Instituto de
Física y
Astronomía

Universidad
de Valparaíso
CHILE

Testing the wind luminosity relation with intensity interferometry of blue supergiants

Elisson Saldanha da Gama de Almeida

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Valparaíso, Chile

Stellar Intensity Interferometry 2024 Workshop, 12/09/2024, Porquerolles, France

NASA, JPL-Caltech, Spitzer Space Telescope

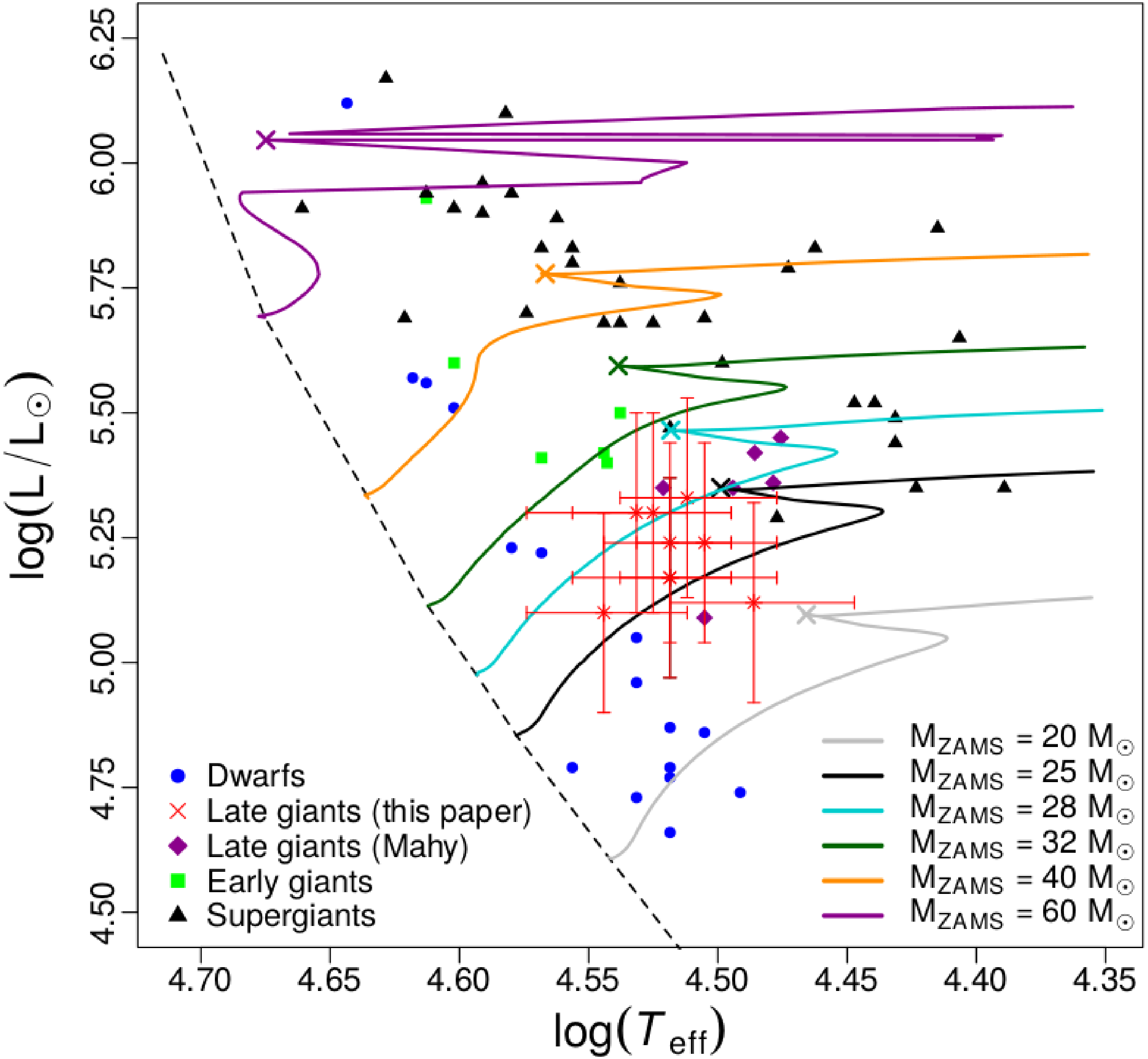
Wind momentum luminosity relation?

Introduction: massive stars and stellar winds in a nutshell

Wind momentum luminosity relation?

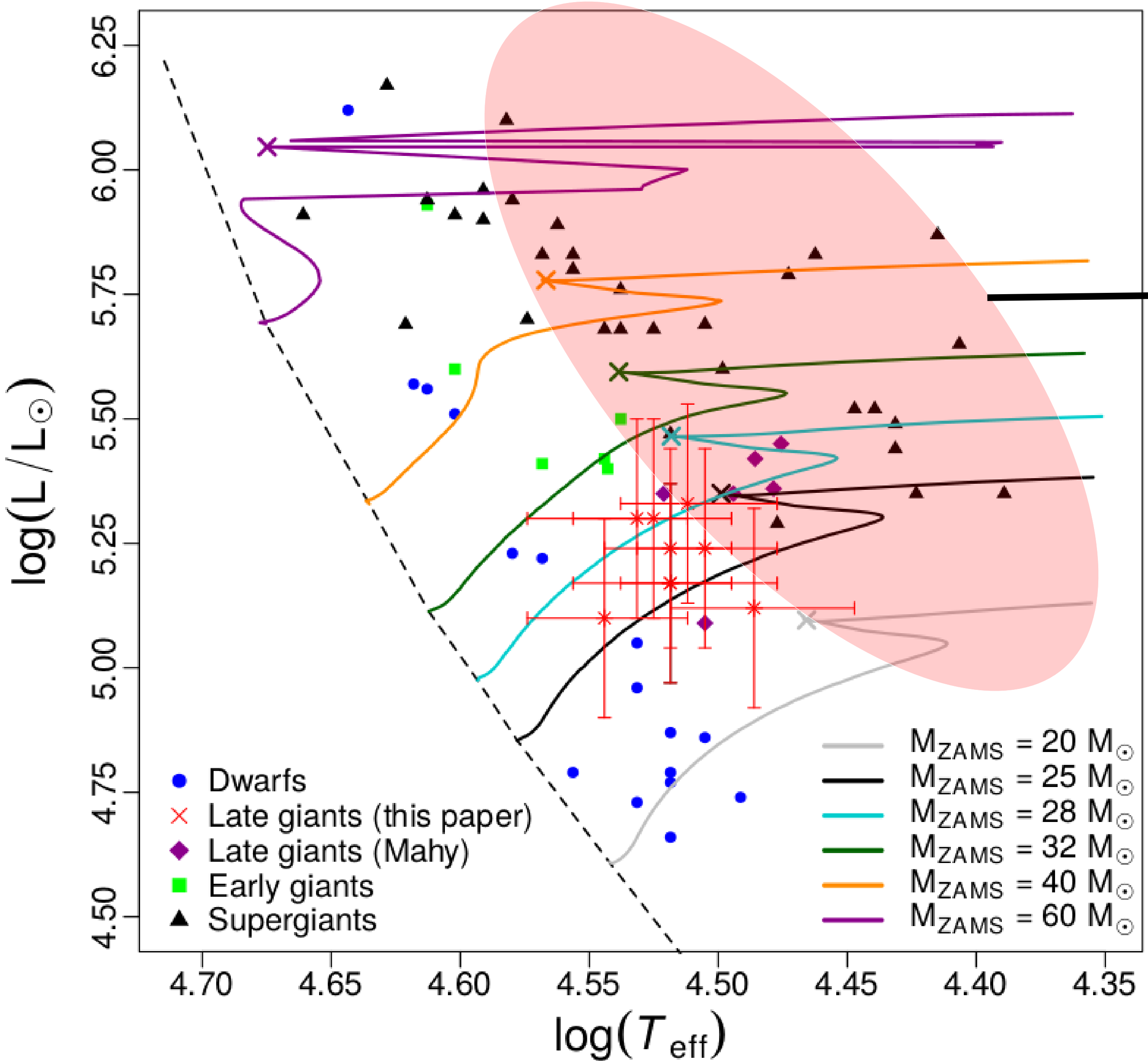
Massive stars and stellar winds!

Introduction: massive stars and stellar winds in a nutshell



de Almeida et al. (2019)

Introduction: massive stars and stellar winds in a nutshell



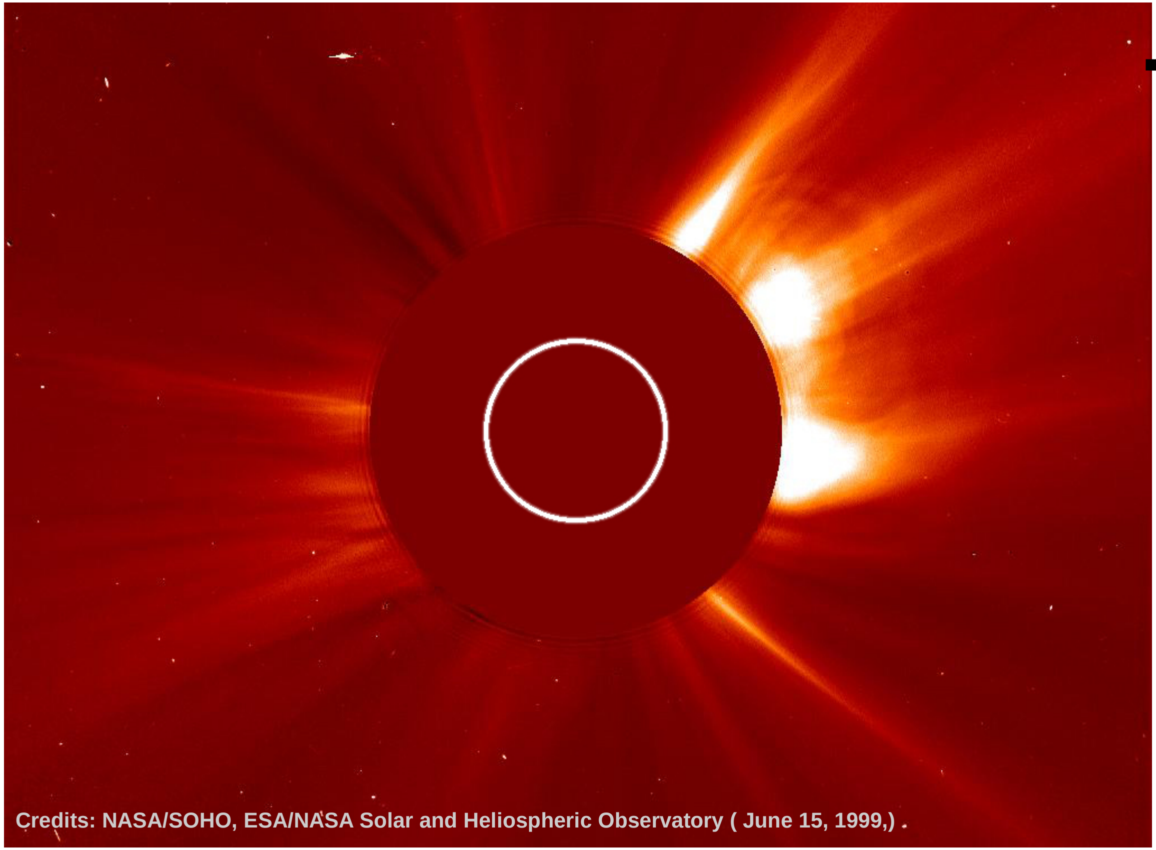
▲ OB supergiants
(blue supergiants):

post-main sequence
massive stars

de Almeida et al. (2019)

Introduction: massive stars and stellar winds in a nutshell

- **Stellar winds:** "**continous** emission of mass from the stellar photosphere"
- Virtually, **all stars** (at least in a certain evolutionary phase) have winds!
- The Sun (main sequence low-mass star) has a stellar wind, the solar wind...



Credits: NASA/SOHO, ESA/NASA Solar and Heliospheric Observatory (June 15, 1999,) .

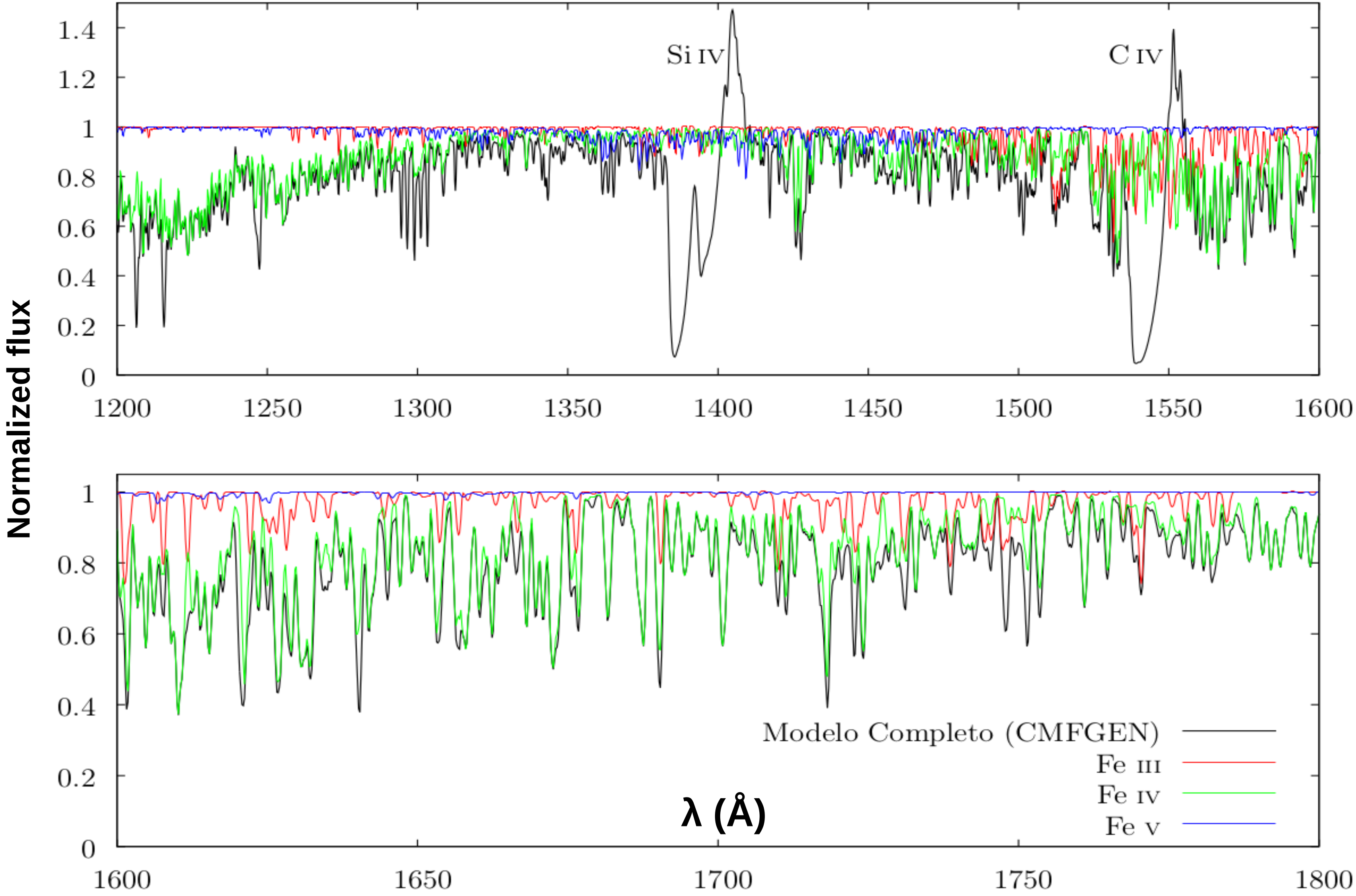
$$\dot{M} \sim 10^{-14}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

- Main sequence **O-type stars:**
  - Much **larger mass-loss rates!**

$$\boxed{\dot{M} \lesssim 10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}$$

Introduction: massive stars and stellar winds in a nutshell

- **Massive stars** have **radiative line-driven winds**:



Introduction: massive stars and stellar winds in a nutshell

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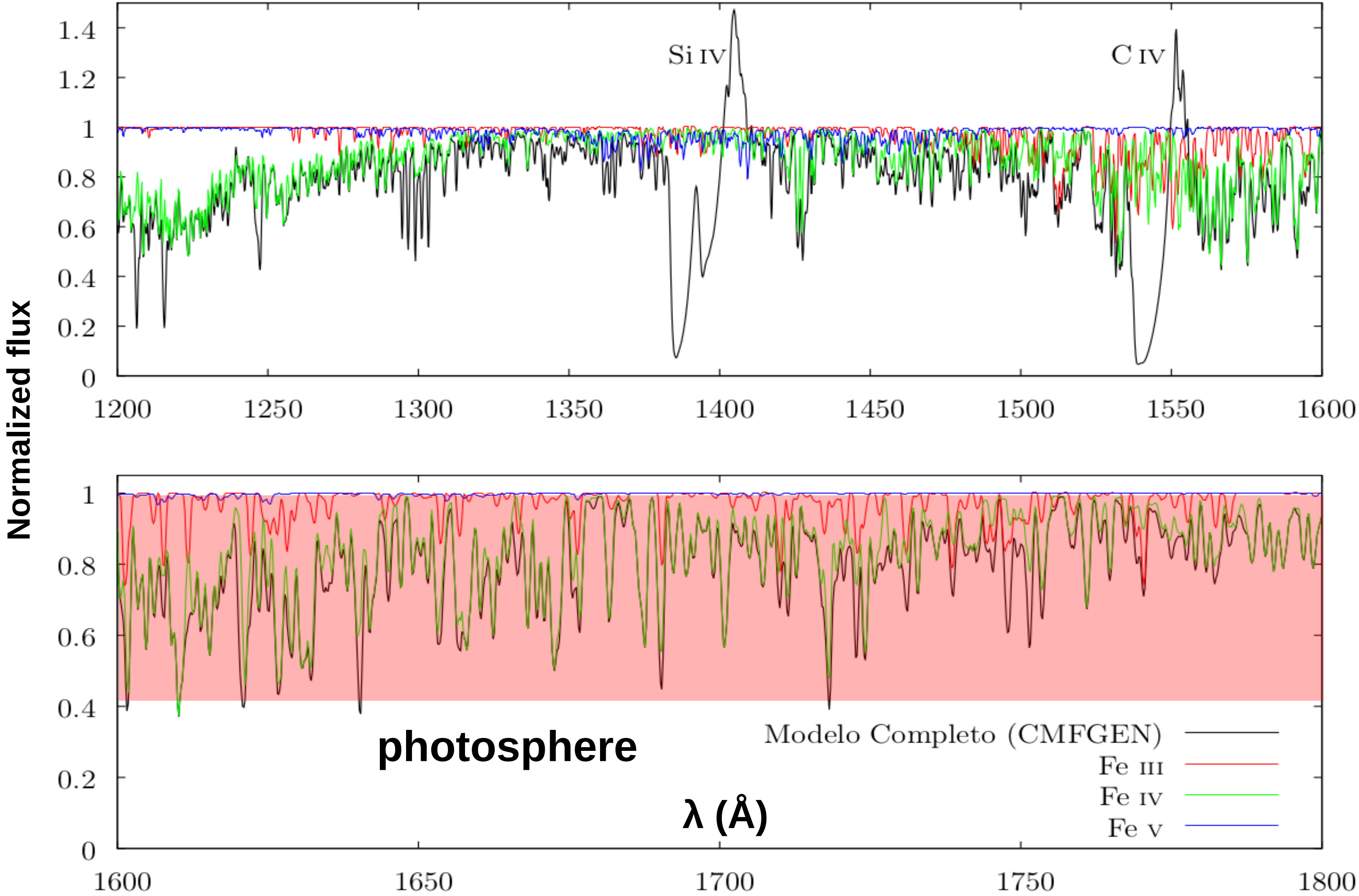

