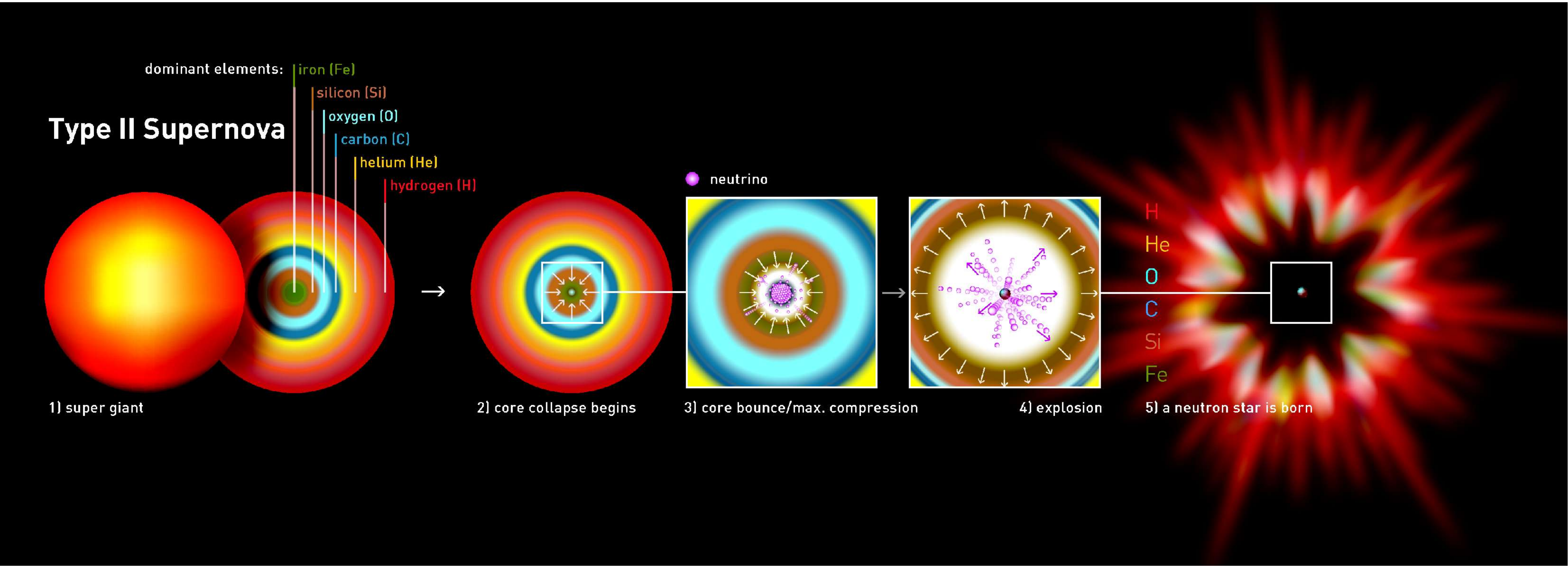
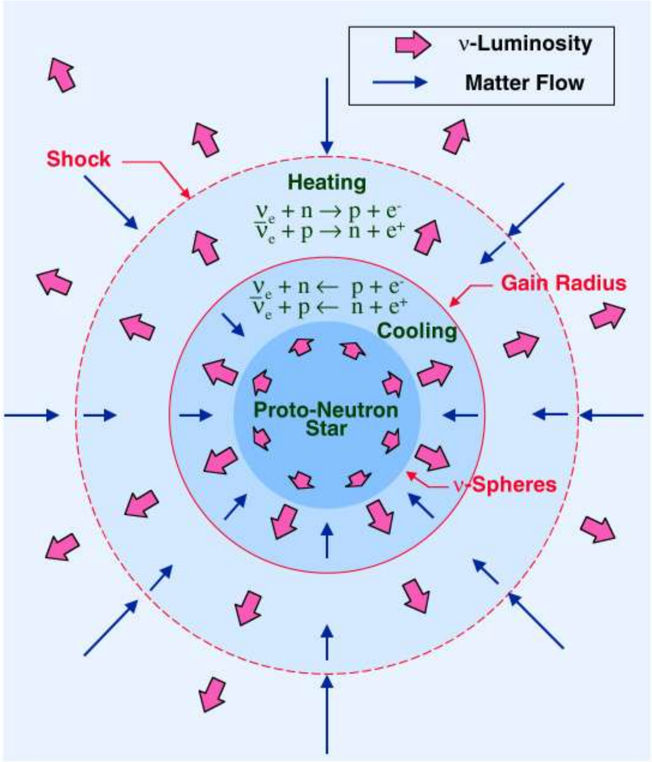
Type II Supernovae (and the r-process?)

- 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 and galactic evolution

Core Collapse Supernovae from Massive Stars



Neutrino-driven Core Collapse Supernovae



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

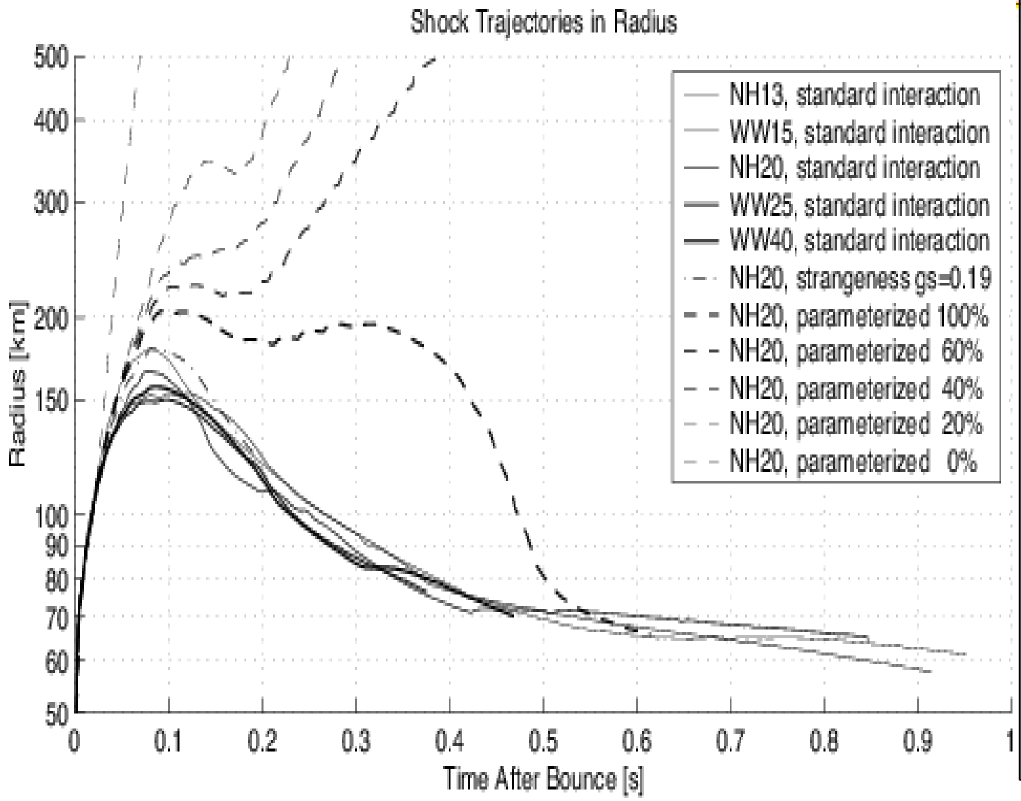
$\nu_e + A' \leftrightarrow A + e^-$ opacity
$\nu + N \leftrightarrow \nu + N$
$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ 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
$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

“Faking” multi-D hydro with neutrinos



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

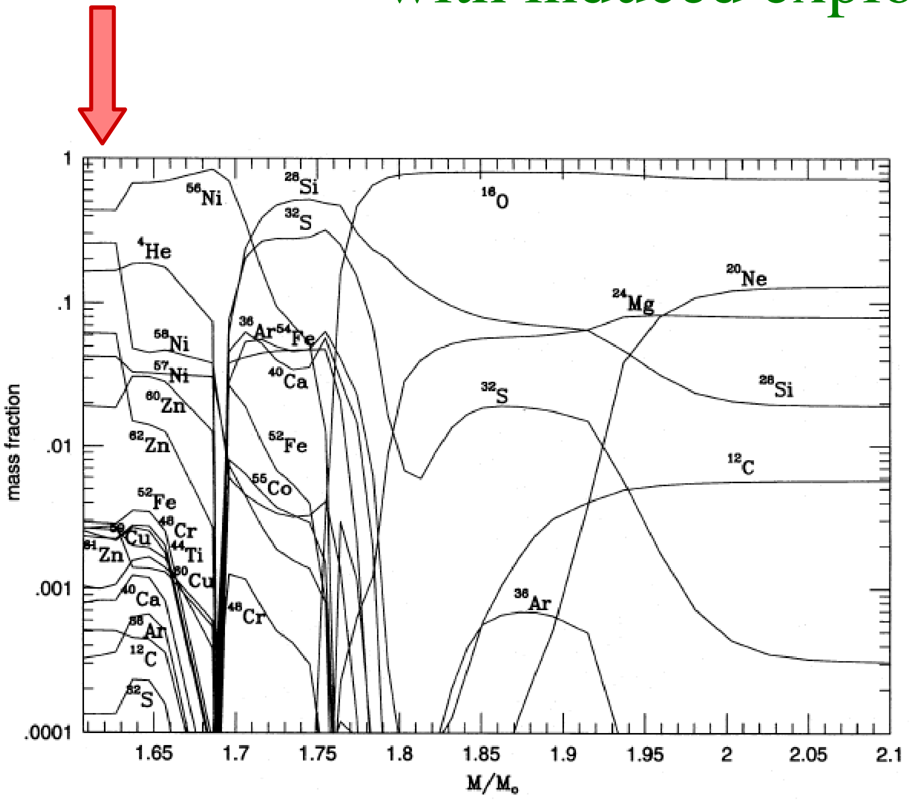
- Multi-D models show convective instabilities
- proto-neutron star core convection leads to faster ν-transport → higher L_ν
- This acts similar to reduced scattering cross sections
- convection in deposition zone → more efficient energy deposition
- This acts similar to higher absorption cross sections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

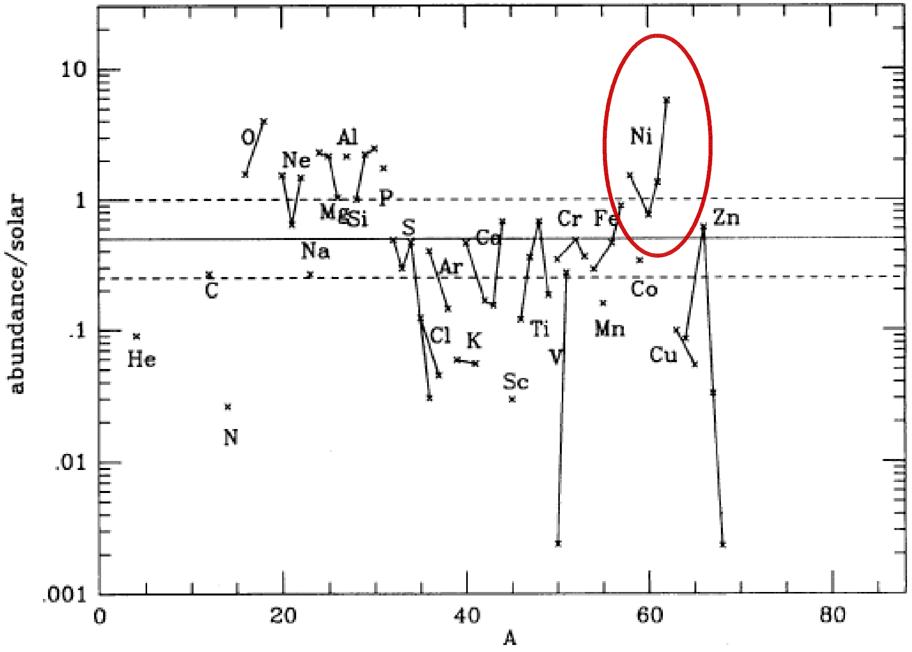
Liebendörfer et al. (2004)
code AGILE/BOLTZTRAN
with full Boltzmann neutrino
transport

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!

