Life and Death of the First Stars

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Overview

- Basics of massive star evolution and nucleosynthesis
- Birth, life, and fate of Pop III stars
- Nucleosynthesis in *very massive* Pop III stars (100–1000 $M_\odot$)
- Nucleosynthesis in *massive* Pop III stars (10–100 $M_\odot$)
- Other ways to blow up massive stars
- The *second (primordial) stars*: A secondary IMF?

IMF of the First Stars

— recall talk by Joe Silk —

Predicted to be heavy to very heavy

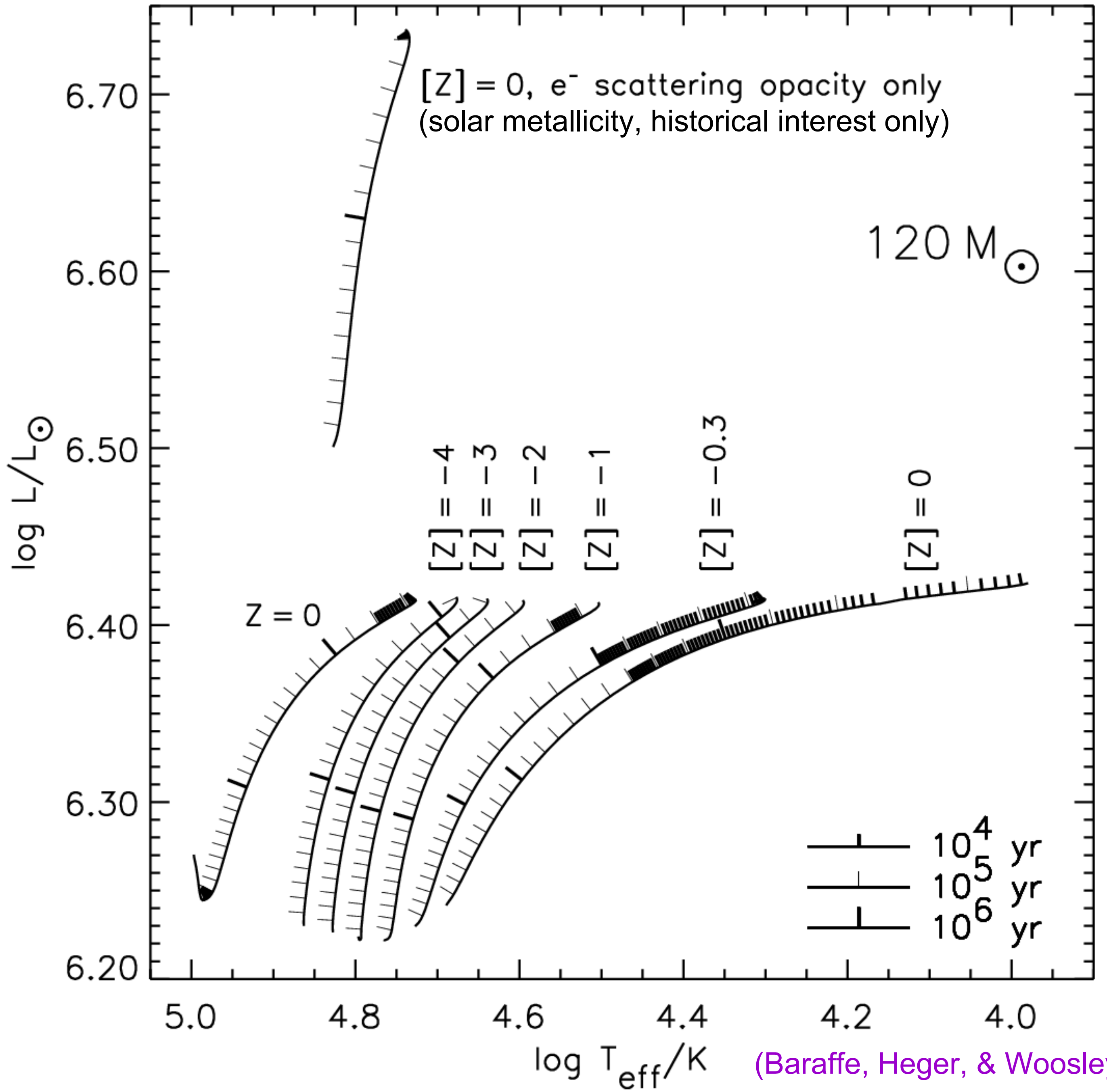
by theory – insufficient cooling due to lack of metal
(e.g., Larson 1999)

and by numerical simulations

(Bromm, Coppi, & Larson 1999, 2002;
Abel, Bryan, & Norman 2000, 2002;
Nakamura & Umemura 2001, 2002;
O'Shea et al. 2005; …)

with a typical mass scale of ~100 $M_{\odot}$**?**

➔The first stars *may* have had a significant very massive population

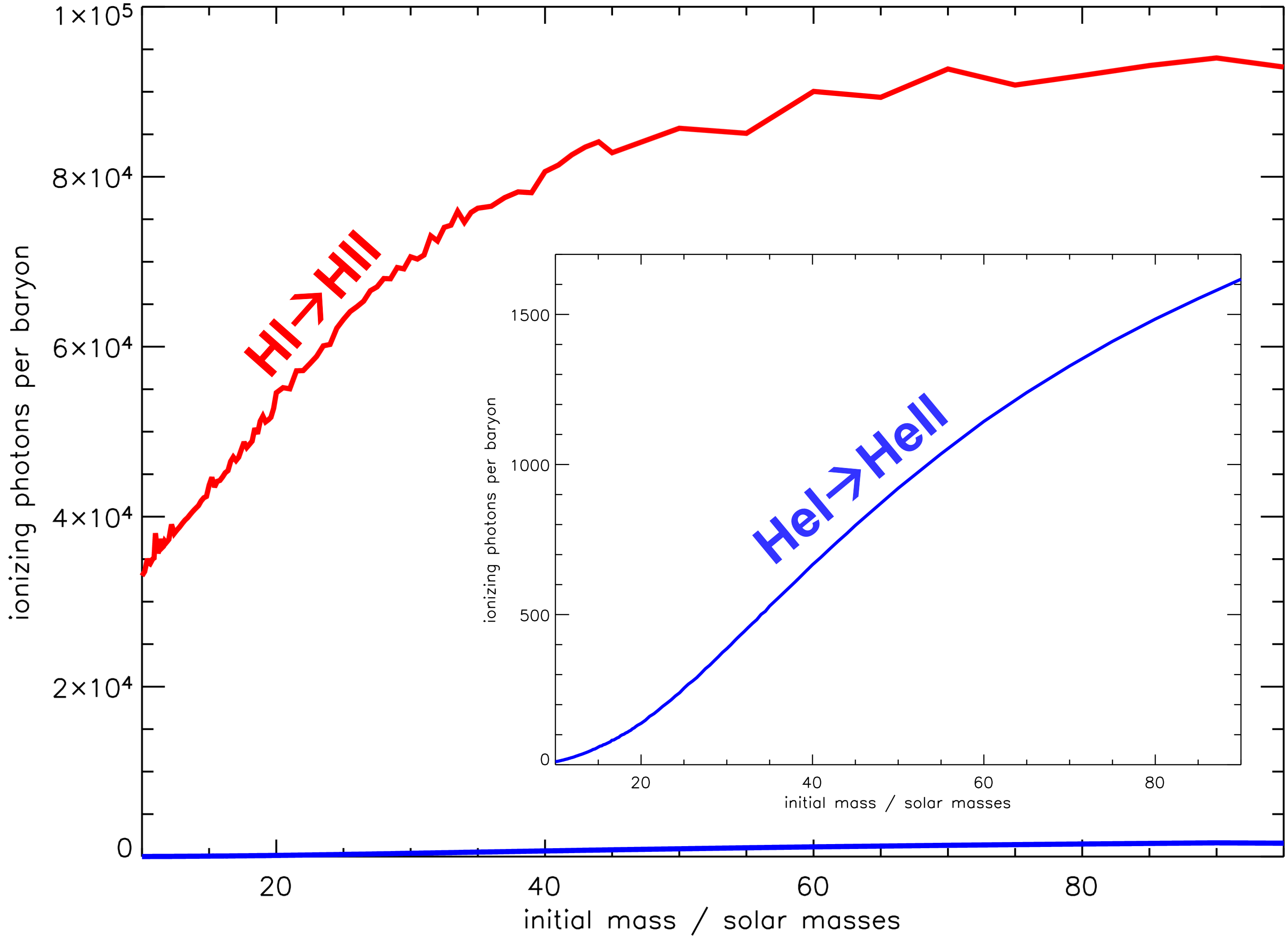


(Baraffe, Heger, & Woosley 2001)

Higher effective temperature for lower initial metallicity

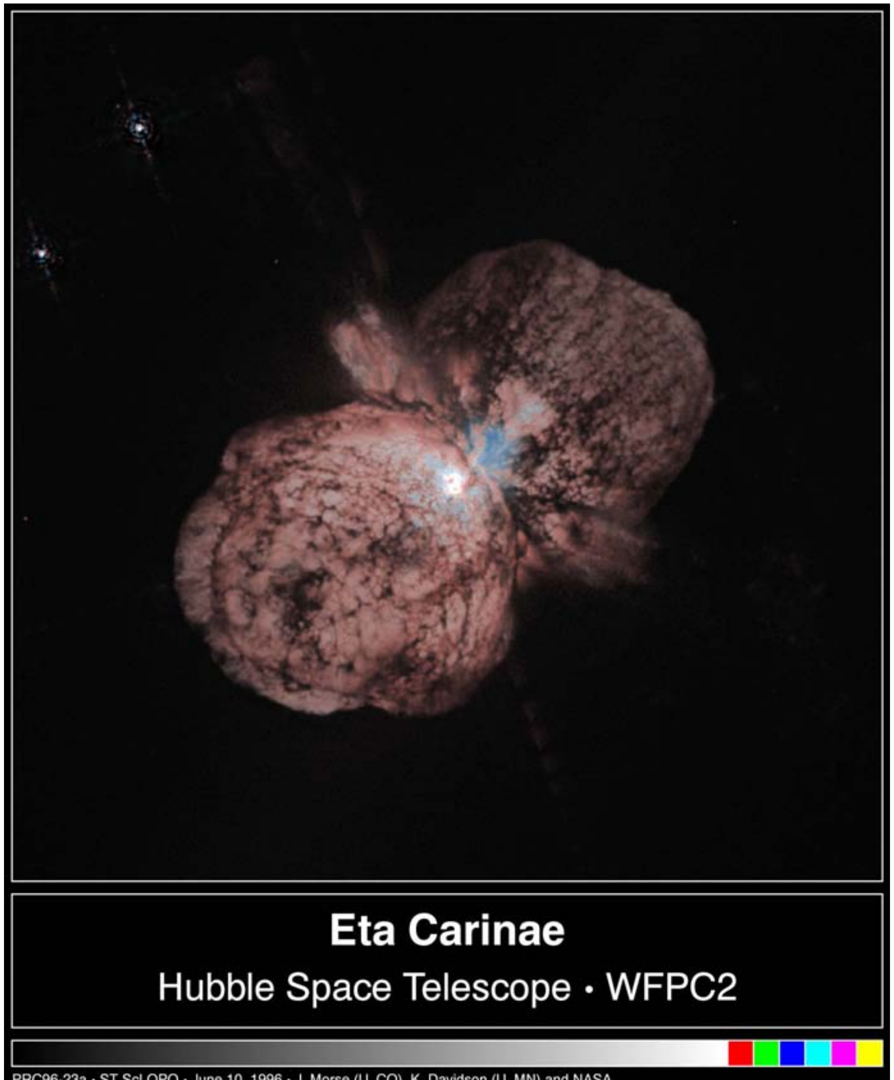
➔ more ionizing photons

Ionizing Photon Fluxes



The number of ionizing photons per baryon strongly depends on the initial stellar mass at low mass, but levels off at high stellar mass (constant stellar temperature).

