Nucleosynthesis in Early Neutrino Driven Winds

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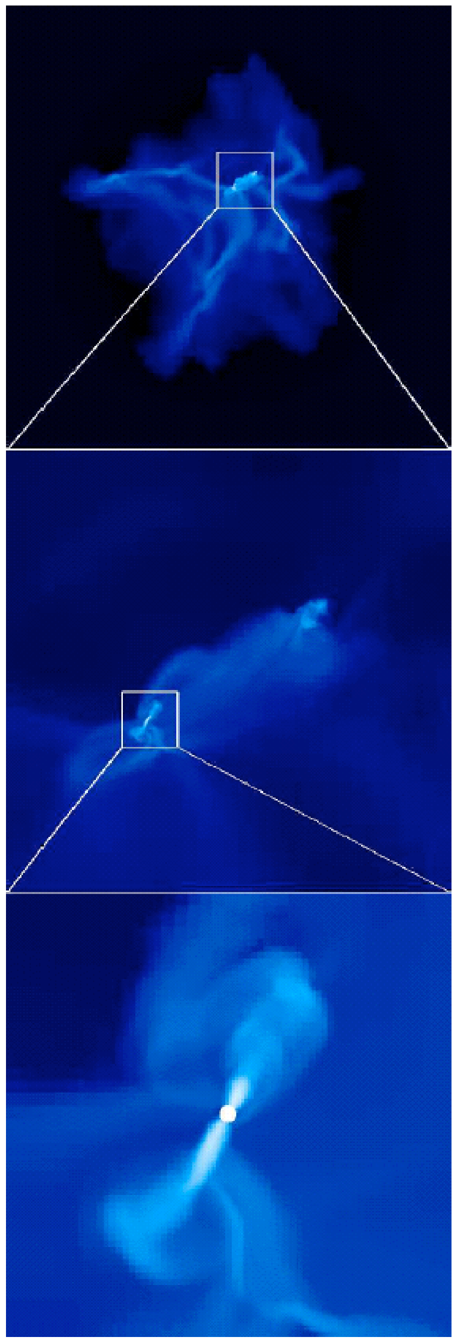
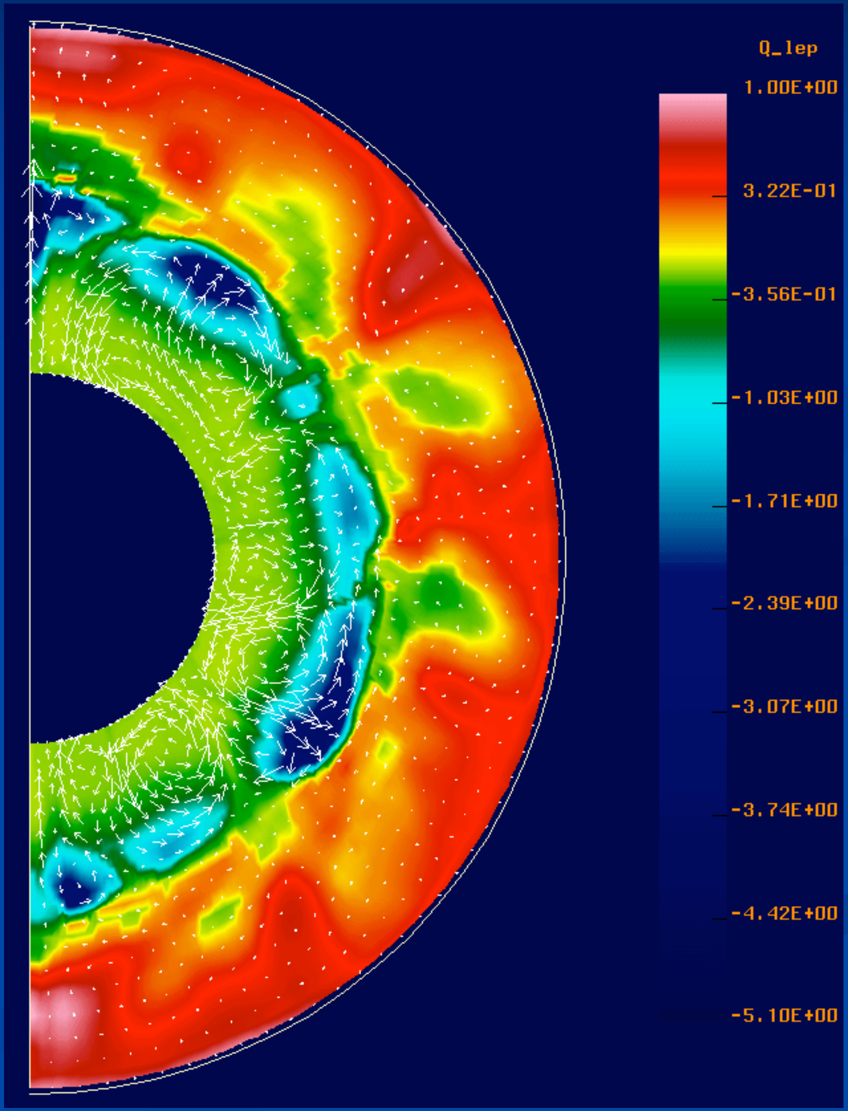


Snowflakes in Hell

- The scene is the “hot bubble” between the NS and accretion shock, a low-ρ region where E_ν deposition is driving mass loss .
- The NS liberates its BE_{grav} (10^{53} erg) over $\tau_{KH} \sim 10$ sec.
- T ~ 1 MeV (T_9 =11.605)
- 2n + 2p -> α until all nucleons are used up, but if an excess of either occurs it is frozen out.
- Between ~ 0.5 MeV α’s reassemble to heavy nuclei, (NSE dist. if $\tau_{exp} > \tau_{HD}$)



Lepton loss and gain rate (per sec per nucleon) at 50 ms for 30 < r < 80 km. The neutrino sphere is at ~50-60 km. The velocity vectors indicate convection.

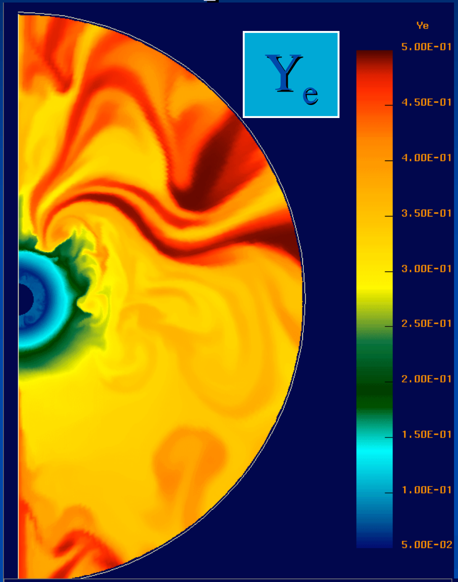
Janka & Muller A&A 306, 167 (1996)

Nucleosynthesis in ν-driven winds are characterized by 3 basic parameters +…

- Composition: Y_e

  The e^- mole number, describes n/p ratio - affects the path of the major nuclear flows - set by L_ν & spectra
- Entropy: s_{rad} (k_B/nuc)
- Exp. timescale: τ_{exp} (s)
- Mass loss rate ($M_{sun}\ s^{-1}$)

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



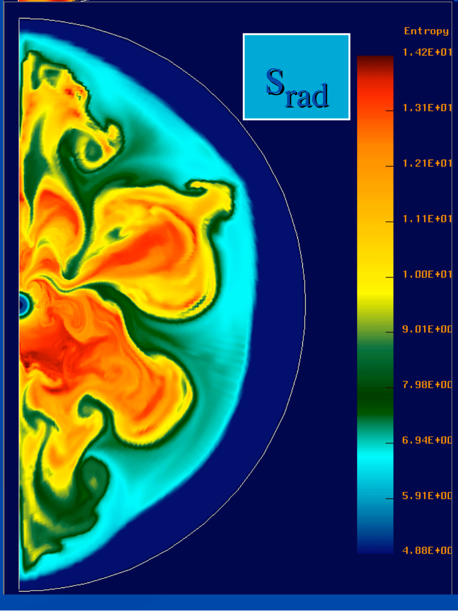
@ t = 170 ms

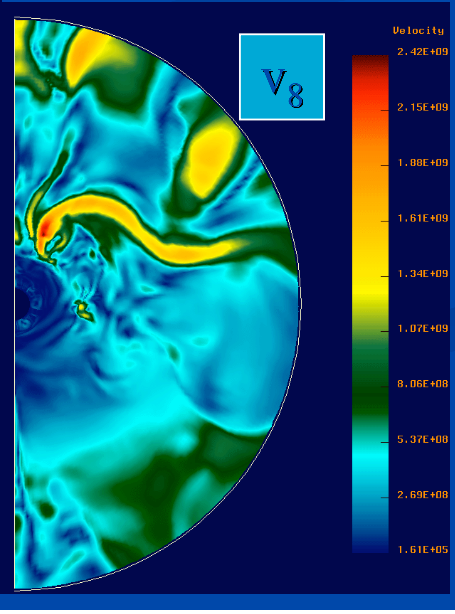
500 < r (km) < 1600

$0.1 < Y_e < 0.5$

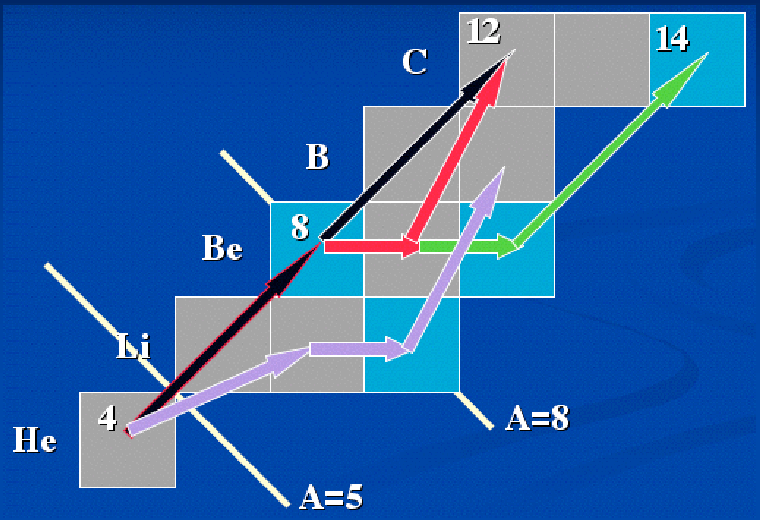
$5 < s_{rad} < 15$

$2 < v_8 < 25$





Affects of s_{rad} & τ_{exp}



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

All proportional to ρ^2 (or more).

$$S_{rad} = 5.2(T^3_{MeV}/\rho_8)$$

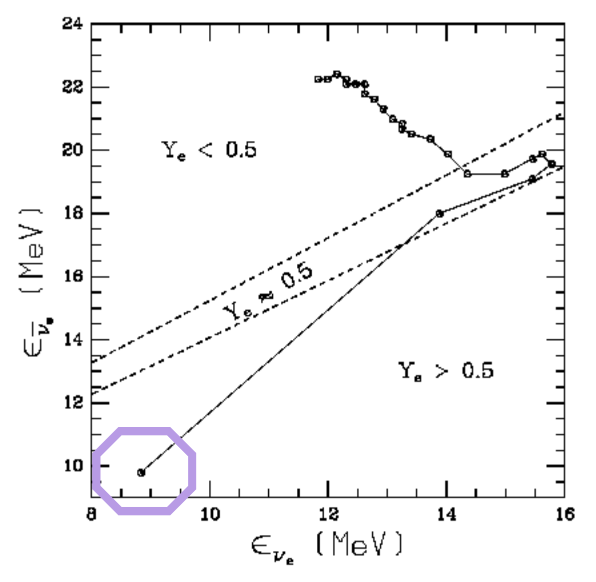
- Low ρ -> high S_{rad} one has inefficient assembly of light particles to heavies ones, n/s high, with the potential for flow to large A.
- High ρ -> low S_{rad} with efficient assembly of light particles to heavies ones, only go to A~60.
- A short expansion time scale also inhibits α-assembly and hence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

What determines Y_e?

