First Stars and First Galaxies, University of Texas, Austin, TX, March 9, 2010

The End of the First Stars

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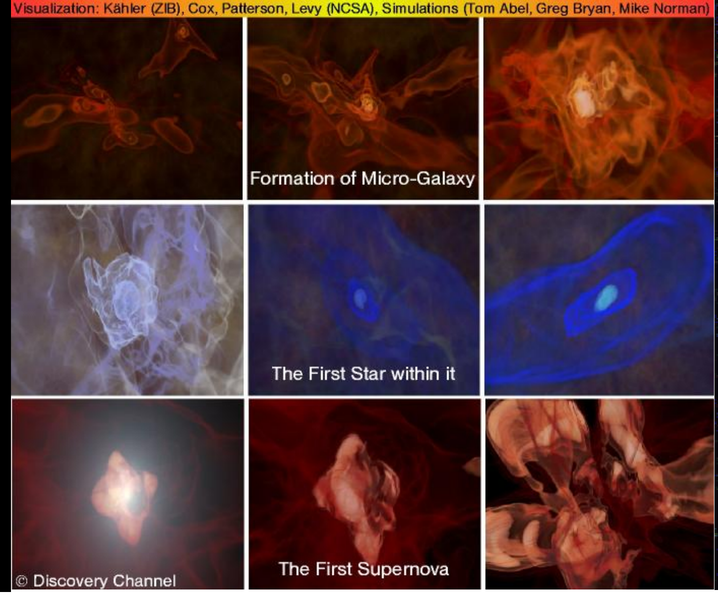
Overview

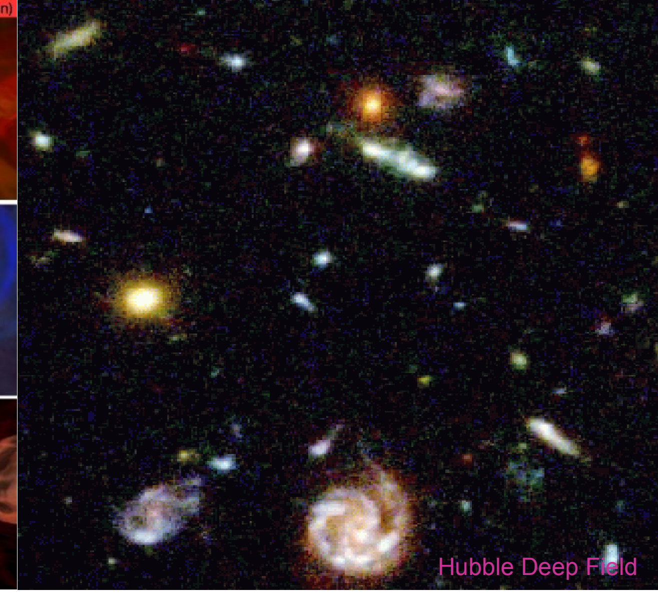
- **Varieties of Stellar Deaths**
- **Really Big Stars**
- **Nucleosynthesis Signatures**

Cosmic Dark Age

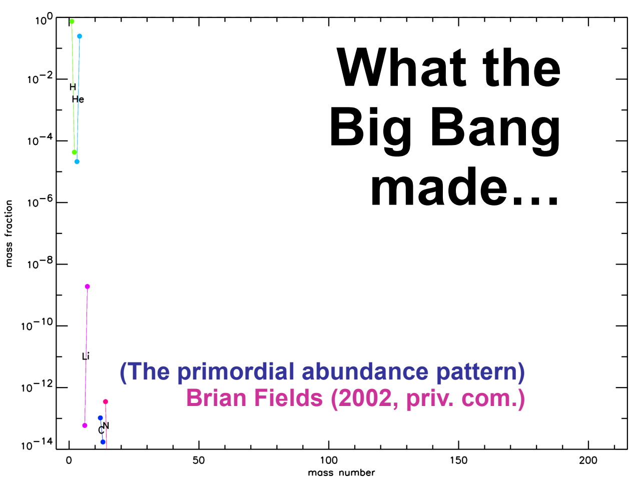
(after recombination)

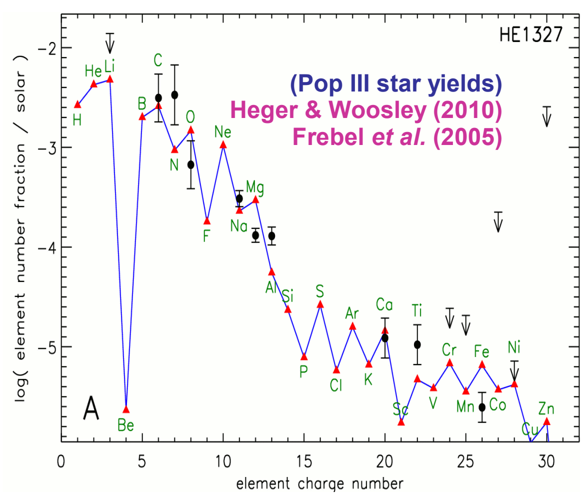
© Alexander Heger

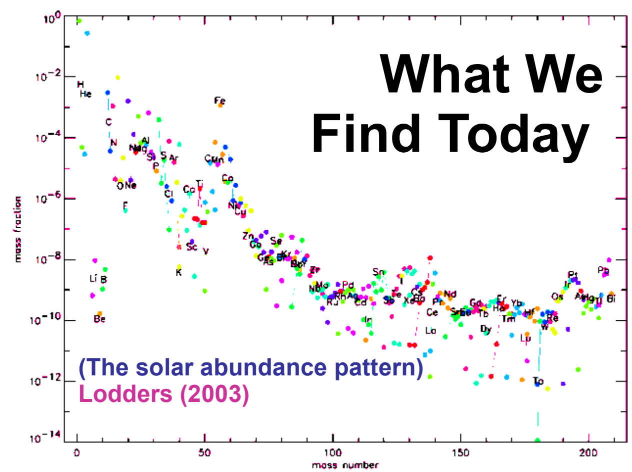




time







Formation and Properties of the First Stars

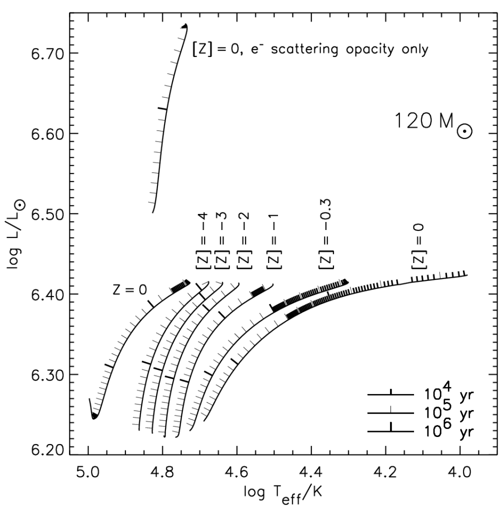
No metals ➔ no metal cooling ➔ more massive stars

(Bromm, Coppi, & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002;Nakamura & Umemura 2001; O'Shea & Norman 2006,...)

➔ typical mass scale ~100 $M_\odot$

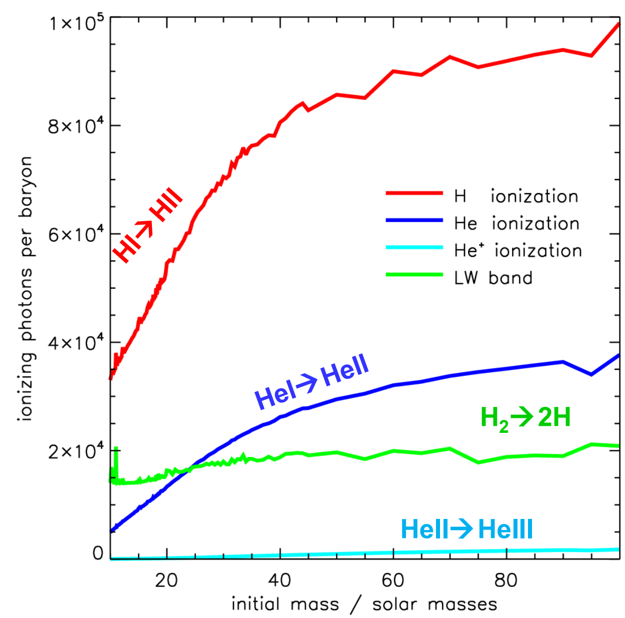
Heating by WIMP annihilation ➔ longer accretion ➔ **even bigger stars**

(Baraffe, Heger, & Woosley 2001)



First stars are very hot and very bright

➔ ionizing radiation



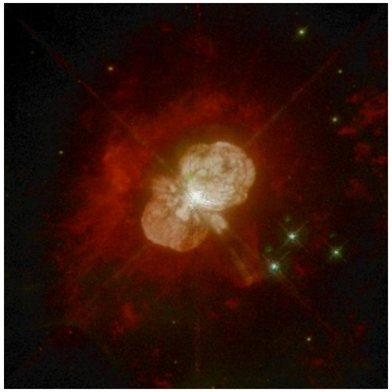
(Heger & Woosley 2007)

No metals ➔ no mass loss ➔ end life as massive stars?

Mass Loss in Very Massive Primordial Stars

- Negligible line-driven winds
  (mass loss ~ metallicity$^{>1/2}$ – Kudritzki 2002)
- No opacity-driven pulsations (no metals – Baraffe, Heger & Woosley 2001)
- Continuum-driven winds and errptions @ $L \sim L_{Edd}$ have to be explored (Smith, Owocki, Shaviv, *et al. 2005*++)
- Epsilon mechanism inefficient in metal-free stars below ~1000 M. (Baraffe *et al.* 2001)
  from pulsational analysis we estimate:
  - 120 solar masses: < 0.2 %
  - 300 solar masses: < 3.0 %
  - 500 solar masses: < 5.0 %
  - 1000 solar masses: < 12. %

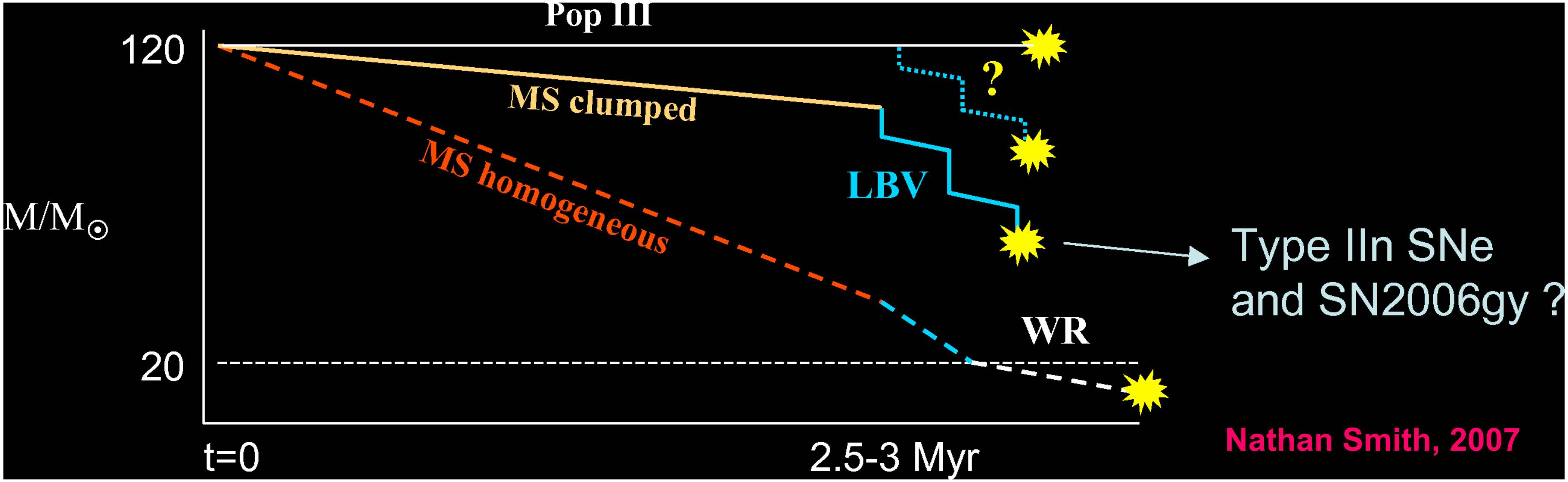
  during central hydrogen burning

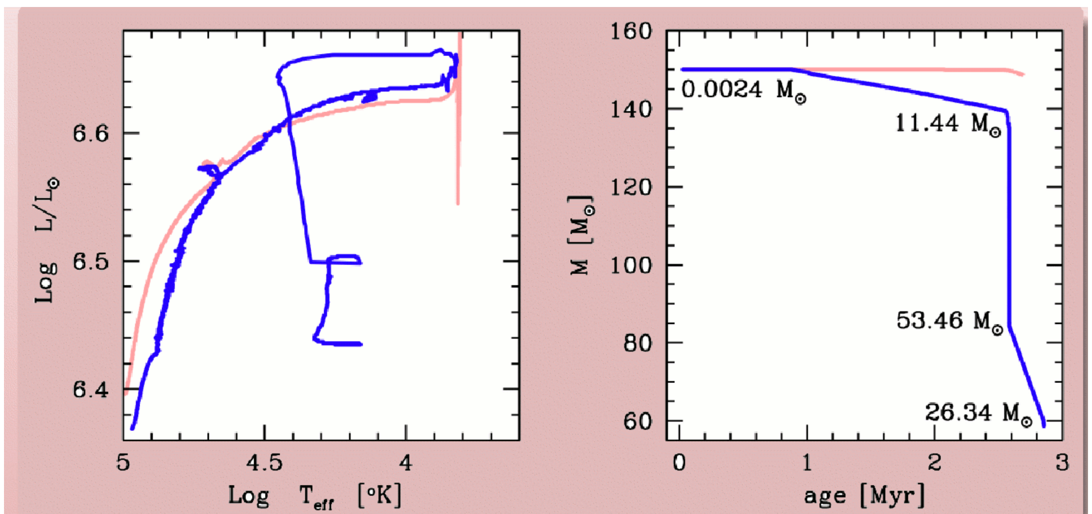


?

- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above ~500 M.
- Rotationally induced ***mixing*** and mass loss, giant eruptions, etc.?

Mass Loss by Giant eruptions?





end of central He-burning: $M = 58.05\ M_{\odot}$
back at break-up limit

Mass Loss due to critical rotation?

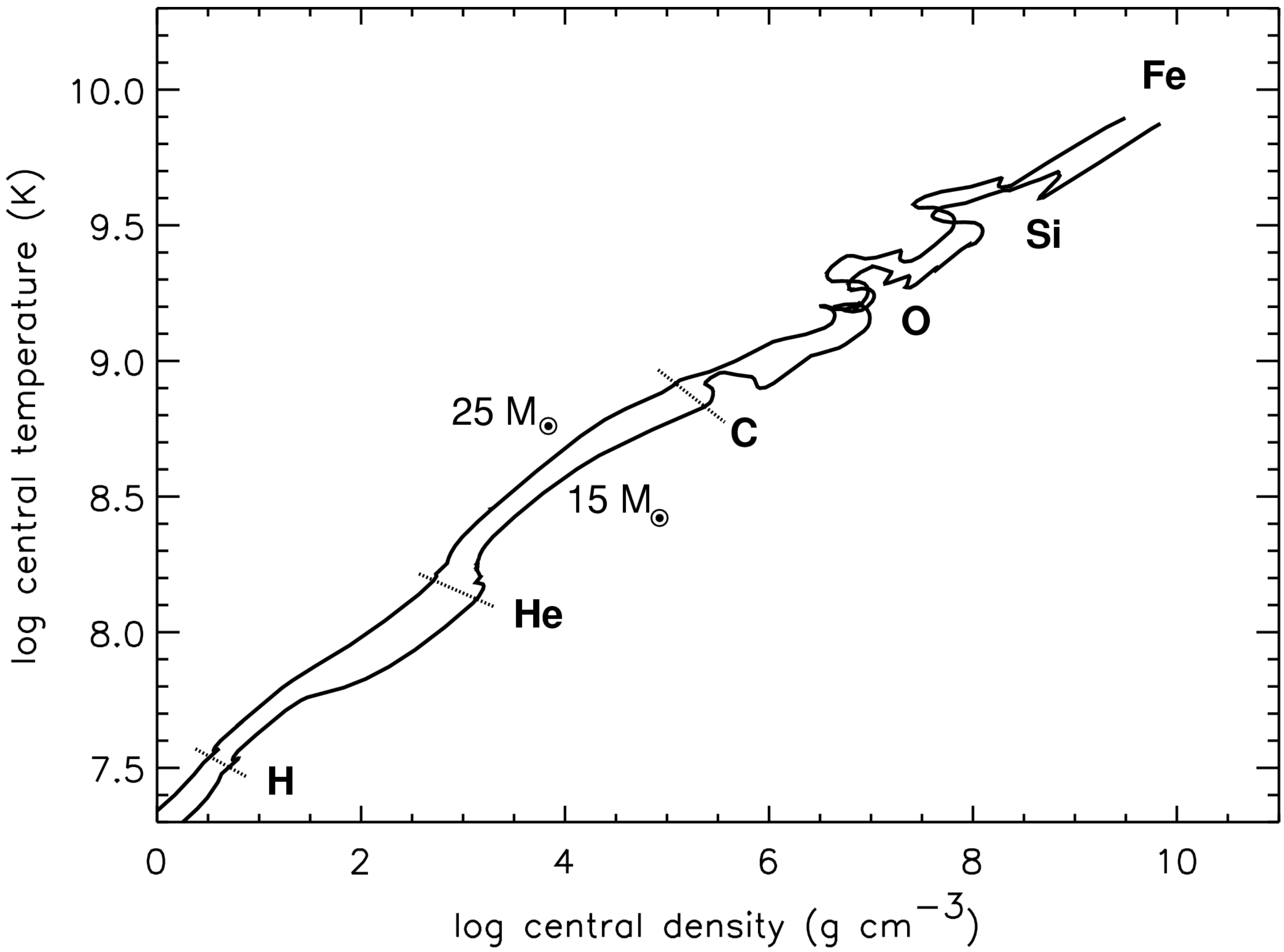
Eikstroem, 2007

What is the fate of the first stars?

