Nucleosynthesis in O-Ne-Mg Supernovae

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Collaborators

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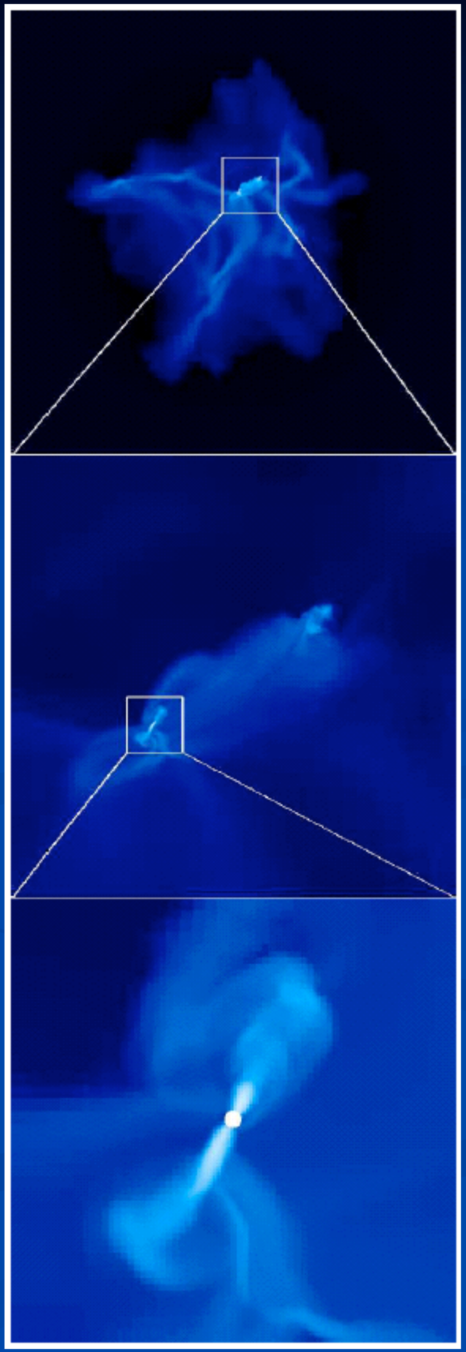
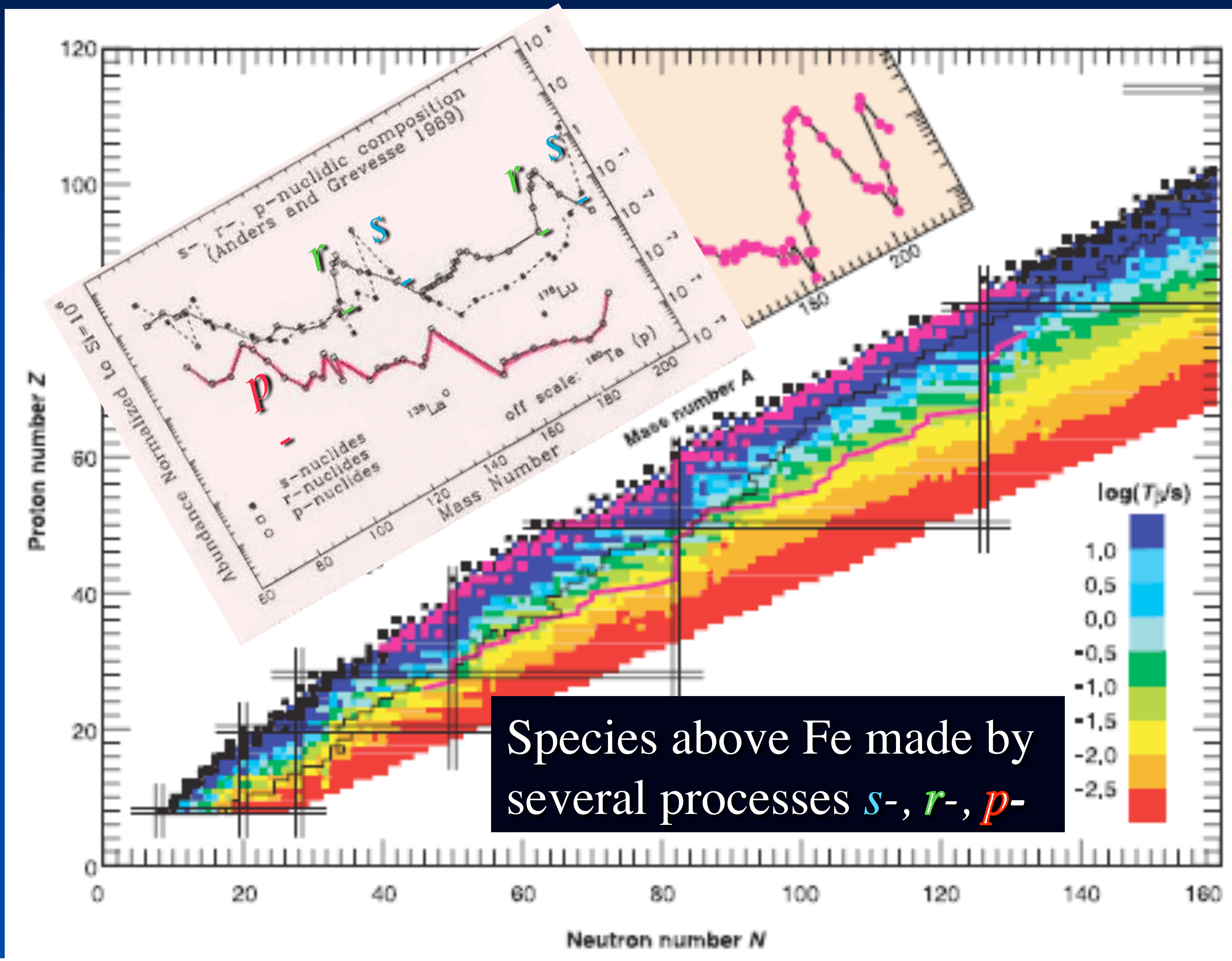
- S. E. Woosley (UC Santa Cruz)

- Y.-Z. Qian (U. Minnesota)



Heavy element Synthesis



Species above Fe made by several processes *s*-, *r*-, *p*-

r-process in SN "light"?

Arguments for:

- IMF predicts many such stars (~ 8-10 M_{sun})
- Cores are not Fe but "light" O-Ne-Mg.
- Only a fraction may explode as ECSNe (4% to at most 20%).

Wheeler *et al.* (98)
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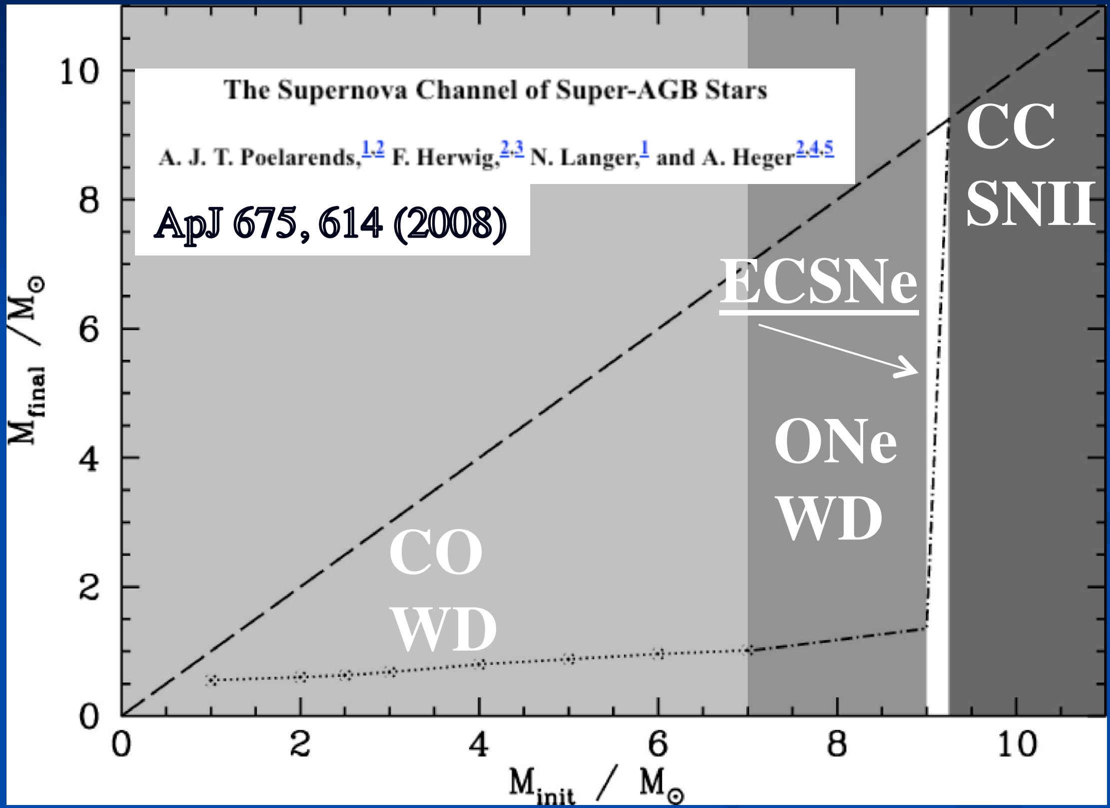


Final mass of the remnant as a function of the initial mass. Remnant regimes are shaded light gray for CO white dwarfs, medium gray for ONe white dwarfs, white for ECSNe, and dark gray for CCSNe. The final mass is either the WD mass or the stellar mass at the time of SN explosion. The dashed line indicates the line of initial mass equal to final mass.

Nucleosynthesis from high-T expansions characterized by 3 basic parameters +…

- Entropy: S_{rad} (k_B/nuc)
- Exp. timescale: τ_{exp} (s)
- Composition: Y_e

The e^- mole number, describes n/p ratio
- set by L_ν & spectra

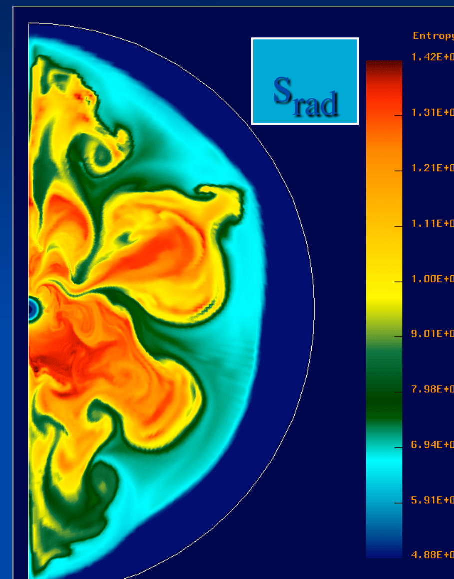
$Y_e < 0.5$: n-rich

$Y_e > 0.5$: p-rich

- Mass loss rate ($M_{sun}\ s^{-1}$)

As the explosion evolves an ejected mass element will inherit some combination of these parameters. For E below ~0.5 MeV they remain fairly constant as the wind proceeds to freeze out.