Introduction: massive stars and stellar winds in a nutshell

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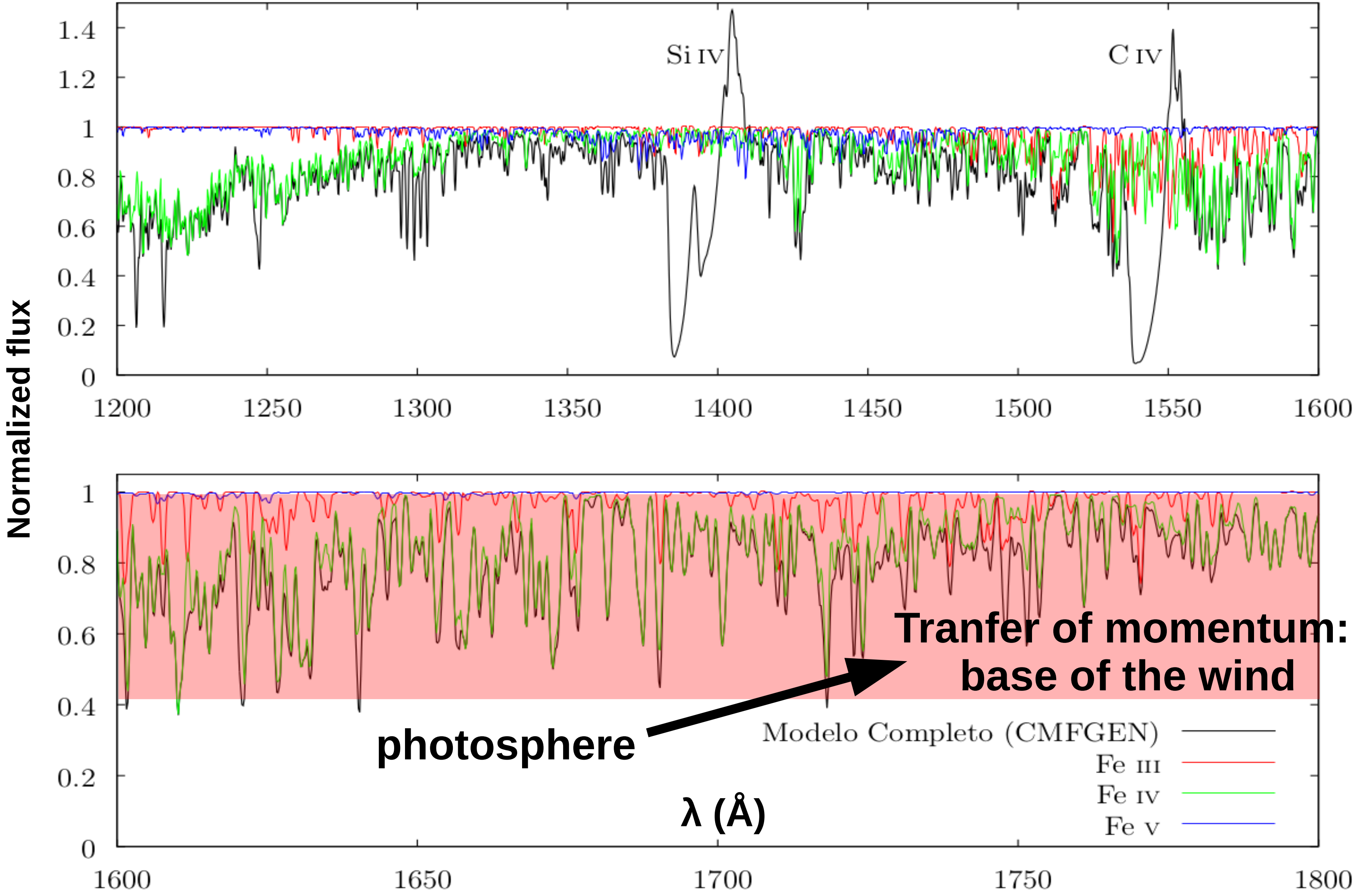

Tranfer of momentum: base of the wind

photosphere

Introduction: massive stars and stellar winds in a nutshell

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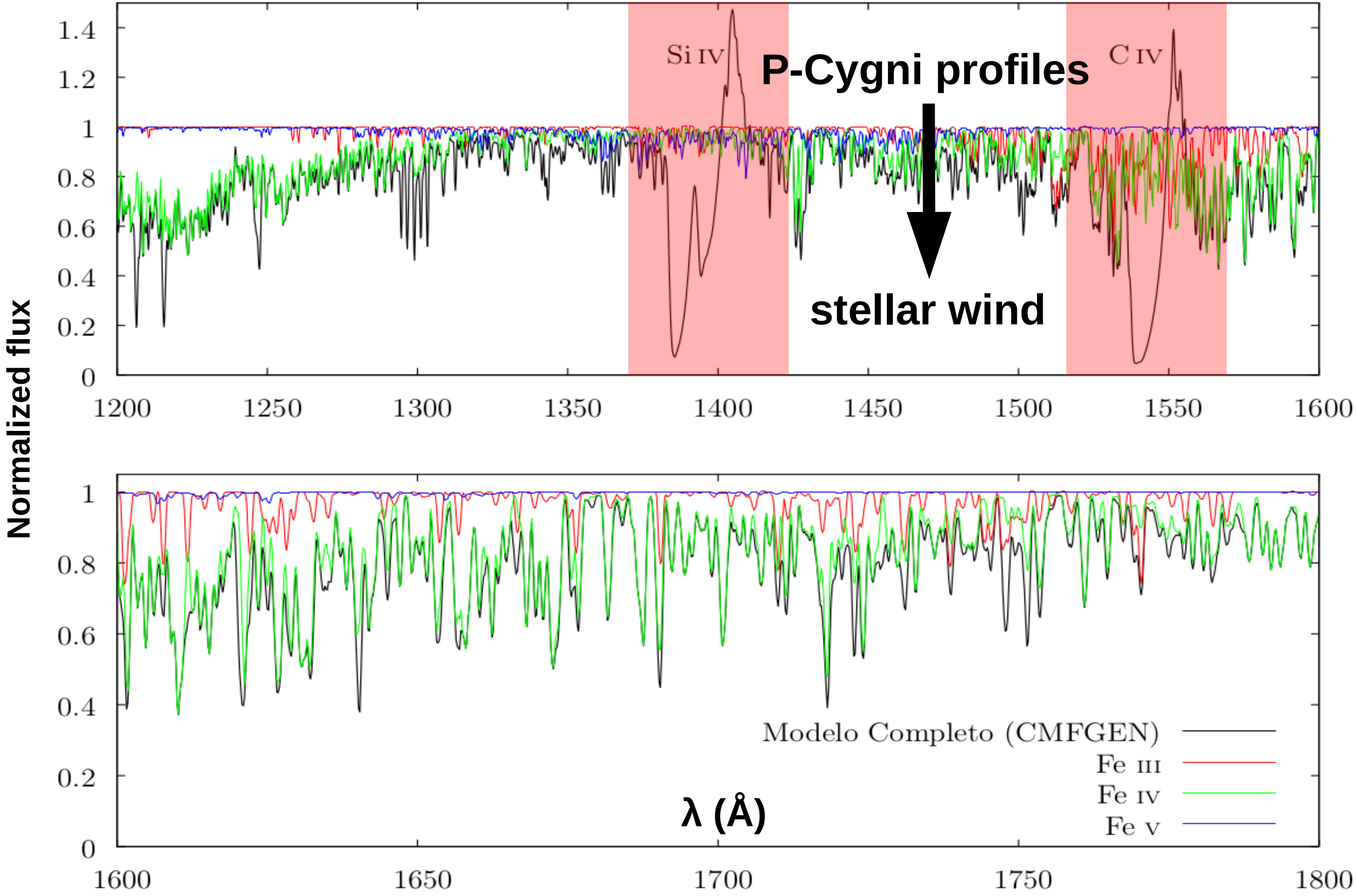

P-Cygni profiles

stellar wind

Introduction: massive stars and stellar winds in a nutshell

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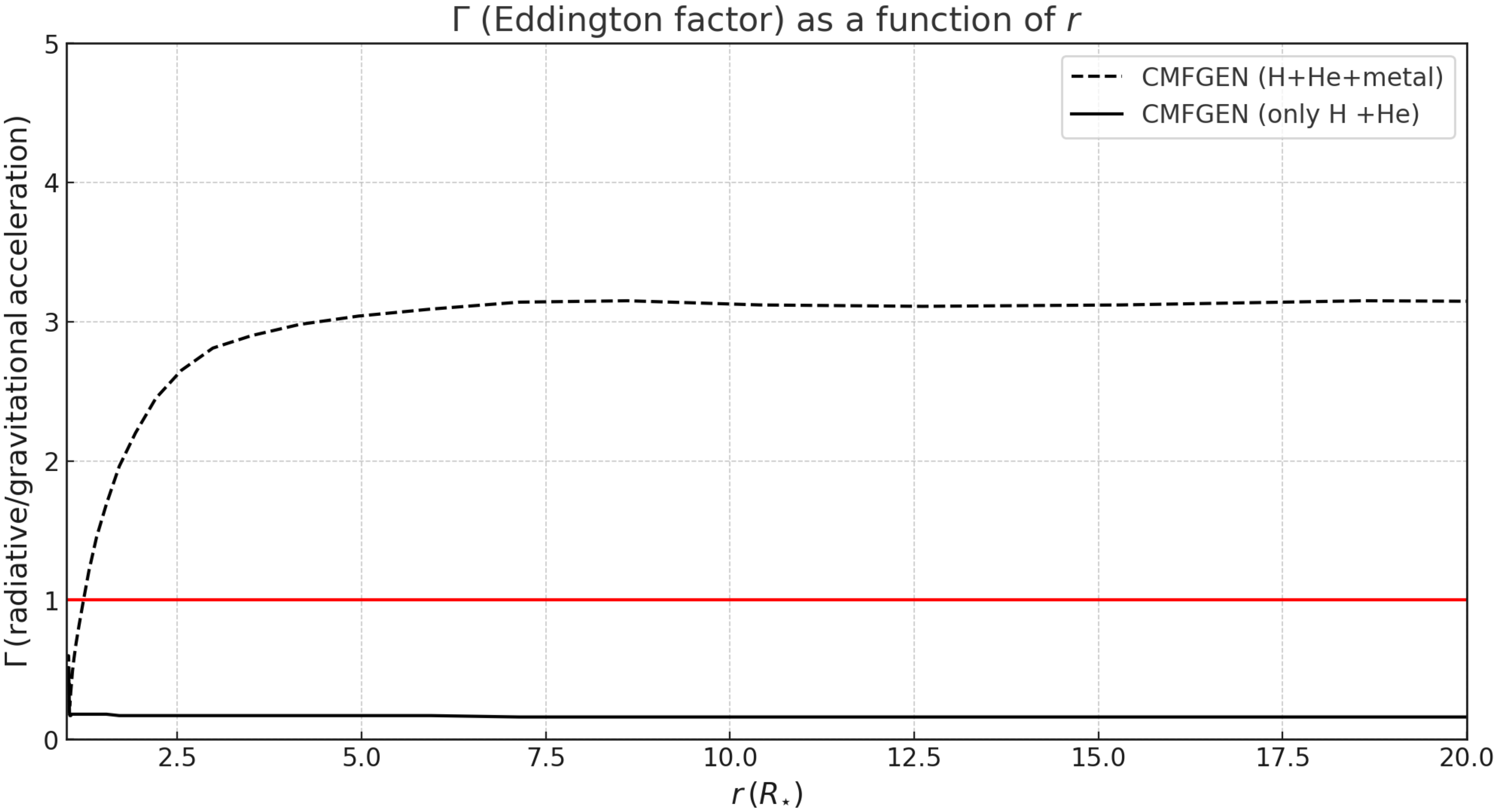
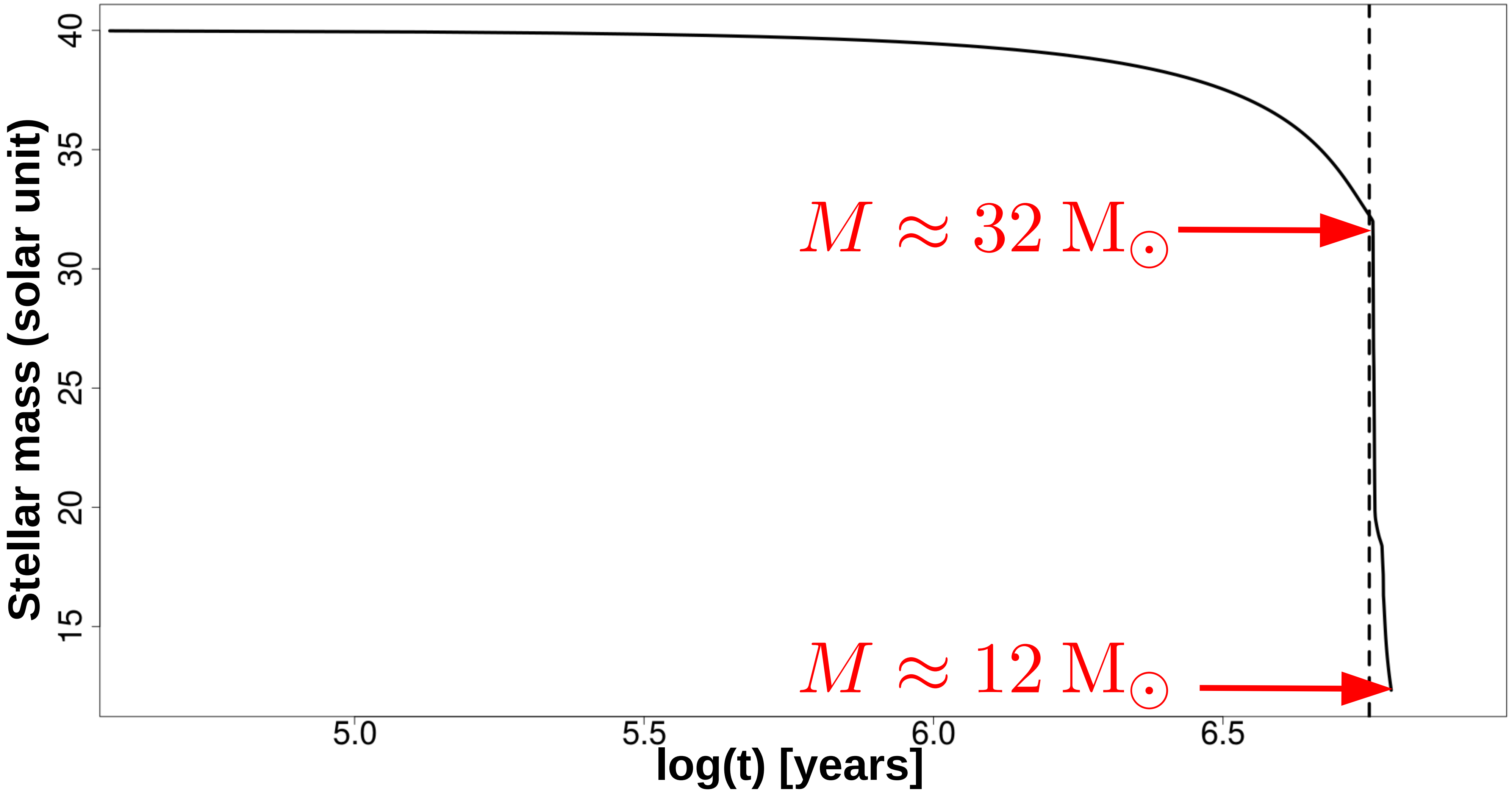


Geneva evolution models (Ekström et al. 2012): $M_{\mathrm{ZAMS}} = 40\ \mathrm{M}_{\odot}$

(spectral-type: ~O5V)



How important are stellar winds for the evolution of massive stars?

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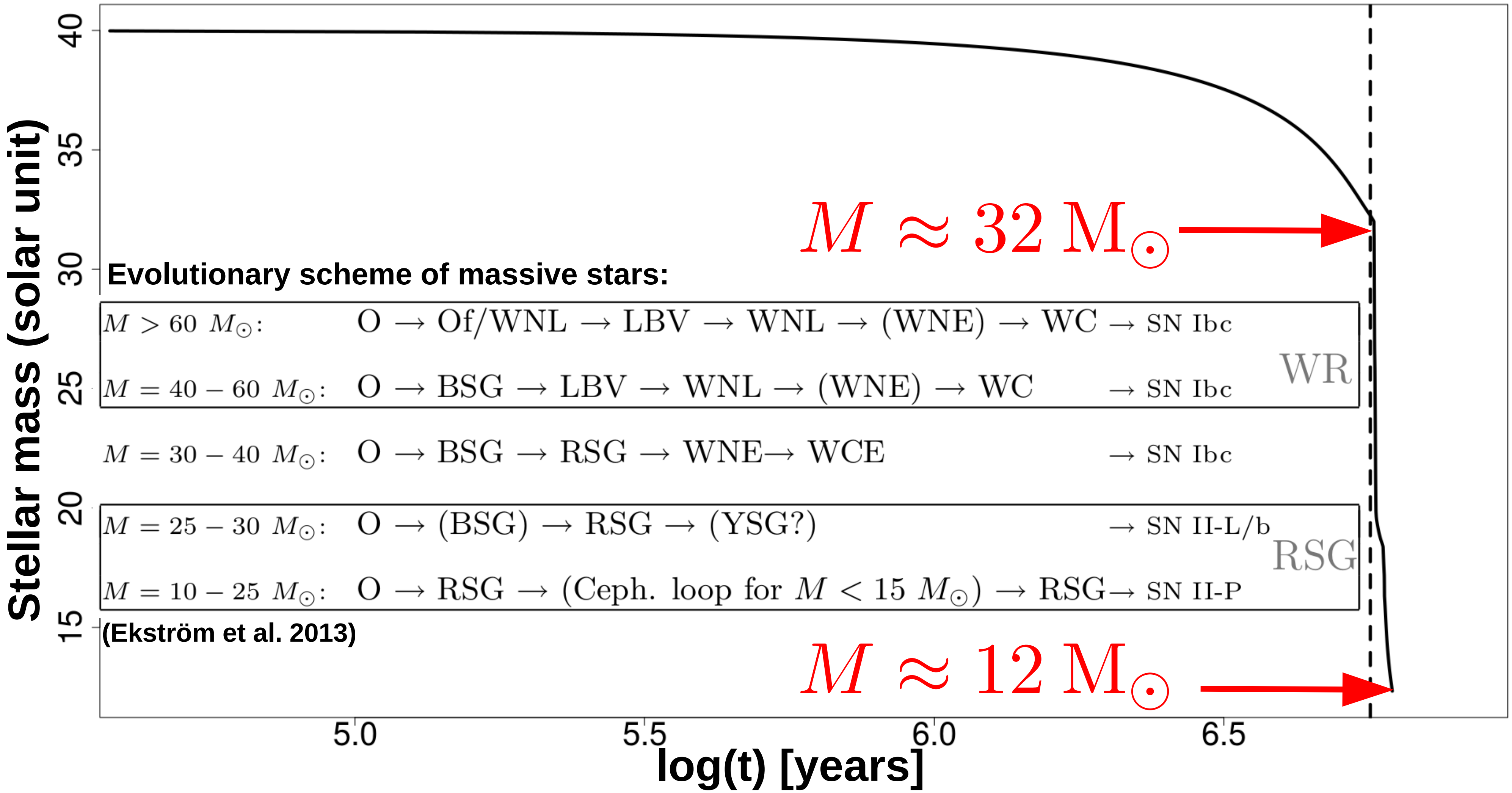

$M \approx 32\ \mathrm{M}_\odot$

$M \approx 12\ \mathrm{M}_\odot$

Evolutionary scheme of massive stars:

WR

$M > 60\ M_\odot$: O → Of/WNL → LBV → WNL → (WNE) → WC → SN Ibc

$M = 40 - 60\ M_\odot$: O → BSG → LBV → WNL → (WNE) → WC → SN Ibc

$M = 30 - 40\ M_\odot$: O → BSG → RSG → WNE → WCE → SN Ibc

RSG

$M = 25 - 30\ M_\odot$: O → (BSG) → RSG → (YSG?) → SN II-L/b

$M = 10 - 25\ M_\odot$: O → RSG → (Ceph. loop for $M < 15\ M_\odot$) → RSG → SN II-P

(Ekström et al. 2013)

How important are stellar winds for the evolution of massive stars?

