Empirical mass-loss rates across the bi-stability jump from B-supergiants

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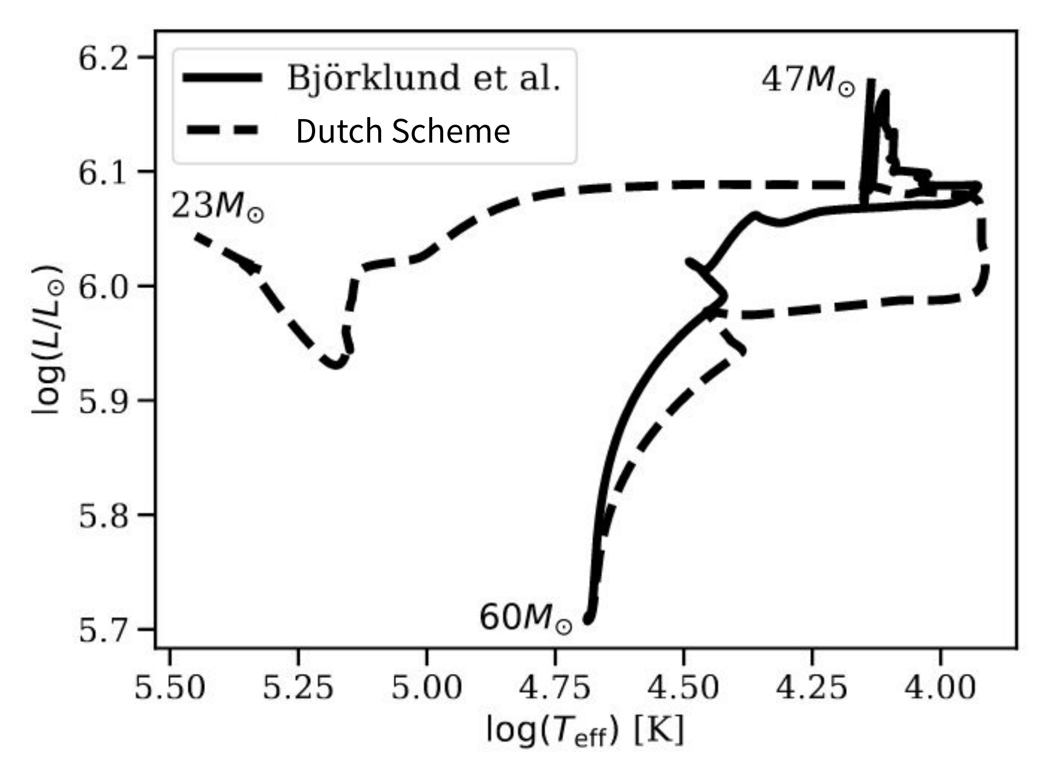
Importance of Mass Loss rates for Stellar Evolution

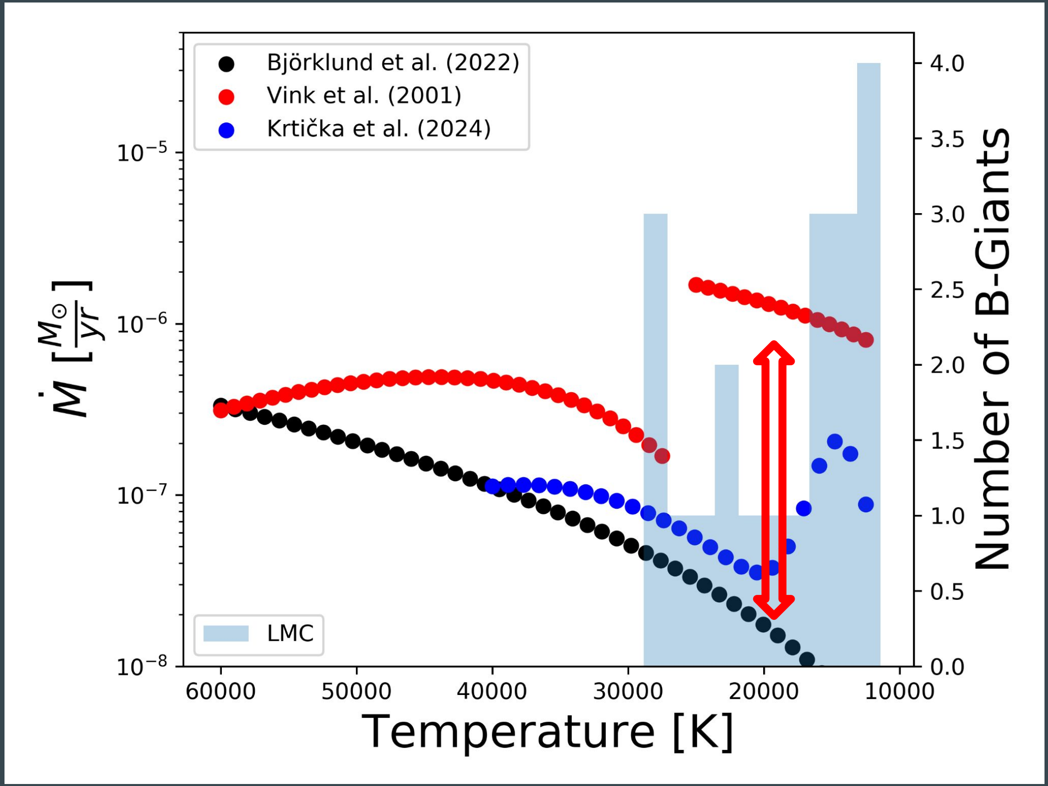
- Stellar evolution is highly influenced by mass loss
  - How to form single WR-stars?
- Need to understand the mechanisms of mass loss in the upper HRD



Björklund et al. 2022

Bi-stability Jump

- Increase in mass-loss rate around 25kK
    - Recombination FeIV ->FeIII
- My goal: use spectroscopy to find/disprove the jump
- Earlier efforts cannot take into account clumping Markova & Puls (2008), de Burgos et al. (2024)
- Need both optical and UV spectroscopy for clumping

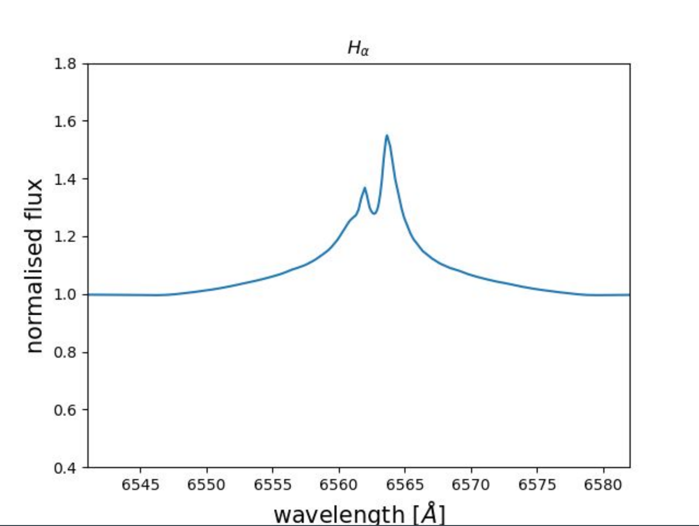


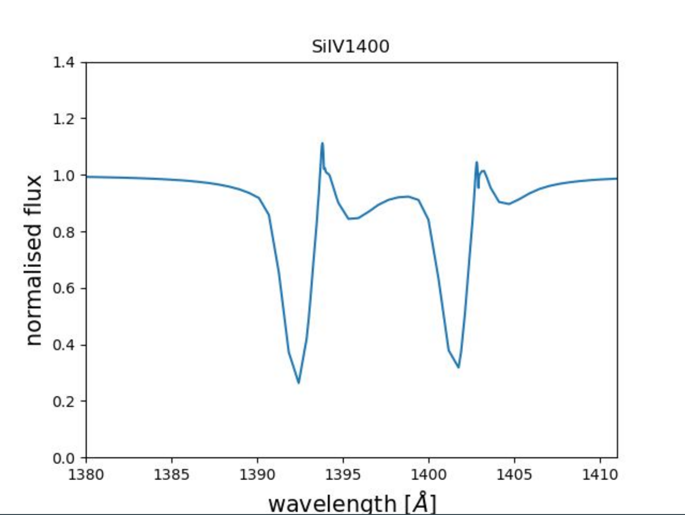
Vink et al. 2023

Bi-stability Jump Empirically

$f_{cl} = 40$
$dM/dt = 8*10^{-8}\ M_{\odot}/yr$

- Optical (H-α) mass loss rate degenerate with clumping



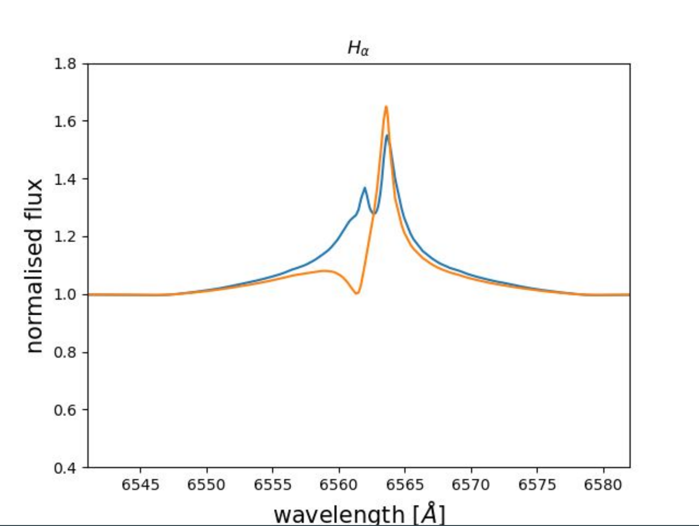


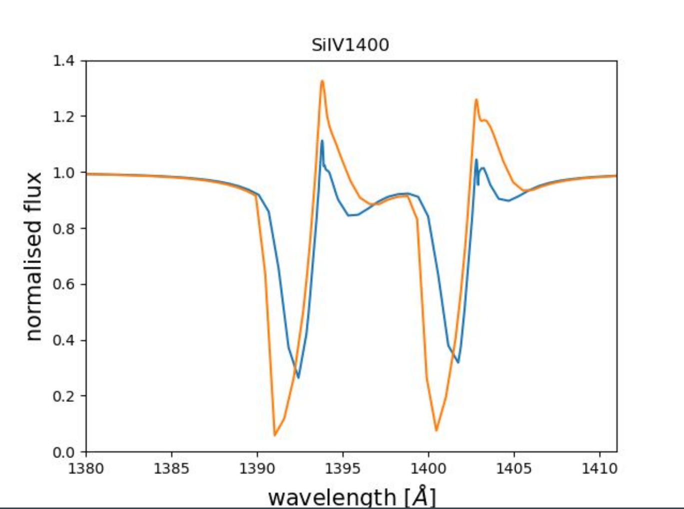
Clumping factor $= <\rho^2>/<\rho>^2$

Bi-stability Jump Empirically

$f_{cl} = 1$
$dM/dt = 5.1*10^{-7}\, M_{\odot}/yr$

- Optical (H-α) mass loss rate degenerate with clumping
- UV-Resonance lines allow for breaking of degeneracy