Janka & Muller A&A 306, 167 (1996)



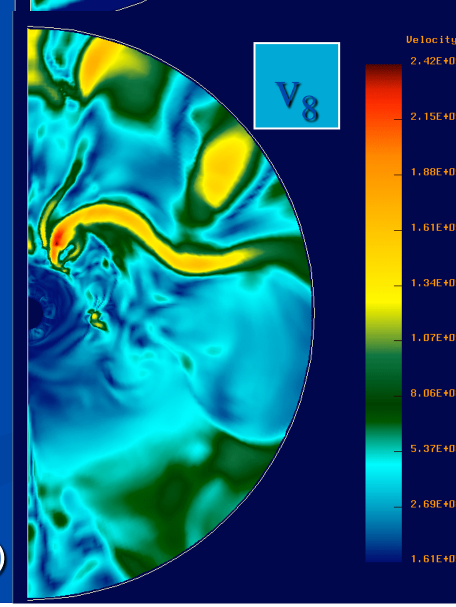
@ t = 170 ms

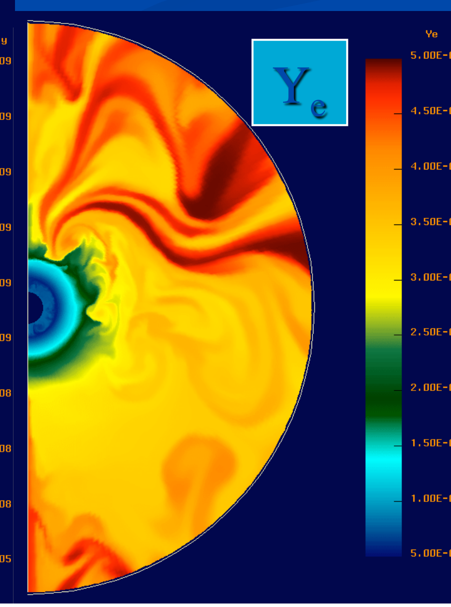
500 < r (km) < 1600

$5 < S_{rad} < 15$

$2 < v_8 < 25$

$0.1 < Y_e < 0.5$

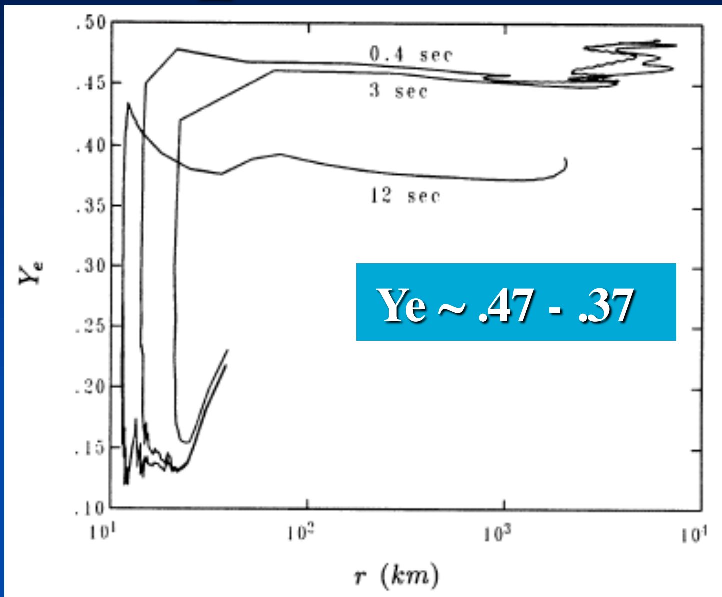


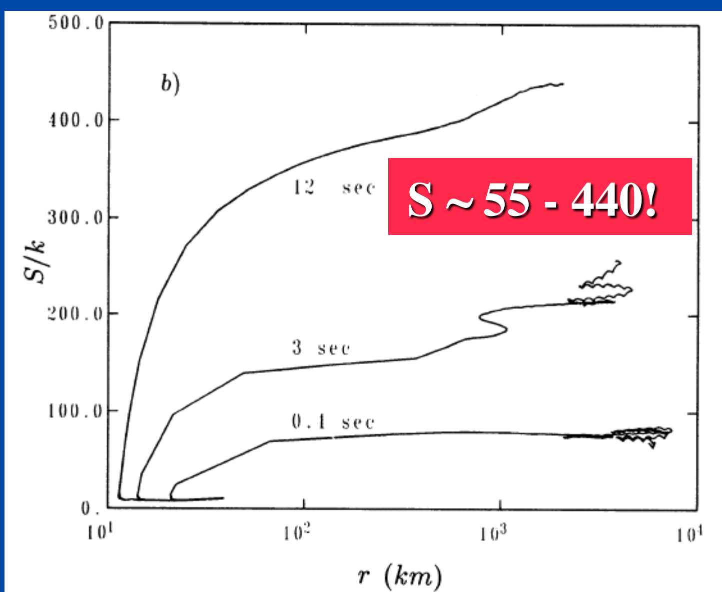


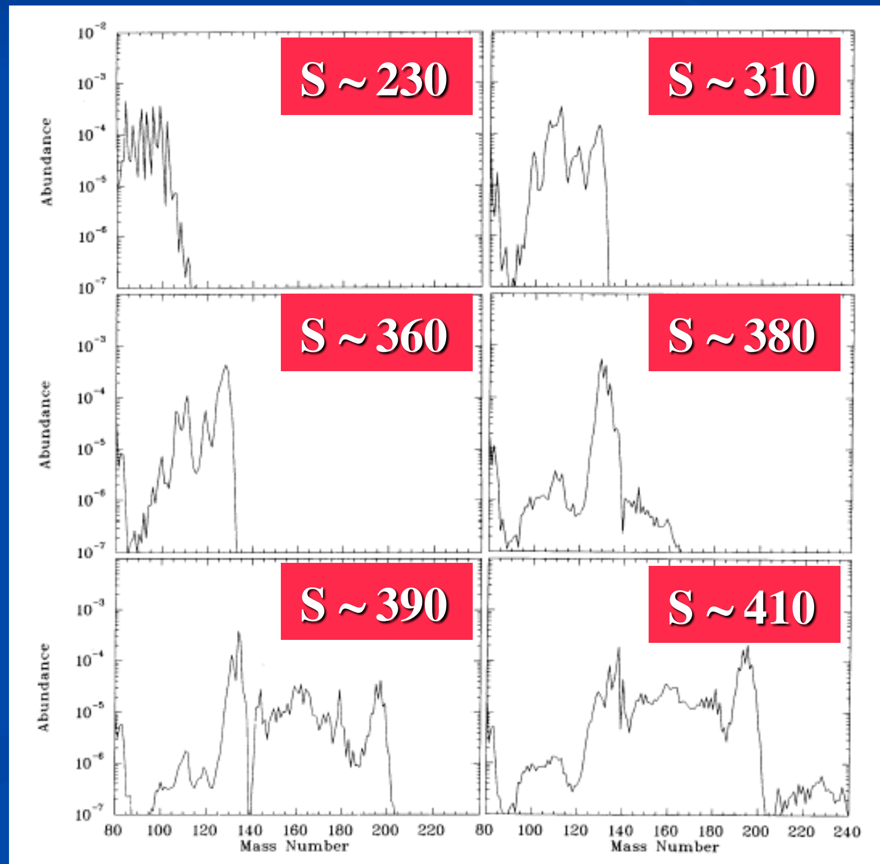
r-process in ν-winds – 1990's

20 M_{sun} delayed-explosion (Woosley, Wilson, Mathews, Hoffman & Meyer ApJ 433, p. 229, 1994)

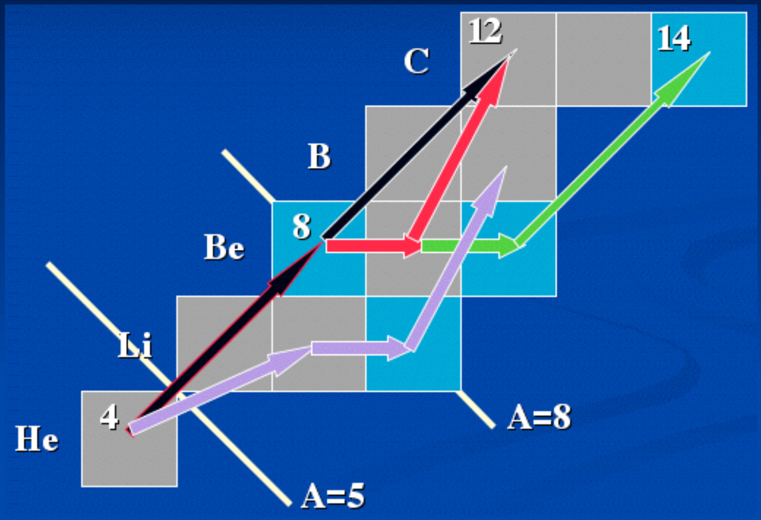
..a range of conditions needed to make *r*-process features.







Affects of S_{rad} & τ_{exp}



- $\alpha(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$
- $3\alpha \rightarrow {}^{12}C$
- $\alpha(\alpha n,\gamma)^{9}Be(n,\gamma)^{10}Be\ (\alpha,\gamma)^{14}C$
- $\alpha(t,\gamma)^{7}Li(n,\gamma)\ {}^{8}Li(\alpha,n)^{11}B$

(top 3 proportional to ρ^2)

$$S_{rad} = 5.2(T^{3}_{MeV}/\rho_{8})$$

- Low ρ -> high S_{rad} one has inefficient assembly of light particles to heavies nuclei, n/s high, with the potential for flow to large mass number (A).
- High ρ -> low S_{rad} with efficient assembly of light particles to heavies ones, only go to iron group (A~60), with a lower n/s.
- A short expansion time scale also inhibits α-particle assembly and hence heavy seed production, leaving many light particles to add onto those seeds that are made.

Nuclear Flows and Y_e

$$F_{net} = Y_I Y_\alpha \rho \lambda_{\alpha\gamma} - Y_L \lambda_{\gamma\alpha}$$

$$\lambda_{\gamma\alpha} = \left(\frac{g_I g_\alpha}{g_L}\right)\left(\frac{G_I}{G_L}\right)\left(\frac{A_I A_\alpha}{A_L}\frac{2\pi kT}{h^2 N_A}\right)^{3/2} \lambda_{\alpha\gamma} e^{-Q_{\alpha\gamma}/kT}$$

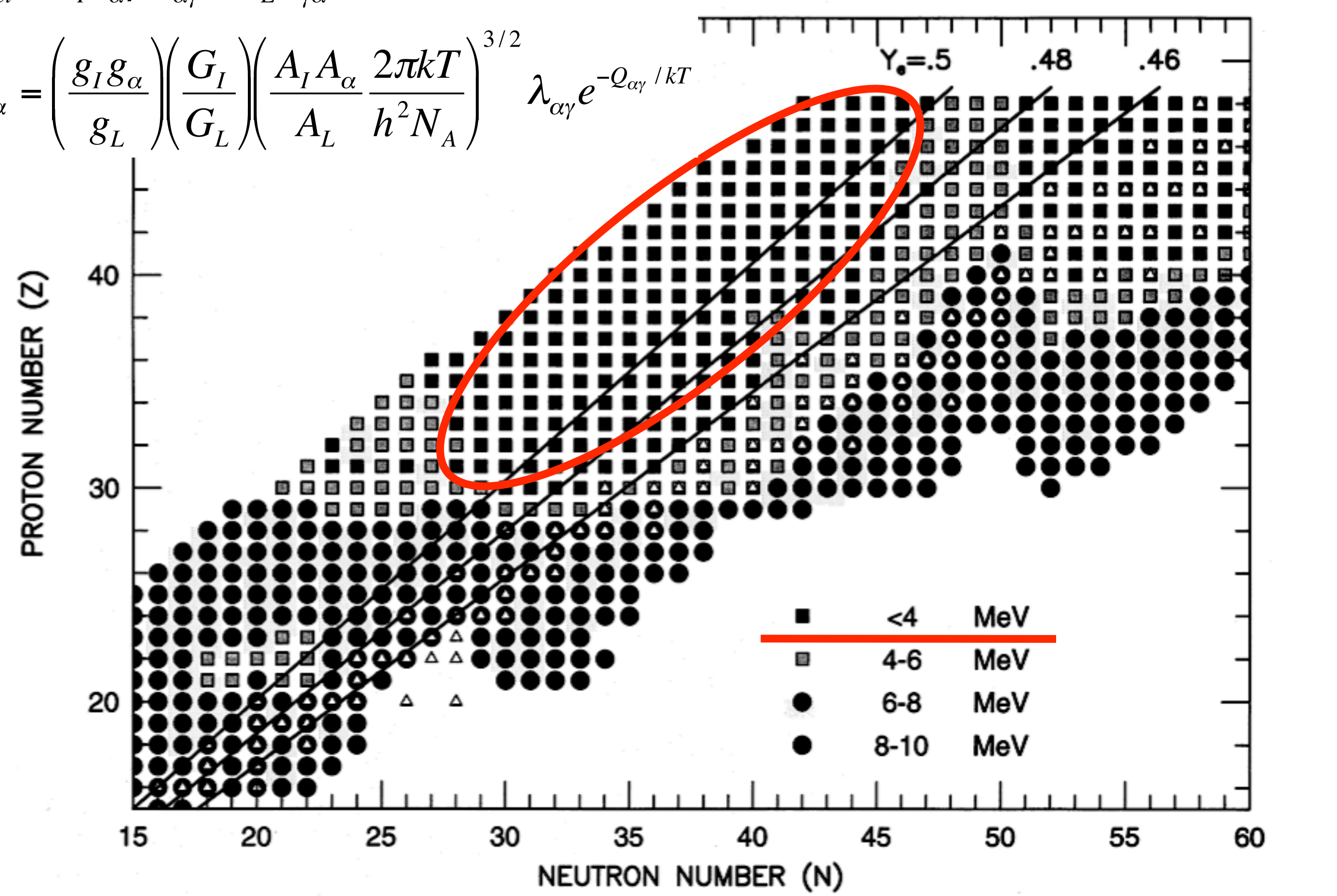


FIG. 5.—Contours of constant α-particle separation energy. The contours are given by the first isotope of each element to have a separation energy less than the specified value. Open triangles indicate locations of the stable isotopes. Three lines of constant Y_e = 0.5, 0.48, and 0.46 are shown.

