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Massive Stars

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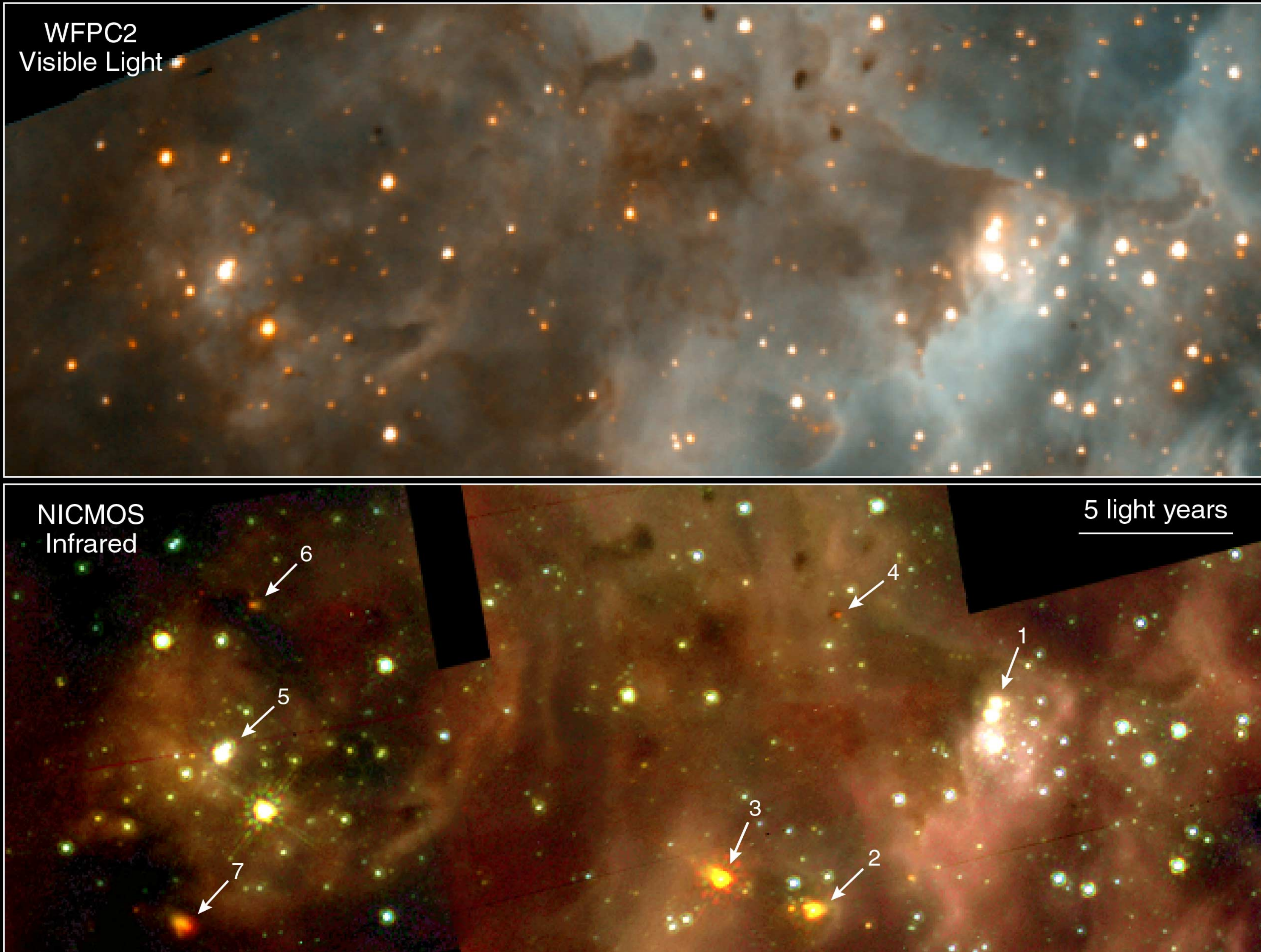
SJTU

ASTRO 3D

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

http://CosmicExplosions.org

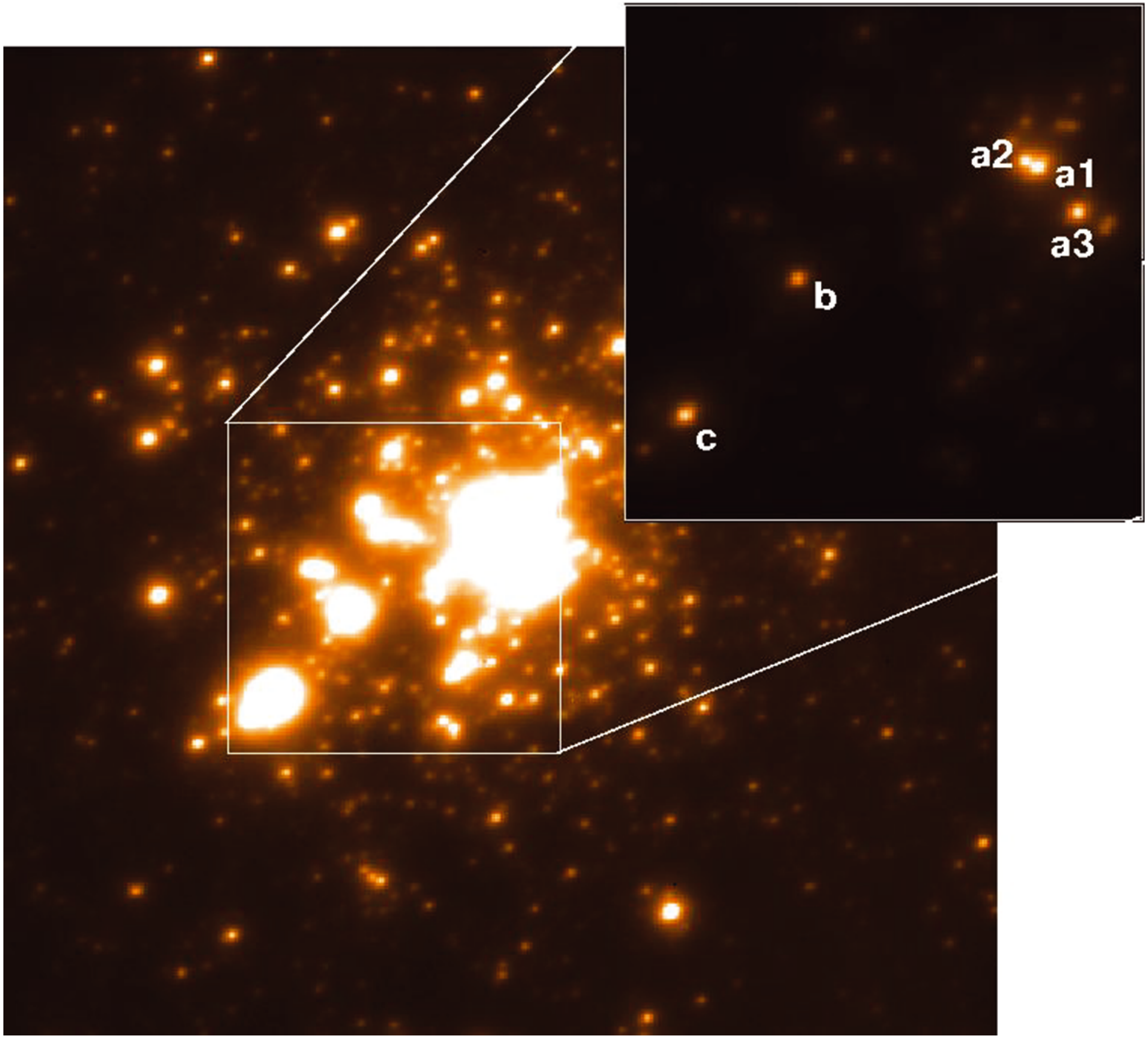


30 Doradus Details

Hubble Space Telescope • WFPC2 • NICMOS

PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

The Most Massive Stars Today



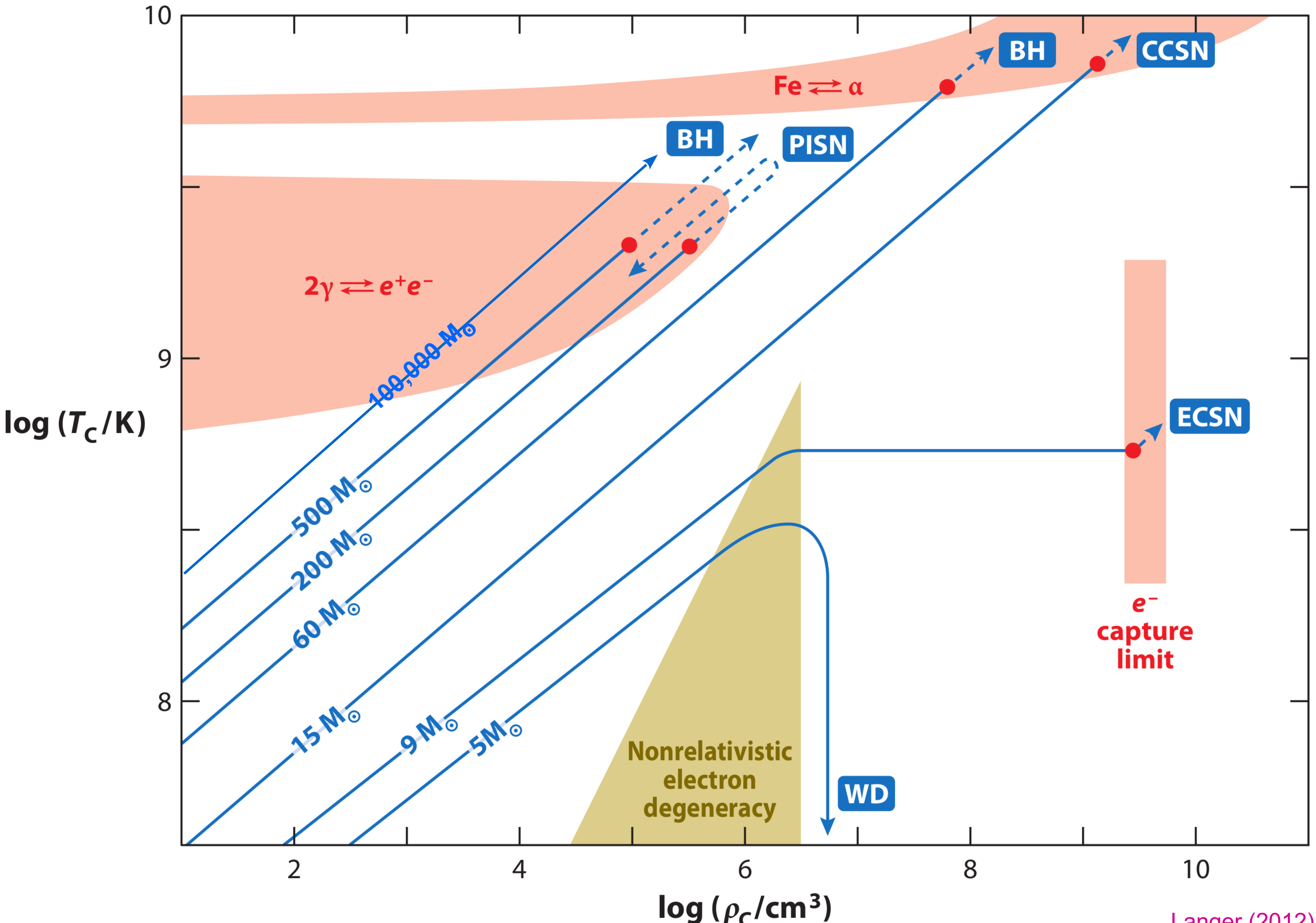
R136

- young massive star cluster
- Age around 1.5 Myr
- Star “a1”: maybe 200 $M_\odot$ initial mass

(Crother et al. 2010)

Eta Car – a really big star in our galaxy today

Evolution of Center for Different Initial Masses

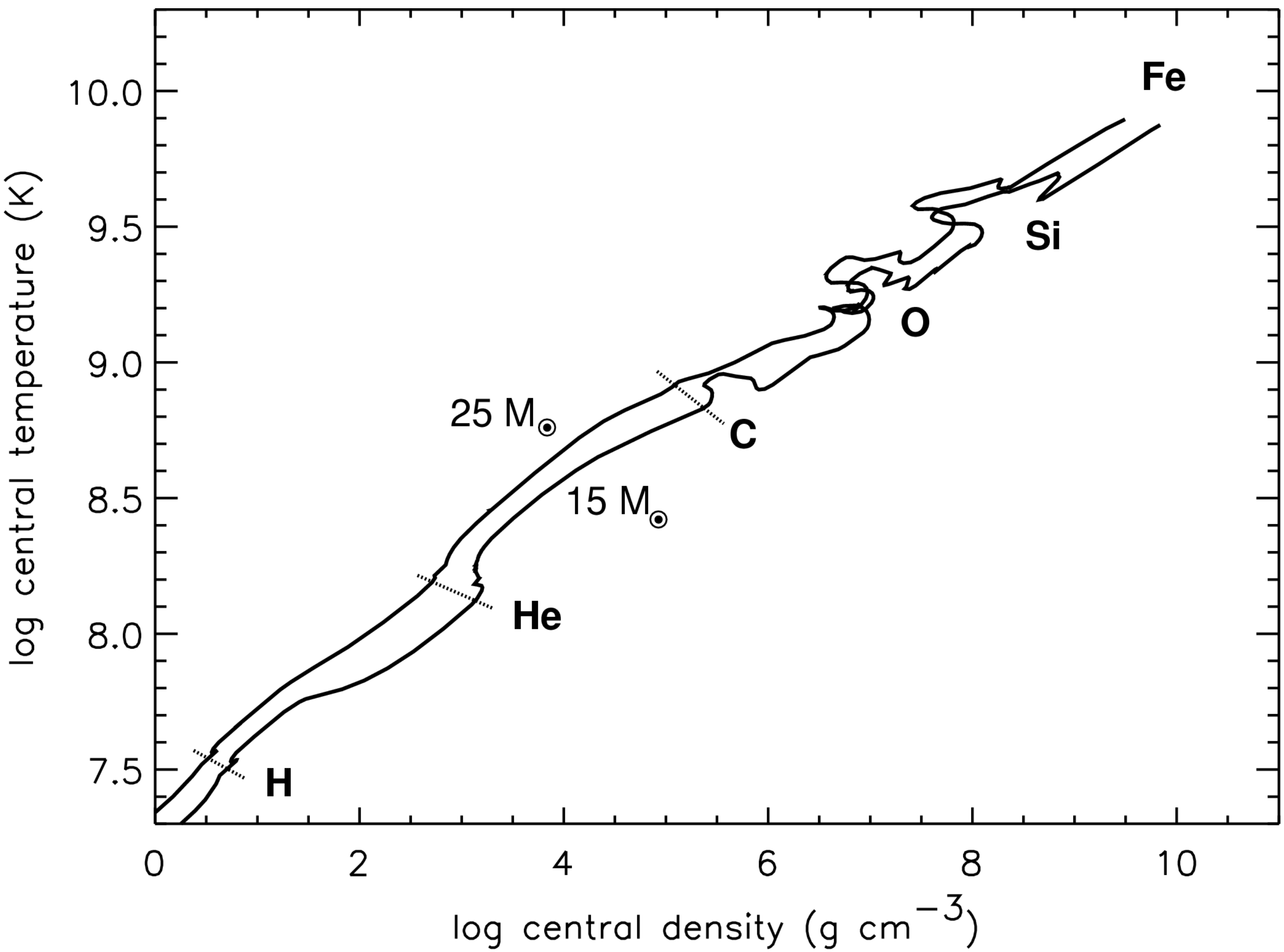


Langer (2012)

