Nucleosynthesis in massive stars and galactic chemical evolution

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Nucleosynthesis in Massive Stars and Galactic Chemical Evolution

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Galactic 1809 keV γ-ray intensity from ^{26}Al decay

Nuclear Theory & Modeling Group

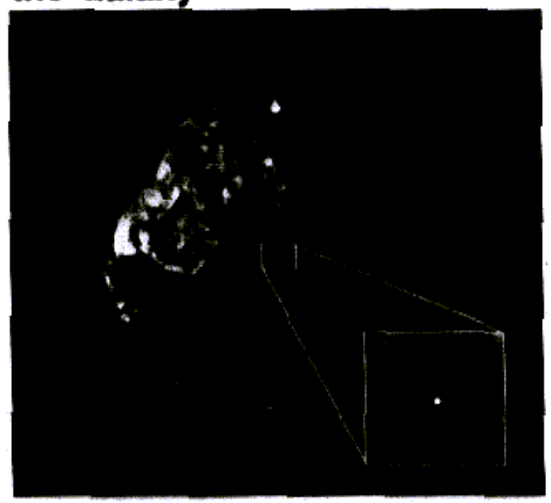
Physics

Why study nucleosynthesis in supernovae?

- **Supernovae provide the requisite conditions for production and ejection of newly formed nuclei into the interstellar medium**
- **Nucleosynthesis - the goal:**

  To develop a complete understanding of the origin of the chemical elements in terms of their nuclear properties and to identify the conditions in which they were assembled
- **This yields:**
  - **Chemical history of stars in our own and distant galaxies**
  - **Chemical evolution of the Galaxy**
- **Diagnostics of:**
  - **Stellar evolution**
  - **Novae**
  - **SN Ia, Ib, II**
  - **Hypernovae**

    γ-ray bursts

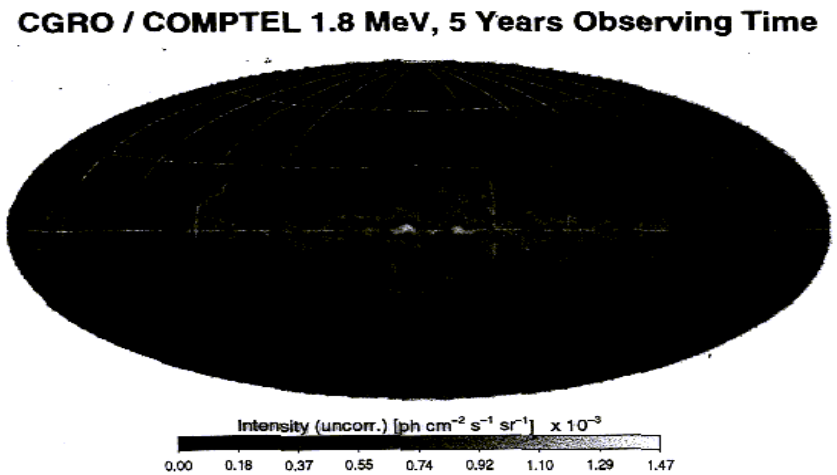


SNR Puppis A and its neutron star in X-rays

Nuclear Theory & Modeling Group

Physics

The Galaxy as seen in the 1.8 MeV γ-ray line of radioactive ^{26}Al.



The distribution of ^{26}Al is confined to the disk of our Galaxy, suggesting a stellar origin.

Type II Supernovae!

Advanced Nuclear Burning Stages

Fuel	Main Product	Secondary Products	Temp 10^9K	τ yr
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O,^{22}Ne s-process	0.2	10^6
C	Ne,Mg	Na	0.8	10^3
Ne	O,Mg	Al,P	1.5	3.0
O	Si,S	Cl,Ar K,Ca	2.0	0.83
Si	Fe	Ti,V,Cr Mn,Co,Ni	3.5	10^{-8}

$M_{zams} > 8 M_\odot$

$\dot{\varepsilon}_\nu \gg \varepsilon_\gamma$

Then Collapse: ($T_9 \gtrsim 10$, $\tau \sim 1$ sec)

Explosion: **light-p process, r-process**

Explosive nucleosynthesis: **ν-process,** γ-process.

Beyond He burning: The BIG Enchilada.

Systematic survey of massive star nucleosynthesis (Woosley & Weaver 1995).

- Calculate grid of massive stars 11-40 $M_\odot$.

- For many initial metallicities (0., 0.01, 0.1, .5, 1., 2. $Z/Z_\odot$).

- Evolve from ZAMS $\rightarrow$ PRESN/collapse + paramaterized explosion with 200 isotope ntwk.

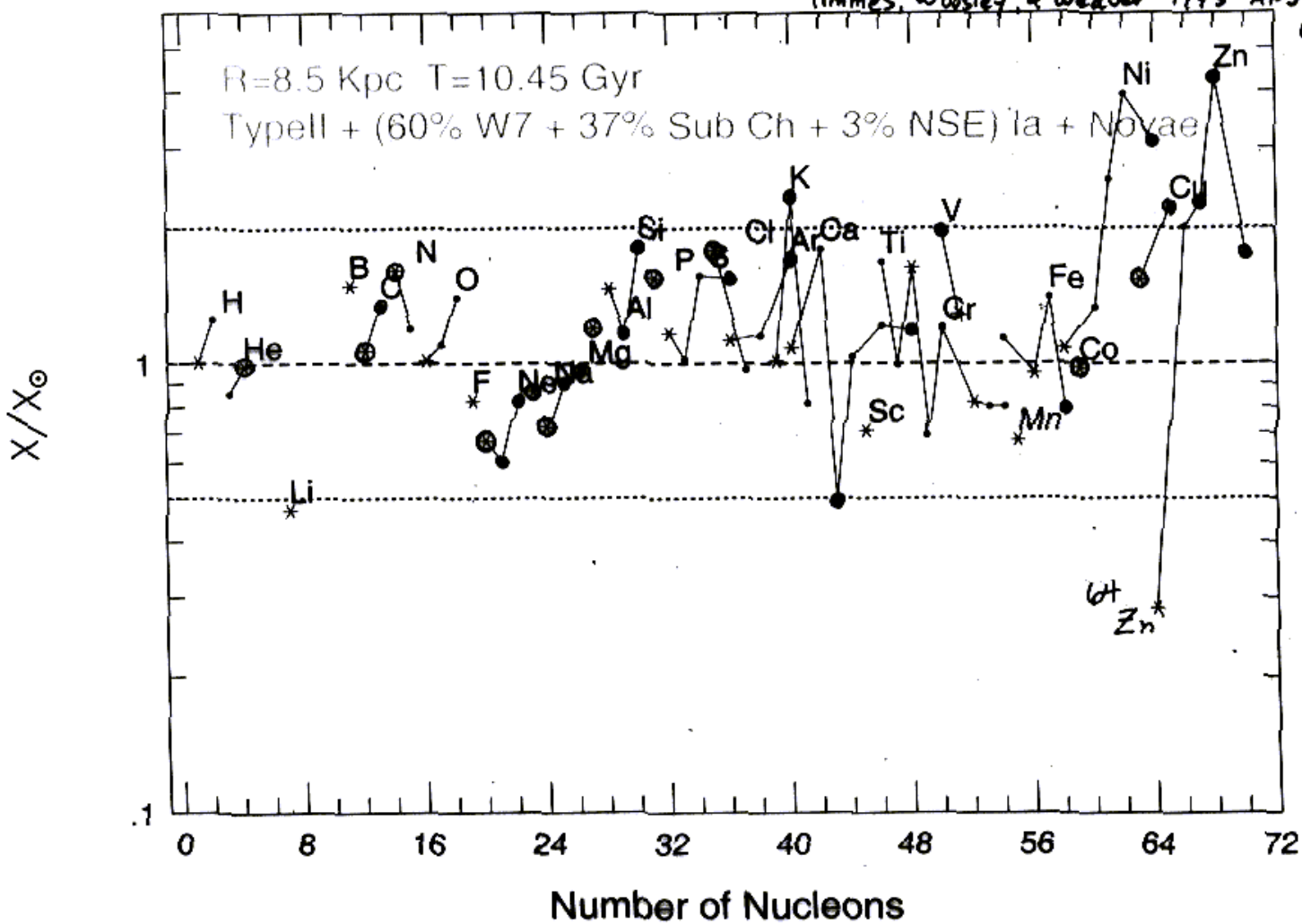
- Feed stellar yields into Galactic Chemical Evolution code (Timmes Woosley & Weaver 1995).