Y_e determines the initial path taken, there after the local landscape (separation energies) dictates the course of events.

Bypassing the Waiting Points

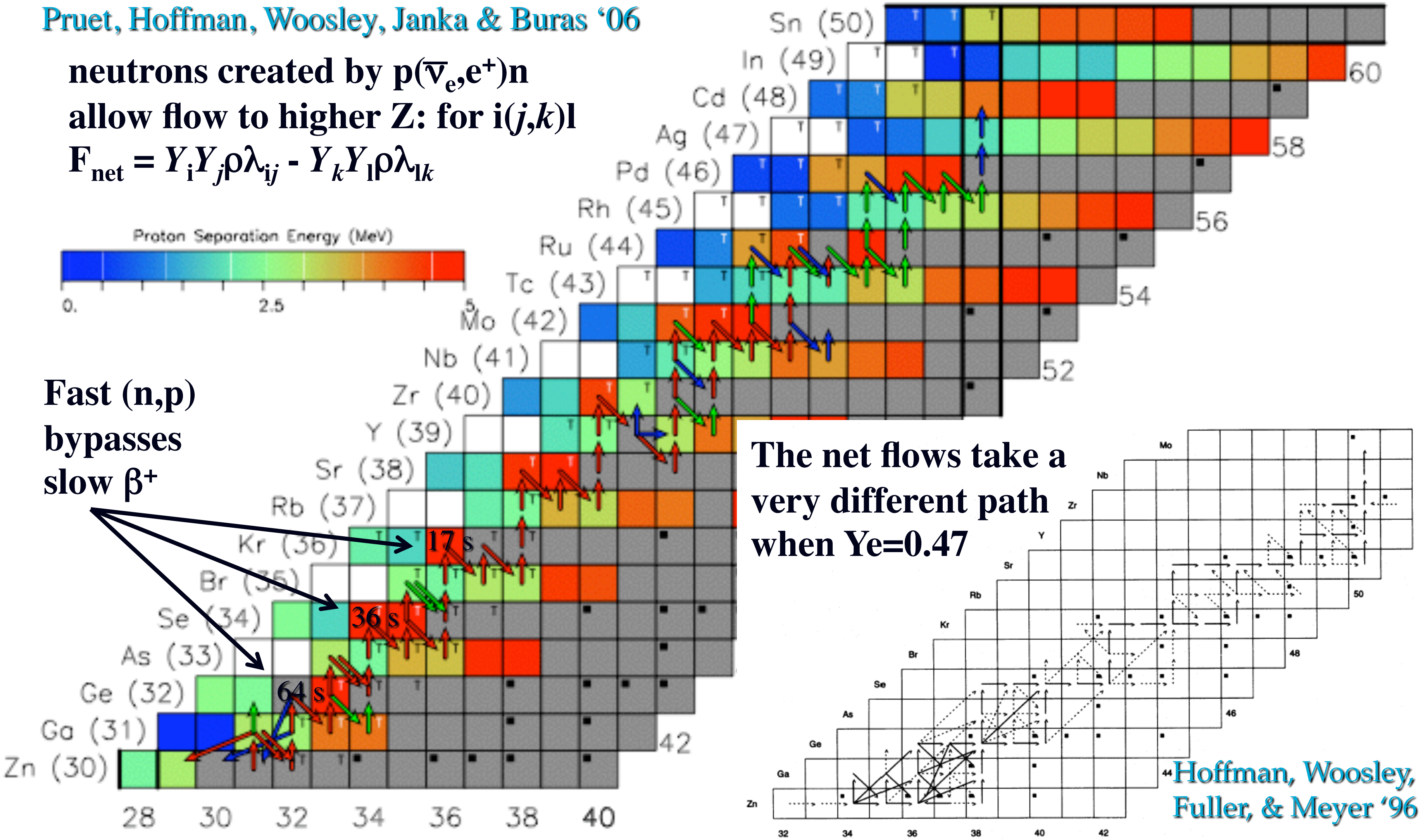
Pruet, Hoffman, Woosley, Janka & Buras '06

neutrons created by p($\overline{\nu}_e$,e^+)n allow flow to higher Z: for i(j,k)l

$$F_{net} = Y_i Y_j \rho \lambda_{ij} - Y_k Y_l \rho \lambda_{lk}$$

Fast (n,p) bypasses slow β^+

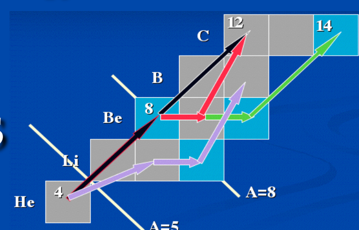
The net flows take a very different path when Ye=0.47

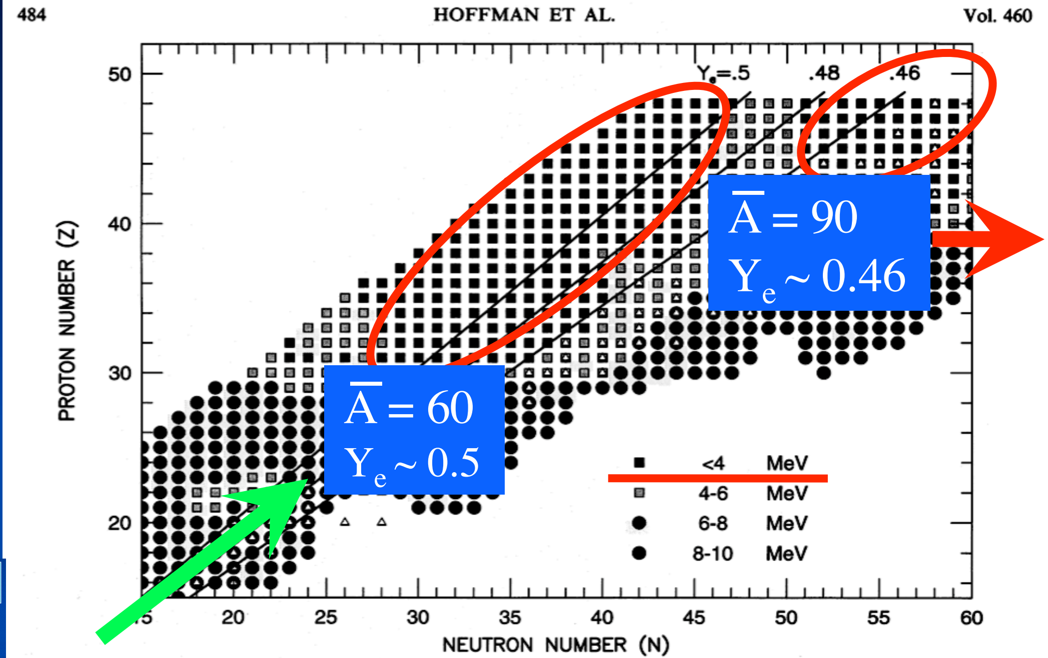


Hoffman, Woosley, Fuller, & Meyer '96

- Q: What combinations of S, Y_e, τ_{exp} are needed to make Au, Pt (3^{rd} r-proc peak)?
- 2n + 2p -> α
- α's re-assemble to make a "seed" distribution with mass fraction X_h & some left

  over α's & n's





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- X_h has an average charge ($\bar{Z}$) and mass ($\bar{A}$) distribution

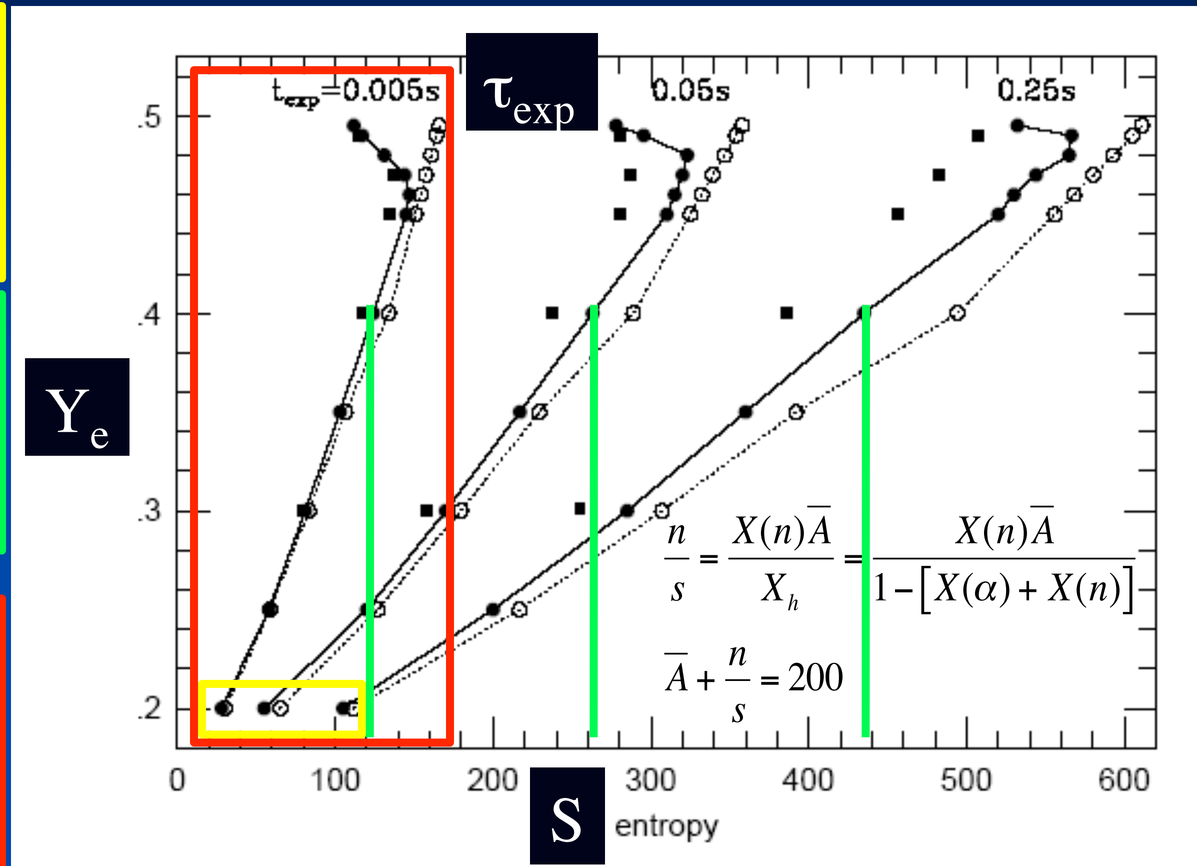
- n/s = neutron to seed ratio

$$\frac{n}{s} = \frac{X(n)\bar{A}}{X_h} = \frac{X(n)\bar{A}}{1-\left[X(\alpha)+X(n)\right]}$$

$$\bar{A} + \frac{n}{s} = 200$$

r-process requirements: S, Y_e, τ_{exp}

- For a low Y_e one can make the r-process at low S regardless of τ_{exp}
- For a given Y_e (0.4) a longer τ_{exp} requires a larger entropy (S)
- For a very short τ_{exp} you can make the *r*-process for modest S even if Y_e is large



Hoffman, Woosley & Qian ApJ 482, 951 (1997)

