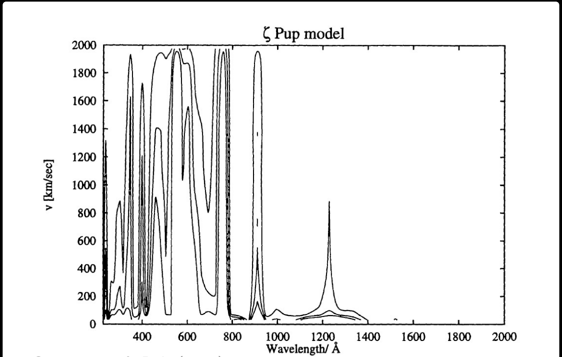

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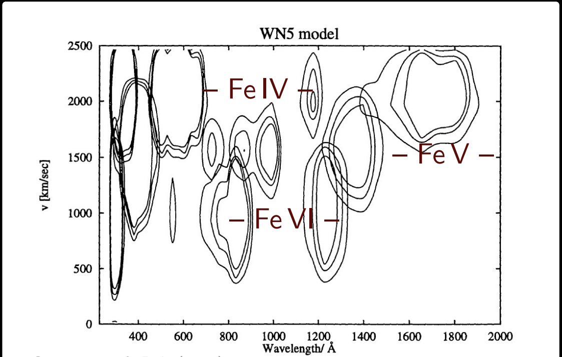
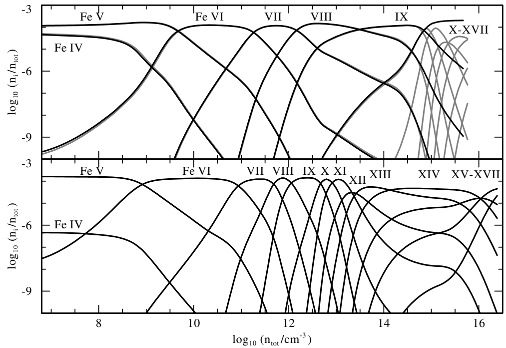


Springmann & Puls (1998)

The role of Fe M-Shell opacities



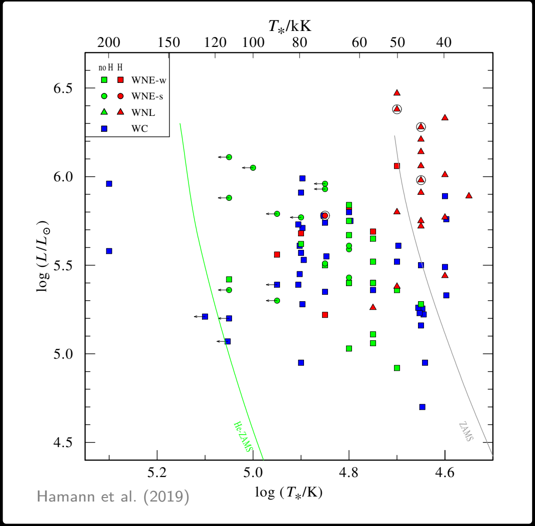
Gräfener & Hamann (2005)

However: To launch a WR wind by M-shell opacities, it needs to start deep in the optically thick atmospheres

Opacity calculation in the 1990s yielded a major “bump” of line transitions for Fe M-Shell ions (Fe IX-XVII)

- consequences throughout astrophysics, including e.g. pulsation regimes
- quickly suspected to be important for WR wind launching (Kato & Iben 1992; Pinnester & Eichler 1995; Nugis & Lamers 2002)
- first consistent model by Gräfener & Hamann (2005) for a WC star
- Fe importance independently confirmed by Vink & de Koter (2005)
  (albeit their models did not include the M-shell ions)

The WR radius problem



Hamann et al. (2019)

Combined HRD with Milky Way WR analyses results:

- WNh stars close to the main sequence as expected
  → could be H-burning or He-burning
- WNE and WC stars have no hydrogen
  → must be (at least) He-burning
- WNE and WC should sit on the HeZAMS, but most do not

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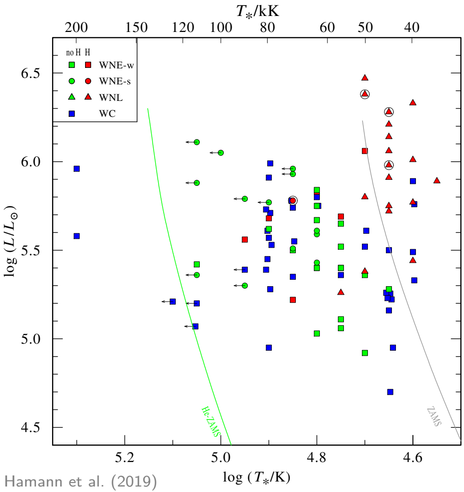

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⇒ *Wolf-Rayet Radius Problem:*
Discrepancy between empirical parameters and stellar structure models
→ similar results for other galaxies and different metallicities

The WR radius problem

Two possible solutions:

- inflated hydrostatic radii
- deep wind launching ("dynamical inflation")

→ coupling of structure and wind physics

Different radius definitions and multiple meanings for T_{eff}:

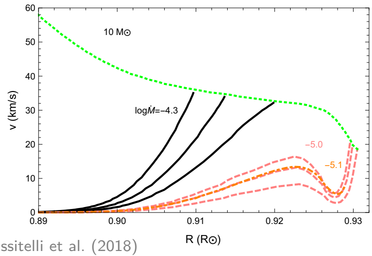
- T_* defined at $\tau \gg 1$

  (typical choices: 20 or 100)

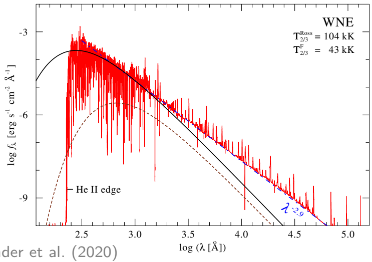
- $T_{2/3}$ defined at the more common $\tau = 2/3$

Problem:

For some purposes, $T_{2/3}$ and $R_{2/3}$ are more "robust", but $T_{2/3}$ does not reflect the radiation field of a WR star

