NIC XVI, Nuclear Astrophysics Summer School 2021, Chengdu, China, September 17, 2021

Evolution of Massive Stars

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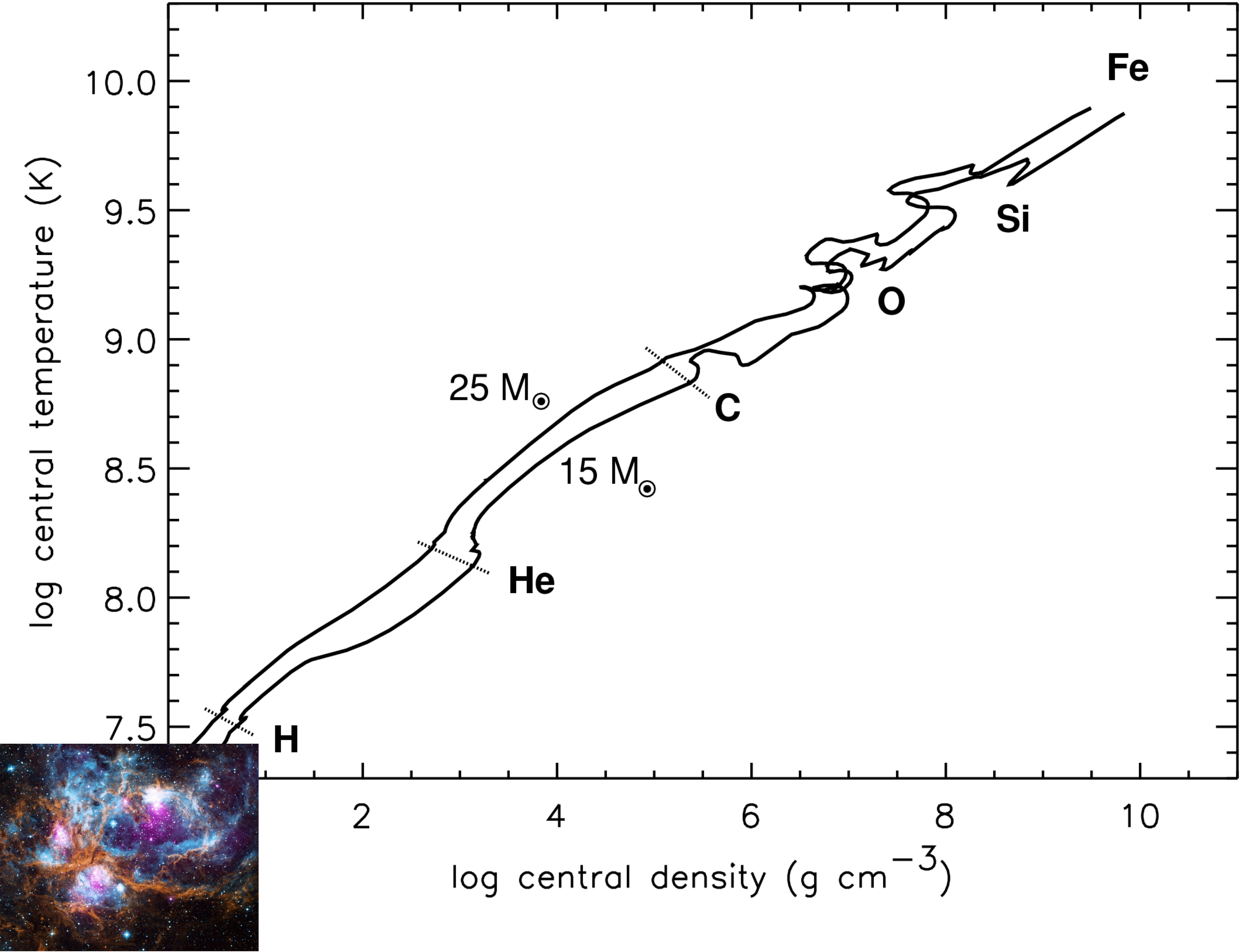
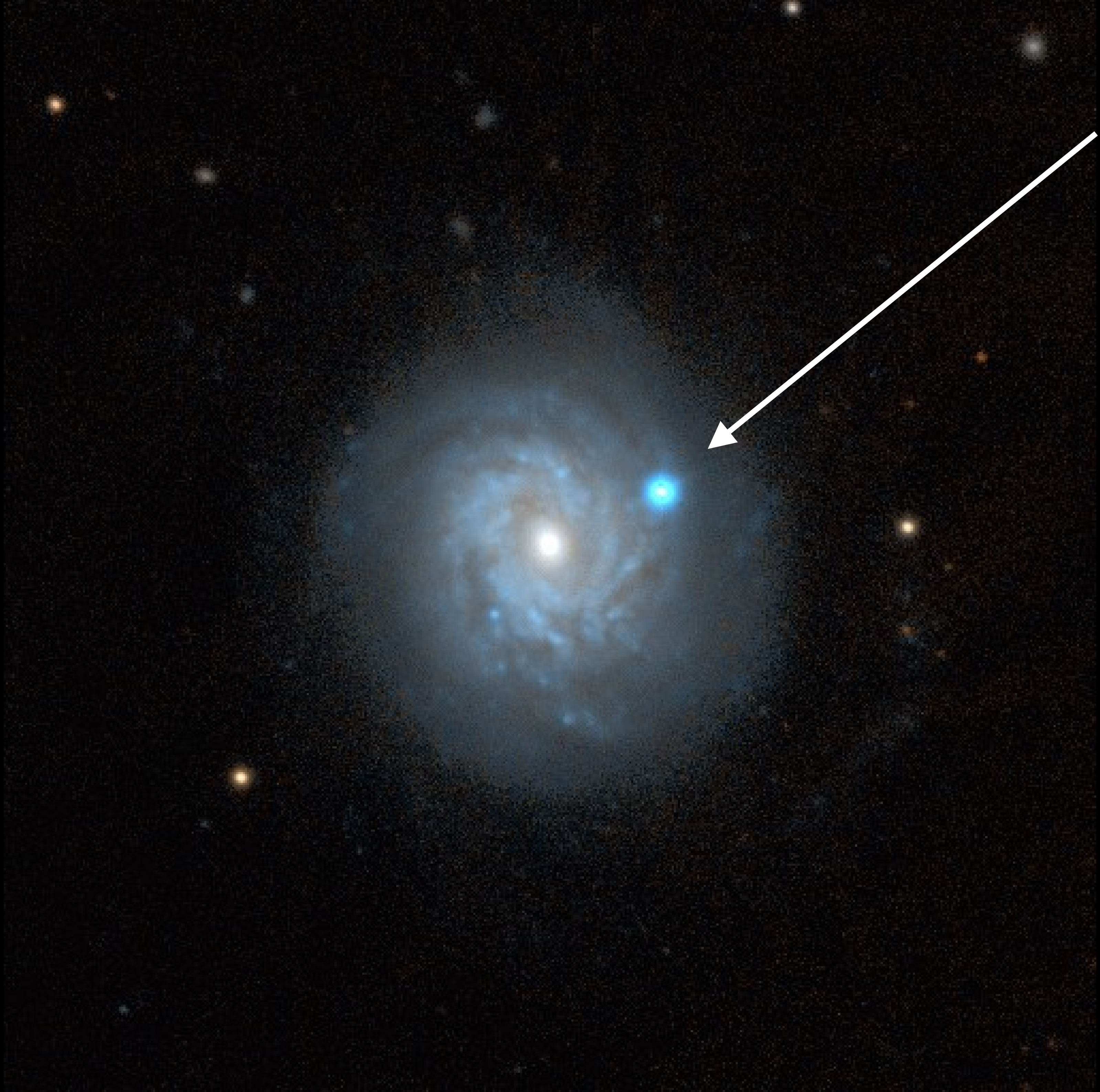
http://CosmicExplosions.org

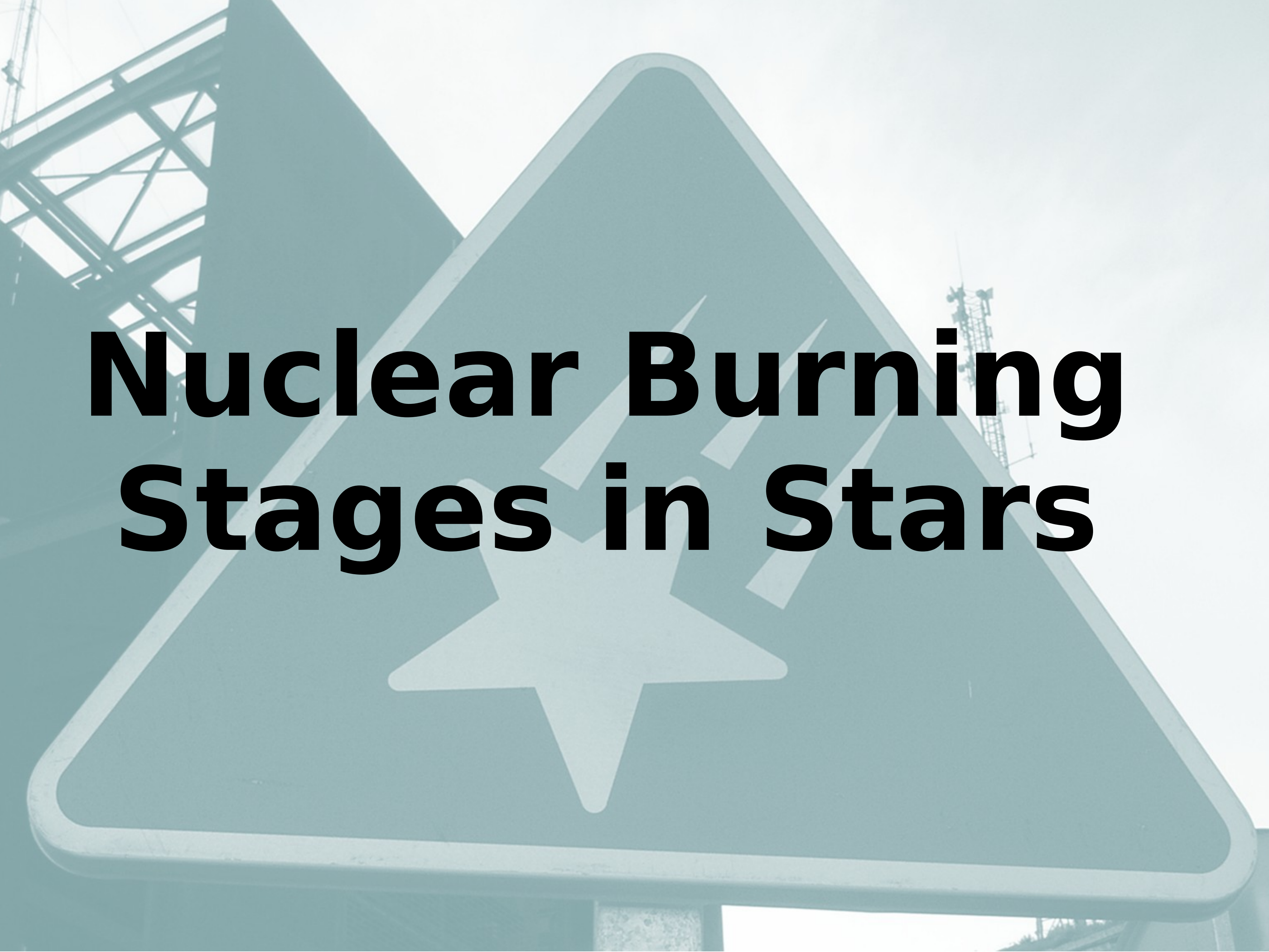
Once formed, the evolution of a star is governed by gravity:
continuing contraction
to higher central densities and temperatures



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



NGC3982



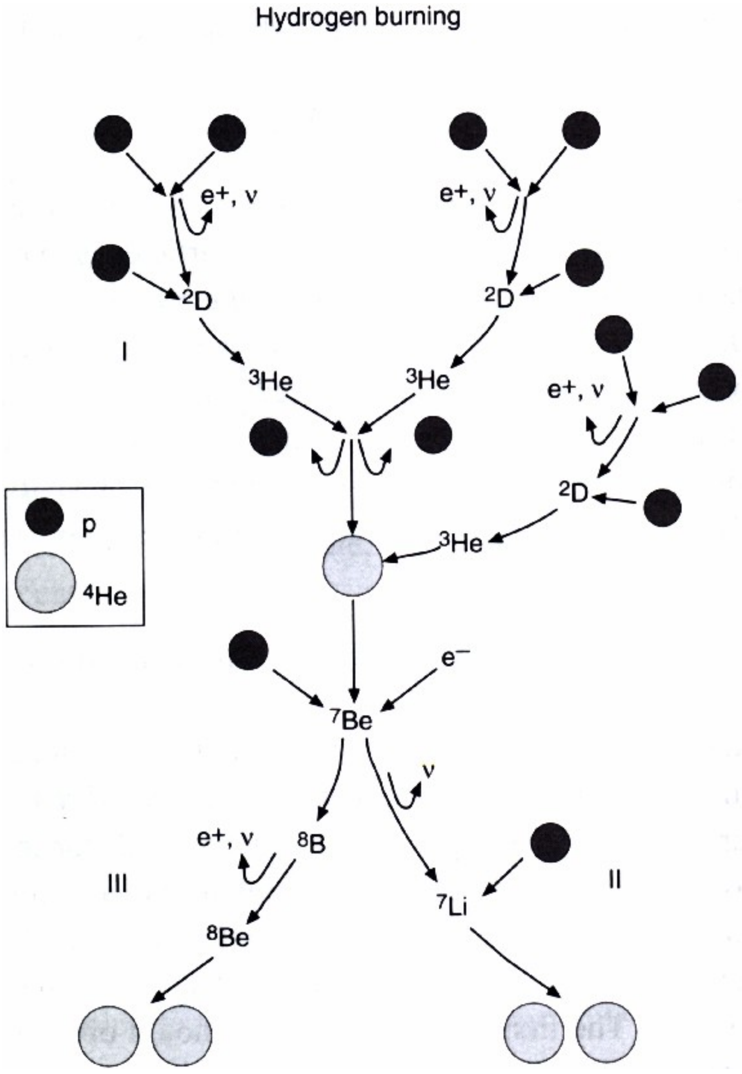
Nuclear Burning Stages in Stars

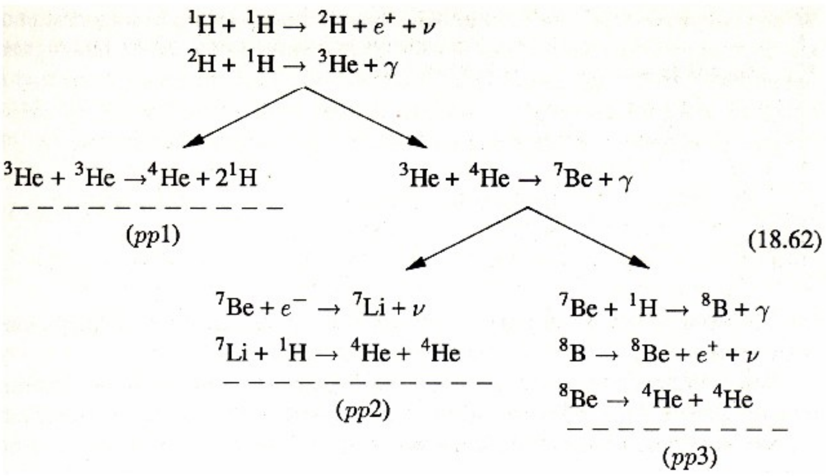
Nuclear burning stages

(20 $M_\odot$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	**He**	**^{14}N**	**0.02**	**10^7**	**$4\,H \xrightarrow{CNO} {}^4He$**

Hydrogen-Burning: pp Chains





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

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

$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$ — (*pp*1)

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

(18.62)

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + {}^1H \rightarrow {}^4He + {}^4He$ — (*pp*2)

$^7Be + {}^1H \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$^8Be \rightarrow {}^4He + {}^4He$ — (*pp*3)

Energy release:

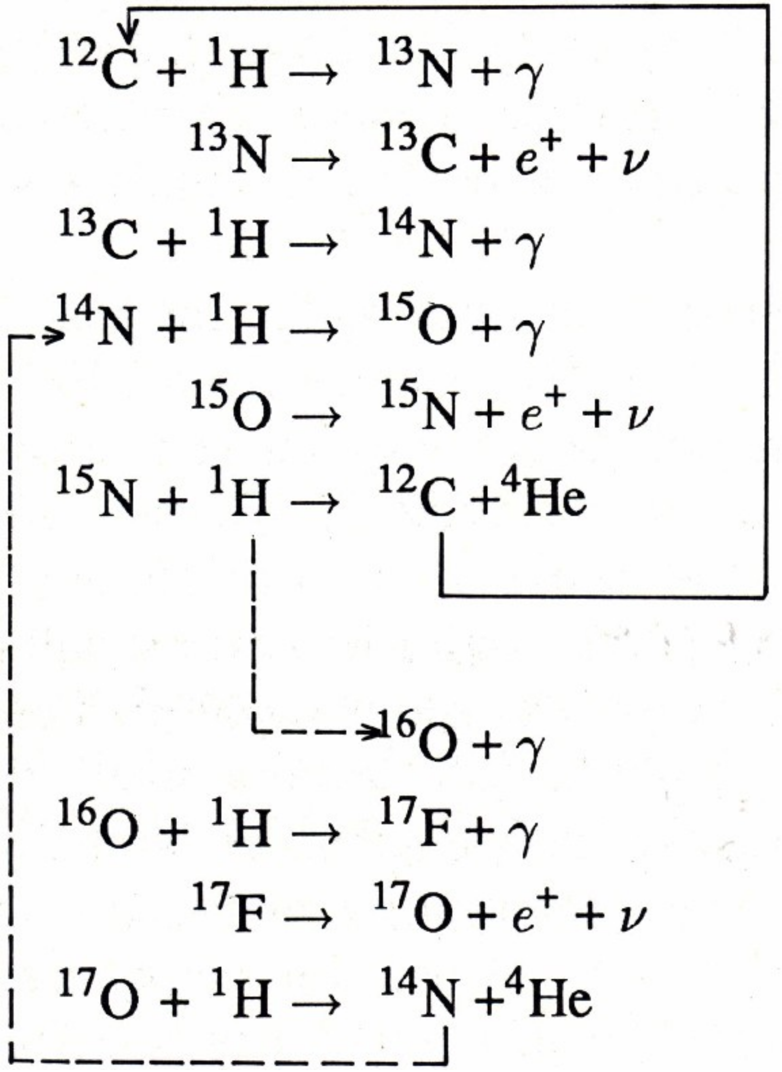
$Q(pp1) = 26.20 MeV$

$Q(pp2) = 25.67 MeV$

$Q(pp3) = 19.20 MeV$

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:
$Q(CNO) = 24.97 MeV$

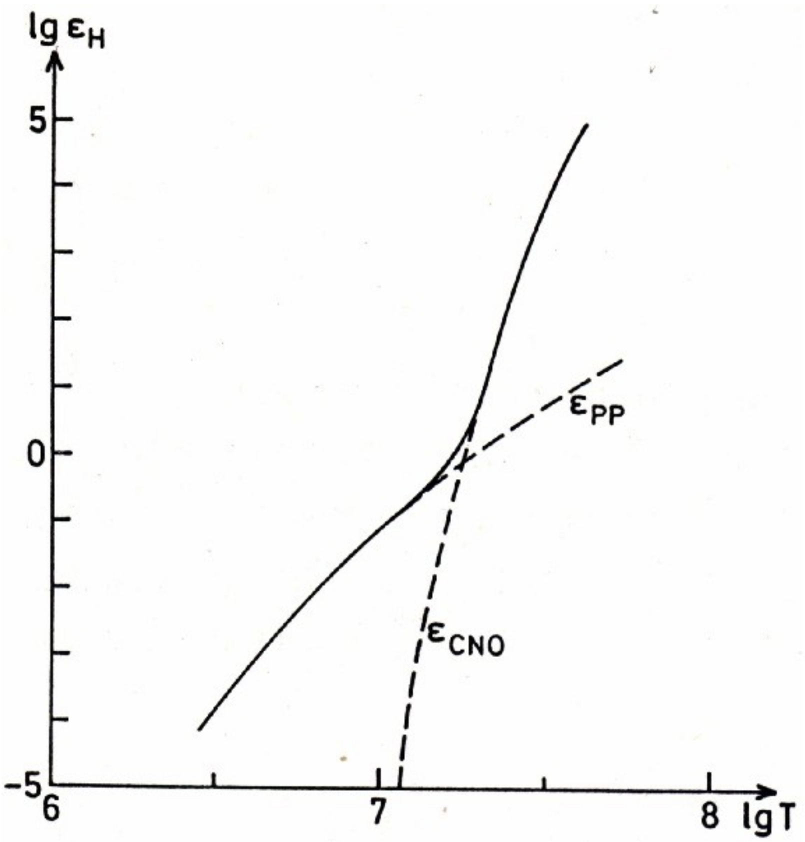
Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

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

Hydrogen Burning: CNO Bi-Cycle

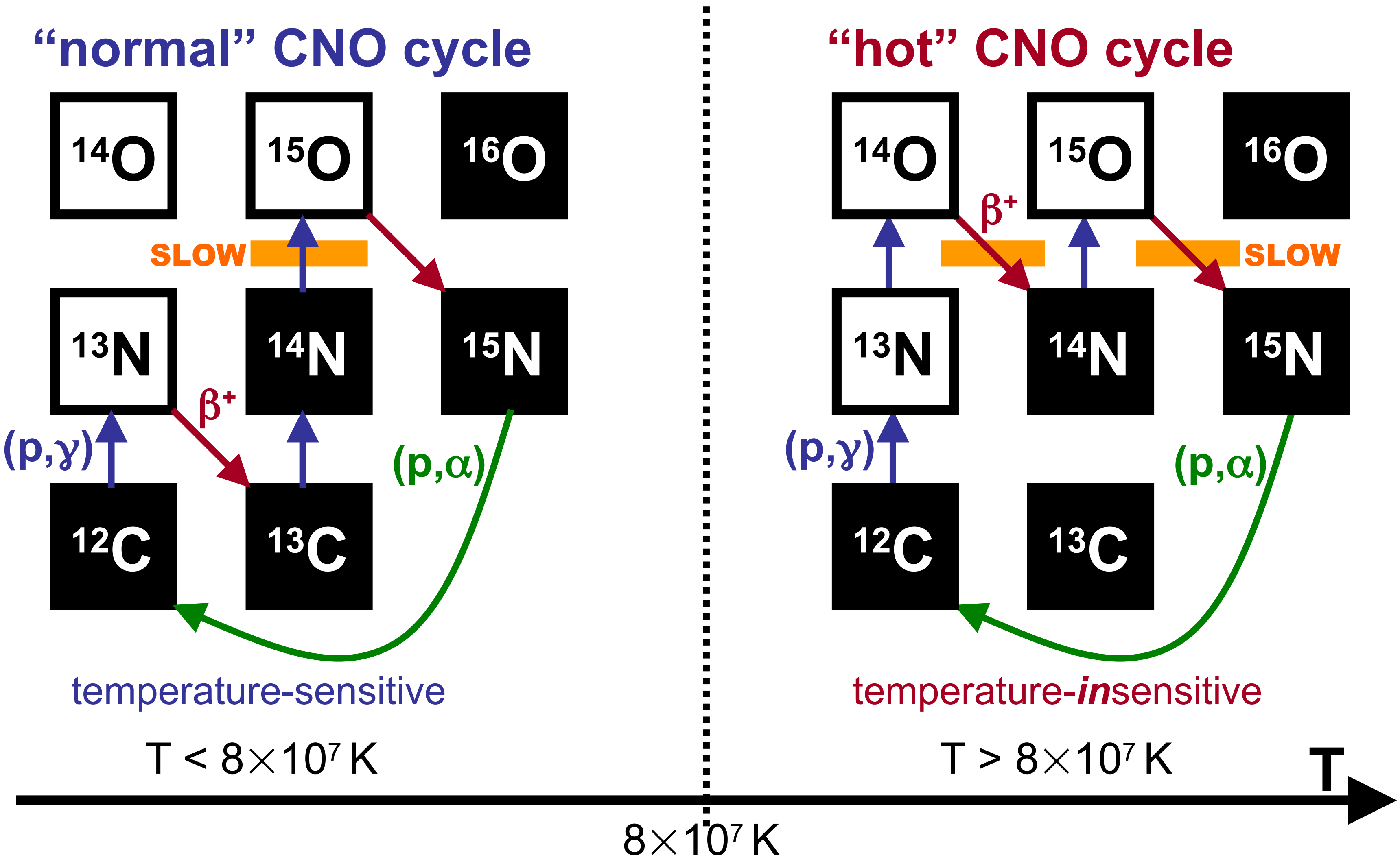
- Usually the beta-decays are fast compared to the capture reactions, (p,γ).
- ^{14}O: $\tau_{1/2} = 70$ sec
  ^{15}O: $\tau_{1/2} = 122$ sec
  ^{13}N: $\tau_{1/2} = 10\,$min
  ^{17}F: $\tau_{1/2} = 64$ sec
  ^{18}O: $\tau_{1/2} = 110\,$min
- ^{14}N(p,γ)^{15}O usually is the slowest “bottleneck” reaction.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

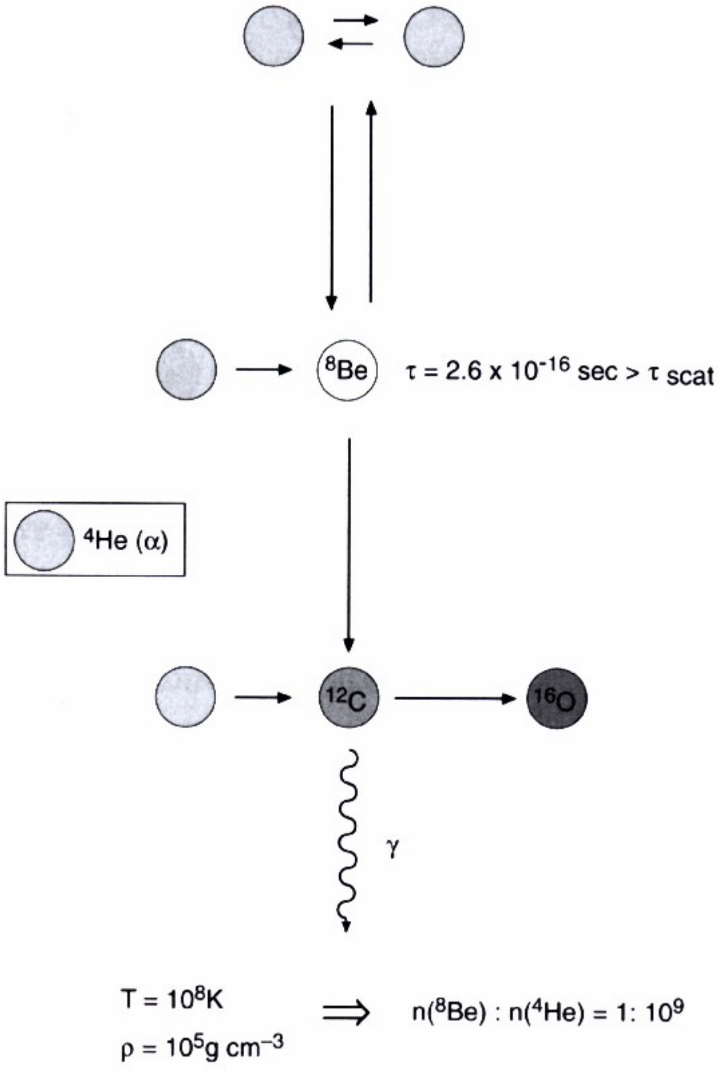
$$\tau_H = \mathbf{11\ h} \left(\frac{0.02}{Z}\right)\left(\frac{X_0}{0.7}\right)$$

