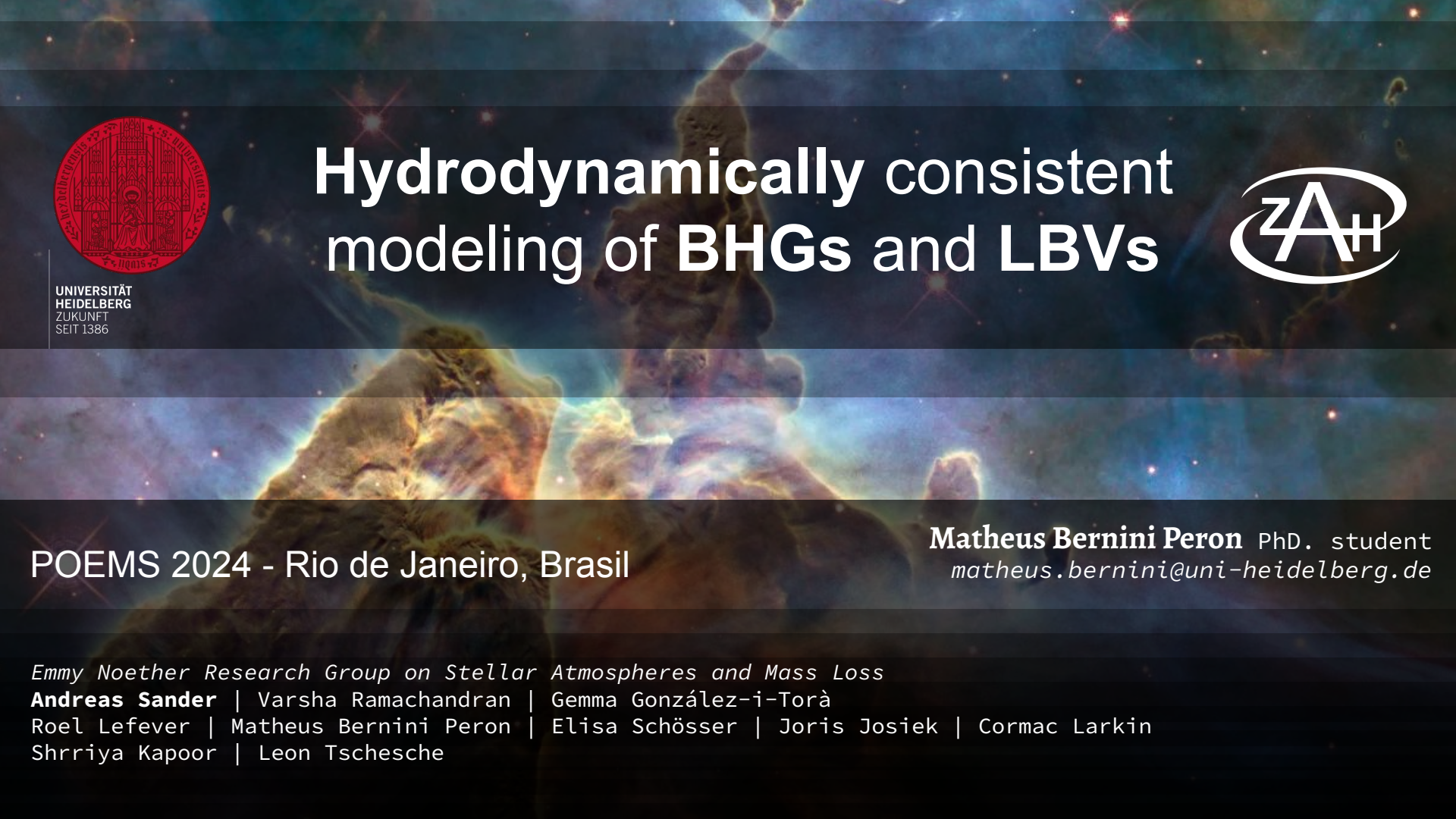

Hydrodynamically consistent modeling of **BHGs** and **LBVs**

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

POEMS 2024 - Rio de Janeiro, Brasil

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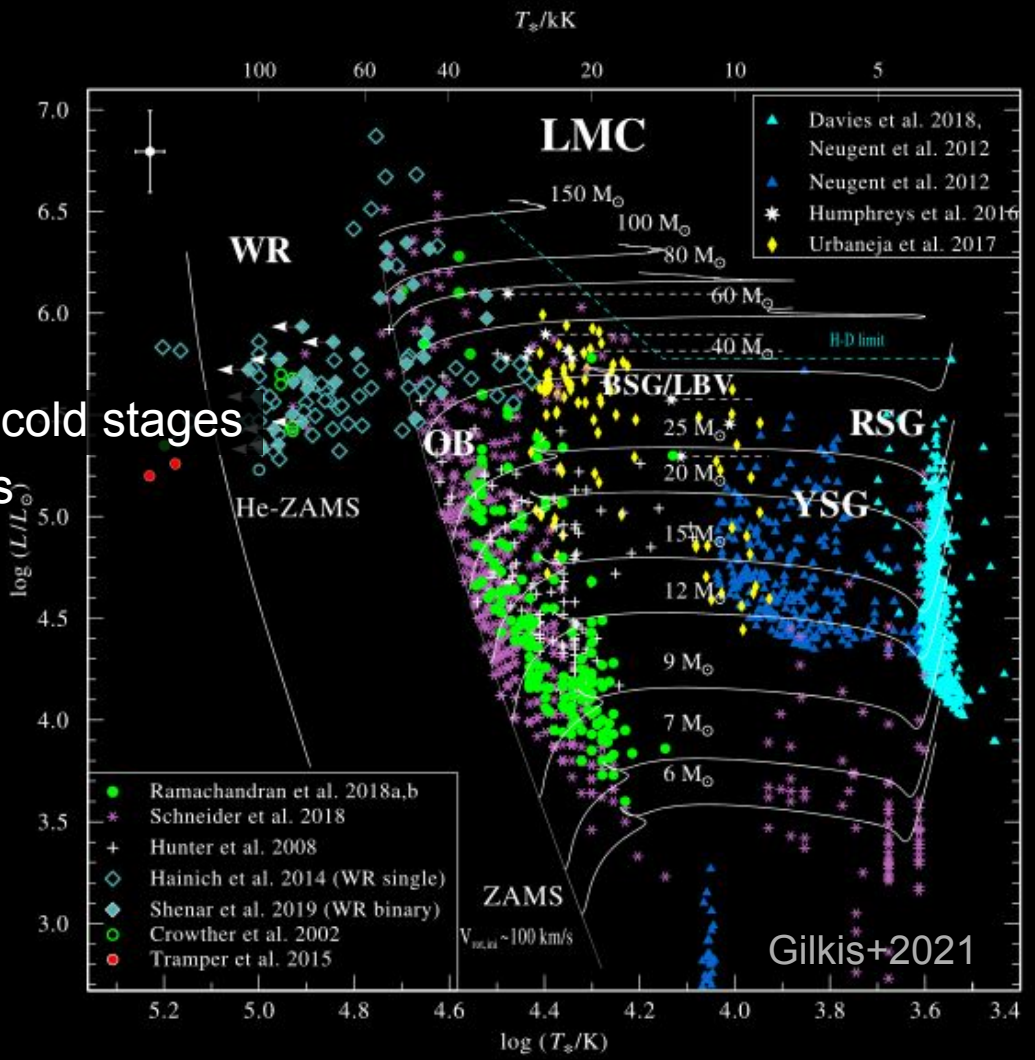
Shrriya Kapoor | Leon Tschesche

Why the “cool hot stars” are important?

- Variety of stars and origins
- Connection between MS and cold stages
- Edge of radiative-driven winds
- Interesting phenomena



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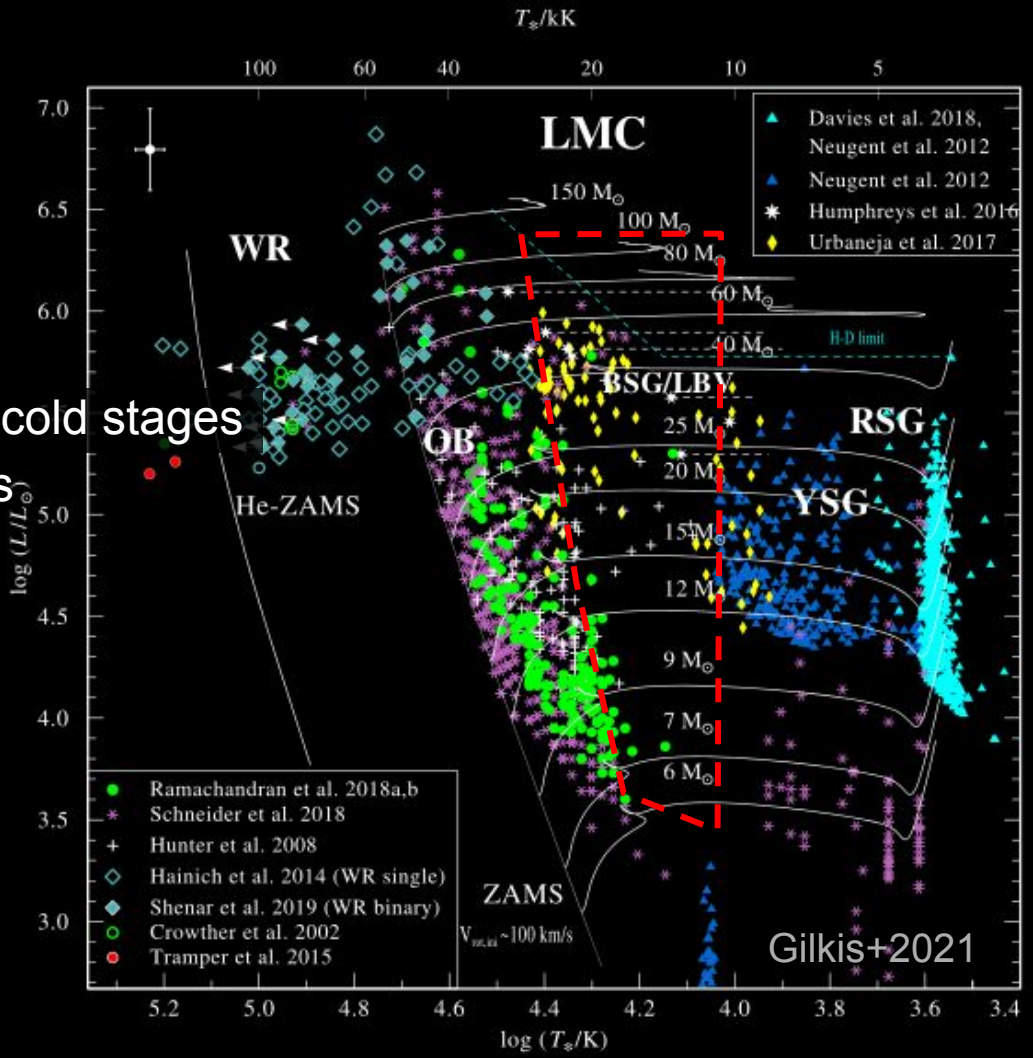
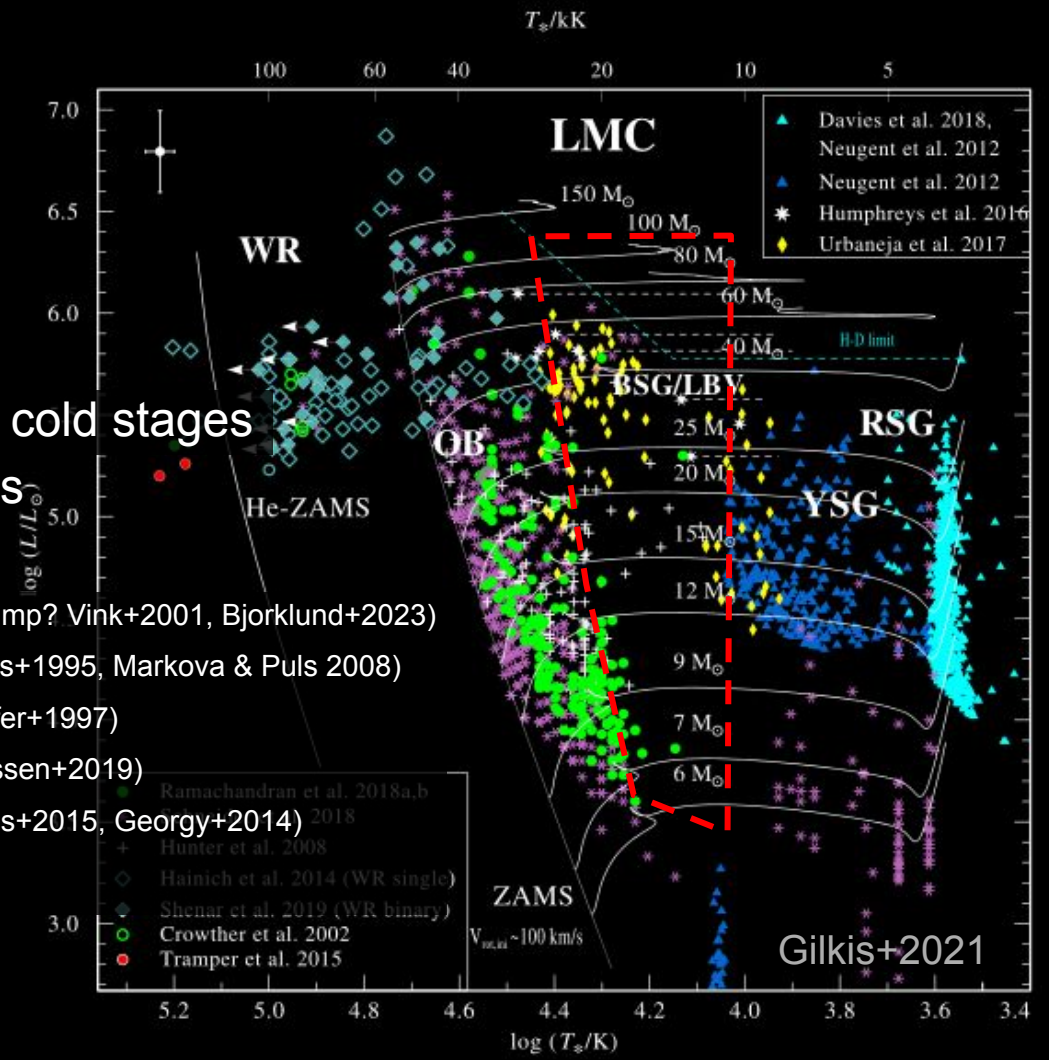
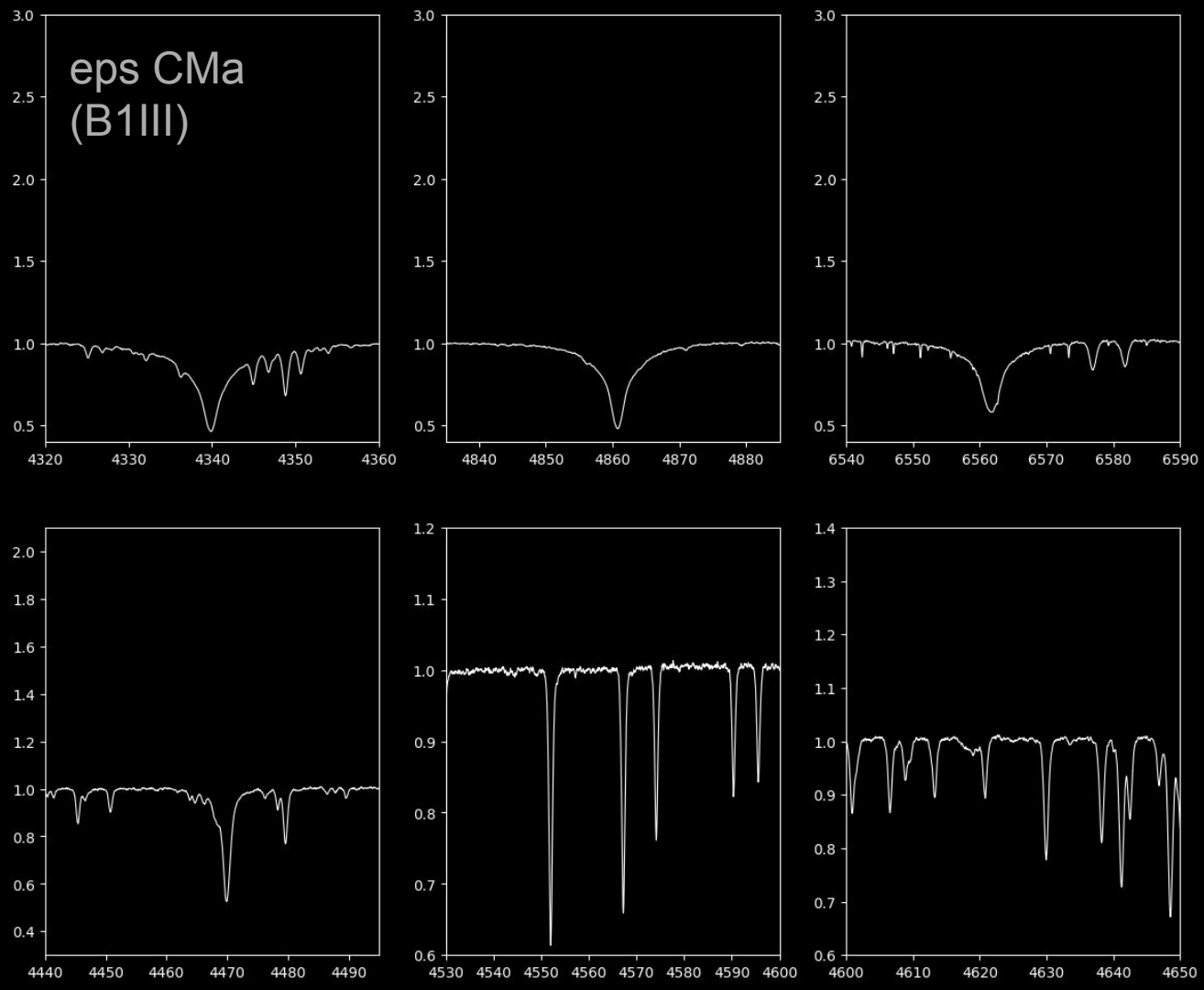


Why the “cool hot stars” are important?

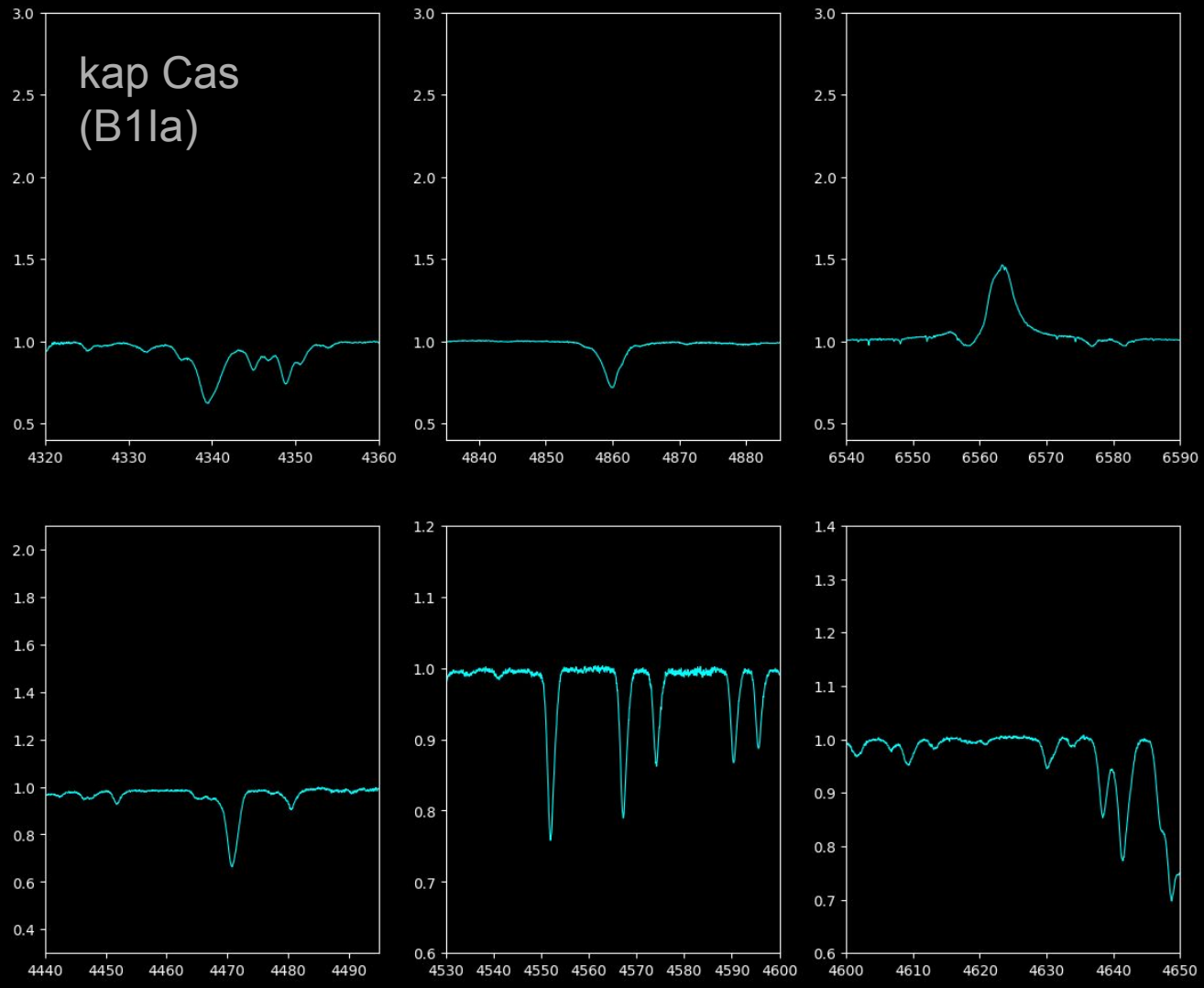
- Variety of stars and origins
- Connection between MS and cold stages
- Edge of radiative-driven winds
- Interesting phenomena
  - Bi-stability jump (to jump or not to jump? Vink+2001, Bjorklund+2023)
  - Drop in rotational velocity (Lamers+1995, Markova & Puls 2008)
  - Drop of X-ray detection (Berghoefer+1997)
  - Change in wind clumping? (Driessen+2019)
  - Pulsational variability (a Cyg, Kraus+2015, Georgy+2014)
  - LBVs, B[e], …



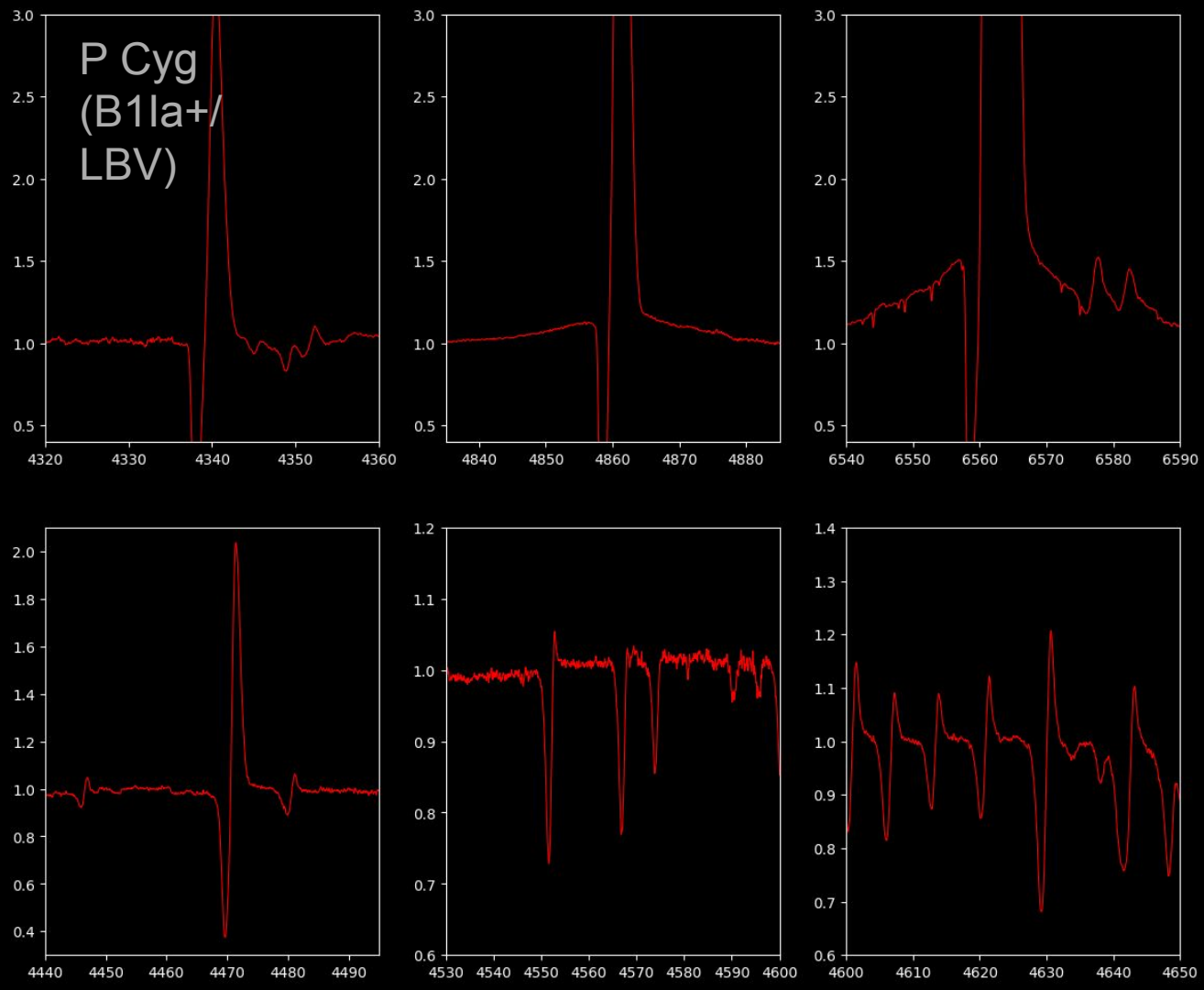
B-hypergiants (BHGs)



