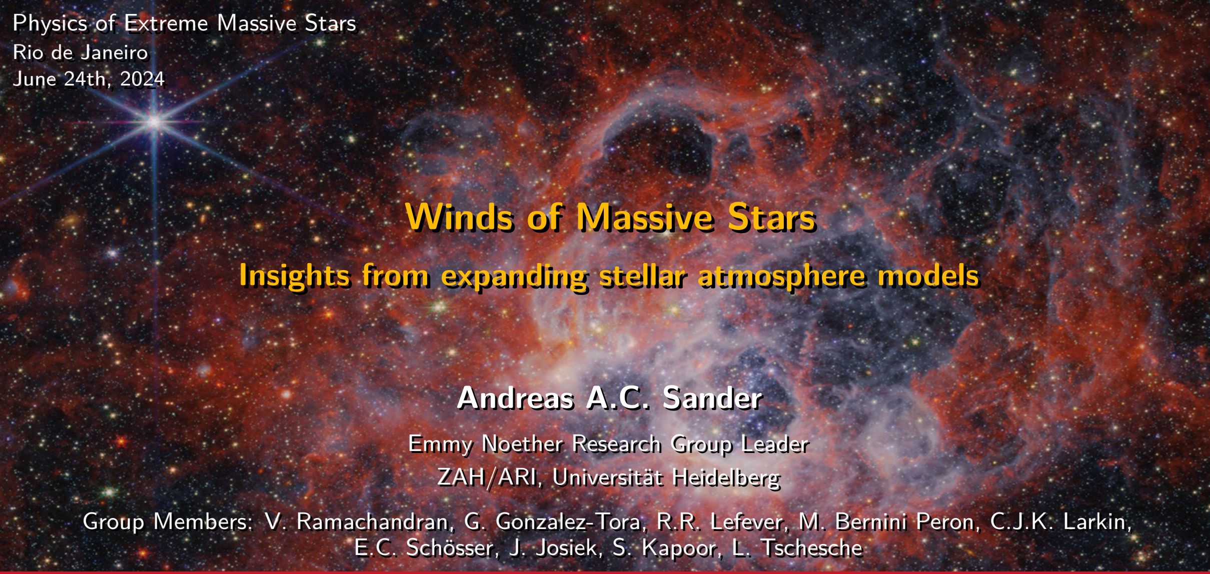

Physics of Extreme Massive Stars
Rio de Janeiro
June 24th, 2024

Winds of Massive Stars

Insights from expanding stellar atmosphere models

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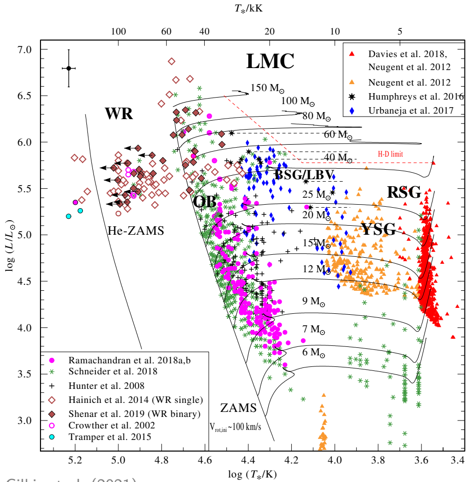
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

ZENTRUM FÜR ASTRONOMIE

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Massive Stars and their winds

"The massive star zoo": Massive stars appear in various flavours



Gilkis et al. (2021)

Stellar winds appear across the upper HRD

Most of the evolutionary lifetime is spent at hot ($T_{\rm eff} > 10\,000$K) temperatures:

→ flux maximum in the UV
  ↪ line-driven winds

→ spectral types: B, O, WNh, WN, WC, WO

→ lots of open questions about the evolutionary connections in the "zoo"

Massive Stars and their winds

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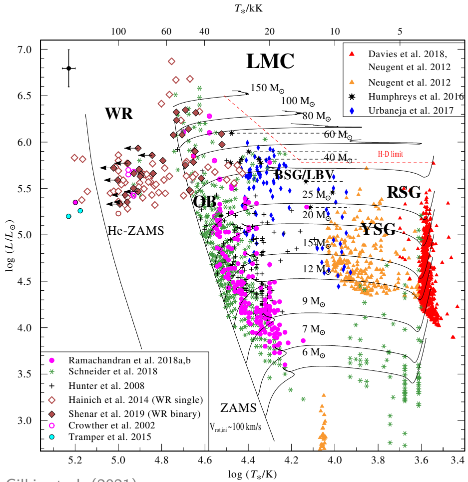

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→ lots of open questions about the evolutionary connections in the "zoo"

Several possible paths, but which are real?
→ study the observed different "zoo" members

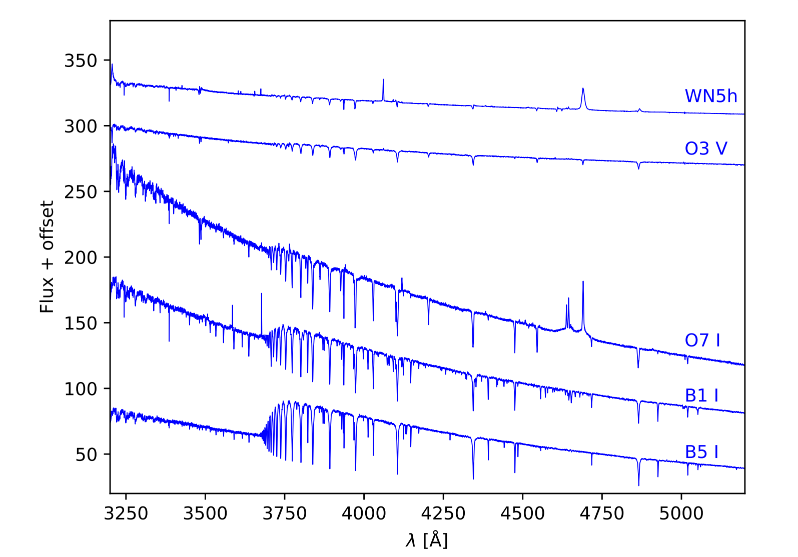
Hot Massive Stars

Photometry alone is usually insufficient to understand hot stars

It's blue:
You can fit any model with $T_{eff} \gtrsim$ *20 kK...*

Spectroscopy is key

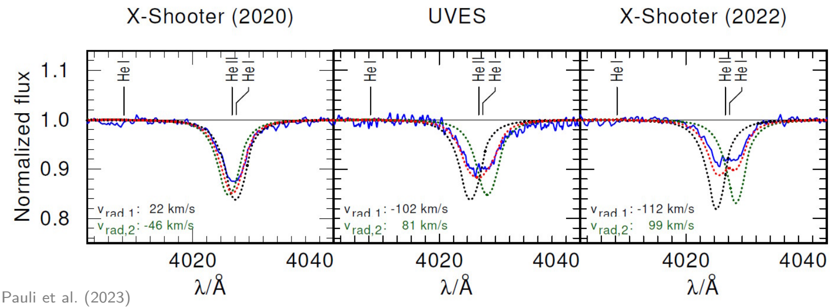
- fundamental stellar parameters
  → Balmer jump vanishes for hottest stars
- abundance information
- wind diagnostic(s)
- ...



Hot Massive Stars

So how to deal with hot, massive stars?

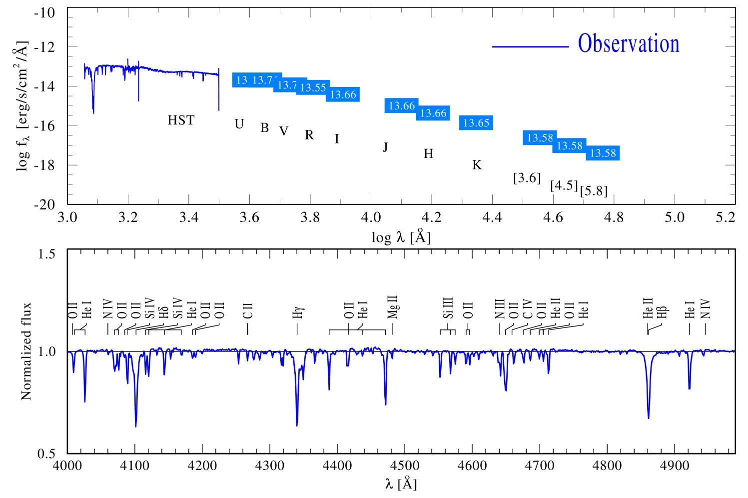
- Perform quantitative spectroscopy to get reliable parameters



Pauli et al. (2023)

- Requires a physical model of the outermost layers of the star: *model atmosphere*

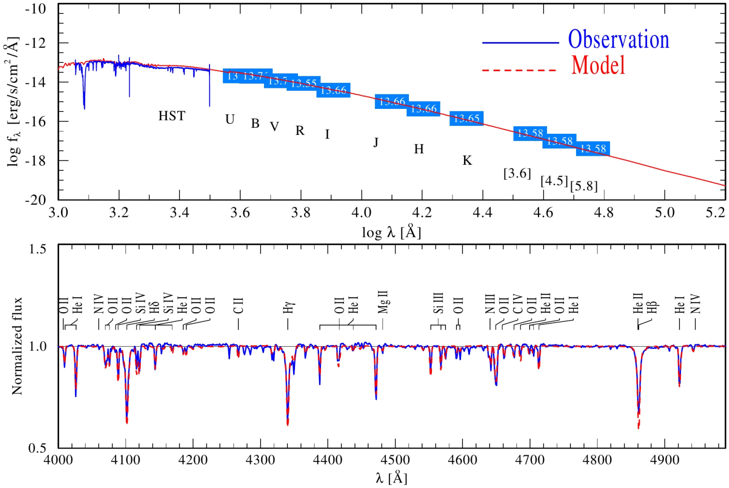
Quantitative Spectroscopy



One coherent model needs to explain the full spectrum and reproduce the SED

- Usually no de-composition into element-specific models possible
- Several specific challenges for hot, massive stars
- Atomic (electronic) data of many species needed

Quantitative Spectroscopy



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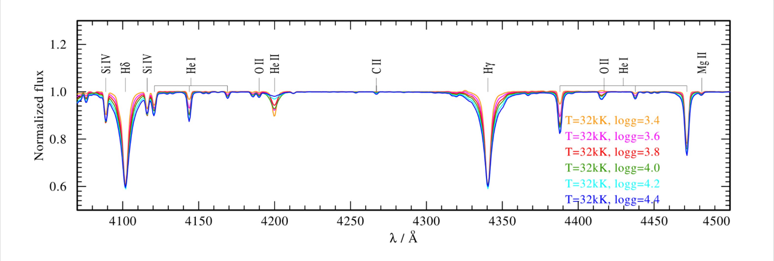
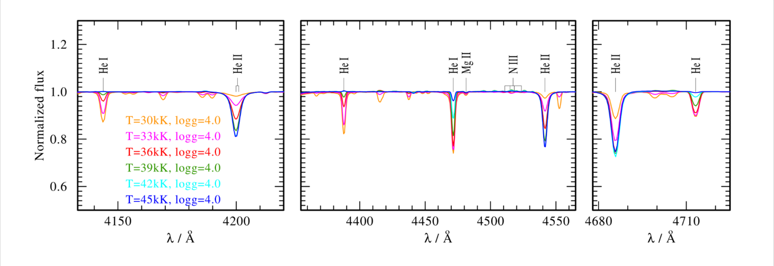
Quantitative Spectroscopy – Diagnostics



