Nucleosynthesis and wind yields of Very Massive Stars

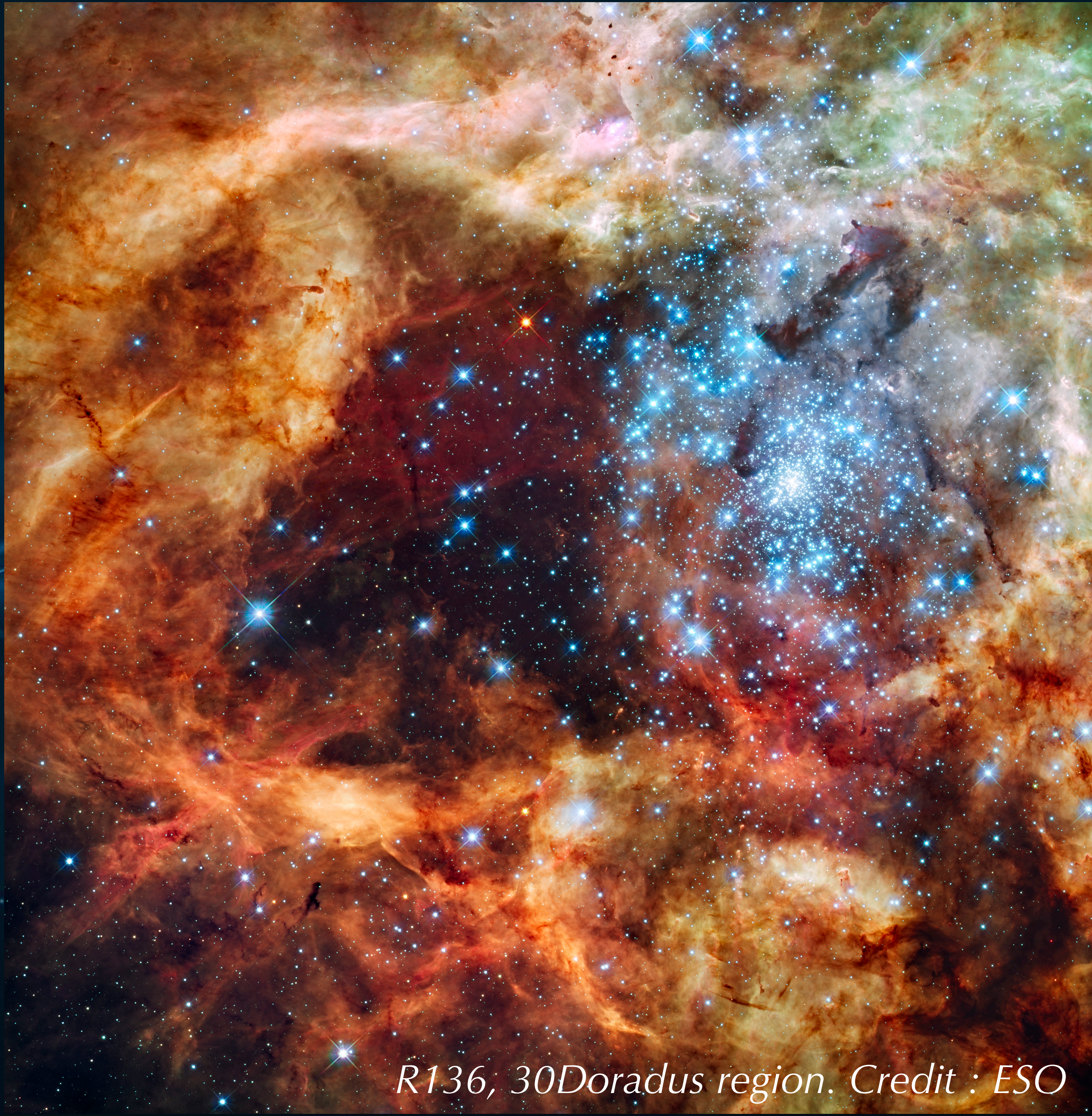
Erin Higgins

Armagh Observatory & Planetarium

Collaborators: Jorick Vink, Raphael Hirschi, Alison Laird, Andreas Sander, Gautham Sabhahit

Very massive stars

- VMS: stars with $M > 100M_\odot$ and extremely high luminosities $\sim 10^6\ L_\odot$
- While few in numbers, they dominate the light, feedback, chemical enrichment of ISM as they lose disproportional amounts of mass when compared to O stars
- Top heavy IMF was found in 30Dor with observational evidence for stars up to $200\text{-}300M_\odot$
- VMS also found in the Arches cluster of the Milky Way with $M \sim 100M_\odot$

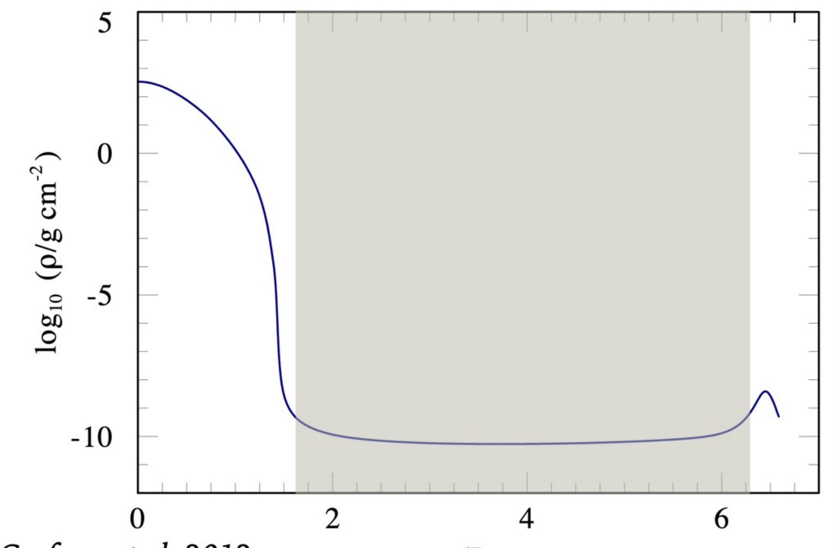


R136, 30Doradus region. Credit : ESO

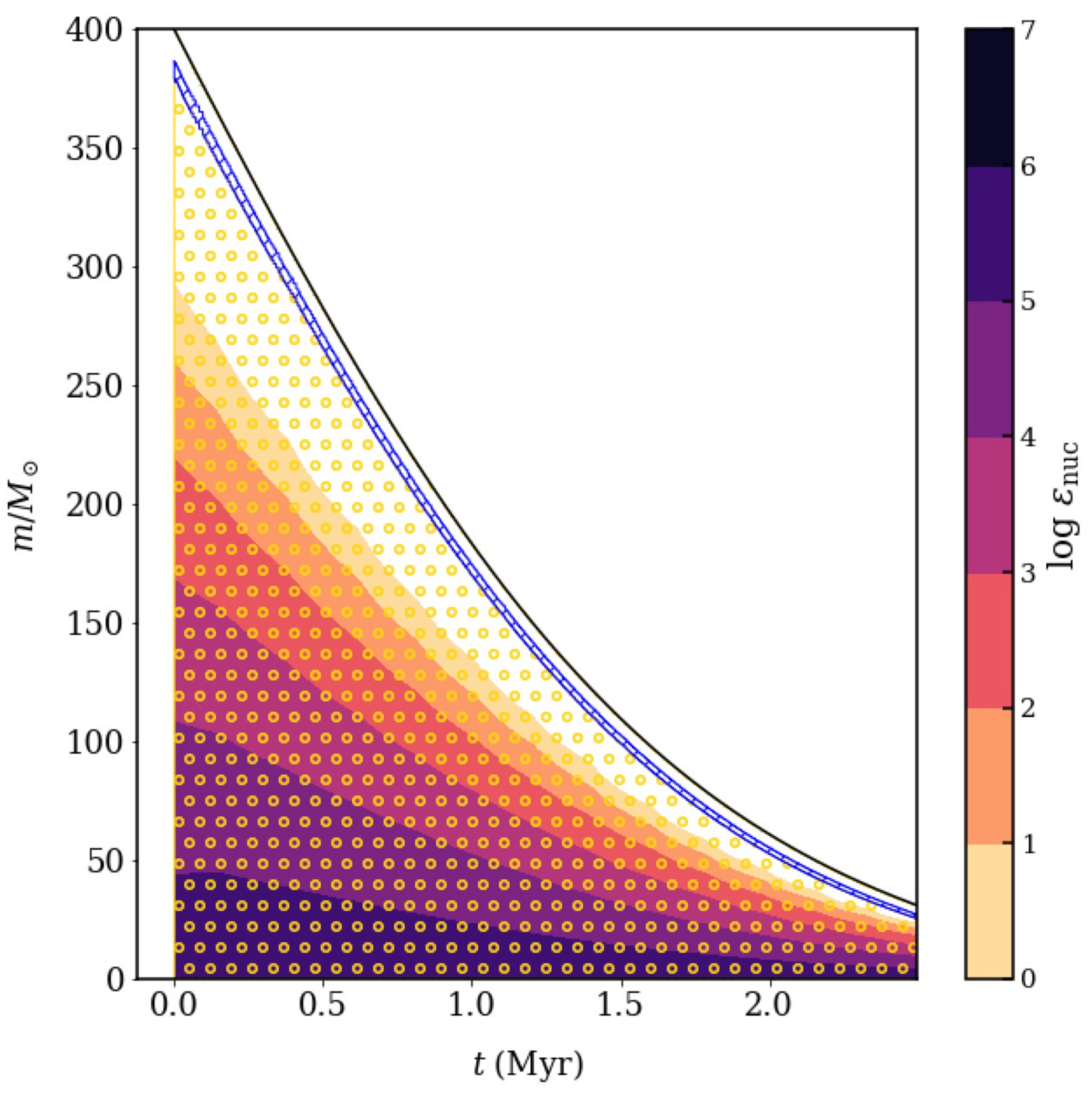
VMS structure and evolution

With high luminosities and masses, they evolve in proximity to the Eddington limit resulting in inflated envelopes and high mass-loss rates