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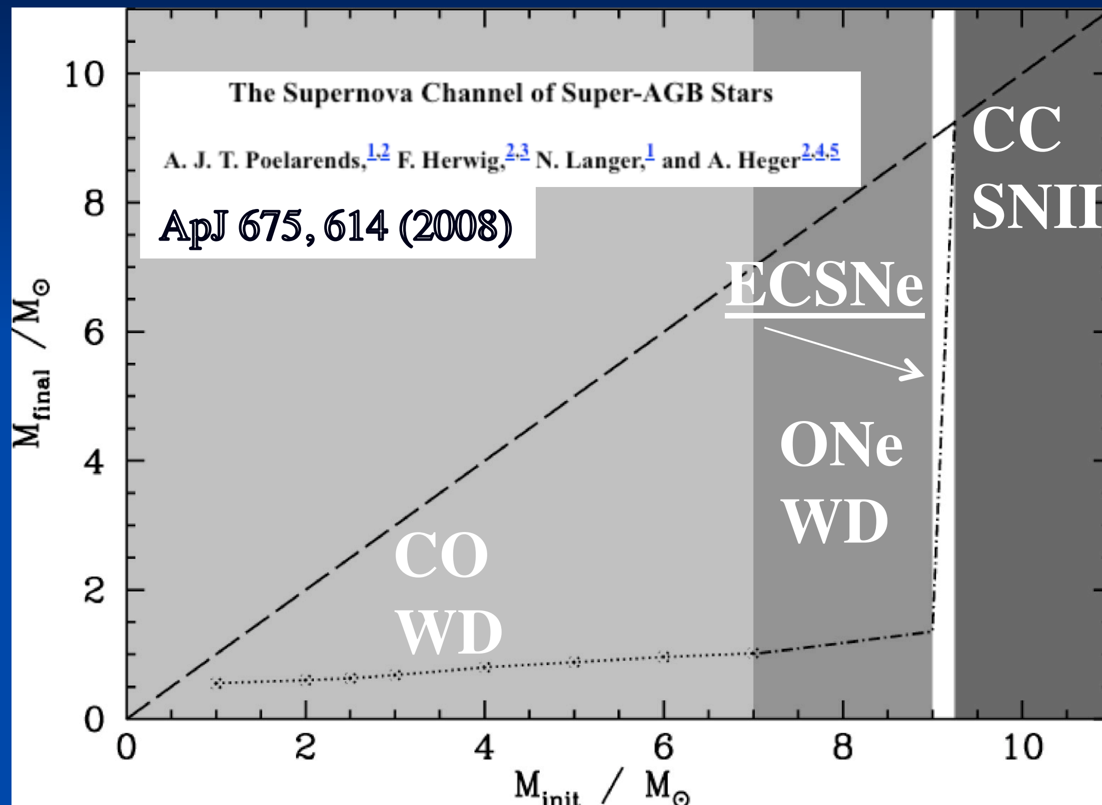

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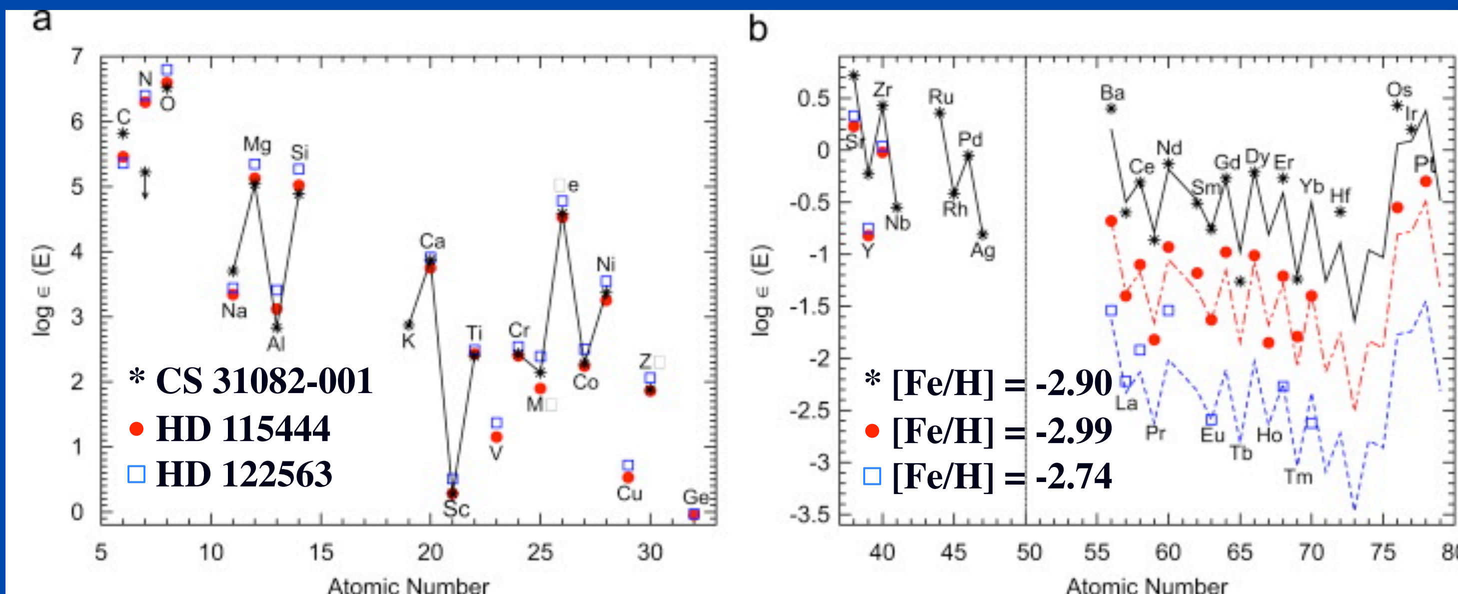
Promising observ. reasons:

- Observations of metal-poor stars suggest heavy *r*-process component (A>130) seems to be decoupled from the main sources of intermediate mass products of stellar evolution

- This main component (O-Ge) evolves with [Fe/H]
- ECSNe do not make much Fe or O-Ge, so any *r*-process can be primary (as required for actinides like U)



Qian & Wasserburg, Phys. Rep. 422, 237 (2007)

Promising theory reasons:

Small, compact, w/ steep ρ-gradients & little overlying matter, a collapse triggered by *e^-* captures would produce a very fast and hot SN shock: FAST expansion timescale, HIGH entropy.

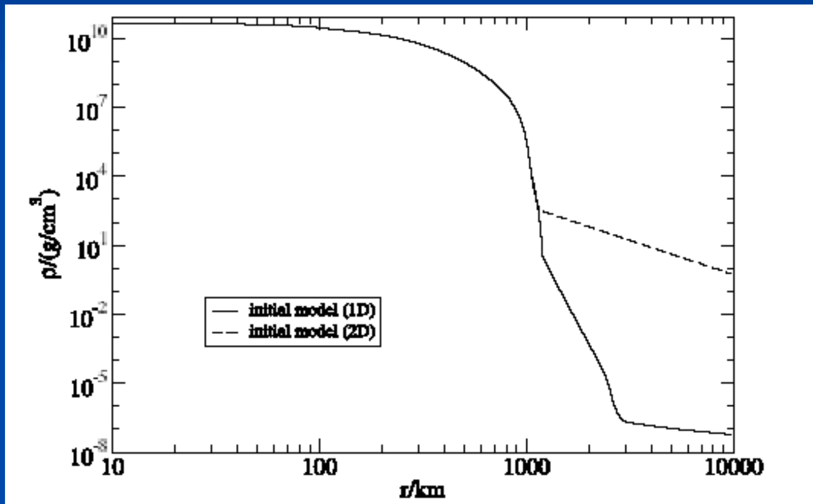
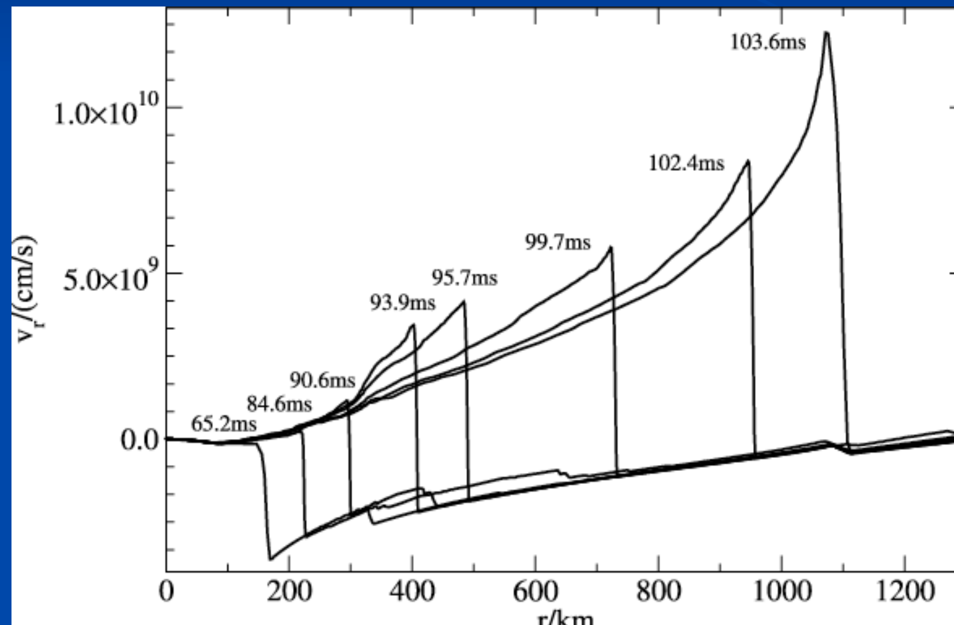


Fig. 1. Density profiles of the initial O-Ne-Mg core models used for the 1D and 2D supernova simulations. The solid curve corresponds to the original core data of Nomoto (1984, 1987), extended at $\rho \lesssim 10^3$ g cm^{-3} by a hydrogen envelope (70% H, 30% He) in hydrostatic equilibrium (Nomoto, private communiation). This stellar structure was used for the spherically symmetric core-collapse simulation in this paper. In contrast, the 2D simulation was done with the same core, but with a dilute, hydrostatic helium shell added at low densities (dashed line). Such a stellar structure was employed previously by Kitaura et al. (2006).



Janka *et al.* A&A 485, 199 (2008)

Promising idea:

- Ning, Qian & Meyer propose an *r*-process might occur in the C-O surface layers *above* an O-Ne-Mg core ECSNe.

- From a PSN model (Nomoto 1984) with an *assumed* shock velocity & using analytic jump conditions they derived a fast expansion timescale and modest entropy that gives for Ye ~ 0.5 conditions suitable for *r*-process nucleosynthesis.

Ning, H., Qian, Y.-Z., & Meyer, B. S. 2007, ApJ, 667, L159

The SN simulations mentioned above showed that the shock speed in the region of interest is $v_{sh} \sim 10^{10}$ cm s^{-1}. For such v_{sh}, the strong shock condition $\rho v_{sh}^2 \gg P$ is satisfied and the energy density of the shocked matter is expected to be dominated by the contributions from relativistic particles (radiation and electron-positron pairs). In this case, the density, velocity, and pressure of the shocked matter (with the subscript "*p*" standing for "postshock") are given by (e.g., Chevalier 1976)

$$\rho_p = 7\rho,\ v_p = \frac{6}{7}v_{sh},\ P_p = \frac{6}{7}\rho v_{sh}^2, \qquad (1)$$

respectively. Using equation (1) and $P_p = (11/12)a_{rad}T_p^4$ with a_{rad} being the radiation constant, we obtain the postshock temperature

$$T_p = 1.05 \times 10^{10}\rho_6^{1/4}v_{sh,10}^{1/2}\ \mathrm{K} \qquad (2)$$

and the postshock entropy in relativistic particles

$$S = \frac{11}{3}\frac{a_{rad}T_p^3}{N_A\rho_p} = 56.1\frac{v_{sh,10}^{3/2}}{\rho_6^{1/4}}\ k\ \mathrm{nucleon}^{-1}, \qquad (3)$$

where ρ_6 is the preshock density in units of 10^6 g cm^{-3}, $v_{sh,10}$ is the shock speed in units of 10^{10} cm s^{-1}, and N_A is Avogadro's number. The entropy S is also a measure of the energy density in relativistic particles relative to that in nonrelativistic ones. Equation (3) gives $S \gg 1$ in the region of interest, so the corresponding energy density of the shocked matter is indeed dominated by relativistic particles.