- Sample chemical evolution at solar location (8.5 Kpc) and time 10.45 Gyr.

- Compare to Solar Abundances (Anders & Grevesse 1987).

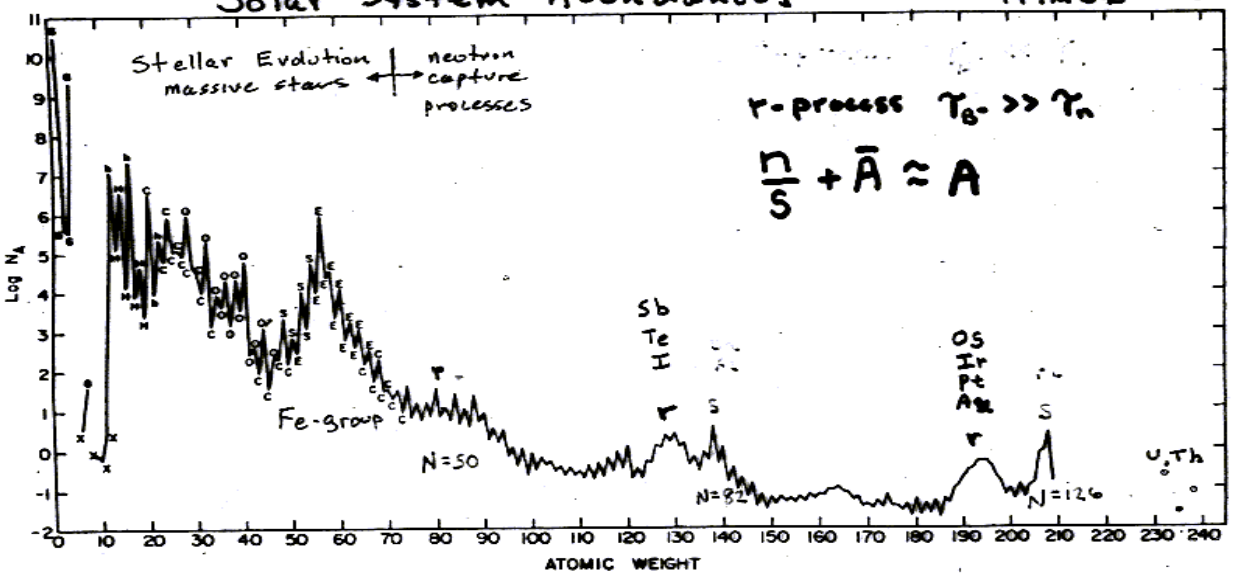
Need mix of various stellar input to account for all isotopes. Even so...

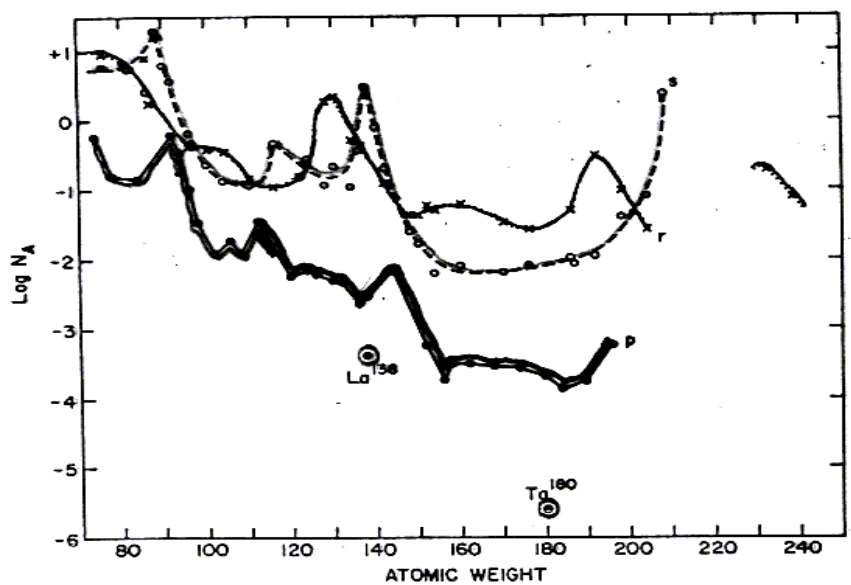
Timmes, Woosley, & Weaver 1995 ApJS 98 617



Solar System Abundances

Trimble '75





— r
— s
o ν
— rp
— γ

N = 50, 82, 126

Nucleosynthetic processes

- **s-process:** operates through addition of thermal neutrons on timescales that are long compared to β^- decay. Weak component ($60 < A < 90$) from massive stars, strong component ($90 < A < 208$) from AGB stars. Follows path of beta stability. Secondary process (requires iron seed from previous generations of stellar evolution).
- **r-process:** produces the most neutron-rich nuclei by rapid addition of neutrons onto seed nuclei above iron on timescales that are short compared to β^- decay. Production site SNII cores? Primary process.
- **p-process:** produces the most proton-rich nuclei bypassed by the s-process. Several variants: rp-process (X-ray bursts) and light-p process (SNII cores) makes $64 < A < 100$; γ-process makes $A>100$, operates in neon-oxygen layers of SNII during explosive nucleosynthesis via photodisintegration of pre-existing r- and s-process seed nuclei. rp-process and light-p are primary, γ-process is secondary.
- **References:**
  - Stellar Evolutiuon: Woosley & Weaver 1995, ApJS 101, 181
  - Galactic Chemical Evolution: Timmes, Woosley, & Weaver 1995, ApJS 98, 1995

Nucleosynthesis above the Fe Group ($Z \gtrsim 30$)

The s-process: weak component occurs in massive stars ($A \leq 90$). AGB stars responsible for the rest.

For 25 $M_\odot$, Both *good and bad news:*

- GOOD: Can co-produce as a group so many isotopes in solar proportions.