- Y_e evolves according to this equation:

$$v\,\frac{dY_e}{dr} = \lambda_{\nu_e n} + \lambda_{e^+ n} - (\lambda_{\nu_e n} + \lambda_{e^+ n} + \lambda_{\bar{\nu}_e p} + \lambda_{e^- p})Y_e\ ,$$

where the rates for weak and ν_e captures obey:

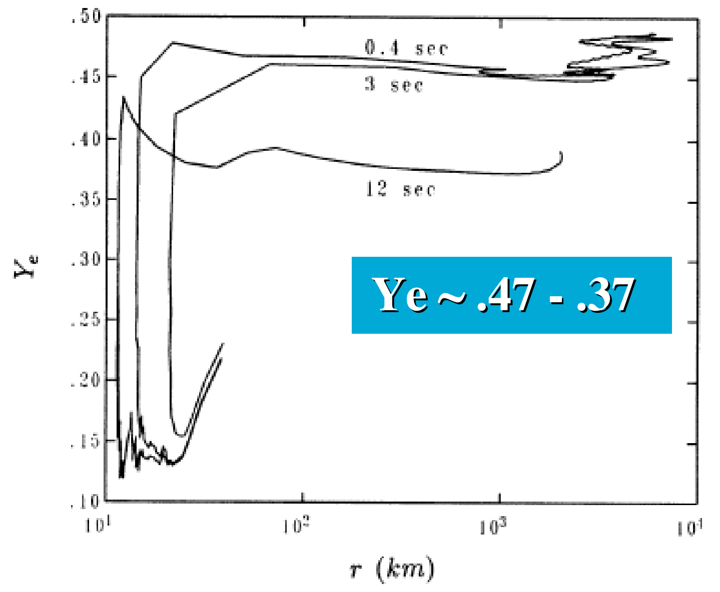


$$\nu_e + n \rightleftharpoons p + e^-\ ,$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+\ .$$

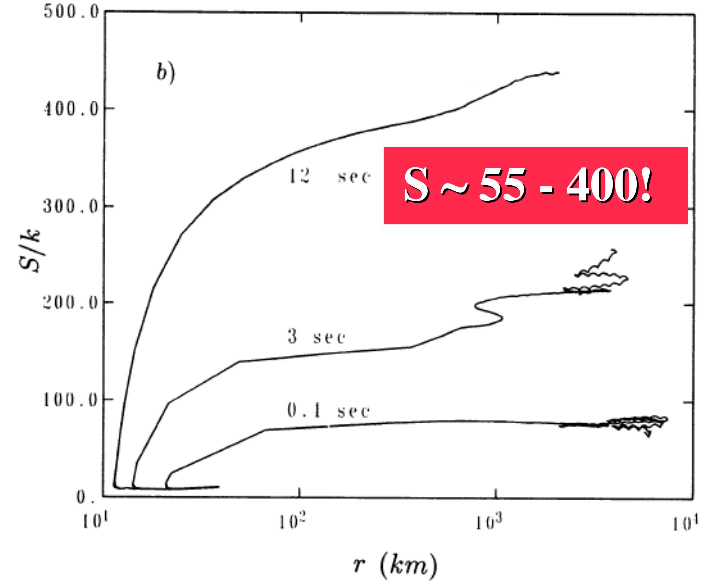
10 years ago it was predicted that at early times $Y_e > 0.5$…

(Woosley & Qian ApJ 671, 331,1996)

but we focused on late times



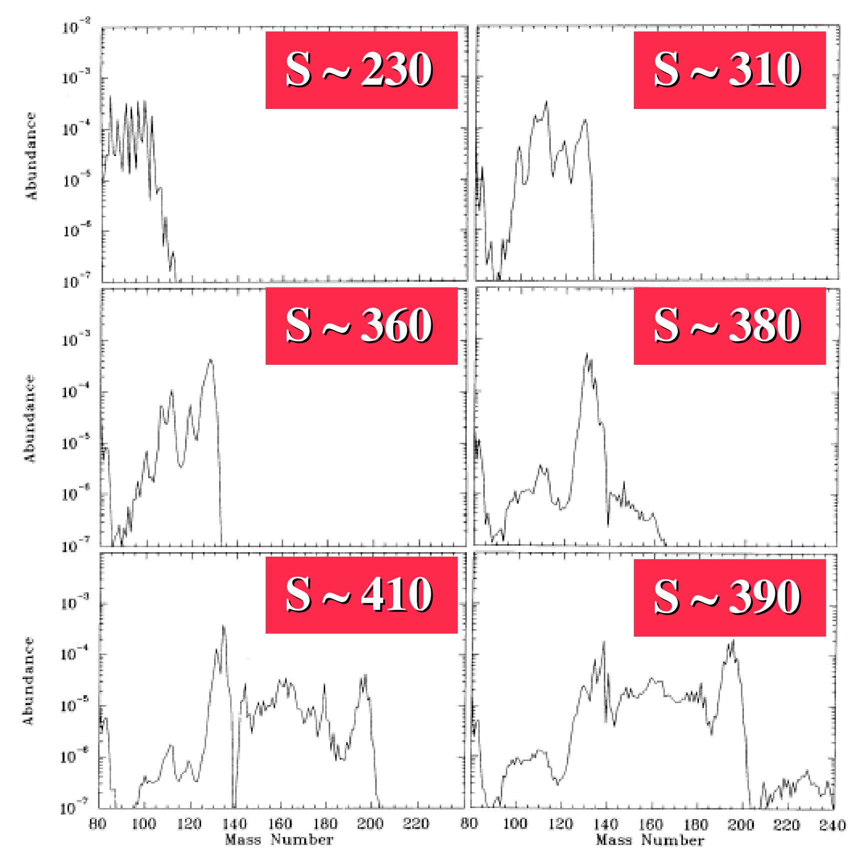
Ye ~ .47 - .37



S ~ 55 - 400!

..and in these winds the seeds of the *r*-process arose.

(Woosley, Wilson, Mathews, Hoffman & Meyer ApJ 433, p. 229, 1994)



