The Big-Three reactions for Astrophysics: $^{12}C(\alpha,\gamma)^{16}O$ - $^{12}C^{12}C$ fusion - $^{22}Ne(\alpha,n\gamma)$

Strasburgo: 29 Maggio 2024

The role of the $^{12}C(\alpha,\gamma)^{16}O$ and $^{12}C^{12}C$ fusion on the physical and chemical evolution of the stars

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Petroselinum crispum
prezzemolo - parsley

Carbon plays a role in the evolution of the vast majority of stars

Both ^{12}C and ^{13}C are part of the big family of the CNO cycle

^{13}C plays a pivotal role in the neutron capture nucleosynthesis

But today we will discuss the role ^{12}C has in the physical and chemical evolution of the stars

1938 September

Hans Albrecht Bethe

Energy Production in Stars*

Published March 1939

H. A. BETHE

Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Direct formation of C^{12}

C^{12} may be formed directly in a collision between 3 α-particles. The calculation of the probability is exactly the same as for the formation of B^9. The nonresonance process gives about the same probability as a resonance of Be^8 at 50 kev. With $\rho = 80$, $x_\alpha = \frac{1}{4}$, $\Gamma = 0.1$ electron-volt, $T = 2 \cdot 10^7$ degrees, the probability is 10^{-56} per α-particle, i.e., about 10^{-37} of the proton combination reaction (1). This gives an even smaller yield of C^{12} than the chains described in this and the preceding section. The process is strongly temperature-dependent, but it requires temperatures of $\sim 10^9$ degrees to make it as probable as the proton combination (1).

The considerations of the last two sections show that there is no way in which nuclei heavier than helium can be produced permanently in the interior of stars under present conditions. We can therefore drop the discussion of the building up of elements entirely and can confine ourselves to the energy production which is, in fact, the only observable process in stars.

1954 (1951)

Ernst Opik

1952

Edwin Ernest Salpeter

6 — THE CHEMICAL COMPOSITION OF WHITE DWARFS

BY

E. J. ÖPIK

Armagh Observatory, N. Ireland

It has been pointed out by the writer (1) that, after the complete exhaustion of hydrogen, but before the final collapse into the white dwarf stage, the internal temperature of stars with masses exceeding 0.5—0.7 $_{\odot}$ may rise high enough for the conversion of all, or most of its helium into heavier elements. The reaction made responsible for this process would consist in triple collisions of helium nuclei leading to the formation of one carbon nucleus, according to

$$\begin{aligned} He^4 + He^4 &\rightarrow (Be^8), && (a)\\ (Be^8) + He^4 &\rightarrow C^{12} + \gamma \; . && (b) \end{aligned} \qquad (1)$$

Reaction (1)(a) would correspond to penetration only, not necessarily followed by the formation of true Be^8. The frequency of the reaction is thus assumed proportional to the encounter cross-section (square of the de Broglie wave-length), and to the probability of penetration (non-resonance case), without the probability factor for radiative capture. The life-time of the temporary nucleus (Be^8) formed is assumed equal to $\sim 8 \times 10^{-21}$ sec, being an estimate of the duration of penetration. The life-time of true Be^8 is probably much shorter, about 10^{-22} sec [(7), *et alias*].

The frequency of the reaction (1)(b) can be calculated with the usual formulae, e.g. those of Gamow or Bethe. Non-resonance capture is assumed in this case also.

Defining the life-time of helium through

$$t_o = -Y \Big/ \left(\frac{dY}{dt}\right), \qquad (2)$$

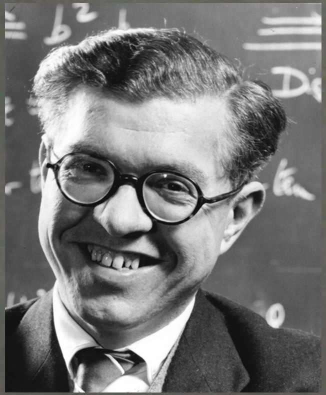
where Y = concentration of helium by weight, from Gamow's formulae [(8), allowance being made for several errata, only partly pointed out by the author] it is found as follows [(1), p. 71] :

$$t_o = 1.5 \times 10^{-12}\, Y^{-2} \rho^{-2}\, T^{4/3}\, e^{37100/T^{1/3}} \text{ (seconds).} \qquad (3)$$

The formula has been checked and should represent well the order of magnitude for the non-resonance processes. Here ρ = density g/cm³, T = temperature °K. The reaction is astrophysically significant for $T > 3 \times 10^8$, and very intense at $T > 4 \times 10^8$ (1).

The formation of C^{12} from helium has been considered also by E.E. Salpeter (2), apparently without a knowledge of the writer's previous suggestion. His method of calculation is not quite clear from his brief note. It seems that reaction (1)(a) he has treated in a manner similar to ours, whereas in (1)(b) he has postulated a resonance process. The outcome is a formula yielding 1.4×10^{13} times higher an energy generation with a practically similar temperature dependence as that of equation (3). Of the discrepancy, a factor of 10^3 - 10^4 seems to refer to reaction (a) and is about equivalent to the omission of the probability of penetration; the rest, a factor of 10^9 — 10^{10}, is about what might be expected for the difference in the rate of a resonance reaction (with low-lying resonance levels), and that of a non-resonance process at $T = 2 \times 10^8$.

1954



Sir Fred Hoyle

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. Hoyle*

Mount Wilson and Palomar Observatories
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California Institute of Technology

Received December 22, 1953

$A_0 = 4$, $Z_0 = 2$, and $A_1 = 8$, $Z_1 = 4$, in the formulae of the previous section. The important energy level of the C^{12} nucleus in the present problem is one very recently identified by Dunbar, Pixley, Wenzel, and Whaling (1953). This level occurs at about 7.68 mev above ground level, which corresponds to a value of E_R of about 0.31 mev. (It will

It can be shown that reaction (25) is the most effective in destroying C^{12}. Hence, to decide how far C^{12} accumulates, it is necessary to compare the rates of reactions (24) and (25). For the latter reaction the value of E_R of main interest is -0.05 mev, corresponding

$3\alpha \to {}^{12}\mathrm{C}$
${}^{12}\mathrm{C}(\alpha, \gamma){}^{16}\mathrm{O}$

1953

D.N.F. Dunbar

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

The 7.68-Mev State in C^{12}

D. N. F. Dunbar,* R. E. Pixley, W. A. Wenzel, and W. Whaling
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68 ± 0.03 Mev. At $E_d=620$ kev, $\theta_{\mathrm{lab}}=90°$, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of $O^{16}:C^{12}:He^4$ that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C^{12}.

An early measurement of the range of the alpha particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} at 7.62 Mev.[4] However, a recent magnetic analysis of this reaction failed to detect a transition to any level in this region of excitation,[5] nor did the level show up in the neutron spectrum[6] from $B^{11}(d,n)C^{12}$. From the

* On leave from the University of Melbourne, Melbourne, Australia.
[1] E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.
[2] E. J. Öpic, Proc. Roy. Irish Acad. **A54**, 49 (1952).
[3] F. Hoyle (private communication).
[4] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).
[5] R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).
[6] W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 586 (1949); V. R. Johnson, Phys. Rev. **86**, 302 (1952).

Adopted nuclear cross sections

PHYSICAL REVIEW C **75**, 015803 (2007)

Expectations for ^{12}C and ^{16}O induced fusion cross sections at energies of astrophysical interest

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(Received 6 October 2006; published 12 January 2007)

The Astrophysical Journal, 567:643–650, 2002 March 1

ASTROPHYSICAL REACTION RATE OF ^{12}C(α, γ)^{16}O

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ELSEVIER
Atomic Data and Nuclear Data Tables
Volume 40, Issue 2, November 1988, Pages 283-334

Thermonuclear reaction rates V ☆

Georgeanne R. Caughlan [1 2], William A. Fowler [1 2 †]

LETTER
https://doi.org/10.1038/s41586-018-0149-

An increase in the ^{12}C + ^{12}C fusion rate from resonances at astrophysical energies

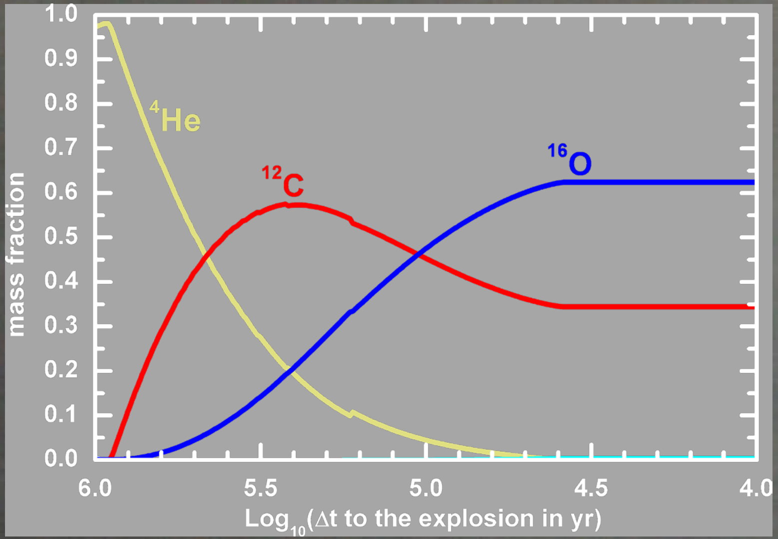
A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

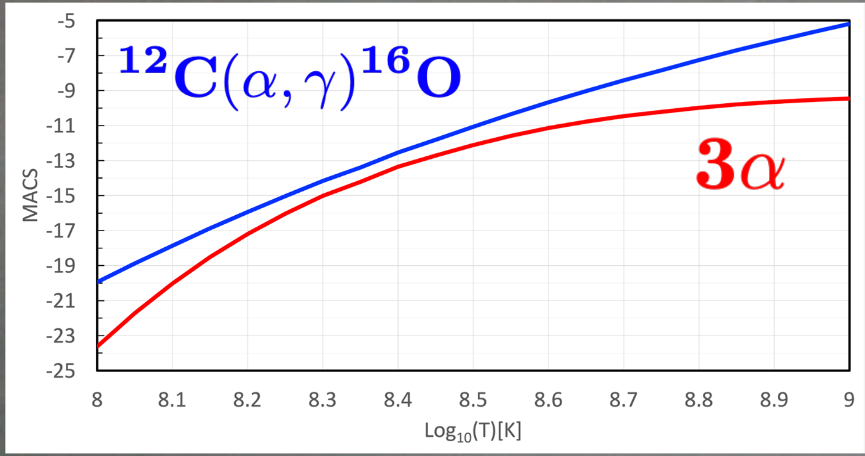
He burning

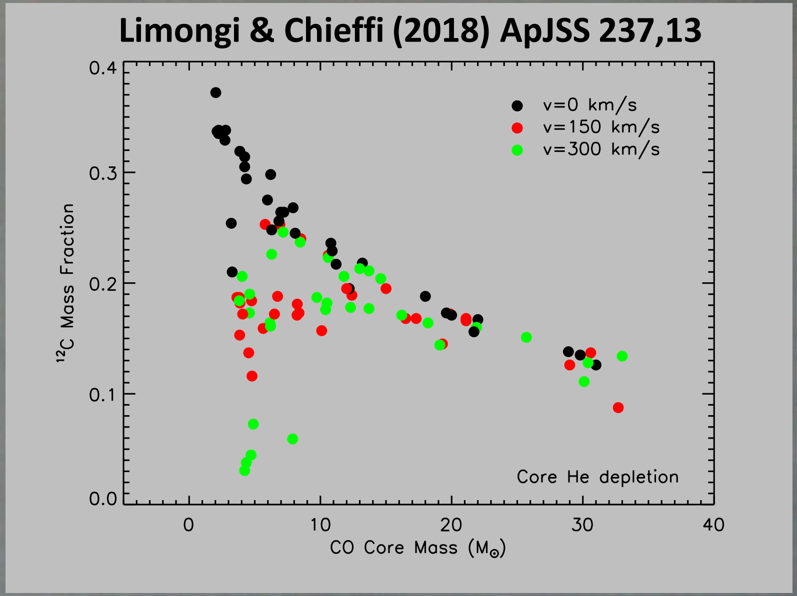
The nuclear processes important in He burning are just the:

$$3\alpha \rightarrow {}^{12}\mathrm{C} \qquad {}^{12}\mathrm{C}(\alpha,\gamma){}^{16}\mathrm{O}$$

Q=7.27 MeV Q=7.16 MeV







He burning

The nuclear processes important in He burning are just two:

$$3\alpha \rightarrow {}^{12}\mathrm{C} \qquad {}^{12}\mathrm{C}(\alpha,\gamma){}^{16}\mathrm{O}$$

