The First Stars:

Life and Death
In the Fast Lane

Stan Woosley(UCSC)
Alexander Heger (LANL)

Sergei Blinnikov (ITEP)
Phil Pinto (UA)

The evolution of Z = 0 massive stars has been studied for many years, e.g. Ezer & Cameron (ApSS, 1971):

Some generalities:

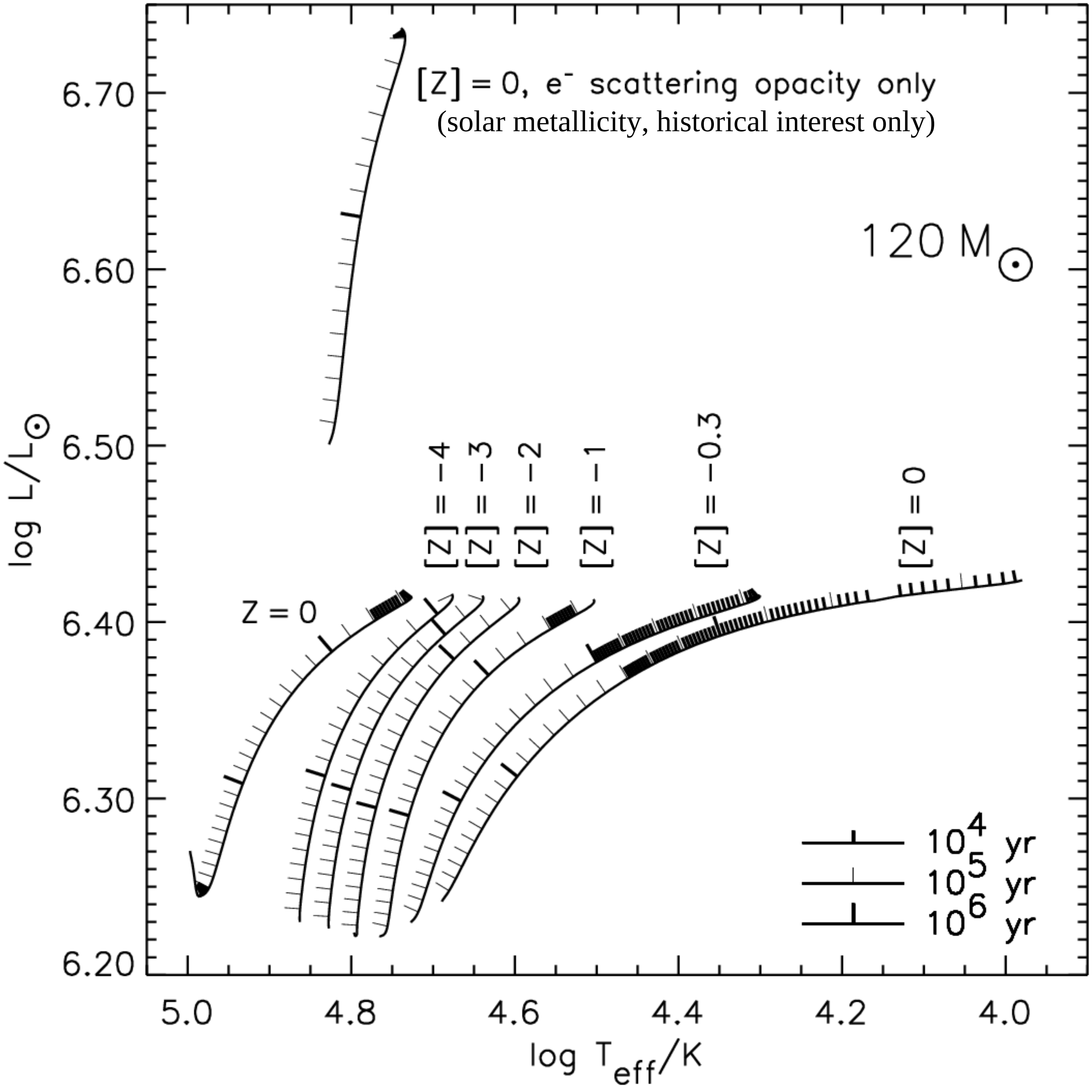
$\kappa = 0$ affects pulsational stability, mass loss, and formation of red giants

H-burning by the CNO cycle following
a trace of He-burning.

Typically on the MS: $T_C = 1.0 \times 10^8$ K; $X_{CNO}=10^{-9}$

Hotter, bluer stars on MS than modern stars.

No mass loss?



Baraffe, Heger, & Woosley
(ApJ, 2001)

Mass	T_{eff}	L_{38}
10	45	0.44
20	55	3.0
50	70	22
100	75	67

at ½ H-depletion

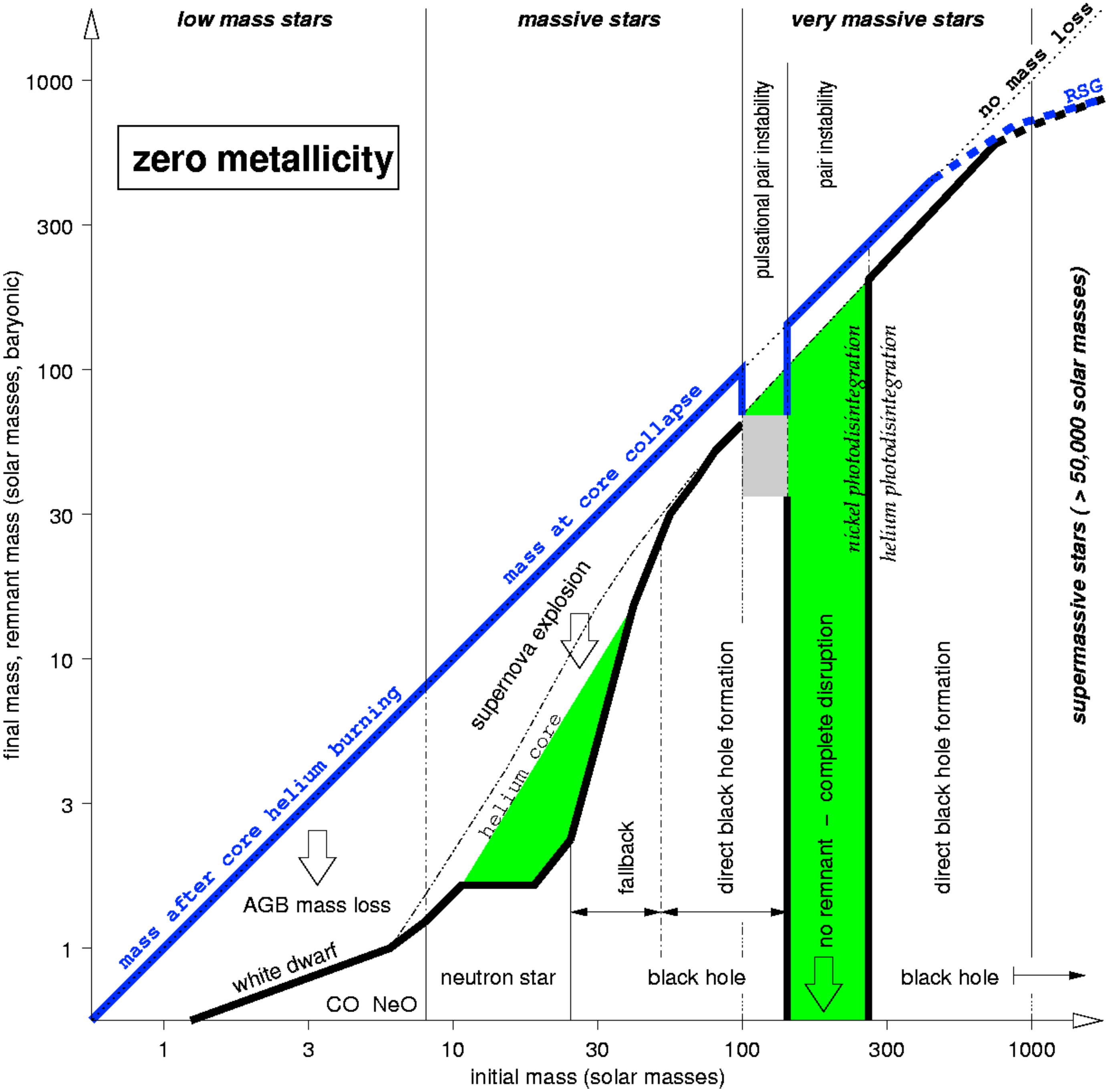
As go to higher masses, the lifetime of the star approaches a constant, and the luminosity is nearly given by the Eddington limit.

Mass (solar)	Lifetime (My)	L (10^{38} erg s^{-1})	L_{38}/M
100	2.7	67	0.67
200	2.2	180	0.90
300	2.0	300	1.00

Such stars are almost fully convective on the MS and in their helium cores

With considerable uncertainty about the critical masses (except the 137) , one can delineate four kinds of deaths.

He Core	Main Seq. Mass	Supernova Mechanism
$2 \leq M \leq 40$	$10 \leq M \leq 90$	Fe core collapse to neutron star or a black hole
$40 \leq M \leq 60$	$90 \leq M \leq 120$	Pulsational pair instability followed by Fe core collapse
$60 \leq M \leq 137$	$120 \leq M \leq 300$	Pair instability supernova
$M \geq 137$	$M \geq 300$	Black hole. Possible GRB


low mass stars
massive stars
very massive stars
zero metallicity
1000
300
100
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
1
3
10
30
100
300
1000
initial mass (solar masses)
mass after core helium burning
mass at core collapse
no mass loss
RSG
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
supernova explosion
helium core
AGB mass loss
white dwarf
CO NeO
neutron star
fallback
direct black hole formation
no remnant – complete disruption
direct black hole formation
black hole
black hole

Survey 1

$Z = 0;\ \ 10 \text{ to } 100\ \mathrm{M}_\odot$

(Heger & Woosley, in preparation)

Big Bang initial composition, Fields (2002), 75% H, 25% He

$10 - 12\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 0.1\ \mathrm{M}_\odot$

$12 - 17\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 0.2\ \mathrm{M}_\odot$

$17 - 19\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 0.1\ \mathrm{M}_\odot$

$19 - 20\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 0.2\ \mathrm{M}_\odot$

$20 - 35\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 0.5\ \mathrm{M}_\odot$

$35 - 50\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 1\ \mathrm{M}_\odot$

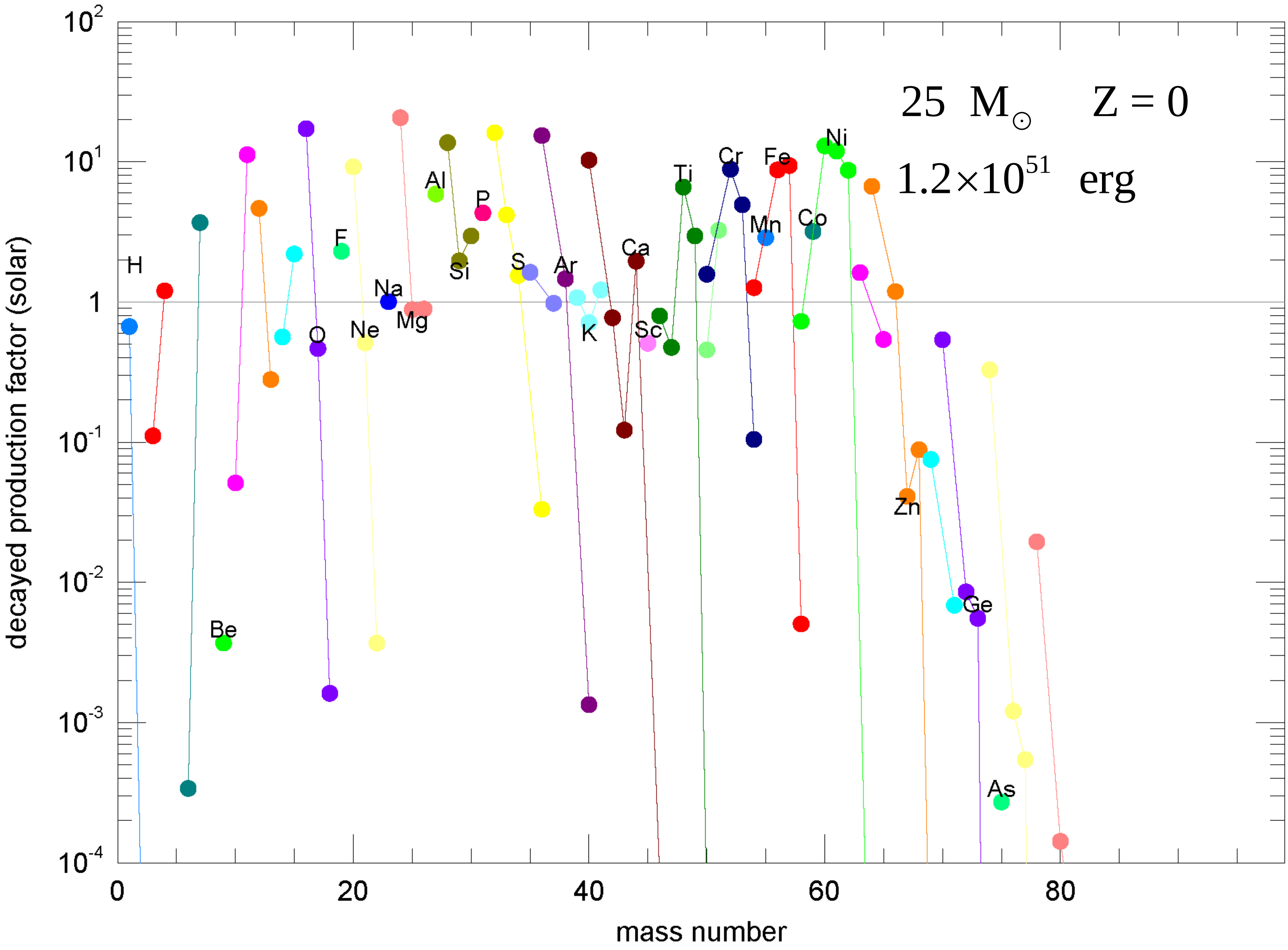
$50 - 100\ \mathrm{M}_\odot \quad \Delta \mathrm{M} = 5\ \mathrm{M}_\odot$

Evolved from main sequence to presupernova and then exploded with pistons near the edge of the iron core ($S/N_A k = 4.0$)

Each model exploded with a variety of energies from 0.3 to 10 x 10^{51} erg.

126 Models
at least 500 supernovae

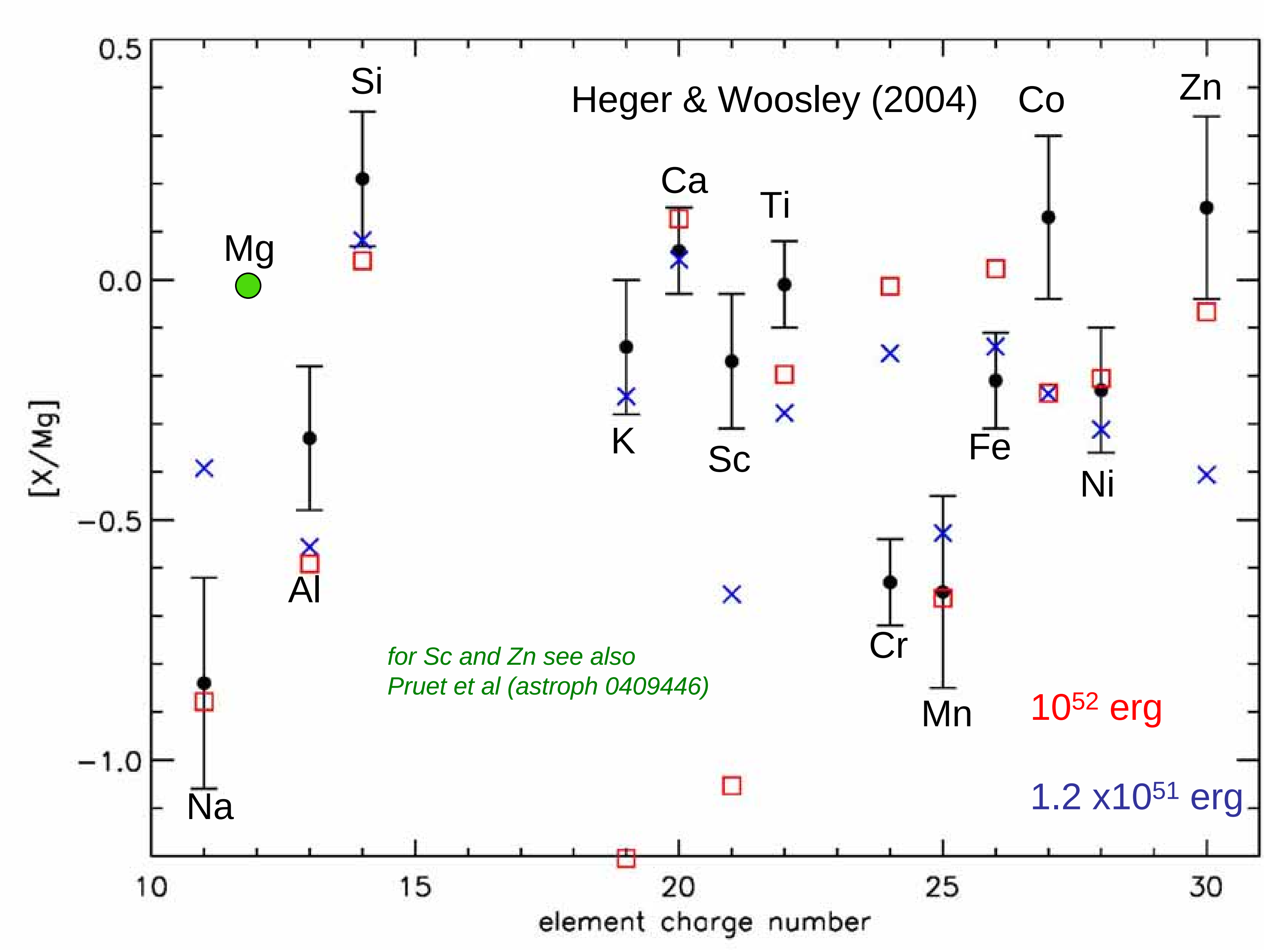
- Use Kepler implicit hydrodynamics code
- Arbitrary equation of state (electrons, pairs, degeneracy, etc.)
- “Adaptive”nuclear reaction network. Nuclei included where flows indicate they are needed. Typically 900 isotopes
- Explosions simulated using pistons and models mixed artificially
- No mass loss
- Approximate light curves calculated using single temperature radiative diffusion. Radioactive decay included.