Once formed, the evolution of a star is governed by gravity:

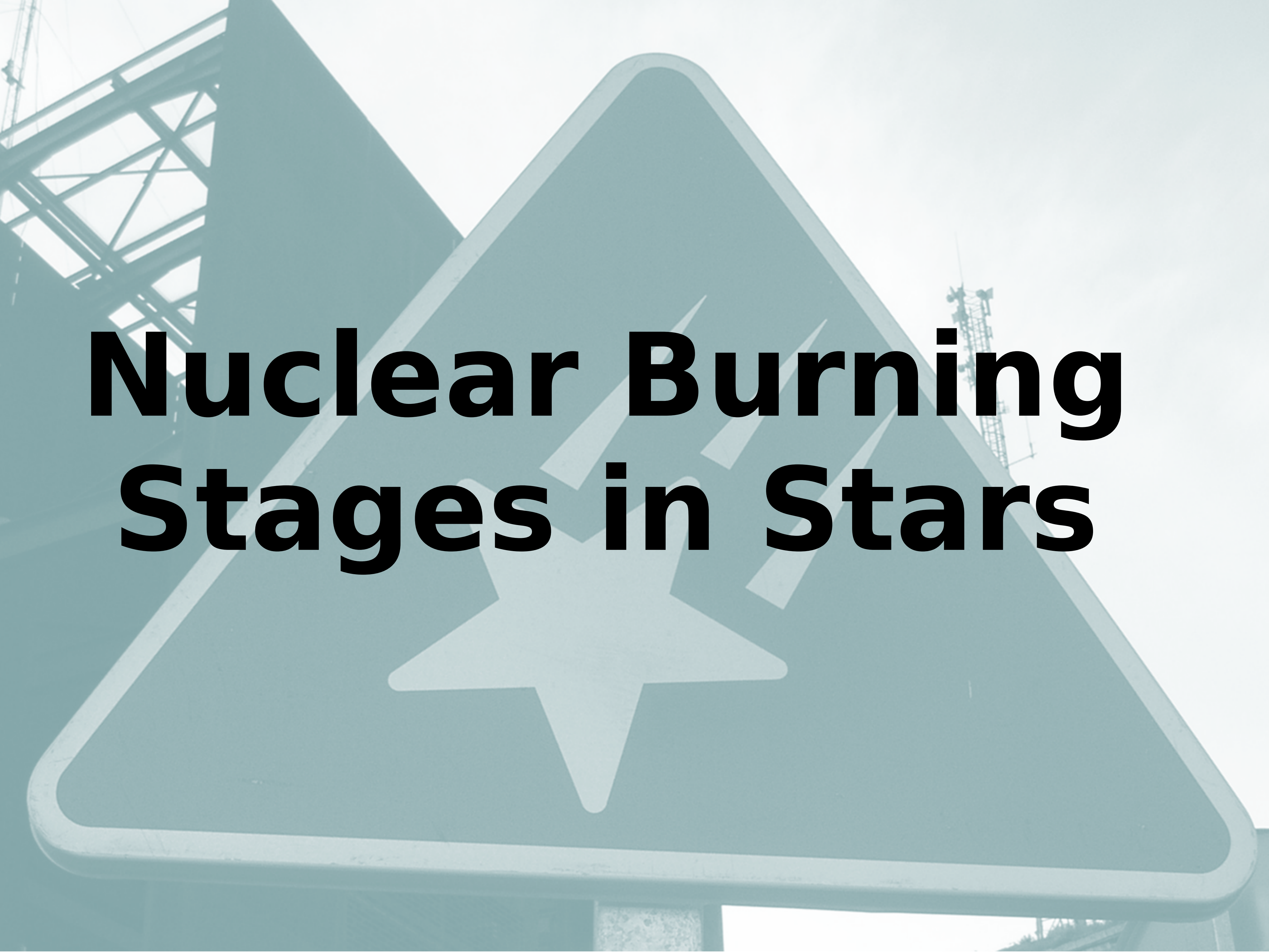
continuing contraction

to higher central densities and temperatures

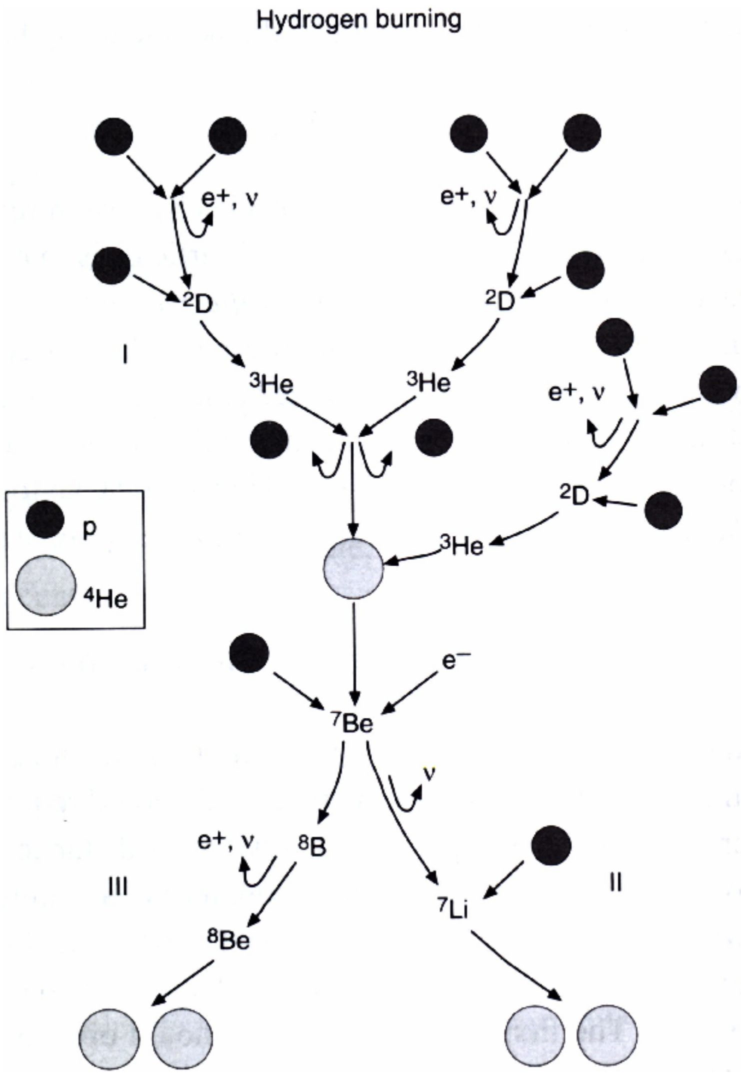


Evolution of central density and temperature of 15 M$_\odot$ and 25 M$_\odot$ stars

Nuclear Burning Stages in Stars



Hydrogen-Burning: pp Chains



$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$$
$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H \quad (pp1)$$

$$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma \qquad (18.62)$$

$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$
$$^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$$
$$(pp2)$$

$$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$$
$$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$$
$$^{8}Be \rightarrow {}^{4}He + {}^{4}He$$
$$(pp3)$$

Energy release:

$Q(pp1) = 26.20 MeV$

$Q(pp2) = 25.67 MeV$

$Q(pp3) = 19.20 MeV$

Reaction rate: $\langle \sigma v \rangle \propto T^4$

Hydrogen Burning: CNO Bi-Cycle

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$
$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$
$$\rightarrow {}^{16}O + \gamma$$
$$^{16}O + {}^{1}H \rightarrow {}^{17}F + \gamma$$
$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu$$
$$^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He$$

Energy release:
$Q(CNO) = 24.97\,MeV$

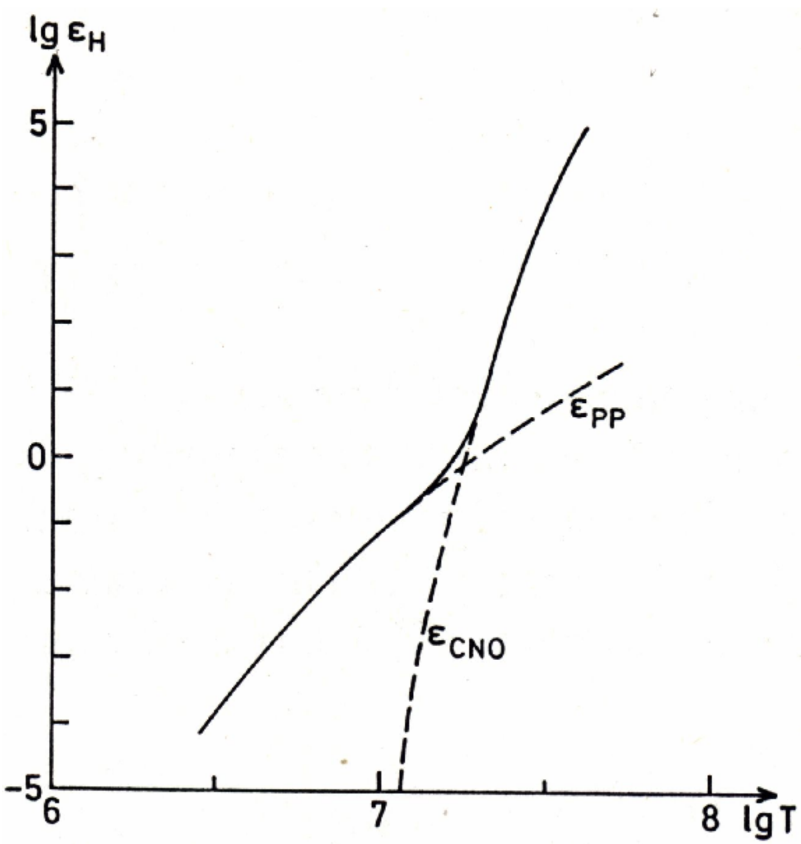
Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

Branching:
CNO-1 : CNO-2 $\sim$ 10,000 : 1

Hydrogen Burning: CNO Bi-Cycle

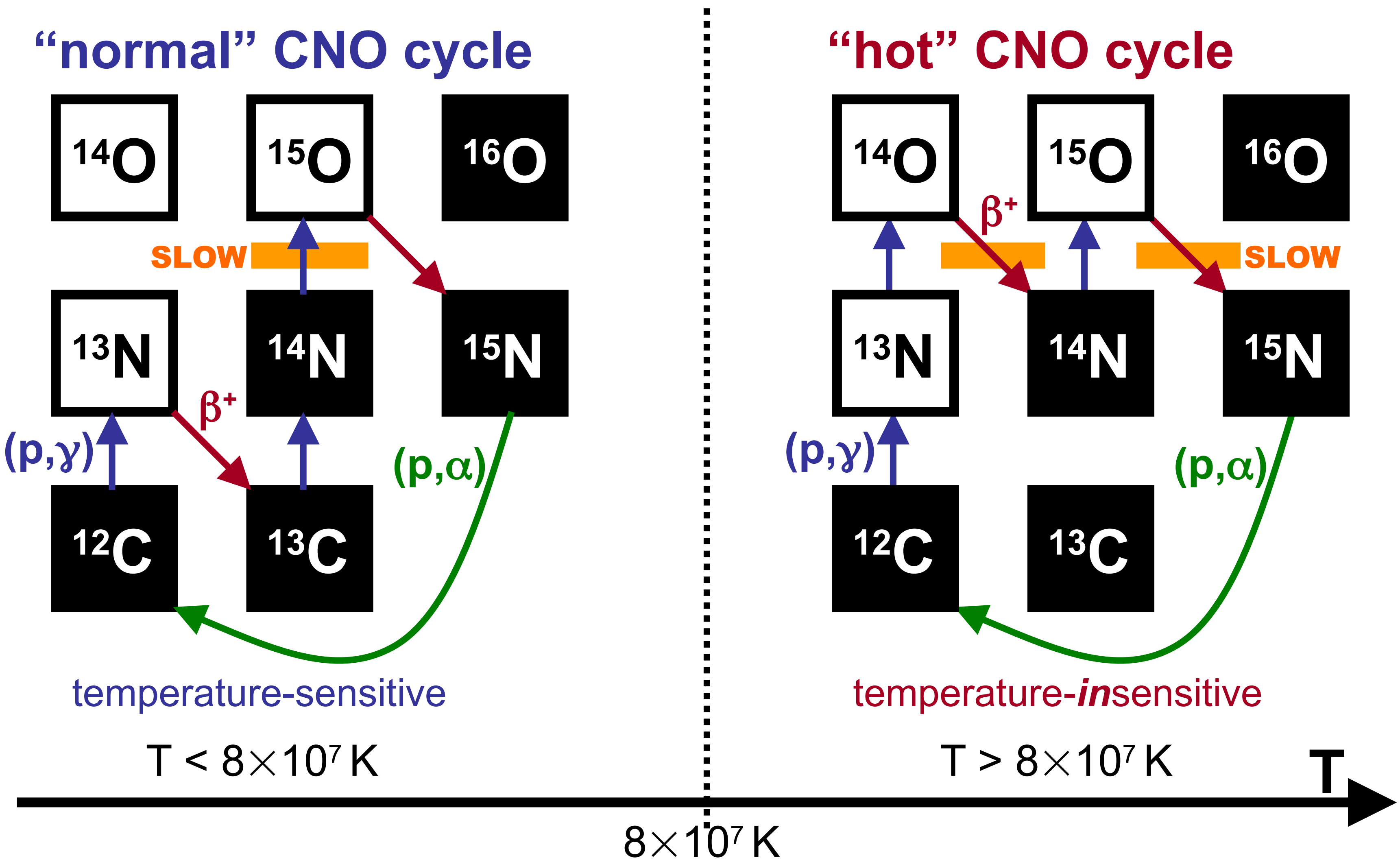
- Usually the beta-decays are fast compared to the capture reactions, (p,γ).
- ^{14}O: $\tau_{1/2} = 70$ sec
  ^{15}O: $\tau_{1/2} = 122$ sec
  ^{13}N: $\tau_{1/2} = 10\,$min
  ^{17}F: $\tau_{1/2} = 64$ sec
  ^{18}O: $\tau_{1/2} = 110\,$min
- ^{14}N(p,γ)^{15}O usually is the slowest “bottleneck” reaction.
- CNO cycle burning converts most CNO isotopes into ^{14}N.