S ~ 230

S ~ 310

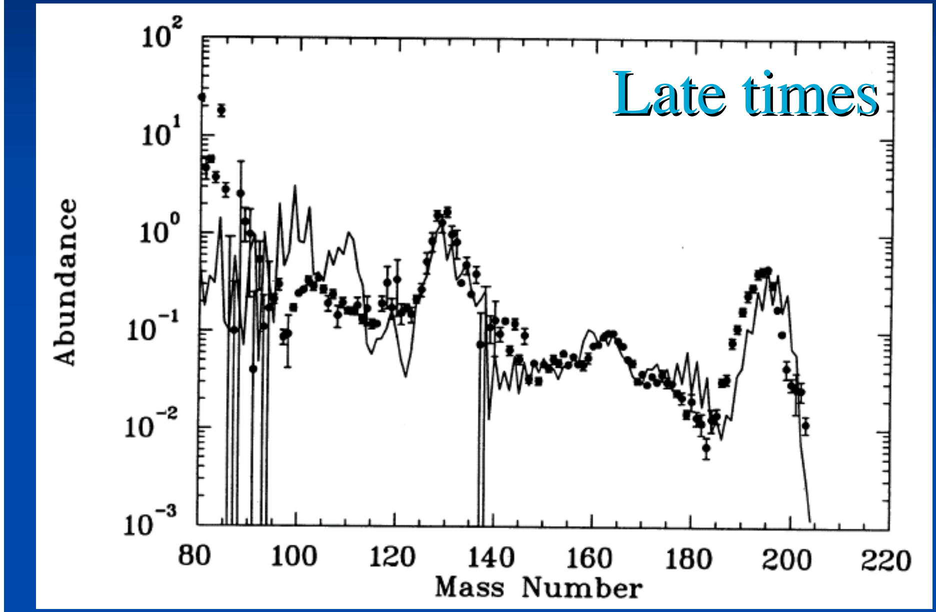
S ~ 360

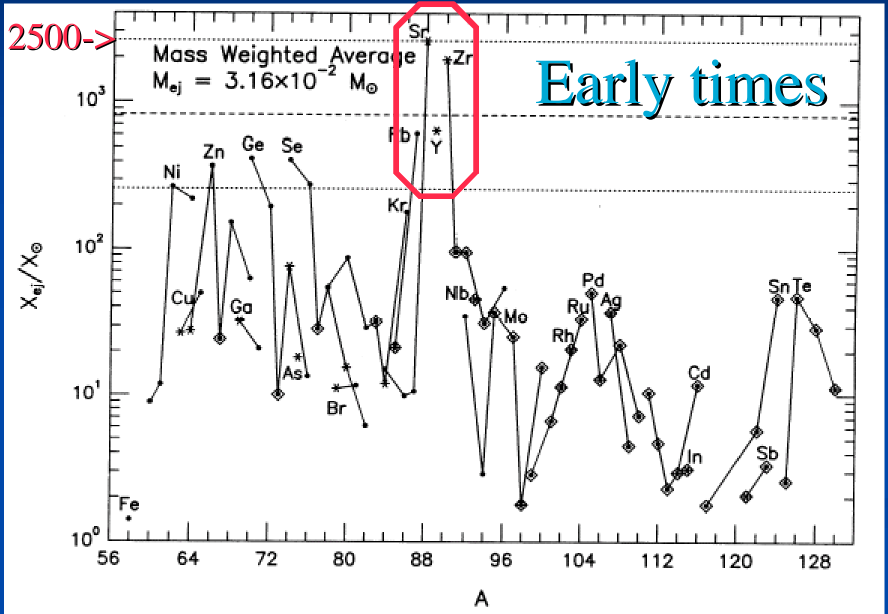
S ~ 380

S ~ 410

S ~ 390

Success & failure

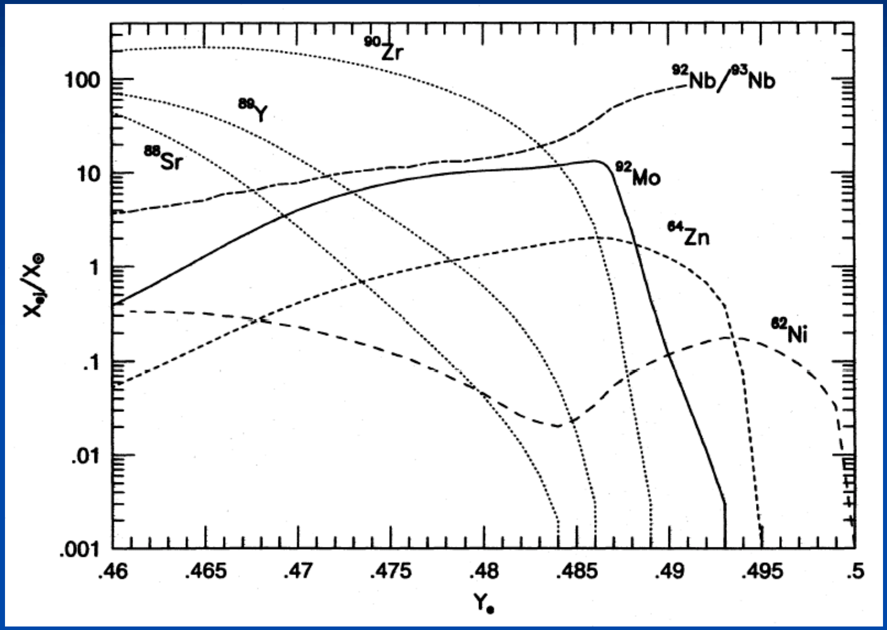


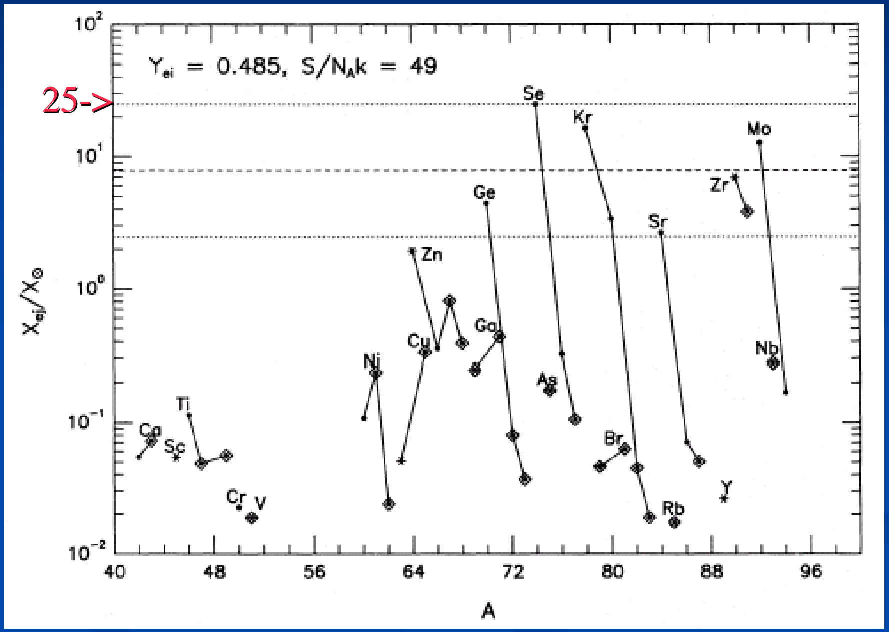


- .37 < Ye < .47
- S ~ 100 - 400 (not reproduced since)
- Late time solution..

- Made N=50 nuclei early.
- If true we would be swimming in Sr, Y, & Zr!
- We tried to fix it…

..by adjusting early time Y_e

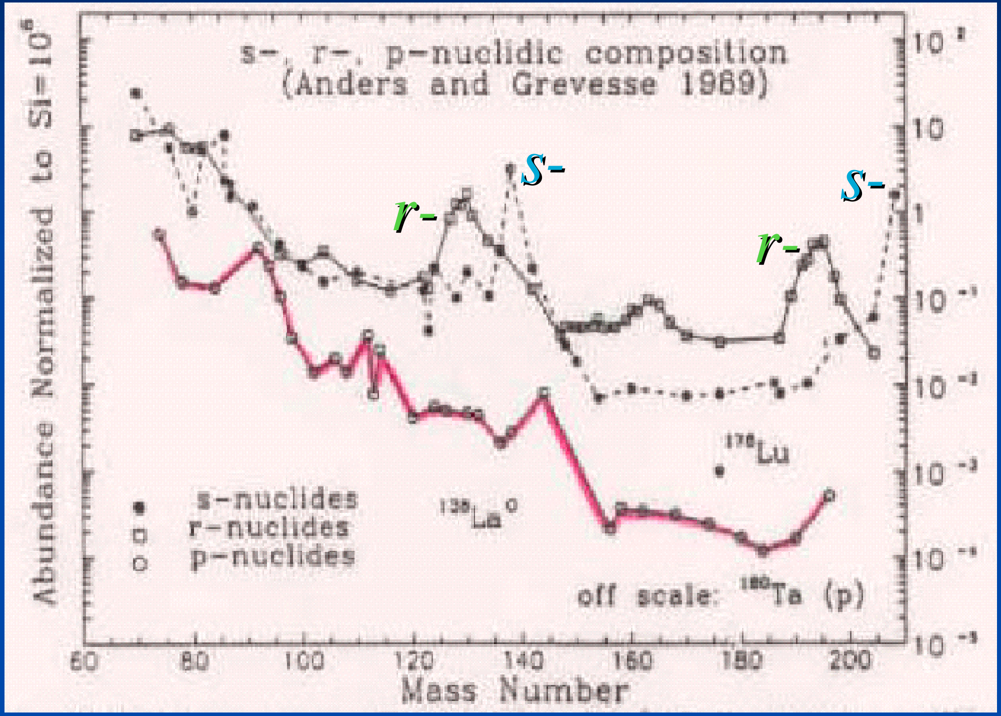


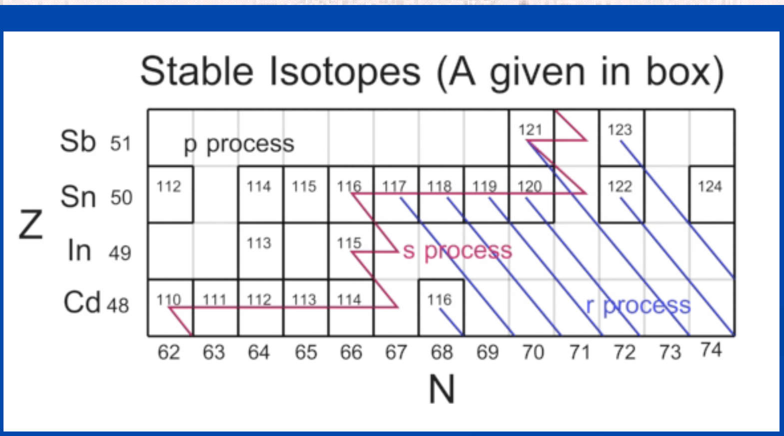


(Hoffman, Woosley, Fuller, & Meyer ApJ 450, p. 478, 1996)

- N=50 problem reduces as Ye increases…
- Light-*p* nuclei start to dominate
- Ye=0.485 works, but it's a tight (and somewhat artificial) constraint.
- One problem, light-*p* production only goes to ^{92}Mo!
- Note: All light *p*-nuclei made as themselves, so nuclear uncertainties are less likely than SN wind physics to explain the dicotomy.

Abundances



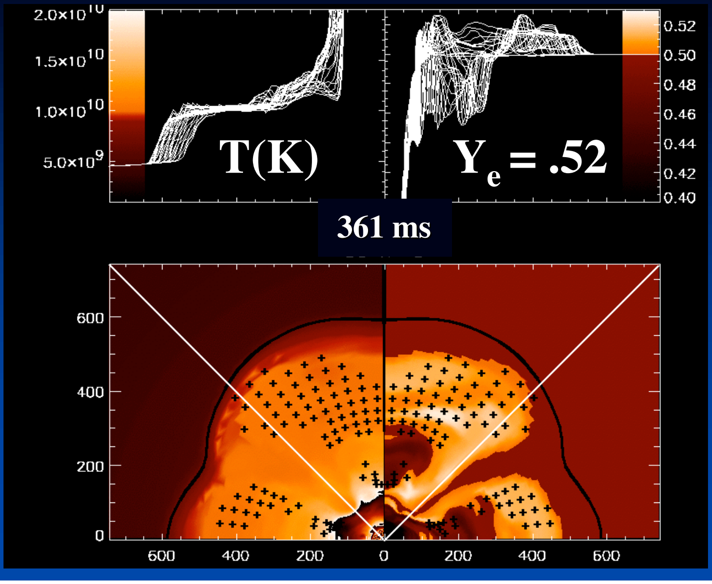


The *p*-nuclei are made in several sites in SNII:

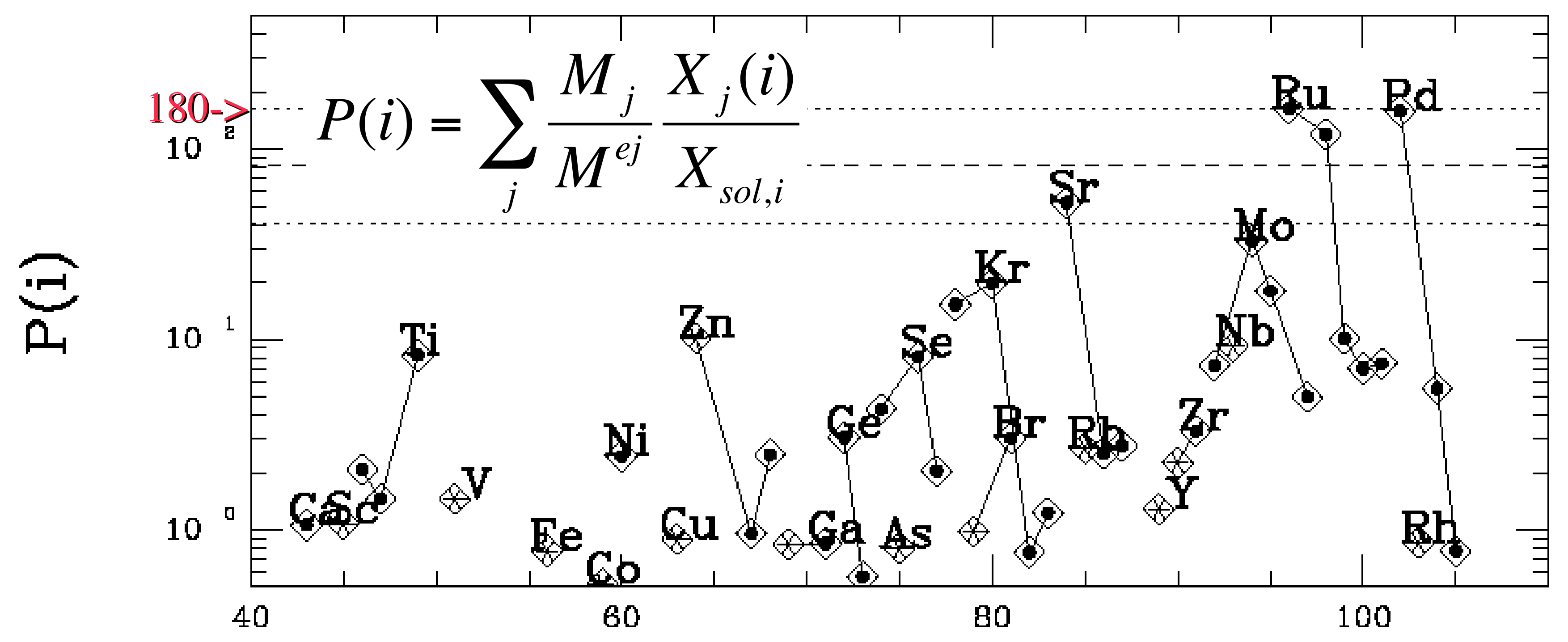
- 74 < A < 92 in pre-SN & explosive burning at base of the O-Ne shell.
- A >110 by the γ-process.

Bypassed by the *s*- and shielded from the *r*-processes, the Mo & Ru *p*-nuclides have always been problematic.

Janka, Buras, & Ramp Nucl. Phys. A 718, 269 (2003)



Over the last 10 years improvements in ν- transport and multi-D simulations now predict *p*-rich conditions at early times: a new paradigm in nucleosynthesis theory, the ν-*rp* process.



$$P(i) = \sum_j \frac{M_j}{M^{ej}} \frac{X_j(i)}{X_{sol,i}}$$

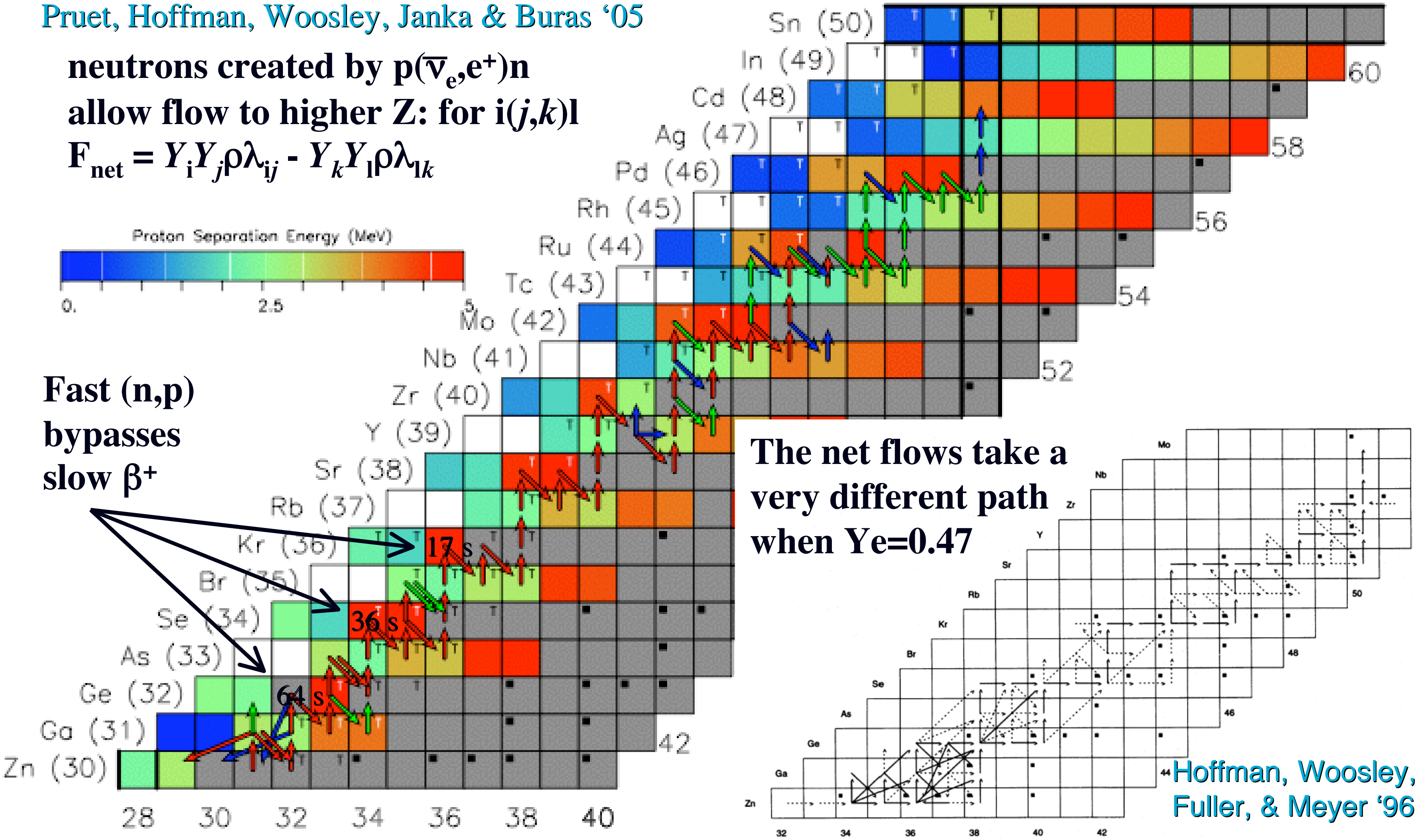
Pruet, Hoffman, Woosley, Janka & Buras ApJ 623, 325 (2005)

Bypassing the Waiting Points

Pruet, Hoffman, Woosley, Janka & Buras '05

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

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



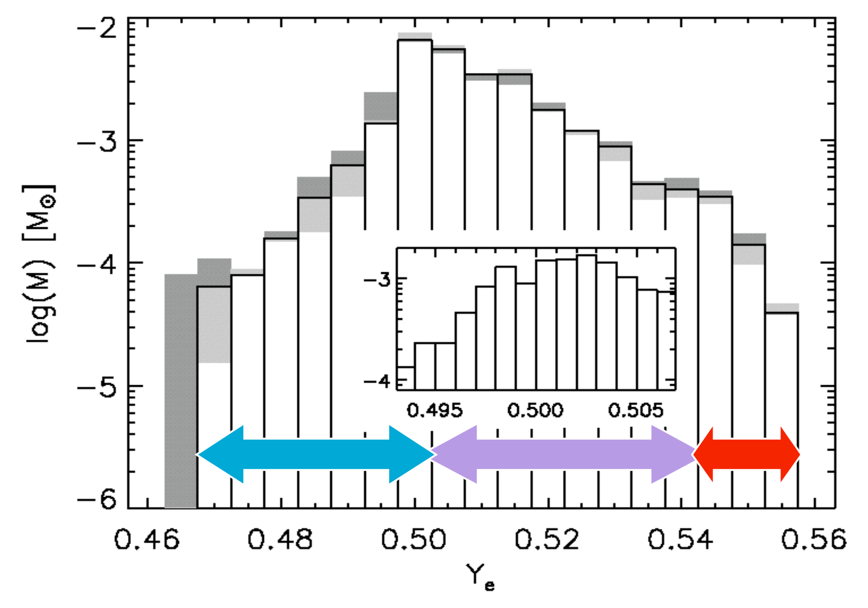
Fast (n,p) bypasses slow β^+

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

Hoffman, Woosley, Fuller, & Meyer '96

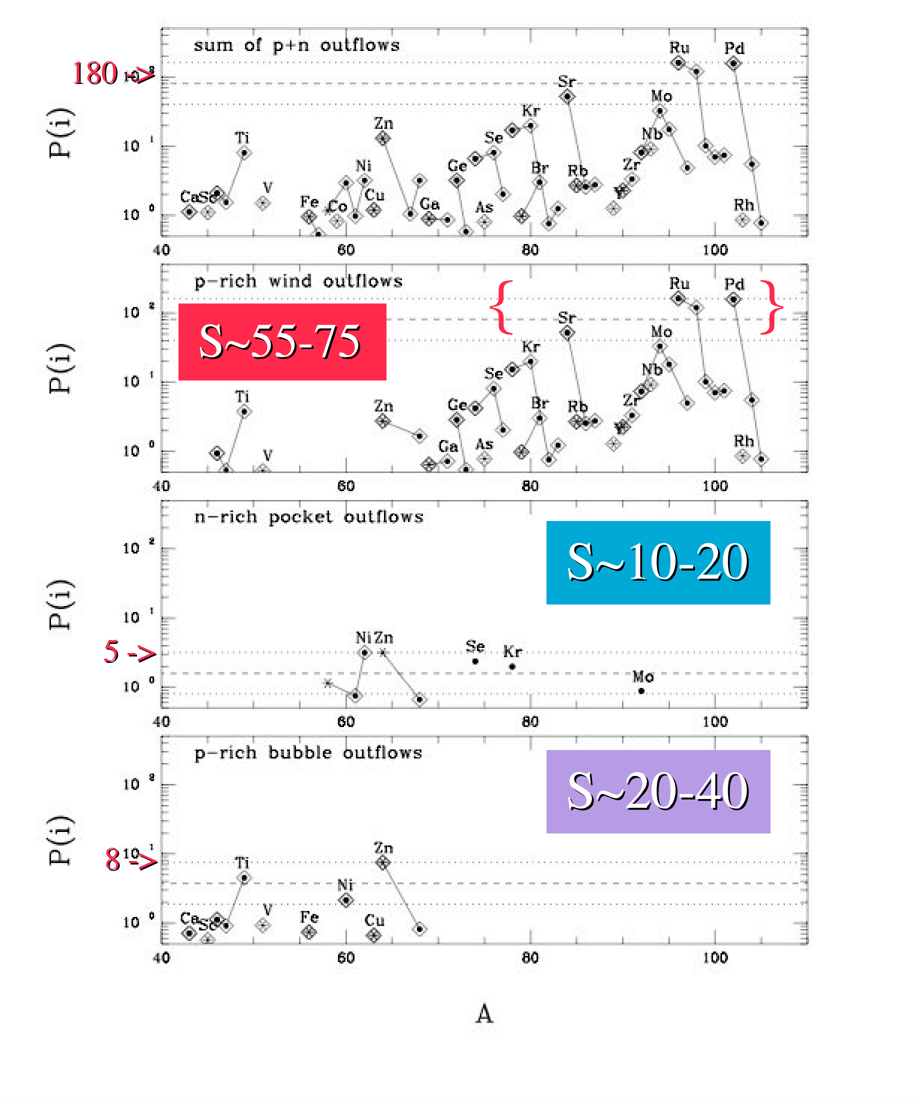
Components of the Ejecta

- n-rich pockets, p-rich bubbles, p-rich winds.



