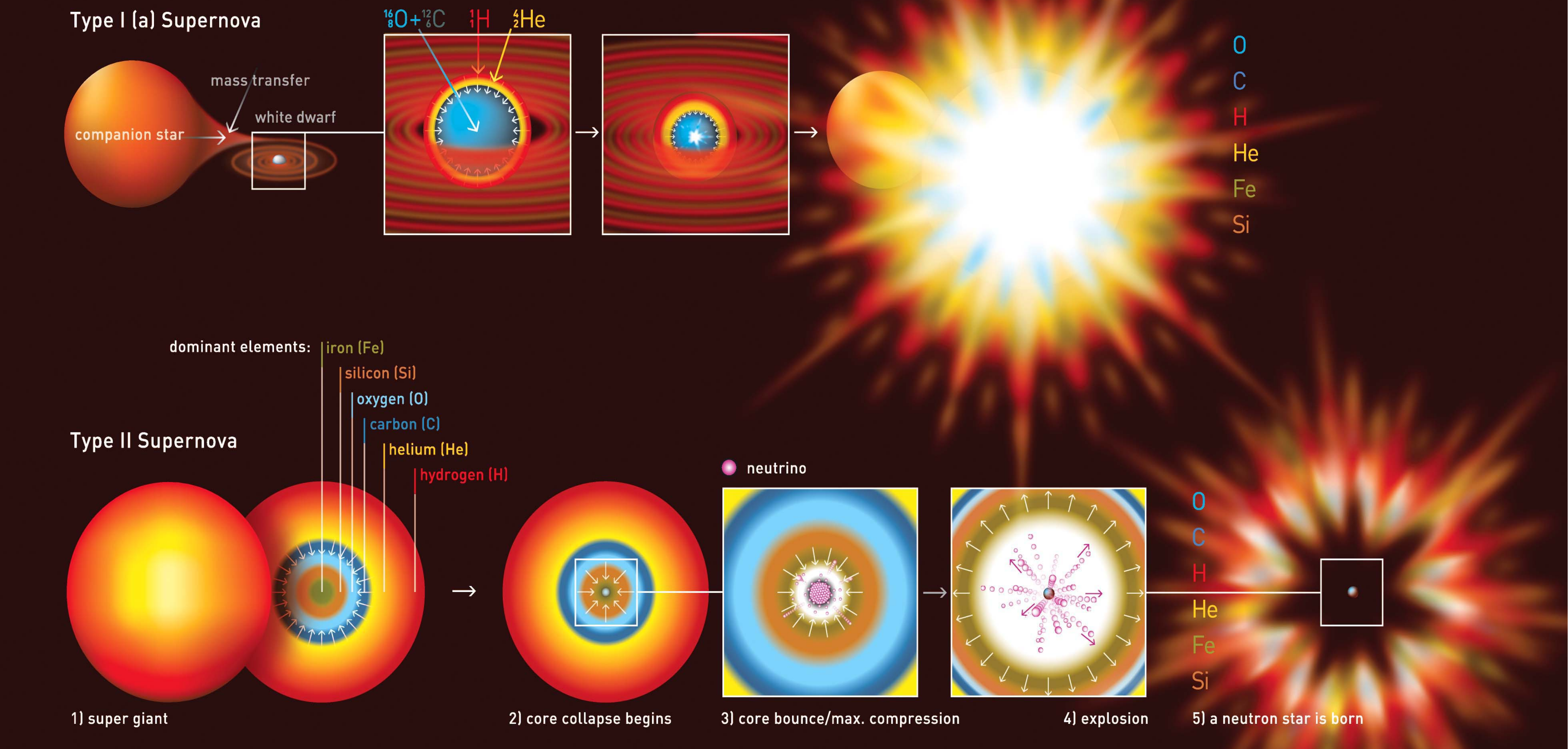
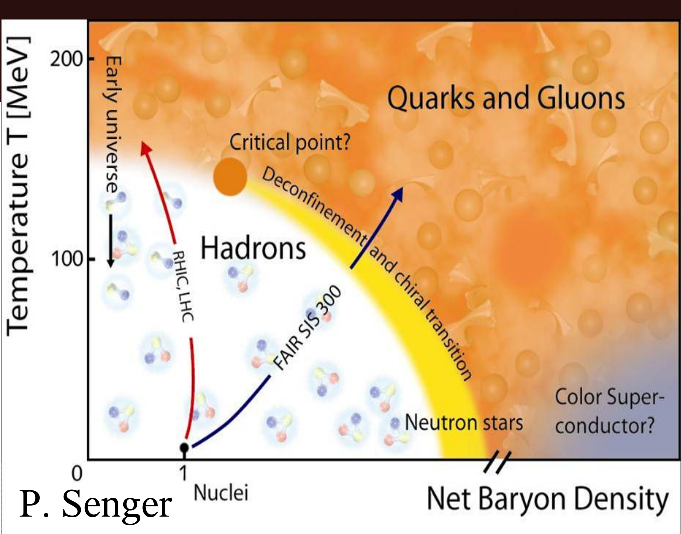
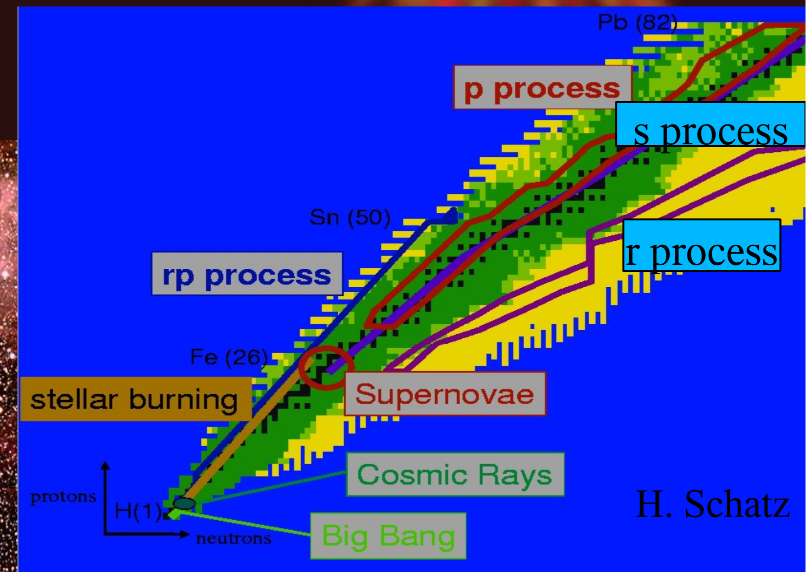
What are the astrophysical sites for producing r-process and other heavy elements?

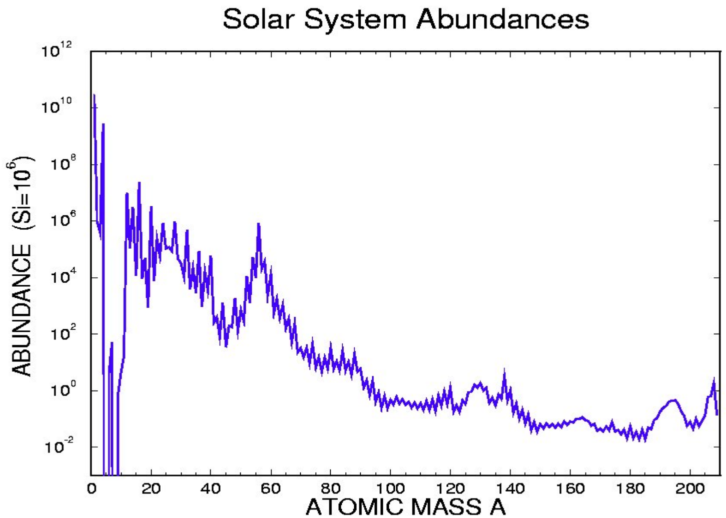
Friedrich-Karl Thielemann
Department of Physics
University of Basel
Switzerland

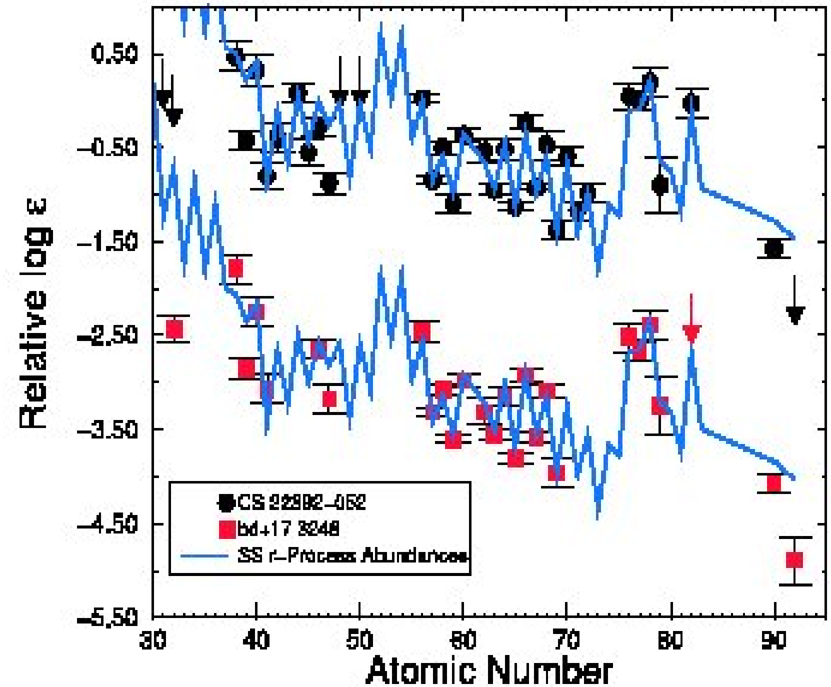

Type I (a) Supernova
$^{16}_{8}O + ^{12}_{6}C$ $^{1}_{1}H$ $^{4}_{2}He$
mass transfer
white dwarf
companion star
O
C
H
He
Fe
Si
dominant elements:
iron (Fe)
silicon (Si)
oxygen (O)
carbon (C)
helium (He)
hydrogen (H)
Type II Supernova
neutrino
O
C
H
He
Fe
Si
1) super giant
2) core collapse begins
3) core bounce/max. compression
4) explosion
5) a neutron star is born


Temperature T [MeV]
200
100
0
1
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-
conductor?
Nuclei
Net Baryon Density
P. Senger


SN 1987A

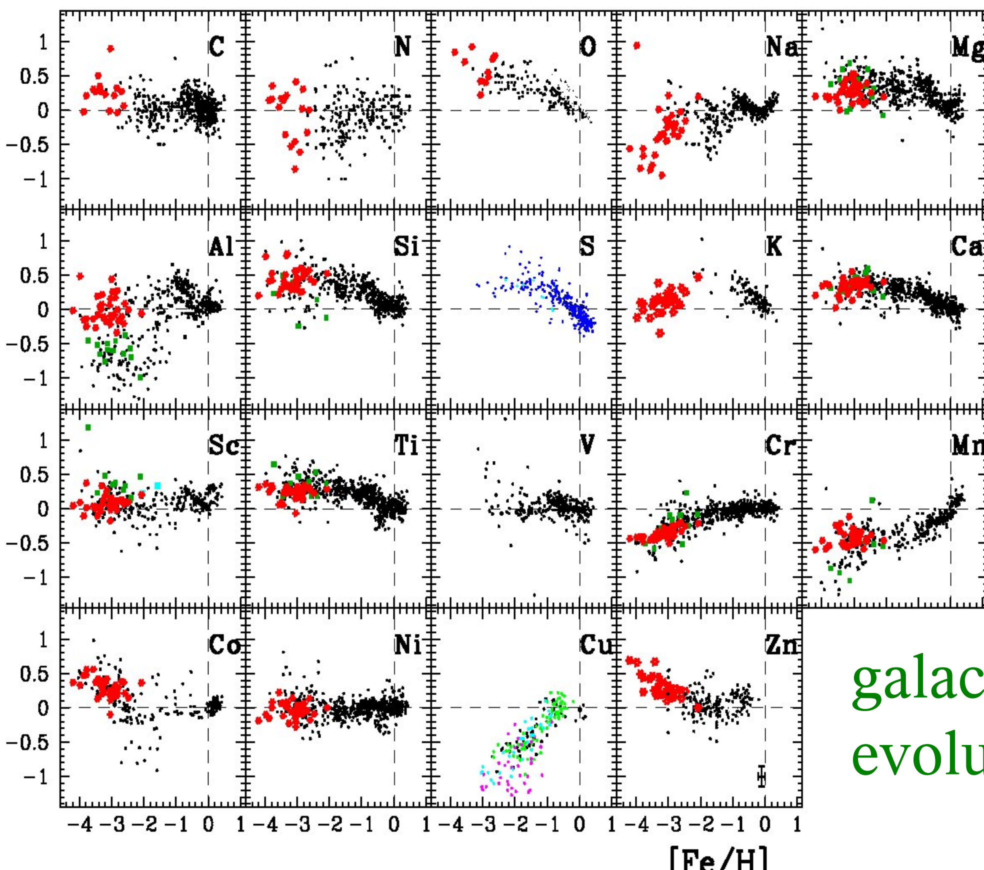

Pb (82)
p process
s process
Sn (50)
r process
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang
H. Schatz



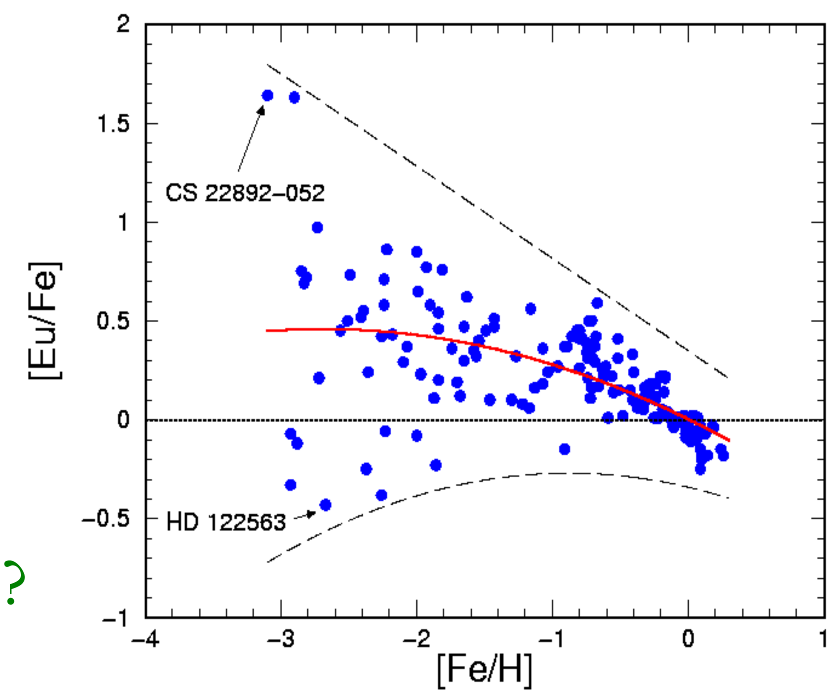


How do we understand: solar system abundances..

low metallicity stars ...



galactic evolution?



Brief Summary of Burning Stages (Major Reactions)

1. Hydrogen Burning — $T = (1\text{-}4)\times10^7$K
   - pp-cycles -> $^{1}H(p,e^{+}\nu)^{2}H$
   - CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$
2. Helium Burning — $T=(1\text{-}2)\times10^8$K
   - $^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $\quad$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   - $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C((\alpha,n)^{16}O)$
3. Carbon Burning — $T=(6\text{-}8)\times10^8$K
   - $^{12}C(^{12}C,\alpha)^{20}Ne$ $\quad$ $^{23}Na(p,\alpha)^{20}Ne$
   - $^{12}C(^{12}C,p)^{23}Na$ $\quad$ $^{23}Na(p,\gamma)^{24}Mg$
4. Neon Burning — $T=(1.2\text{-}1.4)\times10^9$K
   - $^{20}Ne(\gamma,\alpha)^{16}O$
   - $^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$ $\quad$ 30kT = 4MeV
5. Oxygen Burning — $T=(1.5\text{-}2.2)\times10^9$K
   - $^{16}O(^{16}O,\alpha)^{28}Si$ $\quad$ $^{31}P(p,\alpha)^{28}Si$
   - $......,p)^{31}P$ $\quad ...,n)^{31}S(\beta^{+})^{31}P$ $\quad$ $^{31}P(p,\gamma)^{23}S$
6. "Silicon" Burning — $T=(3\text{-}4)\times10^9$K

(all) photodisintegrations and capture reactions possible

⇒ thermal (chemical) equilibrium

ongoing measurements of key fusion reactions at low energies

Global Chemical (=Nuclear Statistical) Equilibrium (NSE)

$$\bar{\mu}(Z,N) + \bar{\mu}_n = \bar{\mu}(Z,N+1)$$
$$\bar{\mu}(Z,N) + \bar{\mu}_p = \bar{\mu}(Z+1,N)$$

$$\bar{\mu}_i = kT \ln\left(\frac{\rho N_A Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right) + m_i c^2$$

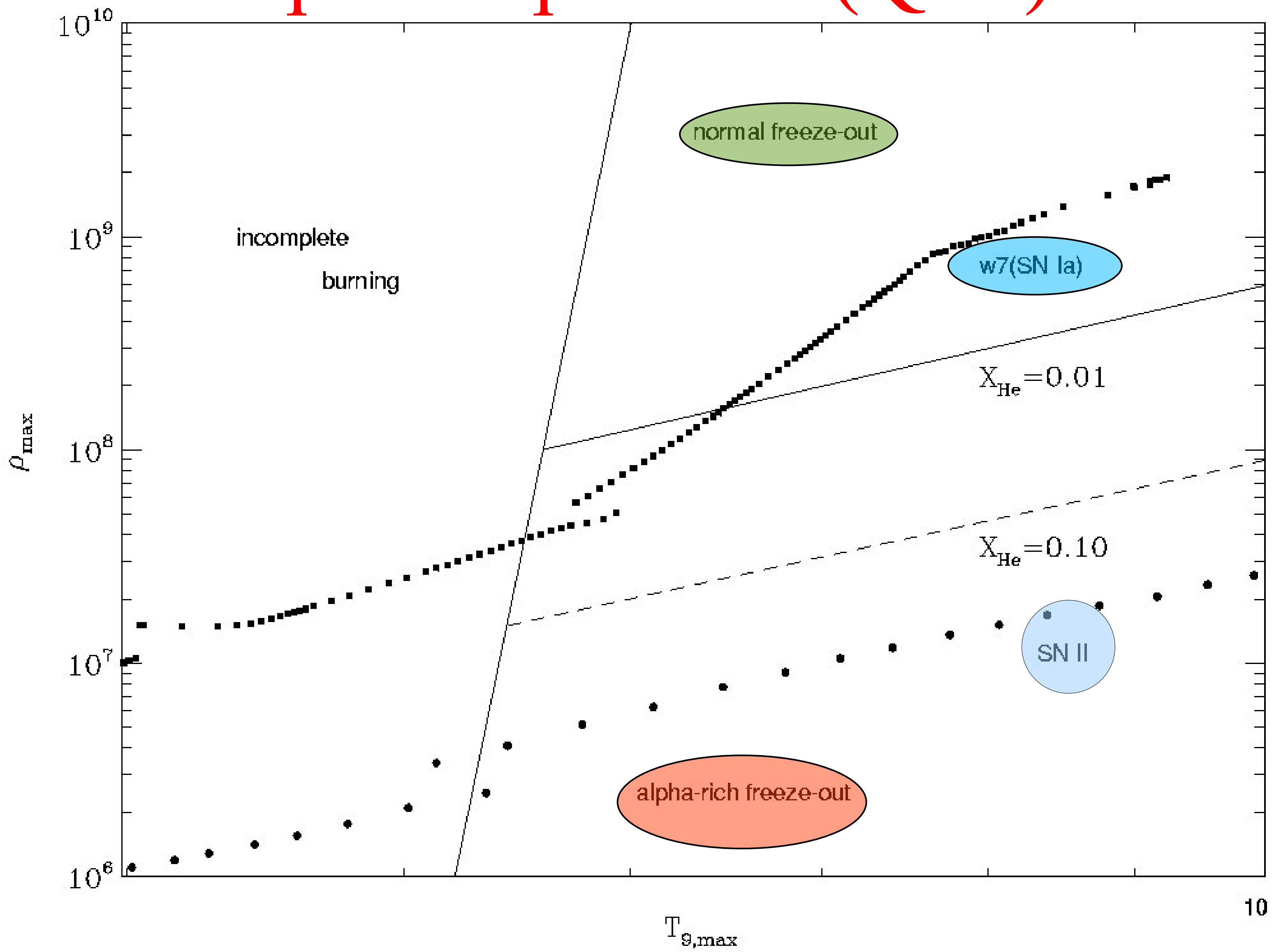
$$N \text{neutrons} + Z \ \text{ protons} \rightleftharpoons (Z,N)$$

$$N\bar{\mu}_n + Z\bar{\mu}_p = \bar{\mu}_{Z,N}.$$

$$Y(Z,N) = G_{Z,N}(\rho N_A)^{A-1}\frac{A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{\frac{3}{2}(A-1)} \exp(B_{Z,N}/kT) Y_n^N Y_p^Z$$

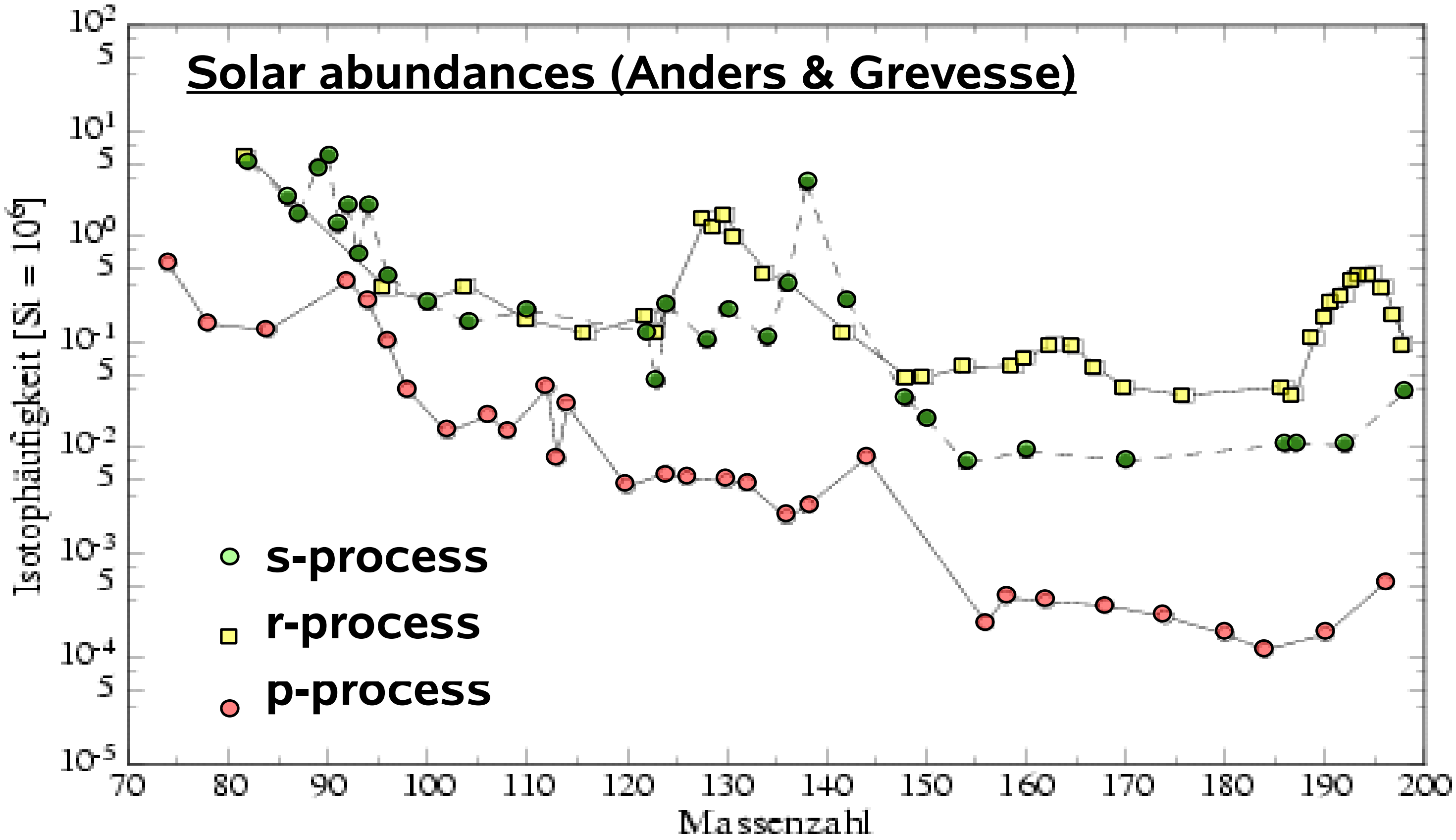
$$\sum_i A_i Y_i = 1$$
$$\sum_i Z_i Y_i = Y_e$$

