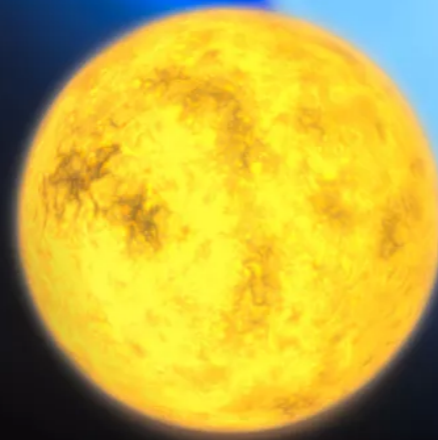


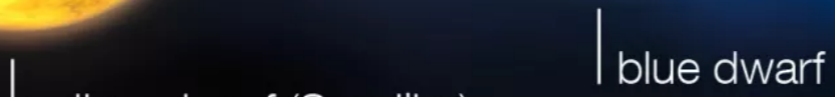
# Evolution of Massive Stars



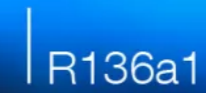
| red dwarf



| yellow dwarf (Sun-like)



| blue dwarf



| R136a1



Norhasliza Yusof  
Universiti Malaya



# BRIEF INTRODUCTION UNIVERSITY OF MALAYA



# MASSIVE STARS: ENGINES OF CREATION

Through their cycle of formation, explosive "death" and reformation, massive stars (at least 8 times bigger than our sun) populate the universe with **new elements**, the raw material of all observable matter, including life.

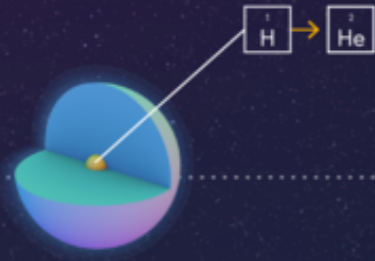


2	6	7	8	9	10	11	12
He	C	N	O	F	Ne	Na	Mg
13	14	15	16	17	18	19	
Al	Si	P	S	Cl	Ar	K	
20	21	22	23	24	25		
Ca	Sc	Ti	V	Cr	Mn		
26	27	28	29	30			
Fe	Co	Ni	Cu	Zn			
31	32	33	34				
Ga	Ge	As	Se				
35	36	37					
Br	Kr	Rb					
38	39						
Sr	Y						
40							
Zr							

## 1 MAIN SEQUENCE STAR

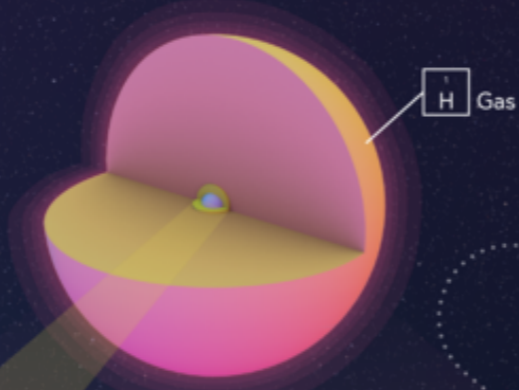
The star is fueled by hydrogen-to-helium fusion in its core.

⌚ Stage lasts 7 million years



## 2 DEVELOPMENT OF MULTI-SHELLED CORE

After hydrogen is exhausted in the core, other elements begin to fuse. Existing elements float above the denser center and form a multi-layered shell.

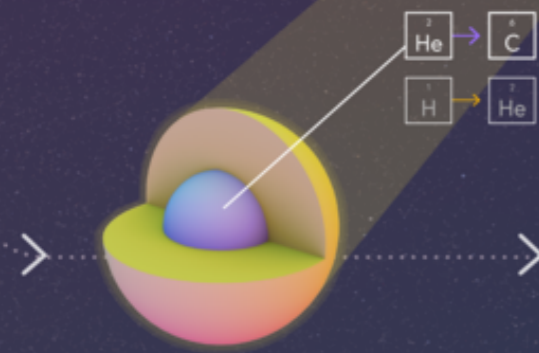


## 7 SUPERNOVA

The iron core cannot produce energy to balance the weight of the layered gas above. In less than one second, the core collapses and the upper layers rebound outward in a dramatic explosion, populating the universe with elements, the building blocks of creation.

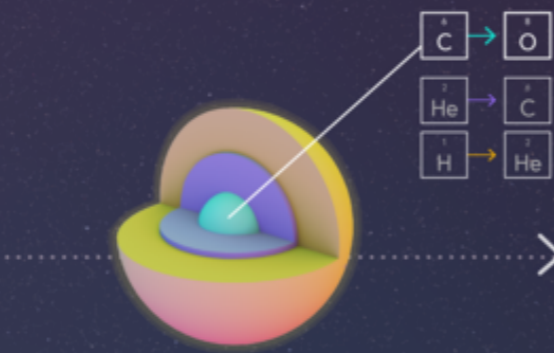
⌚ 0.01 seconds

### MULTI-SHELL CORE



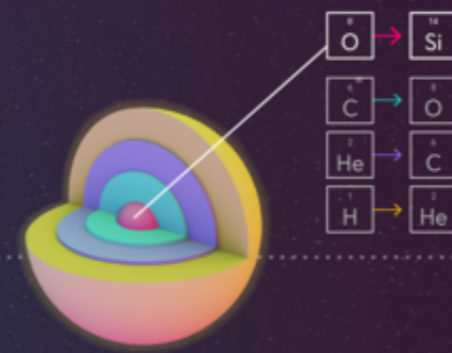
## 3 HELIUM-TO-CARBON FUSION

⌚ 500,000 years



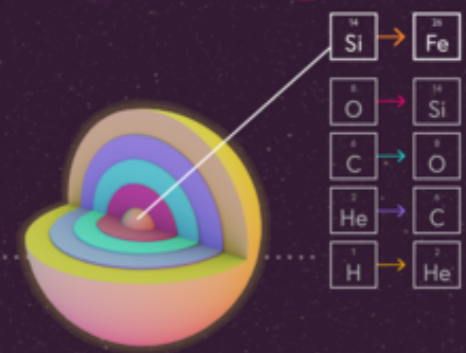
## 4 CARBON-TO-OXYGEN FUSION

⌚ 600 years



## 5 OXYGEN-TO-SILICON FUSION

⌚ 6 months



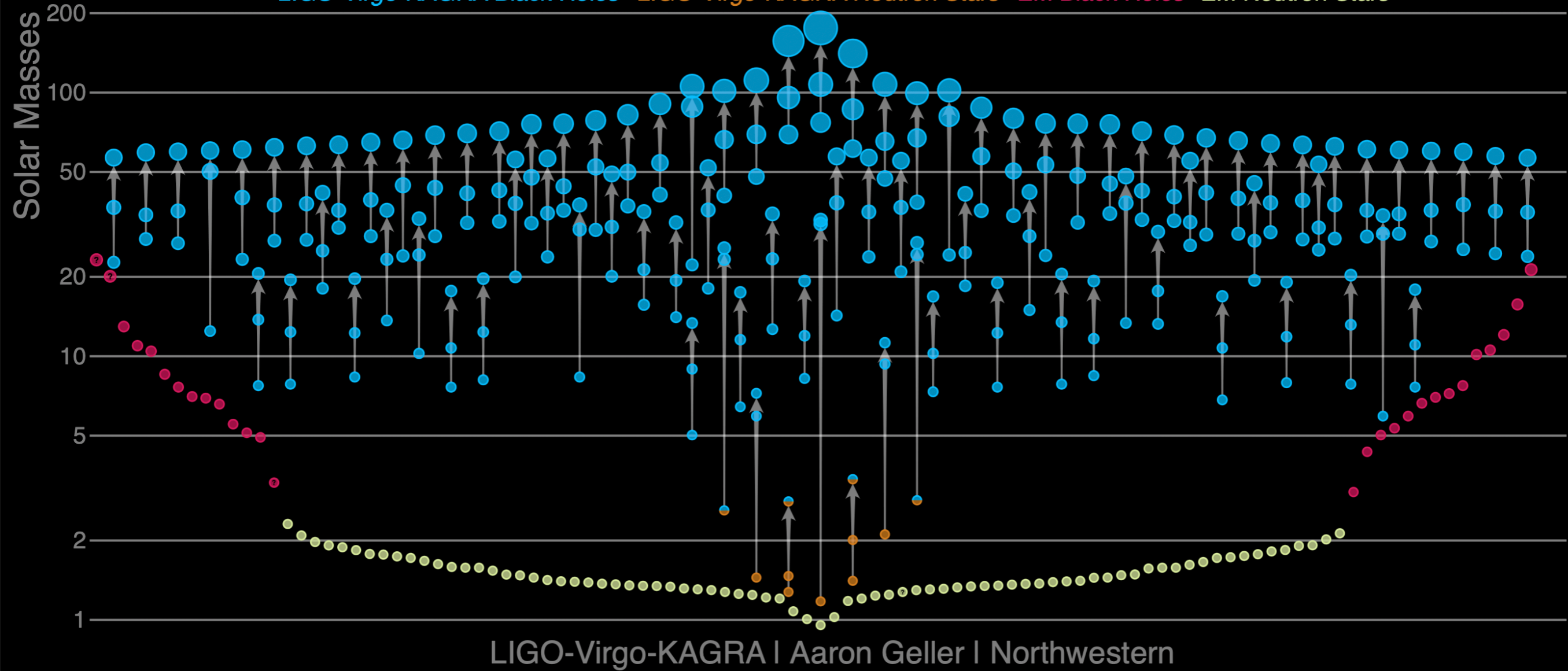
## 6 SILICON-TO-IRON FUSION

⌚ 1 day

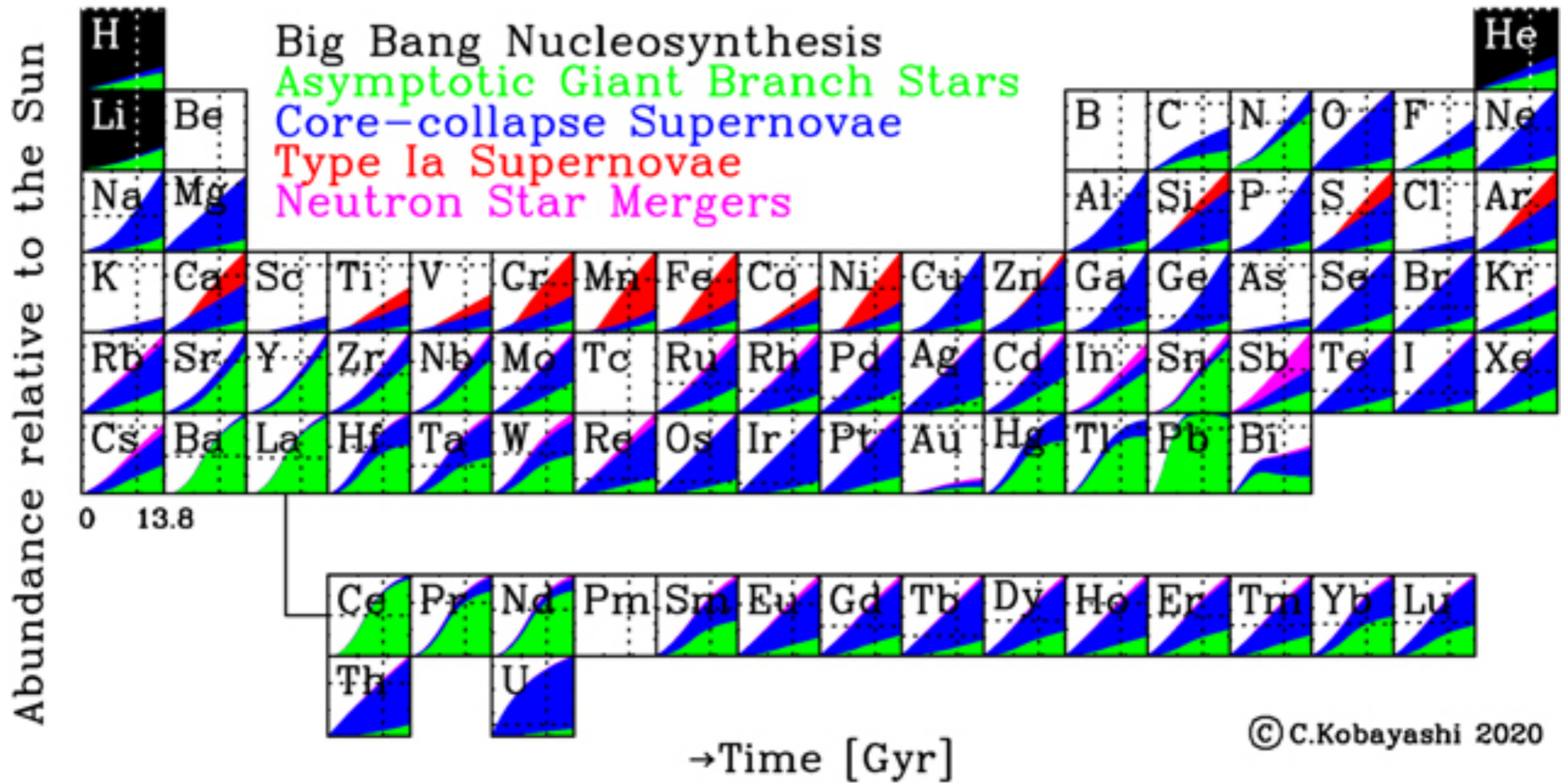
# Masses in the Stellar Graveyard



*LIGO-Virgo-KAGRA Black Holes*   *LIGO-Virgo-KAGRA Neutron Stars*   *EM Black Holes*   *EM Neutron Stars*