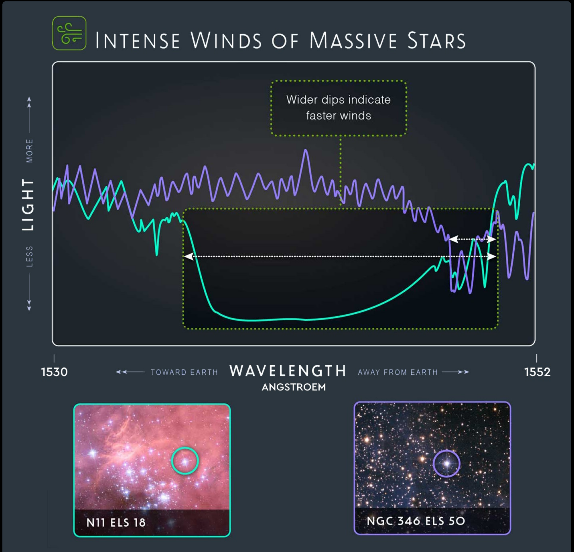


For most stars: T_{eff} only from line ratios (e.g., He I vs. He II)

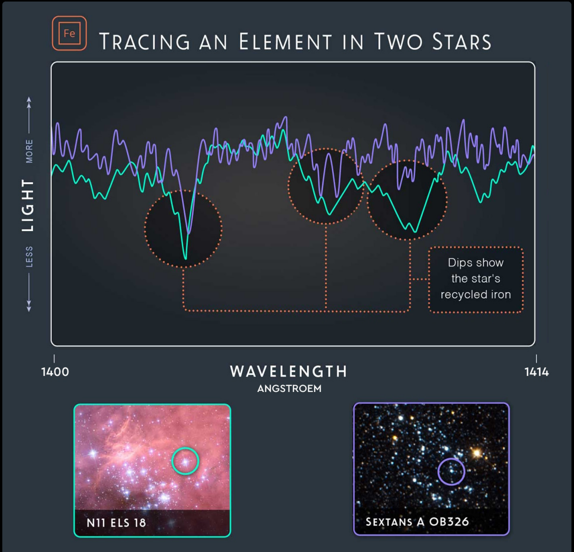
Plus:

- N III, N IV, N V for early O stars
- Si II, Si III, Si IV, He I/Mg II for B stars
- Rotational broadening from metals
- Microturbulence
- Macroturbulence
- wind and clumping diagnostics (UV, Hα)

Quantitative Spectroscopy – UV Diagnostics



Credit: NASA, ESA, Z. Levy



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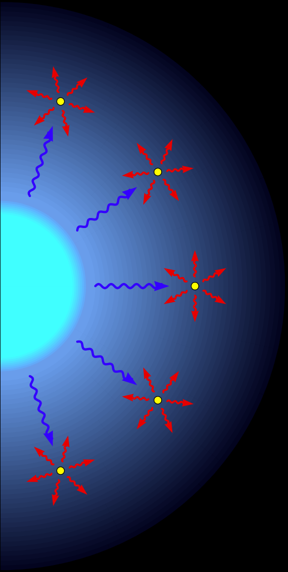
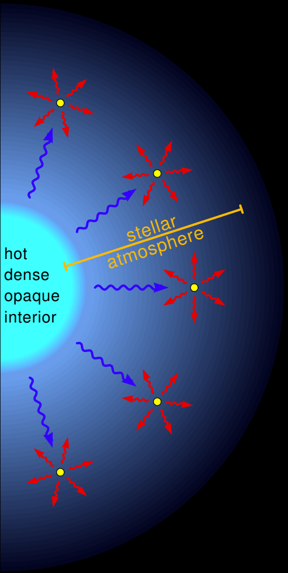
The physical roots of quantitative spectroscopy



Stars are giant balls of gas:

- no hard boundary (→ non-trivial radius definition)

The physical roots of quantitative spectroscopy



Stars are giant balls of gas:

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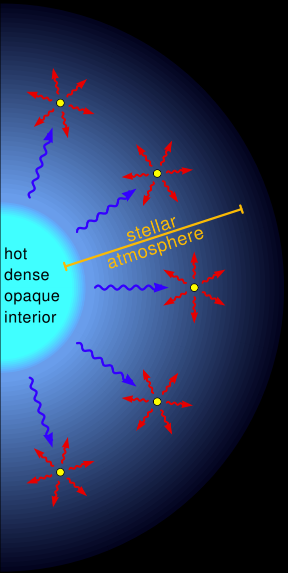
- spectrum stems from a transition layer: *stellar atmosphere*

The physical roots of quantitative spectroscopy



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stellar atmosphere models
=
fundamental tool of astrophysics

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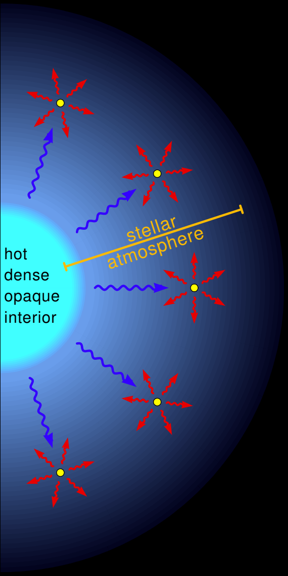

Stars are giant balls of gas:

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stellar atmosphere models
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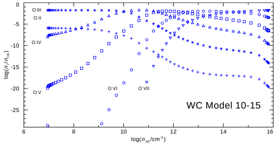
Spectrum formation in hot, massive stars:

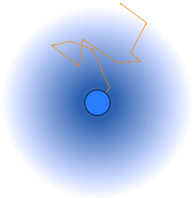
- far outside of thermodynamic equilibrium
- stellar winds → expanding atmosphere
- ionization changes throughout the atmosphere
- emission and absorption lines with multiple broadening mechanisms

⇒ many physical and numerical challenges

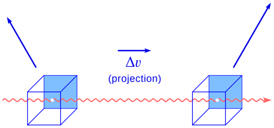
The challenges of expanding stellar atmosphere modelling



non-LTE

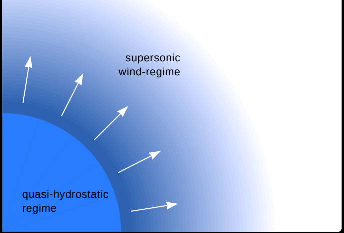


multiple scattering

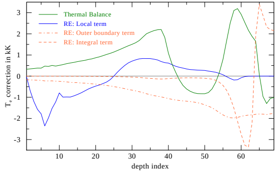


expanding atmosphere

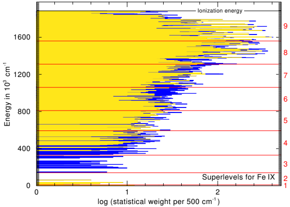
hydrostatic to supersonic



temperature corrections



line blanketing



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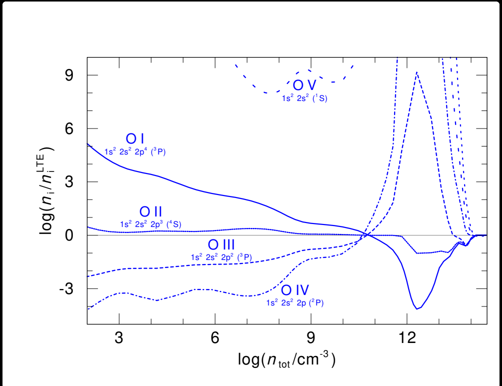
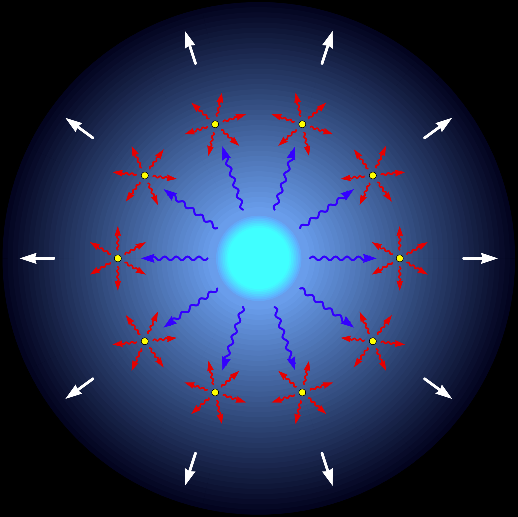


$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = 0 \quad \Rightarrow \quad \underbrace{n_i \sum_{i \neq j} P_{ij}}_{total\ \ loss\ \ rate} = \underbrace{\sum_{i \neq j} n_j P_{ji}}_{total\ \ gain\ \ rate}$$

Departures from LTE are much larger in hot stars than in cool stars:

- → non-LTE cannot be treated as a correction
- → complete non-LTE treatment for establishing the atmosphere stratification
- → iterative solution of the statistical equilibrium equations required (modern models have often 1000 . . . 2000 explicit levels)
- → abundance changes in one element can affect lines of *other* elements

Winds of hot stars: fundamental principles



Stellar winds are ubiquitous in massive stars

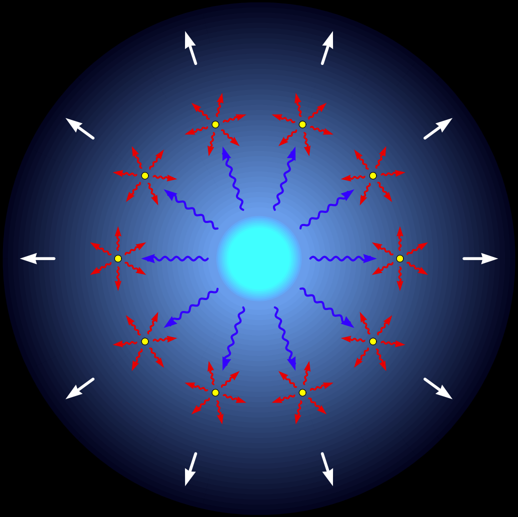
→ can alter the spectrum, need to be modeled

→ *expanding* atmosphere model required

Radiation pressure dominates in hot stars:

- Momentum transfer from photons to matter

Winds of hot stars: fundamental principles



Stellar winds are ubiquitous in massive stars

→ can alter the spectrum, need to be modeled

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Radiation pressure dominates in hot stars:

- Momentum transfer from photons to matter
- Subject to instabilities, but existence of time-averaged stationary solutions

Radiative acceleration vs. gravity in 1D:

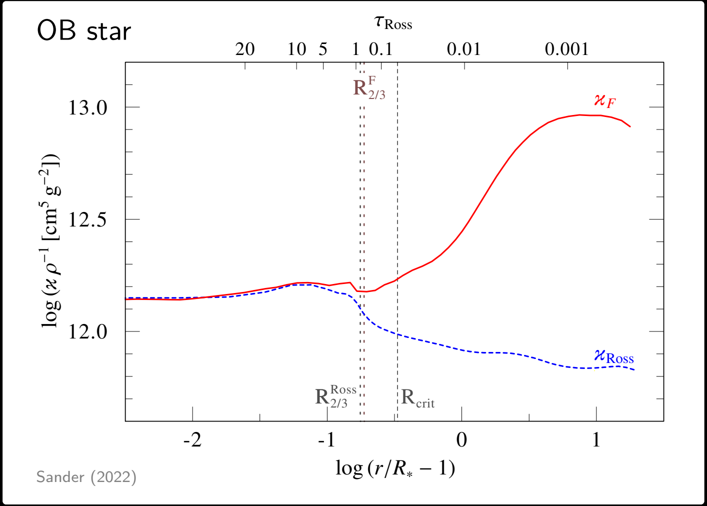
$$\Gamma_{\mathrm{rad}}(r) := \frac{a_{\mathrm{rad}}(r)}{g(r)} = \varkappa_F(r)\frac{L}{4\pi c G M}$$