Q=7.27 MeV **Q=7.16 MeV**

The amount of ^{12}C left by the central He burning scales inversely with the MACS of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

The central He burning lifetime scales directly with the efficiency of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

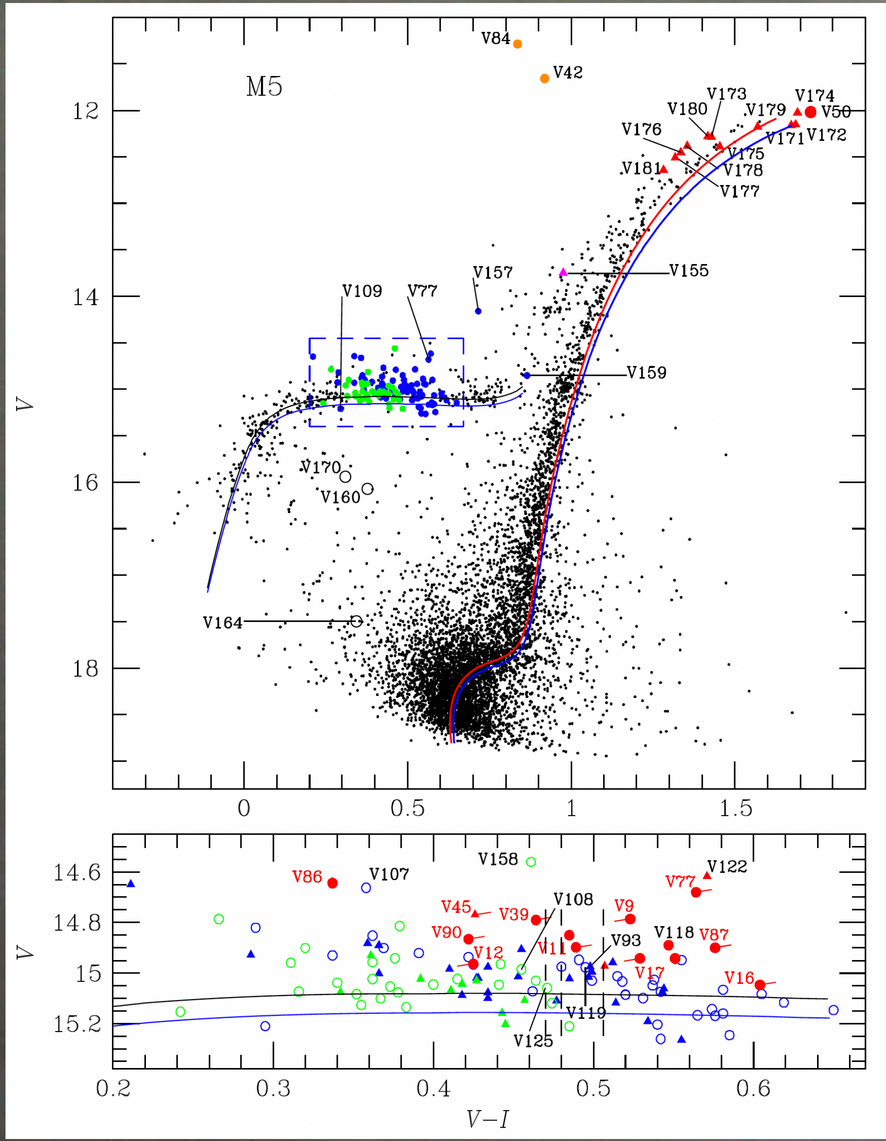
The mass of the He core at the end of the central He burning scales directly with the efficiency of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

The current mass of the star at the end of the central He burning scales inversely with the efficiency of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

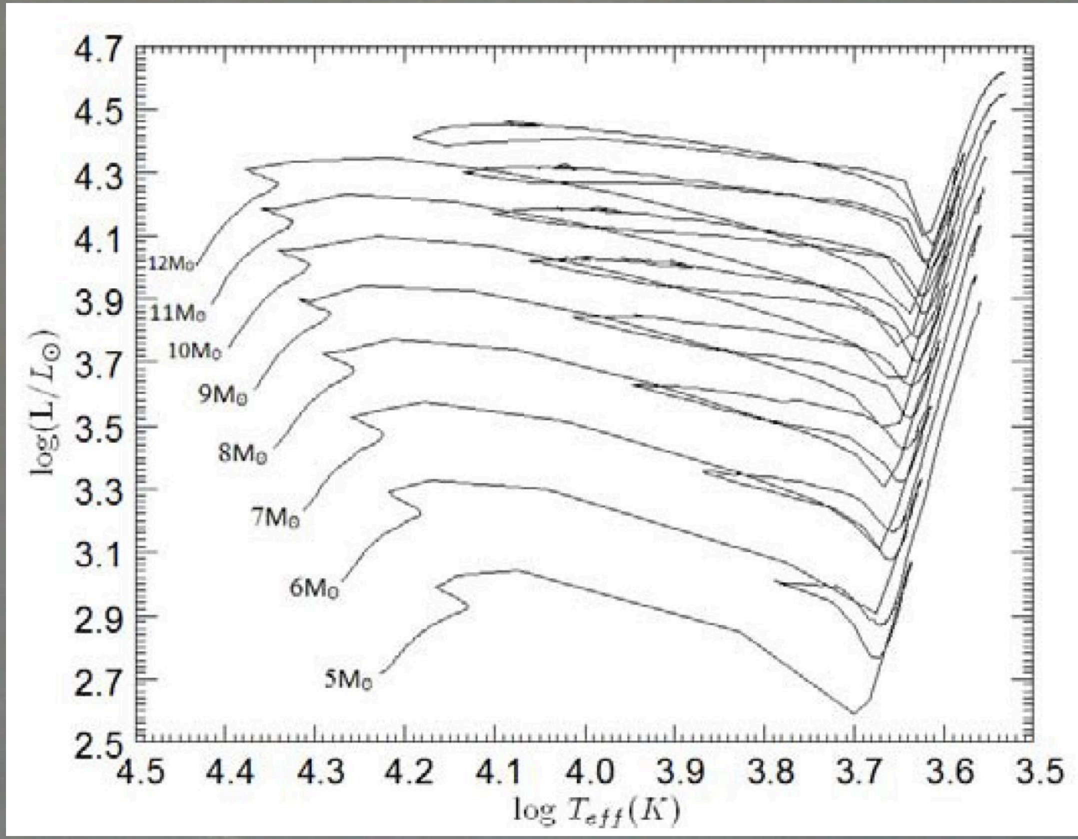
An increase of the MACS of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ changes (moderately) the surface properties of the stars in central He burning together to the time spent by them at each luminosity and effective temperature:

Such an increase probably shows up more clearly in stars of low and intermediate mass

Shape of the HB morphology and the range of masses that enter the Cepheids instability strip (see, Imbriani+ ApJ 2001,558)

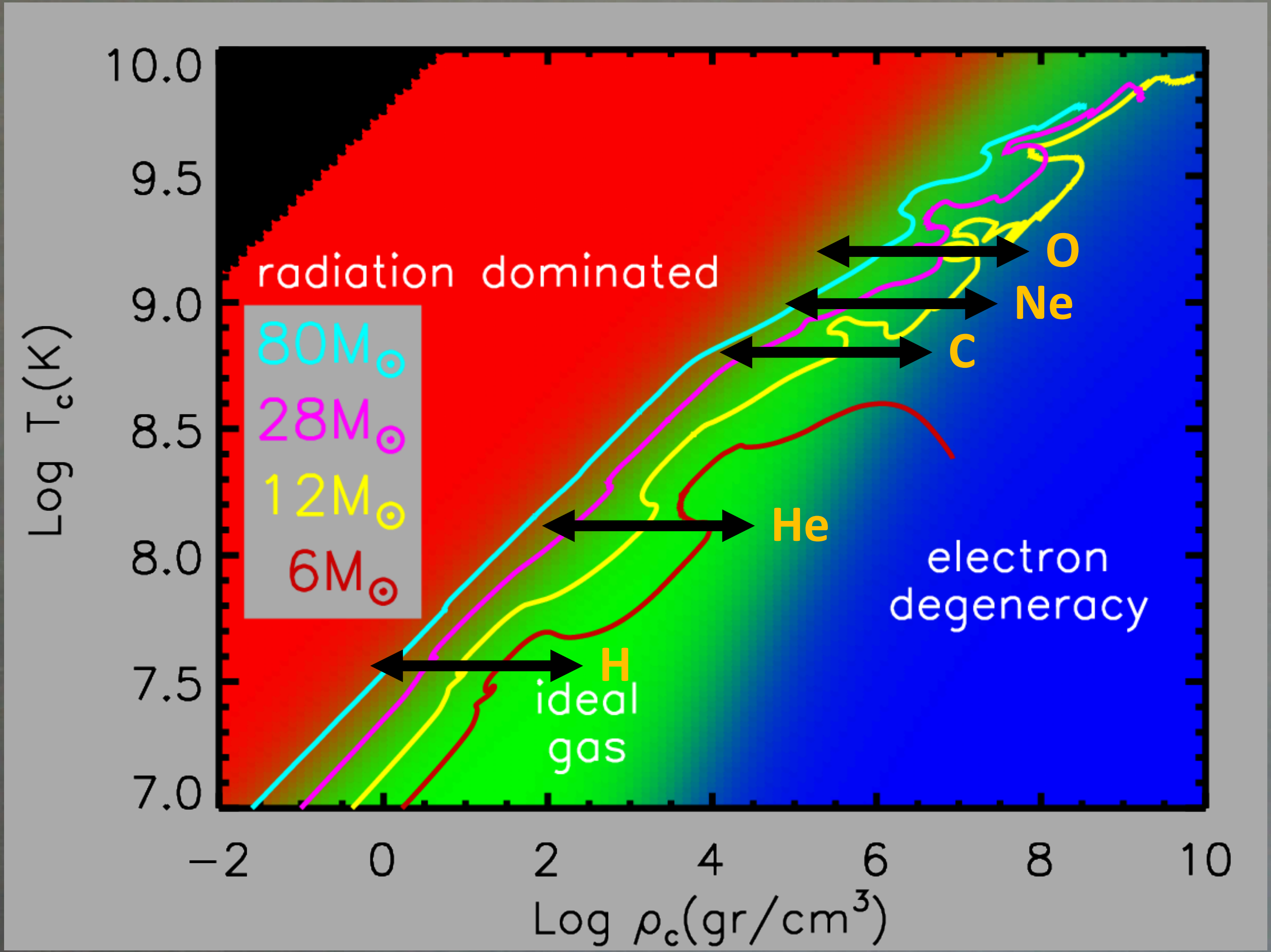


Arellano Ferro+ Astrophys.Space Sci 2016 361,175



Brunish & Becker 1990 ApJ 351, 258

Bono+ 2000 ApJ 543, 955



radiation dominated
80M⊙
28M⊙
12M⊙
6M⊙
O
Ne
C
He
H
ideal gas
electron degeneracy
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Log T_c(K)
−2
0
2
4
6
8
10
Log ρ_c(gr/cm^3)

The $^{12}C(\alpha,\gamma)^{16}O$ shows its importance when in combo with the fusion of $^{12}C^{12}C$

$$RATE_{ij} \propto X_i \, X_j \, \langle MACS \rangle_{ij}$$

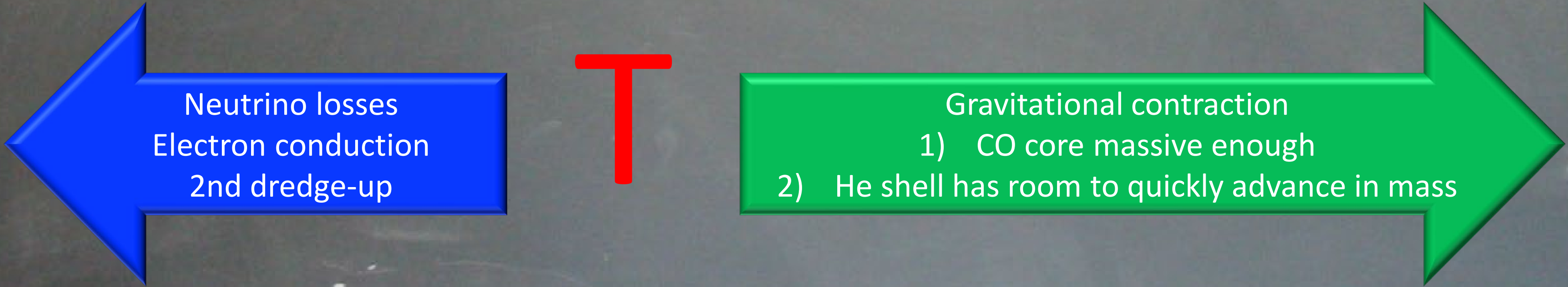
Golden rule

The inner core of a star heats because of the gravitational compression

A star whose inner core does NOT enter the electron degeneracy region, contracts and heats regardless of any nuclear reaction: if anything, the activation of the nuclear reactions actually slows down the contraction and heating of the inner core

A star whose inner core ENTERS the electron degeneracy region, requires active nuclear reactions to raise the temperature: it is the advance of the burning shell(s) that allows the electron degenerate core to heat and eventually ignite a given burning

Hence: which stars form and which do not, an electron degenerate core?

