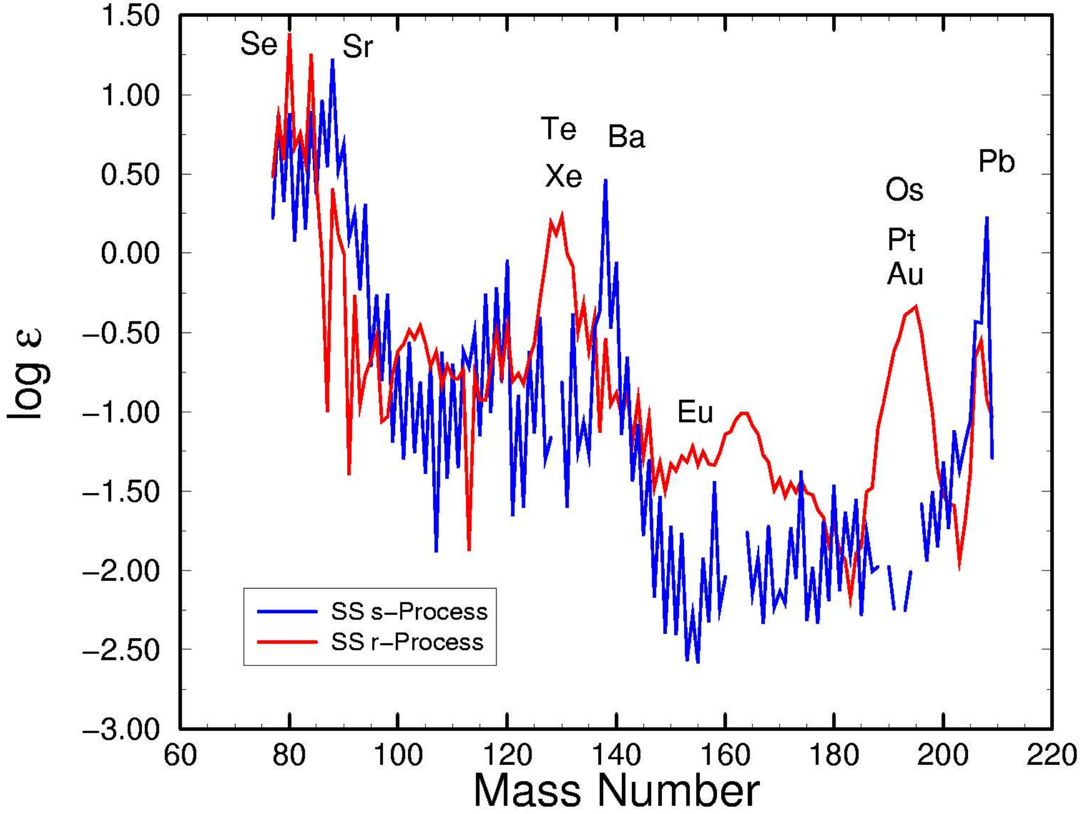
The classical r-process

- Assume conditions where after a charged-particle freeze-out the heavy QSE-group splits into QSE-subgroups containing each one isotopic chain Z, and a high neutron density is left over
- these QSE-groups are connected by beta-decays from Z to Z+1
- neutrons are consumed to form heavier nuclei
- is a steady flow of beta-decays conceivable?

s- and r-decoposition

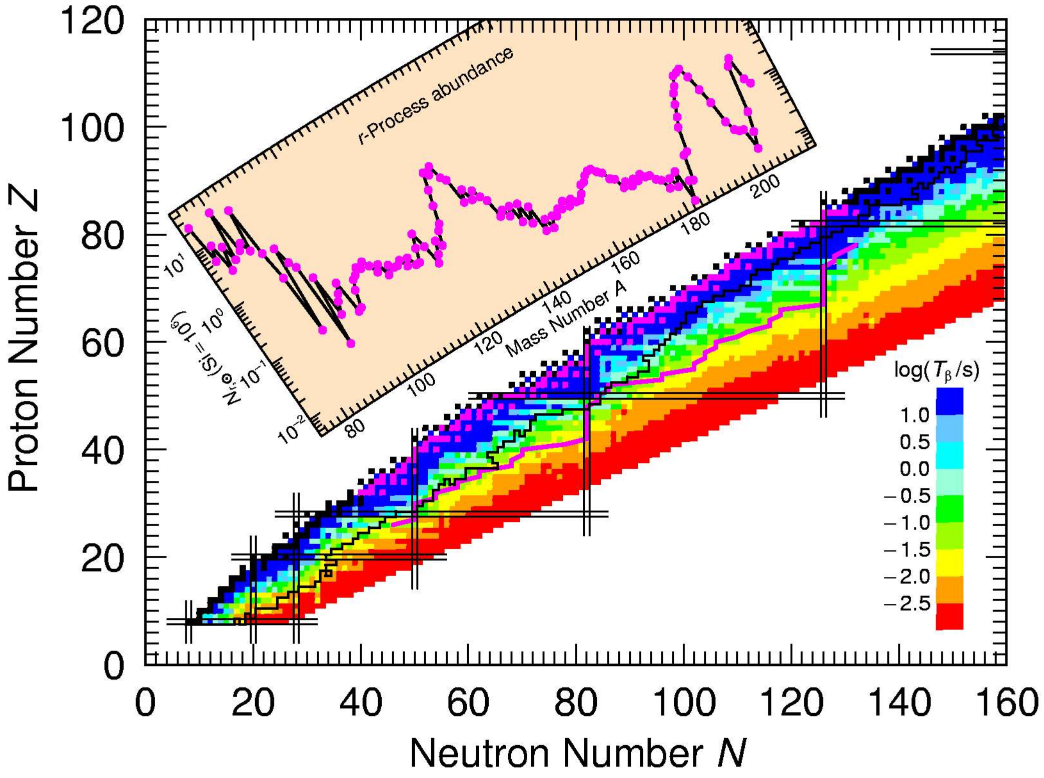


$$
\begin{aligned}
\dot{Y}(Z,A) &= -\lambda_{\beta^-}(Z,A)Y(Z,A) - \rho N_A < \sigma v >_{n,\gamma} Y_n Y(Z,A)\\
&= -\lambda_{\beta^-}(Z,A)Y(Z,A) - < \sigma v >_{n,\gamma} n_n Y(Z,A)\\
&= -\frac{1}{\tau_\beta}Y(Z,A) - \frac{1}{\tau_{n,\gamma}}Y(Z,A).
\end{aligned}
$$

which timescale is shorter? neutron capture inverse proportional to n_n !

Heavy Elements are made by slow and rapid neutron capture events

High neutron densities lead to nuclei far from stability



Nuclear Reactions to be considered: (n, γ), (γ, n)

(β, xn), (β, f), (n, f), inelastic ν-scattering, (ν_e, e^-) ......

The classical r-process

How to predict abundance changes?

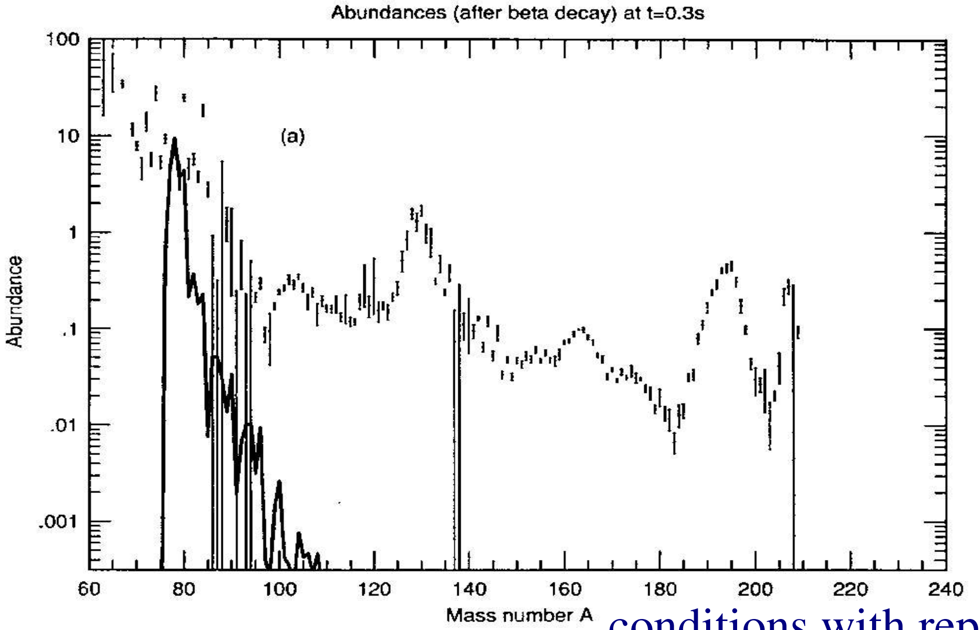
- $\dot{Y}(Z,A) = \sum \lambda_{Z',A'} Y_{Z',A'} + \sum \rho N_A < \sigma v >_{Z',A'} Y_{Z',A'} Y_n$ with $n_n = \rho N_A Y_n$
- $\dot{Y}(Z,A) \approx \lambda_\gamma(Z,A+1) Y(Z,A+1) - < \sigma v >_{Z,A} Y_{Z,A} n_n$ in case (n,γ), (γ,n) rates dominate
- $\dot{Y}(Z,A) = 0$ in chemical equilibrium, $Y(Z,A+1)/Y(Z,A) = f(n_n, T, S_n)$ due to detailed balance relation between $\lambda_\gamma(Z,A+1)$ and $< \sigma v >_{Z,A}$
- abundance maxima for all Z's at same S_n
- $\dot{Y}(Z) = \lambda_\beta(Z-1) Y(Z-1) - \lambda_\beta(Z) Y(Z)$ for summed abundances in isotopic chain and averaged decay rates