Matzner & McKee (1999) showed that v_{sh} at a specific r depends on the preshock density at r and the amount of matter entrained by the shock prior to reaching r. As the region of interest is very thin and adds very little to the matter already entrained by the shock, we expect that the shock speed in this region takes the form $v_{sh} \propto \rho^{-0.19}$ (Matzner & McKee 1999), which gives

$$\frac{dv_{sh}}{dr} = -0.19\left(\frac{d\ln\rho}{d\ln r}\right)\frac{v_{sh}}{r} = 0.19w\left(\frac{v_{sh}}{r}\right). \qquad (4)$$

r-process requirements: S, Y_e, τ_{exp}

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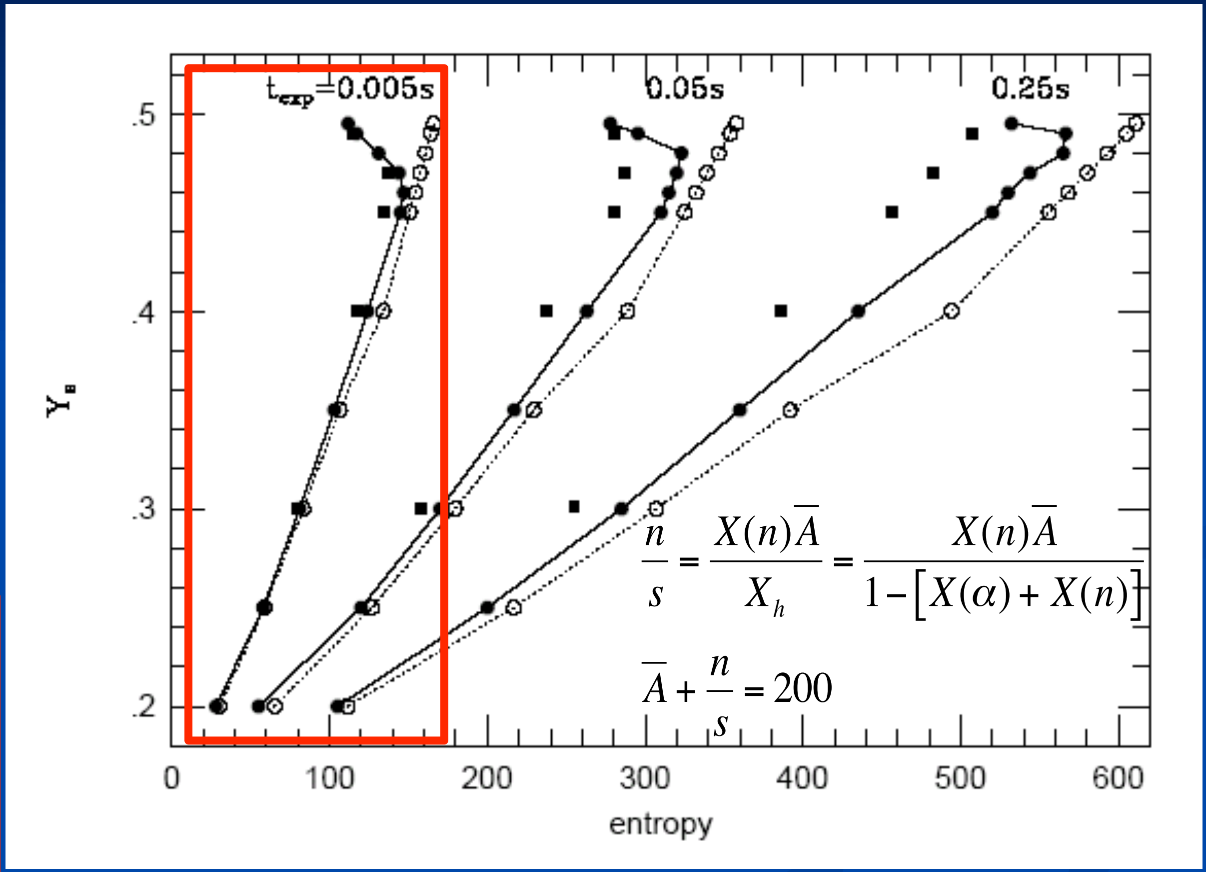
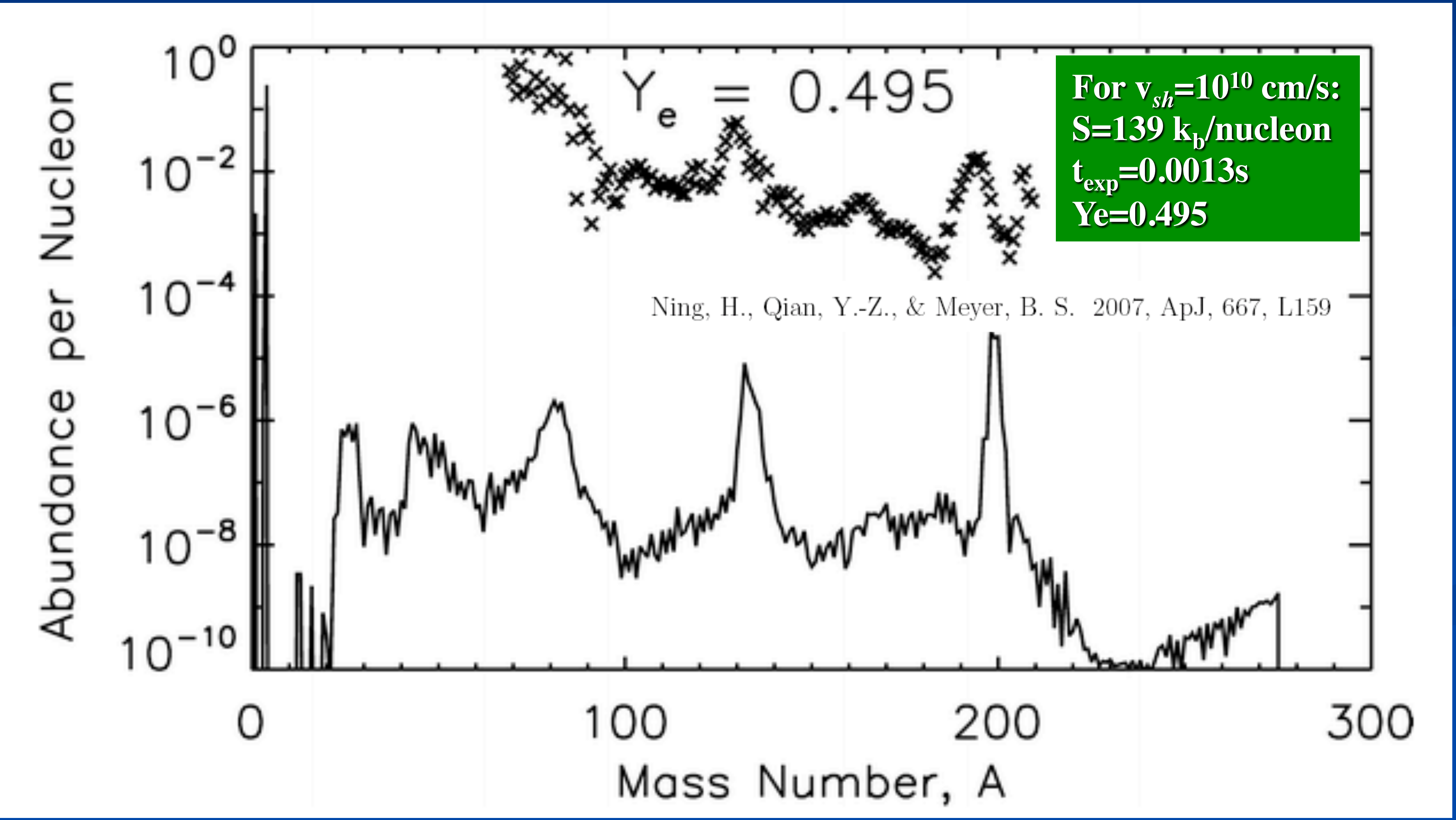


Hoffman, Woosley & Qian ApJ 482, 951 (1997)

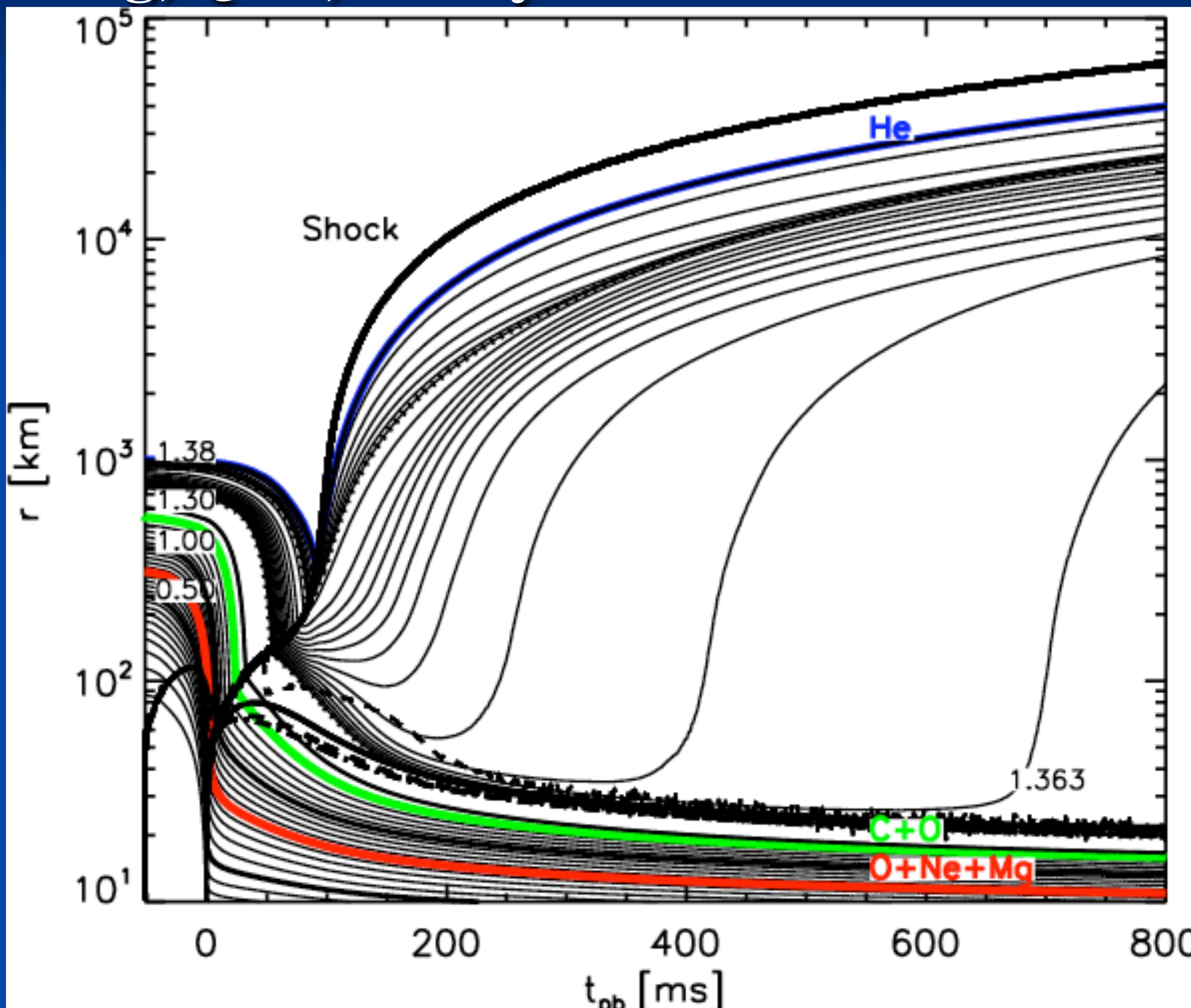
See also: Jordan & Meyer ApJ L131, 617 (2004)