Complete chem. equilibrium (NSE) vs. quasi equilibria (QSE)



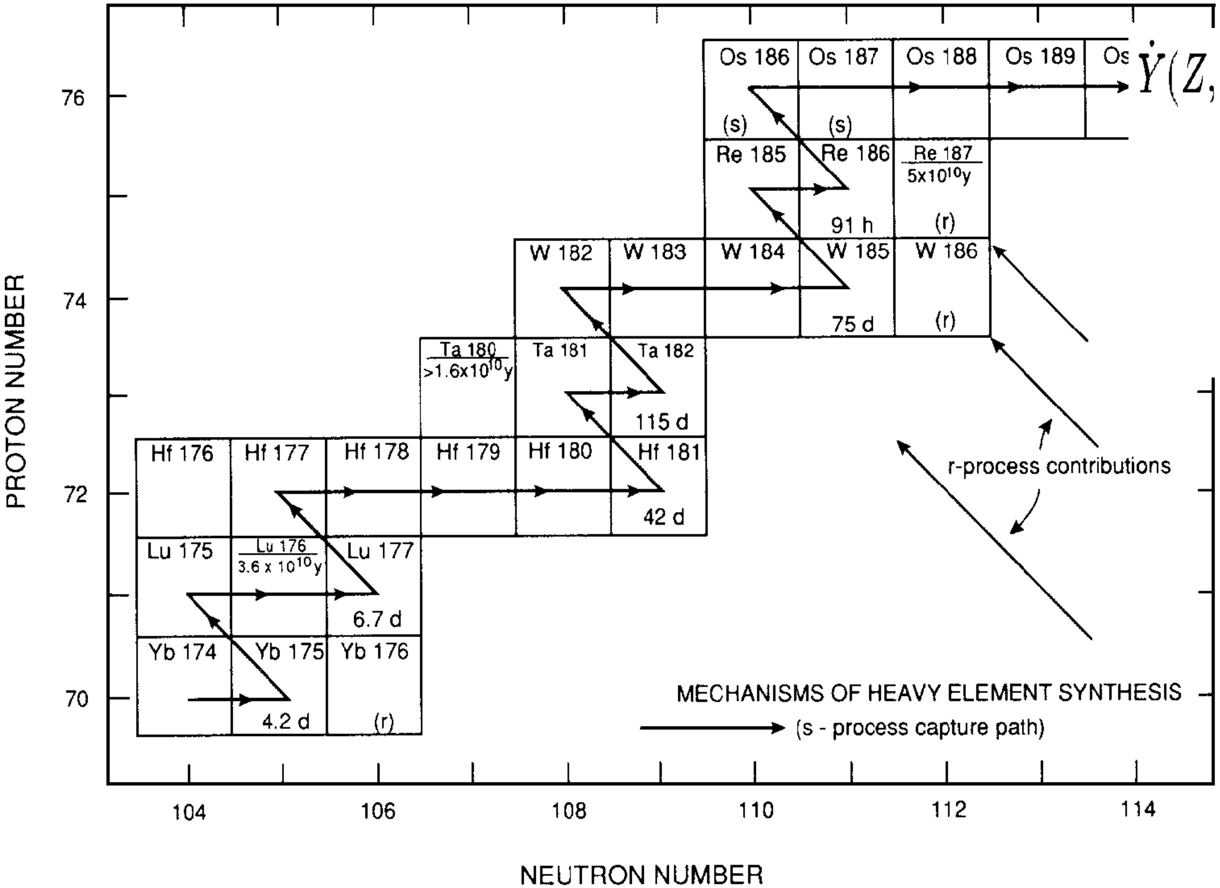
Si-burning in stellar evolution and expl. Si-burning at high densities lead to NSE!

s-process and steady flow



shown are s-, r-, and p-only nuclei!

s-process and steady flow



possible destruction of nucleus (Z,A)

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

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

s(low) or r(apid) capture process

$\tau_n > \tau_\beta$ beta-decay to (Z+1,A)

only one nucleus per A needs to be considered!

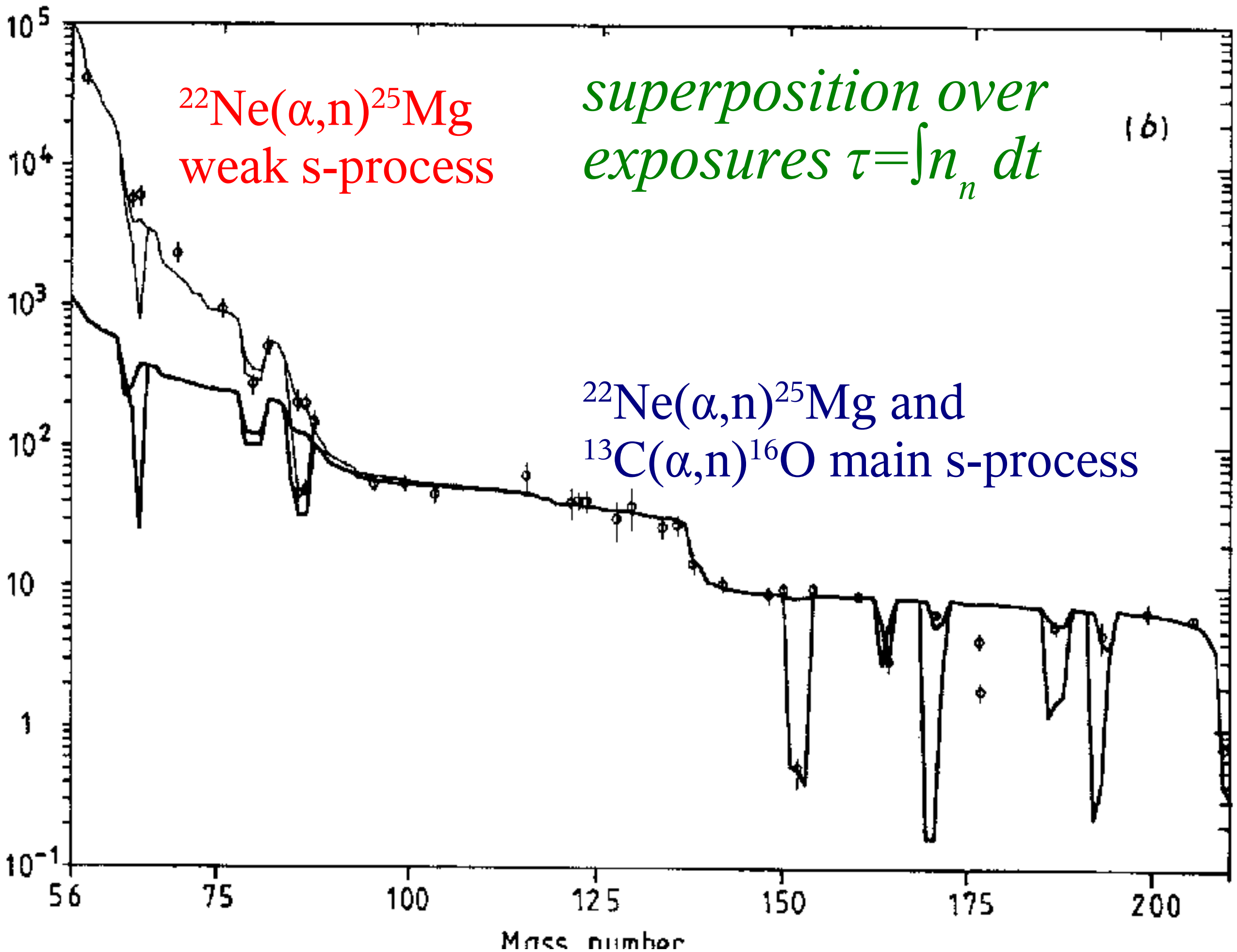
$$\dot{Y}(A) = n_n < \sigma v >_{n,\gamma} Y(A-1) - n_n < \sigma v >_{n,\gamma} Y(A)$$

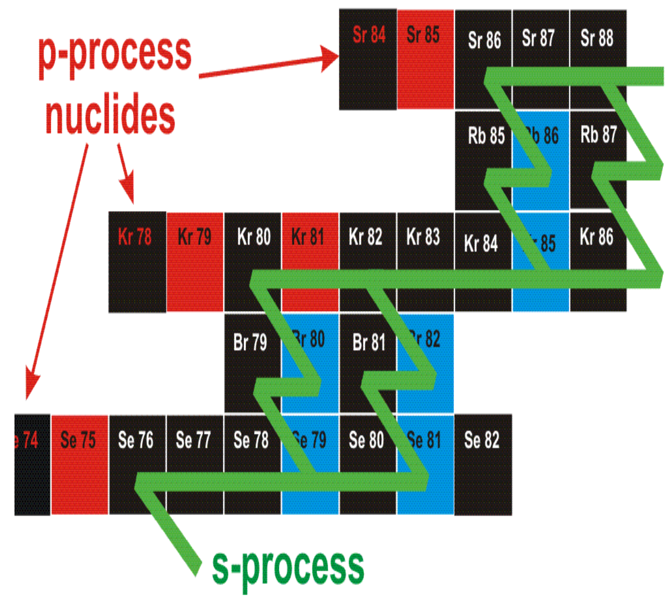
in case of steady flow =0

$\sigma \approx 1/v, < \sigma v > = \sigma(v)v$ therefore

$$\sigma(A-1, 30\ \text{keV})Y(A-1) = \sigma(A, 30\ \text{keV})Y(A)$$

The sigma*N-curve

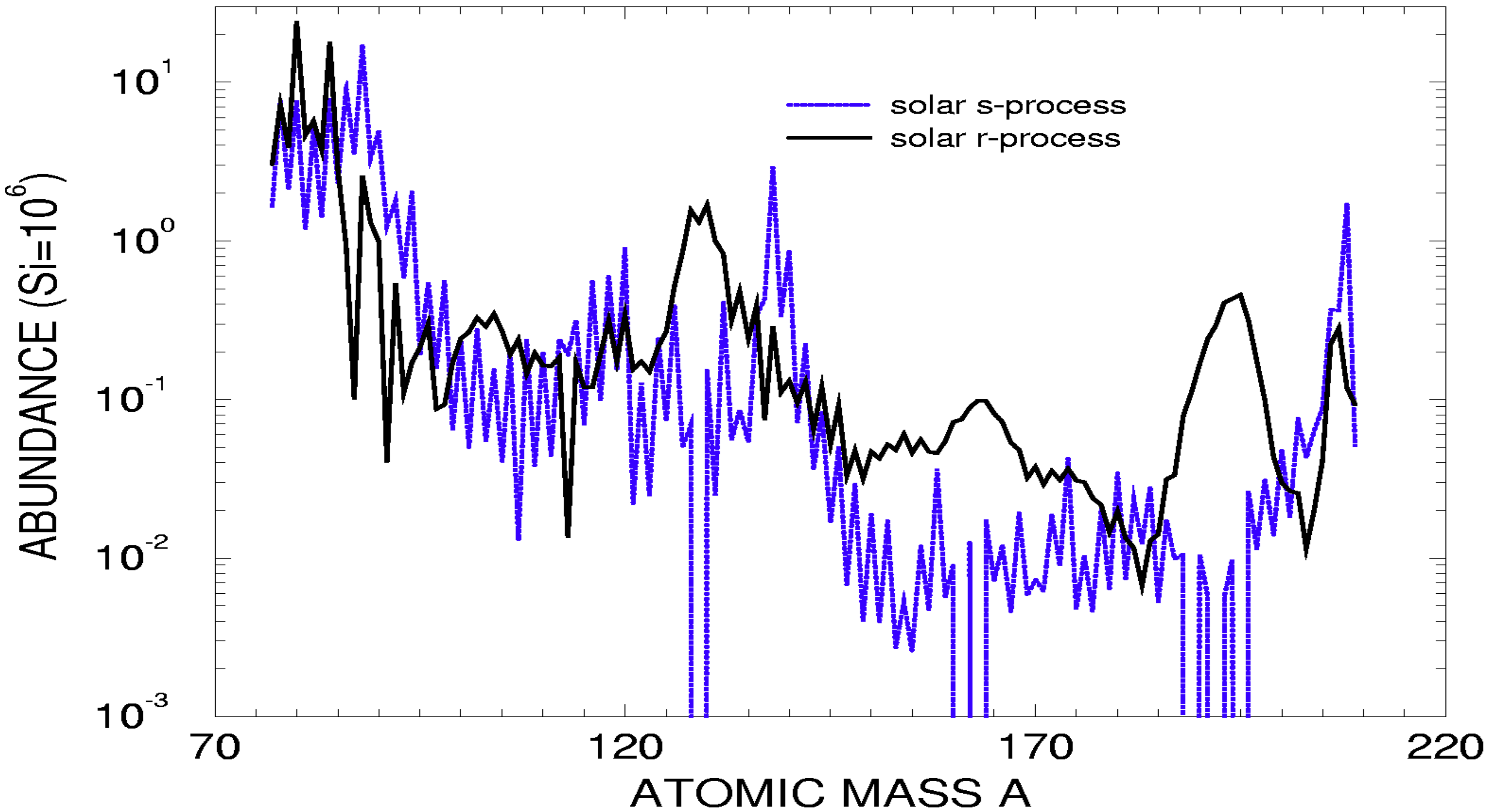




double values due to branchings

a complete steady flow is not given, but in between magic numbers (where the neutron capture cross sections are small) almost attained!

s- and r-decomposition of heavy elements



the almost constant sigma*N-curve leads to a large odd-even staggering in the abundances (due to the odd-even staggering in n-capture cross sections!)

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?

High neutron densities lead to nuclei far from stability, experiencing nuclei with short half-lives

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

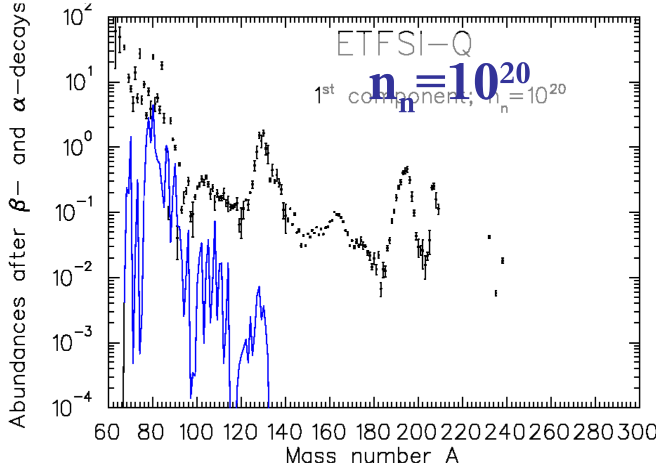
How to predict abundance changes?

- $\dot{Y}(Z,A) = \sum \lambda_{Z',A'} Y_{Z',A'} + \sum \rho N_A < \sigma v >_{Z',A'} Y_{Z',A'} Y_n$ 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

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

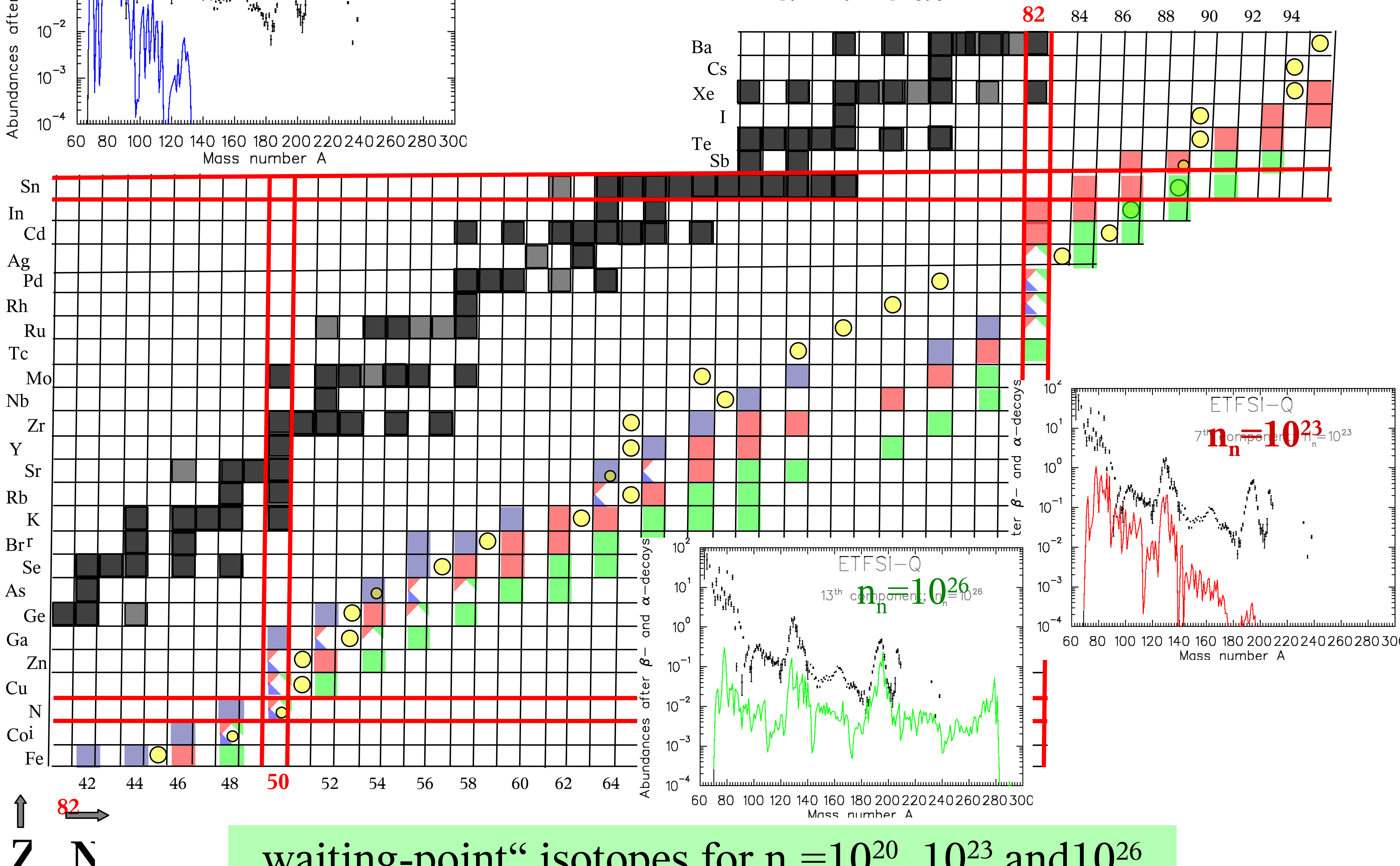
$$\lambda_{\gamma,n}(A+1) = \frac{2G(Z,A)}{G(Z,A+1)} [\frac{A}{A+1}]^{3/2} [\frac{m_u kT}{2\pi\hbar^2}]^{3/2} \langle\sigma v\rangle_{n,\gamma}(A) \exp(-S_n(A+1)/kT)$$