$$\Gamma_{\rm rad}(r) = \frac{\chi l_{\rm rad}}{4\pi G c m} \rightarrow 1$$



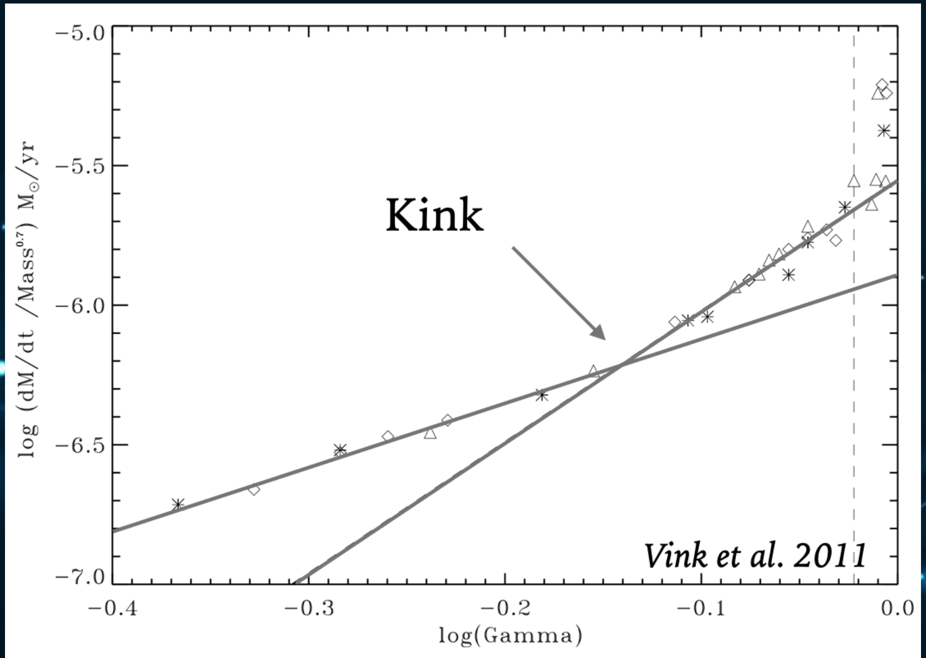
Grafener et al. 2012

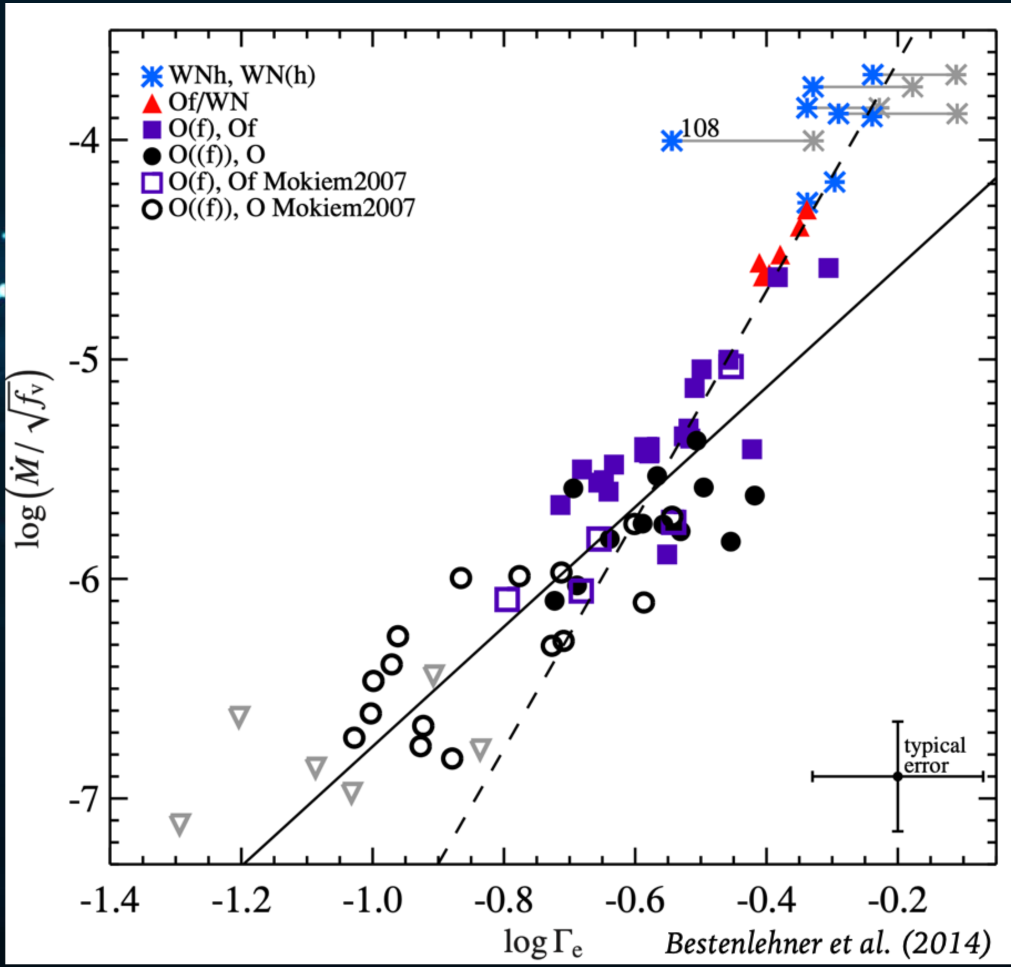


Large convective envelopes leading to chemical homogeneous evolution

Mass Loss of VMS $\dot{M} \propto \Gamma$

Theoretically predicted and observed kink in mass-loss rates

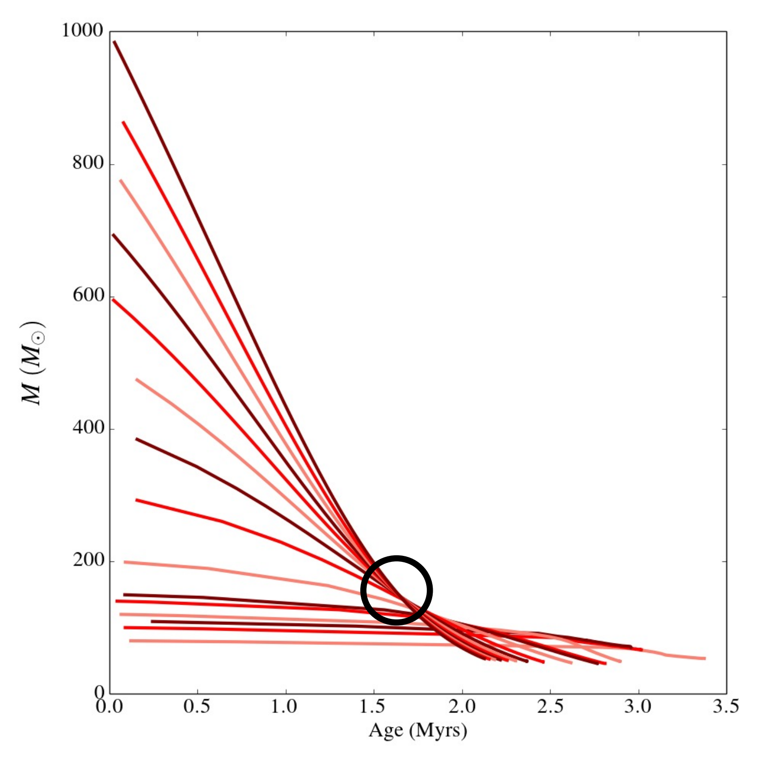




$$\dot{M} \sim M^{0.68}\Gamma_e^{2.2} \quad \text{for} \quad 0.4 < \Gamma_e < 0.7$$

$$\dot{M} \sim M^{0.78}\Gamma_e^{4.77} \quad \text{for} \quad \Gamma_e > 0.7$$

Mass Loss of VMS $\dot{M} \propto \Gamma$

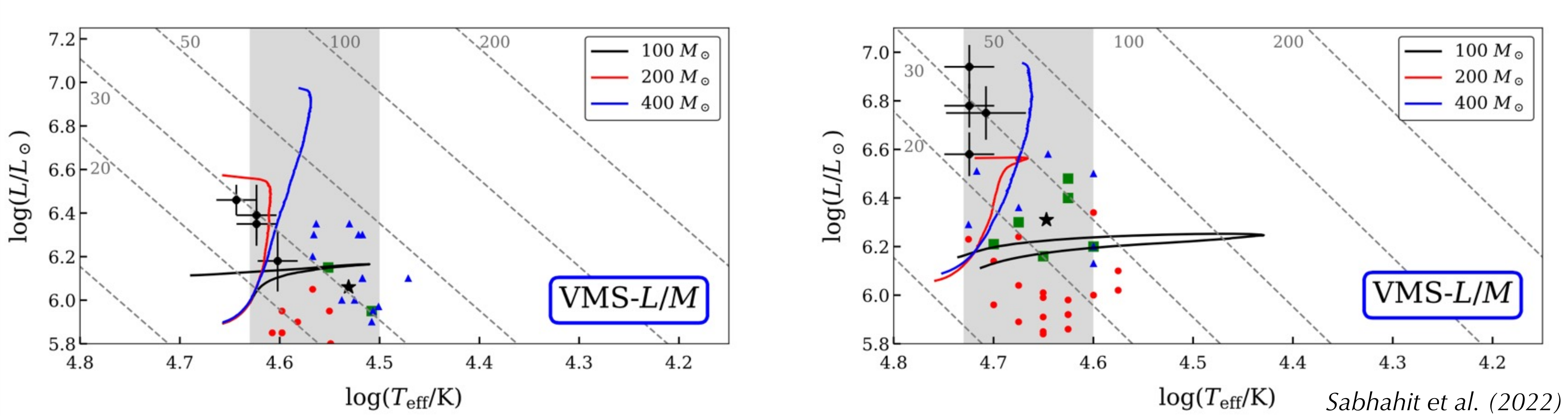


New theoretical mass-loss prescription for stars above and below the transition point (Sabhahit et al., 2022; 2023)

Results lead to vertical evolution in HRD, reproducing the small observed Teff of VMS in the Arches cluster (MW) and Tarantula nebula (LMC).

Also a mass turnover point found in Higgins et al. (2022) for VMS at 1.6Myrs where all M_{init} reach M~50$M_\odot$ at the TAMS.

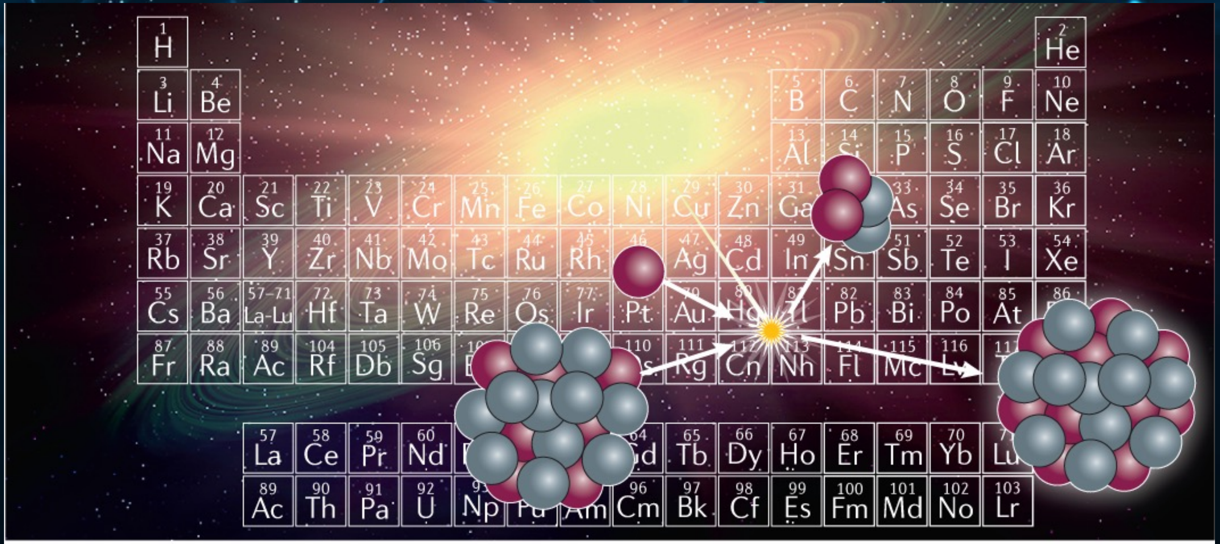
Vertical evolution



Sabhahit et al. (2022)

