Nucleosynthesis and Chemical Evolution, INT, UW, Seattle, USA, August 18, 2014

Supernovae from the First Stars and the Abundance Patterns of Metal-Poor Stars

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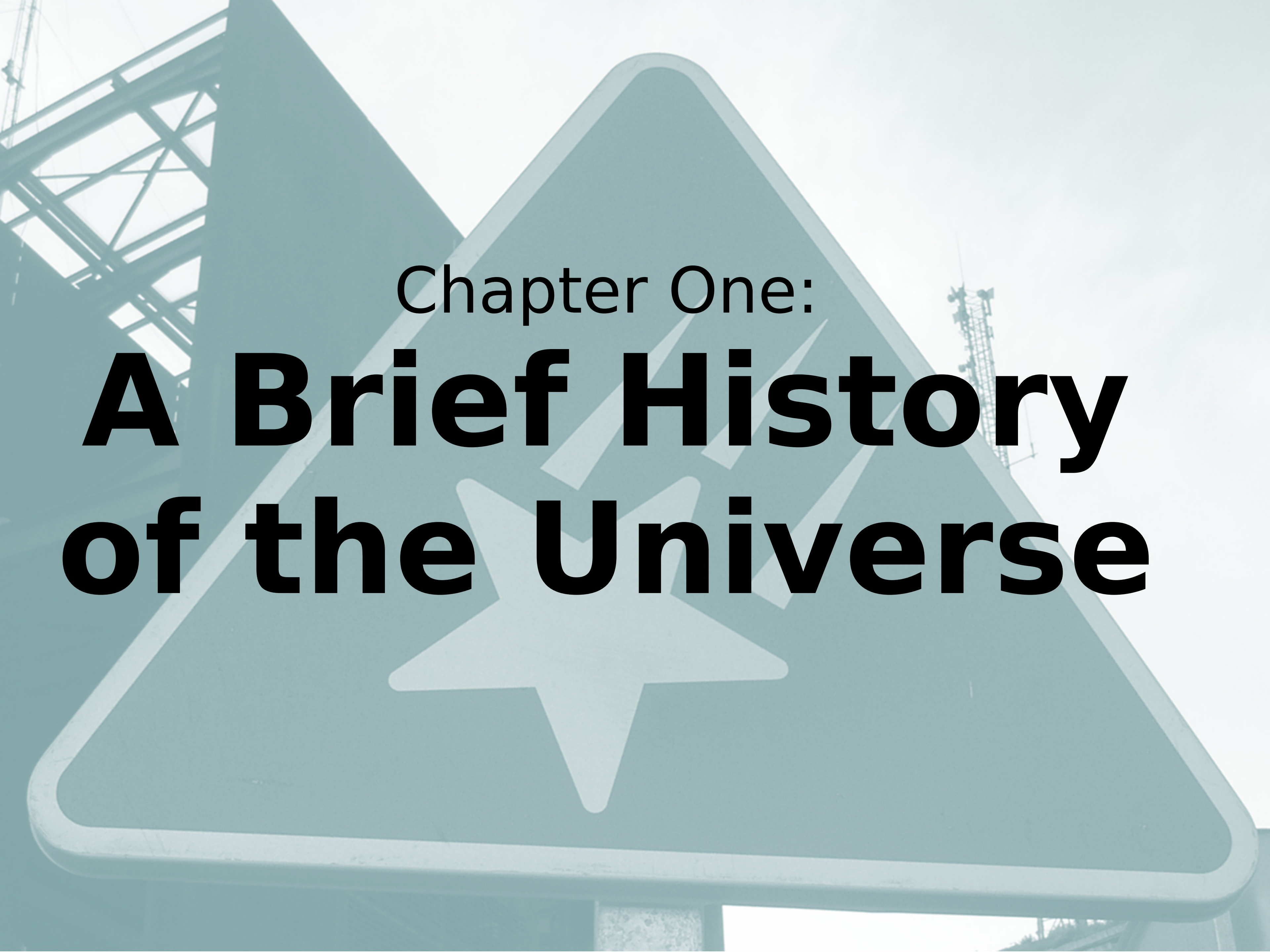
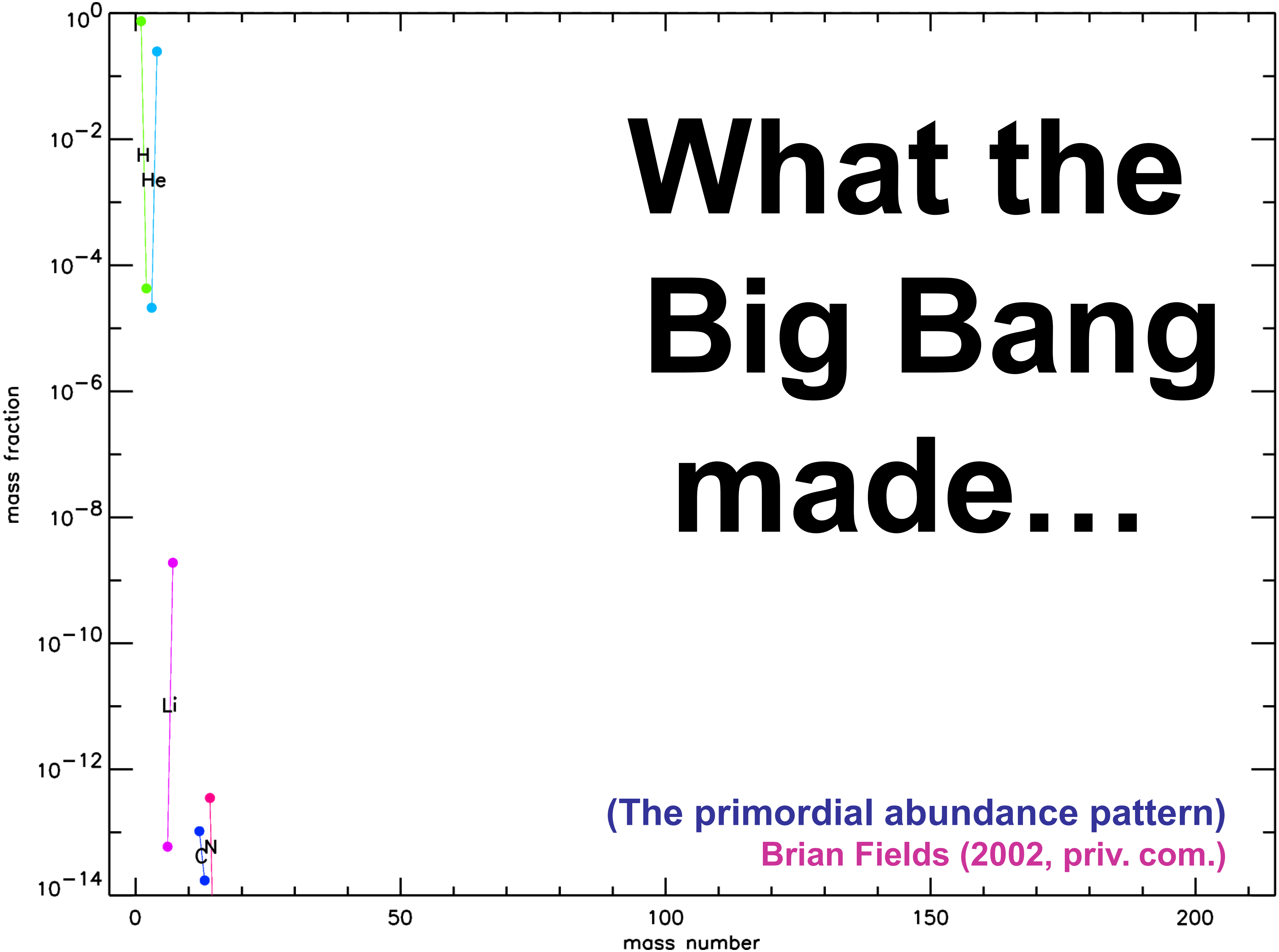
Overview

- Stellar Burning and Nucleosynthesis
- Pair Instability Supernovae
- Yields from Massive Stars
- Yields from Multiple Stars



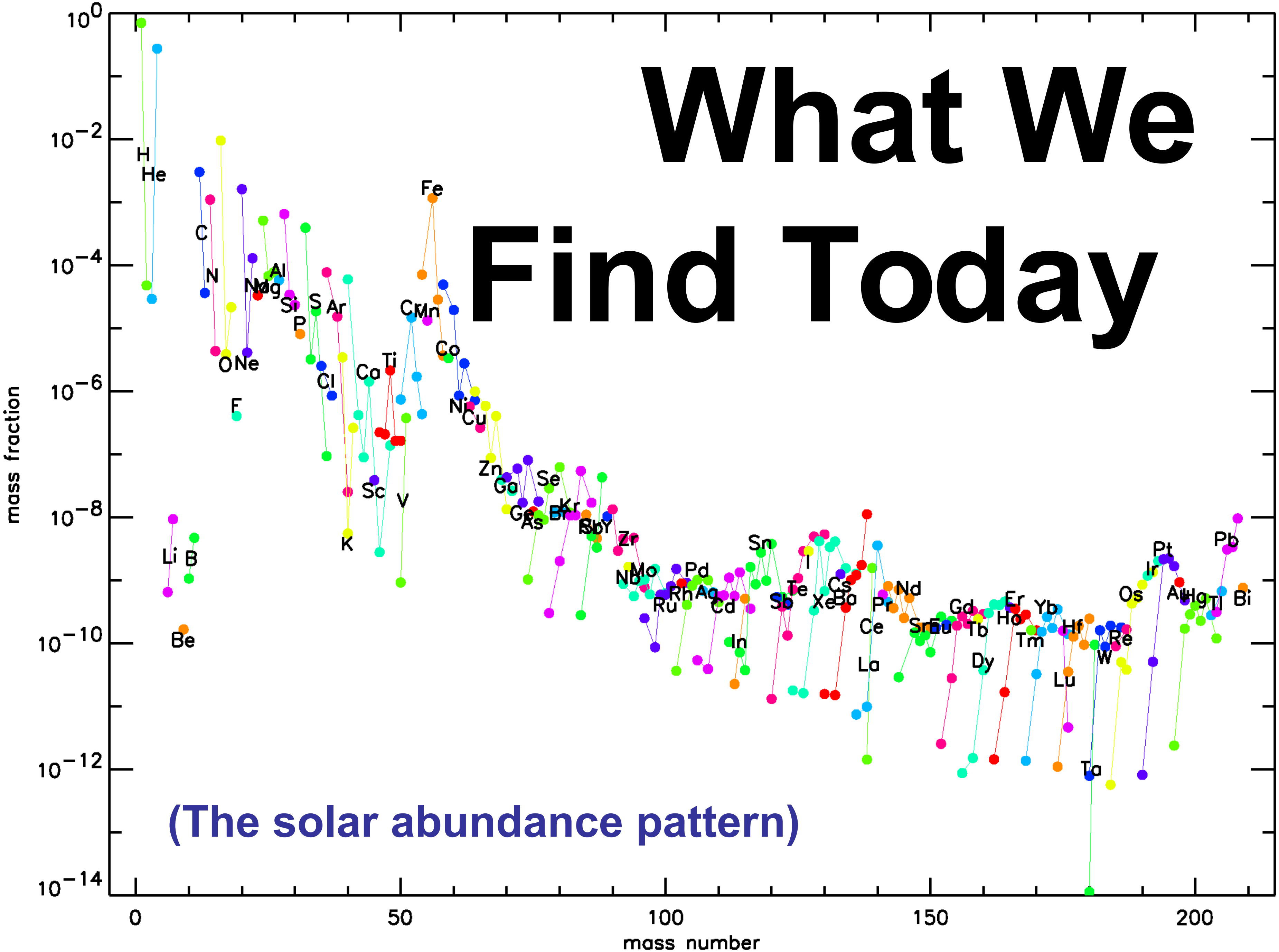
Chapter One:

A Brief History of the Universe



What the Big Bang made...
(The primordial abundance pattern)
Brian Fields (2002, priv. com.)
mass fraction
mass number
H
He
Li
C
N
0
50
100
150
200
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}

What We Find Today

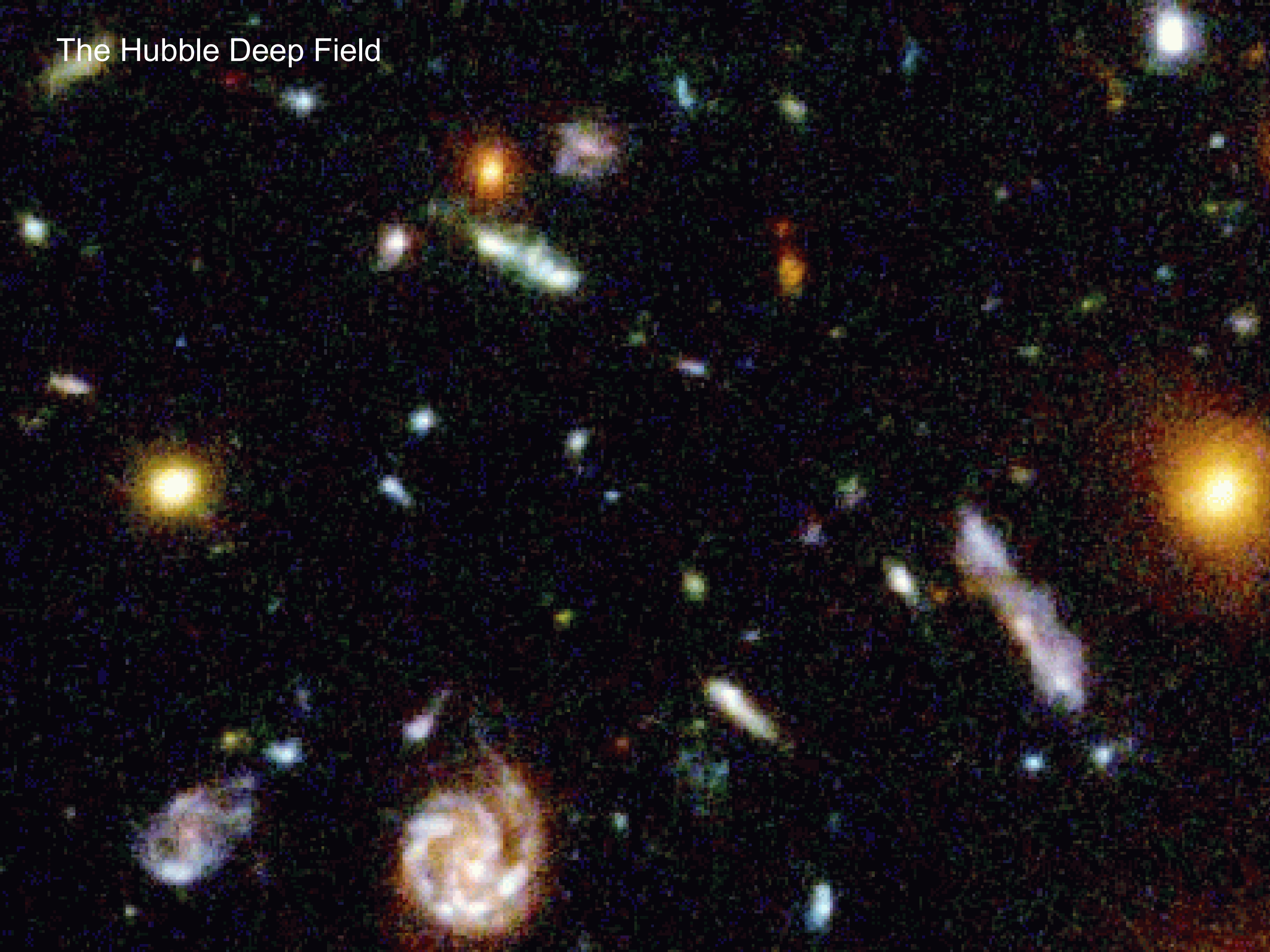


(The solar abundance pattern)

The Cosmic Dark Age

(Alexander Heger 2013)

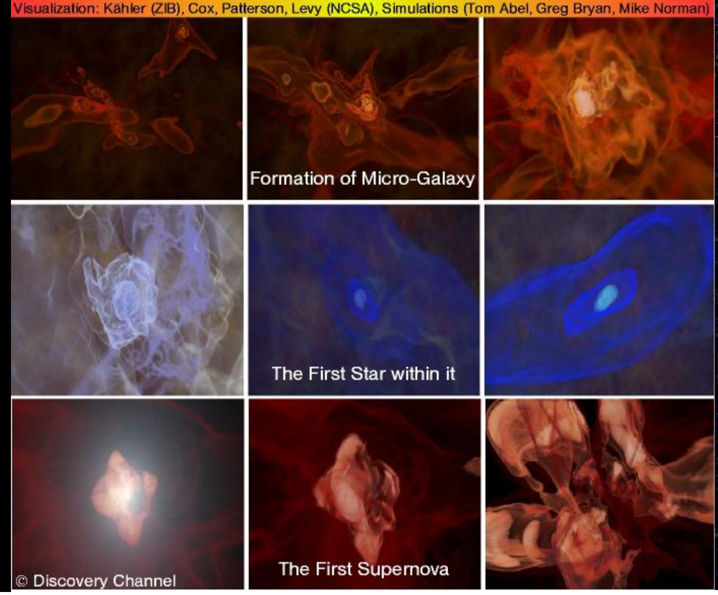
Visualization: Kähler (ZIB), Cox, Patterson, Levy (NCSA), Simulations (Tom Abel, Greg Bryan, Mike Norman)