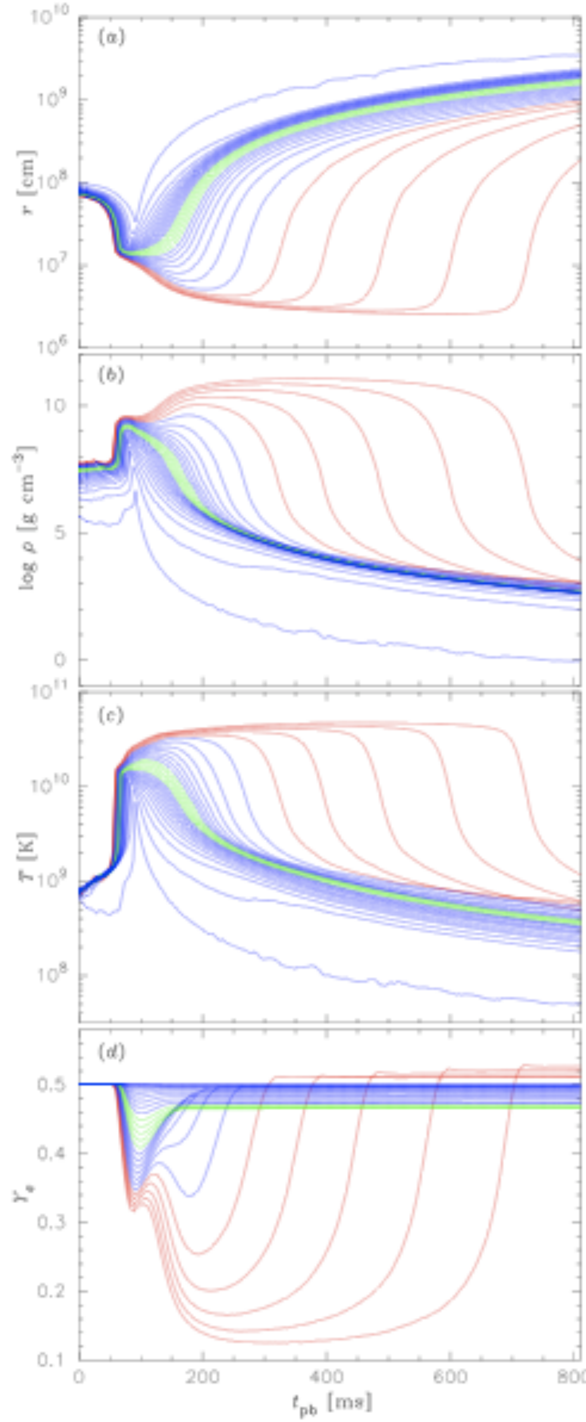
- Small intermediate mass & Fe contributions (<1% X_h, 99% α's)
- A = 80, 130, & 195 peaks, look like scaled *r*-process abundances
- NQM requested a detailed explosion code calculation to see if requisite conditions arise from the same pre-supernova model.



- Janka *et al.* have explored 1-D & 2-D models of the progenitor considered by Ning, Qian, & Meyer

- $Y_e < 0.47$
- $0.47 < Y_e < 0.5$
- $Y_e > 0.5$





Janka *et al.* A&A 485, 199 (2008)

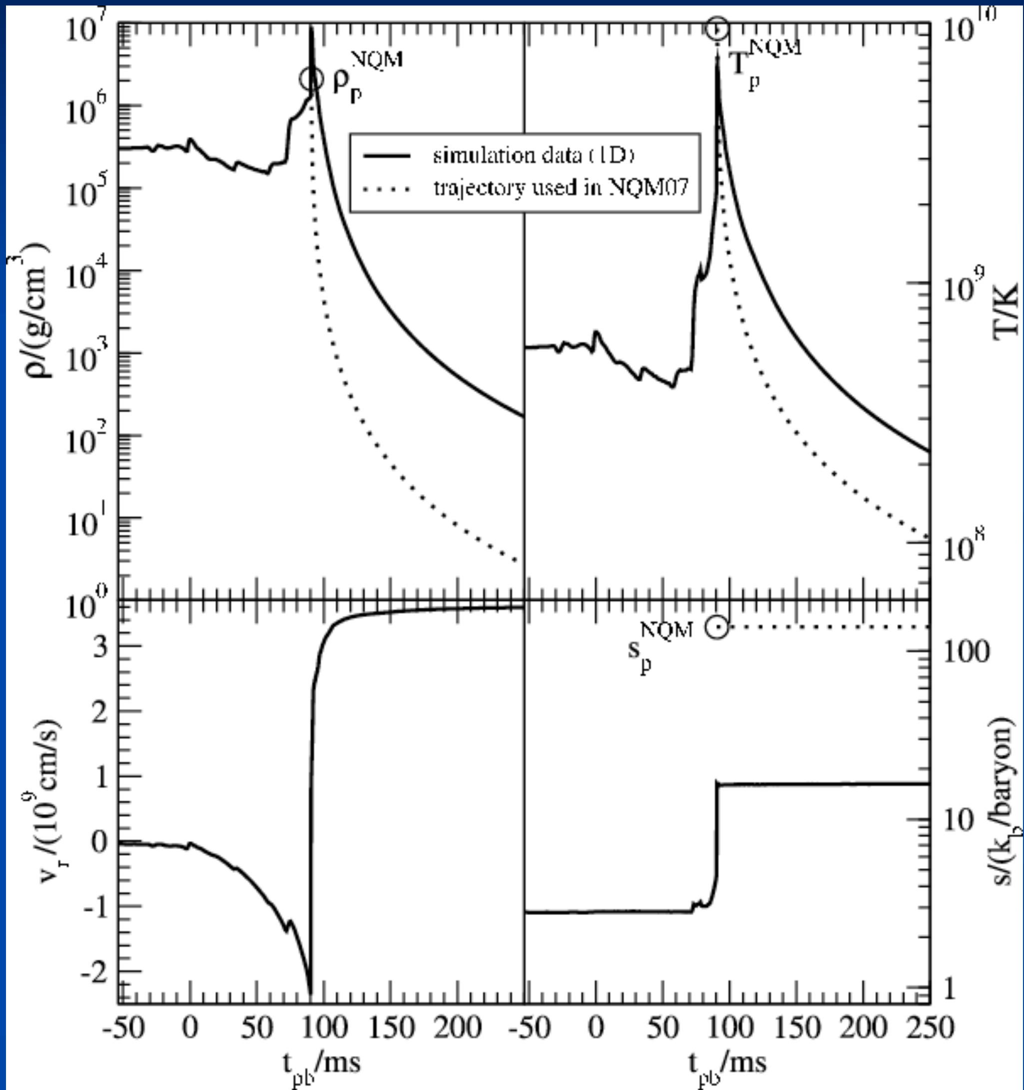
Comparison to Ning *et al.*

- Requisite parameters of entropy & exp. timescale were NOT found because Ning's assumed shock velocity was never achieved

For $v_{sh}=10^{10}$ cm/s:
S=139 k_b/nucleon
t_{exp}=0.0013s
Ye=0.495

- At $T_9 = 9$, Y_e was also lower

- What are the implications for the *r*-process?



Janka *et al.* A&A 485, 199 (2008)

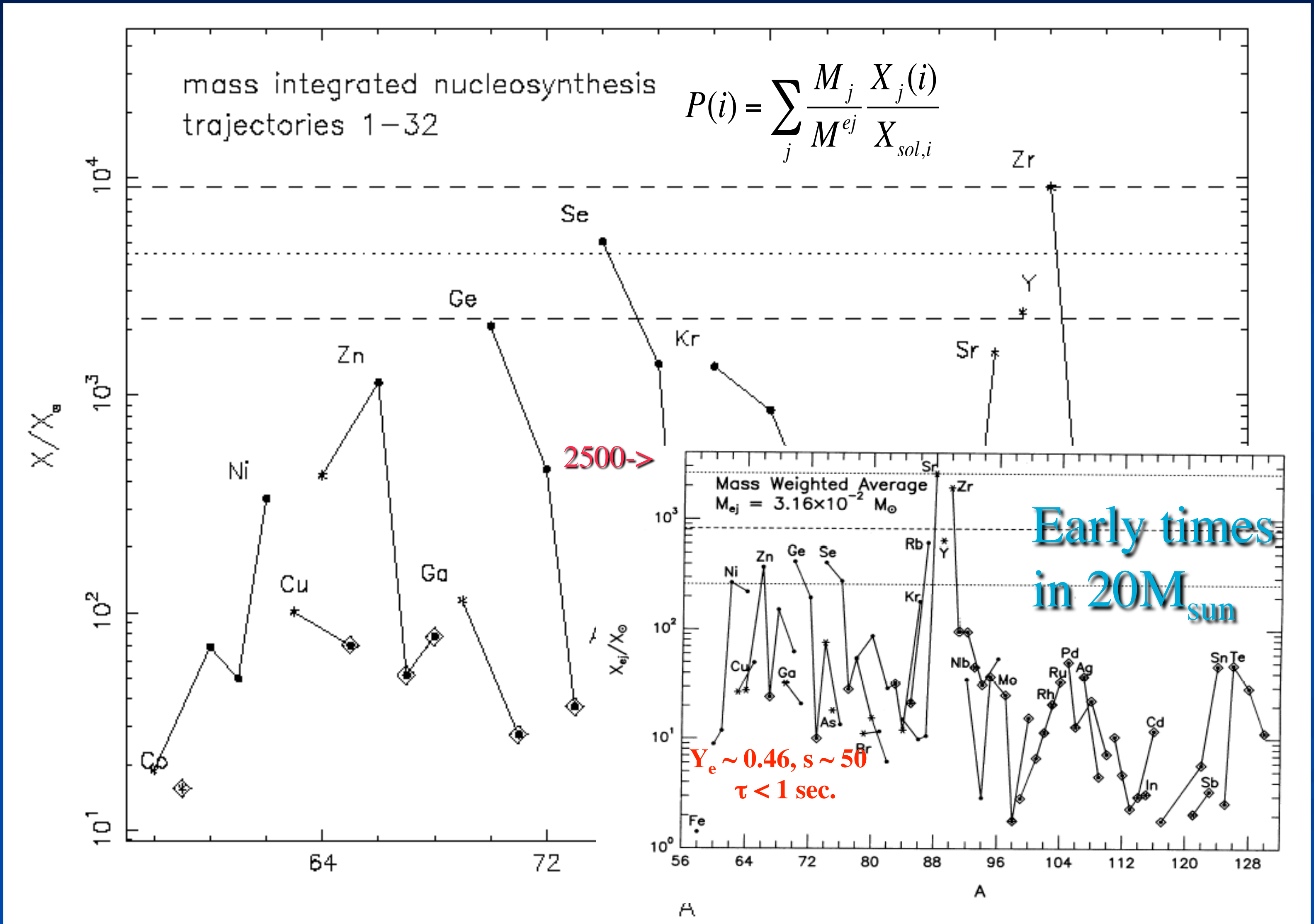
Table 1. Outflow Characteristics

Ning et al. s/k_b=139, Y_e=0.495, τ_{exp}=0.0013 s

traj.[a]	r_7	T_9	s/k_b	Y_e	$\tau_{exp}(s)$	Mass[b]	$X(\alpha)$[c]	^AZ_P	P_{max}
1	1.08	9.2	30	.53	.046	5.00	.74	^{45}Sc	2.95
2	1.09	9.5	29	.52	.051	5.00	.72	^{45}Sc	1.98
3	1.23	9.0	27	.51	.058	10.00	.67	^{49}Ti	3.44
4	1.32	9.1	25	.50	.064	10.00	.59	^{62}Ni	2.04
5	1.47	9.1	24	.50	.073	10.00	.55	^{62}Ni	7.05
6	2.14	9.0	21	.48	.092	5.00	.38	^{64}Zn	45.53
7	2.27	9.1	20	.47	.100	5.00	.28	^{74}Se	1001.58
8	2.40	9.0	19	.47	.107	5.00	.17	^{74}Se	843.23
9	2.46	9.1	18	.46	.114	15.00	.12	^{90}Zr	4928.74
10	2.67	9.1	16	.45	.118	15.00	.04	^{90}Zr	2589.07
11	2.76	9.1	14	.46	.112	5.00	.10	^{74}Se	629.45
12	2.79	9.0	14	.47	.109	10.00	.14	^{74}Se	1346.00
13	2.70	9.0	12	.48	.104	10.00	.21	^{64}Zn	60.97
14	2.68	9.2	11	.49	.099	10.00	.22	^{62}Ni	13.54
15	2.50	9.0	10	.50	.092	10.00	.23	^{62}Ni	4.68
16	2.40	9.0	10	.50	.067	6.00	.24	^{60}Ni	.82
17	2.32	9.0	10	.50	.038	1.00	.31	^{63}Cu	.29
18	2.37	9.1	13	.50	.032	1.00	.43	^{63}Cu	.43
19	2.66	8.0	14	.50	.025	1.00	.49	^{63}Cu	.49
20	2.90	7.1	15	.50	.017	.10	.58	^{63}Cu	.06

Hoffman, Muller & Janka ApJ L127, 626, 2008

O-Ne-Mg Nucleosynthesis



Hoffman, Muller & Janka ApJ L127, 626, 2008

Implications for GCE

- Enrichment of the ISM from a single event

$$\left[\frac{Zr}{H}\right]_{sngle} = \log\left[\frac{Y_{Zr}/M_{mix}}{X(^{90}Zr)_{sun}}\right]$$

$$Y_{Zr} = \sum_j X_j^{Zr} M_j = 1.75x10^{-4}\, M_{sun}$$

$$M_{mix} = 3000\, M_{sun}$$

$$X(^{90}Zr)_{sun} = 1.53x10^{-8}$$

- 4 times solar value!

