A bi-stability jump for Wolf-Rayet stars?

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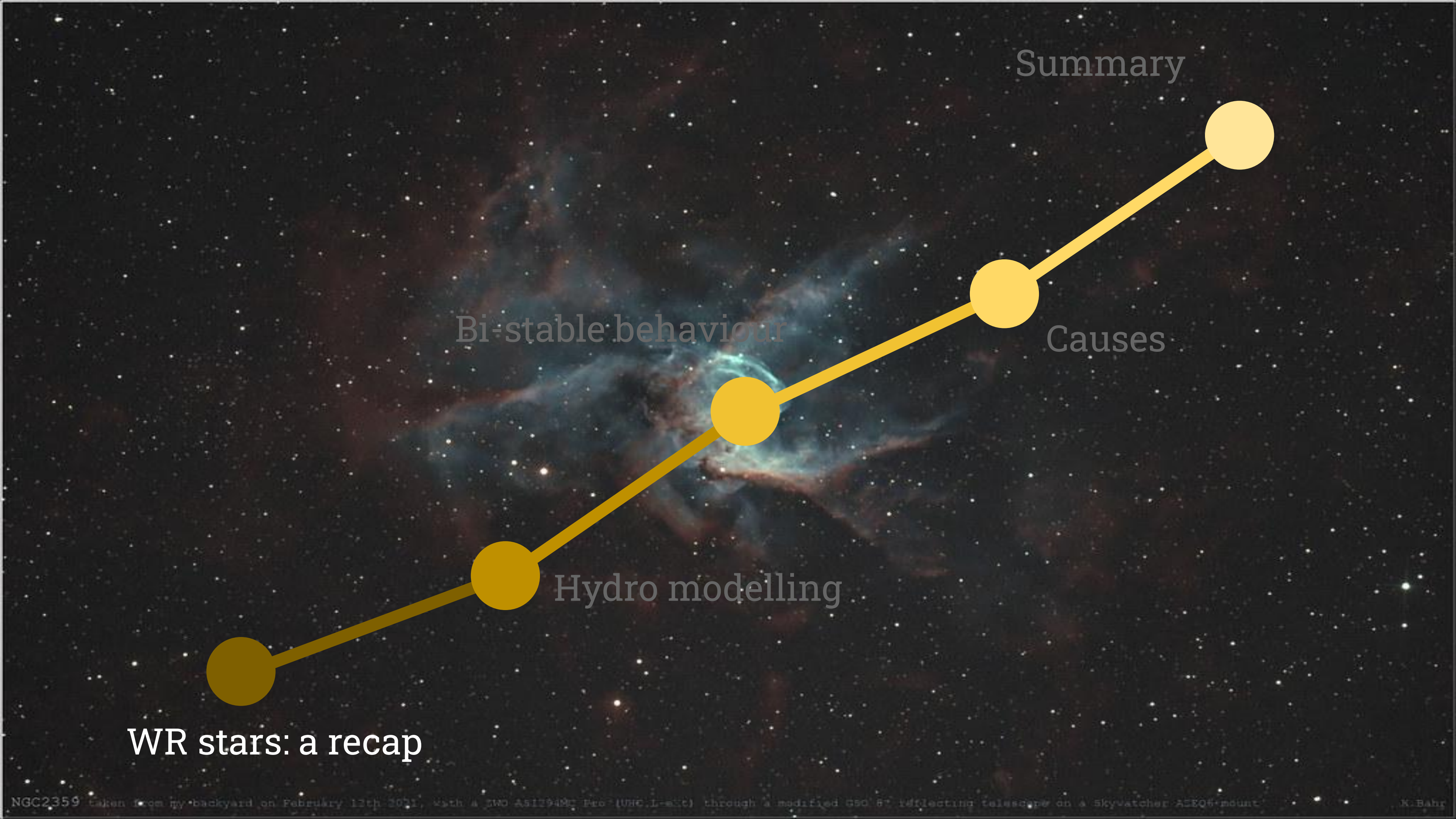

Summary
Causes
Bi-stable behaviour
Hydro modelling
WR stars: a recap
NGC2359

WR stars: a recap

First look

Yugipedia

WR stars: a recap
Spectroscopy

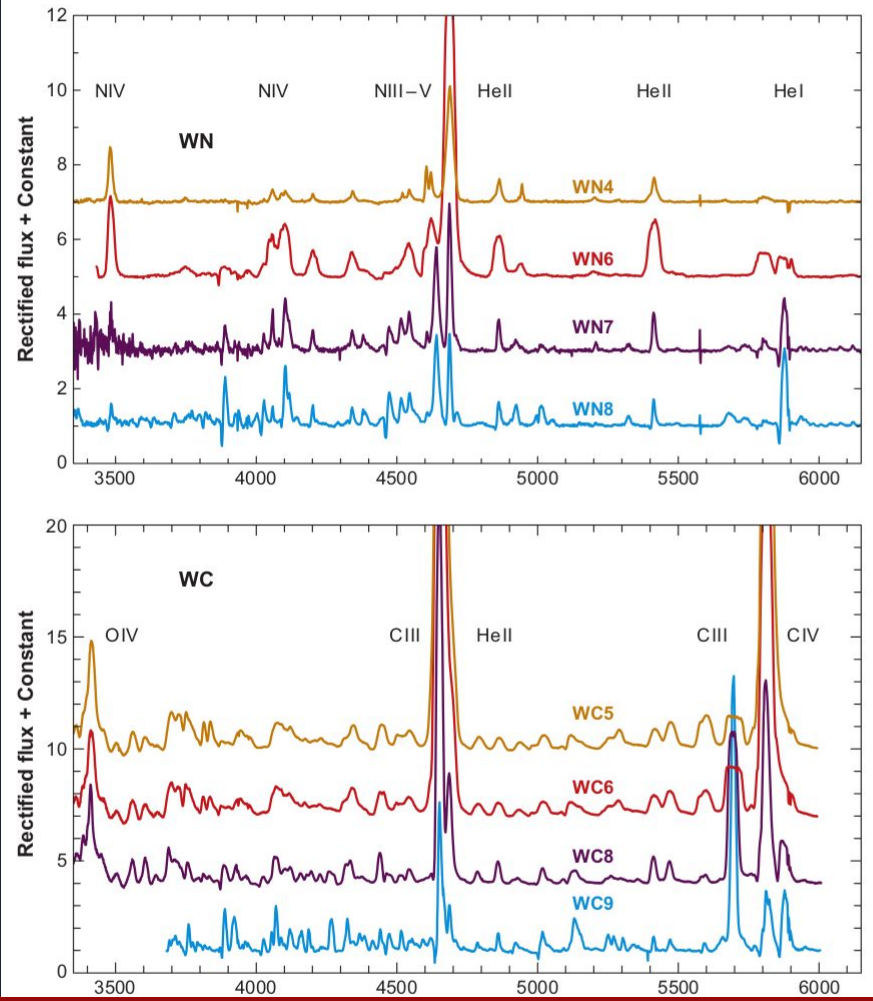
- Typically: massive, evolved stars
  Exceptions:
  - [WR] stars (CSPN)
  - **WNh stars**: O-stars on steroids

- Discovered and defined by their **spectra**

- Loads of strong and broad **emission lines** (WN, WC, WO, ...)

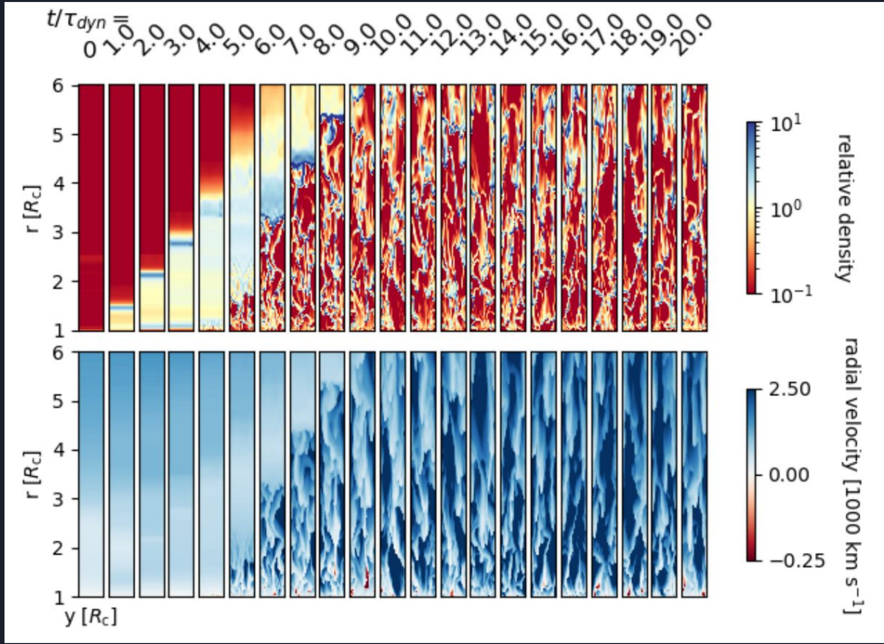
- Cause: powerful **stellar winds**

Crowther et al. 2007



WR stars: a recap
Winds

- Powerful winds lead to **significant mass losses**: 10^{-5} - 10^{-3} $M_\odot$ yr^{-1}
- Very high **terminal velocities v_∞**: 100s to 1000s km s^{-1}
- Strong source of **feedback**: local enrichment, mechanical luminosity L_{mech}
- Mainly caused by **iron opacity**
  - Radiation momentum
  - Multiple Scattering, NLTE, …