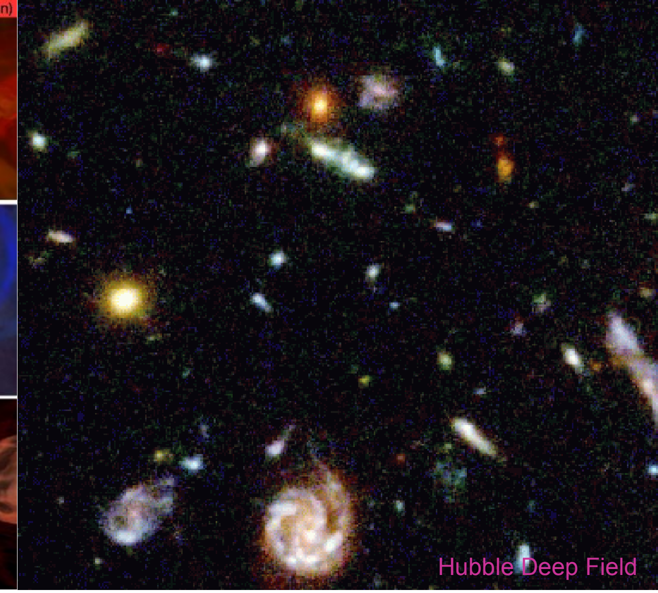

The Hubble Deep Field

Cosmic Dark Age

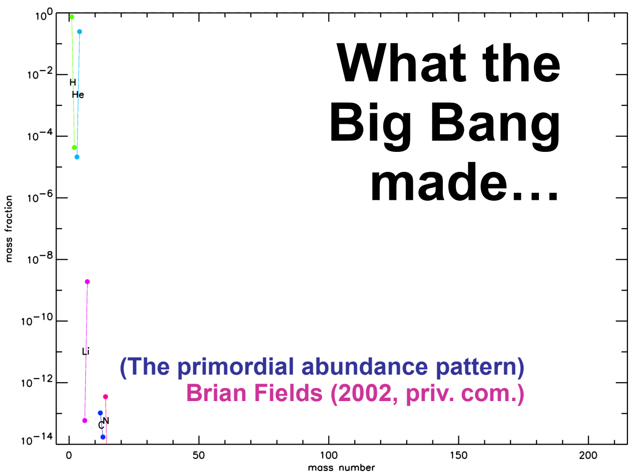
(after recombination)

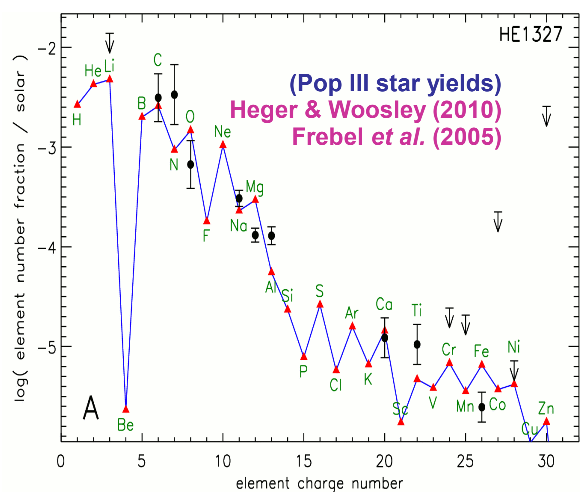
© Alexander Heger

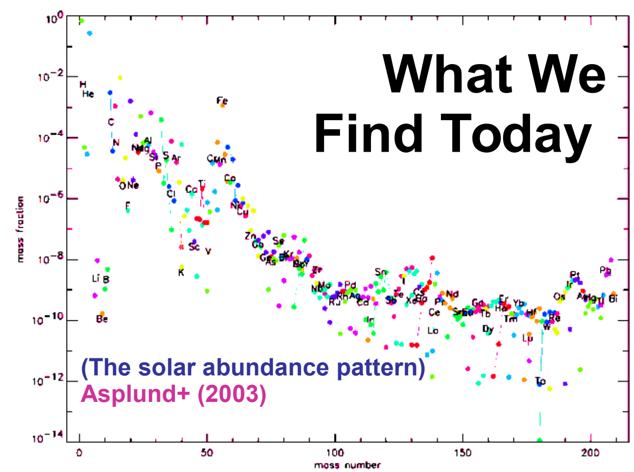




time







Setting the Stage:

Stellar Evolution

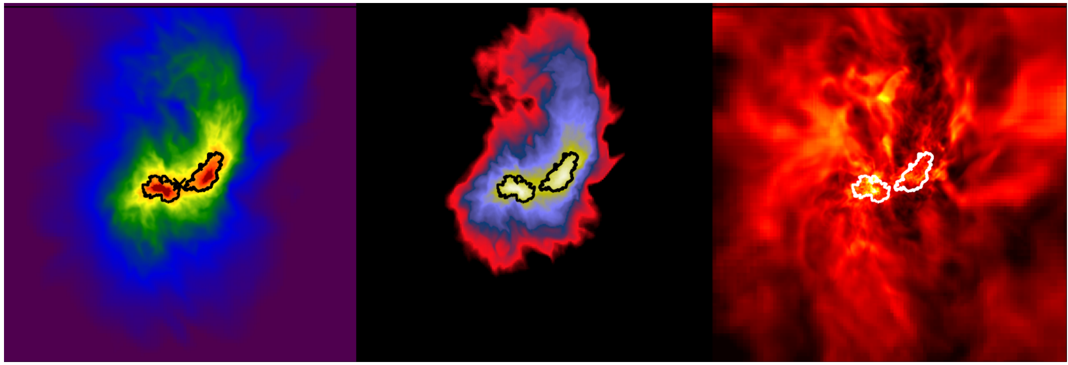
Formation and Mass of the First Stars

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,...)

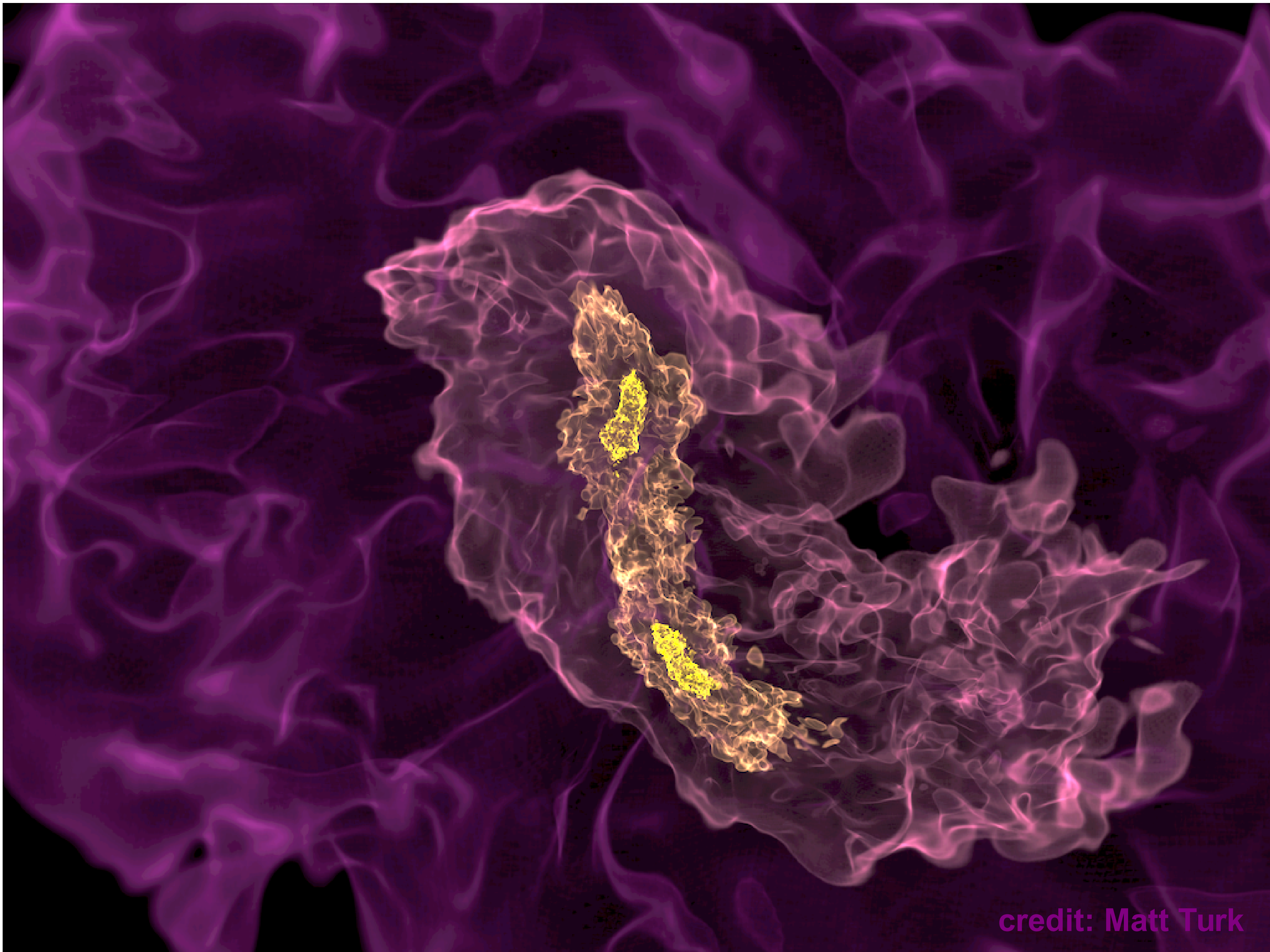
➔ typical mass scale ~10...300 $M_{\odot}$?

- ***Newer*** simulations indicate binaries may exist

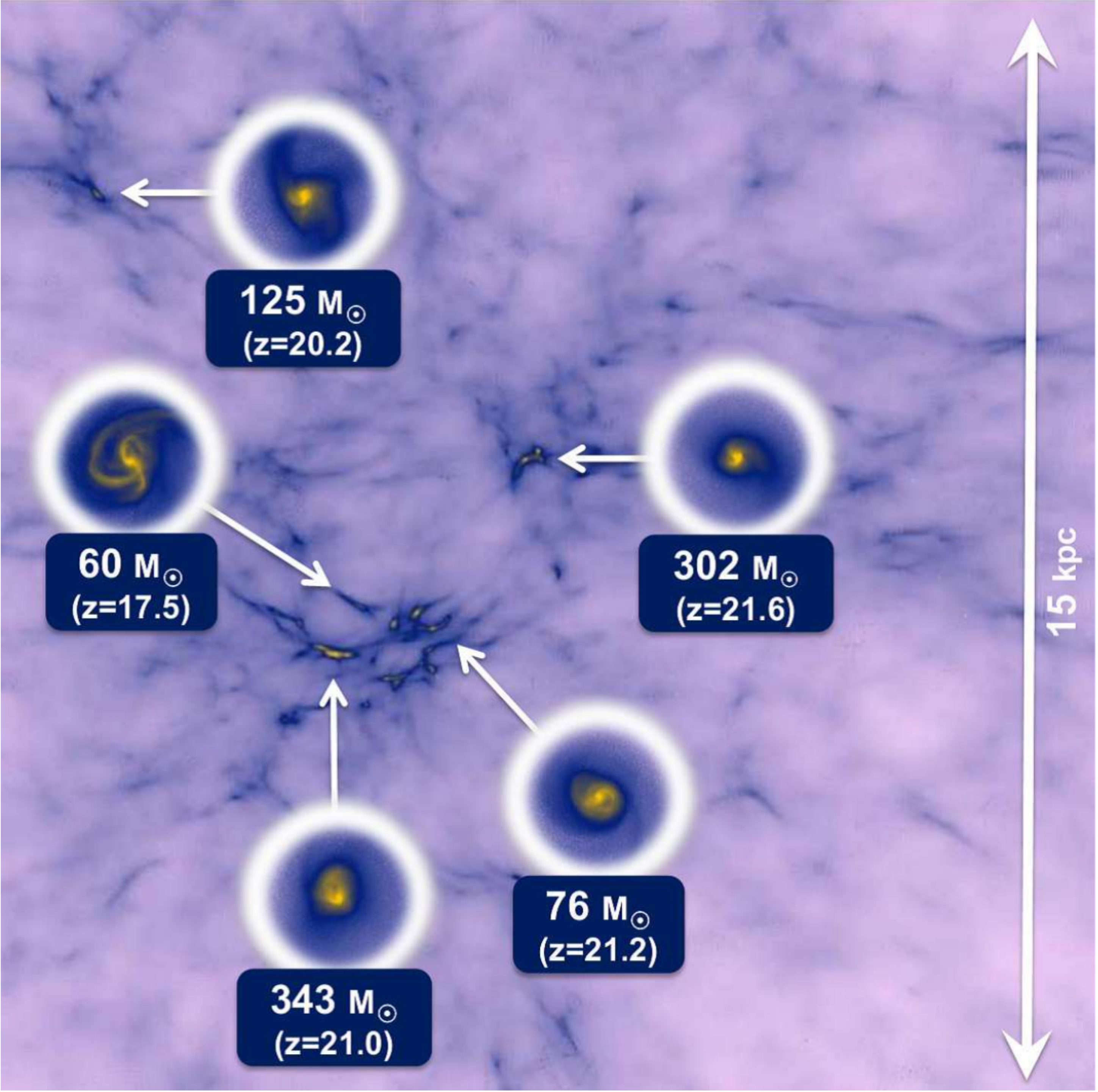


(Turk, Abel, O'Shea 2010)

- **But ...**
  We still don't have a really strong constrain on Pop III star masses in general

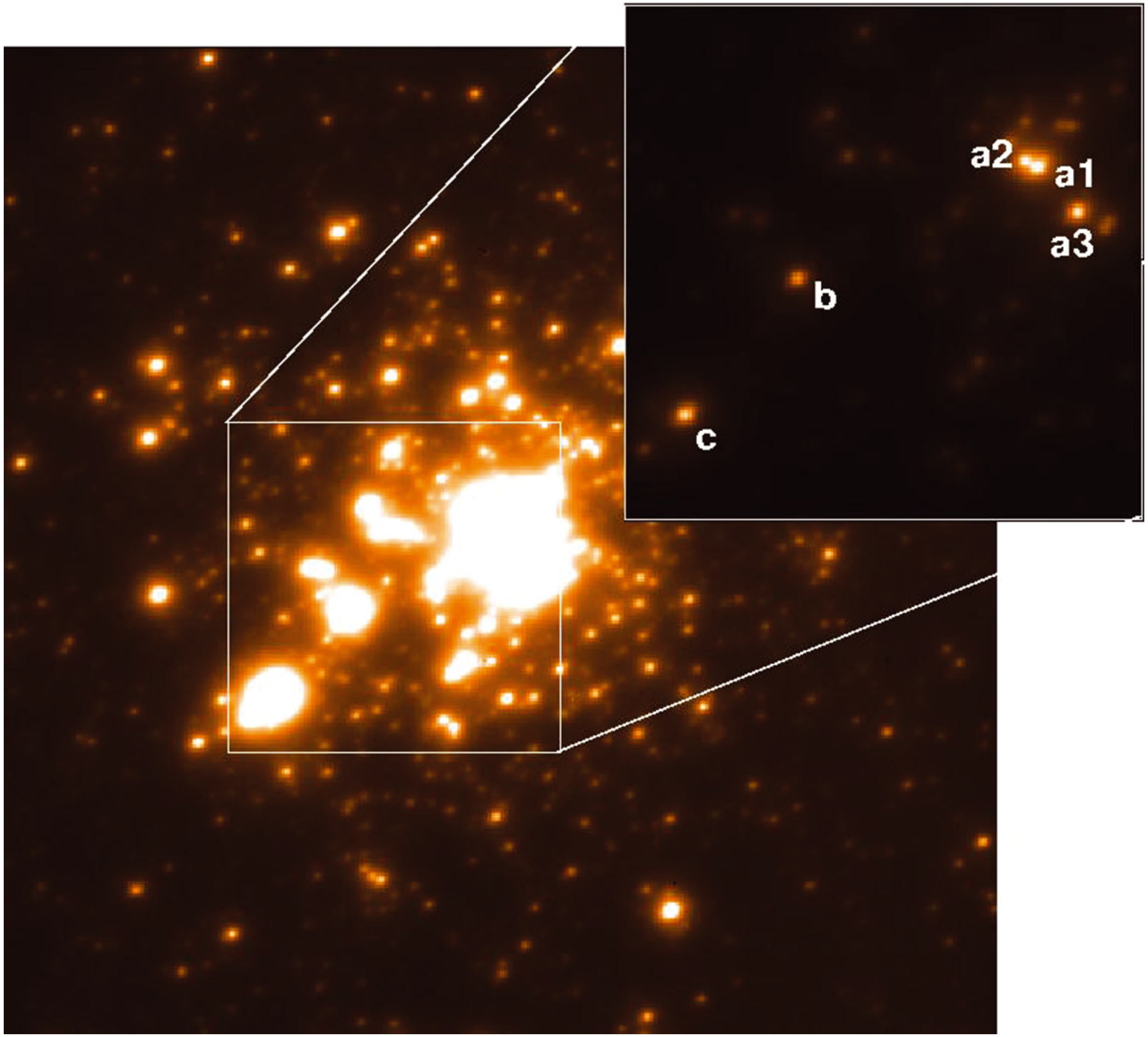

credit: Matt Turk

Formation Environment of the First Stars



(Hirano et al. 2013)

