The First Stars

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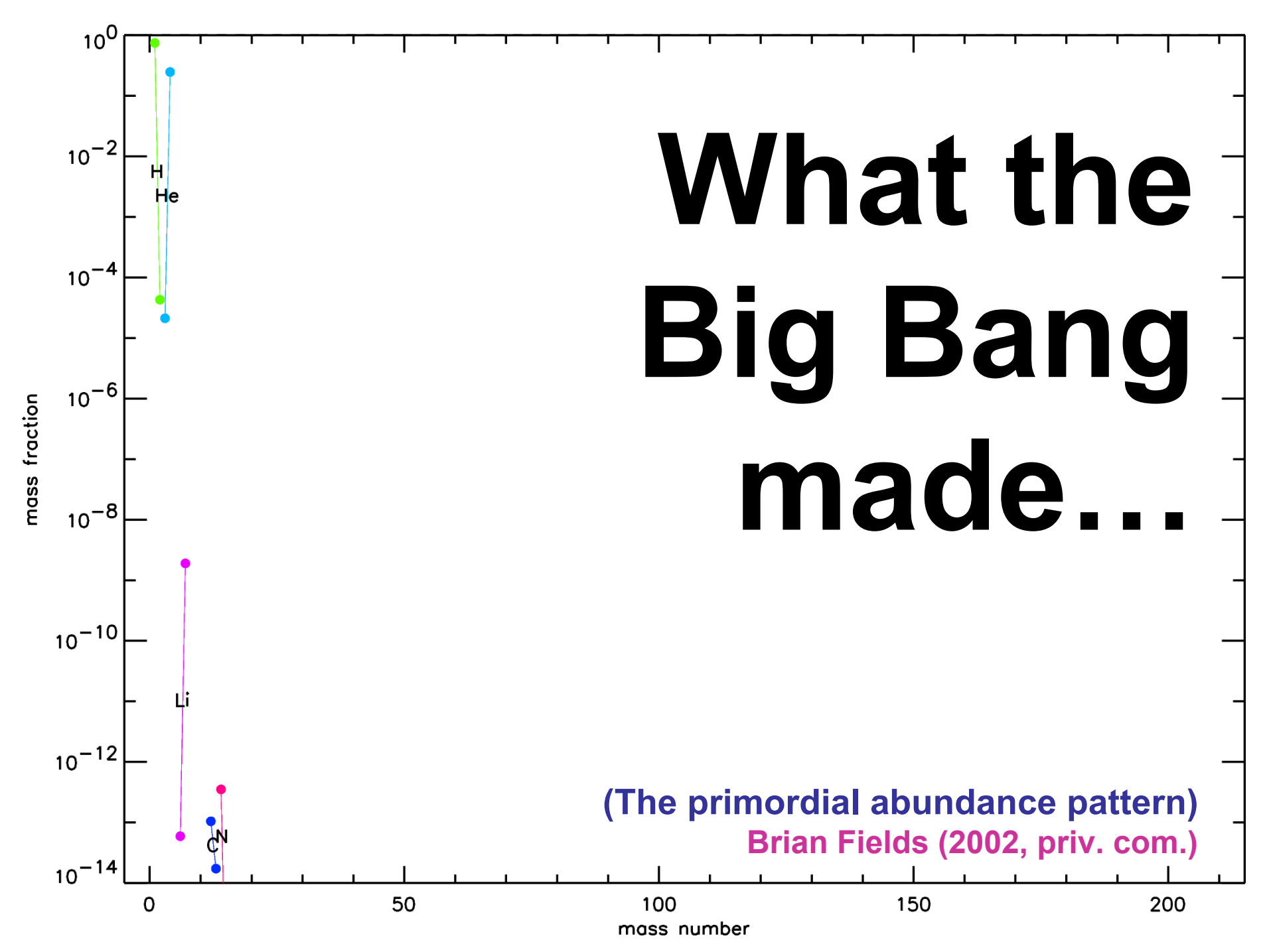