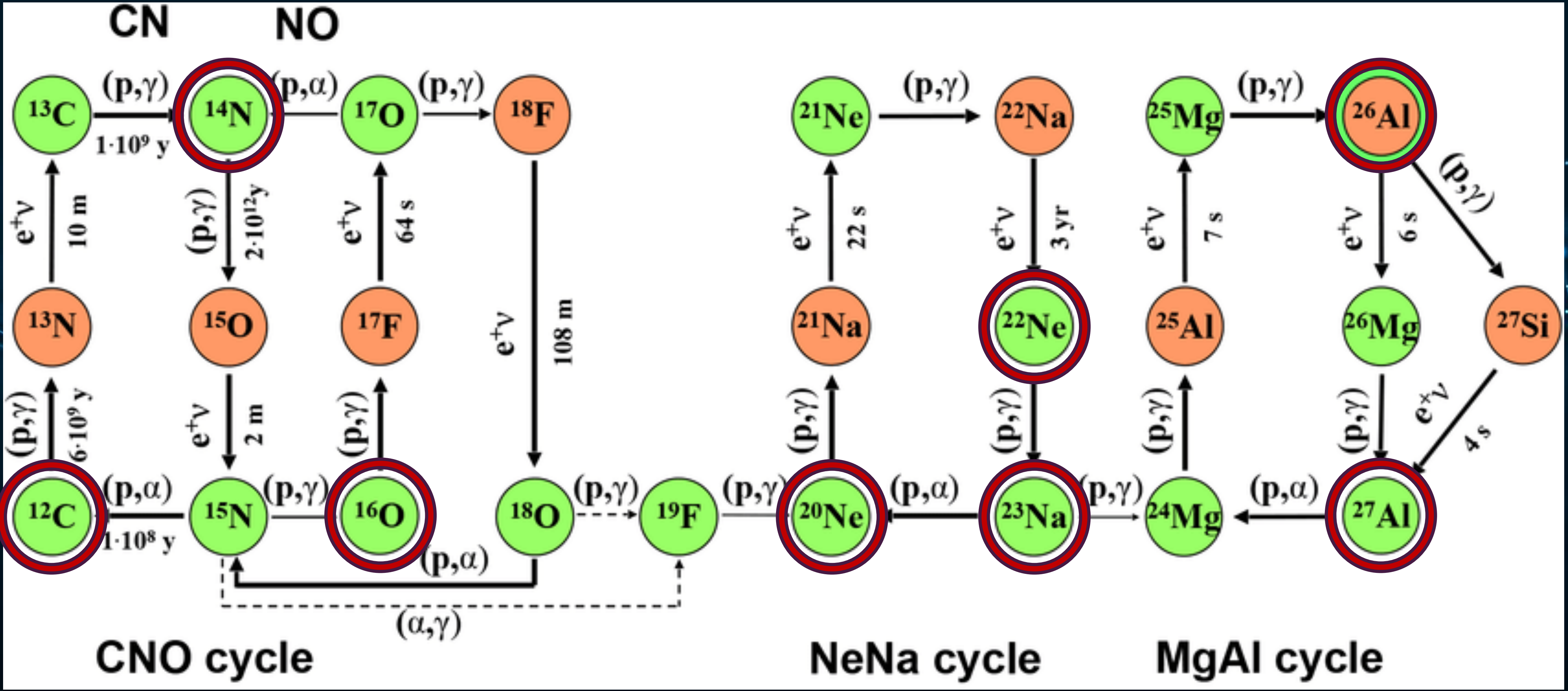
Chemical yields

- The chemical composition of galaxies relies on the production of elements in stars, which are subsequently released in stellar winds and supernovae.
- This rejuvenation of galaxies over generations of stars has led us to the metal-rich environment of our own Galaxy, with abundant quantities of carbon (C), oxygen (O), nitrogen (N) and iron (Fe).
- The origin of elements concerns the stellar nucleosynthesis, wind ejecta and chemical yields, of a given population, providing a broad perspective on galactic chemical evolution



Background image credit: Alamy H2HW1B

Stellar nucleosynthesis



MNRAS **000**, 000–000 (2023) Preprint 31 August 2023 Compiled using MNRAS LaTeX style file v3.0

Stellar Wind Yields of Very Massive Stars

Erin R. Higgins[1★], Jorick S. Vink[1], Raphael Hirschi[2,3], Alison M. Laird[4], Gautham N. Sabhahit
[1]*Armagh Observatory and Planetarium, College Hill, Armagh BT61 9DG, N. Ireland*
[2]*Astrophysics Group, Keele University, Keele, Staffordshire ST5 5BG, UK*
[3]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8583, Japan*
[4]*School of Physics, Engineering and Technology, University of York, York, YO10 5DD, UK*

Accepted. Received

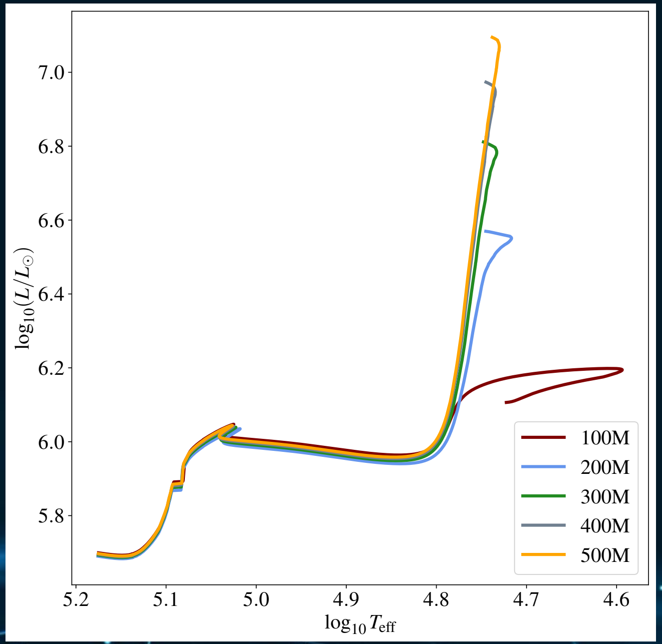
ABSTRACT

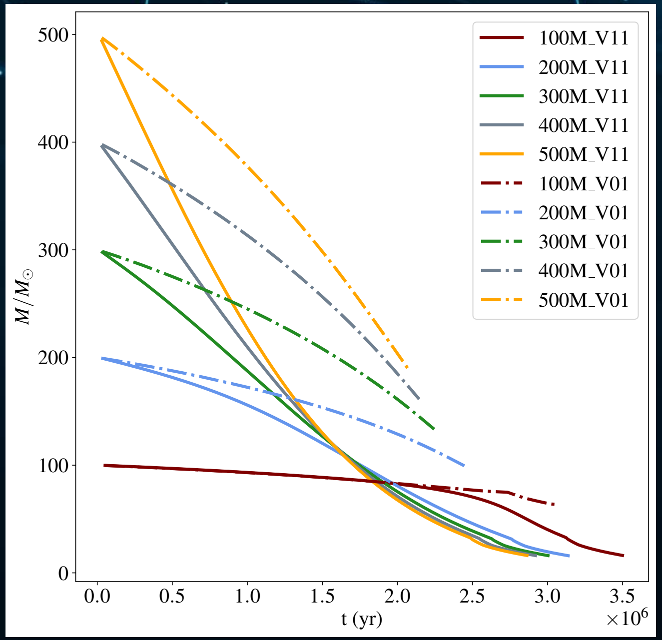
The most massive stars provide an essential source of recycled material for young clusters and galaxies. While very massive stars (VMS, M>100 $M_\odot$) are relatively rare compared to O stars, they lose disproportionately large amounts of mass already from the onset of core H-burning. VMS have optically thick winds with elevated mass-loss rates in comparison to optically thin standard O-star winds. We compute wind yields and ejected masses on the main sequence, and we compare enhanced mass-loss rates to standard ones. We calculate solar metallicity wind yields from MESA stellar evolution models in the range 50 – 500 $M_\odot$, including a large nuclear network of 92 isotopes, investigating not only the CNO-cycle, but also the Ne-Na and Mg-Al cycles. VMS with enhanced winds eject 5-10 times more H-processed elements (N, Ne, Na, Al) on the main sequence in comparison to standard winds, with possible consequences for observed anti-correlations, such as C-N and Na-O, in globular clusters. We find that for VMS 95% of the total wind yields is produced on the main sequence, while only ~ 5% is supplied by the post-main sequence. This implies that VMS with enhanced winds are the primary source of ^{26}Al, contrasting previous works where classical Wolf-Rayet winds had been suggested to be responsible for Galactic ^{26}Al enrichment. Finally, 200 $M_\odot$ stars eject 100 times more of each heavy element in their winds than 50 $M_\odot$ stars, and even when weighted by an IMF their wind contribution is still an order of magnitude higher than that of 50 $M_\odot$ stars.

Key words: stars: massive – stars: evolution – stars: abundances – stars: mass loss – stars: interiors – nuclear reactions, nucleosynthesis, abundances

Stellar models MESA

- Grid of models with M_i = 50-500$M_\odot$ at $Z_\odot$
- Calculated from ZAMS until core O-exhaustion
- New Sabhahit et al. (2022) wind implementation for VMS above the transition point
- Comparison test models for VMS implementing Vink et al. (2001) winds
- Large nuclear network of **92 isotopes** included for relevant reactions until core O-exhaustion
- Chemical yields provided for both MS and post-MS evolution





Stellar wind yields

Ejected masses (*EM*) of each element, integrated over the star's lifetime (or a particular burning phase, **τ**). The surface abundance of a given isotope (X_i^S) as a function of mass lost ($\dot{M}$) at each timestep, provides the overall mass lost of each isotope