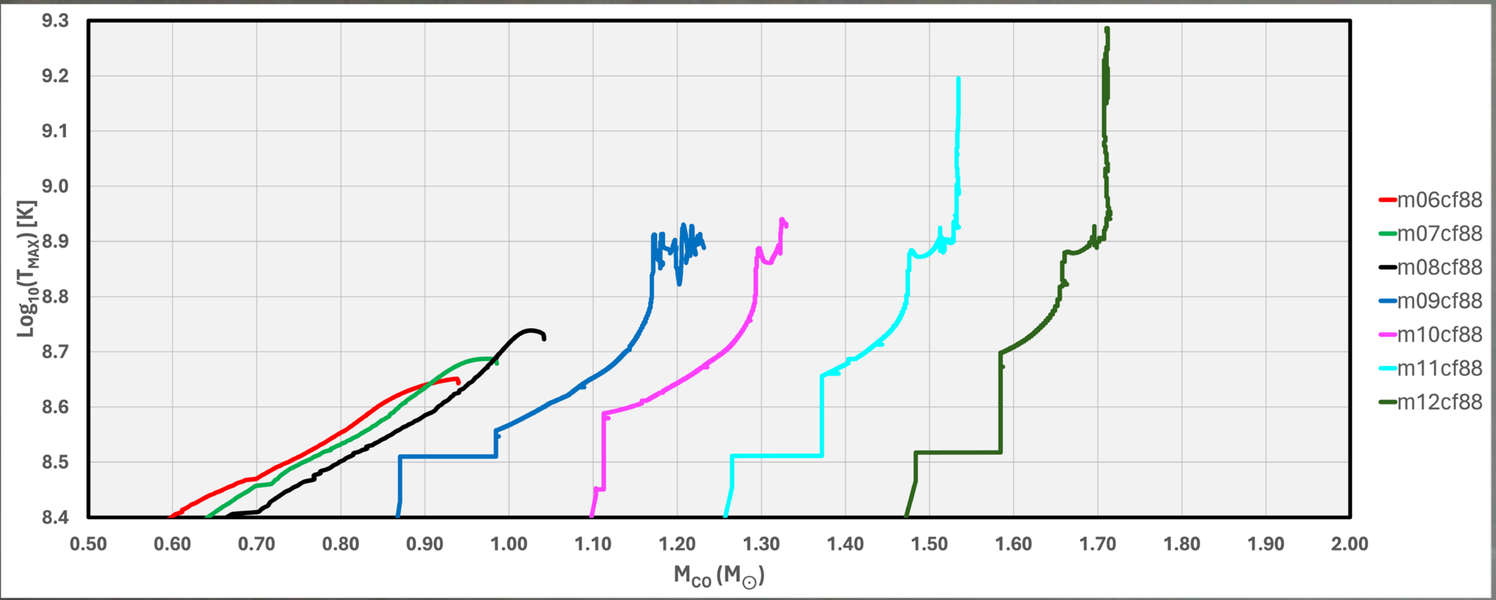

Neutrino losses
Electron conduction
2nd dredge-up
T
Gravitational contraction
1) CO core massive enough
2) He shell has room to quickly advance in mass

Neutrino losses
Electron conduction
2nd dredge-up

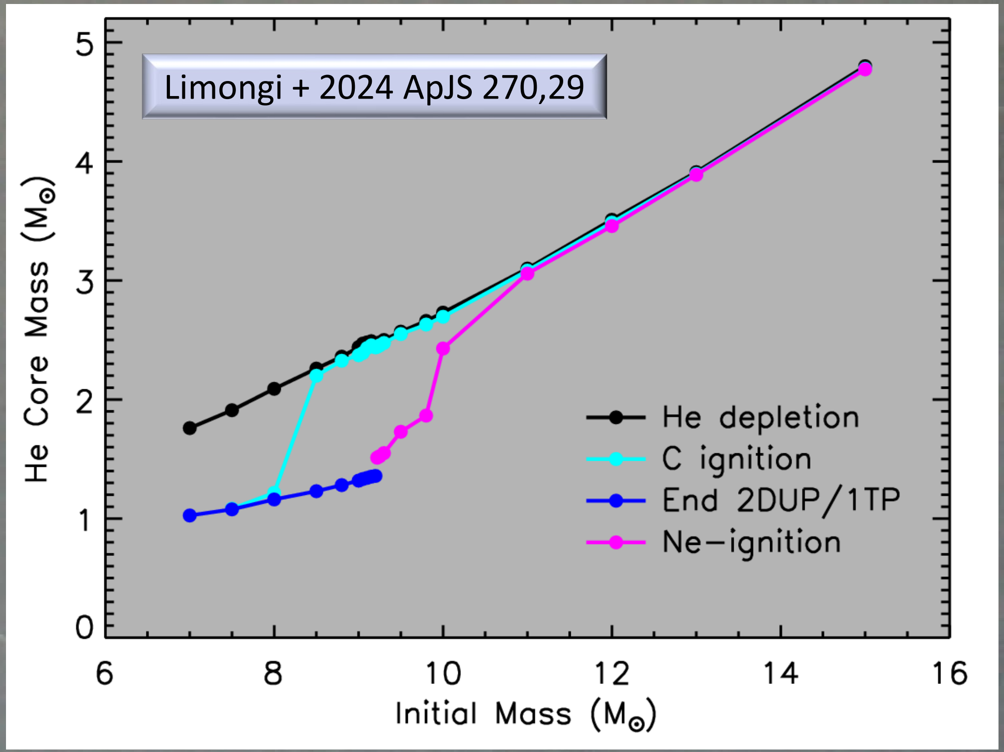
T

Gravitational contraction

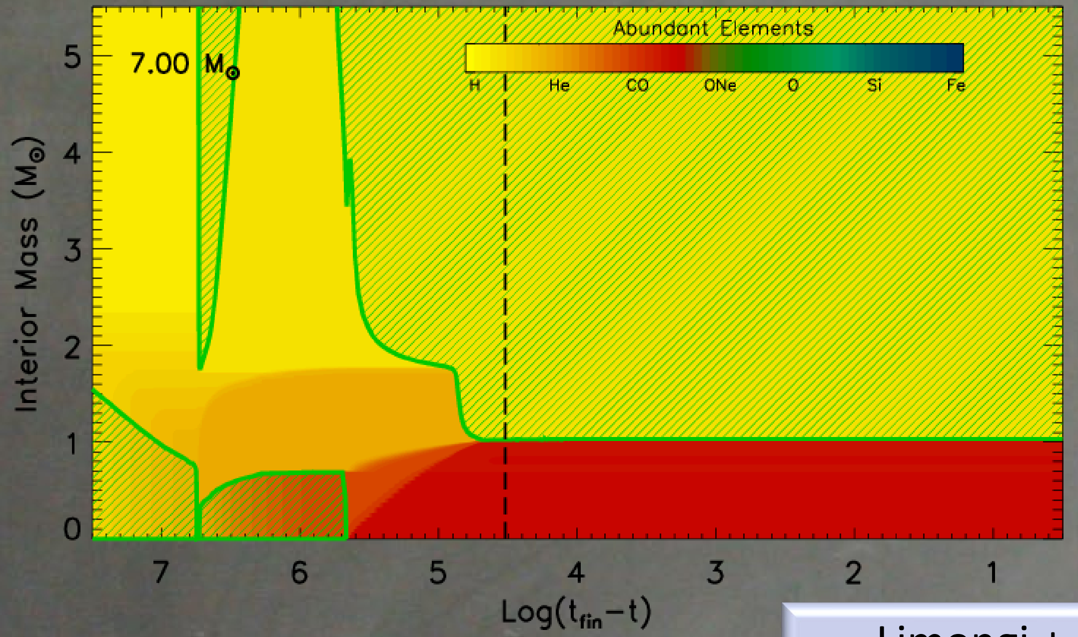
1) CO core massive enough
2) He shell has room to quickly advance in mass

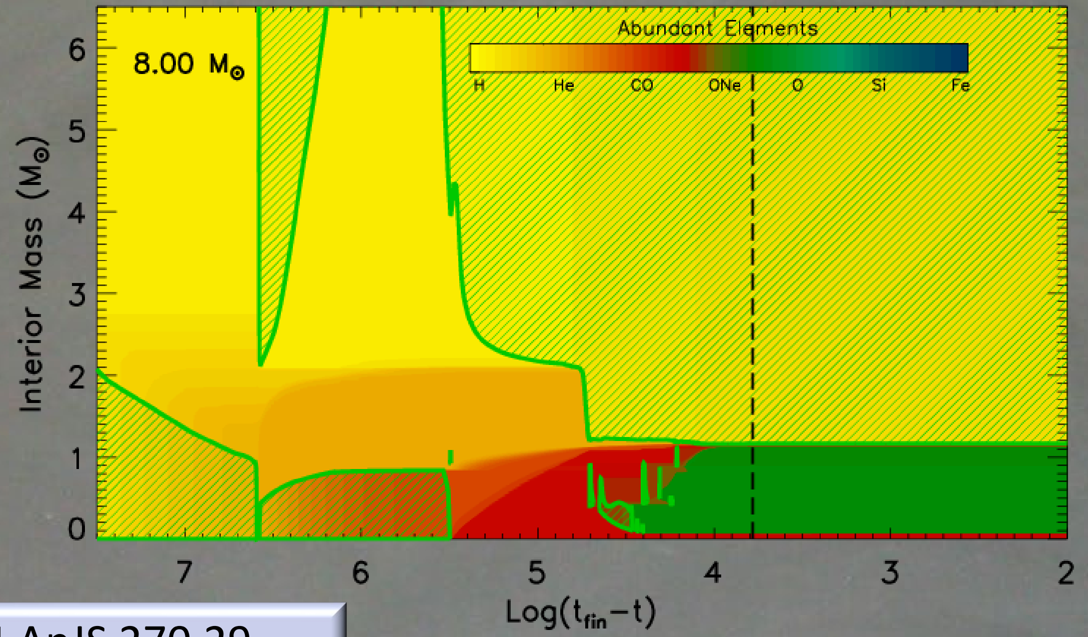


Log10(TMAX) [K]
9.3
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
MCO (M☉)
m06cf88
m07cf88
m08cf88
m09cf88
m10cf88
m11cf88
m12cf88