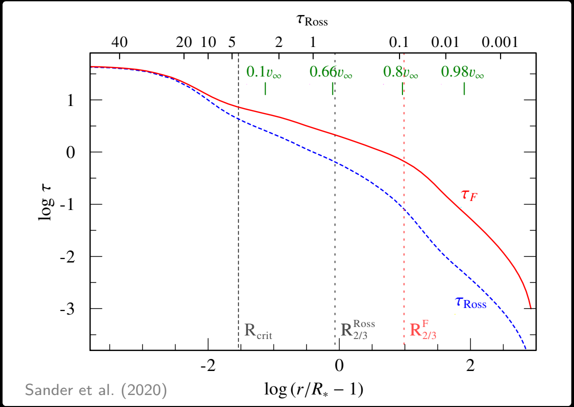


Grassitelli et al. (2018)



Sander et al. (2020)

Deep launching as a solution to the WR radius problem



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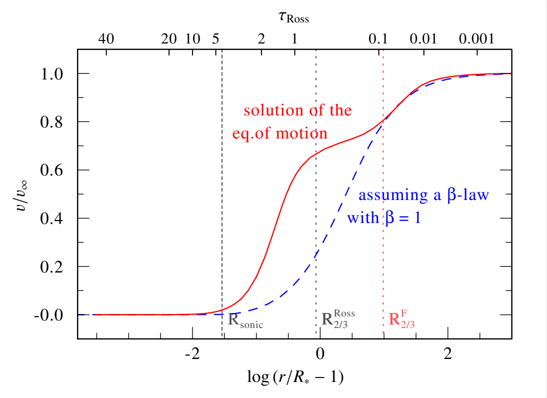
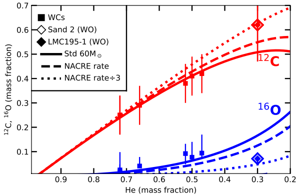


Optically thick WR winds (valid for most, but not all WRs):

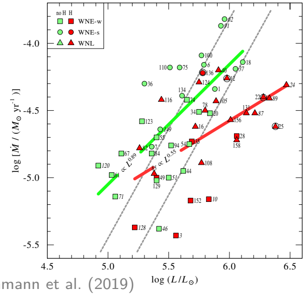
Even the continuum is produced in expanding layers with $v \gg v_{\rm sonic}$ (e.g. Gräfener & Hamann 2004, Sander et al. 2020)

- inferred stellar radii more compact with HD velocity laws
- similar radius problems for (some) WNhs and LBVs

Quantitative spectroscopy of Wolf-Rayet stars



Aadland et al. (2022)



Hamann et al. (2019)

Quantitative spectroscopy of WR stars is vital to understand impact and evolution of evolved massive stars, e.g.

→ the remaining hydrogen content of WN-type stars

(e.g., Hamann et al. 1995, 2006)

→ non-homogeneity of WR winds

(e.g., Koesterke & Hamann 1998, Hillier & Miller 1999)

→ ^{12}C$(\alpha, \gamma)^{16}$O rate from WC and WO stars

(e.g., Aadland et al. 2022)

→ mechanical and ionizing feedback to the ISM

Analysis of many WR stars also yield empirical $\dot{M}(L, Z, \dots)$

(e.g., Nugis & Lamers 2000, Hainich et al. 2015, Shenar et al. 2019)

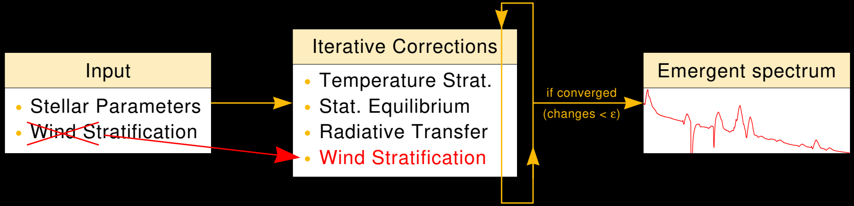
→ default in stellar evolution & population synthesis

→ dangerous extrapolation to unobserved regimes (e.g., $Z < Z_{\rm SMC}$)

Predictions from dynamically consistent atmospheres

Theoretical approach using detailed model atmospheres to derive consistent $v(r)$ and $\dot{M}$

Gräfener & Hamann (2005, 2008), Sander et al. (2017, 2020, 2023)



Input

- Stellar Parameters
- ~~Wind Stratification~~

Iterative Corrections

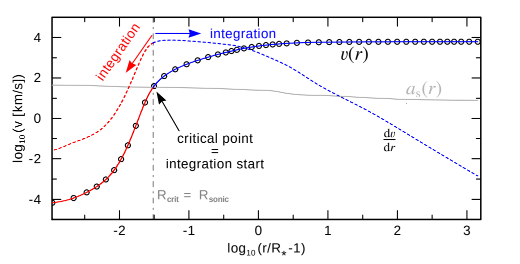
- Temperature Strat.
- Stat. Equilibrium
- Radiative Transfer
- Wind Stratification

if converged (changes < ε)

Emergent spectrum

Additional Iteration Scheme:

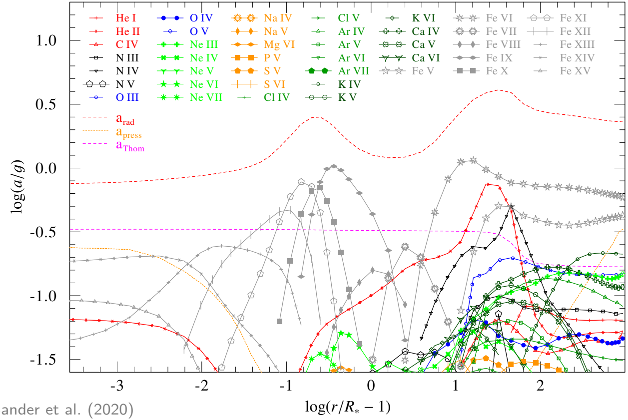
- $v(r)$ via integrating the hydrodynamic equation of motion
- adjustment of $\dot{M}$ via boundary constraint (e.g. total opacity conservation)
- concept goes back to Lucy & Solomon (1970), but scalable implementations only recently



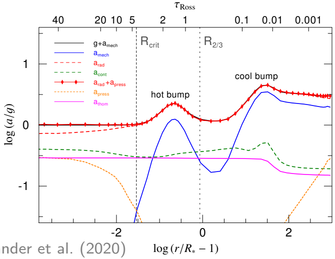
Insights on WR winds from dynamically-consistent atmospheres

