Escape of Lyman radiation from galactic labyrinths 2023
OAC, Kolymbari, Crete
Apr 18th, 2023

Do we know the start of the labyrinth?

The challenge of determining ionizing fluxes from massive stars

Andreas A.C. Sander

Emmy Noether Research Group Leader
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Group Members: V. Ramachandran, R.R. Lefever, M. Bernini-Peron, C.J.K. Larkin, E.C. Schösser

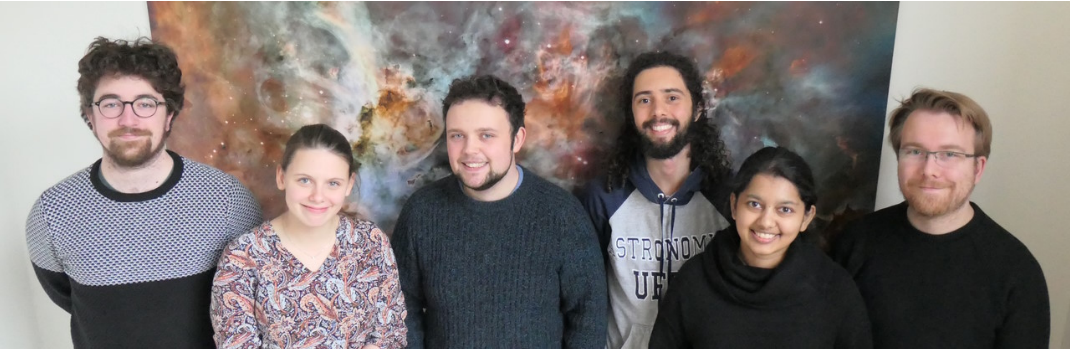
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

ZENTRUM FÜR ASTRONOMIE

UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

Heidelberg Hot Star Atmosphere Group

Emmy Noether Group on stellar atmospheres and mass loss of hot stars



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PhD Student

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Matheus Bernini Peron
PhD Student

Varsha Ramachandran
Postdoc

Andreas Sander
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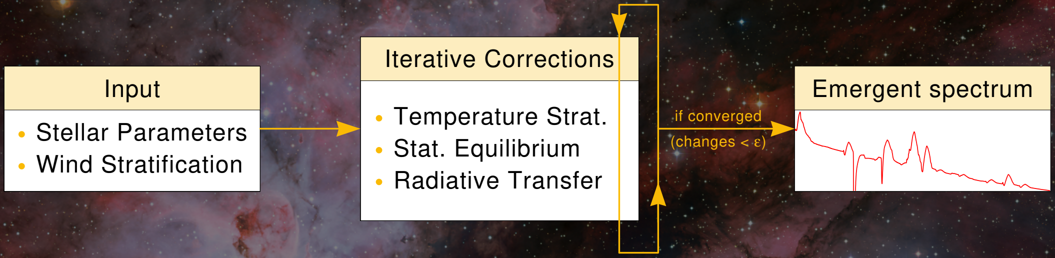
Application and development of stellar atmospheres

Schematic overview of stellar atmosphere calculations:



Input
- Stellar Parameters
- Wind Stratification

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

if converged
(changes < ε)

Emergent spectrum

Application and development of stellar atmospheres

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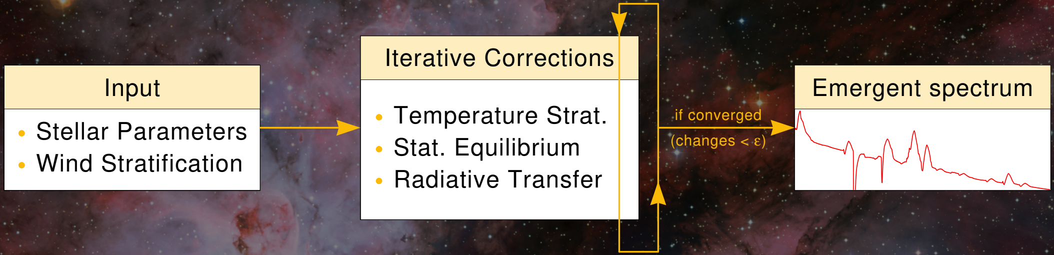

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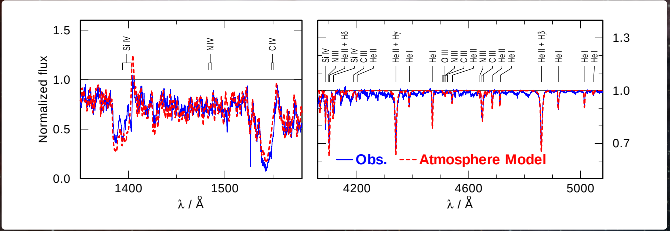

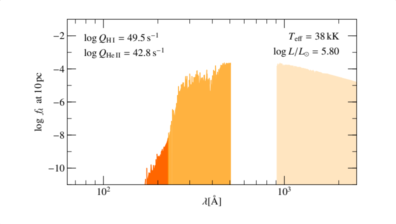

Approximated and self-consistent hydrodynamics

Problem: Atmosphere models commonly
assume stellar winds parameters

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:

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

Approximated and self-consistent hydrodynamics

Problem: Atmosphere models commonly
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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
  - ↪ we observe/measure winds but we do not understand them

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Solution: Consistent hydrodynamical treatment

Use radiative acceleration a_{rad} from detailed radiative transfer

$$a_{\mathrm{rad}}(r) = \frac{1}{c}\int_0^\infty \varkappa_\nu(r) F_\nu(r)\,\mathrm{d}\nu$$

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Consistent wind stratification:

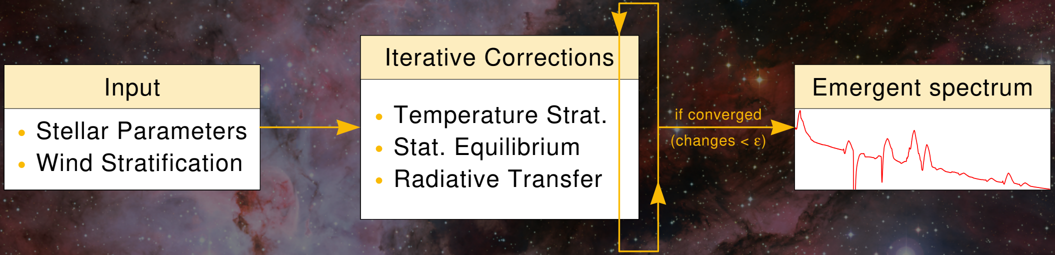
$$\rho(r), v(r), \dot{M}$$

Hydrodynamics:

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

Hot star atmosphere models with dynamical consistency

Inclusion of stationary hydrodynamics yields a new generation of stellar atmospheres:



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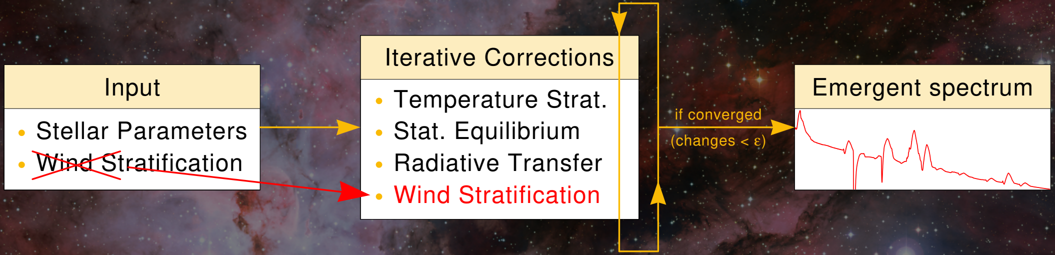

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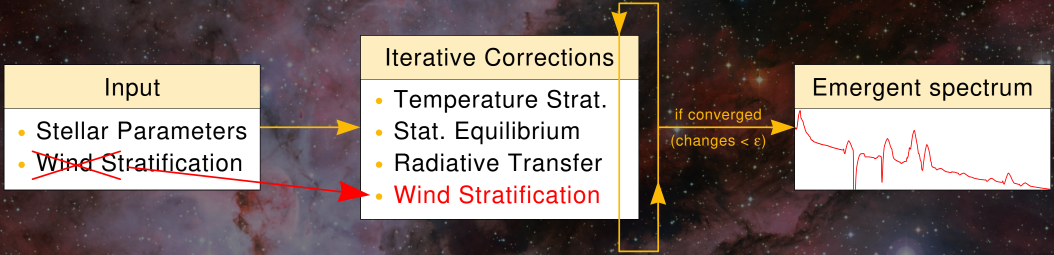

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- Wind velocity field $v(r)$ is output instead of input

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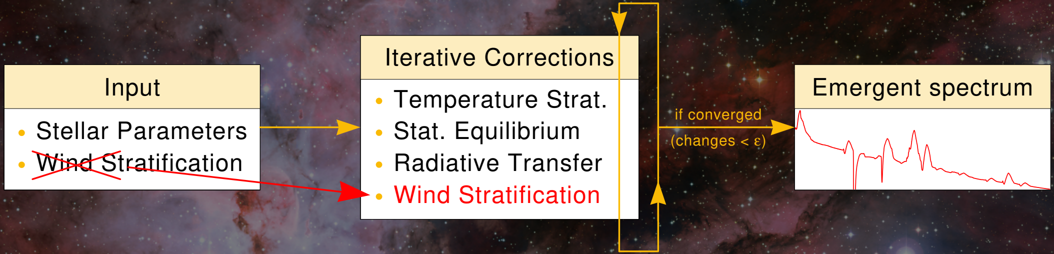

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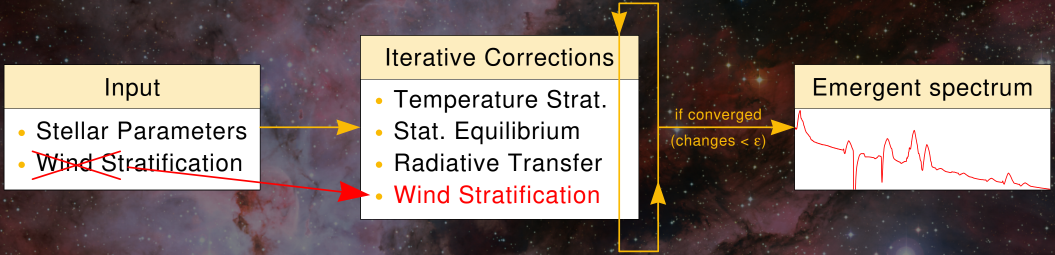

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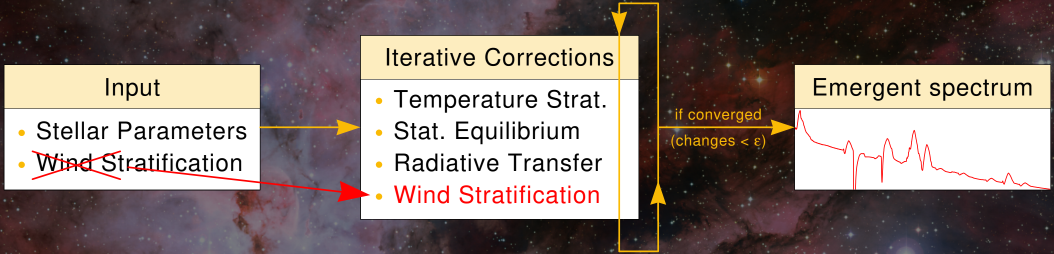

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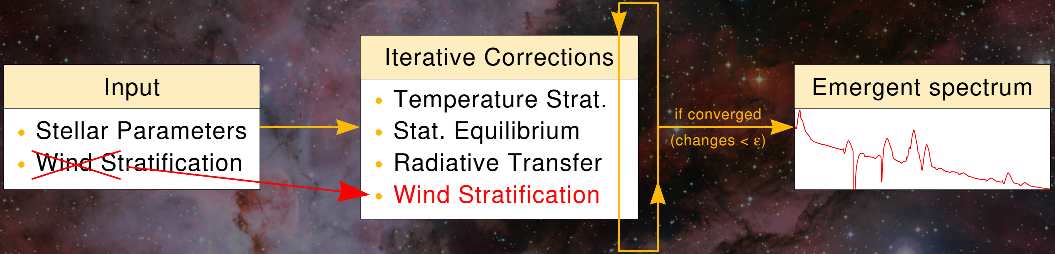