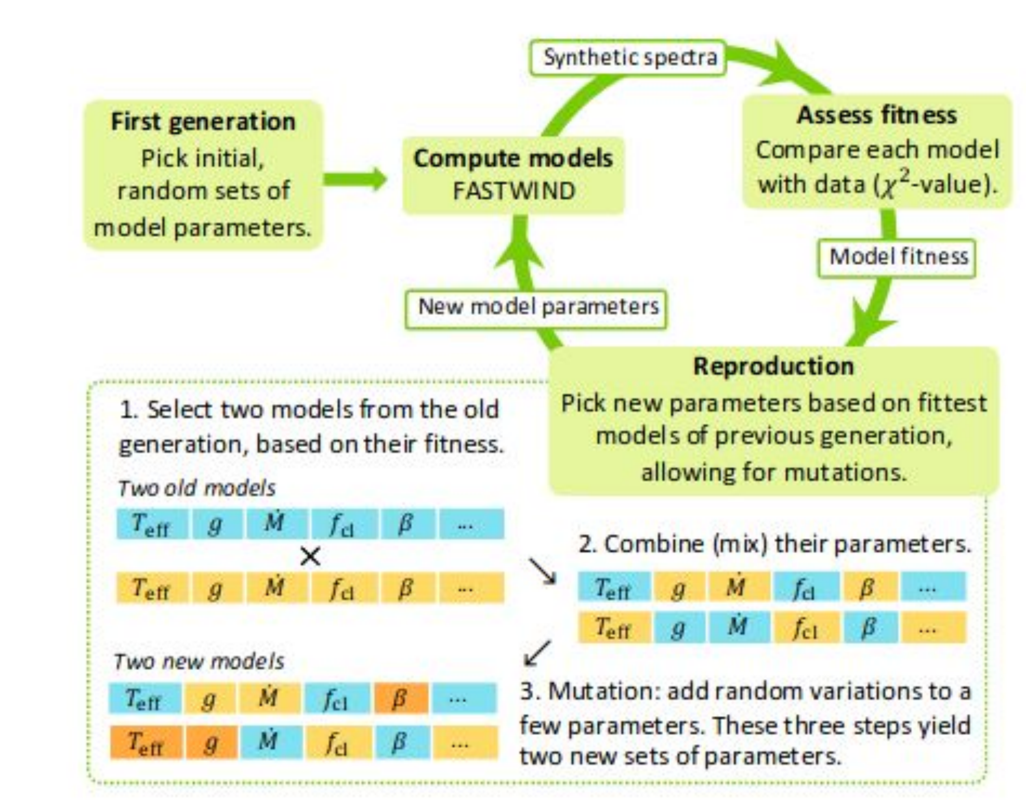




Clumping factor $= \langle\rho^2\rangle / \langle\rho\rangle^2$

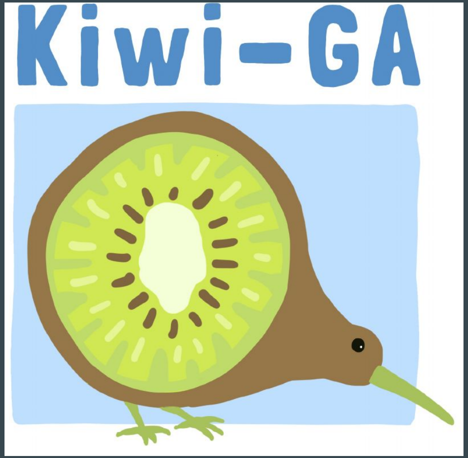
Kiwi-GA

- FASTWIND synthetic spectra (Sundqvist & Puls 2018)
- Kiwi-GA fitting allows for systematic error analyses (Brand et al. 2022)

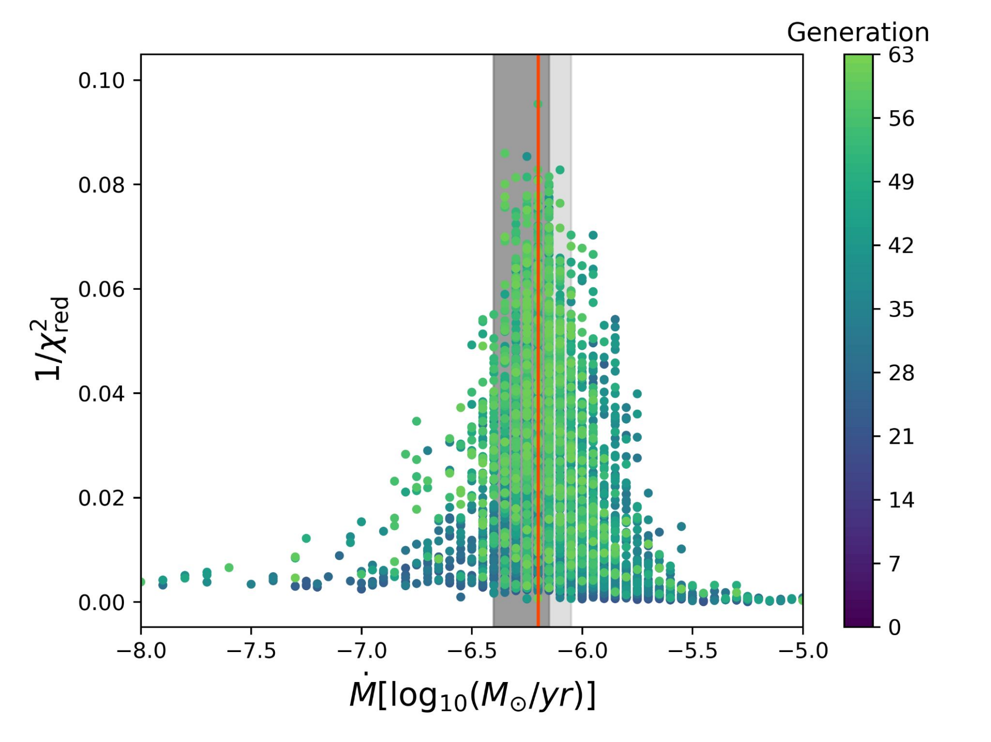


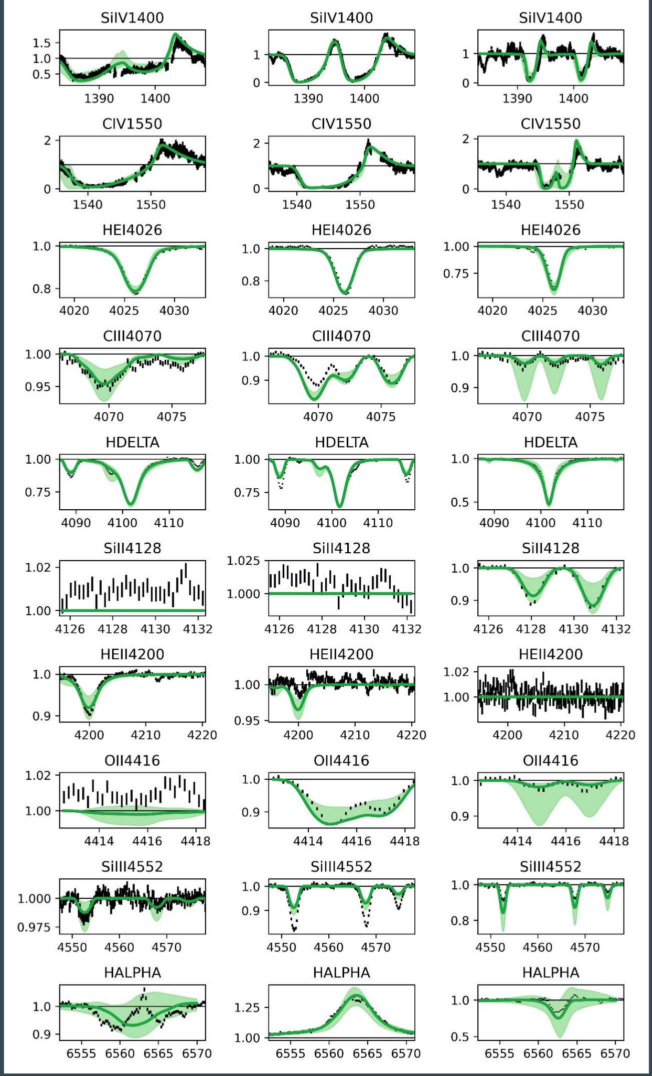
Genetic algorithm in numbers

- For a Kiwi-GA fit for one star
  - 50-70 generations
  - 107 models a generation ~6000 models
  - Not possible with 3D models
  - FASTWIND ~45 min =>190 days
  - Highly parallelized 107 cores =>~ 2 days
- Global fits with Global errors!