# Chemical Enrichment

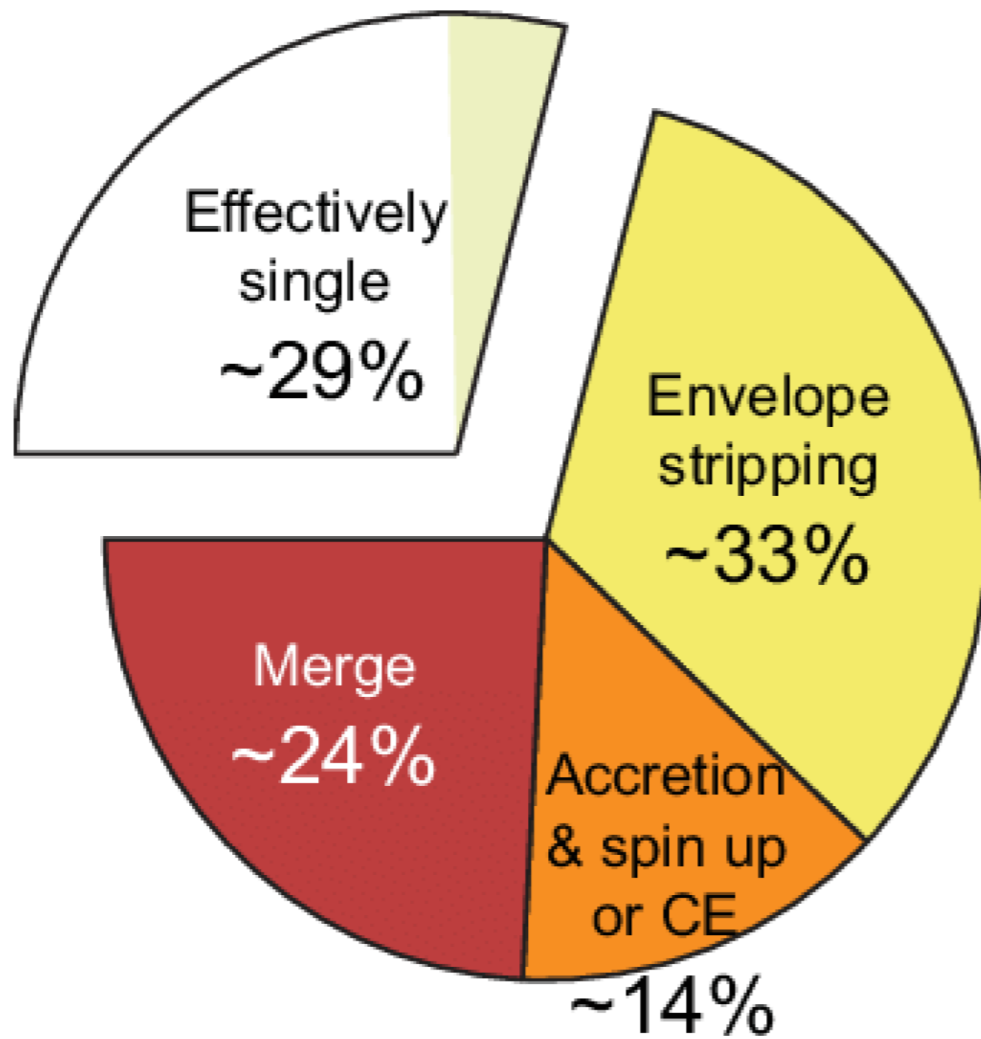


# Massive stars : Unresolved problem?

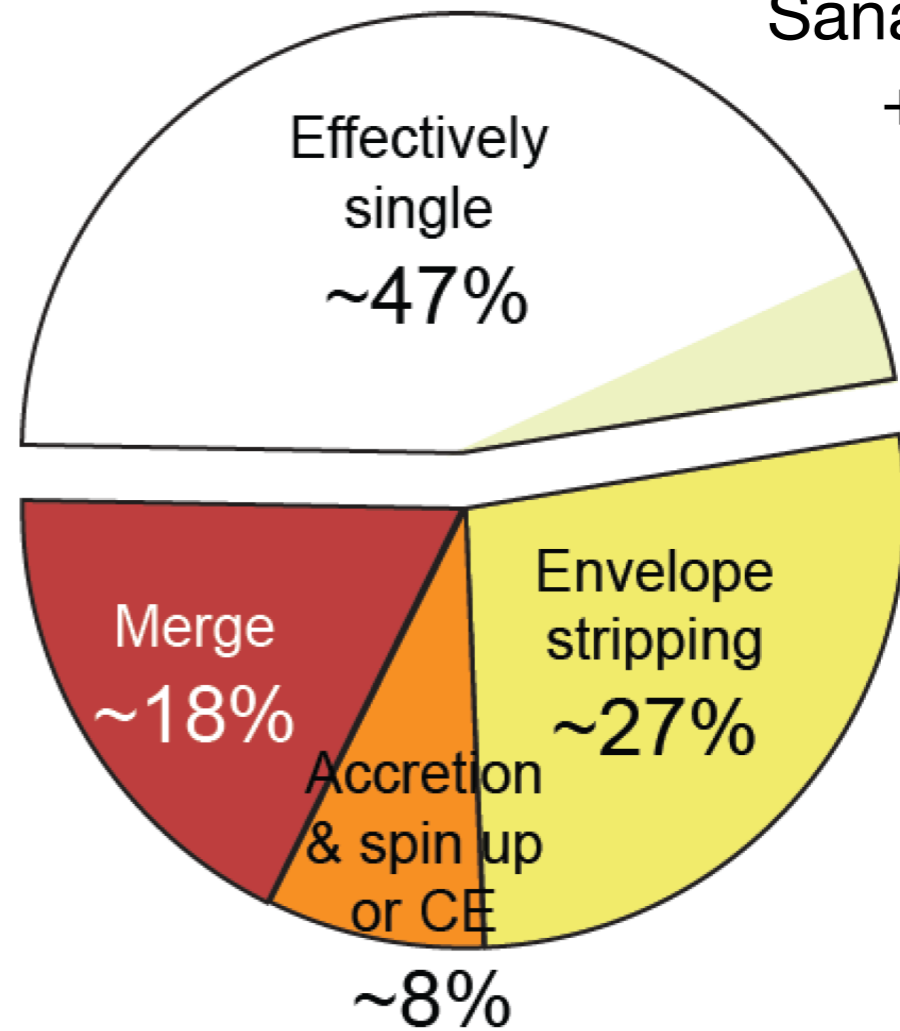
- Poor constrained Internal Physics: overshooting, rotational mixing, convection, magnetic field, nuclear reaction rate?? ....
- Mass loss : Uncertainty in mass loss, clumps in line driven winds
- Multiplicity : large binary fraction, poorly constrained and complex physics (mass transfer, common envelope etc)
- Existence of massive stars : rare due to IMF and short lifetime
- Degeneracy of different internal process hard to break using surface properties

# Single vs Binary?

Sana et al (2012)  
+ de Mink



Milky Way young clusters



VFTS O stars

# Stellar models with rotation I-VII

- 1  2022MNRAS.511.2814Y 2022/04 cited: 12     
**Grids of stellar models with rotation VII: models from 0.8 to 300  $M_{\odot}$  at supersolar metallicity ( $Z = 0.020$ )**  
Yusof, Norhasliza; Hirschi, Raphael; Eggenberger, Patrick *and 11 more*
- 2  2021A&A...652A.137E 2021/08 cited: 19     
**Grids of stellar models with rotation. VI. Models from 0.8 to 120  $M_{\odot}$  at a metallicity  $Z = 0.006$**   
Eggenberger, Patrick; Ekström, Sylvia; Georgy, Cyril *and 14 more*
- 3  2021MNRAS.501.2745M 2021/02 cited: 21     
**Grids of stellar models with rotation - V. Models from 1.7 to 120  $M_{\odot}$  at zero metallicity**  
Murphy, Laura J.; Groh, Jose H.; Ekström, Sylvia *and 10 more*
- 4  2019A&A...627A..24G 2019/07 cited: 52     
**Grids of stellar models with rotation. IV. Models from 1.7 to 120  $M_{\odot}$  at a metallicity  $Z = 0.0004$**   
Groh, J. H.; Ekström, S.; Georgy, C. *and 8 more*
- 5  2013A&A...558A.103G 2013/10 cited: 276     
**Grids of stellar models with rotation. III. Models from 0.8 to 120  $M_{\odot}$  at a metallicity  $Z = 0.002$**   
Georgy, C.; Ekström, S.; Eggenberger, P. *and 11 more*
- 6  2012A&A...542A..29G 2012/06 cited: 230     
**Grids of stellar models with rotation. II. WR populations and supernovae/GRB progenitors at  $Z = 0.014$**   
Georgy, C.; Ekström, S.; Meynet, G. *and 5 more*
- 7  2012A&A...537A.146E 2012/01 cited: 1353     
**Grids of stellar models with rotation. I. Models from 0.8 to 120  $M_{\odot}$  at solar metallicity ( $Z = 0.014$ )**  
Ekström, S.; Georgy, C.; Eggenberger, P. *and 9 more*



# Code comparison

**Table 1.** Main ingredients of the evolutionary models.

	STERN <sup>1</sup>	Geneva <sup>2</sup>	FRANEC <sup>3</sup>	Padova <sup>4</sup>	MESA <sup>5</sup>	STAREVOL <sup>5</sup>
Initial metallicity ( $Z$ )	0.0088	0.0140	0.01345	0.0170	0.014	0.0134
Mixing length parameter ( $l/H_P$ )	1.5	1.6 / 1.0 <sup>†</sup>	2.3	1.68	2.0	1.63
Overshoot parameter ( $d/H_P$ )	0.335	0.1	0.2	~0.5	$f = 0.0/0.01/0.02$ <sup>‡</sup>	0.0/0.1/0.2
Rotation	0–550 km s <sup>-1</sup>	$\Omega/\Omega_{\text{crit}} = 0.4$	300 km s <sup>-1</sup>	0	0/200 km s <sup>-1</sup>	0/220 km s <sup>-1</sup>
Magnetic field	Spruit-Taylor	no	no	no	no	no
Solar mixture	AGS05 <sup>6</sup> with C, N, O, Mg, Si, Fe modified	AGS05 with Ne enhanced (Cunha et al. 2006)	AGSS09 <sup>7</sup>	GN93 <sup>8</sup>	GN93	AGSS09

**References.** 1) [Brott et al. \(2011a\)](#); 2) [Ekström et al. \(2012\)](#); 3) [Chieffi & Limongi \(2013\)](#); 4) [Bertelli et al. \(2009\)](#); 5) this work. Heavy elements solar mixture: 6) [Asplund et al. \(2005\)](#); 7) [Asplund et al. \(2009\)](#); 8) [Grevesse et al. \(1993\)](#). <sup>†</sup> For stars with initial mass  $<40 M_{\odot}$ , the mixing length parameter is  $l/H_P = 1.6$ . For more massive stars, it is defined with respect to the local density scale height and  $l/H_P = 1.0$ . <sup>‡</sup> In MESA the overshooting is implemented as a decreasing exponential with parameter  $f$  (see text).

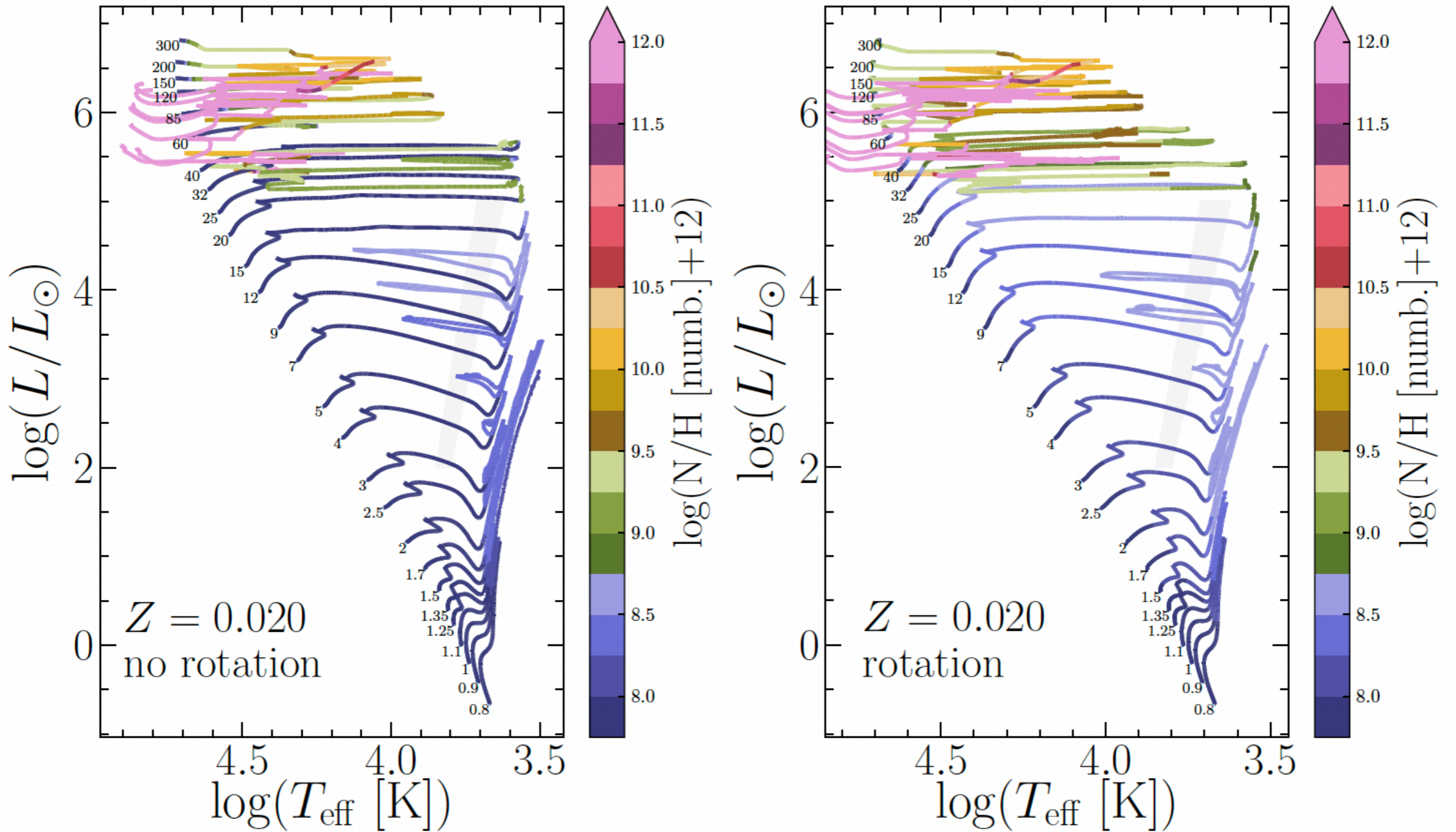
Martins & Palacios (2013)