Nuclear burning stages

(20 $M_\odot$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$

Helium Burning



Step 1:

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

Built up equilibrium abundance of ^{8}Be

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

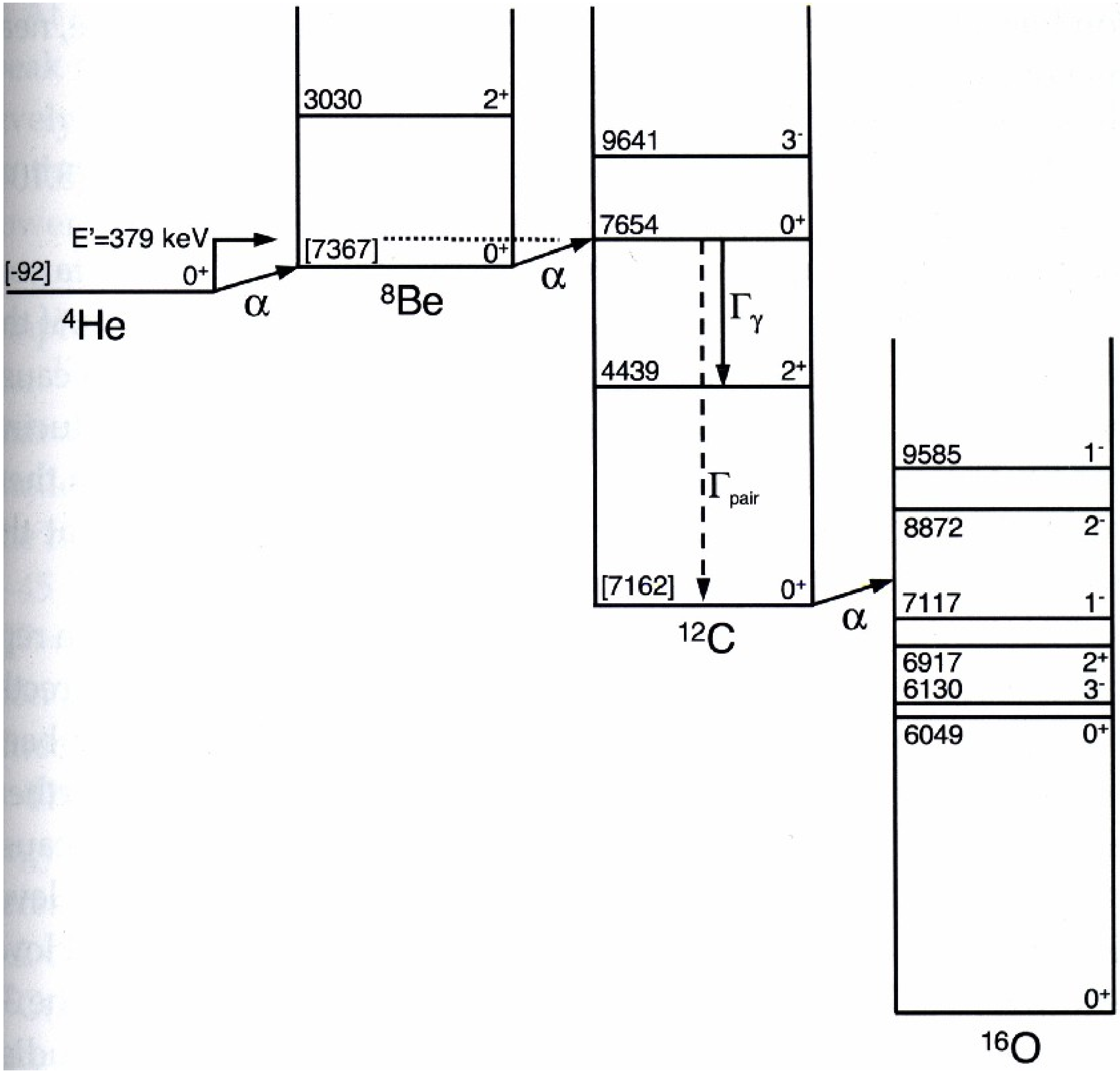
Step 2:

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

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

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

Helium Burning Level Scheme



Additional Helium Burning Reactions

Oxygen Production

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

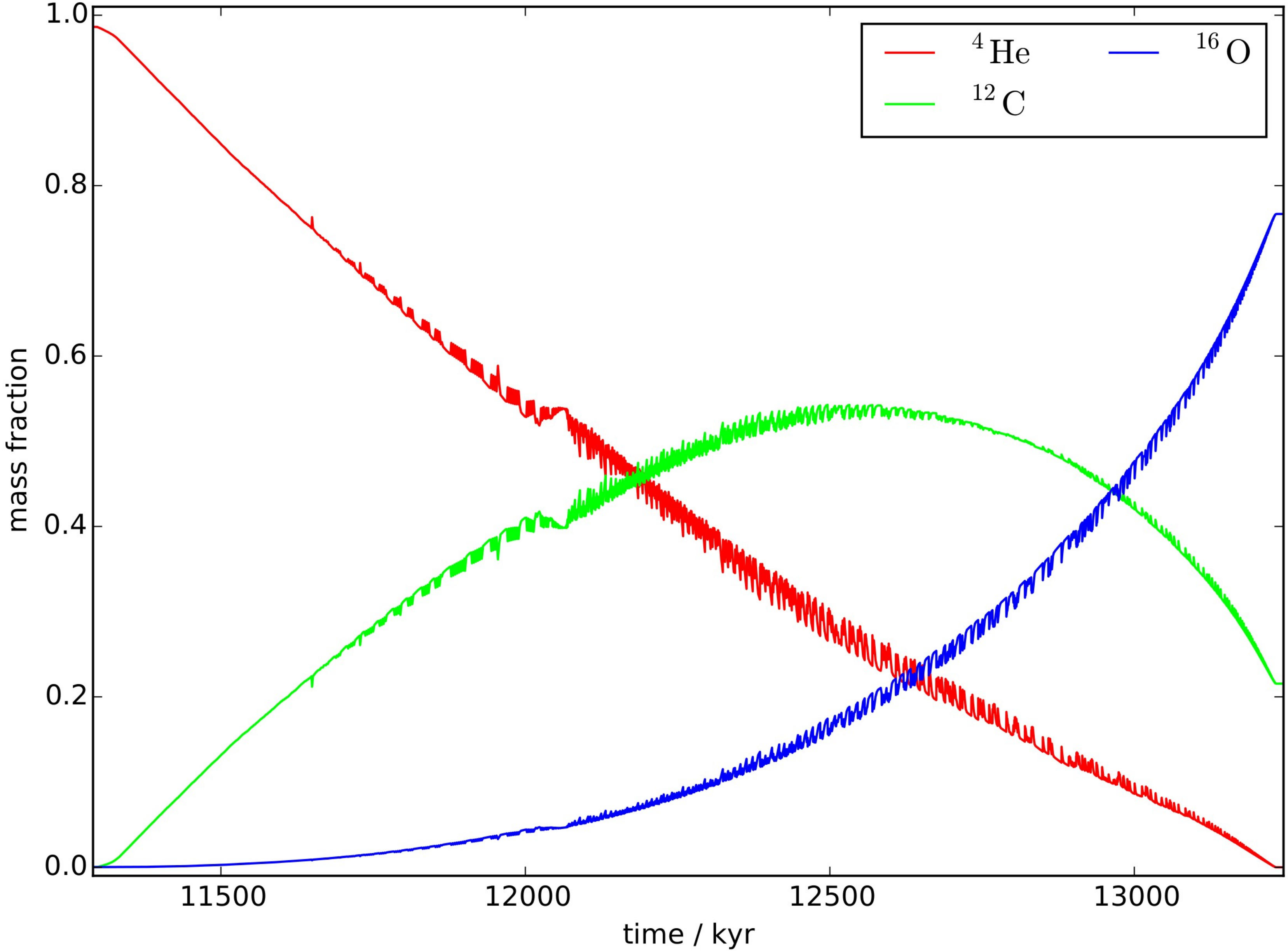
$Q = 7.162\,\mathrm{MeV}$

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

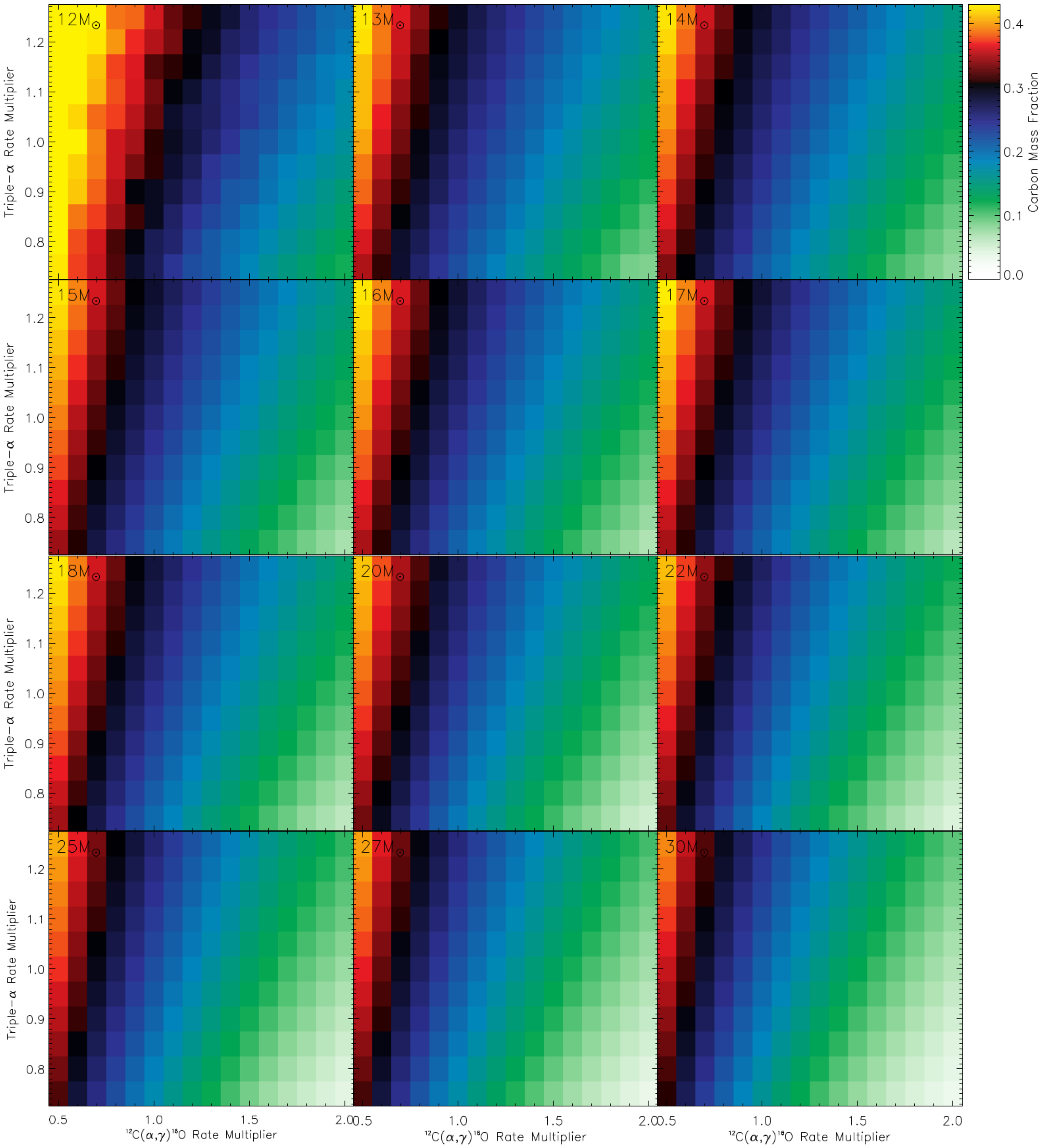
The final abundance of carbon is set by the competition of 3α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reactions;

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

Competition of Helium Burning Reactions



^{12}C Production as a function of ^{12}C(α,γ) 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)

Nuclear burning stages

(20 $M_\odot$ stars)

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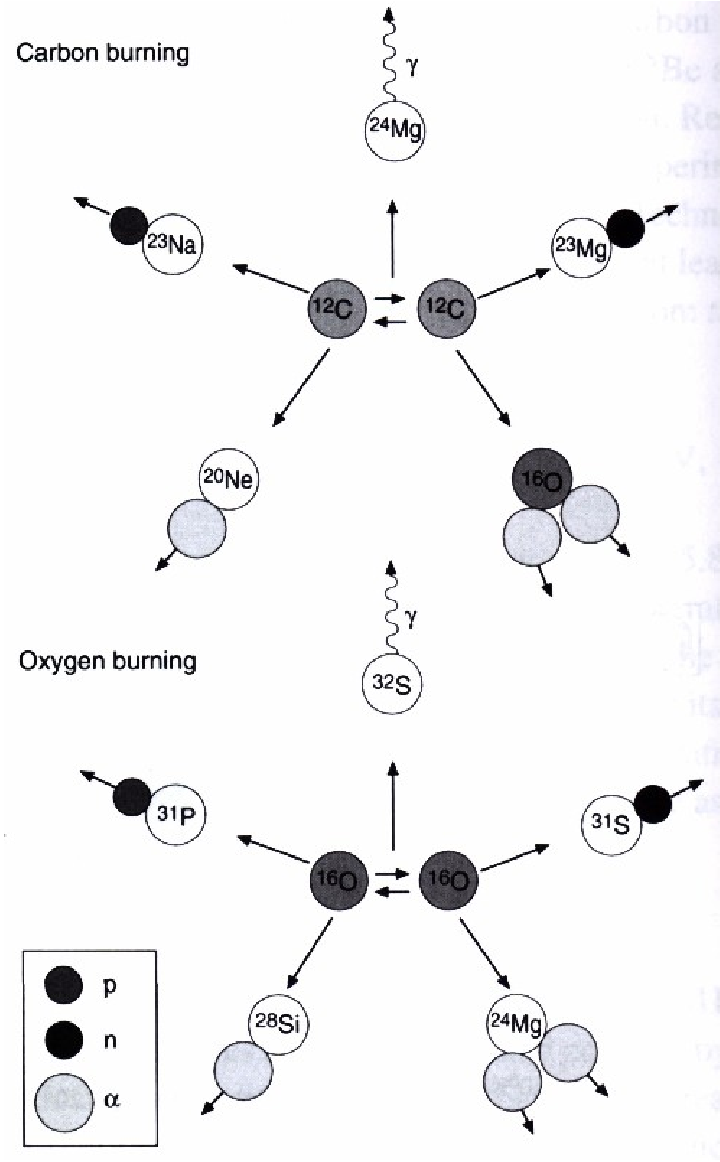
He	**O, C**	**^{18}O, ^{22}Ne** **s-process**	**0.2**	**10^6**	**$3\,He^4 \rightarrow {}^{12}C$** **$^{12}C(\alpha,\gamma)^{16}O$**
C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}C + {}^{12}C$**

Carbon and Oxygen Burning



Carbon Burning

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

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

Oxygen Burning

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

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

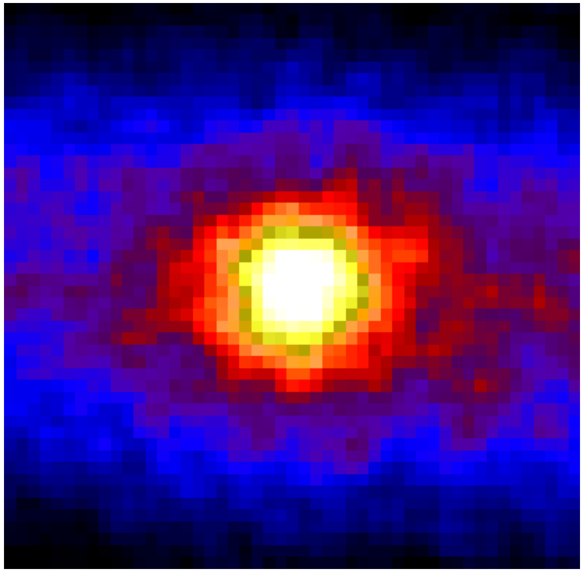
  $e^+ + e^- \rightarrow 2\gamma$

  but sometimes

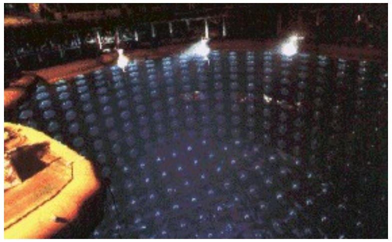
  $e^+ + e^- \rightarrow \overline{\nu}_e + \nu_e$
-
- The neutrinos exit the stars at the speed of light while the e^+, e^-, and the γ's all stay trapped.

- This is an important energy loss with

  $\varepsilon_\nu \approx -10^{15}\,(T/10^9 K)^9$ erg g^{-1} 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



Nuclear burning stages

(20 $M_{\odot}$ stars)

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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	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$

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 $T > 1.5 \times 10^{9}\,\mathrm{K}$.

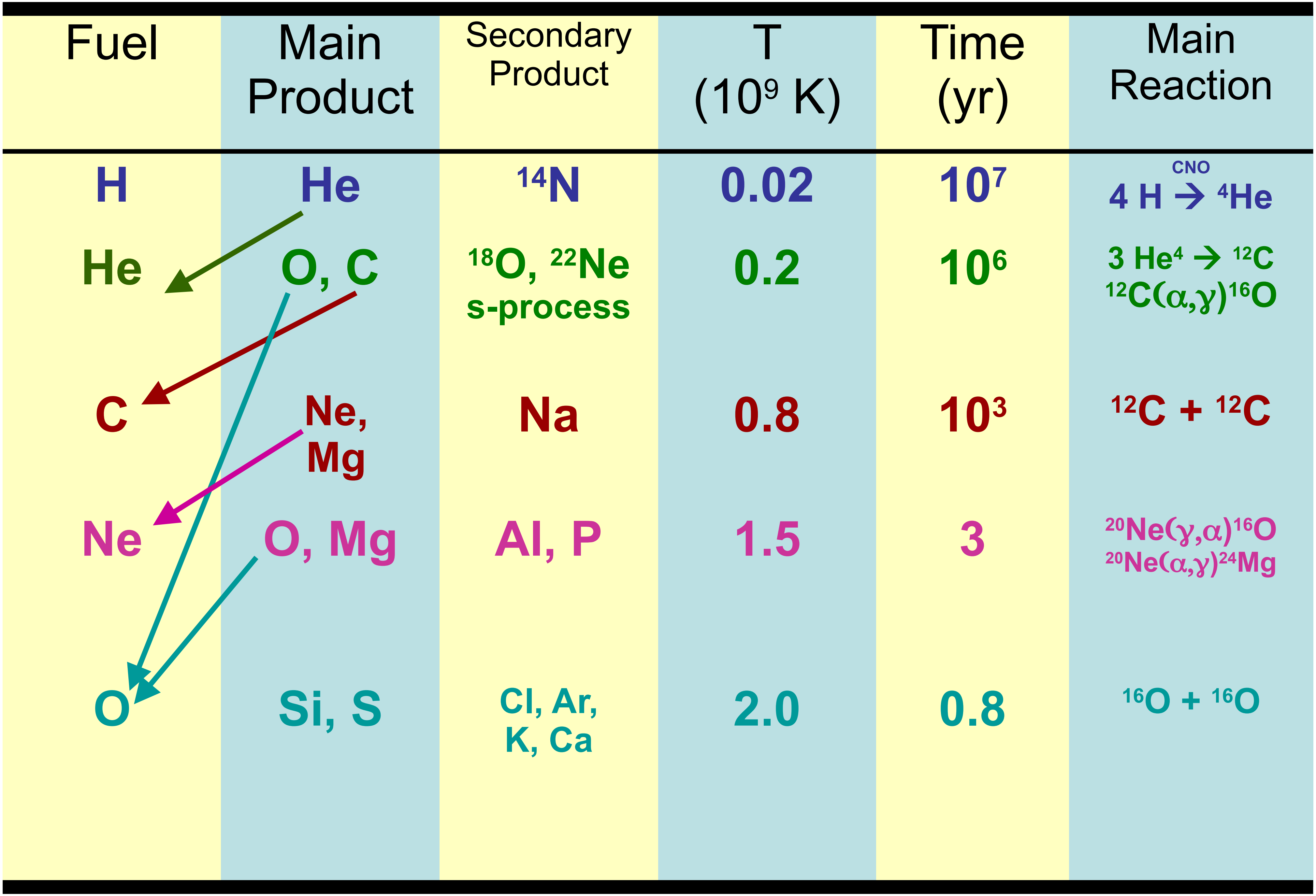
Subsequently, the $^{4}\mathrm{He}$ is captured on another $^{20}\mathrm{Ne}$ nucleus:

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

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

Nuclear burning stages

(20 $M_\odot$ stars)



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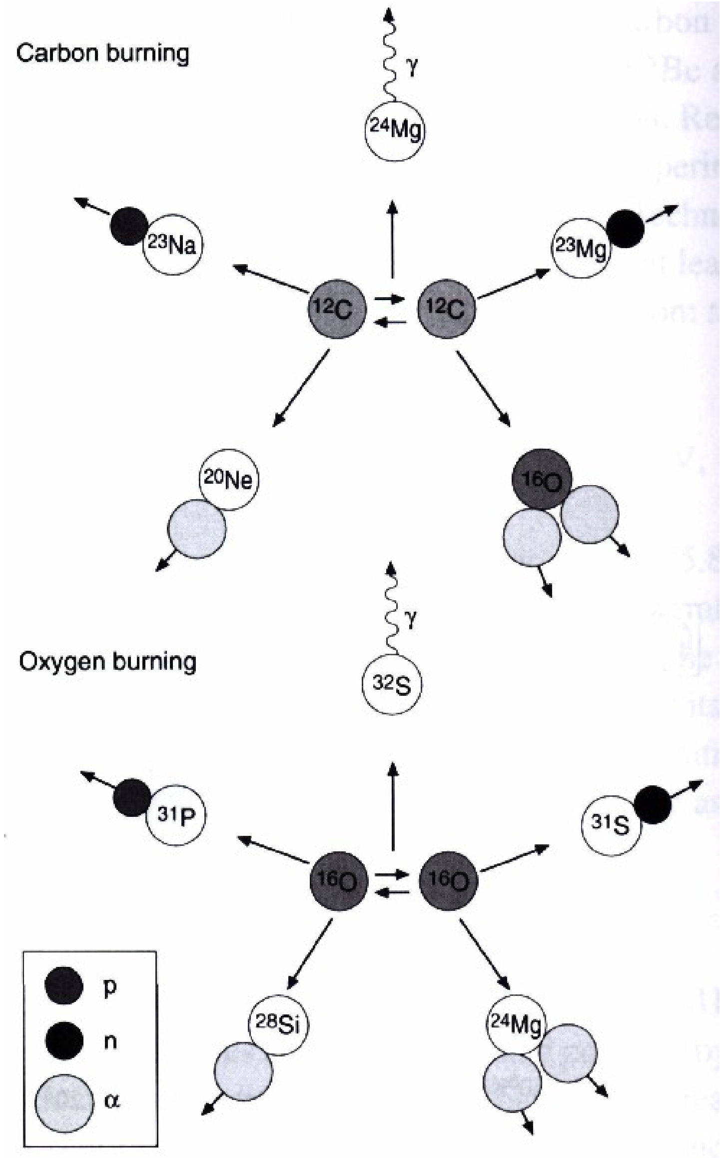
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$

Carbon and Oxygen Burning



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

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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	$^{28}Si(\gamma,\alpha)$…

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".

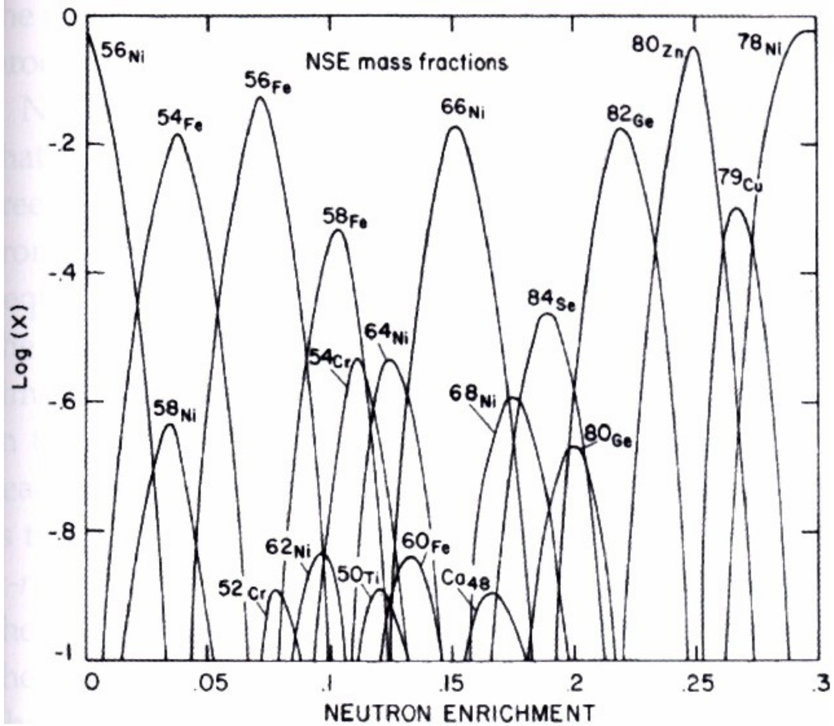
Typical burning temperature is $3 \ldots 3.5 \times 10^9\,\mathrm{K}$.

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.

