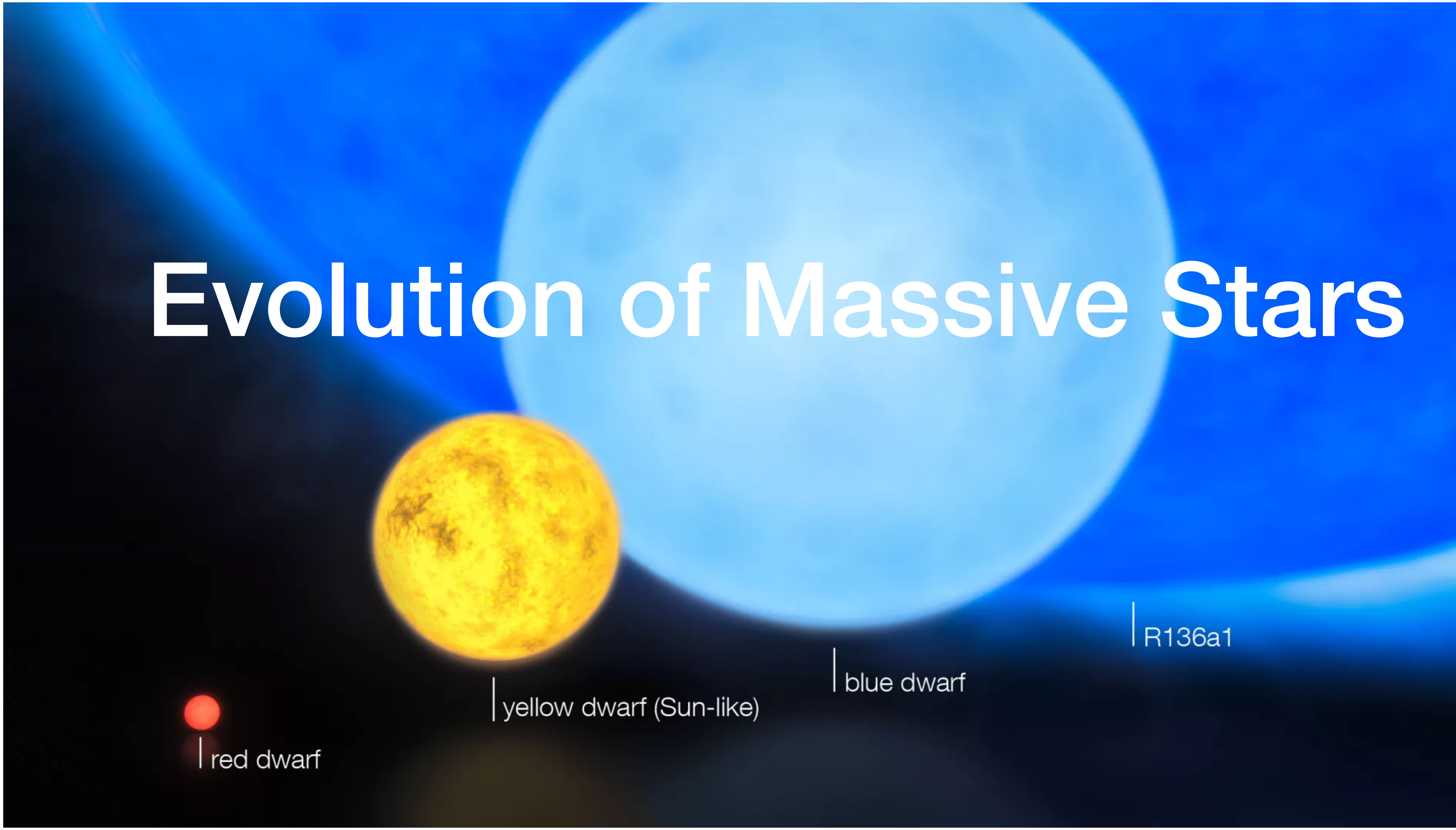
Evolution of Massive Stars



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UNIVERSITÉ DE GENÈVE

BRIEF INTRODUCTION UNIVERSITY OF MALAYA

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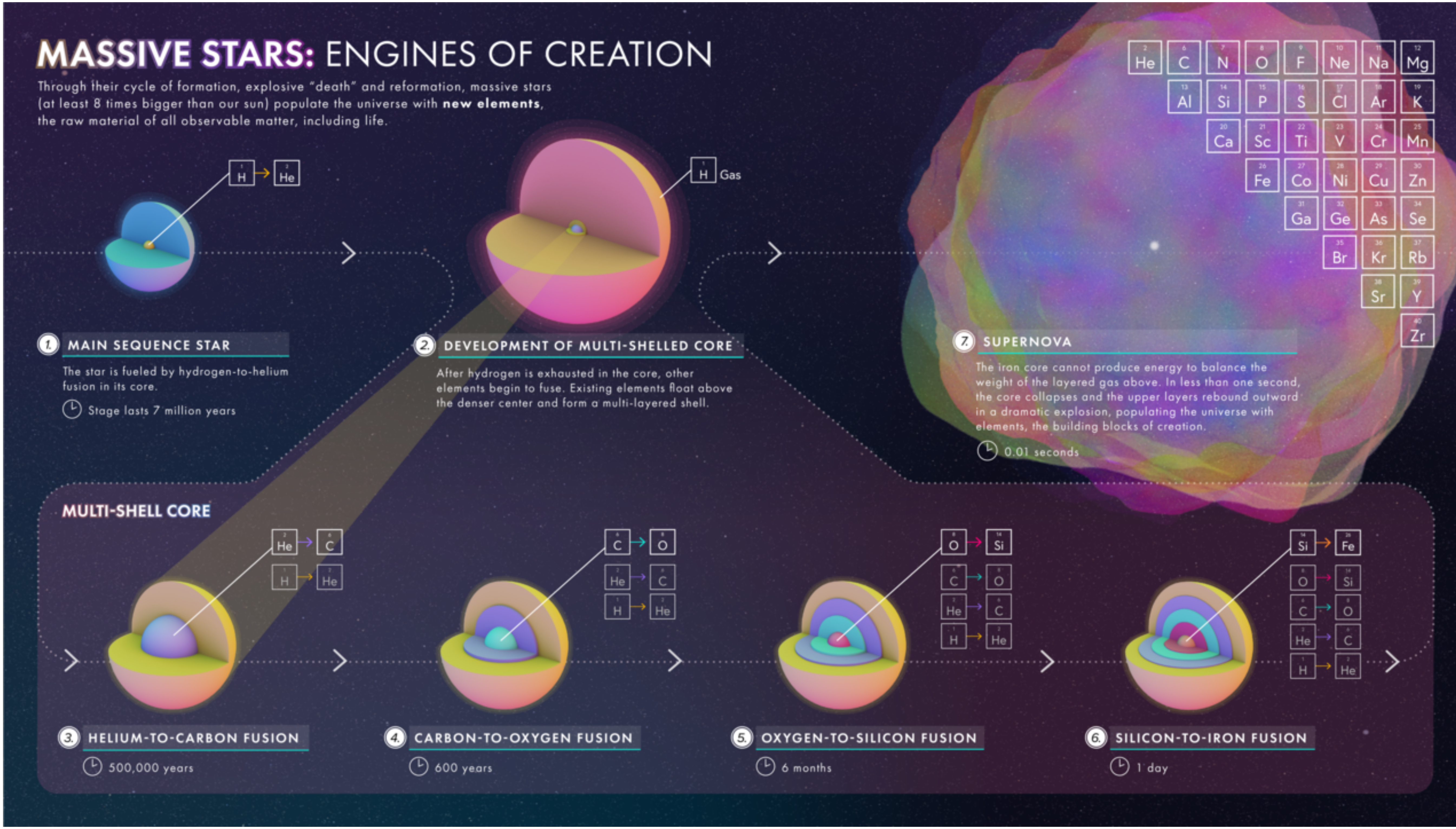
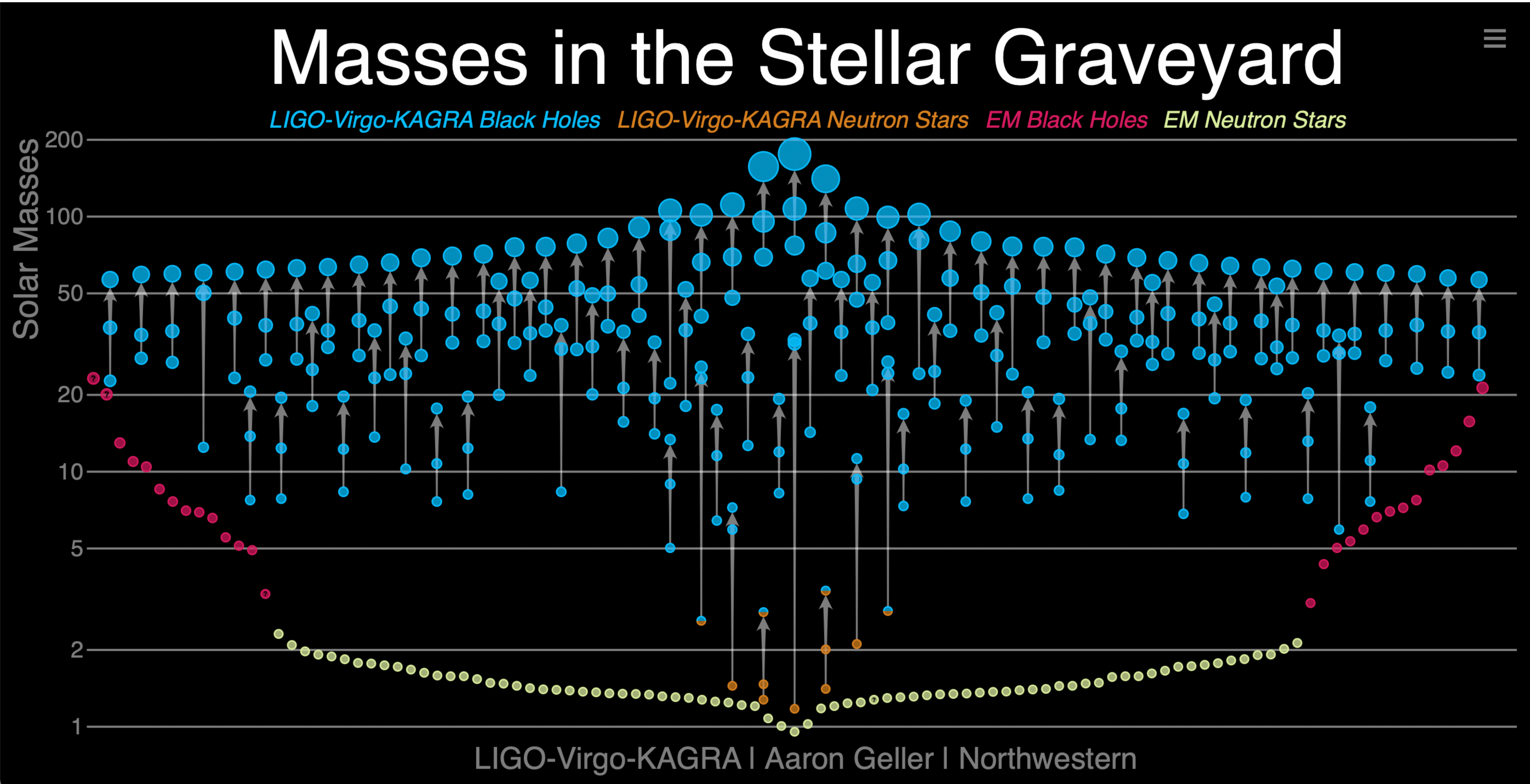
KUALA LUMPUR

