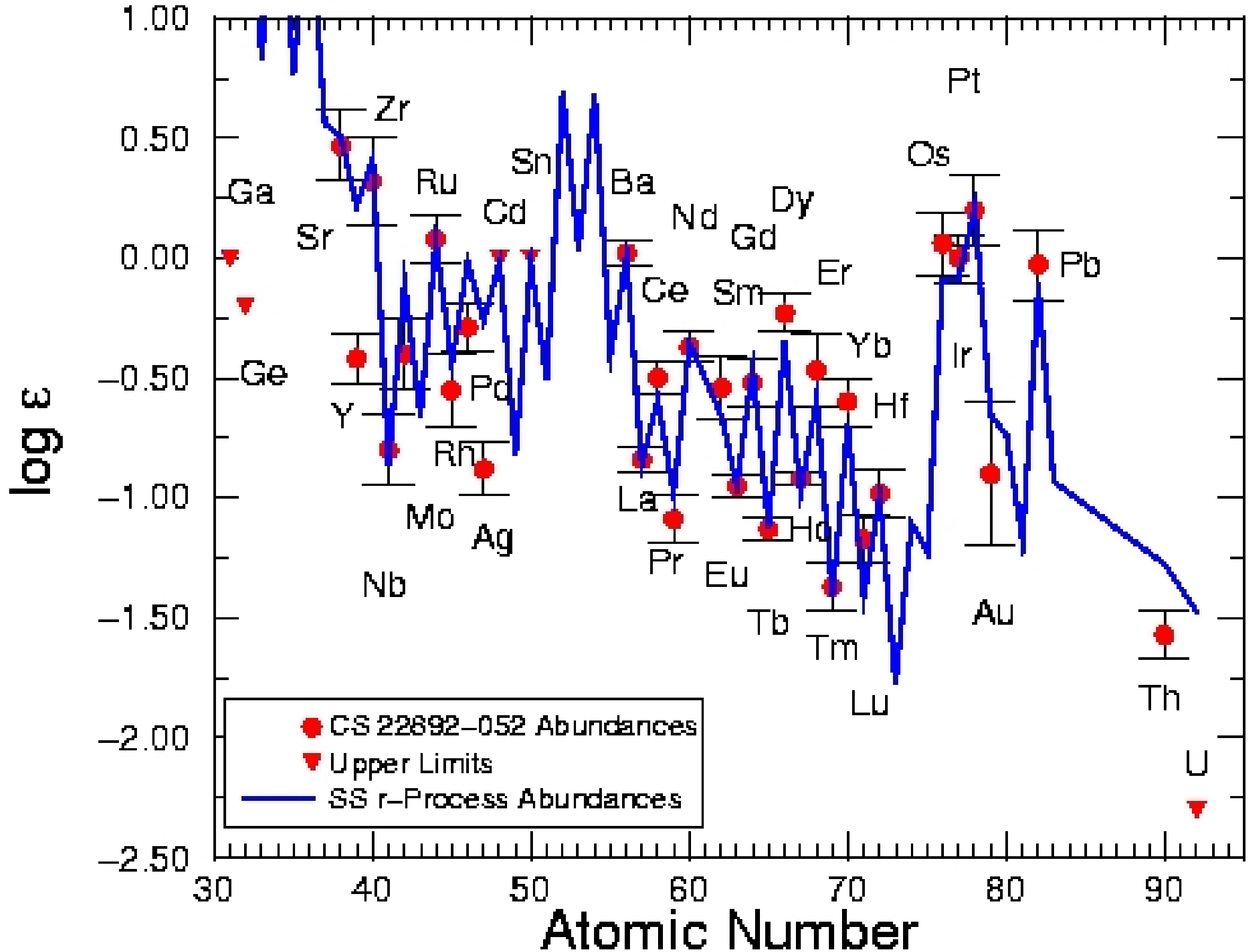
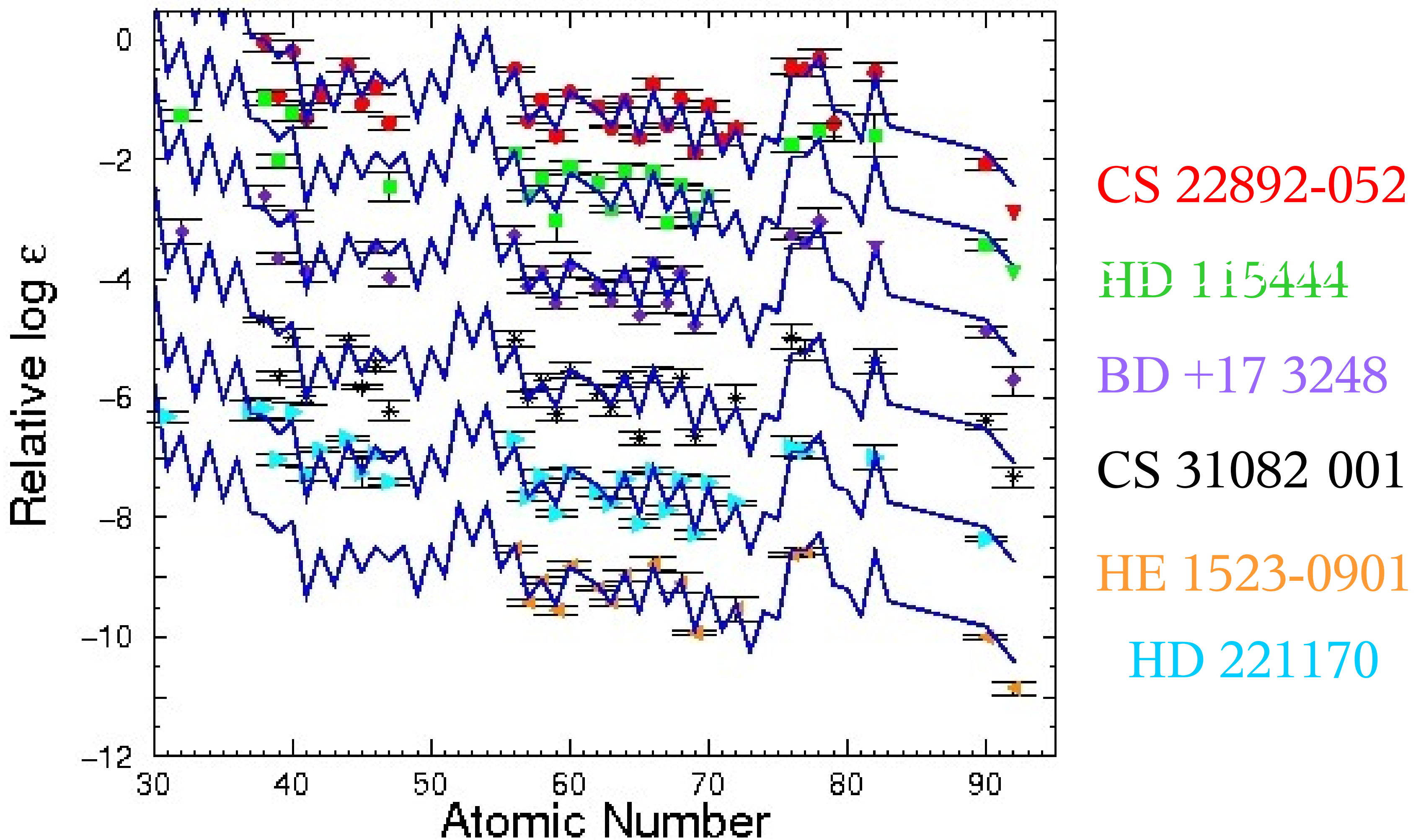
Readdressing Chemical Evolution in Galaxies as a function of metallicity: CS22892-052: A pure r-process star at [Fe/H]=-3.1

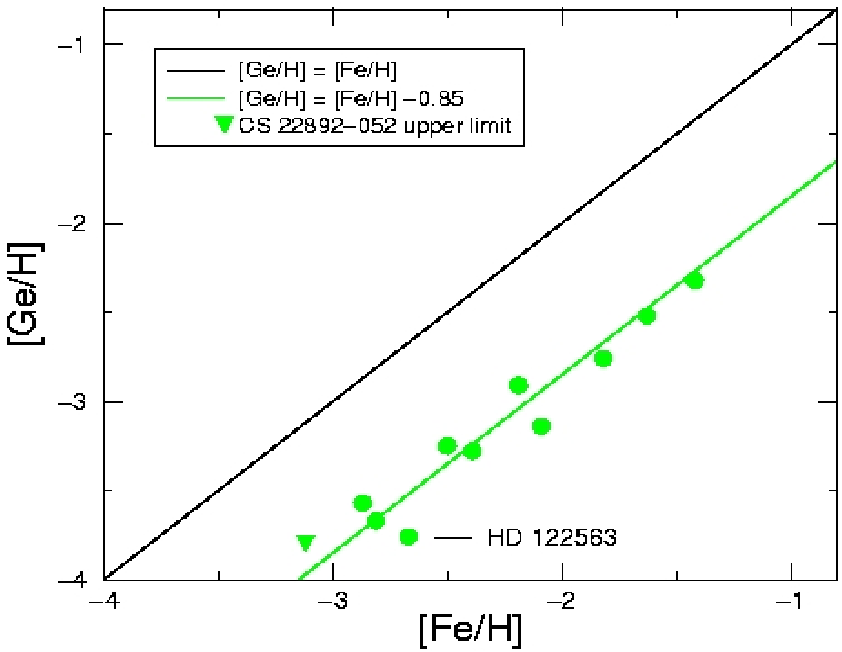
(Cowan et al. 2005)

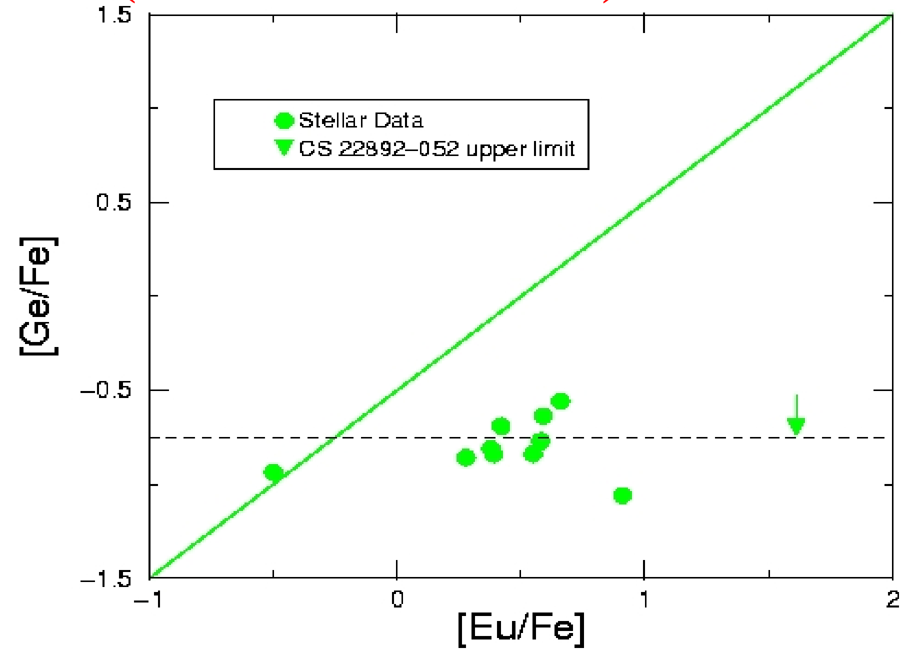


r-process-rich stars at low metallicities

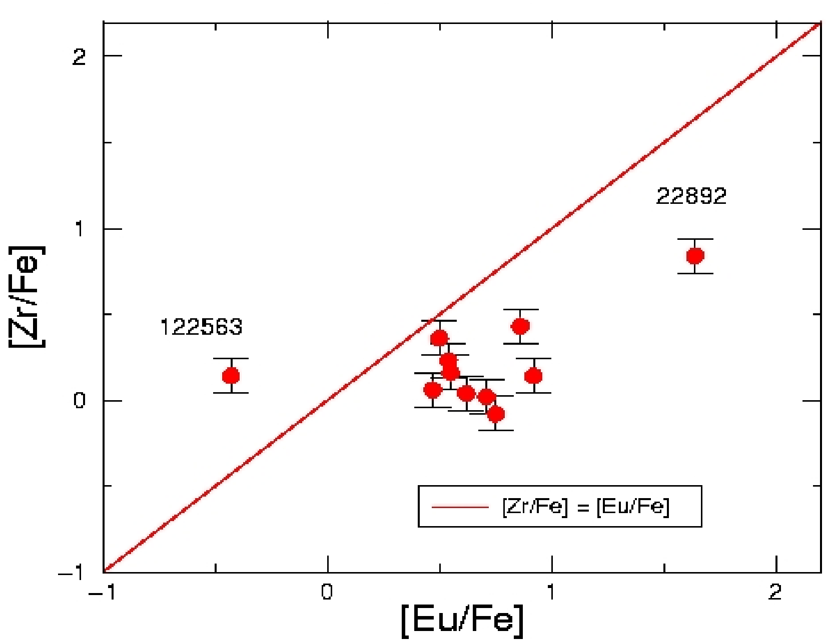


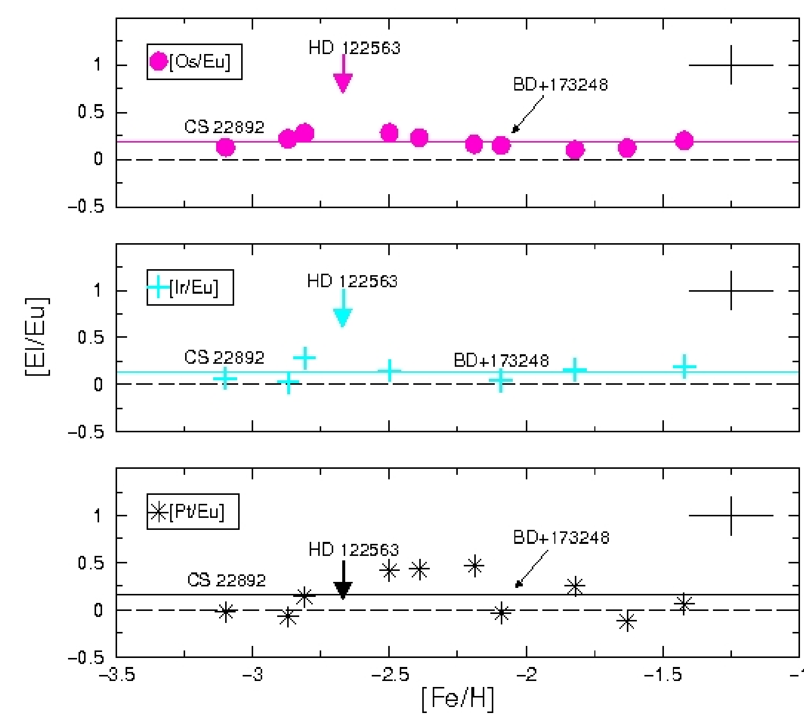
Observational indications: heavy r-process and Fe-group uncorrelated, Ge member of Fe group, Zr intermediate behavior, weak correlations with Fe-group as well the heavy r-elements (Cowan et al. 2005)



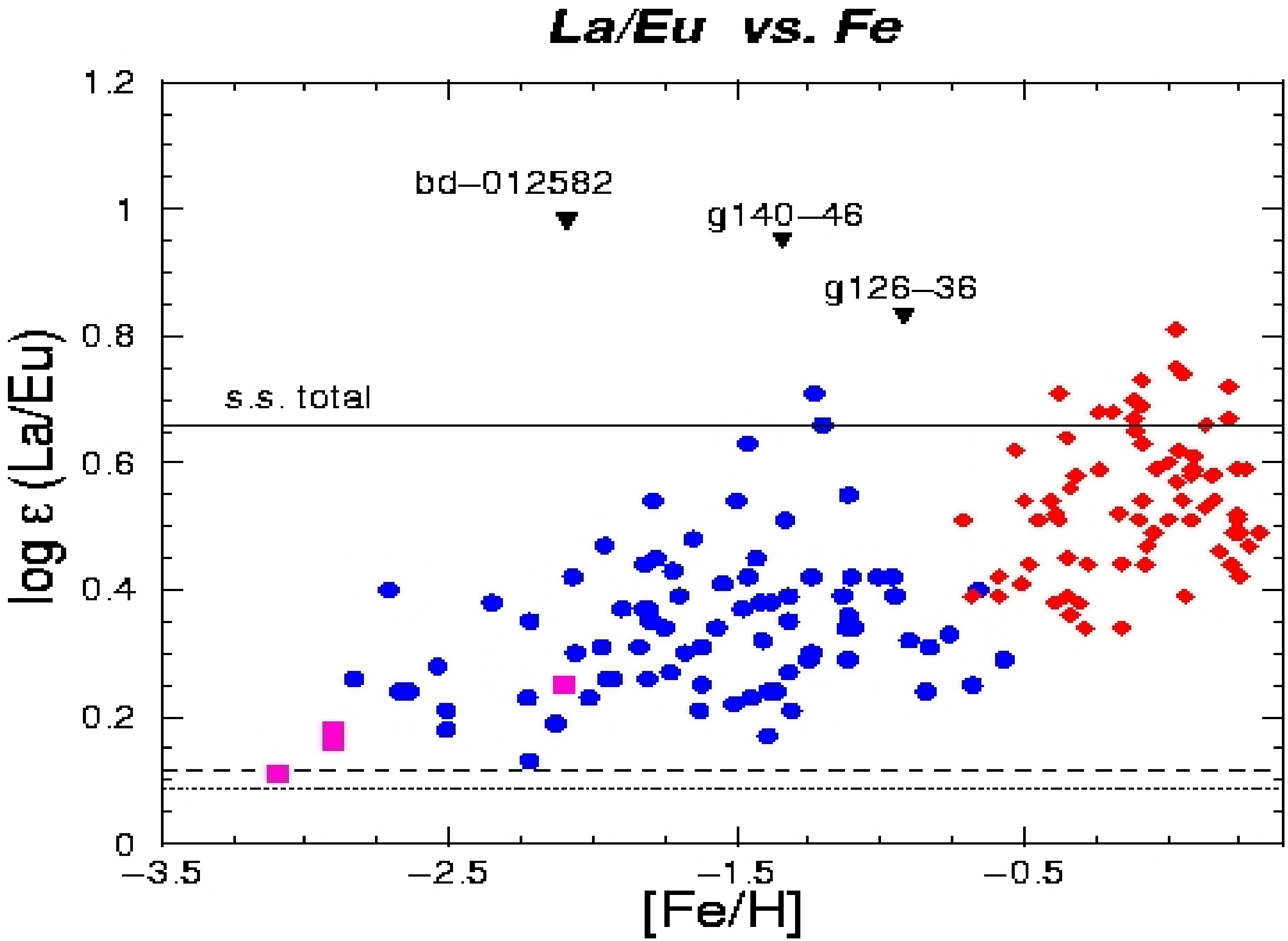


Zr vs. Eu





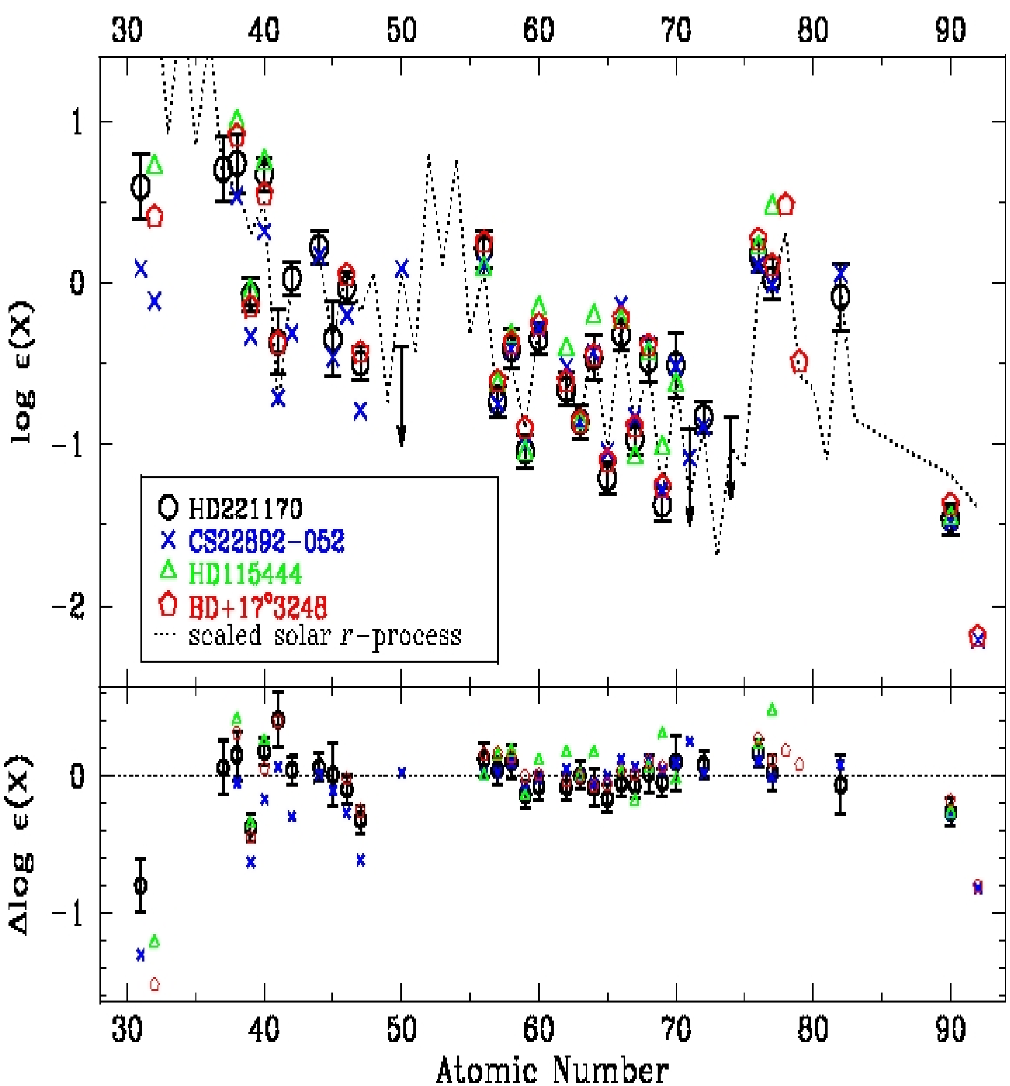
La/Eu (a dominantly s- vs. a dominantly r-process element) reflects at very low metallicities pure r-process ratios while at about [Fe/H]=-2 the s-process comes in to reach the solar ratio at [Fe/H]=0



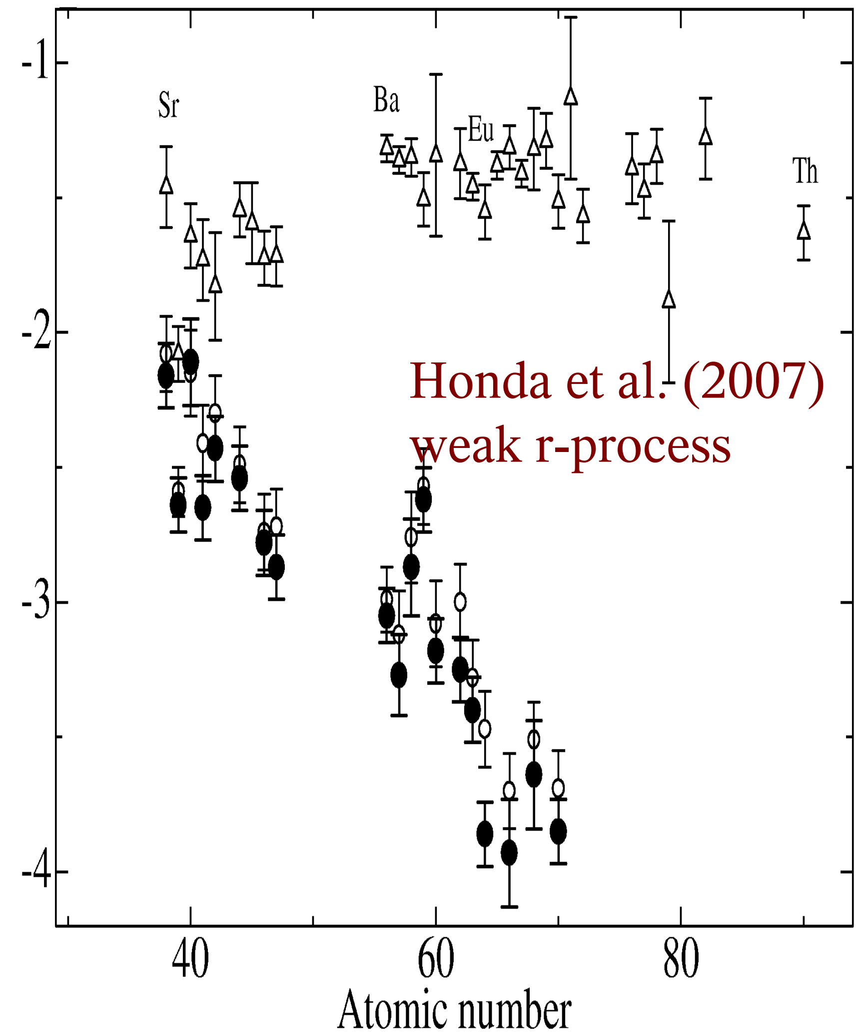
Simmerer et al. (2004)

process enhanced, • halo stars, ♦ disk stars

Almost identical behavior of heavy r-element abundances, variations in light r-elements, often underabundances in comparison to solar r-abundances



Ivans et al. (2006)



Honda et al. (2007)
weak r-process

Fig. 5.— Logarithmic differences from the solar system r-process pattern ($\log\varepsilon_{\mathrm{object}} - \log\varepsilon_{\mathrm{solar-r}}$). The open triangles mean CS 22892-052, the open circles mean HD 122563, and the filled circles mean HD 88609.