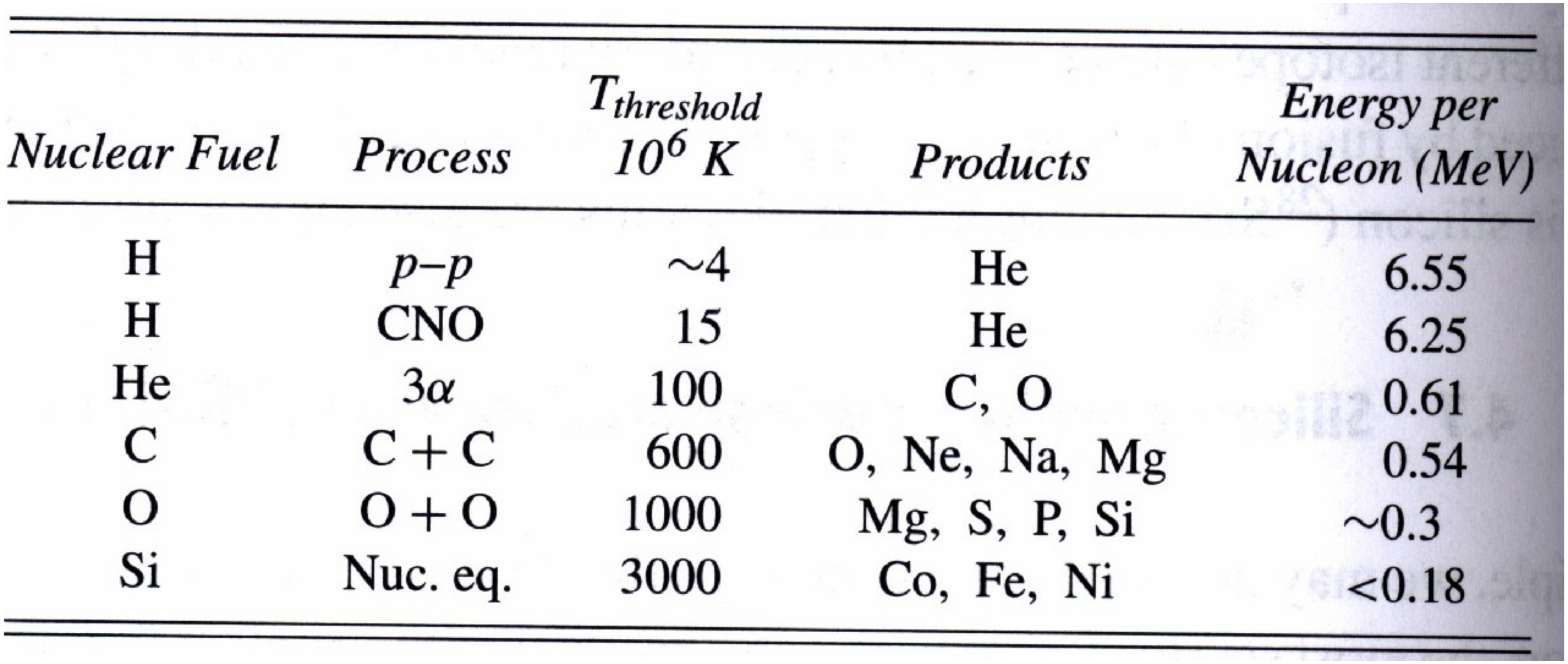
Beyond Silicon Burning



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

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

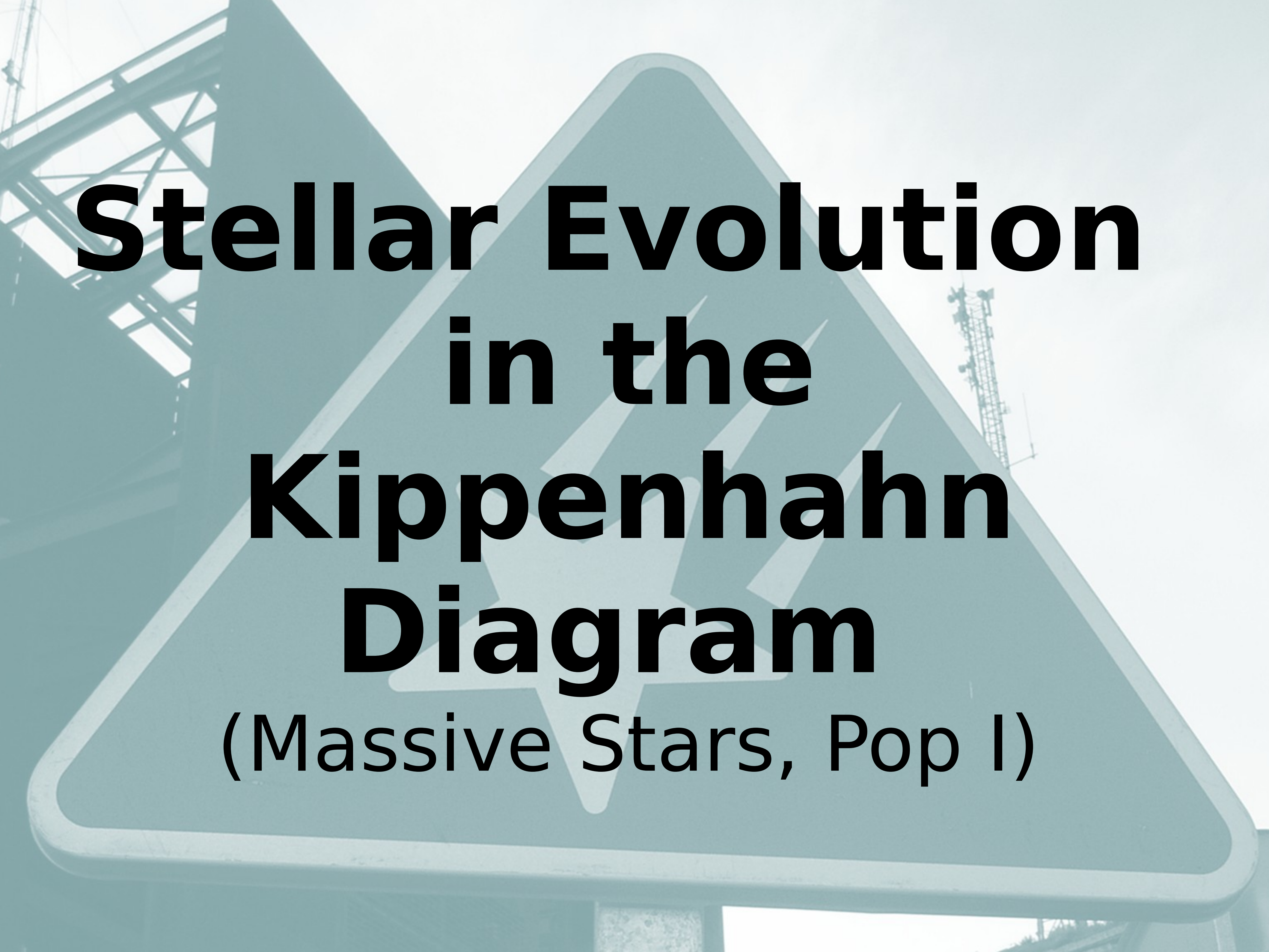
$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu_{e})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

- ^{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

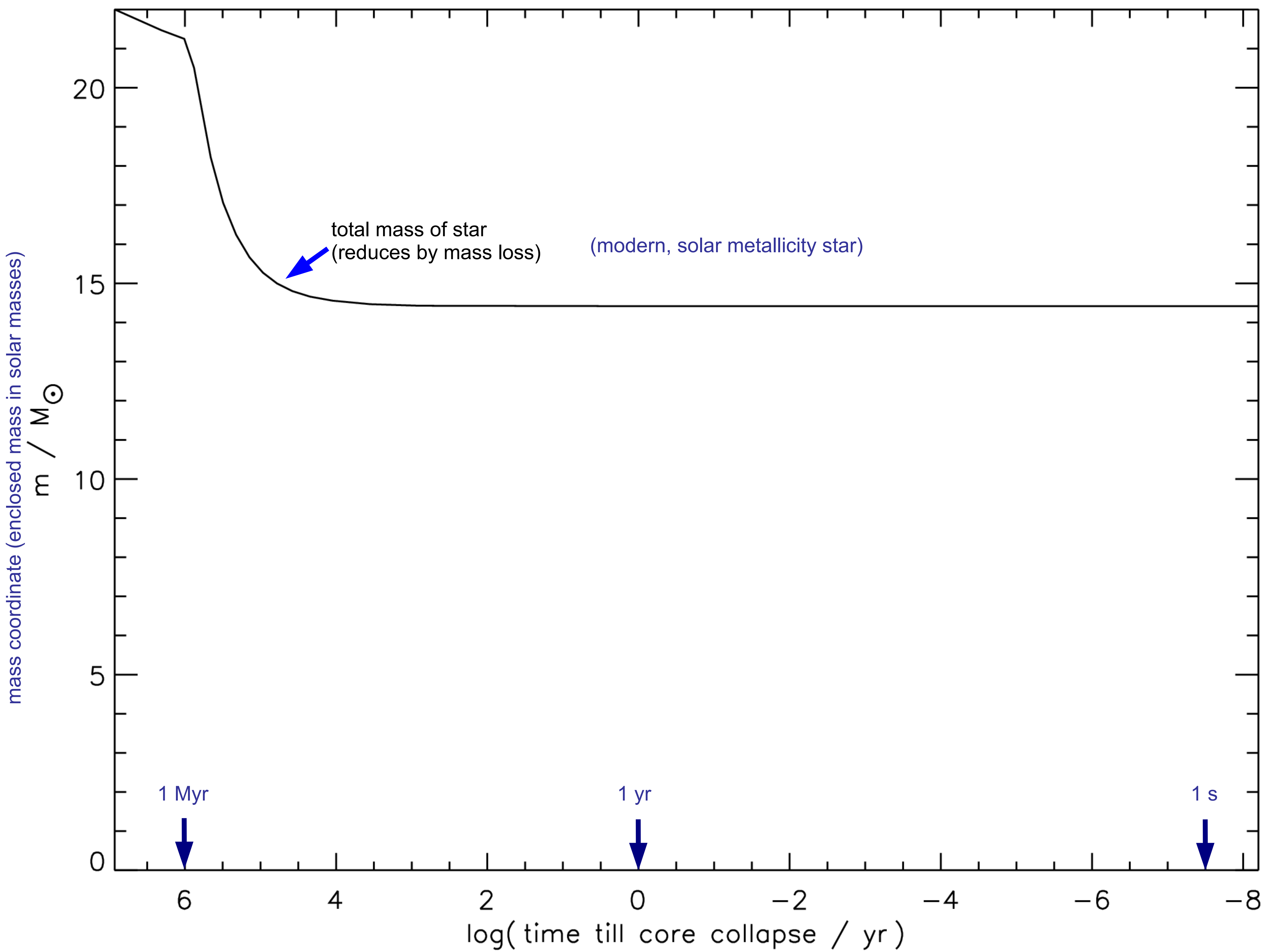
(20 $M_\odot$ star of solar composition)

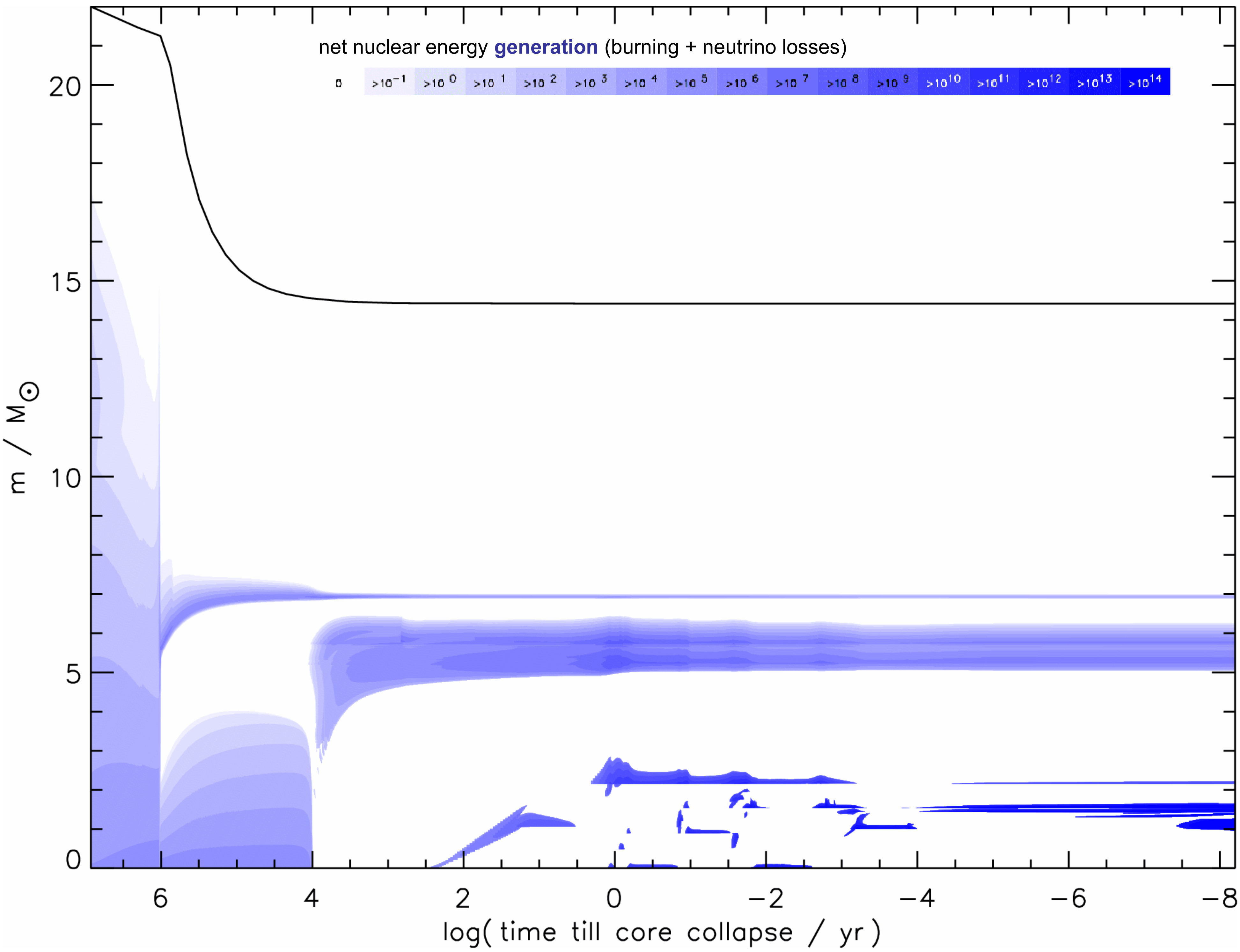
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	**He**	**^{14}N**	**0.02**	**10^7**	**$4\ {}^1H \xrightarrow{CNO} {}^4He$**
He	**O, C**	**^{18}O, ^{22}Ne s-process**	**0.2**	**10^6**	**$3\ {}^4He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$**
C	**Ne, Mg**	**Na**	**0.8**	**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**	**$^{28}Si(\gamma,\alpha)$…**

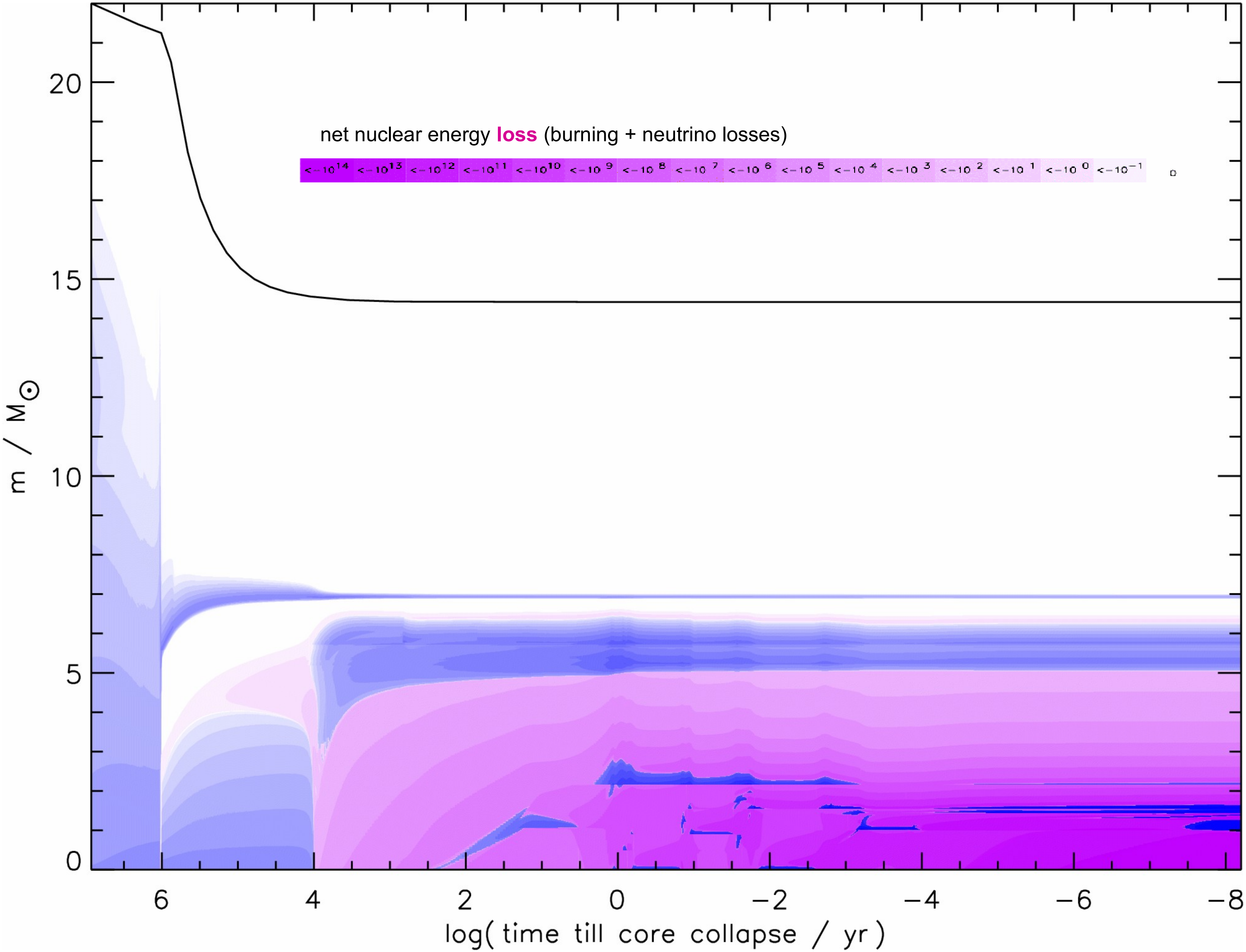


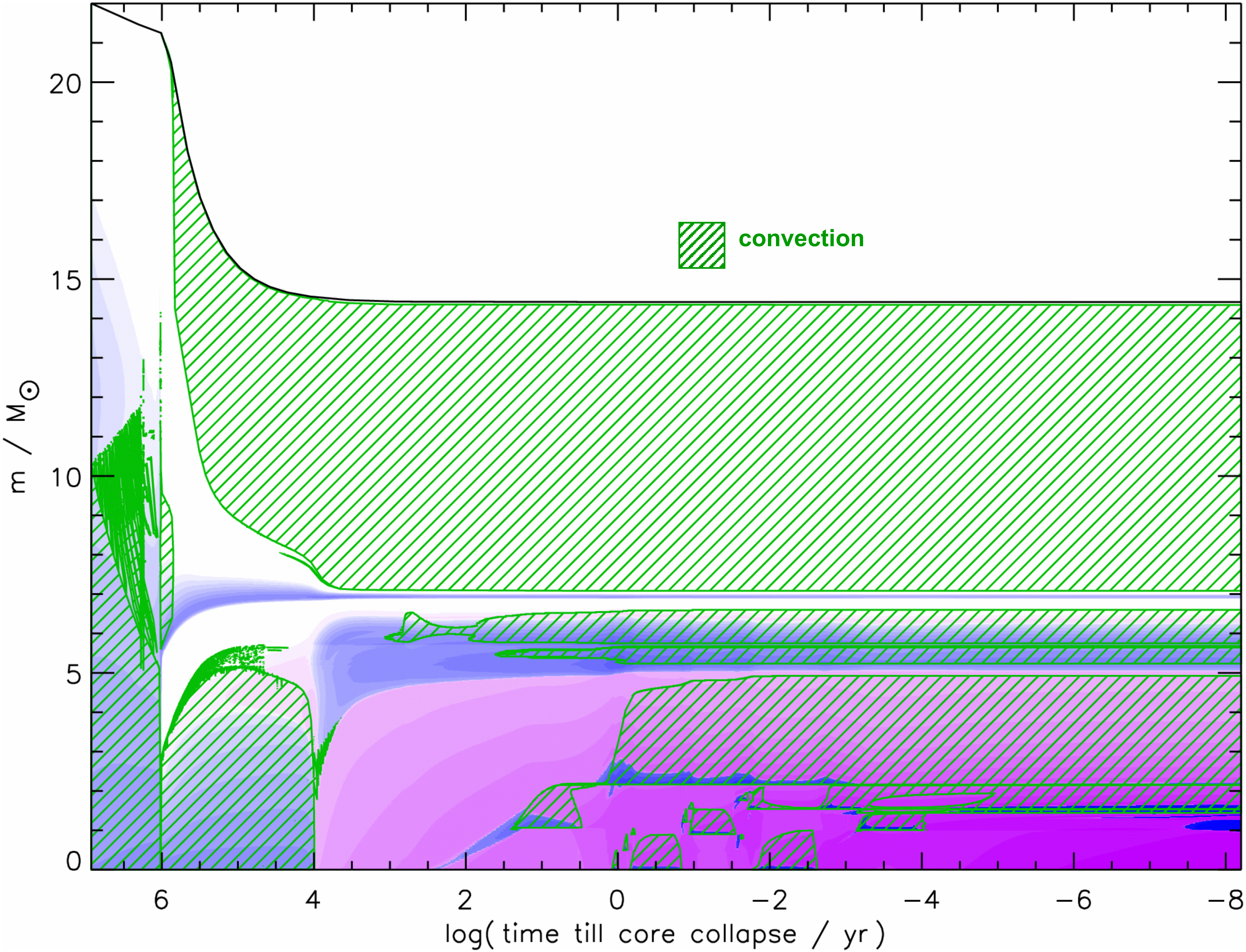
Stellar Evolution in the Kippenhahn Diagram

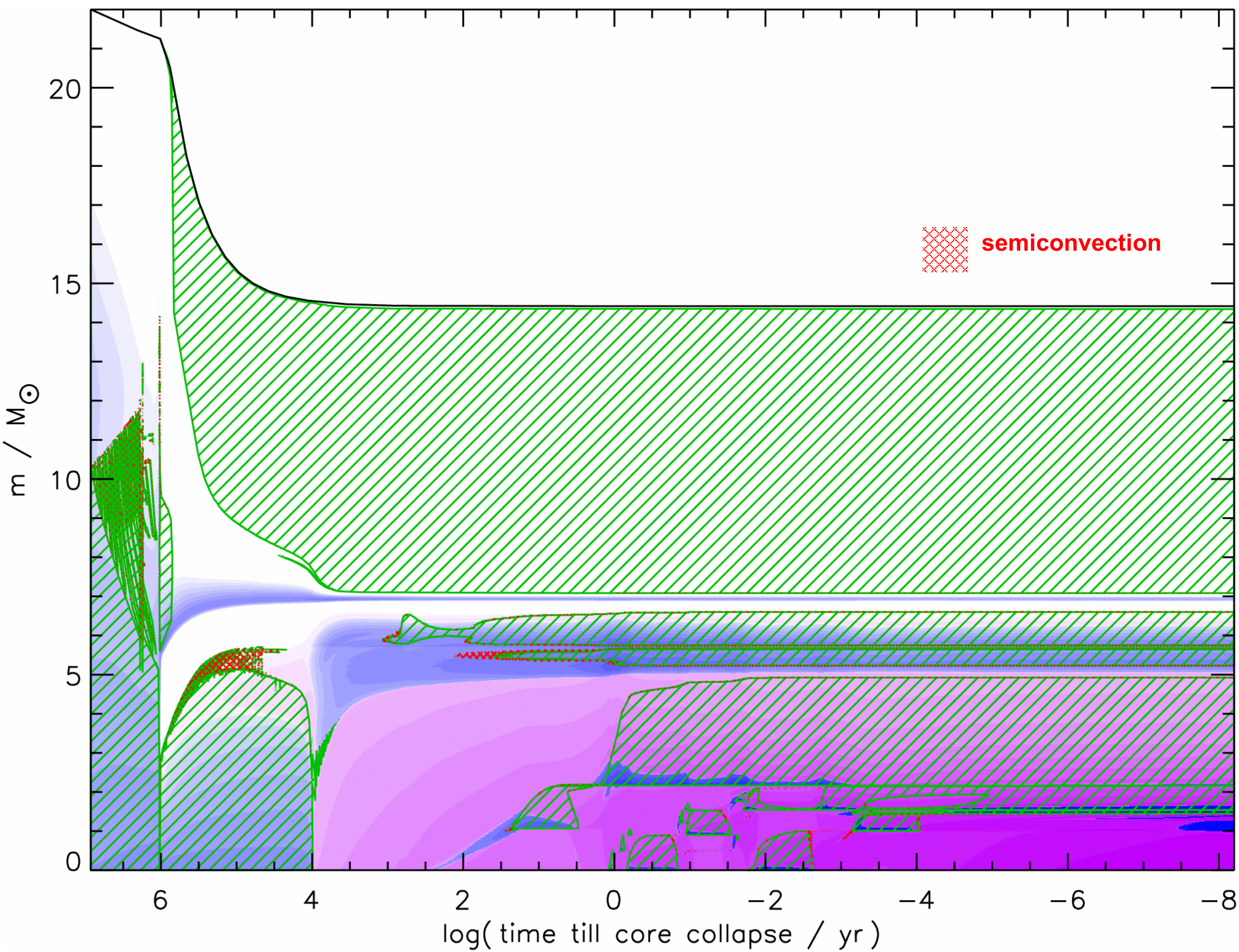
(Massive Stars, Pop I)

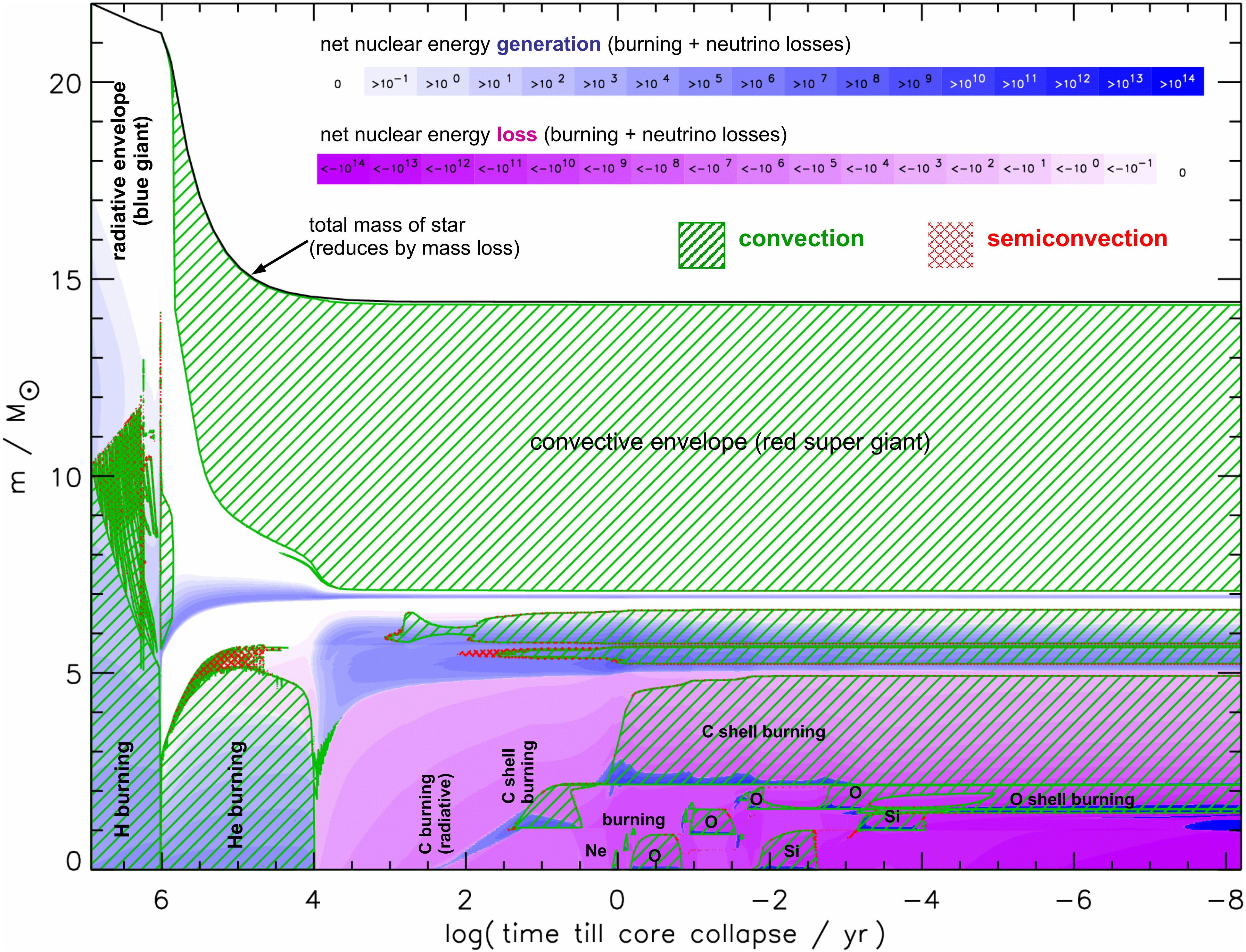

total mass of star
(reduces by mass loss)
(modern, solar metallicity star)
mass coordinate (enclosed mass in solar masses)
$m / M_\odot$
20
15
10
5
0
1 Myr
1 yr
1 s
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)


