LANL, 24 April 2002

The Fate of the First Stars

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Stan Woosley
Isabelle Baraffe
Chris Fryer
Tom Abel

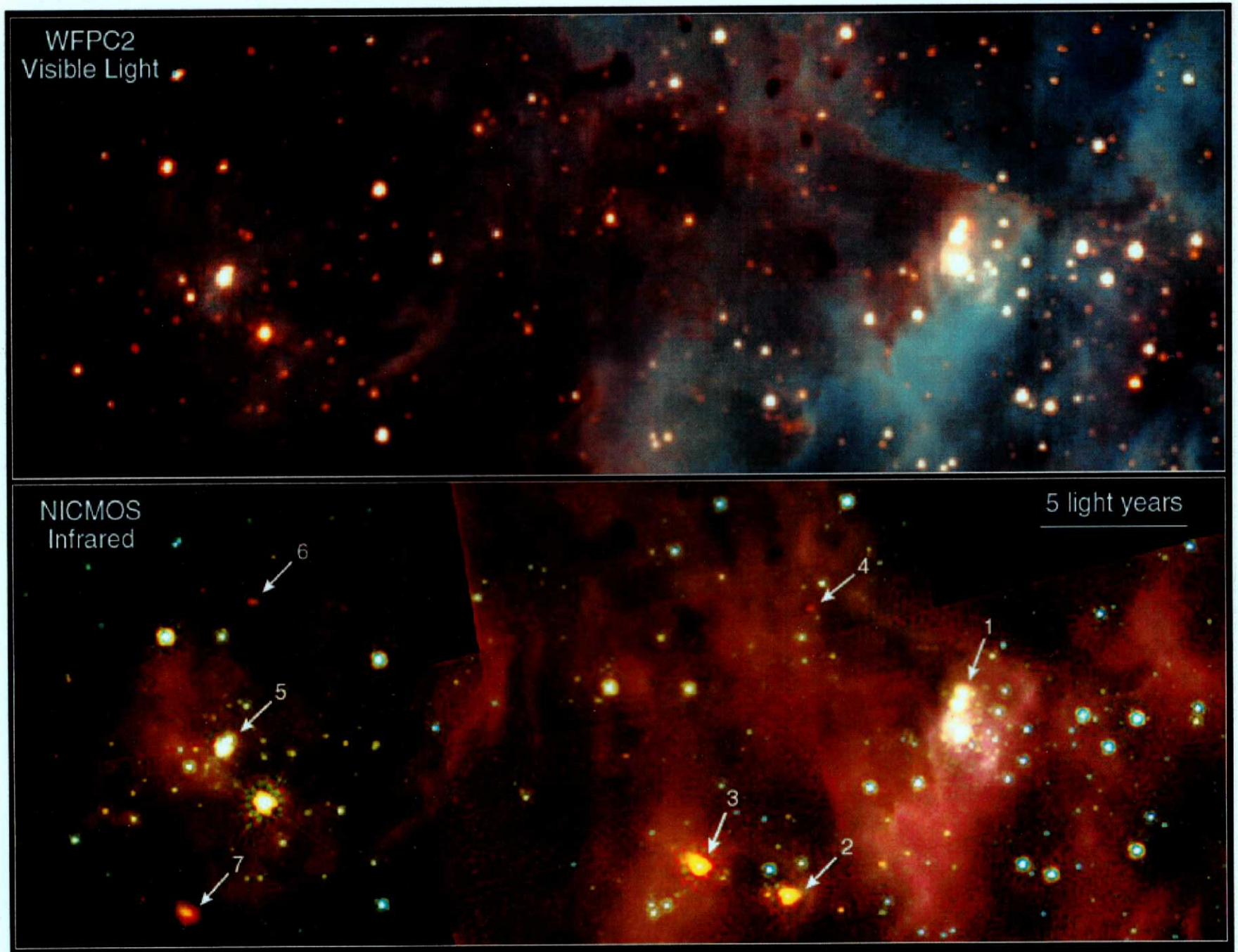
Overview

I Introduction
- Basics of stellar evolution
- The life of modern stars

II Primordial Stars
- Birth
- Life and death
- The ashes

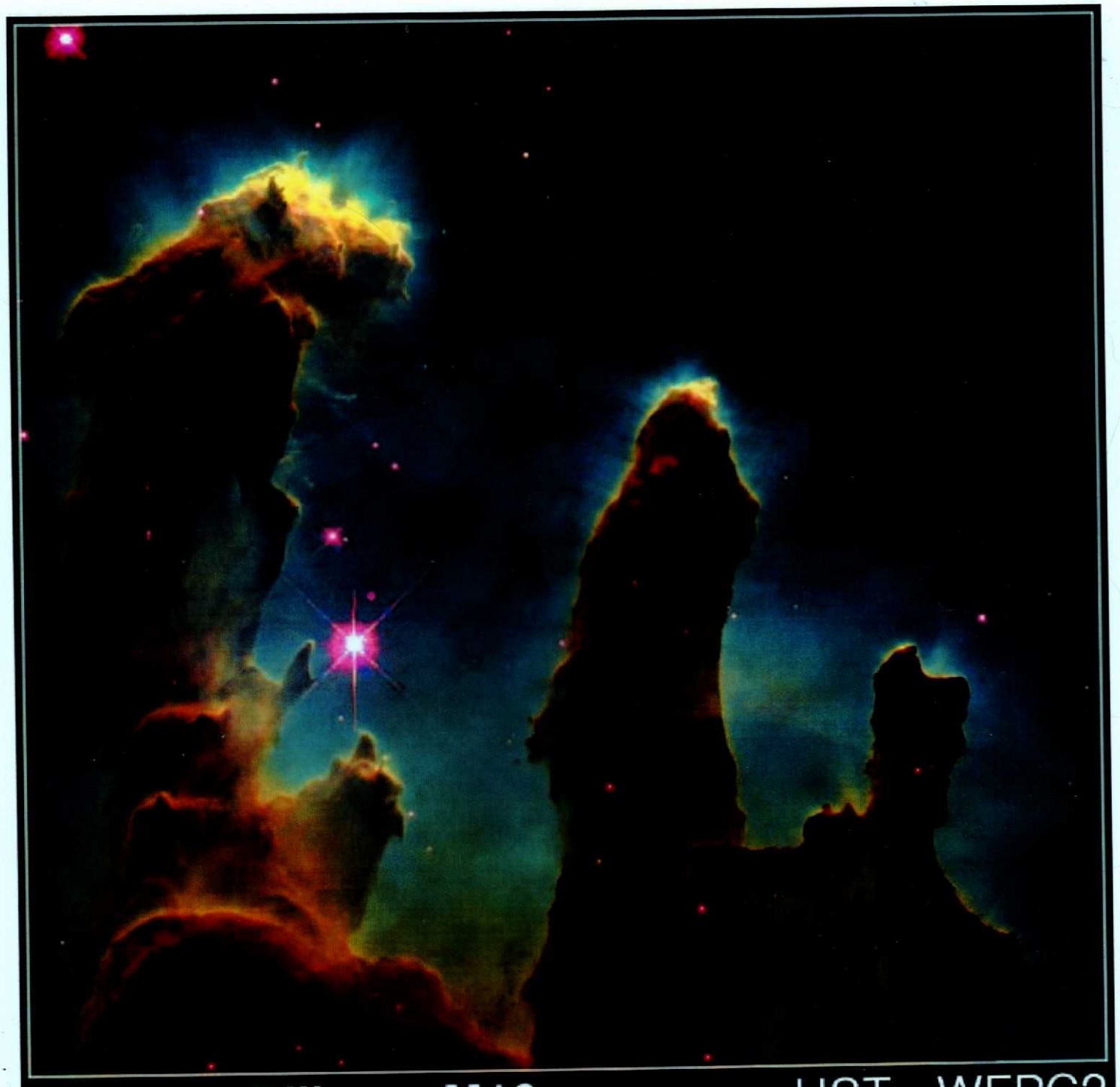
III Conclusions

http://firststars.org



30 Doradus Nebula Details **HST • WFPC2 • NICMOS**

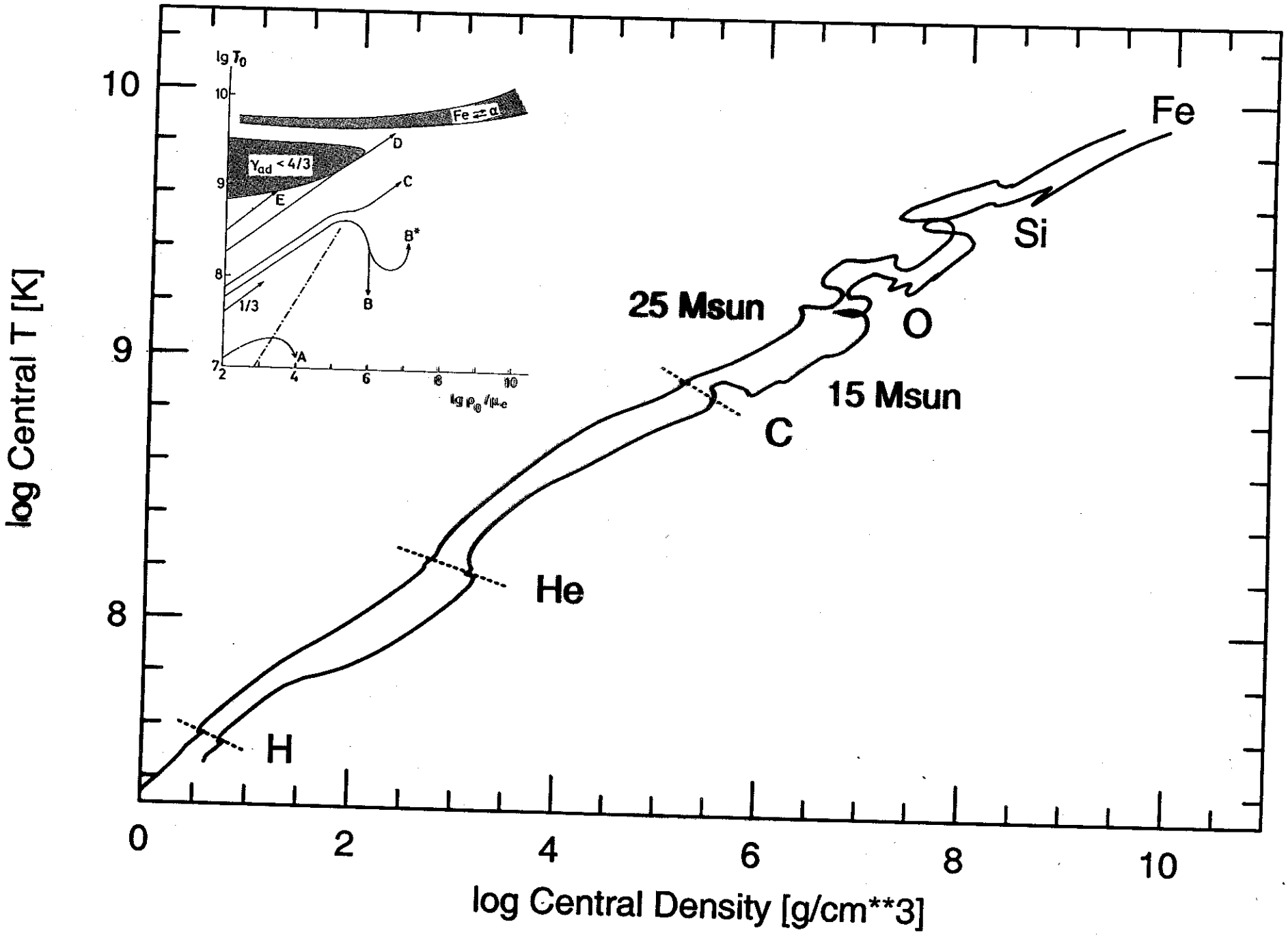
PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA



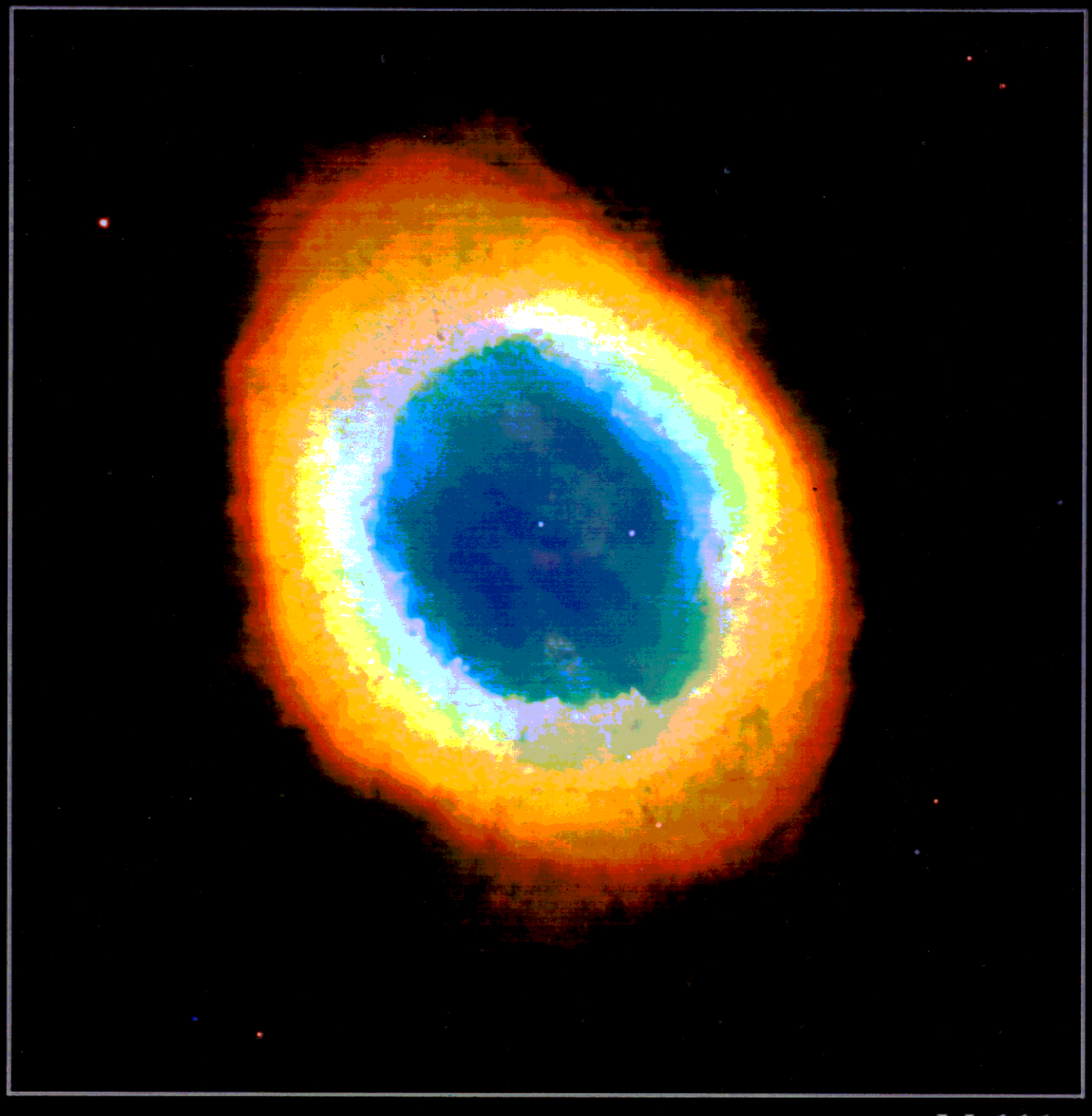
Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995