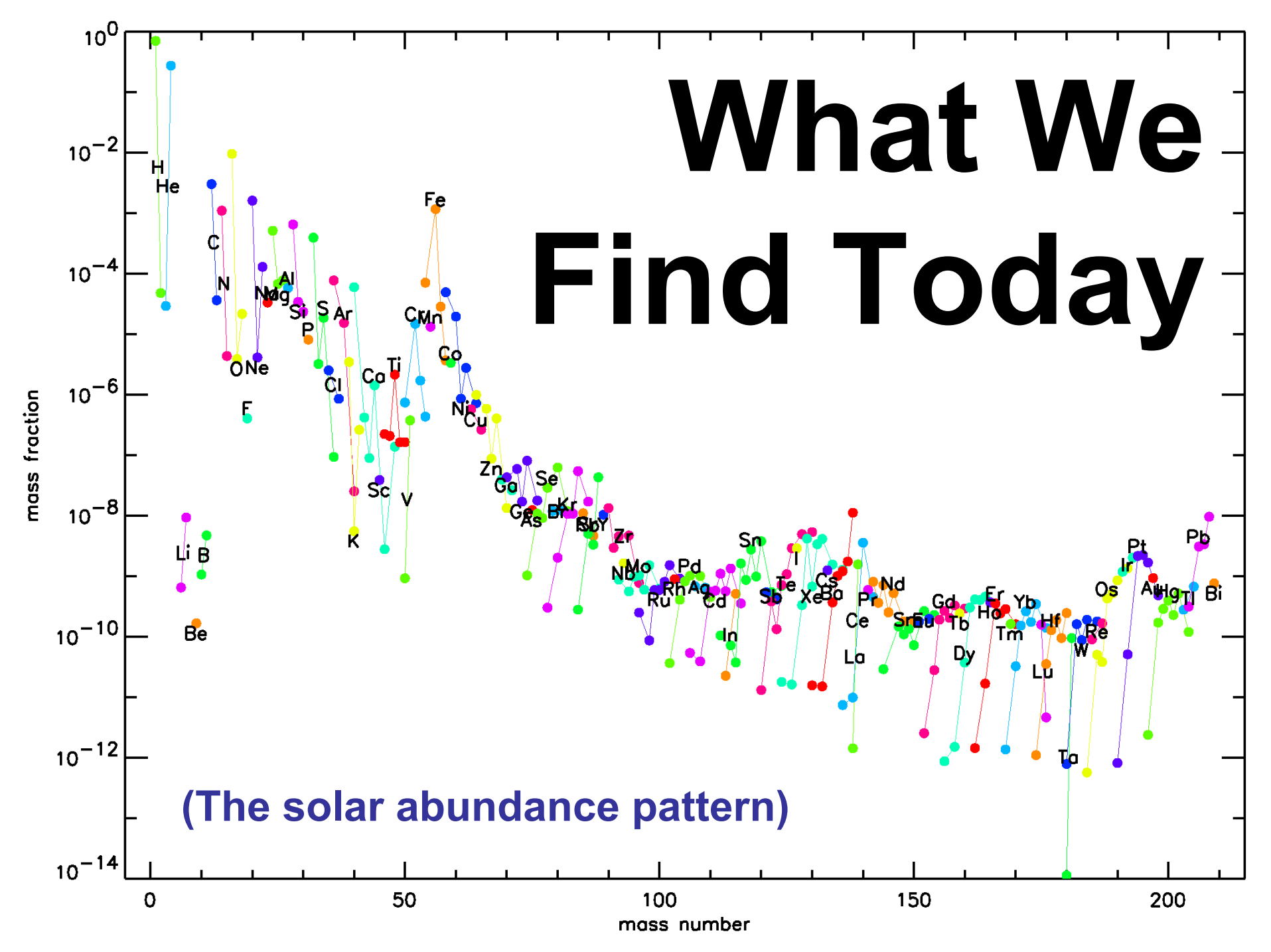
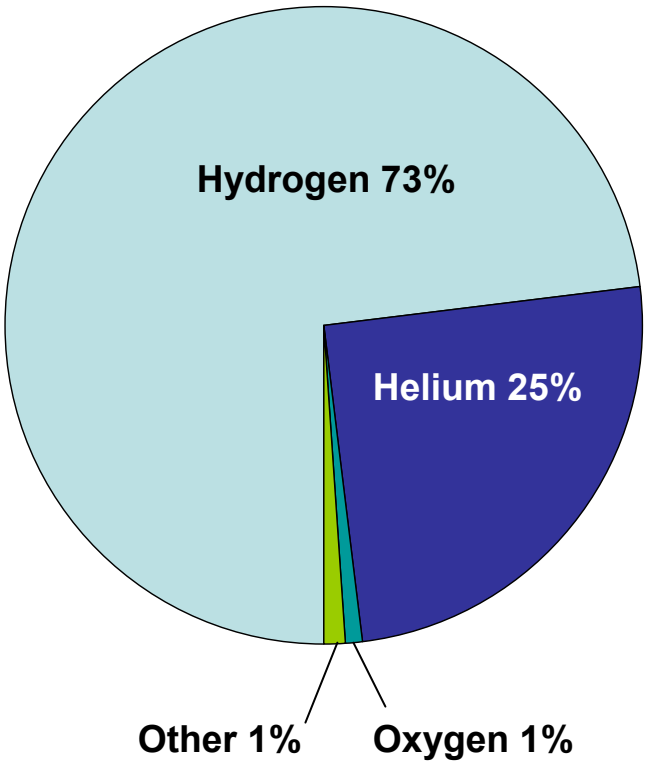