Additional Ingredient



Essentially negligible mass loss in Pop III stars?

in contrast:

Eta Carina

- Galactic star / solar+ metallicity
- Extremely high mass loss rate
- Initial mass: 150-200 $M_\odot$ (?)
- Will likely die as much less massive object

Mass Loss in Very Massive Primordial Stars

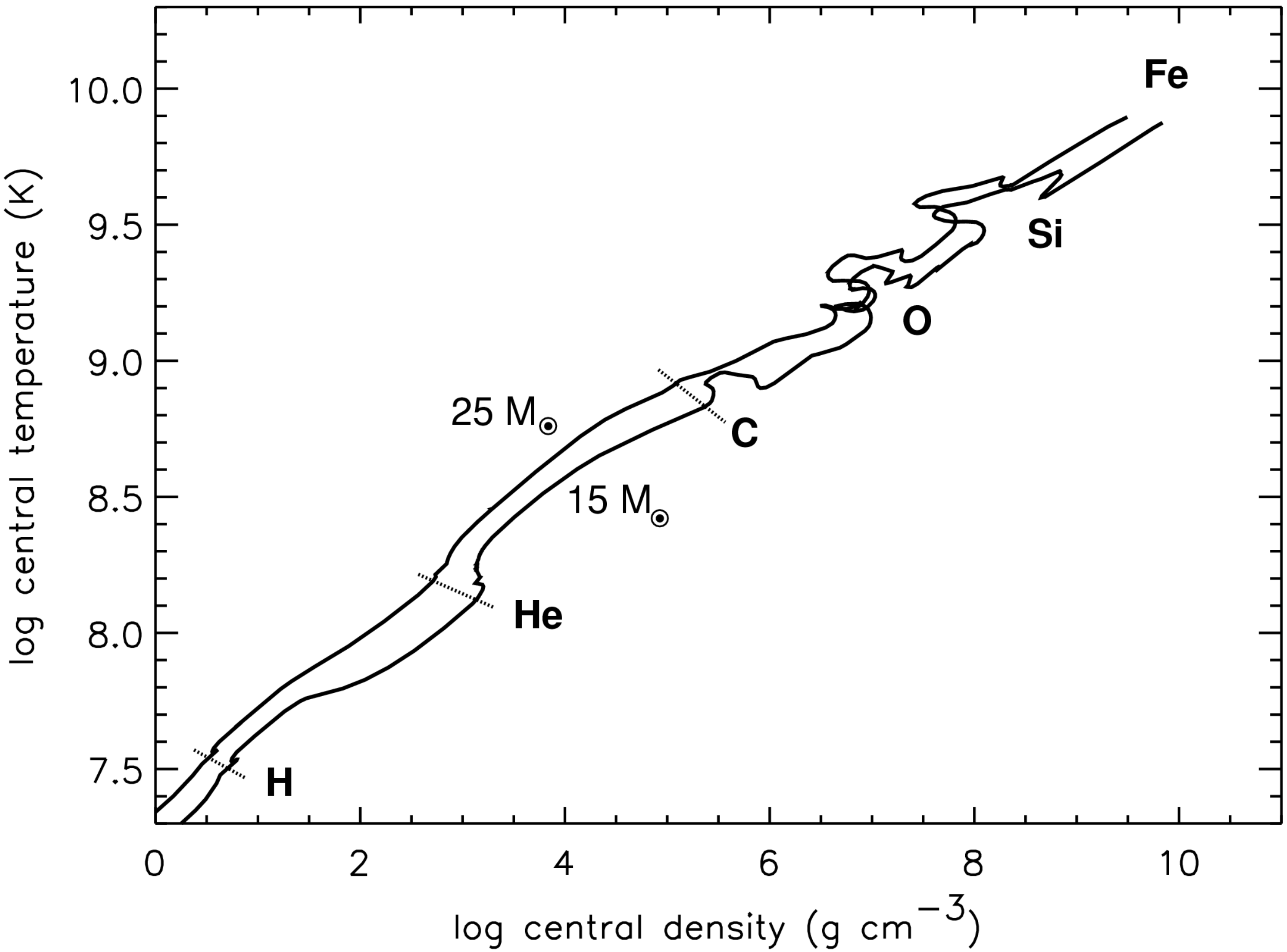
- Negligible line-driven winds
  (mass loss ~ metallicity$^{>1/2}$ – Kudritzki 2002)
- No opacity-driven pulsations (no metals – Baraffe, Heger & Woosley 2001)
- Continuum-driven winds @ $L \sim L_{Edd}$ have to be explored
  (Owocki, Shaviv, *et al.*)
- Epsilon mechanism inefficient in metal-free stars 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
- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above ~500 $M_\odot$
- Post-main sequence and rotationally induced ***mixing*** and mass loss?

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

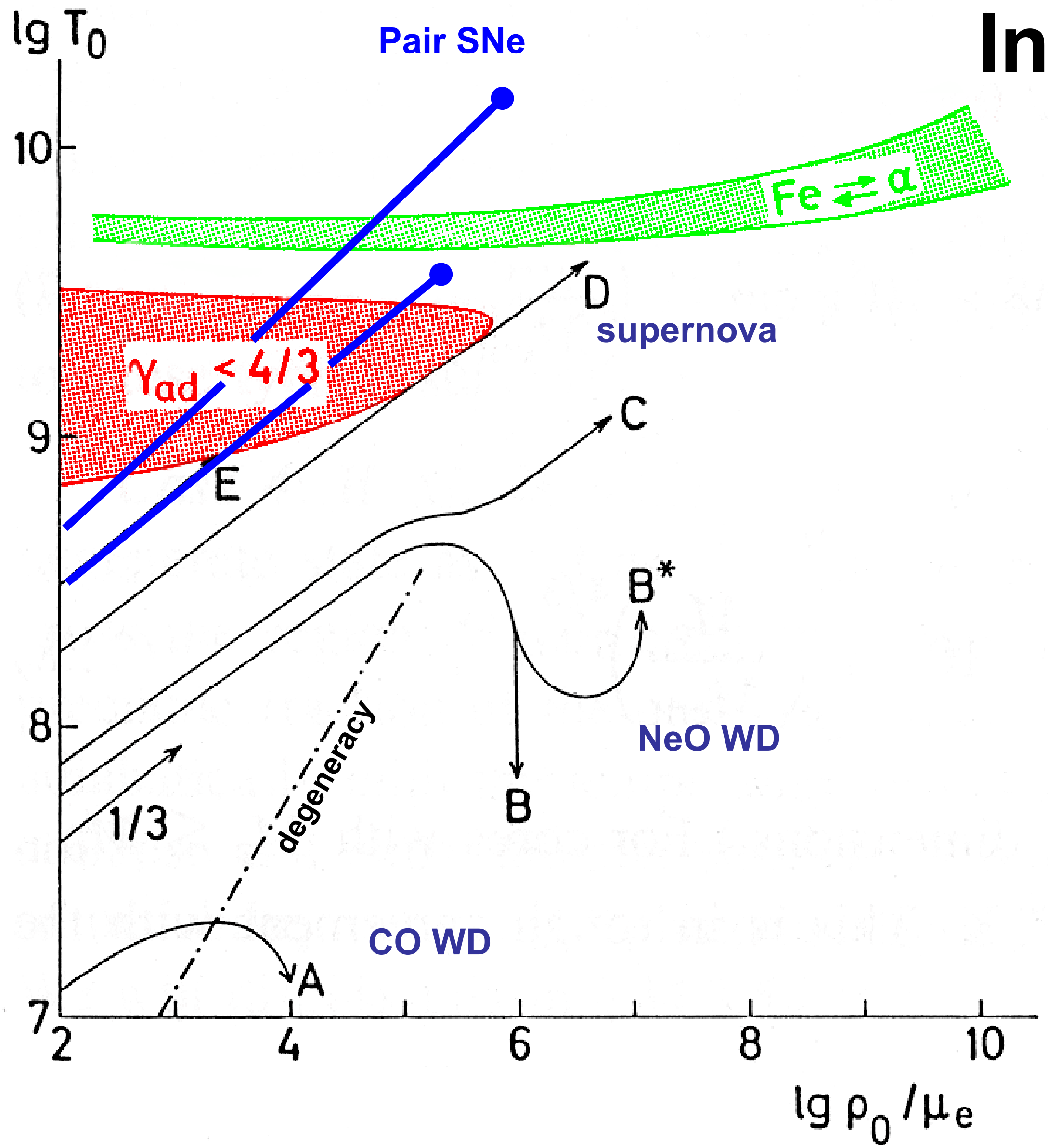
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	He	0.02	10^7	0.1	2×10^6
He	O, C	0.2	10^6	0.3	2×10^5
C	Ne, Mg	0.8	10^3	1.2	10
Ne	O, Mg	1.5	3	2.5	3×10^{-6}
O	Si, S	2.0	0.8	3.0	2×10^{-6}
Si	Fe	3.5	0.02	4.5	3×10^{-7}

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^-)