Observations of post-AGB stars, indicating the intrinsic pollution due to strong s-processing

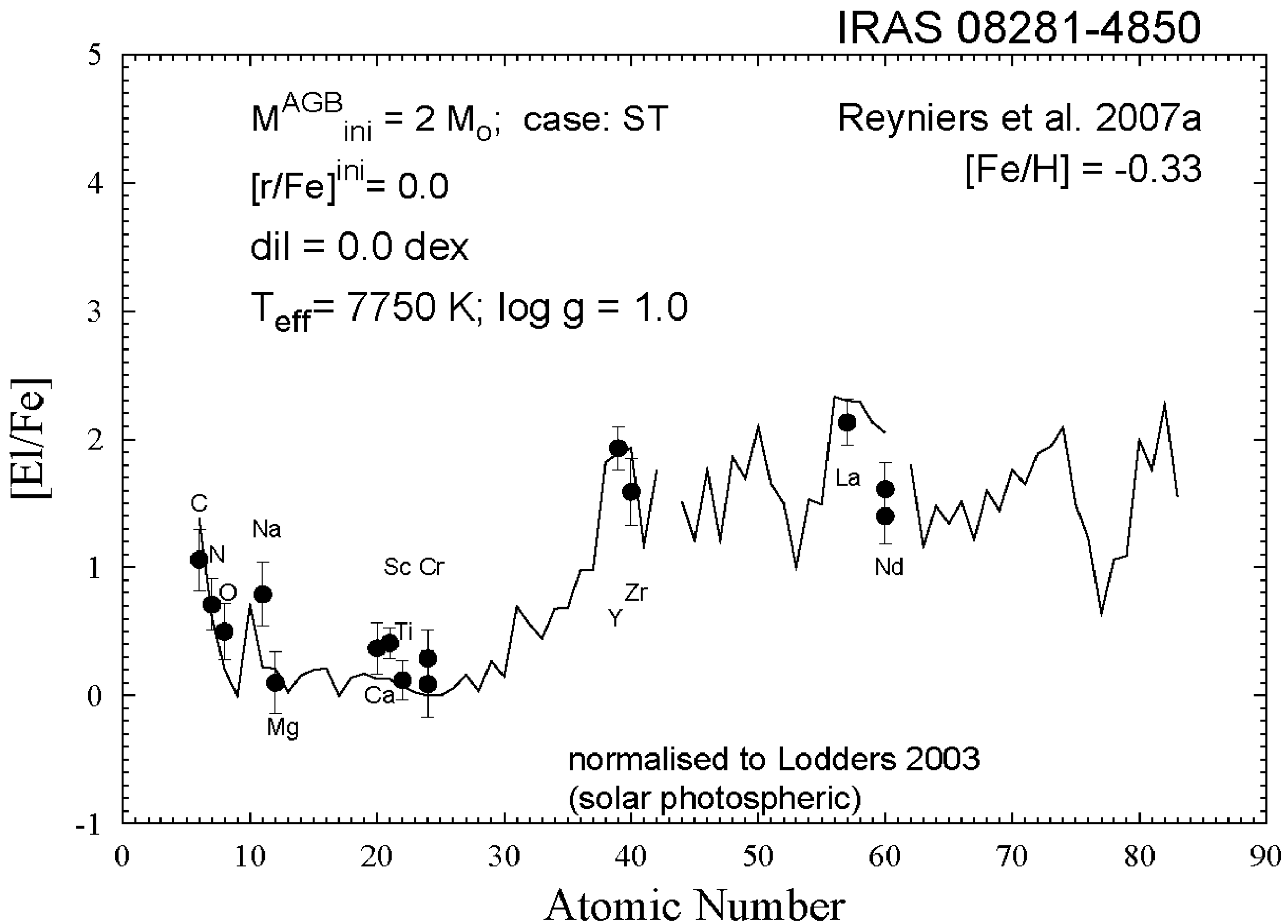
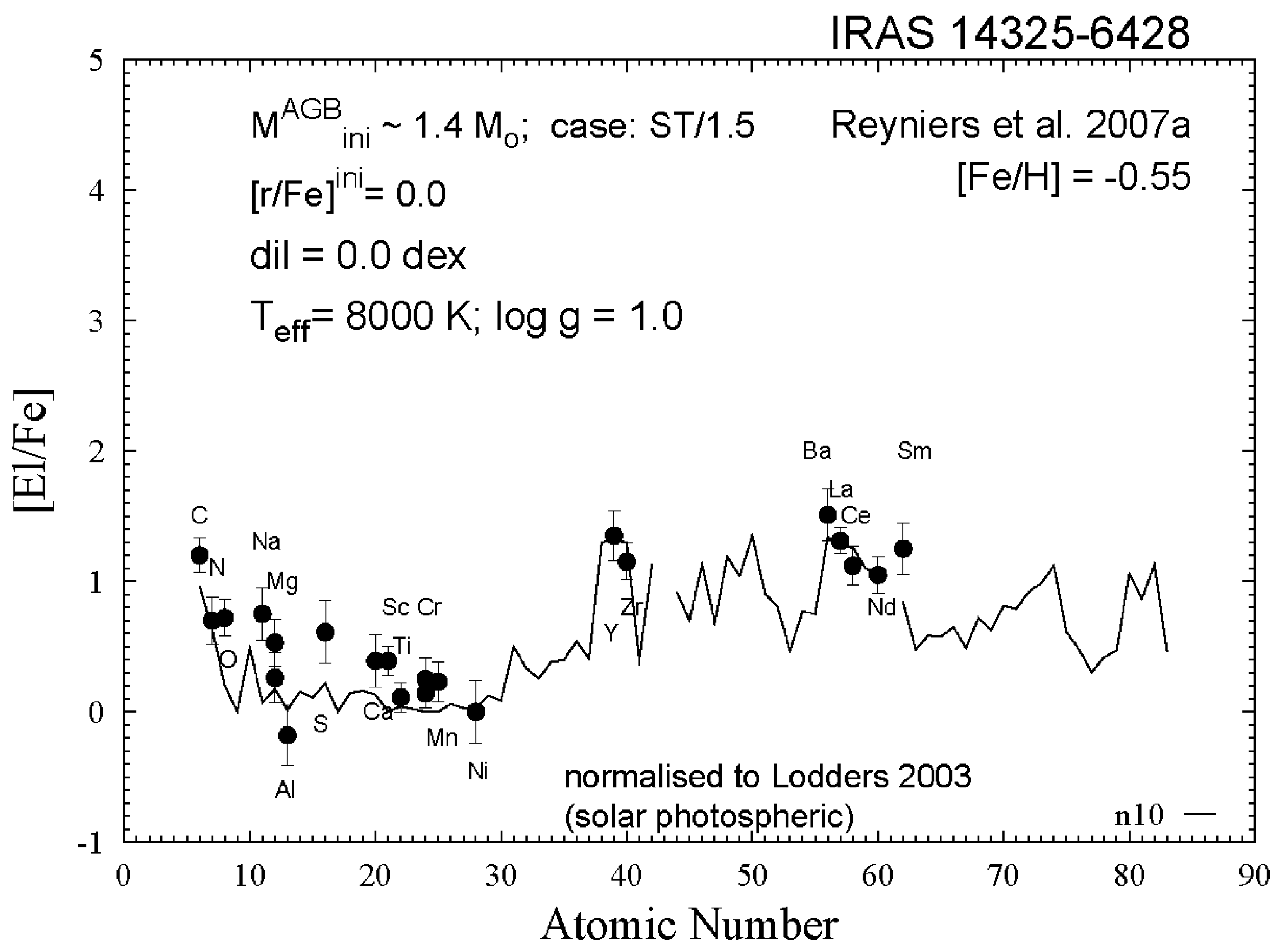


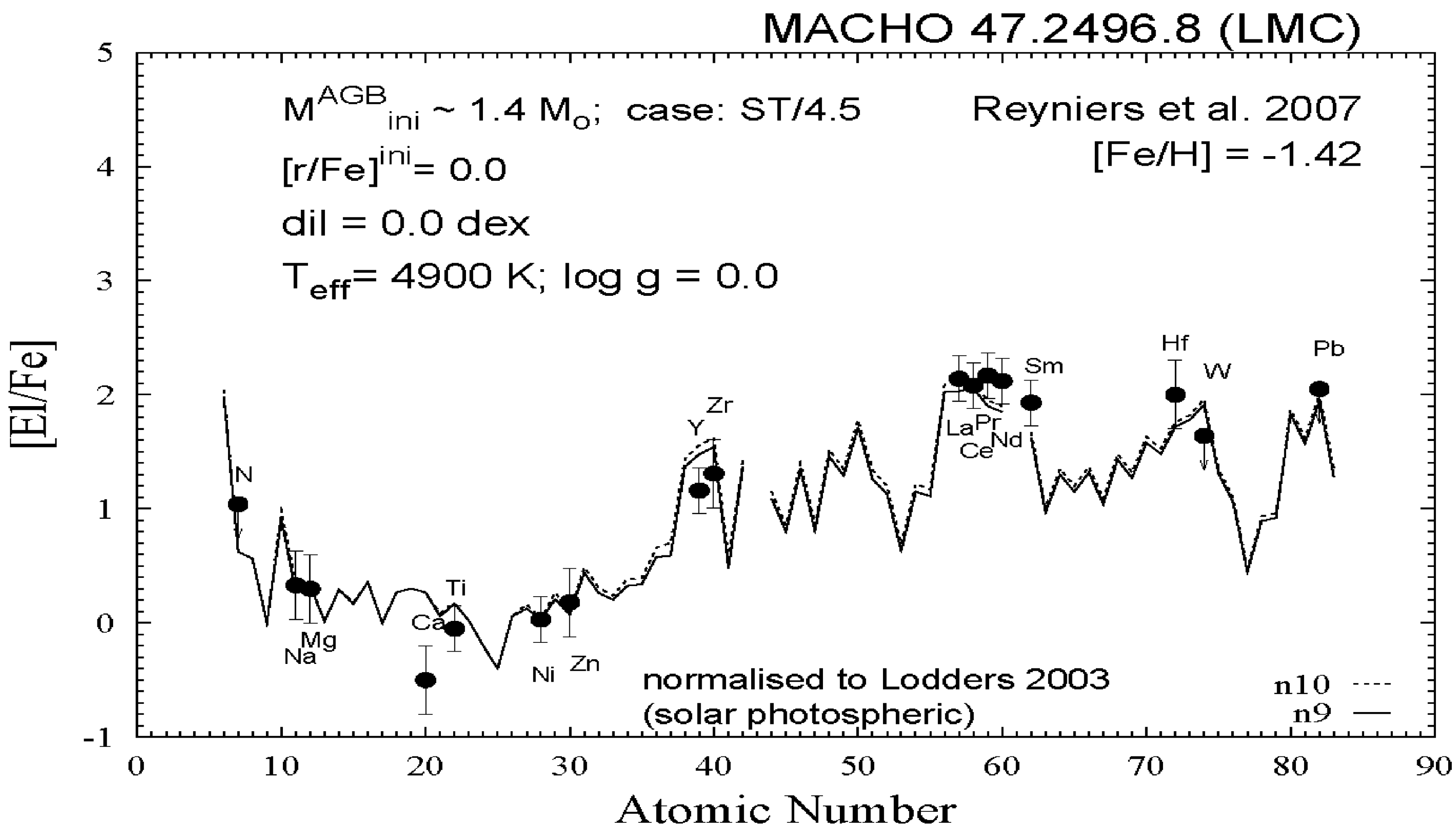
FIGURE 1. Theoretical interpretation of the post-AGB star IRAS 08281-4850 by Reyniers et al. (2007a) [2], with $M_{\rm ini}^{\rm AGB} = 2\ {\rm M}_\odot$, case ST.

Gallino et al. (2008)

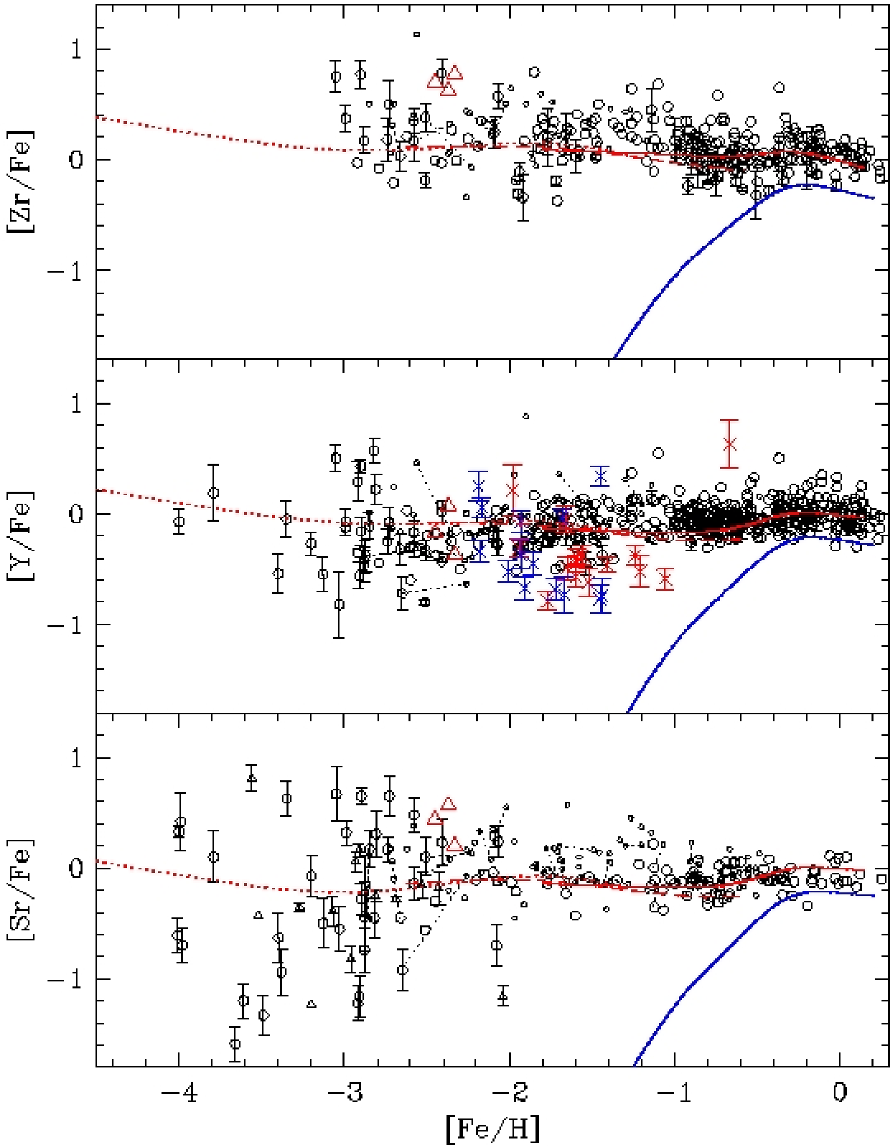
each star showing a specific stage of s-processing, no overall agreement with „solar“ s-process abundances



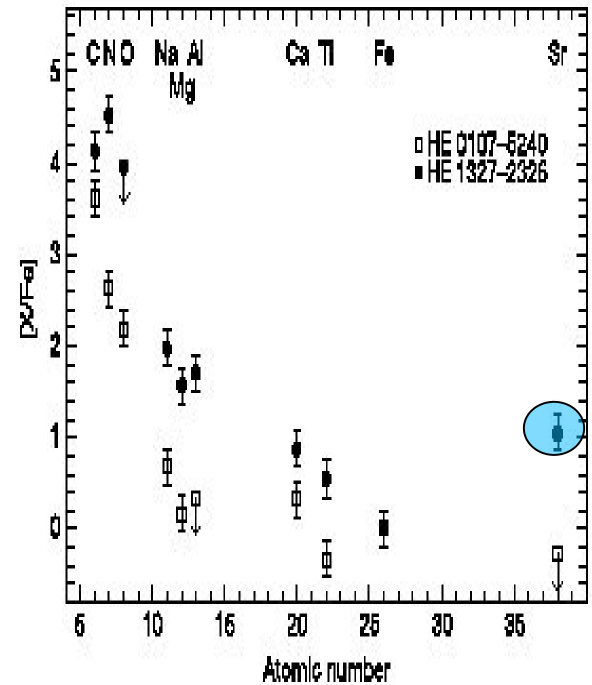
The s-process is secondary process (capturing neutrons on pre-existing Fe-group nuclei). A similar neutron exposure on smaller amounts of Fe-seeds leads to stronger production of the heaviest s-nuclei (so-called lead stars).