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



r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26} and $T_9=1.35$

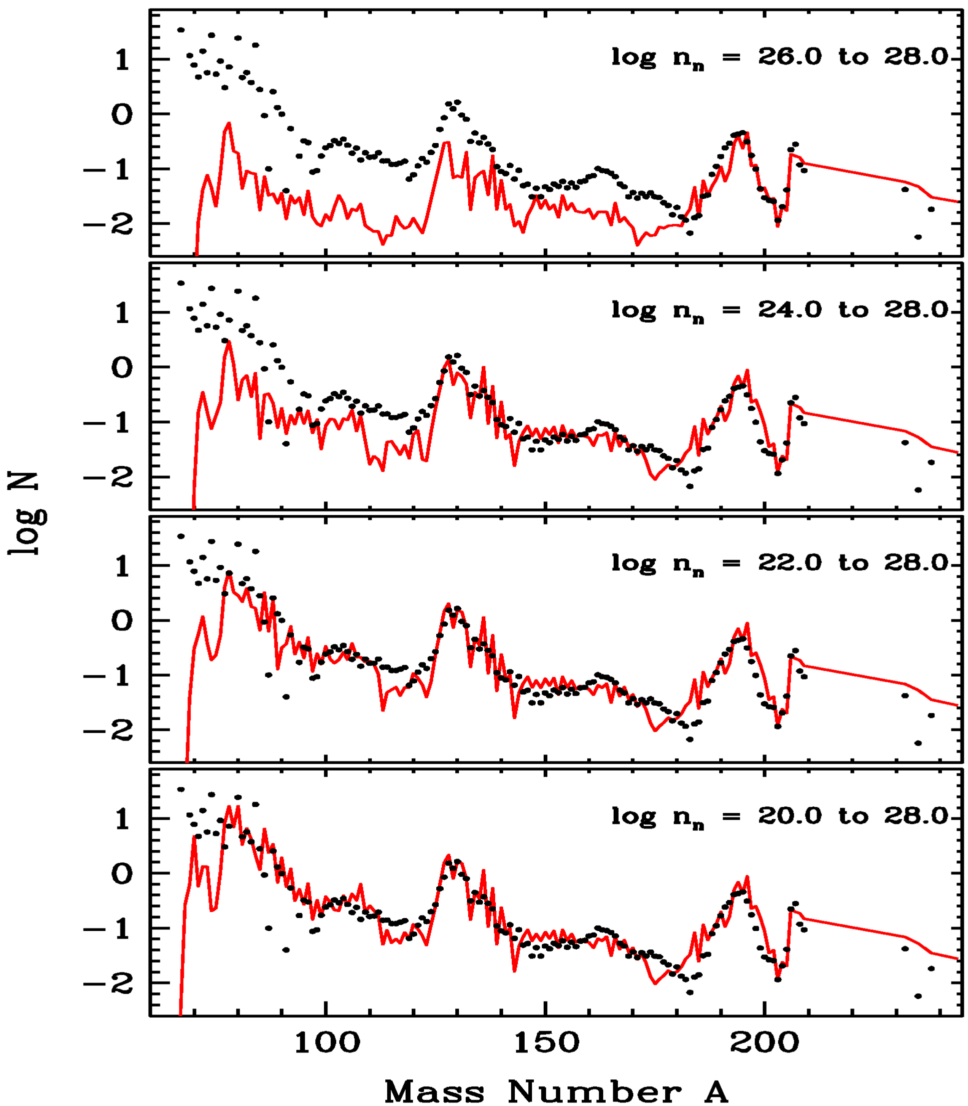
K.-L. Kratz

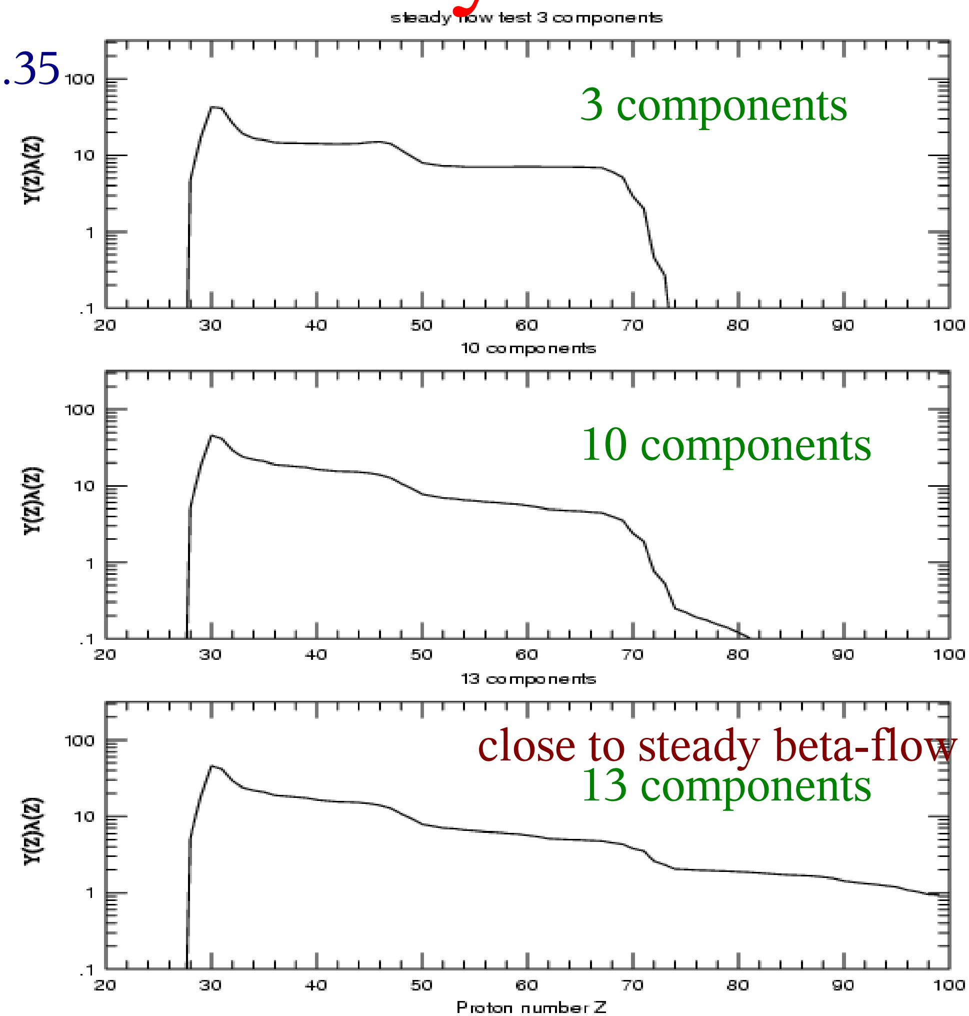


„waiting-point“ isotopes for $n_n=10^{20}$, 10^{23} and10^{26}

Multi-components and steady beta-flow

classical calculation with n_n=const and T_9=const=1.35



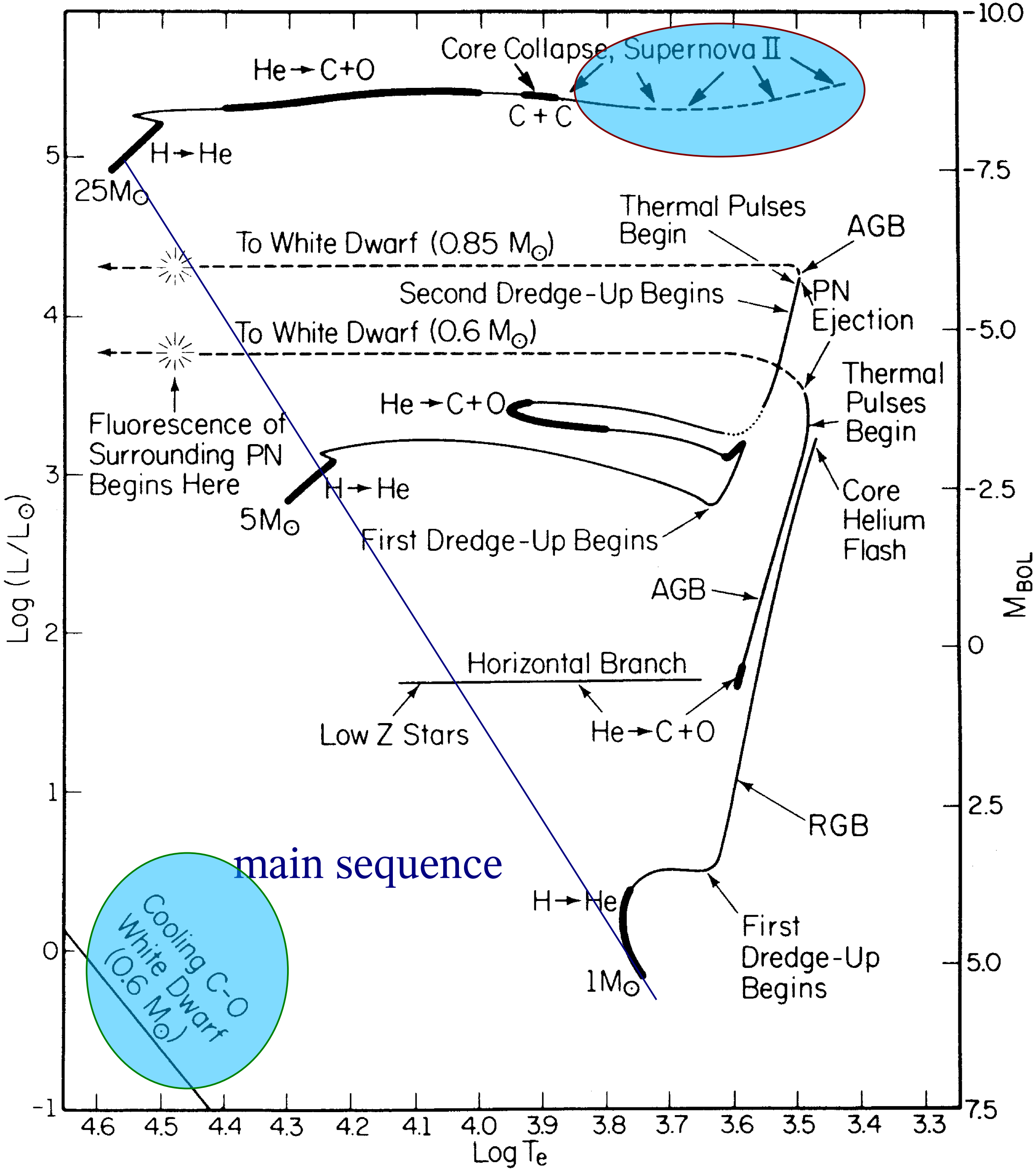


superposition with weights
$w(n_n)=8.36\ 10^6 n_n^{-0.247}$ and $t(n_n)=6.97\ 10^{-2}\ n_n^{0.062}$s

Kratz et al. 1993, Thielemann et al. 1994, Freiburghaus et al. 1999, .. Kratz et al. 2007

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).

Astrophysical Sites



Hertzsprung-Russell Diagram of Stellar Evolution from Iben, showing as end stages

- white dwarfs

and

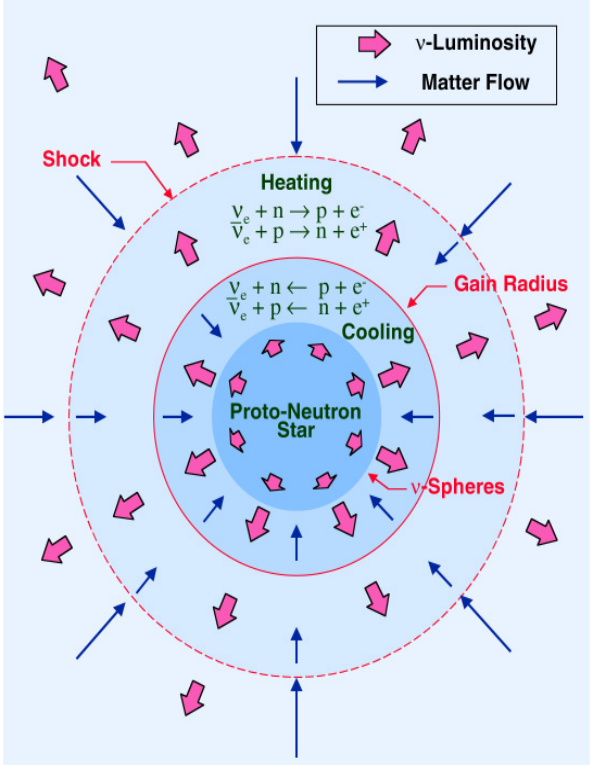
- core collapse (supernovae/neutron stars, black holes, hypernovae, GRBs), pair instability SNe?

influence of reaction cross sections, e-capture in late burning stages, metallicity, rotation, magnetic fields, stellar winds *on final outcome*

Core Collapse Supernovae

- The Supernova Mechanism
- The p-process
- The role of neutrinos (and the explosion mechanism) for the (early) innermost ejecta (the νp-process)
- The late neutrino wind and the r-process
- Alternative scenarios

Neutrino-driven Core Collapse Supernovae



$\nu_e + n \leftrightarrow p + e^-$ heating
$\bar{\nu}_e + p \leftrightarrow n + e^+$

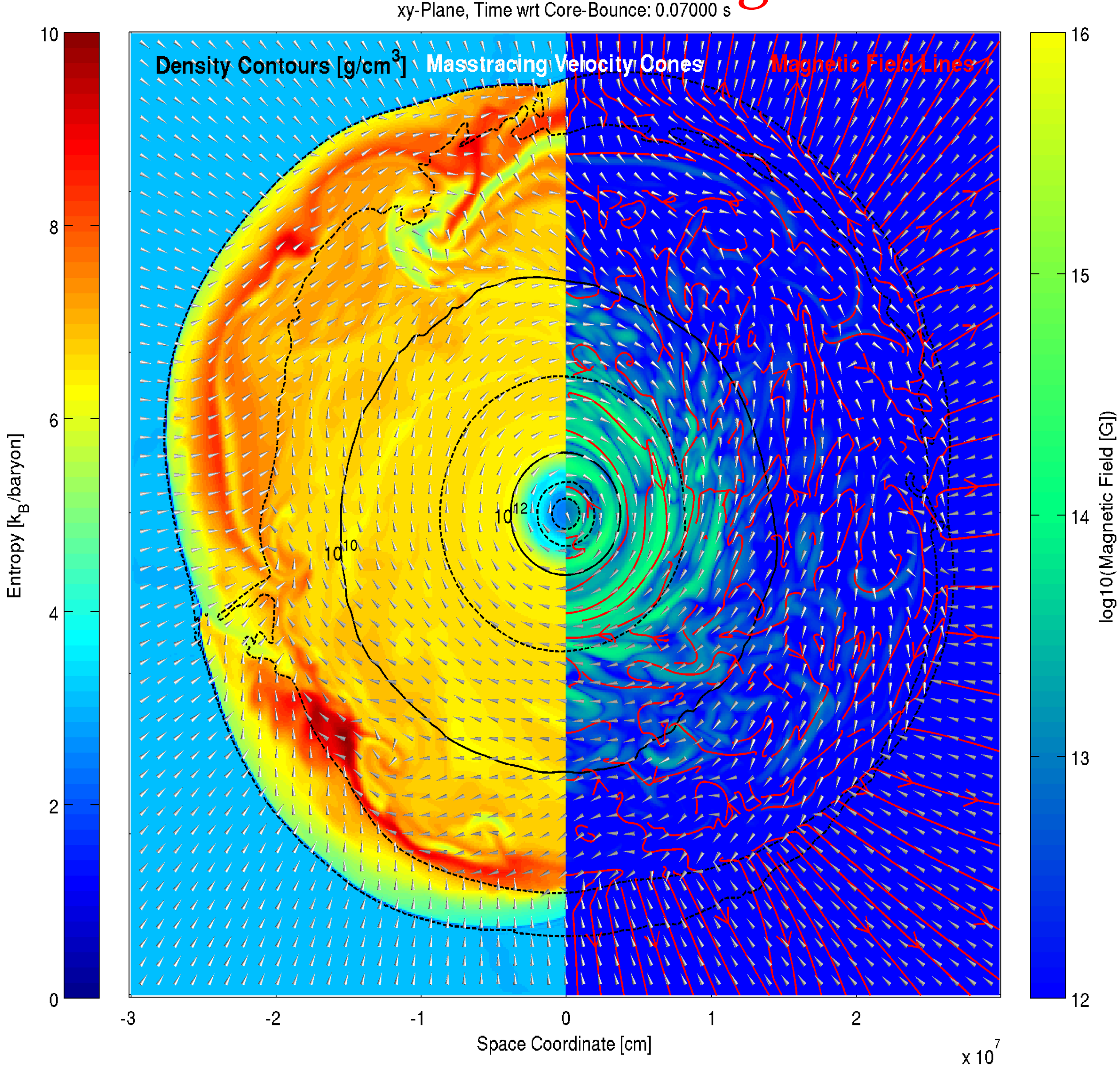
$\nu_e + A' \leftrightarrow A + e^-$ opacity
$\nu + N \leftrightarrow \nu + N$
$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ thermalization
$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\nu = \nu_e, \nu_\mu, \nu_\tau$ source terms
$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

also
$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$
and
$\nu_e + \bar{\nu}_e \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Simulations with Rotation and Magnetic Fields



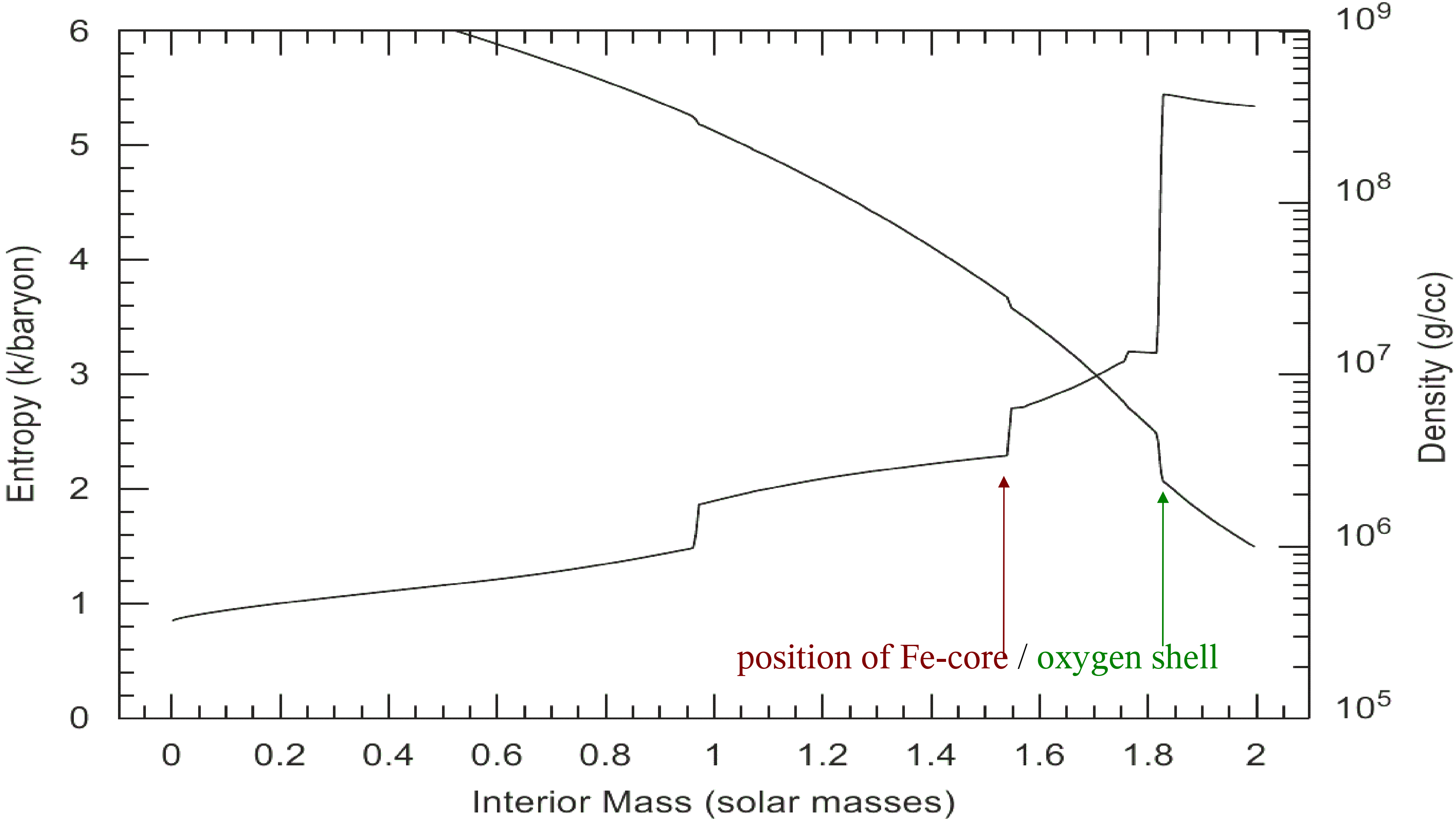
Liebendörfer et al (10) ,Whitehouse et al. (09), see similar 2-3D progress by Janka, Burrows, Mezzacappa groups

entropy and magnetic field strength 0.07s after bounce

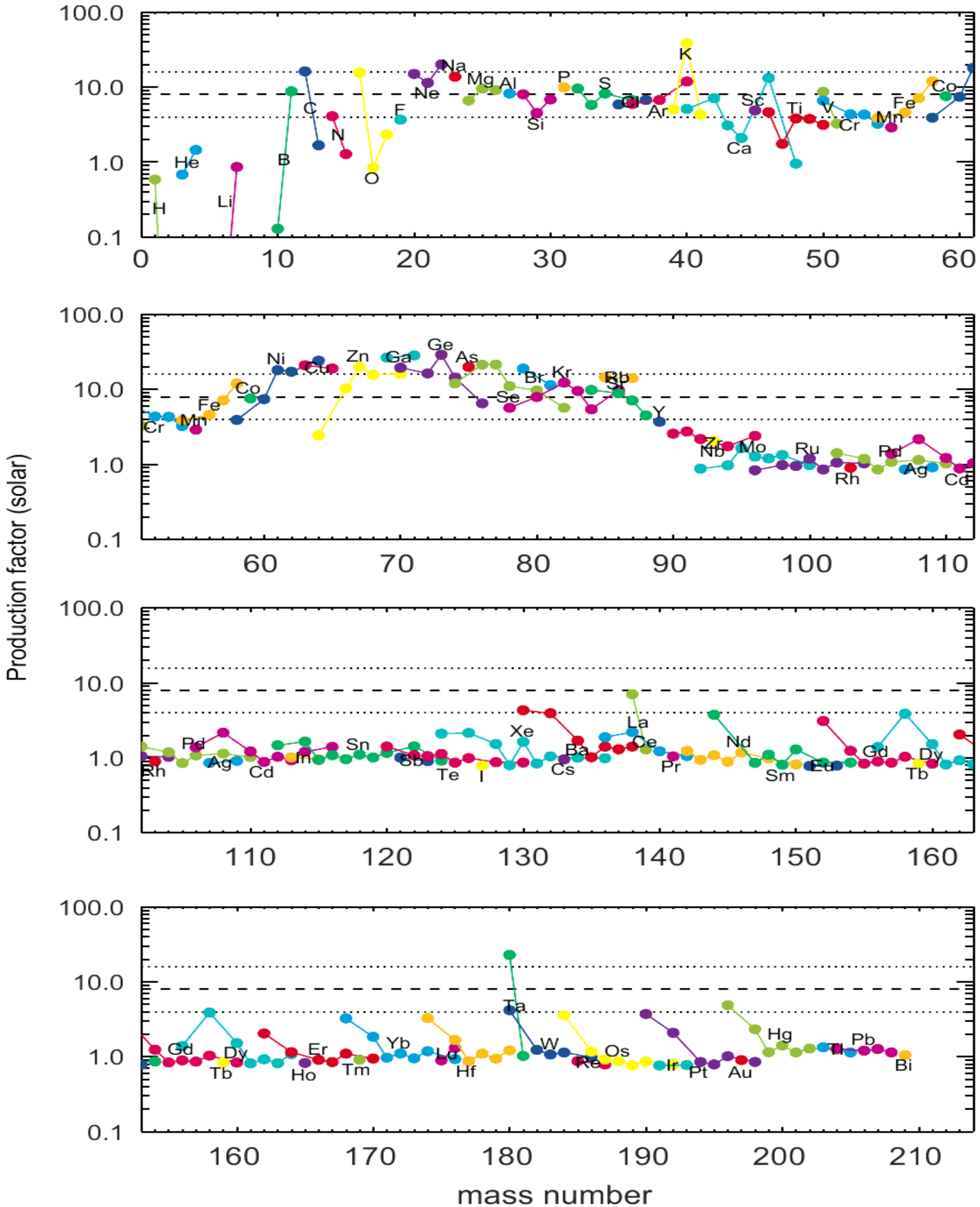
grav. wave signal should be seen with LIGO at 10kpc

full solution of the core collapse SN problem probably includes: 3D, standing accretion shock instability (SASI), accoustic modes, MHD, rotation, collective neutrino flav. oscillations? (Duan et al. 07, Dasgupta et al. 08)

How to invoke induced explosions for nucleosynthesis purposes?



without a self-consistent mechanism nucleosynthesis can only be calculated with induced explosions. Woosley & Heger position a piston with 1.2B at $S=4k_B/b$, Nomoto/Thielemann applied thermal bomb and integrate from outside until expected ^{56}Ni-yield.



