How to disentangle the influence of mass models and astrophysical environment conditions, responsible for producing the r-process abundance pattern(s)

a general review, combined with recent results from Basel, and collaborations with the GSI/TUD, ITEP (Moscow), Oklahoma and Mainz groups

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Brief Summary of Burning Stages (Major Reactions)

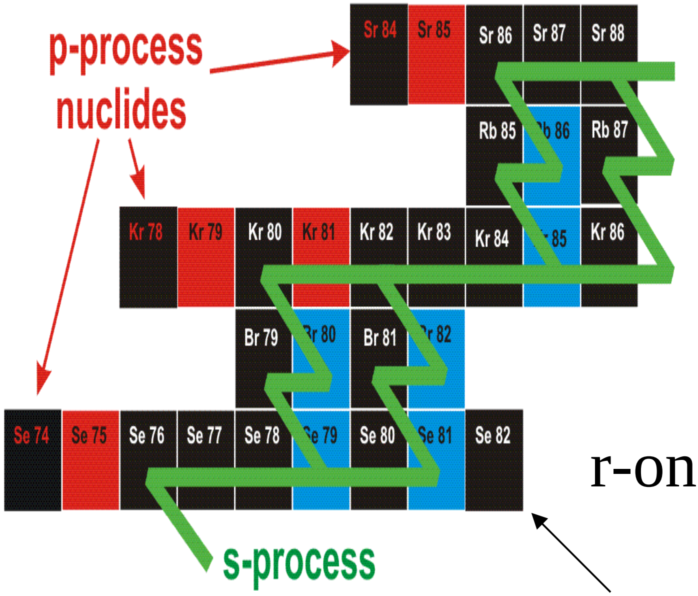
1. Hydrogen Burning T = $(1\text{-}4)\times10^{7}$K
   - pp-cycles -> ^{1}H(p,e$^{+}\nu$)^{2}H
   - CNO-cycle -> slowest reaction ^{14}N(p,γ)^{15}O
2. Helium Burning T=$(1\text{-}2)\times10^{8}$K
   - ^{4}He+^{4}He $\Leftrightarrow$ ^{8}Be ^{8}Be(α,γ)^{12}C[(α,γ)^{16}O]
   - ^{14}N(α,γ)^{18}F(β^{+})^{18}O(α,γ)^{22}Ne(α,n)^{25}Mg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

(all) photodisintegrations and capture reactions possible

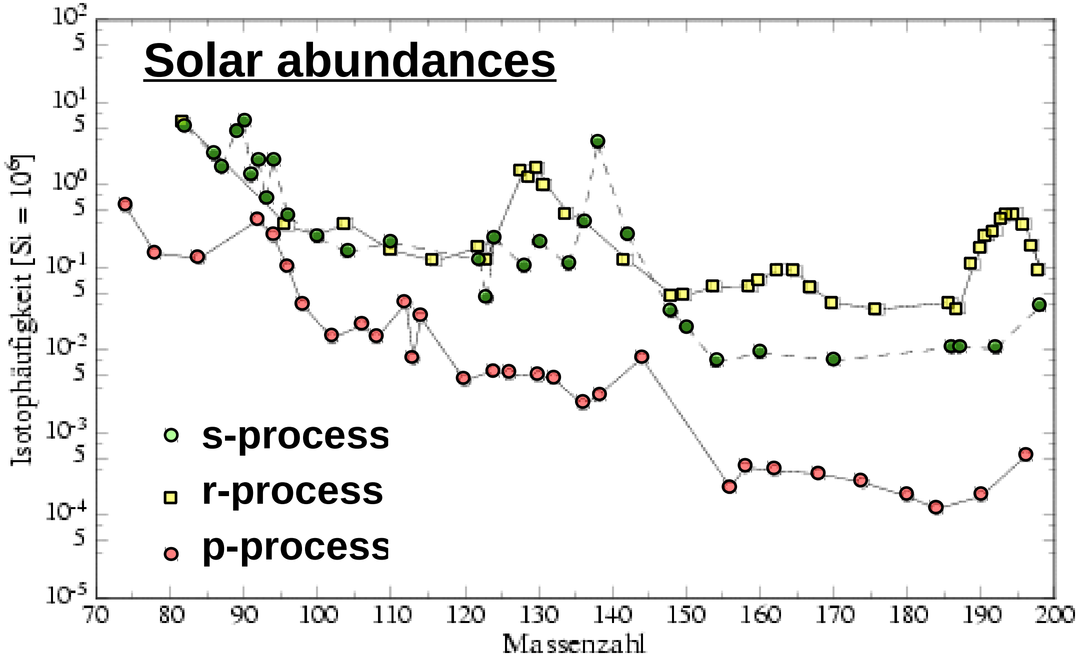
$\Rightarrow$ thermal (chemical) equilibrium

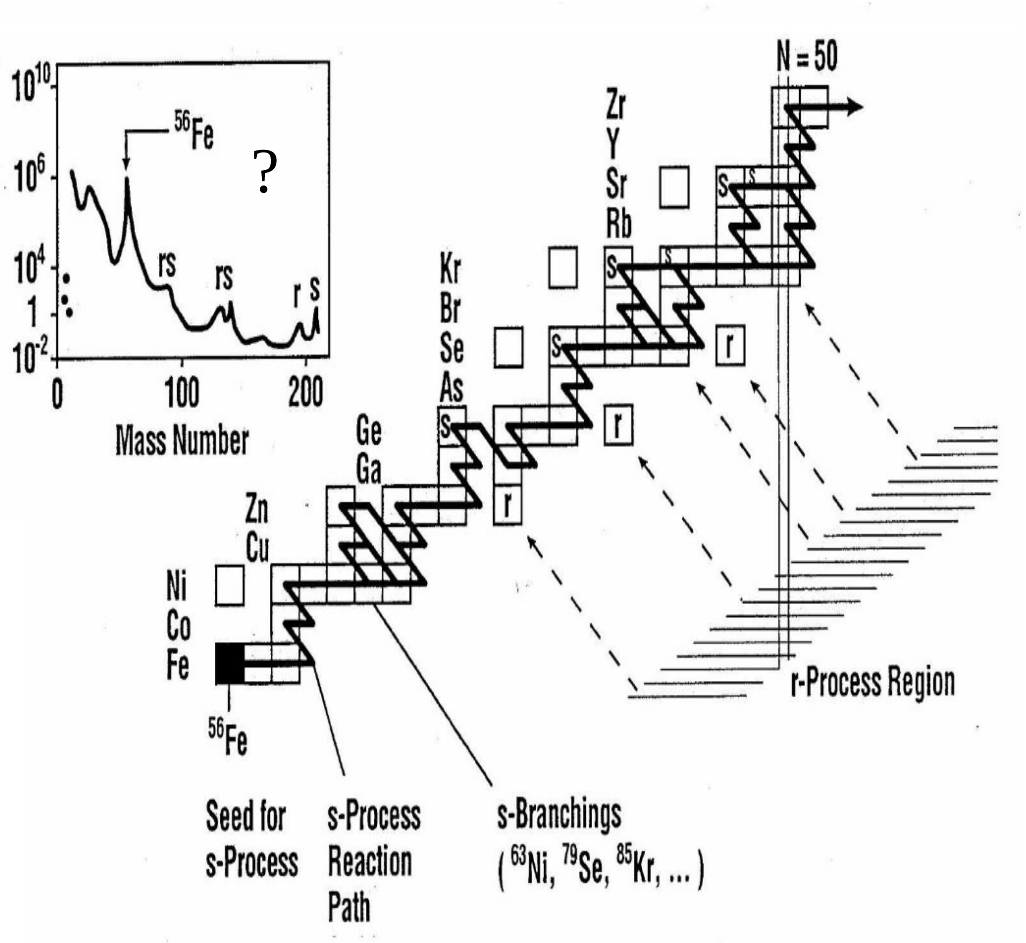
ongoing measurements of key fusion reactions at low energies

Decomposition of the heavy elements



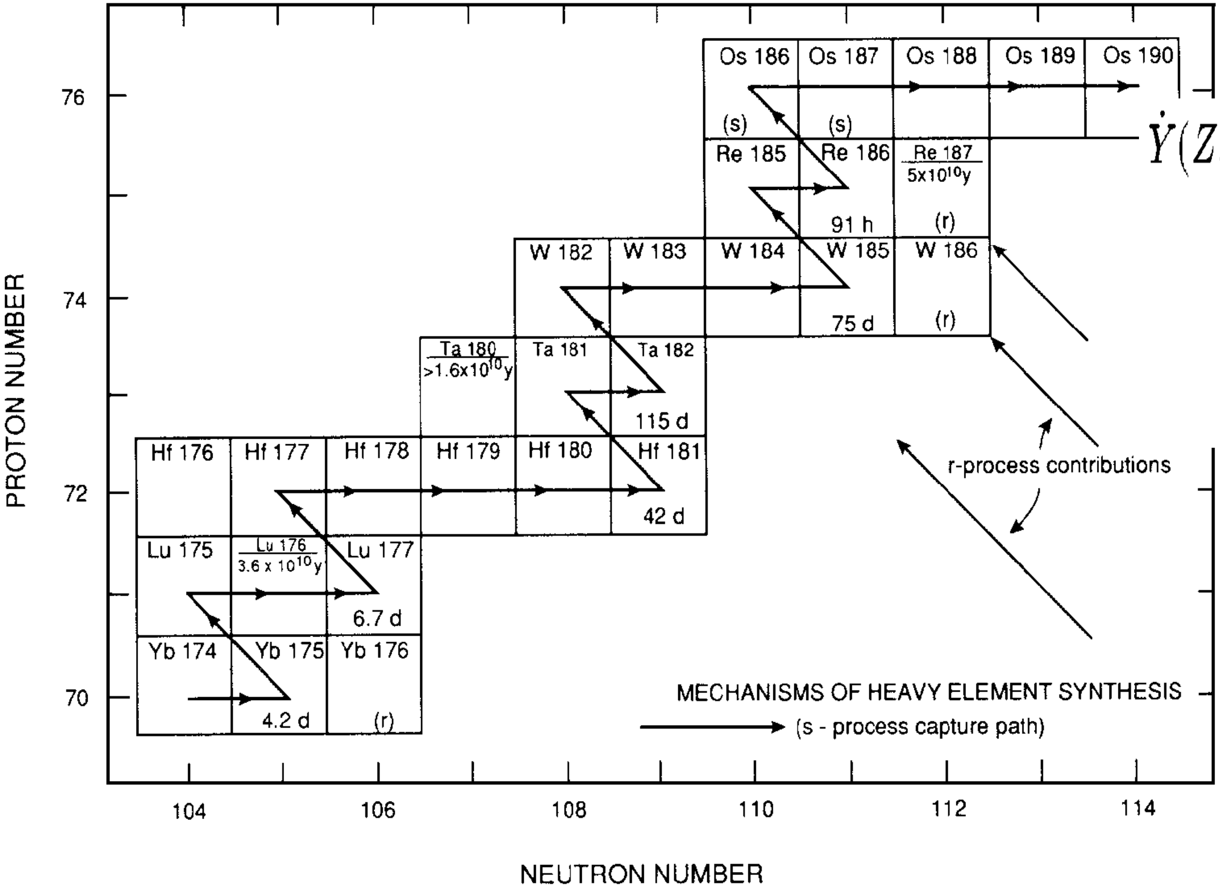
r-only





How do stars contribute to s-, r-, and p-process abundances?

s-process and steady flow



possible destruction of nucleus (Z,A)

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

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

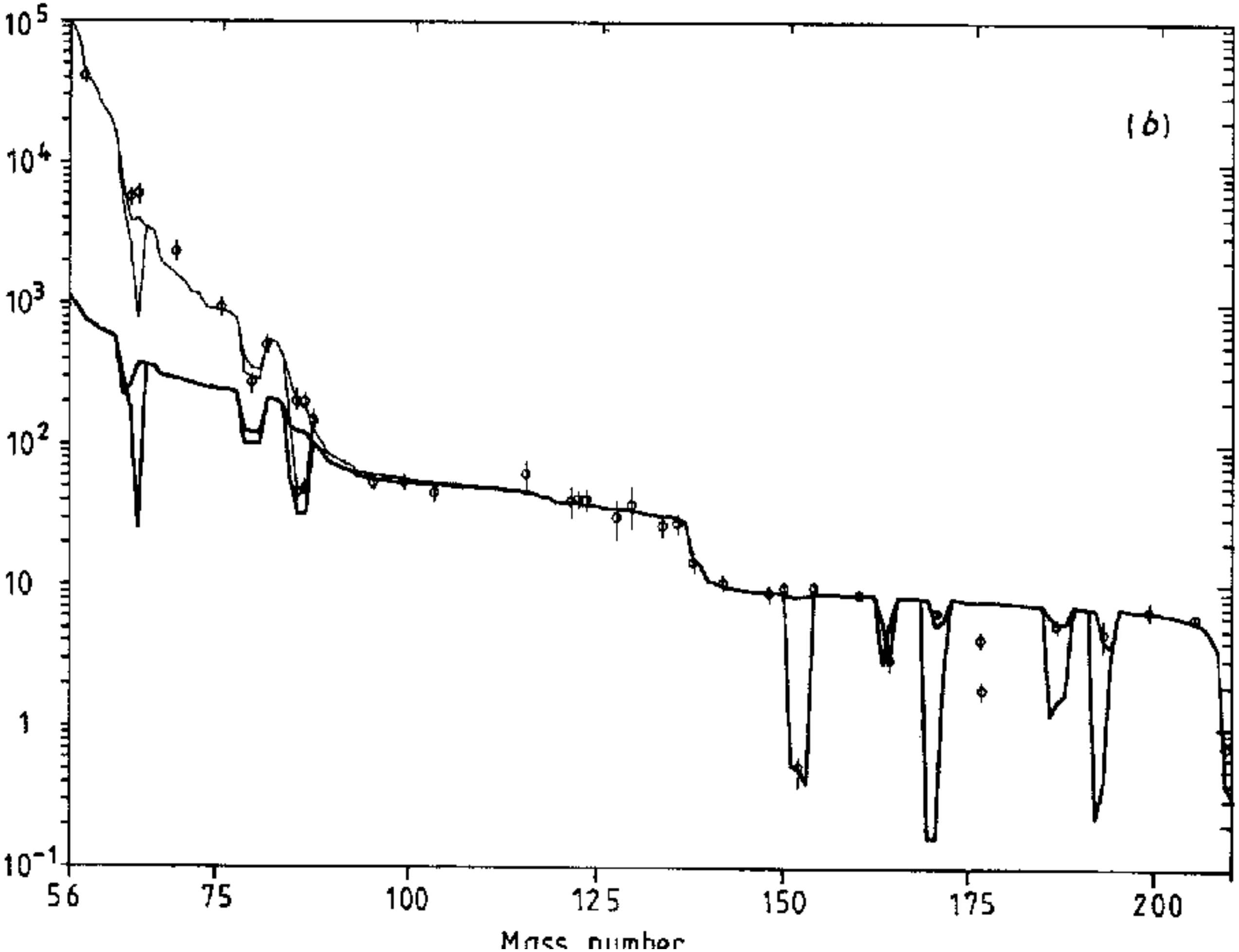
only one nucleus per A needs to be considered!

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

in case of steady flow =0

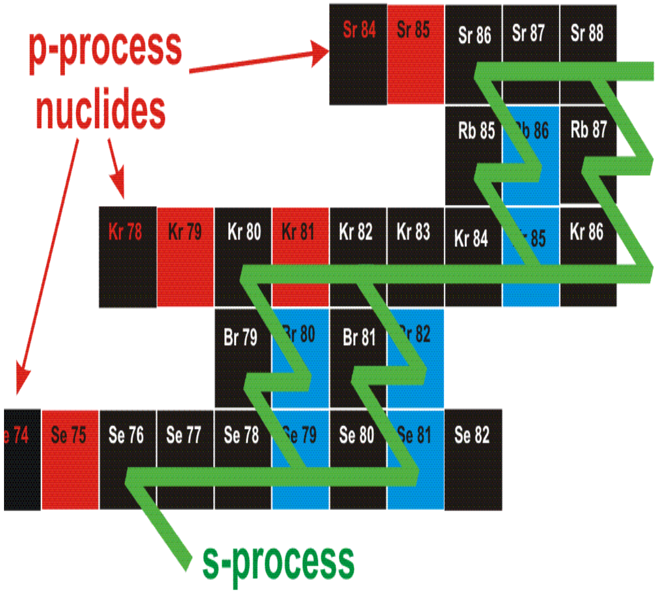
$\sigma \approx 1/v, <\sigma v> \;=\; \sigma(v)v$ therefore $\boxed{\sigma(A-1, 30\ \text{keV})Y(A-1) = \sigma(A, 30\ \text{keV})Y(A)}$

The sigma*N-curve



with a fitted distribution of τ's

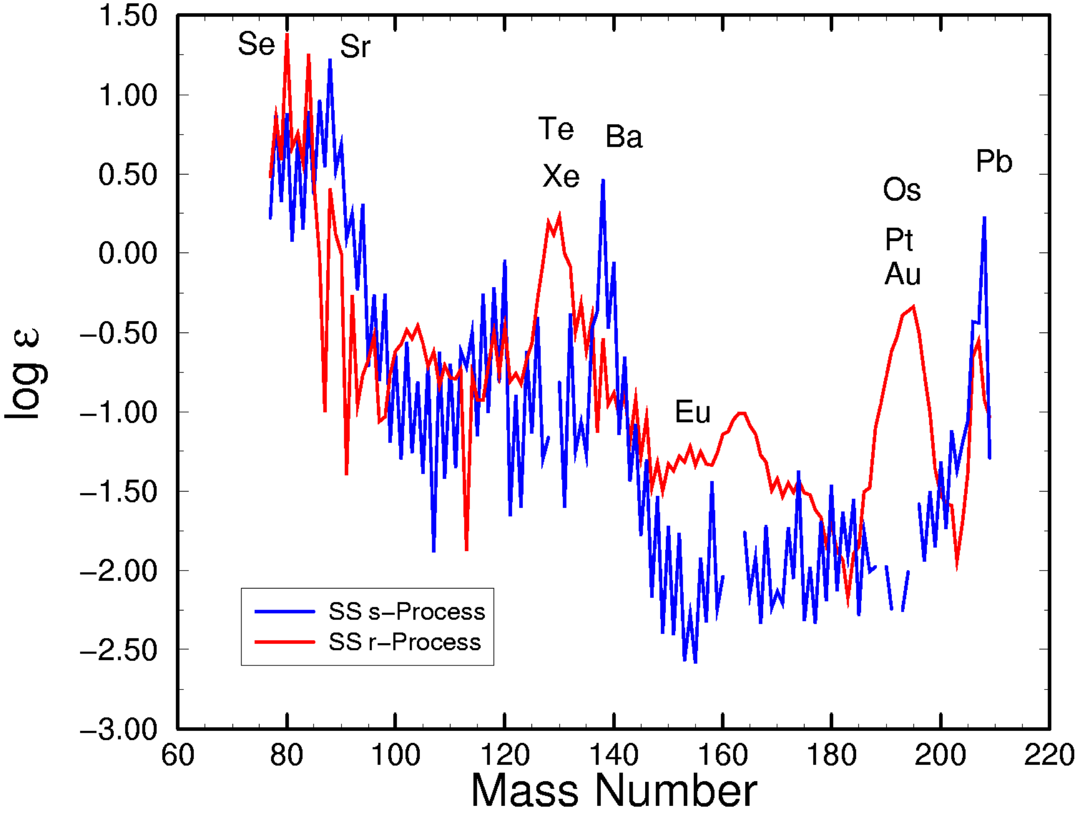
$\tau=\int n_n\,dt$



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-decoposition



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

$$= -\lambda_{\beta^-}(Z,A)Y(Z,A) - < \sigma v >_{n,\gamma} n_n Y(Z,A)$$

$$= -\frac{1}{\tau_\beta}Y(Z,A) - \frac{1}{\tau_{n,\gamma}}Y(Z,A).$$

With increasing neutron density n_n capture becomes faster than beta-decay and nuclei far from stability are produced. The red abundance distribution results from subtracting the s-process contribution from solar abundances ! Is the s-contribution fully understood?

Heavy Elements are made by slow and rapid neutron capture events

s-Process (neutron) Sources

Core burning of massive stars (weak s-process)

1. Helium Burning T=(1-2)x10^{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=(6-8)x10^{8}K

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

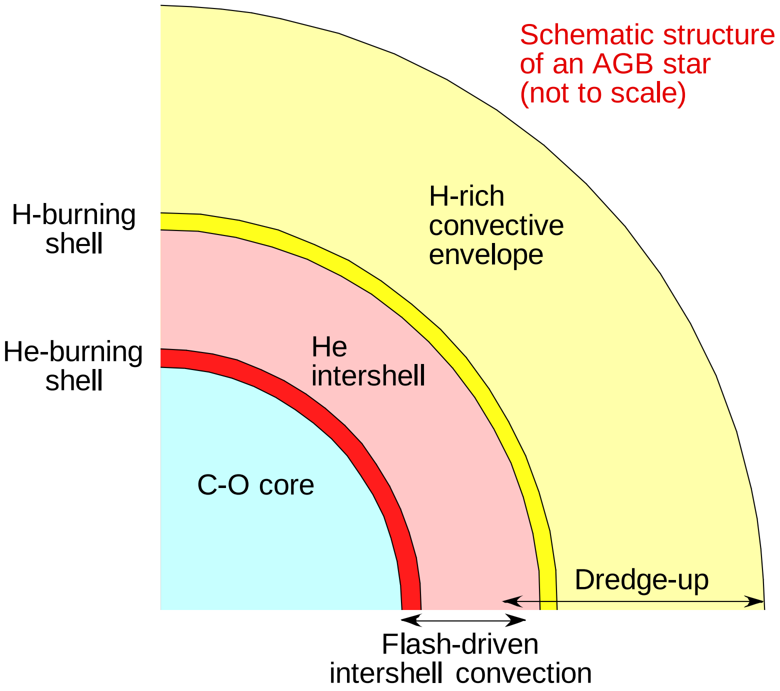
$^{12}C(^{12}C,p)^{23}Na$ $^{13}C(\alpha,n)^{16}O$

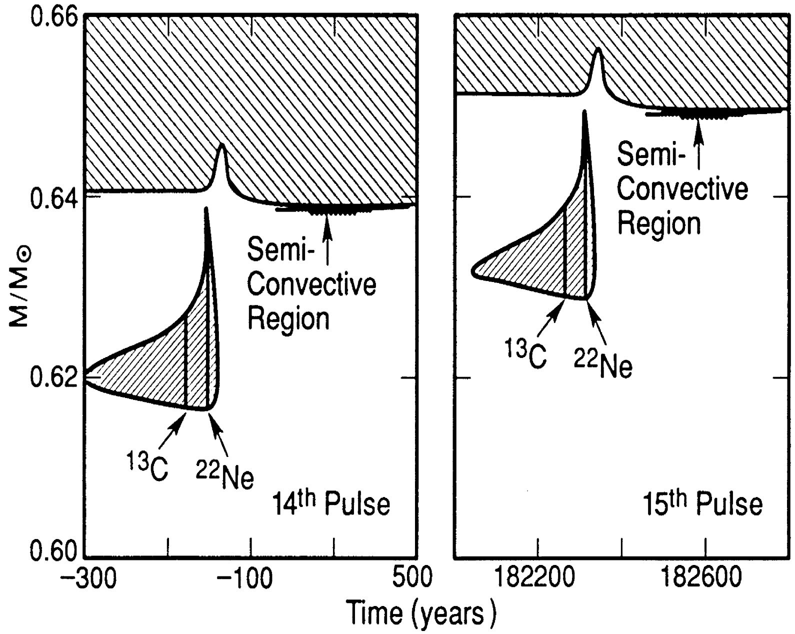
protons as well as alphas are not existing intrinsically in C-burning, as destroyed in prior H-burning and He-burning. They come from the C-fusion reaction

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 a strong neutron source.