J. Hester and P. Scowen (AZ State Univ.), NASA

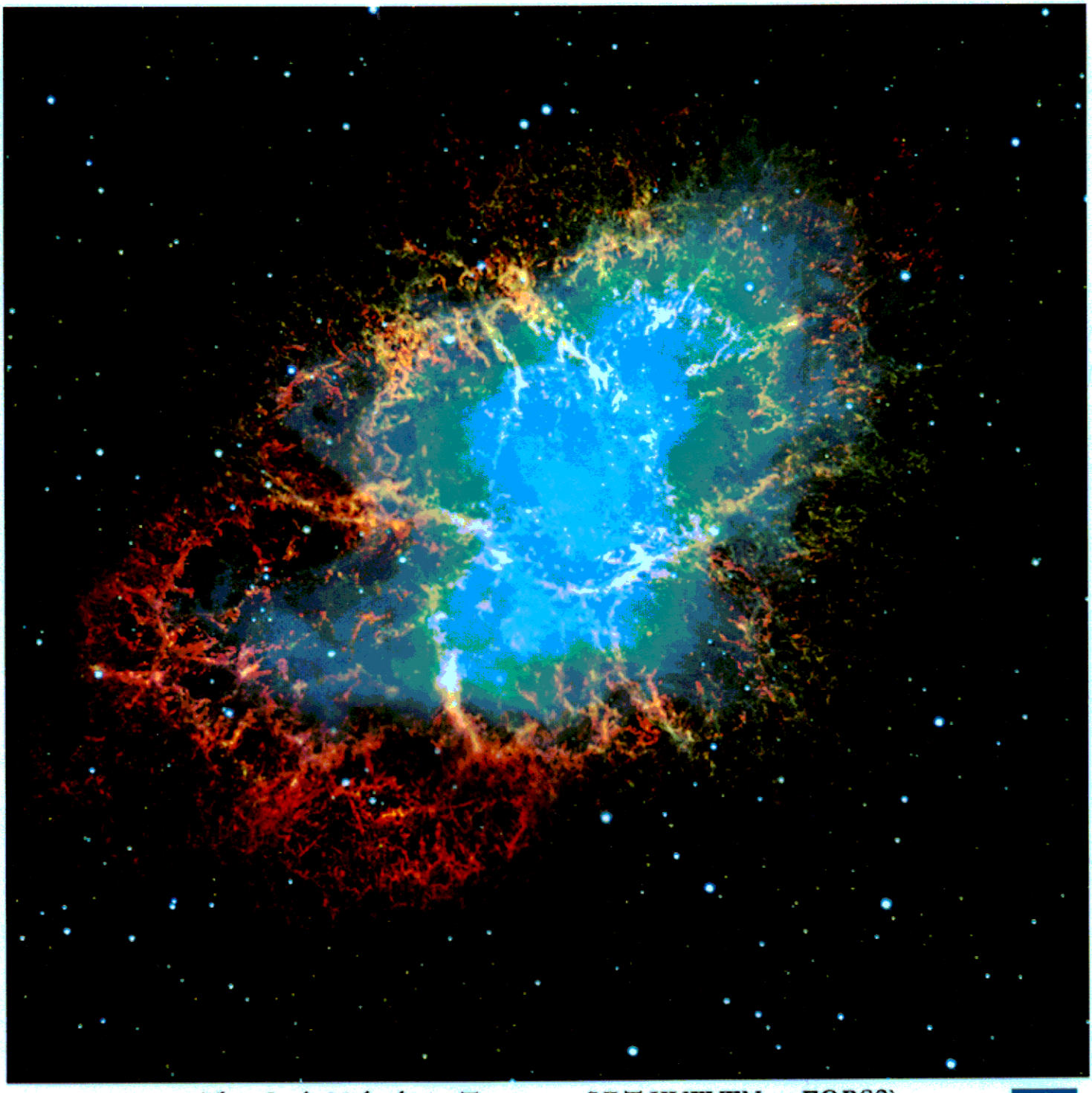

log Central T [K]
log Central Density [g/cm**3]
10
9
8
0
2
4
6
8
10
Fe
Si
O
C
He
H
25 Msun
15 Msun
lg T_0
Fe ⇄ α
$\gamma_{ad} < 4/3$
D
C
E
B*
B
A
1/3
lg ρ_0/μ_e

Ring Nebula



Hubble Heritage

PRC99-01 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

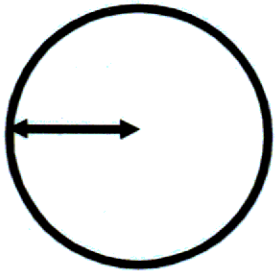


The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

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

© European Southern Observatory

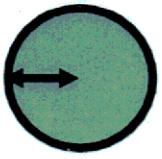
10,000 km



white dwarf

density: 1,000,000 g/cm^3

10 km



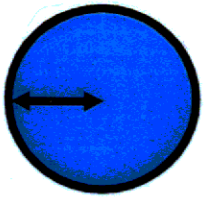
neutron star

density: ~100,000,000,000,000 g/cm^3

3 km

black hole

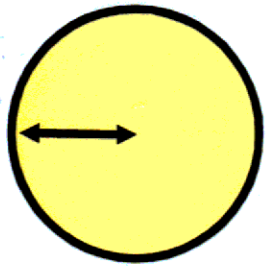
6,000 km



earth

density: 5.5 g/cm^3

700,000 km



sun

density: 1.4 g/cm^3

THE CNO Bi-CYCLE

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$

$$\rightarrow {}^{16}O + \gamma$$

$$^{16}O + {}^{1}H \rightarrow {}^{17}F + \gamma$$

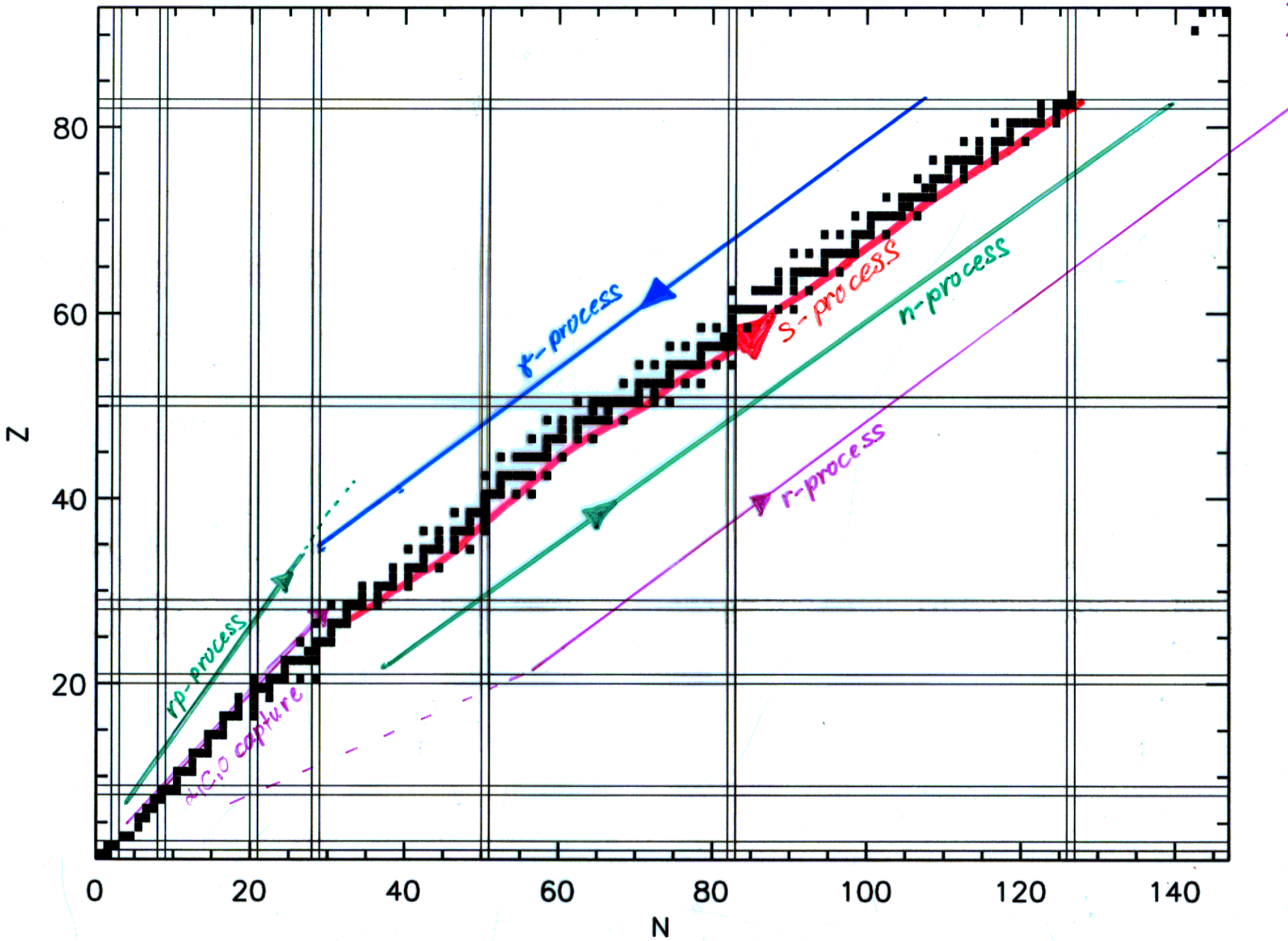
$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu$$

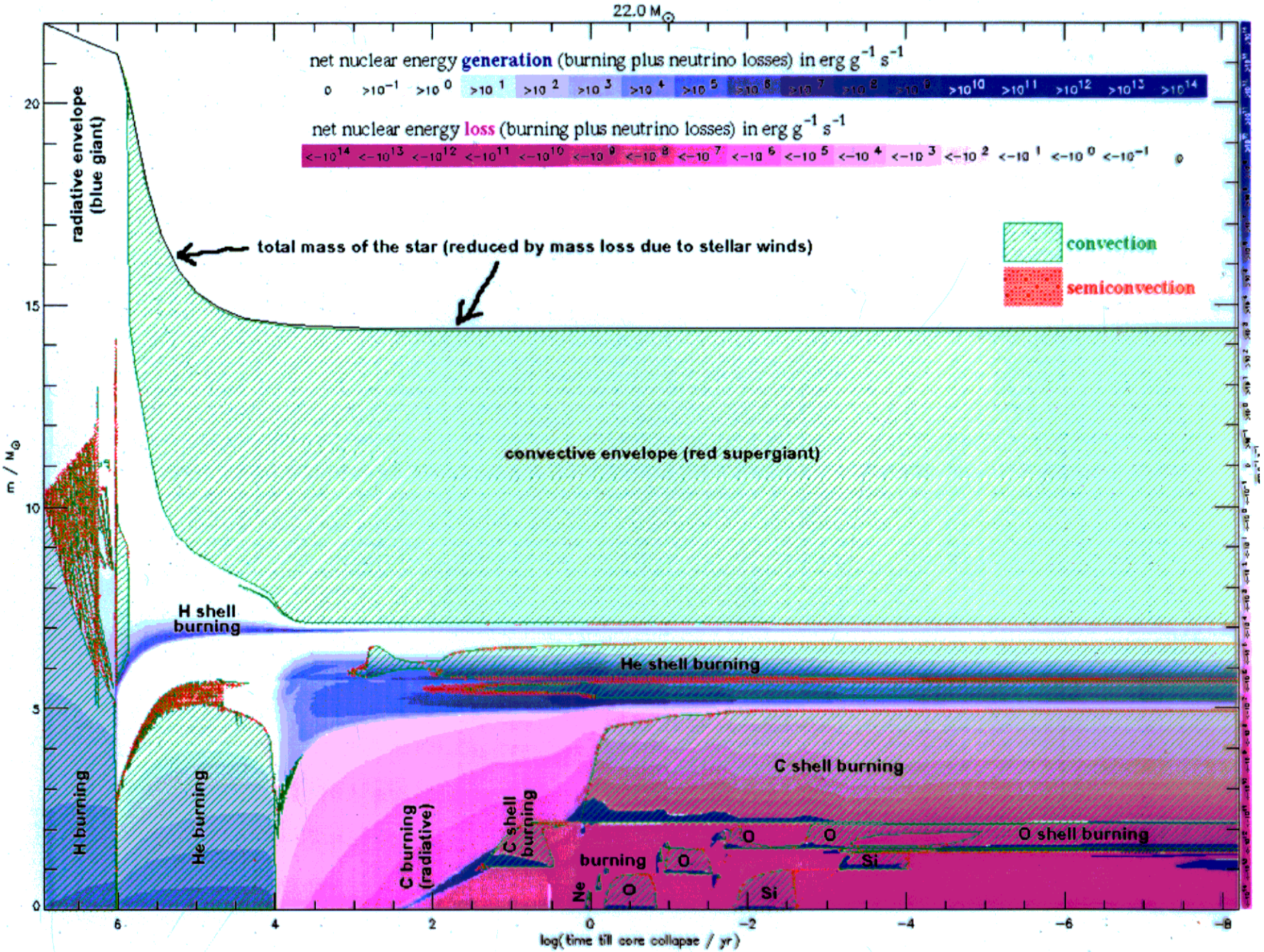
$$^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He$$

Advanced Nuclear Burning Stages

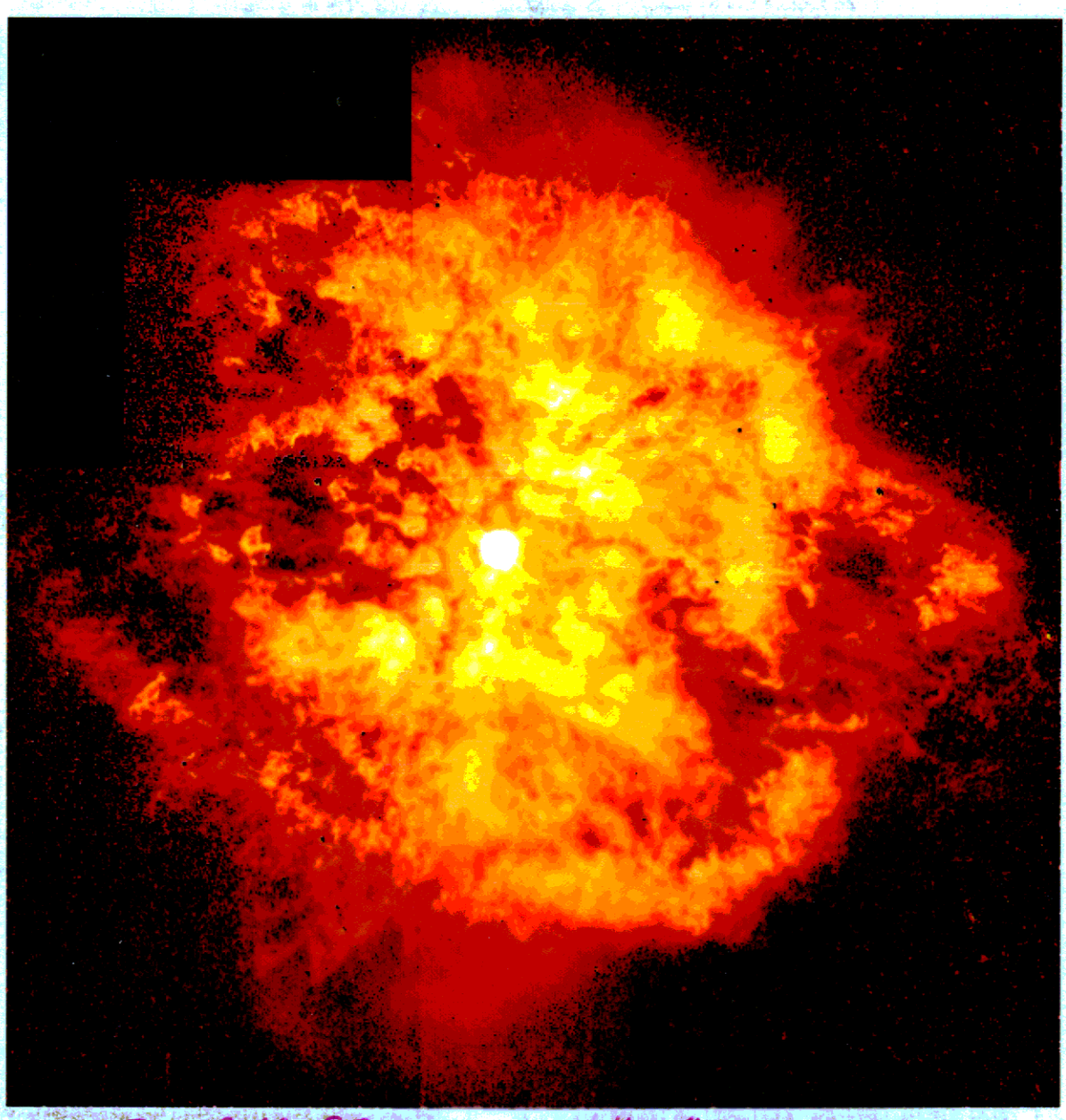
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)	
H	He	^{14}N	0.02	10^7	$4H \xrightarrow{CNO} {}^4He$
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6	$3\alpha \rightarrow {}^{12}C$ ${}^{12}C(\alpha,\gamma){}^{16}O$
C	Ne, Mg	Na	0.8	10^3	${}^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	${}^{20}Ne(\gamma,\alpha)$
O	Si, S	Cl, Ar K, Ca	2.0	0.8	${}^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week	${}^{28}Si(\gamma,\alpha)$


80
60
40
20
Z
0
20
40
60
80
100
120
140
N
γ-process
s-process
n-process
r-process
rp-process
α,C,O capture


22.0 M⊙
net nuclear energy generation (burning plus neutrino losses) in erg g⁻¹ s⁻¹
0 >10⁻¹ >10⁰ >10¹ >10² >10³ >10⁴ >10⁵ >10⁶ >10⁷ >10⁸ >10⁹ >10¹⁰ >10¹¹ >10¹² >10¹³ >10¹⁴
net nuclear energy loss (burning plus neutrino losses) in erg g⁻¹ s⁻¹
<−10¹⁴ <−10¹³ <−10¹² <−10¹¹ <−10¹⁰ <−10⁹ <−10⁸ <−10⁷ <−10⁶ <−10⁵ <−10⁴ <−10³ <−10² <−10¹ <−10⁰ <−10⁻¹ 0
convection
semiconvection
radiative envelope (blue giant)
total mass of the star (reduced by mass loss due to stellar winds)
convective envelope (red supergiant)
H shell burning
He shell burning
C shell burning
O shell burning
H burning
He burning
C burning (radiative)
C shell burning
Ne burning
O
Si
m / M⊙
log(time till core collapse / yr)