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

continuing contraction

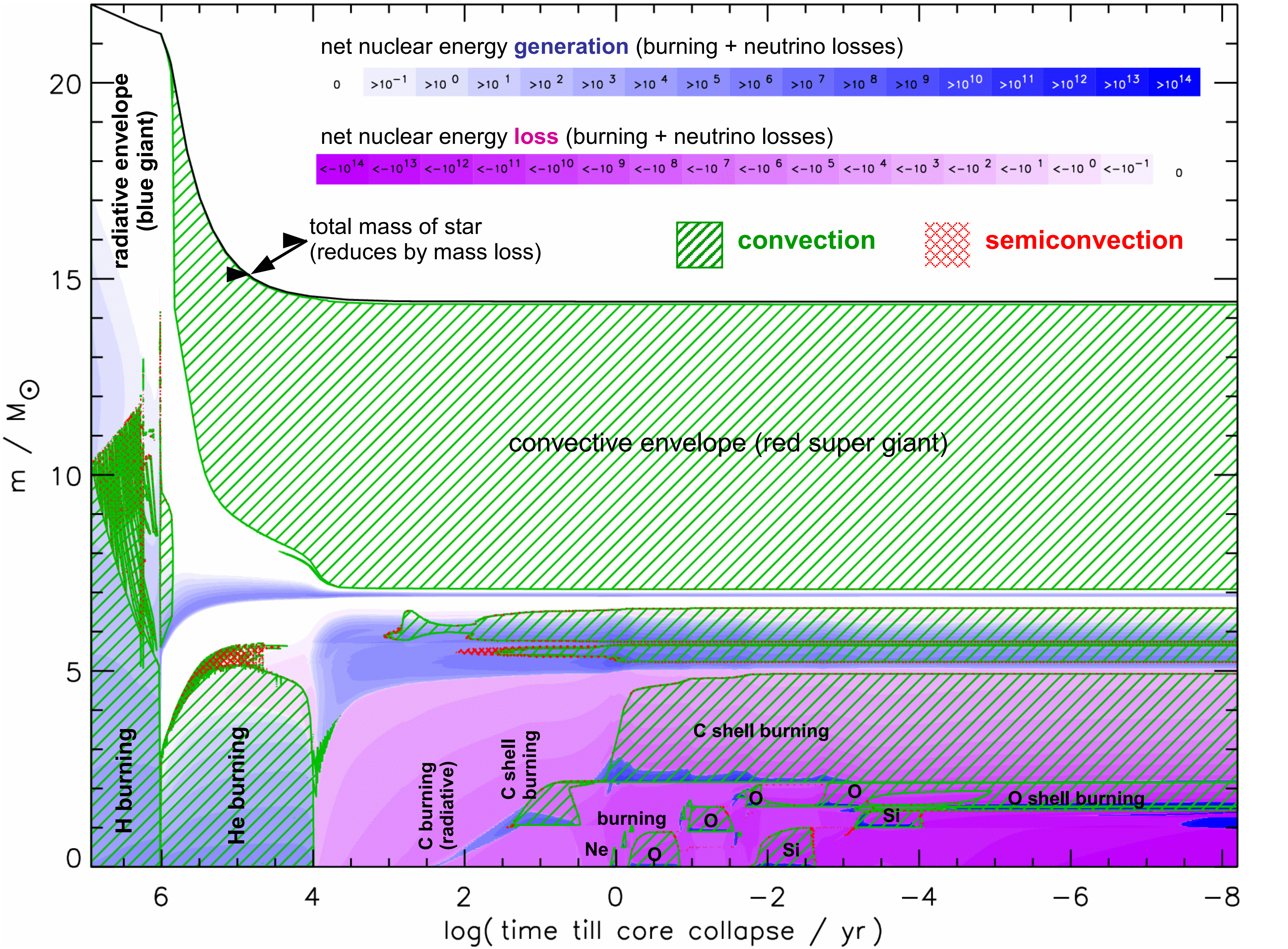
to higher central densities and temperatures



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

Nuclear burning stages

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}


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

(a miracle occurs)

Supernova Explosion

Explosive Nucleosynthesis

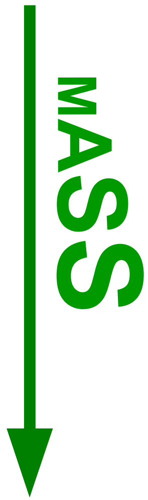
in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process	-	>10 low Y_e	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), (α,γ)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

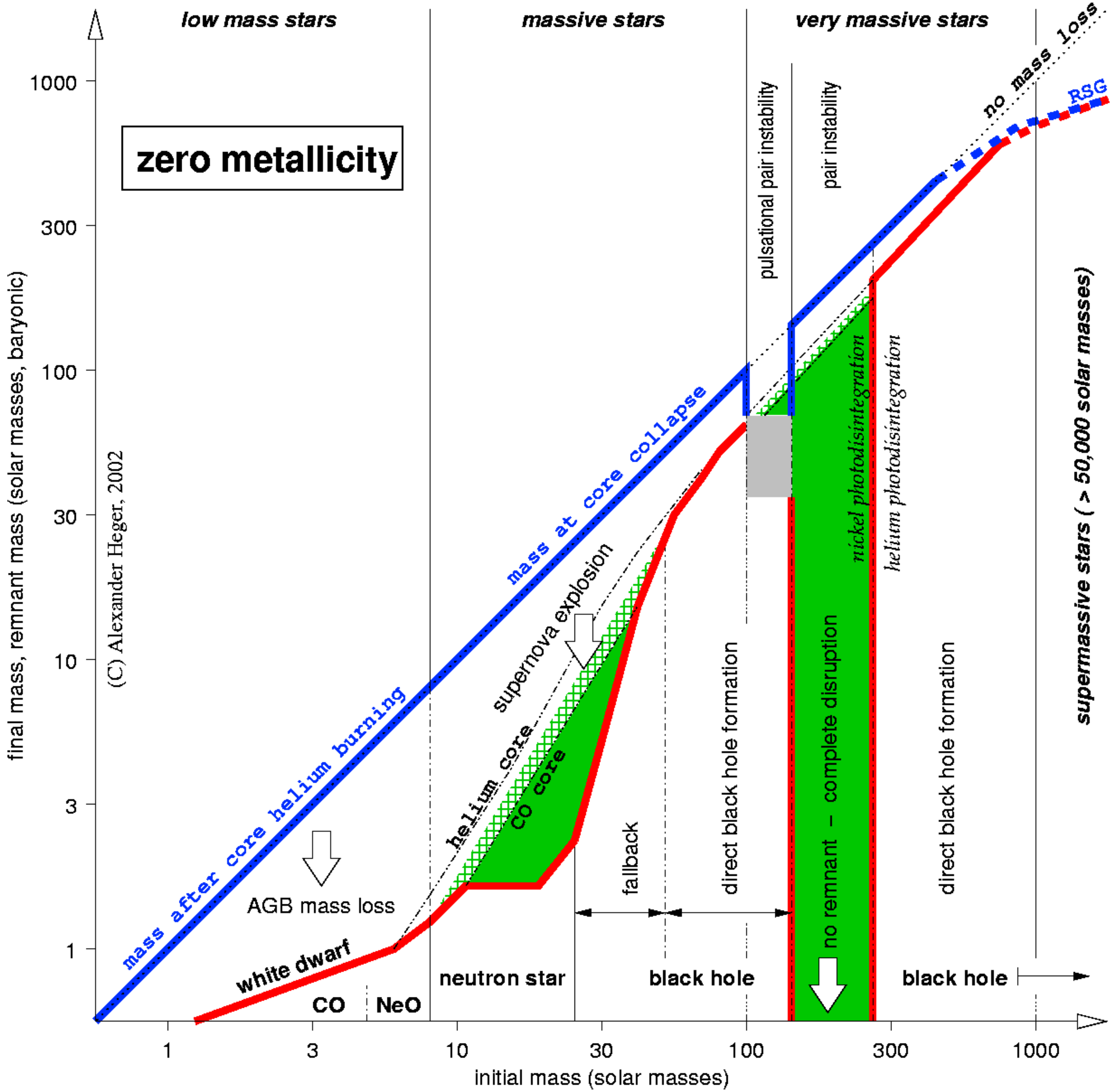
Things that blow up

supernovae


$1B = 10^{51}$ erg

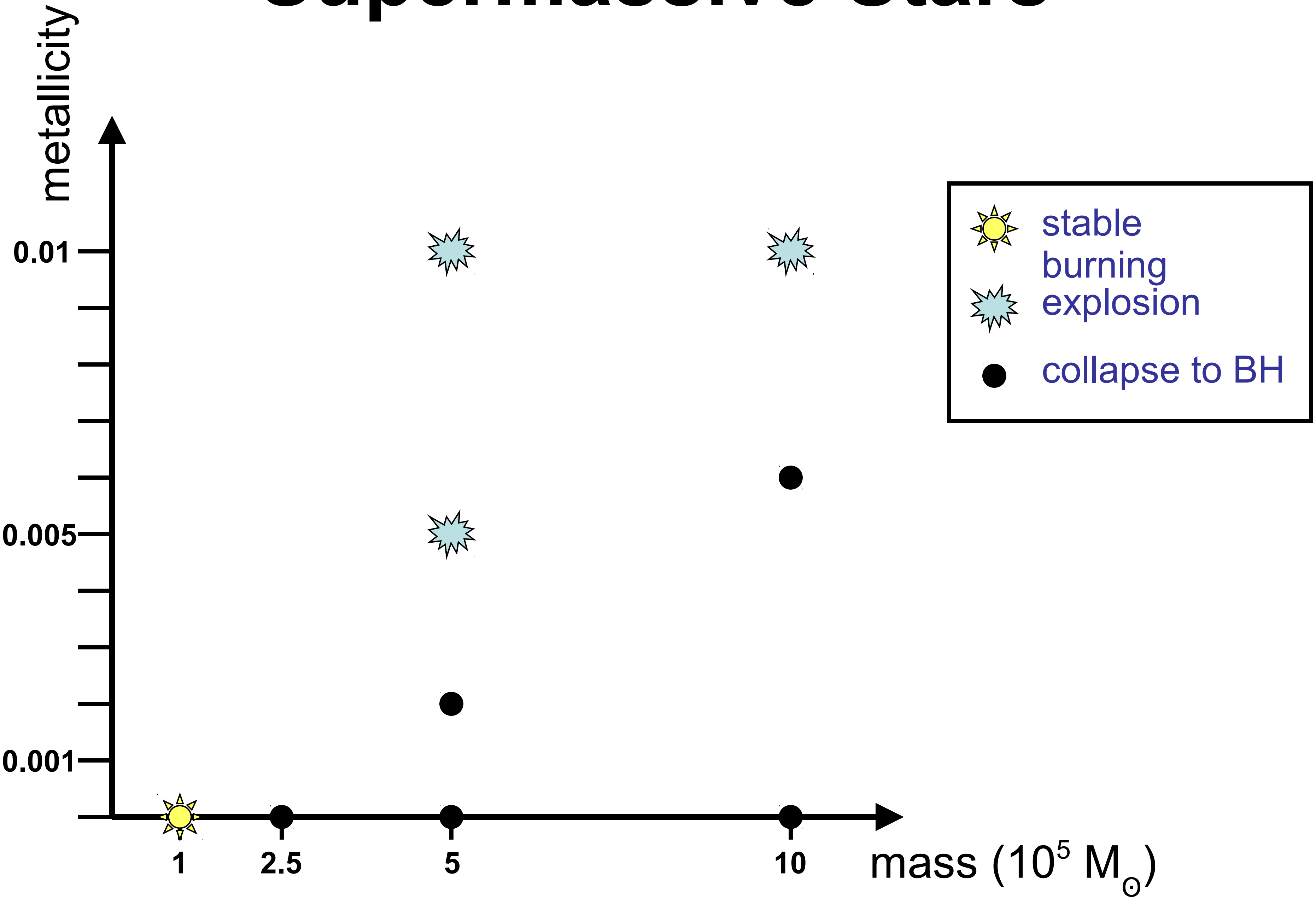


- CO white dwarf ➔ Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B ($1B=10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN, SMBH
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH



Ejected "metals"

Supermassive Stars



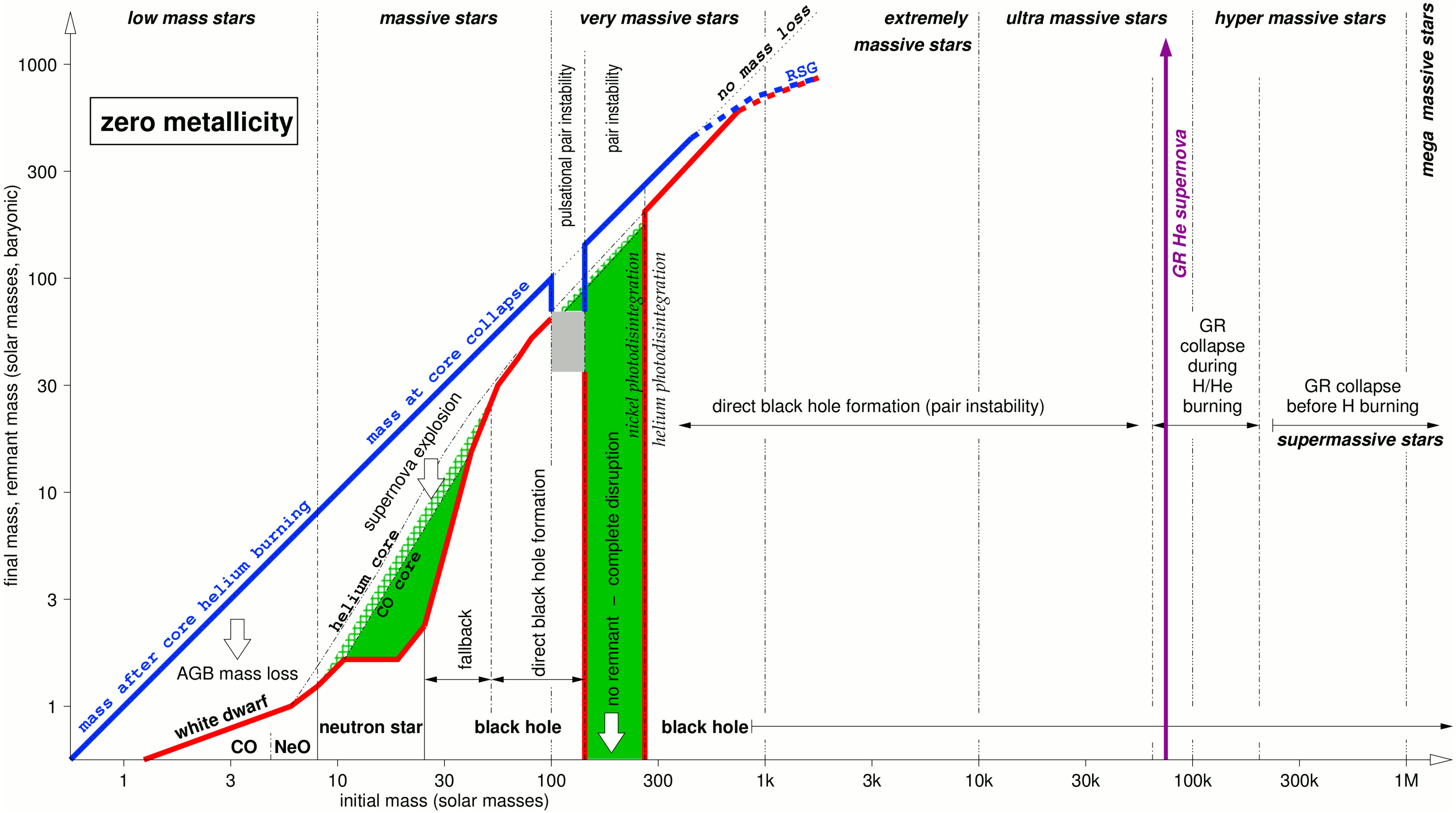
(after Fuller, Woosley, & Weaver 1986)

Supermassive Stars

Can they ever form?

- Collapse due to GR instability (γ_{crit} >4/3)
- Pop III: for M ~ 75,000 $M_\odot$:
  Collapse during H/He burning
- Pop III: for M ~ 150,000 $M_\odot$:
  Collapse before hydrogen burning
- Pop III: for M ~ 80,000 $M_\odot$:
  GR He supernova, E = 150 B

Supermassive Stars

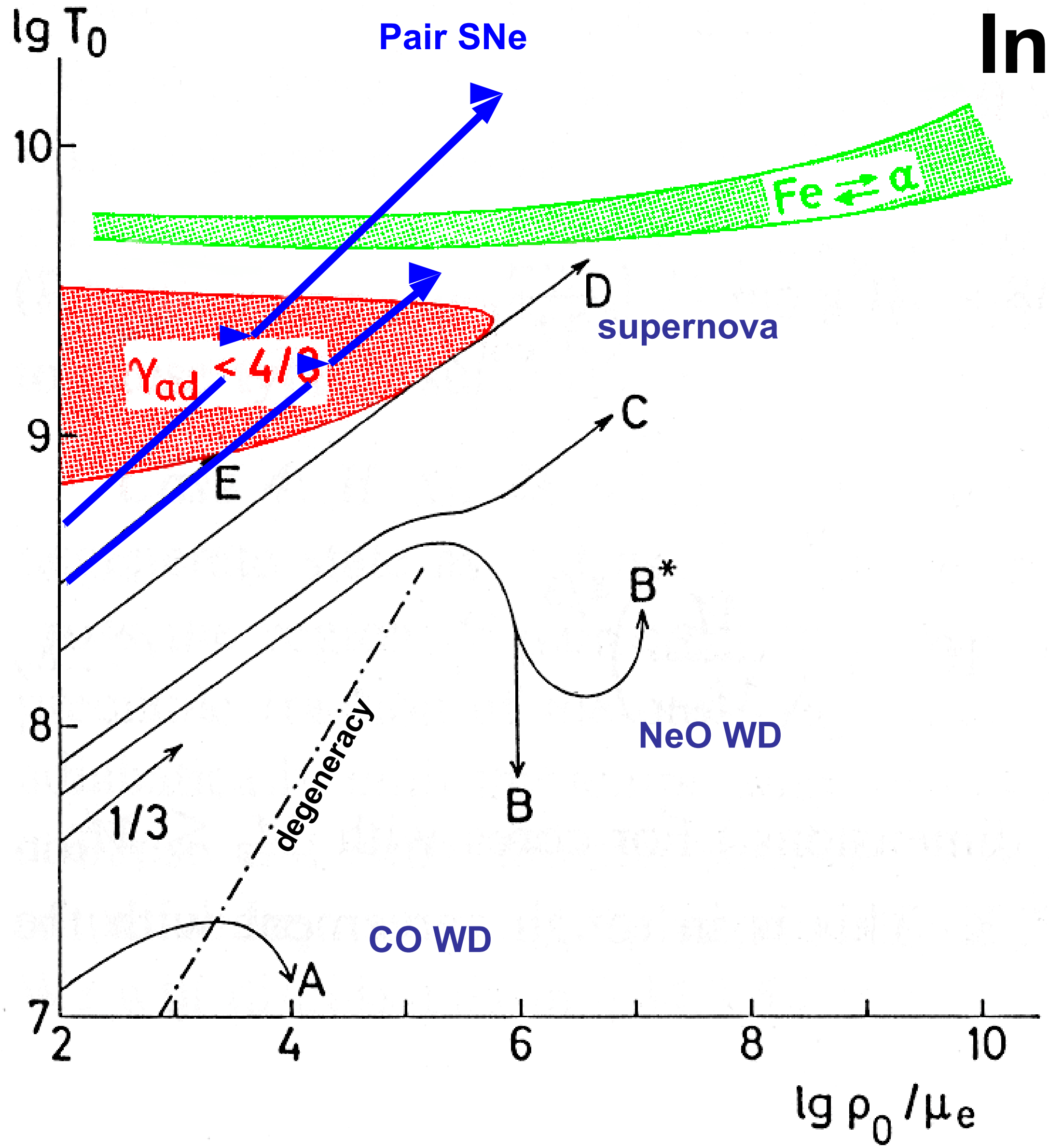


Pair-Instability Supernovae

Many studies in literature since more than 3 decades, e.g.,
Rakavy, Shaviv, & Zinamon (1967)
Bond, Anett, & Carr (1984)
Glatzel, Fricke, & El Eid (1985)
Woosley (1986)