25 M$_\odot$ Z = 0
1.2×10^{51} erg
decayed production factor (solar)
mass number
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
H
Be
O
F
Ne
Na
Mg
Al
Si
P
S
Ar
K
Ca
Sc
Ti
Cr
Mn
Fe
Co
Ni
Zn
Ge
As

Some general features:

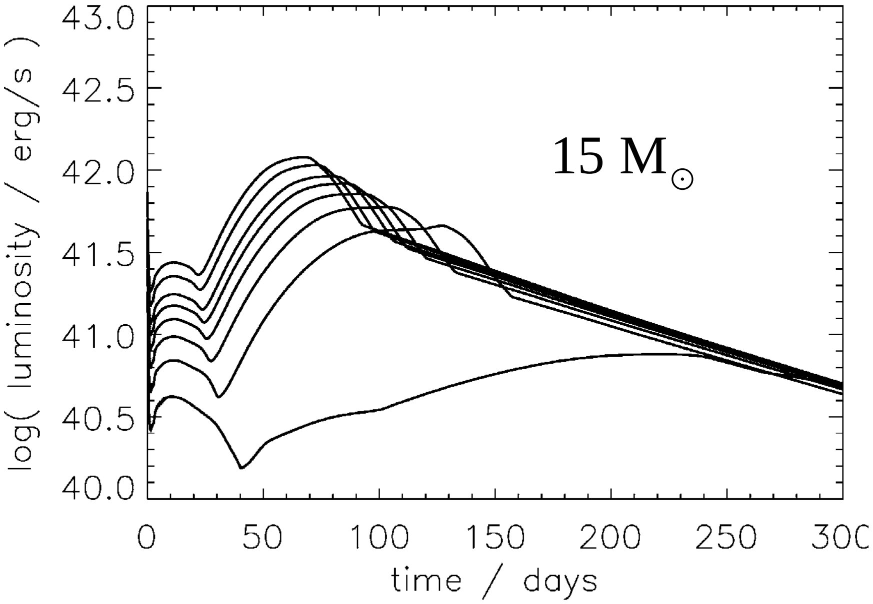
- Large odd-even effect
- No synthesis above A about 64 (does not include neutrino powered wind or proton-rich bubble, which greatly effect, e.g., Sc, Zn Pruet et al astrpho 0409446)
- Primary B and F
- Above M ~ 50, primary N production
- Nucleosynthesis sensitive to mixing and fall back

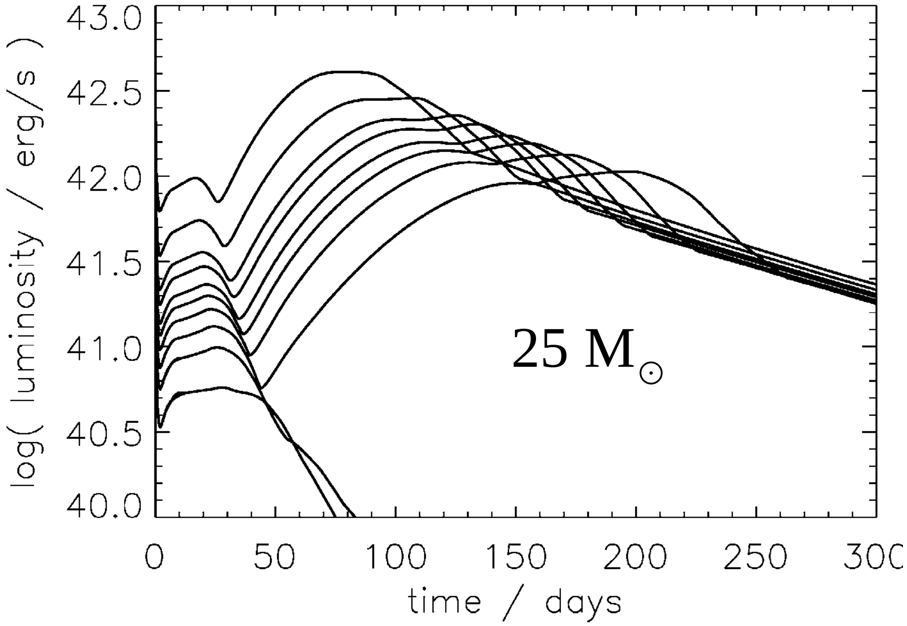


Heger & Woosley (2004)

for Sc and Zn see also
Pruet et al (astroph 0409446)

Data from Cayrel et al, A&A, 416, 1117, (2004) *In most cases, up to about 50 solar masses, the stars are blue supergiants when they die and their light curves are not exceptionally brilliant –much like SN 1987A*



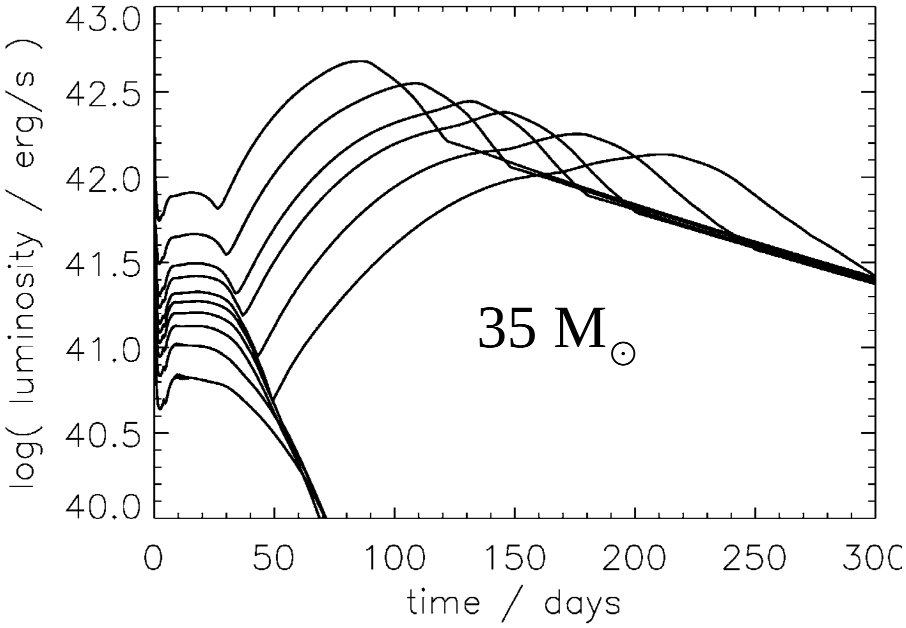


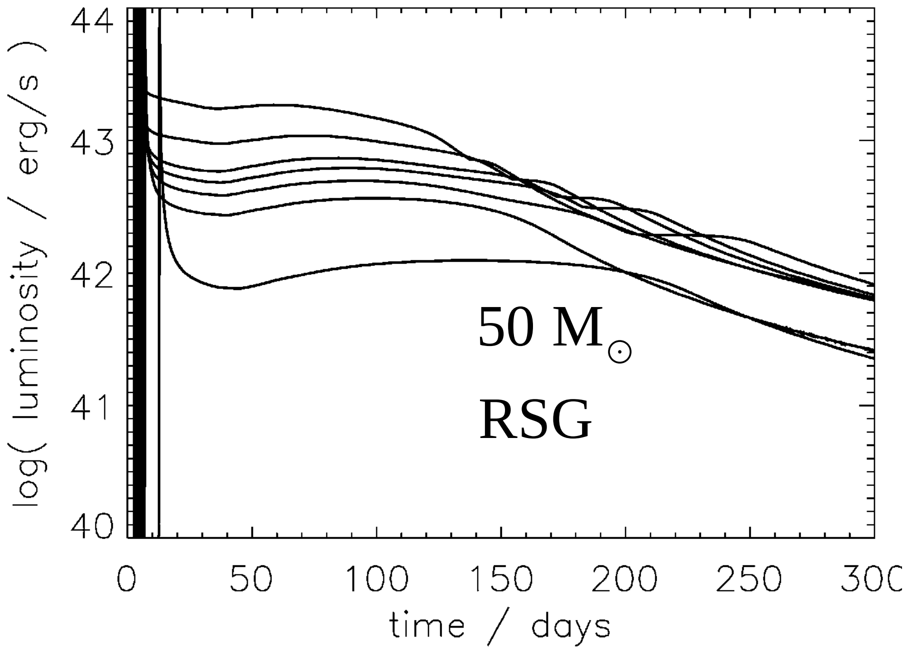
Explosion energies (KE_∞):

0.3 x 10^{51} erg
0.6
0.9
1.2
1.5
1.8
2.4
3.0
5.0
10

Masses of ^{56}Ni (solar masses):

15 $M_\odot$	25 $M_\odot$
0.048	0.
0.057	0.003
0.065	0.22
0.072	0.23
0.078	0.24
0.082	0.25
0.090	0.27
0.095	0.29
--	0.34
--	0.44





Explosion energies (KE_∞):

0.3 x 10^{51} erg
0.6
0.9
1.2
1.5
1.8
2.4
3.0
5.0
10

Masses of ^{56}Ni (solar masses):

35 M$_\odot$	50 M$_\odot$
0.	0.
0.	--
0.	--
0.	0.02
0.27	--
0.28	0.40
0.31	0.42
0.33	0.44
0.37	0.49
0.45	0.59

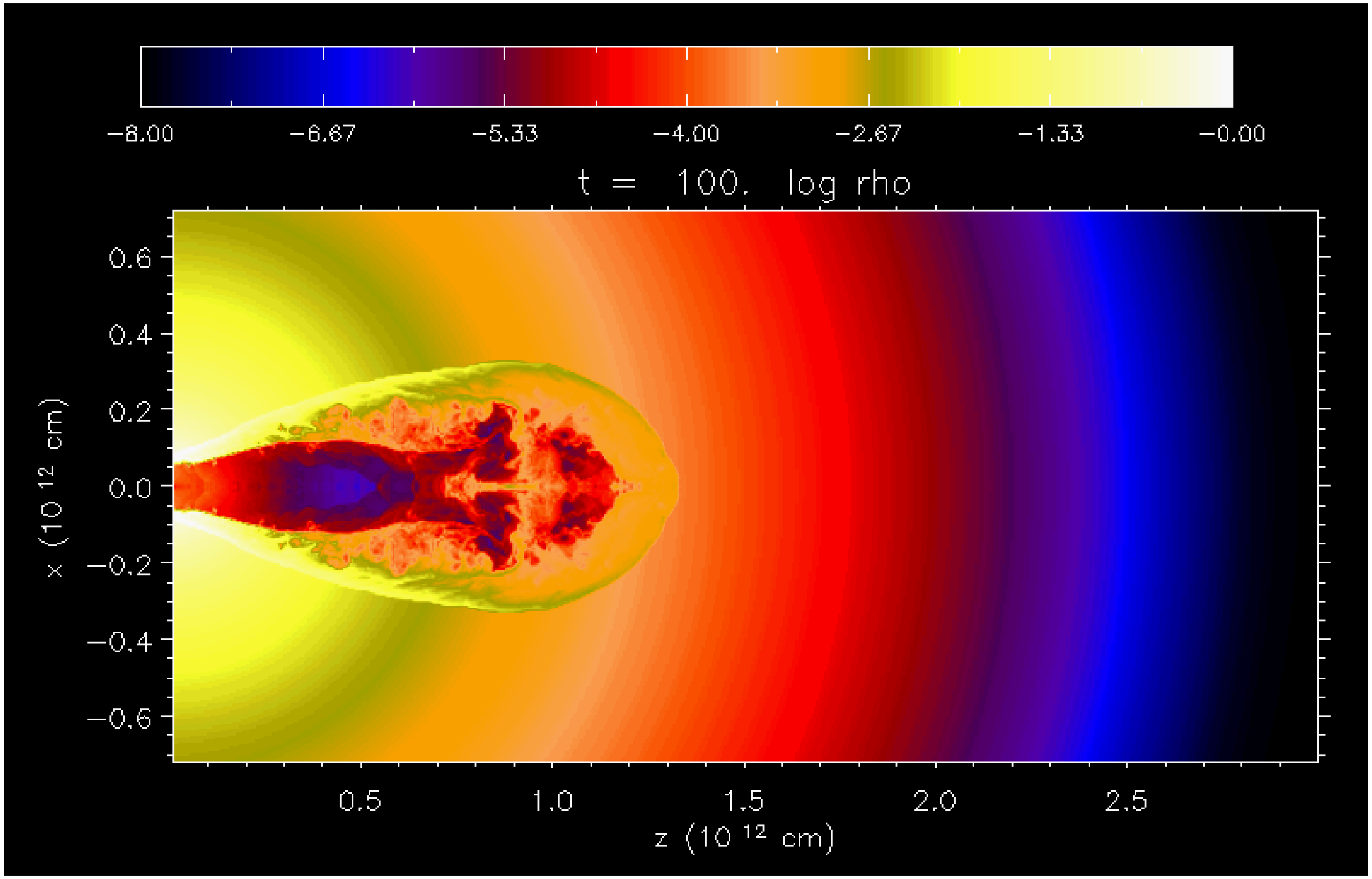
Gamma-Ray Bursts

The low mass loss rates of these stars favors high the formation and collapse of high mass helium cores.

If the rotation rate is high enough and *if* the star loses its hydrogen envelope, a GRB is possible.

Very long duration GRBs (> 100 s in the rest frame) may even be possible with the envelope intact.

Collapsars inside stars that have not lost
their envelopes (Zhang & Woosley, in preparation)



Need to keep the power on for at least the light
crossing time. This implies very long transients – if any.

Pop III (Z = 0) Stars

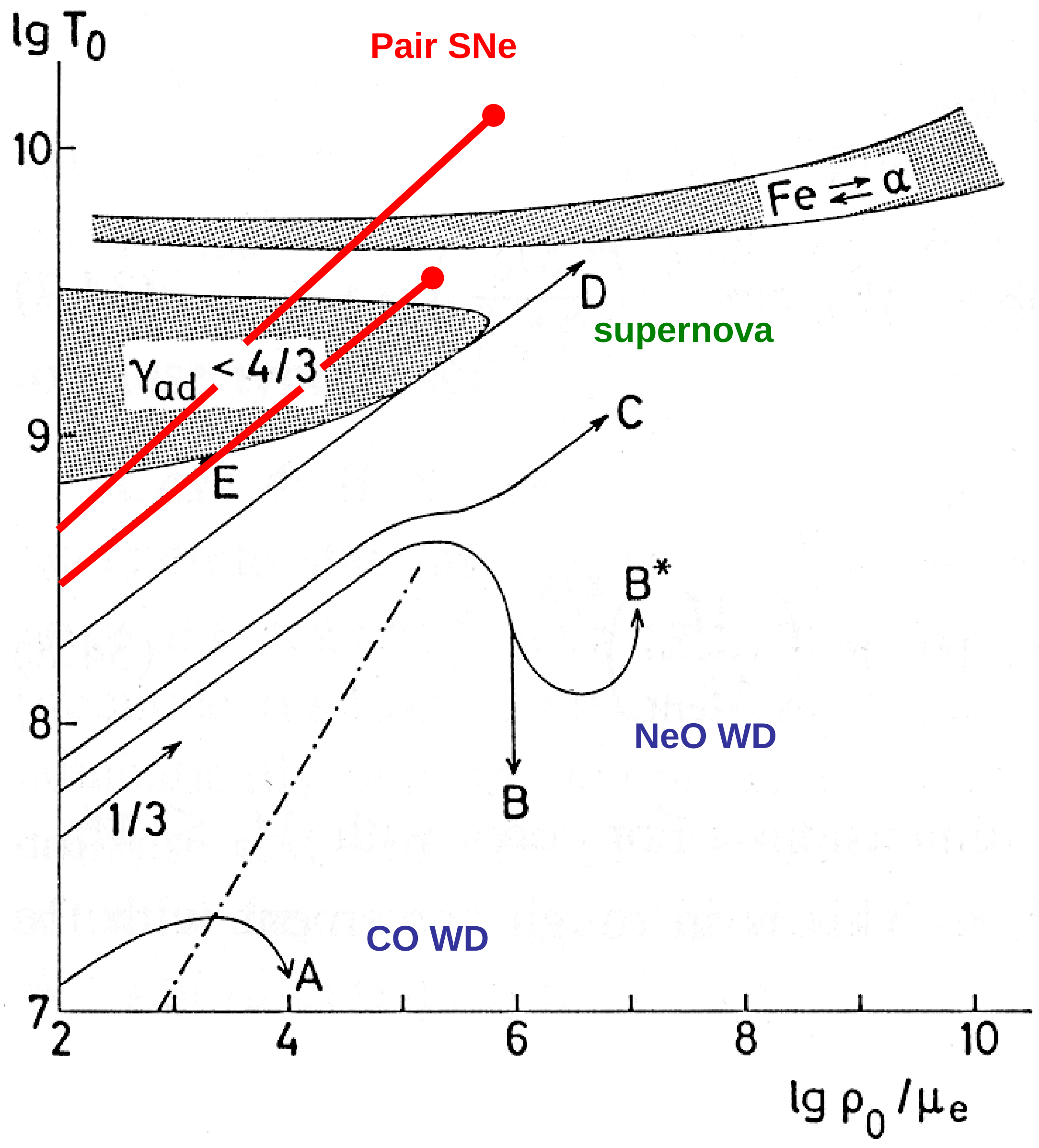
$(100 \leq M/M_\odot \leq 500)$

Good:

- Explosion mechanism well understood
- Mass loss may be negligible
- Initial composition well known
- Pulsationally stable

Many Studies in 1970s and 1980s

Rakavy, Shaviv
Fraley
Barkat
Arnett, Bond, Carr
Ober, El Eid, Fricke
Talbot
Appenzeller
….