WR 124



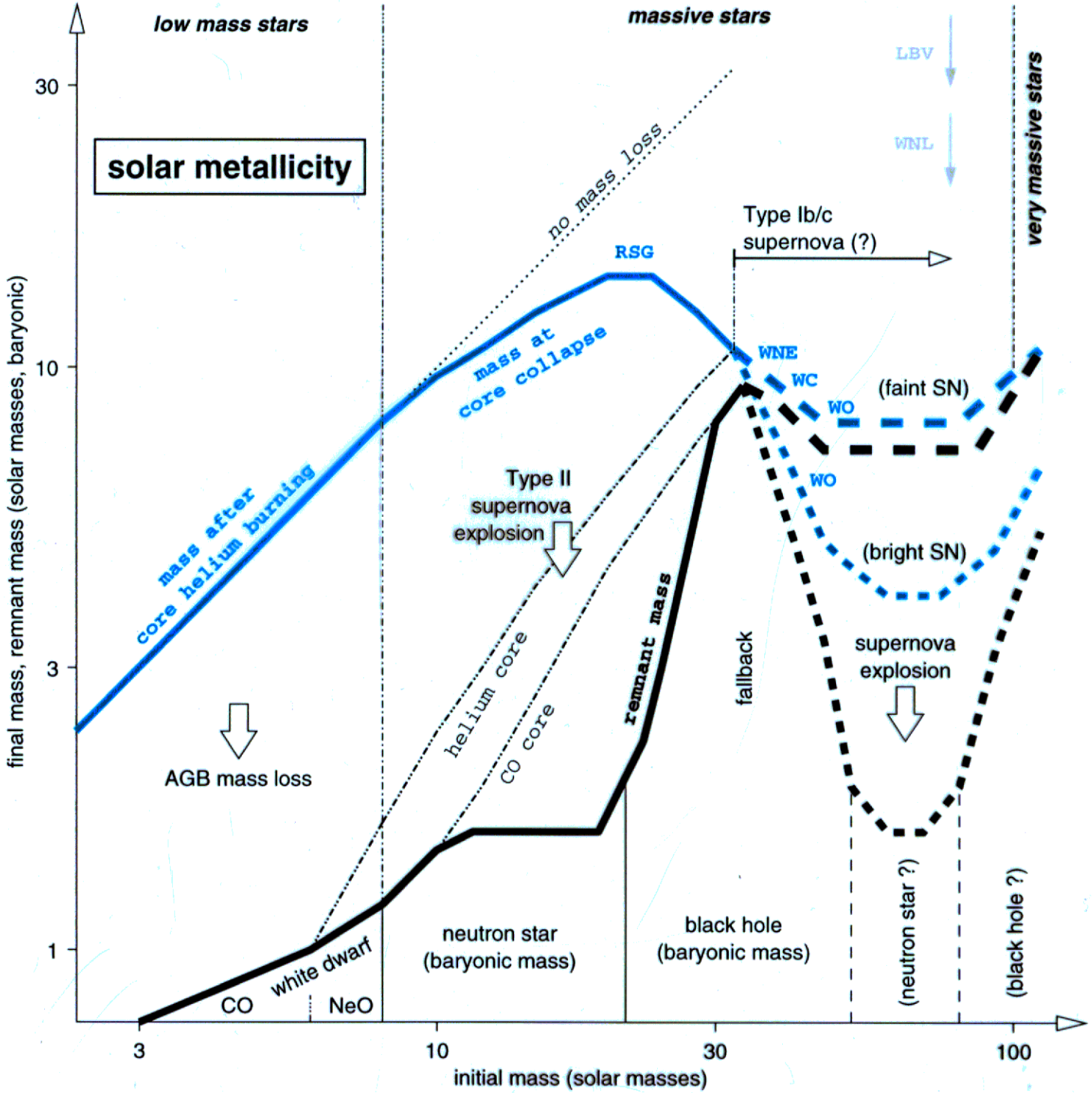
STScI-PR98-38

http://OPOSITE.STSCI.EDU/PUBINFO/PR/1998/38/PR-PHOTOS.HTML

WR 124 in M1-67

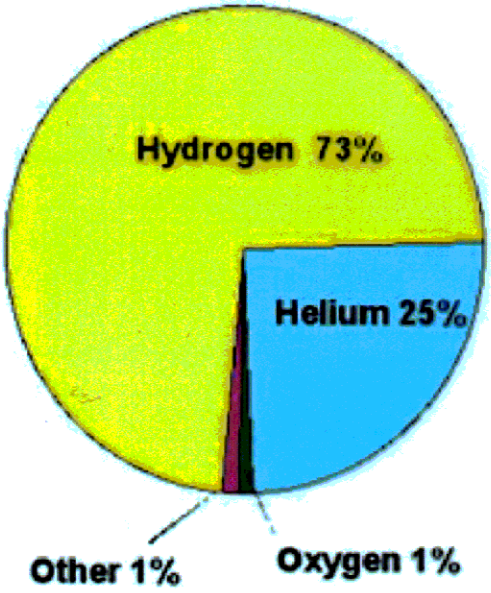
DIAMETER OF THE NEBULA ~ 1000 A.U.

VERY CLUMPY WIND

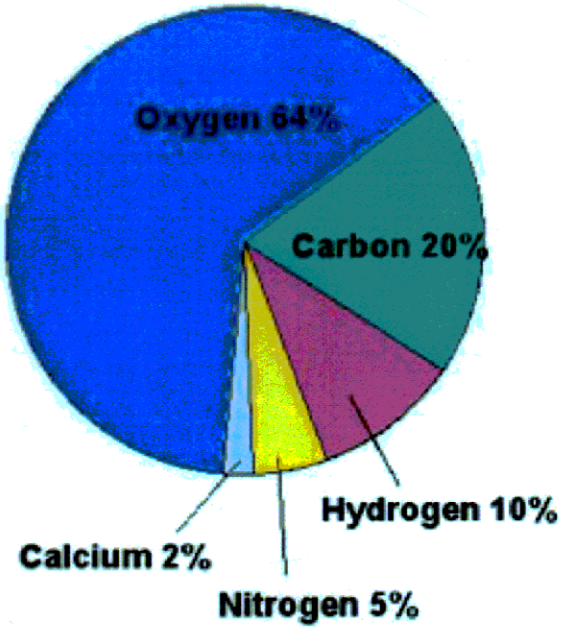

low mass stars
massive stars
very massive stars
solar metallicity
LBV
WNL
no mass loss
Type Ib/c
supernova (?)
RSG
WNE
WC
WO
WO
(faint SN)
(bright SN)
mass at
core collapse
mass after
core helium burning
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
supernova
explosion
AGB mass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

Relative Abundance by Weight

Universe



Humans



FORMATION OF A 200 $M_\odot$ PROTOSTELLAR CORE @ z = 19.1

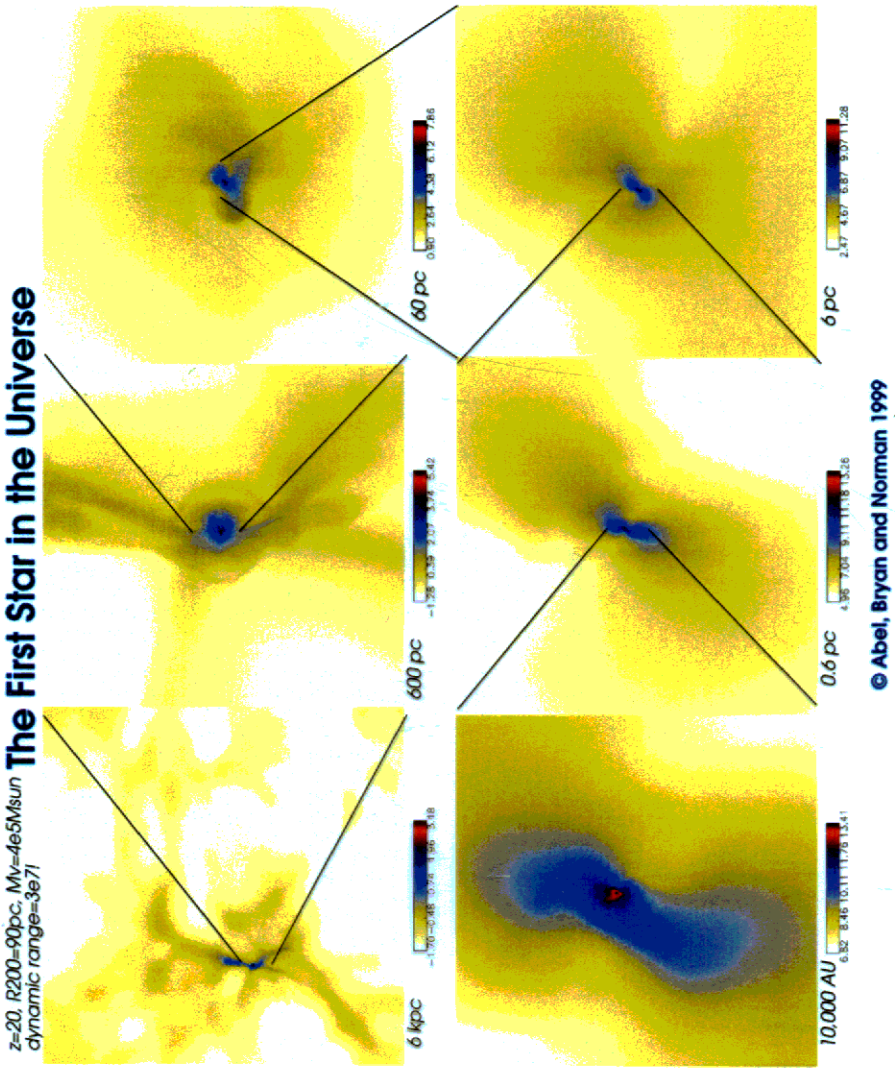


Fig. 3. Million-fold zoom showing the multiscale structure of a primordial protostellar cloud core in the center of a low mass halo at z=19.1. Plotted is the logarithm of the baryon overdensity on a slice passing through the densest structure on the grid. Zoom proceeds clockwise from upper left. Linear scales are proper. The smallest grid cell in the center of the cloud core in the last frame is 2^{-4} pc = 43 AU.

(NORMAN, ABEL, & BRYAN 2000)

FORMATION OF ~ 200 $M_\odot$ CORE → ~ 100 $M_\odot$ STAR ?

LARSON (1999):

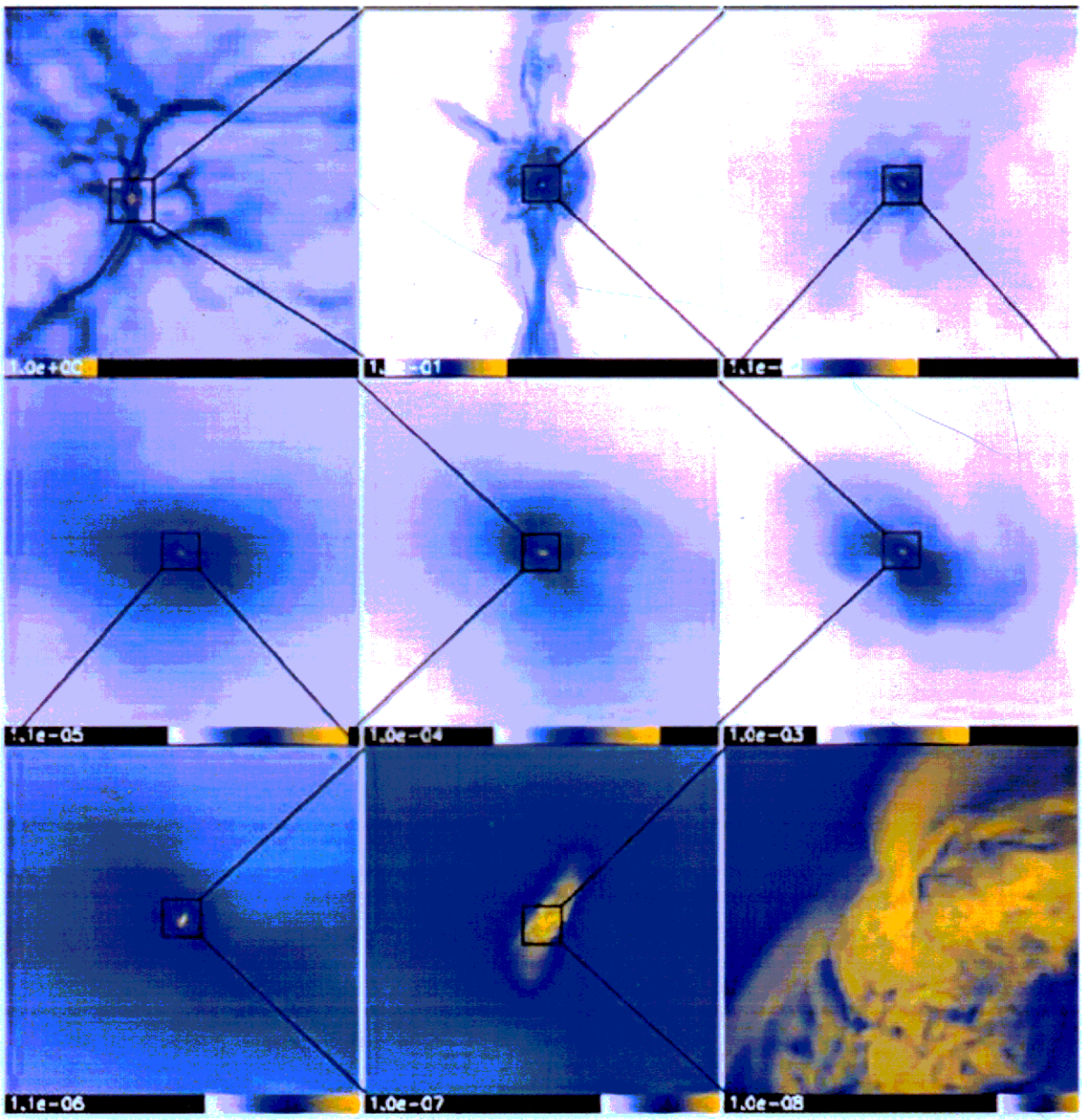
FROM THEORY: AT $z = 0$: JEANS MASS ~ 1000 $M_\odot$ → 100 ... 500 $M_\odot$ STARS

→ IMF DOMINATED BY MASSIVE & VERY MASSIVE STARS

- DUE TO MUCH HIGER TEMPERATURE

↔ COOLING ONLY BY TRACES OF MOLECULAR HYDROGEN

(SINCE THERE ARE NO METALS)



ABEL, BRYAN, NORMAN (2001)

NAKAMURA & UMEMURA (2001)