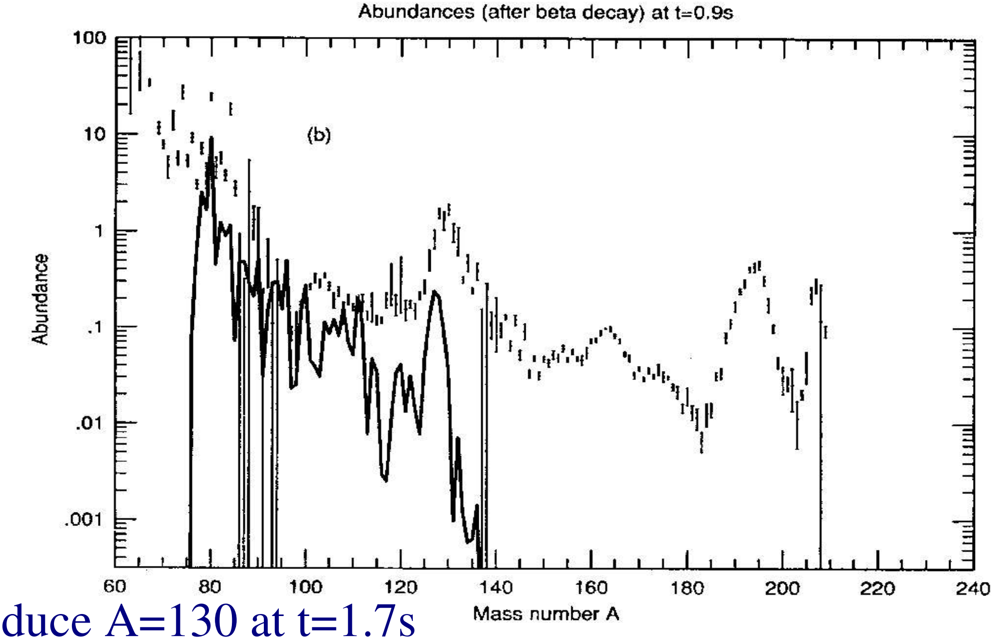
$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{< \sigma v >_{n,\gamma}(A)}{\lambda_{\gamma,n}(A+1)} n_n$$

$$\lambda_{\gamma,n}(A+1) = \frac{2G(Z,A)}{G(Z,A+1)} \left[\frac{A}{A+1}\right]^{3/2} \left[\frac{m_u kT}{2\pi\hbar^2}\right]^{3/2} \langle \sigma v \rangle_{n,\gamma}(A) \exp(-S_n(A+1)/kT)$$

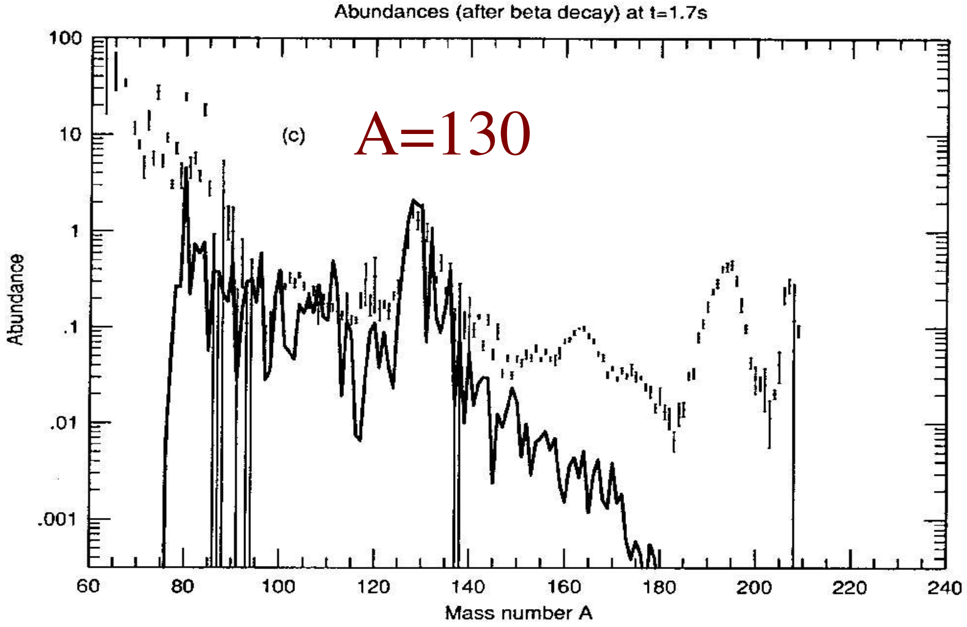
$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A}\right]^{3/2} \left[\frac{2\pi\hbar^2}{m_u kT}\right]^{3/2} \exp(S_n(A+1)/kT)$$

classical calculation with n_n=const and T=const

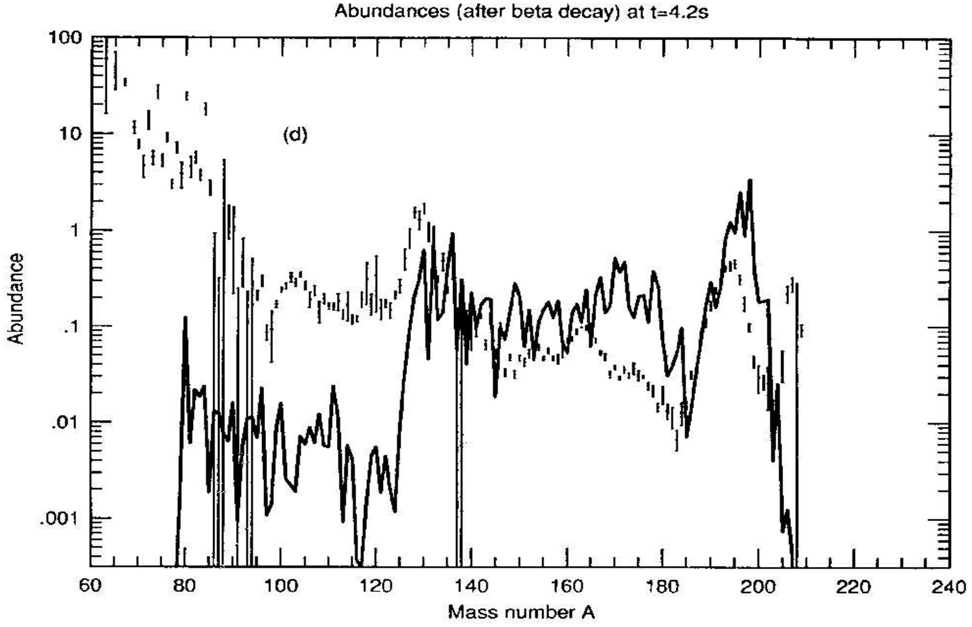

Abundances (after beta decay) at t=0.3s


Abundances (after beta decay) at t=0.9s

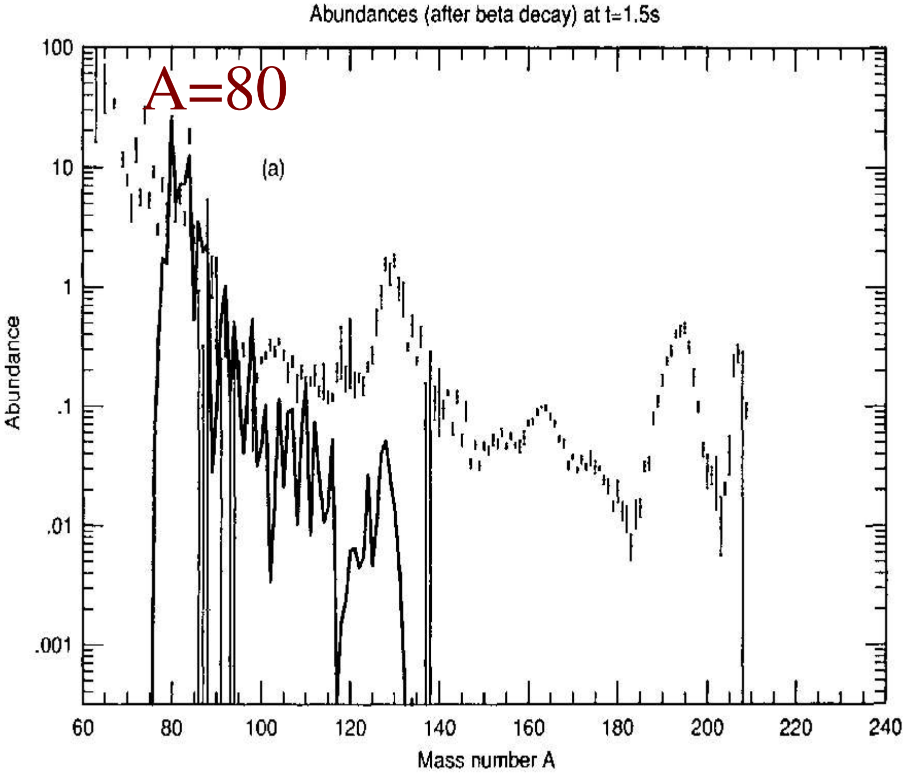
conditions with reproduce A=130 at t=1.7s