Travaglio et al. (2004)



Need for early Sr,Y,Zr before onset of s-process



Frebel et al. (2005)

large variations in Sr between different low-metallicity stars

s-Process (neutron) Sources

Core burning of massive stars (weak s-process)

1. Helium Burning $T=(1\text{-}2)\times10^{8}K$

   $^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$

   $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

2. Carbon Burning $T=(6\text{-}8)\times10^{8}K$

   $^{12}C(^{12}C,\alpha)^{20}Ne$ $^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C$

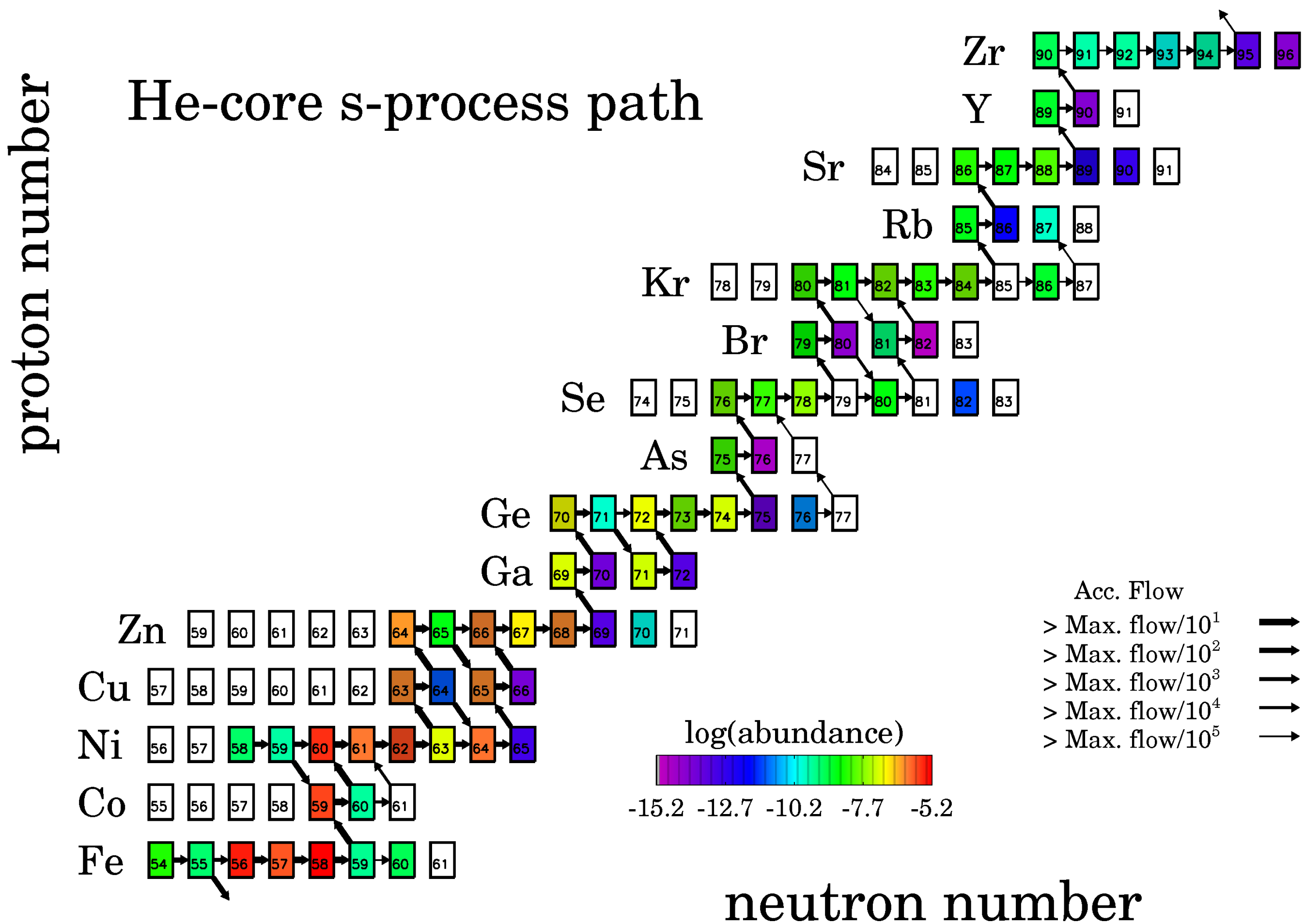
   $^{12}C(^{12}C,p)^{23}Na$ $^{13}C(\alpha,n)^{16}O$

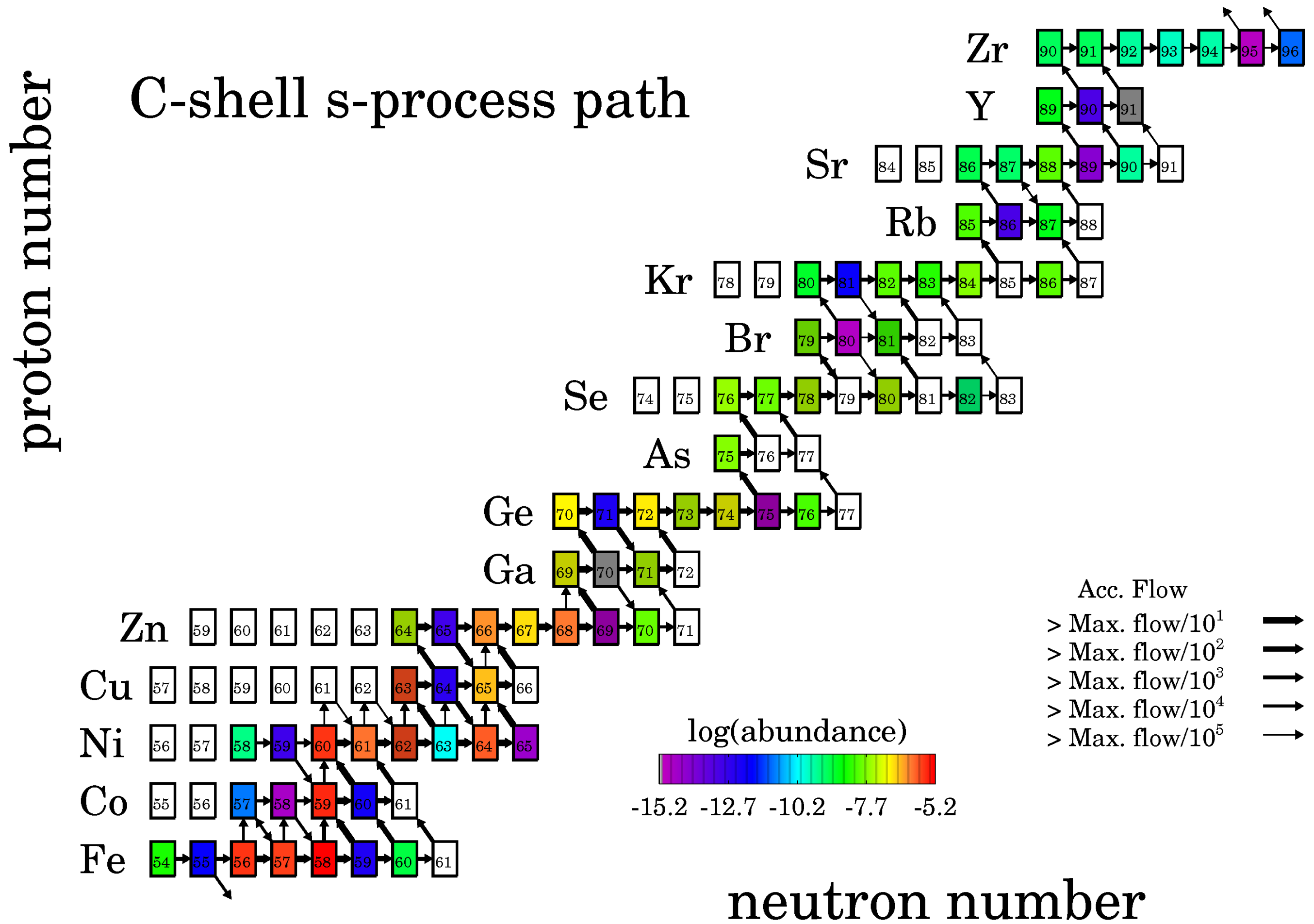
   protons as well as alphas are not existing intrinsically in C-burning, as destroyed in prior H-burning and He-burning. They come from the C-fusion reaction

He-shell flashes in AGB stars (strong s-process)

protons are mixed in from the H-shell and produce ^{13}C (as in 2. above), but the latter can react with the full He-abundance in He-burning and produce strong neutron source.

s-process reaction paths in core He and C-burning

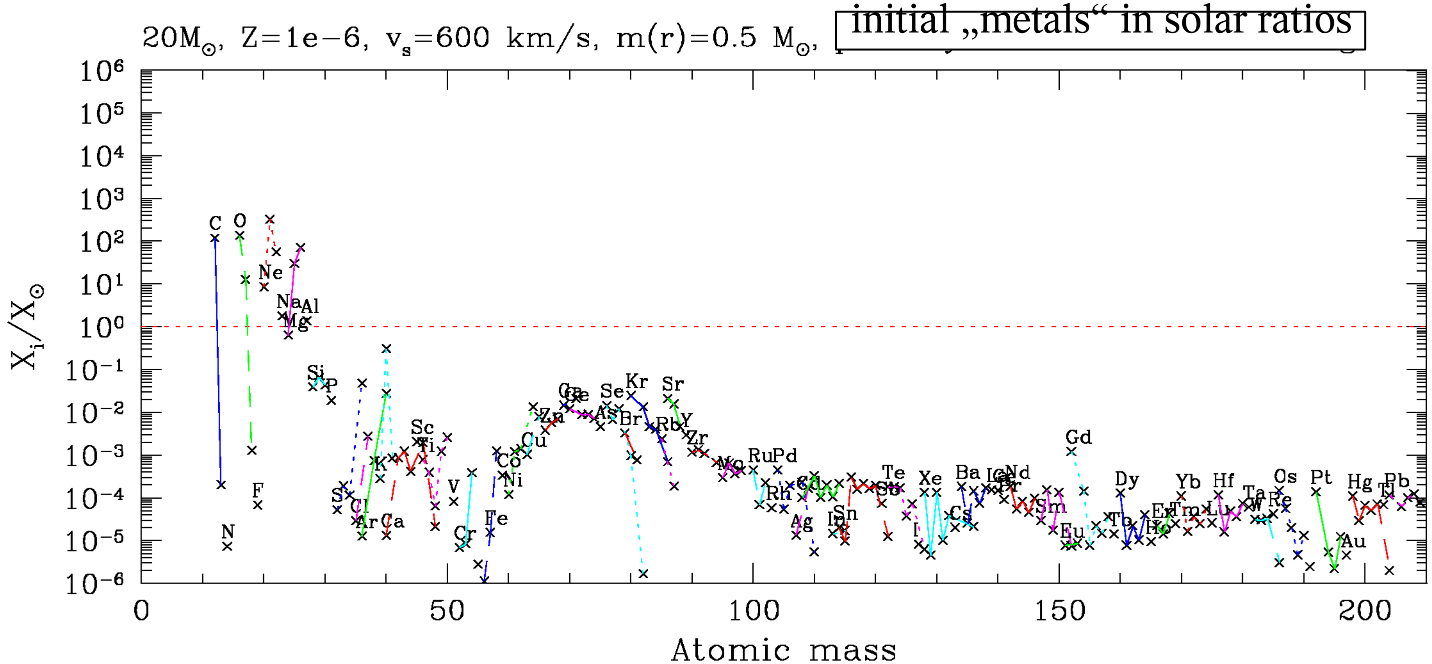




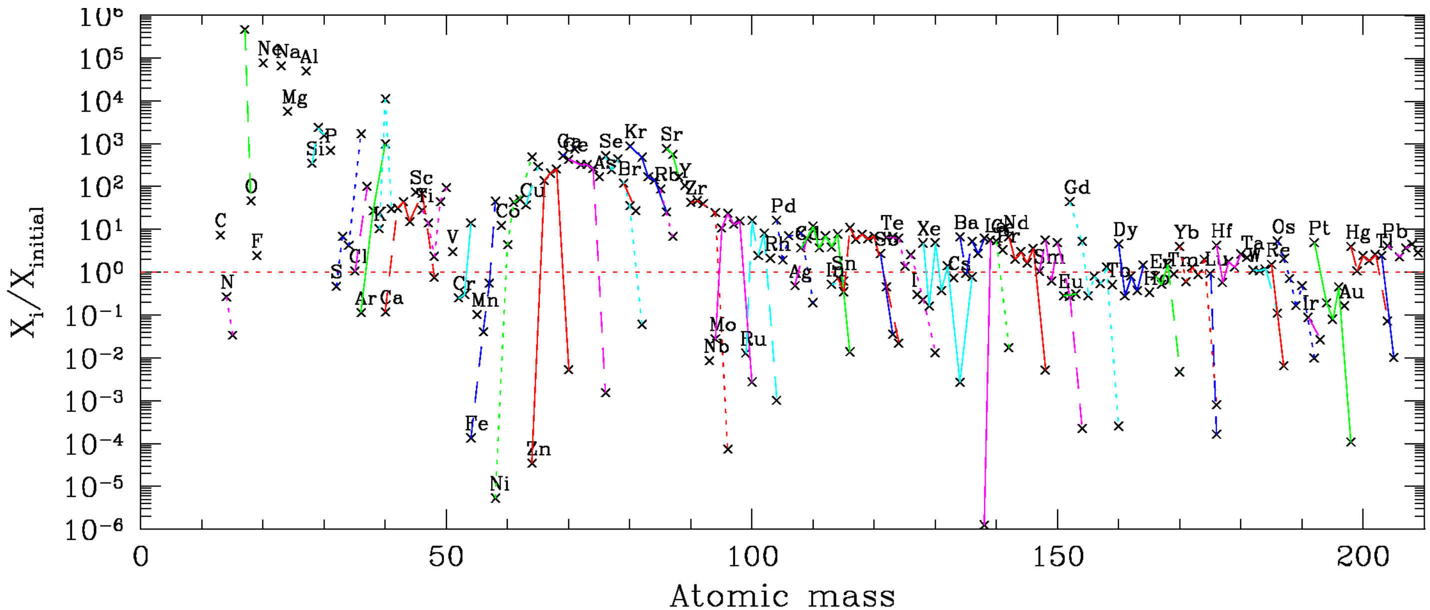
higher temperatures and neutrons densities lead to different branchings (The et al. 2007)

Results after Core He-burning

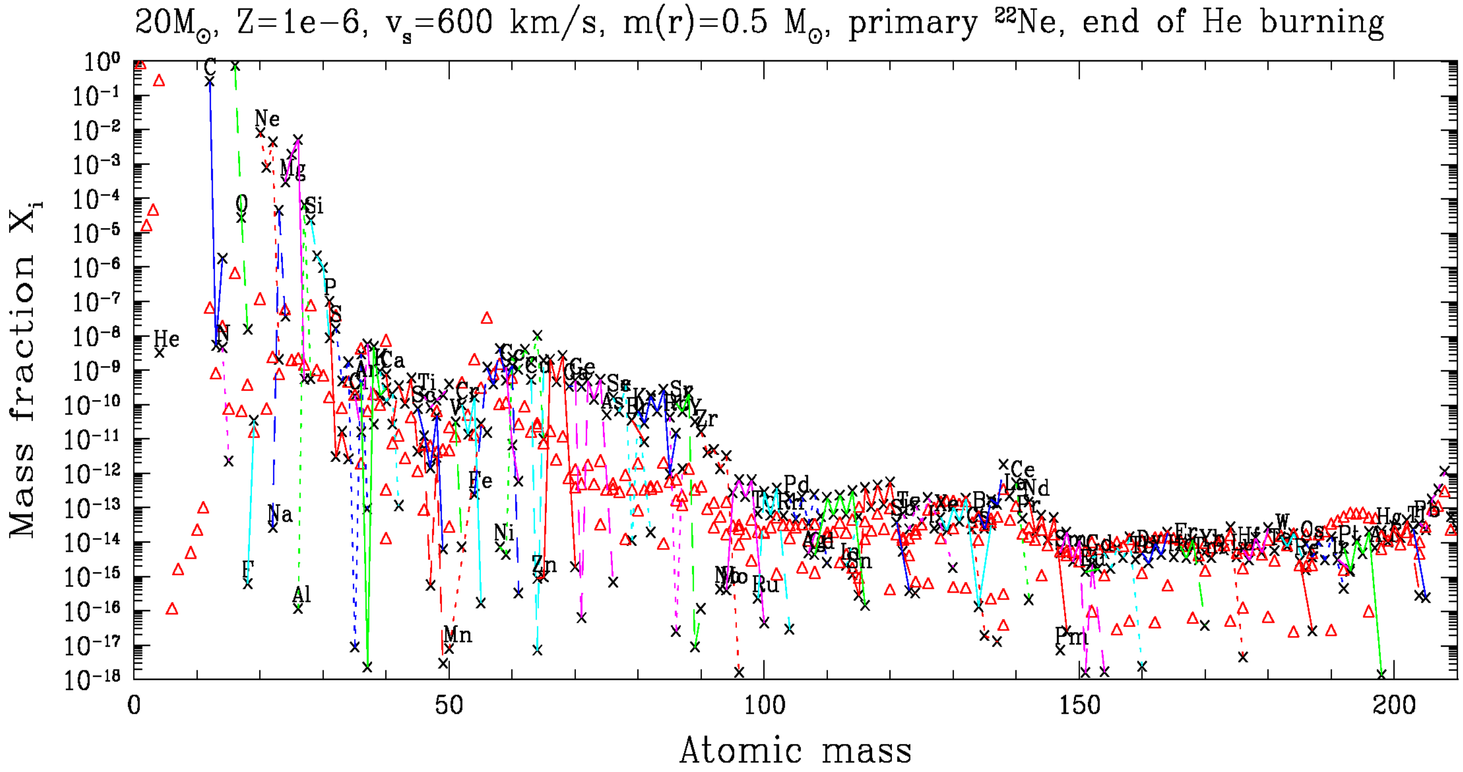
initial „metals" in solar ratios



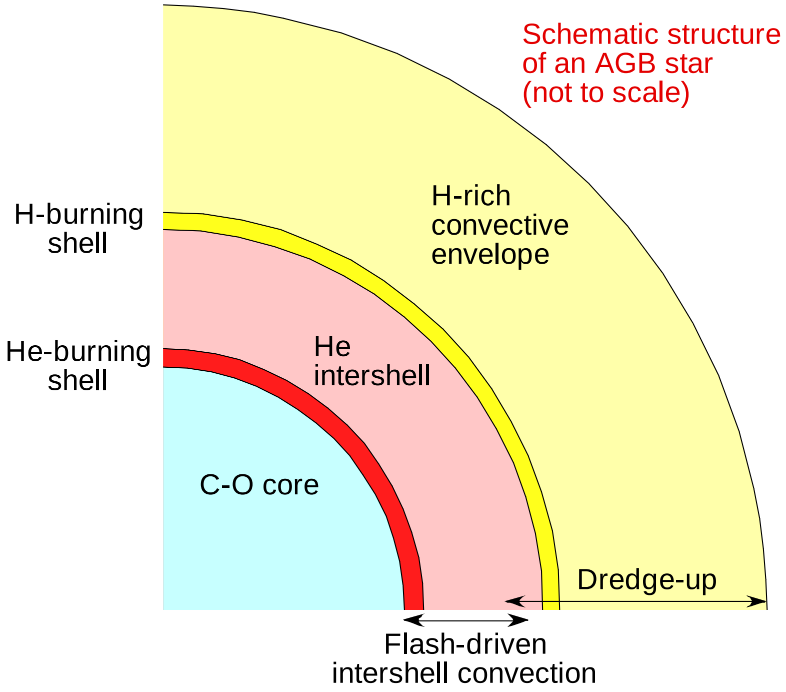
alpha elements enhanced

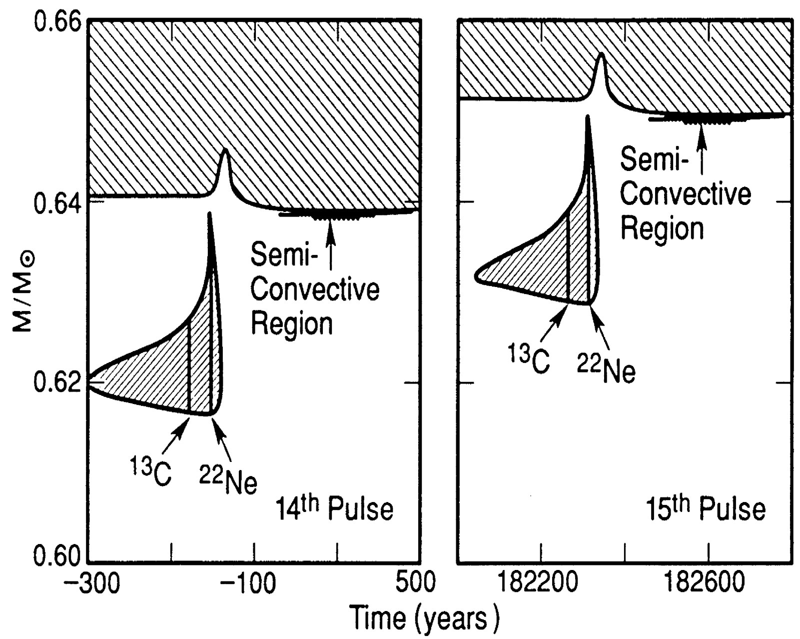


rotating models can mix He-burning products (C,O) into H-burning zones where this is turned via the CNO cycle to ^{14}N and in the following He-burning burned to ^{22}Ne (so-called primary ^{22}Ne), which can lead to a stronger (weak) r-process already at low metallicities

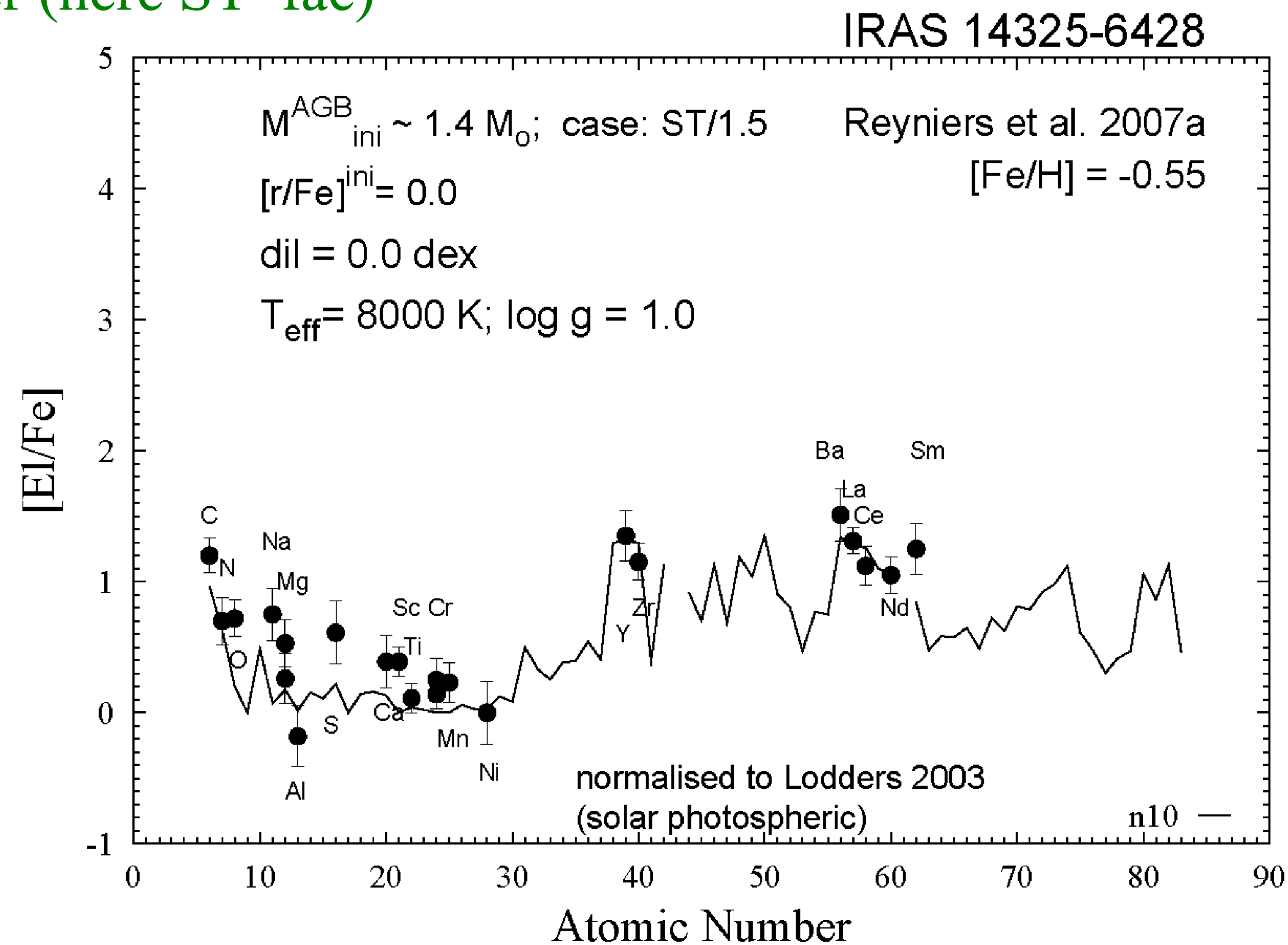


Frischknecht, Hirschi, Thielemann (2008) in low and intermediate mass stars the H- and He-shells are located at small distances. They do not burn in a constant fashion. If the H-burning zone is on, it creates He fuel. After sufficient He is produced in an unburned He-rich zone (leading to sufficient densities and temperatures), He is ignited. The burning is not stable, as the amount of energy created in a shallow zone is not sufficient to lift the overlaying H-shell which would cause expansion + cooling, i.e. steady burning. Instead He-burning, being dependent on the density squared burnes almost explosively (flash), causing then a stronger expansion which even stops H-burning in the H-shell. This behavior repeats in recurrent flashes. H is mixed into the unburned He fuel.