Competition of Hydrogen-Burning Modes



Transition from pp-chains
in low-mass stars (low *T*)
to CNO chains
in high-mass stars (high *T*)

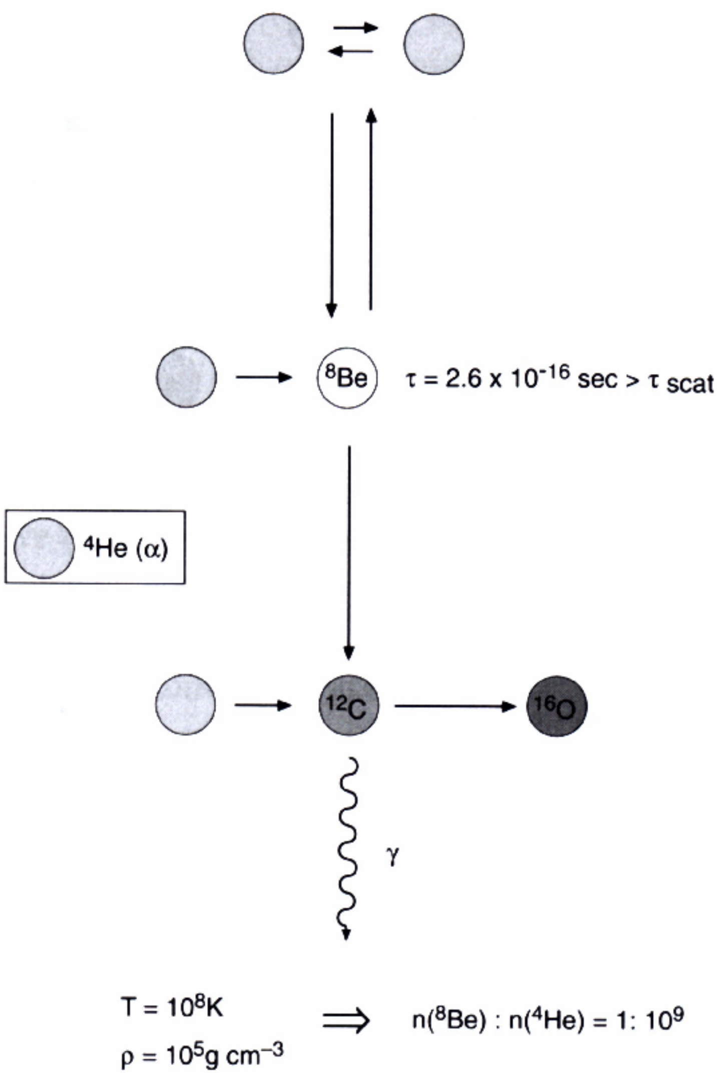
Hydrogen Burning by CNO Cycle



time for an eddy to burn its hydrogen content by **hot** CNO cycle

$$\tau_H = \mathbf{11\ h} \left(\frac{0.02}{Z}\right)\left(\frac{X_0}{0.7}\right)$$

Helium Burning



Step 1:

$^4\text{He} + {}^4\text{He} \rightleftharpoons {}^8\text{Be}$

Built up equilibrium abundance of ^{8}Be

Lifetime of ^{8}Be is only 2.6×10^{-16} s!

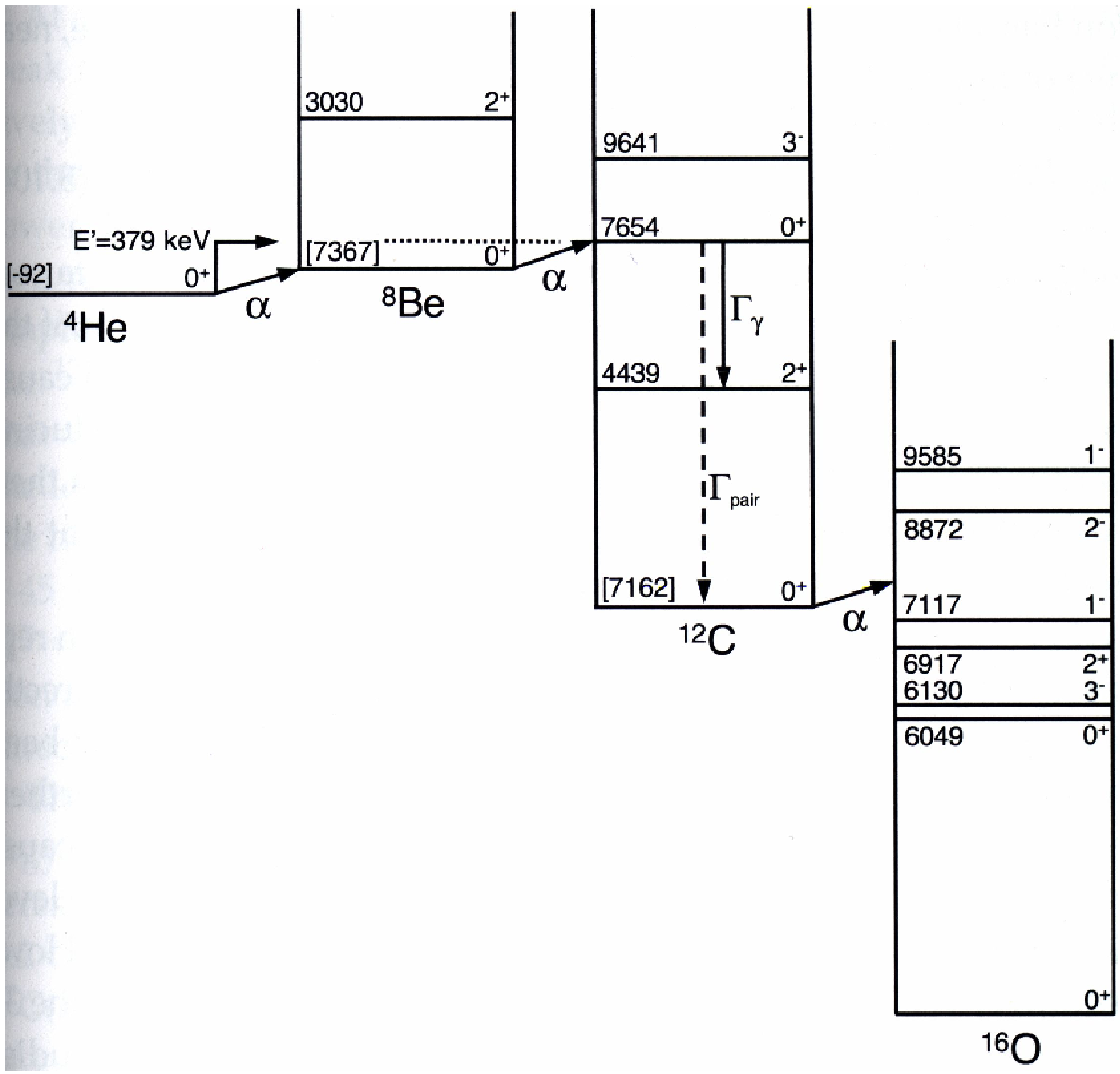
Step 2:

$^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C} + \gamma$

$Q_{3\alpha} = 7.275\,\text{MeV}$

$<\sigma v> \propto \rho^2 T^{40}$

Helium Burning Level Scheme



Additional Helium Burning Reactions

Oxygen Production

$^4\text{He} + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + \gamma$

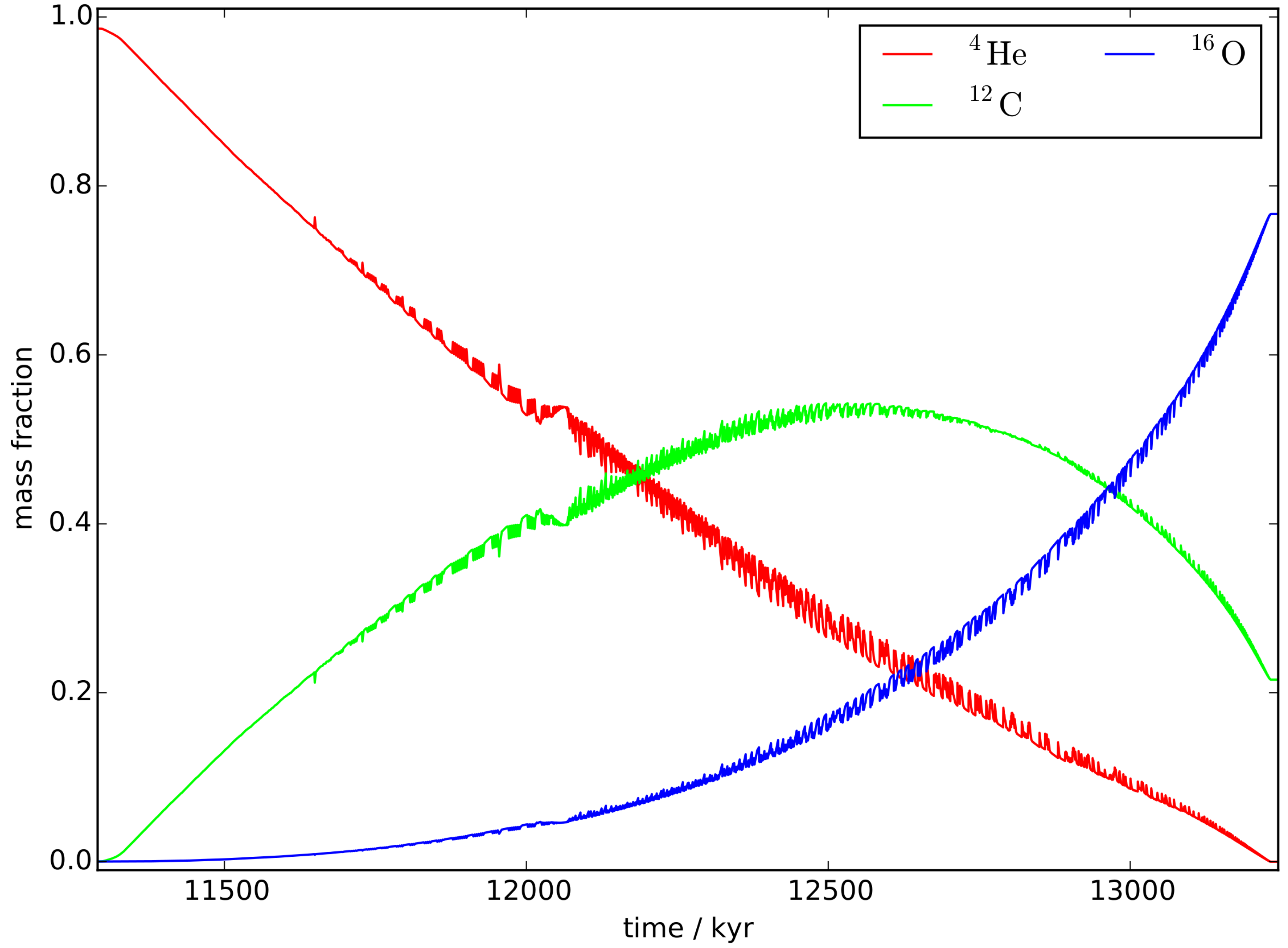
$Q = 7.162\,\text{MeV}$

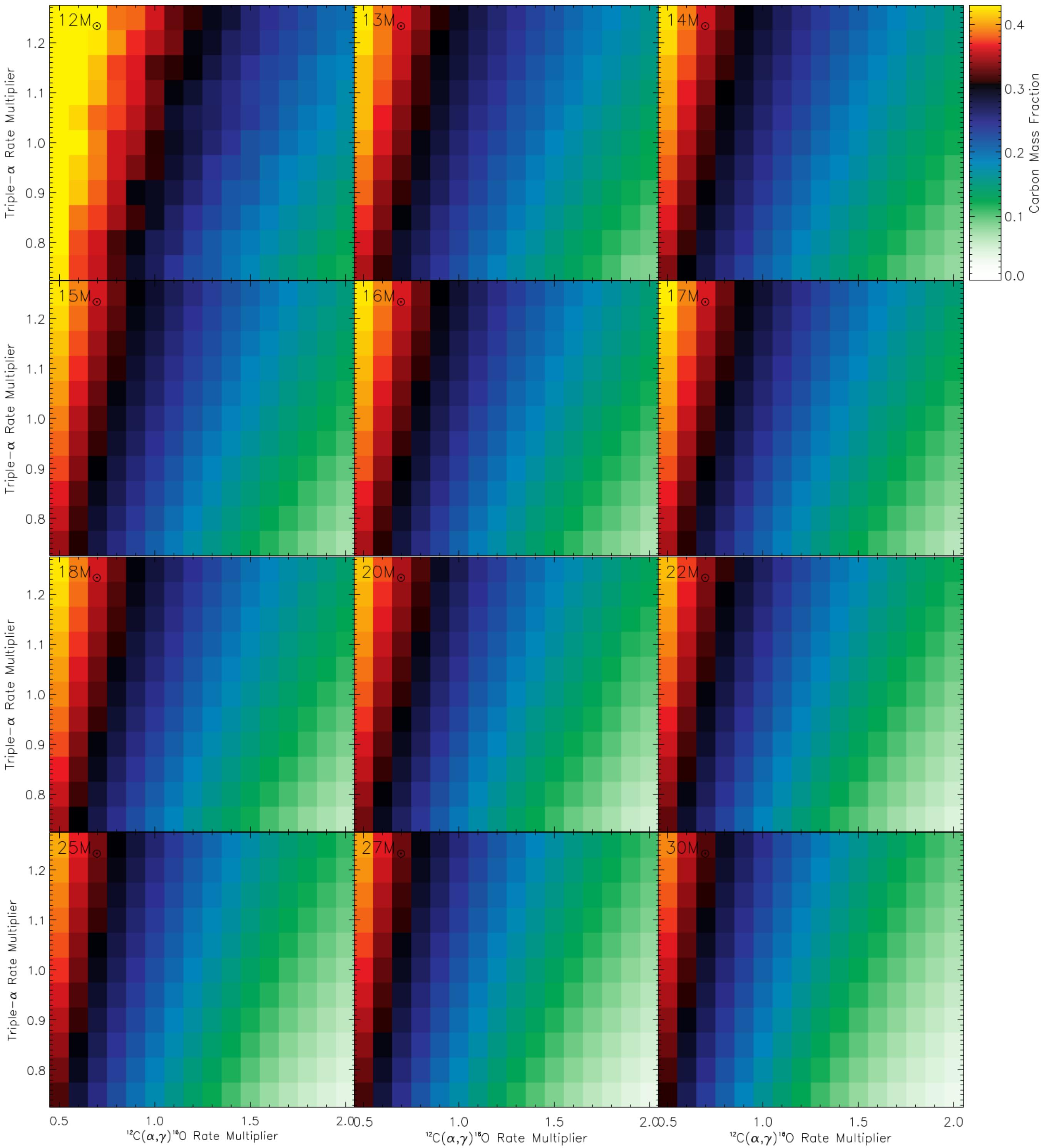
$\langle \sigma v \rangle \;\propto \rho T^{40}$

The final abundance of carbon is set by the competition of 3α and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reactions;

The production of ^{16}O can only start when a sufficient amount of ^{12}C has been made.