Kiwi-GA output

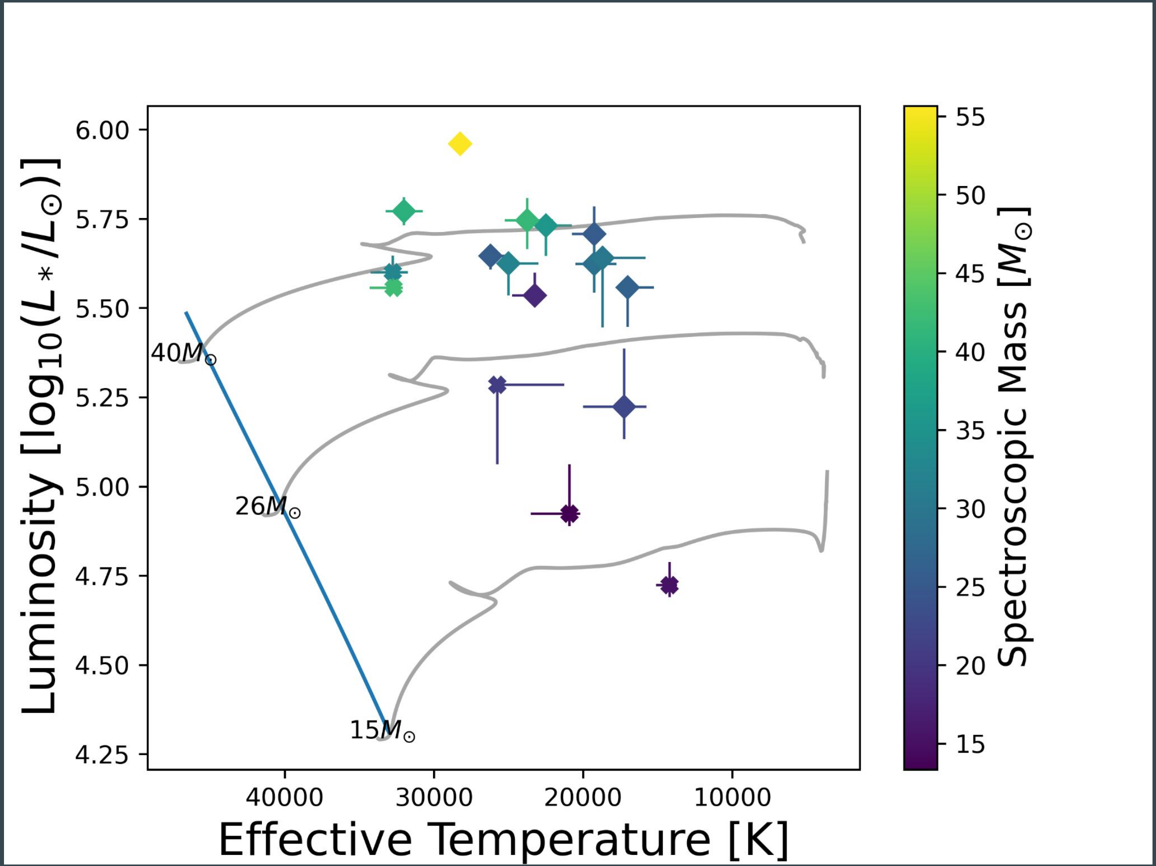




Results from LMC B-supergiants

LMC Sample

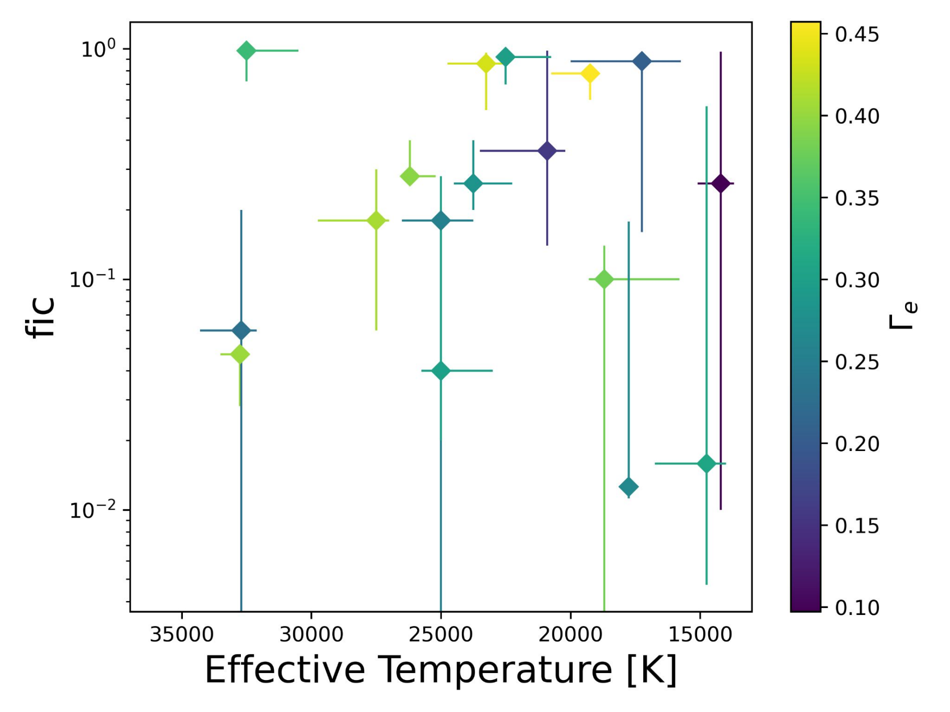
- Mostly in the HR-gap
- Masses from 15-55M☉

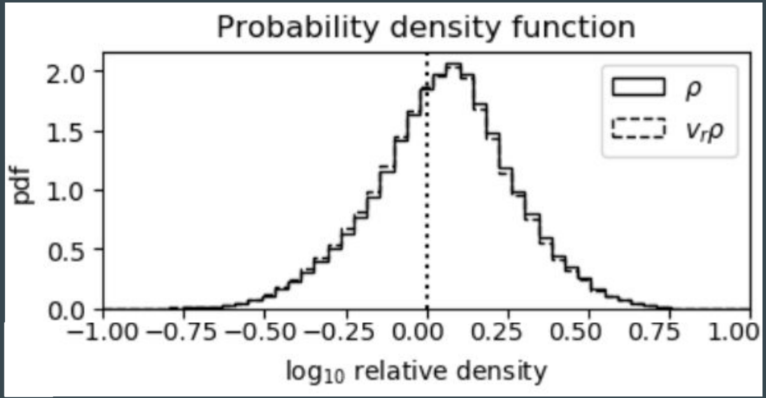


Verhamme et al.
(submitted)

Interclump density

- Large scatter, but high values are the norm rather than exception
- 38 +- 23 % wind mass in interclump medium
- Contrary to other 1D codes

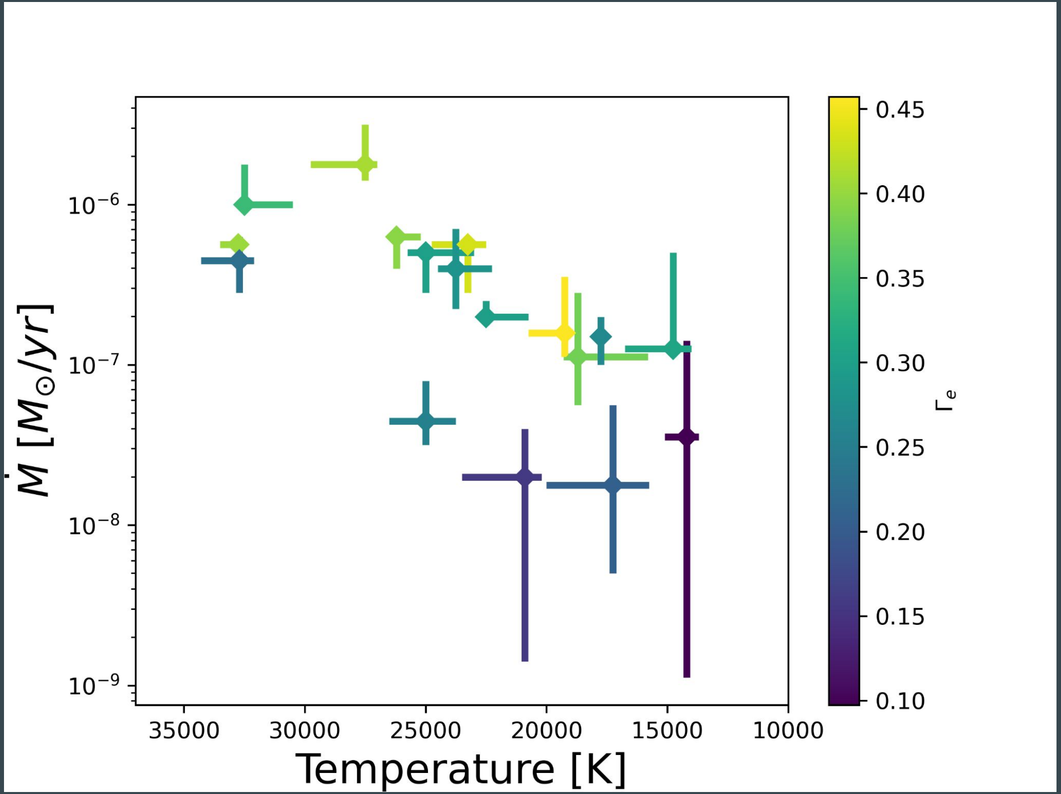




Moens et al. 2022

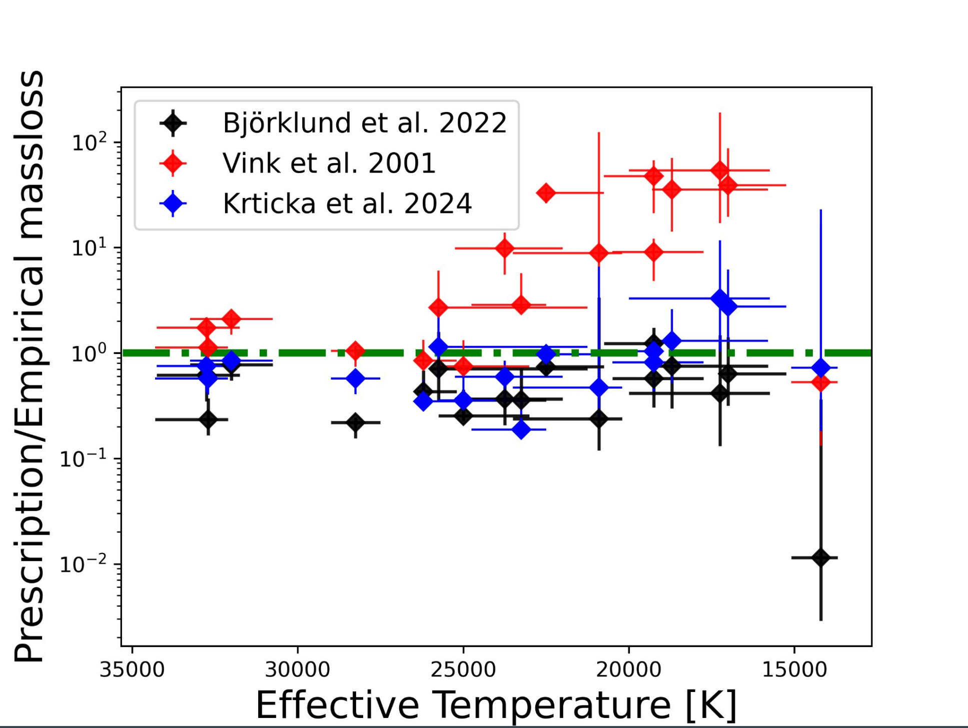
Mass loss rate

- Mass loss decreases with temperature
- Strong effect of Γ_e
- Difficult to say anything for certain due to influence of Mass and Luminosity



Comparison to prescription

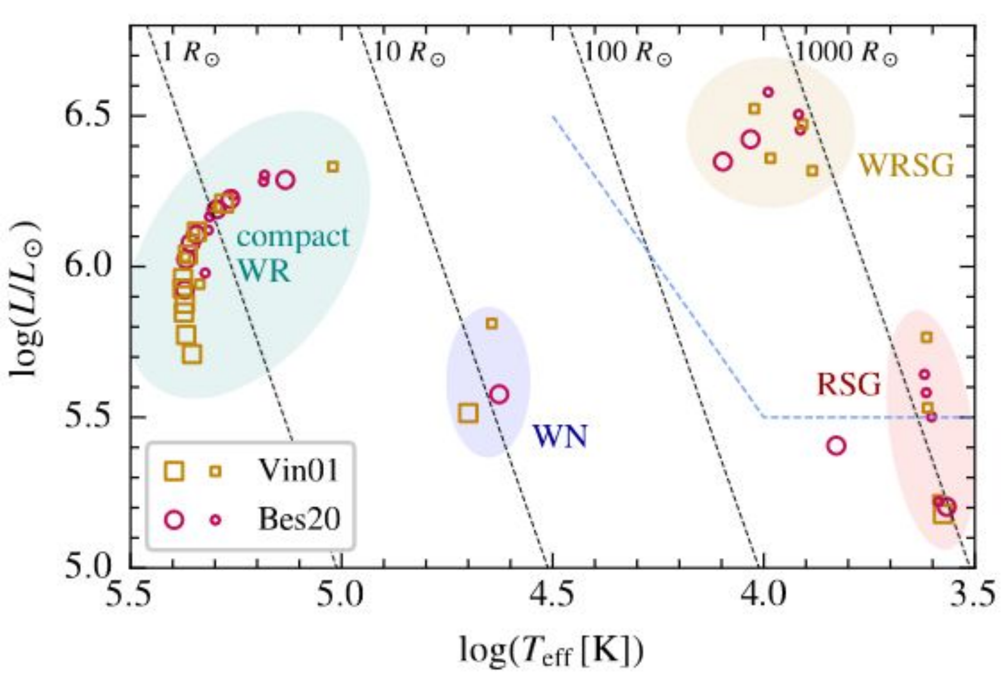
- Vink prescriptions agrees well down to ~23kK
- Below ~23kK overestimation of up to a factor of 100
- Bjorklund prescription relatively consistently underestimates by a factor of 2
- Krticka prescription agrees well over- and under-estimating
  - Bump too cool and localised to check existence