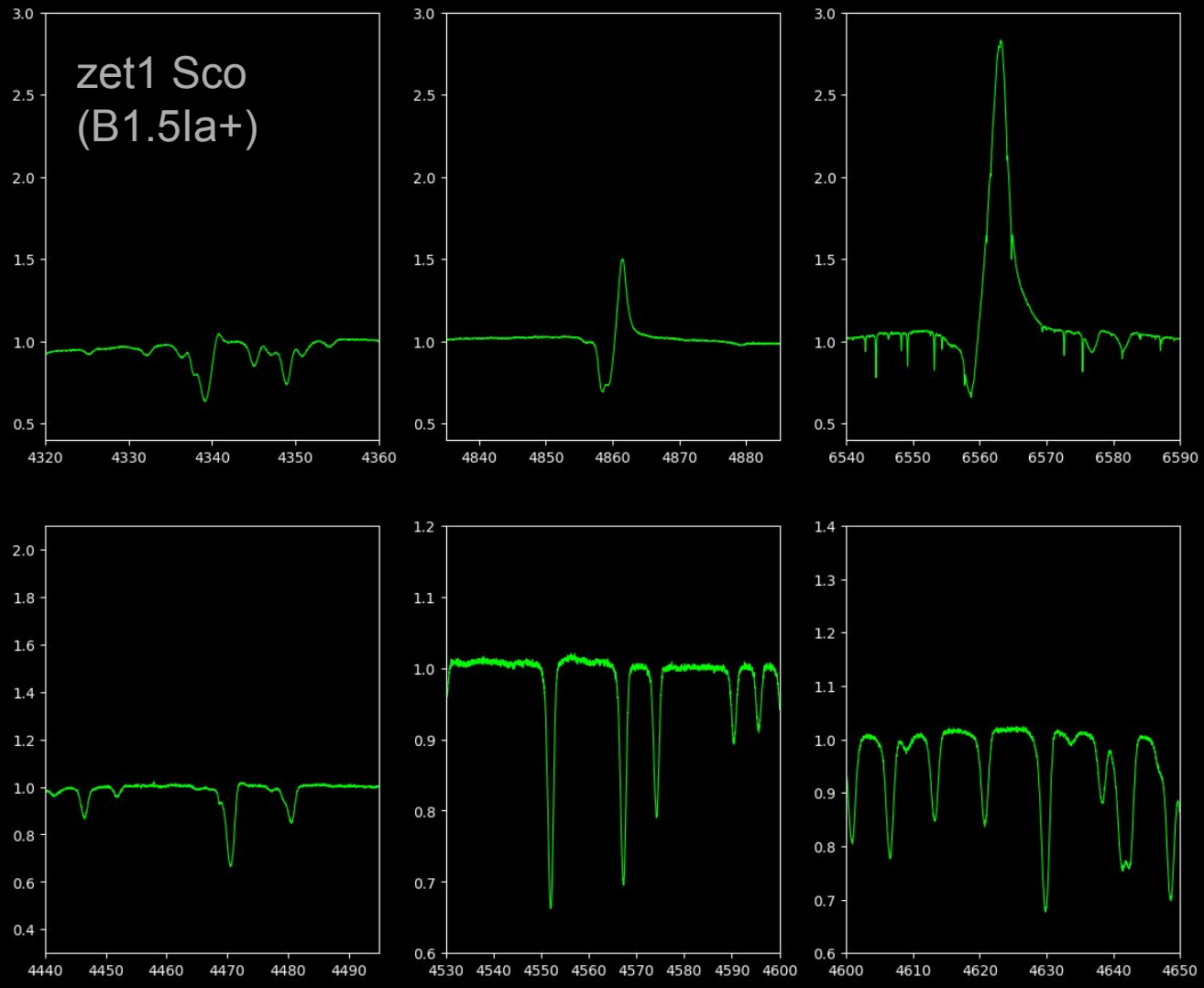
B-hypergiants (BHGs)



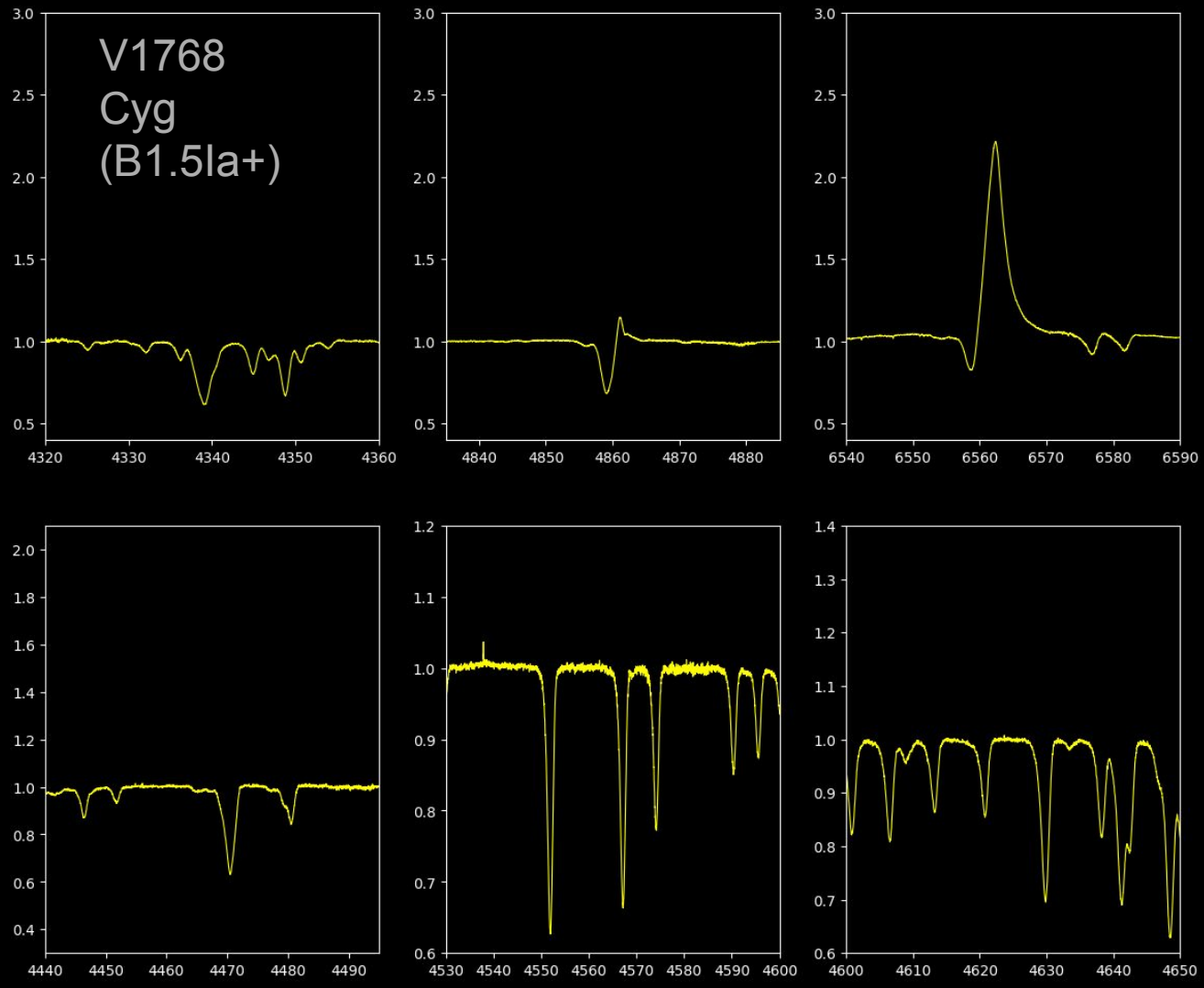
B-hypergiants (BHGs)



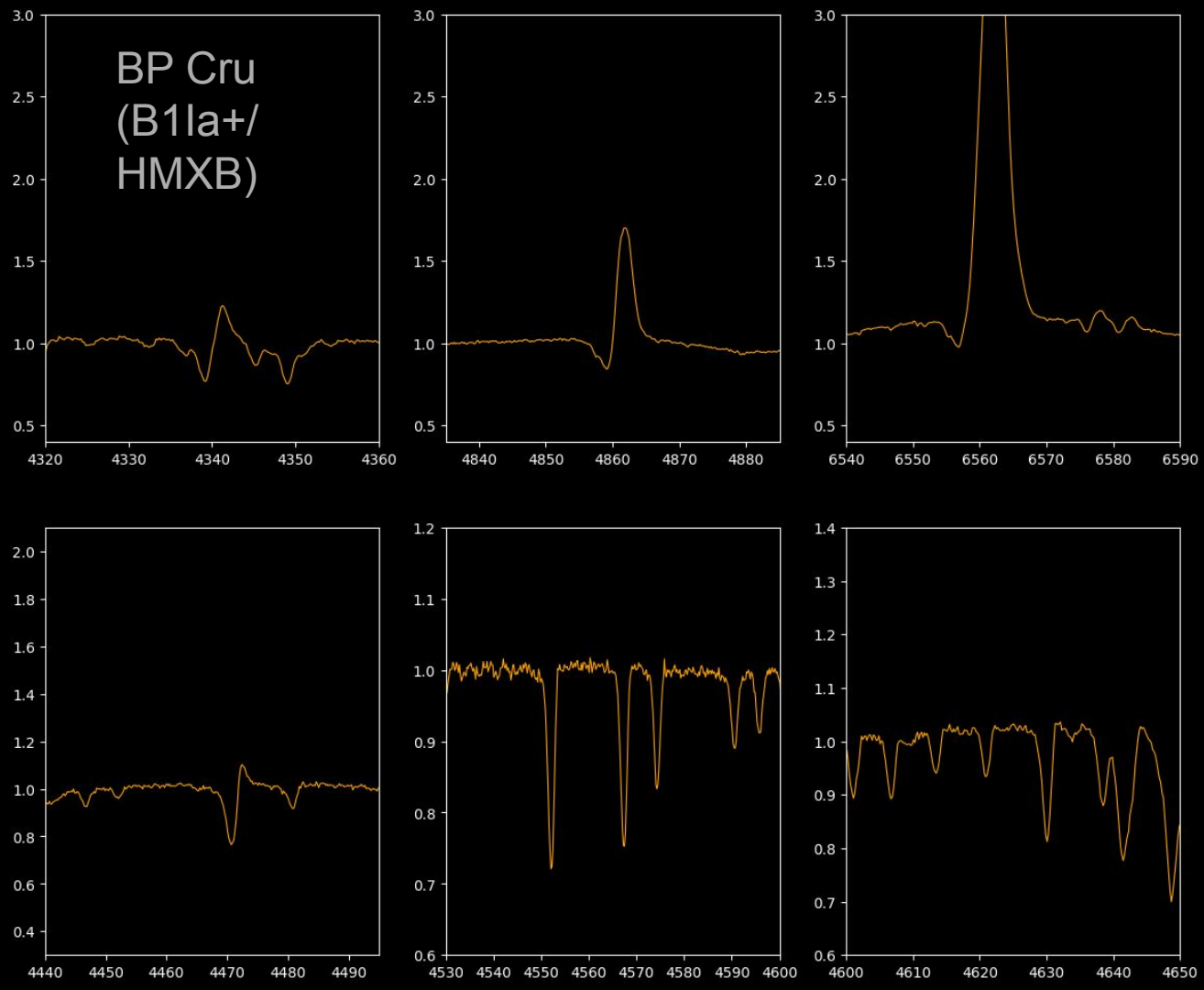
B-hypergiants (BHGs)



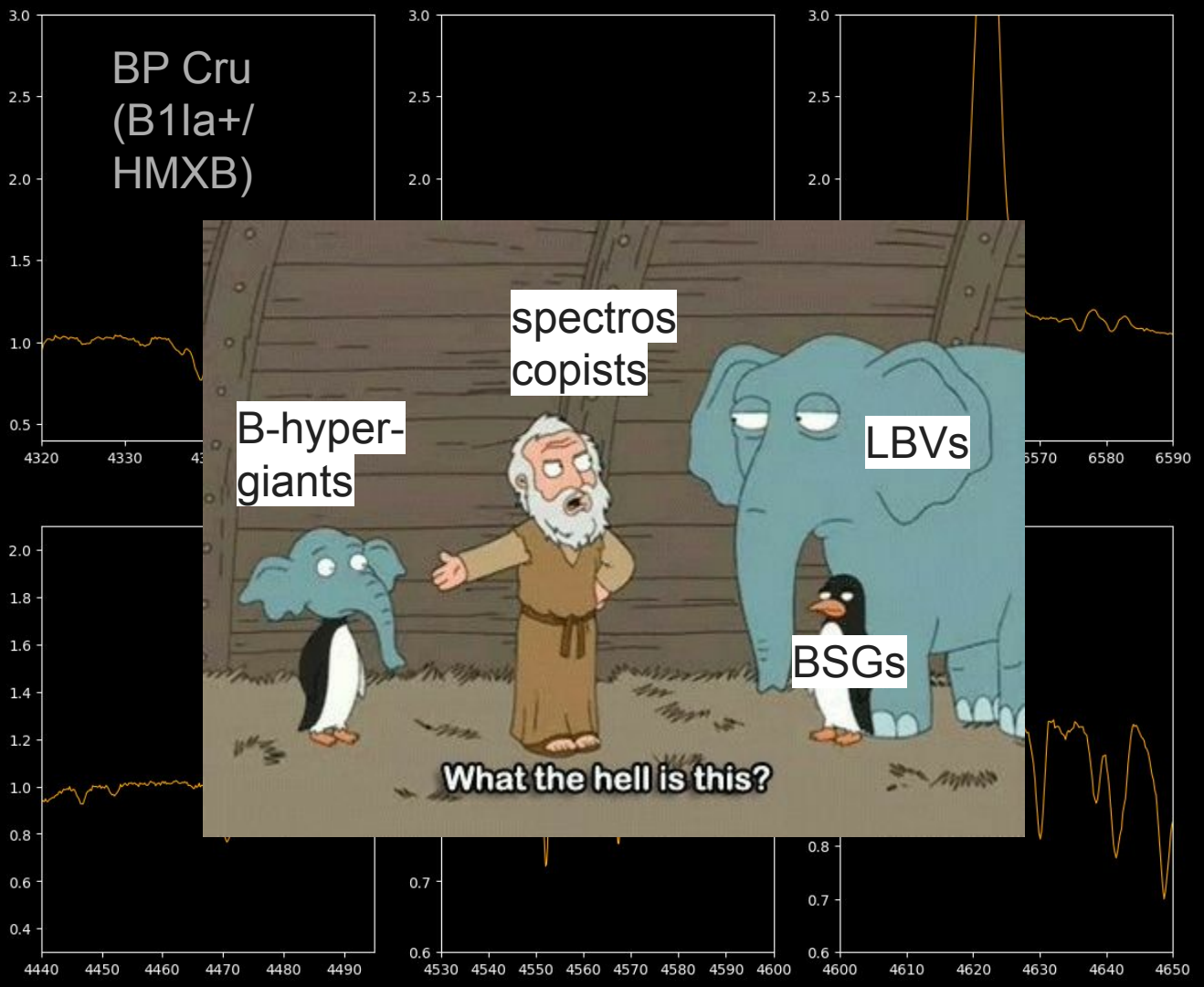
B-hypergiants (BHGs)



B-hypergiants (BHGs)



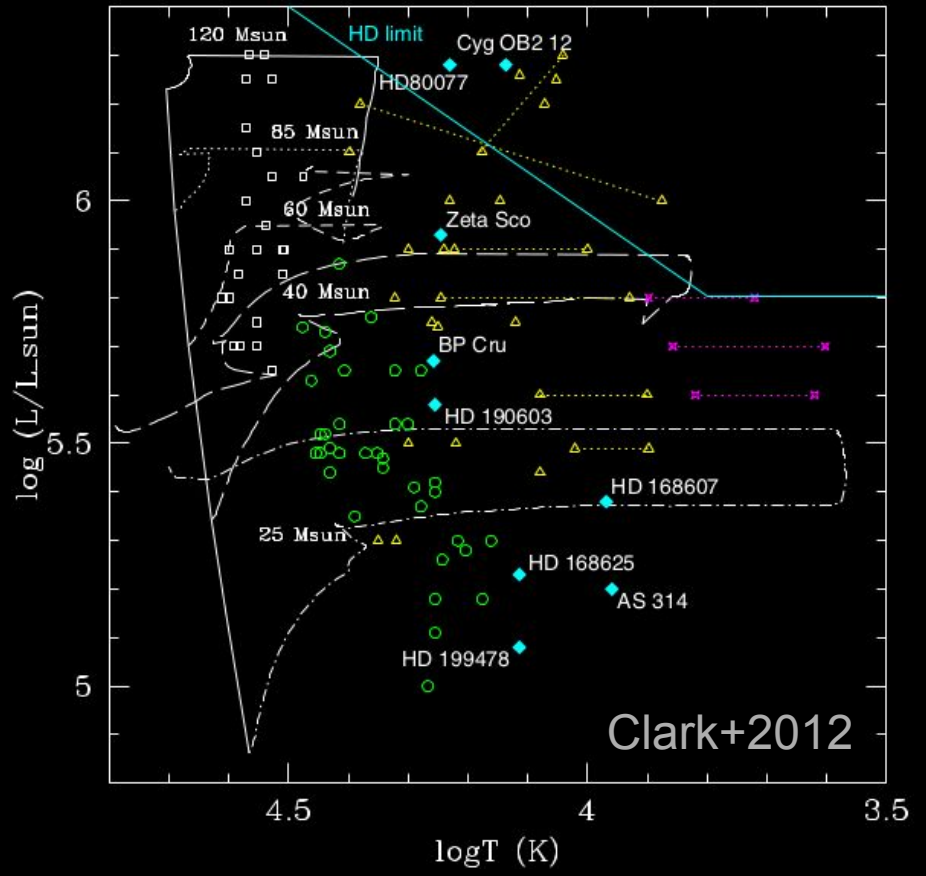
B-hypergiants (BHGs)

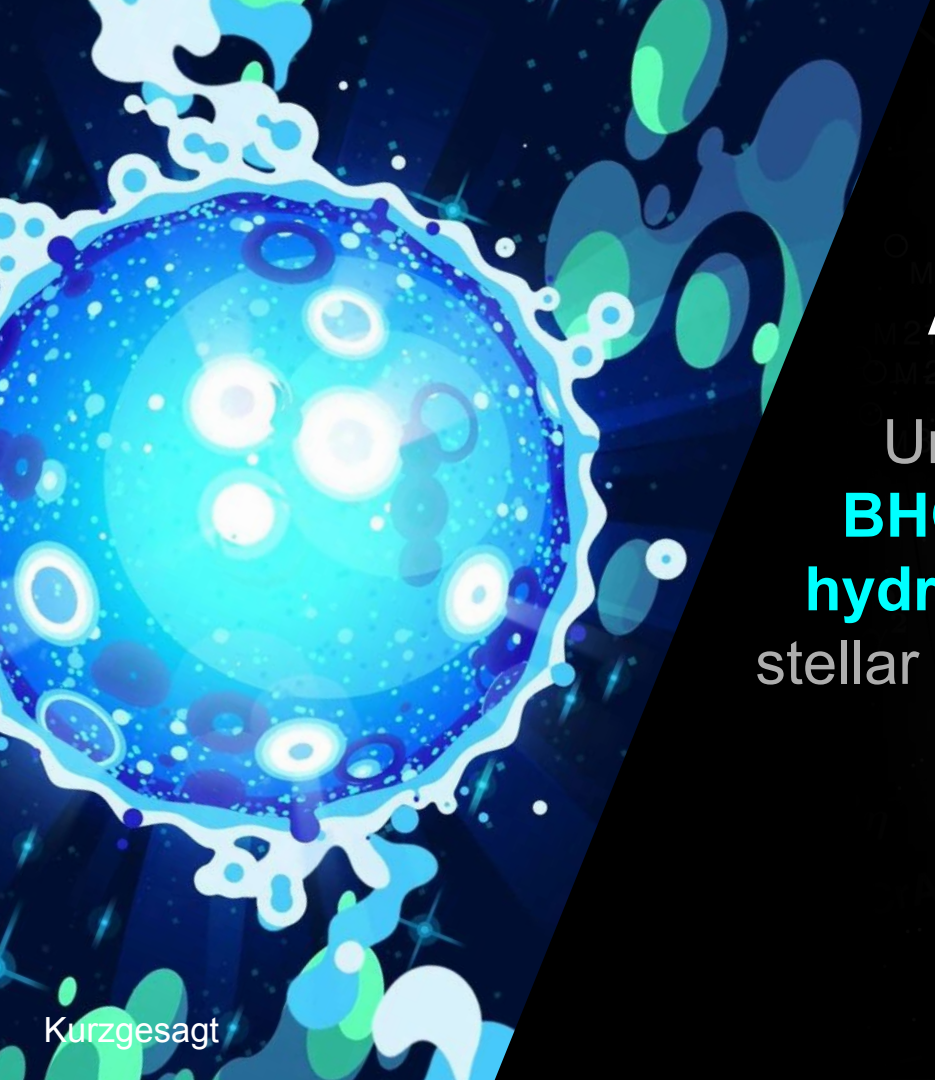


Proper definition of BHG:
van Genderen+1982,
Clark+2012

B-hypergiants (BHGs)

- ~30 known BHGs in the local group
  - Clark+2012, Vink+2023 (XSU), Evans+2015 (VFTS), vanGenderen+1982
- Low binarity fraction
  - Oskinova+2017
- Seldom earlier than B1
  - two exceptions in LMC (Vink+2023, Evans+2015)
- Approaching to the Humphreys-Davidson limit
- Quiescent LBVs?
  - e.g. HD168625, Mahy+2022





Aim:

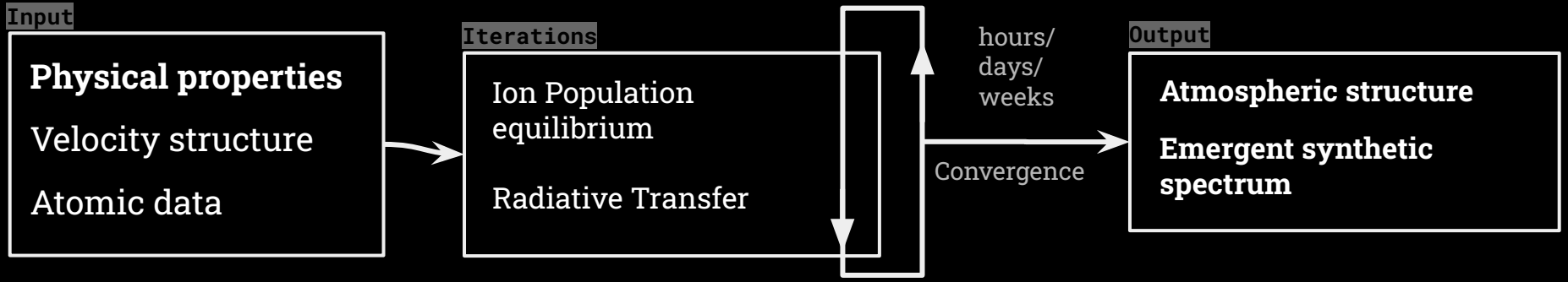
Understanding the **winds of BHGs** (and some LBVs) using **hydrodynamically consistent** stellar atmosphere code **PoWR$_{HD}$**