Instability Regimes



Kippenhahn & Weigert (1990)

adiabatic index < 4/3

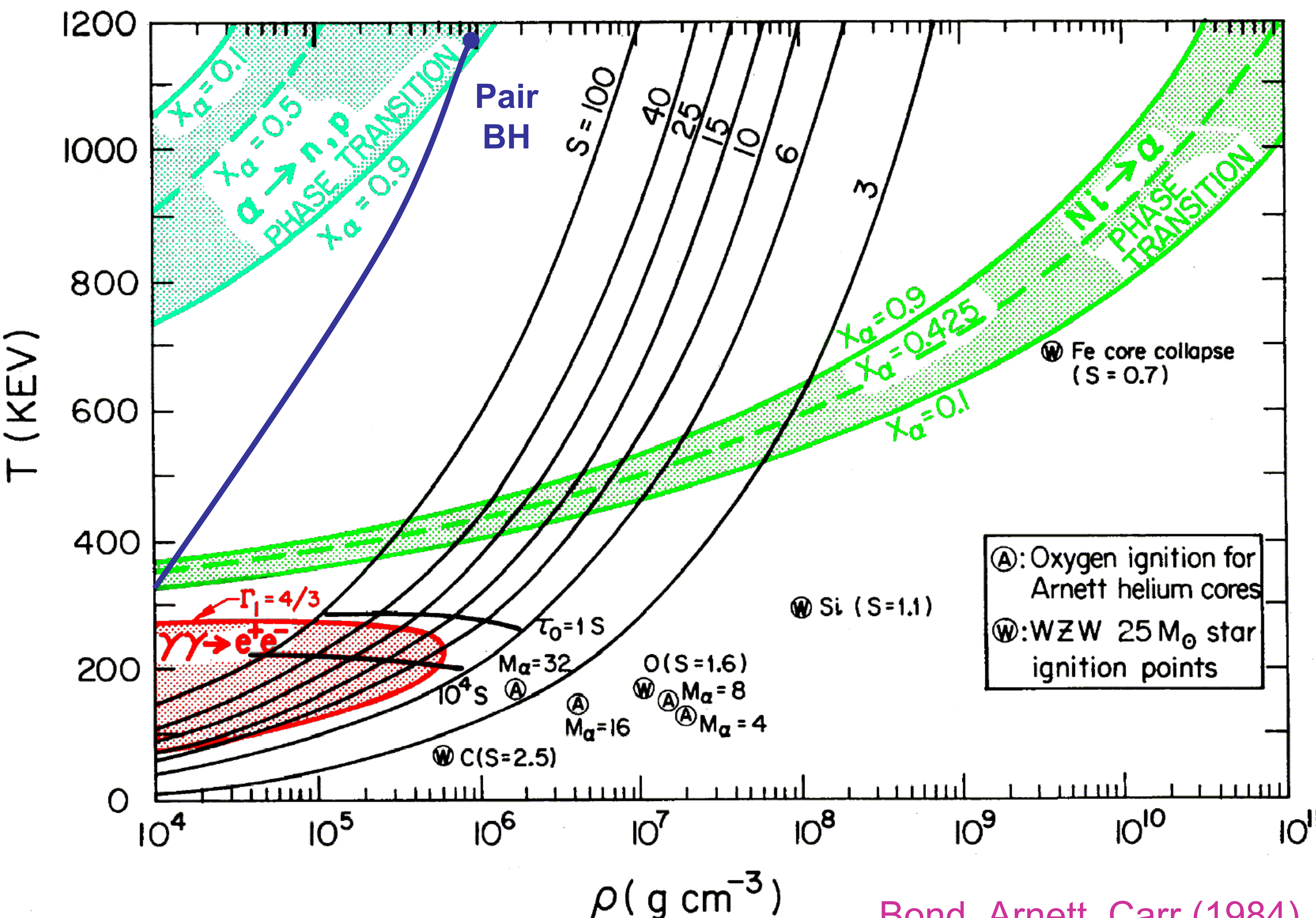
Compression does not result in sufficient increase in pressure (gradient) to balance higher gravity at lower radius

e^+/e^--Pair Instability

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

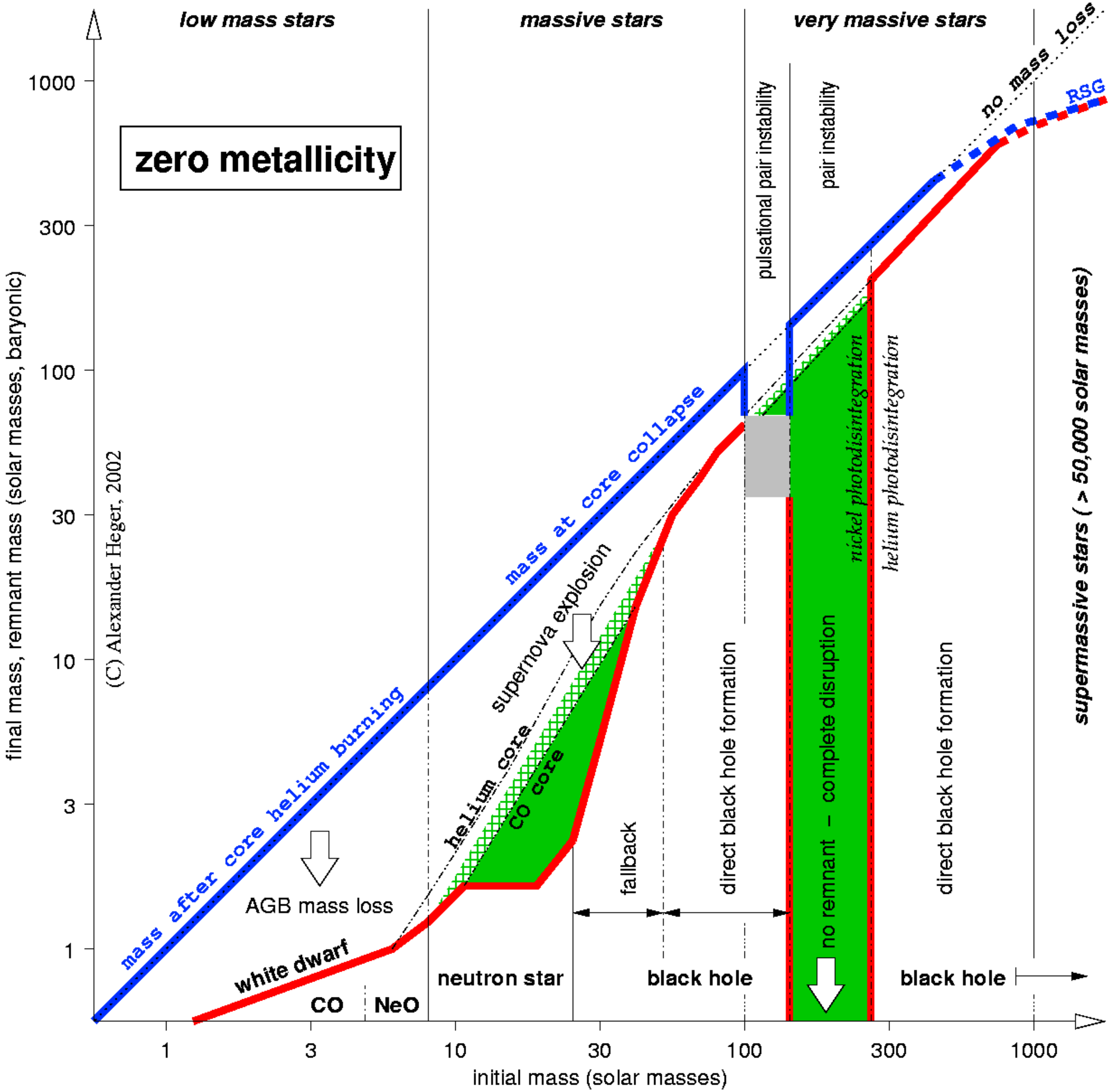
Photo disintegration

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



Bond, Arnett, Carr (1984)

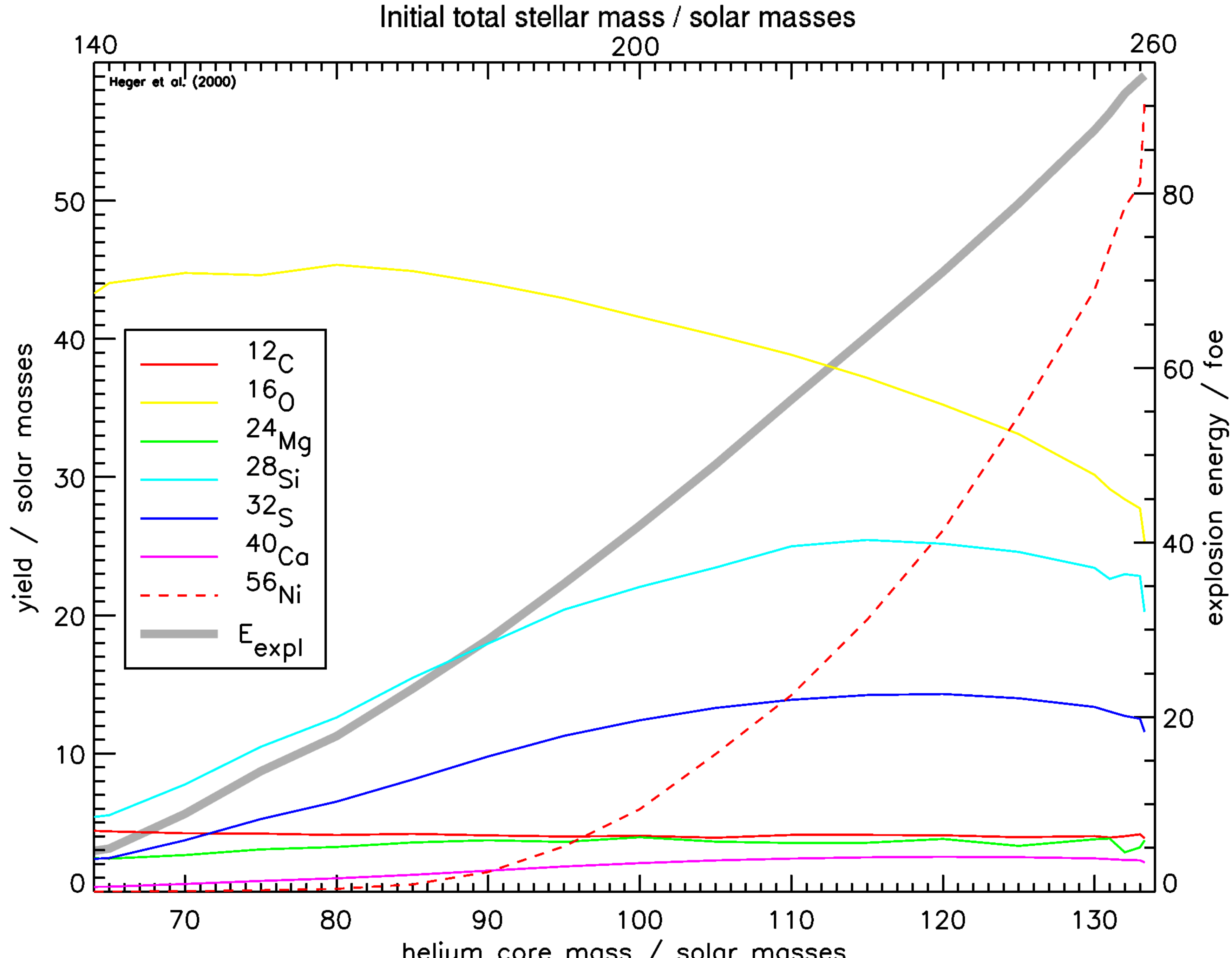
Ejected "metals"