Some recent calculations:
Umeda & Nomoto 2002
Heger & Woosley 2002

Instability Regimes



Kippenhahn & Weigert (1990)

adiabatic index < 4/3

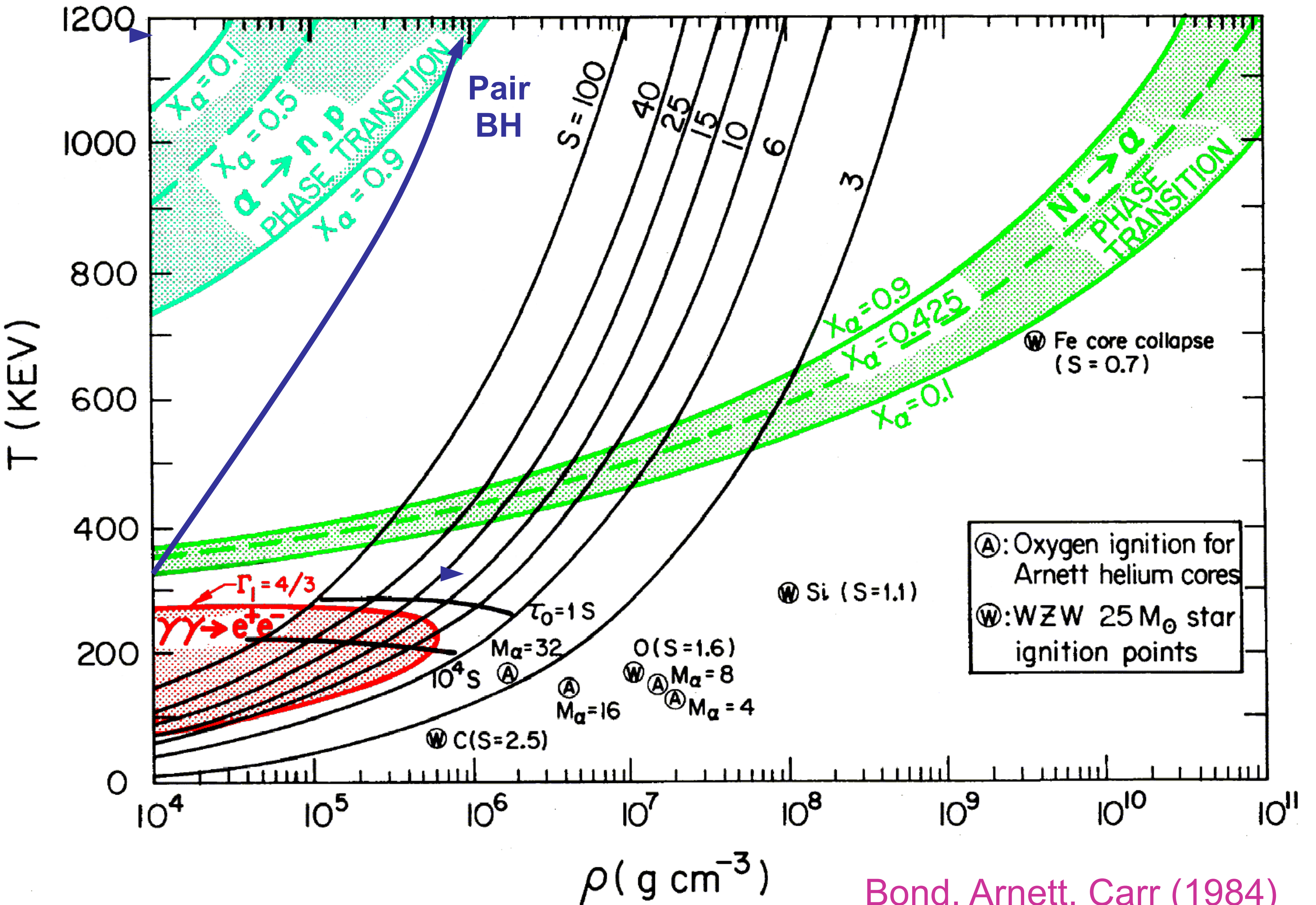
Compression does not result in sufficient increase in pressure (gradient) to balance higher gravity at lower radius

e^+/e^--Pair Instability

Internal gas energy is converted into e^+/e^- rest mass (hard photons from tail of Planck spectrum)

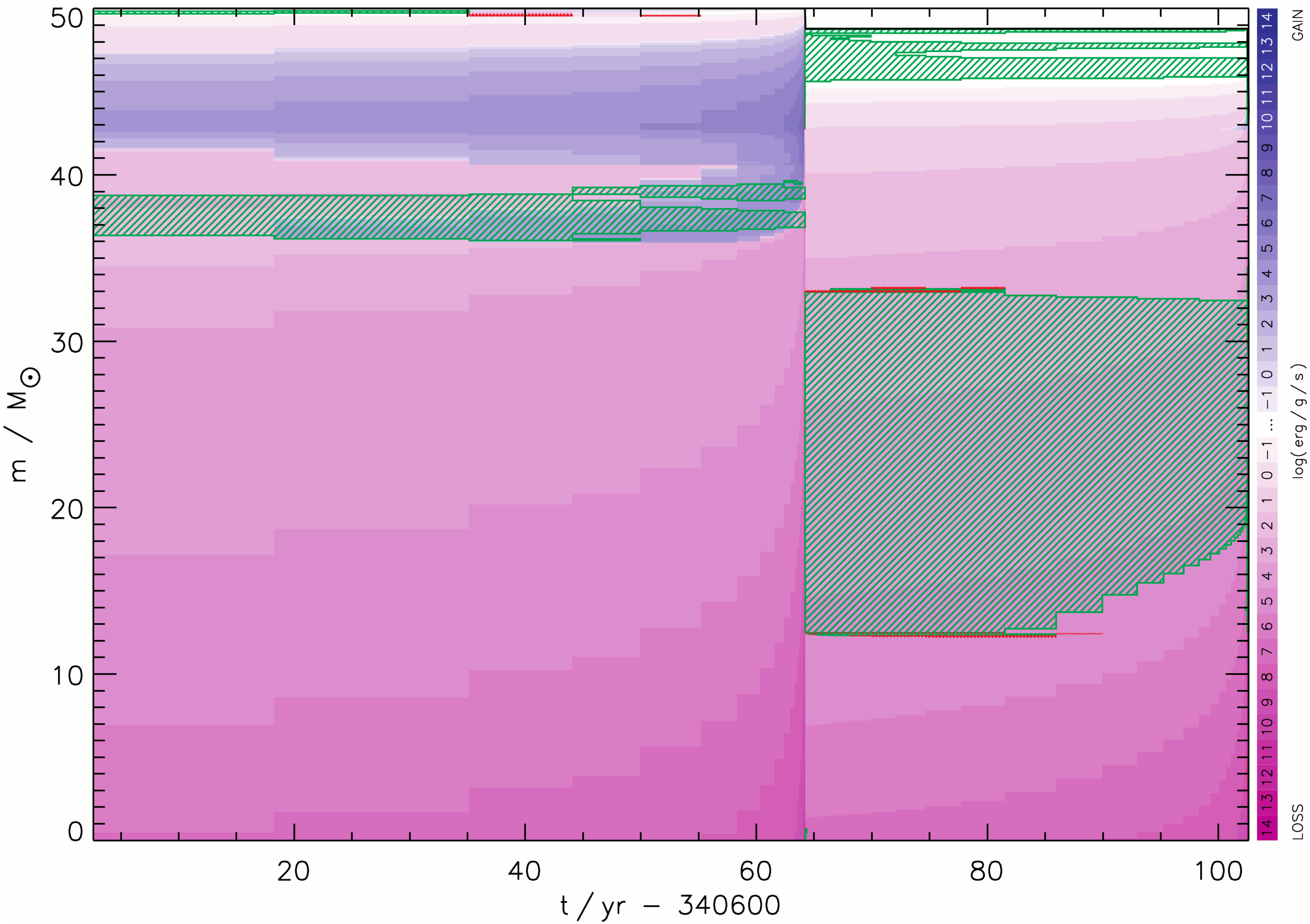
Photo disintegration

Internal gas energy is used to unbind heavy nuclei into alpha particles and at higher temperature those into free nucleons

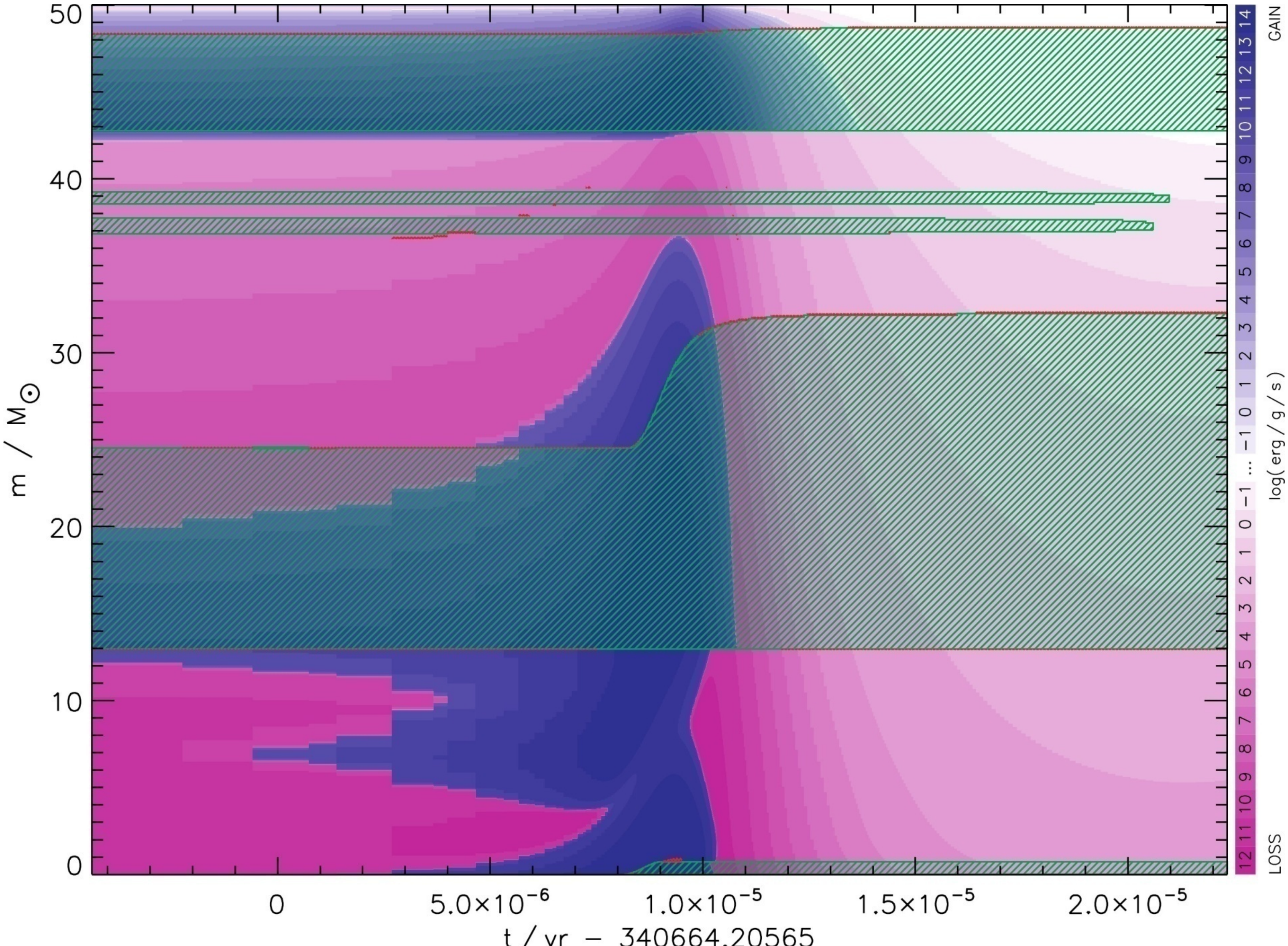


Bond, Arnett, Carr (1984)