Kurzgesagt

Timothy Parker/USFWS

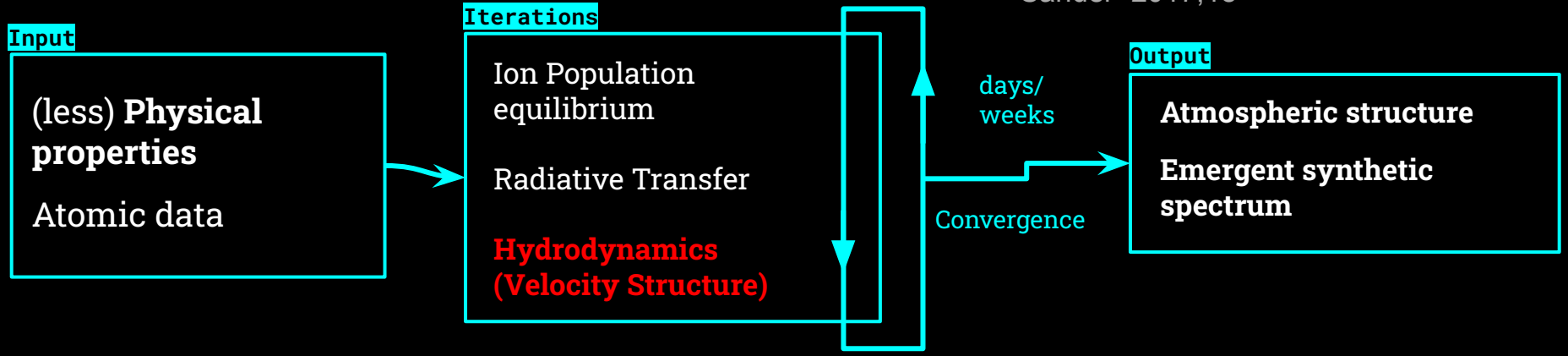
Modeling their atmosphere

Gräfener+2002



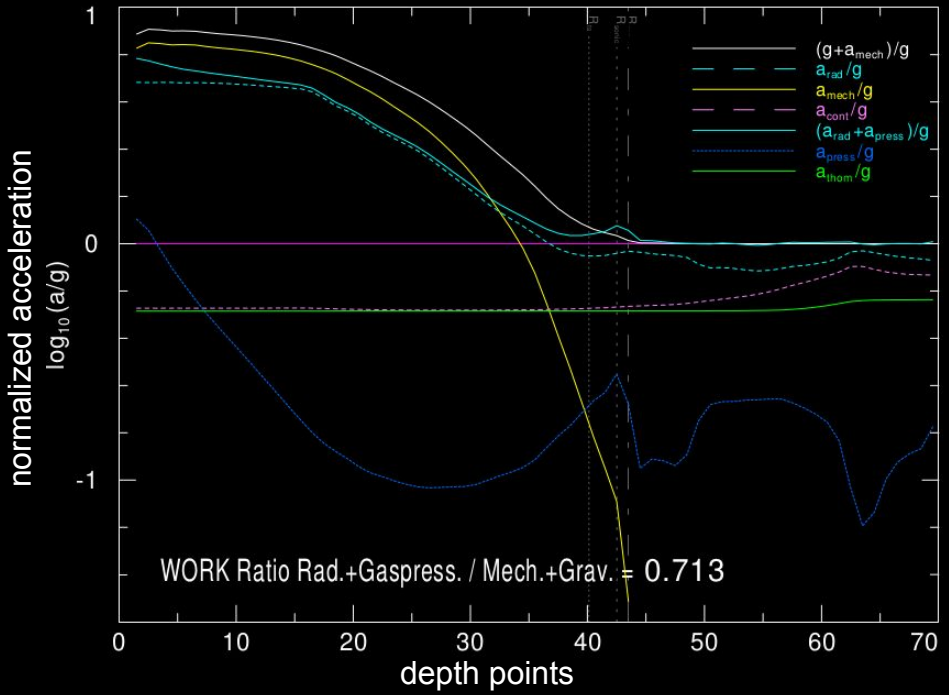
Modeling their atmosphere

Gräfener+2002,
Sander+2017,18



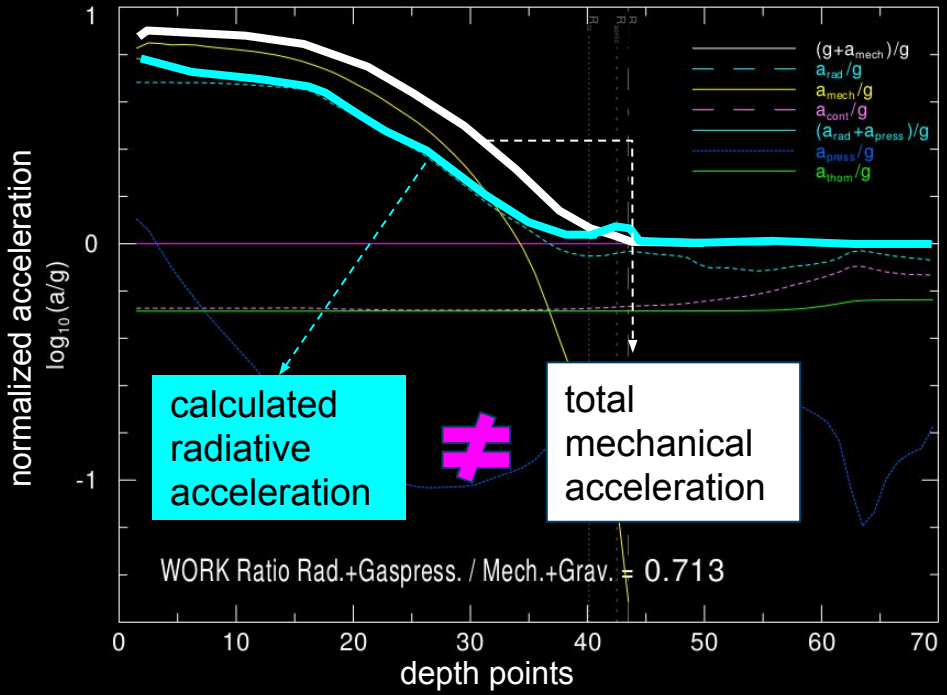
Modeling their atmosphere

Hydrodynamically Inconsistent



Modeling their atmosphere

Hydrodynamically Inconsistent



Computed from the transitions and radiative field

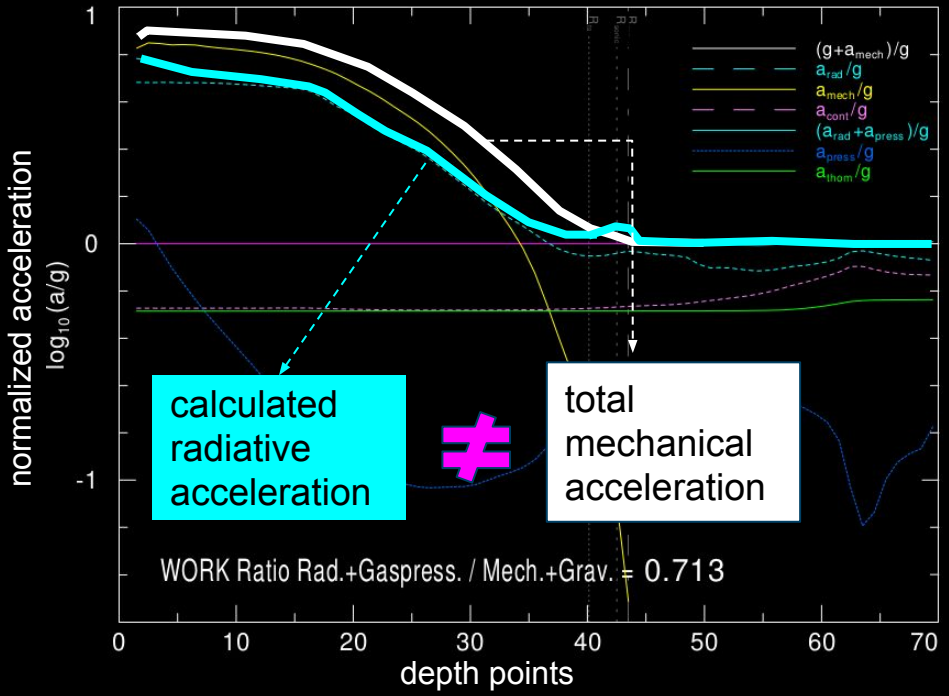
$(a_{rad} + a_{press})$

Inertia term and gravity

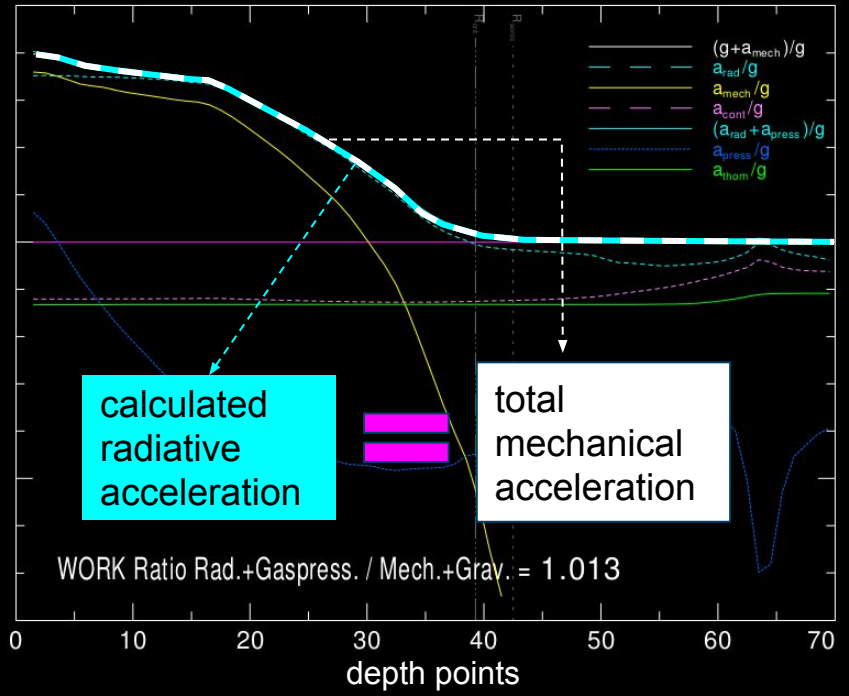
$(g + a_{mech})$

Modeling their atmosphere (but consistently)

Hydrodynamically Inconsistent



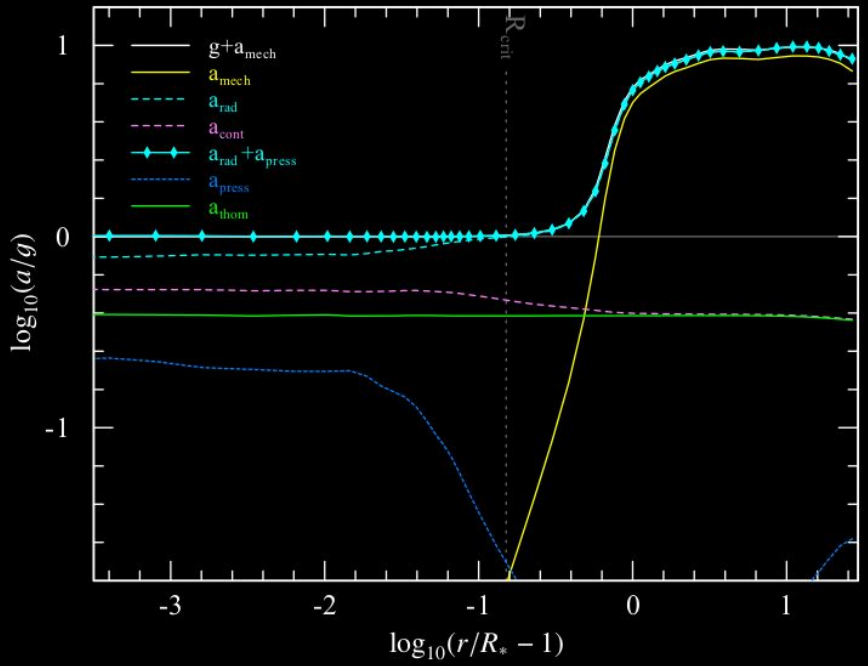
Hydrodynamically Consistent



Coupling hydrodynamics with comoving frame radiative transfer

I. A unified approach for OB and WR stars

A. A. C. Sander, W.-R. Hamann, H. Todt, R. Hainich, and T. Shenar

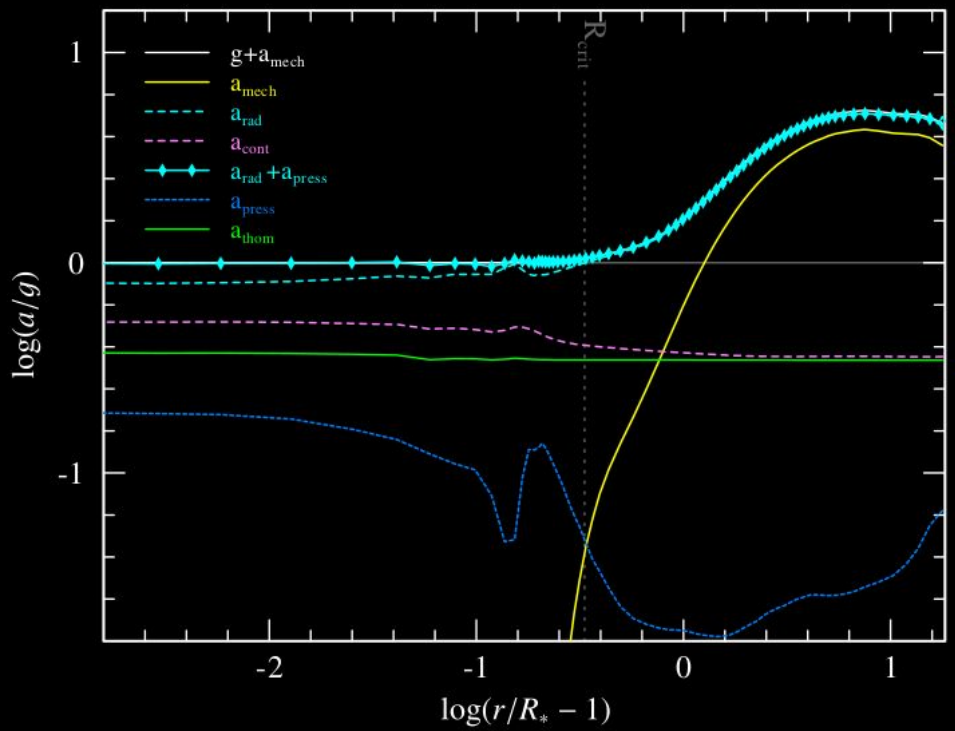


Sander+2017: Z Pup (**O4laf+**)

Coupling hydrodynamics with comoving frame radiative transfer

II. Stellar wind stratification in the high-mass X-ray binary Vela X-1

A. A. C. Sander[1], F. Fürst[2], P. Kretschmar[2], L. M. Oskinova[1], H. Todt[1], R. Hainich[1], T. Shenar[1], and W.-R. Hamann[1]



Sander+2018: Vela X-1 (**B0.5Ia** / HMXB)

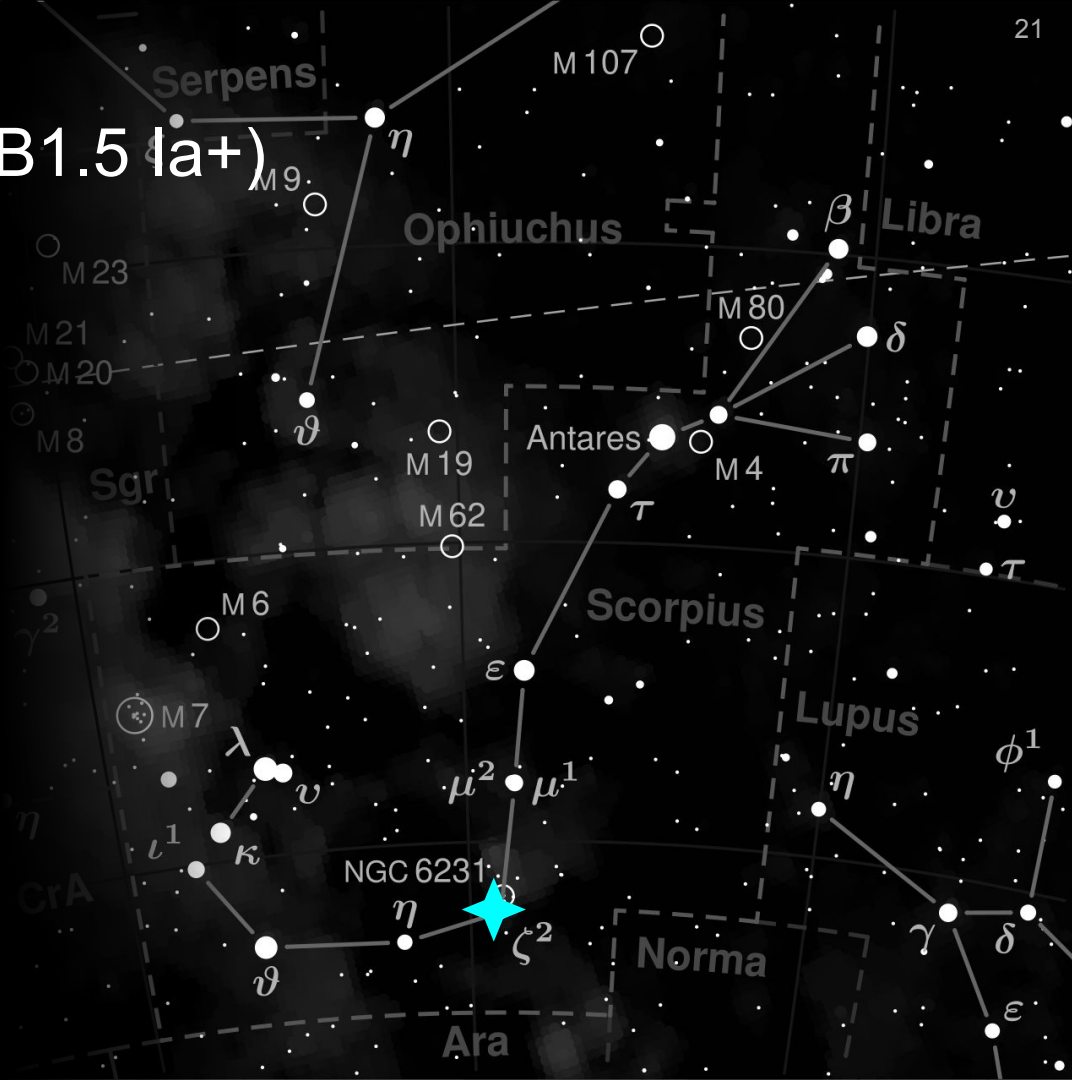
This is a scorpion glowing under UV radiation

Consistent modelling of Z_1 Scorpii (B1.5Ia+)

Timothy Parker/USFWS

Exemplary case: Z_1 Sco (B1.5 Ia+)

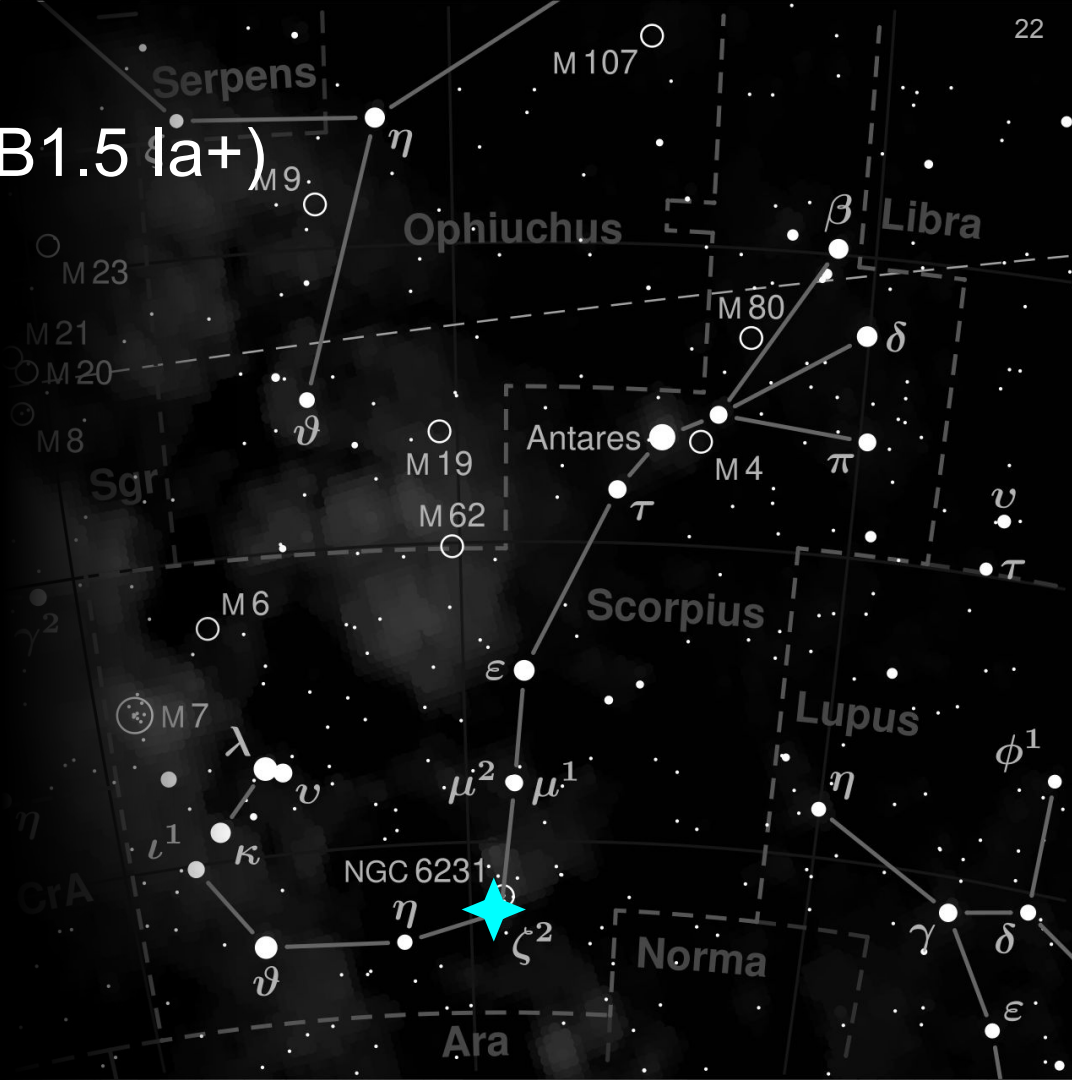
- “bona fide” (early) BHG
- Wide high-quality spectral coverage
  - FUV (FUSE)
  - FIR (ISO)

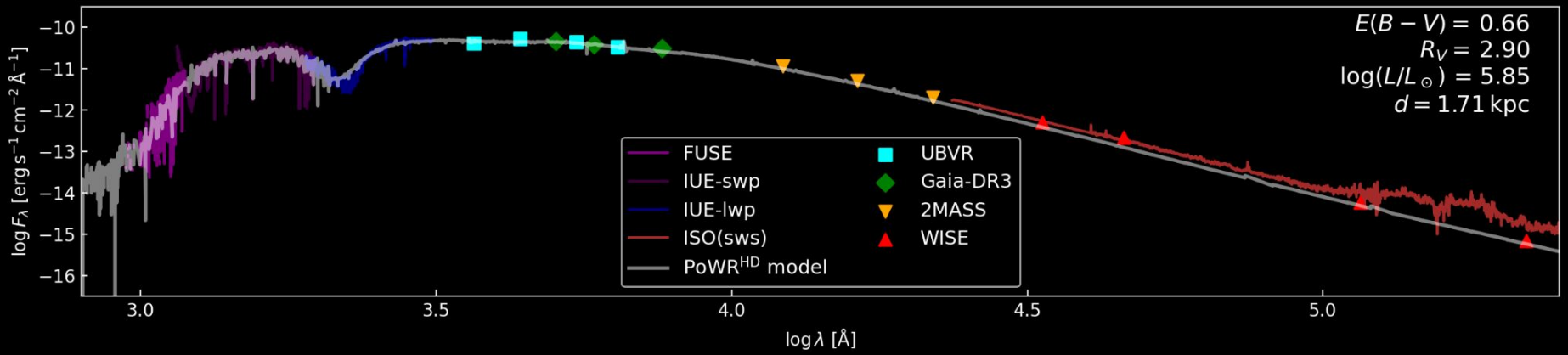


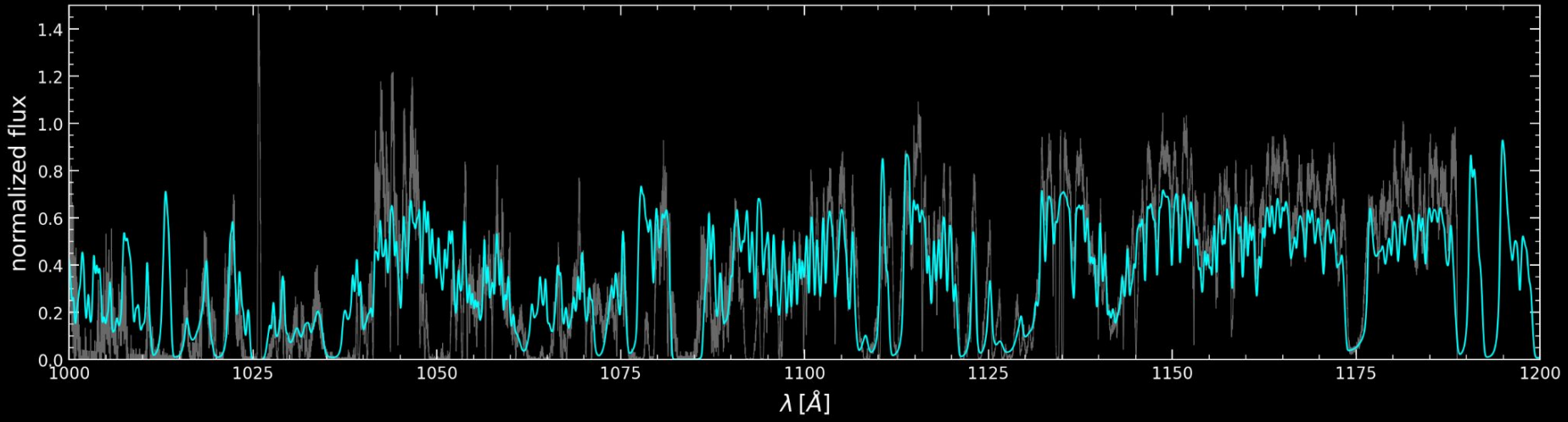
Exemplary case: Z_1 Sco (B1.5 Ia+)