Geneva evolution models (Ekström et al. 2012): $M_{\rm ZAMS} = 40\ \mathrm{M}_\odot$

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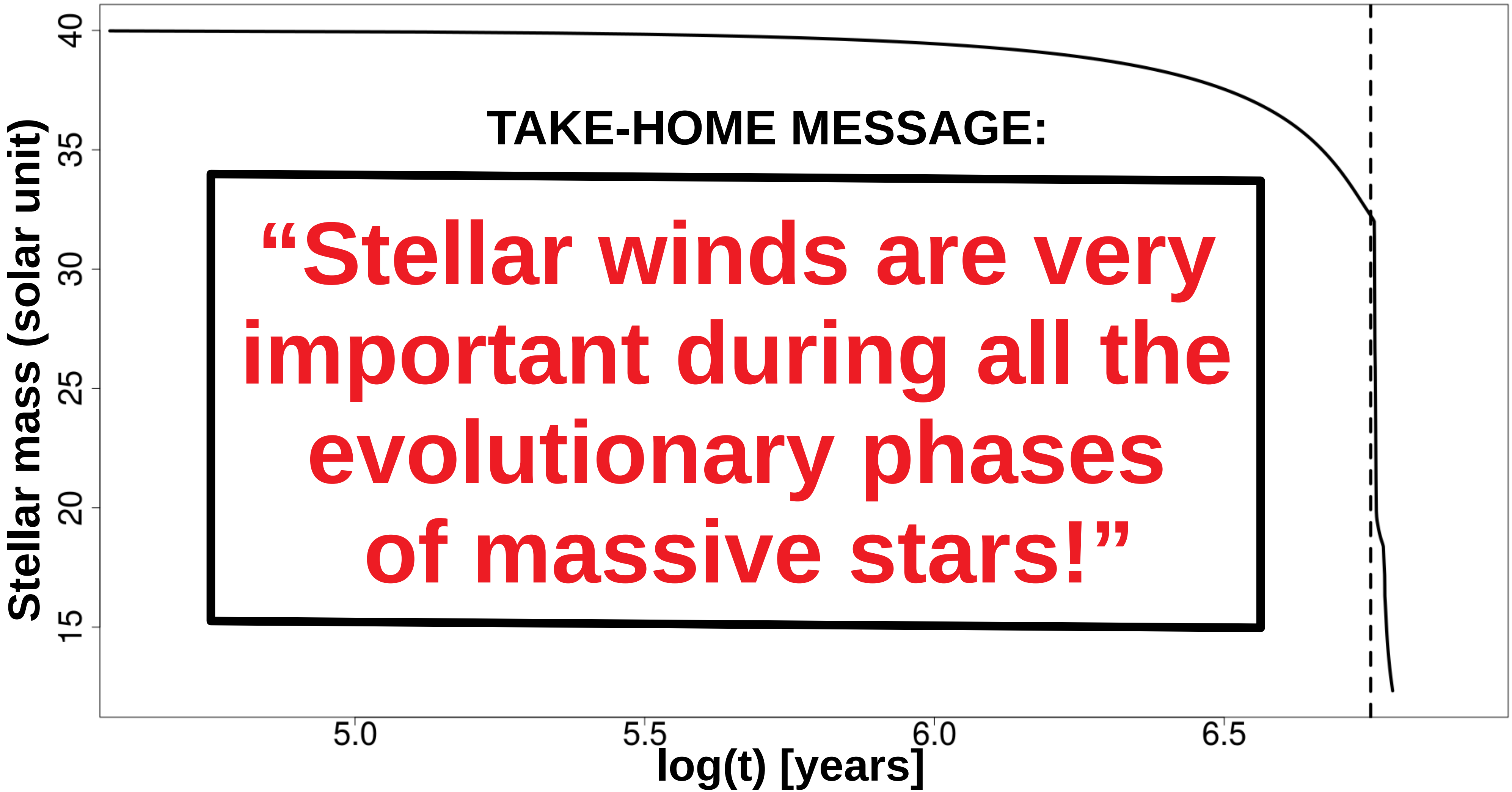
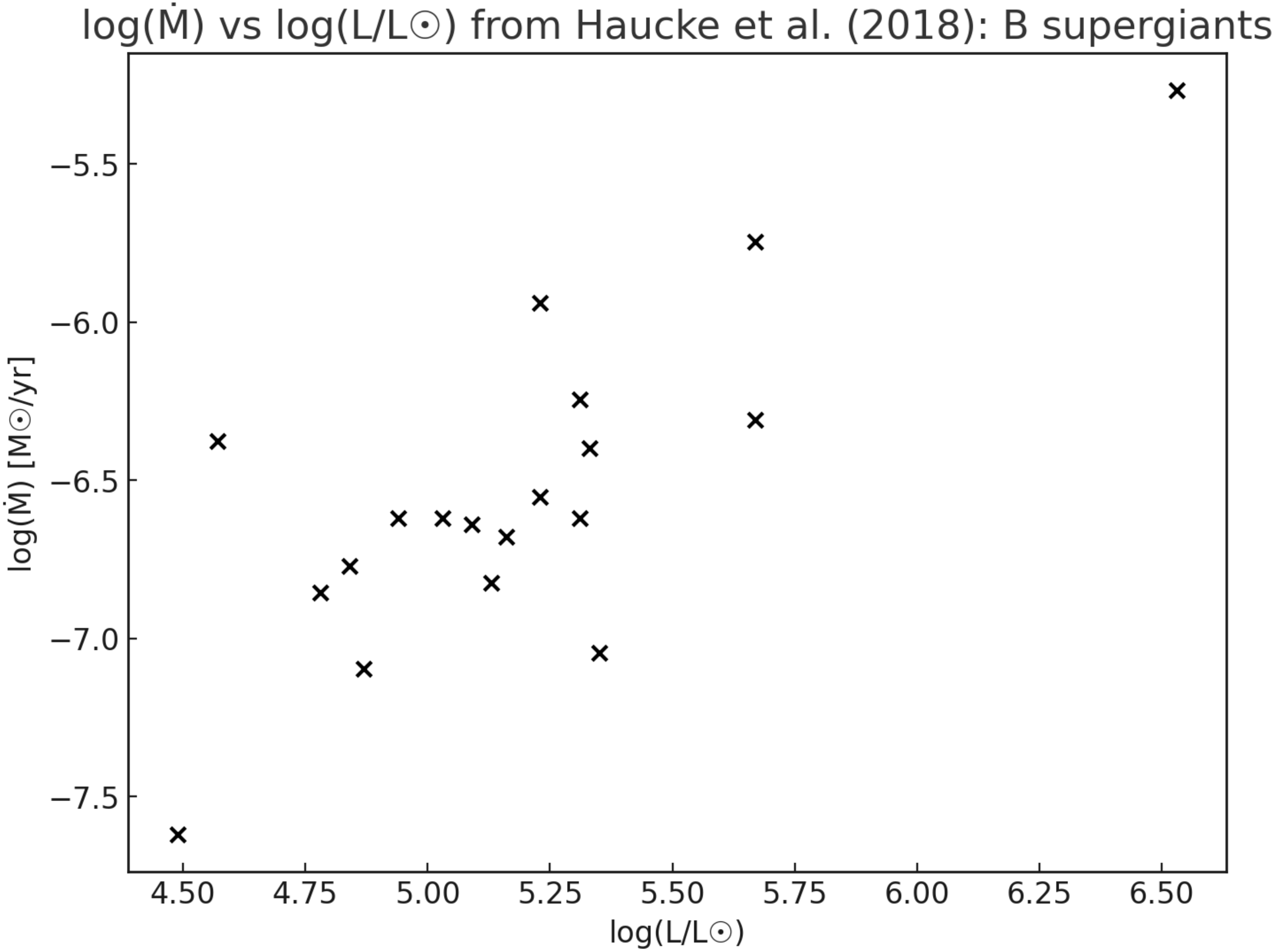


TAKE-HOME MESSAGE:

“Stellar winds are very important during all the evolutionary phases of massive stars!”

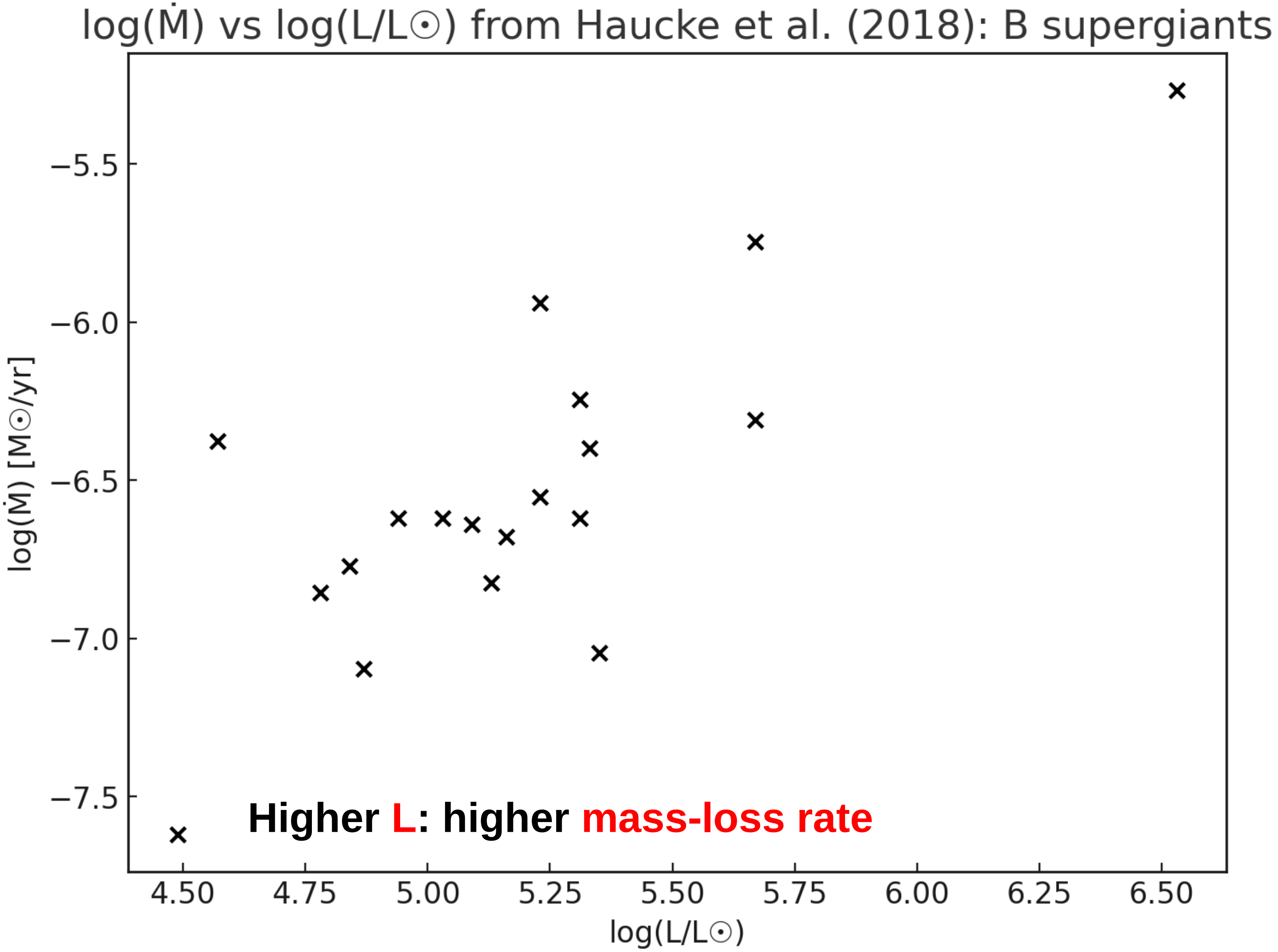
Radiative line-driven winds

“Empirical” mass-loss rates



Radiative line-driven winds

“Empirical” mass-loss rates



Higher L: higher mass-loss rate

Radiative line-driven winds

Theoretical mass-loss rates from Vink & de Koter (2000)

$$\begin{aligned}\log \dot{M} \;=\; & -\; 6.697\,(\pm 0.061)\\ & +\; 2.194\,(\pm 0.021)\,\log(L_*/10^5)\\ & -\; 1.313\,(\pm 0.046)\,\log(M_*/30)\\ & -\; 1.226\,(\pm 0.037)\,\log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right)\\ & +\; 0.933\,(\pm 0.064)\,\log(T_{\rm eff}/40000)\\ & -\; 10.92\,(\pm 0.90)\,\{\log(T_{\rm eff}/40000)\}^2\end{aligned}$$

$$\text{for } 27\,500 < T_{\rm eff} \leq 50\,000\text{K}$$

Higher L: higher mass-loss rate → **Function of other parameters!**

The wind momentum luminosity relation (WLR)

- Motivation for introducing the **(modified) wind momentum** **(Dmom)**:

$$D_{\rm mom} = \dot{M} v_\infty (R_\star / R_\odot)^{0.5}$$

(Kudritzki 1989; Kudritzki 1995): CAK-theory of line-driven winds

...answering the first slide: **the wind momentum luminosity relation (WLR)**

$$\boxed{\log D_{\rm mom} = a + b \log \frac{L}{L_\odot}}$$

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stellar luminosity

metallicity and spectral-type

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...answering the first slide: **the wind momentum luminosity relation (WLR)**

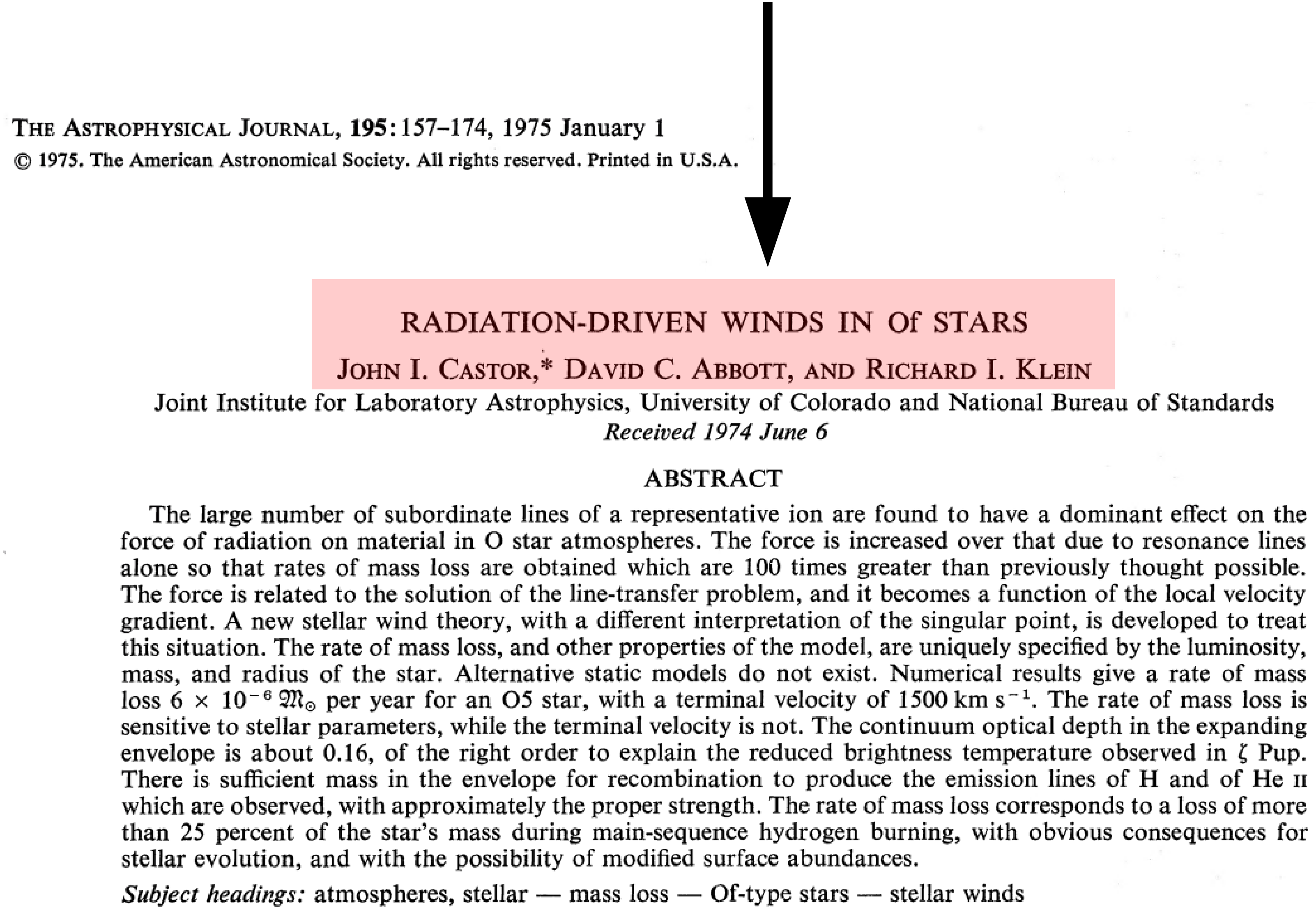
$$\boxed{\log D_{\mathrm{mom}} = a + b \log \frac{L}{L_\odot}}$$

stellar luminosity

metallicity and spectral-type: “Maybe *our problems start here*”

Parenthesis: CAK-theory of radiative line-driven winds

CAK-theory of line-driven winds



THE ASTROPHYSICAL JOURNAL, **195**: 157–174, 1975 January 1

RADIATION-DRIVEN WINDS IN Of STARS

JOHN I. CASTOR,* DAVID C. ABBOTT, AND RICHARD I. KLEIN
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards

Received 1974 June 6

ABSTRACT

The large number of subordinate lines of a representative ion are found to have a dominant effect on the force of radiation on material in O star atmospheres. The force is increased over that due to resonance lines alone so that rates of mass loss are obtained which are 100 times greater than previously thought possible. The force is related to the solution of the line-transfer problem, and it becomes a function of the local velocity gradient. A new stellar wind theory, with a different interpretation of the singular point, is developed to treat this situation. The rate of mass loss, and other properties of the model, are uniquely specified by the luminosity, mass, and radius of the star. Alternative static models do not exist. Numerical results give a rate of mass loss $6 \times 10^{-6}\,\mathfrak{M}_\odot$ per year for an O5 star, with a terminal velocity of 1500 km s^{-1}. The rate of mass loss is sensitive to stellar parameters, while the terminal velocity is not. The continuum optical depth in the expanding envelope is about 0.16, of the right order to explain the reduced brightness temperature observed in ζ Pup. There is sufficient mass in the envelope for recombination to produce the emission lines of H and of He II which are observed, with approximately the proper strength. The rate of mass loss corresponds to a loss of more than 25 percent of the star's mass during main-sequence hydrogen burning, with obvious consequences for stellar evolution, and with the possibility of modified surface abundances.

Subject headings: atmospheres, stellar — mass loss — Of-type stars — stellar winds

WLR: a distance estimation method

- Now we have a simple relationship between a wind quantity (**Dmon**) and **L**:

$$\log D_{\mathrm{mom}} = a + b \log \frac{L}{L_{\odot}}$$

- **So what?**

- If you know (assume?) a certain **WLR** and if you determine **Dmon**:

  Congratulations!