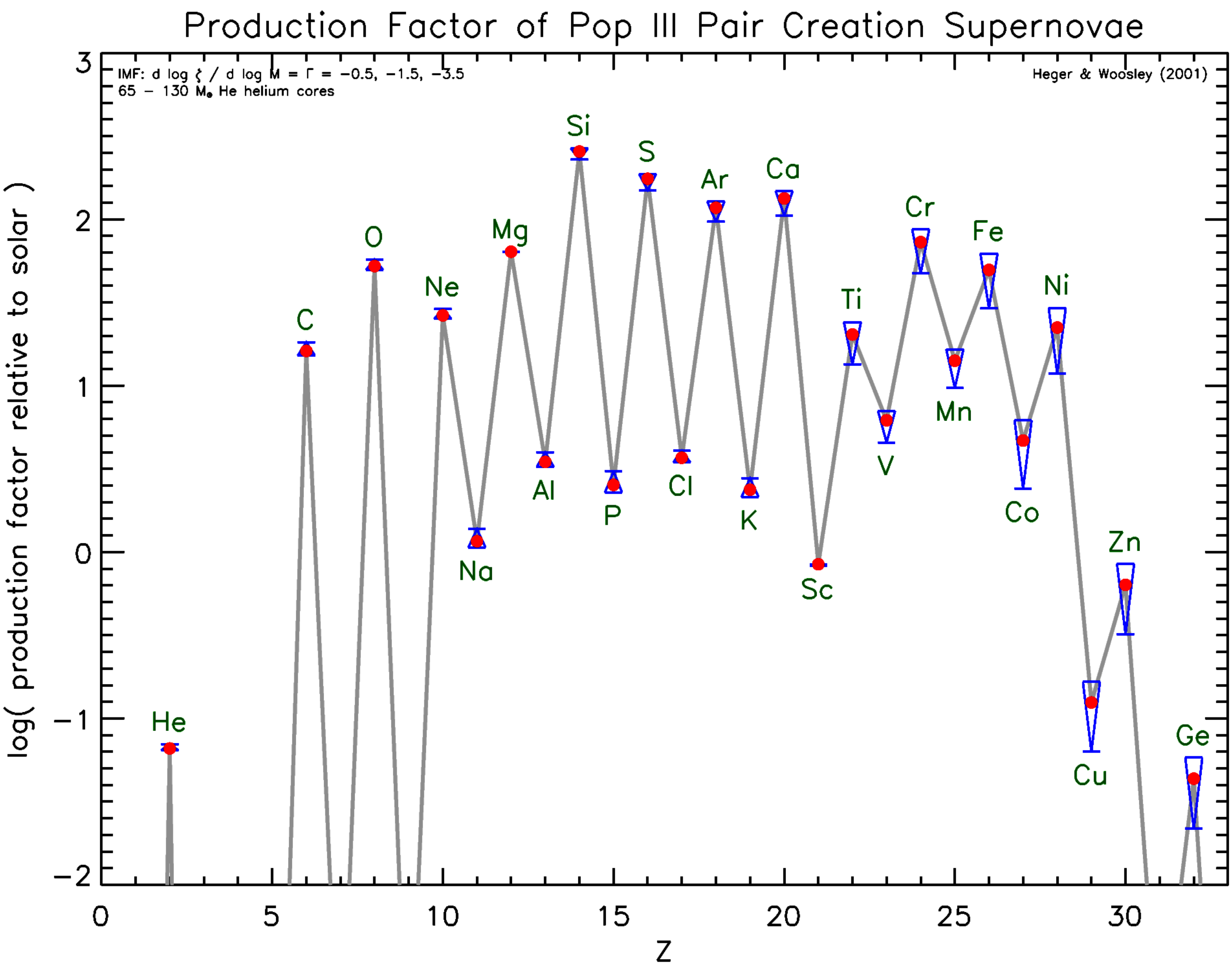
Pair-Instability Supernovae

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 comprise, e.g.,
Umeda & Nomoto 2002
Heger & Woosley 2002



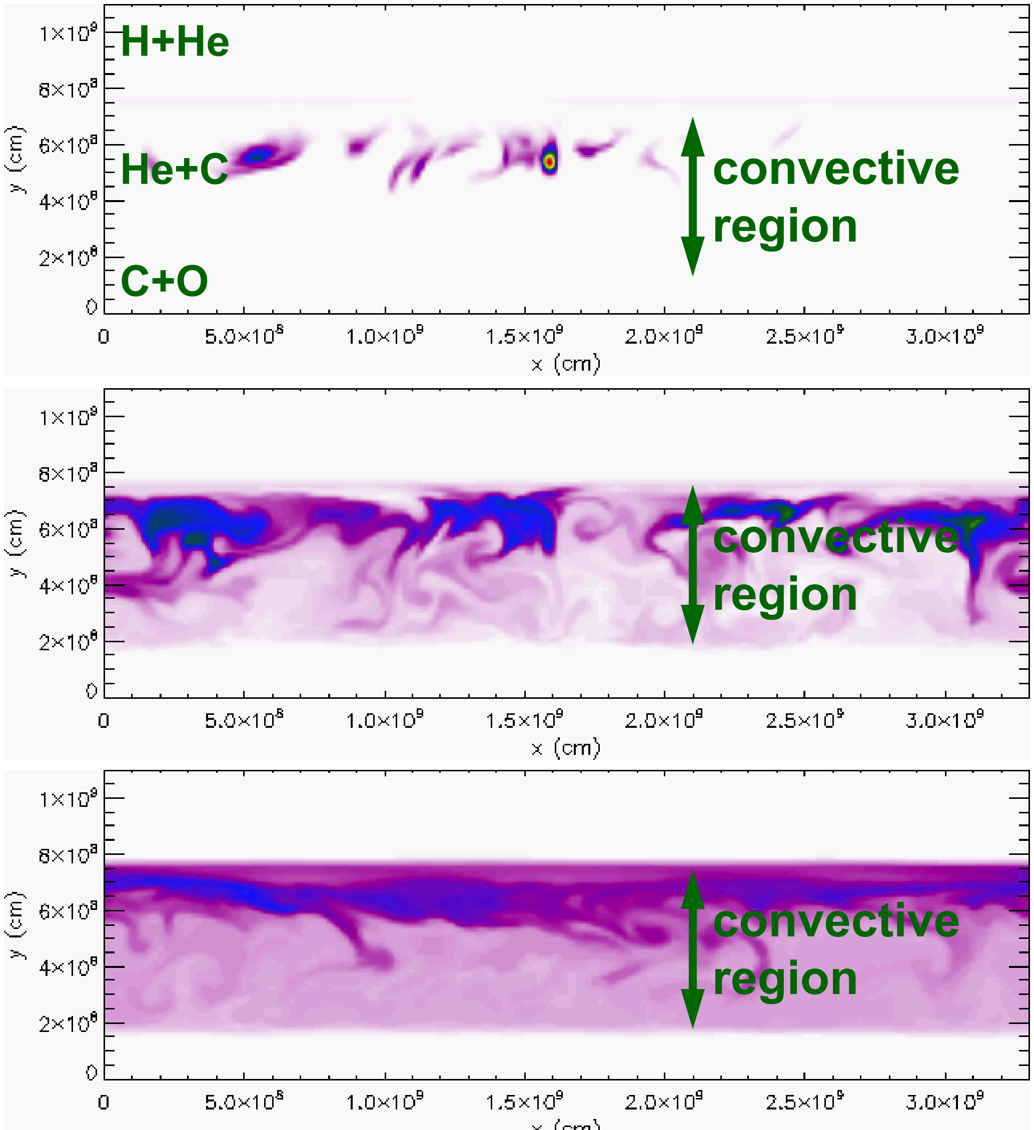
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
yield / solar masses
0
10
20
30
40
50
explosion energy / foe
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses


Production Factor of Pop III Pair Creation Supernovae
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
3
2
1
0
−1
−2
0
5
10
15
20
25
30

➔*Pure* pair-Instability supernovae ejecta do not seem to reproduce the abundances as observed in very metal poor halo stars!

Hydrogen/carbon mixing on post-MS?

(here for AGB star He shell flash)



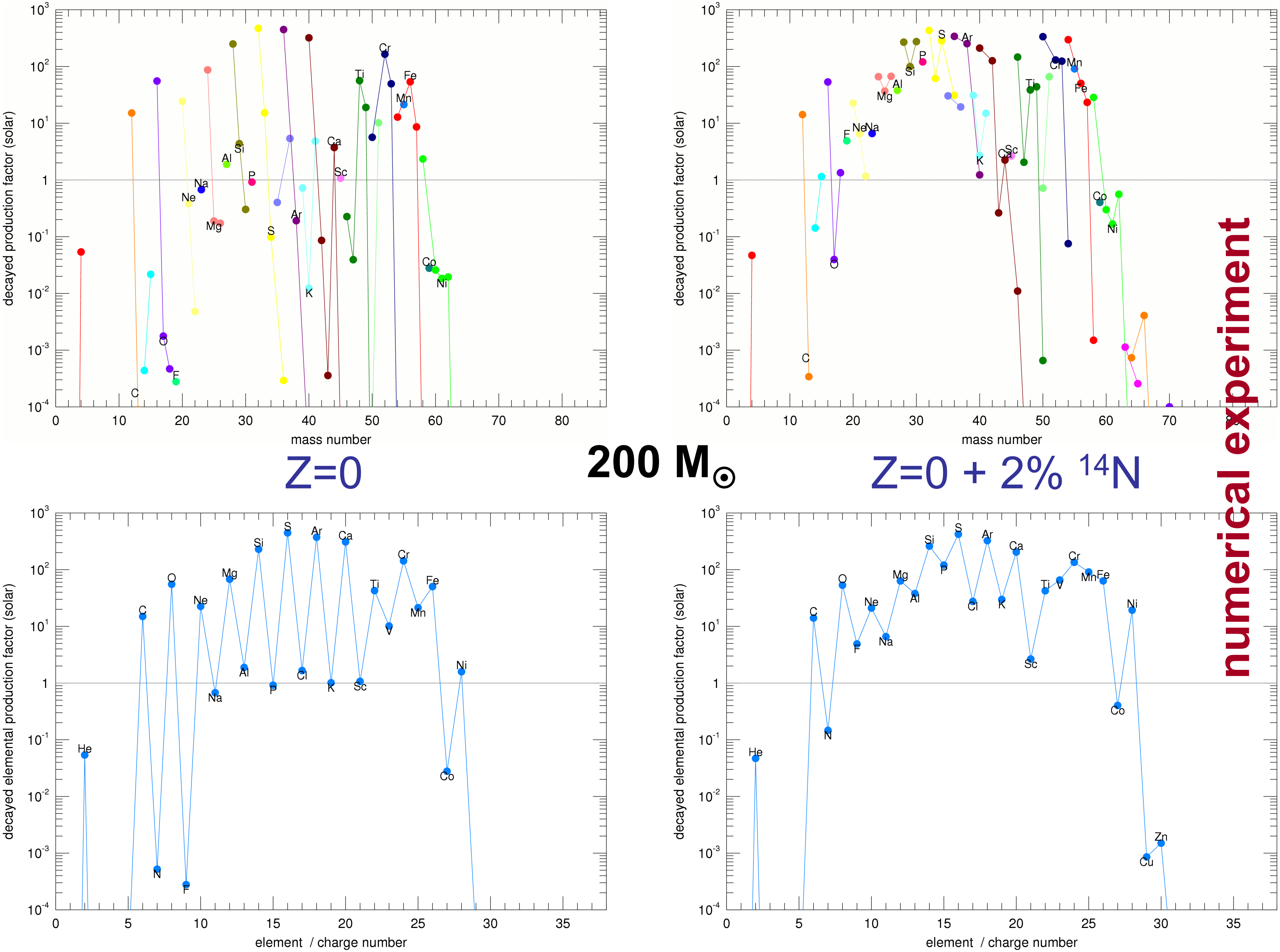
nuclear energy generation
$^{12}C(p,\gamma)^{13}N$