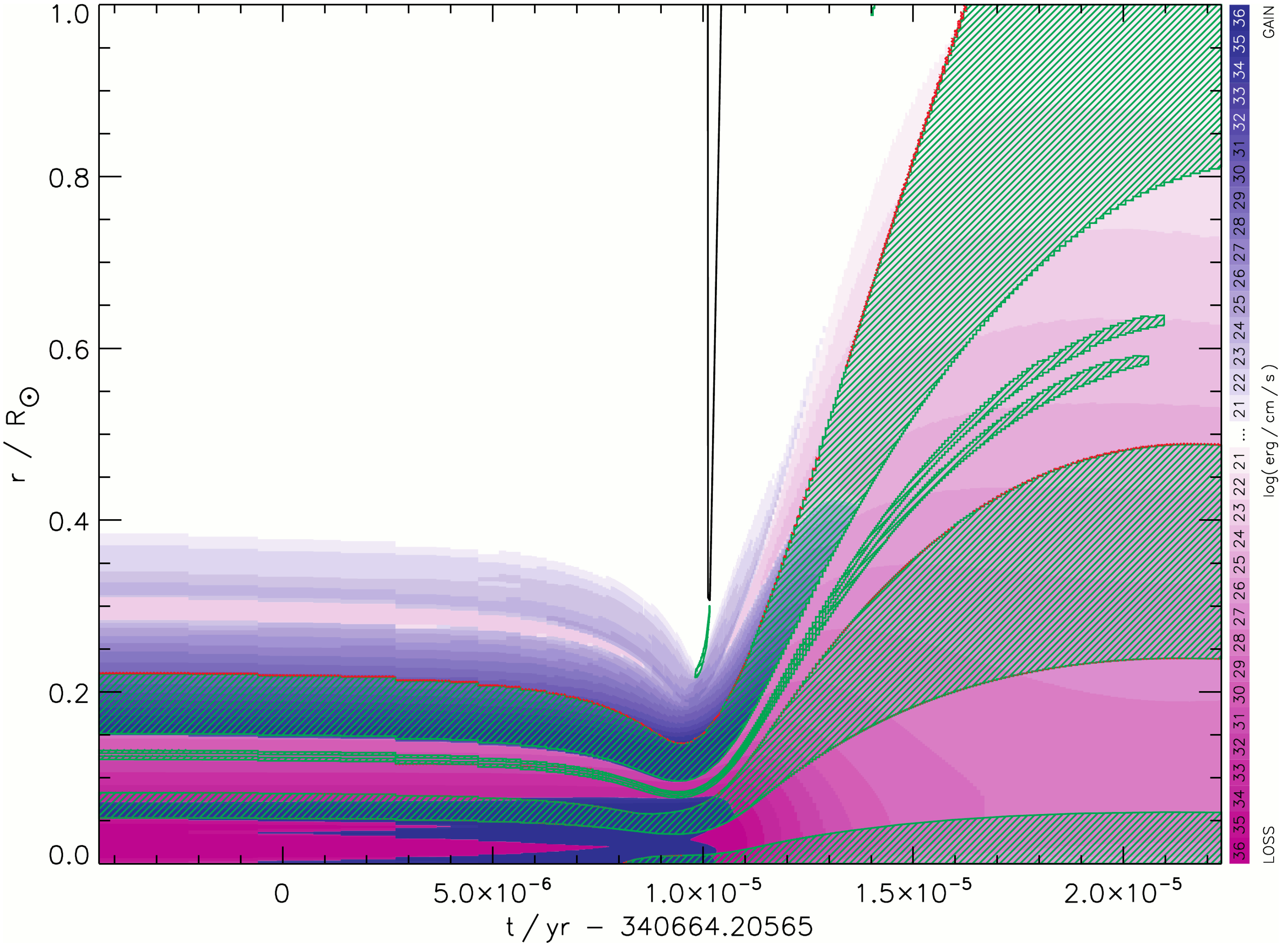
Last 100 yr of a 110 $M_\odot$ Star



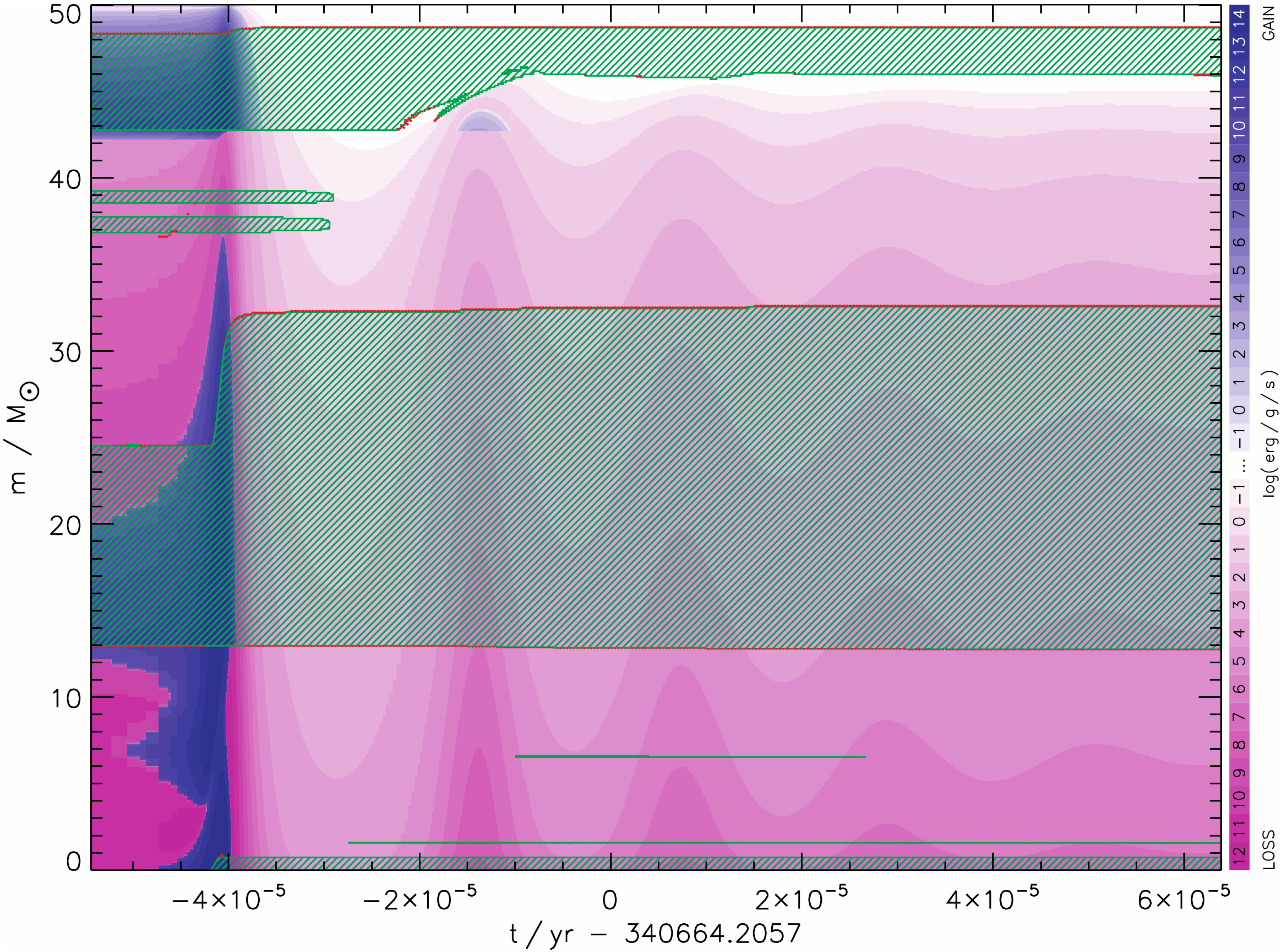
First Pulse of a 110 $M_\odot$ Star



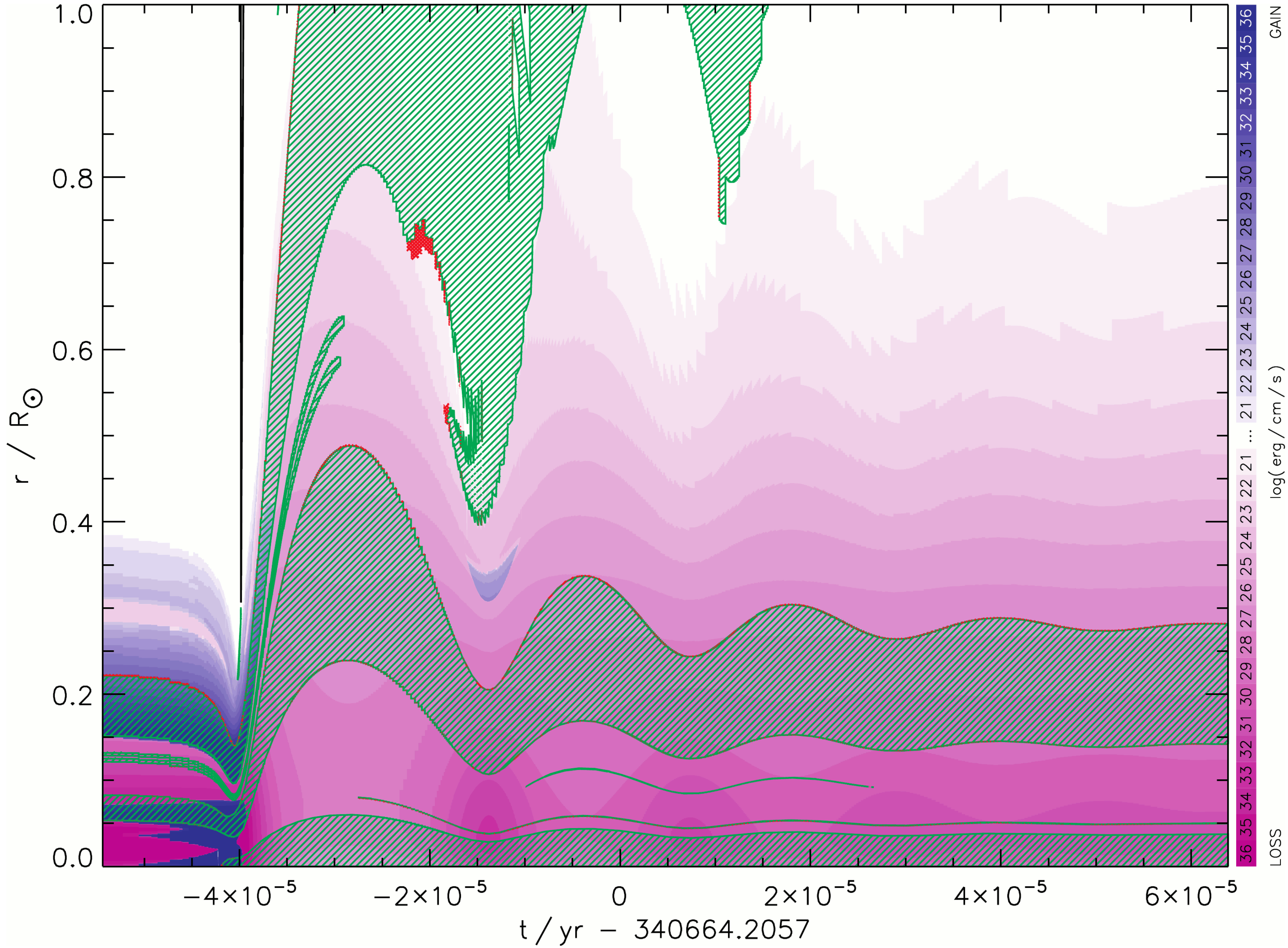
First Pulse of a 110 $M_\odot$ Star



First Pulse of a 110 $M_\odot$ Star - Ringdown



First Pulse of a 110 M☉ Star - Ringdown



Pulsational Pair Instability Supernovae

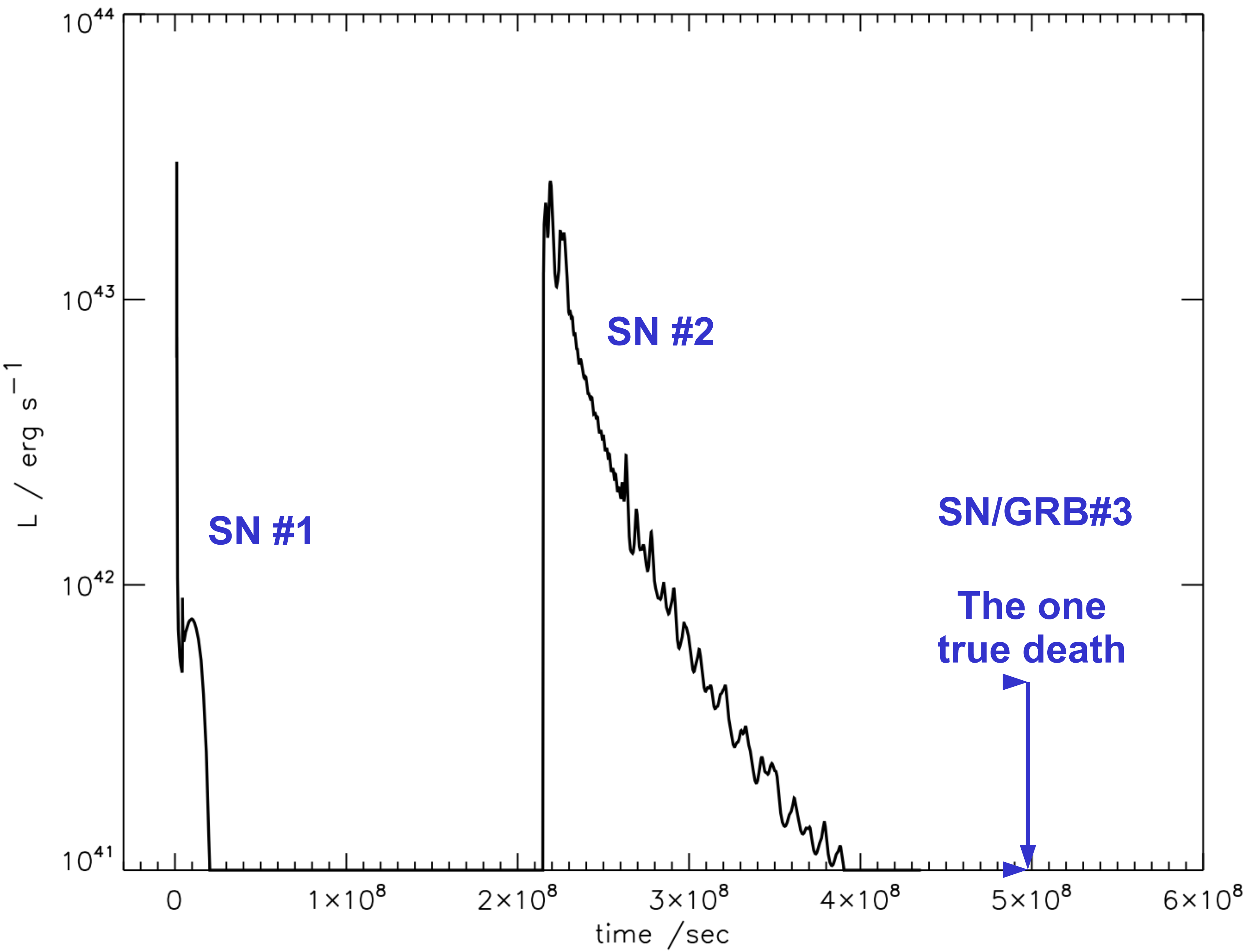
Range of recurrence time, irregular, days to 10,000 yr
- interaction of different burning phases (Ne, O, Si)
- burning to different degrees
- burning locations (central, shell)
- energy of pulse determines cooling time and mechanism:
  - low E ➔ low S ➔ compact, hot ➔ ν cooling
  - high E ➔ high S ➔ cool star ➔ γ cooling only, τ_{KH}

after pulse: ring-down by ν dampening and mechanical dampening by shocks/ejecta from surface of core

ejection of outer layers

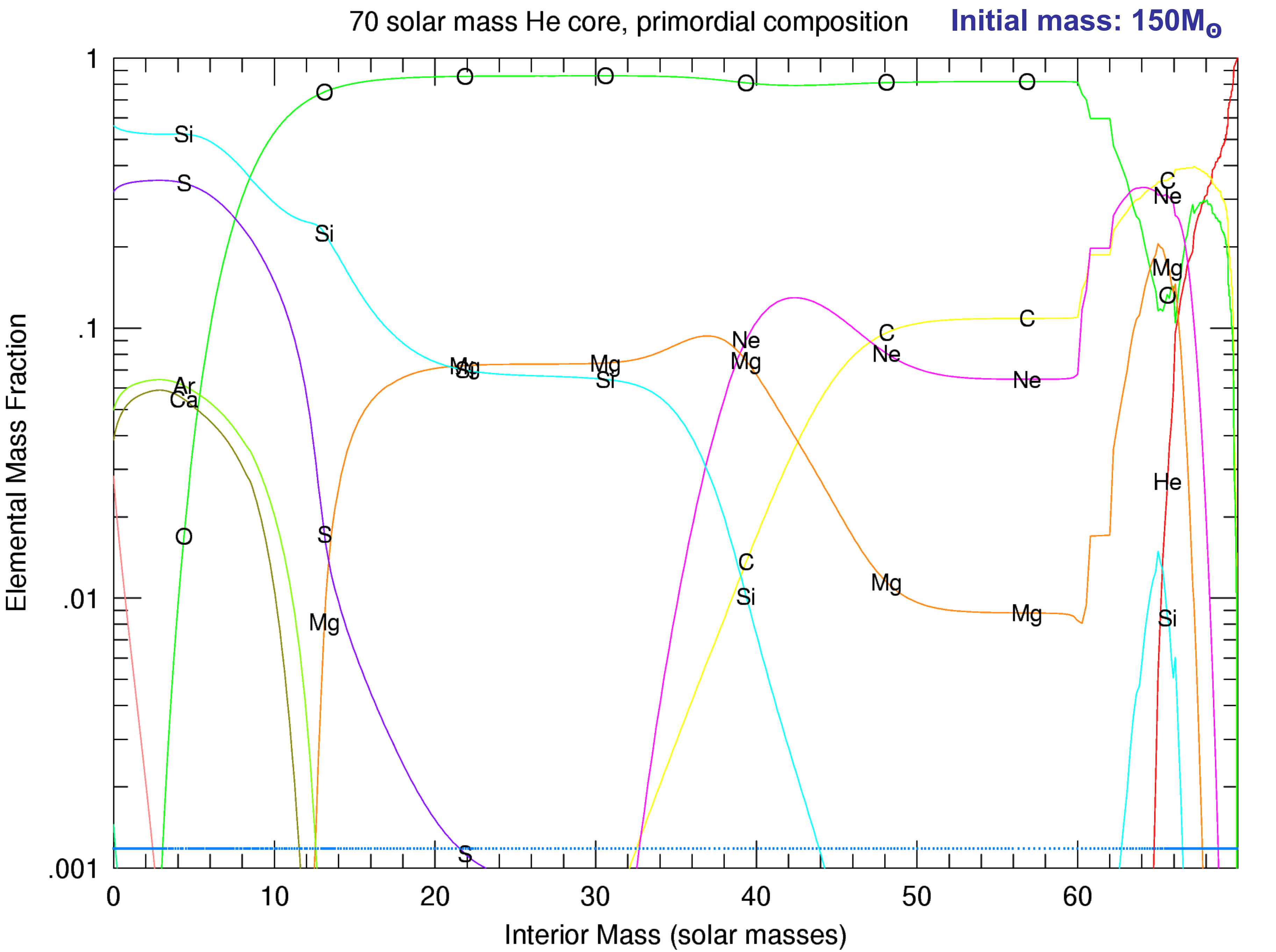
number of pulses varies similarly
typically period after first pulse is longest

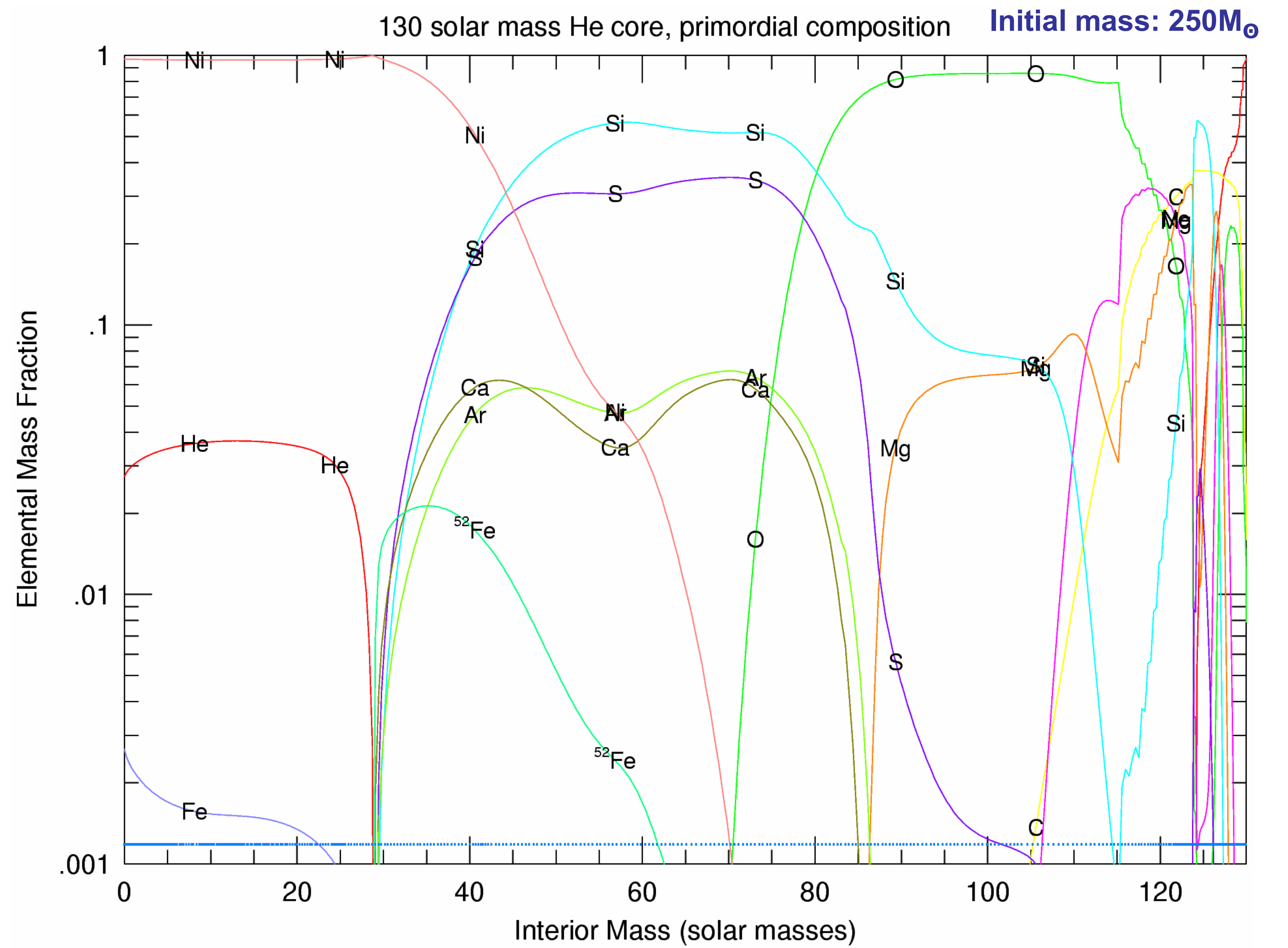
mechanism essentially independent of metallicity



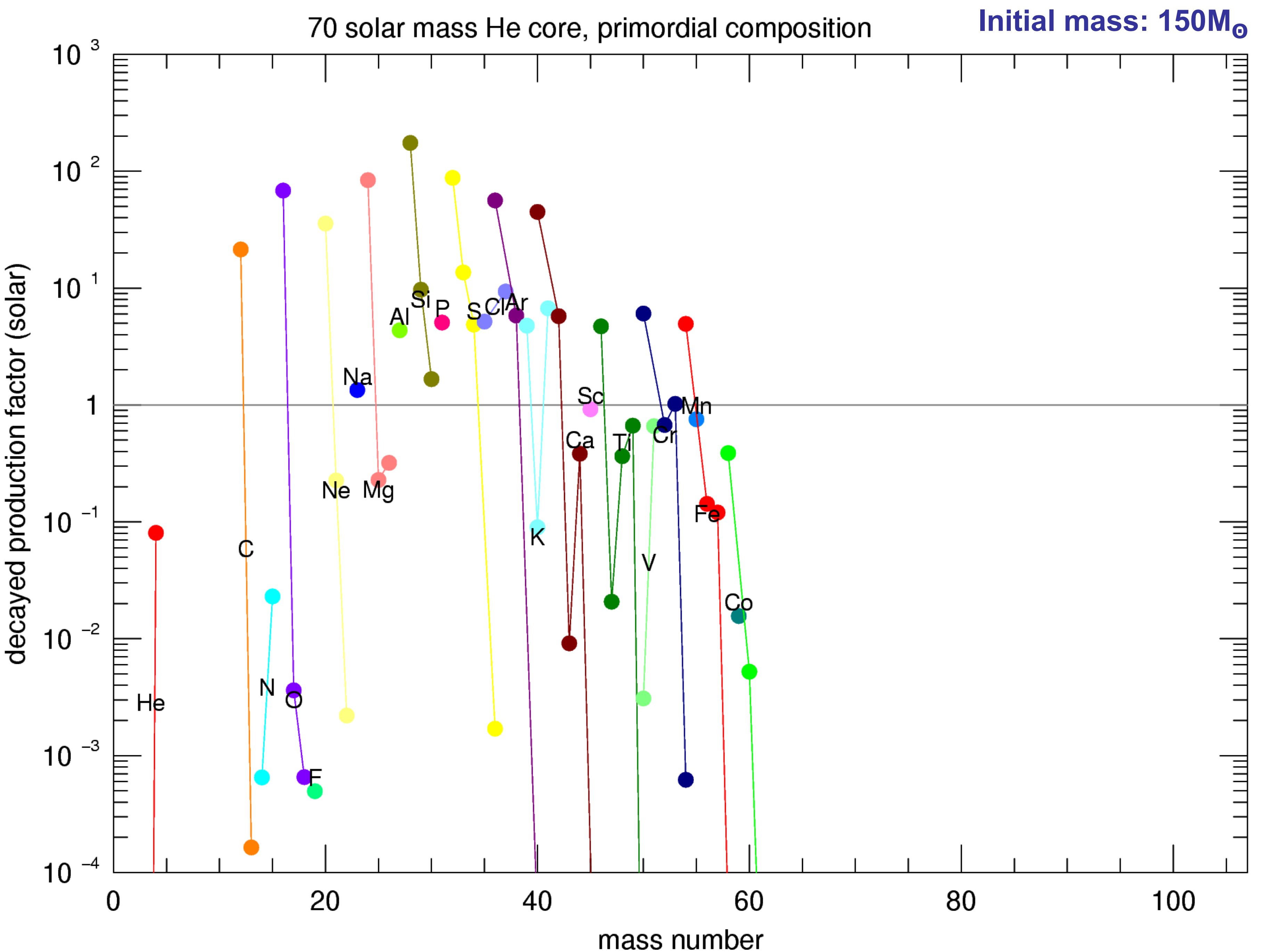
10^{44}
10^{43}
10^{42}
10^{41}
L / erg s^{-1}
0
1×10^8
2×10^8
3×10^8
4×10^8
5×10^8
6×10^8
time /sec
SN #1
SN #2
SN/GRB#3
The one true death