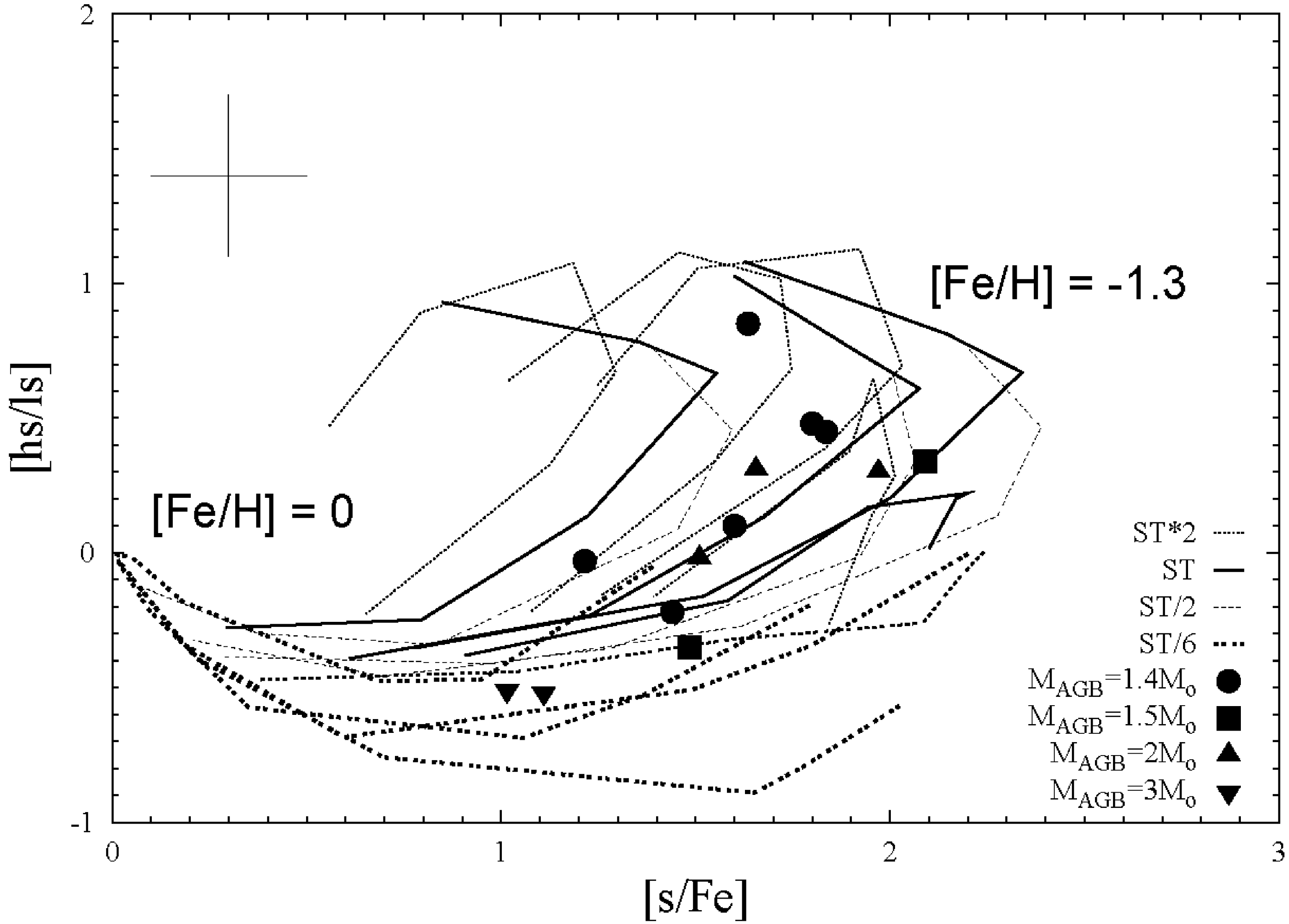




the full process of multi-D mixing is not fully understood yet (resolution and 3D), thus the mixing efficieny is introduced by a paramter (here ST*fac)

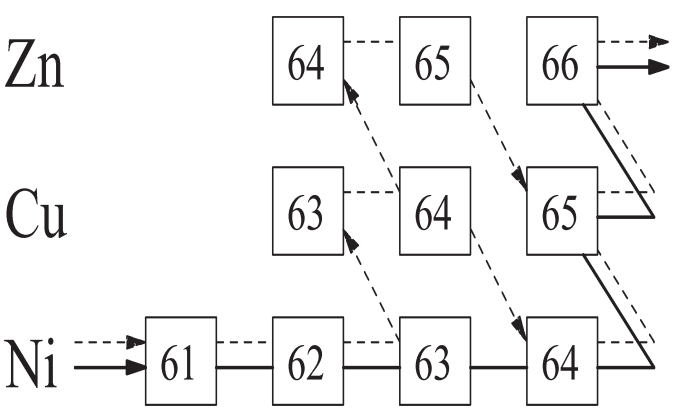


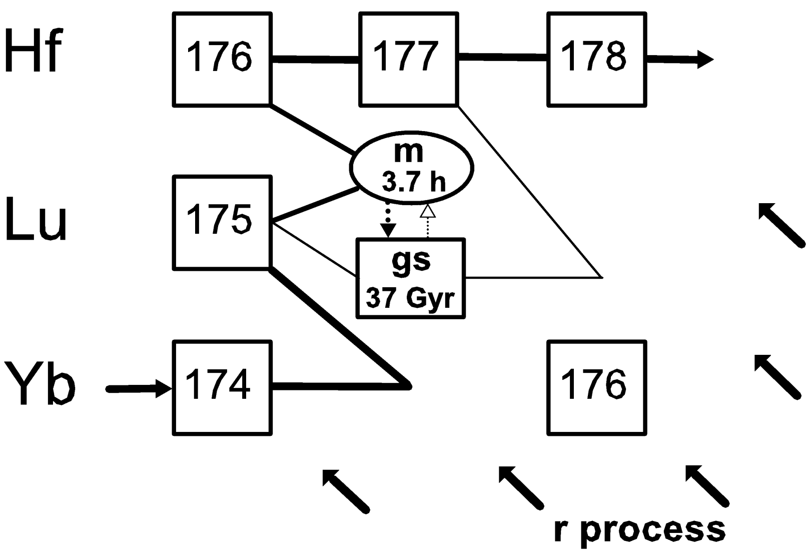
each star shows a specific stage of s-processing, i.e. we have no overall agreement with „solar“ s-process abundances in a single star. Solar s-abundances are only obtained via integrating over an IMF and over galactic evolution with increasing metallicity hs/ls (i.e. high s to low s or the abundances in the third over the first s-process peak) is a measure of the strength of the s-process (whether everything went up to Pb or stopped earlier) and depends on the metallicity (as this changes the Fe-seed and thus the neutron/seed ratio). Of course things depend also on the mixing description „ST".

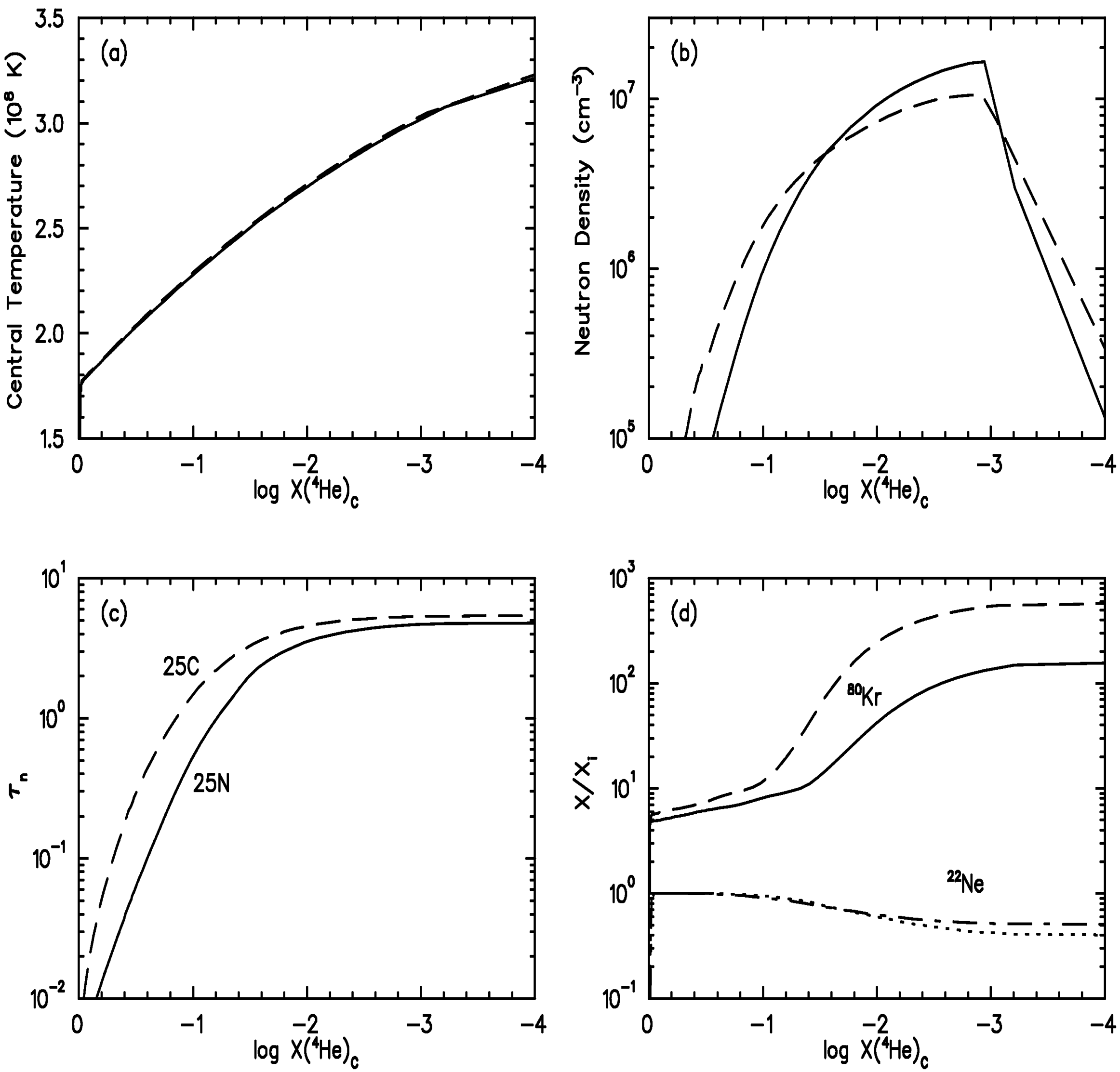


Gallino et al. (2008)

Open questions: branchings and reaction rates







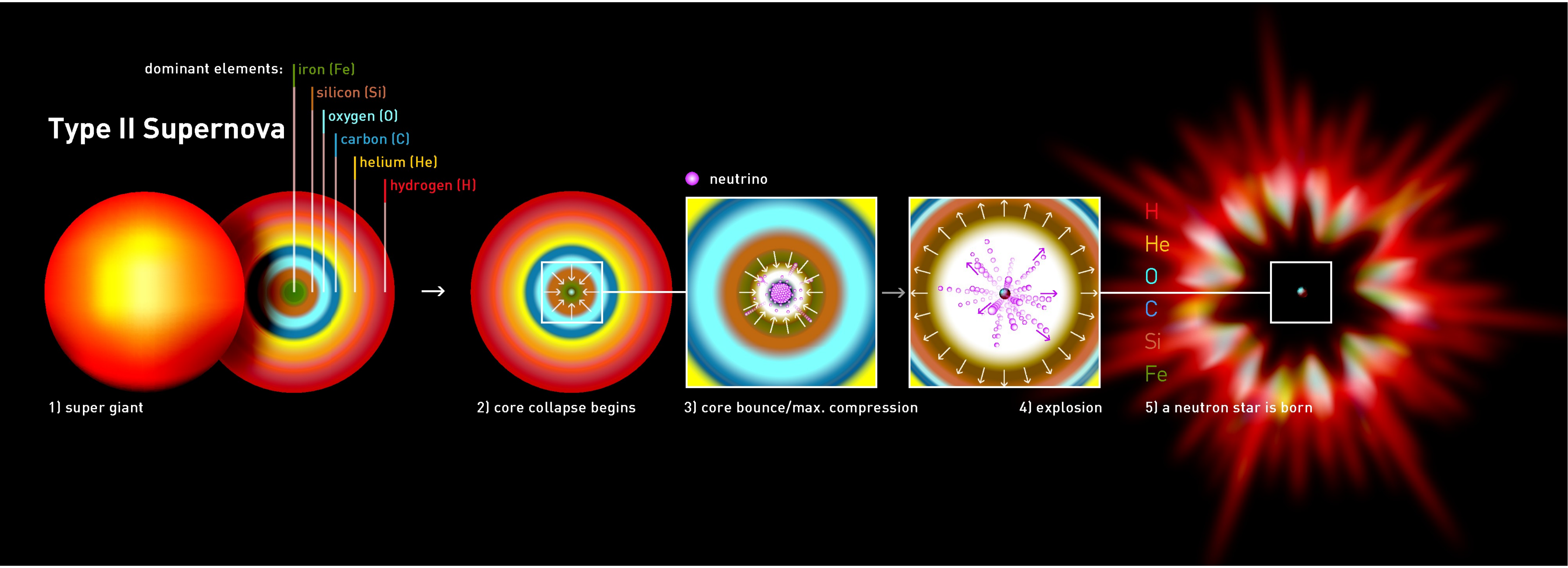
Costa et al. (2008), Heil et al. (2008)

varying ^{22}Ne and ^{12}C rates in weak s-process (The et al. 2007)

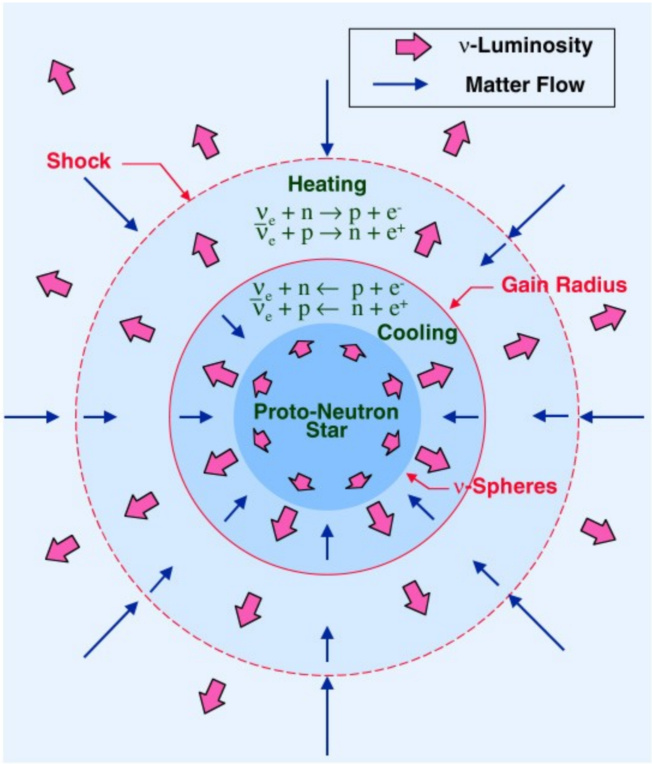
Type II Supernovae nucleosynthesis and the r-process?

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

Core Collapse Supernovae from Massive Stars



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

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

$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

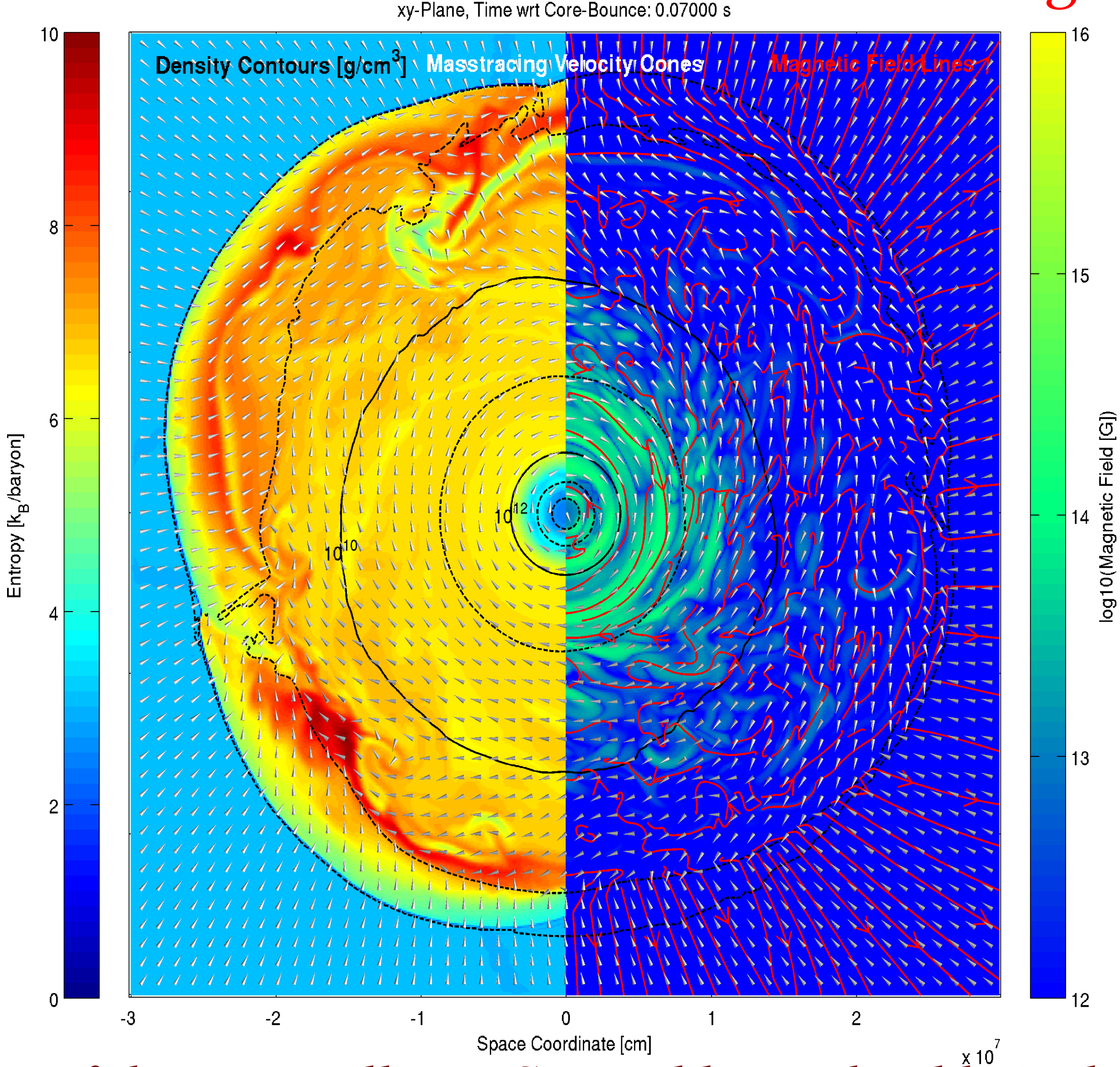
also

$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Simulations with Rotation and Magnetic Fields



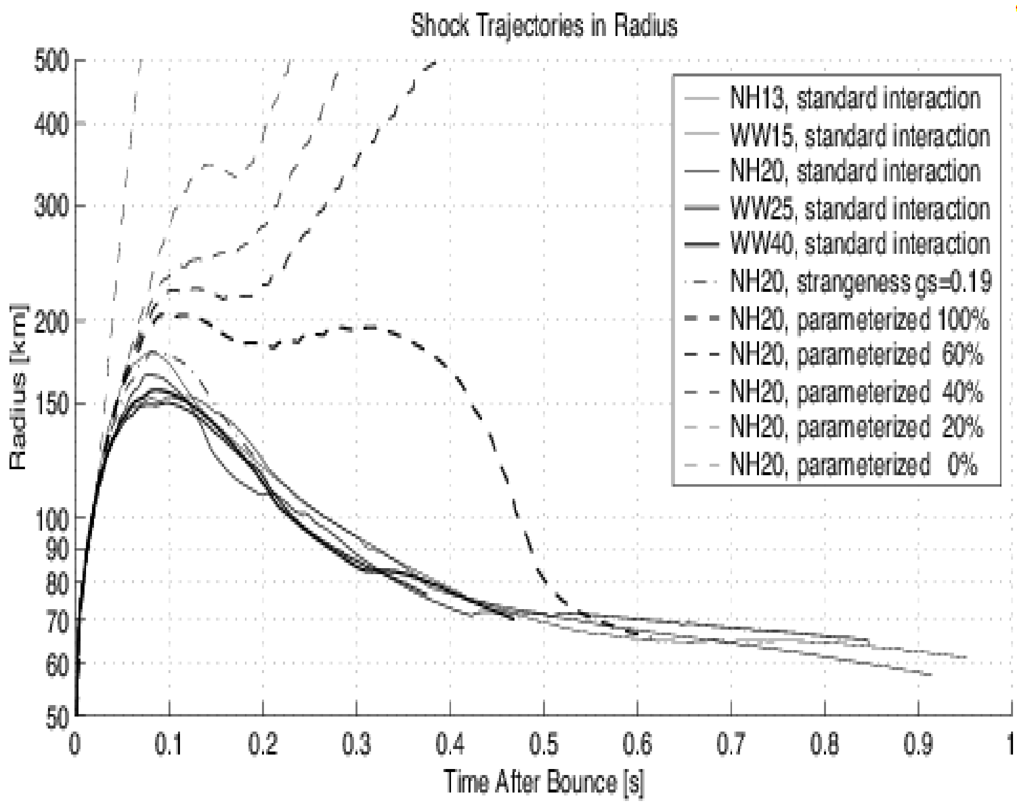
Liebendörfer et al (06) ,Whitehouse et al. (08)

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 prboably includes: 3D, SASI, accoustic modes, MHD, rotation, collective neutrino flav. oscillations? (Duan et al. 07, Dasgupta et al. 08)

“Faking” multi-D hydro with neutrinos



Supernovae do explode, but are changes in ν-scattering or absorption cross sections realistic (uncertainty $\approx$ 20-30%)?