# Code comparison

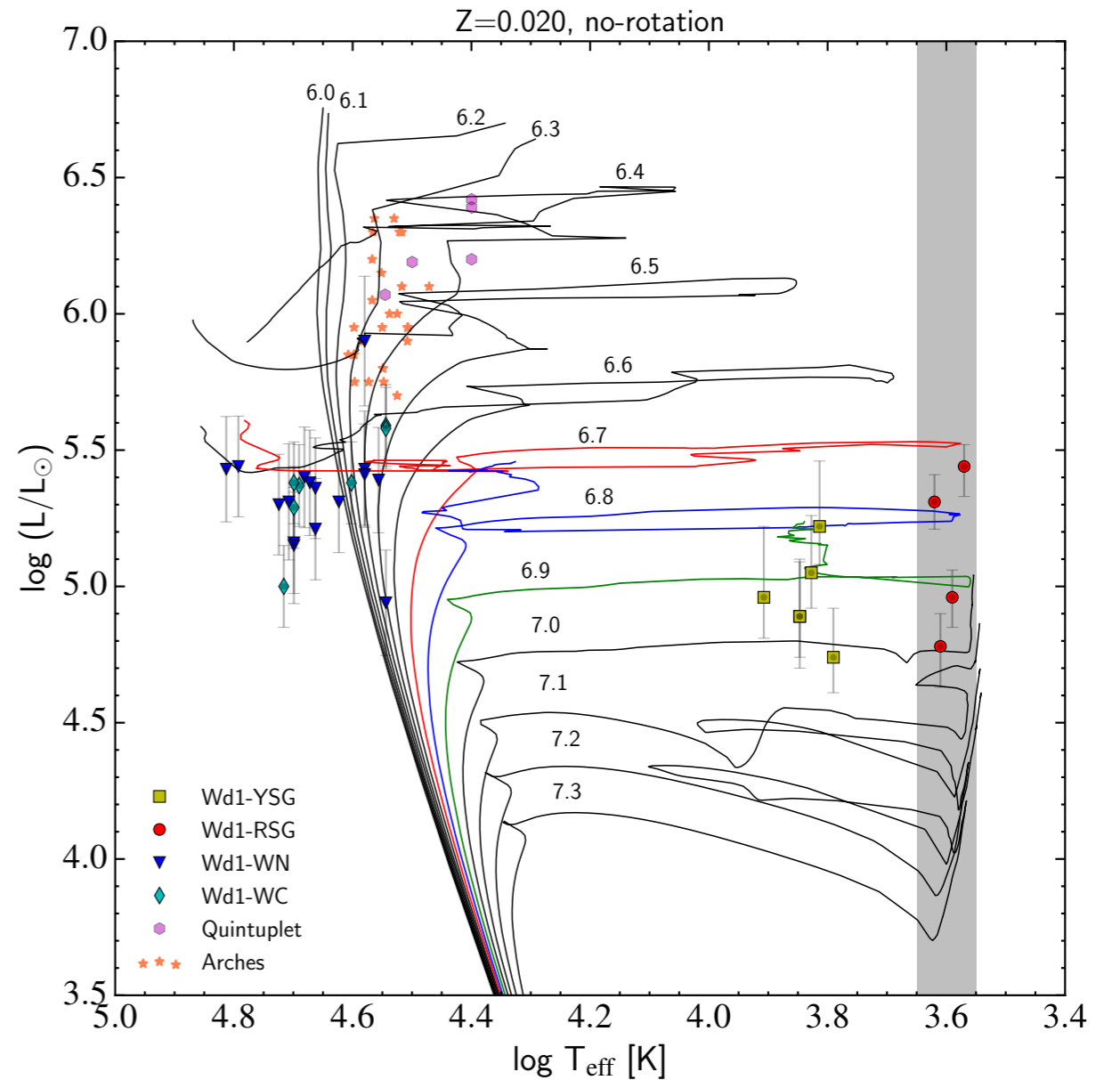
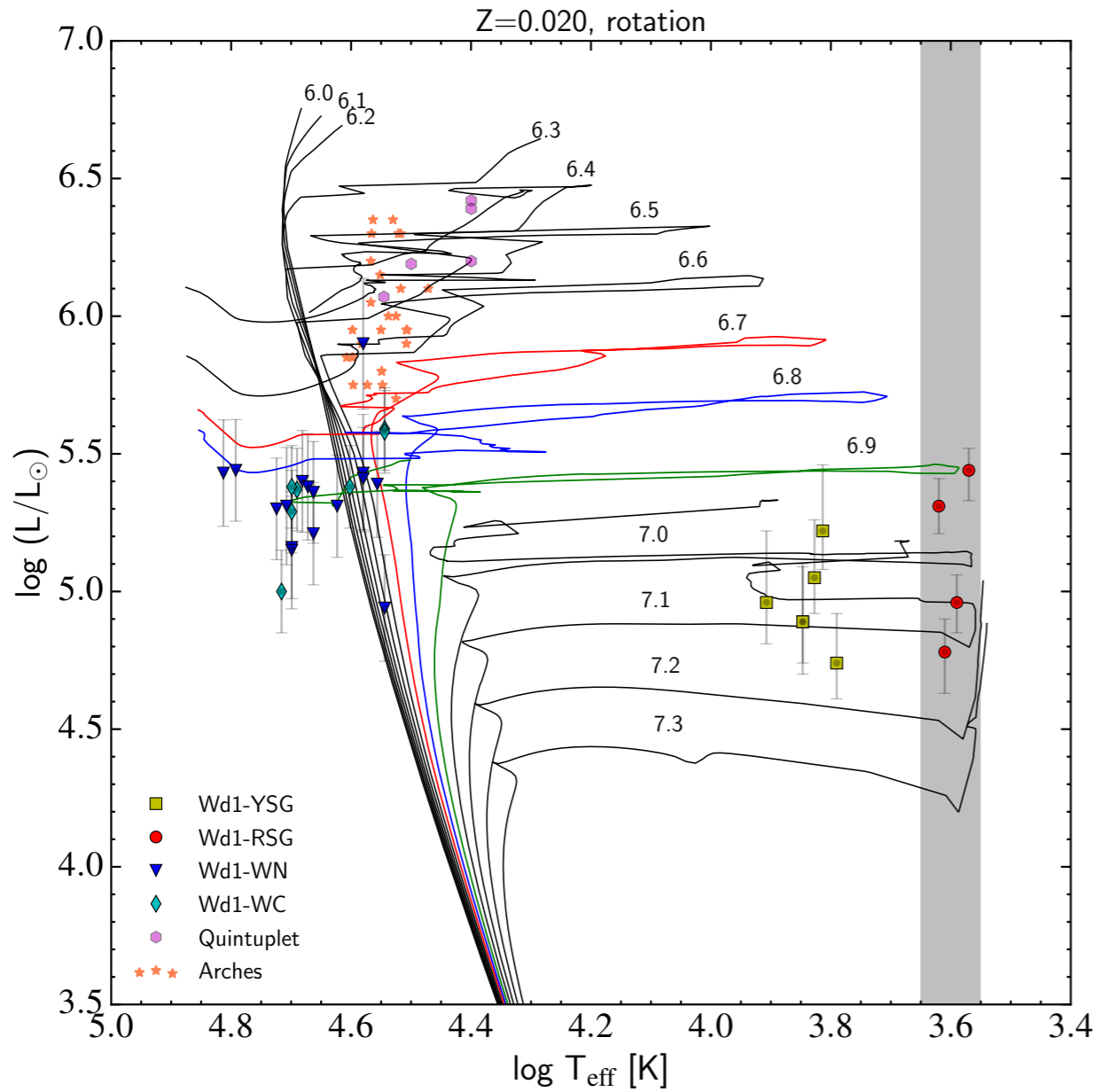
Stellar model	$Z_{\odot}$	Hot wind	Cool wind	Wolf–Rayet wind	Convective boundary	$\alpha_{\text{MLT}}$	Overshoot type	$\alpha_{\text{ovs}}$	$\alpha_{\text{semi}}$
BPASS	0.020	Vink, de Koter & Lamers (2000, 2001)	de Jager, Nieuwenhuijzen & van der Hucht (1988)	Nugis & Lamers (2000)	Schwarzschild (1958)	2.0	Pols et al. (1998)	0.12 <sup>e</sup>	–
BoOST	0.008 <sup>a</sup>	Vink et al. (2000, 2001)	Nieuwenhuijzen & de Jager (1990)	Hamann, Koesterke & Wessolowski (1995) <sup>b</sup>	Ledoux (1947)	1.5	Step	0.335	1.0
Geneva	0.014	Vink et al. (2000, 2001)	de Jager et al. (1988) <sup>c</sup>	Nugis & Lamers (2000)	Schwarzschild (1958)	1.6 <sup>d</sup>	Step	0.1	–
MIST	0.014	Vink et al. (2000, 2001)	de Jager et al. (1988)	Nugis & Lamers (2000)	Ledoux (1947)	1.82	Herwig (2000)	0.016 <sup>e</sup>	0.1
PARSEC	0.015	Vink et al. (2000, 2001)	de Jager et al. (1988)	Nugis & Lamers (2000)	Schwarzschild (1958)	1.74	Bressan, Chiosi & Bertelli (1981)	0.5 <sup>e</sup>	–

Agrawal+  
(2022)

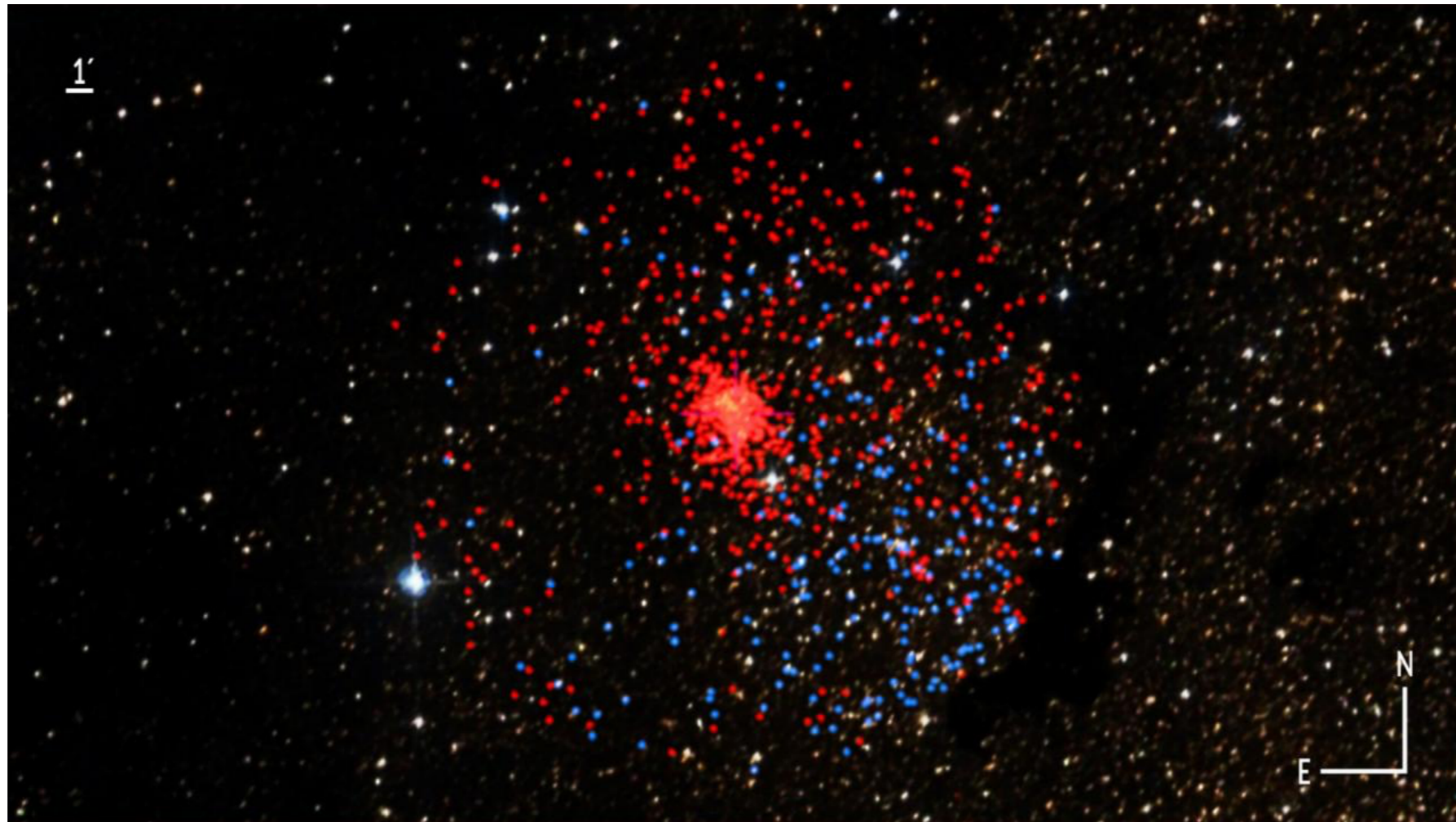
# $Z = 0.02$ (supersolar)