Moens et al. 2023

WR stars: a recap

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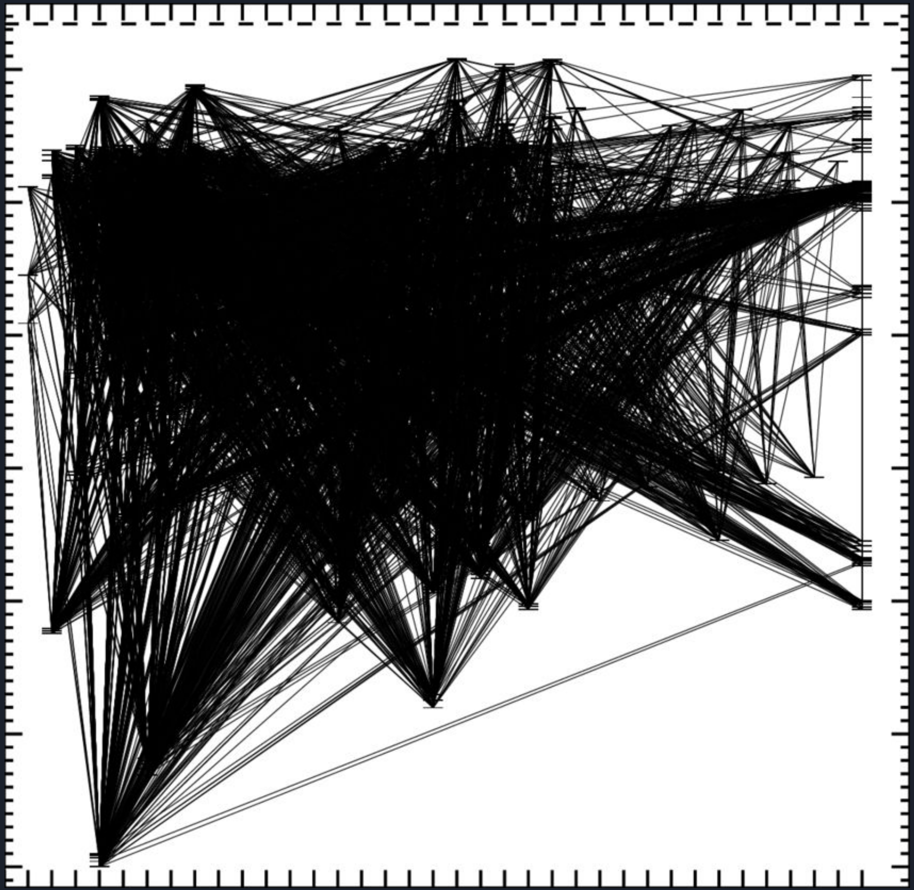
See also Cassandra's talk (coming very soon)!



Short et al. , 2008

WR stars: a recap
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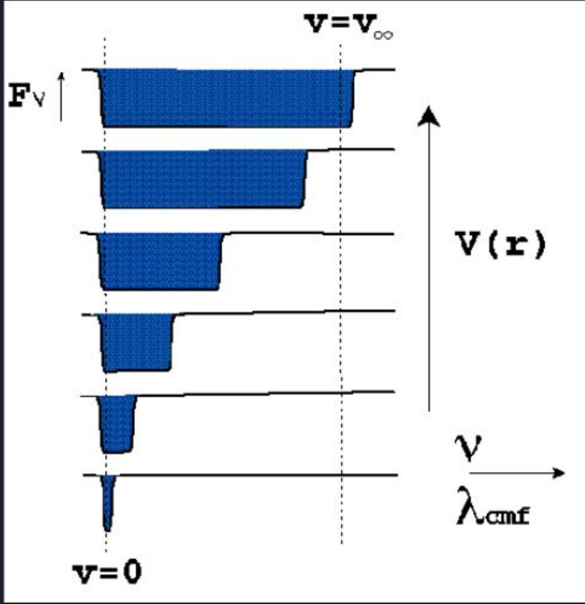
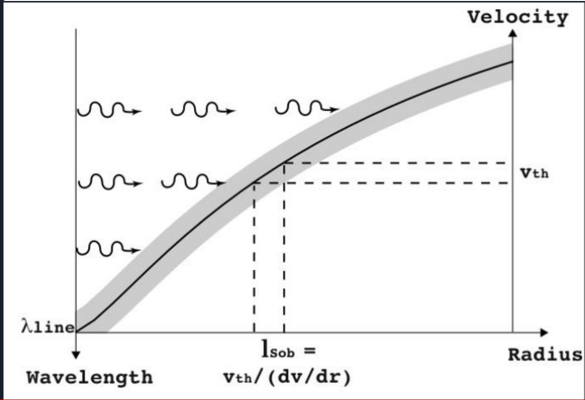
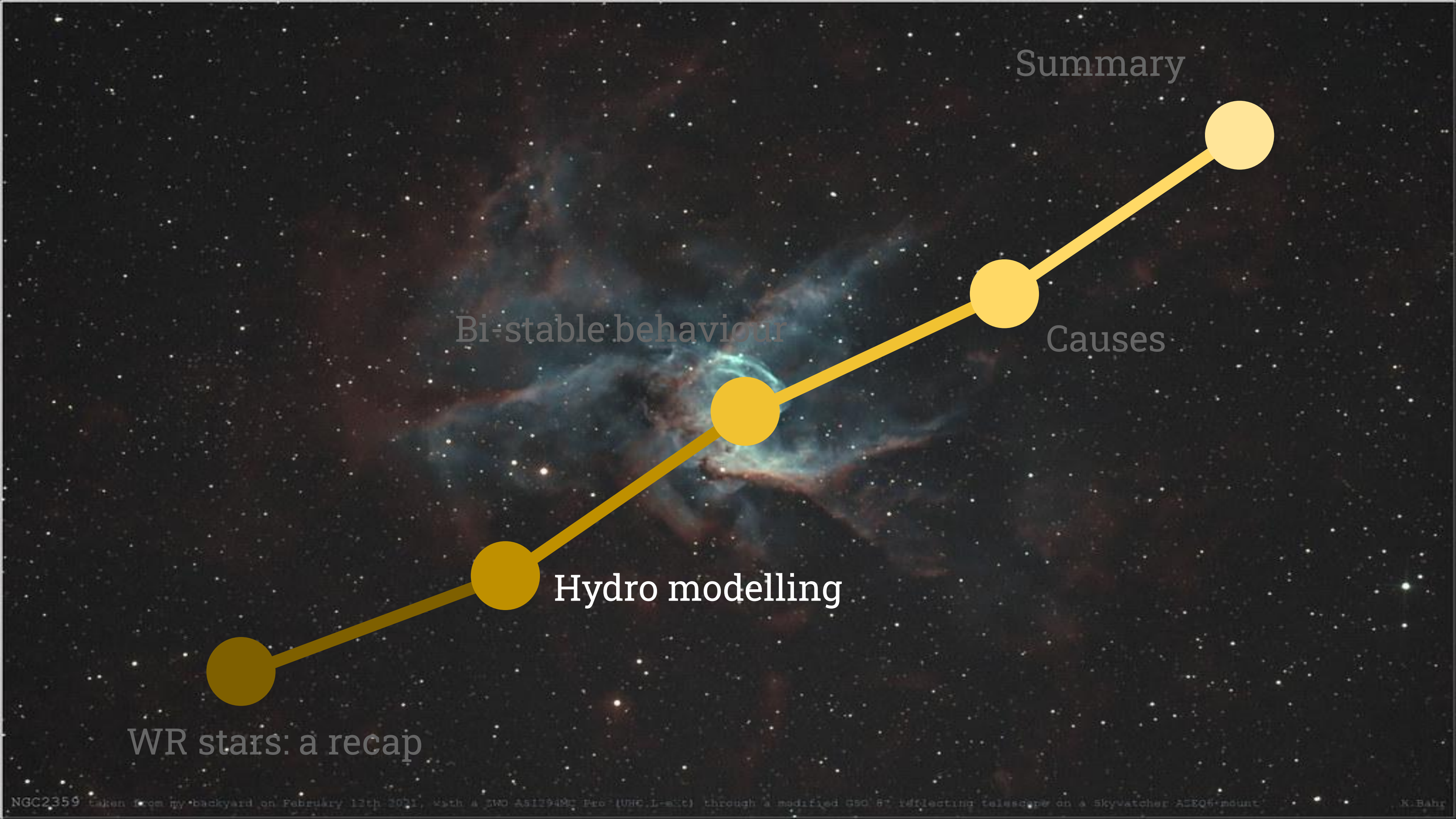
Owocki, 2017



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K.Bahr

Hydro Modelling

Traditional Approach

Input

Stellar Parameters
Chem. abundances

Input #2

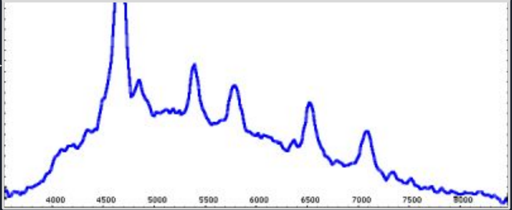
Wind Parameters:
$\dot{M}$, $v(r)$

Iteration

- Temperature stratification
- Statistical equilibrium
- Radiative Transfer

converged

Emergent Spectrum



Hydro Modelling
Principle

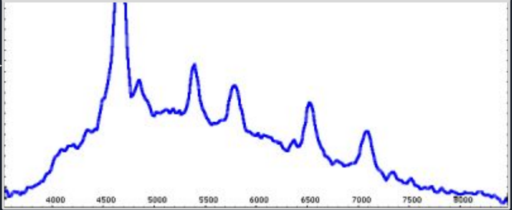
Hydrodynamically consistent (Hydro) modelling:
instead of analytic description,
solve hydrodynamics, calculate $\dot{M}$ and $v(r)$