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}
m / M$_\odot$
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)

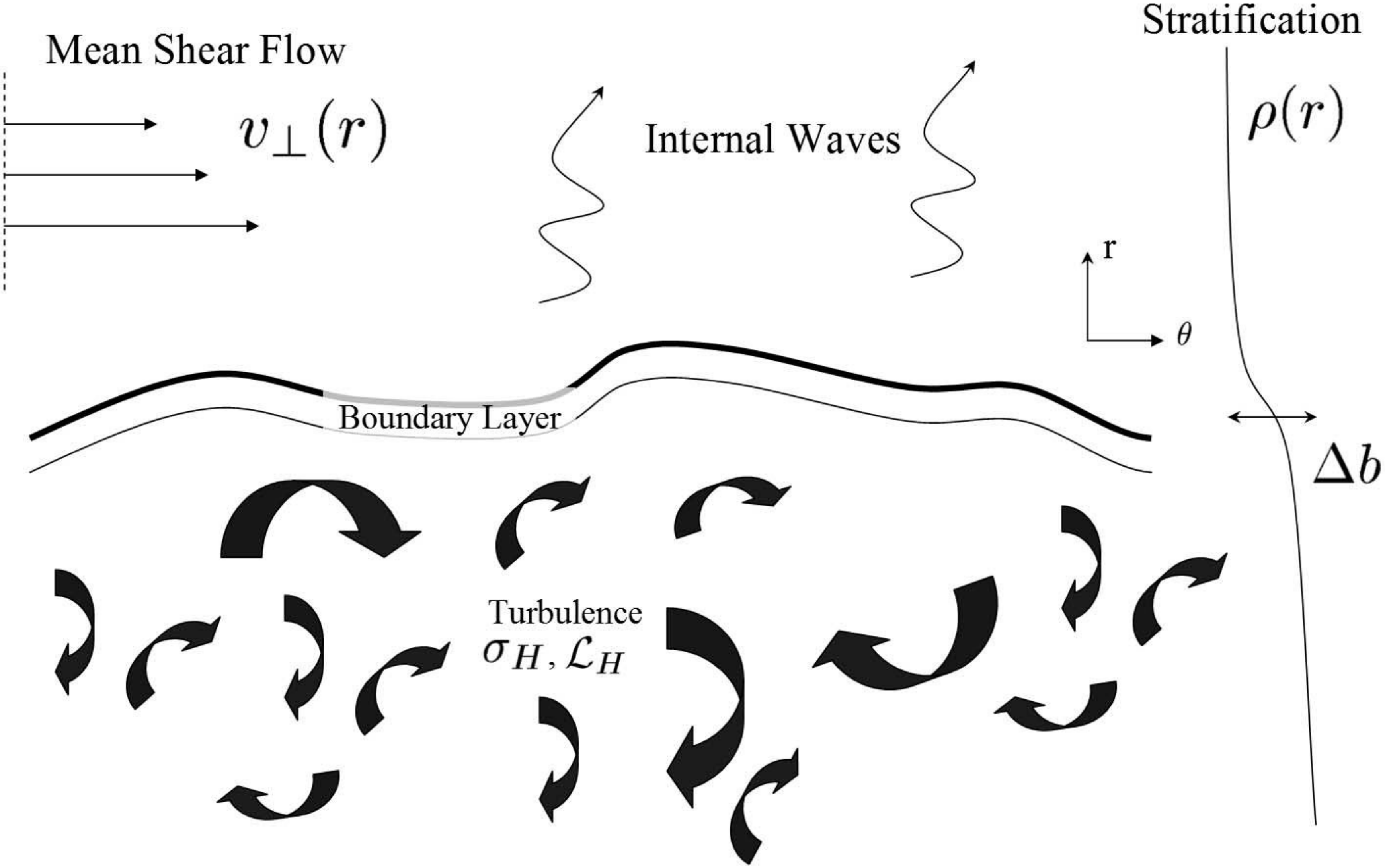

net nuclear energy **loss** (burning + neutrino losses)
$<-10^{14}$
$<-10^{13}$
$<-10^{12}$
$<-10^{11}$
$<-10^{10}$
$<-10^{9}$
$<-10^{8}$
$<-10^{7}$
$<-10^{6}$
$<-10^{5}$
$<-10^{4}$
$<-10^{3}$
$<-10^{2}$
$<-10^{1}$
$<-10^{0}$
$<-10^{-1}$
0
$m\ /\ M_\odot$
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)


convection
m / M$_\odot$
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)


semiconvection
m / M$_\odot$
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)

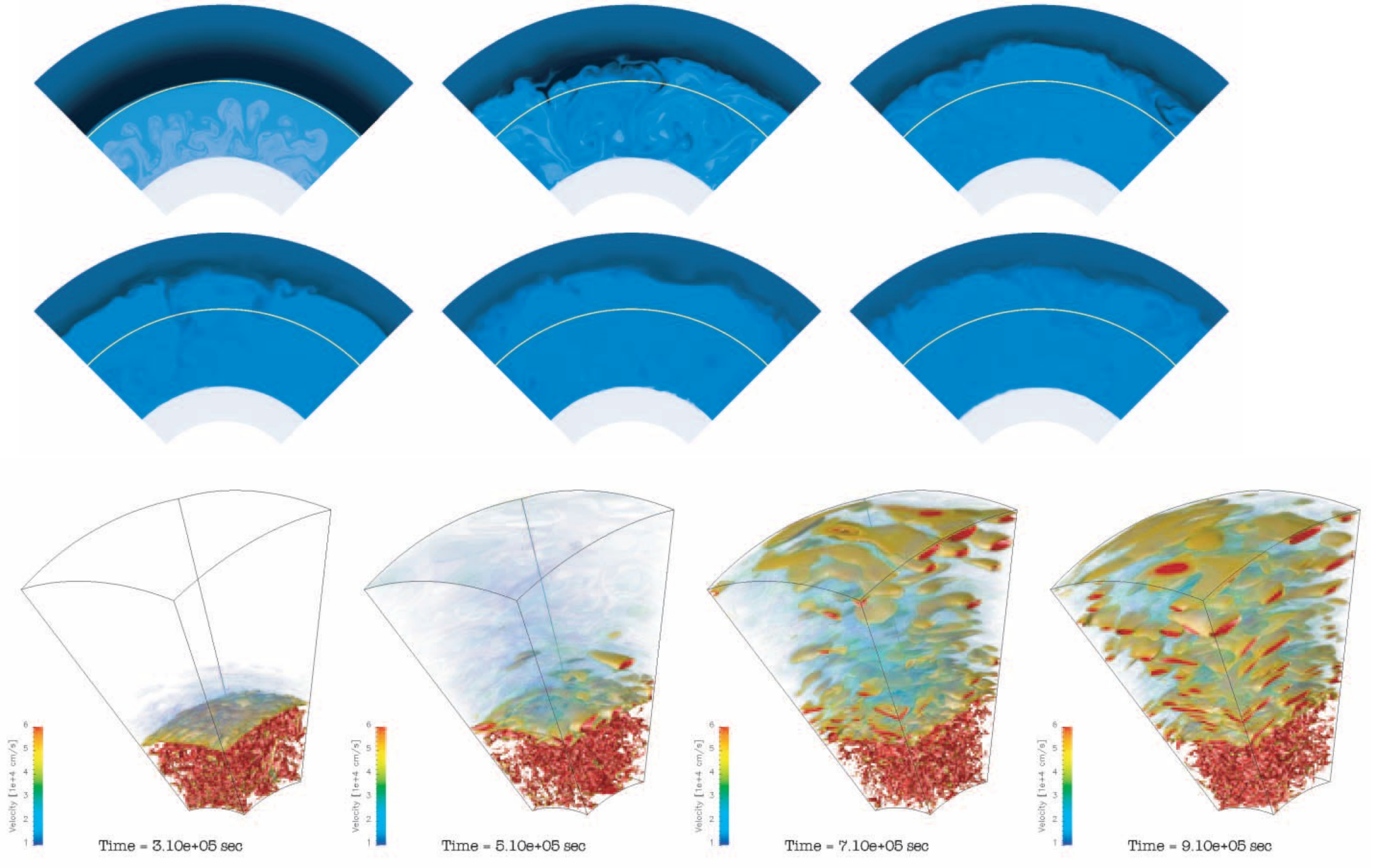

net nuclear energy **generation** (burning + neutrino losses)
0 | >10⁻¹ | >10 0 | >10 1 | >10 2 | >10 3 | >10 4 | >10 5 | >10 6 | >10 7 | >10 8 | >10 9 | >10¹⁰ | >10¹¹ | >10¹² | >10¹³ | >10¹⁴
net nuclear energy **loss** (burning + neutrino losses)
<−10¹⁴ | <−10¹³ | <−10¹² | <−10¹¹ | <−10¹⁰ | <−10 9 | <−10 8 | <−10 7 | <−10 6 | <−10 5 | <−10 4 | <−10 3 | <−10 2 | <−10 1 | <−10 0 | <−10⁻¹ | 0
▨ **convection**
▦ **semiconvection**
total mass of star
(reduces by mass loss)
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
Si
Si
O shell burning
m / M☉
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)

Multi-Dimensional Convection



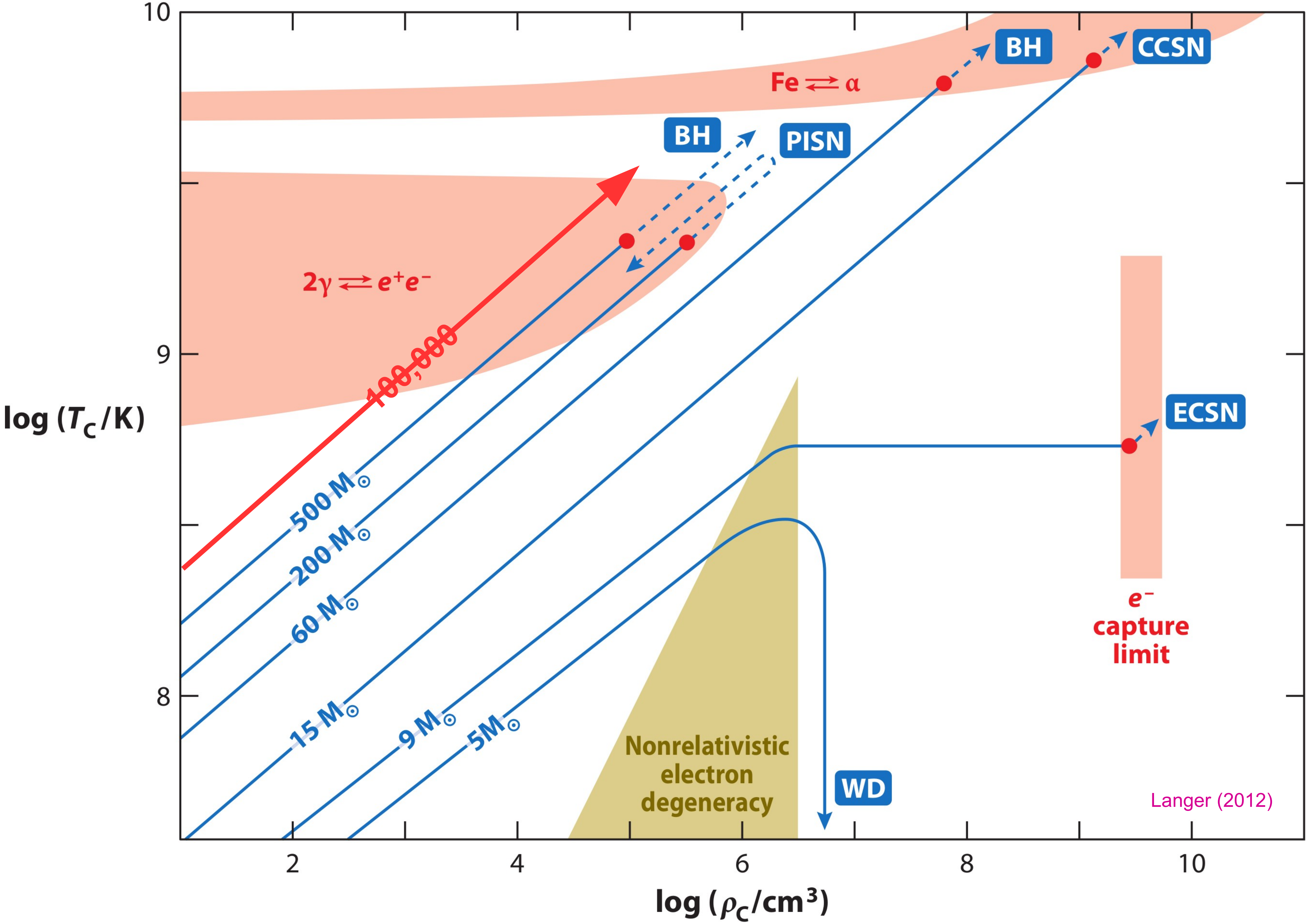
(Meaken & Arnett 2007)

Multi-Dimensional Convection



(Meaken & Arnett 2007)

Evolution of Center for Different Initial Masses

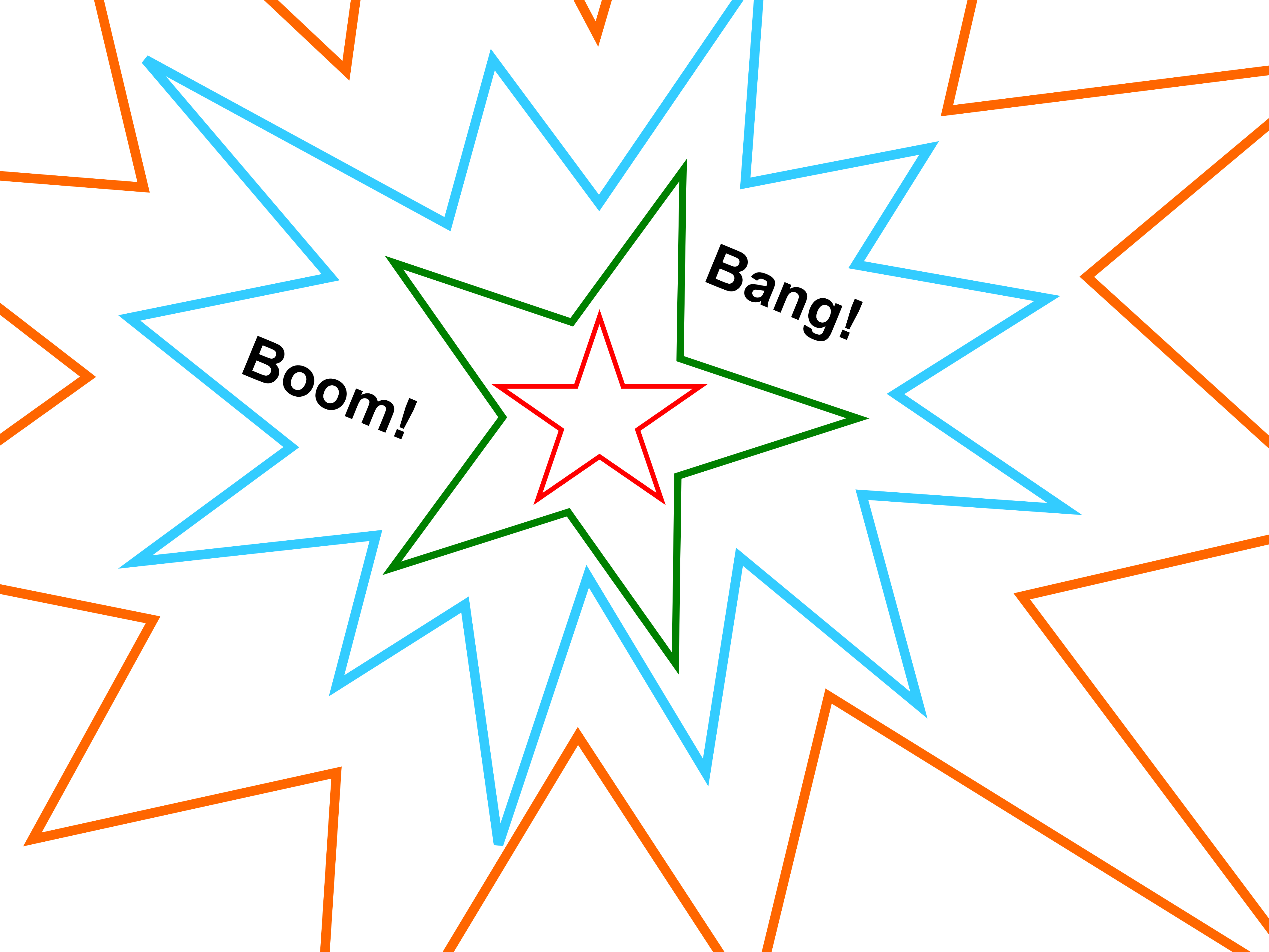


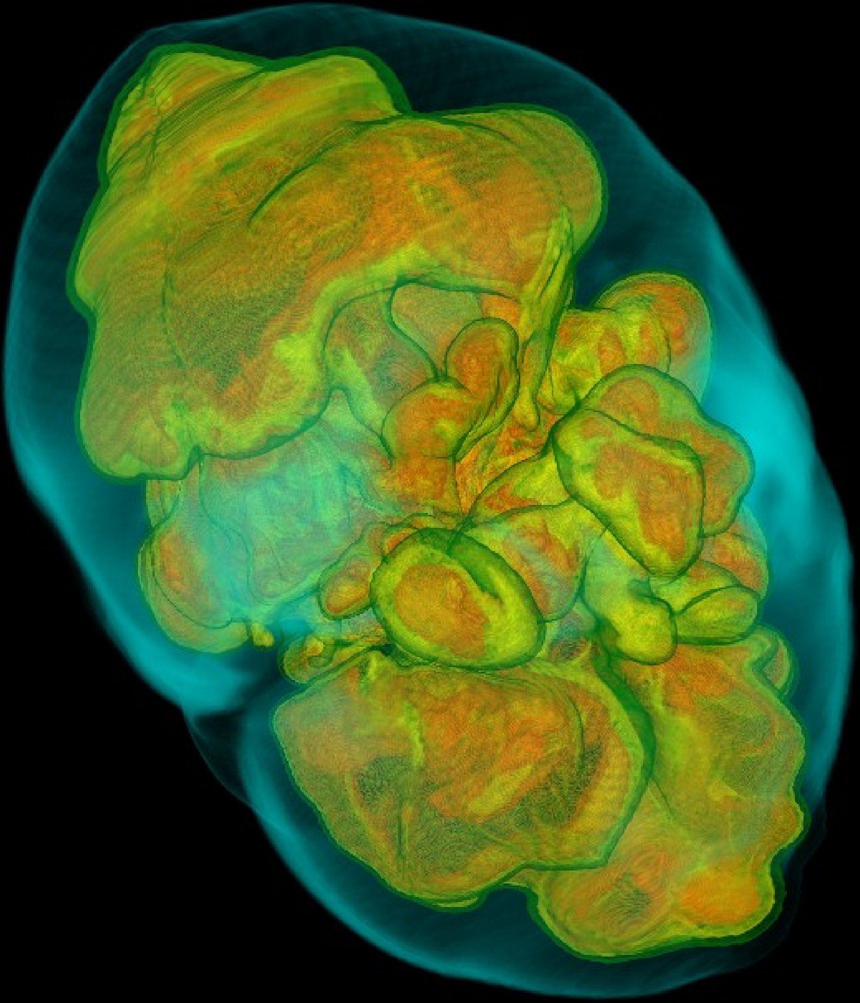
Langer (2012)

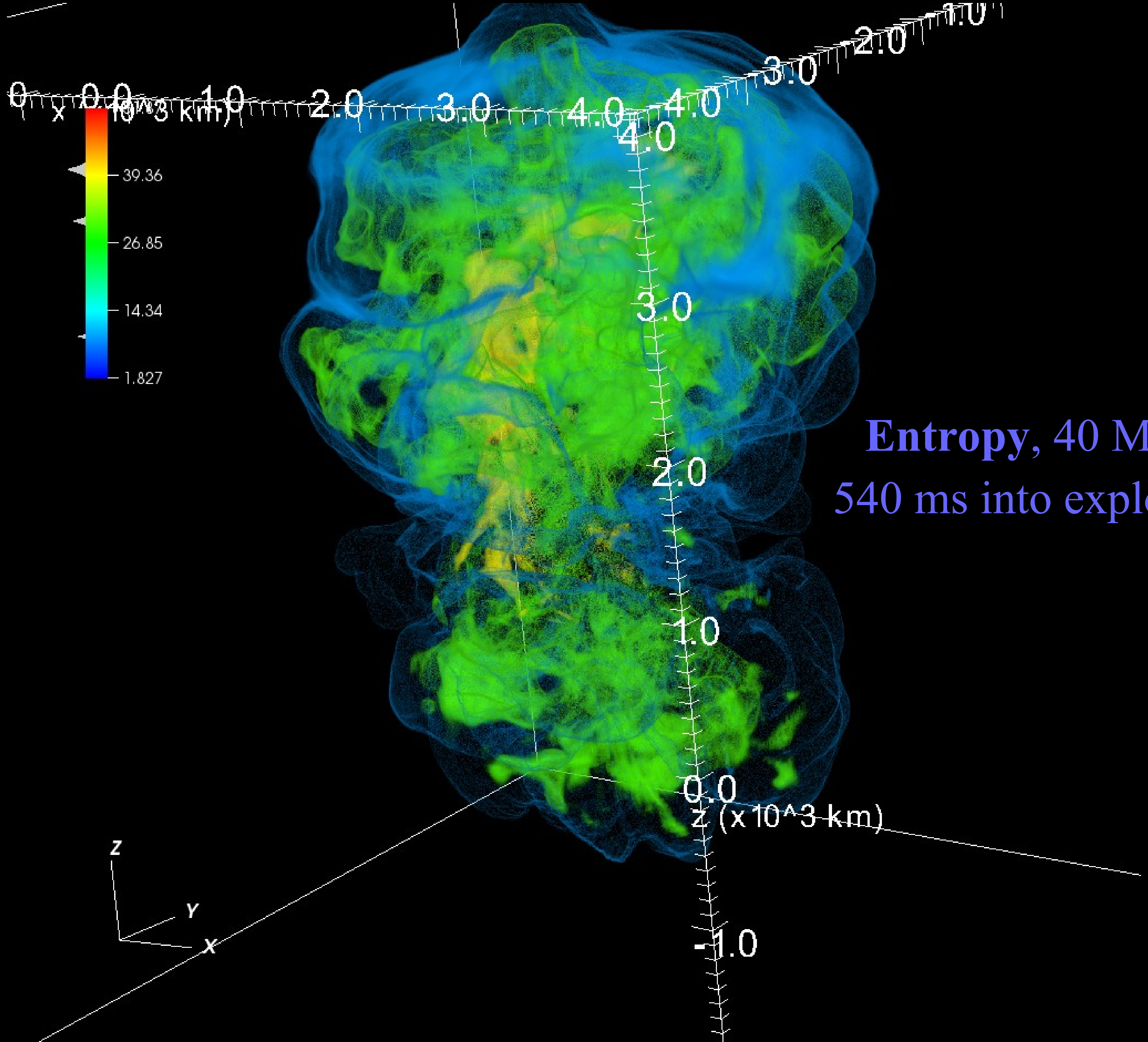
A First Look

Core Collapse Supernovae

(Massive Stars, Pop I)


Boom!
Bang!