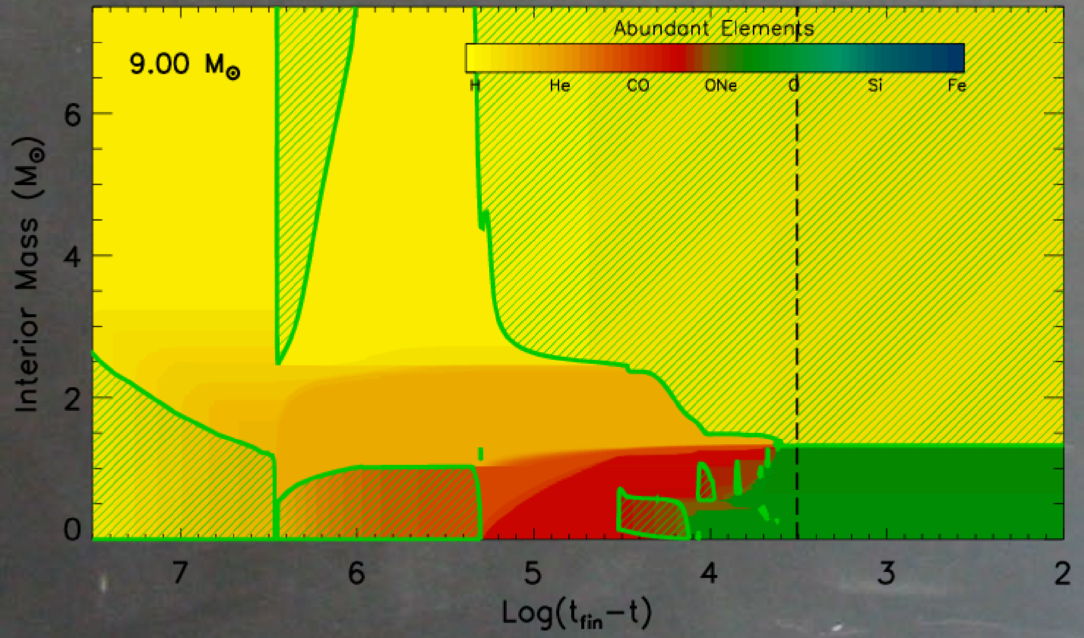


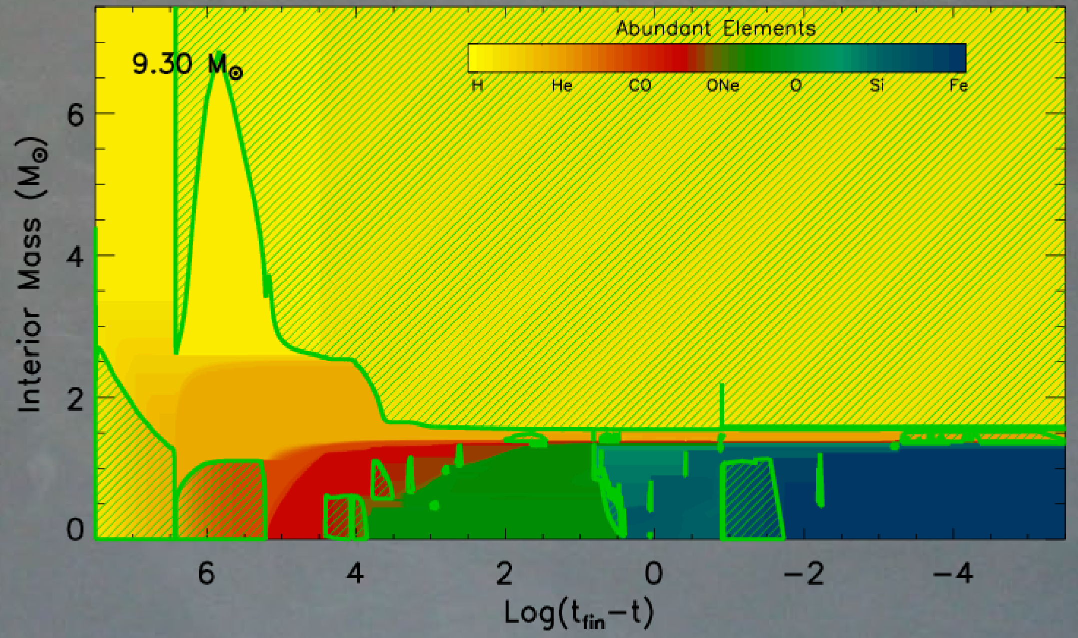
Limongi + 2024 ApJS 270,29
He Core Mass (M☉)
0
1
2
3
4
5
6
8
10
12
14
16
Initial Mass (M☉)
He depletion
C ignition
End 2DUP/1TP
Ne-ignition

