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Winds of Massive Stars

A numerical investigation of the effects of mass loss on the evolution of massive stars

M.Sc. Defense *Joris Josiek*

Image Credit: Wallpaper Abyss

02 June 2023

Image Credit: Wallpaper Abyss

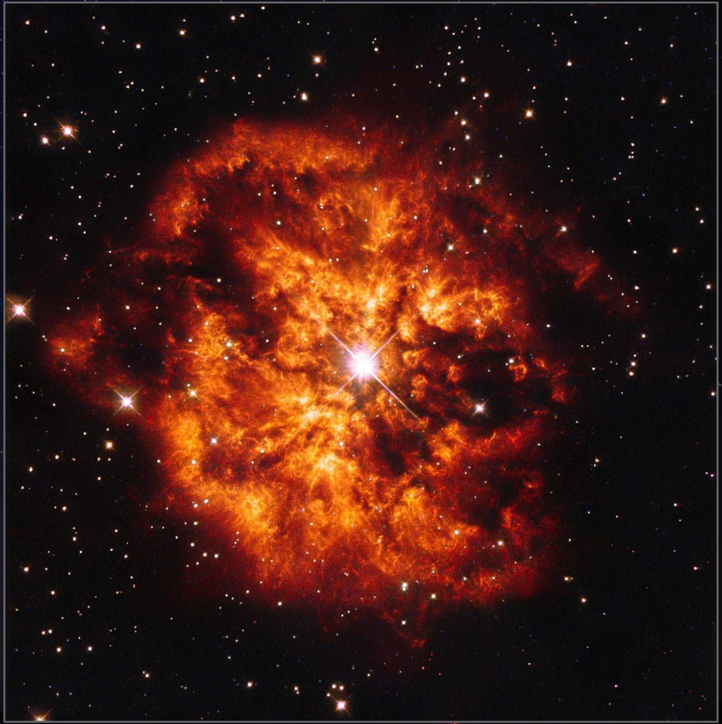
Why study massive stars?

- Rare in the present universe
- High luminosity
- Production of heavy elements
- Strong feedback (e.g. Winds)

A massive star ejects

45–65%

of its own mass during its life.



WR 124 imaged by the Hubble Space Telescope
Credit: NASA/ESA

Outline

1 Context
How do massive stars evolve?
What do we want to investigate?

2 Methods
How do we model stellar evolution?
What are the key physical ingredients?

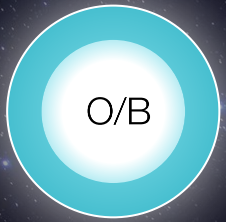
3 Results
What do the models predict?
What can we learn from the results?

4 Discussion
What is the impact, what are the limitations?
What further work could be done?

Context

The Evolution of Massive Stars

Collapsing Cloud of Gas
Increasing density, temperature, pressure



Ignition of Nuclear Fusion in the Core
at around 10^6 K

Main Sequence

Long period of stable fusion of hydrogen to helium in the core
2–10 Million Years

Core contracts after running out of fuel
core temperature increases
envelope inflates

Core Helium Burning

Helium fuses to carbon in the core
Hydrogen fuses to helium in a shell
0.2–1 Million Years

Carbon burning	**2 000 years**
Neon burning	**6 months**
Oxygen burning	**1 year**
Silicon burning	**2 weeks**

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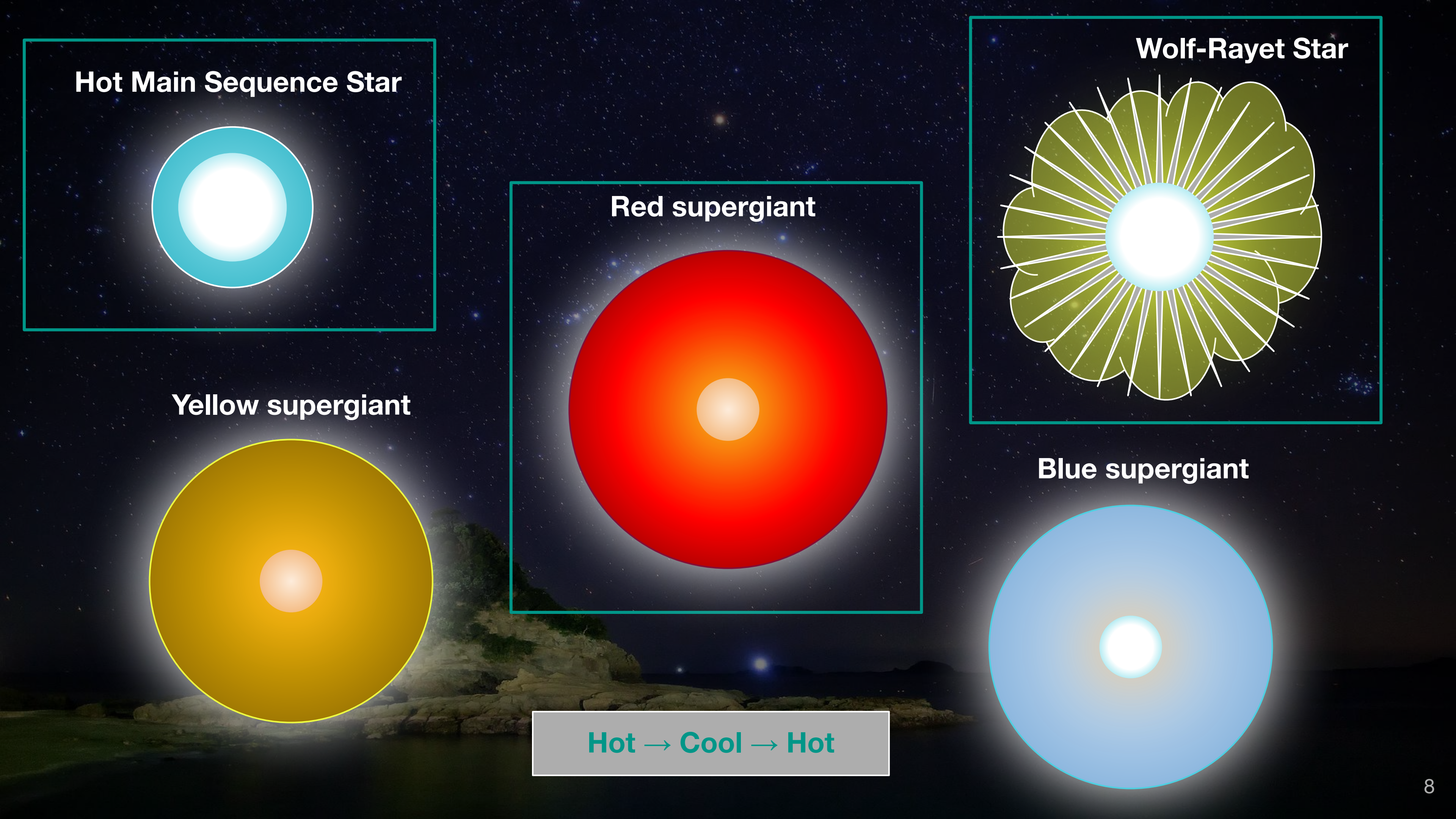
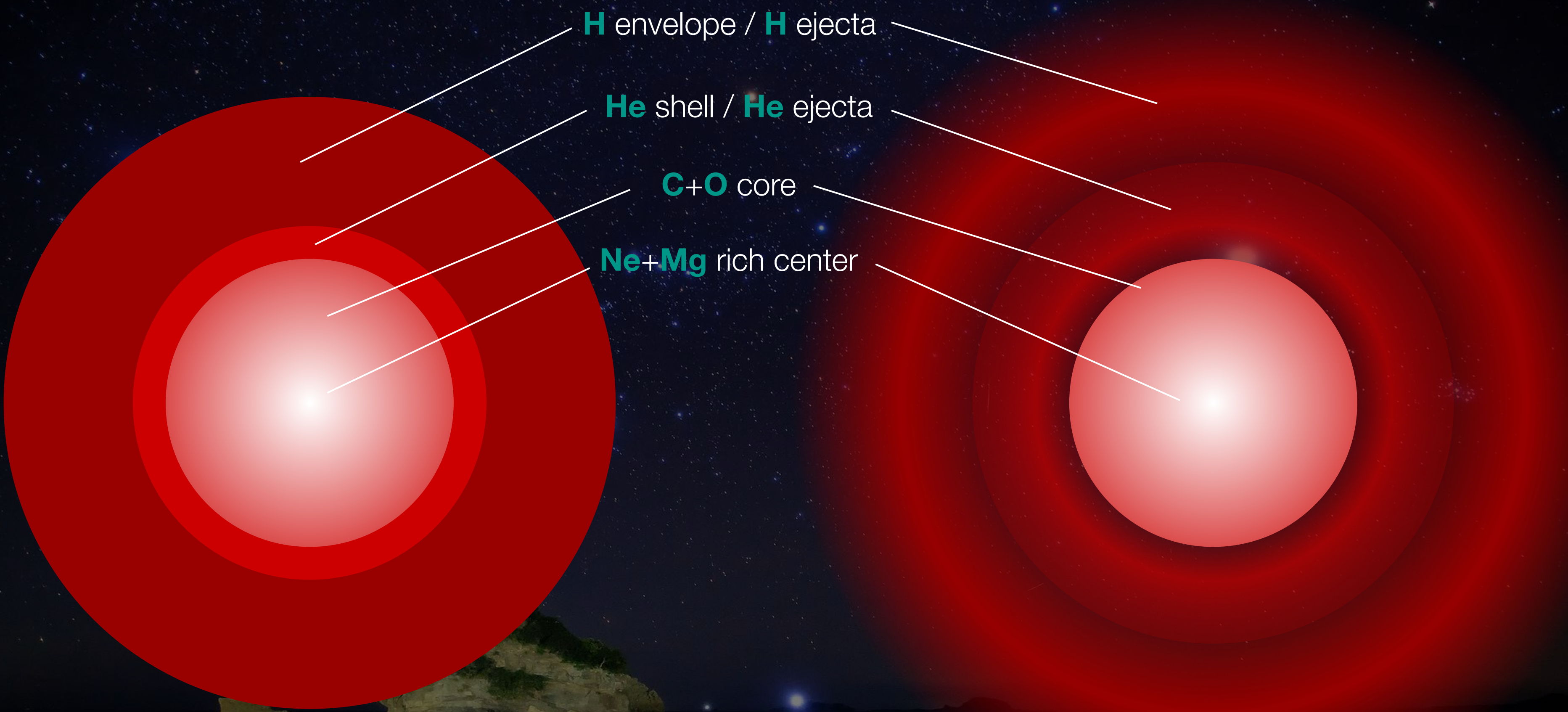