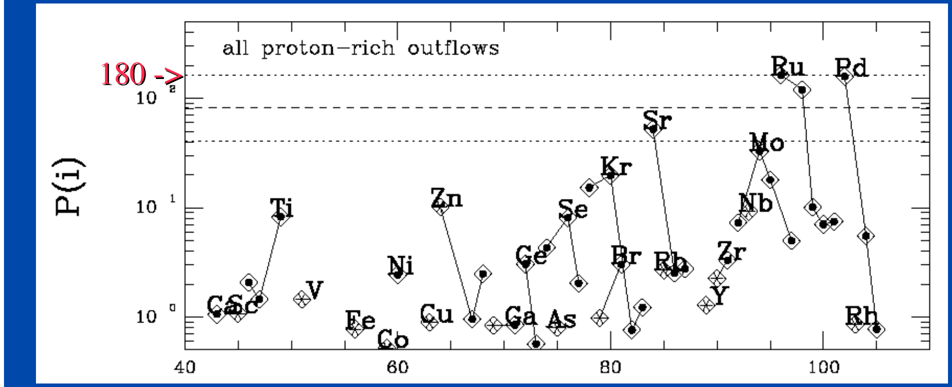
traj.	Y_e	s/k_b	$X(p)$	$X(\alpha)$	X_H	$X(^{56}\mathrm{Ni})$	%^{b}	$\Delta_n{}^c$
1	0.539	54.8	0.078	0.614	0.307	0.244	80	0.2
2	0.548	58.0	0.095	0.714	0.190	0.135	71	0.4
3	0.551	76.7	0.101	0.822	0.075	0.043	57	1.7
4	0.551	71.0	0.102	0.796	0.101	0.063	62	1.1
{ 5	0.556	74.9	0.113	0.831	0.054	0.025	46	2.9 }
6 *	0.558	76.9	0.115	0.840	0.043	0.014	33	3.2

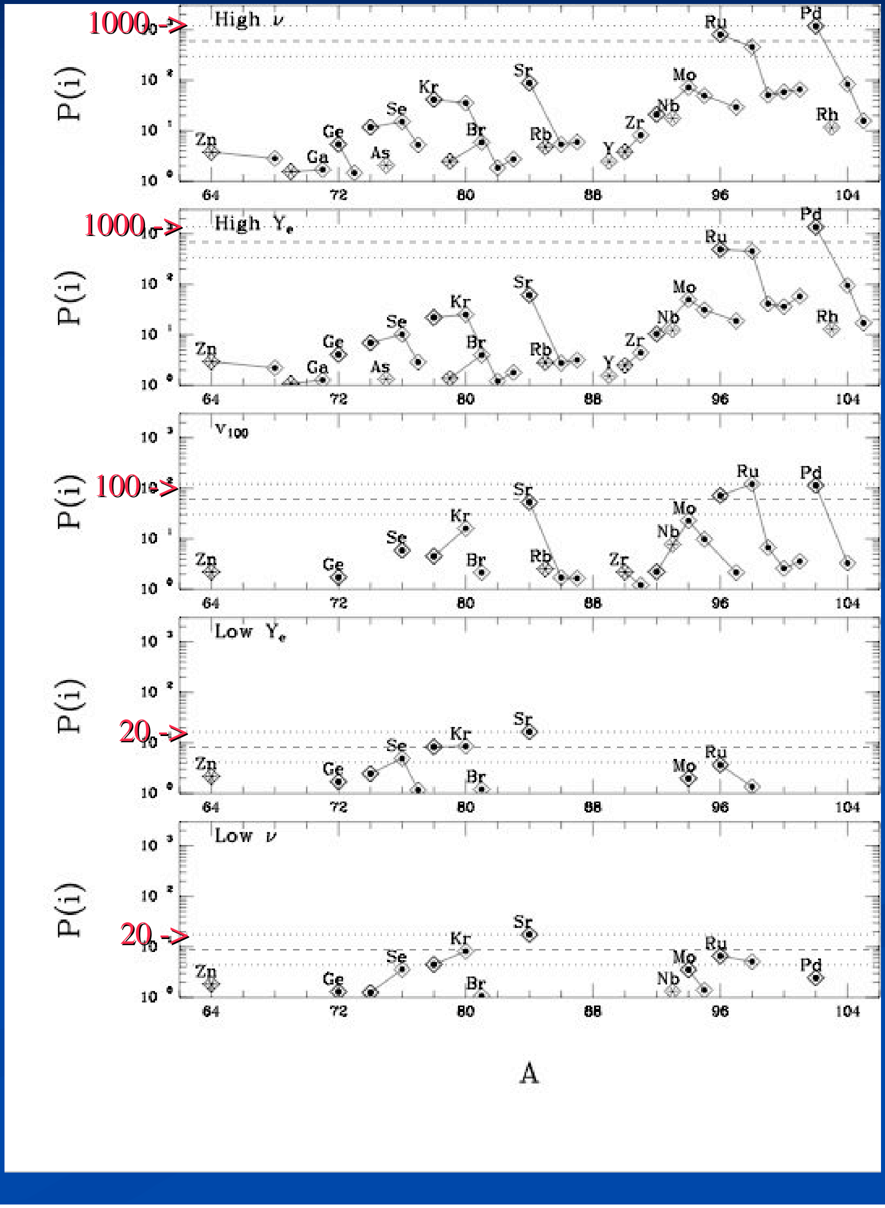
Pruet et. al. ApJ 623, 325 (2005)



Variations of key parameters

- $\bar{\nu}_e$ capture rates +- x2
- Y_e +- 5%
- v_{asym} = 2x10^9 cm s^{-1}

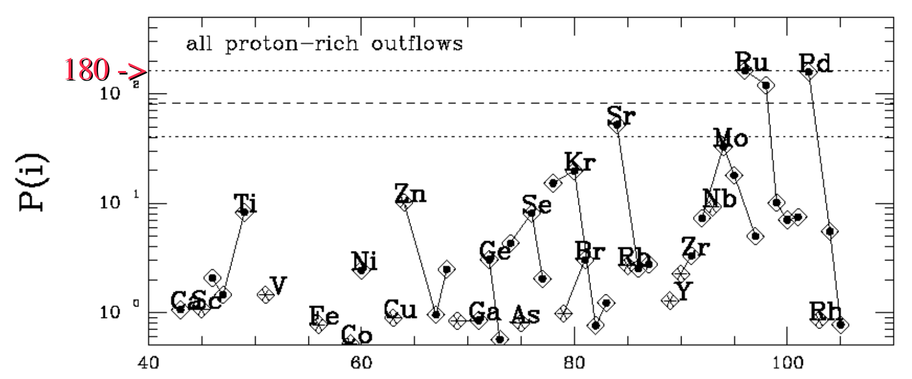




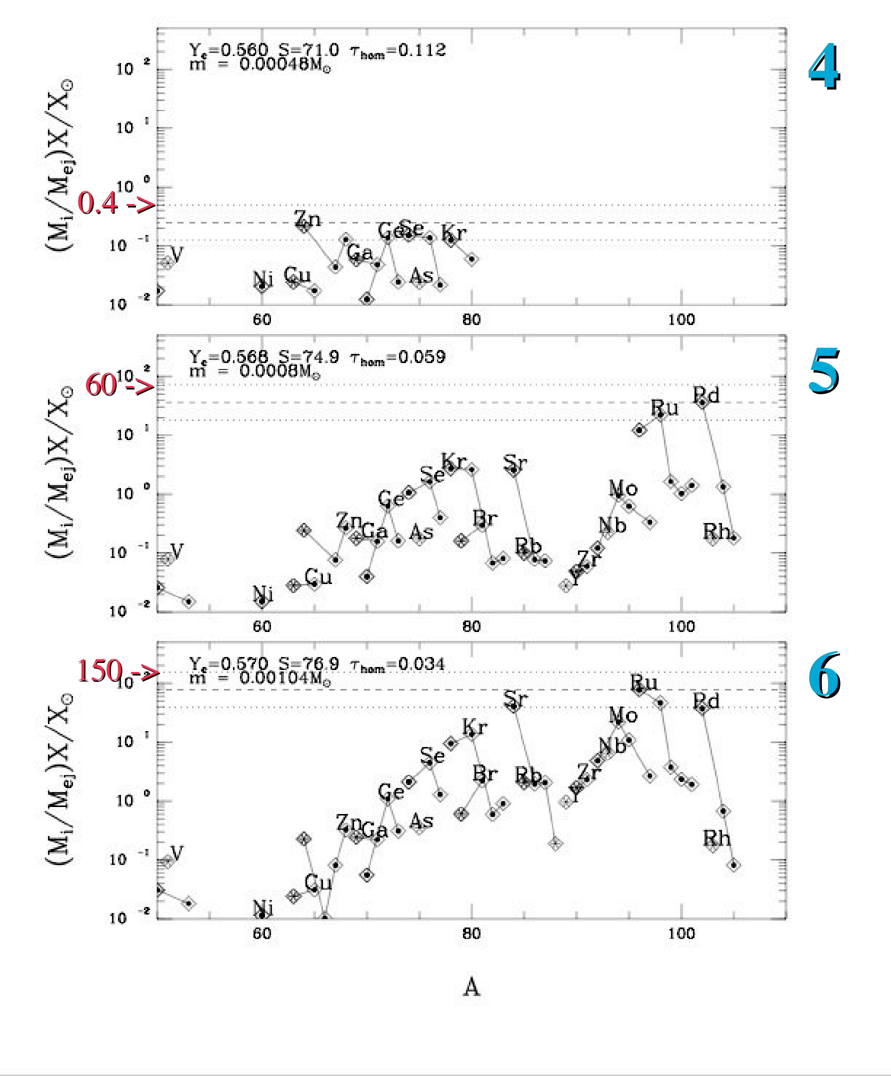
Variations in wind parameters can cause dramatic departure from the nominal case (above). Ye & $\bar{\nu}_e$ mimic each other.