Input
Stellar Parameters
Chem. abundances

Input #2
Wind Parameters:
$\dot{M}$, $v(r)$

Iteration
- Temperature stratification
- Statistical equilibrium
- Radiative Transfer
- **Hydrodynamic equation**

converged

Emergent Spectrum


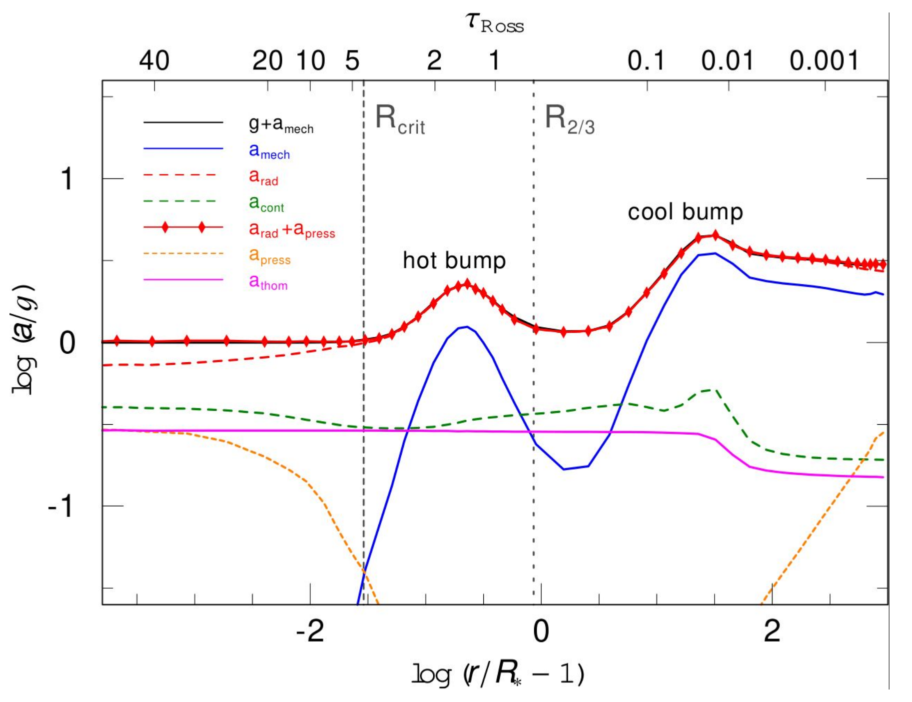
Hydro Modelling
Principle

- Hydro modelling: instead of analytic description, **solve hydrodynamics, calculate $\dot{M}$ and $v(r)$**
- Balance out deceleration and acceleration:

$$g + a_{mech} \approx a_{rad} + a_{press}$$

- Advantages:
  - Consistent wind description
  - Individual ion contributions to driving
  - **Uncover** more **physical behaviours**

Sander et al. 2020



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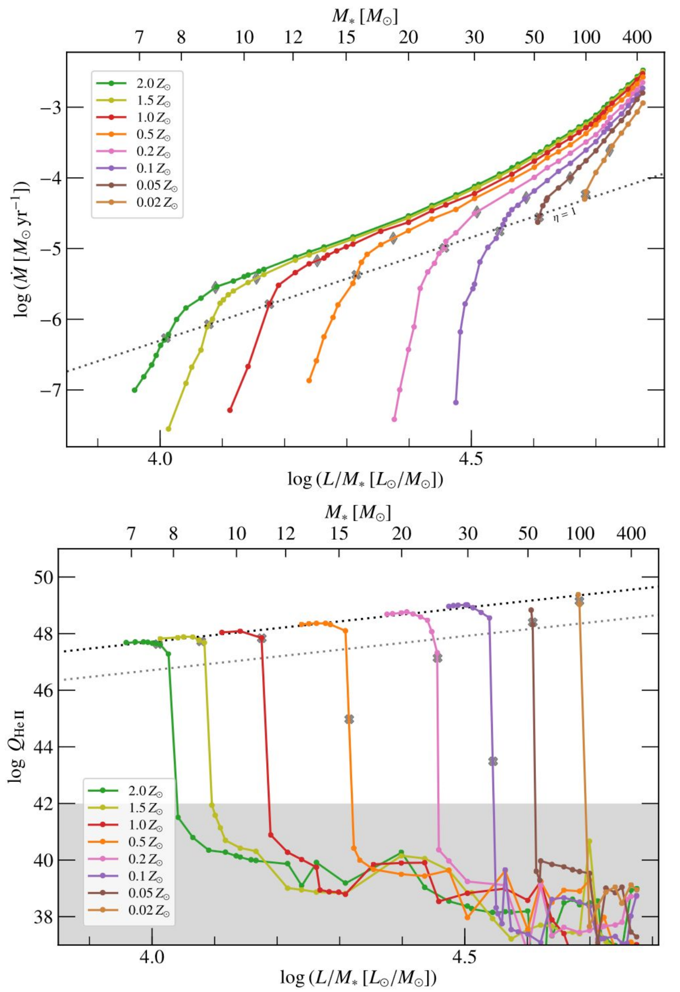

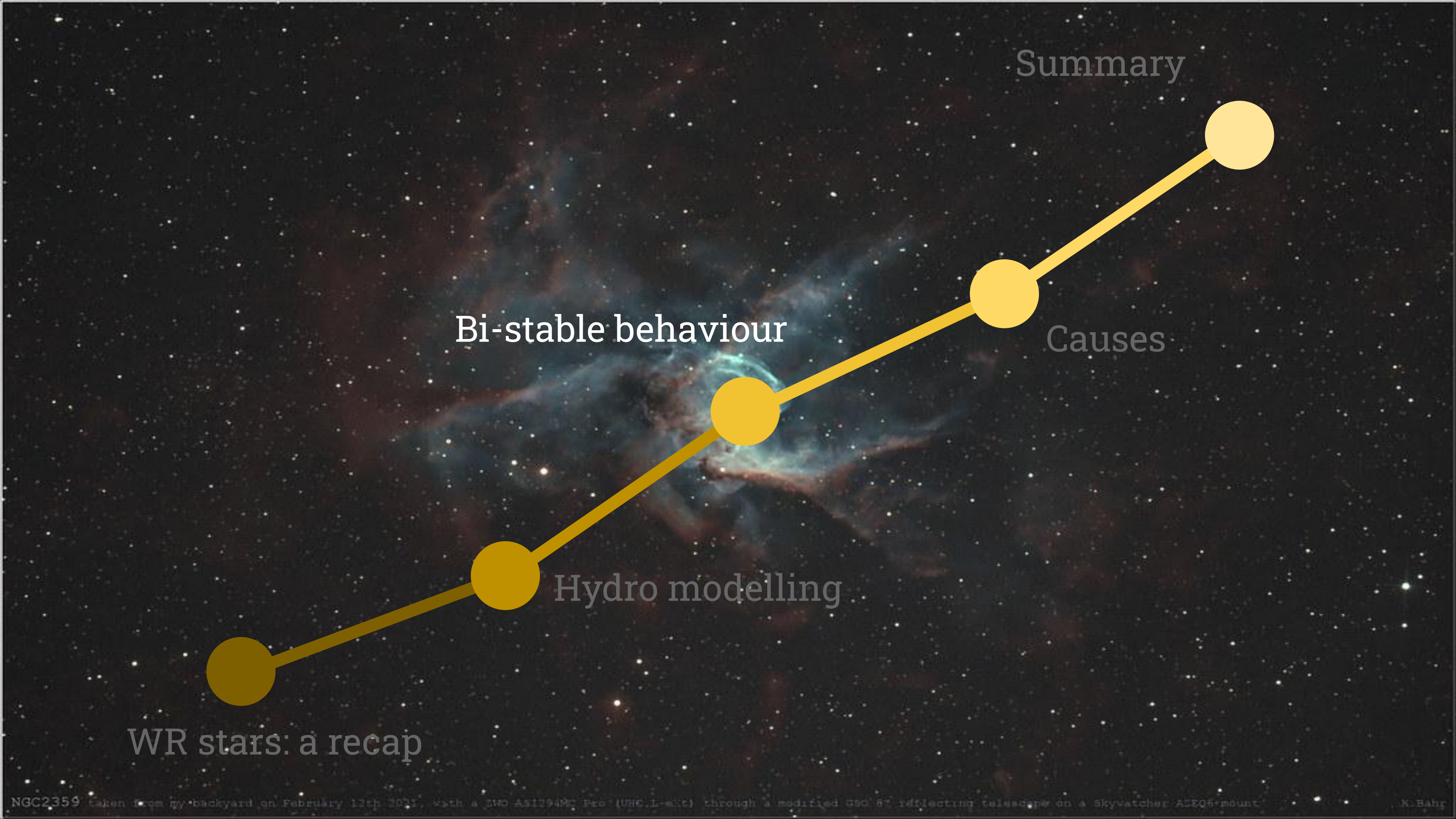
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Bi-stable behaviour