Verhamme et al. (submitted)

Effects of mass-loss on evolution: Revisited

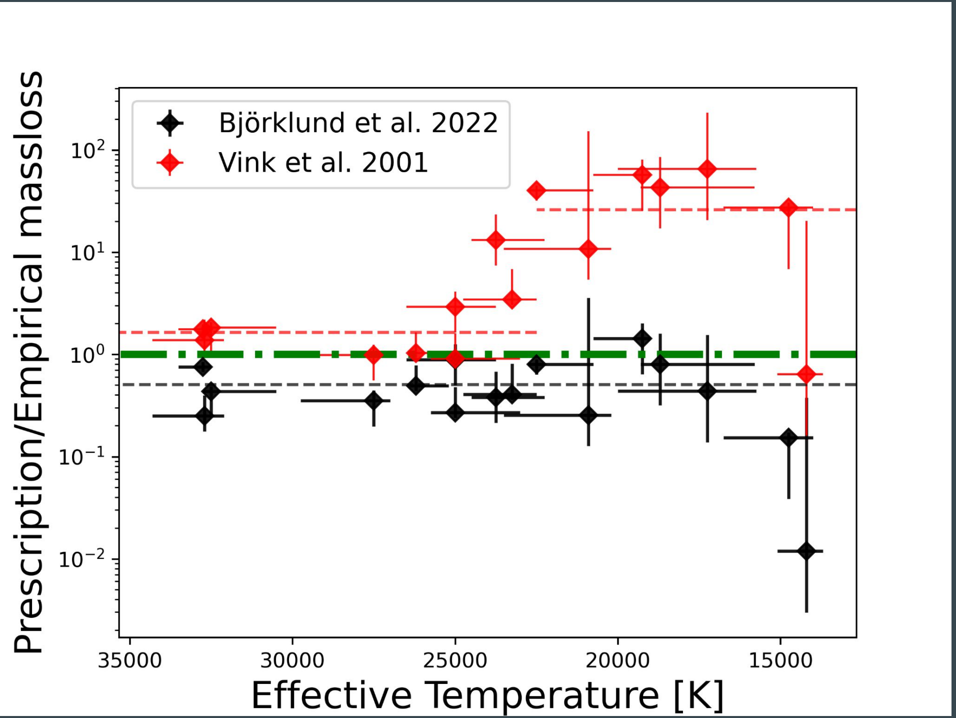
- New mass loss rates for O-stars
- Both LMC and Galactic
- Differences:
  - in end products
  - Chemical yields
  - Convection zones over evolution



Josiek et al. 2024

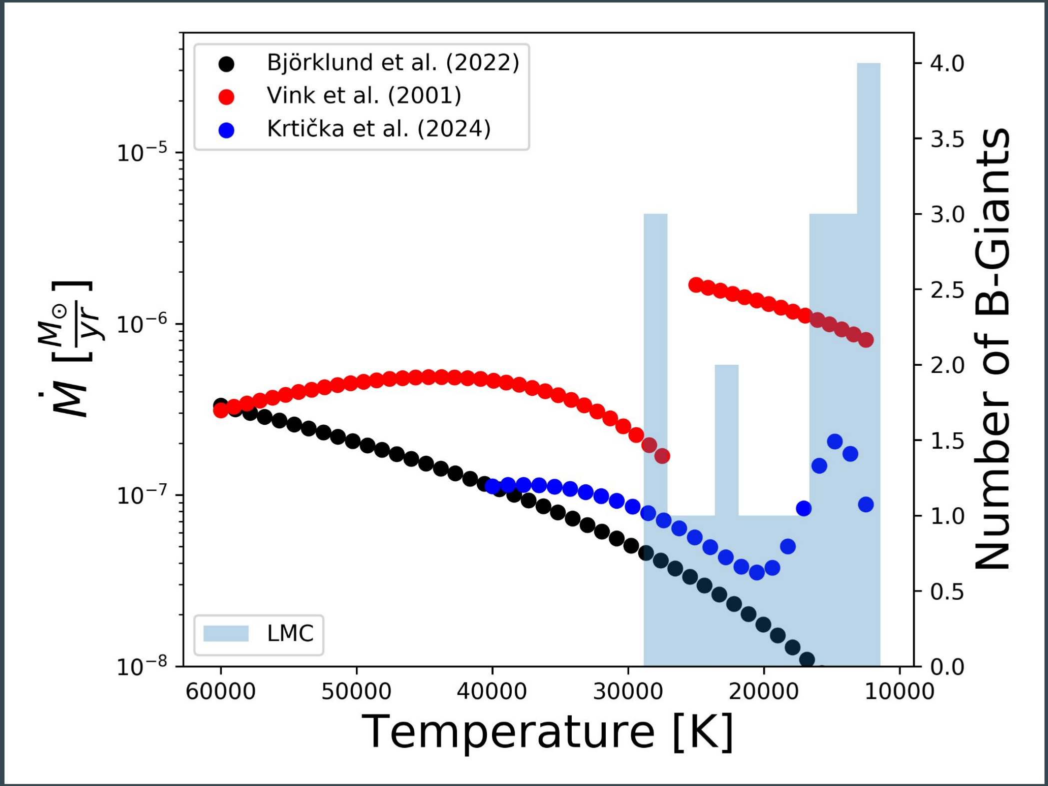
Conclusion

- Mass loss rate prescription clearly not inline with observations
  - LBV winds are a big uncertainty still
- 40% of the wind is in the interclump region
  - improving description should be a focus



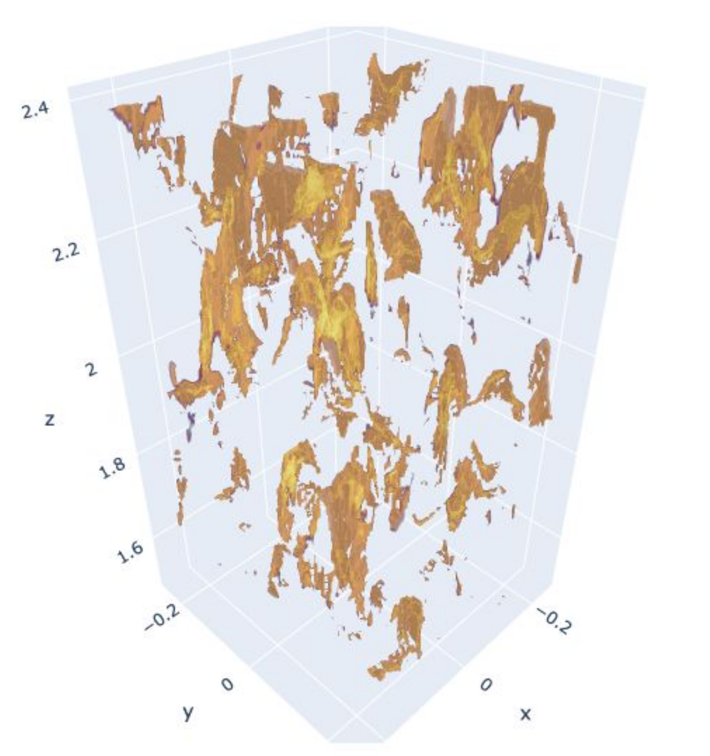
Bi-stability Jump

- Increase in mass-loss rate around 25kK
  - Recombination FeIV ->FeIII
- Recent modelling does not find a jump
- Vink rate is standard for your favourite evolutionary code



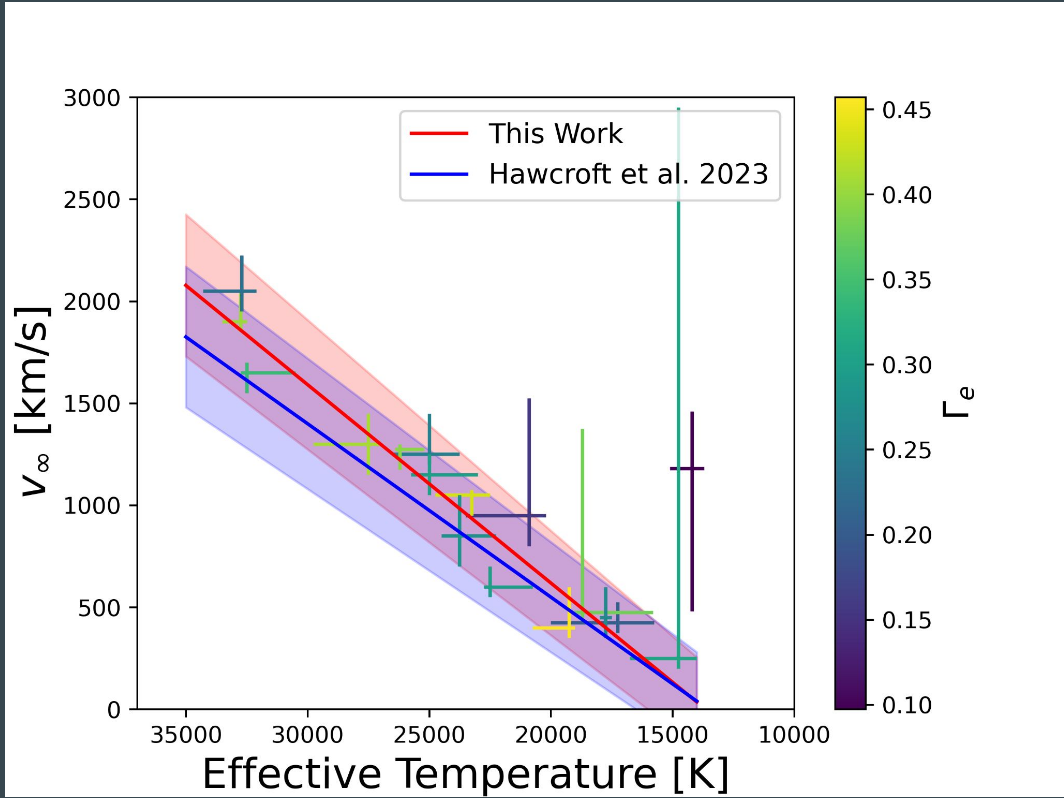
From 3D phenomena to 1D wind

- Clumping is inherently 3D
- 3D models take a long time ~days for one RHD model (+spectra-synthesis ~ 1 day)
  - Improving 3D is ongoing work
- Parameterise the behaviour into 1D FASTWIND
  - Clumping parameter f_{cl}
  - Interclump density f_{ic}
  - Velocity Filling factor f_{vel}