# Isochrones ( $Z=0.02$ )



# Young Massive Stars Cluster - Westerlund 1

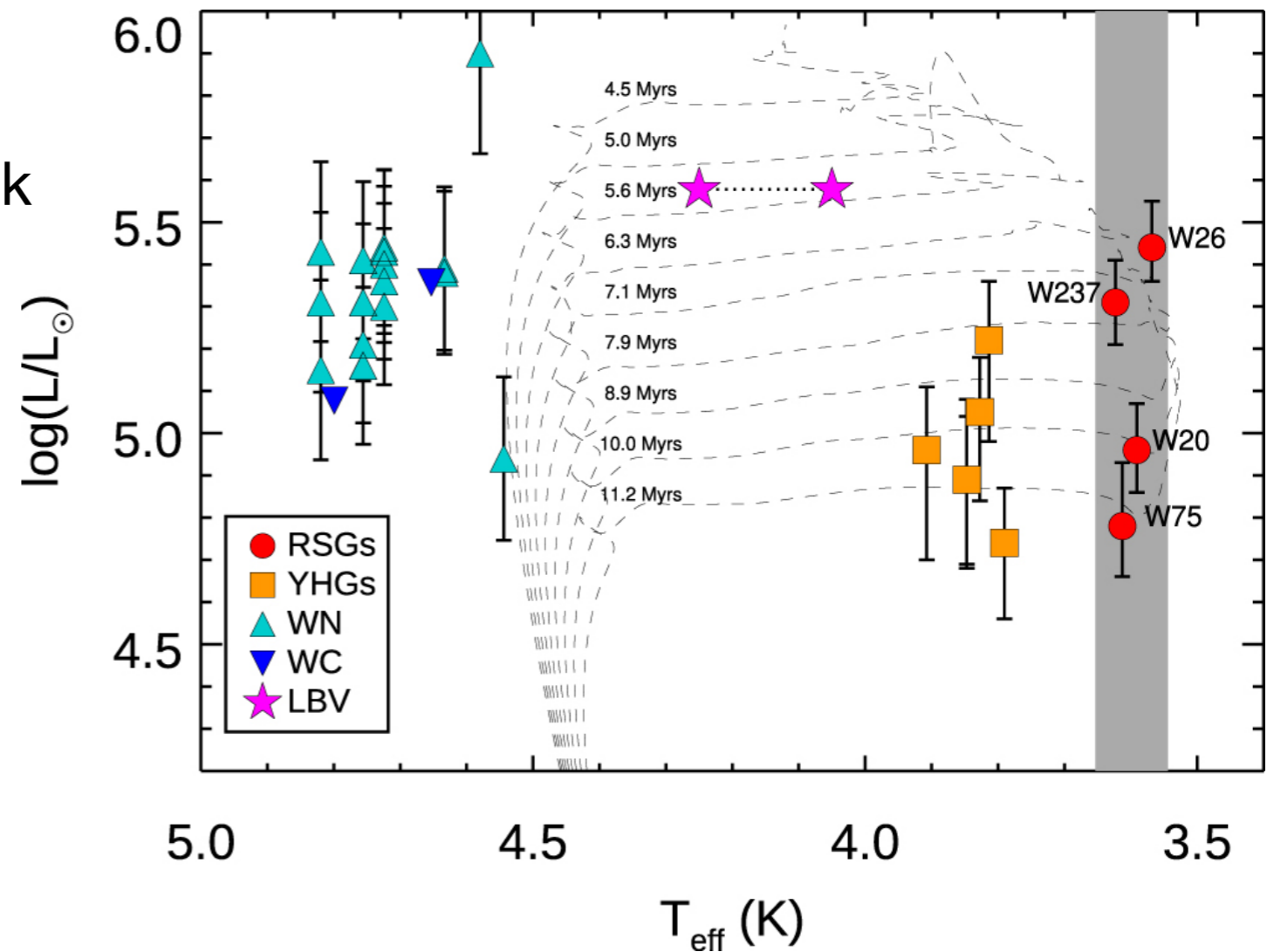


# Westerlund -1

Young star cluster in inner Galactic disk

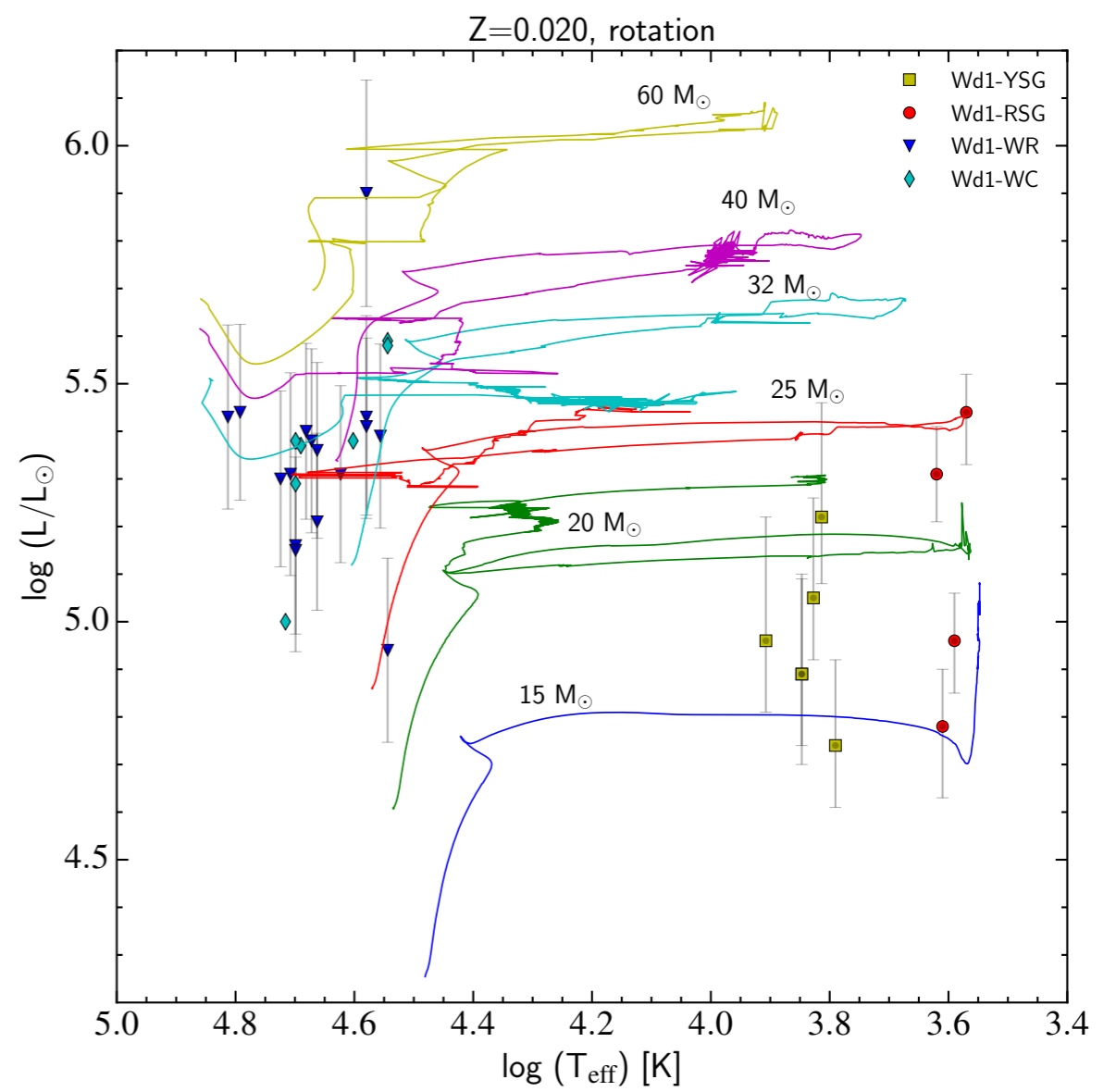
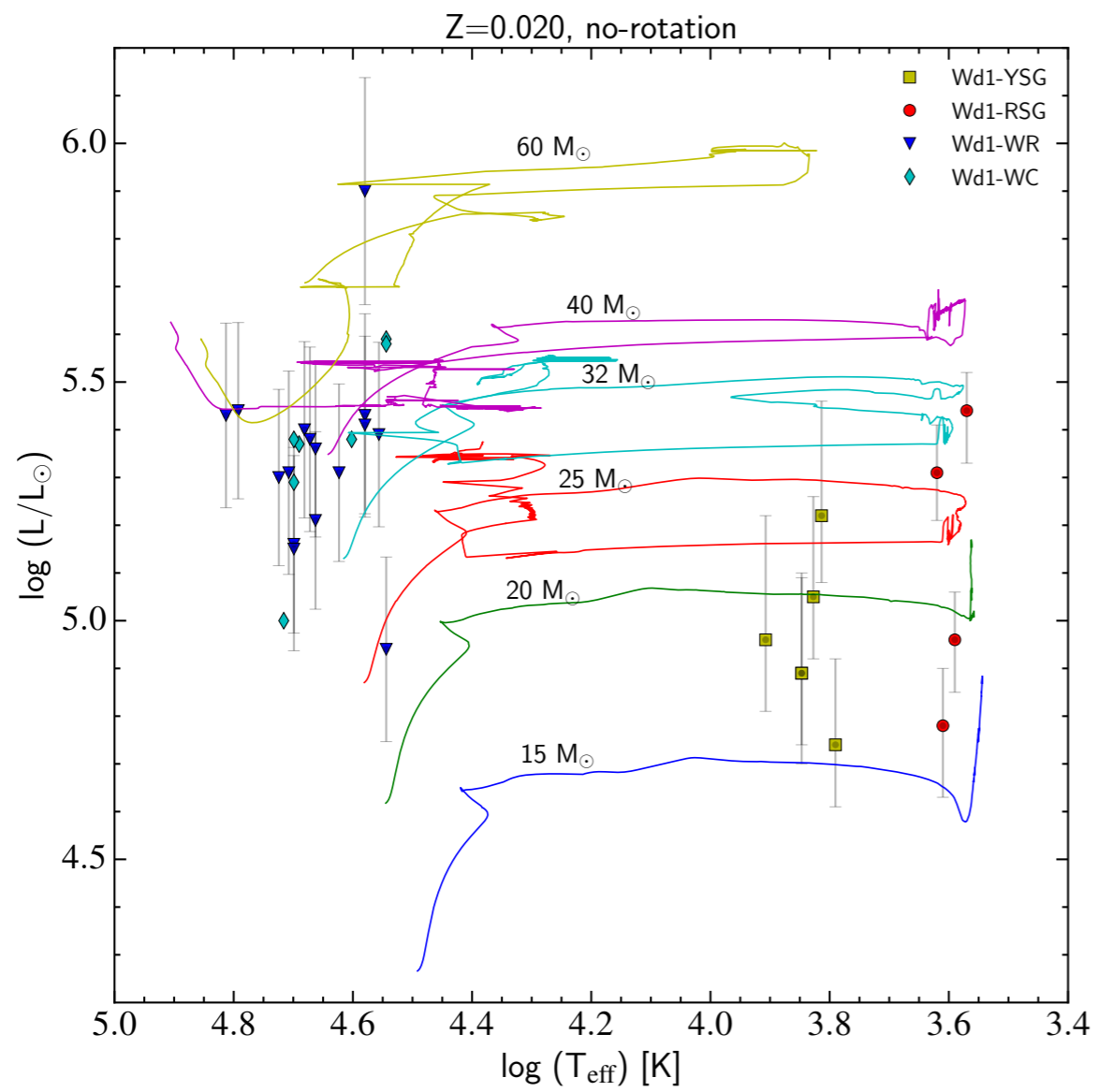
Age ~ 4-5 Myr (Crowther + 2006)

Age ~ 10 Myr (Beasor 2021)

