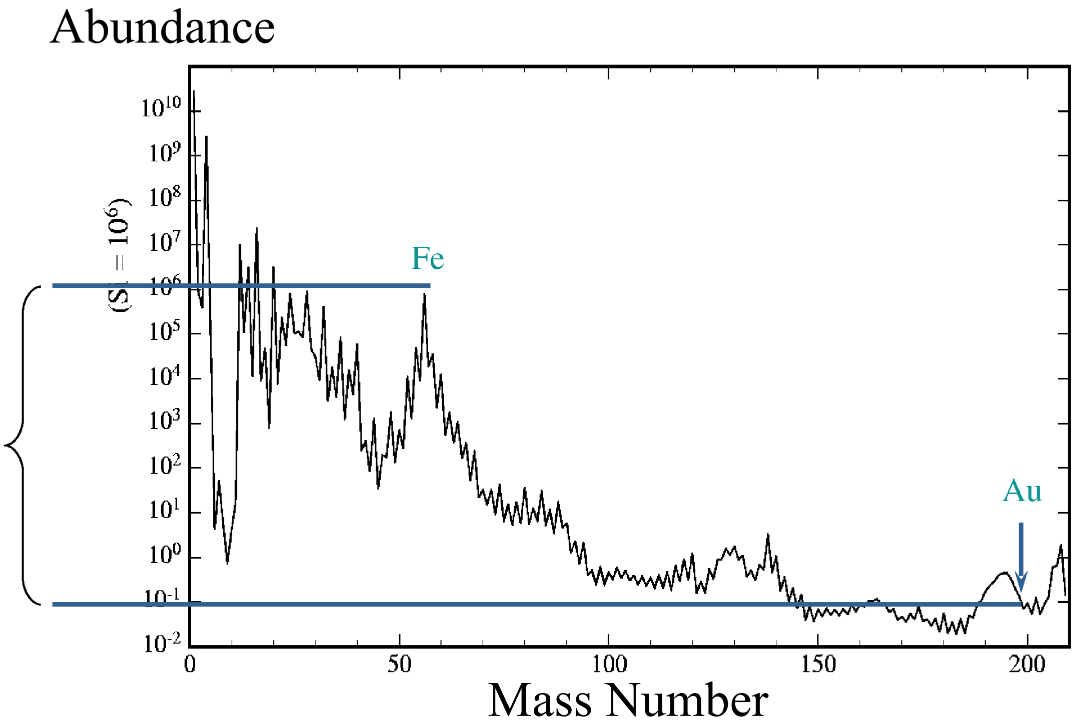
Heavy Nuclei beyond Iron I

- the s-, r- and p- process

Literature: Iliadis, Chap.5.6

Element abundances in the universe

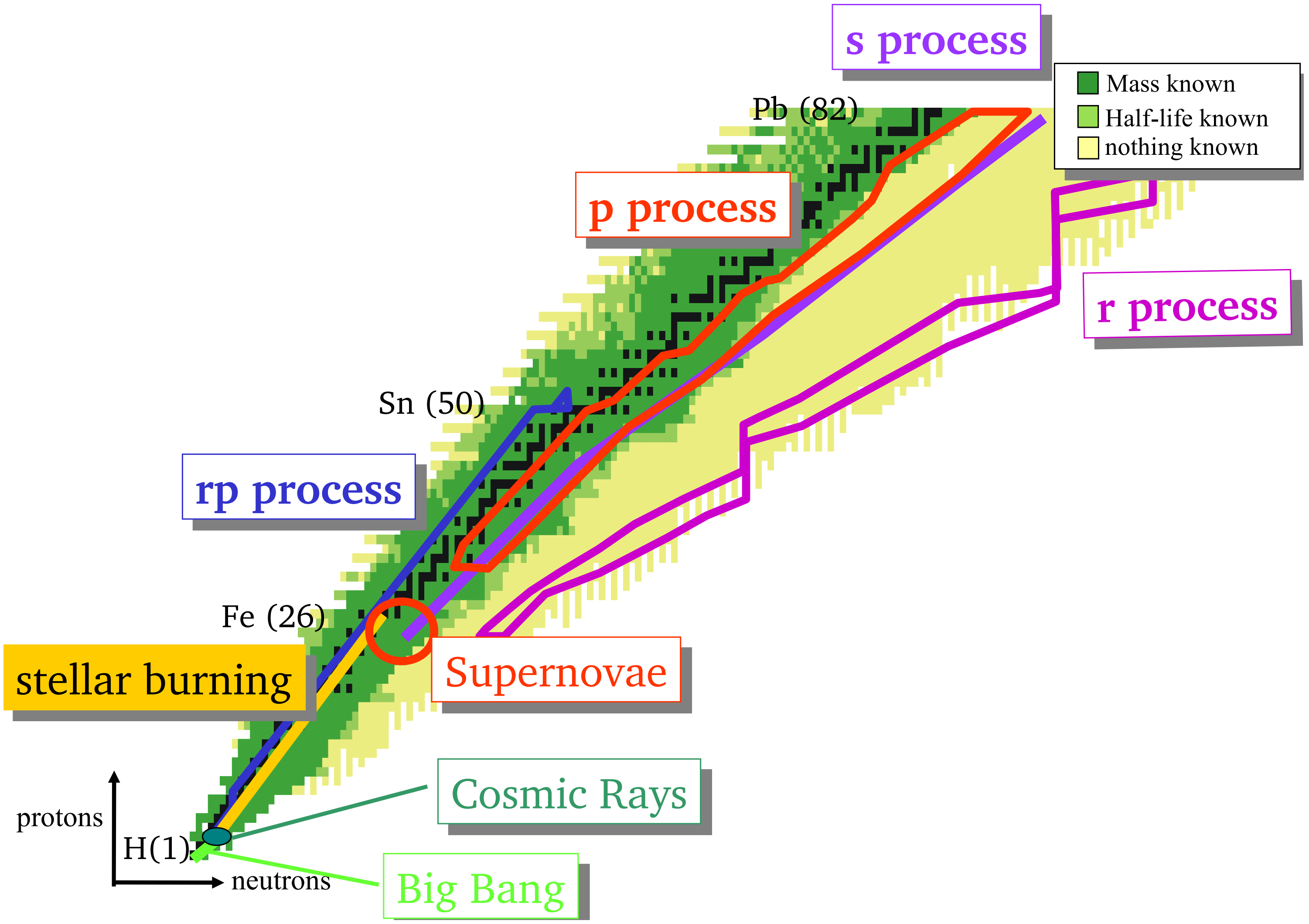


7 orders of
magnitude
less abundant!

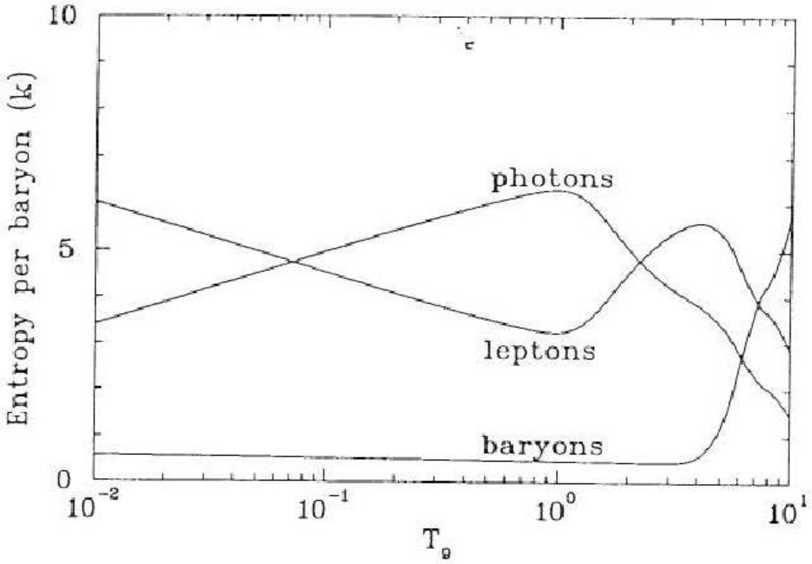
Question 3
How were the elements from
iron to uranium made?

"The 11 Greatest Unanswered Questions of Physics"
based on National Academy of Science Report, 2002

[Committee for the Physics of the Universe (CPU)]


s process
Mass known
Half-life known
nothing known
Pb (82)
p process
r process
Sn (50)
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

Why can NSE be the Building Block?



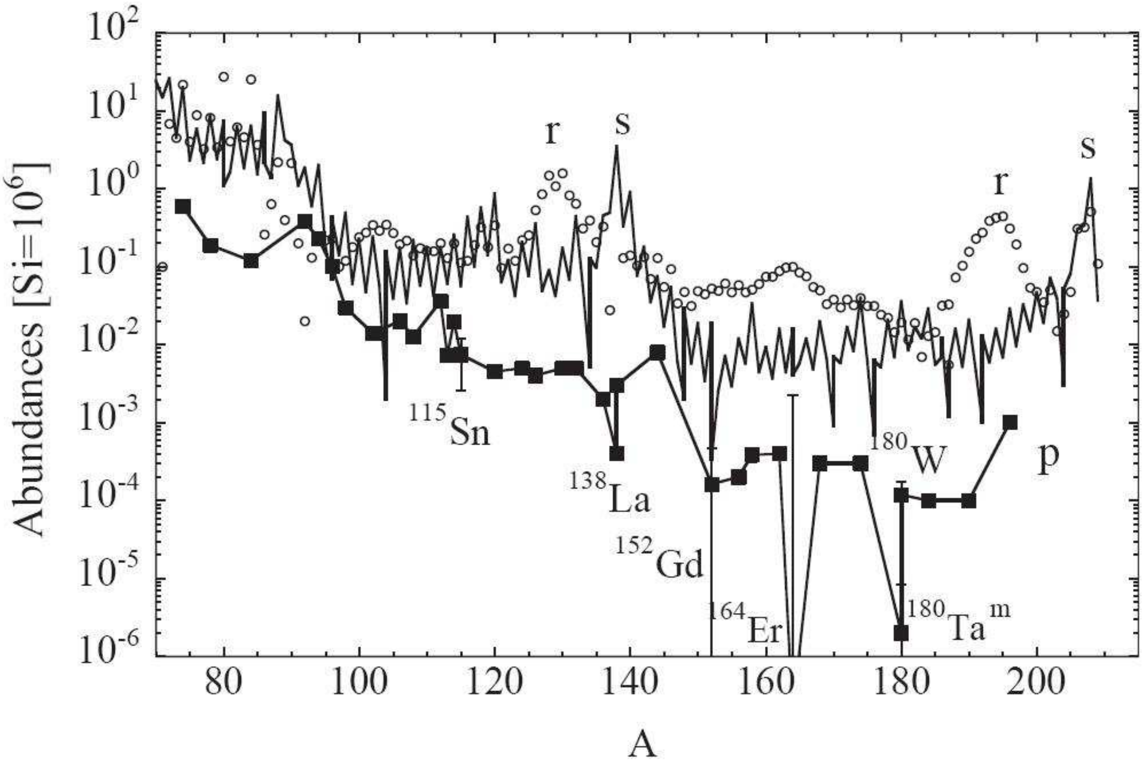
(see homework)

High T, low density => He peak

Low T, high density => Fe peak

& inbetween

Origin of Abundances for Heavy Nuclei



The s, p and r process

Neutron Capture as Building Block for Elements beyond Iron

s-process: slow neutron capture compared to decays and weak reactions

r-process: rapid neutron capture compared to decays and weak reactions

Why do we need several processes?

- double peak structure related to magic neutron numbers N= 50,82, 126

- lower peaks occur which are shifted against double magic numbers (p+n) at A=87, 138, 208

- Some of the peaks have 2 or 3 peaks

- NSE would predict stable nuclei which highest binding energy → Formation is not by NSE

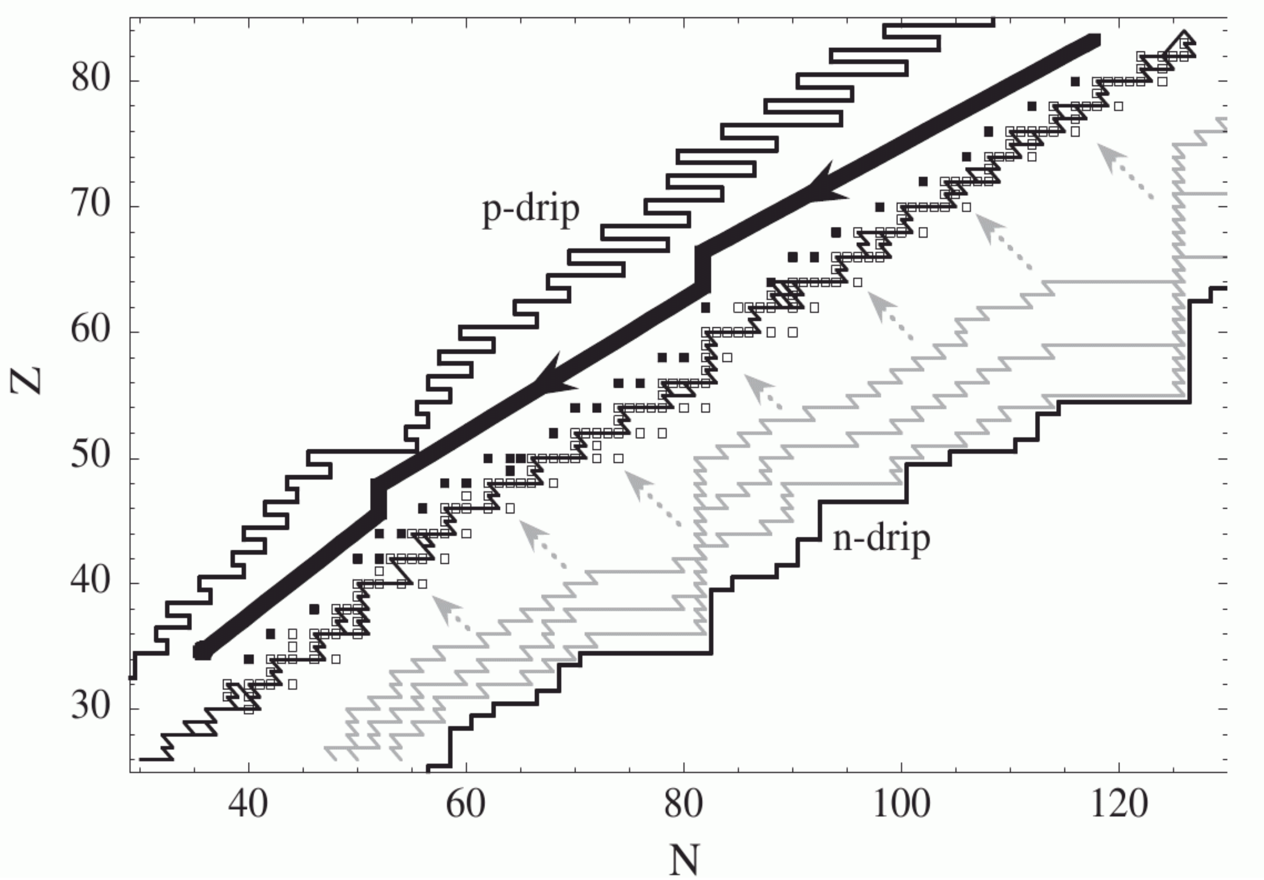
How could these processes work?

- System never reached NSE (s-process)

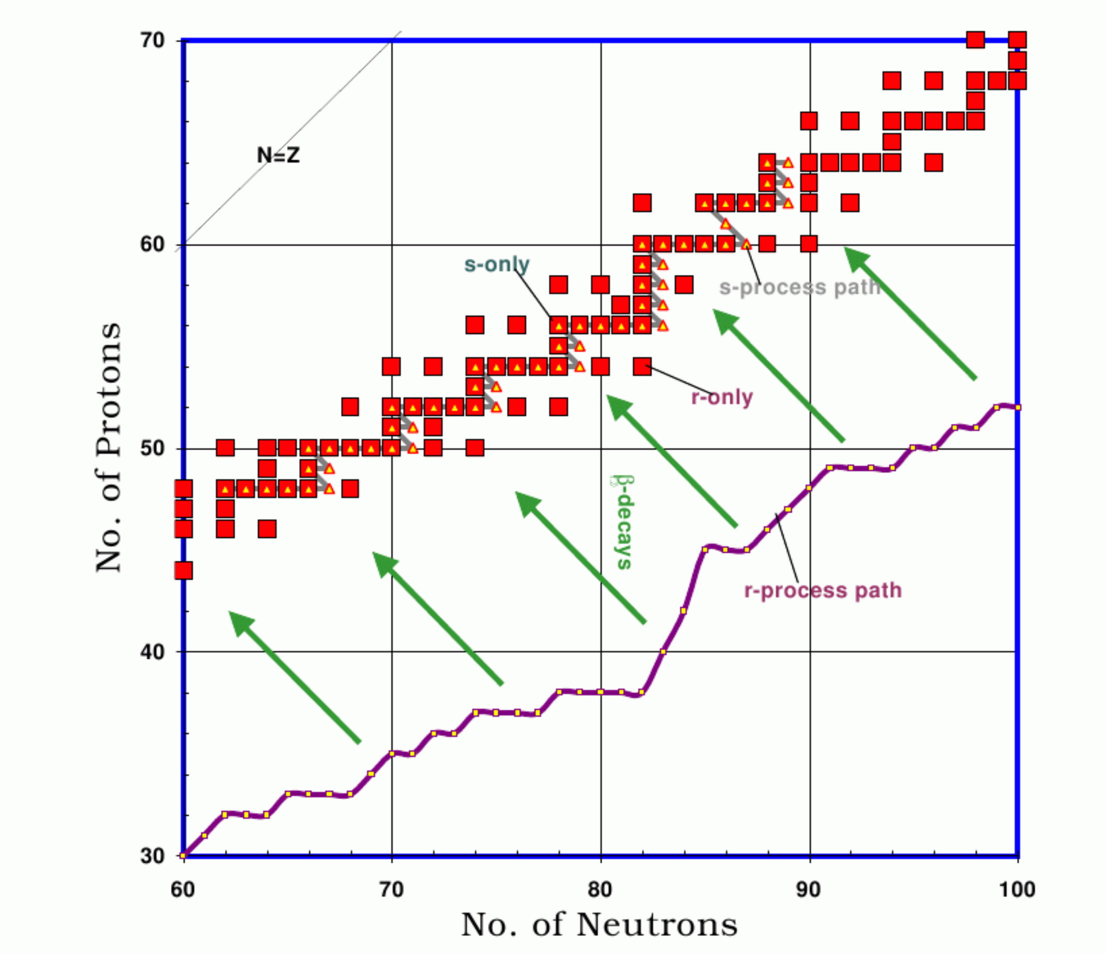
- Ones heavy nuclei are formed, other processes, photons, nucleons & neutrinos, modify abundances (p-process)

- NSE is established at very high T which shifts the the equilibrium to high nucleii, and cools (r-process)

Flow of nuclear reactions

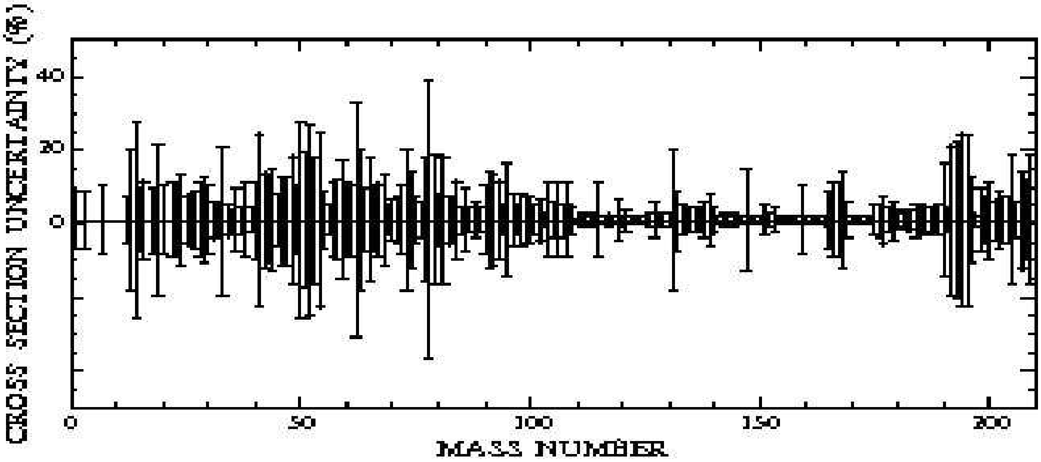


Why do some Nuclei form by s- and r- only?