Wooley & Heger (2007):

Results for initial solar metallicity, integrated over a Salpeter initial mass function and divided by initial abundances -> overproduction factors.

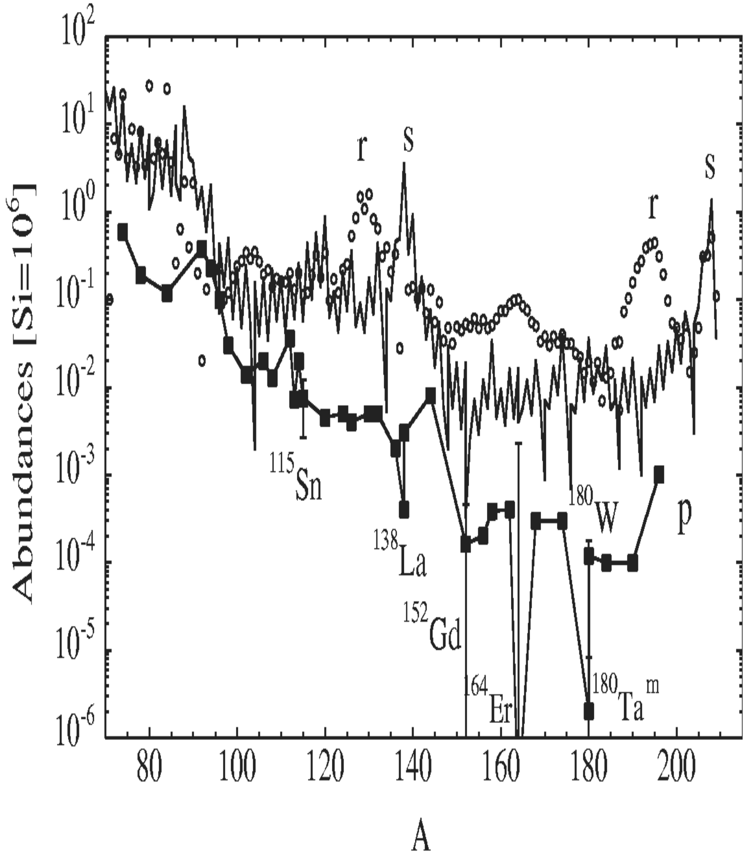
Intermediate mass elements well reproduced, Fe/Ni-group depends on choice of mass cut/location of piston,

well pronounced weak s-process,

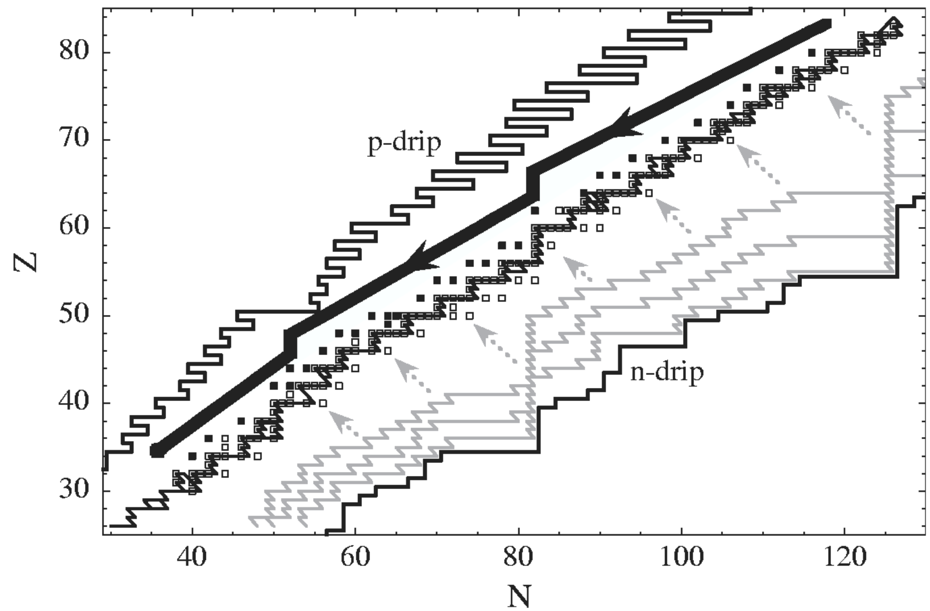
absence of r-process as not included in modeling,

p-process isotopes only well reproduced at high end.

The p-process

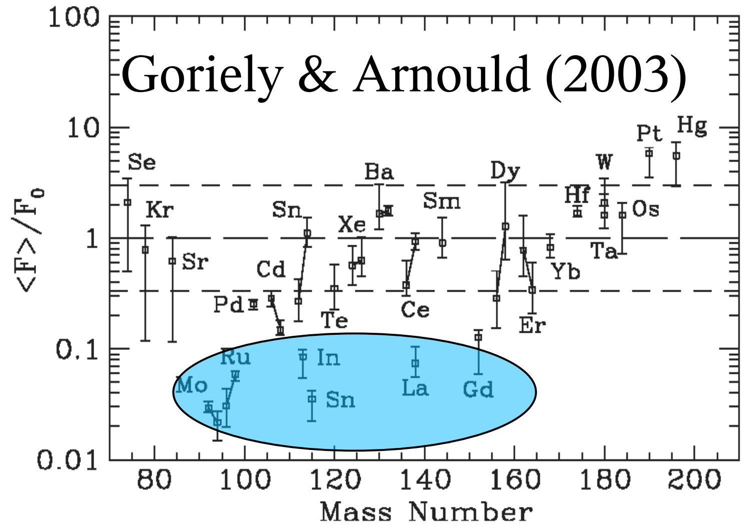


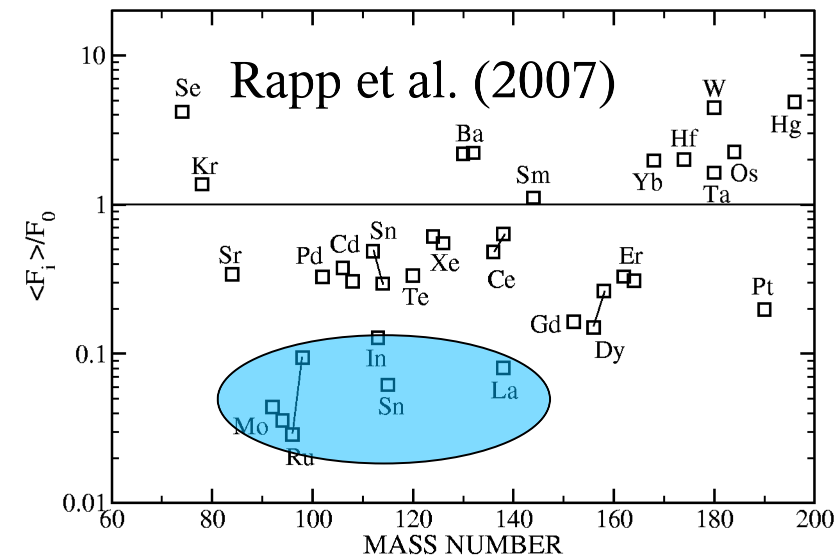
Arnould & Goriely (2003)

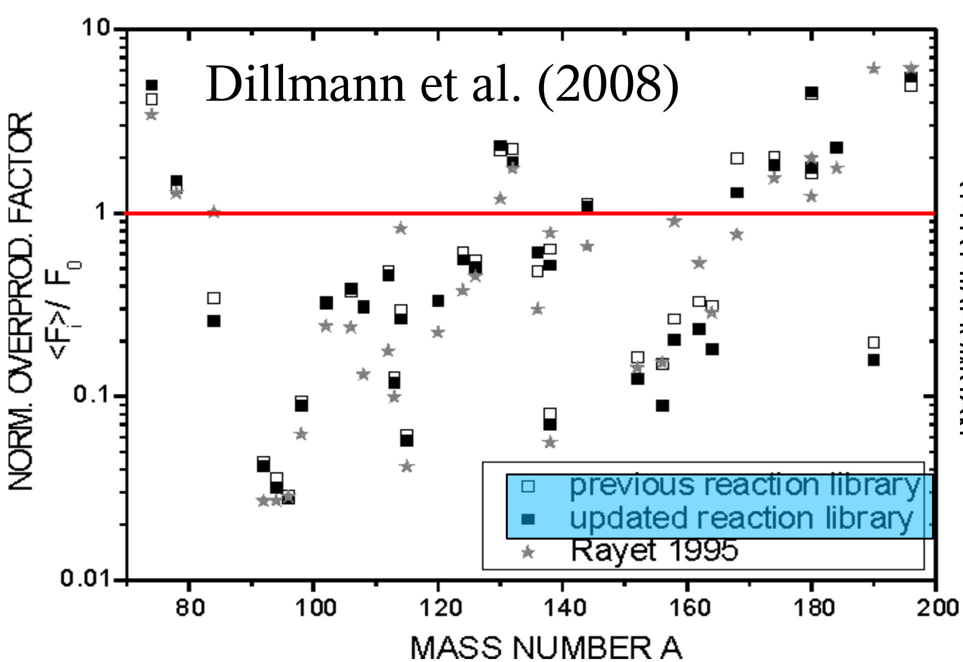


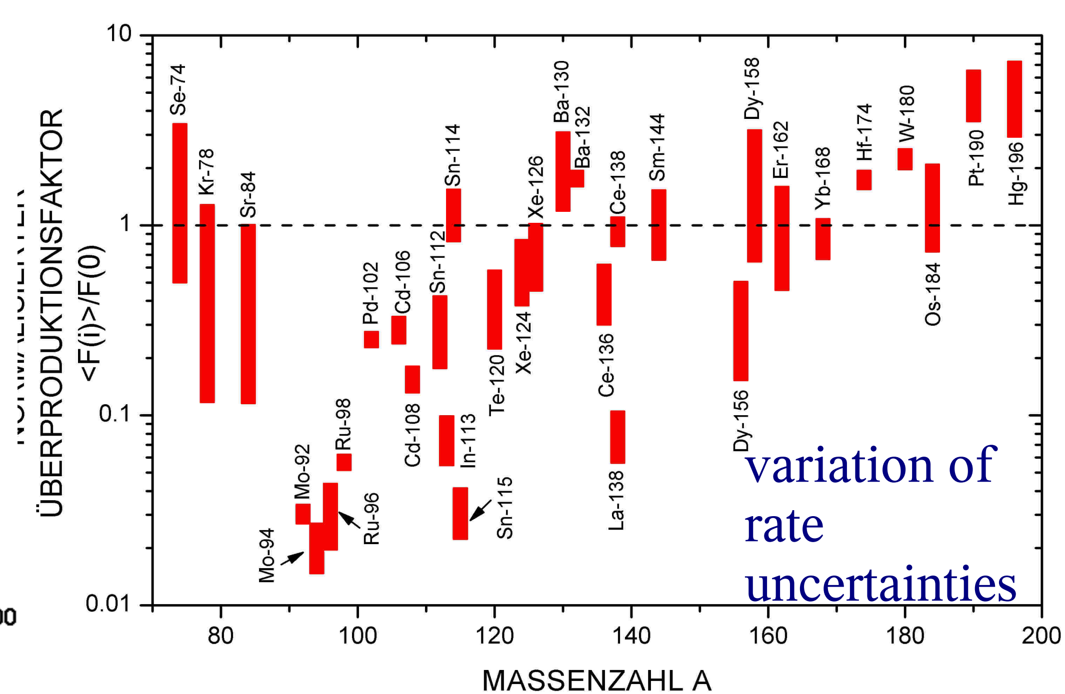
Arnould (1976) and Woosley & Howard (1978) suggested, opposite to initial ideas of B^2FH, photodisintegrations of pre-existing heavy (s-process) nuclei, which occur in the thermal bath of supernova explosions in explosive Ne/O-burning layers with peak temperaturs of 2-3 10^9 K.

Comparison with solar p-only nuclei

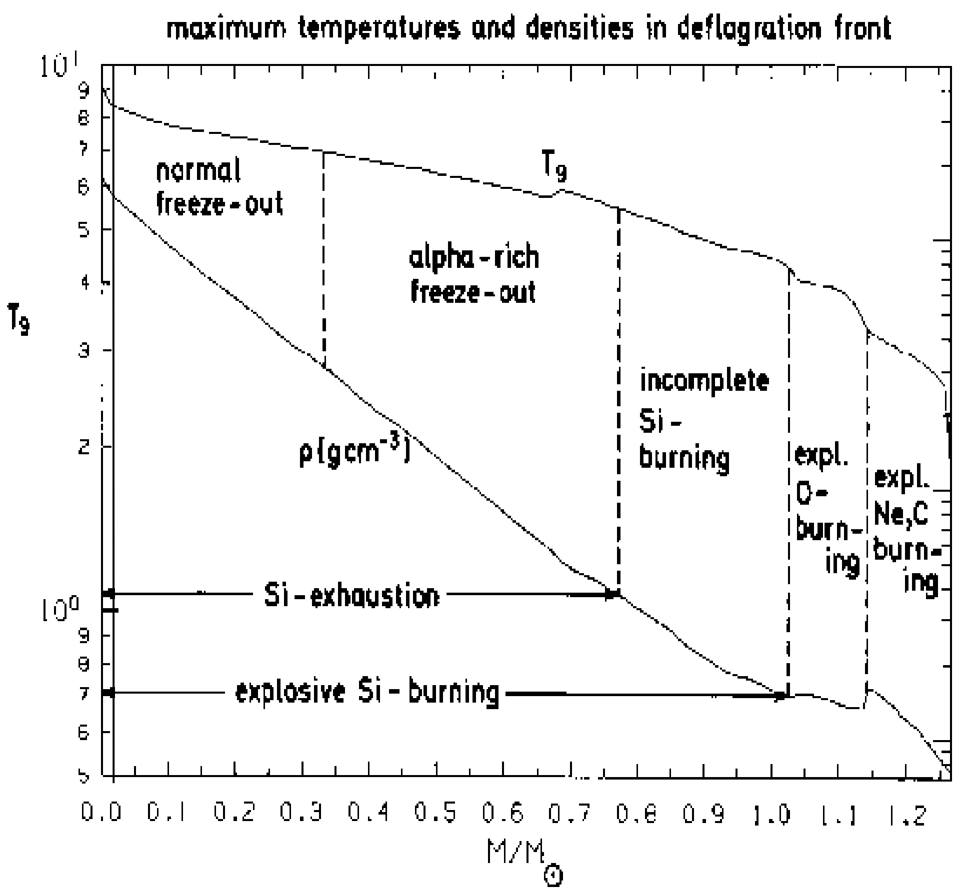


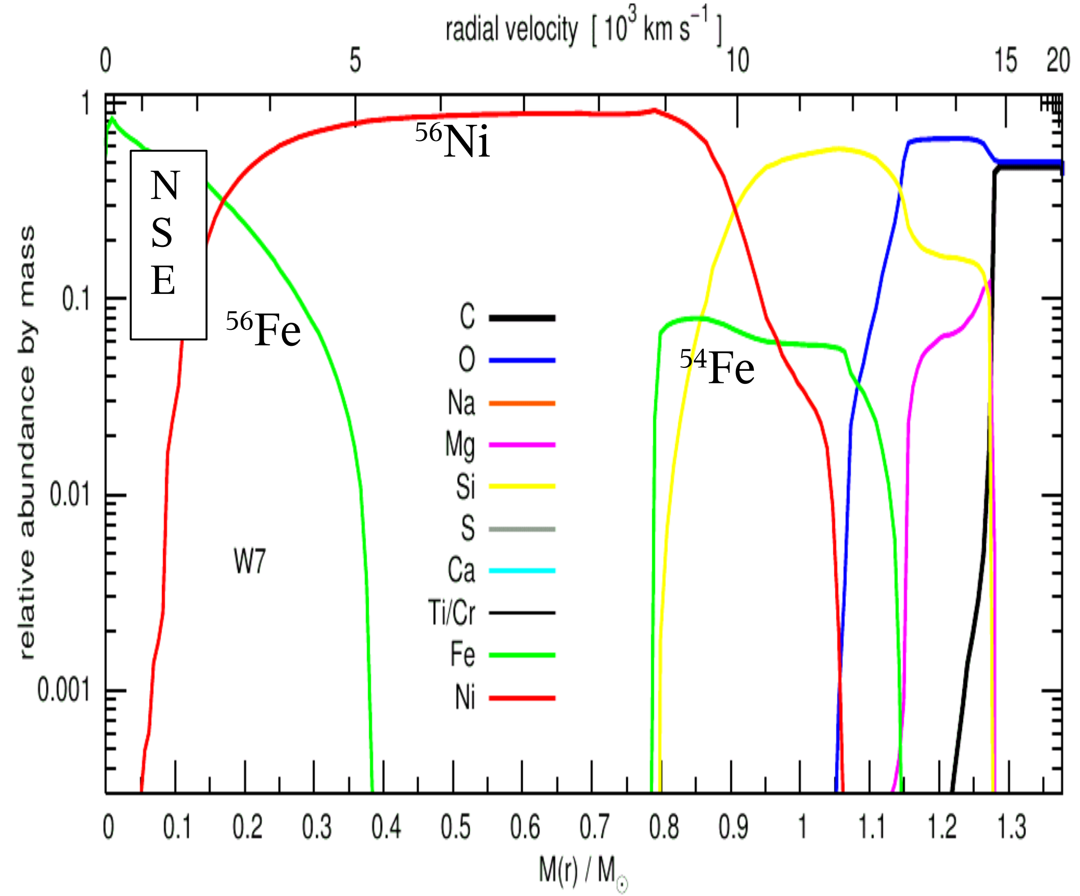






A 1D SN Ia model (W7, Nomoto, Thielemann, Yokoi 1984)





the progenitor started from an accreting 0.6M_{sun} CO-WD in a binary system. Accretion can lead to He-shell flashes like in an AGB star, causing the main s-process to occur. Thus the outer layers, where the explosive O/Ne-burning will take placecan have a composition strongly enhanced in s-process nuclei.

Ideas for solutions

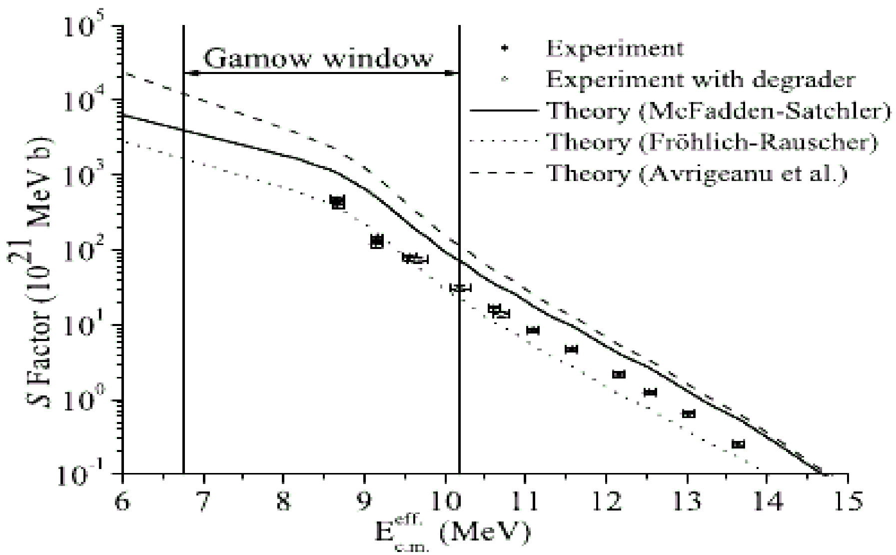


FIG. 3: Measured S factors of ^{113}In(α,γ)^{117}Sb reaction compared to theory using the NON-SMOKER^{WEB} v5.4.2w code [30] with different α+nucleus potentials: by McFadden and Satchler [34], Fröhlich [35, 36], and Avrigeanu et al. [37]. The astrophysically relevant energy range, Gamow window, at 3 GK as an example is also shown.

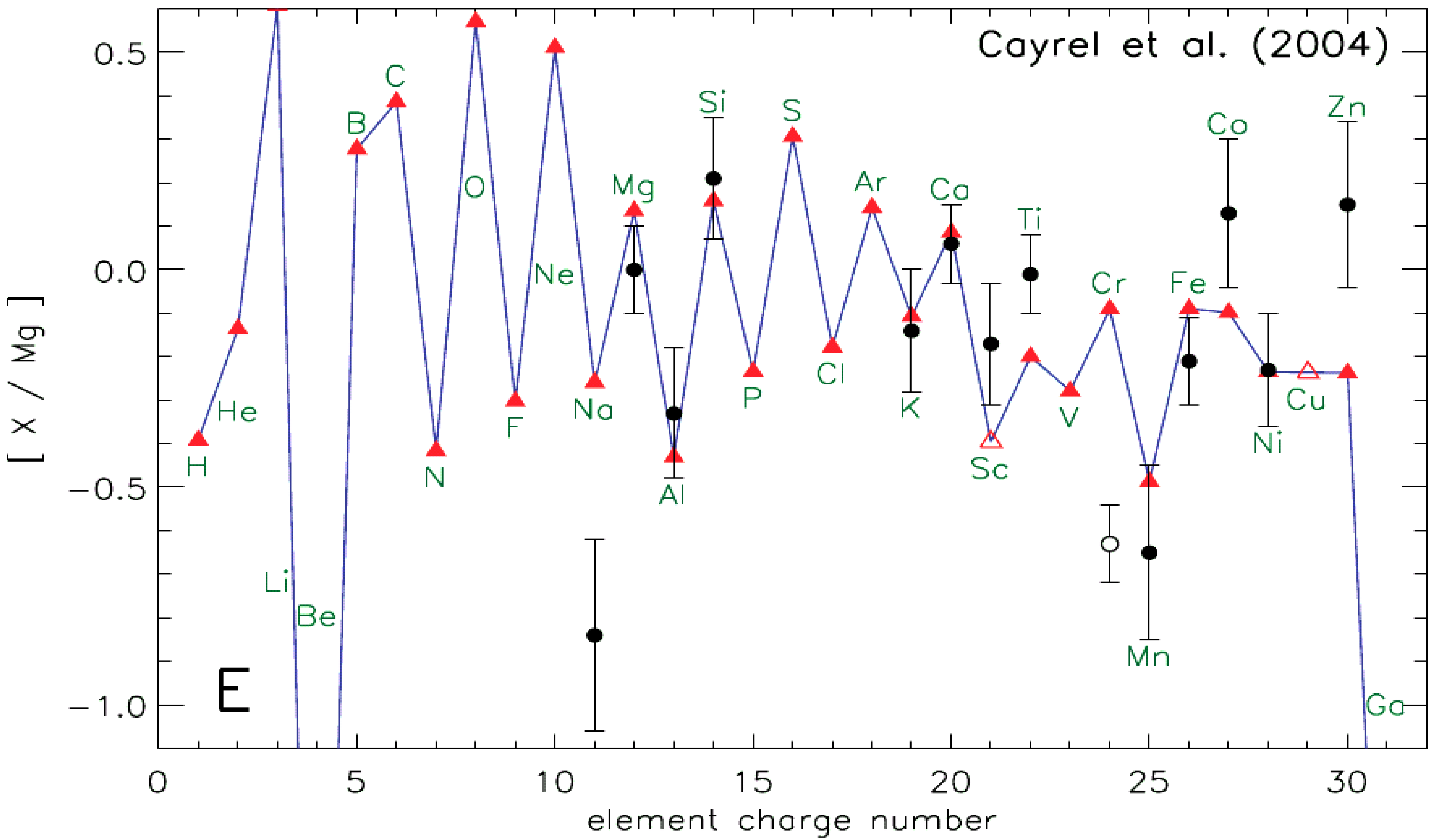
There have been many investigations in p-process related reactions (Gyürky, Hasper, Kiss, Yalcin, Mohr, Sonnabend, Dillmann, Rauscher..) which led to improved understanding of alpha and proton optical potentials, but the problem seems not to be solved by nuclear rate uncertainties. The major difficulty is to produce the low-mass Mo and Ru isotopes, which also have a higher abundance than the typical 1% fraction of p-isotopes for heavier elements.

