Notre Dame, October 13, 2004

Evolution and Nucleosynthesis of Massive Stars

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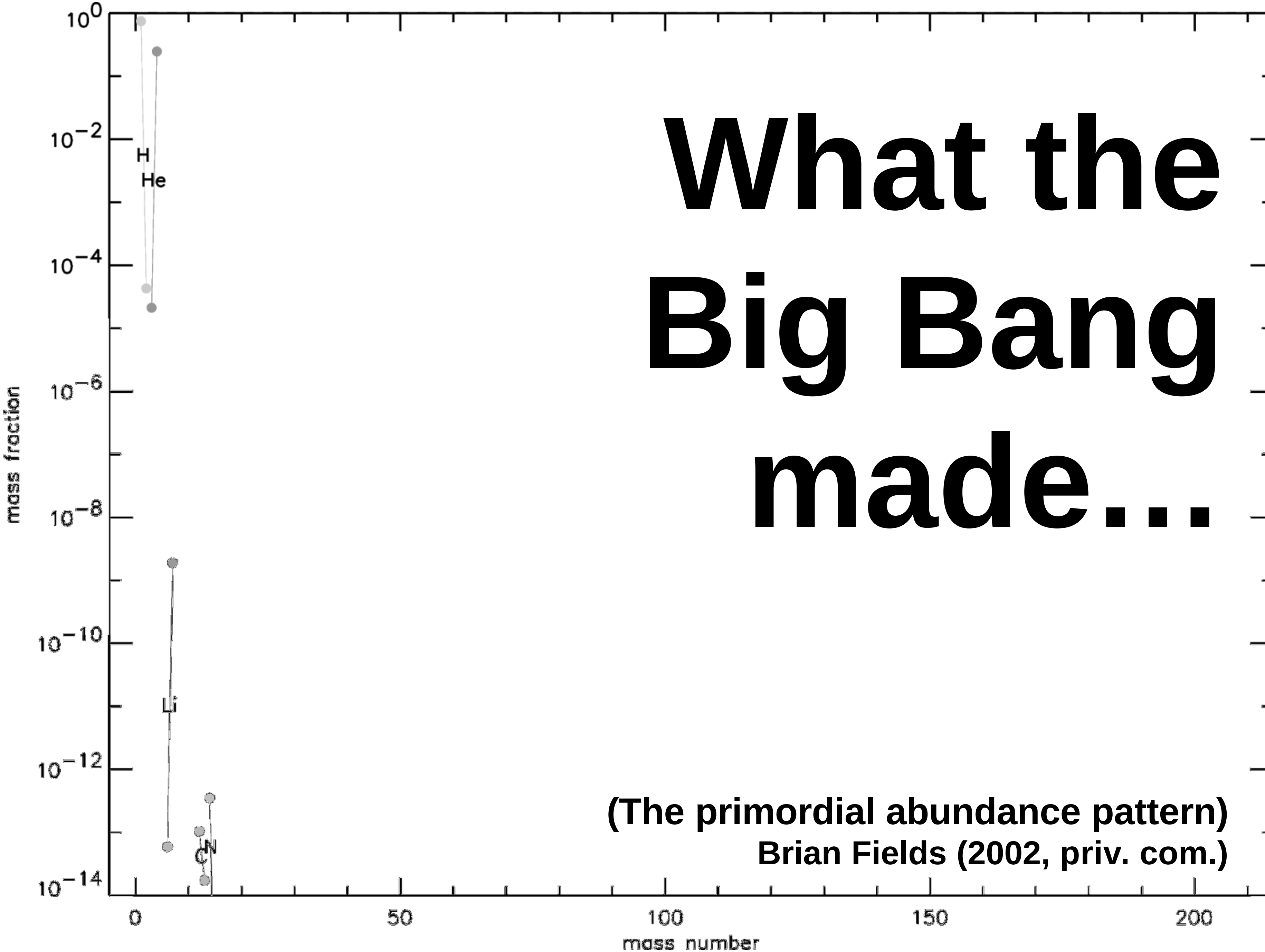
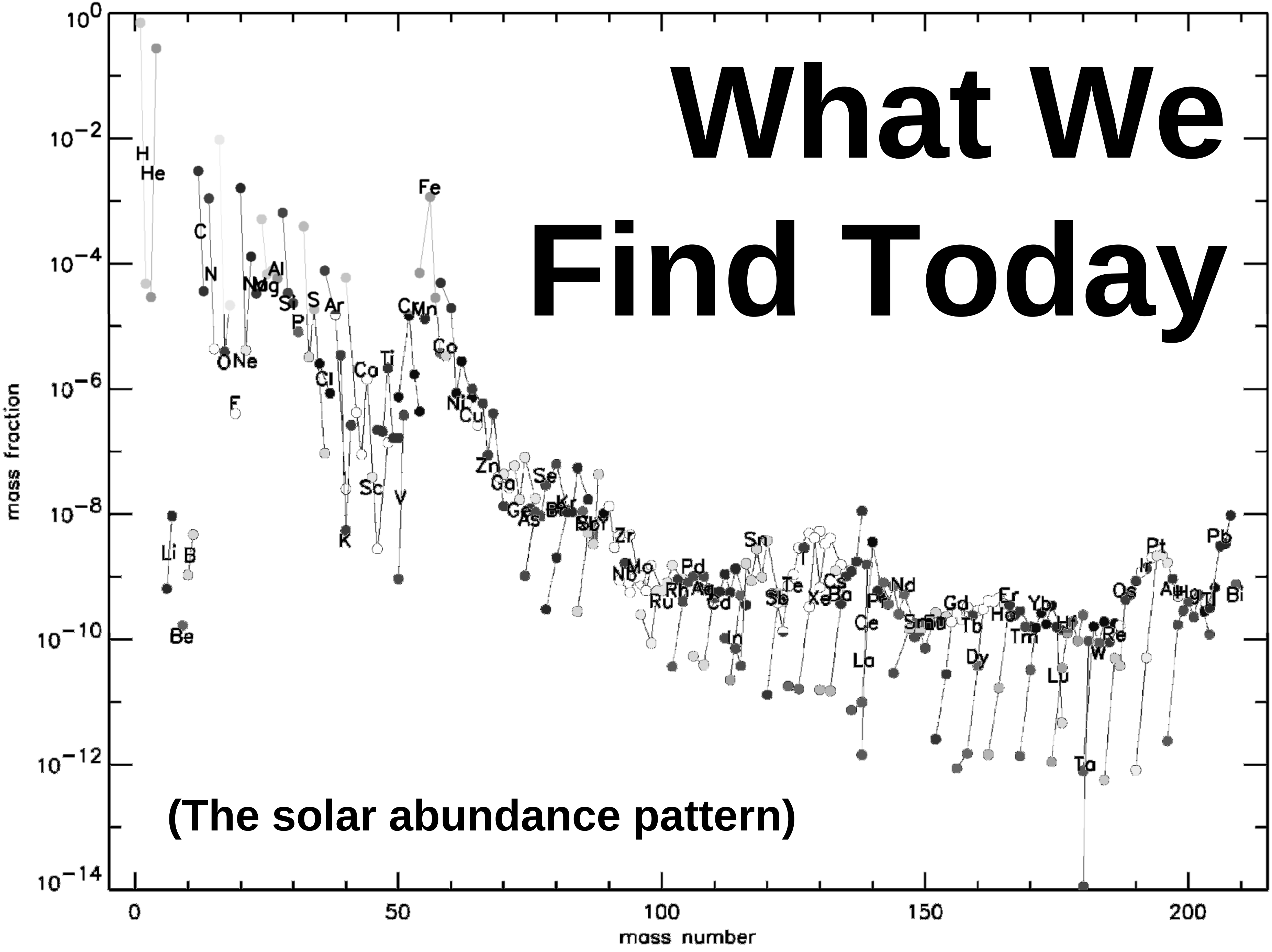
What the Big Bang made...



(The primordial abundance pattern)

Brian Fields (2002, priv. com.)

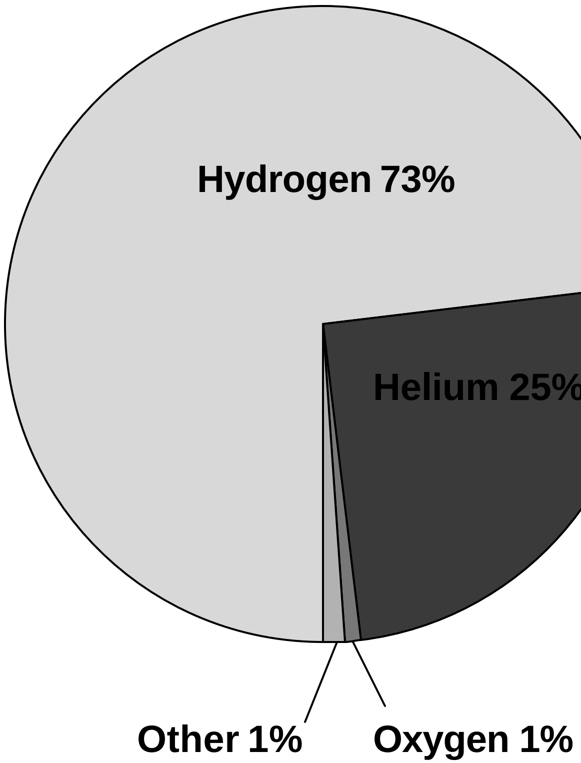
What We Find Today



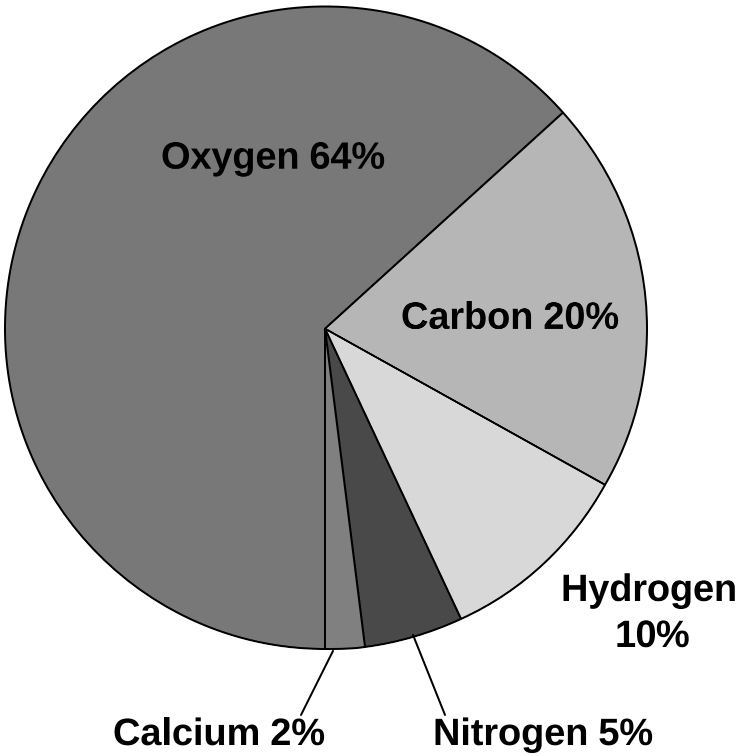
(The solar abundance pattern)

Relative Abundance by Weight

Universe



Humans



Report by the NRC *"Committee on the Universe"* June, 2002

- What is the dark matter? (baryonic, n*, BH)
- What is the nature of dark energy? (SN Ia)
- How did the universe begin? (BB nucleosynthesis)
- Did Einstein have the last say on gravity?
- What are the masses of neutrinos and how have they shaped the evolution of the universe? (flavor mixing in stars and SNe)
- How do cosmic accelerators operate and what are they accelerating? (cosmic rays and GRB jets)
- Are protons unstable?
- Are there new states of matter at exceedingly high temperature and density? (neutron star EOS)
- Are there additional space-time dimensions?
- **How were the elements from iron to uranium made?**
- Is a new theory of matter and light needed at the highest energies?

We want to understand the origin of the elements because:

- It is an interesting problem

- Nuclear transmutation
  is the origin of stellar energy generation

- We can use that understanding as a diagnostic of ...

    - stellar evolution
    - nova and supernova explosions
    - x-ray bursts
    - particle physics
    - the evolution of galaxies and the universe

Specific Nuclear Uncertainties

(massive stars only)

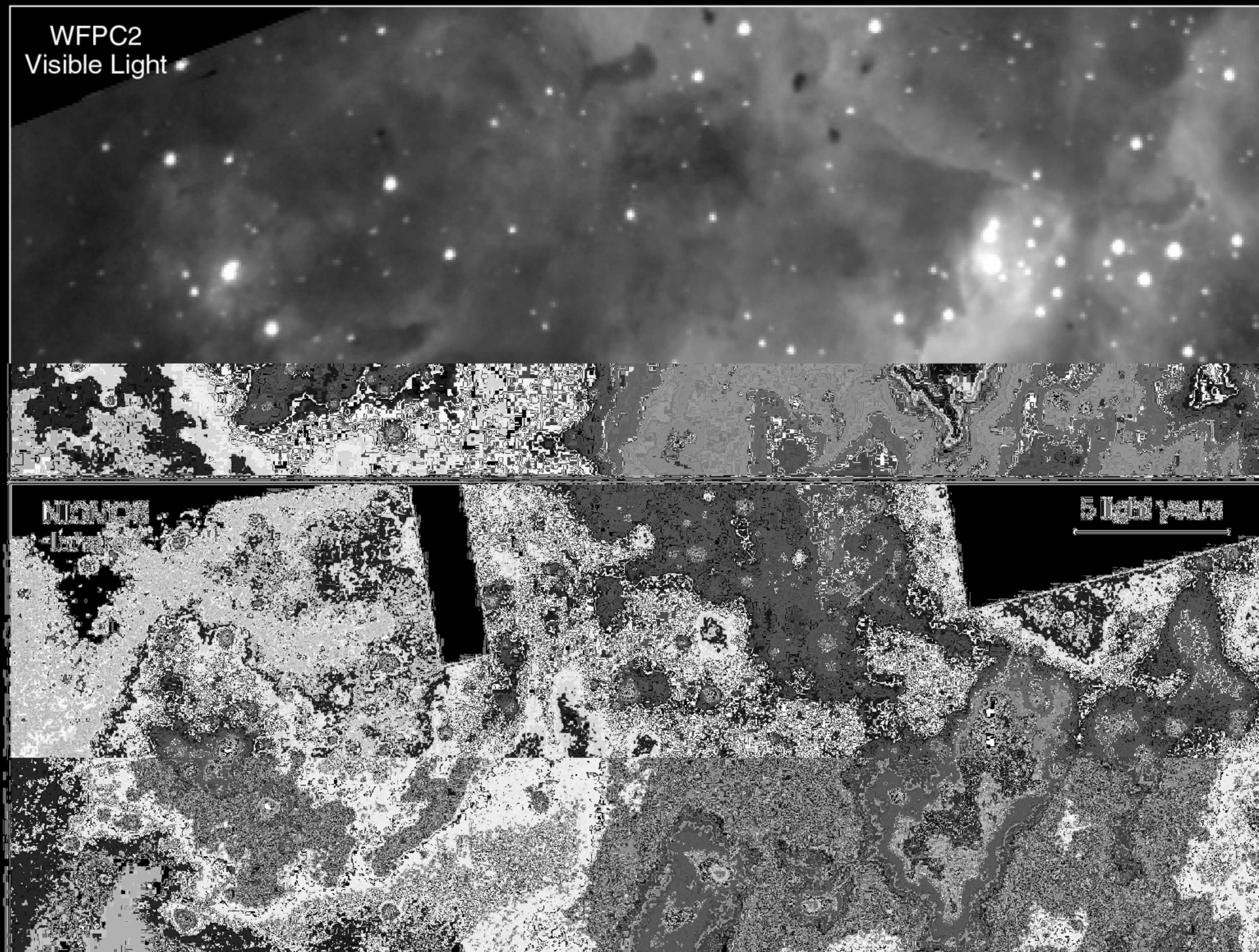
- **$^{12}C(\alpha,\gamma)^{16}O$**
- **$^{22}Ne(\alpha,n)^{25}Mg$**
- $^{12}C(n,\gamma)^{13}C$, $^{16}O(n,\gamma)^{17}O$ and other 30 keV (n,γ) cross sections
- Neutrino spallation of ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{139}La, ^{181}Ta and neutrino charged current reactions with ^{138}Ba, ^{180}Hf
- Weak rates for the iron group, especially ^{60}Co
- Rates for the *rp*-process in proton-rich winds of young neutron stars
- Photodisintegration rates for heavy nuclei for the γ-process
- Mass excesses and half lives for the *r*-process
- Reaction rates affecting the nucleosynthesis of radioactive nuclei: ^{22}Na, ^{26}Al, ^{44}Ti, $^{56,57}Ni$, ^{60}Co
- The nuclear EOS for core collapse supernovae
- Electron capture rates at high densities ($\rho \sim 10^{11} – 10^{13}$) for very heavy nuclei in core collapse (A up to several hundred)

Overview

- The life of massive stars
- The final fates of stars
- Nucleosynthesis in massive stars
- Neutrino nucleosynthesis
- Nuclear reaction uncertainties
- Summary

Star-forming region of 30 Doradus (Tarantula Nebula): Zoom into the central star cluster, R-136

Credit: *Greg Bacon and Zolt Levay (STScI)*



30 Doradus Details

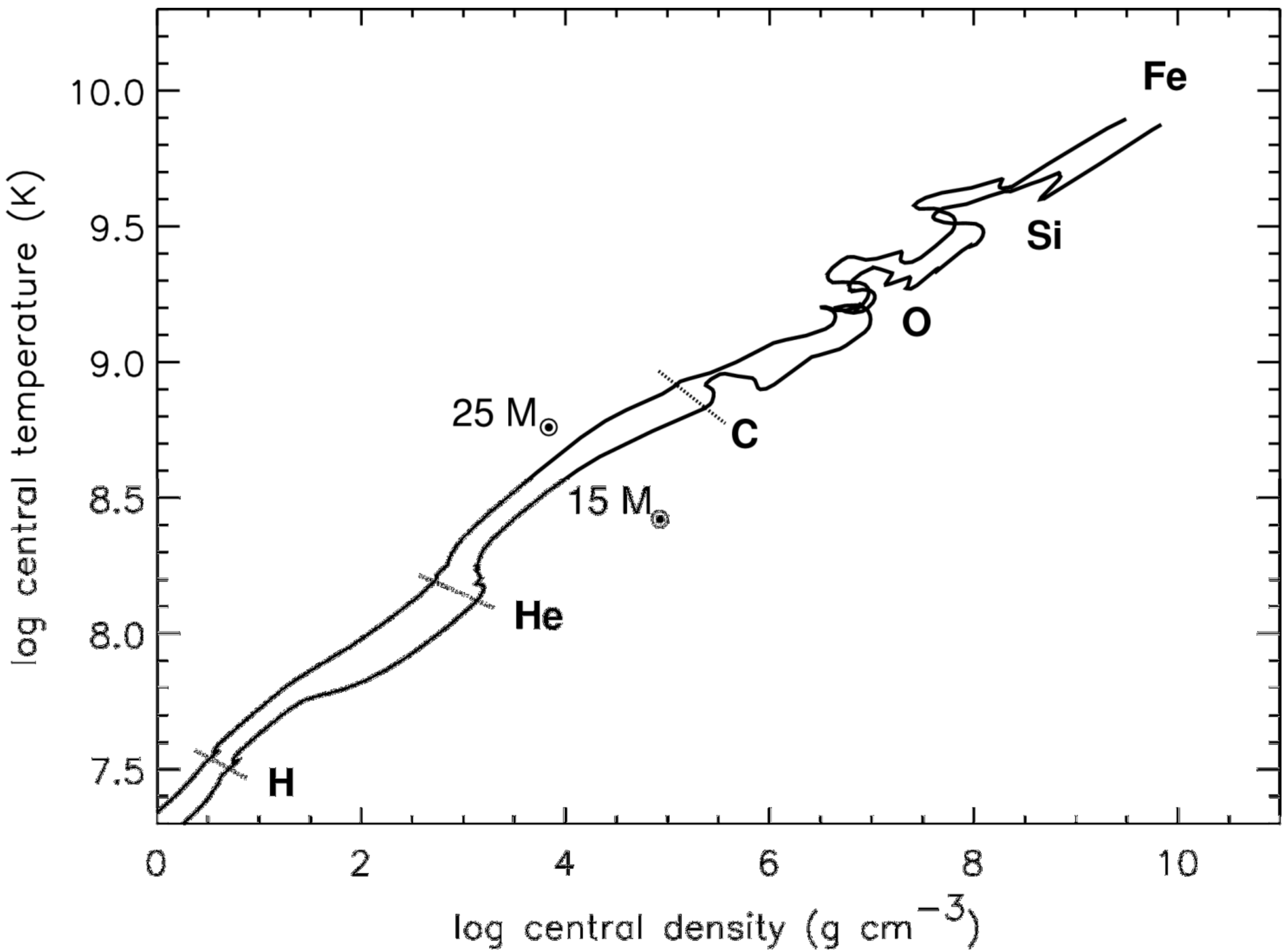
Hubble Space Telescope • WFPC2 • NICMOS

[illegible] • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

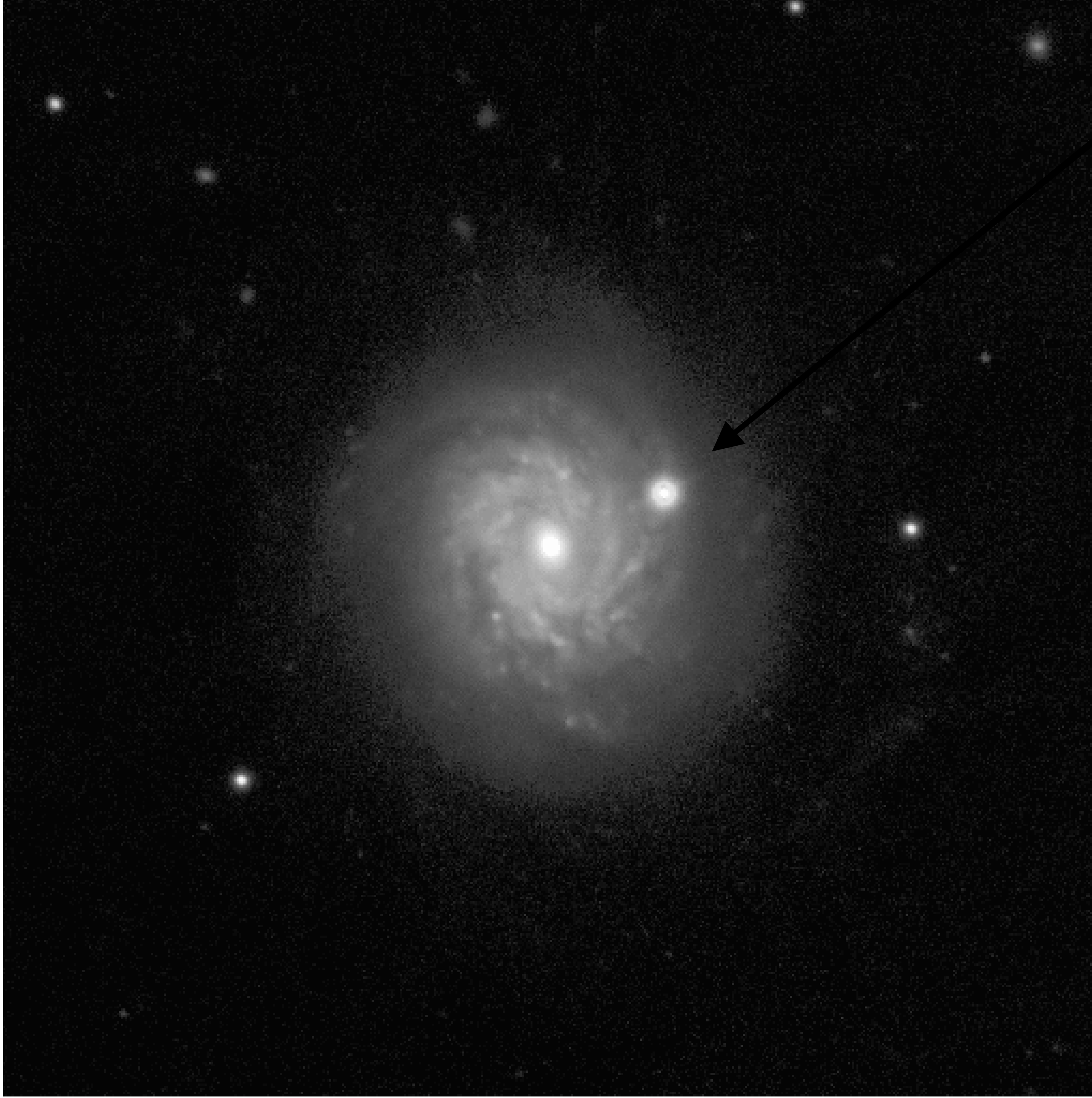
Once formed, the evolution of a star is governed by gravity:

continuing contraction

to higher central densities and temperatures



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

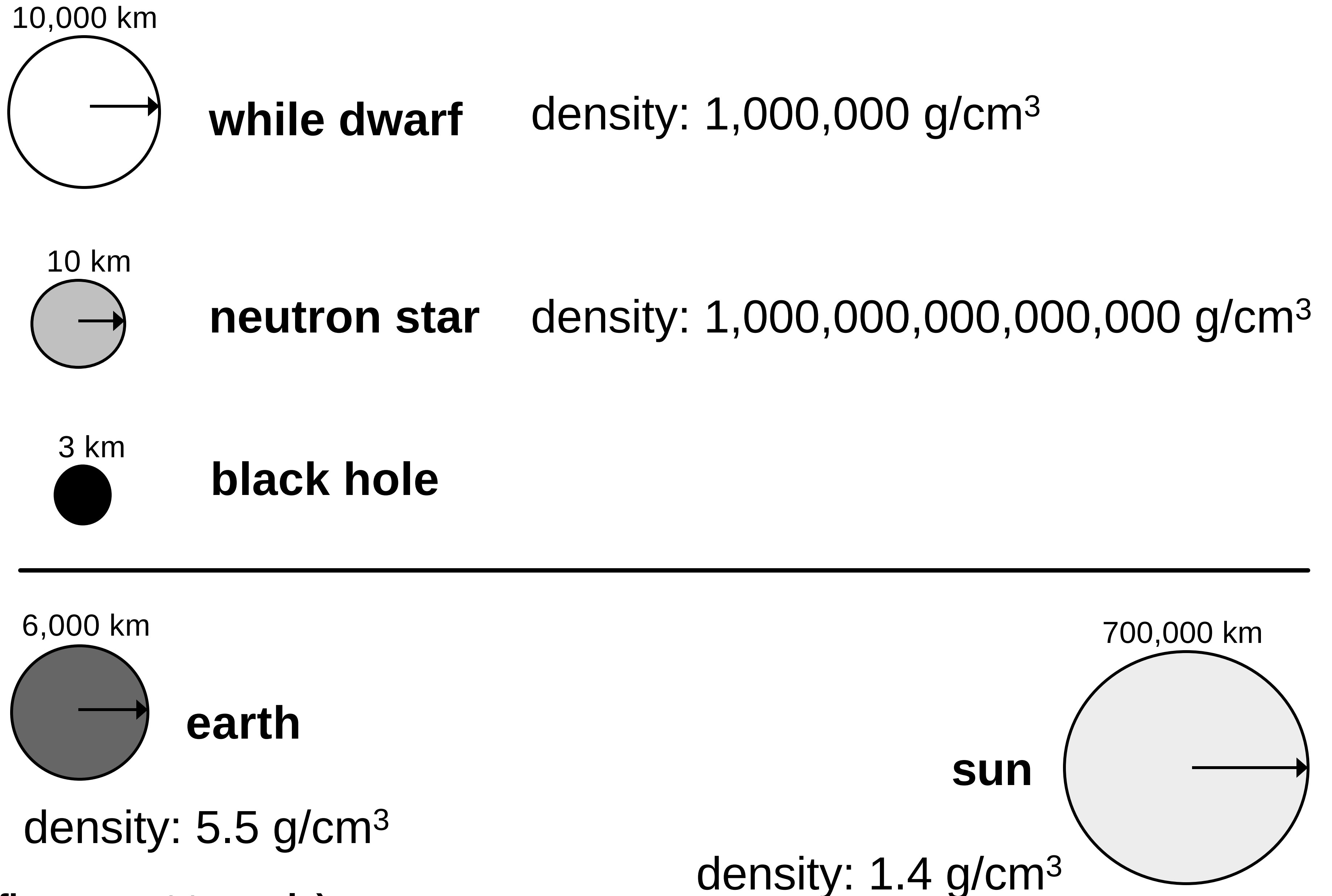


NGC3982

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

Stellar remnants



(figures not to scale)

Nuclear burning stages

(e.g., 20 solar mass star)

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

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He	**O, C**	**^{18}O, ^{22}Ne s-process**	**0.2**	**10^6**	**$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(a,g)^{16}O$**

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C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}C + {}^{12}C$**

Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond

- For T>10^9 K (about 100 keV), occasionally:

  g **?** $e^+ + e^-$

  and usually

  $e^+ + e^-$ **?** 2g

  but sometimes

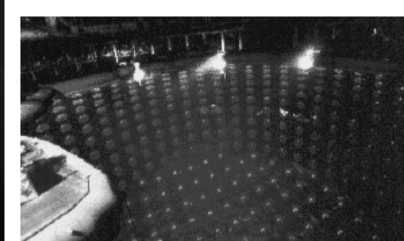
  $e^+ + e^-$ **?** $n_e + \overline{n}_e$

- The neutrinos exit the stars at the speed of light while the $e^{+,}$ e^-, and the g'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 buring 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



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C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}C + {}^{12}C$**
Ne	**O, Mg**	**Al, P**	**1.5**	**3**	**$^{20}Ne(g,a)^{16}O$ $^{20}Ne(a,g)^{24}Mg$**

Nuclear burning stages

(e.g., 20 solar mass star)

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H	**He**	**^{14}N**	**0.02**	**10^7**	**$4\,H \xrightarrow{CNO} {}^{4}He$**
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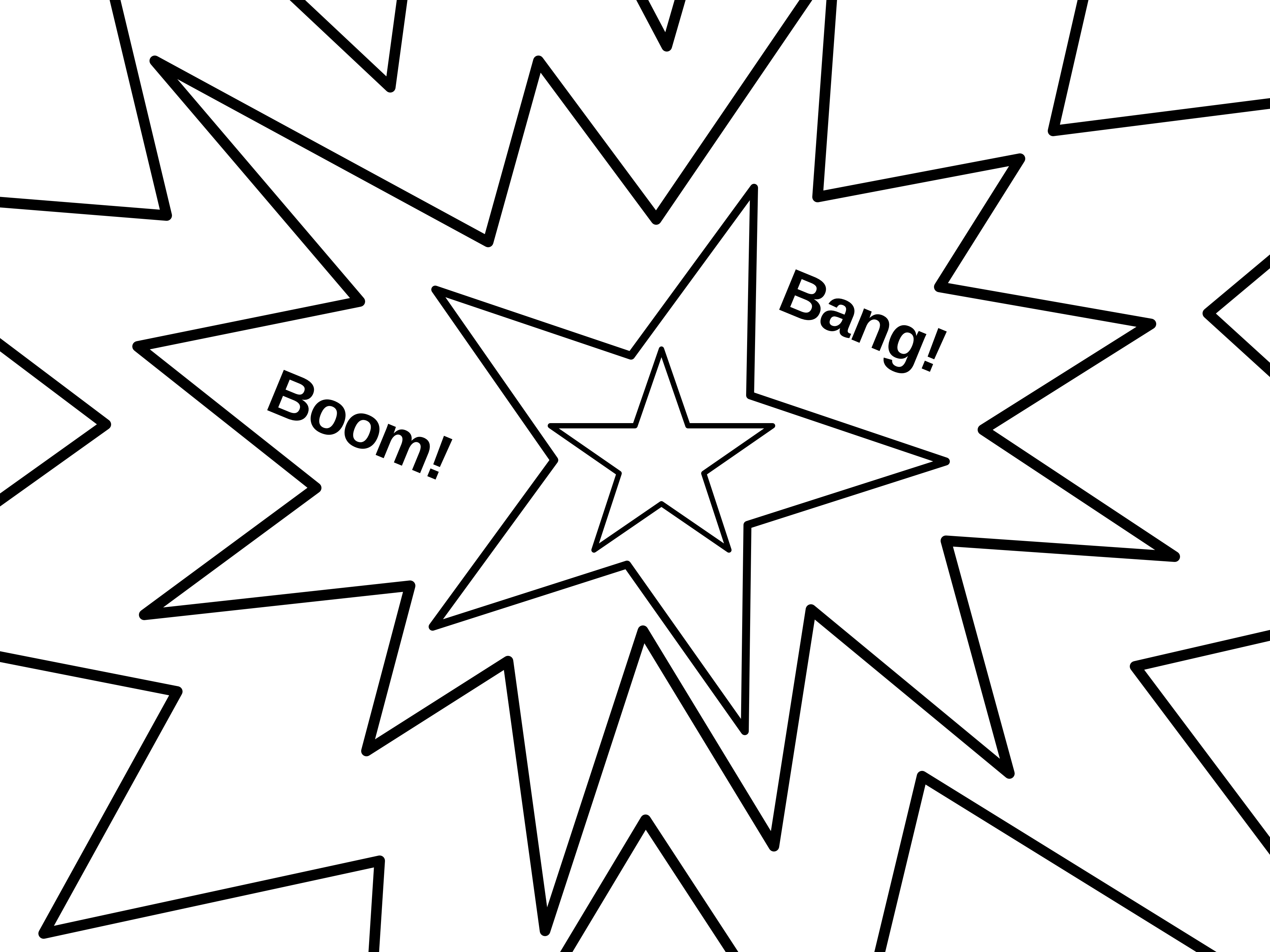
O	**Si, S**	**Cl, Ar, K, Ca**	**2.0**	**0.8**	**$^{16}O + {}^{16}O$**