Nucleosynthesis in Pair-Instability Supernovae

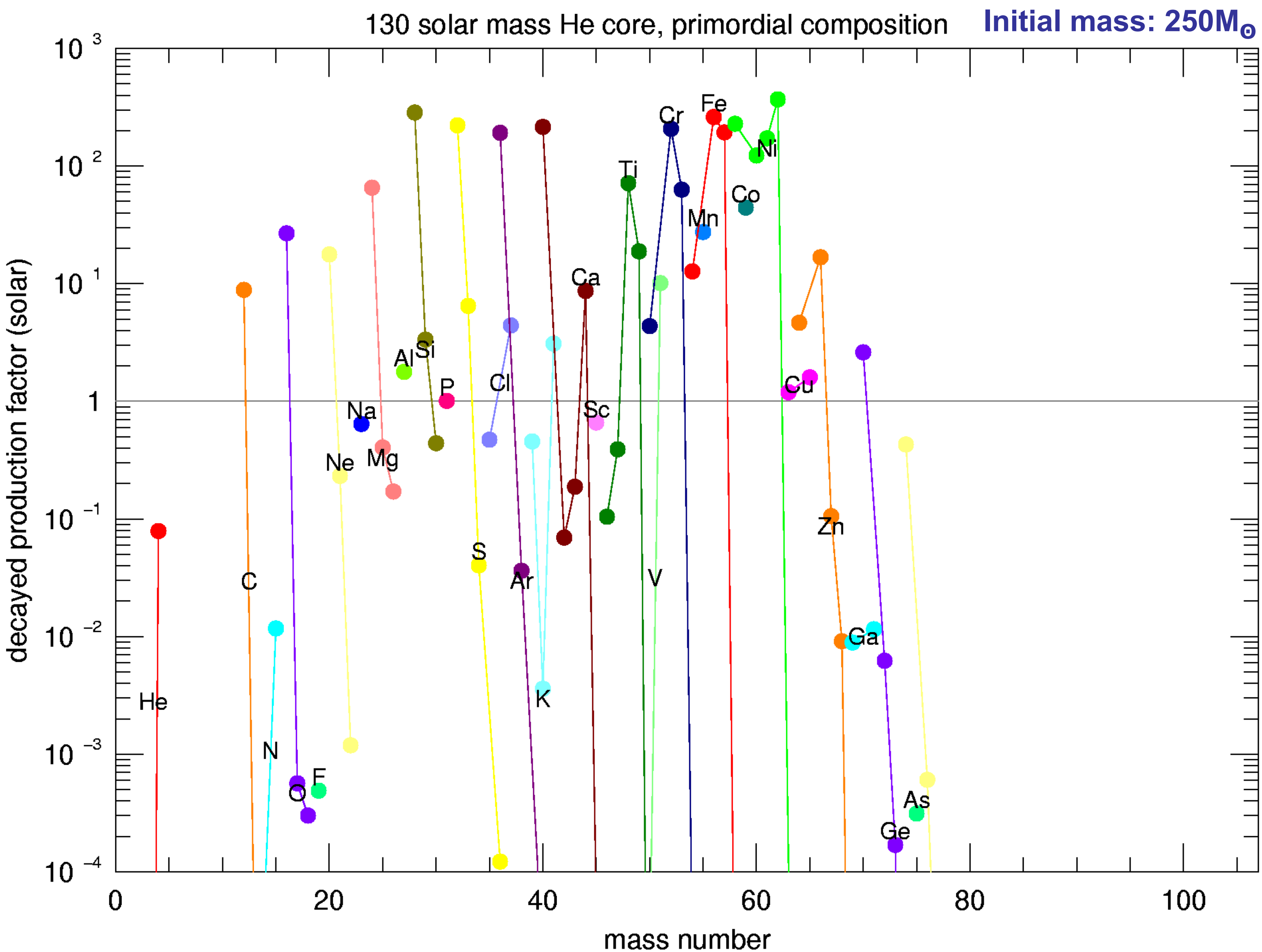

70 solar mass He core, primordial composition
Initial mass: 150M$_\odot$
Elemental Mass Fraction
Interior Mass (solar masses)
1
.1
.01
.001
0
10
20
30
40
50
60
Si
S
Ar
Ca
O
Mg
C
Ne
He



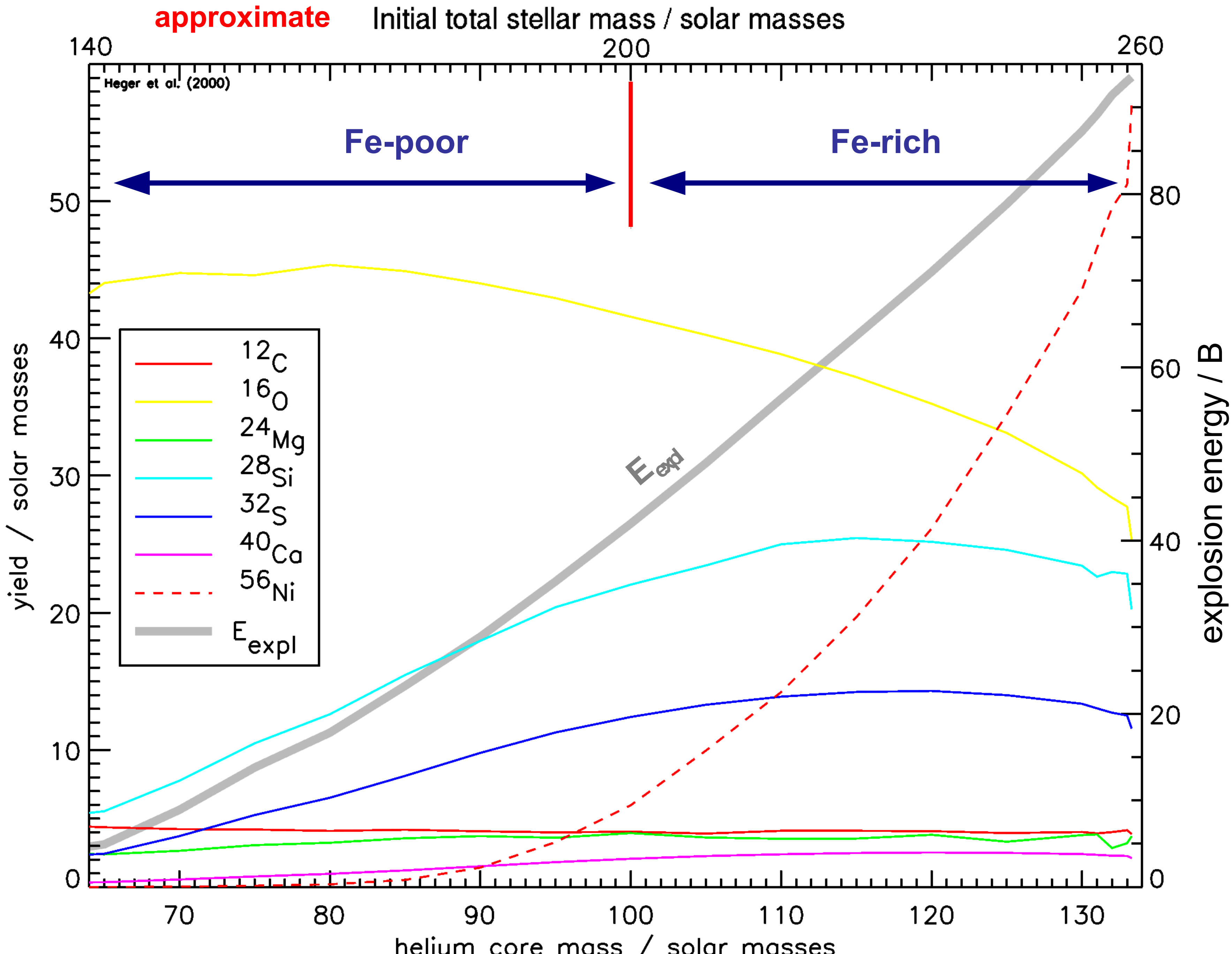
130 solar mass He core, primordial composition
Initial mass: 250M☉
Elemental Mass Fraction
Interior Mass (solar masses)
1
.1
.01
.001
0
20
40
60
80
100
120
Ni
Si
S
O
Ca
Ar
He
Fe
52Fe
Mg
C



70 solar mass He core, primordial composition
Initial mass: 150M☉
decayed production factor (solar)
mass number
He
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co



130 solar mass He core, primordial composition
Initial mass: 250M⊙
decayed production factor (solar)
mass number
He
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

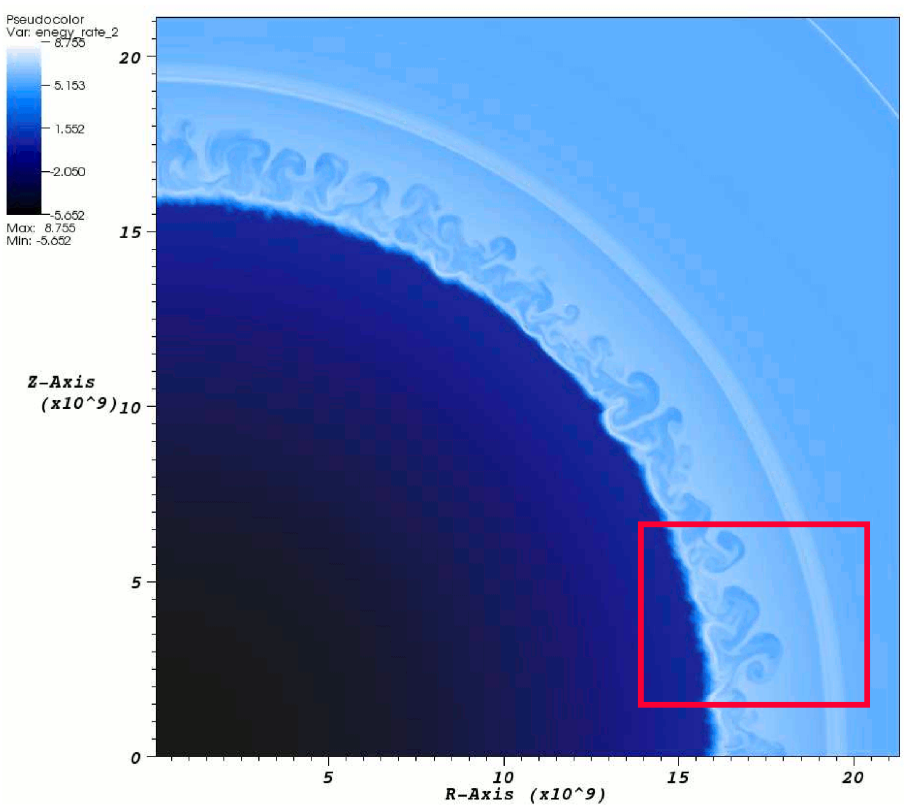


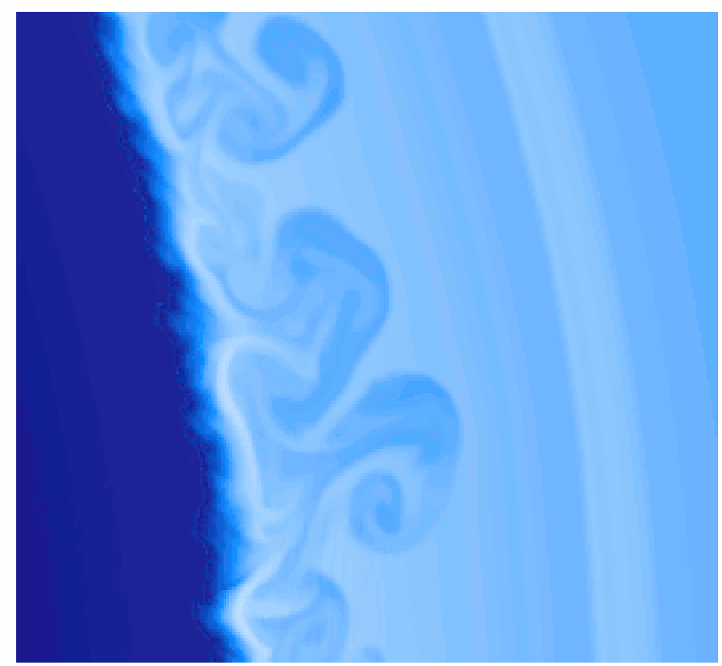
approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
12C
16O
24Mg
28Si
32S
40Ca
56Ni
Eexpl
Eexpl
yield / solar masses
explosion energy / B
0
10
20
30
40
50
70
80
90
100
110
120
130
0
20
40
60
80
helium core mass / solar masses

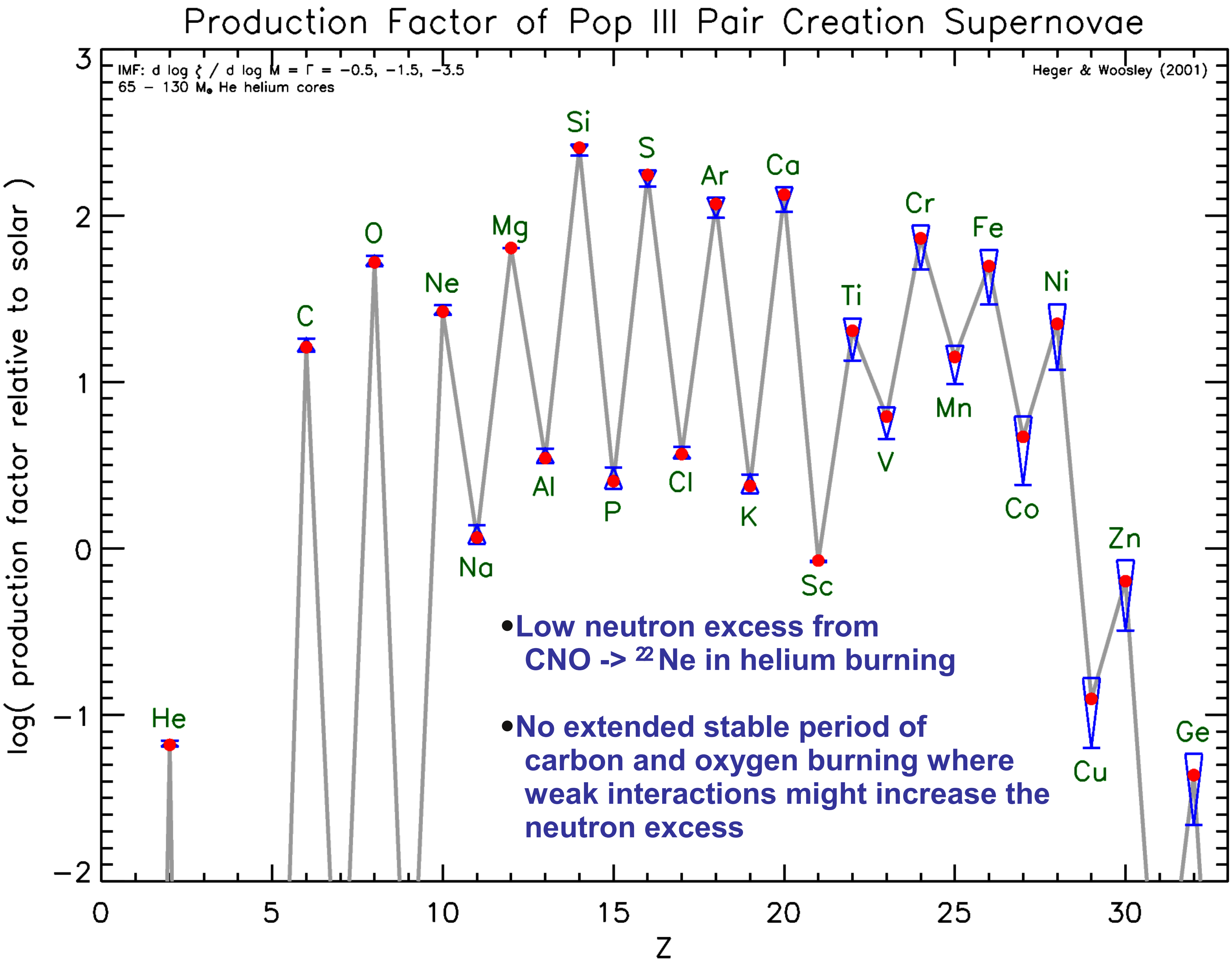
Explosion of a 150 $M_{\odot}$ Star

RT instabilities in the O-burning shell

See also posters by Ken Chen

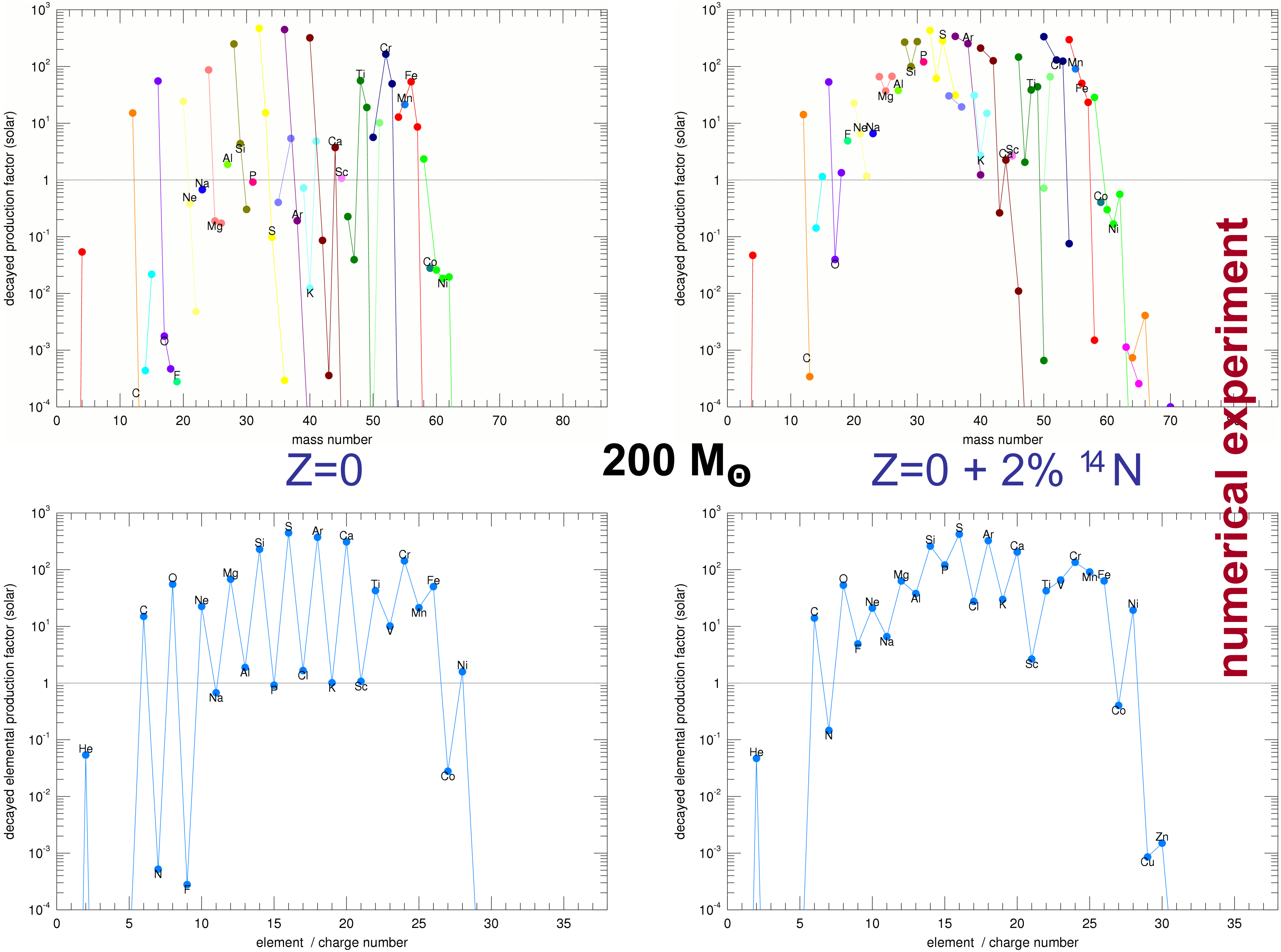





Production Factor of Pop III Pair Creation Supernovae
IMF: d log ζ / d log M = Γ = −0.5, −1.5, −3.5
65 − 130 M☉ He helium cores
Heger & Woosley (2001)
log(production factor relative to solar)
Z
He
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge
•Low neutron excess from CNO -> 22Ne in helium burning
•No extended stable period of carbon and oxygen burning where weak interactions might increase the neutron excess