Hot Main Sequence Star
Red supergiant
Wolf-Rayet Star
Yellow supergiant
Blue supergiant
Hot → Cool → Hot



Stellar structure at the end of central carbon burning

Effects of mass loss: (1) Surface temperature increases, (2) Surface metal-abundance increases.

Method

Modeling stellar evolution

Stellar structure and evolution model

- Hydrodynamics
- Convection
- Mass loss
- Thermodynamics
- Radiation
- Gravity
- Nuclear reactions
- Diffusion

Need to describe the stellar structure and to describe all the relevant physics in an applicable way!

The Geneva stellar evolution code (GENEC)

1) Solving the stellar structure

A star is divided into around **1000 layers**.

Each layer has **local properties**, e.g. temperature, chemical composition, etc.

Physical equations determine how properties change from layer to layer.

The algorithm finds a **stable solution** to the equations.

The Geneva stellar evolution code (GENEC)

1) Solving the stellar structure (1 dimension)

2) Making the structure evolve

The user specifies the initial **global properties**, e.g. mass, chemical composition, rotation rate.

The algorithm computes the **stable stellar structure**.

Changes are applied for a small timestep,

- Chemical structure changes (e.g. nuclear reactions).
- Mass decreases due to **stellar winds**.

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Mass loss in stellar models

- Too complex to implement from first principles → Use **prescriptions**.

$$\frac{\mathrm{d}M}{\mathrm{d}t} = f(L, T_{\mathrm{eff}}, M, X_{\mathrm{surf}}, \ldots)$$

f … function derived **theoretically**, **numerically**, or **empirically**

- Mass loss physics depends on **evolutionary stage** → Multiple prescriptions
- Prescriptions have **two components**:
  - Mass loss rate equation (as above)
  - Validity domain

Mass loss in stellar models

- **Project goal**: compute stellar evolution models with different mass loss prescriptions and compare the results.

Vin01	Vink et al. 2001	Fit on hydrodynamical wind models
Bjo22	Björklund et al. 2022	
Bes20	Bestenlehner 2020	Theoretical model

Mass loss of hot stars (O/B type)

Cro01	Crowther 2001	Observational fit
Bea20	Beasor et al. 2020	

Mass loss of red supergiants (RSG)

Grid parameters

Initial masses:

20, 25, 30, 40, 50, 60, 66, 73, 80, 85, 95, 105, 120 $M_\odot$

Rotation:

0

Metallicity:

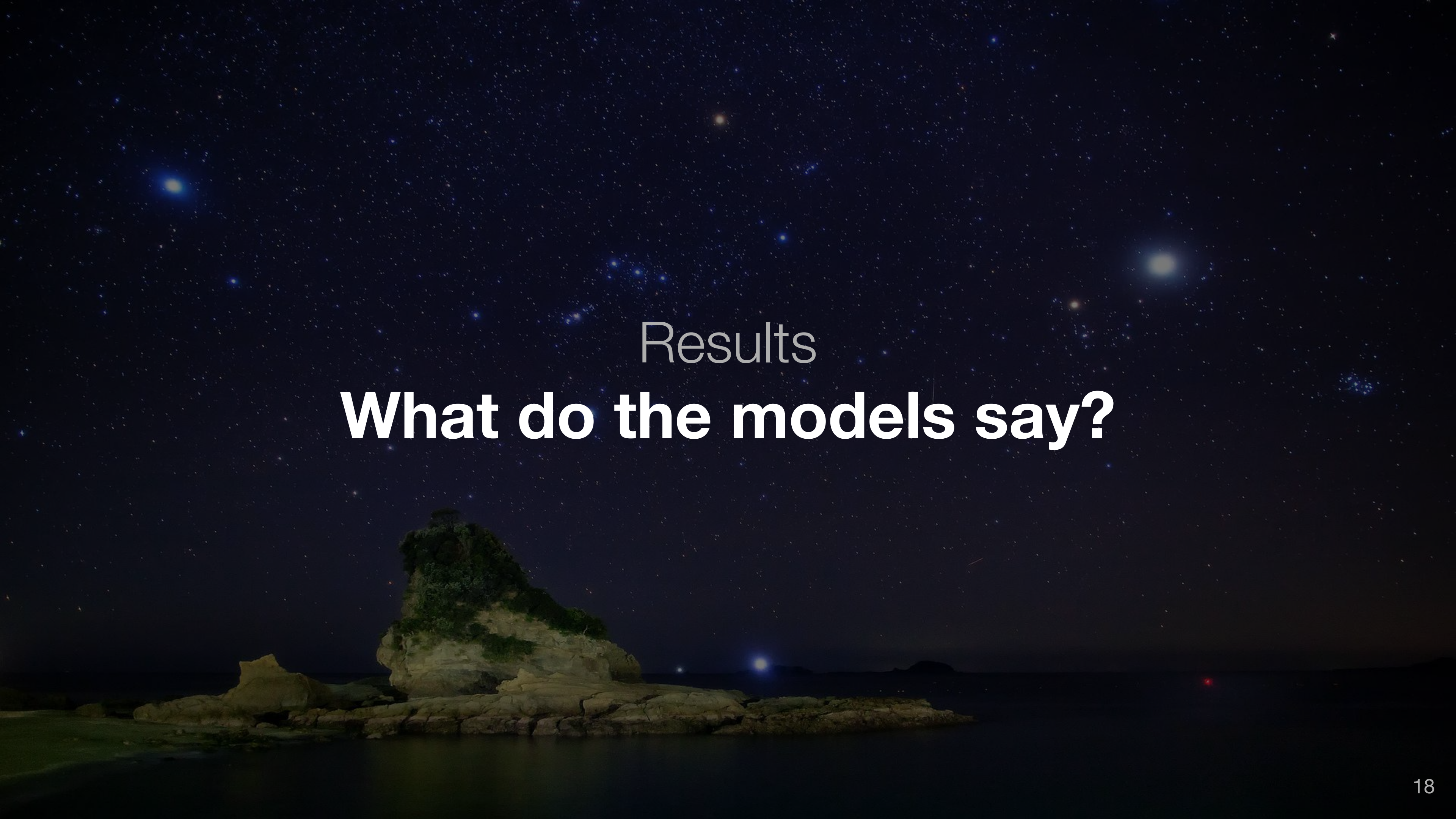
Solar (Z=0.014)