Competition of Helium Burning Reactions





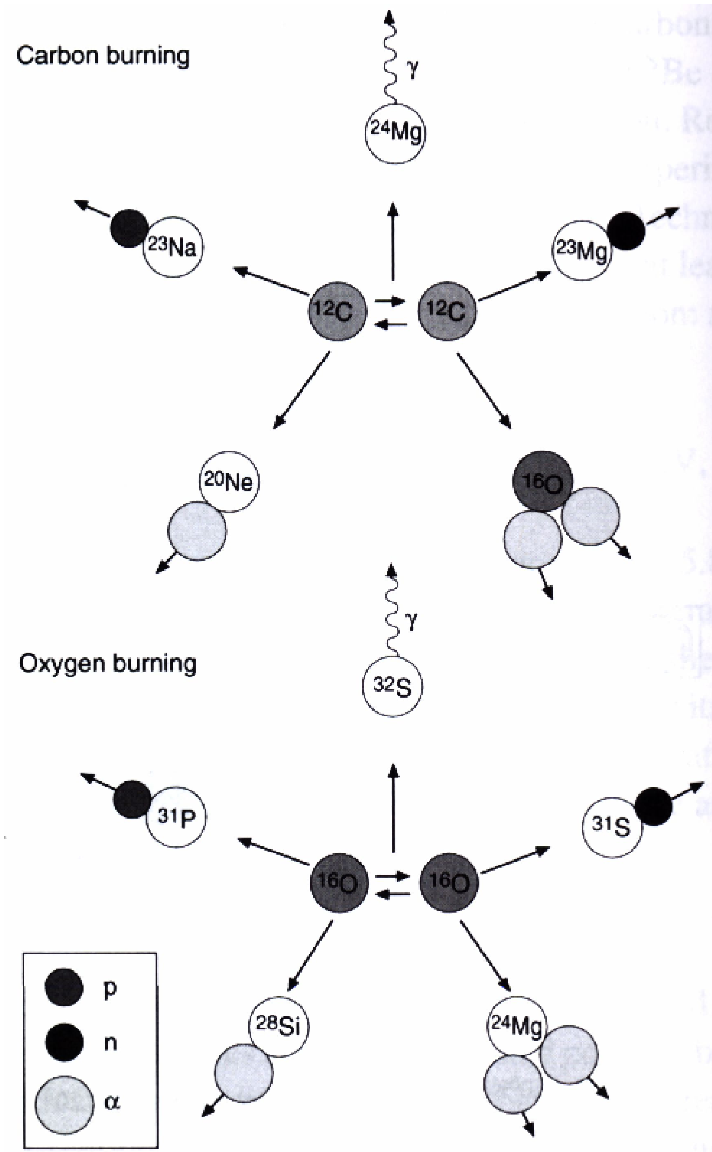
^{12}C Production as a function of $^{12}C(\alpha,\gamma)$ and 3α reaction rates

Carbon mass fraction at the end of helium burning depends the reaction rates and the mass of the star

~2000 stellar models

(West+ 2013)

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg} + \gamma \quad , \quad 13.931 \\
&\rightarrow {}^{23}\mathrm{Mg} + n \quad , \quad -2.605 \\
&\rightarrow {}^{23}\mathrm{Na} + p \quad , \quad 2.238 \\
&\rightarrow {}^{20}\mathrm{Ne} + \alpha \quad , \quad 4.616 \\
&\rightarrow {}^{16}\mathrm{O} + 2\alpha \quad , \quad -0.114
\end{aligned}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

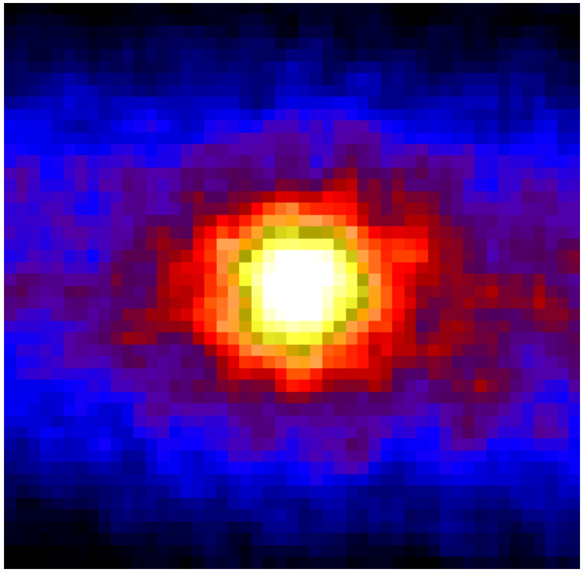
$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{32}\mathrm{S} + \gamma \quad , \quad 16.541 \\
&\rightarrow {}^{31}\mathrm{P} + p \quad , \quad 7.677 \\
&\rightarrow {}^{31}\mathrm{S} + n \quad , \quad 1.453 \\
&\rightarrow {}^{28}\mathrm{Si} + \alpha \quad , \quad 9.593 \\
&\rightarrow {}^{24}\mathrm{Mg} + 2\alpha \quad , \quad -0.393
\end{aligned}
$$

Average $Q = 16\,\mathrm{MeV}$

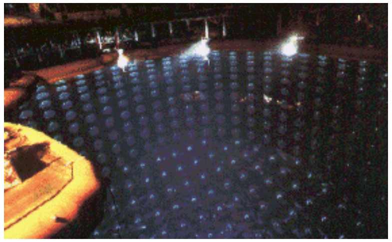
Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond
- For T>10^9 K (about 100 keV), occasionally:
  $$\gamma \rightarrow e^+ + e^-$$
  and usually
  $$e^+ + e^- \rightarrow 2\gamma$$
  but sometimes
  $$e^+ + e^- \rightarrow \overline{\nu}_e + \nu_e$$
-
- The neutrinos exit the stars at the speed of light while the e^+, e^-, and the γ's all stay trapped.

- This is an important energy loss with
  $$\varepsilon_\nu \approx -10^{15}\ (T/10^9 K)^9 \text{ erg g}^{-1}\text{ s}^{-1}$$
- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as T^{-9}



The sun as seen by Kamiokande



Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}\,, \quad Q = -4.73\,\mathrm{MeV}$$

This reaction dominates over the inverse reaction known from helium burning for $T > 1.5 \times 10^9\,\mathrm{K}$.

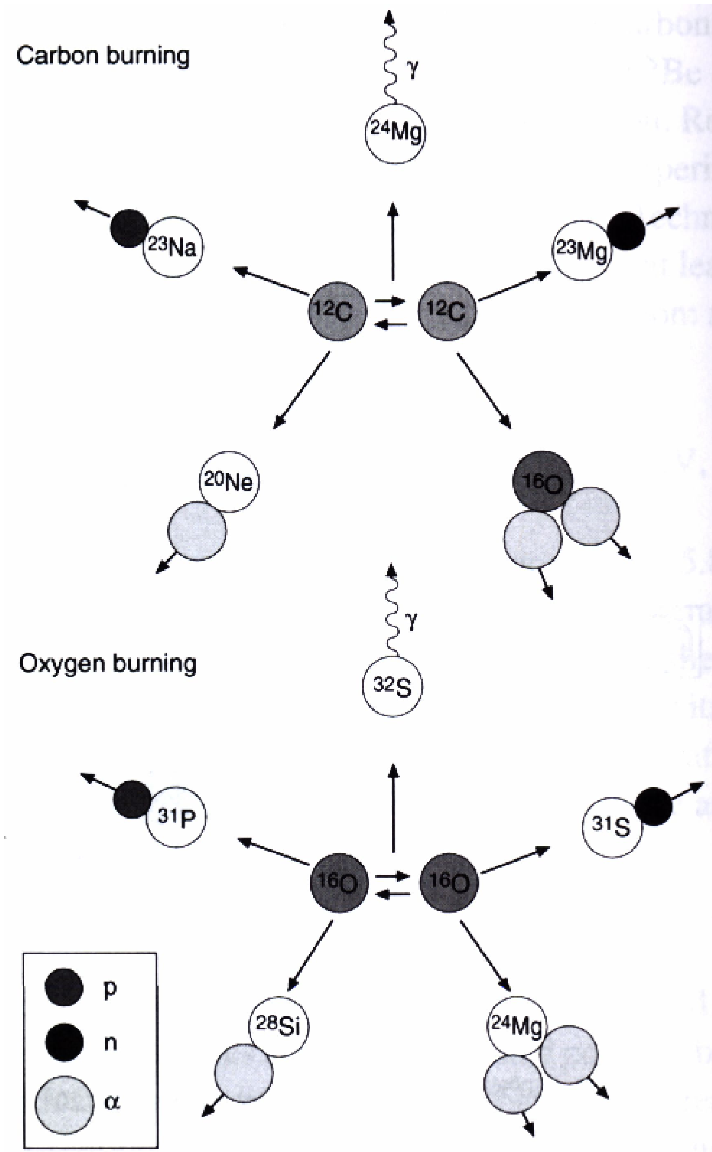
Subsequently, the ^{4}He is captured on another ^{20}Ne nucleus:

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma.$$

The net result is

$$2\,{}^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + \gamma\,, \quad Q = +4.583\,\mathrm{MeV}$$

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{aligned}
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&\rightarrow {}^{23}\mathrm{Mg} + n \quad , & -2.605 \\
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&\rightarrow {}^{16}\mathrm{O} + 2\alpha \quad , & -0.114
\end{aligned}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{32}\mathrm{S} + \gamma \quad , & 16.541 \\
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&\rightarrow {}^{24}\mathrm{Mg} + 2\alpha \quad , & -0.393
\end{aligned}
$$

Average $Q = 16\,\mathrm{MeV}$

Silicon/Sulfur Burning

Actually, often we have more sulfur in the star than there is silicon, but it is custom to call this phase "silicon burning".

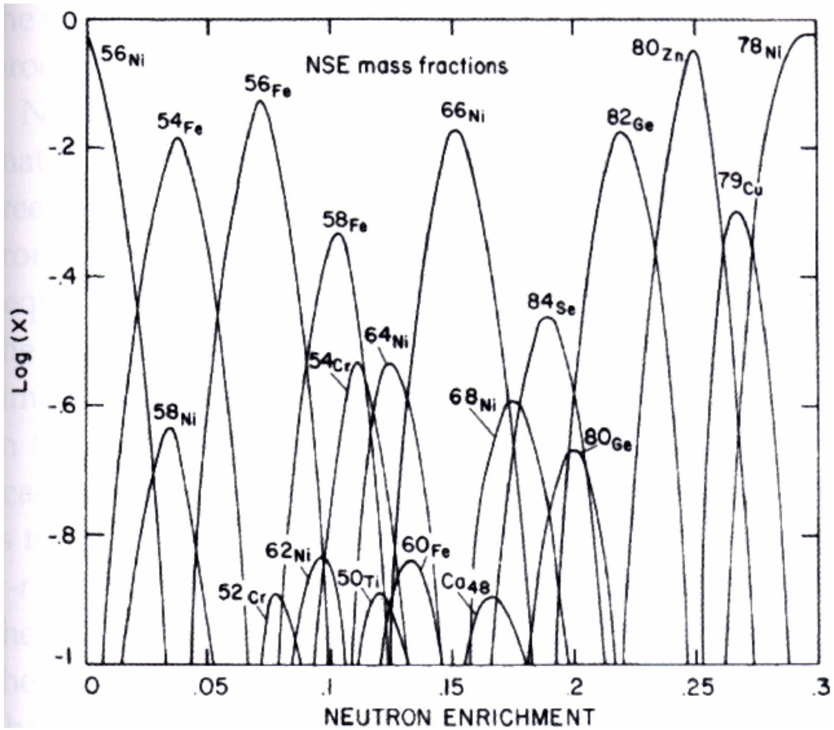
Typical burning temperature is $3 \ldots 3.5 \times 10^9$ K.

Similar to neon burning, silicon burning proceeds as a series of photo-disintegration reactions, mostly, (γ, α), and helium capture reactions, (α, γ) to build up iron group elements.

$$(\gamma, \alpha) \rightleftharpoons (\alpha, \gamma)$$

At the high T and ρ of these conditions, also *weak reactions* occur, converting protons into neutrons and leading to a *neutron excess*. This allows to actually make stable iron isotopes.

Beyond Silicon Burning



NSE distribution for
$T = 3.5 \times 10^9$ K,
$\rho = 10^7$ g/cm^3

After silicon burning T and ρ is so high that the nuclei are in **nuclear statistical equilibrium**, i.e., the reactions are fast compared to the evolution time-scale of the star, and the abundance distribution of the nuclei is given by a *Saha equation*.

Summary of Energies

Nuclear Fuel	*Process*	$T_{threshold}$ 10^6 K	*Products*	*Energy per Nucleon (MeV)*
H	p–p	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C + C	600	O, Ne, Na, Mg	0.54
O	O + O	1000	Mg, S, P, Si	~0.3
Si	Nuc. eq.	3000	Co, Fe, Ni	<0.18

Nitrogen Burning

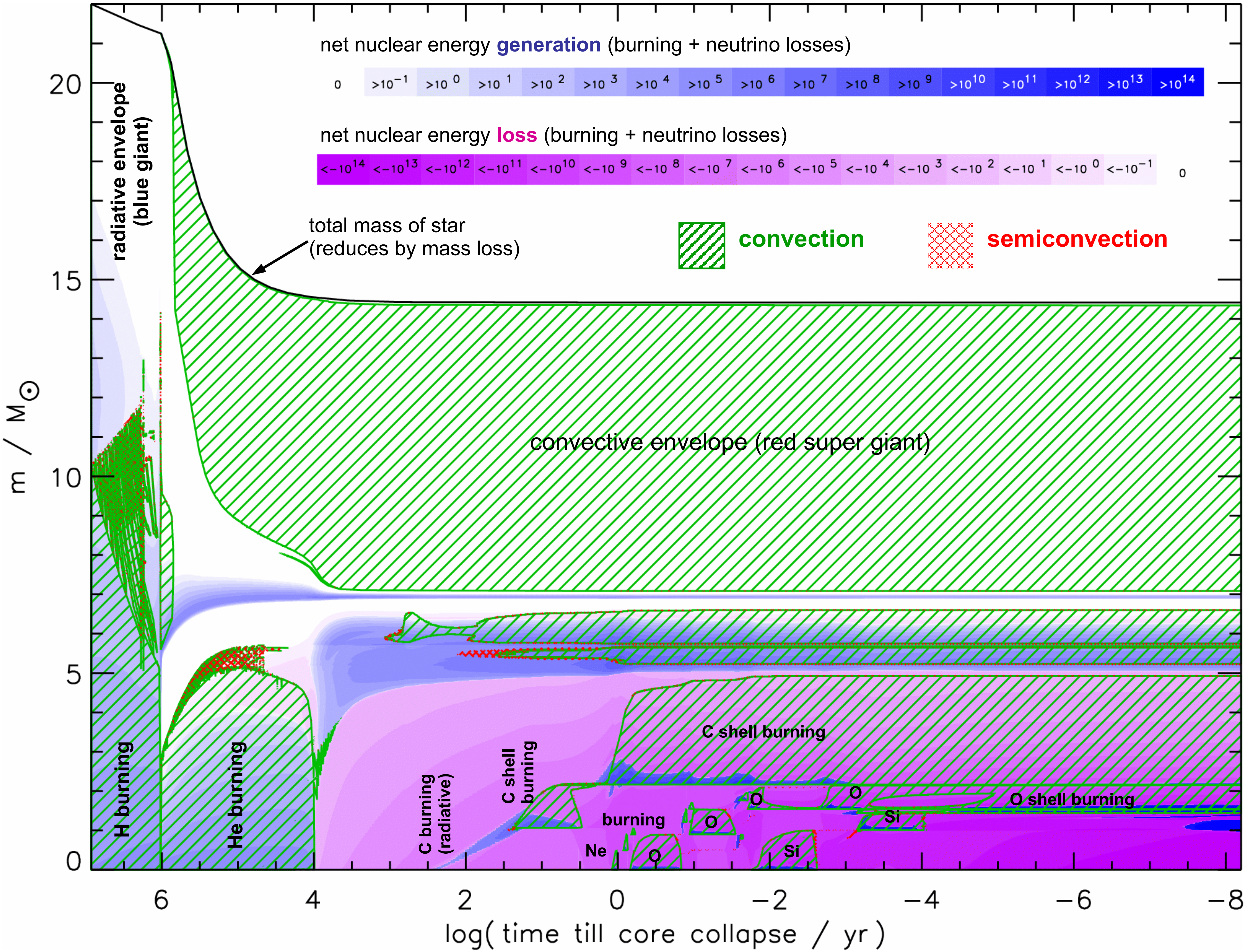
$$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu_{e})^{18}O(\alpha,\gamma)^{22}Ne$$

- ^{14}N is made as slowest reactant in CNO cycle
- It is made from initial metals, not as a primary product
- Depending on metallicity, the abundance can be come significant; it will be more important for more metal-rich stars.
- ^{14}N burning occurs at the onset – before – central helium burning and can have its own convective burning phase, take a few % of helium burning time.