Nuclear burning stages

(e.g., 20 solar mass star)

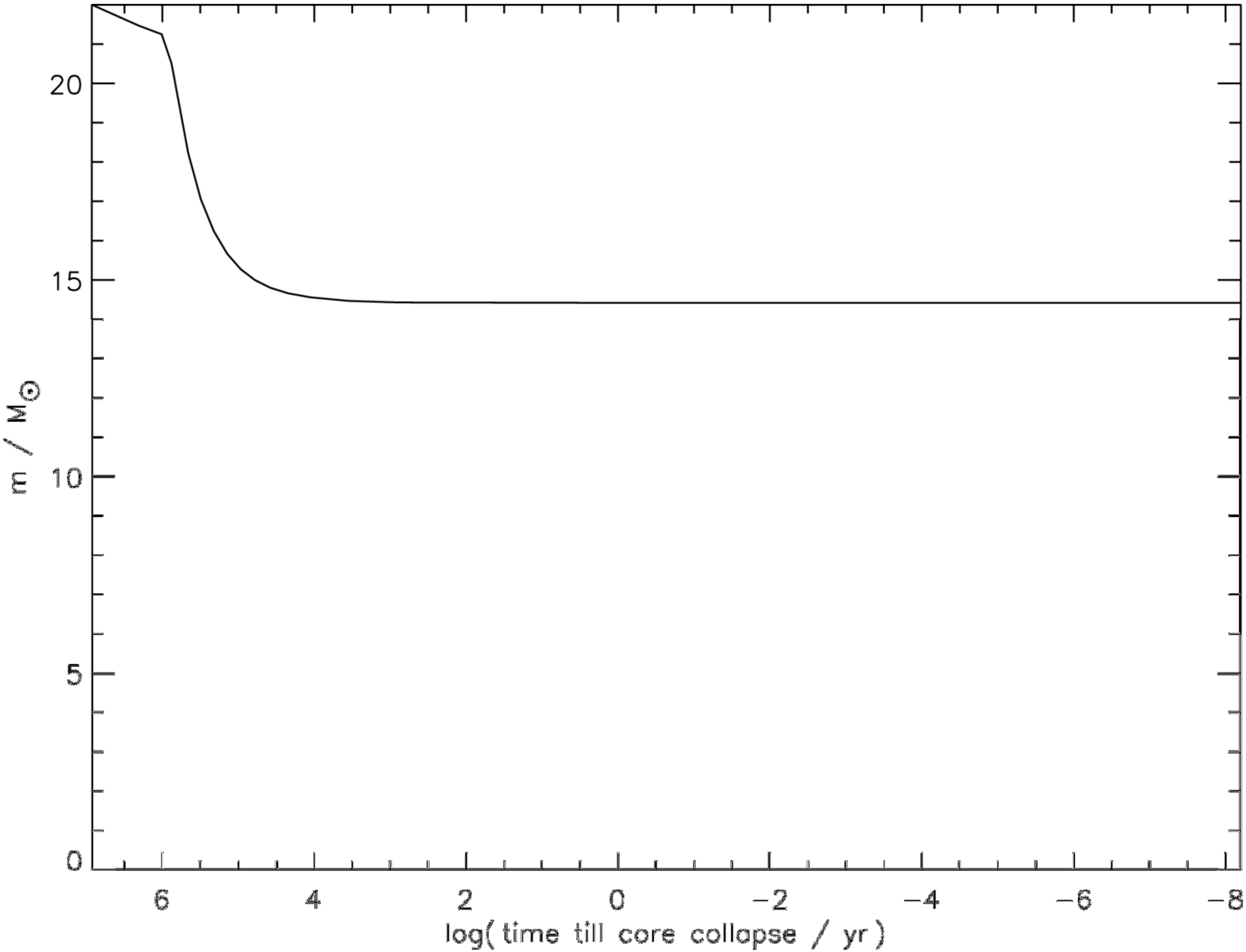
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	**He**	**^{14}N**	**0.02**	**10^7**	**4 H $\xrightarrow{\text{CNO}}$ ^{4}He**
He	**O, C**	**^{18}O, ^{22}Ne s-process**	**0.2**	**10^6**	**3 He^4 → ^{12}C** **^{12}C(a,g)^{16}O**
C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**^{12}C + ^{12}C**
Ne	**O, Mg**	**Al, P**	**1.5**	**3**	**^{20}Ne(g,a)^{16}O** **^{20}Ne(a,g)^{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(g,a)…**


Boom!
Bang!

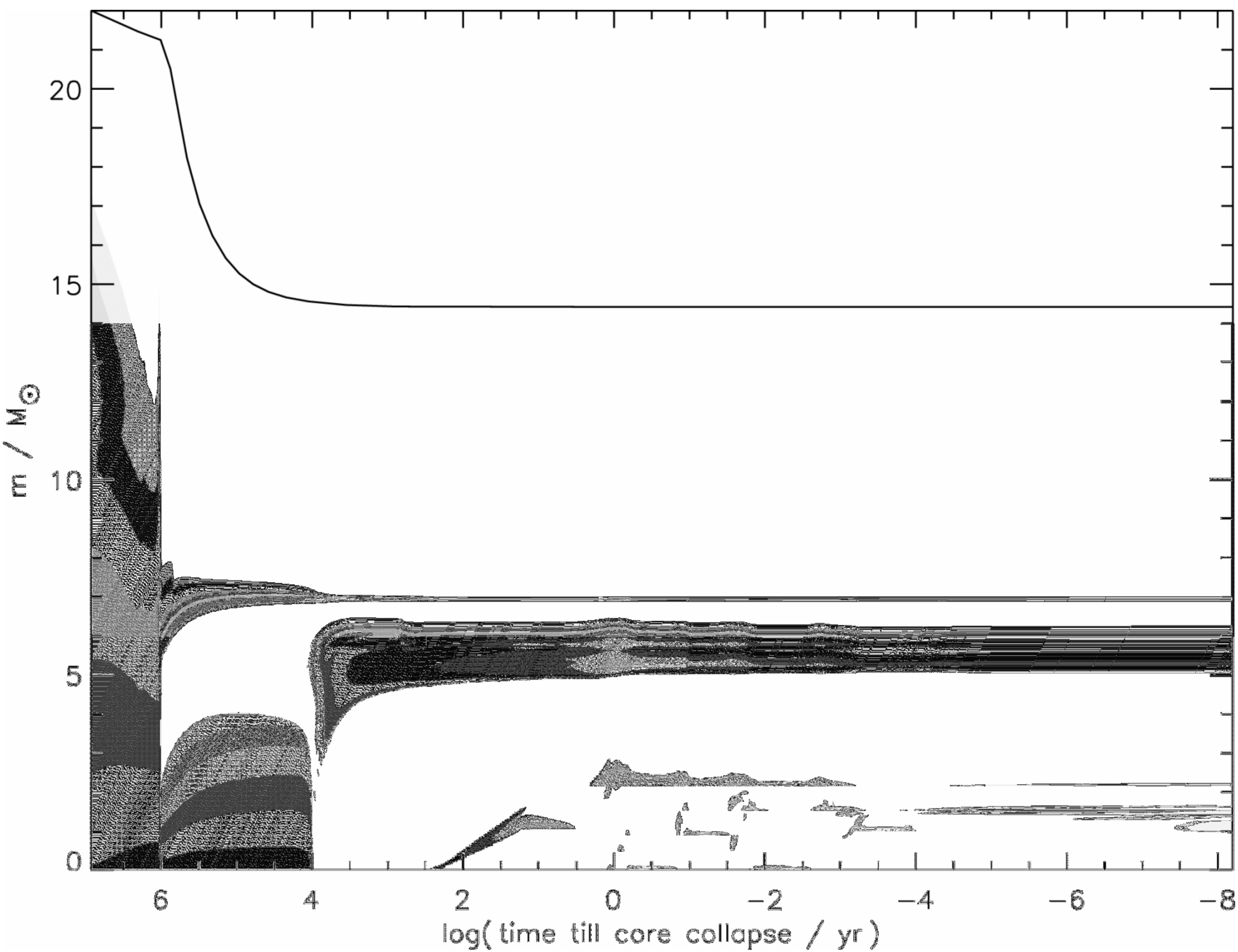
Explosive Nucleosynthesis

in supernovae

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	***r*-process**	-	**>10** **low Y_e**	**1**	**(n,**g), b$^-$
Si, O	**^{56}Ni**	**iron group**	**>4**	**0.1**	(a,g**)**
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**	(g, a**)**
		p-process **^{11}B, ^{19}F, ^{138}La, ^{180}Ta**	**2 - 3**	**5**	(g**,n)**
		n**-process**		**5**	(n**,** n**’),** (n**, e$^-$)**



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



20
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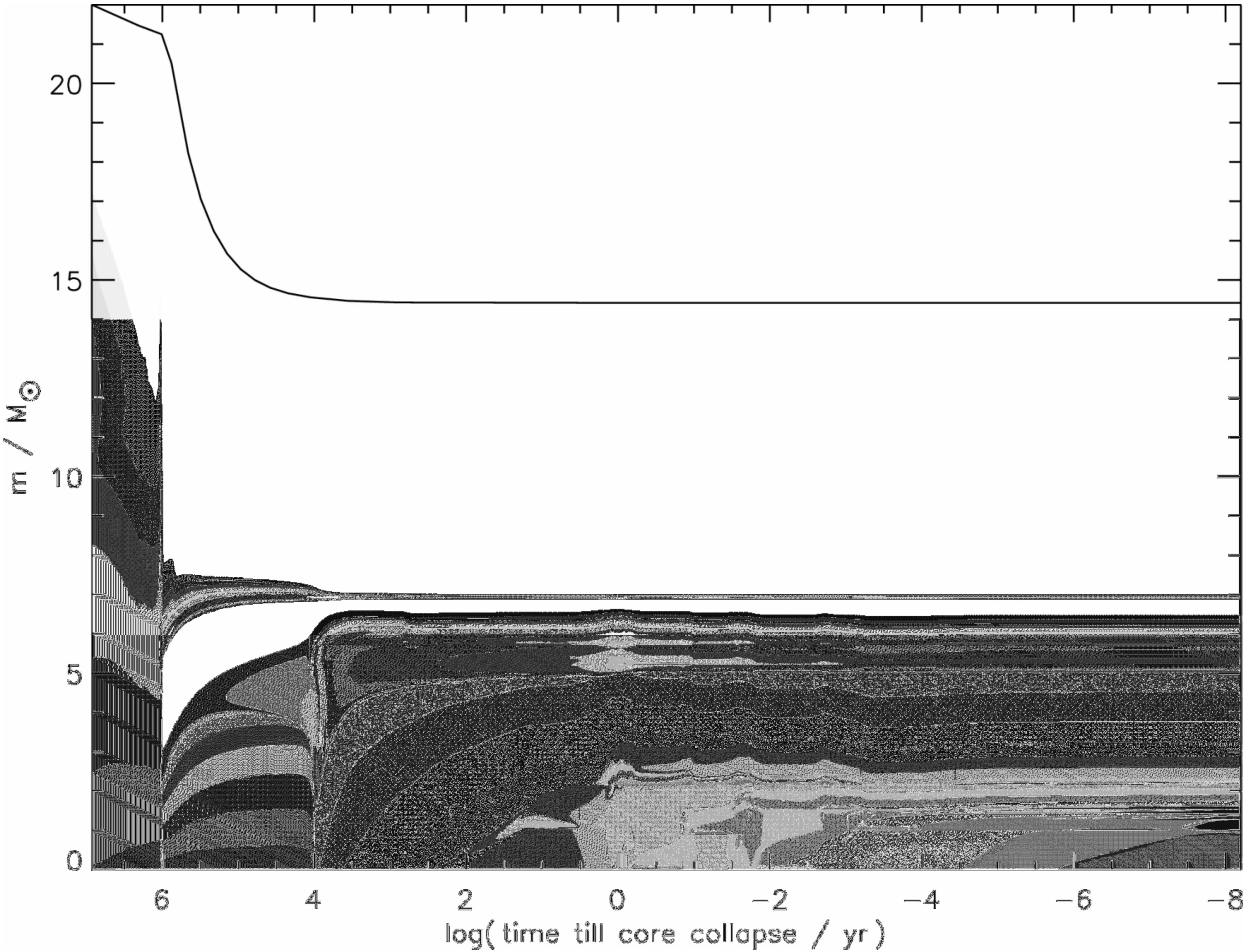
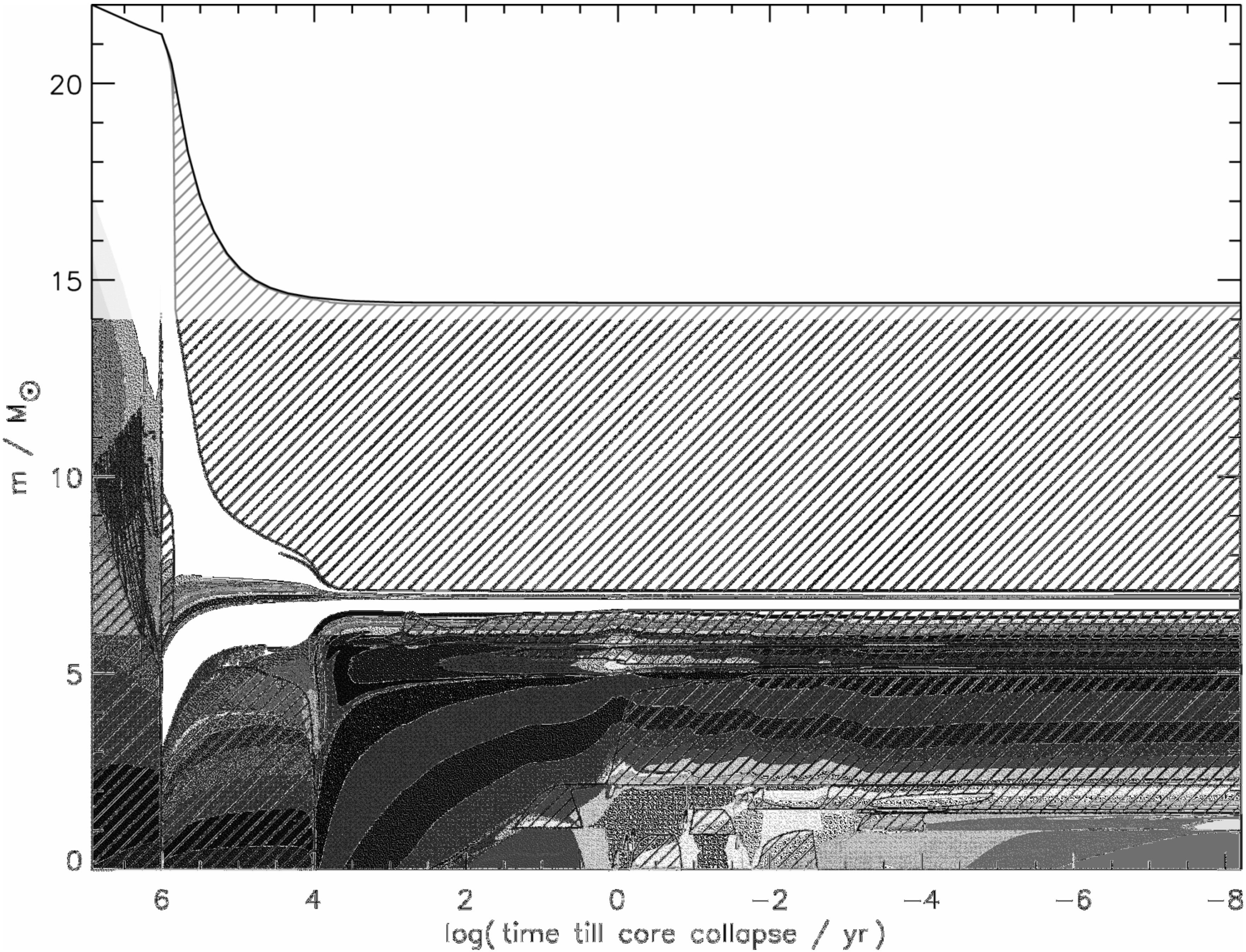
0
m / M☉
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)



20
15
10
5
0
m / M⊙
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)



20
15
10
5
0
m / M⊙
6
4
2
0
−2
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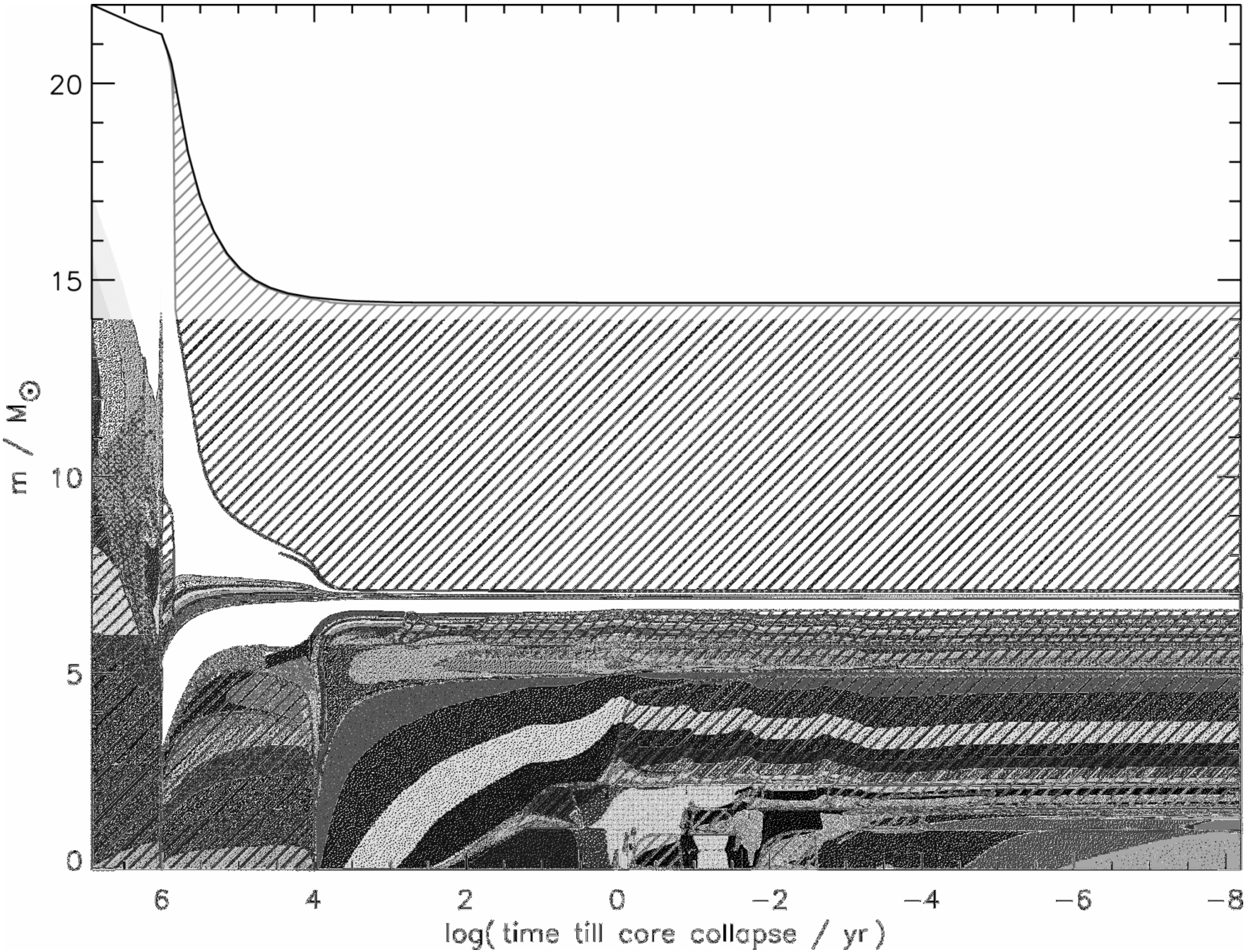
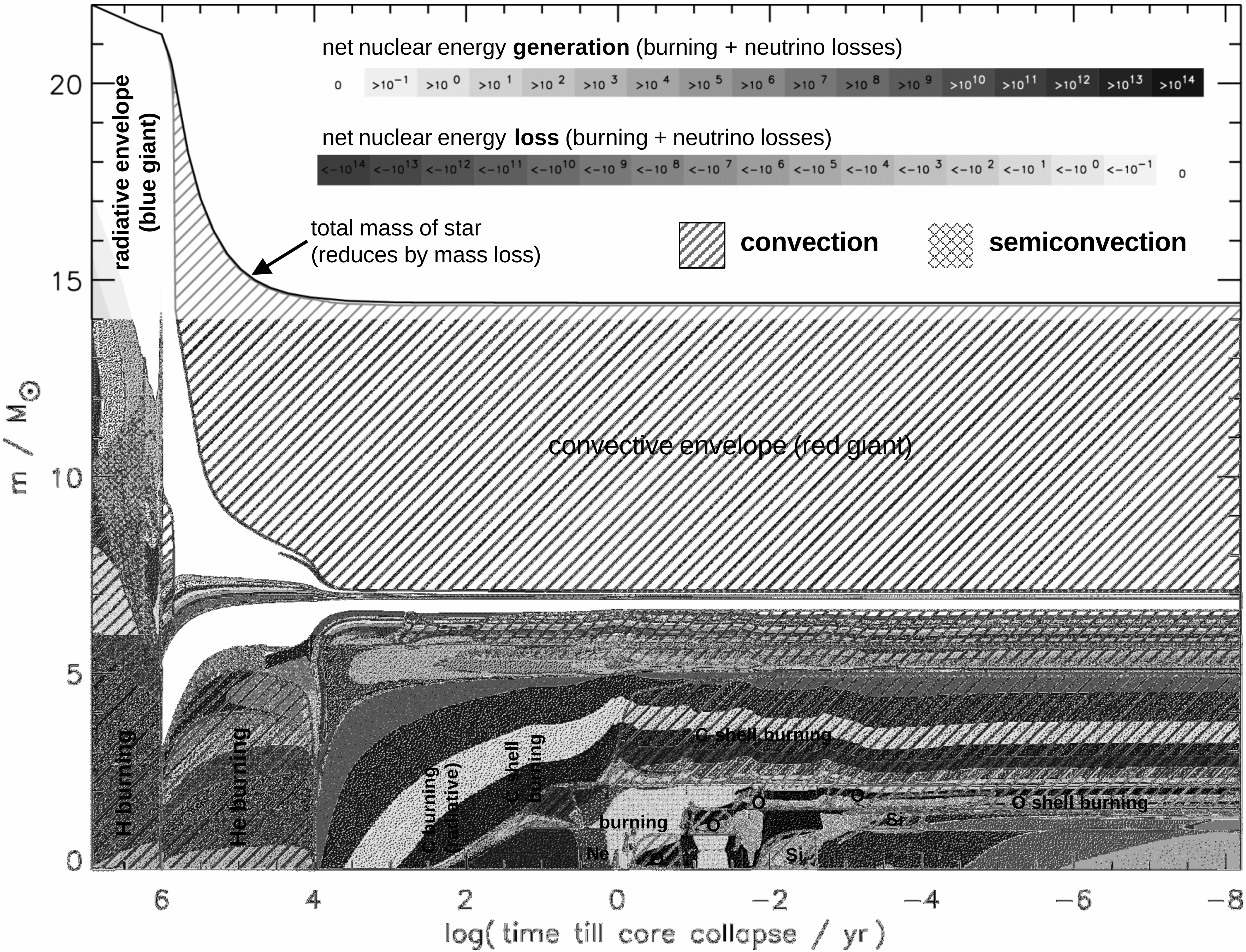
log(time till core collapse / yr)



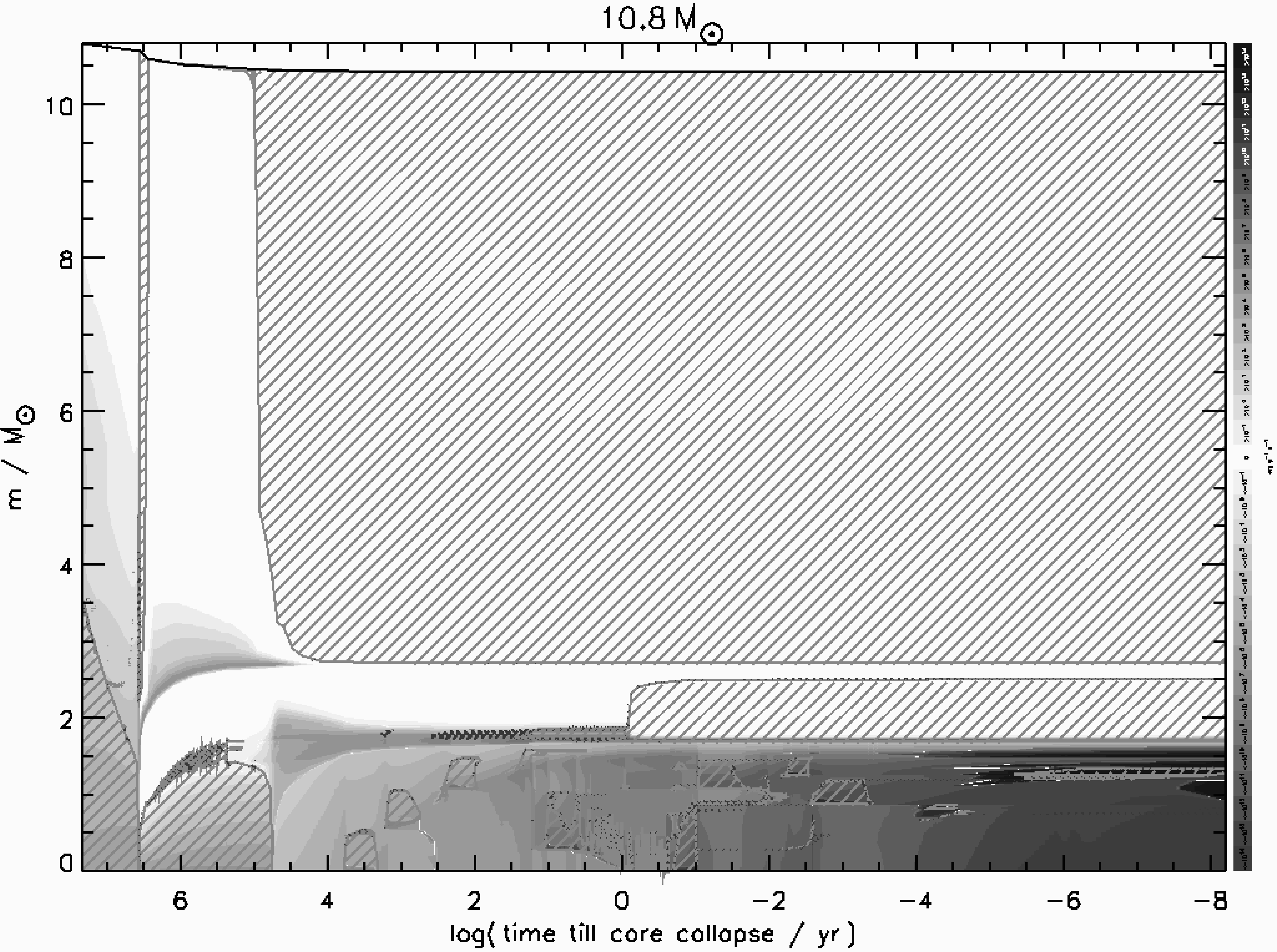
20
15
10
5
0
m / M$_{\odot}$
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)



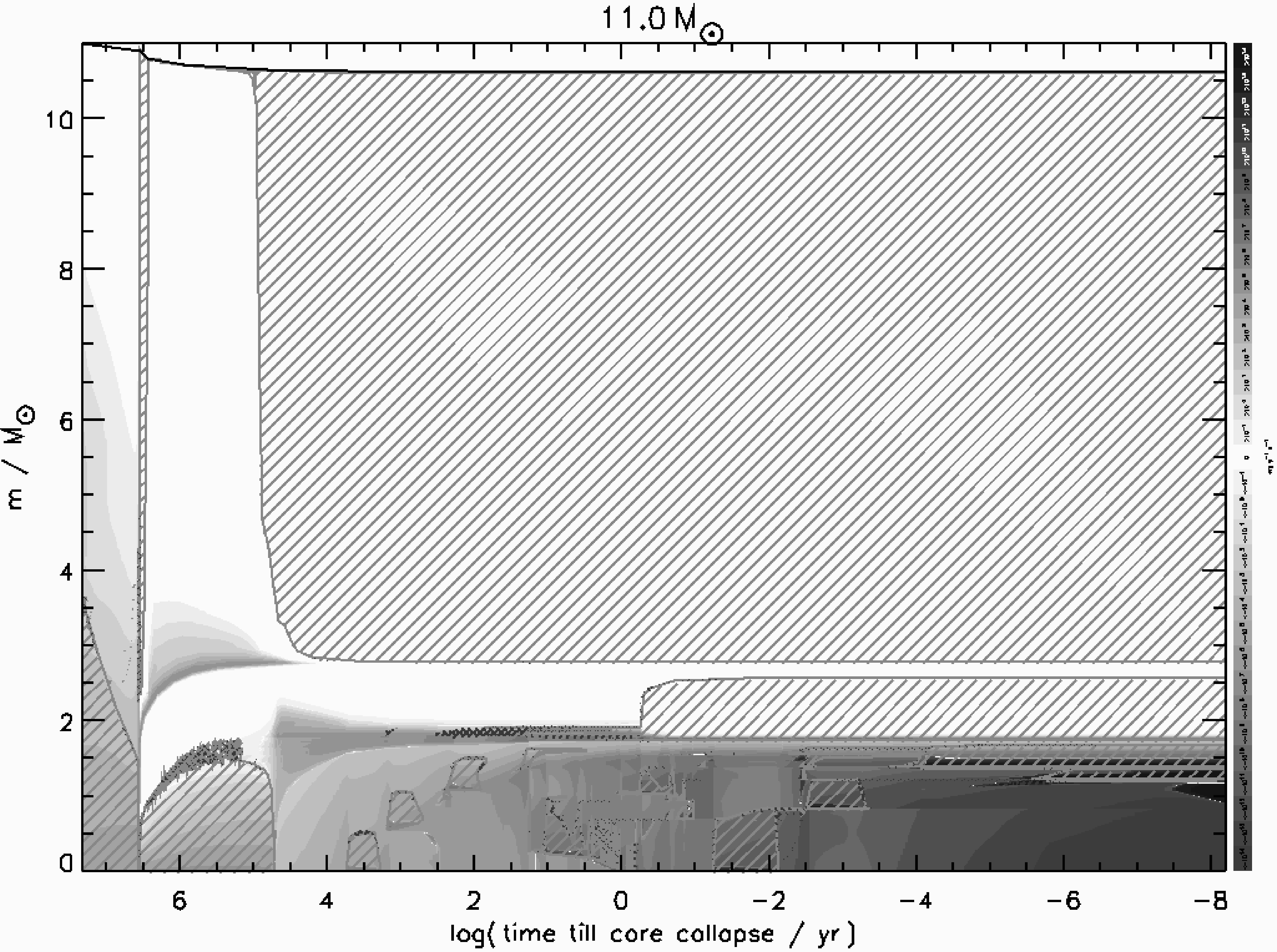
net nuclear energy **generation** (burning + neutrino losses)
0 >10^-1 >10^0 >10^1 >10^2 >10^3 >10^4 >10^5 >10^6 >10^7 >10^8 >10^9 >10^10 >10^11 >10^12 >10^13 >10^14
net nuclear energy **loss** (burning + neutrino losses)
<-10^14 <-10^13 <-10^12 <-10^11 <-10^10 <-10^9 <-10^8 <-10^7 <-10^6 <-10^5 <-10^4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