- Enrichment over the lifetime of the Galaxy

$$\left[\frac{Zr}{H}\right]_{all} = \log\left[\frac{Y_{Zr} f_{SN} t_{Gal}}{M_{gas} X(^{90}Zr)_{sun}}\right]$$

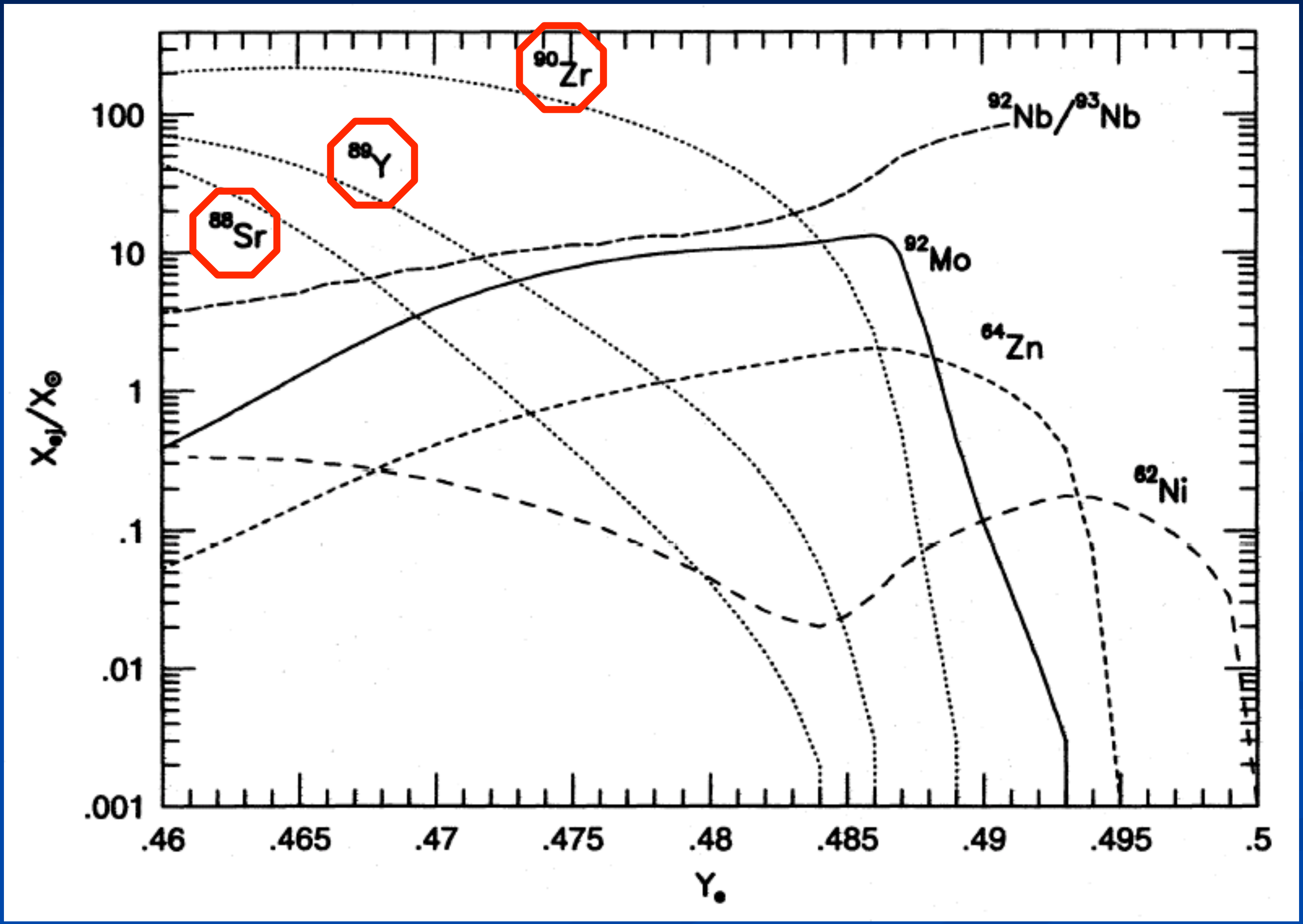
$$M_{gas} = 10^{10}\, M_{sun}$$

$$t_{Gal} = 10^{10}\, yr$$

$$f_{SN} = once / 3000 yrs$$

- 10-50 times solar!

N=50 vs. Y_e in CCSNII



(Hoffman, Woosley, Fuller, & Meyer ApJ 450, p. 478, 1996)

Sensitivity to Y_e

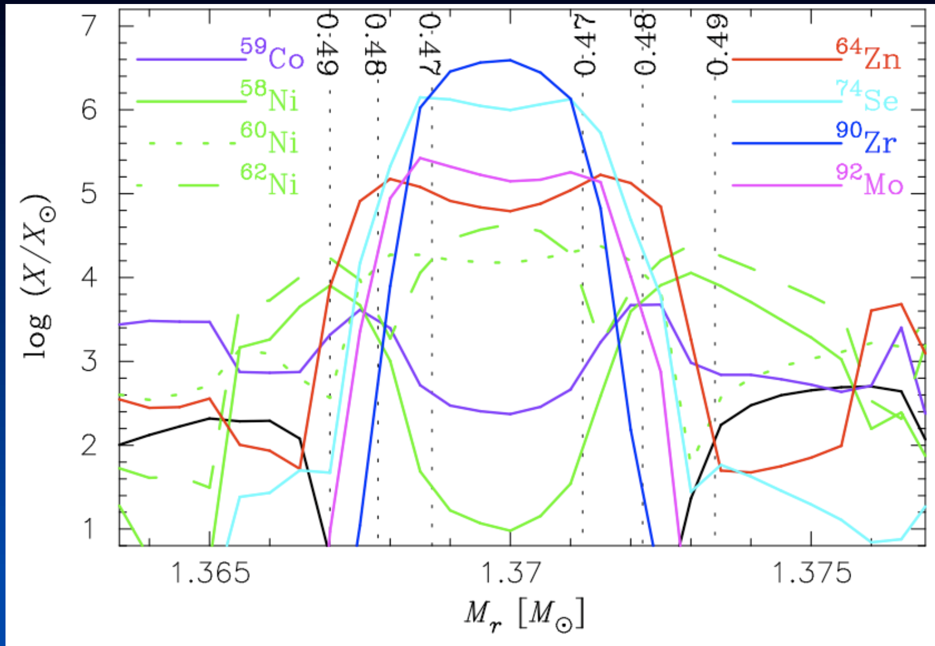
- But IMF says there are many 8-10 M_{sun} stars: What went wrong?

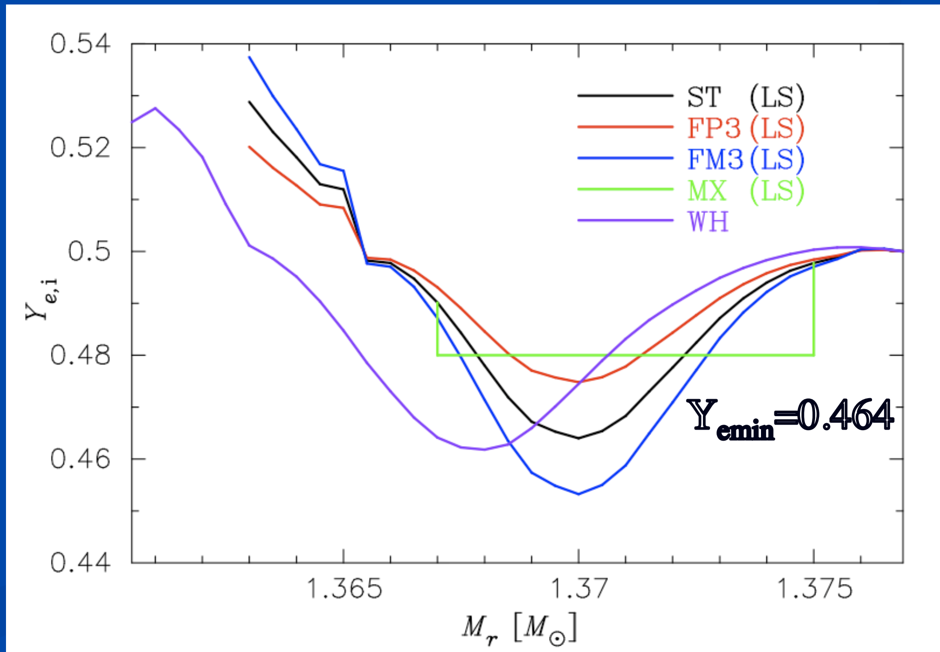
  Let's focus on Y_e:

- ST: "standard case"
- FP3: "softer Y_e dist."
- FM3: "harder Y_e dist."

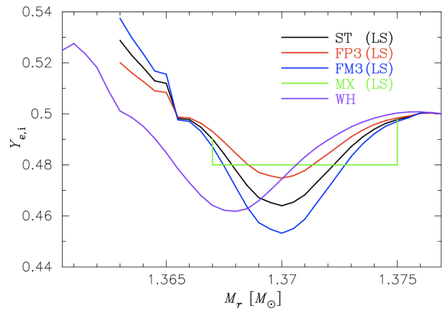
$$Y_{e_i} = Y_{e_i} + (0.5 - Y_{e_i}) \times f$$