Mass loss

Surface abundance

$$EM_{im} = \int_0^{\tau(m)} \dot{M}\, X_i^S(m,t)\, dt$$

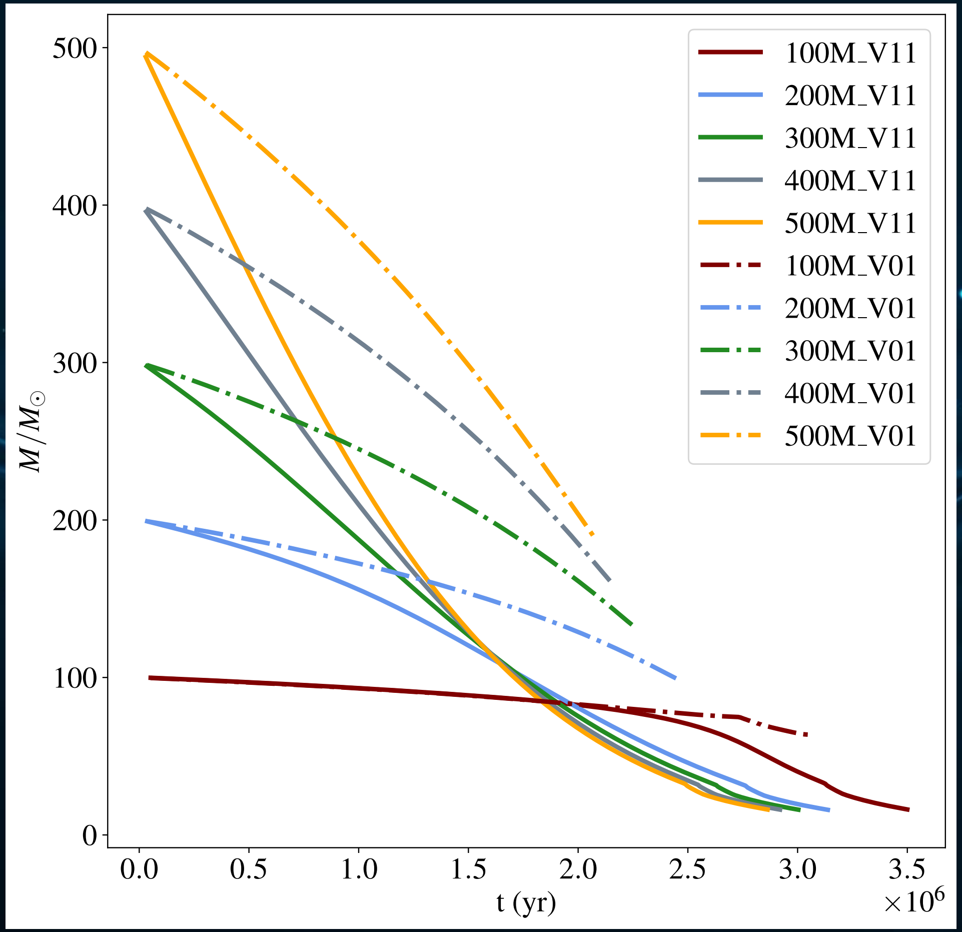
Integrated over the stellar lifetime

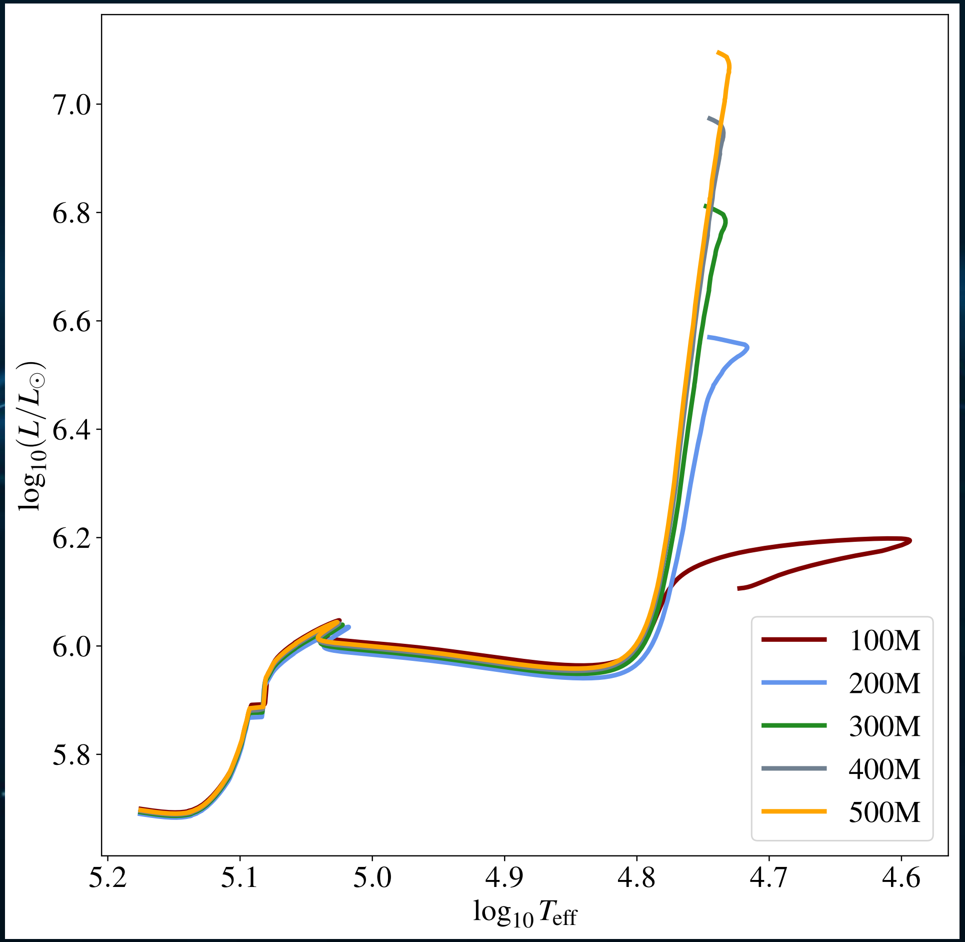
Net chemical yields

Alternatively, the **net** yield can be calculated (m_i) which provides the **change in a given element released back into the host environment**. The difference is that the initial surface abundance of a given isotope (X_i^0) is first subtracted at each timestep, giving the net yield of each isotope. This calculation is most commonly used in GCE models and comparisons with observed chemical trends in stellar populations.

$$m_i^{\mathrm{wind}} = \int_0^{\tau(m)} \dot{M}(m,t)\,\underbrace{[X_i^S(m,t) - X_i^0]}_{\text{Change in abundance as a function of the initial abundance}}\,dt$$

Stellar models MESA





Higgins et al., (2023)

Effects of winds

Difference of ~100$M_\odot$ in mass lost, and therefore yields

300$M_\odot$

Vink 2001 mass loss rates (right)

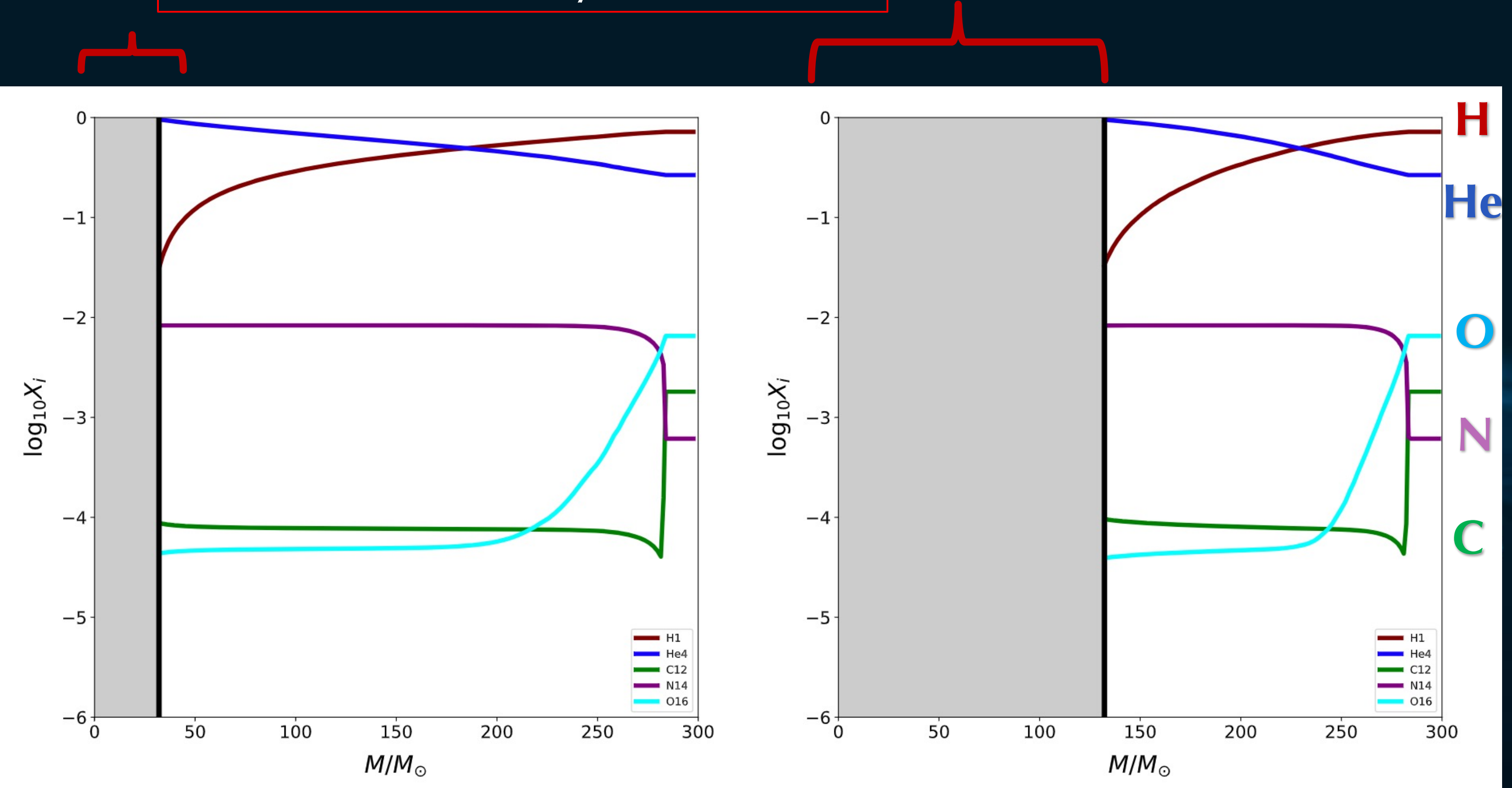
Vink 2011 rates; Sabhahit 2022 mass loss implementation (left)

Core H-burning only

Grey shaded region = H-exhausted core

Time evolution = right to left

VMS with enhanced (Sabhahit 2022) winds eject **up to 10 times more** H-burning products of ^{14}N, ^{20}Ne, ^{23}Na, and ^{26}Al than VMS with standard V01 winds



(a) Enhanced V11 optically-thick winds for VMS

(b) Standard V01 optically-thin O star winds applied to VMS

Figure 1. Time evolution of the surface abundance of H, He, C, N and O as a function of mass, for 300 $M_\odot$ models at $Z_\odot$. As the star loses mass the time evolution follows from right to left. We apply the optically-thick, enhanced wind prescription outlined in equation (2) on the left, and the standard optically-thin, O star wind prescription from equation (1) on the right. The white region shows the mass lost over the MS lifetime, while the grey shaded region illustrates the remaining TAMS stellar mass with the black line denoting the TAMS.

Time evolution of surface isotopes as a function of stellar mass

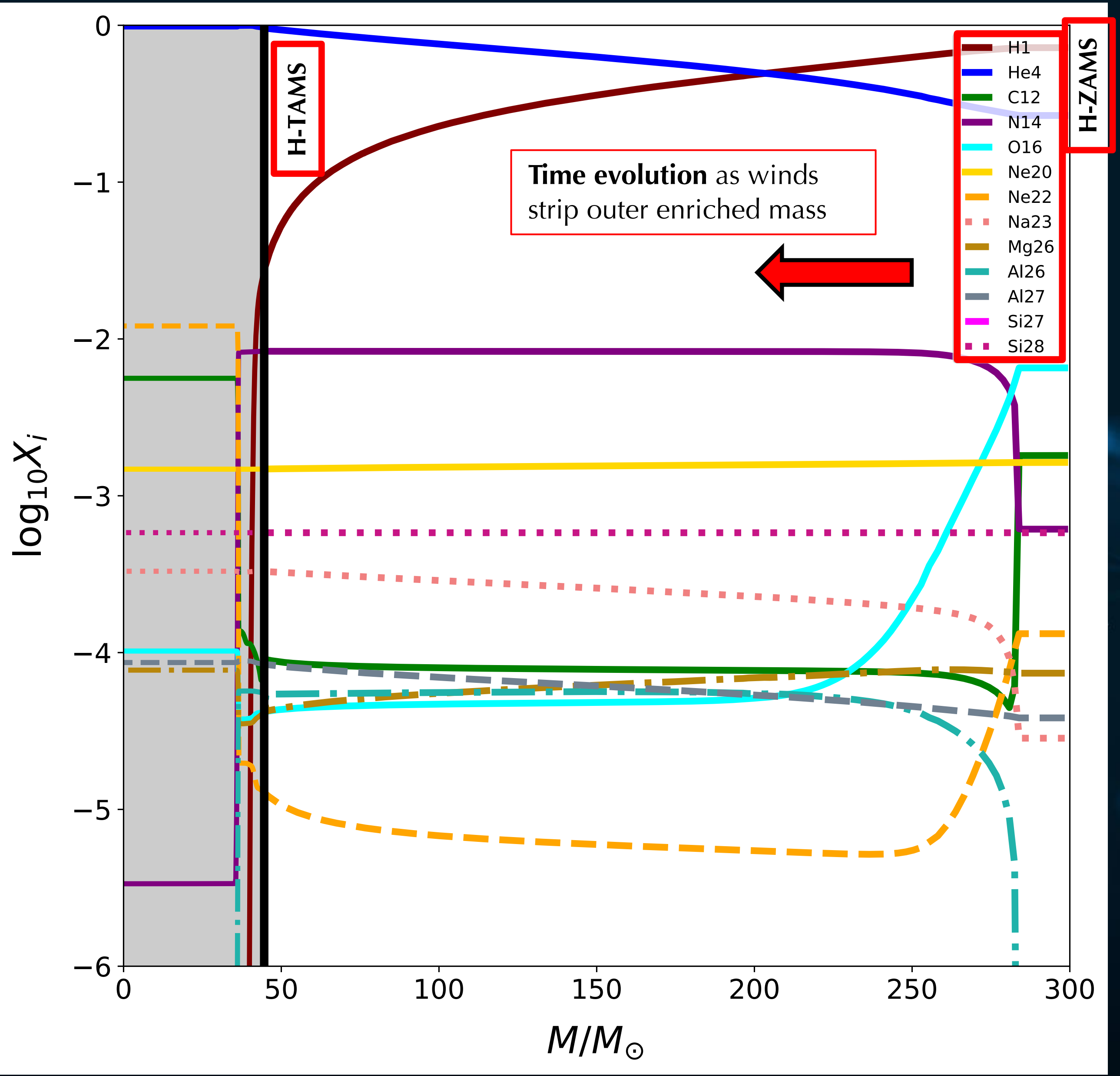
<u>During Core H-burning:</u>

N increases, C and O decrease (CNO cycle)