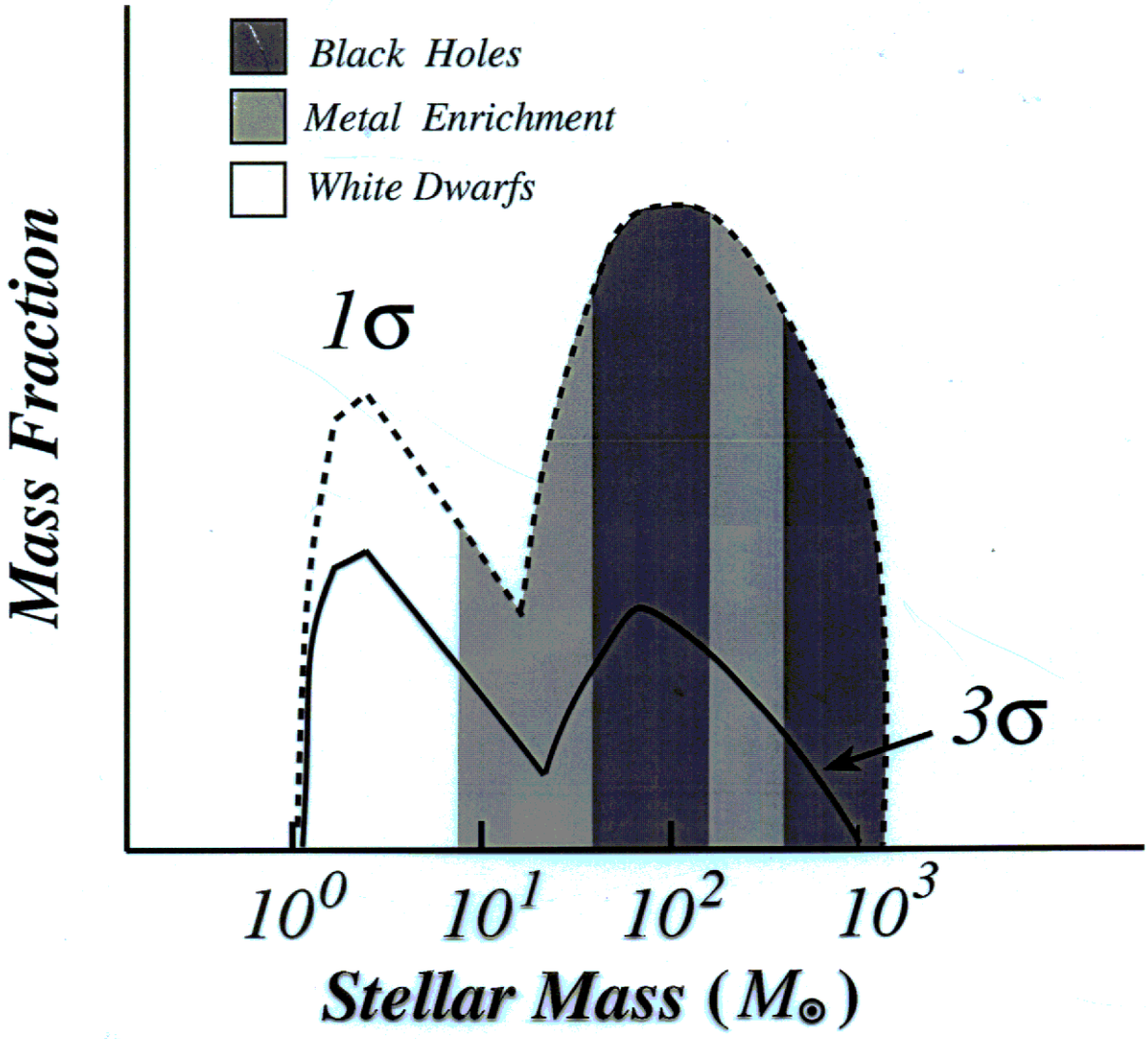
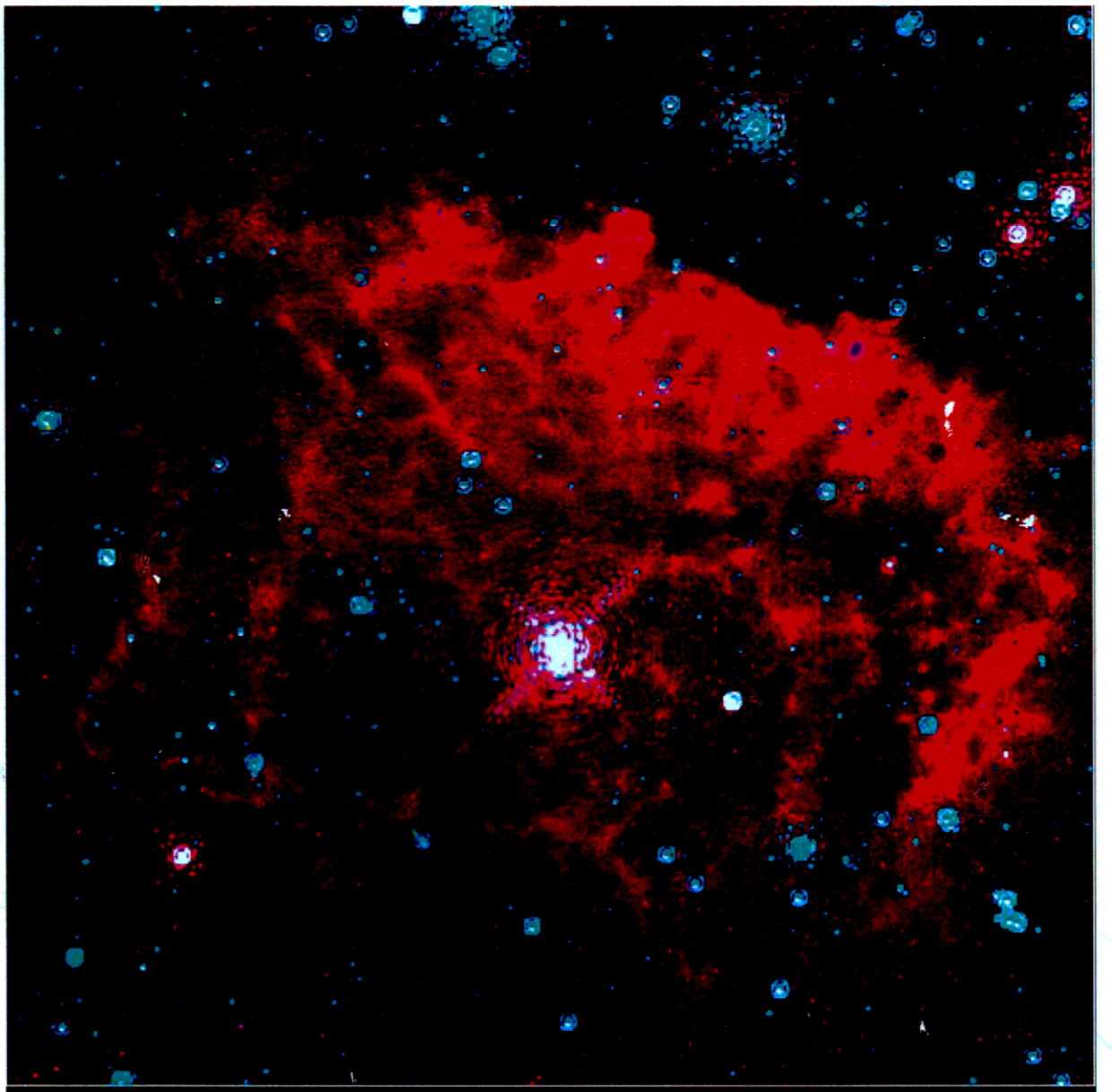


FIG. 8.—Schematic IMF of Population III stars. Solid and dashed lines are the IMFs for 3 σ and 1 σ density fluctuations, respectively. The IMF of Population III stars is likely to be bimodal and approximated by a superposition of two power-law–like components with two different peaks of $m_{p1} \approx 1$–$2\ M_\odot$ and $m_{p2} \approx$ a few times 10–$10^2\ M_\odot$. The relative height of the first peak descends with time compared to the second peak. According to a recent theory of stellar evolution, stars with masses between 1–2 and 8 $M_\odot$ are likely to evolve to white dwarfs that may reside in galactic halos as baryonic dark matter. Stars with masses between 8 and 35 $M_\odot$ probably evolve to supernovae and eject heavy elements in the intergalactic medium. Stars with masses between 35 and $10^2\ M_\odot$ and greater than 250 $M_\odot$ are likely to collapse into black holes and may be responsible for baryonic dark matter. Stars with masses between 10^2 and 250 $M_\odot$ probably explode as supernovae and inject heavy elements into the intergalactic medium.

THE PROBLEM

CAN VERY MASSIVE STARS RETAIN THEIR MASS?



PRC97-33 • ST ScI OPO • October 8, 1997 • D. Figer (UCLA) and NASA

KUDRITZKI (2000):

RADIATION-DRIVEN WINDS:

$\dot{M} \sim \sqrt{Z}$

(OVER WIDE RANGE OF Z)

LANDERS ET AL. (2001):

$\dot{M} \sim Z^{\sim 0.6}$

THE PISTOL STAR

$\sim 150 \ldots 200\ M_\odot$

GALACTIC STAR

EXTREMELY HIGH MASS LOSS RATE

UNKNOWN: CONTINUUM-DRIVEN WINDS

Mass Loss in Very Massive Primordial Stars

- negligible line-driven winds
  (mass loss $\propto \sqrt{\text{metallicity}}$)

- no opacity-driven pulsations
  (no metals)

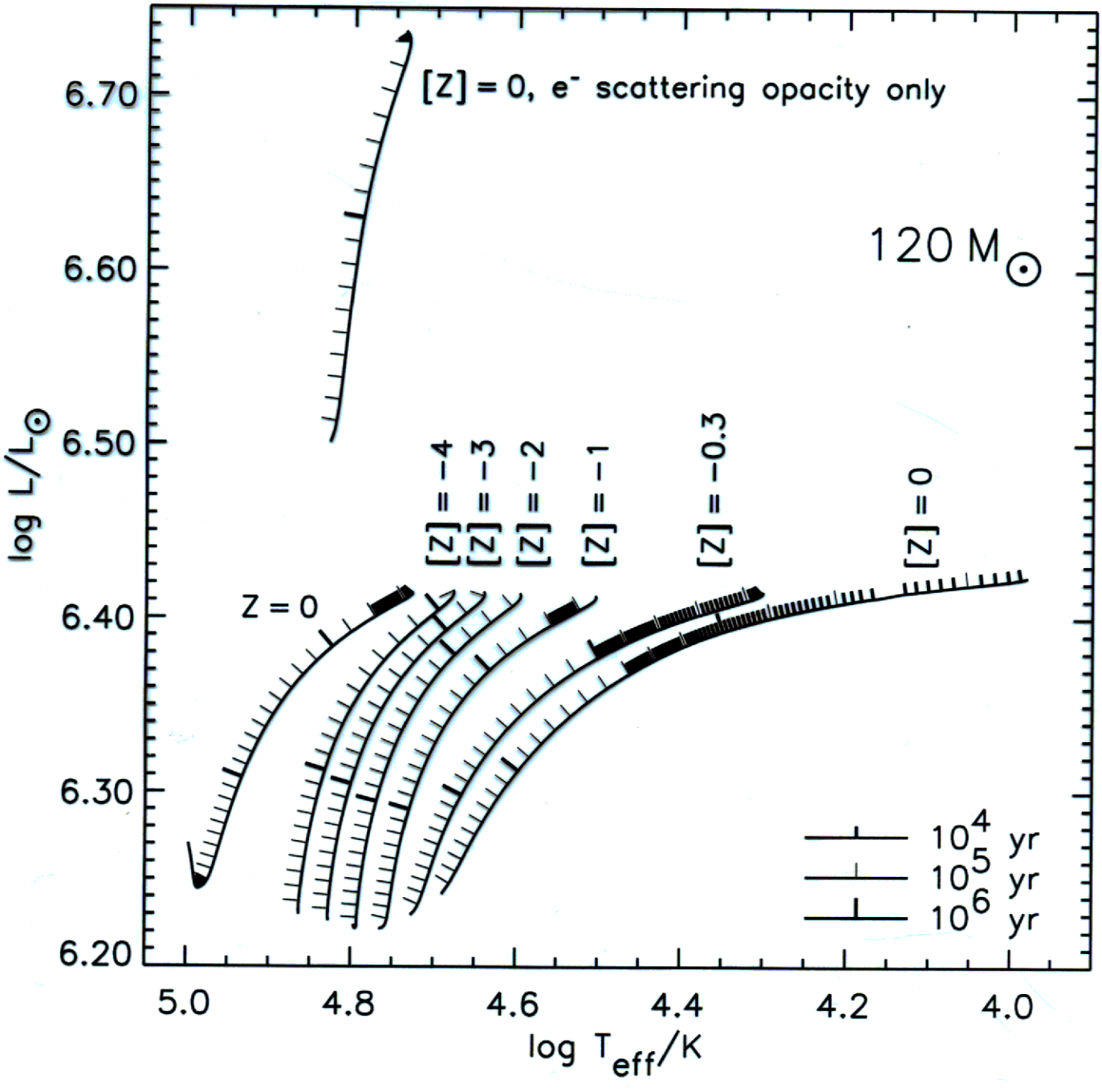
- continuum-driven winds not yet understood
  likely small contribution

- epsilon mechanism inefficient in metal-free stars
  below $\lesssim$ 1000 solar masses
  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.

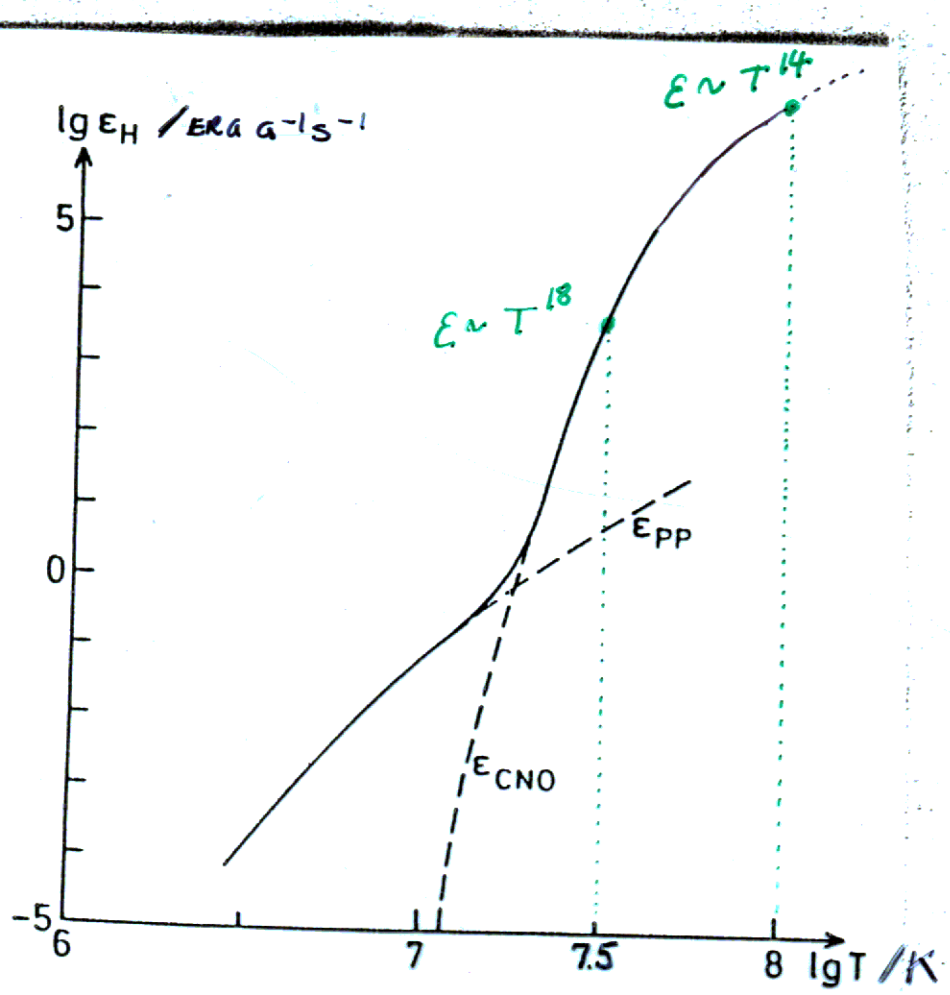
- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars $\gtrsim$ 500 solar masses


[Z] = 0, e⁻ scattering opacity only
120 M⊙
[Z] = −4
[Z] = −3
[Z] = −2
[Z] = −1
[Z] = −0.3
[Z] = 0
Z = 0
10^4 yr
10^5 yr
10^6 yr
log L/L⊙
log T_eff/K
6.70
6.60
6.50
6.40
6.30
6.20
5.0
4.8
4.6
4.4
4.2
4.0

KUDRITZKI (2000): RADIATION DRIVEN WINDS: $\dot{M} \sim \sqrt{Z}$

→ WHAT OTHER MASS LOSS MECHANISMS EXIST?

CALCULATIONS SHOW THAT THIS RELATION SEEMS VALID DOWN TO QUITE LOW VALUE OF Z!



THE ε - MECHANISM

[ε := SPECIFIC ENERGY GENERATION RATE]

FOR DRIVING PULSATIONS

$\frac{\partial \ln \varepsilon}{\partial \ln T} \gg 1$, $\frac{d \ln L}{d \ln M} > 1$ → EFFECT BECOMES MORE IMPORTANT FOR HIGHER MASS

↳ $\varepsilon|_{T_{max}, \rho_{max}} \gg \bar{\varepsilon} \times \frac{\rho_{max}}{\bar{\rho}}$ → DRIVING OF PULSATIONS