Uncertainties in Capture Rates

Most rates have been measured from the ground state for stable isotopes



- problem, excited states
- unstable isotopes

=> s-process cross section are relatively good

r- process cross sections rely on H-F calculations

The 'classical' s-process Model

Basic 'setup': τ(β-decay) < τ(n-capture)

- neutron capture produce to an β-unstable isotope
- subsequent β-decays to stable isotope

Rate equations simplify to

$$\frac{dN_A}{dt} = -N_n \langle \sigma v \rangle_A N_A + N_n \langle \sigma v \rangle_{A-1} N_{A-1}$$

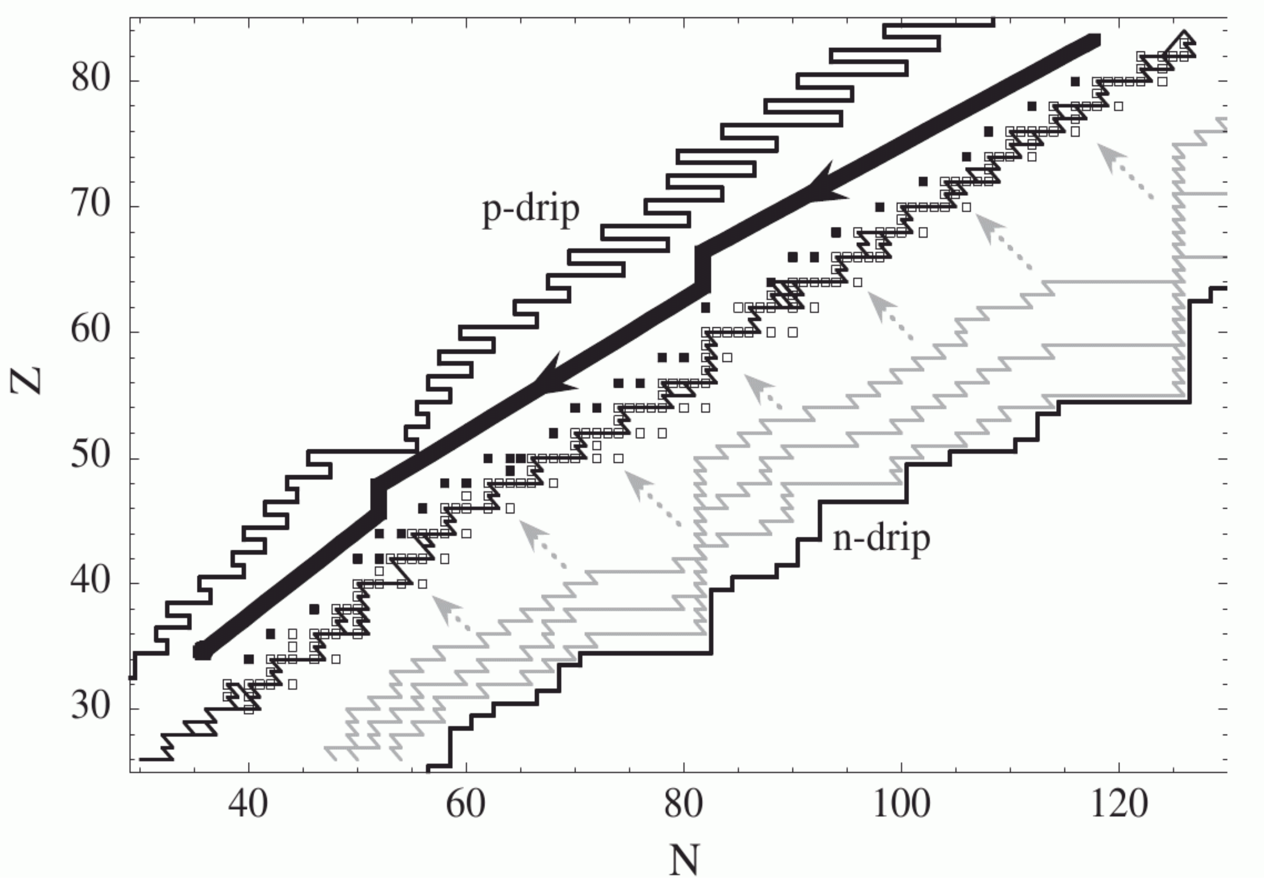
Neutrino cross sections are $\sigma \sim \frac{1}{v}\,\sigma_A$ (see earlier)

$$\boxed{\frac{dN_A}{d\tau} = -\sigma_A N_A + \sigma_{A-1} N_{A-1}}$$

Stationarity -> each component constant

Modeling: neutrino bursts on time scales $\tau = \int N_n v_T dt$

Flow of nuclear reactions



Main and the Weak s-Process components

Main Component: Origin of 90< A < 204

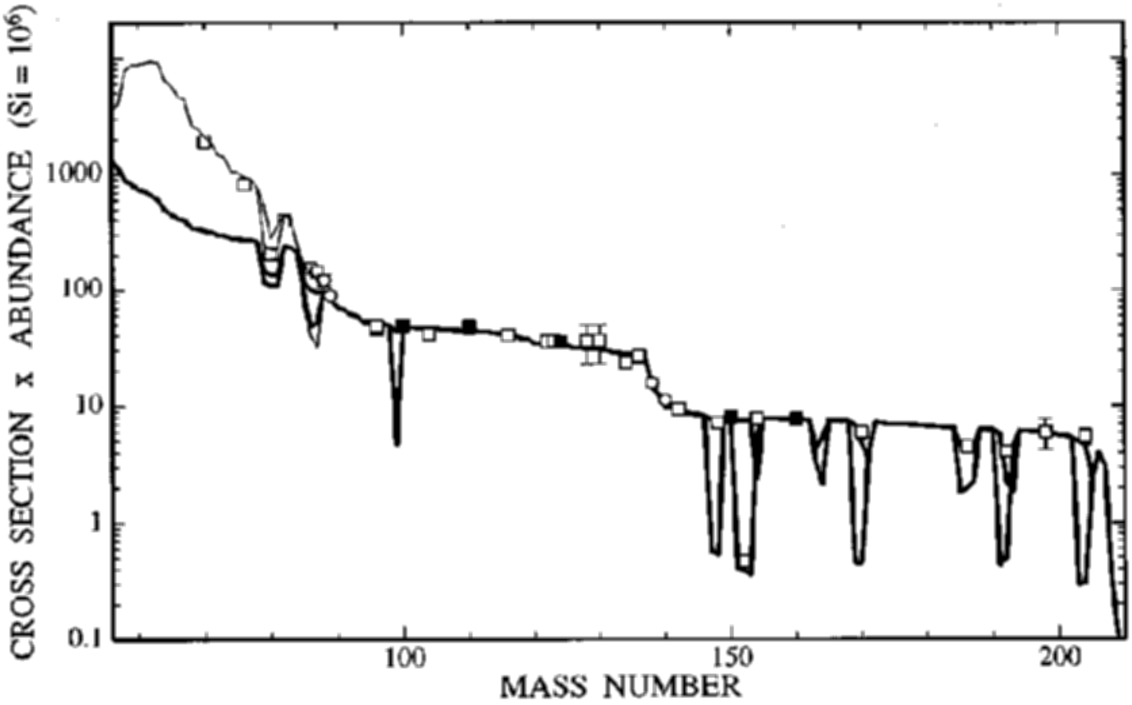
needs about 0.04% of Fe as 'seed'

Weak Component: A around 90

Remark: possible third component with 204 < A < 209

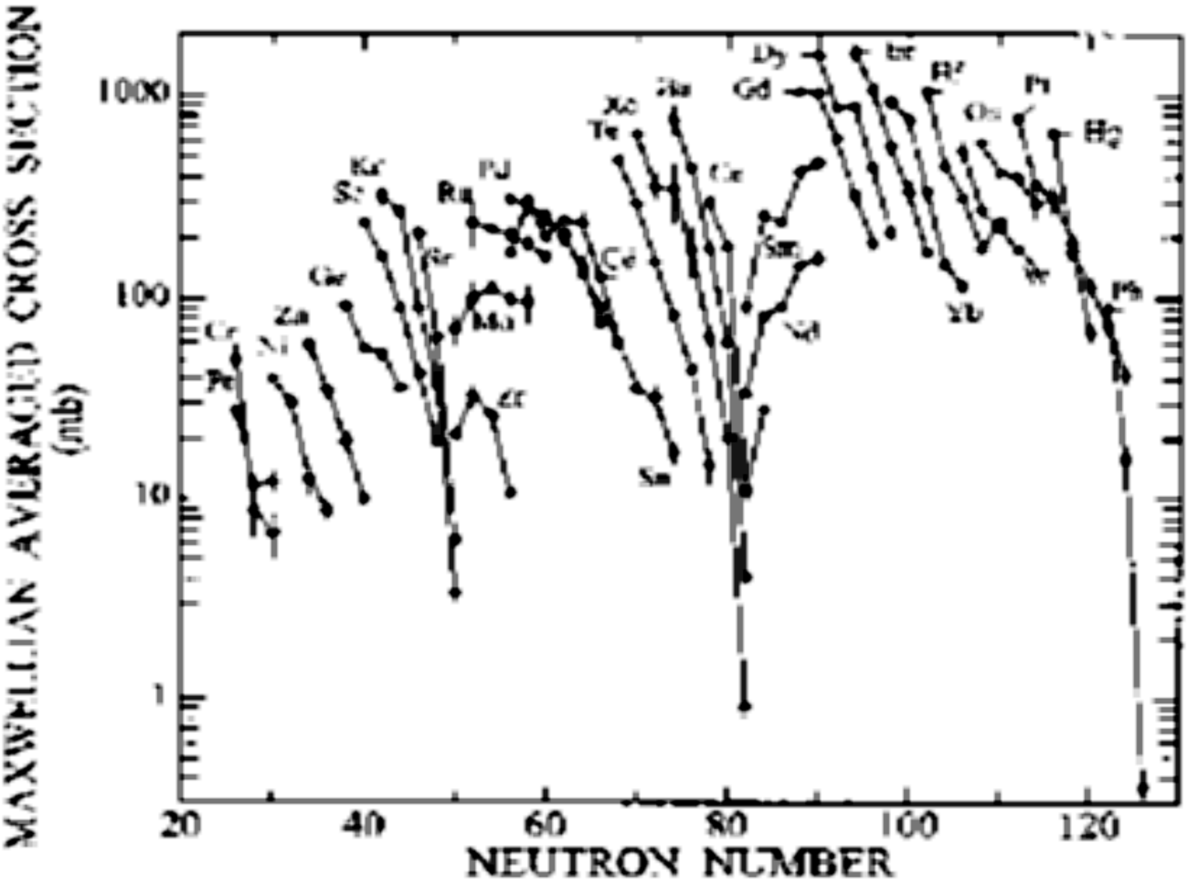
Upper Limit at when isotopes become α-unstable!

Test of the Model

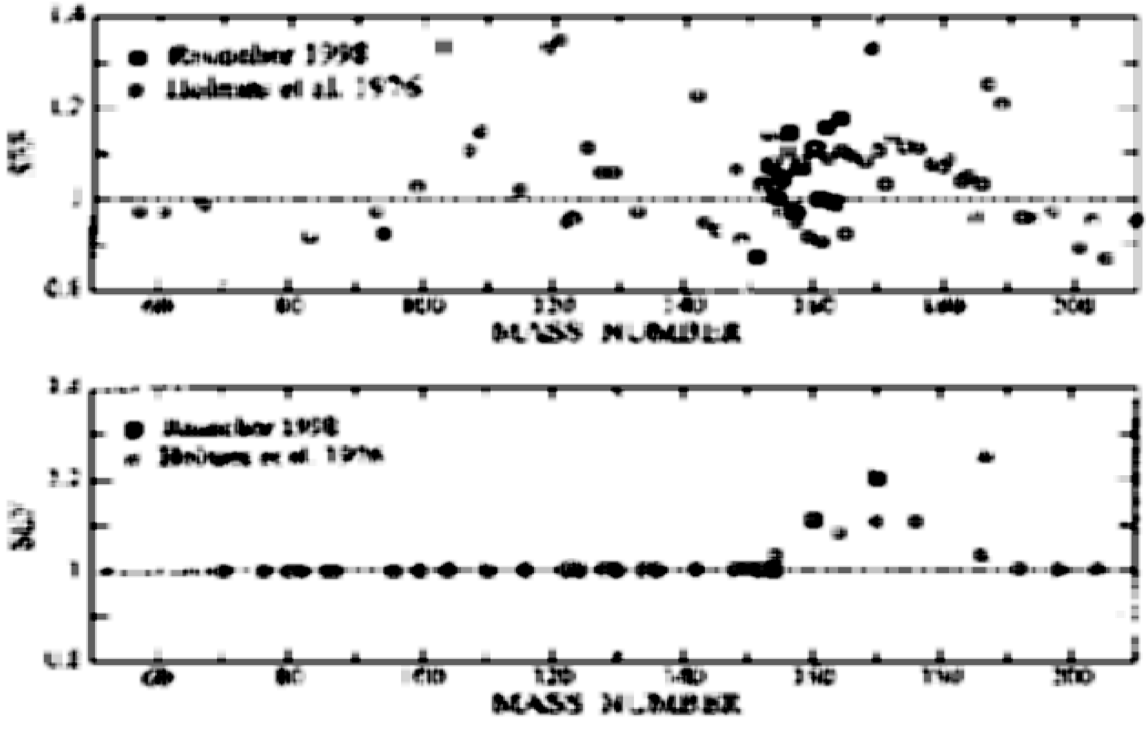


Main s-process with burst of 0.07 m/b

Neutron Capture Cross Sections



Uncertainties due to Excited Nuclear States



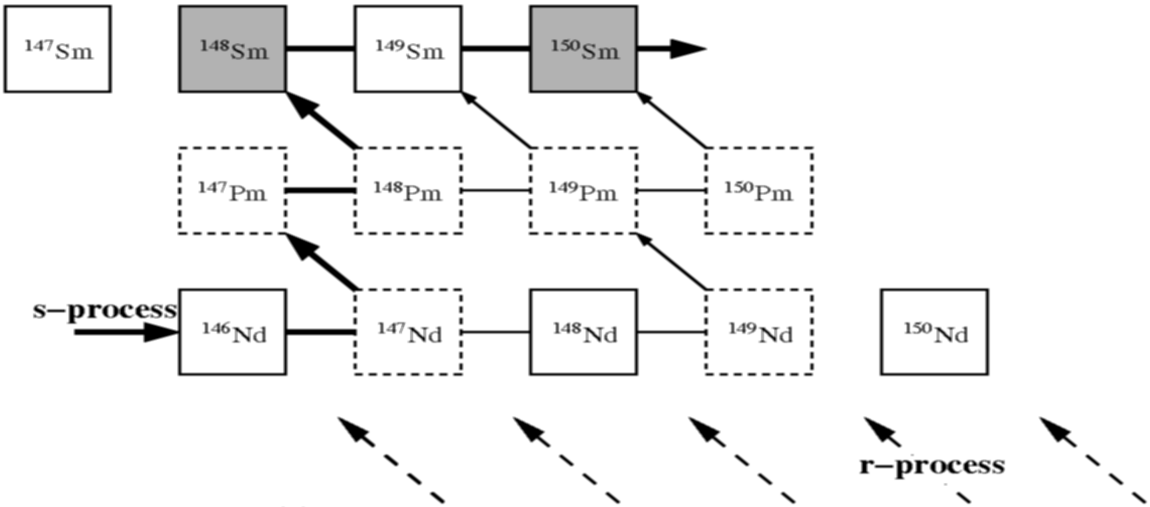
Modification: Consider Branching Points

At which T & rho becomes β-decay timescales comparable comparable to neutron capture, and at which isotopes ?