What the Big Bang made…
(The primordial abundance pattern)
Brian Fields (2002, priv. com.)
mass fraction
mass number
H
He
Li
C
N
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0
50
100
150
200

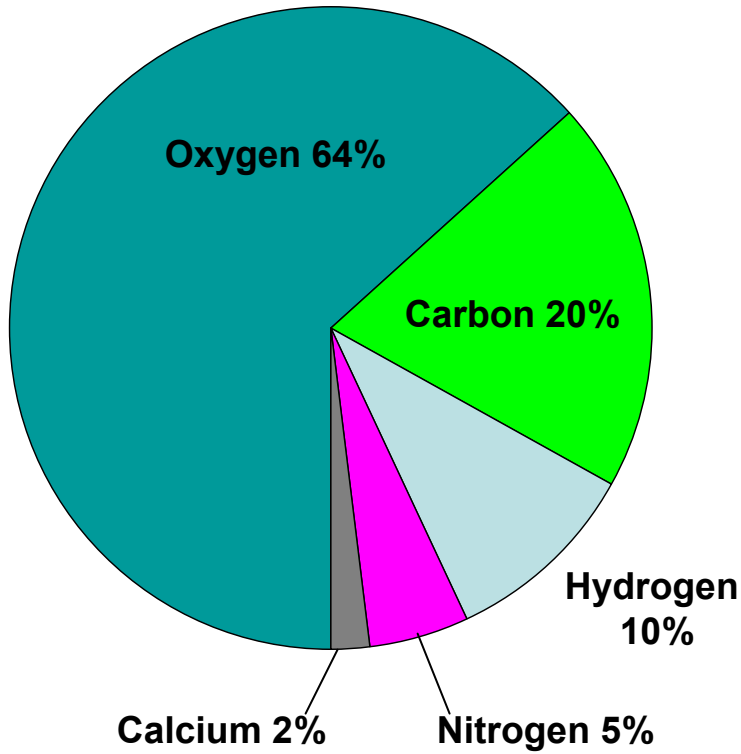

What We Find Today
(The solar abundance pattern)
mass fraction
mass number
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
0
50
100
150
200
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi

Relative Abundance by Weight

Universe



Humans

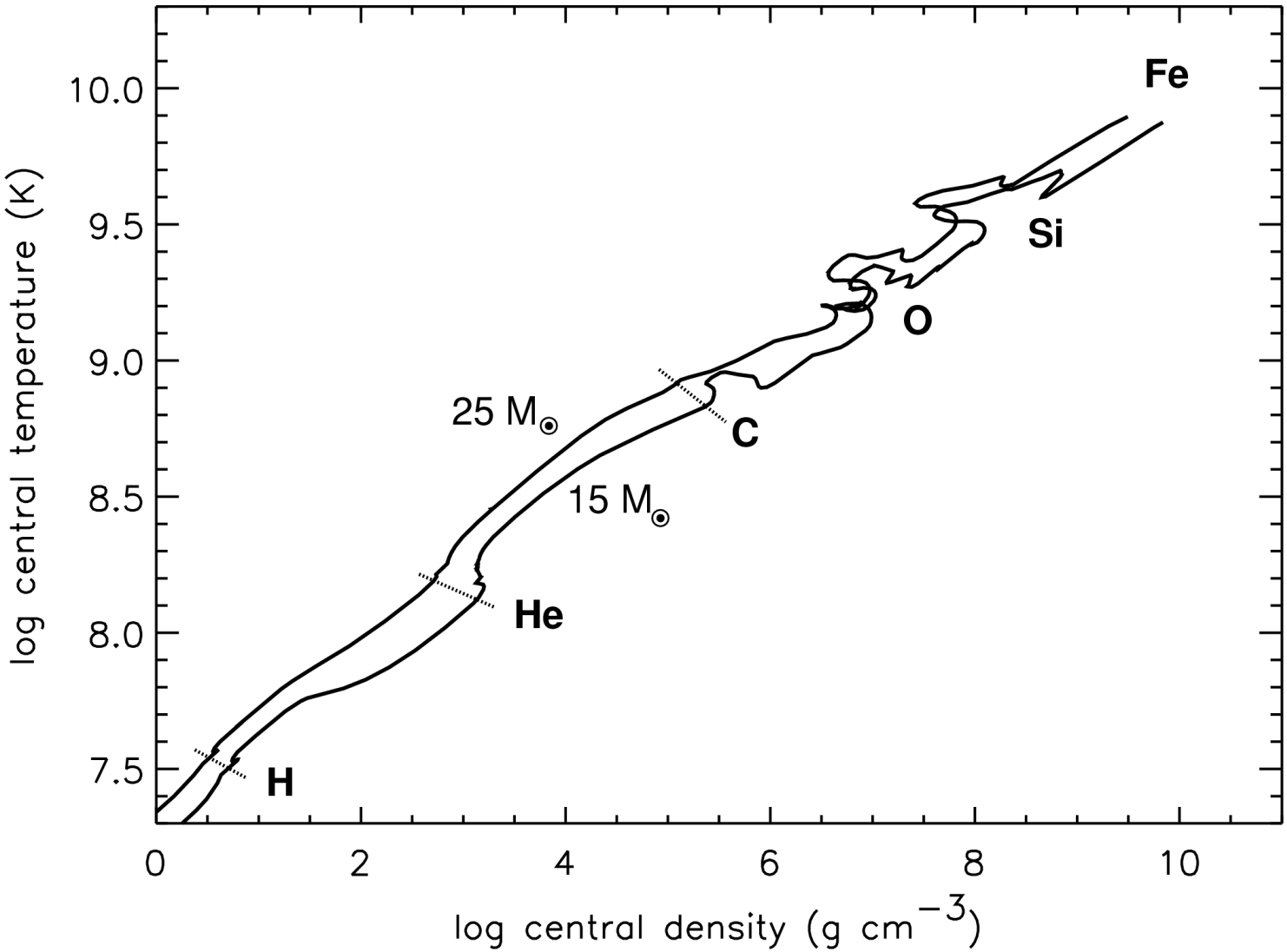



Visualization: Kähler (ZIB), Cox, Patterson, Levy (NCSA), Simulations (Tom Abel, Greg Bryan, Mike Norman)
Formation of Micro-Galaxy
The First Star within it
© Discovery Channel
The First Supernova