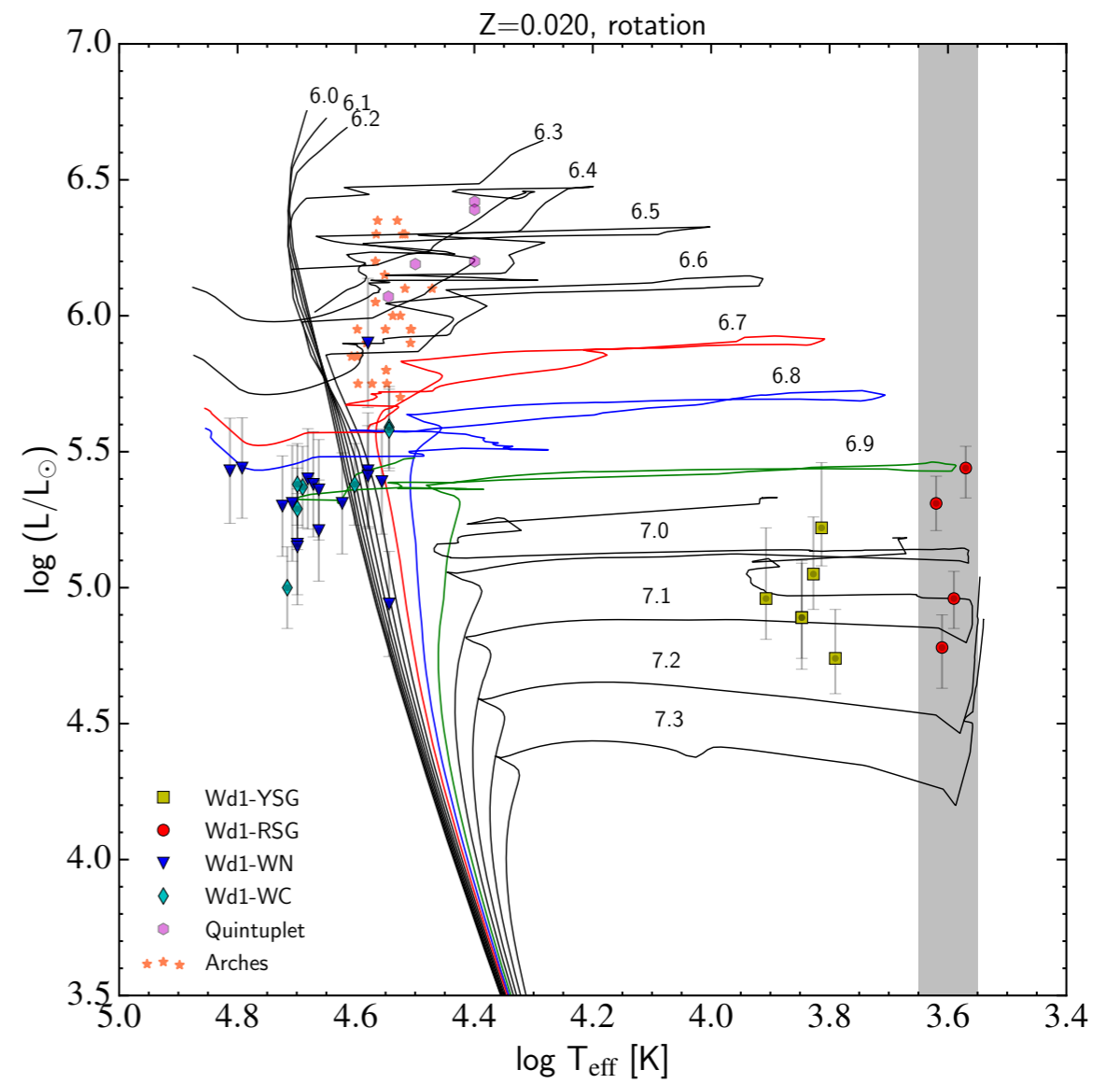
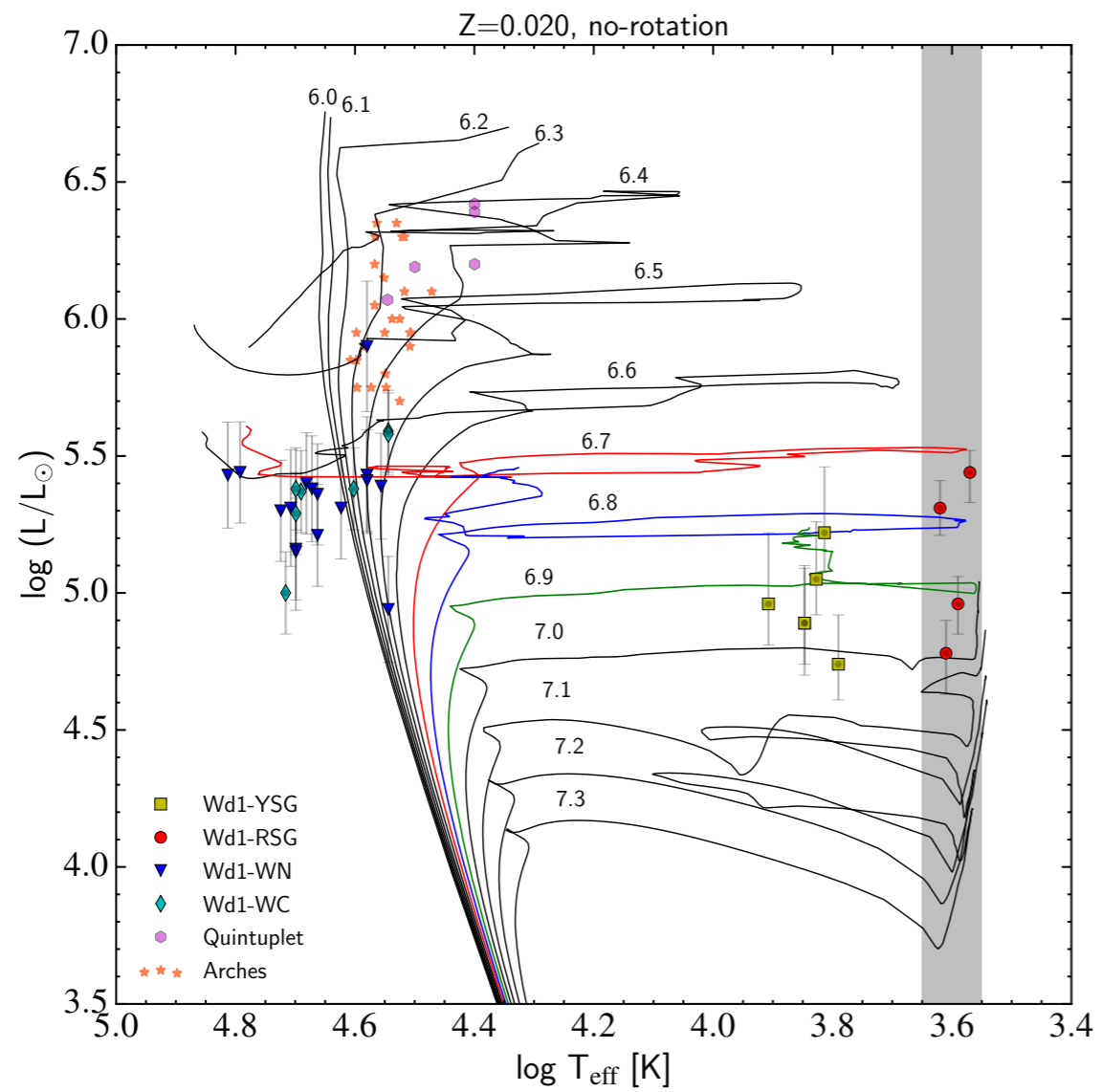


Metallicity is not known???

Beasor et al (2021)



Yusof et al (2022)

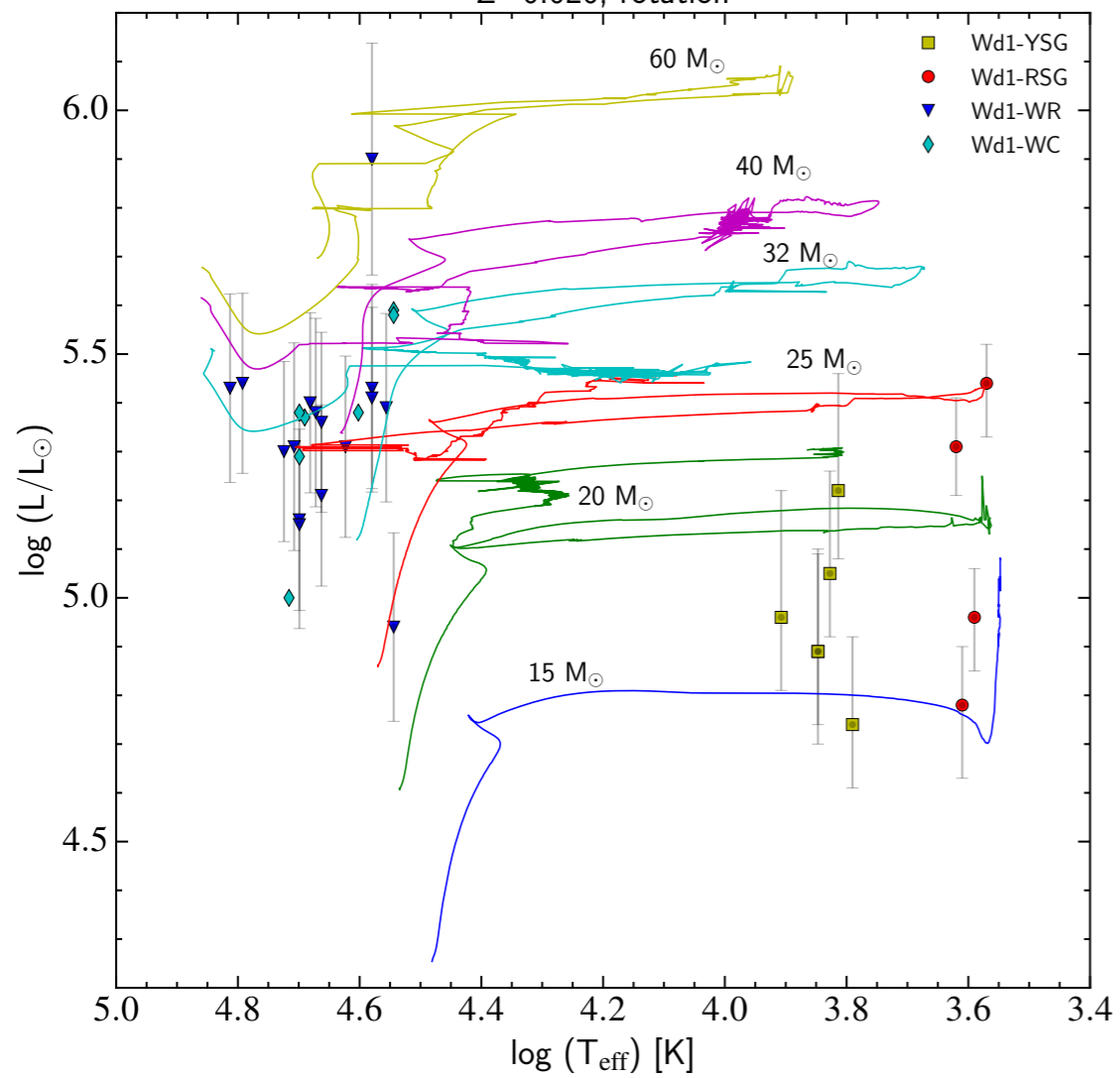


Yusof et al (2022)