^{23}Na increases quickly

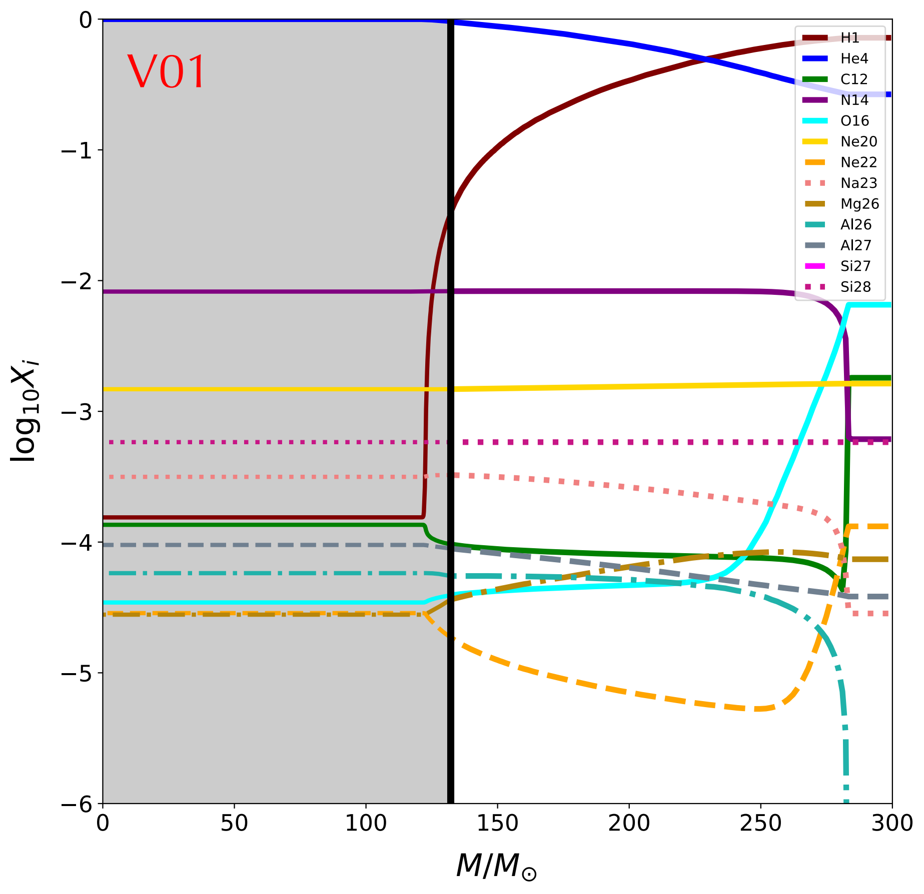
^{20}Ne remains constant and ^{22}Ne increases at onset of core He-burning

^{26}Al increases and then remains constant during H-burning



Higgins et al., (2023)

Consequences of enhanced winds



Higgins et al., (2023)

During Core H-burning:

V11 models eject ~2x more H, He, N, Ne, Na and Si, and up to 10x more Al than V01 models

$M_i/M_\odot$	$\dot{M}$	^{1}H	^{4}He	^{12}C	^{14}N	^{16}O	^{20}Ne	^{22}Ne	^{23}Na	^{26}Mg	^{26}Al	^{27}Al	^{28}Si
100	V11	27.418	38.339	0.033	0.422	0.118	0.105	0.002	0.013	4.88E-3	2.271E-3	3.454E-3	0.039
200	V11	67.603	97.182	0.041	1.234	0.148	0.261	0.003	0.038	0.011	7.391E-3	0.009	0.097
300	V11	115.623	146.385	0.045	2.046	0.167	0.416	0.004	0.060	0.017	0.013	0.015	0.154
400	V11	166.382	192.622	0.050	2.846	0.196	0.571	0.005	0.082	0.023	0.018	0.021	0.221
500	V11	222.696	239.014	0.065	3.649	0.264	0.736	0.007	0.104	0.029	0.023	0.026	0.272
100	V01	22.805	12.598	0.030	0.166	0.117	0.058	2.248E-3	4.339E-3	3.170E-3	4.005E-4	1.491E-3	0.021
200	V01	46.798	52.162	0.037	0.682	0.140	0.158	3.008E-3	0.020	7.549E-3	3.313E-3	5.328E-3	0.058
300	V01	68.392	94.944	0.040	1.221	0.150	0.258	3.795E-3	0.038	0.011	6.796E-3	9.865E-3	0.096
400	V01	91.733	140.717	0.045	1.794	0.164	0.366	4.867E-3	0.056	0.014	0.011	0.015	0.137
500	V01	119.558	186.017	0.056	2.380	0.197	0.480	6.361E-3	0.075	0.018	0.015	0.020	0.180

Table 4. Ejected masses calculated with equation (4) for V11 and V01 models during core H-burning only. Initial masses and ejected masses are provided in solar mass units.

A key point is that the ejected mass of each isotope strongly depends on which burning phase the mass is lost, and therefore where mass-loss rates are high

Chemical yields and ejected masses

On the MS, 95% of the total wind yields are produced, compared to just 5% of the total wind yields which are ejected on the post-MS.

Single stars with initial masses below 80$M_\odot$ do not eject any ^{26}Al, but VMS eject 10^{-2} to 10^{-3} of ^{26}Al and could be responsible for the significant mass of ^{26}Al observed in our Galaxy.

Enhanced Vink 2011 rates only

100$M_\odot$ star ejects 100 times more ^{12}C, ^{22}Ne, ^{23}Na and ^{28}Si, than a 50$M_\odot$ star

	$M_i/M_\odot$	^{1}H	^{4}He	^{12}C	^{14}N	^{16}O	^{20}Ne	^{22}Ne	^{23}Na	^{26}Mg	^{26}Al	^{27}Al	^{28}Si
EM	50	5.698	2.105	0.014	4.85E-3	0.052	0.013	1.04E-3	2.25E-4	5.85E-4	0	3.03E-4	4.60E-3
	80	22.131	33.552	4.788	0.268	1.337	0.099	0.195	0.0129	6.113E-3	1.33E-3	3.35E-3	0.036
	100	27.617	51.069	3.203	0.476	0.808	0.130	0.135	0.019	6.54E-3	2.68E-3	4.70E-3	0.049
	200	67.670	109.516	2.973	1.288	0.767	0.286	0.126	0.043	0.013	7.77E-3	0.011	0.107
	300	115.687	158.687	3.061	2.101	0.822	0.444	0.130	0.066	0.019	0.013	0.016	0.165
	400	169.343	206.126	3.125	2.903	0.880	0.602	0.134	0.088	0.025	0.018	0.022	0.223
	500	222.756	251.503	3.175	3.703	0.935	0.761	0.137	0.109	0.031	0.023	0.028	0.282
Net yields	50	-5.75E-5	5.99E-7	-7.87E-7	3.64E-8	-1.24E-10	-2.55E-11	-3.01E-11	2.89E-11	-1.16E-12	0	-5.99E-13	-9.08E-12
	80	-22.932	16.906	4.675	0.230	0.928	-3.56E-3	0.186	0.0111	1.49E-3	1.33E-3	9.47E-4	-4.69E-5
	100	-32.668	28.800	3.051	0.425	0.261	-0.006	0.124	0.016	3.49E-4	2.68E-3	1.49E-3	-9.76E-6
	200	-64.112	60.617	2.640	1.176	-0.435	-0.014	0.101	0.038	-7.45E-4	7.77E-3	3.55E-3	1.06E-5
	300	-87.268	83.717	2.548	1.927	-1.036	-0.019	0.092	0.057	-1.96E-3	0.013	5.43E-3	2.27E-5
	400	-107.453	103.880	2.431	2.667	-1.634	-0.025	0.083	0.077	-3.31E-3	0.018	7.26E-3	3.36E-5
	500	-126.185	122.608	2.300	3.406	-2.234	-0.030	0.073	0.095	-4.72E-3	0.023	9.09E-3	4.40E-5

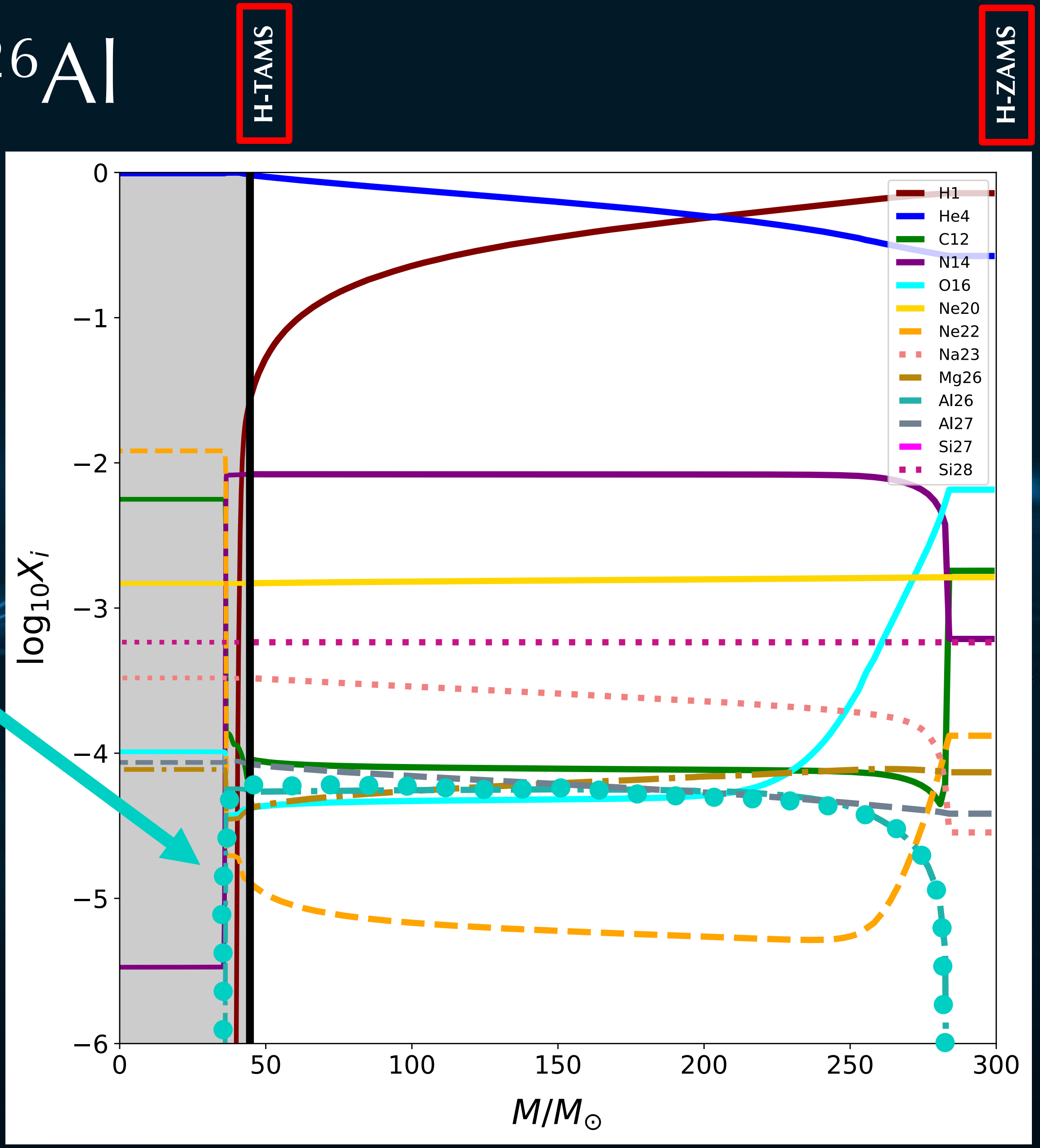
Table 5. Ejected masses (top) and net yields (bottom) calculated with equations (4) and (3) respectively, for V11 models over the complete evolution until core O-exhaustion. Initial masses, ejected masses, and yields are provided in solar mass units.