Change of the stellar structure as a function of initial mass

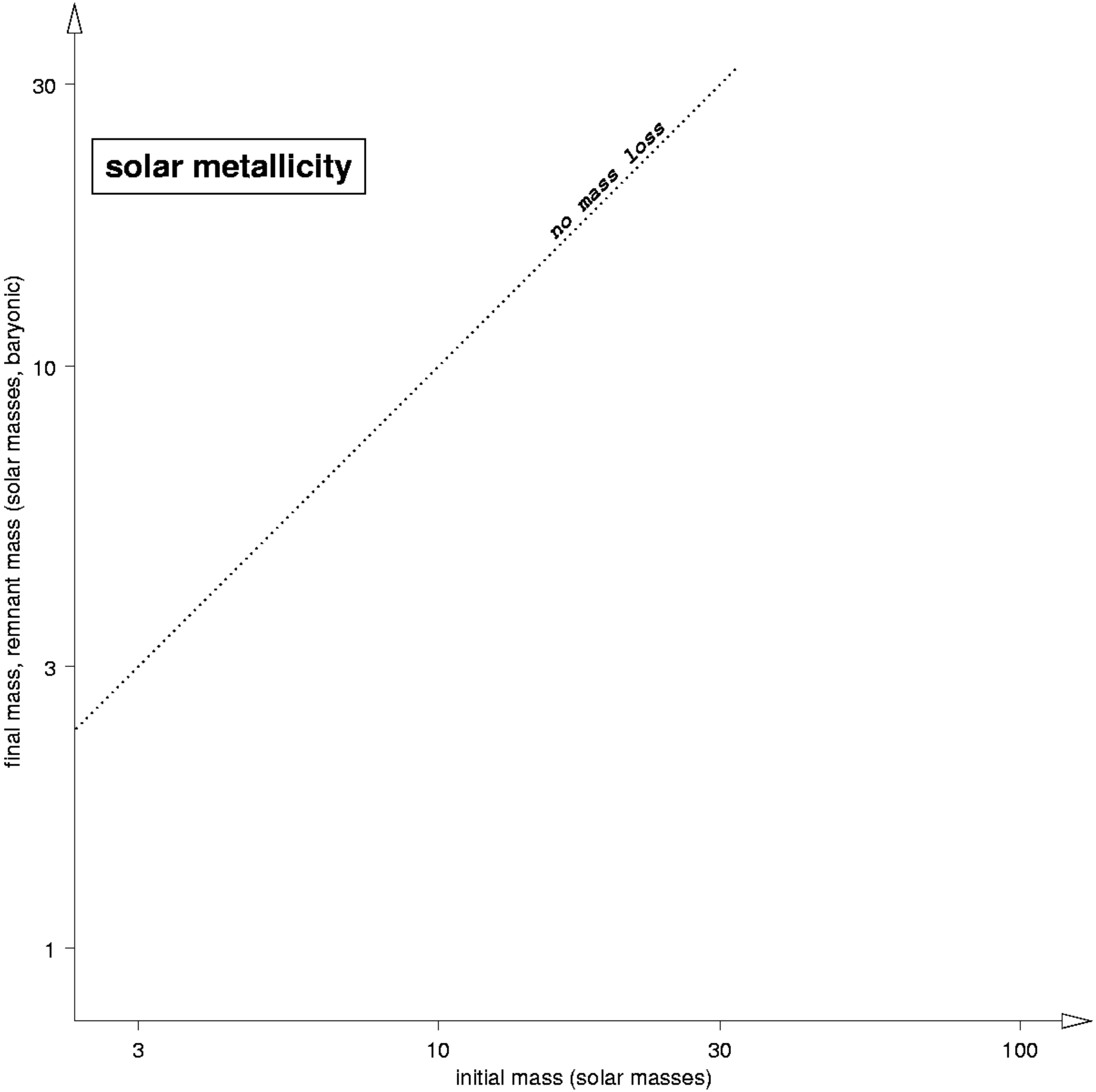
- Mass loss becomes more important
- The “cores” becomes bigger,
  the density gradients more shallow
- The evolution time-scale of all burning phases accelerates
- Central carbon burning becomes radiative, central entropy and Y_e increase

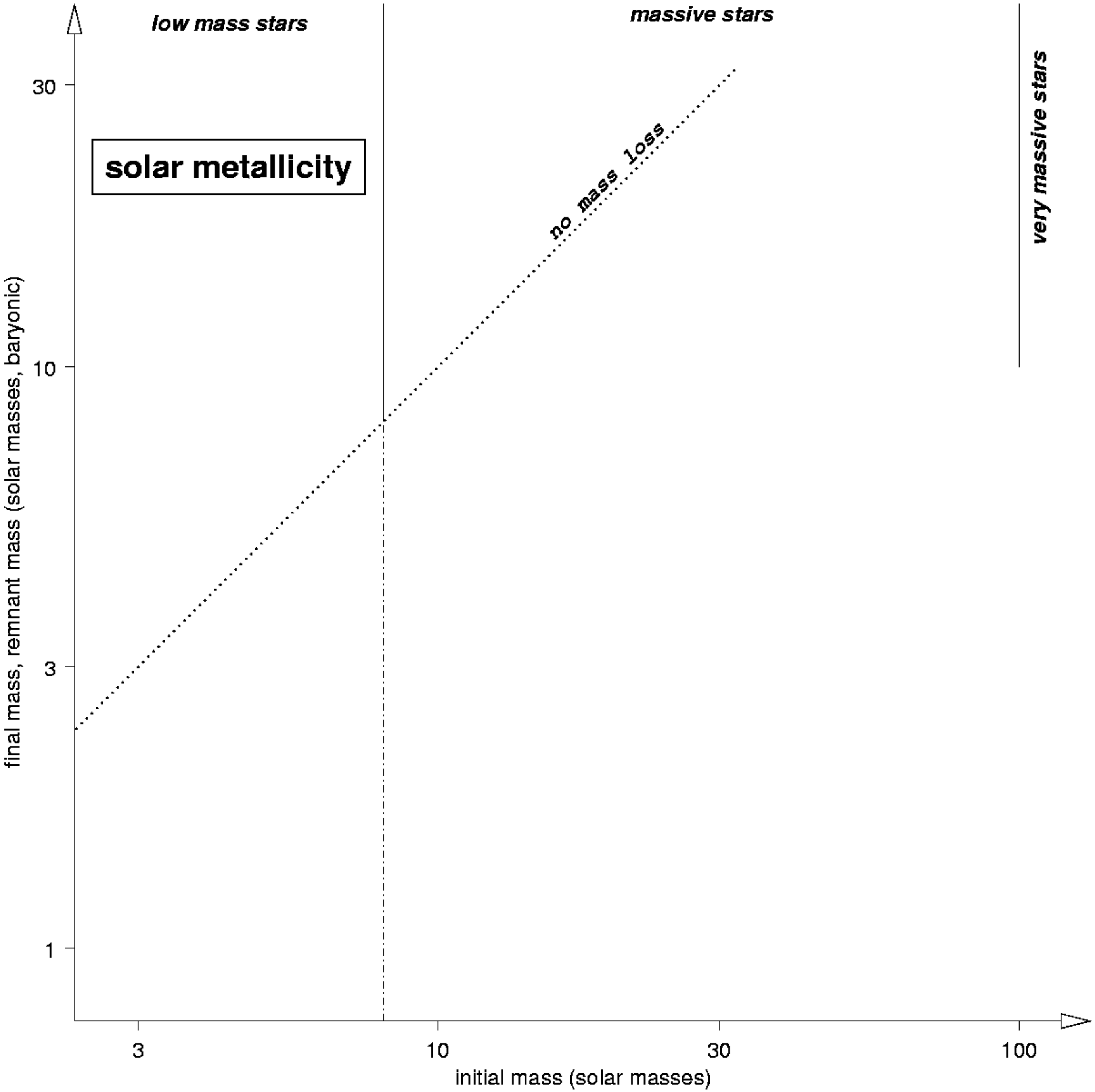


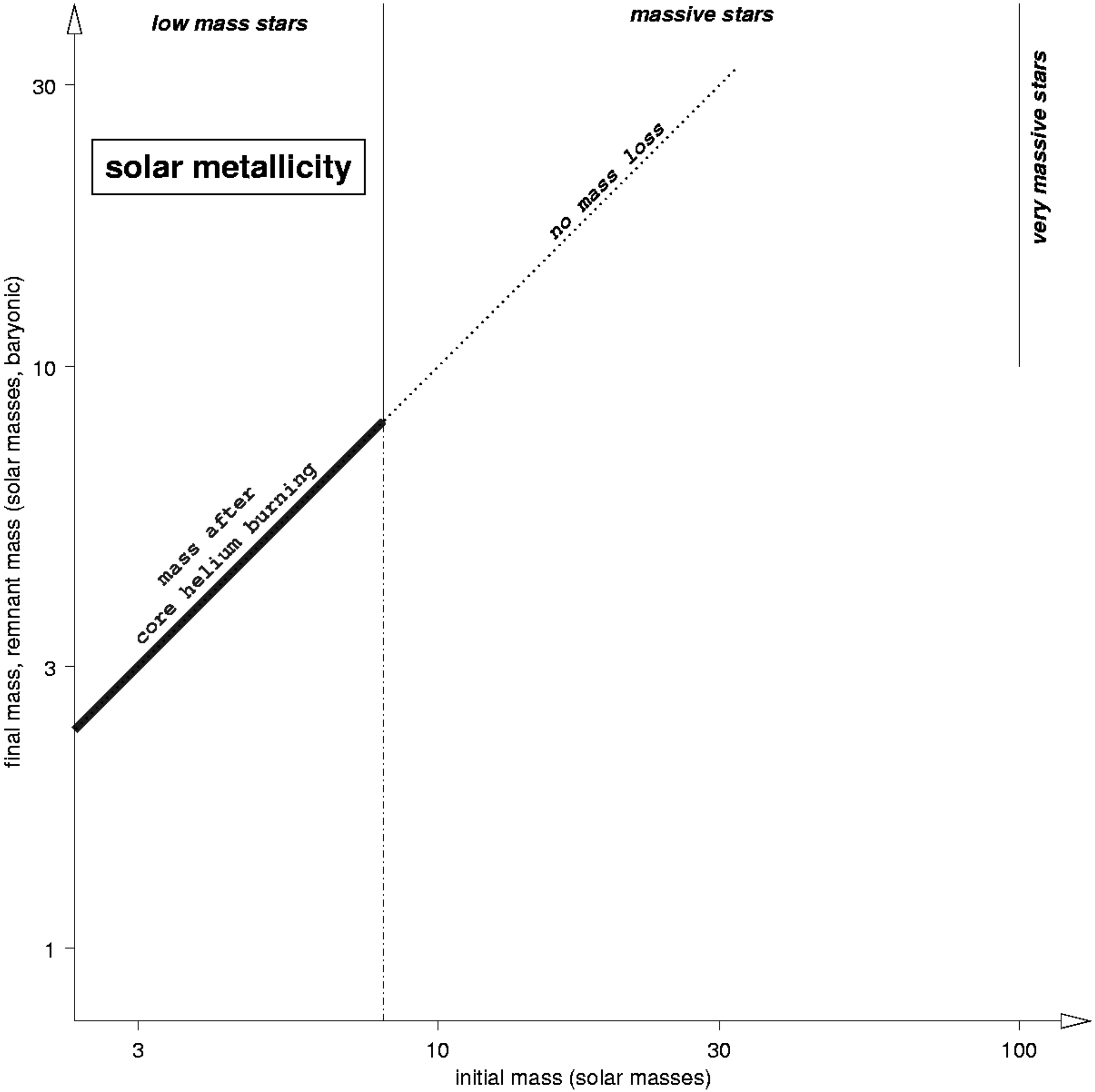
10.8 M⊙
m / M⊙
log(time till core collapse / yr)



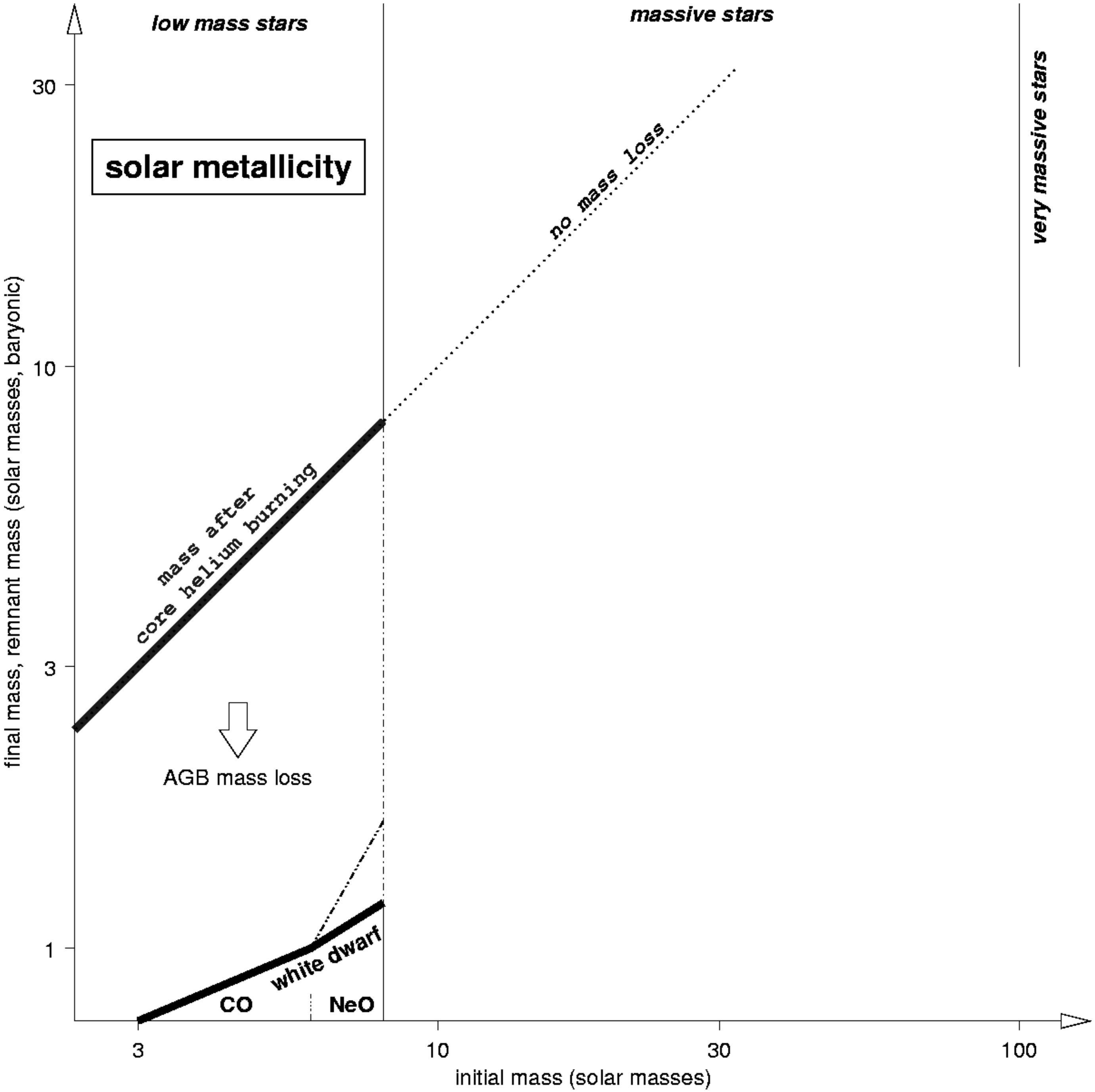
11.0 M$_\odot$
m / M$_\odot$
log(time till core collapse / yr)

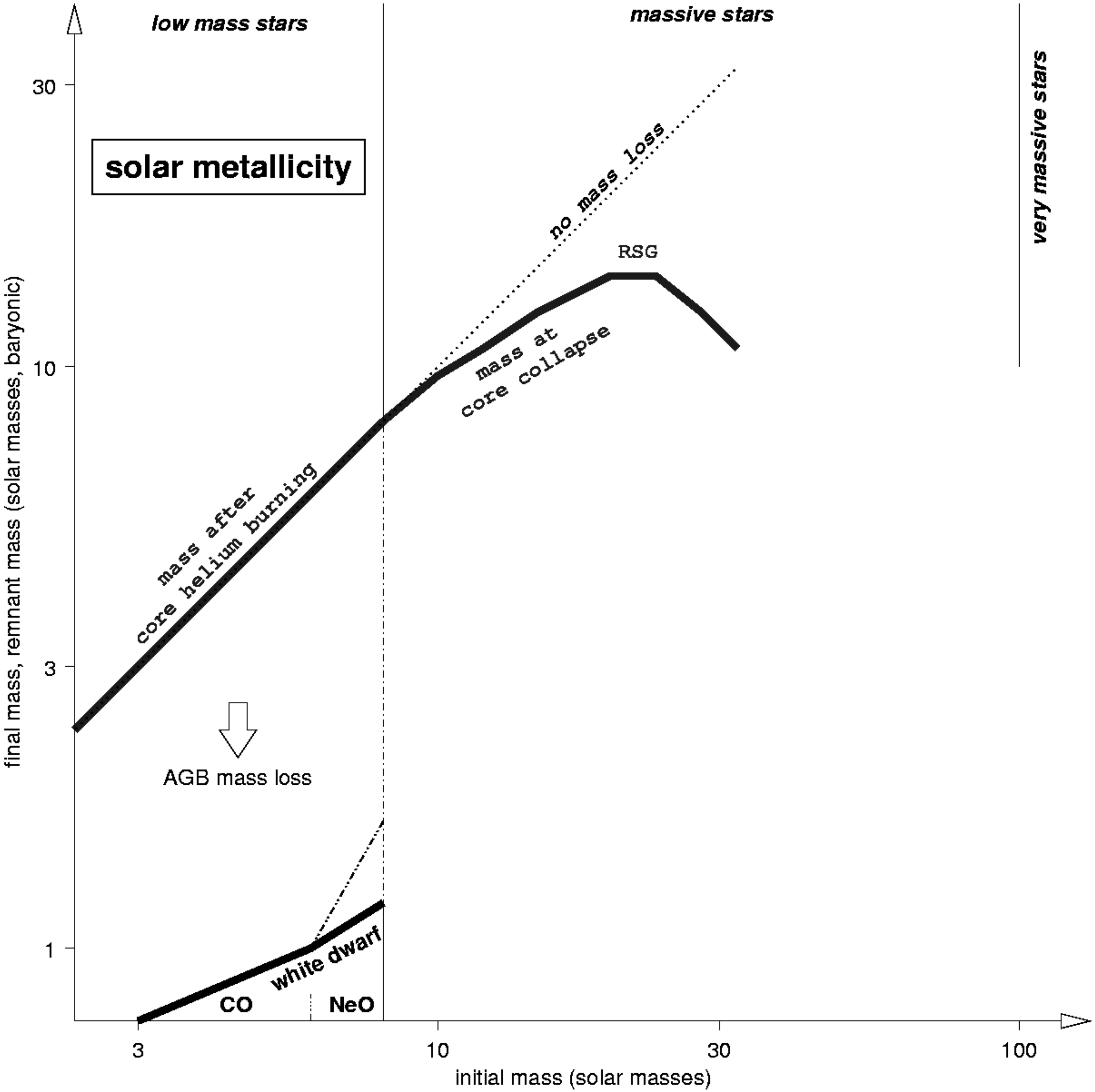

solar metallicity
no mass loss
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
30
10
3
1
3
10
30
100

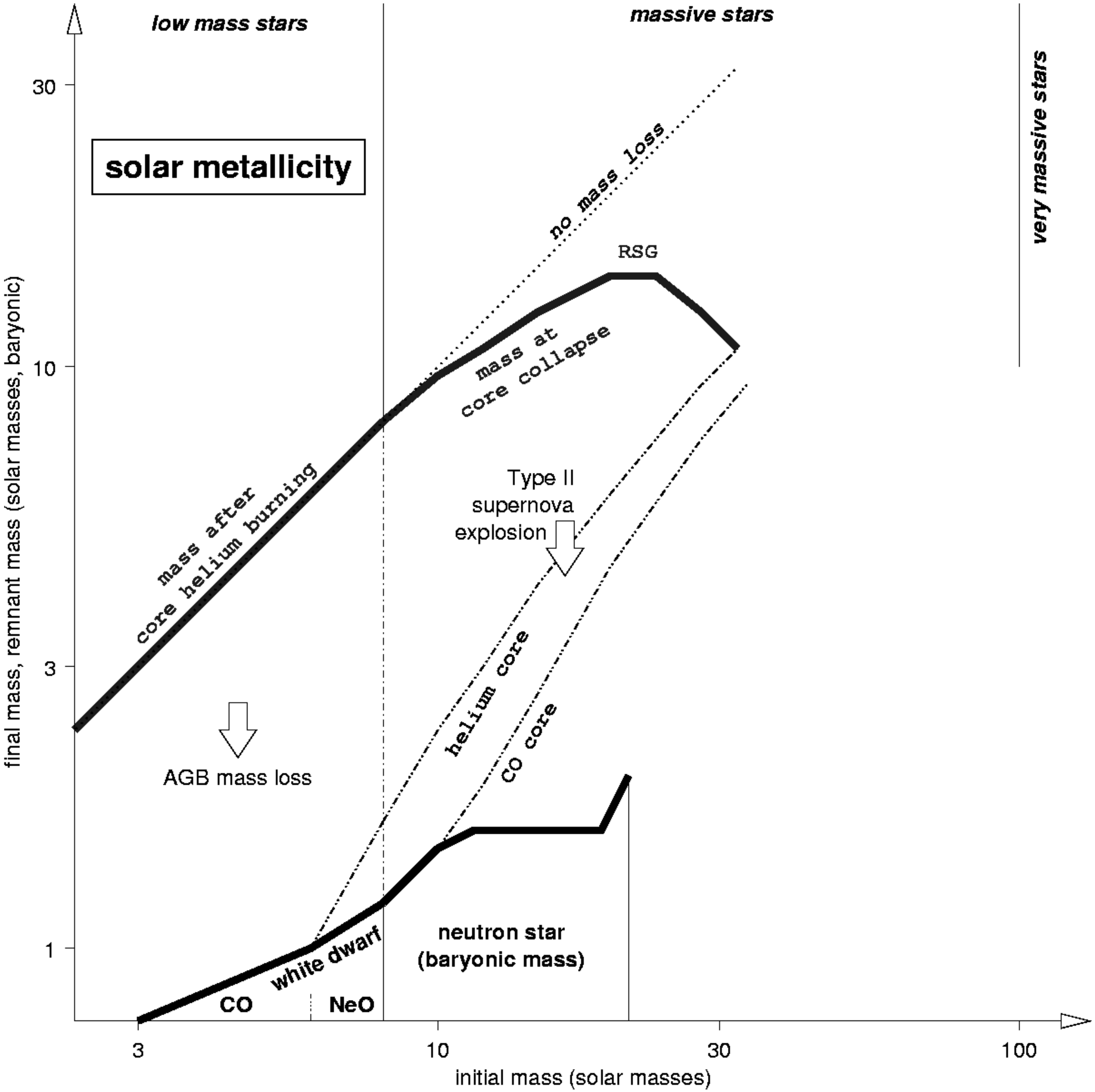

low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)

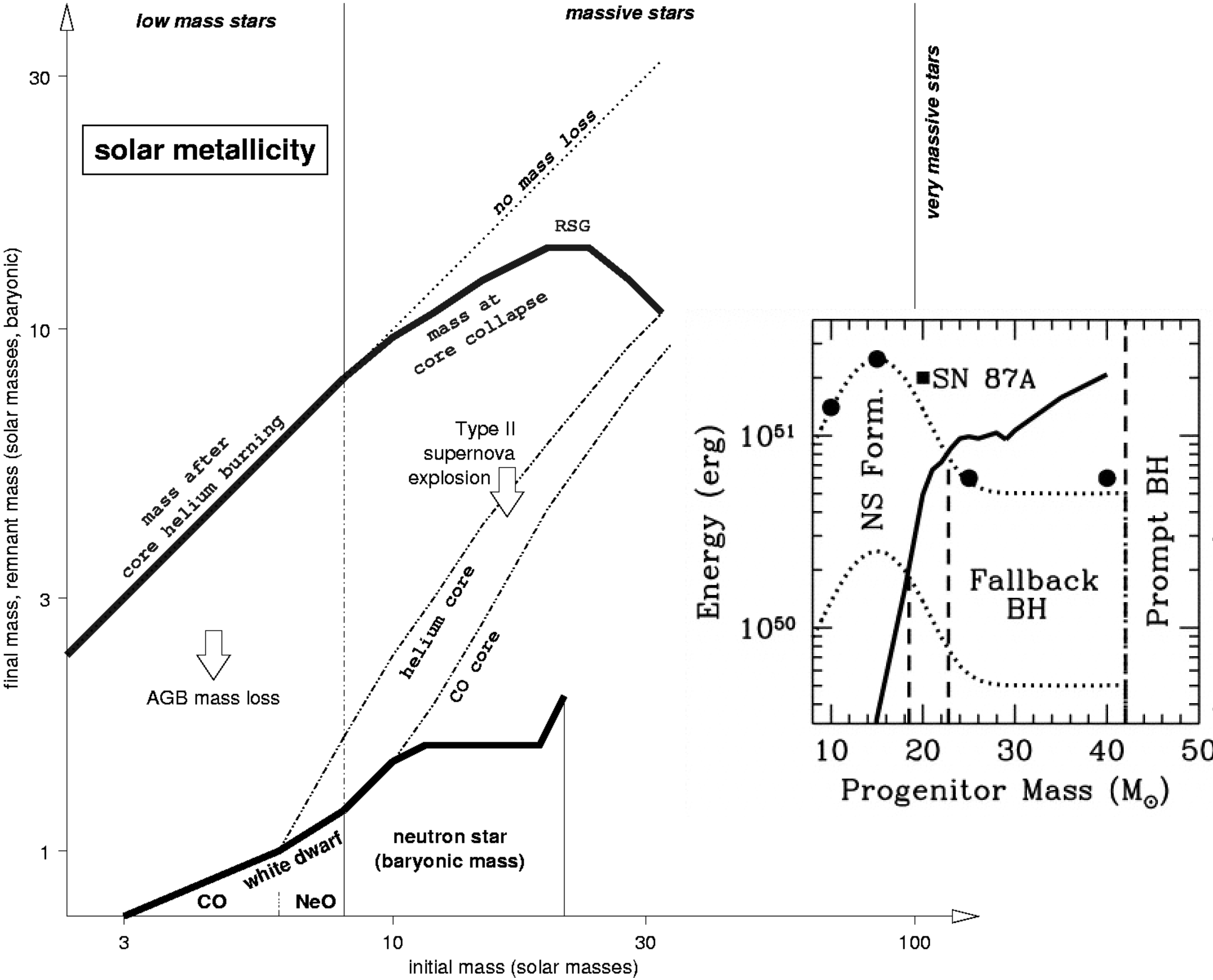


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
mass after
core helium burning
30
10
3
1
3
10
30
100
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)


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

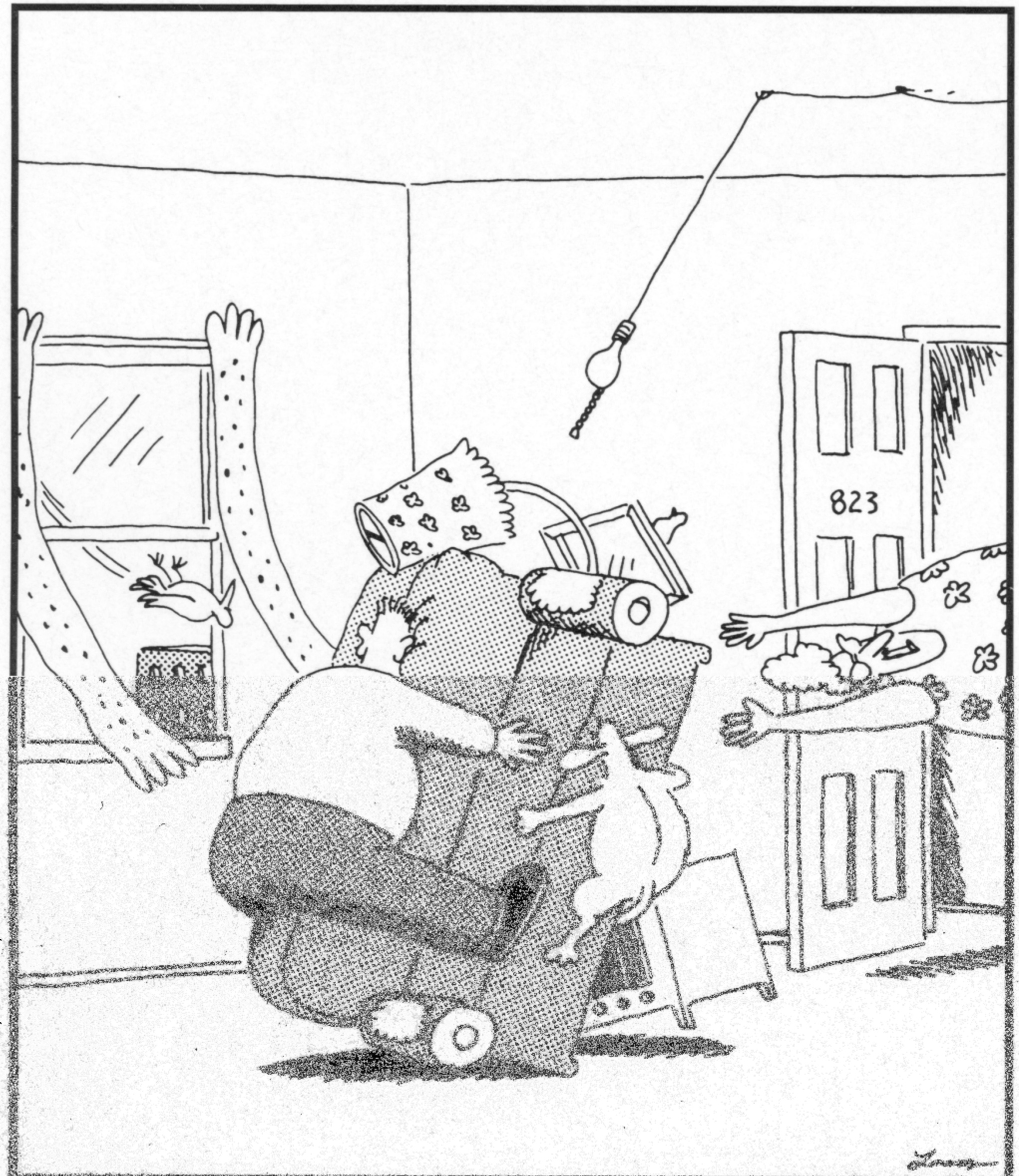


(Fryer & Kalogera 2001;
see also: Burrows 1999)