Dynamically-consistent atmospheres crucial to understand cWR stars:

- Crucial role of Fe M-Shell opacities in wind launching (Gräfener & Hamann 2005; Sander et al. 2020, 2023)
- Strong non-monotonic behaviour of $\varkappa_F$



Sander et al. (2020)



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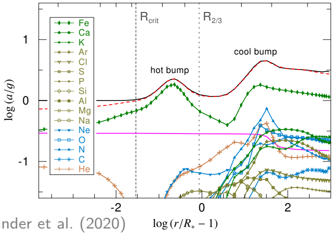
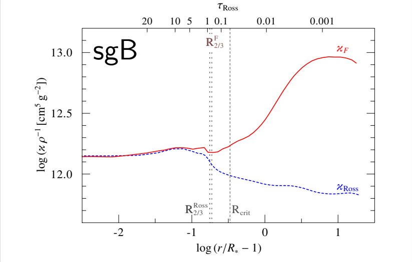
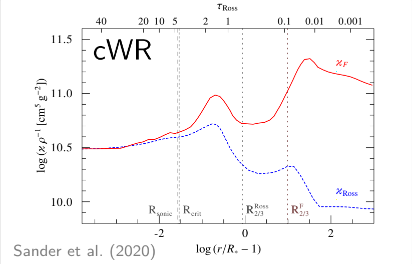


Sander et al. (2020)

Breakdown of the CAK description in WR winds





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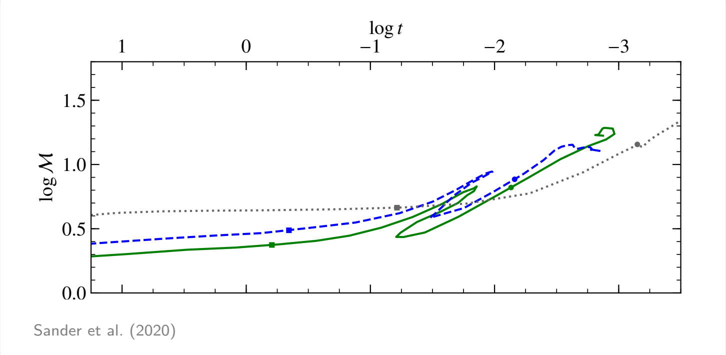


Sander et al. (2020)

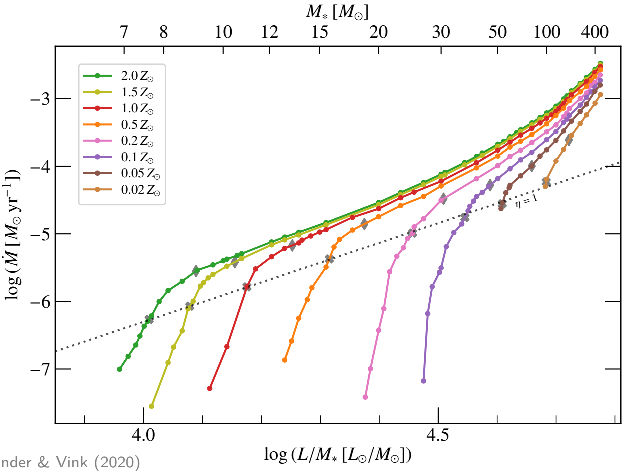
Failure of the CAK parametrization for cWR winds:

- optically thick, but supersonic layers
- optical depth parameter t not monotonic in τ or r
- multi-peak structure in the opacities not mapped

Modelling WR stars with WN-type composition

Model series: H-free WR stars with WN composition

- variables: L/M, Z
- fixed He-ZAMS L(M)
- fixed T_*



Sander & Vink (2020)

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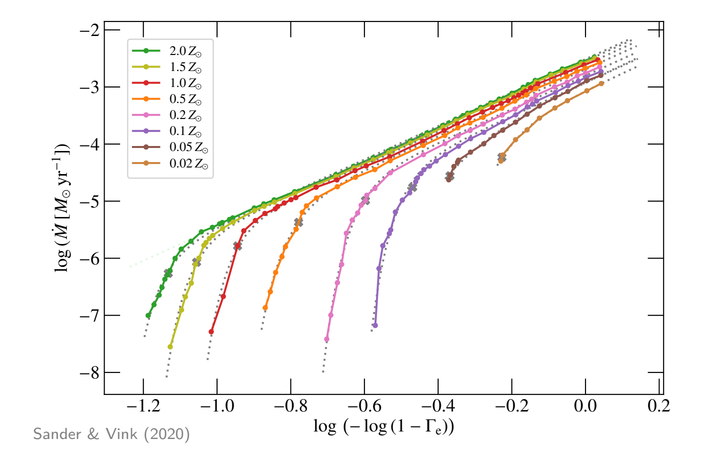
Model sequences yield two regimes with different trends:

- dense winds (≈LTE at R_{sonic})
- optically thin winds
- transition correlates, but not coincides with $\eta \approx 1$



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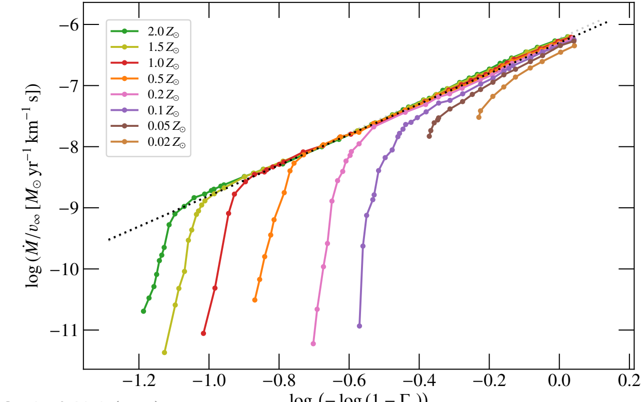