+ DAMPENING IN ENVELOPE

AT Z = 0

$\frac{\partial \ln \varepsilon}{\partial \ln T}$ ↓

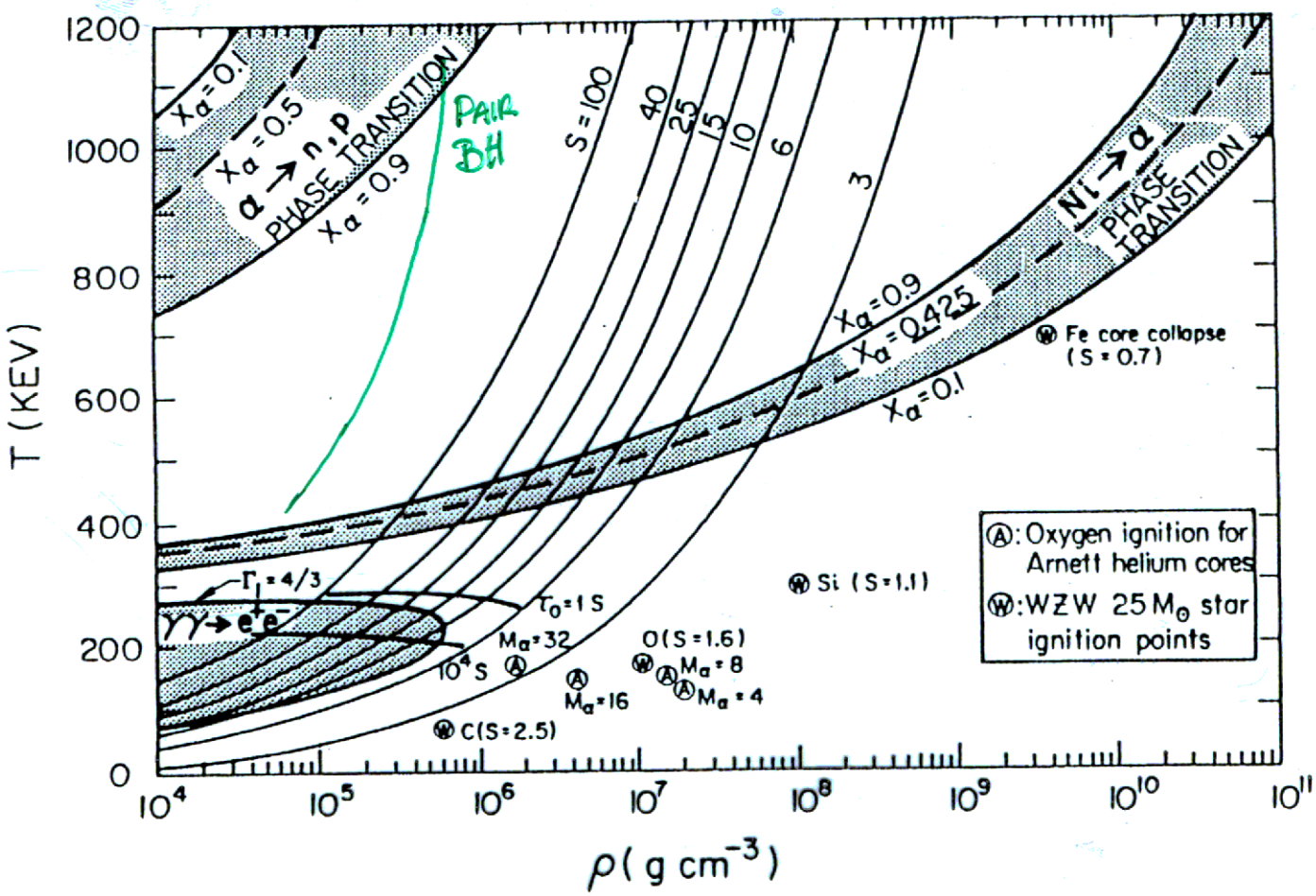
DAMPENING IN ENVELOPE ↓

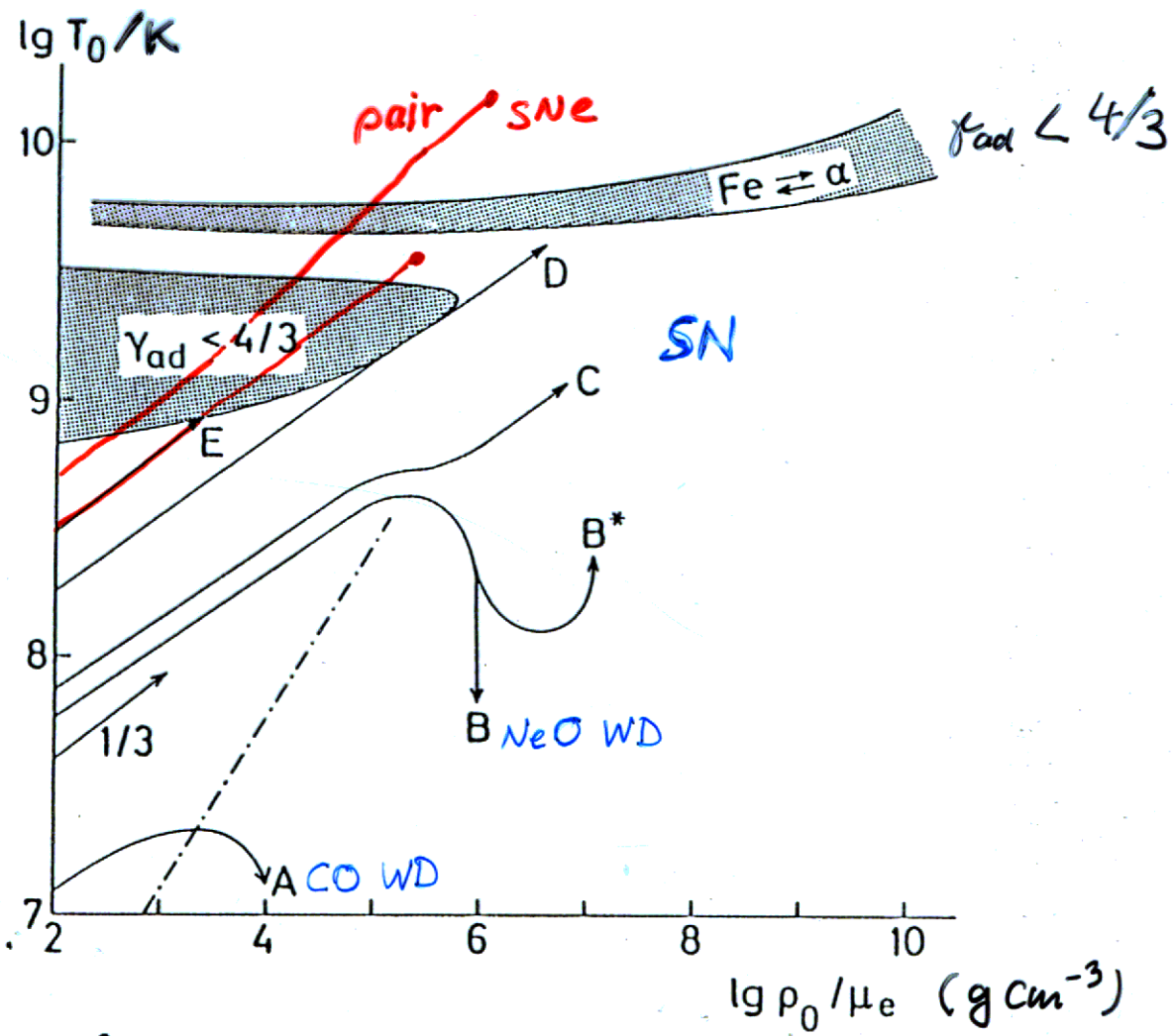
} → ?

← HIGHER T SINCE NO INITIAL CNO → $T_c \gtrsim 10^8$ K 3α PROCESS PRODUCES PRIMARY C

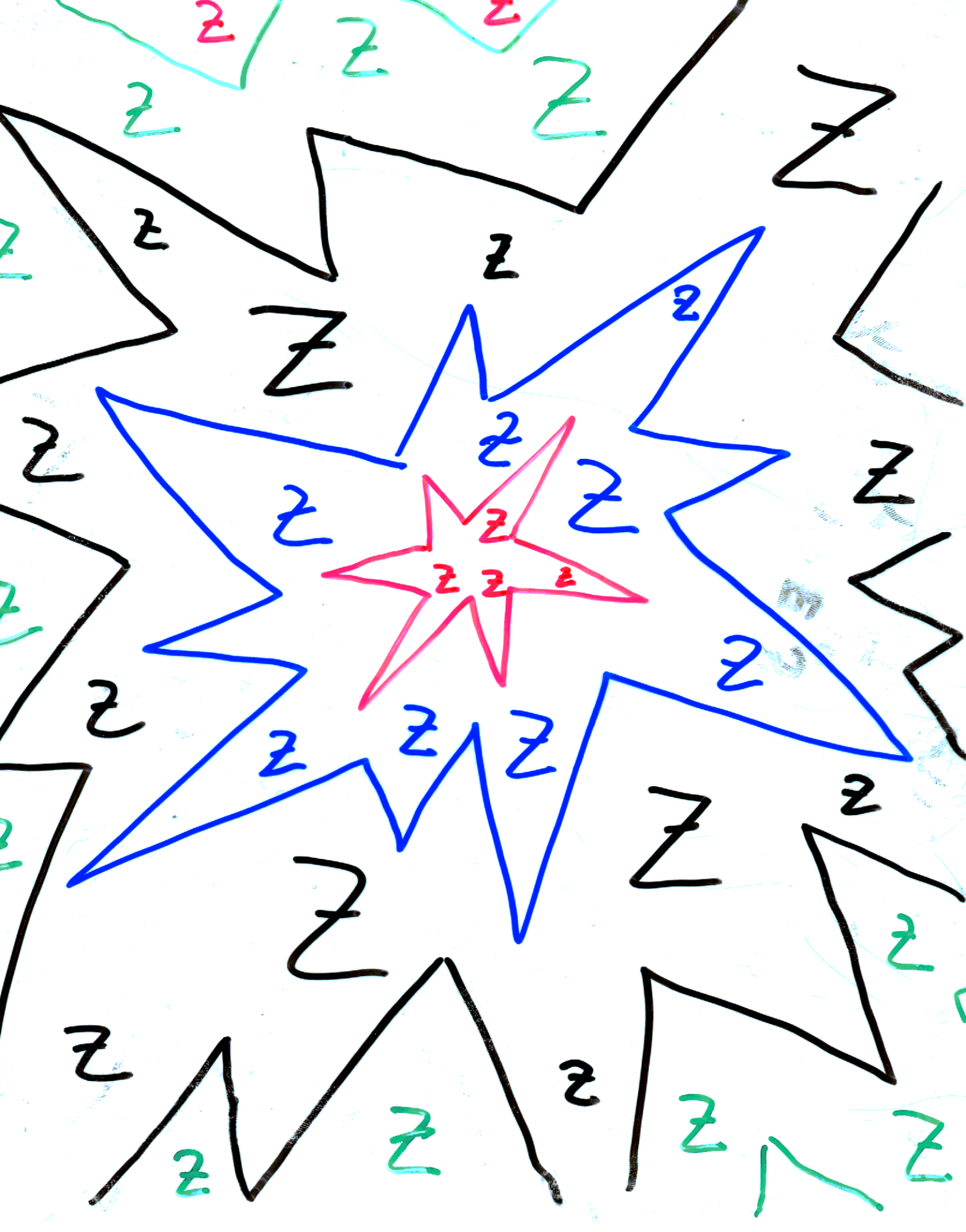
← MORE COMPACT

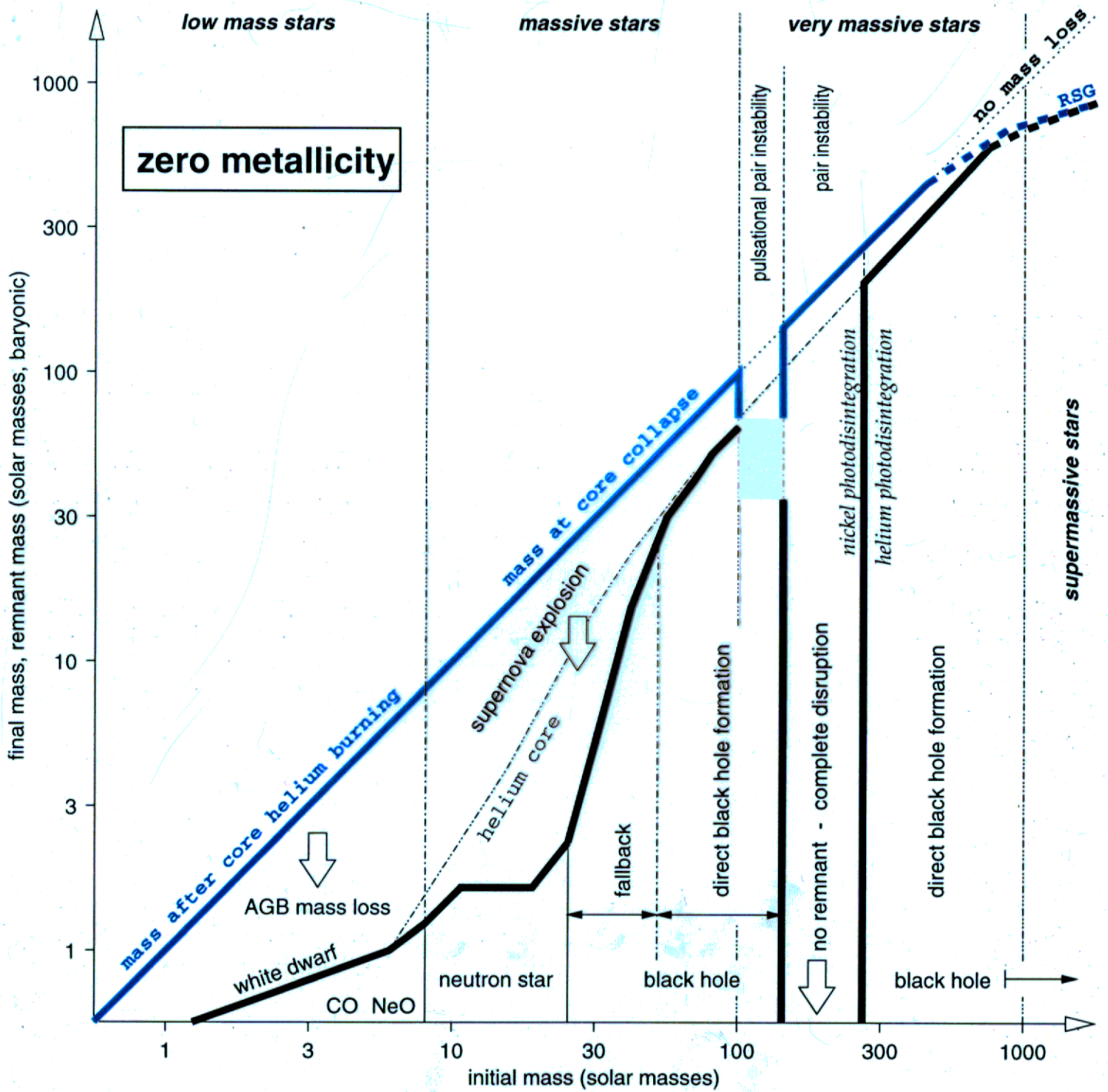
BOND, ARNETT, AND CARR (1984)



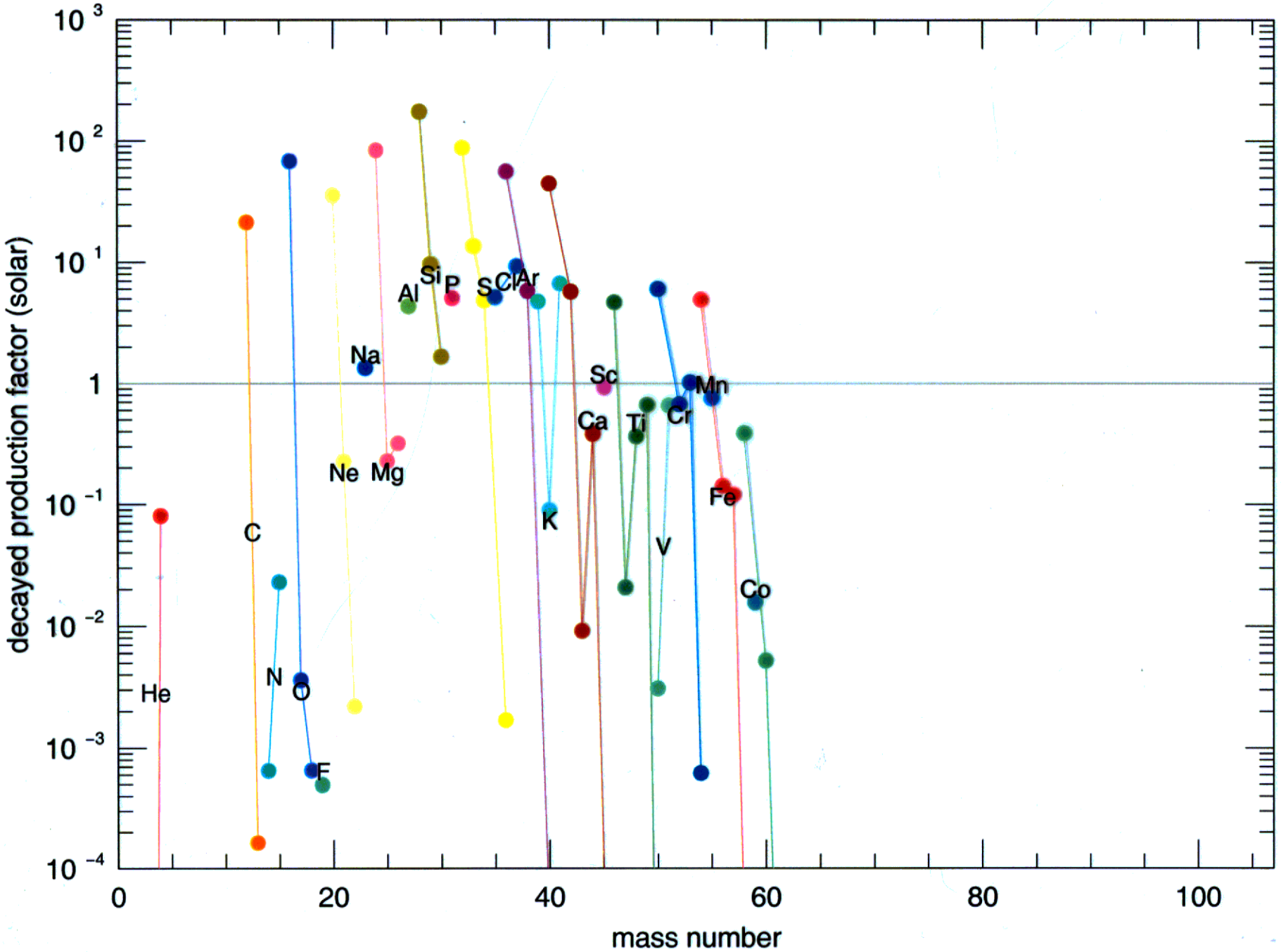


(KIPPENHAHN & WEIGERT, 1992)