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

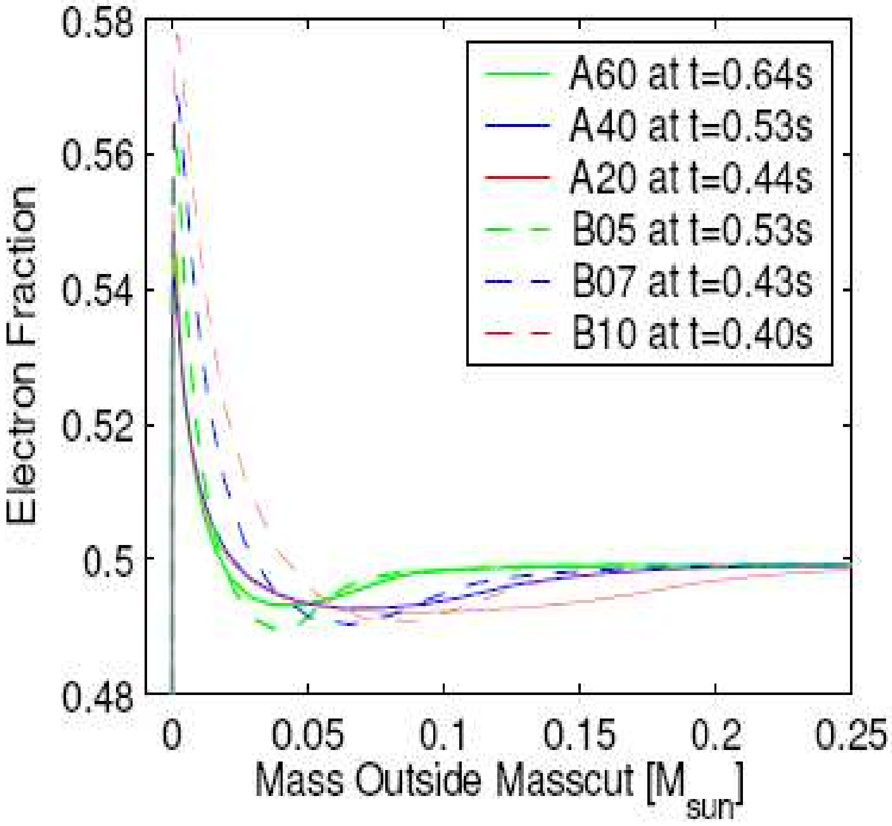
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

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

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

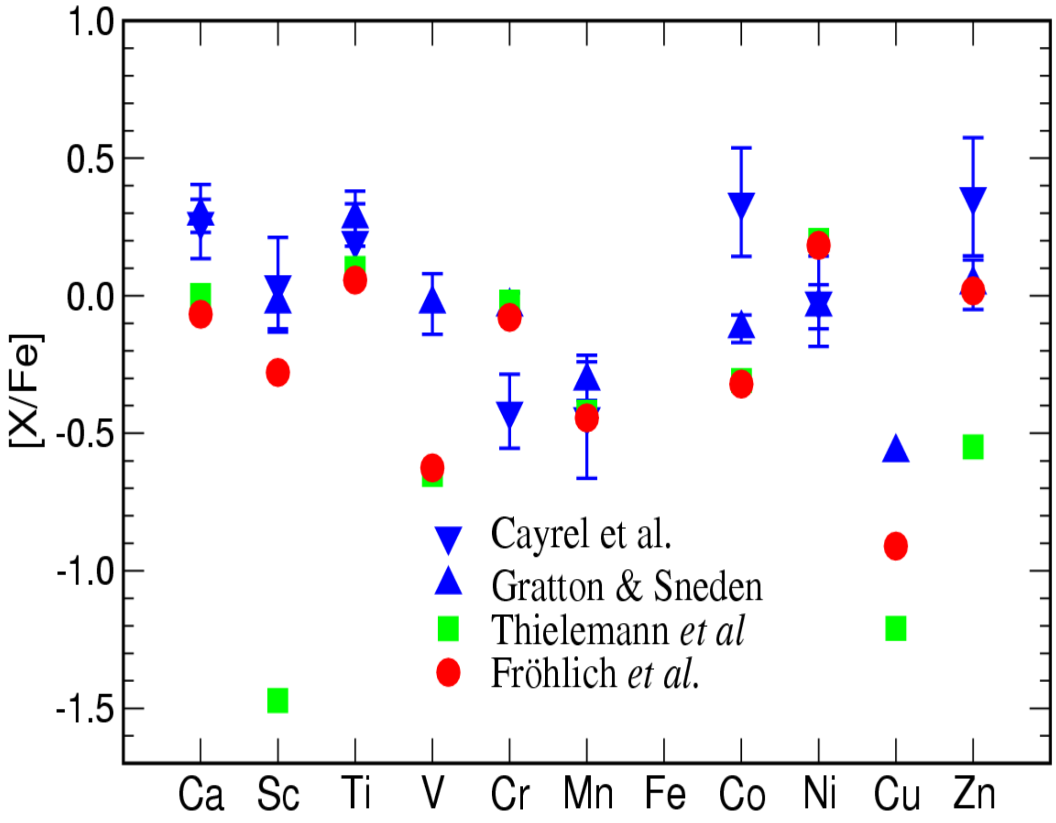
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- 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



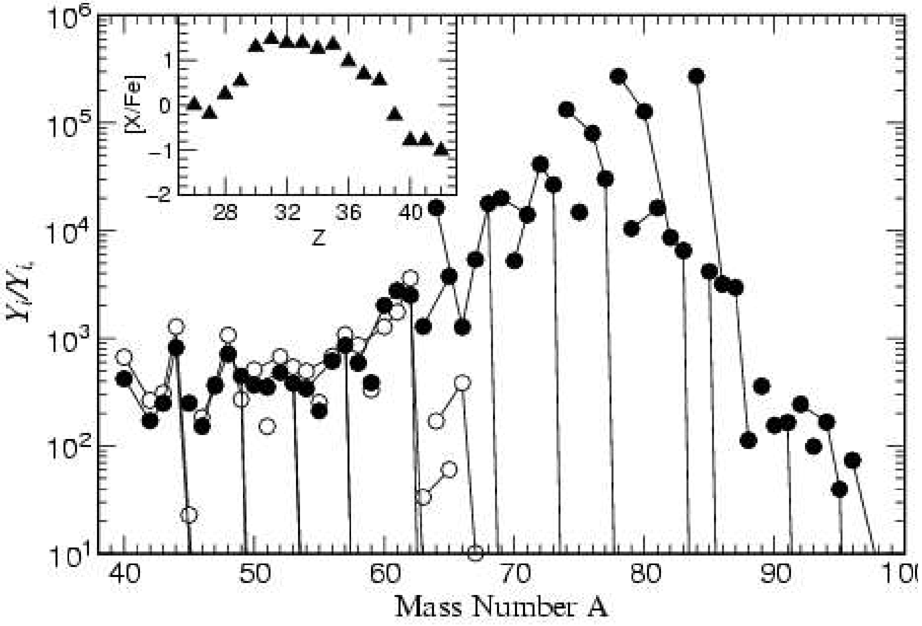
Fröhlich et al. (2006a)

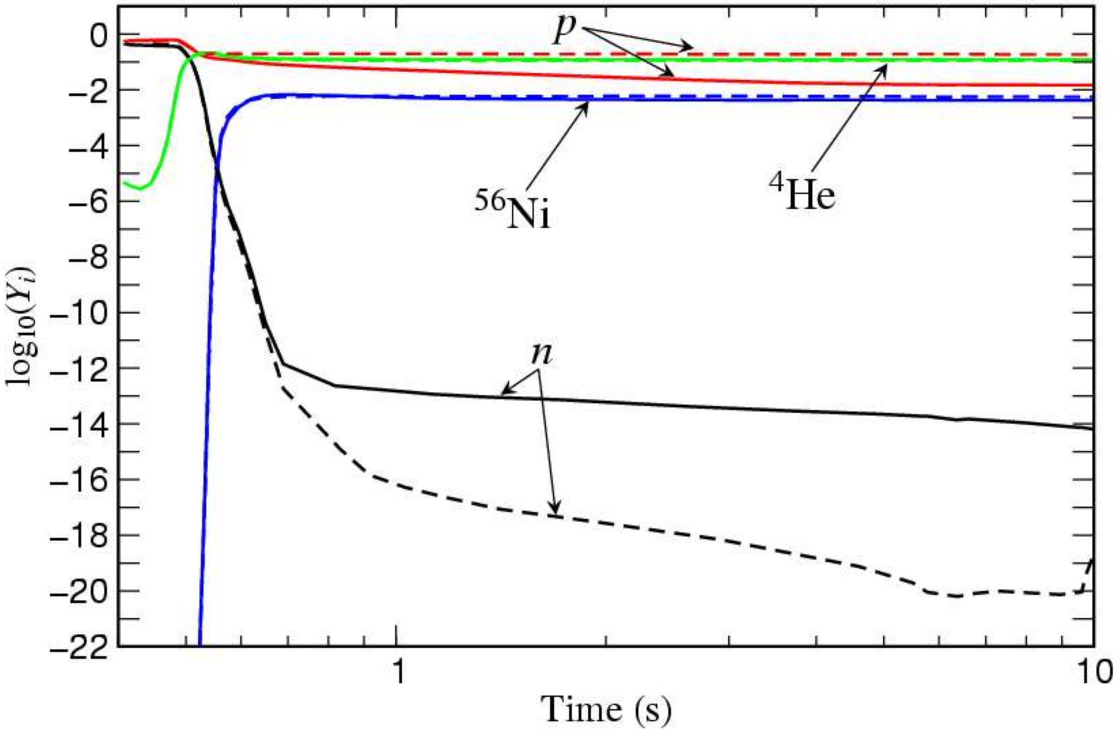
Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

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

νp-process

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





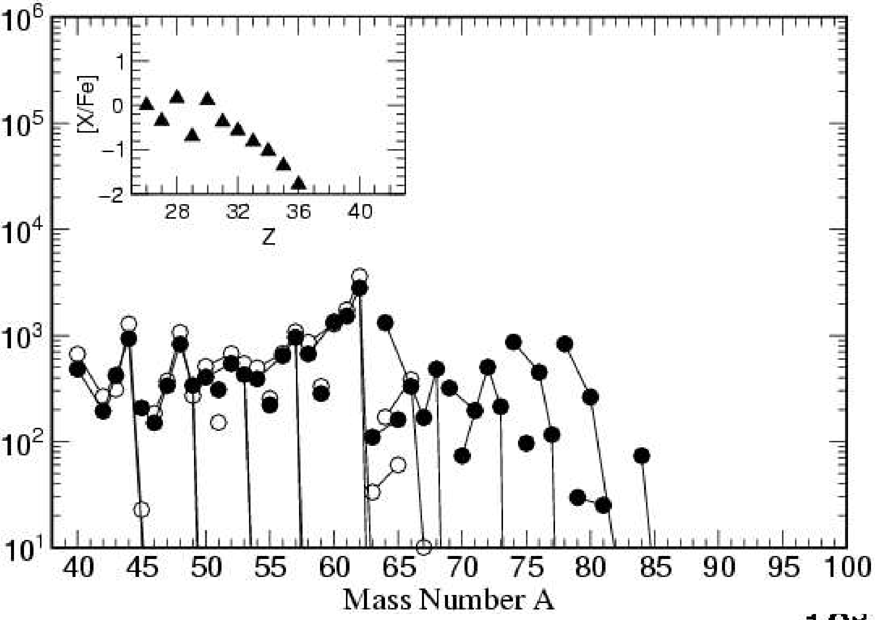
Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei)