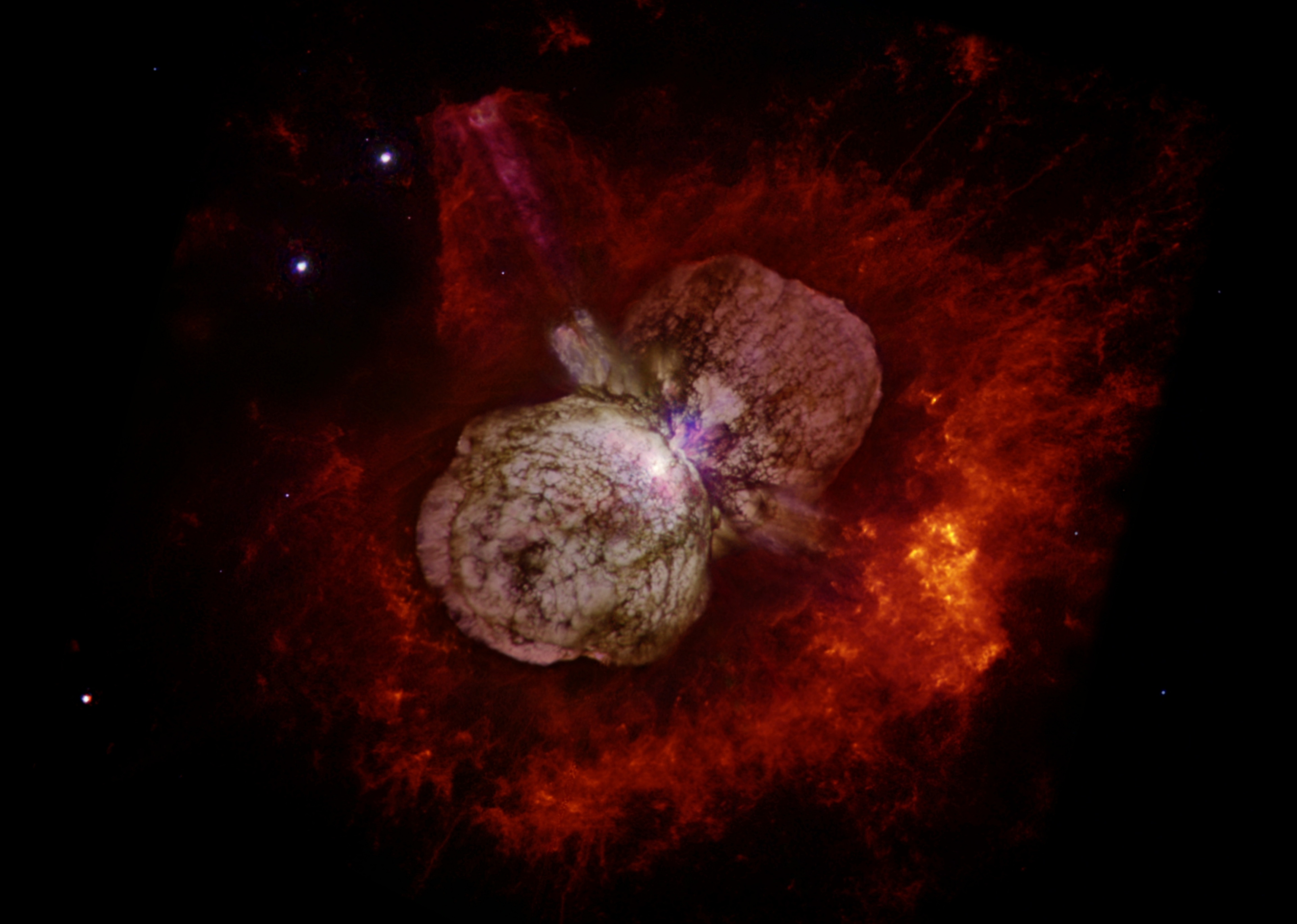
The Most Massive Stars Today



R136

- young massive star cluster
- Age around 1.5 Myr
- Star "a1": maybe 200 $M_\odot$ initial mass

(Crother et al. 2010)

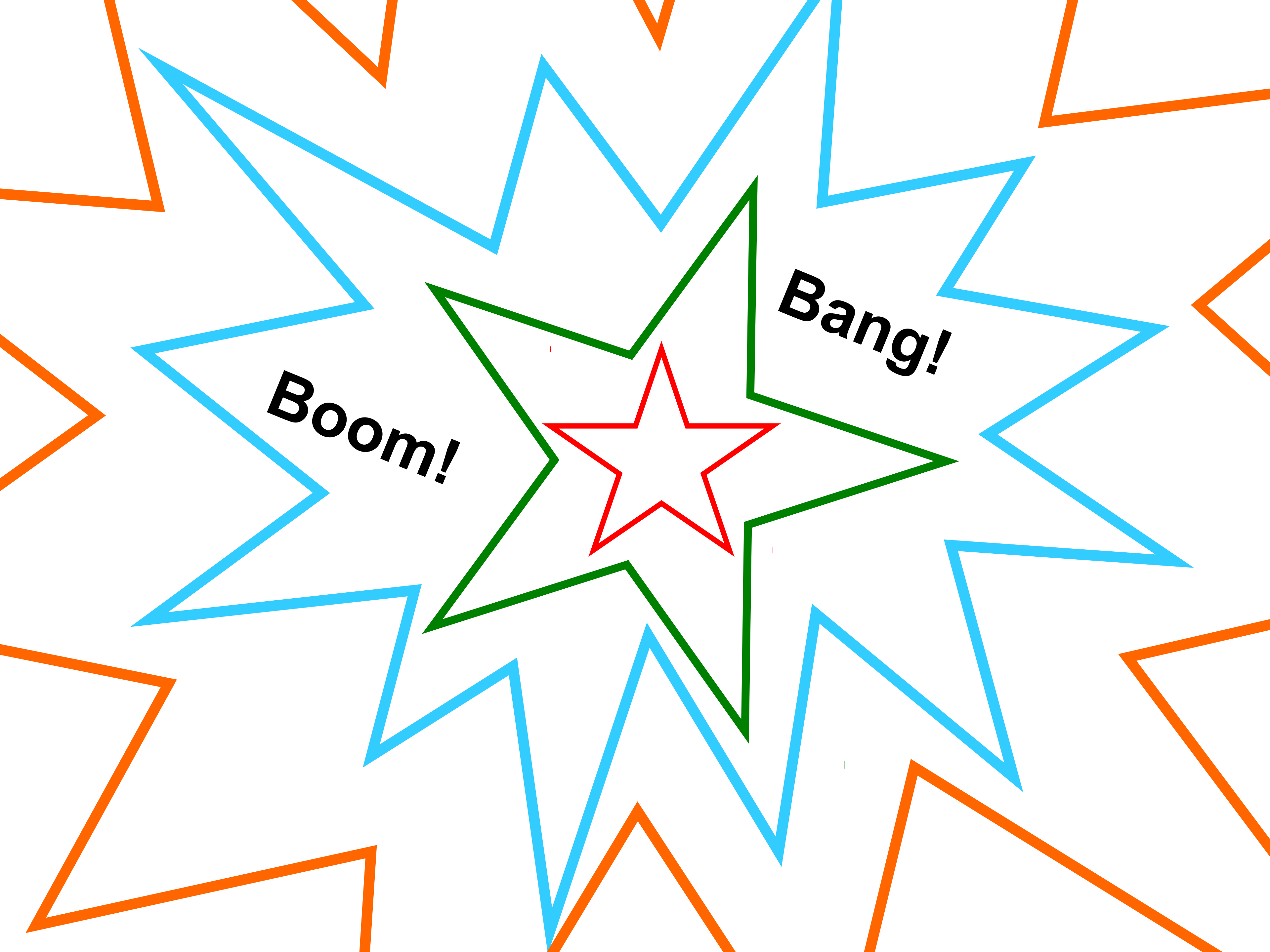


Eta Car – a really big star in our galaxy today

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}


The
Death
of the
Stars


Boom!
Bang!

Explosive Nucleosynthesis

in supernovae from massive stars

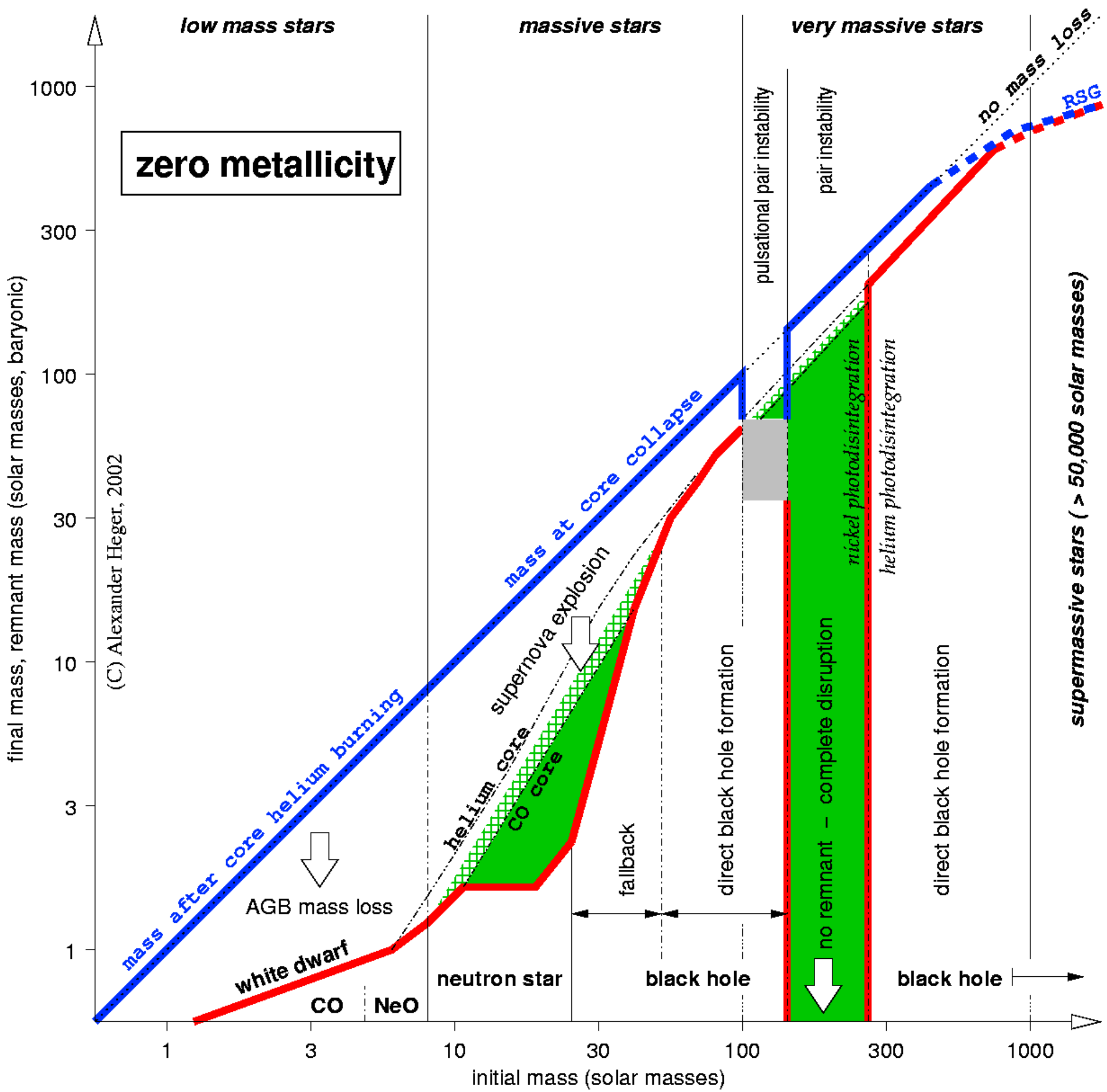
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process *νp*-process	-	>10?	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	^{16}O + ^{16}O
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Taxonomy of Massive Stars

MASS

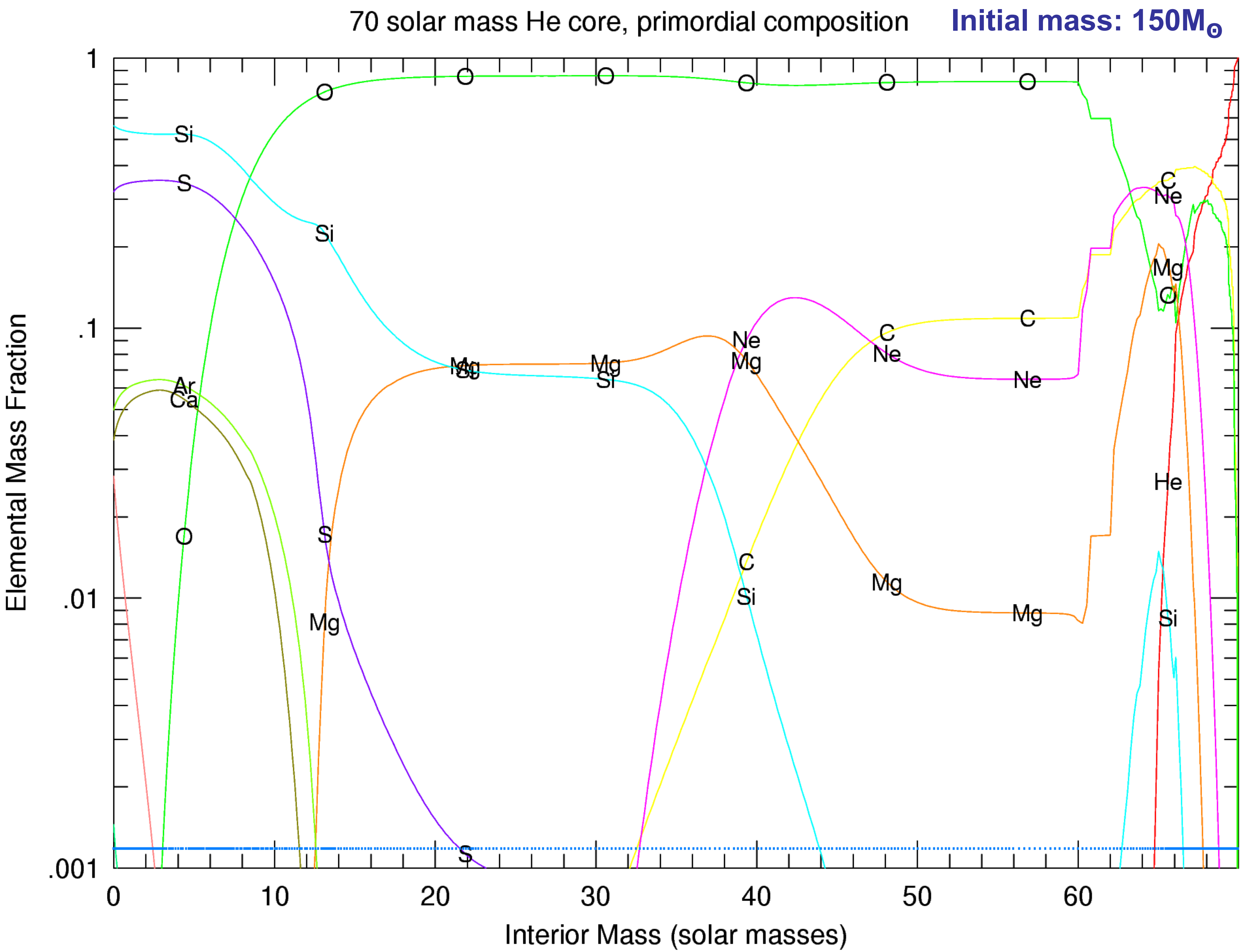
- AGB/SAGB/ECSN
- Off-center Si burning
- Off-center Ne/O burning
- Off-center C burning
- “normal” massive stars
- Pulsational pair SNe
- Pair SNe
- Direct Collapse to Black Hole
- Extremely Massive Stars
- Ultramassive Stars
- Supermassive Stars