Abundances (after beta decay) at t=1.7s

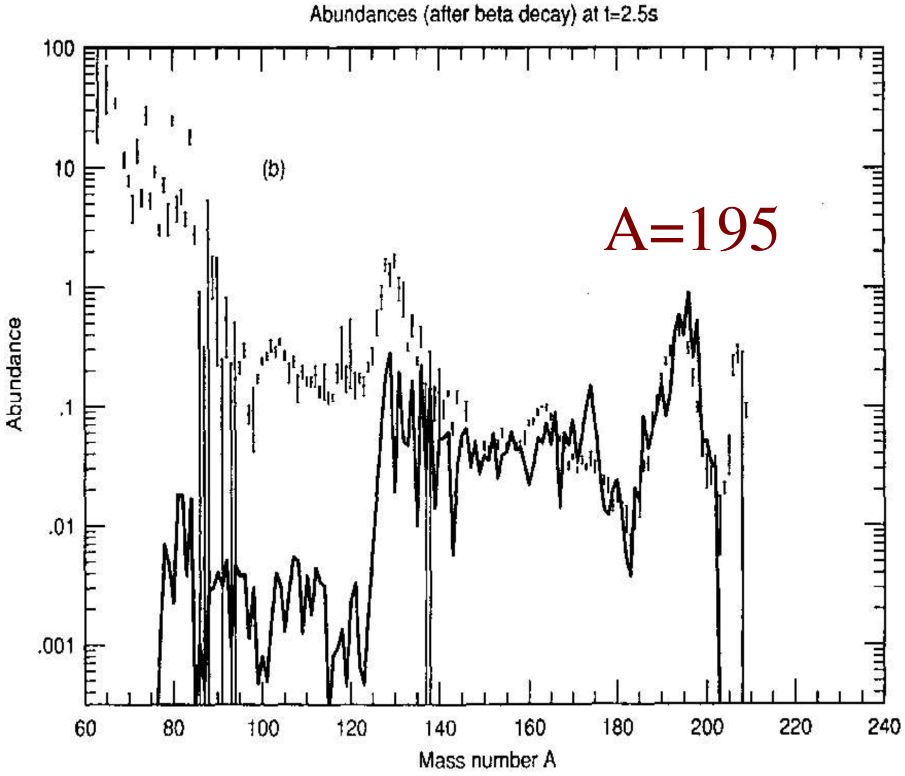
A=130


Abundances (after beta decay) at t=4.2s

A=80 and 195 peaks



t=1.5s

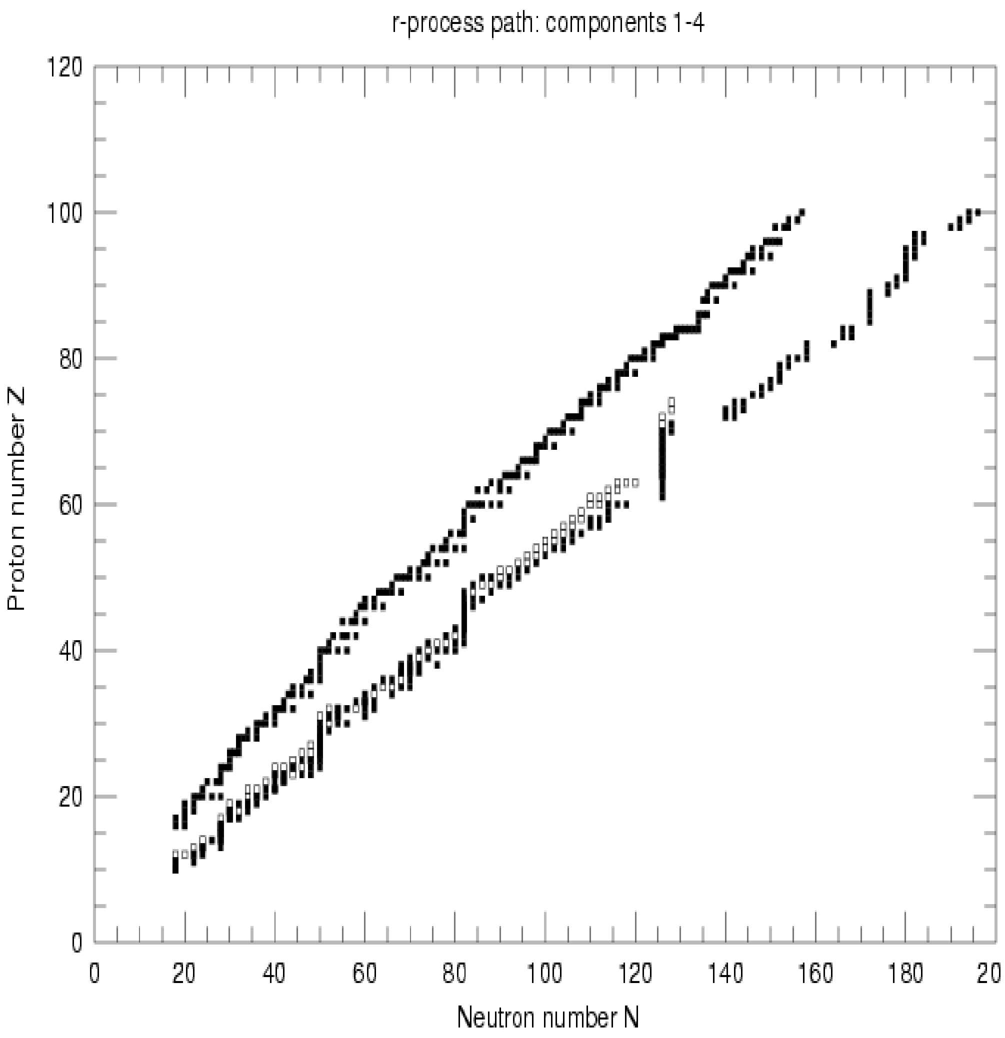


t=2.5s

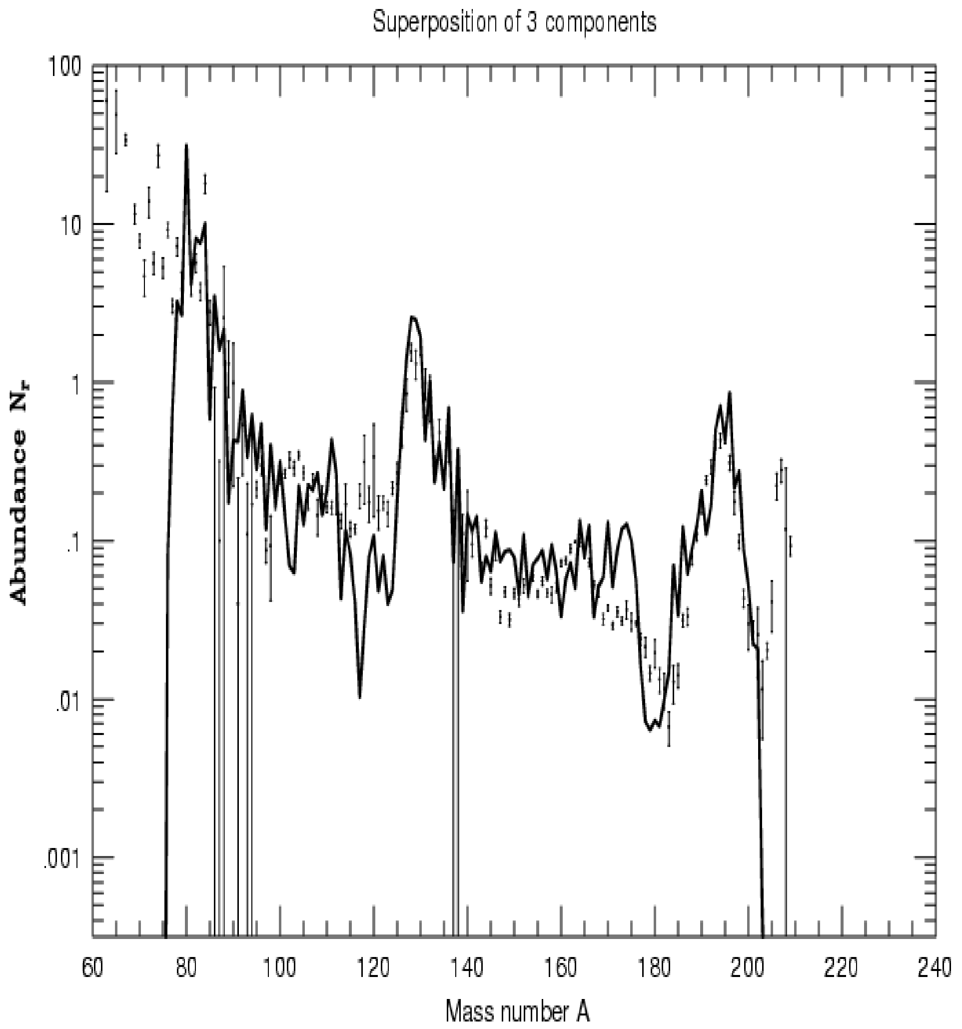
three components produce the A=80, 130, and 195 peaks during "comparable" timescales (for the first time experimental half-lives and masses are known in the r-process path at A=80 and 130)!