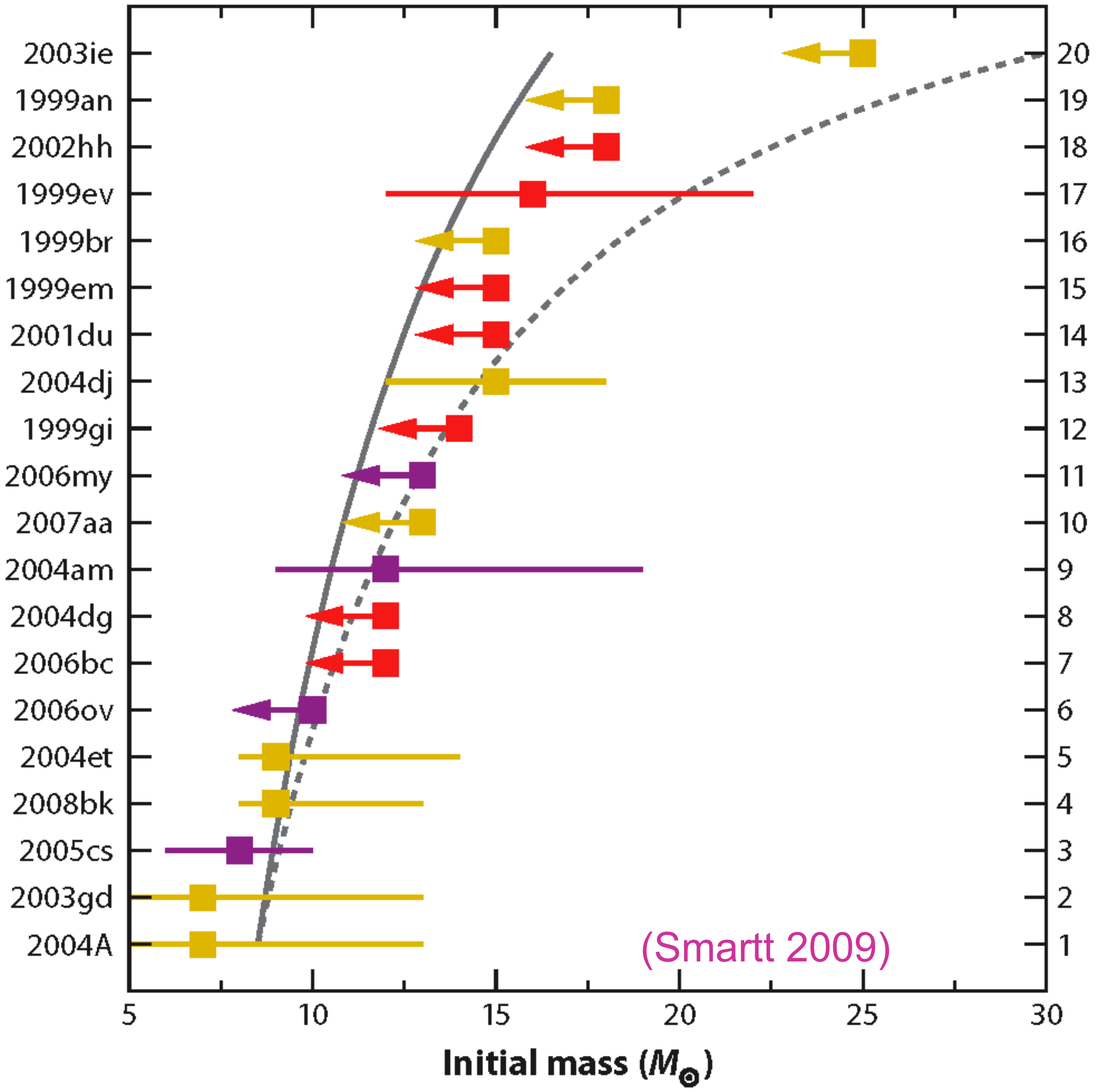




Entropy, 40 M_o star
540 ms into explosion

Mueller, Chan, Heger (2018)

Supernova Progenitor Masses



(Smartt 2009)

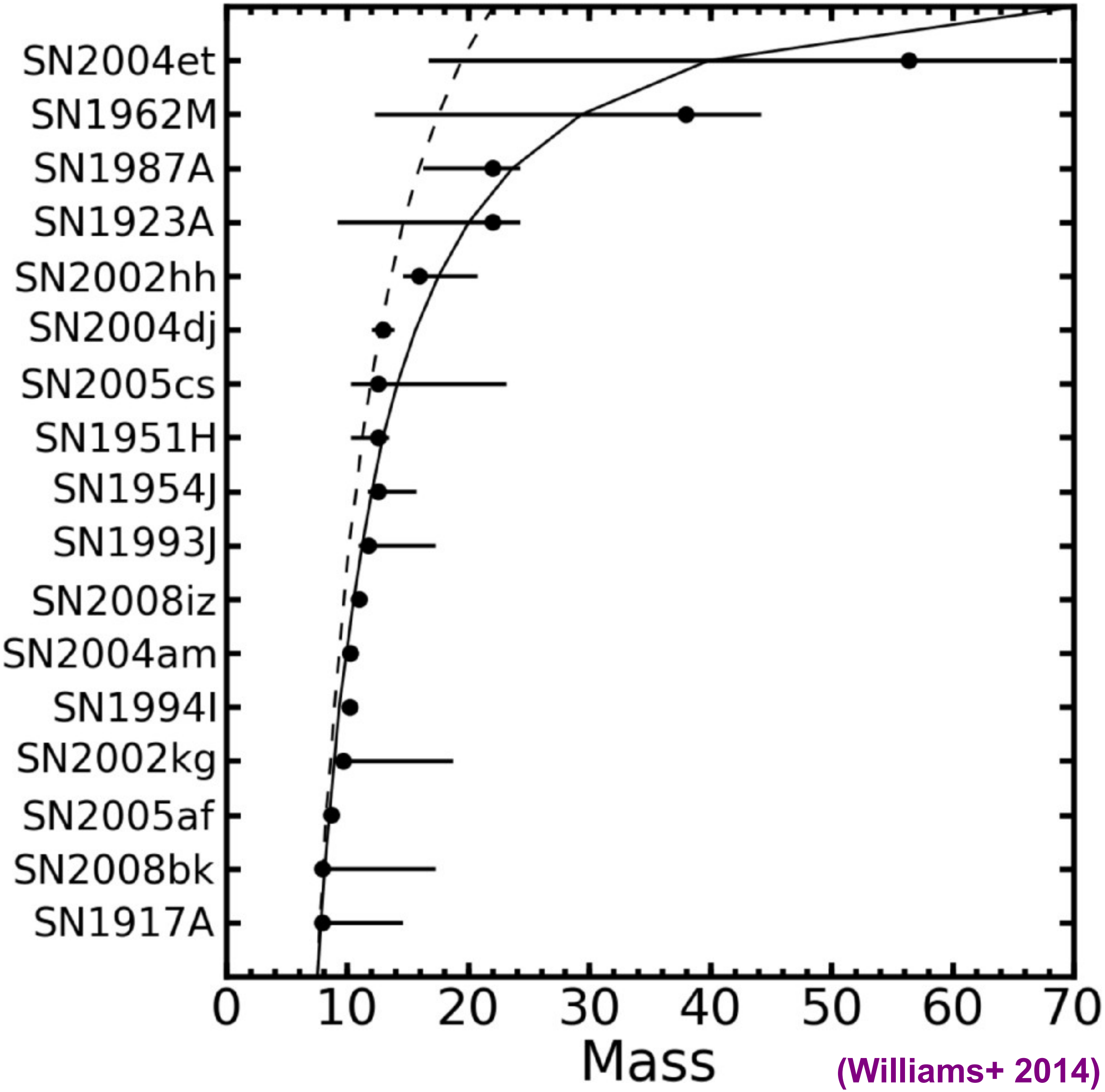
Presupernova stars for Type IIp and II-L

Solid Line:
Salpeter IMF with
16.5 $M_\odot$ cutoff

Dotted Line:
Salpeter IMF with
35 $M_\odot$ cutoff

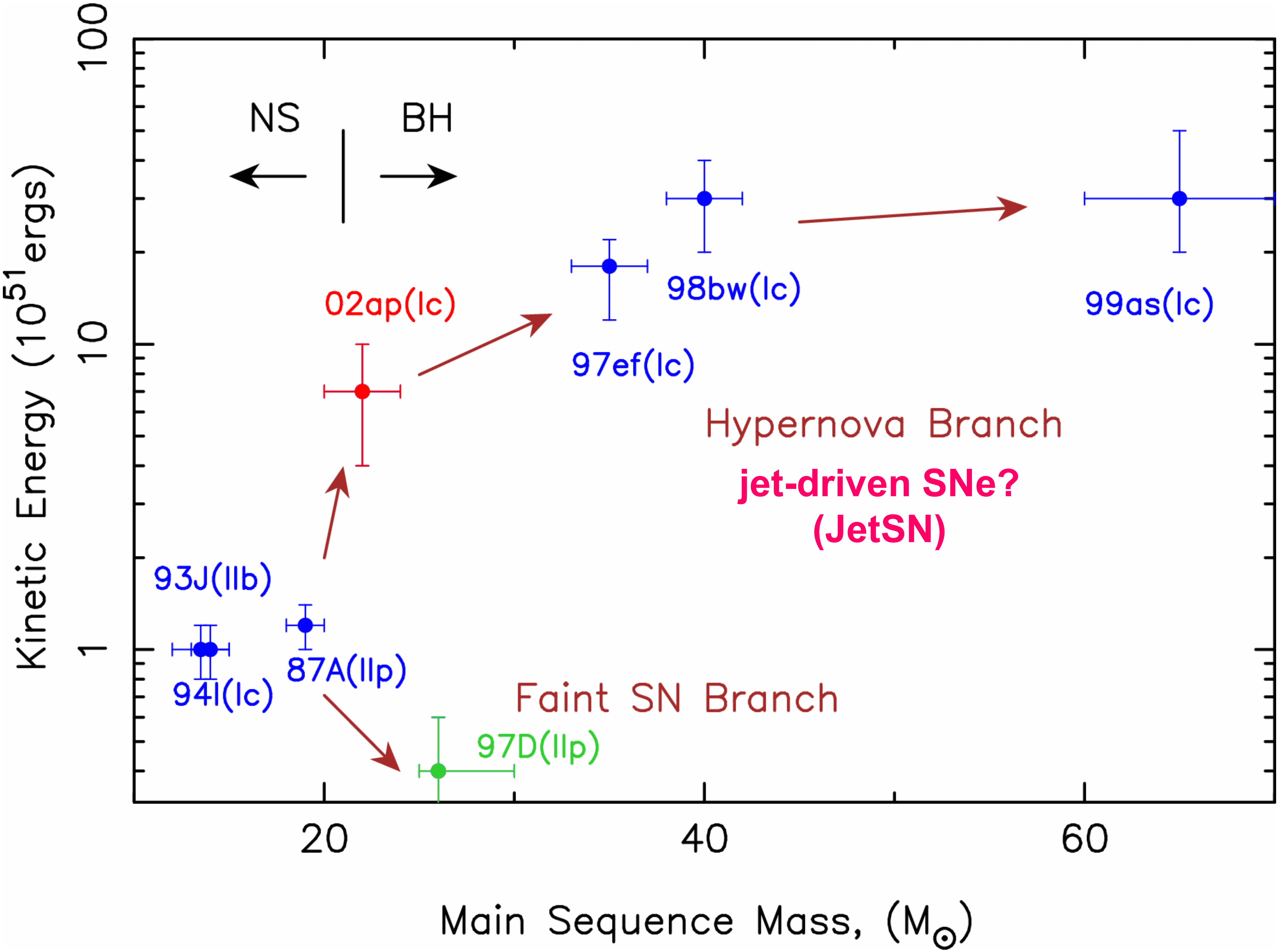
► Exclude stars with $M_{\text{initial}} > 20\ M_\odot$ as Type IIP/IIL progenitors at 95% confidence level?

Estimates of Supernova progenitor masses

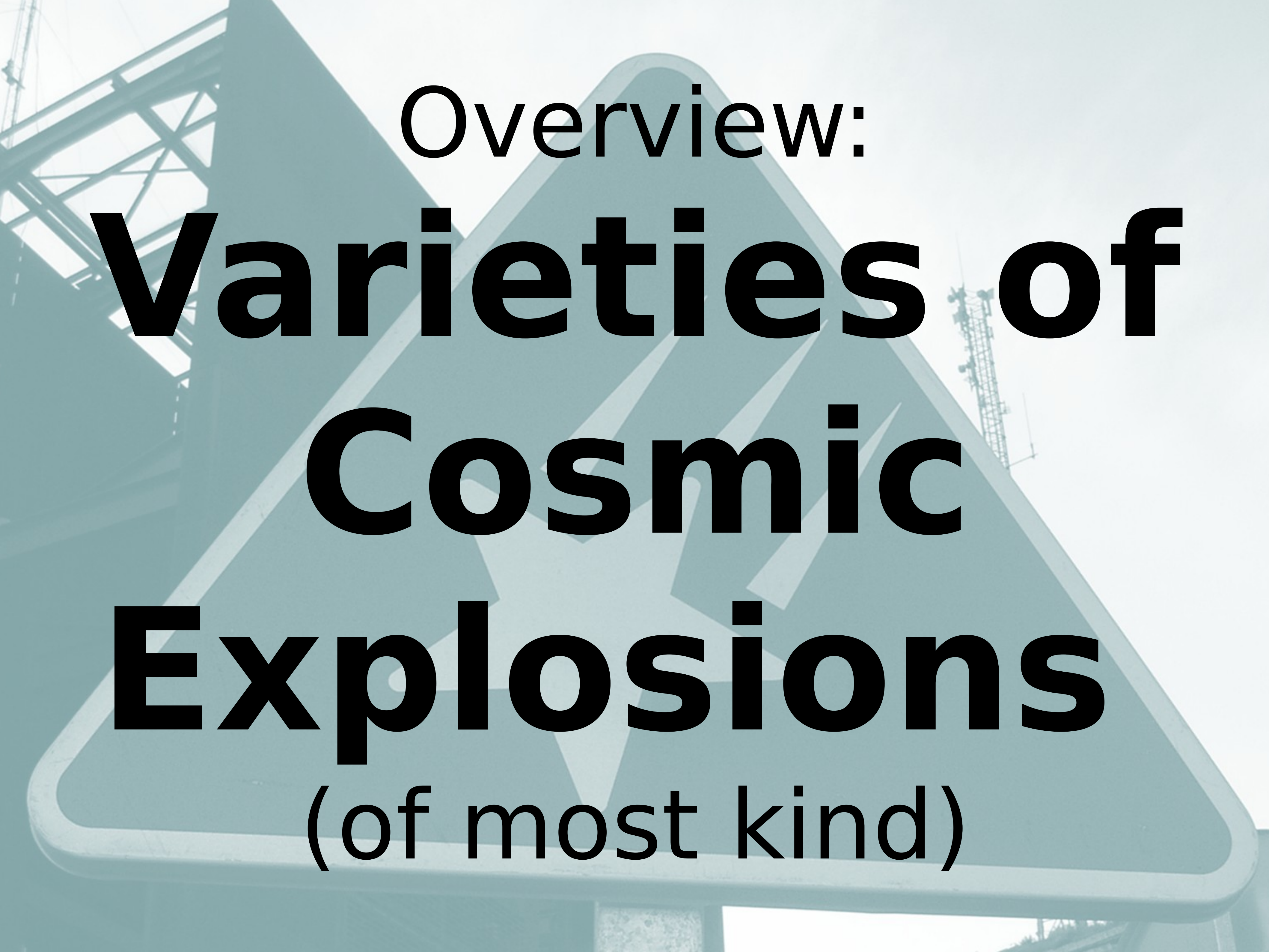


(Williams+ 2014)

Consistent with upper mass limit of $20\ M_\odot$ but also allows higher upper mass limit for supernovae



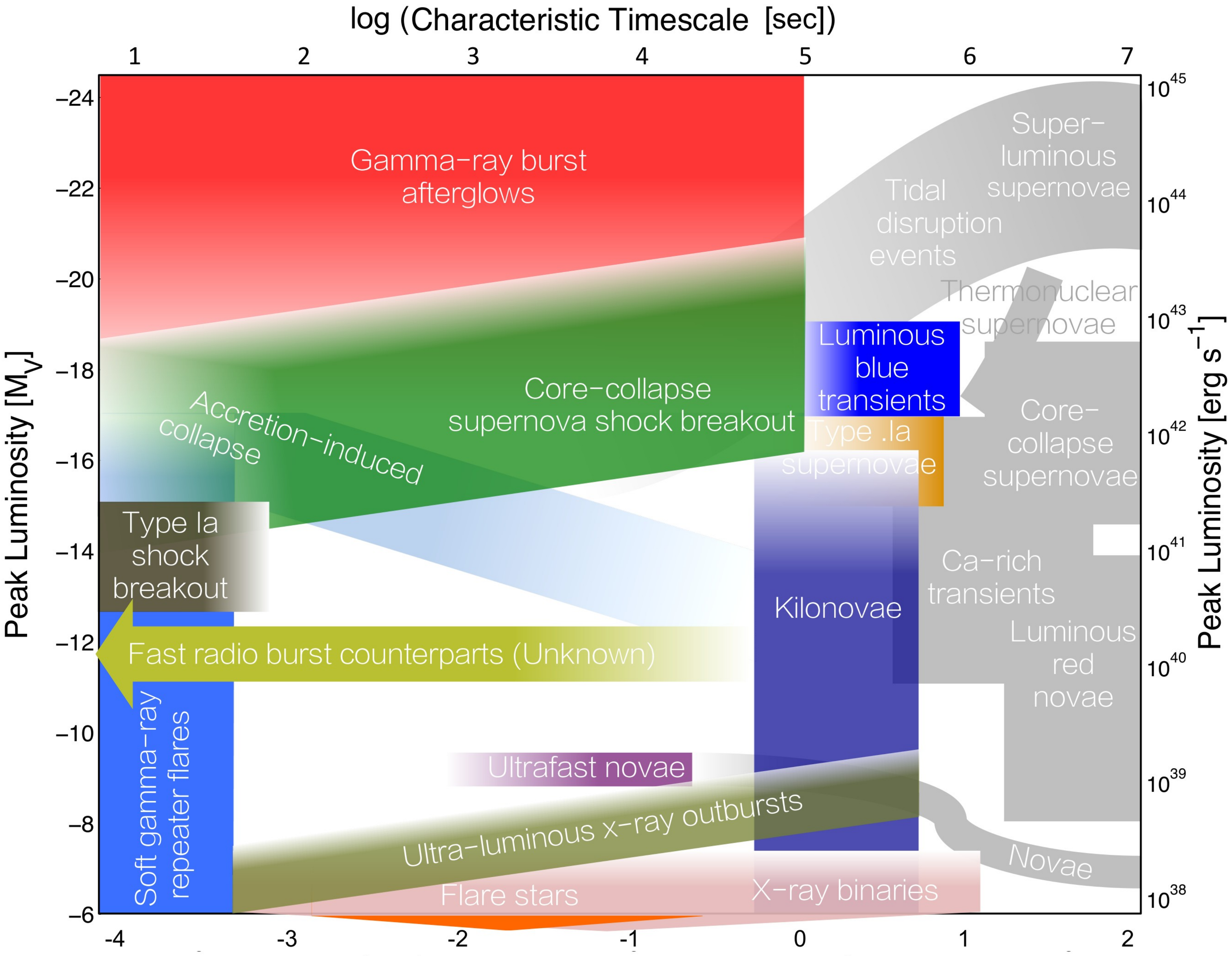
(Nomoto 2002, priv. com.)



Overview:

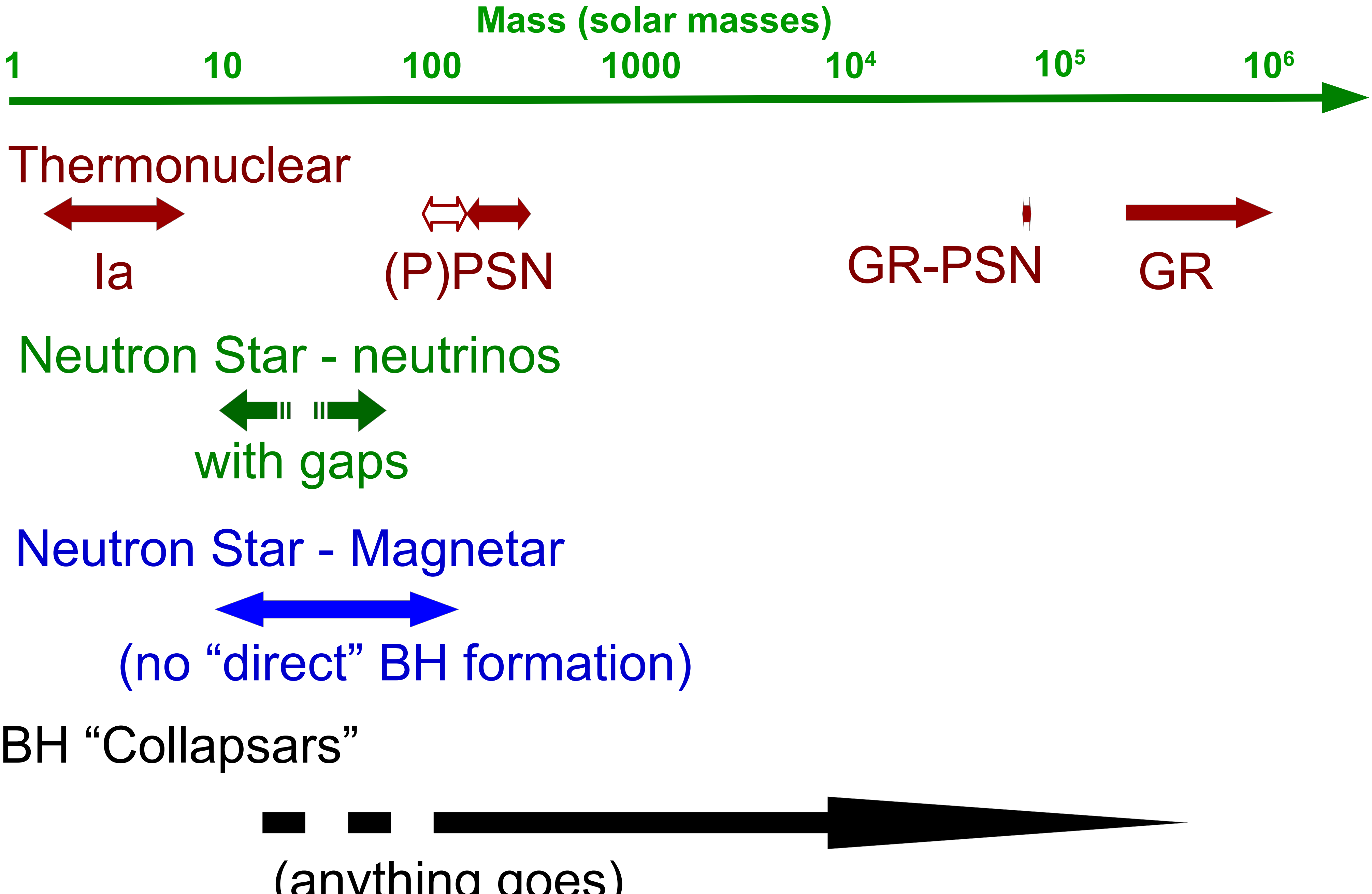
Varieties of Cosmic Explosions

(of most kind)



(Cooke 2020, priv. com.)

The Engines of SNe



Mass (solar masses)

1 10 100 1000 10^4 10^5 10^6

Thermonuclear

Ia

(P)PSN

GR-PSN

GR

Neutron Star - neutrinos

with gaps

Neutron Star - Magnetar

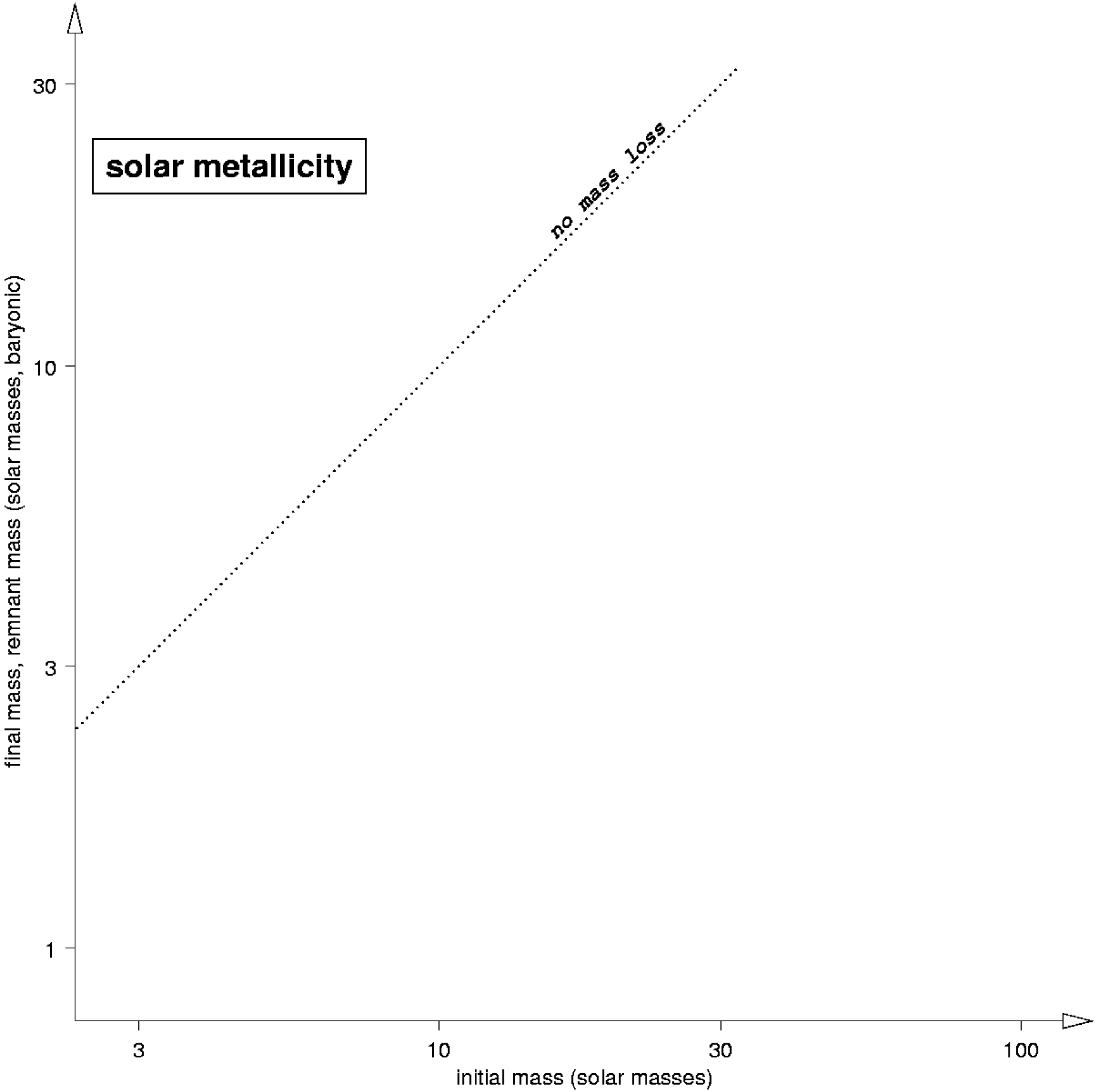
(no "direct" BH formation)

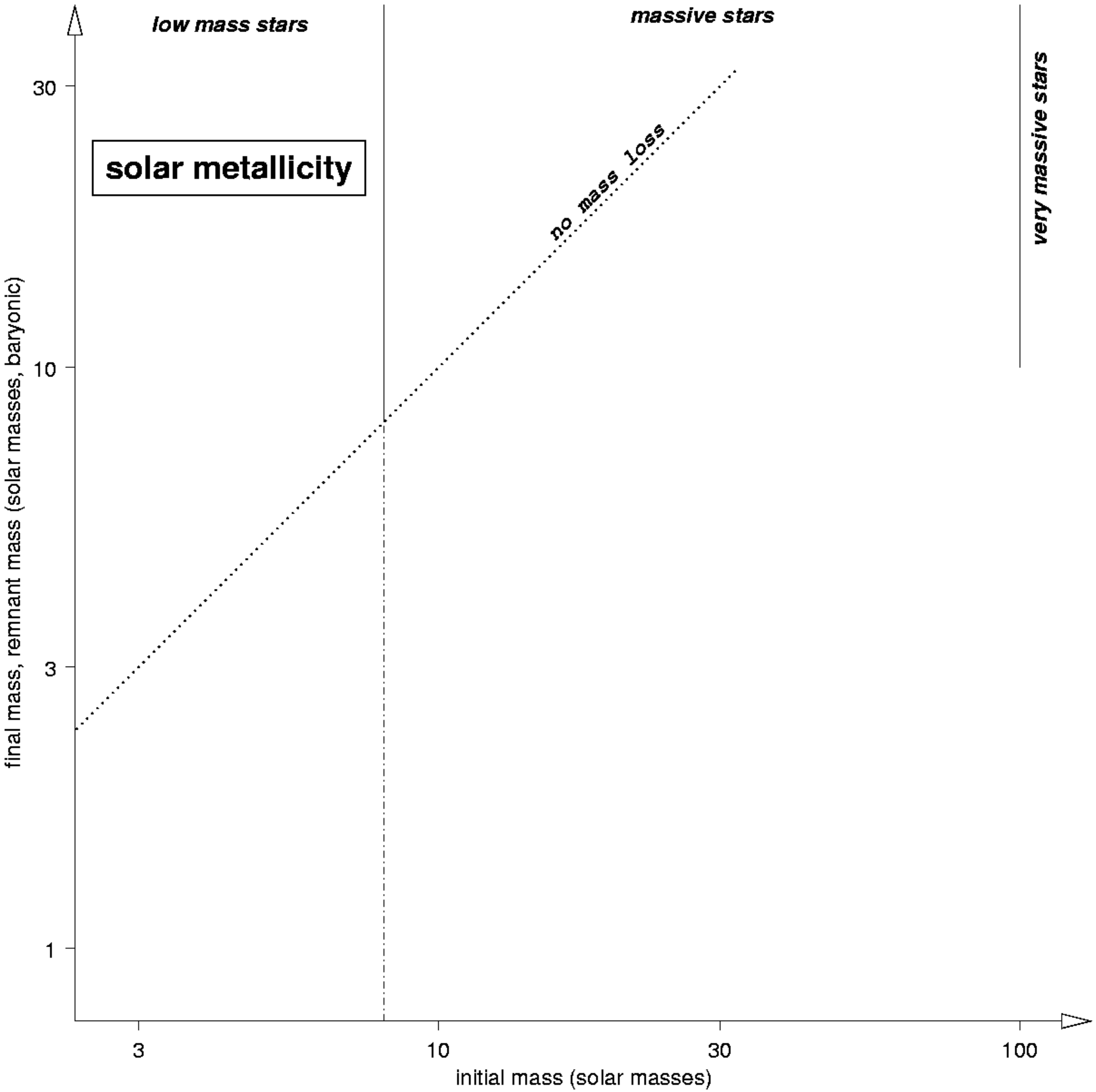
BH "Collapsars"