Possible solutions:

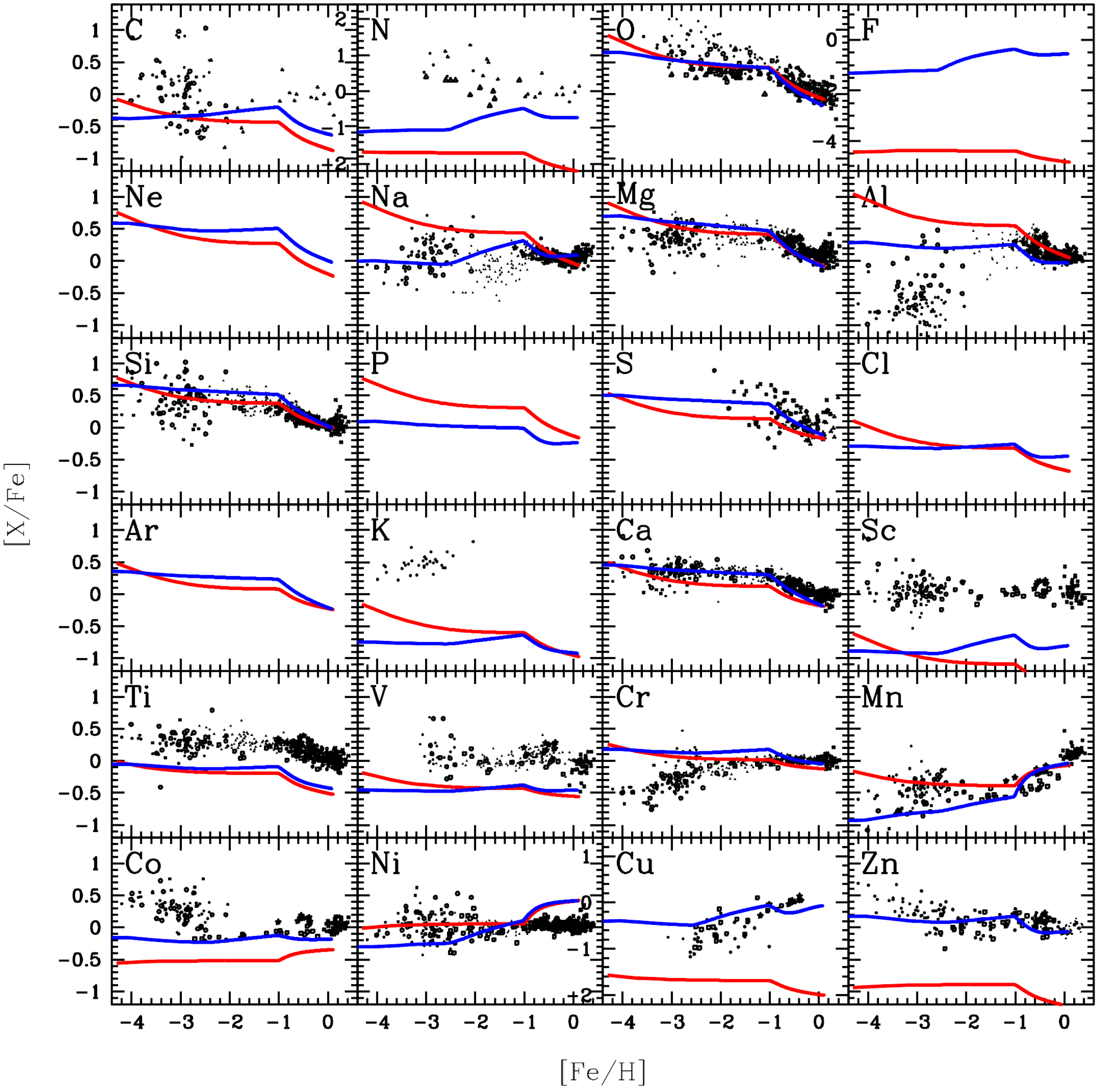
(a) analyze environments which start with a different seed composition being then exposed to the photon flux (e.g. extent of prior s-processing as possibly found in the accreted He-burning layers of SNe Ia, Howard et al. 1991, Kusakabe et al. 2009, Travaglio et al. 2010, but not a solution for LEPP elements at low metallicities!)

(b) invent different environment with capture reactions for light p-isotopes.

Pop III yields (Heger & Woosley 2009)
Evolution of metal-free stars



Cayrel et al. (2004). taken as representative sample for low metallicity stars (representing type II supernova yields). E: "Standard" IMF integration of yields from M = 10 − 100 $M_{\odot}$, explosion energy E = 1.2 B (underproduction of Sc, Ti, Co and Zn).



Nomoto et al. (2006)

chemical evolution with Salpeter IMF

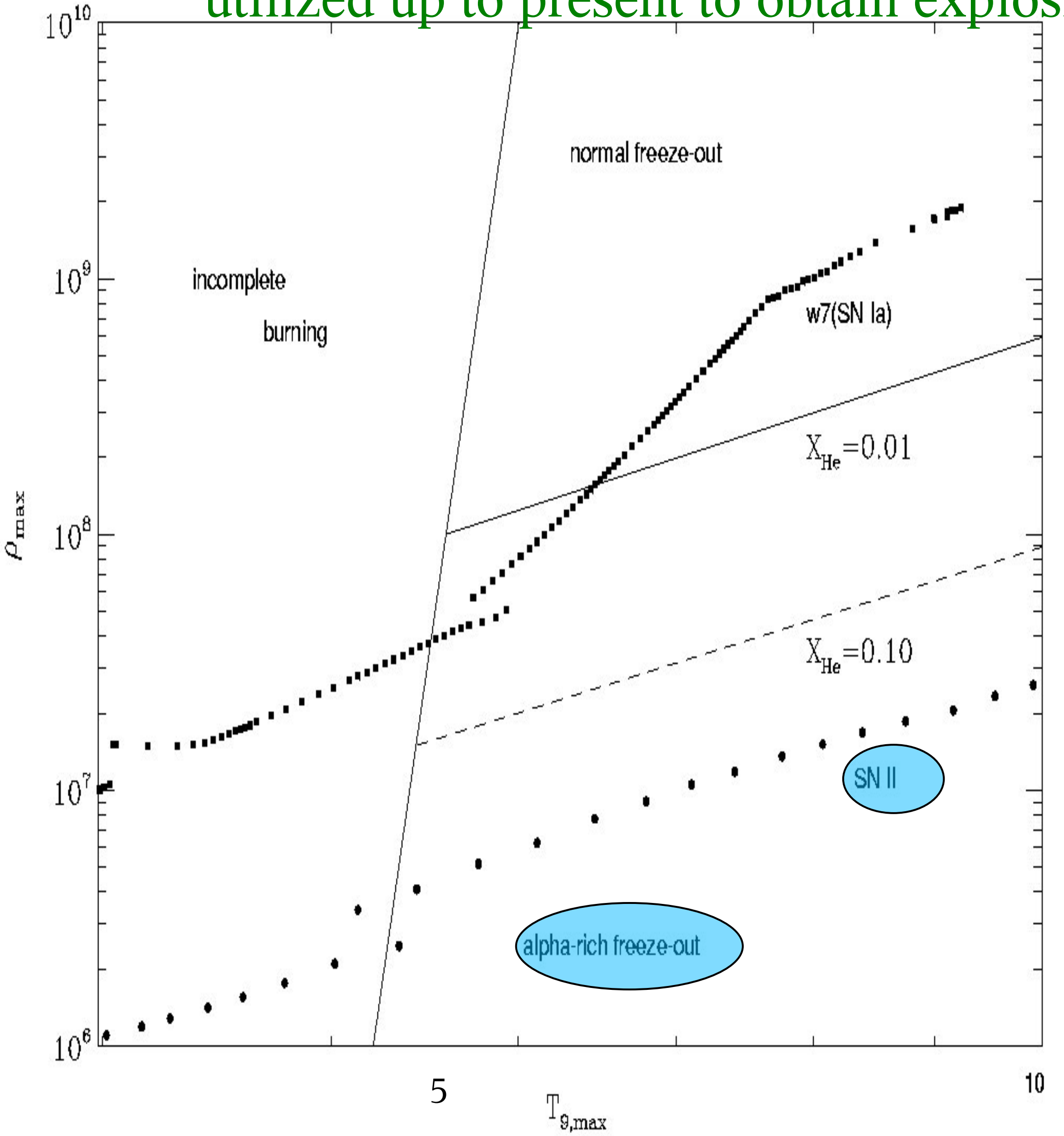
red – regular supernova explosions with 1B

blue – 50% of stars >25M_{sol} are assumed to become hypernovae with an explosion energy of 10B

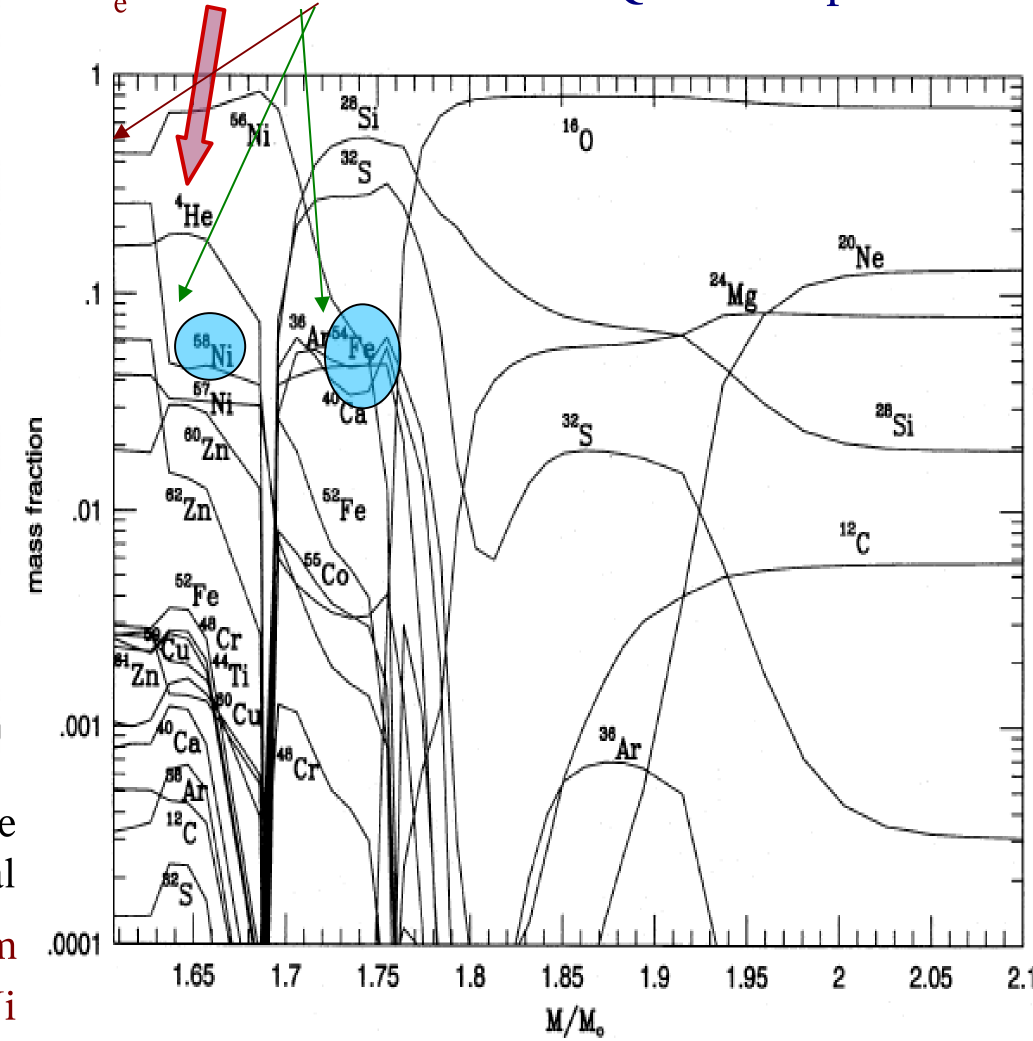
(improves Co, Cu and Zn, but not Sc and Ti, which is needed as well, other explanations?)

Nucleosynthesis problems in "induced" piston or thermal bomb models

utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of 10^{51} erg



disconnected light element (n,p,He) and Si-Fe QSE-cluster, high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe), Y_e determines dominant QSE-isotope.



prior results of Thielemann, Nomoto, Woosley, Chieffi .. made use of initial stellar structure (and Y_e!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni

In exploding models matter in innermost ejected zones becomes proton-rich (Y_e>0.5)

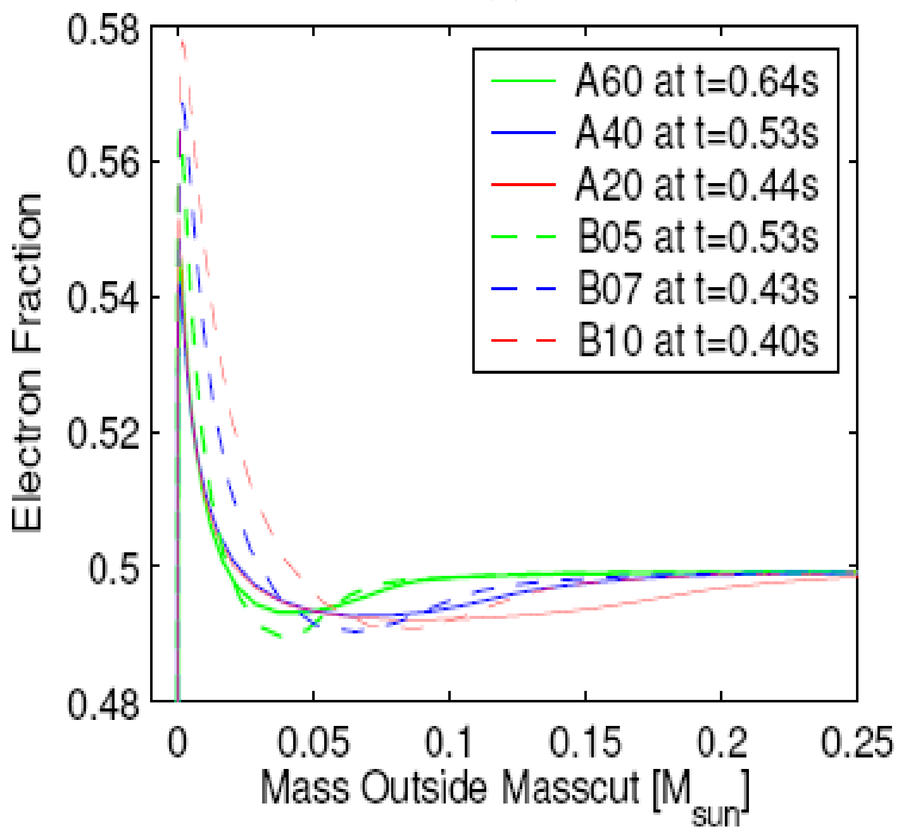
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

Y_e dominantly determined by $e^{\pm}$ and $\nu_e, \bar{\nu}_e$ captures on neutrons and protons

$$\nu_e + n \leftrightarrow p + e^-$$

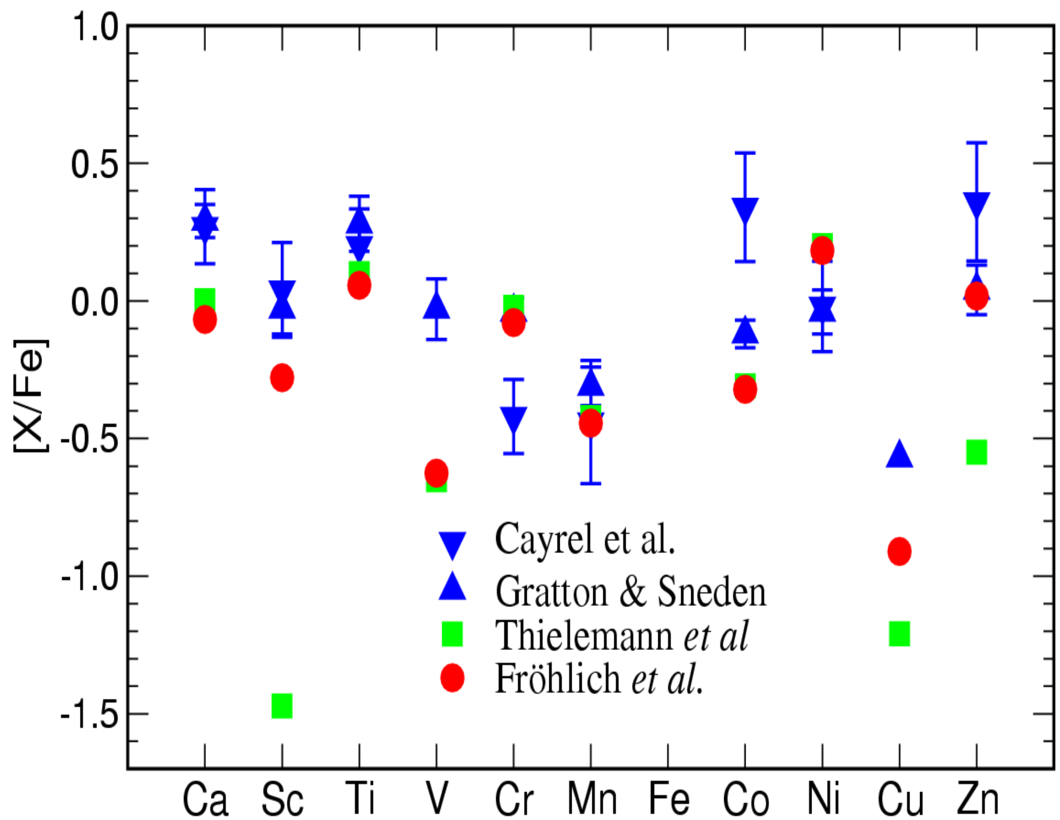
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity → higher luminosity, dominate in neutrino wind → neutron-rich ejecta



Liebendörfer et al. (2003), Fröhlich et al. (2006a), Pruet et al. (2005)

Improved Fe-group composition



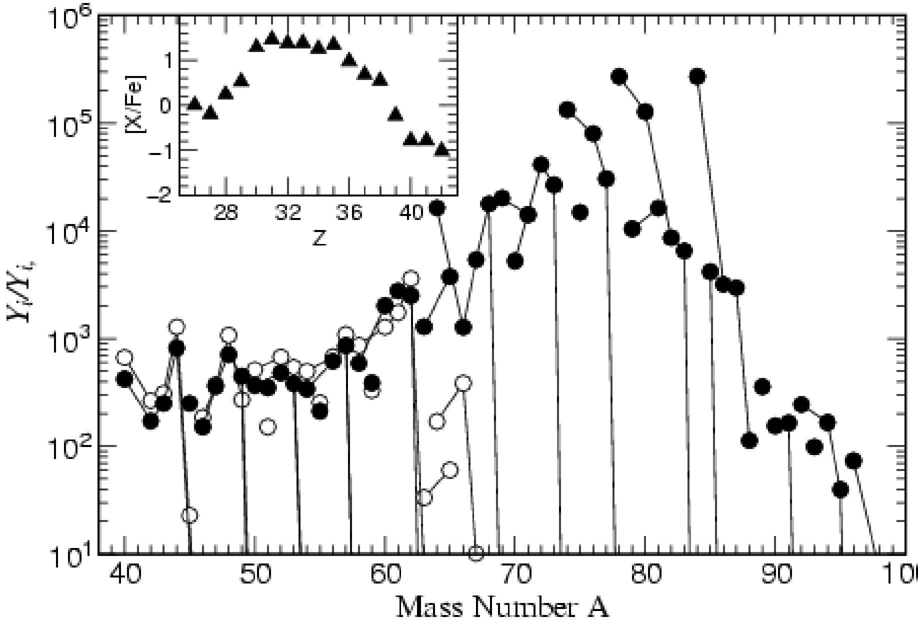
Fröhlich et al. (2004, 2006a), see also Pruet et al. (2005)

Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

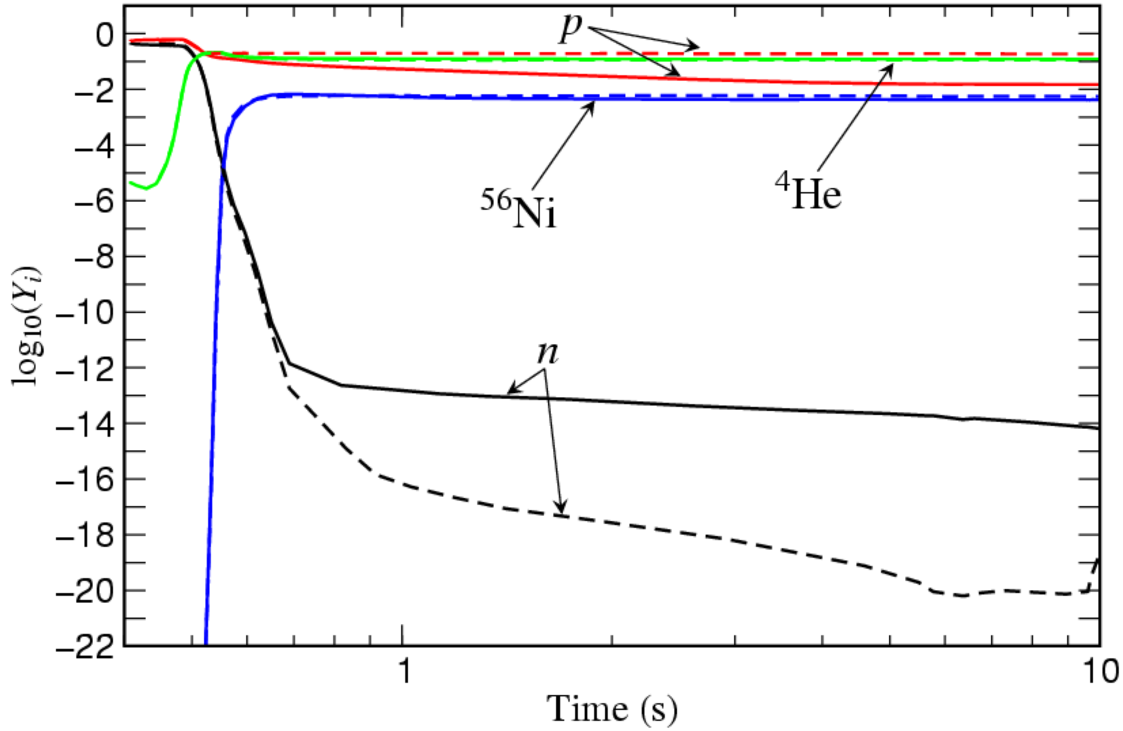
This effect improves the Fe-group composition in general (e.g. Sc) and extends it to Cu and Zn!