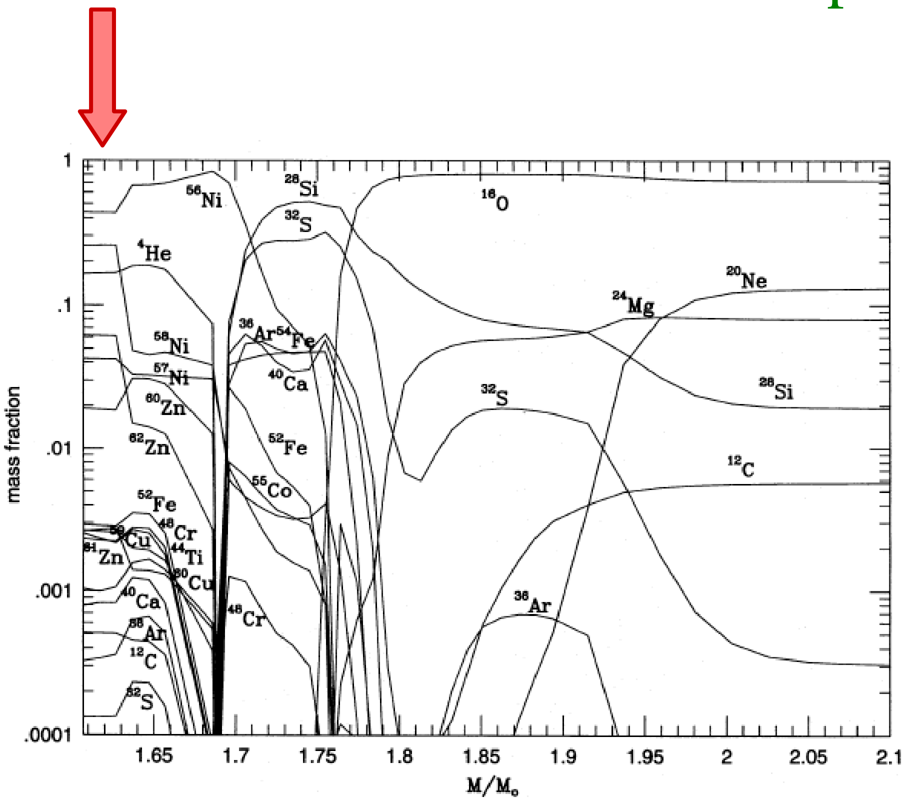
- Multi-D models show convective instabilities
- proto-neutron star core convection leads to faster ν-transport $\rightarrow$ higher L_ν
- This acts similar to reduced scattering cross sections
- convection in deposition zone $\rightarrow$ more efficient energy deposition
- This acts similar to higher absorption cross sections
- $\rightarrow$ multi-D models are expected to explode!

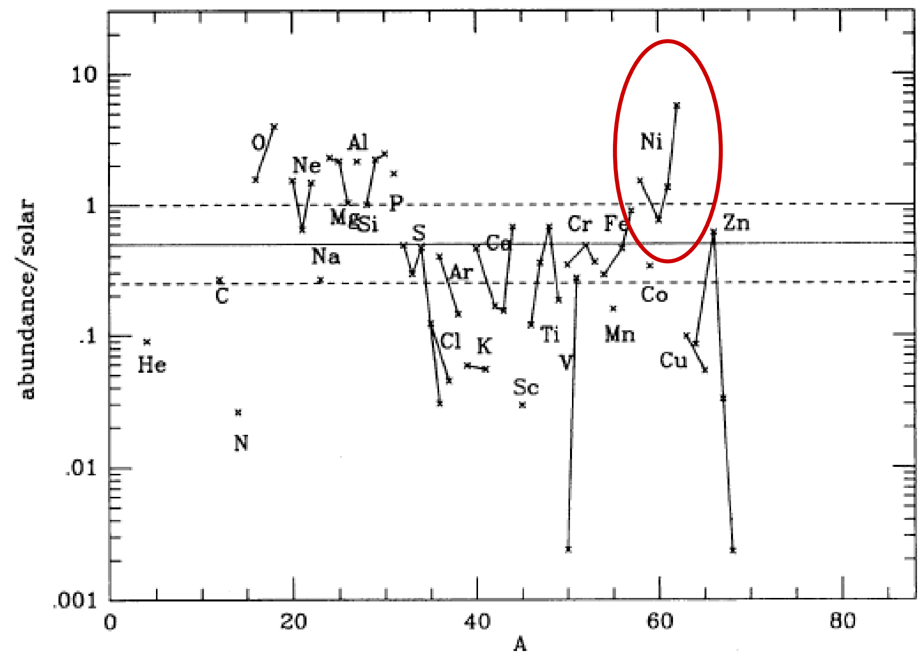
Liebendörfer et al. (2004) code AGILE/BOLTZTRAN with full Boltzmann neutrino transport

We make use of 1D models and reduction factors on neutrino scattering or enlargement factors in neutrino absorption in order to obtain typical explosion energies

Nucleosynthesis problems in "induced" piston or thermal bomb models

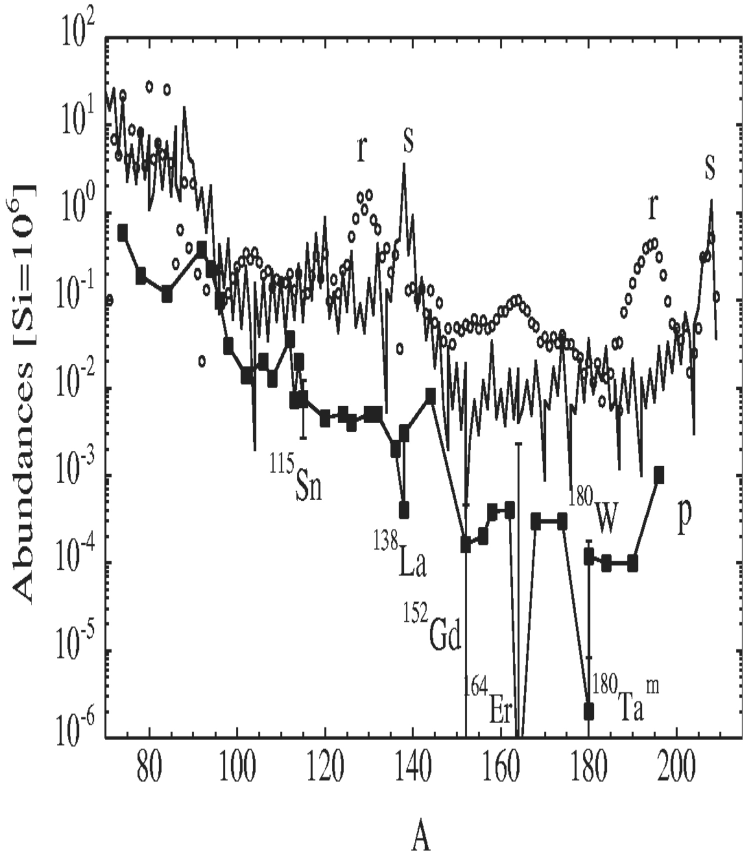
utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of 10^{51} erg



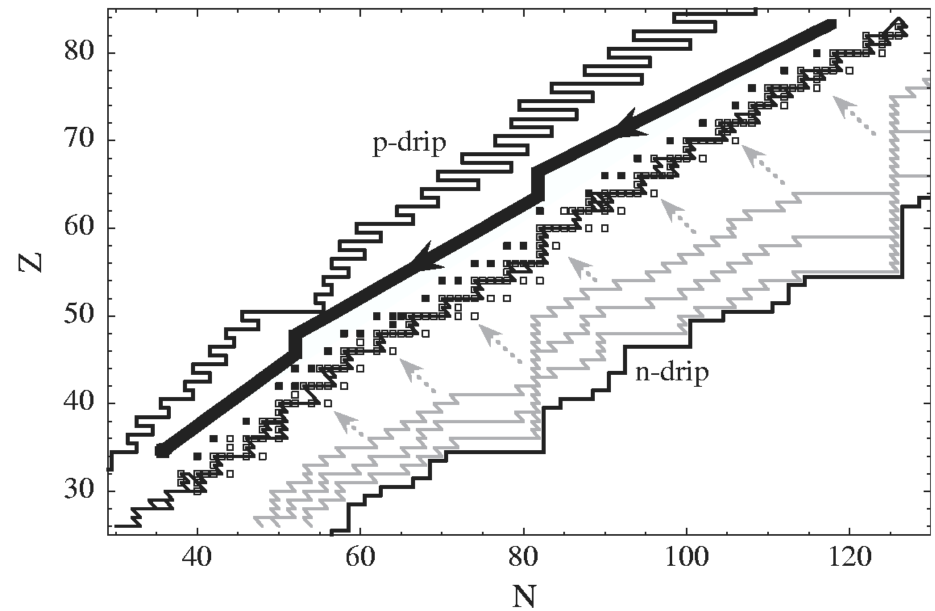


prior results of Thielemann, Nomoto, Woosley, Chieffi .. made use of initial stellar structure (and Y_e!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go mucch beyond Ni!

The p-process

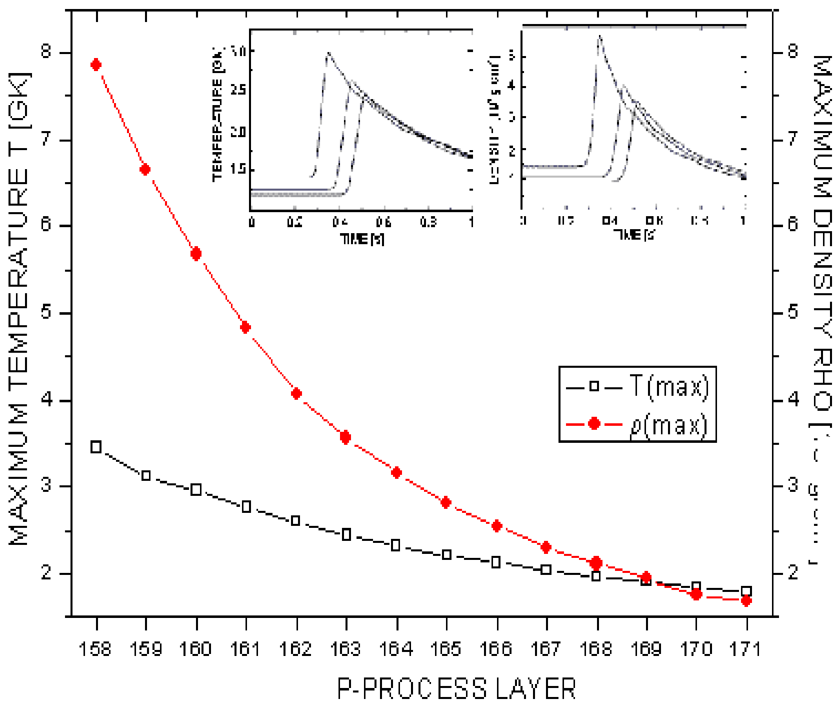


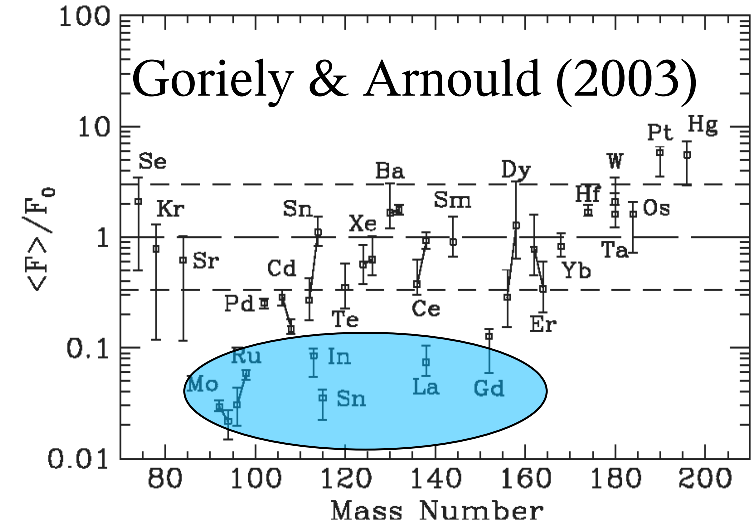
Arnould & Goriely (2003)



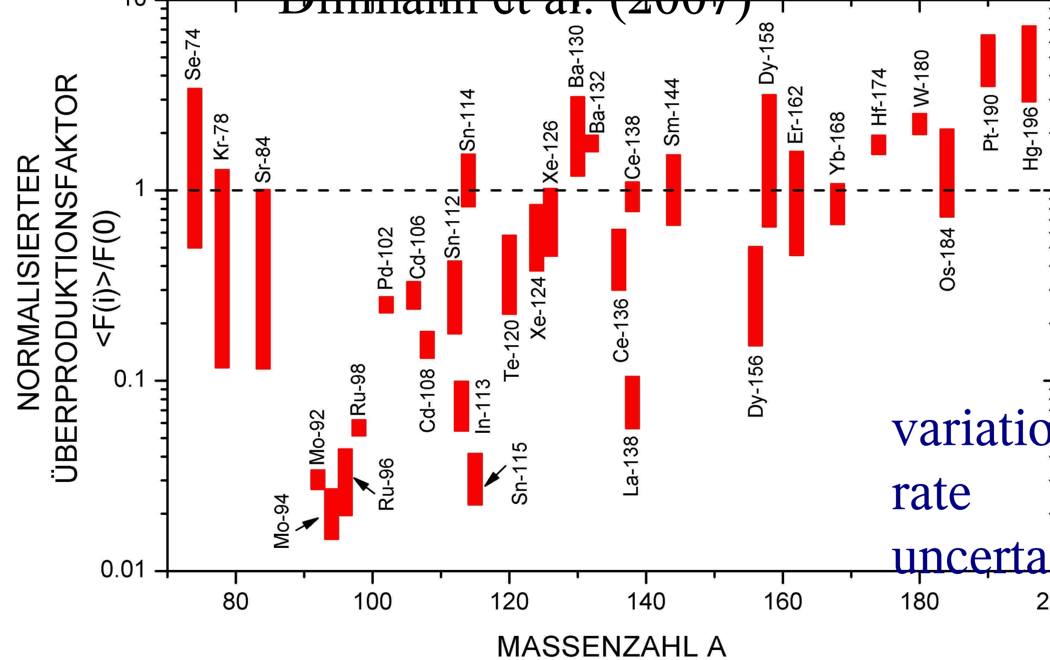
Arnould (1976) and Woosley & Howard (1978) suggested, opposite to initial ideas of B^2FH, photodisintegrations of pre-existing heavy (s-process) nuclei, which occur in the thermal bath of supernova explosions in explosive Ne/O-burning layers with peak temperaturs of 2-3 10^9 K.

explosive Ne/O-Burning zones Comparison with solar p-only nuclei





Dillmann et al. (2007)



variation of rate uncertainties

Dillmann et al. (2007), followin p-(gamma)-process calculation within the framework of Rayet e al. (1995) for a $25M_{sol}$ star c Yoshida et al. (2002) to verify th impact of nuclear uncertainties.

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

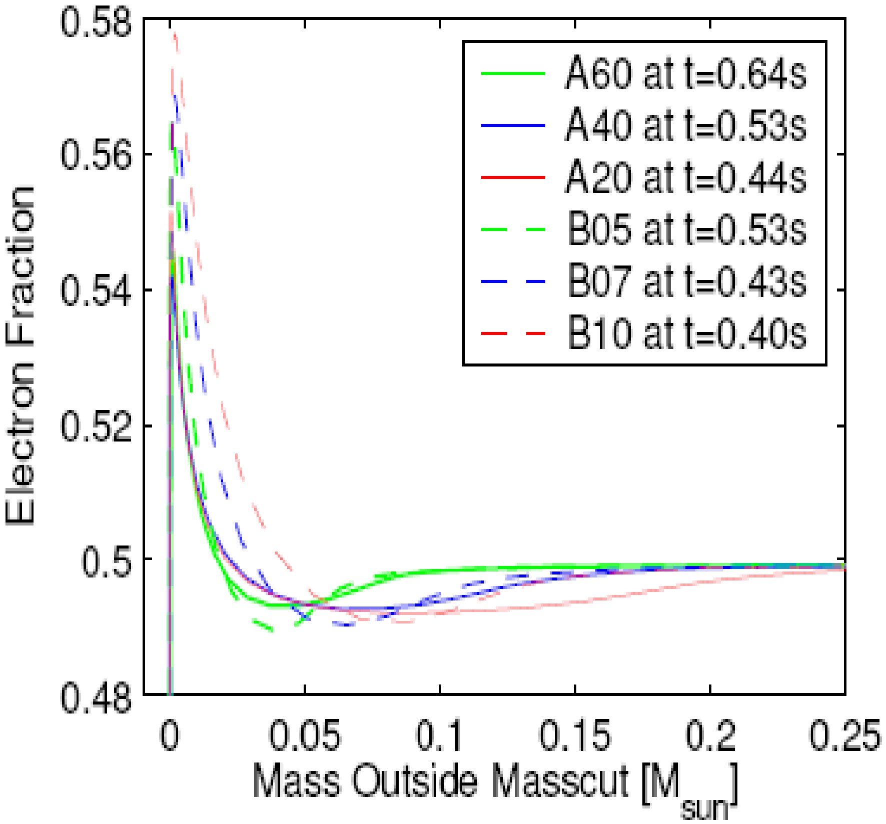
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

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

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

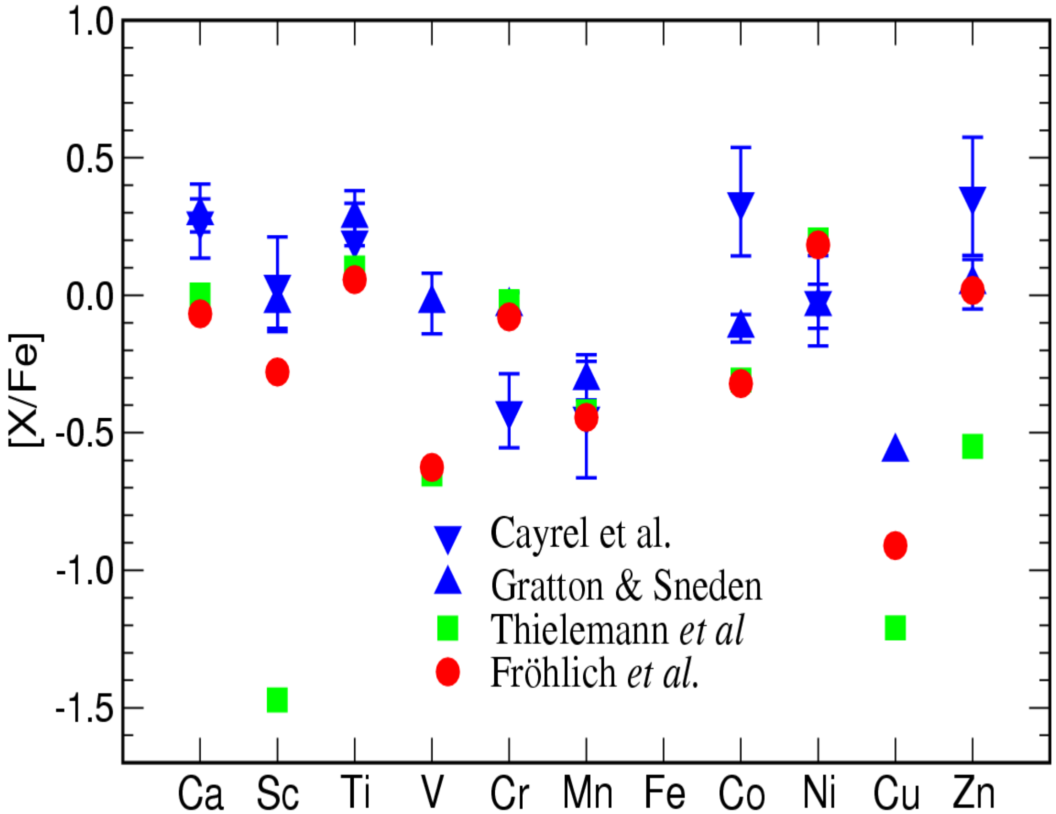
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- 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



Fröhlich et al. (2006a)
A: neutrino scattering cross sections scaled (%)
B: neutrino absorption cross sections scaled (factor)

Improved Fe-group composition



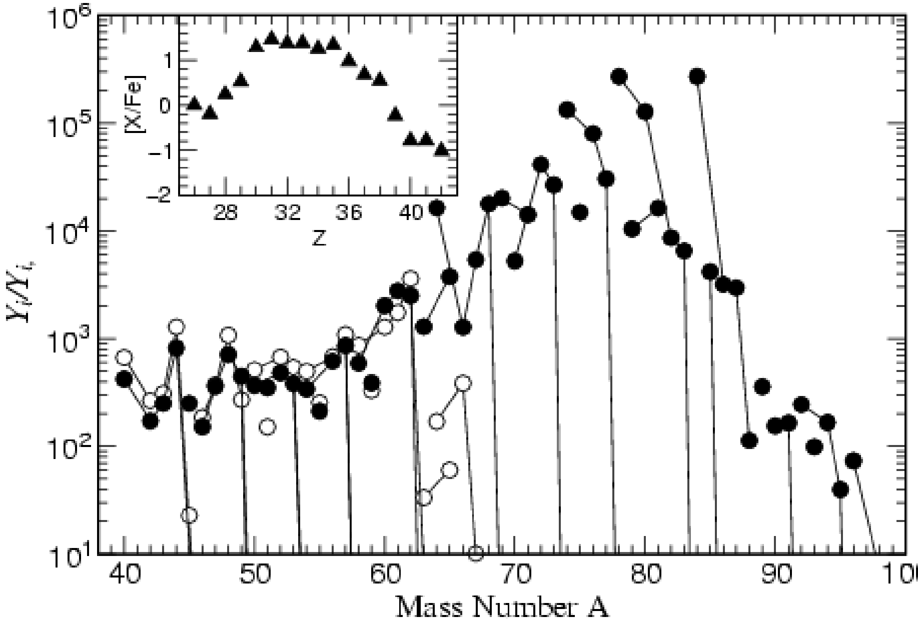
Fröhlich et al. (2004,2006a), see also Pruet et al. (2005)

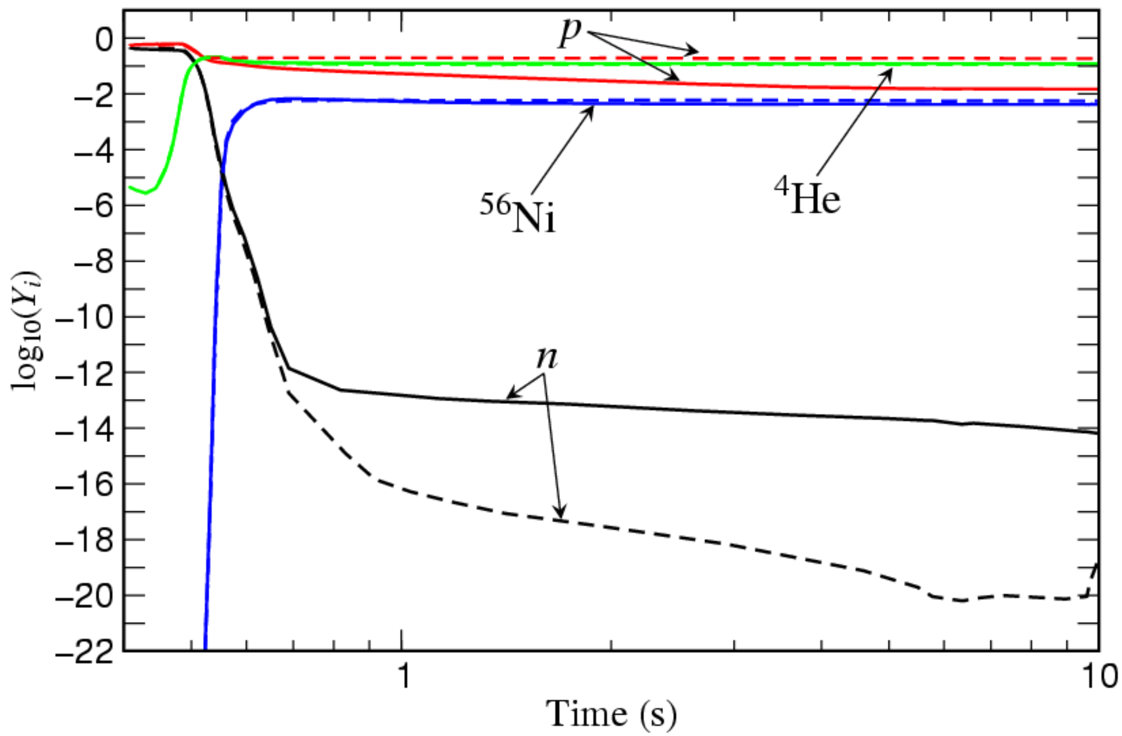
Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

This effect improves the Fe-group composition in general and extends it to Cu and Zn!