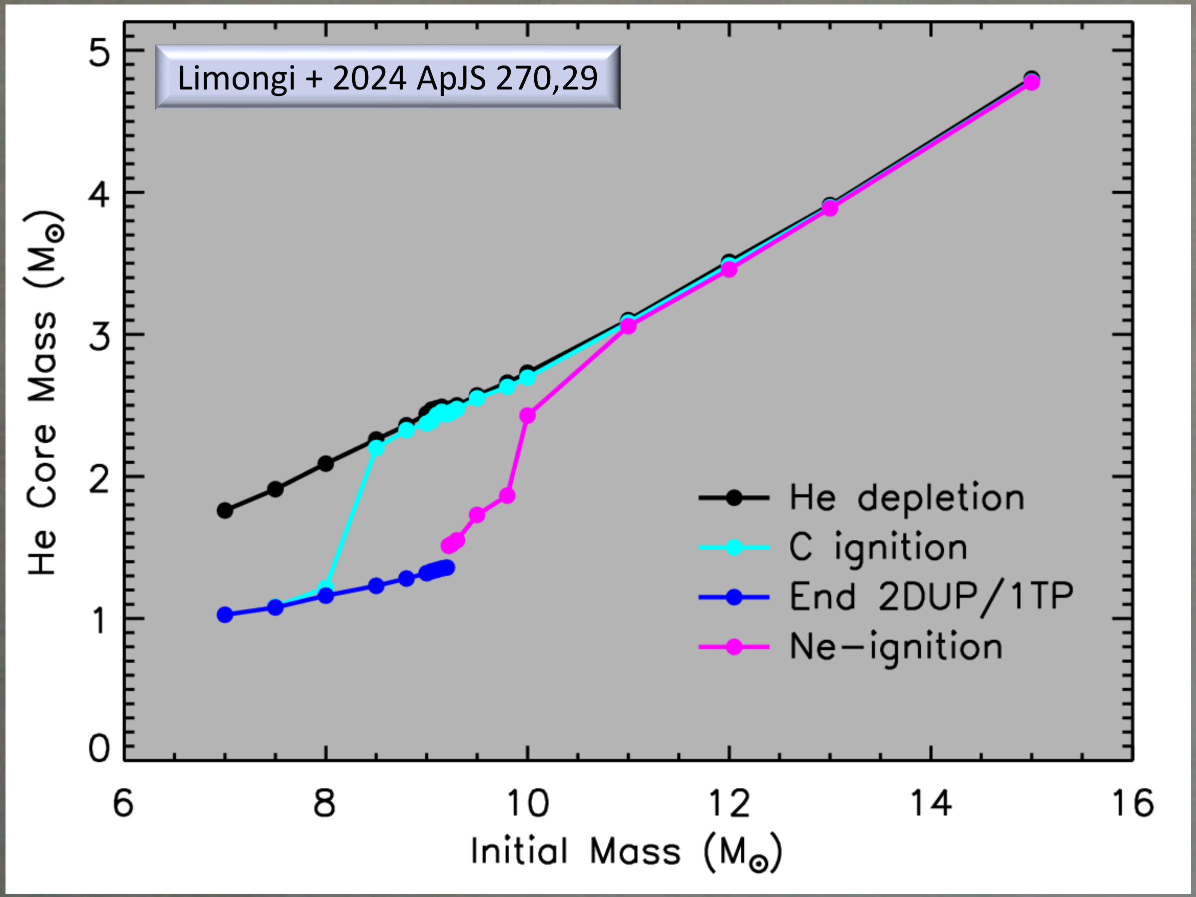


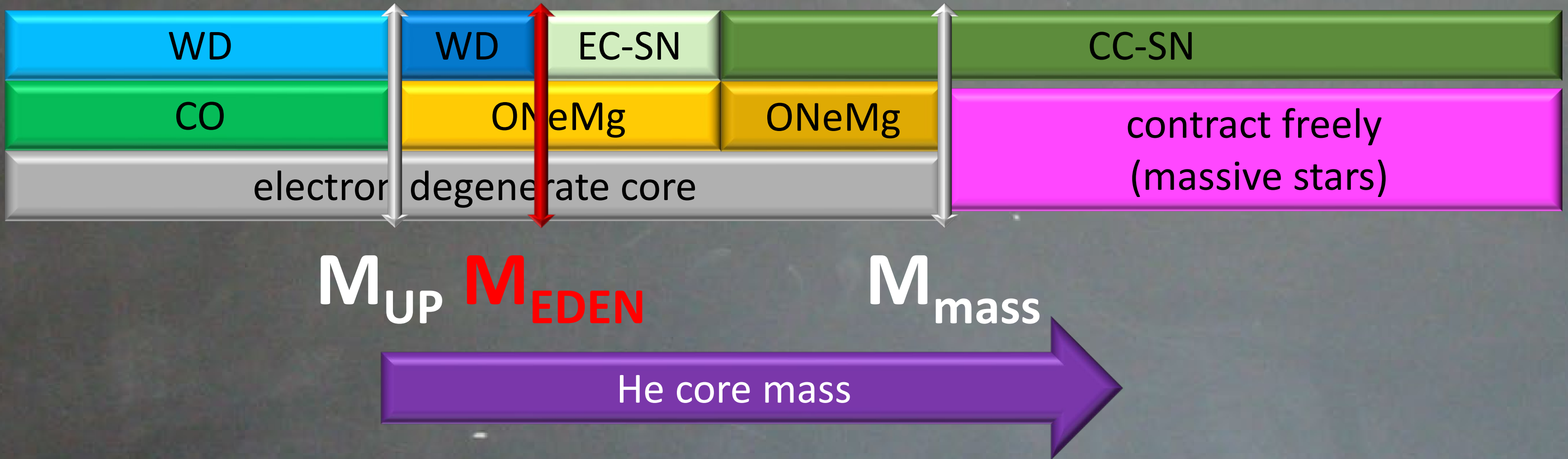


Limongi + 2024 ApJS 270,29

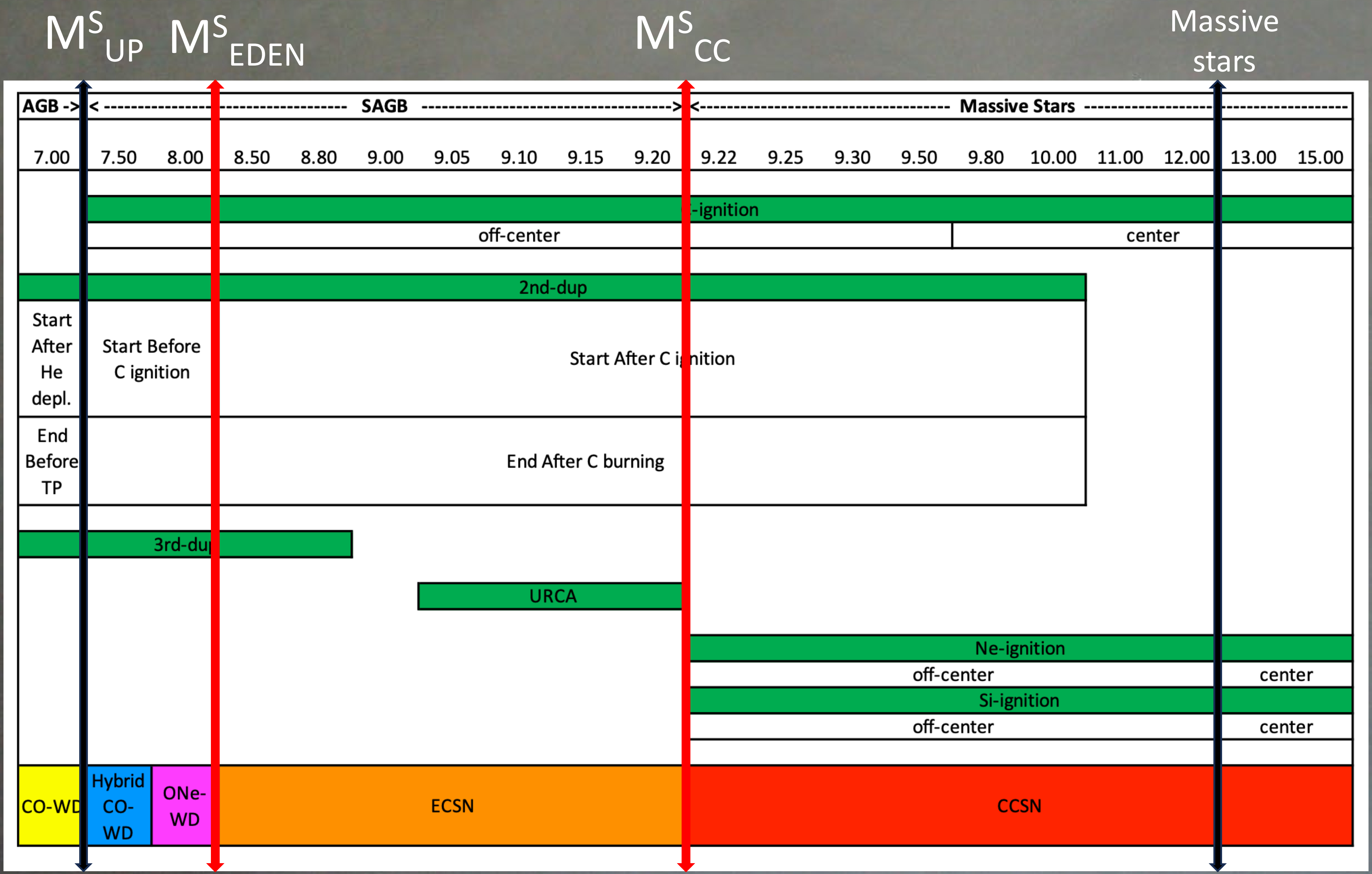


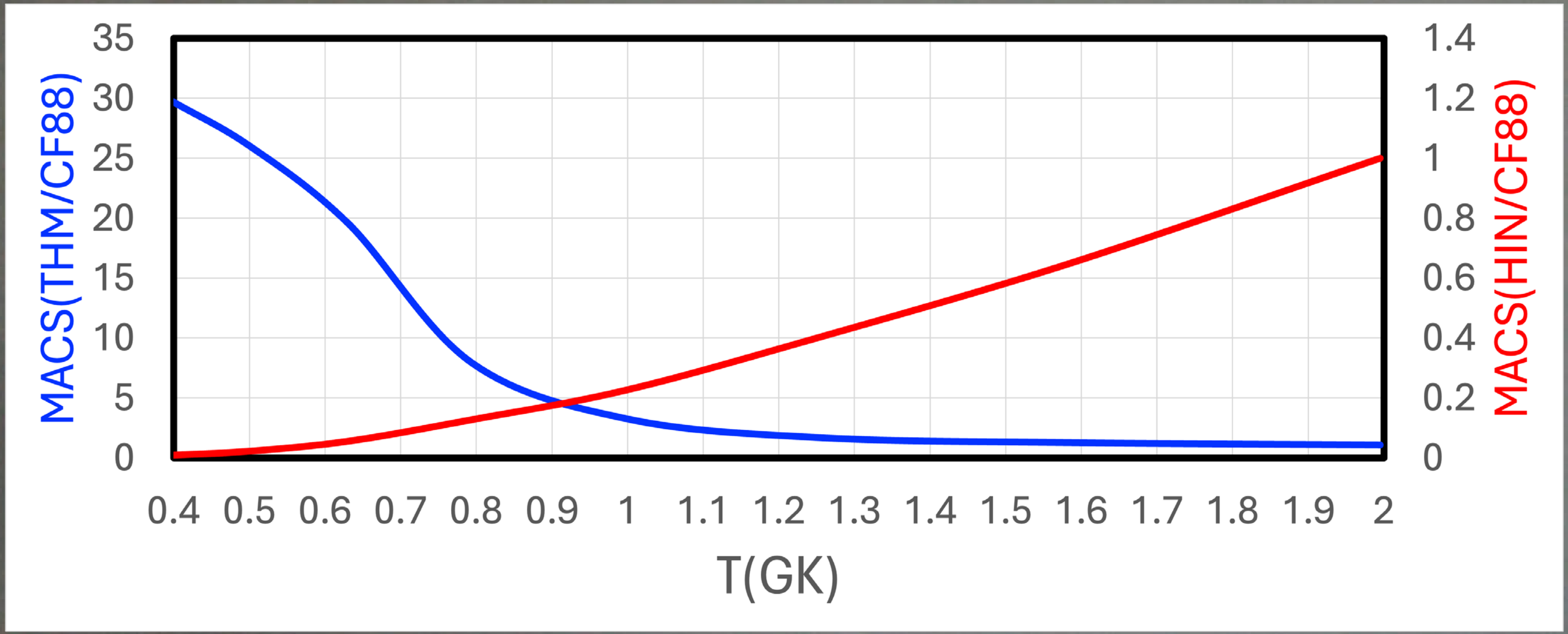


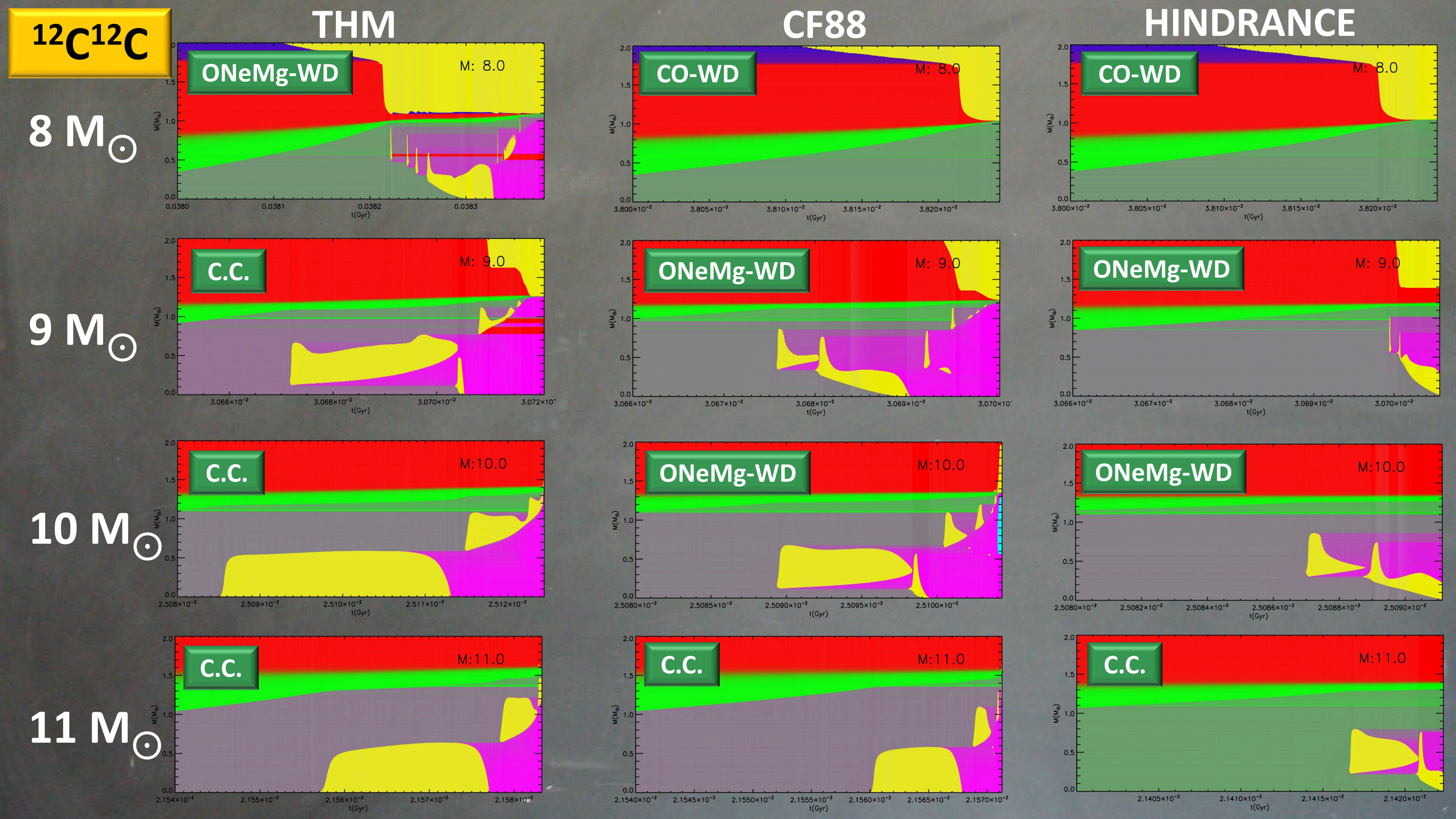

Limongi + 2024 ApJS 270,29
He Core Mass (M⊙)
Initial Mass (M⊙)
He depletion
C ignition
End 2DUP/1TP
Ne−ignition
0
1
2
3
4
5
6
8
10
12
14
16


WD
WD
EC-SN
CC-SN
CO
ONeMg
ONeMg
contract freely
(massive stars)
electron degenerate core
M_{UP}
M_{EDEN}
M_{mass}
He core mass

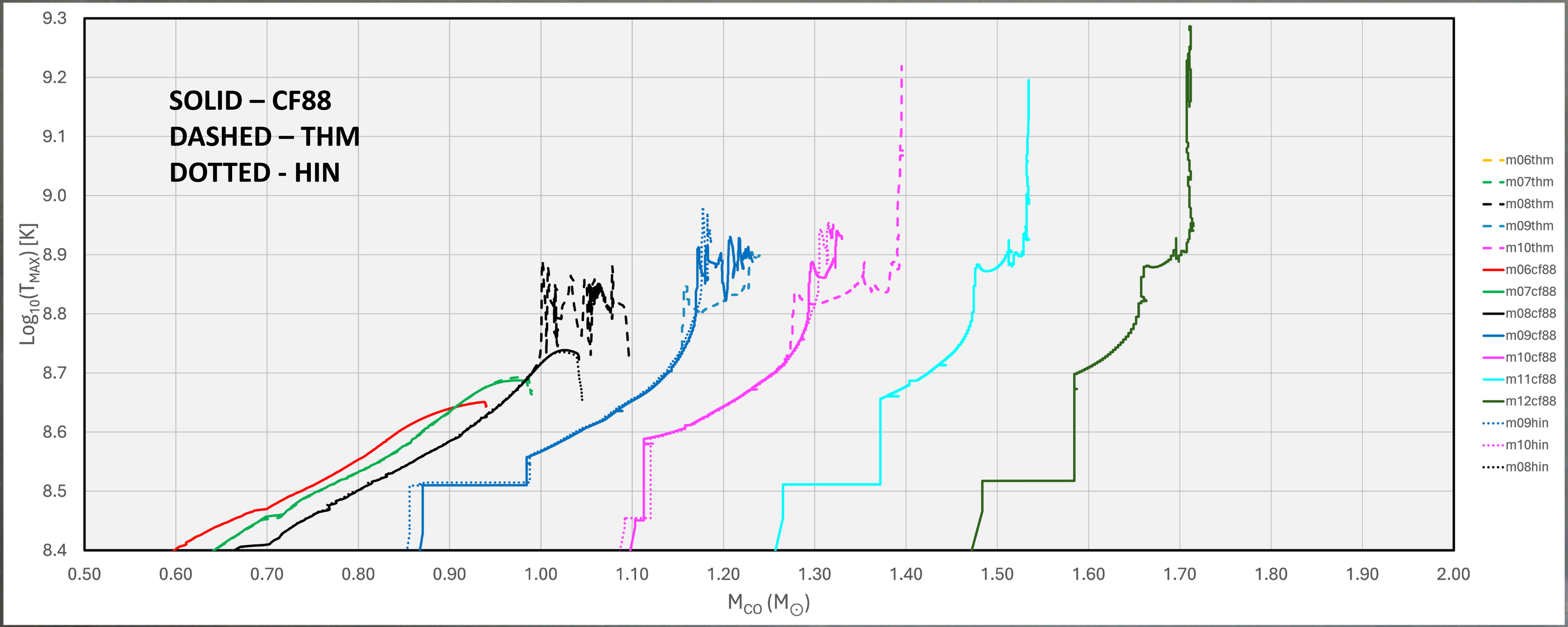
Limongi + 2024 ApJS 270,29




35
30
25
20
15
10
5
0
MACS(THM/CF88)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
MACS(HIN/CF88)
0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
T(GK)



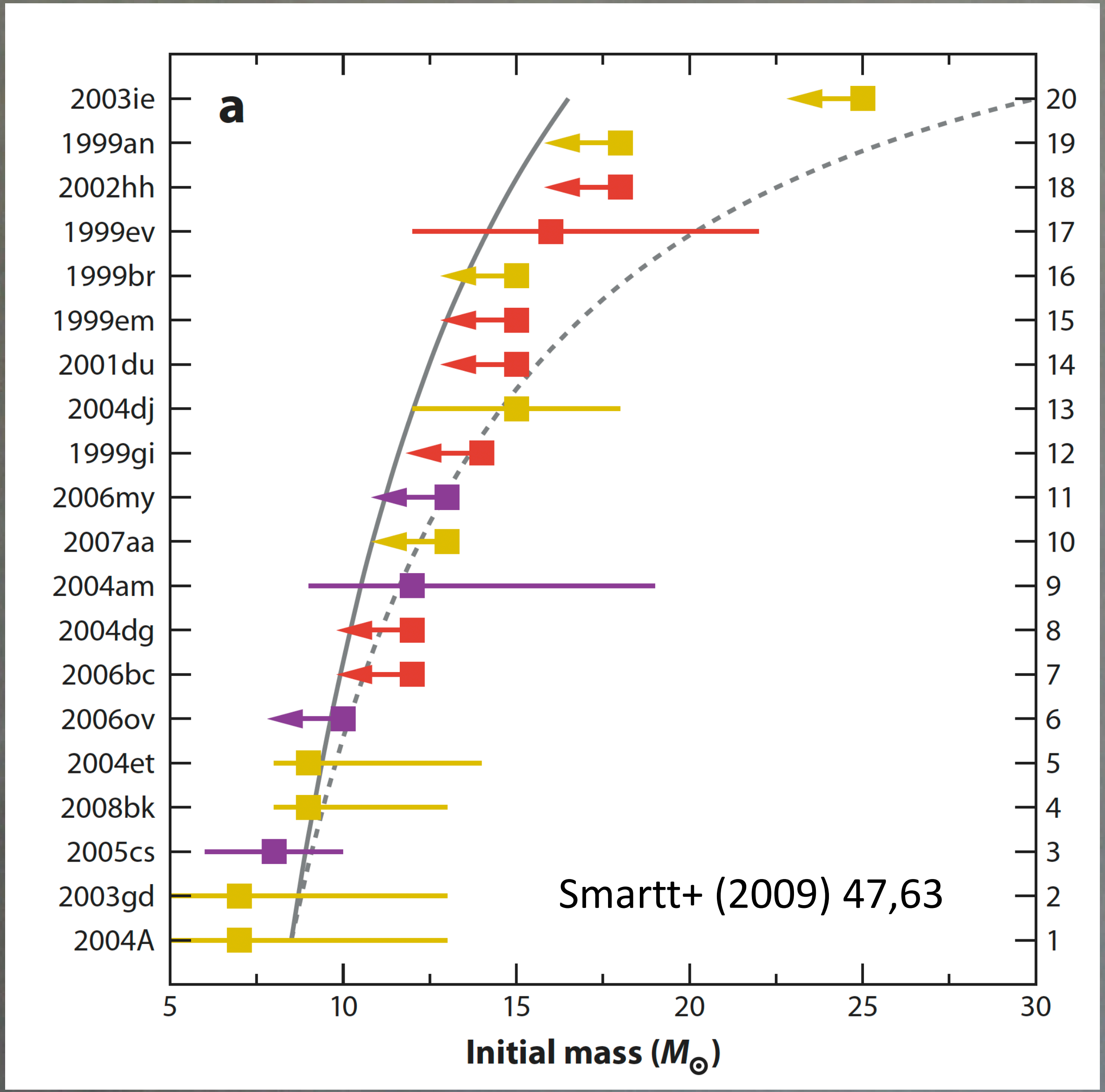
12C12C
THM
CF88
HINDRANCE
8 M⊙
9 M⊙
10 M⊙
11 M⊙
ONeMg-WD
CO-WD
CO-WD
C.C.
ONeMg-WD
ONeMg-WD
C.C.
ONeMg-WD
ONeMg-WD
C.C.
C.C.
C.C.
M: 8.0
M: 9.0
M:10.0
M:11.0
M(M⊙)
t(Gyr)