$\varkappa_F$: flux-weighted mean opacity

⇒ main wind-defining quantities: L, M, $\varkappa_F$

The flux-weighted opacity

Major source of complication: $\varkappa_F \neq \varkappa_{\text{Rosseland}}$

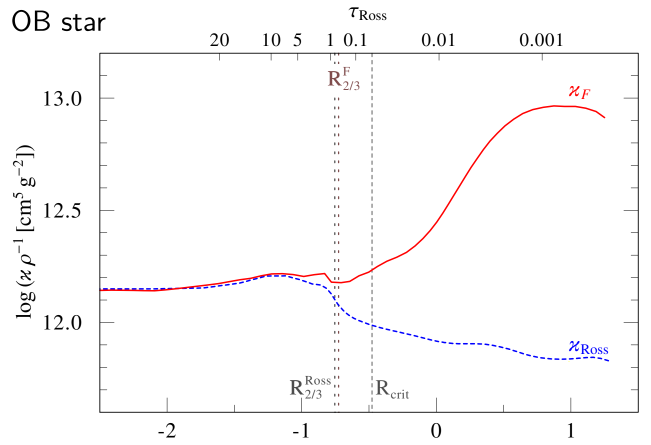


Sander (2022)

Radiative driving depends on flux-weighted opacity (red) instead of Rosseland opacity (blue):

The flux-weighted opacity

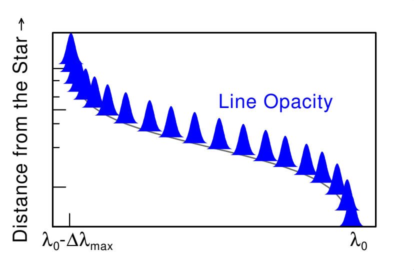
Major source of complication: $\varkappa_F \neq \varkappa_{\text{Rosseland}}$



Sander (2022)

Radiative driving depends on flux-weighted opacity (red) instead of Rosseland opacity (blue):

Opacities significantly higher in the wind than e.g. given by OPAL, due to Doppler-shifting of the lines:



$\Rightarrow$ can use much wider λ-range

Comoving Frame (CMF) Radiative Transfer Calculations

“Brute Force” numerical solution of the (spherical) radiative transfer equation(s)

- Opacities/Emissivities ($\varkappa_\nu$, η_ν) stay isotropic (despite the expanding atmosphere)
- typically 200 000 ... 400 000 wavelength points λ_k (depending on required line width resolution)
- initial value problem: start at blue edge, solve for each λ_k using solution for λ_{k-1}
- at each λ_k: equation system coupled in space (r)

⇒ $\sim 10^9$ intensities ($\lambda_k \cdot r_l \cdot p_j$)

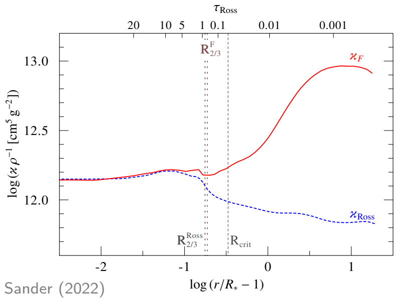
Benefits:

- implicit multiple scattering and line overlapping
- no Sobolev approximation → realistic line force

$$a_{\mathrm{rad}}(r) = \frac{4\pi}{c} \int\limits_0^\infty \varkappa_\nu H_\nu \mathrm{d}\nu = \frac{\varkappa_F L}{4\pi c r^2}$$

Each RT computation with detailed atomic data takes few minutes

⇒ Atmosphere codes with iterated CMF RT require hours to days



Sander (2022)

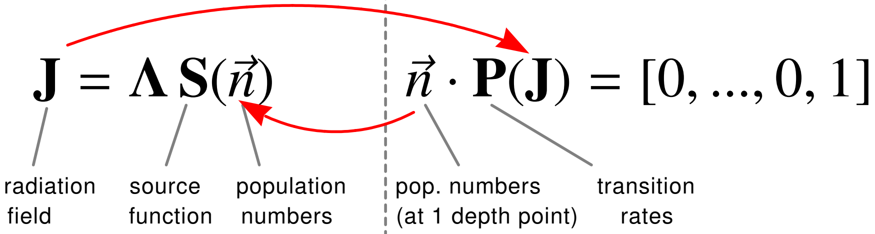
The complexity of non-LTE stellar atmosphere modelling

Radiation Transfer

Symbolically: linear mapping Λ

Rate Equations (Statistical Equilibrium)

Set of linear eqns. at each spatial point



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

→ Coupling in space

→ Coupling in frequency

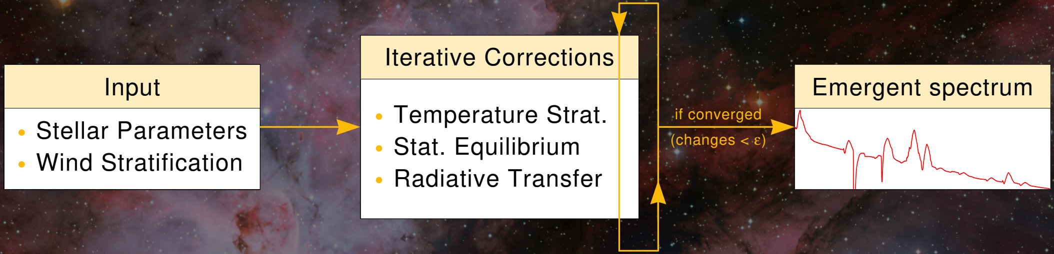
Radiative transition rates:
Frequency integrals

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

→ **high-dimensional, non-linear, fully coupled in space and frequency**

Hot star atmosphere models: State of the art

Schematic overview of stellar atmosphere calculations:



Input

- Stellar Parameters
- Wind Stratification

Iterative Corrections

- Temperature Strat.
- Stat. Equilibrium
- Radiative Transfer

if converged

(changes $< \varepsilon$)

Emergent spectrum

Hot star atmosphere models: State of the art

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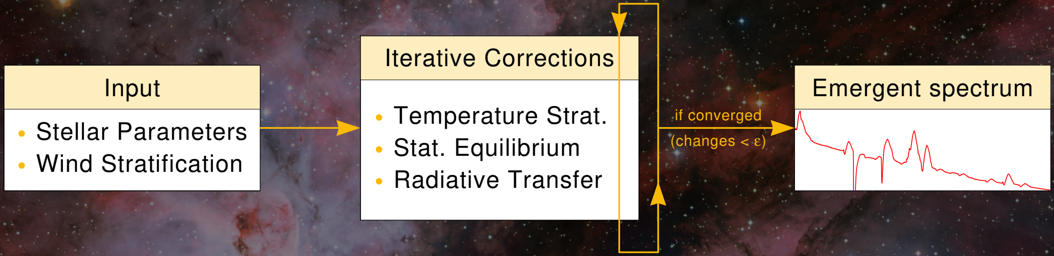

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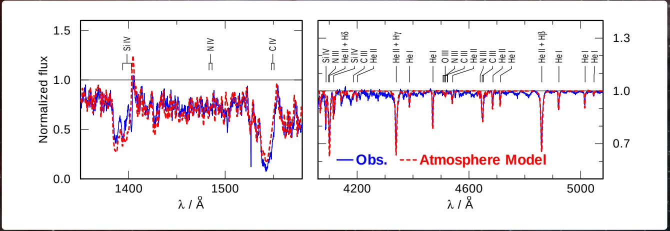
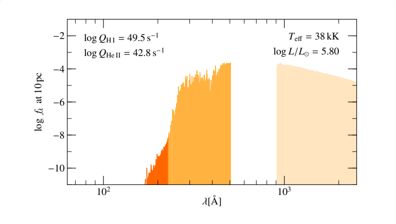
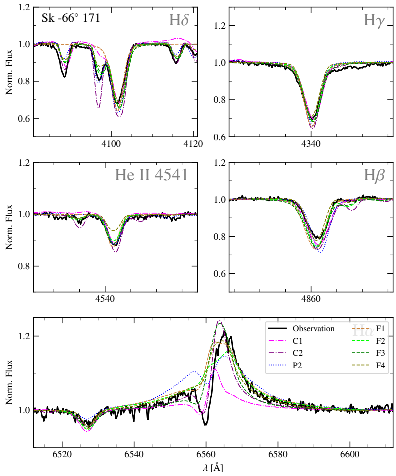




What about different model atmosphere codes?

How much do the results differ between different analysis methods?

- XShootU Paper IV (Sander et al., submitted)
- “blind test”
  → avoid any aims to meet “expected” values
- Concept: Everybody does what they “usually do”
  exceptions: We use the same spectra
  (re-normalization allowed) and photometry
- 3 expanding atmosphere codes:
  CMFGEN, FASTWIND, PoWR
- 8 different methods
  (from coarse grids to tailored models)



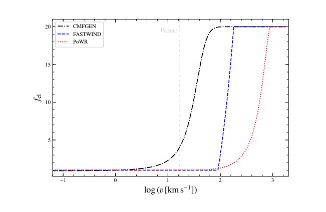
Sander et al. (2024, submitted)

Comparison of different hot star atmosphere codes

	static		— expanding —	
	TLUSTY	FASTWIND	CMFGEN	PoWR$^{\mathrm{HD}}$
geometry	plane-parallel	spherical	spherical	spherical
blanketing	yes	approx. (v10)	yes	yes
wind + X-rays	no	yes	yes	yes
clumping	no	micro+macro	micro	micro
HD wind option	no wind	yes (v11)	yes (LambertW)	yes
calculation time	hours	$<$ 1 hour (v10)	hours	hours
spectral synthesis	SYNSPEC	included	included	included

Considerable differences in the implementations, e.g.:

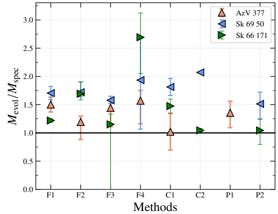
- Clumping formalism and onset description
- Treatment of wind-intrinsic X-rays
- more approximations in FASTWIND (v10) to gain speed



Results from different atmosphere codes

Results from XShootU IV:

- Comparable parameters, a bit more scatter than expected
- Tailored fits generally better, reddening differences matter
- Turbulent pressure promising to reduce mass discrepancy
- It is usually okay to combine results from different methods



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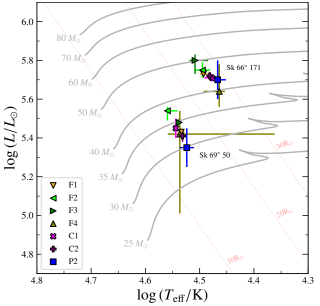
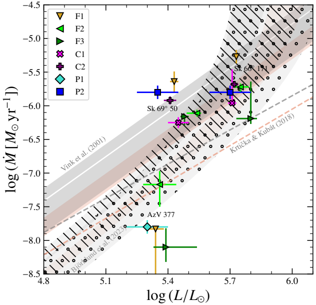
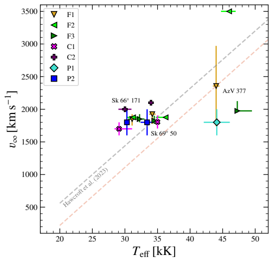




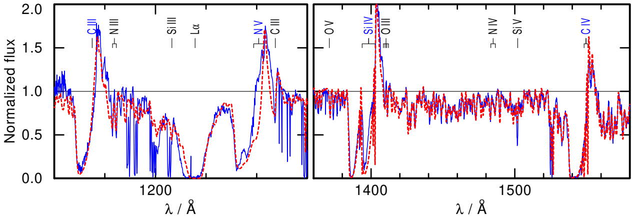


Empirical stellar and wind parameters

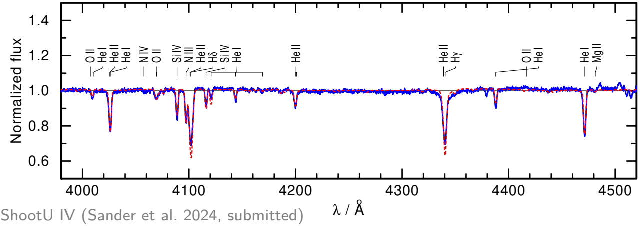
Quantitative spectral analysis

Standard wind description:

- assumed β- oder 2β-velocity law for $v(r)$
- choice of $v(r)$ affects predicted spectrum
- formally "independent" adjustment of stellar and wind parameters



XShootU IV (Sander et al. 2024, submitted)



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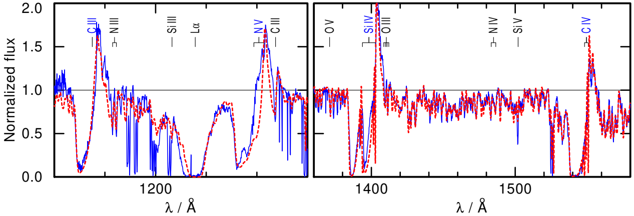
Unified model for star and wind
$\rightarrow$ consistent parameters?