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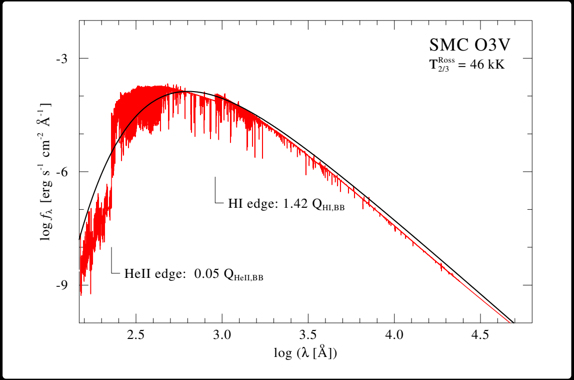
- Additional iteration layer due to update of wind density profile
- Requires detailed atomic data, even if not relevant for the spectrum

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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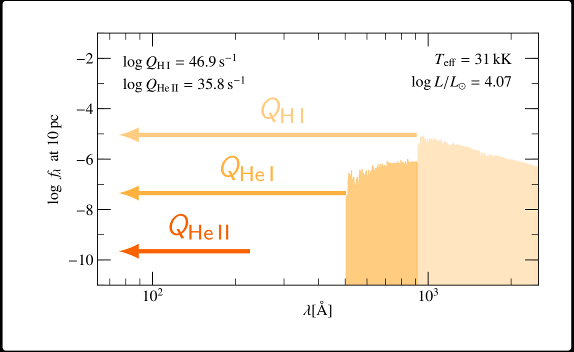

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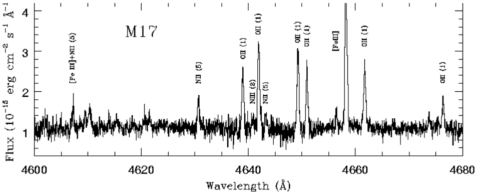
Most common:

	$\lambda_{\rm edge}$	$\nu_{\rm edge}$
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

Obtaining ionizing fluxes

Usually we have no direct observational access to the extreme UV:
How do we know anything about ionizing fluxes?

Measuring nebular emission lines:



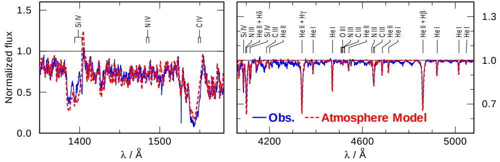
García-Rojas et al. (2007)

Strategy:

→ measure or model emission lines, e.g., Hα

→ infer ionizing flux (for Hα: $Q_{\text{H I}}$)

Stellar atmosphere models:



Data from Shenar et al. (2015)

Strategy:

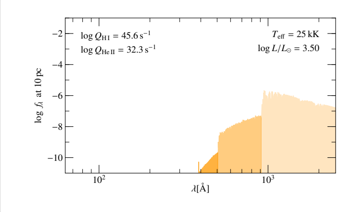
→ reproduce observations in UV/opt/IR

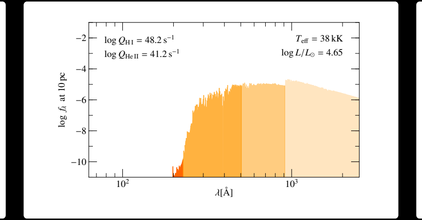
→ infer (E)UV properties from the model

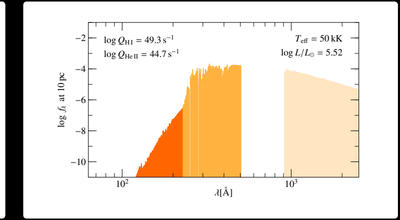
Hot Stars on the Main Sequence

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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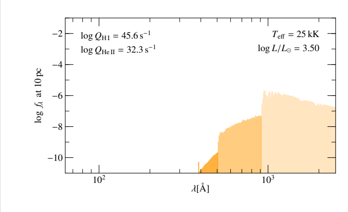
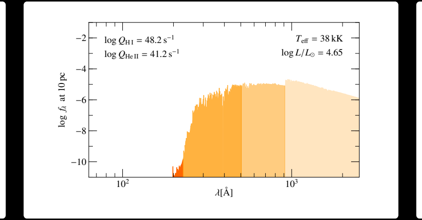
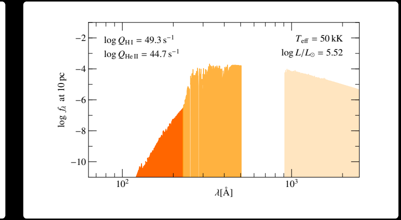
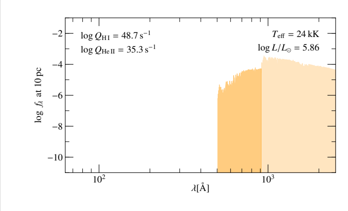
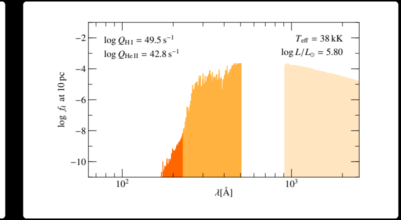