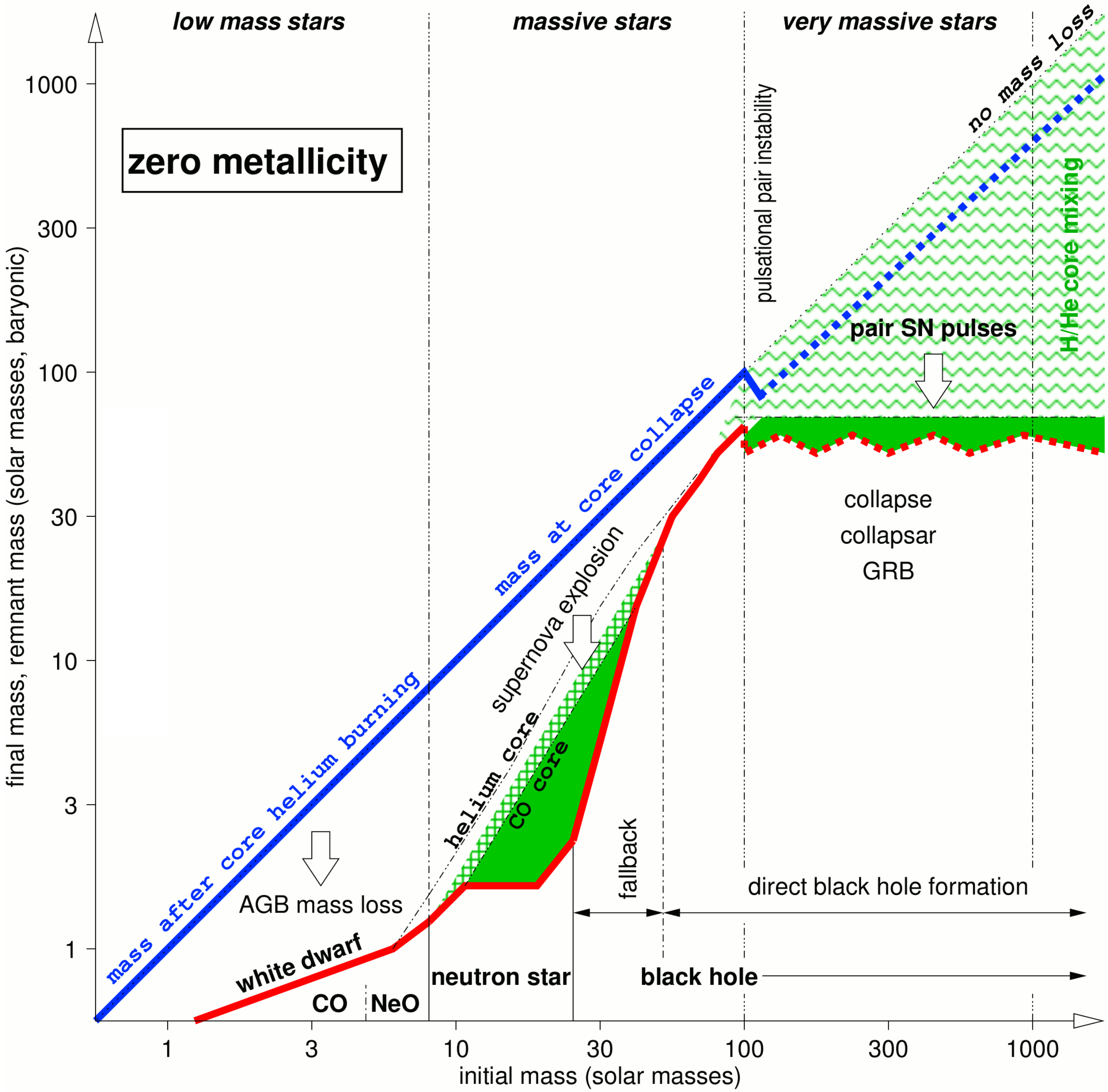
➔Problem

Pair-Instability Supernovae do not reproduce the abundances as observed in very metal poor halo stars!

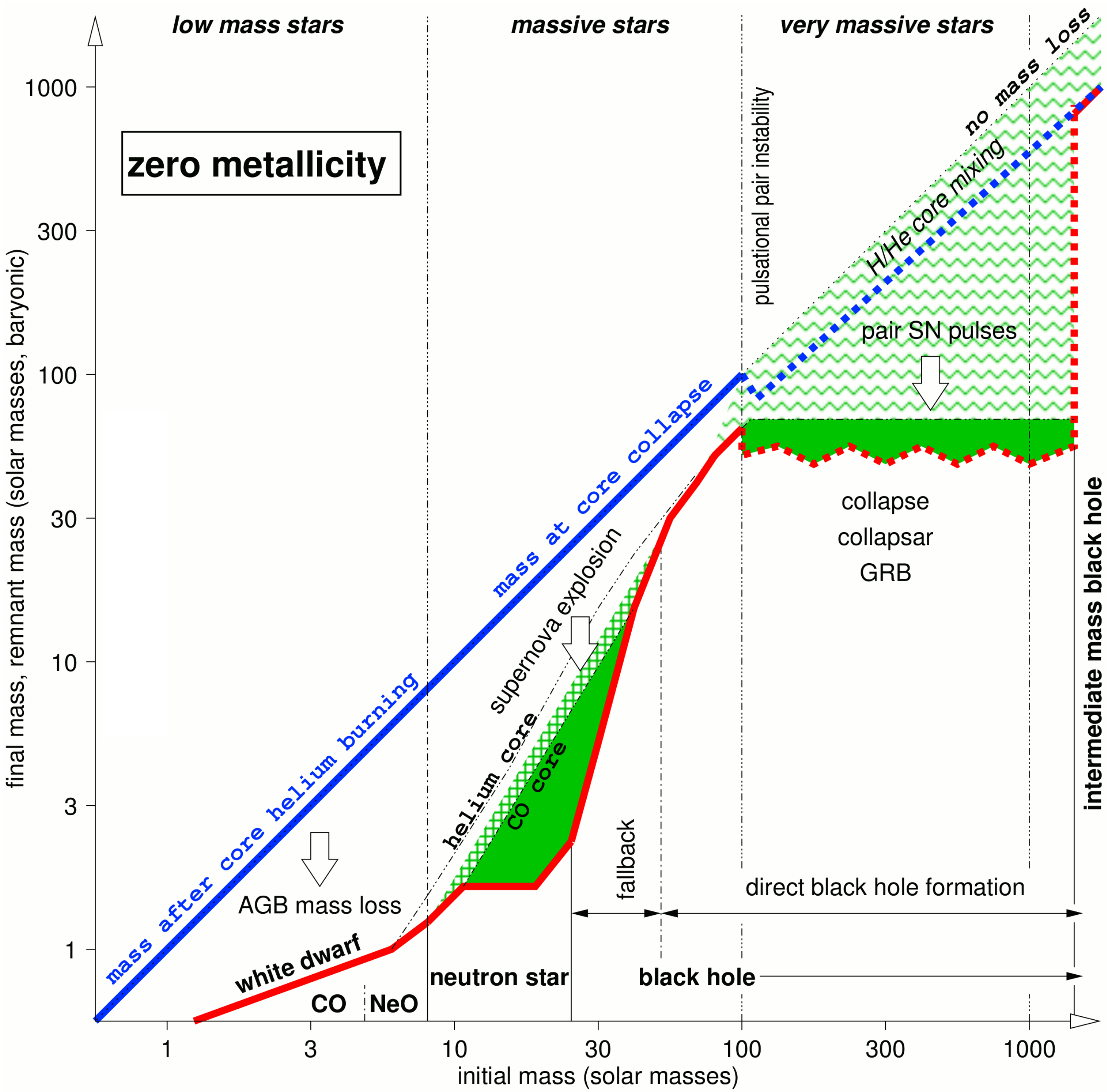


200 M$_\odot$
Z=0
Z=0 + 2% ^{14}N
numerical experiment
decayed production factor (solar)
mass number
decayed elemental production factor (solar)
element / charge number

Pulsational Pair SN Scenario



Pulsational Pair SN Scenario



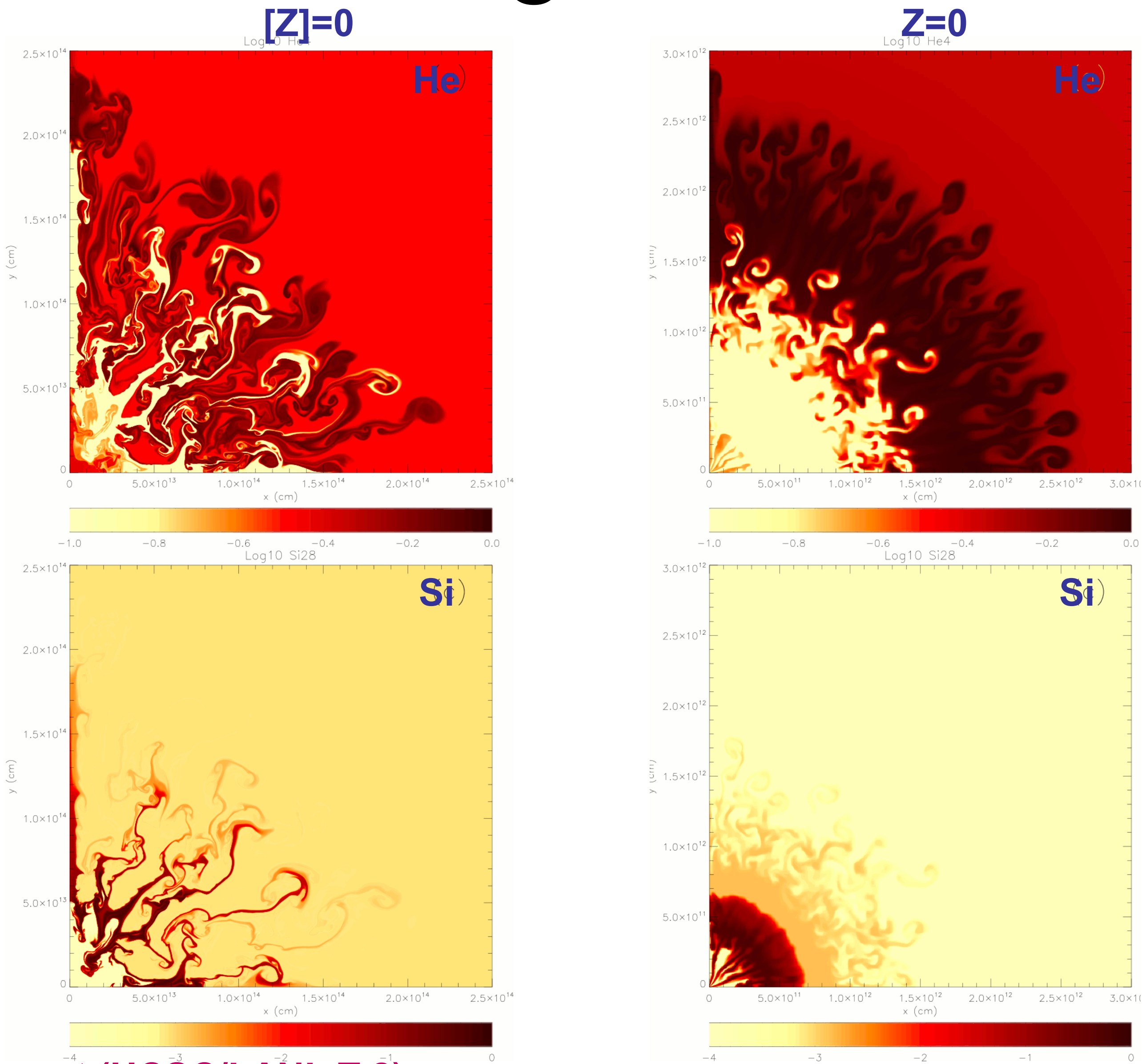
Nucleosynthesis from Stars 10-100 $M_\odot$

Mixing in 25 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

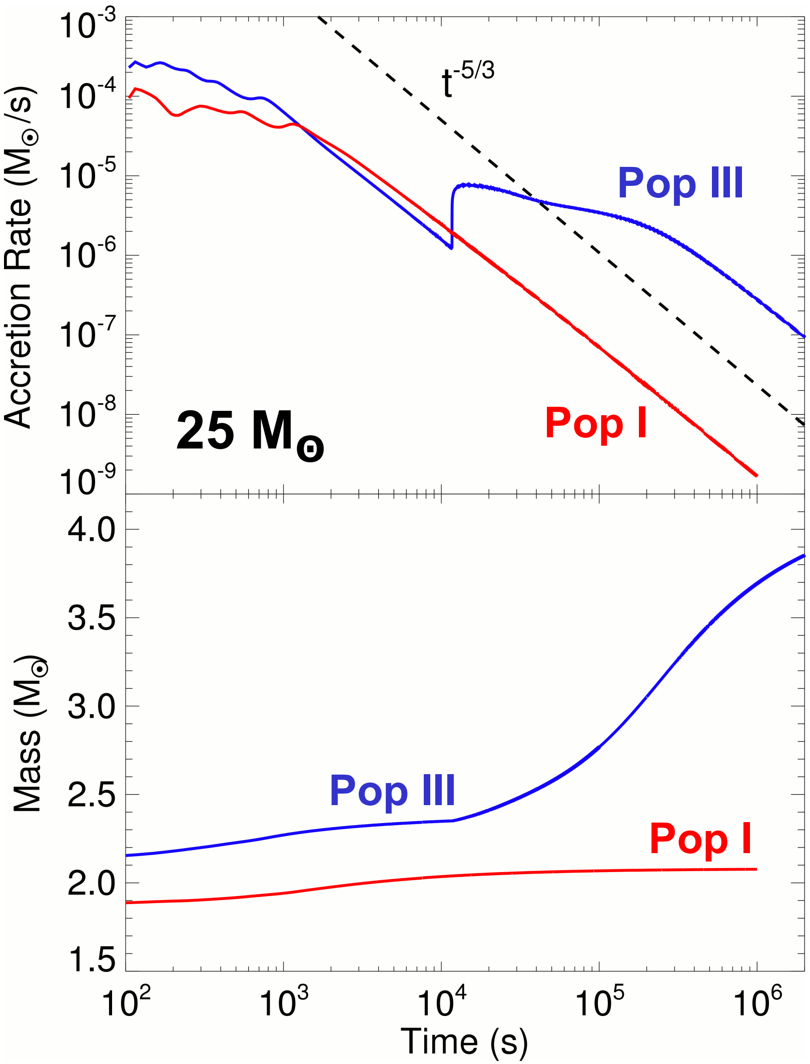
➔ Pop III stars show much less mixing than modern Pop I stars due to their compact hydrogen envelope

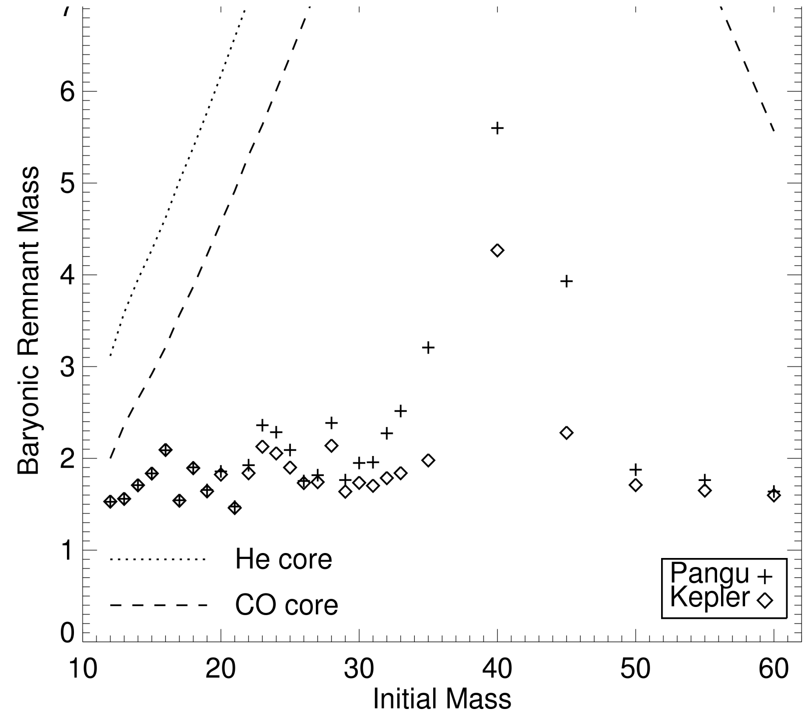


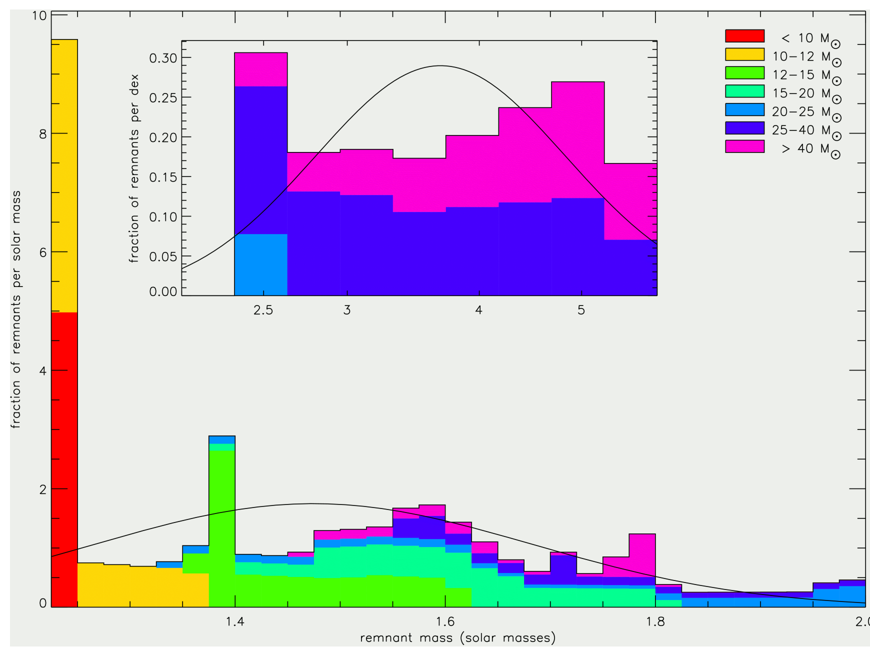
Simulations: Candace Joggerst (UCSC/LANL T-2)