Modification: Consider Branching Points

At which T & rho becomes β-decay timescales comparable comparable to neutron capture, and at which isotopes ?

a) neutron densities of about 4E8 1/ccm



Branching at ^{148}Pm:

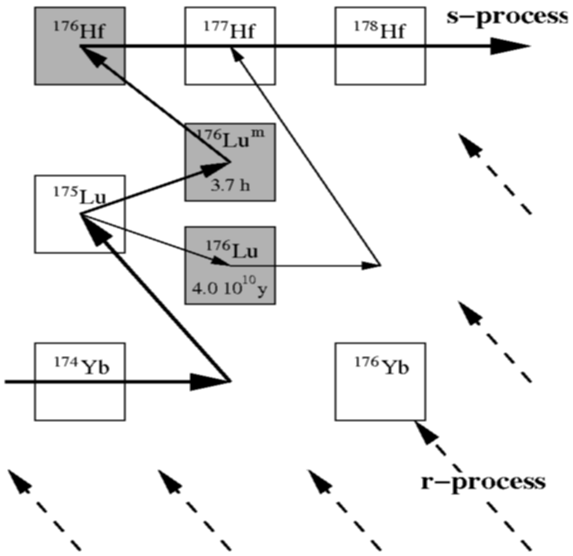
$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} = \frac{\langle\sigma v\rangle N(^{148}Sm)}{\langle\sigma v\rangle N(^{150}Sm)} \approx 0.9$$

Modification: Consider Branching Points

At which T & rho becomes β-decay timescales comparable

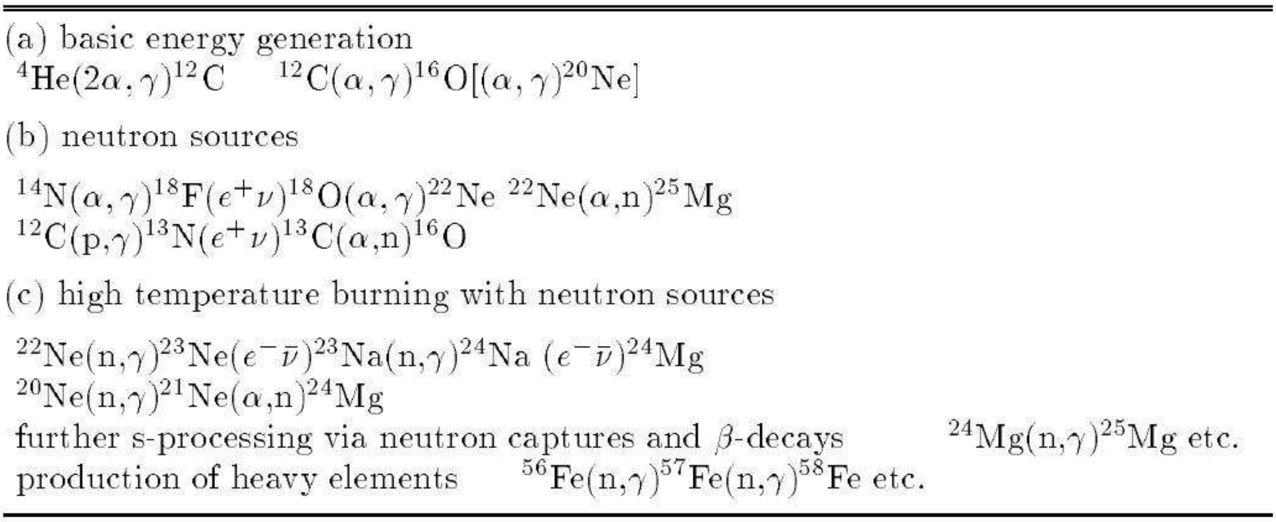
comparable to neutron capture, and at which isotopes ?

b) T above 2.5 to 3.5 E8 K



Origin of Neutrons
during
Stellar Evolution

Major Reactions during He Burning



(a) basic energy generation

$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}[(\alpha,\gamma)^{20}\mathrm{Ne}]$

(b) neutron sources

$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(e^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$
$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$

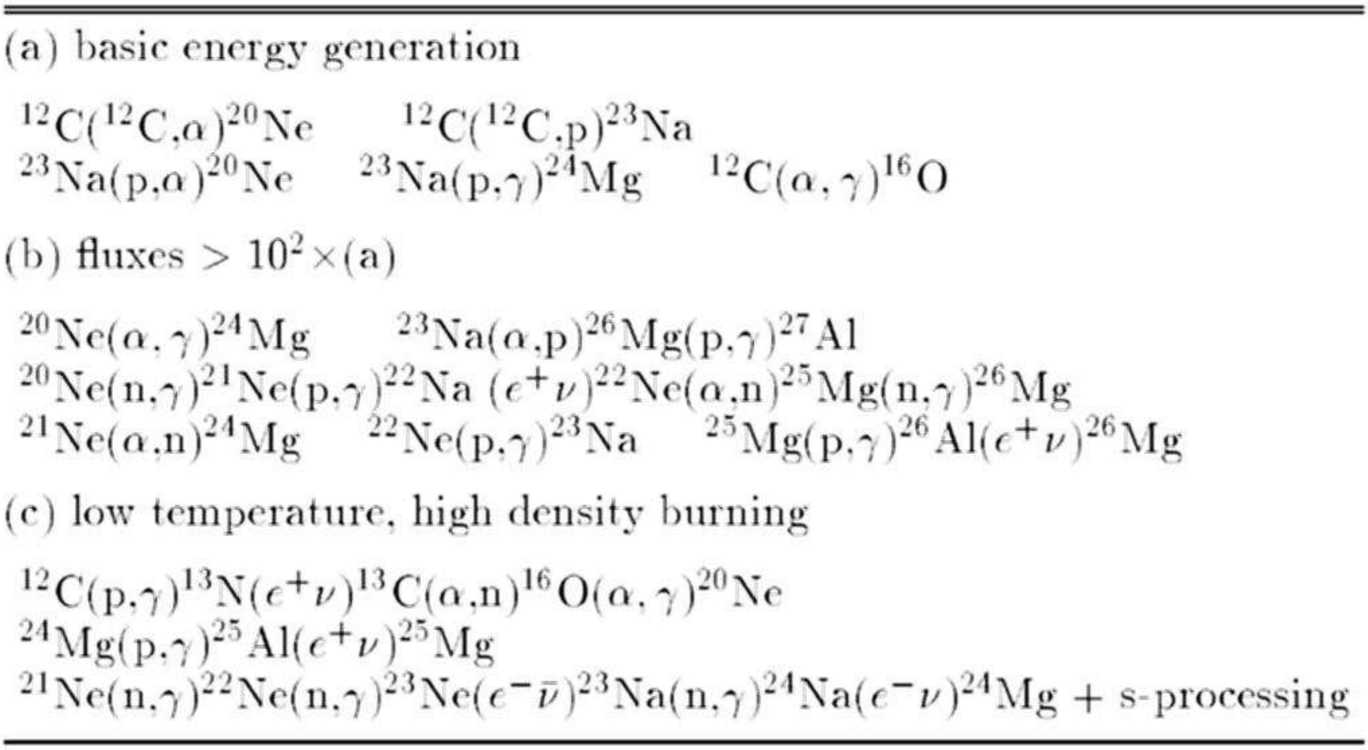
(c) high temperature burning with neutron sources

$^{22}\mathrm{Ne}(\mathrm{n},\gamma)^{23}\mathrm{Ne}(e^{-}\bar{\nu})^{23}\mathrm{Na}(\mathrm{n},\gamma)^{24}\mathrm{Na}\ (e^{-}\bar{\nu})^{24}\mathrm{Mg}$
$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}$
further s-processing via neutron captures and β-decays $^{24}\mathrm{Mg}(\mathrm{n},\gamma)^{25}\mathrm{Mg}$ etc.
production of heavy elements $^{56}\mathrm{Fe}(\mathrm{n},\gamma)^{57}\mathrm{Fe}(\mathrm{n},\gamma)^{58}\mathrm{Fe}$ etc.

s-process: Slow neutron Capture

- as soon as you produce neutrons, they react because the lack of Coulomb barrier

Major Reactions during Carbon Burning



(a) basic energy generation

$^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ $^{12}\mathrm{C}(^{12}\mathrm{C},\mathrm{p})^{23}\mathrm{Na}$
$^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ $^{23}\mathrm{Na}(\mathrm{p},\gamma)^{24}\mathrm{Mg}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

(b) fluxes $> 10^2 \times$(a)

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$ $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}$
$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\mathrm{p},\gamma)^{22}\mathrm{Na}\ (e^{+}\nu)^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}$
$^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}$ $^{22}\mathrm{Ne}(\mathrm{p},\gamma)^{23}\mathrm{Na}$ $^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}(e^{+}\nu)^{26}\mathrm{Mg}$

(c) low temperature, high density burning

$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$
$^{24}\mathrm{Mg}(\mathrm{p},\gamma)^{25}\mathrm{Al}(e^{+}\nu)^{25}\mathrm{Mg}$
$^{21}\mathrm{Ne}(\mathrm{n},\gamma)^{22}\mathrm{Ne}(\mathrm{n},\gamma)^{23}\mathrm{Ne}(e^{-}\bar{\nu})^{23}\mathrm{Na}(\mathrm{n},\gamma)^{24}\mathrm{Na}(e^{-}\nu)^{24}\mathrm{Mg}$ + s-processing

Major Production During Ne-Burning

(a) basic energy generation

$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $\quad$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

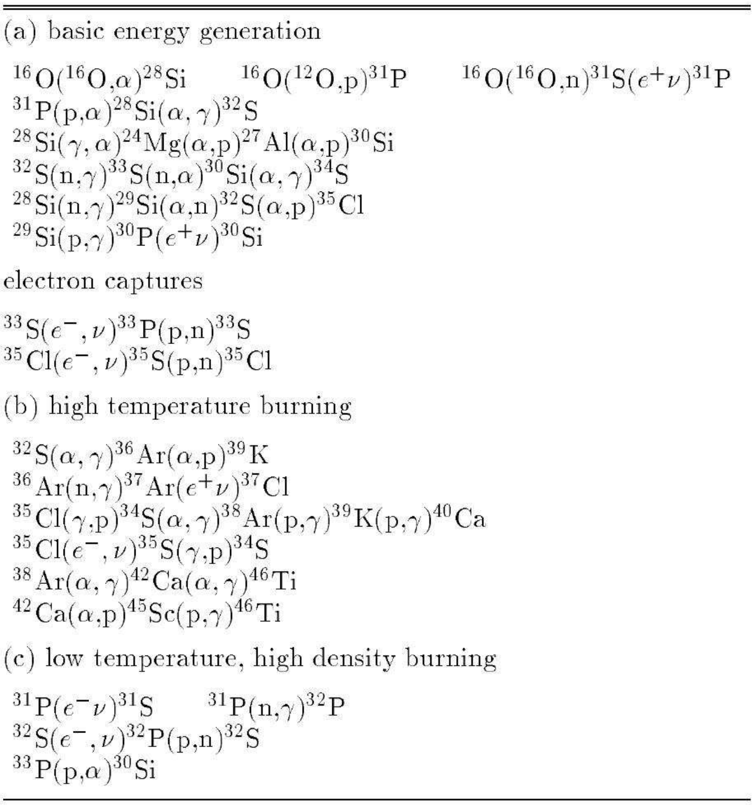
(b) fluxes $> 10^2 \times$(a)

$^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ $\quad$ $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}(\alpha,\mathrm{n})^{29}\mathrm{Si}$
$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}(\mathrm{n},\gamma)^{25}\mathrm{Mg}(\alpha,\mathrm{n})^{28}\mathrm{Si}$
$^{28}\mathrm{Si}(\mathrm{n},\gamma)^{29}\mathrm{Si}(\mathrm{n},\gamma)^{30}\mathrm{Si}$
$^{24}\mathrm{Mg}(\alpha,\mathrm{p})^{27}\mathrm{Al}(\alpha,\mathrm{p})^{30}\mathrm{Si}$
$^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}(\mathrm{n},\gamma)^{28}\mathrm{Al}(e^{-}\bar{\nu})^{28}\mathrm{Si}$

(c) low temperature, high density burning

$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}(\mathrm{n},\gamma)^{27}\mathrm{Mg}(e^{-}\bar{\nu})^{27}\mathrm{Al}$
$^{22}\mathrm{Ne}$ left from prior neutron-rich carbon burning

Major Processes during Oxygen Burning



(a) basic energy generation

^{16}O(^{16}O,α)^{28}Si　^{16}O(^{12}O,p)^{31}P　^{16}O(^{16}O,n)^{31}S($e^{+}\nu$)^{31}P
^{31}P(p,α)^{28}Si(α,γ)^{32}S
^{28}Si(γ,α)^{24}Mg(α,p)^{27}Al(α,p)^{30}Si
^{32}S(n,γ)^{33}S(n,α)^{30}Si(α,γ)^{34}S
^{28}Si(n,γ)^{29}Si(α,n)^{32}S(α,p)^{35}Cl
^{29}Si(p,γ)^{30}P($e^{+}\nu$)^{30}Si

electron captures

^{33}S(e^{-},ν)^{33}P(p,n)^{33}S
^{35}Cl(e^{-},ν)^{35}S(p,n)^{35}Cl

(b) high temperature burning

^{32}S(α,γ)^{36}Ar(α,p)^{39}K
^{36}Ar(n,γ)^{37}Ar($e^{+}\nu$)^{37}Cl
^{35}Cl(γ,p)^{34}S(α,γ)^{38}Ar(p,γ)^{39}K(p,γ)^{40}Ca
^{35}Cl(e^{-},ν)^{35}S(γ,p)^{34}S
^{38}Ar(α,γ)^{42}Ca(α,γ)^{46}Ti
^{42}Ca(α,p)^{45}Sc(p,γ)^{46}Ti

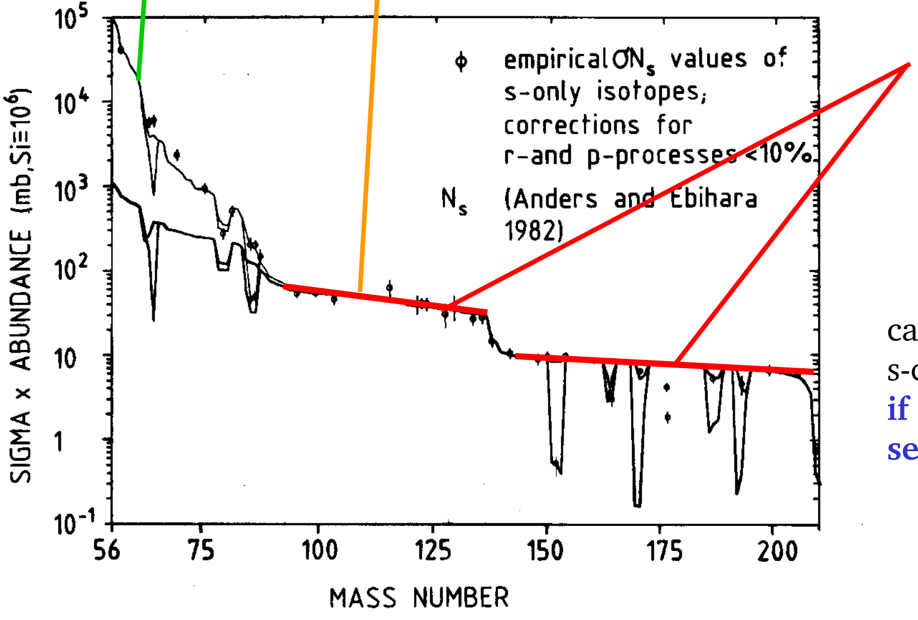
(c) low temperature, high density burning

^{31}P($e^{-}\nu$)^{31}S　^{31}P(n,γ)^{32}P
^{32}S(e^{-},ν)^{32}P(p,n)^{32}S
^{33}P(p,α)^{30}Si

The sites of the s-process

weak s-process: **core He/ shell C burning in massive stars**

main s-process: **He shell flashes in low mass TP-AGB stars**



approx. steady flow

$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

↓

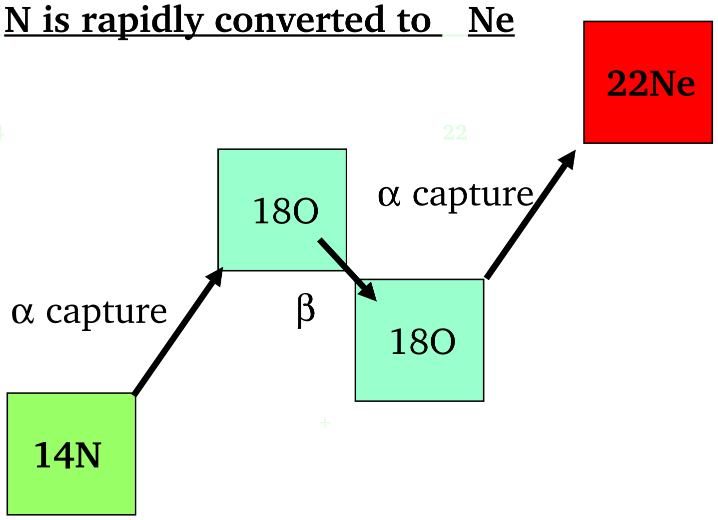
can easily interpolate
s-contribution for s+r-nuclei
if neutron capture cross sections are known

The weak s-process

Site: Core He burning (and shell C-burning) in massive stars

He burning core contains initially ^{14}N

^{14}N is rapidly converted to ^{22}Ne



14N

α capture

18O

β^+

18O

α capture

22Ne

Towards the end of He burning T~3e8 K: **^{22}Ne(α,n)** provides a neutron source

→ preexisting Fe (and other nuclei) serve as seed for a (secondary) s-process

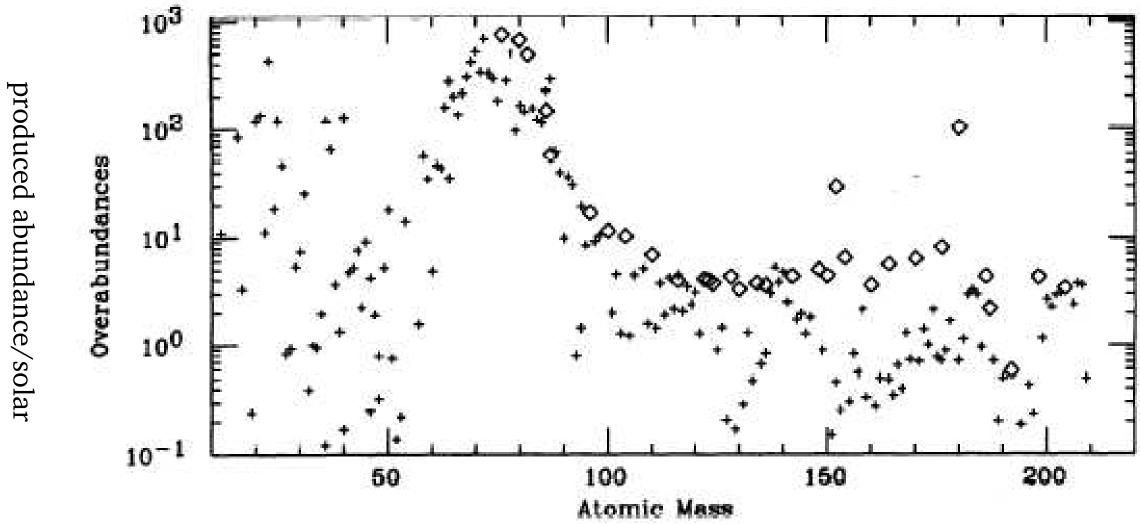
Typical conditions (Raiteri et al. ApJ367 (1991) 228 and ApJ371(1991)665:

Temperature	2.2 - 3.5 e8 K
Density	1 - 3e3 g/cm
Average neutron density	7e5 cm
Peak neutron density	2e7 cm
Neutron exposure τ)	0.206 / mb

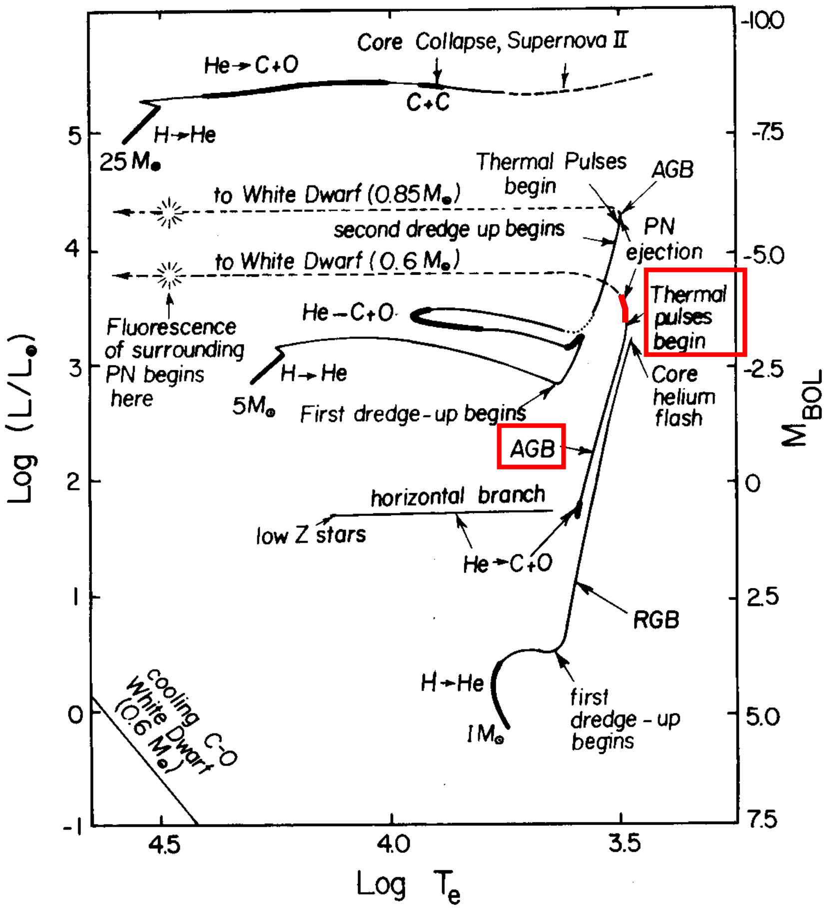
) time integrated neutron flux

$$\tau = \int j_n(t)\,dt$$

Results:



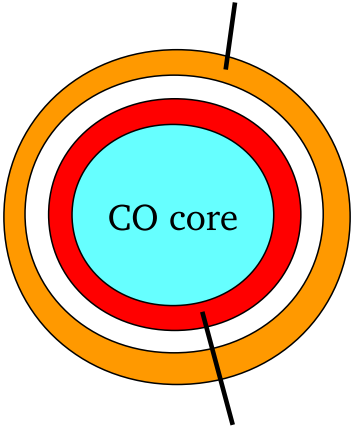
The main s-process



Site: low mass TP-AGB stars

(thermally pulsing stars
on the asymptotic giant
branch in the HR diagram,
1.5 - 3 solar masses)

H-burning shell

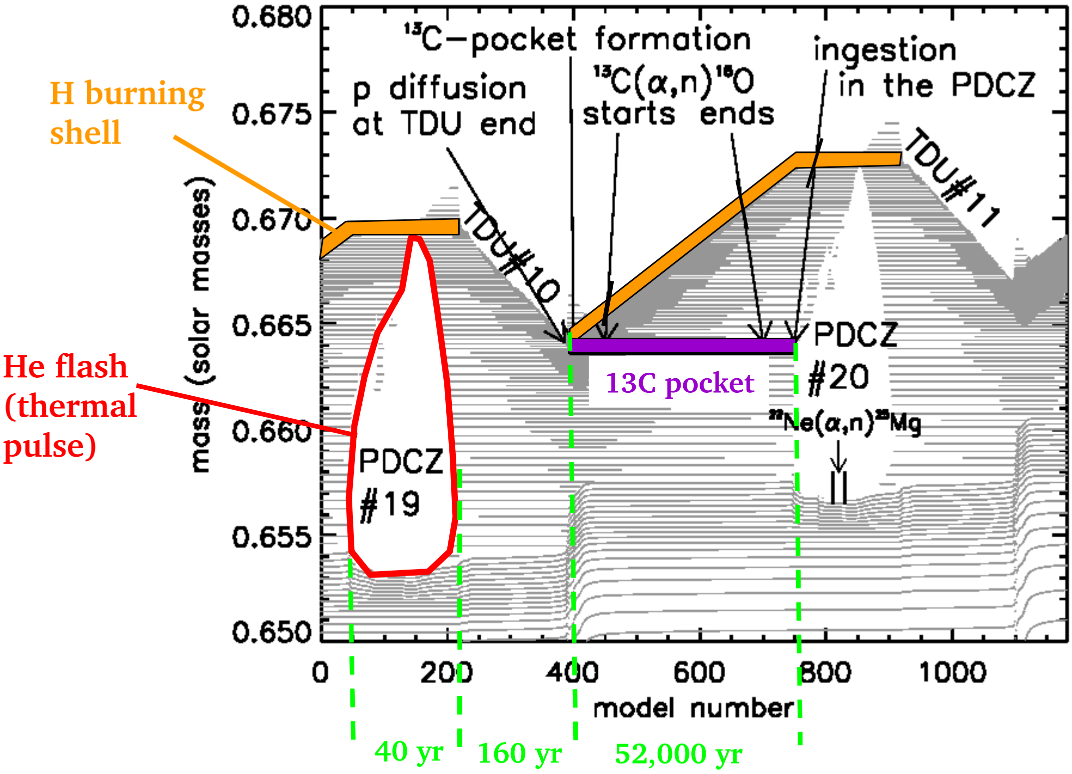


He-burning shell

unstable - burns in flashes
(thin shell instability)

H/He burning in a TP-AGB star

- number of He flashes in stars life: few – 100
- period of flashes: 1000 – 100,000 years



s-process in:

- **He flash**

via Ne(α,n)

C pocket

- 22

13

via C(α,n)

13

(Lugaro et al. ApJ586(2003)1305)

Conditions during the main s-process

	^{13}C(α,n) in pocket	**^{22}Ne(α,n) in He flash**
Temperature	0.9 E8 K	2.7 E9K
Neutron density	7 E7 /ccm	1E7 ccm
Duration	20,000 yr	few years
Neutron exposure τ)	0.1 / mb	0.01 / mb

weaker but longer
main contribution
(90% of exposure)

short, intense burst
slight modification
of abundances
(branchings !)

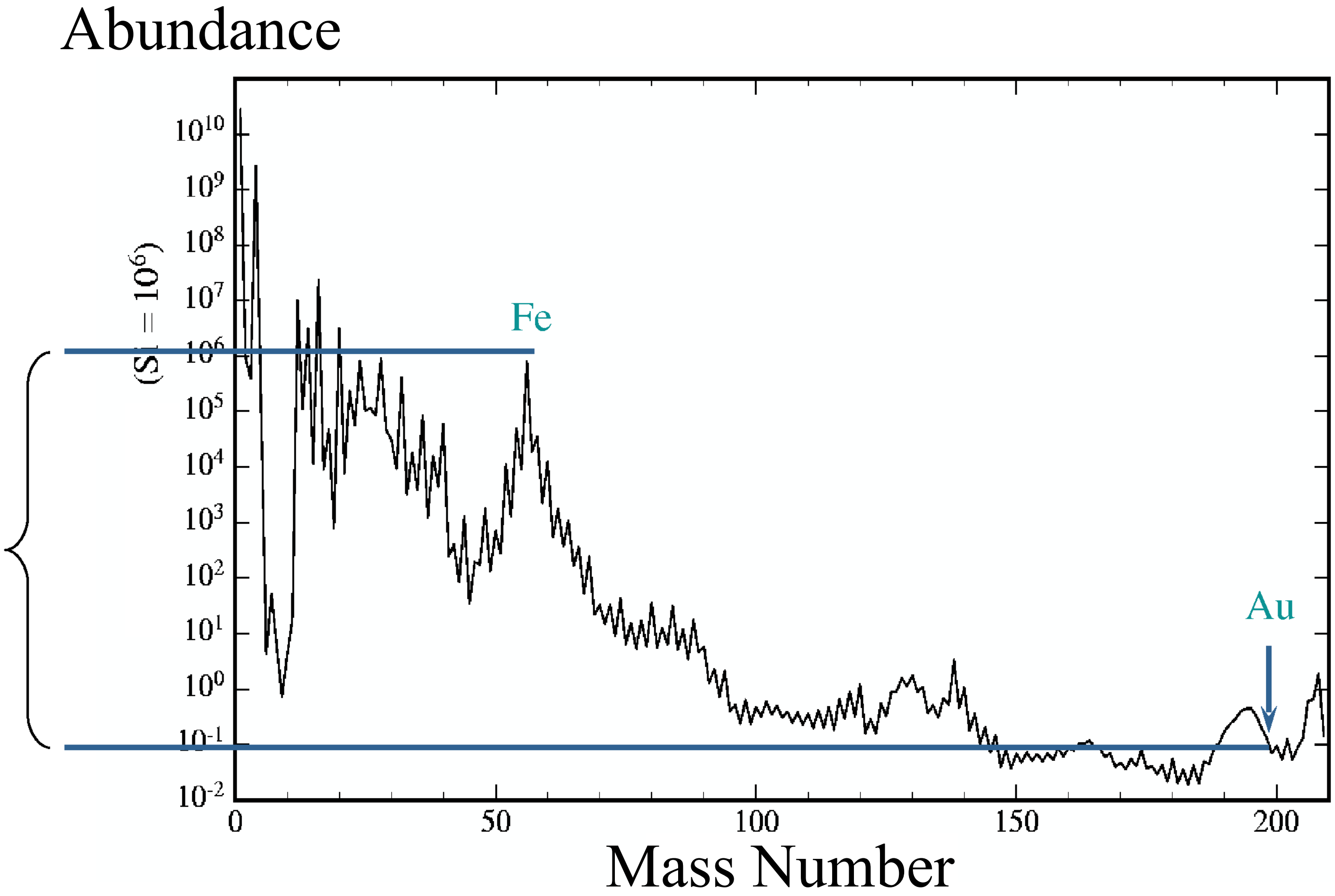
Heavy Nuclei beyond Iron II

- the r- process

- the p-process

Literature: Iliadis, Chap.5.6

Element abundances in the universe



7 orders of
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- System never reached NSE (s-process)

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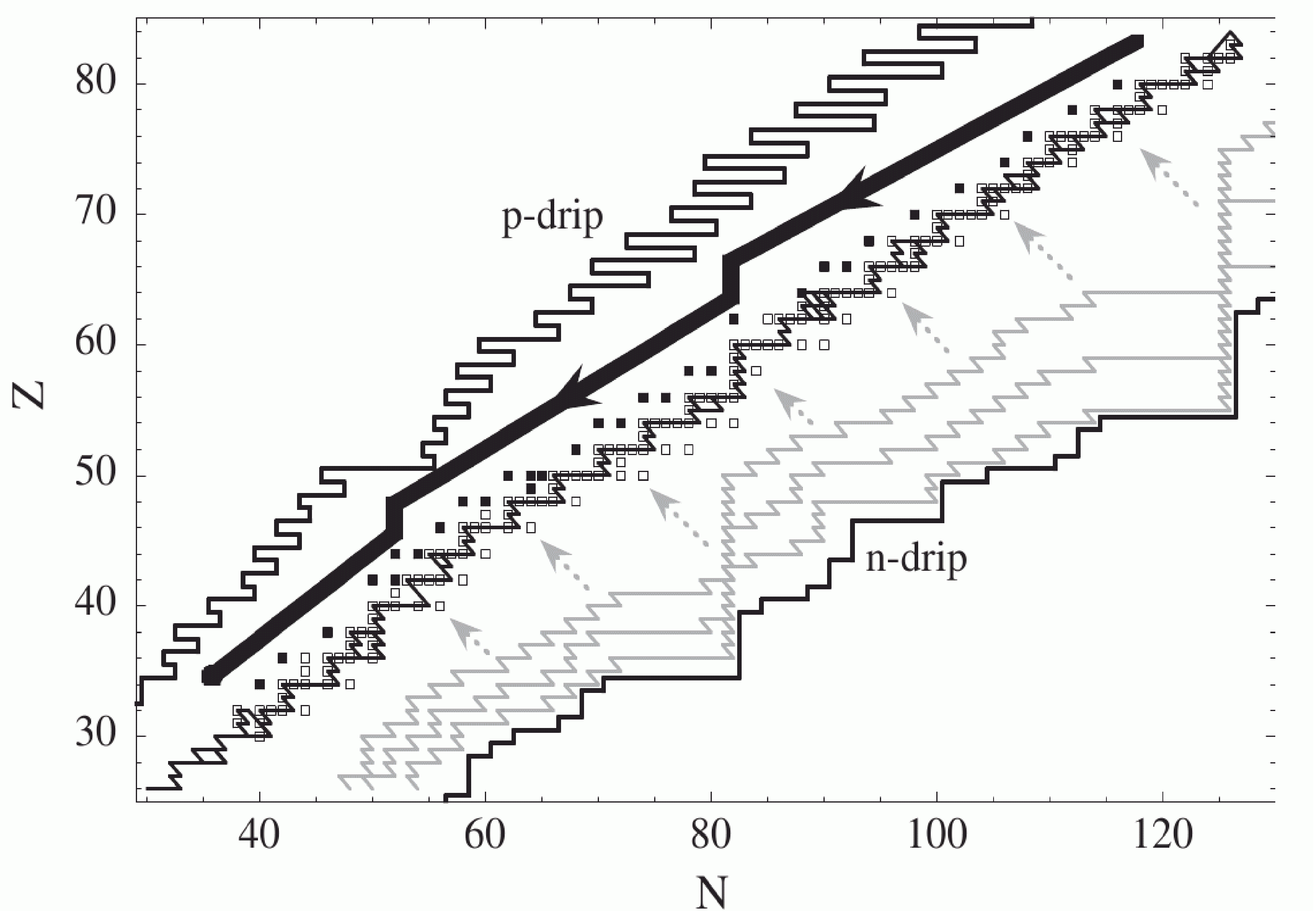
- NSE is established at very high T which shifts the the equilibrium to high nucleii, and cools + neutron capture (r-process)

Flow of nuclear reactions



The 'classical' s-process Model

Basic 'setup': τ(β-decay) < τ(n-capture)

- neutron capture produce to an β-unstable isotope
- subsequent β-decays to stable isotope

Rate equations simplify to

$$\frac{dN_A}{dt} = -N_n\langle\sigma v\rangle_A N_A + N_n\langle\sigma v\rangle_{A-1} N_{A-1}$$

Neutrino cross sections are $\sigma \sim \frac{1}{v}$ σ (see earlier)

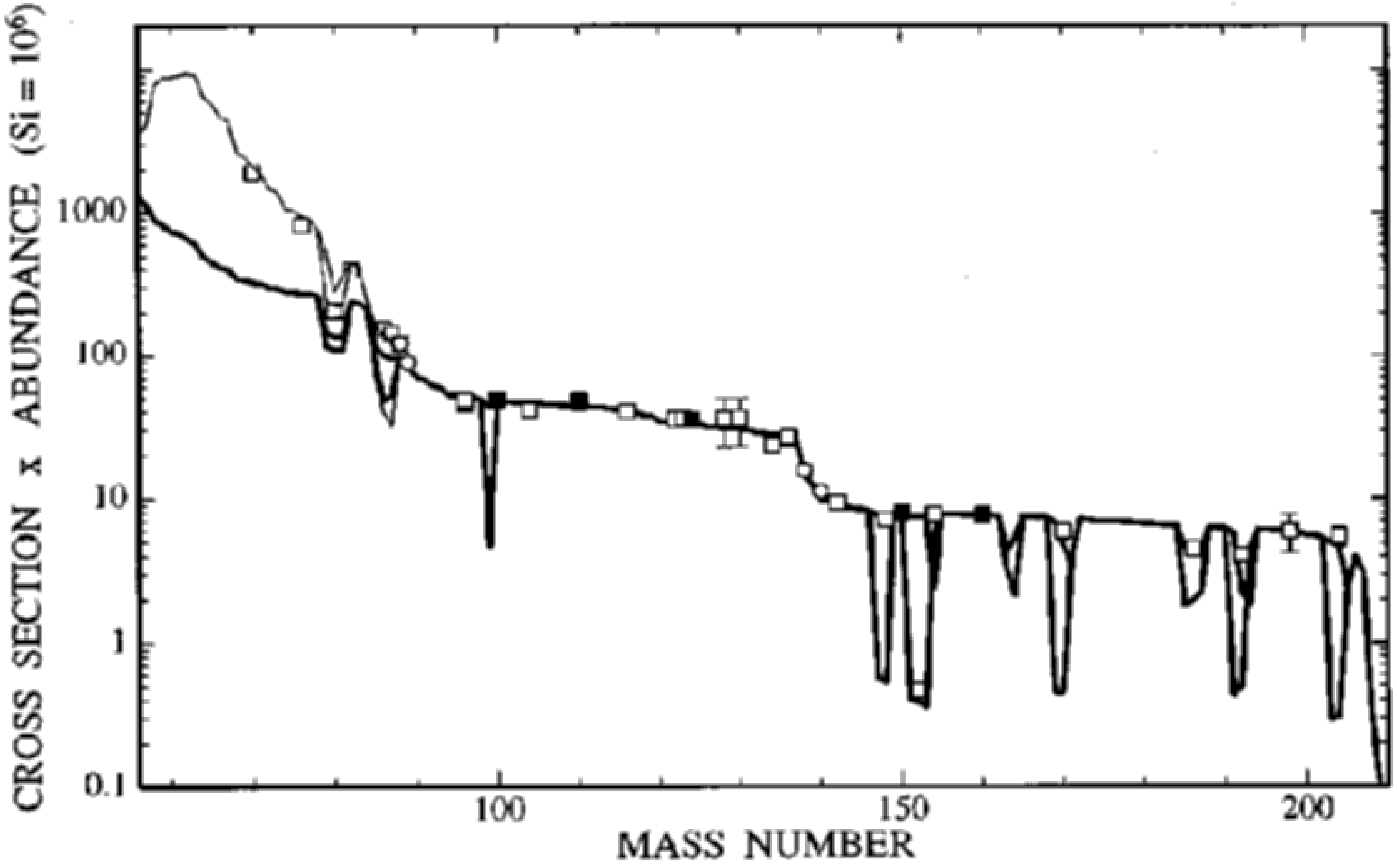
$$\boxed{\frac{dN_A}{d\tau} = -\sigma_A N_A + \sigma_{A-1} N_{A-1}}$$