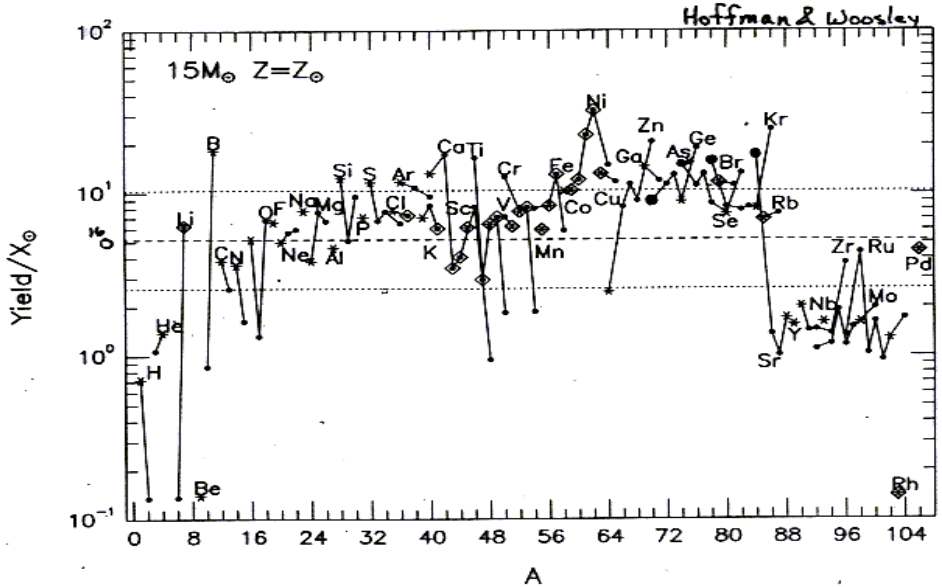
- BAD: but it may be too much of a good thing (compared to ^{16}O say).

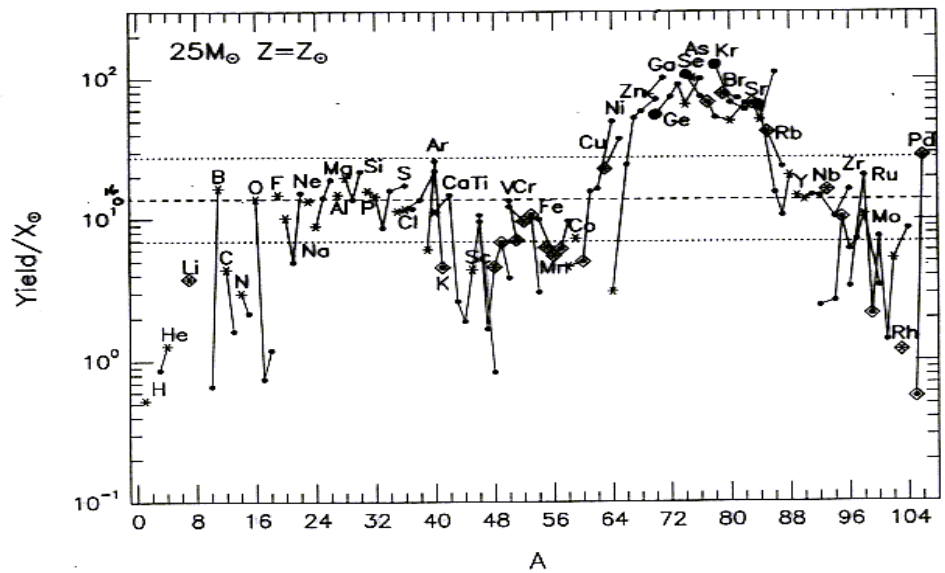
- s-process is *secondary*, ok to slightly overproduce in $Z=Z_\odot$ stars. Expect lower production (compared to ^{16}O) at lower metallicity. OVERPRODUCTION MAY PERSIST. Solution may involve improved cross sections [(n,γ), (α,n)] or stellar model (rotation, convection), maybe both.