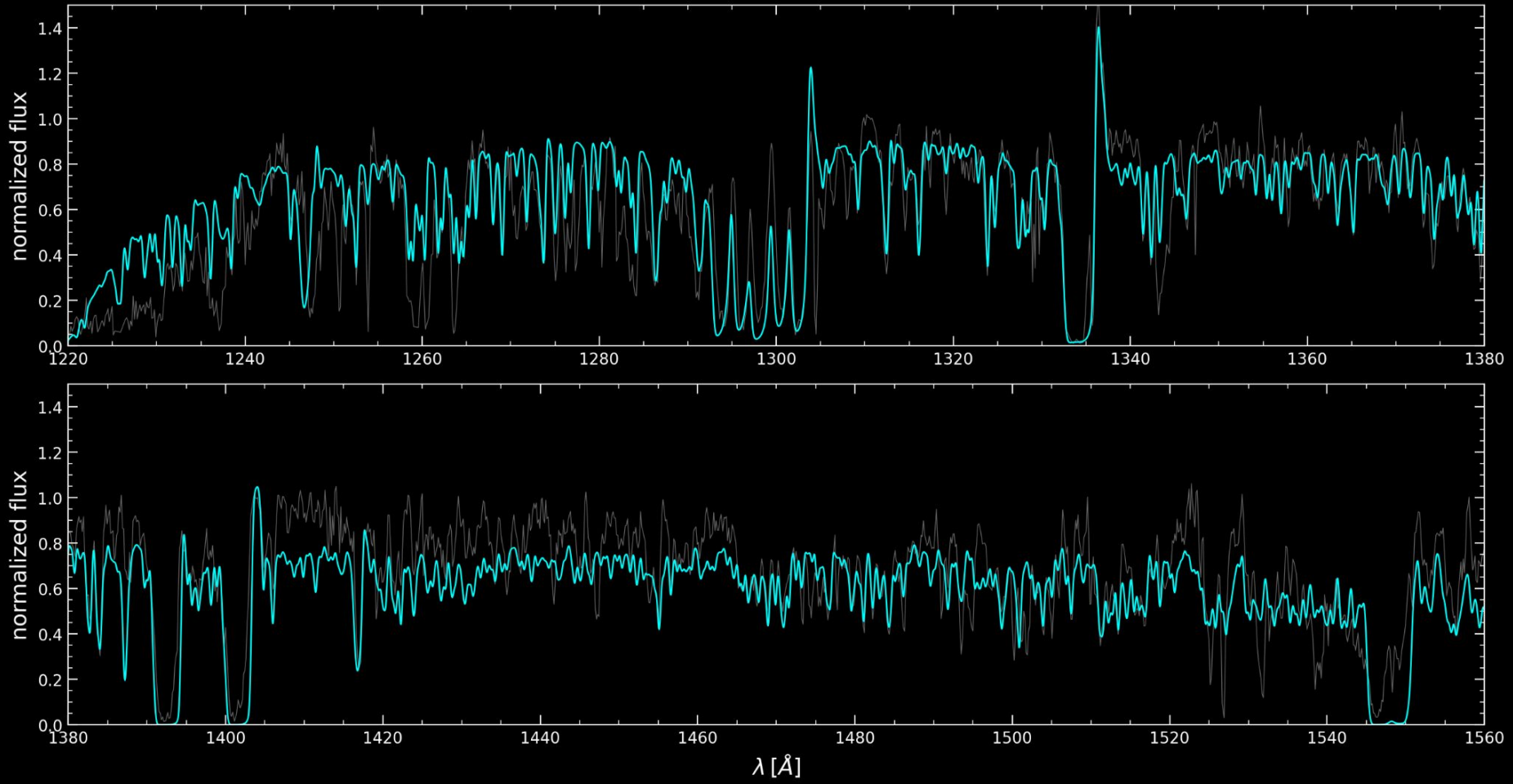
- “bona fide” (early) BHG
- Wide high-quality spectral coverage
  - FUV (FUSE)
  - FIR (ISO)

Perfect for a pilot study on consistent models of BHGs




$E(B-V) = 0.66$
$R_V = 2.90$
$\log(L/L_\odot) = 5.85$
$d = 1.71$ kpc
FUSE
IUE-swp
IUE-lwp
ISO(sws)
PoWR^{HD} model
UBVR
Gaia-DR3
2MASS
WISE
$\log F_\lambda$ [erg s^{-1} cm^{-2} Å^{-1}]
$\log\lambda$ [Å]


normalized flux
λ [Å]


normalized flux
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1220
1240
1260
1280
1300
1320
1340
1360
1380
normalized flux
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560
λ [Å]

(By the way… X-rays!)

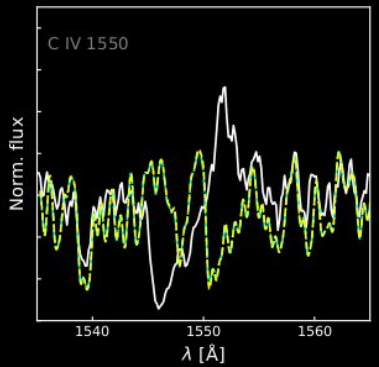
A&A, 677, A50 (2023)
https://doi.org/10.1051/0004-6361/202346469

Astronomy & Astrophysics

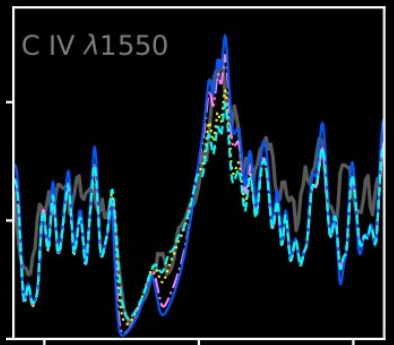
Bernini-Peron+2023

Clumping and X-rays in cooler B supergiant stars

M. Bernini-Peron[1,2], W. L. F. Marcolino[2], A. A. C. Sander[1], J.-C. Bouret[3], V. Ramachandran[1], J. Saling[4], F. R. N. Schneider[4,1], L. M. Oskinova[5], and F. Najarro[6]



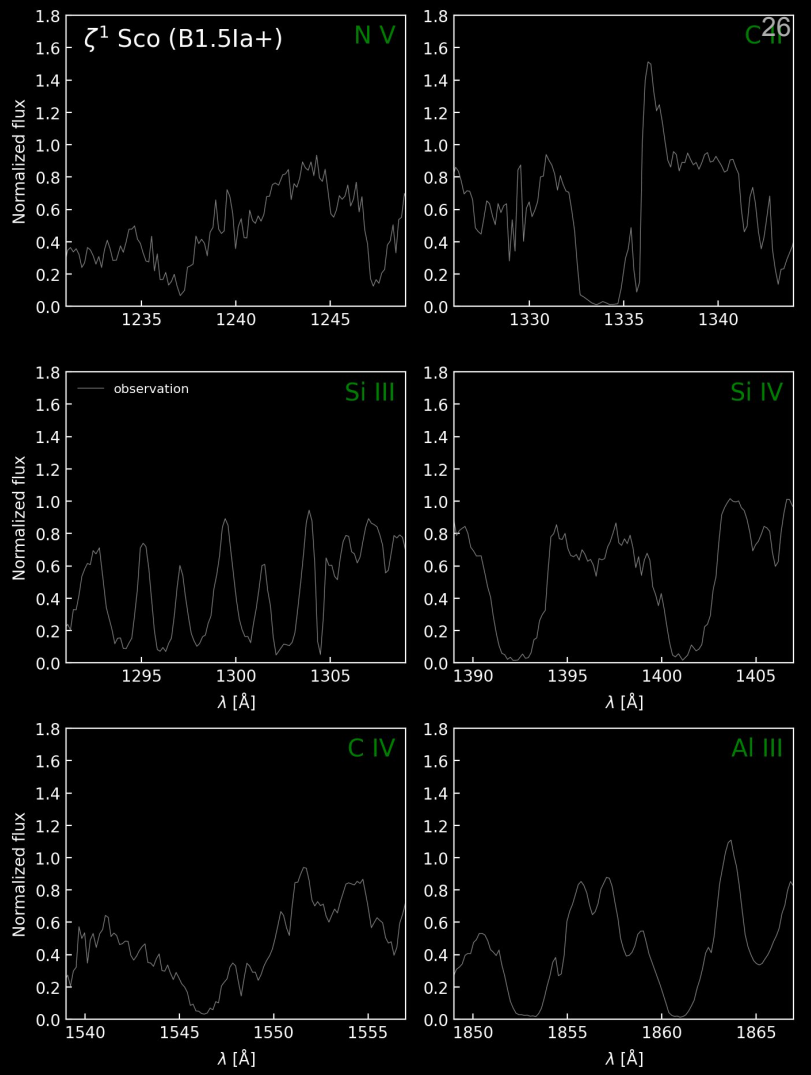
X-rays
in the wind



Late BSGs models need X-rays!

X-rays in Z_1 Sco

- No X-ray detection…
  - Upper limit = log (L_X/L) = 7.3 (Berghoefer+1997)
- … but shows superionization!



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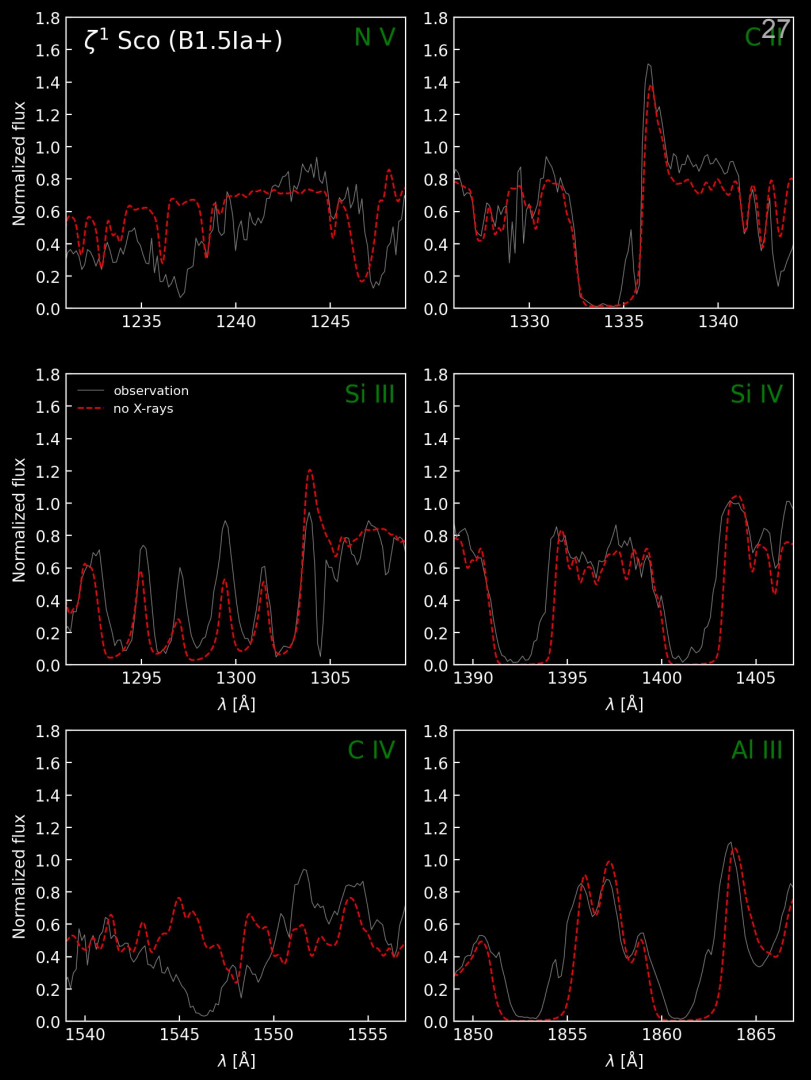

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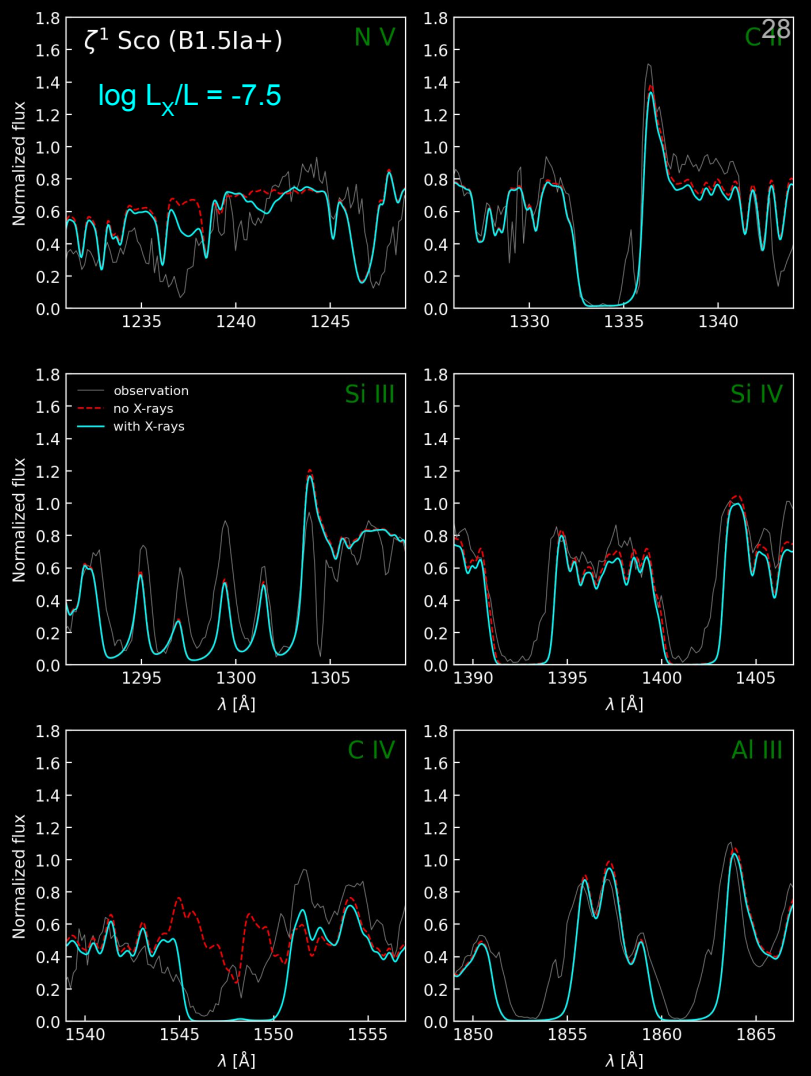
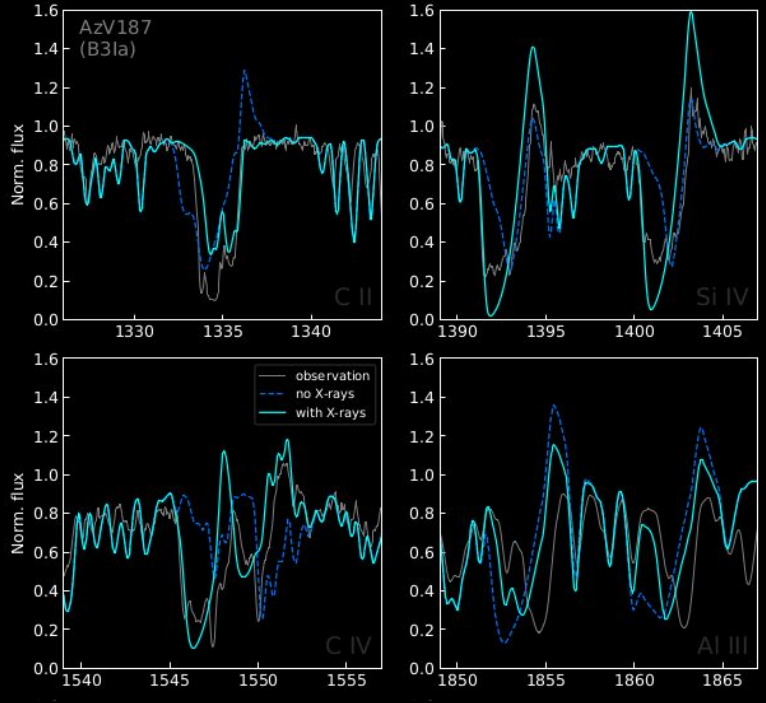
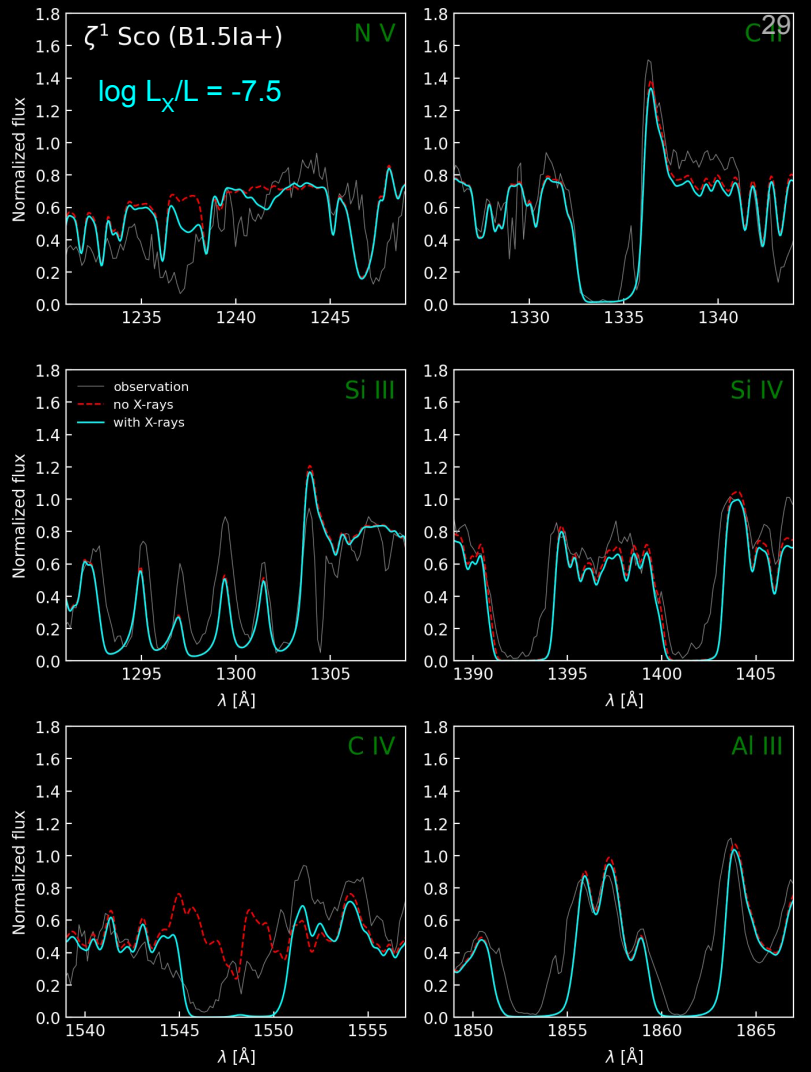


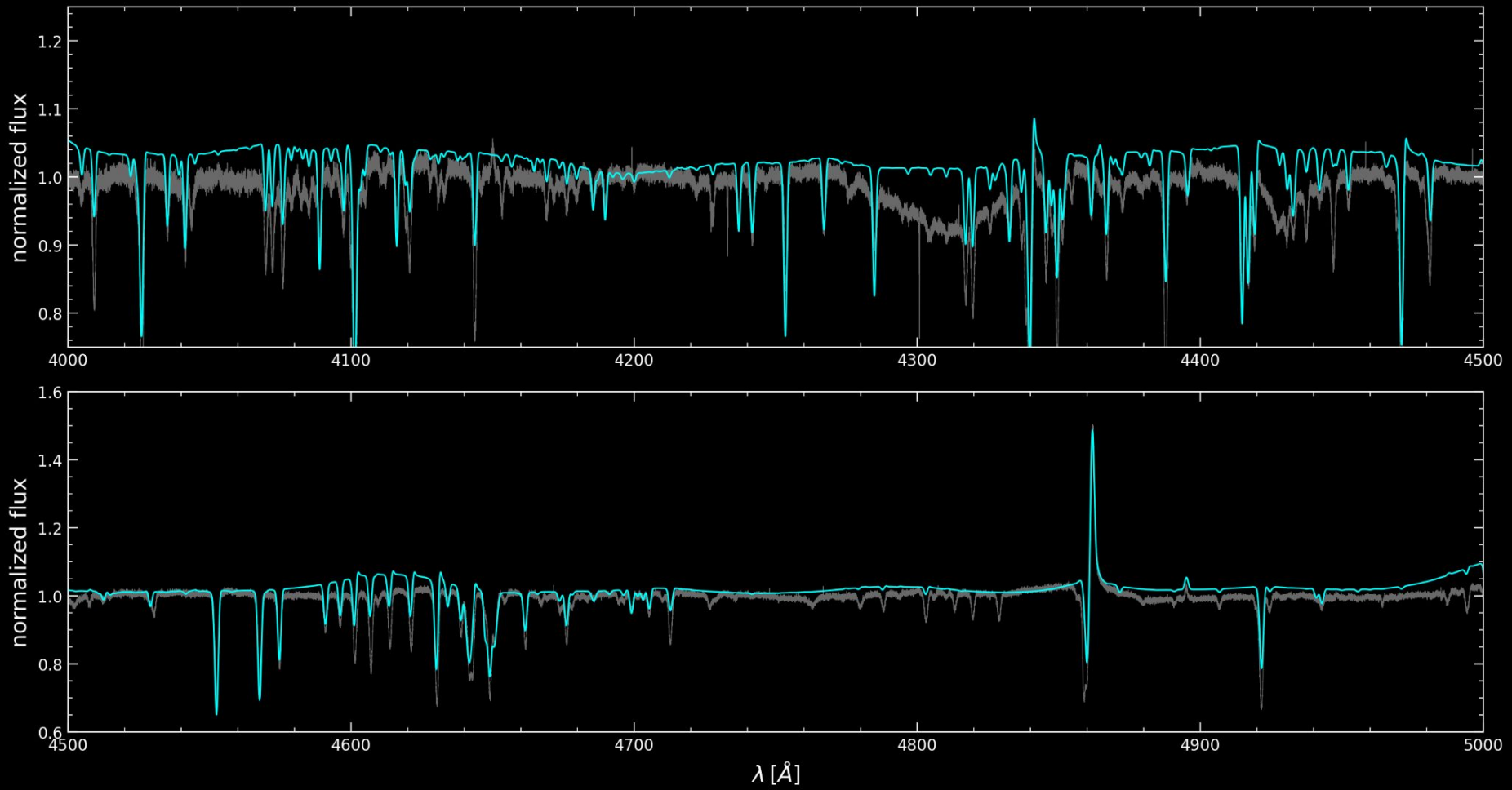
X-rays in Z_1 Sco

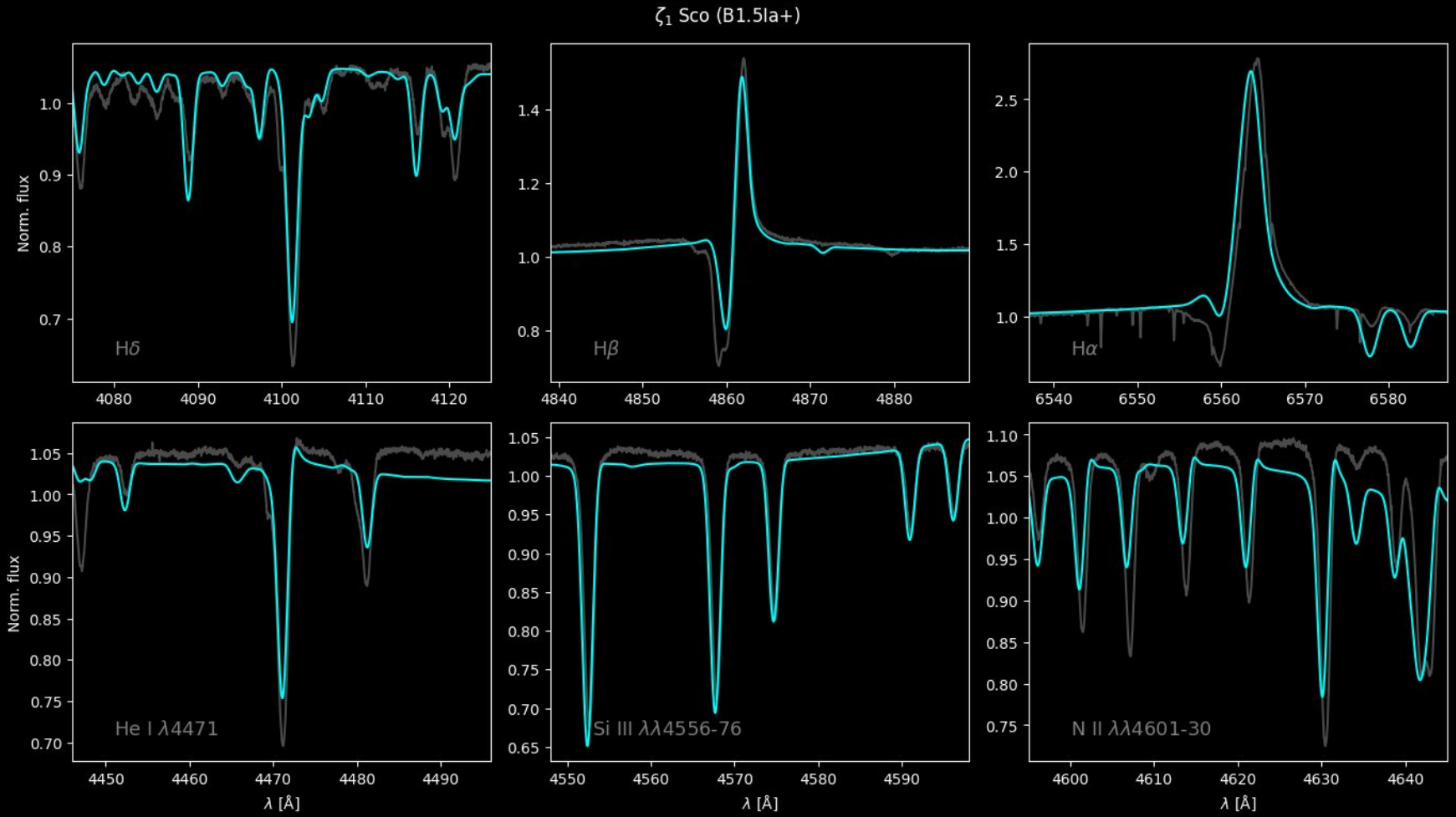
XShootU Paper VII - Bernini-Peron+(subm.²)