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, He is ignited in an unburned He-rich zone (at sufficient densities and temperatures). The burning is not stable, 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.


Schematic structure of an AGB star (not to scale)



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

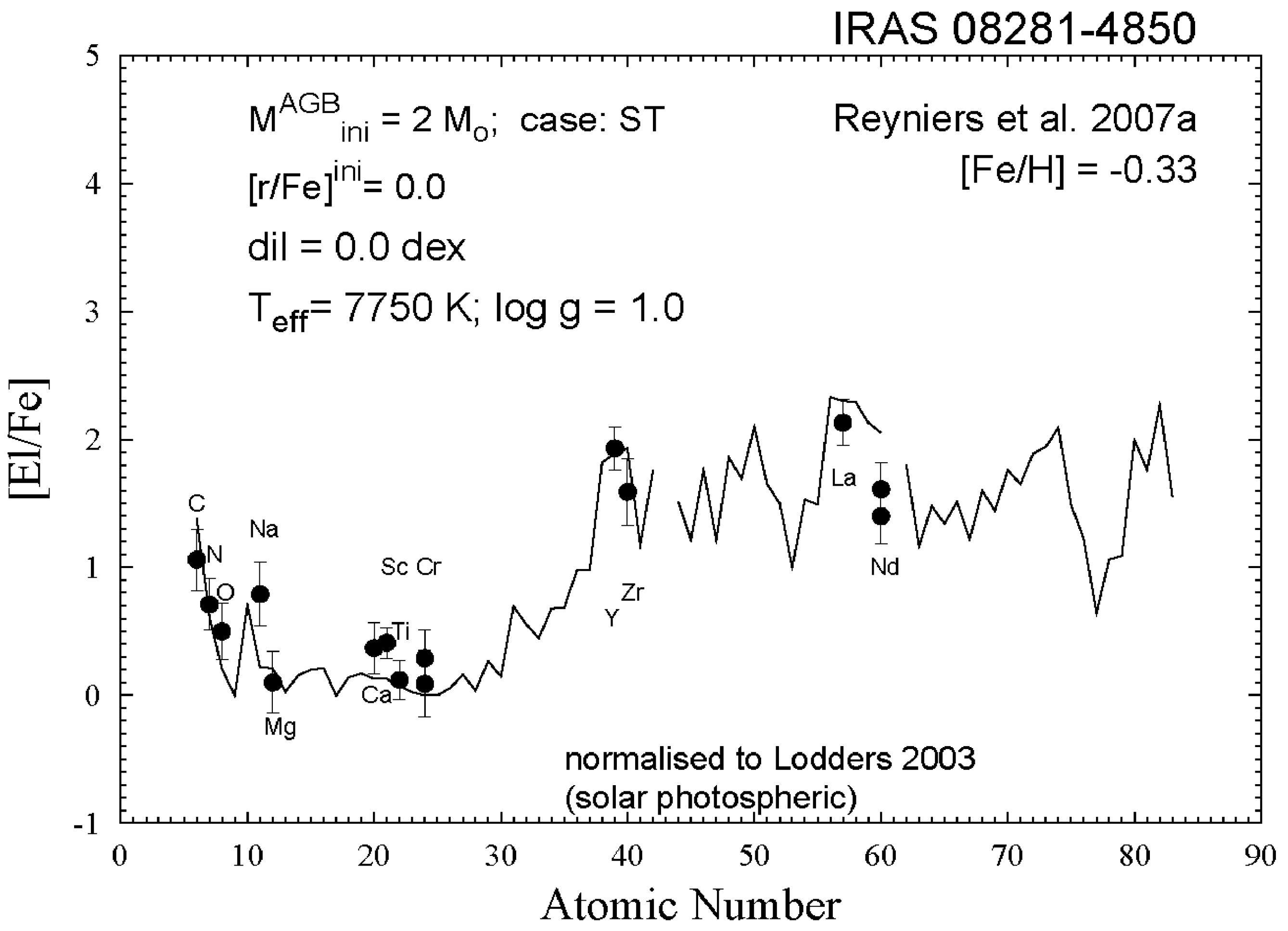
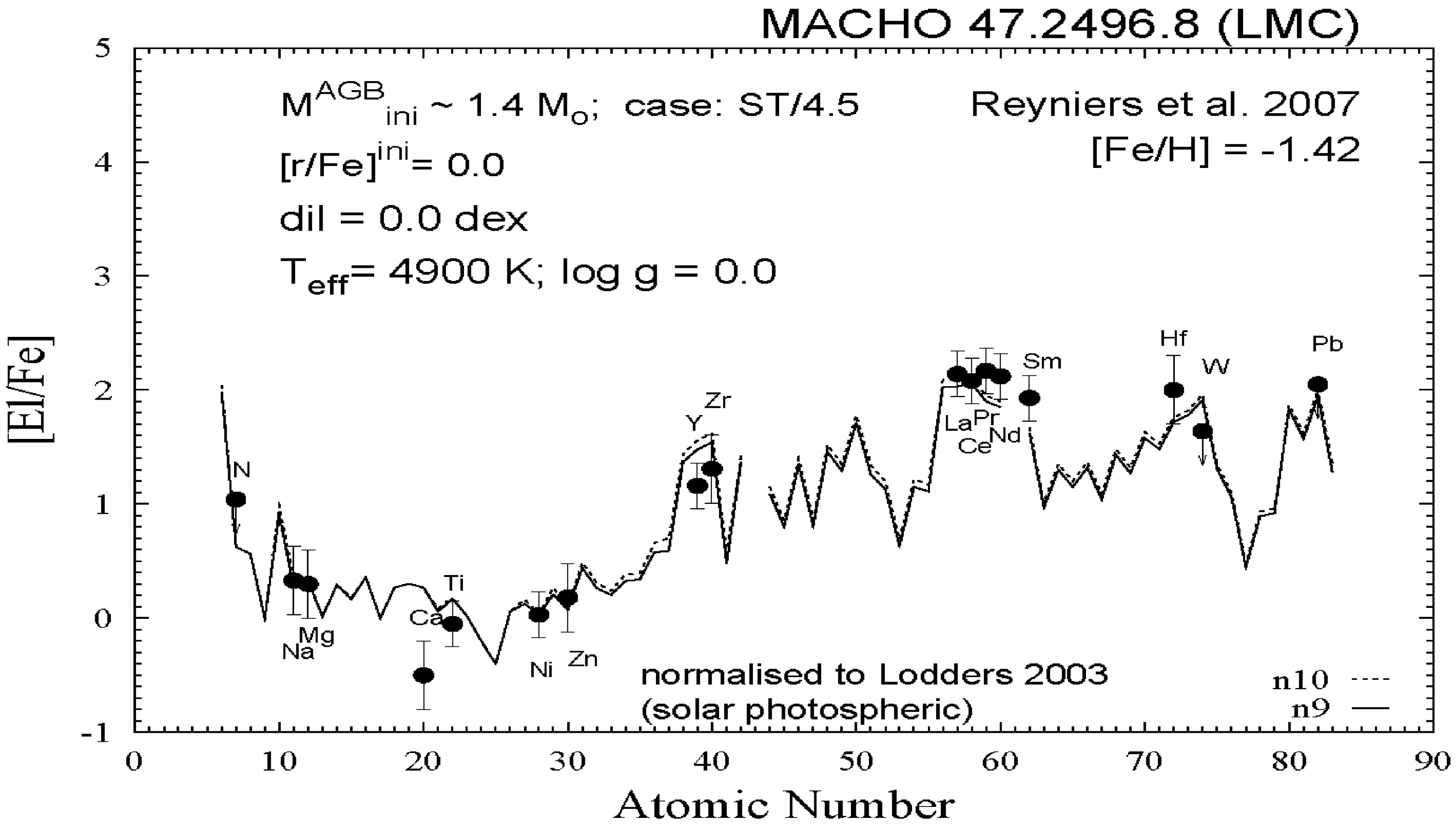


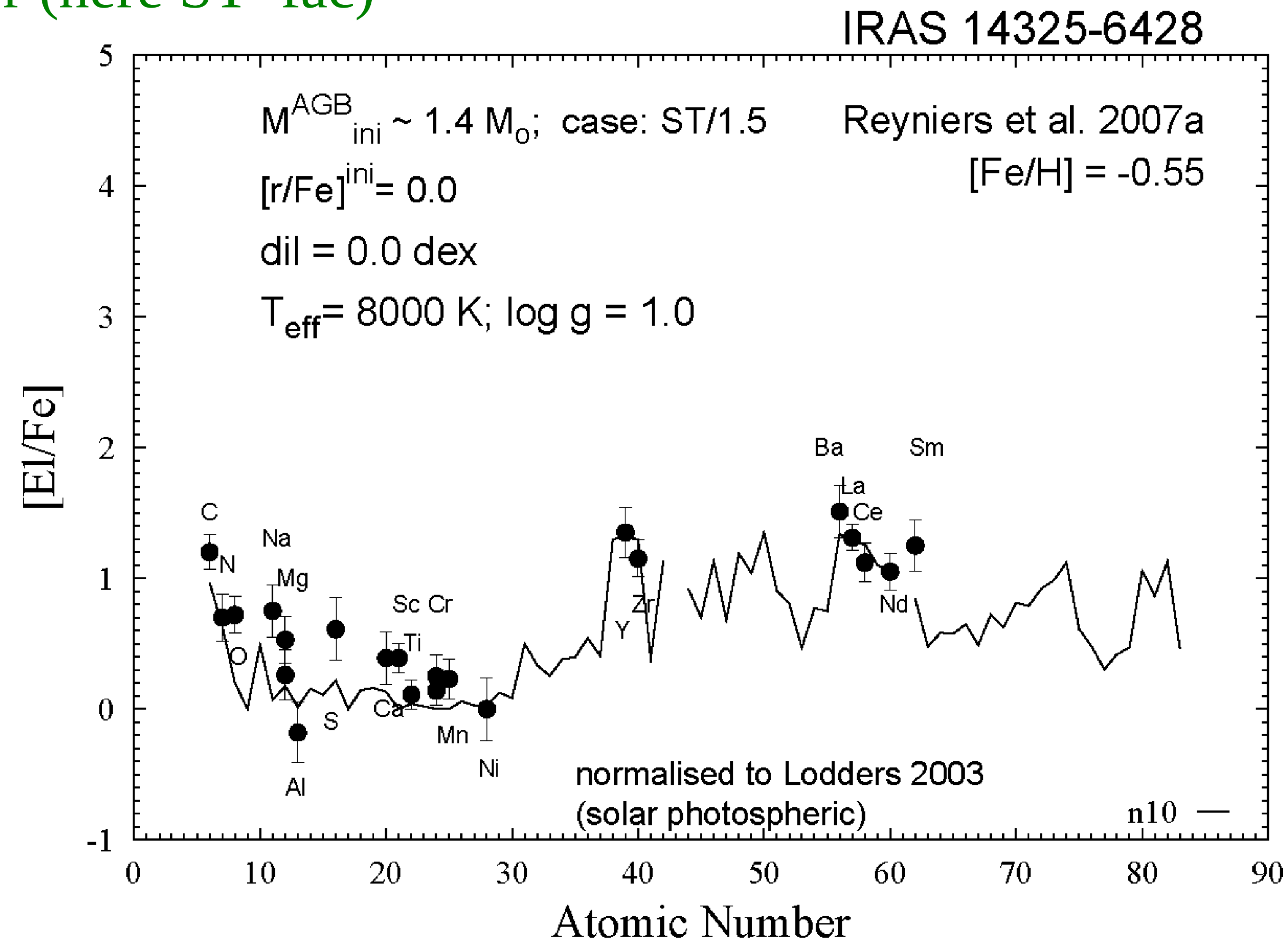
FIGURE 1. Theoretical interpretation of the post-AGB star IRAS 08281-4850 by Reyniers et al. (2007a) [2], with $M_{\mathrm{ini}}^{\mathrm{AGB}} = 2\ \mathrm{M}_{\odot}$, case ST.

Gallino et al. (2008)

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).



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

The classical r-process

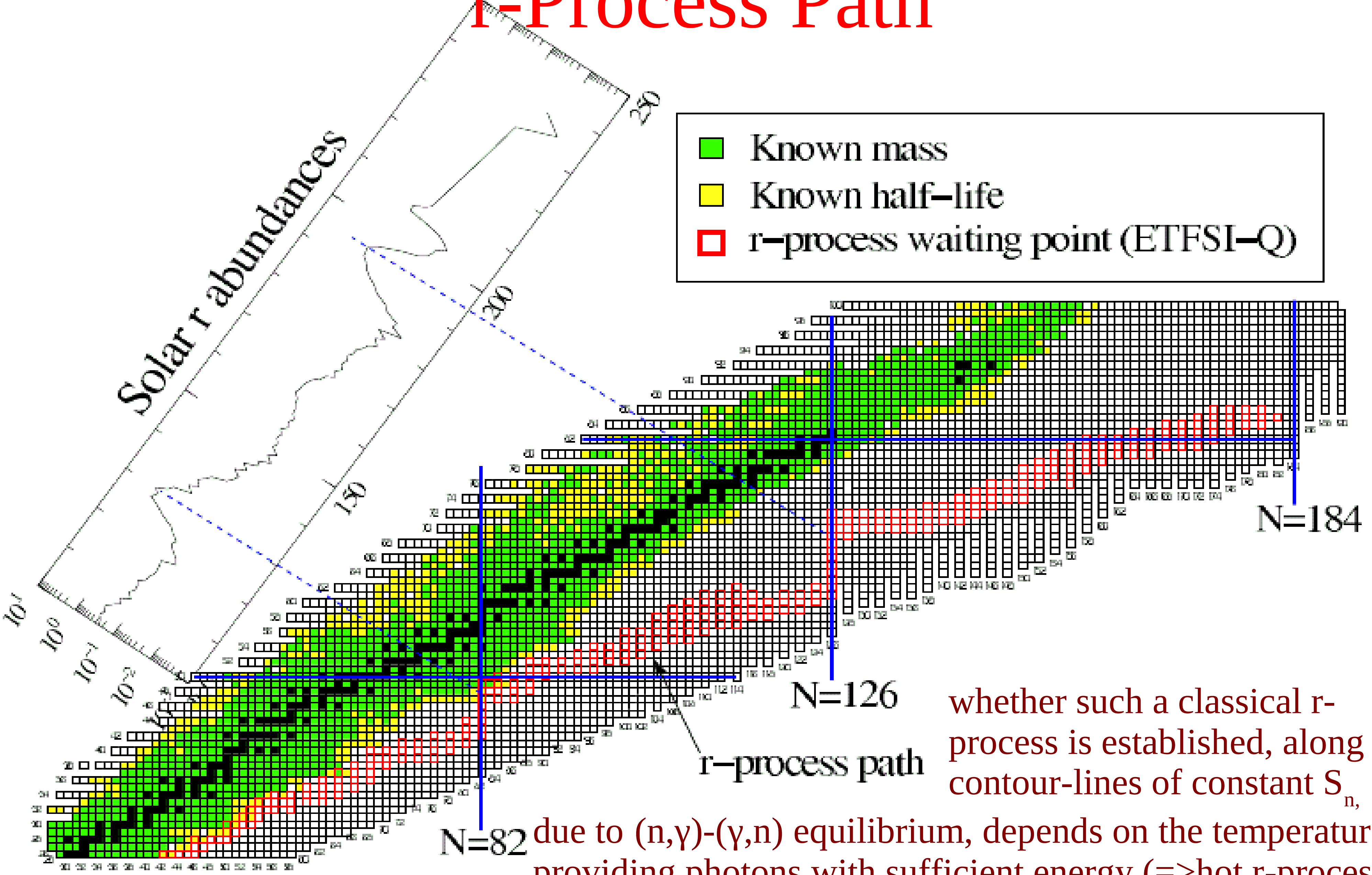
- Assume conditions where after a charged-particle freeze-out the heavy QSE-group splits into QSE-subgroups containing each one isotopic chain Z, and a high neutron density is left over
- In each of these QSE-subgroups (isotopic chains) a chemical equilibrium between neutron captures and photodisintegrations leads to abundance maxima at the same S_n (determined by n_n and T)
- 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^-), (ν_e,e^+)

r-Process Path

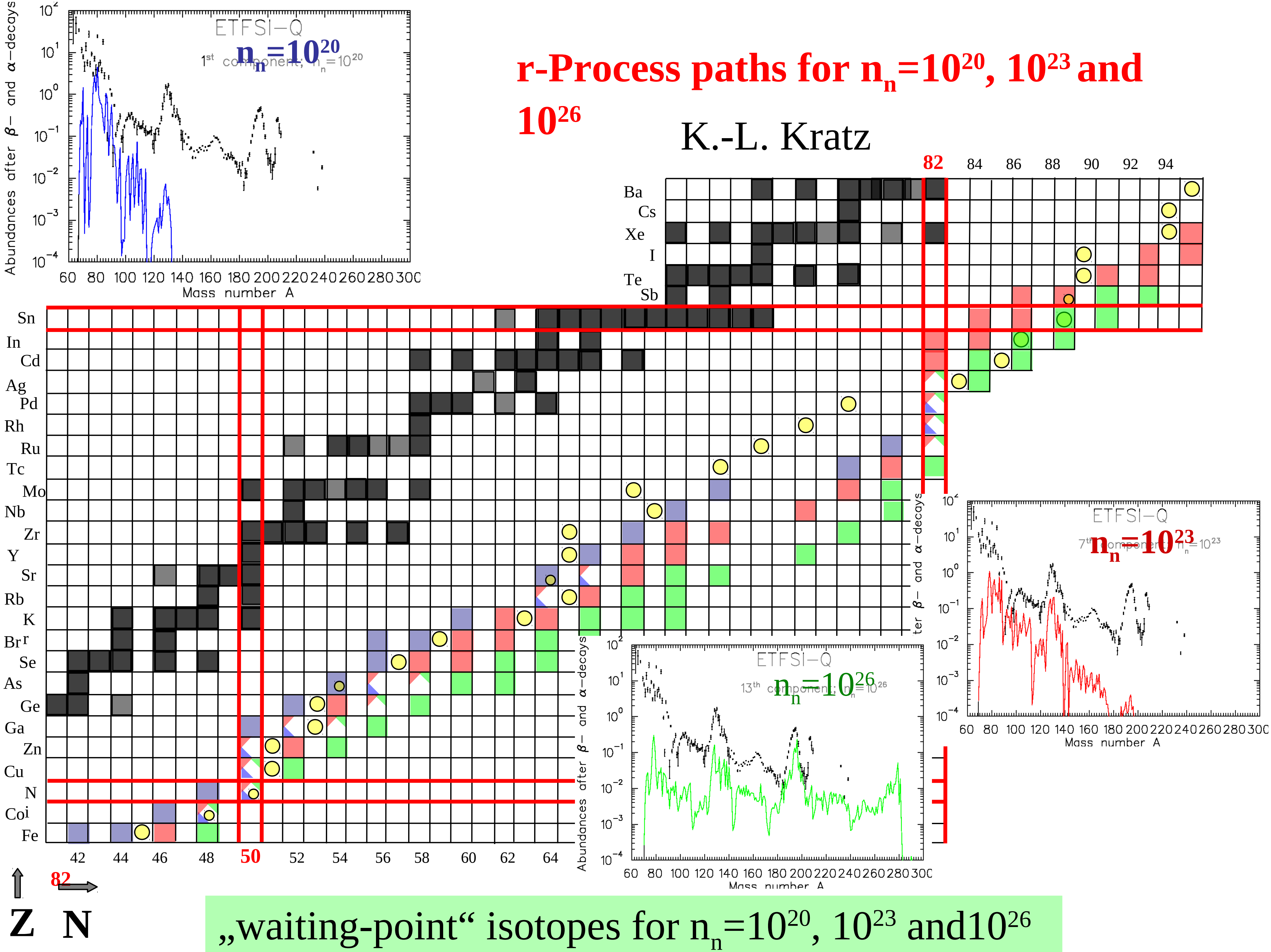


whether such a classical r-process is established, along contour-lines of constant S_{n}, due to (n,γ)-(γ,n) equilibrium, depends on the temperature, providing photons with sufficient energy (=>hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might not be established (=>smeared-out distribution, cold r-process)

G. Martinez-Pinedo

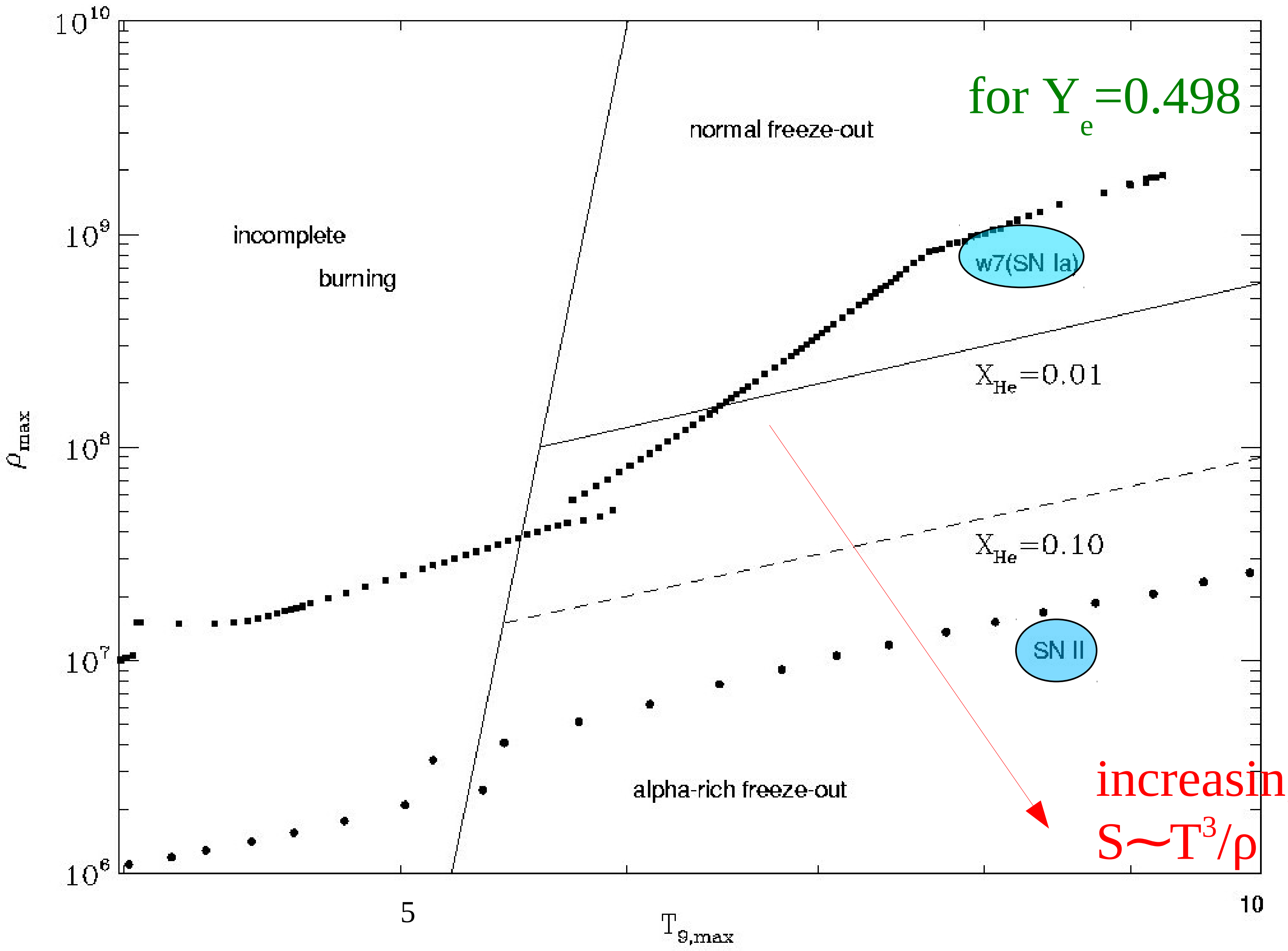
r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26}