Variations of key parameters

- Changes in all three in the unmodified wind shows dramatic sensitivity between traj's 4, 5, & 6

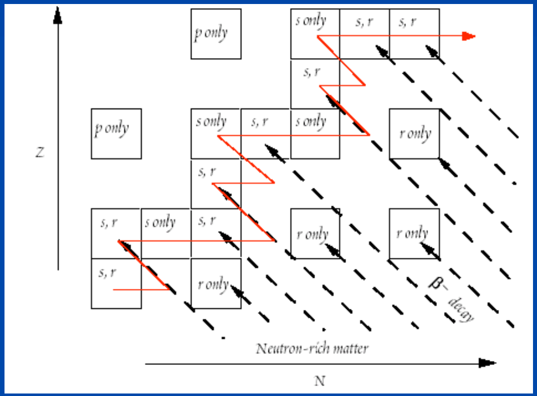


6 units of entropy (from 71-77), a small change in Ye (5%), and a big one in τ_{exp} (50%) makes or breaks light-*p* production.

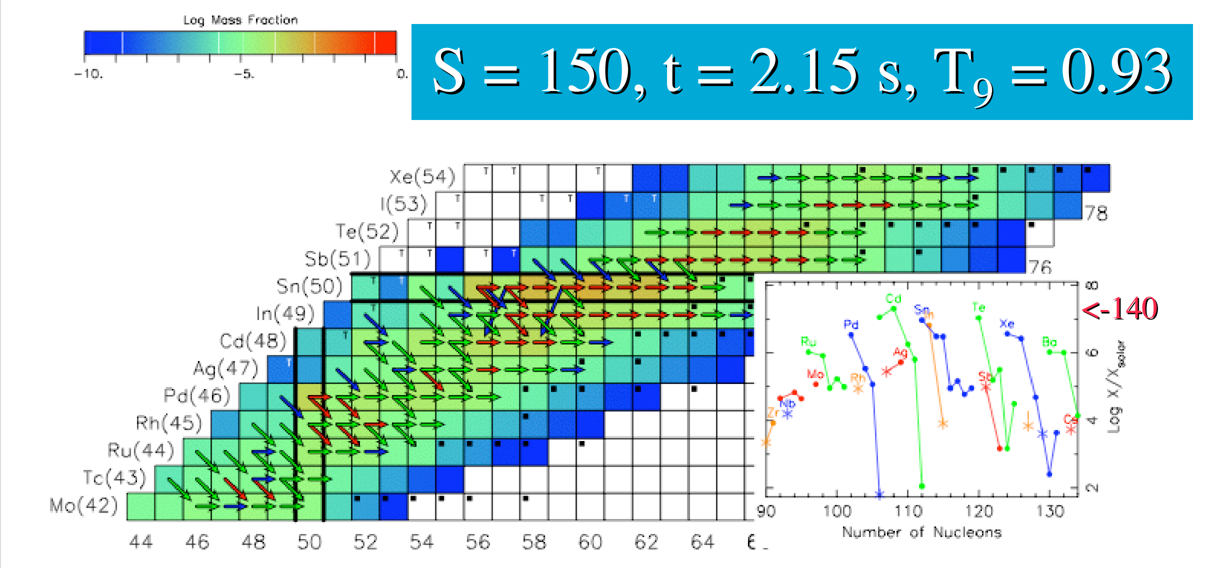


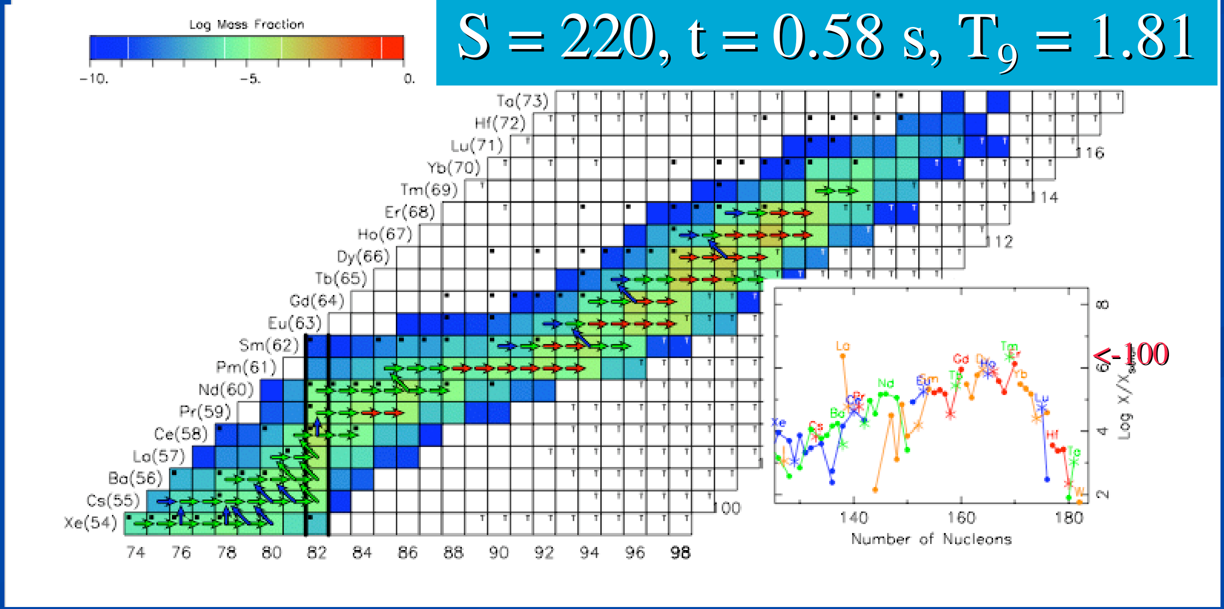
Large Variations on Entropy

Entropy x 2:
X_{seed} lower (n/s higher)
hence flow to higher Z.
A new designation: “*p,s*”
for “*s*-only” or “*r,s*”?

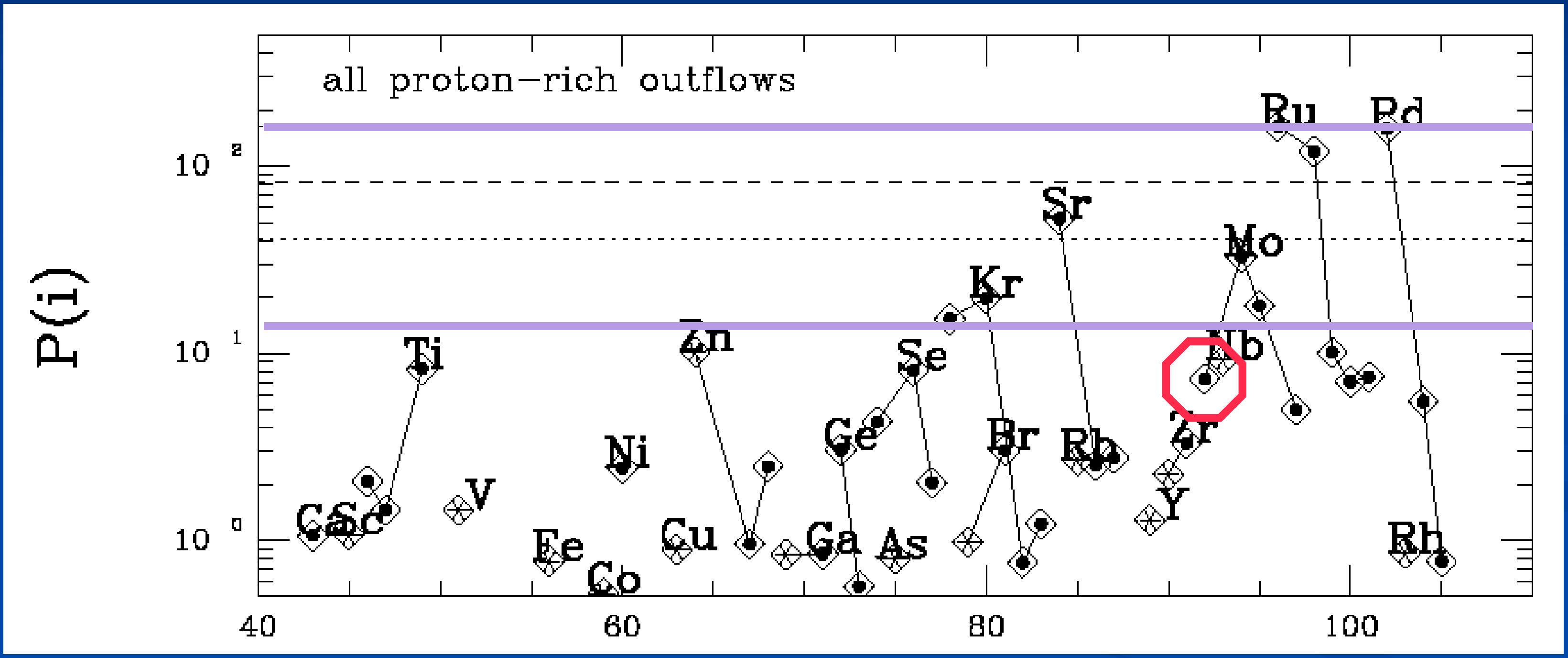


Entropy x 3: Flow to even
higher Z now passes
through valley of stability,
making “*r,s*” and “*r*-only”
nuclei in a *p*-rich
environment!
Loss of light *p*-nuclei.