νp–process

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



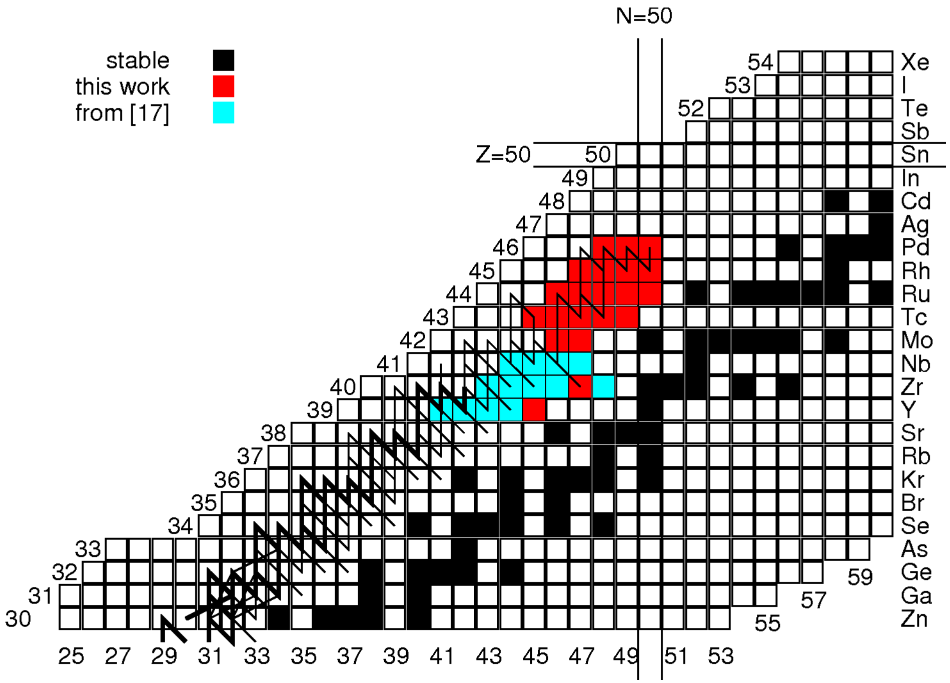


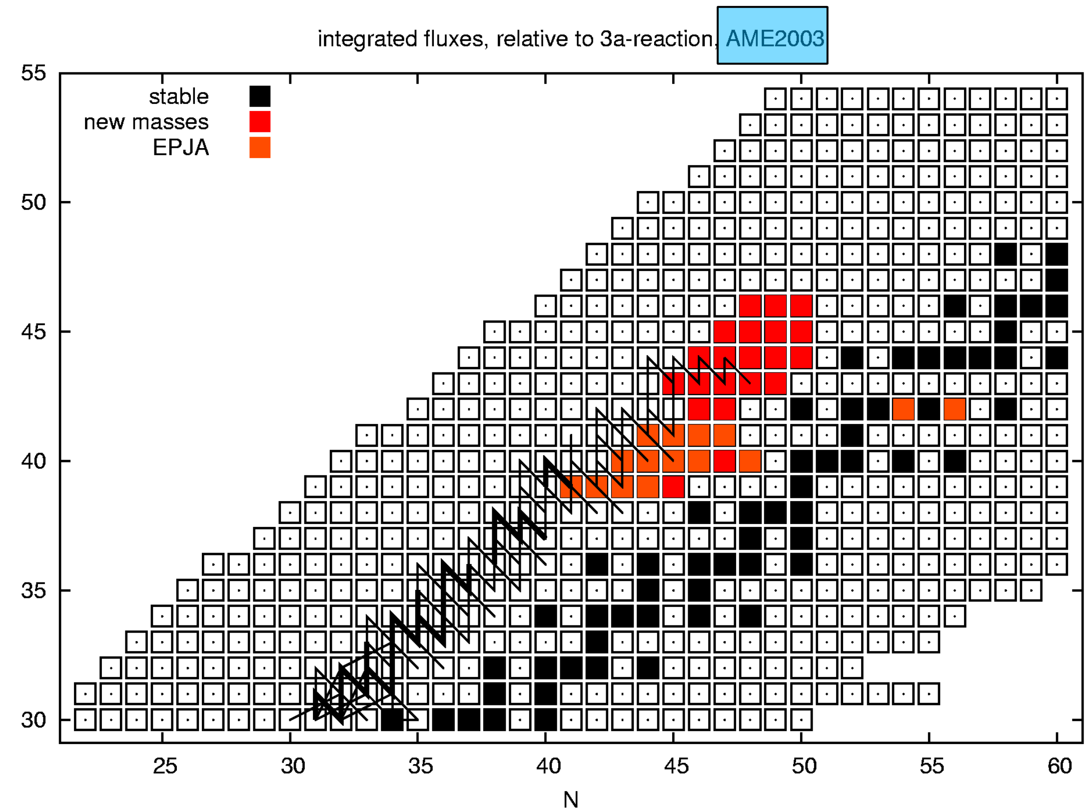
Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei),
see also Pruet et al. (2006), Wanajo (2006)

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.

Effect of new mass measurements Jyväskylä and GSI

Weber et al. (2008), see also Hoffman et al. (2008)

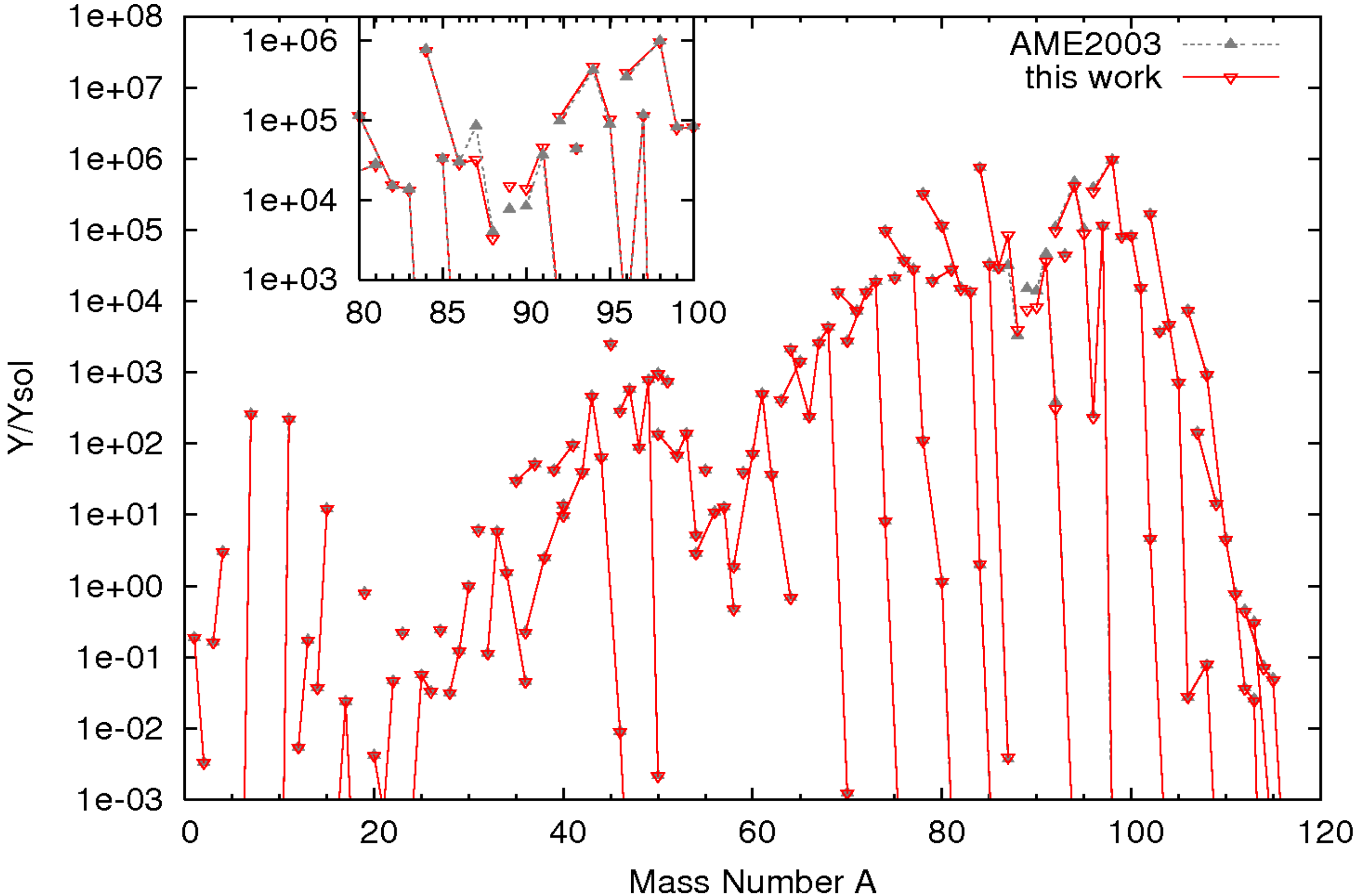




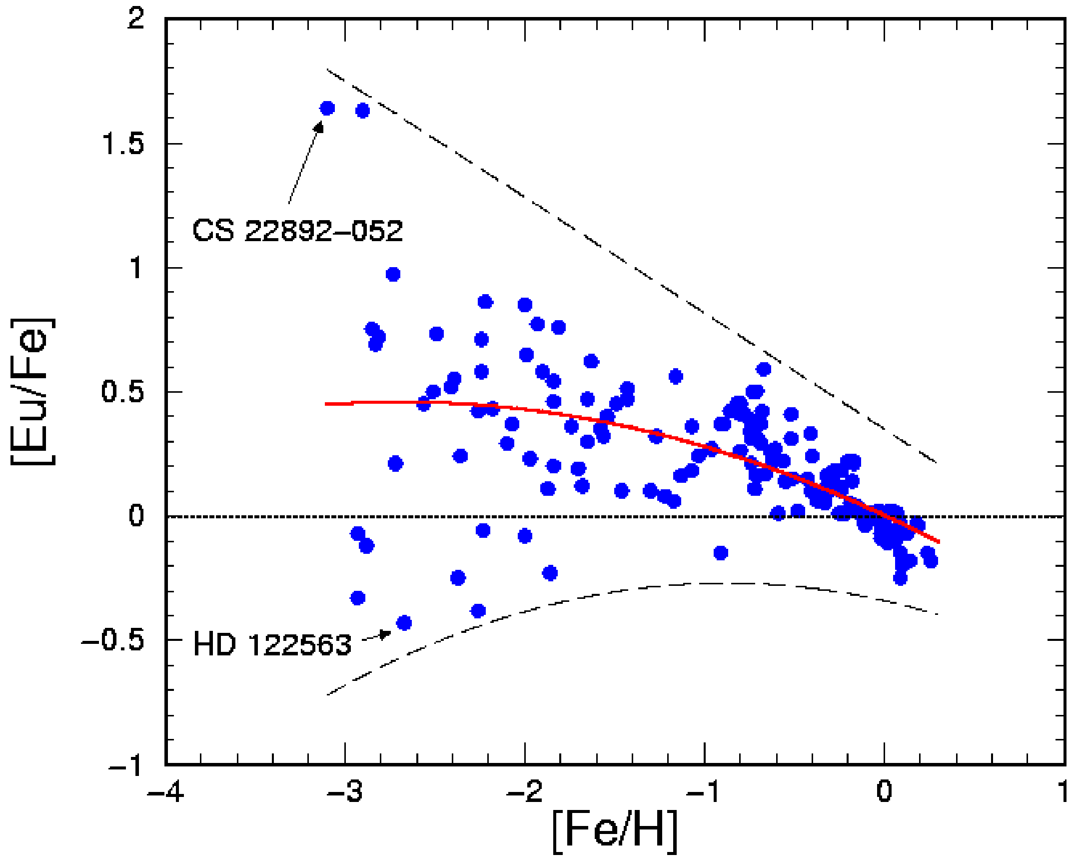
In addition, variations in explosion dynamics and neutrino luminosity are expected

permits to explain on the one hand that in some cases only large overabundances of Sr are found, on the other hand early abundances of Sr,Y, Zr as well as possible p-process nuclei up to A=120

Effect of Mass Changes



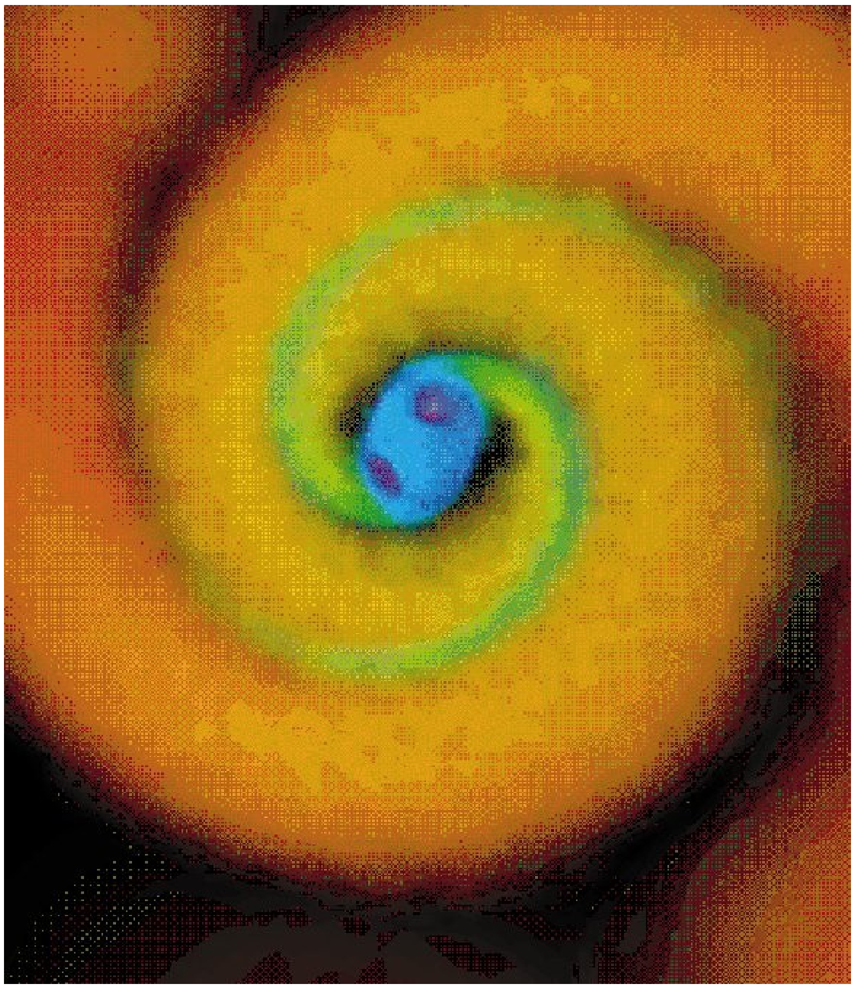
Constraints on r-Process Sites



"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)

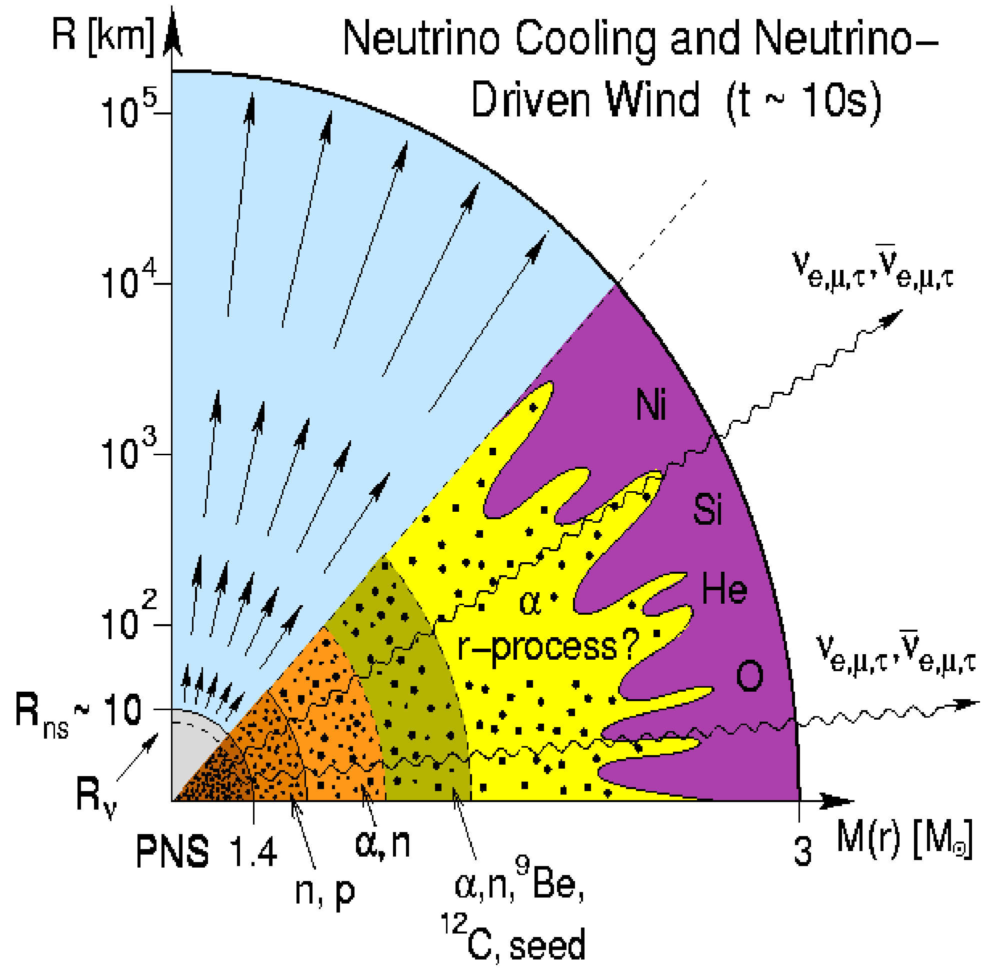
What is the site of the r-process?

from S. Rosswog



NS Mergers, problems: ejection too late in galactic evolution

from H.-T. Janka



SN neutrino wind, problems: high enough entropies attained?