Nuclear Burning Stages

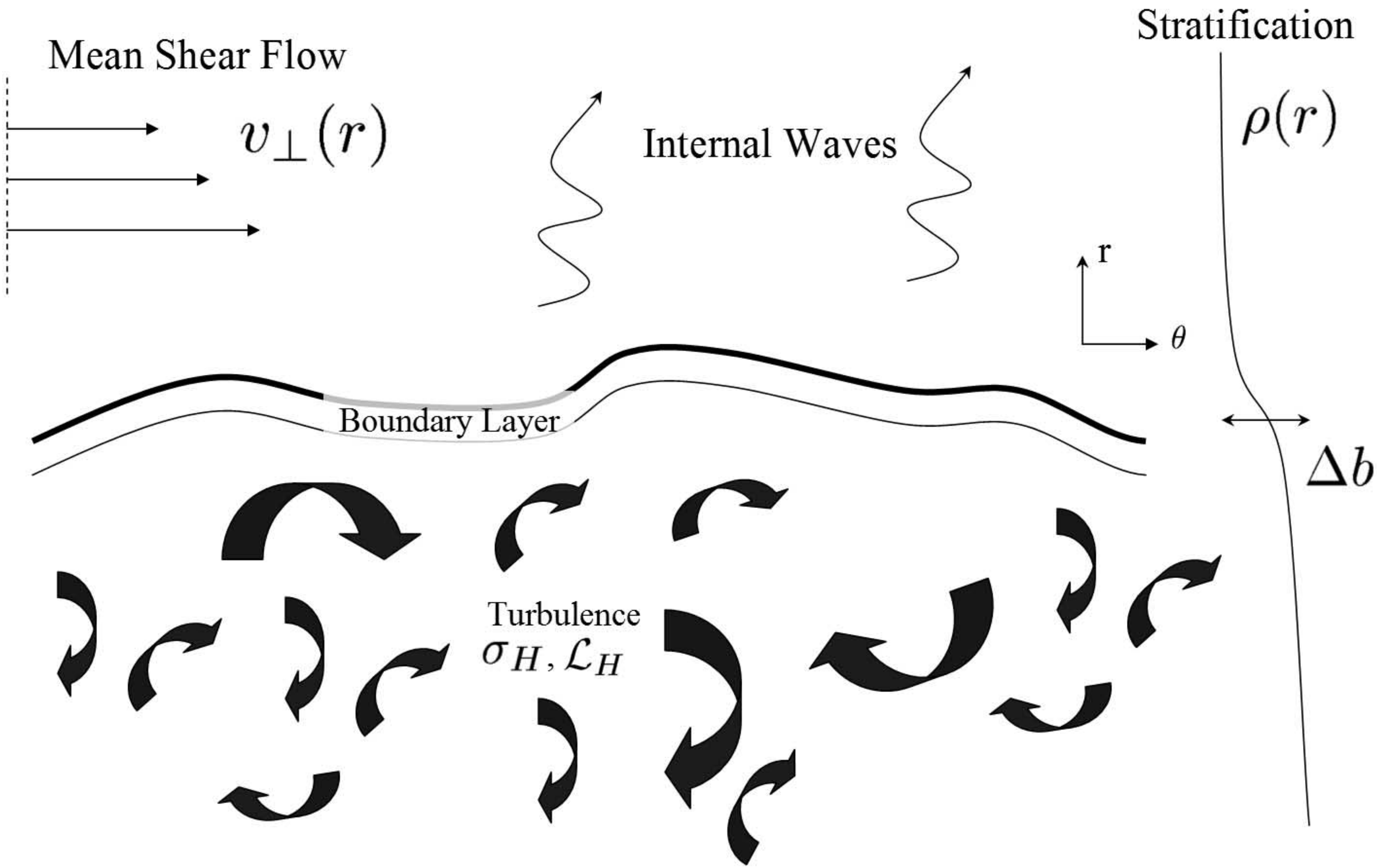
(20 $M_\odot$ star of solar composition)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…



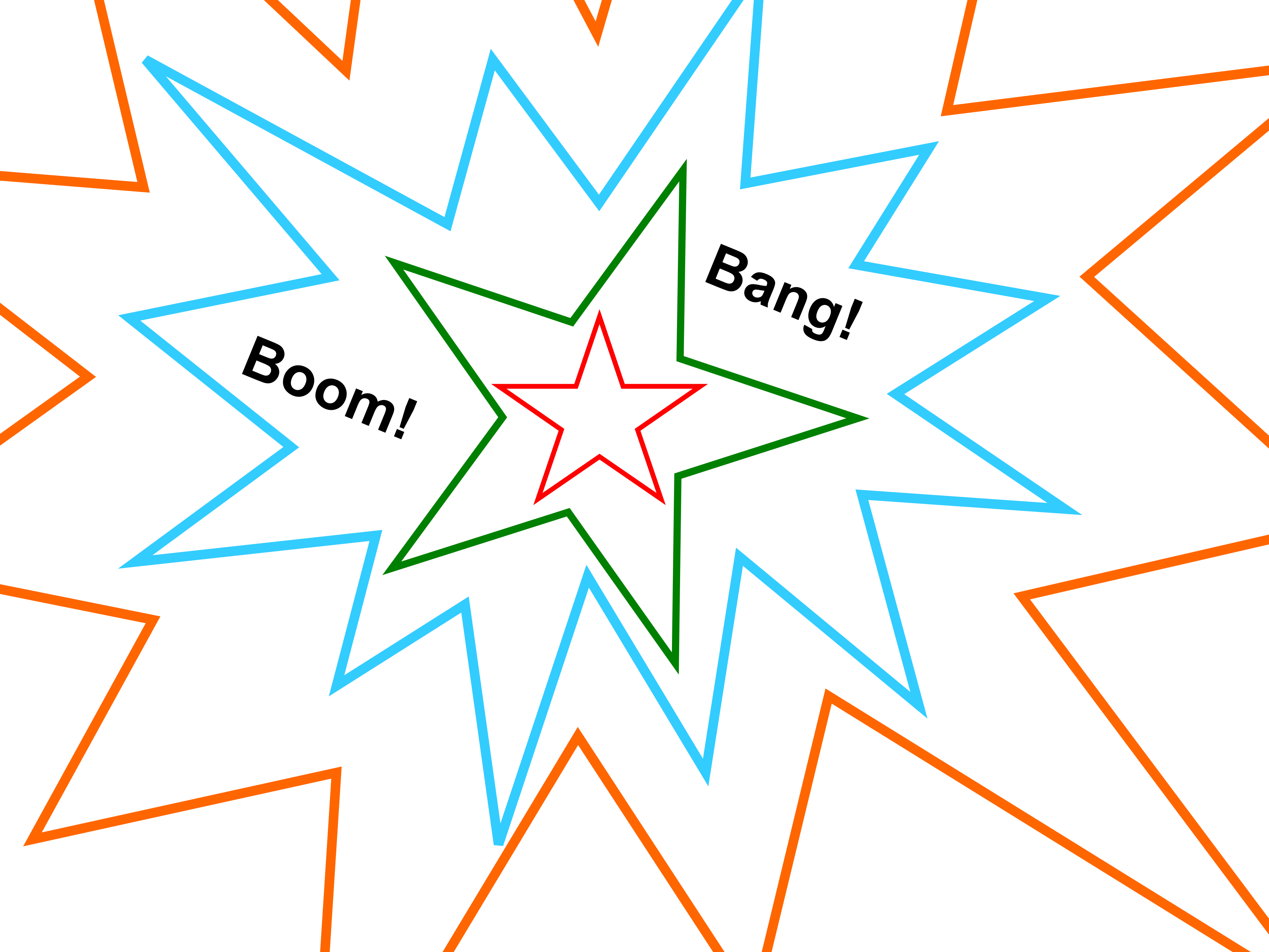
net nuclear energy generation (burning + neutrino losses)
0 >10^−1 >10^0 >10^1 >10^2 >10^3 >10^4 >10^5 >10^6 >10^7 >10^8 >10^9 >10^10 >10^11 >10^12 >10^13 >10^14
net nuclear energy loss (burning + neutrino losses)
<−10^14 <−10^13 <−10^12 <−10^11 <−10^10 <−10^9 <−10^8 <−10^7 <−10^6 <−10^5 <−10^4 <−10^3 <−10^2 <−10^1 <−10^0 <−10^−1 0
total mass of star
(reduces by mass loss)
convection
semiconvection
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
O
O
O
O shell burning
Si
Si
m / M⊙
log(time till core collapse / yr)
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8

Mufti-Dimensional Convection



(Meaken & Arnett 2007)


The
Death
of the
Stars


Boom!
Bang!

Explosive Nucleosynthesis

in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process? νp-process	-	>10?	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}O + ^{16}O$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Overview:

Scales

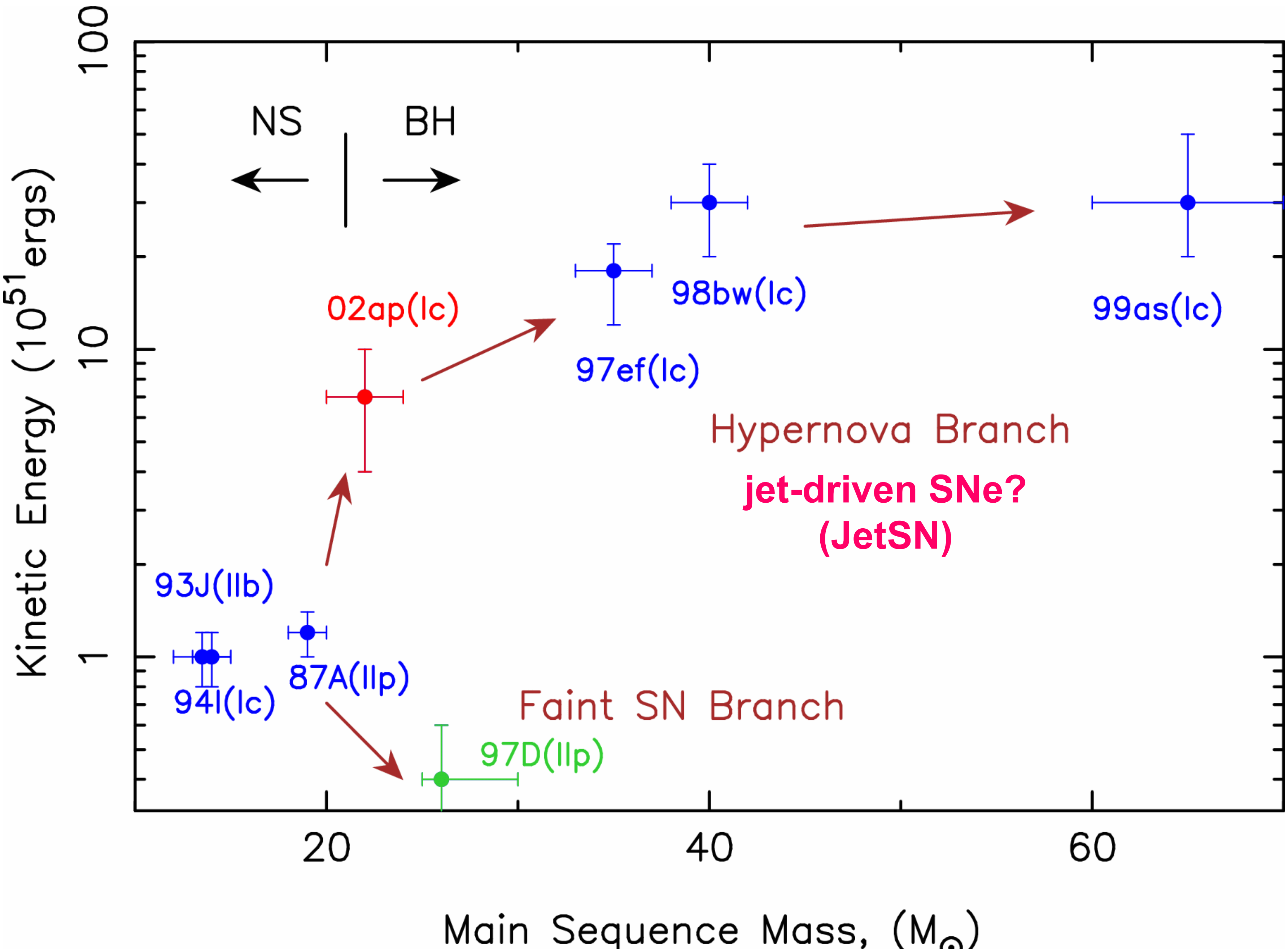
Energy Scales

Log E	Explosion	Thermonuclear
39	X-ray Bursts	√
40	Long-Duration He Bursts	√
41		
42	X-ray Superbursts	√
43		
44		
45	Classical Novae	√
46		
48	Faint SN (visible LC?)	
49	SN (visible LC)	
50	Bright SN (LC?)	
51	SN (kinetic)	SN Type Ia total
52	Hypernova? GRB?	Pair-SN total (low-mass end)
53	SN (neutrinos – several 10^{53}erg)	Pair-SN total (upper limit)
54	*(a lot of energy - 0.5 $M_{\odot}$ c^2)*	
55	GR He SN	GR He SN (upper limit)
56	GR H SN, Z > 0 (Fuller *et al.* 1986)	√