S = 150, t = 2.15 s, T_9 = 0.93

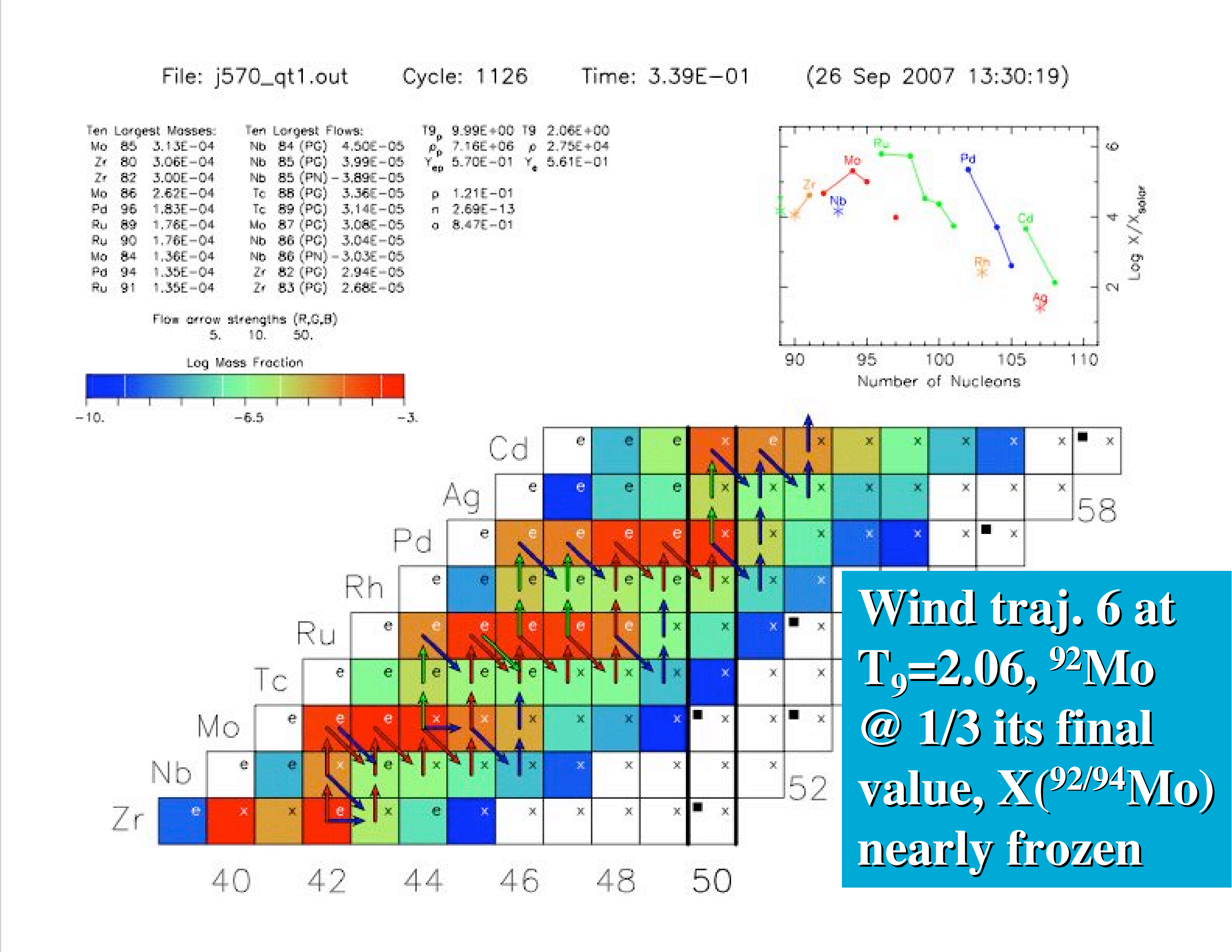

S = 220, t = 0.58 s, T_9 = 1.81

une mouche dans la soupe…



- Light p-nuclei from ^{78}Kr - ^{102}Pd all co-produced, (within x5-10 of maximum - ^{96}Ru) EXCEPT ^{92}Mo. WHY?

A Closer Look…



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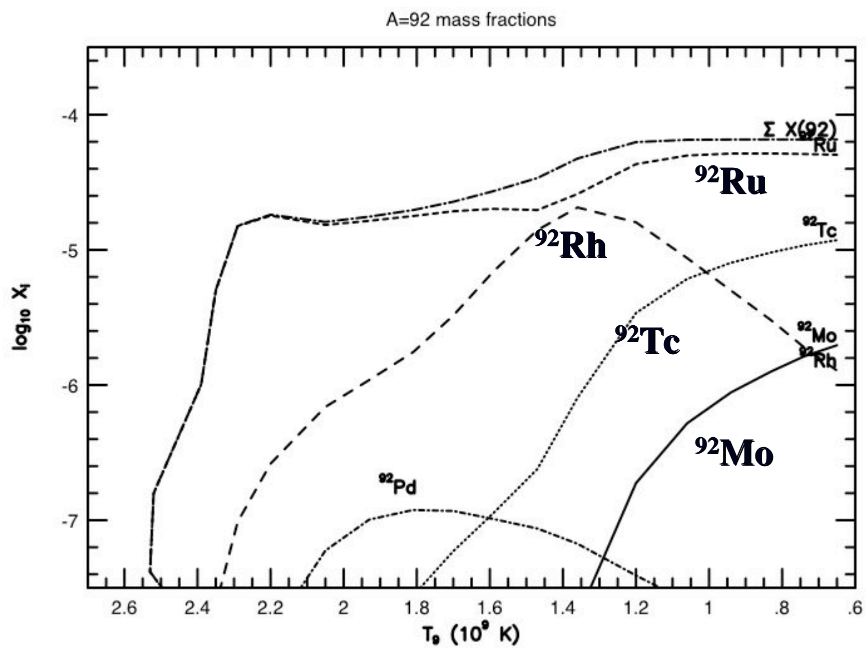
File: j570_qt1.out     Cycle: 1126     Time: 3.39E-01     (26 Sep 2007 13:30:19)

Ten Largest Masses:      Ten Largest Flows:               T9p  9.99E+00  T9  2.06E+00
 Mo  85   3.13E-04        Nb  84 (PG)   4.50E-05          ρp   7.16E+06  ρ   2.75E+04
 Zr  80   3.06E-04        Nb  85 (PG)   3.99E-05          Yep  5.70E-01  Ye  5.61E-01
 Zr  82   3.00E-04        Nb  85 (PN) - 3.89E-05
 Mo  86   2.62E-04        Tc  88 (PG)   3.36E-05           p   1.21E-01
 Pd  96   1.83E-04        Tc  89 (PG)   3.14E-05           n   2.69E-13
 Ru  89   1.76E-04        Mo  87 (PG)   3.08E-05           α   8.47E-01
 Ru  90   1.76E-04        Nb  86 (PG)   3.04E-05
 Mo  84   1.36E-04        Nb  86 (PN) - 3.03E-05
 Pd  94   1.35E-04        Zr  82 (PG)   2.94E-05
 Ru  91   1.35E-04        Zr  83 (PG)   2.68E-05