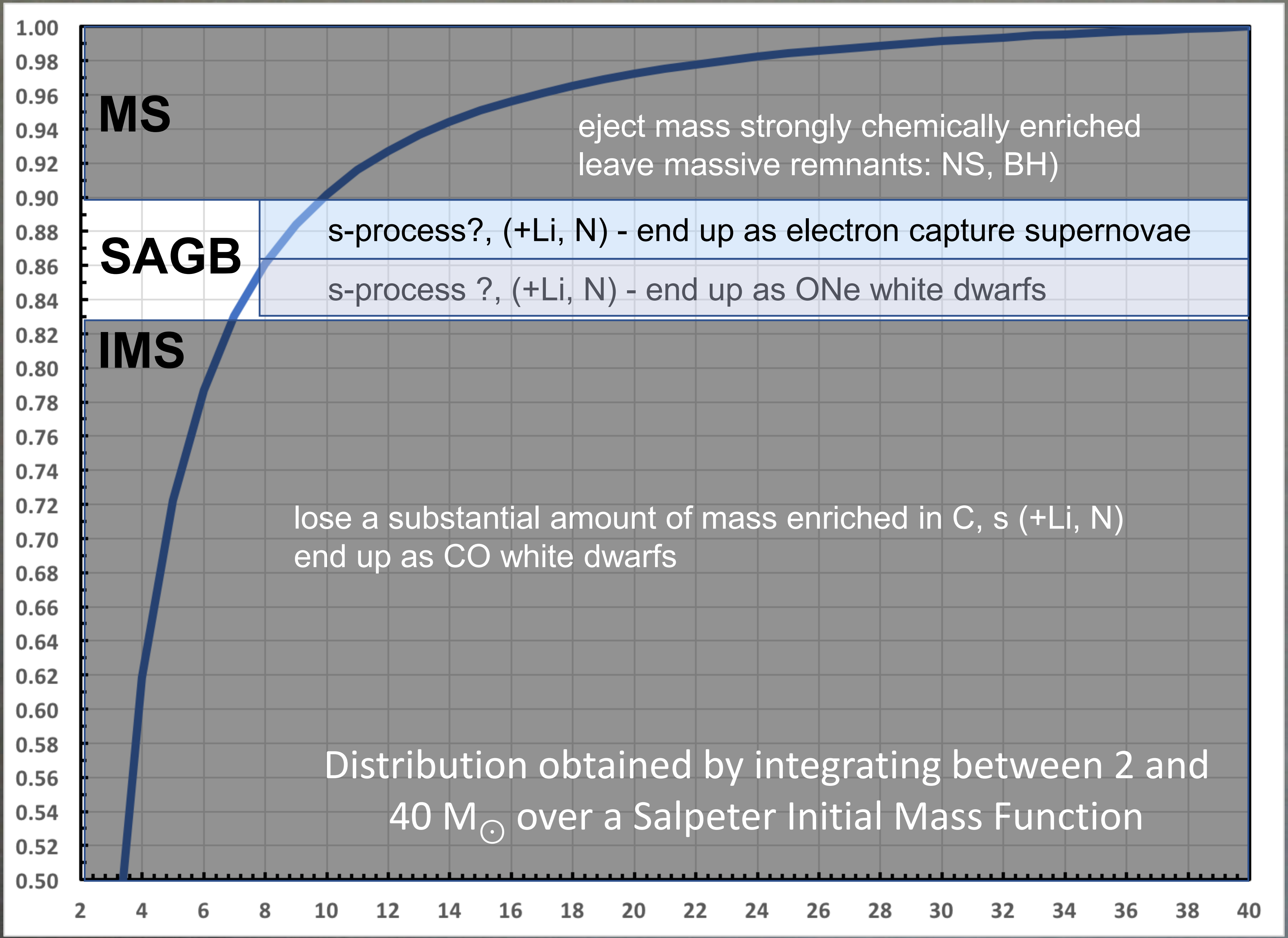

SOLID – CF88
DASHED – THM
DOTTED - HIN
9.3
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
$Log_{10}(T_{MAX})$ [K]
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
M_{CO} ($M_{\odot}$)
m06thm
m07thm
m08thm
m09thm
m10thm
m06cf88
m07cf88
m08cf88
m09cf88
m10cf88
m11cf88
m12cf88
m09hin
m10hin
m08hin

Qualitative threshold masses (Schwarzchild criterion adopted to fix the borders of the convective regions):

	$^{12}C^{12}C$ fusion		
	HINDRANCE	CF88	THM
M_{UP} CO-WD / ONeMg WD	8.5/9.0 $M_{\odot}$	8.0/8.5 $M_{\odot}$	7.0/7.5 $M_{\odot}$
M_{CC} Minimum core collapse star	10.5/11.0 $M_{\odot}$	10.0/10.5 $M_{\odot}$	9.5/10.0 $M_{\odot}$

Masses of SN type II P





MS
eject mass strongly chemically enriched
leave massive remnants: NS, BH)
SAGB
s-process?, (+Li, N) - end up as electron capture supernovae
s-process ?, (+Li, N) - end up as ONe white dwarfs
IMS
lose a substantial amount of mass enriched in C, s (+Li, N)
end up as CO white dwarfs
Distribution obtained by integrating between 2 and 40 $M_\odot$ over a Salpeter Initial Mass Function
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
0.62
0.60
0.58
0.56
0.54
0.52
0.50
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

C burning in massive stars

The devastating impact of the combo $^{12}C(\alpha,\gamma)^{16}O$ + $^{12}C^{12}C$ on the evolution of these stars

Massive stars do not need at all nuclear reactions to contract and heat up to their final collapse

But

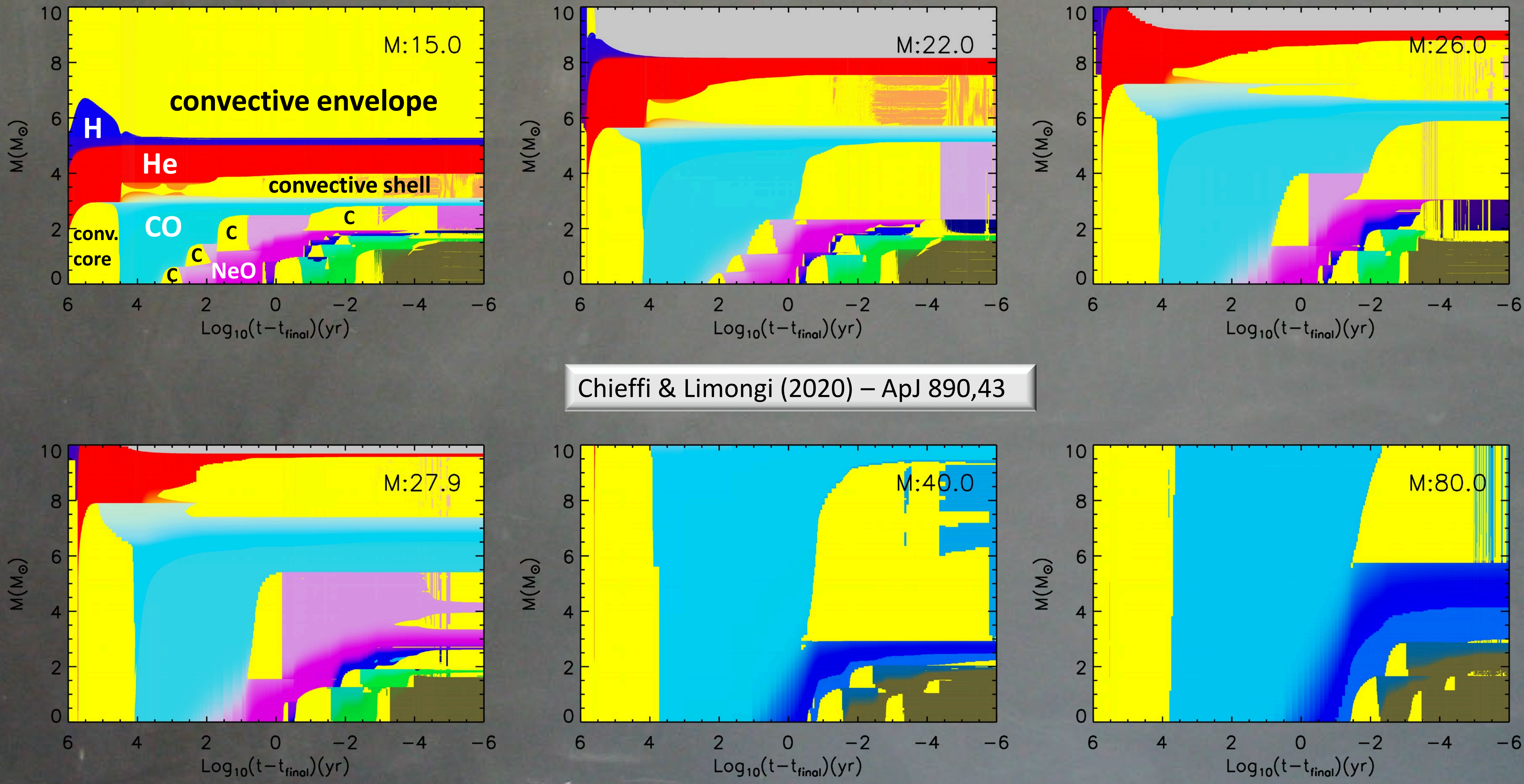
nuclear reactions (and in particular C burning) sculpt the final shape of the binding energy at the onset of the c.c.