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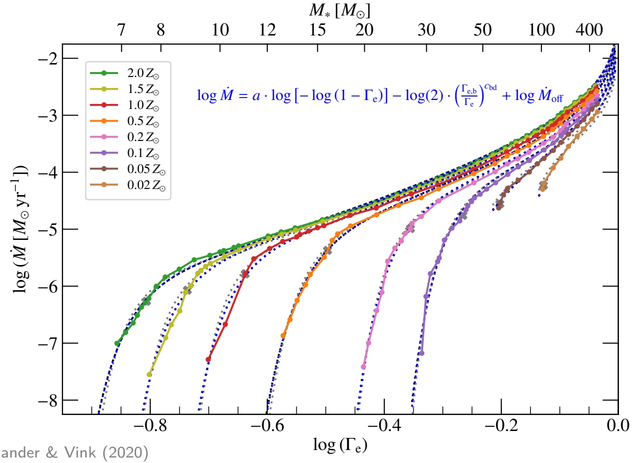
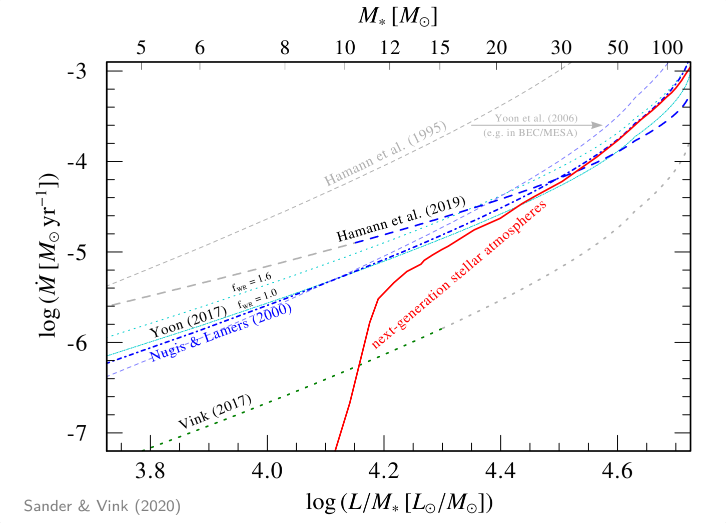


$$\log \dot{M} = a \cdot \log\left[-\log\left(1-\Gamma_{\mathrm{e}}\right)\right] - \log(2) \cdot \left(\frac{\Gamma_{\mathrm{e,b}}}{\Gamma_{\mathrm{e}}}\right)^{c_{\mathrm{bd}}} + \log \dot{M}_{\mathrm{off}}$$

Sander & Vink (2020)

Model series: Classical WR stars with WN-type composition

Comparison with traditional WR mass-loss recipes at $Z_{\odot}$:



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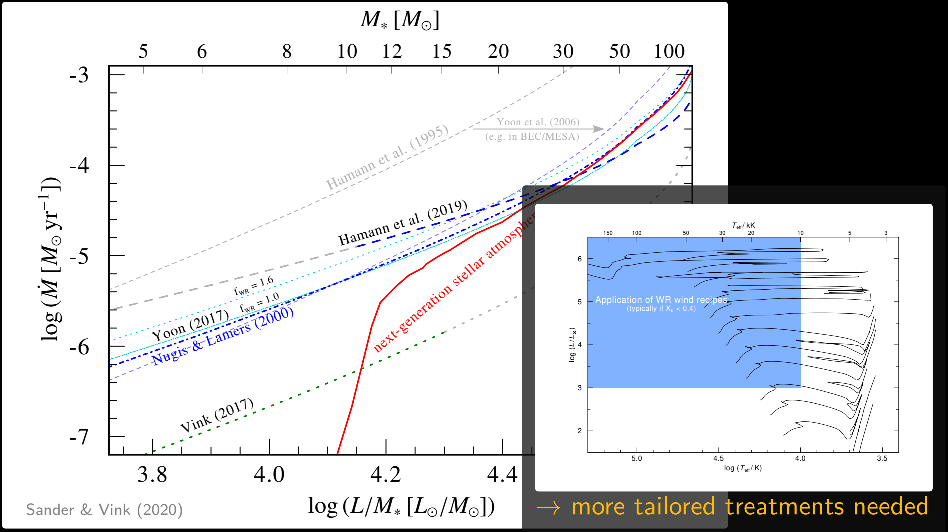
Comparison with traditional WR mass-loss recipes at $Z_\odot$:

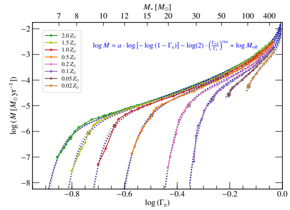


Sander & Vink (2020)

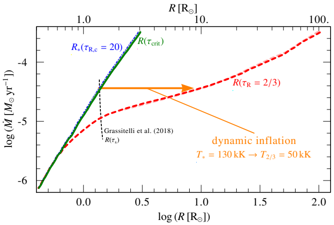
→ more tailored treatments needed

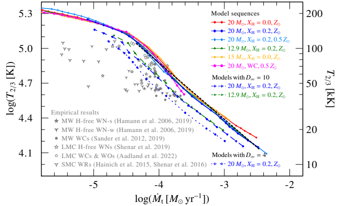
Insights: Wind driving and mass-loss rates of classical WR stars

New cWR-$\dot{M}$ from Sander & Vink (2020) and Sander et al. (2023):



Sander & Vink (2020)





Sander et al. (2023)

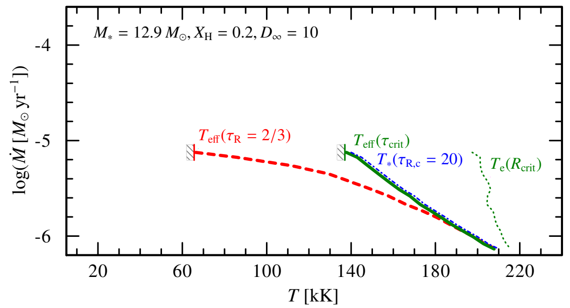
- cWR winds scale fundamentally different than OB star winds
- cWR winds are launched deep in the optically thick atmosphere (at $T_e \approx 200\,\mathrm{kK}$)
- surprisingly shallow metallicity-scaling for dense winds: $\dot{M} \propto Z^{0.3}$
- strong L/M- and Z-dependent breakdown of $\dot{M}$ → consequences for observed WR pop.
- for constant L and M: $\dot{M} \propto R_{\mathrm{crit}}^3 \propto T_{\mathrm{eff}}(\tau_{\mathrm{crit}})^6$

Limits of deep wind launching

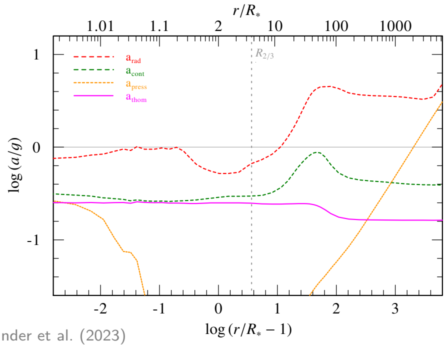
Can we explain all WR stars as compact stars with extended wind envelopes?