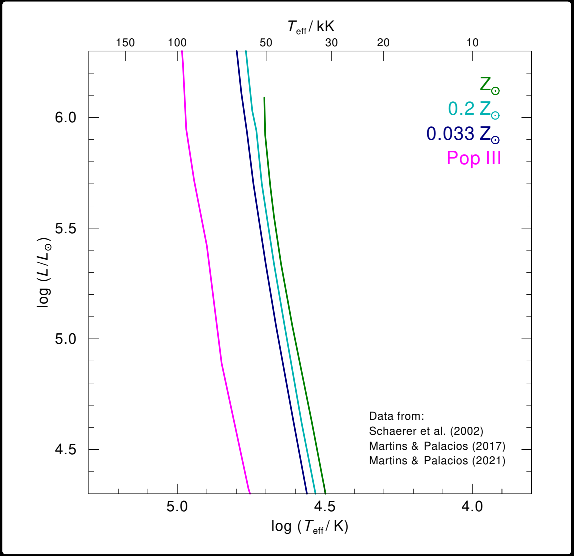
Evolved stars with $T_{\mathrm{eff}} \leq T_{\mathrm{ZAMS}}$:

→ stars reach higher L

→ more ionizing flux, but
T_{eff}-dependency dominates

→ little contribution to $Q_{\mathrm{He\,II}}$

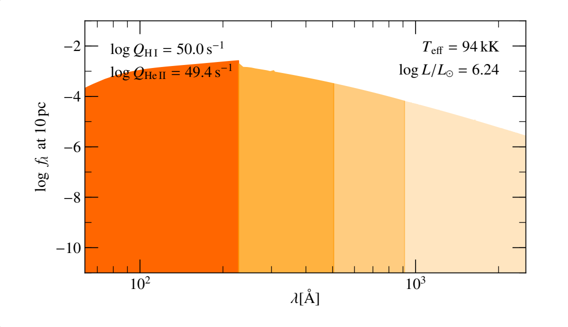
Population III Stars



Data from:
Schaerer et al. (2002)
Martins & Palacios (2017)
Martins & Palacios (2021)

Lower metallicity:
ZAMS moves to higher temperatures

Significant for Pop III ($Z = 0$) stars



→ example for $M_{\rm ini} = 120\,M_\odot$ (Schaerer et al. 2002)
→ see also Tumlinson & Shull (2000)

Post-MS stars

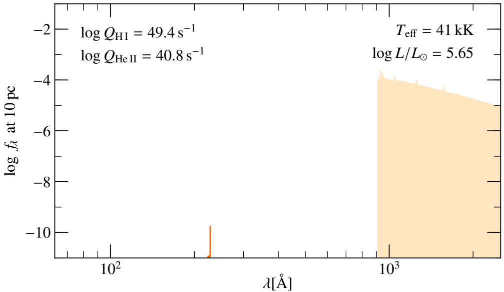
Hot stars left of the main sequence:
Evolved stars that have lost (part of) their hydrogen envelope

(either by self-stripping or via a companion)

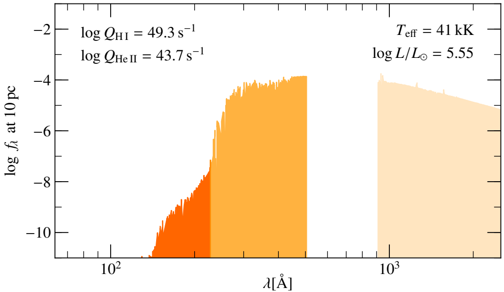
Example: AzV 476 – the earliest ecplising O-type binary in the SMC (O4 IV-III + O9 V)

(Detailed spectroscopic analysis by Pauli et al. 2022)

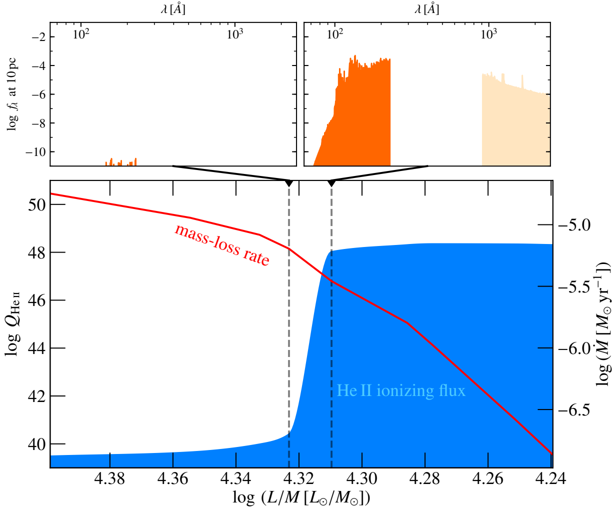
Analysis of the Primary:



Prediction based on binary evol. model:



He II ionizing flux depends on stellar winds



Sander et al. (in prep.)

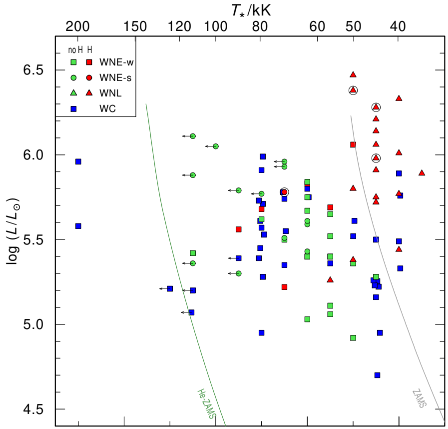
He II ionizing photons can be consumed to drive (strong) stellar winds

- → Dense wind: He recombination
  ↪ opaque to He^+ photons
- → typically in sgO and WR stars
- → Dynamically-consistent atmosphere calculations reveal abrupt transition
- → Origin of observed nebular He II in low metallicity galaxies?

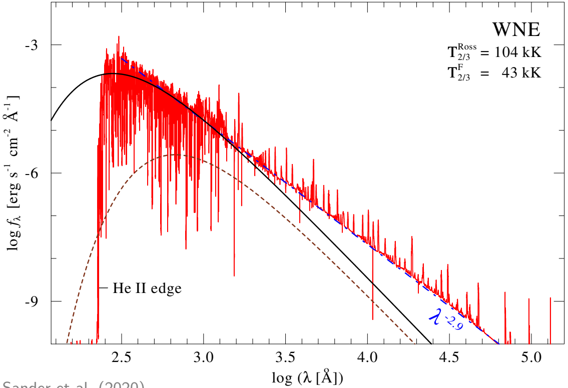
Caution: Absolute numbers depend on the stellar temperatures (models here: $T_* = \text{const.}$)

Classical Wolf-Rayet stars

Classical WR stars: Helium-burning stars with little to no hydrogen
↪ high temperatures → good sources of ionizing feedback?