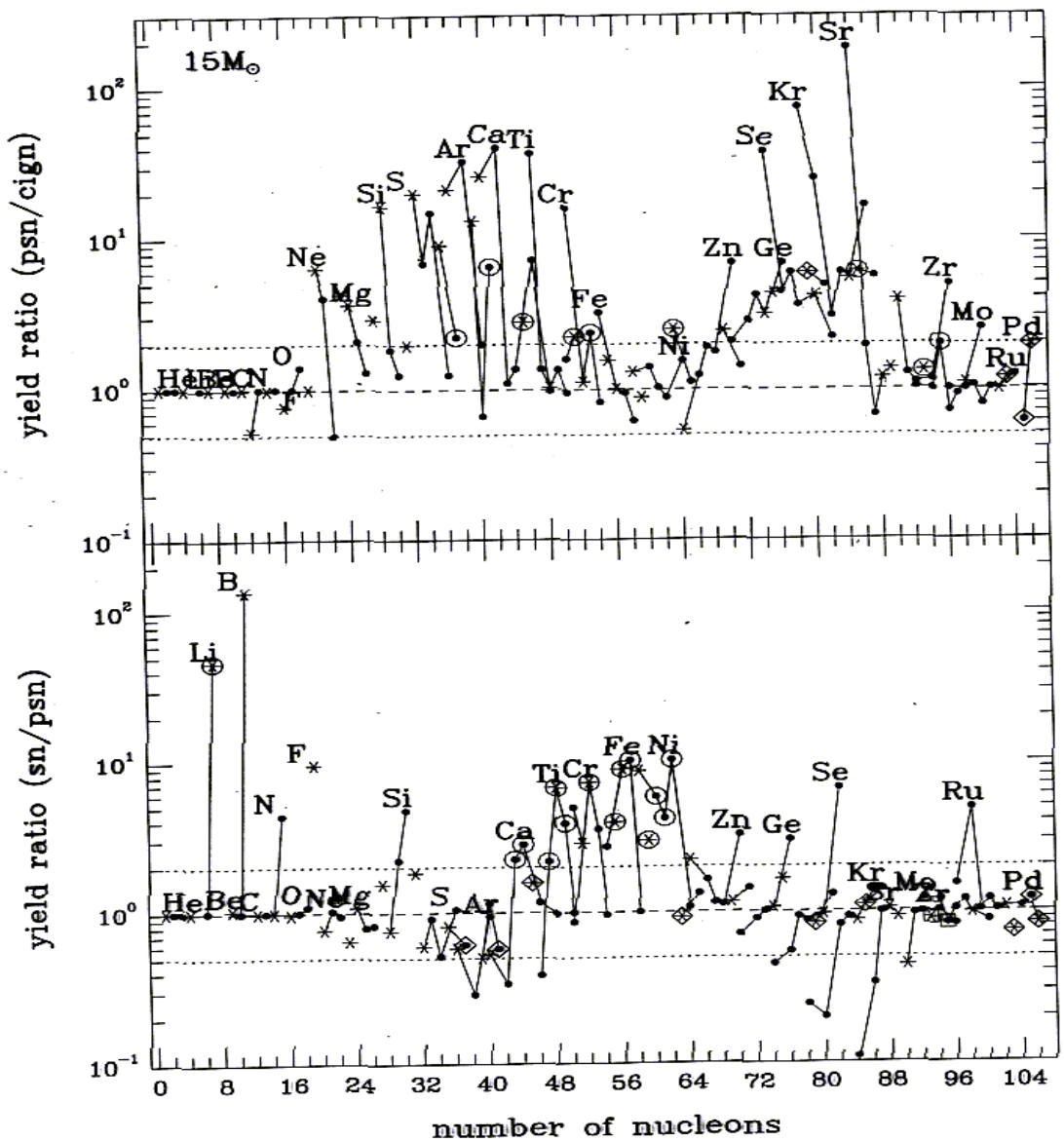
CF88 rates

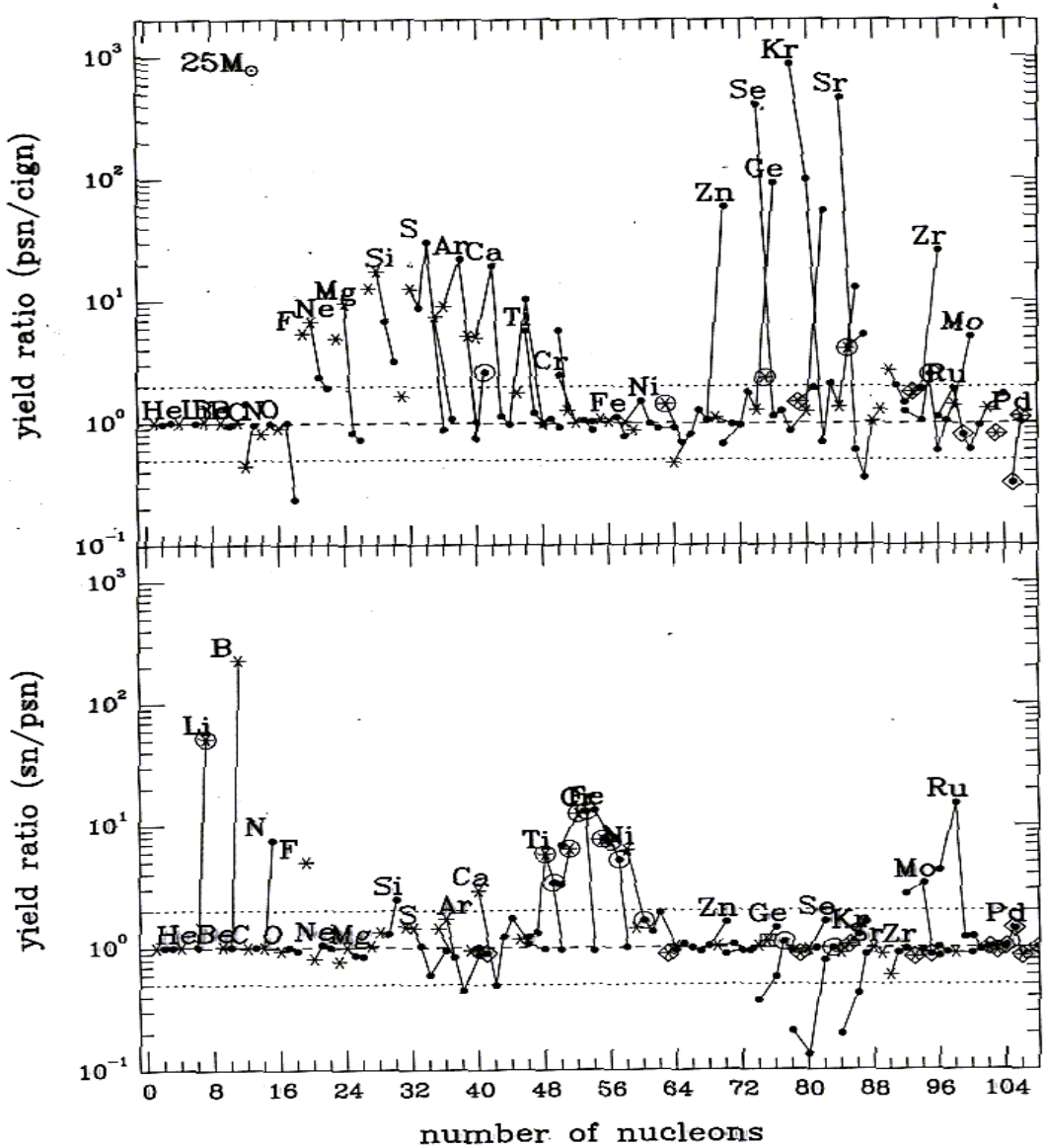
Hoffman & Woosley in prep.

light
● = p-proce






15M⊙
yield ratio (psn/cign)
yield ratio (sn/psn)
number of nucleons
He
B
C
N
O
F
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
Ni
Zn
Ge
Se
Kr
Sr
Zr
Mo
Ru
Pd
Li
Be
0
8
16
24
32
40
48
56
64
72
80
88
96
104


25M⊙
yield ratio (psn/cign)
yield ratio (sn/psn)
number of nucleons
He
Li
Be
B
C
N
O
F
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
Ni
Zn
Ge
Se
Kr
Sr
Zr
Mo
Ru
Pd

Note the production of light p-nuclei, made in last few hours of stars life in the convective oxygen zone via photo-disintegration of existing s-process nuclei. Some r-process isotopes of the same elements are also made here and both should scale with the s-process yield.

The Next Step: BIGGER IS BETTER!

Revisit WW95 and TWW95 with improvements to Stellar Model and Nuclear Physics.

- OPAL opacities (Inglesias LLNL)
- Improved Convection (Woosley)
- Mass Loss (Heger, Woosley)
- Rotation (Heger, Woosley)
- H-Bi coverage (Hoffman)
- Strong & EM rates (Rausher/Hoffman)
- Weak rates (Langanke & Martinez)
- ν-loss rates (Itoh)
- ν-capture rates (McLaughlin, Haxton, Qian)
- exp. rates $A \lesssim 28$ (Wiesher, NACRE)

Heger, Hoffman, Rauscher + Woosley
2000 Ringberg Castle Proceedings

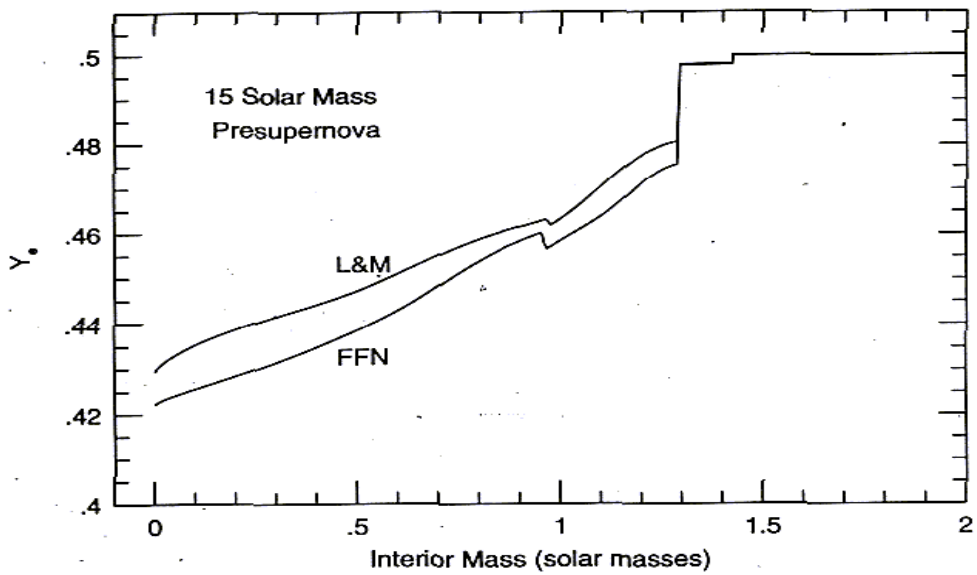
Table 1: Properties of stellar models at the onset of core collapse (*first section*) and integrated stellar yields of some important radioactive nuclei (*second section*).