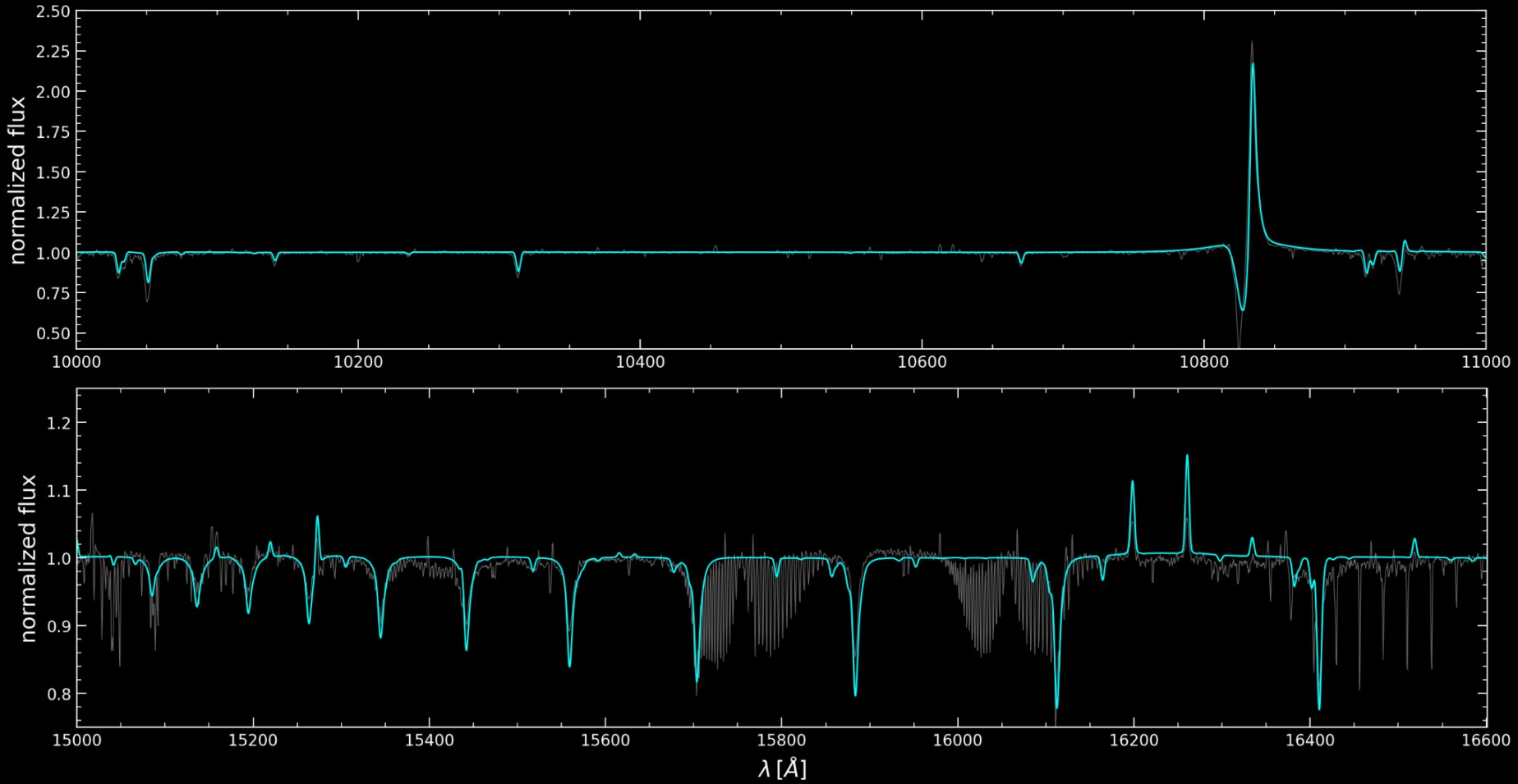


Behaves differently to BSGs (thinner winds)!




normalized flux
1.2
1.1
1.0
0.9
0.8
4000
4100
4200
4300
4400
4500
normalized flux
1.6
1.4
1.2
1.0
0.8
0.6
4500
4600
4700
4800
4900
5000
λ [Å]


ζ1 Sco (B1.5Ia+)
Norm. flux
Hδ
Hβ
Hα
He I λ4471
Si III λλ4556-76
N II λλ4601-30
λ [Å]

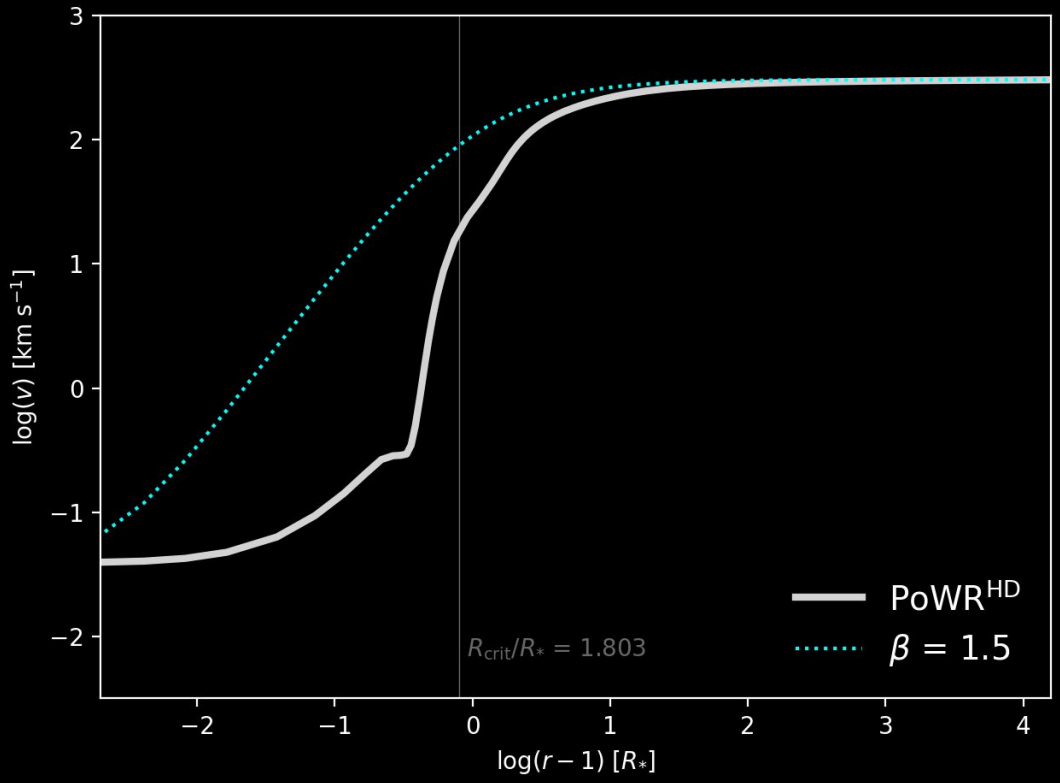

normalized flux
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
10000
10200
10400
10600
10800
11000
normalized flux
1.2
1.1
1.0
0.9
0.8
15000
15200
15400
15600
15800
16000
16200
16400
16600
λ [Å]

How our results compare to literature?

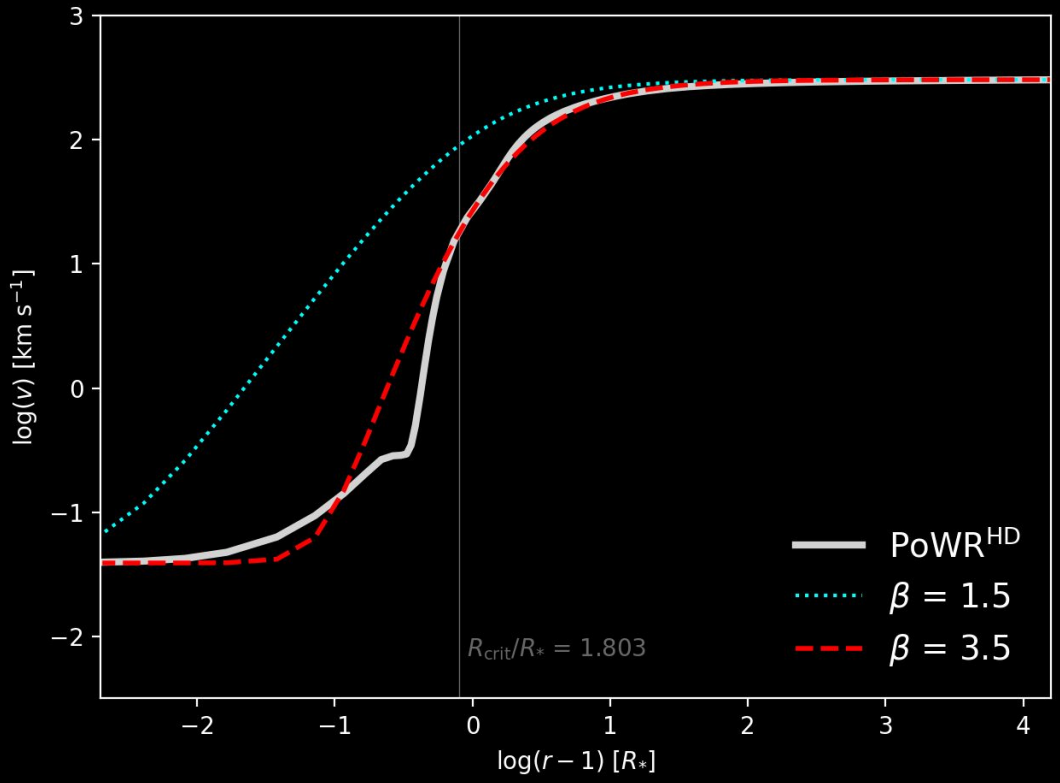
Study	T_{eff} ($^2/_3$)[kK]	logg ($^2/_3$)	log L/Lsun {distance source}	dM/dt [Msun/Myr]	clump	Vinf
This work	**17.7**	**2.04**	**5.85** **{GaiaDR3, BJ21}**	**4.5**	**0.66**	**305** +120 v_{turb}
Crowther+2006	18.0	2.20	6.10 {Sco OB1, B99}	6.0	–	390 +39 {v_{turb}}
Clark+2012	17.2	1.97	5.93 {Sana+06}	1.6	0.06	390 +39 {v_{turb}} ?
Mahy+2022	–	–	6.10 {GaiaEDR3}	–	–	–
Rubio-Diez+2022	–	–	–	<6.2	0.4 – 1	–