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

continuing contraction

to higher central densities and temperatures

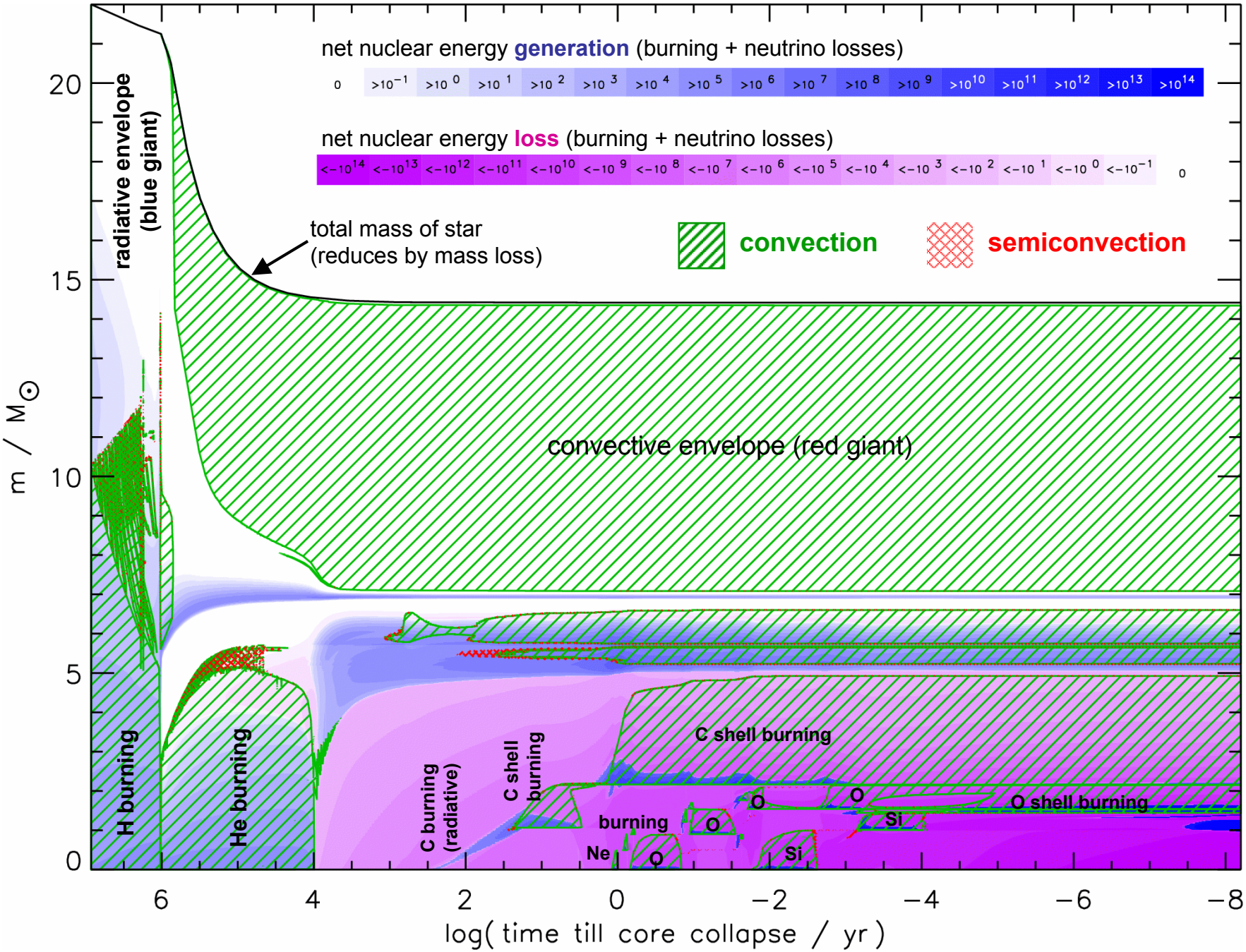


Evolution of central density and temperature of 15 $M_\odot$ and 25 $M_\odot$ stars

Nuclear burning stages

(e.g., 20 solar mass star)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\ H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
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	0.02	$^{28}Si(\gamma,\alpha)\ldots$