Kippenhahn & Weigert (1990)

Instability Regimes

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

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Mass Loss in Very Massive Primordial Stars

- Negligible line-driven winds (mass loss ~ metallicity$^{1/2}$)
- No opacity-driven pulsations (no metals)
- Continuum-driven winds not yet well understood
  likely very small contribution
- Epsilon mechanism inefficient in metal-free stars below ~1000 $M_\odot$
  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

Baraffe, Heger, and Woosley (2001)

- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above ~500 $M_\odot$

Problematic:

- Their existence
- Mixing between H envelope and He convective core makes primary nitrogen resulting in radical restructuring of the star

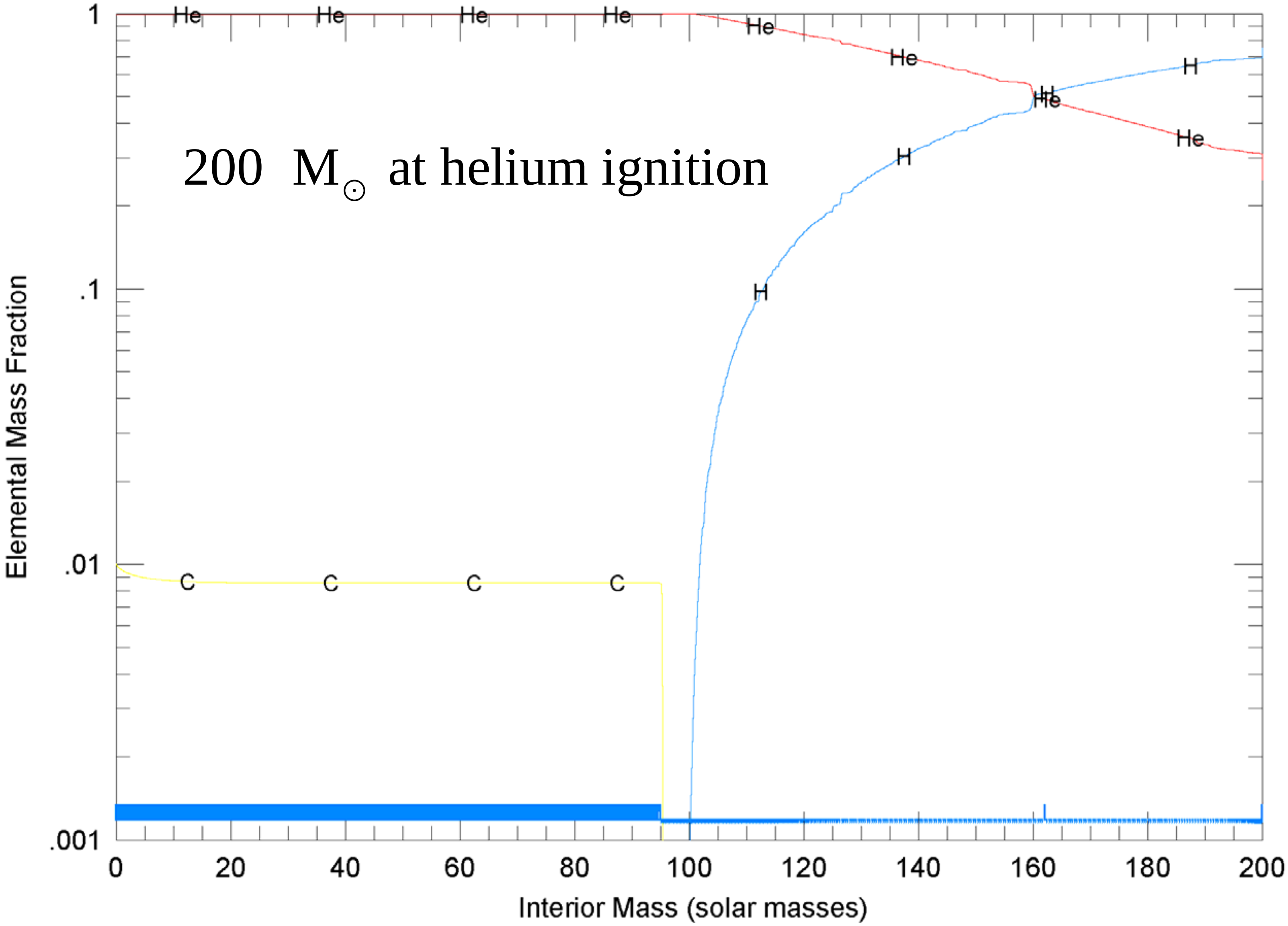
Sensitive to overshoot mixing, rotation
Determines whether star is BSG or RSG at death

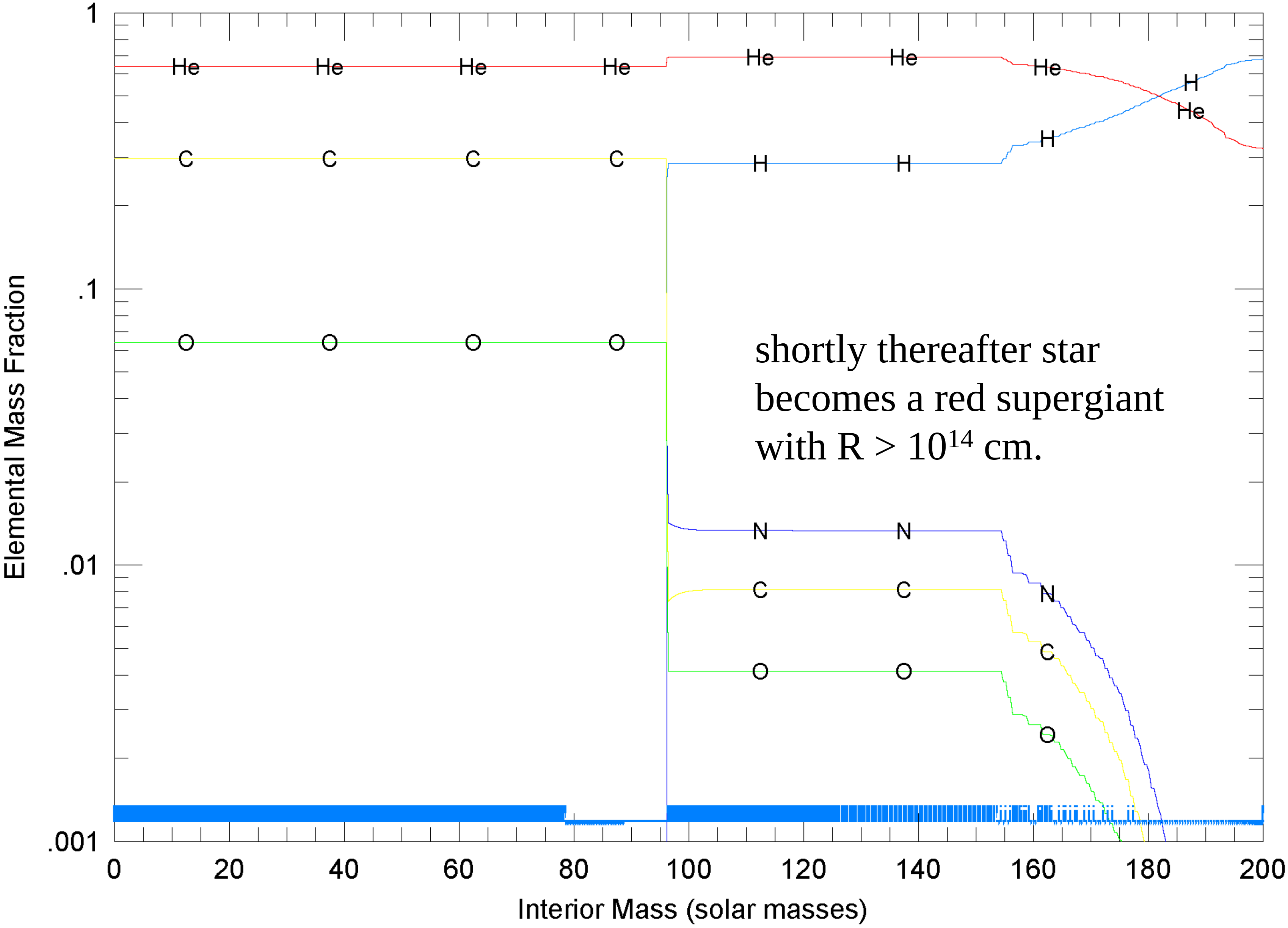
- Rotation (no observations for guidance)

Two 300 $M_\odot$ stars with v_{rot} = 10%, 30% Keplerian
have final helium core masses of 137 and 190 $M_\odot$

- Lack of opacity tables for CNO rich Fe deficient matter

200 $M_\odot$ at helium ignition





shortly thereafter star becomes a red supergiant with R > 10^{14} cm.

With rotation and standard overshoot and semiconevcetive parameter settings this happens for all the Z =) stars over 100 solar masses

Problem:

What to do about mass loss rates in red supergiants with high “metallicity” (CNO) but devoid of anything heavier than neon.

And if the helium core is uncovered (Wolf-Rayet star) what do we use for the mass loss there?

Uncharted territory.

Here we have neglected mass loss (unless the star is in a binary).

Survey 2:

Helium Cores:

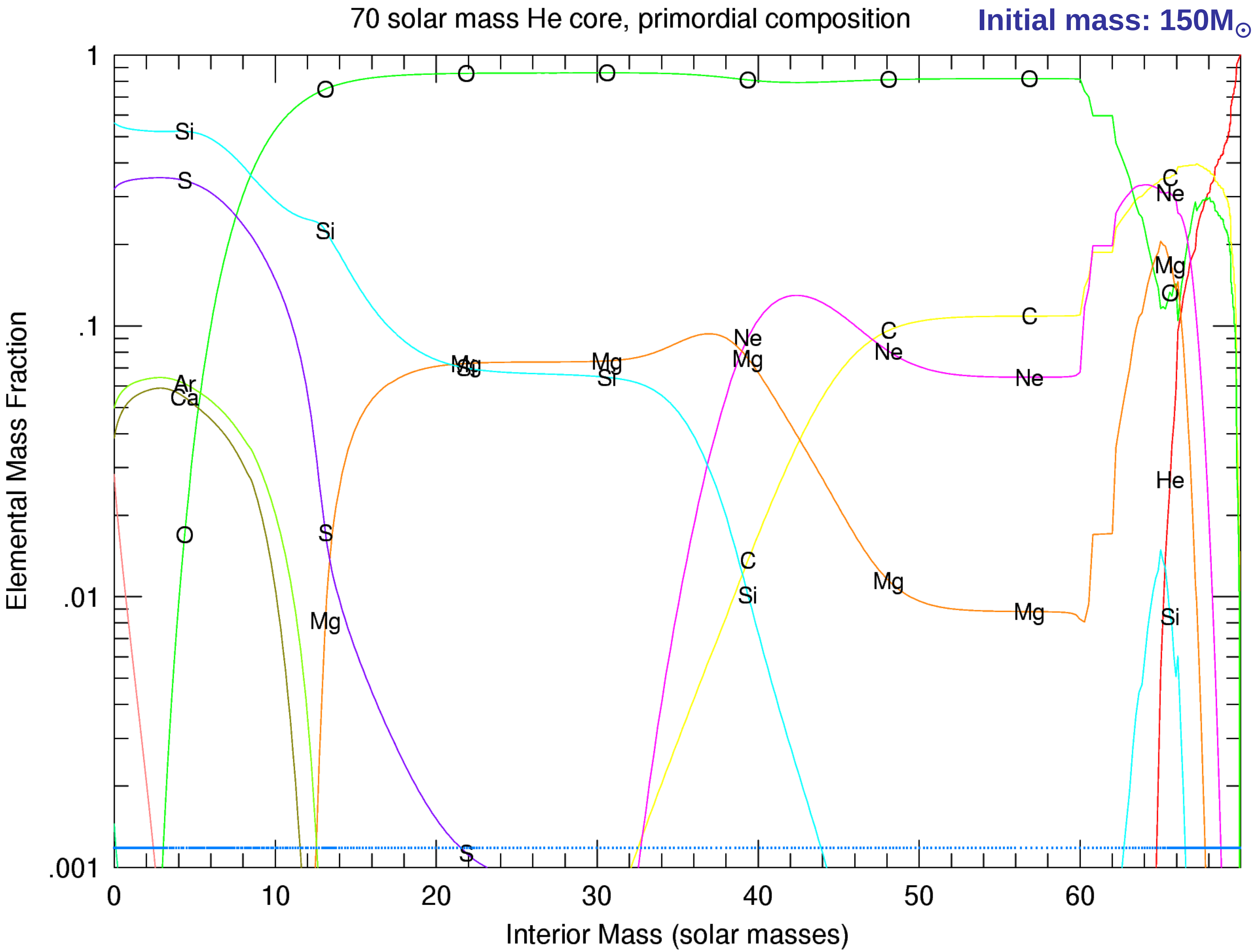
$60 - 135\ M_{\odot} \qquad \Delta M = 5\ M_{\odot}$

Full Stars:

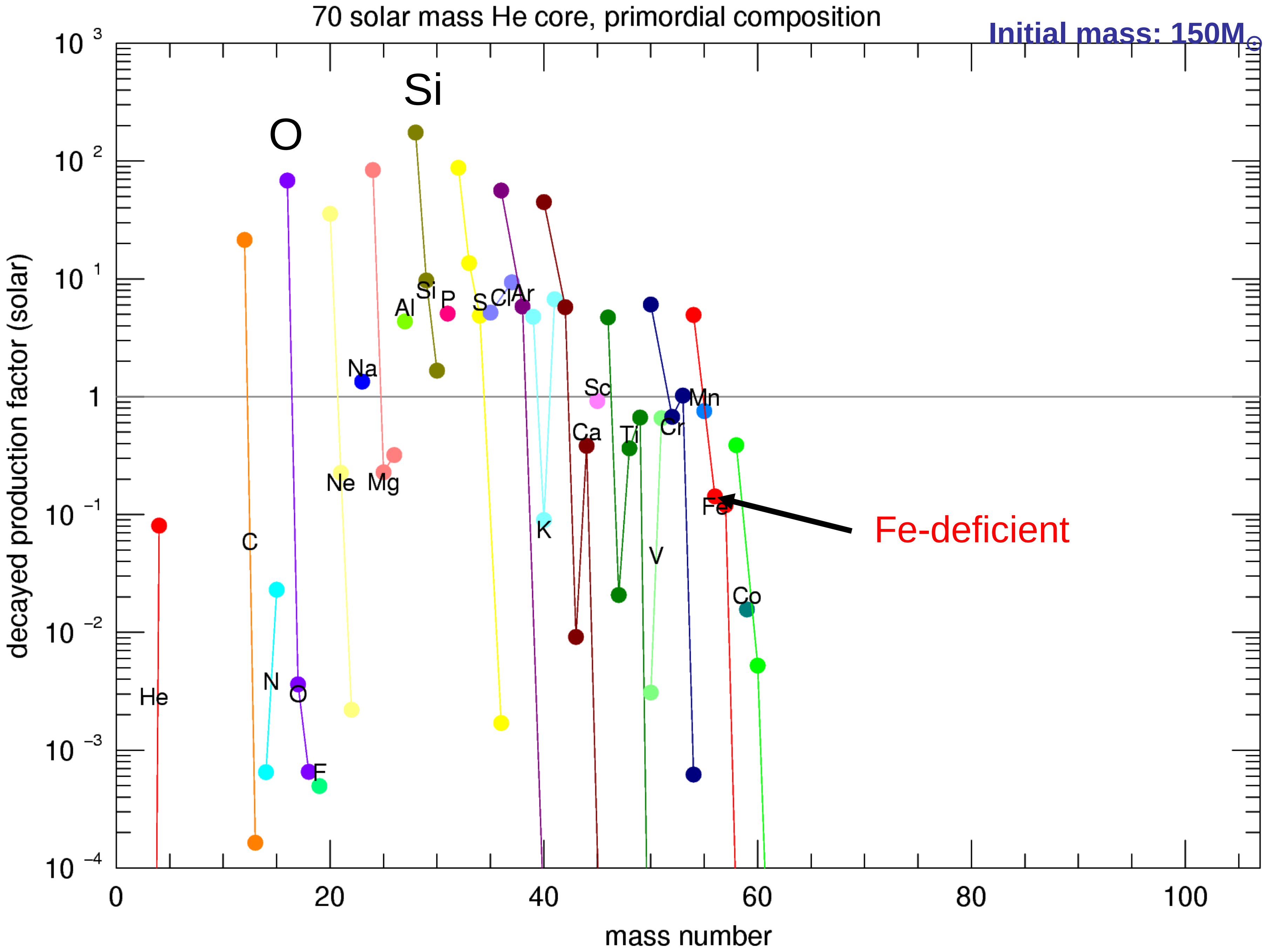
$150,\ 200,\ 250,\ 300\ M_{\odot}$

Nucleosynthesis and light curves

Initial mass: 150$M_\odot$



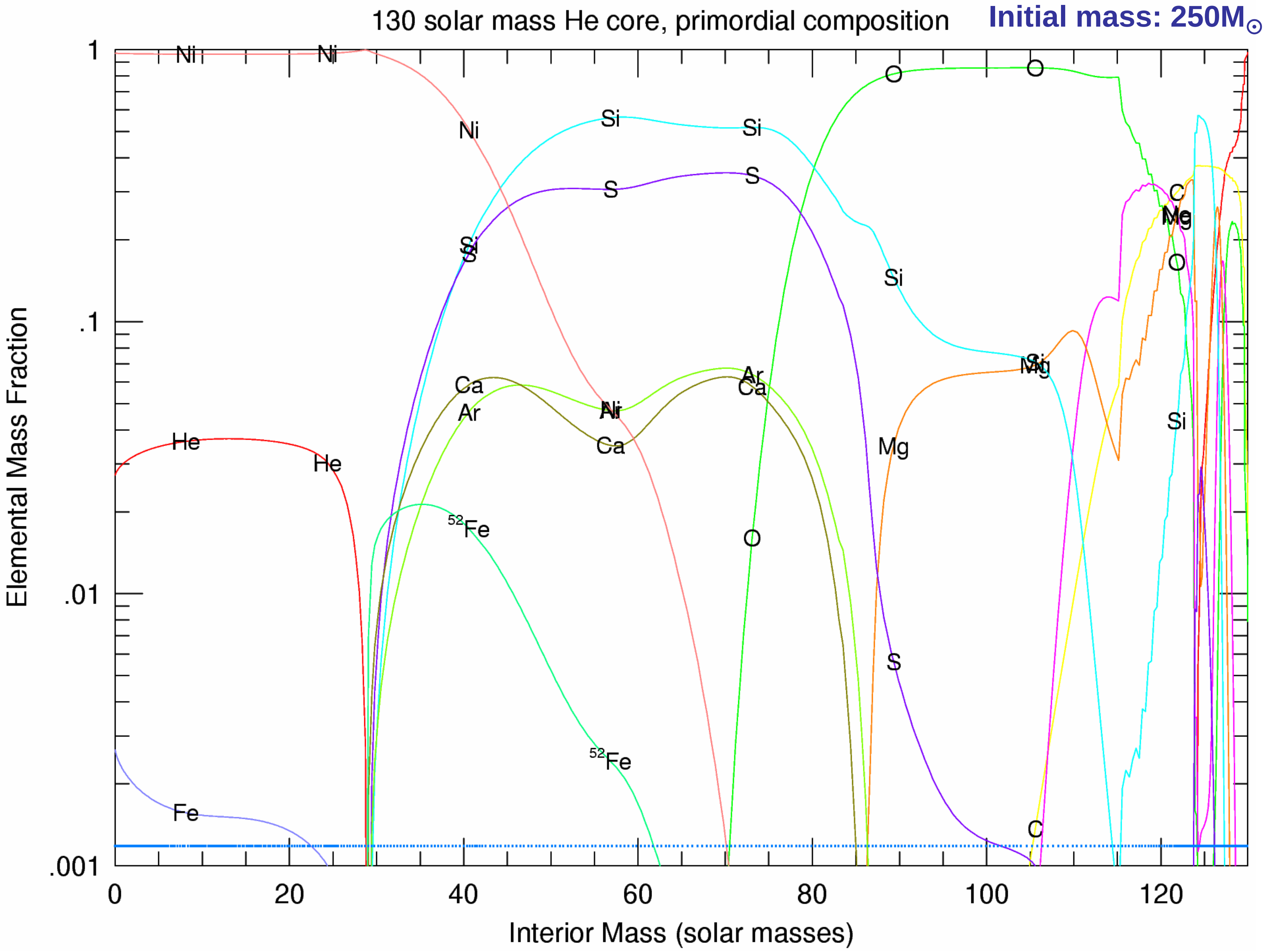
70 solar mass He core, primordial composition