Fallback

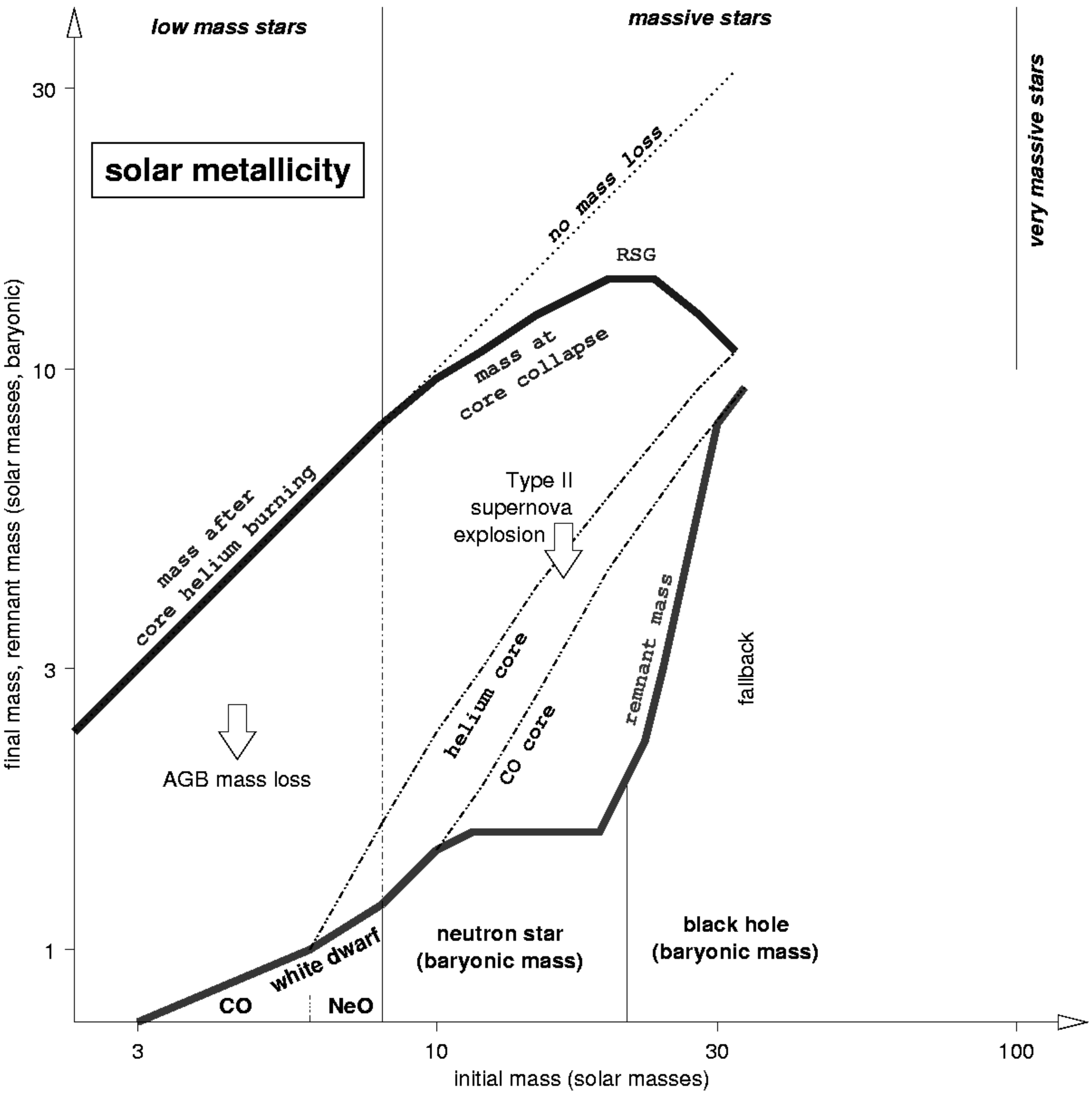
in supernovae

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



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

The Far Side, Dec20, 2002


low mass stars
massive stars
very massive stars
solar metallicity
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RSG
mass at
core collapse
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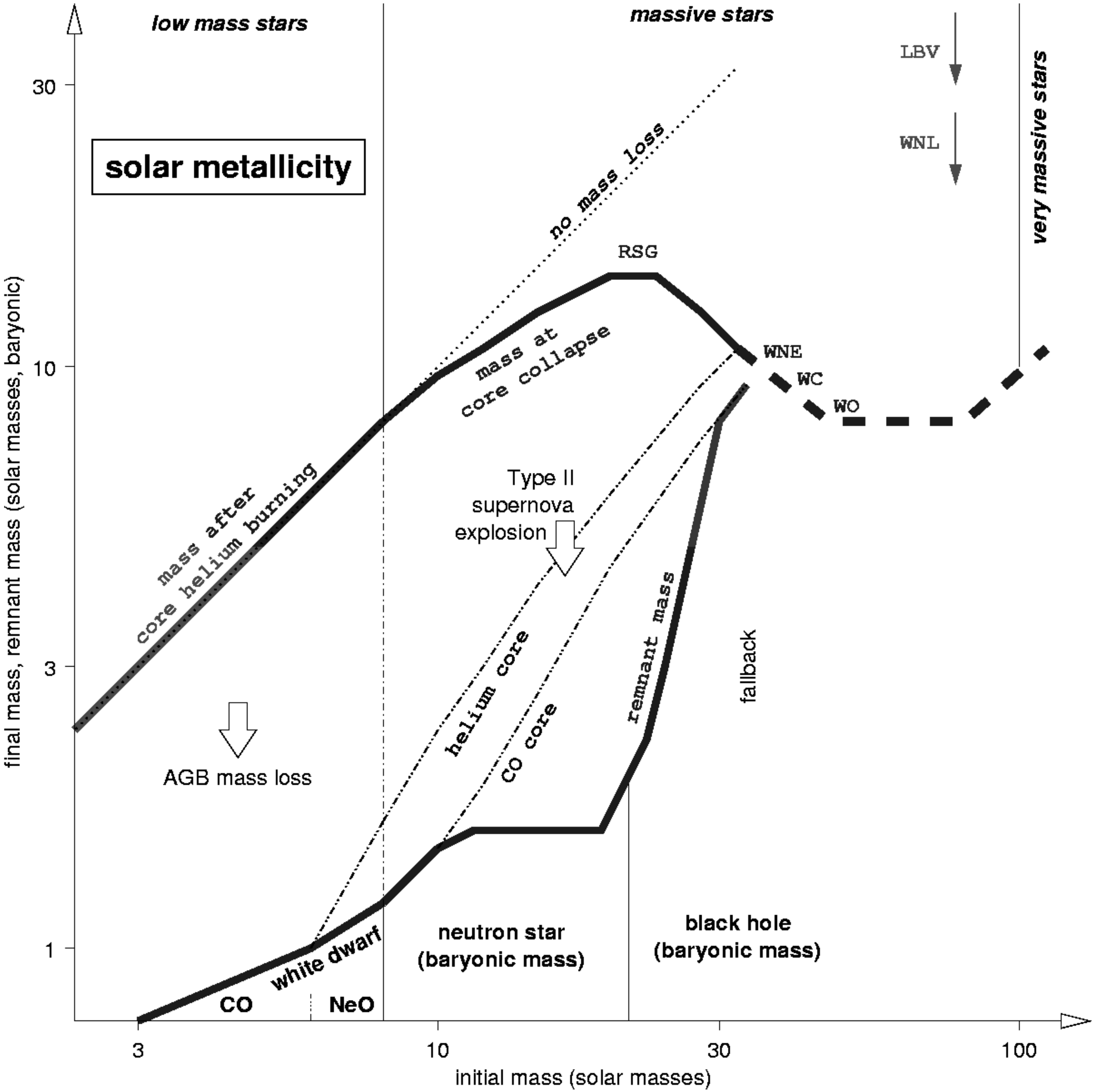
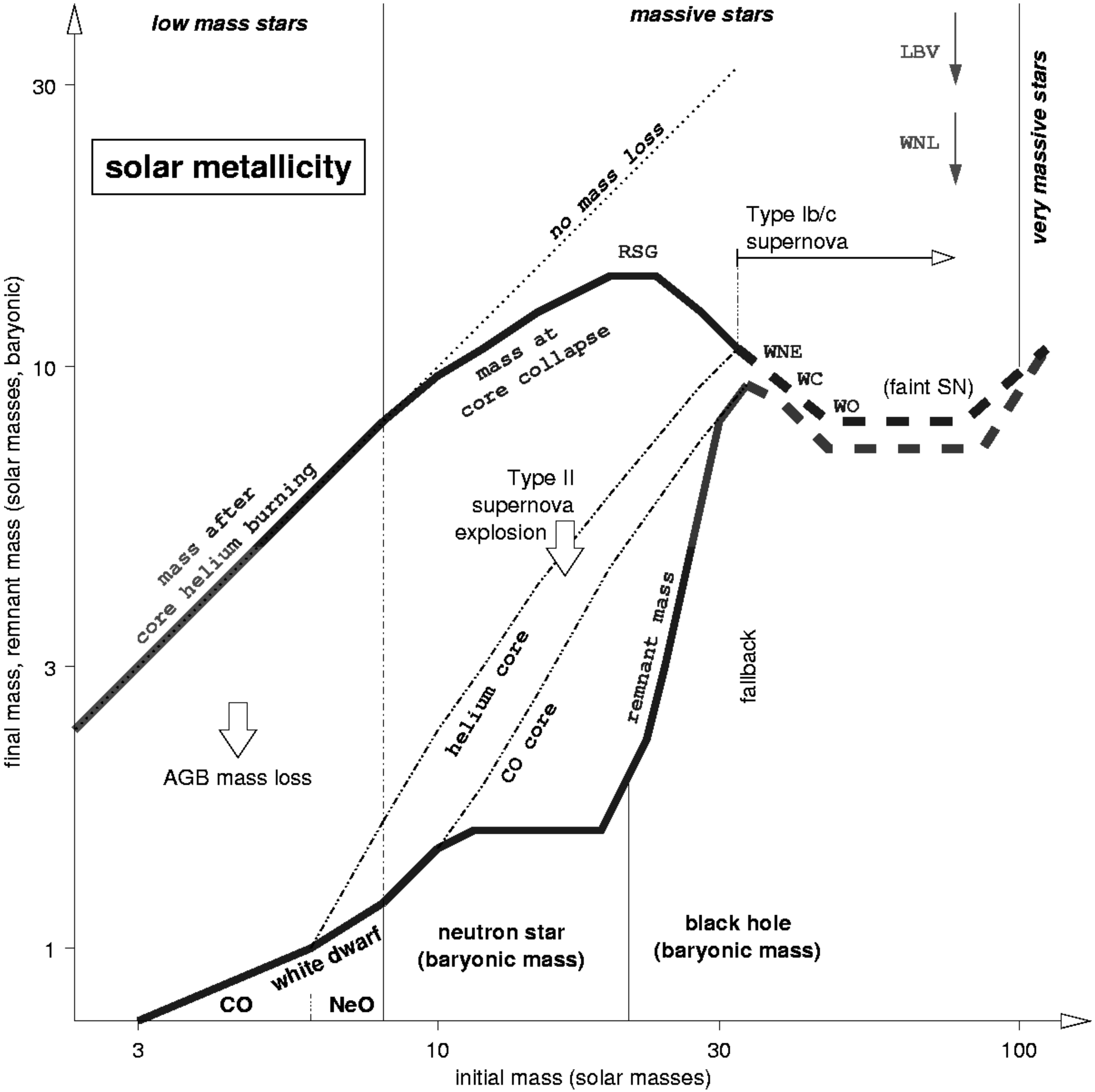
core helium burning
Type II
supernova
explosion
AGB mass loss
helium core
CO core
remnant mass
fallback
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic mass)
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
30
10
3
1
3
10
30
100

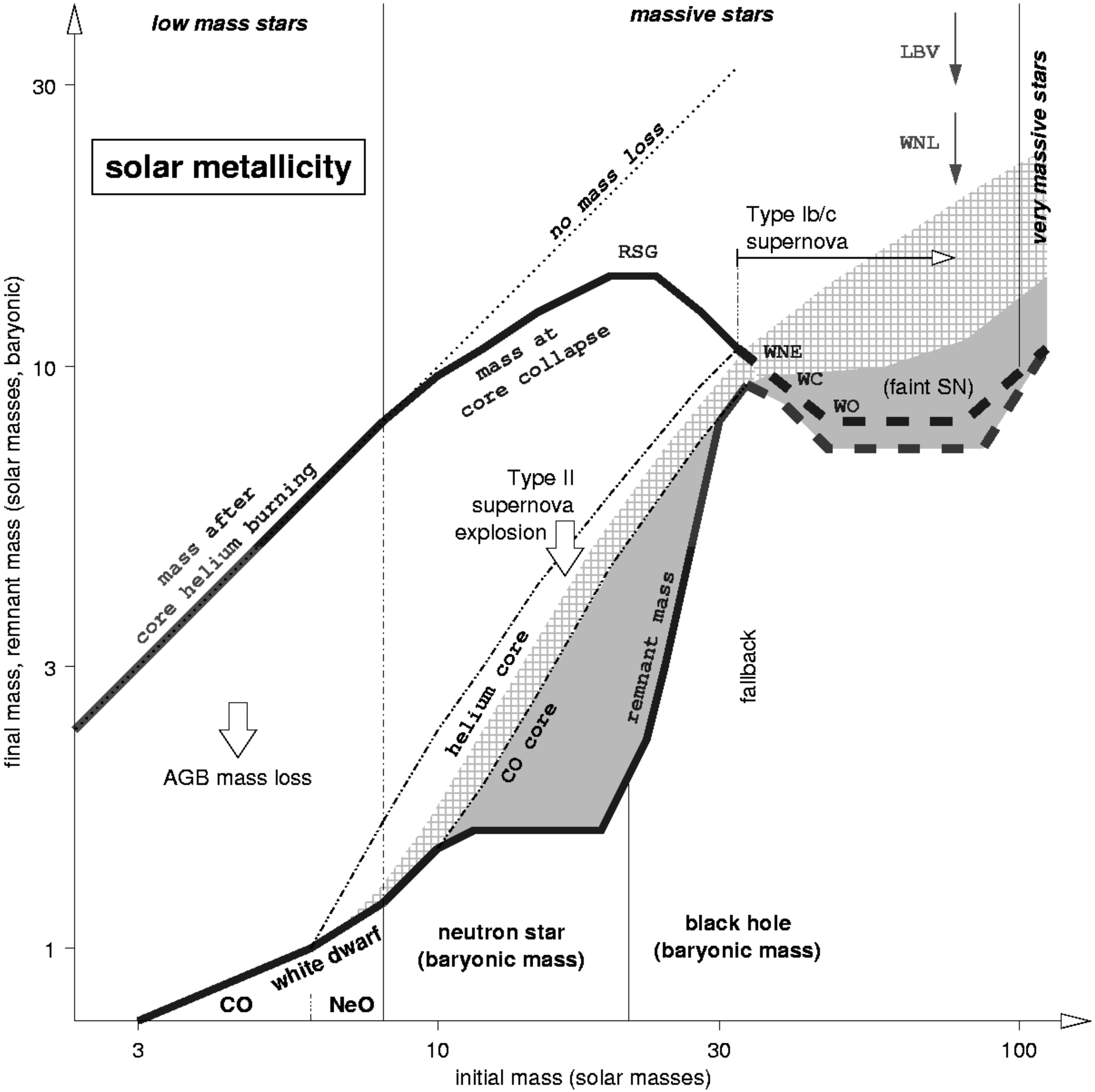


low mass stars
massive stars
very massive stars
solar metallicity
LBV
WNL
no mass loss
RSG
WNE
WC
WO
mass at
core collapse
mass after
core helium burning
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
AGB mass loss
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic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



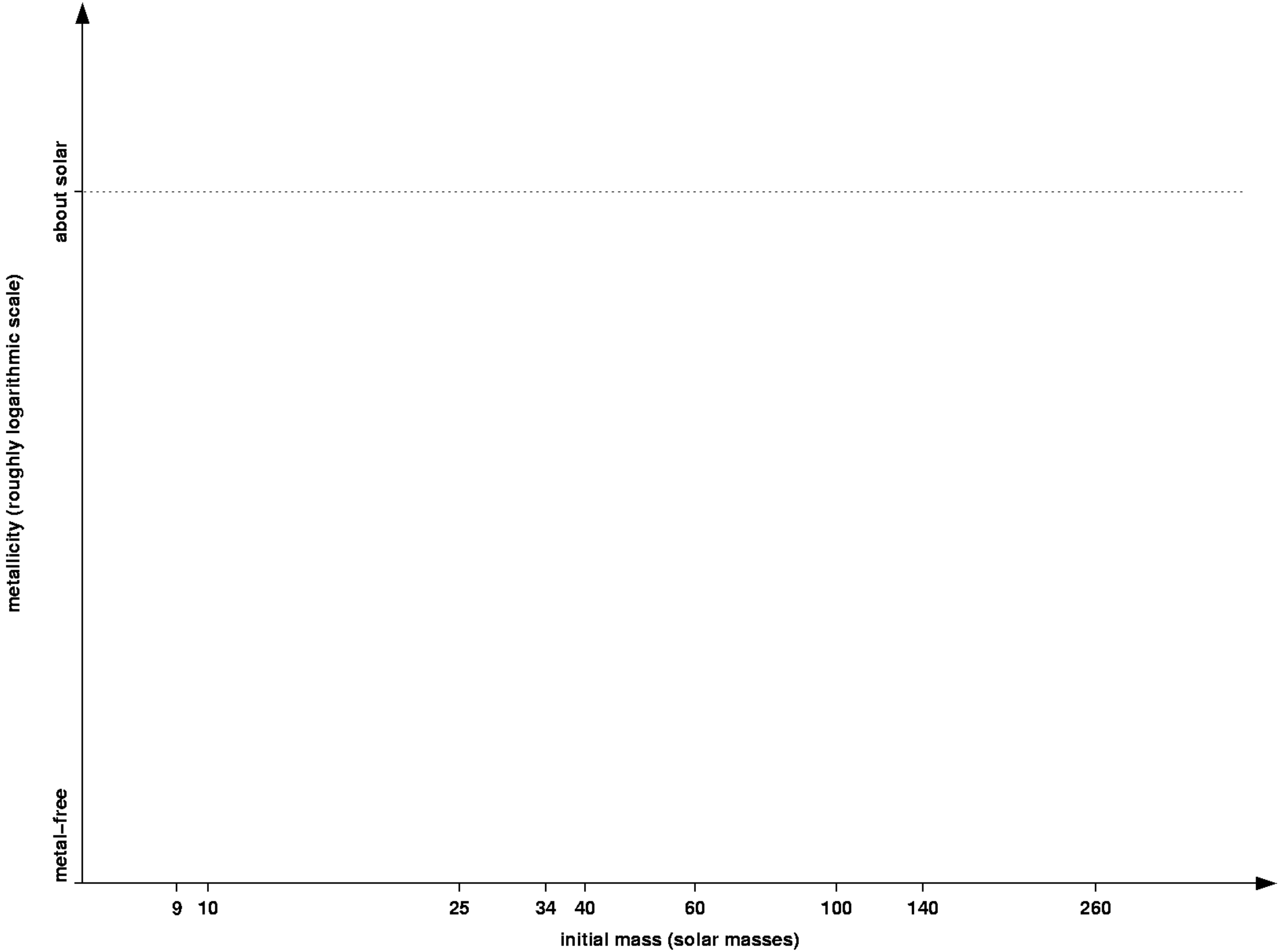
low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
LBV
WNL
Type Ib/c
supernova
WNE
WC
WO
(faint SN)
mass at
core collapse
mass after
core helium burning
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
AGB mass loss
white dwarf
CO
NeO
neutron star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

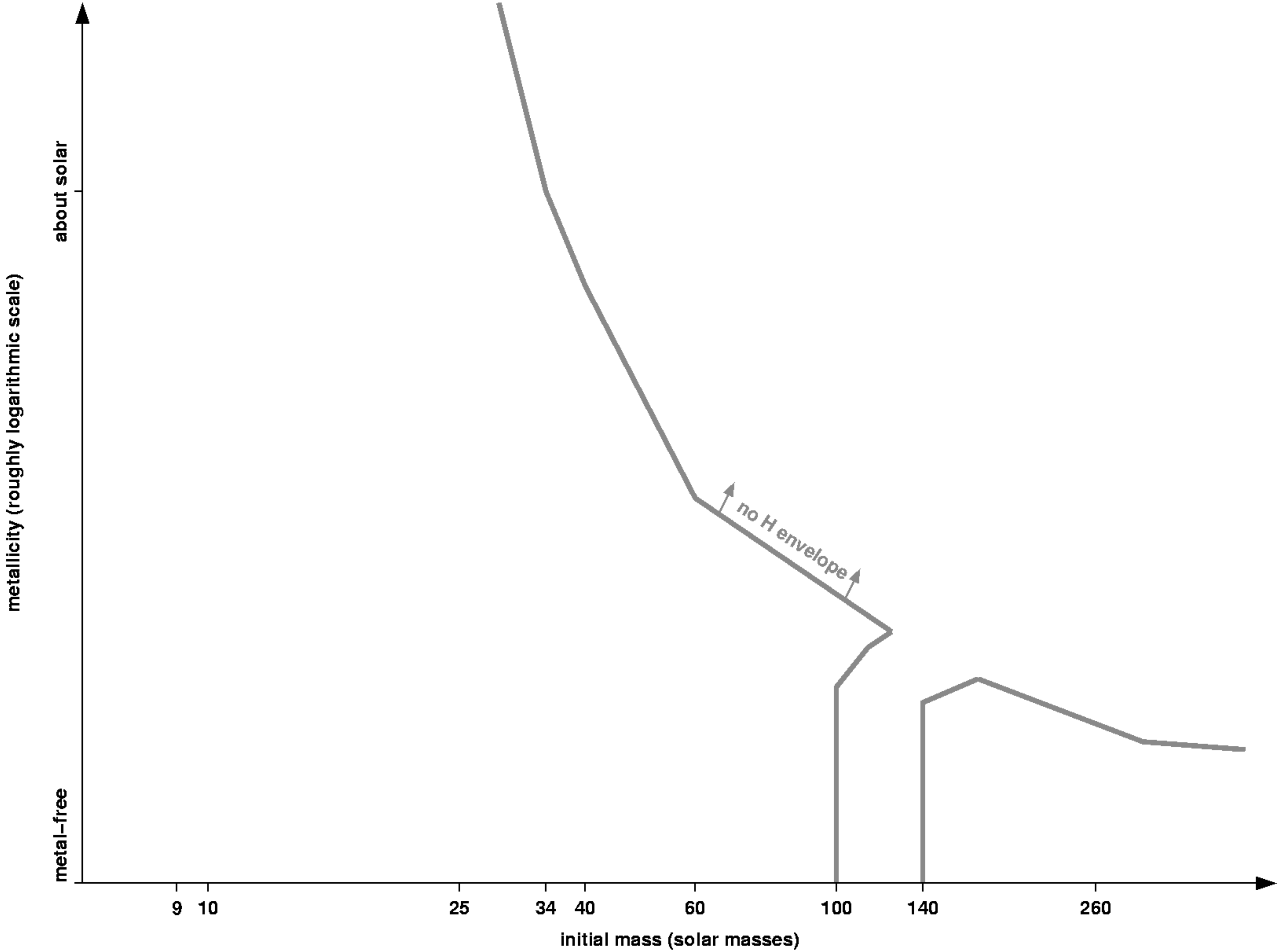
Ejected “metals”



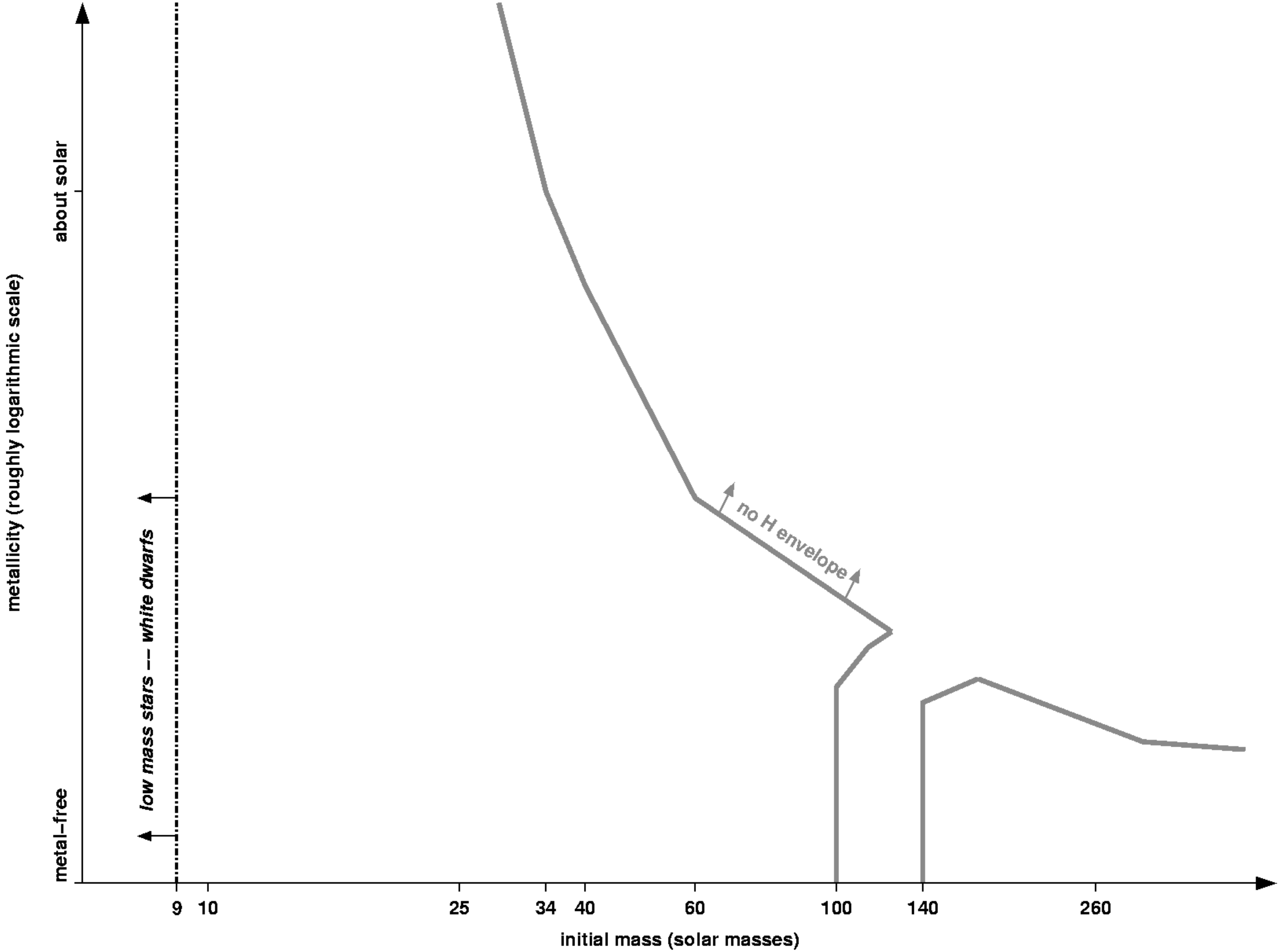
Massive Star Fates as Function of Mass and Metallicity

(single stars)

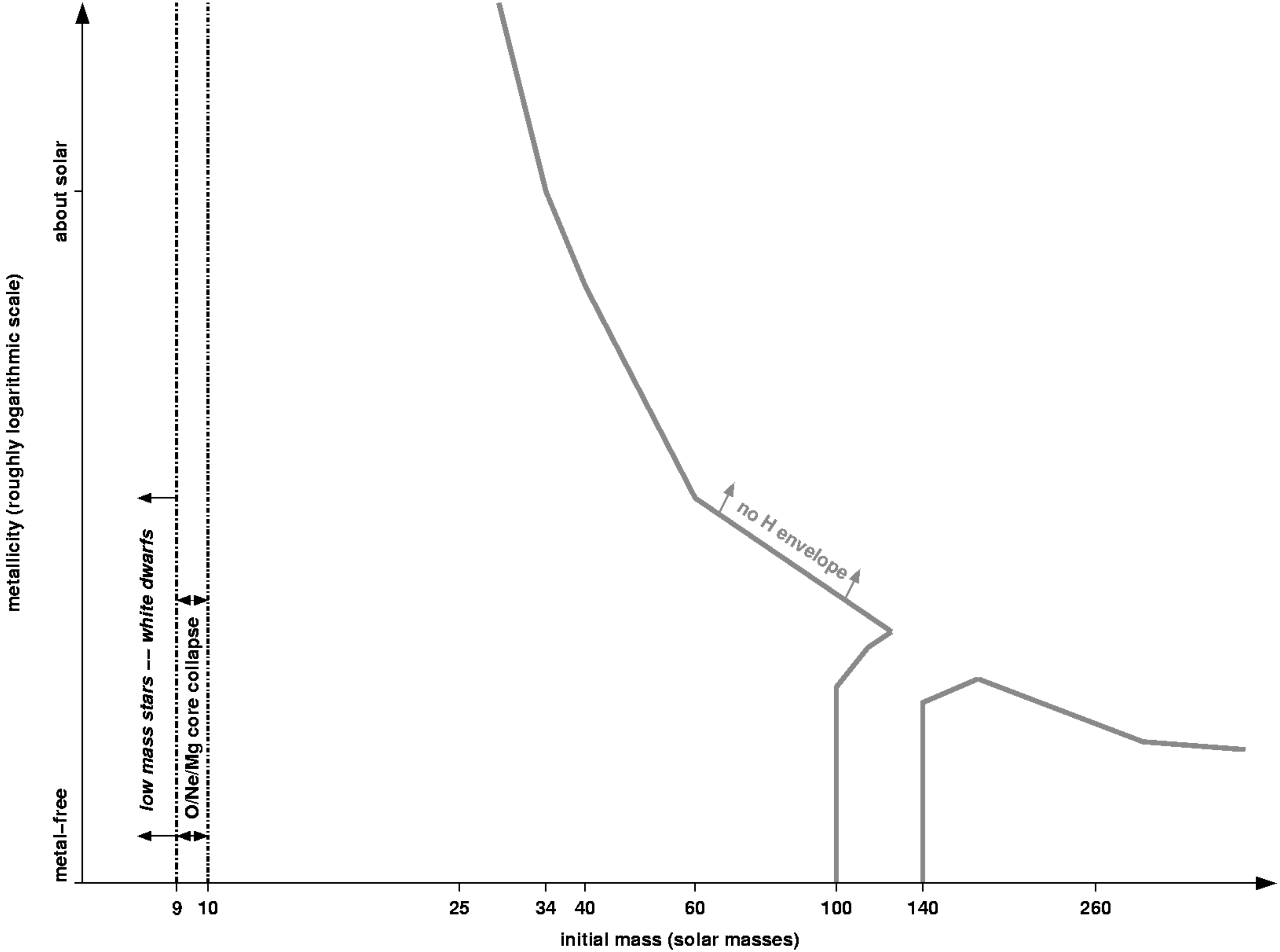

about solar
metallicity (roughly logarithmic scale)
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