K.-L. Kratz



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

Explosive Si-Burning



for $Y_e=0.498$

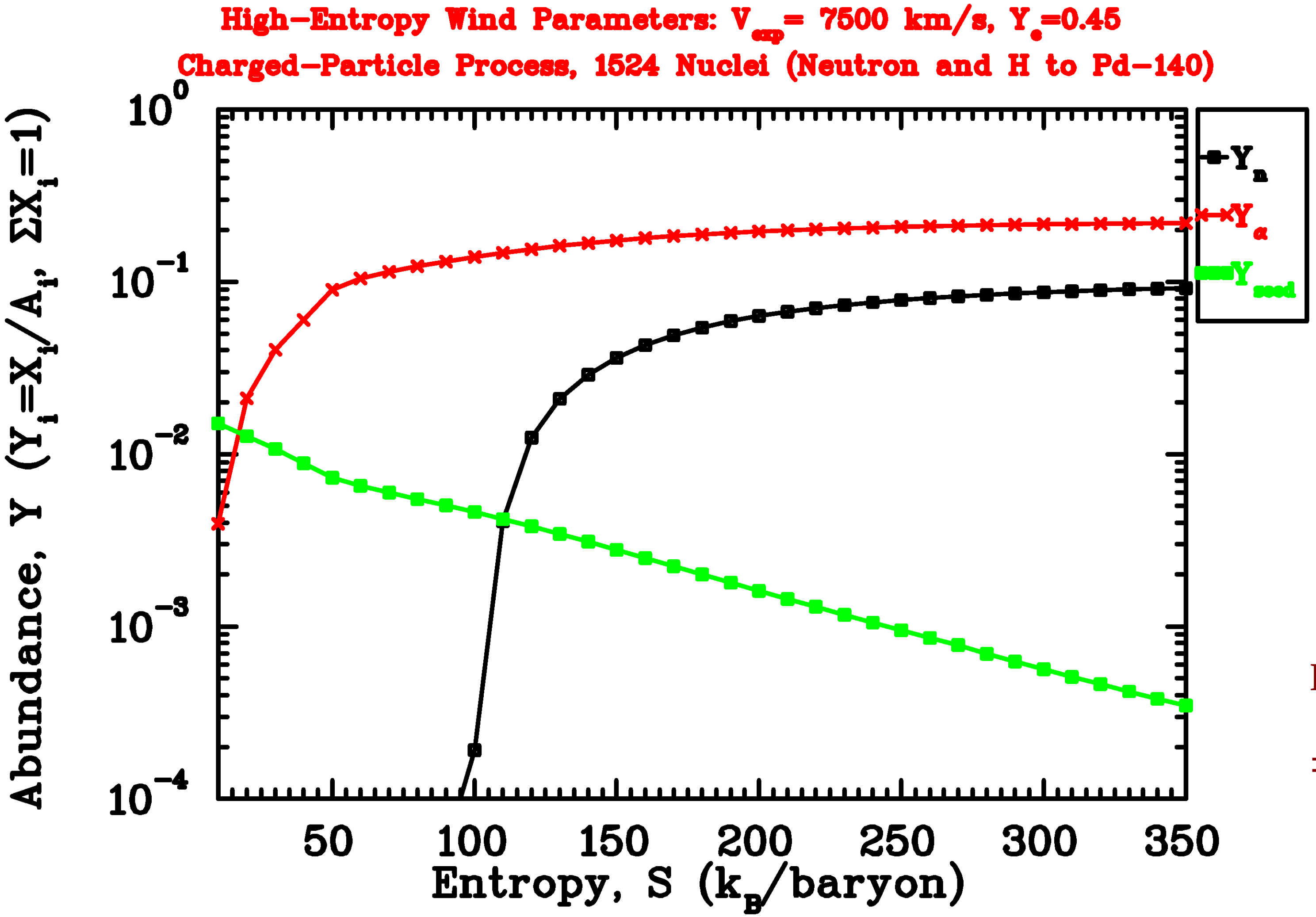
increasing entropy

$S \sim T^3/\rho$

Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^4He to C and beyond freeze out earlier (alpha-rich freeze-out).

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

Farouqi et al. (2010)

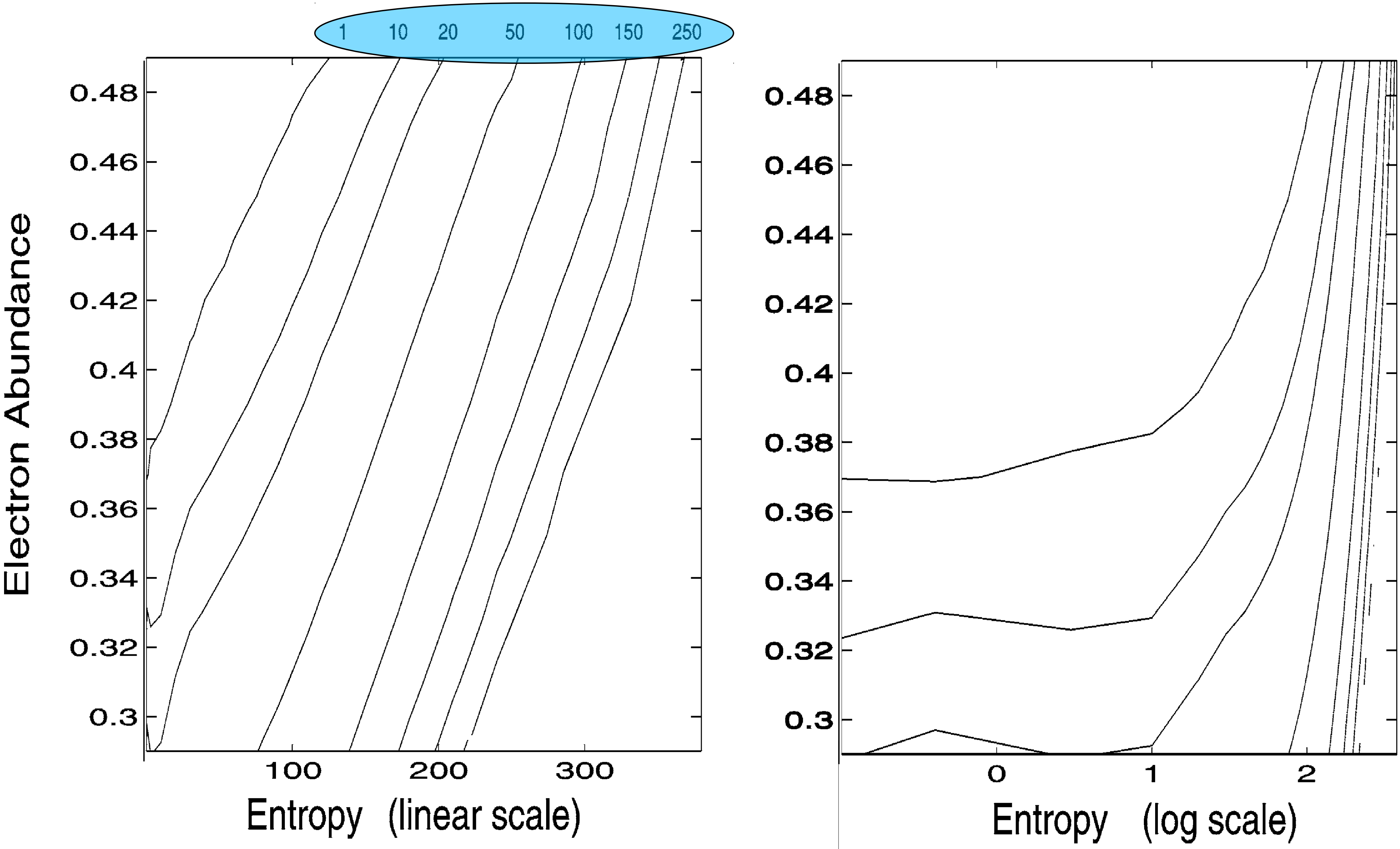


n/seed

$=Y_n/Y_{seed}$

The essential quantity for a successful r-process to occur is to have a n/seed ratio so that $A_{seed}+n/seed=A_{actinides}$*!*

n/seed ratios as function of S and Y_e



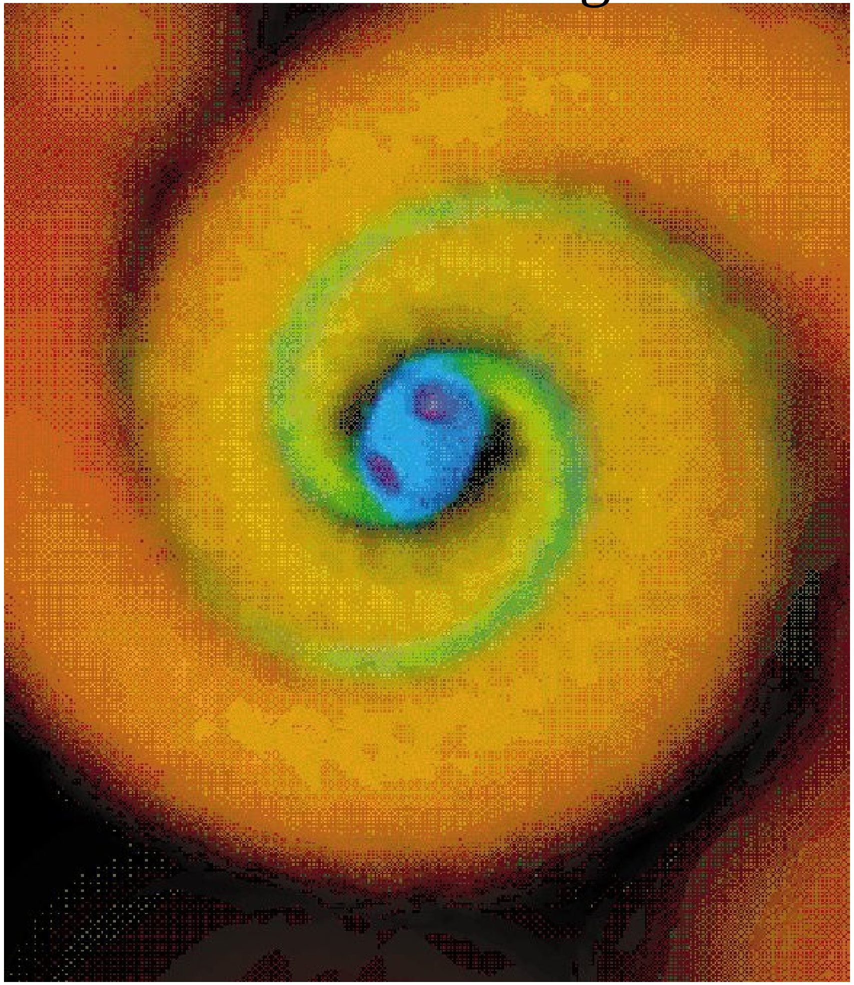
neutrino wind?

Freiburghaus et al. (1999)

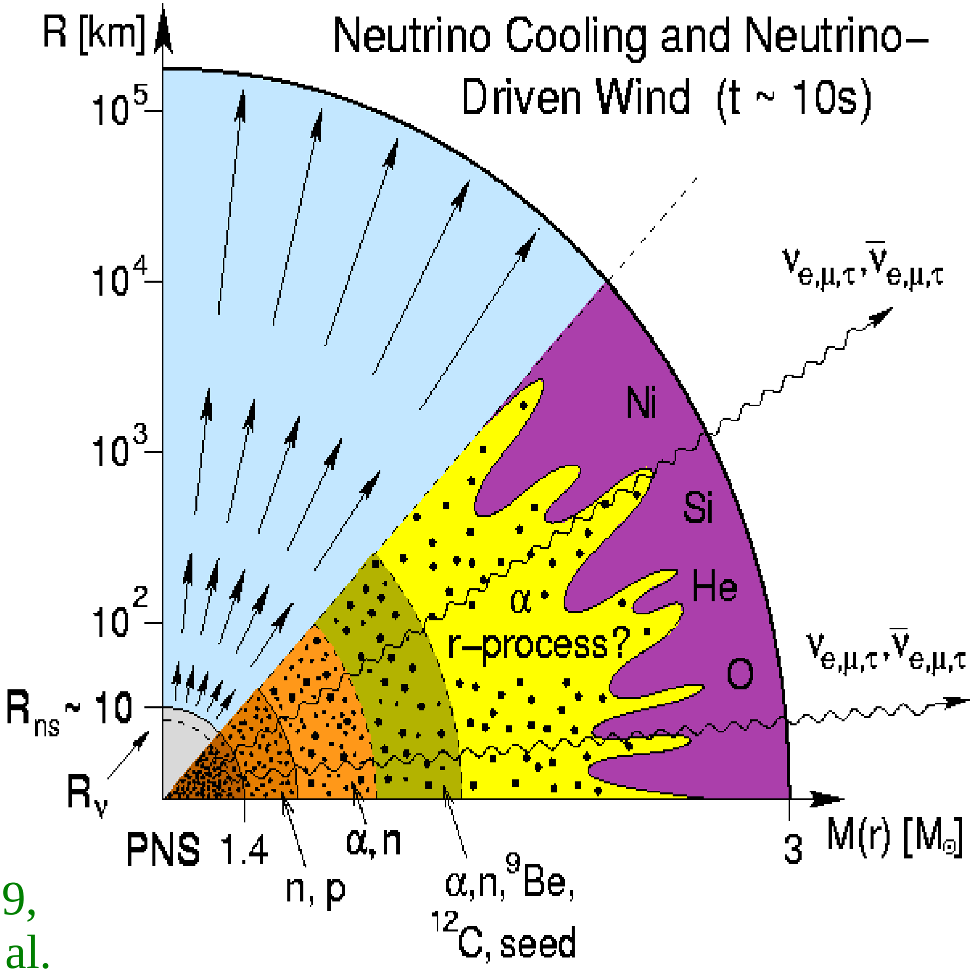
Neutron star mergers and polar jets?

What is the site of the r-process?

from S. Rosswog



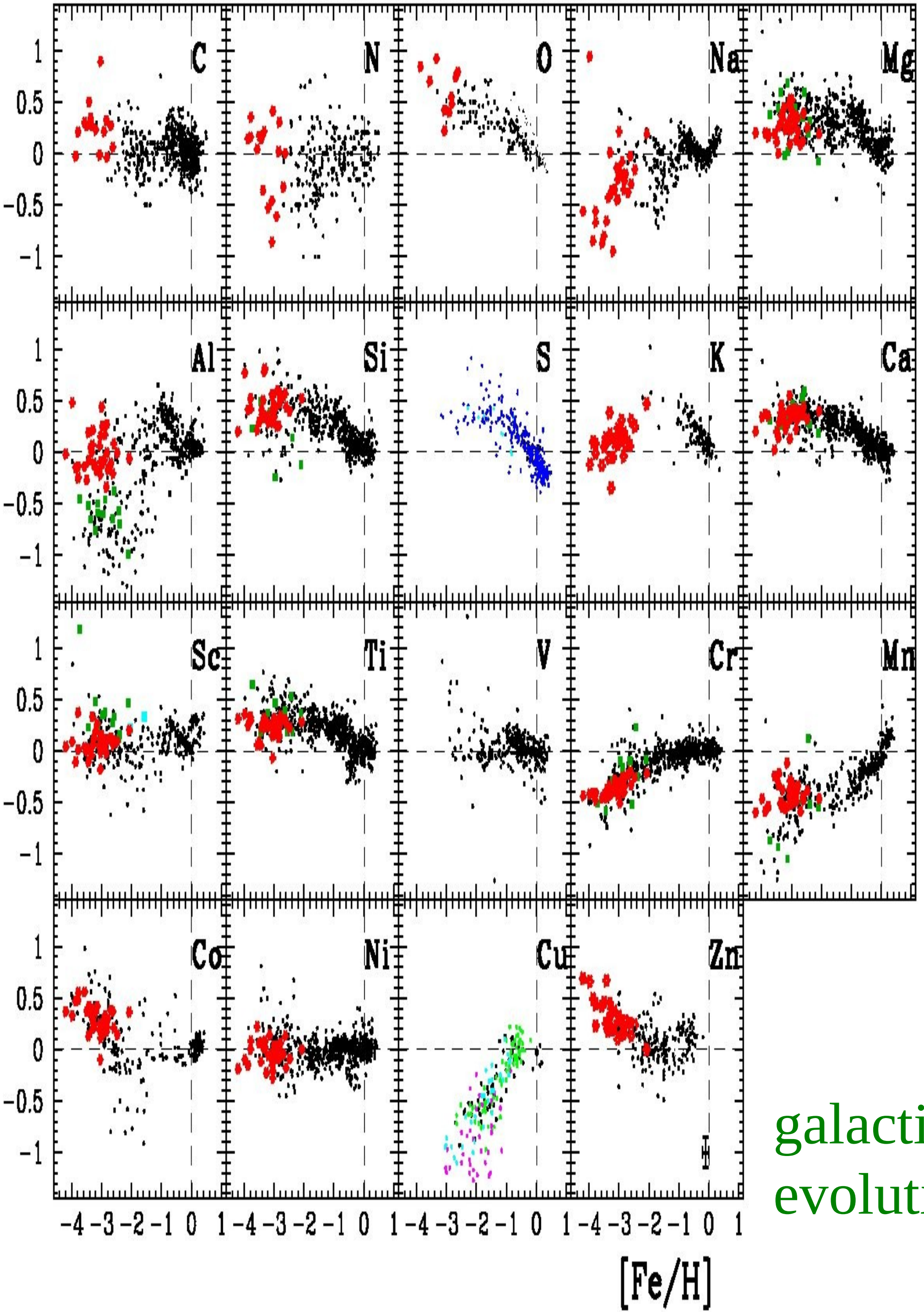
from H.-T. Janka



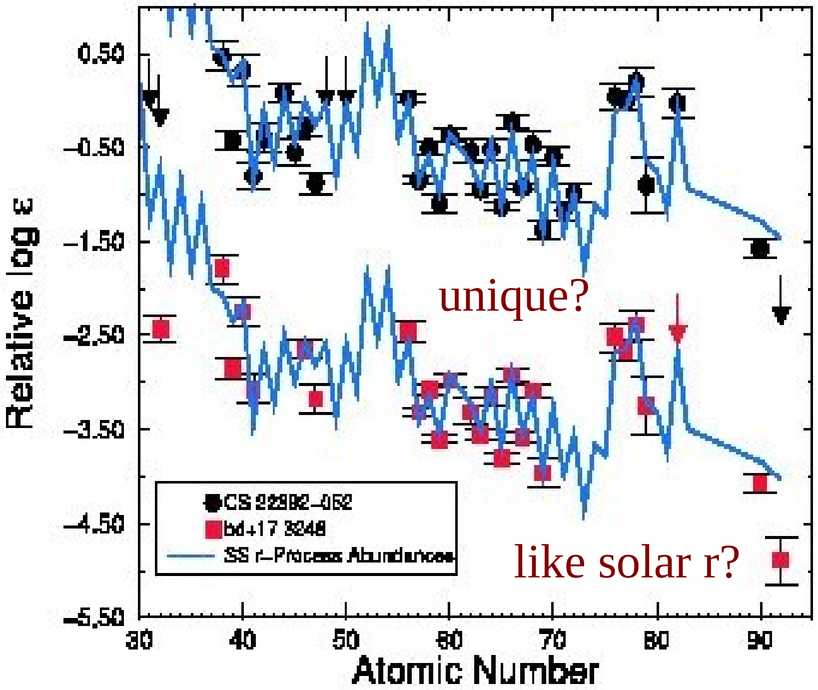
NS mergers, BH-NS mergers (Freiburghaus et al. 1999, Rosswog.., Panov et al., Bauswein et al., Korobkin et al. 2012.)
or alternatively polar jets from supernovae (Cameron 2003, Fujimoto et al. 2008, Winteler et al. 2012)

SN neutrino wind (originally introduced by Hoffmann, Woosley, Meyer, Howard..), problems: high enough entropies attained? Ye<0.5? neutrino properties???

How do we understand:



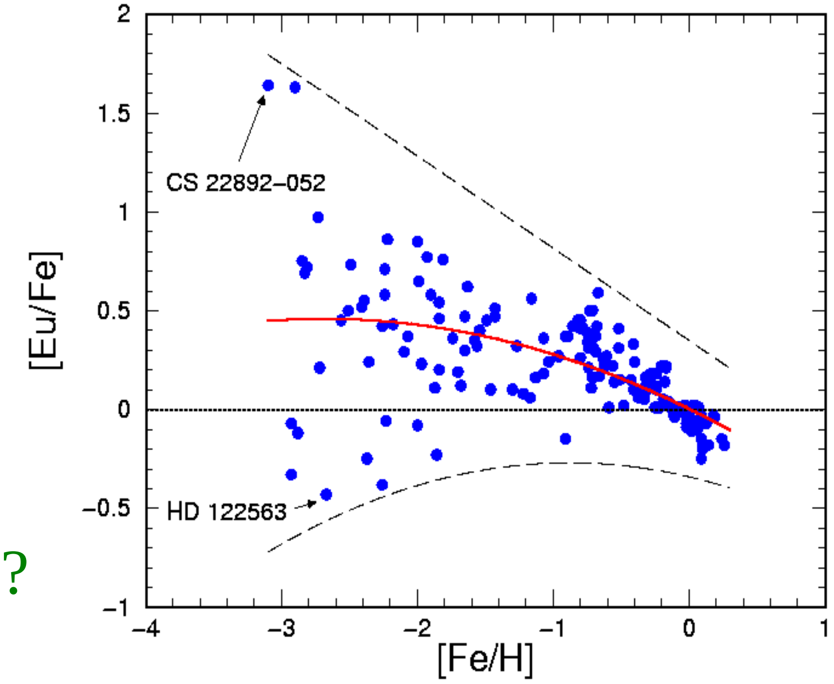
galactic evolution?



unique?

like solar r?

low metallicity stars ...