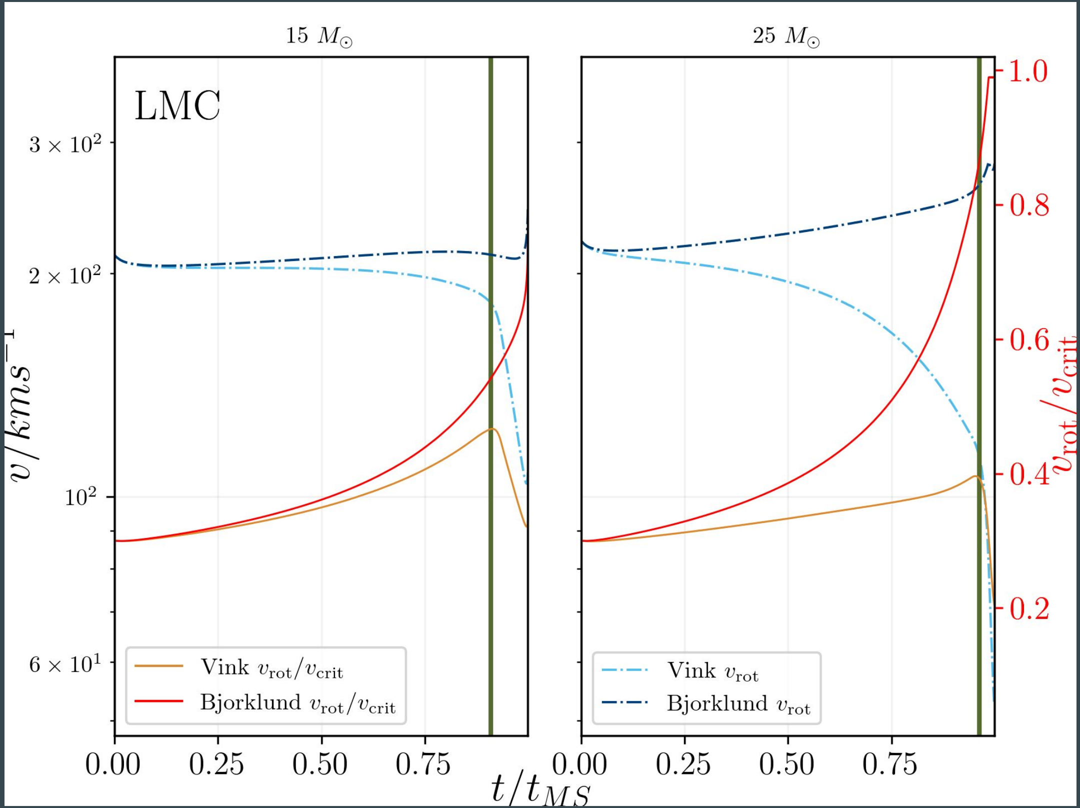
Terminal wind speed

- Terminal wind speed linear with effective temperature
- No large influence from Γ_E
- $\Gamma_E = g_r/g_g \propto L_\odot/M_\odot$
- Very similar to Hawcroft et al. 2023



Effects of Rotation

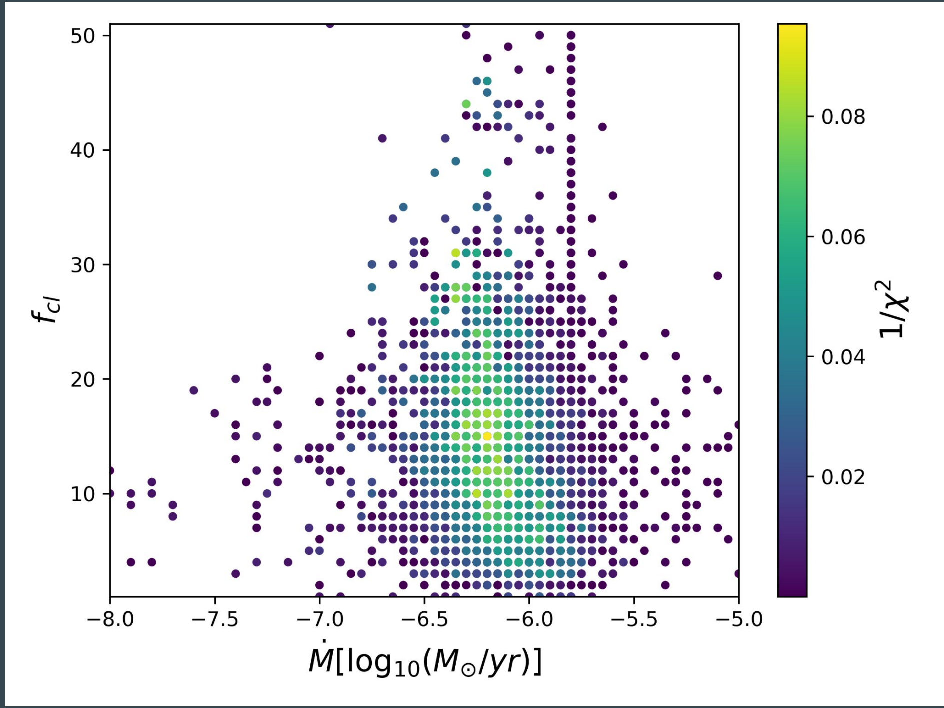
- Mass loss transports angular momentum away and thus reduces rotation
- Influences the creation of Be-stars



Adapted from: Nick Van Wouwe

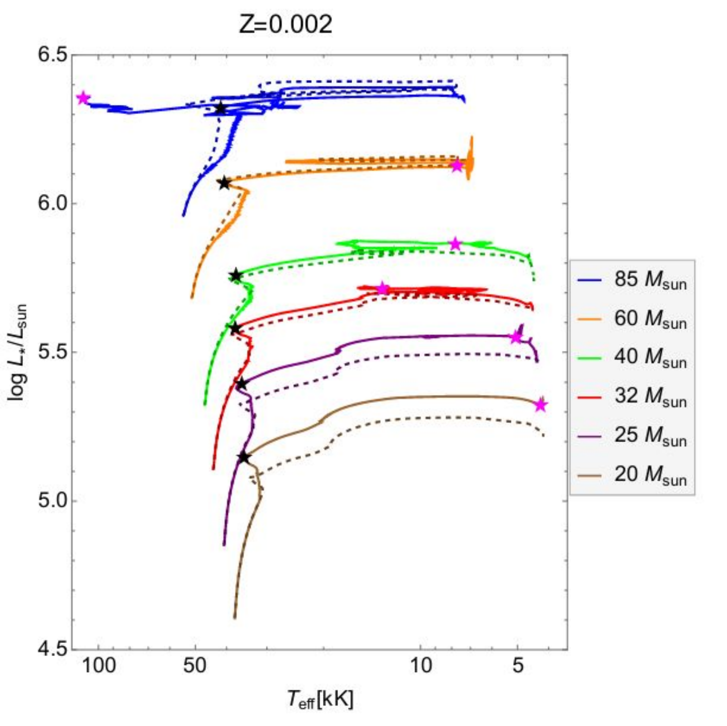
Clumping degeneracy

- Correlation between mass-loss and clumping is clearly visible
- Well defined peak in mass-loss is still found



Effects of mass-loss on evolution: Revisited

- SMC study reducing mass loss by factor 2-6 depending on Mass
- Clear differences in end products
- Changes in surface abundance



Gormaz-Matamala et al. 2024

Effects of interclump density

Traditionally: $D = f_{cl}$

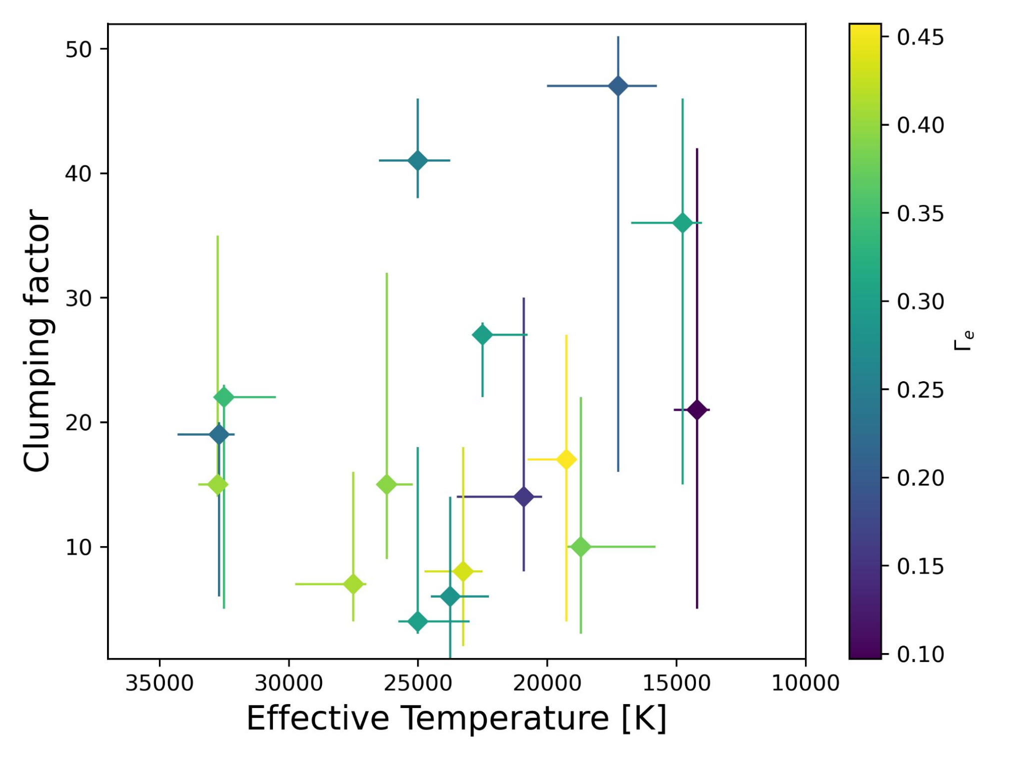
$f_{vol} = 1/f_{cl}$

Does not hold for 2 component medium (Sundqvist & Puls 2018)

SK-68 8	FASTWIND	Equal clumping factor	Equal volume filling
Clumping factor	8	8	22
Interclump Density	0.82	N/A	N/A
Volume filling factor	0.046	0.125	0.046
Clump Overdensity (D)	40	8	22