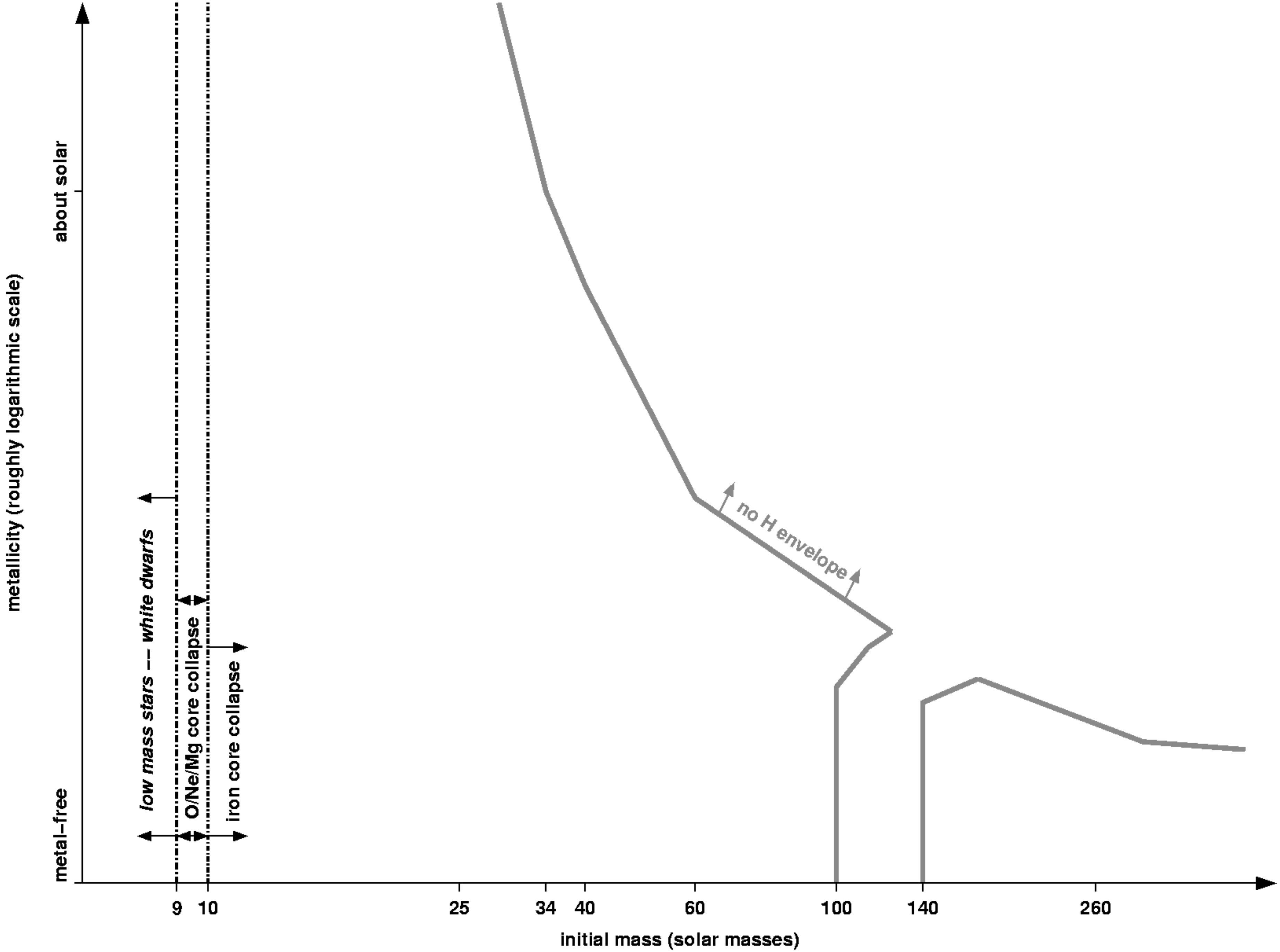
about solar
metallicity (roughly logarithmic scale)
metal-free
no H envelope
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



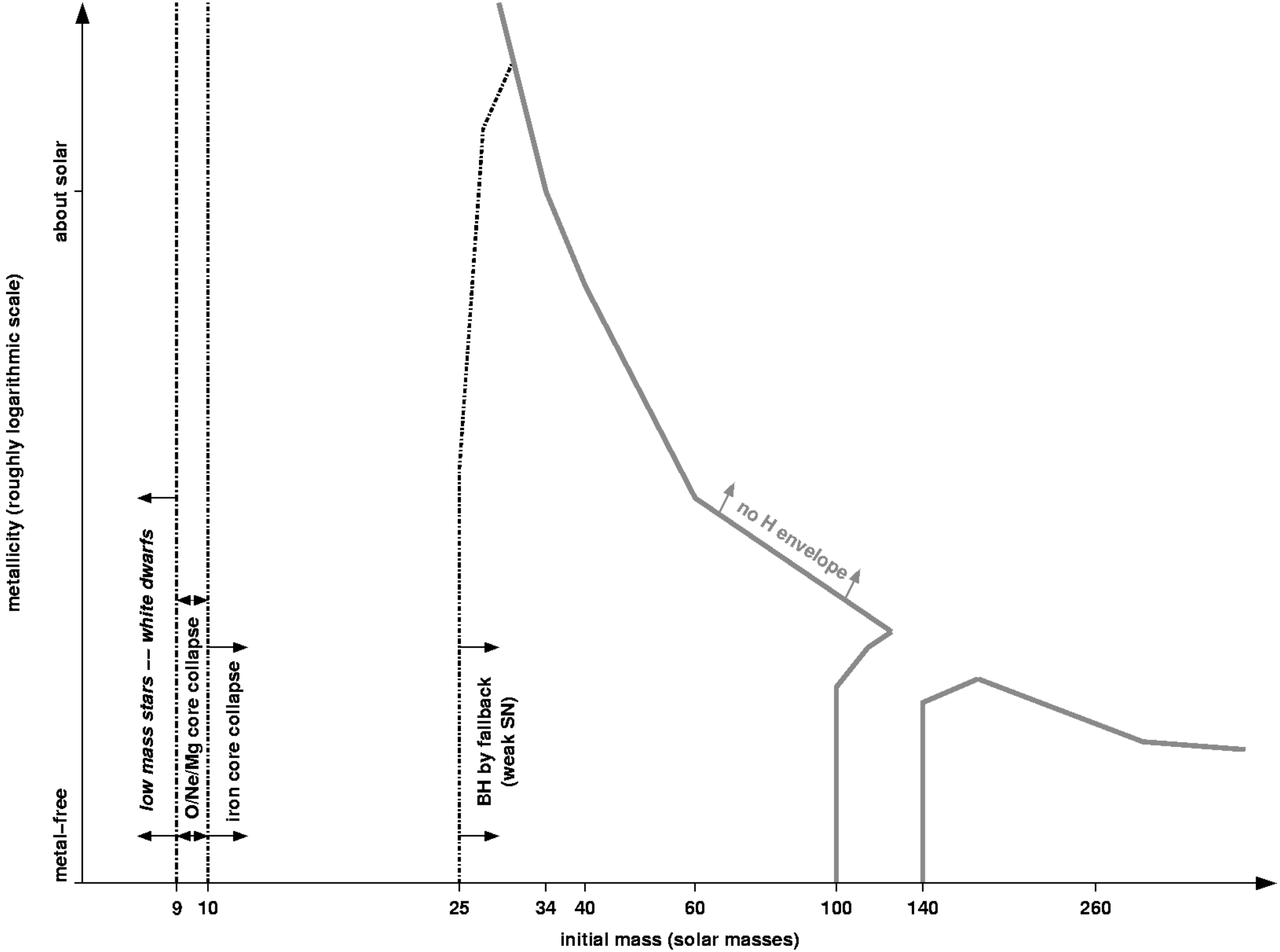
metallicity (roughly logarithmic scale)
about solar
metal-free
low mass stars -- white dwarfs
no H envelope
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



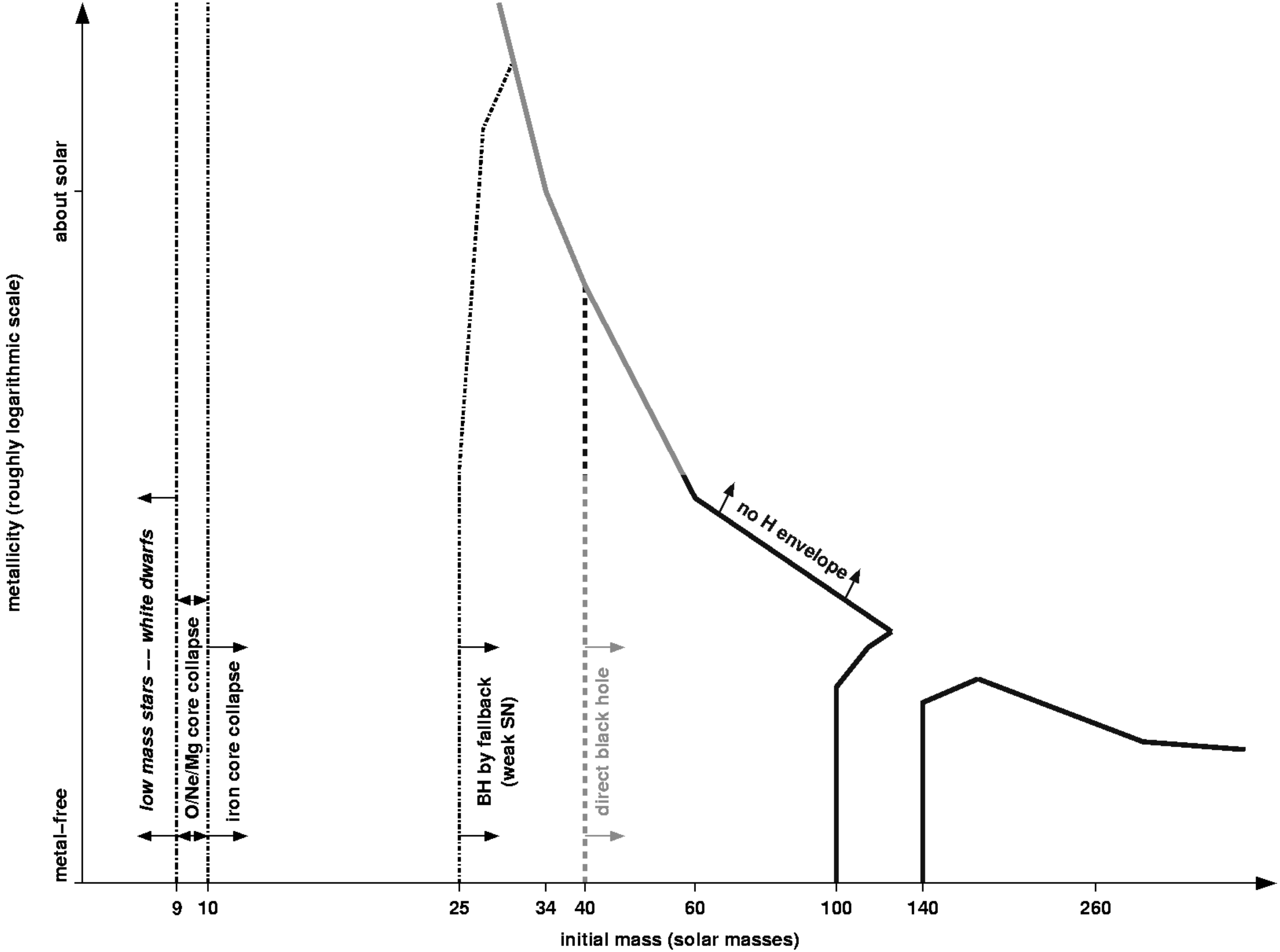
about solar
metallicity (roughly logarithmic scale)
metal-free
low mass stars -- white dwarfs
O/Ne/Mg core collapse
no H envelope
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



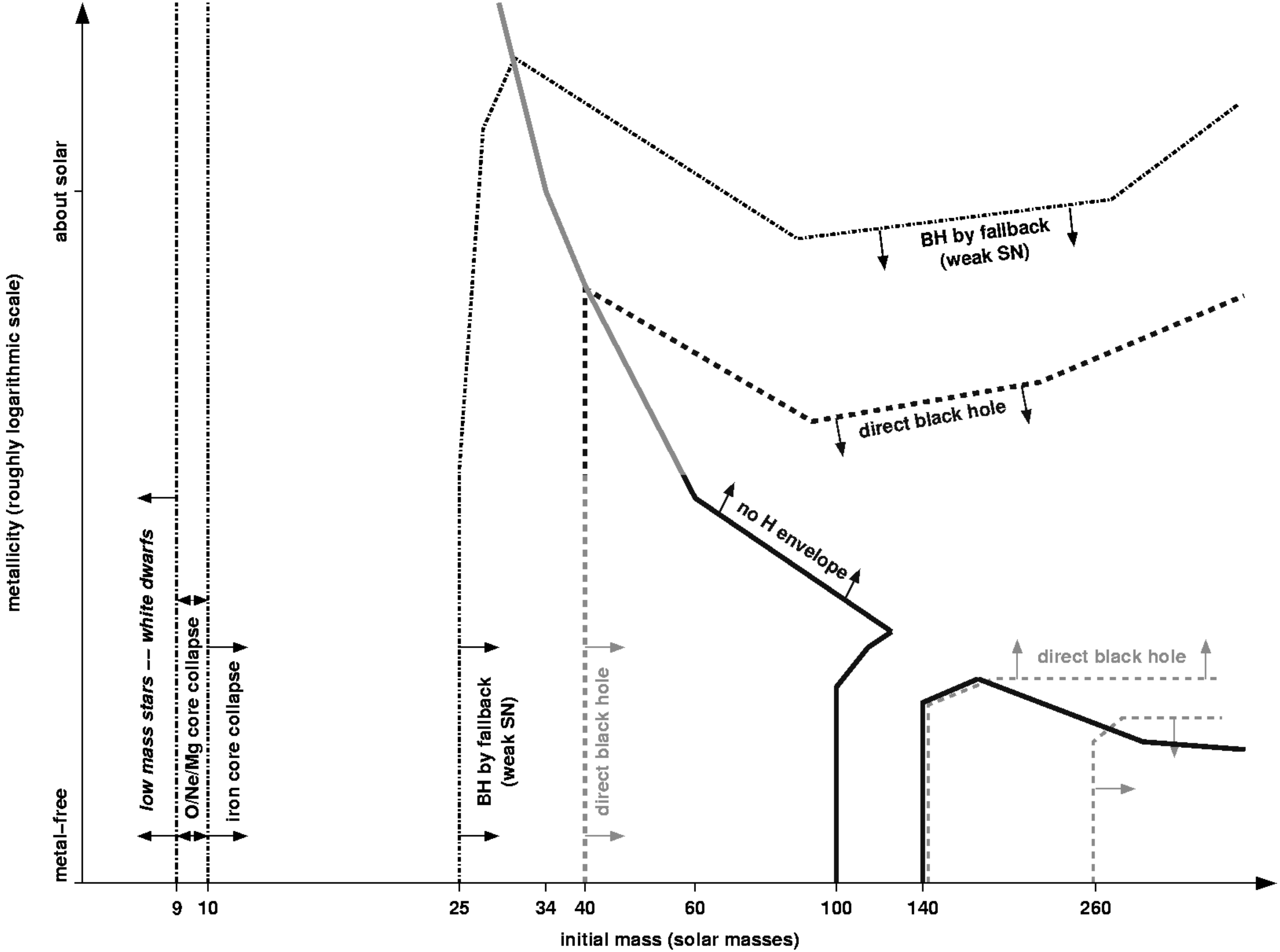
about solar
metallicity (roughly logarithmic scale)
metal-free
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
no H envelope
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



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



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



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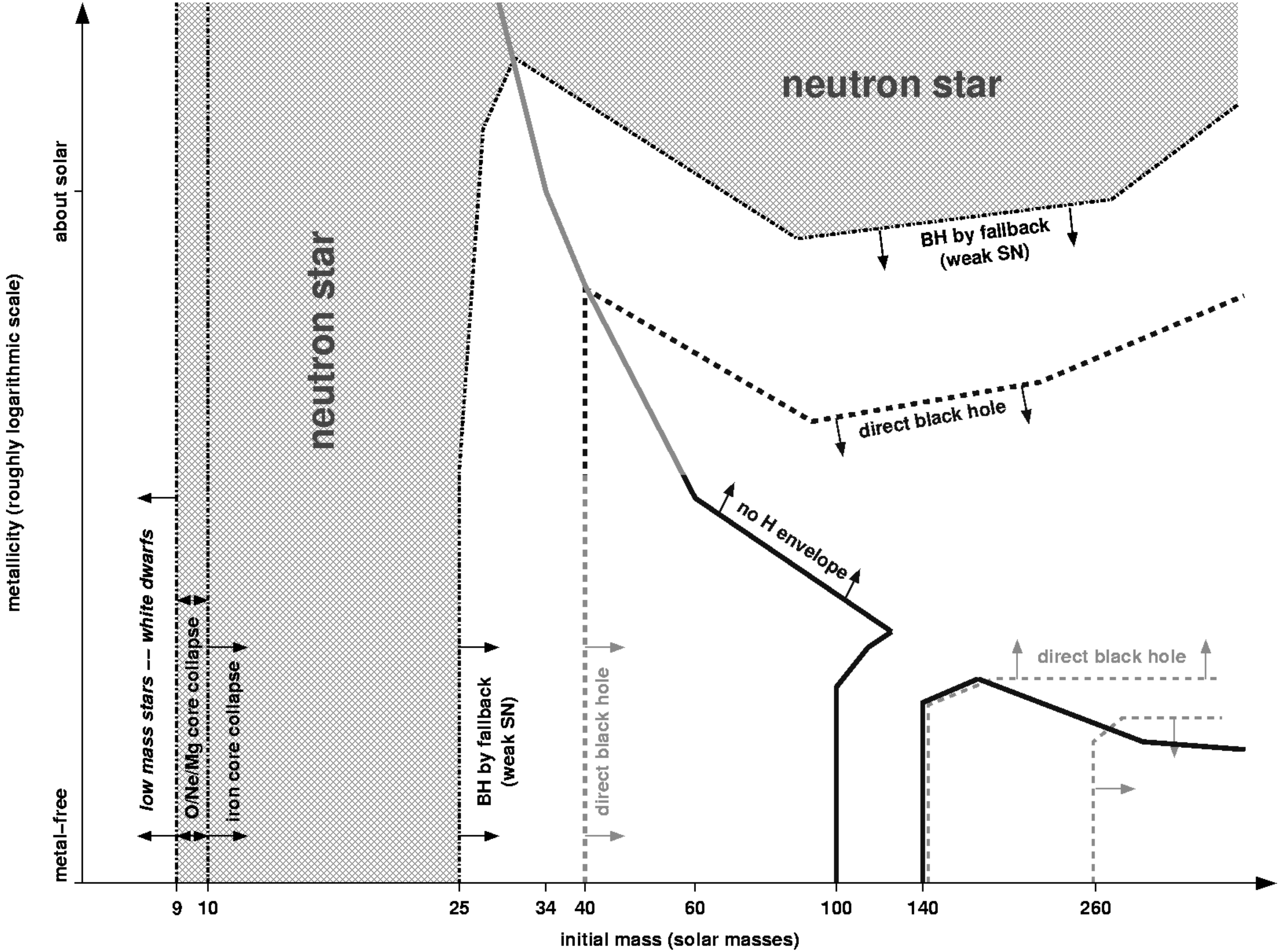
BH by fallback (weak SN)
direct black hole
BH by fallback (weak SN)
direct black hole
no H envelope
direct black hole



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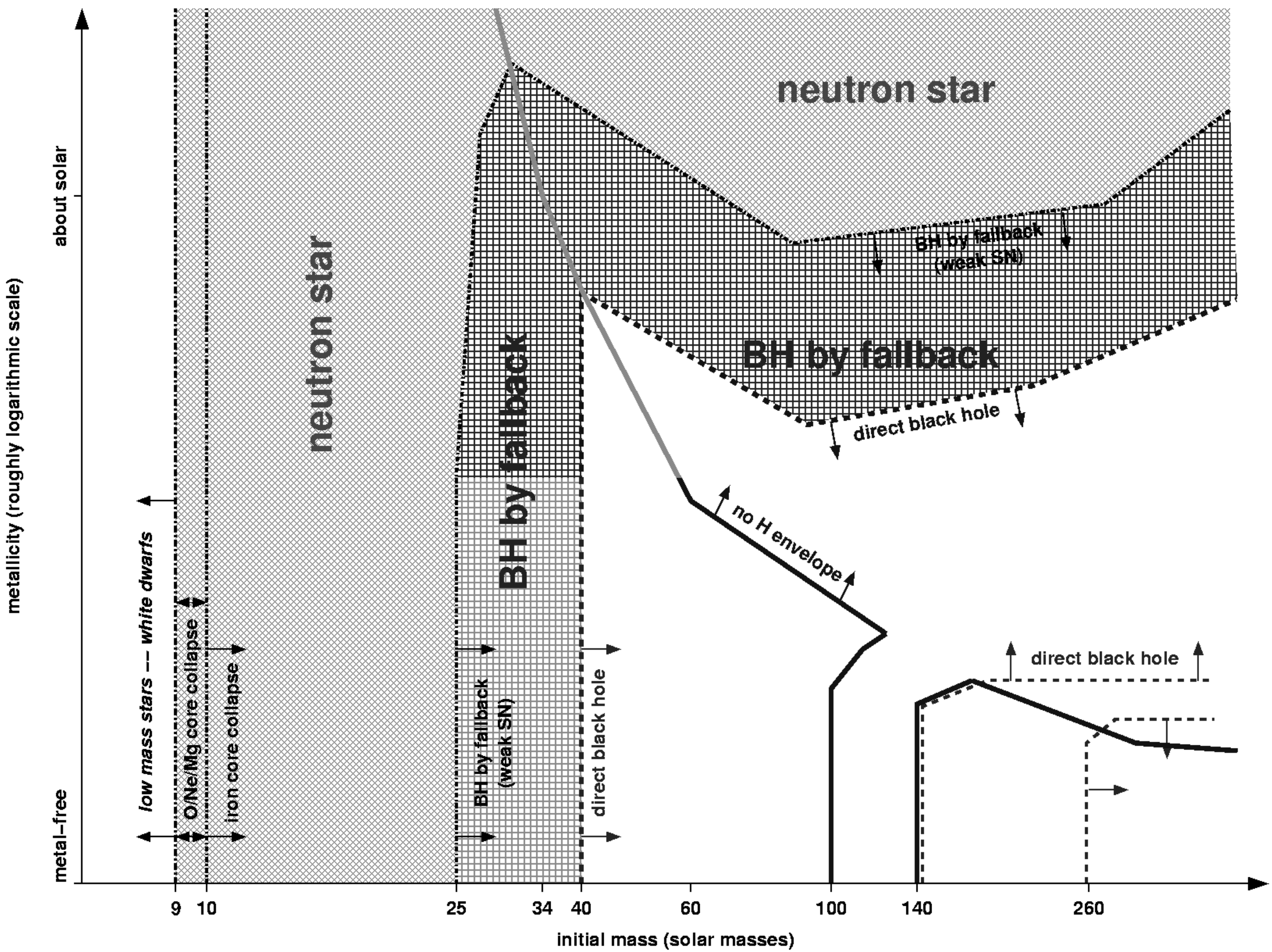
140
260
initial mass (solar masses)


neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback (weak SN)
direct black hole
no H envelope
direct black hole
low mass stars -- white dwarfs
O/Ne/Mg core collapse
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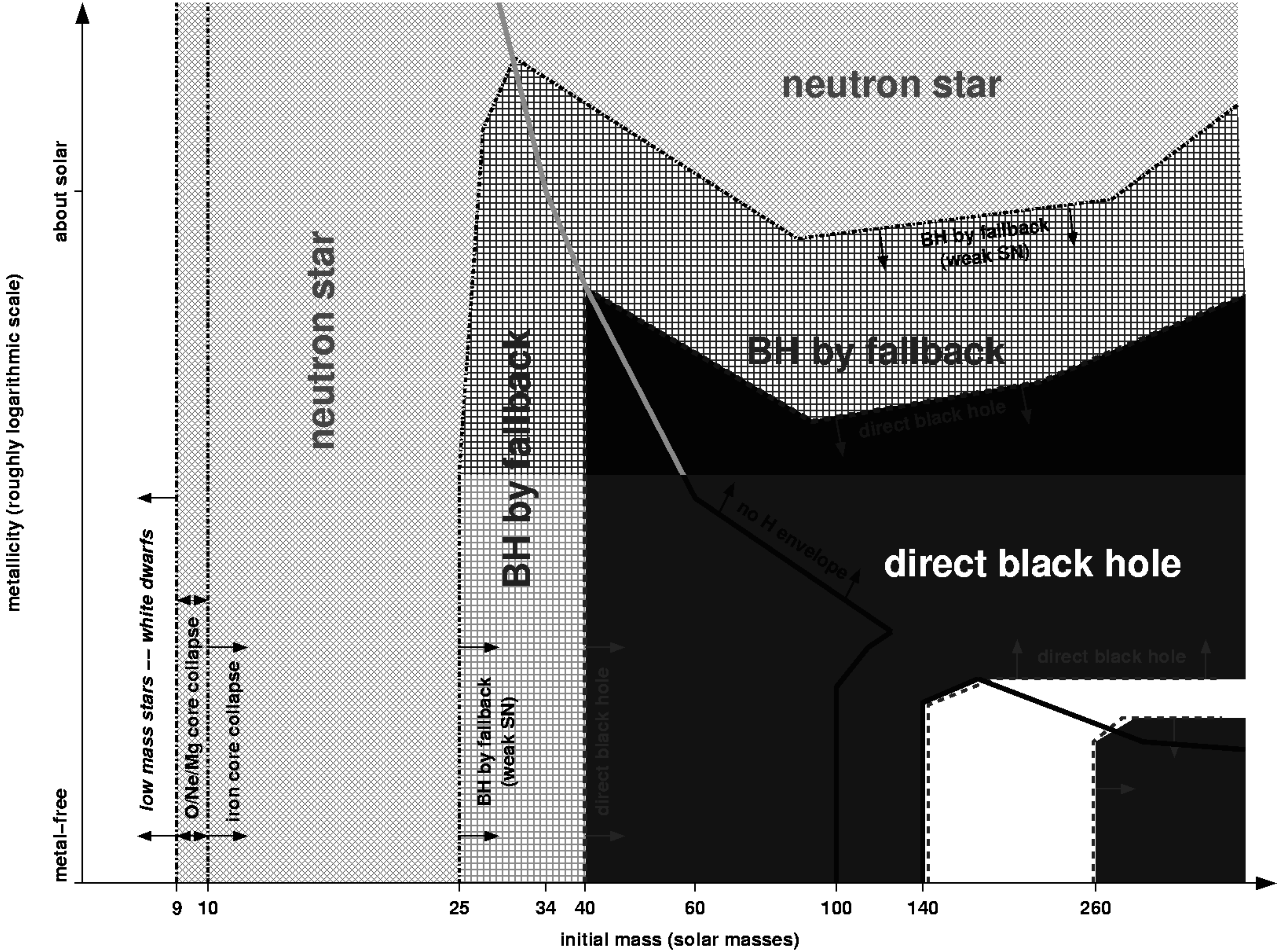
initial mass (solar masses)


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
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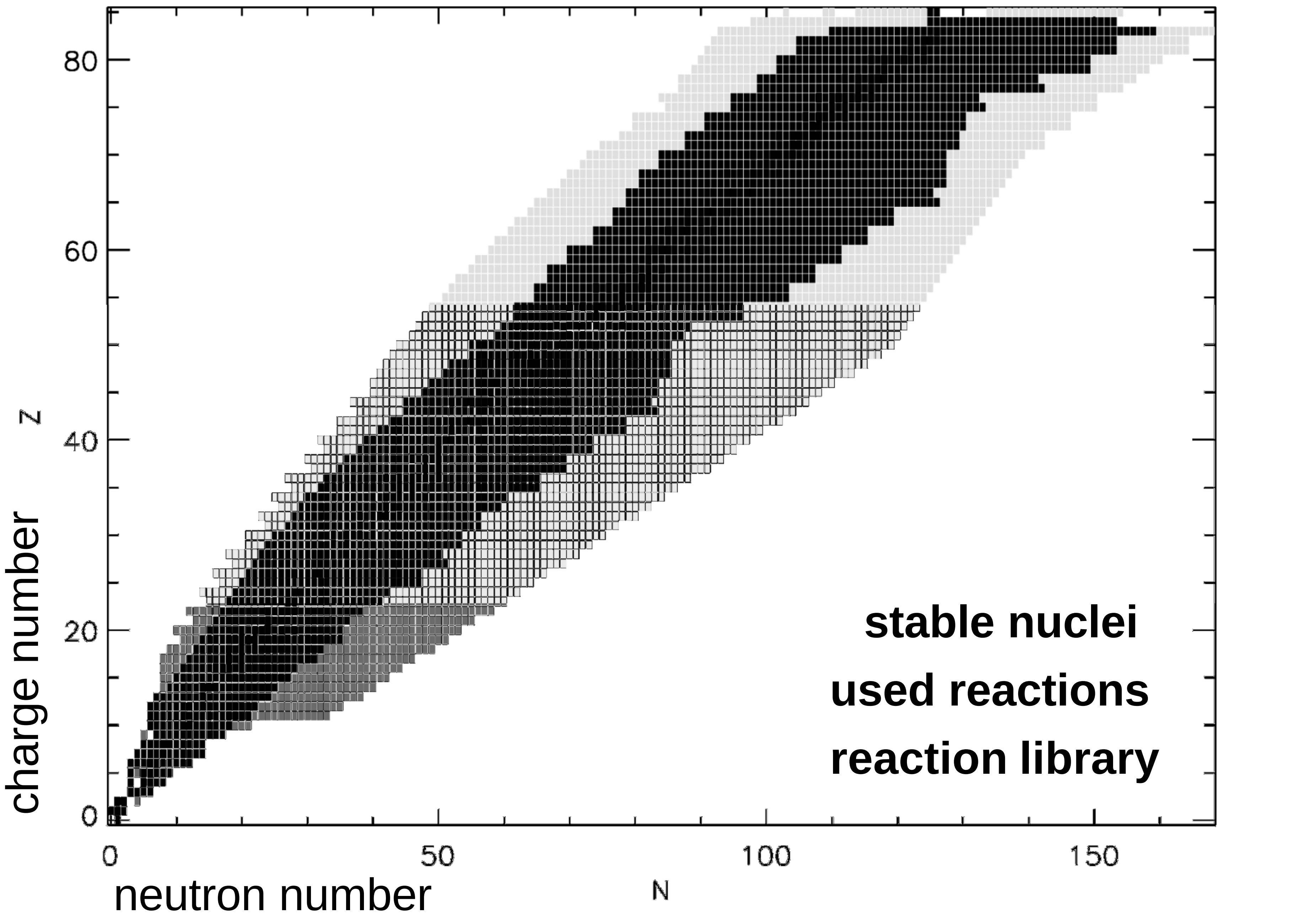
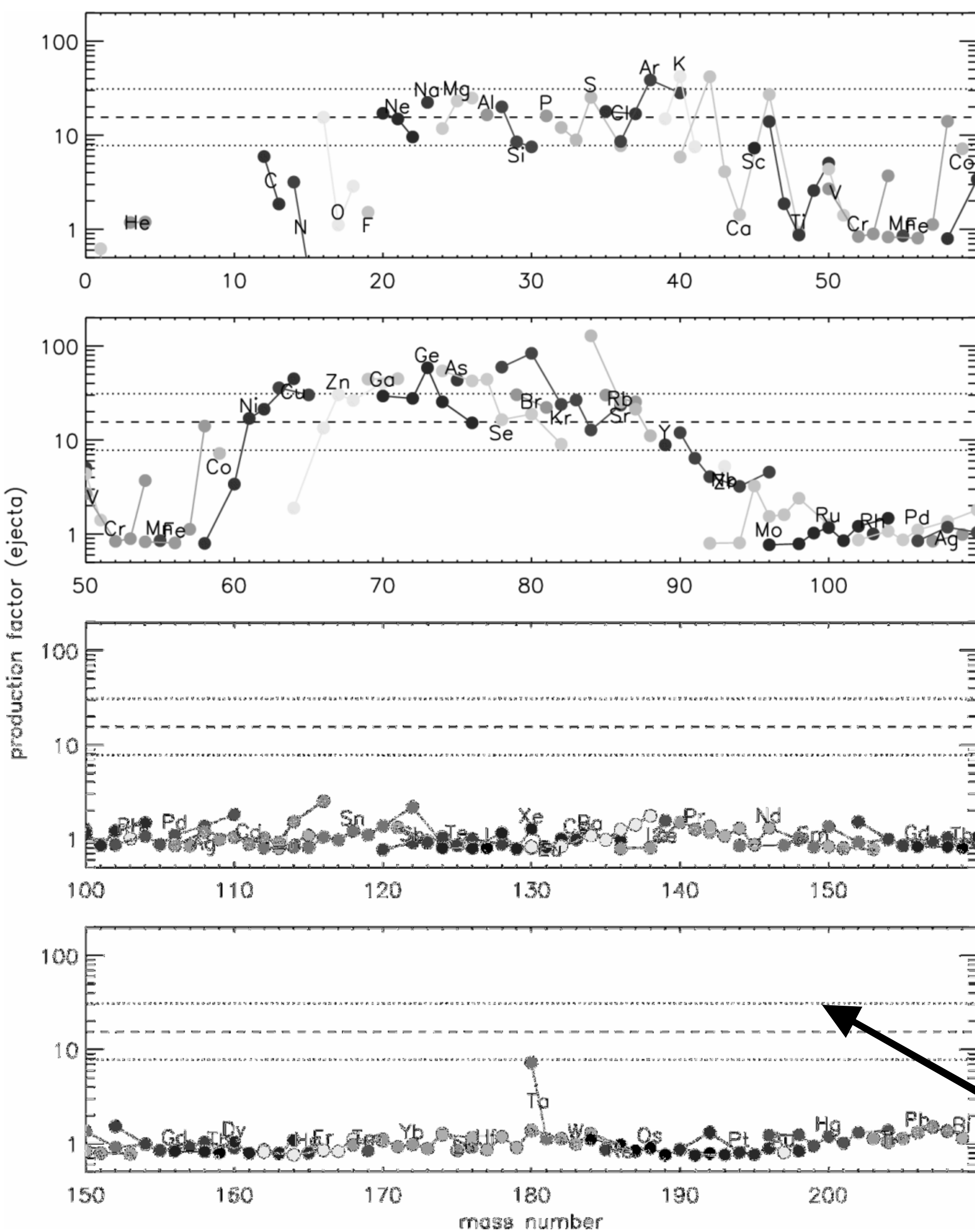
metallicity (roughly logarithmic scale)
about solar
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