O/B mass loss:

Vin01, **Bjo22**, **Bes20**

RSG mass loss:

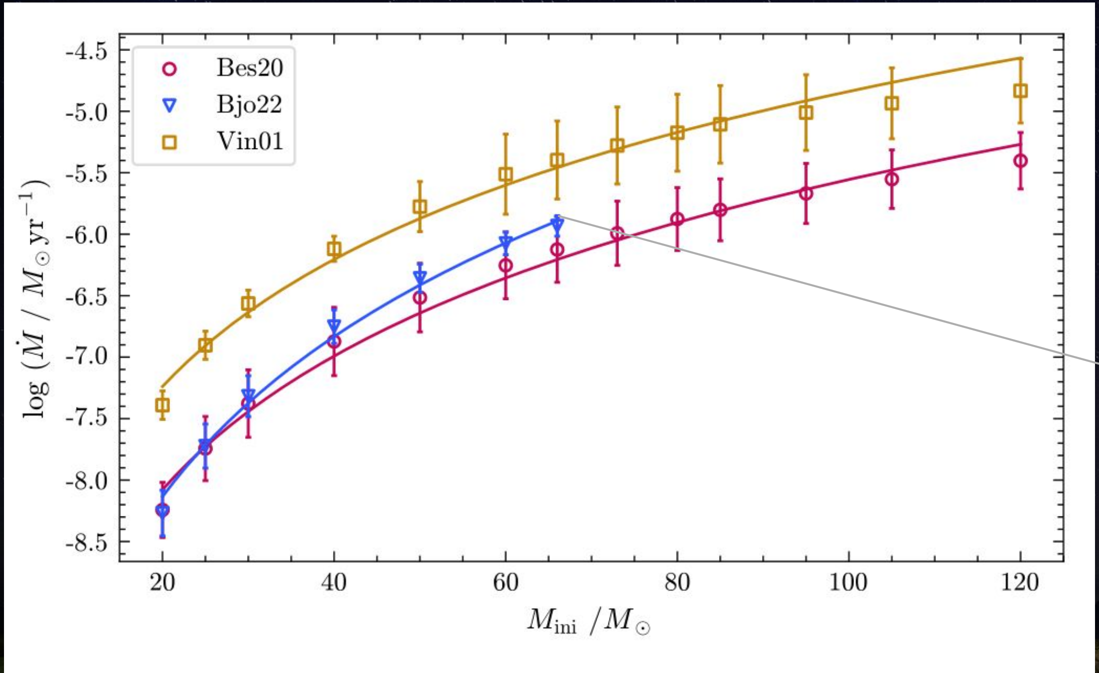
Cro01, **Bea20**



Results

What do the models say?

Characterizing the mass loss prescriptions

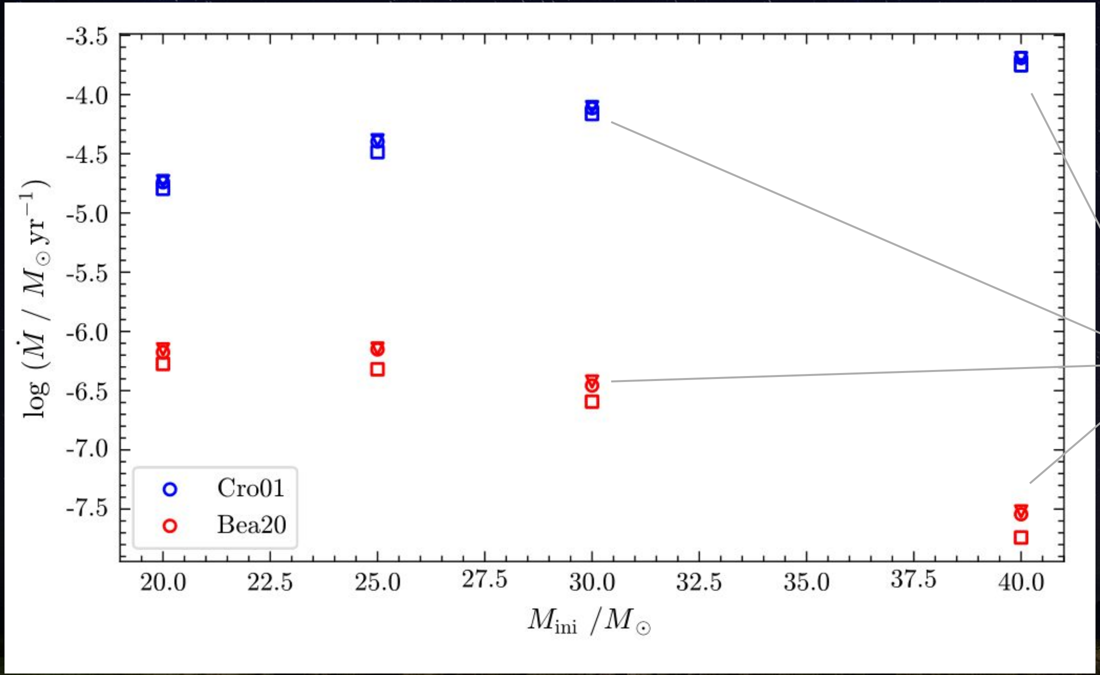


Bes20 is approx. **10x lower** than **Vin01** across the entire mass range.

Bjo22 is only valid for the lower mass range.

Time-averaged mass loss rate during the main sequence.