Hamann et al. (2019)

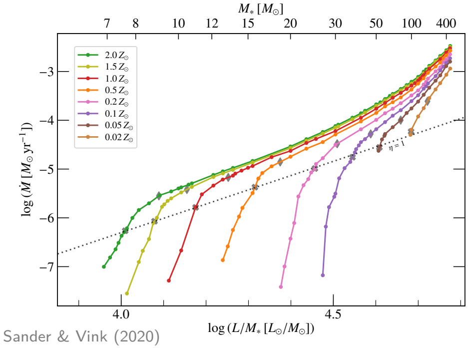


Sander et al. (2020)

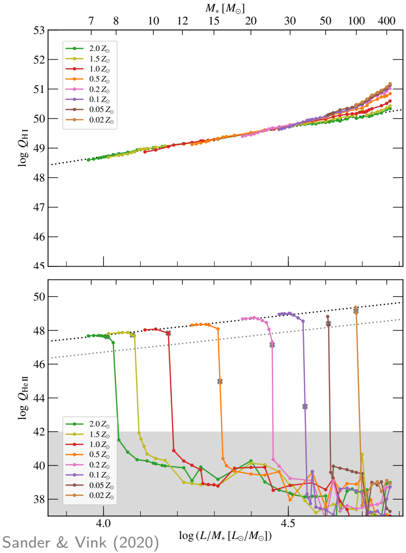
Problem: Winds are often too dense → no $Q_{\rm He\,II}$
(see also Smith et al. 2002, Crowther & Hadfield 2006)

The winds of He-burning stars

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



Sander & Vink (2020)



Sander & Vink (2020)

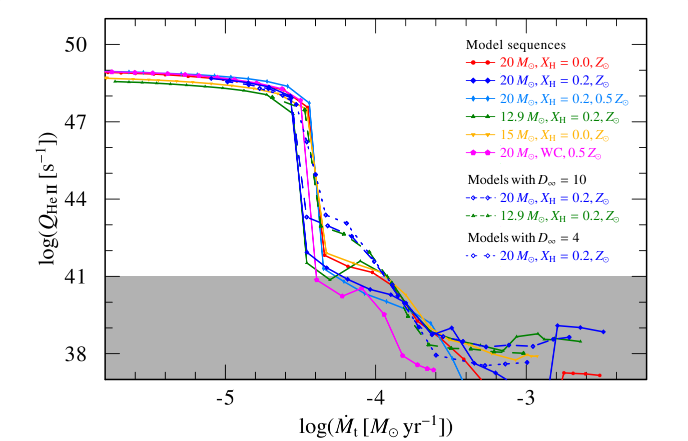
Predictions for $\dot{M}_{\mathrm{WR}}$ from HD modelling:

- → steep decline of $\dot{M}_{\mathrm{WR}}$ when winds get optically thin
- → $Q_{\mathrm{H\,I}}$ mostly independent of wind strength ($\dot{M}$, Z)
- → Below transition: huge sources of He II ionizing flux

Helium stars as sources of He II ionizing flux

WR-type mass loss is radius/temperature-dependent:

characteristic "transformed mass-loss rate" for regime that yields He II ionizing flux



Sander et al. (2023)

Empirical ionizing flux determinations for WR stars

low-Z example:

SMC WN stars

weak-winded,
early-type stars
=
strong $Q_{\mathrm{He\,II}}$
emitters

WRs at higher Z can also be strong emitters, e.g.:

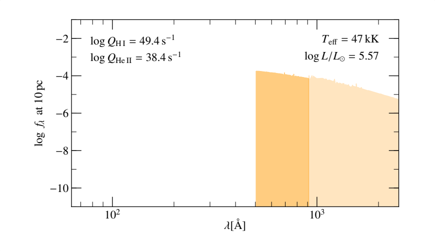
→ WN3ha (or WN3/O3)

→ WO stars

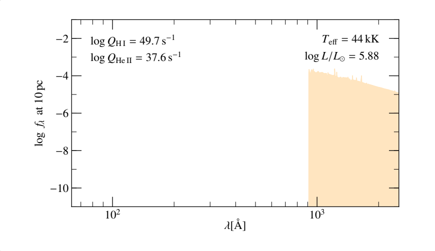
In contrast: No $Q_{\mathrm{He\,II}}$ from any known WC star

(Models: Hainich et al. 2015)

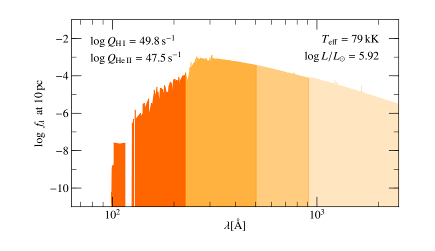
SMC AB 2 (WN5ha)



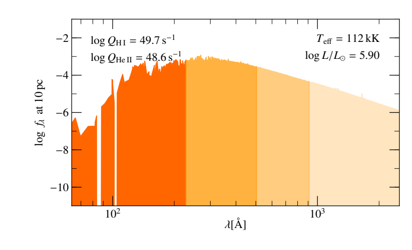
SMC AB 4 (WN6h)



SMC AB 1 (WN3ha)

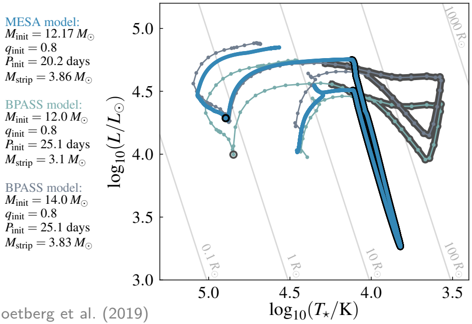


SMC AB 12 (WN3ha)