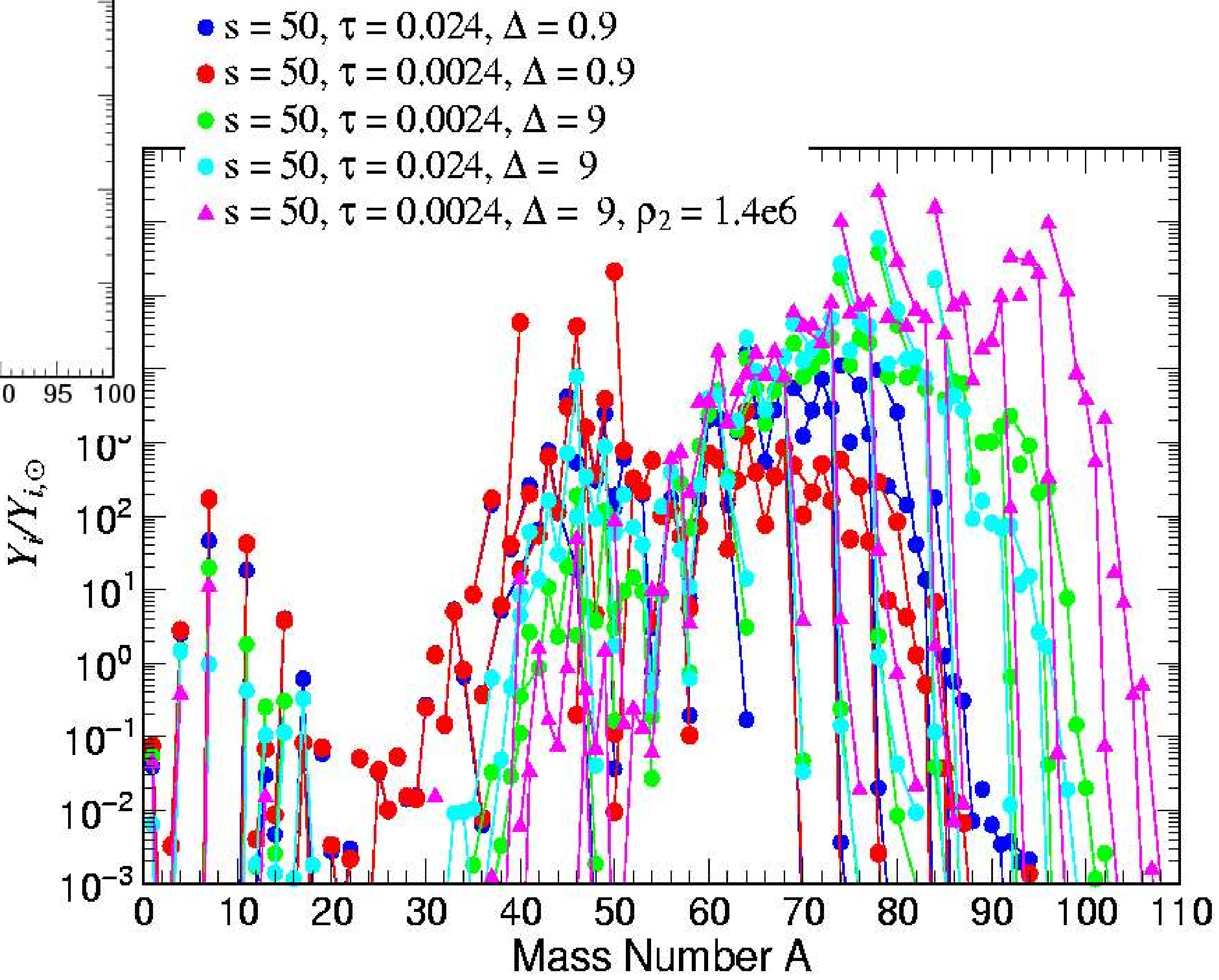
A new process, which could solve some observational problems of Sr, Y, Zr in early galactic evolution and the problem of light p-process nuclei.

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

Variations in explosion dynamics and neutrino luminosity

Fröhlich et al. (2006b), see also Pruet et al. (2006)

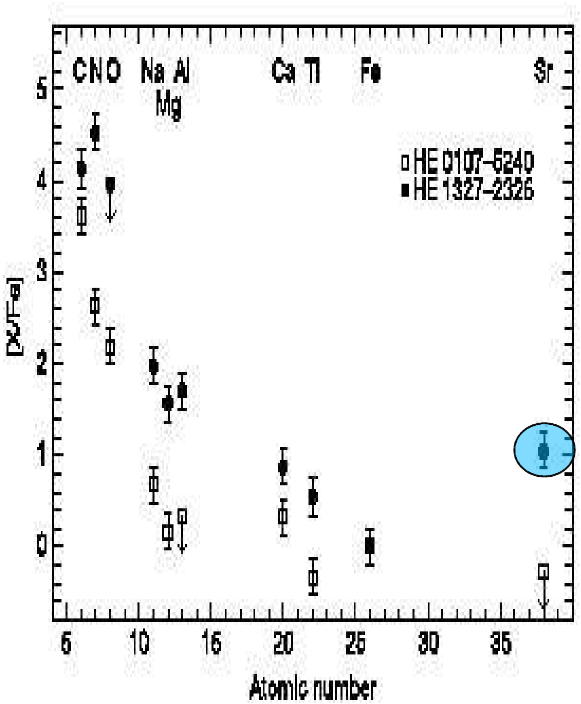


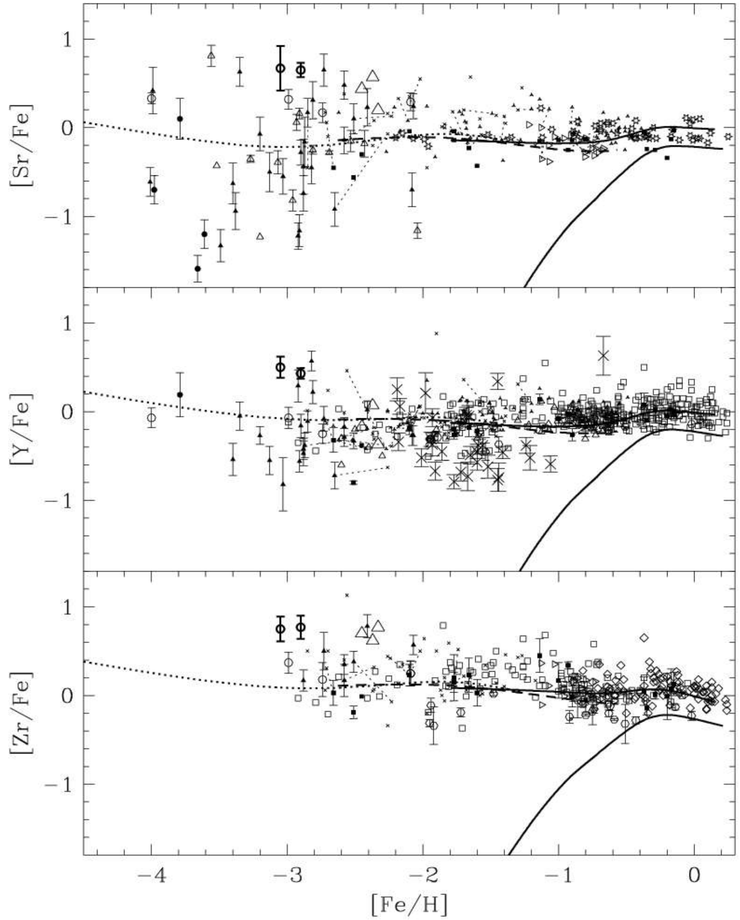


permits to explain on the one hand that in some cases only large overabundances of Sr are found, on the other hand early abundances of Sr,Y, Zr as well as possible p-process nuclei up to A=120

Observations of Sr, Y, Zr in low- metallicity stars

Travaglio et al. (2004)



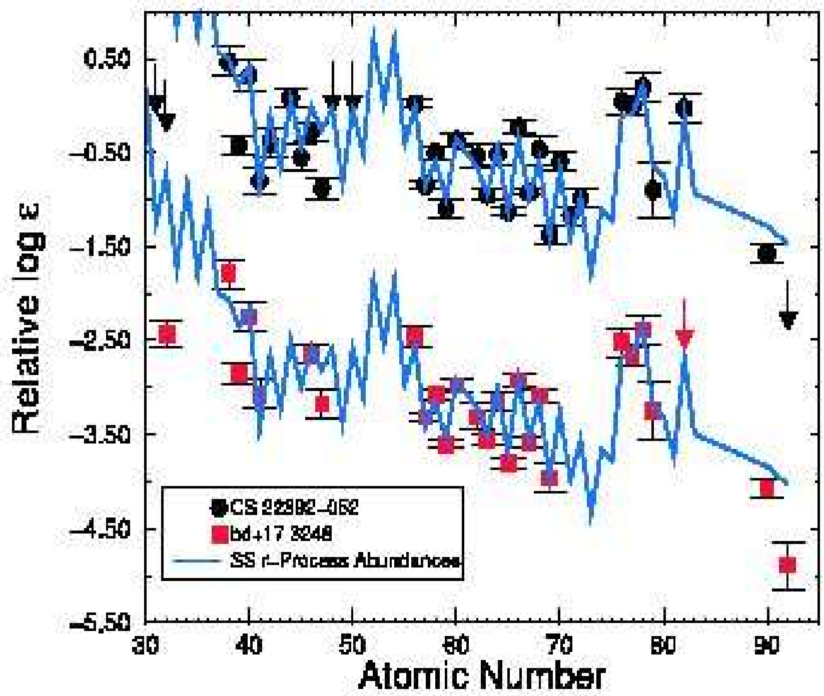


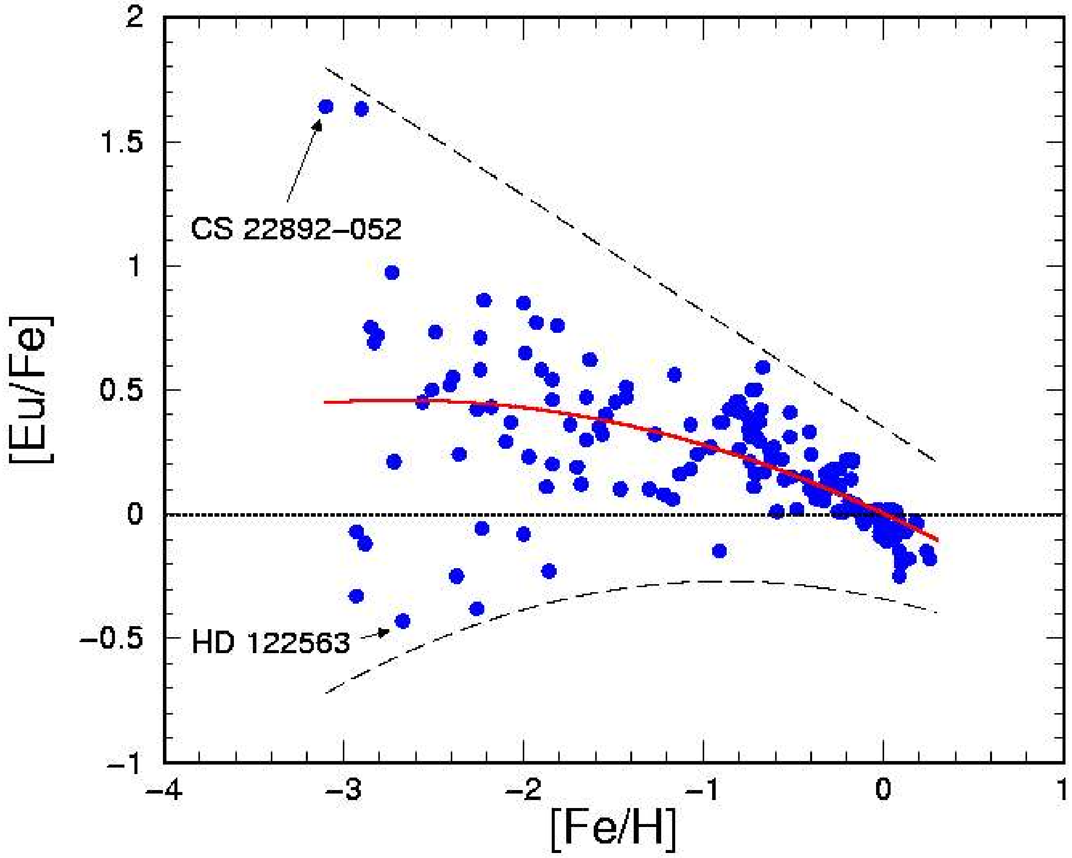
Frebel et al. (2005)