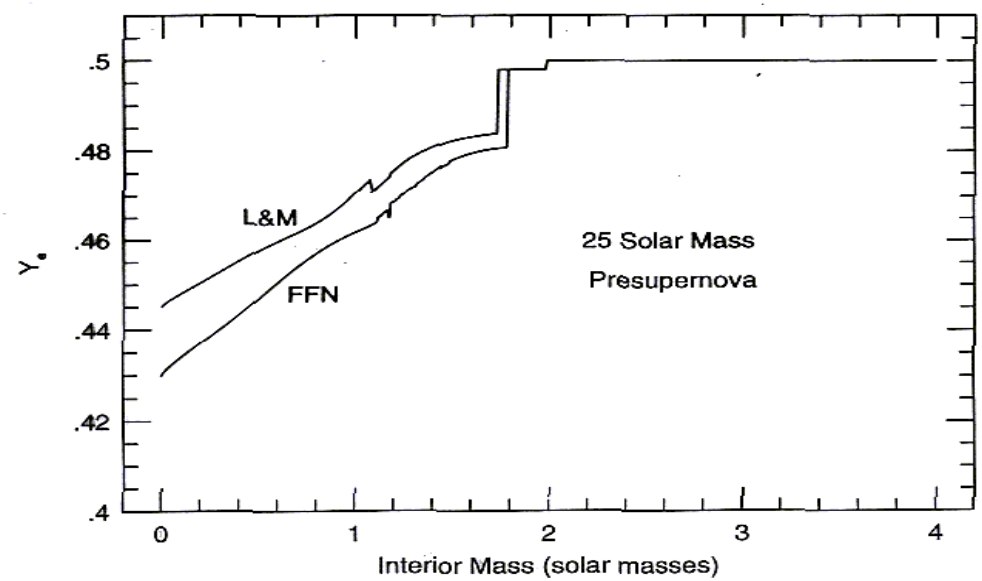
		this work			WW95 [32]		
initial mass	(10^{34} g)	3	4	5	3	4	5
	($M_\odot$)	15.08	20.11	25.14	15.08	20.11	25.14
final mass	($M_\odot$)	12.64	14.23	13.87	15.08	20.11	25.14
He core	↓ ($M_\odot$)	4.16	6.20	8.19	4.36	6.67	9.13
C/O core	($M_\odot$)	2.82	4.57	6.38	2.47	4.37	6.54
Ne/O core	($M_\odot$)	1.87	2.27	2.77	1.81	2.44	2.81
Si core	($M_\odot$)	1.75	2.07	2.11	1.77	2.02	2.06
"Fe" core	($M_\odot$)	1.55	1.47	1.74	1.32	1.74	1.78
delept. core	($M_\odot$)	1.29	1.47	1.59	1.29	1.74	1.78
central Y_e	↑	0.436	0.439	0.444	0.422	0.430	0.430
Pist. location	($M_\odot$)	1.29	1.47	1.74	1.29	1.74	1.78
remnant mass	($M_\odot$)	1.72	1.76	2.31[a]	1.43	2.06	2.41[b]
		radioactive yields					
^{26}Al	∼ ($M_\odot$)	$4.66\cdot10^{-5}$	$4.89\cdot10^{-5}$	$1.45\cdot10^{-4}$	$4.30\cdot10^{-5}$	$3.47\cdot10^{-5}$	$1.27\cdot10^{-4}$
^{44}Ti	↓ ($M_\odot$)	$1.75\cdot10^{-5}$	$8.89\cdot10^{-6}$	$2.75\cdot10^{-6}$	$5.68\cdot10^{-5}$	$1.38\cdot10^{-5}$	$1.95\cdot10^{-6}$
^{56}Ni	∼ ($M_\odot$)	$9.08\cdot10^{-2}$	$7.67\cdot10^{-2}$	$5.07\cdot10^{-3}$↑	$1.15\cdot10^{-1}$	$8.80\cdot10^{-2}$	$7.26\cdot10^{-5}$
^{60}Fe	↑ ($M_\odot$)	$7.16\cdot10^{-5}$	$2.84\cdot10^{-5}$	$1.45\cdot10^{-4}$	$2.66\cdot10^{-5}$	$1.12\cdot10^{-5}$	$2.10\cdot10^{-5}$

[a] $1.5\cdot10^{51}$ erg explosion

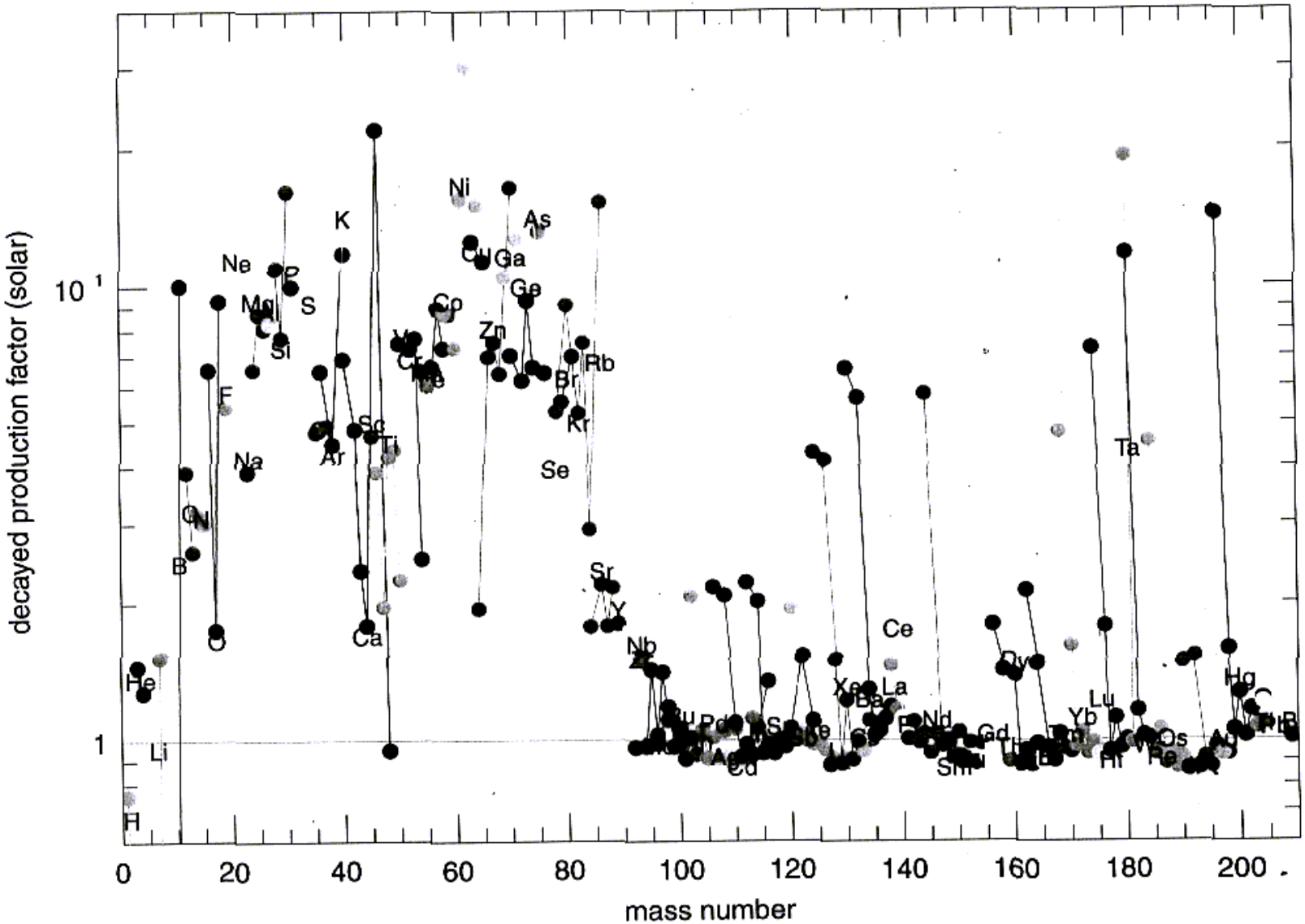
[b] in [32] a remnant mass of 2.07 $M_\odot$ is given in error for the $1.2\cdot10^{51}$ erg explosion. This change decreases significantly the yields of ^{56}Ni and ^{44}Ti (WW95: $1.29\cdot10^{-1}$ $M_\odot$ and $3.04\cdot10^{-5}$ $M_\odot$, respectively).