^{13}N mass fraction

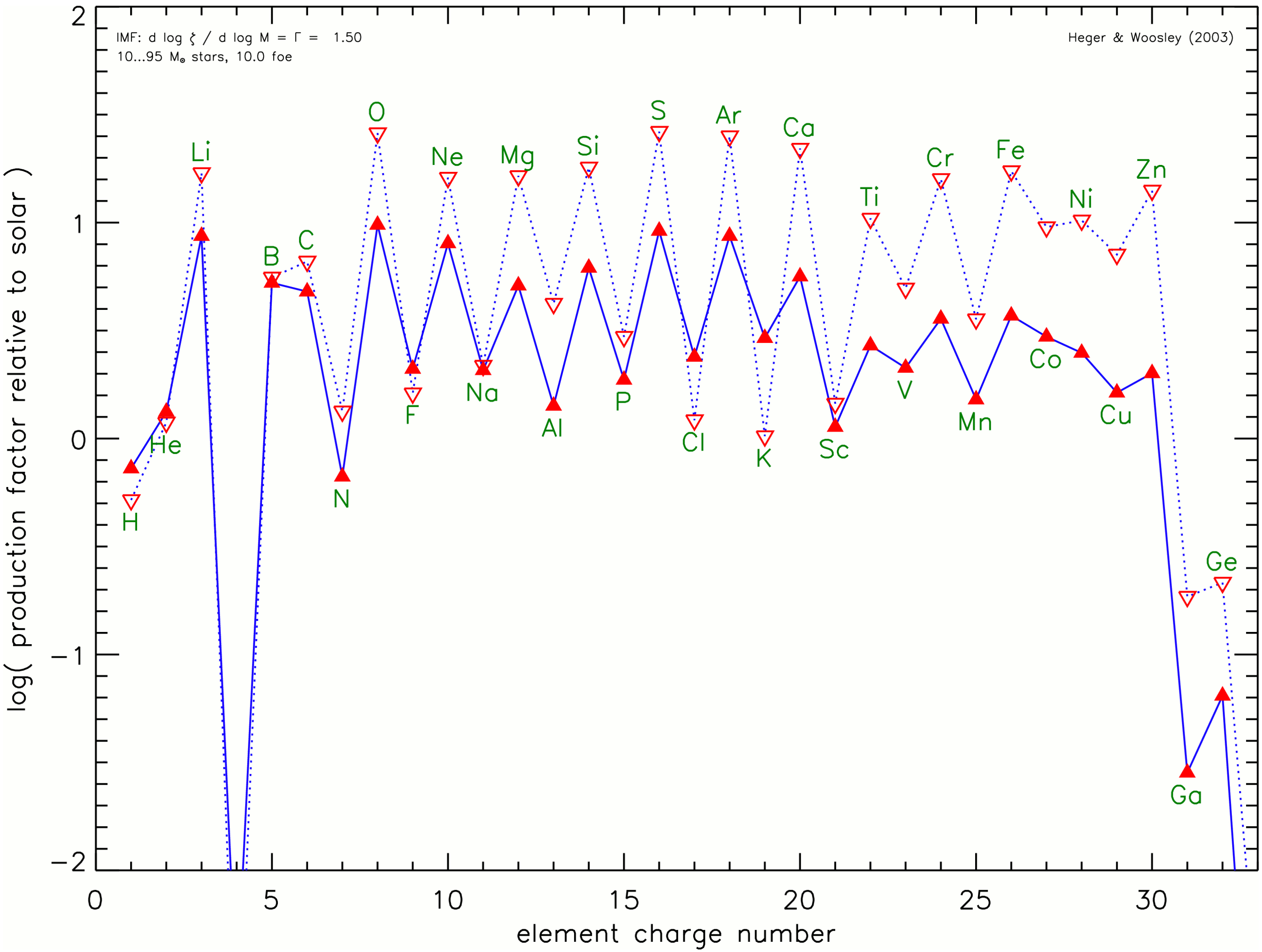
^{13}N mass fraction (later)

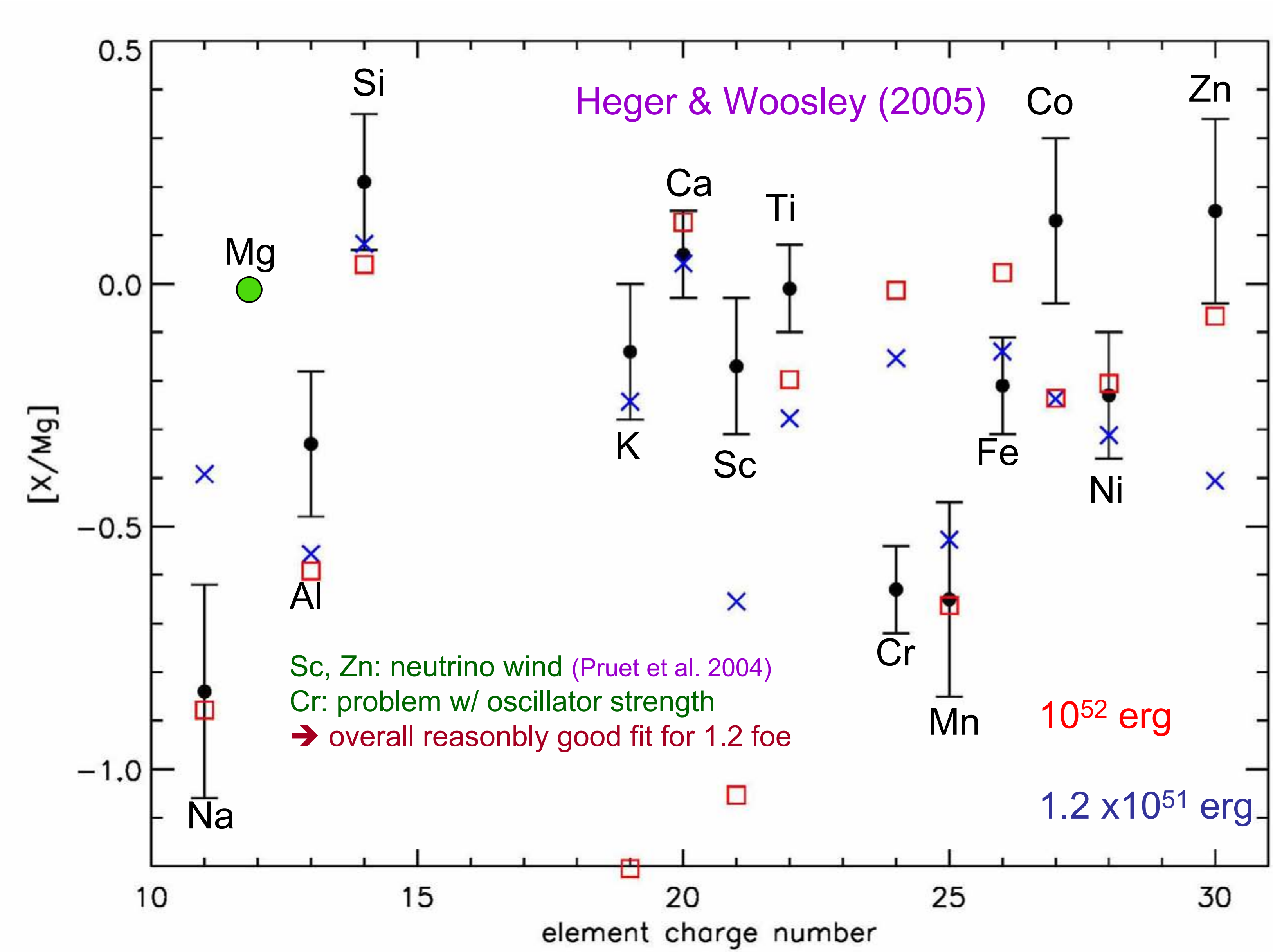
➔ **burning – mixing feedback**

Herwig, Heger, Frytag (2006)


200 M⊙
Z=0
Z=0 + 2% ¹⁴N
numerical experiment
decayed production factor (solar)
mass number
decayed elemental production factor (solar)
element / charge 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