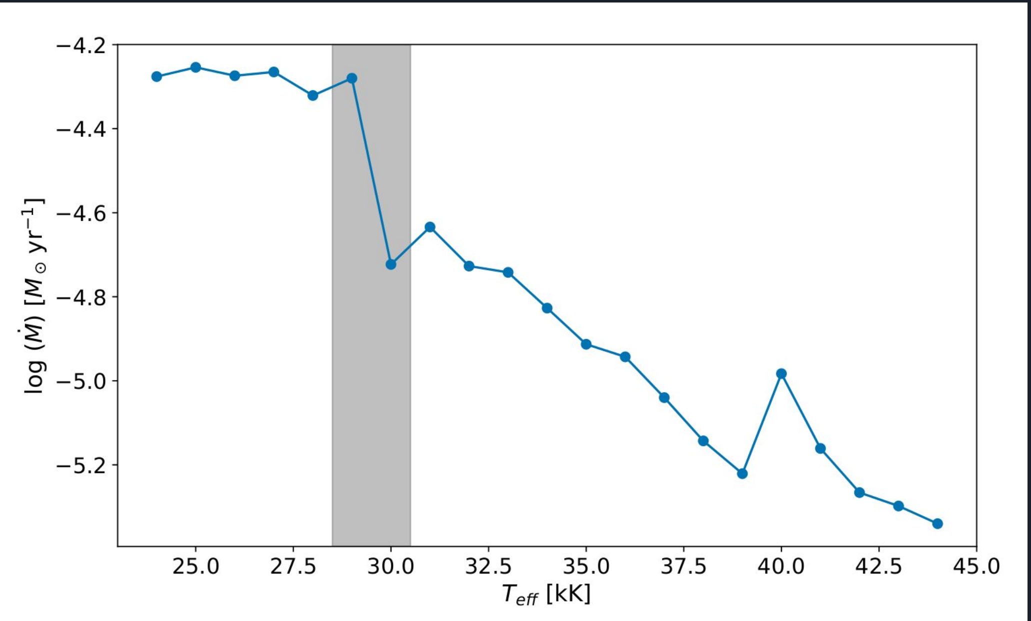
$Z_\odot$ Model sequence

NASA/JPL-Caltech/Potsdam Univ.

- WNh-star model based on **Peony star** (a.k.a. **WR 102ka**)
- Range of (core) temperatures
  24 kK < T_* < 44 kK ; ΔT_* = 1kK
- Constant parameters:
  - **M_*** = 69 $M_\odot$
  - **log L_*** = 6.3 [$L_\odot$]
  - e.g. **X_H** = 0.2 (all **X_m** constant)
  - Same **clumping law**

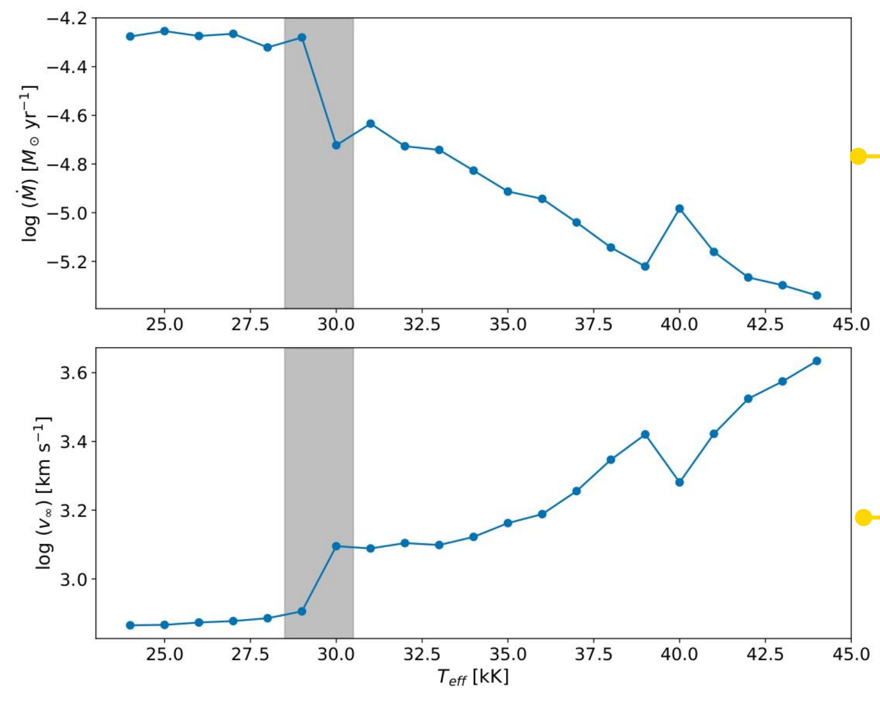
Bi-stable behaviour

$\dot{M}$ behaviour



- Going up in T_* , **suddenly $\dot{M}$ drops** by 0.5 DEX (~factor 3 difference)
- Seeming **change in $\dot{M}$ regime** as well;
  - ± constant when < $T_* \cong 29$ kK
  - decreasing when > $T_* \cong 30$ kK
- Secondary behaviour at e.g. ~40 kK
- Directly coupled to $\boldsymbol{v_\infty}$ **increase** for increasing temperatures
- **Bi-stable behaviour** similar to what happens with B-supergiants**?**

Bi-stable behaviour
$\dot{M}$ behaviour



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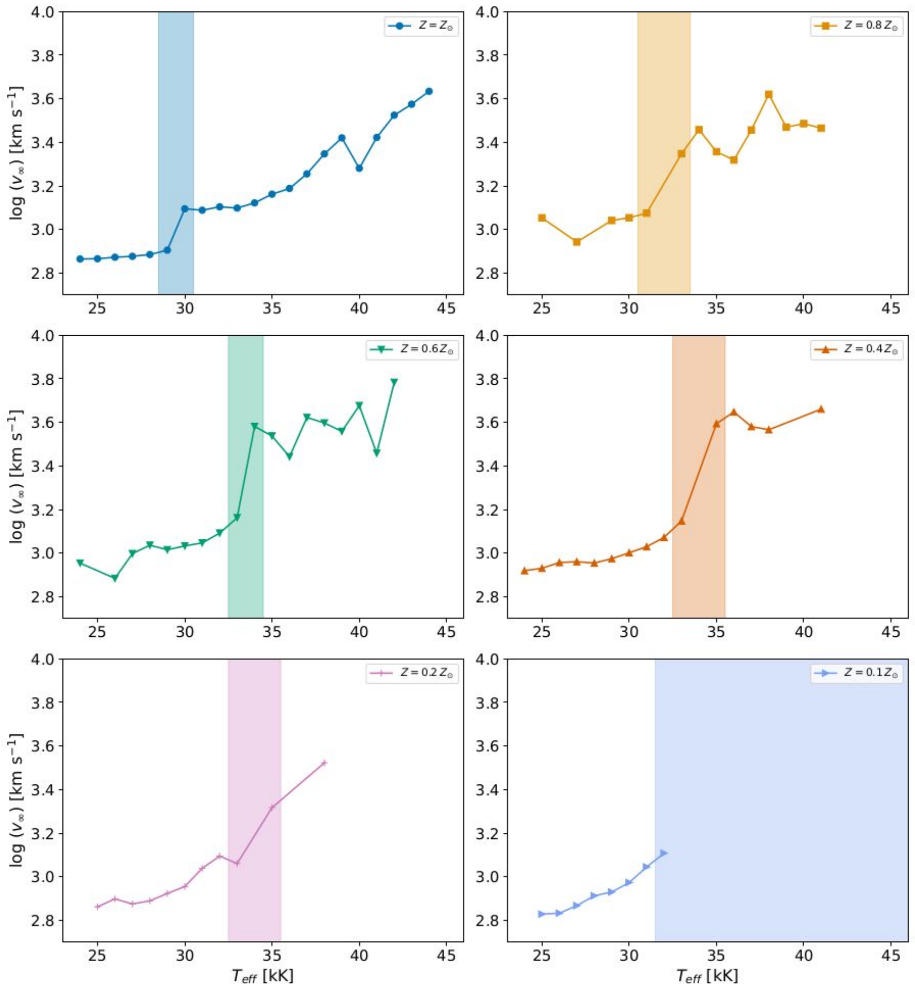
Bi-stable behaviour
Z-dependence

- **Additional series** with 0.8 - 0.6 - 0.4 - 0.2 and 0.1 times $Z_\odot$

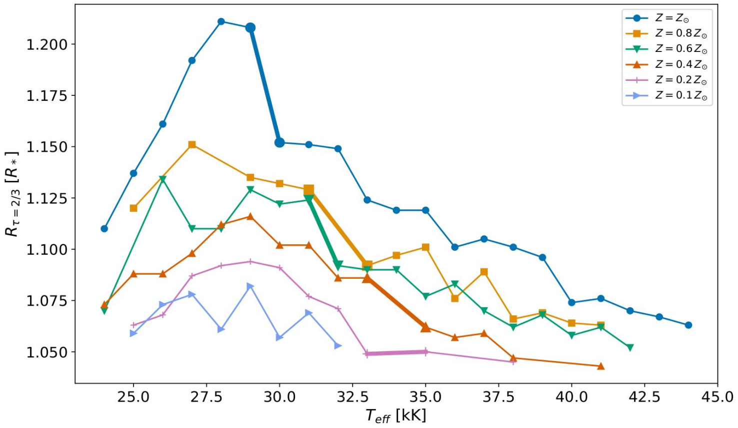
- **Similar "jump" behaviour** as with the $Z_\odot$ case
  $\longrightarrow$ two regimes persist over lower Z