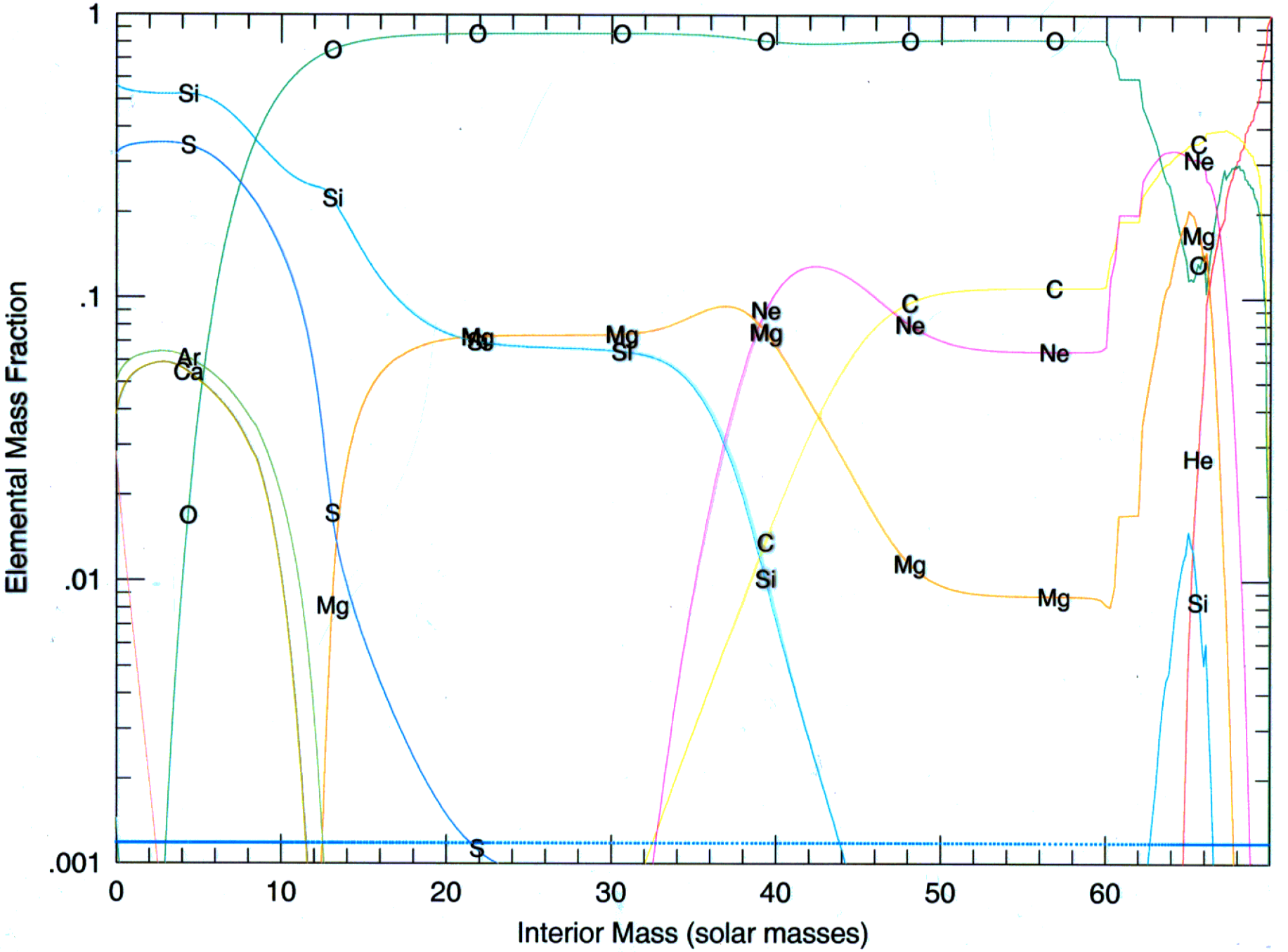

low mass stars
massive stars
very massive stars
zero metallicity
final mass, remnant mass (solar masses, baryonic)
1000
300
100
30
10
3
1
initial mass (solar masses)
1
3
10
30
100
300
1000
mass after core helium burning
mass at core collapse
no mass loss
RSG
supernova explosion
helium core
AGB mass loss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

70 solar mass He core, primordial composition



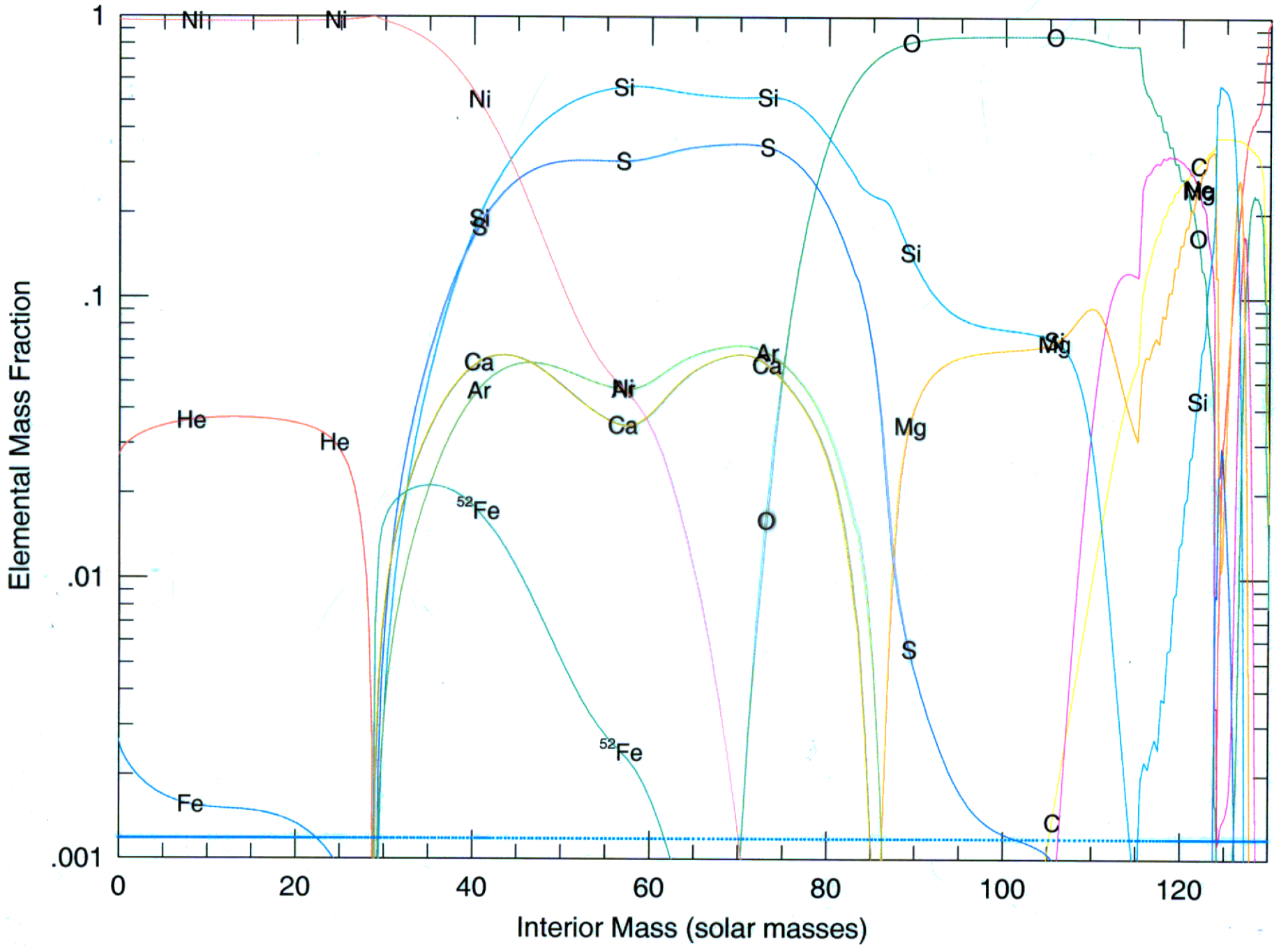
70 solar mass He core, primordial composition

~160 $M_\odot$ star



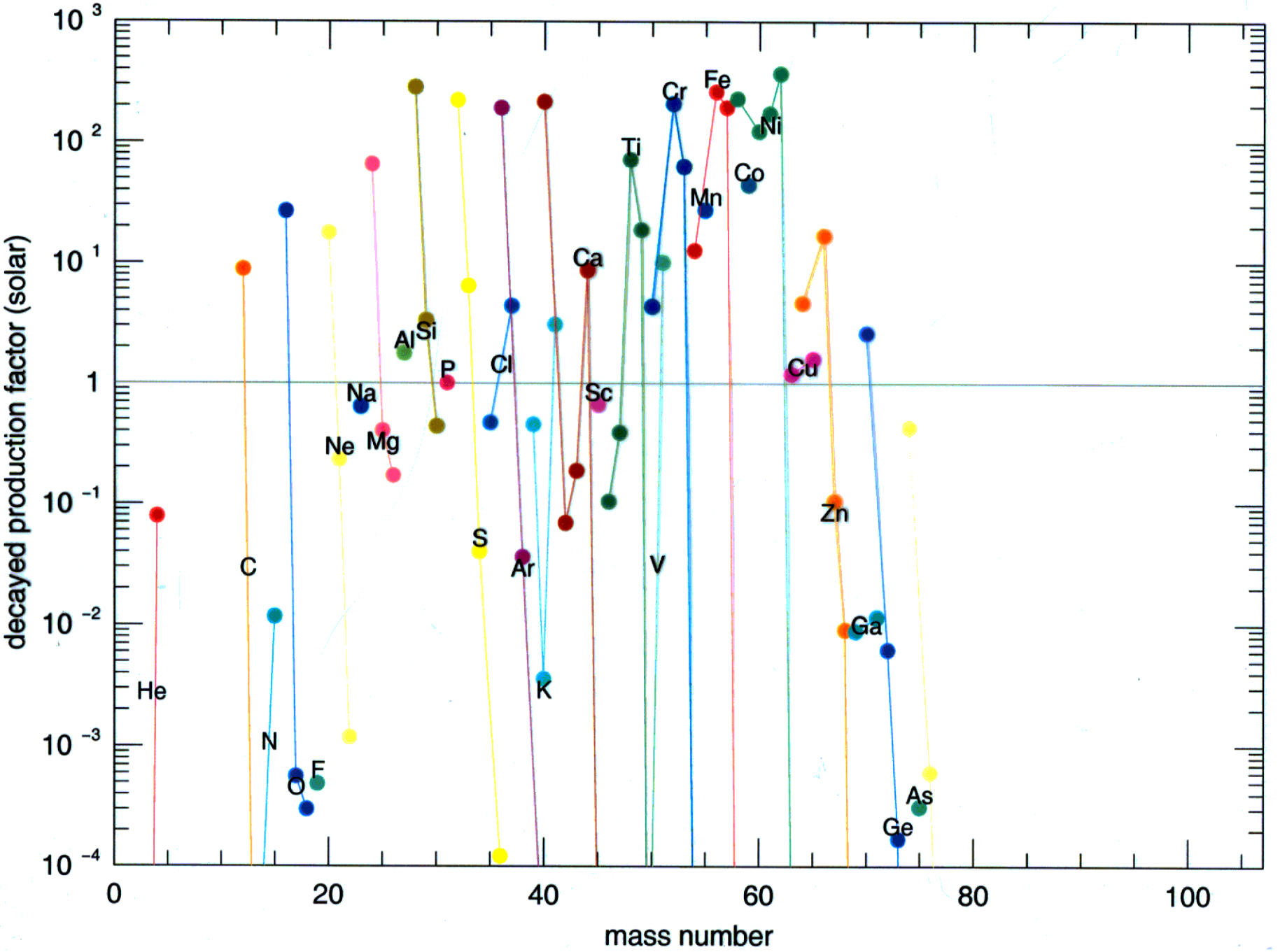
130 solar mass He core, primordial composition