1.2 foe and 10 foe explosions





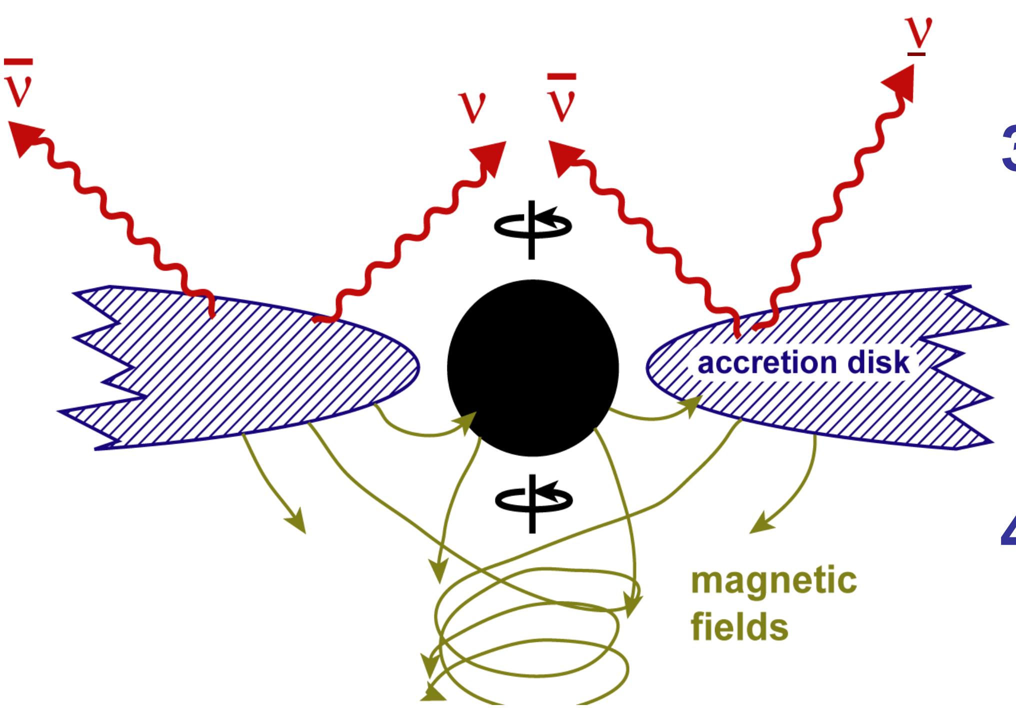
(Data from Cayrel et al. 2003, A&A, 416, 1117)

How else can massive stars explode?

(and very massive stars)

$25M_\odot < M < 100M_\odot$,
$M > 250M_\odot$

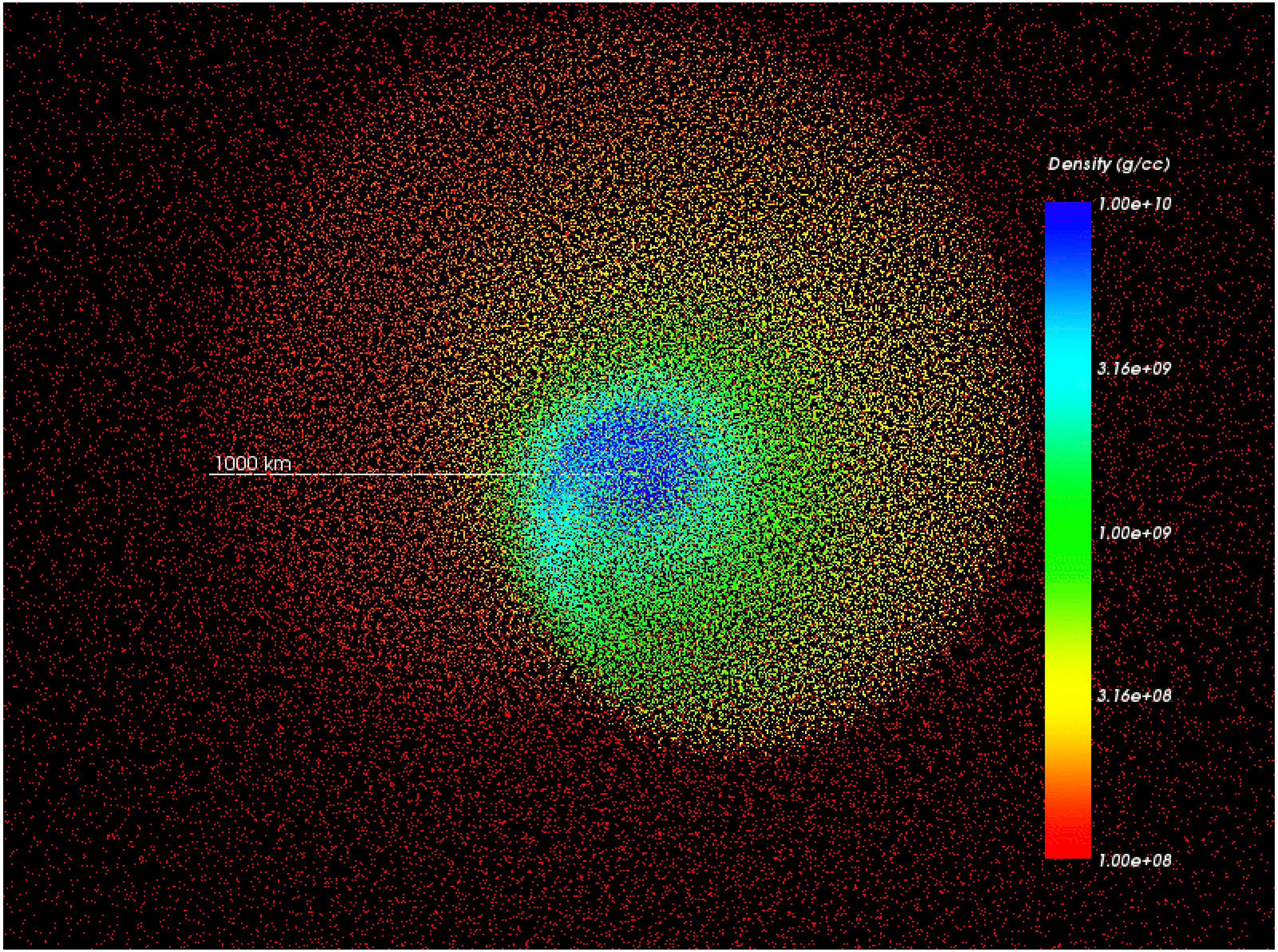
The "Collapsar Engine"



1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

Spiral Wave in Accretion Disk around Black Hole

Rockefeller & Fryer (2005)