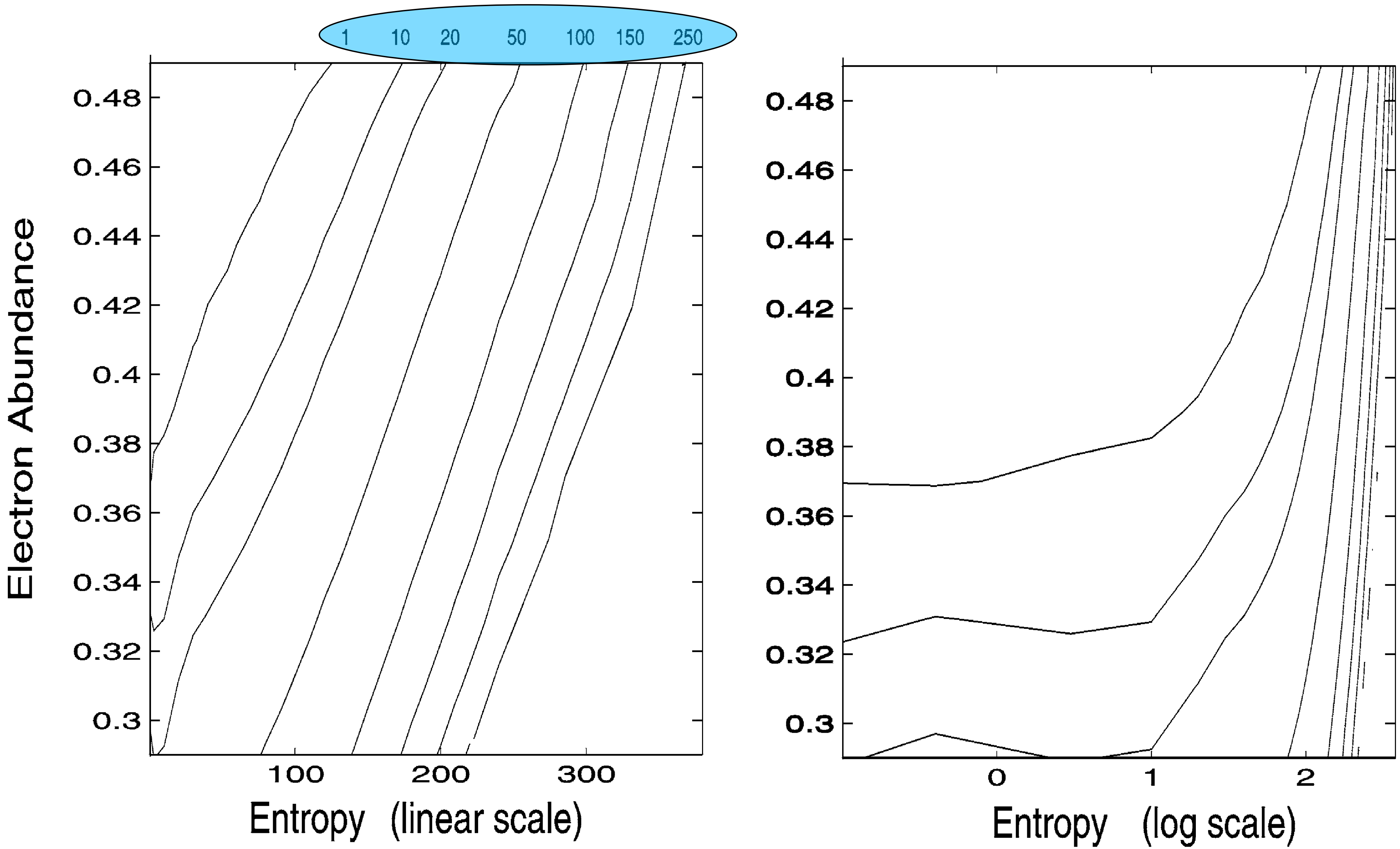
Working of the r-Process

- (complete) Explosive Si-Burning
- 1. (very) high entropy alpha-rich (charged-particle) freeze-out with upper equilibrium 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

  (Meyer, Howard, Takahashi, Hoffman, Qian, Woosley, Freiburghaus, Thielemann, Mathews, Kajino, Wanajo, Otsuki, Terasawa, Farouqi, Goriely ...)
- 2. low entropies and normal freeze-out with very low Y_e, leading also to large n/seed ratios
  - S_n function of Y_e

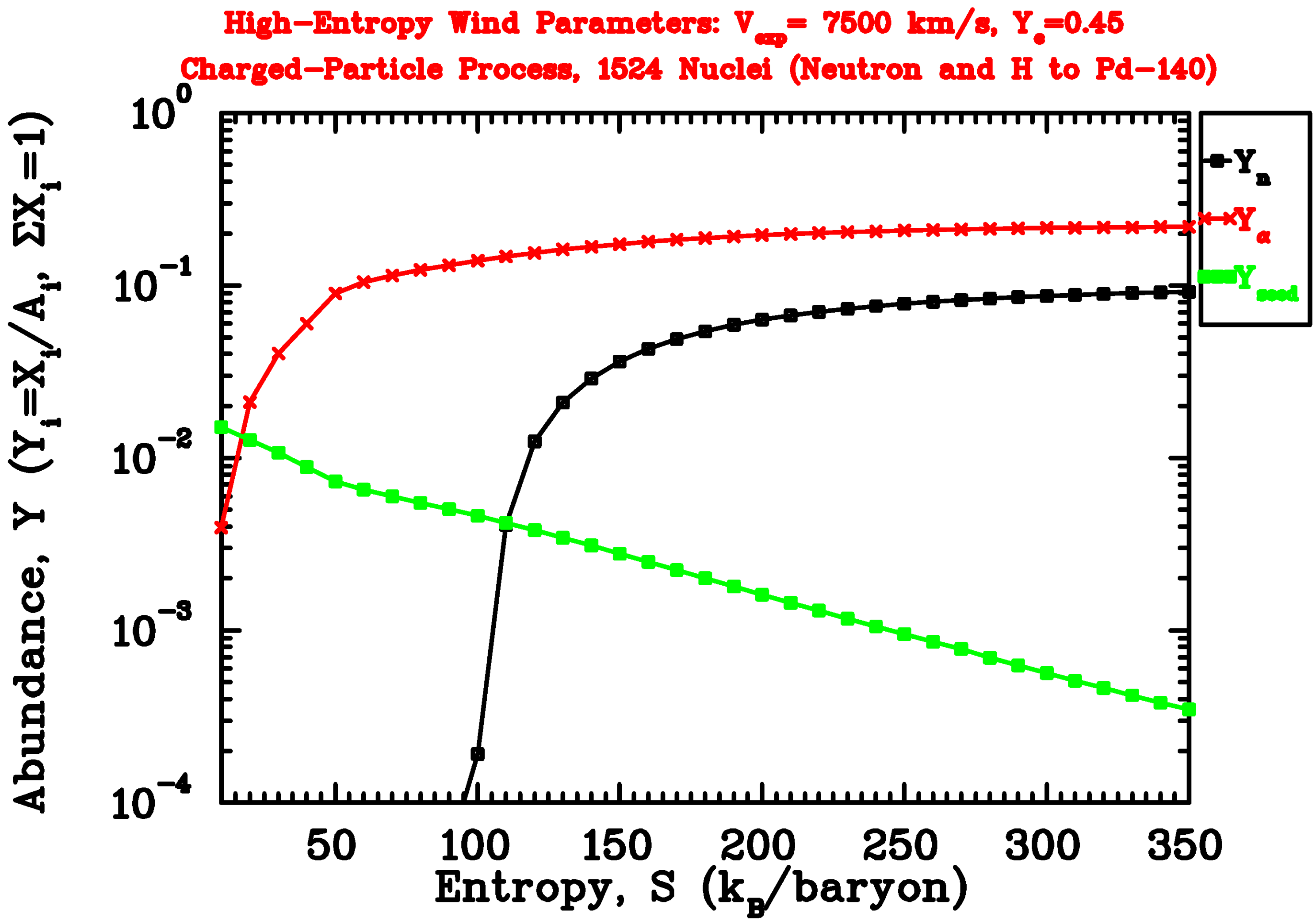
  (Freiburghaus, Rosswog, Thielemann)

n/seed ratios as function of S and Y_e



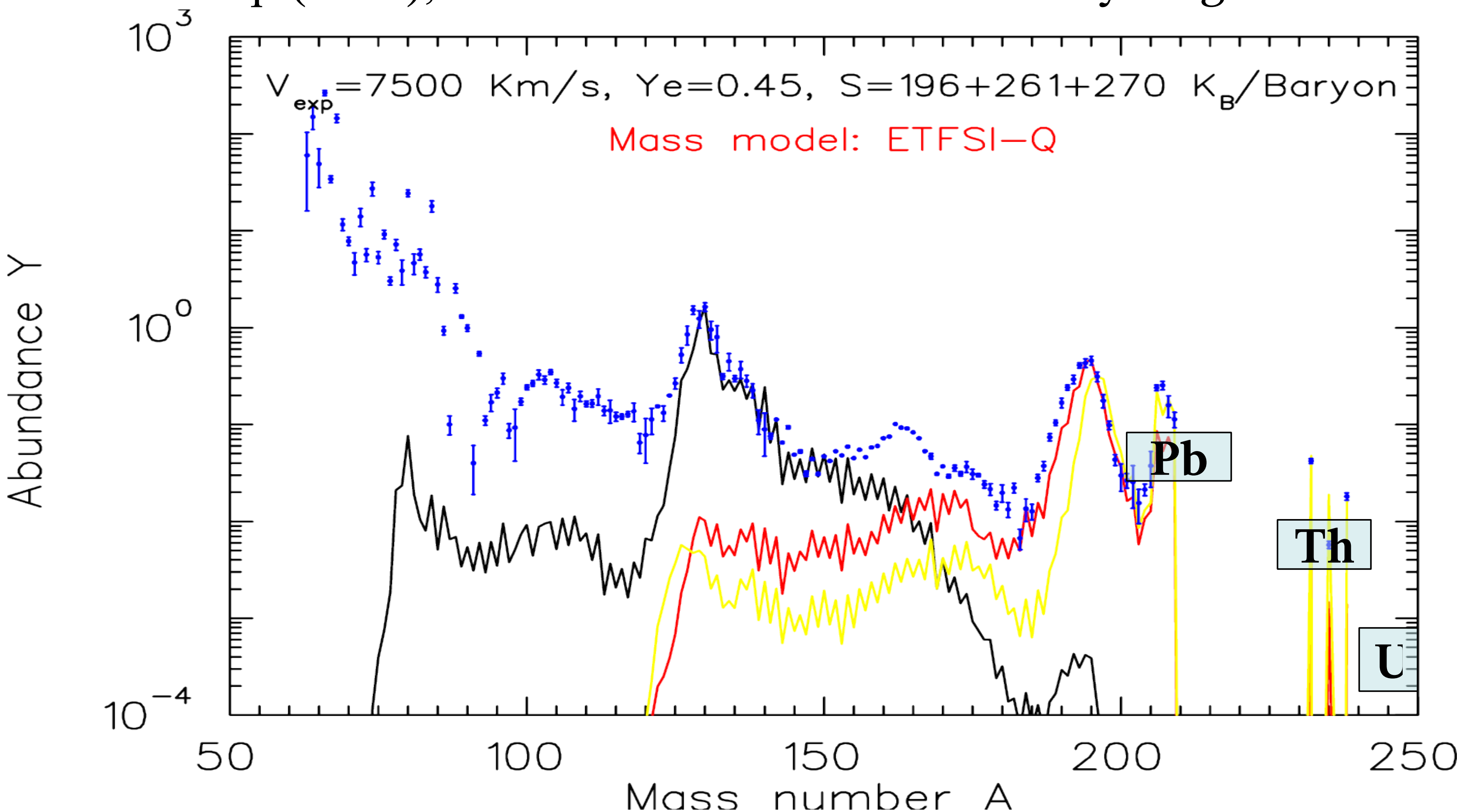
Freiburghaus et al. (1999)

n/seed ratios for high entropy conditions are are function of entropy



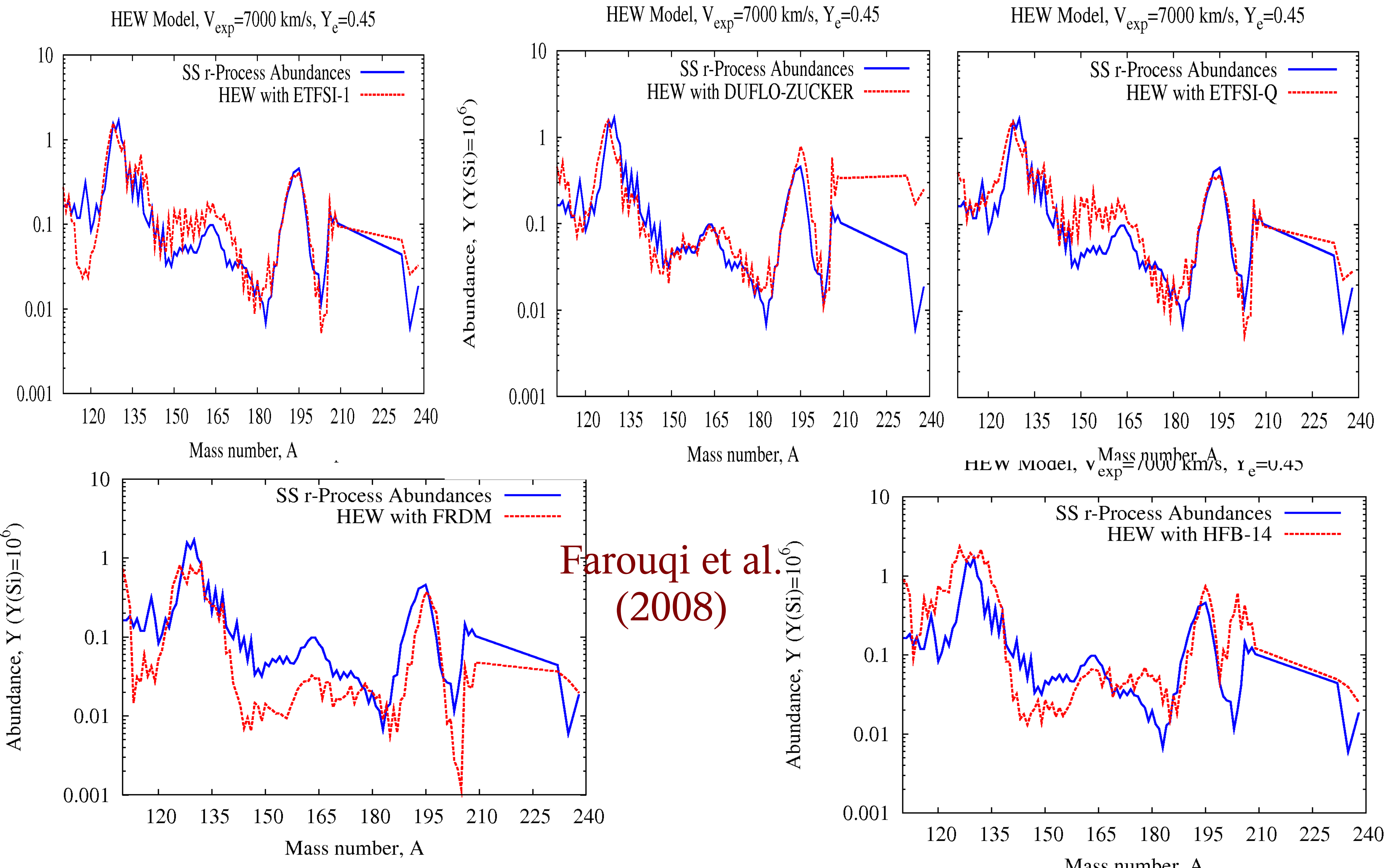
Individual Superpositions of Entropy Components

Farouqi (2005), above S=270-280 fission back-cycling sets in



Thesis K. Farouqi 2005: entropies up to about 280, higher entropies lead to fission back-cycling! Low (high) entropies produce essentially an alpha-rich freeze-out around A=80 without neutrons left and leave abundance features which do not fit the A=80 peak. However from meteorites as well as low metallicity stars we know that another process (weak r-process) must be responsible here.

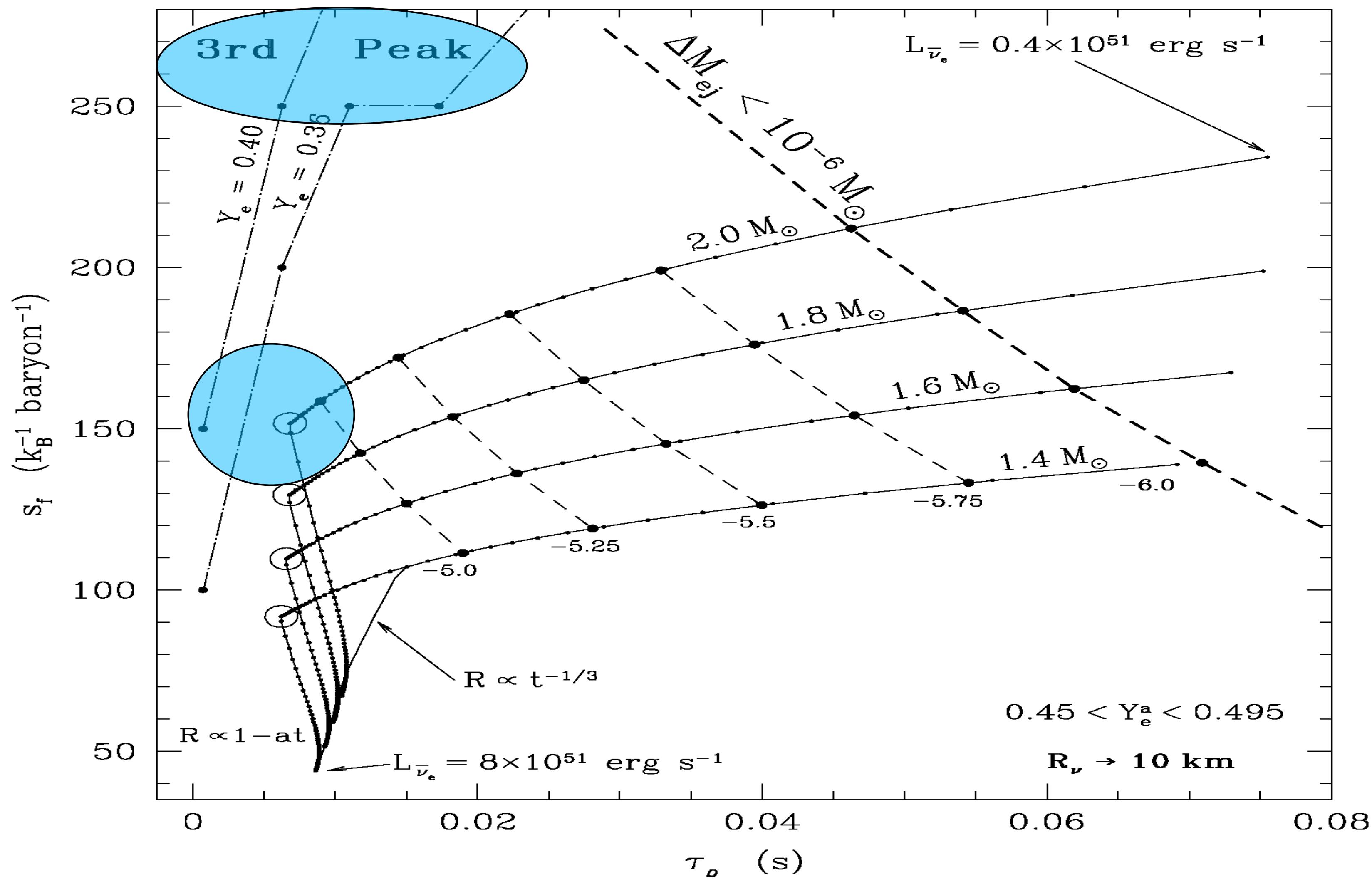
Superposition of entropies for different mass models



Farouqi et al. (2008)

a superposition of expansion velocities might be needed as well, if running into preexpanded material, shocks etc. (Arcones et al. 2007, Panov & Janka 2008)

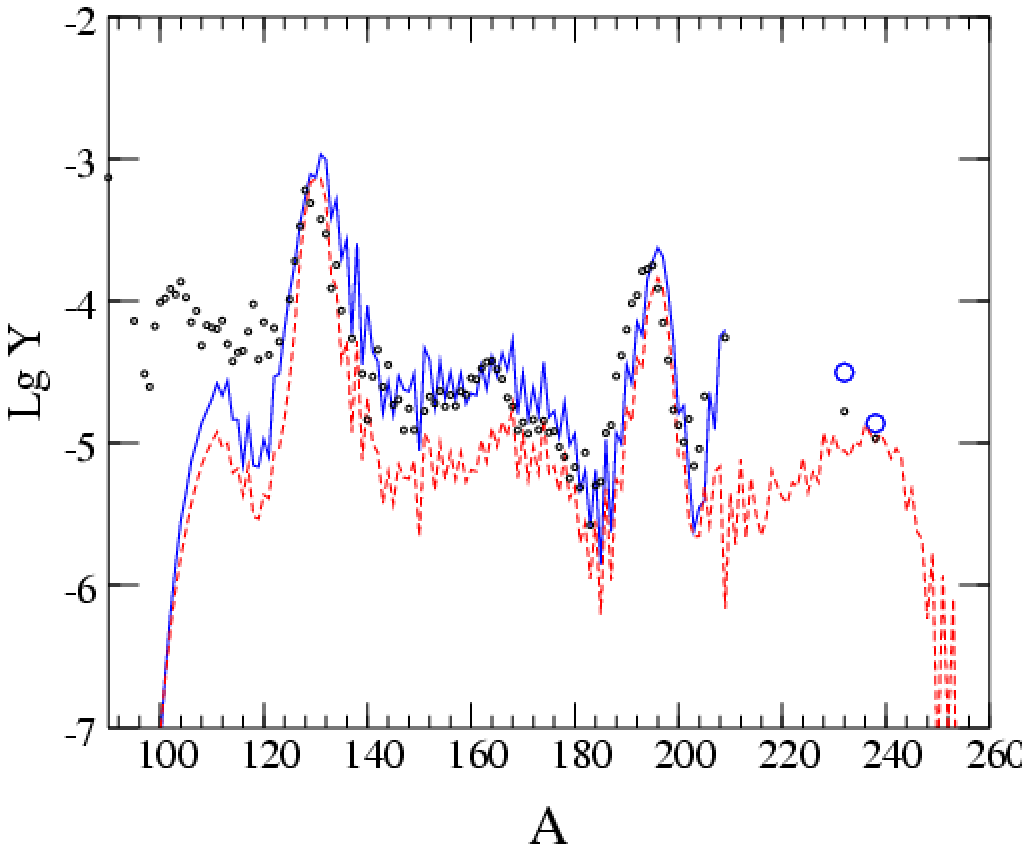
Finding high entropies seemed extremely difficult in neutrino wind (Thompson et al. 2001)!



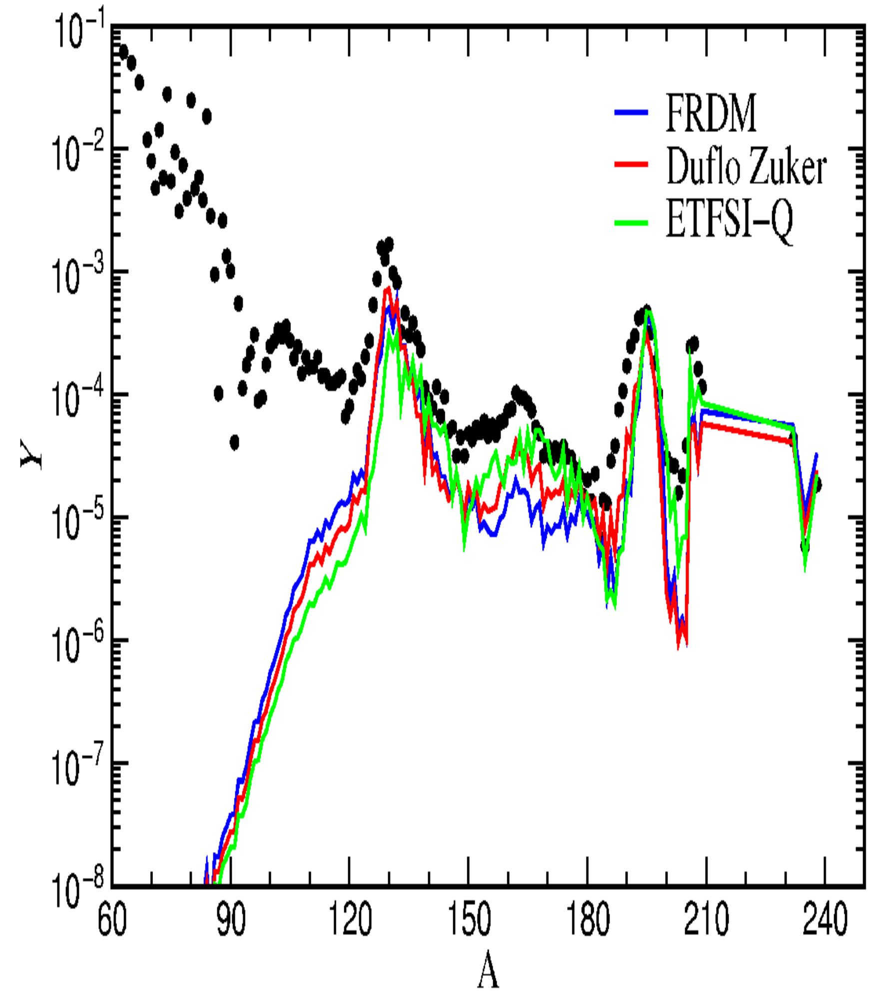
Only very massive neutron stars seemed to come close to conditions (entropies) which can produce the third peak!!!