A

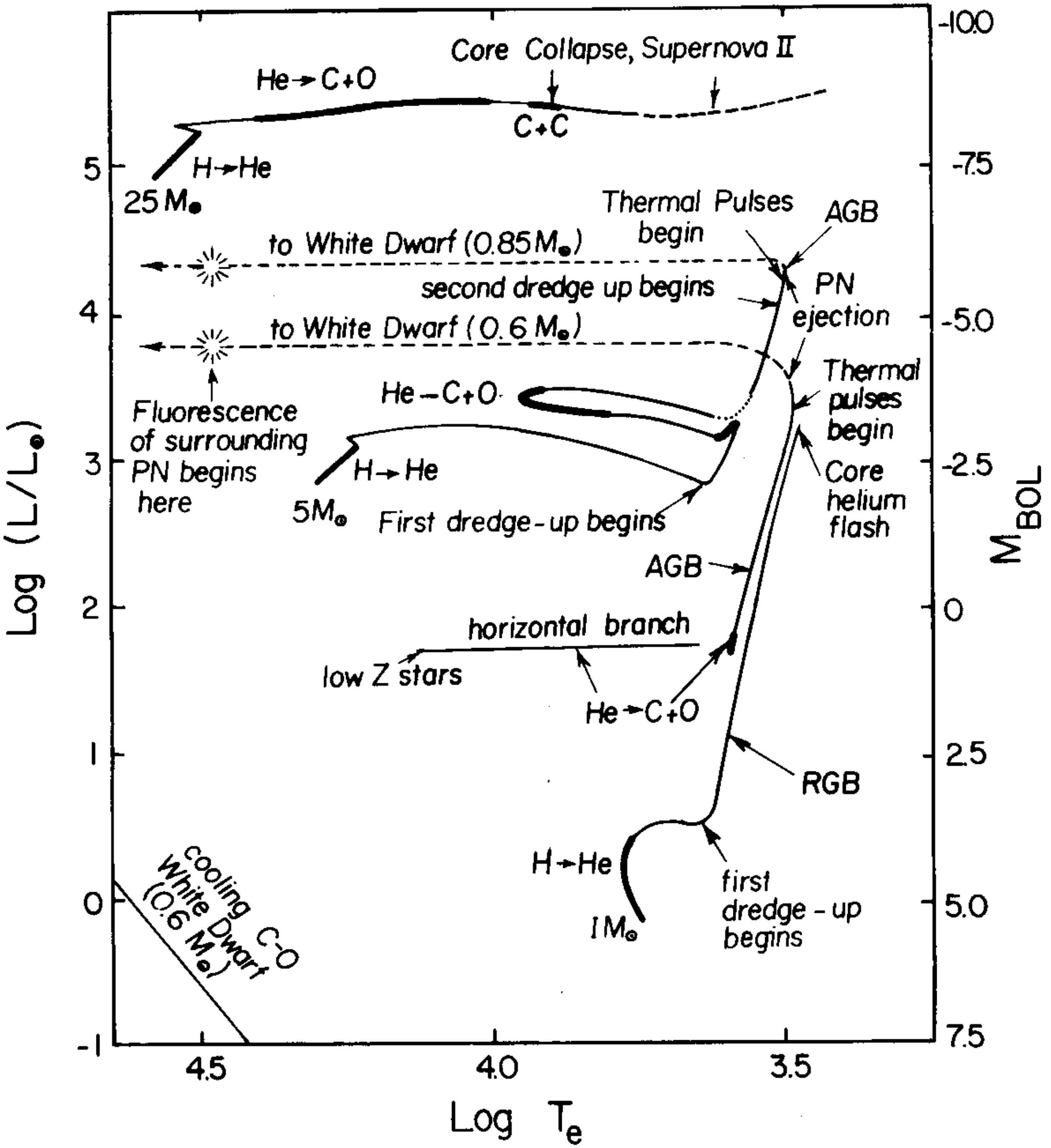
Stationarity -> each component constant

Modeling: neutrino bursts on time scales $\tau = \int N_n v_T dt$

Test of the Model

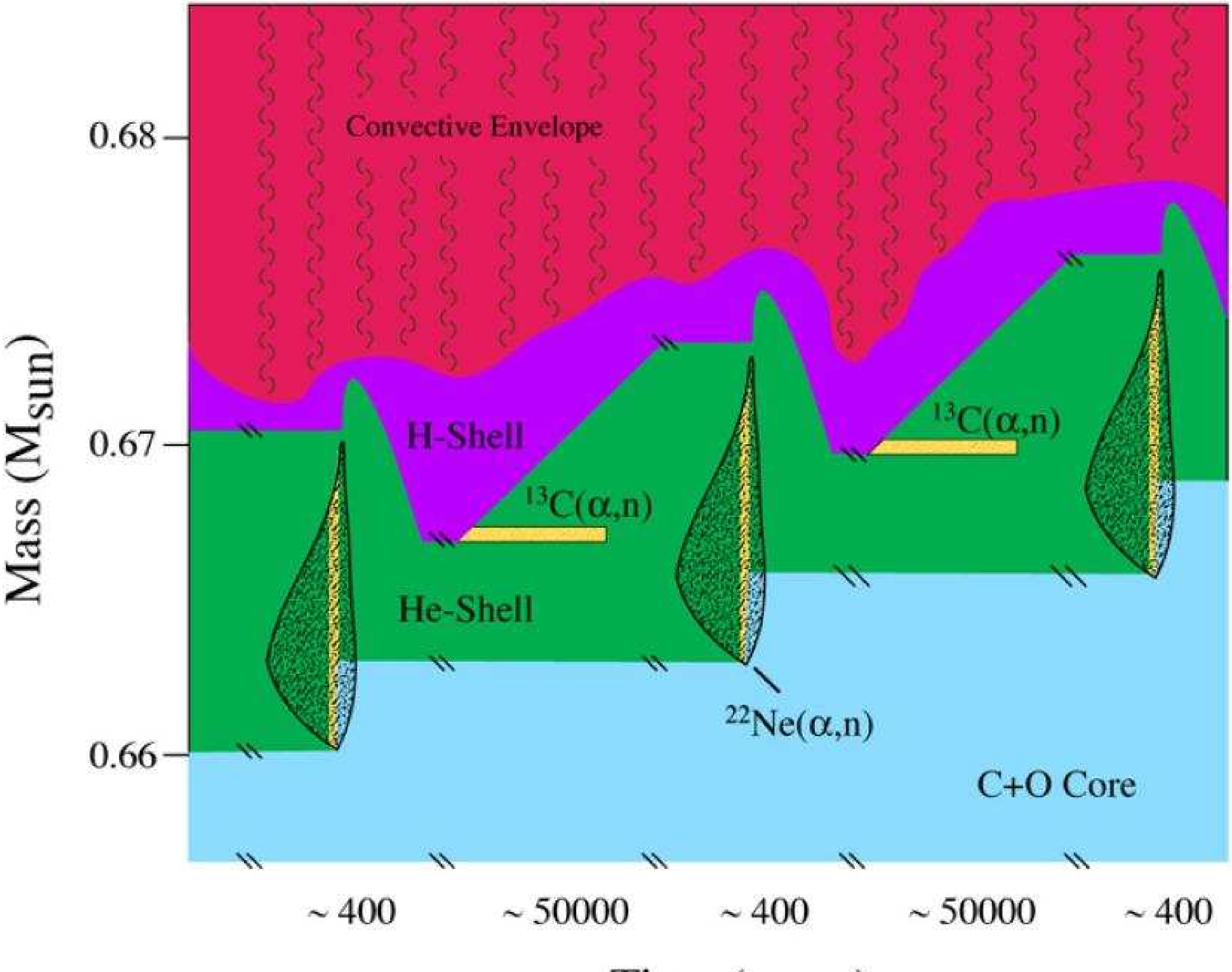


Main s-process with burst of 0.07 m/b

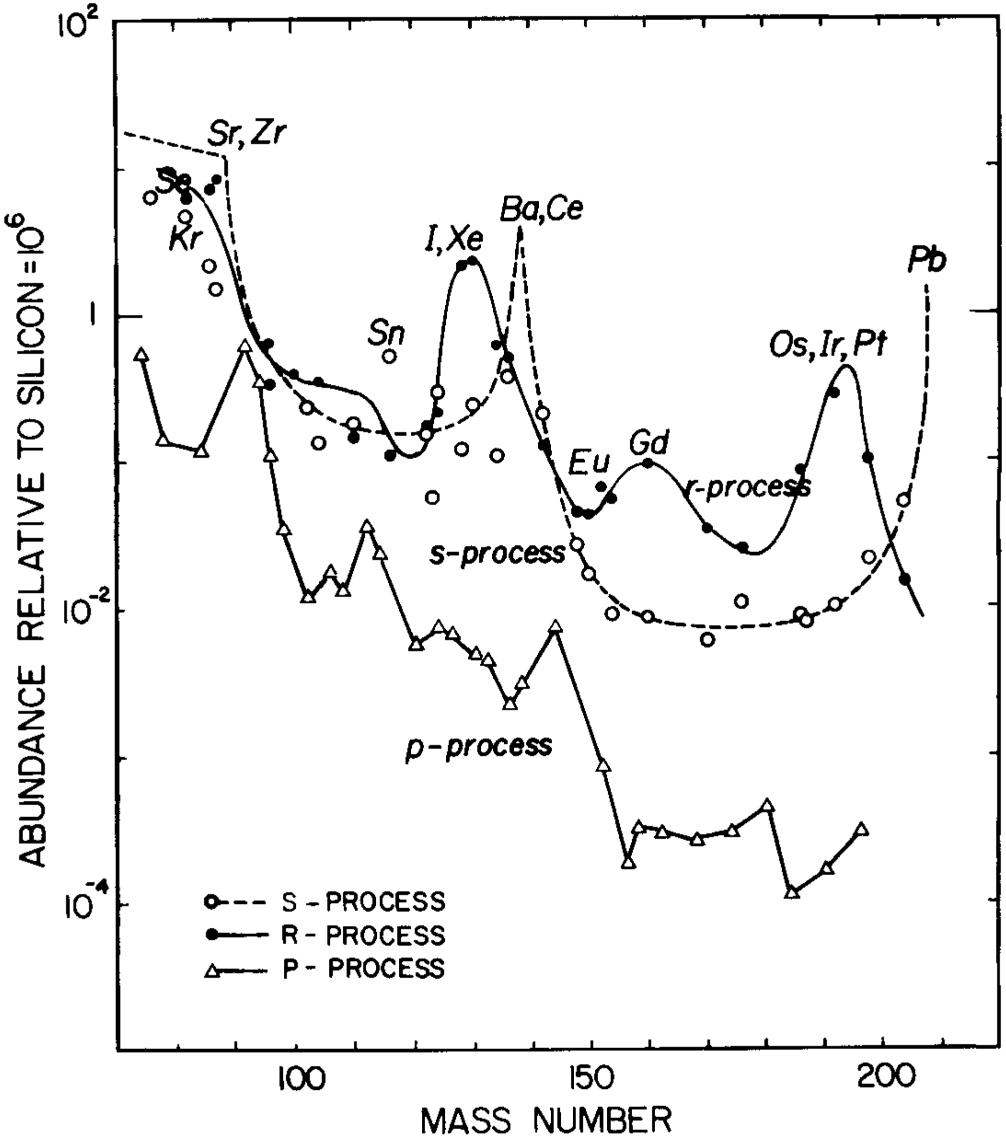


Pagel, Fig. 5.14

Main s-process in Thermal Pulses



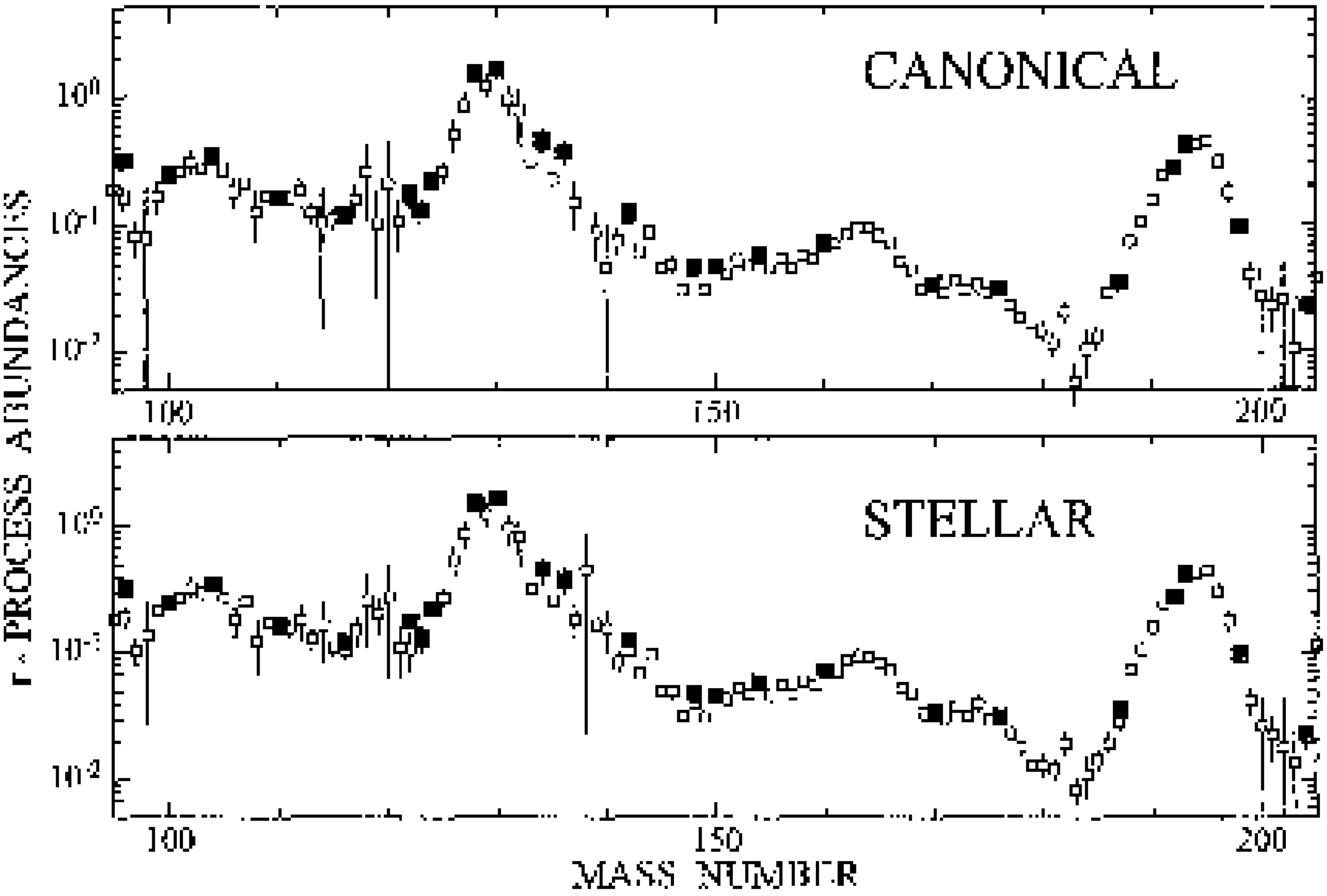
The origin of heavy elements in the solar system



(Pagel, Fig 6.8)

R- Process Abundances

(subtract s- and p- process from solar abundance)



Basic Physics of the r-Process

- (n,γ) ⟷ (γ ,n)
- process runs along constant neutron separation energy

- beta-decay from Z -> Z-1
- flow equilibrium governed by beta decay times
- freeze-out after neutron source stops
- finally, beta-decay to stable isotopes

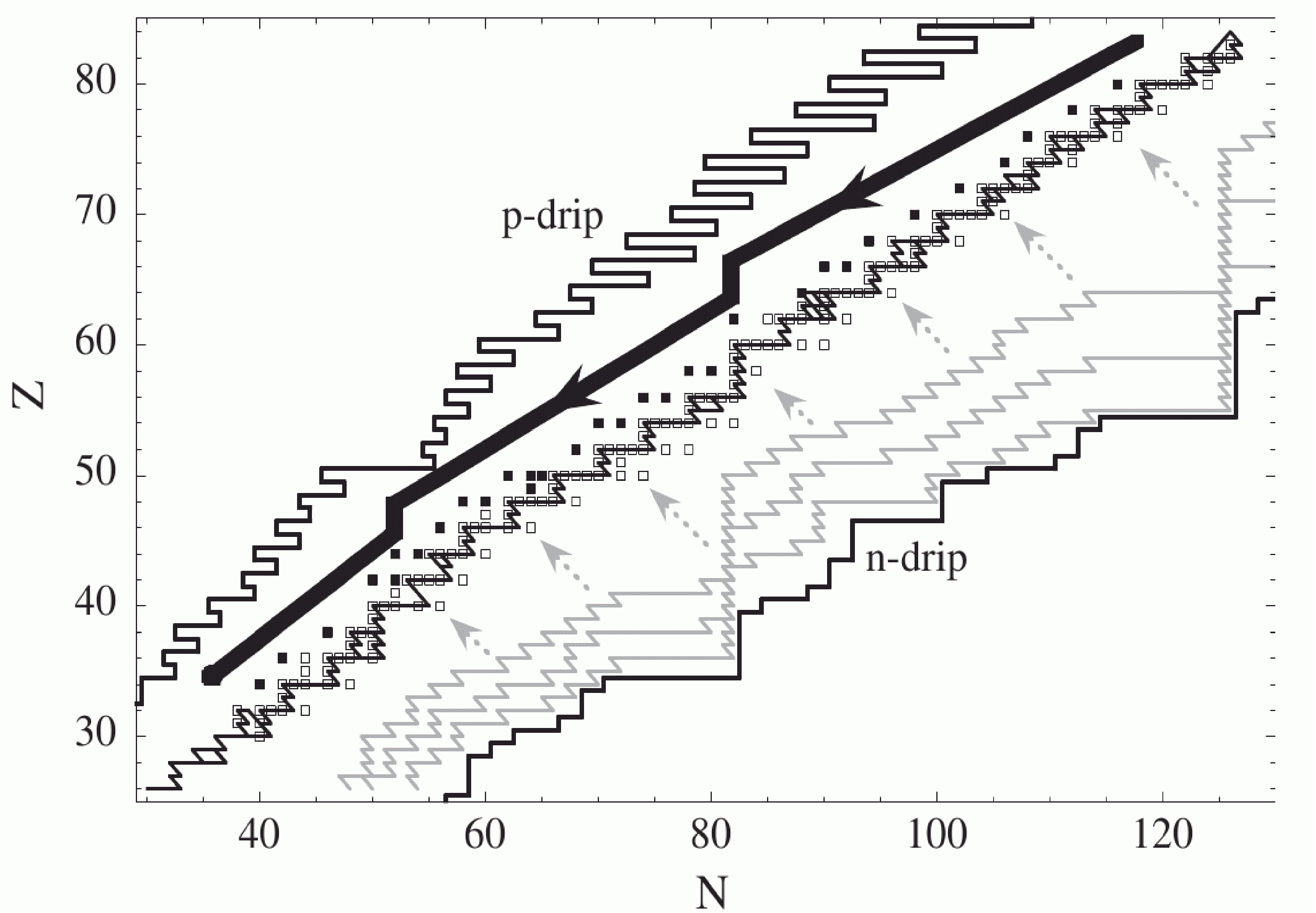
Equilibrium: $\mu_n + \mu(Z,A) = \mu(Z,A+1)$