large variations in Sr between different low-metallicity stars

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

Observational Constraints on r-Process Sites





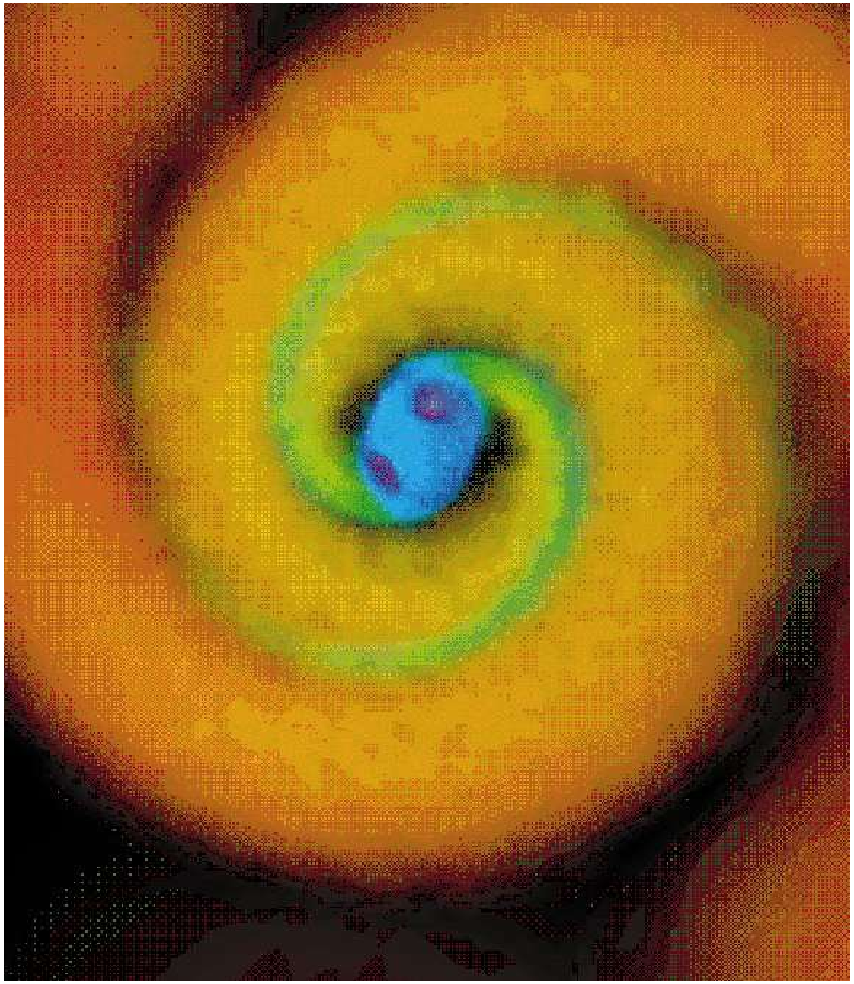
Cowan and Sneden

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)

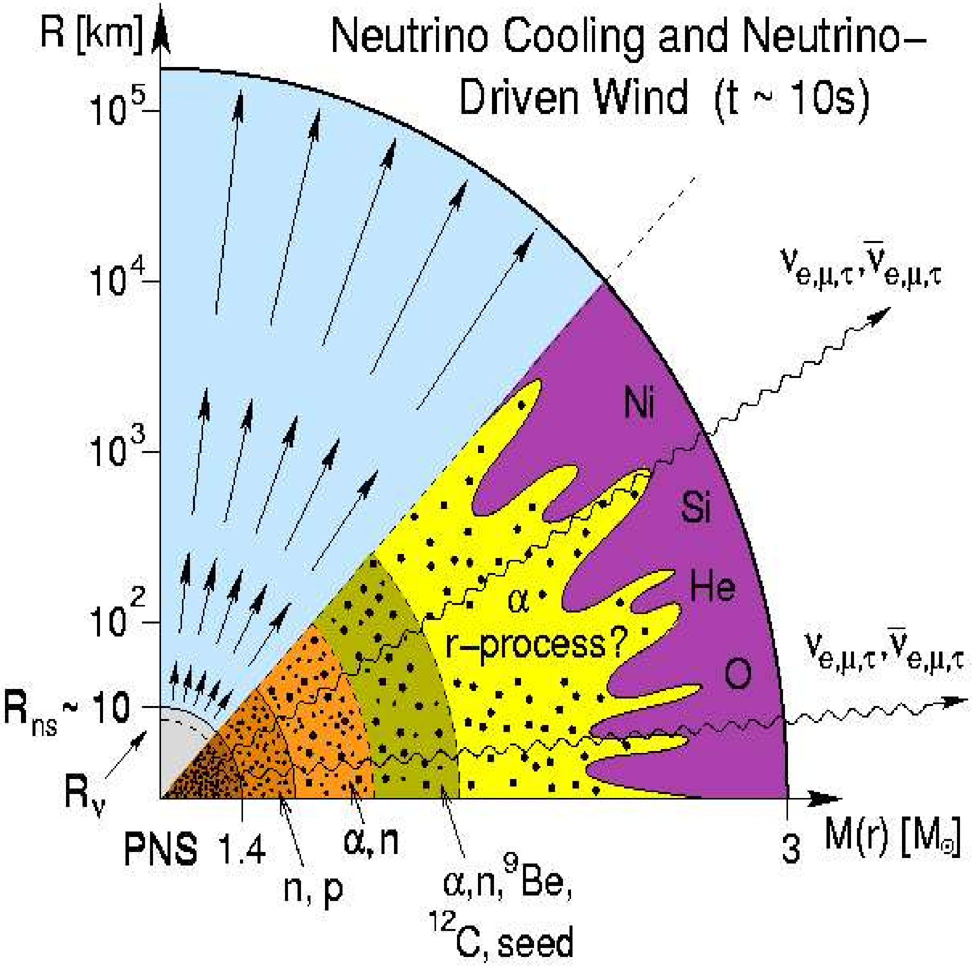
What is the site of the r-process?

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

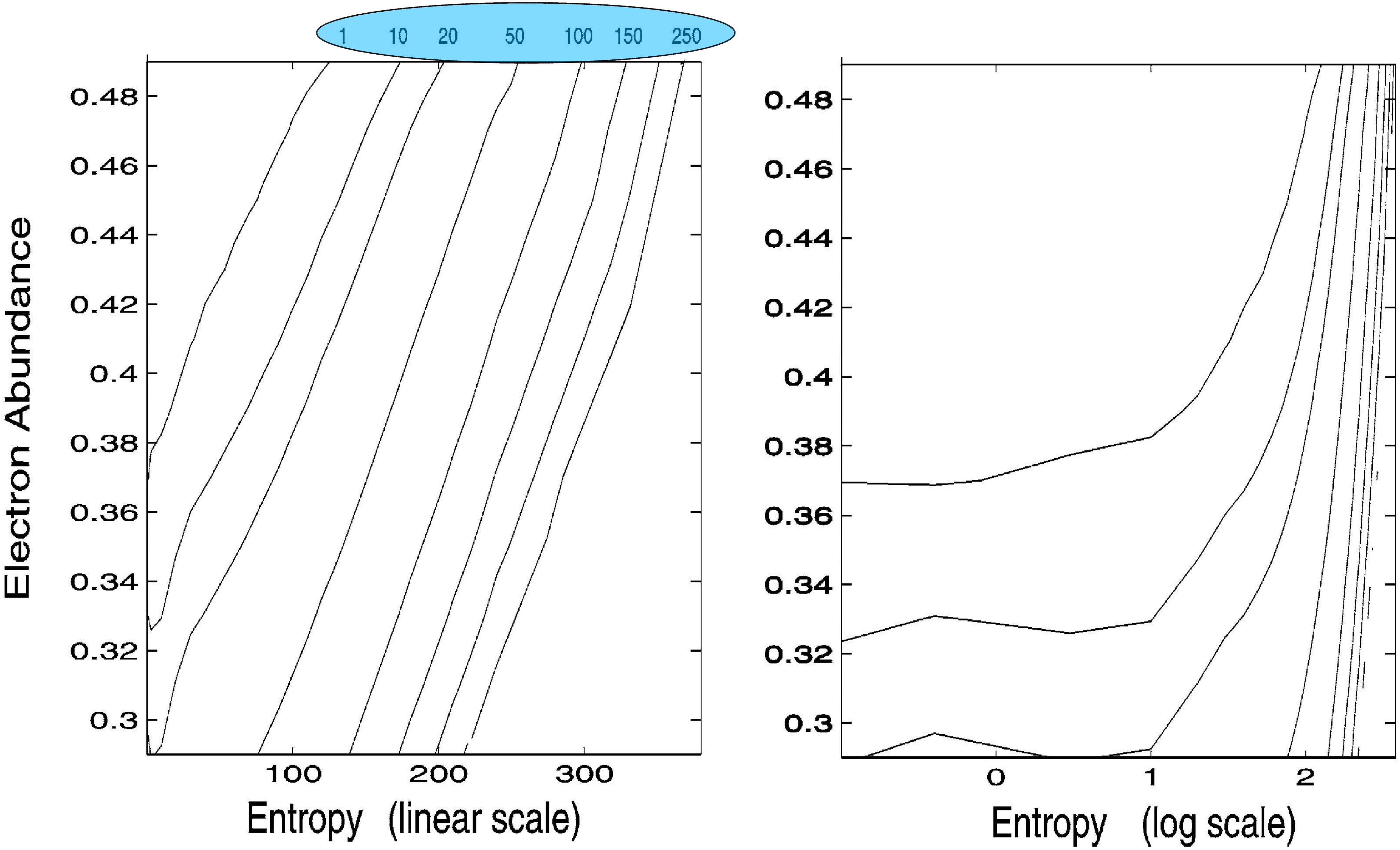
- 1. (very) high entropy alpha-rich (charged-particle) freeze-out with upper equilibrium extending up to A=80
  - quasi-equilibria in isotopic chains (chemical quilibrium for neutron captures and photodisintegrations) with maxima at specific neutron separation energies S_n
  - neutron/seed(A=80) ratio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

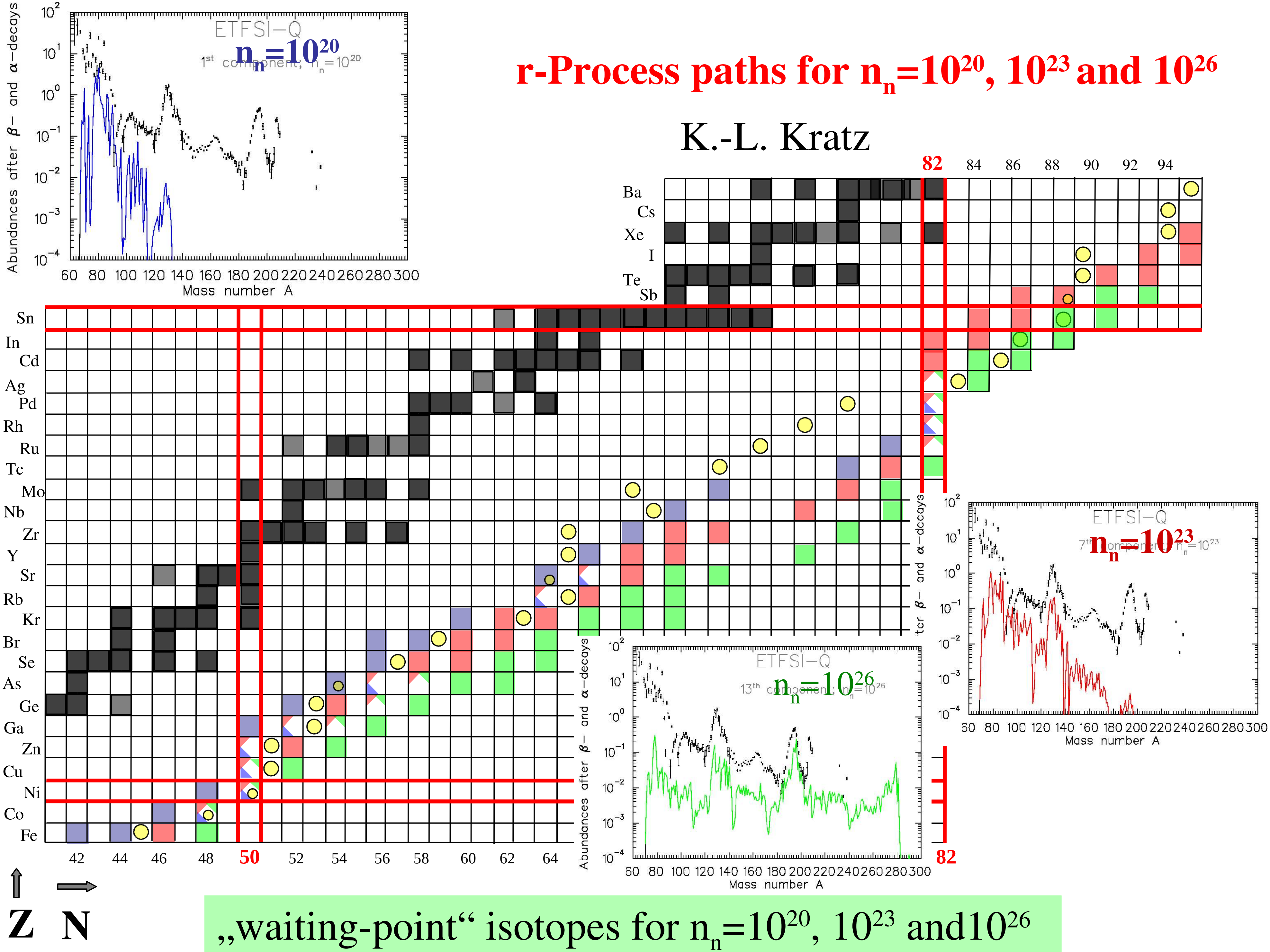
n/seed ratios as function of S and Y_e



Freiburghaus et al. (1999)