What is the site of the r-process(es)?

- **Neutrino-driven Winds (in supernovae?) ?** ***Arcones, Burrows, Janka, Farouqi, Hoffman, Kajino, Kratz, Martinez-Pinedo, Mathews, Meyer, Qian, Takahara, Takahashi, FKT, Thompson, Wanajo, Woosley … (no!?)***

- Electron Capture Supernovae ? ***Wanajo and Janka (weak!)***

- SNe due to quark-hadron phase transition ***Fischer, Nishimura, FKT (if? weak!)***

- **Neutron Star Mergers?** ***Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin***

- Black Hole Accretion Disks? ***MacLaughlin, Surman, Wanajo, Janka, Ruffert***

- Explosive He-burning in outer shells (???) ***Cameron, Cowan, Truran, Hillebrandt, FKT, Wheeler, Nadyozhin, Panov***

- CC Neutrino Interactions in the Outer Zones of Supernovae ***Haxton, Qian (abundance pattern ?)***

- **Polar Jets from Rotating Core Collapse?** ***Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura, Nishimura, Takiwaki, FKT, Winteler***

What determines the neutron/proton or proton/nucleon=Ye ratio?

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 ?

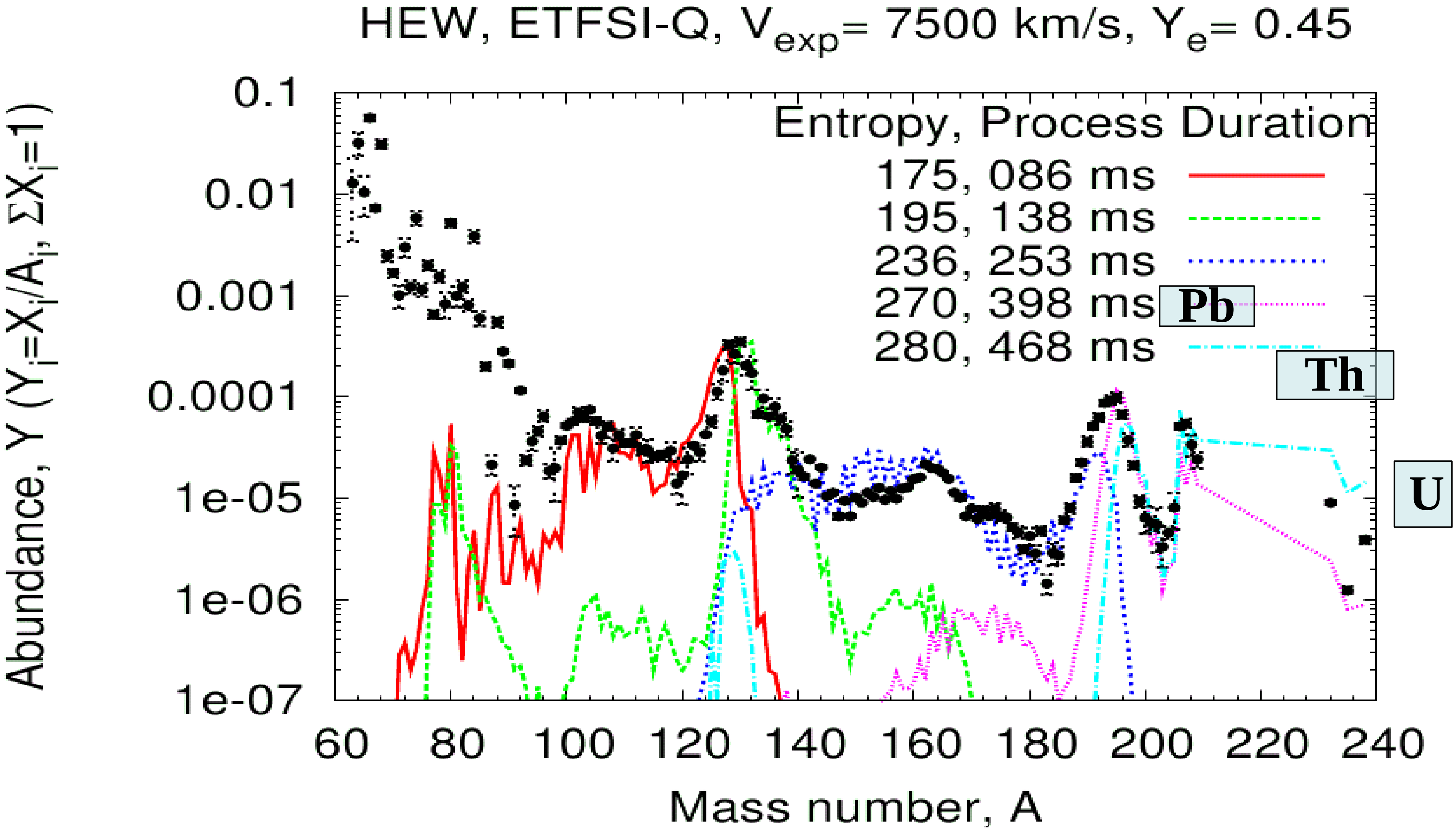
If neutrino flux sufficient to have an effect (scales with $1/r^2$), and total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with $E_{av,\nu} - E_{av,\nu} > 4(m_n - m_p)$ lead to $Y_e < 0.5$!

General strategy for a successful r-process:

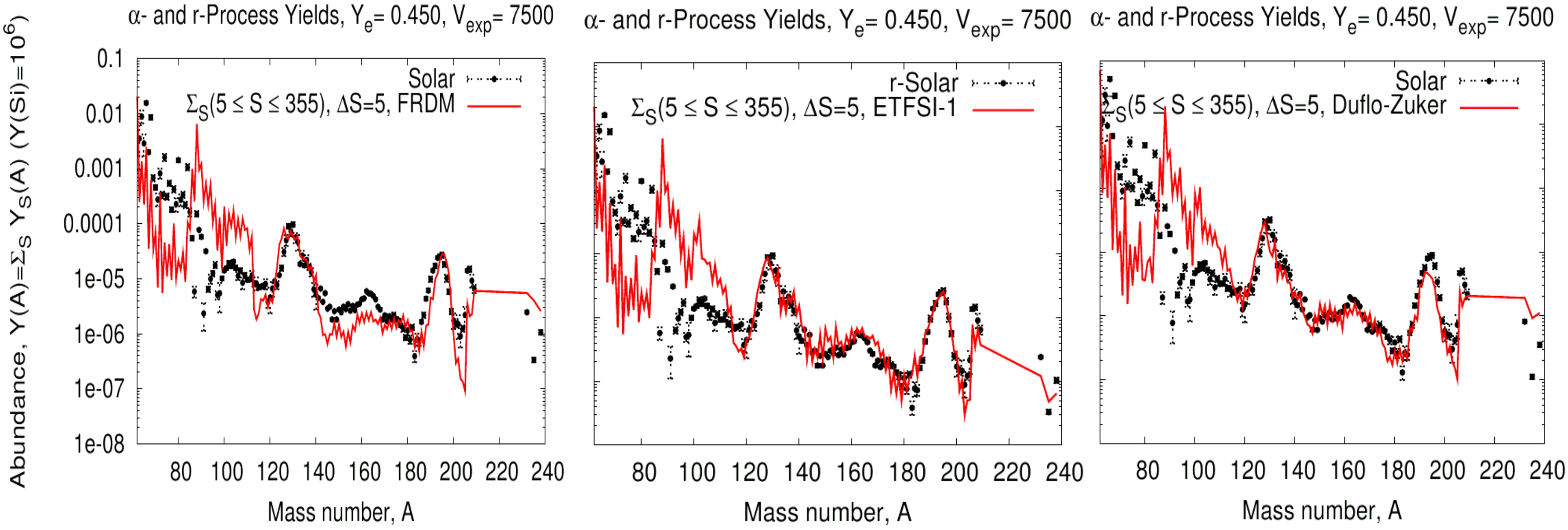
1. either highly neutron-rich initial conditions + fast expansion (avoiding neutrino interactions!)
2. have neutrino properties to ensure (at least slightly) neutron-rich conditions (+ high entropies)
3. invoke (sterile?/collective) neutrino oscillations

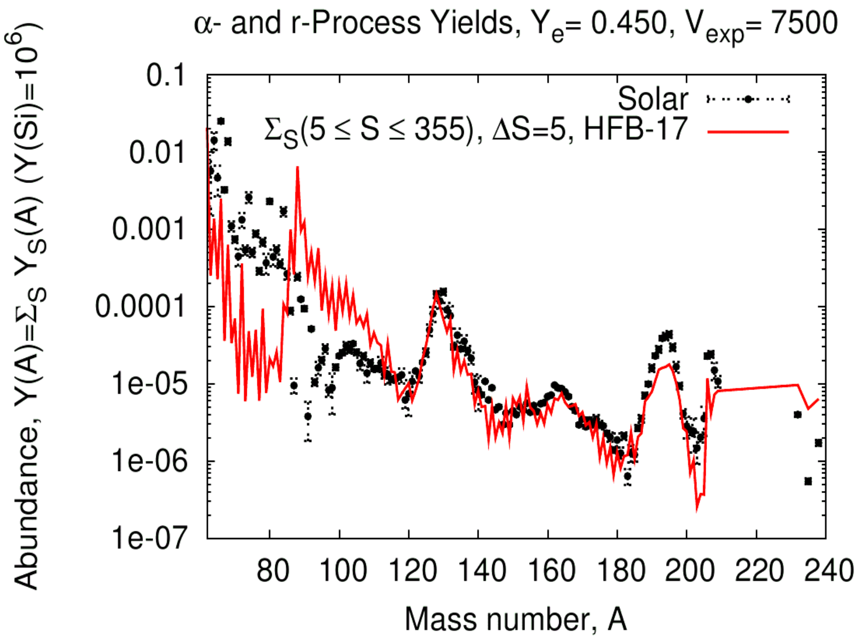
Individual Entropy Components in high entropy neutrino wind (hot r-process)

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



Superposition of entropies for different mass models

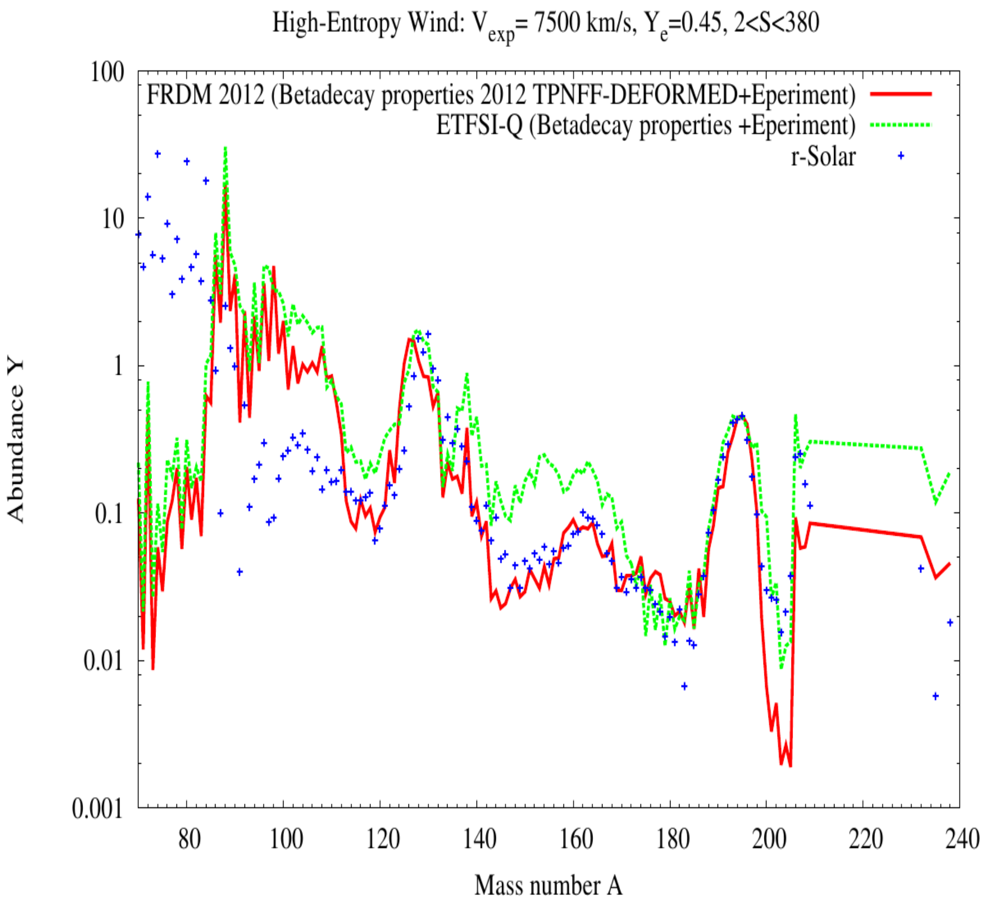




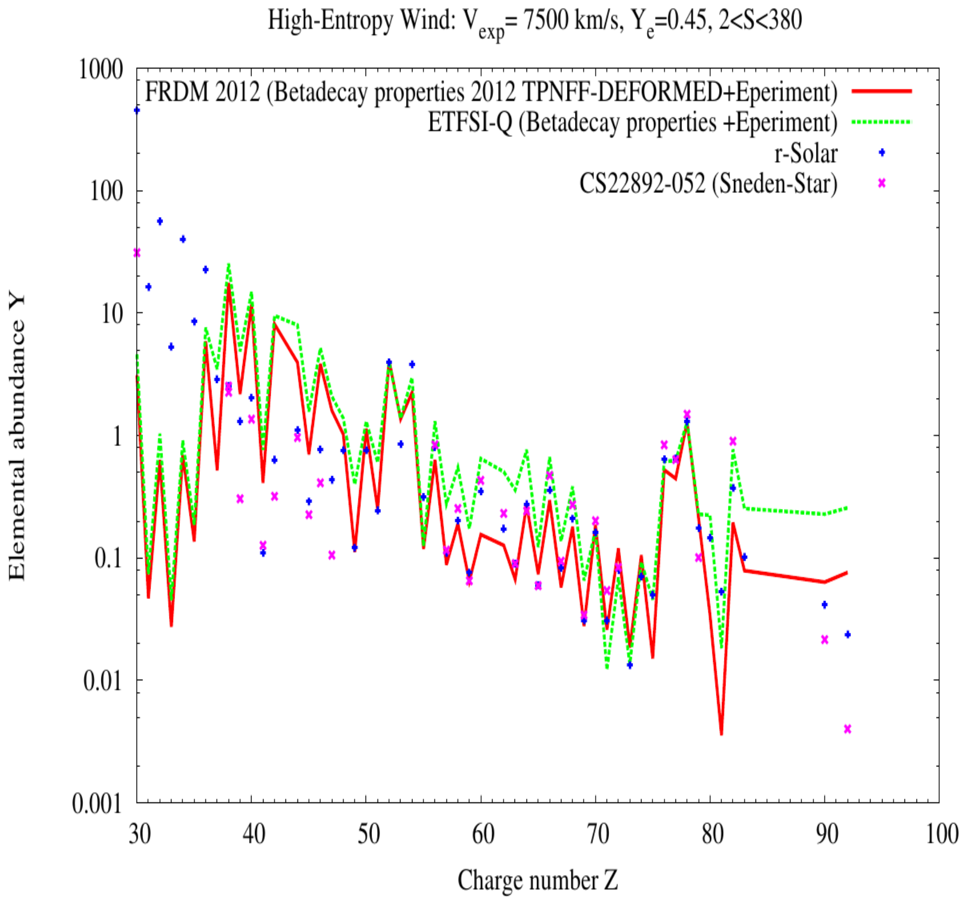
Farouqi et al. (2010)

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.



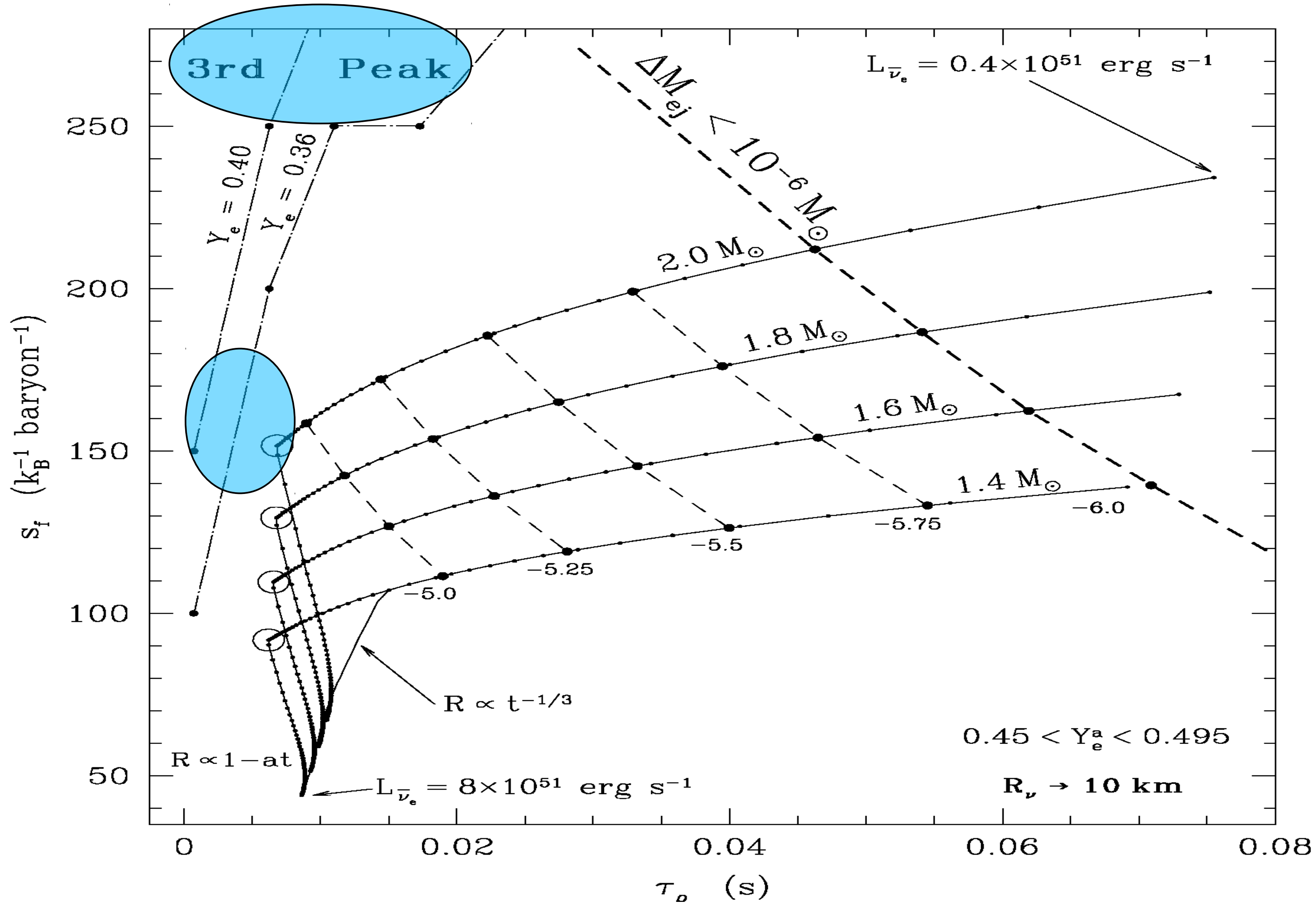
Isotopes



Elements

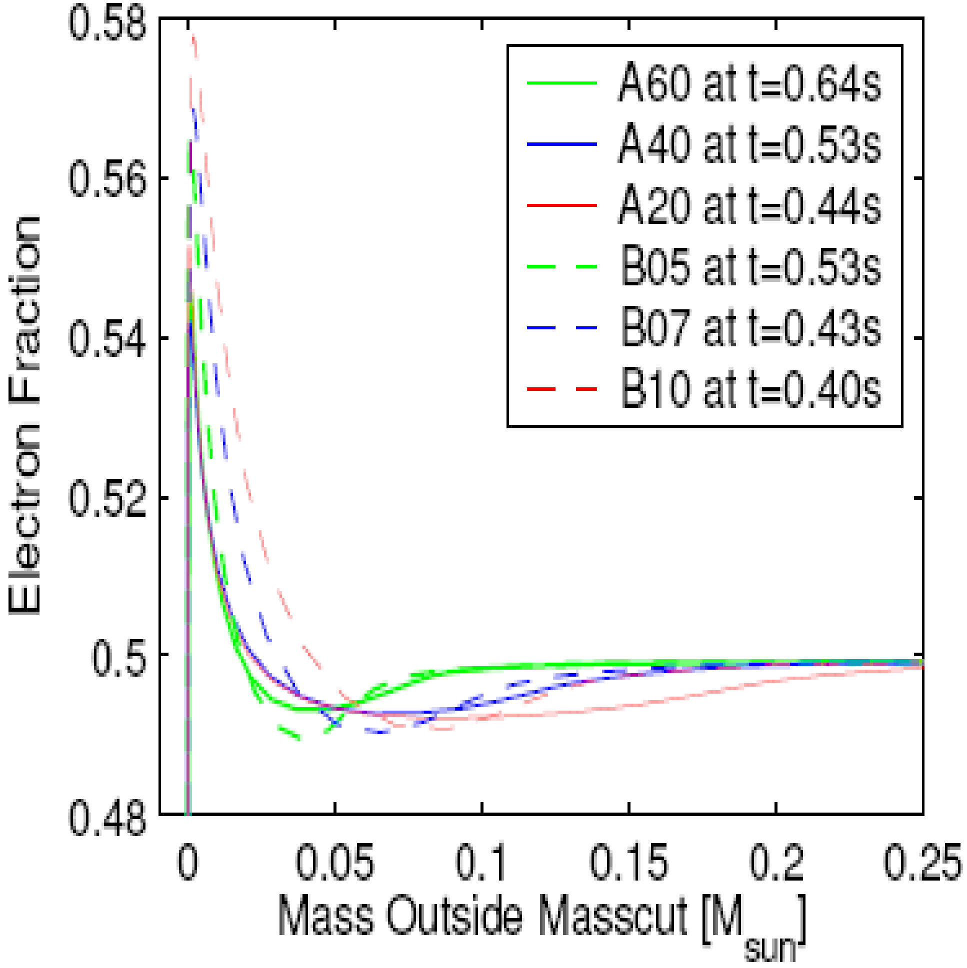
Application of the NEW FRDM (Möller 2012, in red)! (Farouqi & Kratz)
These are all parameter studies with an assumed entropy distribution,
for a given Ye and expansion timescale. The main question is, whether
supernovae can provide these conditions!!

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!!!