(i.e., is the radius problem solved?)

→ we obtain "hard boundaries" for wind launching from the hot iron bump
→ late WR subtypes should always have huge emission lines → not observed
⇒ there is probably also a regime with inflated *hydrostatic* radii



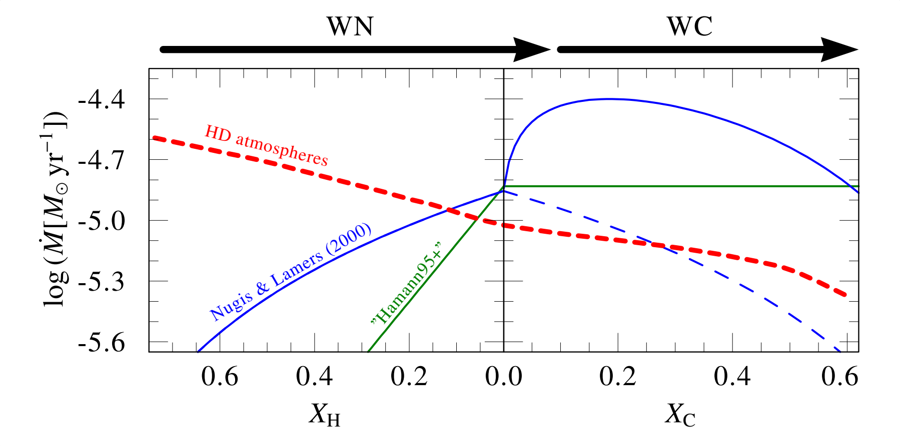
data from Sander et al. (2023)



Sander et al. (2023)

Abundance-dependency of Wolf-Rayet winds

For constant stellar parameters: $\dot{M}$ expected to decrease for WNh → WN → WC



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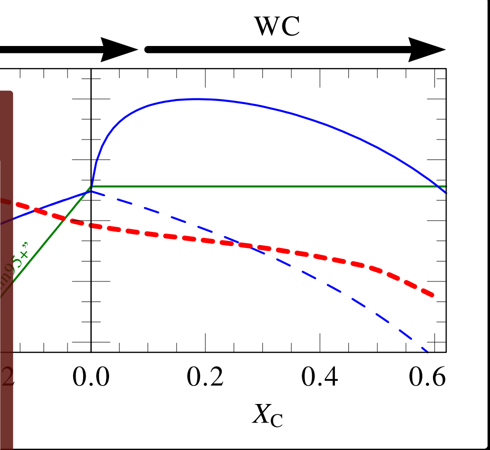
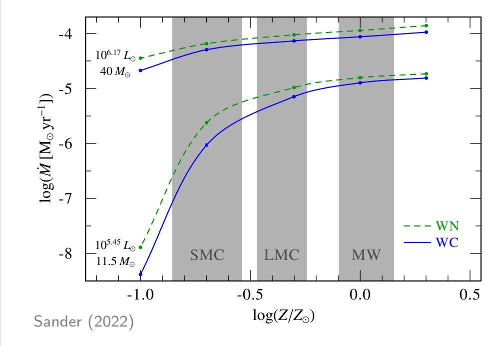


Metallicity-dependence of WNs and WCs:



Sander (2022)

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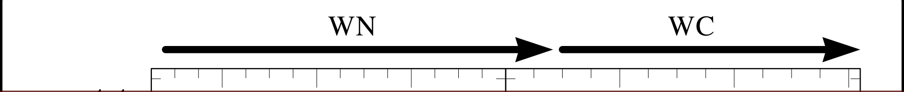

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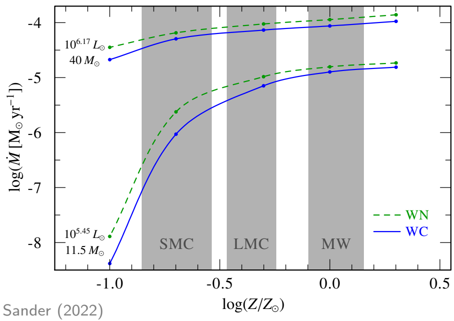


Sander (2022)

Similar $\dot{M}$-behaviour for all cWR subtypes

For the same L, M, R:

- WNh stars have slightly *higher* $\dot{M}$
- WC stars have slightly *lower* $\dot{M}$

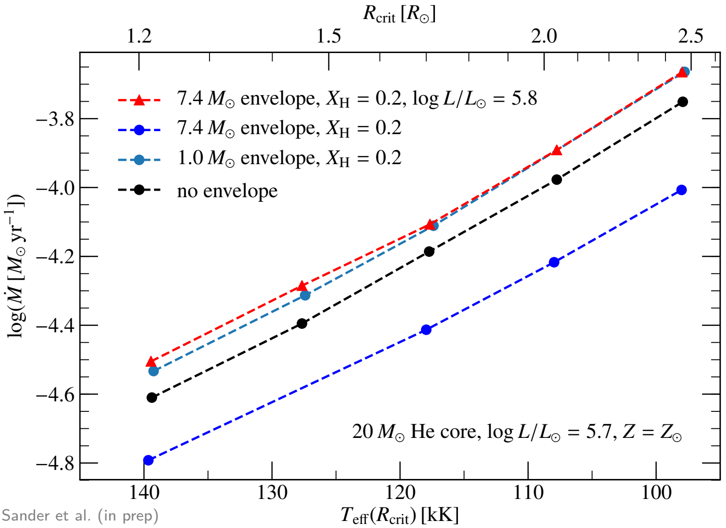
→ Different budget of free electrons (→ Γ_e)

→ Contrary to currently employed recipes

→ $\dot{M}$ set by Γ_e and $\varkappa_\mathrm{Fe}$, higher C & O abundances in WCs affect mainly v_∞
(unless there is an inflated radius regime for late-type WCs)