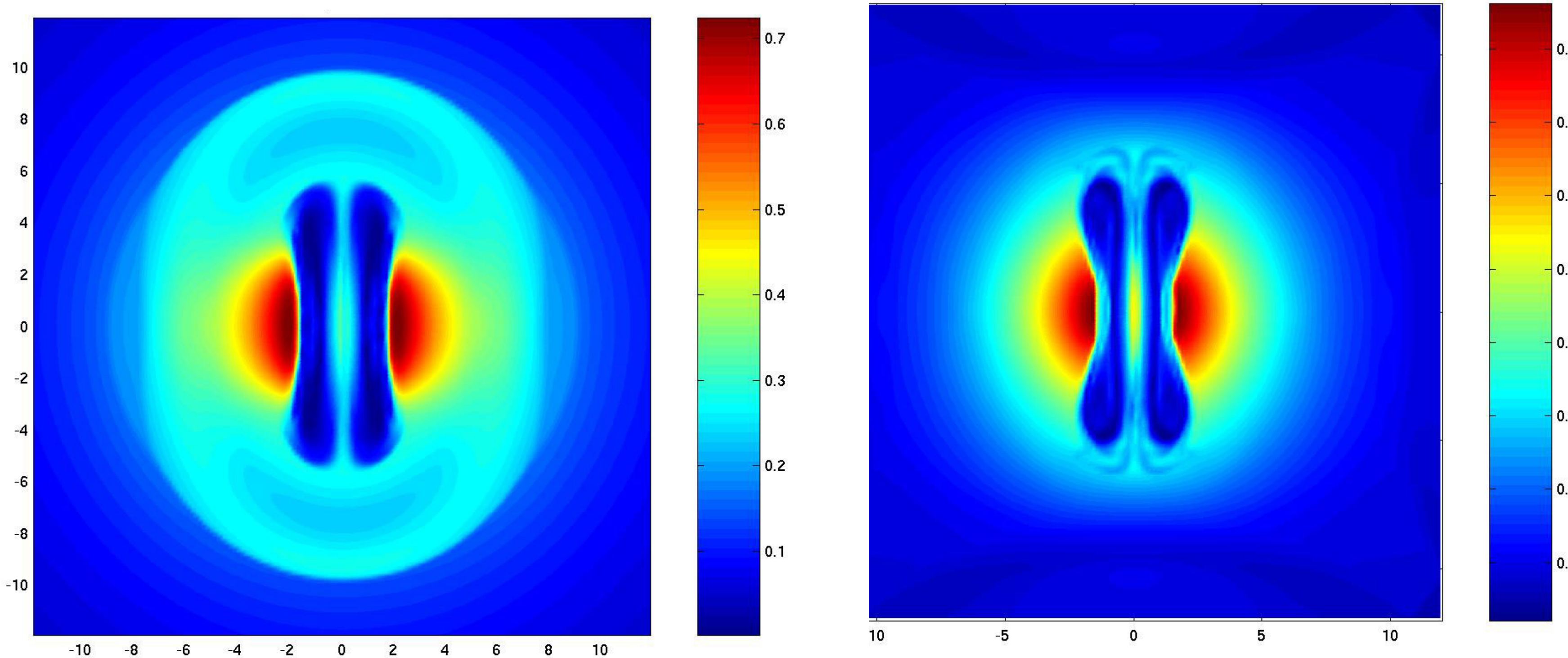


density – 3D SPH collapse calculation

MHD / jet-driven explosion

t = 11s

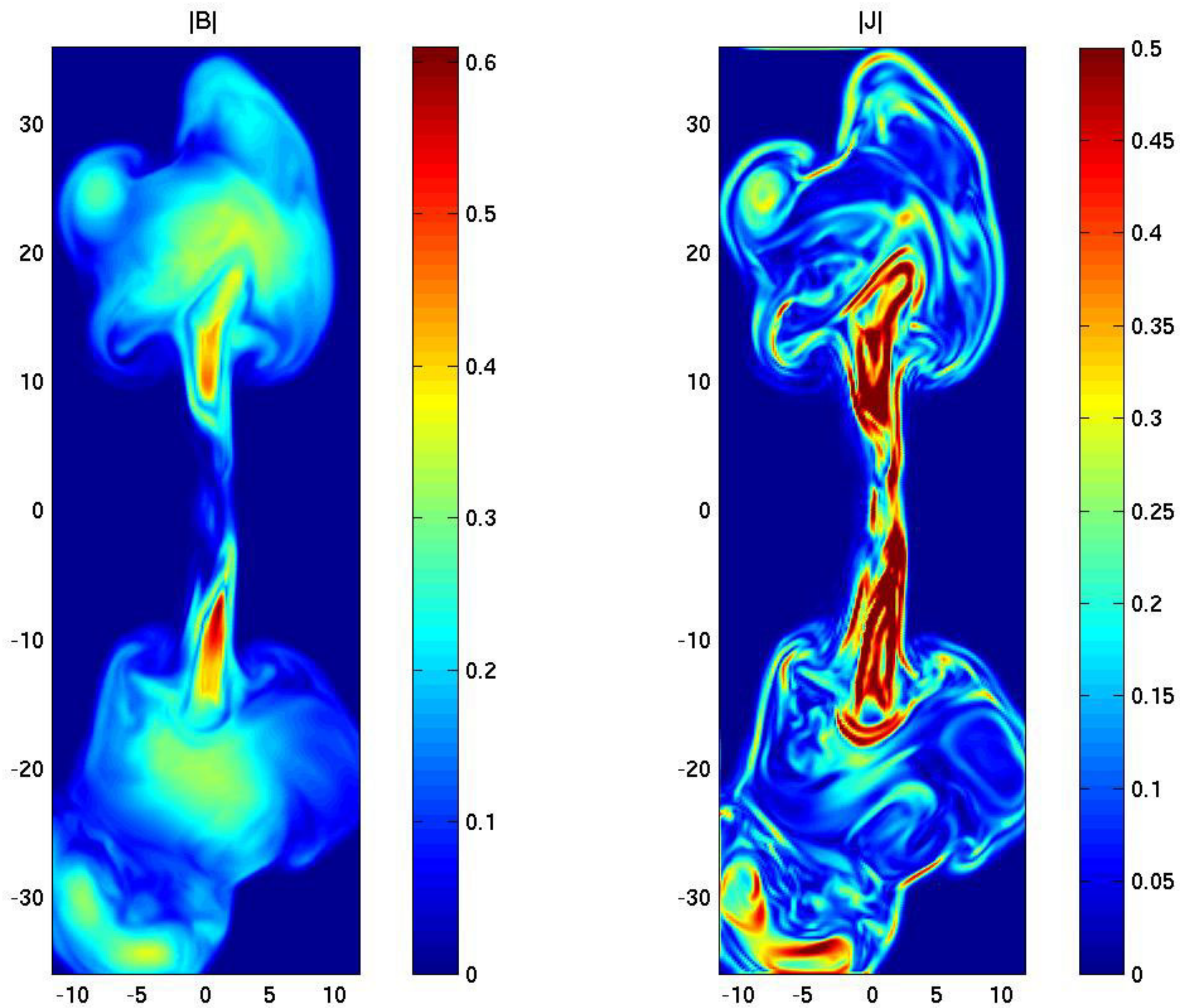
t = 20s



pressure

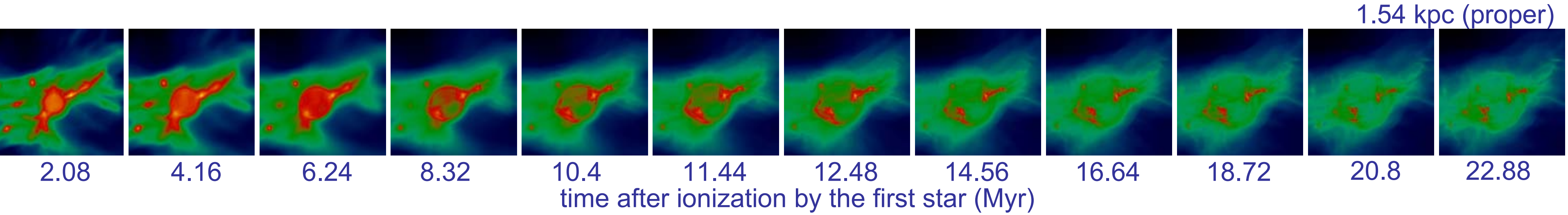
Li & Li (2005)

|B| |J|

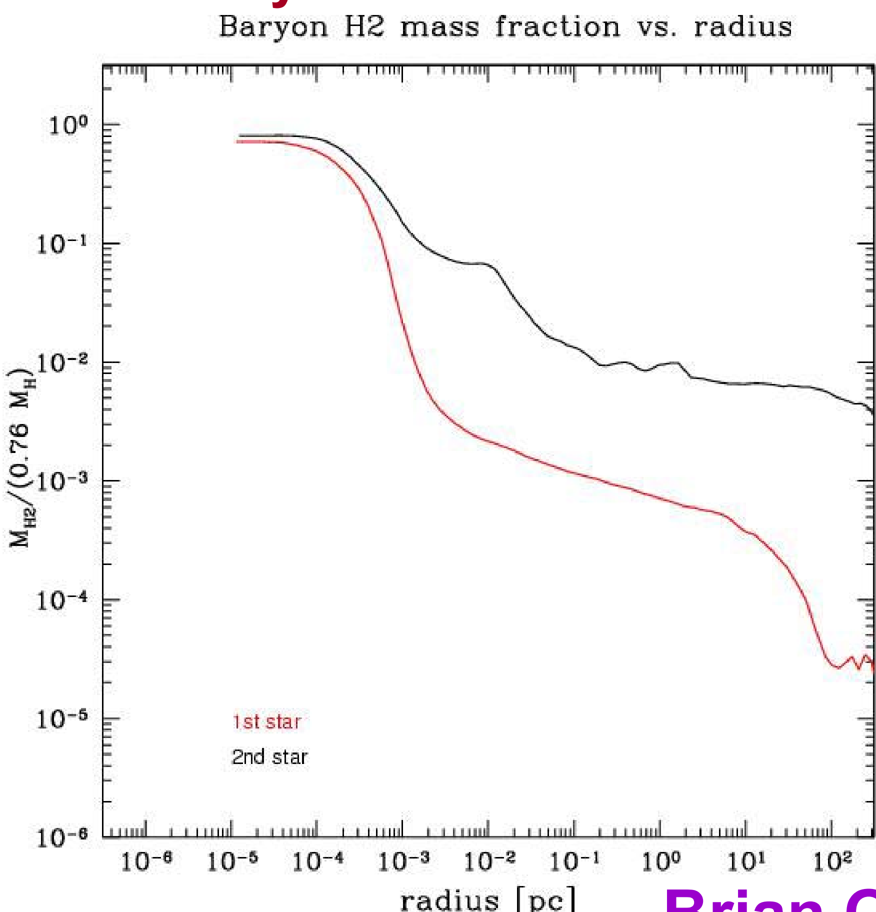


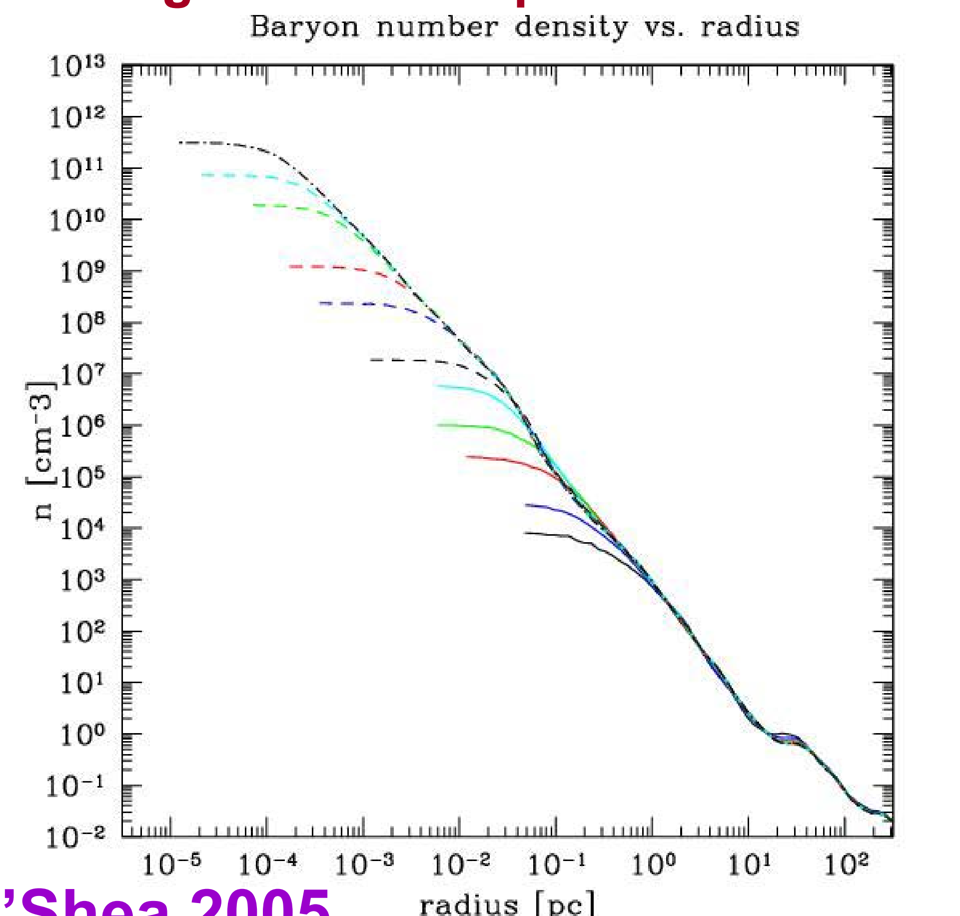
Li & Li (2005)