νp–process

$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p; \quad {}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge}; \ldots$$



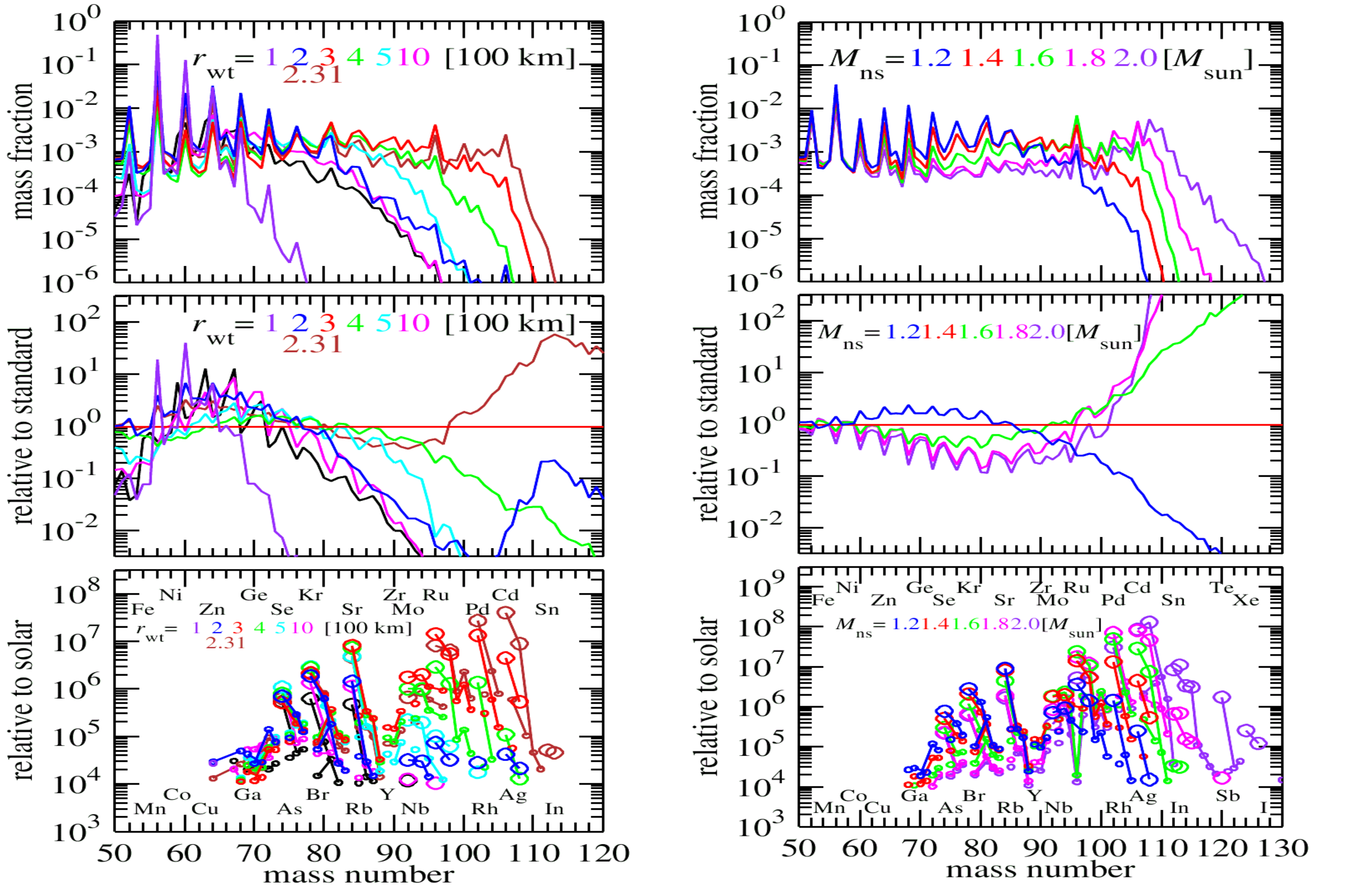
Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei)
see also Pruet et al. (2006), Wanajo (2006)



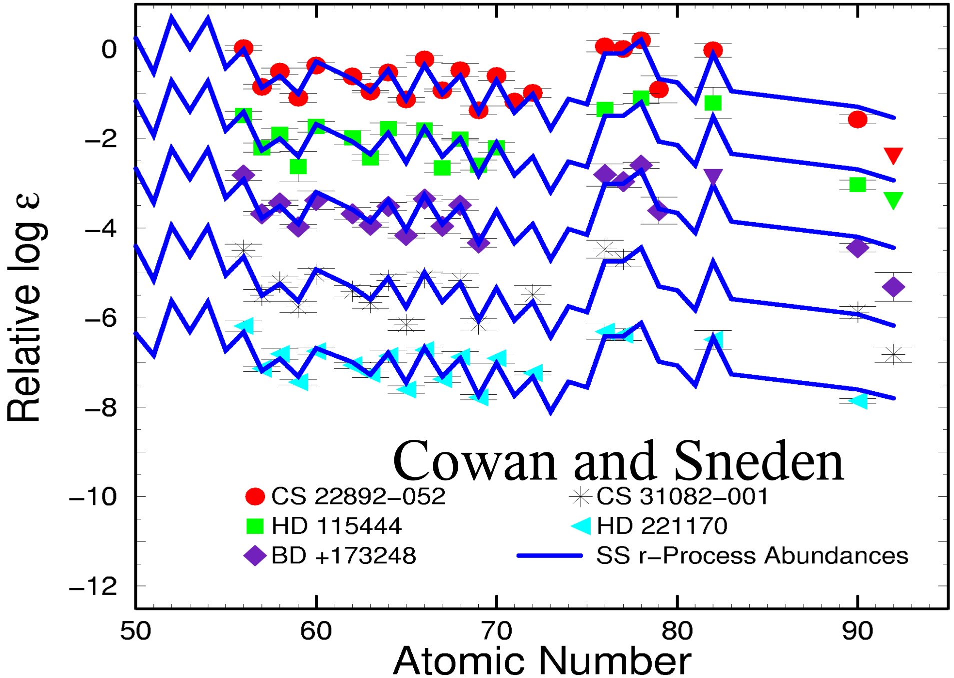
A new process, which could solve some observational problems of Sr, Y, Zr in early galactic evolution and the problem of light p-process nuclei.

Anti-neutrino capture on protons provides always a small background of neutrons which can mimic beta-decay via (n,p)-reactions.

vp-process studies (Wanajo, Janka, Kubono 2010), including different neutron star masses and reverse shock effects/positions

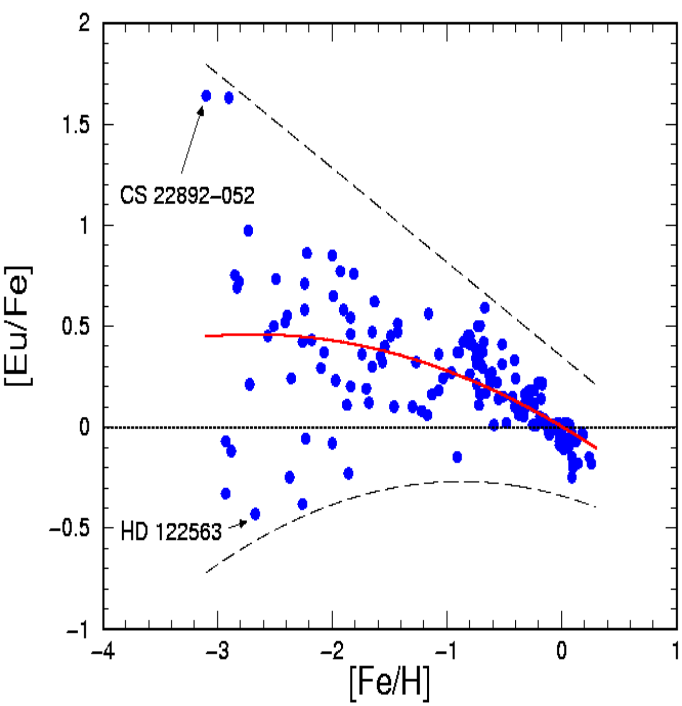


Observational Constraints on r-Process Sites

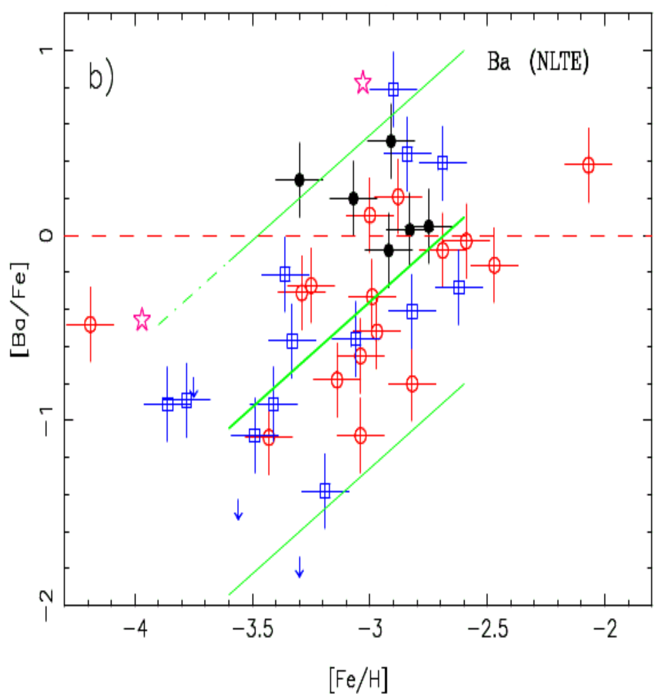


apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event which nevertheless consists of a superposition of ejected mass zones

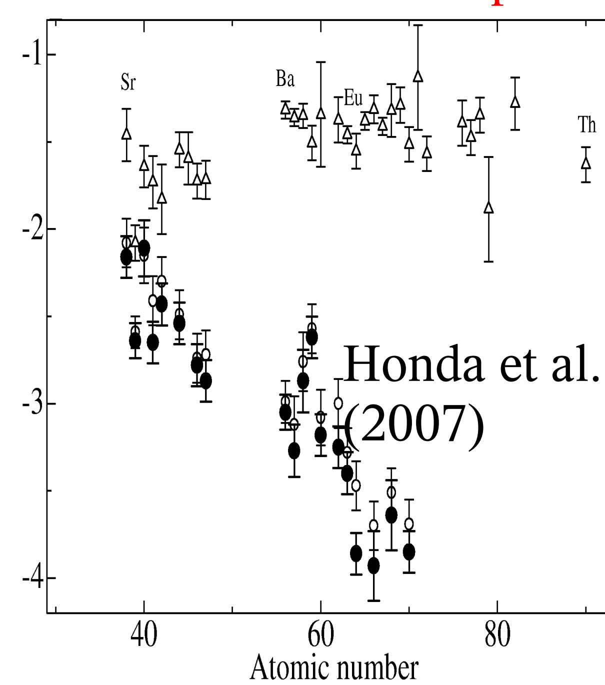
"rare" event, which must be related to massive stars due to "early" appearance at low metallicities (behaves similar to SN II products like O, but with much larger scatter)



Andrievsky et al. (2009)



Observations of the weak r-process?



Working of the r-Process

(complete) Explosive Si-Burning

- 1. (very) high entropy alpha-rich (charged-particle) freeze-out
  with upper equilibrium group extending up to A=80
  - *quasi-equilibria in isotopic chains (chemical quilibrium for neutron captures and photodisintegrations) with maxima at specific neutron separation energies S_n*
  - neutron/seed(A=80) ratio and S_n of r-process path dependent on entropy and Y_e

  high entropy neutrino wind in Core Collapse Supernovae

(many parameter studies: Meyer, Howard, Takahashi, Janka, Hoffman, Qian, Woosley, Freiburghaus, Thielemann, Mathews, Kajino, Wanajo, Otsuki, Terasawa, Mocelj, Farouqi, Kratz, Goriely, Martinez-Pinedo, Arcones, Panov, Petermann ...)

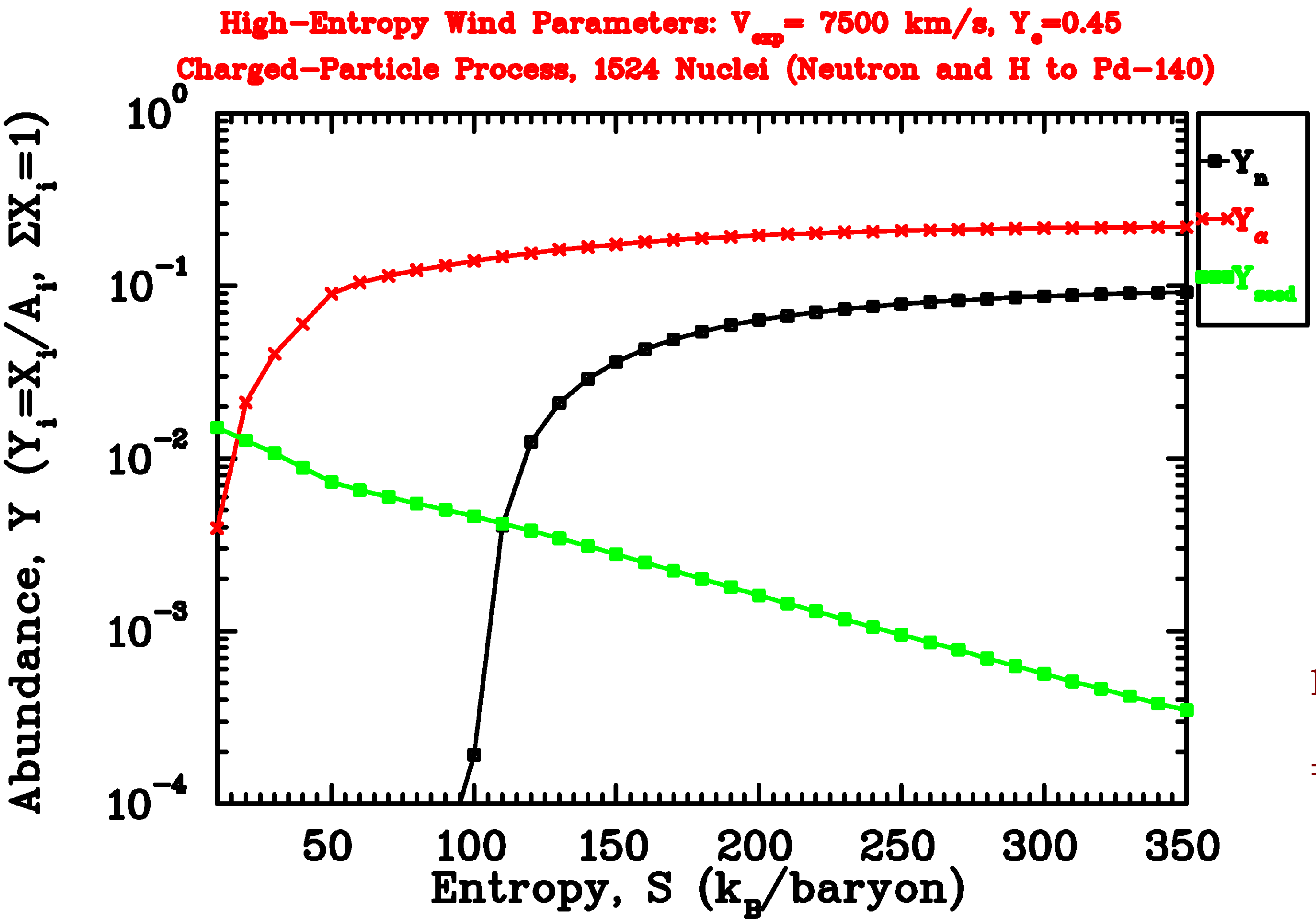
- 2. low entropies and normal freeze-out with very low Y_e ,

from expanding neutron star-like matter
  leading also to large n/seed ratios
  - S_n function of Y_e

  (Freiburghaus, Rosswog,Thielemann, Panov, Goriely, Janka)

neutron stars mergers, jet ejection in (fast) rotating MHD scenarios n/seed ratios for high entropy conditions are are function of entropy

Farouqi et al. (2010)

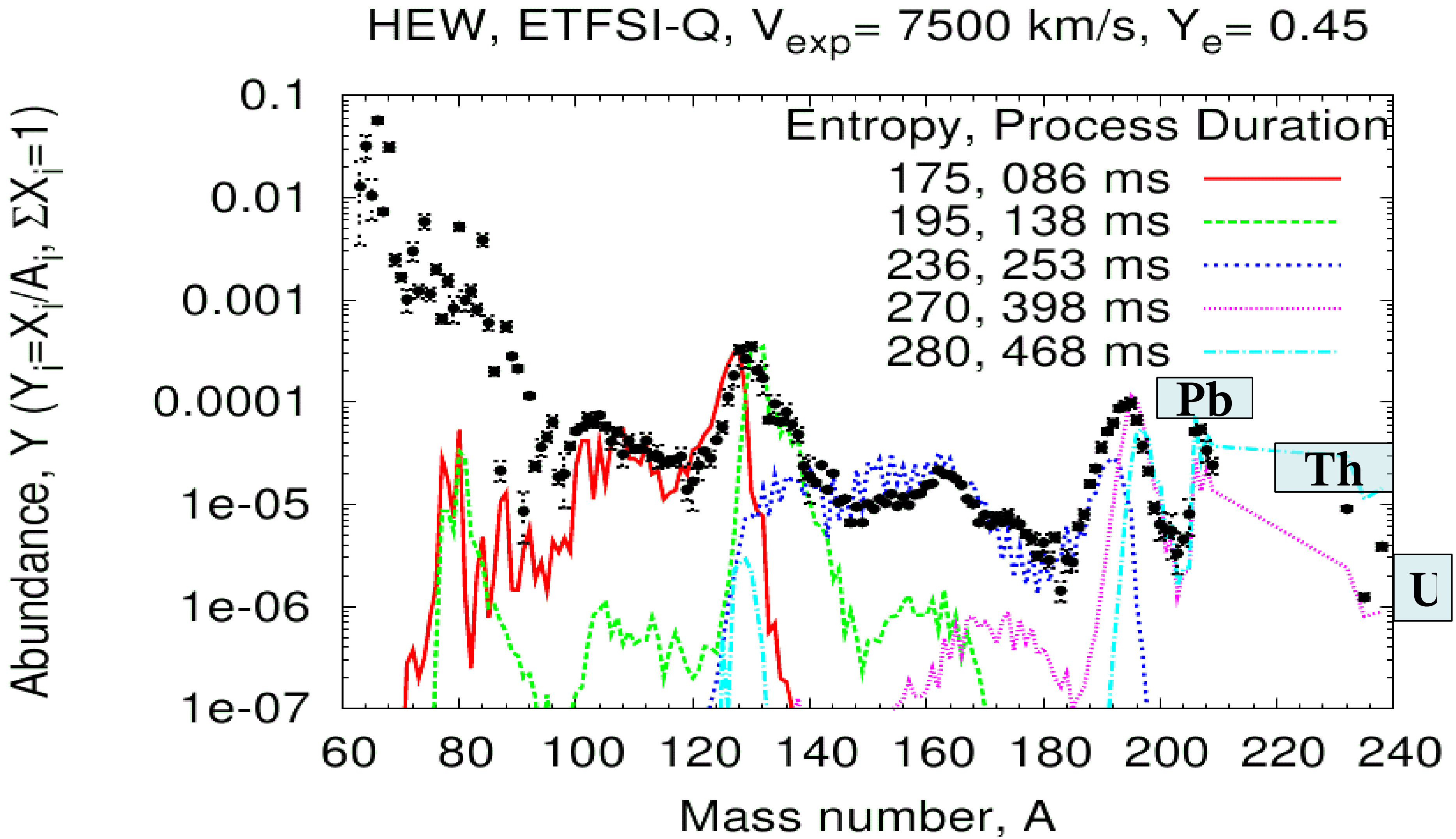


n/seed

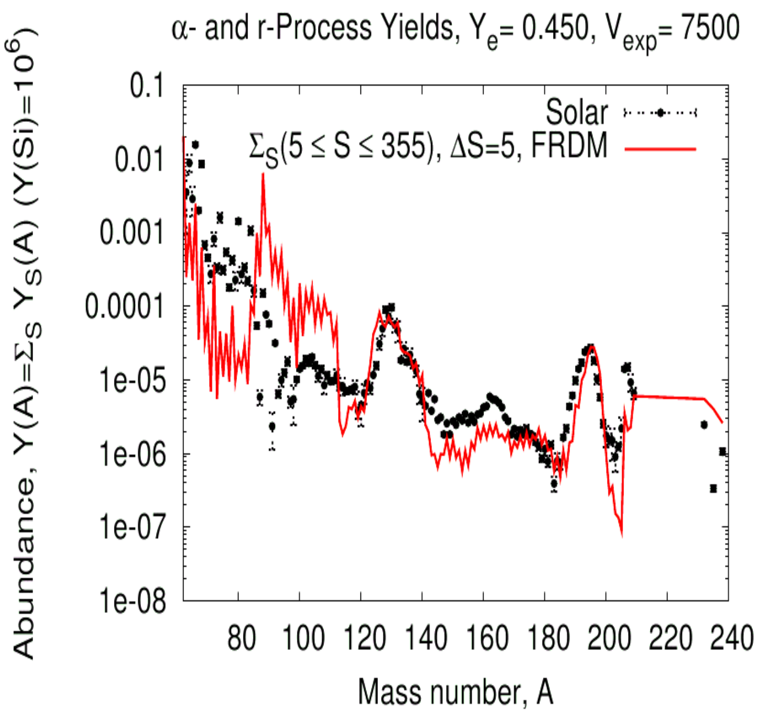
$=Y_n/Y_{seed}$

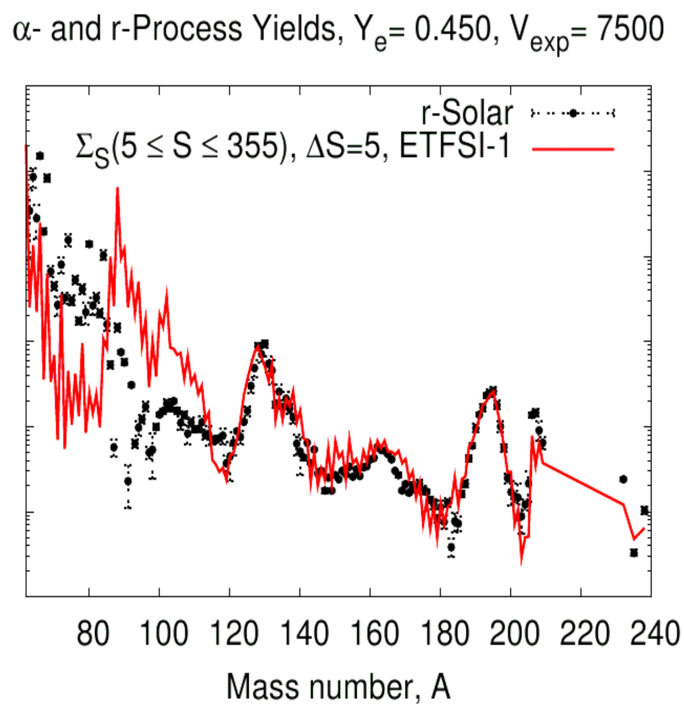
Individual Entropy Components

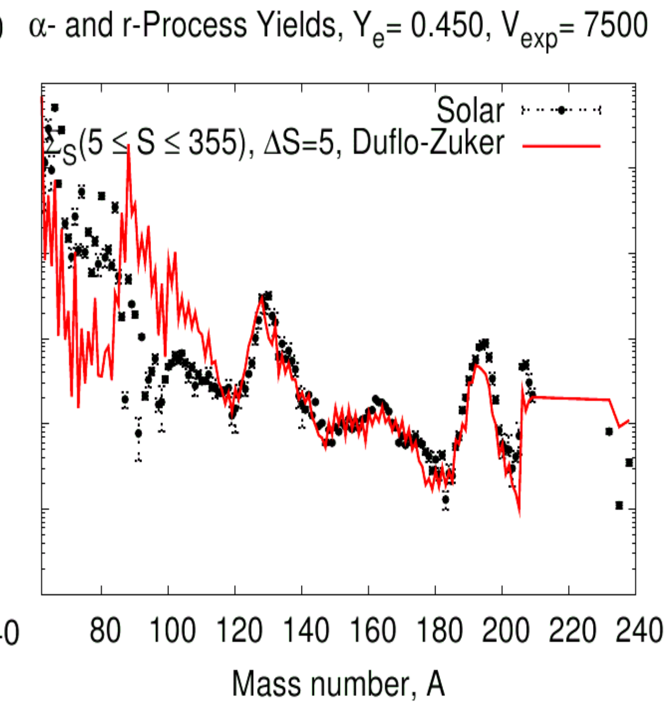
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in