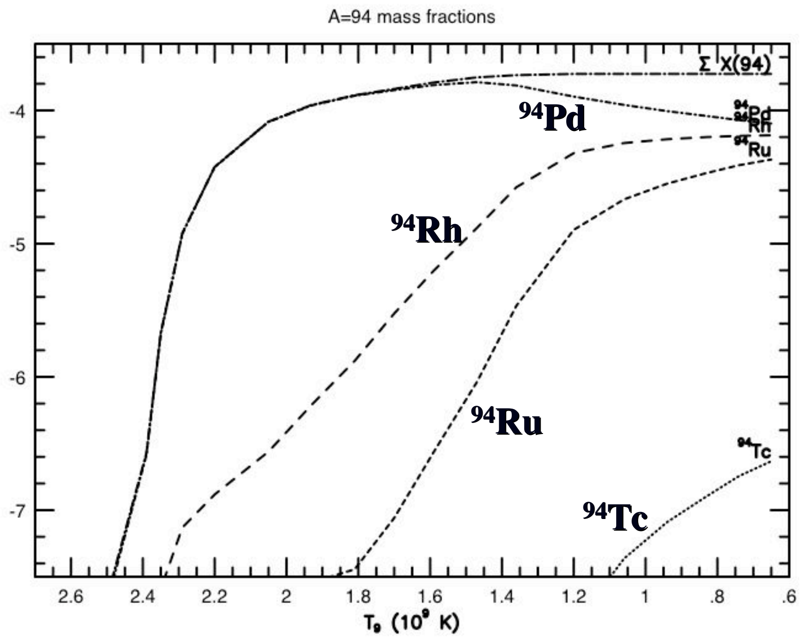
       Flow arrow strengths (R,G,B)
             5.    10.    50.
```

Wind traj. 6 at T_9=2.06, ^{92}Mo @ 1/3 its final value, X($^{92/94}$Mo) nearly frozen

The Ones that Count

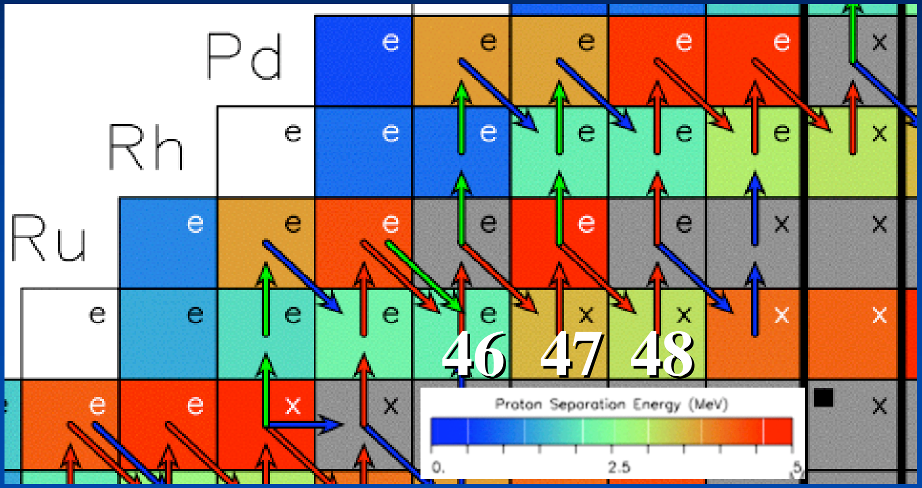


Wind traj. 6: $X(T_9)$ A=92,94 isobars that decay to ^{92,94}Mo. ^{92}Ru is most important, affects both.



So: what's affecting the net flows?

Physics on the Edge



Strong (p,γ) flows along N=48 largely determine ^{92}Ru & ^{94}Pd.

$$F_{net} = Y_I Y_p \rho \lambda_{p\gamma} - Y_L \lambda_{\gamma p}$$

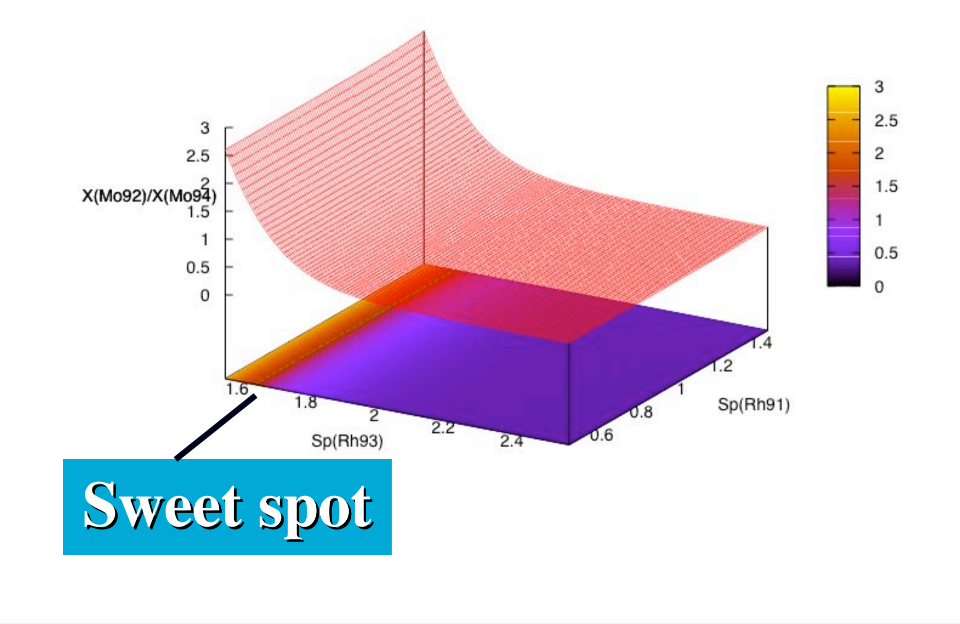
$$\lambda_{\gamma p} = \left(\frac{g_I g_p}{g_L}\right)\left(\frac{G_I}{G_L}\right)\left(\frac{A_I A_p}{A_L}\frac{2\pi kT}{h^2 N_A}\right)^{3/2} \lambda_{p\gamma} e^{-Q_{j\gamma}/kT}$$

S_p+-ΔS_p from AW2003

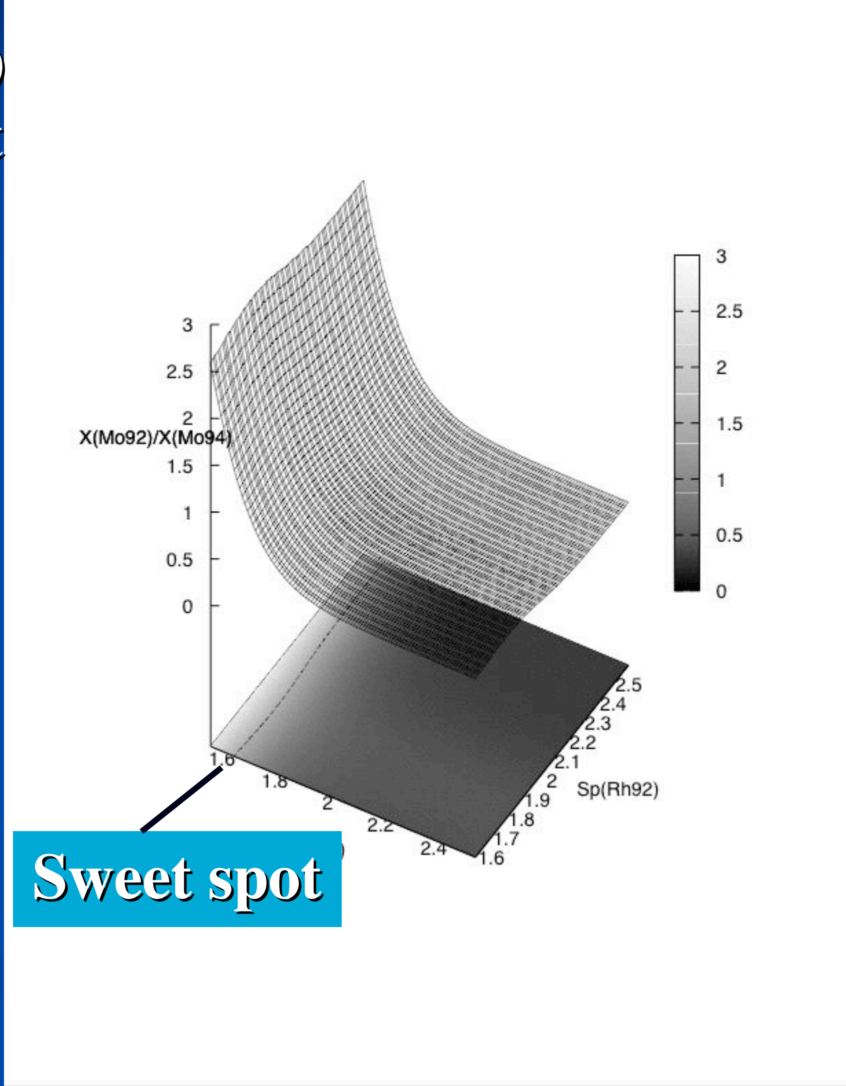
Nucleus	Proton separation energy	Source
^{90}Ru	4.75 ± 0.36 MeV	Extrapolation
^{91}Ru	4.74 ± 0.76 MeV	Extrapolation
^{92}Ru	5.71 ± 0.36 MeV	Extrapolation
^{91}Rh	1.09 ± 0.50 MeV	Extrapolation
^{92}Rh	1.99 ± 0.71 MeV	Extrapolation
^{93}Rh	2.05 ± 0.50 MeV	Extrapolation
^{92}Pd	3.68 ± 0.64 MeV	Extrapolation
^{93}Pd	3.63 ± 0.57 MeV	Extrapolation
^{94}Pd	4.47 ± 0.57 MeV	Extrapolation

Which S_p is most important?

In wind trajectory 6 we vary $S_p(^{91,92}Rh)$ vs. $S_p(^{93}Rh)$ by 1σ. Irrespective of first two, the $X(^{92}Mo)/X(^{94}Mo)$ solar ratio (=1.57) occurs for $S_p(^{93}Rh)$=1.64 MeV.

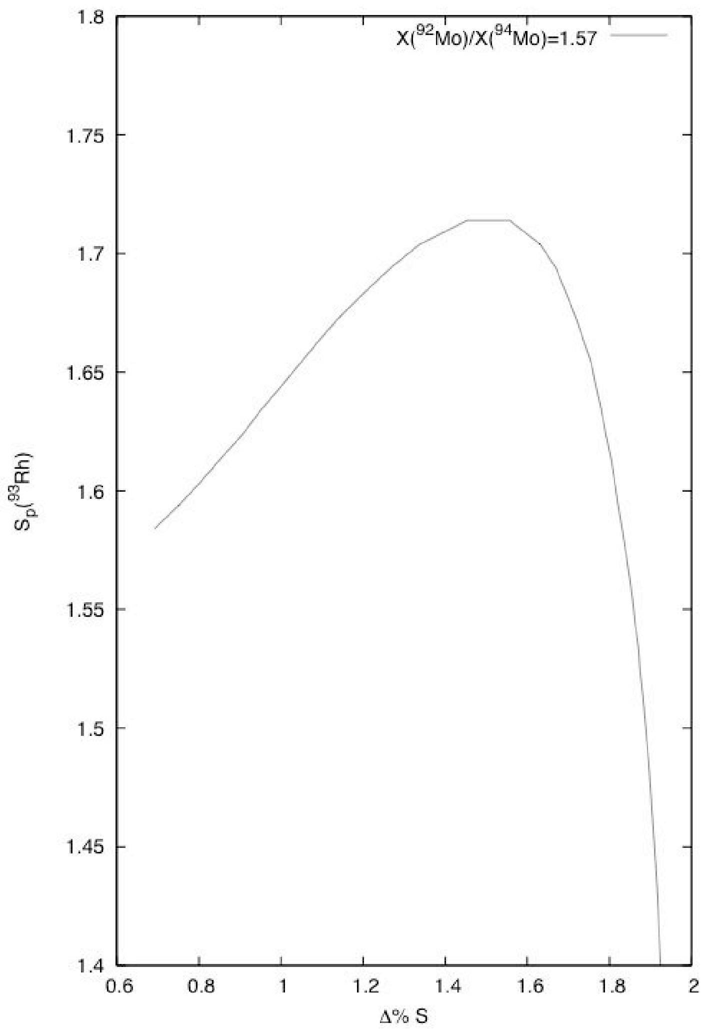


Sweet spot



Sweet spot

A Robust Solution?

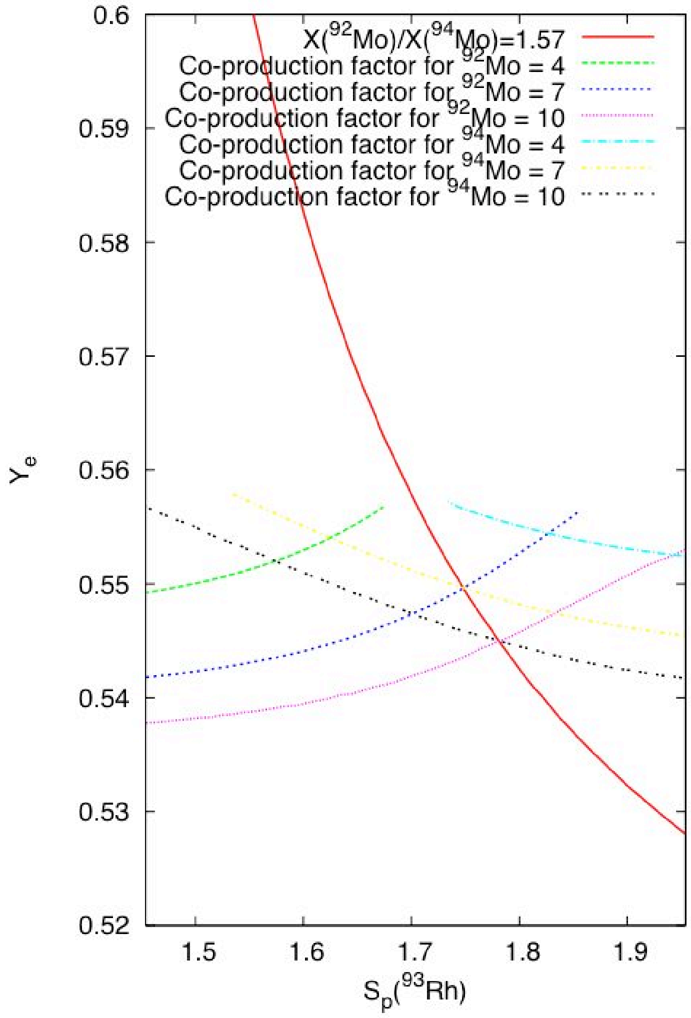


The dependence of the solar ratio X(^{92}Mo)/ X(^{92}Mo) to variations in entropy and in the outgoing wind of trajectory 6.

$S_p(^{93}Rh)$ = 1.64 +- 0.1 MeV is a solution for the range of entropy considered (0.8 - 1.6, 1.0 is nominal).

Note, for a X(^{92}Mo)/ X(^{92}Mo) ratio of 1.57 there is no solution for Sp(^{93}Rh) > 1.71 MeV. This is and upper bound.

A Robust Solution?



The solid red line shows the solution for $S_p(^{93}Rh)$ and Y_e when the ^{92}Mo/^{94}Mo ratio in the outgoing wind of trajectory 6 is solar (=1.57+-0.02).

Also shown are the solutions where both ^{92}Mo and ^{94}Mo are co-produced within factors of 4, 7, and 10 of the maximum overproduction. A factor of 7 is acceptable.

Conclusions

- The ν*rp*-process in the unmodified outlfows of Janka et al. co-produce the light *p*-nuclei from Kr to Pd, except ^{92}Mo.
- This can be recovered if $S_p(^{93}\mathrm{Rh})$ = 1.64 +- 0.1 MeV (5 times less than its current assigned error of 0.5 MeV).
- The solution appears robust with respect to reasonable uncertainties in wind parameters.
- This is the first time that this range of light *p*-nuclei have been co-produced in a single nucleosynthetic process.
- An experiment at TRIUMF using Dragon has been approved to measure these crucial mass excesses (Ruiz & Dilling, S1124, 9 shifts at med-high priority).

Disclaimer