Fallback and Remnants

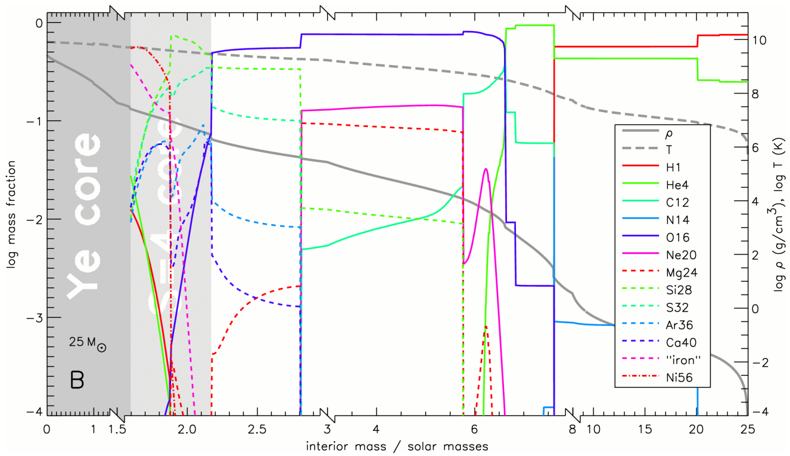
(Zhang, Woosley, Heger 2007)





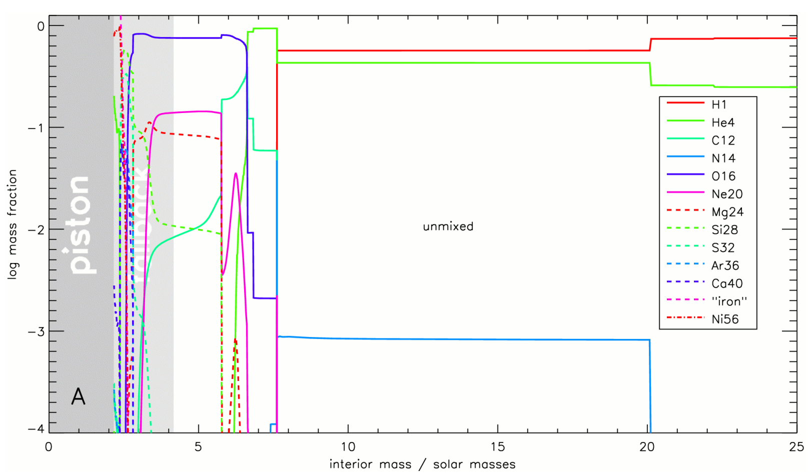


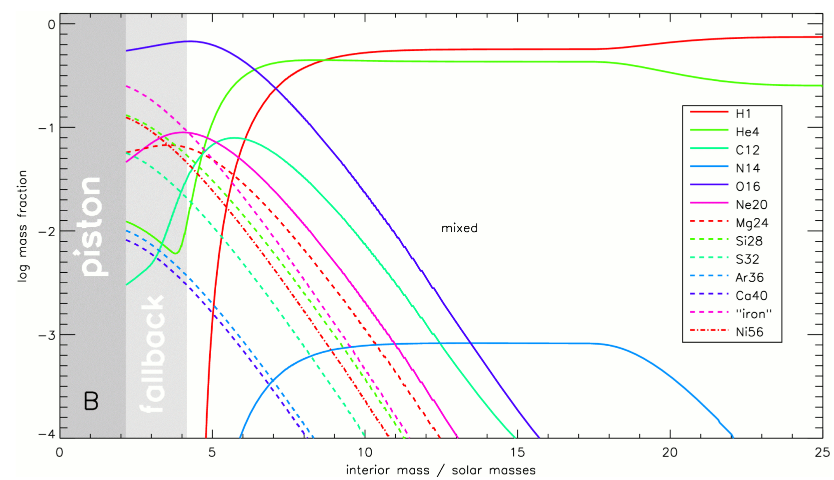
Supernovae, Nucleosynthesis, & Mixing



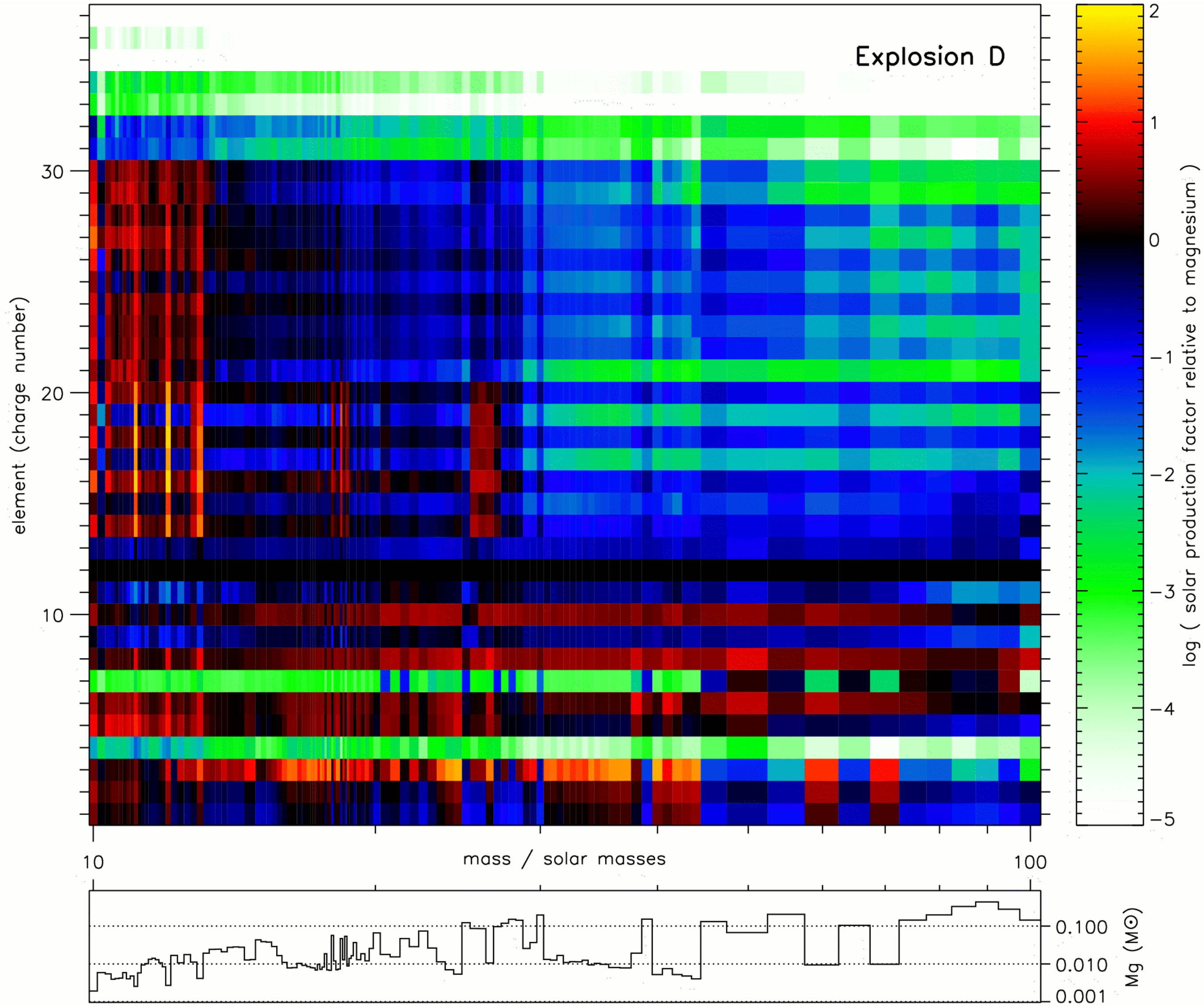
SN, no mixing

SN + mixing





Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

120 stellar masses

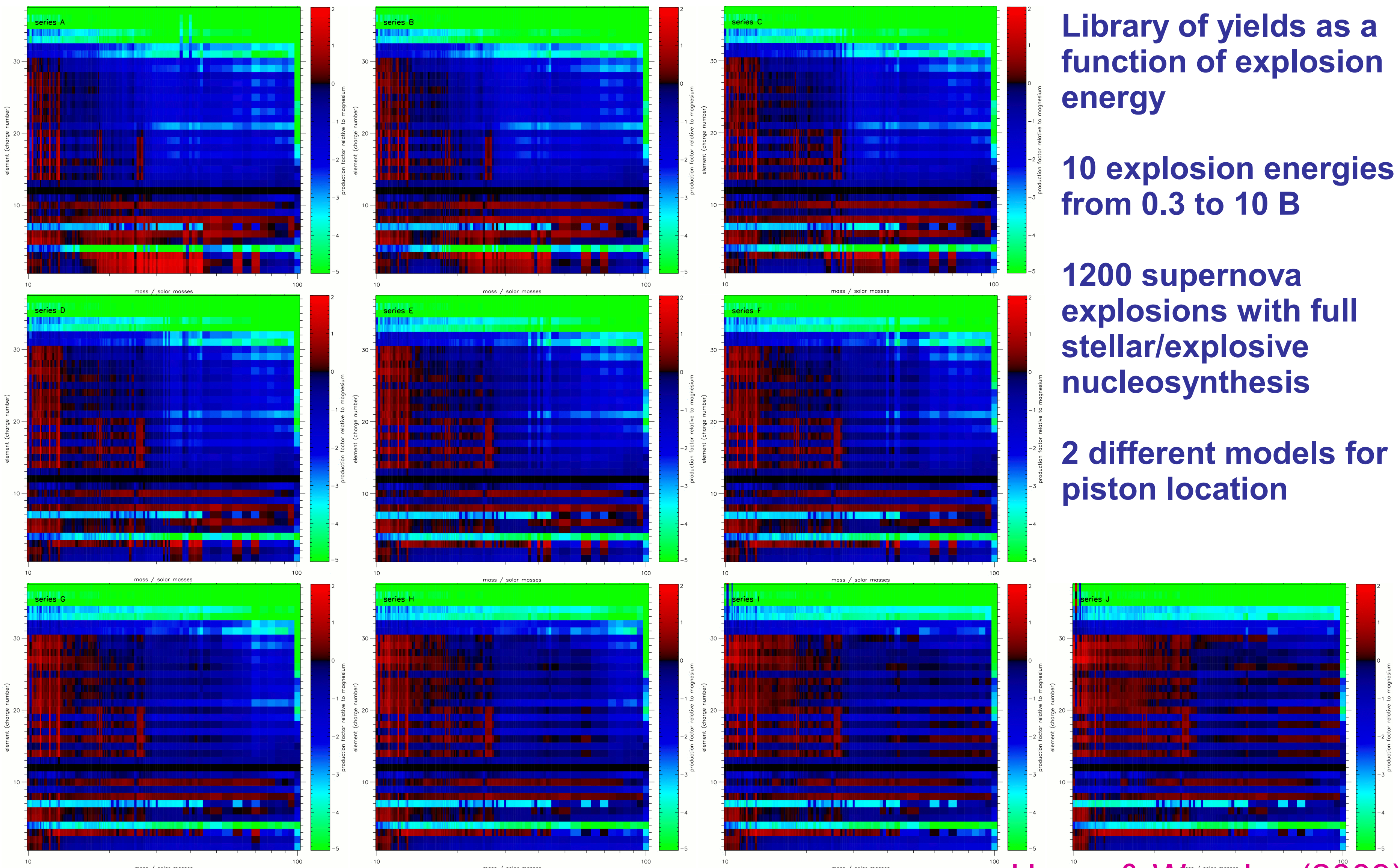
"complete" reaction network

normalized to Mg

RESULTS:
e.g.,
Production of ^{7}Li by neutrino interaction in very compact stellar envelope!

Heger & Woosley, in prep., (2009)

Pop III Nucleosynthesis Grid



Library of yields as a function of explosion energy

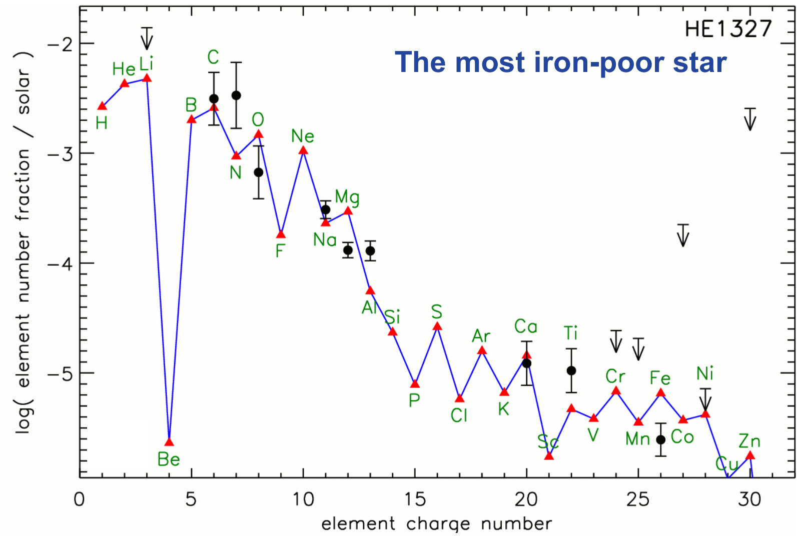
10 explosion energies from 0.3 to 10 B

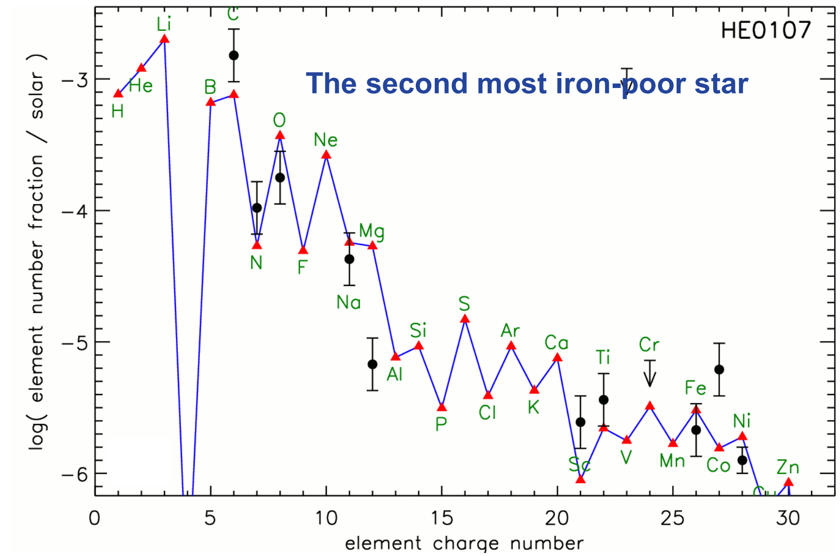
1200 supernova explosions with full stellar/explosive nucleosynthesis

2 different models for piston location

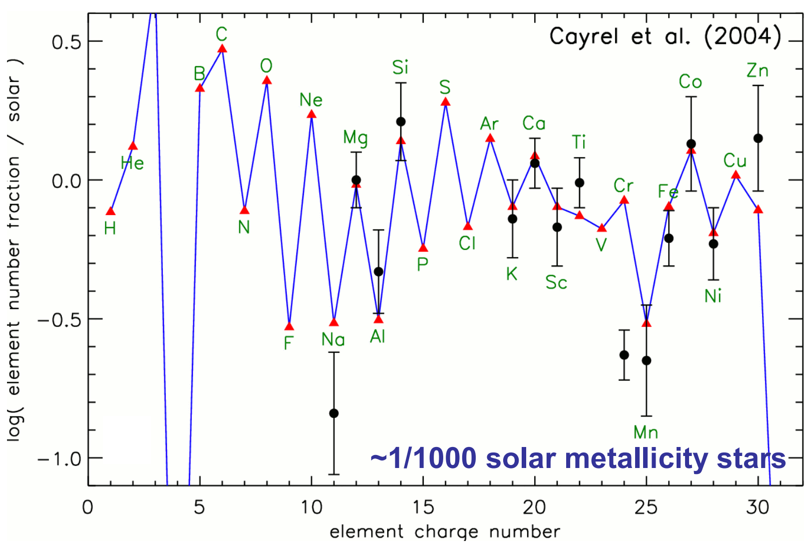
Heger & Woosley (2009)