The Calculations

- Complete stellar evolution calculations including all relevant isotopes up to bismuth
- We include most recent experimental and theoretical nuclear reaction rates
- Supernova explosion and explosive nucleosynthesis is followed in (one-dimensional) hydrodynamic calculation (explosion model parameterized)
- Nucleosynthesis by “hot” neutrinos form the proto-neutron star is included



stable nuclei
used reactions
reaction library
charge number
Z
neutron number
N
0
20
40
60
80
0
50
100
150



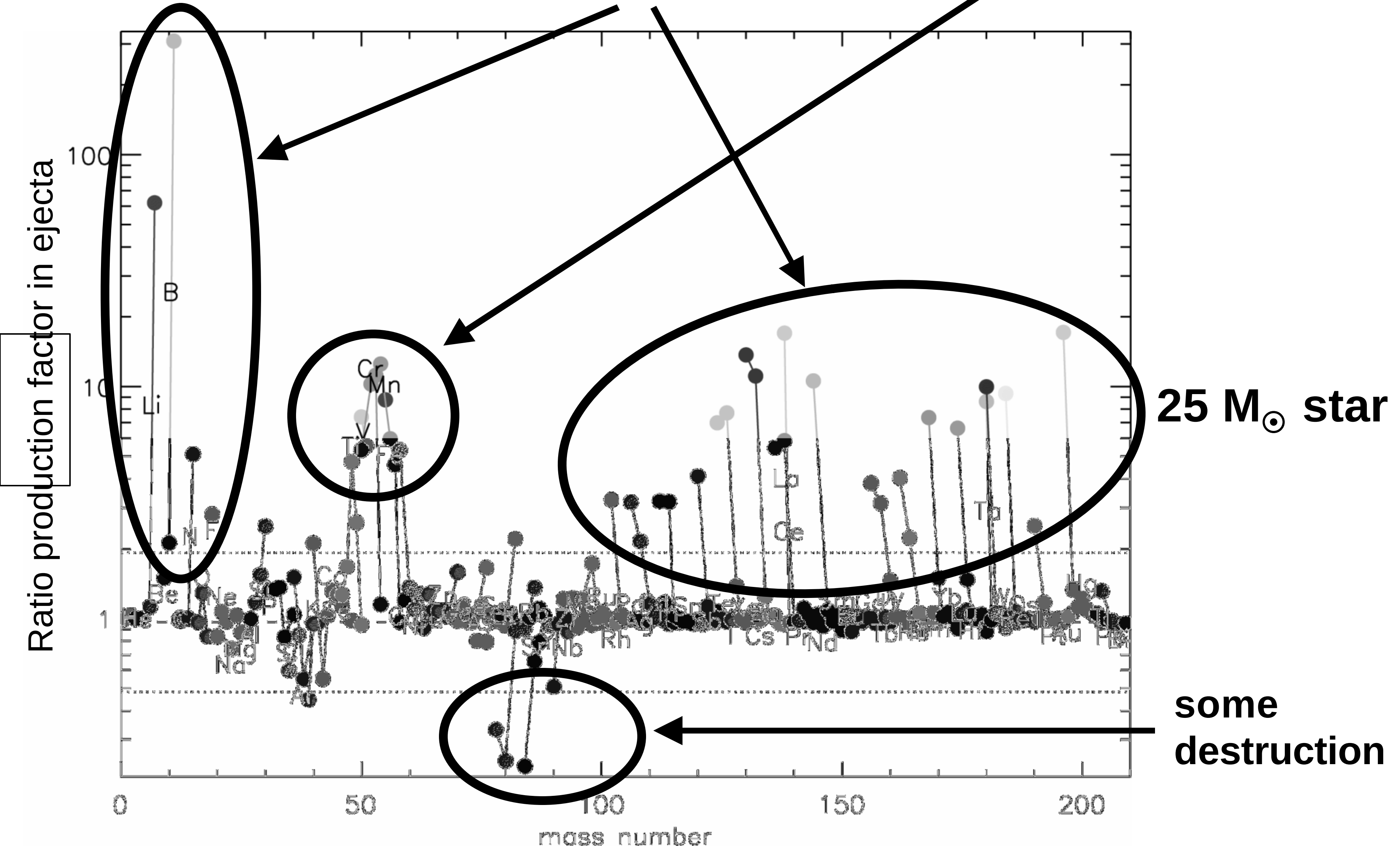
25 $M_\odot$ star

Presupernova production factors relative to solar composition

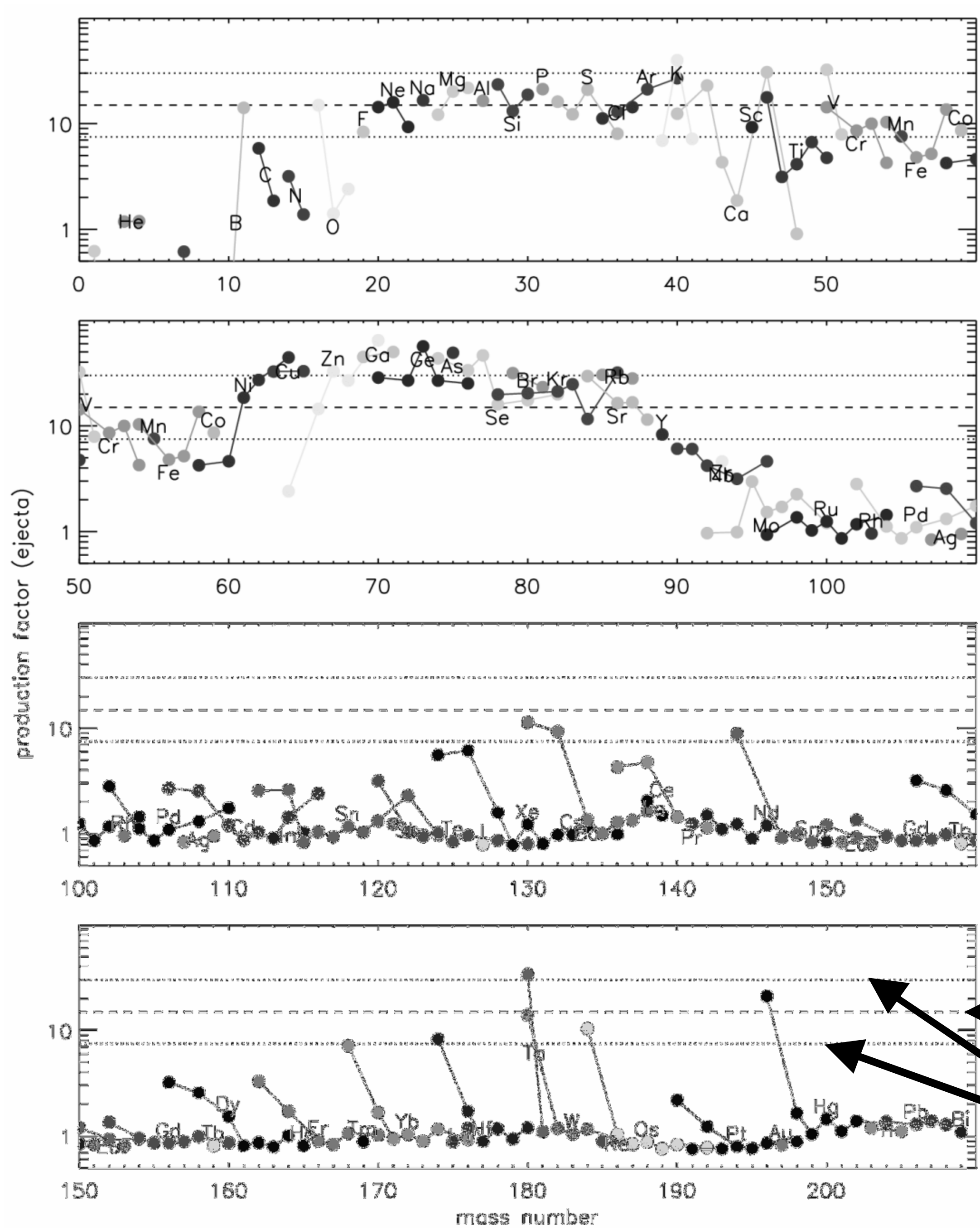
“band of acceptable co-production” defined by **^{16}O** production (± a factor 2)

Explosive Nucleosynthesis contribution

➔production of p-process and iron group

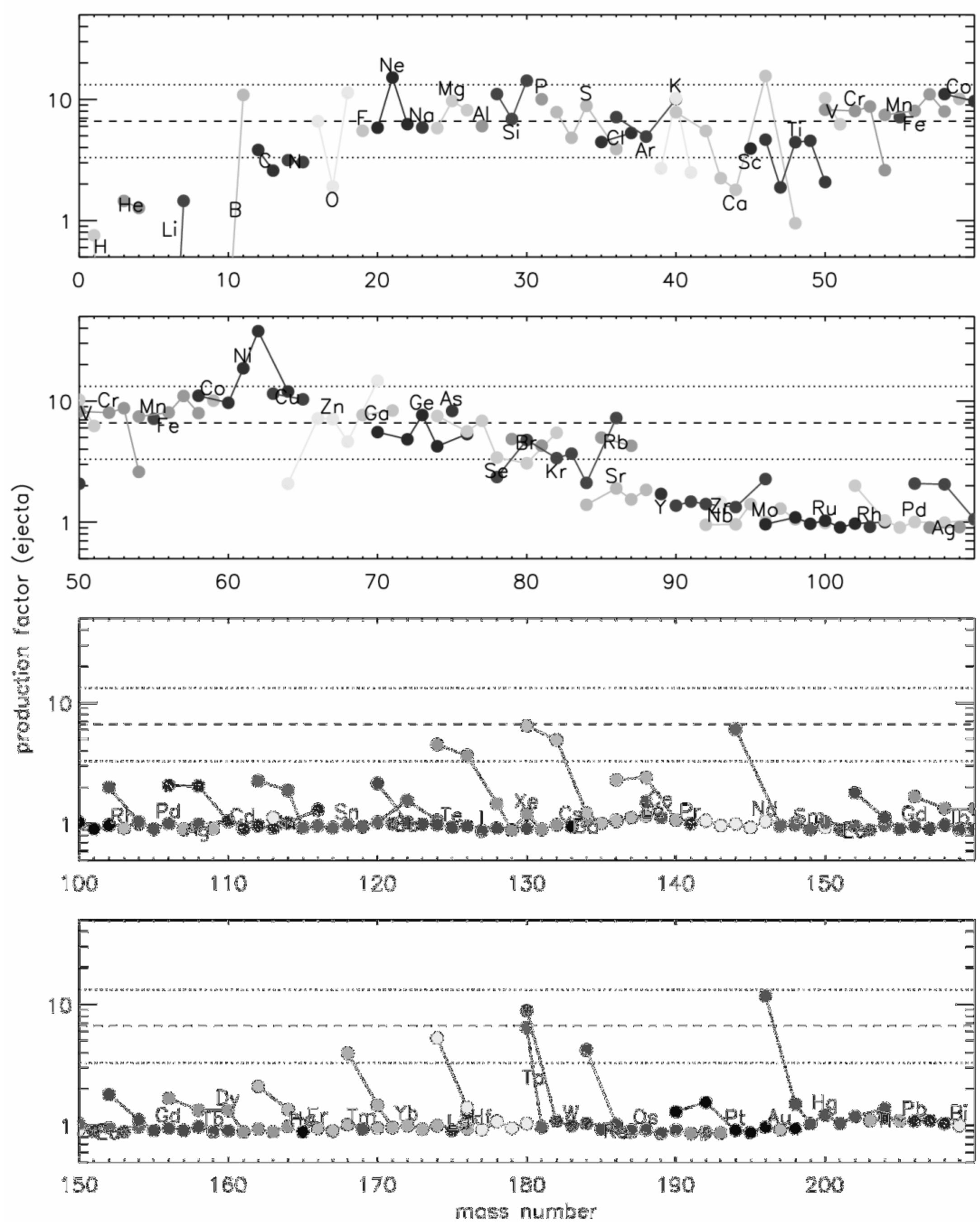


25 $M_\odot$ star



Production factors relative to solar composition

"band of acceptable co-production" defined by ^{16}**O** production (± a factor 2)



15 $M_\odot$ star

Production factors relative to solar composition

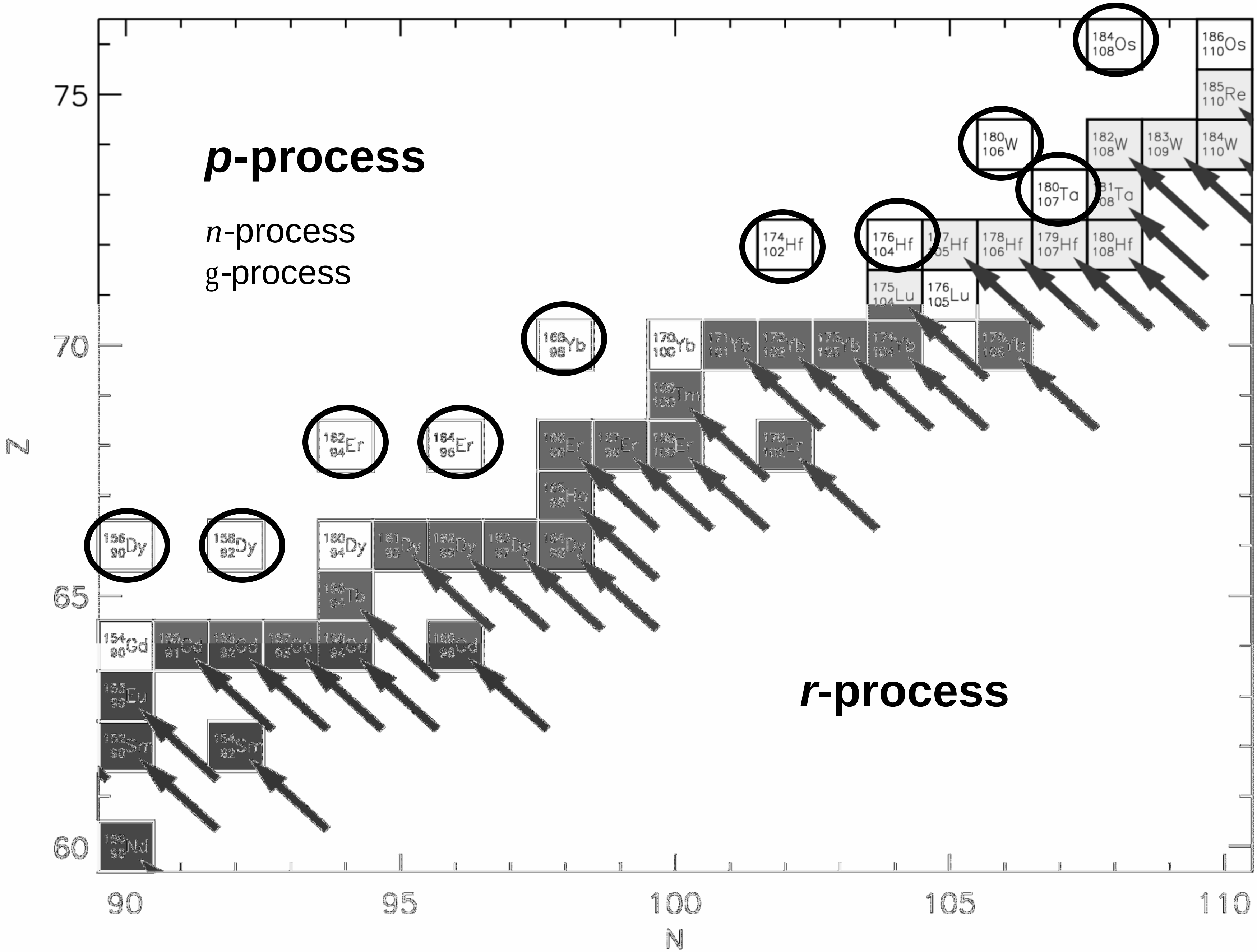
“band of acceptable co-production” defined by ^{16}O production (± a factor 2)

The Results

- Current stellar model can produce most of the isotopes up to a mass number of A ≈ 85 in about solar abundances (relative to oxygen)
- many proton-rich heavy elements ("*p*-process elements") are also well co-produced in about solar abundance ratio by the g-process and the n-process
- some light and some rare heavy isotopes are produced by the n-process and may dominate their elemental production (^{11}B, ^{19}F, ^{138}La, ^{180}Ta)

The *p*-process

- Production of (mostly rare) proton-rich nuclei from **abundant** neighbors
- γ-process: photo-sublimation, mostly (γ,n) reactions close to valley of stability
- ν-process:
  - neutral current (ν,ν') scattering to excited nucleus that decays by particle emission
  - charges current (ν,e^-), (ν,e^+); excited daughter nucleus can *also* decay by particle emission {γ, n, p, a}*



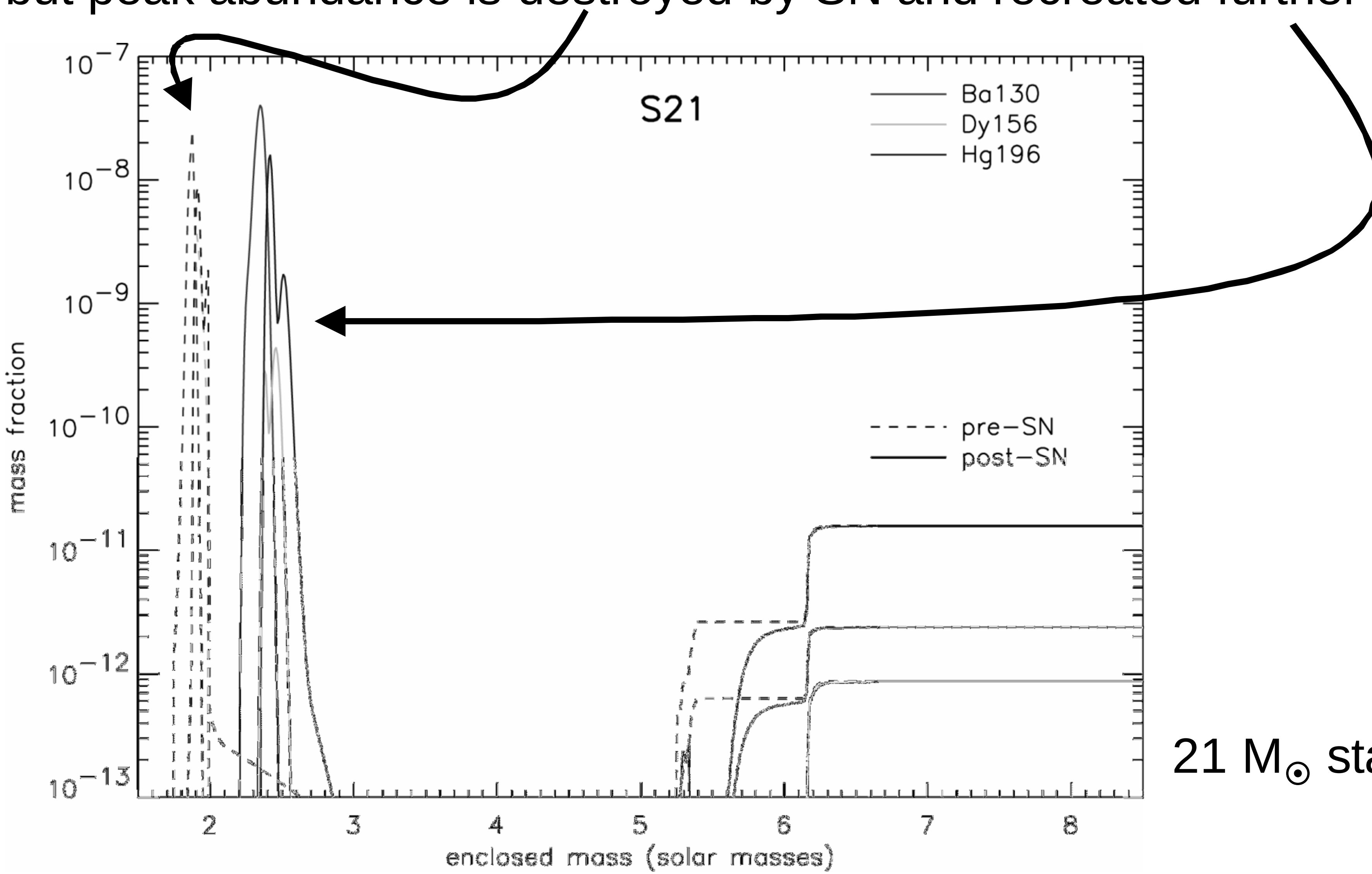
p-process
n-process
g-process
r-process
Z
N
60
65
70
75
90
95
100
105
110
184 108 Os
186 110 Os
185 110 Re
180 106 W
182 108 W
183 109 W
184 110 W
180 107 Ta
174 102 Hf
176 104 Hf
178 106 Hf
179 107 Hf
180 108 Hf
175 104 Lu
176 105 Lu

The p-process

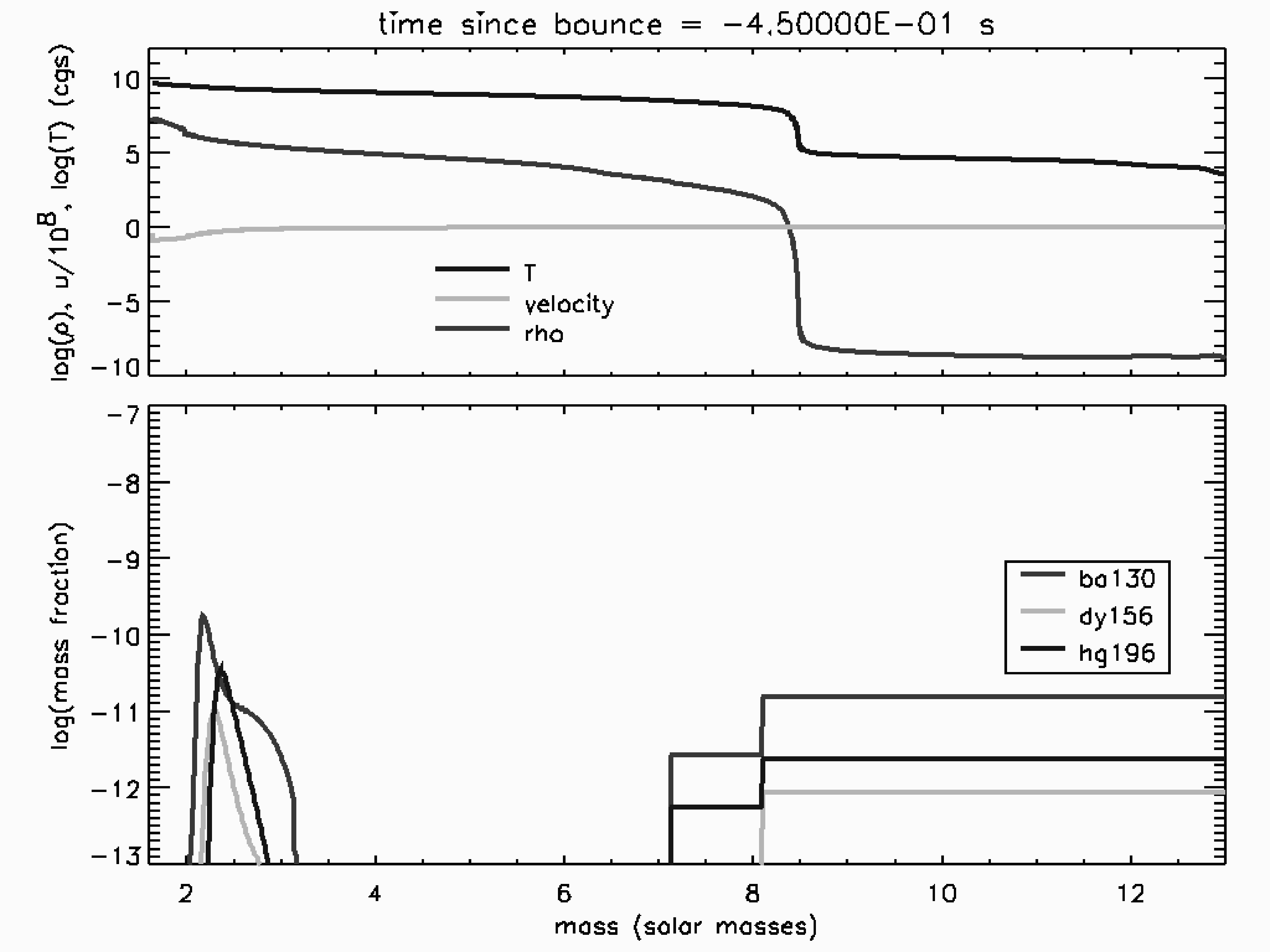
- Production of (mostly rare) proton-rich nuclei from **abundant** neighbors
- γ-process: photo-sublimation,
  mostly (γ,n) reactions close to valley of stability
- ν-process:
  - neutral current (ν,ν') scattering to excited nucleus that decays by particle emission
  - charges current (ν,e^-), (ν,e^+); excited daughter nucleus can *also* decay by particle emission {γ, n, p, a}*

“Relocation” of the p-process

p-process can be made in implosive O shell burning,
but peak abundance is destroyed by SN and recreated further out

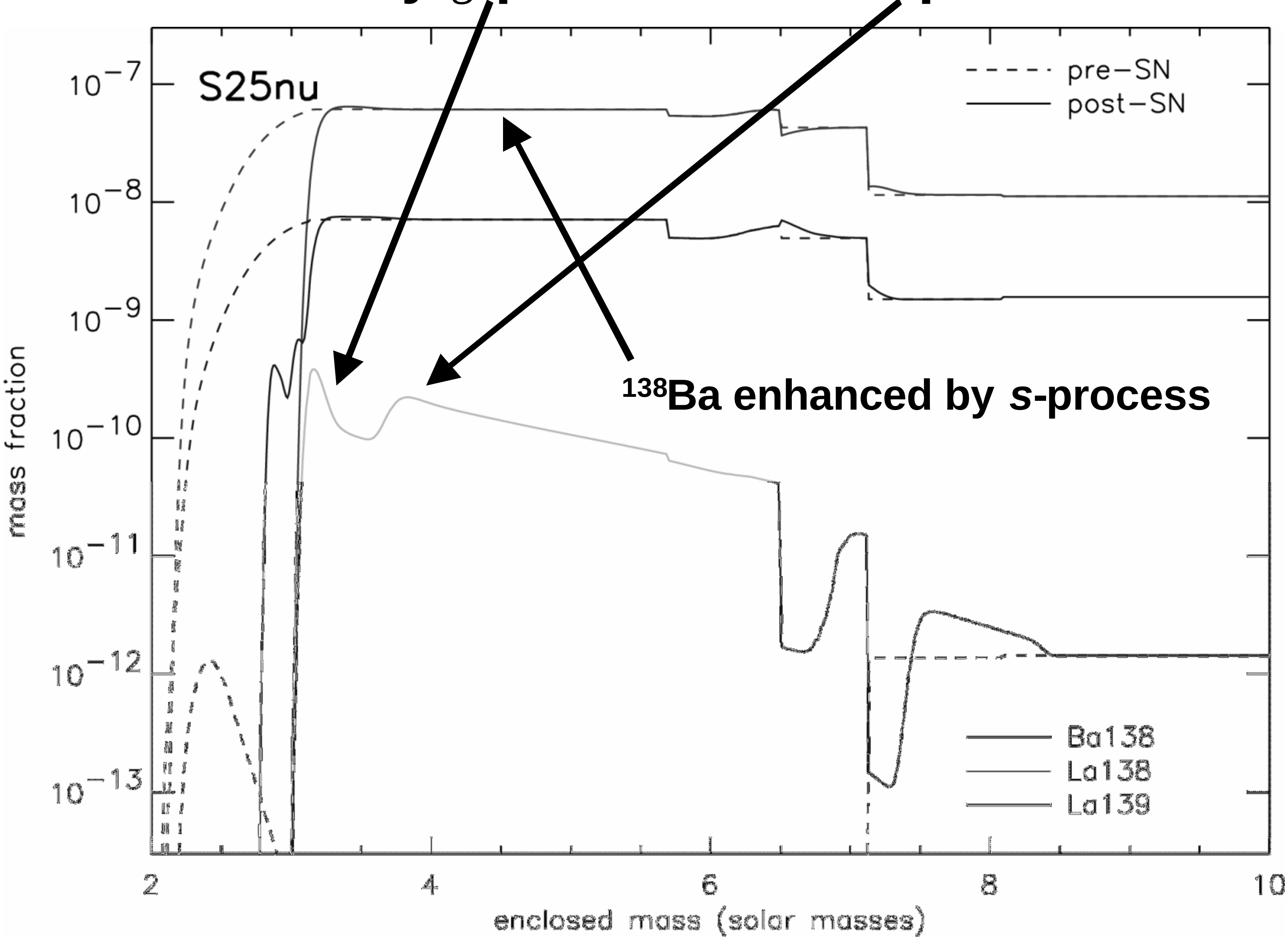


21 $M_\odot$ star


time since bounce = -4.50000E-01 s
log(ρ), u/10^8, log(T) (cgs)
10
5
0
-5
-10
T
velocity
rho
log(mass fraction)
-7
-8
-9
-10
-11
-12
-13
ba130
dy156
hg196
2
4
6
8
10
12
mass (solar masses)