http://arXiv.org/abs/astro-ph/00063

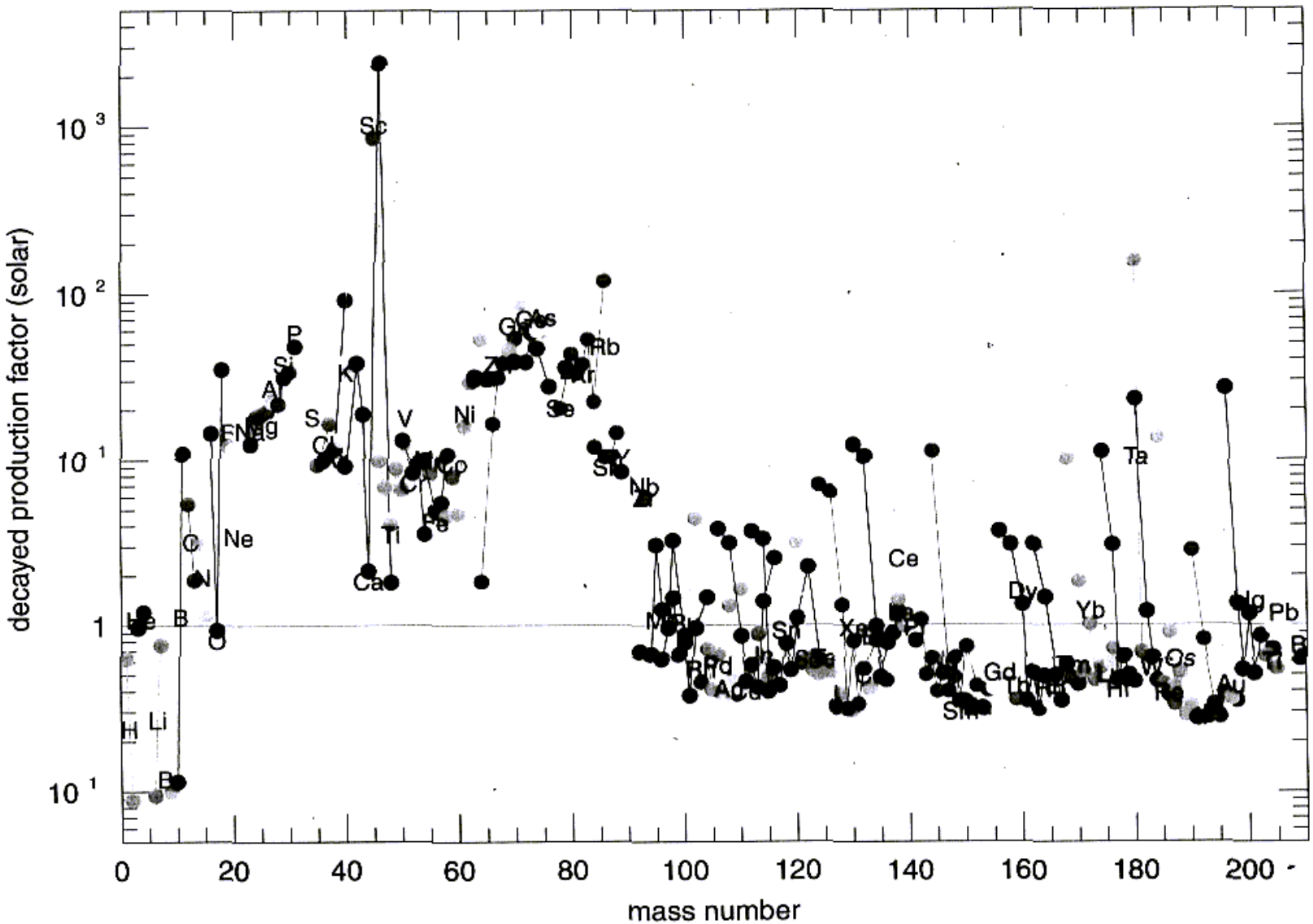

15 Solar Mass
Presupernova
L&M
FFN
Y_e
.5
.48
.46
.44
.42
.4
0
.5
1
1.5
2
Interior Mass (solar masses)


25 Solar Mass
Presupernova
L&M
FFN
Y_e
.5
.48
.46
.44
.42
.4
0
1
2
3
4
Interior Mass (solar masses)

15 $M_\odot$

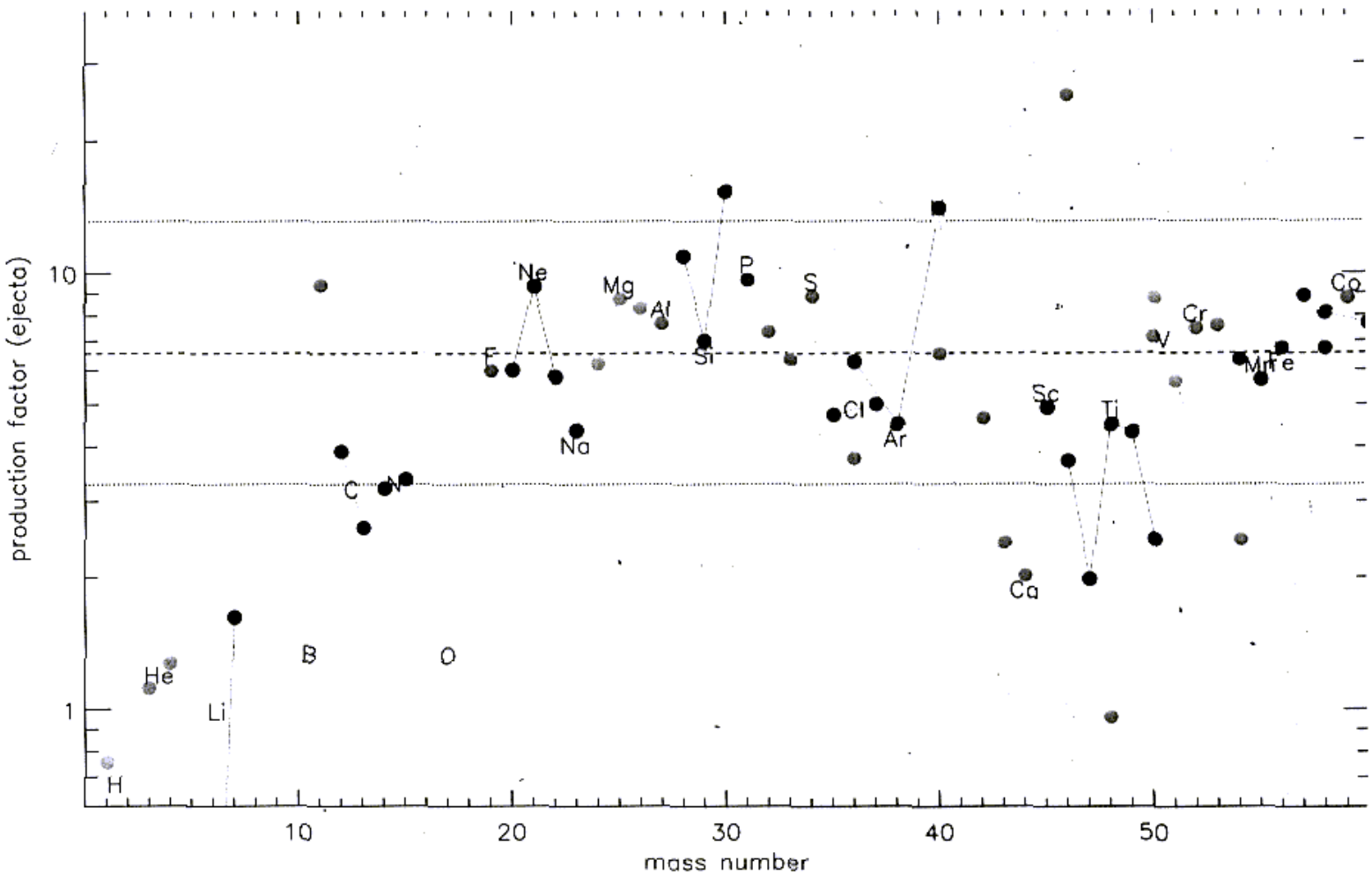

decayed production factor (solar)
10 1
1
mass number
0
20
40
60
80
100
120
140
160
180
200