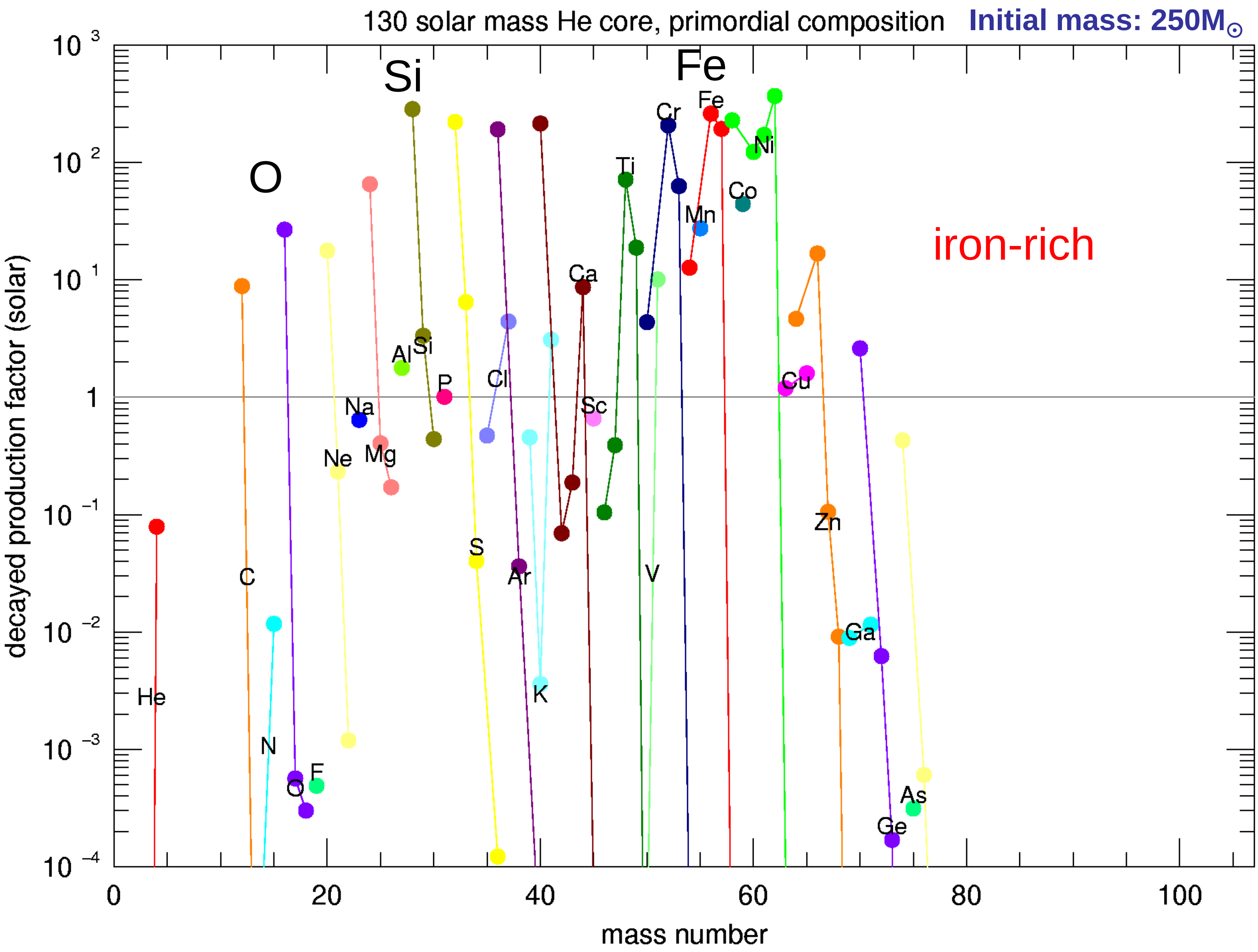


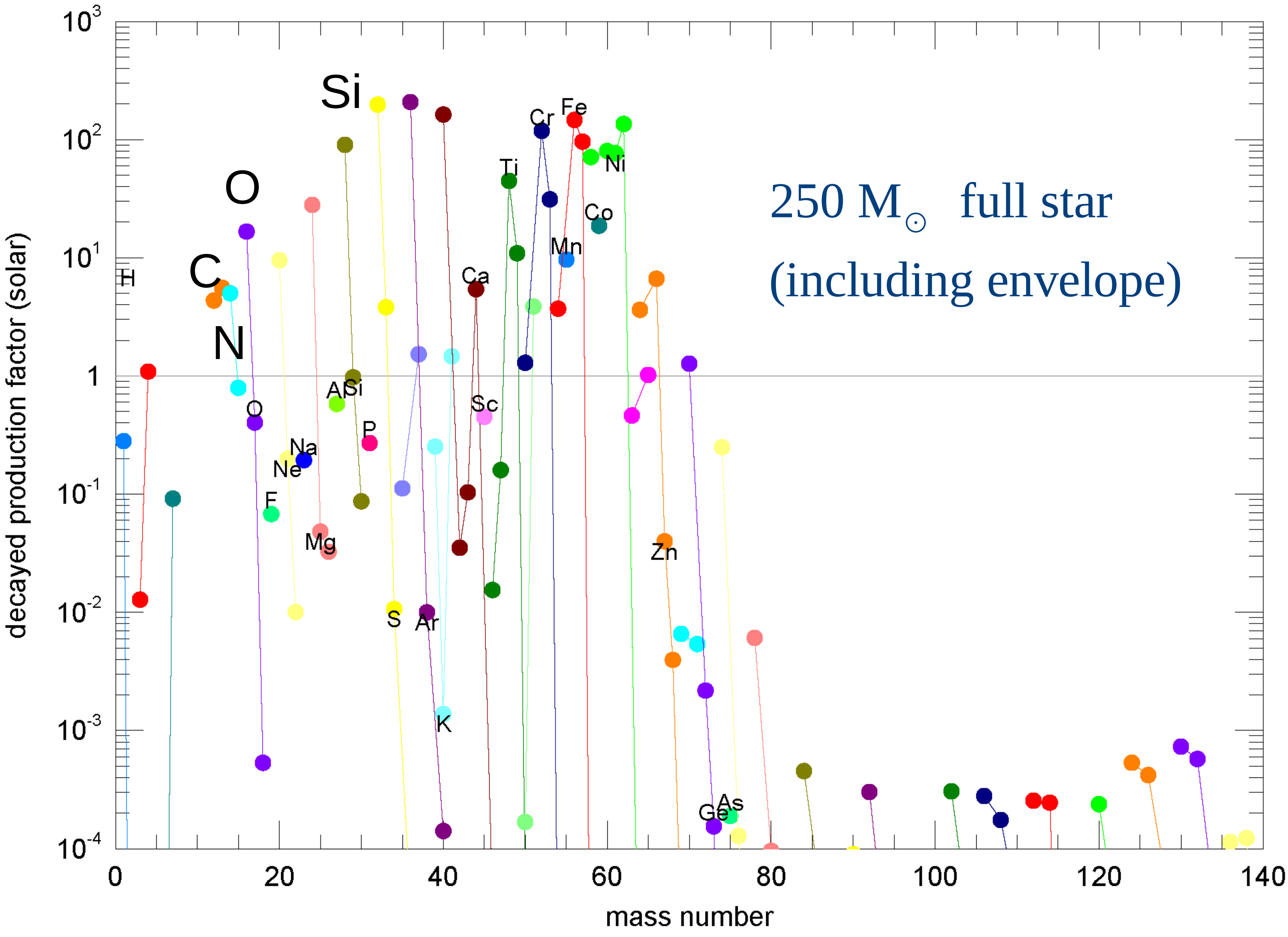
Initial mass: 150M$_\odot$

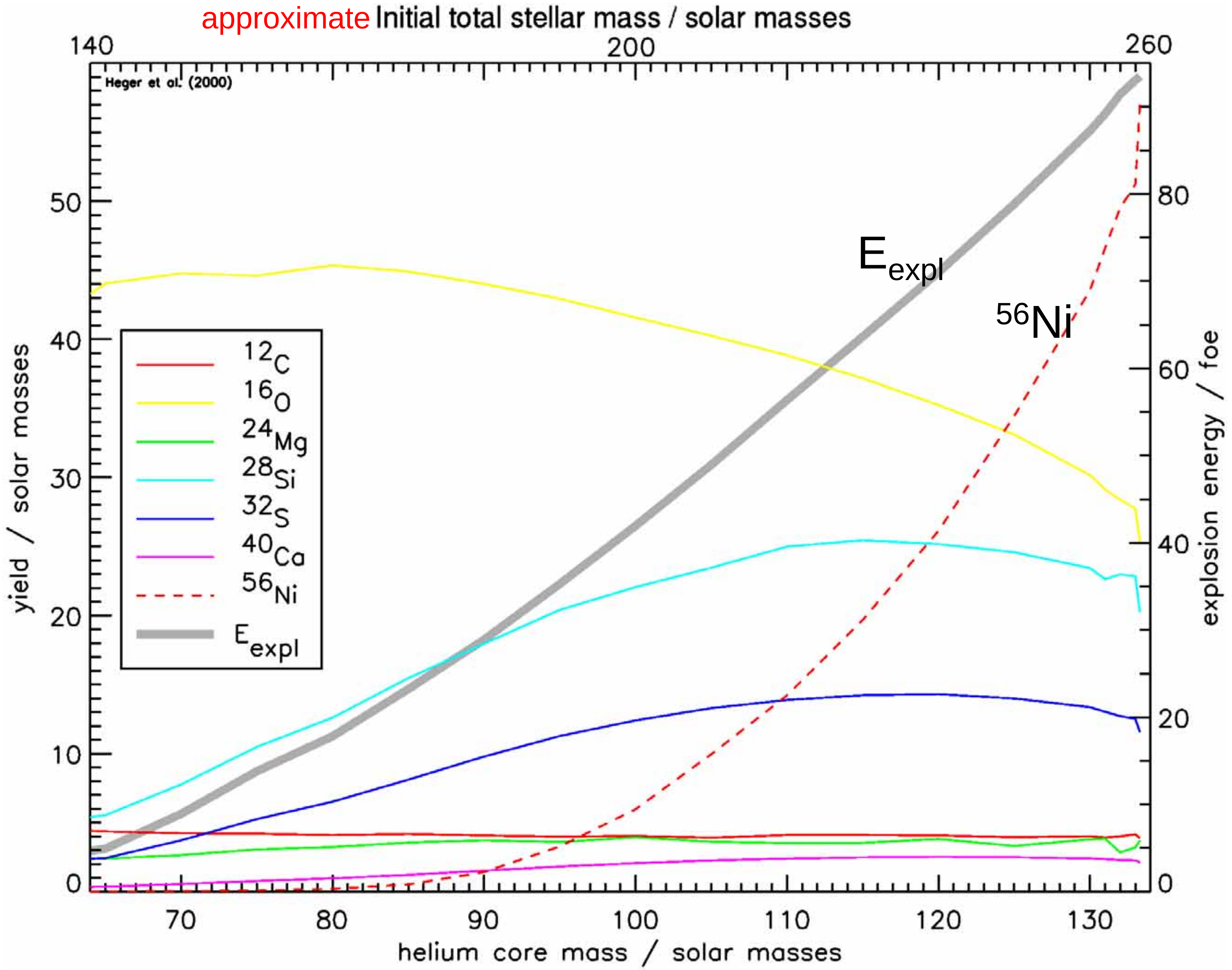
Fe-deficient

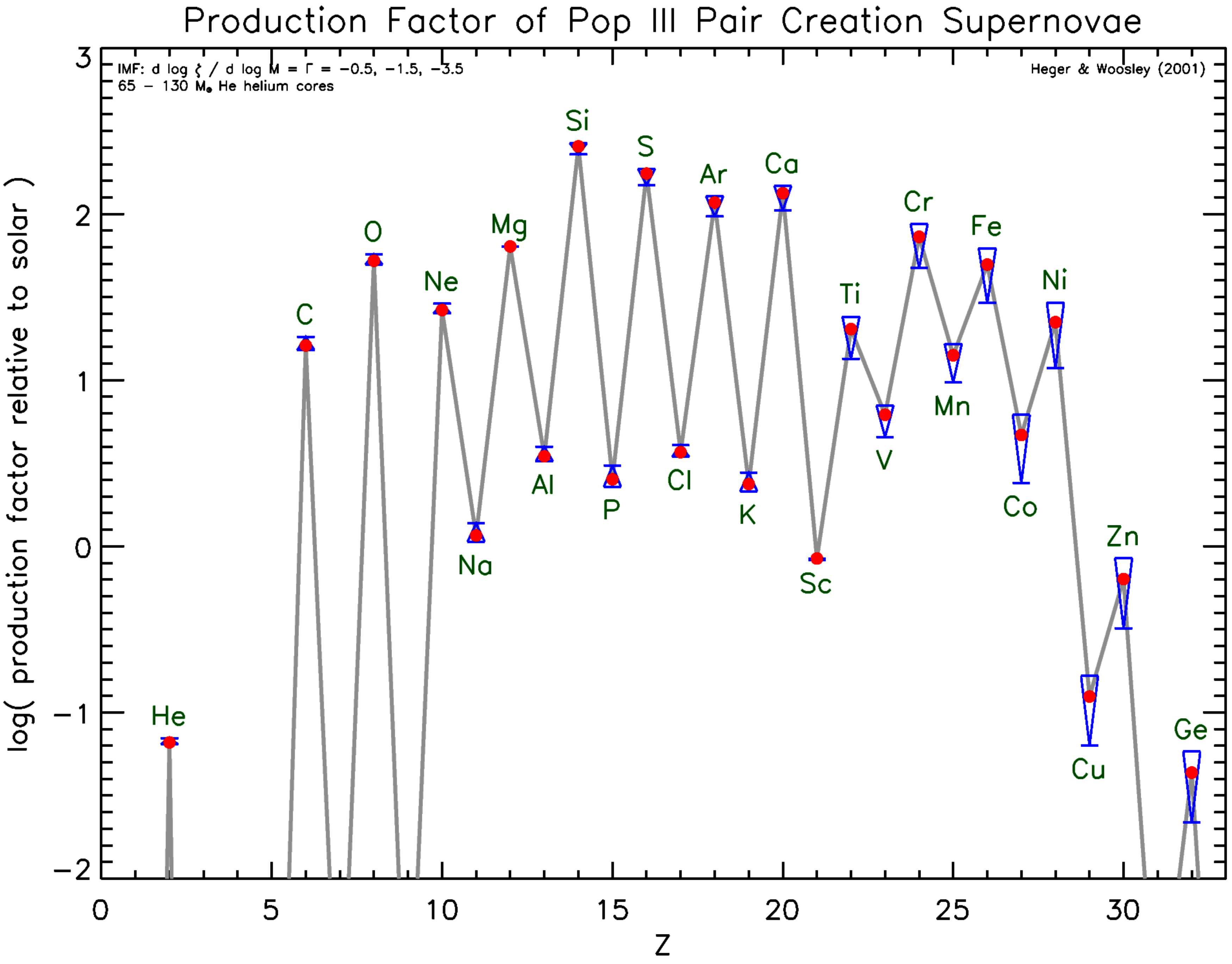
Initial mass: 250M$_\odot$



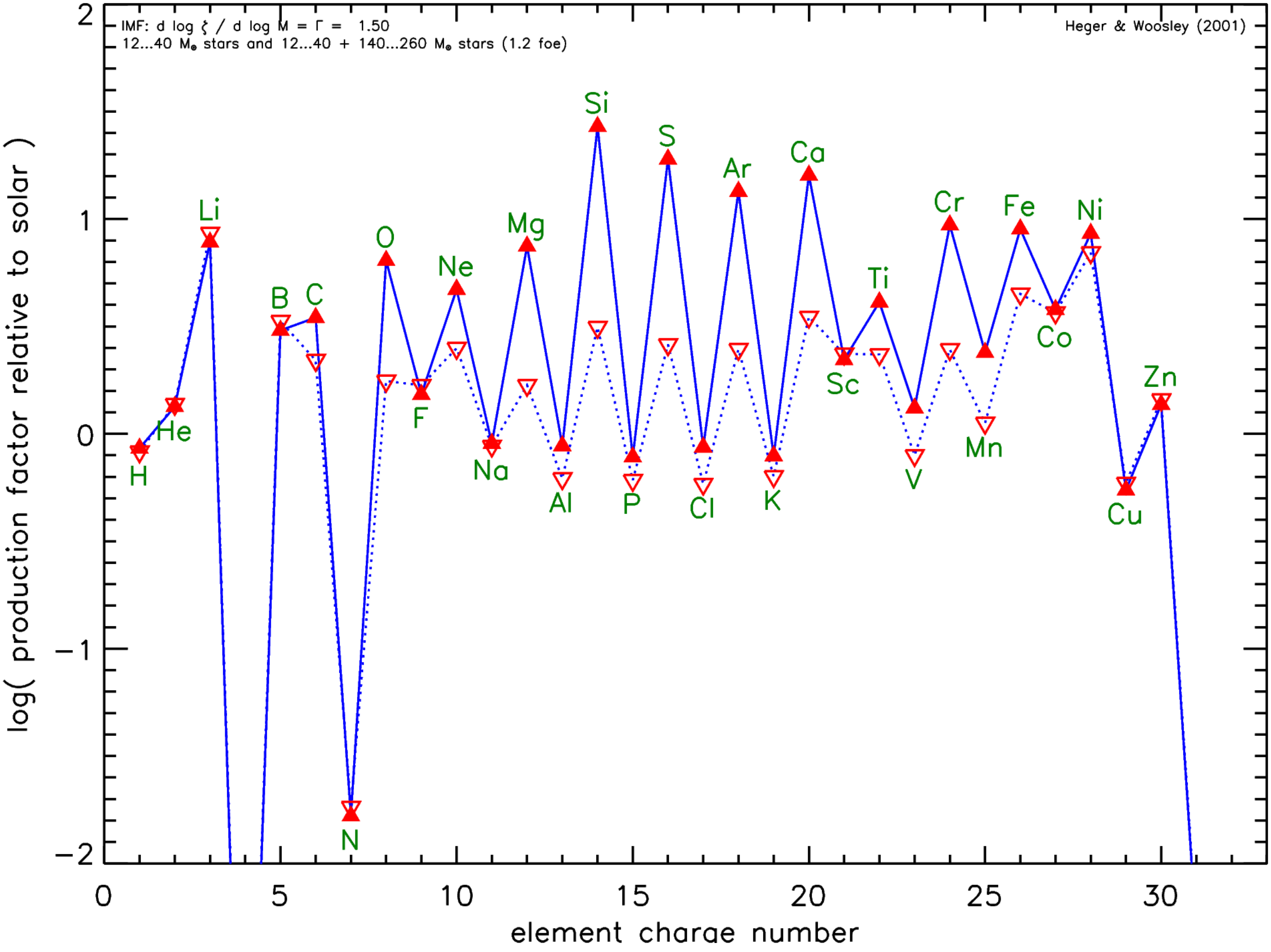

130 solar mass He core, primordial composition
Initial mass: 250M⊙
iron-rich
O
Si
Fe
He
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
decayed production factor (solar)
mass number
10^{3}
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100


250 $M_\odot$ full star
(including envelope)
decayed production factor (solar)
mass number
10^{3}
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100
120
140
H
C
N
O
O
F
Ne
Na
Mg
Al
Si
Si
P
S
Ar
K
Ca
Sc
Ti
Cr
Mn
Fe
Co
Ni
Zn
Ge
As


approximate Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
E$_{expl}$
^{56}Ni
^{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 / foe
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses


Production Factor of Pop III Pair Creation Supernovae

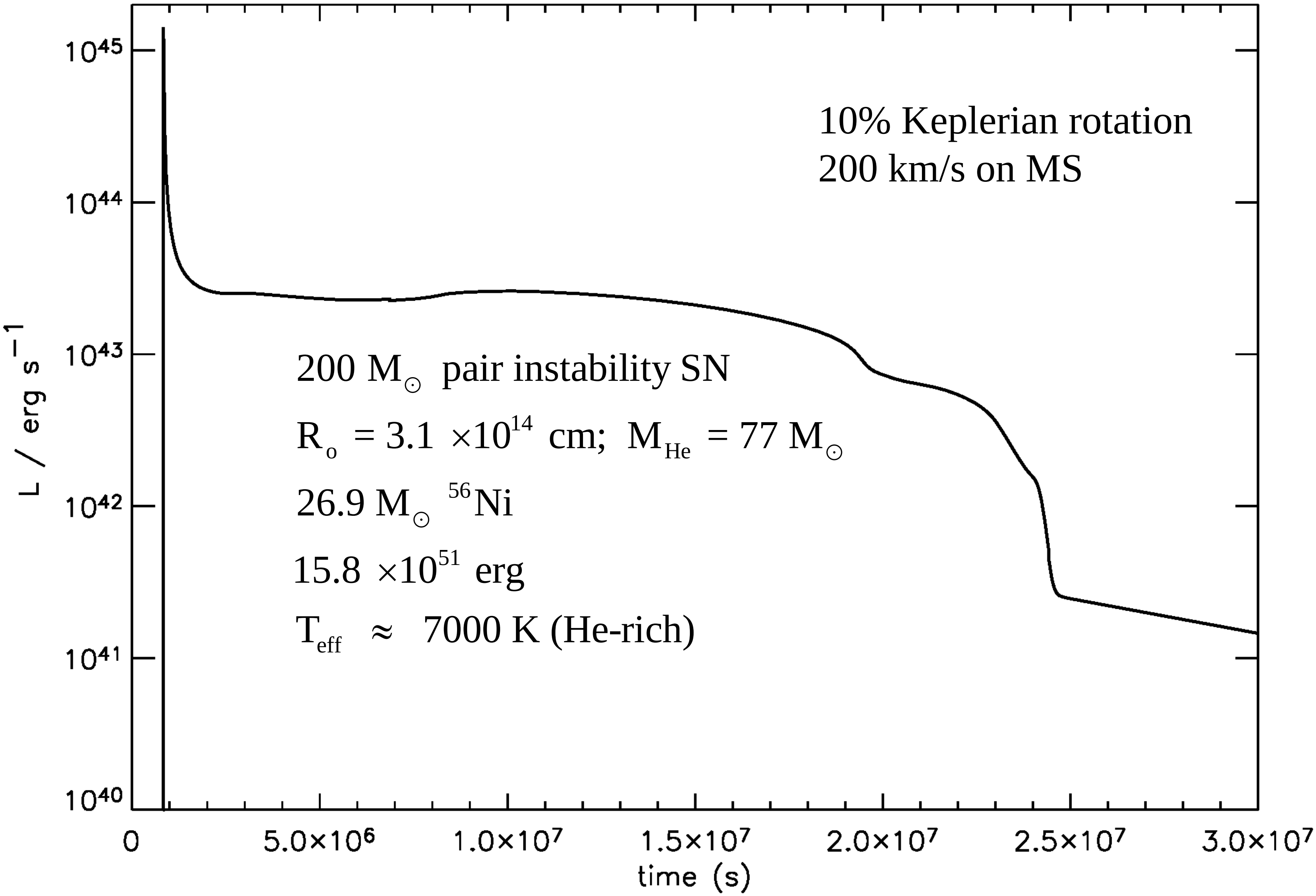
Production Factor of Primordial Massive Stars



Bright Supernovae at the edge of the Universe?

- Explosion energy up to 10^{53}erg
  (50-100x that of “normal” supernovae)

- Up to 50 solar masses of radioactive ^{56}Ni
  (50-100x that of “normal” supernovae)