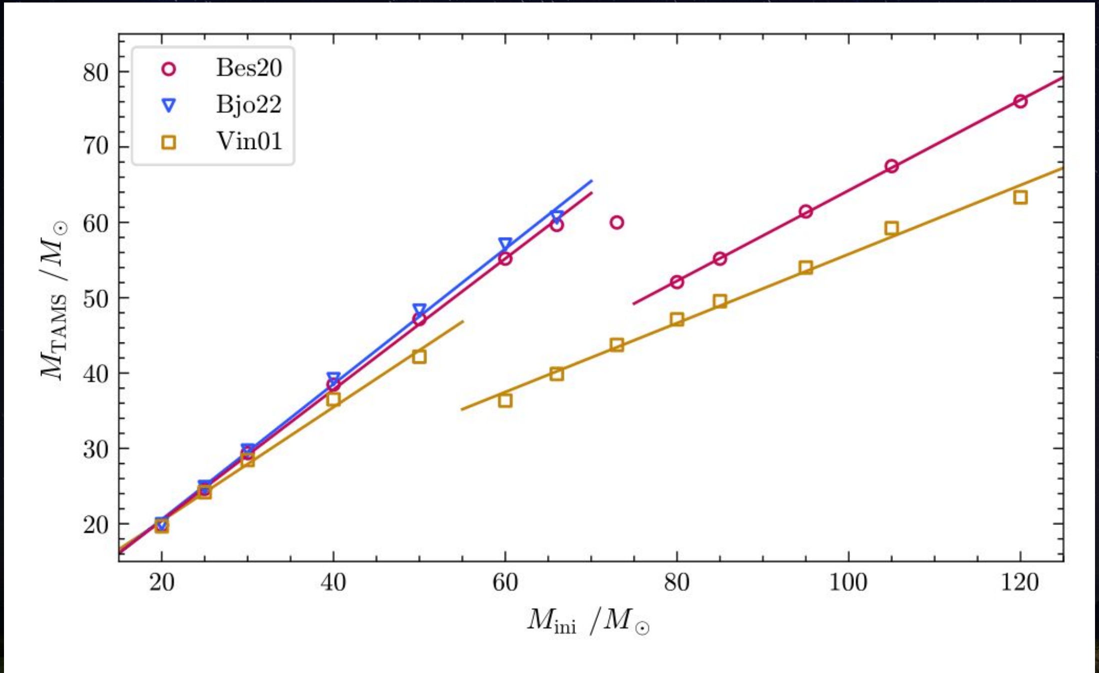
Characterizing the mass loss prescriptions



Observations of RSGs at such high masses are extremely rare.

Time-averaged mass loss rate during the RSG phase.

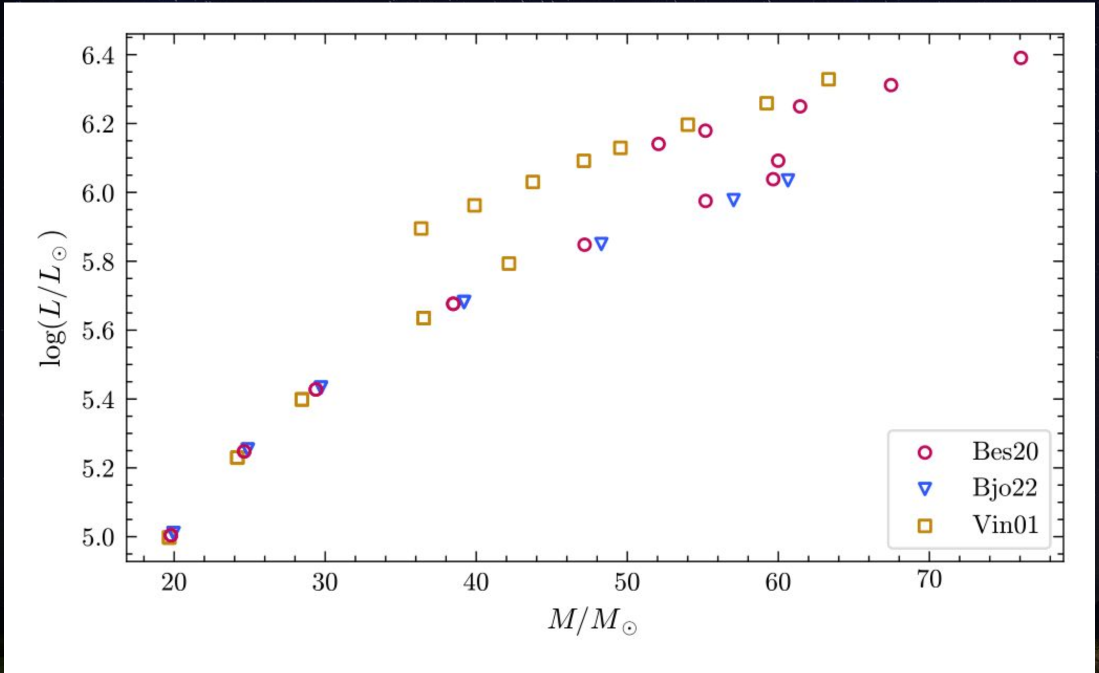
Main sequence evolution



Two mass loss regimes.

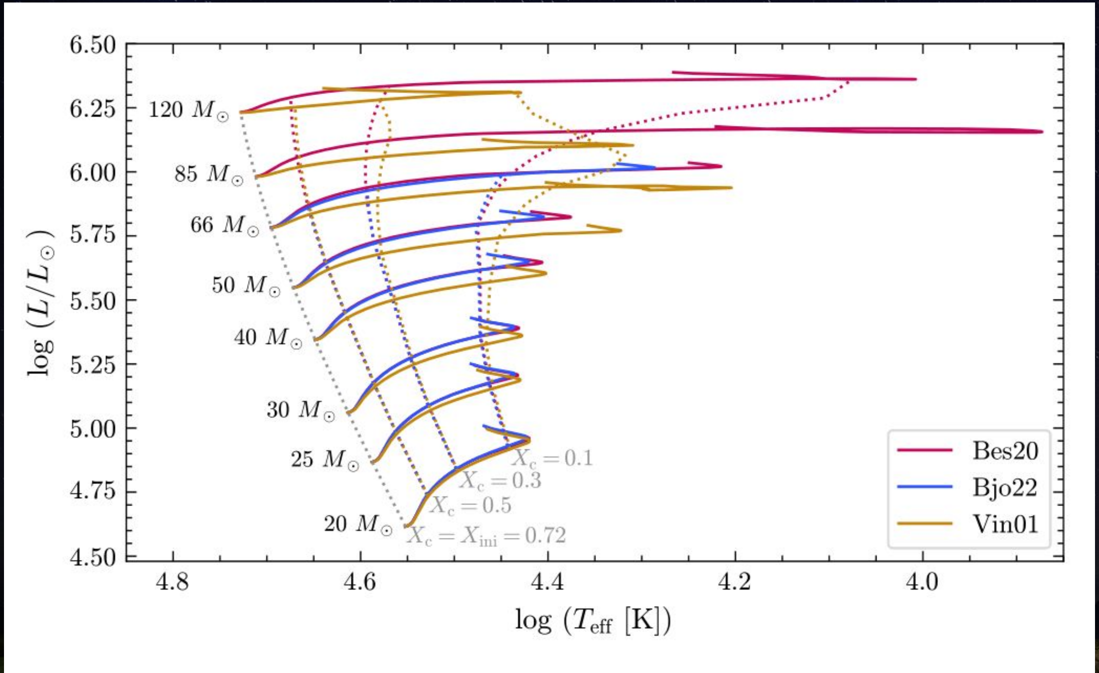
Mass at the end of the main sequence (TAMS)