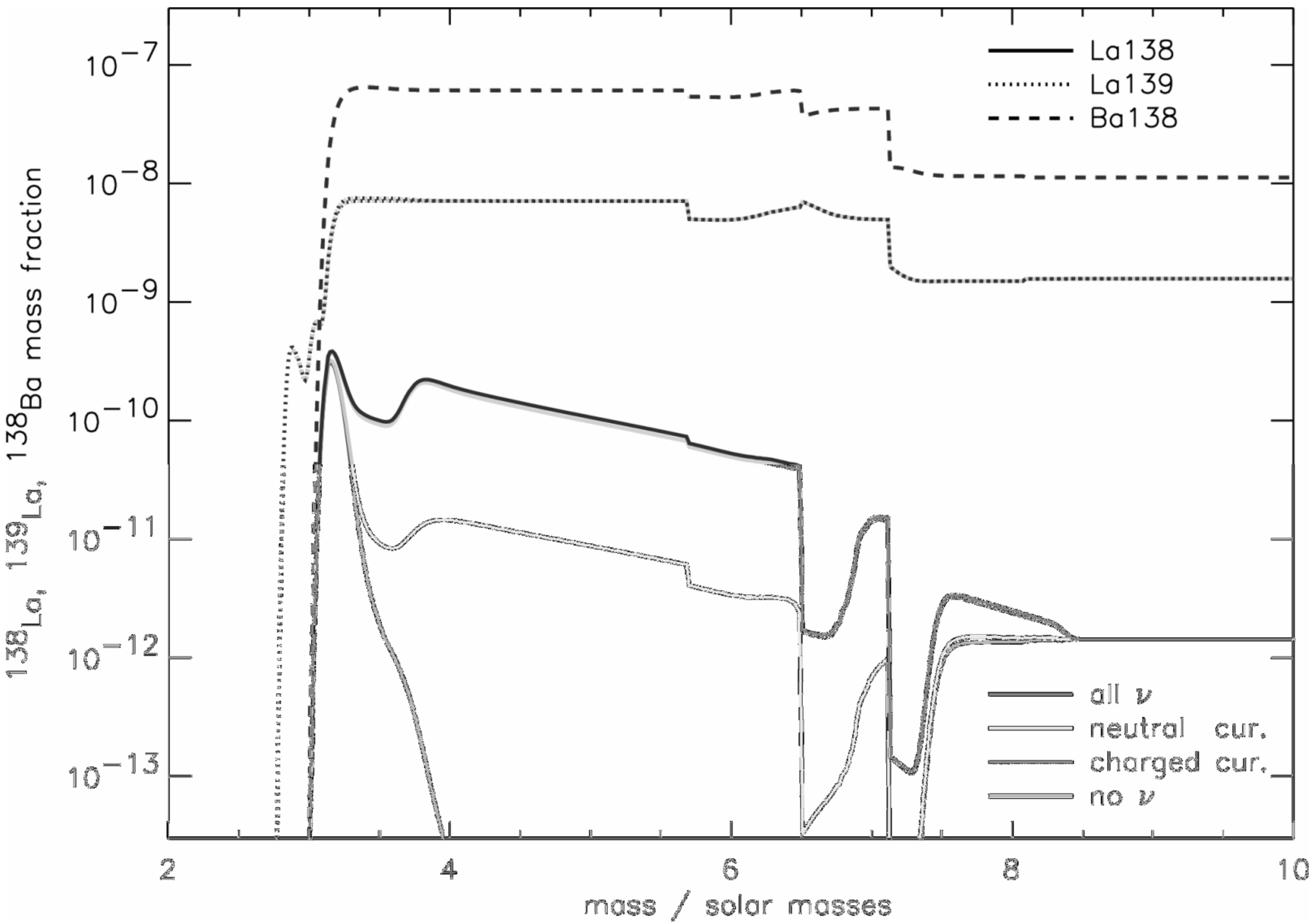
The Production of ^{138}La

by g-process and n-process



The Production of ^{138}La

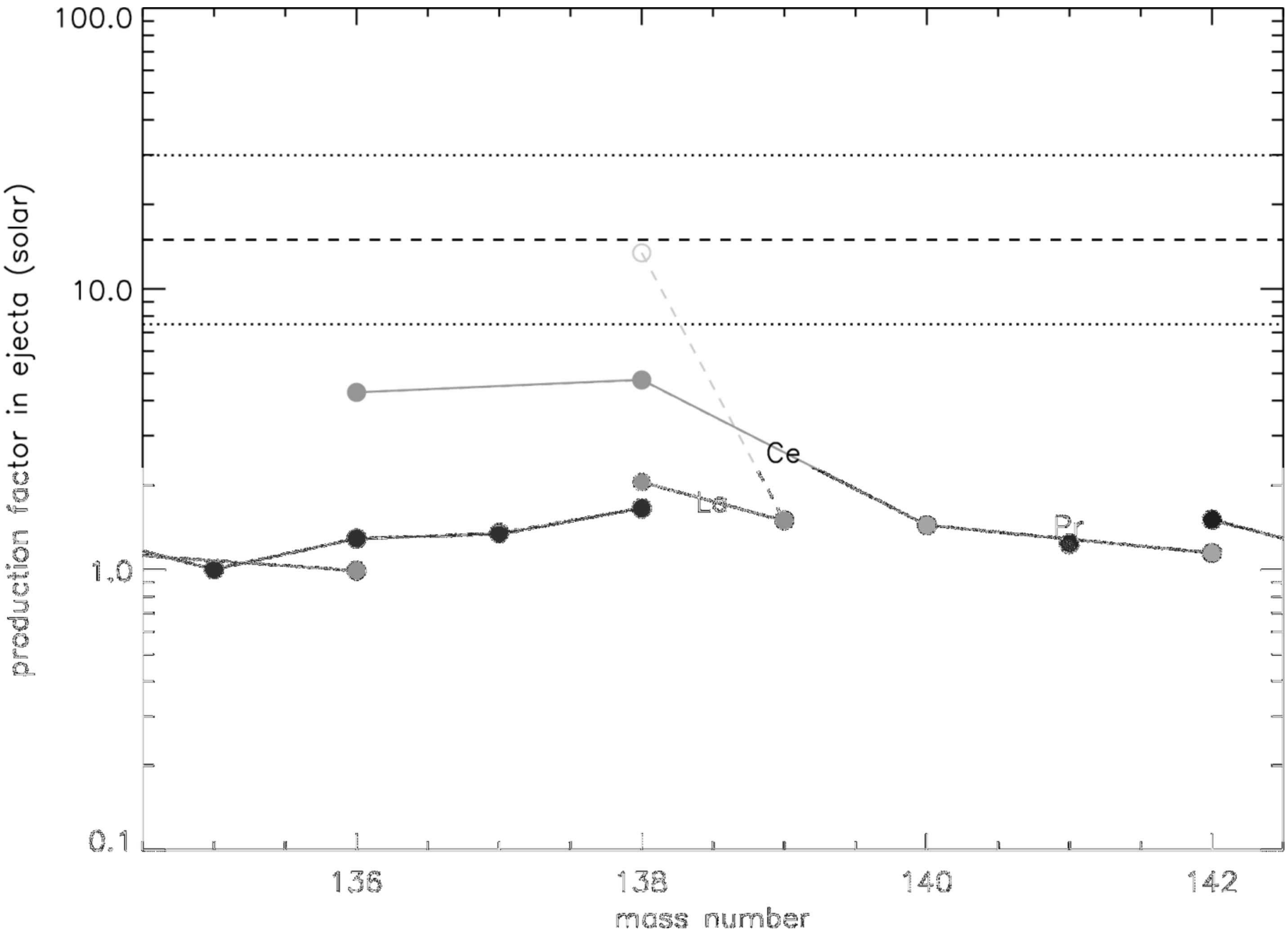
by γ-process and ν-process

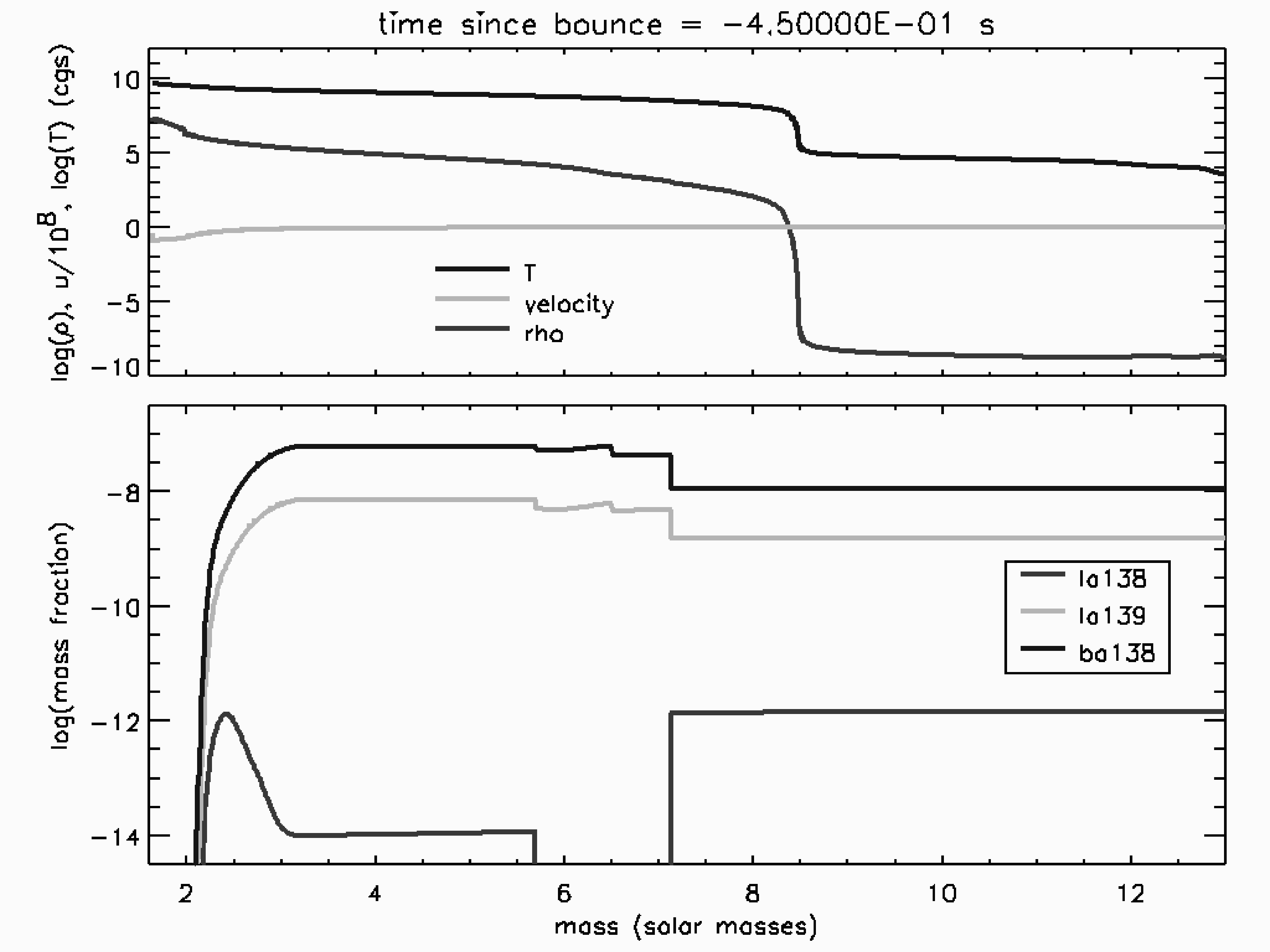


The Impact of $^{138}Ba(n,e^-)^{138}La$

➔ ^{138}La is coproduced in solar ratio

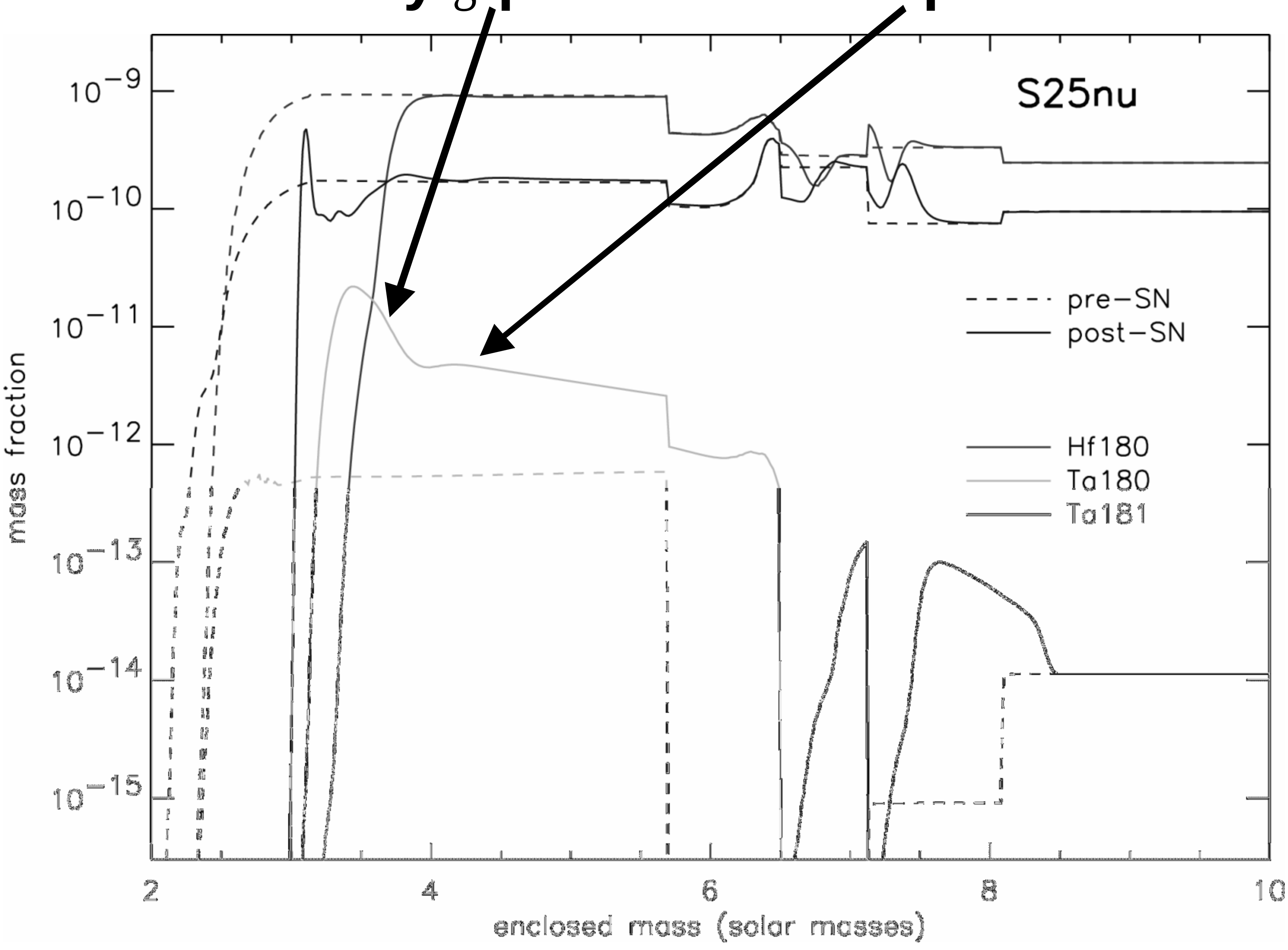
with respect to ^{16}O




time since bounce = -4.50000E-01 s
log(ρ), u/10^8, log(T) (cgs)
10
5
0
-5
-10
T
velocity
rho
log(mass fraction)
-8
-10
-12
-14
la138
la139
ba138
2
4
6
8
10
12
mass (solar masses)

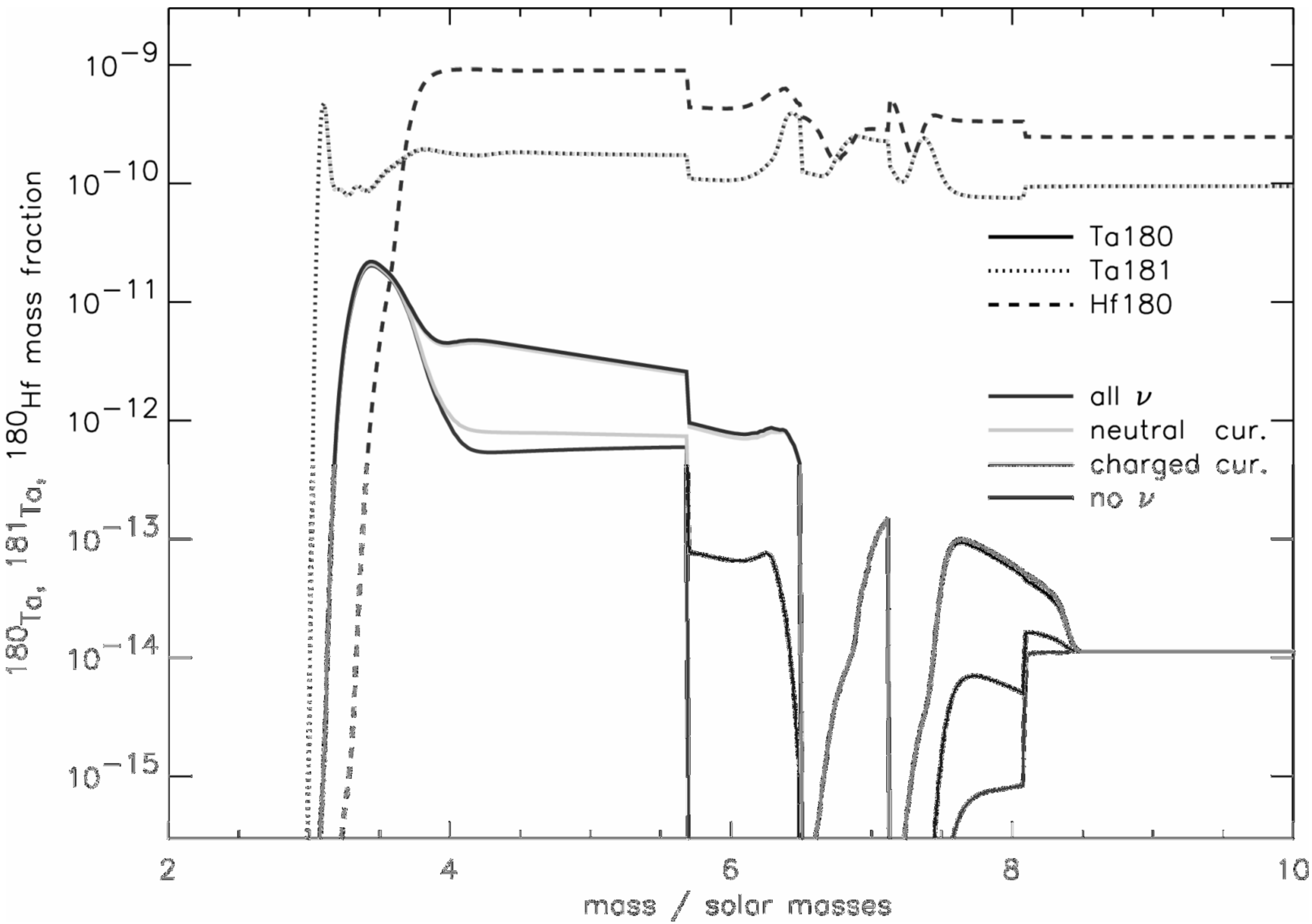
The Production of ^{180}Ta

by γ-process and ν-process



The Production of ^{180}Ta

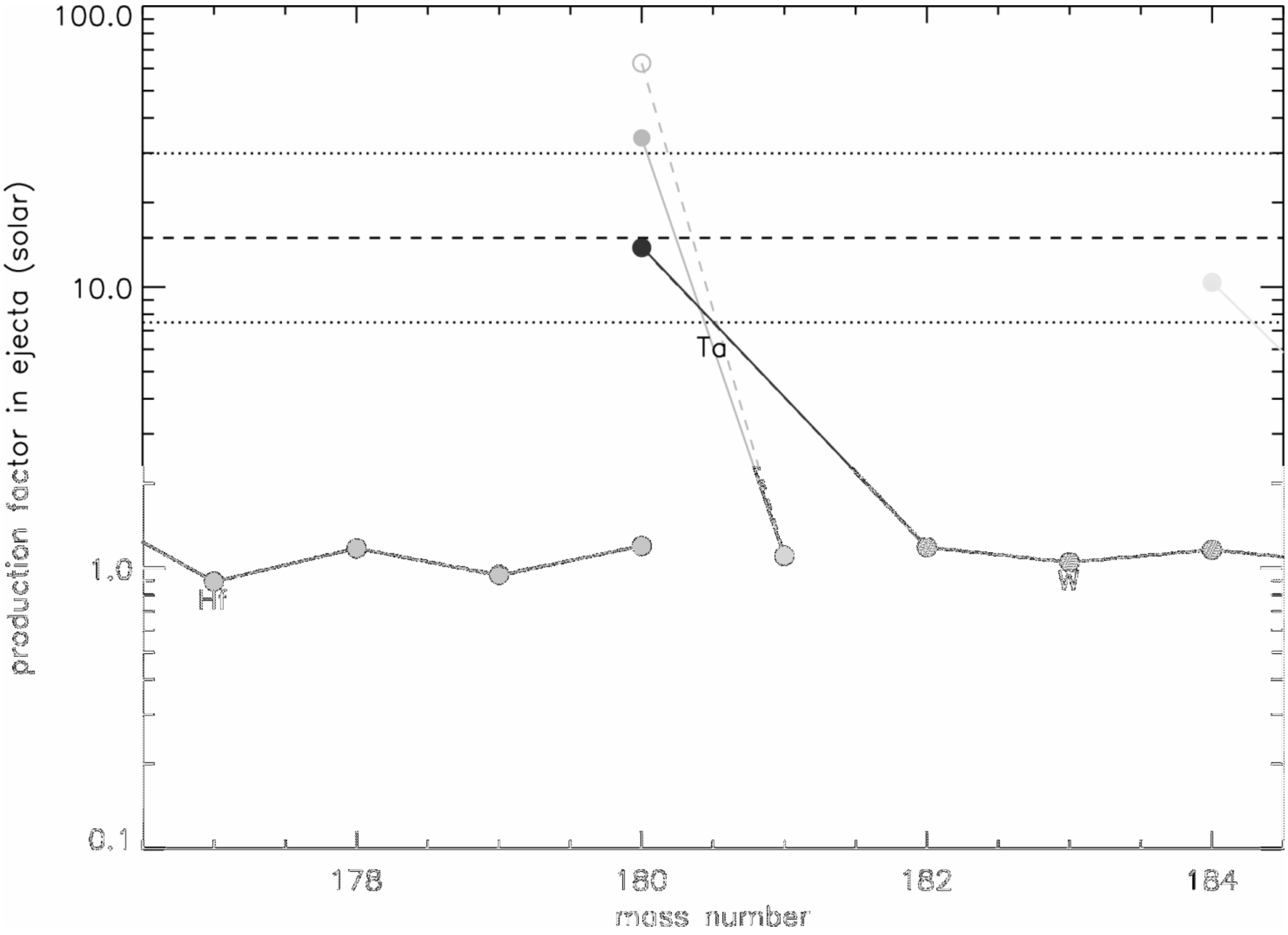
by γ-process and ν-process



ν-process production of ^{180}Ta

little production by $^{181}Ta(\nu,\nu' n)^{180}Ta$

➔**production dominated by $^{181}Ta(\gamma,n)^{180}Ta$ and $^{180}Hf(\nu_e,e^-)^{180}Ta$**



Neutrino Nucleosynthesis

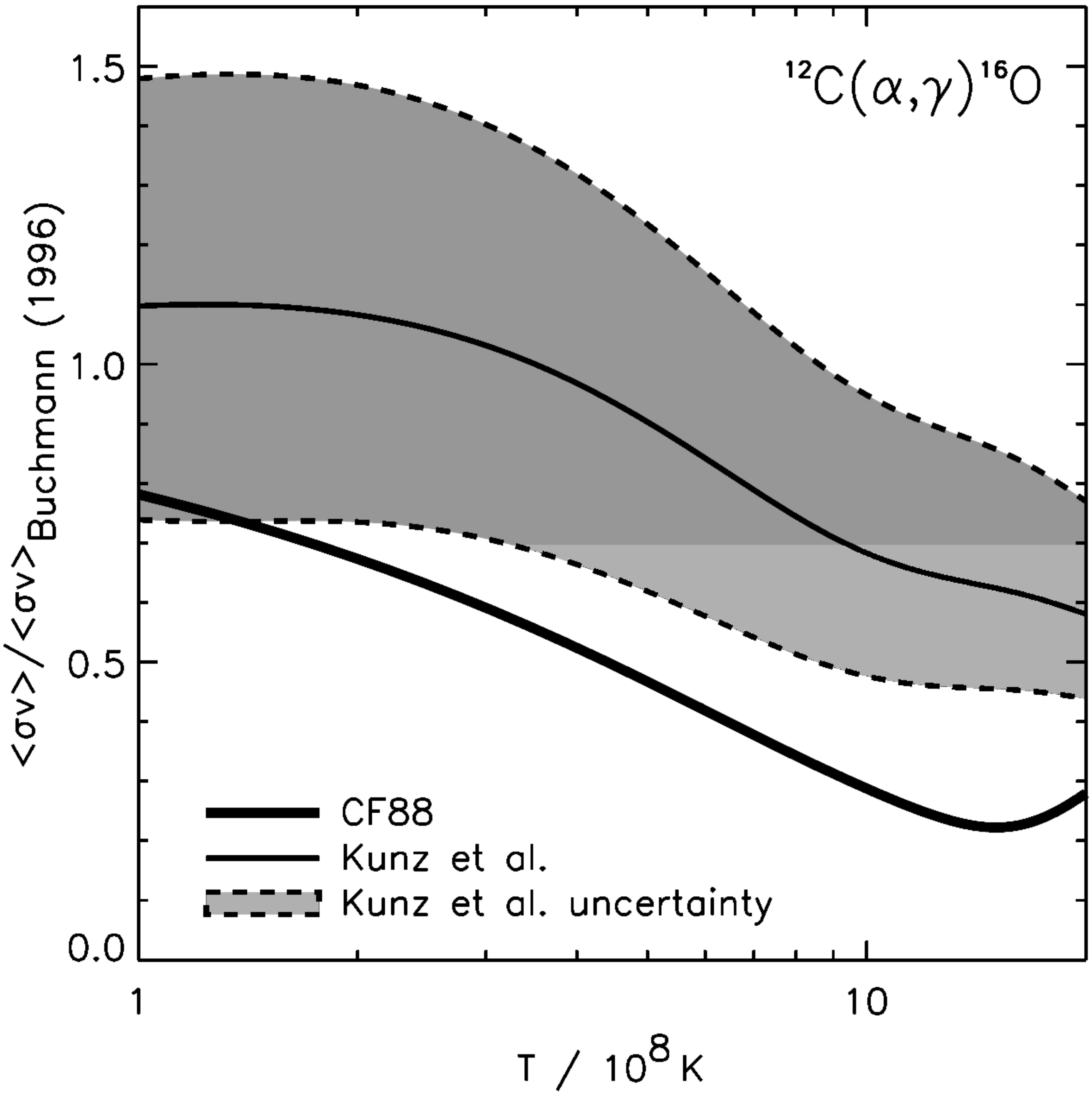
- ^{138}La consistently produced by ^{138}Ba(ν,e$^-$)^{138}La for T(ν_e) = 4 MeV
- Very sensitive to neutrino temperature:
  - for T(ν_e) = 6 MeV: **2**× higher ^{138}La yield (too high)
  - for T(ν_e) = 8 MeV: **5**× higher ^{138}La yield (too high)

➔Fossil ν-process abundances in the sun *may* constrain ν temperature (and oscillations?)
(combination of ^{11}B, ^{19}F, ^{138}La, ^{180}Ta, …)
while *current* solar neutrinos constrain Δm^2

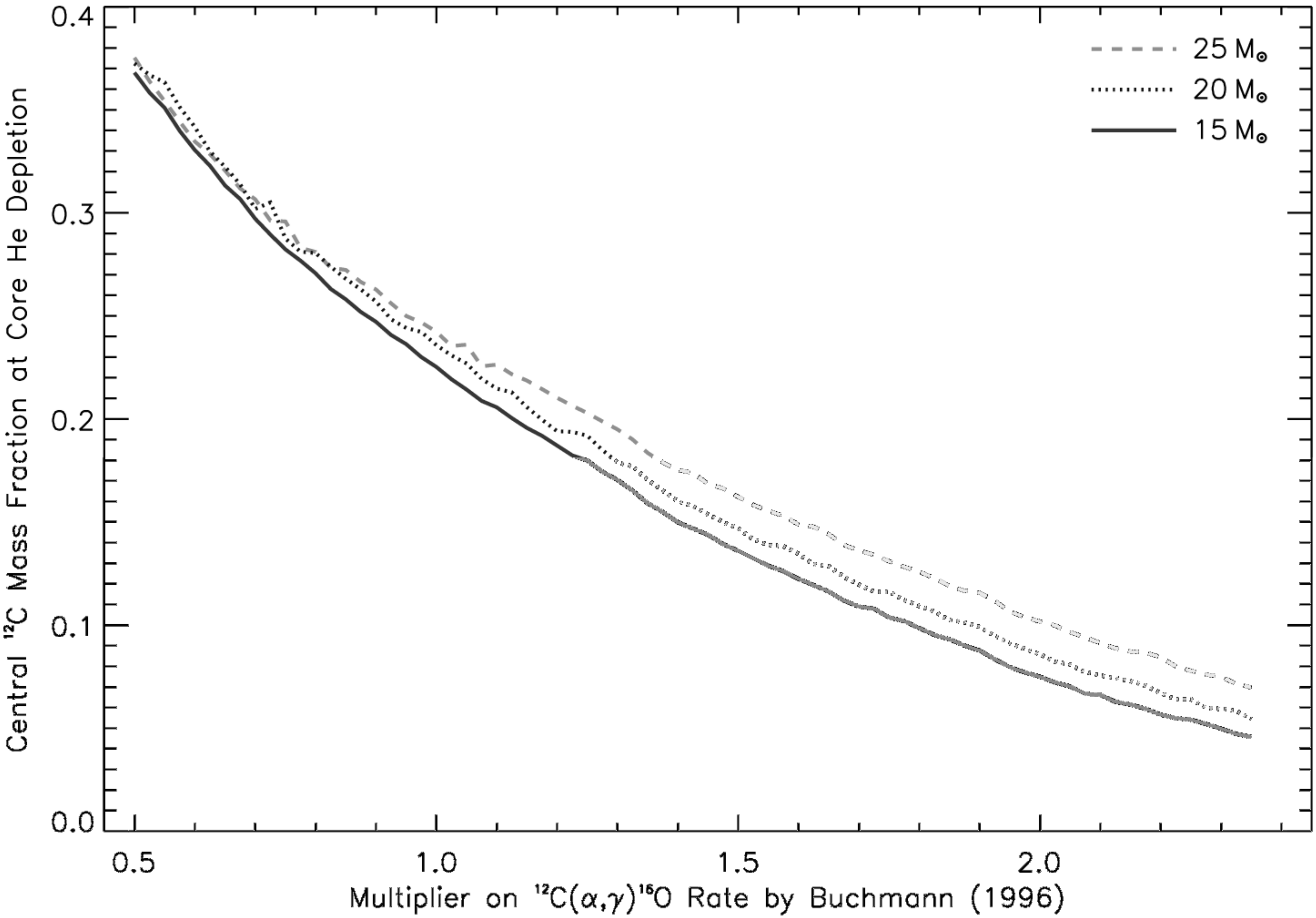
Nuclear Reaction Rate Uncertainties

…are some of the key uncertainties in current stellar evolution and nucleosynthesis modeling