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

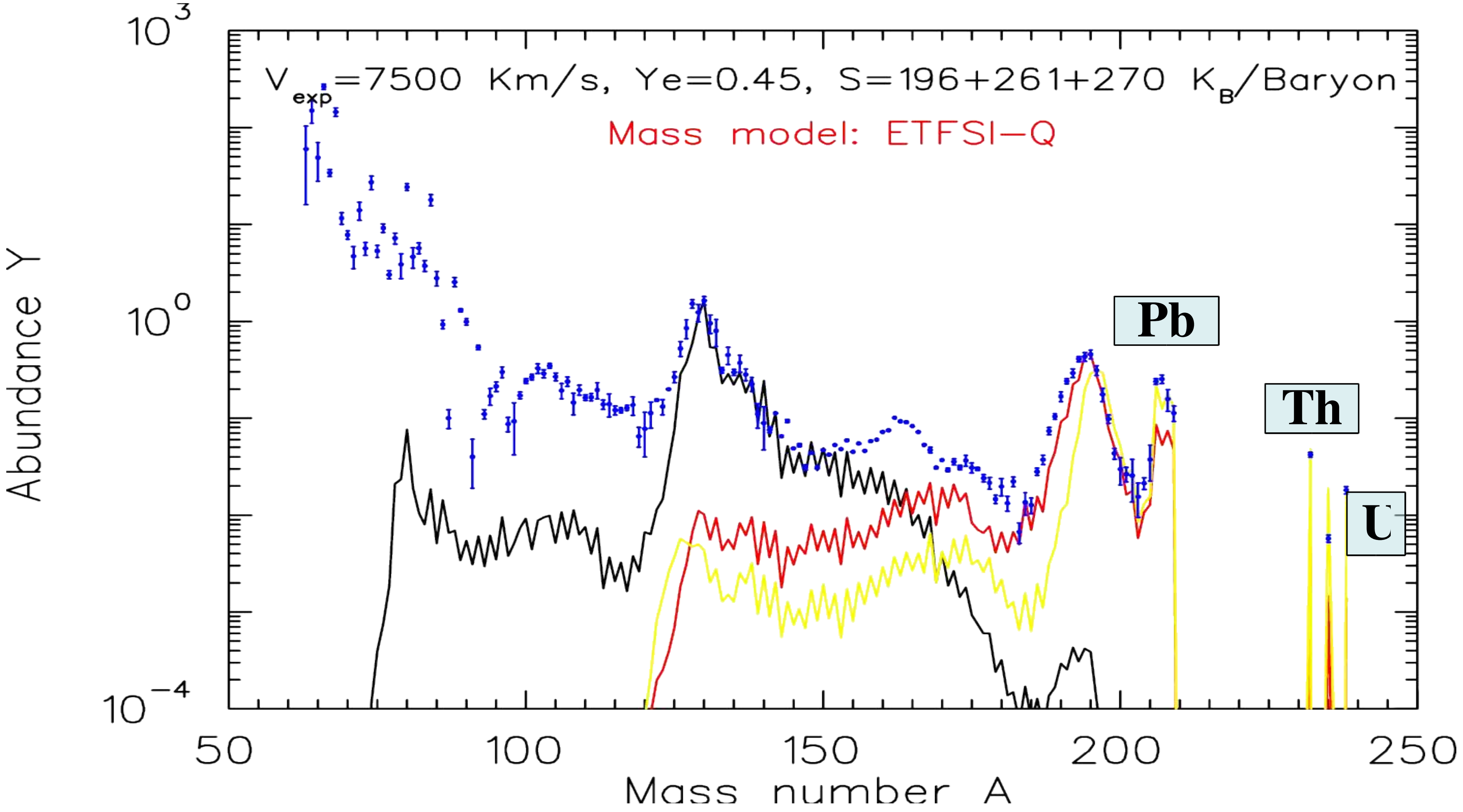
K.-L. Kratz



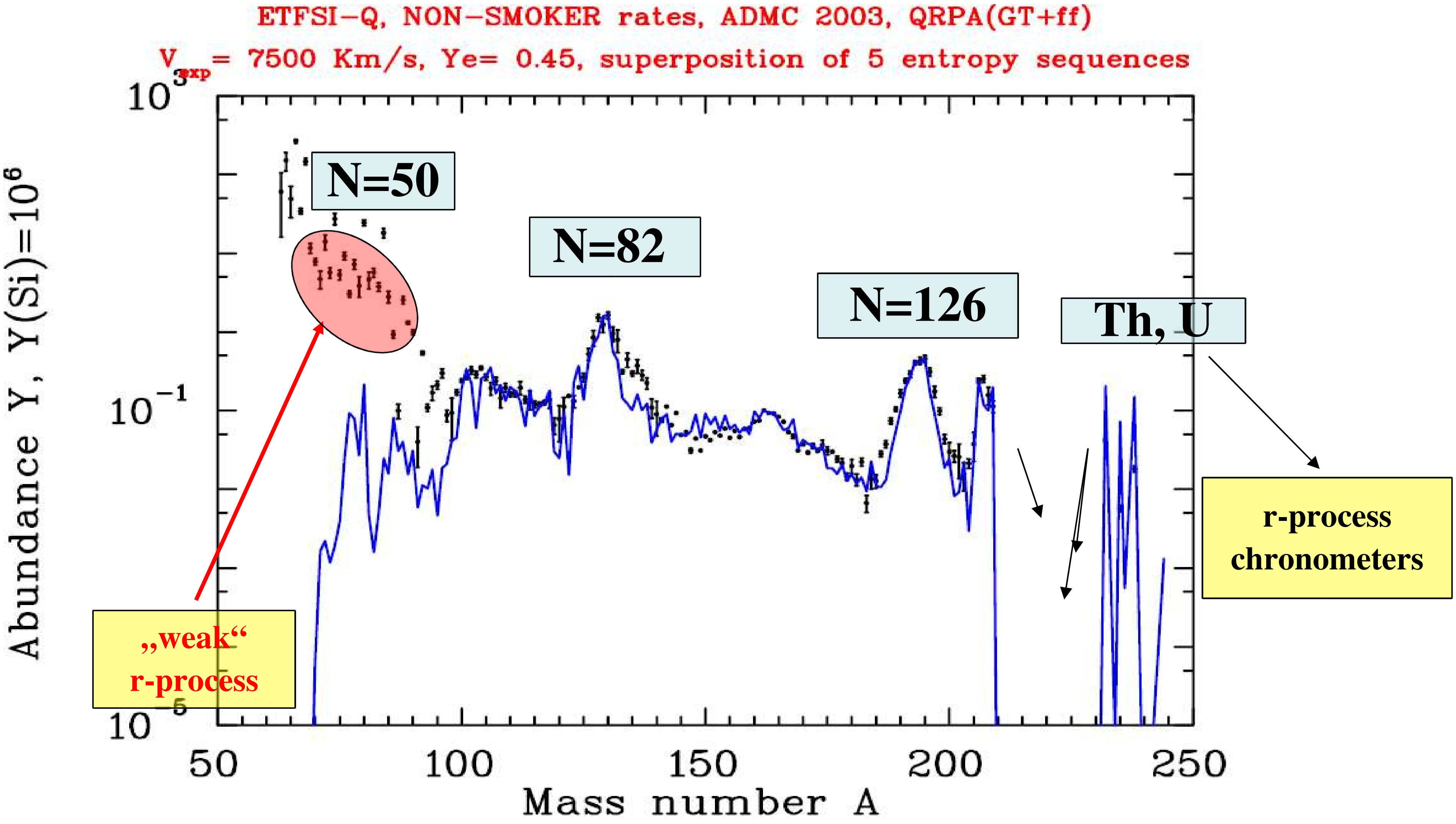
„waiting-point“ isotopes for $n_n=10^{20}$, 10^{23} and10^{26}