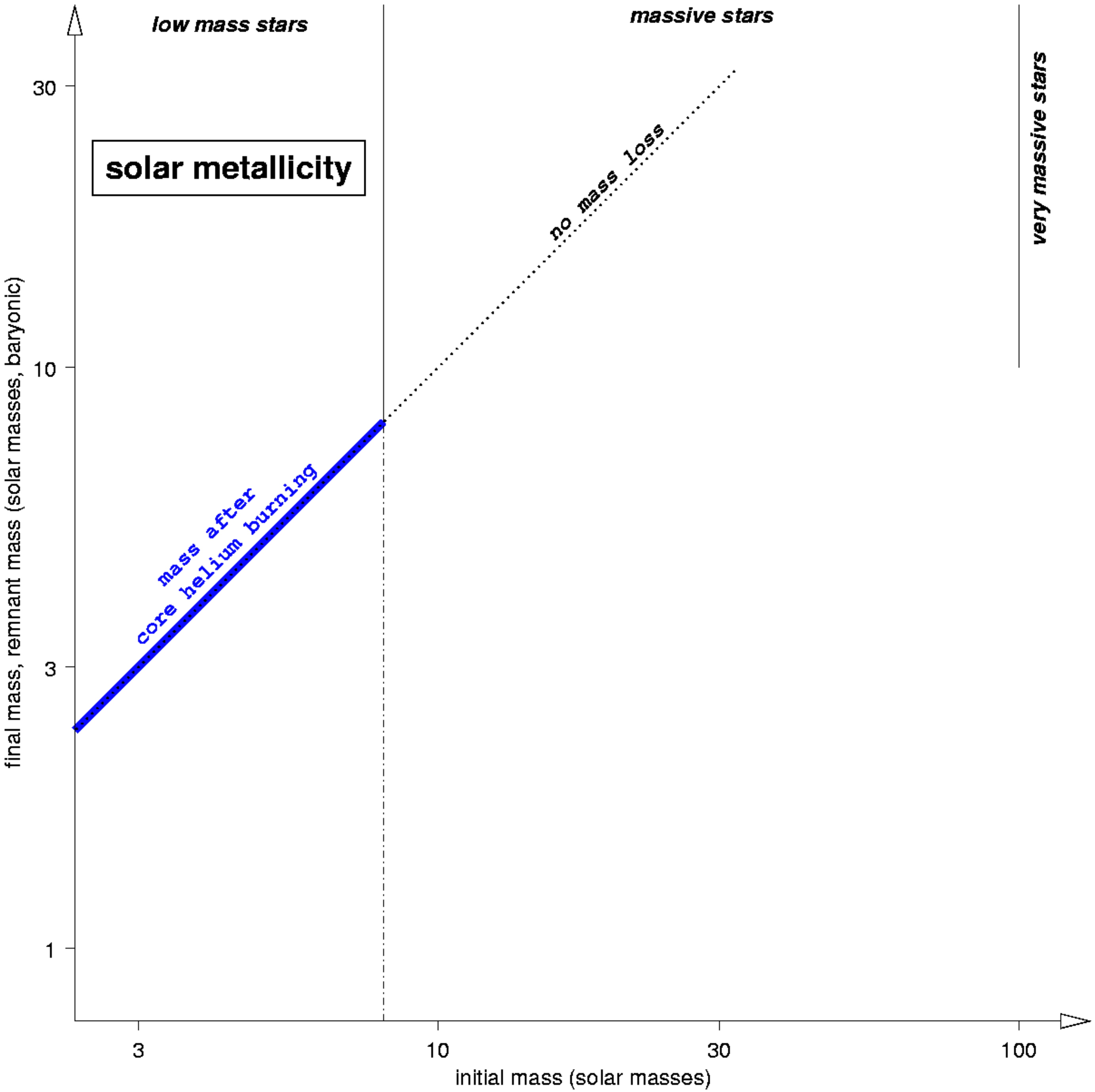
(anything goes)

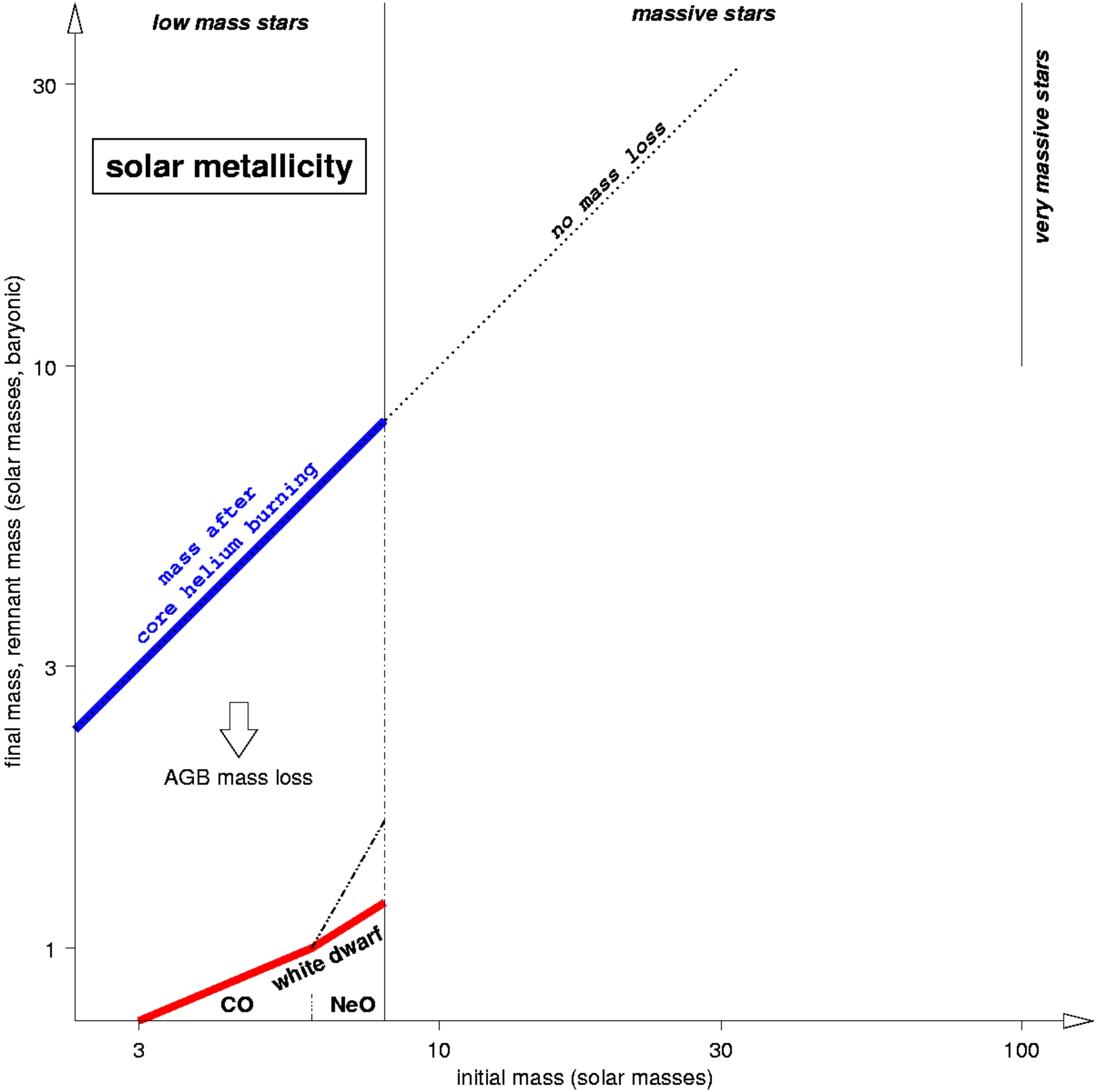
Massive Star Fates as Function of Initial Mass

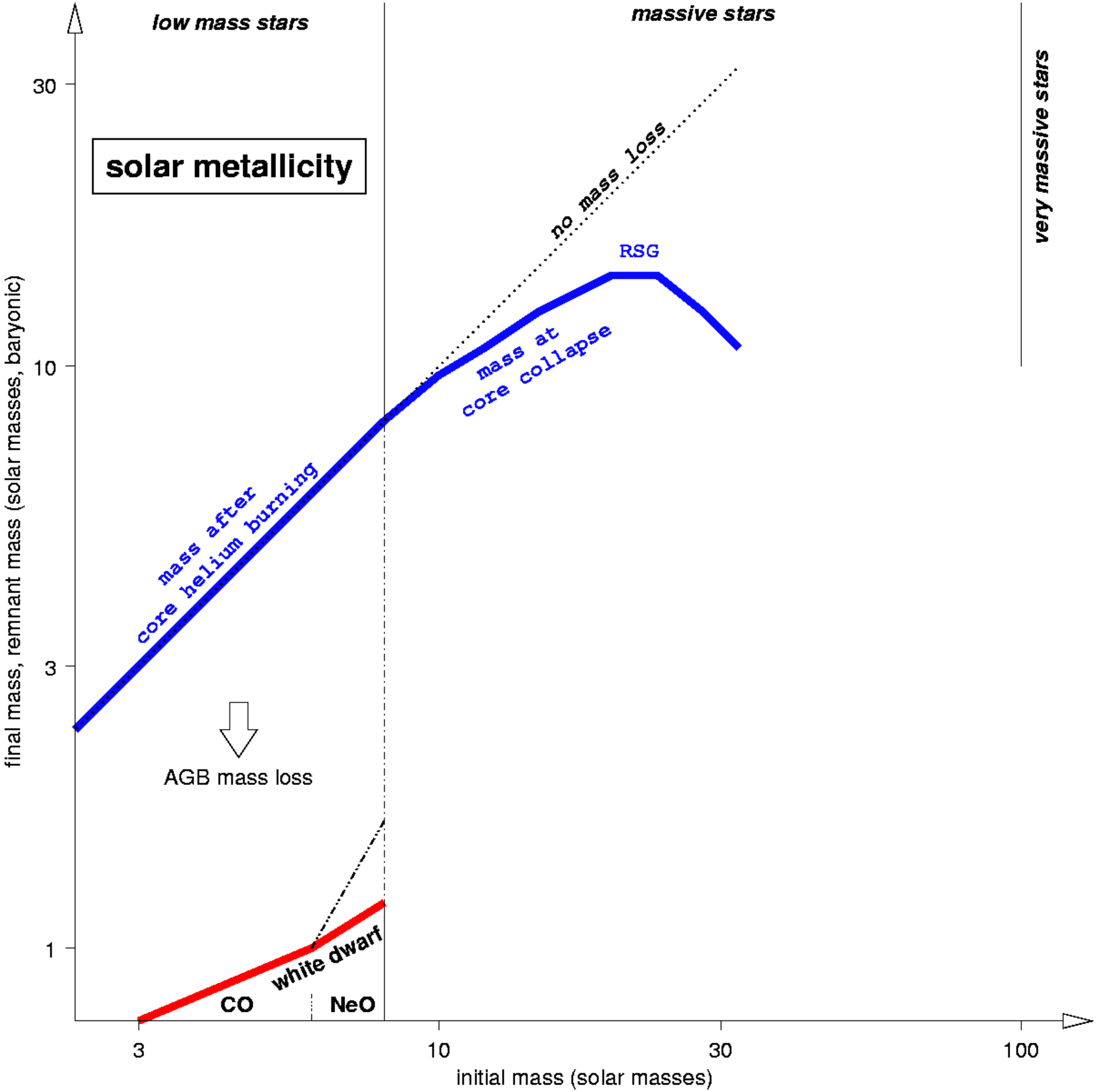
(solar metallicity)

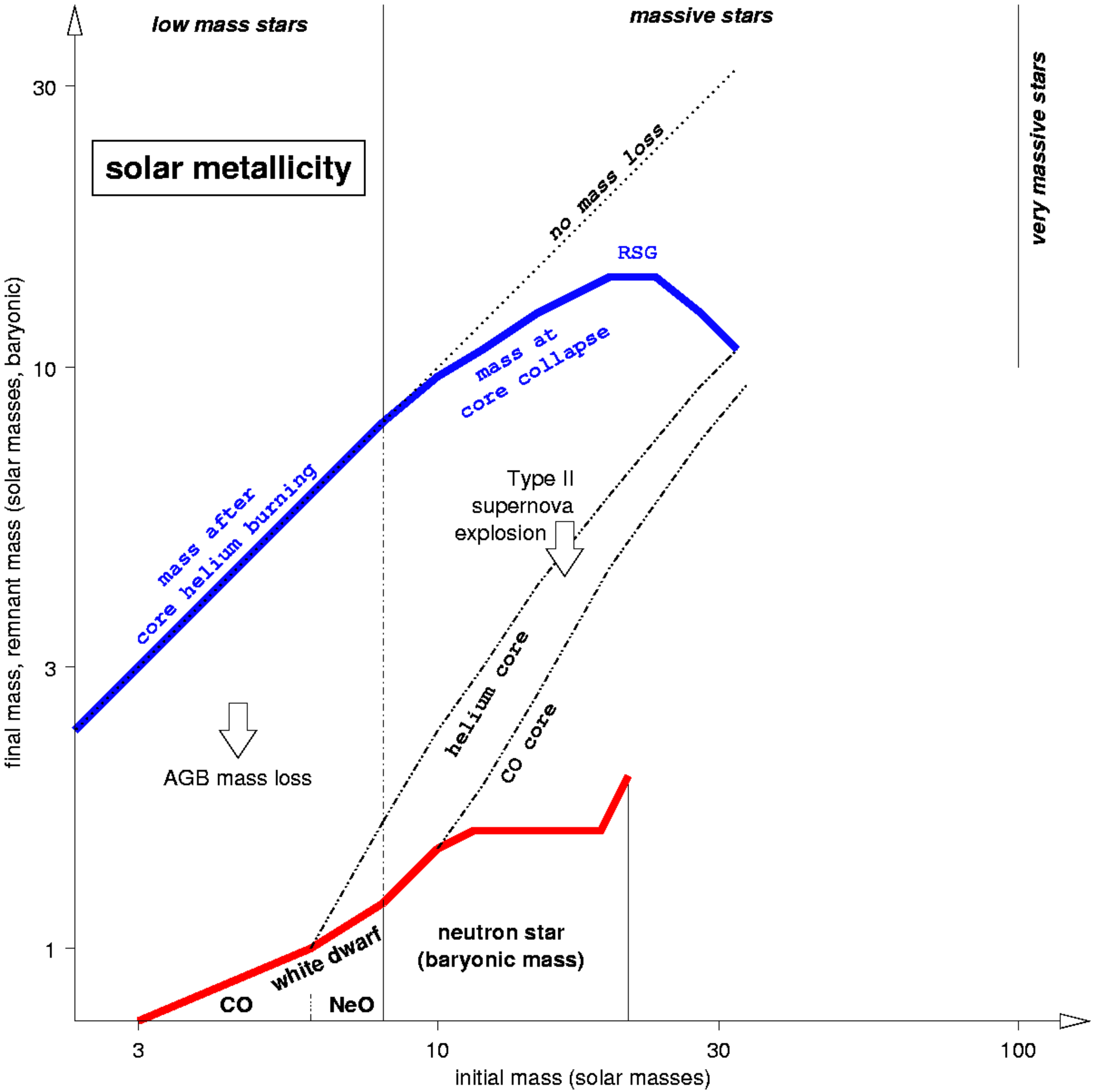

solar metallicity
no mass loss
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)

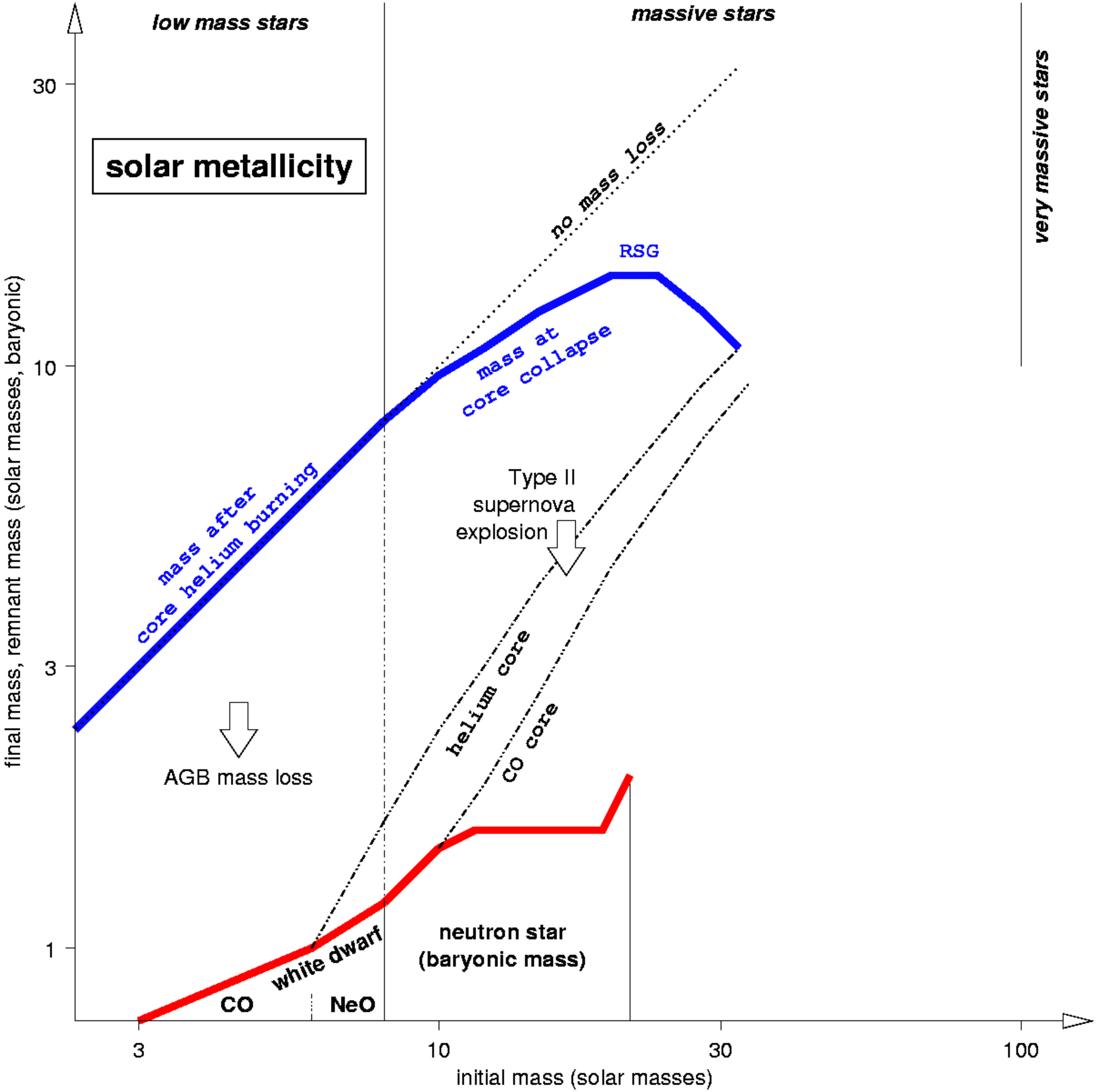

low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)

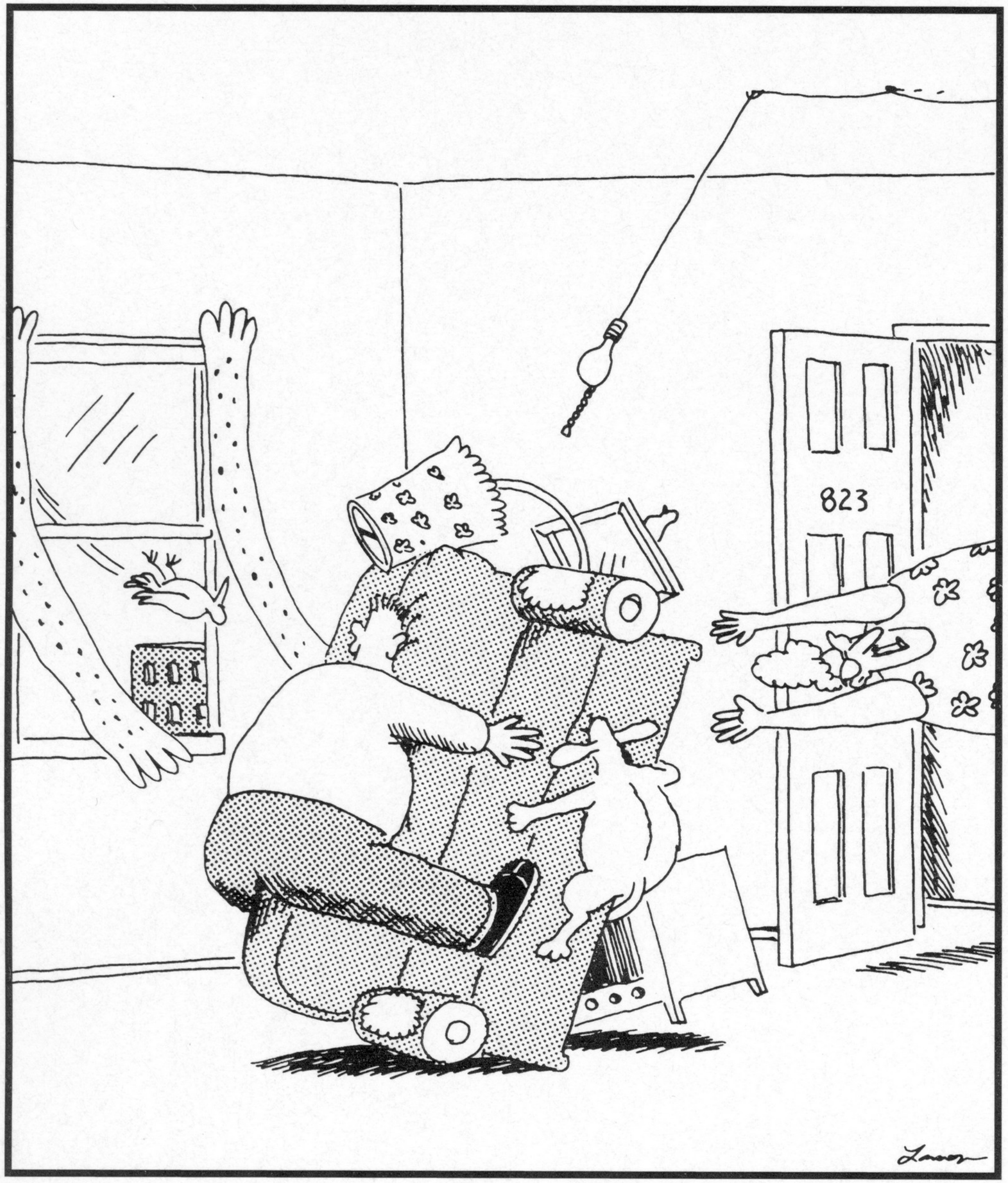
low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
mass after
core helium burning
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
mass after
core helium burning
AGB mass loss
white dwarf
CO
NeO
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass at core collapse
mass after core helium burning
AGB mass loss
white dwarf
CO
NeO
30
10
3
1
3
10
30
100
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass at core collapse
mass after core helium burning
Type II supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star (baryonic mass)
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass at
core collapse
mass after
core helium burning
Type II
supernova
explosion
AGB mass loss
helium core
CO core
white dwarf
CO
NeO
neutron star
(baryonic mass)
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)



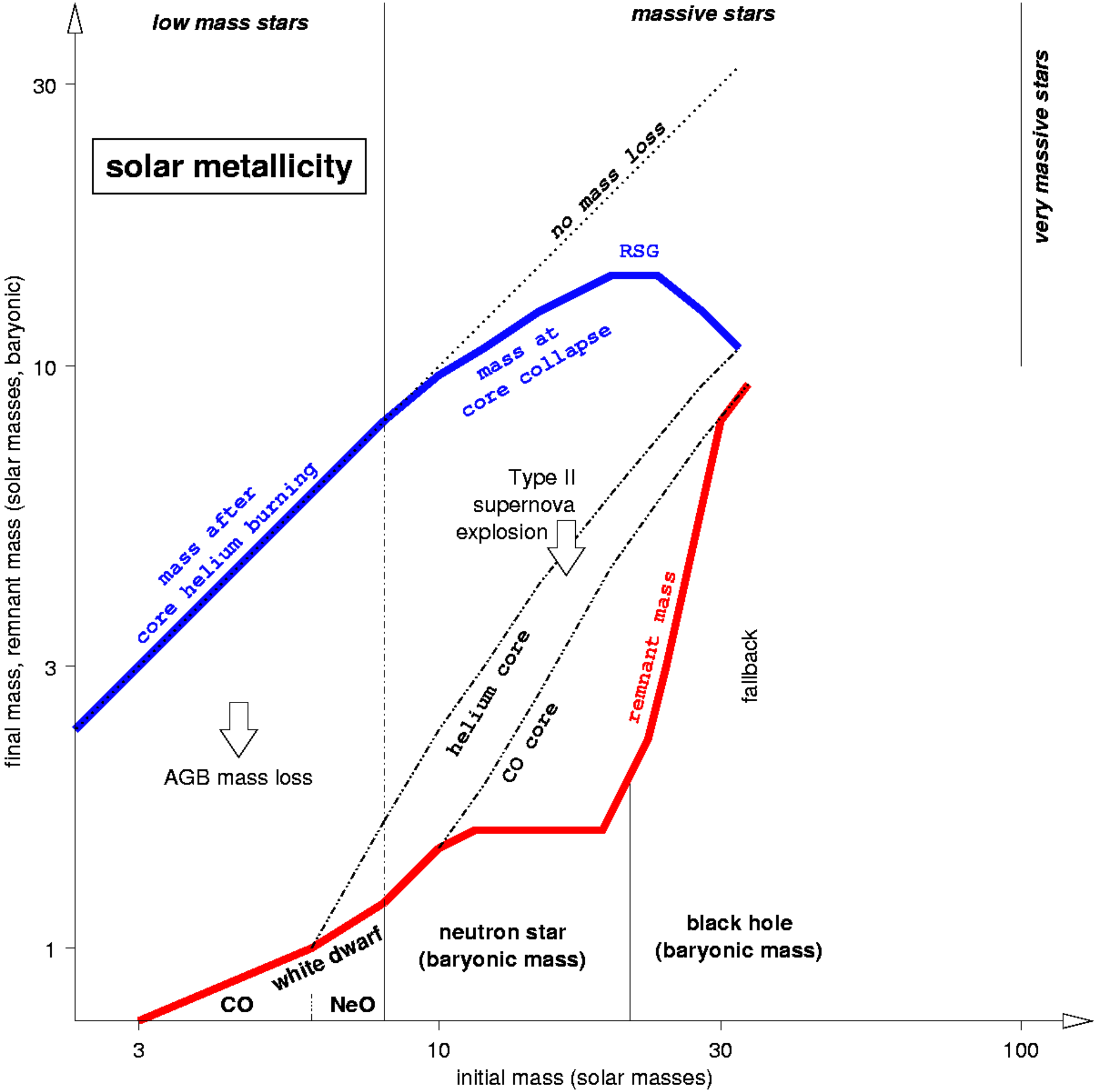
Suddenly, through forces not yet fully understood, Darren Belsky's apparment became the center of a new black hole.