Main sequence evolution



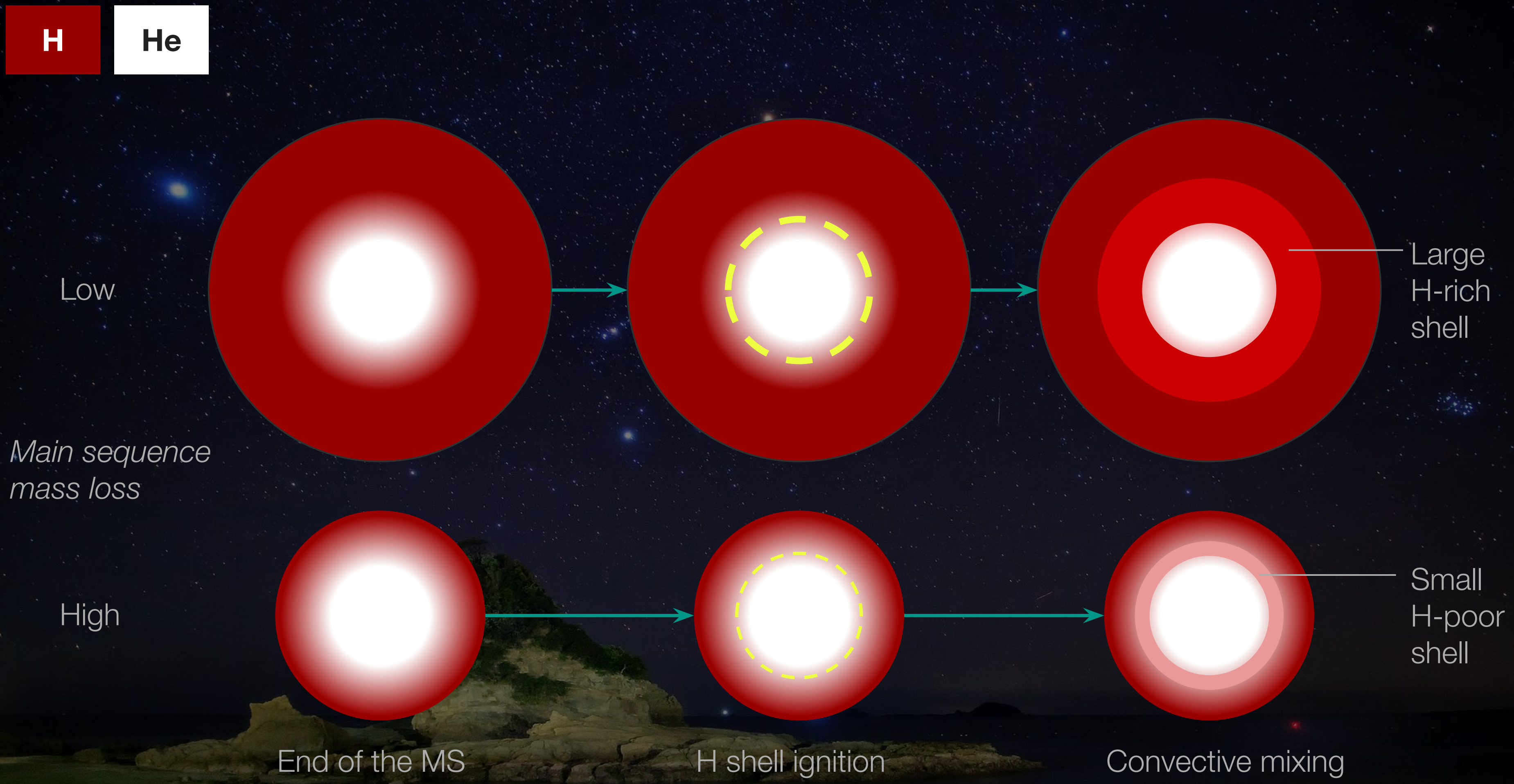
Mass-luminosity relation at the end of the main sequence

Main sequence evolution



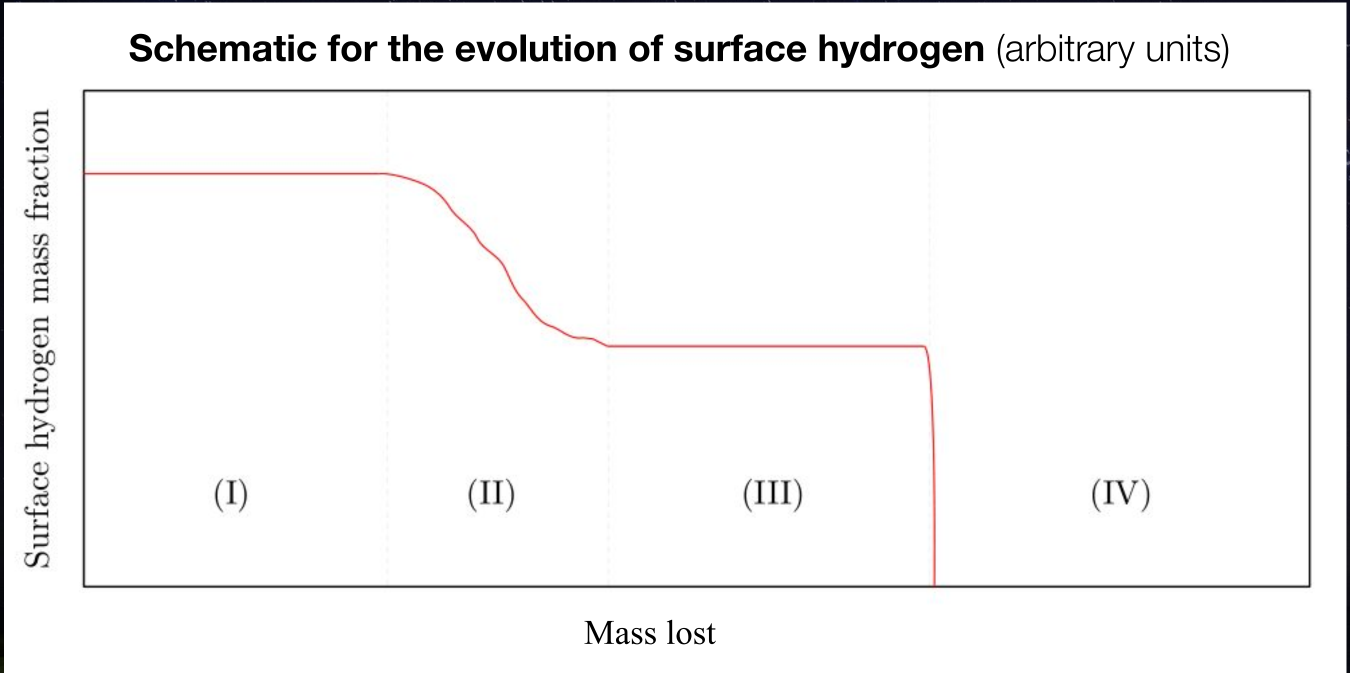
Main sequence evolution in the Hertzsprung-Russell Diagram (HRD)

After the Main Sequence



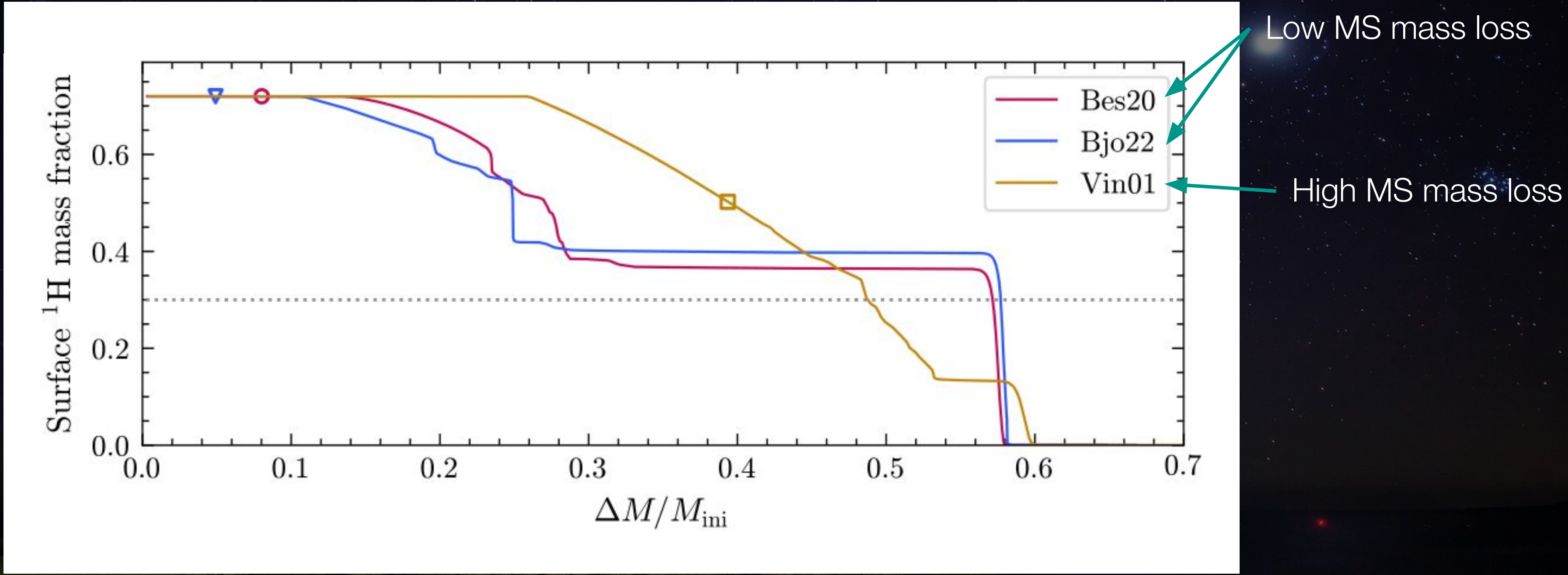
(Joris, take a drink!)