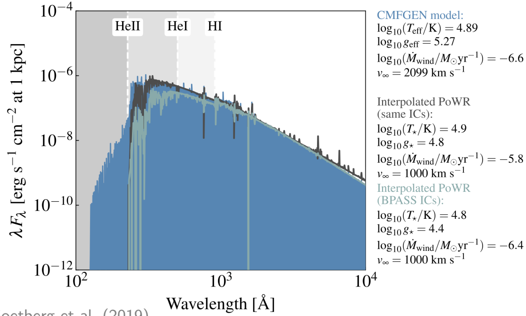


Non-WR hydrogen-stripped stars

Hot, hydrogen-stripped stars → predicted in large numbers by binary evolution



Goetberg et al. (2019)



Goetberg et al. (2019)

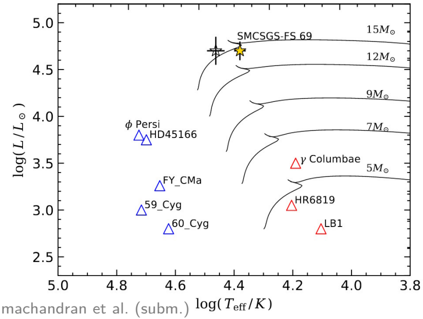
→ current searches find only every few stars

→ maybe no WR-type spectral signatures?

→ evolution models usually treat them as WR stars

→ significant contribution to $Q_{\rm He\,II}$?

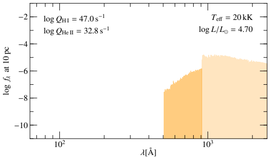
Non-WR hydrogen-stripped stars



Ramachandran et al. (subm.)

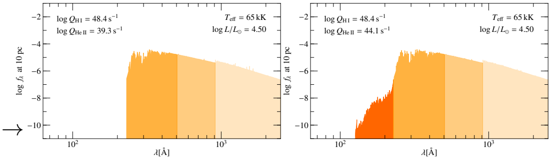
So far: Partially stripped stars found, not sitting on He ZAMS → observational hunt still on

- → mass-loss rates for stripped stars need UV
- → contribution to $Q_{\rm He\,II}$ highly uncertain

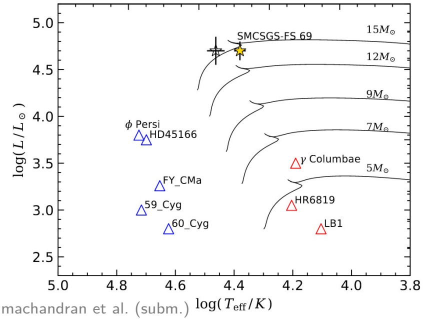


← observed

predicted →



Non-WR hydrogen-stripped stars



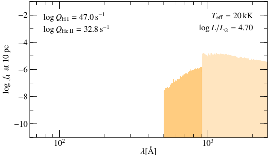
Ramachandran et al. (subm.)

So far: Partially stripped stars found, not sitting on He ZAMS → observational hunt still on

→ mass-loss rates for stripped stars need UV

→ contribution to $Q_{\text{He II}}$ highly uncertain

Open question:
Does binary evolution (e.g. mass transfer, winds) work different than we think?



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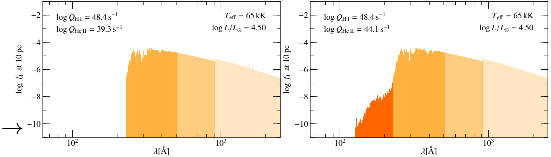
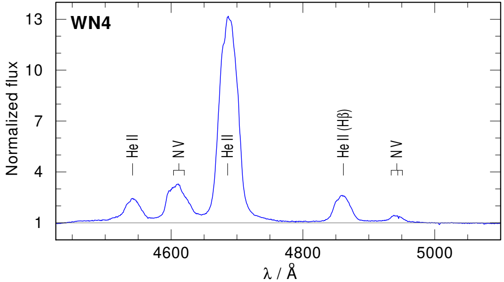
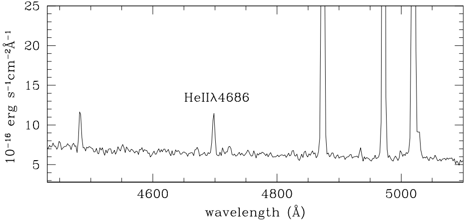


He II emission as a tracer of He II ionizing flux

Broad He II emission:



Narrow He II emission:



Kehrig et al. (2015)

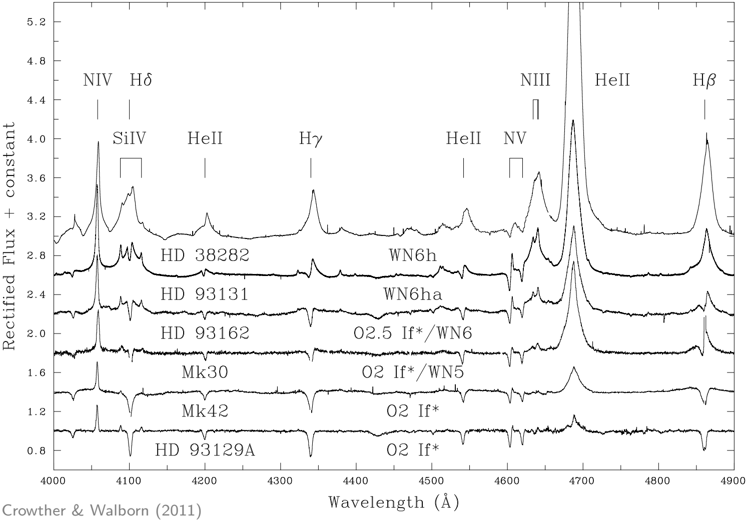
Highly energetic ionizing flux above 54 eV ($Q_{\text{He II}}$) can be traced by *nebular* He II emission, in particular He II 1640 Å (UV) and He II 4686 Å (opt)