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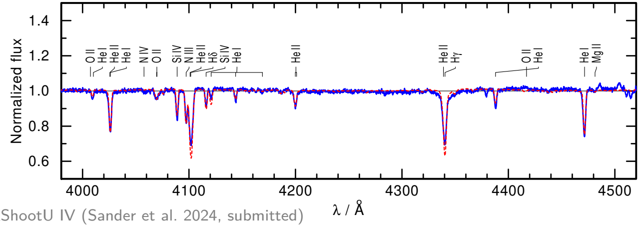

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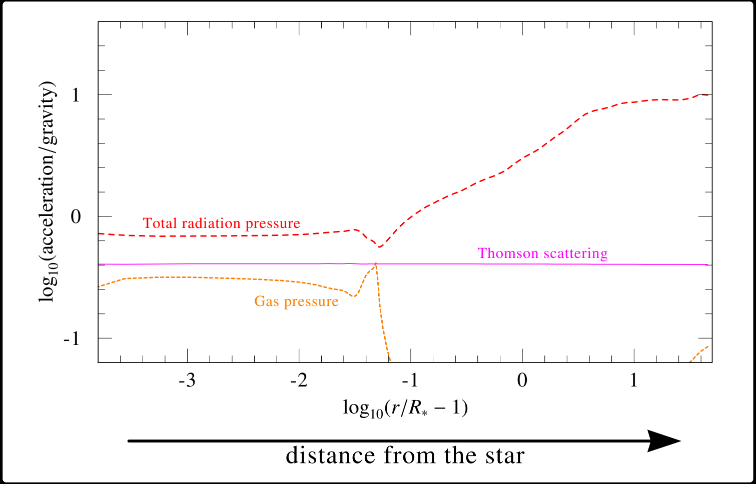
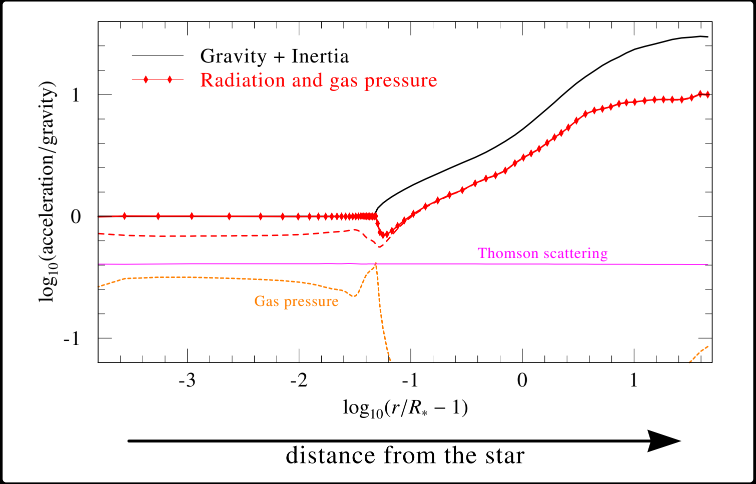
Stellar properties versus wind assumptions



Typical hot star atmosphere models *assume* stellar winds parameters (e.g., $\dot{M}$, v_∞)

Stellar properties versus wind assumptions



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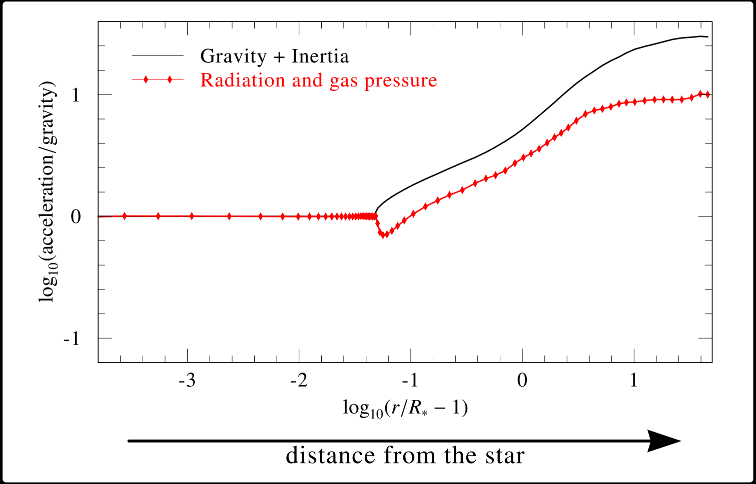
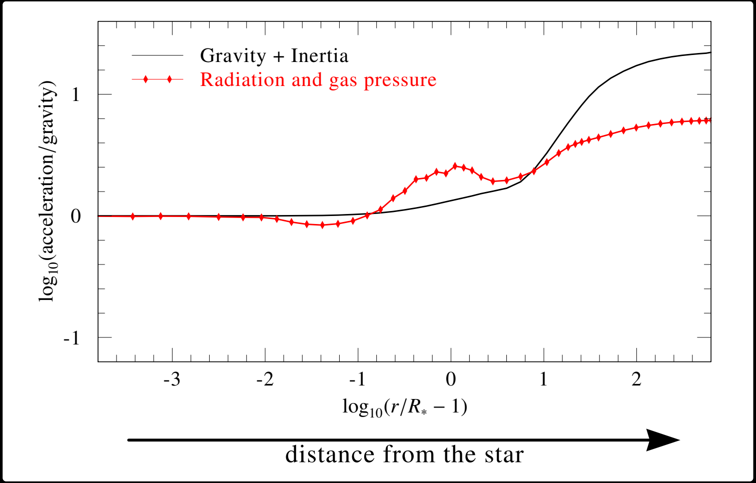


Typical hot star atmosphere models *assume* stellar winds parameters (e.g., $\dot{M}$, v_∞)

→ force balance violated

$$v\frac{\mathrm{d}v}{\mathrm{d}r} + g \neq a_{\mathrm{rad}} + a_{\mathrm{press}}$$

Stellar properties versus wind assumptions



Typical hot star atmosphere models *assume* stellar winds parameters (e.g., $\dot{M}$, v_∞)

→ force balance violated

→ global balance does not ensure local balance

$$v\frac{\mathrm{d}v}{\mathrm{d}r} + g \neq a_{\mathrm{rad}} + a_{\mathrm{press}}$$

Prediction of wind parameters via Hydrodynamics

Inherent inconsistencies between star and wind

→ balance of rad. pressure and gravity is violated

→ wind is too strong/weak for what can be driven

→ degeneracies for different wind assumptions

⇒ no insights on radiative driving

Radiative Transfer:

$$\mathbf{J}_\nu = \mathbf{\Lambda}_\nu \mathbf{S}_\nu(\vec{n}, v)$$

$\mathbf{J}_\nu$: radiation field (angle-averaged intensity)
$\vec{n}$: atomic level population numbers

Rate Equations:

$$\vec{n} \cdot \mathbf{P}(\mathbf{J}) = \vec{b}$$

$v(r)$: wind velocity (as a function of radius)
$\dot{M}$: wind mass-loss rate

Fixed wind stratification:

$$\rho(r), v(r), \dot{M}$$

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Solution: Consistent hydrodynamical treatment

Use radiative acceleration a_rad from detailed radiative transfer

$$a_\mathrm{rad}(r) = \frac{1}{c} \int\limits_0^\infty \varkappa_\nu(r) F_\nu(r) \mathrm{d}\nu$$

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$$\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{g}{v}\frac{\tilde{\mathcal{F}}(\mathbf{J}, \vec{n})}{\tilde{\mathcal{G}}(v, \vec{n})}$$

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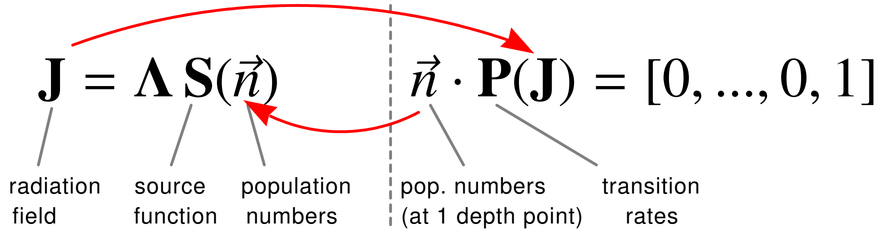
The complexity of non-LTE stellar atmosphere modelling

Radiation Transfer

Symbolically: linear mapping Λ

Rate Equations (Statistical Equilibrium)

Set of linear eqns. at each spatial point



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

radiation field

source function

population numbers

pop. numbers (at 1 depth point)

transition rates

→ Coupling in space

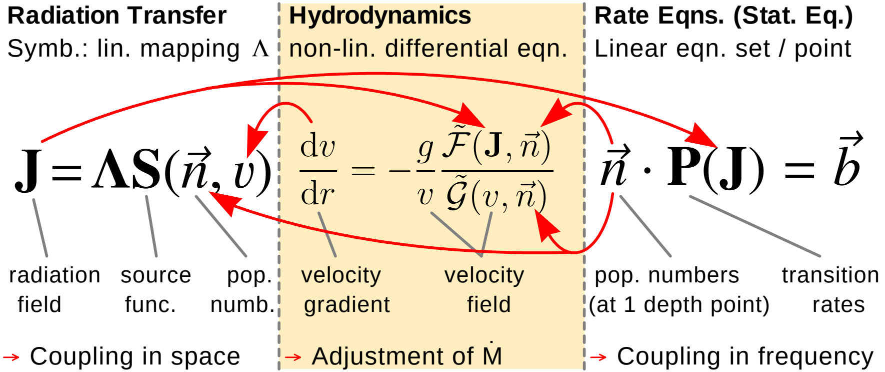
→ Coupling in frequency

Radiative transition rates:
Frequency integrals

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

→ **high-dimensional, non-linear, fully coupled in space and frequency**

The complexity of non-LTE stellar atmosphere modelling



Radiation Transfer
Symb.: lin. mapping Λ

$$\mathbf{J} = \mathbf{\Lambda}\mathbf{S}(\vec{n}, v)$$

radiation field
source func.
pop. numb.