Effect of leftover hydrogen envelopes

Leftover hydrogen in WN stars: higher Γ_e
$\rightarrow$ enhances $\dot{M}$ for fixed stellar parameters



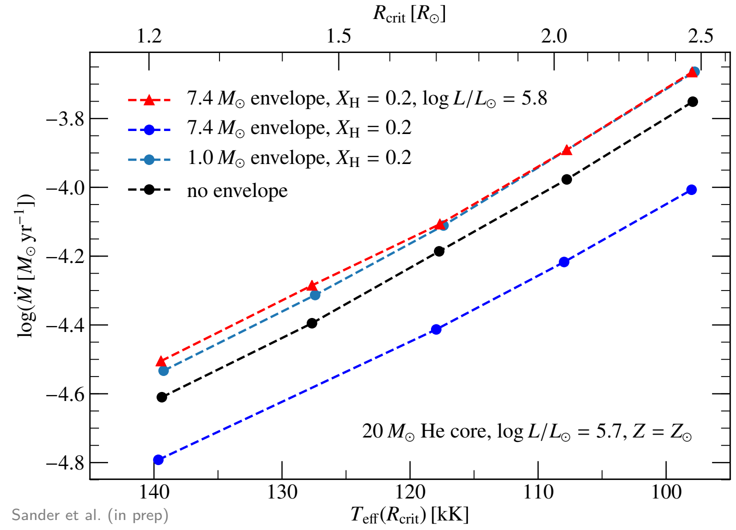
Sander et al. (in prep)

Effect of leftover hydrogen envelopes

Leftover hydrogen in WN stars: higher Γ_e
→ enhances $\dot{M}$ for fixed stellar parameters

Real situation more complex
→ competitive process

- free electron budget
- additional gravitational pull
- structural response (radius expansion, shell-burning)



Sander et al. (in prep)

WR mass-loss rates and mechanical feedback

Mass-loss rates typically on the order of $10^{-5} \ldots 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$

$$\textit{Mechanical feedback}: \quad L_\mathrm{mech} = \frac{1}{2}\dot{M}v_\infty^2$$

→ v_∞ can be more decisive than $\dot{M}$

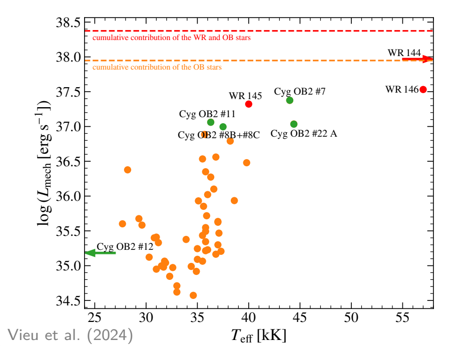
→ earlier subtypes typically more influential

Diagnostic issue:

optical emission lines can underestimate v_∞

Example: opt: ~1700 km/s, UV: ~2500 km/s (Lefever et al. 2023)

↪ factor of two in L_mech



Vieu et al. (2024)

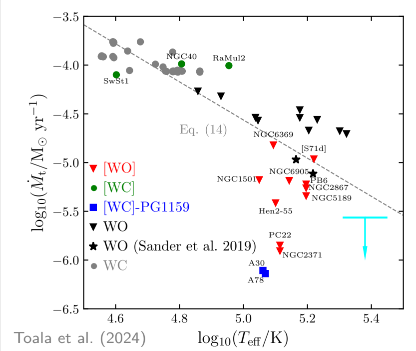
Cyg OB2: → see talk by Thibault Vieu and poster by Cormac Larkin

	SpT	$\log \dot{M}$	v_∞	$\log L/L_\odot$	$\log L_\mathrm{mech}$	Source
WR 102hb	WN9h	−4.52	400 km/s	6.42	36.5	Liermann et al. (2010)
WR 114	WC5	−4.51	3200 km/s	5.39	38.3	Sander et al. (2019)

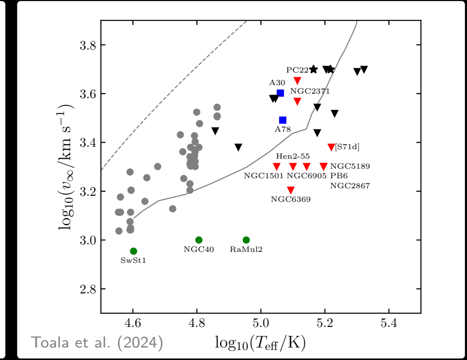
cWR winds across the mass ladder

Are massive and low-mass WO winds similar?

→ literature analysis (10 [WO], 3 [WC], 2 [WC]-PG 1159) with distance updates



Toala et al. (2024)



Toala et al. (2024)

$\dot{M} \approx 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$

$v_\infty \approx 3000\,\mathrm{km/s}$

→ $L_\mathrm{mech} \approx 10^{36}\,\mathrm{erg/s}$

$$\dot{M}_\mathrm{t} \propto \frac{\dot{M}}{v_\infty} L^{3/4}$$

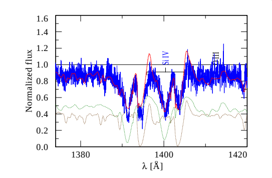
- Massive and low-mass objects mix in the $\dot{M}_\mathrm{t}(T_{2/3})$ plane
- reasonable agreement with observed and theoretical $v_\infty(T_{2/3})$ trend
- WD merger Pa 30 aligns with WO $\dot{M}(L)$ trend despite $v_\infty \approx 15\,000\,\mathrm{km\,s}^{-1}$

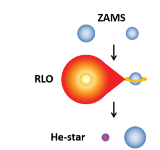
(Partially) stripped, non-WR stars

Varsha Ramachandran

Winds in the regime between classical Wolf-Rayet stars and subdwarfs

- "compact" stripped stars
  → $\dot{M} \lesssim 10^{-9}$ (Götberg et al. 2023)
- "bloated" stripped stars
  → hidden in the OB population

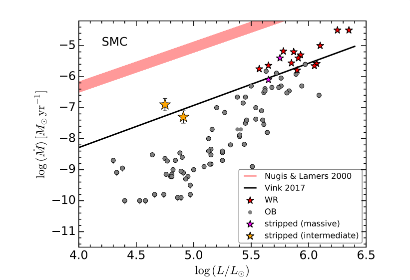




Langer et al. (2020)