Following three S_n's for timescales t_1,t_2,t_3

Kratz, Bitouzet, Thielemann, Möller, Pfeiffer and permutations 1993-1999



r-process path: components 1-4

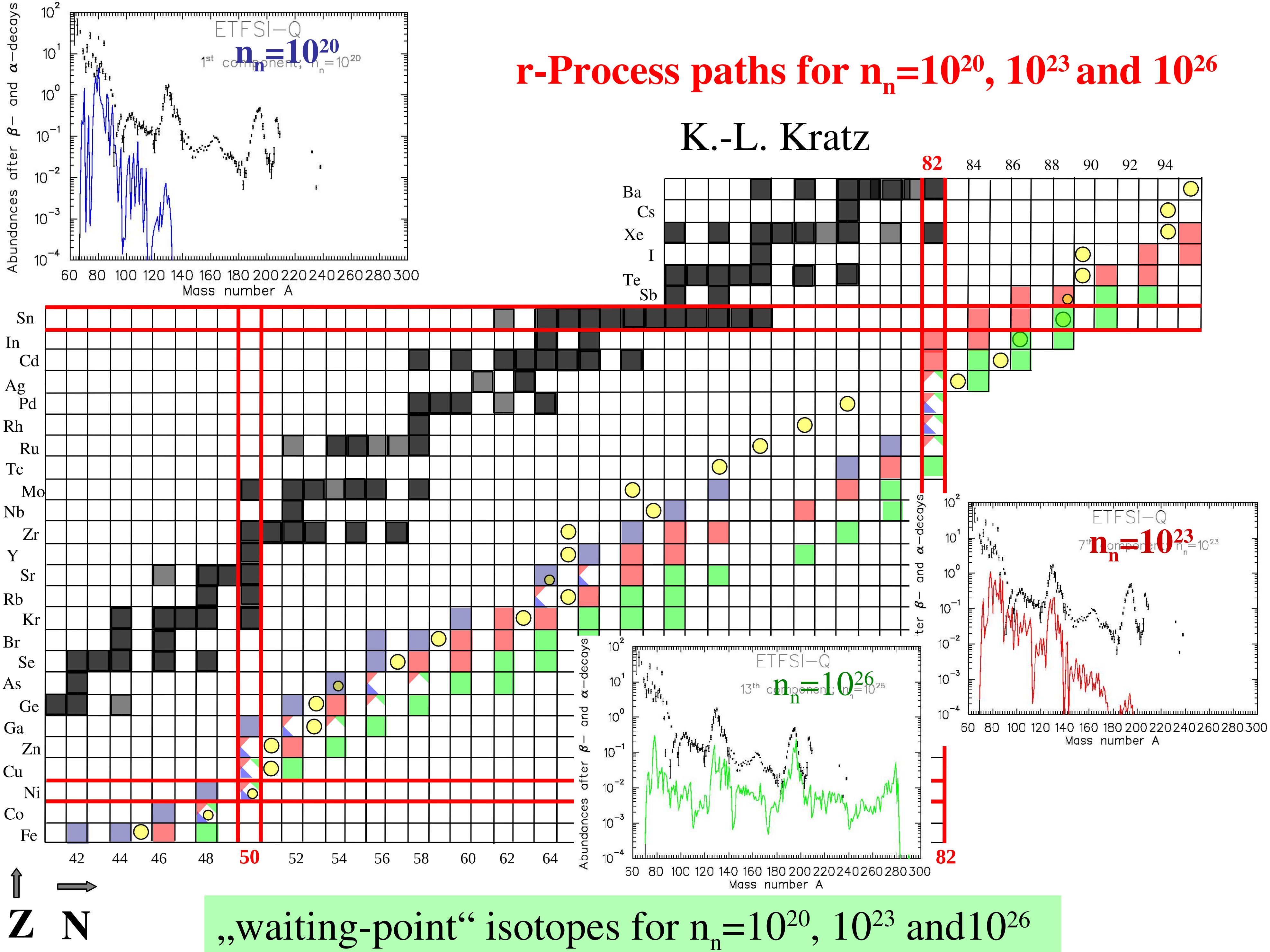


Superposition of 3 components

constant n_n and T for timescale t and afterwards instantaneous beta-decay

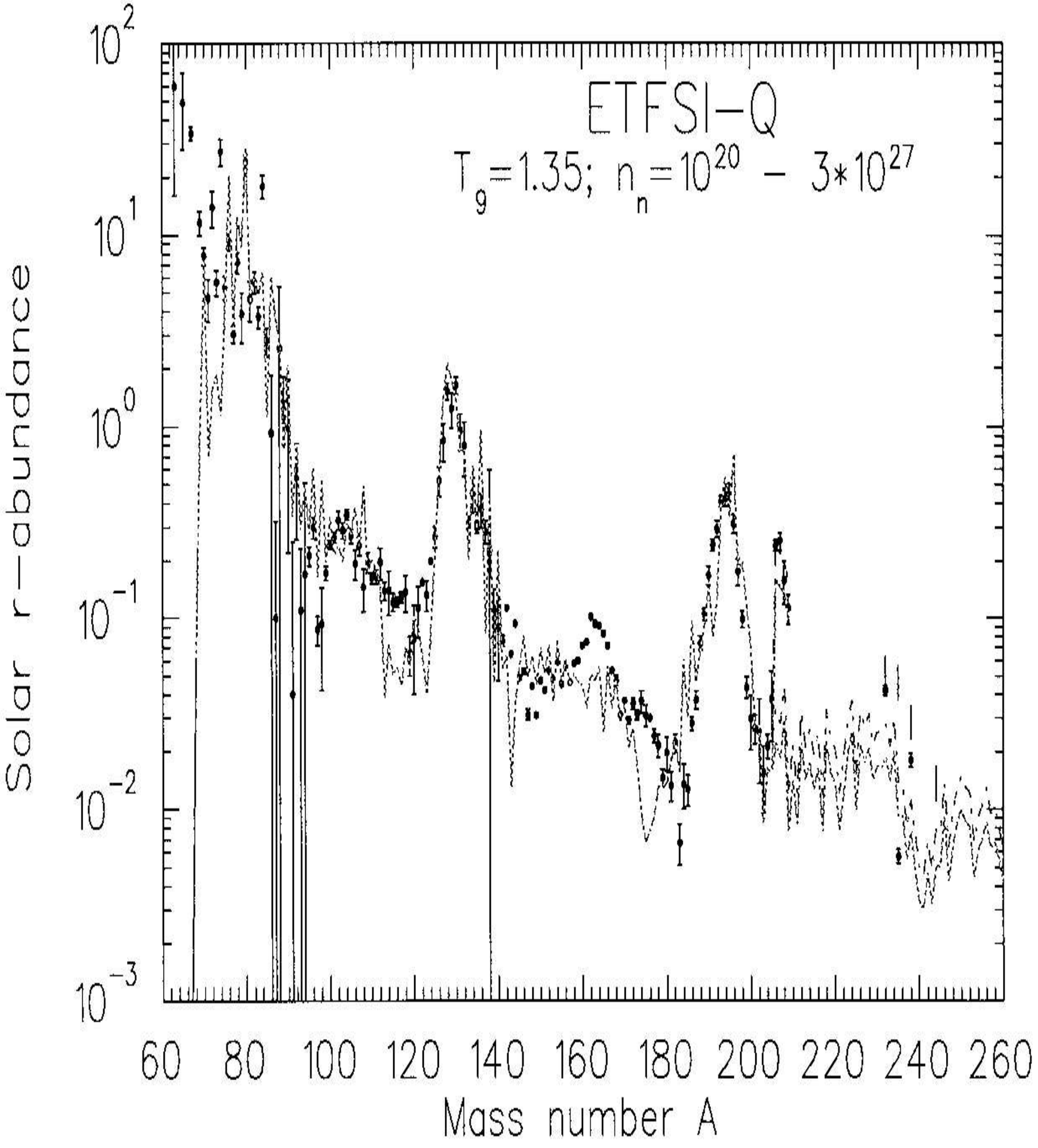
r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26}