massive stars

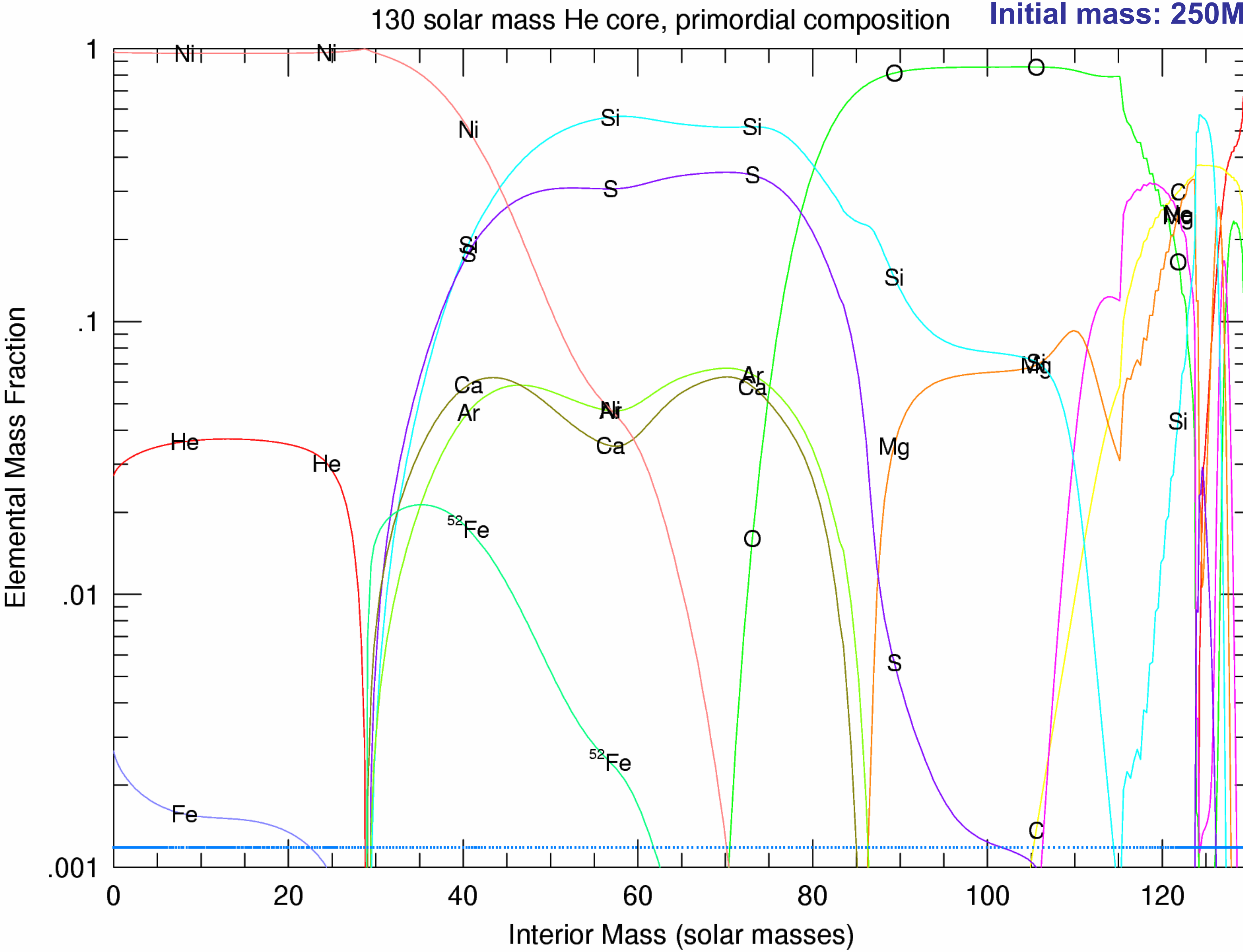


Ejected “metals”

Nucleosynthesis in Pair-Instability Supernovae

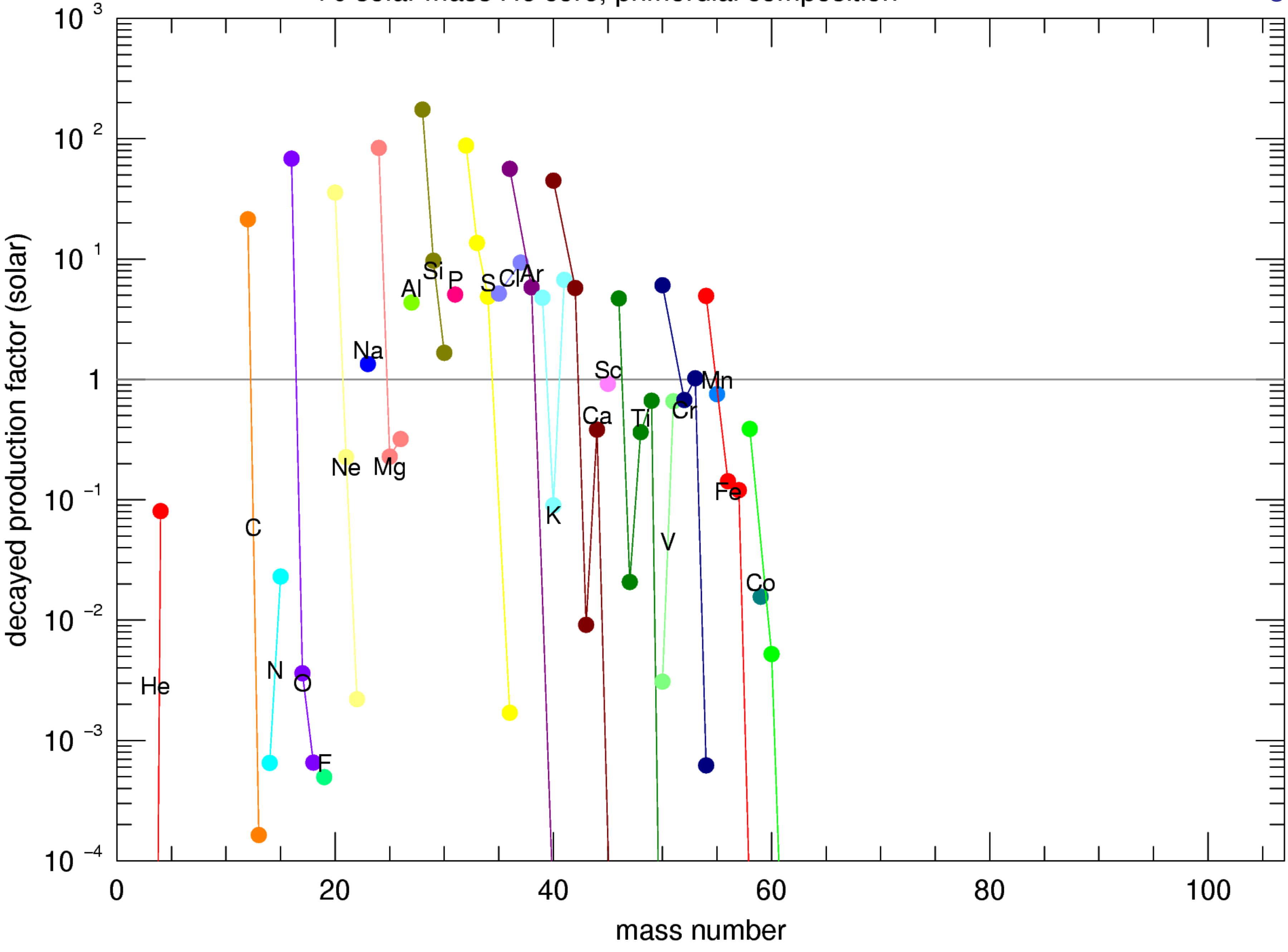

70 solar mass He core, primordial composition
Initial mass: 150M$_\odot$
Elemental Mass Fraction
Interior Mass (solar masses)
1
.1
.01
.001
0
10
20
30
40
50
60
Si
S
O
Ar
Ca
Mg
Ne
C
He

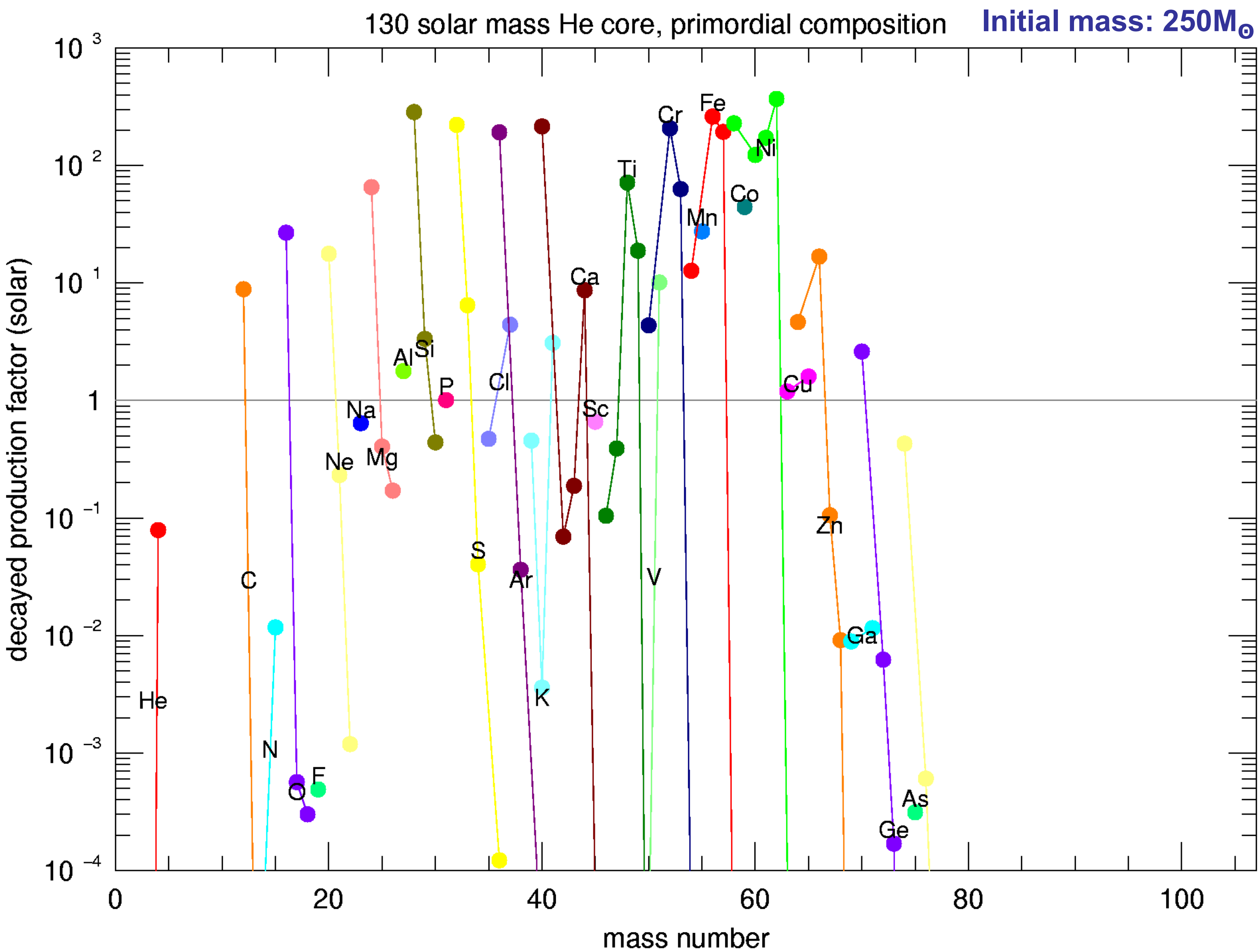
Initial mass: 250$M_\odot$

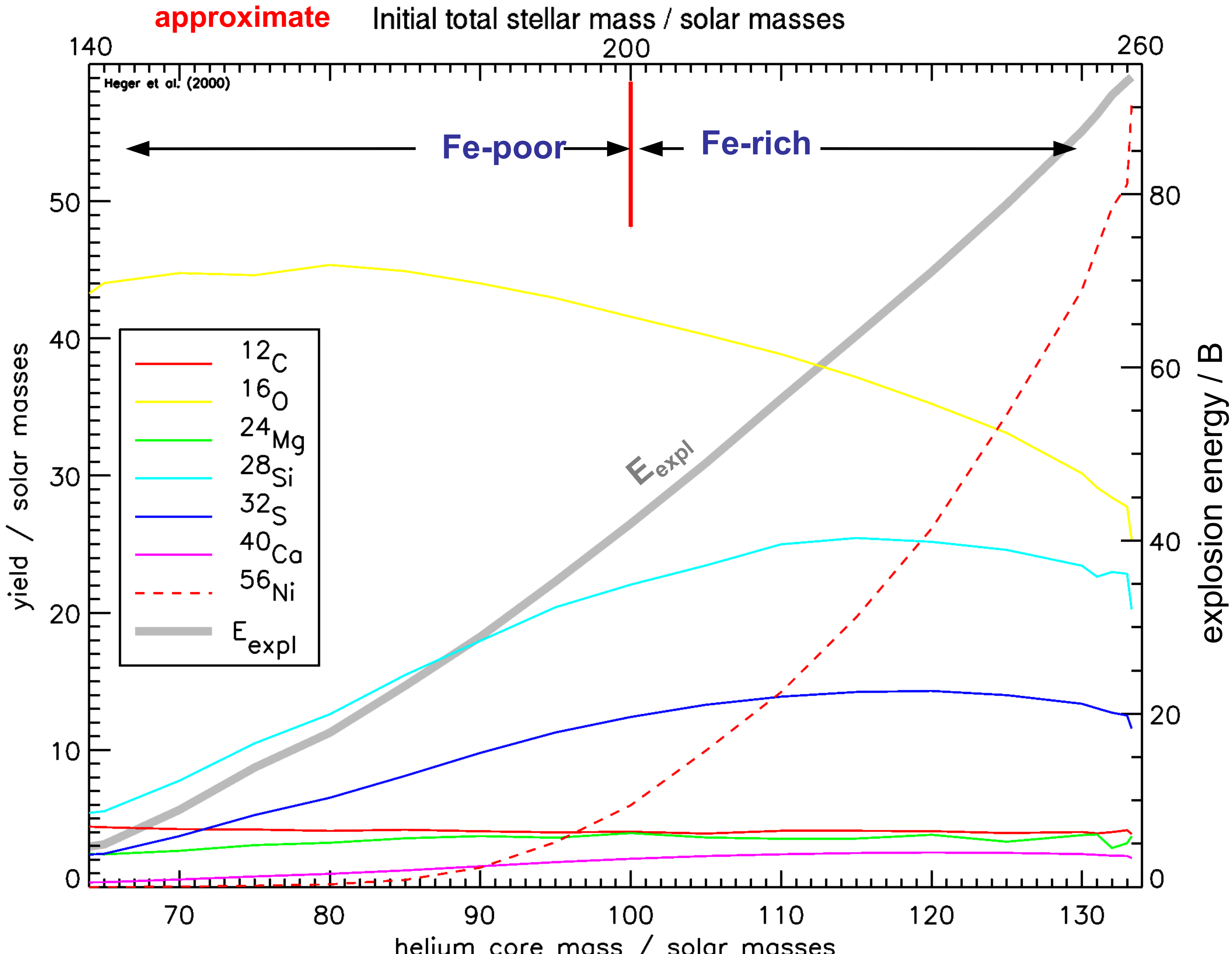


70 solar mass He core, primordial composition

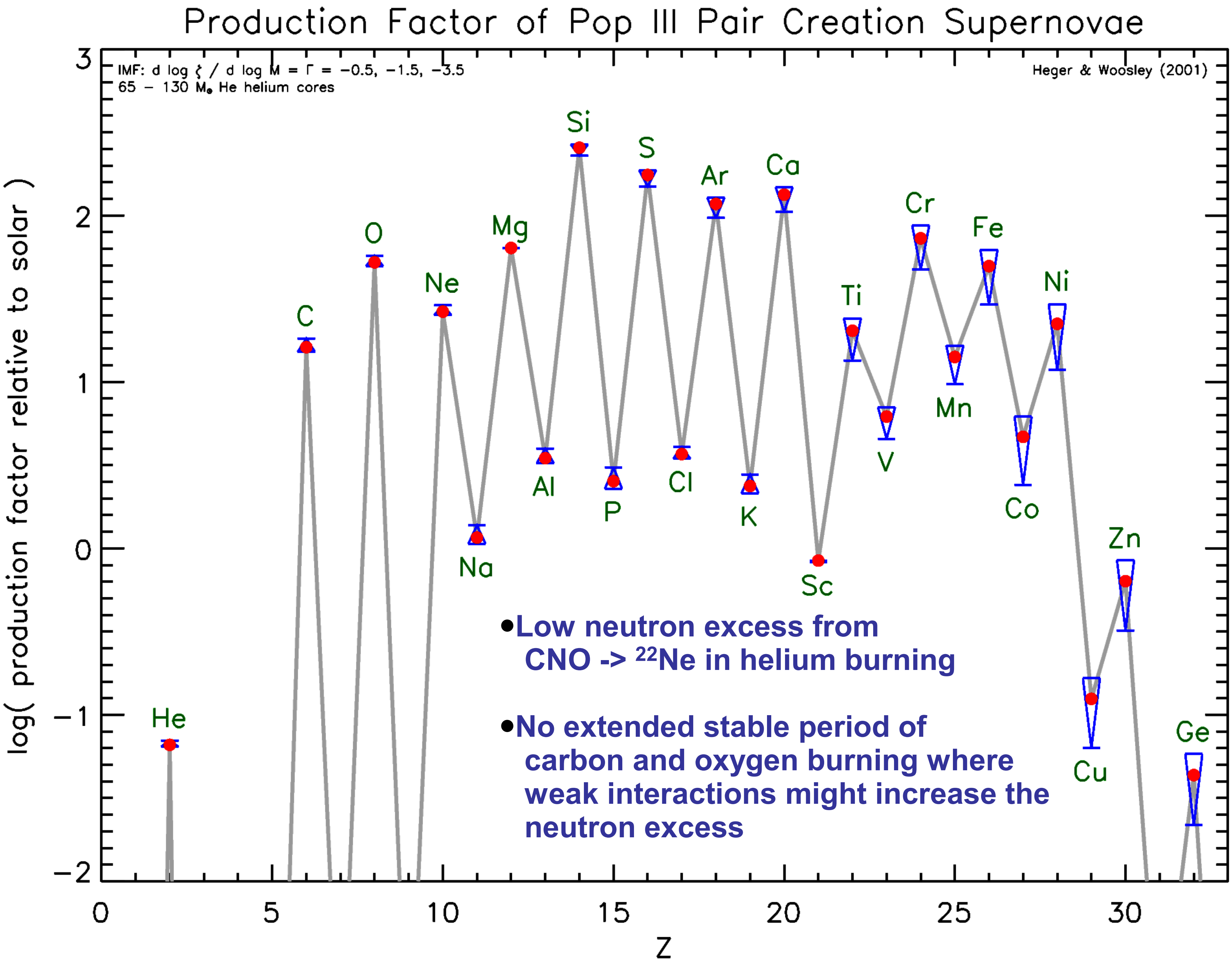
Initial mass: 150M$_\odot$




130 solar mass He core, primordial composition
Initial mass: 250M☉
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
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