Contrary, hot stars with dense winds show *broad* He II lines

→ usually either broad or narrow He II in unresolved populations

→ stellar emission lines usually broader than nebular lines

Spectral morphology of hot Stars



Crowther & Walborn (2011)

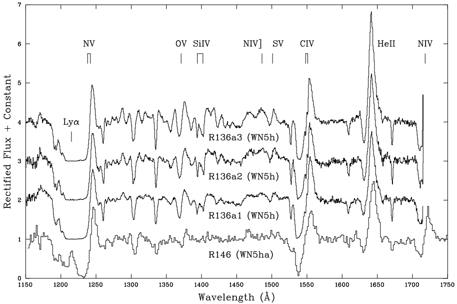
high-mass end of the main sequence ($\Gamma_e \to 1$):
Of → Of/WNh → WNh

Very Massive Stars:

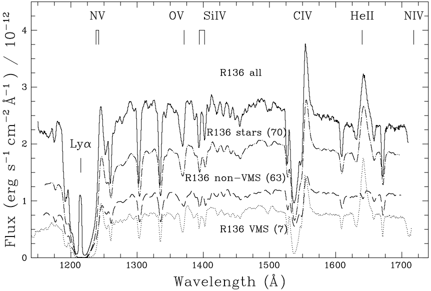
- $M_{\mathrm{ini}} > 100\,M_\odot$
- H-burning, WNh-type
- Observed so far at $Z \geq Z_{\mathrm{LMC}}$
- How do they look at lower Z?
- Contribution to $Q_{\mathrm{H\,I}}$ and $Q_{\mathrm{He\,II}}$?

Very Massive Stars: Observations

Best studied observations of VMS: R136 cluster in the LMC



Crowther et al. (2016)



Crowther et al. (2016)

VMS create *broad* He II 1640 in young clusters that could not yet form classical WR stars

Very Massive Stars: Observations

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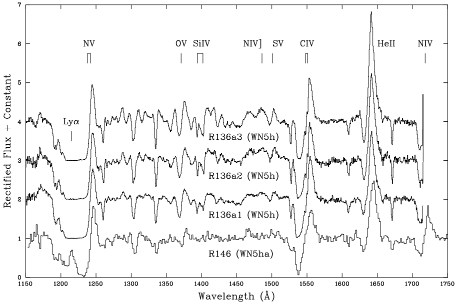
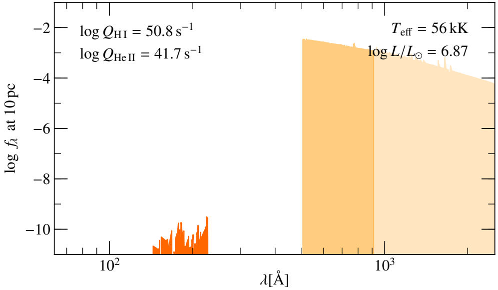


Crowther et al. (2016)

Inferred model SED for R136a1:



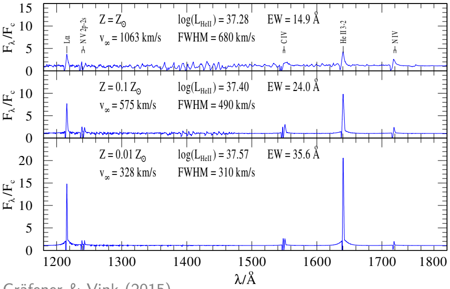
VMS create *broad* He II 1640 in young clusters that could not yet form classical WR stars

But: These VMS are not a (significant) He II ionizing source (despite being an enormous source of $Q_{\rm H\,I}$)

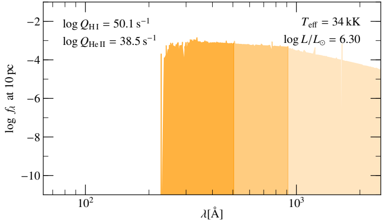
Very Massive Stars and He II emission

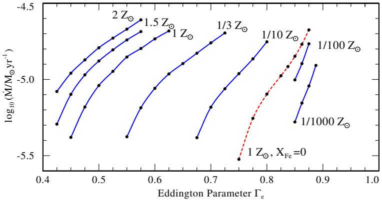
Very Massive Stars as potential sources of narrow He II emission

Stars very close to $\Gamma_e \to 1$ at $Z \ll Z_\odot$:
$\to$ high $\dot{M}$, but low v_∞
$\to$ narrow He II emission, but no $Q_{\text{He II}}$



Gräfener & Vink (2015)

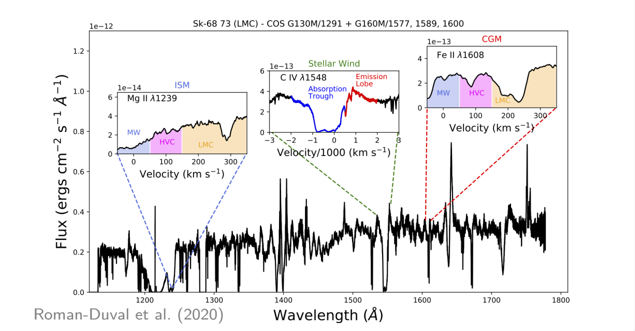




Gräfener & Hamann (2008)

Very high Γ_e required $\to$ realized in nature?