K.-L. Kratz

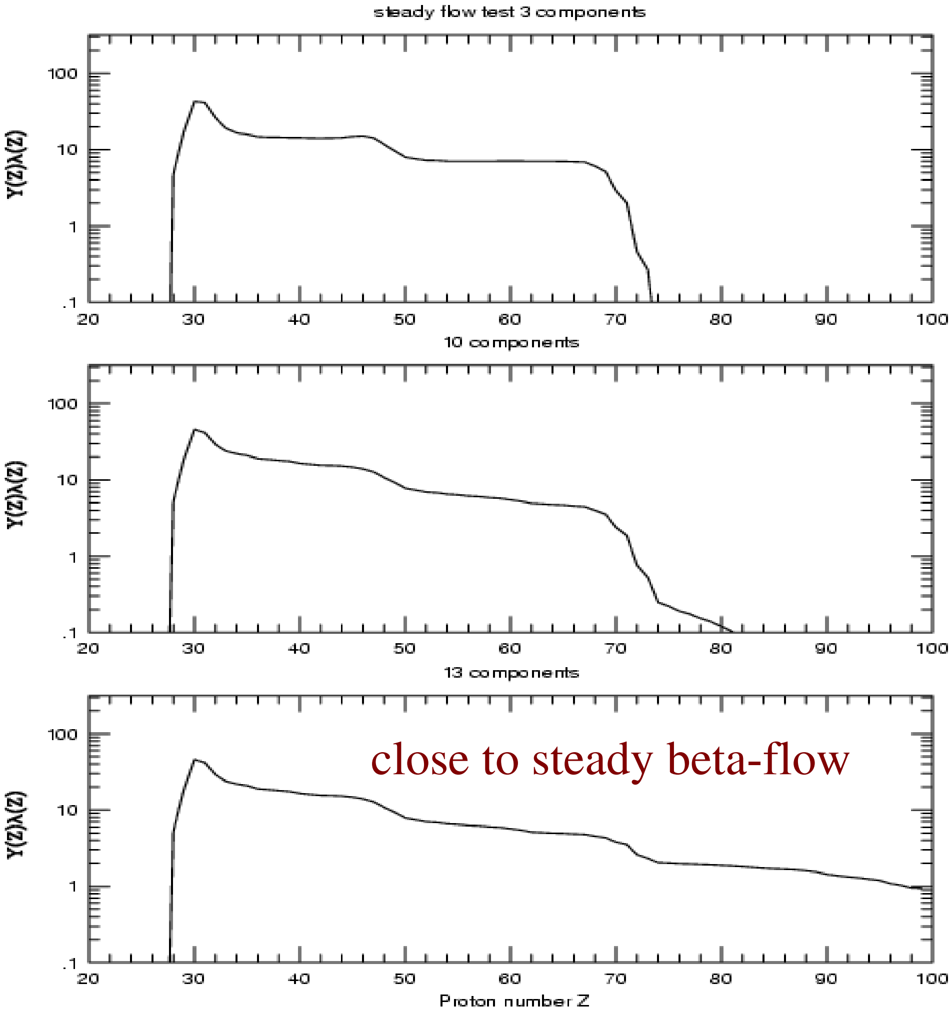


„waiting-point“ isotopes for $n_n=10^{20}$, 10^{23} and10^{26}

Multi-components and steady beta-flow



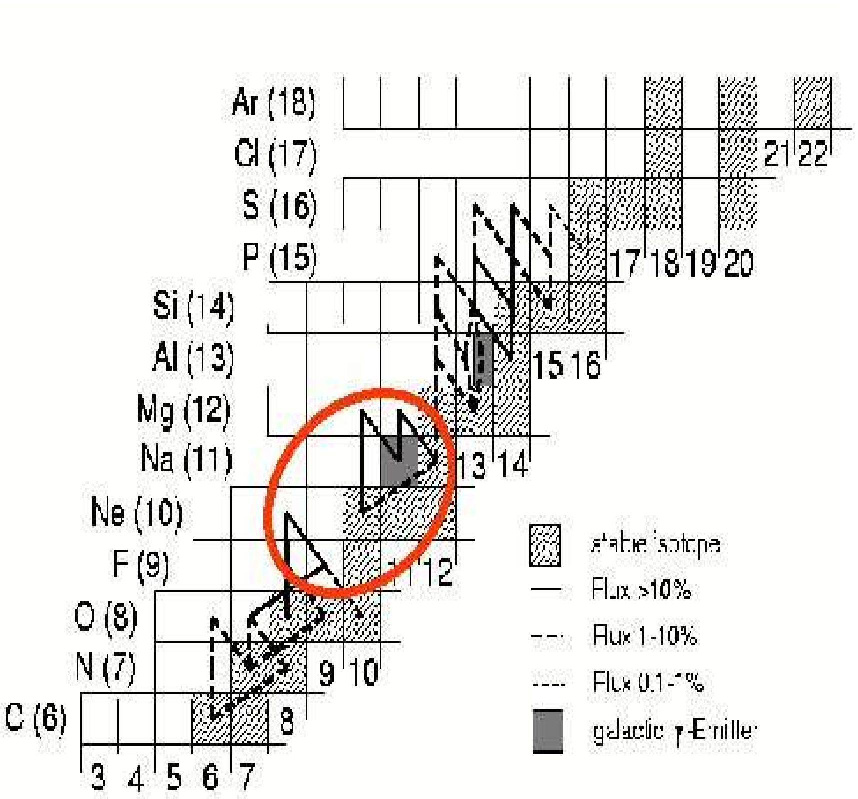
superposition with weights $w(n_n)=8.36\ 10^6 n_n^{-0.247}$ and $t(n_n)=6.97\ 10^{-2}\ n_n^{0.062}$s

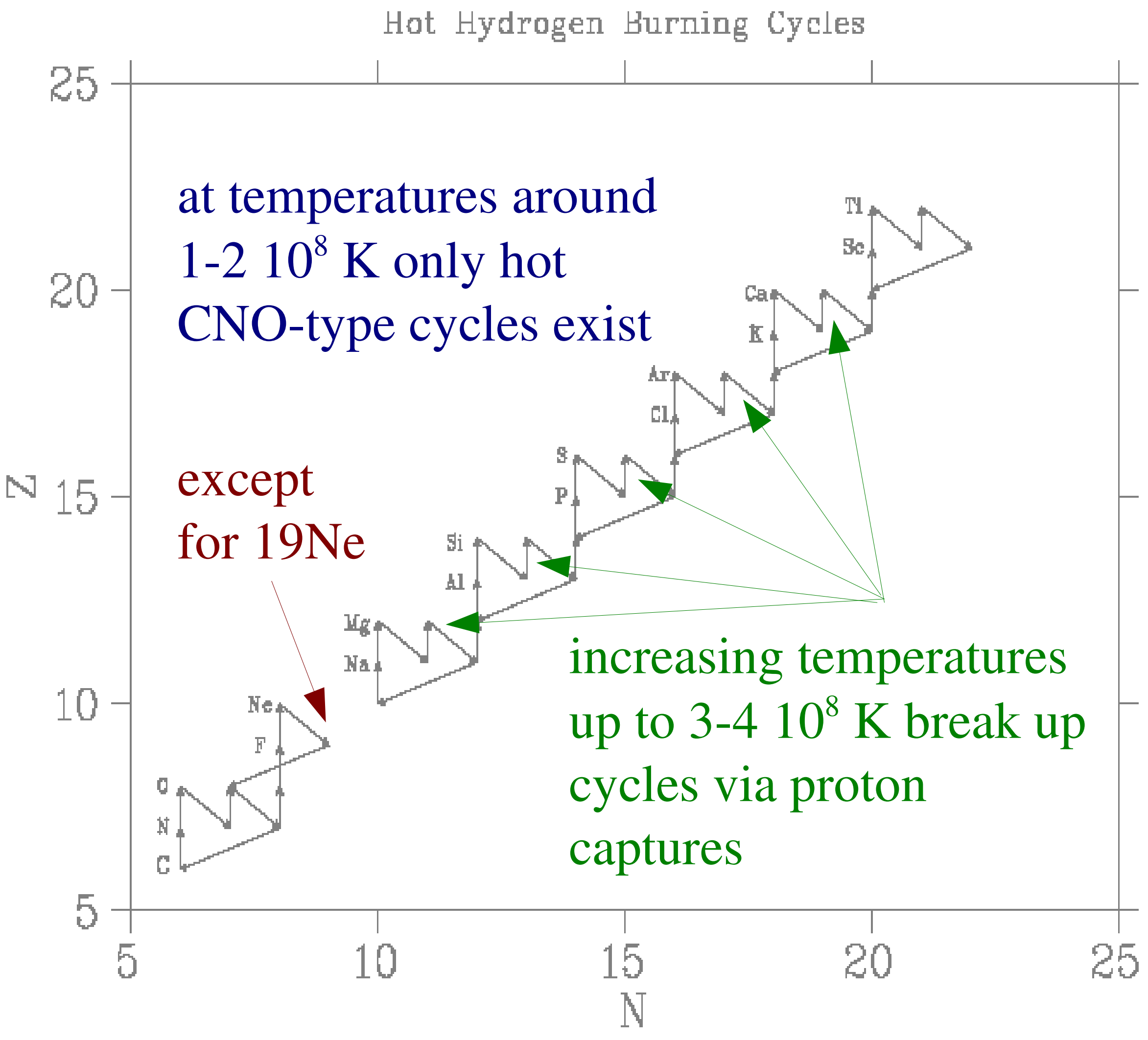


close to steady beta-flow

decay rate of complete Z-chain multiplied with total abundance of Z-chain close to constant in between magic numbers (where long half-lives are encountered).

Explosive H-burning and the onset of the rp-process





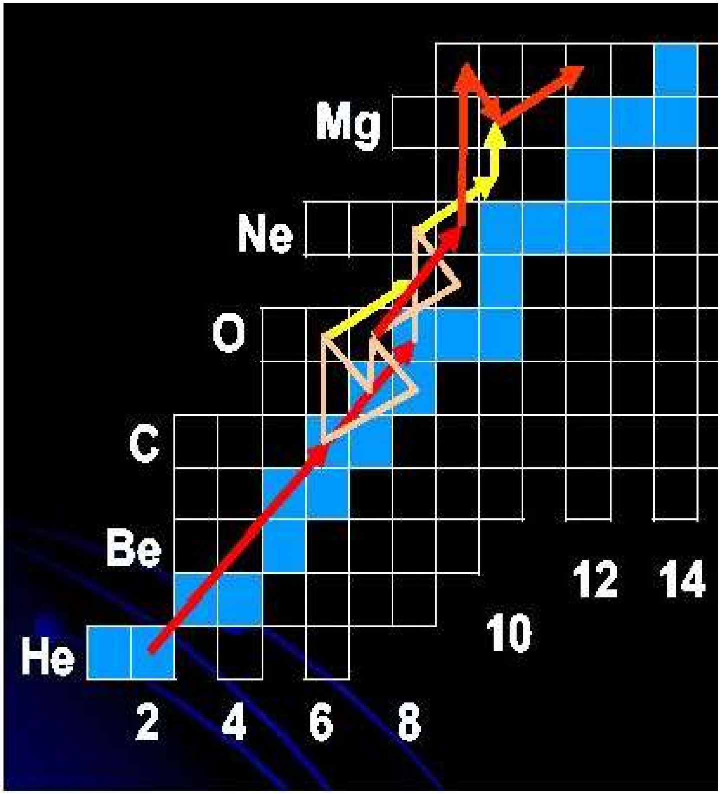
at temperatures around 1-2 10^8 K only hot CNO-type cycles exist