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



Liebendörfer et al. (2003),
Fröhlich et al. (2006a,b),
Pruet et al. (2005, 2006)
Wanajo (2007)

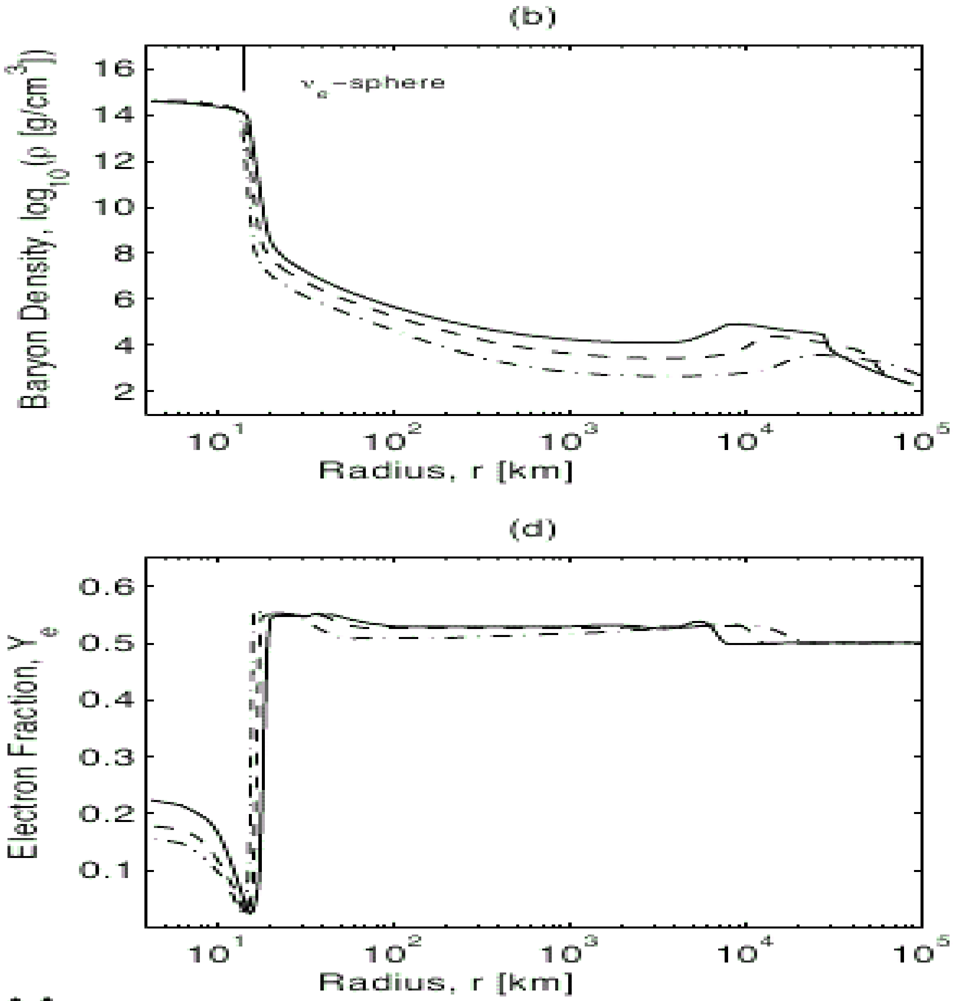
Discovery of the νp-process!

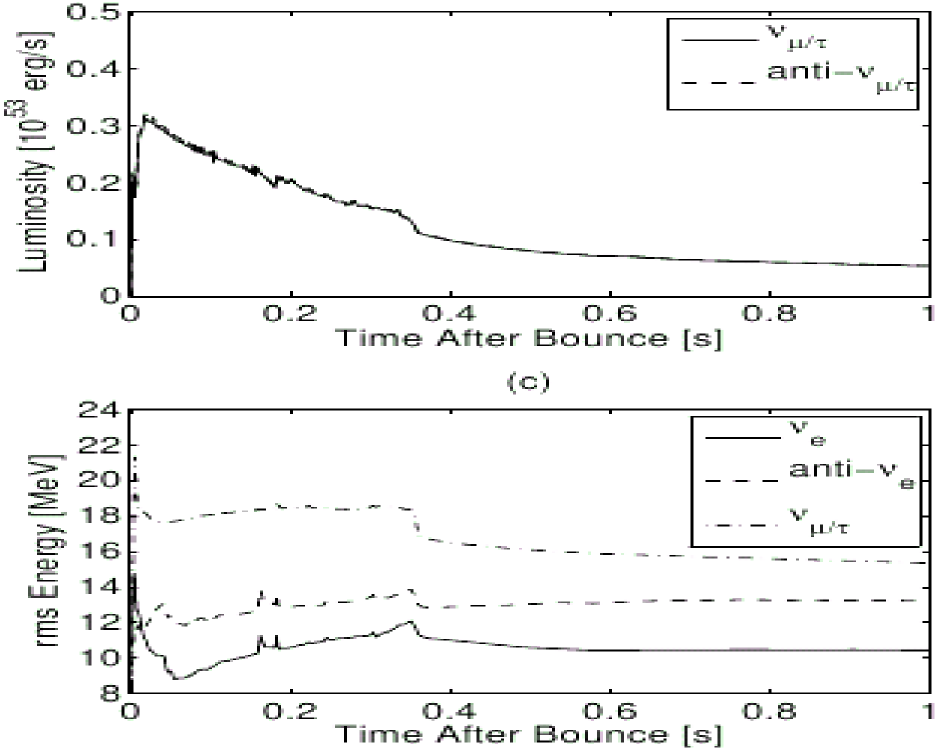
only effective for small radii (neutrino flux ~ $1/r^2$)

Long-term evolution up to 20s, transition from explosion to neutrino wind phase

Fischer et al. (2010)

these findings saw! a longterm proton-rich composition, late(r) transition to neutron-rich ejecta possible?





18 M_{sun} star, left at different times, up to 22s after bounce.

Inclusion of medium Effects, potential U in dense medium

Martinez-Pinedo et al. 2012, see also Roberts et al., Roberts & Reddy 2012

$$E_i(\boldsymbol{p}_i) = \frac{\boldsymbol{p}_i^2}{2m_i^*} + m_i + U_i, \quad i = n, p$$

$$E_{\nu_e} = E_{e^-} - (m_n - m_p) - (U_n - U_p)$$
$$E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p) + (U_n - U_p)$$

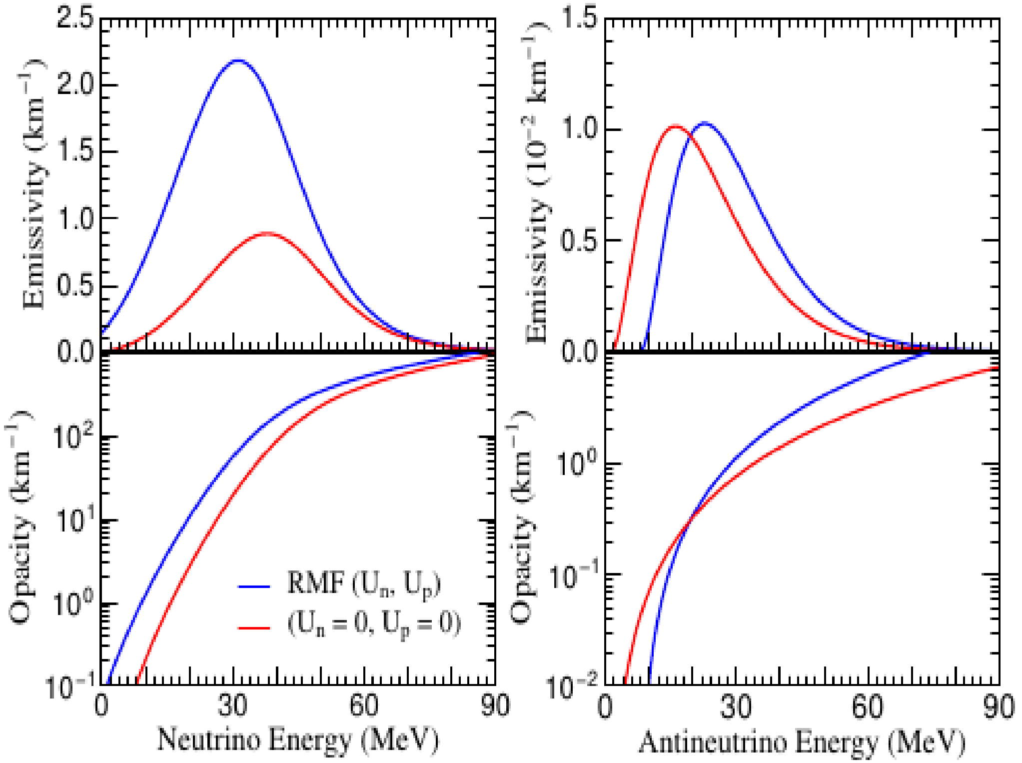
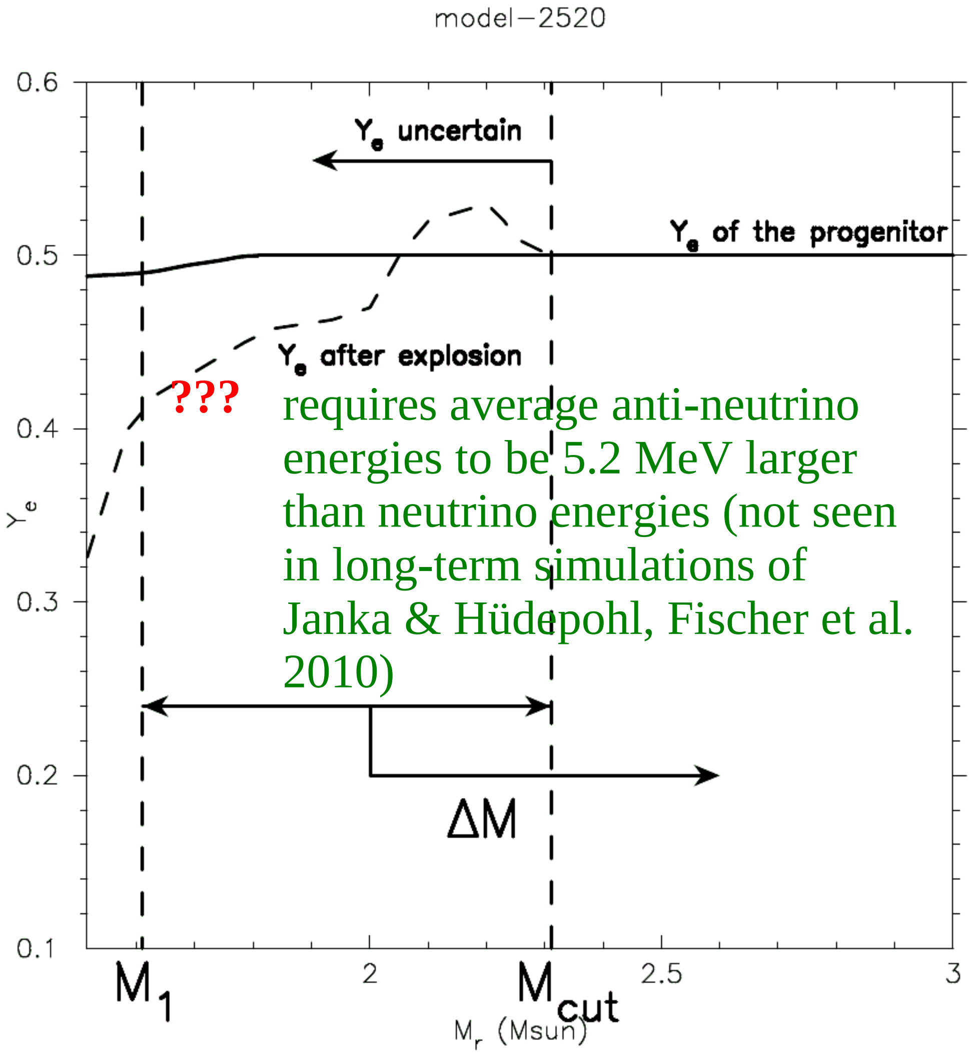


FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4! *Effect still not fully tested for hot neutrino wind?*

Possible Variations in Explosions and Ejecta



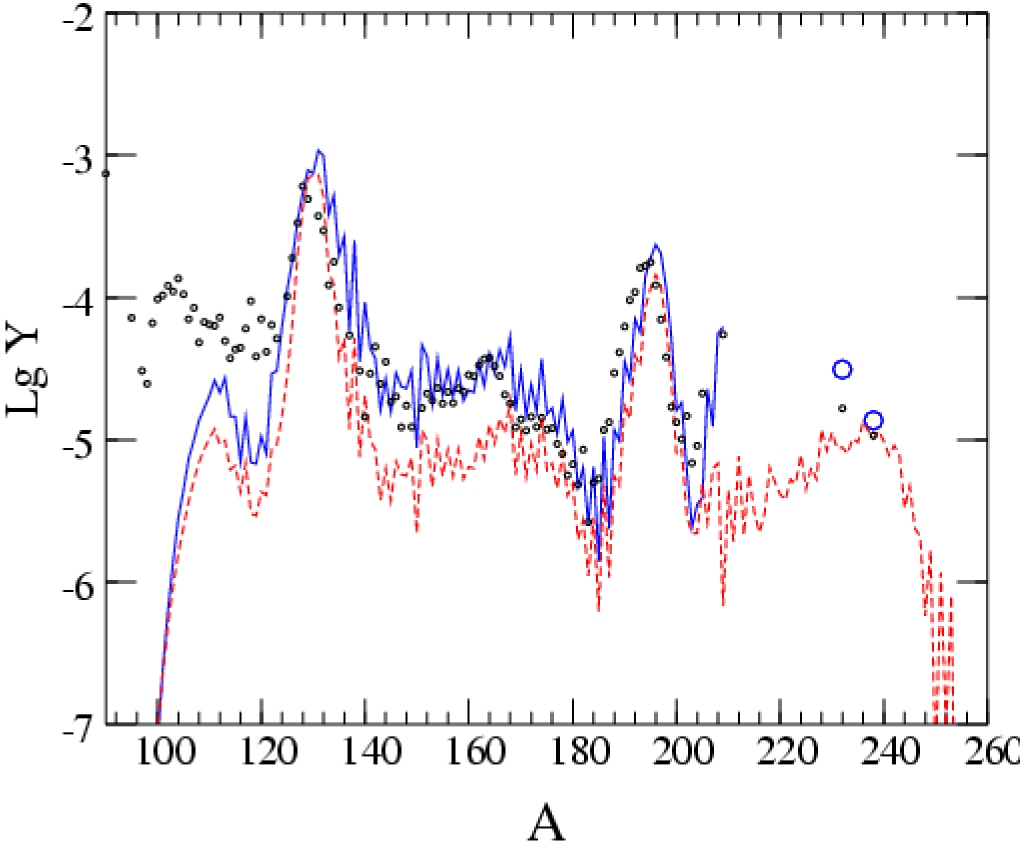
???

requires average anti-neutrino energies to be 5.2 MeV larger than neutrino energies (not seen in long-term simulations of Janka & Hüdepohl, Fischer et al. 2010)

Izutani et al. (2009)

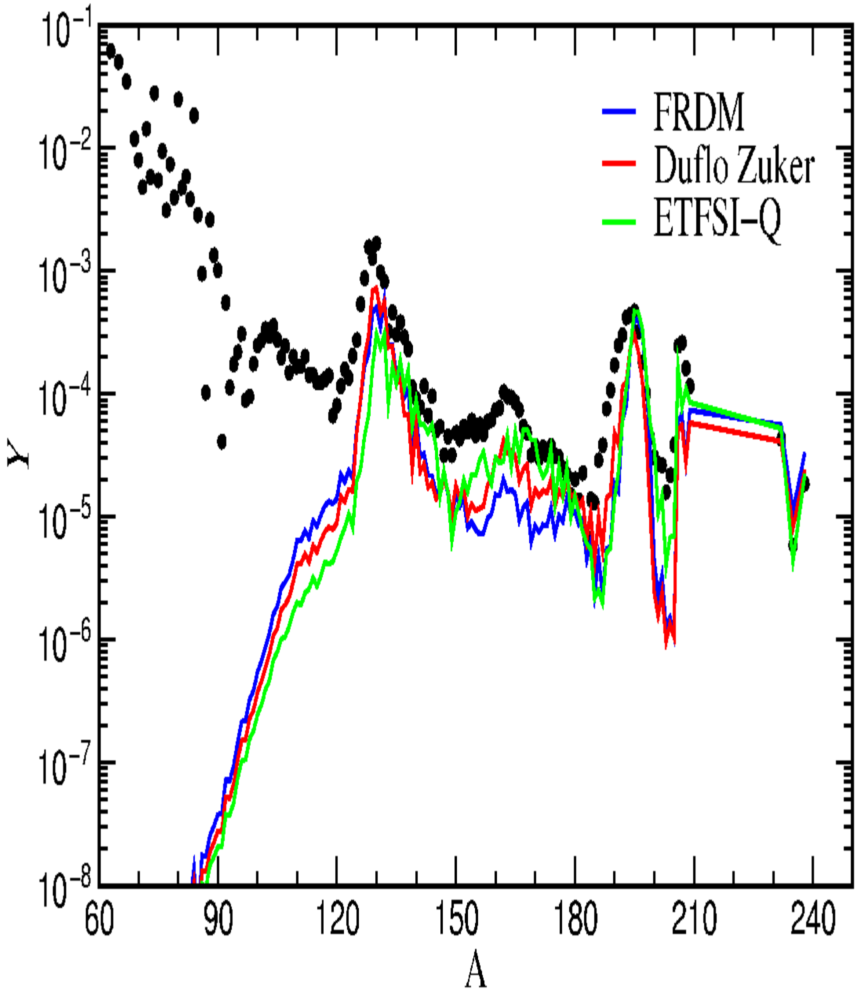
- *regular explosions with neutron star formation, neutrino exposure, νp-process, moderately neutron-rich neutrino wind and weak r-process or more* **??** *(see e.g. Arcones & Montes 2011, Roberts et al. 2010)*
- *under which (special?) conditions can very high entropies or very neutron-rich ejecta be obtained which produce the main r-process nuclei?*

Fission Cycling in Neutron Star Mergers



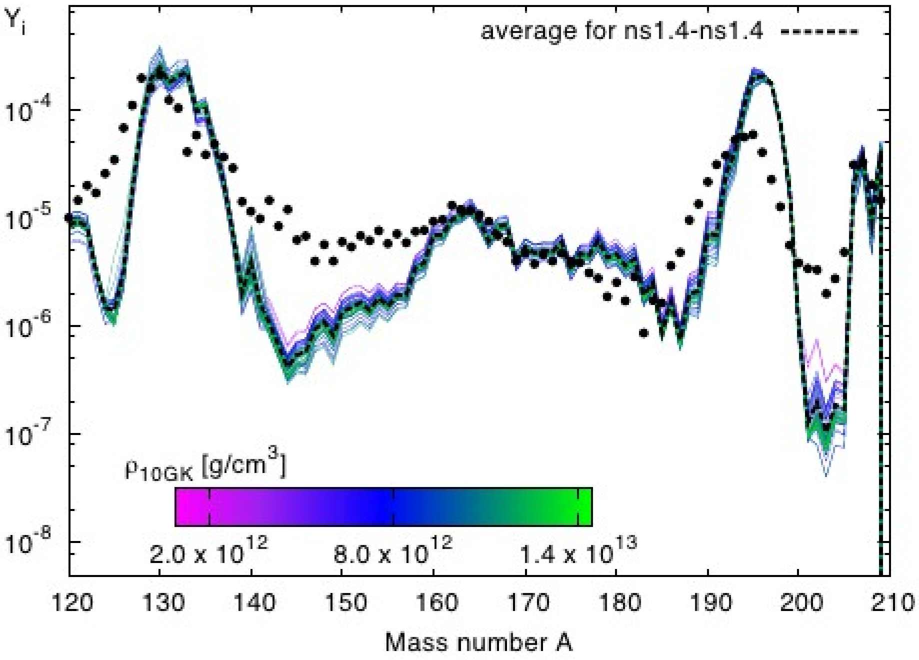
Panov, Korneev and Thielemann (2007, 2009)
with parametrized fission yield contribution
(see also Goriely, Bauswein, Janka 2011)

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

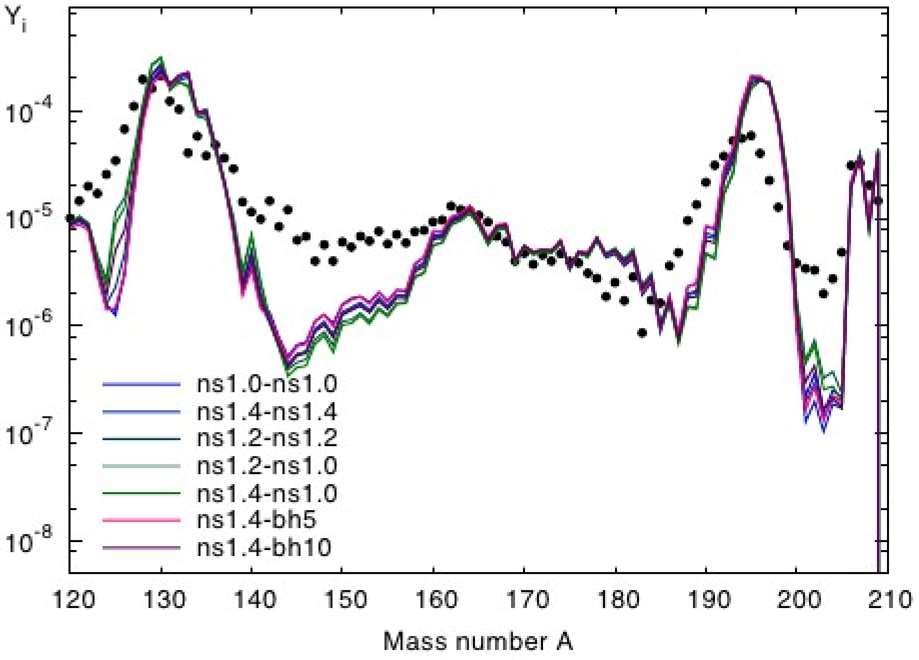


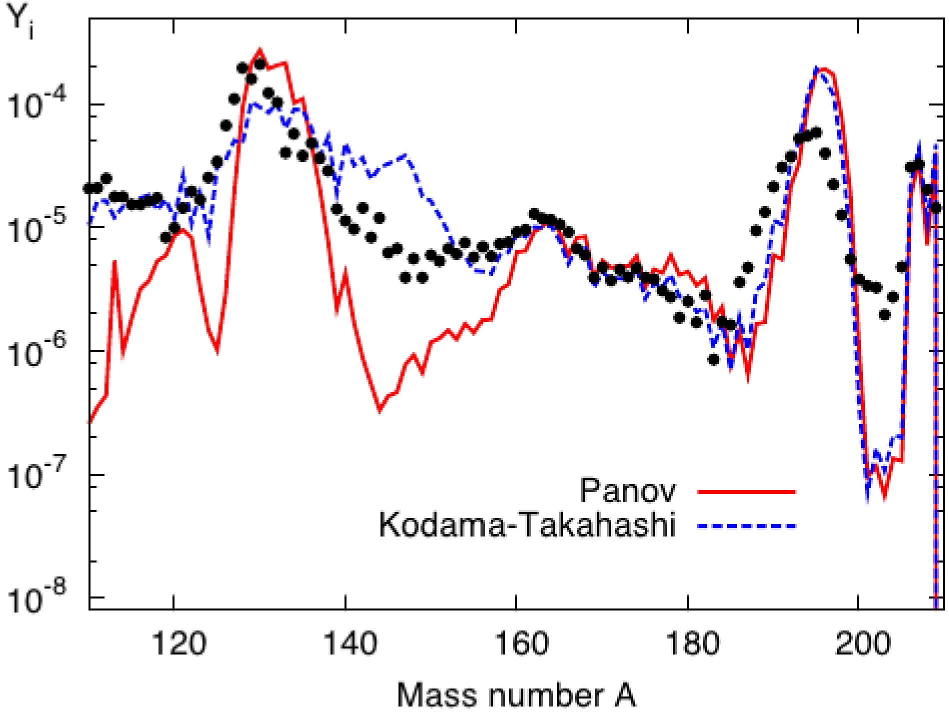
Martinez-Pinedo et al. (2006)