ATTENTION:

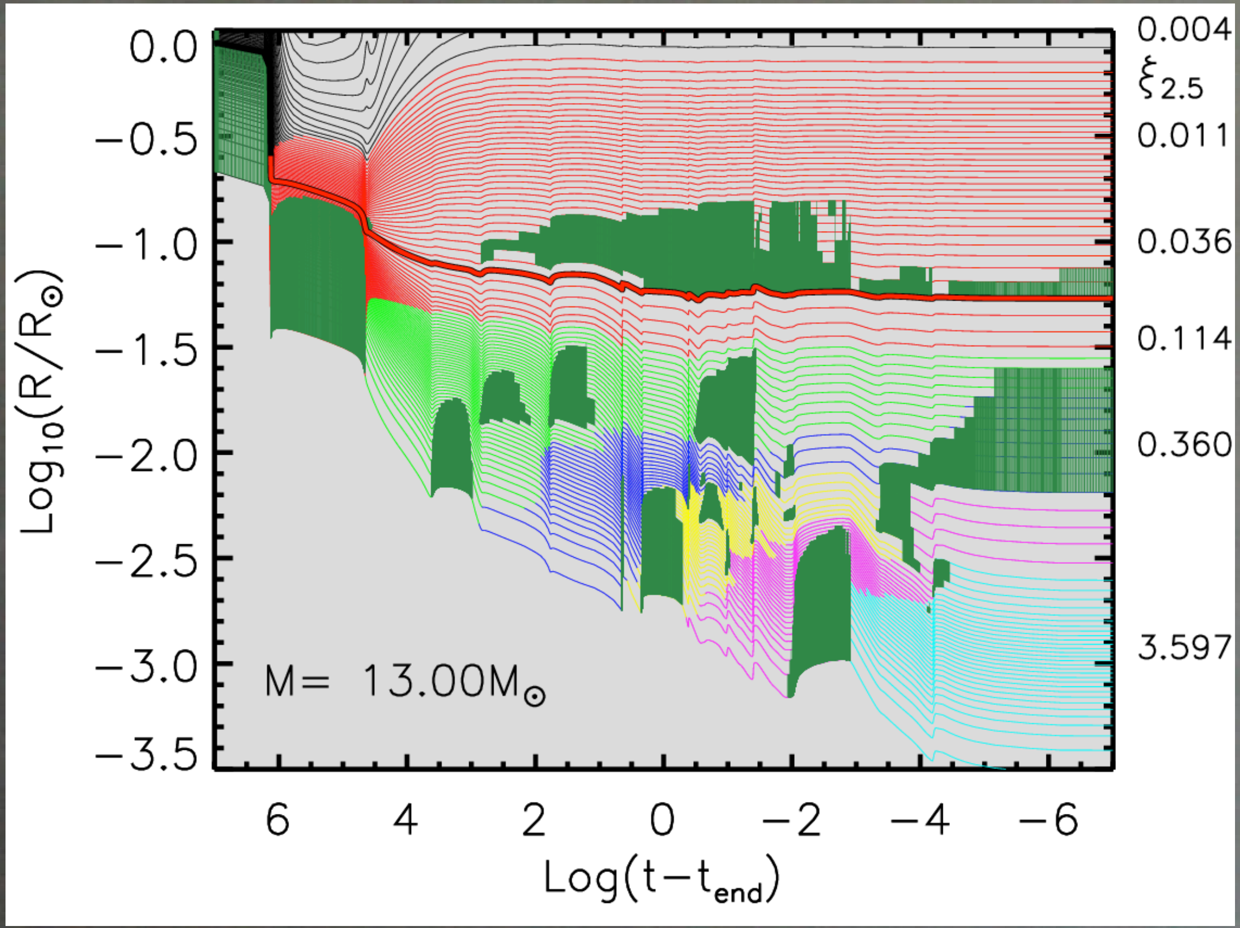
1) The final fate of a massive star depends on the shell C burning and NOT the core C burning

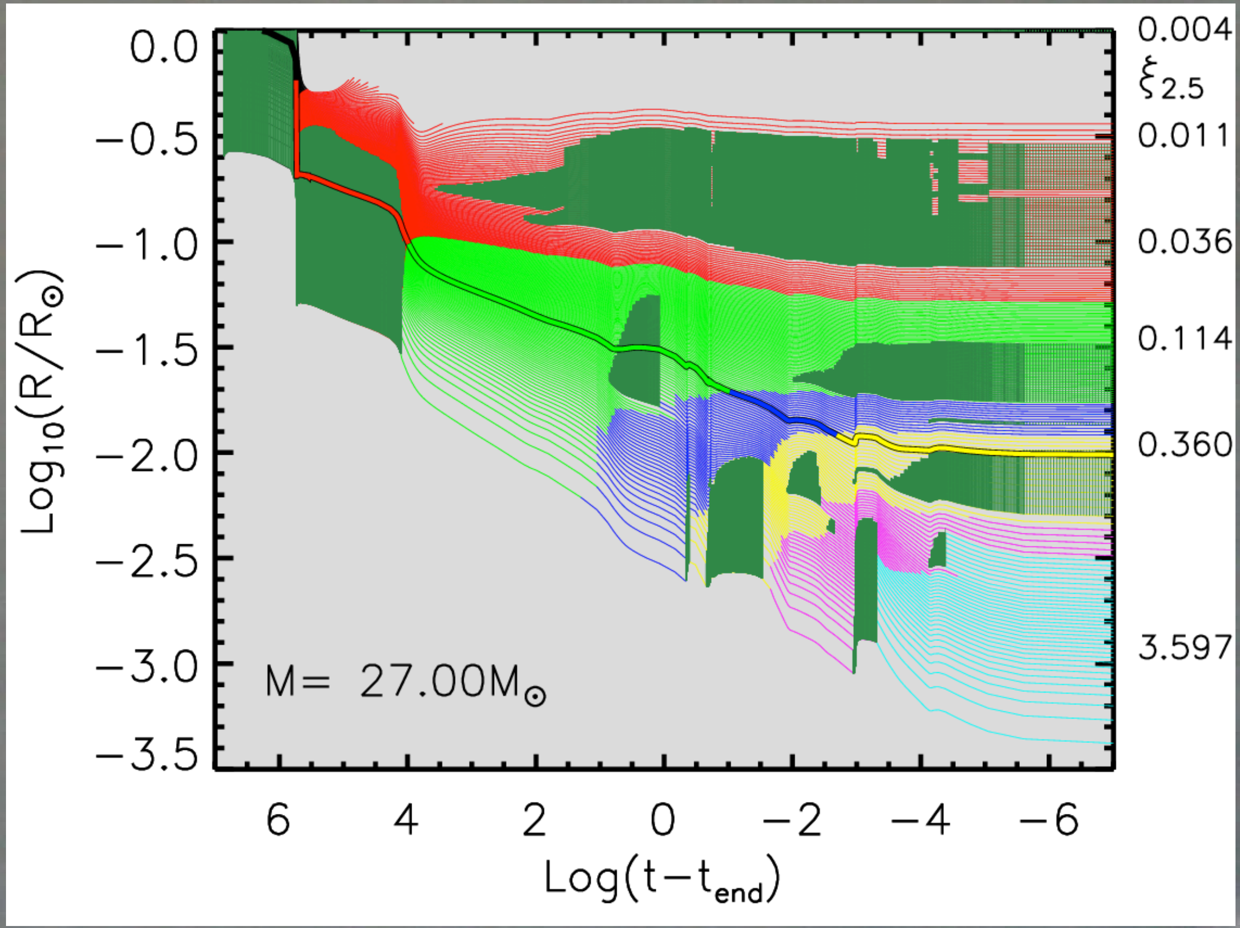
2) a fine grid of models REQUIRED to understand the role of C burning

C burning



Chieffi & Limongi (2020) – ApJ 890,43


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
$Log_{10}(R/R_\odot)$
6
4
2
0
−2
−4
−6
$Log(t-t_{end})$
$M= 13.00M_\odot$
0.004
$\xi_{2.5}$
0.011
0.036
0.114
0.360
3.597


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
$Log_{10}(R/R_\odot)$
6
4
2
0
−2
−4
−6
$Log(t-t_{end})$
$M= 27.00M_\odot$
0.004
$\xi_{2.5}$
0.011
0.036
0.114
0.360
3.597

C burning

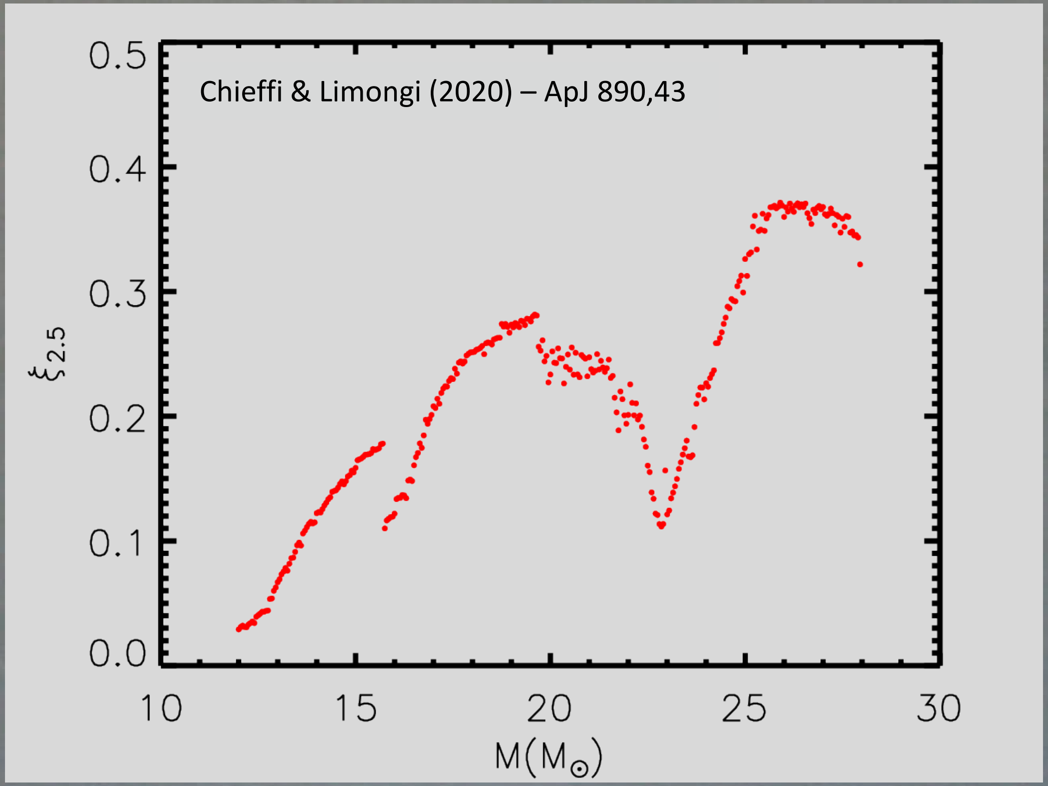
The final Mass-Radius relation is extremely important because it determines the final binding energy of a star (its compactness) at the beginning of the core collapse and hence the possibility of getting a succesful explosion or not.

A simple way to determine how compact a star is at the onset of the core collapse has been proposed by O' Connor & Ott in 2011 (ApJ 730,70)

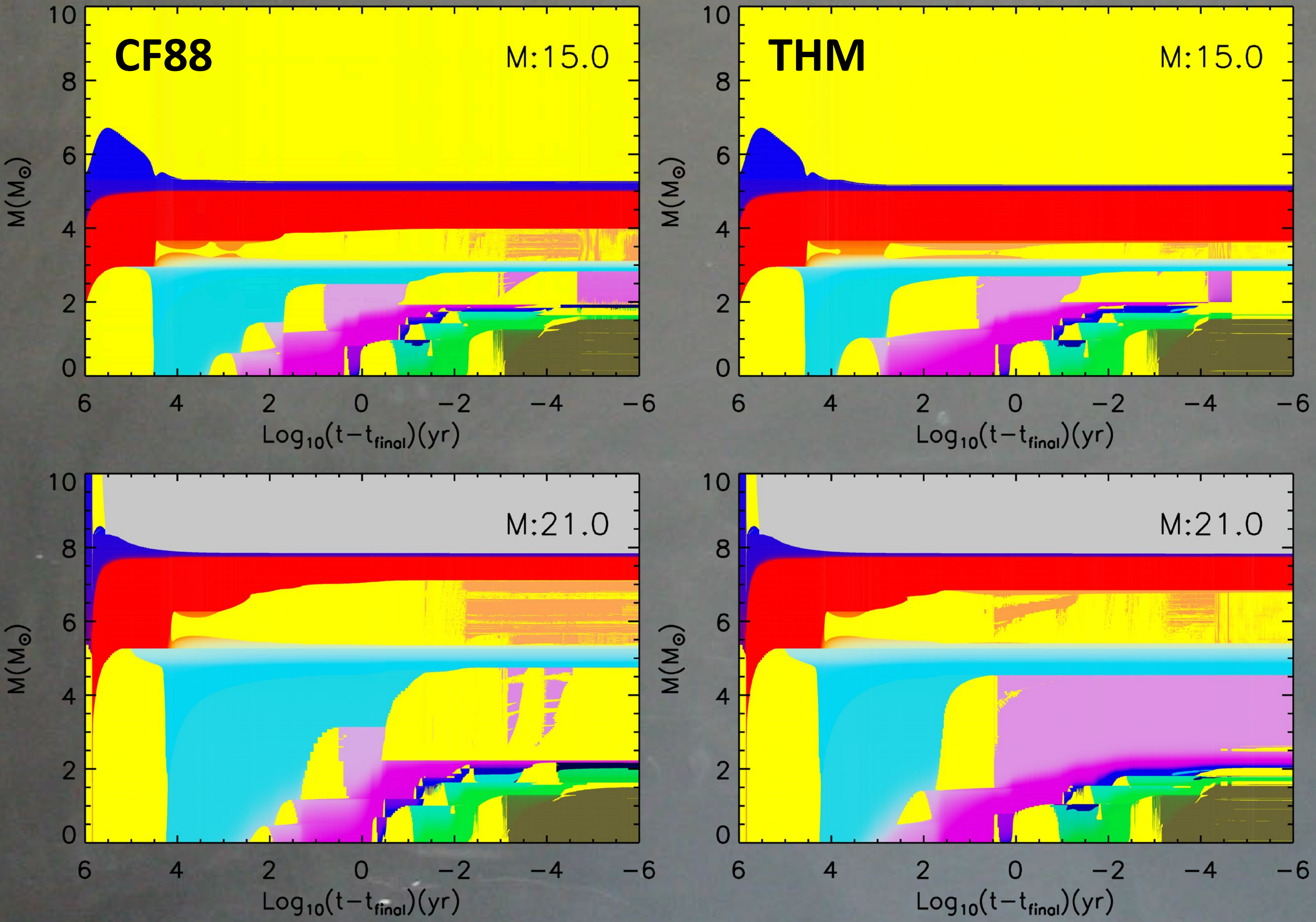
Compactness parameter ξ
(O' Connor & Ott 2011, ApJ 730,70)