  You can are able to estimate the **stellar luminosity** **and the distance!**

WLR: a distance estimation method

- **Now** we have a simple relationship between a wind quantity (**Dmon**) and **L**:

$$\log D_{\mathrm{mom}} = a + b \log \frac{L}{L_{\odot}}$$

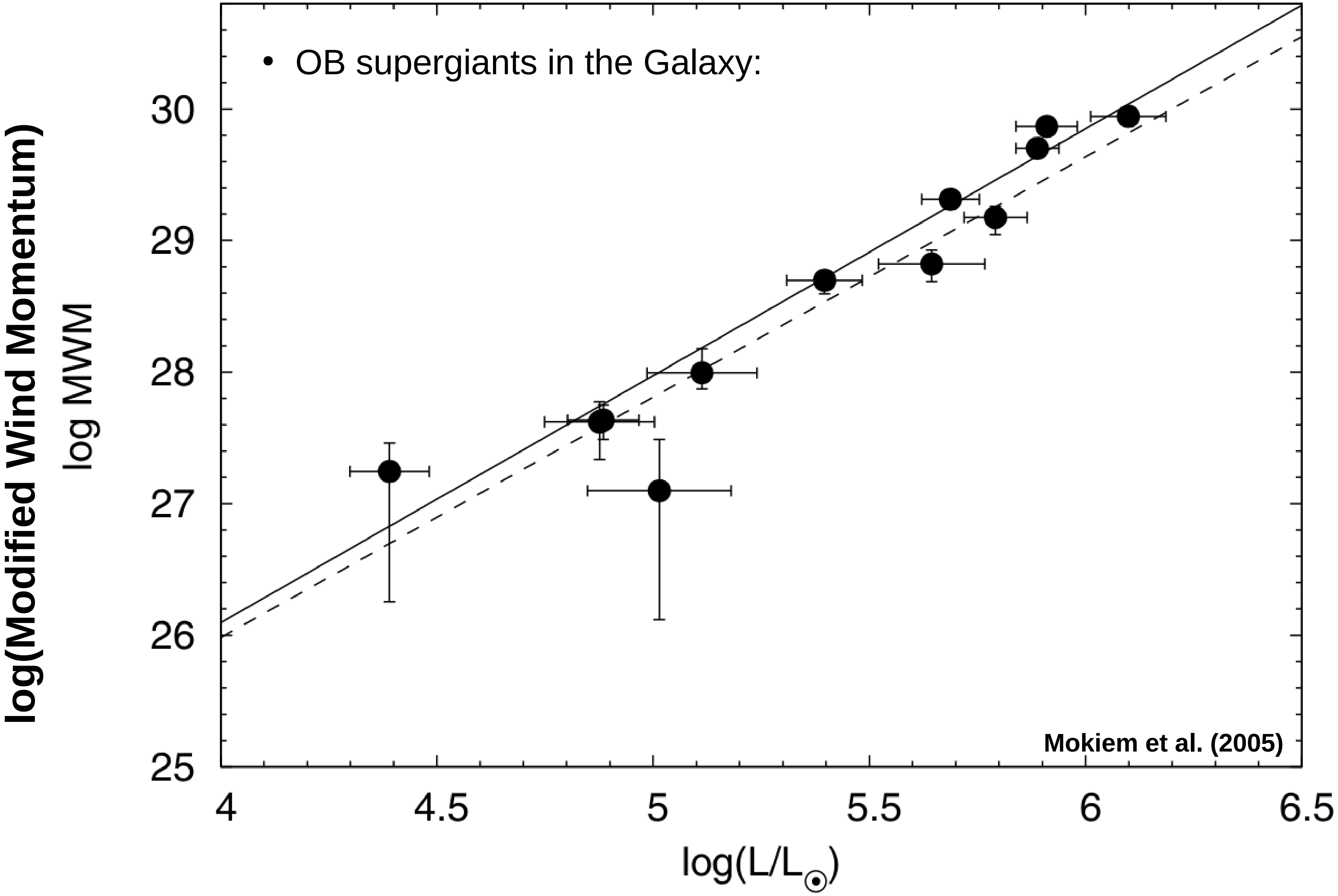
Derived from the CAK-theory: **does it work indeed?**

Short answer:

“**Yes, the WLR for massive hot stars works,** ***but with problems...***”

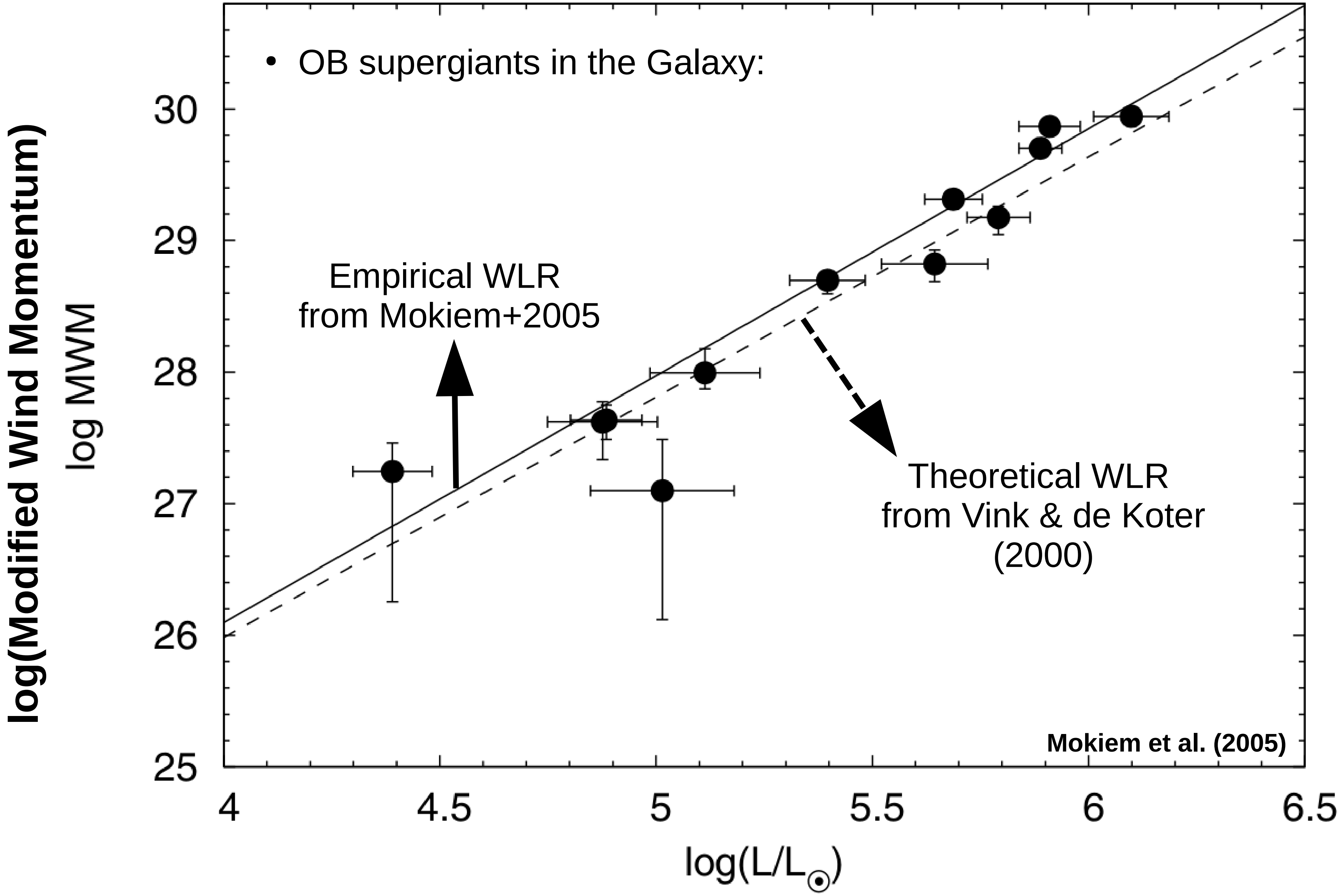
Tests on the WLR (spectroscopy): Galaxy

- OB supergiants in the Galaxy:



Mokiem et al. (2005)

Tests on the WLR (spectroscopy): Galaxy



- OB supergiants in the Galaxy:

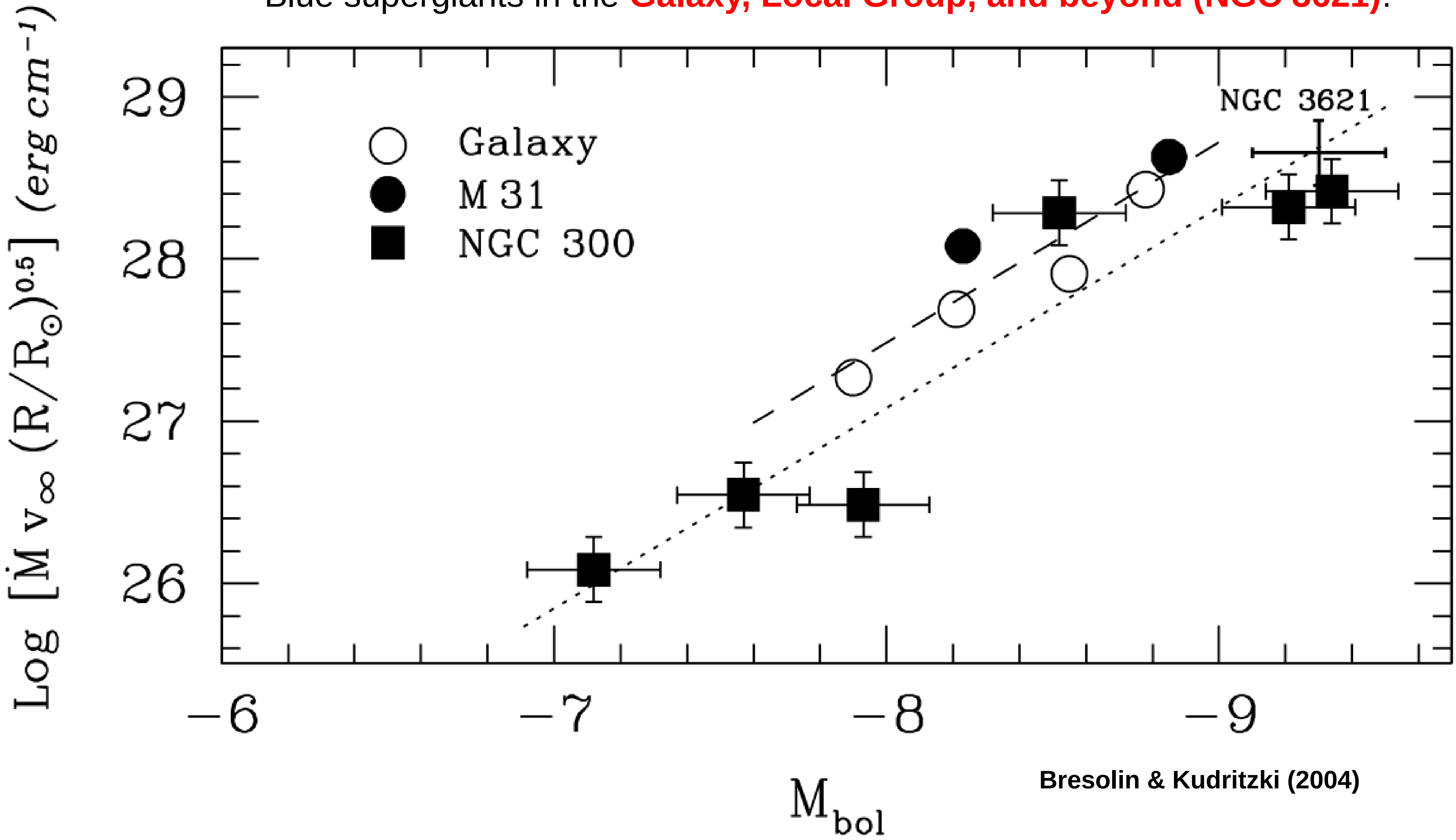
Empirical WLR
from Mokiem+2005

Theoretical WLR
from Vink & de Koter
(2000)

Mokiem et al. (2005)

Tests on the WLR (spectroscopy): beyond the Galaxy

- Blue supergiants in the **Galaxy, Local Group, and beyond (NGC 3621)**:



Bresolin & Kudritzki (2004)

Tests on the WLR (spectroscopy): beyond the Galaxy

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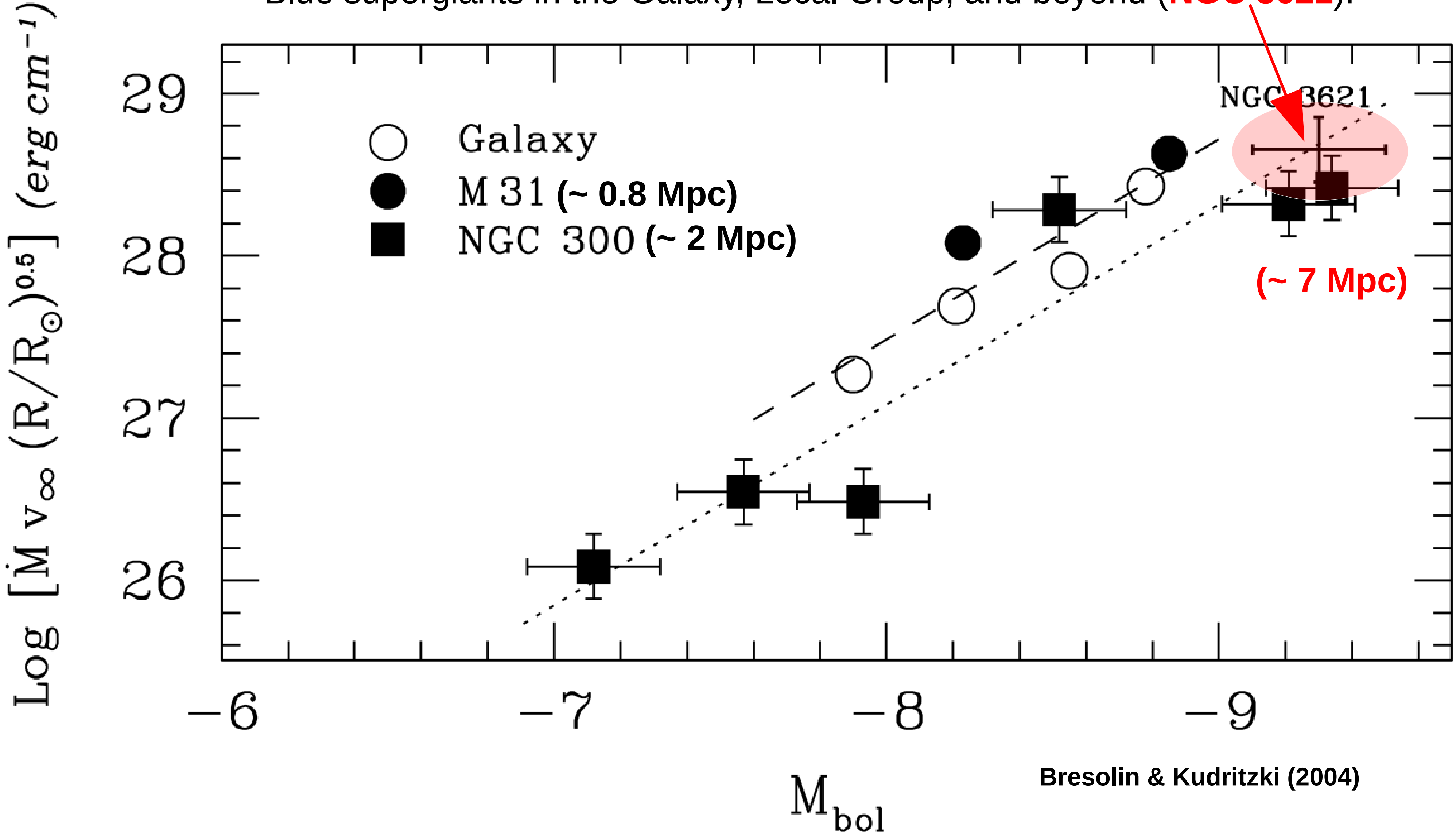
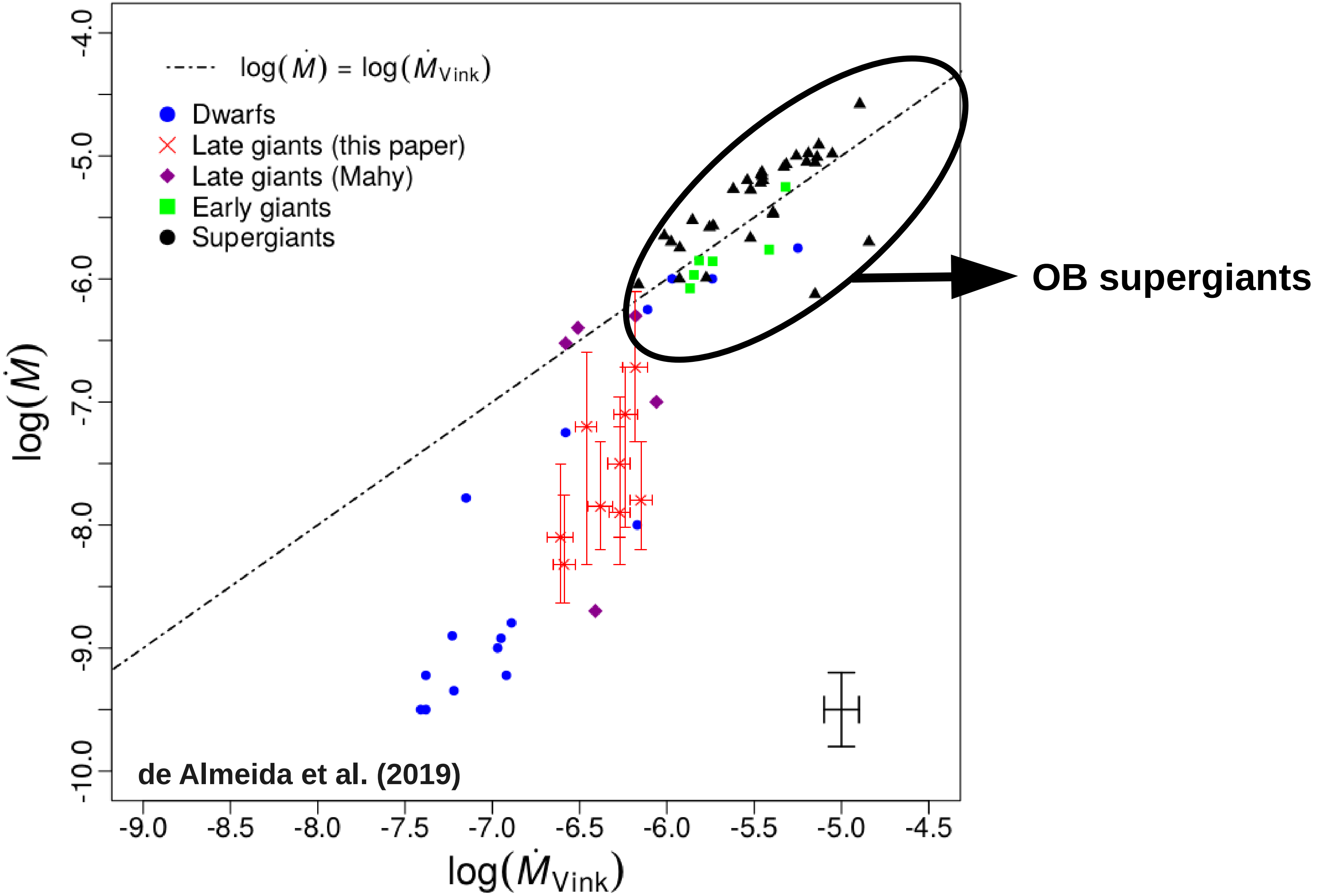


Bresolin & Kudritzki (2004)