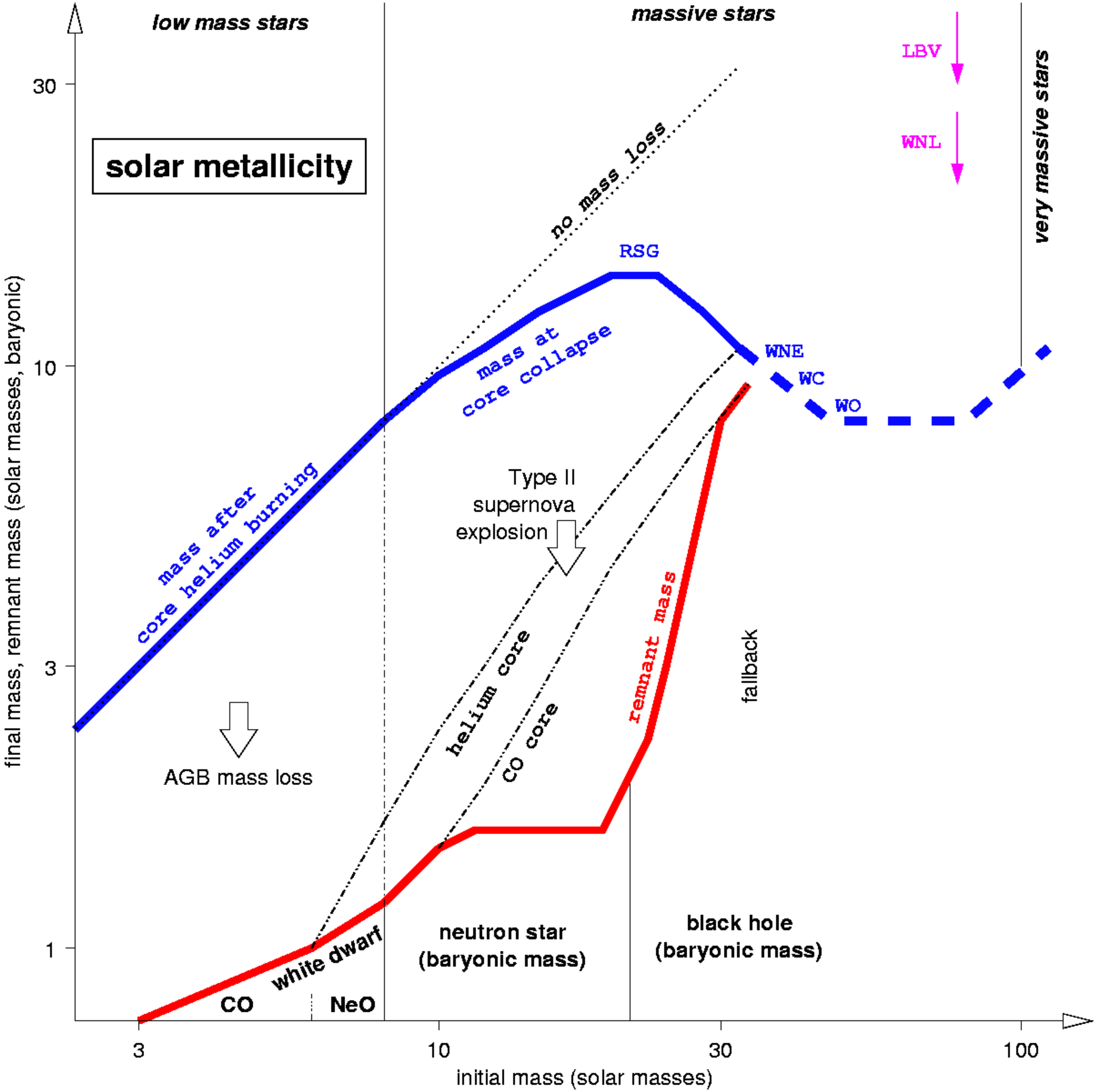
The Far Side, Dec20, 2002

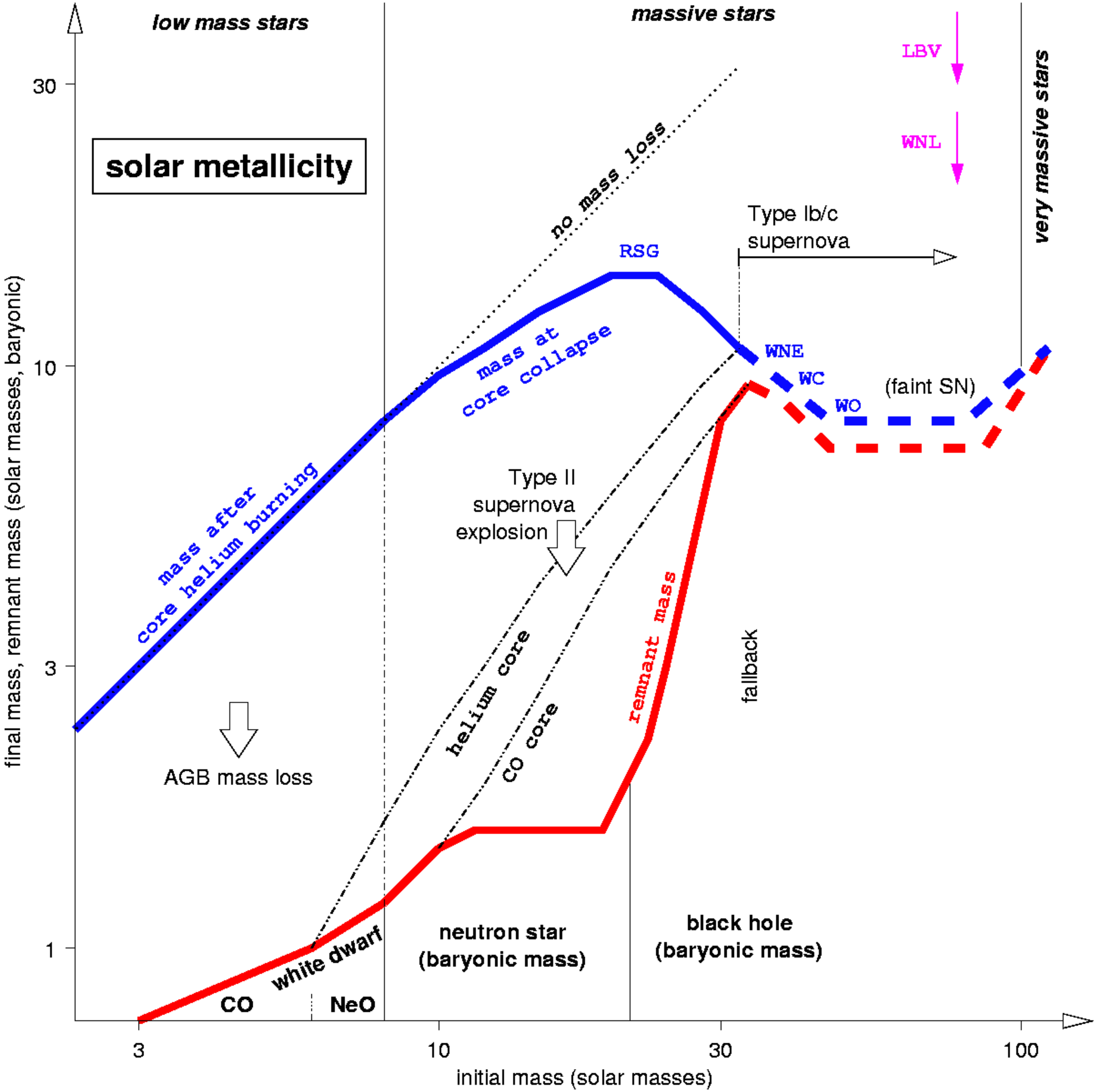
Fallback

in supernovae

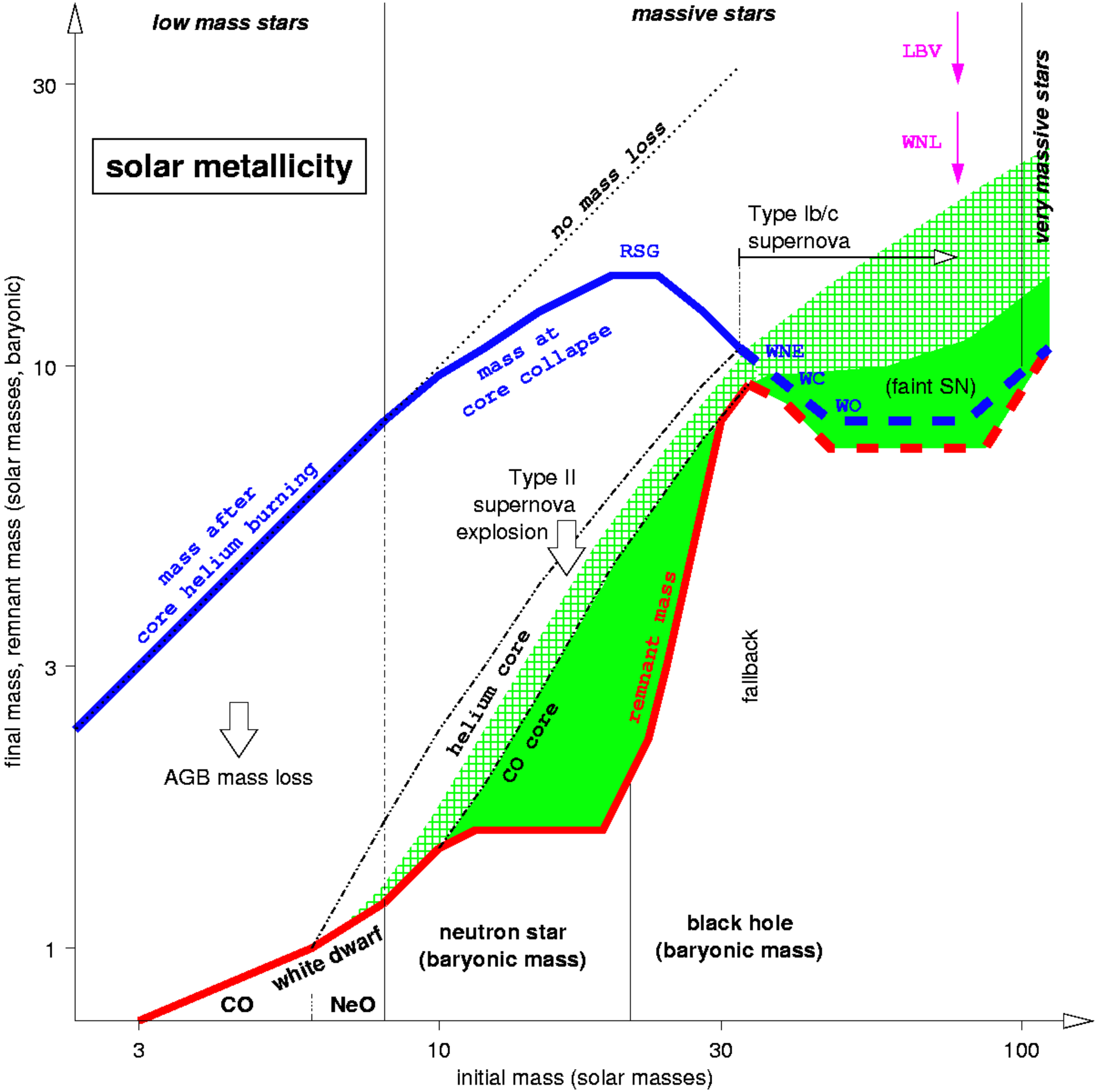
can swallow the metals produced in the hydrostatic and explosive burning phases and can lead to the delayed formation of a **black hole**

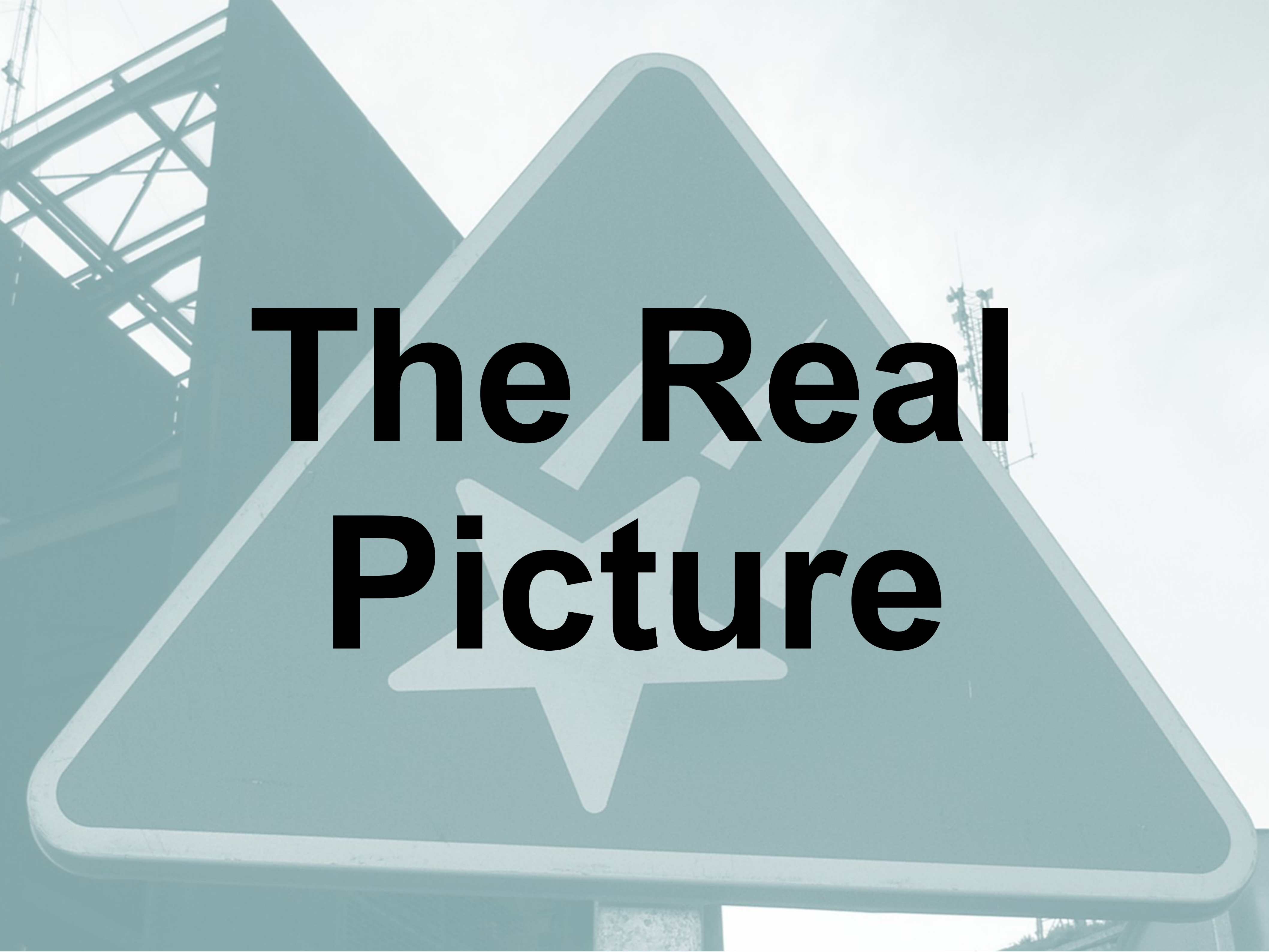

low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass at core collapse
mass after core helium burning
Type II supernova explosion
AGB mass loss
helium core
CO core
remnant mass
fallback
white dwarf
CO
NeO
neutron star (baryonic mass)
black hole (baryonic mass)
final mass, remnant mass (solar masses, baryonic)
30
10
3
1
initial mass (solar masses)
3
10
30
100


low mass stars
massive stars
very massive stars
solar metallicity
LBV
WNL
no mass loss
RSG
WNE
WC
WO
mass after core helium burning
mass at core collapse
Type II supernova explosion
helium core
CO core
remnant mass
fallback
AGB mass loss
white dwarf
CO
NeO
neutron star (baryonic mass)
black hole (baryonic mass)
30
10
3
1
3
10
30
100
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)

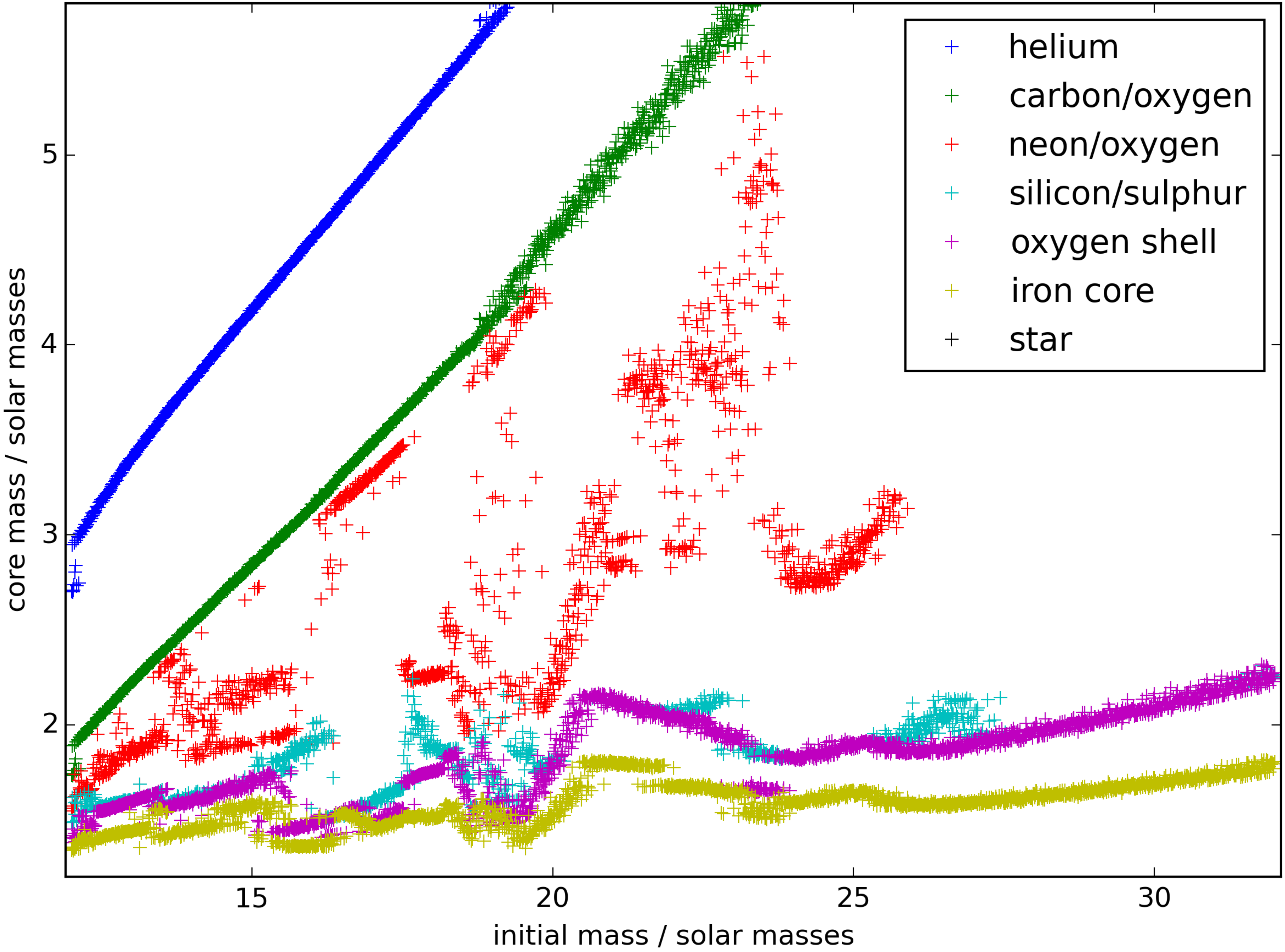

low mass stars
massive stars
very massive stars
solar metallicity
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)
LBV
WNL
no mass loss
RSG
Type Ib/c
supernova
mass at
core collapse
WNE
WC
WO
(faint SN)
mass after
core helium burning
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
AGB mass loss
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic mass)

Ejected “metals”

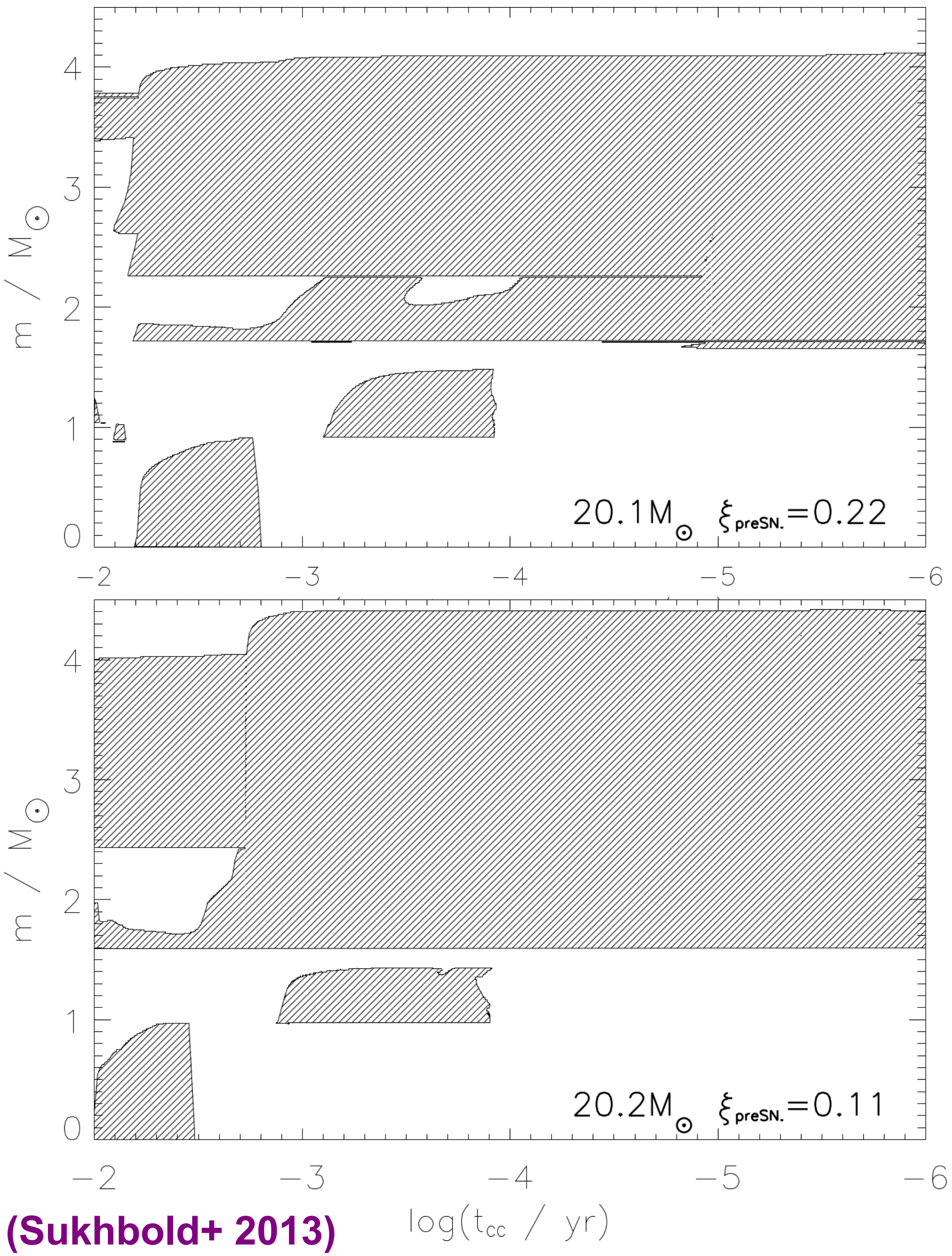




The Real Picture


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

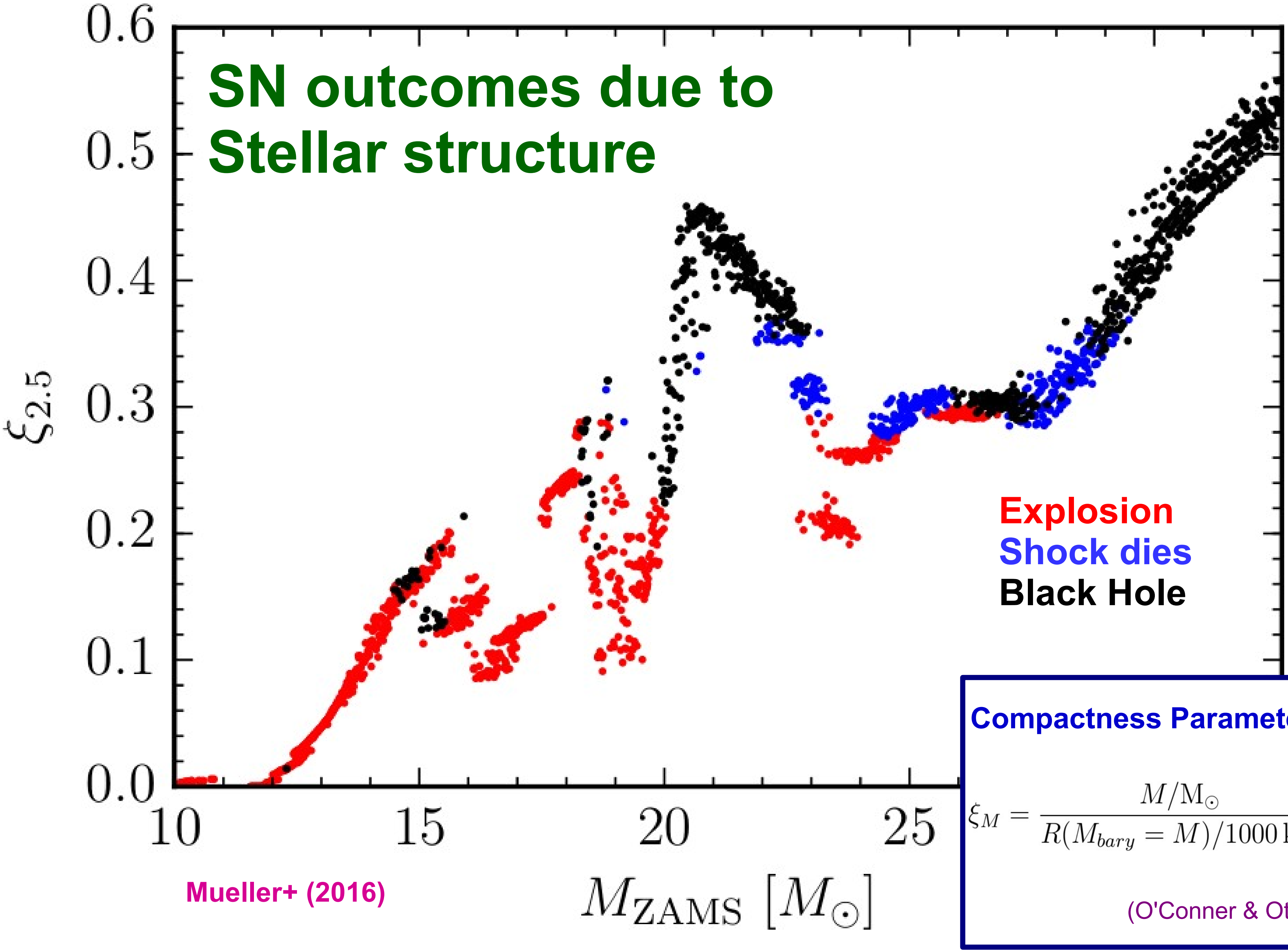
Sensitivity of Structure to Initial Mass



Small changes in initial mass can result in large changes in progenitor structure

(Sukhbold+ 2013)

Signatures of Stellar Structure?