Formation of the *Second Stars*



Ionization by the first star initiates second generation of primordial stars





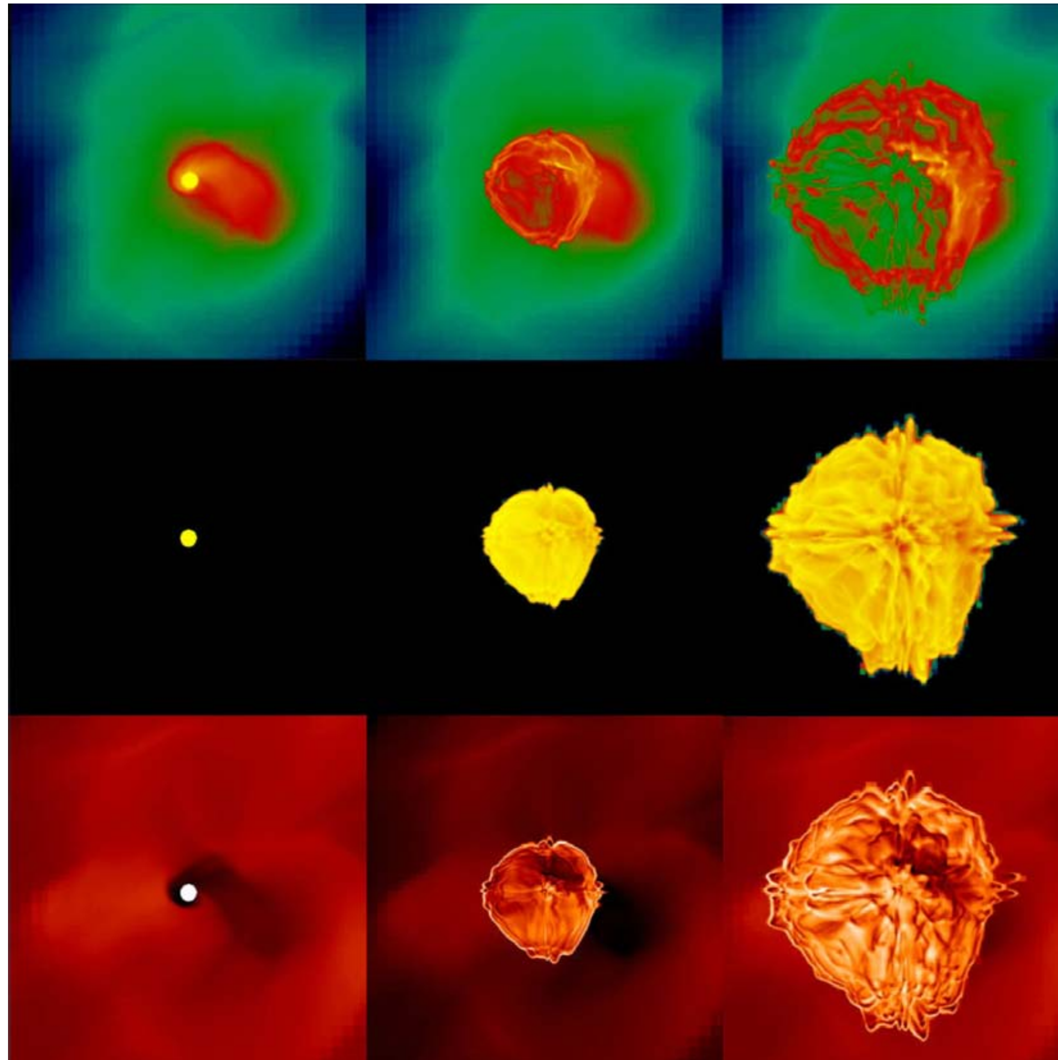
Brian O'Shea 2005

Explosion of 30 $M_\odot$ Pop III Star

gas density

metal density

gas temperature



t=0

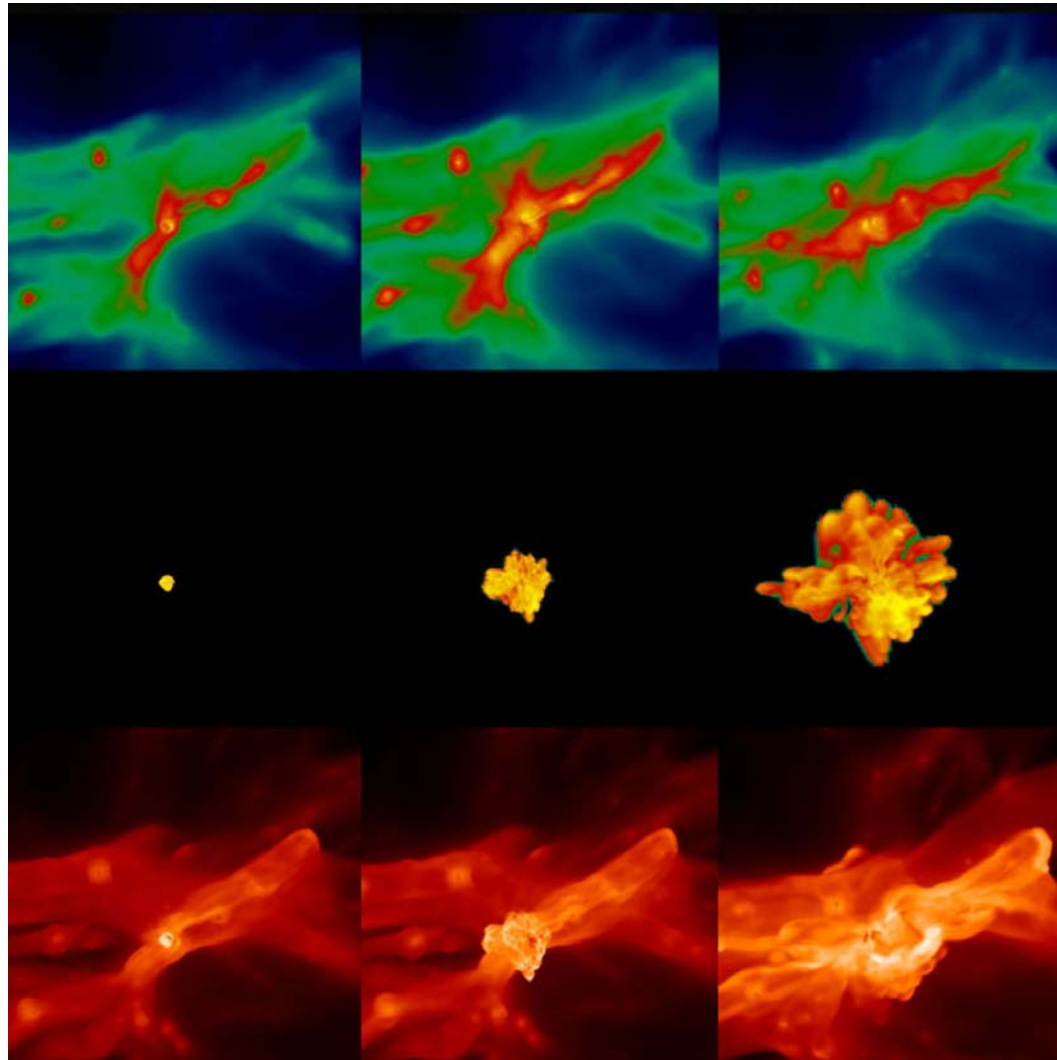
$t=2.7x10^5yr$

$t=5.5x10^5yr$

field of view: 93 pc proper

Brian O'Shea (2005)

Explosion of 30 $M_\odot$ Pop III Star

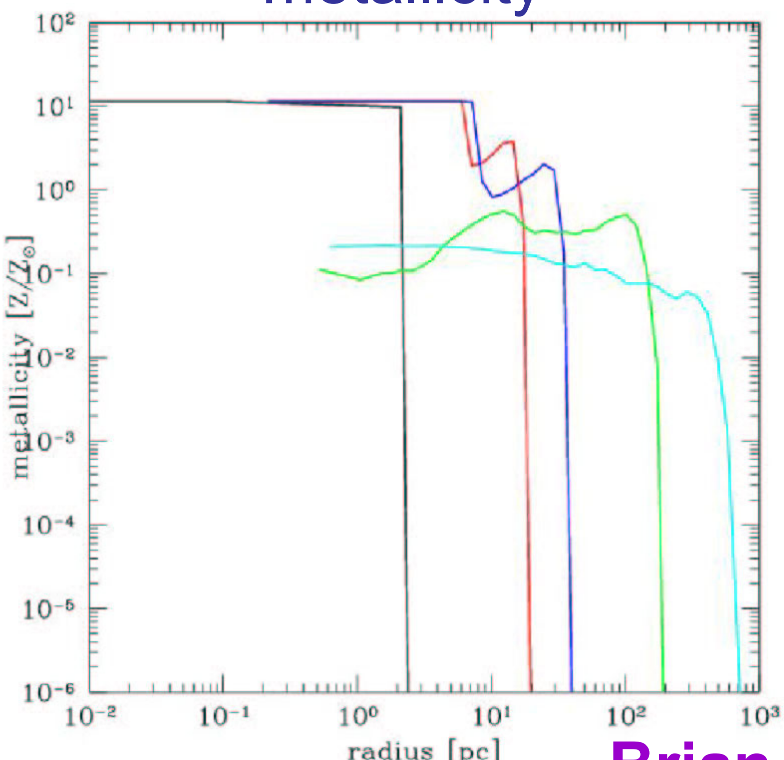


Brian O'Shea (2005)

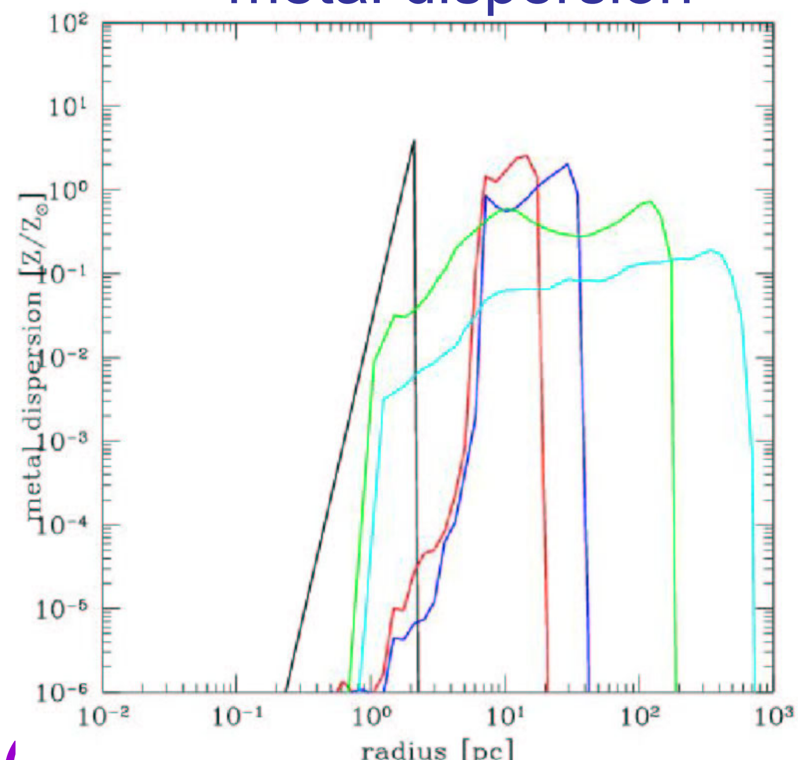
Explosion of 30 $M_\odot$ Pop III Star

- supernova from first star will entirely disrupt parent halo
- gas enriched out to large distance and wide range of metallicities
- enriched gas ends up in later generations of nearby halos

metallicity



metal dispersion



Brian O’Shea ([illegible])

Summary

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

- Even stars of several 100 solar masses might survive (if rotating slowly, no winds, no pulsational instability)
- They can encounter the pair-instability, **but**:
  - strong odd-even effect that has not been observed to date
  - No heavy elements beyond iron group produced
  - No *r*-process, no *s*-process – **not *directly* observed to date**
- Strong odd-even abundance pattern in pair-SNe

➔ No compelling observational evidence for $M \gtrsim 140\ M_\odot$ stars

Need to understand

- **IMF of primordial star formation**
- **Dispersion of metals in the early universe**
  - **Where did the ashes of the first stars go?**
  - **Where were currently found UMP stars made?**