10% Keplerian rotation
200 km/s on MS

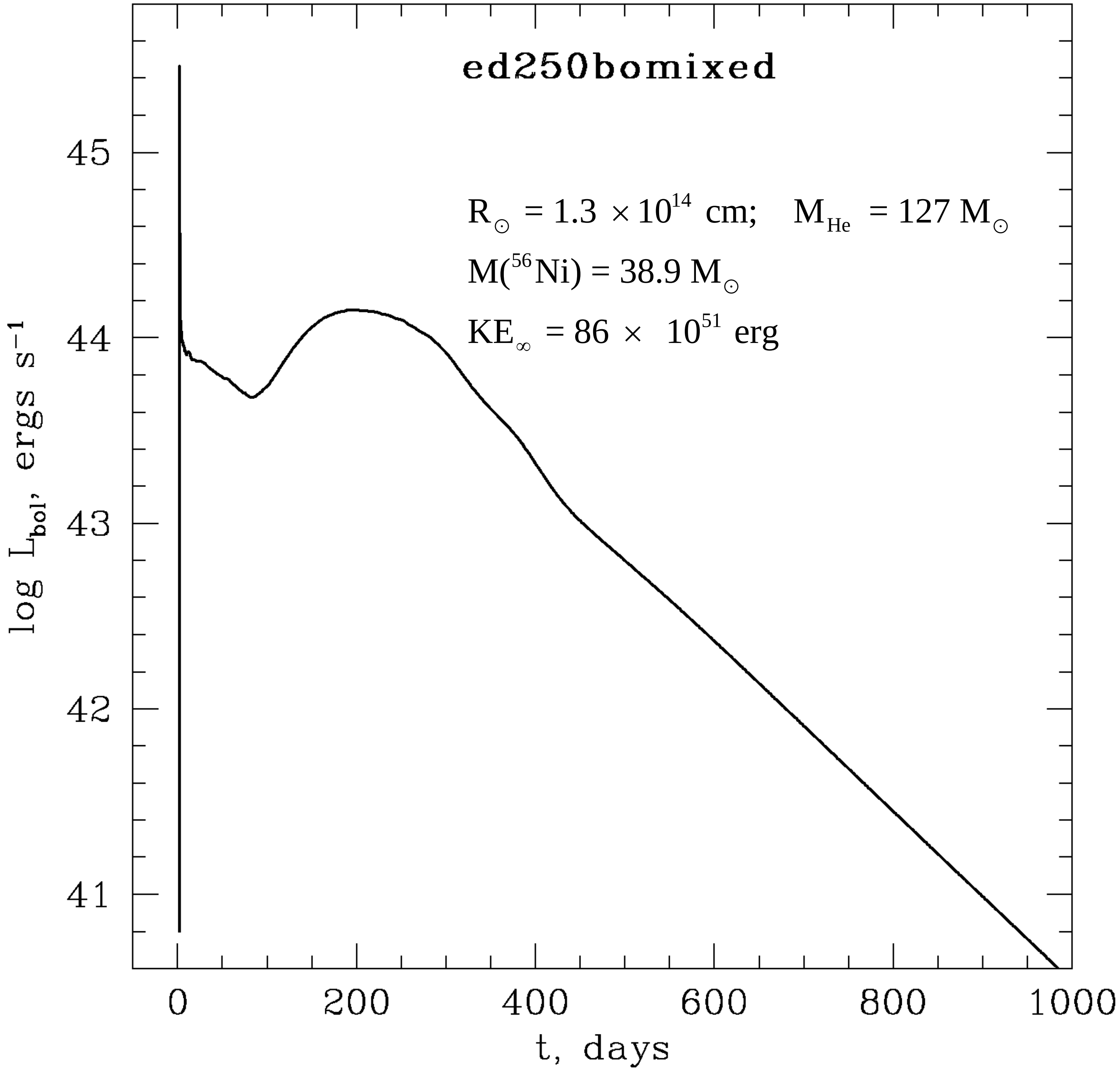
200 $M_\odot$ pair instability SN

$R_o = 3.1 \times 10^{14}$ cm; $M_{He} = 77\ M_\odot$

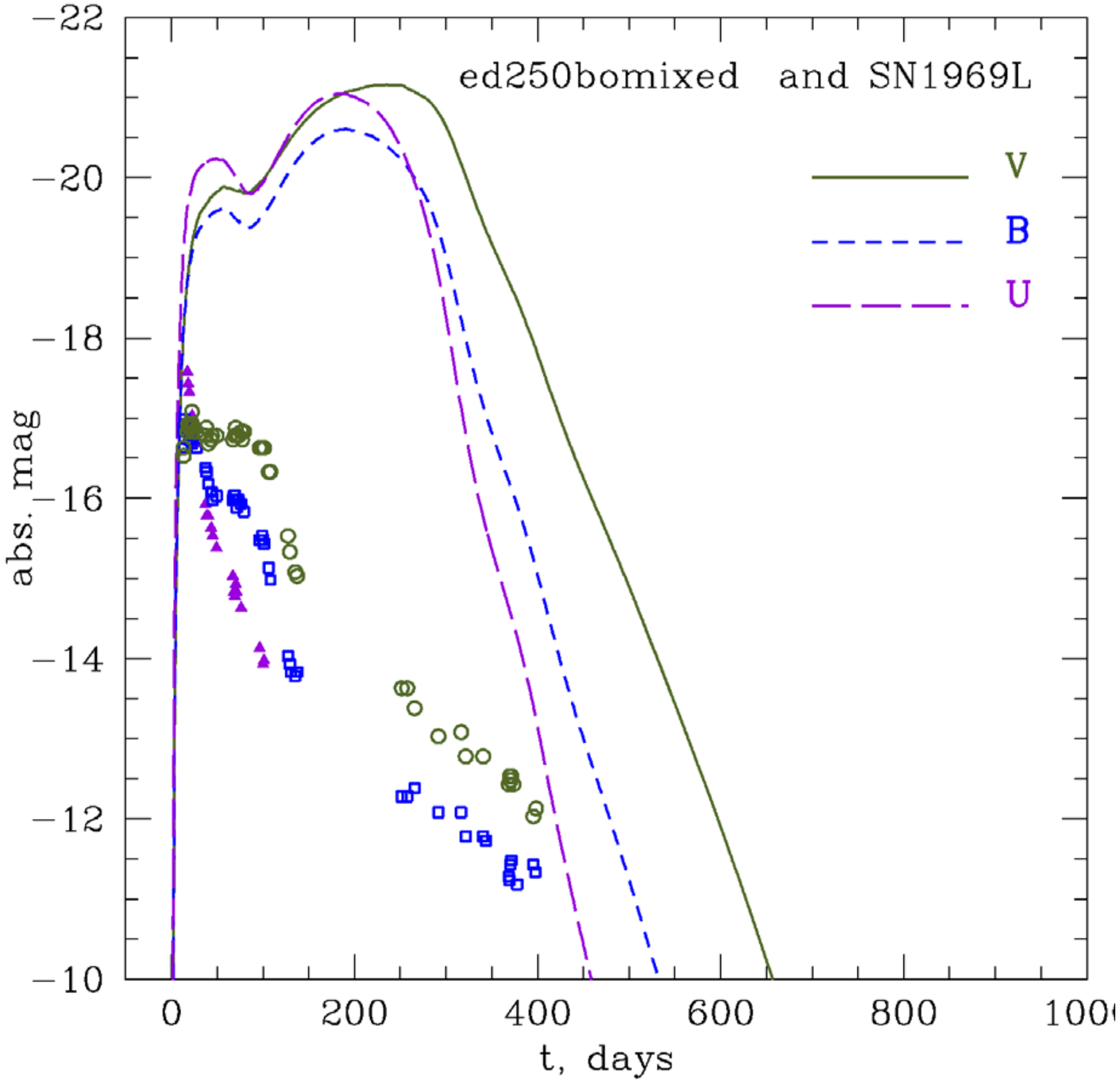
26.9 $M_\odot$ ^{56}Ni

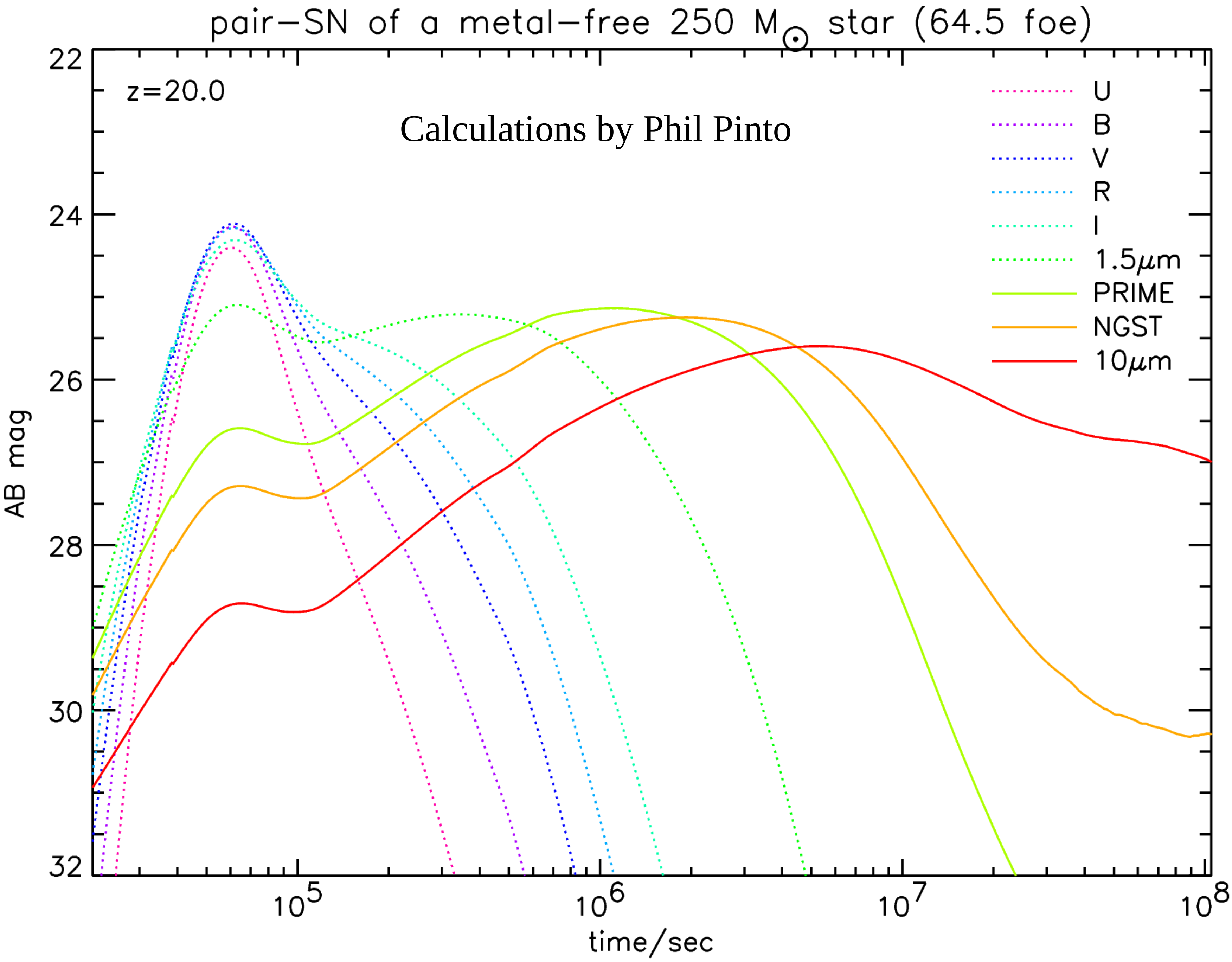
15.8×10^{51} erg

$T_{eff} \approx 7000$ K (He-rich)

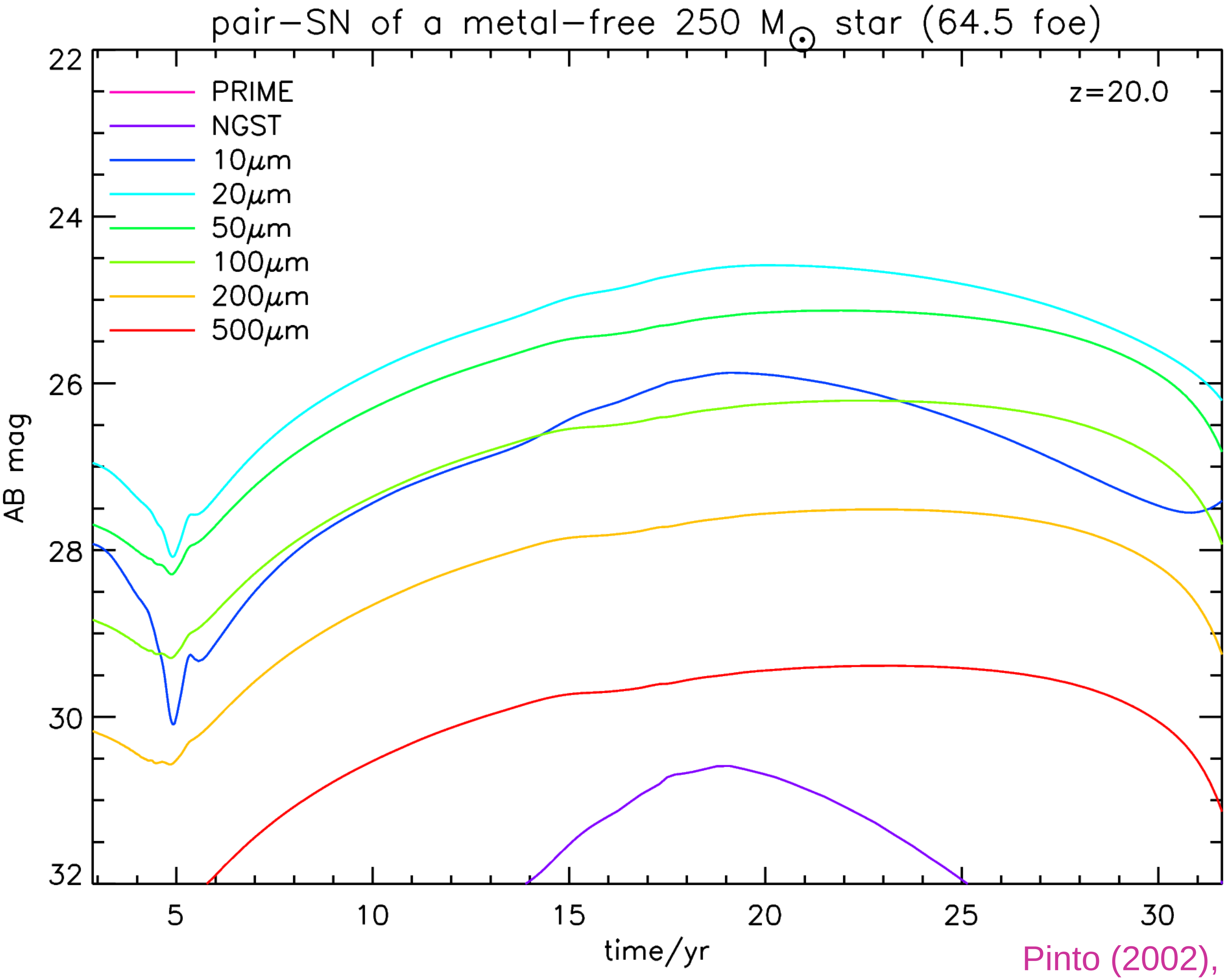


Calculations by
Sergei Blinnikov

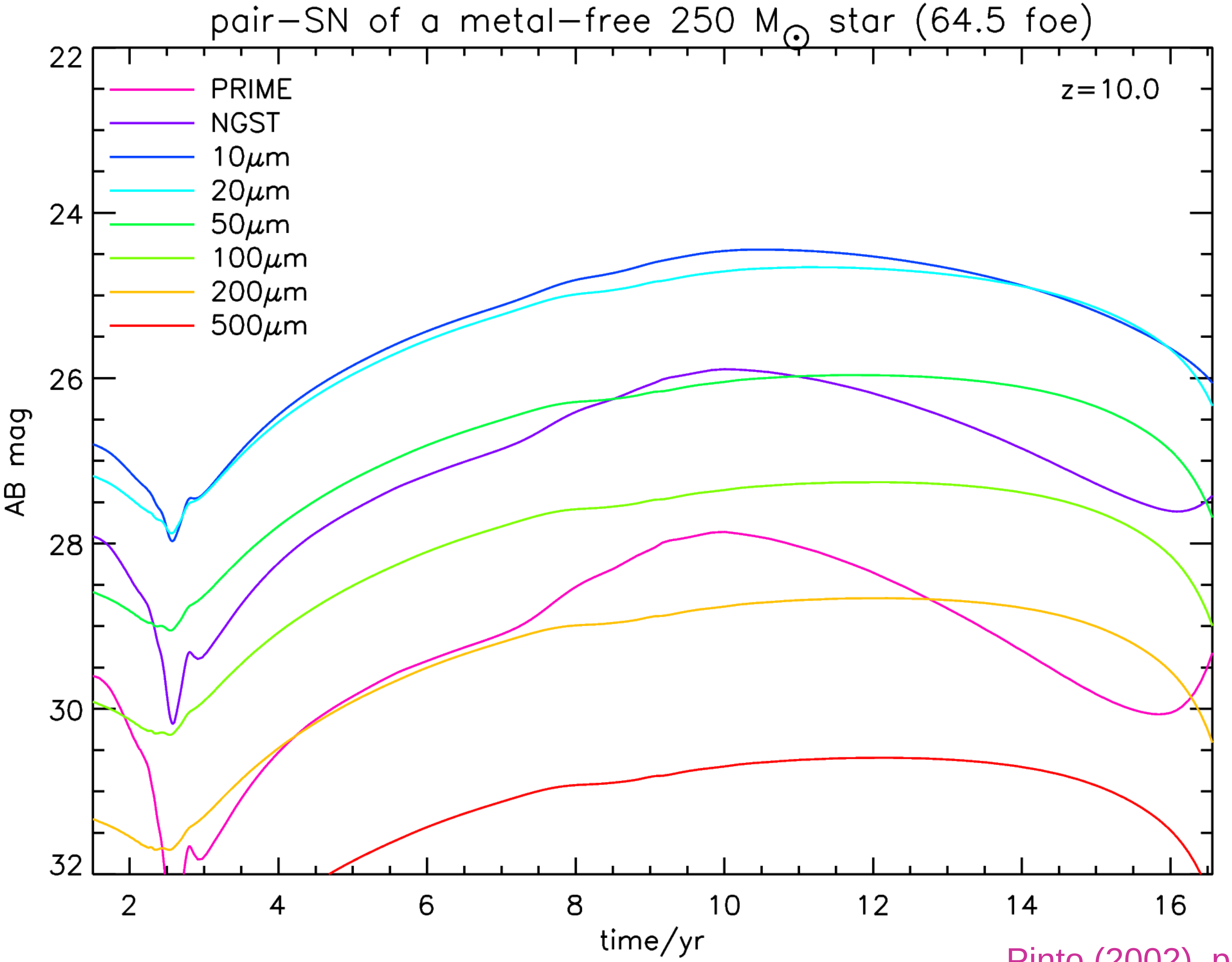

ed250bomixed and SN1969L
V
B
U
−22
−20
−18
−16
−14
−12
−10
abs. mag
0
200
400
600
800
t, days



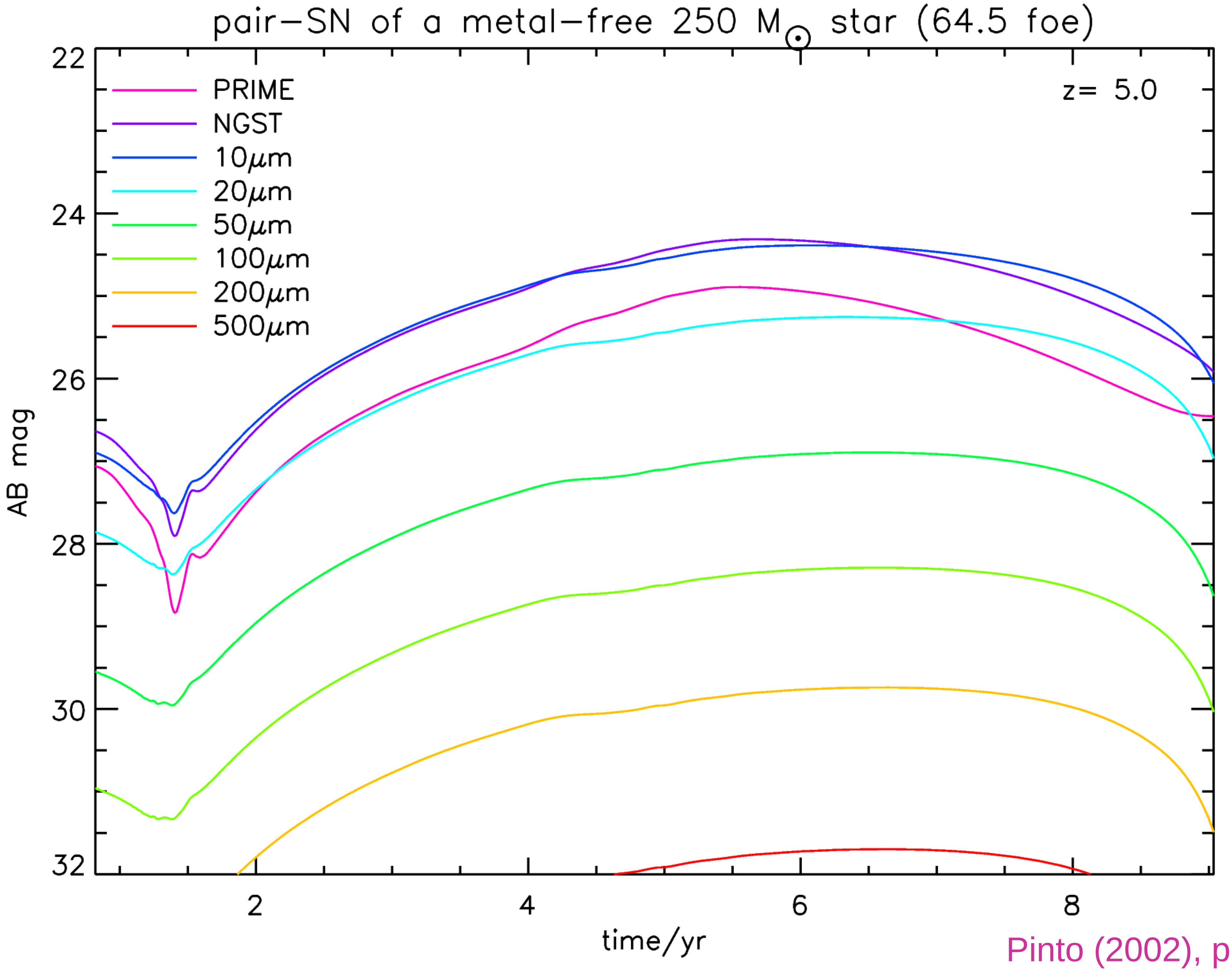
Calculations by Phil Pinto



Pinto (2002), p.c.