Individual Superpositions of Entropy Components

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



Superposition of 5 entropies



N=50

N=82

N=126

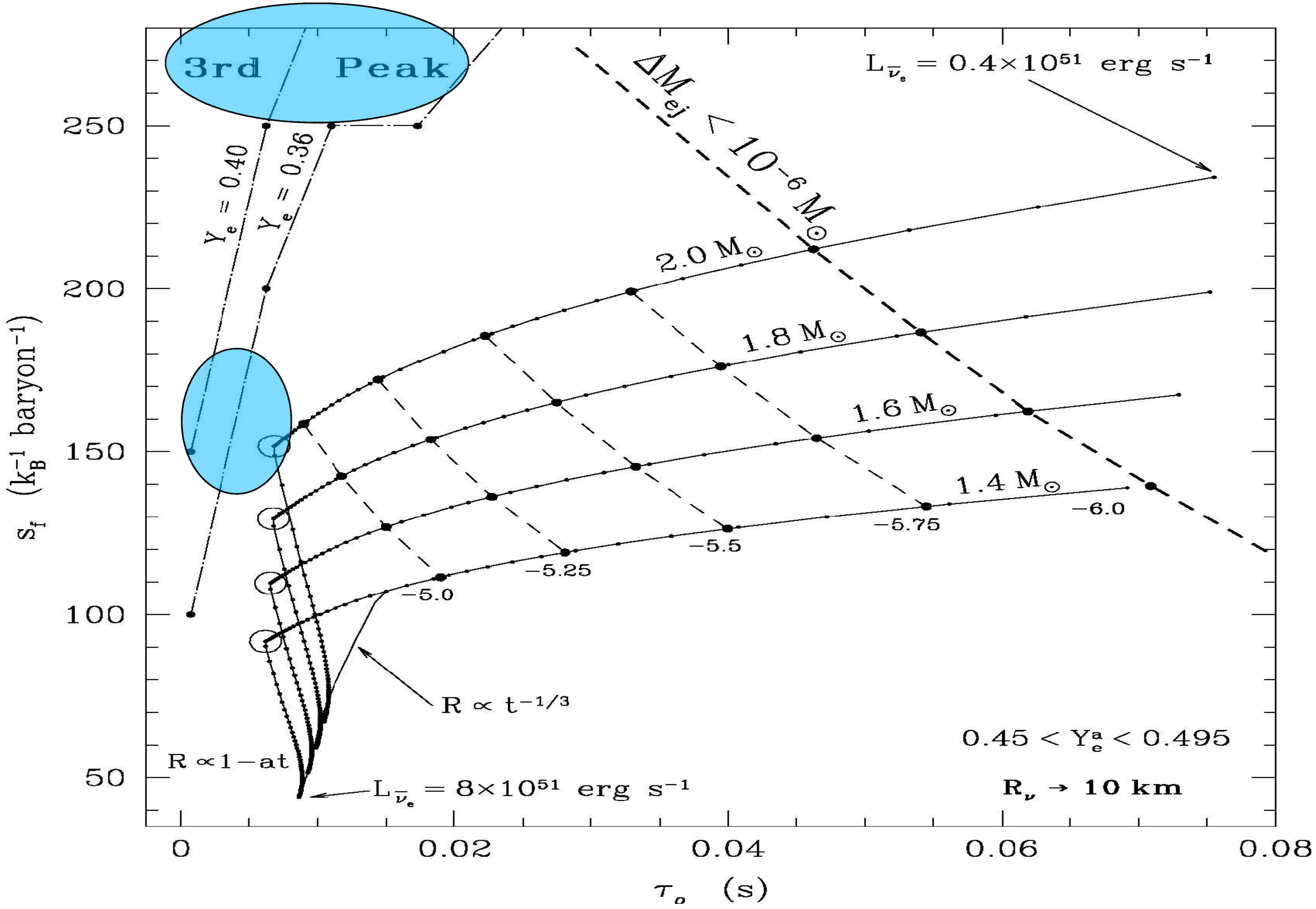
Th, U

r-process chronometers

„weak“ r-process

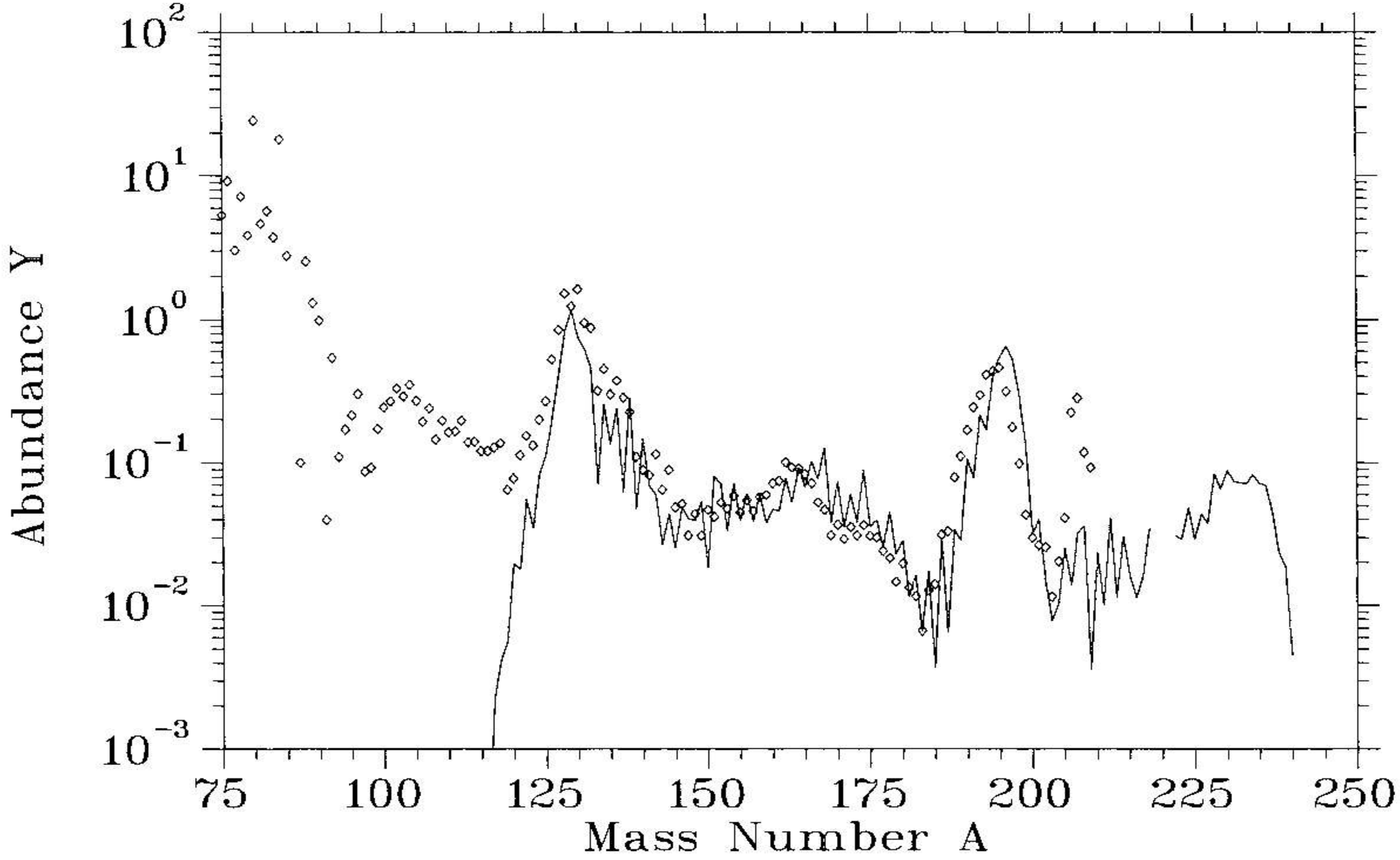
Thesis K. Farouqi 2005: entropies up to about 280, higher entropies lead to fission back-cycling! Low (high) entropies produce essentially an alpha-rich freeze-out around A=80 without neutrons left and leave abundance features which do not fit the A=80 peak. However from meteorites as well as low metallicity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

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



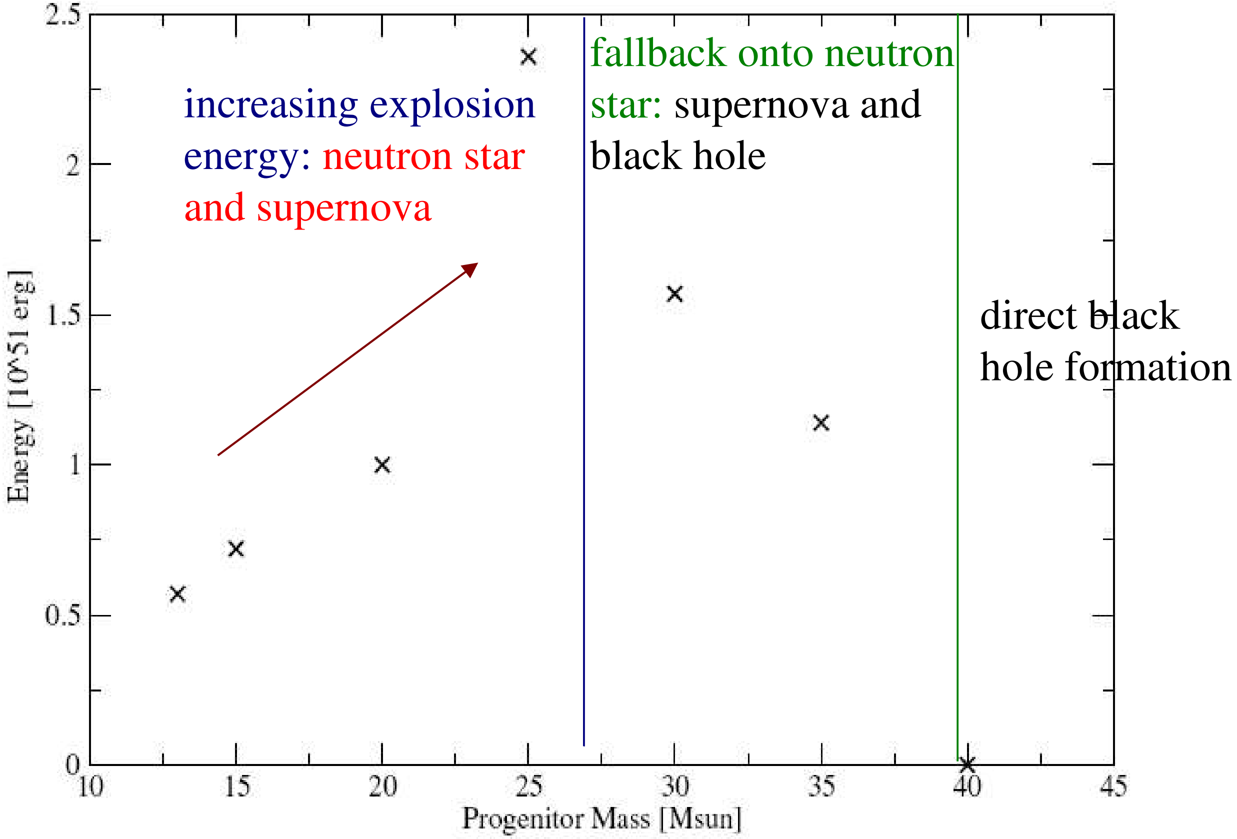
Only very massive neutron stars seemed to come close to conditions (entropies) which can produce the third peak!!!

Fission Cycling in Neutron Star Mergers



Freiburghaus et al. (1999) with simplified symmetric fission for nuclei with A>250, complete lack of nuclei below A=115

Self-consistent explosion models absolutely needed!



Liebendörfer et al. (2006), explosions via changed neutrino properties

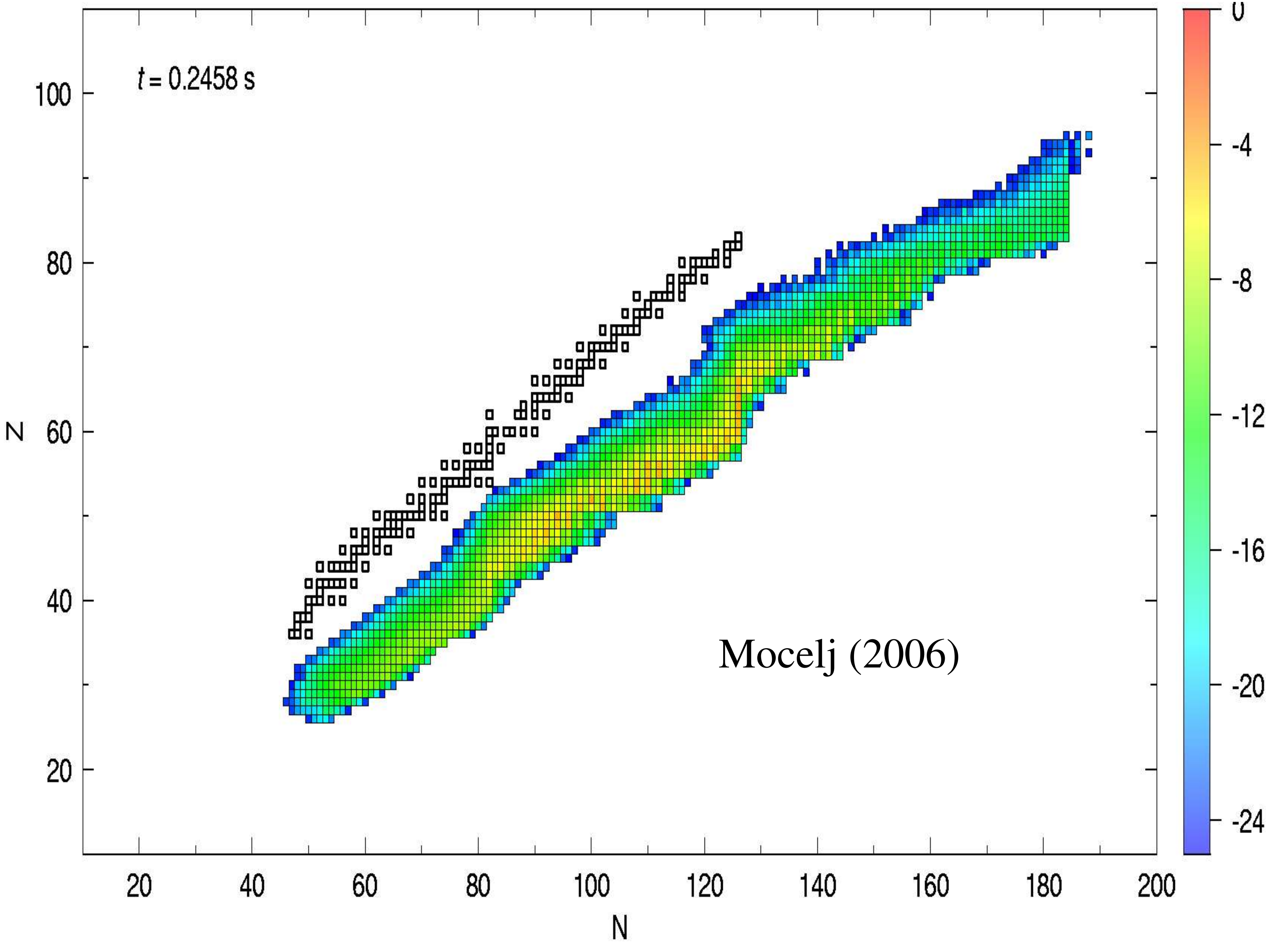
only with models which provide the explosion energy and the properties of the innermost ejected matter we can give a clear prediction of the Fe-group composition and possible r-process ejecta.

Most recent models of the Garching, Arizona, Los Alamos and Basel groups (in 2D) see apparently high enough entropies for the r-process in the fall back.