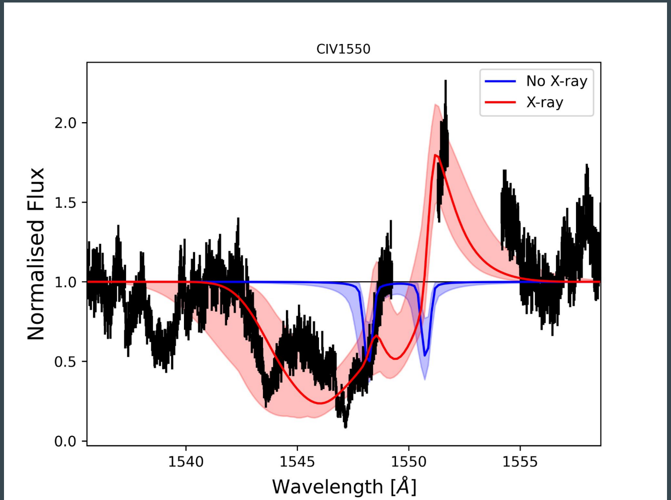
Clumping factor

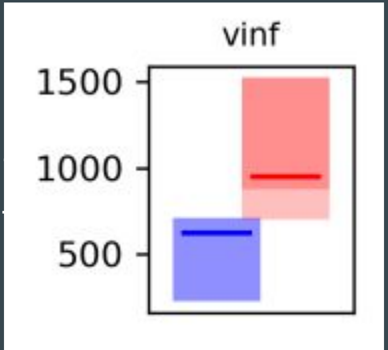
- No real behaviour over temperature
- Large scatter
- From LDI simulations (Driessen et al. 2019)
    - O-stars ~20
    - B-stars ~5

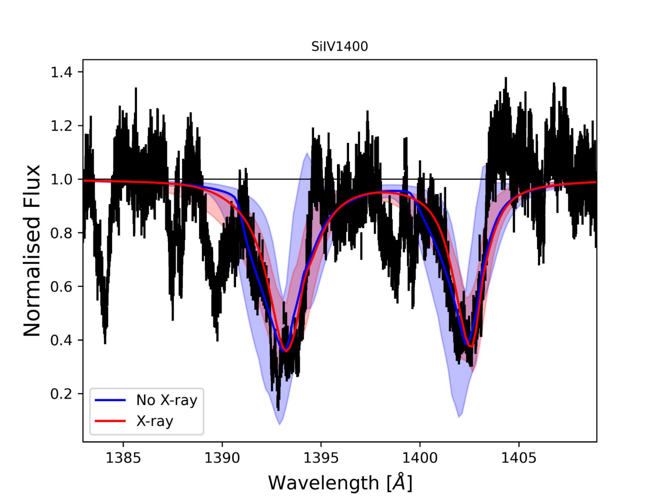


X-ray effects on Terminal wind speed

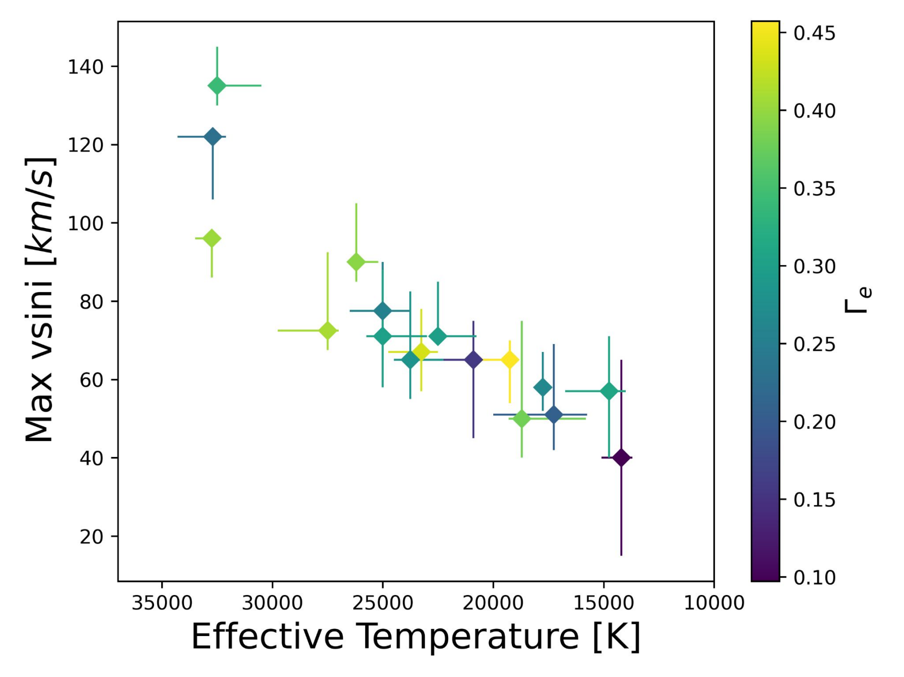
- Some cool B-stars have strong CIV features in the wind
- X-rays allow for these lines to be fitted without changing the other lines
- Big effect on measured Velocity

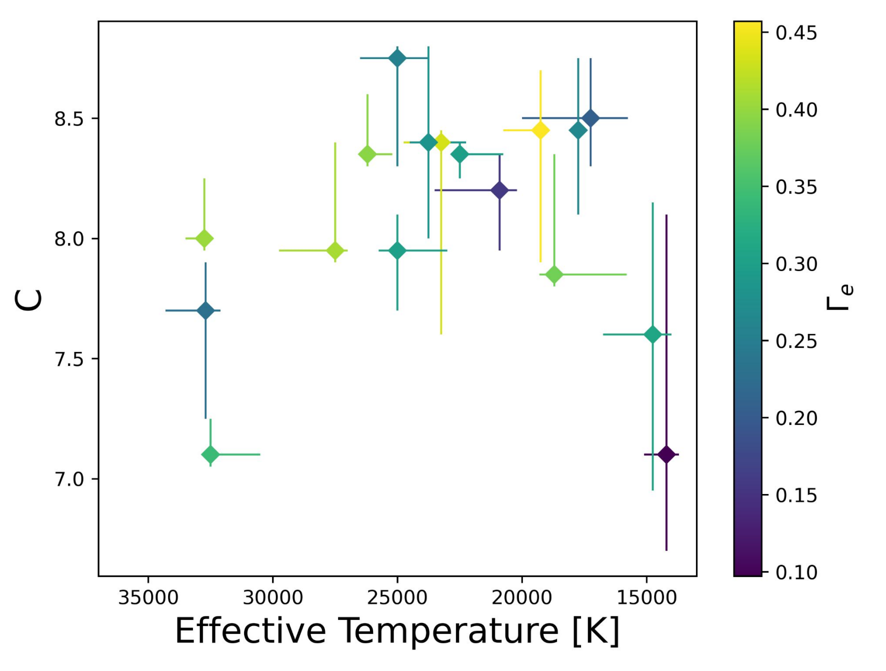






Stellar Parameters

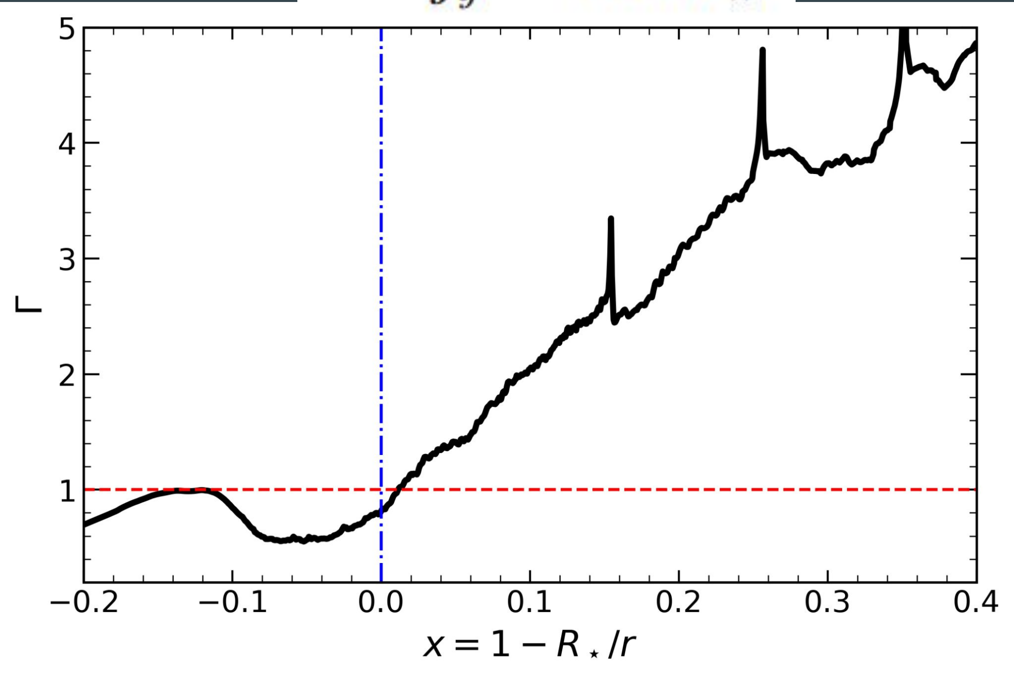




Radiation driven winds

- Strong 10^{-4}-$10^{-7}\,M_\odot$/yr
- Clumped
  - Line Deshadowing Instability
  - Subsurface turbulence
- High velocity (~1000km/s)
- Strongly influenced by metallicity
- One of the important parameters is Γ

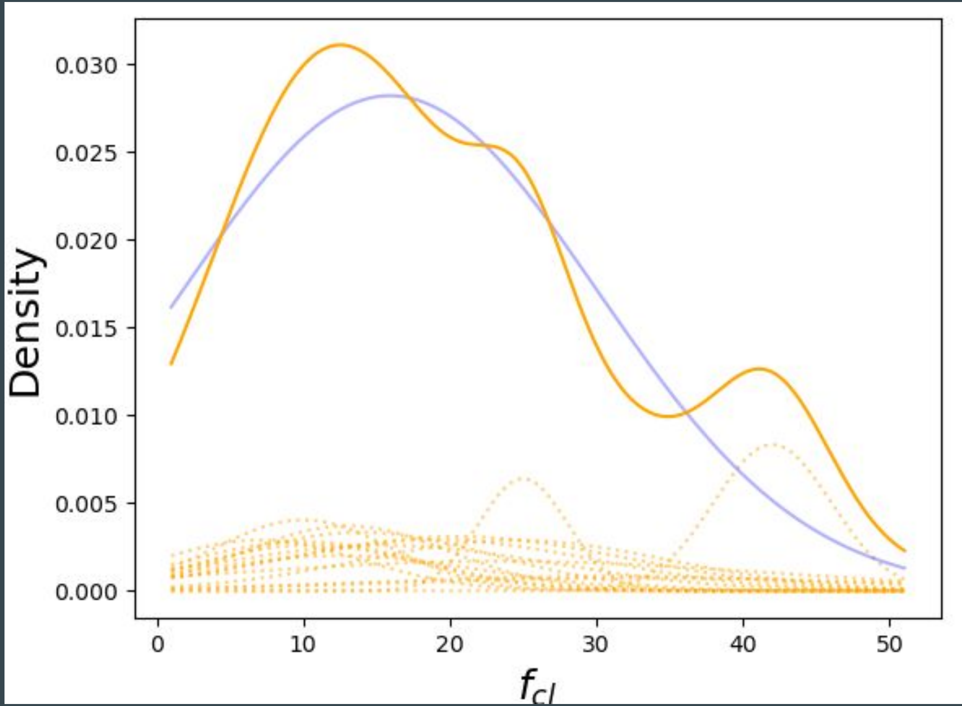
$$\Gamma \equiv \frac{g_r}{g_g} = \frac{L_\star \kappa}{4\pi G M_\star c}$$