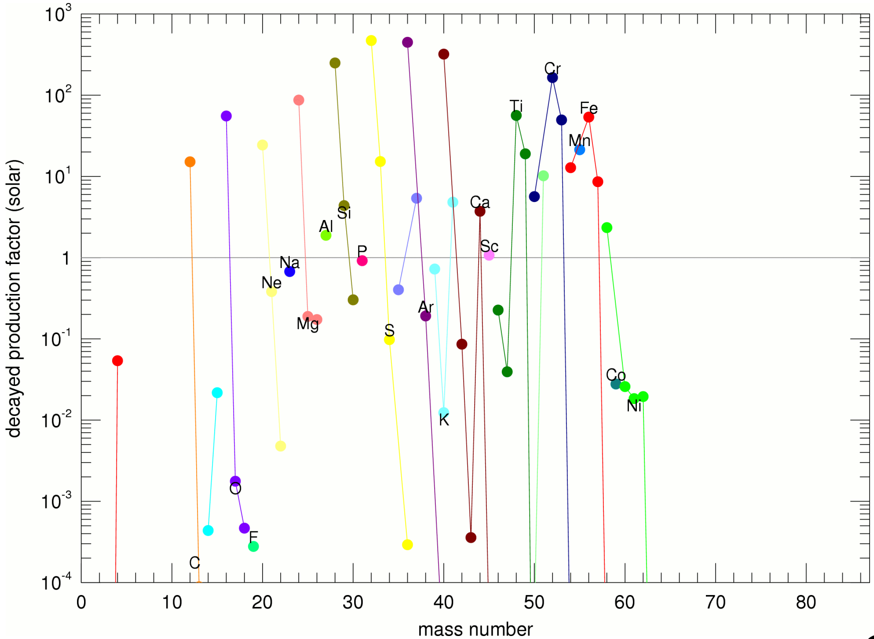


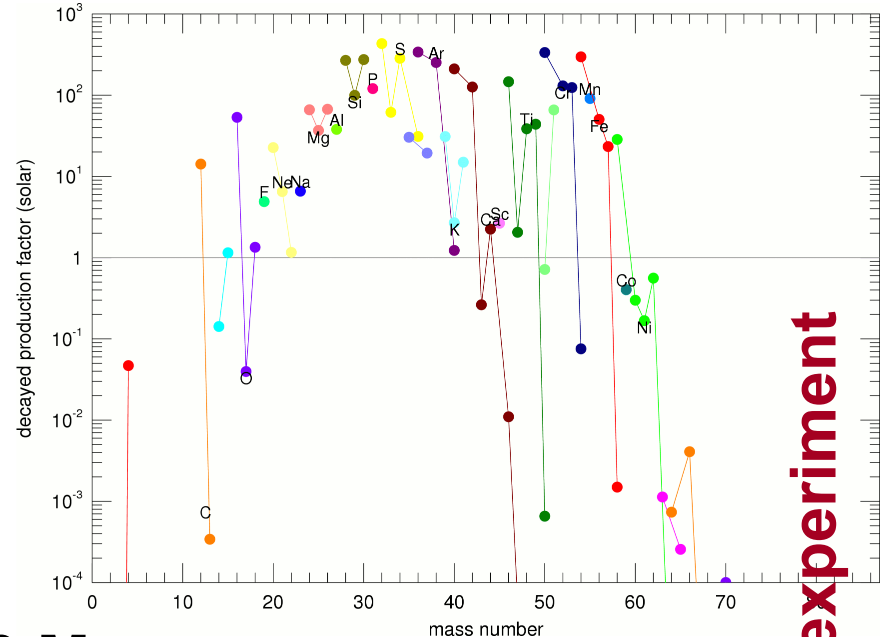
approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E expl
12C
16O
24Mg
28Si
32S
40Ca
56Ni
E expl
yield / solar masses
explosion energy / B
0
10
20
30
40
50
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses


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
•Low neutron excess from CNO -> ^{22}Ne 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!