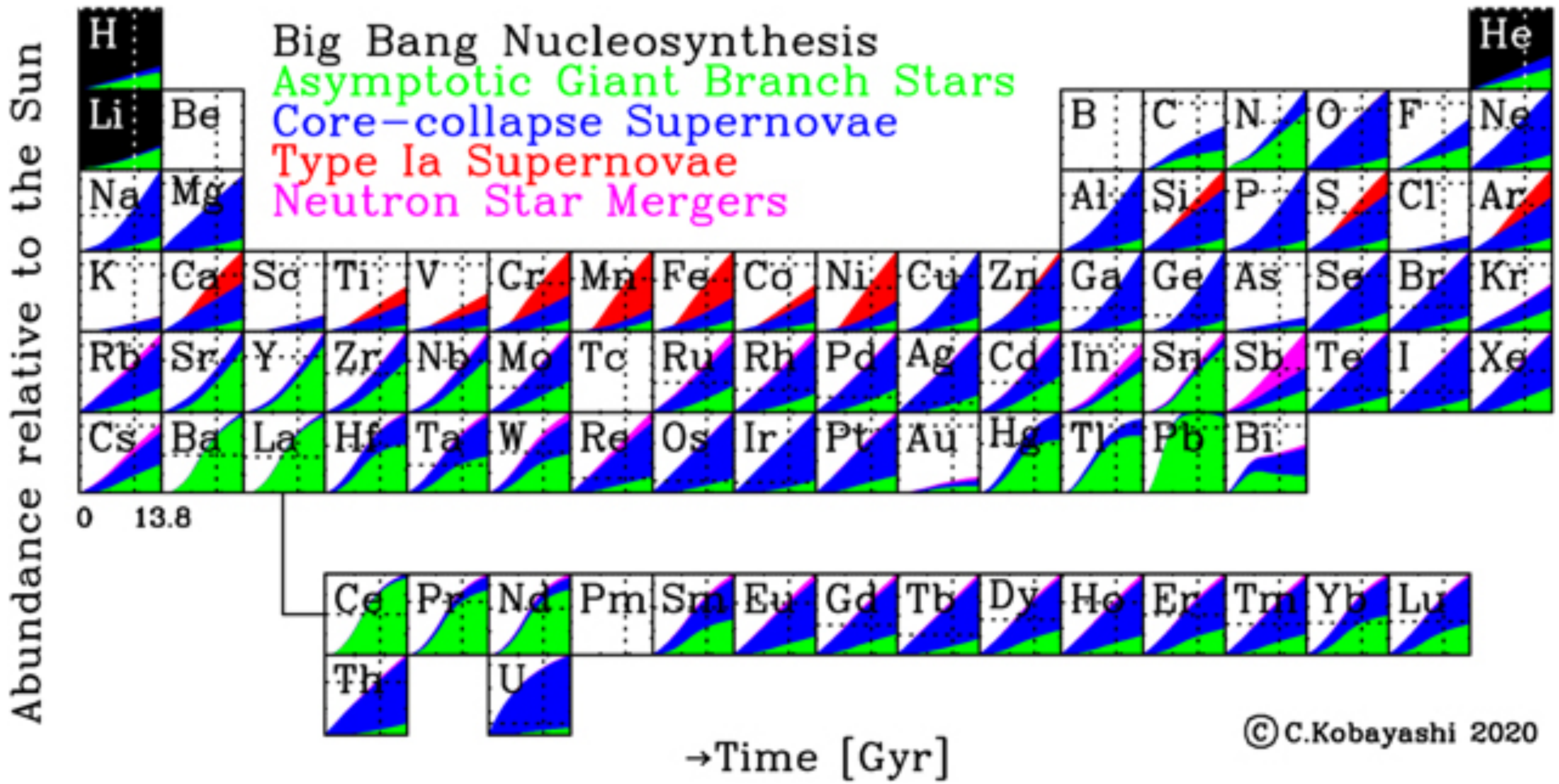


https://hubblesite.org/



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Chemical Enrichment

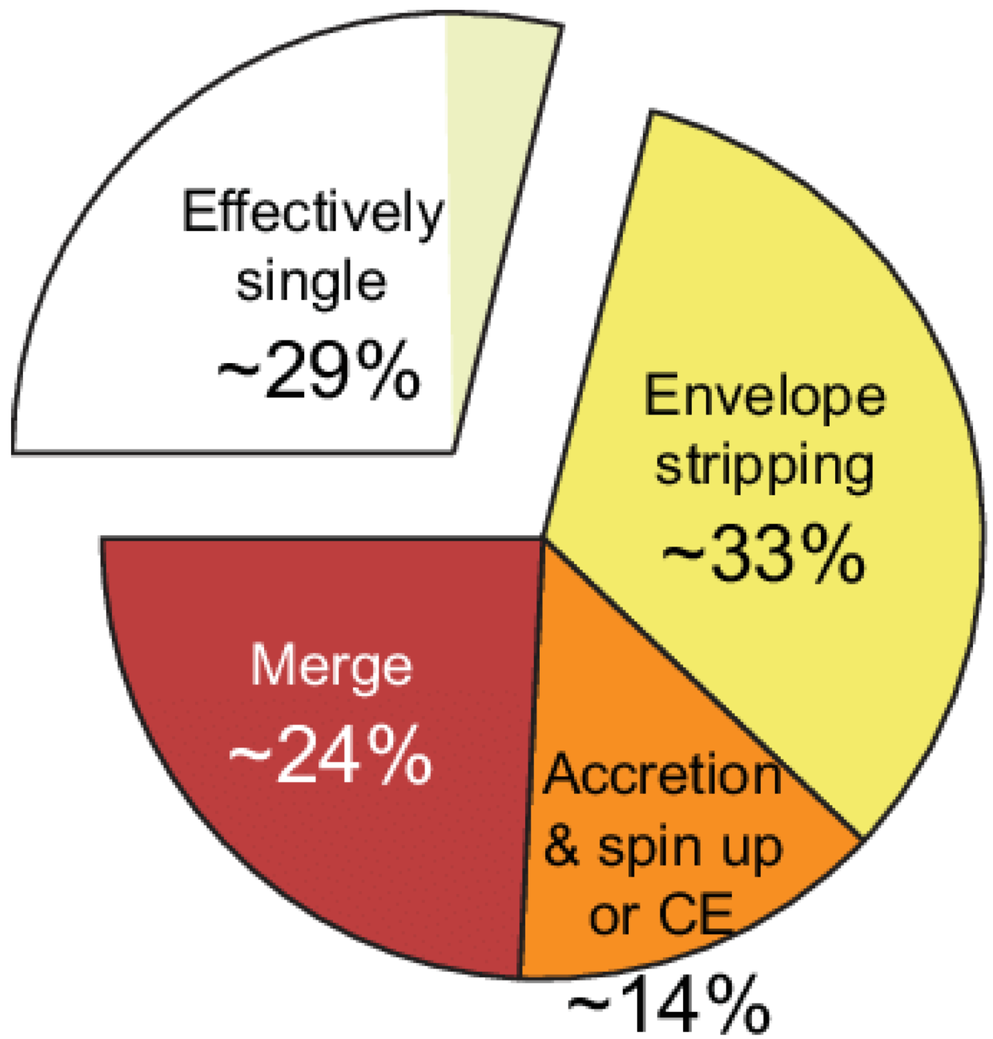


Massive stars : Unresolved problem?

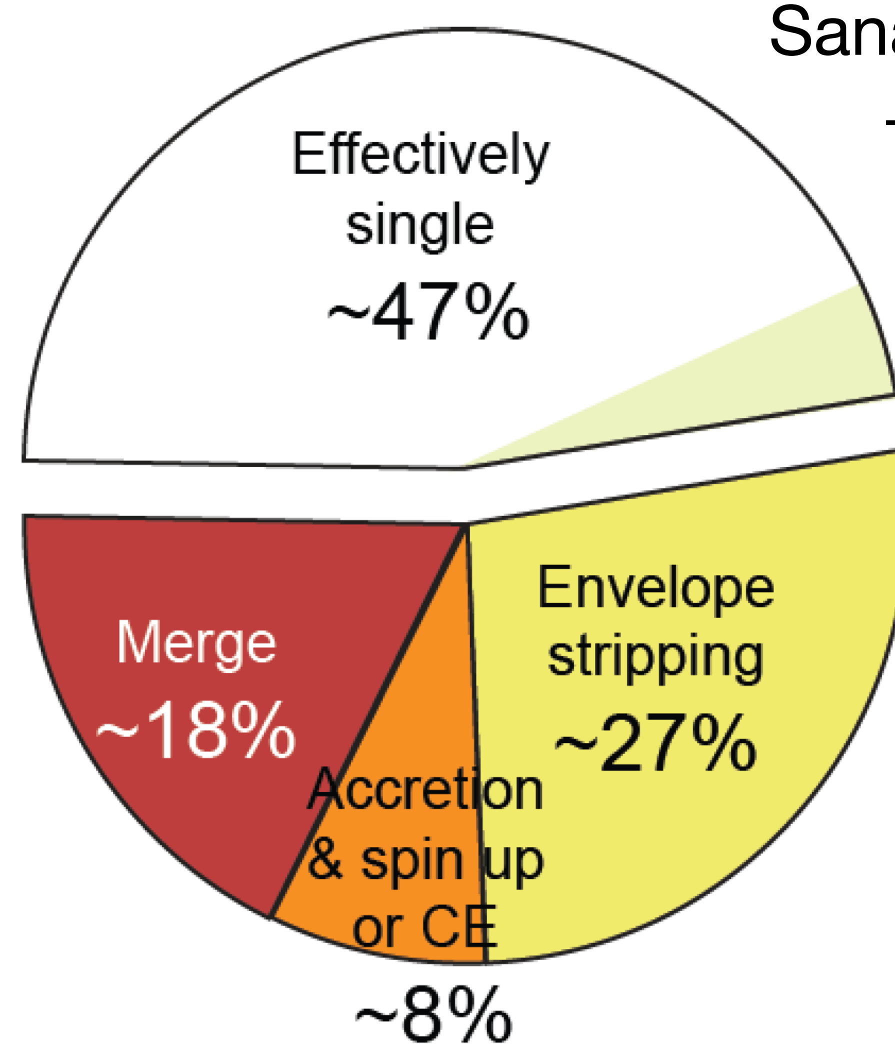
- Poor constrained Internal Physics: overshooting, rotational mixing, convection, magnetic field, nuclear reaction rate?? ….
- Mass loss : Uncertainty in mass loss, clumps in line driven winds
- Multiplicity : large binary fraction, poorly constrained and complex physics (mass transfer, common envelope 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[1]	Geneva[2]	FRANEC[3]	Padova[4]	MESA[5]	STAREVOL[5]
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†	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‡	0.0/**0.1**/0.2
Rotation	0–550 km s^{-1}	$\Omega/\Omega_{crit} = 0.4$	300 km s^{-1}	0	0/200 km s^{-1}	0/220 km s^{-1}
Magnetic field	Spruit-Taylor	no	no	no	no	no
Solar mixture	AGS05[6] with C, N, O, Mg, Si, Fe modified	AGS05 with Ne enhanced (Cunha et al. 2006)	AGSS09[7]	GN93[8]	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). † 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 $l/H_\rho = 1.0$. ‡ In MESA the overshooting is implemented as a decreasing exponential with parameter f (see text).

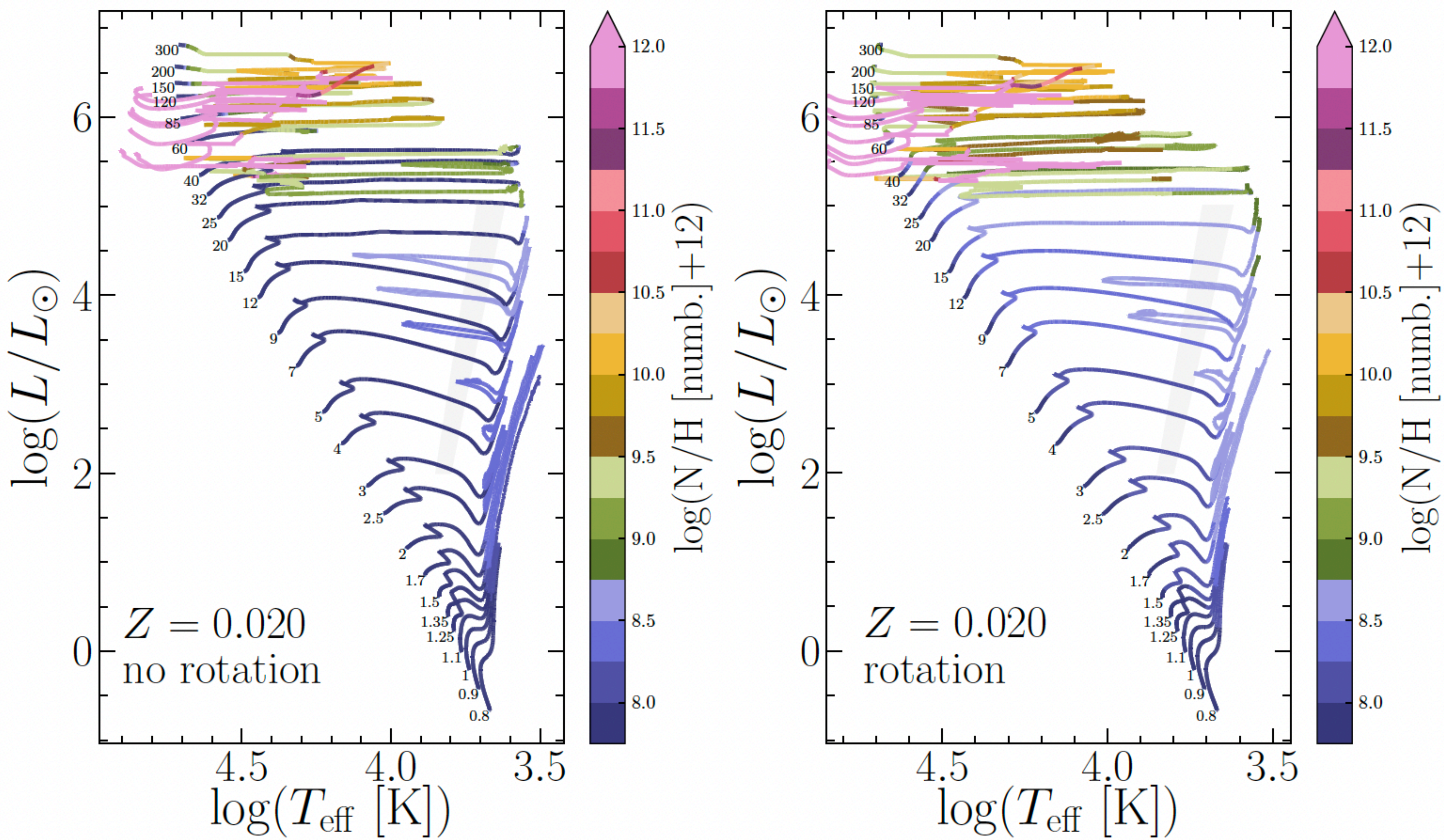
Martins & Palacious (2013)