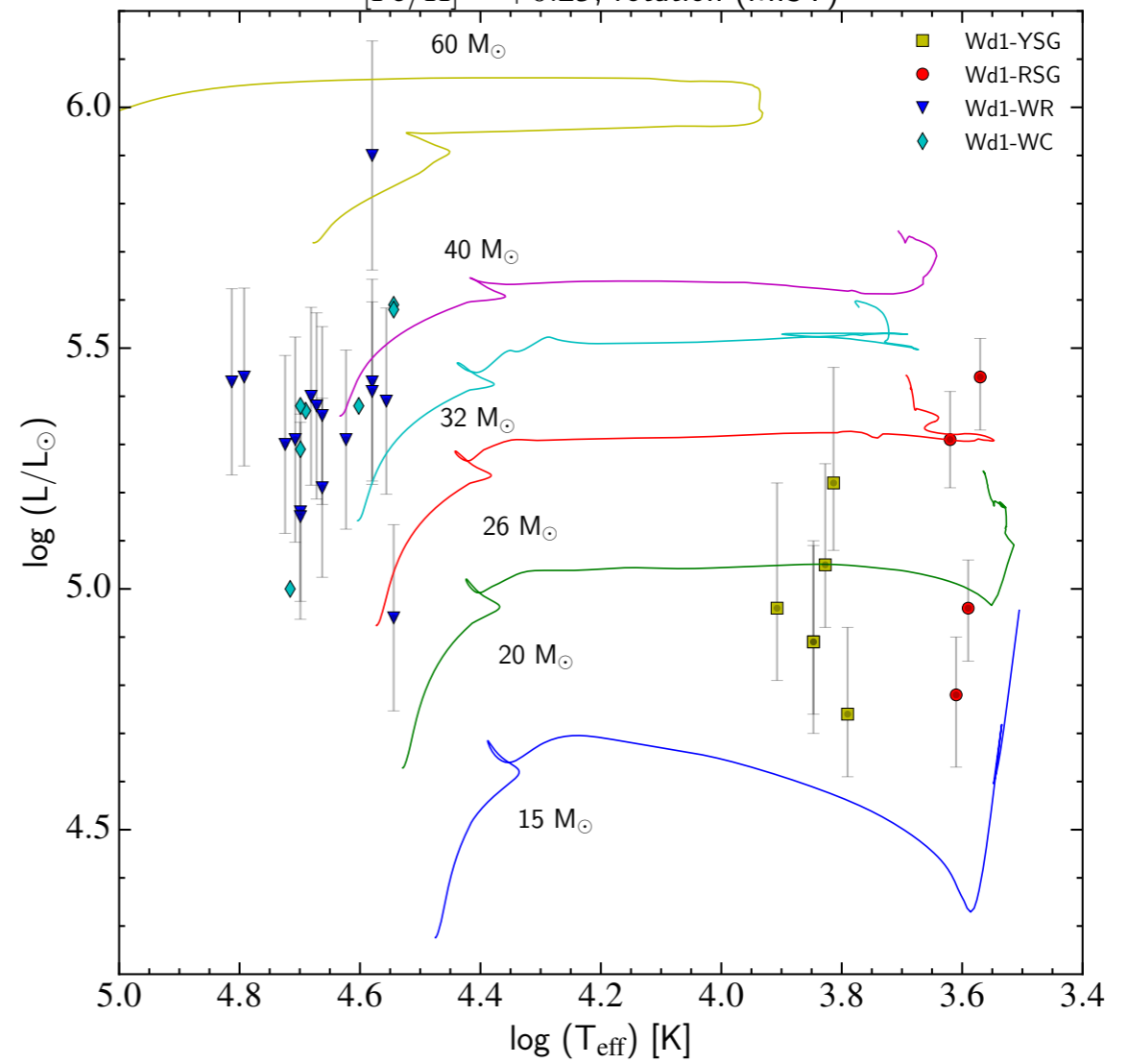
# GENEVA

Z=0.020, rotation



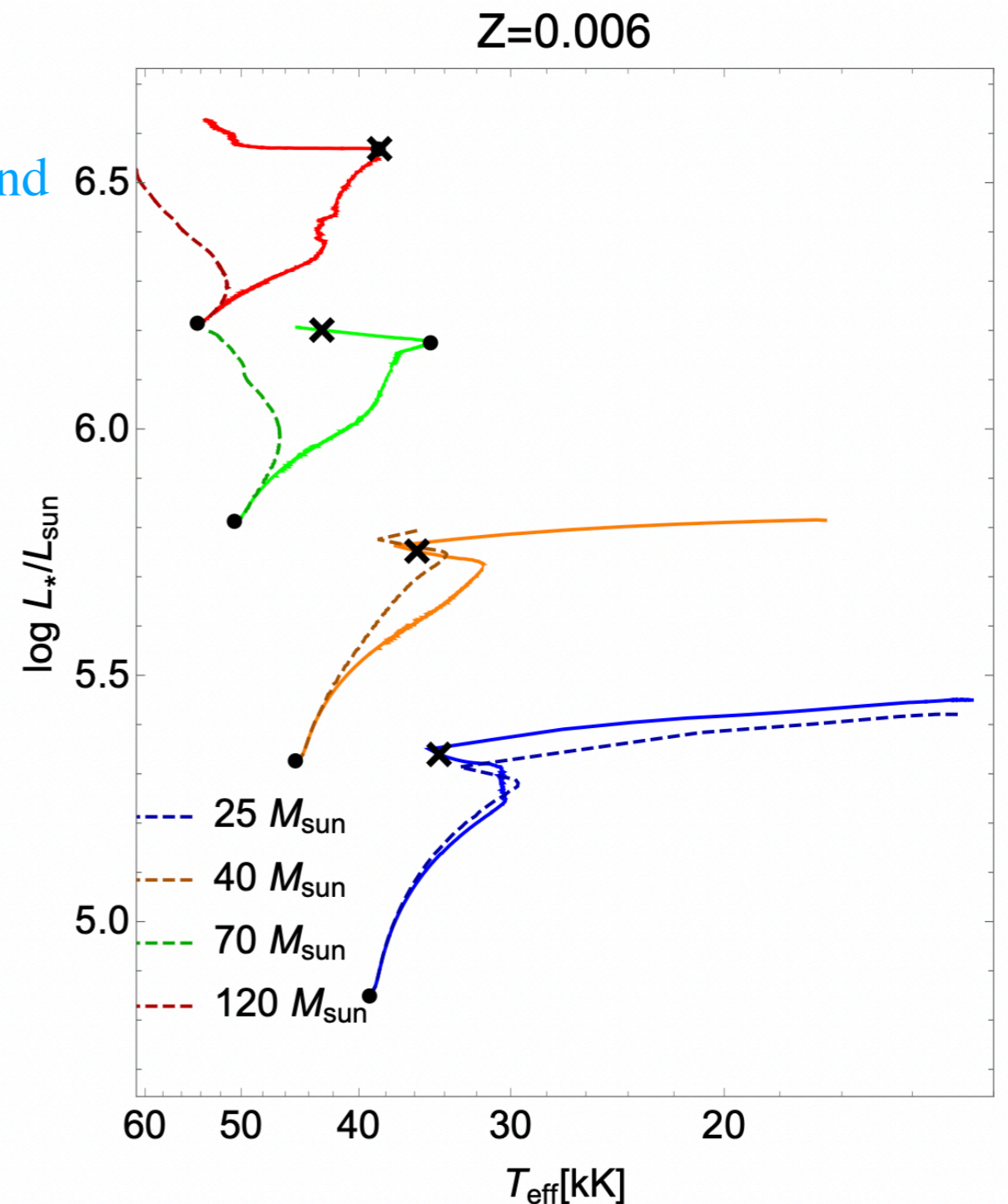
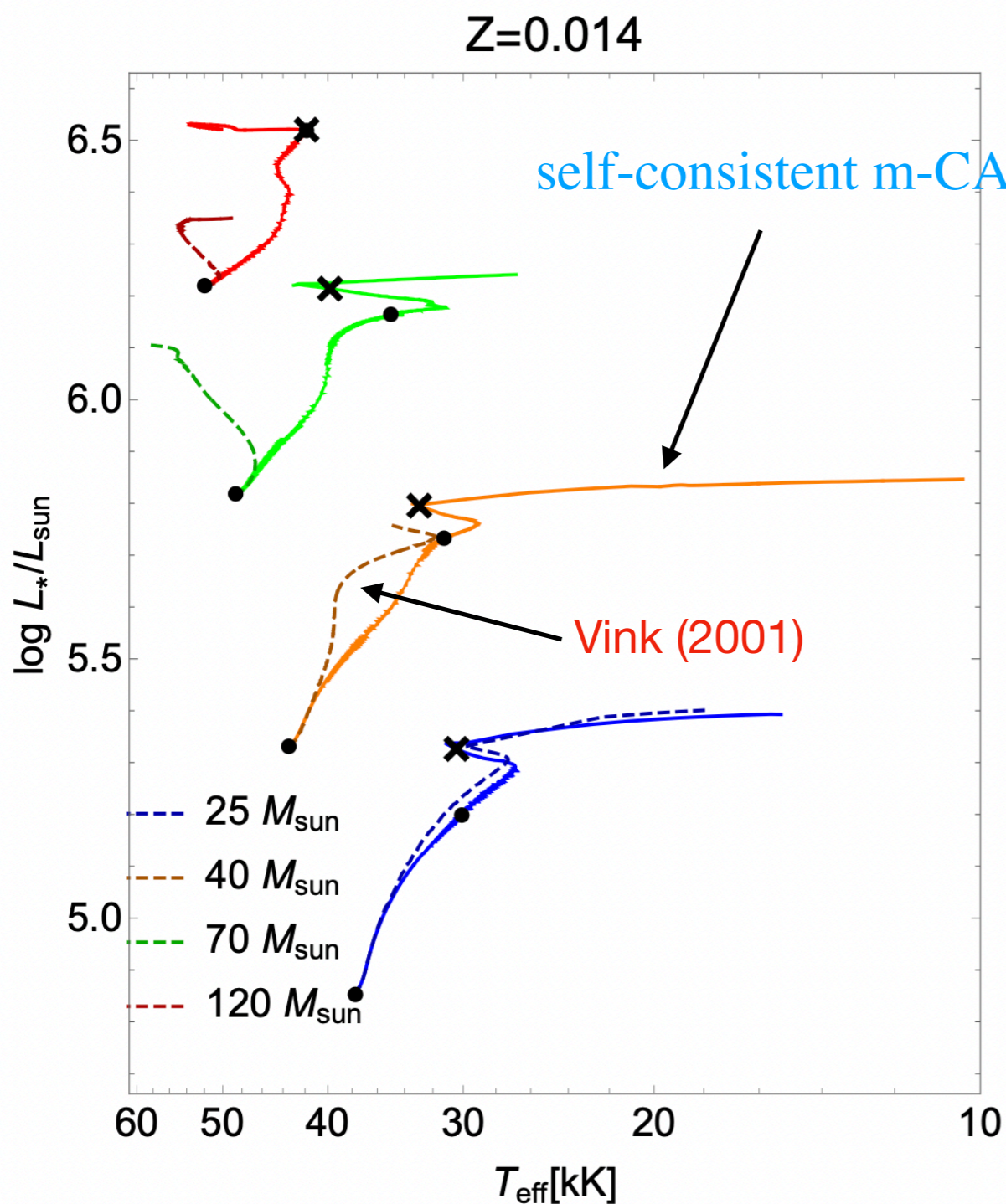
# MIST

[Fe/H] = +0.25, rotation (MIST)

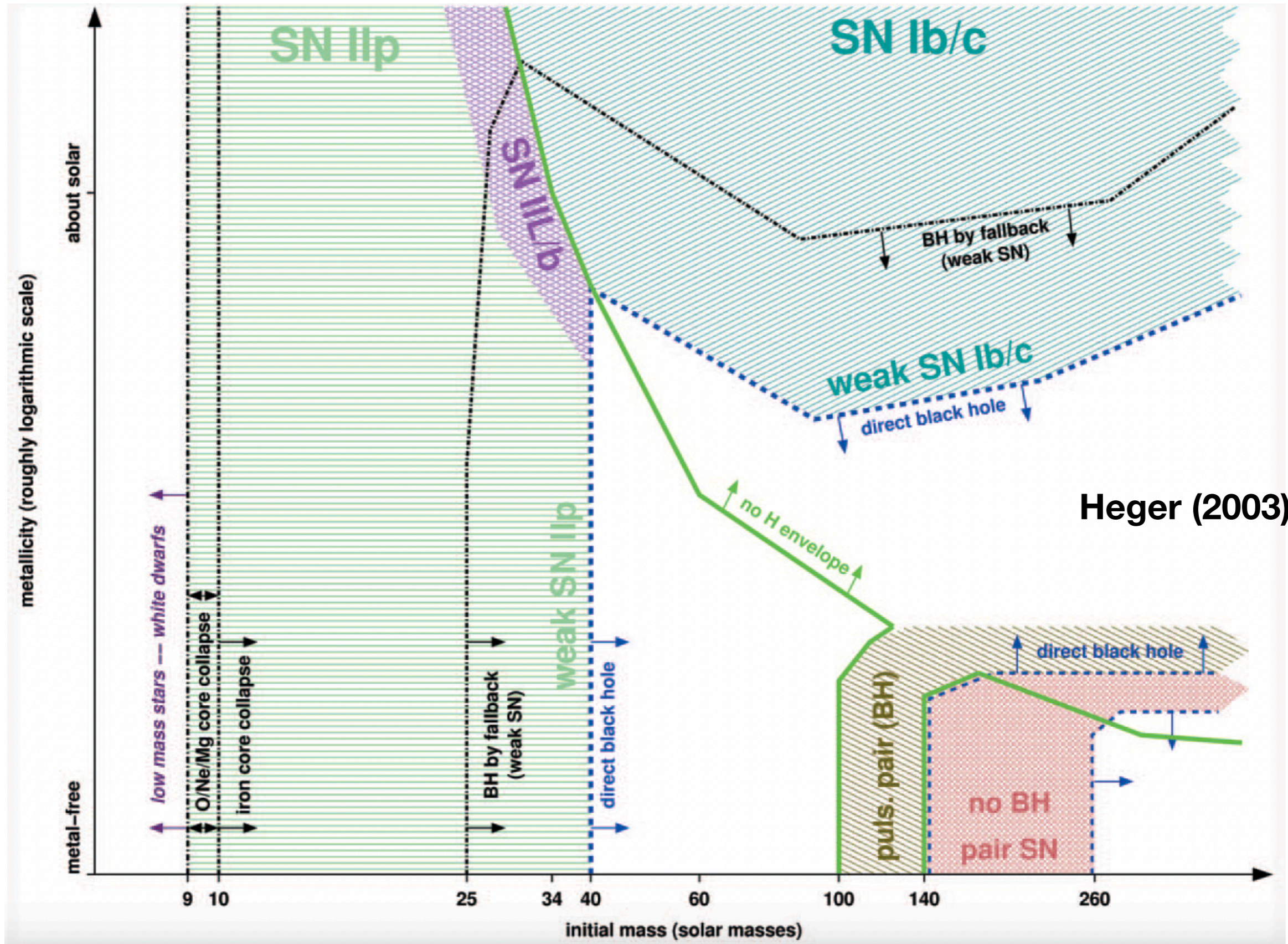


Yusof et al (2022)

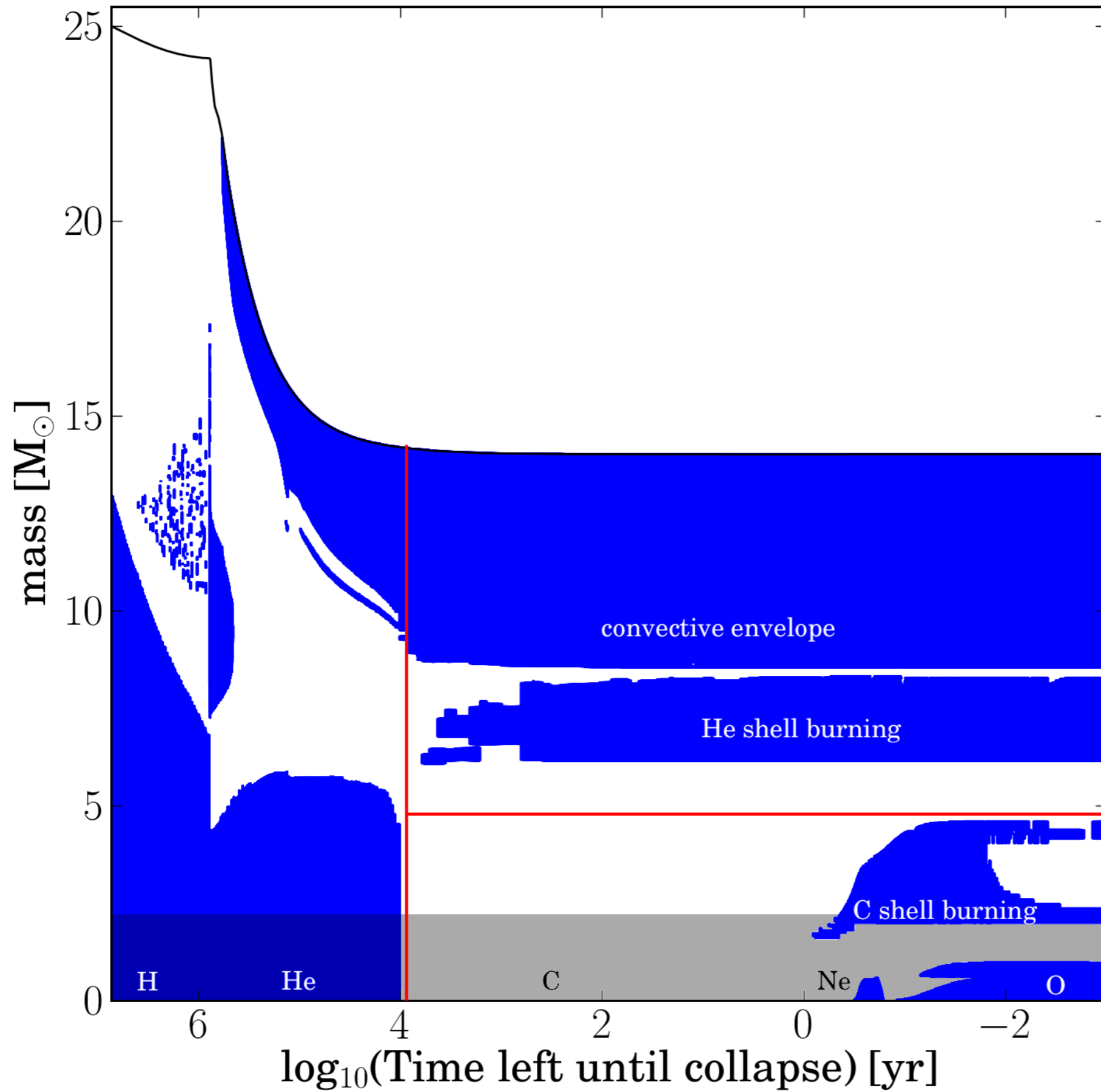
# Change of mass loss impact the evolution of MS?