Production of radioisotope ^{26}Al

- We find that the radioisotope ^{26}Al which was previously thought to be produced and ejected by classical WRs, is mainly ejected from VMS

- Increases by a factor of 10-100 early in MS - and very little ^{26}Al remains in the WRs produced from VMS

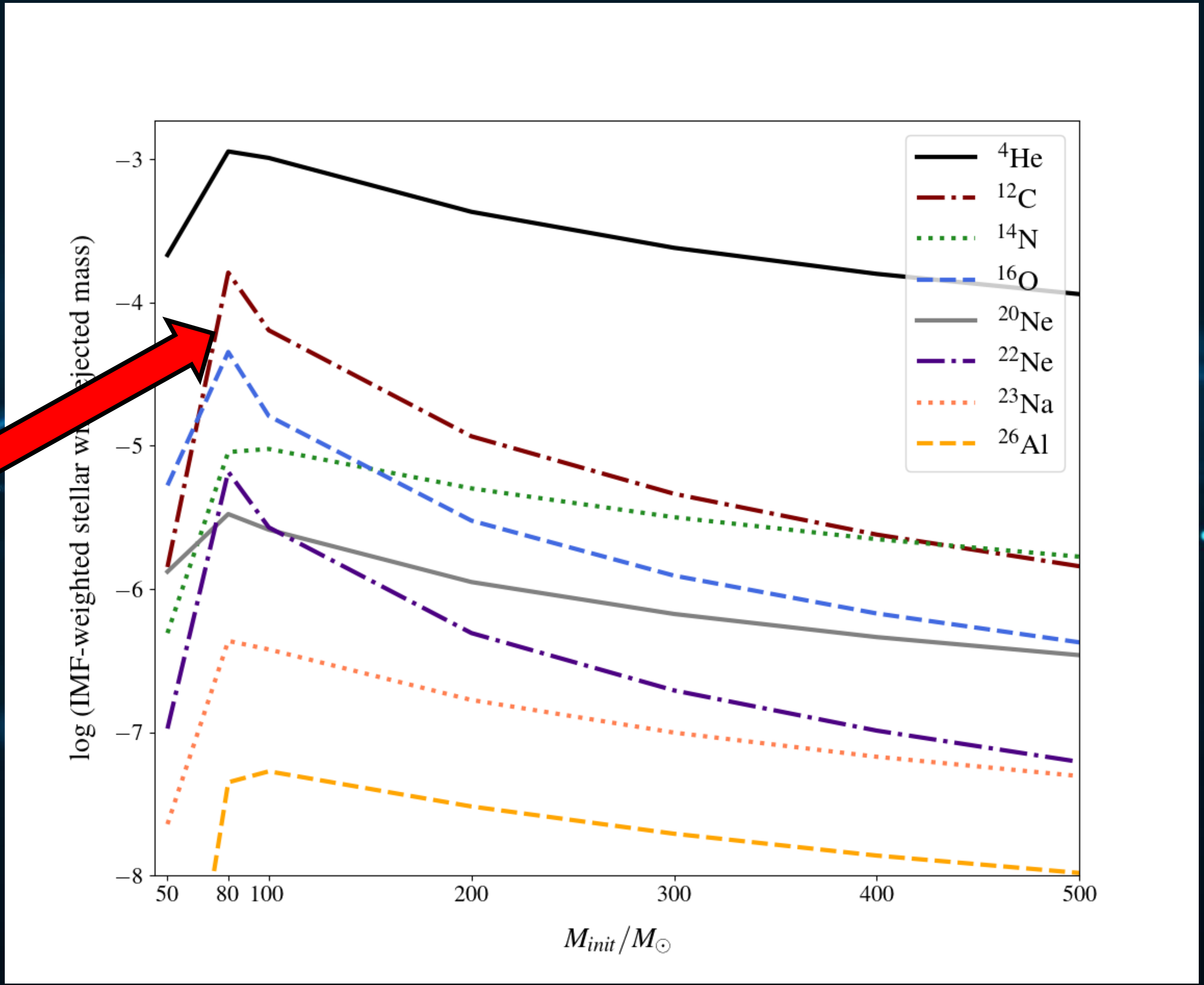
- This has consequences for the enrichment of our Solar system which has been observed to have ~3$M_\odot$ of ^{26}Al which was a key heating source for the Earth's early formation



Higgins et al., (2023)

IMF-weighted yields

Interestingly, we discover that the intermediate mass range of transition stars with M_{init} = 80-100M eject more ^{12}C and ^{16}O than higher mass stars as they do not experience CHE, or do not lose a significant amount of ^{4}He before it is processed on the post-MS.



IMF-weighted yields

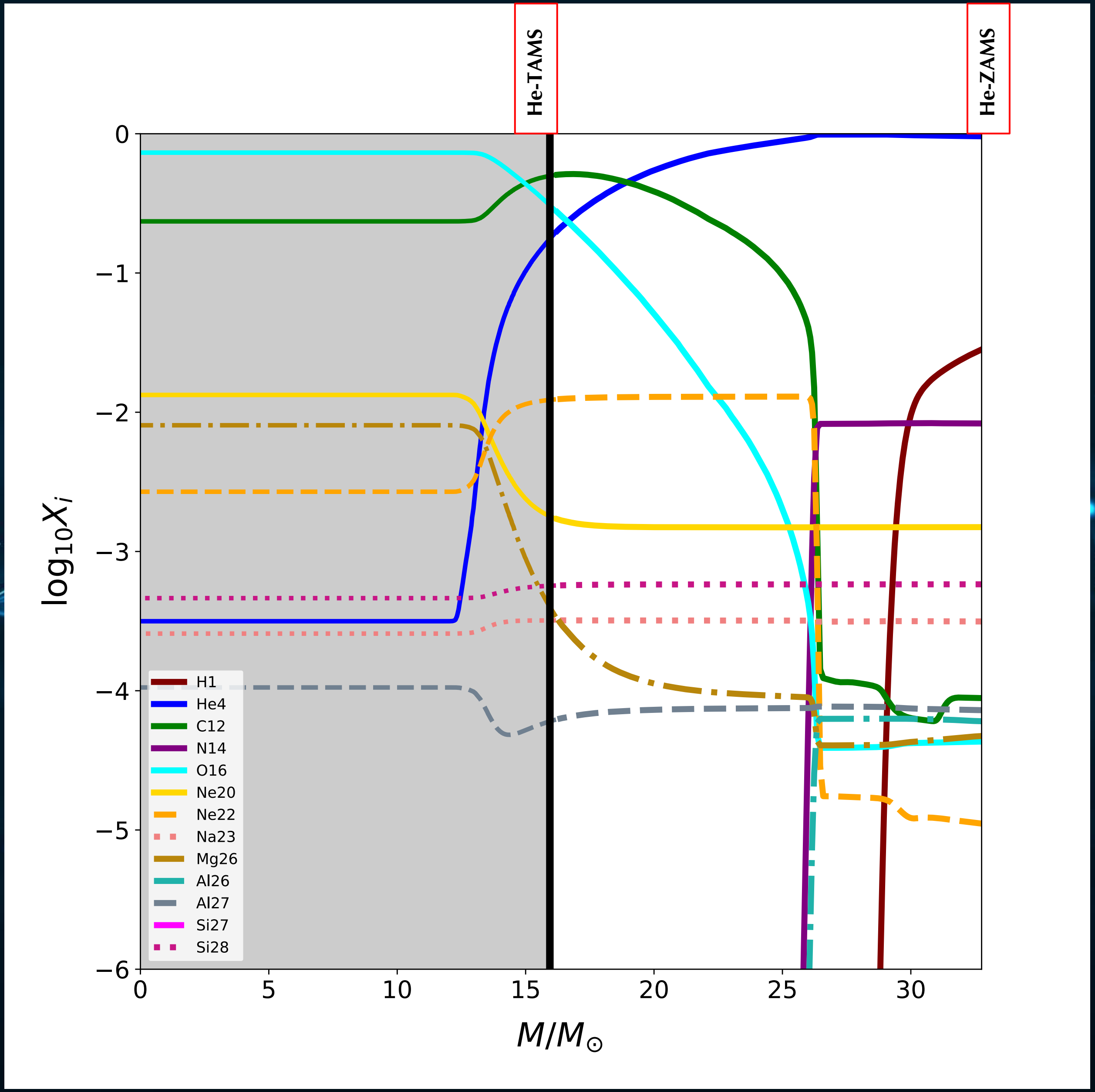
During the entire evolution of VMS yield 10 times more H-processed elements than M < $50M_\odot$ O stars **even when weighted by an IMF**, and they yield positive amounts of ^{4}He, ^{14}N, ^{12}C, and ^{22}Ne, relative to their initial abundances when compared to O stars.

$M_i/M_\odot$	^{4}He	^{12}C	^{14}N	^{16}O	^{20}Ne	^{22}Ne	^{23}Na	^{26}Al
50	3.54E-10	-4.66E-10	2.15E-11	-7.33E-14	-1.51E-14	-1.78E-14	1.71E-14	0
80	4.09E-03	1.13E-03	5.57E-05	2.25E-04	-8.63E-07	4.50E-05	2.69E-06	3.22E-07
100	4.56E-03	4.84E-04	6.74E-05	4.14E-05	-9.51E-07	1.97E-05	2.54E-06	4.25E-07
200	2.57E-03	1.12E-04	4.99E-05	-1.85E-05	-5.95E-07	4.29E-06	1.61E-06	3.30E-07
300	1.65E-03	5.01E-05	3.79E-05	-2.04E-05	-3.73E-07	1.81E-06	1.12E-06	2.56E-07
400	1.18E-03	2.77E-05	3.03E-05	-1.86E-05	-2.84E-07	9.44E-07	8.76E-07	2.05E-07
500	9.13E-04	1.71E-05	2.54E-05	-1.66E-05	-2.23E-07	5.44E-07	7.07E-07	1.71E-07
50	1.25E-03	8.28E-06	2.87E-06	3.08E-05	7.69E-06	6.18E-07	1.33E-07	0
80	8.13E-03	1.16E-03	6.49E-05	3.24E-04	2.40E-05	4.72E-05	3.12E-06	3.22E-07
100	8.09E-03	5.08E-04	7.54E-05	1.28E-04	2.06E-05	2.14E-05	3.01E-06	4.25E-07
200	4.65E-03	1.26E-04	5.47E-05	3.26E-05	1.21E-05	5.35E-06	1.83E-06	3.30E-07
300	3.13E-03	6.02E-05	4.13E-05	1.62E-05	8.73E-06	2.56E-06	1.30E-06	2.56E-07
400	2.35E-03	3.56E-05	3.30E-05	1.00E-05	6.85E-06	1.52E-06	1.00E-06	2.05E-07
500	1.87E-03	2.36E-05	2.76E-05	6.96E-06	5.67E-06	1.02E-06	8.12E-07	1.71E-07

Table 6. IMF-weighted net yields (top) and ejected masses (bottom) calculated with equation (6), for V11 models over the complete evolution until core O-exhaustion. We adopt the IMF of Schneider et al. (2018) where $M^{-1.90}$.

Consequences for the post-MS

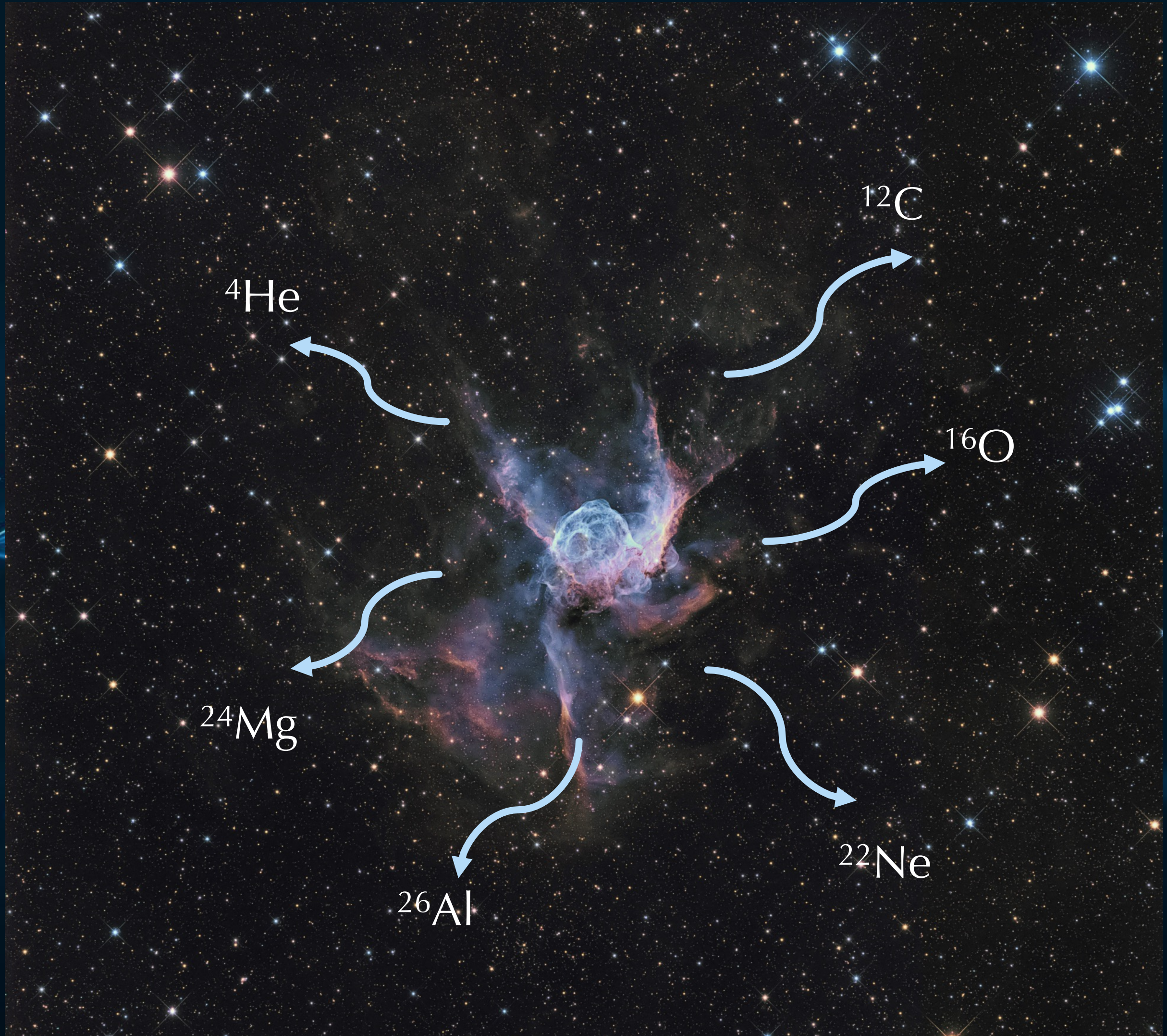
- New Sabhahit et al. 2022 wind prescription for VMS leads to He-ZAMS masses of ~32$M_\odot$ at $Z_\odot$ regardless of initial VMS mass