Code comparison

Stellar model	$Z_\odot$	Hot wind	Cool wind	Wolf–Rayet wind	Convective boundary	α_{MLT}	Overshoot type	α_{ovs}	α_{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[e]	–
BoOST	0.008[a]	Vink et al. (2000, 2001)	Nieuwenhuijzen & de Jager (1990)	Hamann, Koesterke & Wessolowski (1995)[b]	Ledoux (1947)	1.5	Step	0.335	1.0
Geneva	0.014	Vink et al. (2000, 2001)	de Jager et al. (1988)[c]	Nugis & Lamers (2000)	Schwarzschild (1958)	1.6[d]	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[e]	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[e]	–

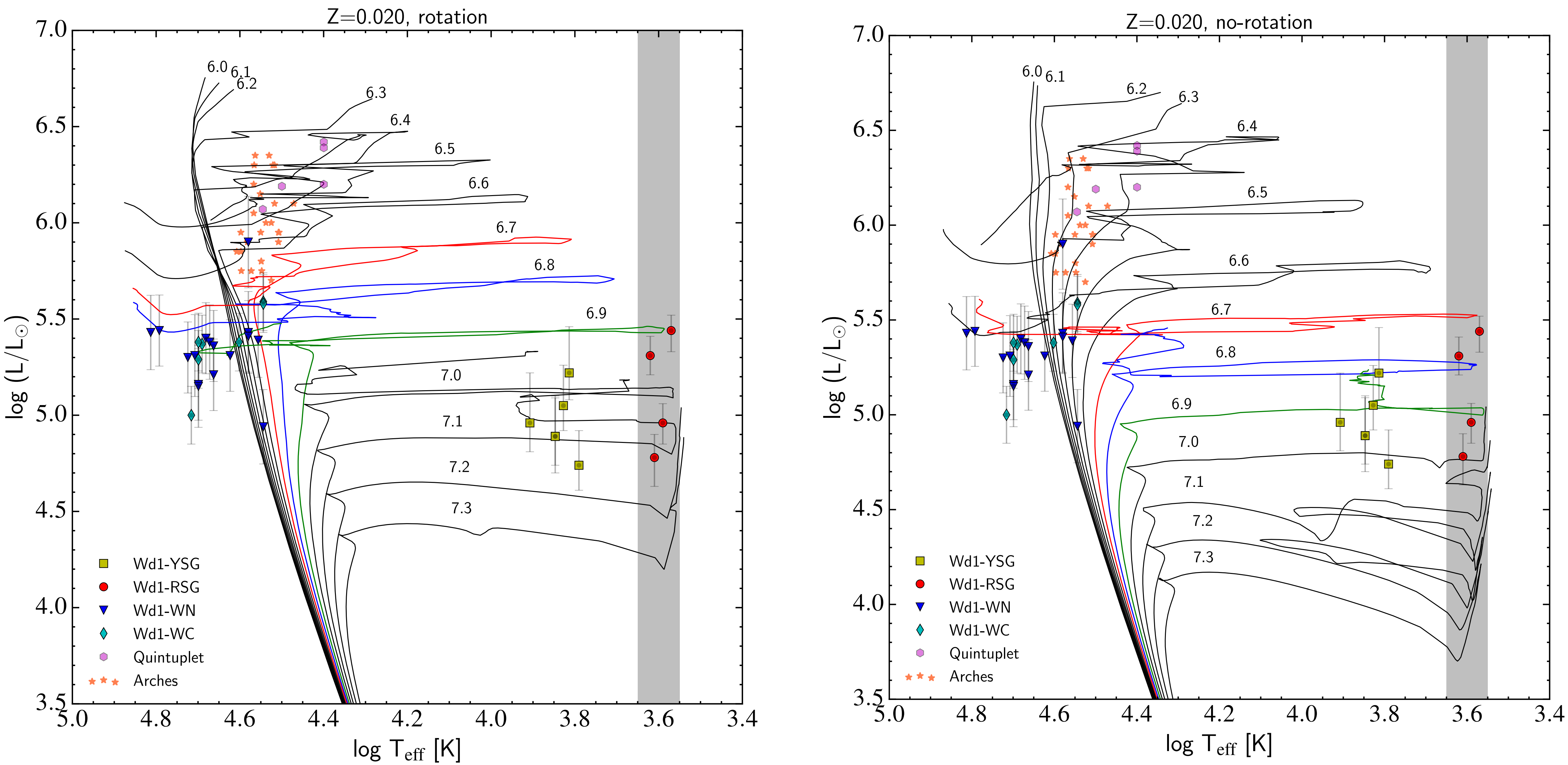
Agrawal+
(2022)

Z = 0.02 (supersolar)



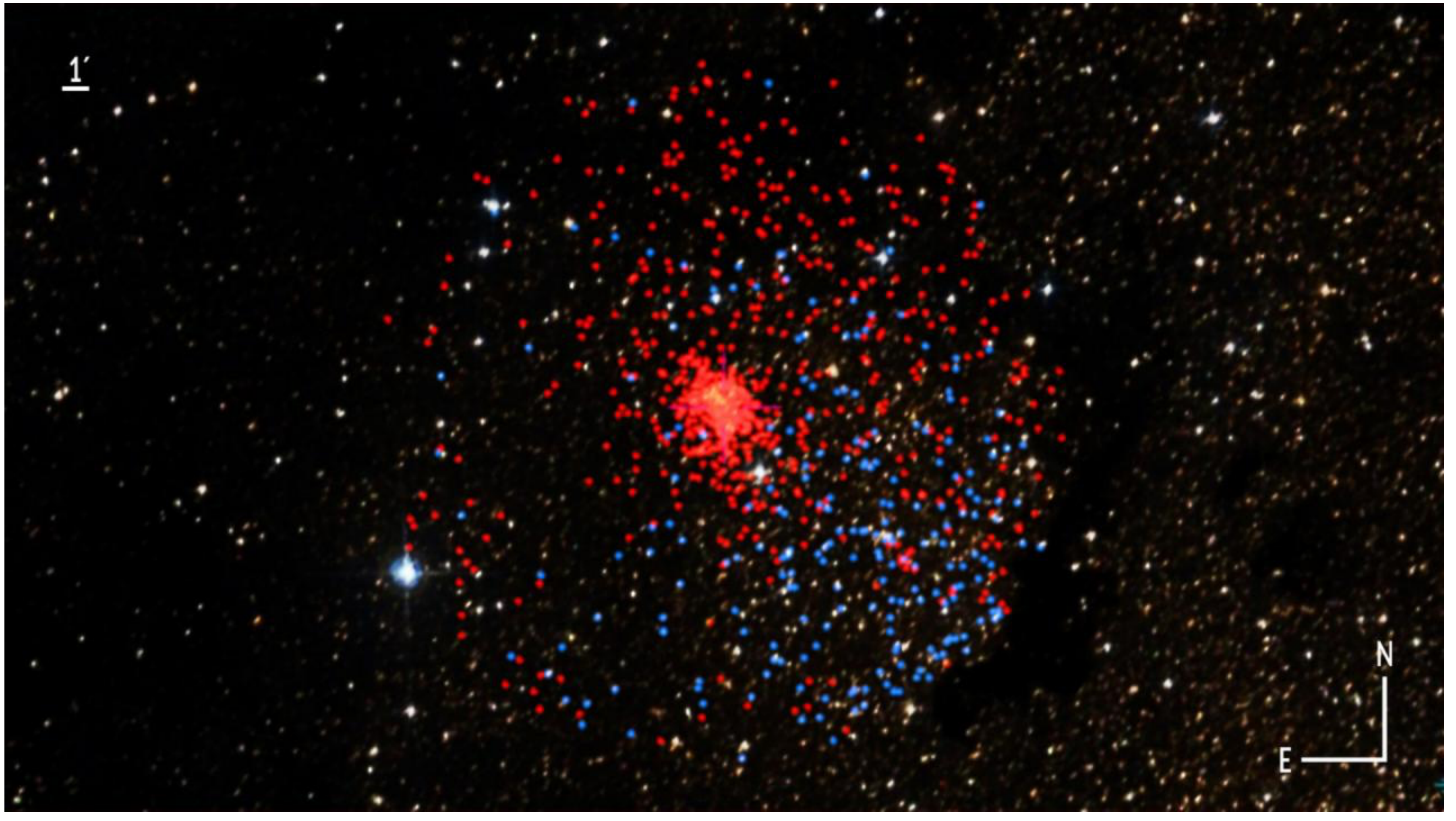
Yusof et al, MNRAS 2022

Isochrones (Z=0.02)