H
He
Li
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
K
Ar
Ca
Sc
Ti
Ni
Cu
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Nb
Ce
La
Nd
Gd
Dy
Yb
Lu
Hf
Ta
Os
Hg

25 M☉

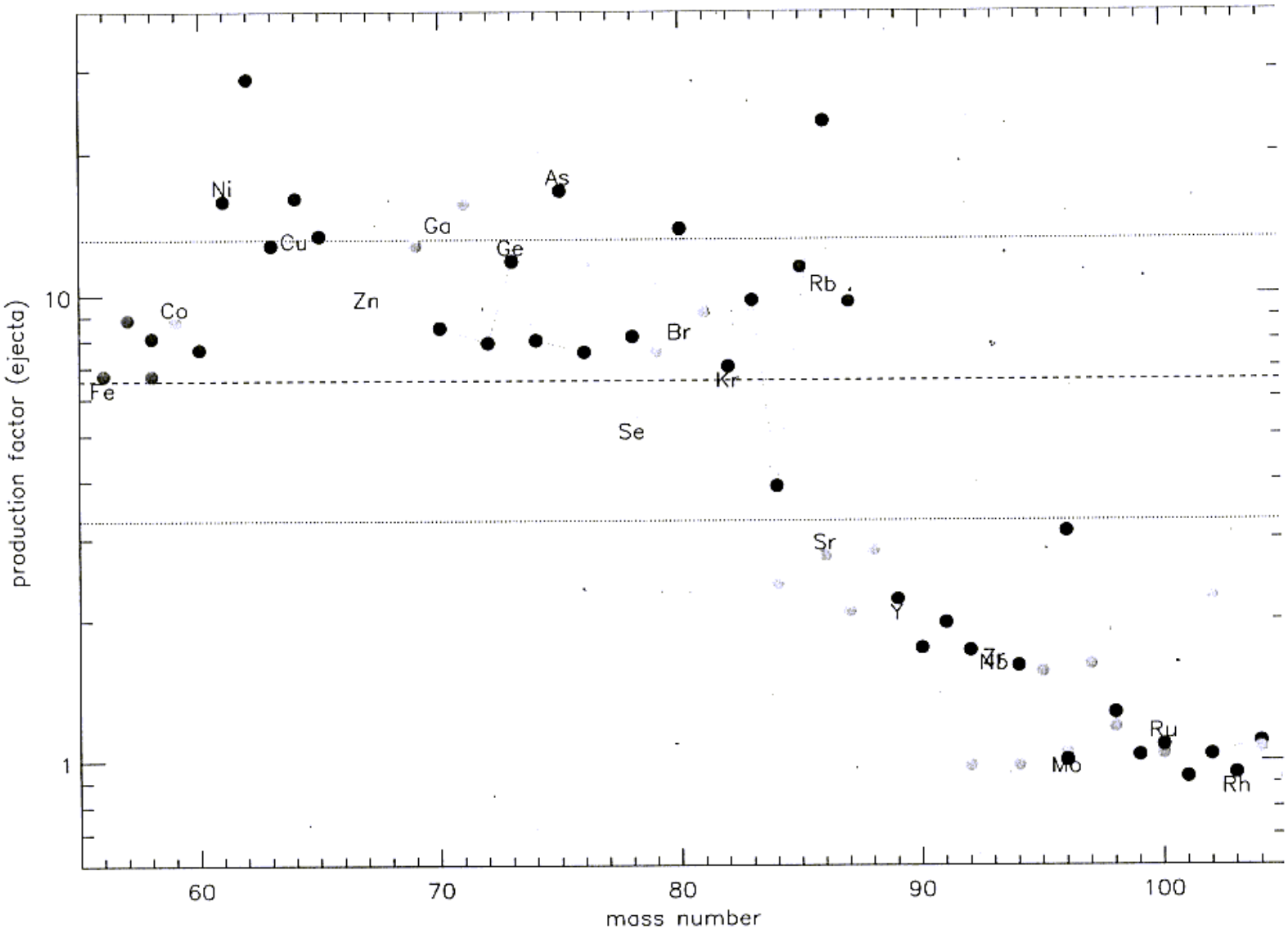


decayed production factor (solar)
mass number
10 3
10 2
10 1
1
10 1
0
20
40
60
80
100
120
140
160
180
200
Sc
P
Si
Al
Mg
Na
F
S
Cl
K
V
Ni
Ca
Ti
Fe
Co
Ne
C
N
O
B
Li
H
Rb
Se
Nb
Ce
Dy
Yb
Ta
Pb
Os
Au
Gd
Sm
Sn
Rd