Entropies beyond 270 k_B/nucleon

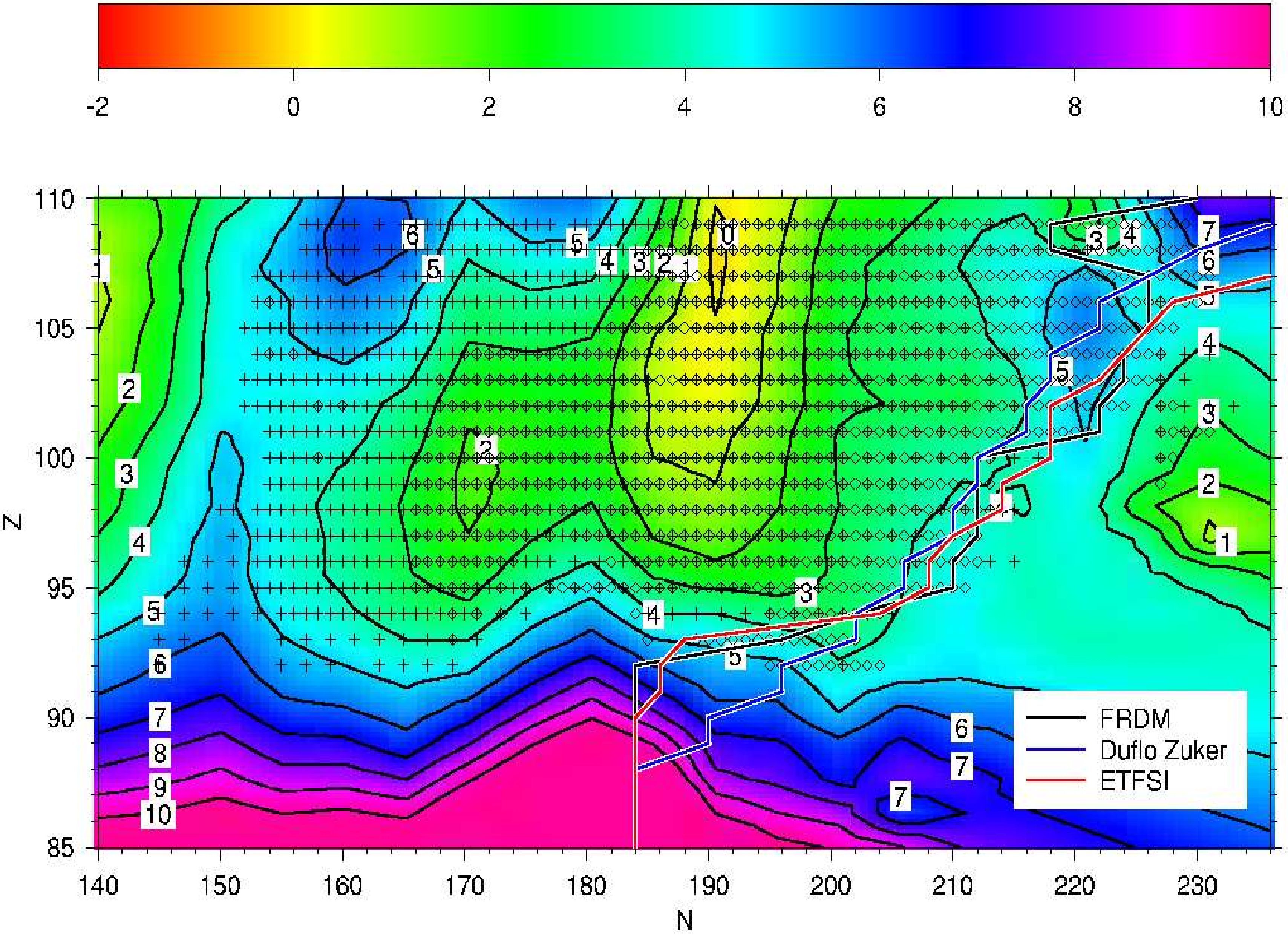
- adiabatic expansions (Freiburghaus et al. 1999), expansion timescale 50ms, Ye=0.45.
- full nuclear network (n,p,..Eu) before alpha-rich freeze-out
- r-process code Z<110, A<340 (Mocelj, Martinez-Pinedo)
- n-capture and (n,f) cross sections (Panov, Rauscher, Thielemann)
- beta-decay rates (Möller, Pfeiffer, 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)


t = 0.2458 s
Z
100
80
60
40
20
N
20
40
60
80
100
120
140
160
180
200
0
-4
-8
-12
-16
-20
-24

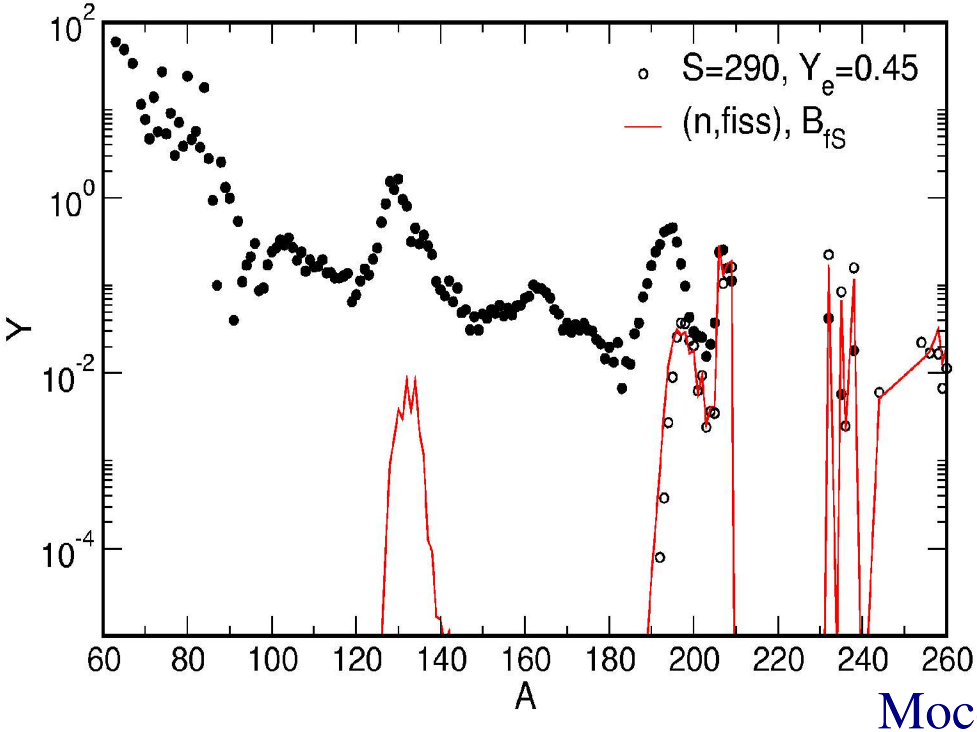
Mocelj (2006)

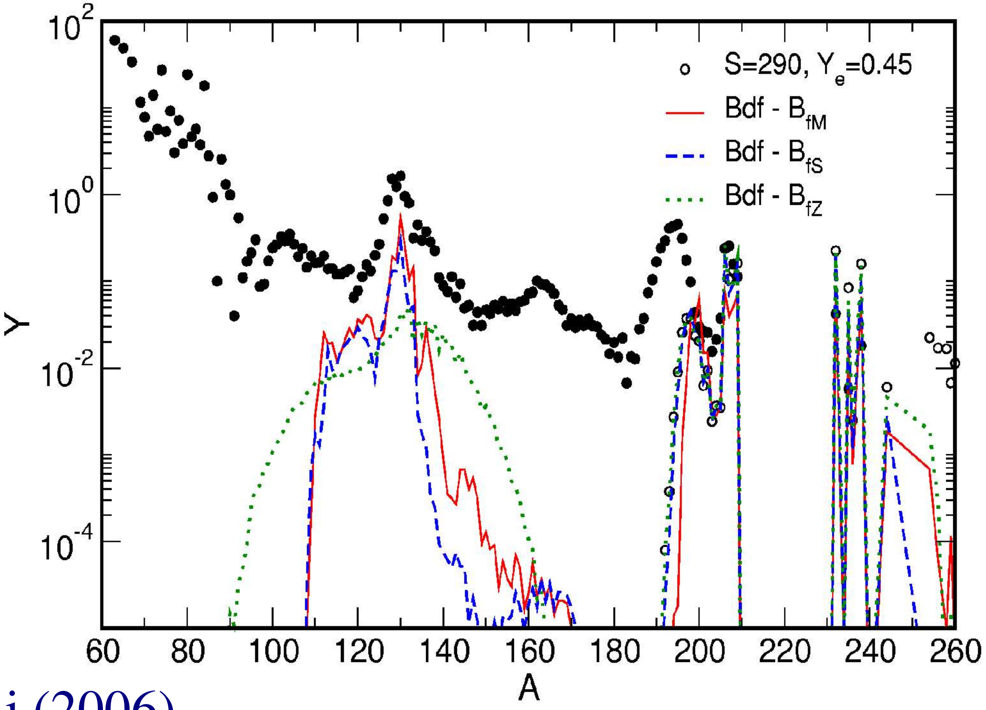
Myers & Swiatecki Barriers



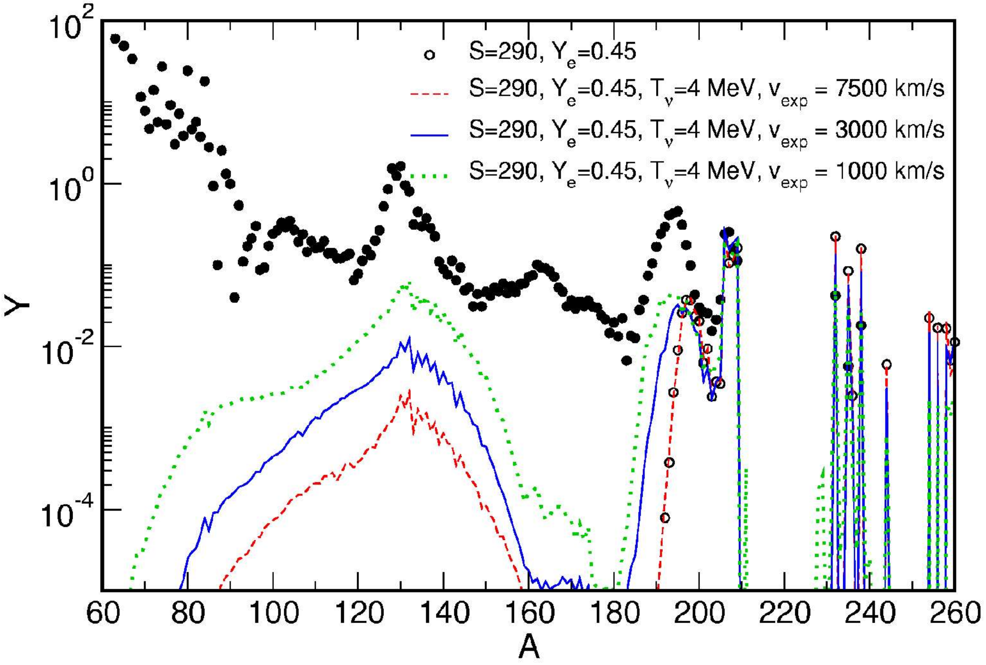
Martinez-Pinedo et al. (2007)