Yusof et al, MNRAS 2022

Young Massive Stars Cluster - Westerlund 1



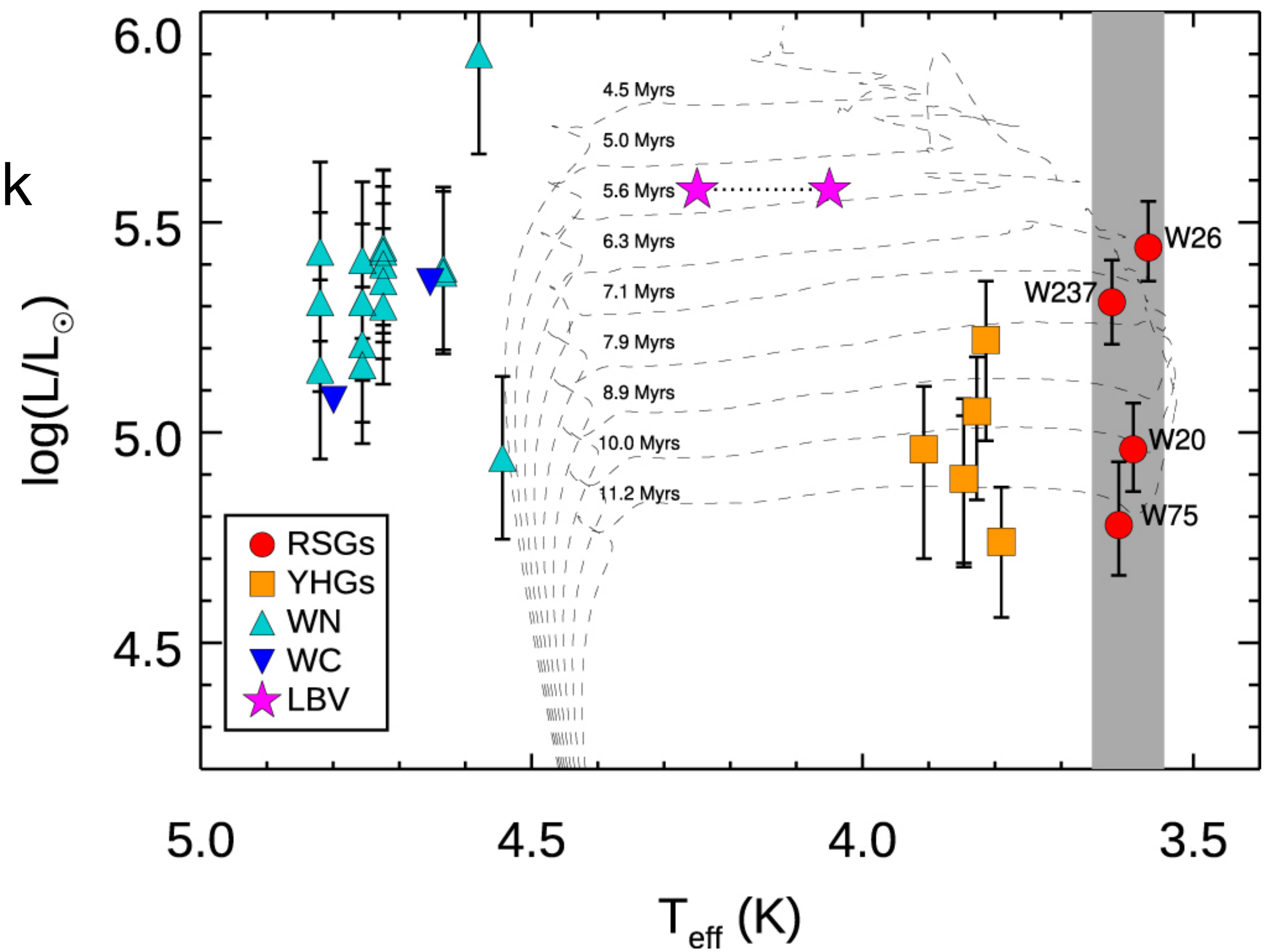
Westerlund -1

Young star cluster in inner Galatic disk

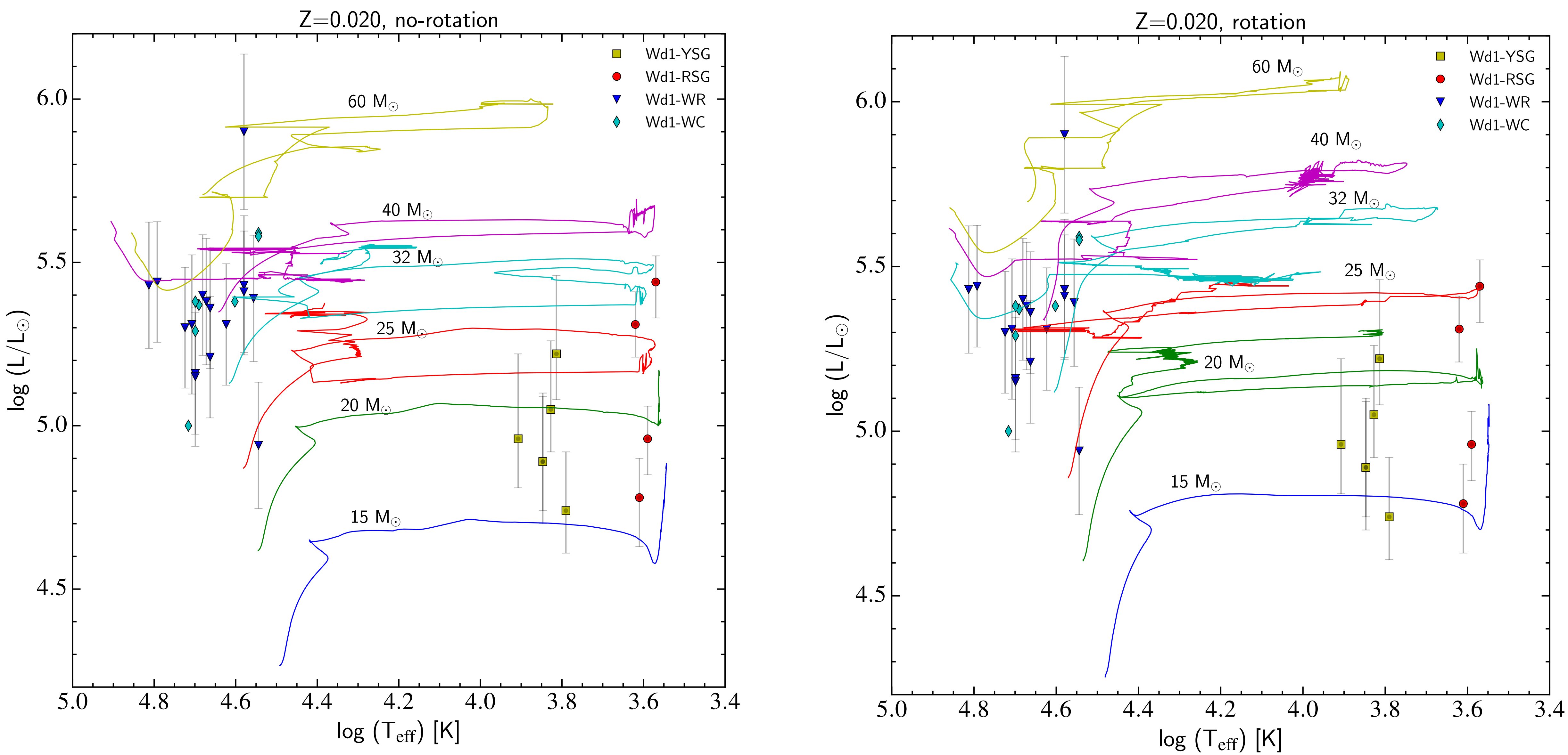
Age ~ 4-5 Myr (Crowther + 2006)

Age ~ 10 Myr (Beasor 2021)

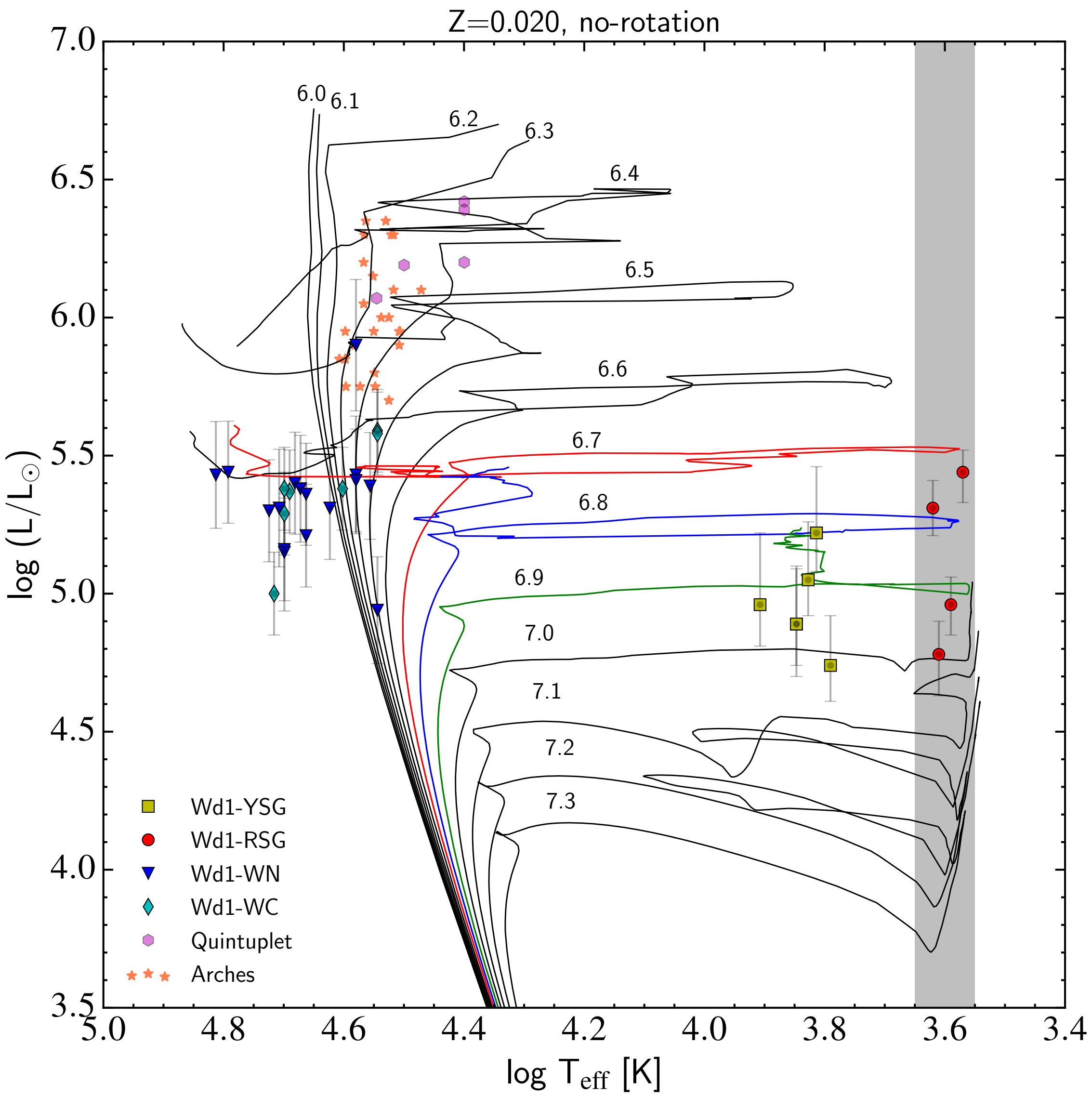
Metallicity is not known???

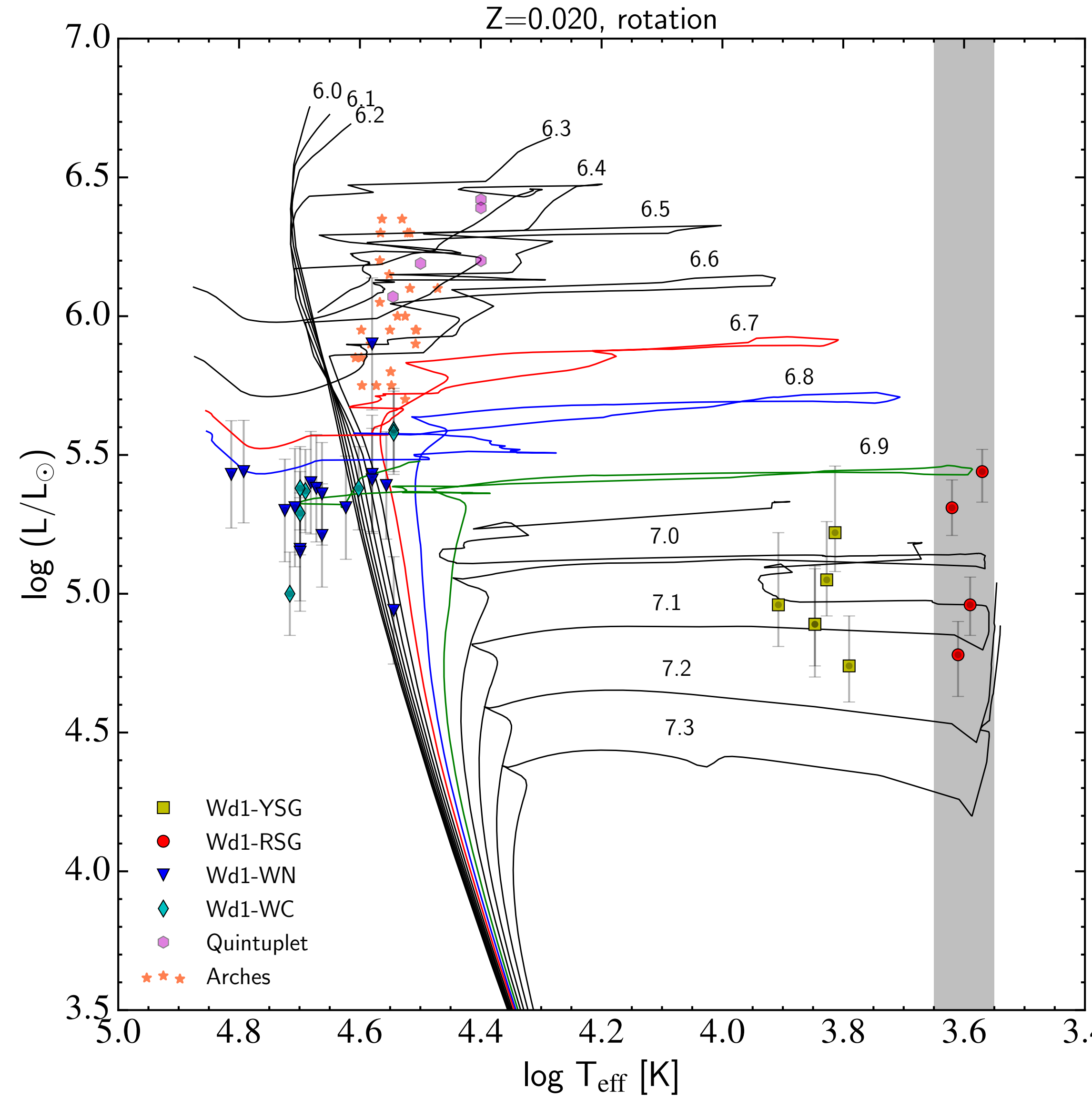


Beasor et al (2021)