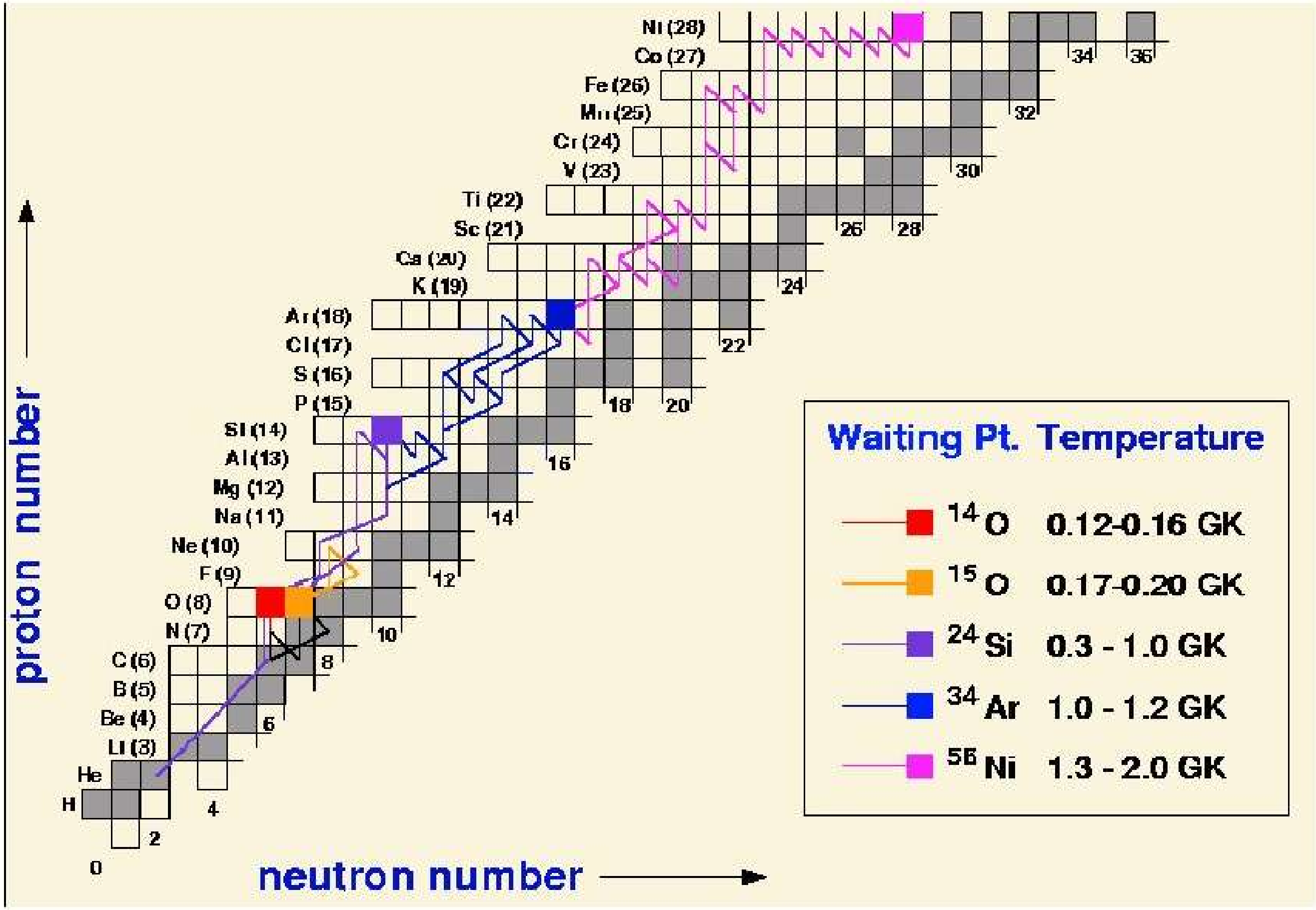
except for 19Ne

increasing temperatures up to 3-4 10^8 K break up cycles via proton captures

Break-out from hot CNO at 4-5 10^8 K

Wiescher, Görres, Thielemann, van Wormer, Schatz, Rembges ..

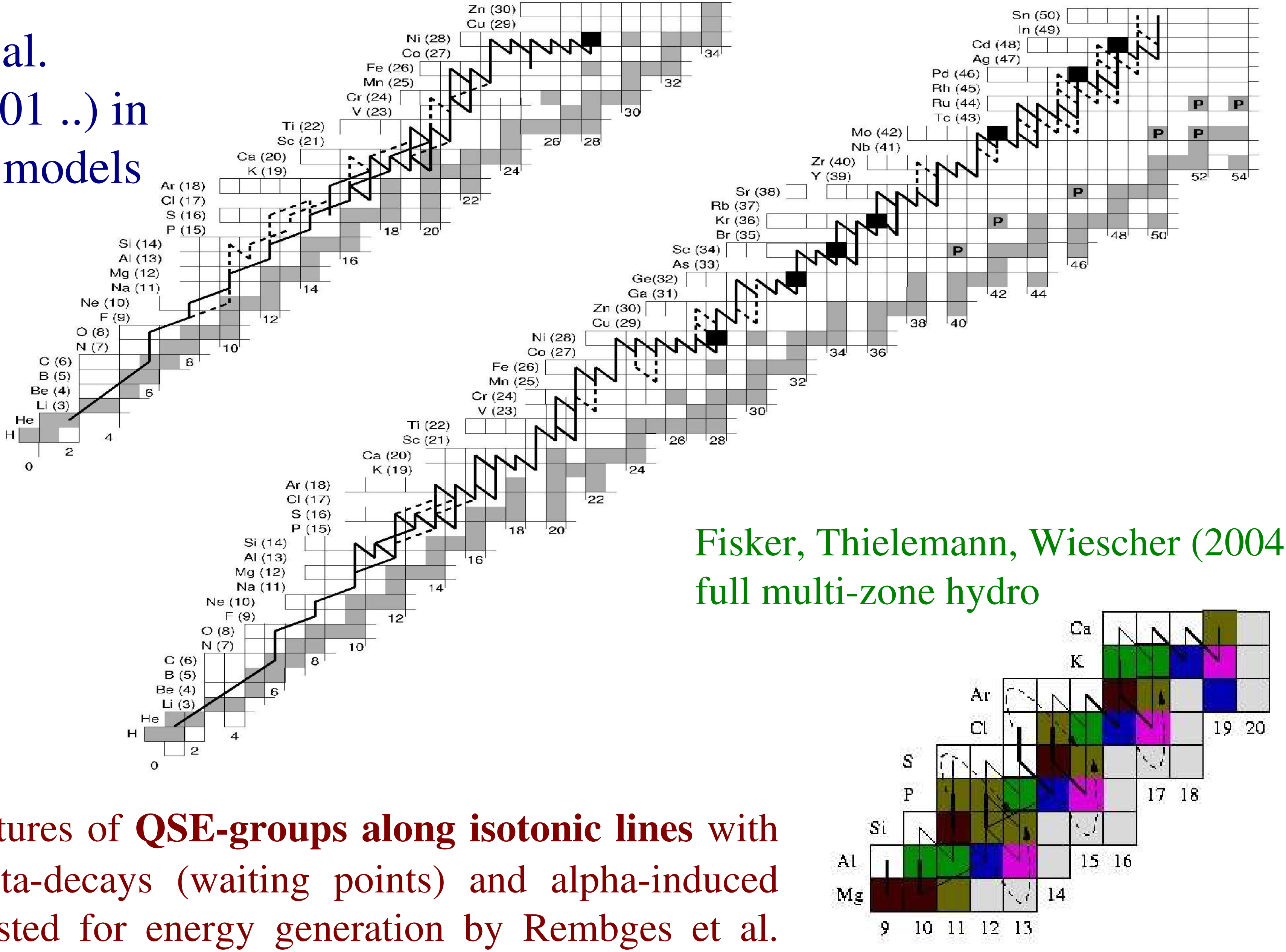




at Z above 20 a sequence of rapid proton captures and beta-decays (rp-process), for smaller target charges (Coulomb barriers) (a,p) reactions possible

rp-process (encounters p-drip line, endpoint Sb-Te cycle)

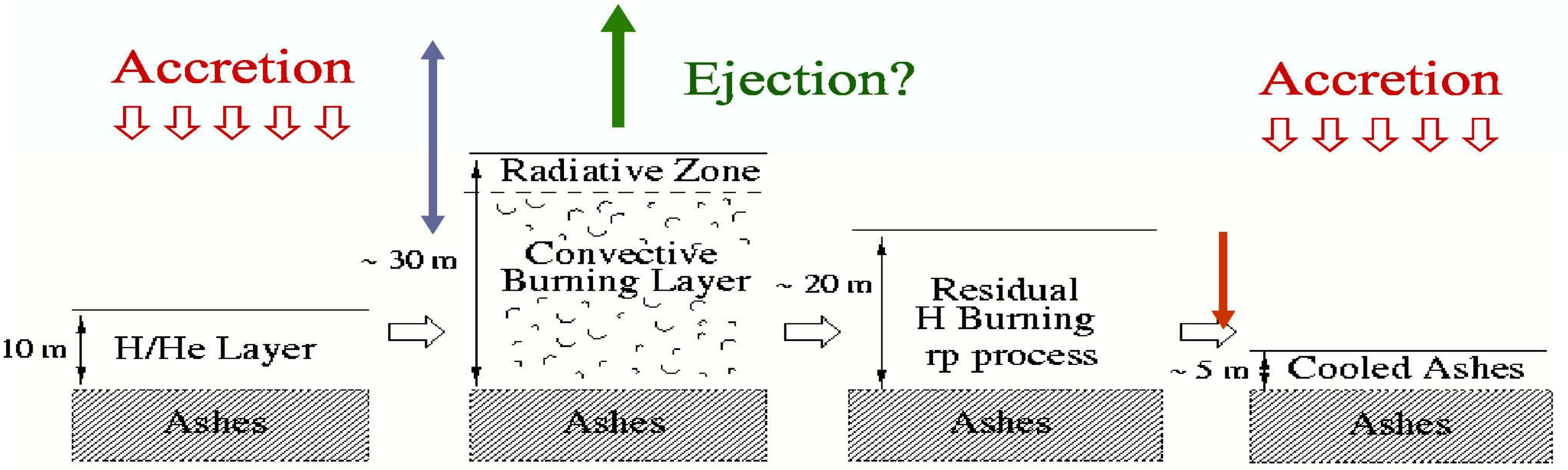
Schatz et al. (1998, 2001 ..) in one-zone models