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
convection
semiconvection
radiative envelope (blue giant)
total mass of star (reduces by mass loss)
convective envelope (red giant)
H burning
He burning
C burning (radiative)
C shell burning
C shell burning
Ne burning
O
O
O
Si
Si
O shell burning
m / M⊙
log(time till core collapse / yr)
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8

Explosive Nucleosynthesis

in supernovae

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)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	**2 - 3**	**5**	(γ,n)
		ν-process		**5**	(ν, ν'), (ν, e^-)

IMF of the First Stars

Predicted to be heavy to very heavy

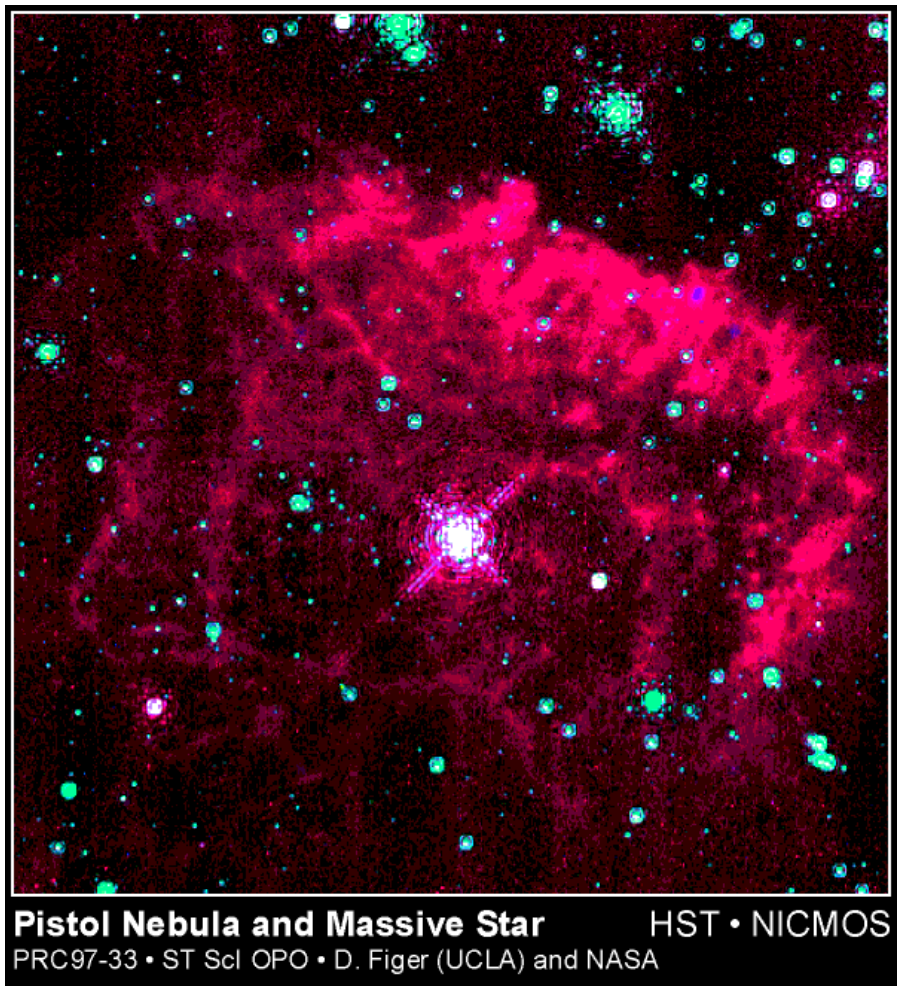
by theory – insufficient cooling due to lack of metal
(e.g., Larson 1999)

and by numerical simulations
(Bromm, Coppi, & Larson 1999, 2002;
Abel, Bryan, & Norman 2000, 2002;
Nakamura & Umemura 2001)