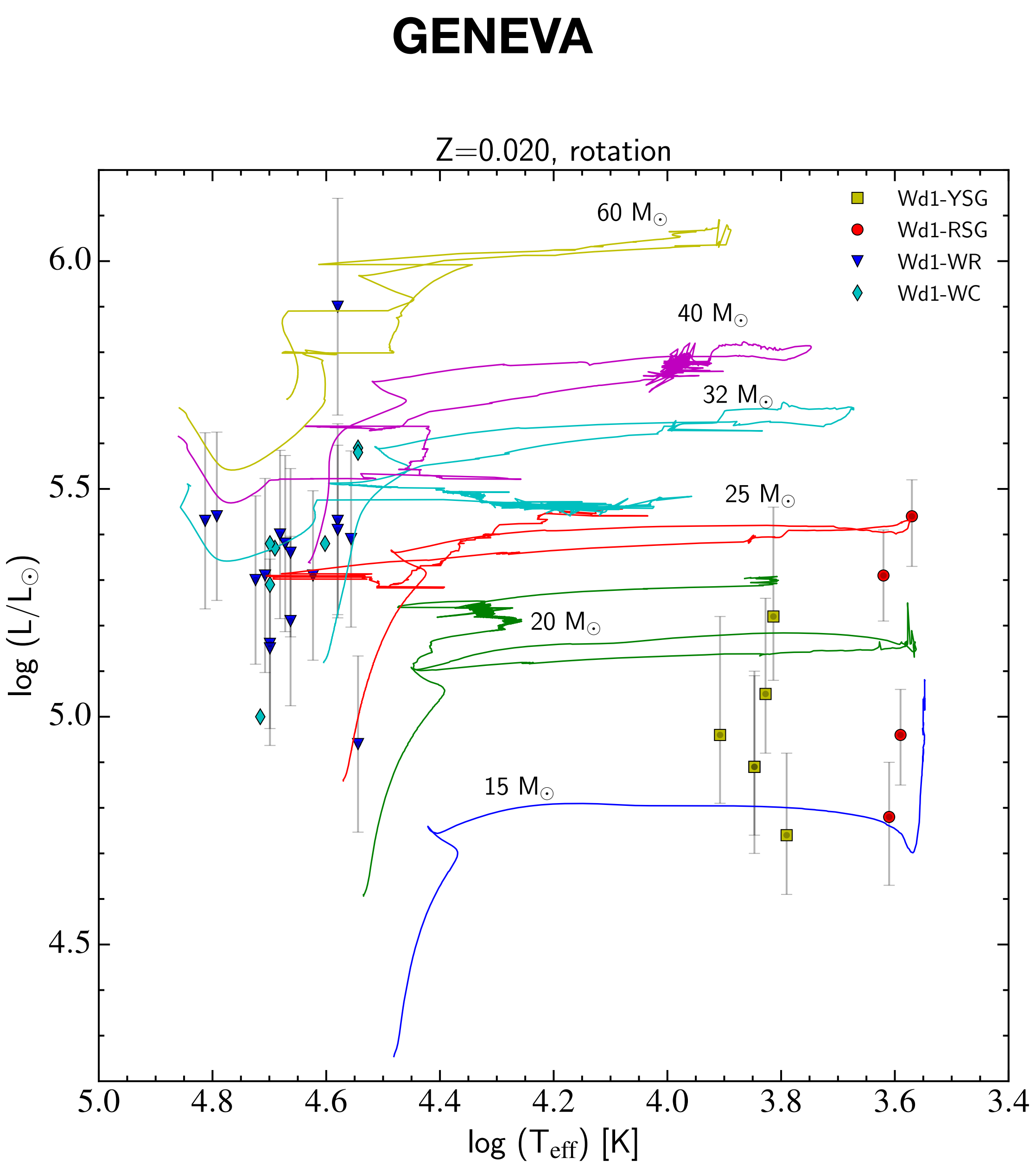


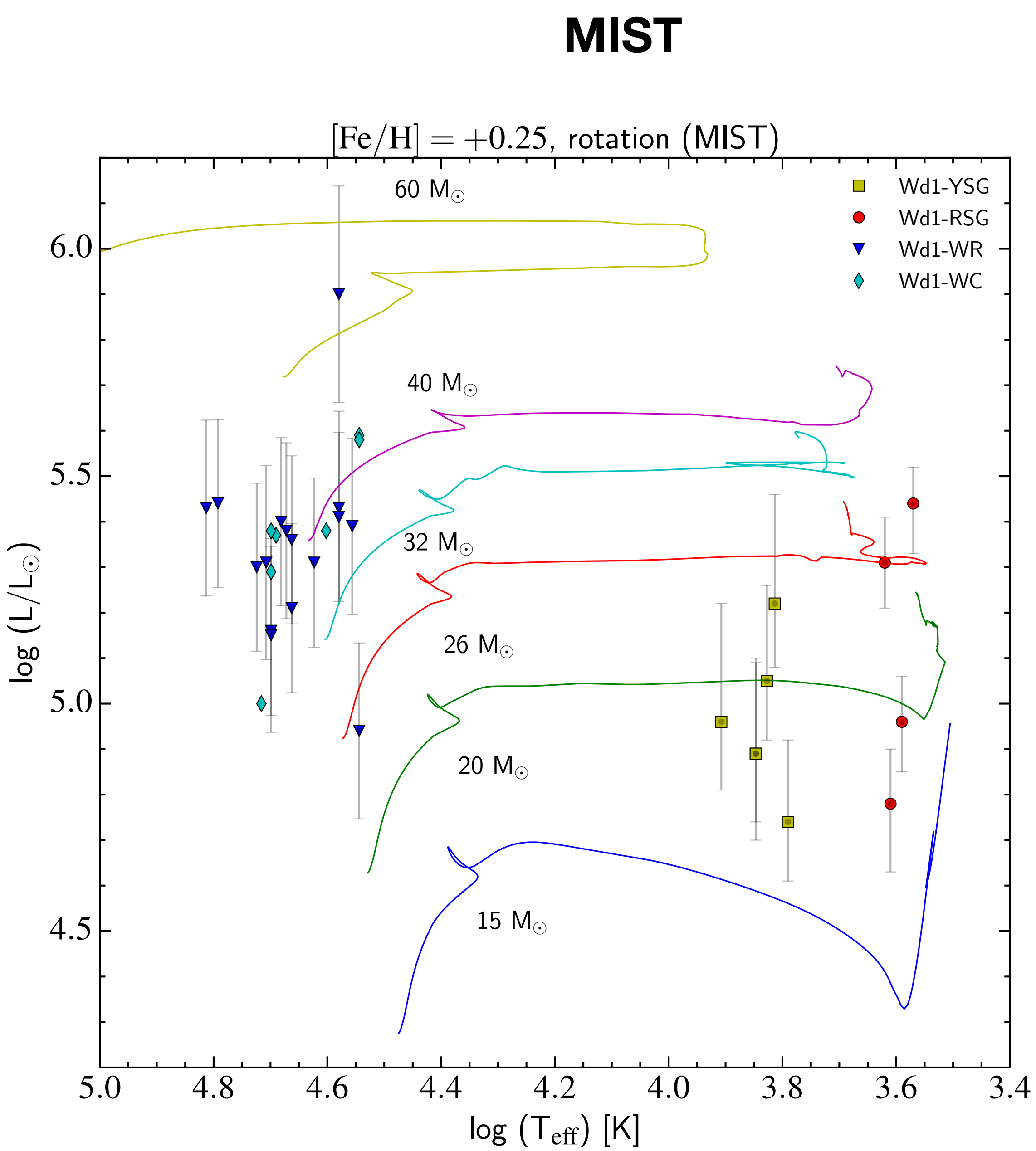
Yusof et al (2022)





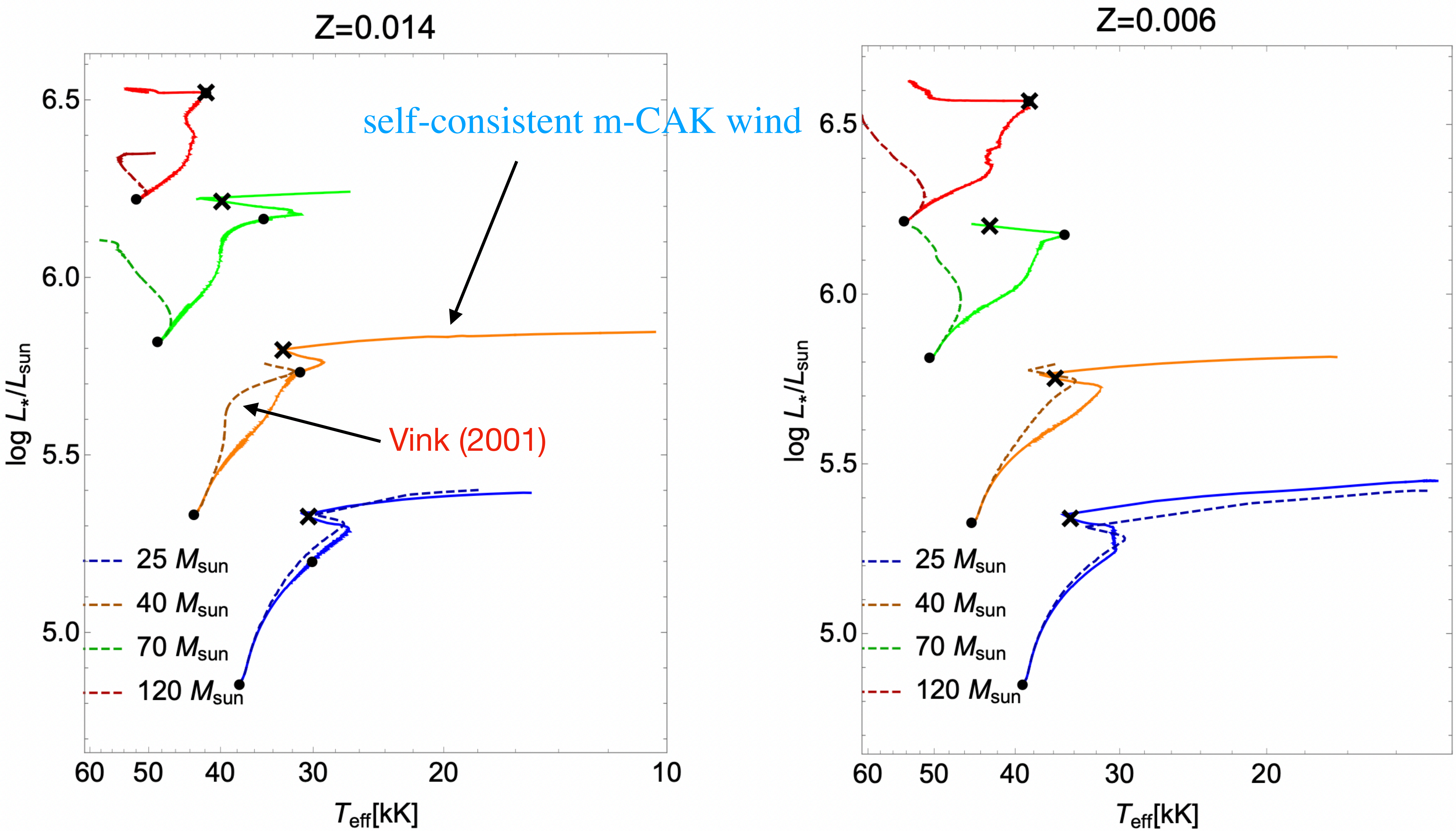
Yusof et al (2022)