Higgins et al., (2023)

Chemical enrichment from cWRs

As these stars lose mass through strong Z-dependent winds, they enrich their environment with material including freshly synthesised isotopes which are key tracers in galaxy evolution and star formation

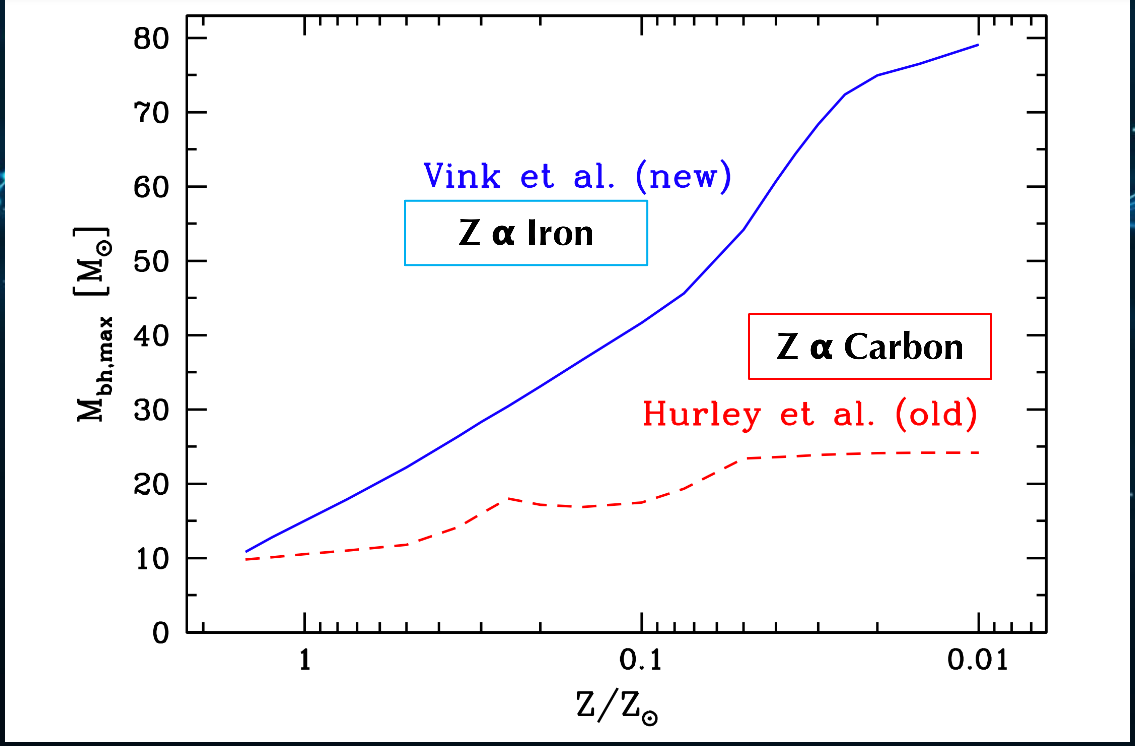


Thor's Helmet Nebula, NGC2359 (Credit: ESO)

Hydrodynamically-consistent stellar atmospheres of Wolf-Rayet winds

- Hamman et al., (1995)
- Nugis & Lamers, (2000)
- Vink & de Koter, (2005)
- Sander & Vink, (2020)

$$\dot{M}_{WR} \propto Z_{Fe}$$



Belczynski et al., 2010

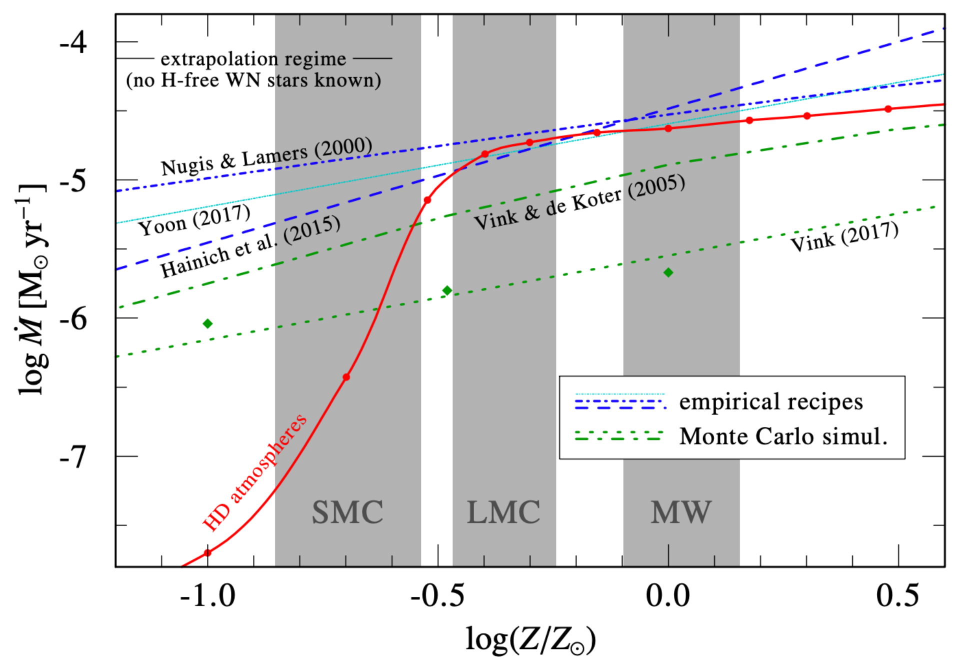
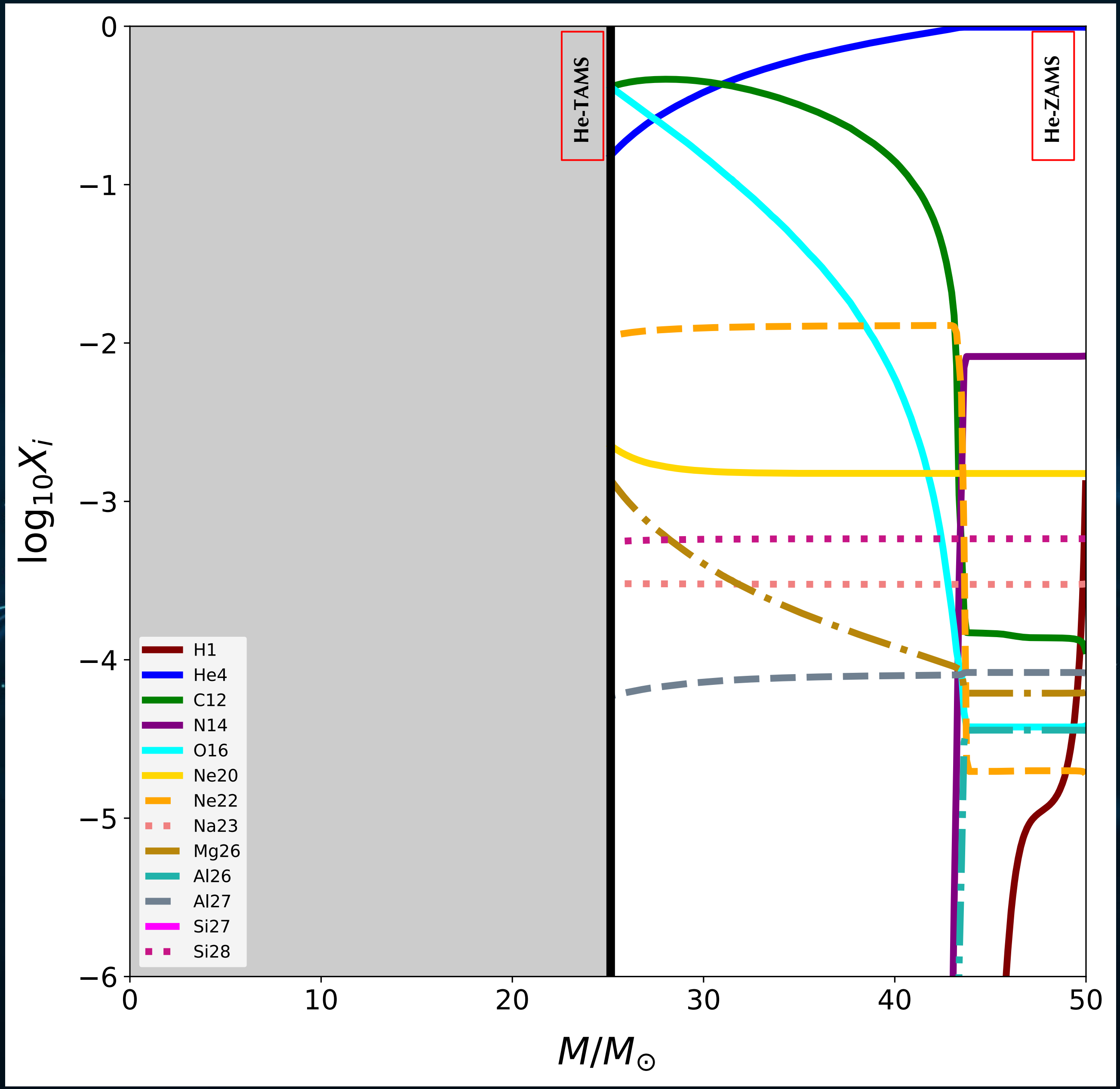


Figure 16. Mass-loss rate $\dot{M}$ as a function of metallicity Z for our hydrogen-free atmosphere models with $20\,M_\odot$, compared to different empirical and theoretical recipes evaluated for $X_H = 0$. The green diamonds denote the individual models from Vink (2017).