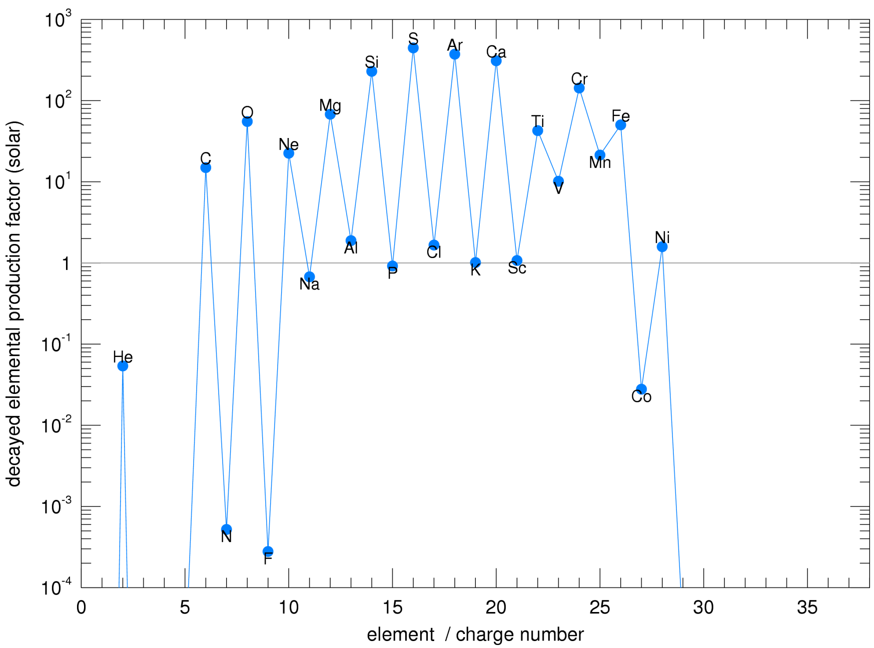


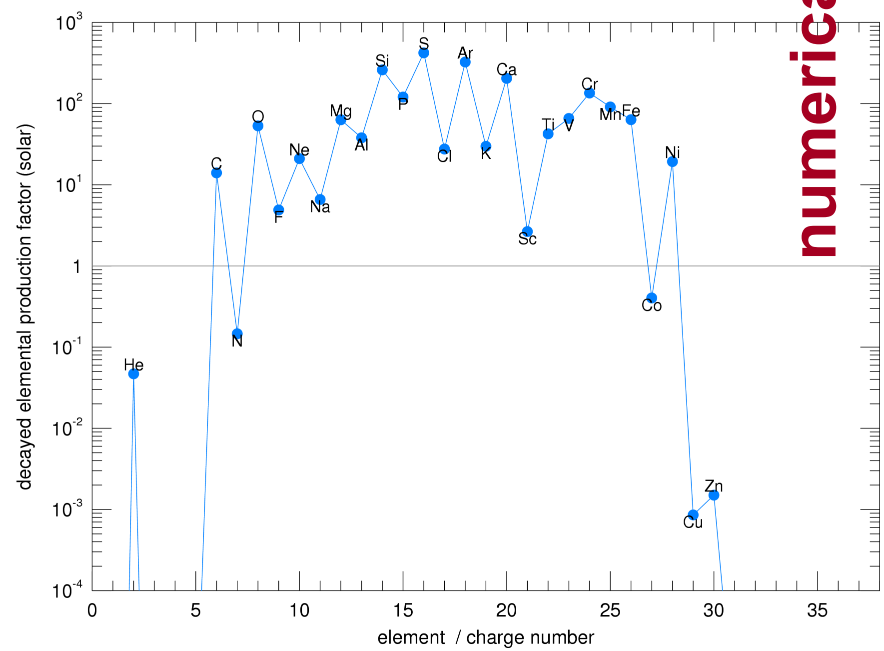


200 $M_\odot$

Z=0

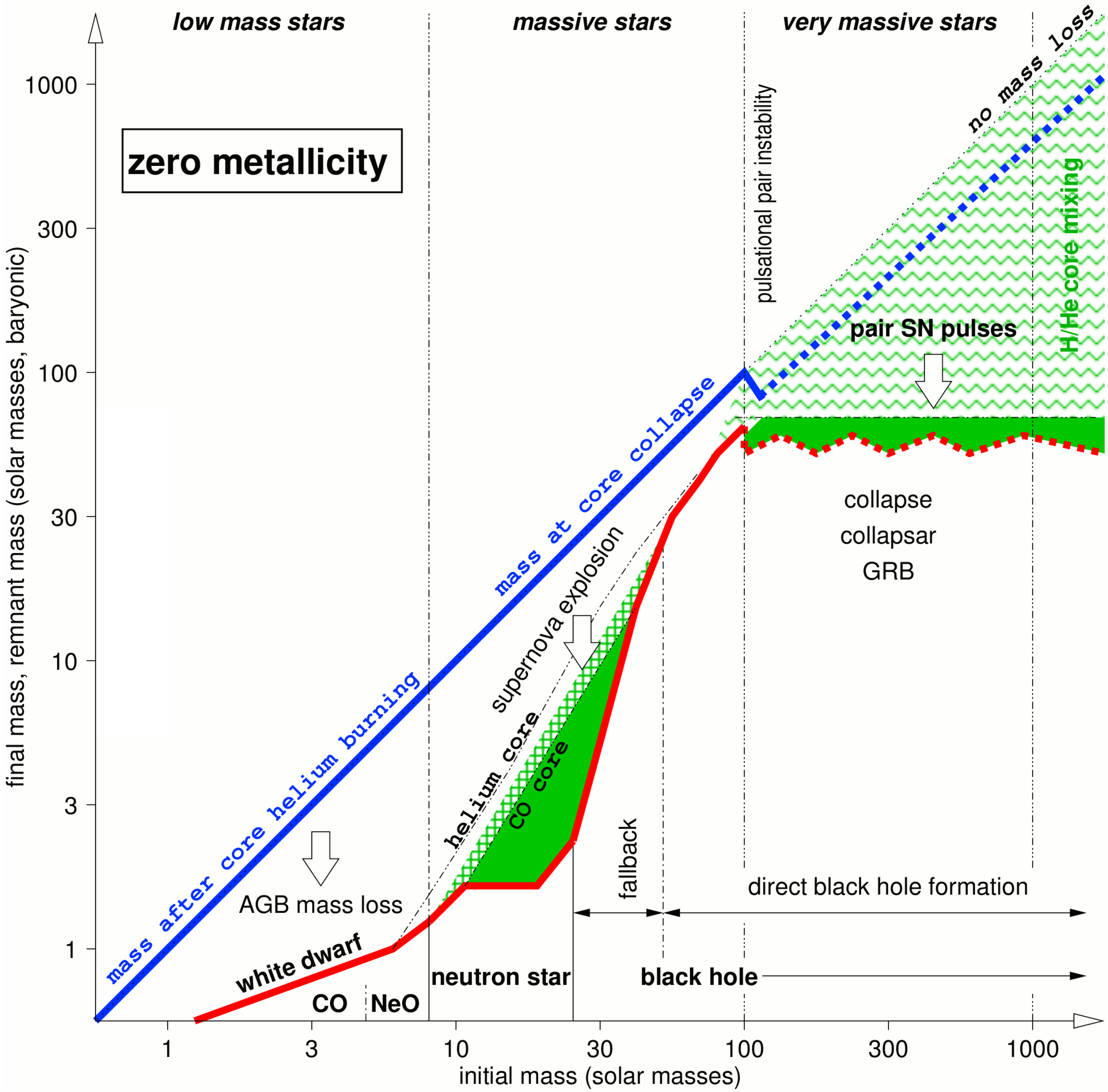
Z=0 + 2% ^{14}N



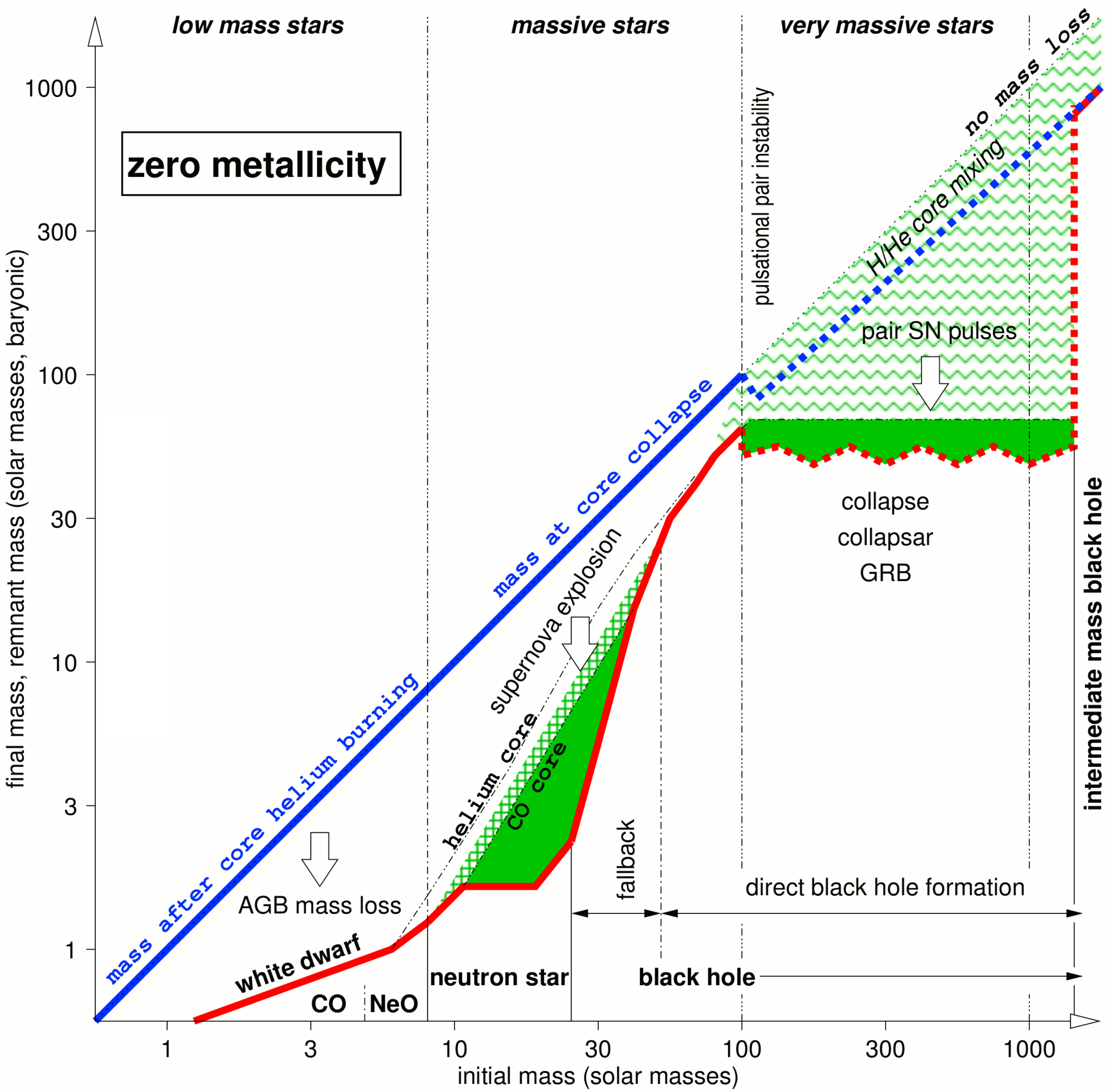


numerical experiment

Pulsational Pair SN Scenario I



Pulsational Pair SN Scenario II



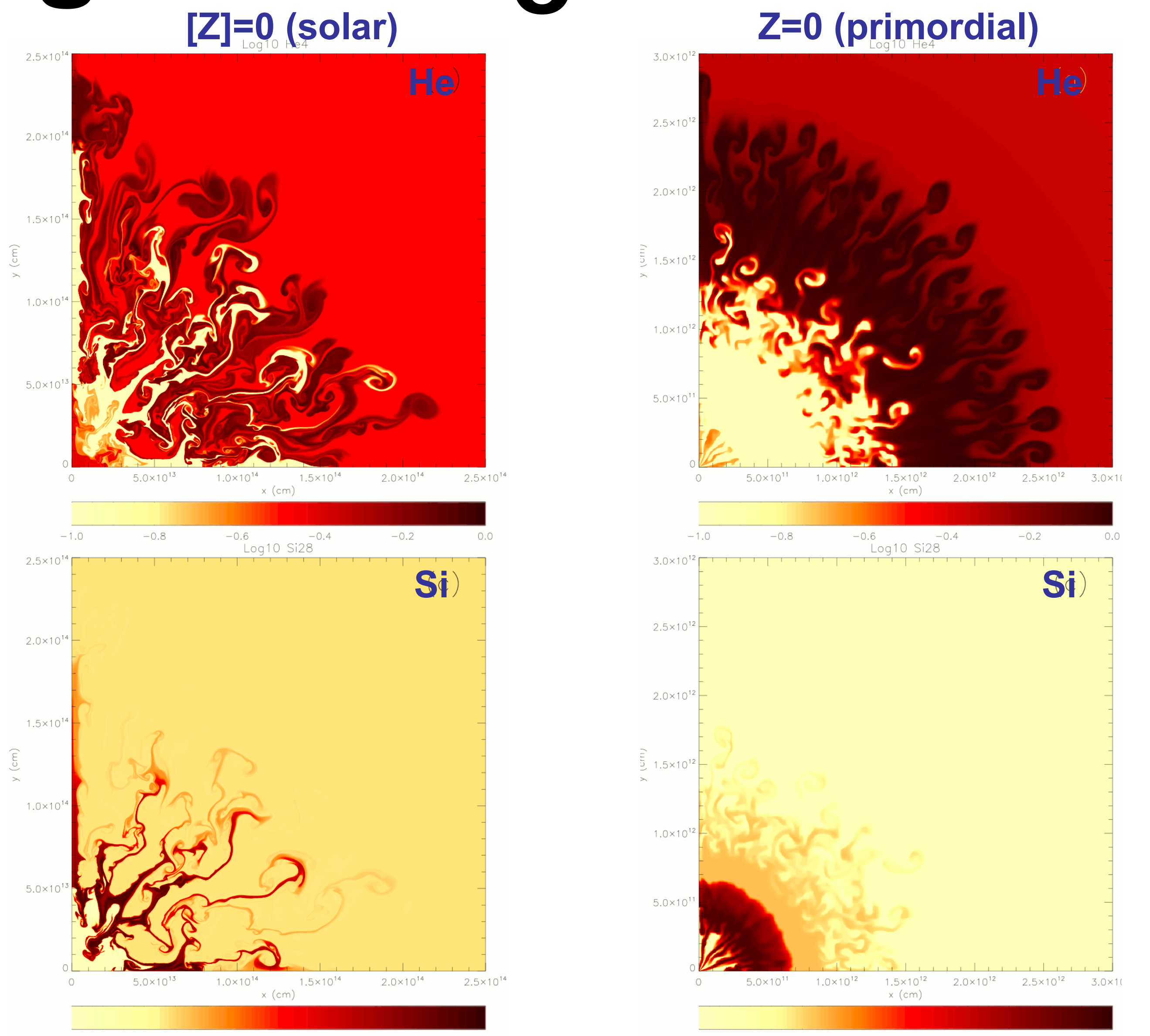
Nucleosynthesis in Massive Pop III Stars

Mixing in 25 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

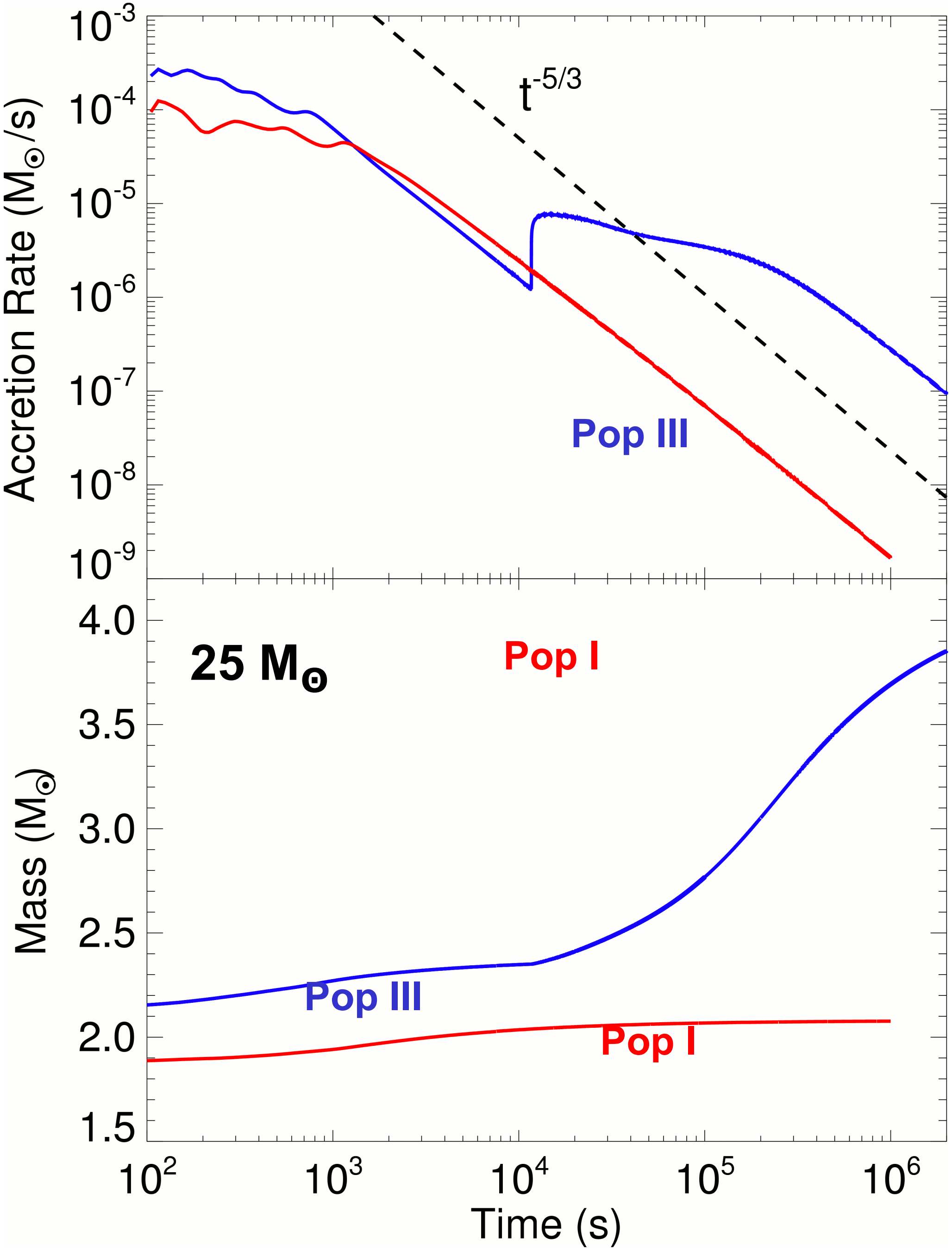
Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

➔ 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)

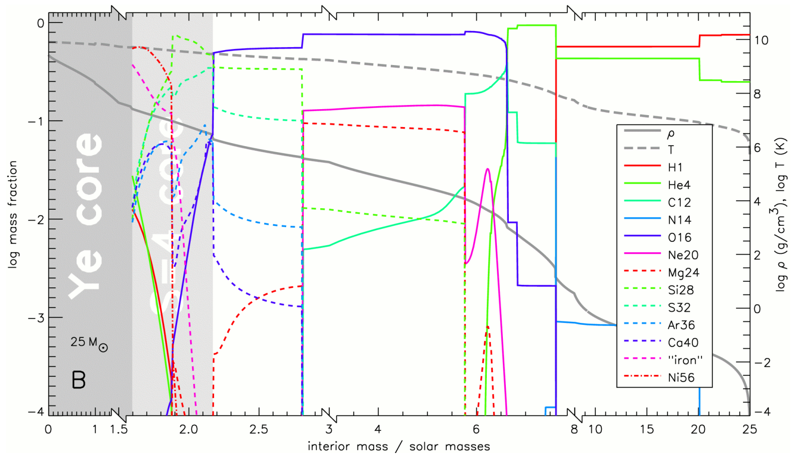
Fallback and Remnants



➔ **Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope**

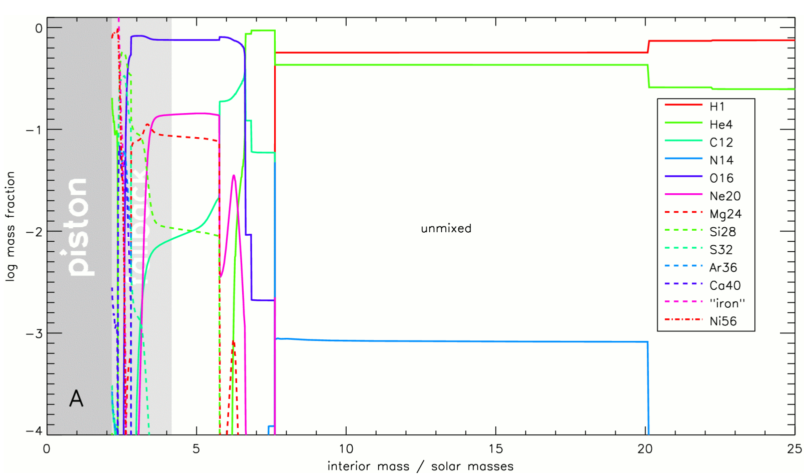
(Zhang, Woosley, Heger 2007)