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

because beta decays, left side ≈ 1

$$\bar{S}_n = kT \ln\left[\frac{2}{N_n}\left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2}\right]$$

Flow of nuclear reactions



Basic Equations to Describe the Flow

Abundances: $Y(Z) = \sum_A Y(Z,A)$

Decays $\lambda_\beta(Z) = \frac{1}{Y(Z)} \sum_A Y(Z,A)\lambda_\beta(Z,A)$

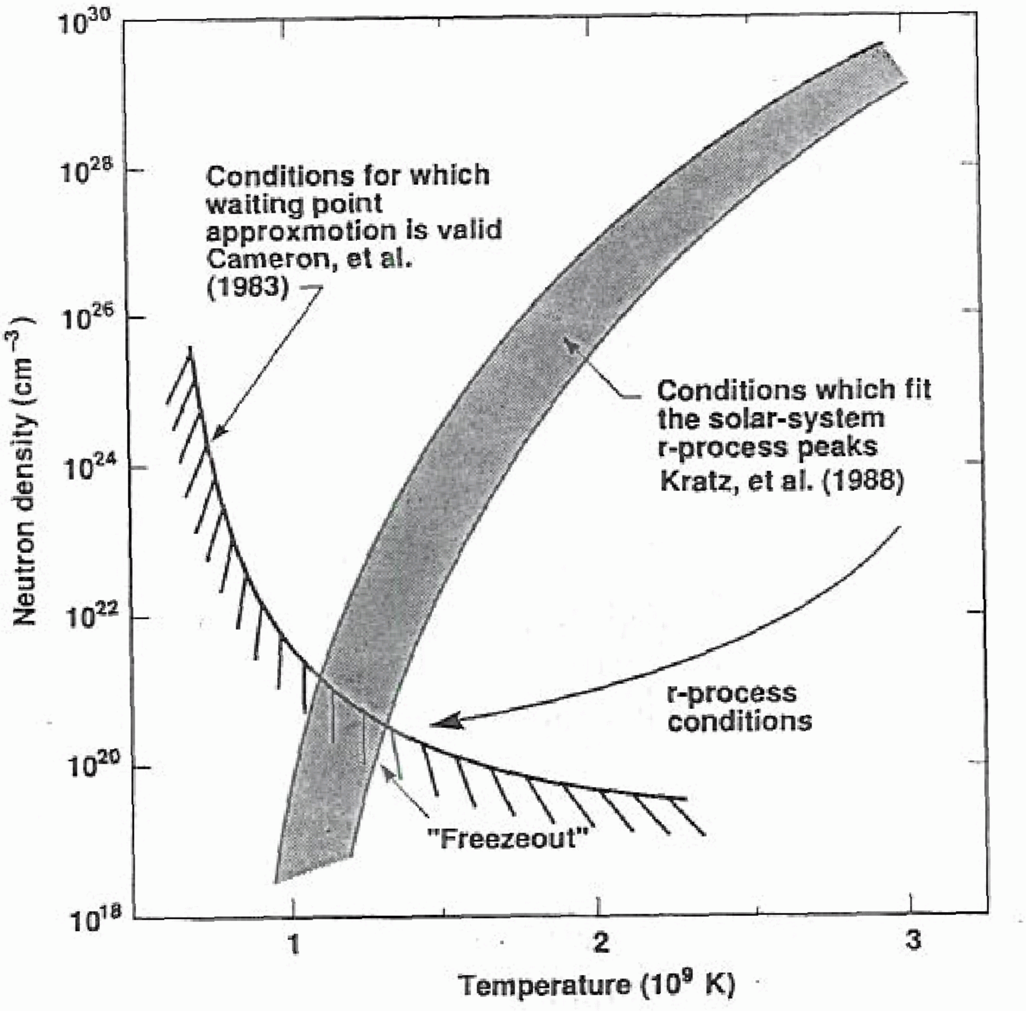
Change of $\dot{Y}(Z) = Y(Z-1)\lambda_\beta(Z-1) - Y(Z)\lambda_\beta(Z)$

Abundance Ratios if Stationary:

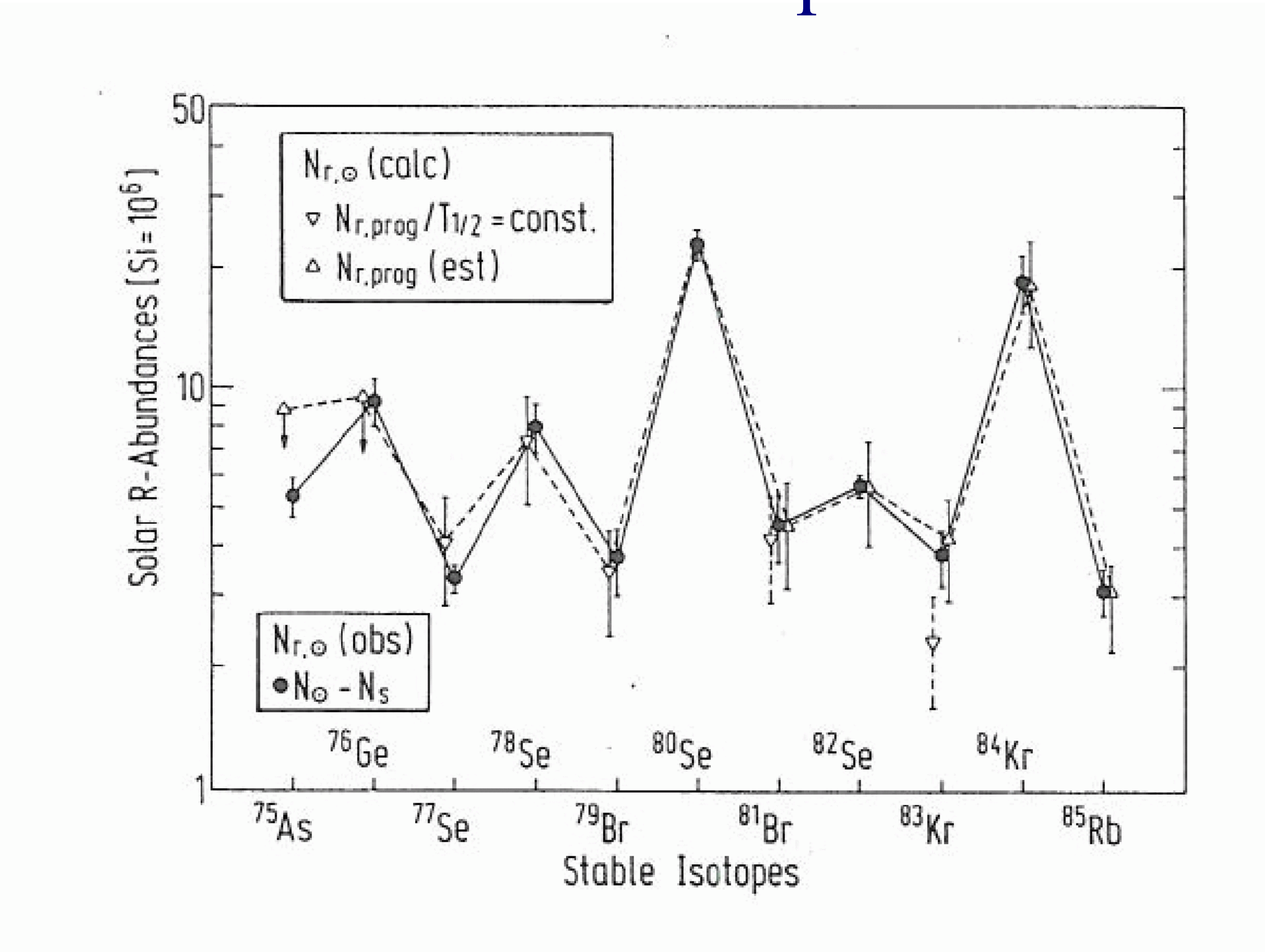
$$\frac{Y(Z)}{Y(Z-1)} = \frac{\lambda_\beta(Z-1)}{\lambda_\beta(Z)} = \frac{\tau_\beta(Z)}{\tau_\beta(Z-1)}$$

The "Waiting-Point" Approximation

Abundances are proportional to the beta-decay rates

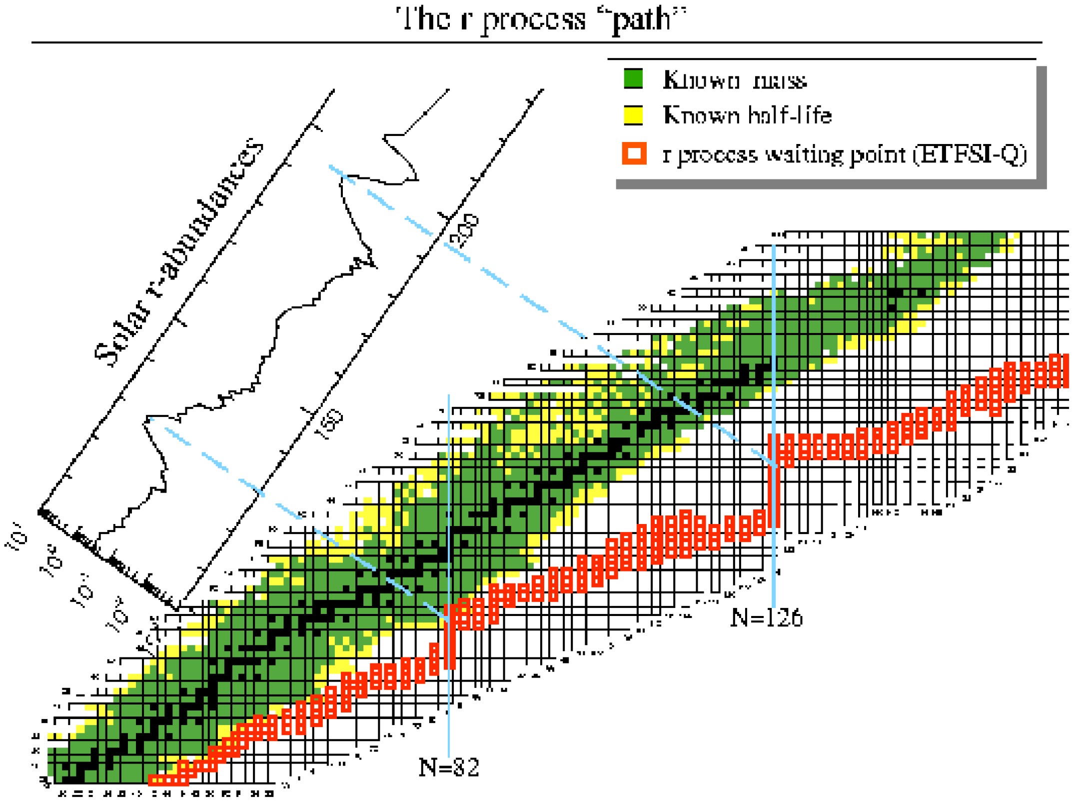


Comparison of solar Abundances with Beta-flow Models in Equilibrium



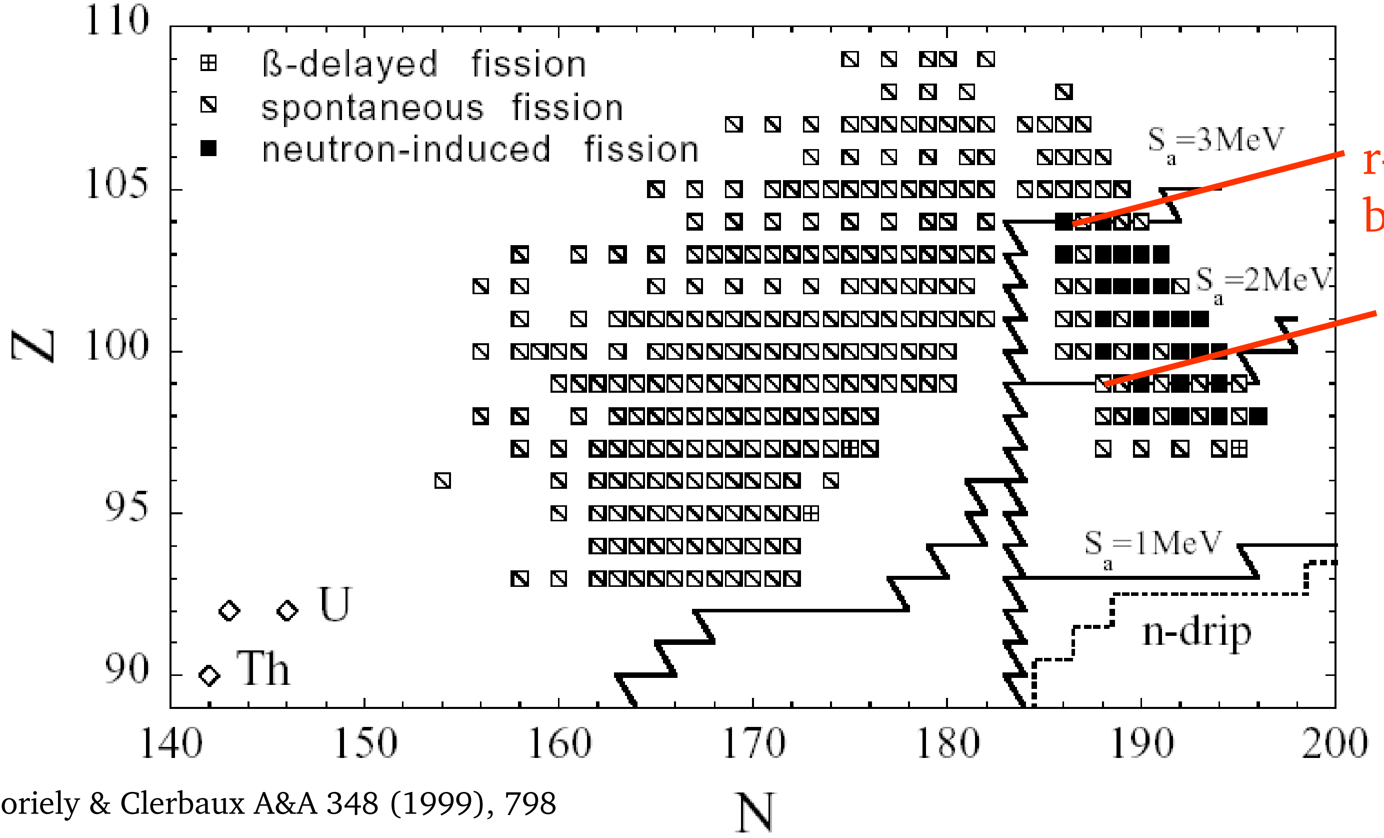
Rem.: Note uncertainties in decay rates

r-Process Path and Waiting Points



$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$
$(n, \gamma) \rightleftarrows (\gamma, n)$ implies $S_n \approx 2$ MeV

Fission as Cutoff for r-Process in (N,Z)

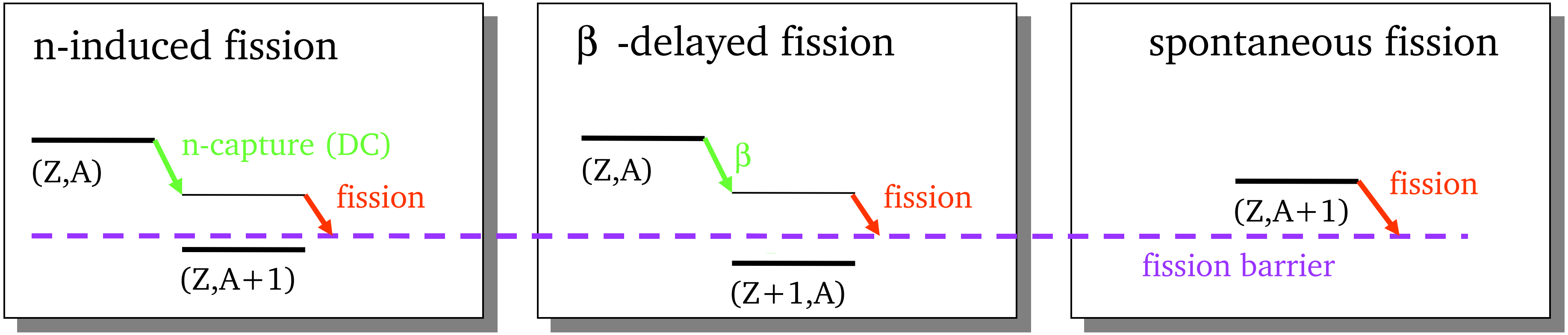


r-process ended by n-induced fission

or spontaneous fission

(different paths for different conditions)

(Goriely & Clerbaux A&A 348 (1999), 798)



n-induced fission

(Z,A)

n-capture (DC)

fission

(Z,A+1)

β -delayed fission

(Z,A)

β

fission

(Z+1,A)

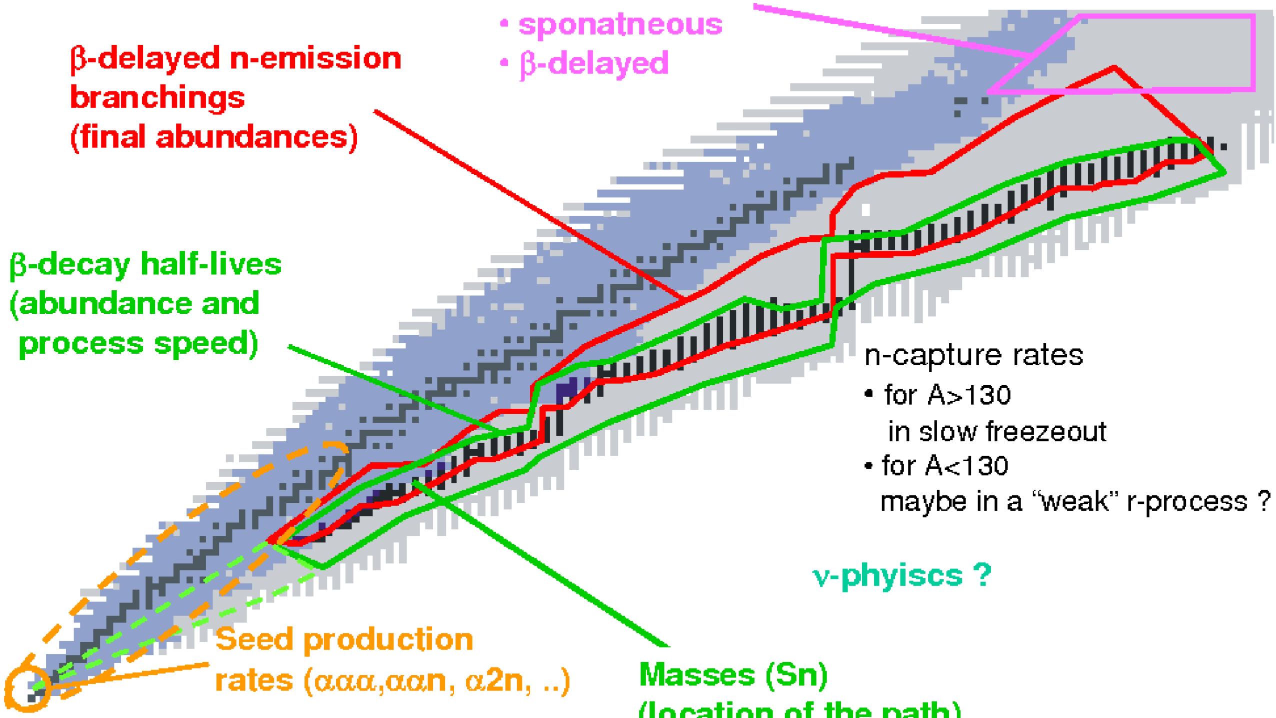
spontaneous fission

(Z,A+1)

fission

fission barrier

Relevant Nuclear Processes (& Uncertainties)



Fission rates and distributions:
- n-induced
- sponatneous
- β-delayed

β-delayed n-emission
branchings
(final abundances)

β-decay half-lives
(abundance and
process speed)

n-capture rates
- for A>130
  in slow freezeout
- for A<130
  maybe in a "weak" r-process ?