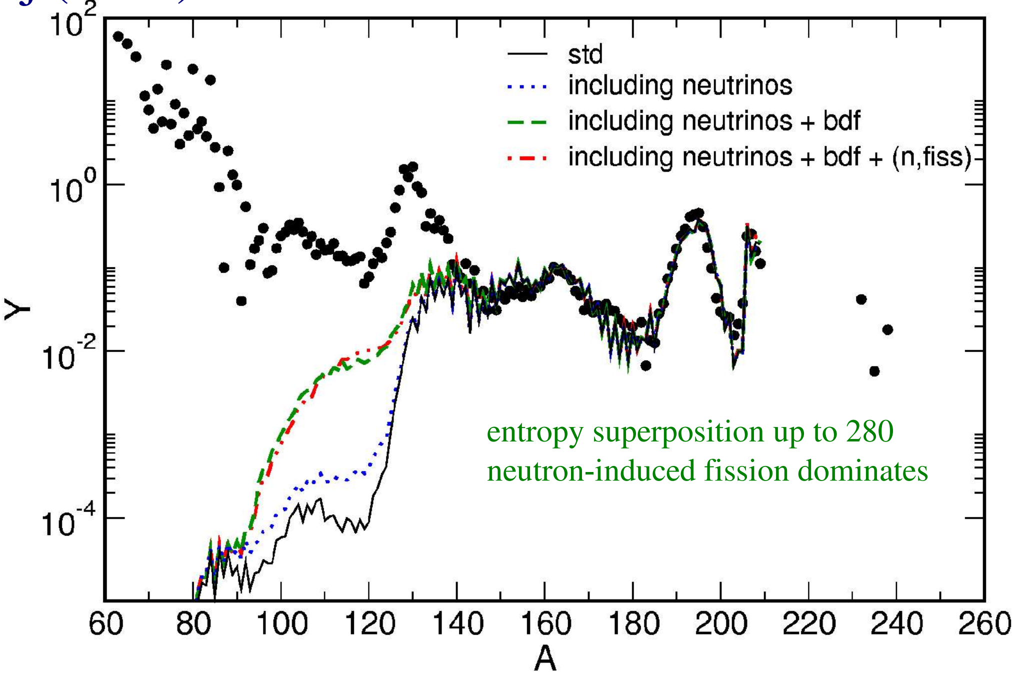
Influence of different fission modes





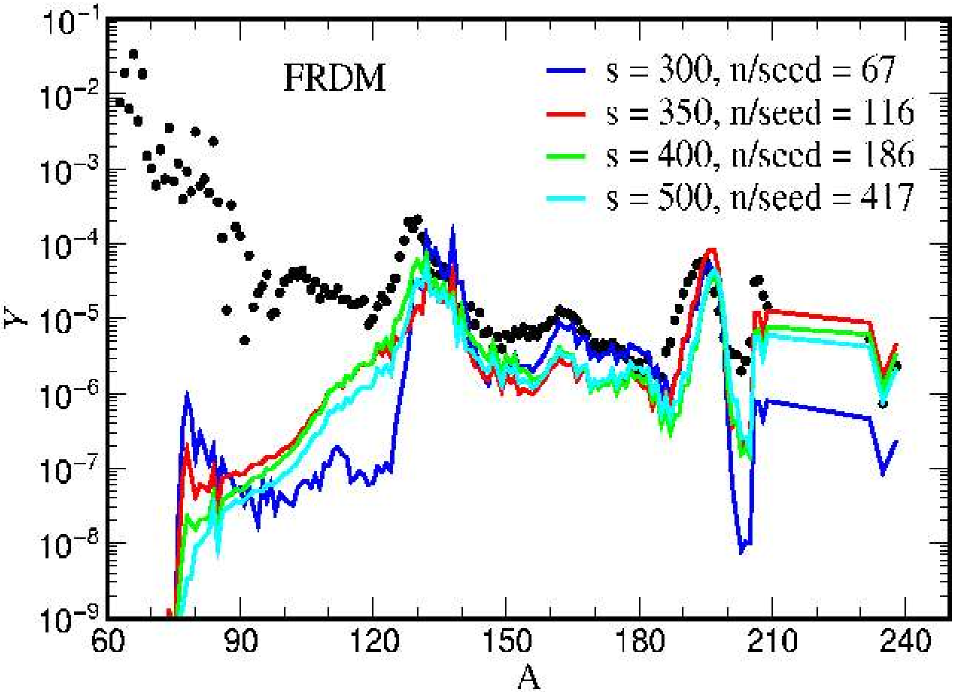
Mocelj (2006)

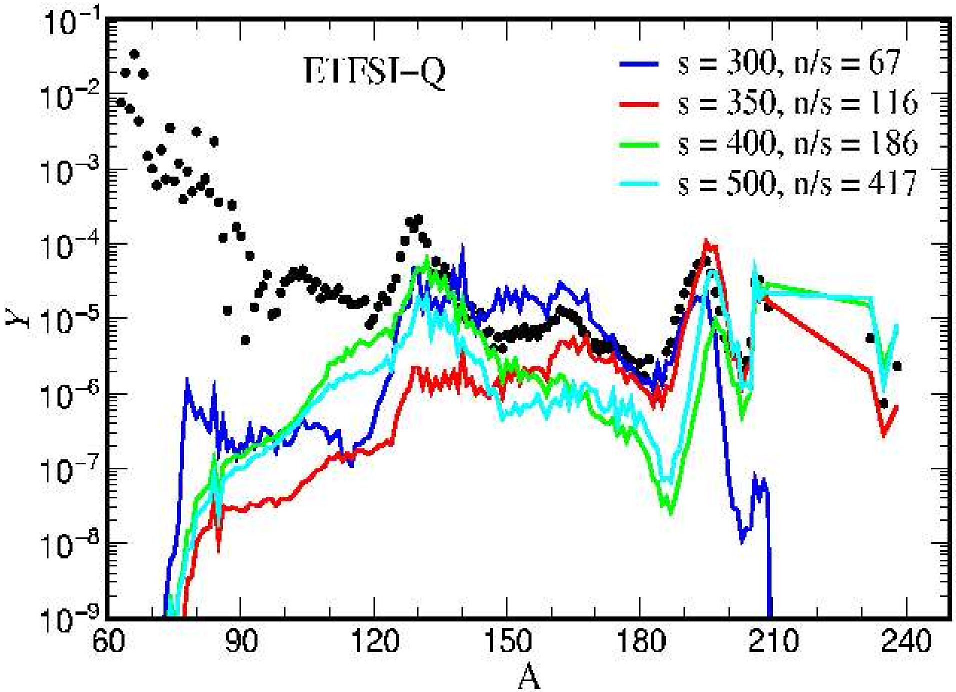




entropy superposition up to 280
neutron-induced fission dominates

Full fission “cycling” for different mass models

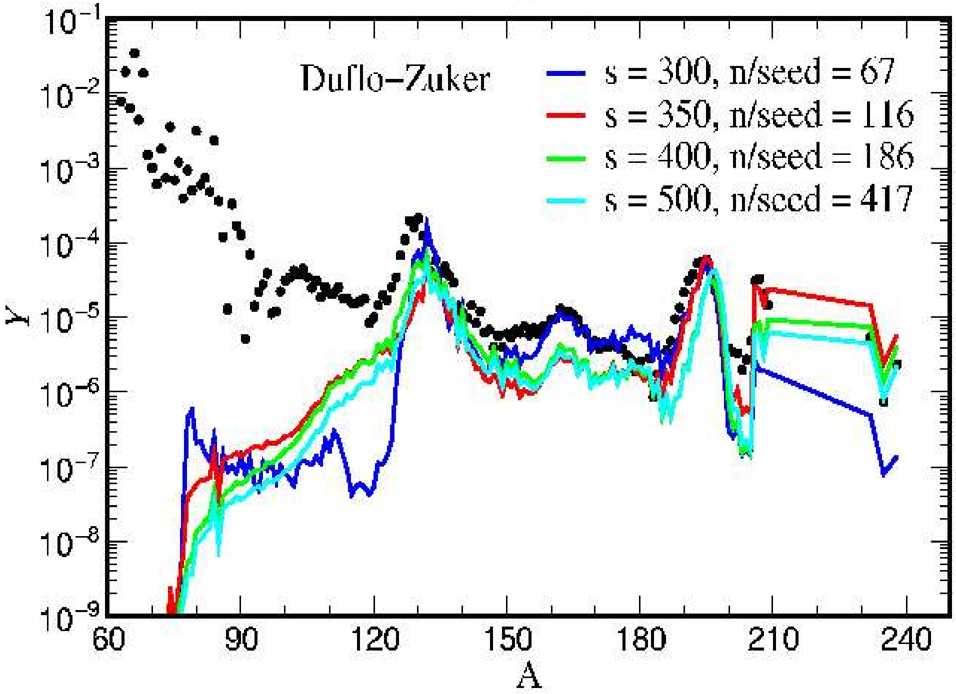




Differences are due to different shell structure at $N = 82$

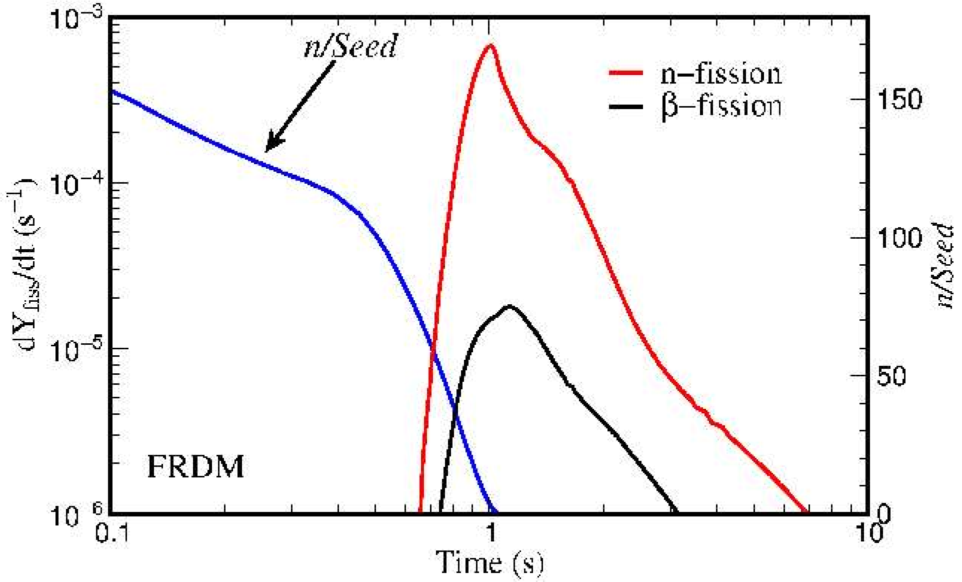
only one entropy component!

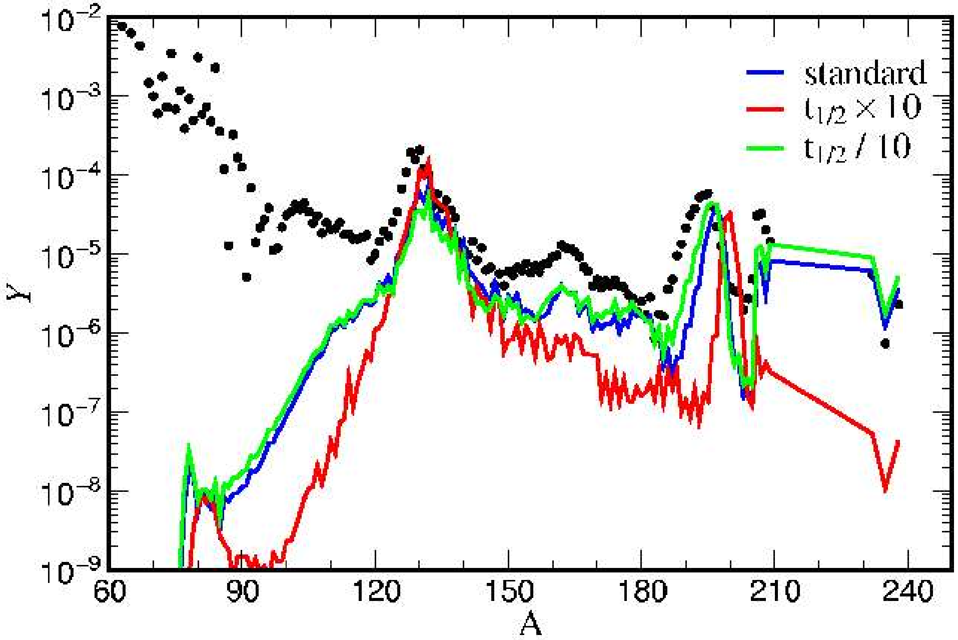
Martinez-Pinedo et al. (2007)



late neutron capture during freeze-out

- Matter accumulated at $N = 184$ ($A \sim 270$) will fission in the decay to “stability”.
- During the decay will reach a region with large fission probabilities and fission will take place. Mainly neutron induced (chain reaction in atomic bomb).
- The released neutrons can produce mayor shifts in the $A \sim 195$ peak if the beta decay halflives are too long. They are responsible for a kind of weak r (strong s) process with $N_n \sim 10^{16}$ cm^{-3}. Sensitive to (n, γ) cross sections.





repeating neutron star merger calculations

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