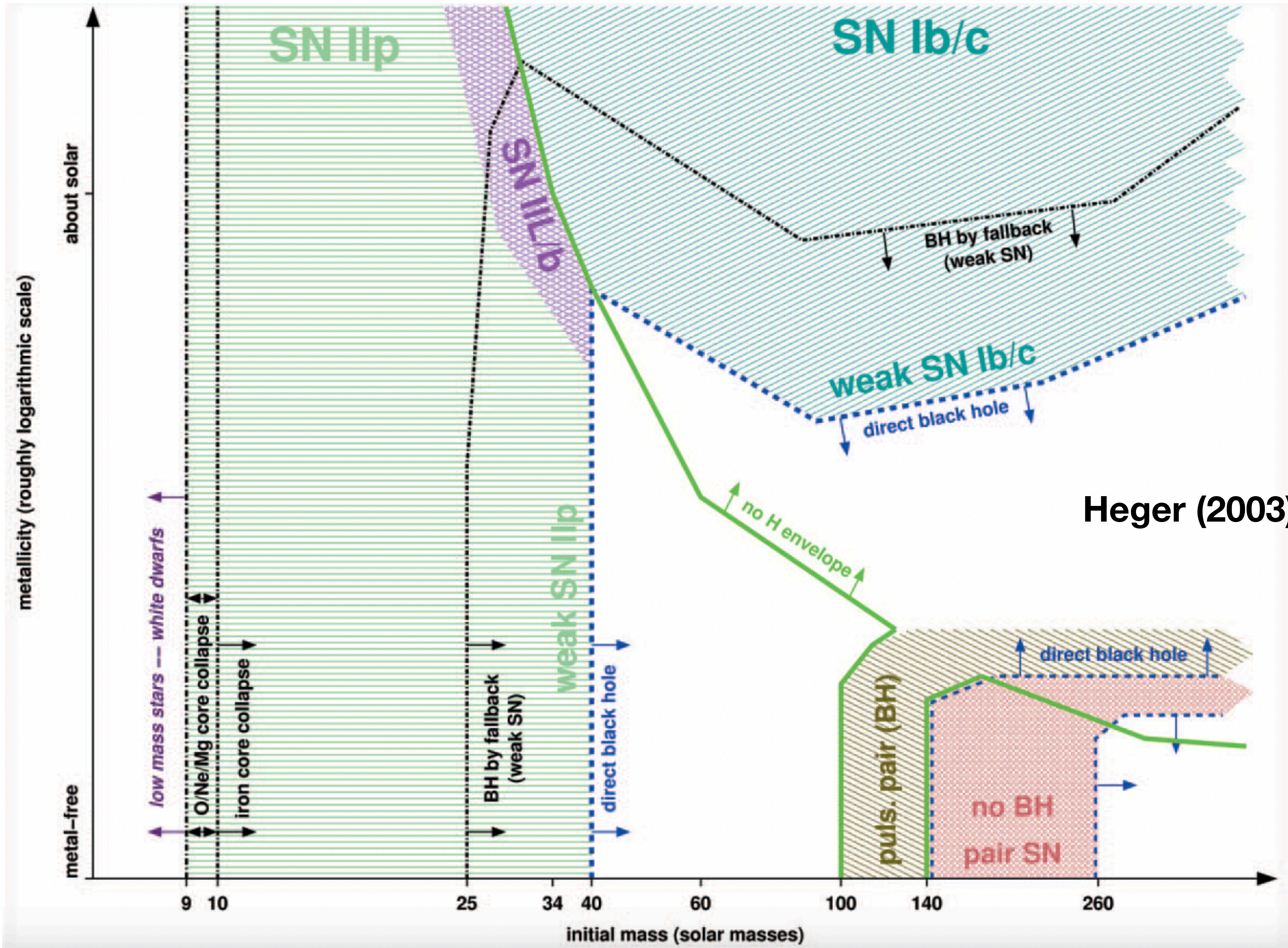
Yusof et al (2022)

Change of mass loss impact the evolution of MS?



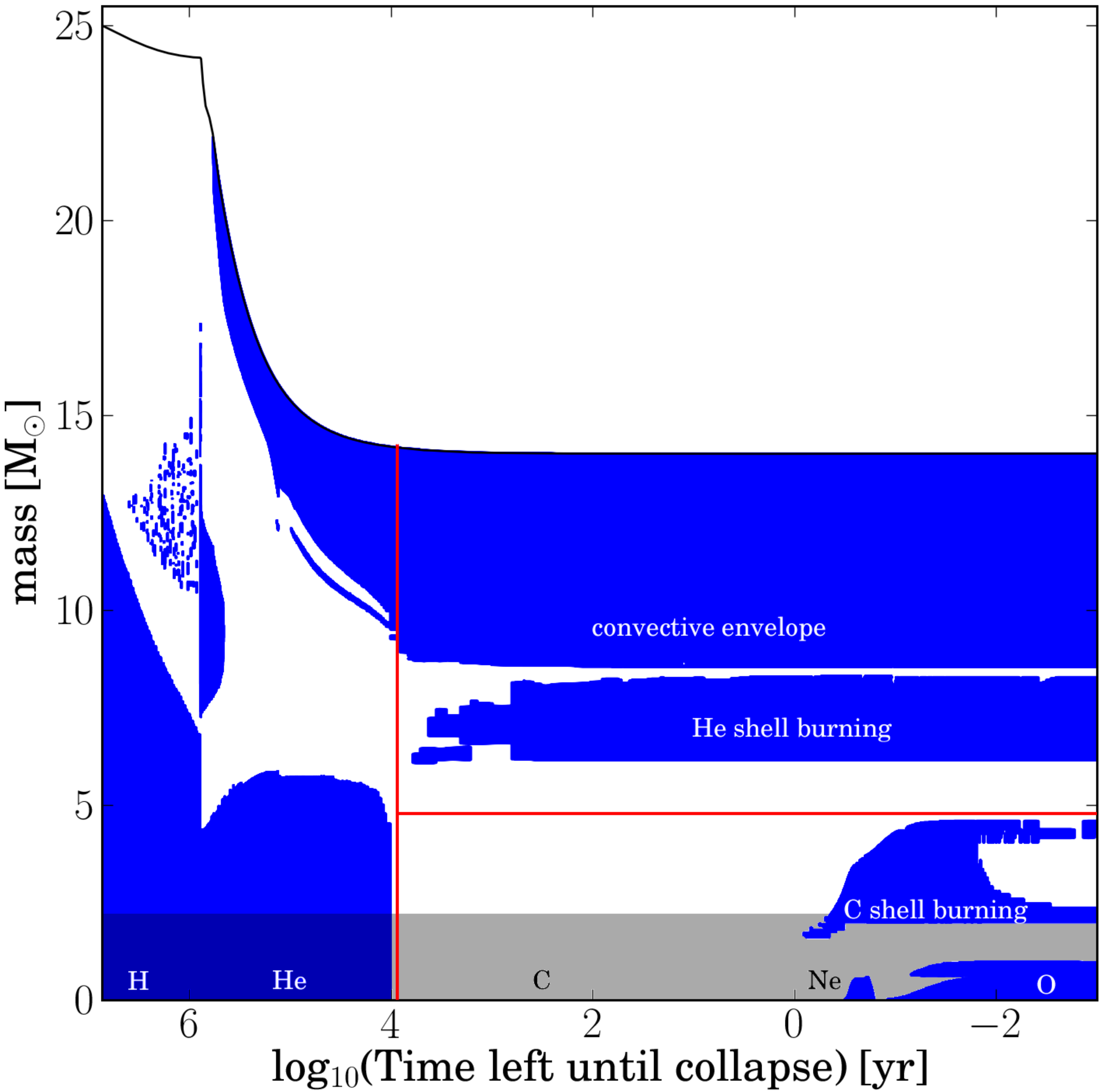
Gormaz-Matamala, 2023

Fate of MS



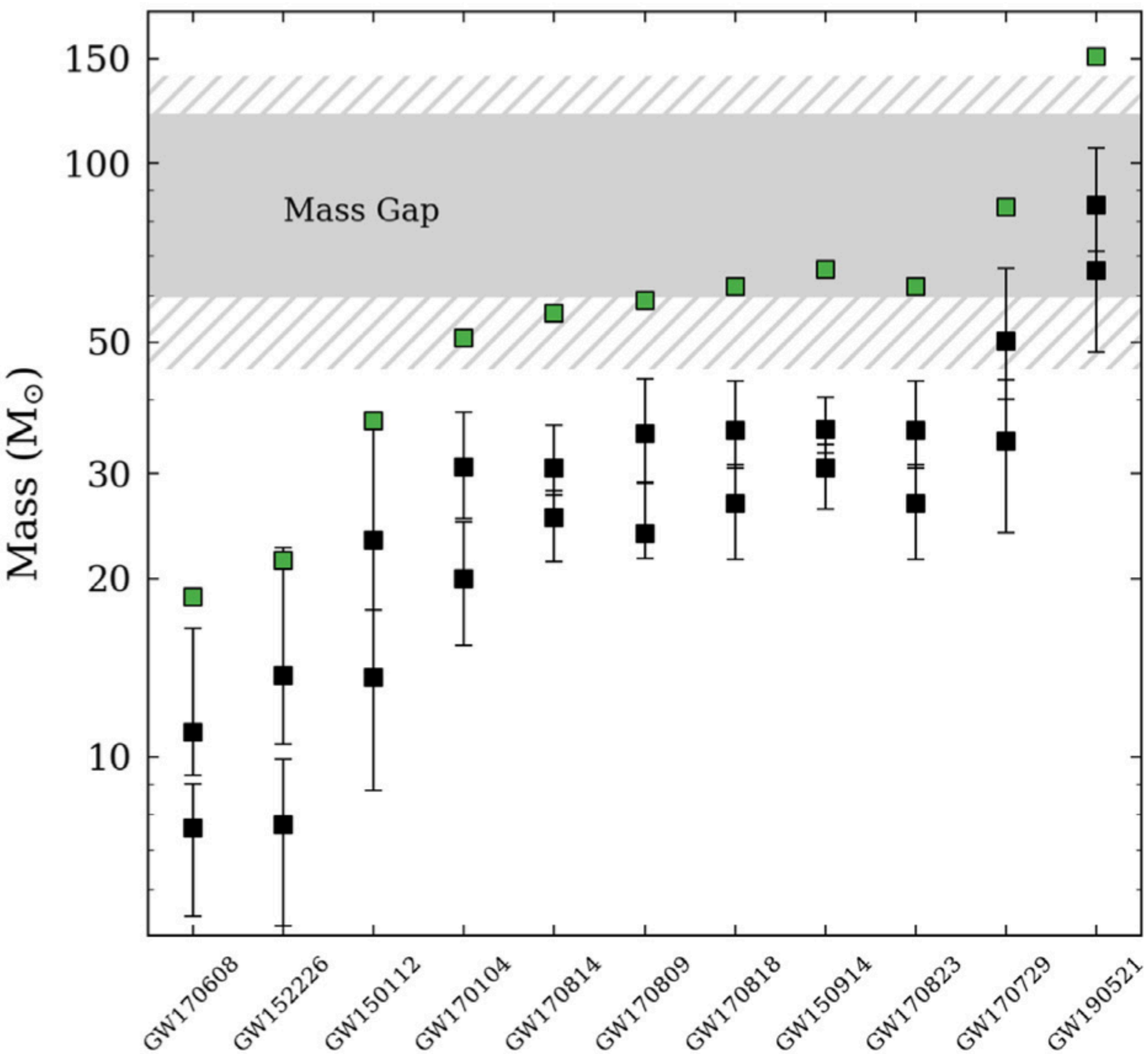
Heger (2003)