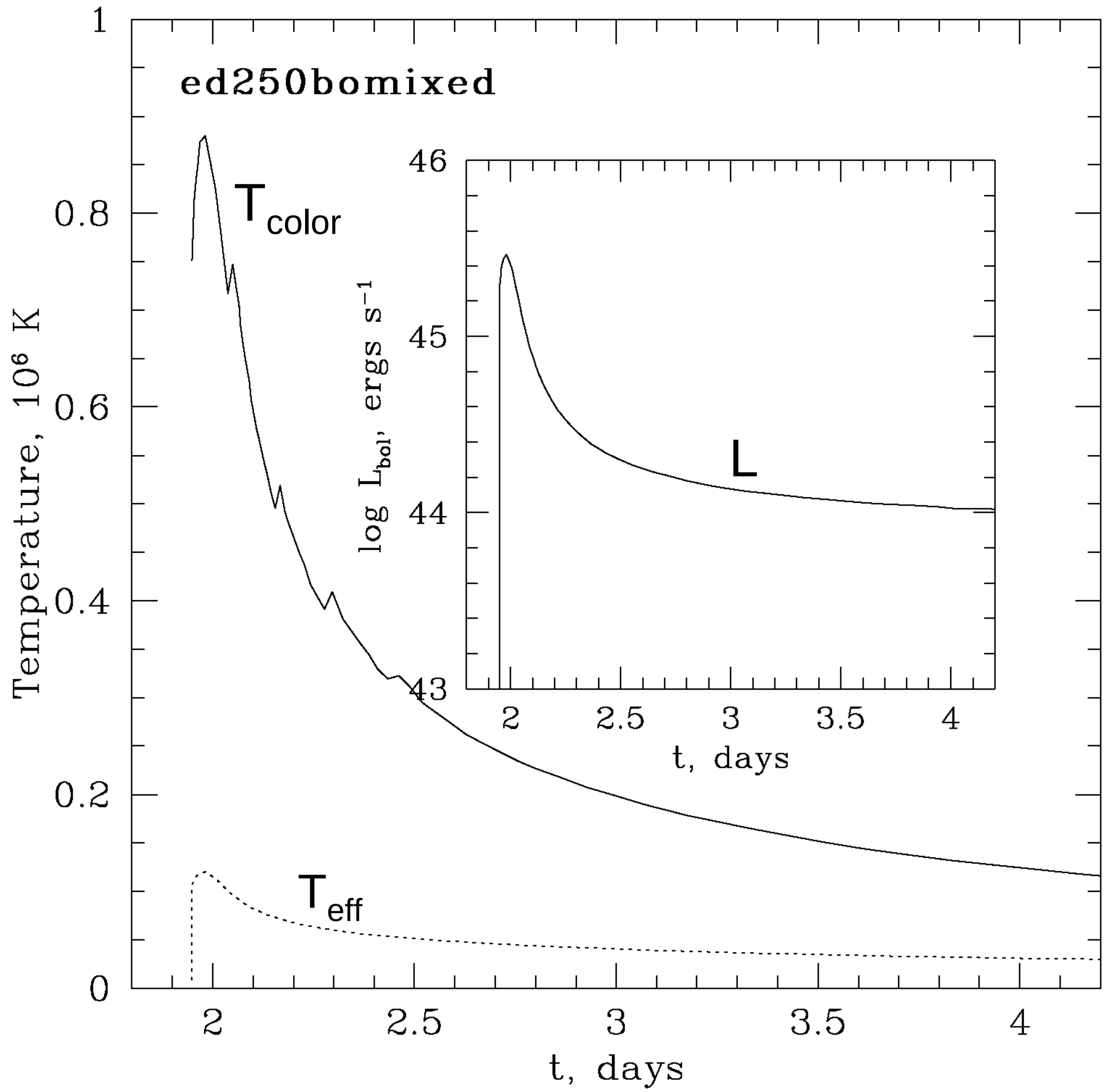


Pinto (2002), p.c.



Pinto (2002), p.c.

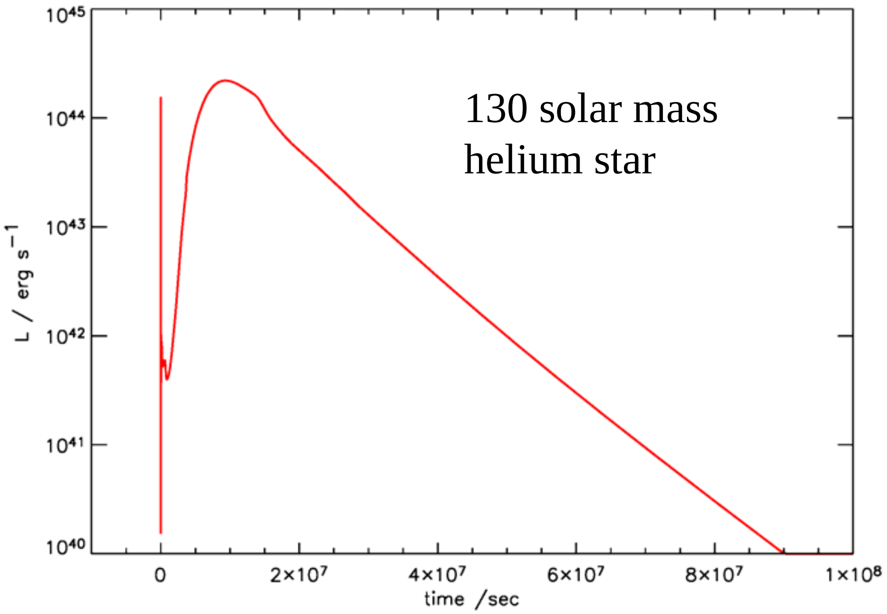
Shock break out

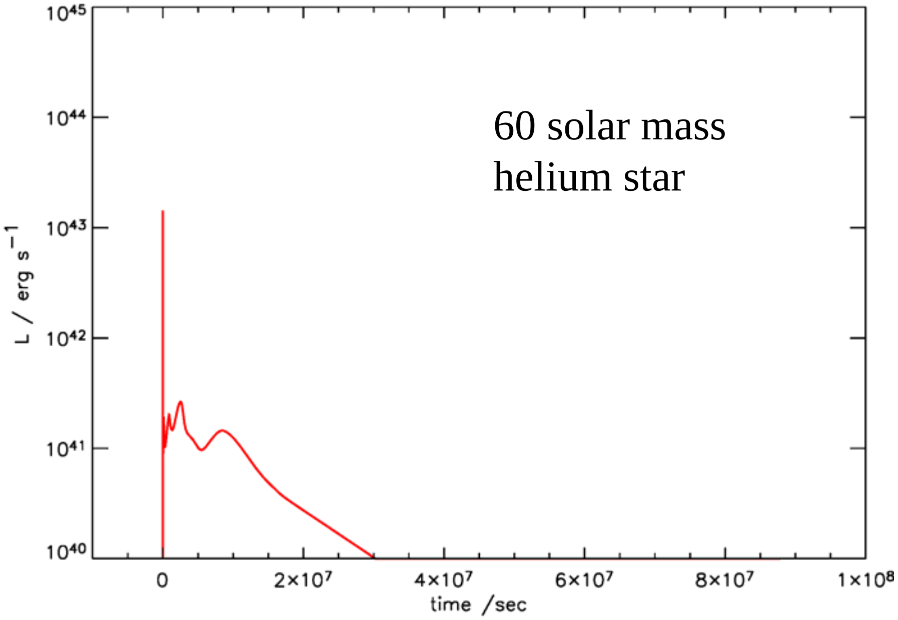


In the frame of the supernova

Calculations by
Sergei Blinnikov

$L \sim 2 \times 10^{45}$ erg s^{-1}
for two hours with
$T_{color} \sim 10^6$ K.

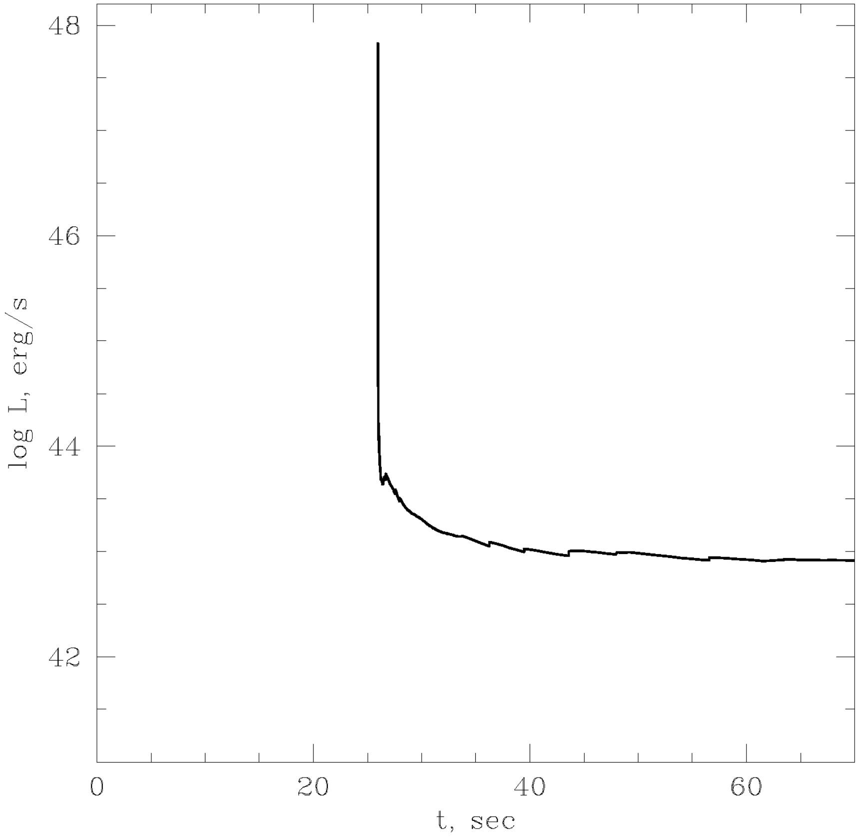


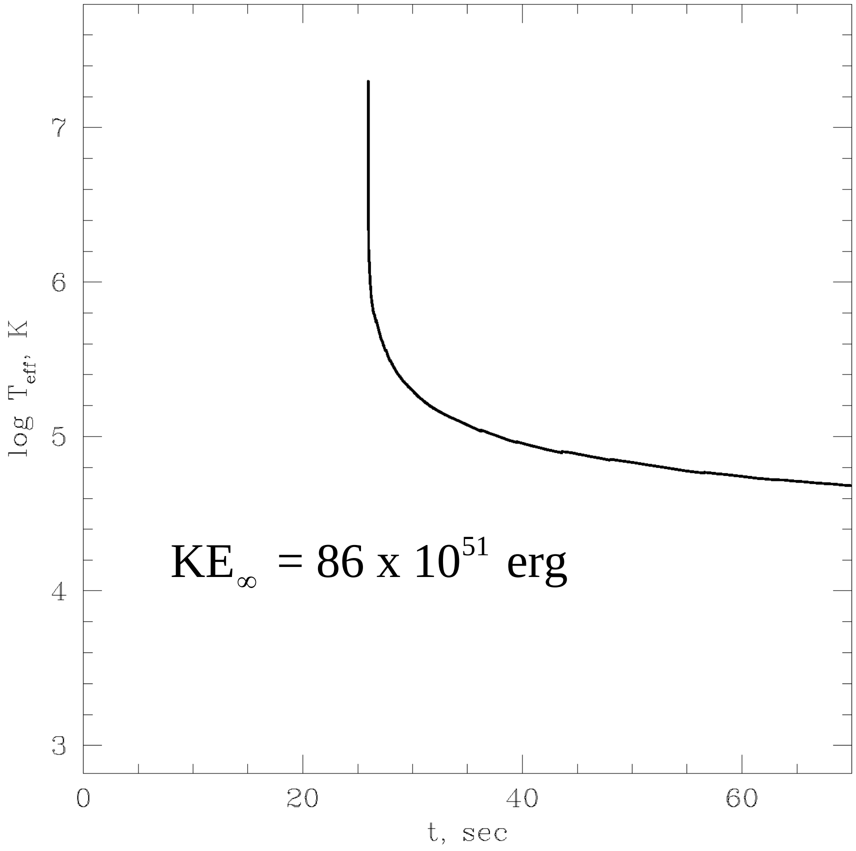


Should the stars lose their hydrogen envelopes they could be even brighter (or fainter),

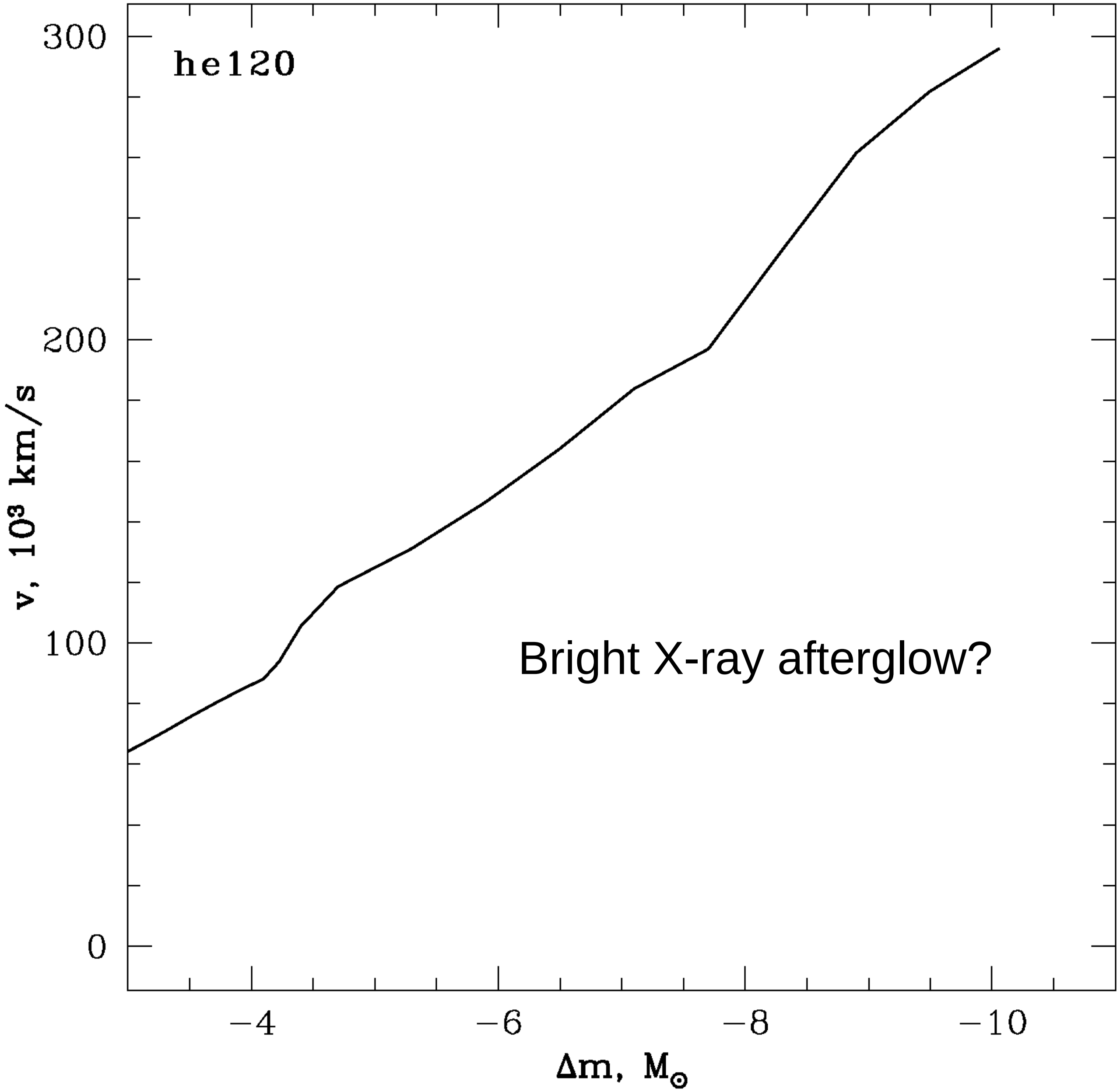
Mass	60	130
^{56}Ni	0.0001	40.3 $M_\odot$
KE_∞	1.2×10^{51} erg	8.6×10^{52} erg

calculation by Sergei Blinnikov



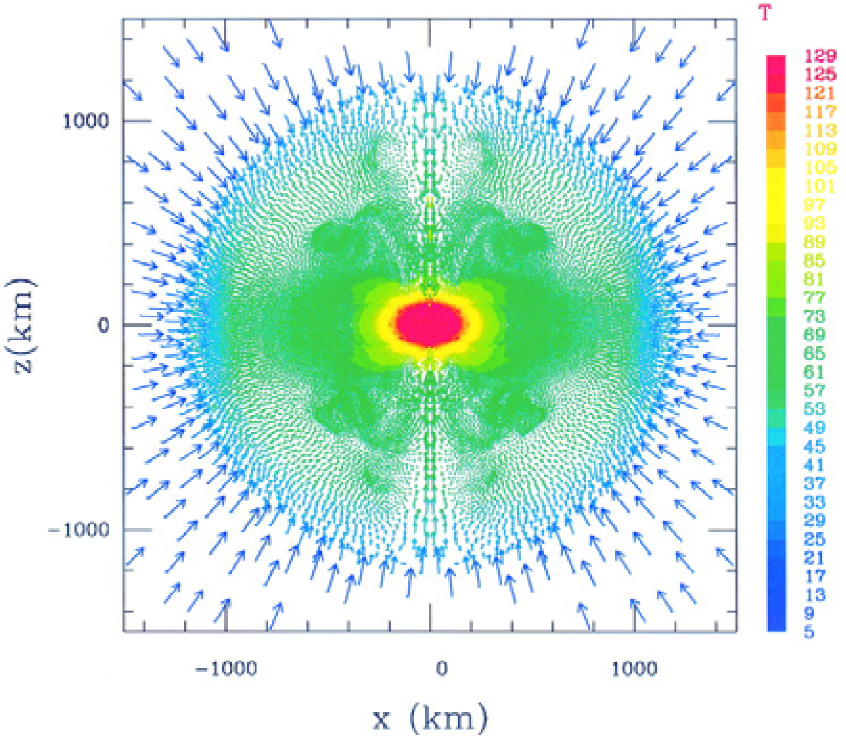


Break out transient for 120 solar mass helium core explosion. Calculation poorly resolved, Duration about 0.1 s. Relativistic beaming reduces dependence on light crossing time. L ~ 10^{45} erg s^{-1} at 10^7 K.