Recent neutron star merger updates (Korobkin et al. 2012)



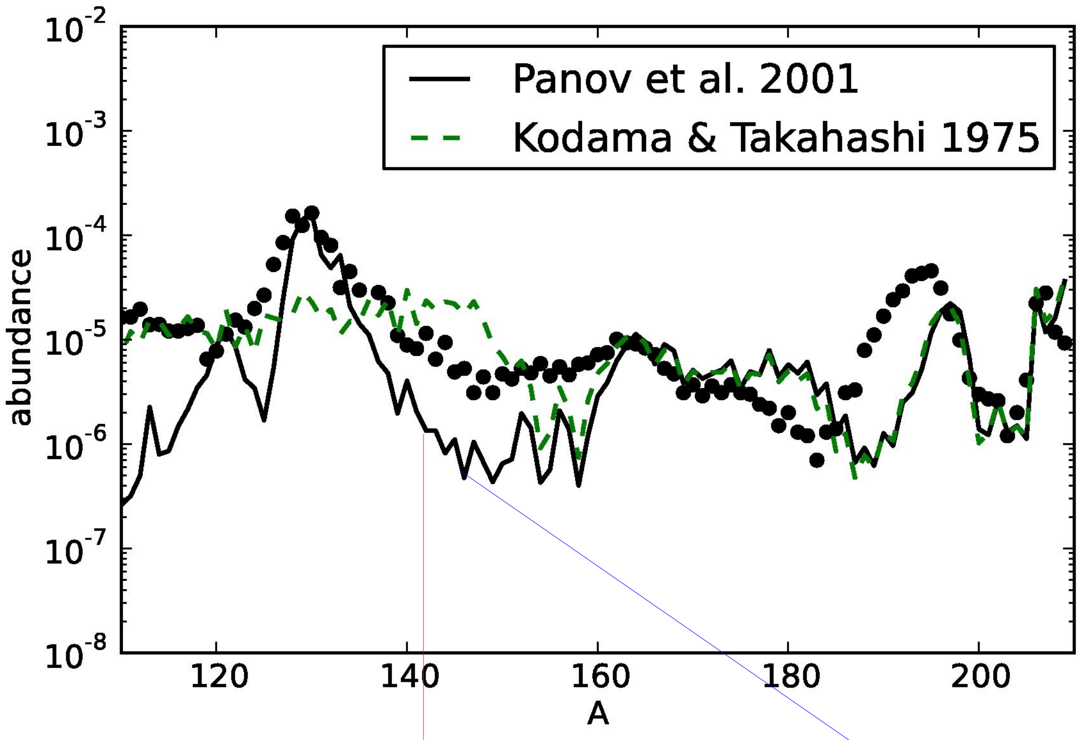
Variation in neutron star masses
fission yield prescription

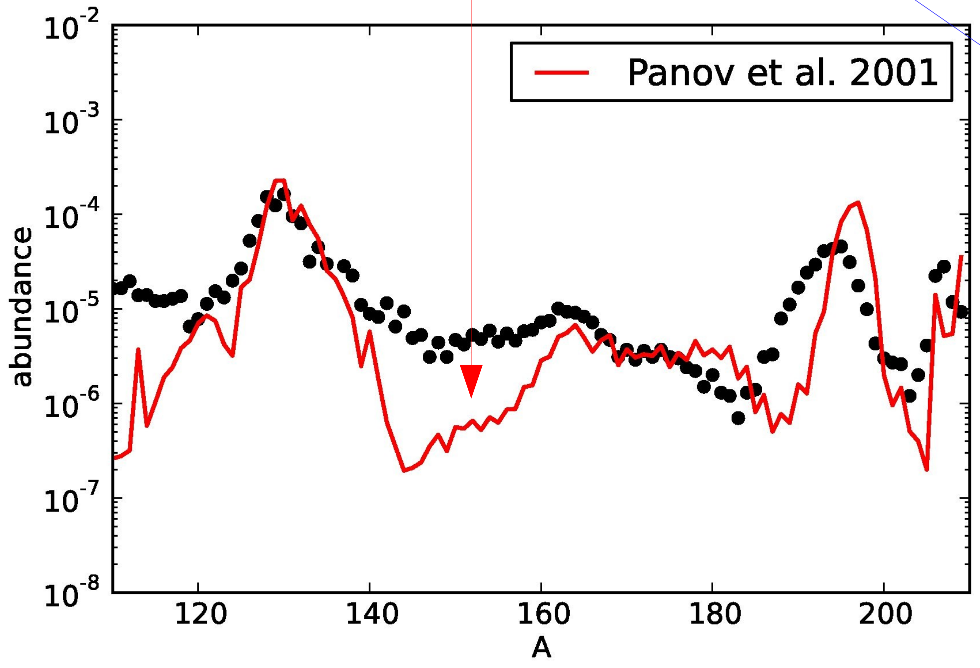


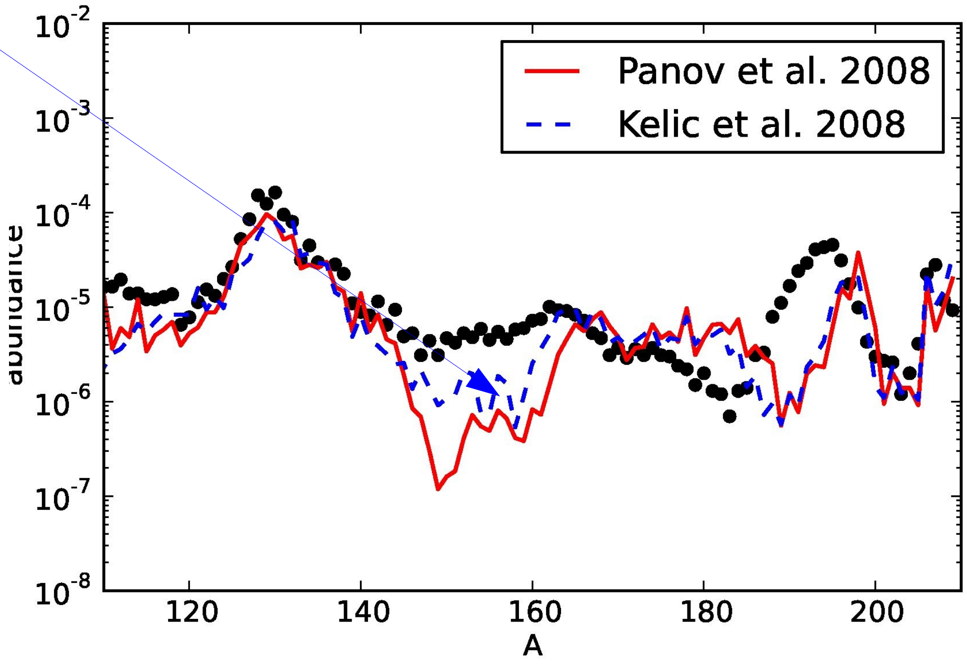


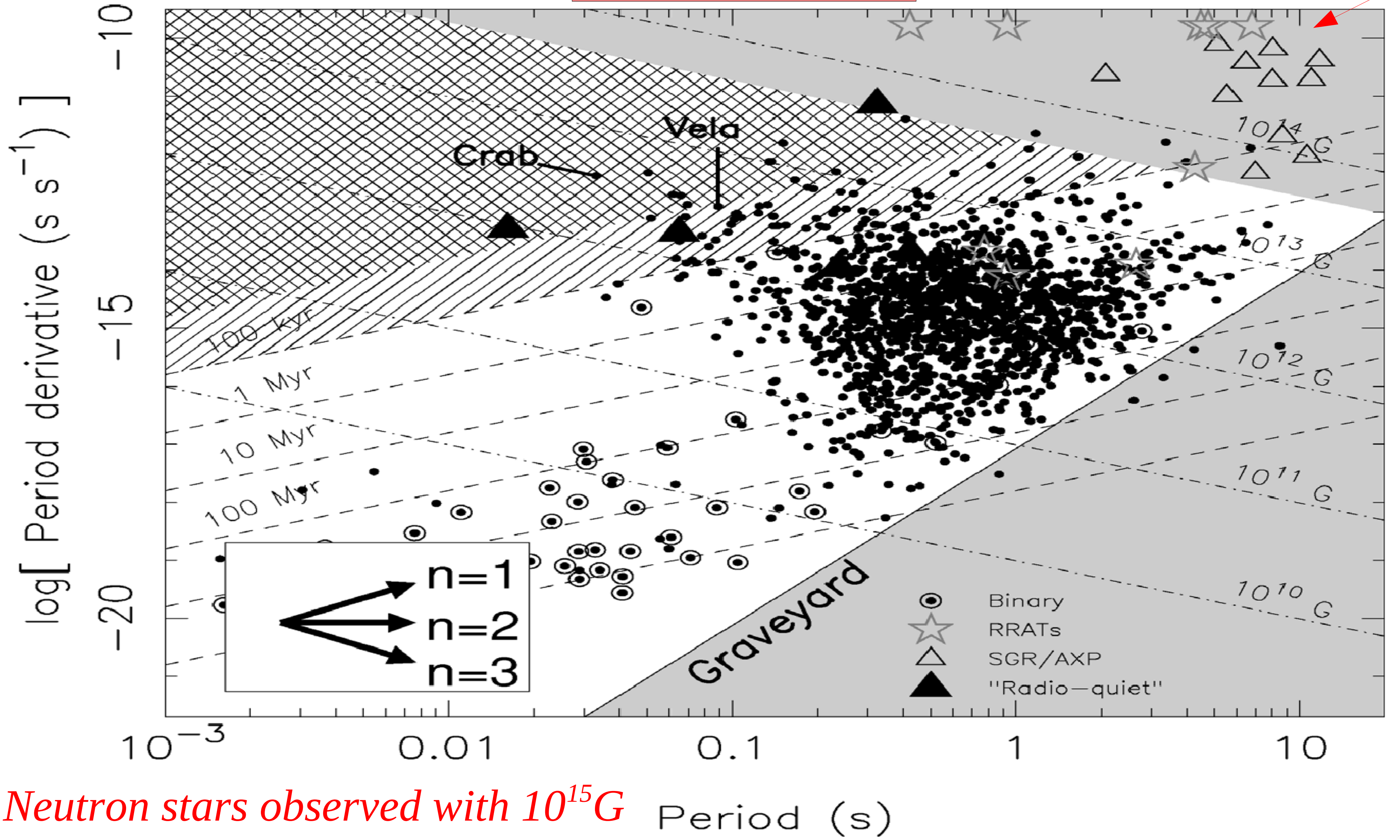
Preliminary!!!

Update in reaction library
(still FRDM 95 masses)
and fission fragment
distributions
(Eichler et al. 2013)









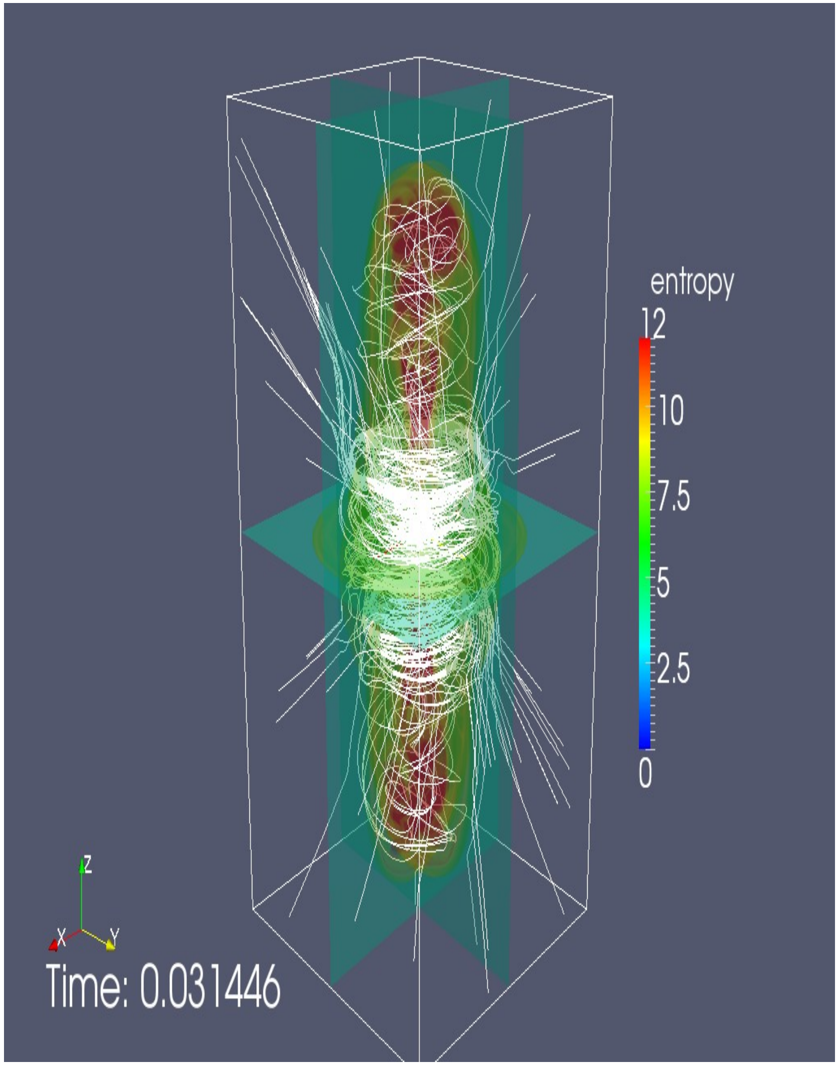
Neutron stars observed with 10^{15}G

Figure 2. The P–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, ‘radio-quiet’ pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age τ_c and magnetic field B are also shown. The single hashed region shows ‘Vela-like’ pulsars with ages in the range 10–100 kyr, while the double-hashed region shows ‘Crab-like’ pulsars with ages below 10 kyr. The grey regions are areas where radio pulsars are not predicted to exist by theoretical models. The inset at the bottom-left indicates the expected direction of movement for pulsars with a braking index of $n = 1$, 2 and 3, respectively.

r-process in MHD Jets from fast rotating models with high magnetic fields?

Details of 3D MHD CCSN Model (Winteler, Käppeli et al. 2012)

- 3D inner $(600\text{km})^3$ cube
  - MHD code FISH (Käppeli et al 2011)
  - Neutrino transport: 3D spectral leakage scheme (A.Perego)
- Outside followed by 1D spherically symmetric code AGILE (Liebendörfer et al. 2002)
- Progenitor: $15M_{sol}$ (Heger et al 2005)



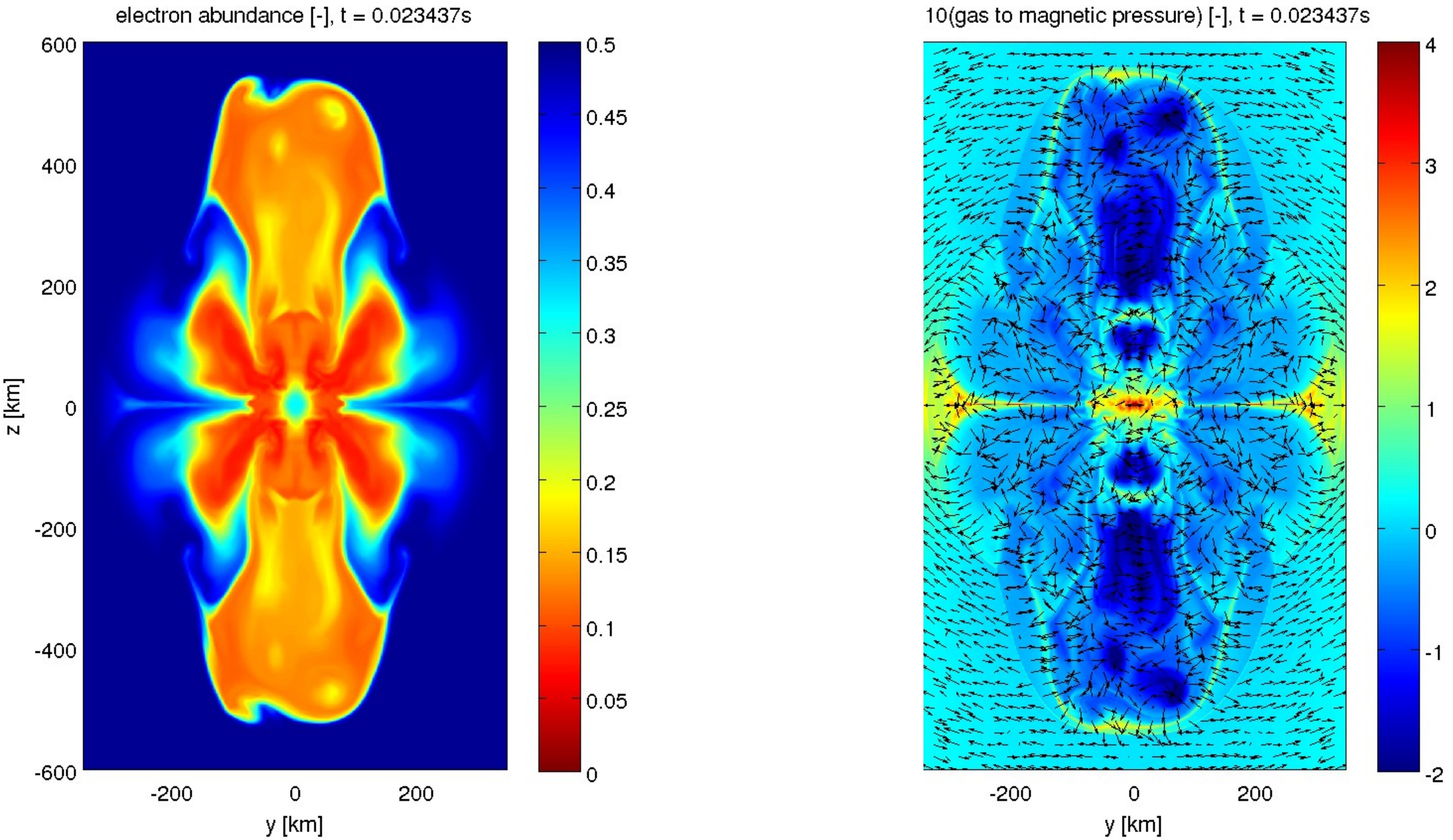
Low entropy, low Ye (compression to high densities) ,

fast expansion; earlier promising r-process results in 2D (Nishimura et al 2006, 2008)