Surface hydrogen depletion



Typical track of the hydrogen depletion curve

Surface hydrogen depletion



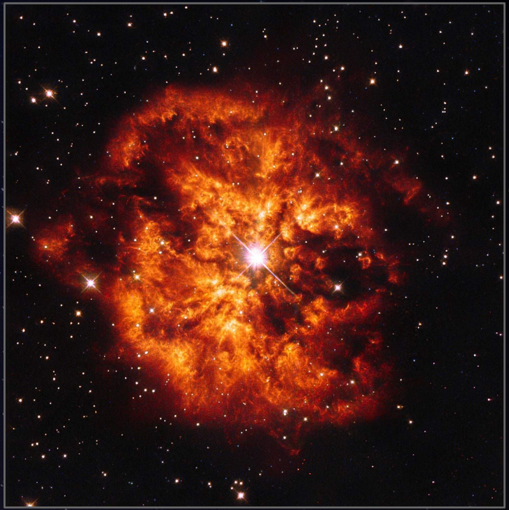
Hydrogen depletion curve for the 60 solar mass models

Wolf-Rayet stars

Spectral type with strong and broad emission lines; signatures of optically thick wind
Spectroscopic Definition

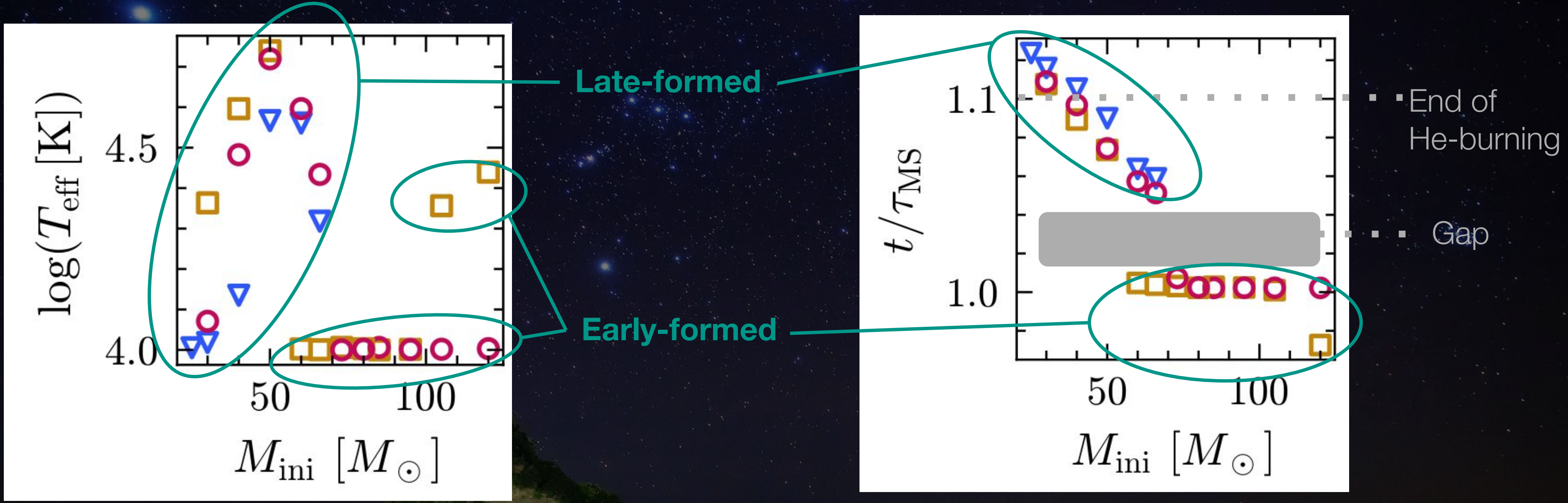
≠

Hot: $T_{eff} > 10\,000$ K
Hydrogen-poor: $X_s < 0.3$
Theoretical Definition



Nitrogen lines (hotter)	**WNL**	$X_s > 10^{-5}$	N < C	$T_{eff} < 10^{5.25}$ K
Nitrogen lines (cooler)	**WNE**	$X_s < 10^{-5}$		
Carbon lines	**WC**		C > N	
Oxygen lines	**WO**			$T_{eff} > 10^{5.25}$ K