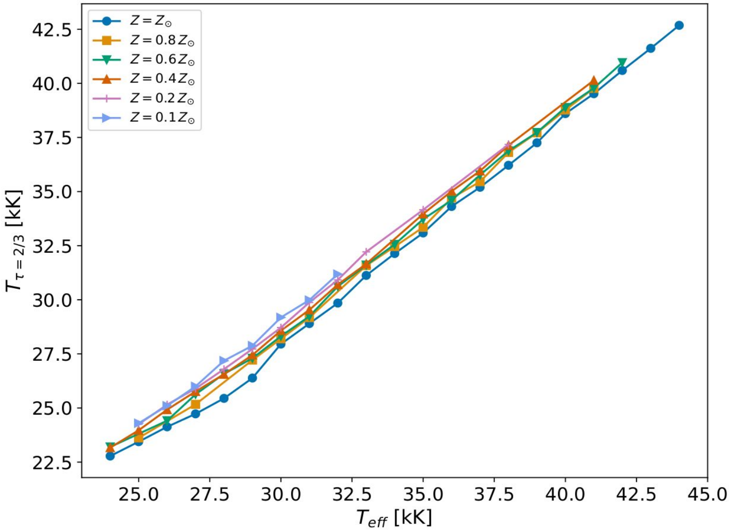
- **Seeming shift of T_{jump}** to higher values for lower Z
  Opposite to 'classical' jump in B supergiants!

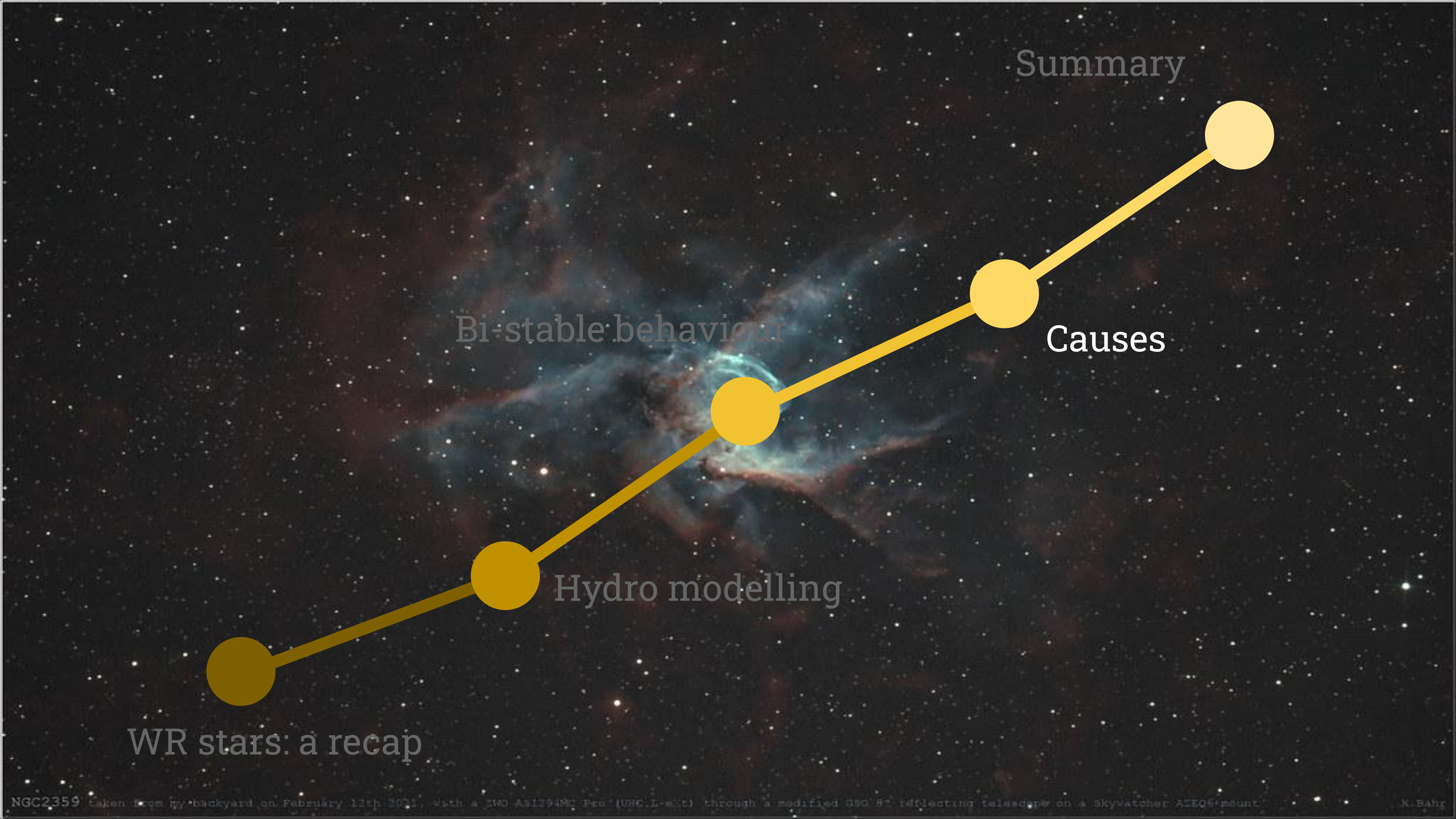


Bi-stable behaviour
Z-dependence

- How does the effective surface react?
- R at τ = ⅔ : **rising trend turns over for** increasing T_*
  ⟶ connected to seeming jump temperature from v_∞ ?
- T at τ = ⅔ : steady increase for increasing T_*
  only mild (expected) **dependence** on Z



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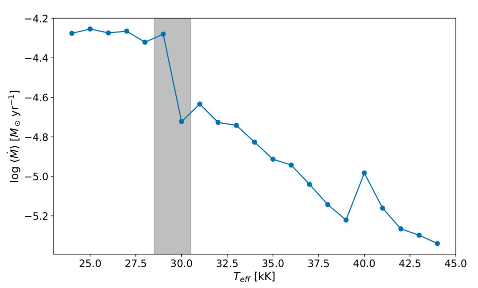
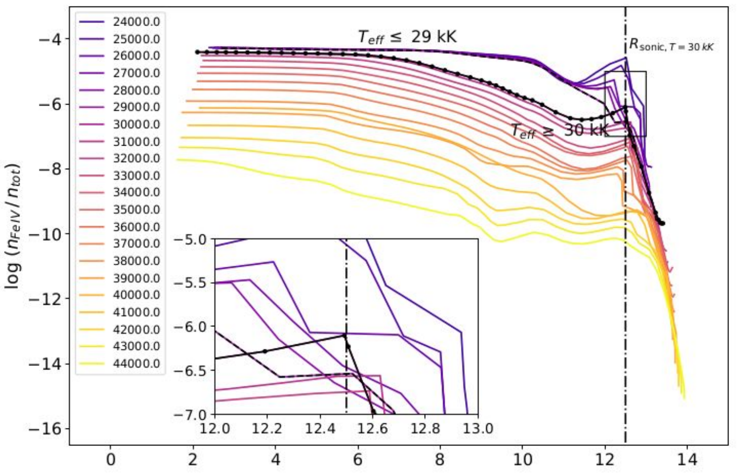
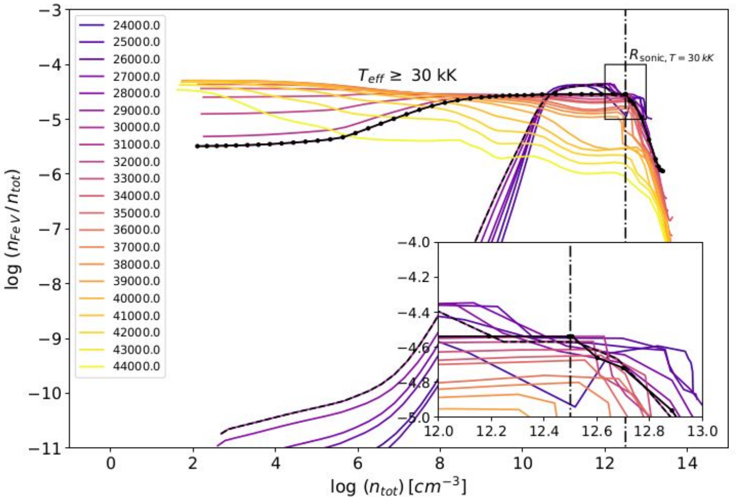
Causes
Population Numbers

- Main **wind driving** around R_{sonic} done by **iron**
- Strongly depends on **dominating iron ion**
- Noticeable **'gap' around 29 - 30 kK** for $Z_\odot$
  → Strong switch further on in the wind
- **Fe IV and Fe V overhaul**
  → in contrast with
  B-supergiant case
- Presence of a **secondary gap** at ~ 40 kK