3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 x10^{12} Gauss,

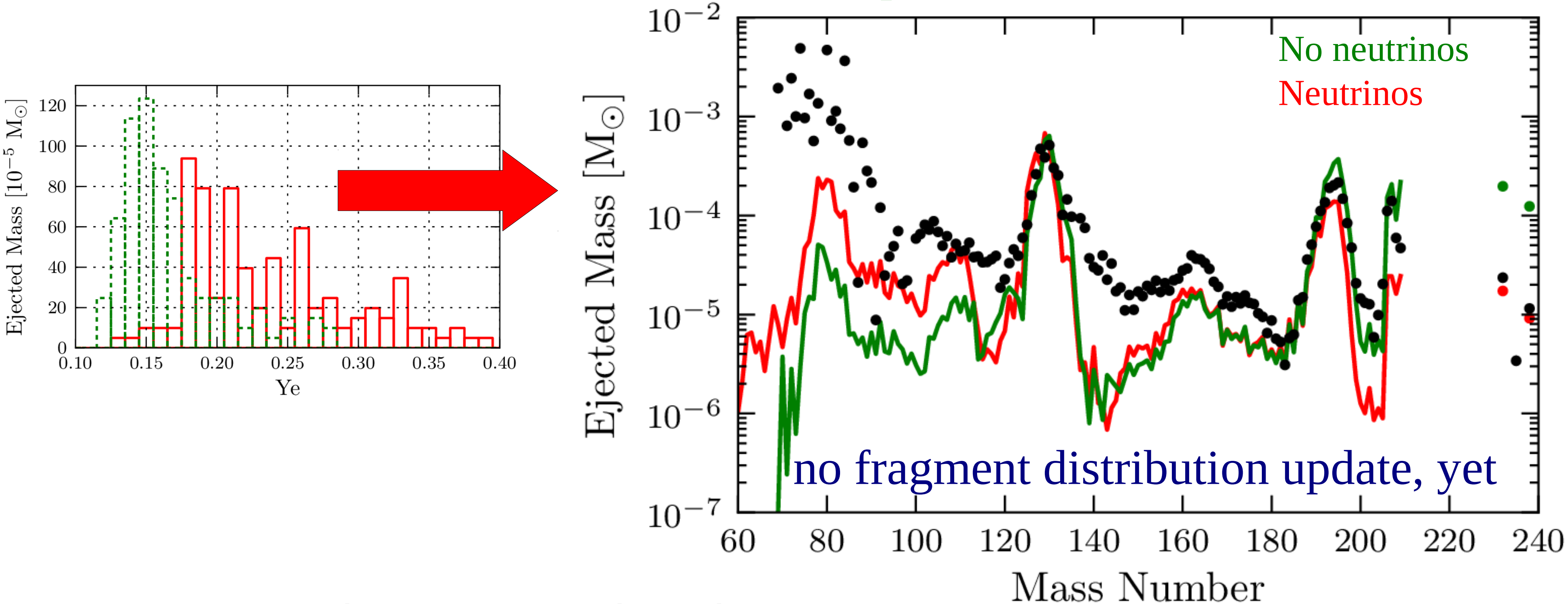
results in 10^{15} Gauss neutron star



3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012

Nucleosynthesis results

neutrino effect small opposite to neutrino wind with slow expansion velocities

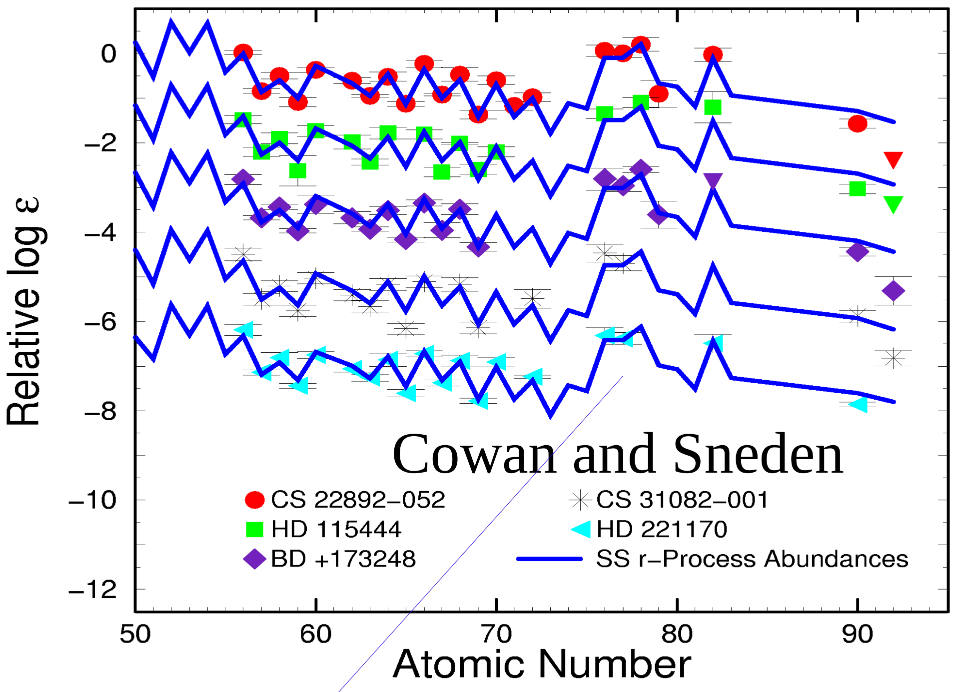


no fragment distribution update, yet

- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

$$M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_\odot$$

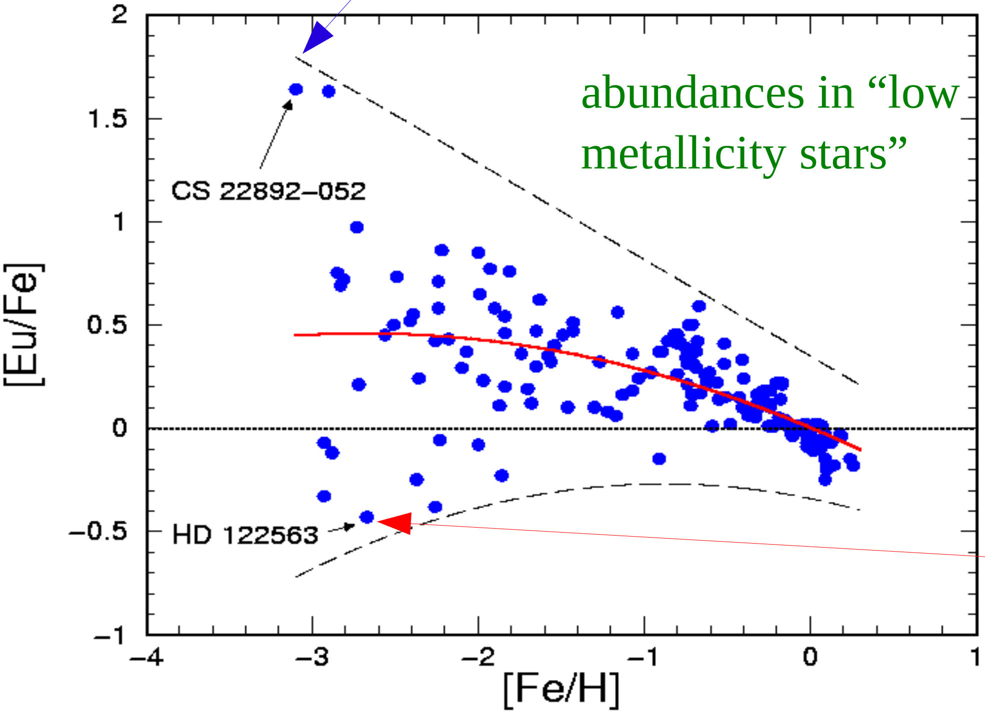
Observational Constraints on r-Process Sites

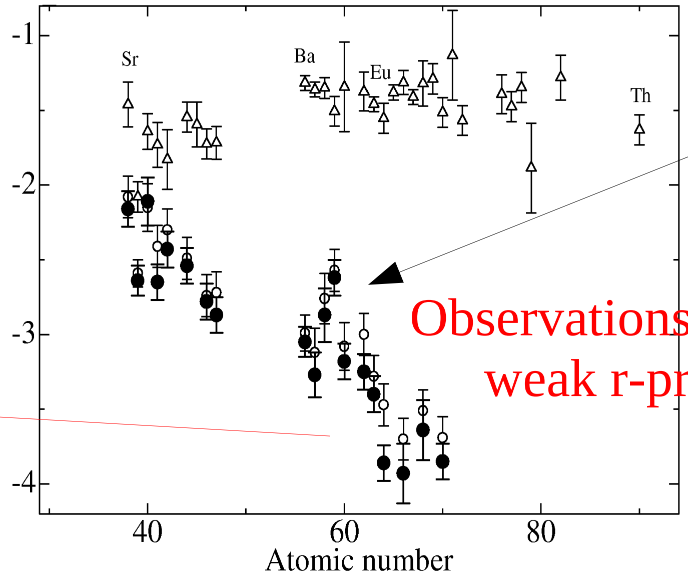


apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

Weak (non-solar) r-process in Honda-type stars

related to massive stars due to “early” appearance at low metallicities (behaves similar to SN II products like O, but with much larger scatter), but why the large scatter?

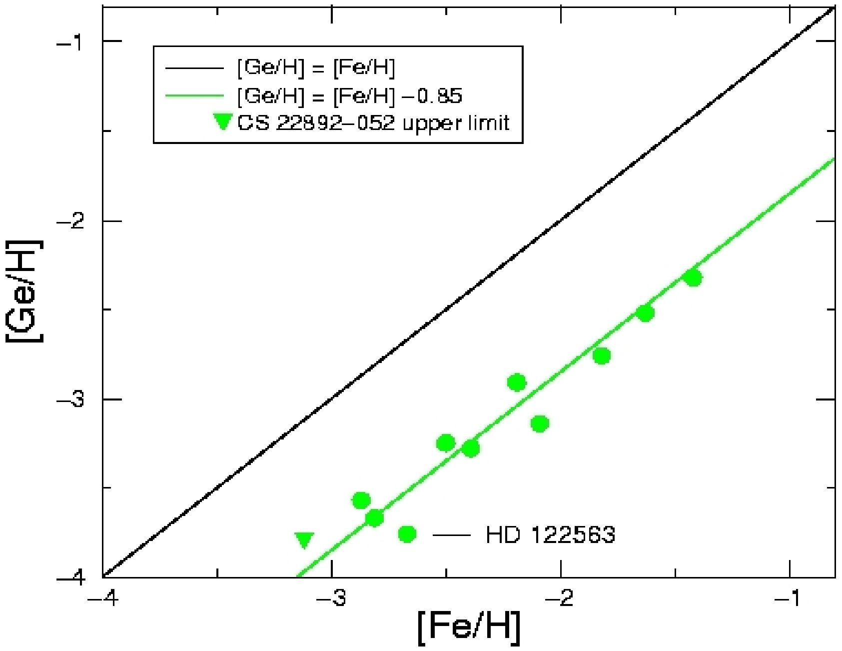


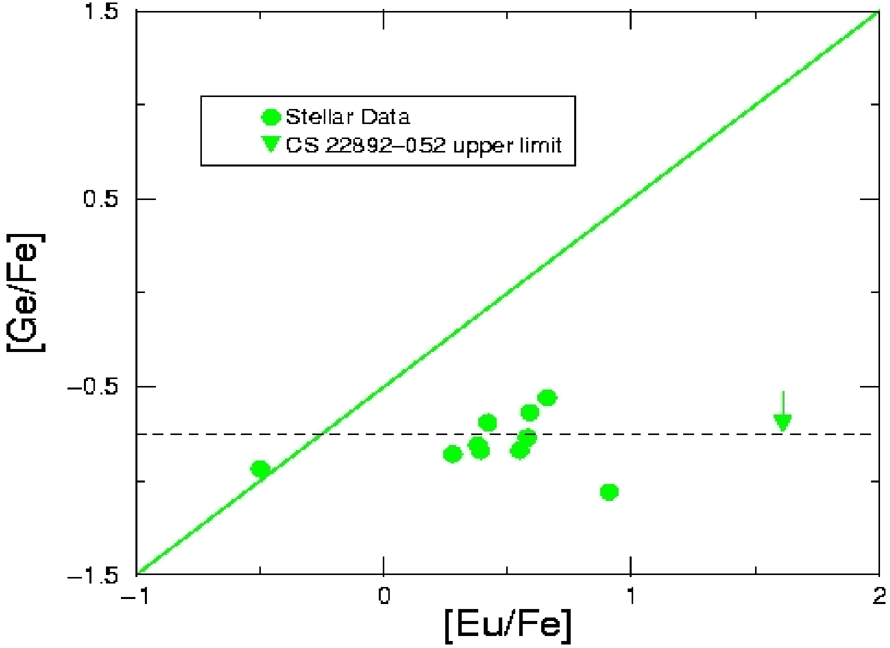


Observations of a/the? weak r-process?

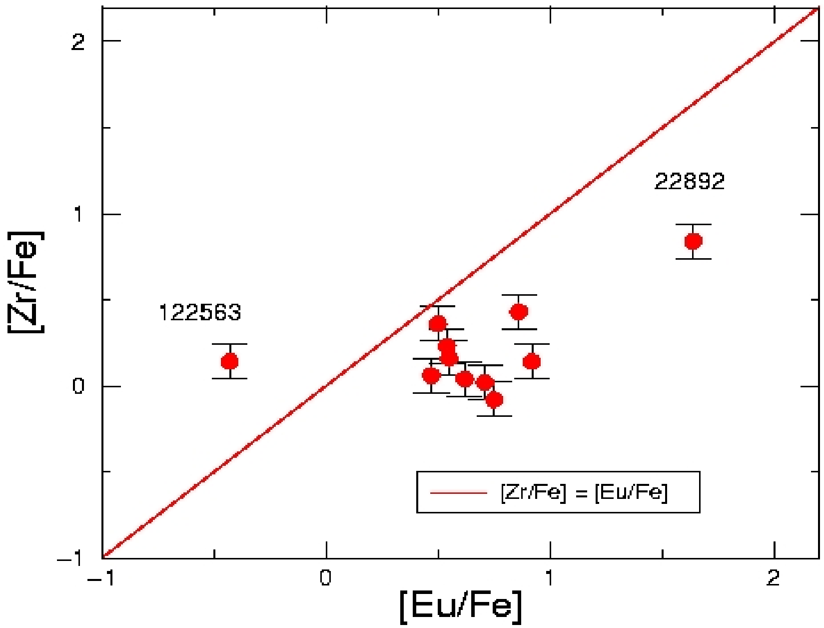
Honda et al. (2007)

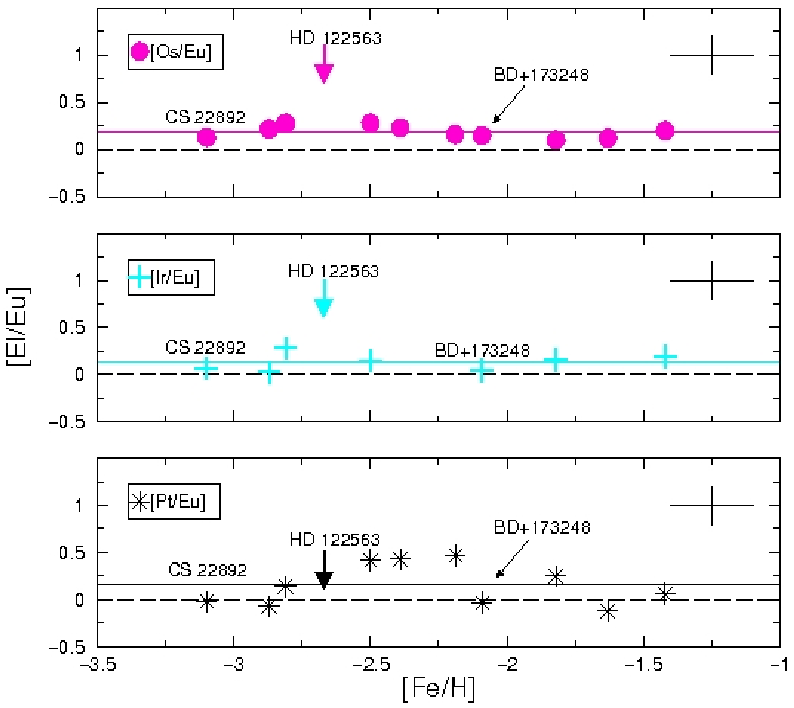
Observational indications: heavy r-process and Fe-group uncorrelated, Ge member of Fe group, Zr intermediate behavior, weak correlations with Fe-group as well the heavy r-elements (Cowan et al. 2005)



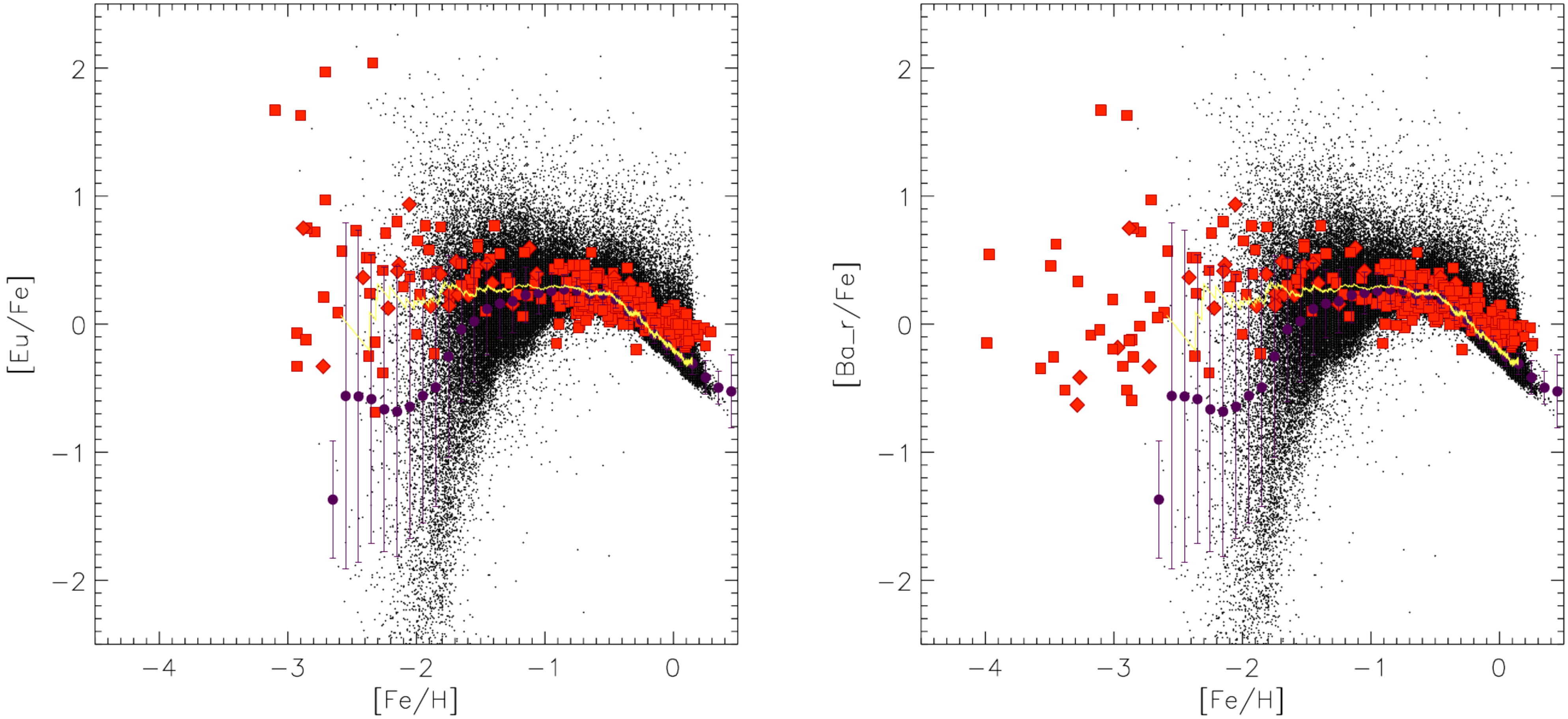


Zr vs. Eu





Argast et al. (2004): Do neutron star mergers show up too late in galactic evolution?



ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

Although they can be the dominant contributors in late phases?

Galactic chemical evolution

- If all r-process material in the Galaxy from CCSNe:

10^{-4}-10^{-5} M_{sol} required per event (here: 6 10^{-3} M_{sol})

  → if only 1 CCSN in 10-100 produces a jet, this could account for sufficient r-process material

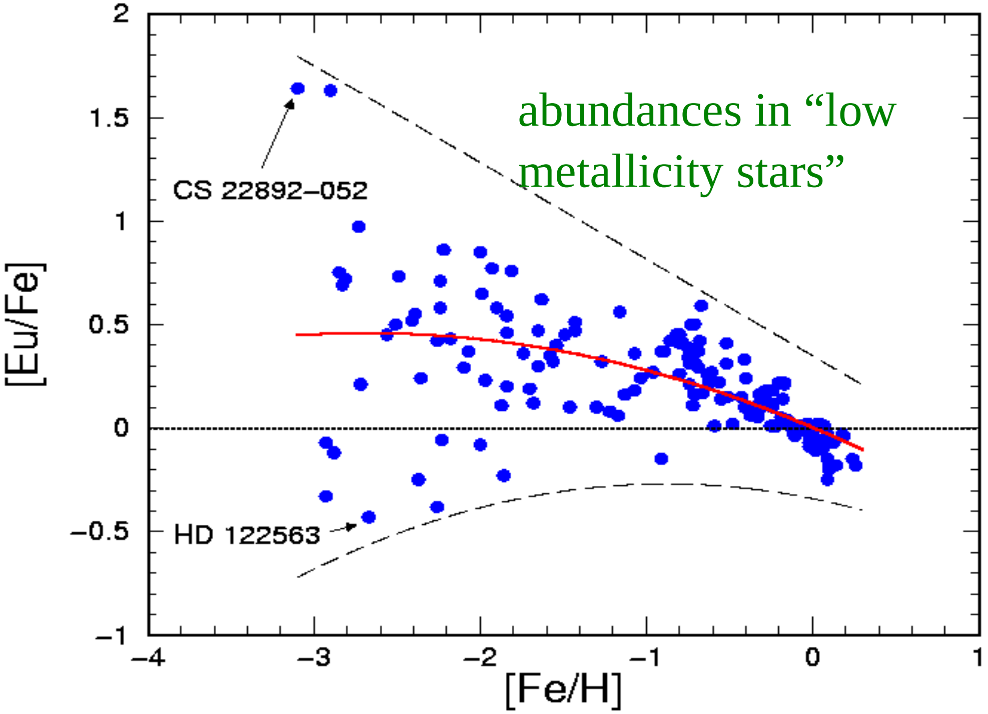
  → would explain scatter in r-process elements at low [Fe/H]

  (neutron star mergers would have similar behavior in frequency and ejecta, only deficiency: occurrance too late???)

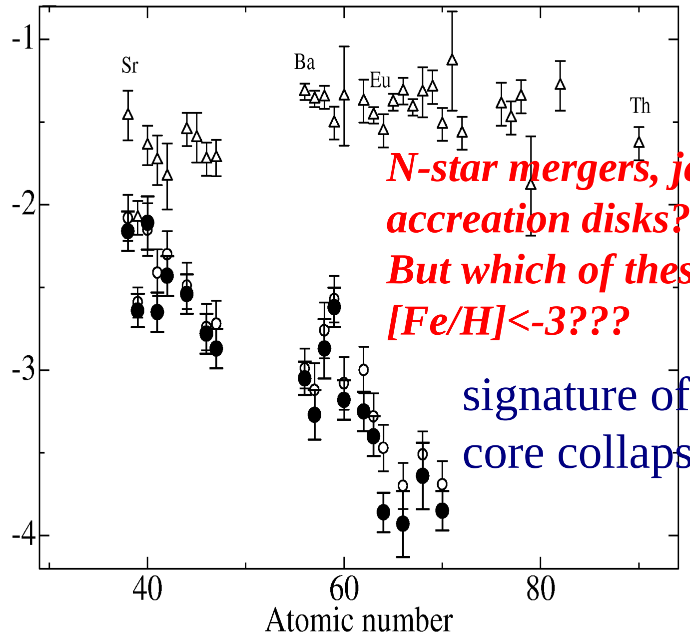
  - *only needed at low [Fe/H], later neutron star mergers could take over*

- progenitor configuration (B, Ω):
  - Not reached in common evolutionary paths (Heger 2005)
  - Possible for small fraction (~1%) of low metallicity models (Woosley&Heger 2006)
- *present magnetar knowledge permits ~1% of CCSNe resulting in magnetars (Kramer 2009, Koveliotou et al. 1998)*

Observational Constraints on r-Process Sites



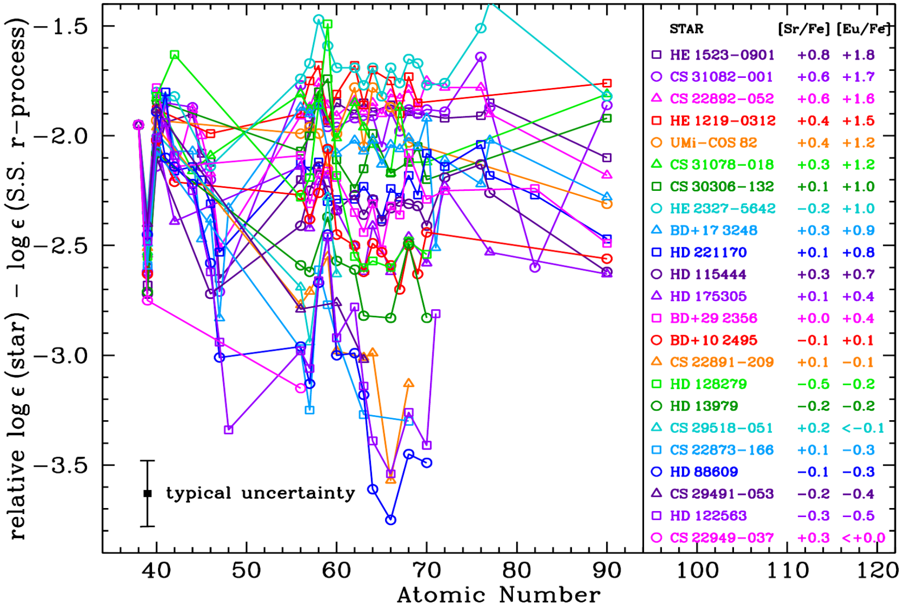
abundances in “low metallicity stars”



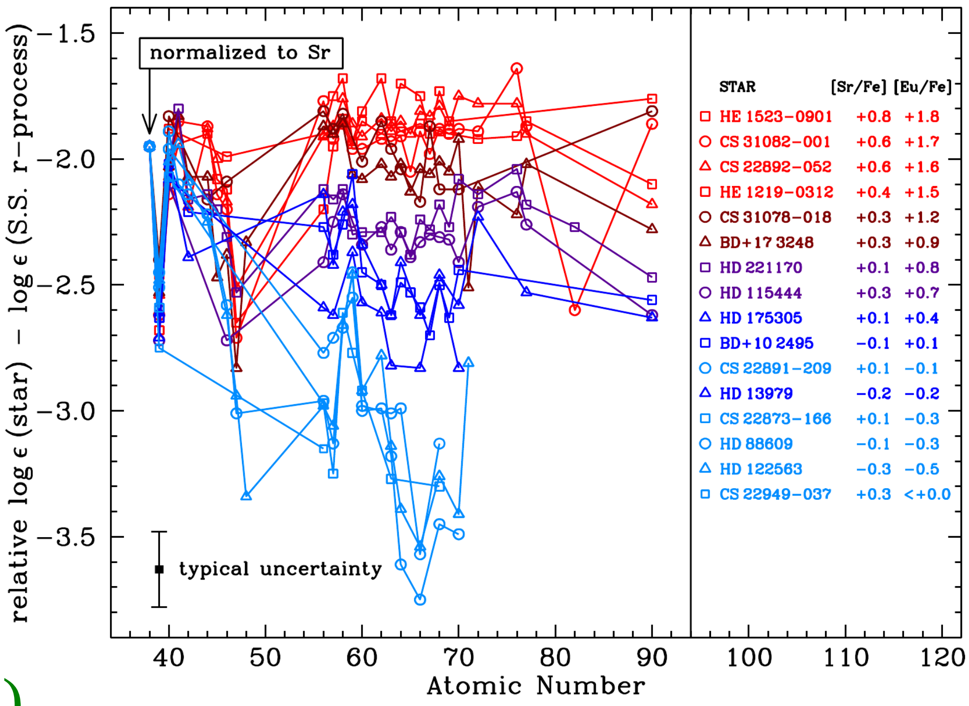
N-star mergers, jets, black hole accreation disks?