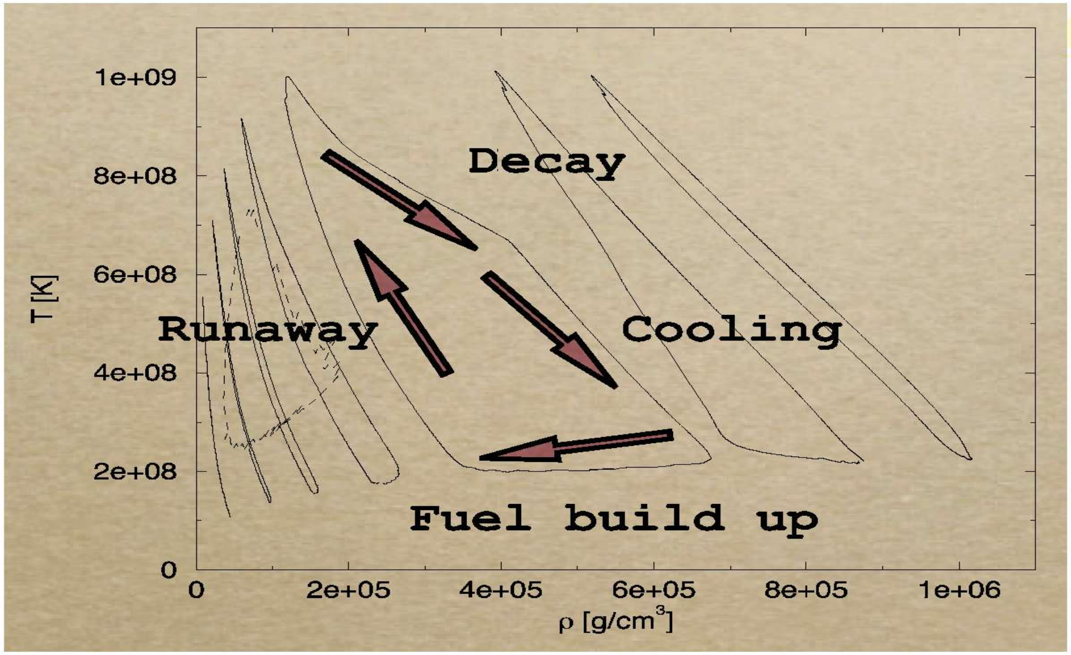
Fisker, Thielemann, Wiescher (2004), full multi-zone hydro

develops features of **QSE-groups along isotonic lines** with links via beta-decays (waiting points) and alpha-induced reactions (tested for energy generation by Rembges et al. 1999)

rp-process in realistic hydro models

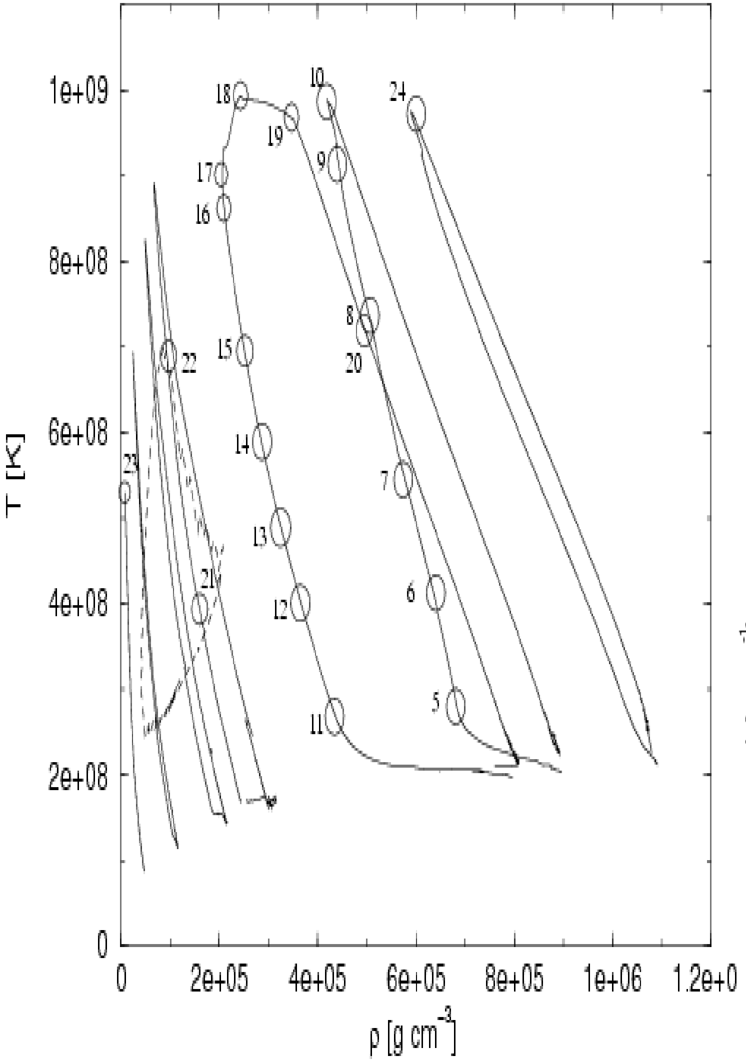


thesis?

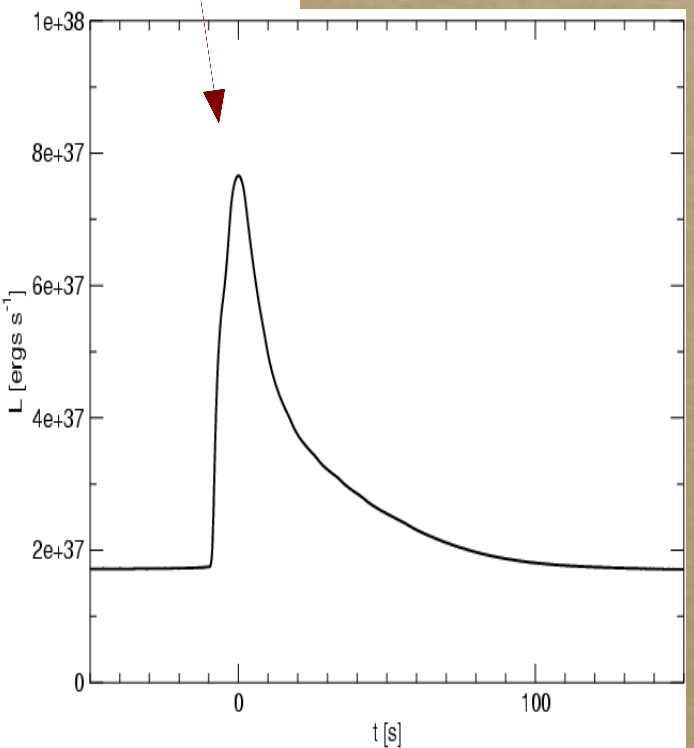


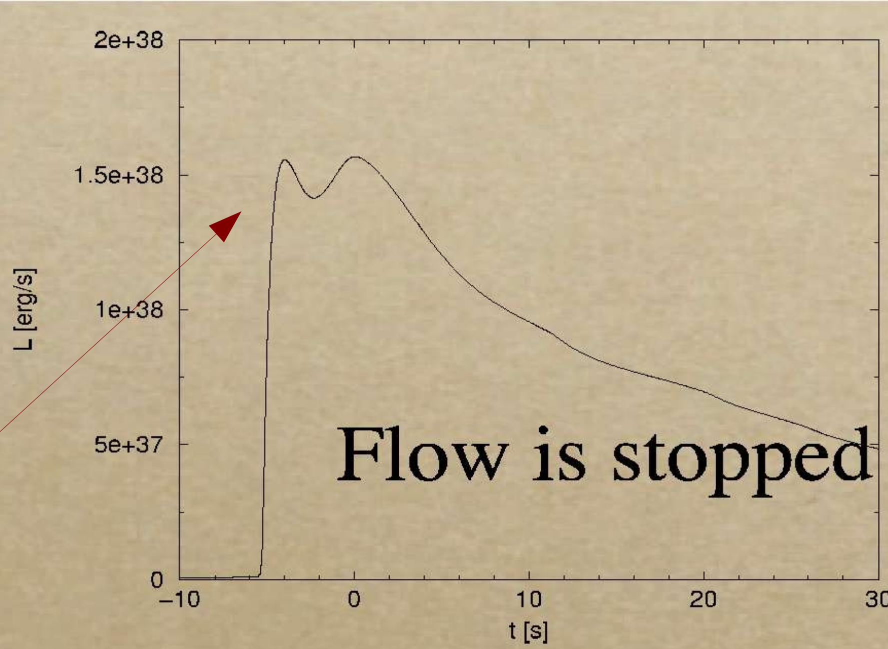
detailed modeling is more complex than QSE-network and identifies reaction sensitivities and drip-line dependence (Fisker, Schatz, Thielemann 2007)