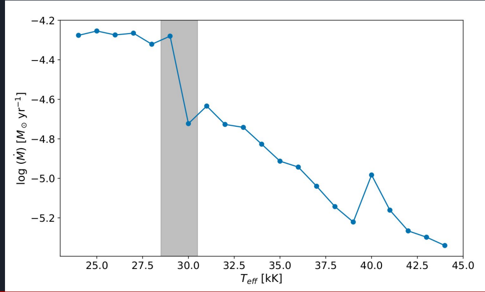
Causes
Radiation Acceleration

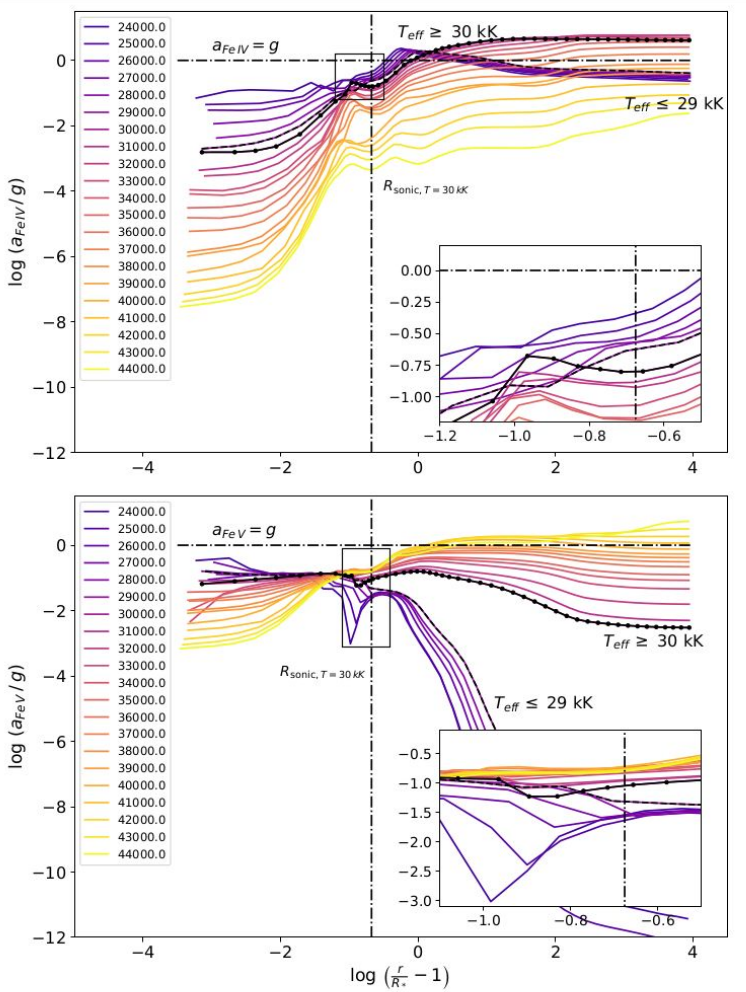
- Detailed look at ion-specific line driving in the wind
  ⟶ **Fe IV** and **Fe V**

- Ion switch around R_{sonic} induces **difference in line driving**:
  - below T_* ≅29 kK; Fe IV main driver
  - above T_* ≅30 kK; Fe V contributes strongly

- $a_{Fe\ IV}$ / $a_{Fe\ V}$ ratio shows clear

  regime differences





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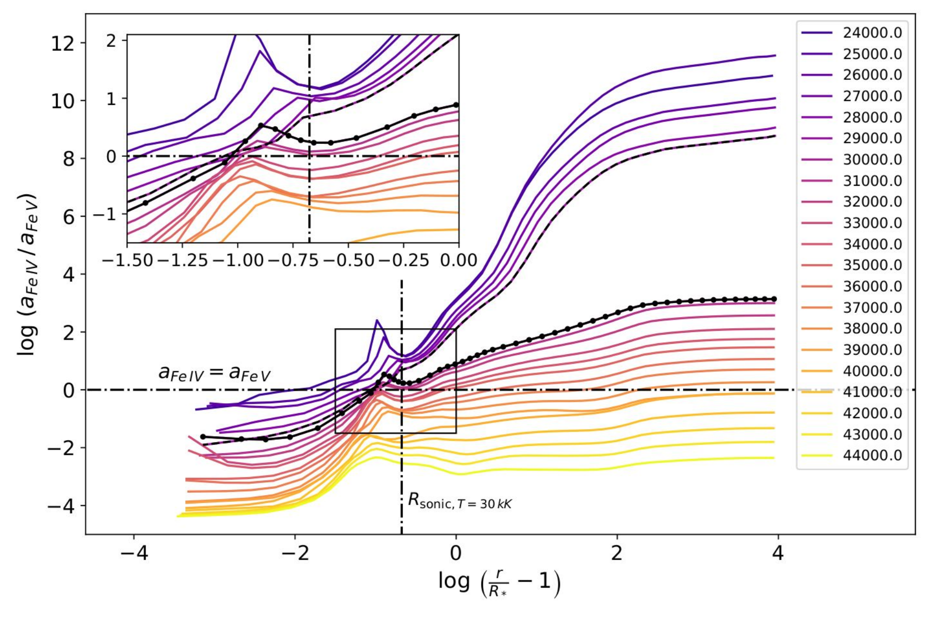

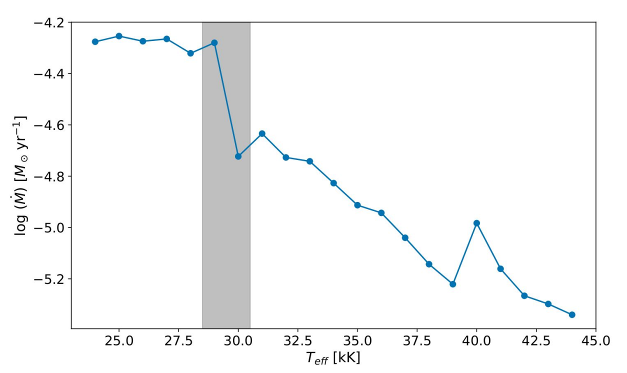

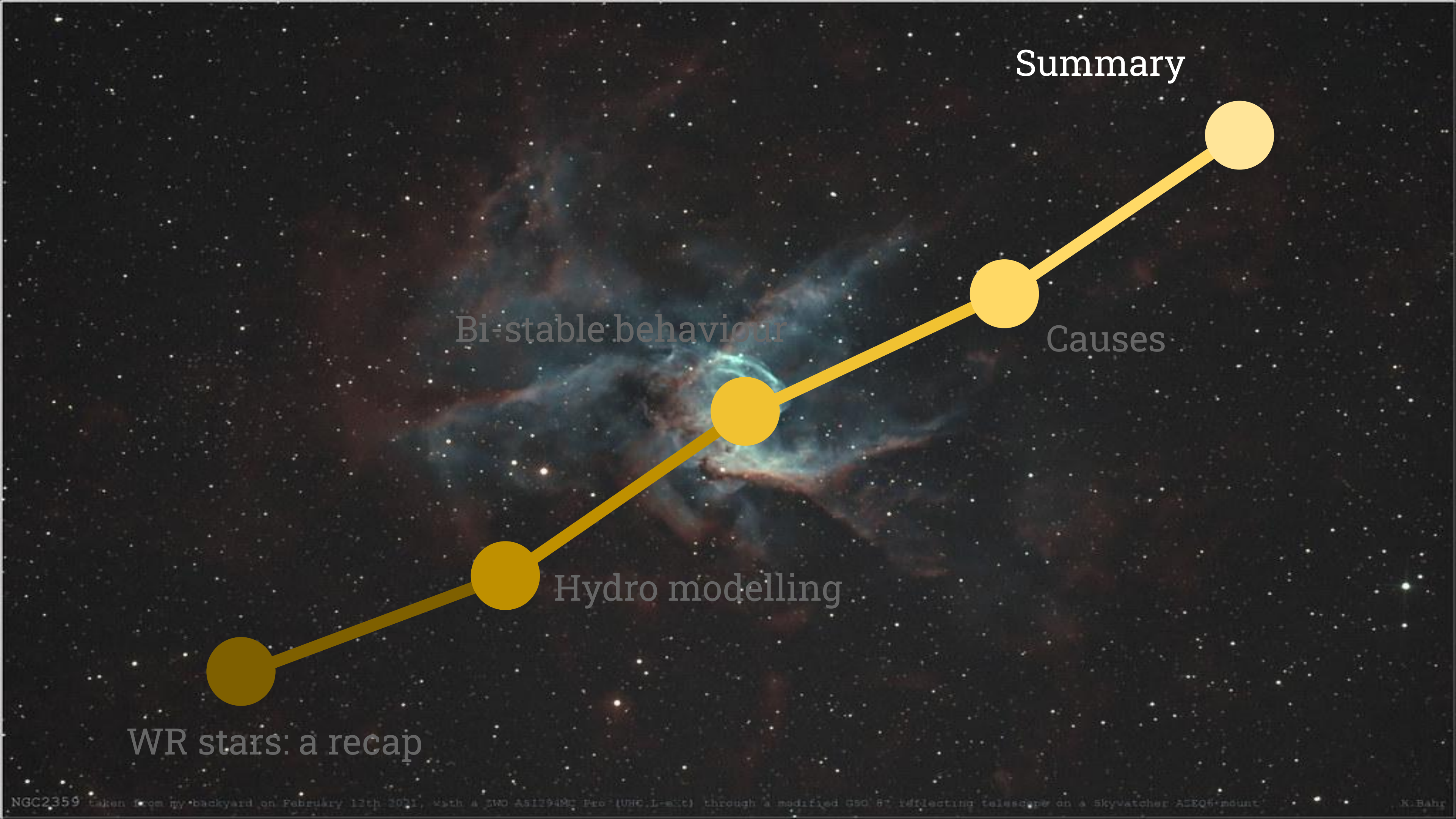
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Summary