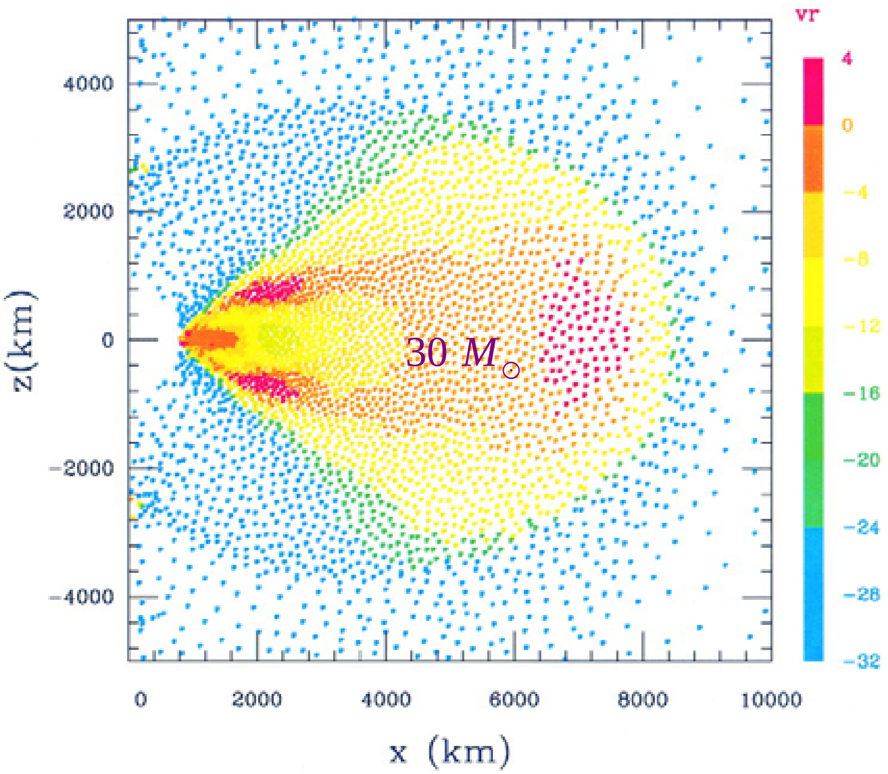


Bright X-ray afterglow?

Temperature in 10^9 K just prior to black hole formation. about 90 solar masses quickly accretes into the black hole.



radial velocity 6.5 s after black hole formation



Pair-instability collapse for M ~ 300 solar masses

(Fryer, Woosley, & Heger ApJ, 550, 372, 2001)

$$M_{BH} \sim 100\ M_\odot$$

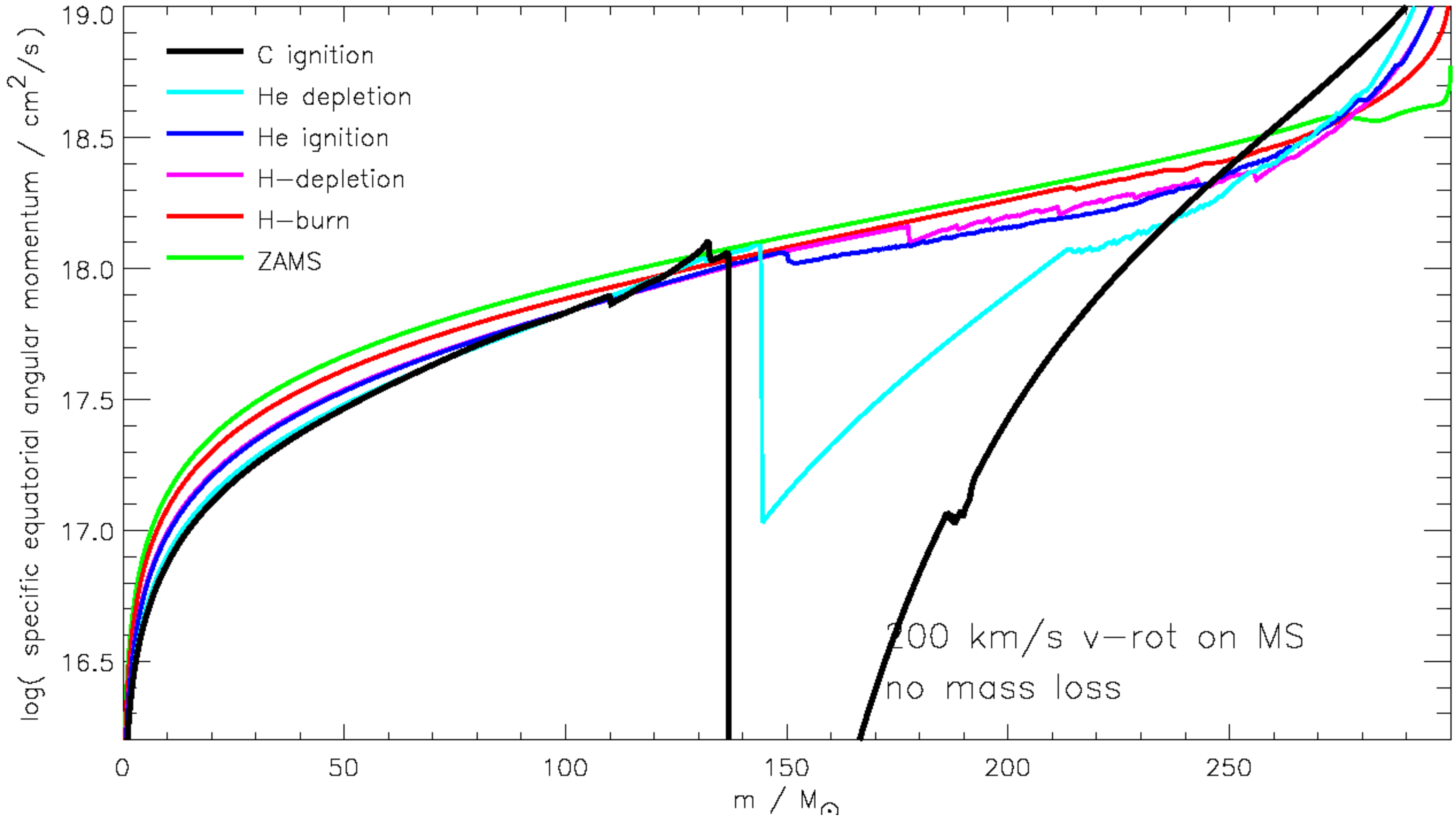
$$\dot{M} \sim 1-10\ M_\odot\ \mathrm{sec}^{-1}$$

$$\tau \sim 10-100\ \mathrm{sec} \times (1+z) \quad z \sim 15$$

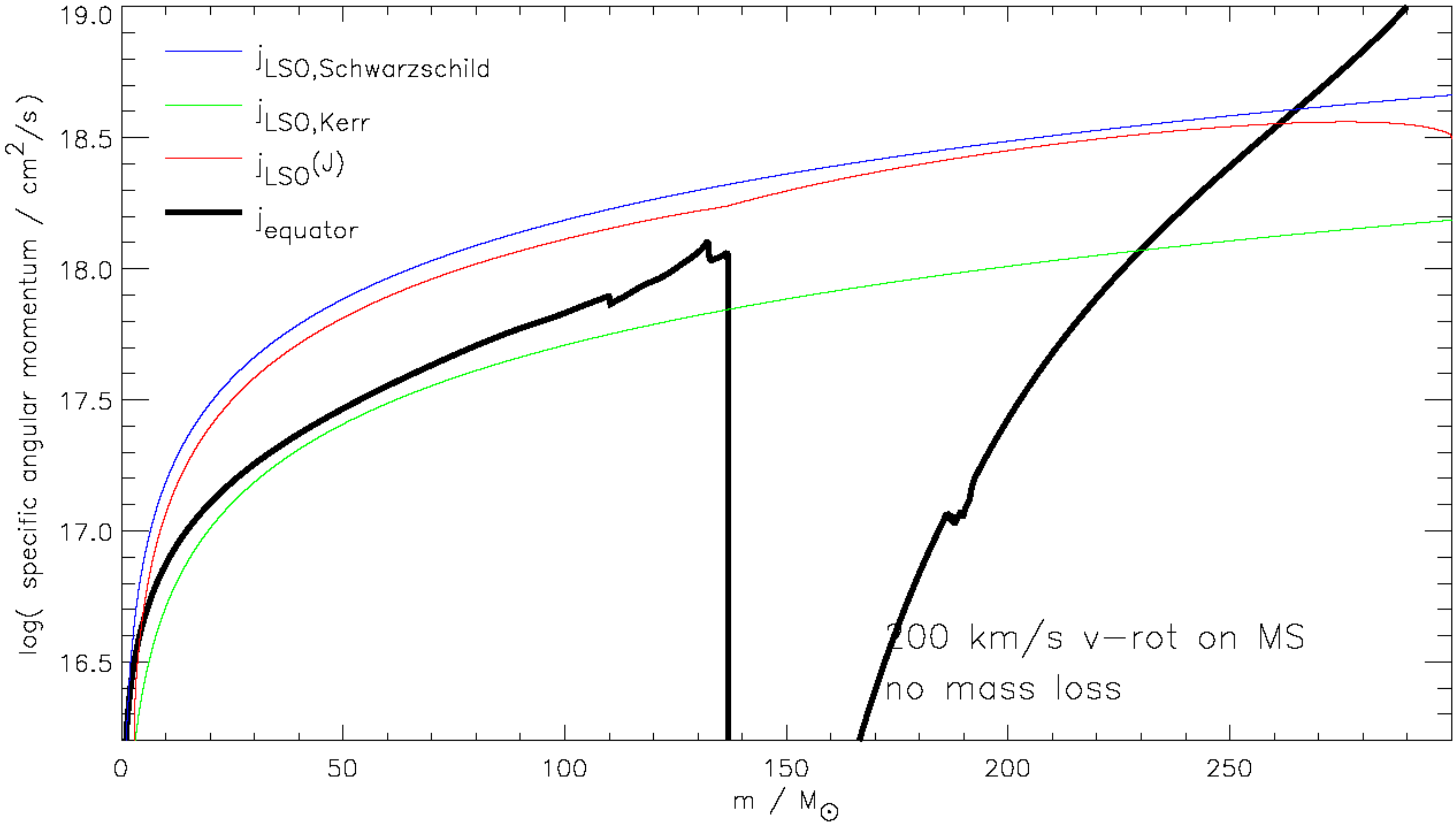
$$E_{iso} \sim 10^{55}\ \mathrm{erg}$$

Possible observational challenge:
long time scale, soft spectrum.

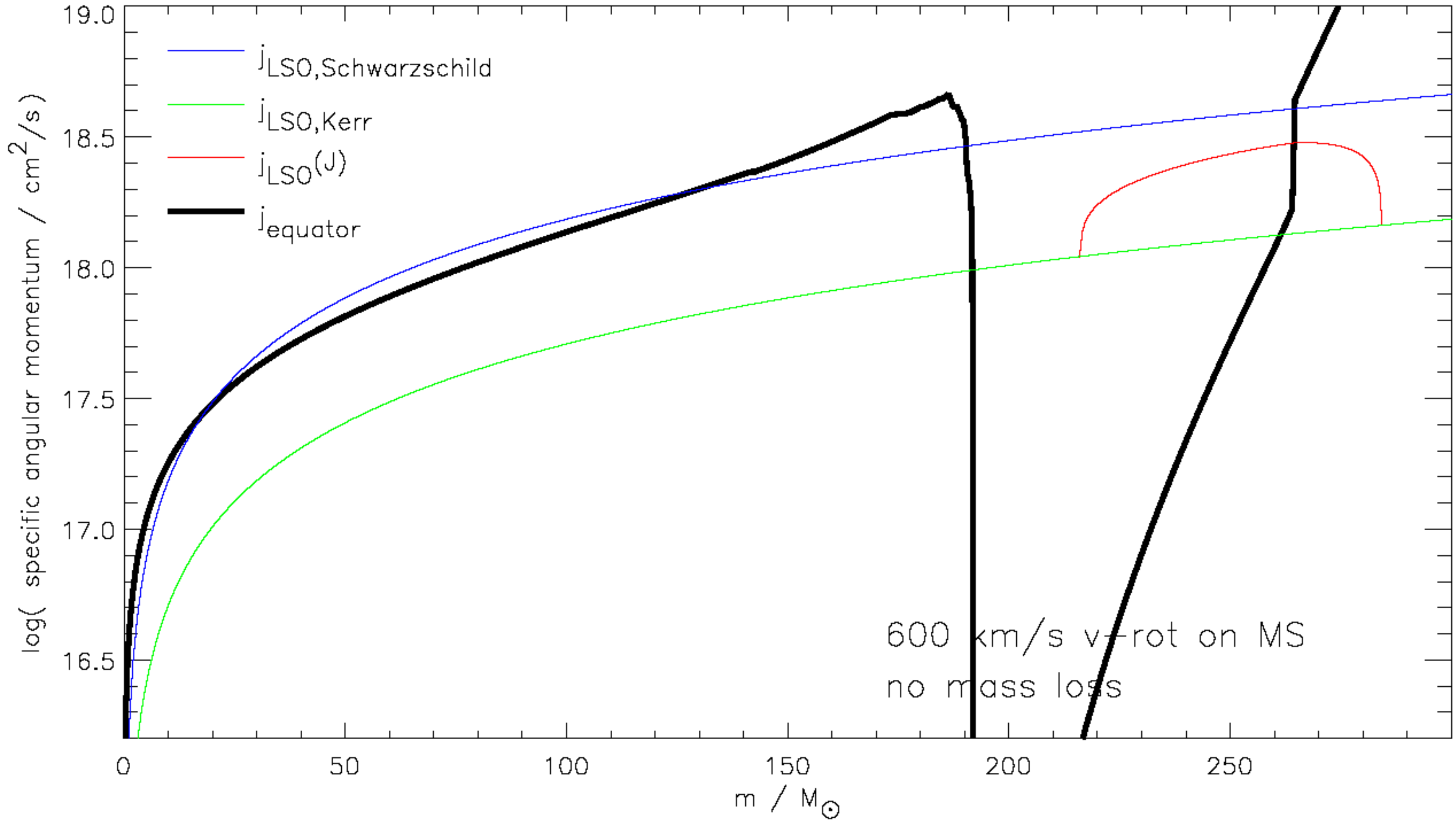
Is the envelope on or off?
Does the star have enough rotation?



log(specific equatorial angular momentum / cm^2/s)
19.0
18.5
18.0
17.5
17.0
16.5
0
50
100
150
200
250
m / $M_\odot$
C ignition
He depletion
He ignition
H–depletion
H–burn
ZAMS
200 km/s v–rot on MS
no mass loss



19.0
18.5
18.0
17.5
17.0
16.5
log(specific angular momentum / cm^2/s)
0
50
100
150
200
250
m / M$_\odot$
$j_{LSO,Schwarzschild}$
$j_{LSO,Kerr}$
$j_{LSO}(J)$
$j_{equator}$
200 km/s v-rot on MS
no mass loss


19.0
18.5
18.0
17.5
17.0
16.5
log(specific angular momentum / cm^2/s)
0
50
100
150
200
250
m / $M_\odot$
$j_{LSO,Schwarzschild}$
$j_{LSO,Kerr}$
$j_{LSO}(J)$
$j_{equator}$
600 km/s v-rot on MS
no mass loss

Summary

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

- Stars of up to 500 solar masses may remain intact until they die
- Primary nitrogen production, RSG formation, rotation, and mass loss make the final outcome uncertain
- Very bright light curves and break out transients potentially observable. Also potential GRB source.
- Nucleosynthetic signature is novel, but so far no compelling evidence for M > 100 solar masses.
- Rotation as function of metallicity is a big unknown