$$f = \pm 0.1, \pm 0.2, \pm 0.3$$





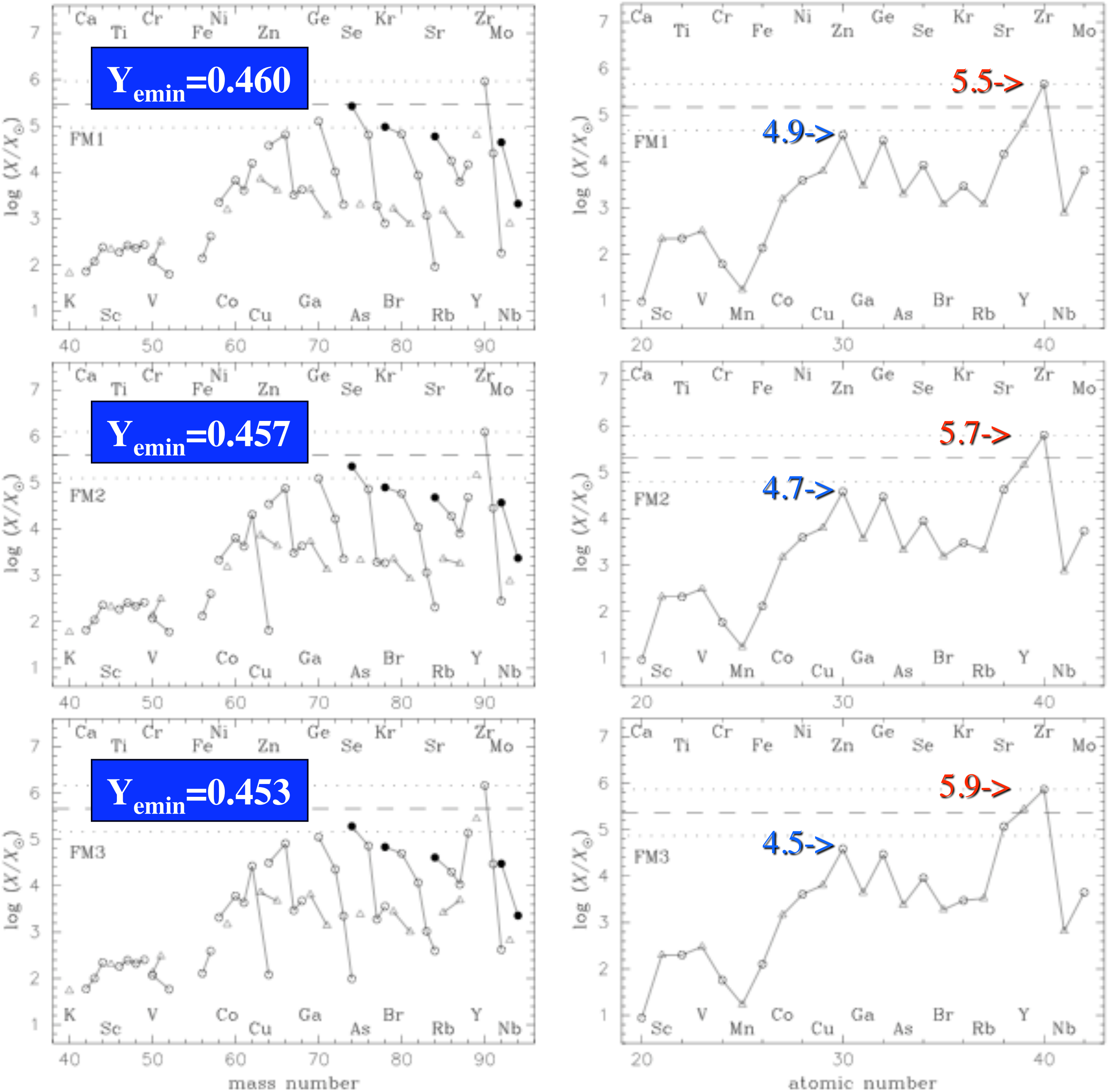
Wanajo *et al.* (2009) ApJ 695, 208

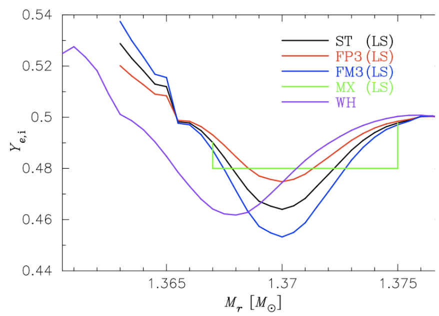


HARDER:
FM=-.1, -.2, -.3 makes things Worse!
X/X_{sun} gets larger.

^{90}Zr problem gets worse, light-*p* is suppressed.

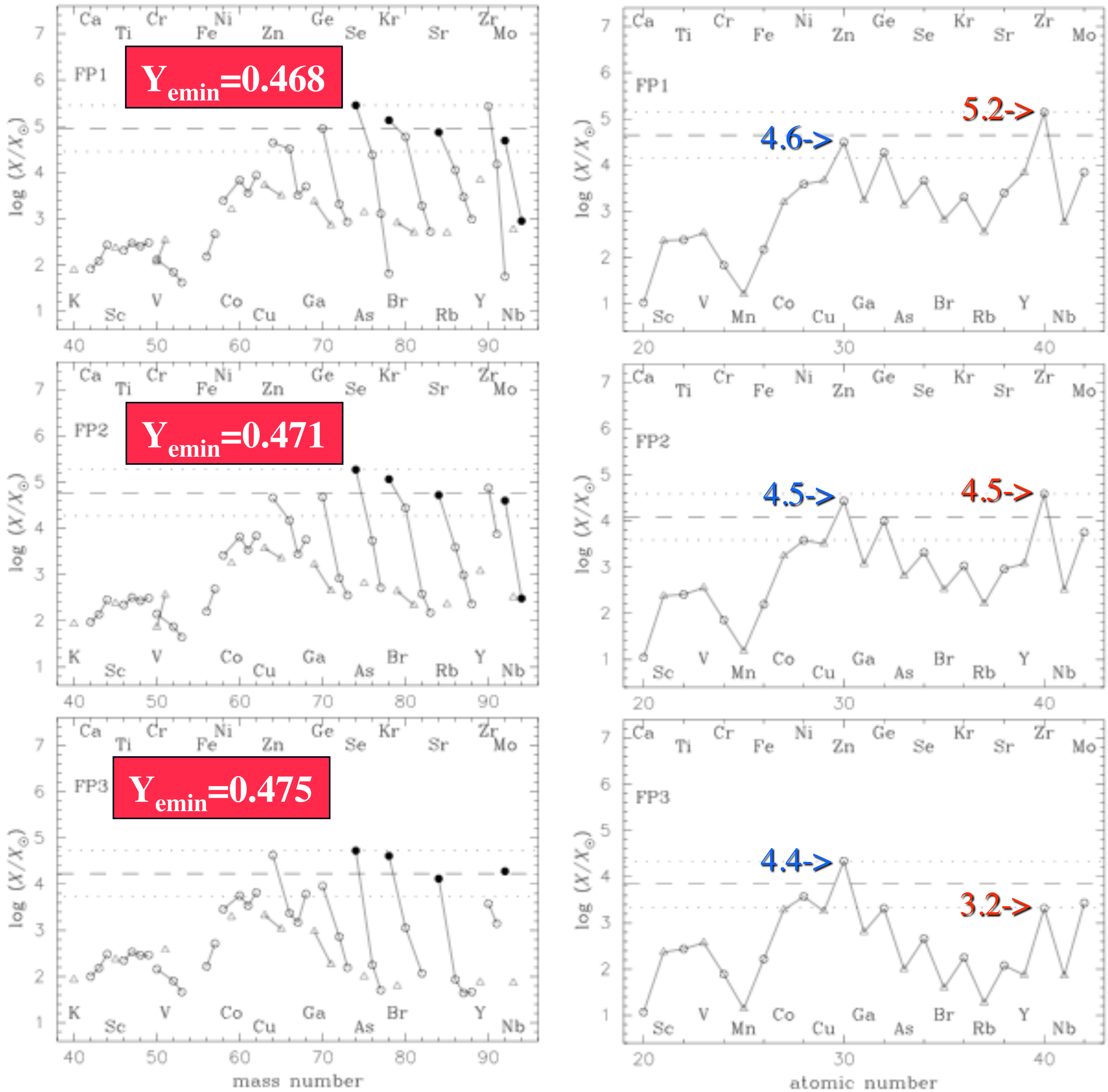
Wanajo *et al.* 2008 (arXiv:0810.3999)





SOFTER:
FP = .1, .2, .3
1-2% change makes things Better!
X/X_{sun} gets smaller.

^{90}Zr problem recedes, now ^{64}Zn is king & light-*p*!



FP3 Implications for GCE

- Enrichment of the ISM from a single event

$$\left[\frac{Zn}{H}\right]_{sngle} = \log\left[\frac{Y_{Zn}/M_{mix}}{X(^{64}Zn)_{sun}}\right]$$

$$Y_{Zn} = \sum_j X_j^{Zn} M_j = 6.51\times10^{-4}\, M_{sun}$$

$$M_{mix} = 3000\, M_{sun}$$

$$X(^{64}Zn)_{sun} = 1.12x10^{-6}$$

- 0.19 times solar value

- Enrichment over the lifetime of the Galaxy

$$\left[\frac{Zn}{H}\right]_{all} = \log\left[\frac{Y_{Zn} f_{SN} t_{Gal}}{M_{gas} X(^{64}Zn)_{sun}}\right]$$

$$M_{gas} = 10^{10}\, M_{sun}$$

$$t_{Gal} = 10^{10}\, yr$$

$$f_{SNII} = 2/century$$

$$f_{SN_{low}} = 4\%\, f_{SNII} = 0.0008\, yr^{-1}$$

$$f_{SN_{high}} = 20\%\, f_{SNII} = 0.004\, yr^{-1}$$

- 0.46 to 2.3 times solar

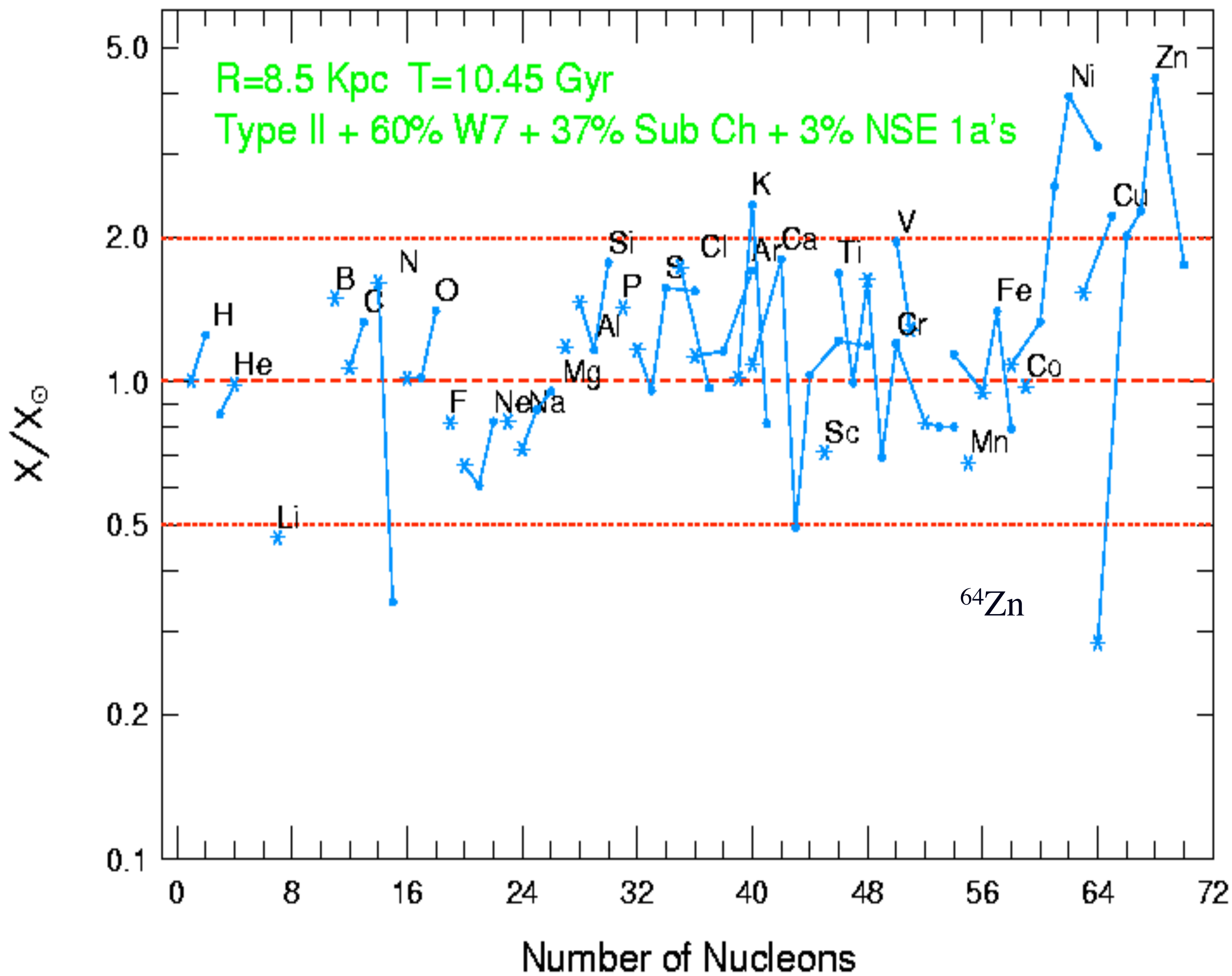


FIG. 29: The agreement in Fig. 28 is greatly improved if the iron group production from three varieties of Type Ia supernovae (see text and Table 3) is included as well as classical novae (Timmes - private communication).

Considerations

- Nuclear physics: flows are near valley of stability – masses & rates (AME03 & RT) not a major source of error
- Neutrino reactions on heavy species: not an issue (radii to large), reasonable variations explored – no *r*-process
- Explosion model: based on very modern treatment, issues of fallback negligible. 2D calculation gives very similar conditions (S_{rad}, Y_e, τ_{exp}) to spherically symmetric case explored here.
- Pre-SN model: based on Nomoto (1984)

Conclusions

- High entropy is (still) hard to get.
- Nucleosynthesis in the CO layers overlying an ONeMg ECSNe do NOT provide conditions for the *r*-process.
- With an acceptable 2% modification of the Y_e profile in a modern explosion calculation of the Nomoto PSN model the over-production of ^{90}Zr is eliminated in favor of ^{64}Zn .
- In CCSNe the site of the *r*-process remains elusive.

Disclaimer