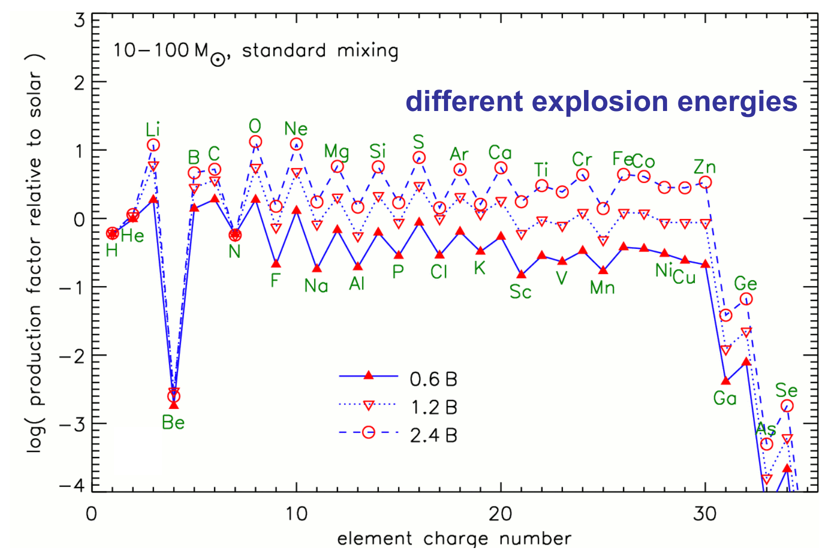
Comparison to Observational Data

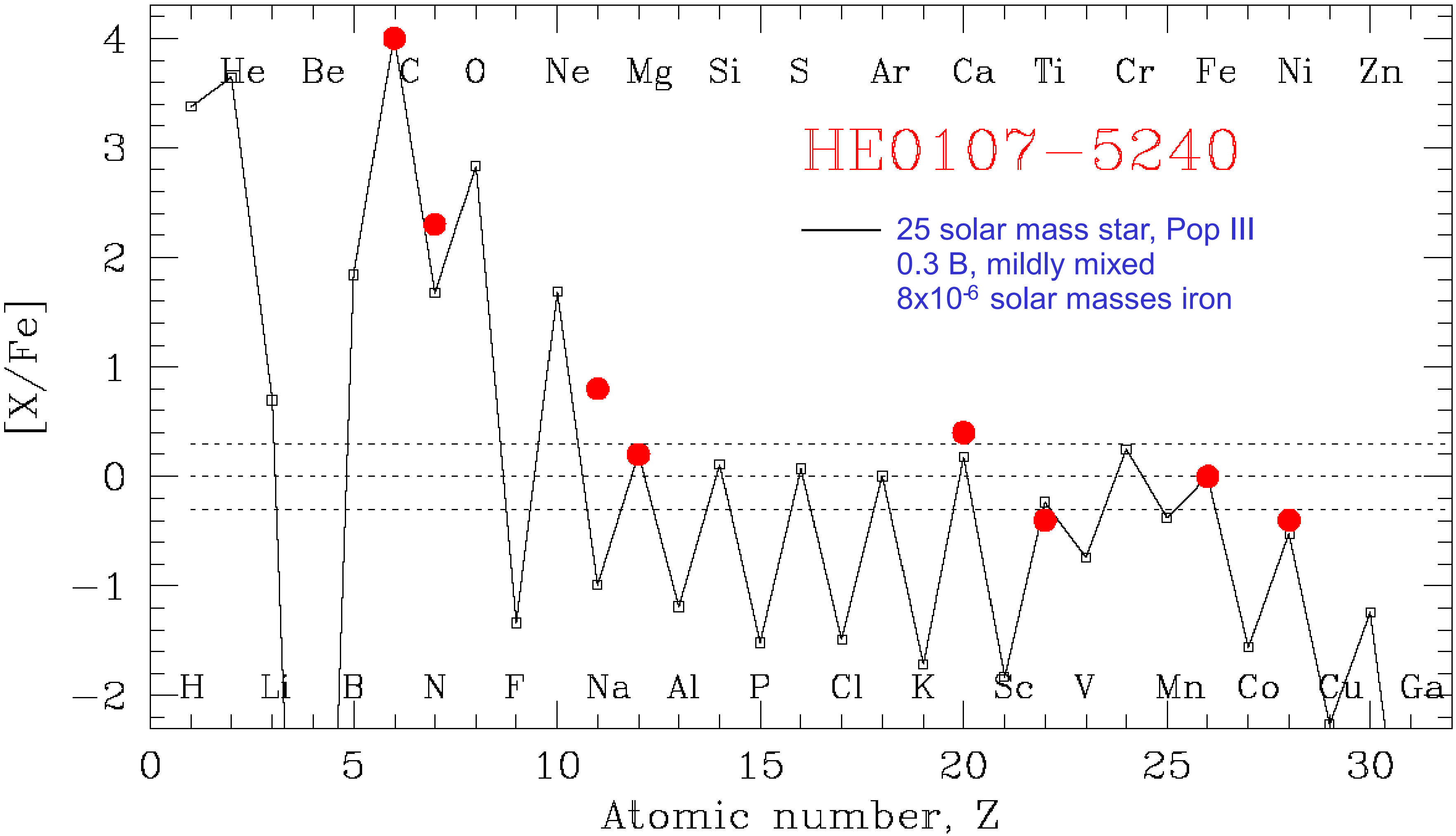




Heger & Woosley (2009), Similar good fits from Ken Nomoto's Group

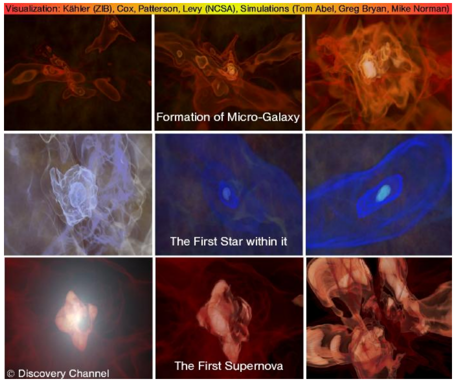




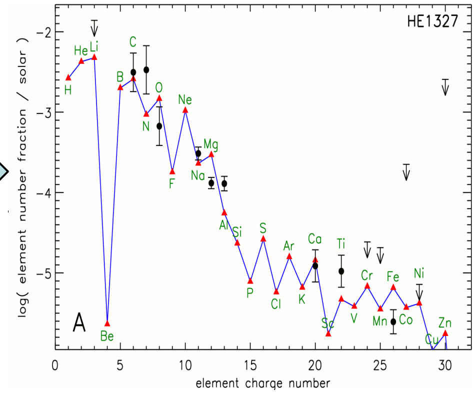


Umeda & Nomoto, Nature, 422, 871, (2003)

Reconstruction of the IMF



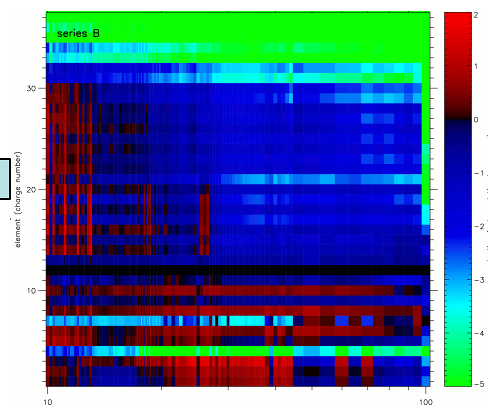
primordial stars form, nucleosynthesis ejected



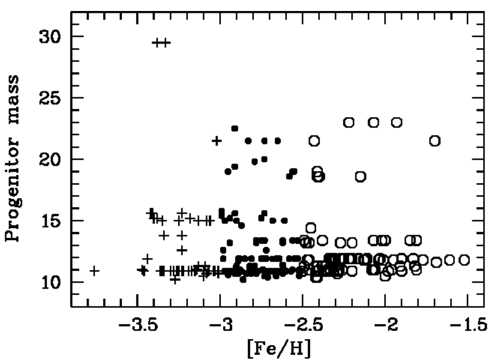
ejecta incorporated in low-Z halo stars

find low-Z halo stars (HERES, SEGUE, …)

measure abundances (VLT, KECK, …)

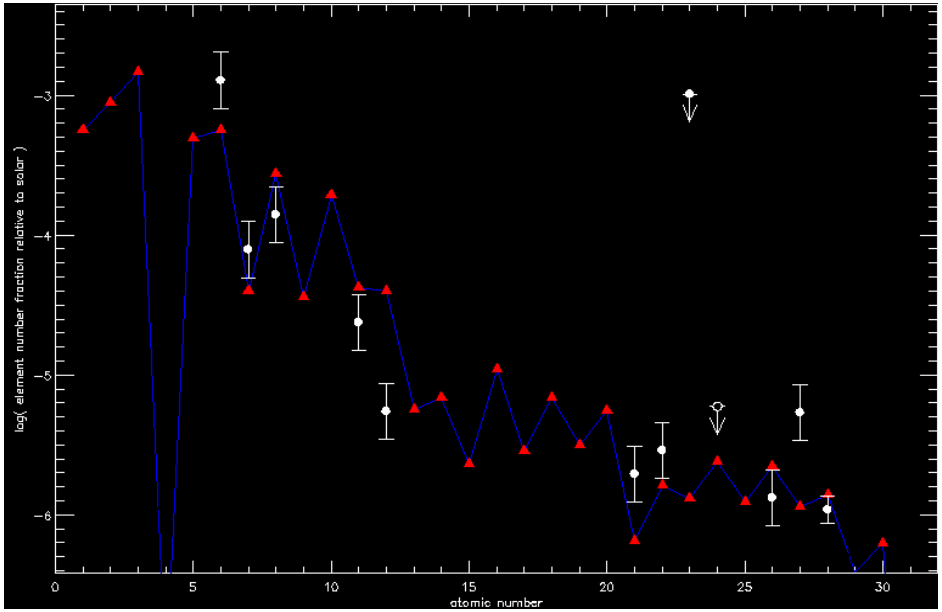


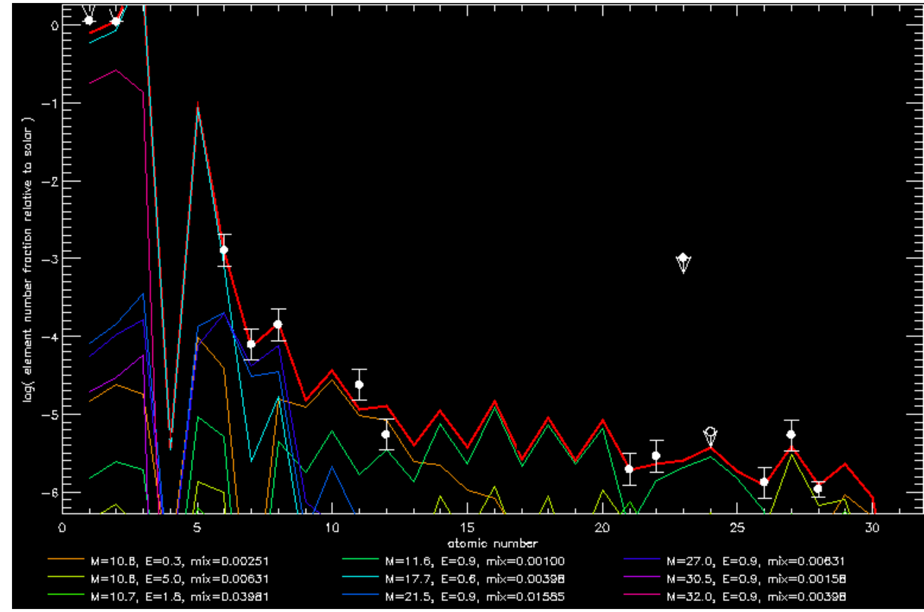
compare abundances to primordial star nucleosynthesis library



obtain IMF of population of progenitor stars

Multi-Star Fit





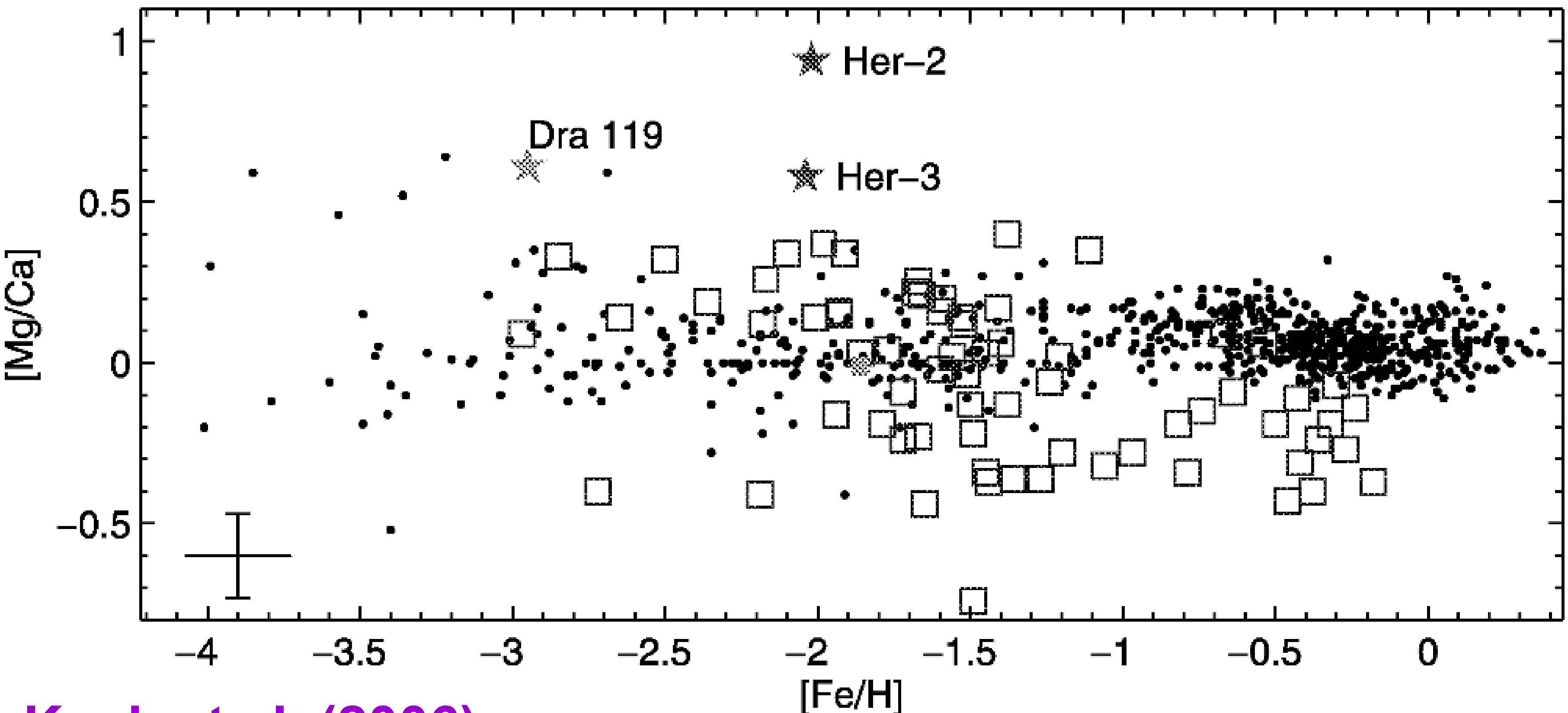
best single star fit: $\sigma^2 = 4.3974$

sample multi-star fit: $\sigma^2 = 0.5293$

weight	mass	energy	mixing
1.728E-05	10.6	0.3	0.00251
5.036E-07	10.6	5.0	0.00631
1.475E-07	10.7	1.8	0.03981
1.811E-06	11.6	0.9	0.00100
6.472E-01	17.7	0.6	0.00398
9.789E-05	21.5	0.9	0.01585
6.957E-05	27.0	0.9	0.00631
2.211E-05	30.5	0.9	0.00158
2.004E-01	32.0	0.9	0.00398

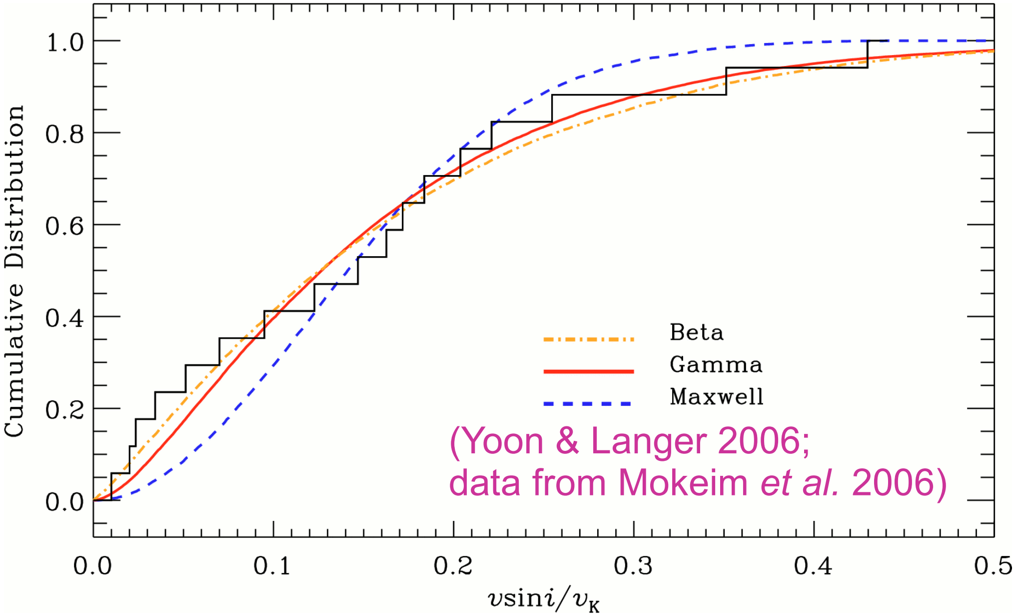
Finding First Star Ashes

Explosion models predict much material is mixing up to metallicity 1/100 solar
==> **Where are these stars?**
They are rare!



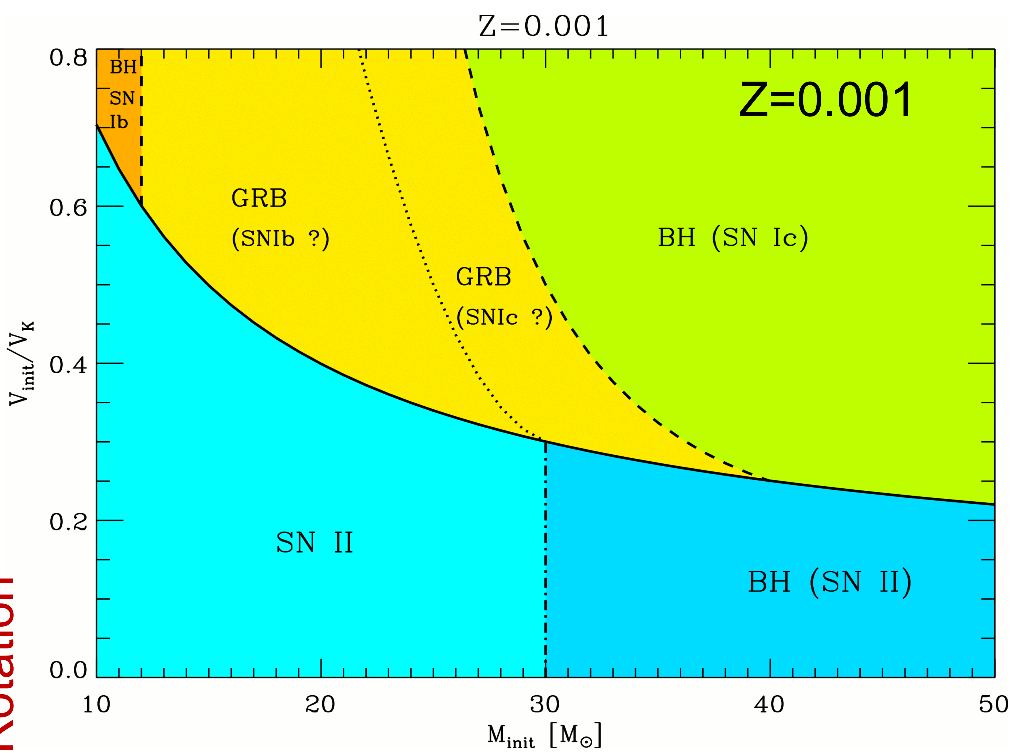
Koch et al. (2006)

Black Holes and GRBs from Rotating Stars



A small fraction of single stars is born rotating rapidly

The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.



Rotation

(Yoon & Langer 2006)

Summary

Due to their unique composition, the birth, life and death of primordial stars is very different from later generations.

- Even stars of several 100 $M_{\odot}$ might keep most of their mass until collapse or explosion

➔But no observational abundance evidence for pure pair SN

- Pop III Stars with $\gtrsim$100 $M_{\odot}$ may encounter mixing during core helium burning, making lots of CNO and little Fe++
- Some supermassive Pop III stars may still make powerful SN

Ultra Metal-Poor stars

- Stars of 10-15 $M_{\odot}$ seem to give good fits for many UMP stars

➔ Reconstruction of primordial IMF from stellar yields?