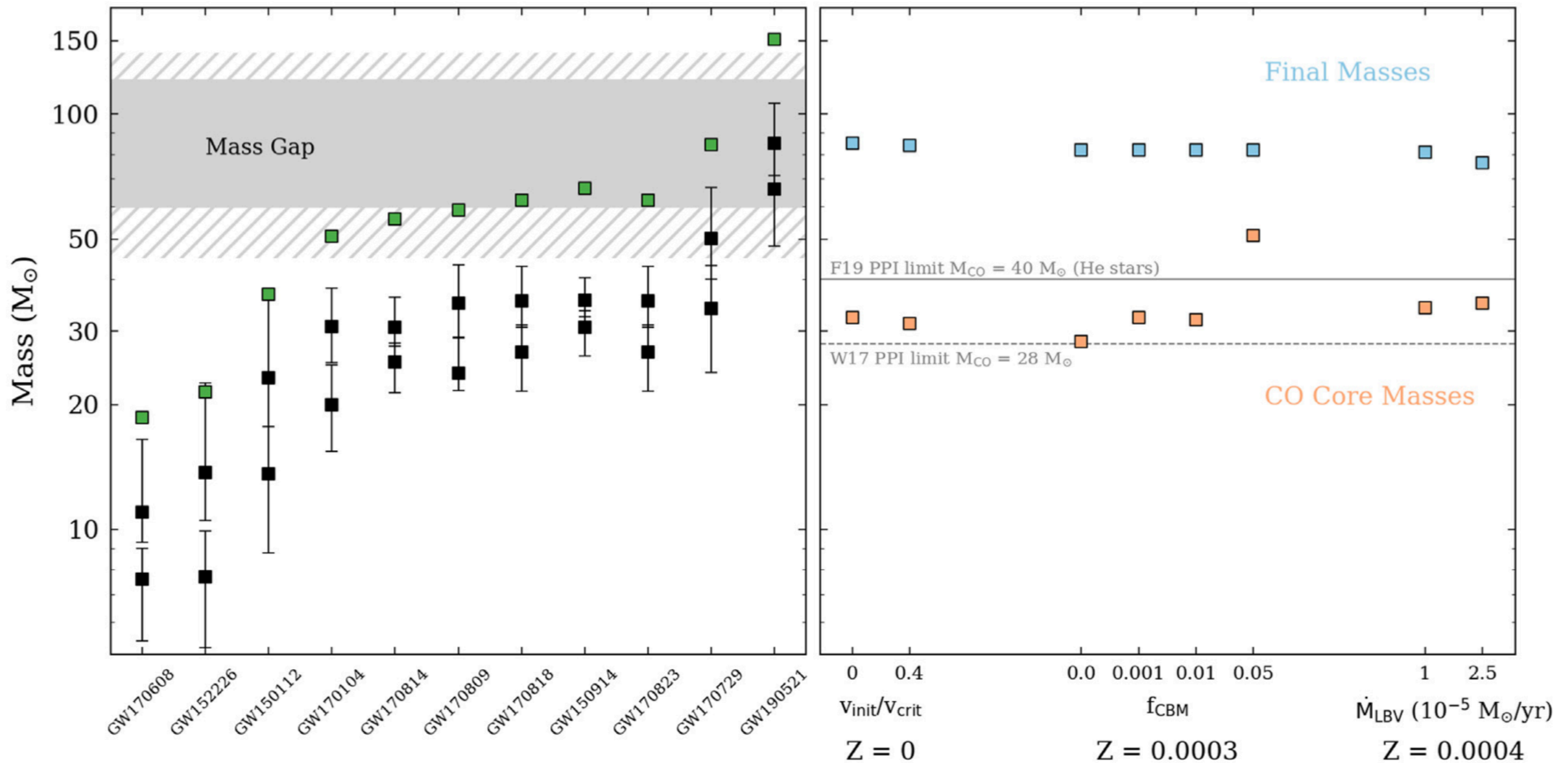
# Fate of MS



$M=25.0 M_{\odot}$ ,  $v_{\text{ini}}/v_{\text{crit}}=0.0$ ,  $Z=0.014$

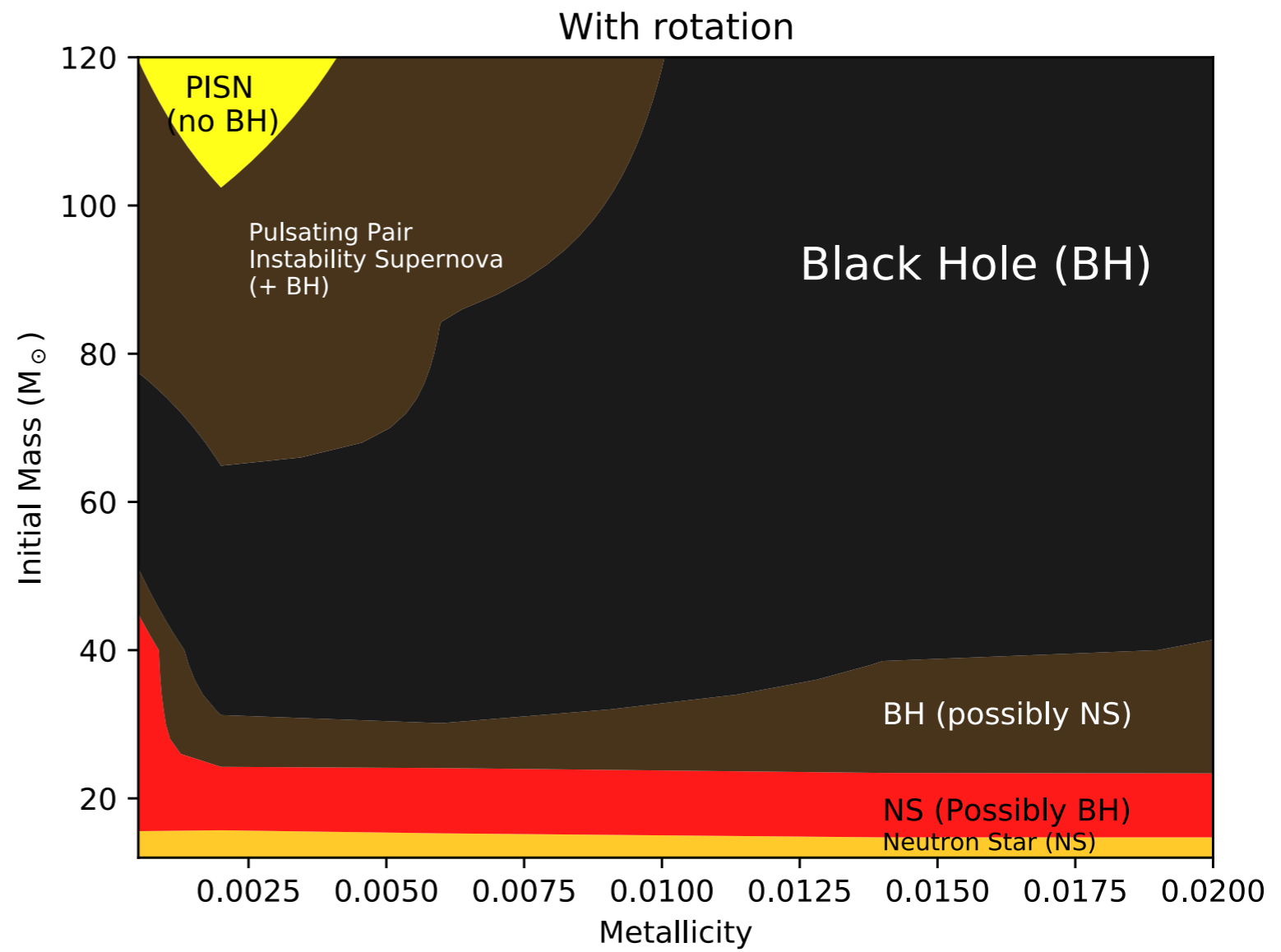
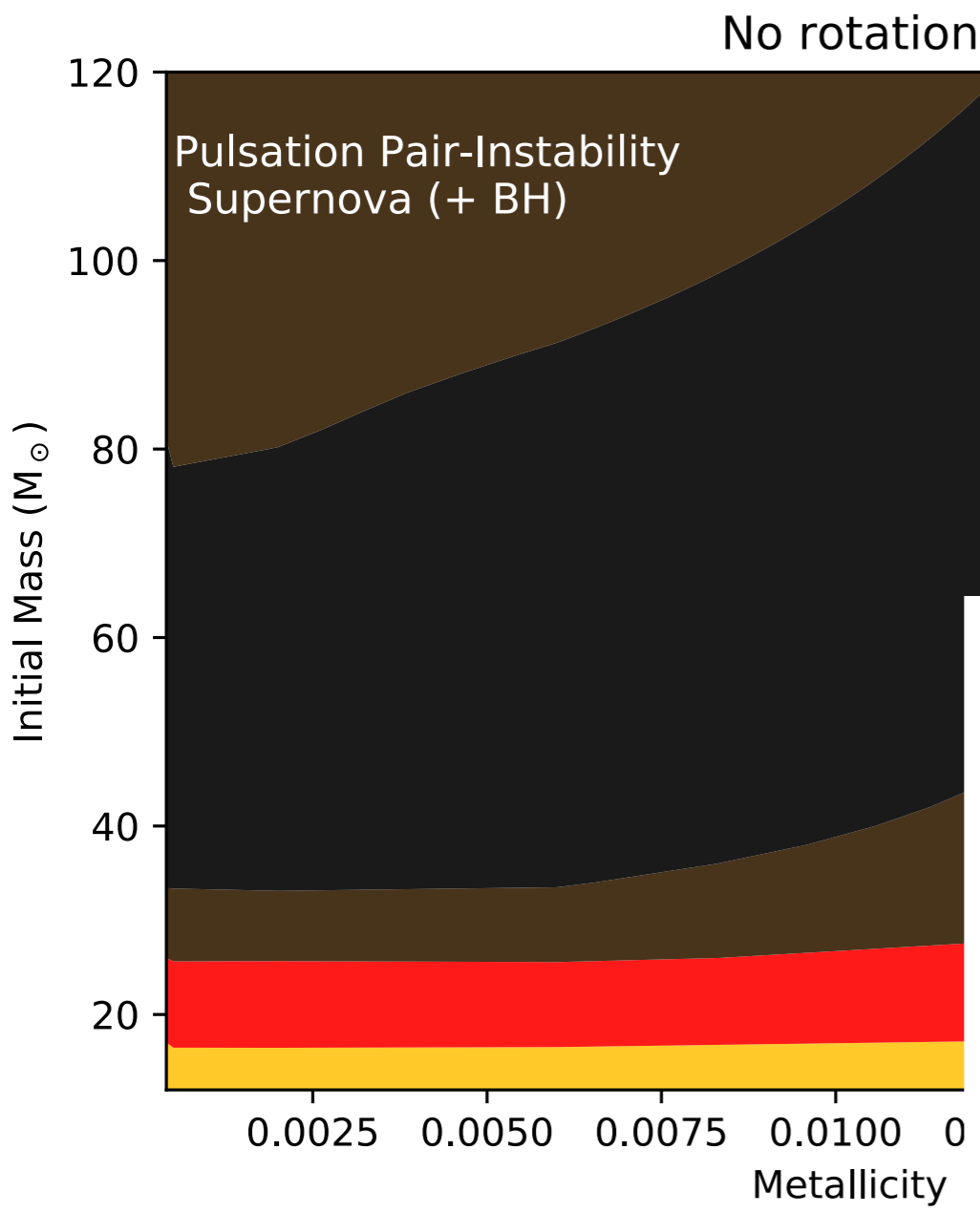