The ULLYSES legacy observations



Roman-Duval et al. (2020)

ULLYSES:

- ≈ 1000 HST DDT orbits (+ archival data)
- half of them devoted to ≈250 massive stars
- O, B, and WR stars in the LMC and SMC

+ a few OB stars in low-metal dwarfs

(NGC 3109, Sext A, archival: WLM, IC 1613, Leo P)

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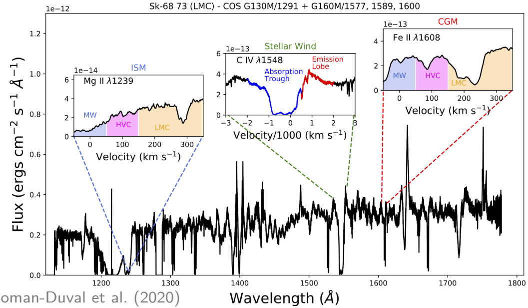

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Aim: Create a UV spectroscopic legacy library

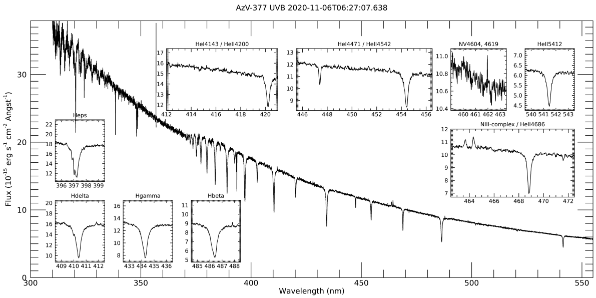
- Targets selected from atlas criteria
- Does not guarantee "prototypical" stars → spectral analyses necessary

The X-Shooting ULLYSES (XShootU) collaboration

Open collaboration:

Website: massivestars.org/xshootu

- Large ESO Programme (125.5 hrs, PI: J.S. Vink): XShooter spectra for all (original) ULLYSES targets
- necessary optical (+NIR) complement for obtaining robust stellar properties
- 13 working groups devoted to different scientific aspects



Sana et al. (in prep.)

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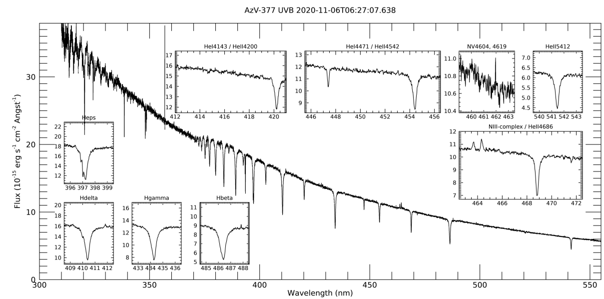
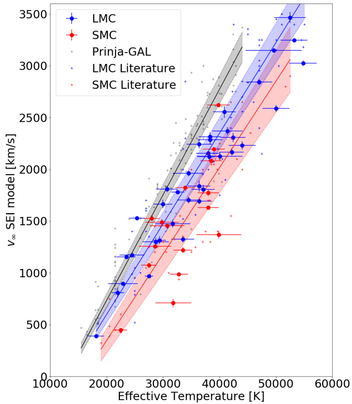


Sana et al. (in prep.)

- Sophisticated data reduction and distributed spectral analysis of (eventually) all targets
- Enables distinction of “prototypical” and “non-standard” (e.g., binary evolution) objects
- Analysis yields accurate ionizing fluxes (incl. $Q_{\mathrm{He\,II}}$)

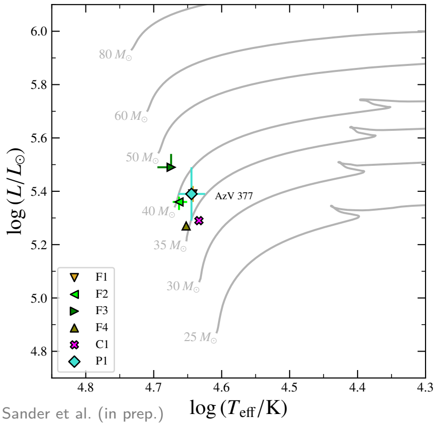
X-Shooting ULLYSES: first results

Determination of wind velocities from UV spectroscopy



Hawcroft et al. (2023)

Exemplary comparison of different atmosphere analysis codes and methods



Sander et al. (in prep.)

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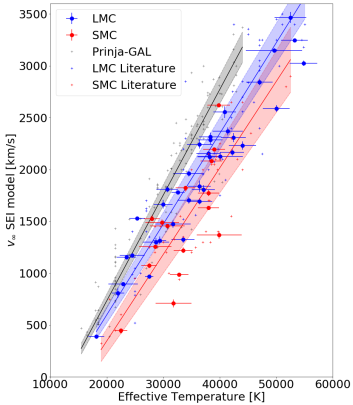

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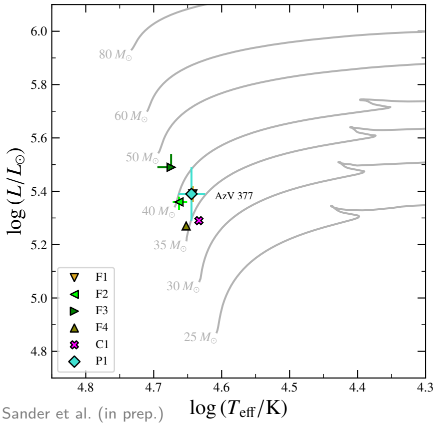

Sander et al. (in prep.)

$Q_{\text{H I}}$

F2: 49.14

C1: 49.25

P1: 49.08

$Q_{\text{He II}}$

F2: 43.79

C1: 44.08

P1: 43.38

→ no large discrepancies

Summary: Ionizing fluxes from massive stars

- Robust individual ionizing fluxes require quantitative spectroscopy
  - → Black bodies are insufficient to predict ionizing fluxes
  - → Spectra necessary to determine precise temperatures
  - → He II ionizing flux ($Q_{\mathrm{He\,II}}$) requires wind measurement
- Wolf-Rayet winds are occurring close to the (full) Eddington Limit
  - → at low Z: Higher L/M needed to reach WR-type mass loss
    - ↪ massive BHs easier to form already at $Z \approx 0.1\,Z_{\odot}$
  - → winds absorb $Q_{\mathrm{He\,II}}$, but WRs are huge sources of $Q_{\mathrm{H\,I}}$
- Stellar sources for $Q_{\mathrm{He\,II}}$ require high T_{eff} and thin winds
  - → most massive main sequences stars for $Z \rightarrow 0$
  - → classical Wolf-Rayet stars with weak winds (e.g. WN3ha, WO)
    - ↪ characteristic "transformed mass-loss rate": $\log \dot{M}_{\mathrm{t}} < -4.5$
  - → hot, hydrogen-depleted stars below the WR regime ("stripped stars")
    - ↪ rarely found yet, possibly different than typically assumed