Tests on the WLR (spectroscopy): problems

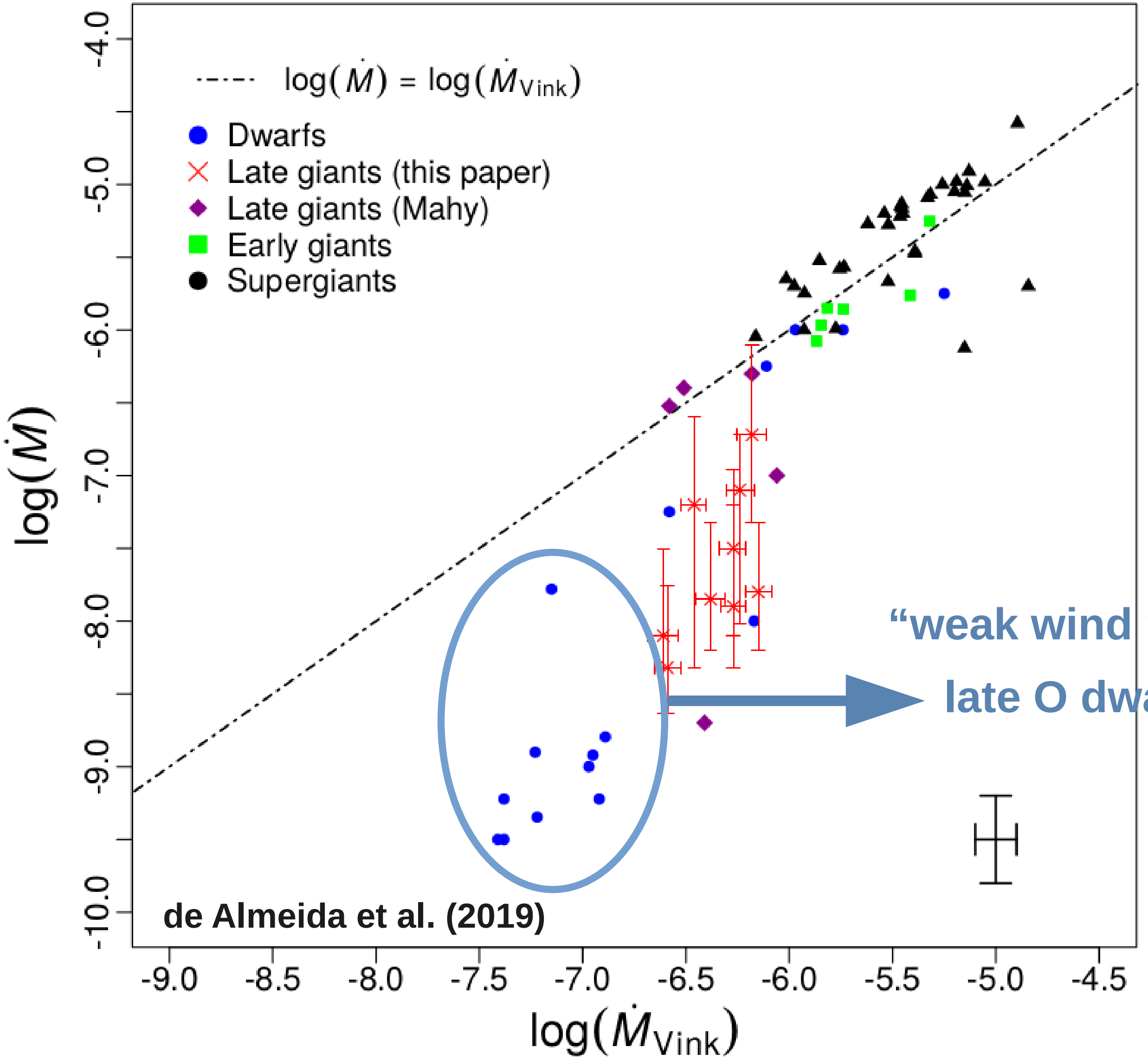
Mass-loss rates from spectroscopy



Theoretical mass-loss rates (Vink & de Koter 2000)

Tests on the WLR (spectroscopy): problems

Mass-loss rates from spectroscopy



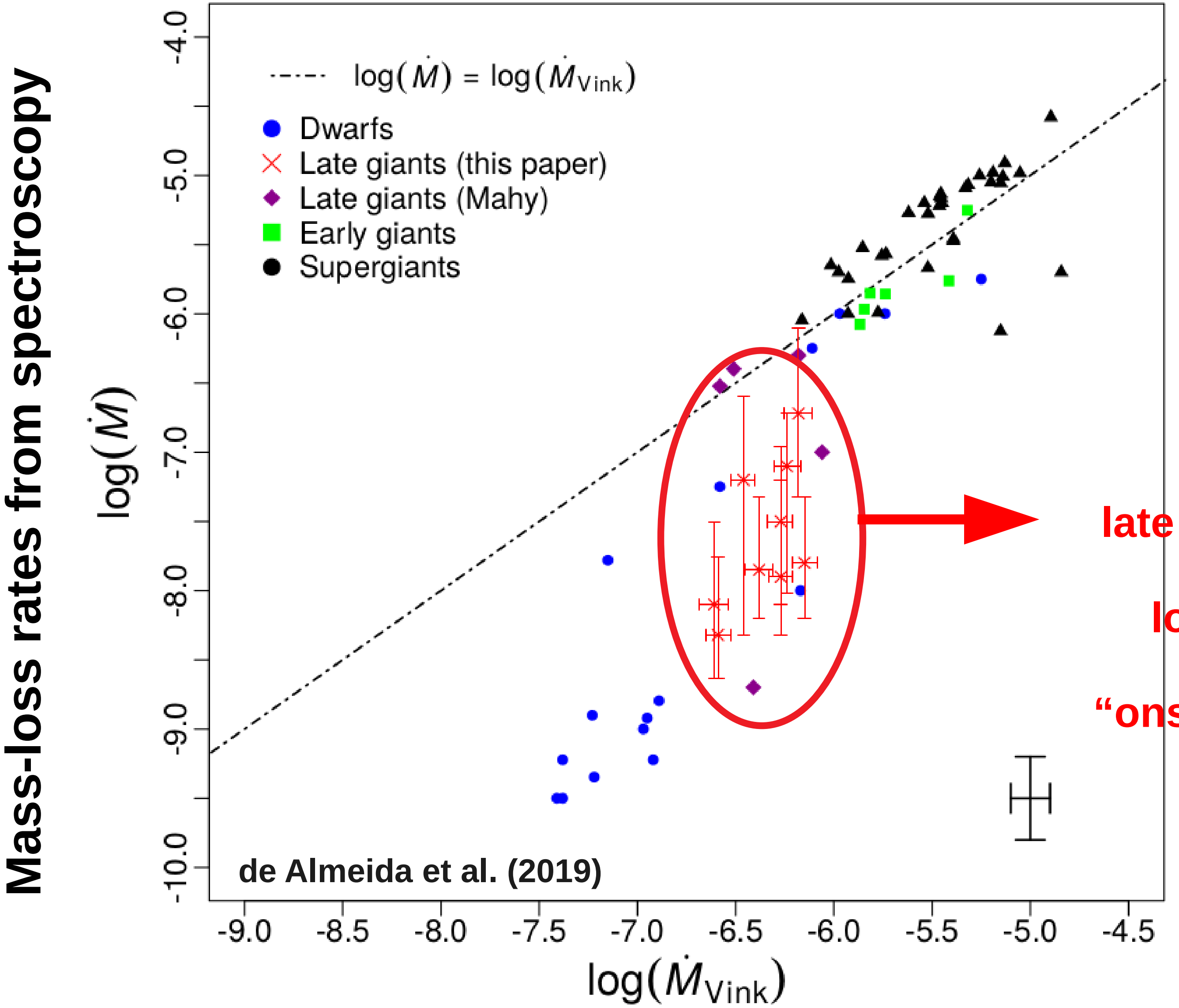
de Almeida et al. (2019)

“weak wind phenomenon”

late O dwarfs (O8-9V)

Theoretical mass-loss rates (Vink & de Koter 2000)

Tests on the WLR (spectroscopy): problems



de Almeida et al. (2019)

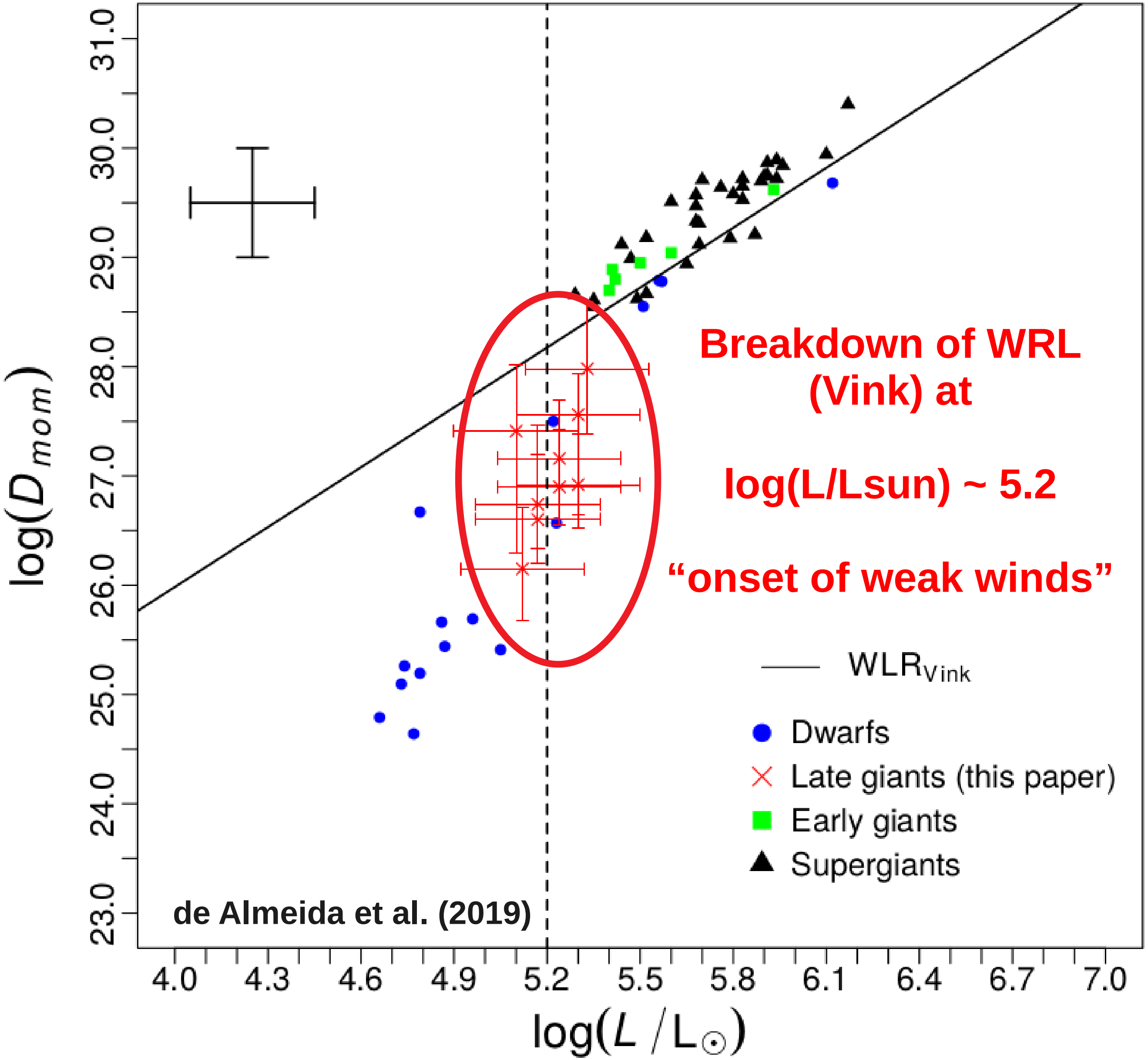
late O giants (O8-9III):

log(L/Lsun) ~ 5.2

“onset of weak winds”

Theoretical mass-loss rates (Vink & de Koter 2000)

Tests on the WLR (spectroscopy): problems



Breakdown of WRL (Vink) at

log(L/Lsun) ~ 5.2

"onset of weak winds"

de Almeida et al. (2019)

Tests on the WLR (spectroscopy): Massive Star Group at Valparaíso

NASA, JPL-Caltech, Spitzer Space Telescope

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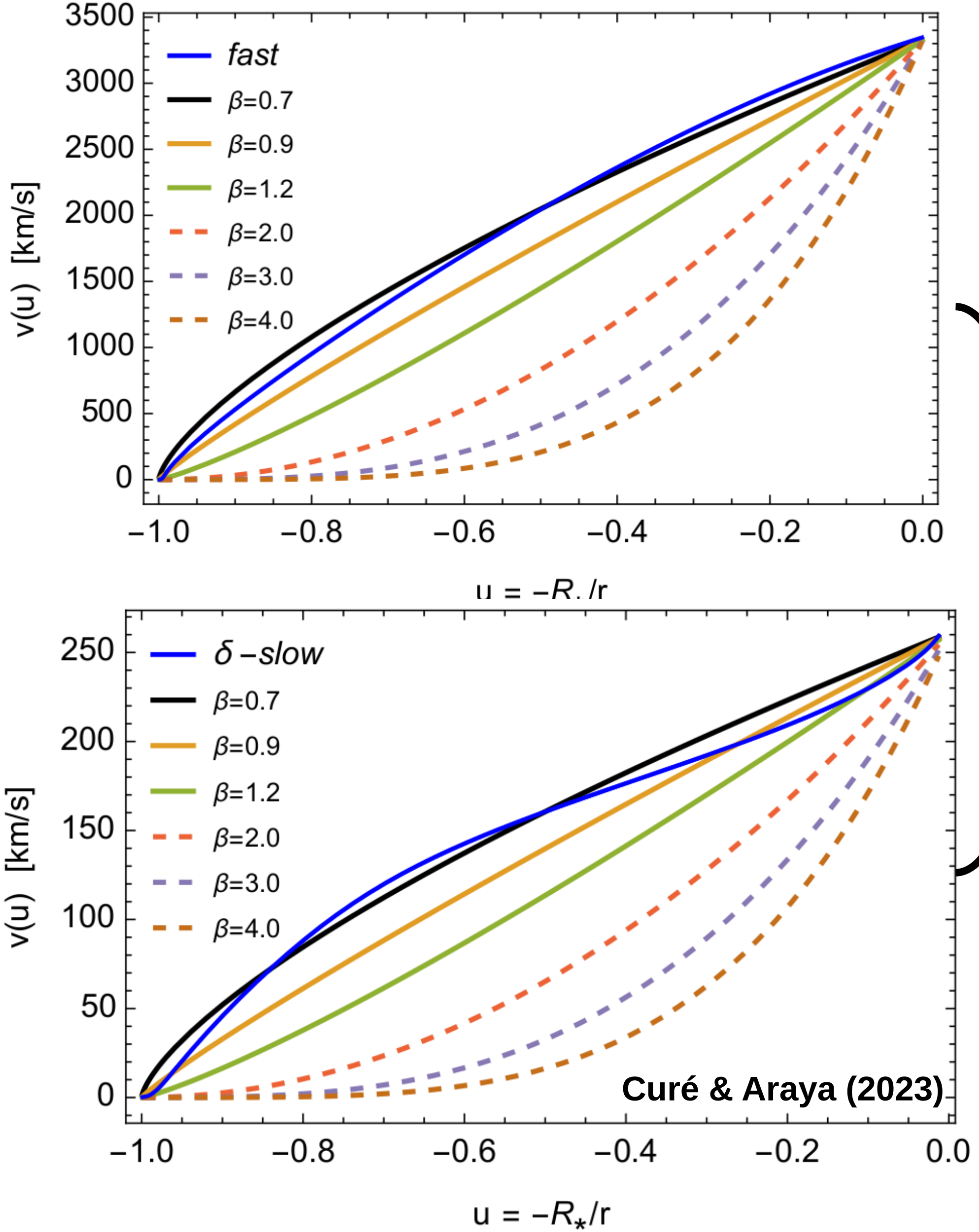


Curé & Araya (2023)

v(r) predicted from HYDWIND
(wind hydrodynamics)

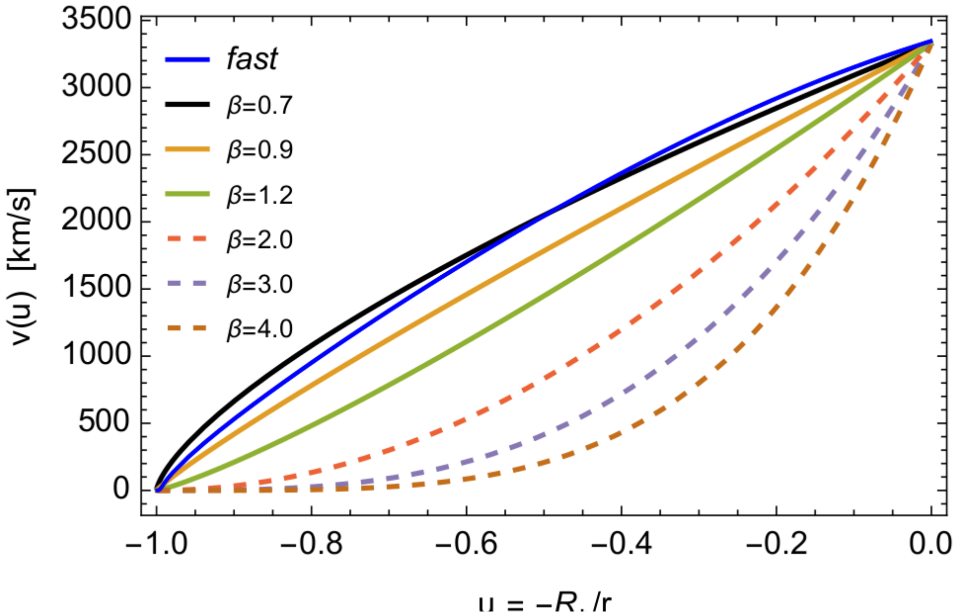
X

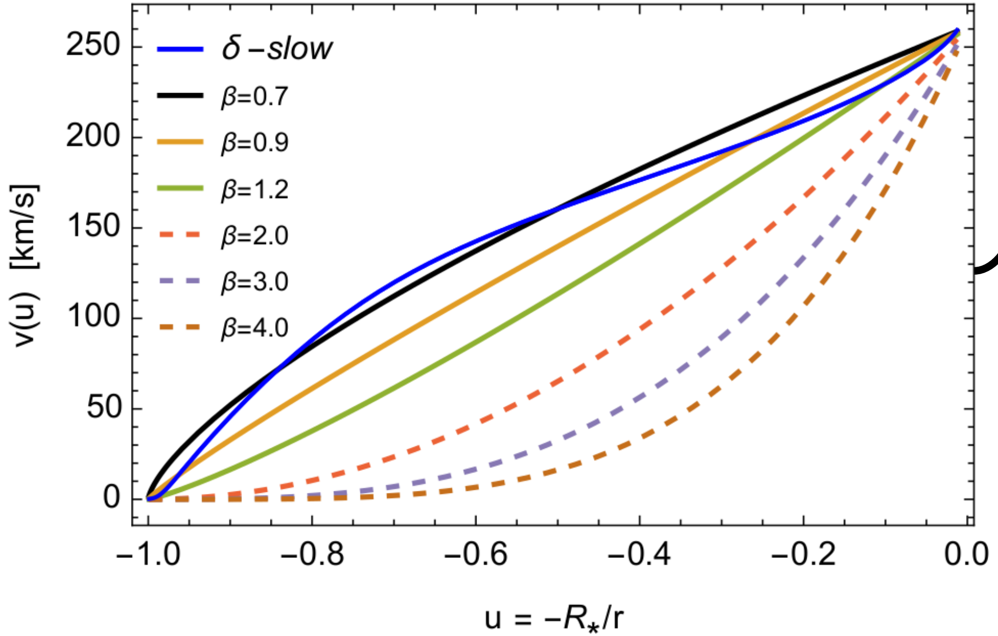
v(r) adopted using the β-law approximation:

$$v(r) = v_\infty \left(1 - \frac{R_\star}{r}\right)^\beta$$

Ad hoc: parameterizing v(r)!