Search for "suspicious" UV and optical signatures:

- Ramachandran et al. (2023): Discovery of an intermediate-mass stripped star in the SMC (opt. only)
- Ramachandran et al. (2024, XShootU VIII): Three partially stripped stars with UV+optical spectra
- First $\dot{M}$ determination for these kind: $\dot{M} \approx \dot{M}_{\text{Vink 2017}}$
  → severe implications for binary evolution models

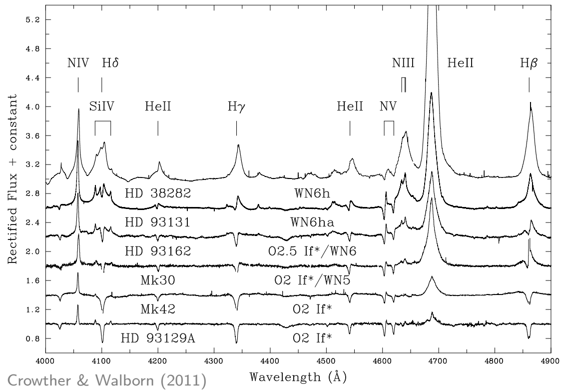


Ramachandran et al. (2024)

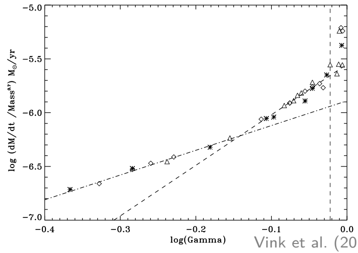
Very Massive WNh Stars

H-burning stars close to the Eddington Limit:

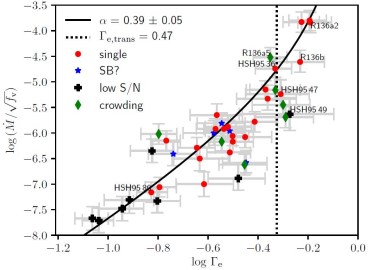
- Transition in $\dot{M}$-behaviour → Gautham's talk
- significant impact to young massive populations
- *Careful:* Not every WNh is very massive or H-burning



Crowther & Walborn (2011)



Vink et al. (2011)



Bestenlehner et al. (2020)

Wolf-Rayet stars as sources of ionizing feedback

Number of photons beyond an ionization edge:

$$Q_{\text{edge}} = \int\limits_{\nu_{\text{edge}}}^{\infty} \frac{F_\nu}{h\nu}\,\mathrm{d}\nu$$

	λ_{edge}	ν_{edge}
Q_0 aka $Q_{\text{H\,I}}$	911.6 Å	13.6 eV
Q_1 aka $Q_{\text{He\,I}}$	504.3 Å	24.6 eV
Q_2 aka $Q_{\text{He\,II}}$	227.9 Å	54.4 eV

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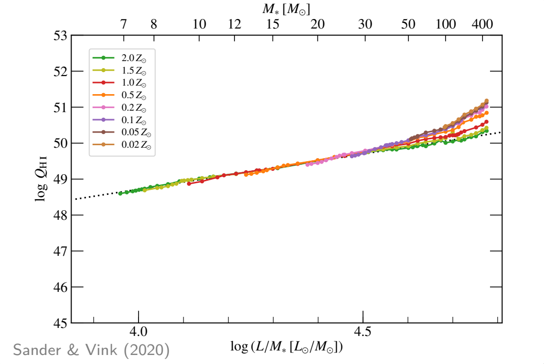
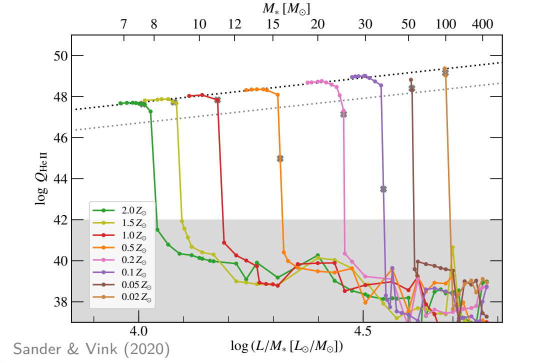
High T_* and $L \rightarrow$ strong sources of $Q_{\mathrm{H\,I}}$



Sander & Vink (2020)

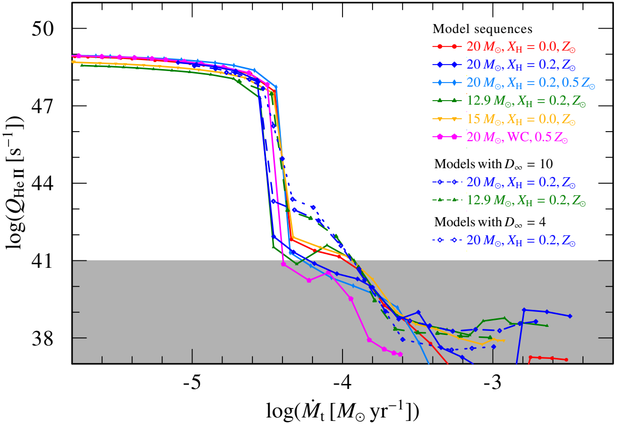
$Q_{\mathrm{He\,II}}$ crucially dependent on $\dot{M}_{\mathrm{WR}}$



Sander & Vink (2020)

Wolf-Rayet stars and He II ionizing flux

Characteristic "transformed mass-loss rate" $\dot{M}_\mathrm{t}$ for regime that yields He II ionizing flux

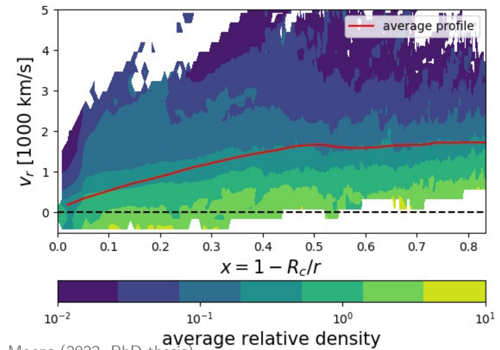


Sander et al. (2023)