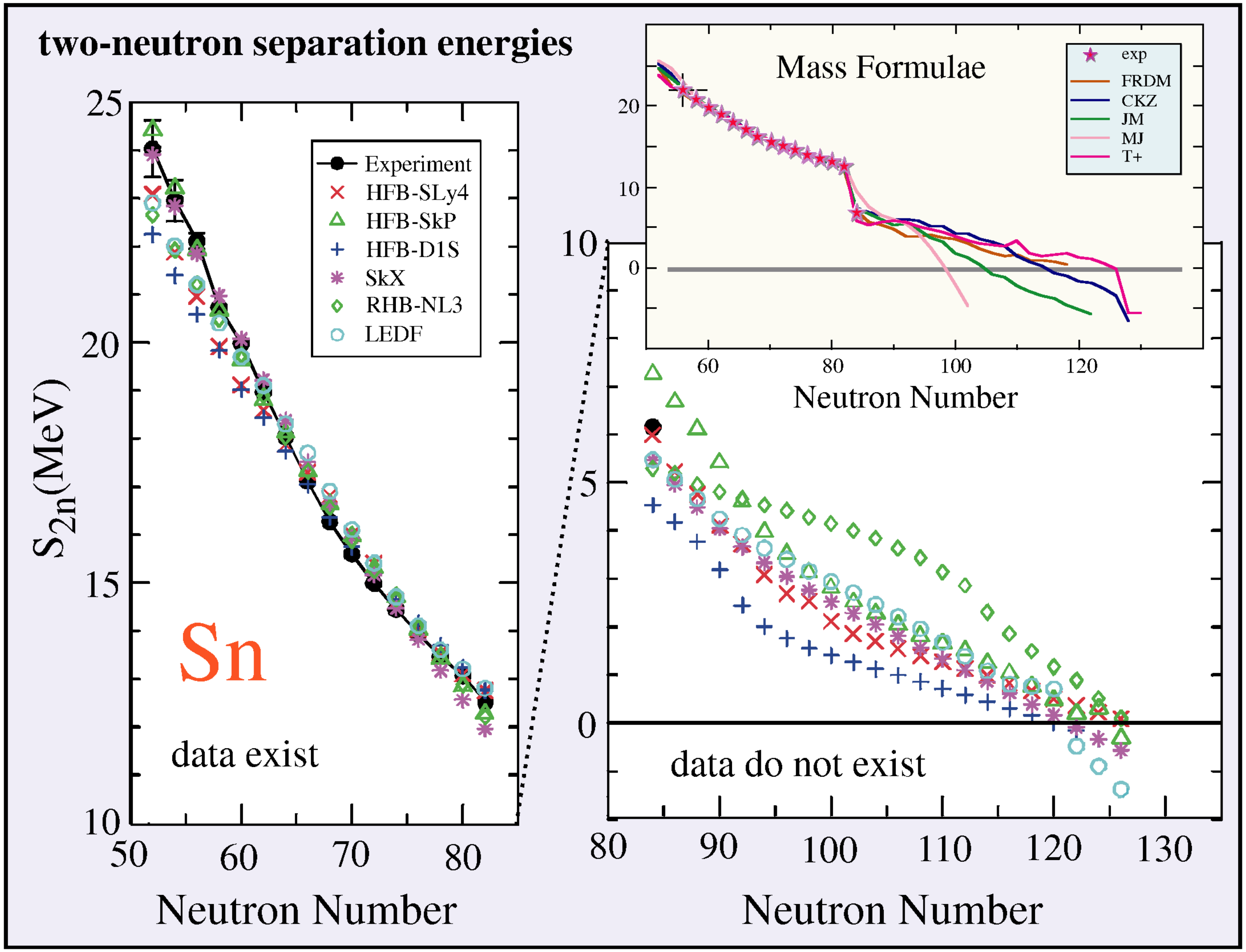
ν-phyiscs ?

Seed production
rates (ααα,ααn, α2n, ..)

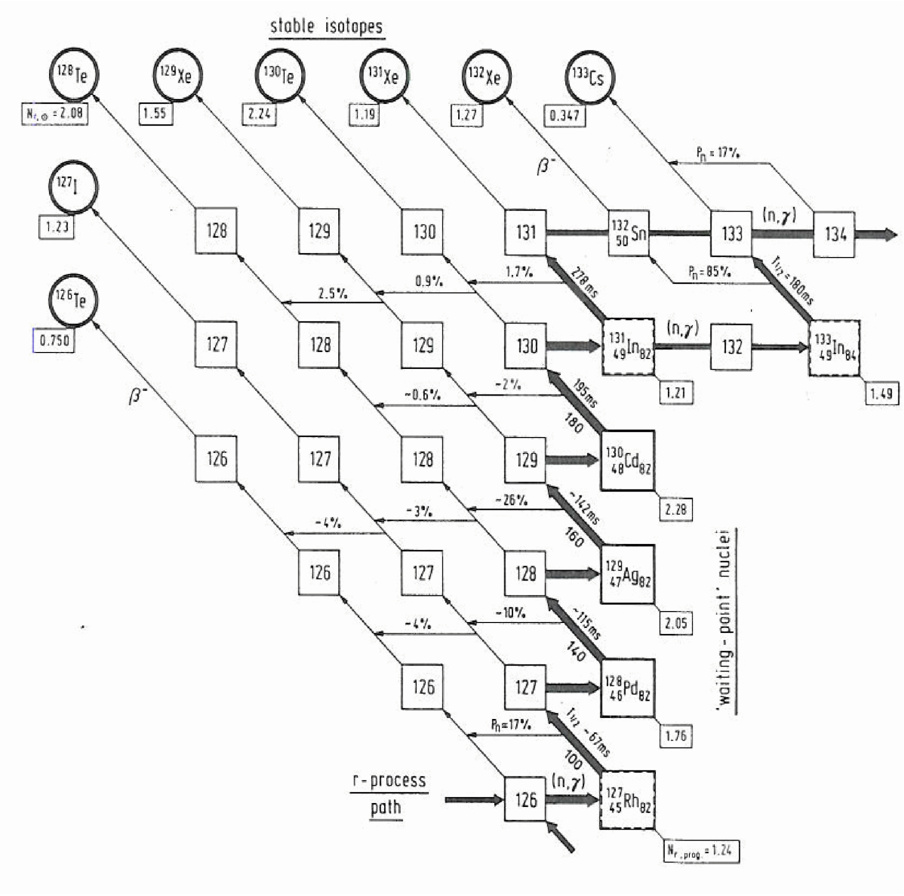
Masses (Sn)
(location of the path)

from Thielemann et al.

Mass Predictions for n-rich Nuclei



Magic Neutron Numbers



- (Z,N$_{magic}$) have

  low separation energy for (Z,N$_{magic}$+1)

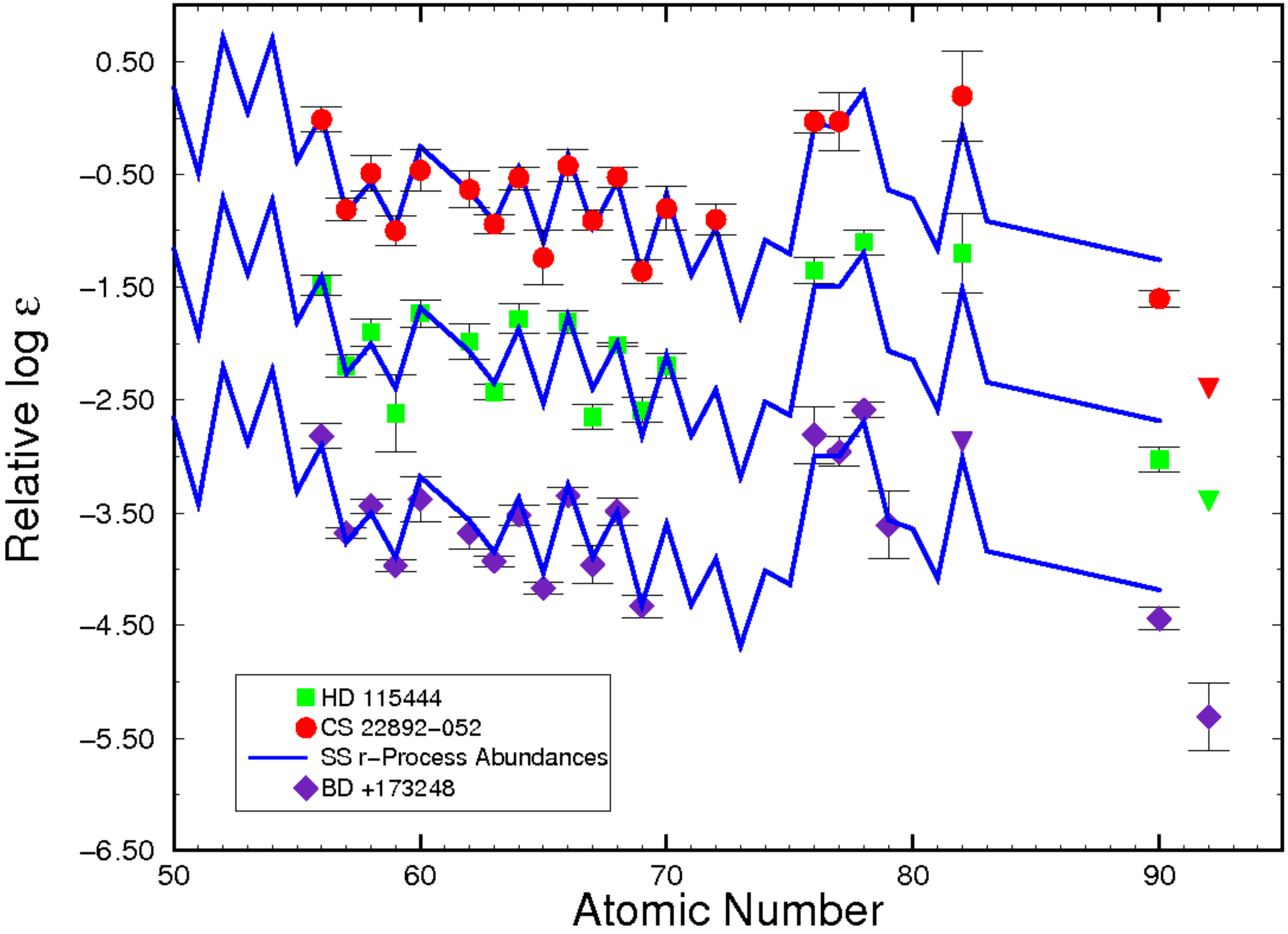
- (γ,n) hinders progress

- beta decay (Z,N$_{magic}$)-> (Z+1,N$_{magic}$-1)

- n capture to (Z+1,N$_{magic}$)

  till it can compete with γ

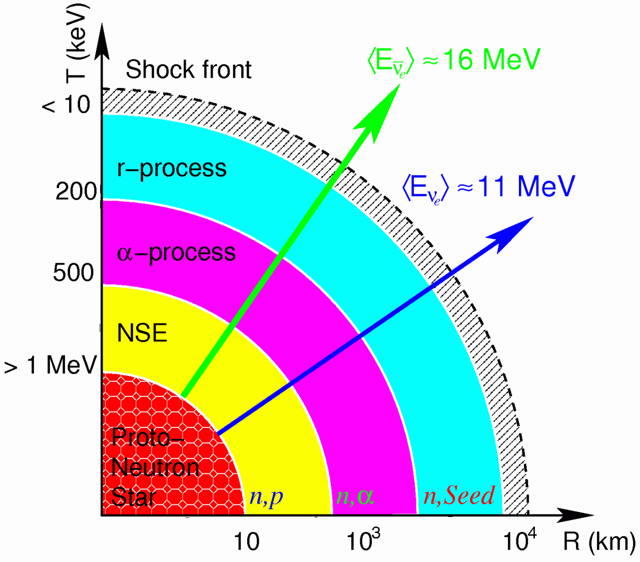
r–Process Abundances in Halo Stars



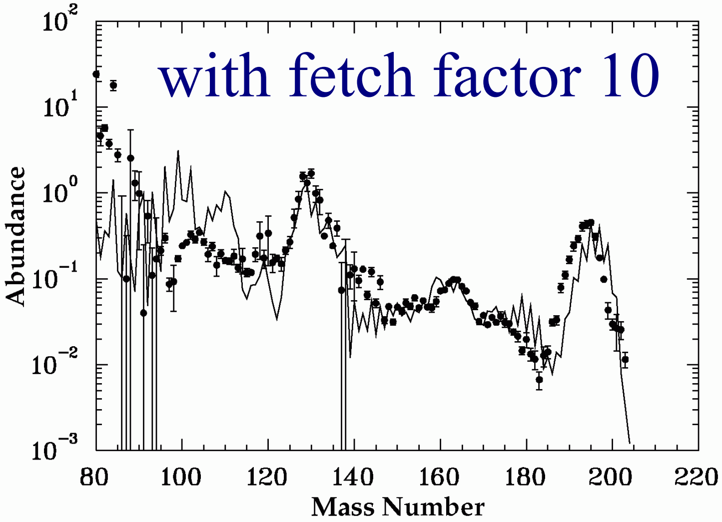
from Sneeden et al.

Possible r-Process Side I: Core Collapse SN

Neutrino-driven wind



(S. Woosley *et al*)



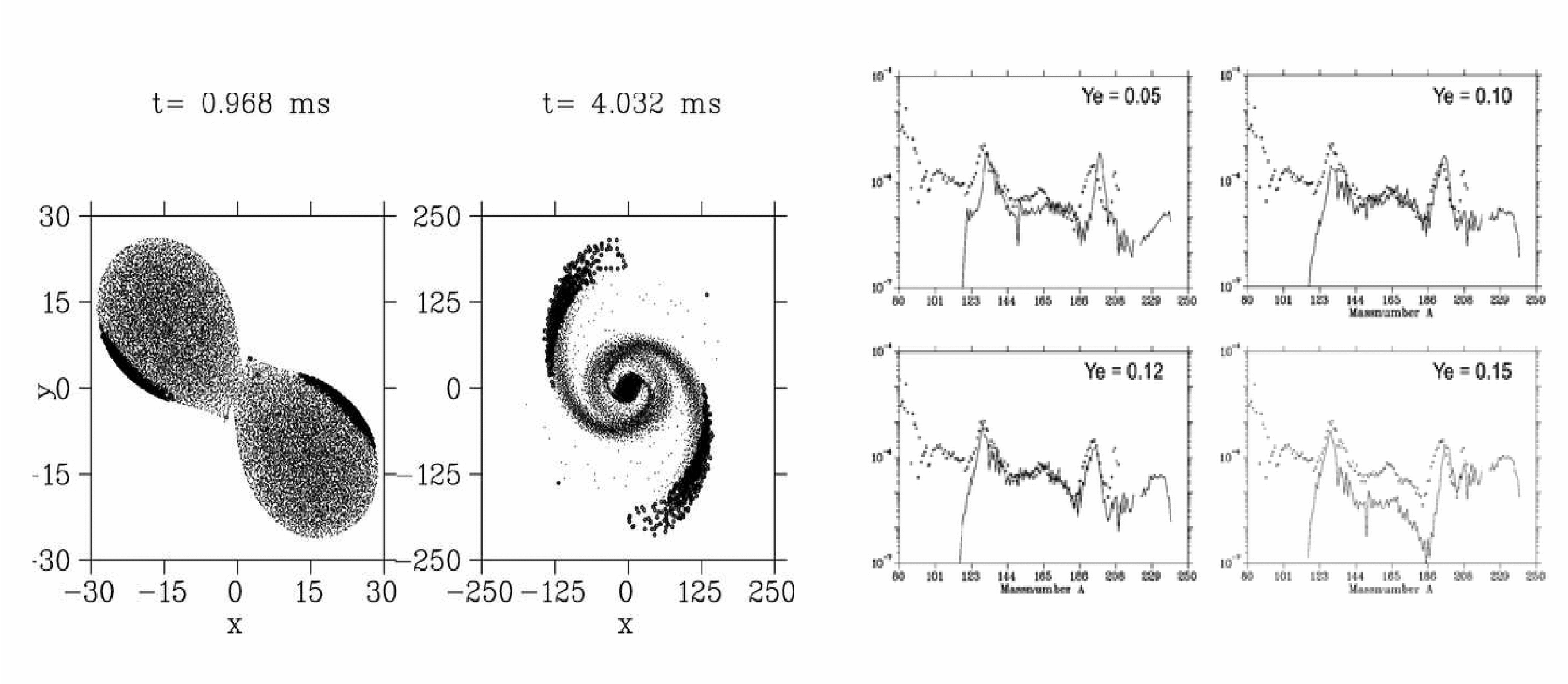
with fetch factor 10

- Neutrino-wind from (cooling) NS
  $\nu_e + n \rightarrow e^- + p$
  $\bar{\nu}_e + p \rightarrow e^+ + n$
- α-process (formation seed nuclei)
  $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be} + \gamma$
  $\alpha + {}^9\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$

- Expansion adiabatic (Entropy constant) and $r \sim e^{t/\tau}$.
- Main parameter determining the nucleosynthesis is the neutron to seed ratio

Problem: Time evolution of T and rho right but Energy densities are too low by factors of 5 to 10 !!!