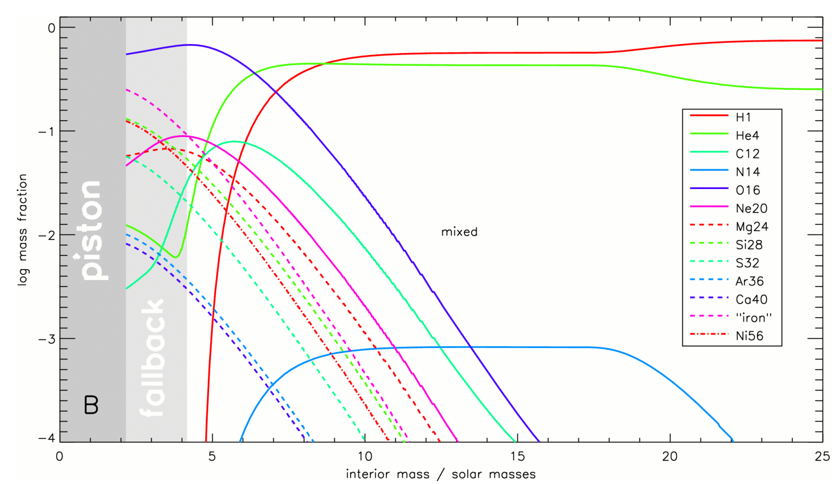
Supernovae, Nucleosynthesis, & Mixing



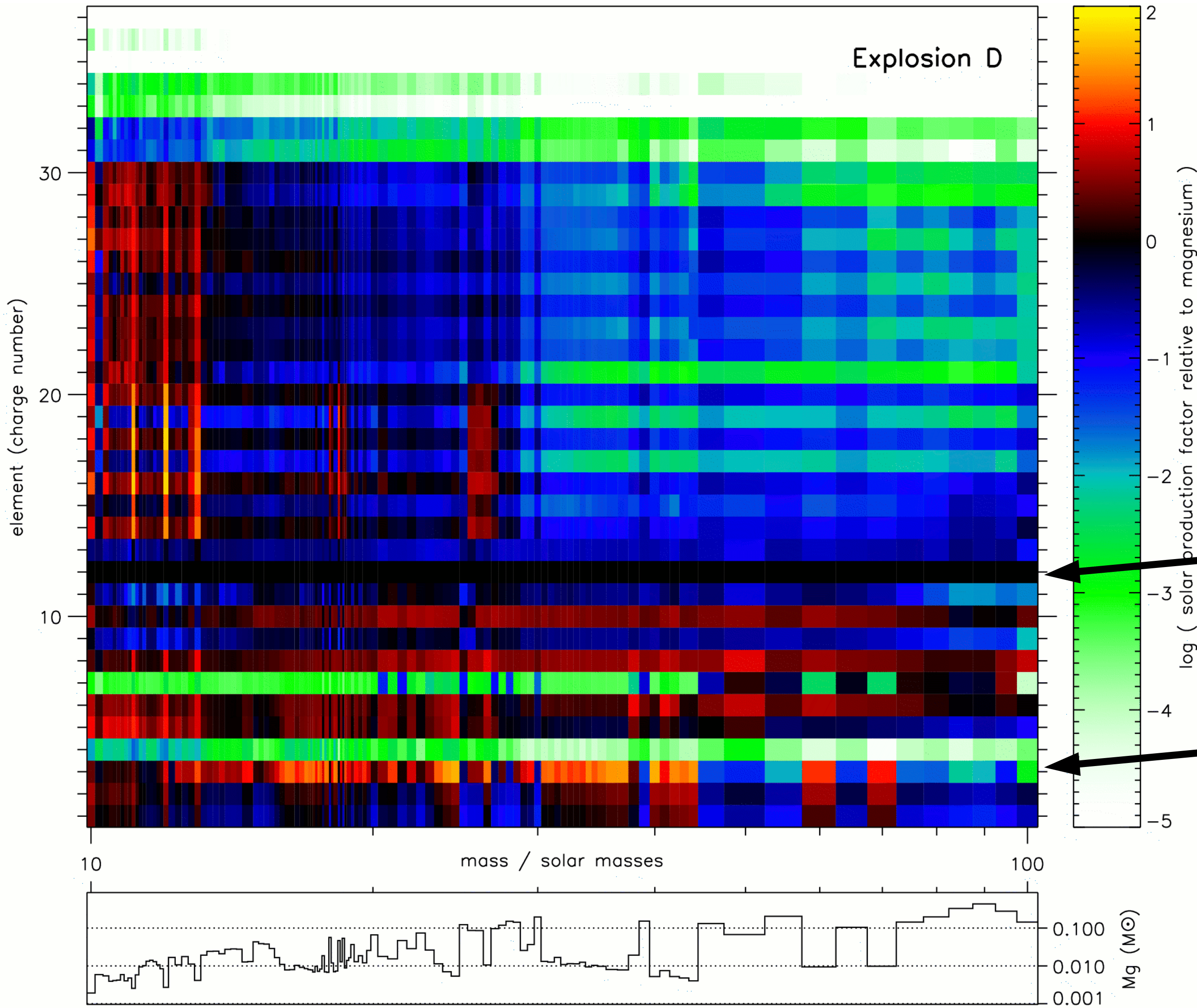
SN, no mixing

SN + mixing





Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

120 stellar masses

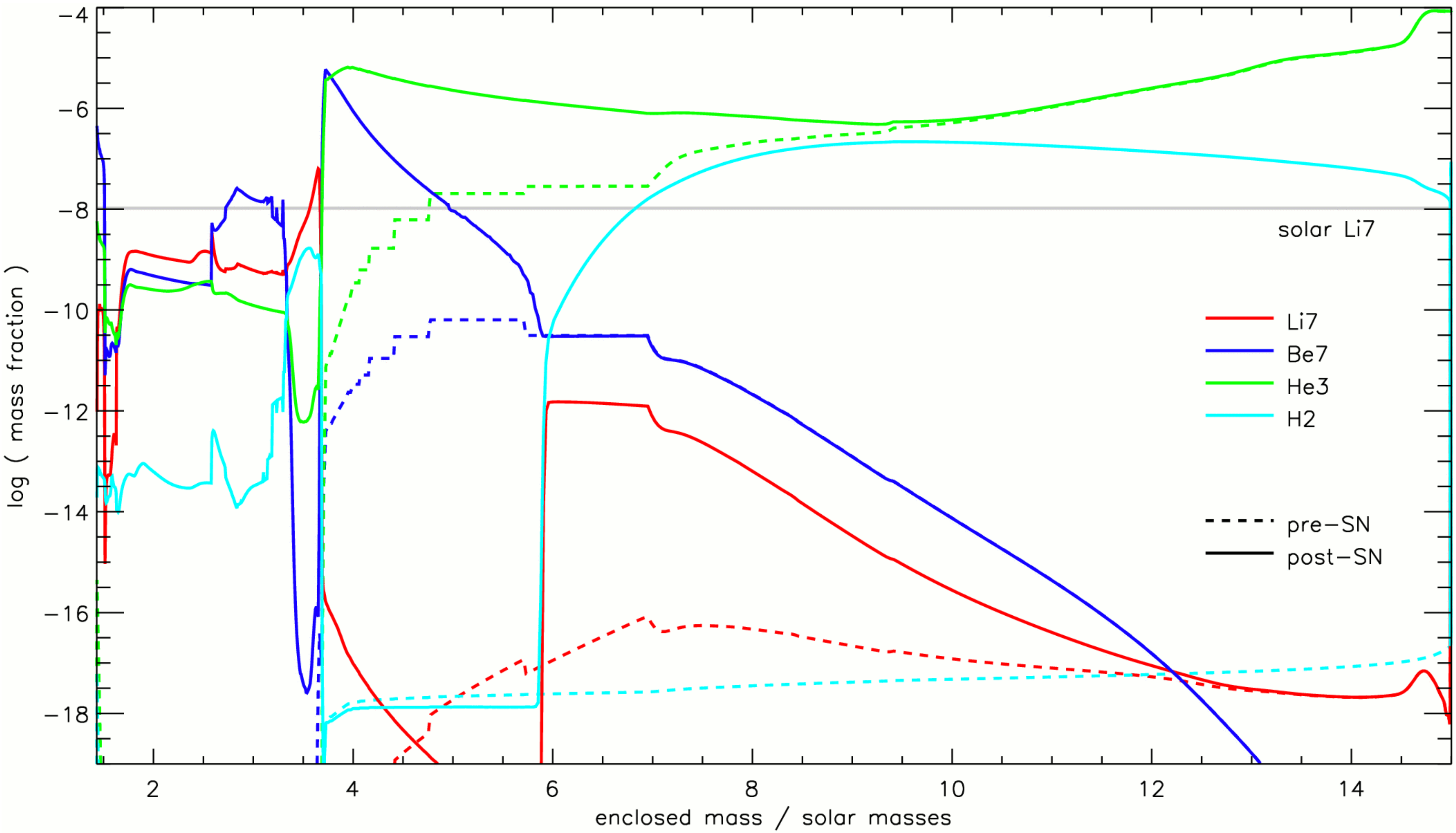
"complete" reaction network

normalized to Mg

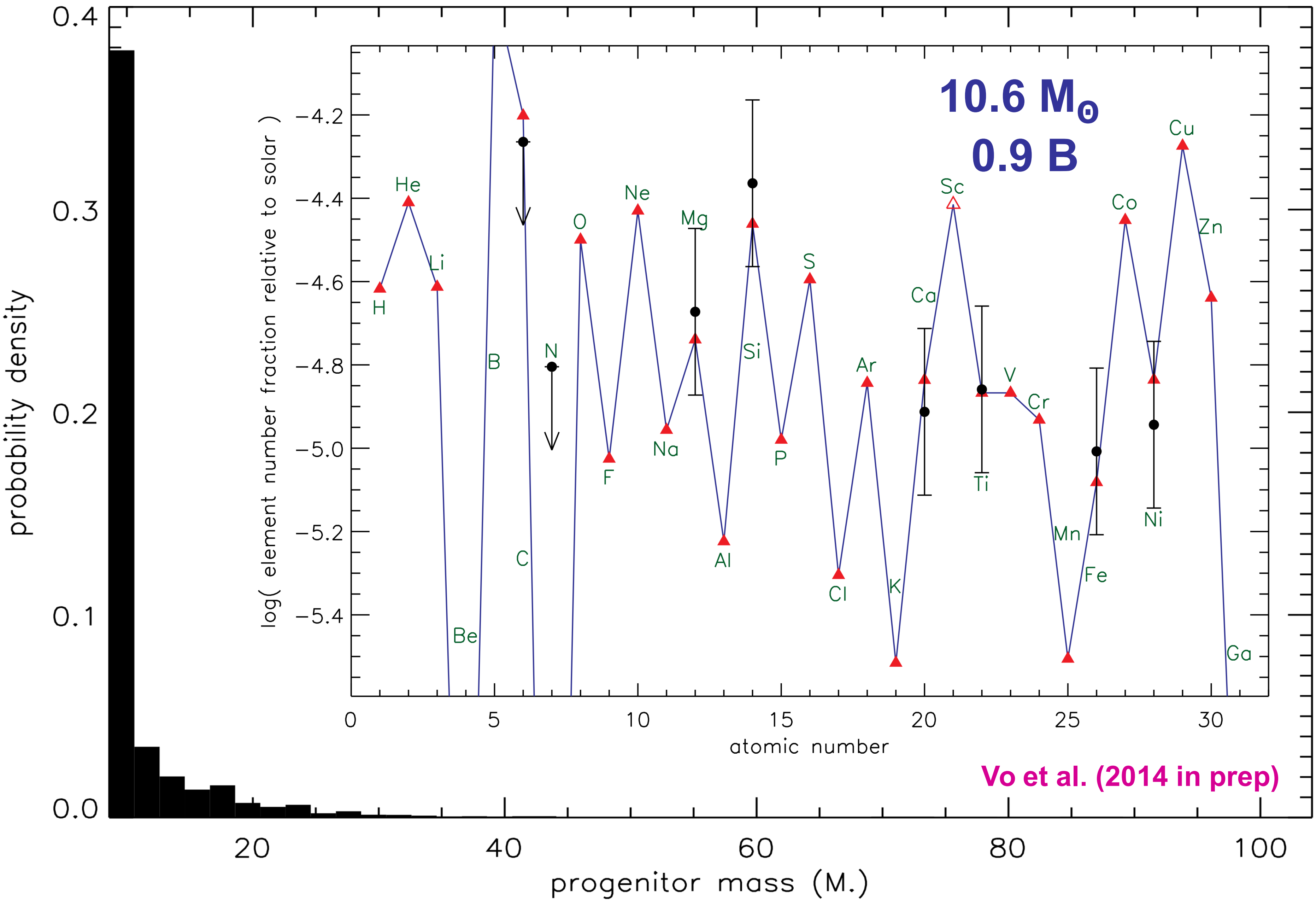
RESULTS:
e.g.,
Production of ^{7}Li by neutrino interaction in very compact stellar envelope!

Heger & Woosley (2010)

Production of ^{7}Li by p(ν,e^{+})n



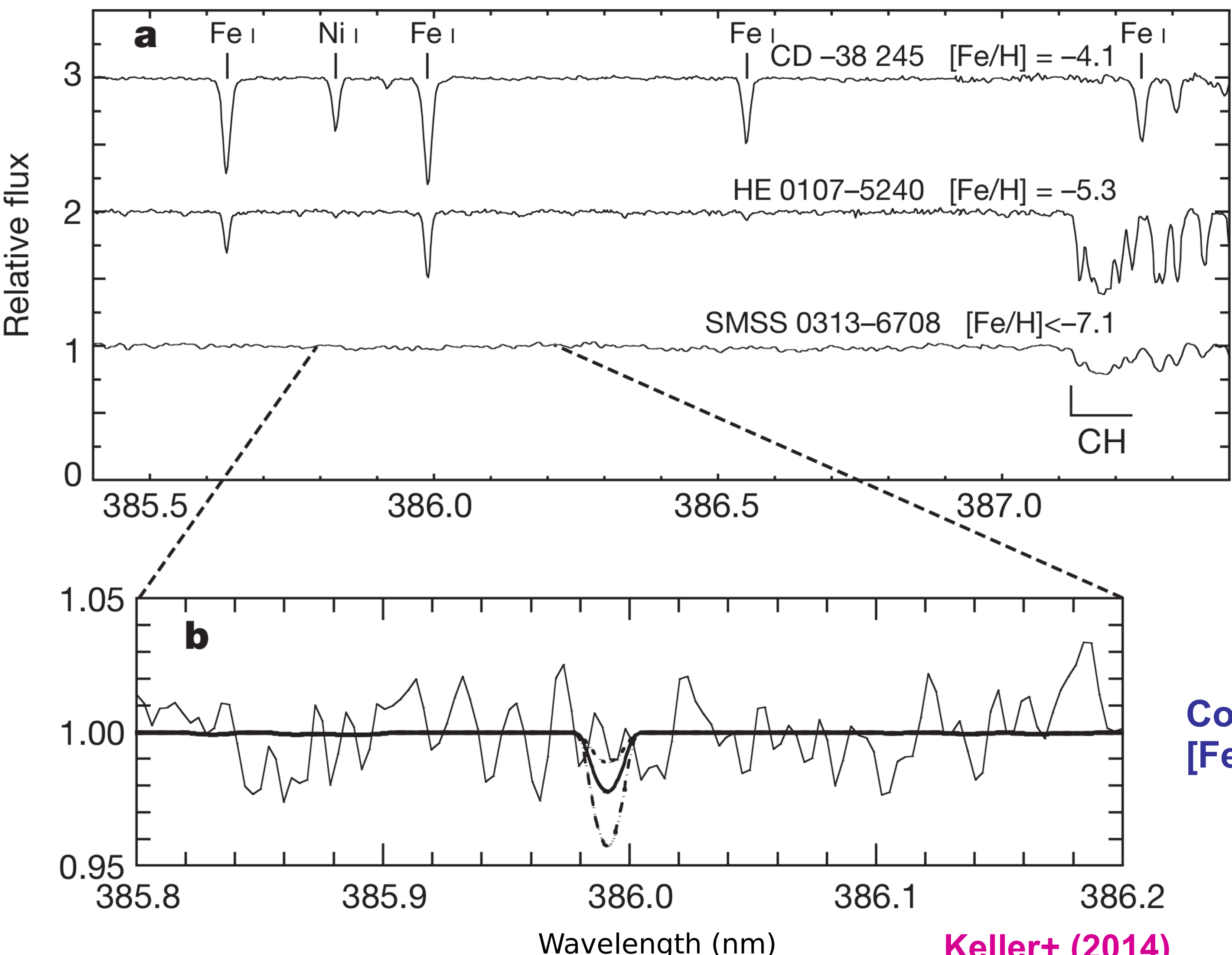
Fit to Caffau Star



SMSS J031300.362670839.3

The "Iron-Free" Star

[Fe] < -7.1 (3σ)



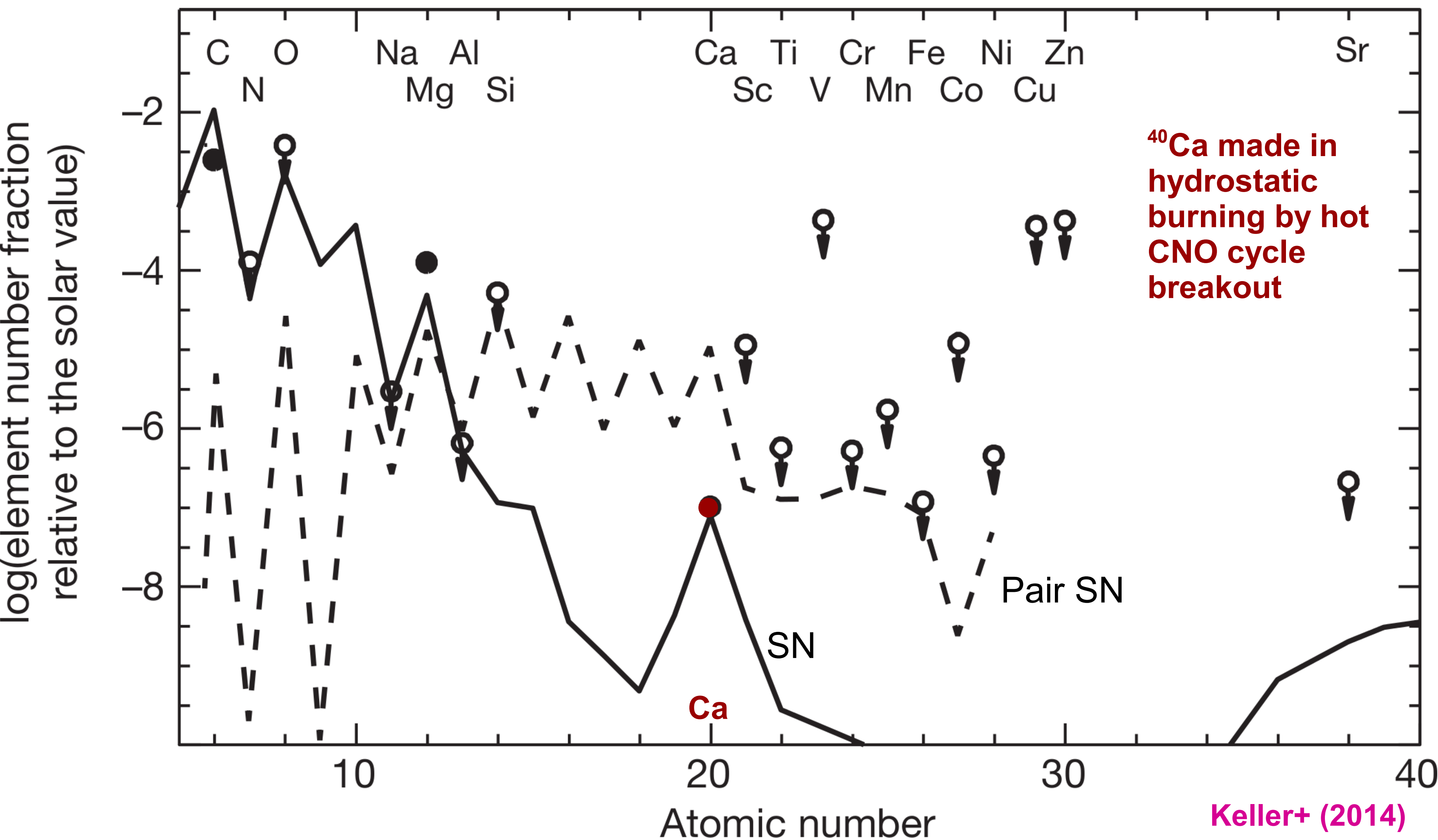
Comparison with spectra of other UMP stars

Comparison with [Fe/H] = -7.5, -7.2, -6.9

Keller+ (2014)