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

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

Additional Ingredient

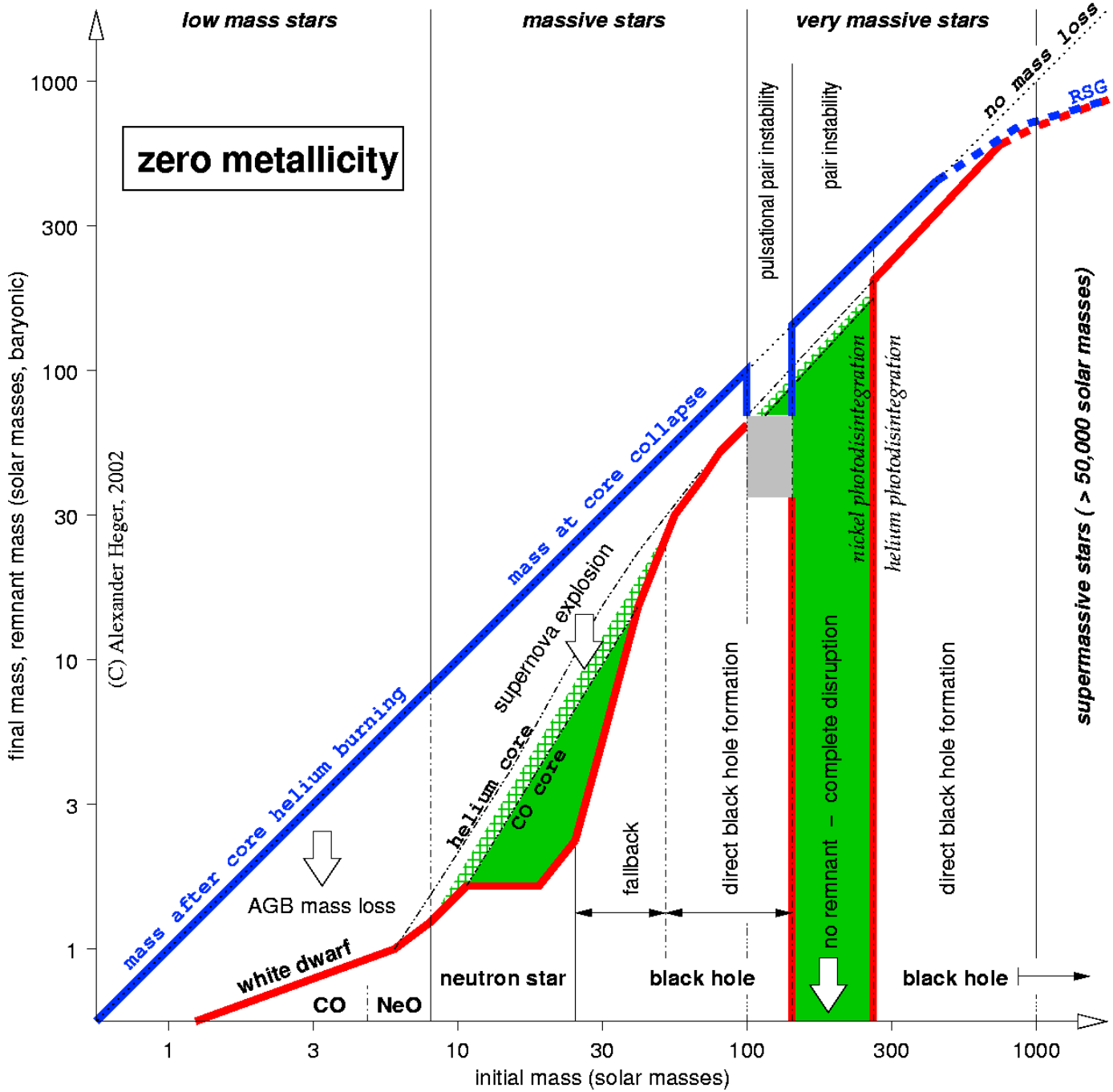


Essentially negligible mass loss in Pop III stars

in contrast:

The Pistol Star

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

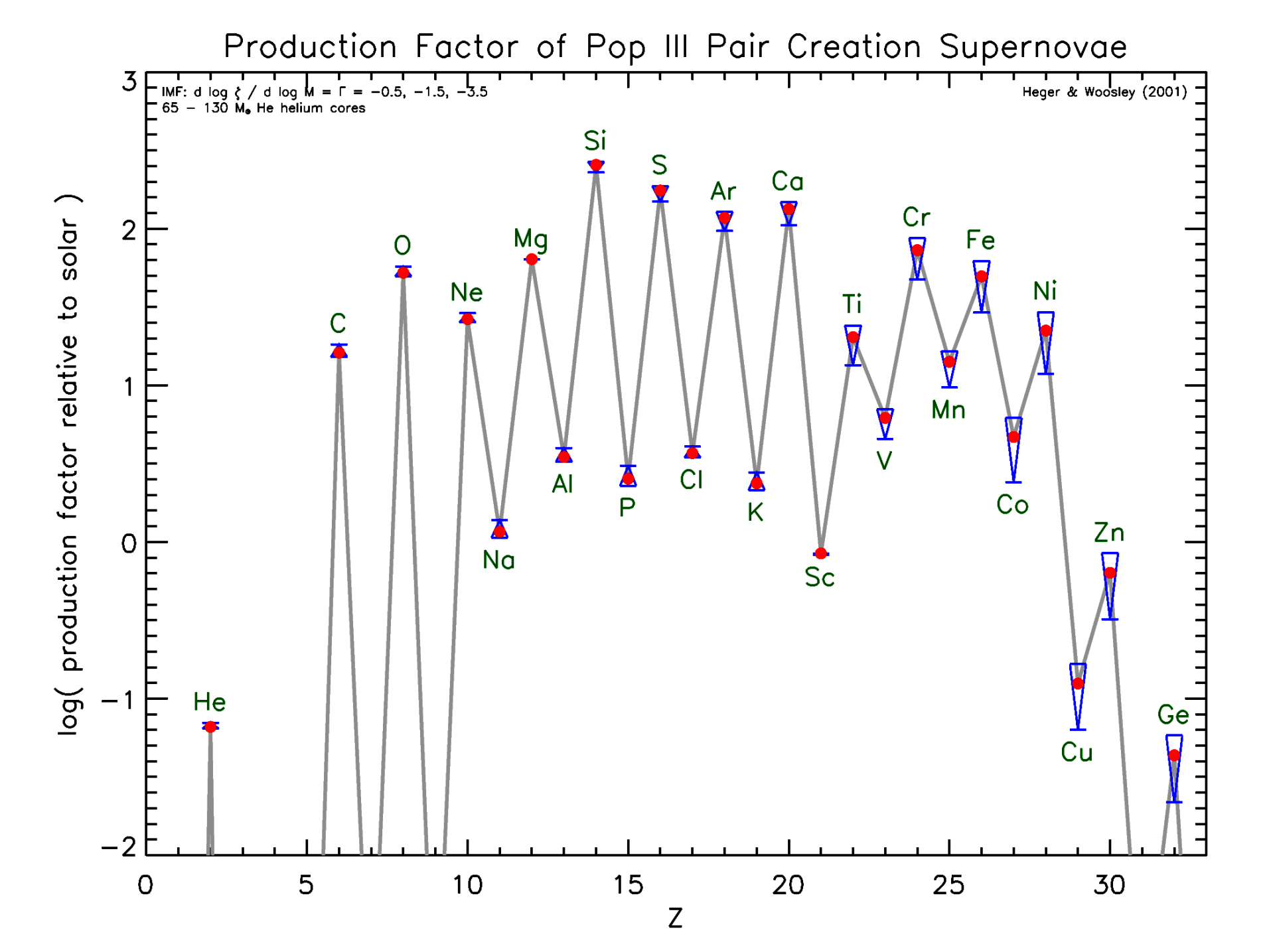


Ejected "metals"

Pair-Instability Supernovae

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

Some recent calculations:
Umeda & Nomoto 2001
Heger & Woosley 2002


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

Production factor of massive and very massive Pop III stars