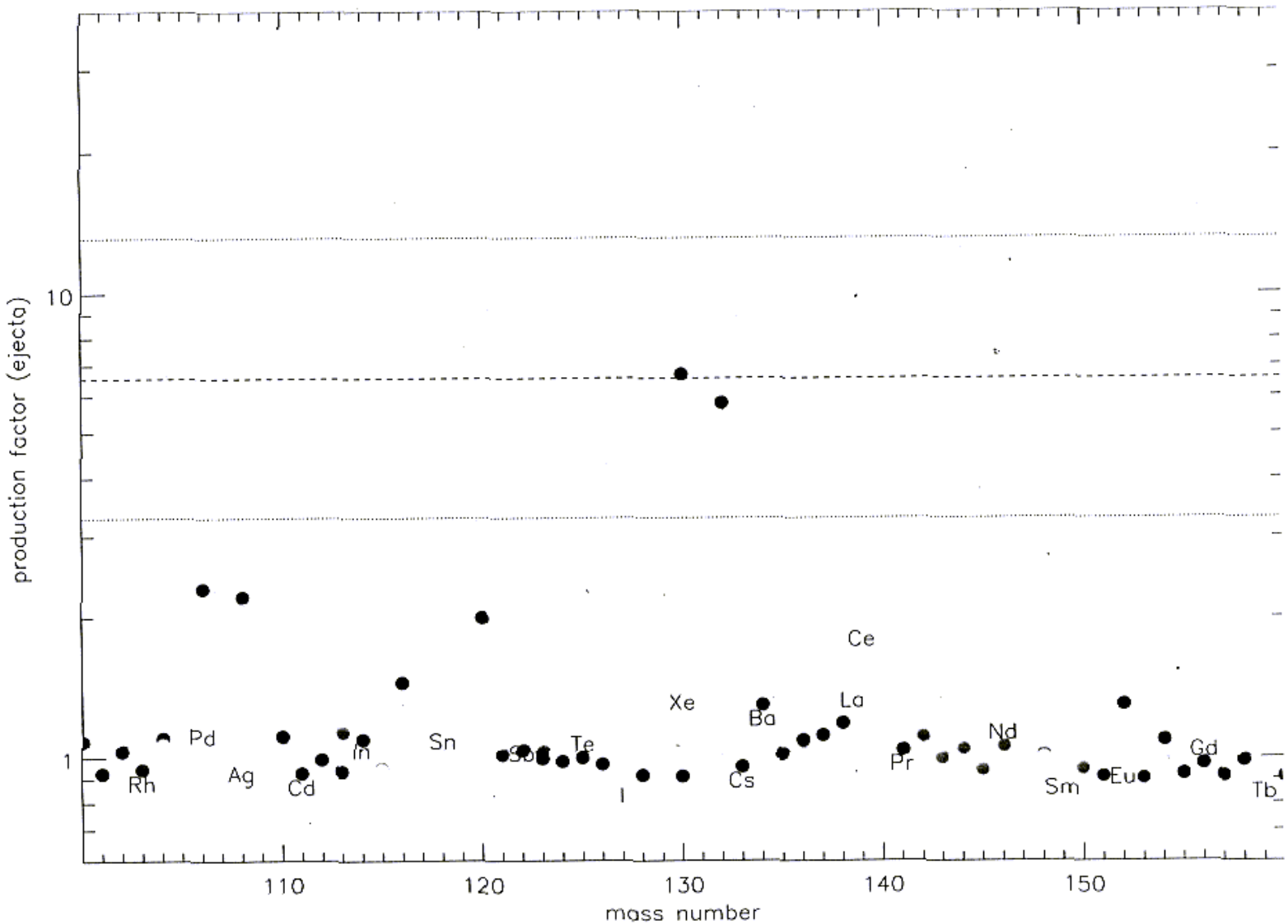
15 $M_\odot$

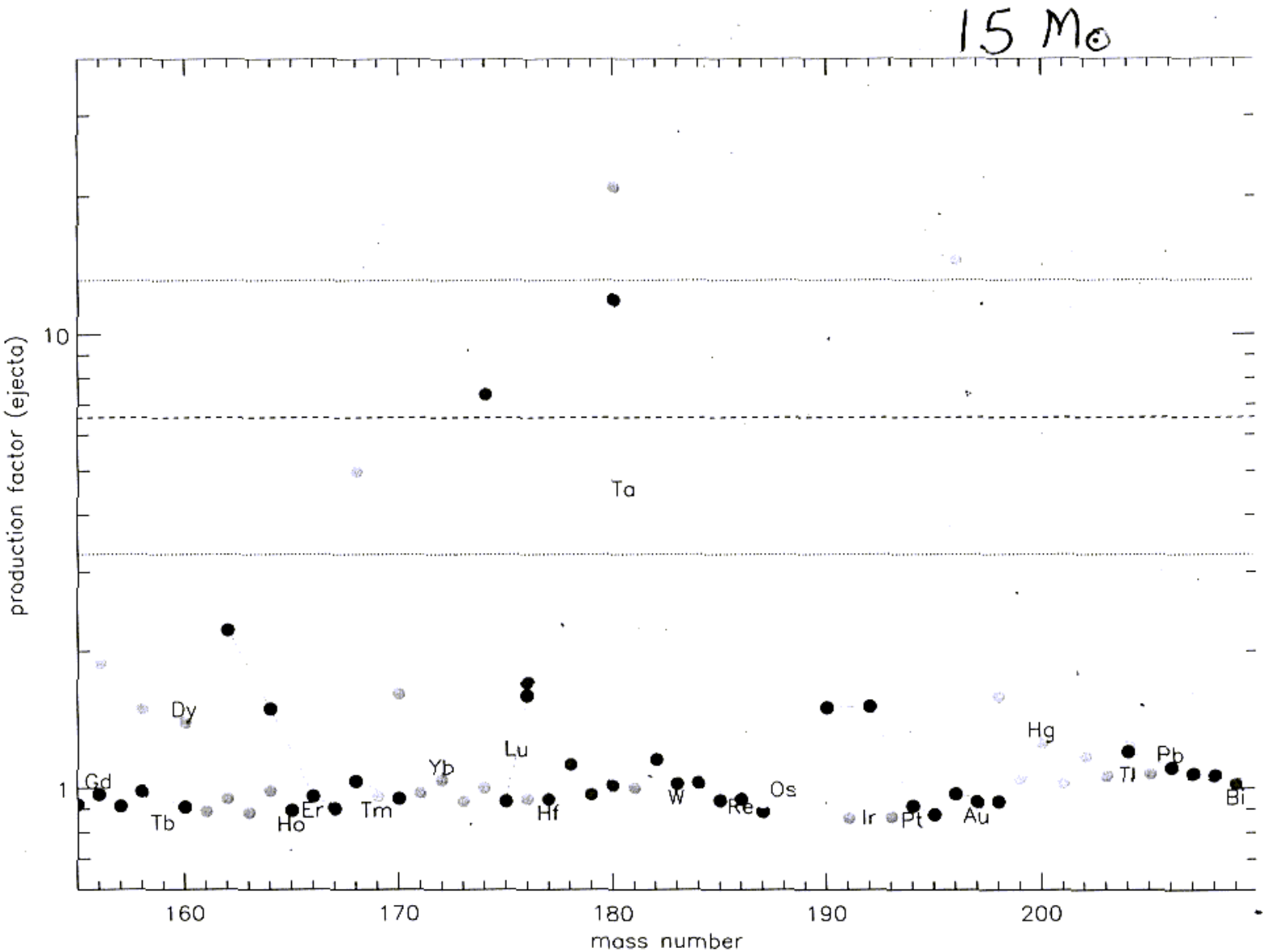

production factor (ejecta)
10
1
mass number
10
20
30
40
50
H
He
Li
B
O
C
N
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
Ca
Sc
Ti
V
Cr
Mn
Fe
Co

15 $M_\odot$


production factor (ejecta)
10
1
60
70
80
90
100
mass number
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh

1.5 M☉


production factor (ejecta)
10
1
Pd
Rh
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
110
120
130
140
150
mass number


15 M⊙
production factor (ejecta)
10
1
Ta
Dy
Gd
Tb
Ho
Er
Tm
Yb
Lu
Hf
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
160
170
180
190
200
mass number

Words to live by

"There is something facinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."

Mark Twain in *Life on the Mississippi.*

cited at the beginning of Fowler, Caughlan, & Zimmerman, ARAA **13**, 69 (1975).

Stellar nucleosynthesis is becoming a mature field rich with diverse and highly detailed observational data. The "factor of two" accuracy that was adequate in the past may not do justice to the observations of the future, be they from the laboratory or the observatory.