→ Coupling in space

Hydrodynamics
non-lin. differential eqn.

$$\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{g}{v}\,\frac{\tilde{\mathcal{F}}(\mathbf{J},\vec{n})}{\tilde{\mathcal{G}}(v,\vec{n})}$$

velocity gradient
velocity field

→ Adjustment of $\dot{M}$

Rate Eqns. (Stat. Eq.)
Linear eqn. set / point

$$\vec{n}\cdot\mathbf{P}(\mathbf{J}) = \vec{b}$$

pop. numbers (at 1 depth point)
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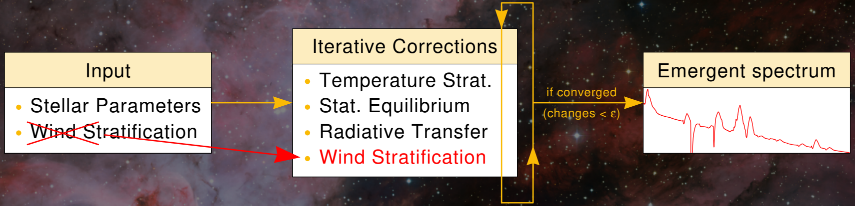
Hot star atmosphere models with dynamical consistency

Inclusion of stationary hydrodynamics yields a new generation of stellar atmospheres:
(Sander et al. 2017, 2018, 2020, 2023)



Input
- Stellar Parameters
- ~~Wind Stratification~~

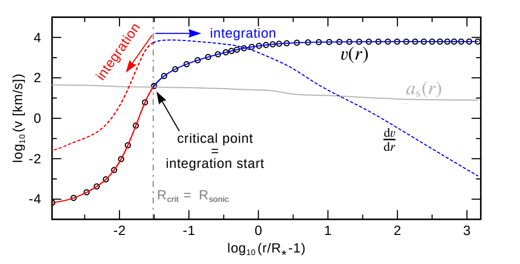
Iterative Corrections
- Temperature Strat.
- Stat. Equilibrium
- Radiative Transfer
- Wind Stratification

if converged
(changes < ε)

Emergent spectrum

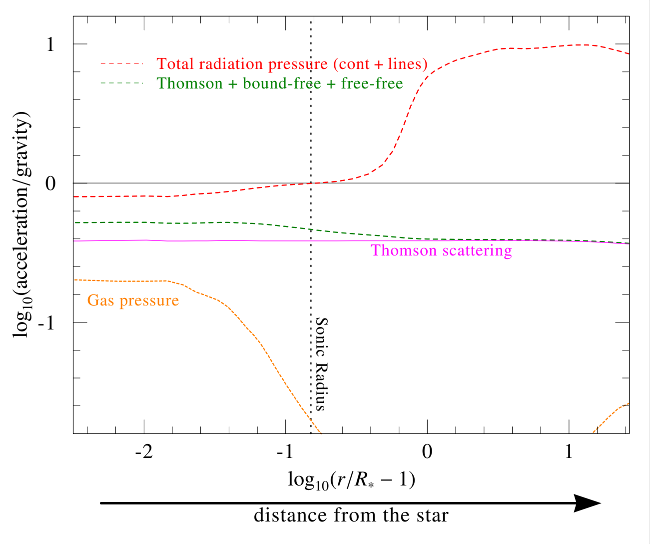
Additional Iteration Scheme:

- ▶ $v(r)$ via integrating the hydrodynamic equation of motion
- ▶ adjustment of $\dot{M}$ via boundary constraint (e.g., total opacity conservation)
- ⇒ prediction of wind parameters from given stellar parameters



Dynamical consistency: local force balance

Detailed local $a_{\mathrm{rad}}(r)$ is used to obtain wind solution:



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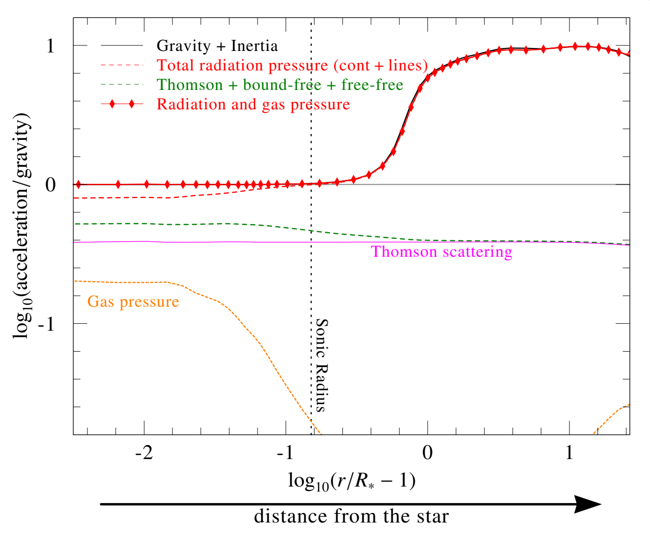
Detailed local $a_{\mathrm{rad}}(r)$ is used to obtain wind solution:

Implemented in multiple atmospheres codes, can be used to predict $\dot{M}$ and v_∞, e.g. in

→ METUJE (e.g., Krtička & Kubát 2010, 2017, 2018)
→ PoWR (e.g., Gräfener & Hamann 2005; Sander et al. 2017)
→ FASTWIND (Sundqvist et al. 2019, Björklund et al. 2020)
→ CMFGEN (via LambertW, Gormaz-Matamala et al. 2021)

careful:
significant differences in the detailed methods (e.g., assumptions, num. treatment, locality)



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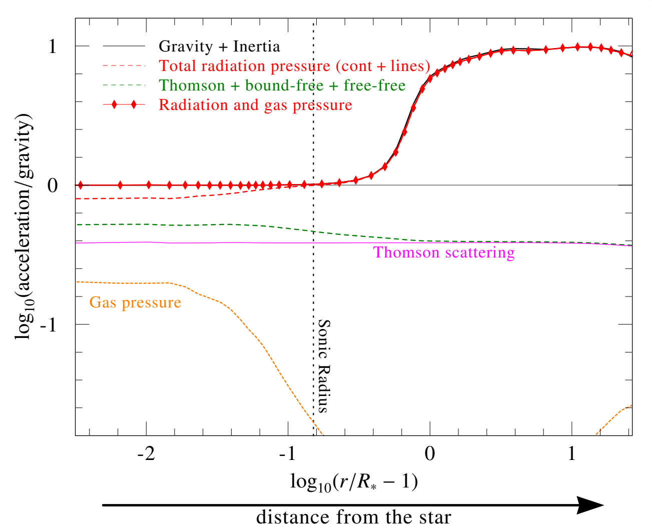
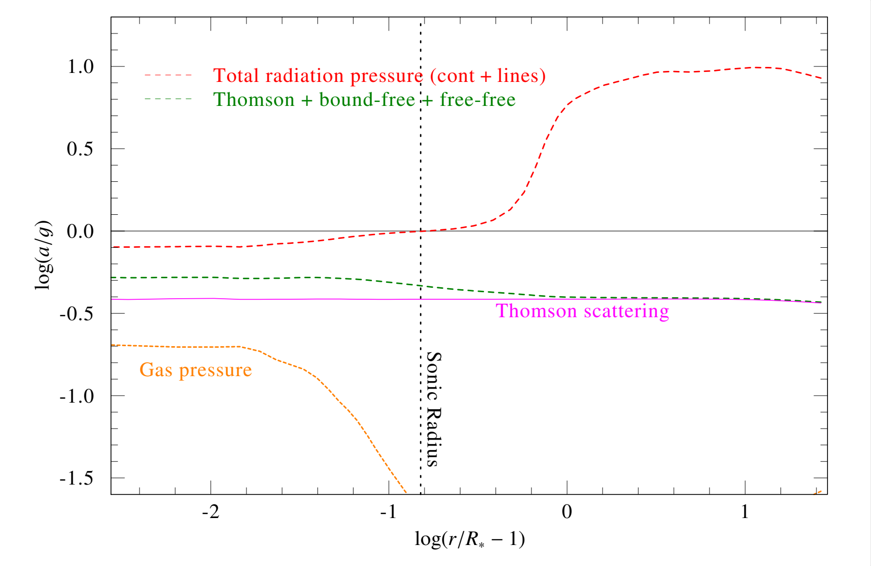
Hydrodynamic coupling numerically expensive
→ limited to 1D in the foreseeable future
→ 3D effects only in parametrized form



Theoretical insights: Studying hot star wind driving

Use detailed (CMF) atmosphere models to investigate contributions to a_{rad} on the level of:



Example:
O supergiant ζ Pup
$T_{\text{eff}} = 41\,\text{kK}$

Theoretical insights: Studying hot star wind driving

Use detailed (CMF) atmosphere models to investigate contributions to $a_{\rm rad}$ on the level of:

- elements

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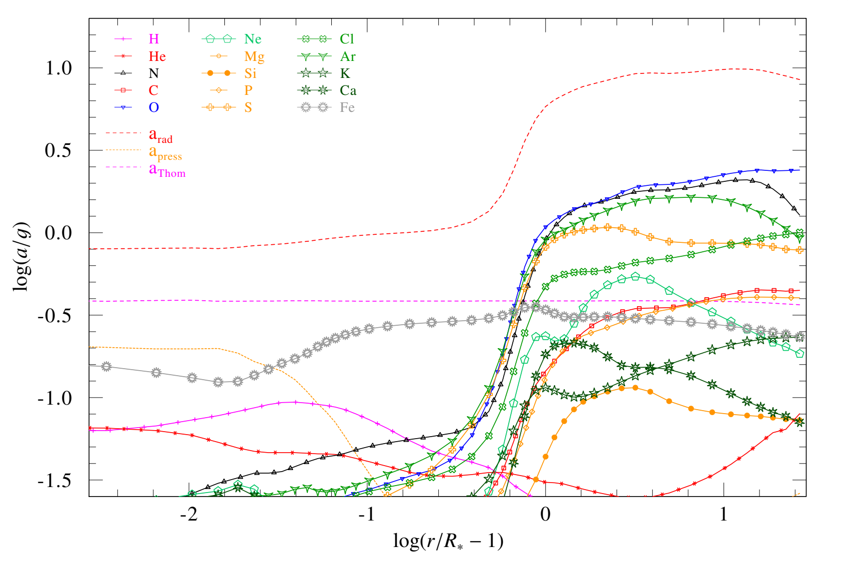

Theoretical insights: Studying hot star wind driving

Use detailed (CMF) atmosphere models to investigate contributions to a_{rad} on the level of:

- elements
- individual ions

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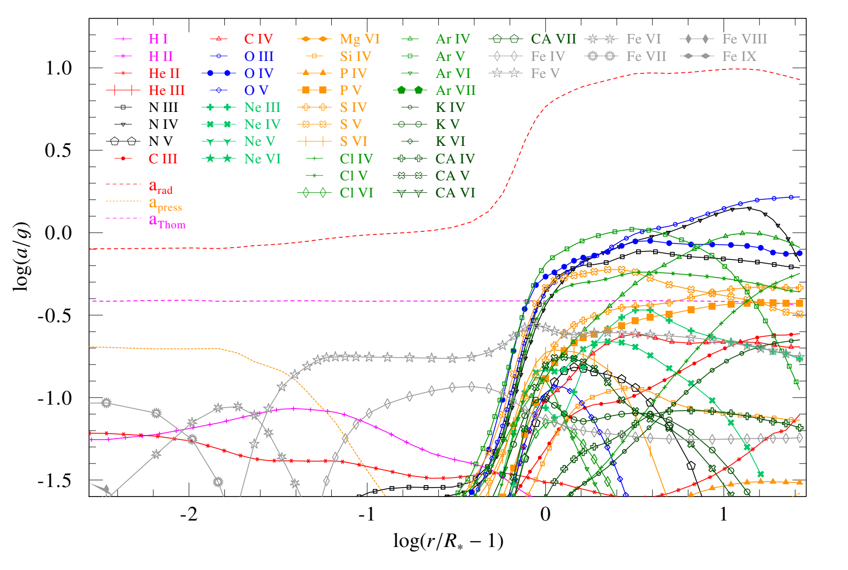
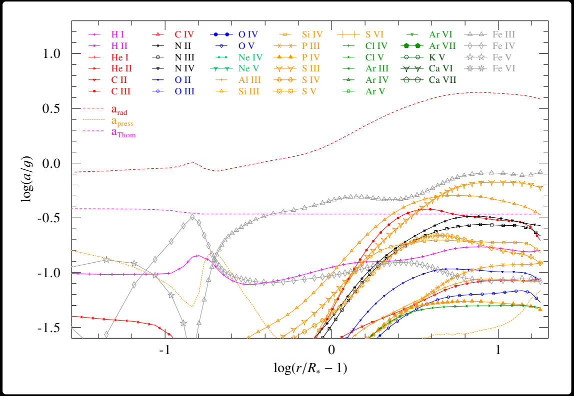
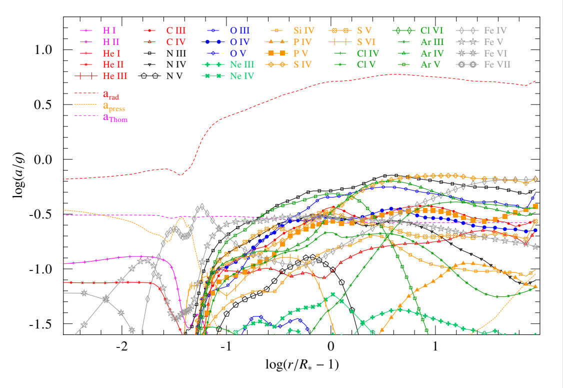