$$\xi_i = \frac{M_i(M_\odot)}{R_i(10^3\ km)}$$

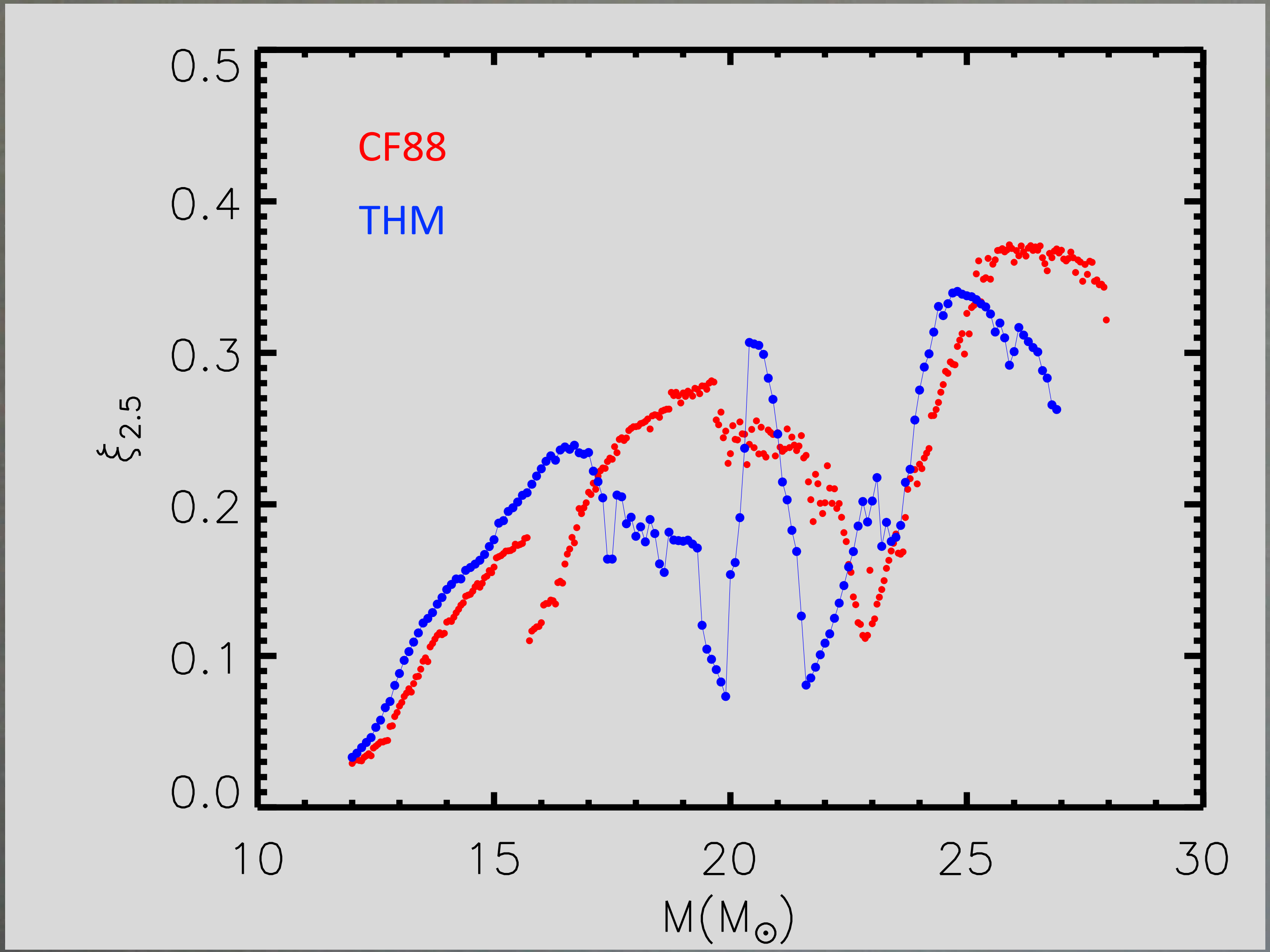
Best value ➔ i=2.5 $M_\odot$



C burning



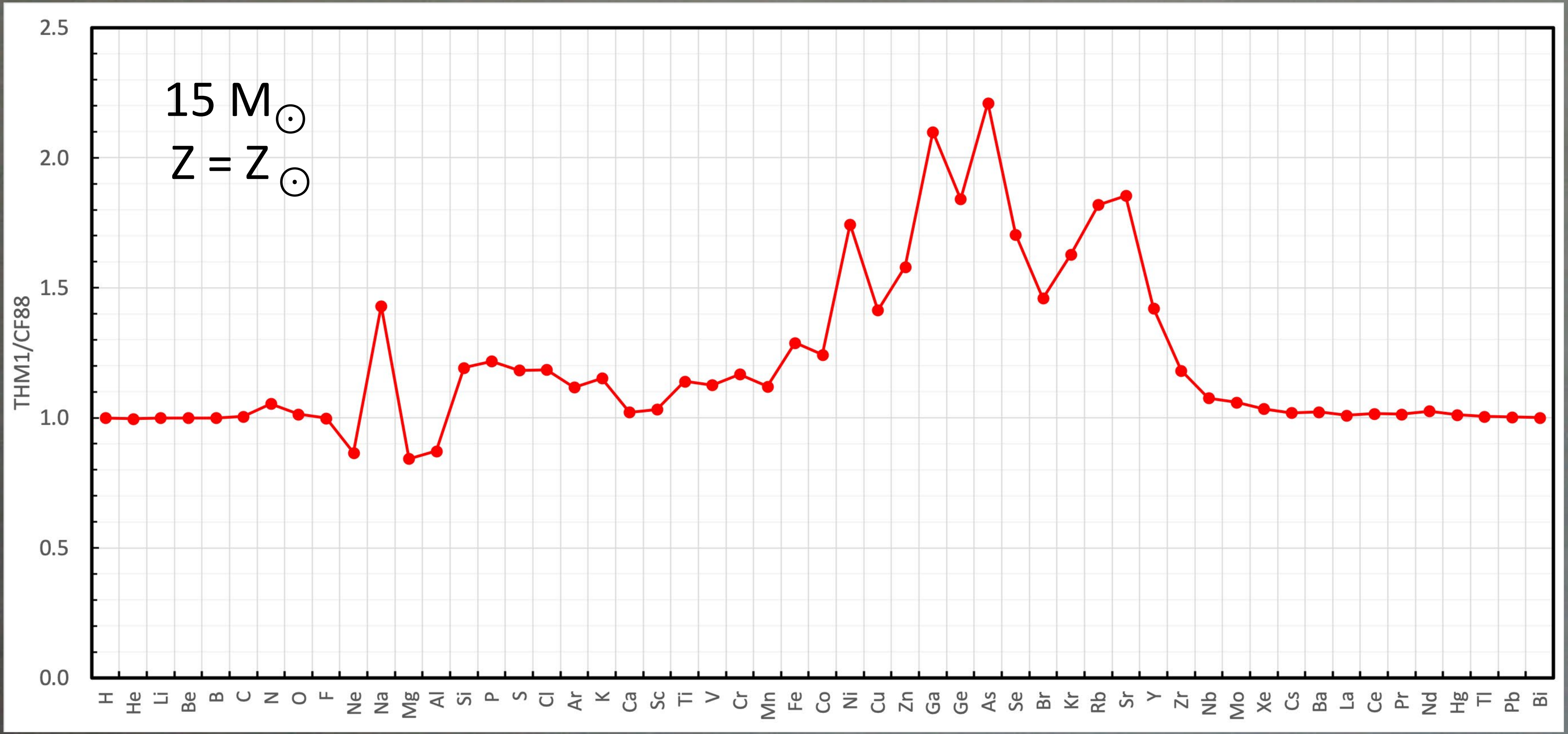
C burning

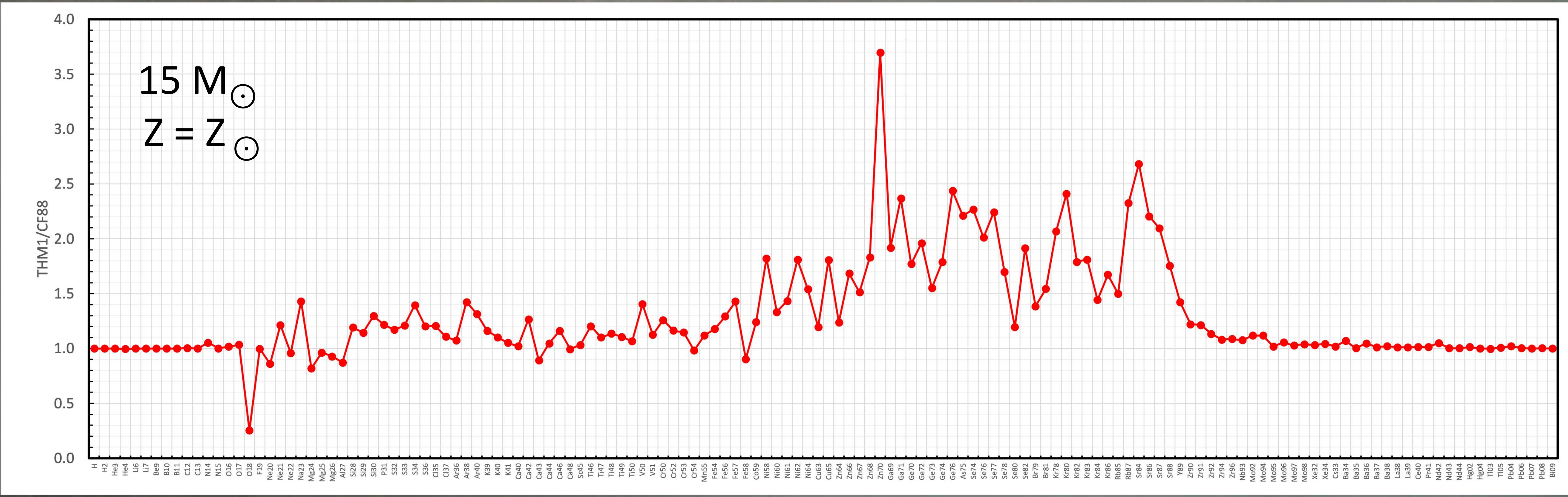


Explosion fixed by requiring that the final kinetic energy of the ejecta is 1.2 FOE

15 $M_\odot$

	Remnant mass	^{56}Ni
CF88	1.47 $M_\odot$	0.16 $M_\odot$
THM	1.40 $M_\odot$	0.21 $M_\odot$


15 M☉
Z = Z☉
THM1/CF88
2.5
2.0
1.5
1.0
0.5
0.0
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Xe Cs Ba La Ce Pr Nd Hg Tl Pb Bi


15 $M_\odot$
$Z = Z_\odot$
THM1/CF88
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

Messages:

To study the influence of a variation in the efficiency of the C burning on the evolution of a star it is MANDATORY to follow the evolution up to the core collapse and then follow the passage of the shock wave

To create a global picture is necessary to compute a full grid of models spanning an extended mass interval

The idea that it exists a mass limit that separates stars that follow path A from those that follow path B must be ABANDONED: rotation, magnetic fields, initial c.c. all work in the direction of creating a range of transition mass

REMEMBER: beyond the cental He burning, a generation of stars born with different masses does not form any more a uniparametric family of stars whose leading parameter is the mass (He core mass / CO core mass) but becomes a BI-PARAMETRIC family of stars whose evolution is controlled by both the CO core mass and the amount of ^{12}C left by the central He burning


THANK YOU
stjerner
sterren
istilel
izarrekin puntuatua
zvijezde
звезди
Sterne
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明星
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Hviezdičky
sterre
stars
yjet
sidera
зірки
bituin
Звездице
estrelas
yildiz
tähte
כוכבים
csillagok
Tähdet
звезди
sêr
estrellas