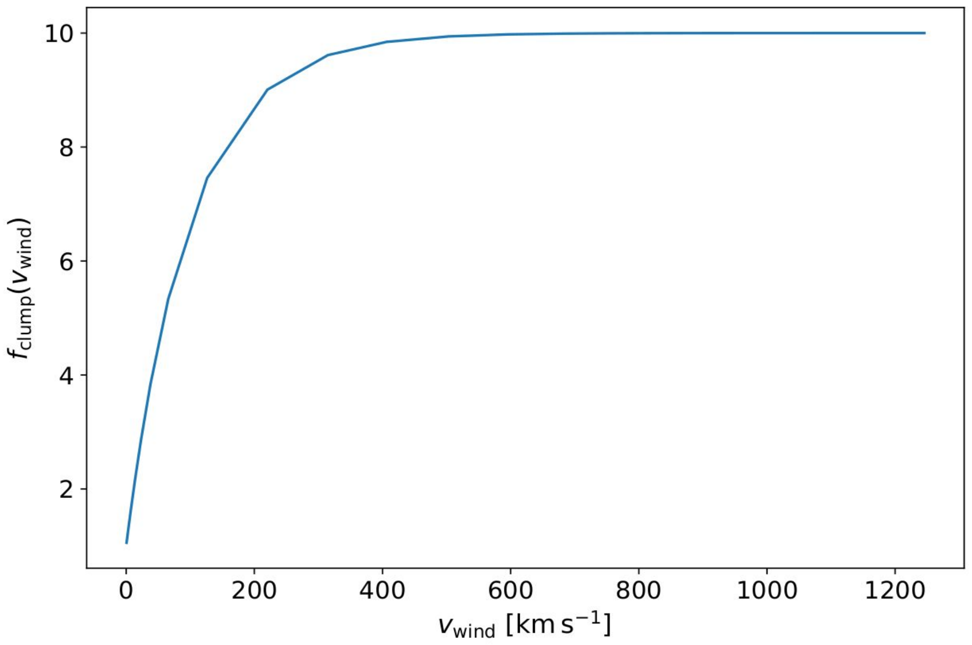
- Temperature sequence of **WNh stars**: 24 kK < T_* < 44 kK

- Seeming **bi-stable behaviour** for v_∞ and $\dot{M}$

- Strong **switch in population numbers** of Fe IV and Fe V
  → In contrast with 'classical' bi-stability jump

- Ionization switch seems to cause **overturn in wind driving**
  → leads to very different wind regime
  all this coming **soon** in Lefever et al. (2024, in prep)!

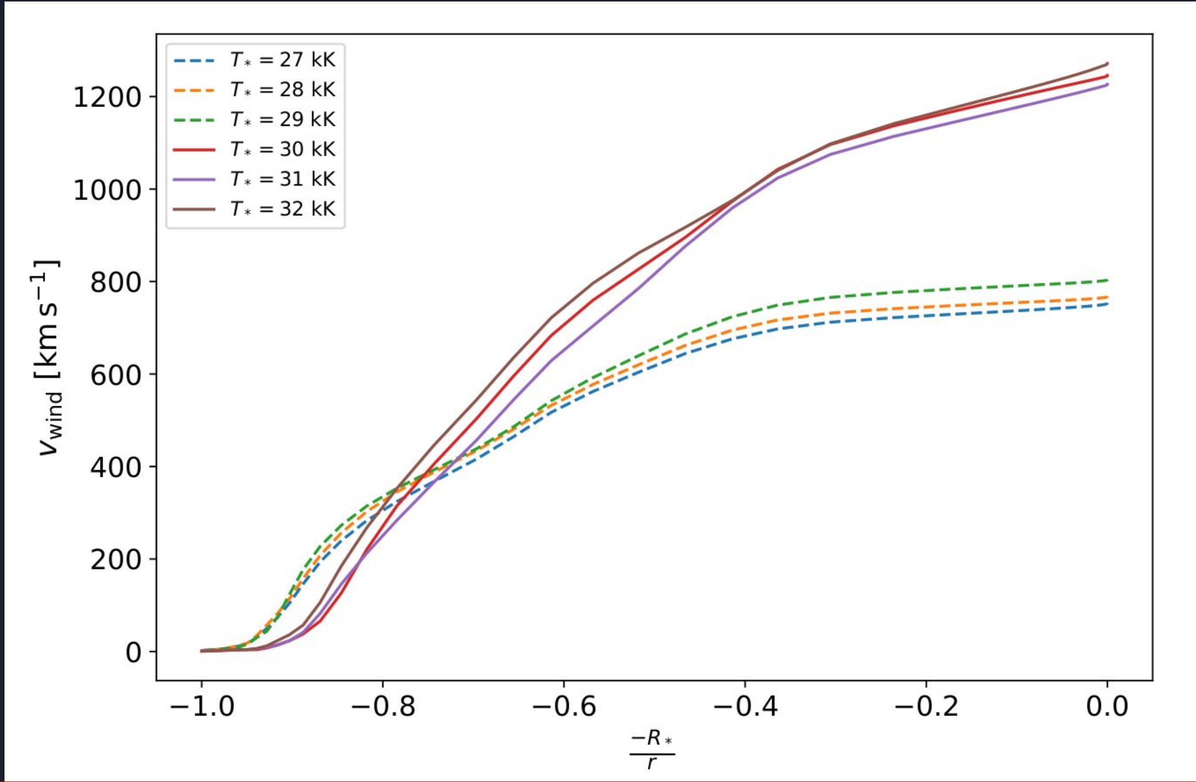
Backup
Clumping law



$$f = f_\infty + (1 - f_\infty)\,\exp\left(-\frac{v(r)}{v_{\rm cl}}\right)$$ (Martins et al. 2009)