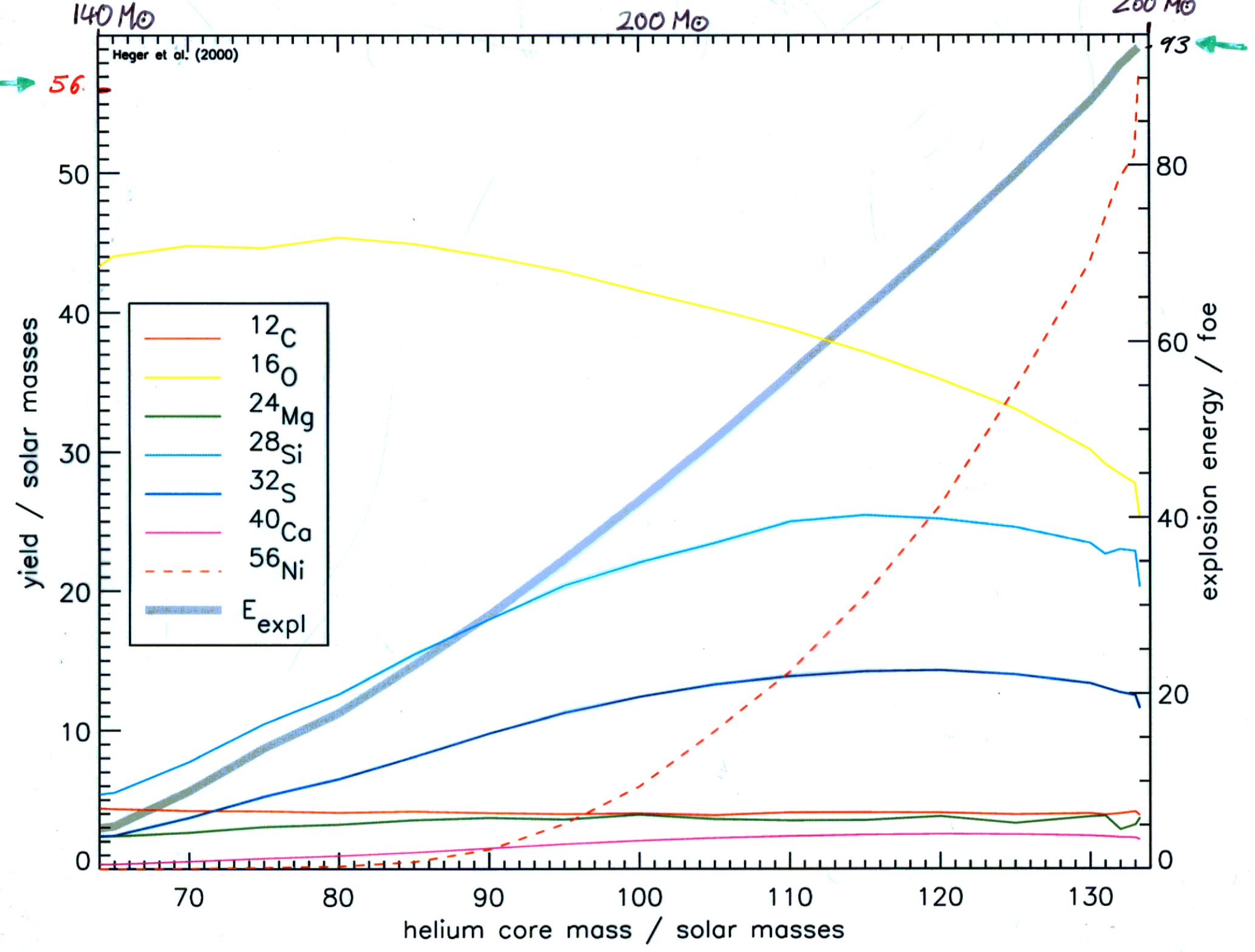
~ 250 $M_\odot$ star

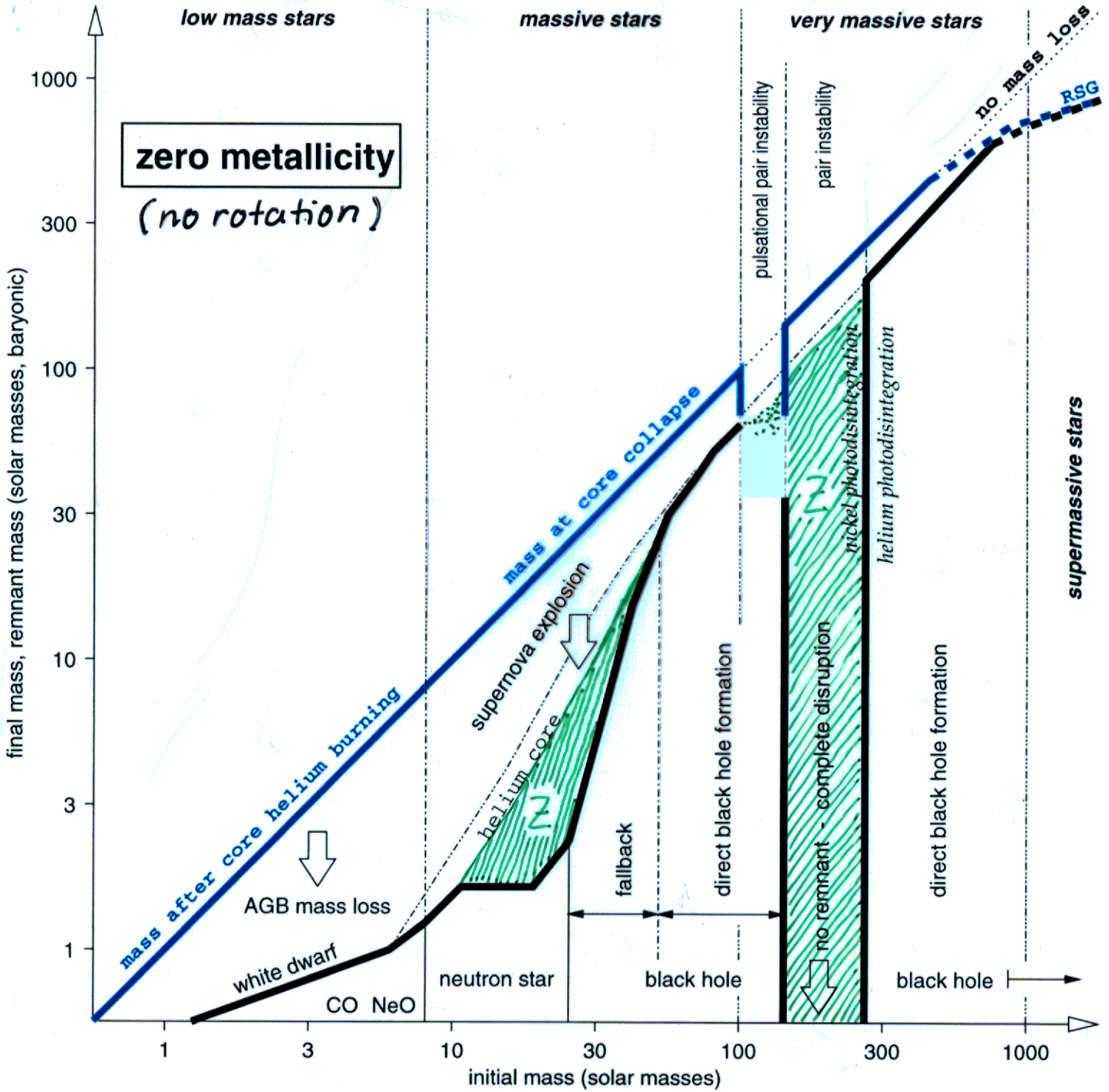


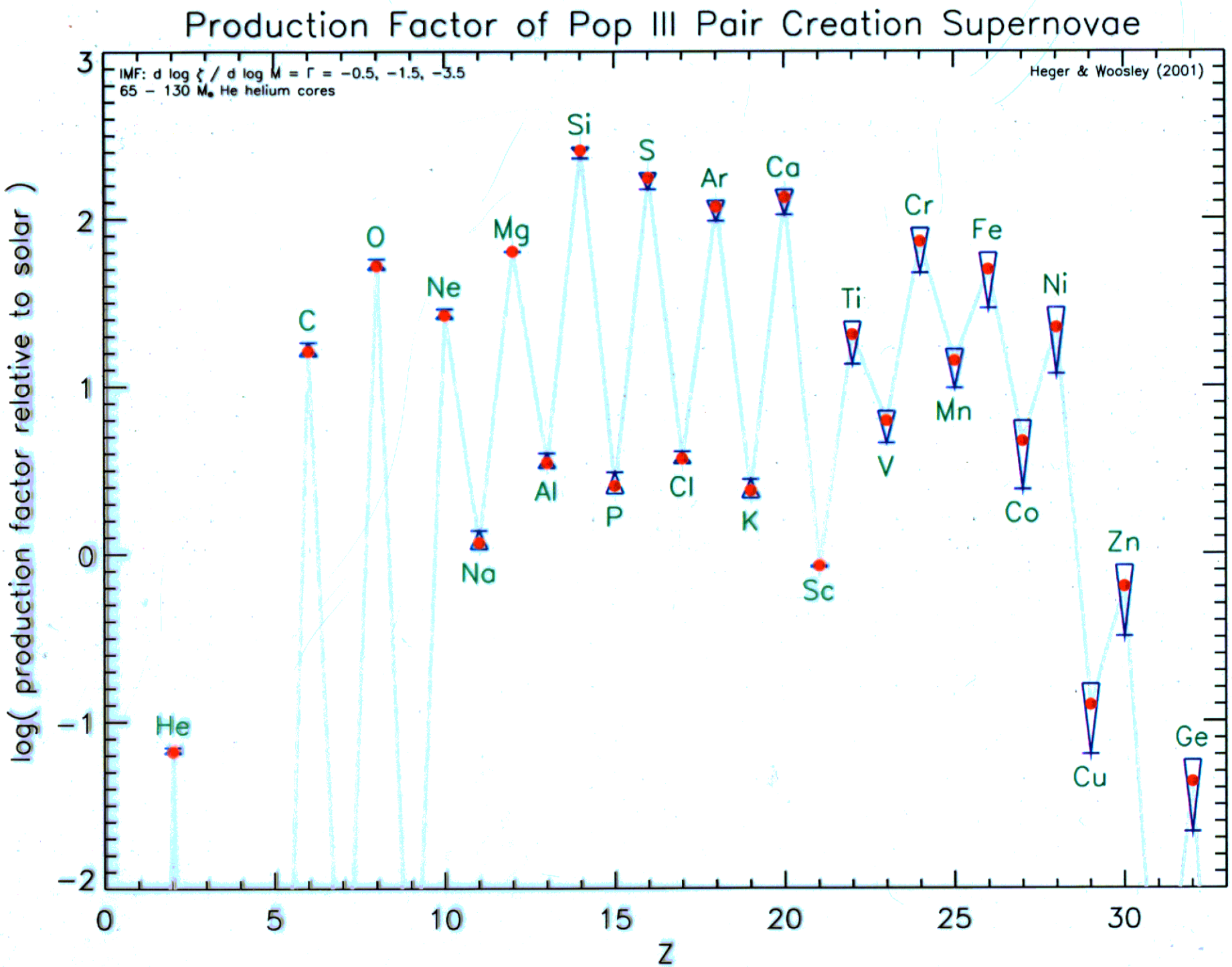
130 solar mass He core, primordial composition

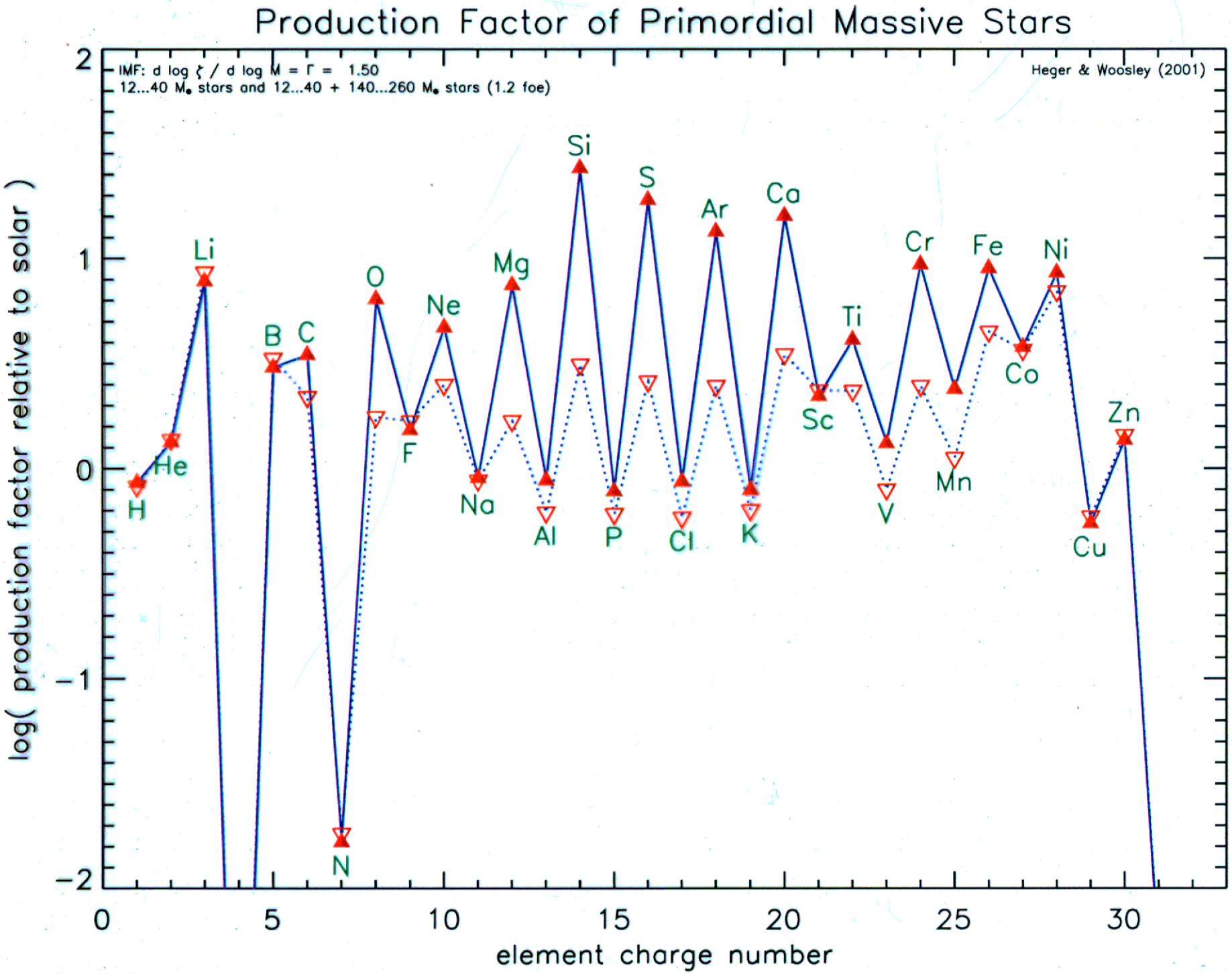
~ 250 $M_\odot$ star




140 M⊙
200 M⊙
260 M⊙
Heger et al. (2000)
56
93
yield / solar masses
explosion energy / foe
helium core mass / solar masses
0
10
20
30
40
50
0
20
40
60
80
70
80
90
100
110
120
130
12C
16O
24Mg
28Si
32S
40Ca
56Ni
Eexpl


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


Production Factor of Pop III Pair Creation Supernovae
IMF: d log ξ / 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


Production Factor of Primordial Massive Stars
IMF: d log ζ / d log M = Γ = 1.50
12...40 M☉ stars and 12...40 + 140...260 M☉ stars (1.2 foe)
Heger & Woosley (2001)
log(production factor relative to solar)
element charge number
H
He
Li
B
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
2
1
0
−1
−2
0
5
10
15
20
25
30

Bright Supernovae at the Edge of the Universe

- explosion energy up to 10^{53} erg
  (50 – 100× that of "normal" supernovae)

- up to 50 solar masses of radioactive ^{56}Ni
  (100× that of Type Ia supernovae)

- Assuming that 10^{-6} of all baryons go into stars of 250 solar masses, at a red shift of 20, the rate of events could be as high as one every 6 sec.
  (For a current standard cosmology, $\Omega_\Lambda = 0.7$, $\Omega_{\text{matter}} = 0.3$, $H_0 = 65$ km/s/Mpc, $\Omega_{\text{baryons}} = 0.02/h^2 = 0.047$)

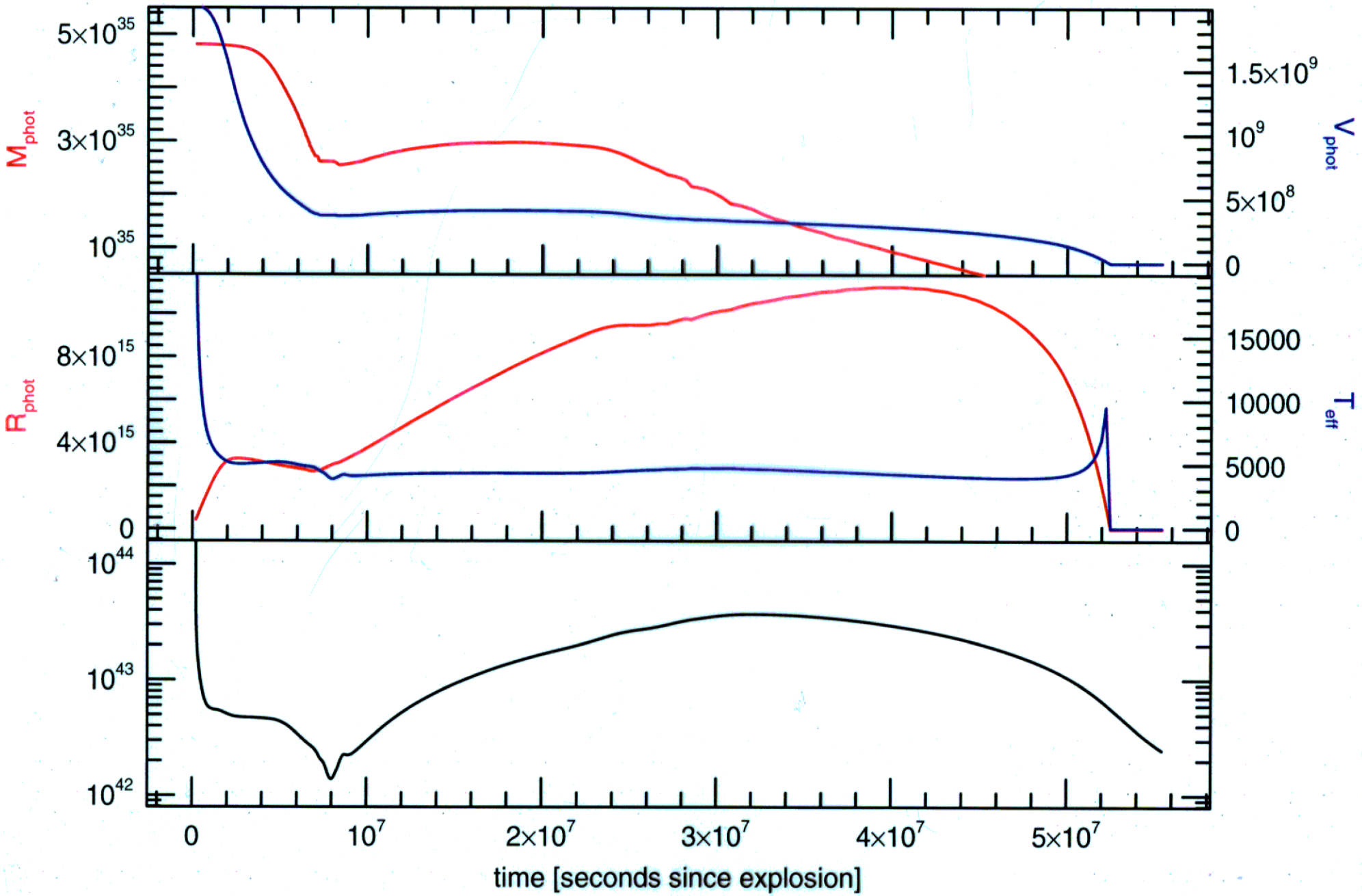
- They would last about 10 yr in the observer frame
  (due to large mass)

- This computes to ~1000 of these objects are visible per square degree at any given time
  (assuming no extinction)

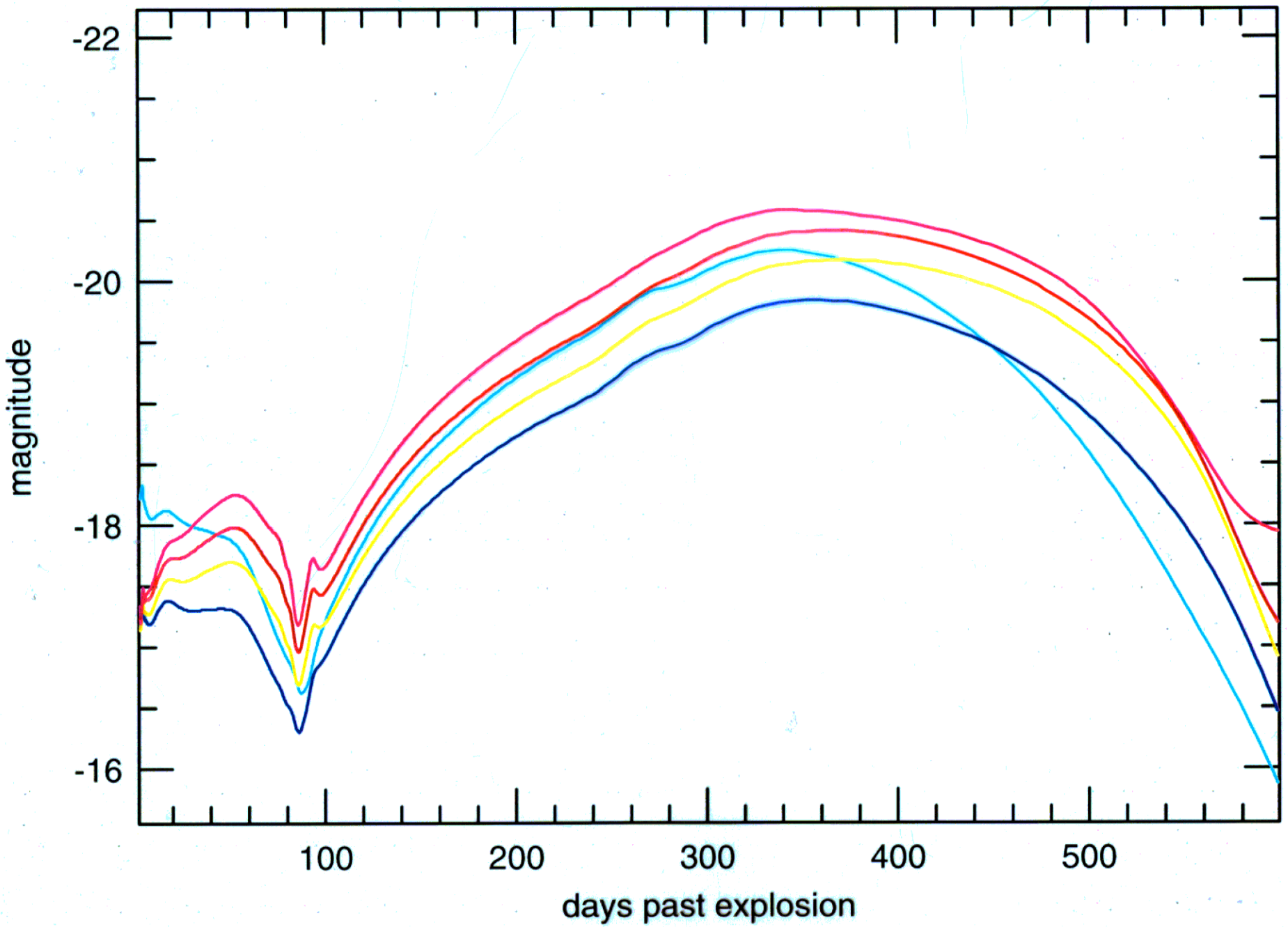
- They are intrinsically a few times brighter than Type Ia supernovae
  (in bolometric luminosity)
  Note that the bolometric luminosity of an object at a redshift of 20 is not much less than that of an object with at redshift of a few, where Type Ia supernovae have already been observed!