Tests on the WLR (spectroscopy): Massive Star Group at Valparaíso





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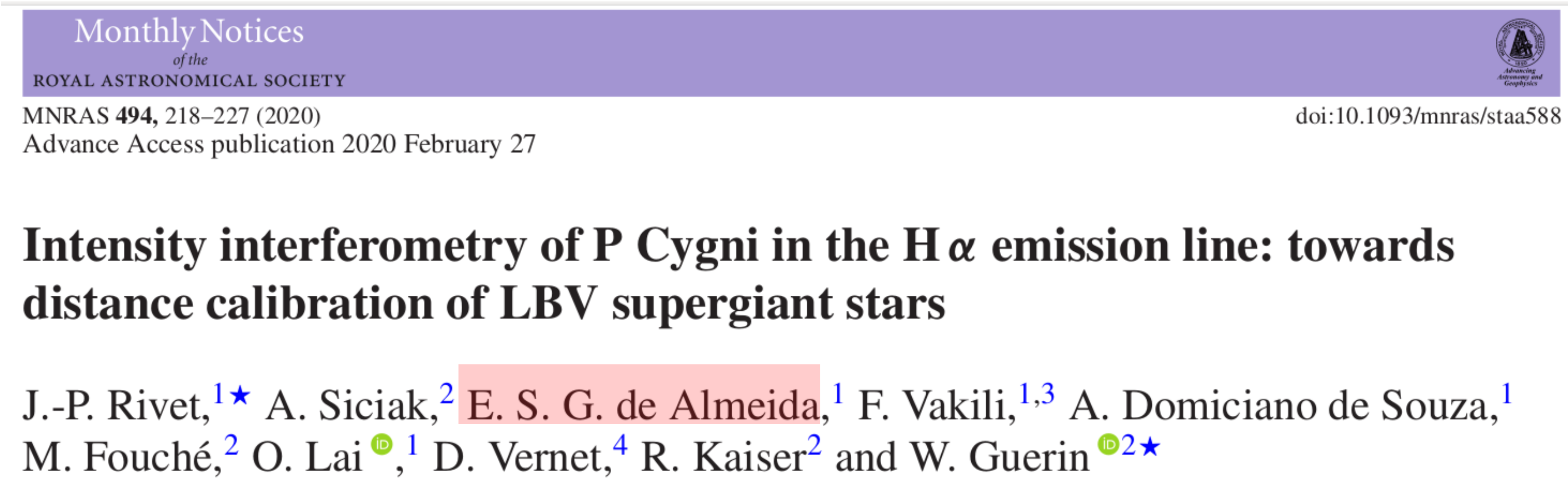
Intensity interferometry of massive hot stars (blue supergiants)



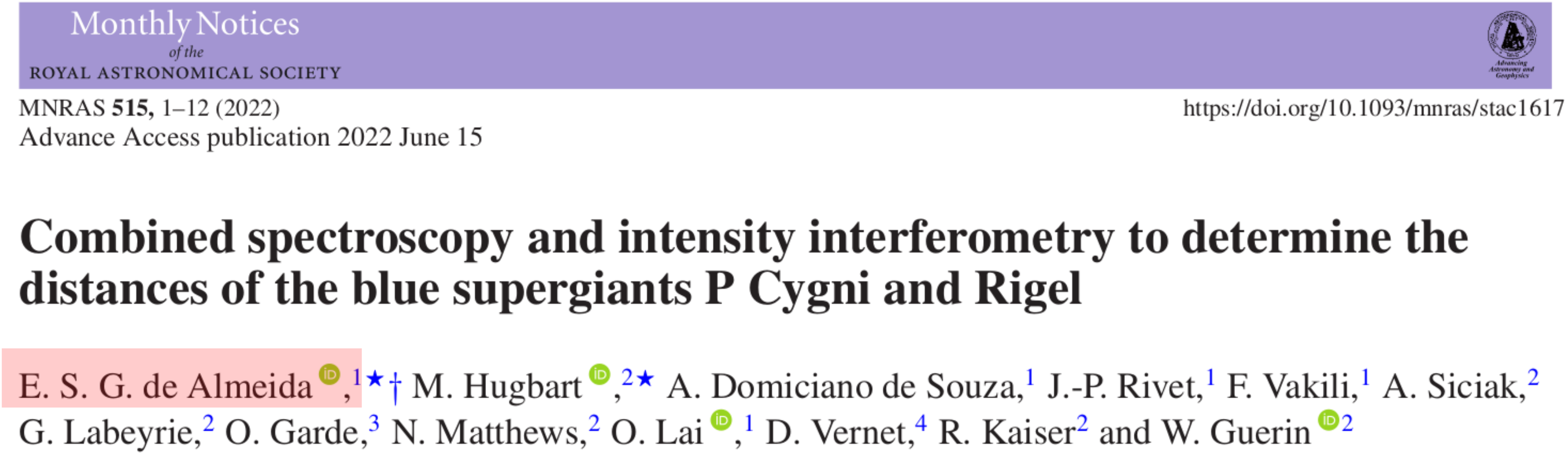
Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **494,** 218–227 (2020)
Advance Access publication 2020 February 27

doi:10.1093/mnras/staa588

Intensity interferometry of P Cygni in the H α emission line: towards distance calibration of LBV supergiant stars

J.-P. Rivet,[1★] A. Siciak,[2] E. S. G. de Almeida,[1] F. Vakili,[1,3] A. Domiciano de Souza,[1] M. Fouché,[2] O. Lai,[1] D. Vernet,[4] R. Kaiser[2] and W. Guerin[2★]



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **515,** 1–12 (2022)
Advance Access publication 2022 June 15

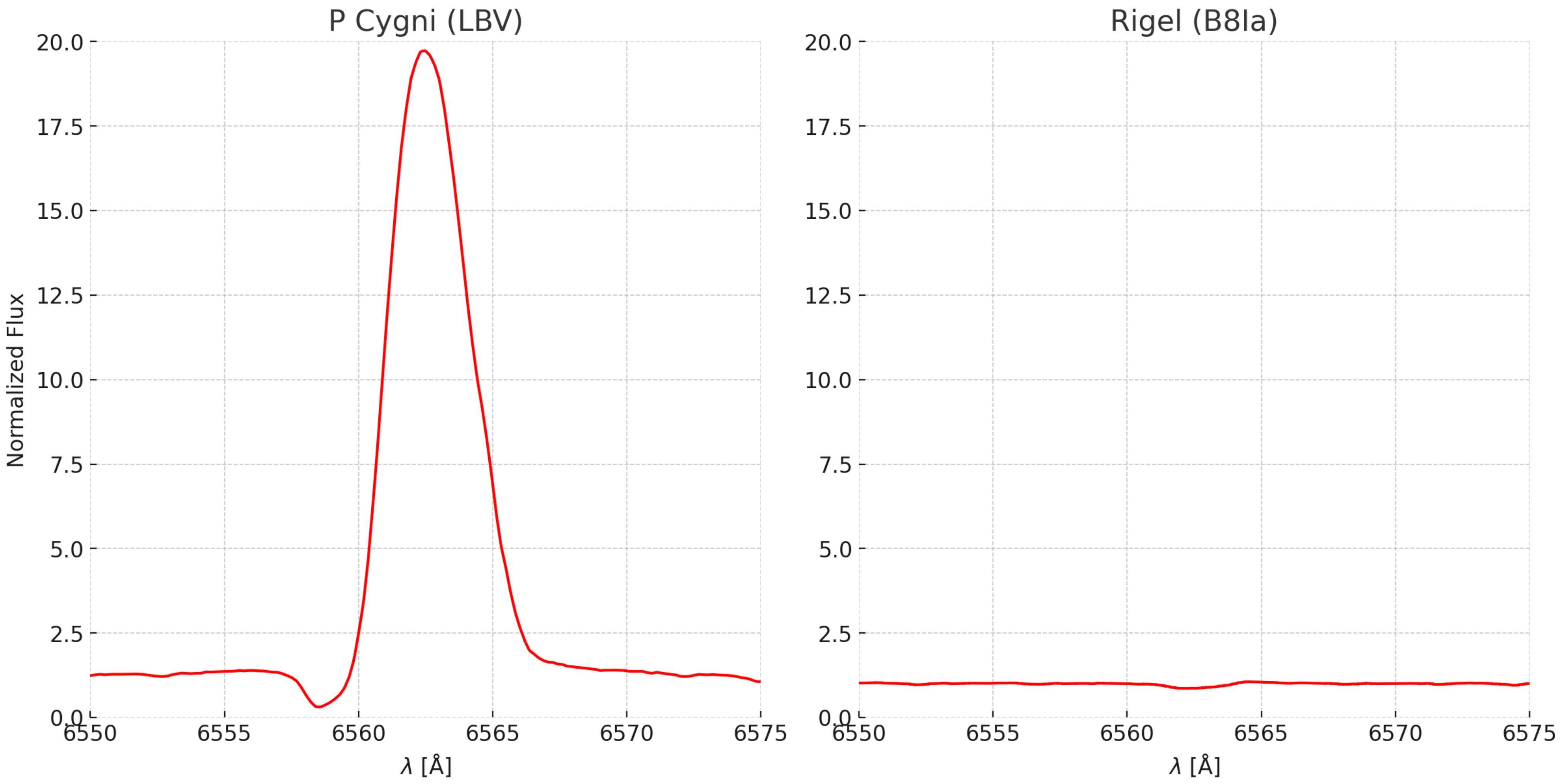
https://doi.org/10.1093/mnras/stac1617

Combined spectroscopy and intensity interferometry to determine the distances of the blue supergiants P Cygni and Rigel

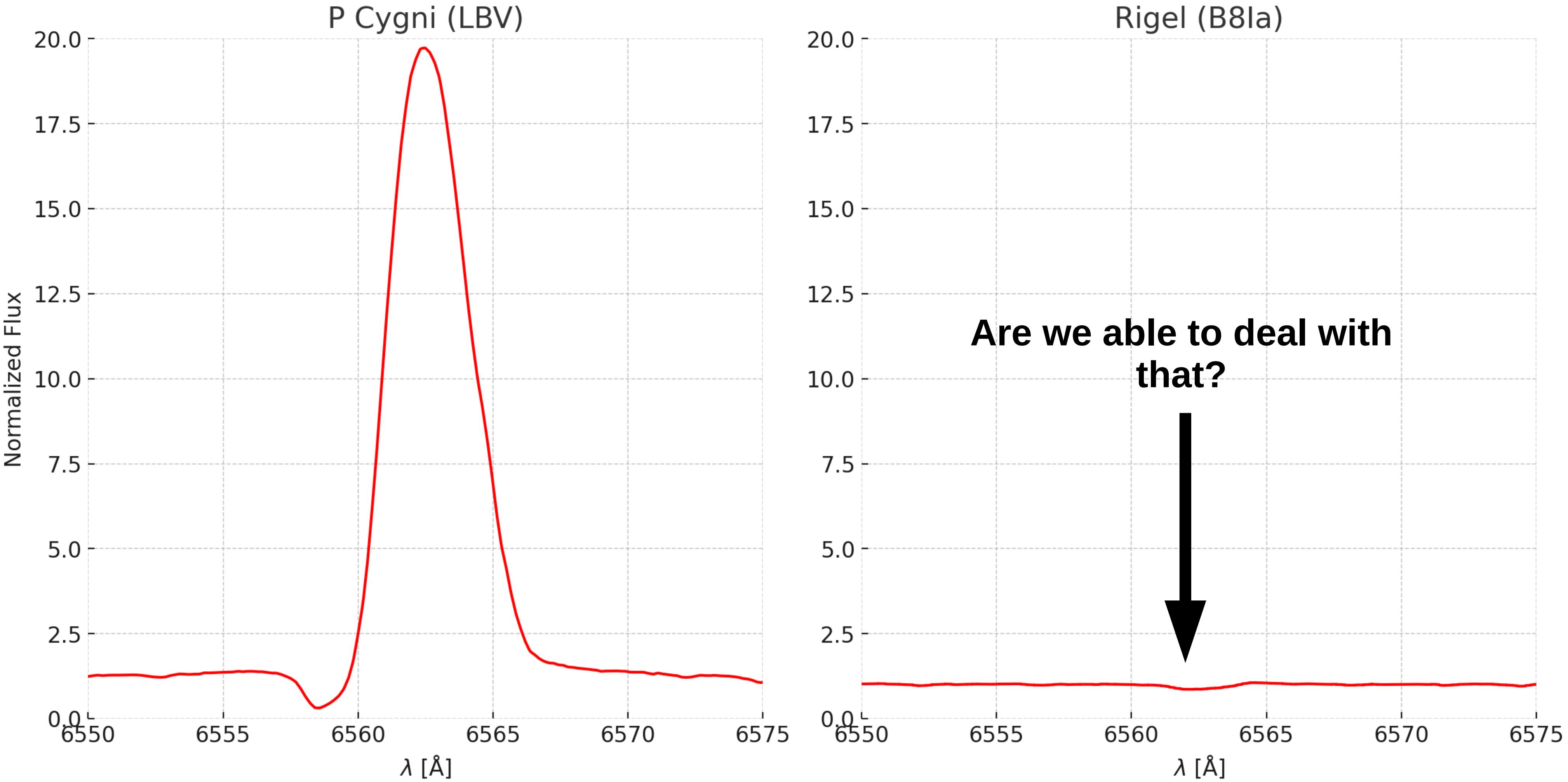
E. S. G. de Almeida,[1★†] M. Hugbart,[2★] A. Domiciano de Souza,[1] J.-P. Rivet,[1] F. Vakili,[1] A. Siciak,[2] G. Labeyrie,[2] O. Garde,[3] N. Matthews,[2] O. Lai,[1] D. Vernet,[4] R. Kaiser[2] and W. Guerin[2]

Hα Intensity interferometry and spectroscopy + CMFGEN radiative transfer

Intensity interferometry of massive hot stars (blue supergiants)



Intensity interferometry of massive hot stars (blue supergiants)

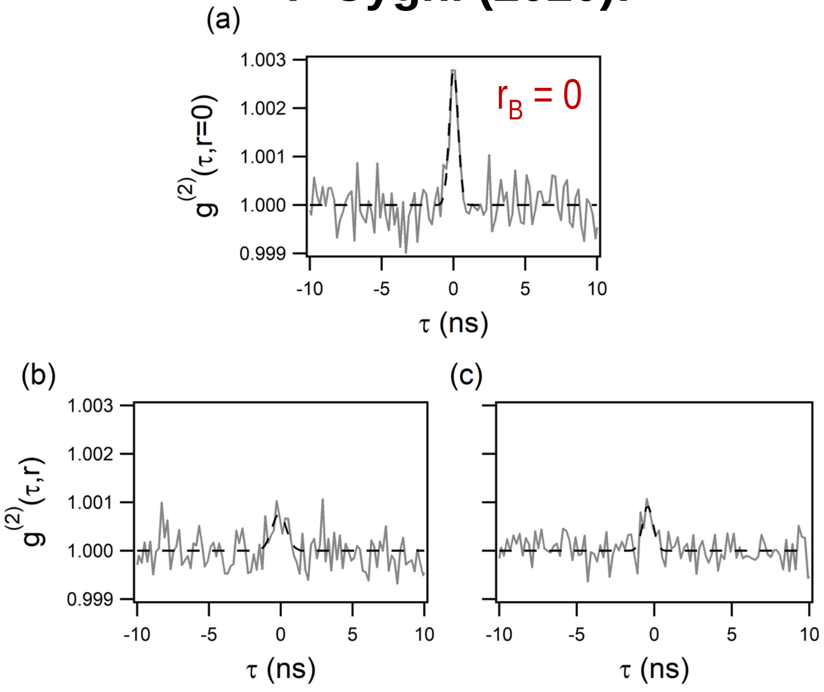


Are we able to deal with that?

Intensity interferometry of P Cygni and Rigel at Calern

- II of P Cygni (2018 and 2020) and Rigel (2020) at Calern
  - Bandwidth Δλ = 1 nm, central wavelength λ0 = 656.3 nm (center at Hα)

P Cygni (2020):



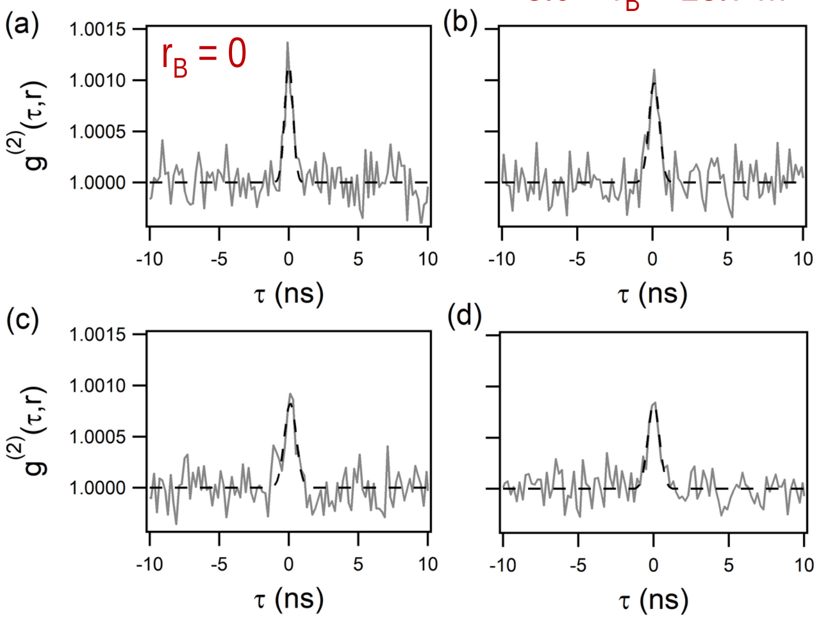
$r_B = 0$

$9.5 < r_B < 13.4$ m

$13.4 < r_B < 15$ m

de Almeida et al. (2022)

Rigel:



$r_B = 0$

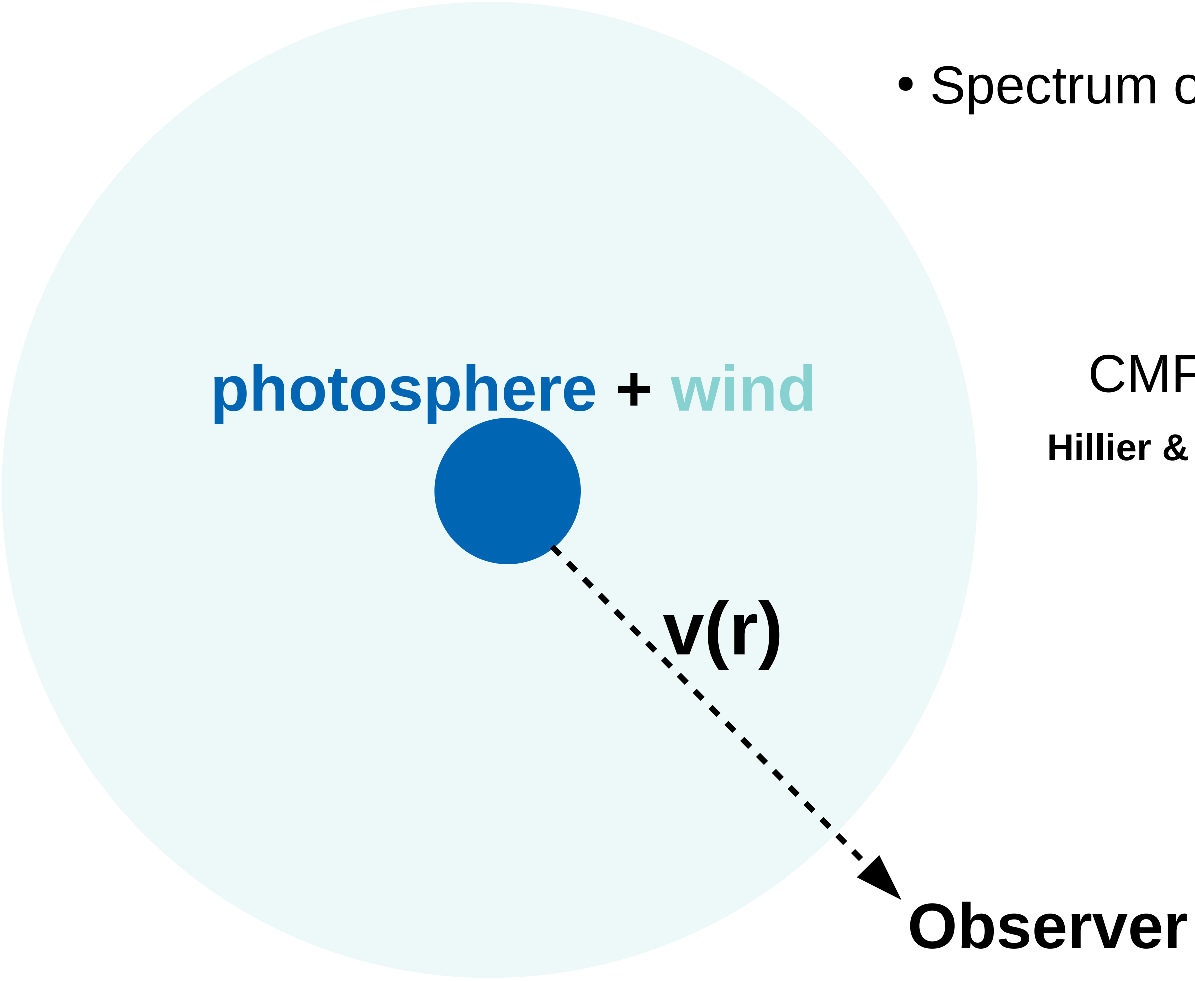
$8.9 < r_B < 13.7$ m

$13.7 < r_B < 14.7$ m

$14.7 < r_B < 15$ m

de Almeida et al. (2022)