Backup

Velocity differences



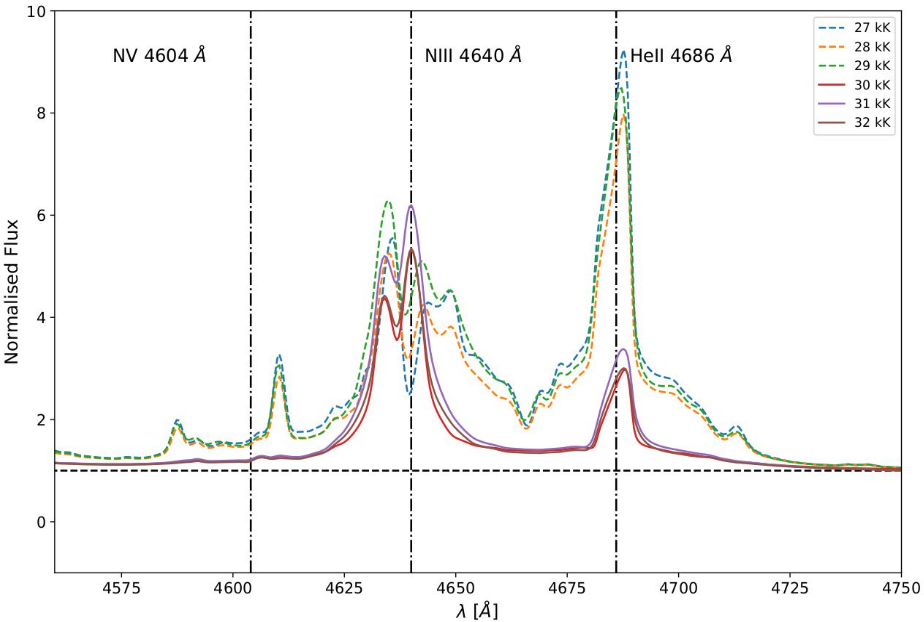
Backup

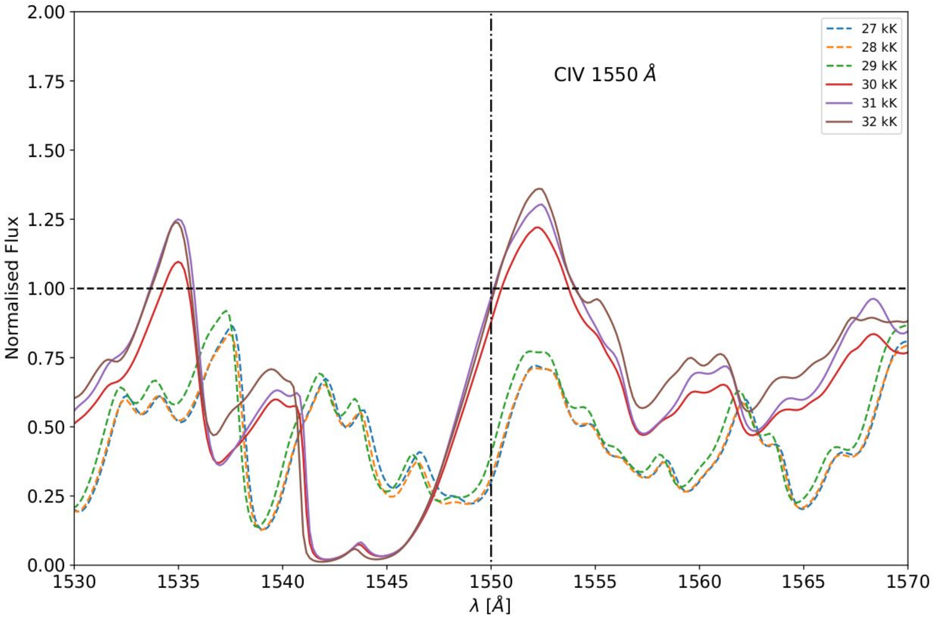
Used ions and elements

Table A.1. Elements, ions and abundances in this study

Element	X_m	Ions
H	(0.2)	I, II
He	(0.63)	I, II, III
N	(0.015)	I, II, III, IV, V
C	(10^{-4})	I, II, III, IV, V, VI
O	(0.15)	I, II, III, IV, V, VI
Ne	$(1.3 \cdot 10{-}3)$	I, II, III, IV, V, VI, VII
Na	$(2.7 \cdot 10{-}5)$	I, II, III, IV, V
Mg	$(7.0 \cdot 10{-}4)$	I, II, III, IV
Al	$(7.0 \cdot 10{-}5)$	I, II, III, IV, V
Si	$(6.7 \cdot 10{-}4)$	I, II, III, IV, V, VI
P	$(5.8 \cdot 10{-}6)$	II, III, IV, V, VI
S	$(3.1 \cdot 10{-}4)$	I, II, III, IV, V, VI, VII
Cl	$(8.2 \cdot 10{-}6)$	III, IV, V, VI, VII
Ar	$(7.3 \cdot 10{-}5)$	I, II, III, IV, V, VI, VII, VIII
K	$(3.1 \cdot 10{-}6)$	I, II, III, IV, V, VI, VII
Ca	$(6.1 \cdot 10{-}5)$	II, III, IV, V, VI, VII, VIII
Fe	$(1.4 \cdot 10{-}3)$	II, III, IV, V, VI, VII

Backup
Spectral imprint

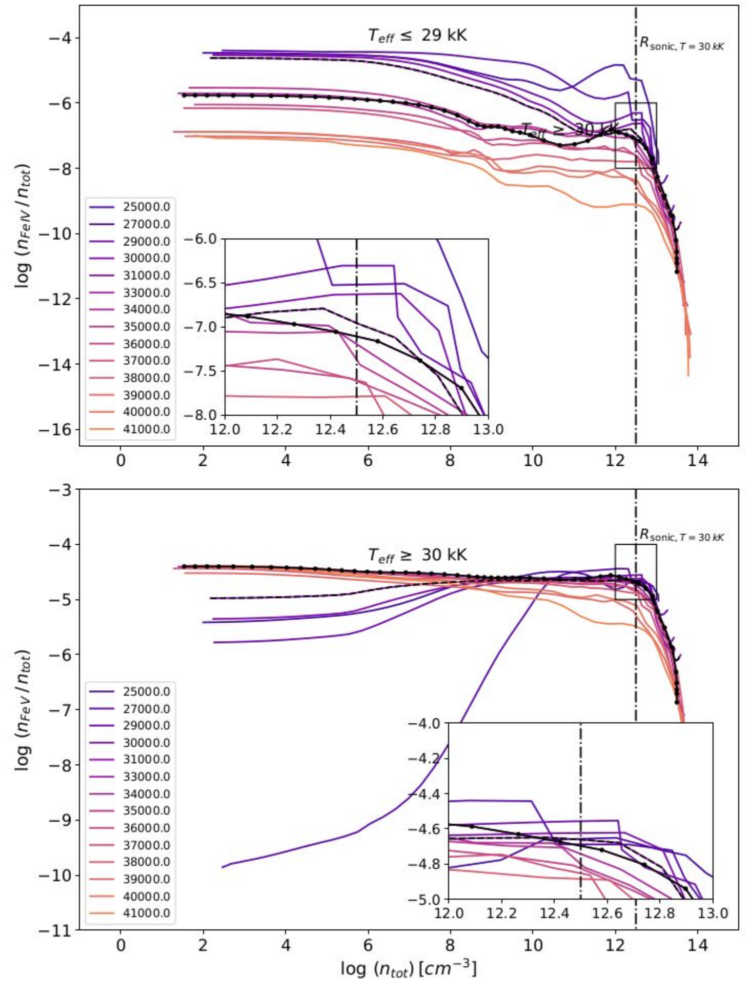




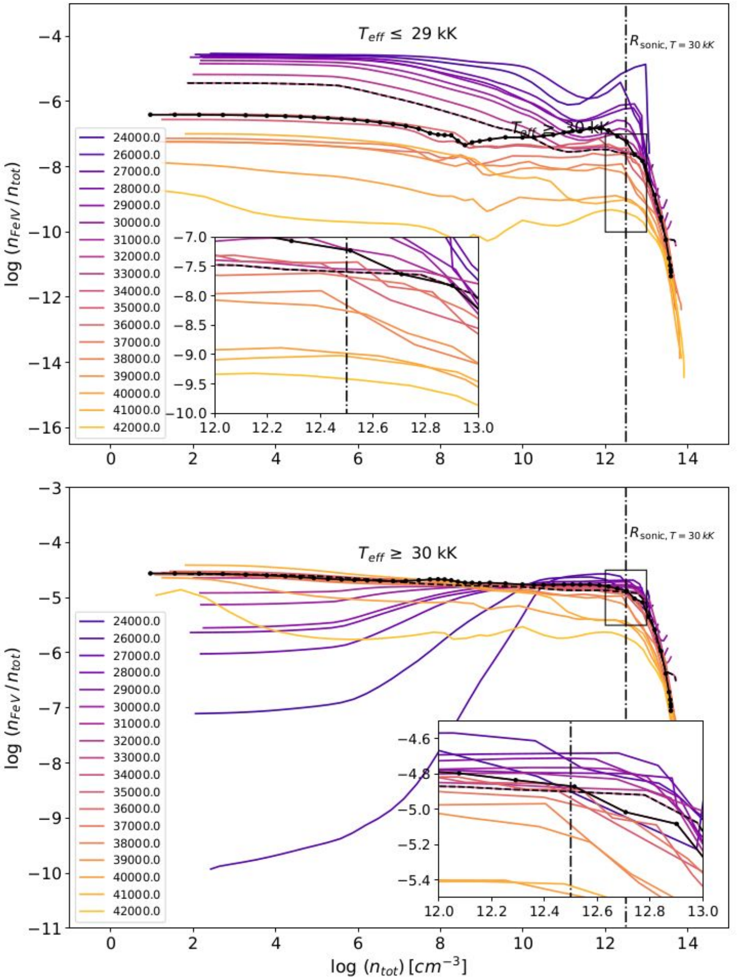
Backup

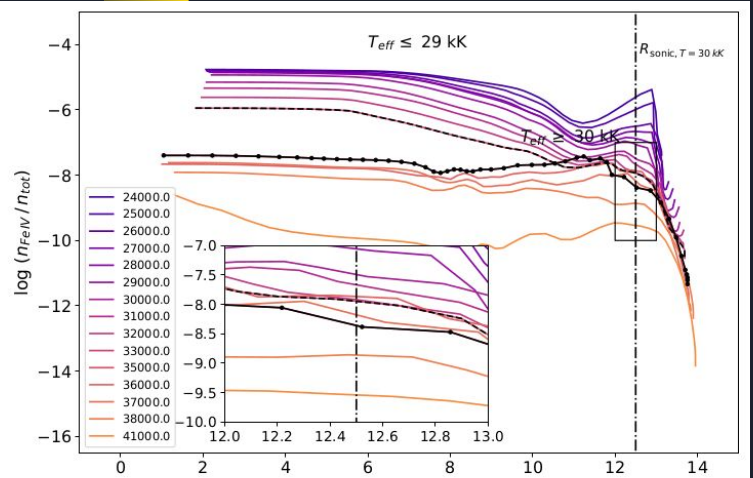
Popnums

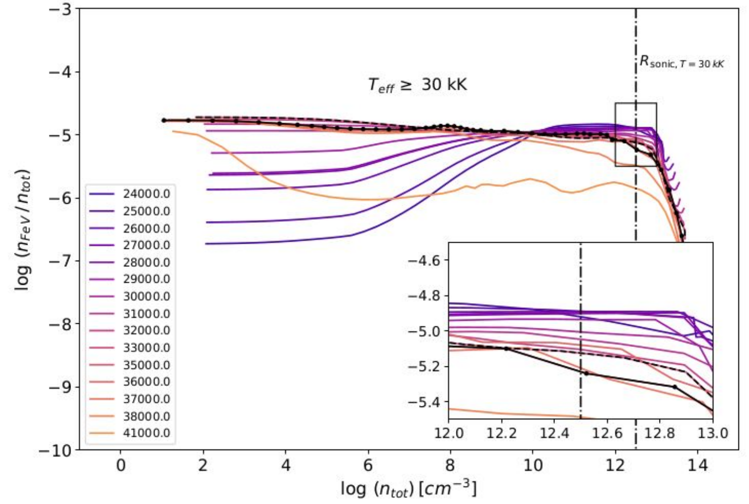
← 0.8 $Z_\odot$



0.6 $Z_\odot$ →







Backup

Popnums

← 0.4 $Z_{\odot}$

0.2 $Z_{\odot}$ →