Radiative driving: OB-type winds

$T_{\mathrm{eff}} = 25\,\mathrm{kk}$



$T_{\mathrm{eff}} = 34\,\mathrm{kk}$

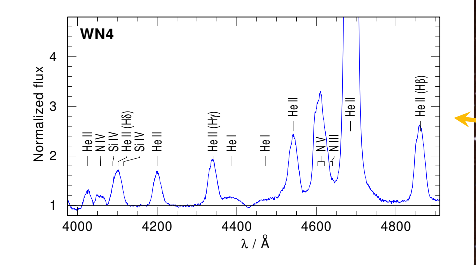


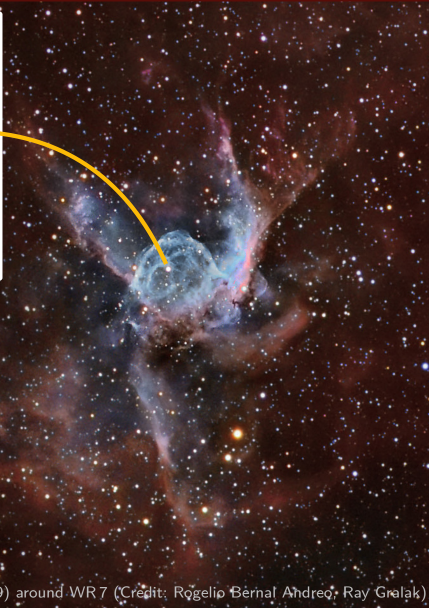
- Fe opacities usually play key role for launching winds
- Acceleration in the (outer) wind maintained by a variety of elements: Individual importance depends significantly on the stellar parameters

Wolf-Rayet Winds

Thor's Helmet (NGC 2359) around WR 7 (Credit: Rogelio Bernal Andreo, Ray Gralak)

Wolf-Rayet Winds





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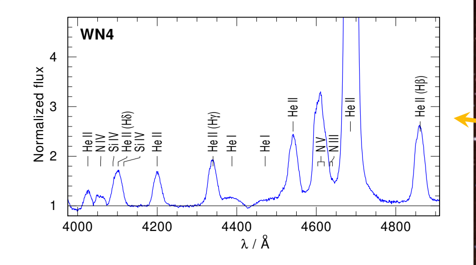
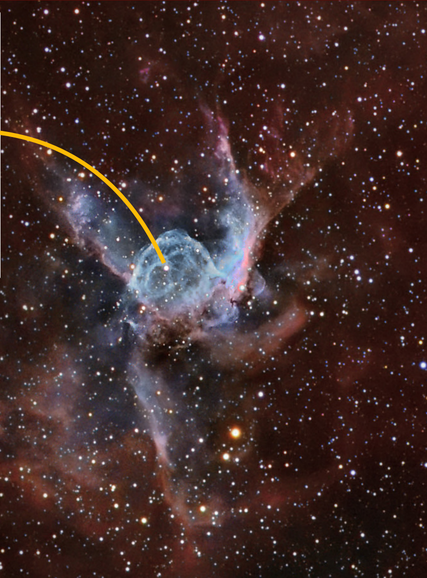


Wolf-Rayet (WR) stars are a *spectroscopic* definition:

- optical spectra with strong and broad emission lines
- WR star spectra indicate strong mass outflow (Beals 1929)



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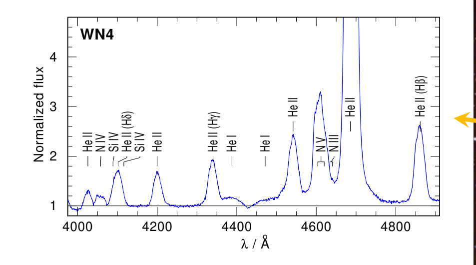

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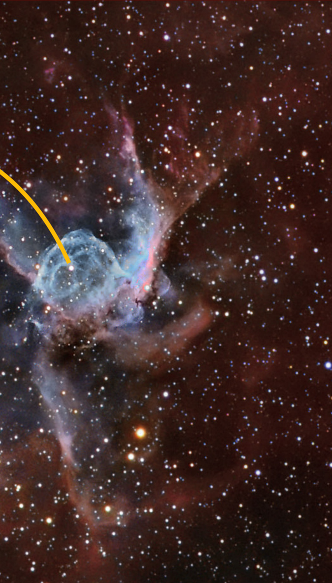
Two (main) flavours:

- classical WR stars: core He-burning, evolved
  ↪ partially or completely depleted in hydrogen
- very massive WNh stars: core H-burning, barely evolved
  ↪ extension of the main sequence ("O stars on steroids")



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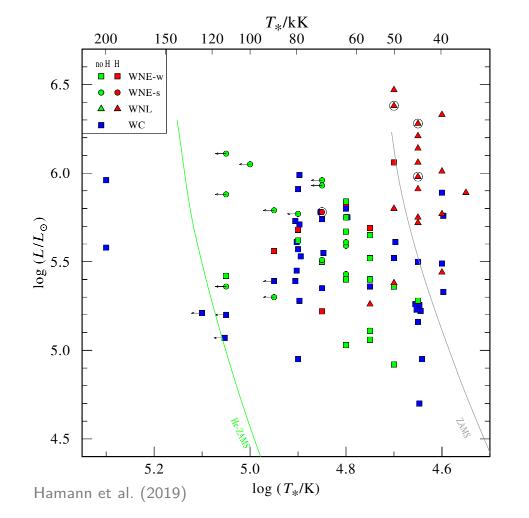
The Wolf-Rayet radius problem



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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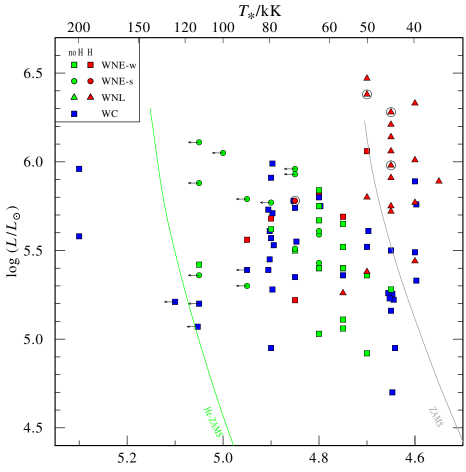

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⇒ *Wolf-Rayet Radius Problem:*
Discrepancy between empirical parameters and stellar structure models
→ similar results for other galaxies and different metallicities

The Wolf-Rayet radius problem

Two possible solutions:

- inflated hydrostatic radii
- deep wind launching (“dynamical inflation”)

→ coupling of structure and wind physics

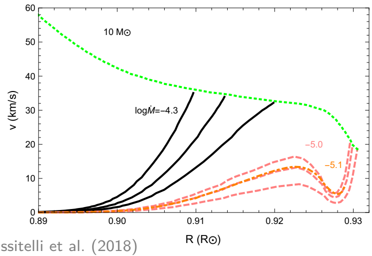
Different radius definitions and multiple meanings for T_{eff}:

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

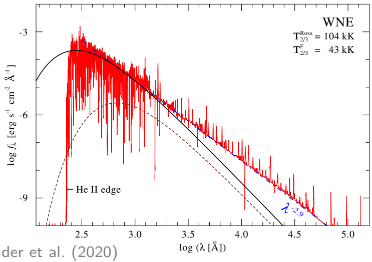
  (typical choices: 20 or 100)

- $T_{2/3}$ 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

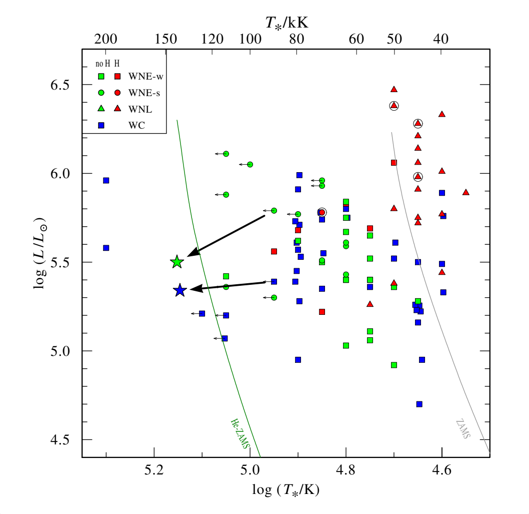


Grassitelli et al. (2018)



Sander et al. (2020)

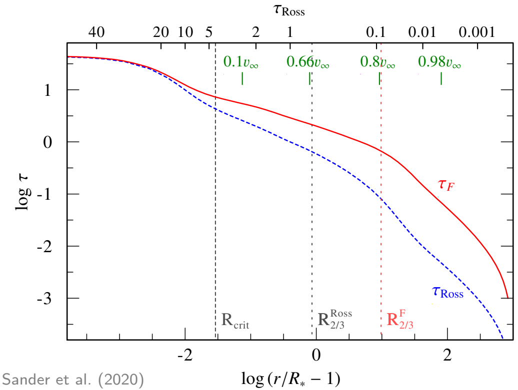
Deep launching as a solution to the WR radius problem



Spectral analysis with dynamically-consistent model atmospheres:

- New, complex technique (e.g. v_∞ not a free parameter)
- First example cases show: H-free WN and WC stars can move to the HeZAMS
- Viable for all WRs?
  - → open question (Sander et al. 2023)
  - → 3D wind onset models could help
  - → see next talks

Deep launching as a solution to the WR radius problem



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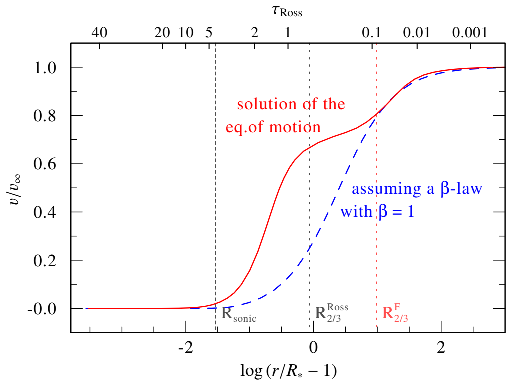


Optically thick WR winds (valid for most, but not all WRs):

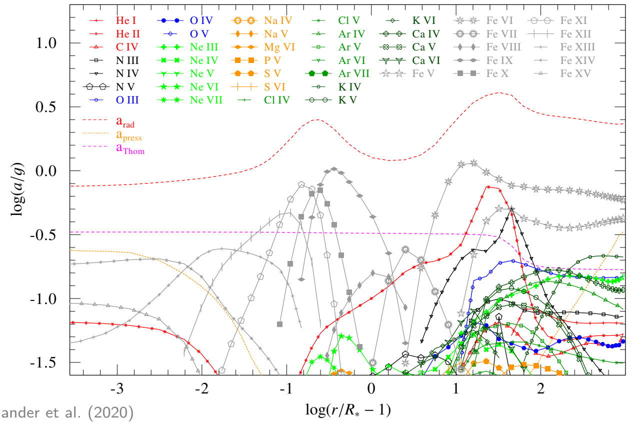
Even the continuum is produced in expanding layers with $v \gg v_{\rm sonic}$ (e.g. Gräfener & Hamann 2004, Sander et al. 2020)