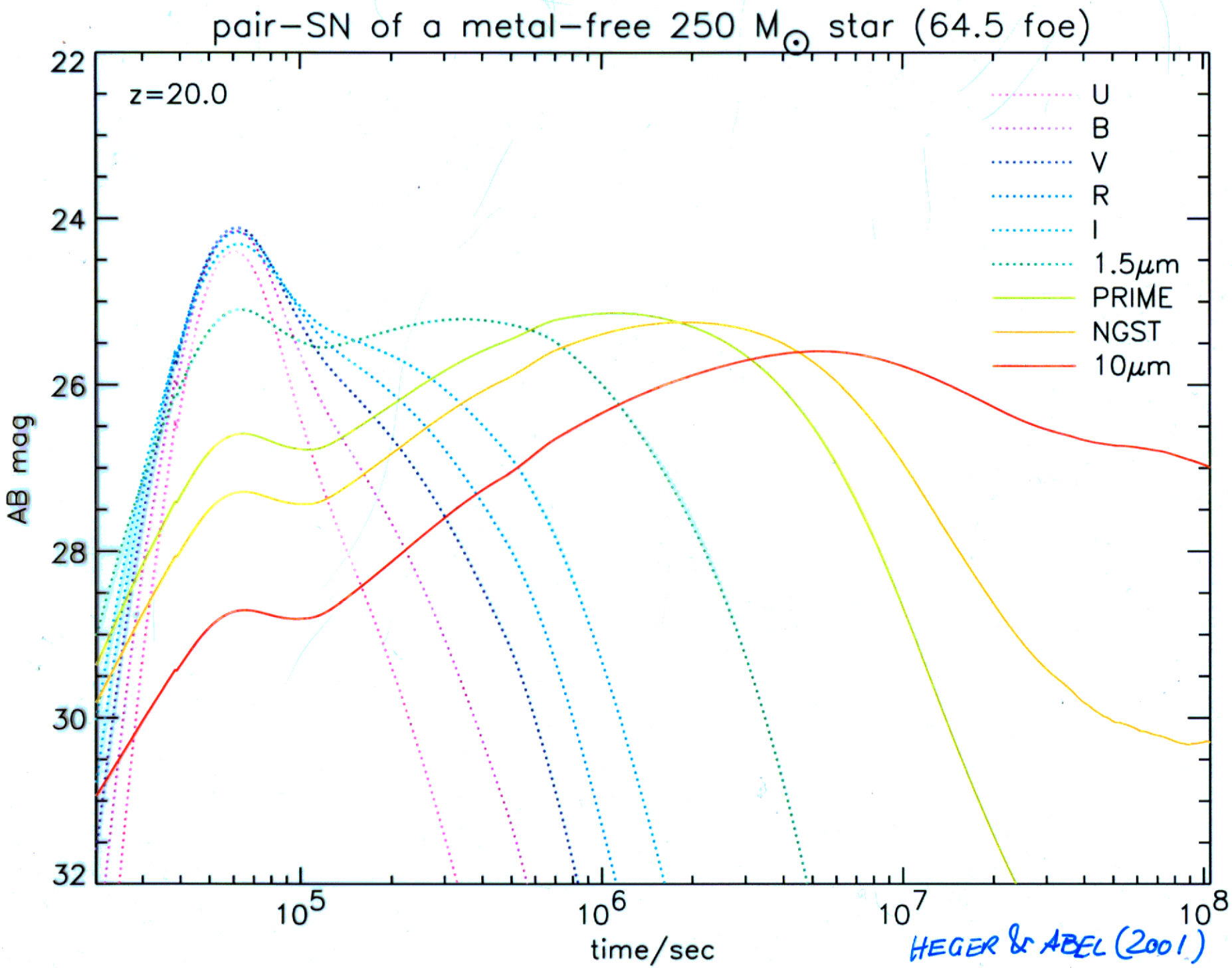
- Only observable in the near infrared
  (due to absorption by neutral hydrogen short of 1215 Å, redshifted by a factor 1+redshift)

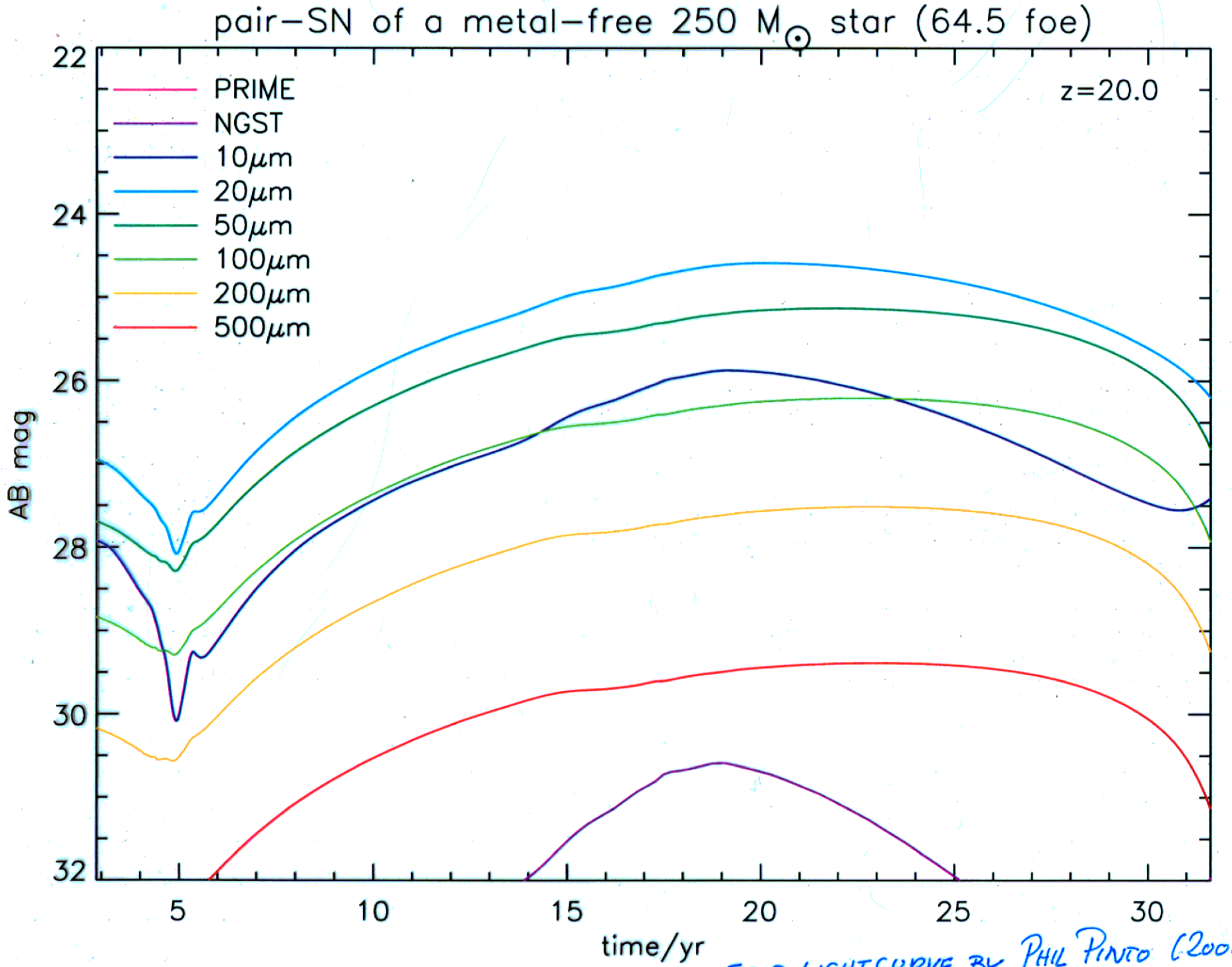
PHIL PINTO (2002)



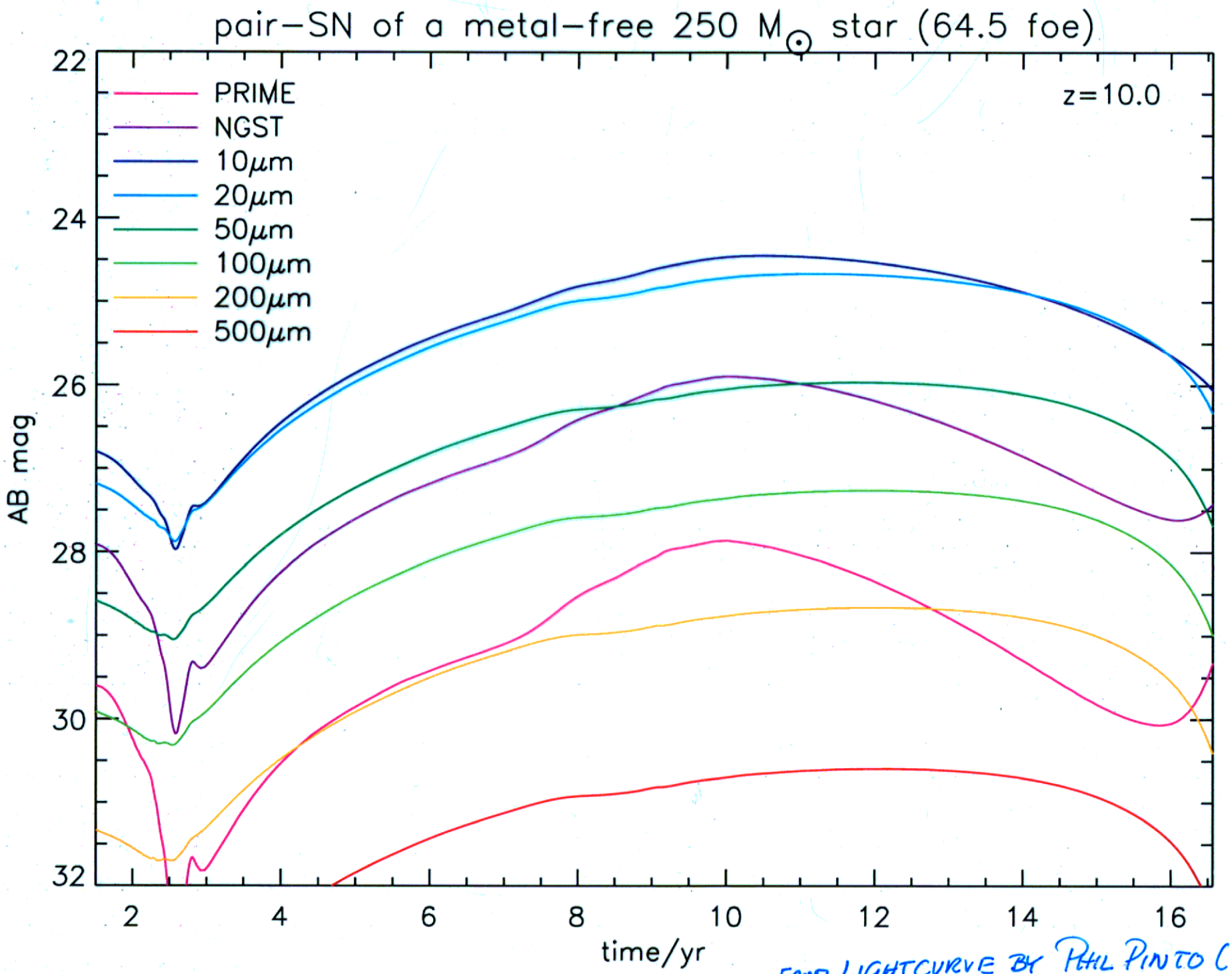
PHIL PINTO (2002)



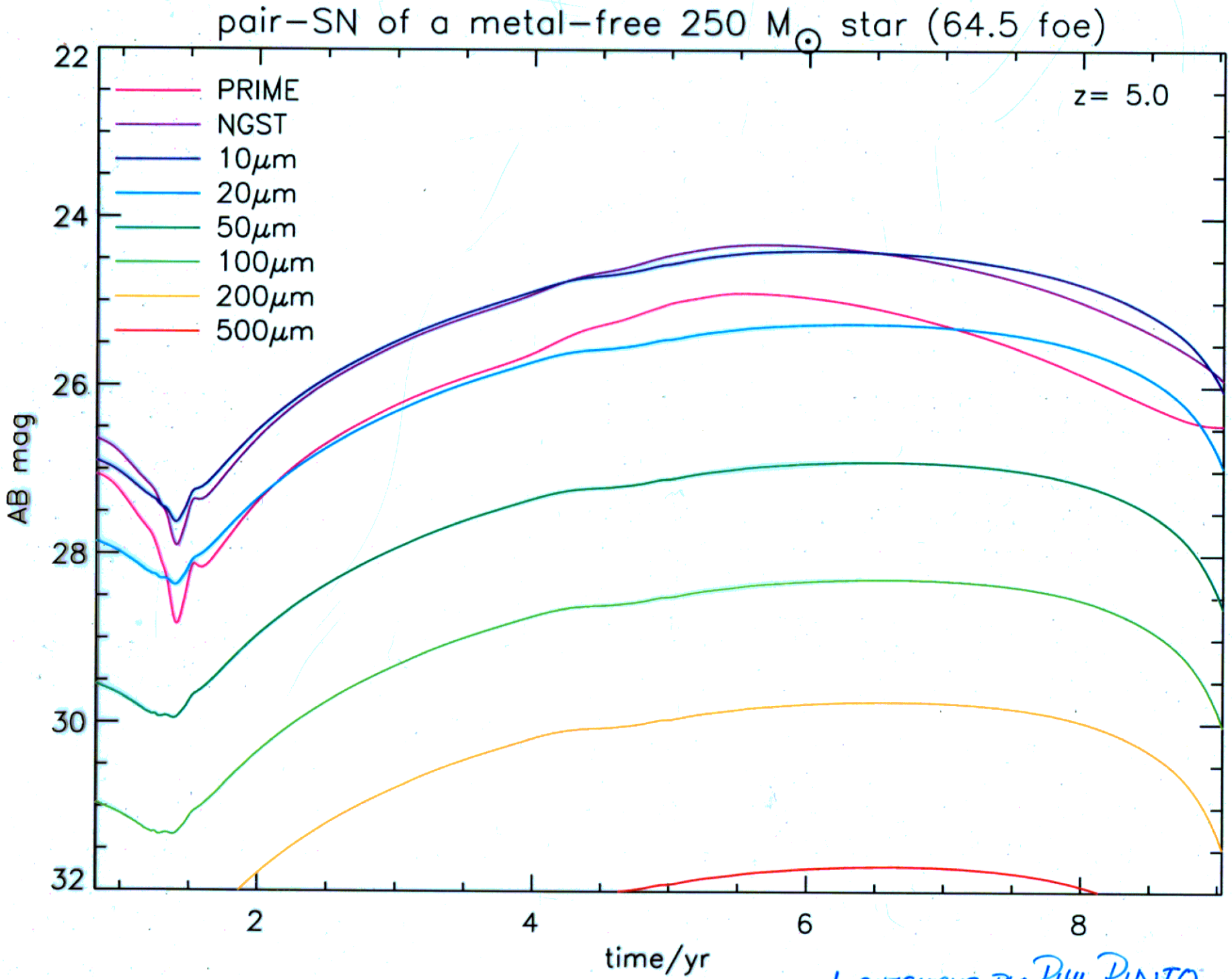

pair−SN of a metal−free 250 M⊙ star (64.5 foe)
z=20.0
U
B
V
R
I
1.5μm
PRIME
NGST
10μm
AB mag
22
24
26
28
30
32
10^5
10^6
10^7
10^8
time/sec
HEGER & ABEL (2001)



FROM LIGHTCURVE BY PHIL PINTO (2002)



FROM LIGHTCURVE BY PHIL PINTO (2002)



FROM LIGHTCURVE BY PHIL PINTO

Summary

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

- They are likely born much more massive.
  (mass scale: 100 solar masses)
- They are more compact and hotter.
  (typically 100,000 K for a 100 solar mass star)
- Even stars of several 100 solar masses might not lose significant amounts of mass before death.
  (no winds, no epsilon mechanism)
- They can encounter the pair-creation instability:
  - energetic explosions of up to 100× that of "normal" supernovae (10^{53} erg kinetic energy)
  - up to 50 solar masses ^{56}Ni ejected
  - might be seen directly by NGST – out to red shift 20!
- Peculiar nucleosynthesis pattern from pair-creation supernovae:
  - no heavy elements beyond zinc produced
  - no *r*-process, no *s*-process
- Odd-even elemental pattern in all massive stars, but particularly strong in pair-creation supernovae.

Outlook

- Influence of rotation on mass limits and nucleosynthesis.
- Multi-dimensional simulations of pair-instability supernovae.
- Detailed study of pulsational pair instability.
- Search for stars with VMS nucleosynthesis pattern.