# GW190521 the merger of black holes from the first stellar generations?

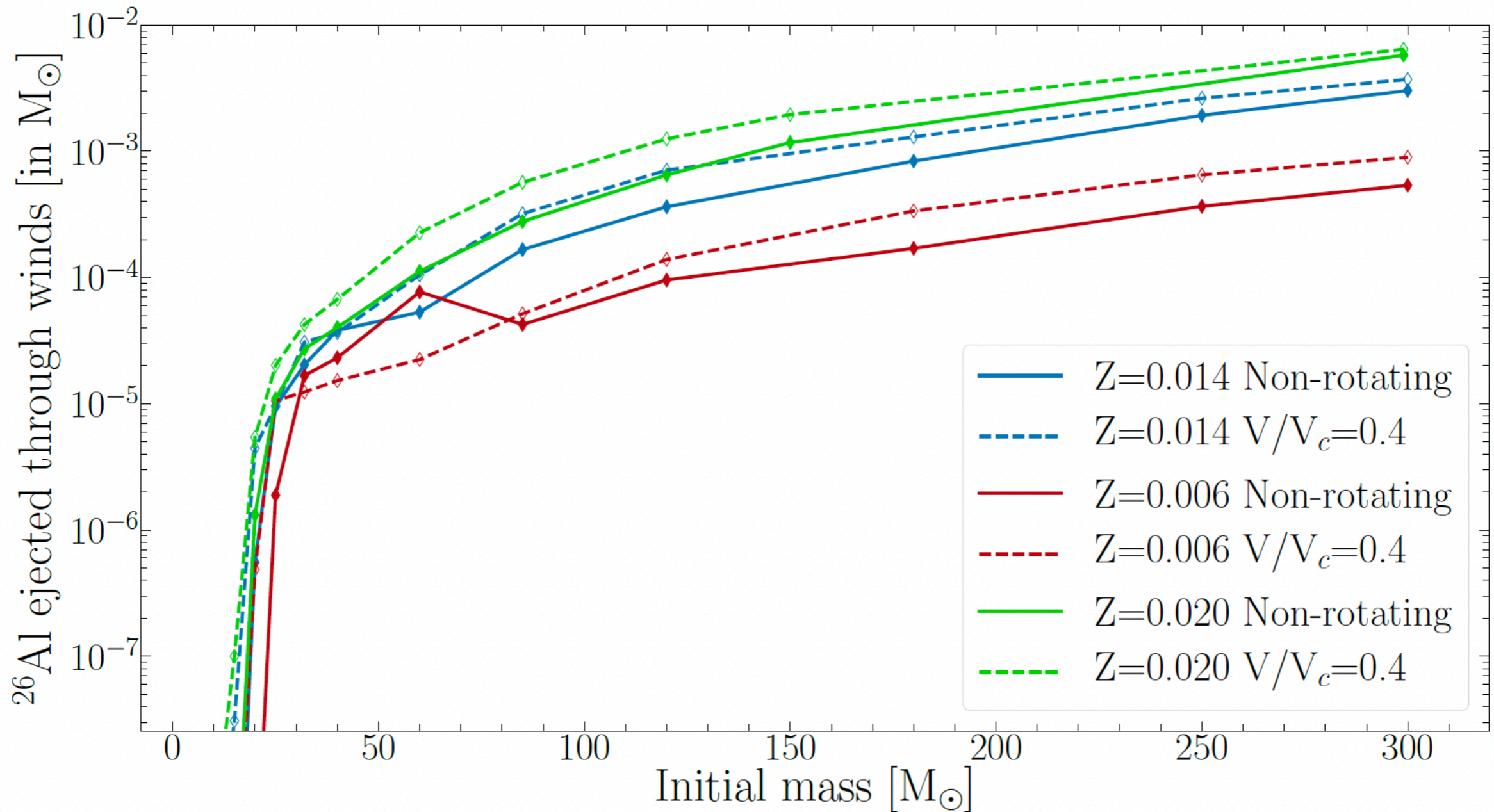


Pre-merger and final BH masses from LIGO/Virgo observations in O1/O2 with GW190521 and the predicted region of the mass gap due to pair-instability.

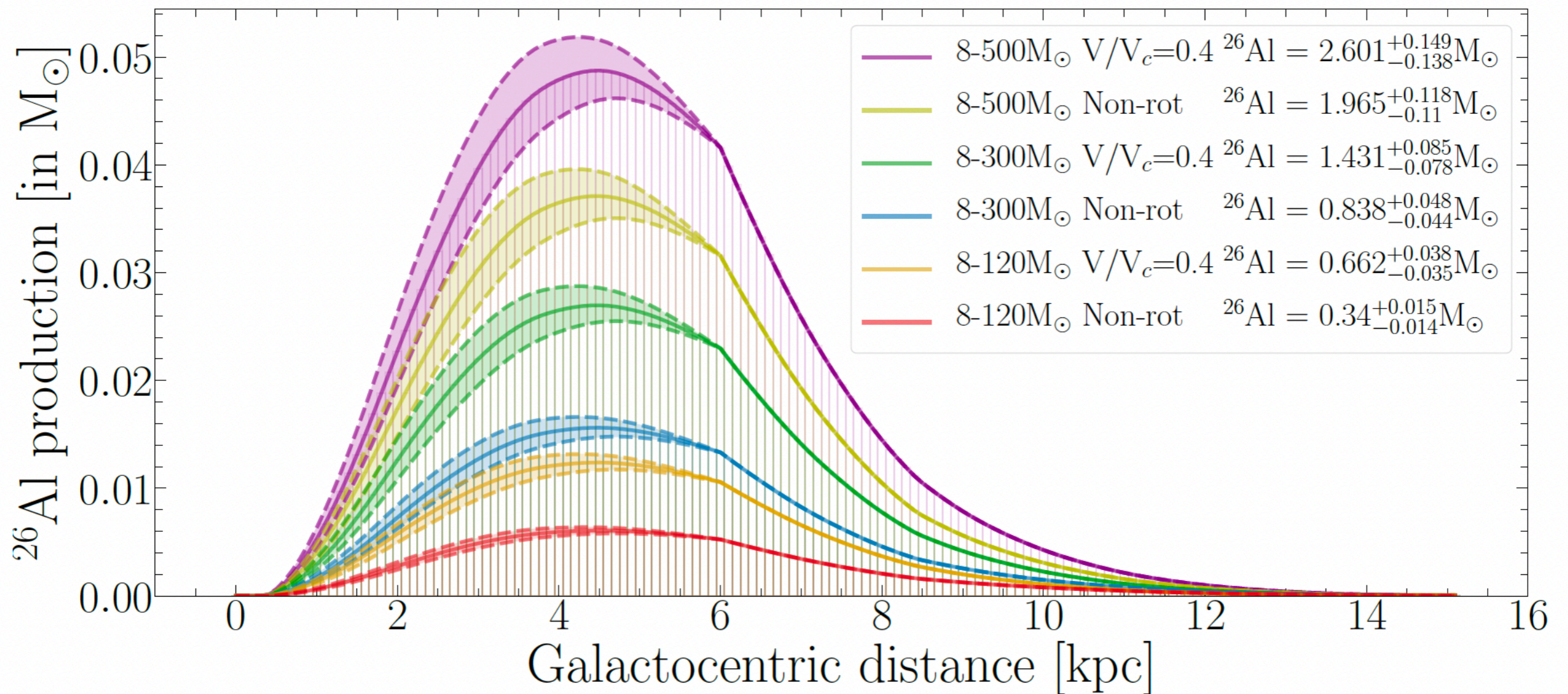
Final masses (blue) and CO core masses (red) of selected 85  $M_{\odot}$  models



# Very massive star winds as sources of the short-lived radioactive isotope $^{26}\text{Al}$



Martinet et al (2022)

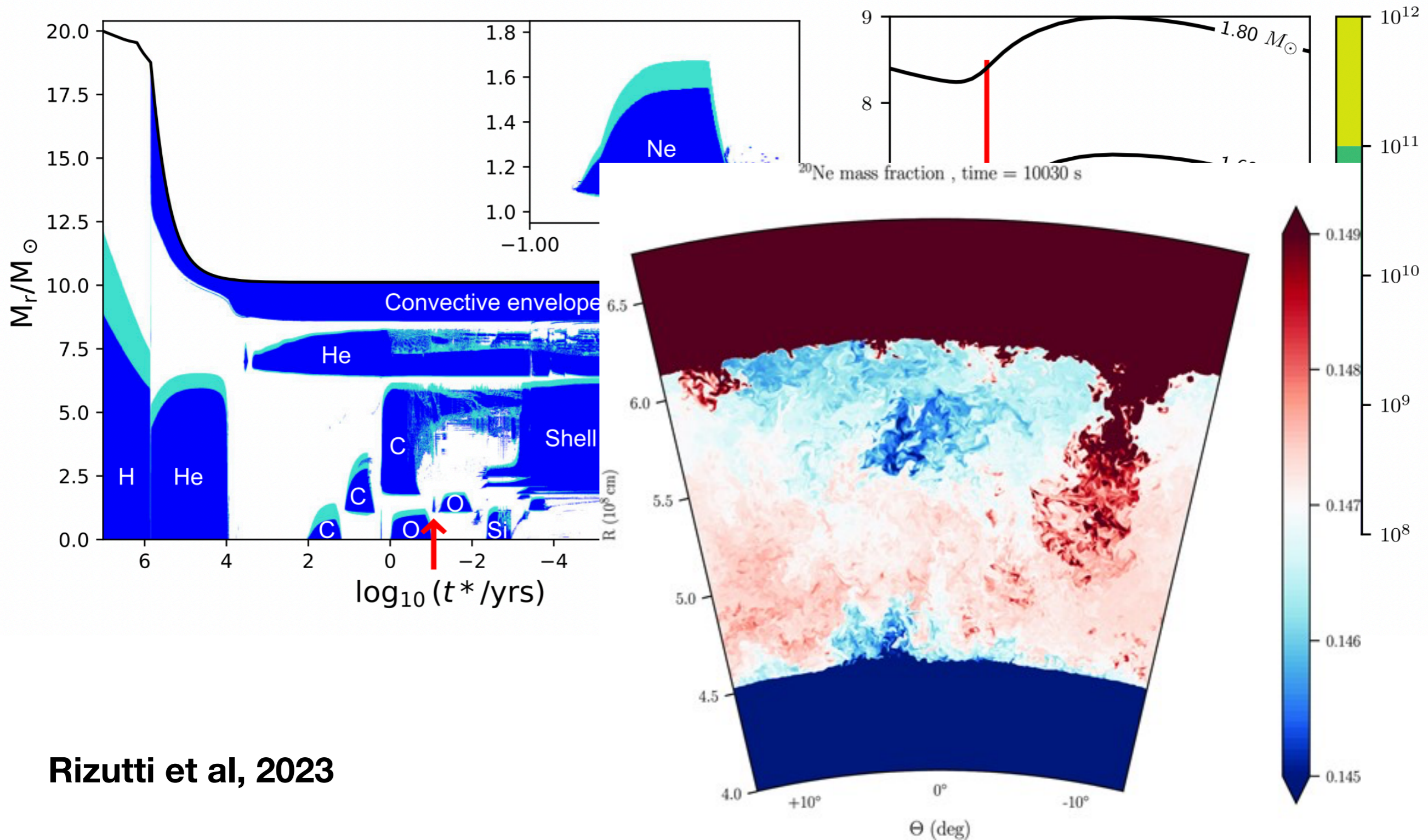


*Rotational mixing is also very significant, as a population of rotating massive stars produces twice the amount of  $^{26}\text{Al}$  as a population of non-rotating stars*

*Initial mass increases the mass loss and the convective core size for VMS. This means that increasing the upper mass limit for VMS (e.g., 300–500  $M_{\odot}$ ) would also result in an even larger increase of the  $^{26}\text{Al}$  galactic production*



# 3D Modelling



Rizutti et al, 2023

# SUMMARY & OPEN QUESTIONS

- Many uncertainties in the evolution of massive stars
- More precise/updated physics inputs need from time to time - but does it agree with observations?
- Changes in mass loss prescription → change the fate of the MS
- Is 3D modelling can be the answered to all the uncertainties?

# Database

Welcome on the database for stellar models.

You'll find below the links to the stellar evolution tracks computed by our group.

These tracks come from two distinct codes:

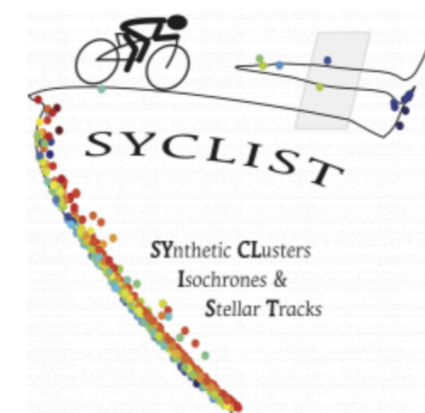
▼ The Geneva Code

All the tracks referenced below are available in our

[interactive tools webpage](#)

Tracks, isochrones, and spectra can also be downloaded through the link in the references. A description of the electronic tables provided can be found [here](#)

- **GRIDS OF STELLAR MODELS WITH ROTATION** [ [tracks](#) ] — [ [isochrones](#) ]
  - *I. Models from 0.8 to 120  $M_{\odot}$  at solar metallicity ( $Z = 0.014$ )*  
Ekström et al. (2012) A&A 537, A146 [ [A&A](#) - [ADS](#) - [arXiv](#) ]
  - *II. Wolf-Rayet populations and supernovae/GRB progenitors at  $Z = 0.014$*   
Georgy et al. (2012) A&A 542, A29 [ [A&A](#) - [ADS](#) - [arXiv](#) ]
  - *III. Models from 0.8 to 120  $M_{\odot}$  at a metallicity  $Z = 0.002$*   
Georgy et al. (2013) A&A 558, A103 [ [A&A](#) - [ADS](#) - [arXiv](#) ]
  - *IV. Models from 1.7 to 120  $M_{\odot}$  at a metallicity  $Z = 0.0004$*   
Groh et al. (2019) A&A 627, A24 [ [A&A](#) - [ADS](#) - [arXiv](#) ]
  - *V. Models from 1.7 to 120  $M_{\odot}$  at zero metallicity*  
Murphy et al. (2021) MNRAS 501, 2745 [ [MNRAS](#) - [ADS](#) - [arXiv](#) ]
  - *VI. Models from 0.8 to 120  $M_{\odot}$  at a metallicity  $Z = 0.006$*   
Eggenberger et al. (2021) A&A 652, 137 [ [A&A](#) - [ADS](#) - [arXiv](#) ]
  - *VII: Models from 0.8 to 300  $M_{\odot}$  at supersolar metallicity ( $Z = 0.020$ )*  
Yusof et al. (2022) MNRAS 511, 2814 [ [MNRAS](#) - [ADS](#) - [arXiv](#) ]



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