Neutron Star Mergers

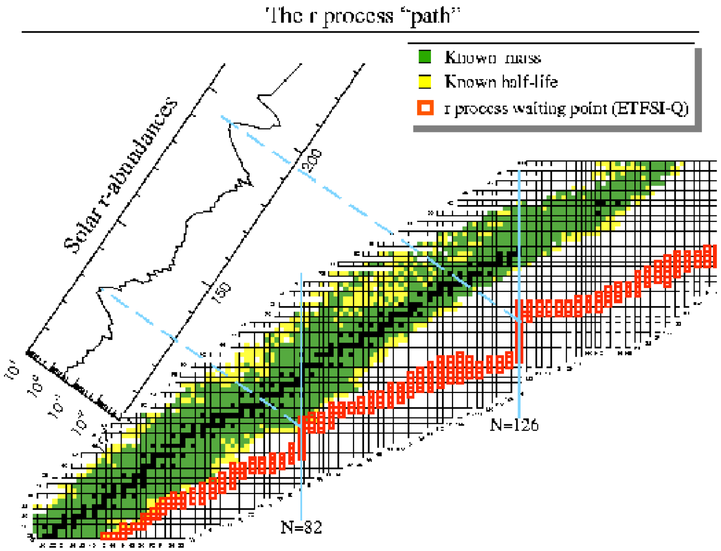


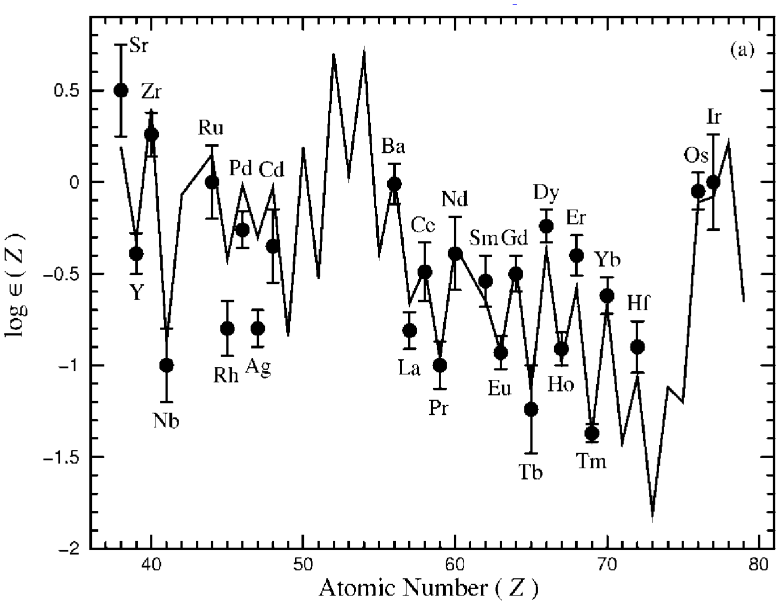
Rosswog et al. 2006

Problem: energies/entropies are ok but mergers are too rare

Mystery: r-process pattern depends on T, rho and the evolution with time (freeze out)

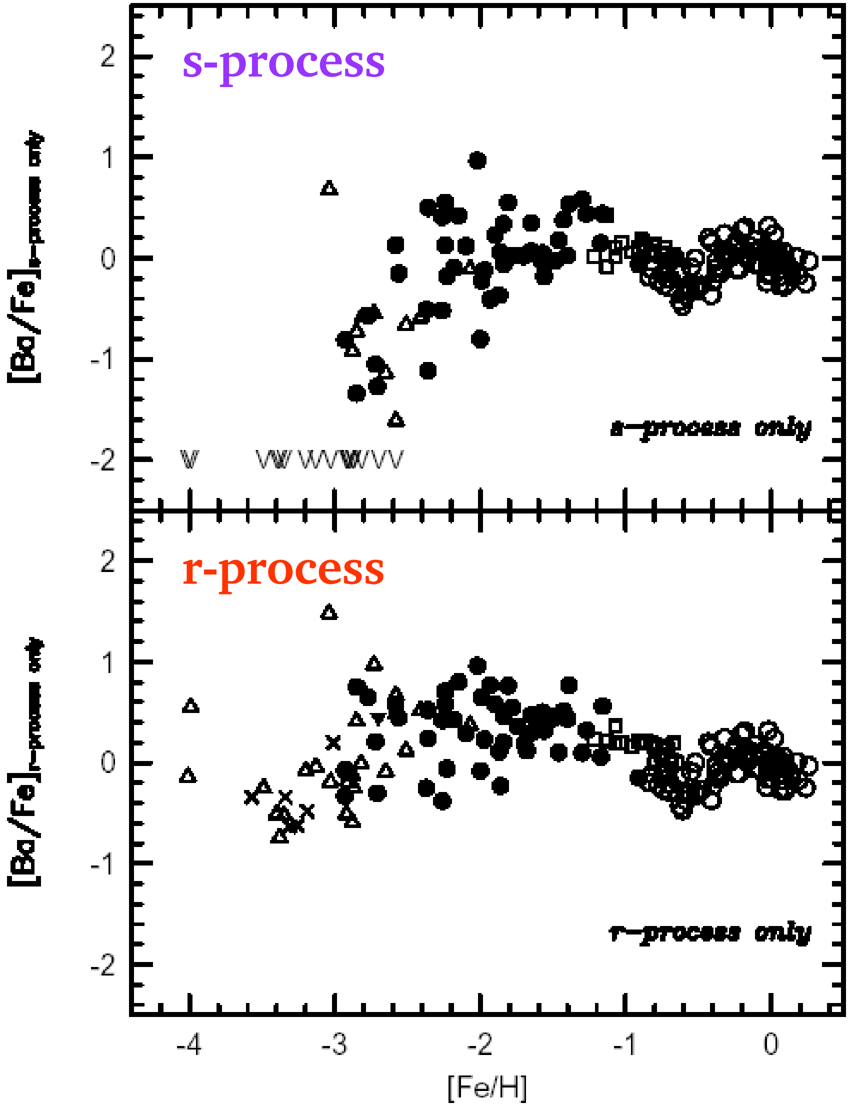
However, r-process pattern is always the same and independent from the Fe-abundance !!!!





r- and s-process elements in stars with varying metallicity

(Burris et al. ApJ 544 (2000) 302)



→ ~age

s-process:

later in time

=> long evolution of star

=> lower mass stars

gradual onset

=> mass range

r-process:

sudden onset & early

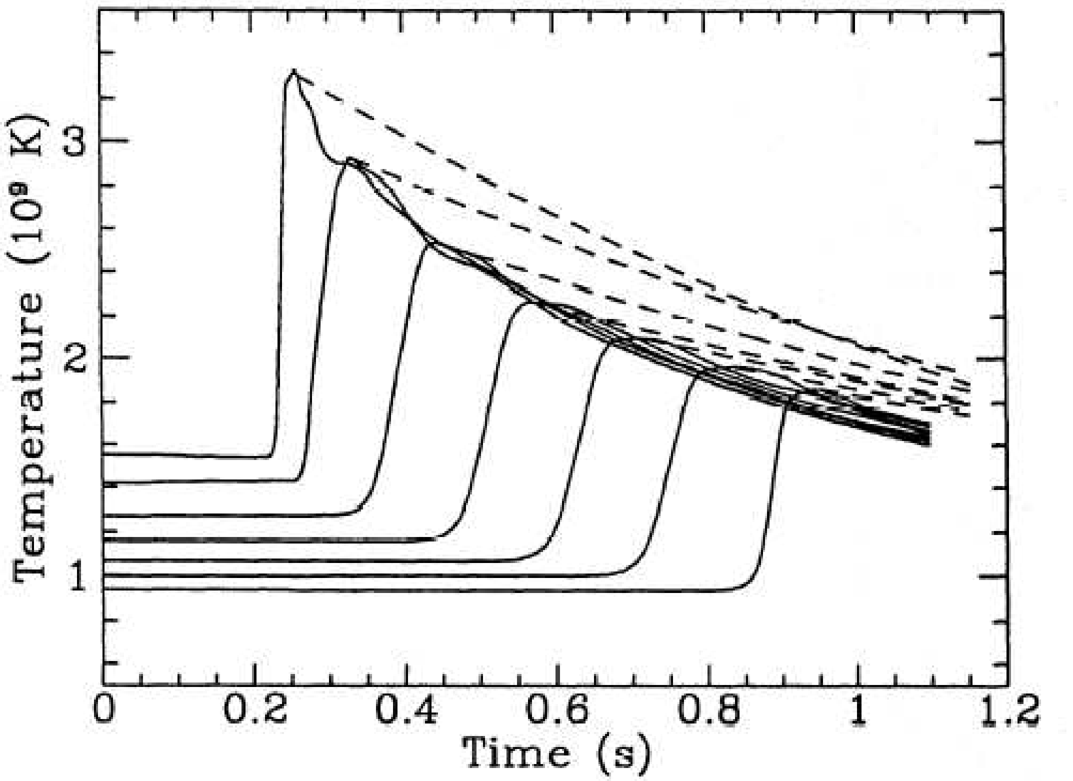
=> mostly massive stars

→ confirms massive stars as r-process sites (but includes SN and NS-mergers)

The p-process

- produces p-rich, usually rare (0.1-1% isotopic fraction), stable isotopes
- Site: Supernova shock passing through O-Ne layers of progenitor star

Conditions at different locations in O/Ne layers during a Supernova:



(Rayet et al. A&A298 (1995) 517)

The p-Process Mechanism

- (γ,n)-reactions produces proton rich isotopes

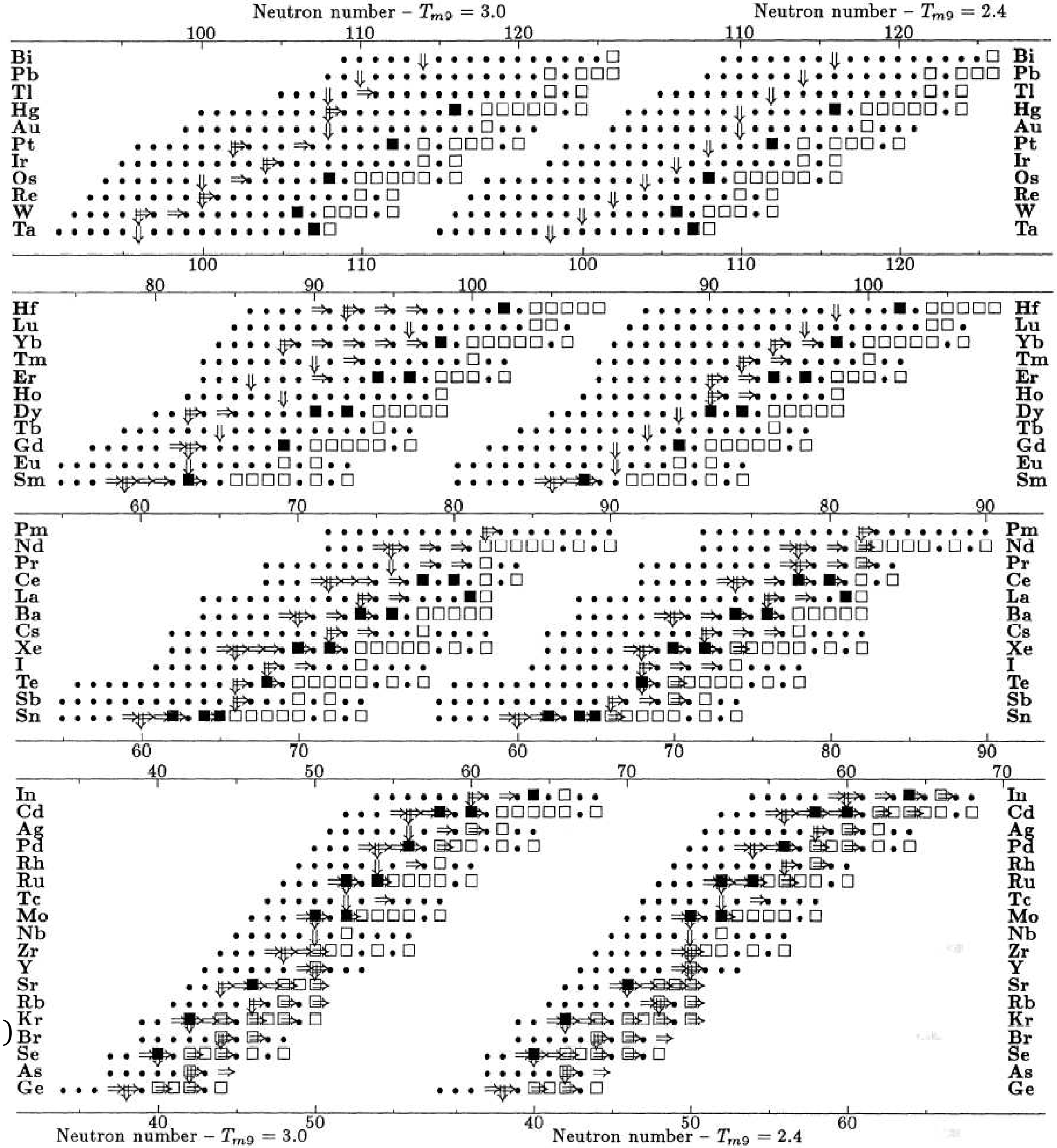
- till cascade down via (γ,p) and (γ,α) in the direction to Fe

- If T drops fast, NSE is not reached and proton-rich isotopes survive

- if the disintegration time scales are large, e.g. 92Mo (N=50) and 144Sm(N=82) (neutron magic numbers)

p-process path

Rayet et al. A&A227(1990)271

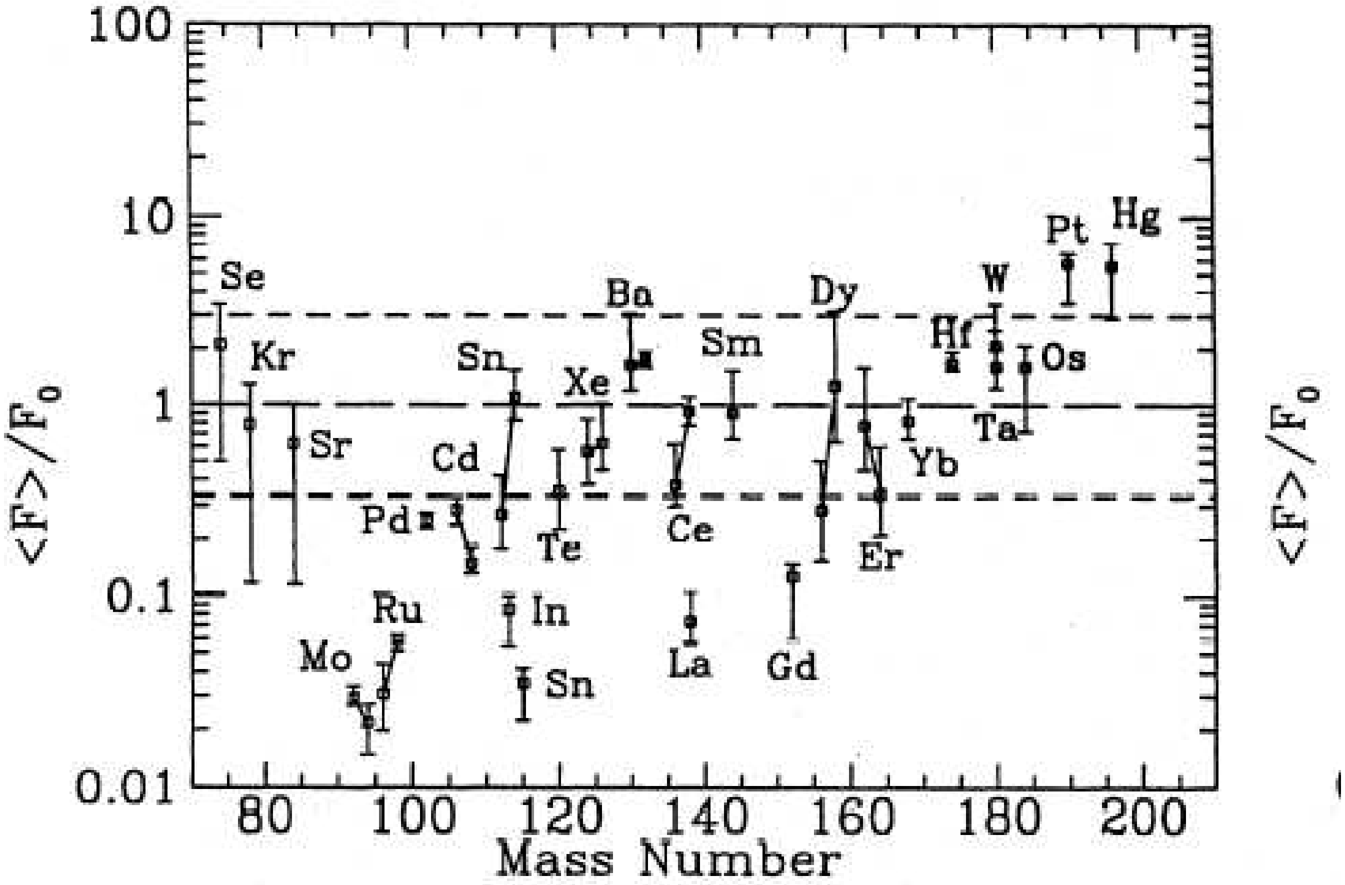


■ p-nuclei

→ (γ ,n) flow stopped by (n,γ)

↓ flow proceeds via (γ ,p) or (γ ,α)

p-process model results



PROBLEM:
underproduction of Mo and Ru by factor of 10 to 100

(Rayet et al. A&A298 (1995) 517)