Radiative transfer modeling with the code CMFGEN



- Spectrum of hot stars: **photosphere + wind**

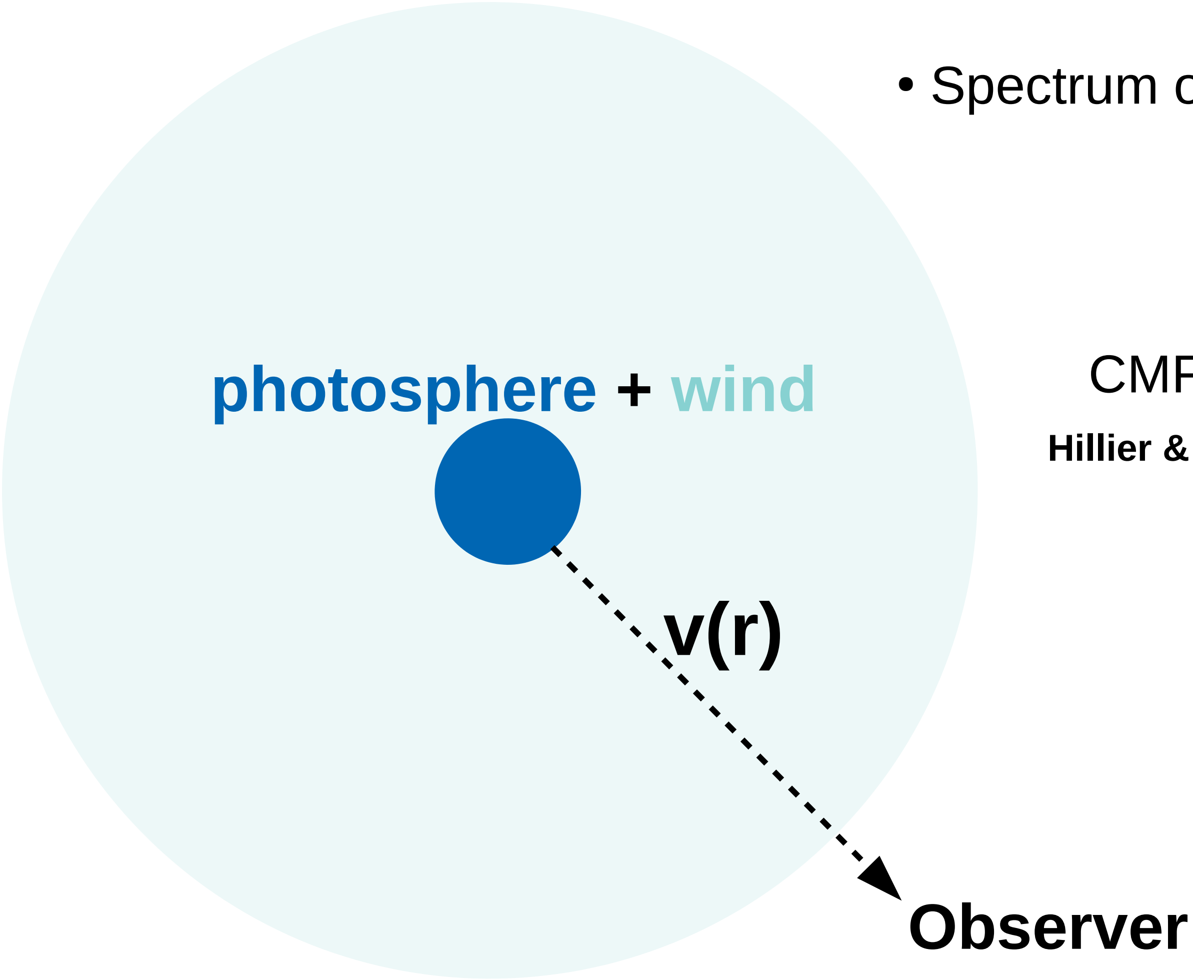
CMFGEN: **non-LTE transfer transfer**

Hillier & Miller (1998)

stellar parameters

$$\boxed{L_\star \; T_{\rm eff} \; \log(g)}$$

Radiative transfer modeling with the code CMFGEN



- Spectrum of hot stars: **photosphere + wind**

↓

CMFGEN: **non-LTE transfer transfer**

Hillier & Miller (1998)

↓

wind parameters

$\boxed{\dot{M} \quad v_\infty \quad \beta\,\mathrm{law}}$

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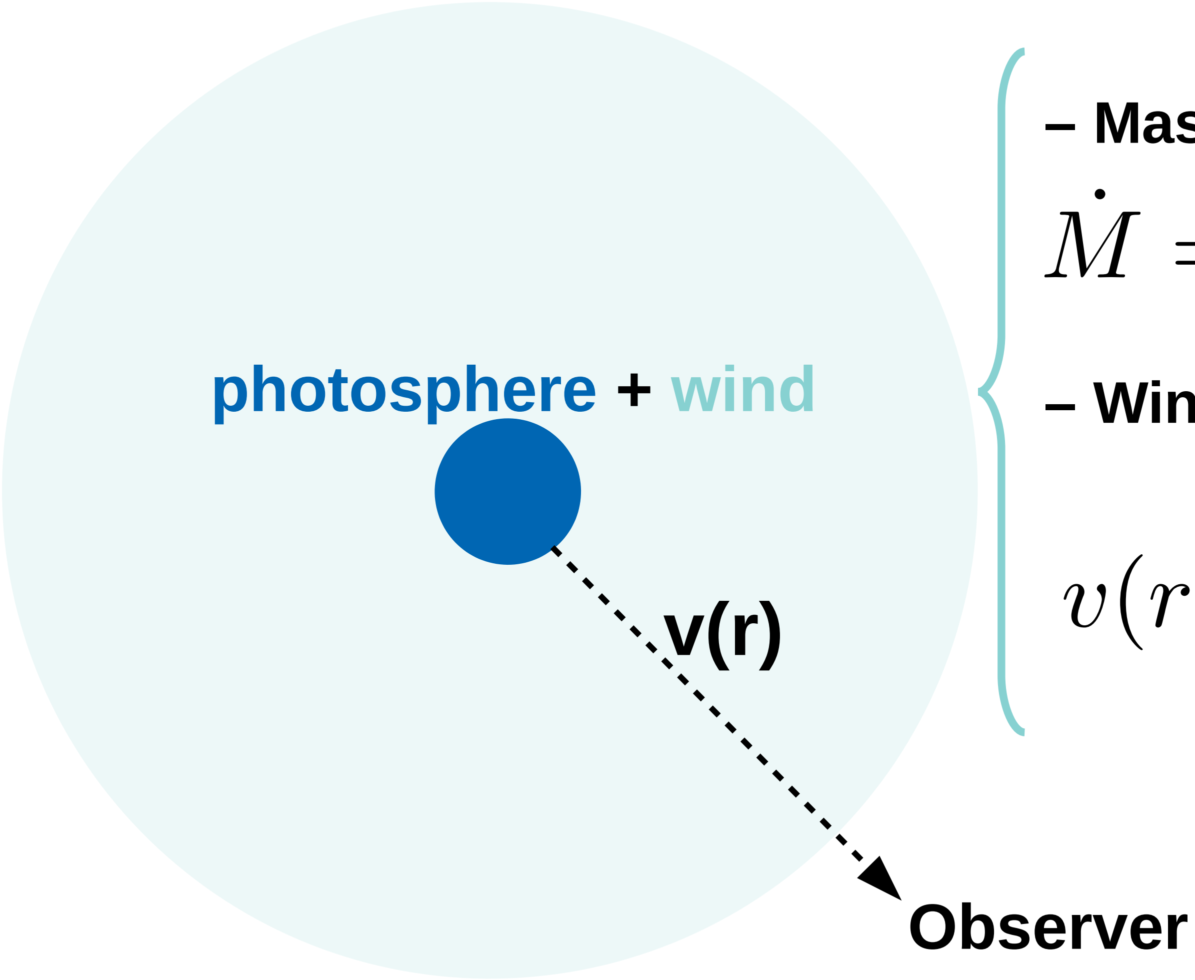


- **Mass-loss rate:** $\dot{M}$

$$\dot{M} = 4\pi r^2 \rho(r) v(r)$$

- **Wind velocity:** $v(r)$

$$v(r) = v_\infty \left(1 - \frac{R_\star}{r}\right)^\beta$$

wind parameters

$$\boxed{\dot{M} \;\; v_\infty \;\; \beta\,\mathrm{law}}$$

Radiative transfer modeling with the code CMFGEN

- CMFGEN: **complex chemical composition**

  – H, He, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Ti, Cr, Mn, Fe, Co, and Ni

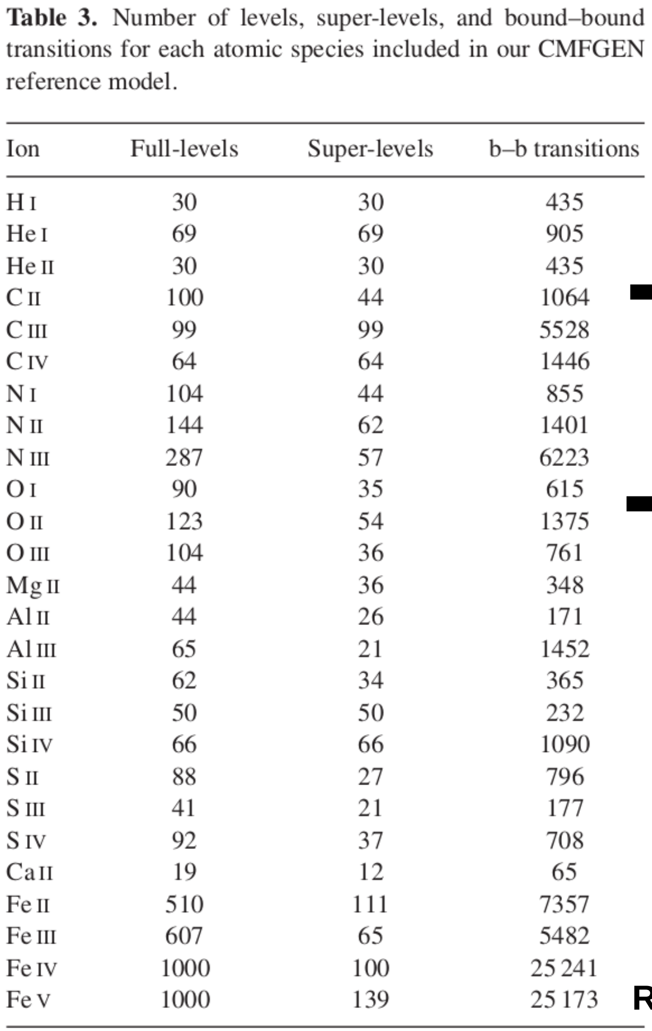


Table 3. Number of levels, super-levels, and bound–bound transitions for each atomic species included in our CMFGEN reference model.

Ion	Full-levels	Super-levels	b–b transitions
H I	30	30	435
He I	69	69	905
He II	30	30	435
C II	100	44	1064
C III	99	99	5528
C IV	64	64	1446
N I	104	44	855
N II	144	62	1401
N III	287	57	6223
O I	90	35	615
O II	123	54	1375
O III	104	36	761
Mg II	44	36	348
Al II	44	26	171
Al III	65	21	1452
Si II	62	34	365
Si III	50	50	232
Si IV	66	66	1090
S II	88	27	796
S III	41	21	177
S IV	92	37	708
Ca II	19	12	65
Fe II	510	111	7357
Fe III	607	65	5482
Fe IV	1000	100	25 241
Fe V	1000	139	25 173

CMFGEN atomic data for P Cygni

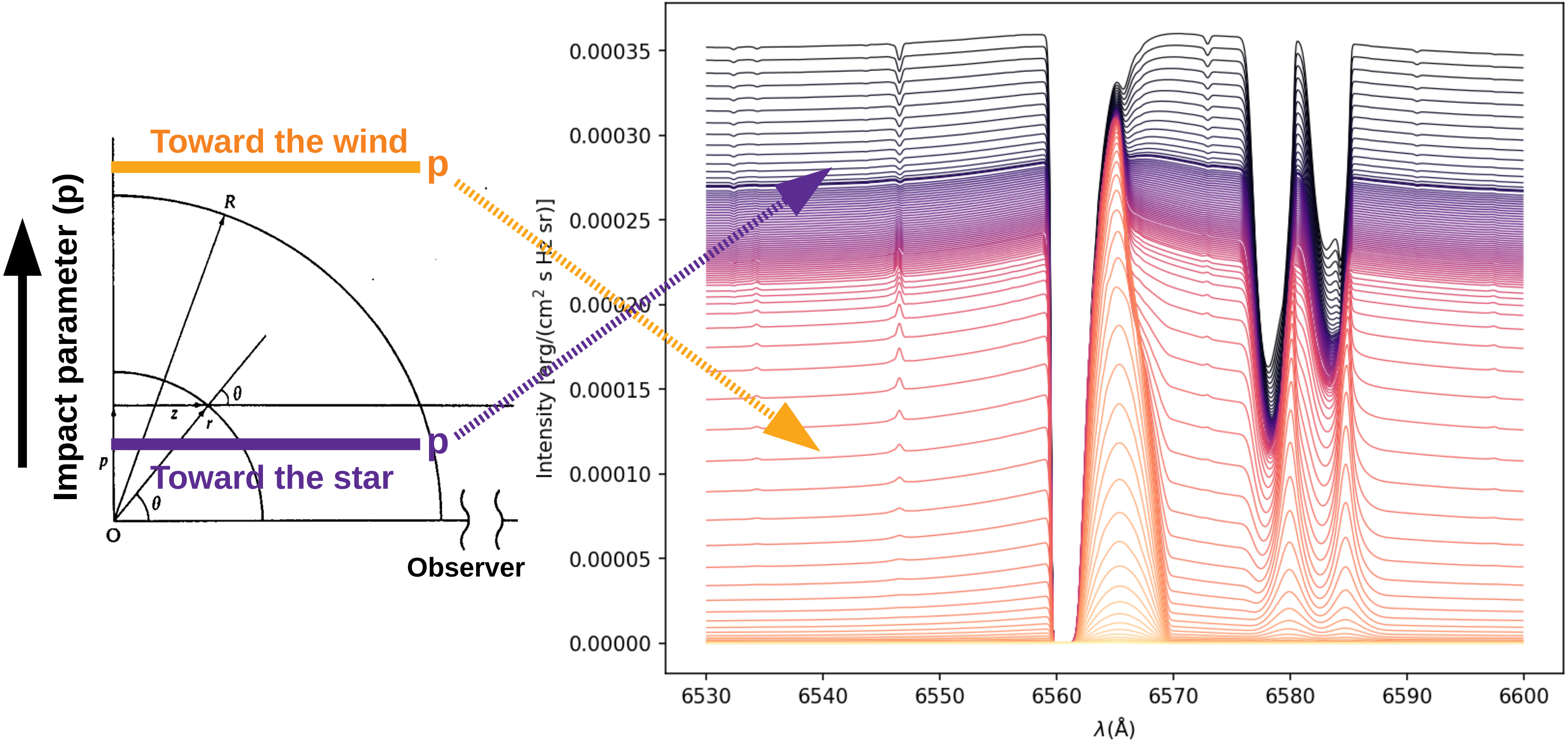
Computational cost: ~6h – 24h

Rivet et al. (2020)

Radiative transfer modeling with the code CMFGEN

- CMFGEN: **spherically symmetric wind (1-D model)**
  - 1-D Intensity profiles I(p)

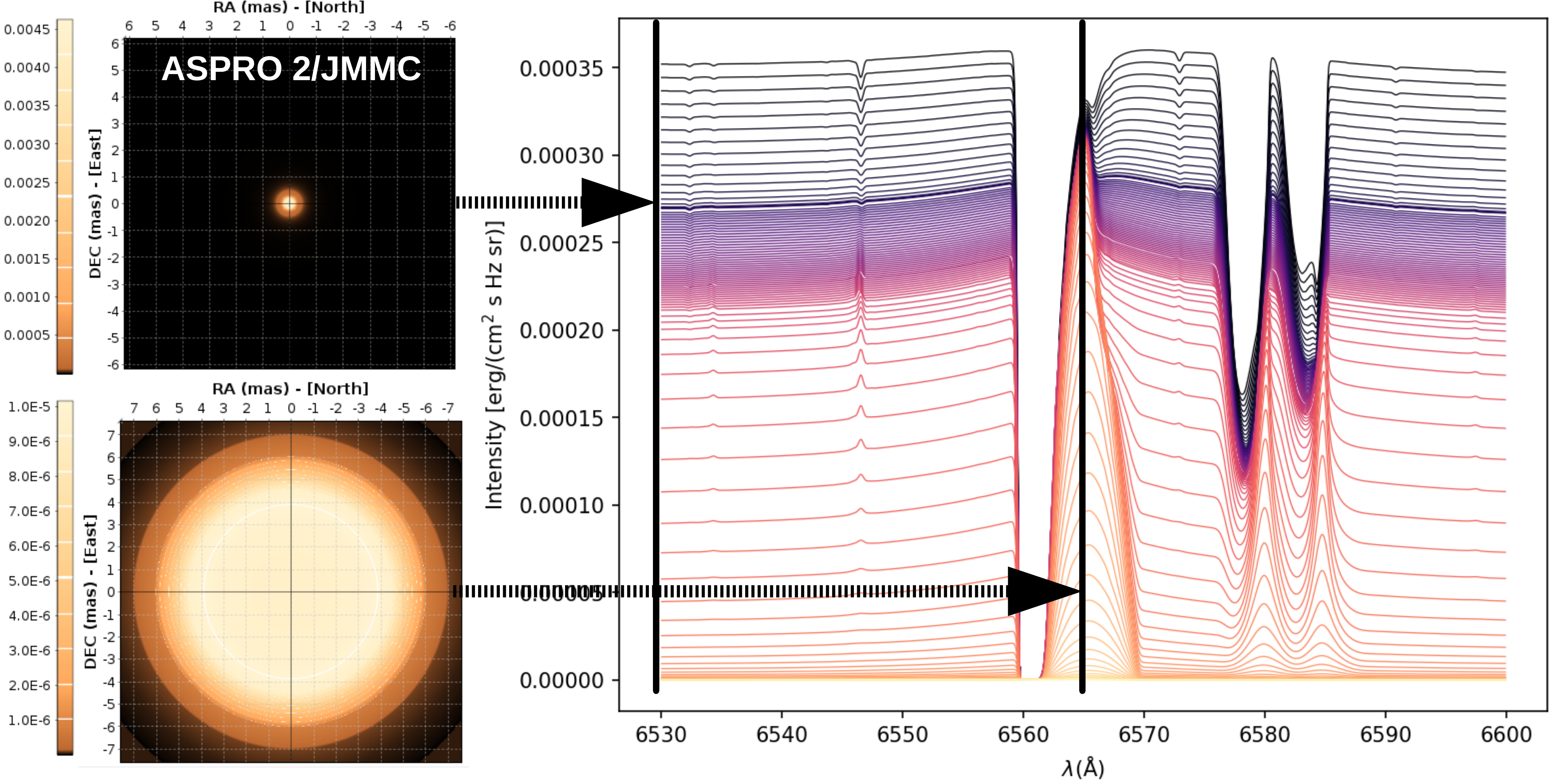
Test CMFGEN for P Cygni’s study



Radiative transfer modeling with the code CMFGEN

- CMFGEN: **spherically symmetric wind (1-D model)**
  - Converting 1-D intensity profiles into 2-D intensity maps