Overview:

Varieties of Cosmic Explosions

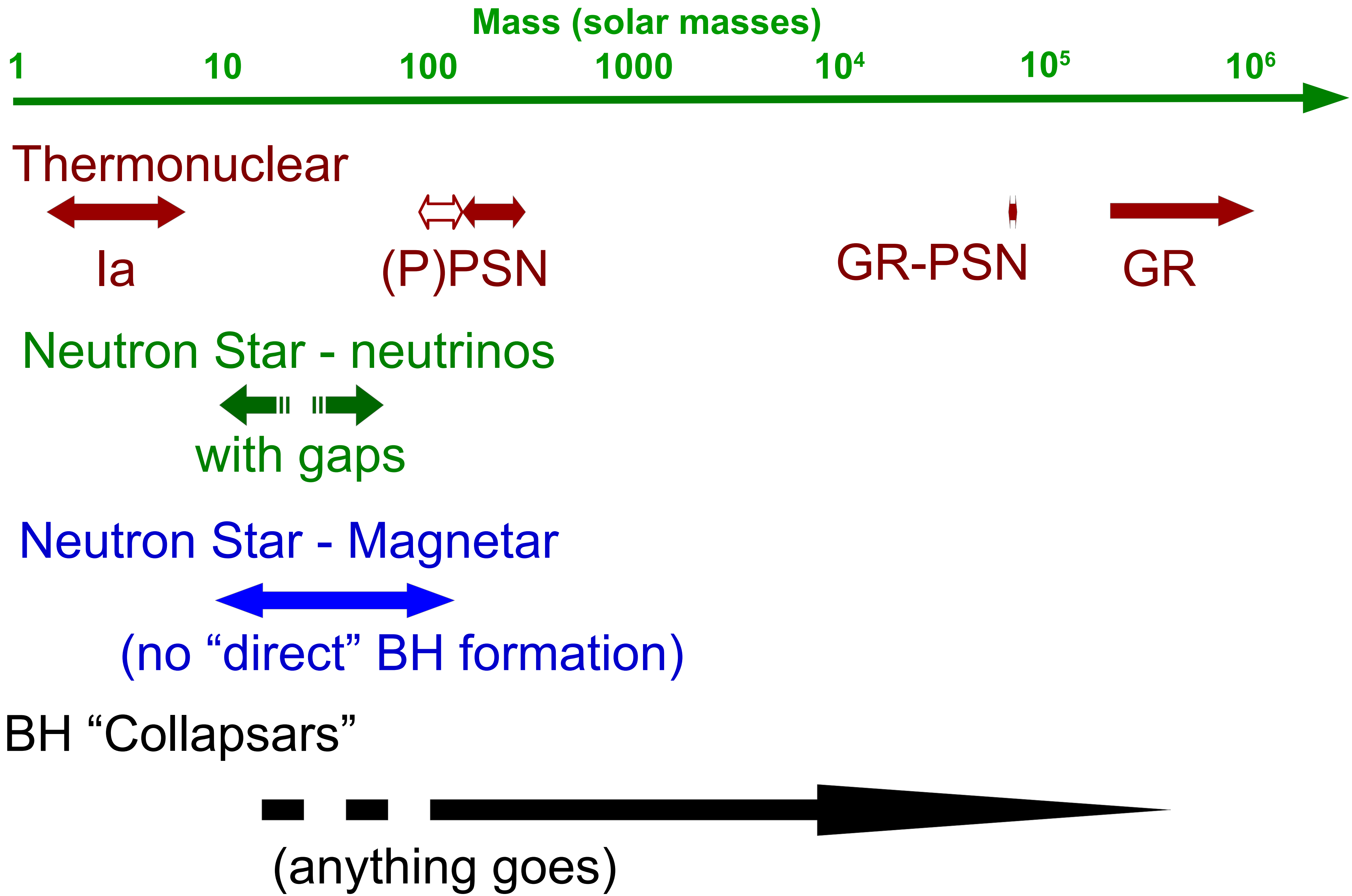
(of most kind)



(Nomoto 2002, priv. com.)

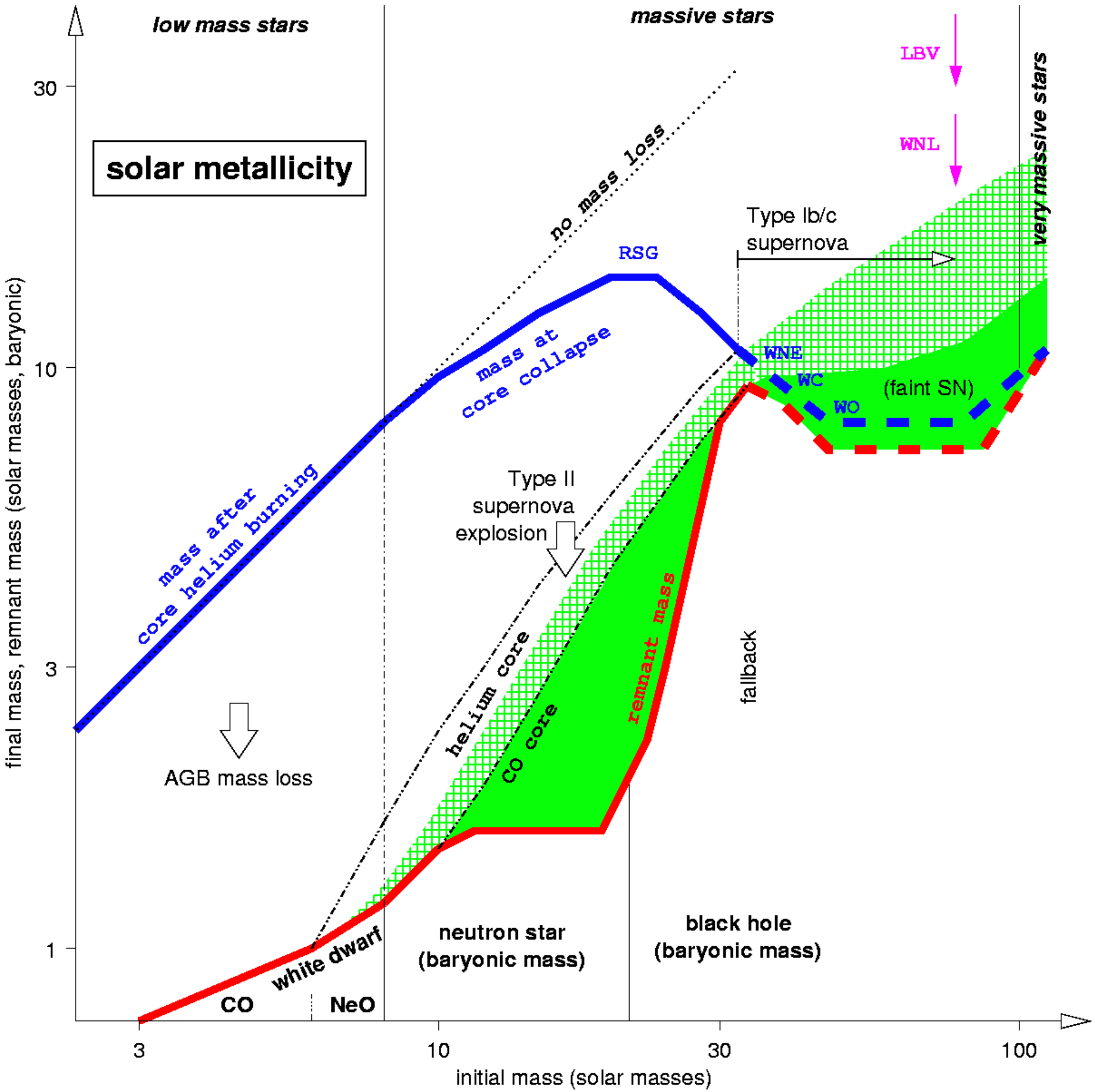
Fates...

The Engines of SNe

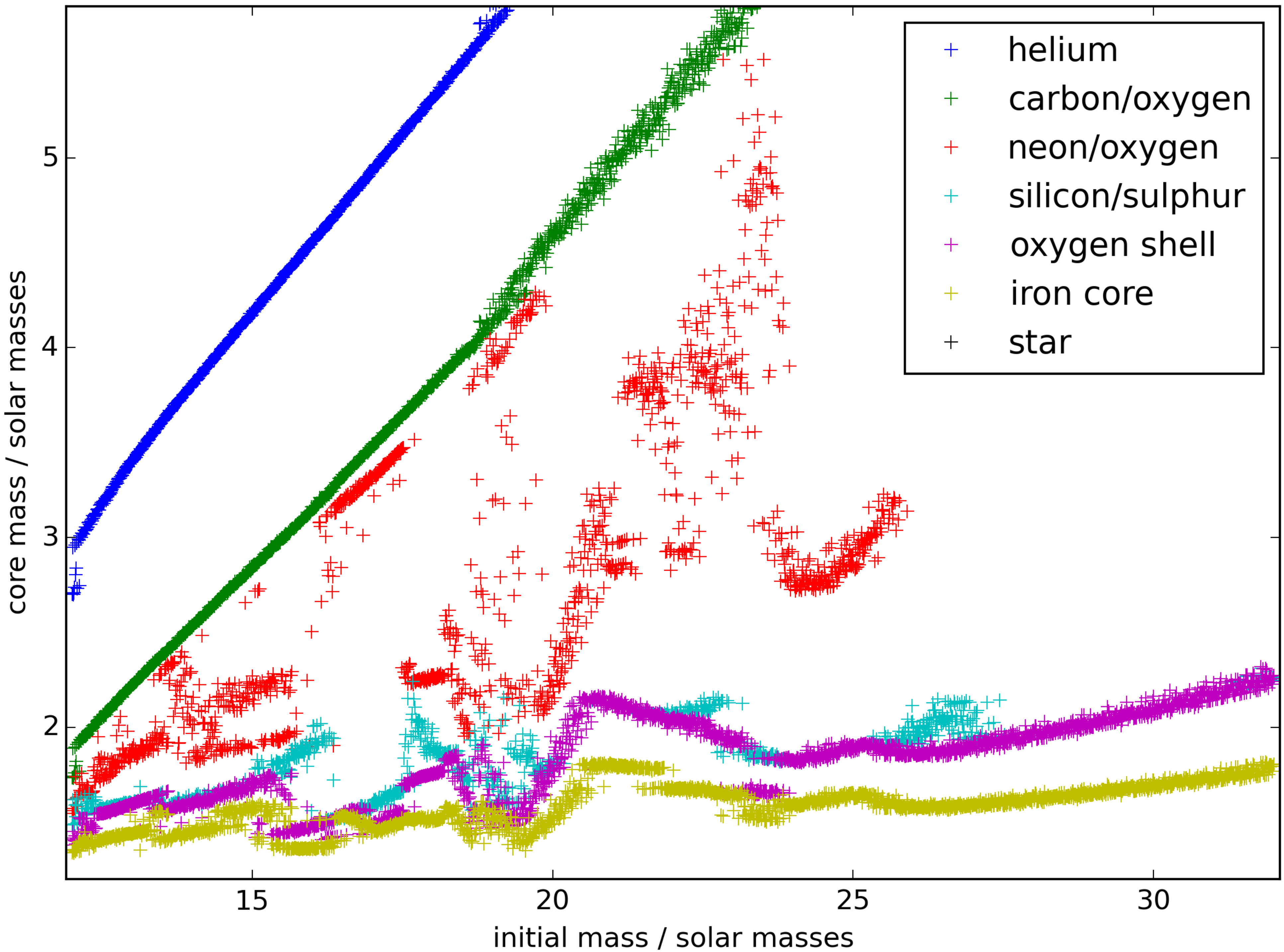


Massive Star Fates as Function of Initial Mass

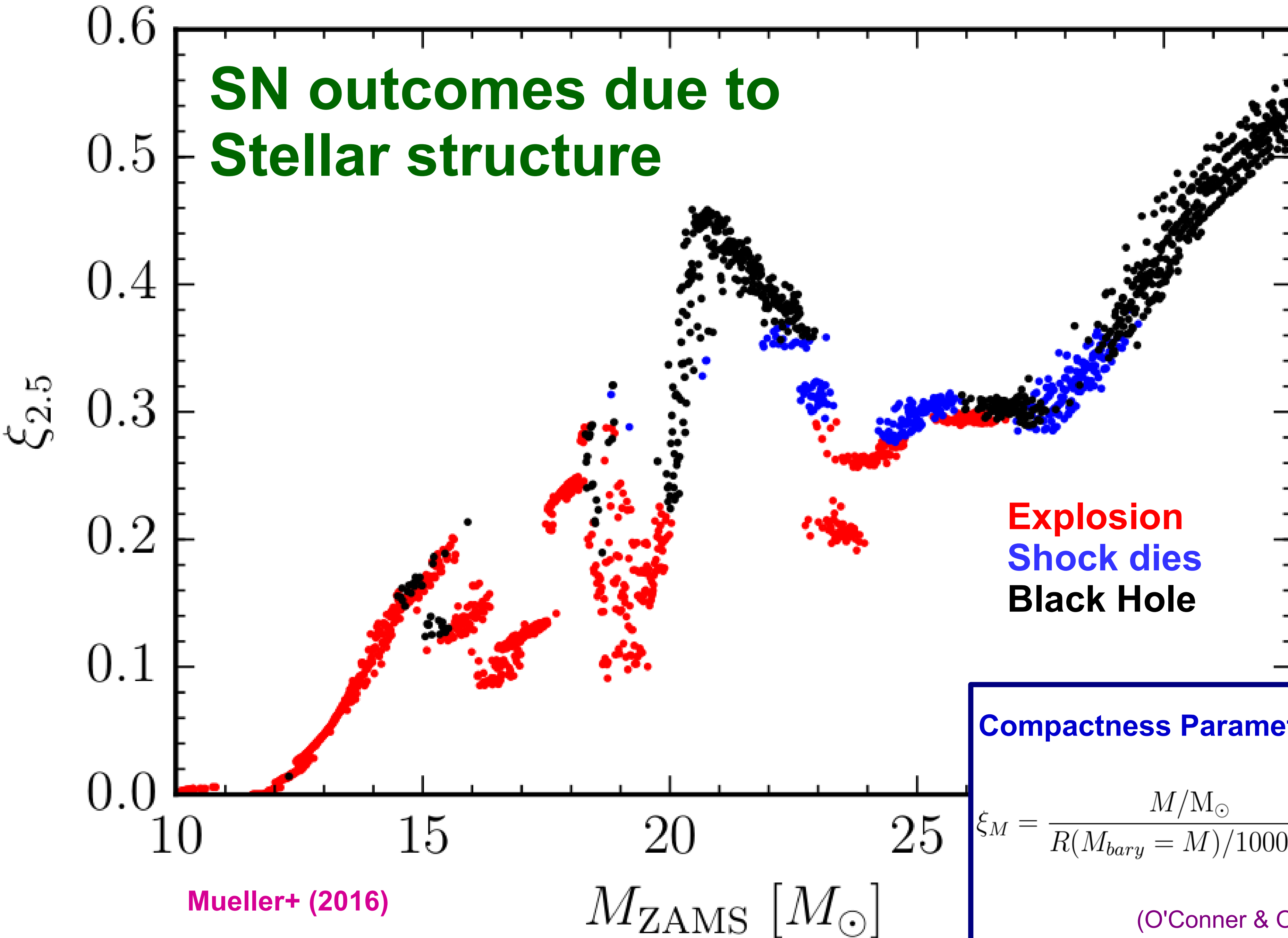
(solar metallicity)



Ejected “metals”


helium
carbon/oxygen
neon/oxygen
silicon/sulphur
oxygen shell
iron core
star
core mass / solar masses
initial mass / solar masses
2
3
4
5
15
20
25
30

Signatures of Stellar Structure?