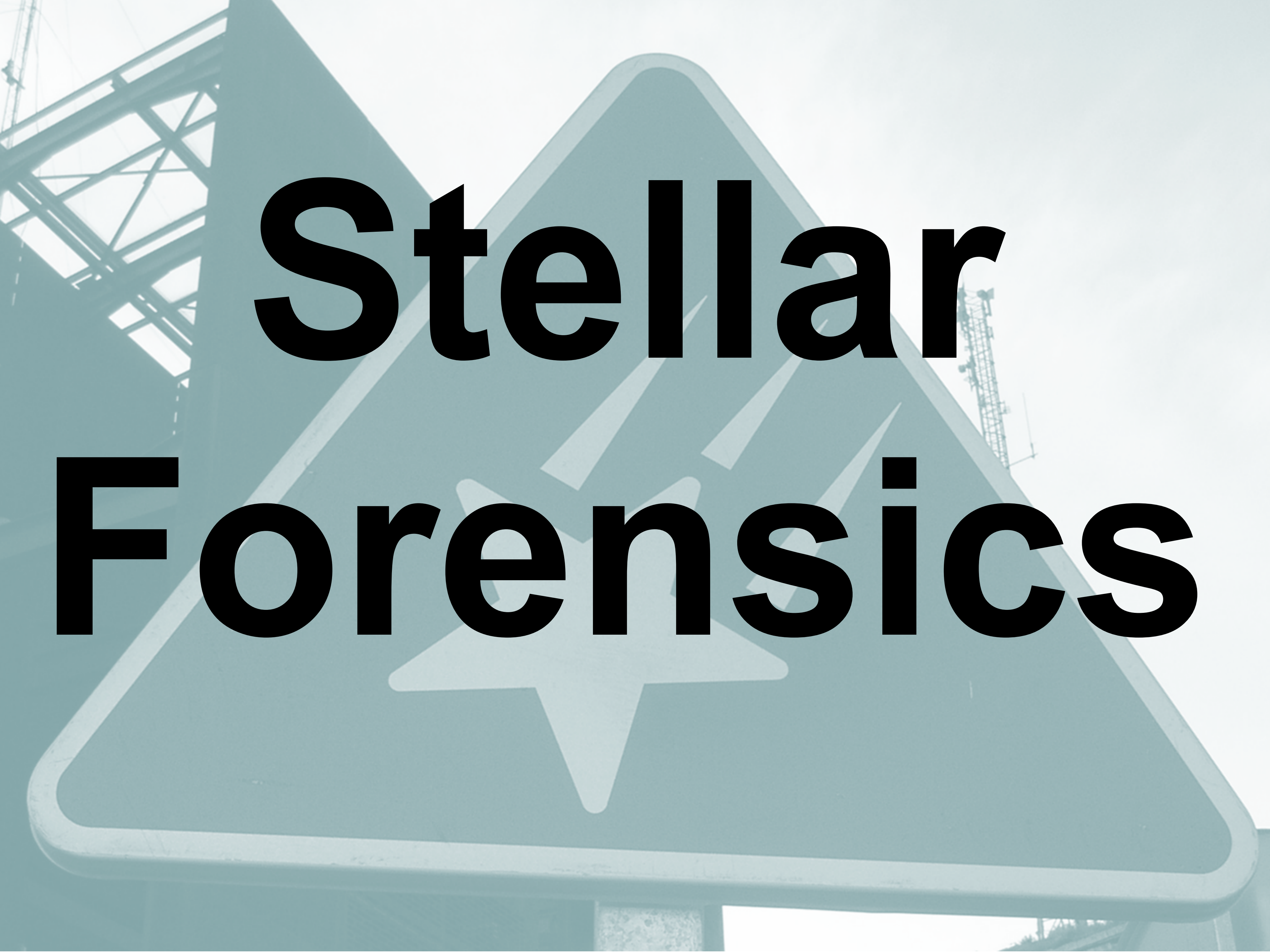
SMSS J031300.362670839.3

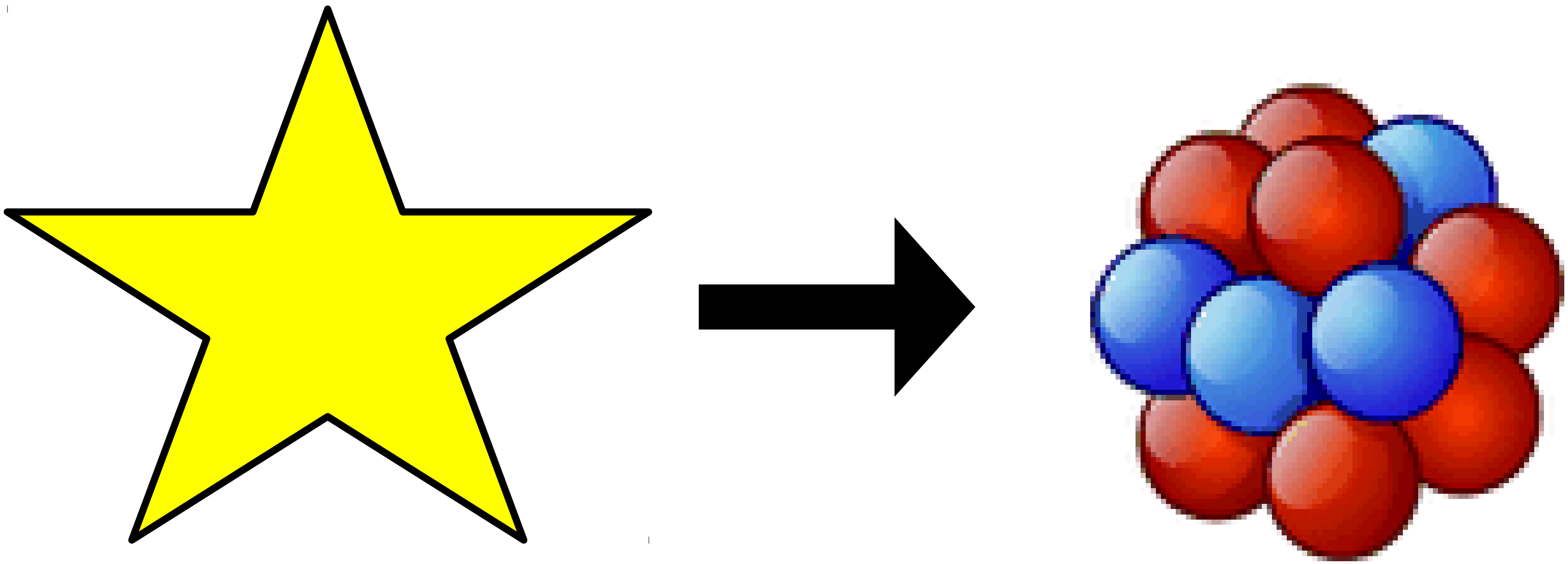
[Fe] < -7.1 (3σ)



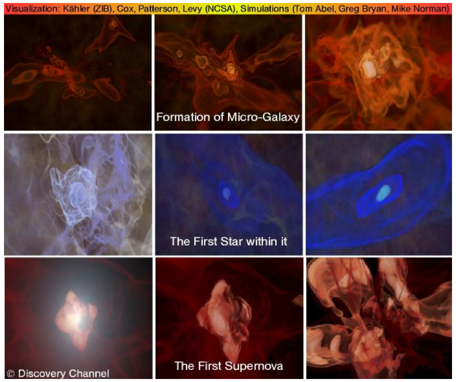
Keller+ (2014)

Stellar Forensics

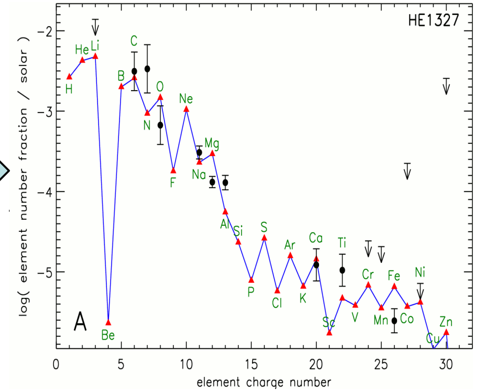




Reconstruction of the IMF



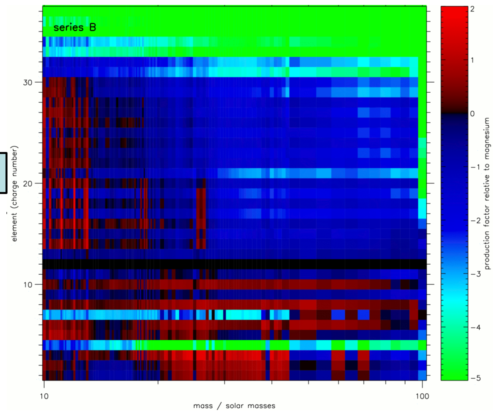
primordial stars form, nucleosynthesis ejected



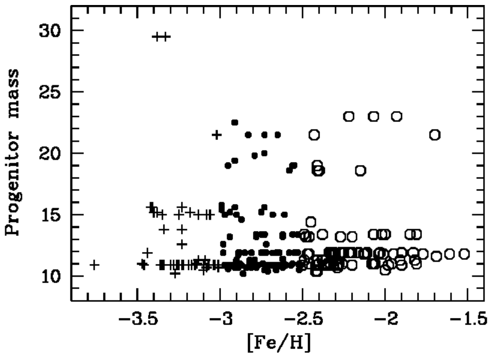
ejecta incorporated in low-Z halo stars

find low-Z halo stars (HERMES / SkyMapper / GALAH)

measure abundances (VLT, KECK, Gemini, …)



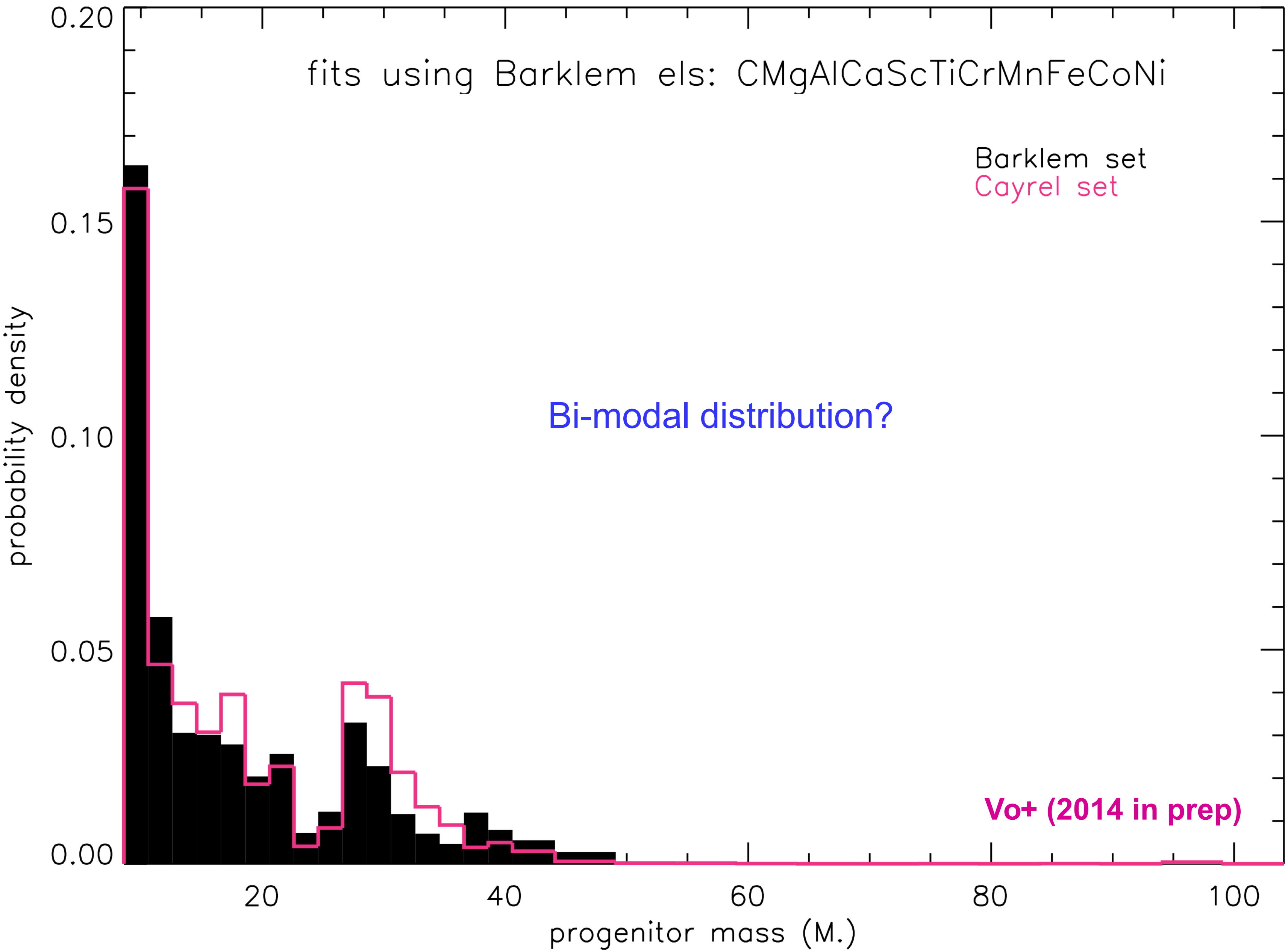
compare abundances to primordial star nucleosynthesis library



obtain IMF of population of progenitor stars

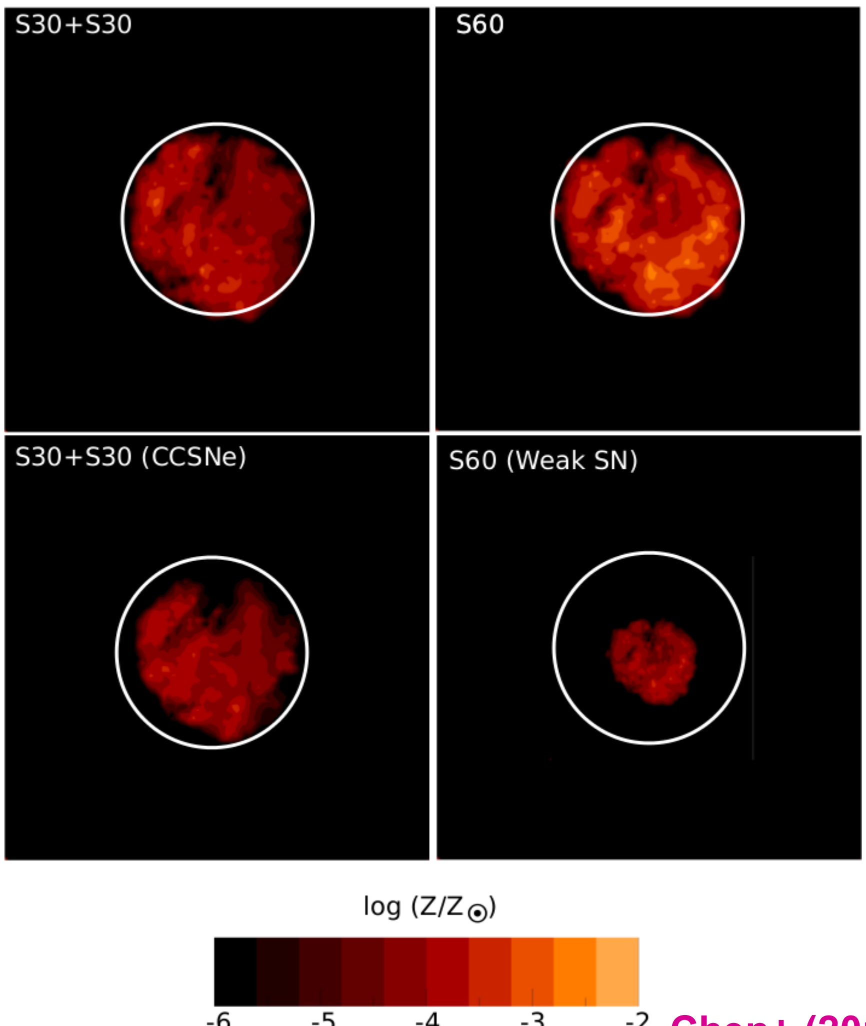
Frebel, priv. com. (2007)

Reconstruction of the IMF

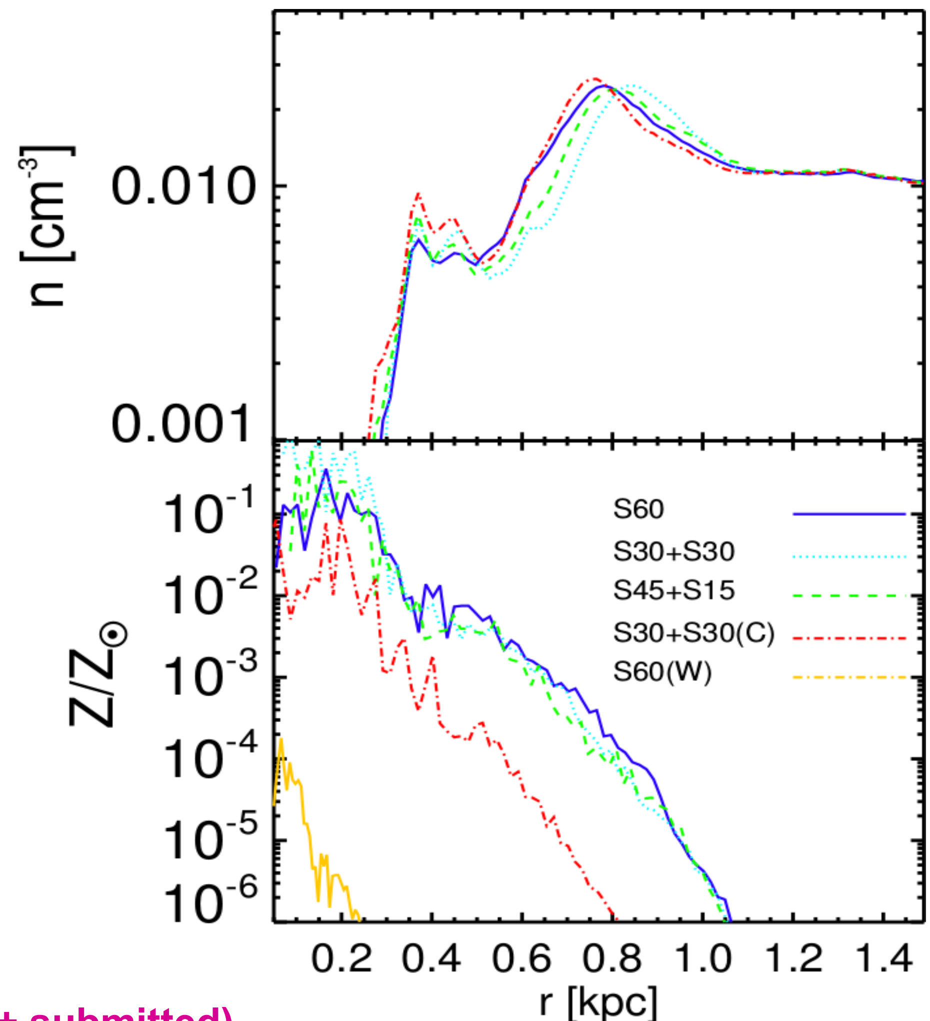


Enrichment from Single and Binary Stars

Spatial distribution of metal for different SN model with same total stellar mass



Metal enrichment as a function of distance from centre of DM halo for different SN model with same total stellar mass



Chen+ (2014+ submitted)

Fit Your Own Star

http://starfit.org

Website under development by Conrad Chan

- **Use genetic algorithm or complete search**
- **Upload your own observational star data**
- **Upload your own data base**

Summary

The IMF or the First Stars – and hence how they come to pass – still remains elusive without direct observational data

- IMF may have bimodal distribution for single stars
- For some stars the abundance pattern is very suggestive of originating from two stars, *possibly binary stars*
- Stellar forensics, determining abundance patterns of what the first stars left behind, may be our best tool in the near future (e.g., constraints on pair-SNe).
- Nucleosynthesis ashes of Pair-Instability SNe have not been directly observed