Ignition and burning cycles for adjacent zones during one outburst



possible lightcurve shapes



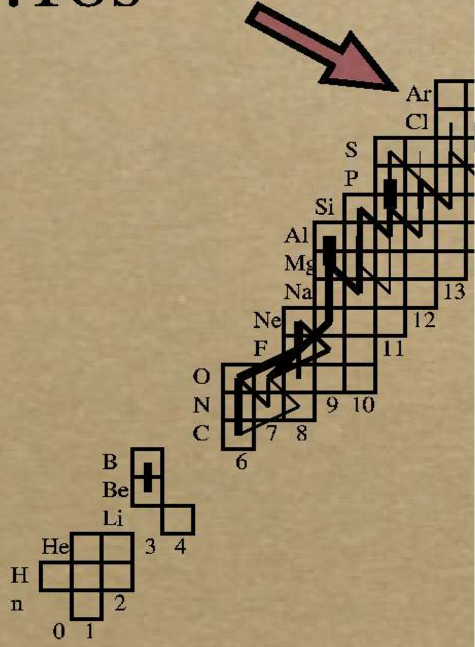


Flow is stopped at

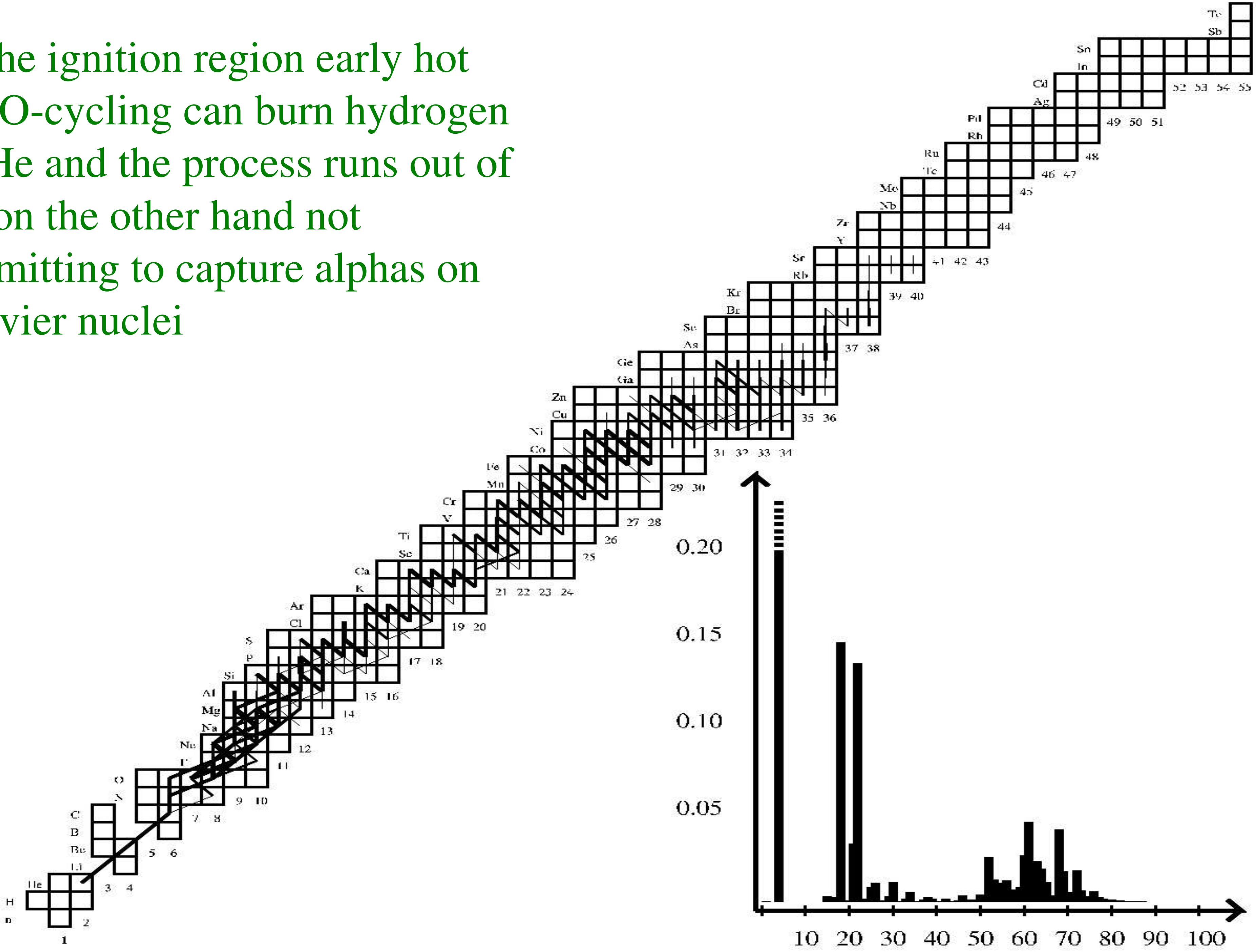
^{31}Cl is photodisintegrated

^{30}S becomes a waiting point;

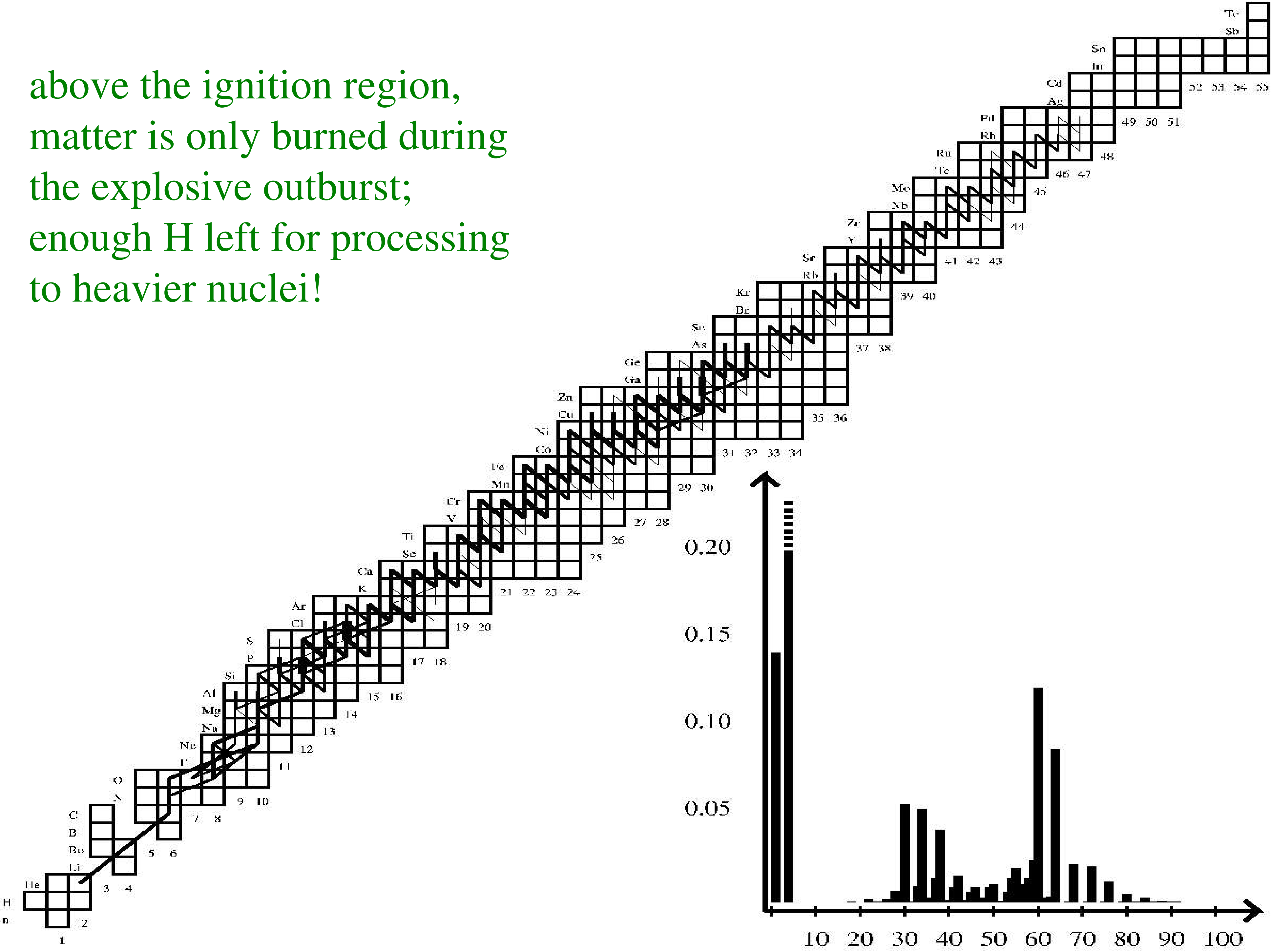
$T_{1/2}$=1.18s



in the ignition region early hot CNO-cycling can burn hydrogen to He and the process runs out of H, on the other hand not permitting to capture alphas on heavier nuclei



above the ignition region,
matter is only burned during
the explosive outburst;
enough H left for processing
to heavier nuclei!



Lessions learned

- Multi-zone modeling absolutely important for full understanding
- only a sufficiently high ^{15}O(a,g)^{19}Ne(p,g)^{20}Na permits a thermonuclear runaway and a burst
- the (a,p) process can proceed up to A=36 (Coulomb barrier) and might pass through possible beta-decay waiting points, like e.g. ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{38}Ca
- the rp-process depends on the (remaining) H-concentration and proton captures with either very small (chemical equilibrium) or negative Q-values (two proton capture). Important nuclei are ^{21}Mg, ^{38}Ca, ^{60}Zn, ^{64}Ge, ^{68}Se, ^{72}Kr, ^{76}Sr, ^{80}Zr ...
- previously unexpected is the possible flow via hot CNO-type cycles up to the Ca-Ni region in pre-outburst hot H-burning, which depends on many individual reactions.