Fission Cycling in Neutron Star Mergers

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



Panov and FKT (2007) with parametrized fission yield contribution



Martinez-Pinedo et al. (2006)

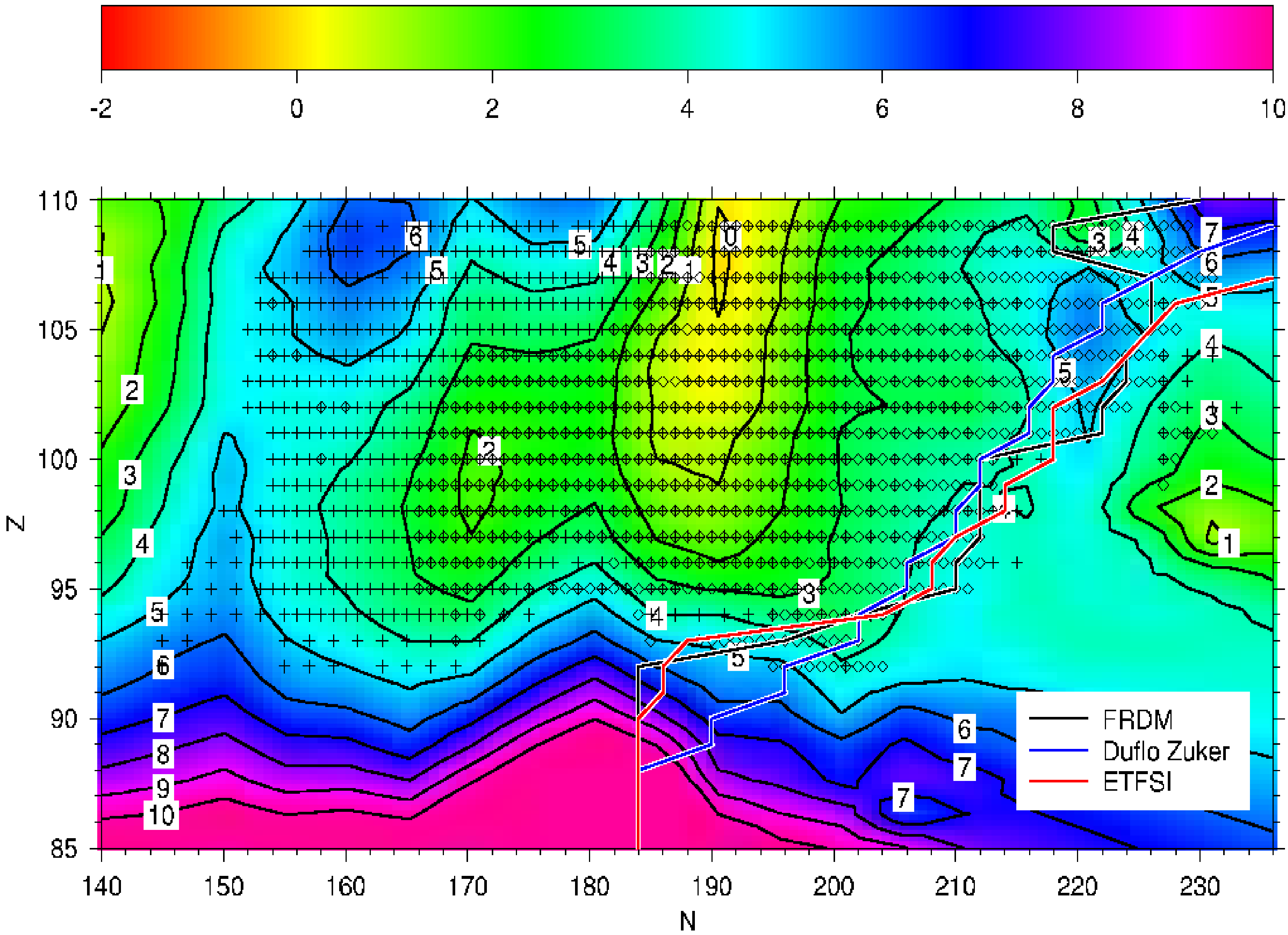
in principle contradicted from gal. evol. calc., but similar conditions in SN polar jets? (Cameron 2003, see also recent calculations with rotation and magnetic fields!)

Entropies beyond 270 k_B/nucleon

- adiabatic expansions (Freiburghaus et al. 1999), expansion timescale 50ms, Ye=0.45.
- full nuclear network (n,p,..Eu) before alpha-rich freeze-out
- r-process code Z<110, A<340 (Mocelj, Martinez-Pinedo)
- n-capture and (n,f) cross sections (Panov, Rauscher, Thielemann)
- beta-decay rates (Möller, Pfeiffer, Kratz) and beta-delayed fission
- neutrino absorption and induced fission (Zinner, Martinez-Pinedo, Langanke)
- fission fragment distributions from ABLA code (Zinner, Kelic, Schmidt

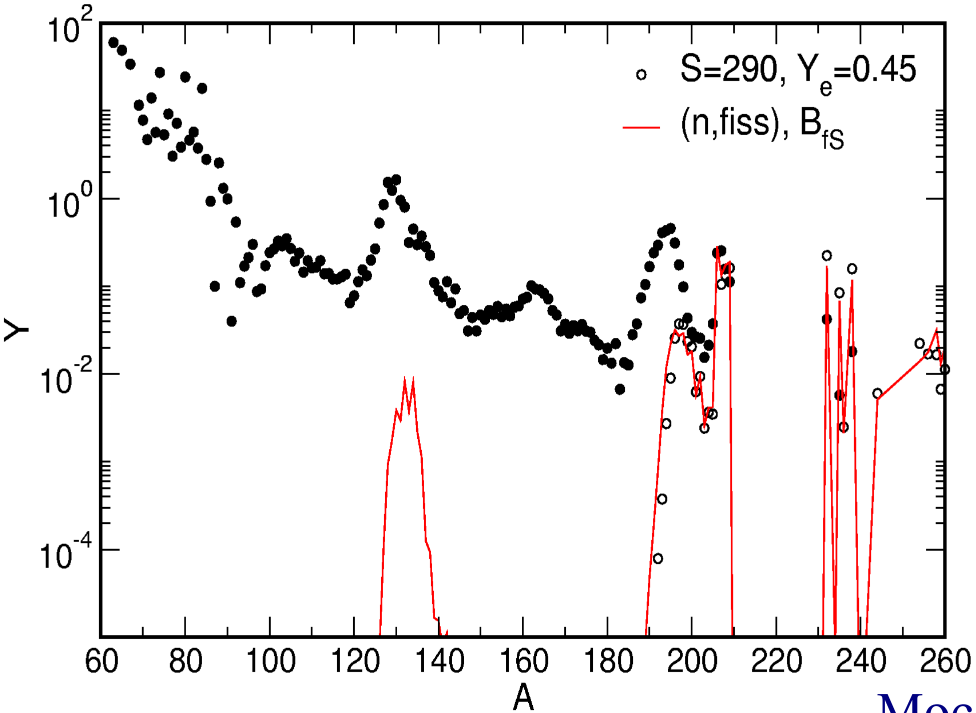
Ph.D. thesis D. Mocelj (2006)

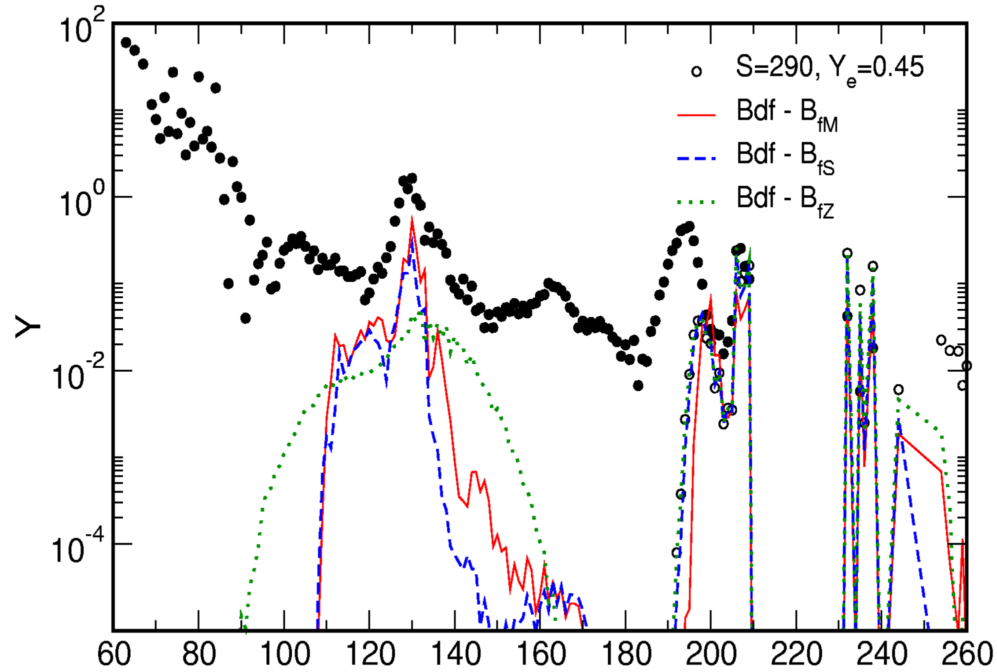
Myers & Swiatecki Barriers



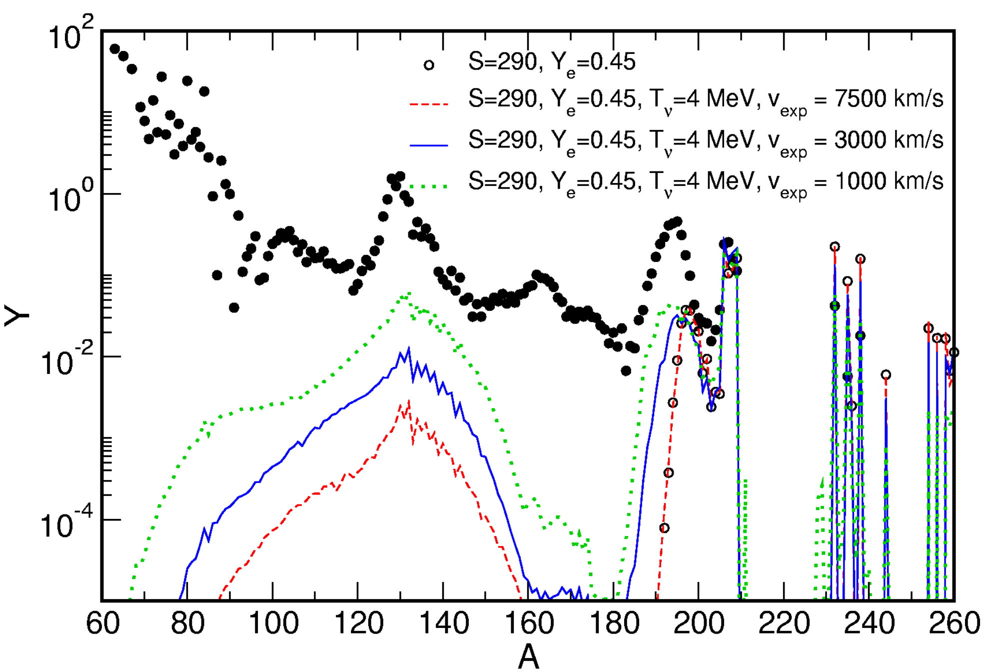
Martinez-Pinedo et al. (2007)

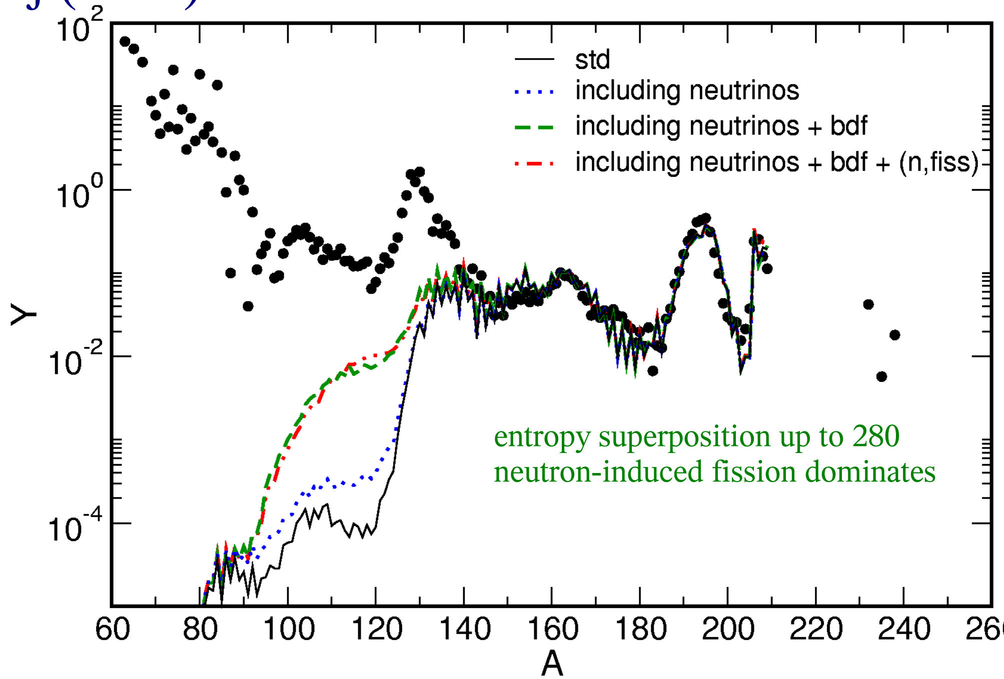
Influence of different fission modes



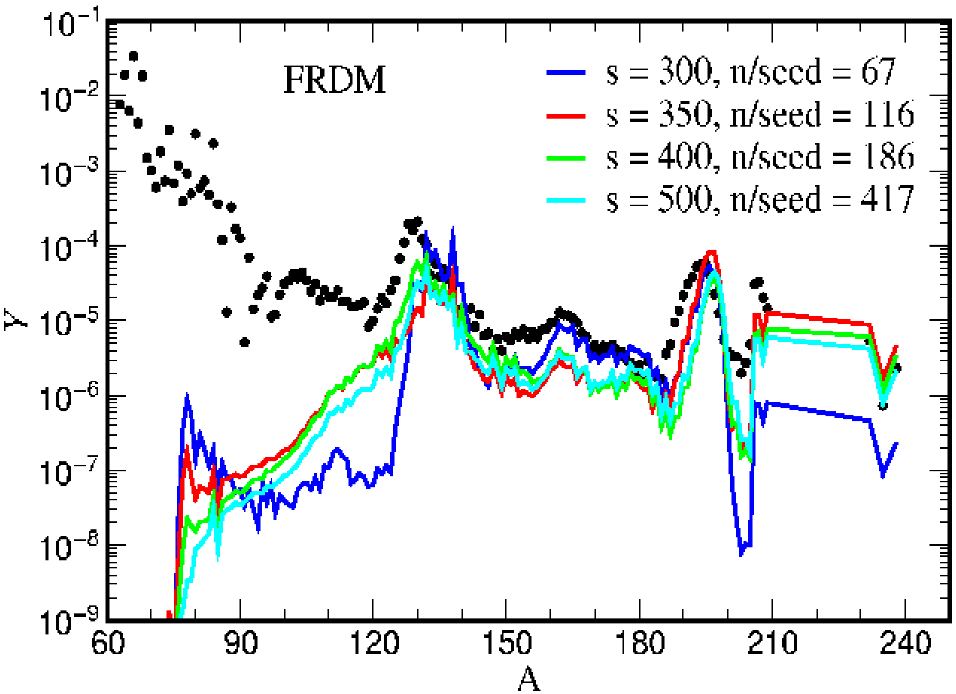


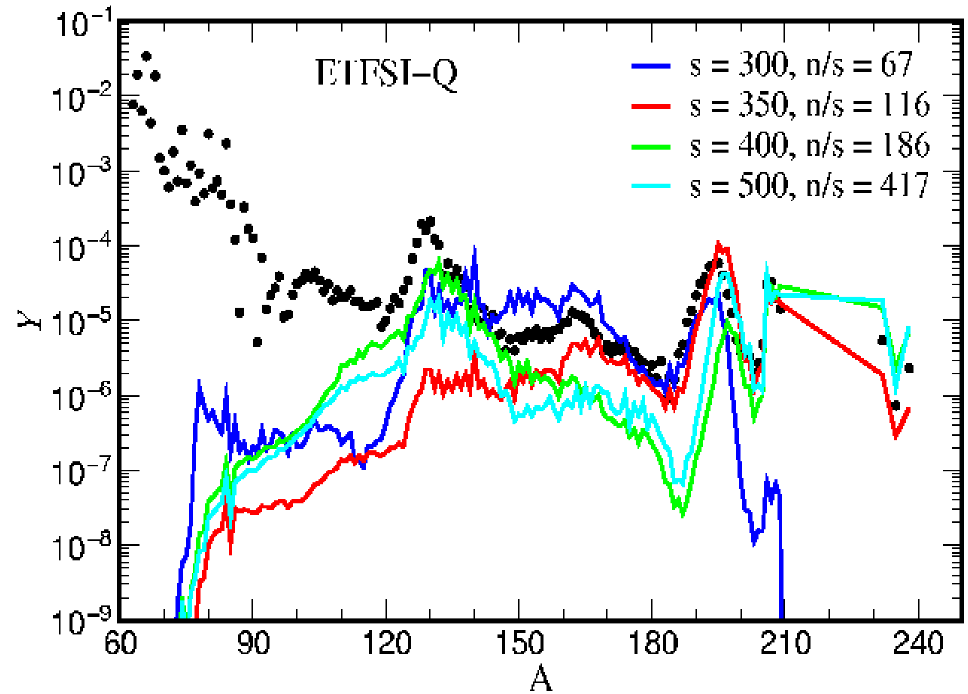
Mocelj (2006)



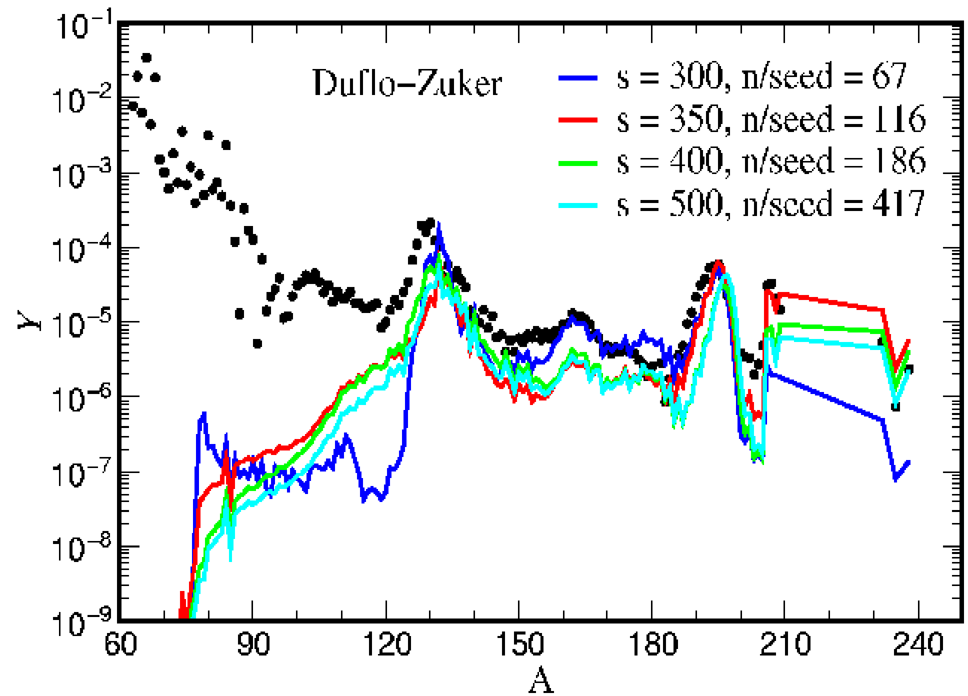


Full fission "cycling" for different mass models





Differences are due to different shell structure at $N = 82$



only one entropy component!

Martinez-Pinedo et al. (2007)

Further alternative Scenarios

accretion disks around black holes after merger events (Surman et al. 2008)

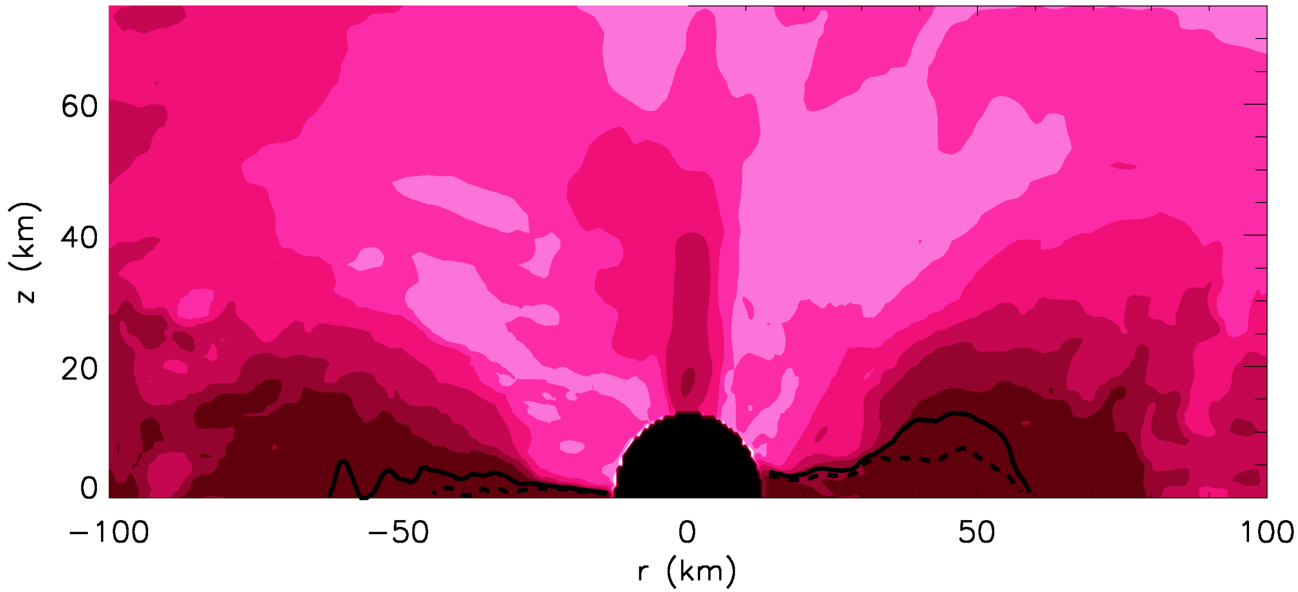


Fig. 2.— Shows density along a vertical slice of the disk. The shaded regions, from lightest to darkest, show densities of $10^{8.5}$, 10^{9}, $10^{9.5}$, 10^{10}, $10^{10.5}$, and 10^{11} g/cm^{3}. The solid line shows the electron neutrino surface while the dashed line shows the electron antineutrino surface. The dark center indicates the inner boundary of the numerical merger model.

r-process possible if choosing a fast ejection/expansion timescale