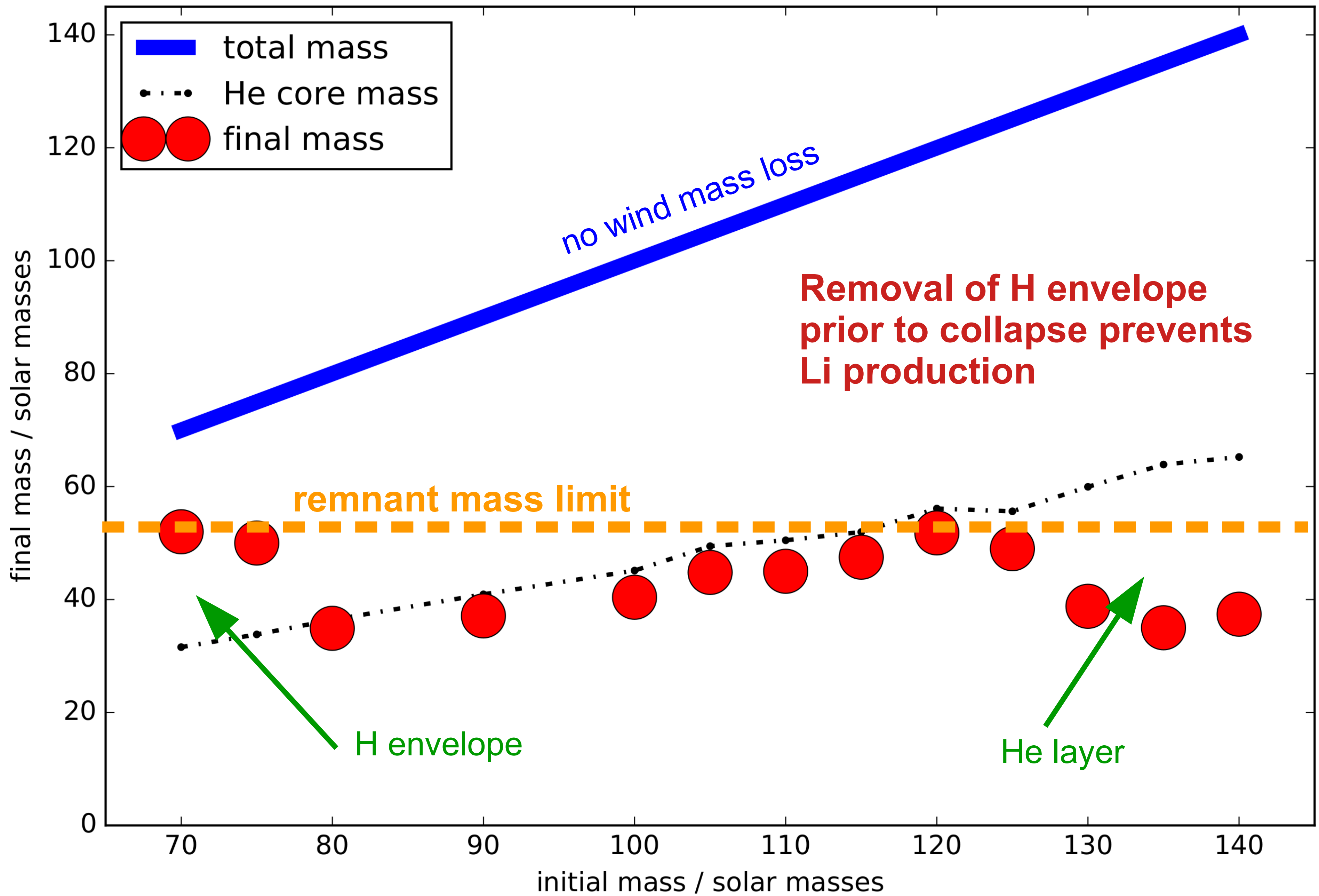
Mueller+ (2016)

Compactness Parameter

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\bigg|_{t_{bounce}},$$

(O'Conner & Ott 2011)

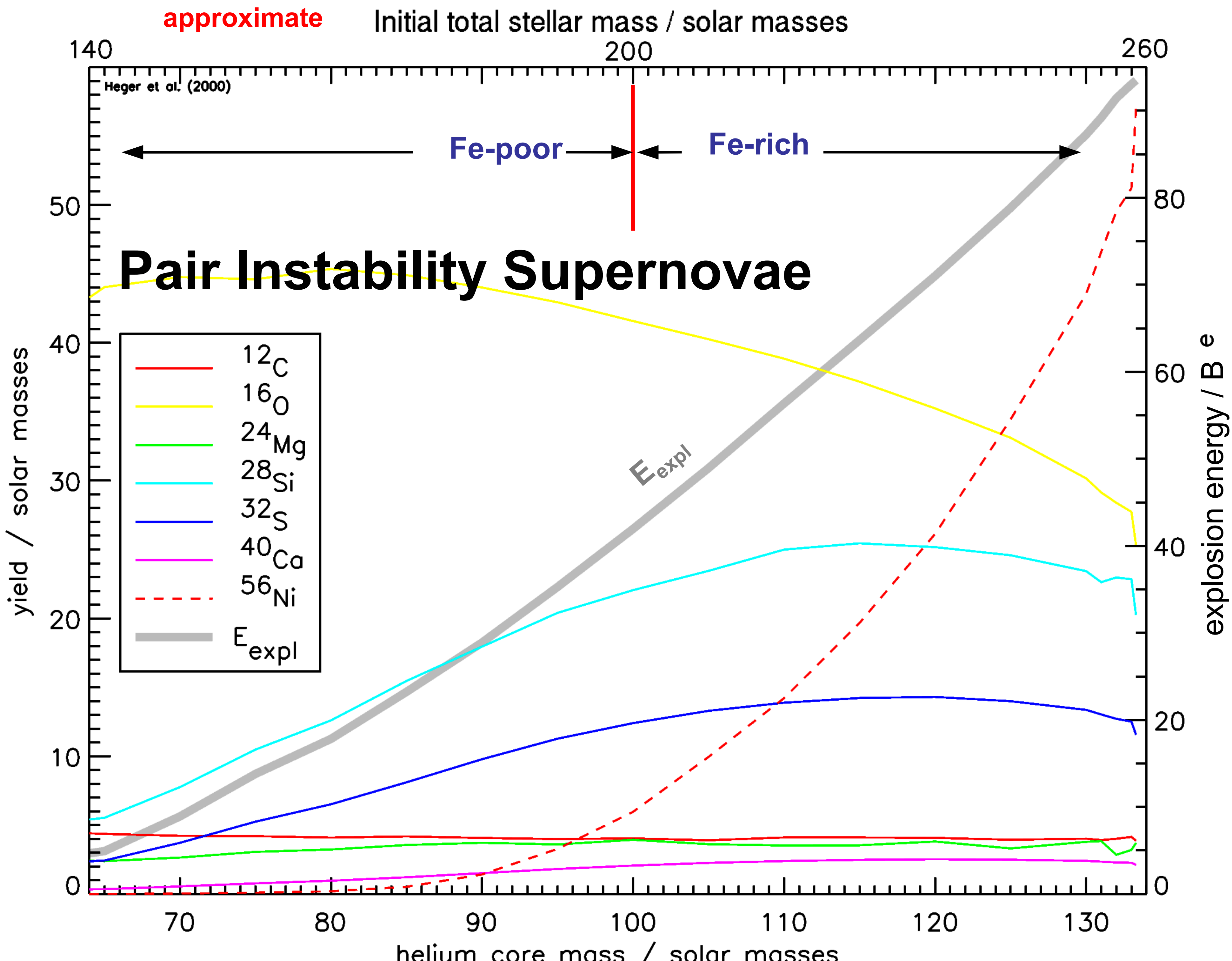
Pulsational Pair Instability Supernovae



Plot after data from Woosley (2016)

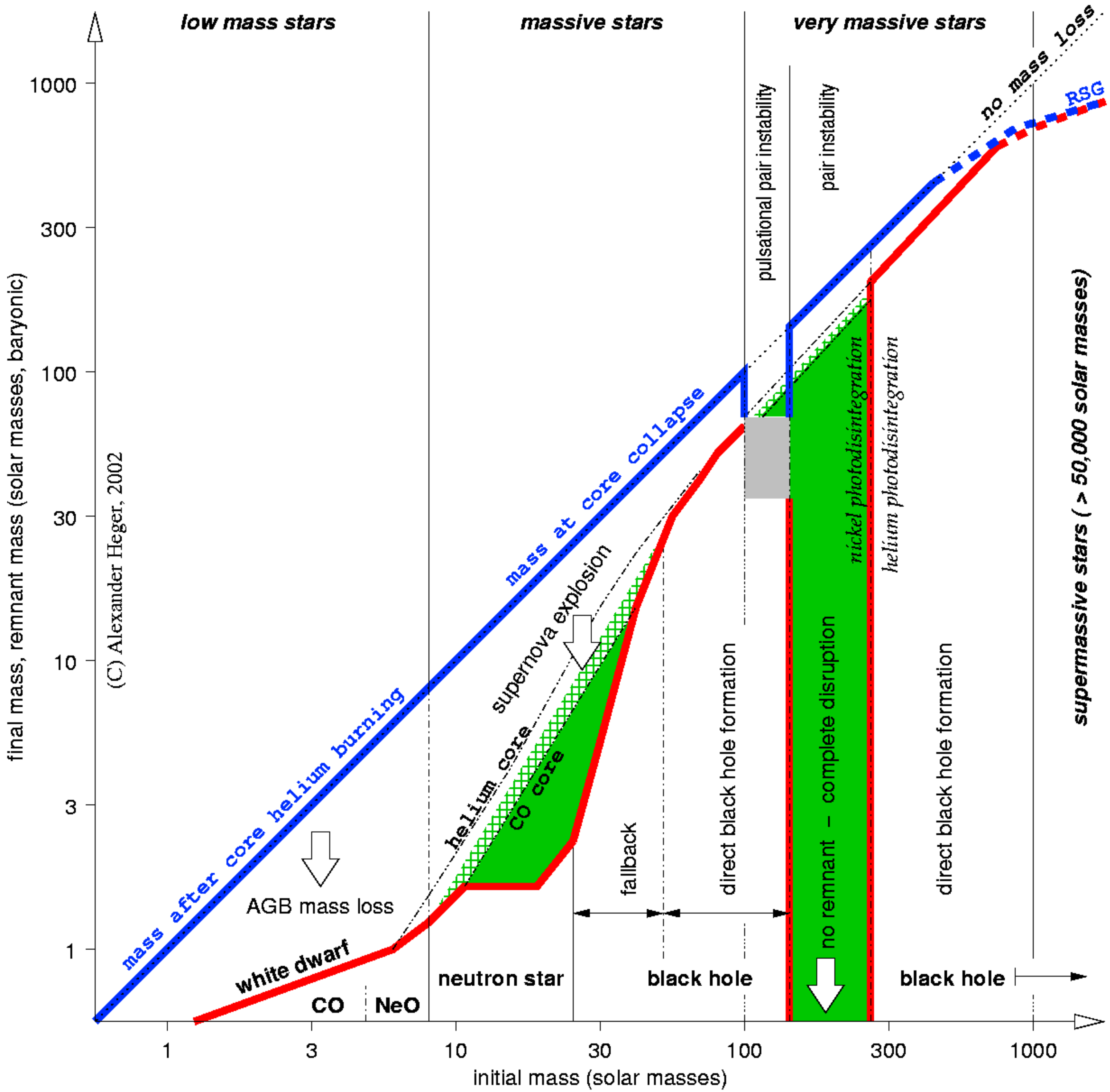
Nuclear Burning Stages

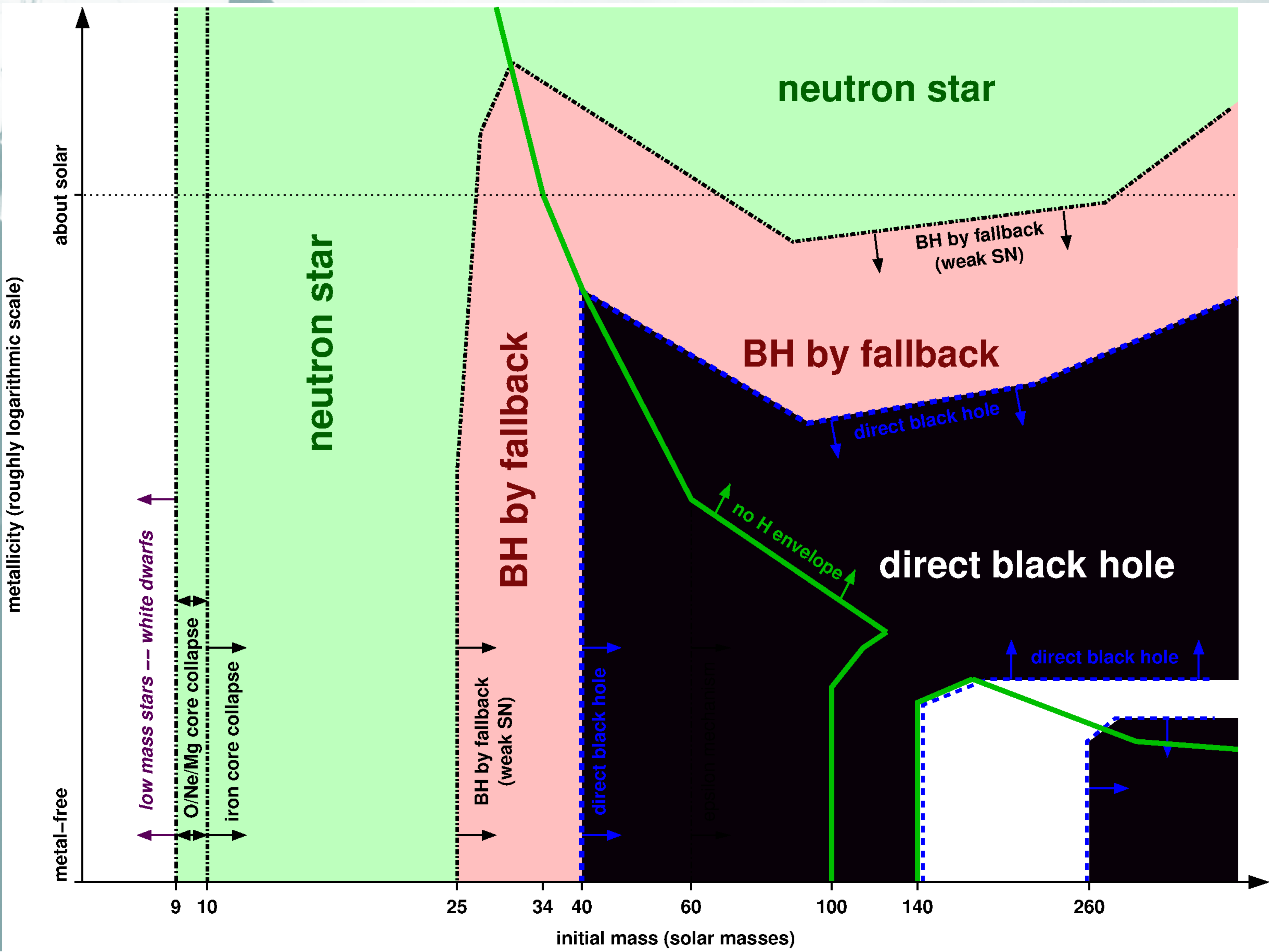
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	He	0.02	10^7	0.1	2×10^6
He	O, C	0.2	10^6	0.3	2×10^5
C	Ne, Mg	0.8	10^3	1.2	10
Ne	O, Mg	1.5	3	2.5	3×10^{-6}
O	Si, S	2.0	0.8	3.0	2×10^{-6}
Si	Fe	3.5	0.02	4.5	3×10^{-7}