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

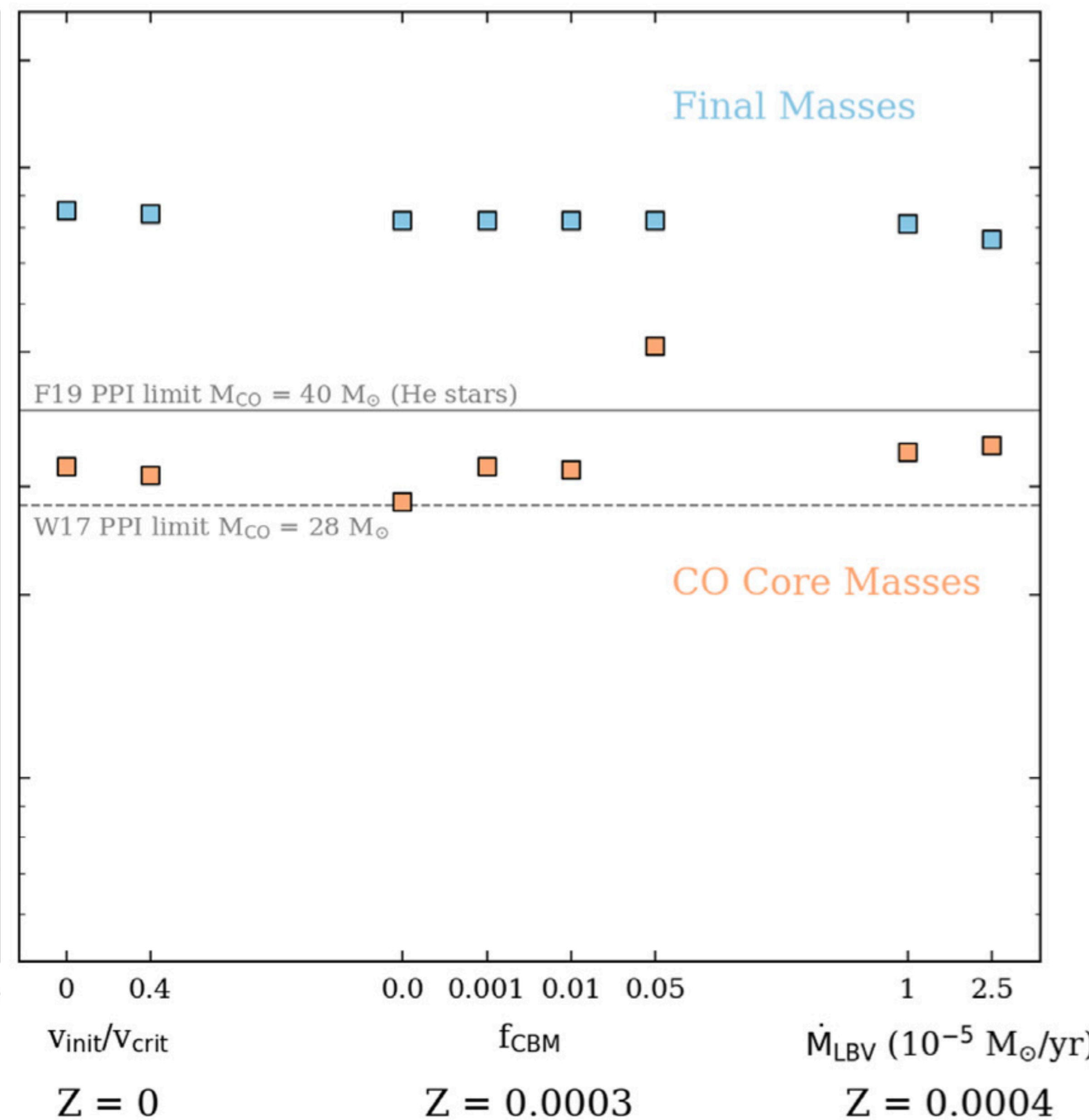


Frischknecht et al. 2015

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

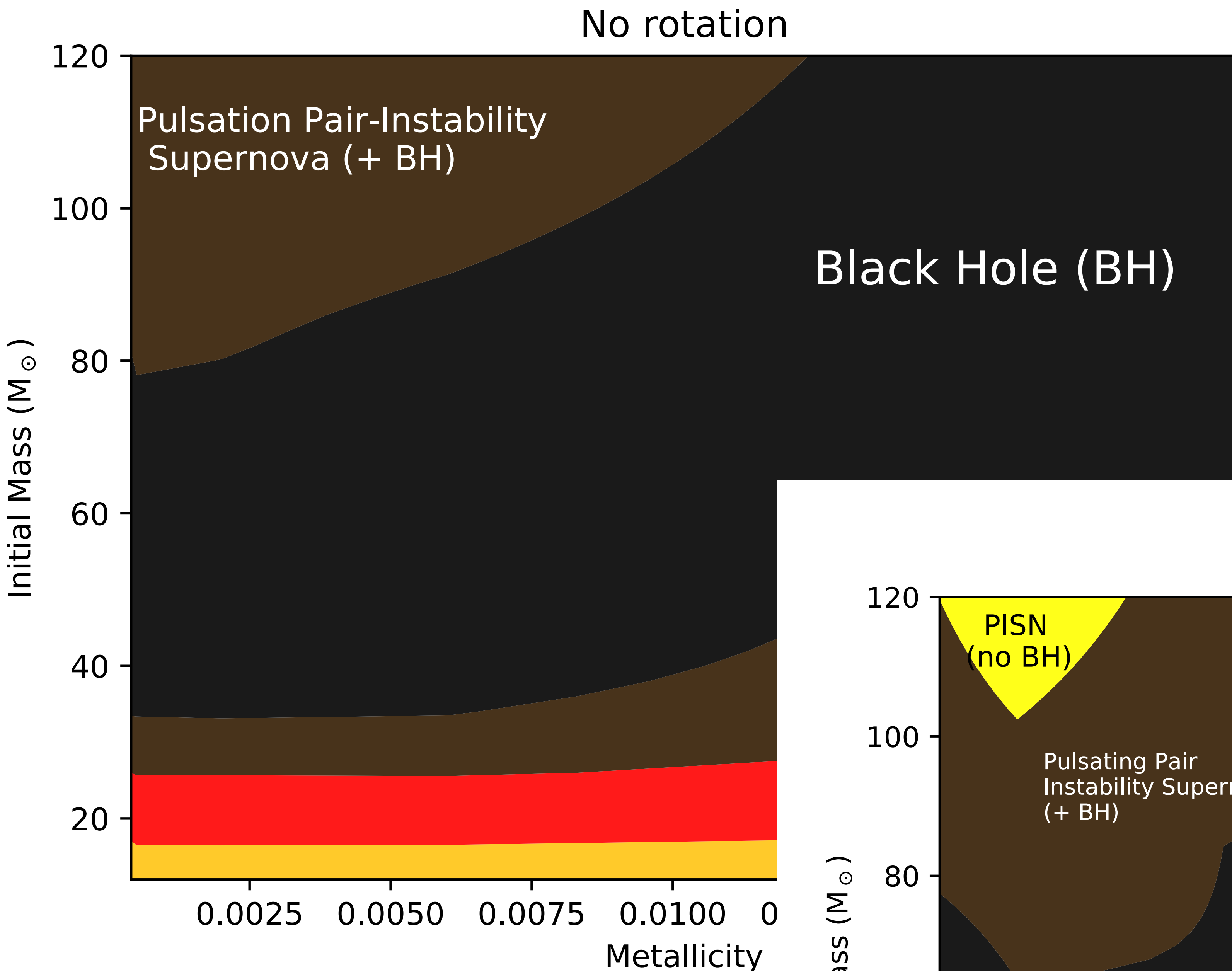


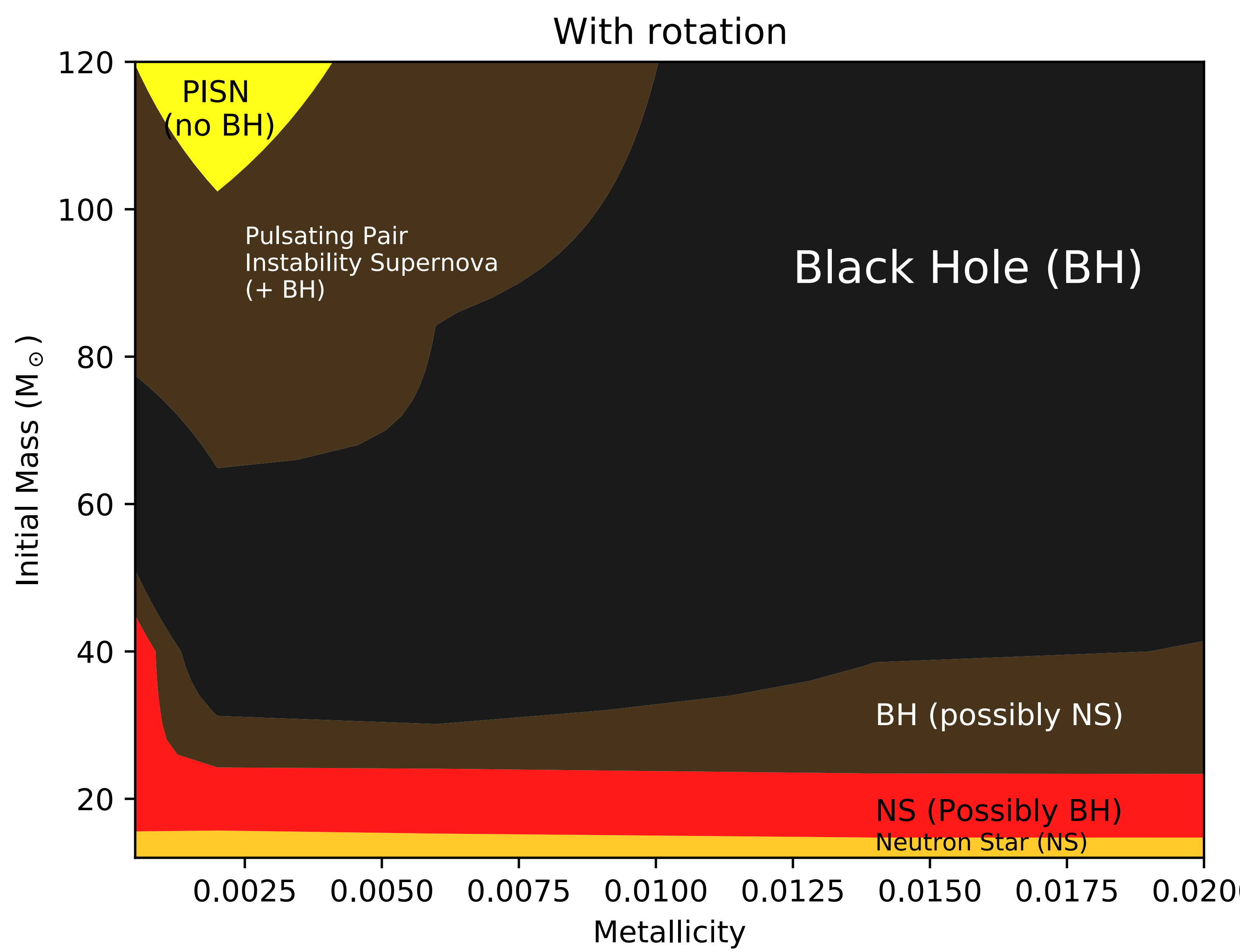
Pre-merger and final BH masses from LIGO/Virgo observations in O1/O2 with GW190521 and the predicted region of the mass gap due to pair-instability.



Final masses (blue) and CO core masses (red) of selected 85 M$_\odot$ models

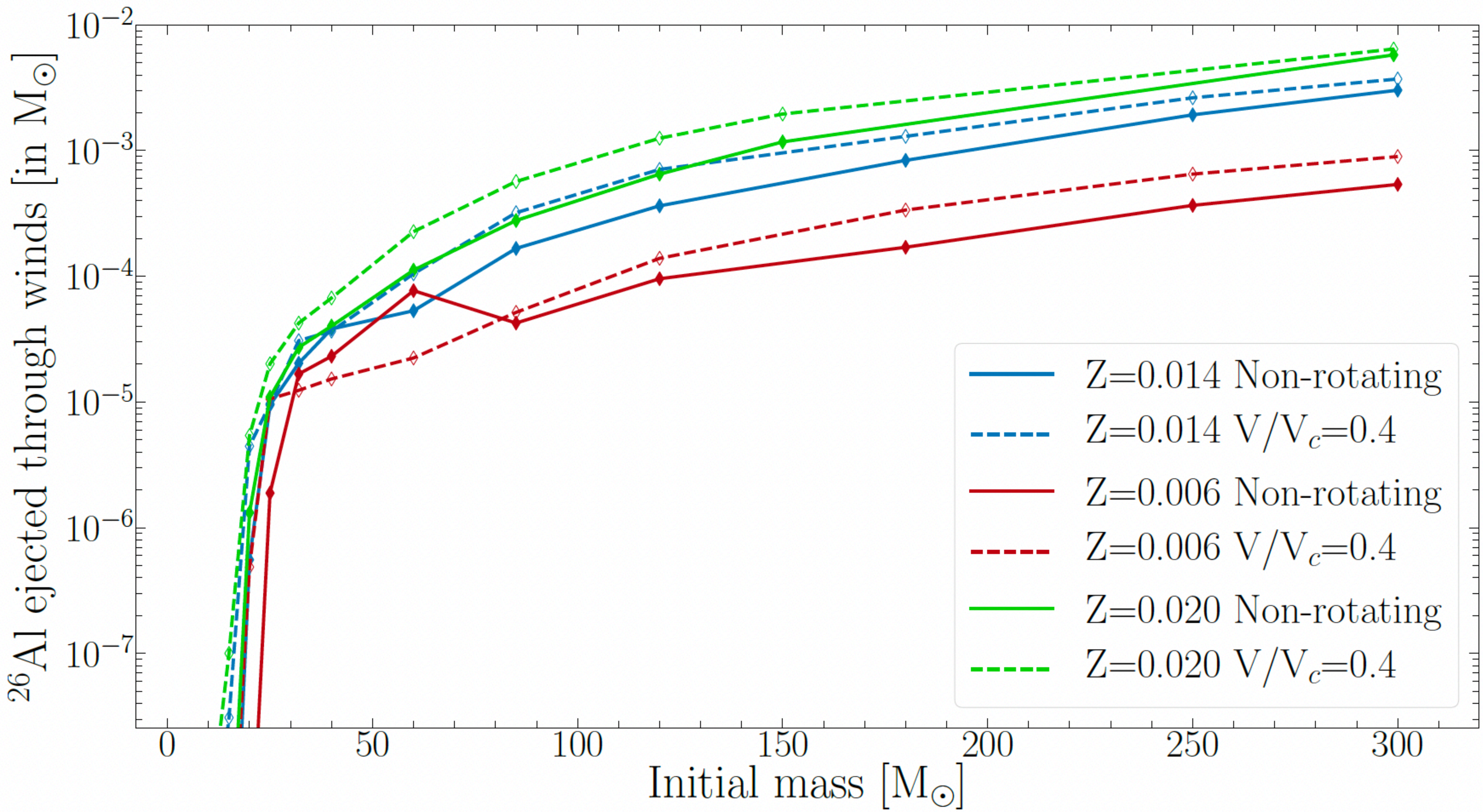
Farrell et al (2020)