Dissecting the model

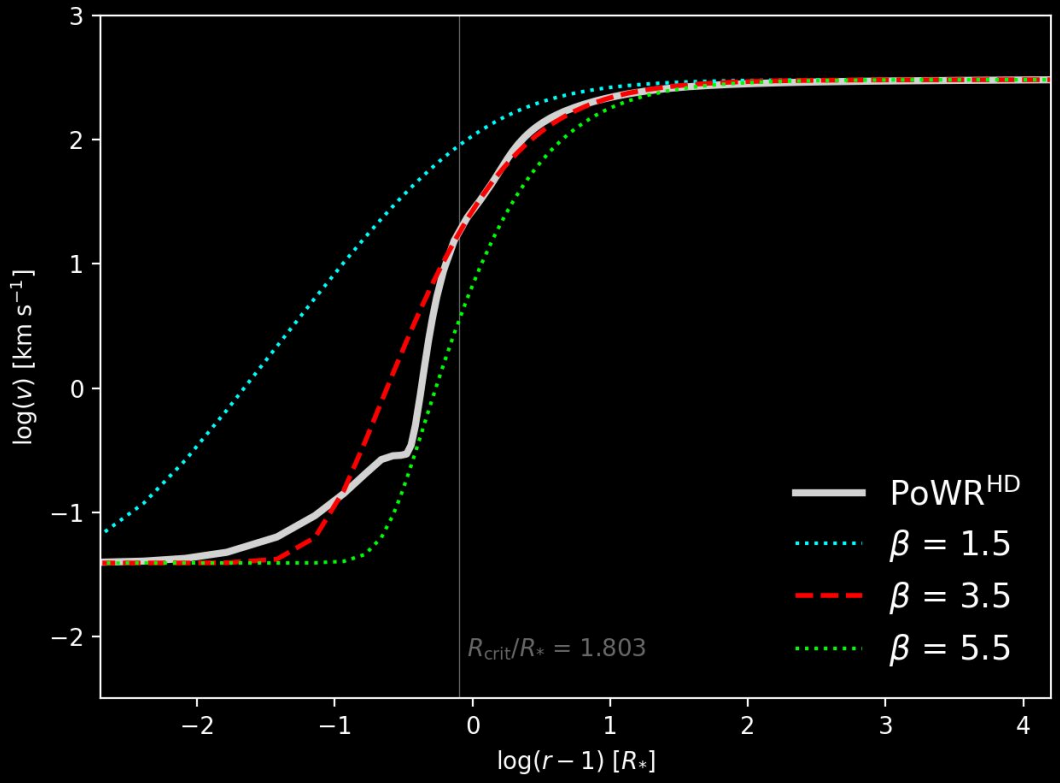
The velocity field



The velocity field

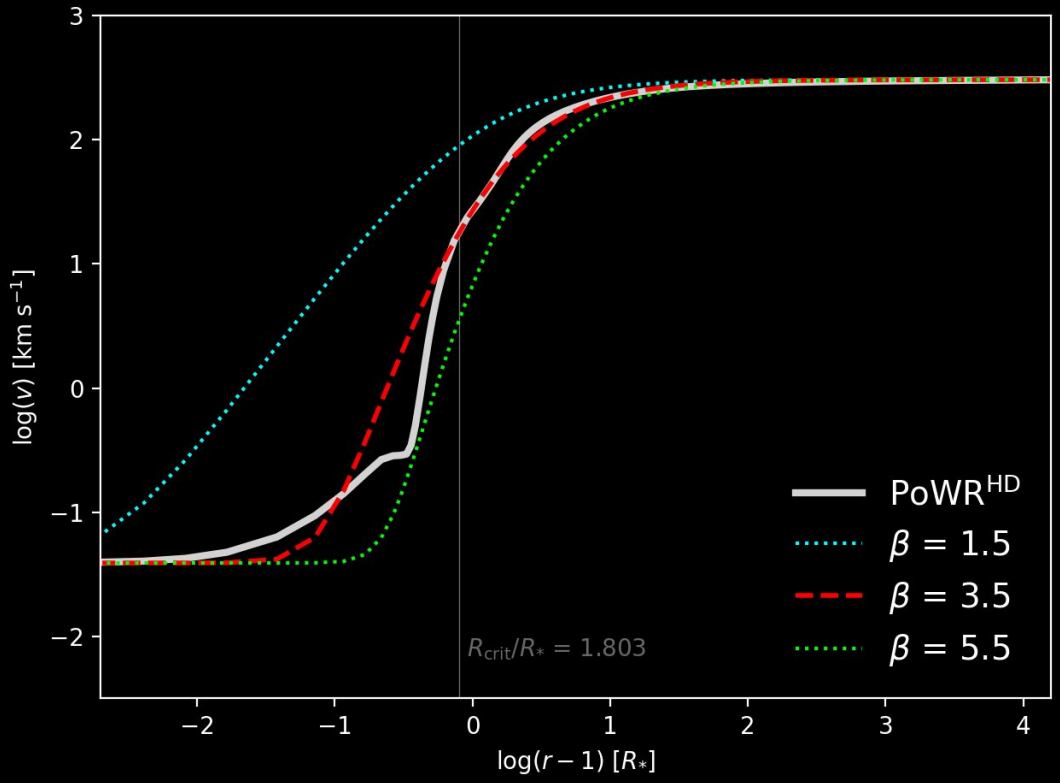


The velocity field



Higher betas (slightly) favored

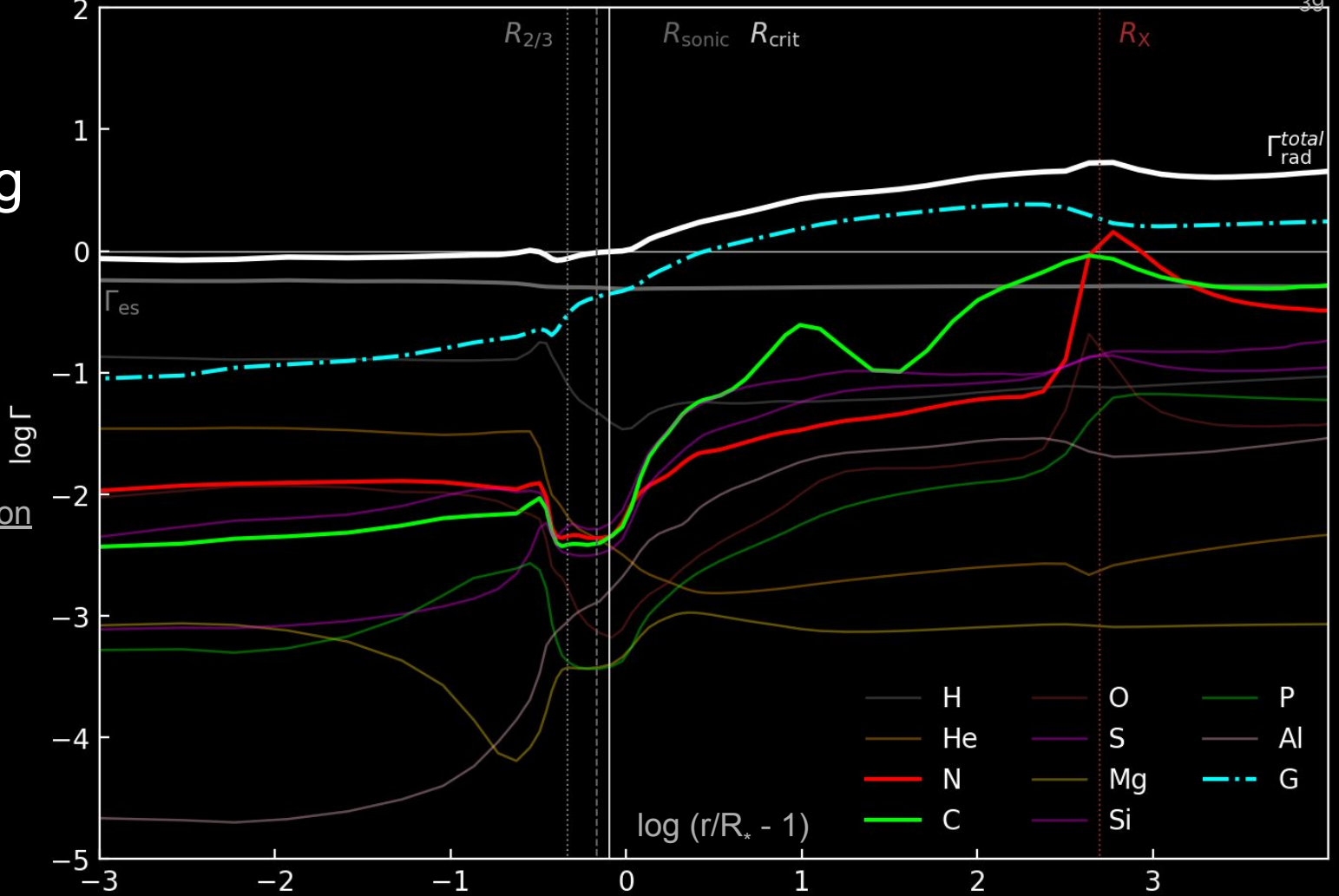
The velocity field



Higher betas (slightly) favored

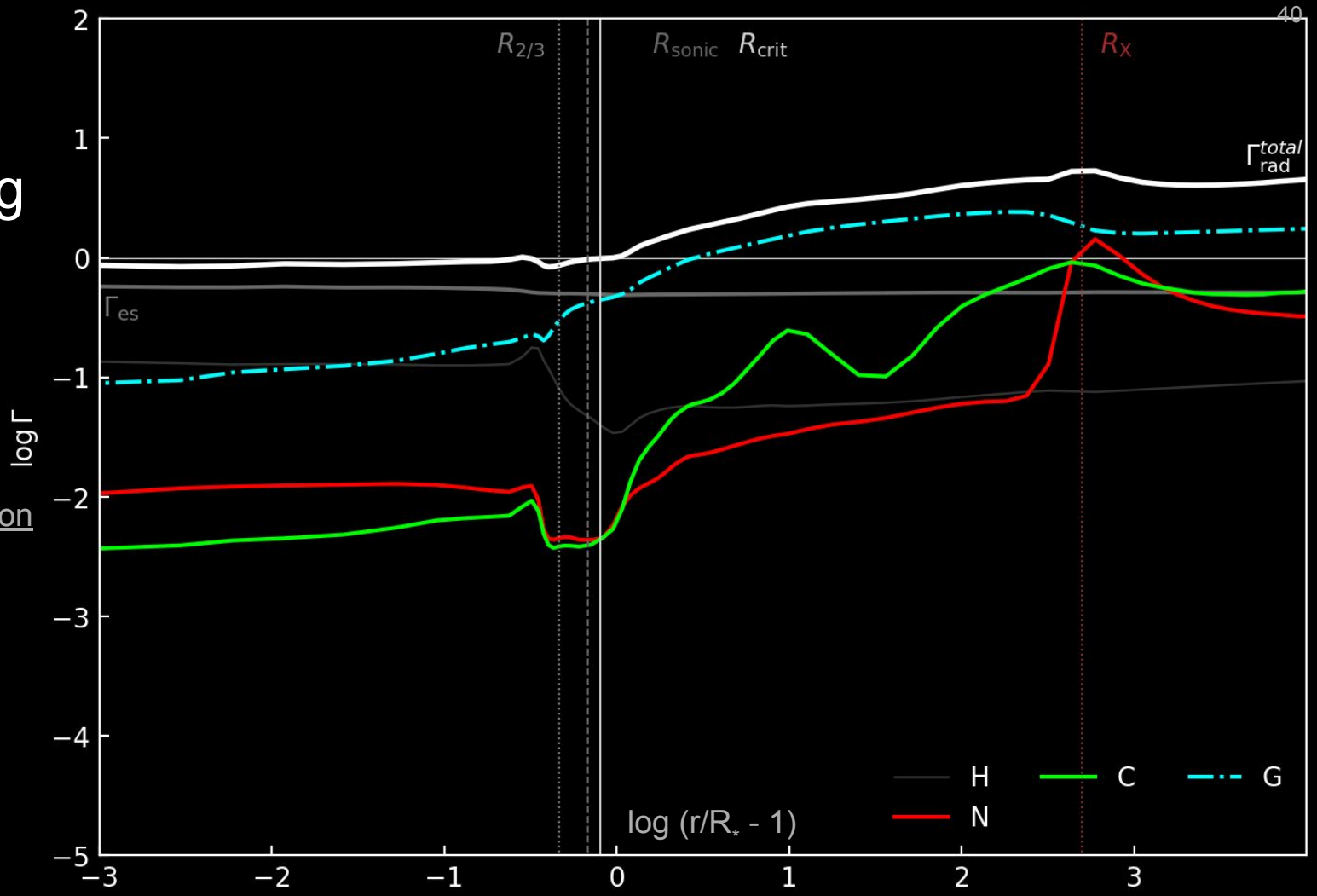
Though beta law is not really adequate…

Wind Launching

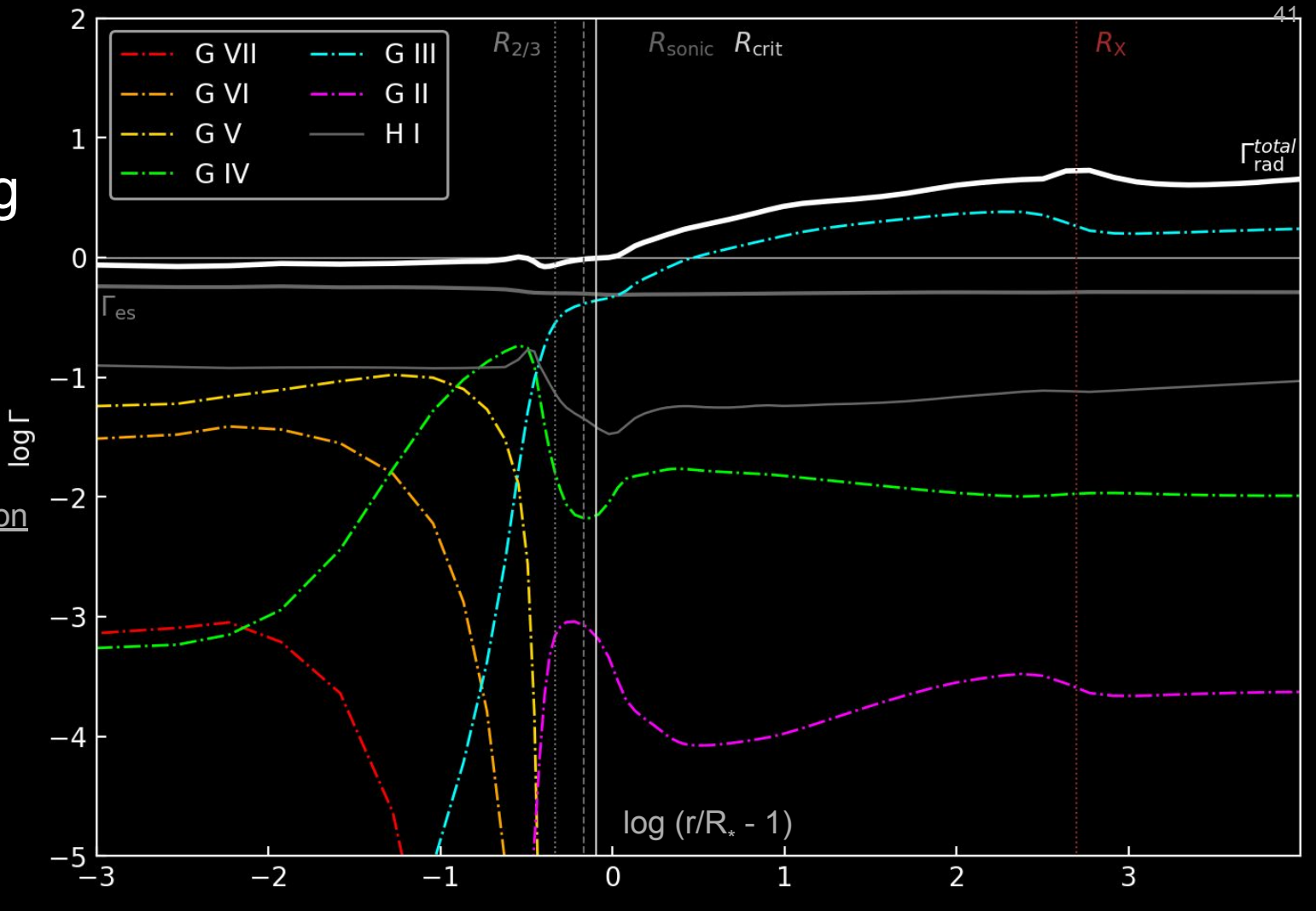


acceleration
gravity

Wind Launching

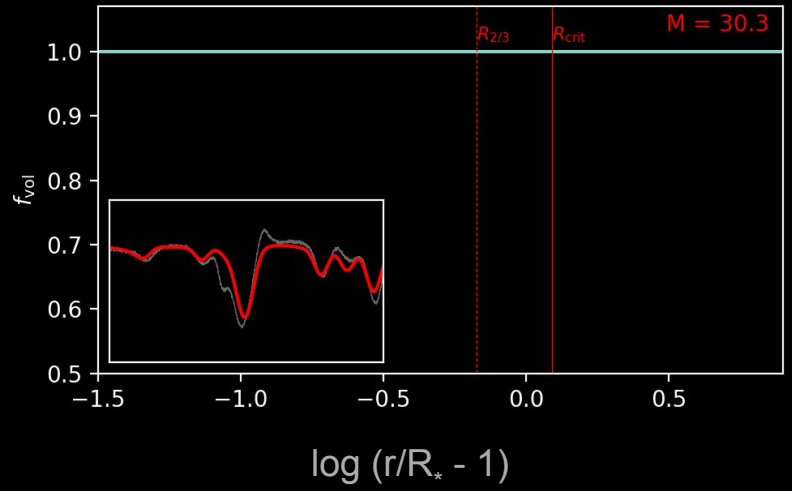


Wind Launching

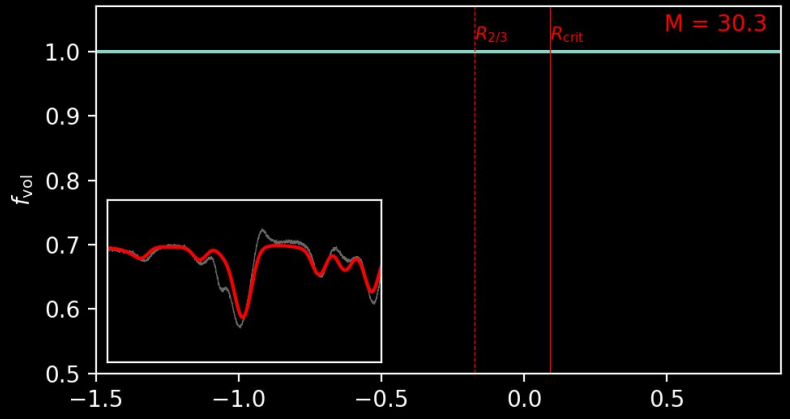


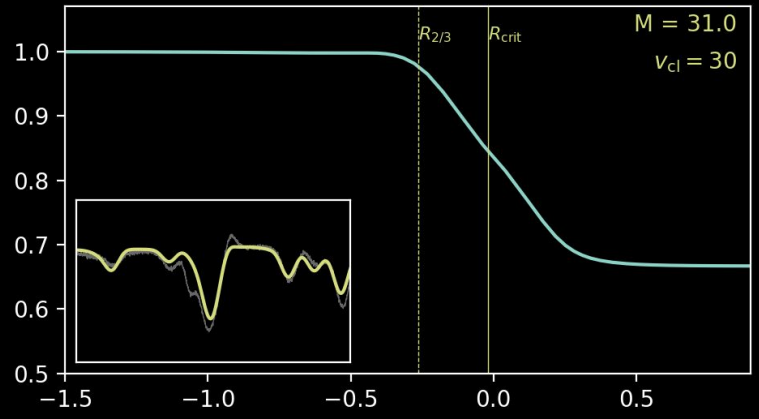
acceleration
gravity

Clumping



Clumping

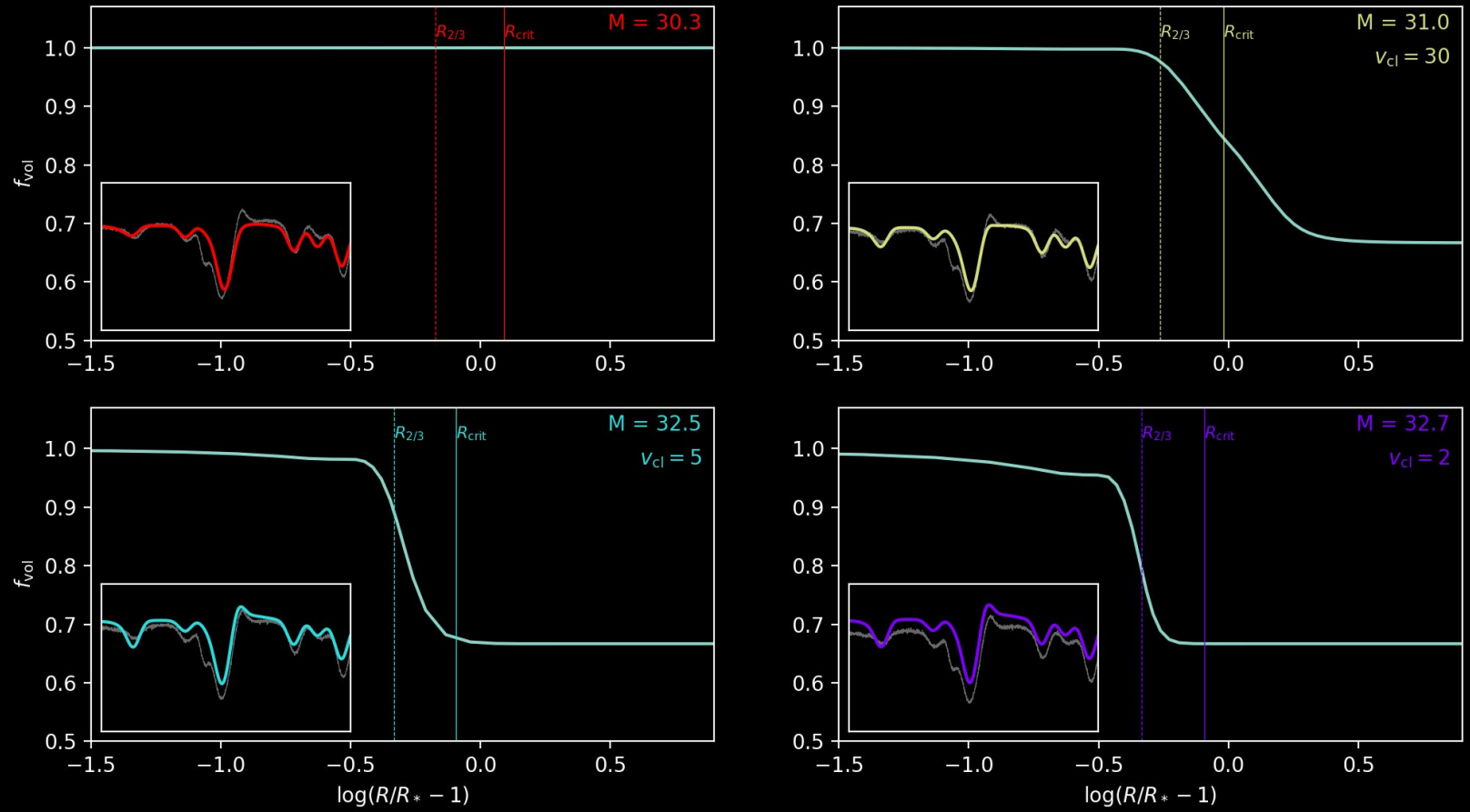




Najarro+2011 → traditional CMFGEN: subsonic onset of clumping in LBVs

Debnath+2024 → 3D models: subsonic clumping onset in O stars as well/

Clumping



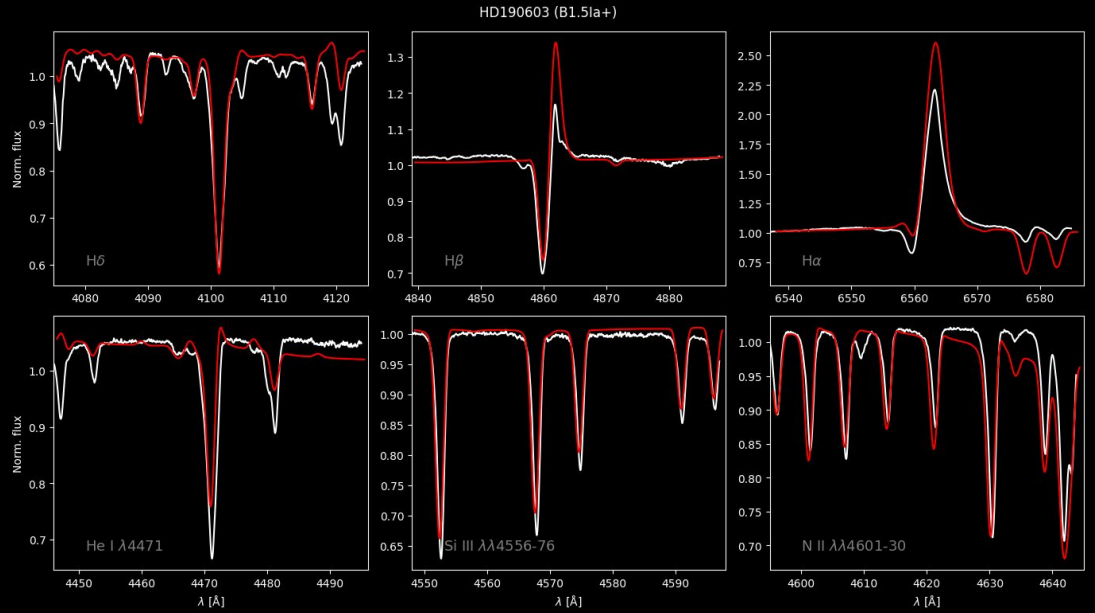
Other hydro BHGs in the oven

V1768 Cyg (B1.5Ia+)

BP Cru (B1Ia+)

AzV 78 (B1Ia+)

P-Cyg (B1Ia+ / LBV)



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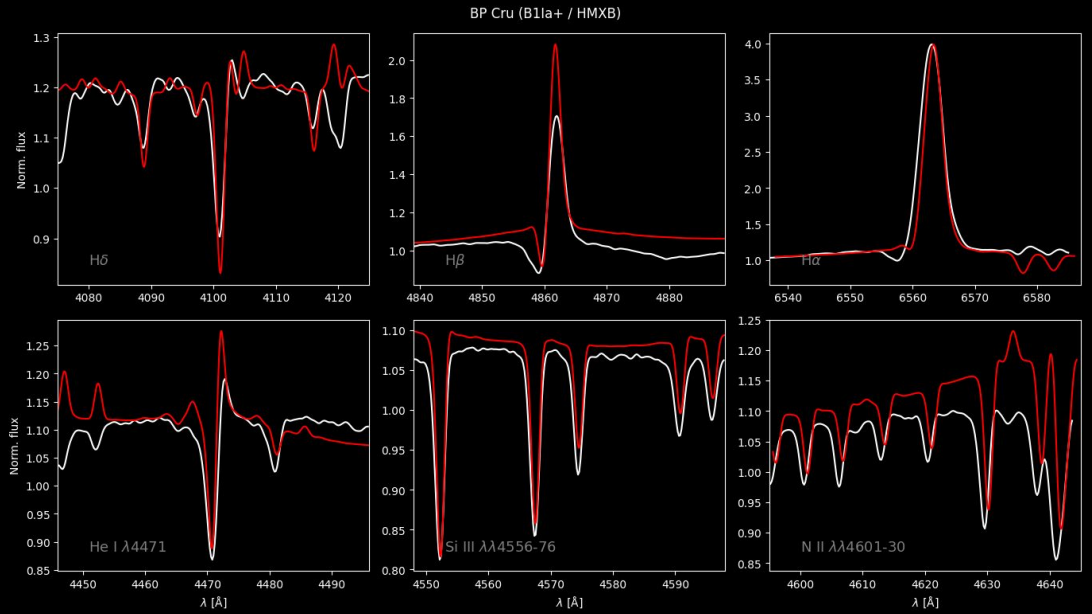

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AzV 78 (B1Ia+) **{SMC star!!}**

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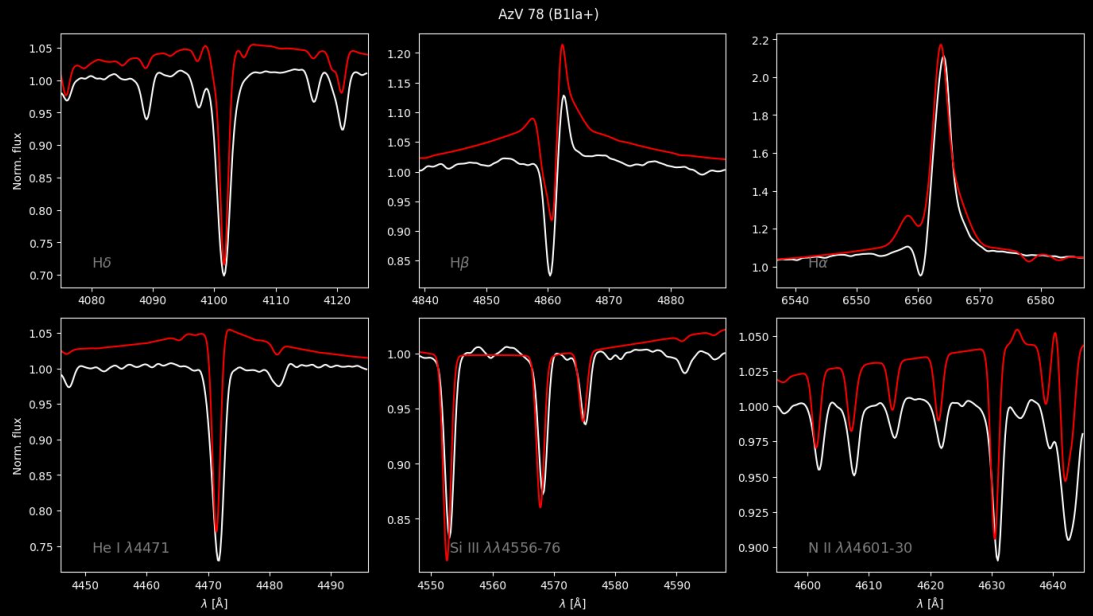

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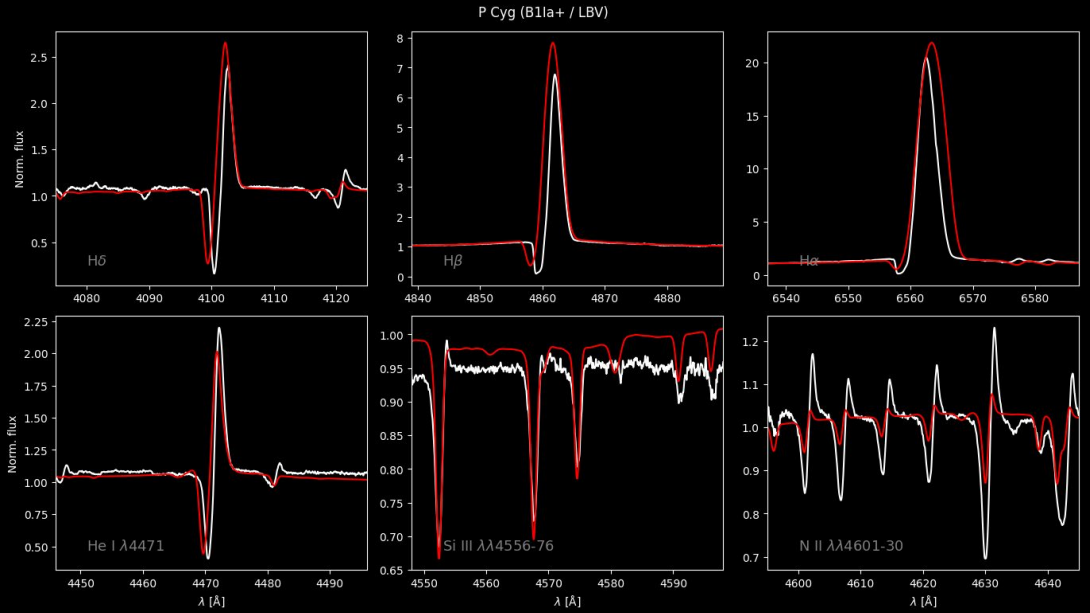
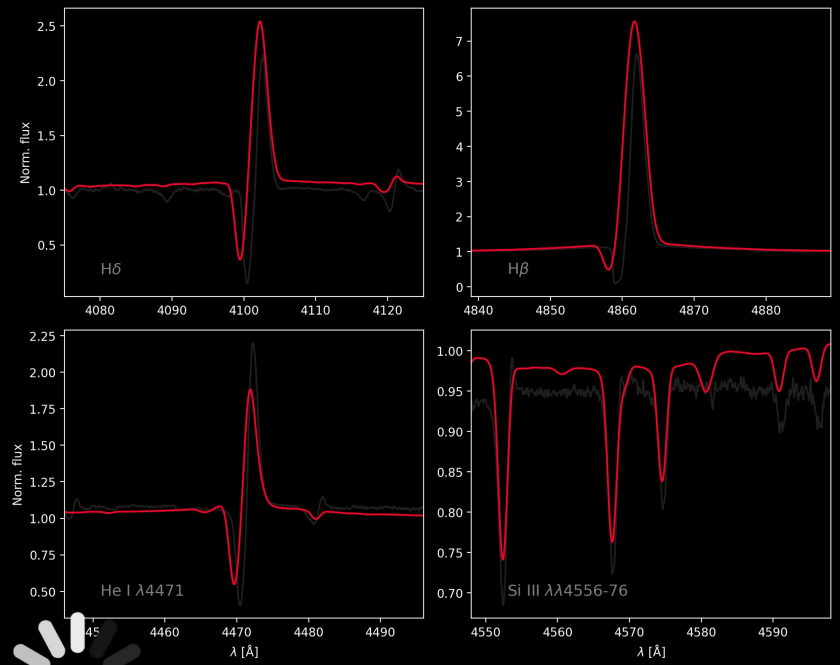
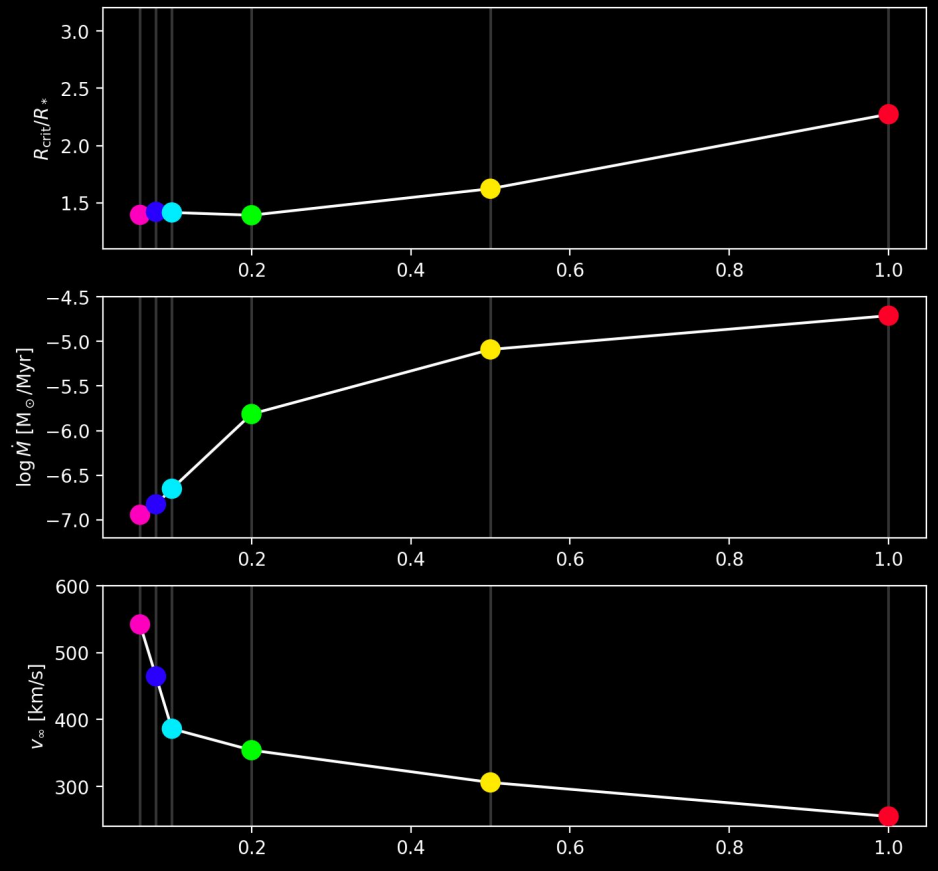