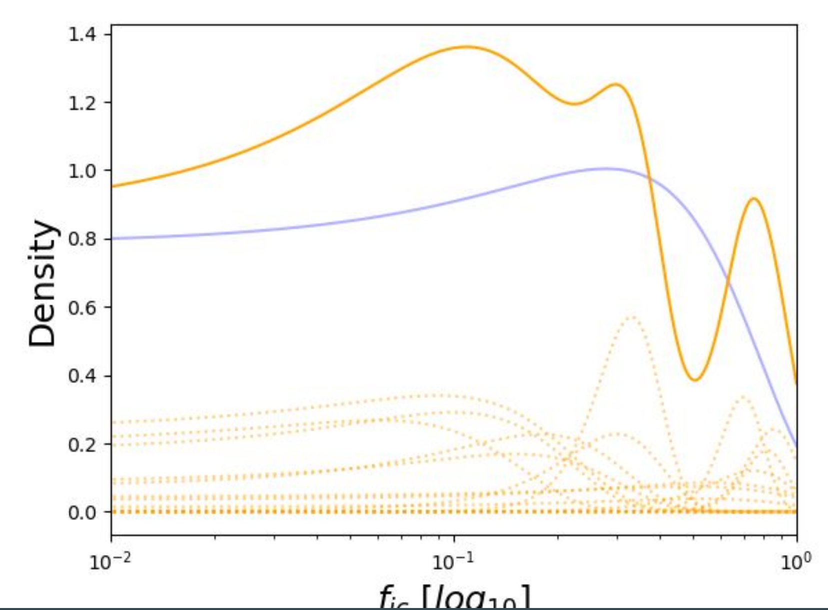
Debnath et al. 2024

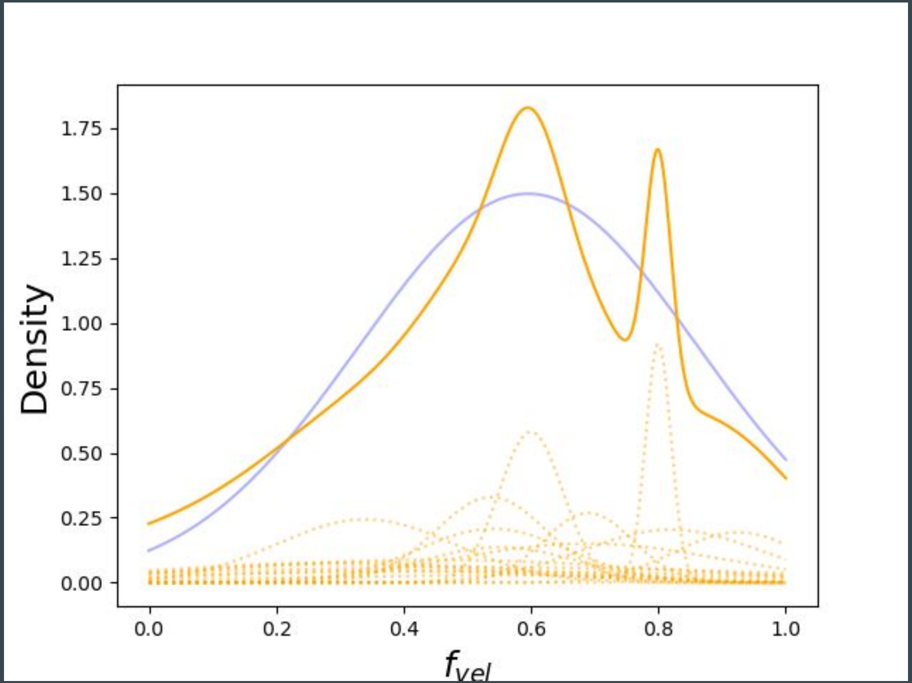
Clumping parameters of the sample

- Density estimates from gaussian distributions
- New gaussian fits allow for error estimate



Clumping parameters of the sample

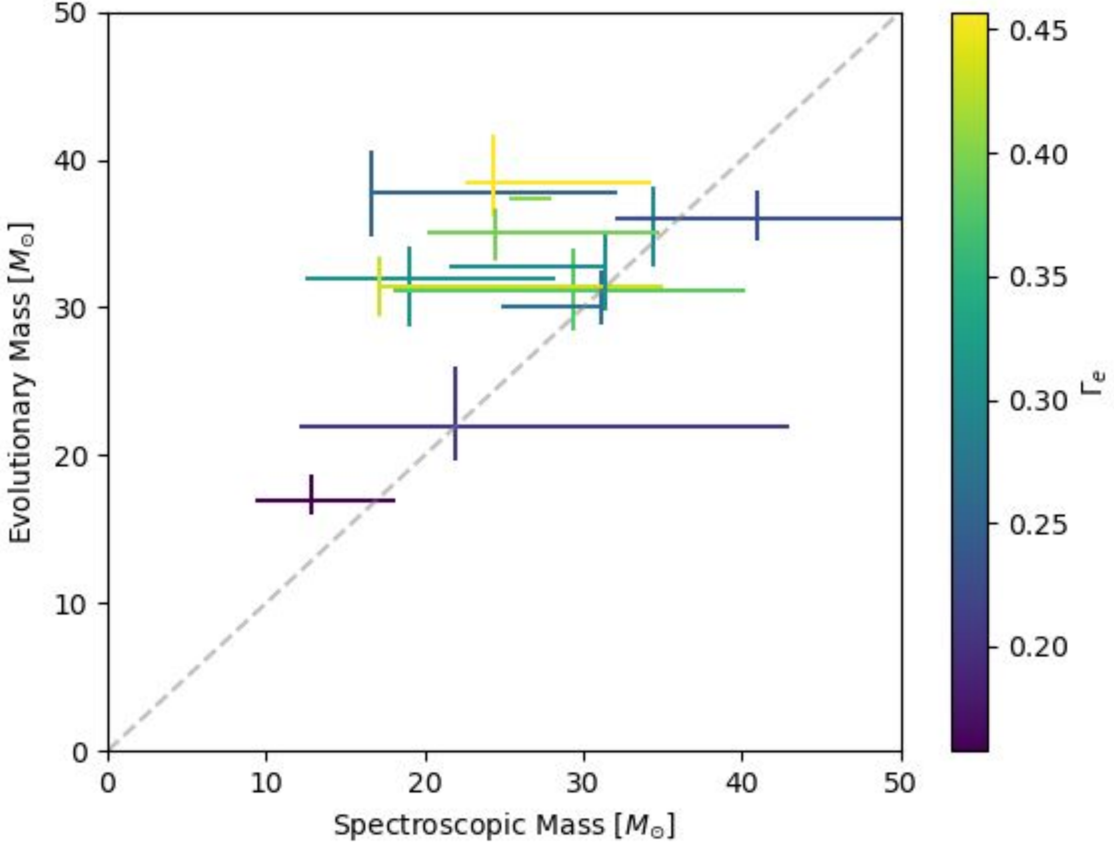




2-step approach?

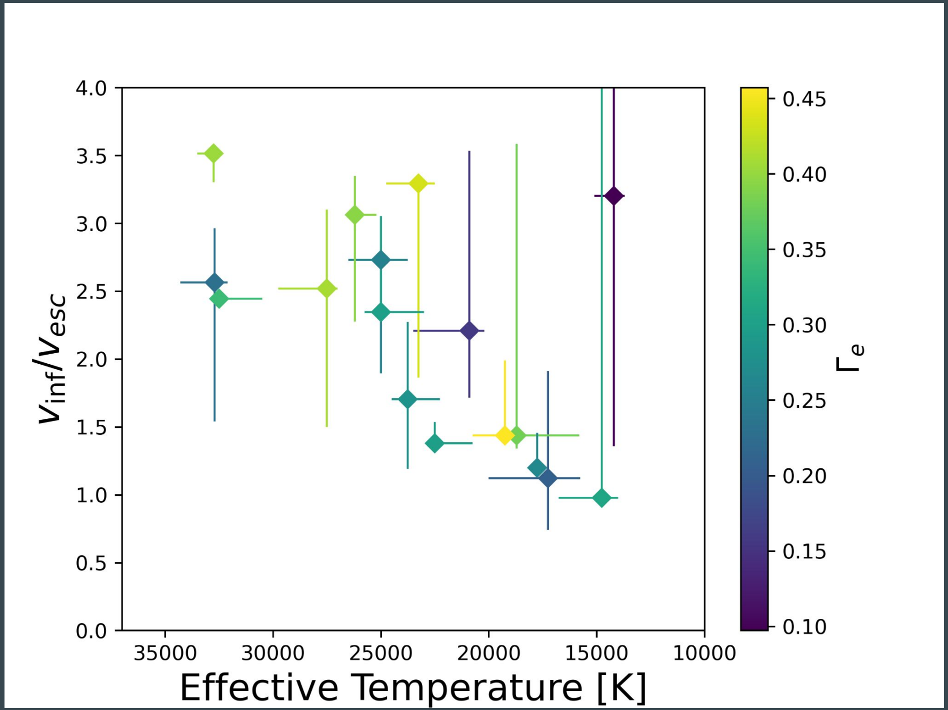
- Most of the stellar parameters should be possible to determine from optical only:
  - Teff from SiII/SiIII/SiIV and HeI/HeII strength
  - Logg from balmer lines
- Use best fit of the optical only as initial guess in the full fit

Make some sort of graphic!