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

Radiative driving: Wolf-Rayet winds

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 $\varkappa_F$



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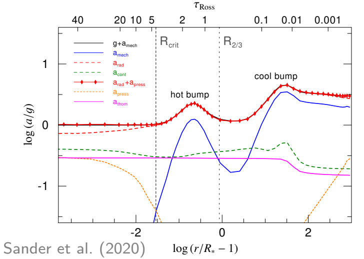

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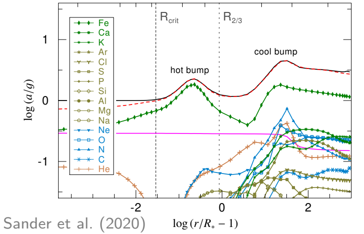
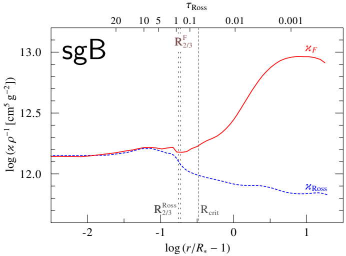
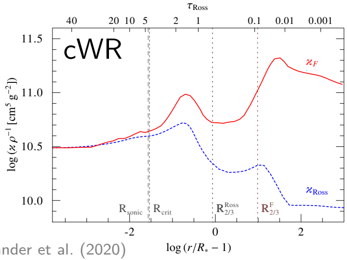


Sander et al. (2020)

Breakdown of the CAK description in WR winds





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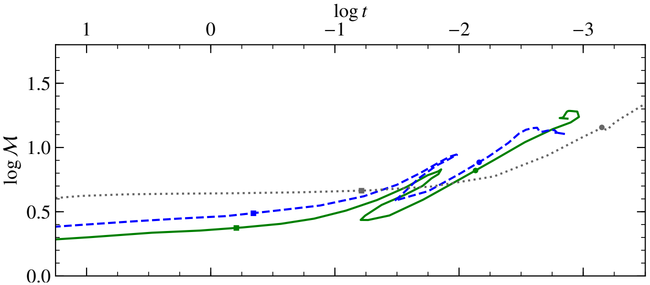


Sander et al. (2020)

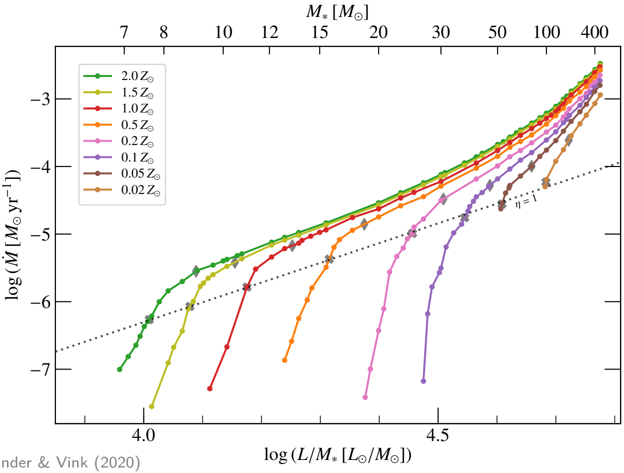
Failure of the CAK parametrization for cWR winds:

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

Predictions from dynamically-consistent models

PoWR$^{\mathrm{HD}}$ 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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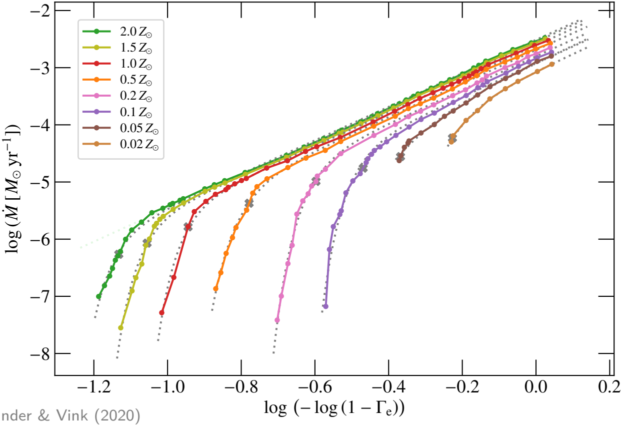
Model sequences yield two regimes with different trends:

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



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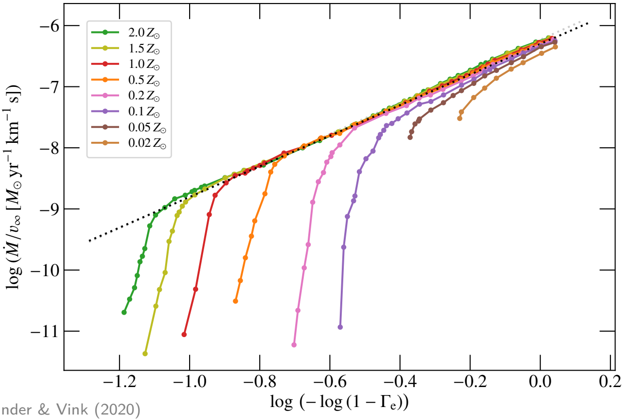

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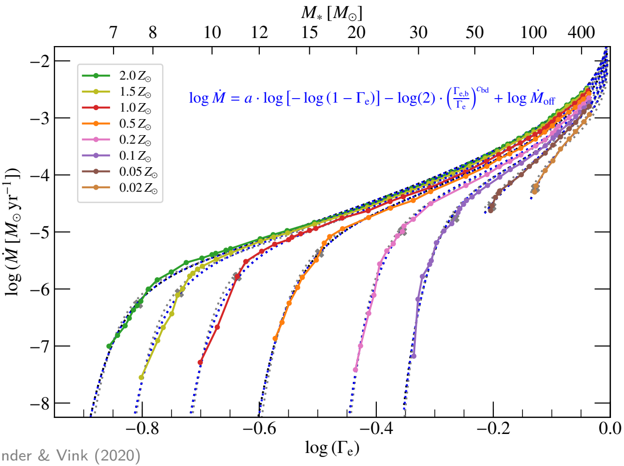
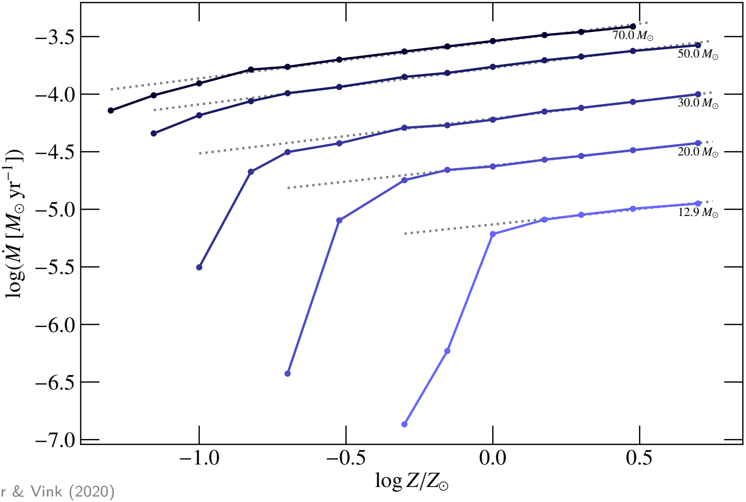


Sander & Vink (2020)

Metallicity-dependent breakdown of WR-type mass loss



Sander & Vink (2020)

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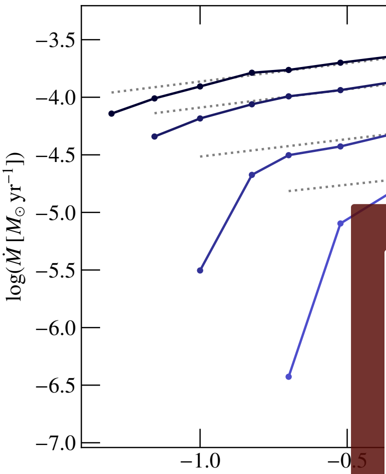
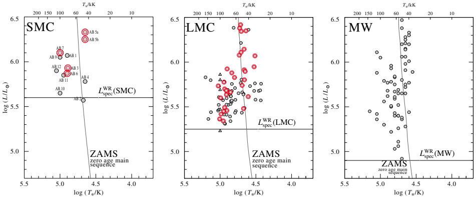


Sander & Vink (2020)

Different breakdown for different masses:

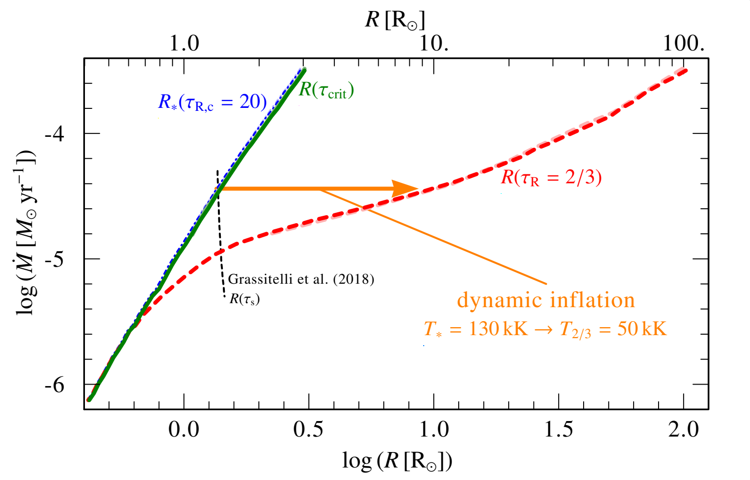


Shenar et al. (2020)

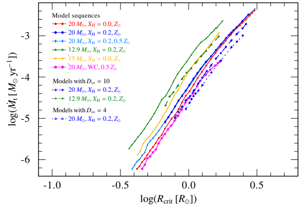
⇒ (qualitatively) in line with observations

Radius/Temperature-dependency of Wolf-Rayet winds

Extended atmospheres → radius-dependency study in Sander et al. (2023)



$\dot{M} \propto R_{\mathrm{crit}}^3$



Sander et al. (2023)

⇒ can be treated as "correction" to Sander & Vink (2020)

Limits of deep wind launching

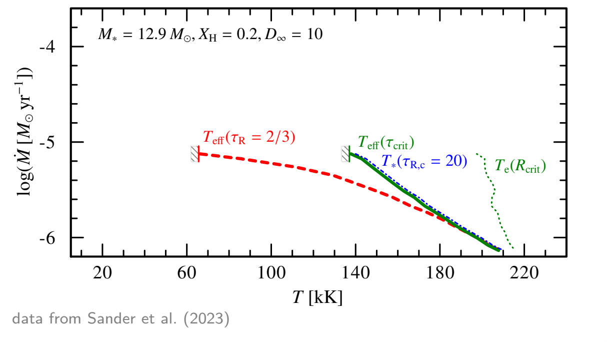
Can we explain all WR stars as compact stars with extended wind envelopes?