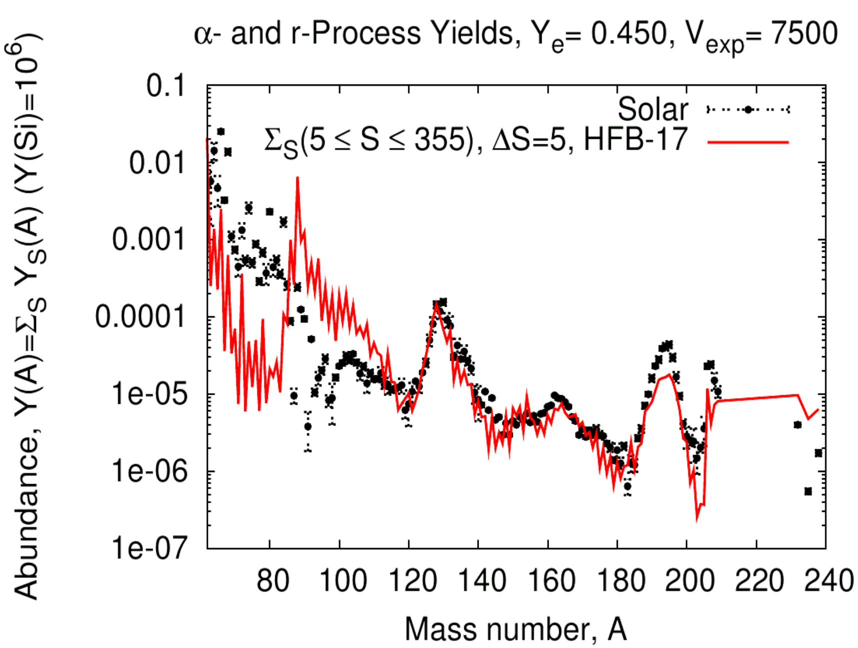


Superposition of entropies for different mass models







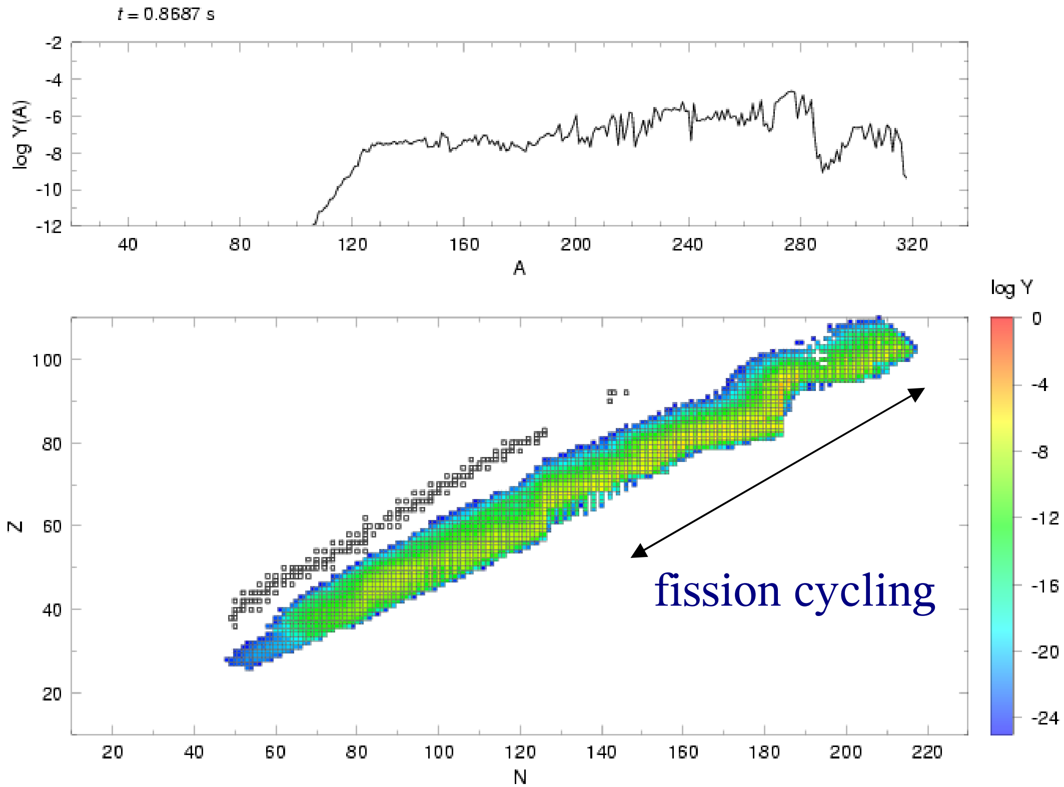


Farouqi et al. (2010)

This is a set of superpositions of entropies with a given expansion speed (or timescale) and Y_e.

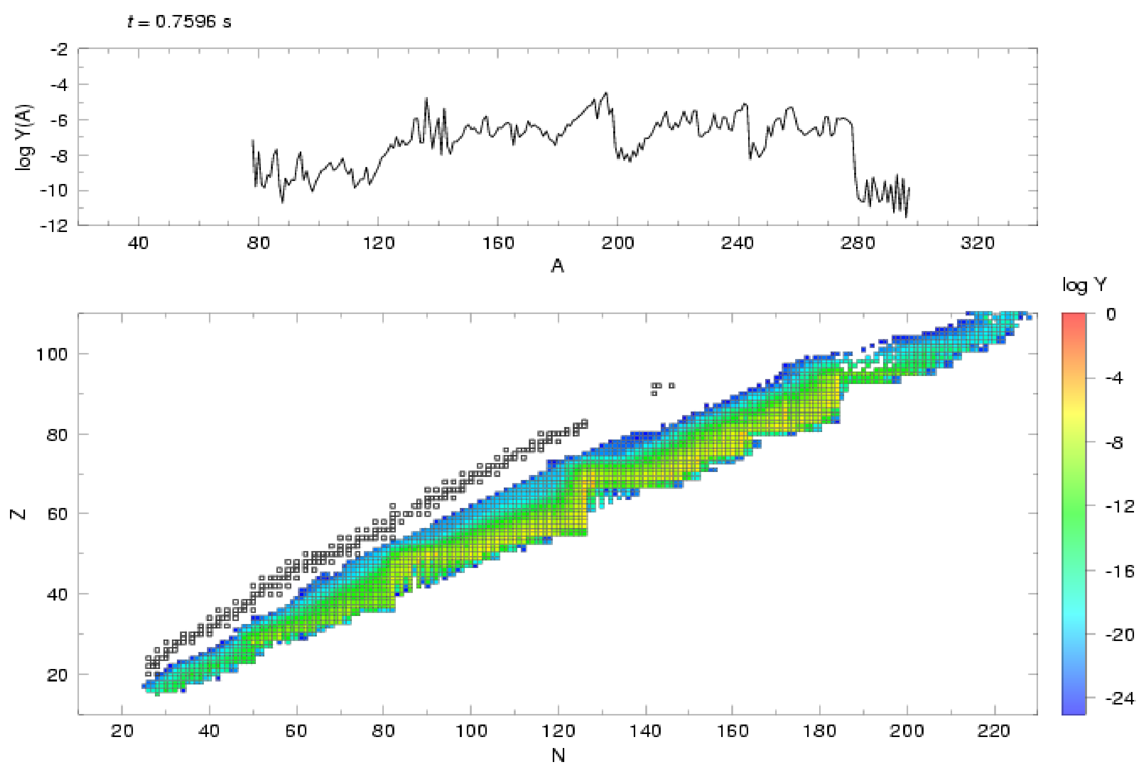
A superposition of expansion velocities might be needed as well, if running into preexpanded material, shocks etc. (Arcones et al. 2007, Panov & Janka 2009, Wanajo 2008). That relates also to the question whether we have a "hot" or "cold" r-process, if chemical equilibria are attained and how long they persist (see also Arcones & Martinez-Pinedo 2010).

Entropies beyond 270 k_B/nucleon



r-process progress

masses: ETFSI
barriers: Mamdouh et al. (2001)



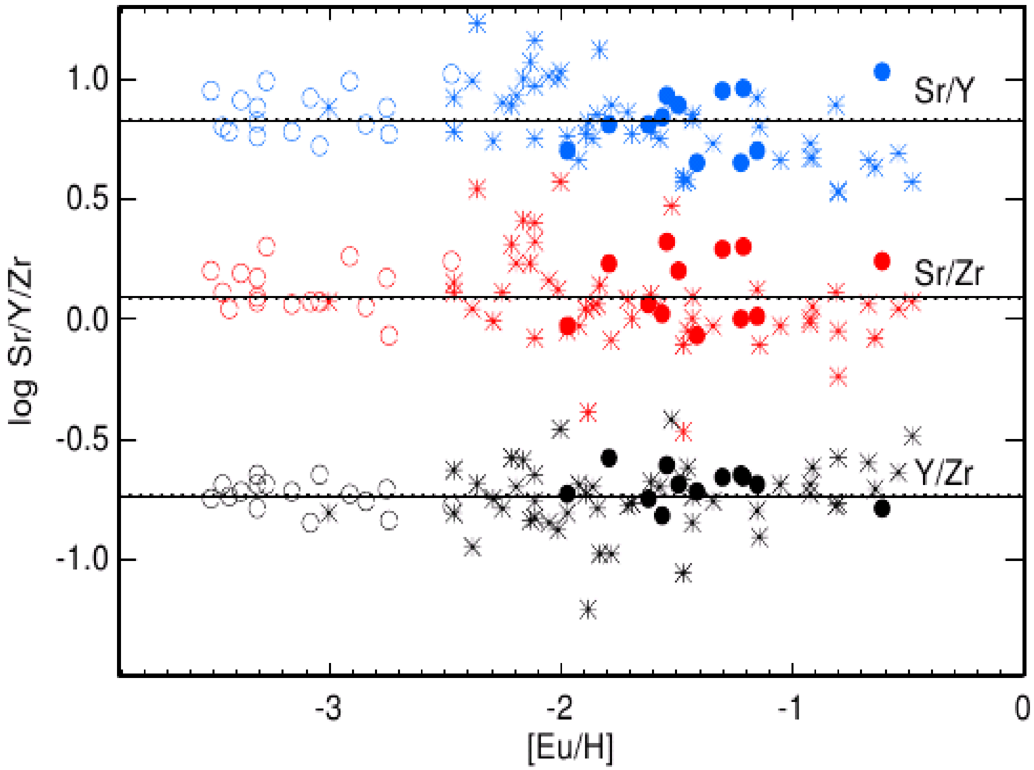
masses: FRDM
barriers: Myers & Swiatecki (99)

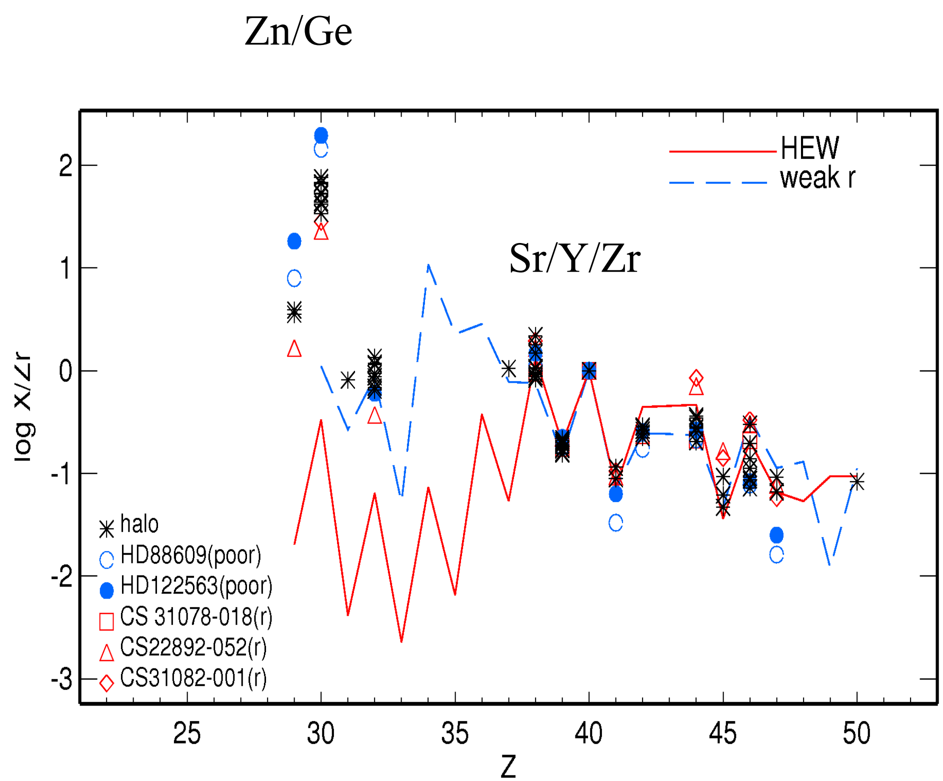
Martinez-Pinedo et al. (2007)

see also Petermann et al. (2010)

and recent (n,f)-predictions by Panov et al (2010)

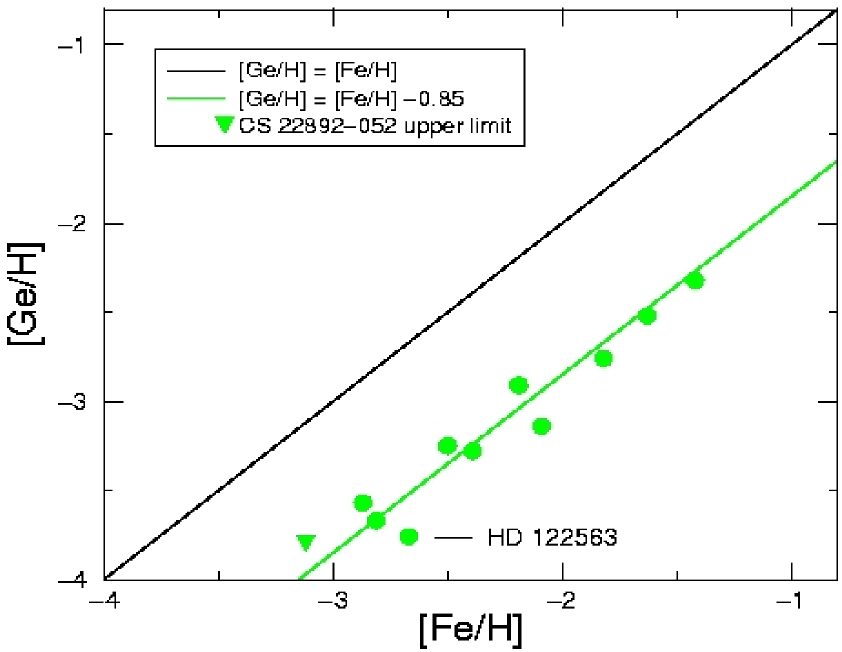
Can Sr/Y/Zr be co-produced with r-process elements in high entropy environments?

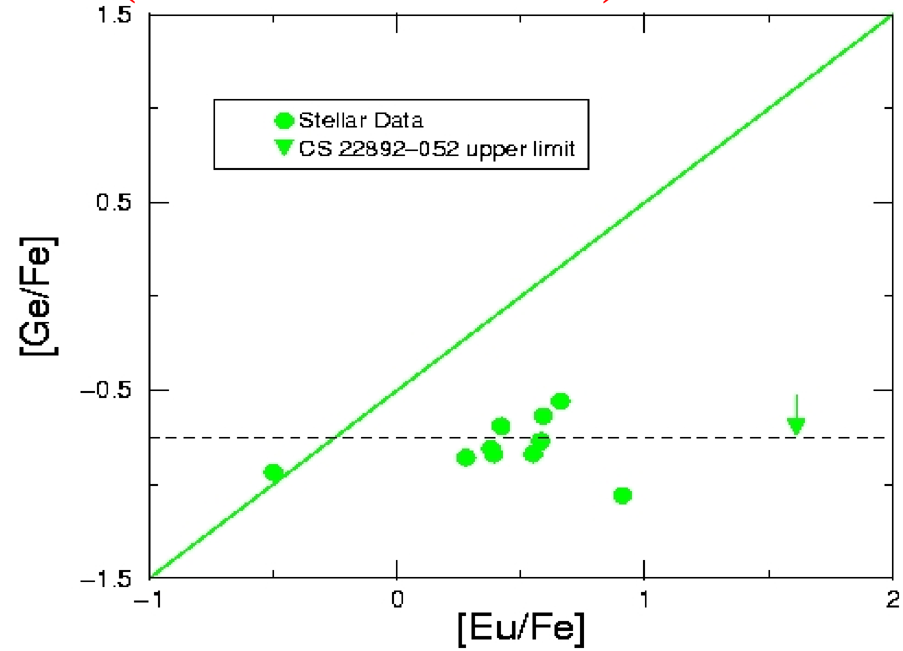




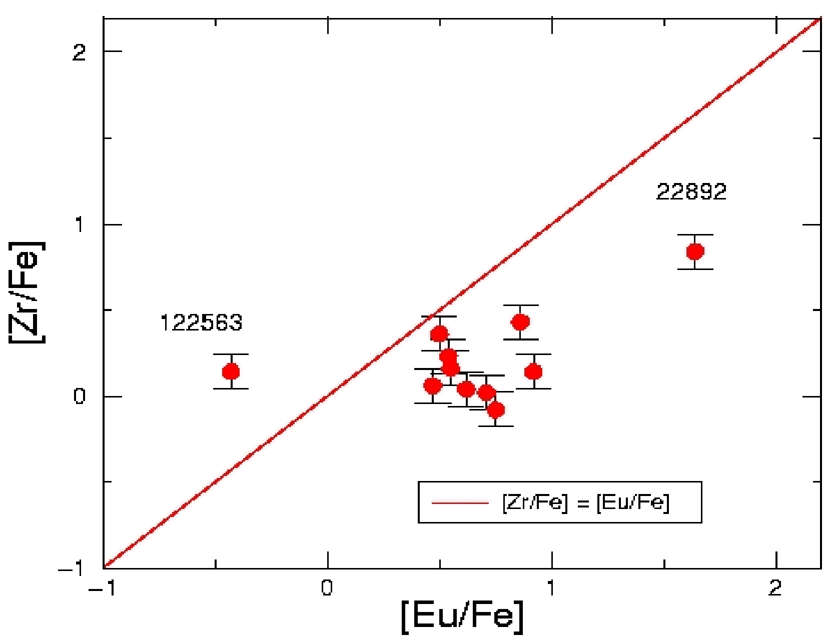
early work of Hoffman et al. (1996) seemed to indicate that such ratios are highly Ye-dependent (for low entropies S<50). It turns out that for reasonably high entropies the observed ratios can reproduced by integrating over entropies and Ye's (Farouqi et al. 2009, Arcones & Montes 2010, Wanajo et al. 2010)

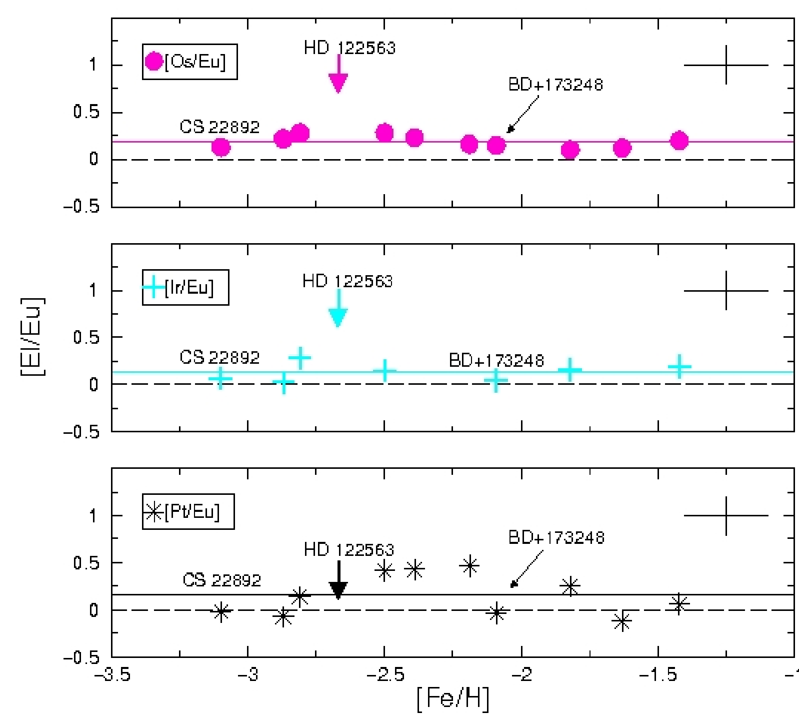
Observational indications: heavy r-process and Fe-group uncorrelated, Ge member of Fe group, Zr intermediate behavior, weak correlations with Fe-group as well the heavy r-elements (Cowan et al. 2005)