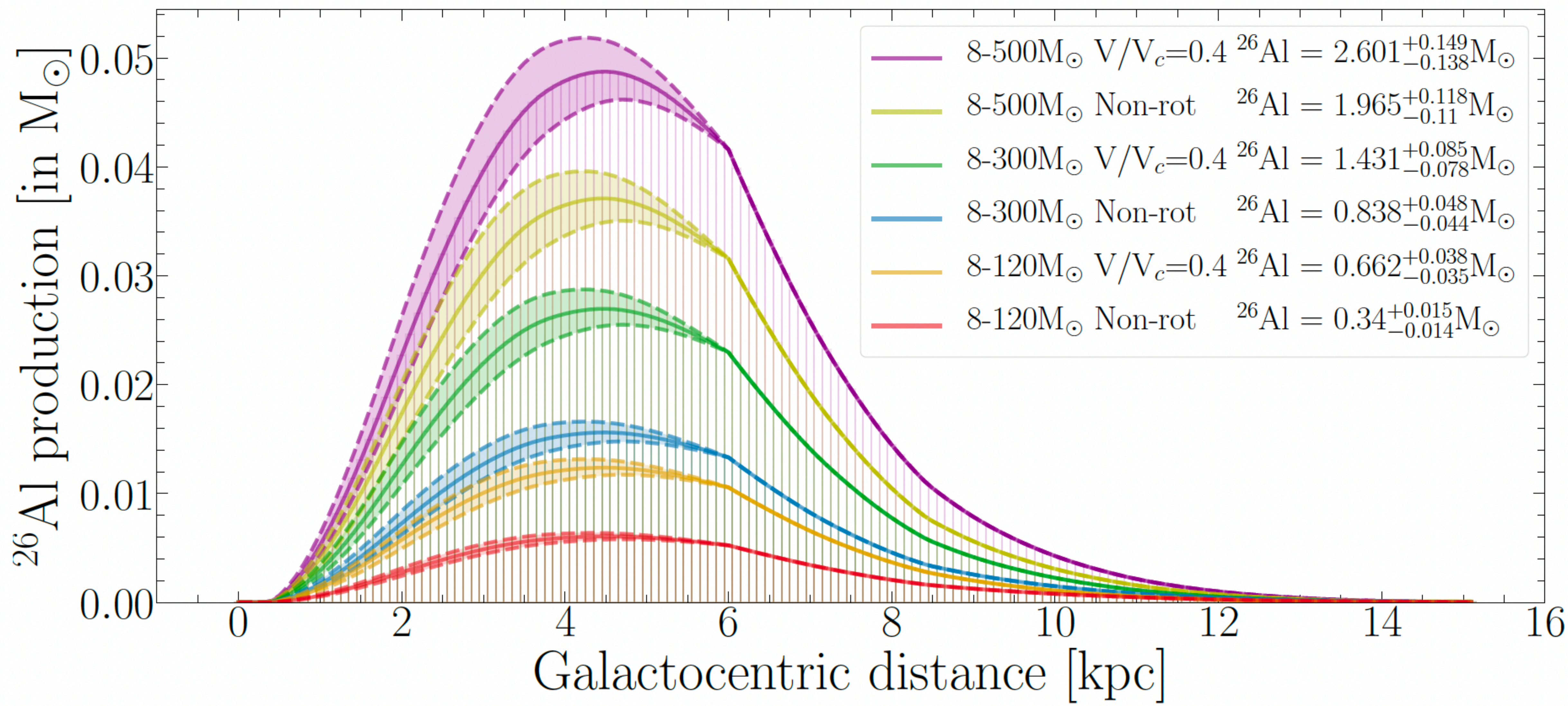
Hirschi et al (in prep)

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



Martinet et al (2022)

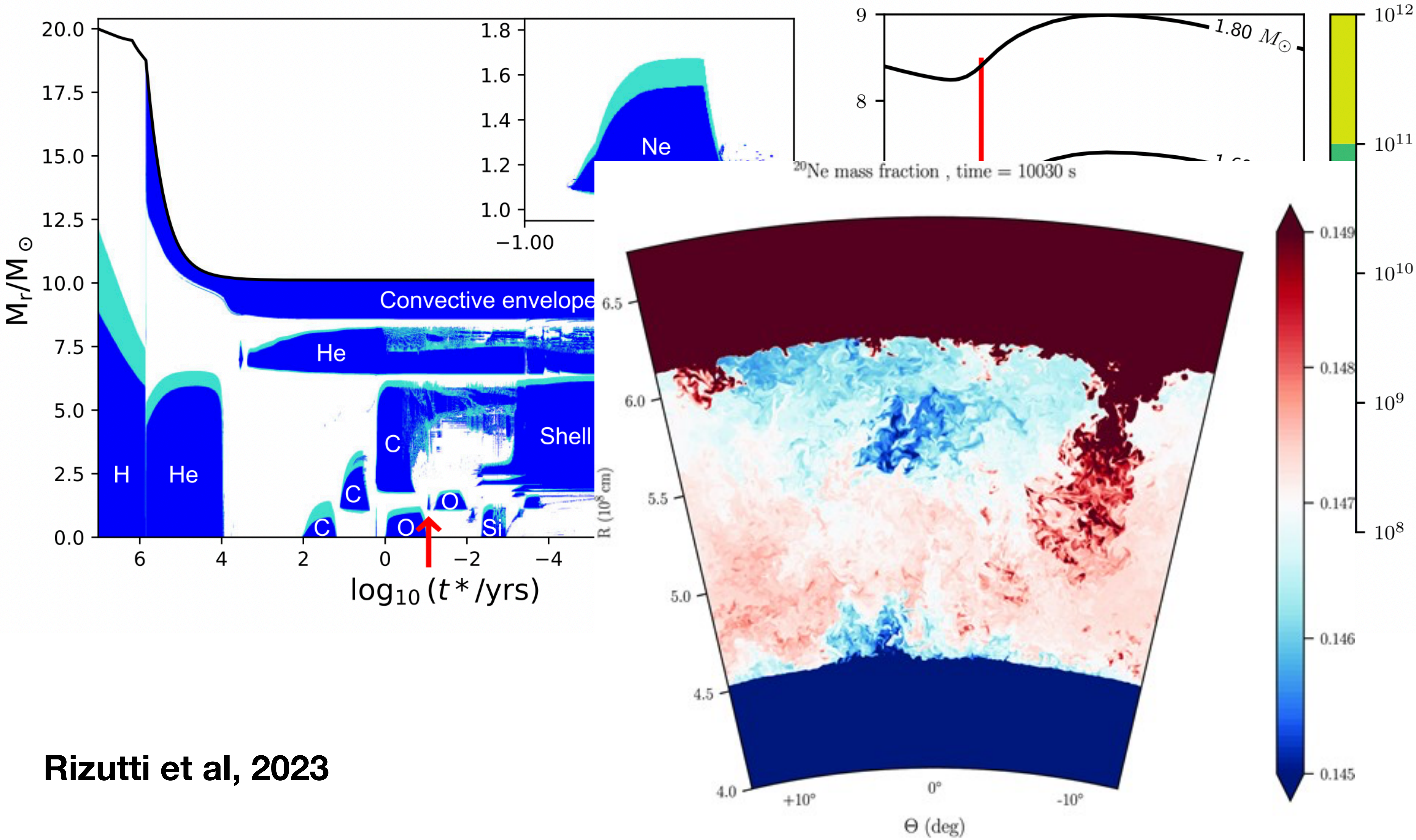
Martinet et al (2022)



Rotational mixing is also very significant, as a population of rotating massive stars produces twice the amount of ^{26}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}Al galactic production

3D Modelling

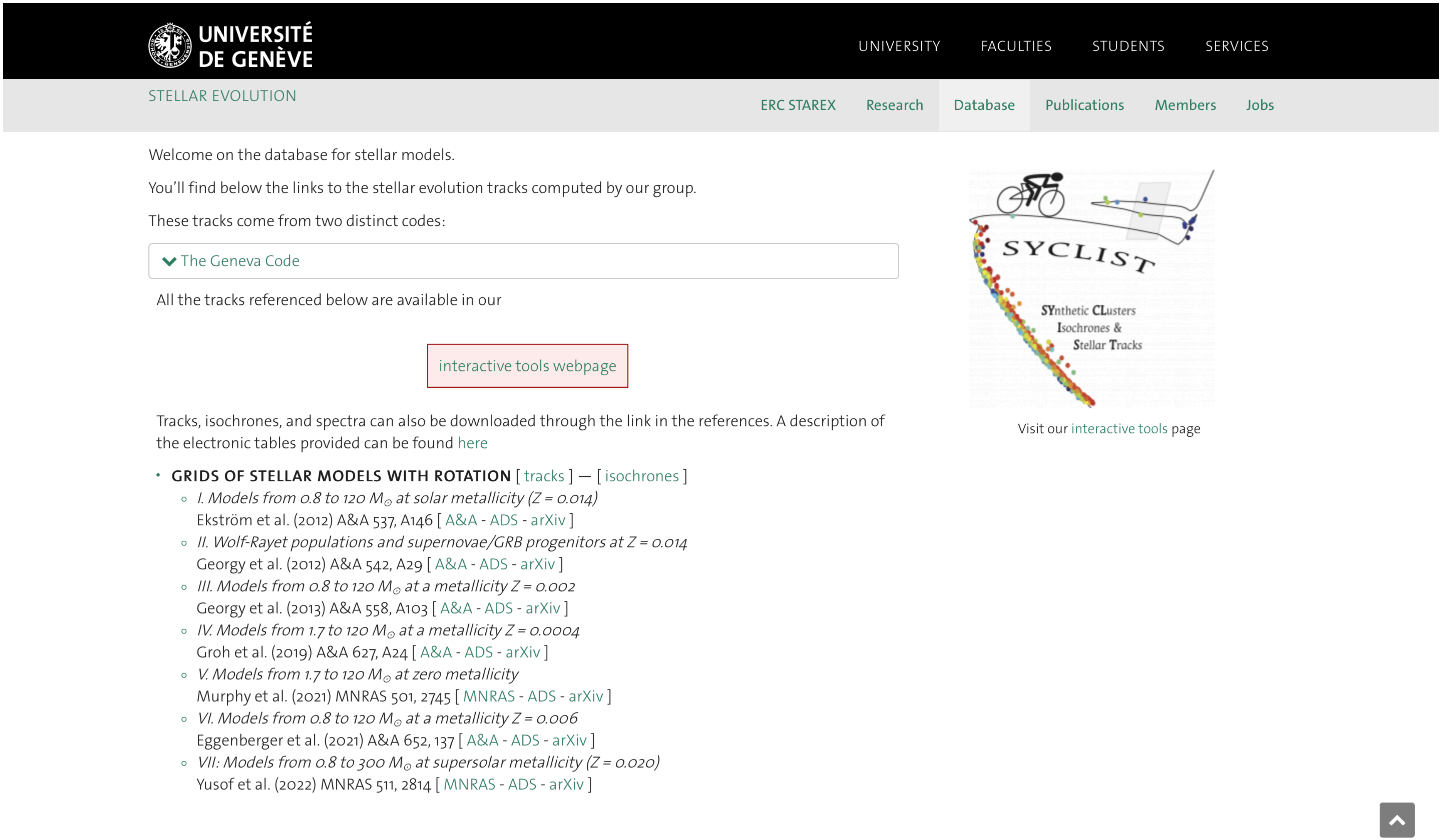


Rizutti et al, 2023

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



https://www.unige.ch/sciences/astro/evolution/en/database/