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

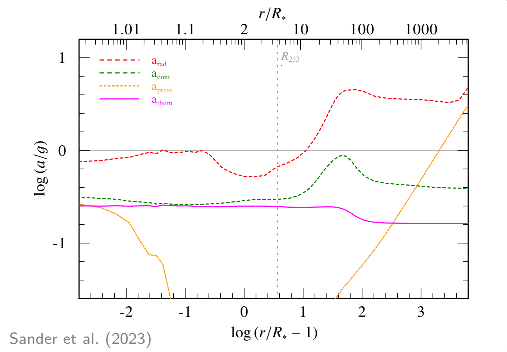
→ we obtain "hard boundaries" for wind launching from the hot iron bump

→ late WR subtypes should always have huge emission lines → not observed

⇒ there is probably also a regime with inflated *hydrostatic* radii



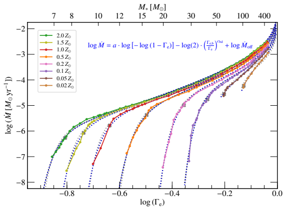
data from Sander et al. (2023)



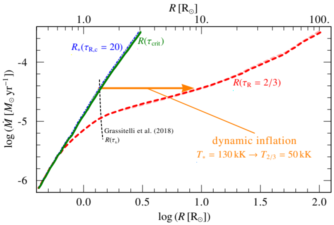
Sander et al. (2023)

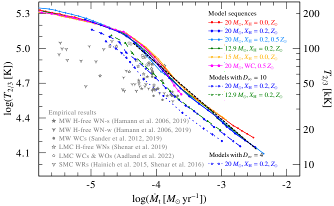
Wind driving and mass-loss rates of classical WR stars

HD atmosphere models enable pioneering theoretical insights on Wolf-Rayet winds:



Sander & Vink (2020)





Sander et al. (2023)

- cWR Winds are launched deep in the optically thick atmosphere (at $T_e \approx 200\,\mathrm{kK}$)
- cWR winds scale fundamentally different than OB star winds
- 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: $\dot{M} \propto R_\mathrm{crit}^3 \propto T_\mathrm{eff}(\tau_\mathrm{crit})^6$

The Ionizing Flux of hot, massive stars

Hot stars are not black bodies

- (non-LTE) opacities in the stellar atmosphere change the spectral shape
- strong "blanketing" effect by Fe line opacities

Number of photons beyond an ionization edge:

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

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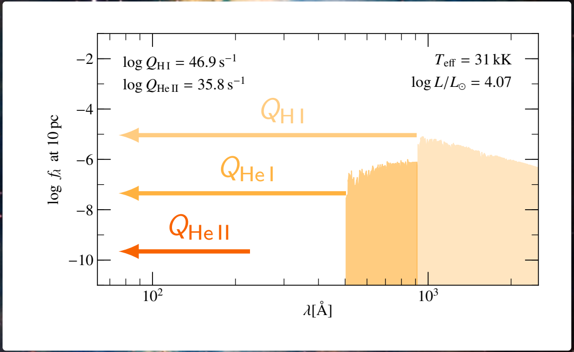

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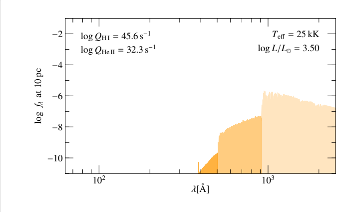
Most common:

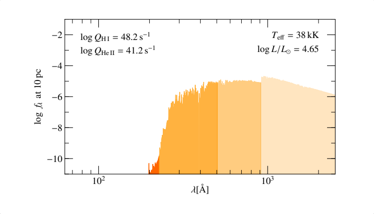
	$\lambda_{\rm edge}$	$\nu_{\rm edge}$
Q_0 aka $Q_{\rm H\,I}$	911.6 Å	13.6 eV
Q_1 aka $Q_{\rm He\,I}$	504.3 Å	24.6 eV
Q_2 aka $Q_{\rm He\,II}$	227.9 Å	54.4 eV

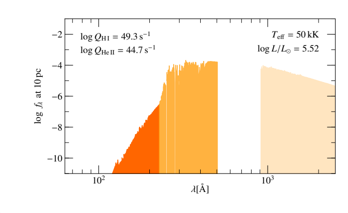
Hot Stars on the Main Sequence

Climbing up the main sequence:

- Gradual increase in $Q_{\mathrm{H\,I}}$ and $Q_{\mathrm{He\,I}}$ towards higher MS masses (and thus luminosities)
- Only the hottest, i.e. most massive MS stars contribute non-negligible $Q_{\mathrm{He\,II}}$







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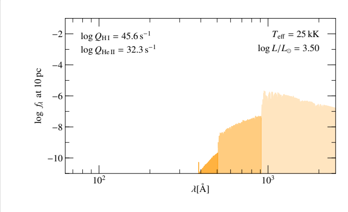

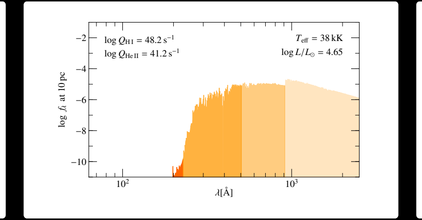

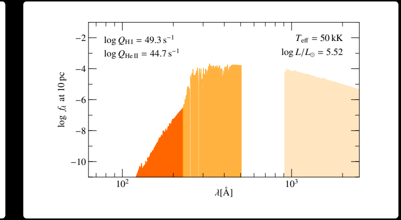

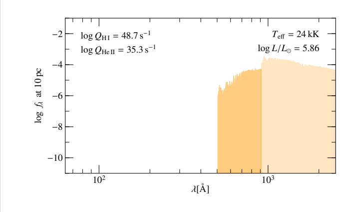

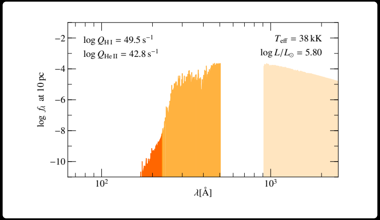

Evolved stars with $T_{\mathrm{eff}} \leq T_{\mathrm{ZAMS}}$:

$\rightarrow$ stars reach higher L
$\rightarrow$ more ionizing flux, but
T_{eff}-dependency dominates
$\rightarrow$ little contribution to $Q_{\mathrm{He\,II}}$

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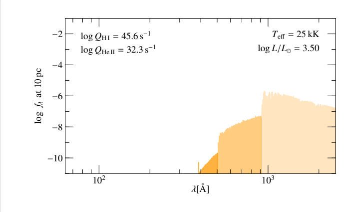

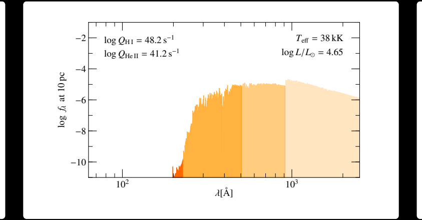

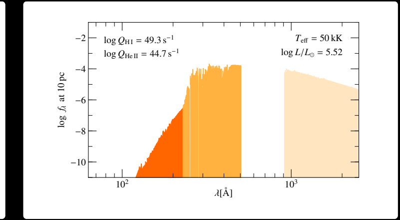

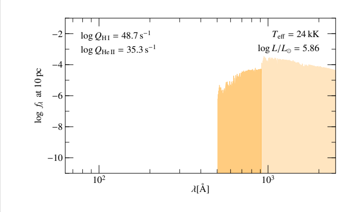

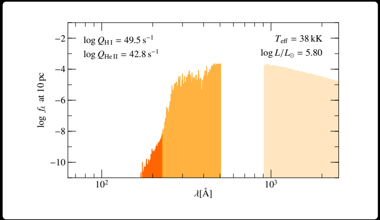

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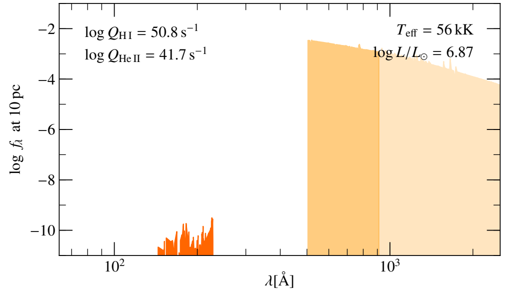
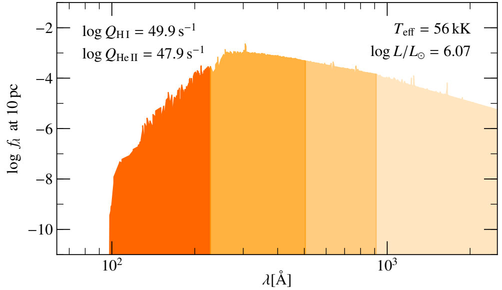
What about Wolf-Rayet stars?

Observations of WR stars with strong ionizing flux



Sander (2022)



Sander (2022)

Above: WN5h star in the LMC
→ too strong wind
→ insignificant $Q_{\mathrm{He\,II}}$

Right: WN3ha star in the SMC
→ huge source of He II ionizing flux

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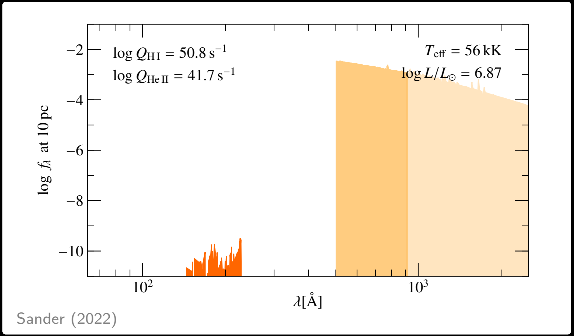

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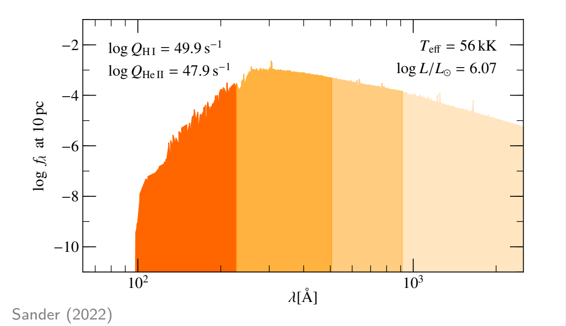

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→ too strong wind
→ insignificant $Q_{\mathrm{He\,II}}$

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→ huge source of He II ionizing flux

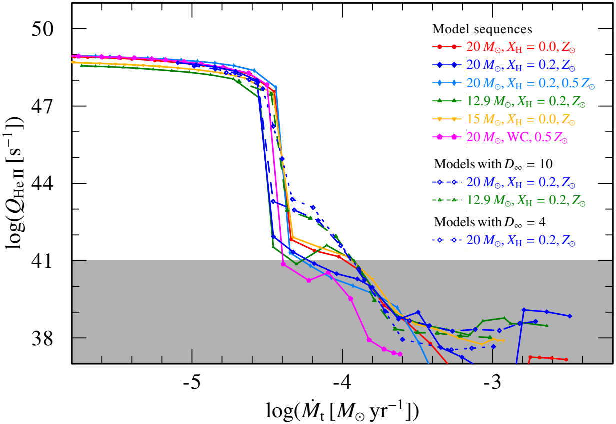
Generally: Earlier spectral types at lower Z

But: $Q_{\mathrm{He\,II}}$ not obvious from optical spectrum
→ UV spectroscopy required

⇒ Oncoming approved HST observations for more systematic study and quantification

Wolf-Rayet stars and He II ionizing flux

Theoretical study using dynamically-consistent atmosphere models for cWR stars:
Characteristic “transformed mass-loss rate” $\dot{M}_\mathrm{t}$ for regime that yields He II ionizing flux



Sander et al. (2023)

Summary: Studying massive star winds with atmosphere models

Expanding atmosphere models are a fundamental astrophysical tool:

- for O and WR stars: only way to determine fundamental parameters
- inclusion of proper wind treatment essential to get correct results
- frequent usage so far only in 1D, stationary models (but with full non-LTE)

Wind insights from dynamically-consistent models (PoWR$^{\mathrm{HD}}$ and others)

- Coupling of detailed radiative transfer and hydrodynamics

$\Rightarrow$ high computational cost → non-standard technique (for now)

$\Rightarrow$ ongoing development efforts necessary (e.g., insights from 3D)

- OB regime: tendency towards lower, but non-negligible mass-loss rates
- cWR regime: dynamically inflated atmospheres, new scalings and trends
- lots of open questions for other regimes → ongoing efforts
- high-dimensional problem → observational constraints crucial