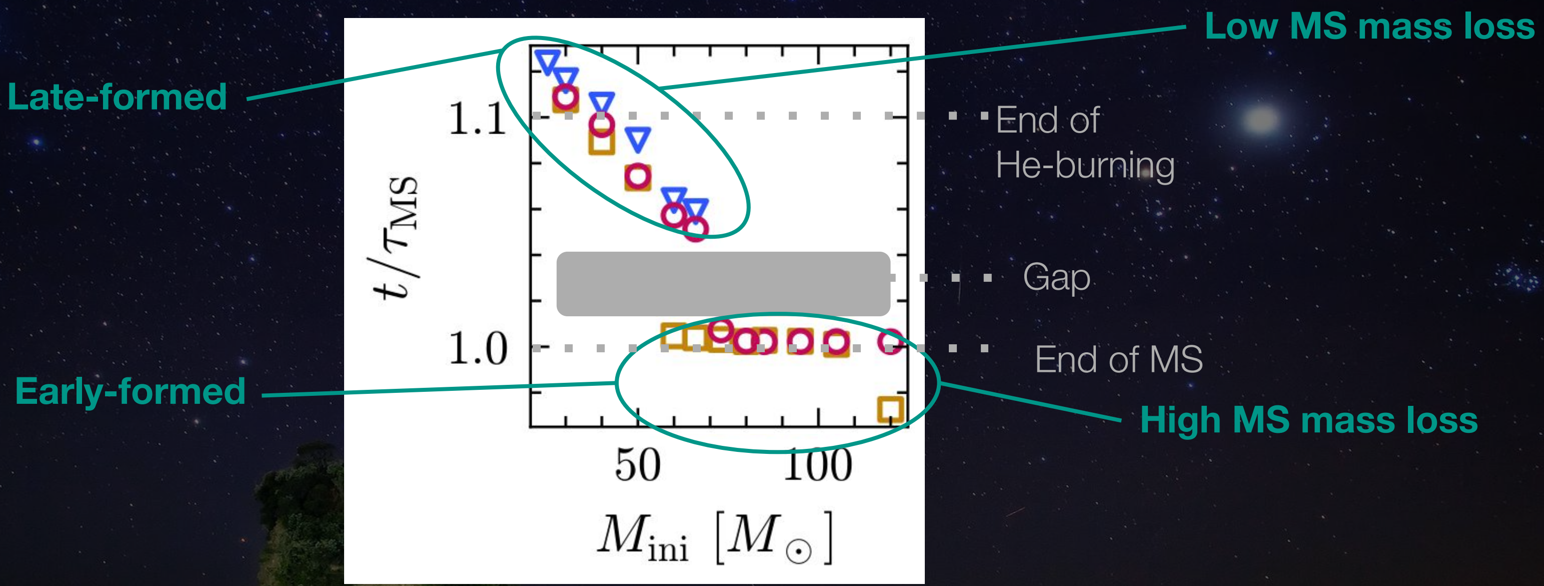
Formation of Wolf-Rayet stars



* ≤ 40$M_\odot$: *Only models with strong RSG winds become WR*

Properties at the onset of the WR phase

Formation of Wolf-Rayet stars



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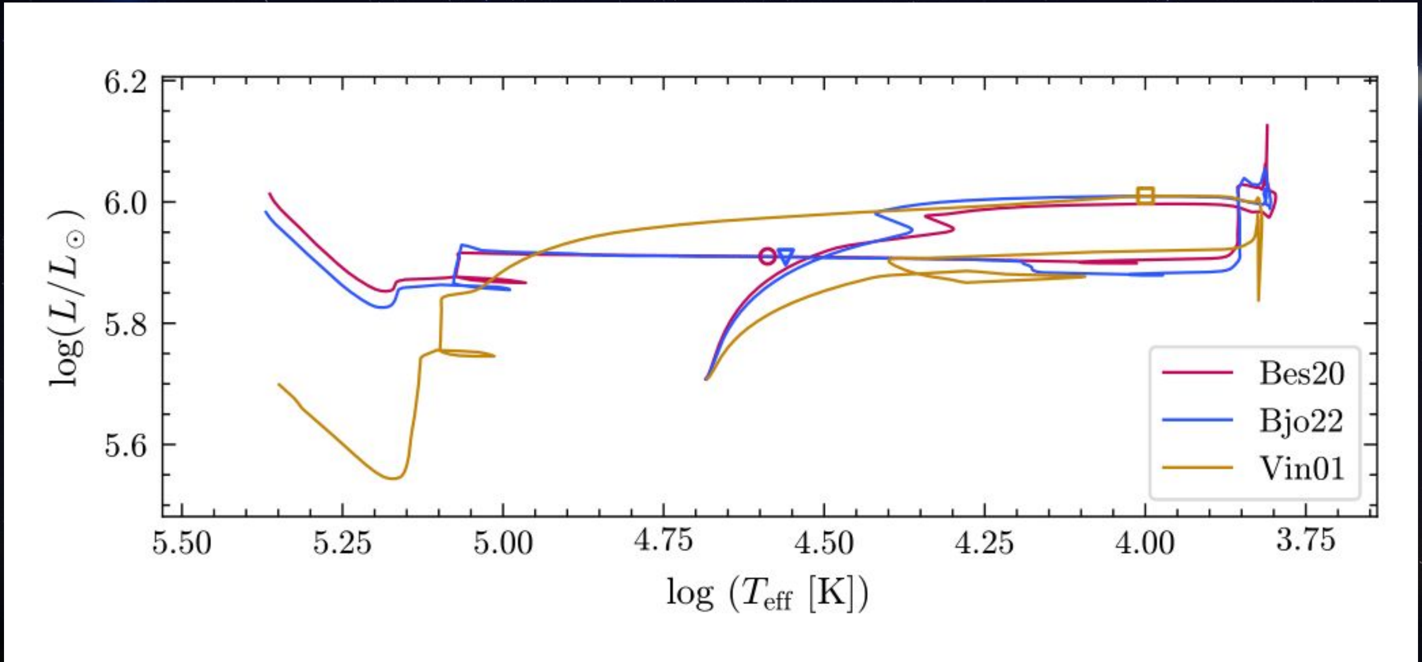
Properties at the onset of the WR phase

Evolution of Wolf-Rayet stars



60 solar mass evolution in the HRD

Evolutionary paths for post-MS massive stars

Low Mass Loss Regime

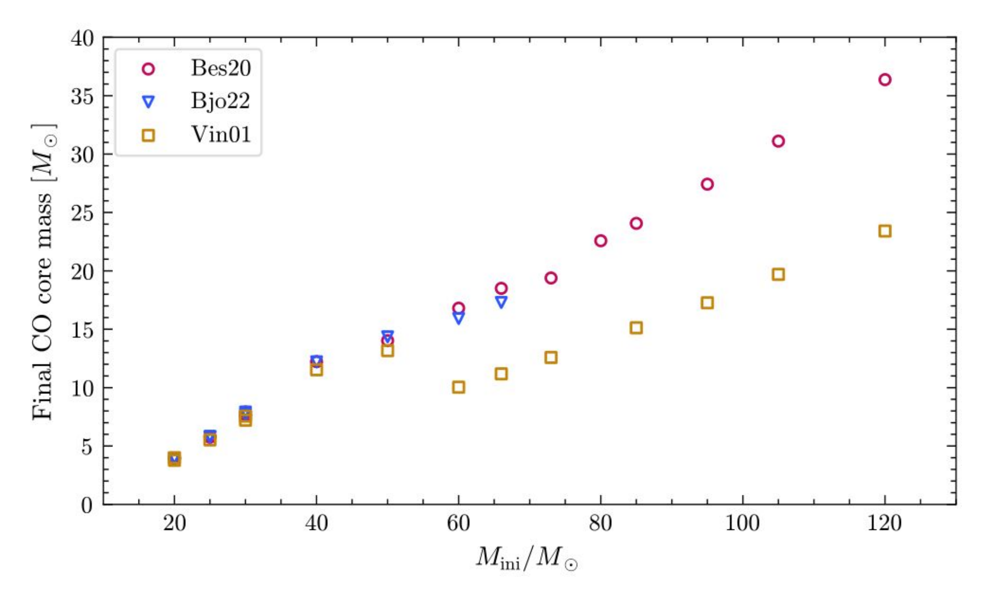
RSG/YSG
→ Surface temp. incr. with mass loss → BSG
→ H-rich shell removed → **H-depleted WR star**

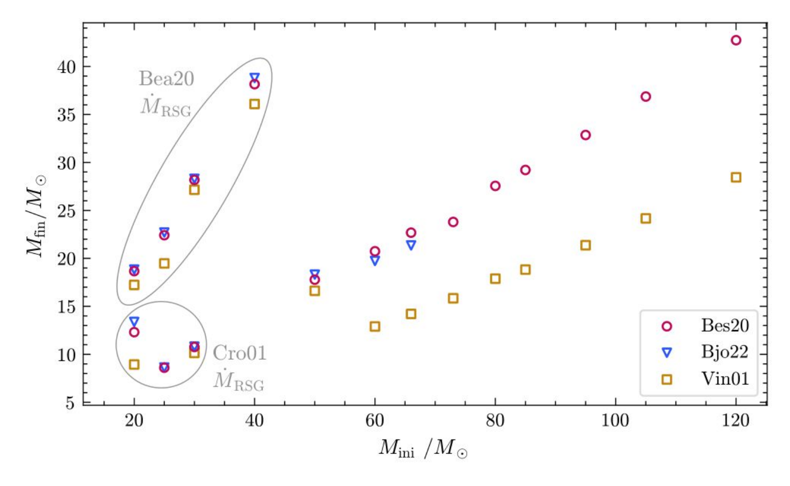
High MS Mass Loss Regime

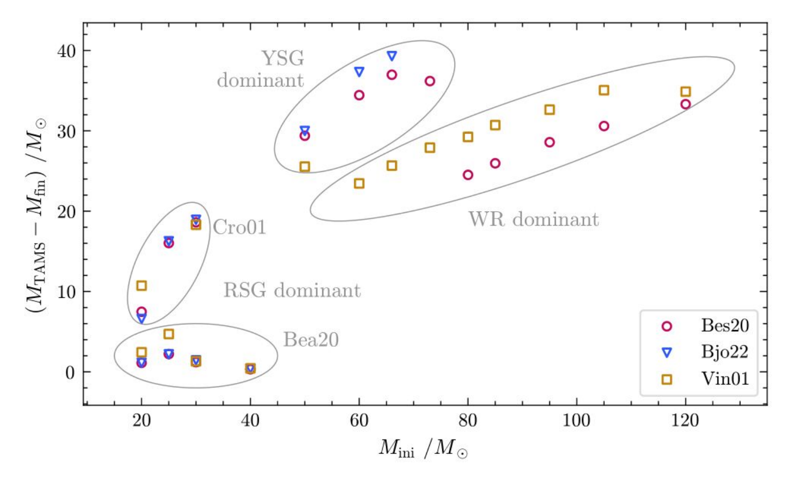
Short YSG
→ Surface temp. incr. with mass loss
→ H-poor shell exposed → **H-poor WR star**