- $^{12}C(\alpha,\gamma)^{16}O$

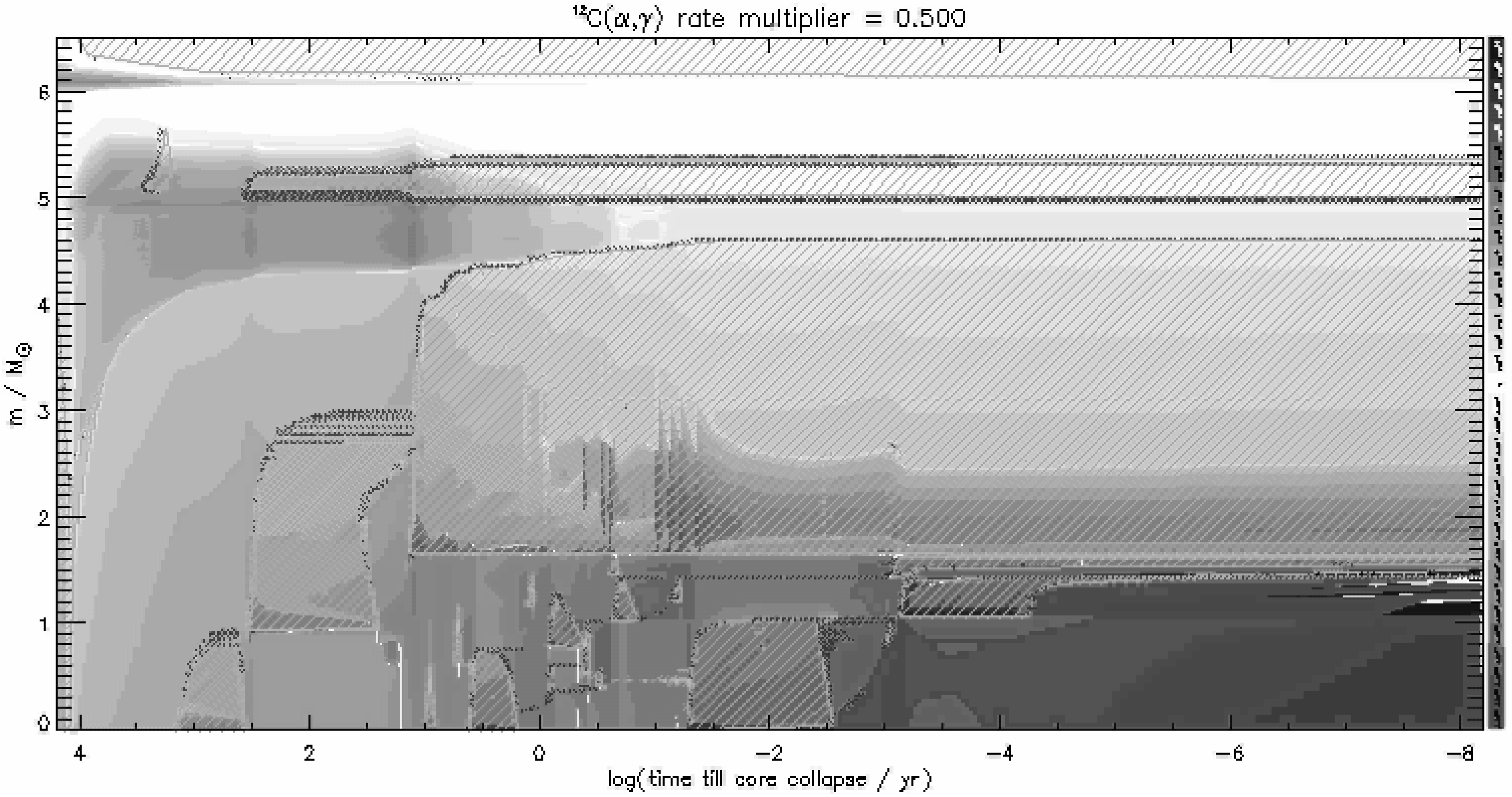


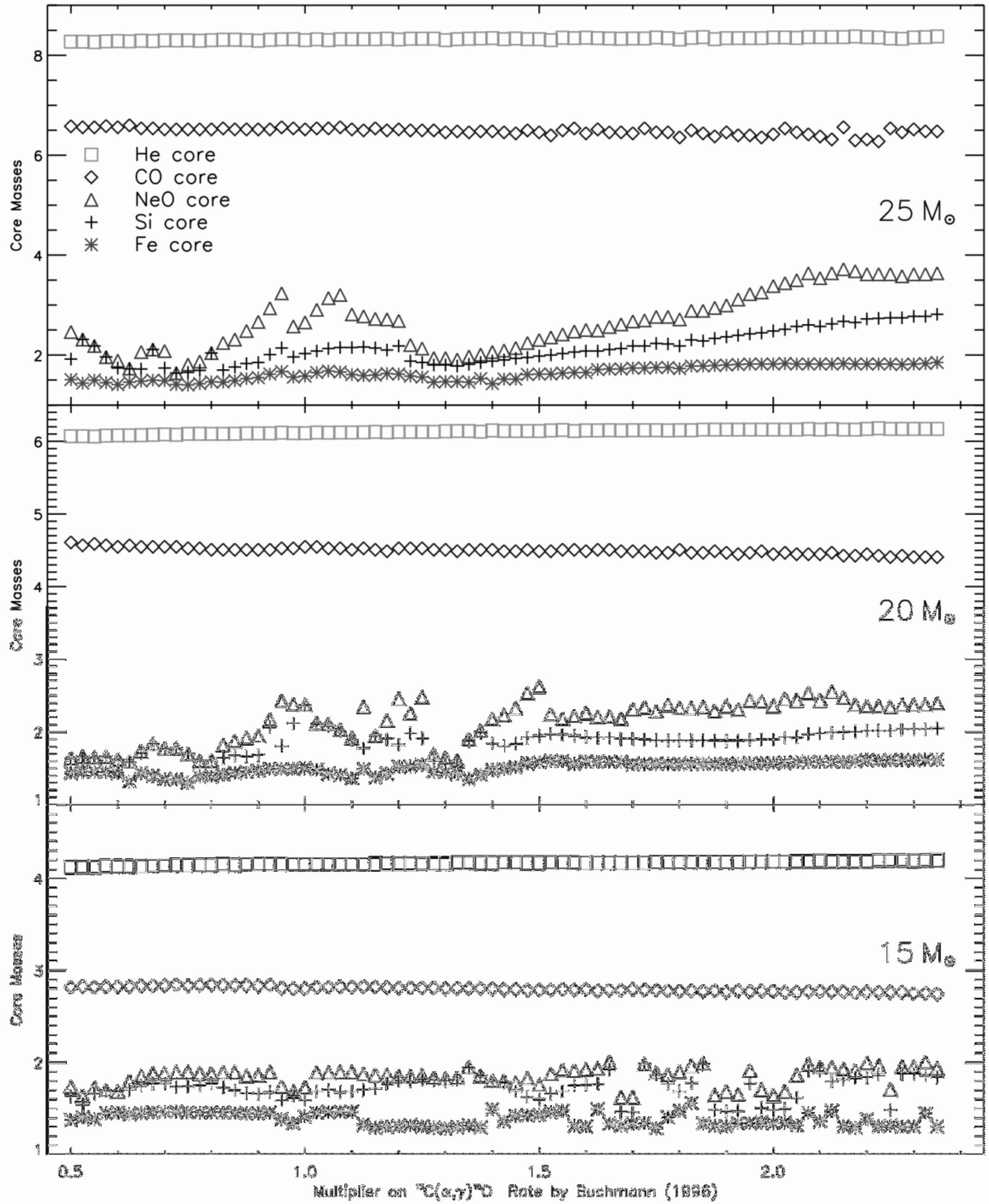
current uncertainty in $^{12}C(a,g)^{16}O$ rate is ±30% (1 s)

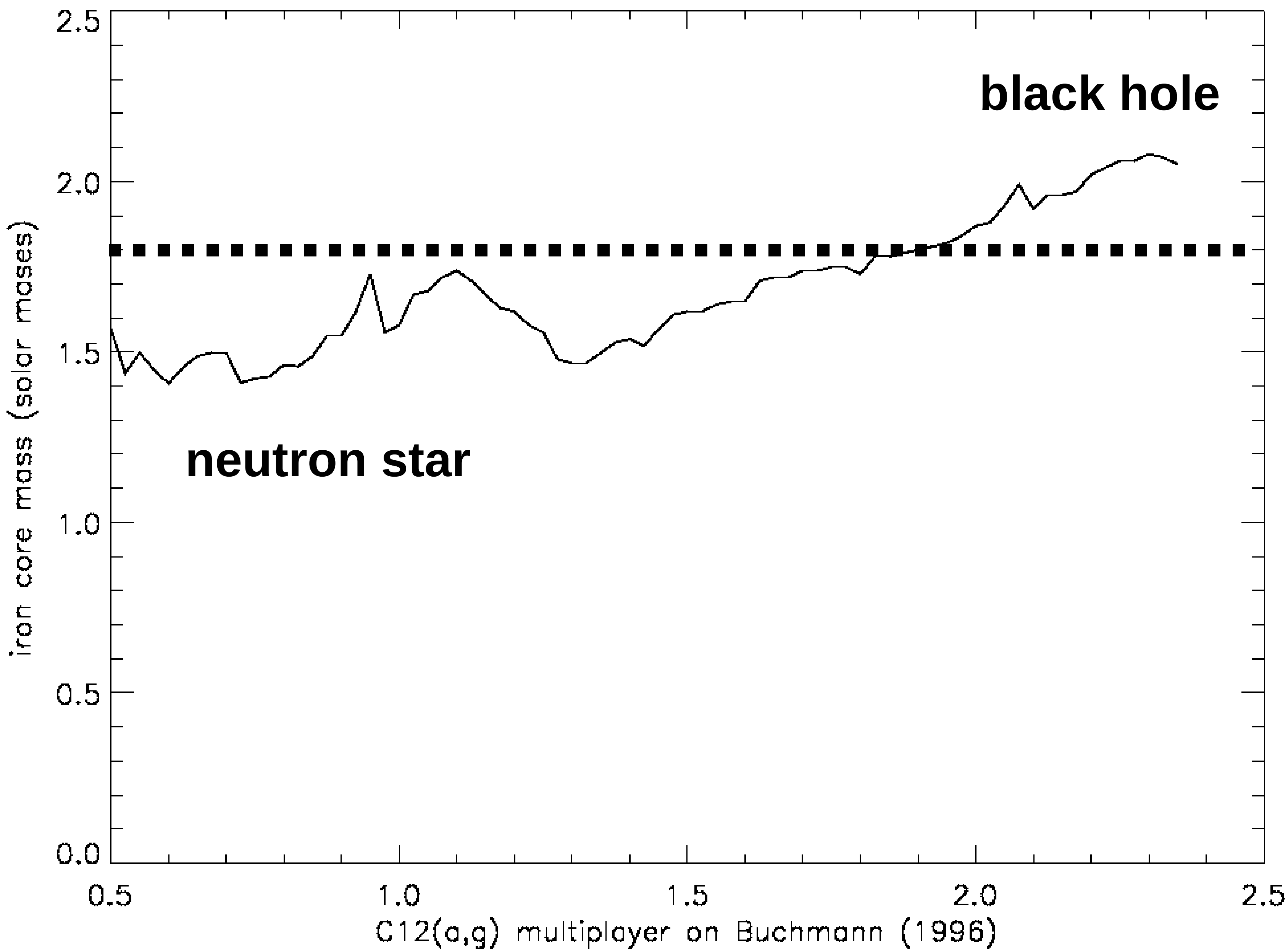


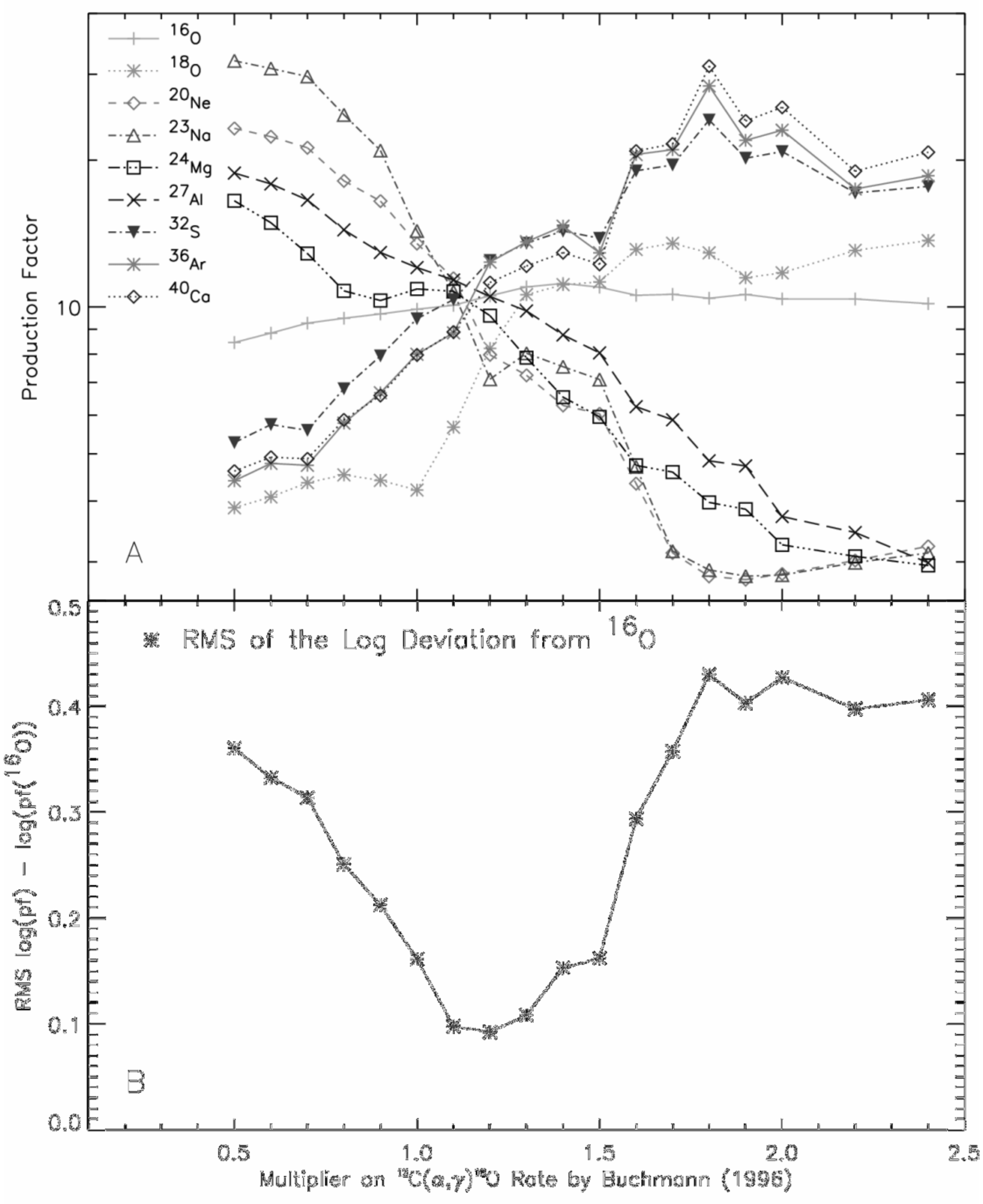
25 M⊙
20 M⊙
15 M⊙
Central ¹²C Mass Fraction at Core He Depletion
Multiplier on ¹²C(α,γ)¹⁶O Rate by Buchmann (1996)
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0

Variation of the $^{12}C(\alpha,\gamma)^{16}O$ rate in a $20 M_\odot$ star




He core
CO core
NeO core
Si core
Fe core
25 M⊙
20 M⊙
15 M⊙
Core Masses
Multiplier on ¹²C(α,γ)¹⁶O Rate by Buchmann (1996)


black hole
neutron star
iron core mass (solar mases)
C12(a,g) multiplayer on Buchmann (1996)
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5



try to fix the **^{12}C(α,γ)^{16}O** rate from nucleosynthesis constraints:

~1.2 x Buchmann's rate

or

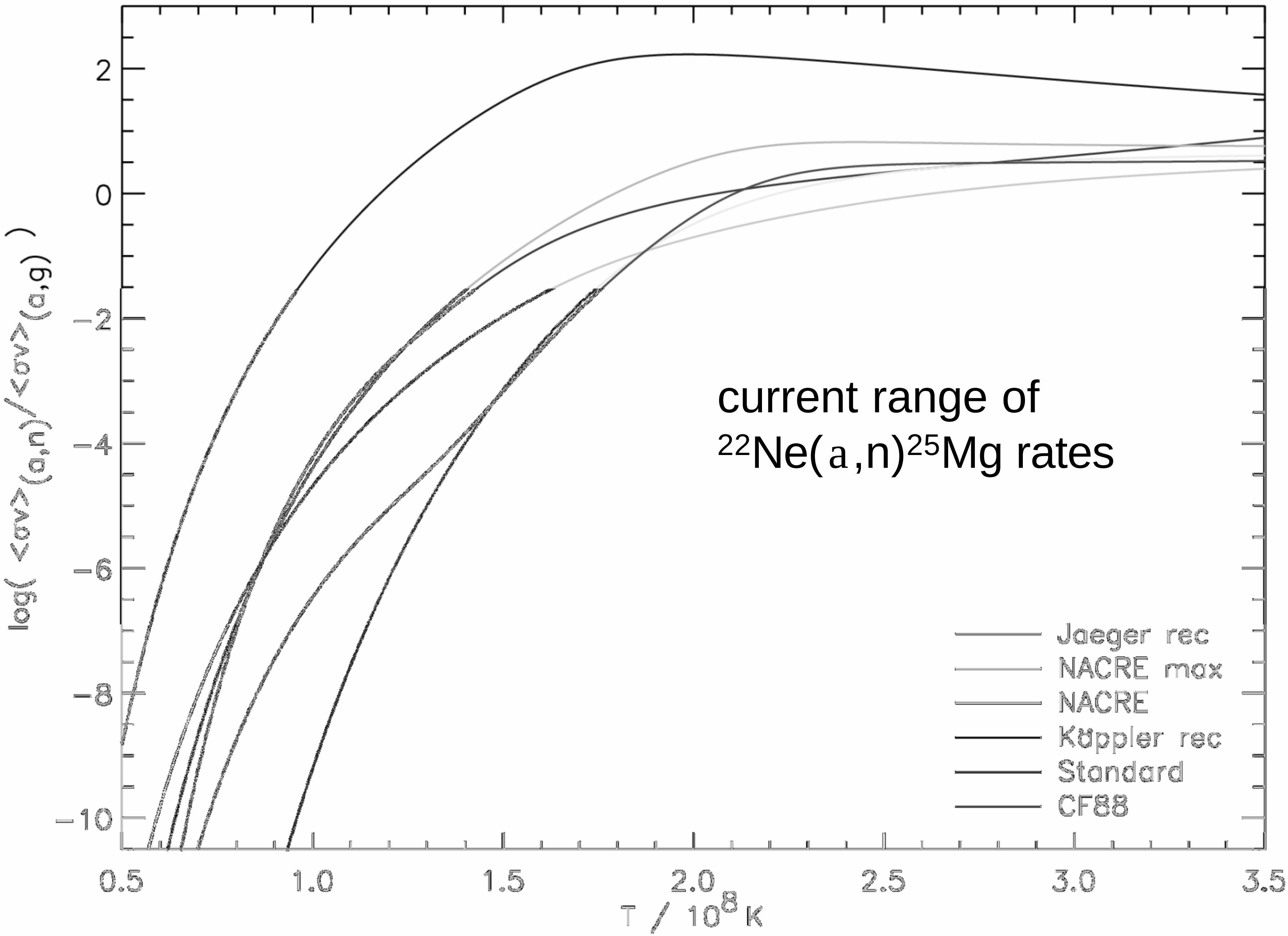
170 keV barn at 300 keV

Boyes, Heger & Woosley (2002)

Nuclear Reaction Rate Uncertainties

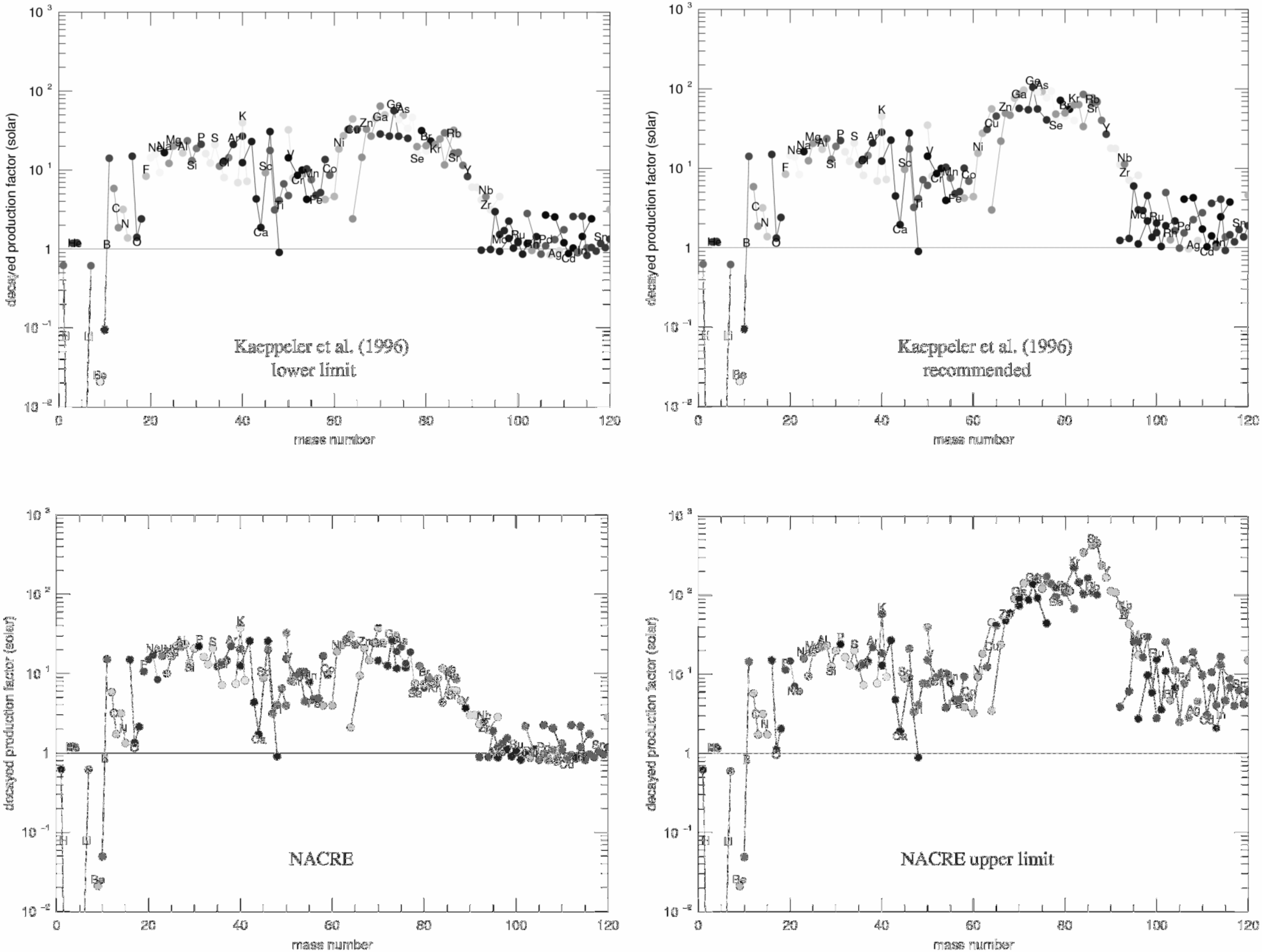
…are some of the key uncertainties in current stellar evolution and nucleosynthesis modeling

- $^{12}C(a,g)^{16}O$
- $^{22}Ne(a,n)^{25}Mg$



current range of
22Ne(a,n)25Mg rates
Jaeger rec
NACRE max
NACRE
Küppler rec
Standard
CF88
log(<σv>(a,n)/<σv>(a,g))
T / 10^8 K
2
0
−2
−4
−6
−8
−10
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Final Abundances 25 Msun



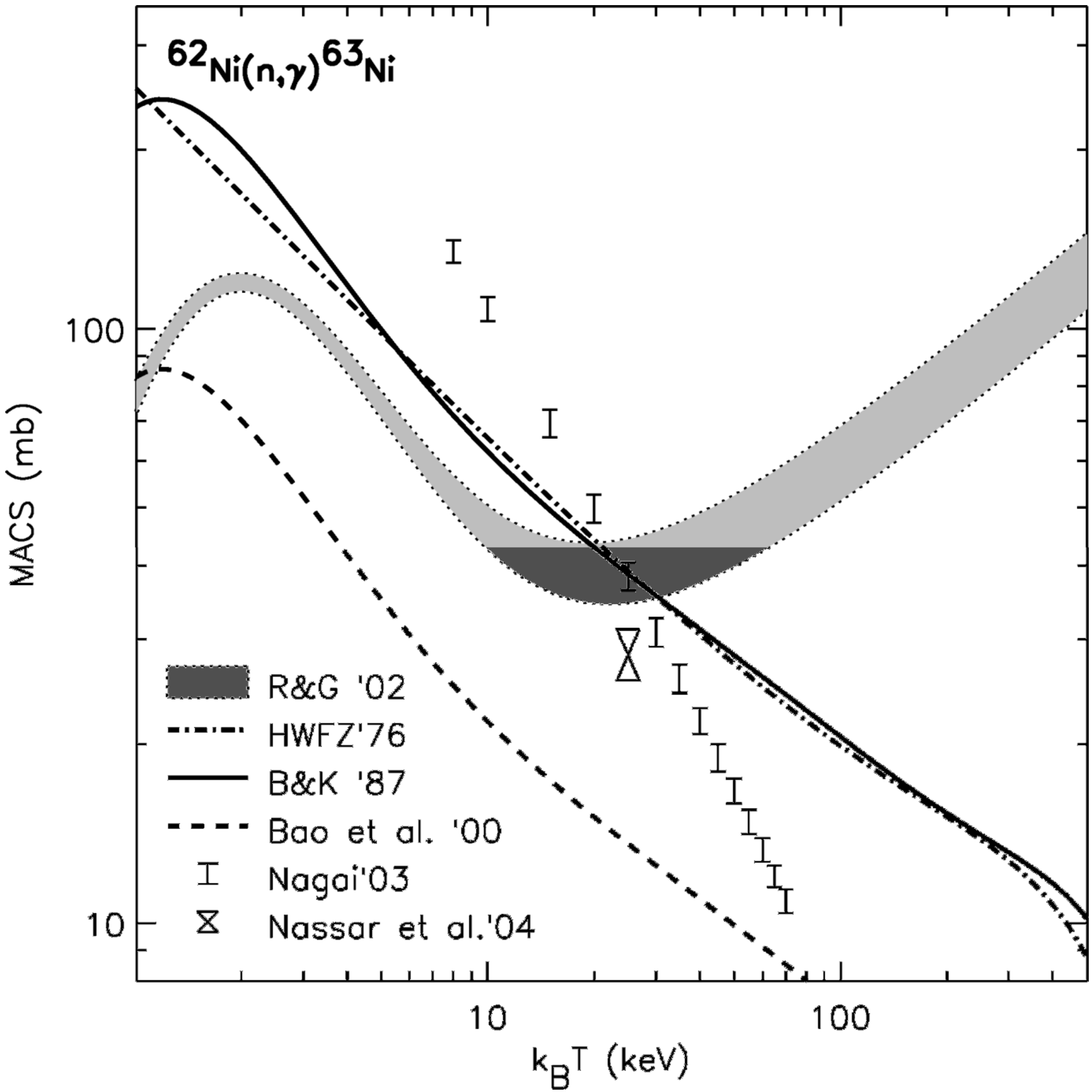
Nuclear Reaction Rate Uncertainties

…are some of the key uncertainties in current stellar evolution and nucleosynthesis modeling

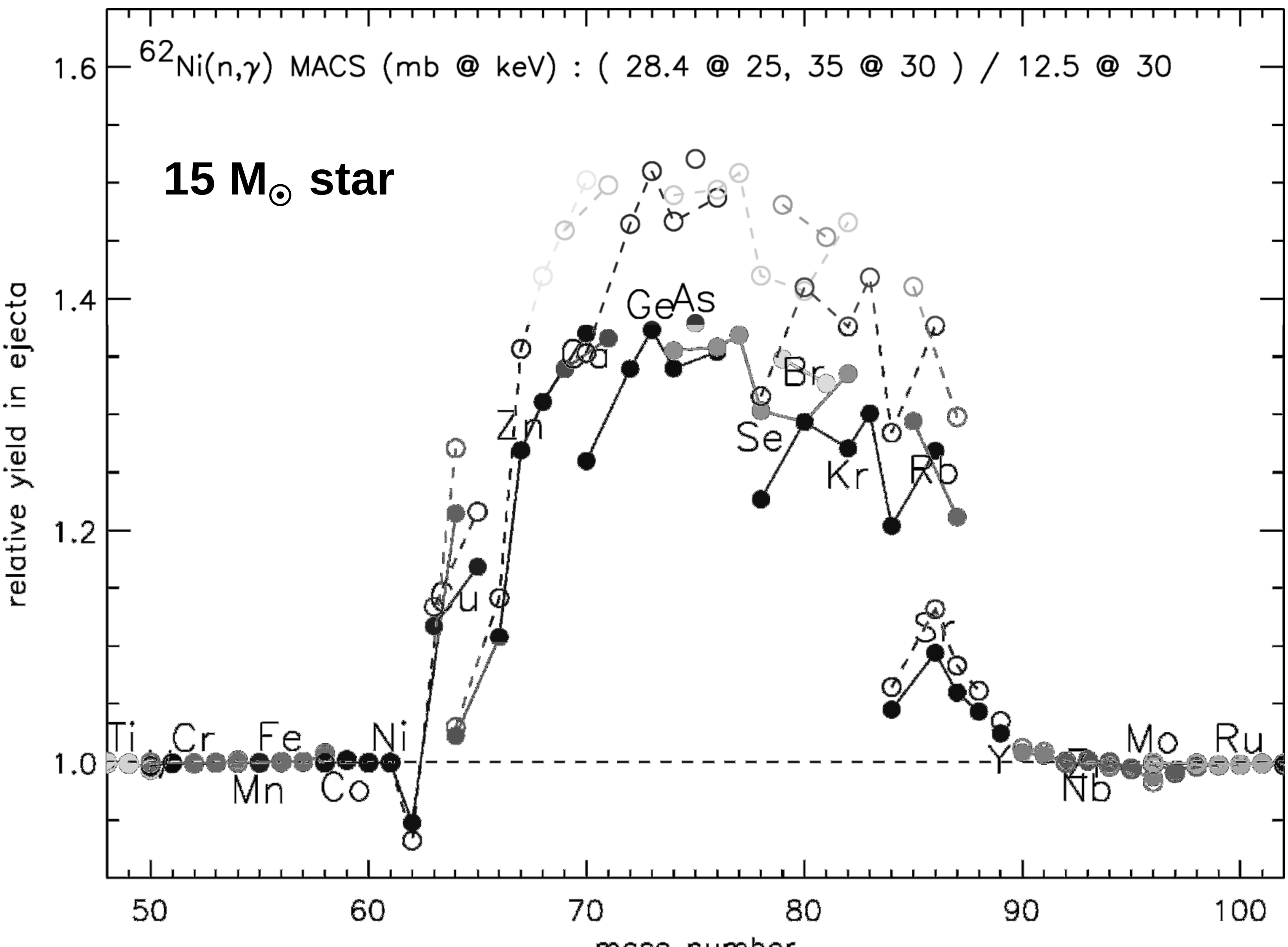
- ^{12}C(a,g)^{16}O

- ^{22}Ne(a,n)^{25}Mg

- ^{62}Ni(n,g)^{63}Ni



recent evaluations of the $^{62}Ni(n,g)^{63}Ni$ rate



^{62}Ni(n,γ) MACS (mb @ keV) : (28.4 @ 25, 35 @ 30) / 12.5 @ 30
15 M$_\odot$ star
relative yield in ejecta
mass number
1.6
1.4
1.2
1.0
50
60
70
80
90
100
Ti
Cr
Fe
Ni
Mn
Co
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru

Summary

Massive stars are the dominant source of oxygen most “heavier” material.

- Massive stars produce
  - Oxygen and other “alpha elements”
  - The *s*-process up to mass number ~90
  - The proton-rich nuclei by the g-process (^{11}B, ^{19}F, ^{180}Ta, …)
  - Rare and light isotopes by the ν-process (^{138}La, ^{11}B, ^{180}Ta, ^{19}F)
  - Possibly of being the site of the *r*-process
- ν-process is probe for SN n temperature and n oscillations
- Important uncertain nuclear reaction rates comprise
  - ^{12}C(a,g)^{16}O (stellar evolution calculations still favor 170 keV barn at 300 keV)
  - ^{22}Ne(a,n)^{25}Mg
  - ^{22}Ne(a,n)^{25}Mg / ^{22}Ne(a, g)^{26}Mg branching ratio
  - Neutron capture cross sections for weak *s*-process component