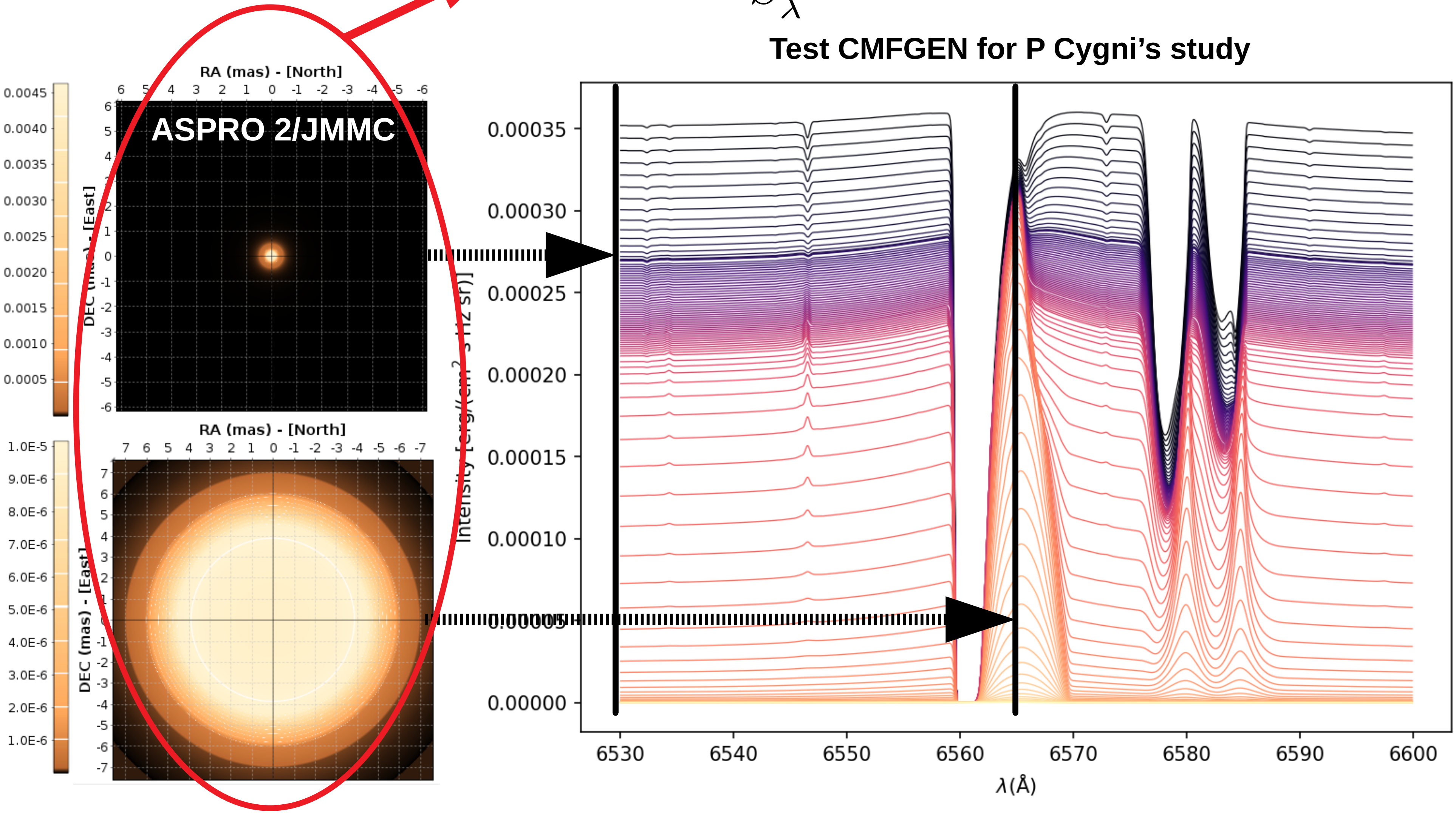
Test CMFGEN for P Cygni’s study



Radiative transfer modeling with the code CMFGEN

$$\widetilde{V}(u, v, \lambda) = \frac{\int\int S(\alpha, \delta, \lambda) \exp\left[-2i\pi(u\alpha + v\delta)\right] d\alpha\, d\delta}{S_\lambda^{\text{total}}}$$

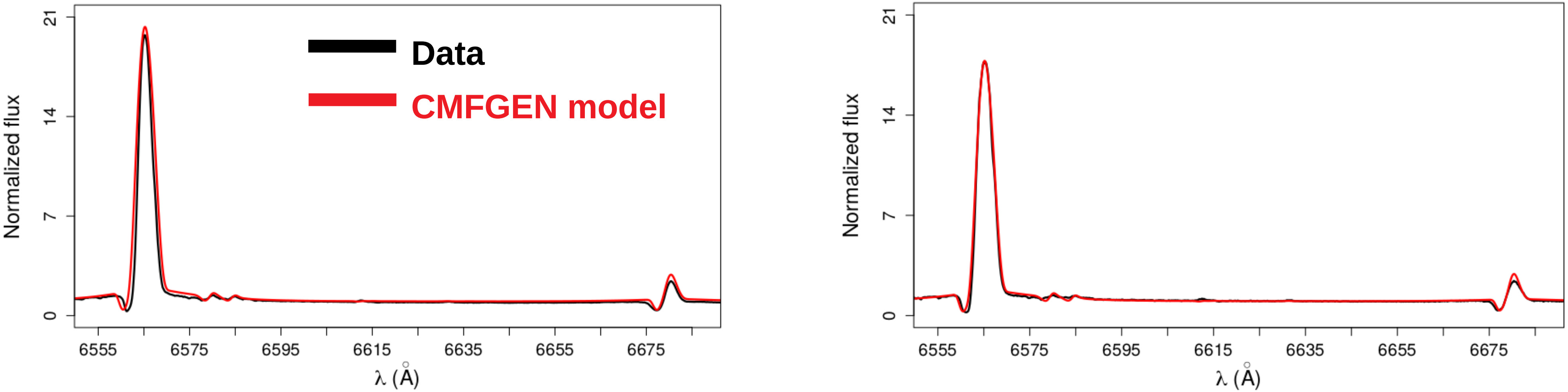
Test CMFGEN for P Cygni's study



Result for P Cygni: spectroscopic modeling and distance estimation

- **“First step”**: physical model (CMFGEN) that reproduces the spectroscopic data

P Cygni (LBV star)



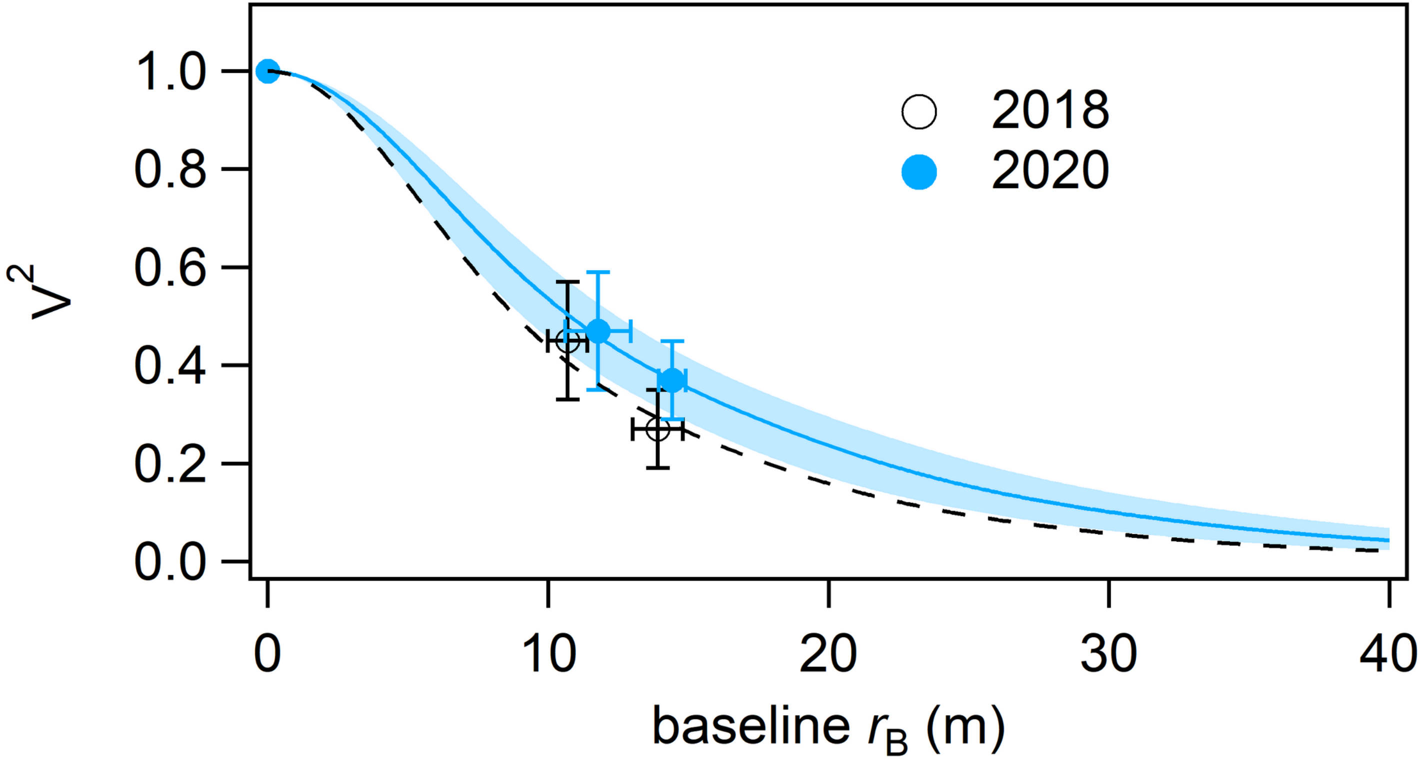
2018 observation: Rivet et al. 2020

2020 observation: de Almeida et al. 2022

$$\dot{M} = 4.0 \text{ x } 10^{-5}\ M_{\odot}/\mathrm{yr} \quad \longrightarrow \quad \dot{M} = 3.3 \text{ x } 10^{-5}\ M_{\odot}/\mathrm{yr}$$

Varying only the **mass-loss rate**: reduction of ~18%

Result for P Cygni: spectroscopic modeling and distance estimation



From modeling the visibility curve:

d = 1.56 ± 0.25 kpc (2018)

d = 1.67 ± 0.26 kpc (2020)

d = 1.61 ± 0.18 kpc

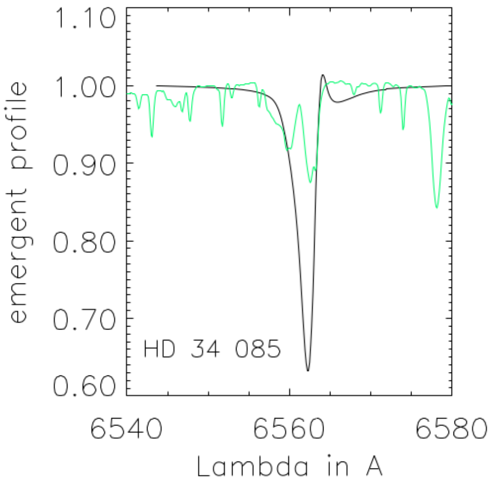
Gaia eDR3: ~ 1.60 kpc
1.60 (+0.21 – 0.17) kpc

Result for Rigel: spectroscopic modeling and distance estimation

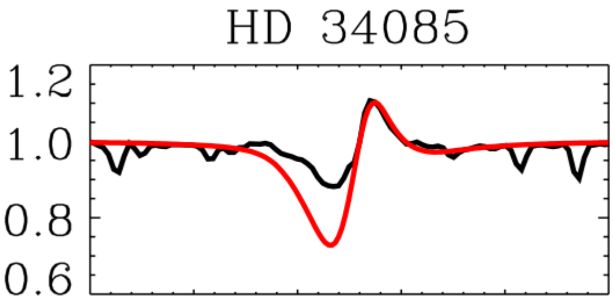
Rigel (B supergiant)

- **Previous** quantitative spectroscopic studies on Rigel:

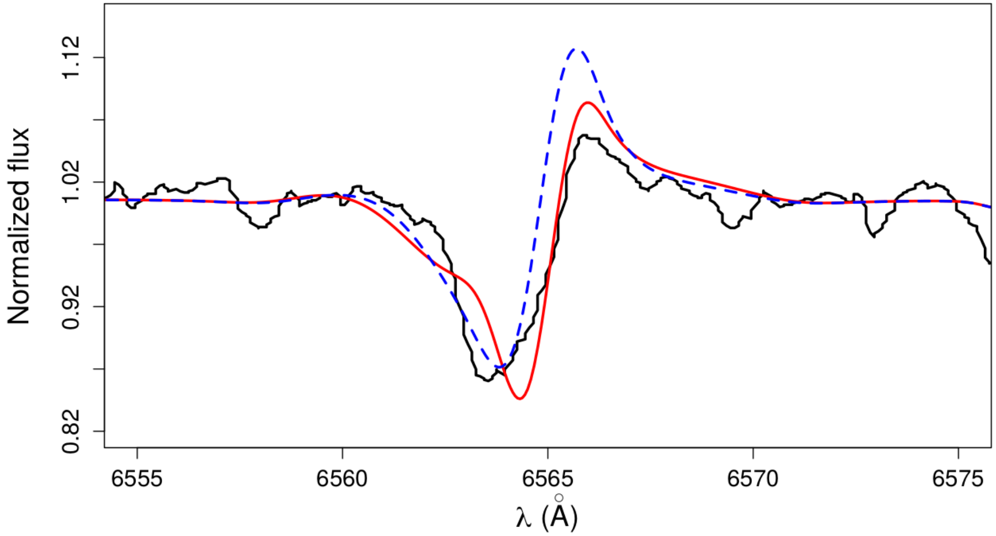
Markova et al. (2008):



Haucke et al. (2018):



de Almeida et al. (2022):



- **Our modeling** of Rigel Hα profile (2020)

Result for P Cygni: spectroscopic modeling and distance estimation

Rigel (B supergiant)

- **β:** wind velocity law exponent

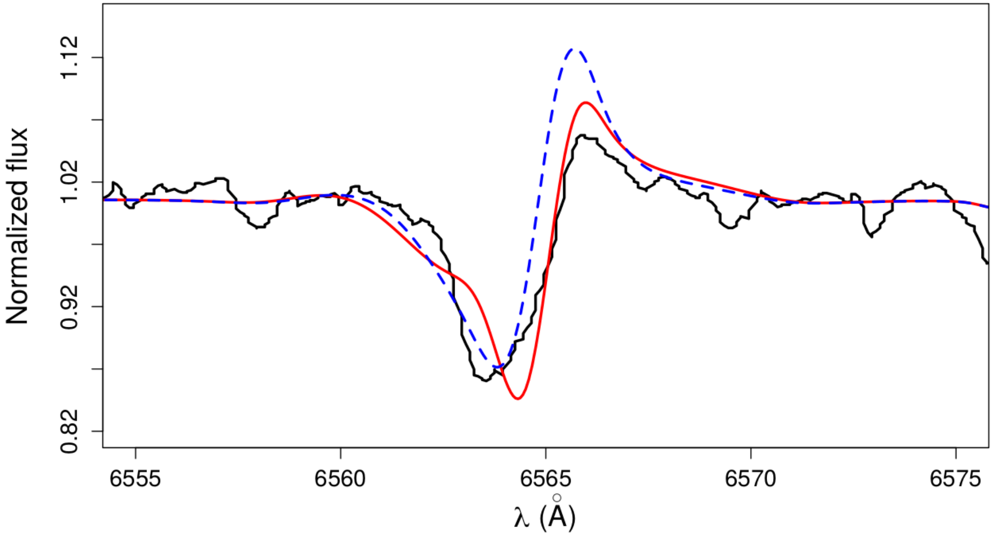
━ β = 1.0
╍ β = 1.5

No significant effect on the inferred distance:
d = 0.26 ± 0.02 kpc

- **Hippacos distance: ~ 0.27 kpc (0.27 ± 0.03 kpc)**

de Almeida et al. (2022):

- **Our modeling** of Rigel Hα profile (2020) →



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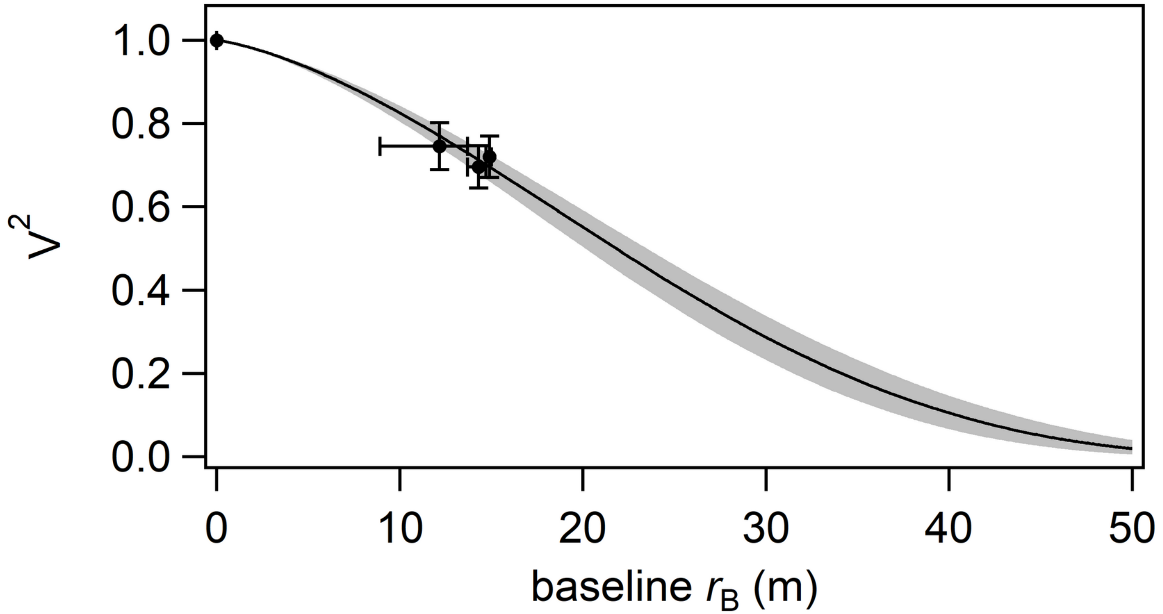
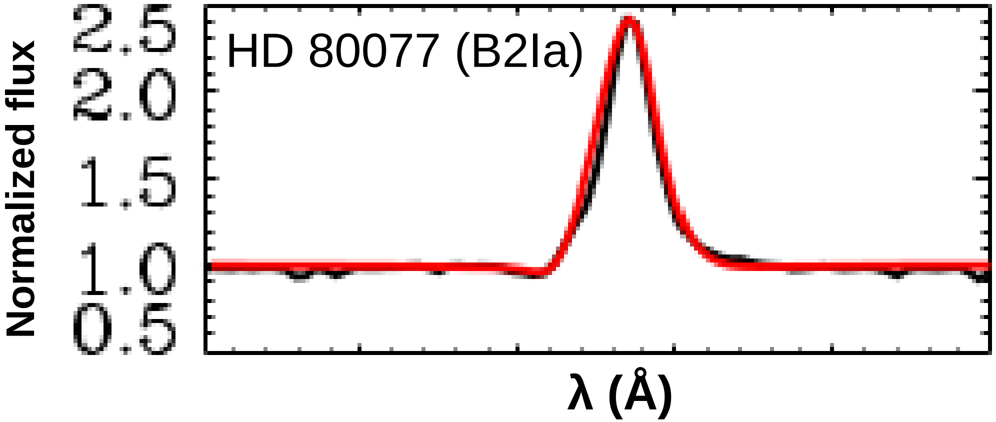


Final remarks and perspectives

- ***“Testing the wind momentum luminosity relation with II of blue supergiants”***
- So, have we tested that? **No** **(two stars: P Cygni and Rigel).**
- Nevertheless, in these 2 articles, we set a **method for distance estimation**
- To test the WLR(s) we have to observe a large sample of blue supergiant: **~10 objects (II + Hα spectroscopy); to be modeled with CMFGEN**
- Initial sample to be built.
- Haucke et al. (2018): 19 BSGs modeled with radiative transfer models (FASTWIND)



Final remarks and perspectives

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- To test the WLR(s) we have to observe a large sample of blue supergiant:
  ~10 objects (II + Hα spectroscopy); to be modeled with CMFGEN
- Initial sample to be built.
- **An easy task?** **Not at all**...blue supergiants show high variability in the Hα line.

↓

Interesting!

(i) Testing the validity of WLR as a reliable distance estimation

(ii) Possible new insights about the wind properties of massive stars

Final remarks and perspectives

Thank you / Merci!

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