Z-dependence

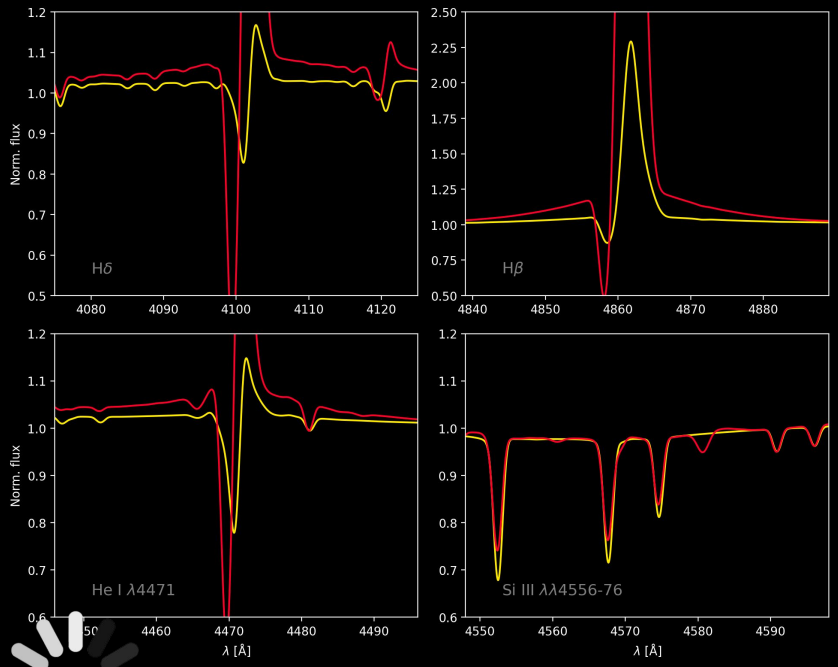


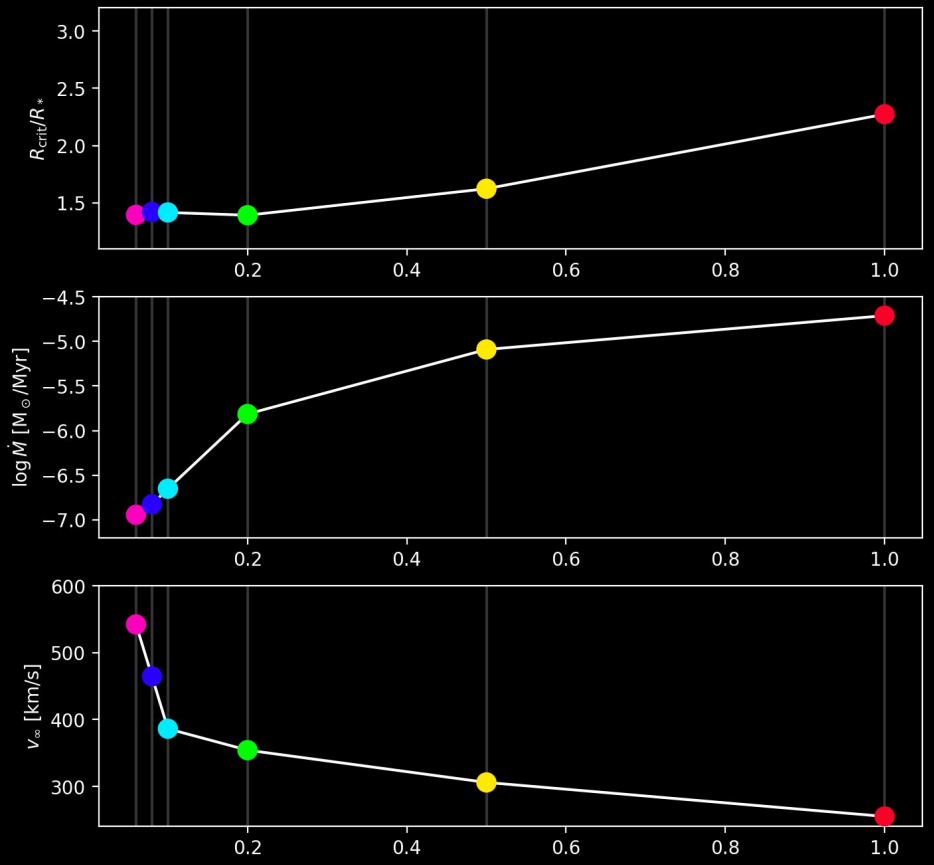


Loading...

0.50 {LMC}

Z-dependence

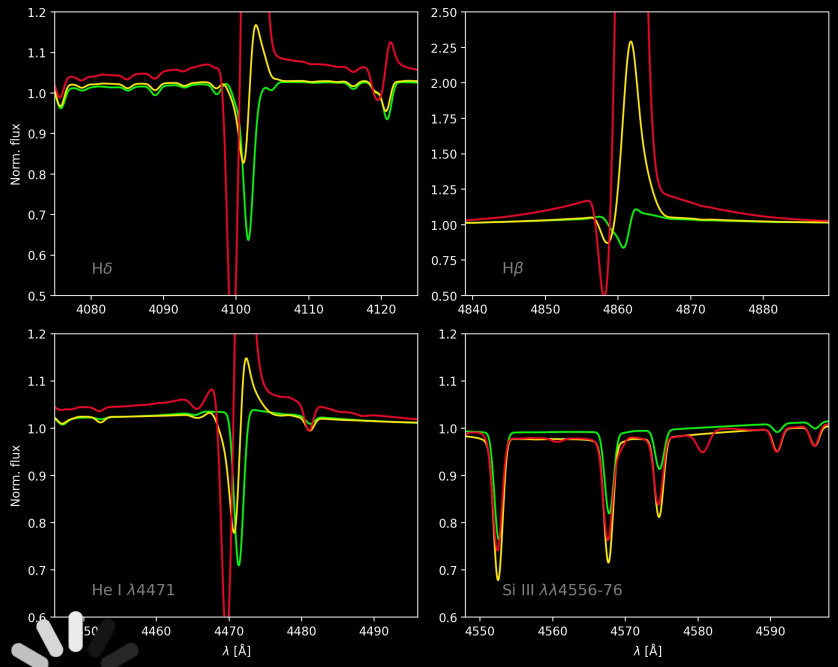


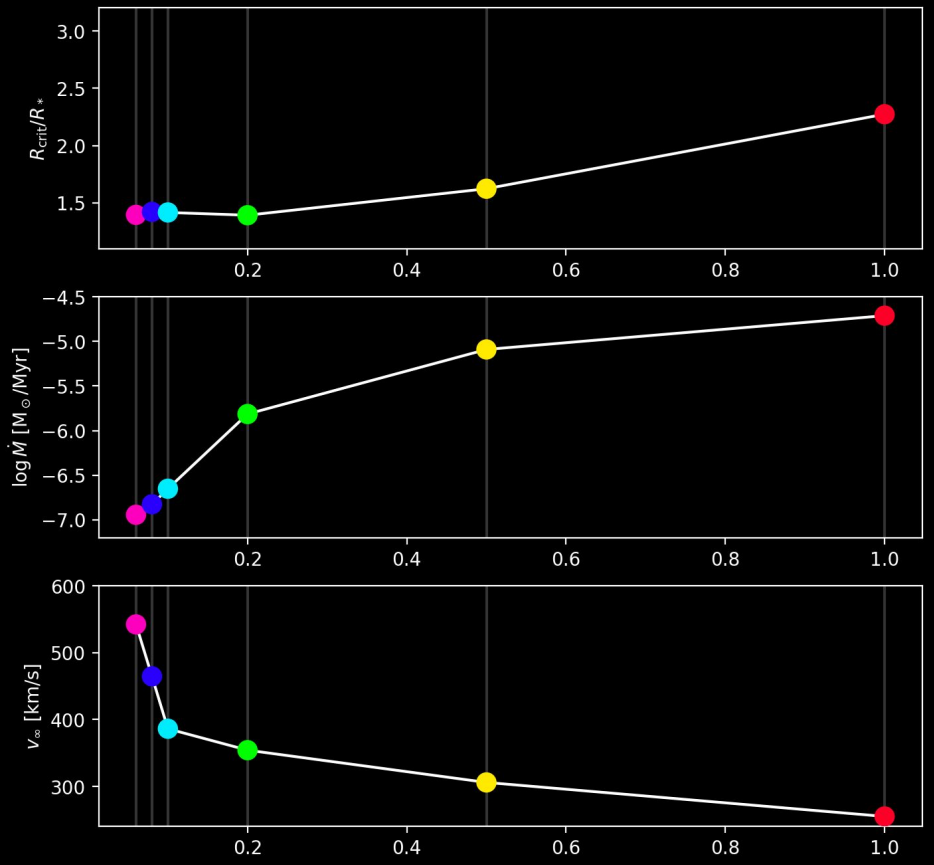


Loading...

0.20 {SMC}

Z-dependence





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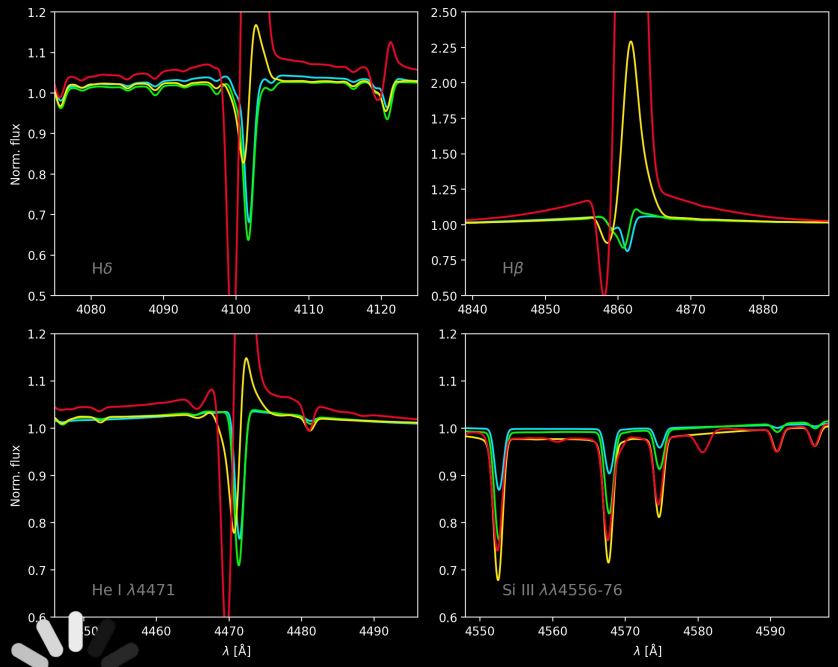
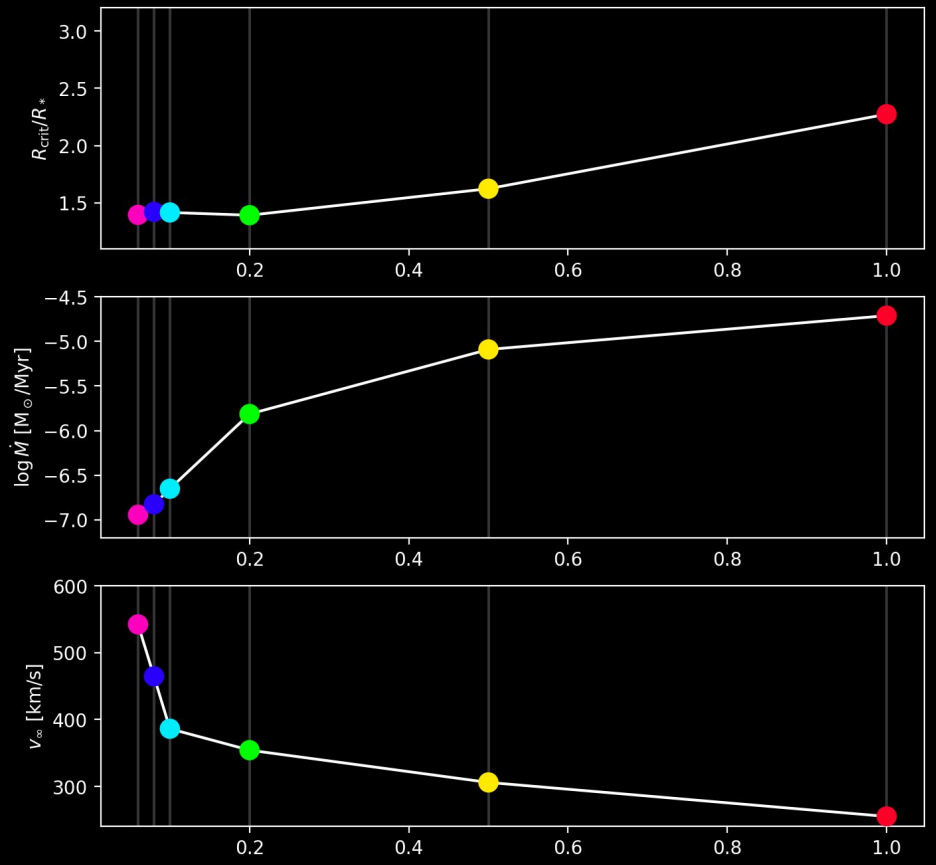
0.10

Z-dependence



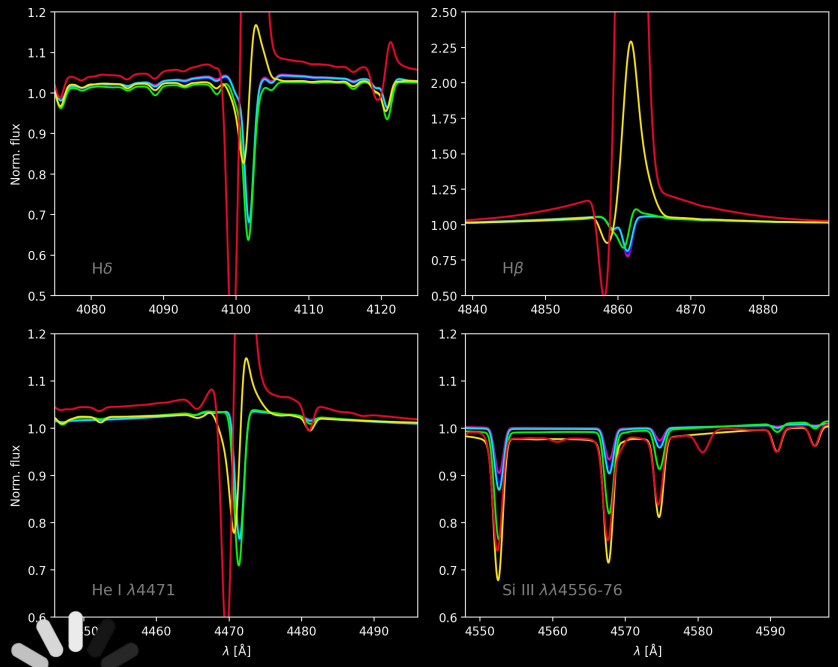


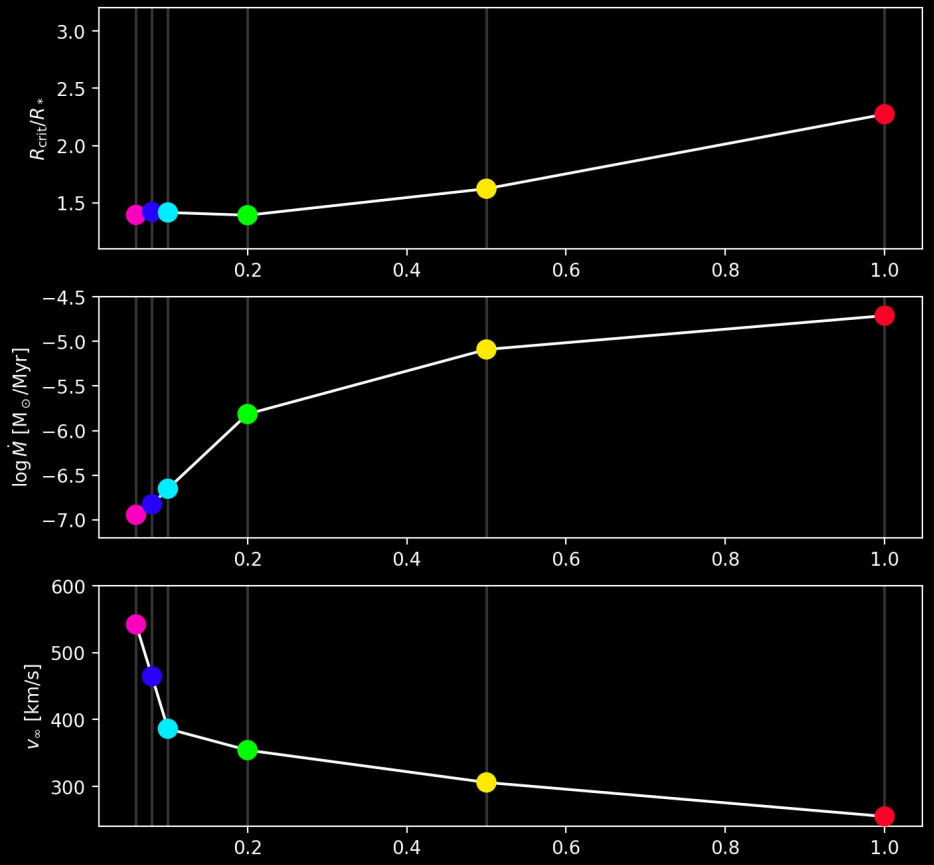
metalicity (Z/Zsun)

Loading...

0.06, 0.07

Z-dependence





metalicity (Z/Zsun)

Loading...

Conclusions

Main Results

- **1st Hydrodynamically consistent model** of a prototypical BHG (**Z_1 Sco**)
- **Fe III** is the main wind **driver**
- **Beta law not adequate** → High beta if you insist, though
- **Low X-ray luminosity** and far onset + **different behaviors to BSGs**
- (mildly) **Clumped photosphere**

On going

- Models of **more BHGs/LBVs** → What their different spectra tell about their physics?
- Investigation of the effects of **metallicity** on the **wind driving** in BHGs/LBVs

Conclusions

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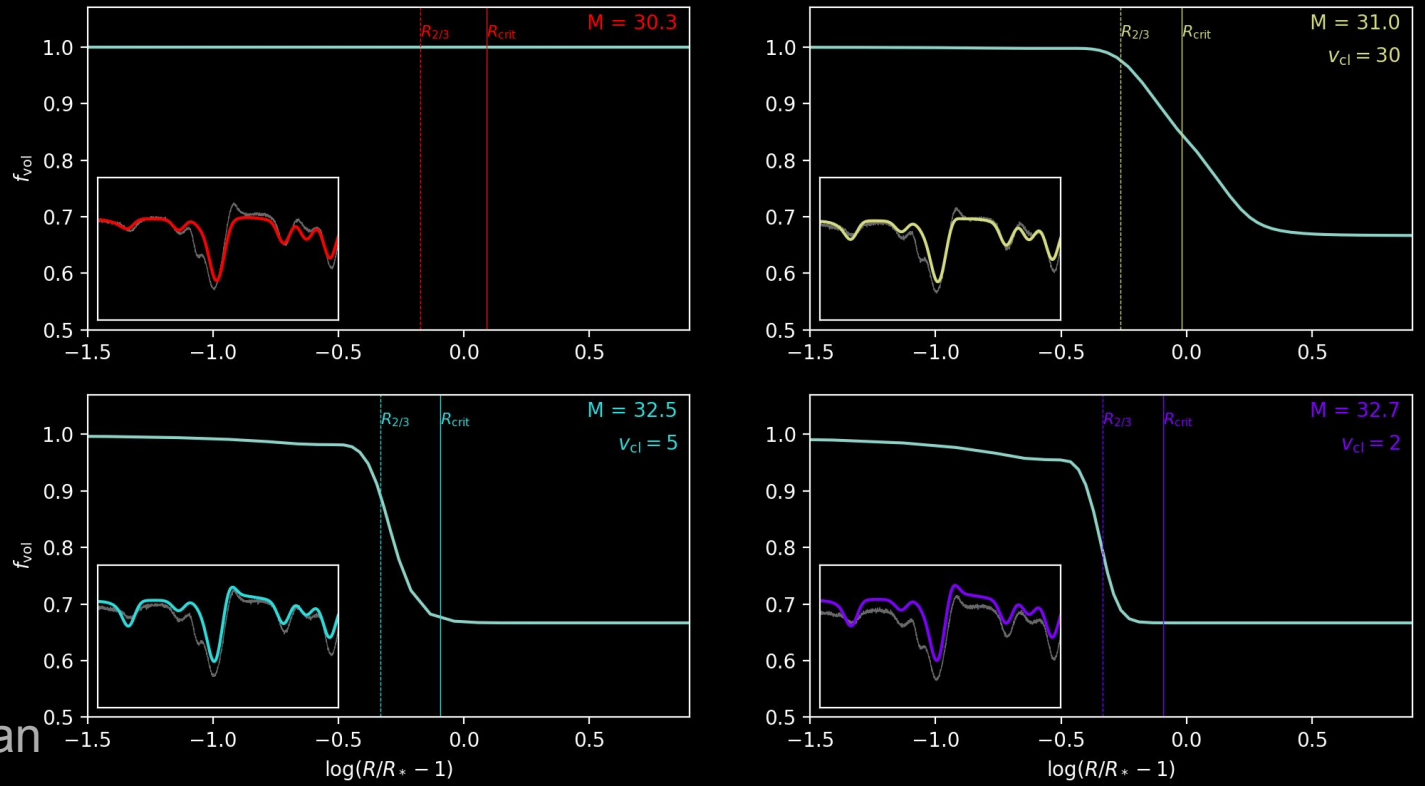
- Investigation of the effects of **metallicity** on the **wind driving** in BHGs/LBVs
- Models of **more BHGs/LBVs** → What their different spectra tell about their physics?
- Understanding of **complex mass-loss behavior** with temperature across the **"Bi-stability Jump region"** for **LBVs**

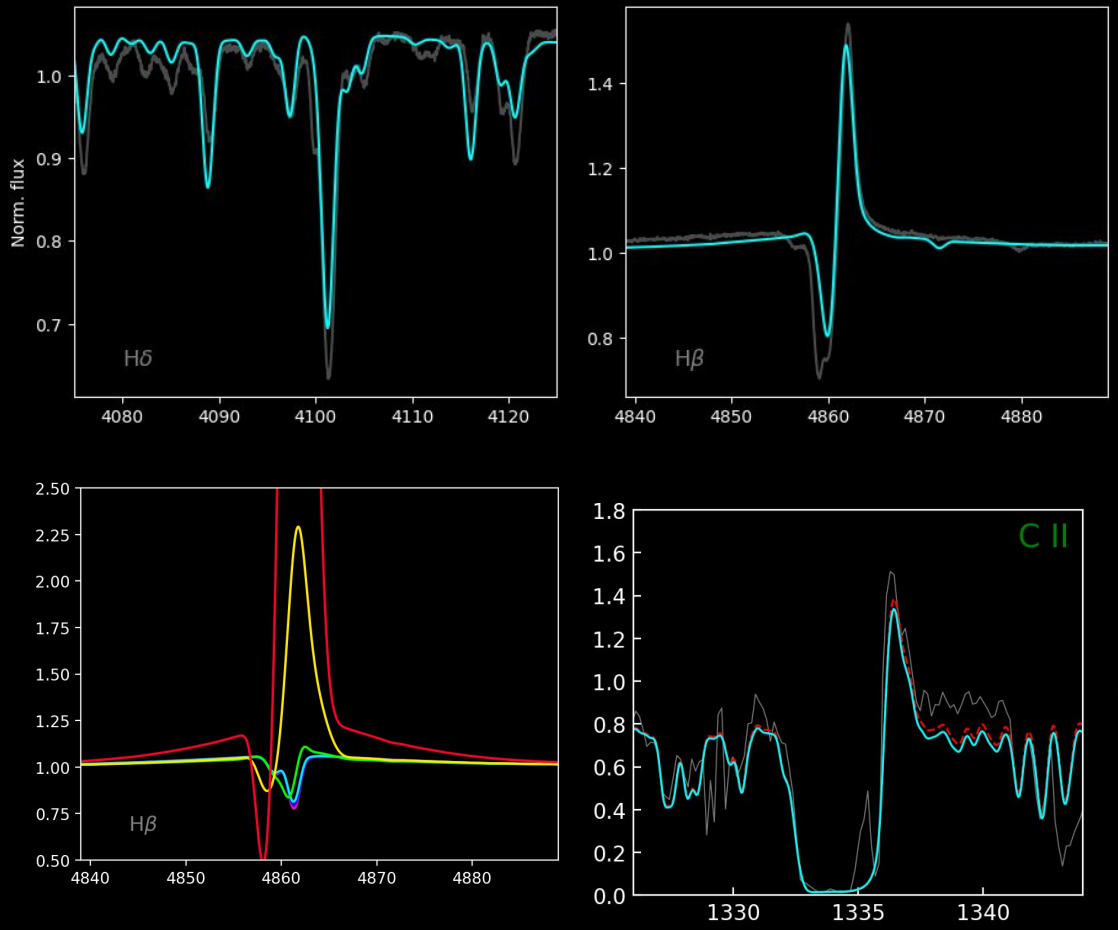
Thanks ^_^

Back up & Extra

Clumping



Recall Dwapayan talk

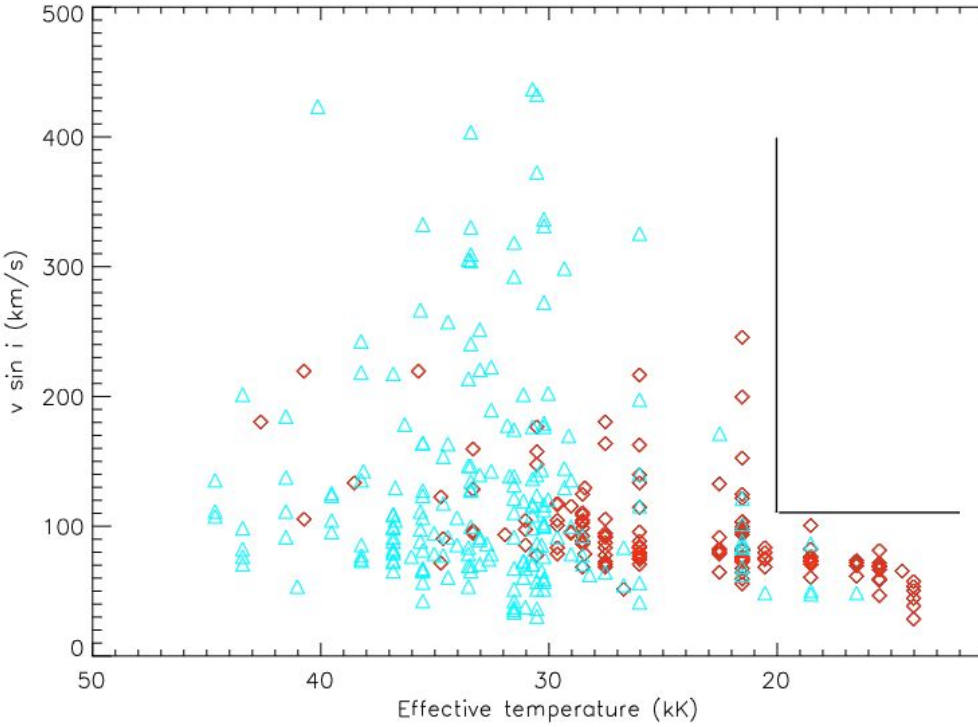


Hydrodynamically Consistent Models of **B-Hypergiants** & **LBVs**

Matheus Bernini Peron
ZAH/ARI, Universität Heidelberg

Why the “cool hot stars” are important?