Sander & Vink (2020, MNRAS, 499)

Stellar yields of pure Helium stars or cWRs

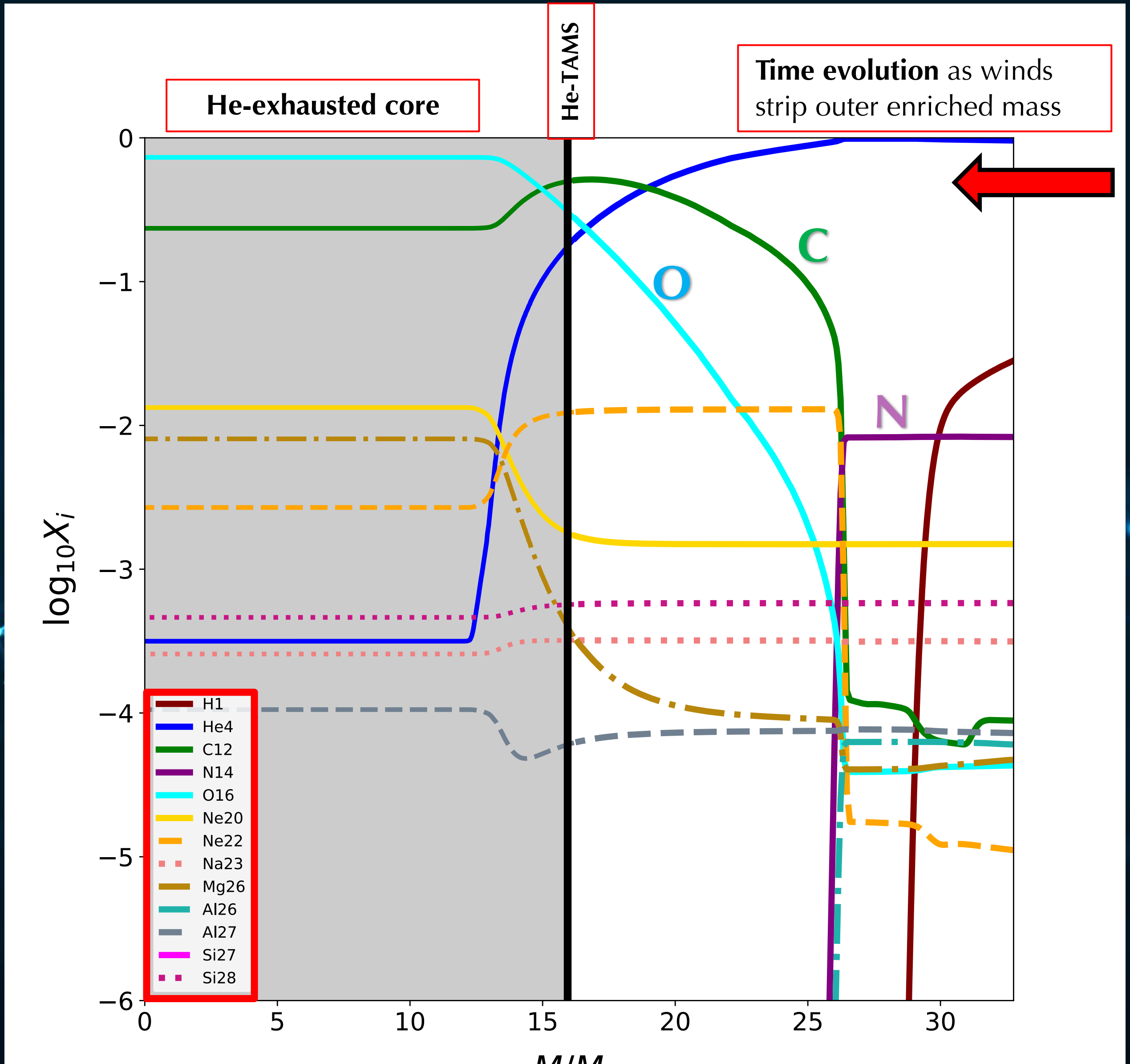
- Grid of models with M_i = 8-50$M_\odot$
- Sander & Vink 2020 wind prescription
- Large nuclear network of 92 isotopes included for relevant reactions until core O-exhaustion
- Chemical yields provided for WR subtypes



Higgins et al., (2024)

Nucleosynthesis

- Comparison with post-MS VMS formation of cWRs from Paper I
- N-rich WR at He-ZAMS, but quickly stripped to show C-enrichment
- Ne-Na cycle shows ^{22}Ne as the most abundant Ne isotope which would be observed in WRs
- These WRs (~30$M_\odot$) eject a factor of 10 more in mass of ^{12}C (~3$M_\odot$) and ^{22}Ne (~0.2$M_\odot$) through stellar winds than MS stars



$M_\mathrm{i} = 100M_\odot$

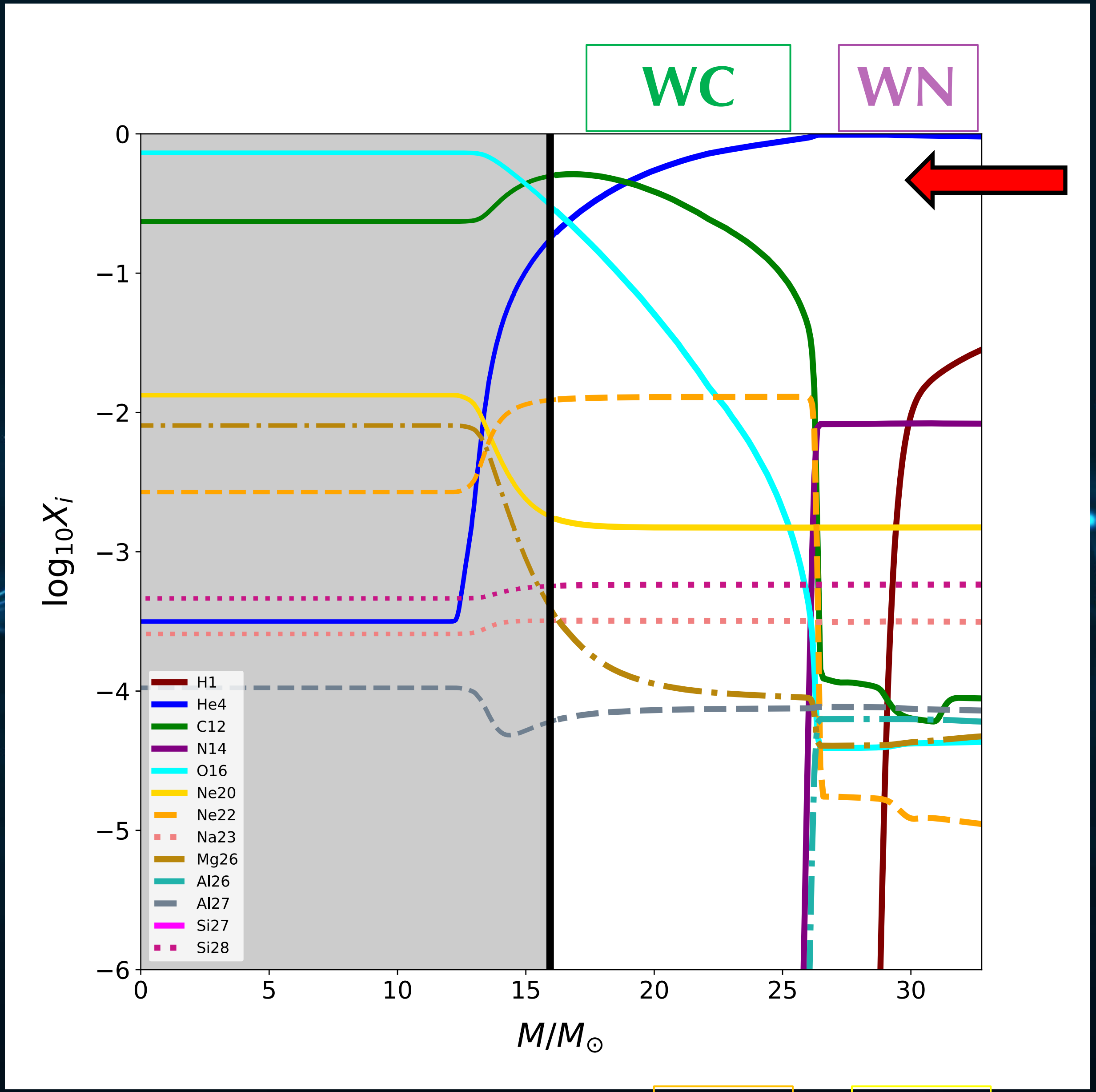
Higgins et al., (2024)

Observable WR subtypes

The observable surface enrichment (and therefore the WR subtype) is dominated by when stars lose mass.

If stars lose a significant amount of N-rich material during the MS, then the WR will appear as a WC star much earlier in the post-MS evolution.

Here the WN star is quickly stripped to show C-enrichment, presenting as a WC star for the majority of the He-burning stage.



^{22}Ne ^{20}Ne

Neutron densities of cWRs

We confirm that during core He-burning, cWRs produce a significant number of neutrons for the weak s-process via the reaction

$$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$$

We find central neutron densities of $3.21\times10^{7}\mathrm{cm}^{-3}$ for a $30\mathrm{M}_{\odot}$ stripped cWR model compared to $N_n = 1.56\times10^{7}\mathrm{cm}^{-3}$ from Frischknecht et al. (2016)

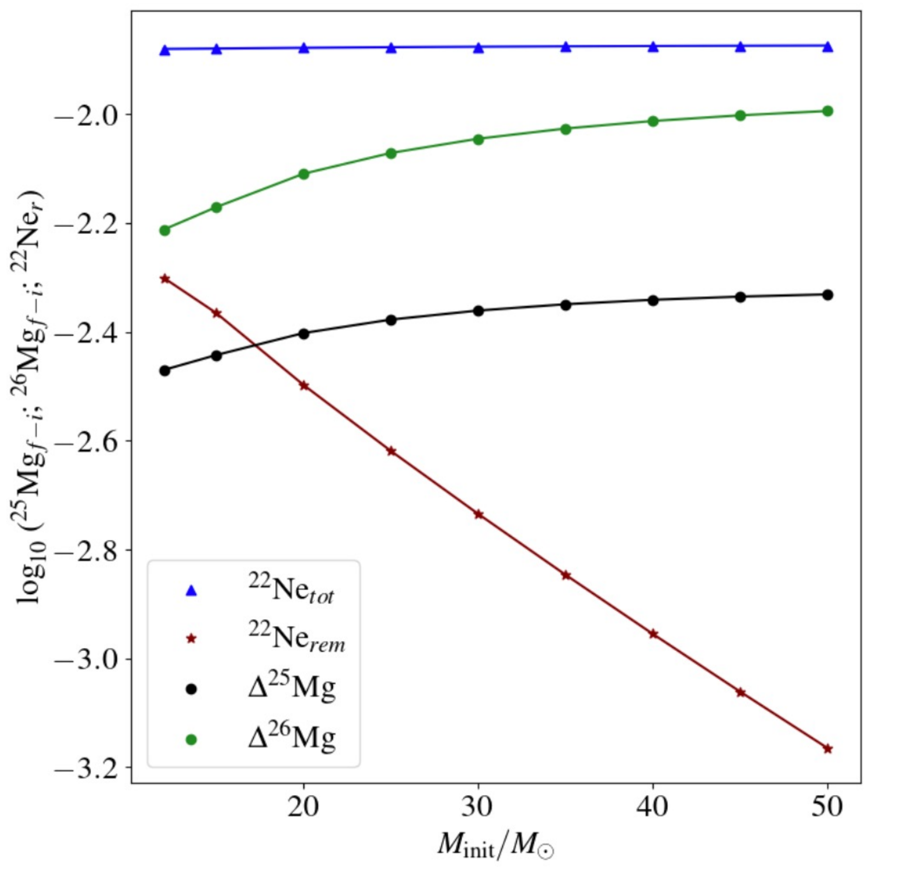


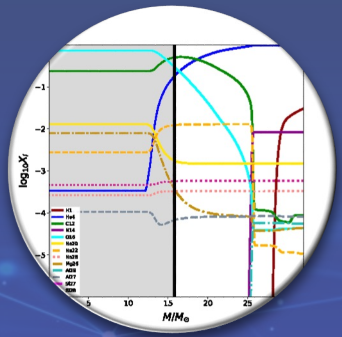
Figure 7. Amount of ^{25}Mg or ^{26}Mg synthesised (in mass fractions) during core He-burning (black dots, green dots), and remaining ^{22}Ne (red stars) at He-exhaustion as a function of initial He-ZAMS mass of each model in our grid. The total ^{22}Ne ($\Delta^{25}\mathrm{Mg}_{\mathrm{f-i}} \times 22/25 + \Delta^{26}\mathrm{Mg}_{\mathrm{f-i}} \times 22/26 + {}^{22}\mathrm{Ne}_{\mathrm{r}}$) is shown with blue triangles.

Conclusions

95% of chemical yields from VMS are lost on the MS with only 5% lost during the post-MS. So the majority of yields will be H-processed (^{26}Al, N, He)

Even when weighted by an IMF, 100M$_\odot$ stars still eject 10 times more nucleosynthesised elements than a 50M$_\odot$ star

New Sabhahit et al (2023) enhanced winds for VMS change yields by ~100M$_\odot$



Isotopes such as ^{22}Ne may be key tracers for cWR evolution and the enrichment of galaxies

Detailed nucleosynthesis provides insight into the progression of WR subtypes and their origins

Thank you for your attention!