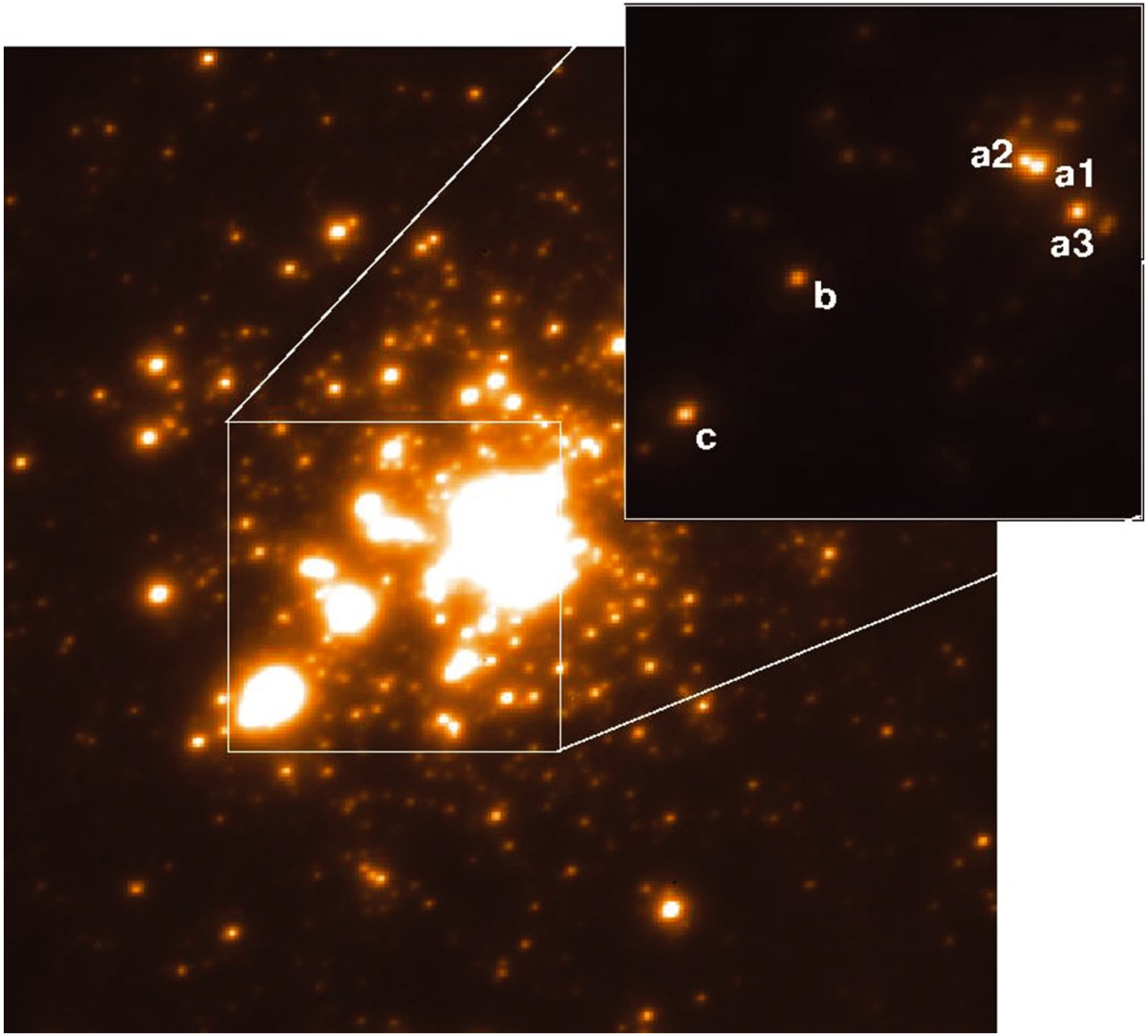
Mueller+ (2016)

Compactness Parameter

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

(O'Conner & Ott 2011)

The Most Massive Stars Today



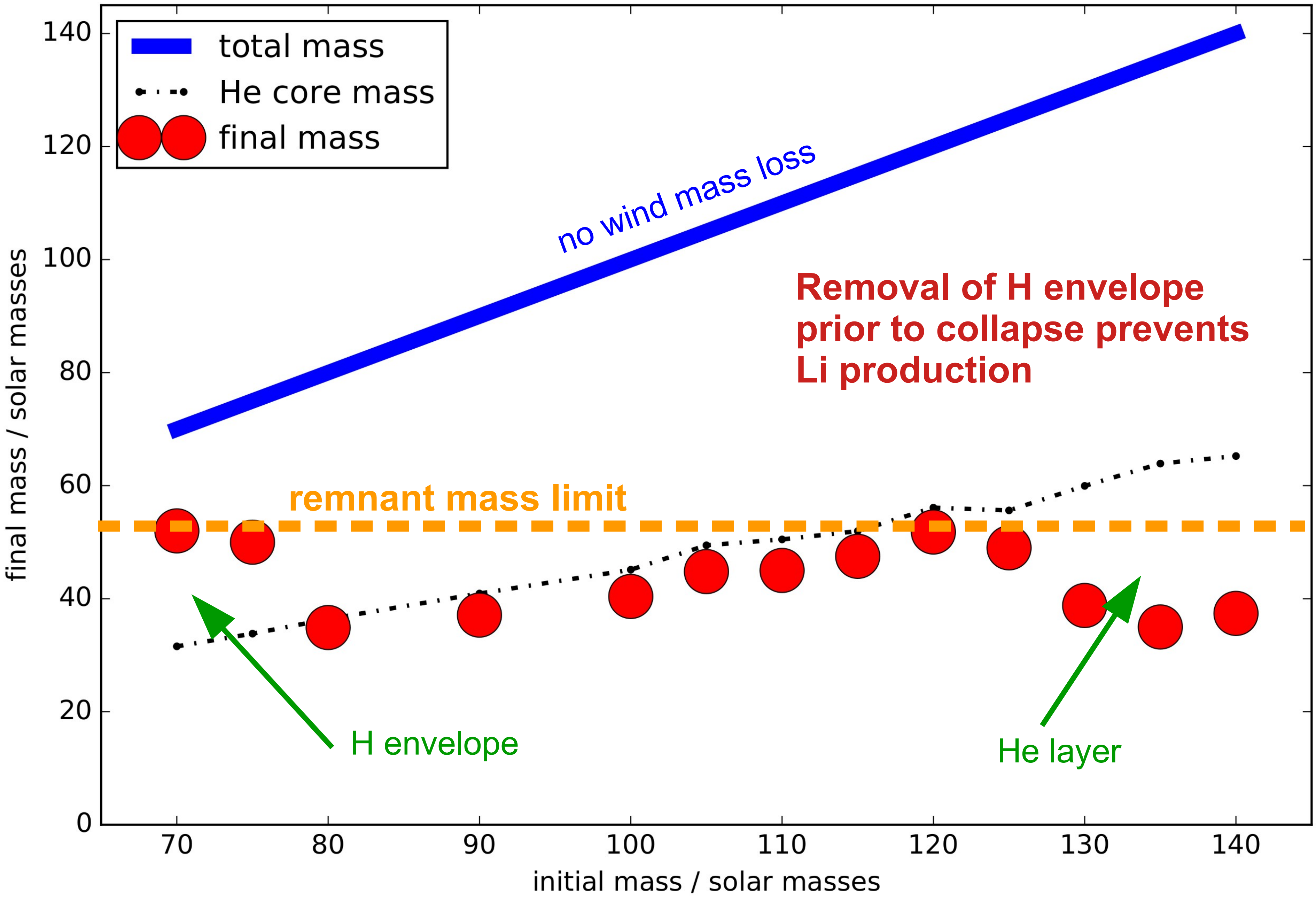
R136

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

(Crother et al. 2010)

Pulsational Pair-Instability Supernovae

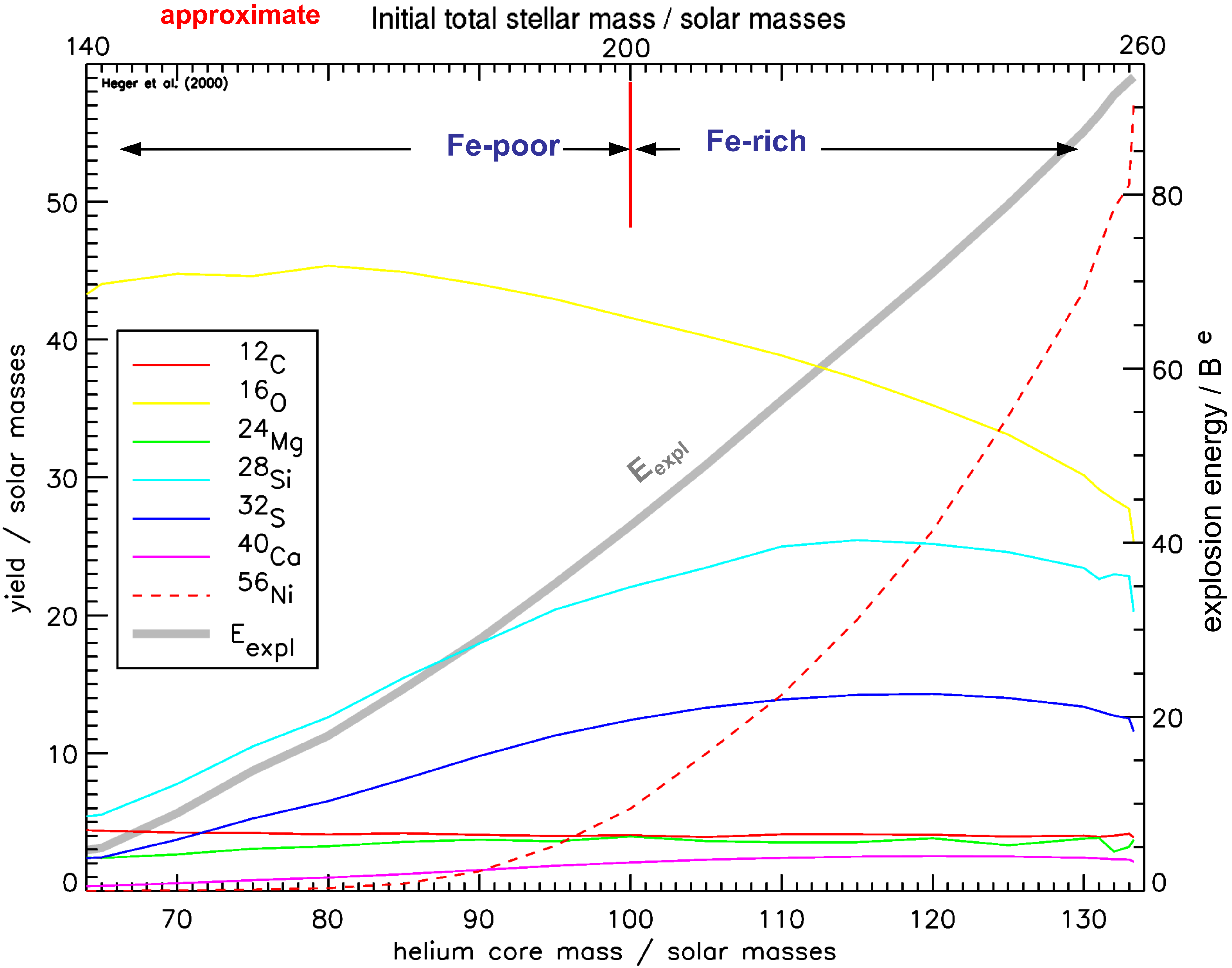
Pulsational Pair Instability Supernovae

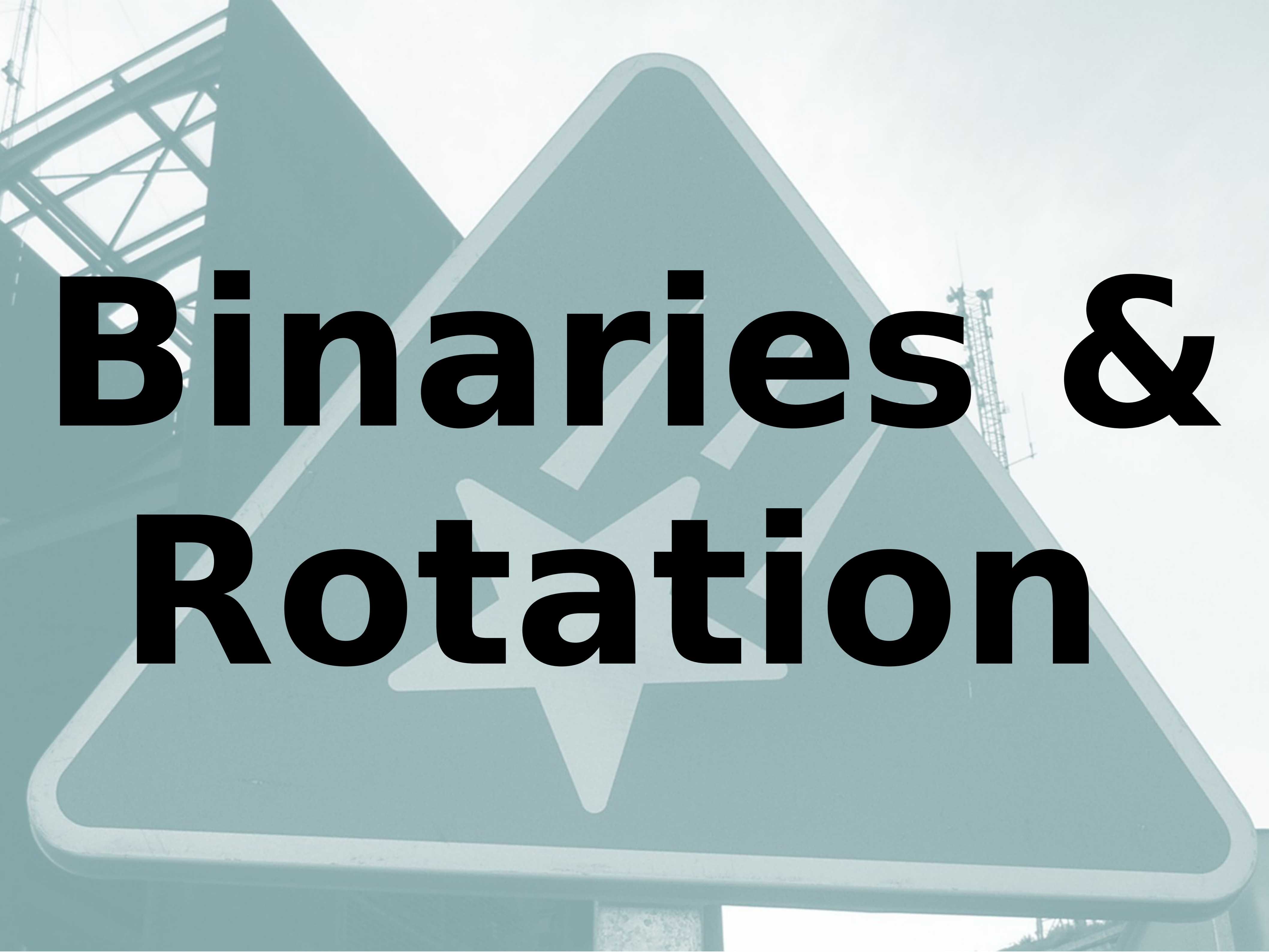


Removal of H envelope prior to collapse prevents Li production

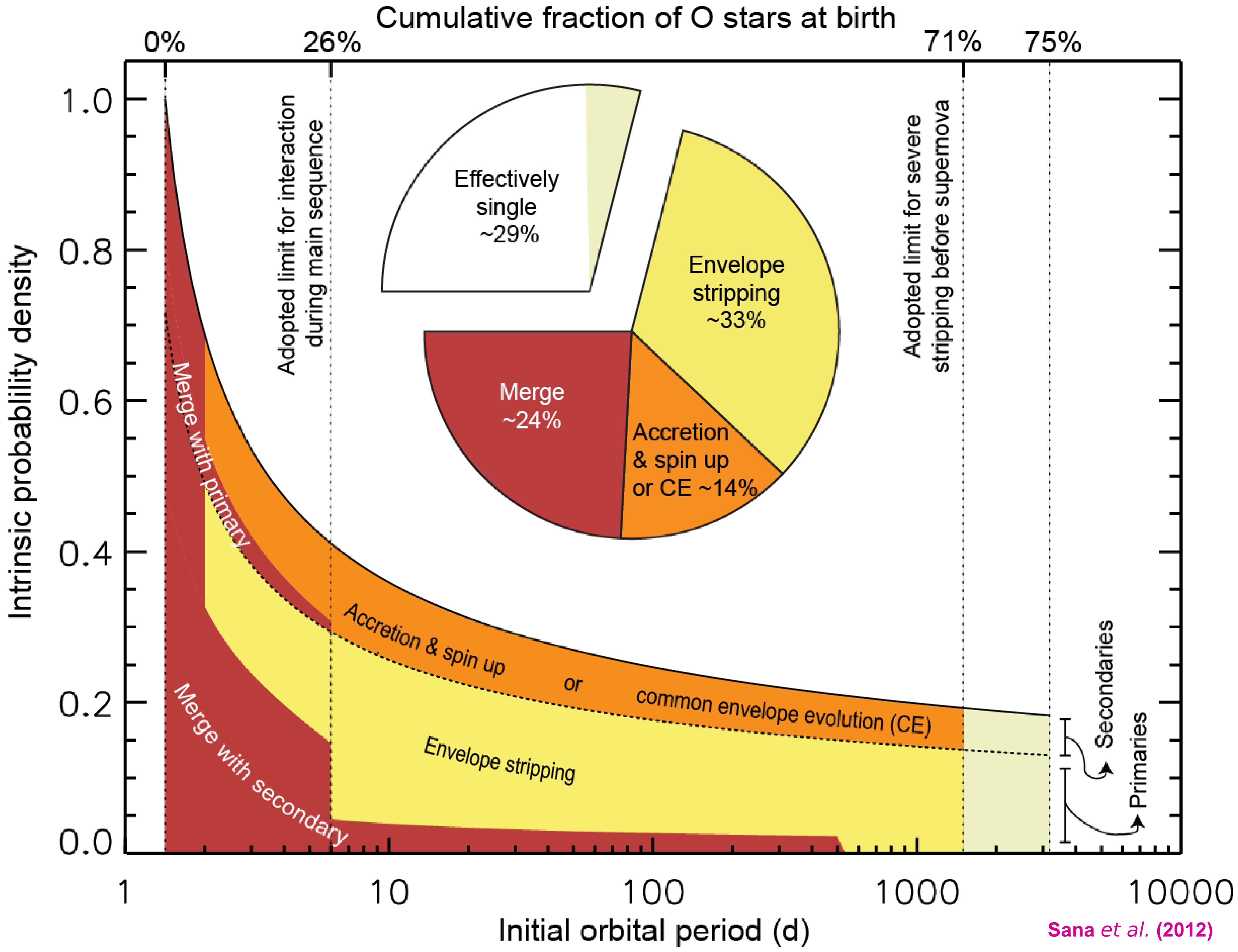
Plot after data from Woosley (2016)

Pair-Instability Supernovae


approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E_{expl}
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
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

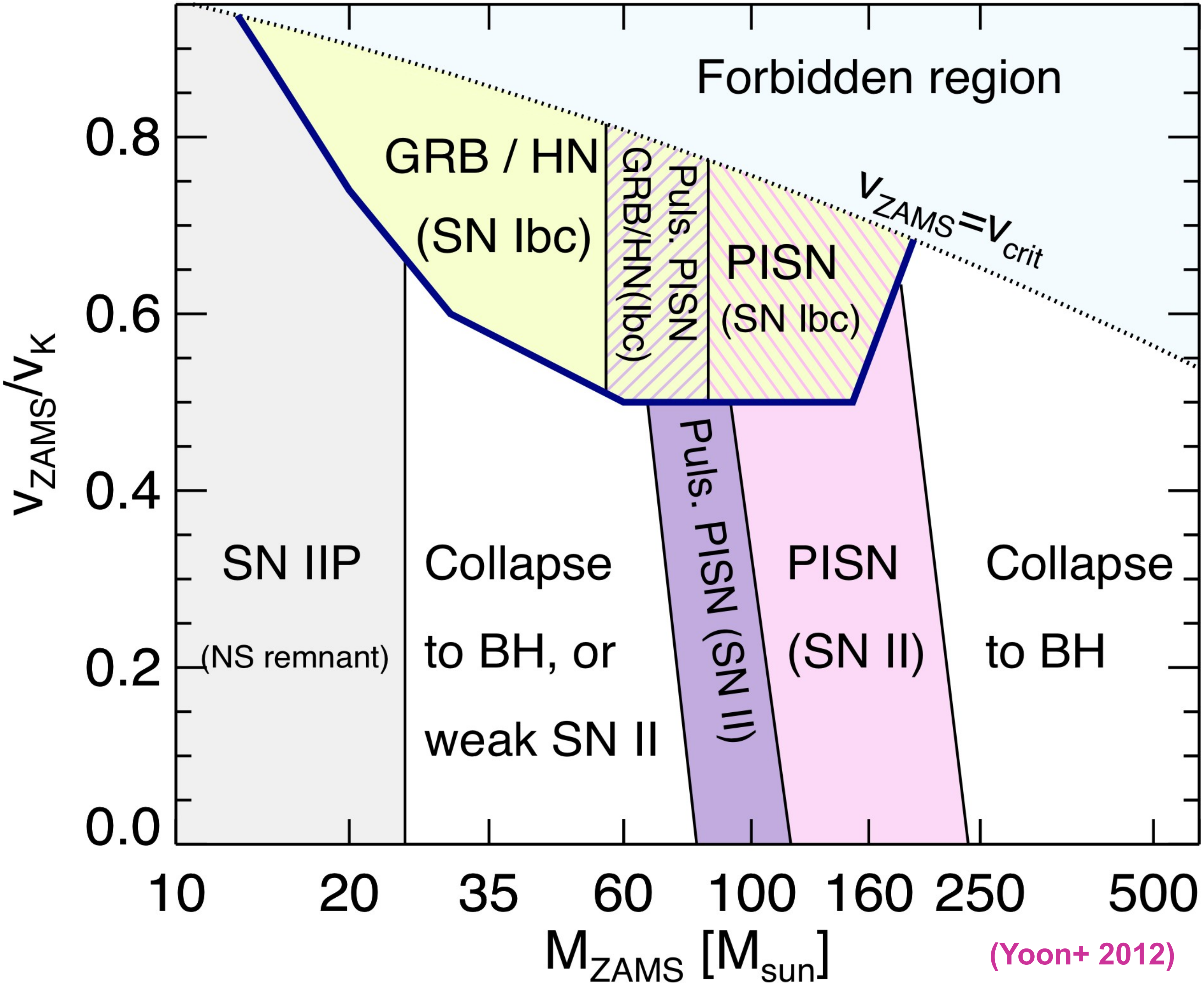


Binaries & Rotation



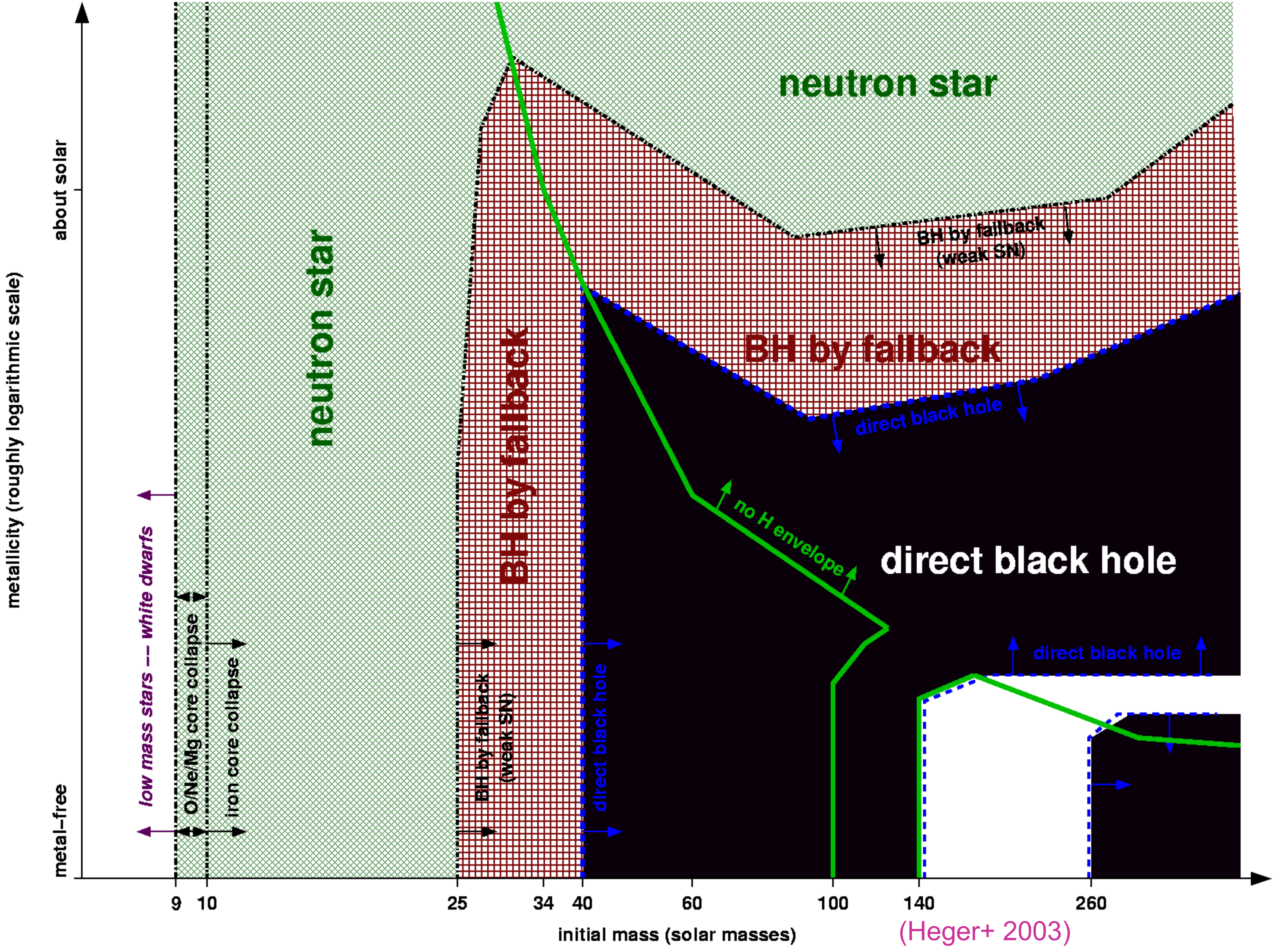
Sana *et al.* (2012)

Final fates of rotating massive Pop III stars



(Yoon+ 2012)

Stellar Remnants throughout the Ages of the Universe


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)
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

(Heger+ 2003)