- Variety of stars and origins
- Connection between MS and cold stages
- Edge of radiative-driven winds
- Interesting phenomena
  - Bi-stability jump
  - Drop in rotational velocity
  - Drop of X-ray detection
  - Change in wind clumping?
  - Pulsational variability (a Cyg)
  - LBVs
  - …



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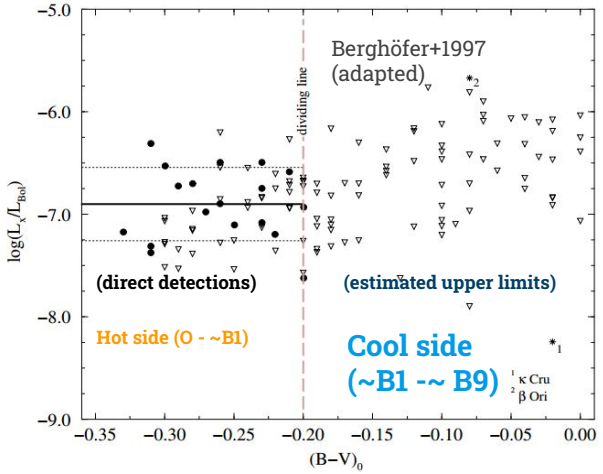
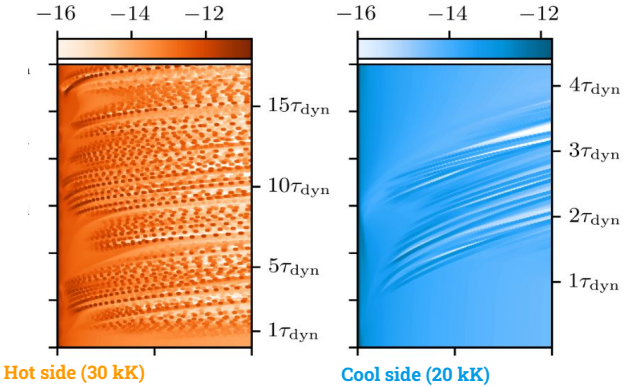
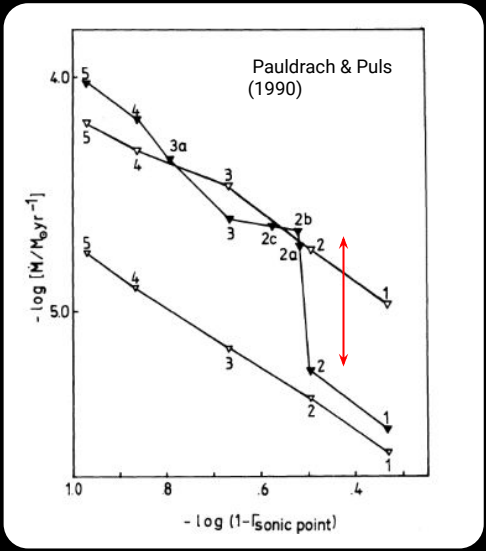


Driessen+2019 (adapted)

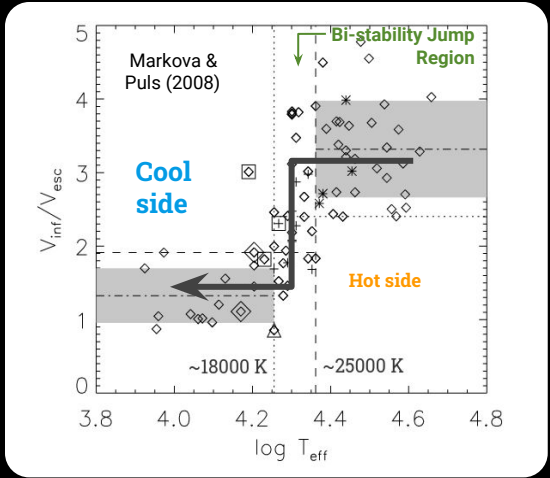


Bi-Stability Jump

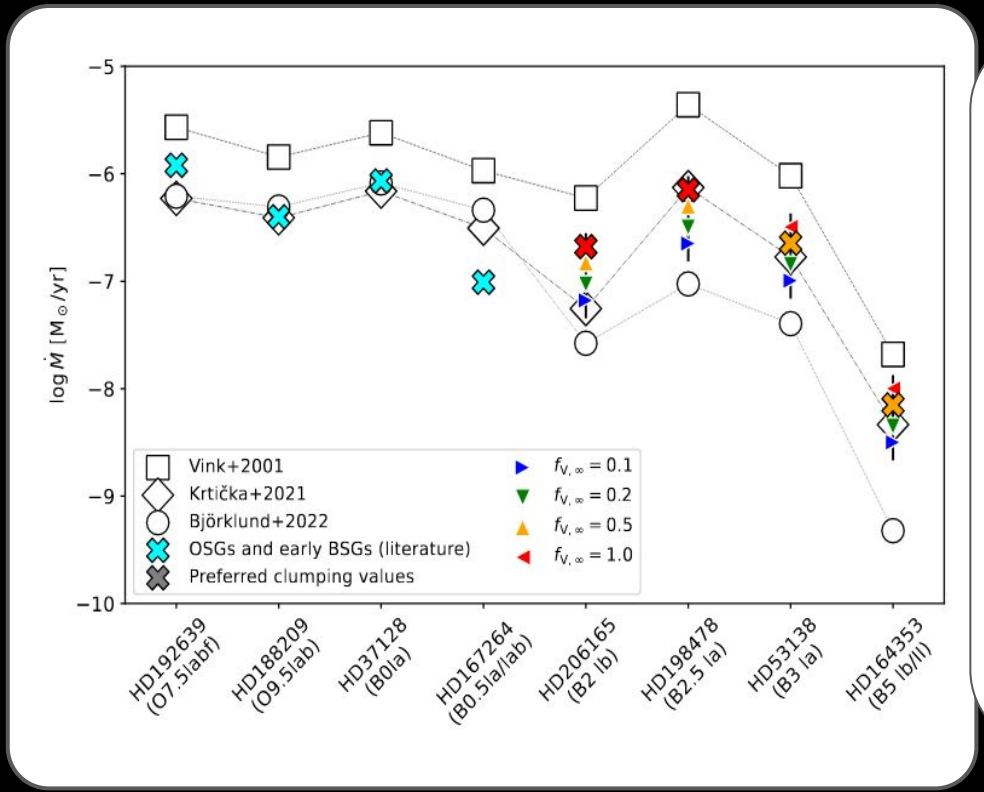
- **Theoretical motivation:**
  - Pauldrach&Puls (1990)
- “Two solutions” with different wind properties found for P Cygni (B1Ia+, LBV)

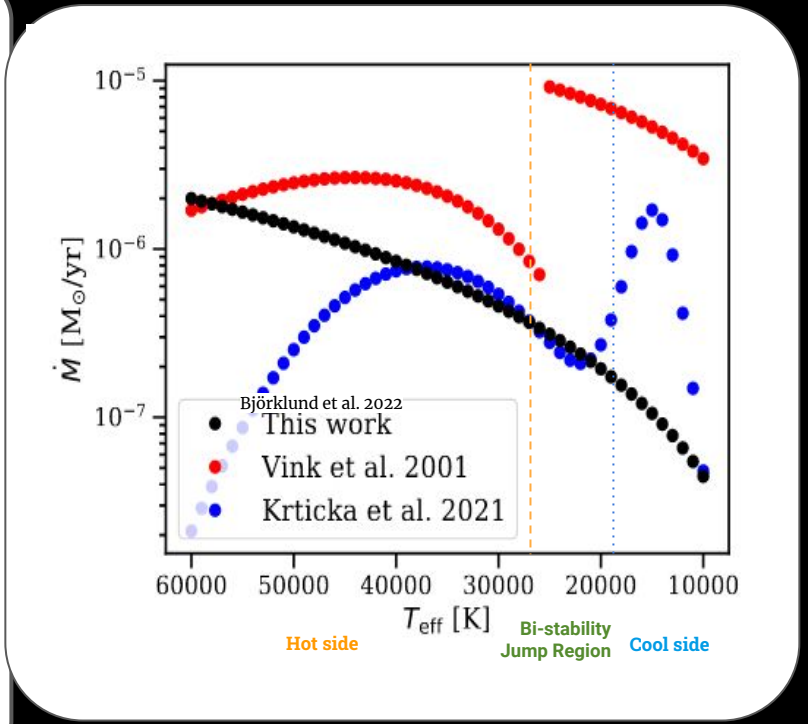


- **Observational motivation:**
  - Lamers+1995, Markova+2008
- Sharp drop of the terminal velocity of cool BSGs after T_{eff} ~ 21kK

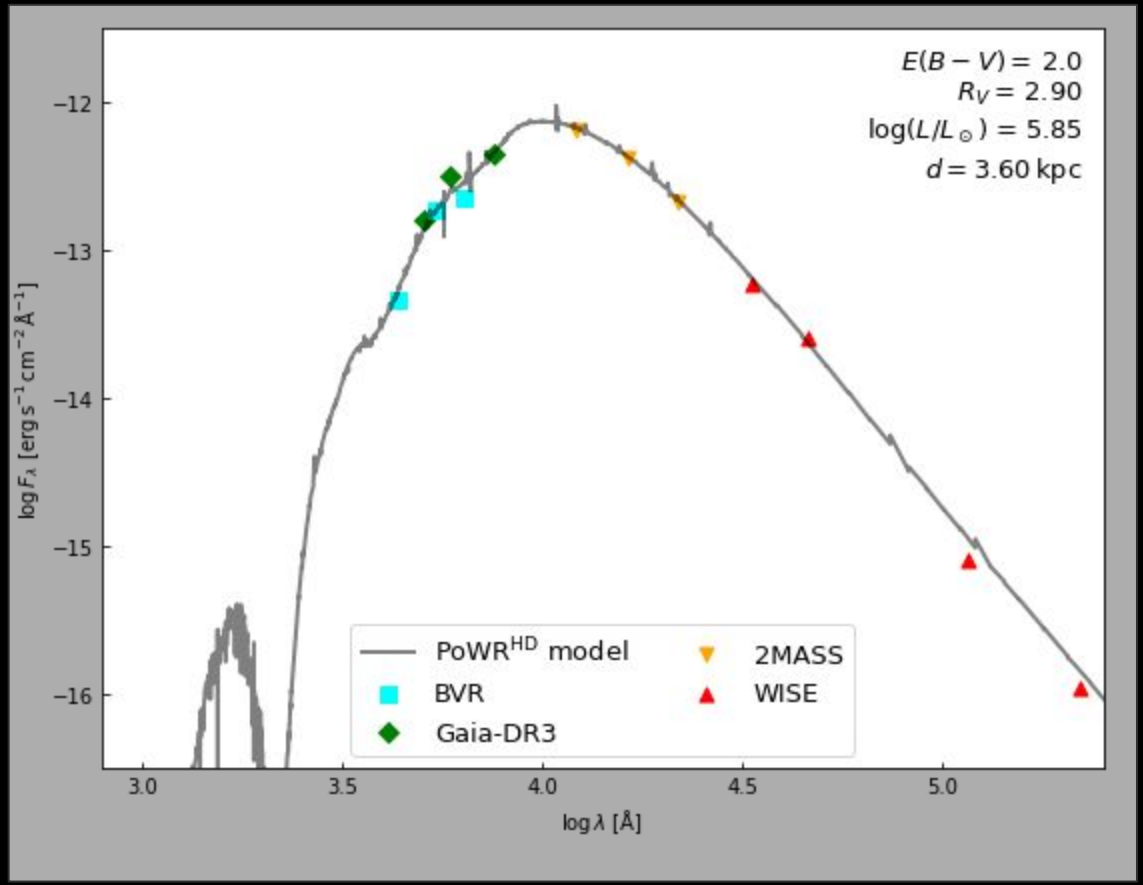


- **Today’s concept:**
- (Possible) Increase in Mass-loss rates due to ionization changes
  - (Fe IV to III)
    - Vink+1999,2000
    - Krticka+2021
    - Bjoerklund+2022

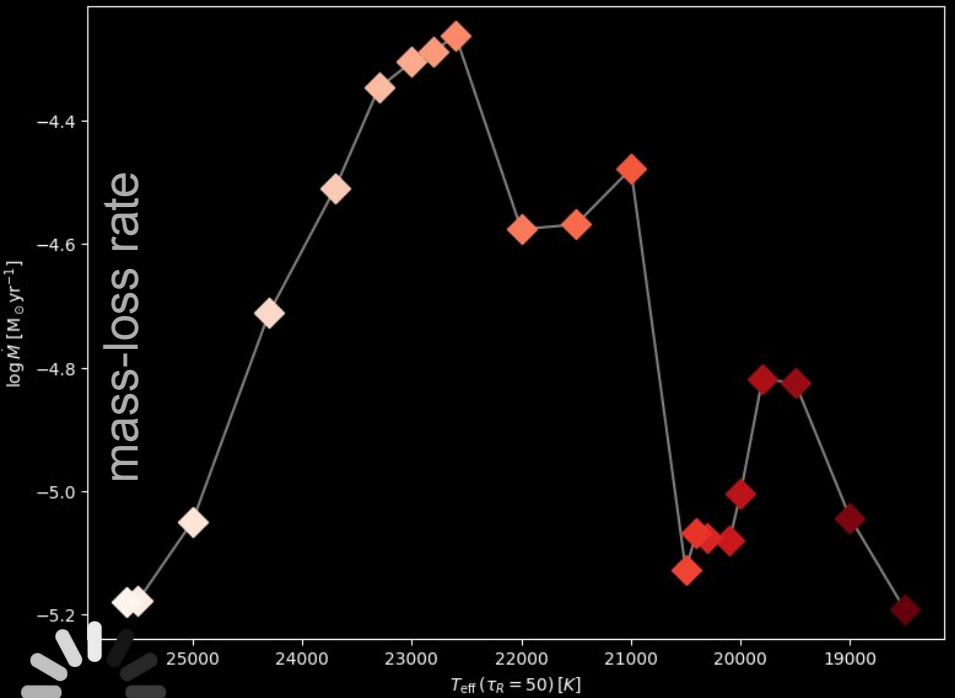

log $\dot{M}$ [$M_\odot$/yr]
−5
−6
−7
−8
−9
−10
Vink+2001
Krtička+2021
Björklund+2022
OSGs and early BSGs (literature)
Preferred clumping values
$f_{V,\infty} = 0.1$
$f_{V,\infty} = 0.2$
$f_{V,\infty} = 0.5$
$f_{V,\infty} = 1.0$
HD192639 (O7.5Iabf)
HD188209 (O9.5Iab)
HD37128 (B0Ia)
HD167264 (B0.5Ia/Iab)
HD206165 (B2 Ib)
HD198478 (B2.5 Ia)
HD53138 (B3 Ia)
HD164353 (B5 Ib/II)


$\dot{M}$ [$M_\odot$/yr]
10^{-5}
10^{-6}
10^{-7}
Björklund et al. 2022
This work
Vink et al. 2001
Krticka et al. 2021
60000
50000
40000
30000
20000
10000
$T_{\rm eff}$ [K]
Hot side
Bi-stability Jump Region
Cool side

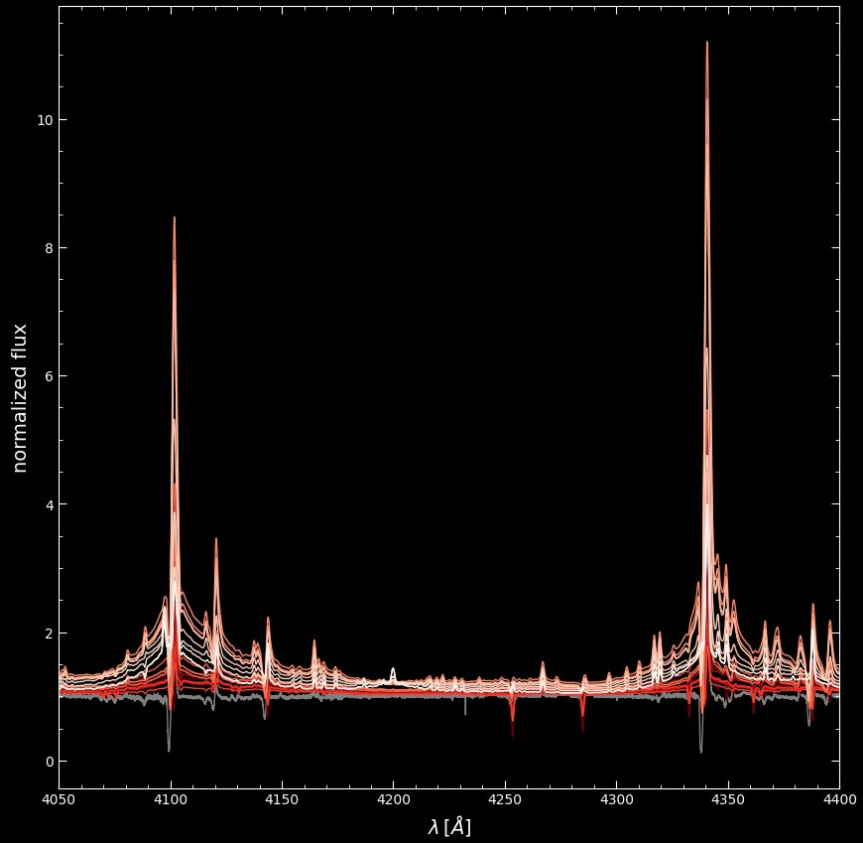
BP Cru


$E(B-V) = 2.0$
$R_V = 2.90$
$\log(L/L_\odot) = 5.85$
$d = 3.60$ kpc
PoWR^{HD} model
BVR
Gaia-DR3
2MASS
WISE
$\log F_\lambda$ [erg s^{-1} cm^{-2} Å^{-1}]
$\log \lambda$ [Å]
−12
−13
−14
−15
−16
3.0
3.5
4.0
4.5
5.0

$M(T_{eff})$ in LBV-like stars?



T_{eff} (τ = 50)



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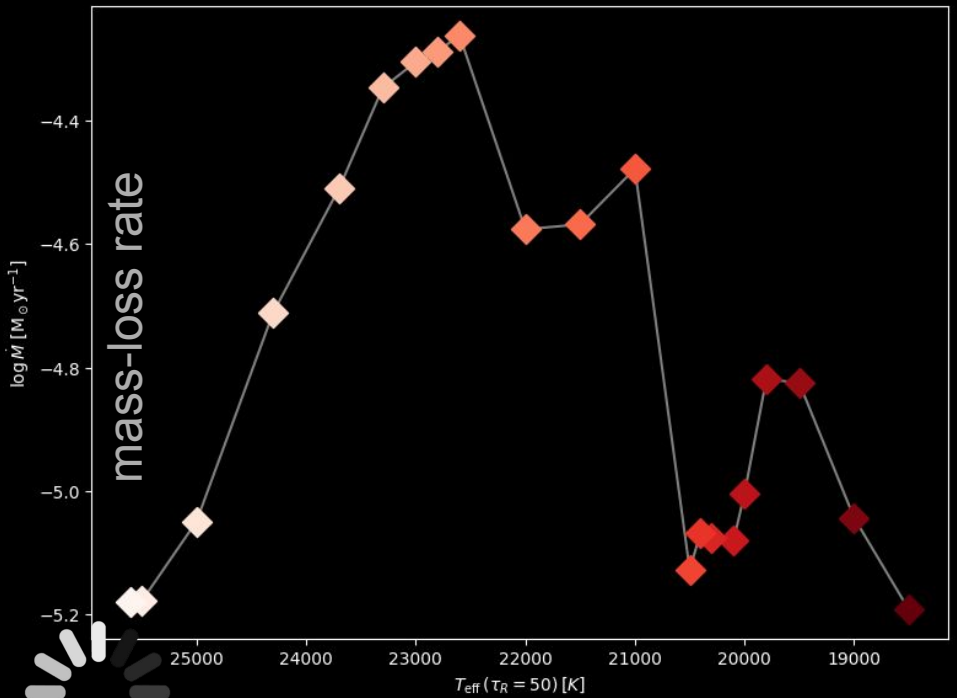
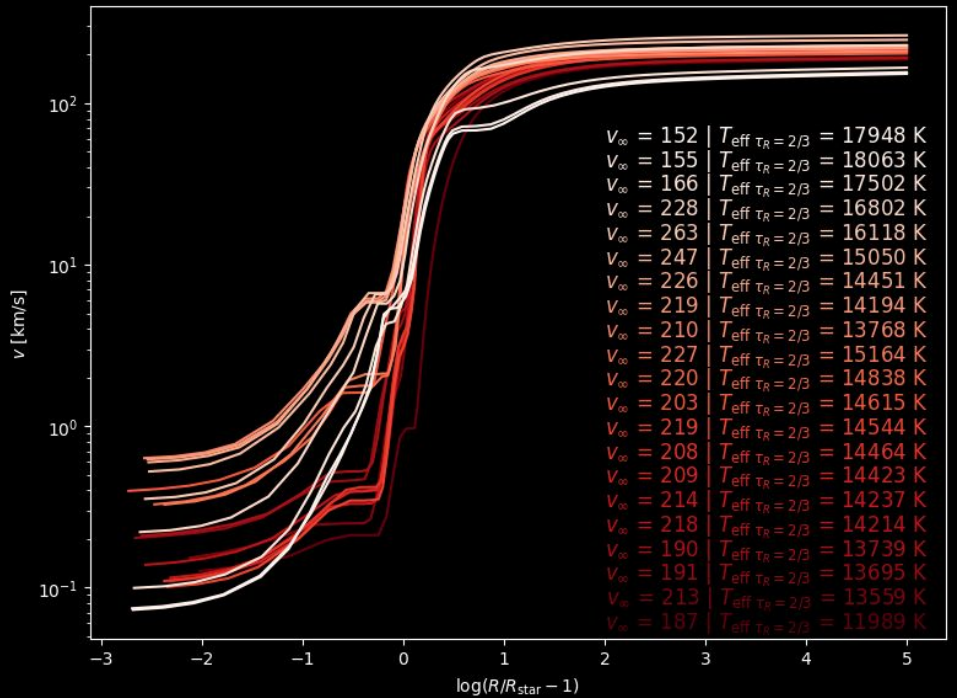
M(T_{eff}) in LBV-like stars?



T_{eff} (τ = 50)



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