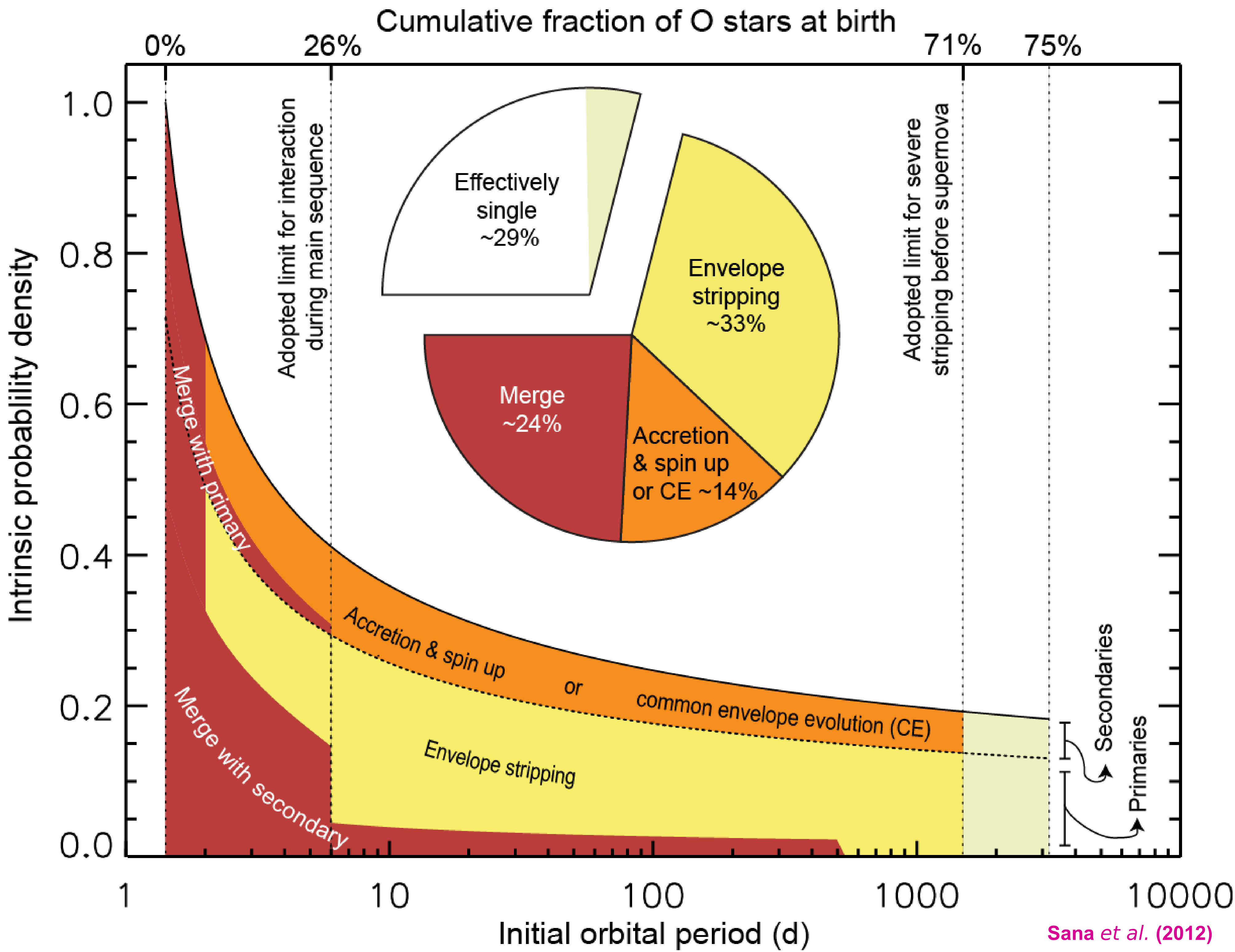
approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
Pair Instability Supernovae
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
E_{expl}
yield / solar masses
0
10
20
30
40
50
explosion energy / B e
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses

No Stellar Wind

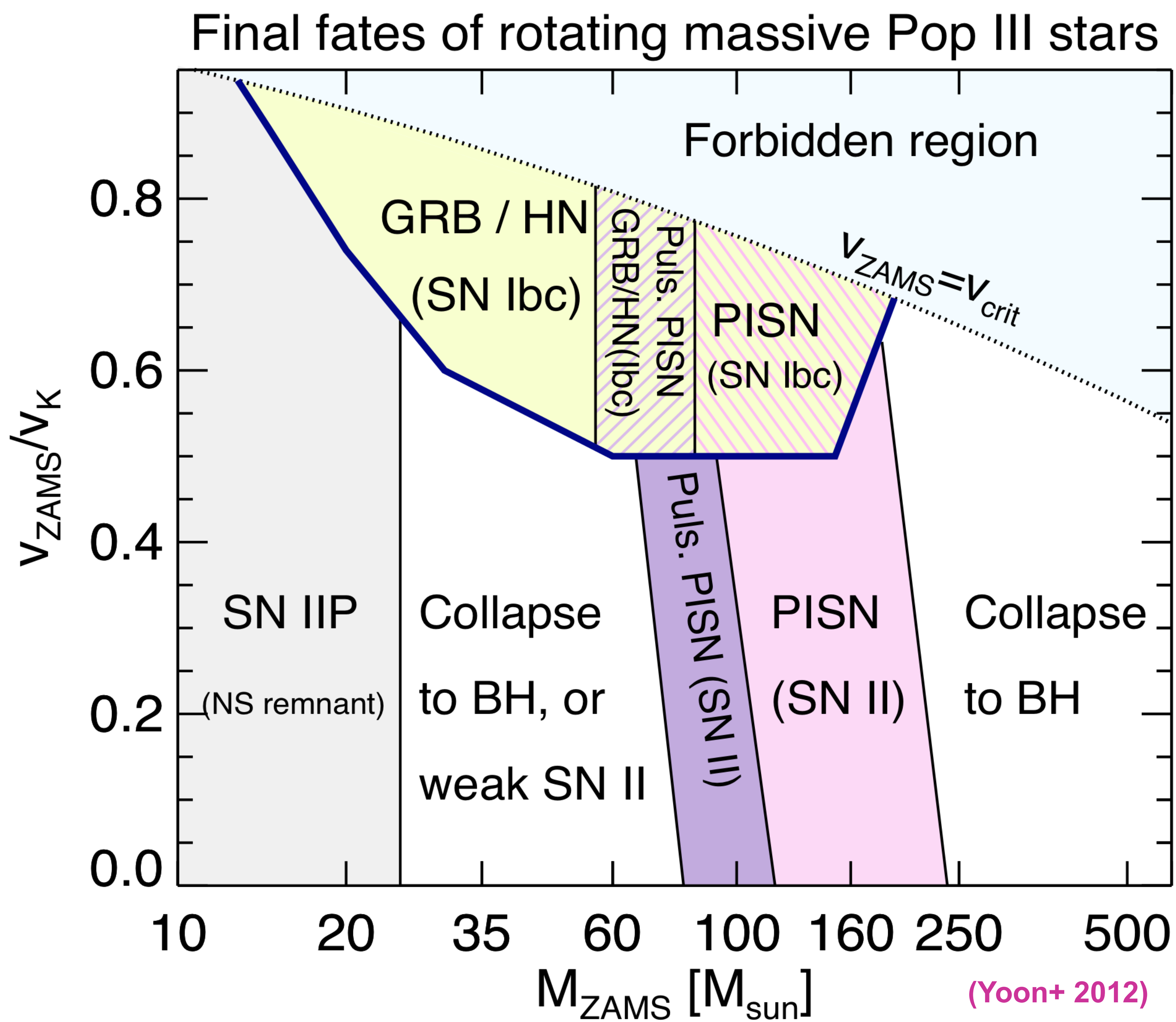




neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback (weak SN)
BH by fallback (weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
about solar
metal-free
metallicity (roughly logarithmic scale)
initial mass (solar masses)
9
10
25
34
40
60
100
140
260

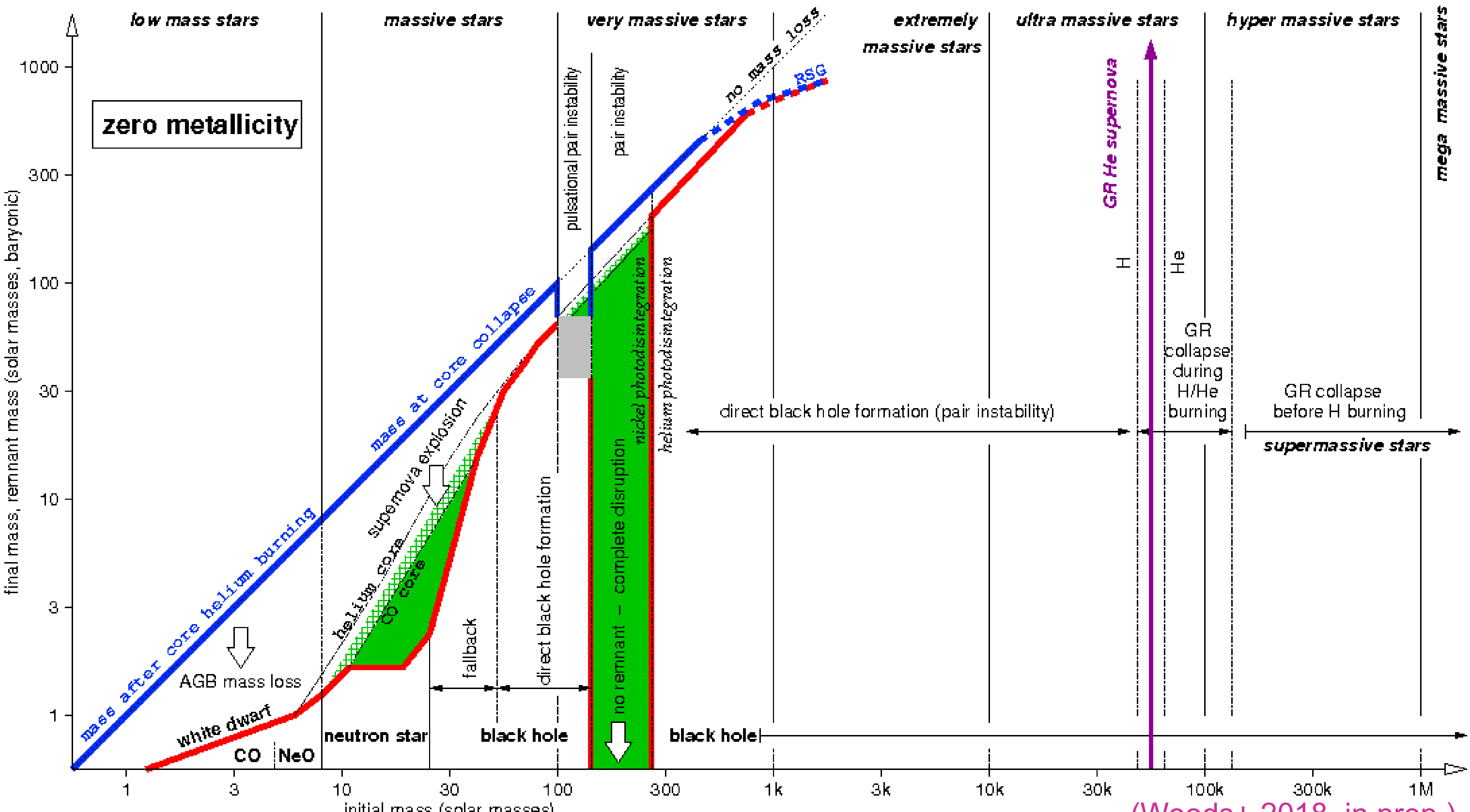


Cumulative fraction of O stars at birth
0%
26%
71%
75%
Adopted limit for interaction during main sequence
Adopted limit for severe stripping before supernova
Effectively single ~29%
Envelope stripping ~33%
Merge ~24%
Accretion & spin up or CE ~14%
Merge with primary
Merge with secondary
Accretion & spin up
or
common envelope evolution (CE)
Envelope stripping
Secondaries
Primaries
Intrinsic probability density
0.0
0.2
0.4
0.6
0.8
1.0
1
10
100
1000
10000
Initial orbital period (d)
Sana et al. (2012)



Final fates of rotating massive Pop III stars
Forbidden region
$v_{ZAMS}=v_{crit}$
GRB / HN
(SN Ibc)
GRB/HN(Ibc)
Puls. PISN
PISN
(SN Ibc)
SN IIP
(NS remnant)
Collapse
to BH, or
weak SN II
Puls. PISN (SN II)
PISN
(SN II)
Collapse
to BH
0.0
0.2
0.4
0.6
0.8
v_{ZAMS}/v_K
10
20
35
60
100
160
250
500
M_{ZAMS} [M_{sun}]
(Yoon+ 2012)

Supermassive Stars



(Woods+ 2018, in prep.)