Multi-D wind modelling effects

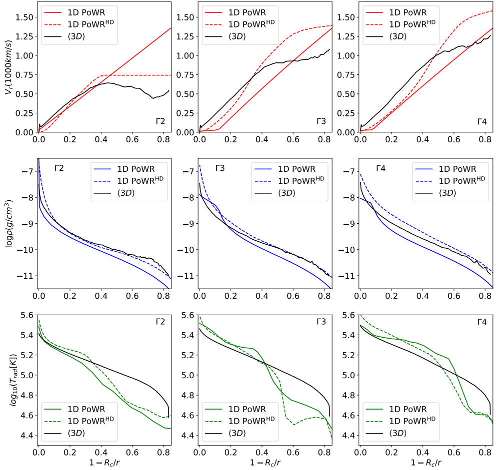
Current insights on $\dot{M}_{WR}$ *all stem from spherically symmetric models* → *3D effects?*

Velocity distribution and averaged profile:



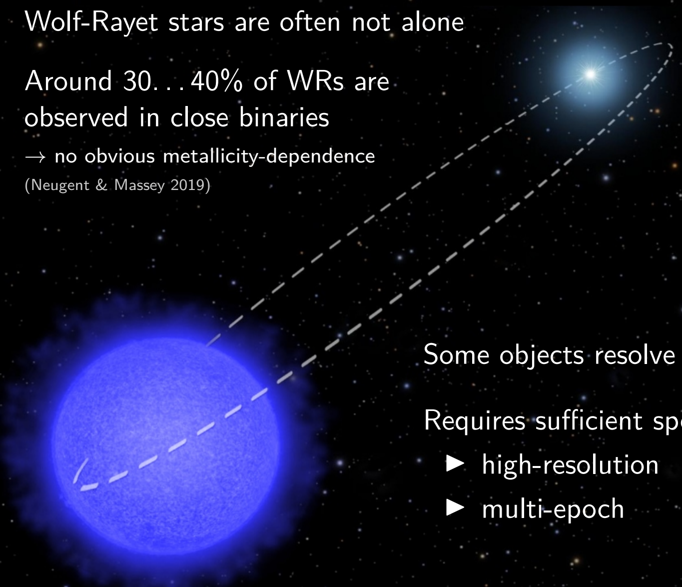
Moens (2022, PhD thesis)

1D approximations of 3D averaged profiles:



González-Torà et al. (in prep.)

Binaries and multiple systems



Wolf-Rayet stars are often not alone

Around 30. . . 40% of WRs are observed in close binaries

→ no obvious metallicity-dependence

(Neugent & Massey 2019)

Most common: cWR + OB

(e.g. WR 133: WN5 + O9; WR 30: WC6 + O7.5)

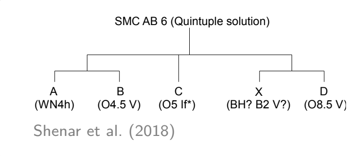
Very massive stars: WNh + WNh

(e.g. WR43A: WN6h + WN6h)

Some objects resolve into higher multiple systems

Requires sufficient spectra:

- high-resolution
- multi-epoch



Shenar et al. (2018)

Background Image Credit: NASA, ESA, and A. Feild (STScI)

How to produce WR stars?

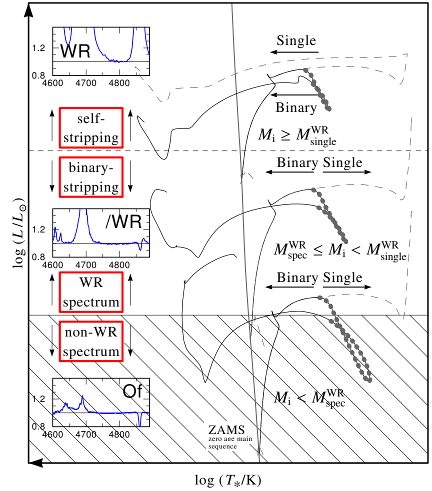
Evolutionary paths towards WR stage still very uncertain and debated.

- Intrinsic stripping challenged by lower wind $\dot{M}$
- High multiplicity fraction among OB progenitors

But: Multiplicity is only part of a bigger puzzle

- WC stage requires intrinsic stripping of a WN
- Single WN stars in the SMC seem to require self-stripping (e.g., Schootemeijer et al. 2024)
- Absence of long-period cWR binaries at lower Z
- No “smoking gun” SN progenitor
  → direct BH collapse seems common

The known WR population is likely a mixture of objects with multiple origins.



Shenar et al. (2020)

Summary: Wolf-Rayet Stars

WR $=$ spectroscopic definition, but synonymously used for:

- very massive stars: WNh spectral type
  core H-burning, “O stars on steroids”
- classical Wolf-Rayet stars: WNh, WN, WC, WO
  massive, core He-burning, hydrogen-depleted

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WR spectra caused by high L/M → strong winds $\left(\dot{M} \approx 10^{-5}\,\frac{M_\odot}{\text{yr}}\right)$

- detectable also among multiples and whole populations
- winds are launched by iron-group elements
  ↪ strong metallicity-dependence (→ massive BHs)

Careful: Not all hydrogen-free stars are WR stars!

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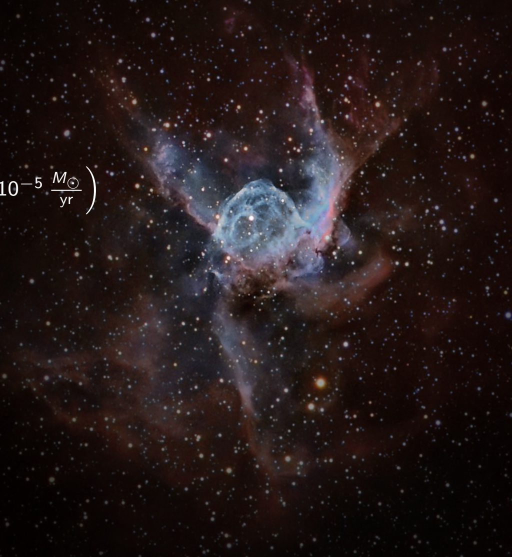

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- strong sources of mechanical and ionizing feedback
- dust production in WC+O binaries

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WR formation still unclear (likely mix of self- & binary stripping), ≈ 40% in close binaries