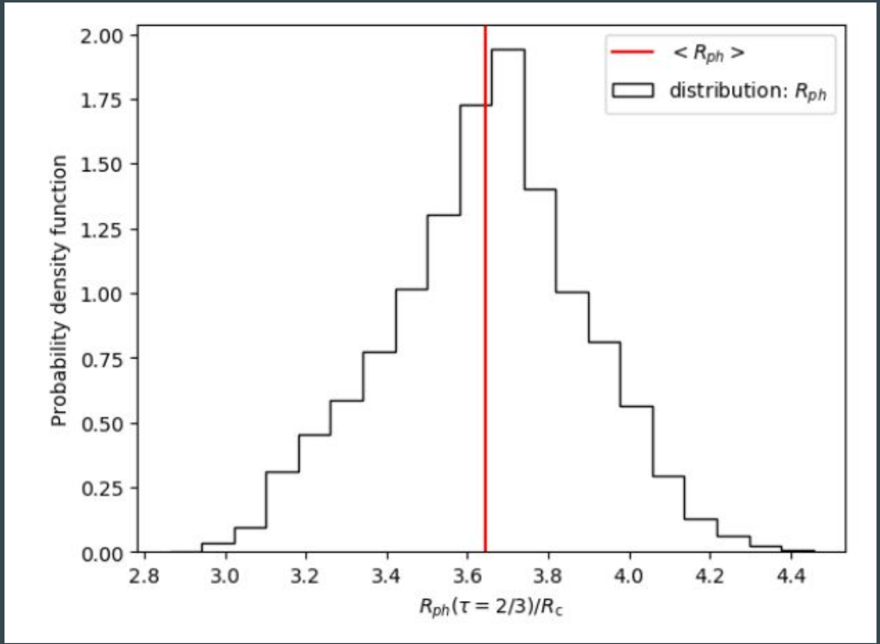
50
40
30
20
10
0
0
10
20
30
40
50
Evolutionary Mass [$M_\odot$]
Spectroscopic Mass [$M_\odot$]
0.45
0.40
0.35
0.30
0.25
0.20
Γ_e

Vinf/Vesc



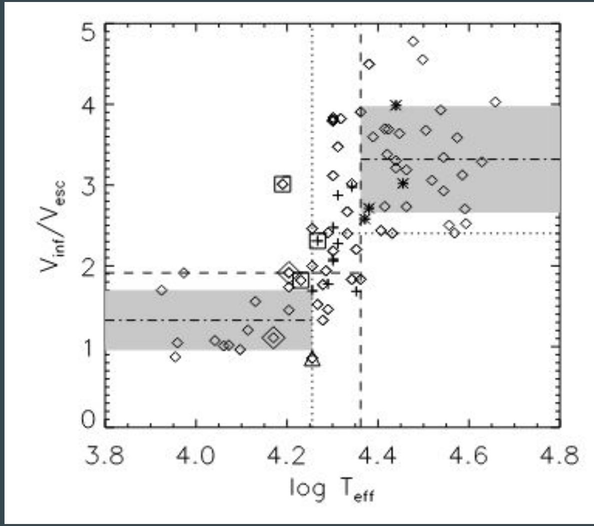
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
v_{inf}/v_{esc}
35000
30000
25000
20000
15000
10000
Effective Temperature [K]
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
Γ_e

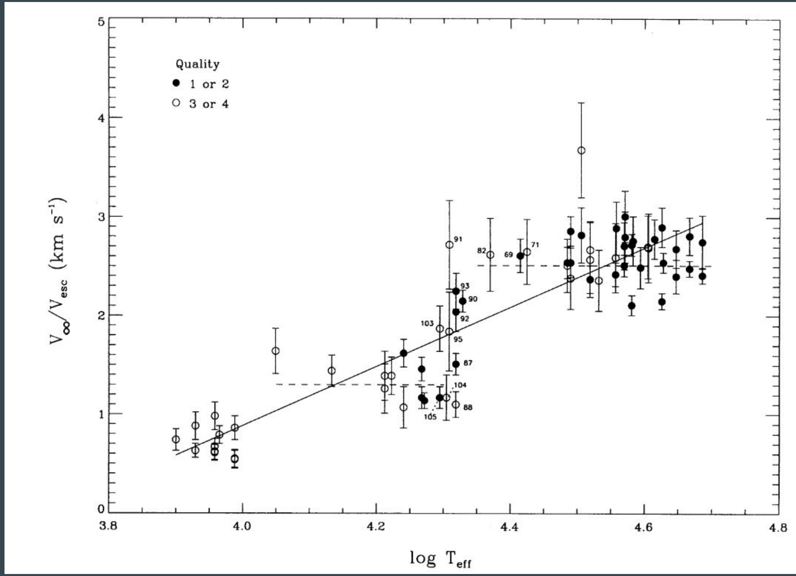
Effects of interclump density

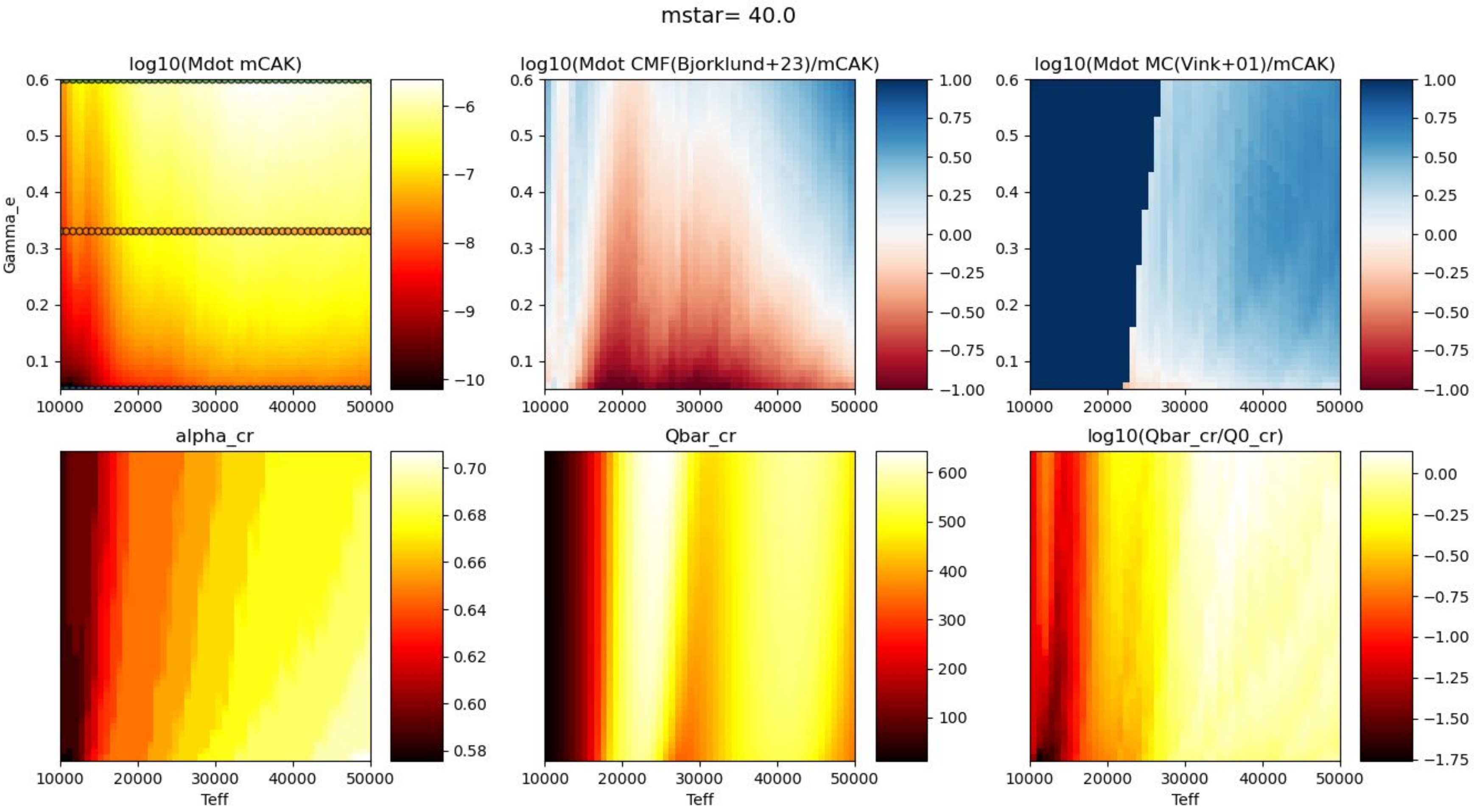


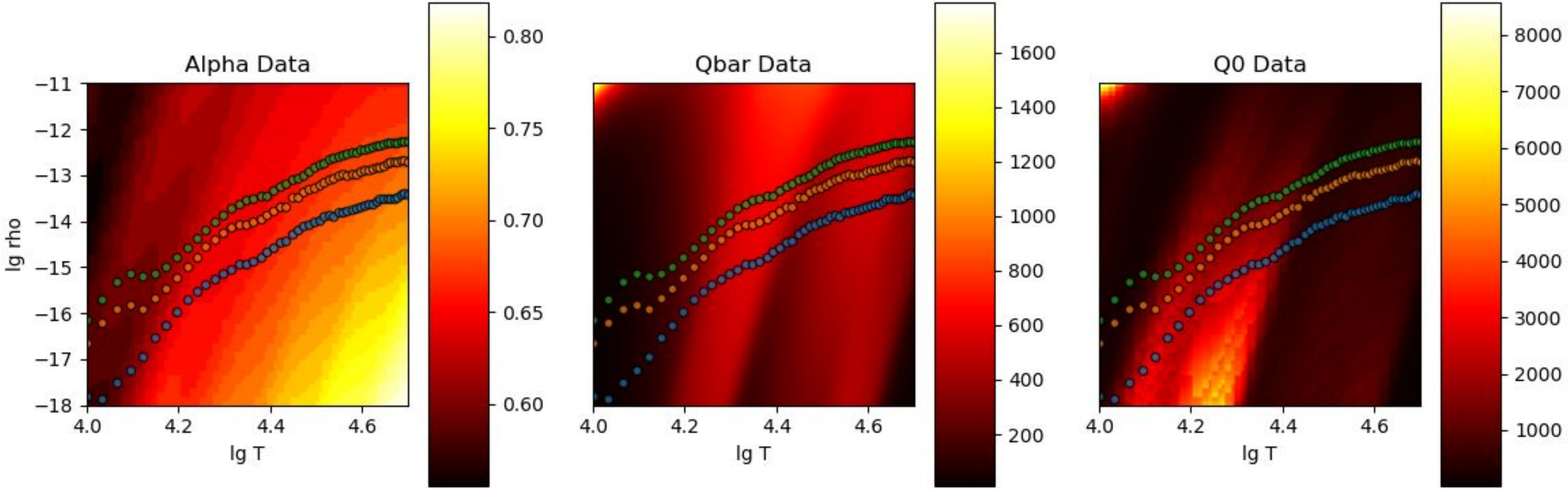
Bi-stability jump

- Observed as sudden drop of vinf/vesc around 20kK
- Caused by recombination of FeIV -> FeIII
- Might coincide with mass loss increase






mstar= 40.0
log10(Mdot mCAK)
log10(Mdot CMF(Bjorklund+23)/mCAK)
log10(Mdot MC(Vink+01)/mCAK)
Gamma_e
alpha_cr
Qbar_cr
log10(Qbar_cr/Q0_cr)
Teff
Teff
Teff


Alpha Data
Qbar Data
Q0 Data
lg rho
lg T
−11
−12
−13
−14
−15
−16
−17
−18
4.0
4.2
4.4
4.6
0.80
0.75
0.70
0.65
0.60
1600
1400
1200
1000
800
600
400
200
8000
7000
6000
5000
4000
3000
2000
1000