Zr vs. Eu





Y_e and the neutrino wind

Y_e dominantly determined by $e^{\pm}$ and ν_e, $\bar{\nu}_e$ captures on neutrons and protons

$$\nu_e + n \leftrightarrow p + e^-$$

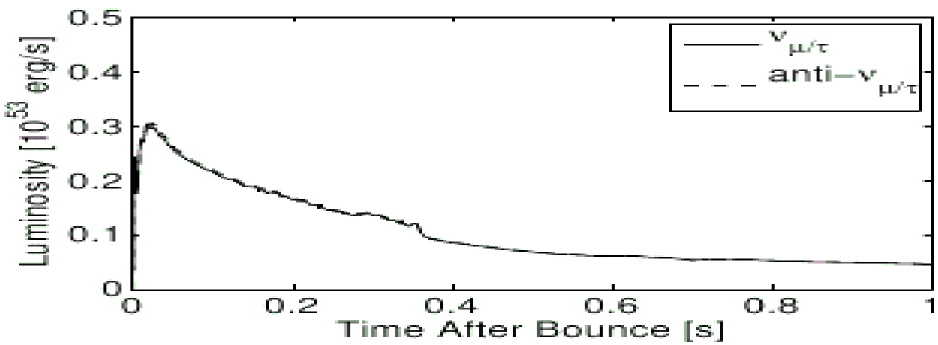
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

neutrino sphere radii determine neutrino energies

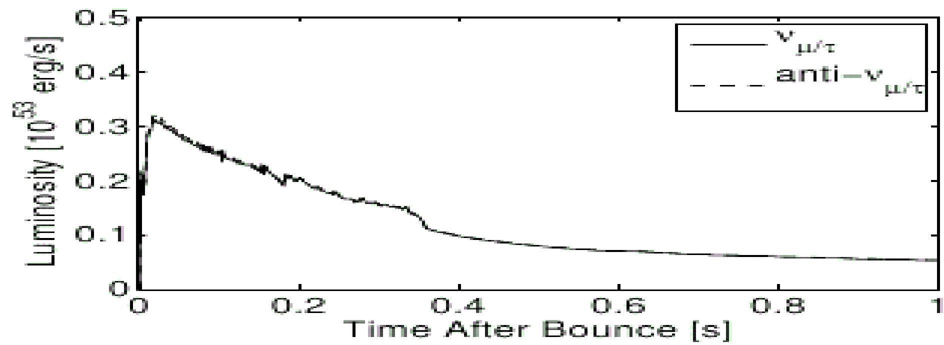
- if el.-degeneracy lifted for high T $\rightarrow$ ν_e-capture dominates $\rightarrow$ due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity $\rightarrow$ higher luminosity, dominate in neutrino wind $\rightarrow$ neutron-rich ejecta

from Fischer et al. (2010), conditions for 10 and 18M_{sol} which produce proton-rich composition for first 20s:

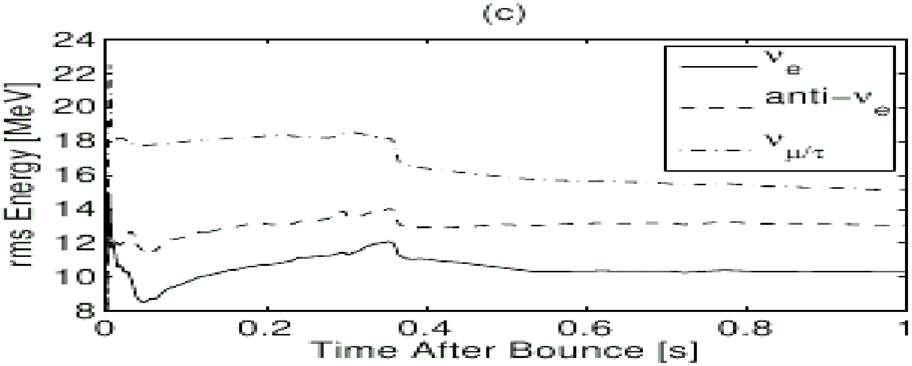
For similar neutrino and anti-neutrino luminosities average antineutrino energies have to be more than 5MeV higher than the average neutrino energies, in order to make matter neutron-rich. Is there a chance for this to happen at (very) late time???

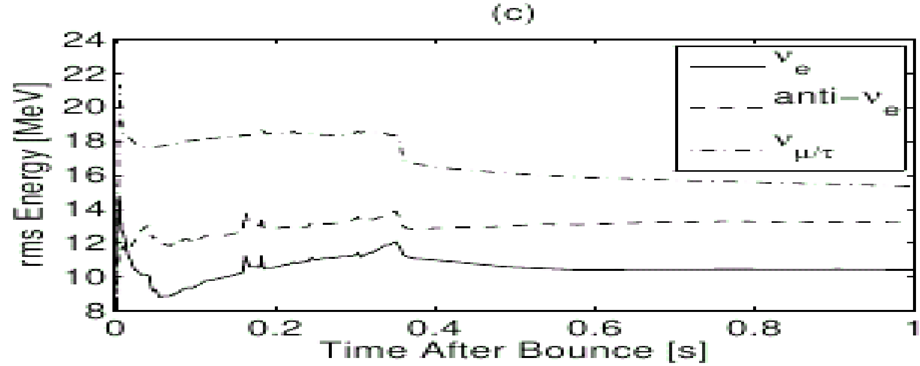


(c)

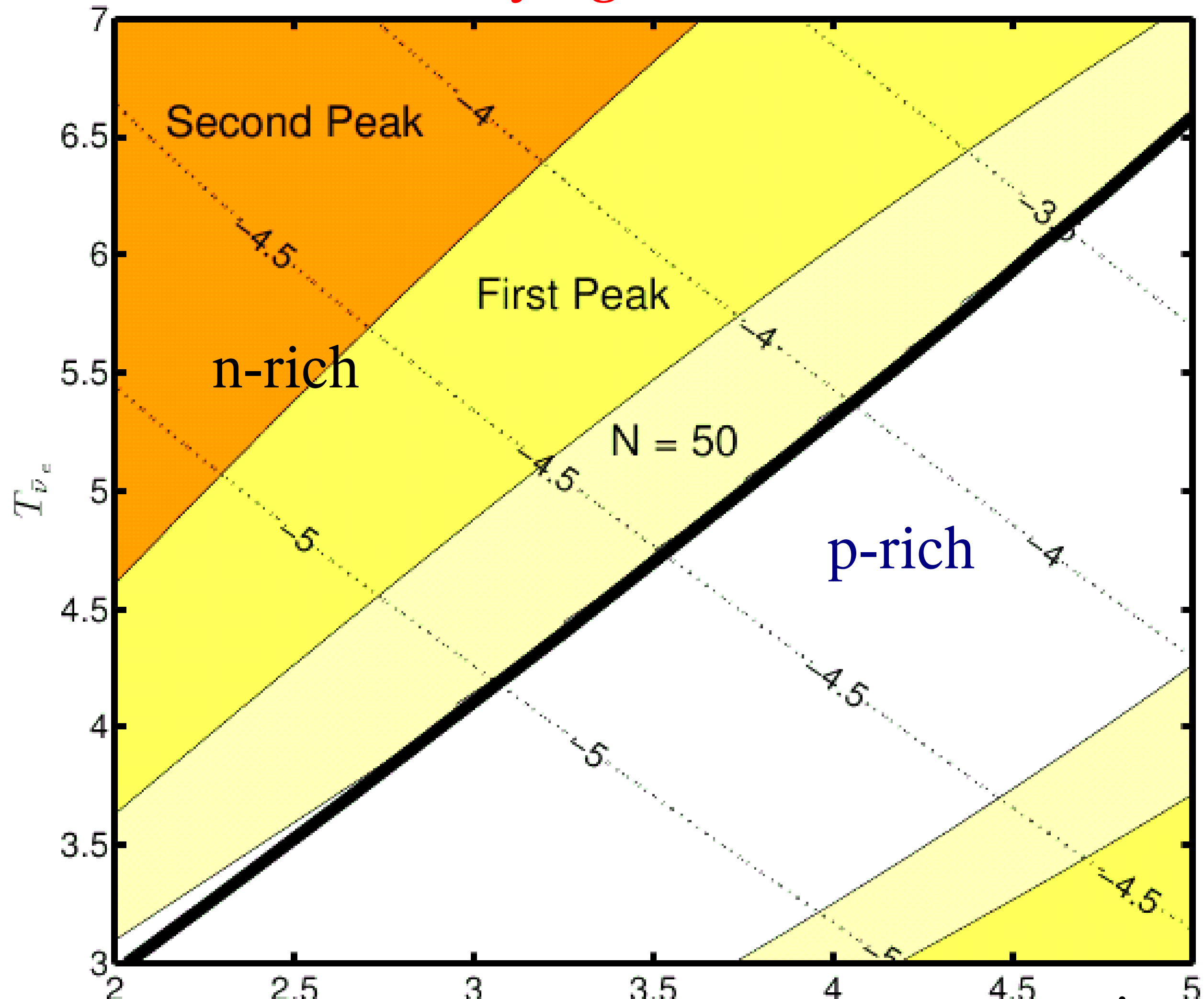


(c)



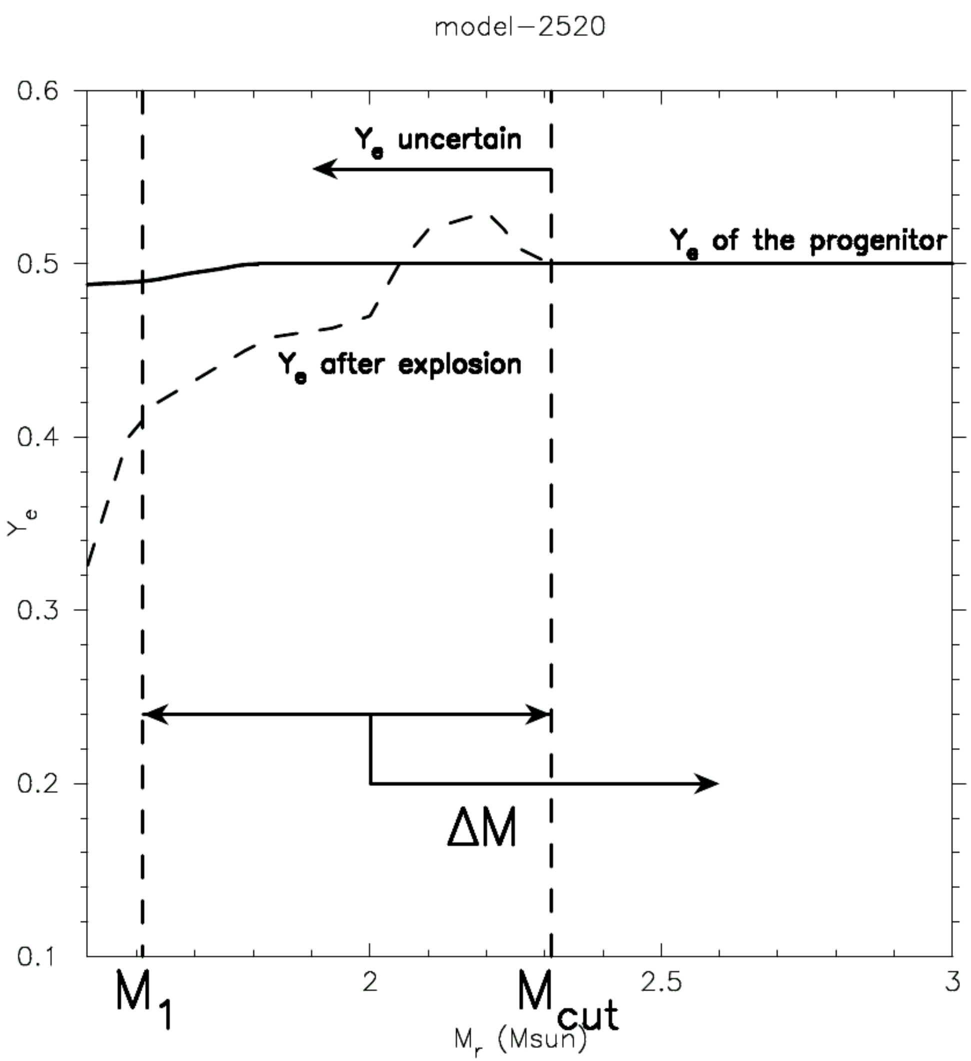


Nucleosynthesis in neutrino winds of varying conditions, from the νp to the r-process (Roberts, Woosley, Hoffman 2010): parametrized tests of varying the neutrino/antineutrino temperature



Assuming $L_{\nu_e,tot} = 10^{51}(\langle \breve{T}_\nu \rangle / 3.5\,\mathrm{MeV})^4\ \mathrm{erg\,s}^{-1}$ as neutrino luminosity, split between neutrinos and antineutrinos (with a 1.4M_{sol} neutron star and a 10 km neutrino sphere), different neutrino temperatures result in changes in Ye.

Possible Variations in Explosions and Ejecta



Izutani et al. (2009)

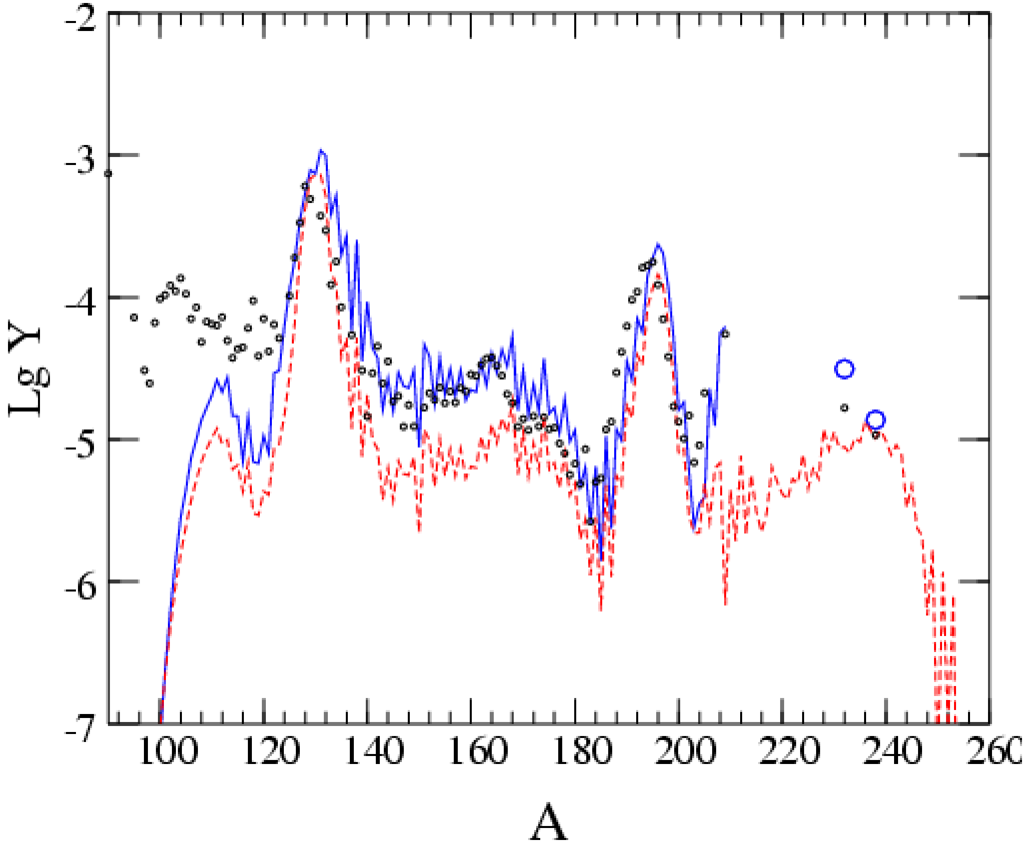
massive stars experience fallback and delayed black hole formation diminishing innermost ejecta: only Fe-group from explosive Si-burning?

regular explosions with neutron star formation, neutrino exposure, νp-process, moderately neutron-rich neutrino wind and weak r-process?

under which (special?) conditions can very high entropies or very neutron-rich ejecta be obtained which produce the main r-process nuclei?

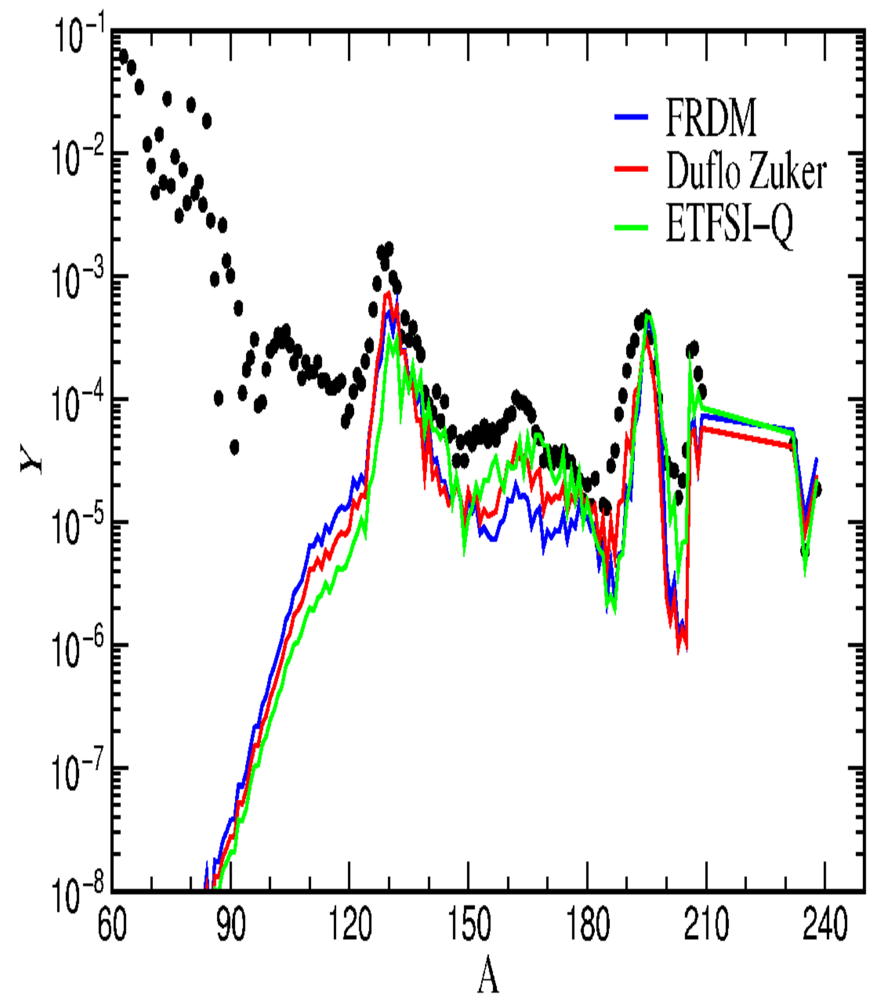
MHD jets from collapse with rotation (Cameron 2003 ...) or neutron star mergers (Rosswog,Freiburghaus..1999) or black hole accretion disks?

Fission Cycling in Neutron Star Mergers



Panov and Thielemann (2007) with parametrized fission yield contribution

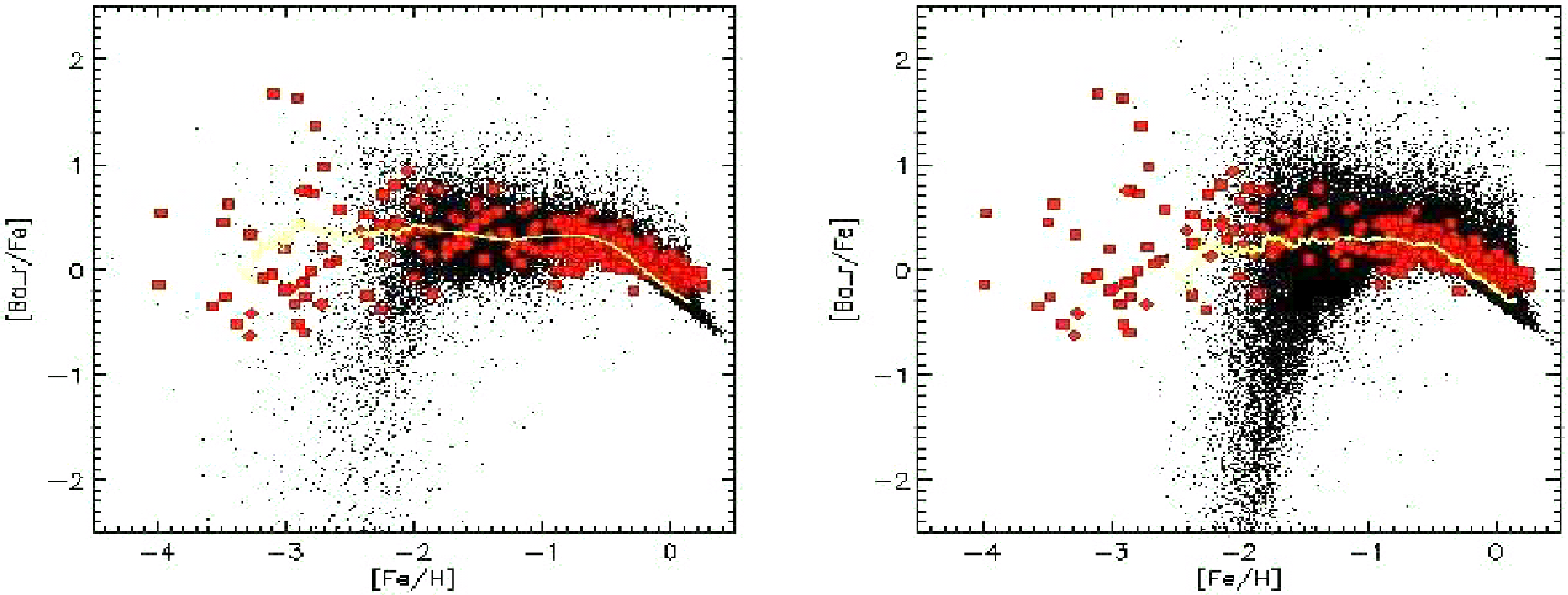
Trajectory from Freiburghaus, Rosswog, and Thielemann 1999 ($Y_e = 0.1, n/Seed = 238$).



Martinez-Pinedo et al. (2006)

in principle contradicted from gal. evol. calc., but similar conditions in SN polar jets? (Cameron 2003, Fujimoto 2008)

Are neutron star mergers consistant with r-process abundances in galactic evolution?



from Argast et al. (2004) with a NS-merger rate of 10^{-3} and 10^{-4} per year in the Milky Way. r-process matter is coming in too late in comparison with observations. Ishimaru & Wanajo (2010) try to find a way out by having the Milky Way form out of dwarf galaxies with different star formation rates.

Heavy Element Summary

The explanation of solar system abundances above Fe is much more complicated than originally envisioned (r- and p-process).

1. The classical p/γ-process cannot reproduce the light p-isotopes and another process has to contribute these nuclei (νp-process) and/or p/γ-process in different locations..

2. Also the r-process comes in at least two versions (weak-main/strong). The weak r-process is probably related to regular core collapse supernovae and might emerge from the late neutrino wind. The main/strong r-process comes apparently in each event in solar proportions, but the events are rare. The site is not found, yet. Speculations include rotating core collapse events with jet ejection, neutron star mergers and even accretion disks around black holes.