During the WR phase: stripping of layers, very hot surface (> 100 000 K)

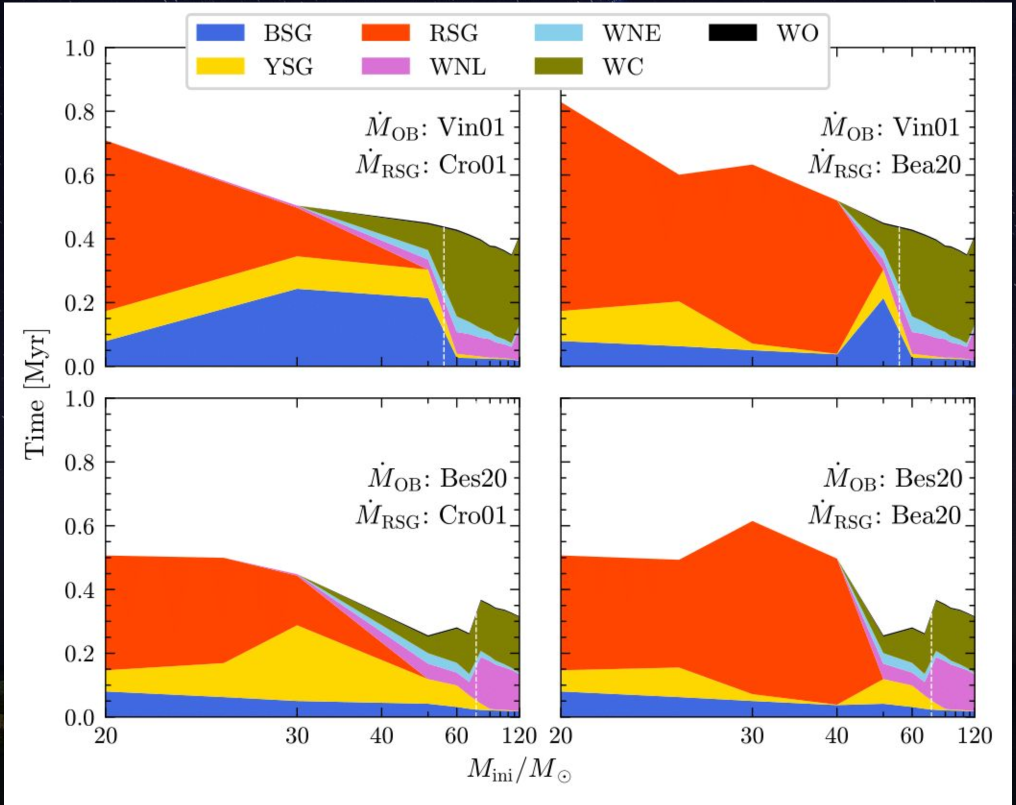
Evolutionary endpoint

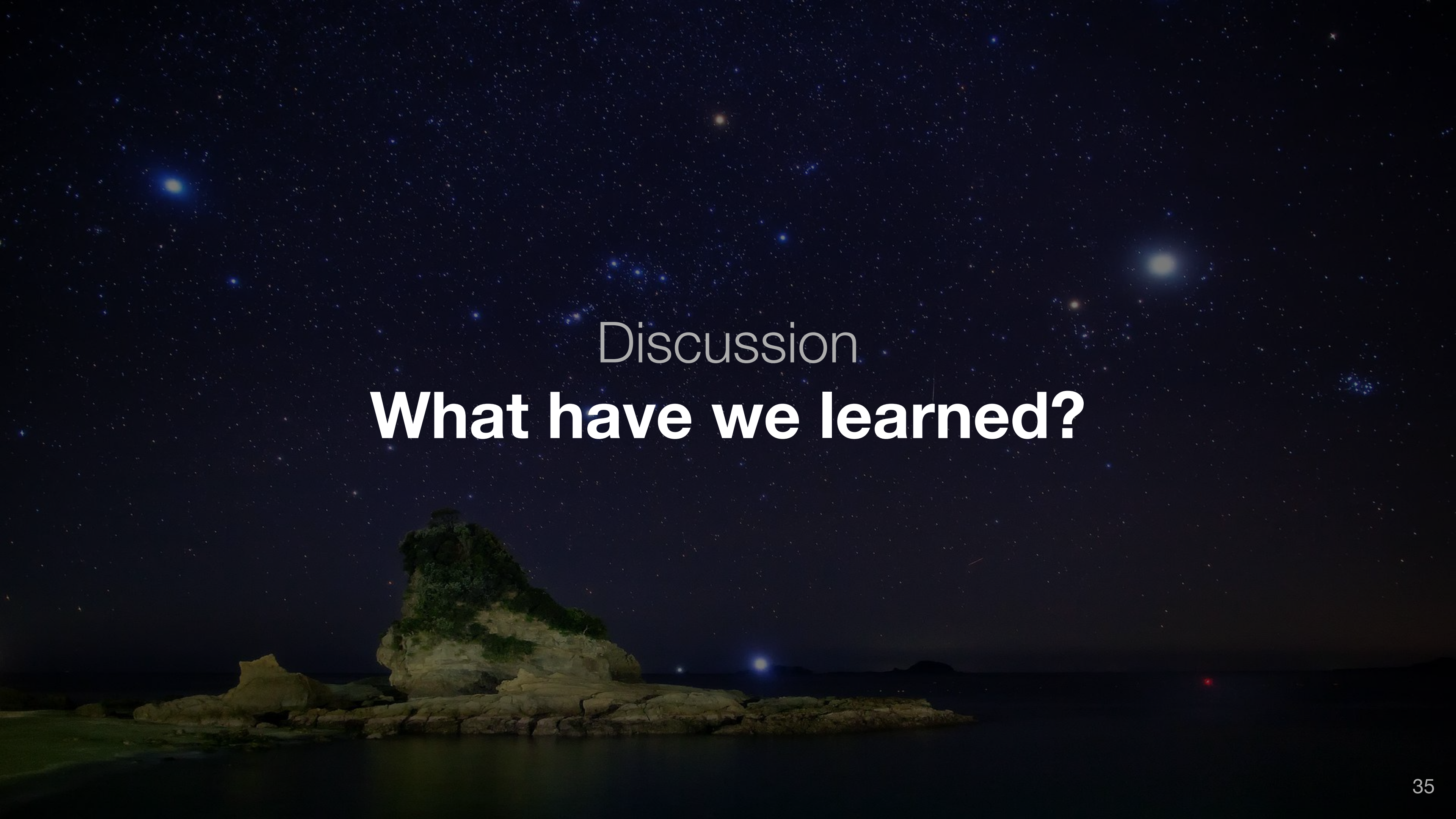






Stellar Populations





Discussion

What have we learned?

❶ There are two distinct regimes for main-sequence mass loss.

(According to two of the mass loss prescriptions)

❷ Main sequence mass loss impacts the stellar structure deeply.

Structure of **convective zones** (hydrogen shell, MS core)

❸ There are two formation channels for Wolf-Rayet* stars.

Late-formed: **O/B → RSG/YSG → BSG → WNE (→ WC/WO)**
Early-formed: **O/B → WNL → WNE → WC/WO**

** For theoretical Wolf-Rayet stars!*

Impact and limitations

- Can **predict complete evolution** just from MS mass loss.
- Insights into evolution of massive stars in the **single-star**, **non-rotating** picture.
- Investigated mass loss rates cover a **wide range**.
- No judgement of mass loss prescriptions possible (lack of observable criteria)
- No evaluation of the effects of **metallicity**, **binarity** and **rotation**.

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(According to two of the mass loss prescriptions)

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