But which of these for [Fe/H]<-3???

signature of regular core collapse SNe?



	STAR	[Sr/Fe]	[Eu/Fe]
□	HE 1523−0901	+0.8	+1.8
○	CS 31082−001	+0.6	+1.7
△	CS 22892−052	+0.6	+1.6
□	HE 1219−0312	+0.4	+1.5
○	UMi−COS 82	+0.4	+1.2
△	CS 31078−018	+0.3	+1.2
□	CS 30306−132	+0.1	+1.0
○	HE 2327−5642	−0.2	+1.0
△	BD+17 3248	+0.3	+0.9
□	HD 221170	+0.1	+0.8
○	HD 115444	+0.3	+0.7
△	HD 175305	+0.1	+0.4
□	BD+29 2356	+0.0	+0.4
○	BD+10 2495	−0.1	+0.1
△	CS 22891−209	+0.1	−0.1
□	HD 128279	−0.5	−0.2
○	HD 13979	−0.2	−0.2
△	CS 29518−051	+0.2	<−0.1
□	CS 22873−166	+0.1	−0.3
○	HD 88609	−0.1	−0.3
△	CS 29491−053	−0.2	−0.4
□	HD 122563	−0.3	−0.5
○	CS 22949−037	+0.3	<+0.0



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○	HD 88609	−0.1	−0.3
△	HD 122563	−0.3	−0.5
□	CS 22949−037	+0.3	<+0.0

Roederer and Cowan (2013)

Summary

Nuclear Masses determine the r-process path (far from stability) and thus are essential for its correct understanding. How strongly they impact the final abundances depends on the freeze-out conditions (and timescales) from n,γ-γ,n equilibrium and whether this was achieved - hot or cold r-process.

While masses determine the r-process path, beta-decay timescales determine the process speed (and are proportional to abundances – in case a steady flow equilibrium is approaches).

Fission and fission fragment distributions are important in highly neutron-rich conditions and an extensive n/seed ratio

The r-process in astrophysical environments comes in at least two versions (weak-main/strong)??

Does the neutrino wind in core collapse SNe lead initially to proton-rich conditions (and νp-process, LEPP) or also to a weak r-process (extending up to Eu)?

Weak r-process contributions are also possible in EC SNe and Quark-Hadron EoS SNe.

The main/strong r-process comes apparently in each event in solar proportions, but the events are rare. The site is not clearly identified, yet. Options include rotating core collapse events with jet ejection, neutron star mergers and accretion disks around black holes (either from mergers or massive star collapse).

How to identify the signatures in chemical evolution for these different contributions?

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

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

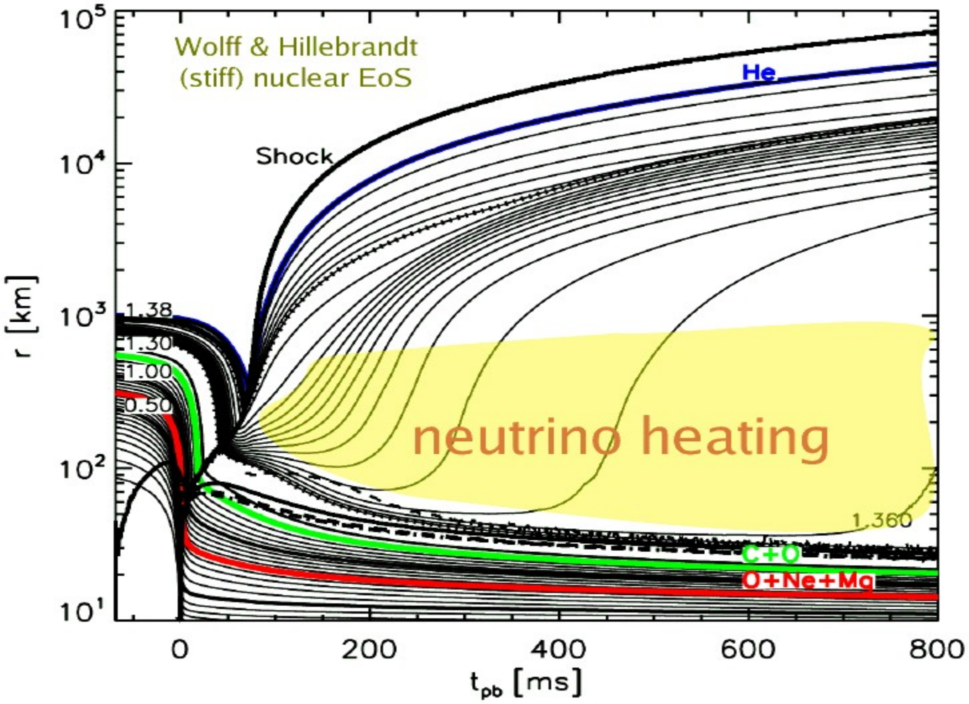
2. low entropies and normal freeze-out with very low Y_e , from expanding neutron star-like matter leading also to large n/seed ratios
   - S_n function of Y_e

(Freiburghaus, Rosswog, Thielemann, Panov, Goriely, Janka, Martinez-Pinedo, Korobkin, Arcones, Winteler, Nishimura, Fujimoto)

Supernovae in 1D

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

"Electron-capture supernovae"
or "ONeMg core supernovae"

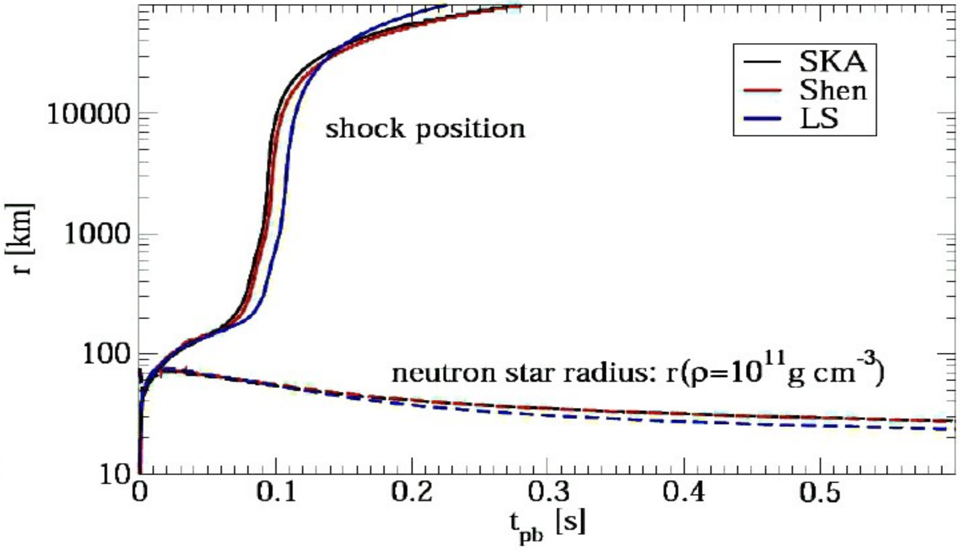


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

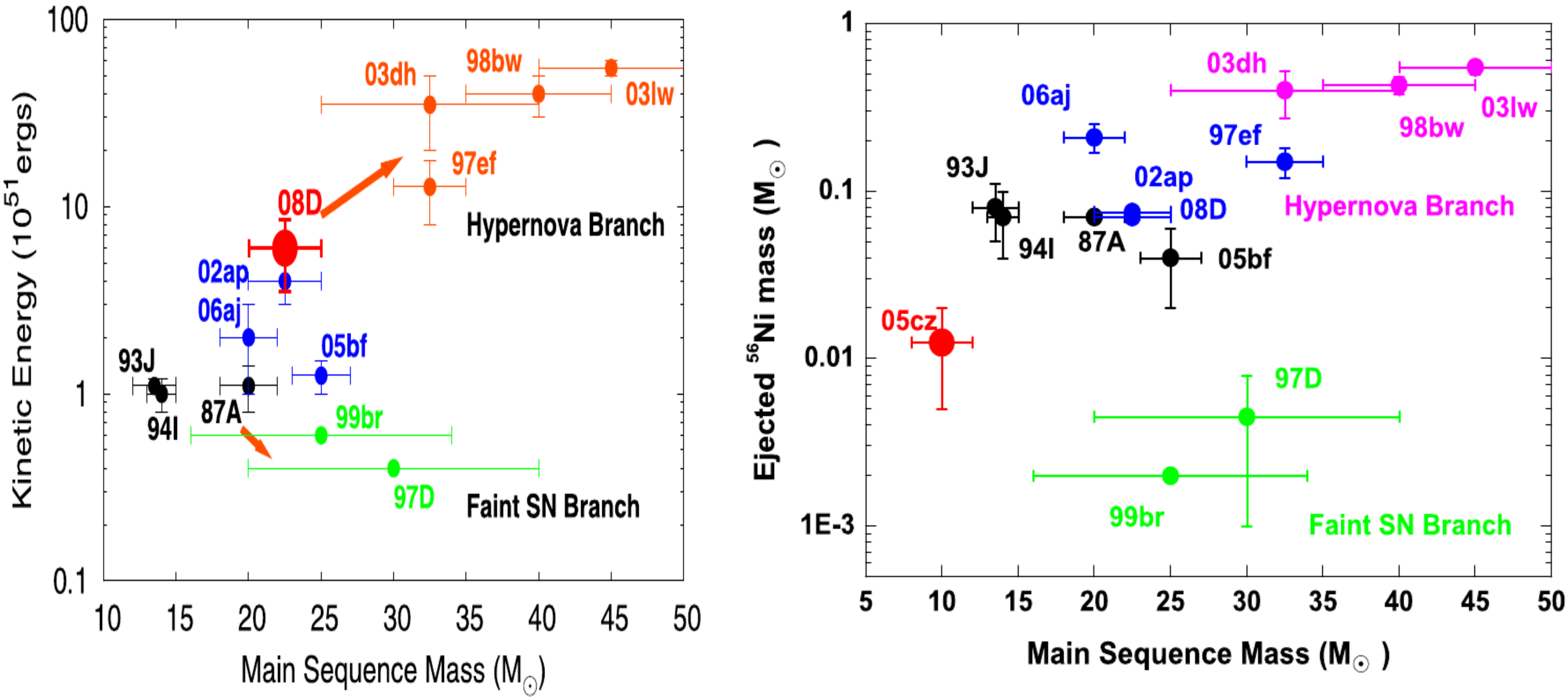
Fischer et al. 2010

Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)

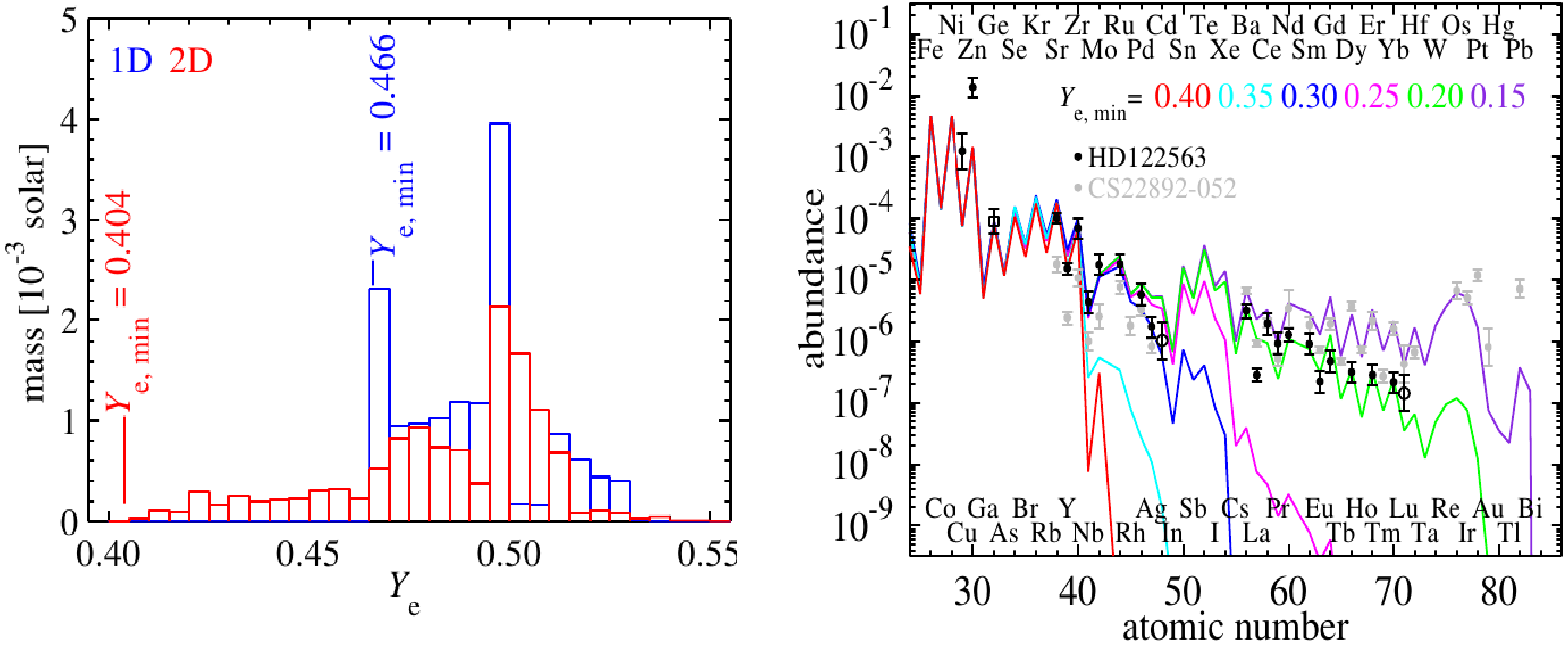


Transition Supernovae to Faint Supernovae and Hypernovae



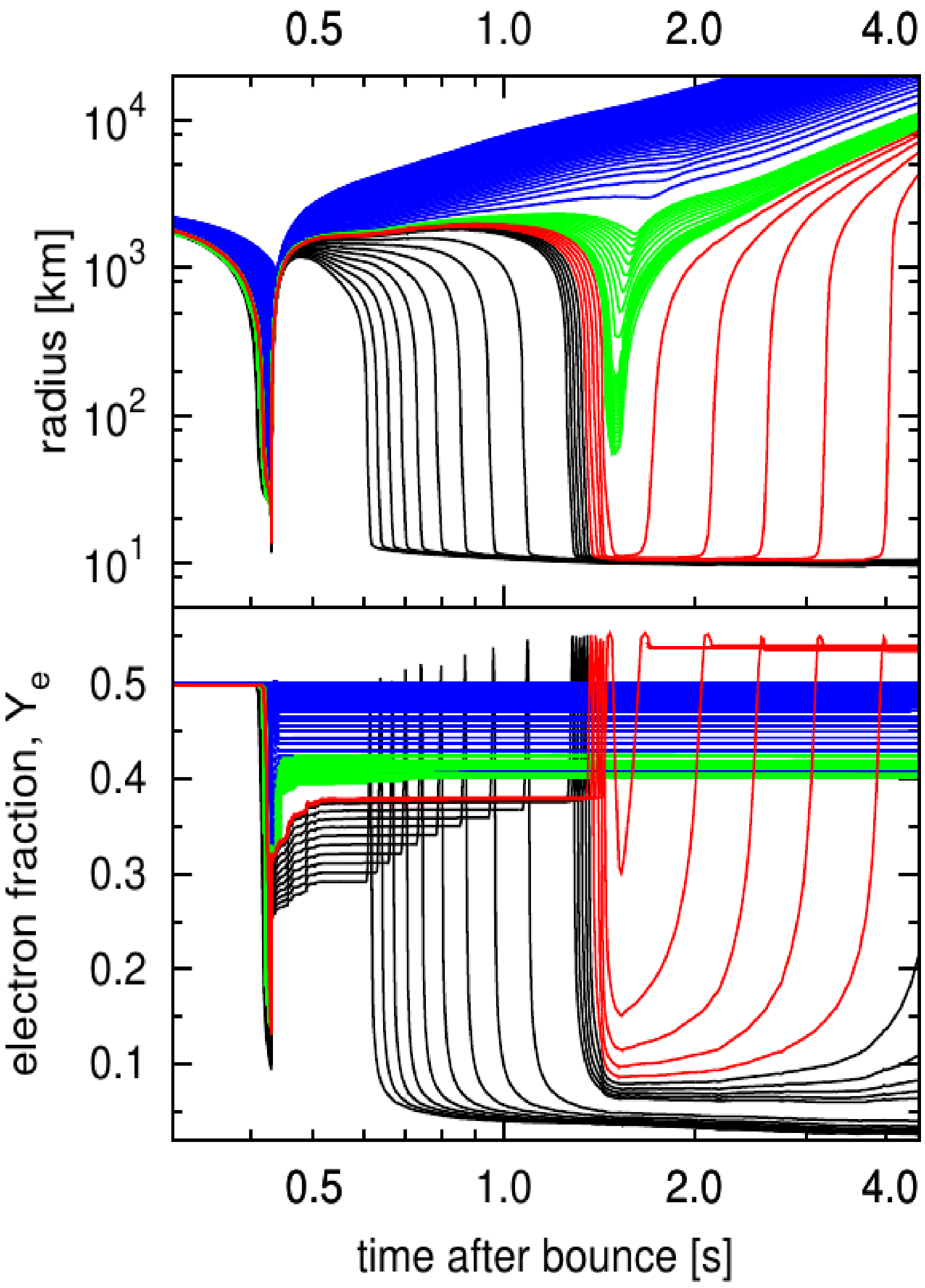
Nomoto et al. (2011)

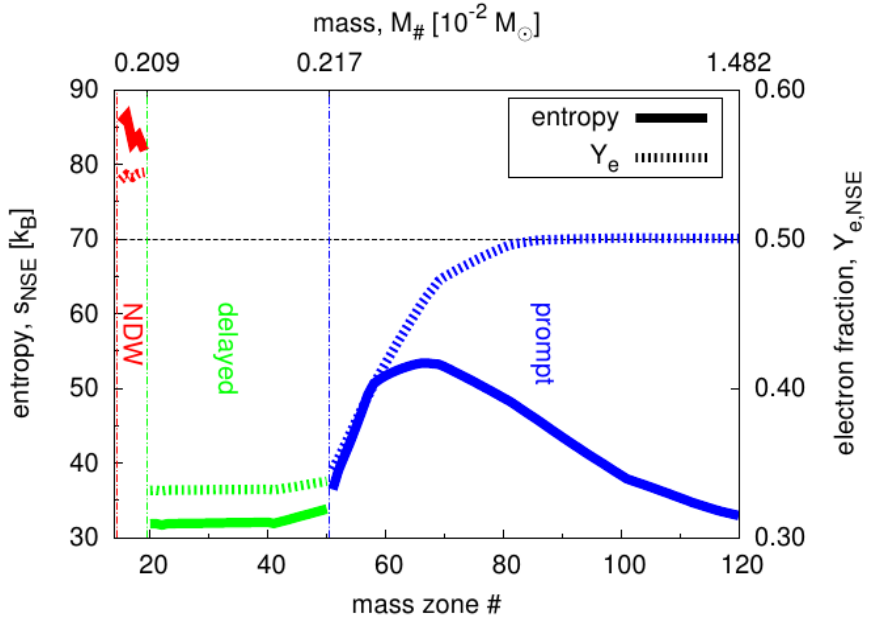
Wanajo & Janka 2011, EC Supernovae in 1 and 2D

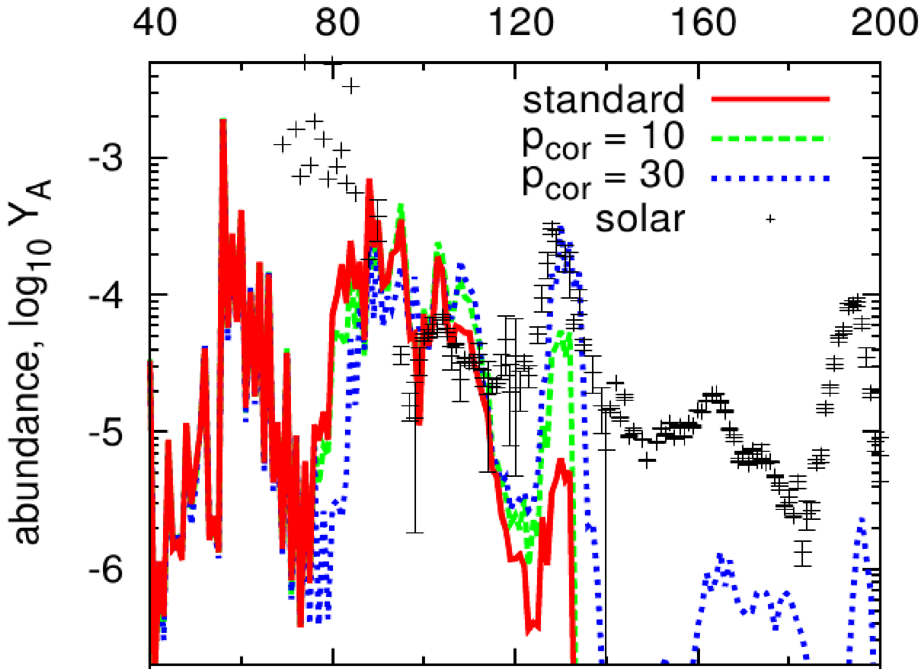


Ye in EC Supernovae due to compression (e-capture)!

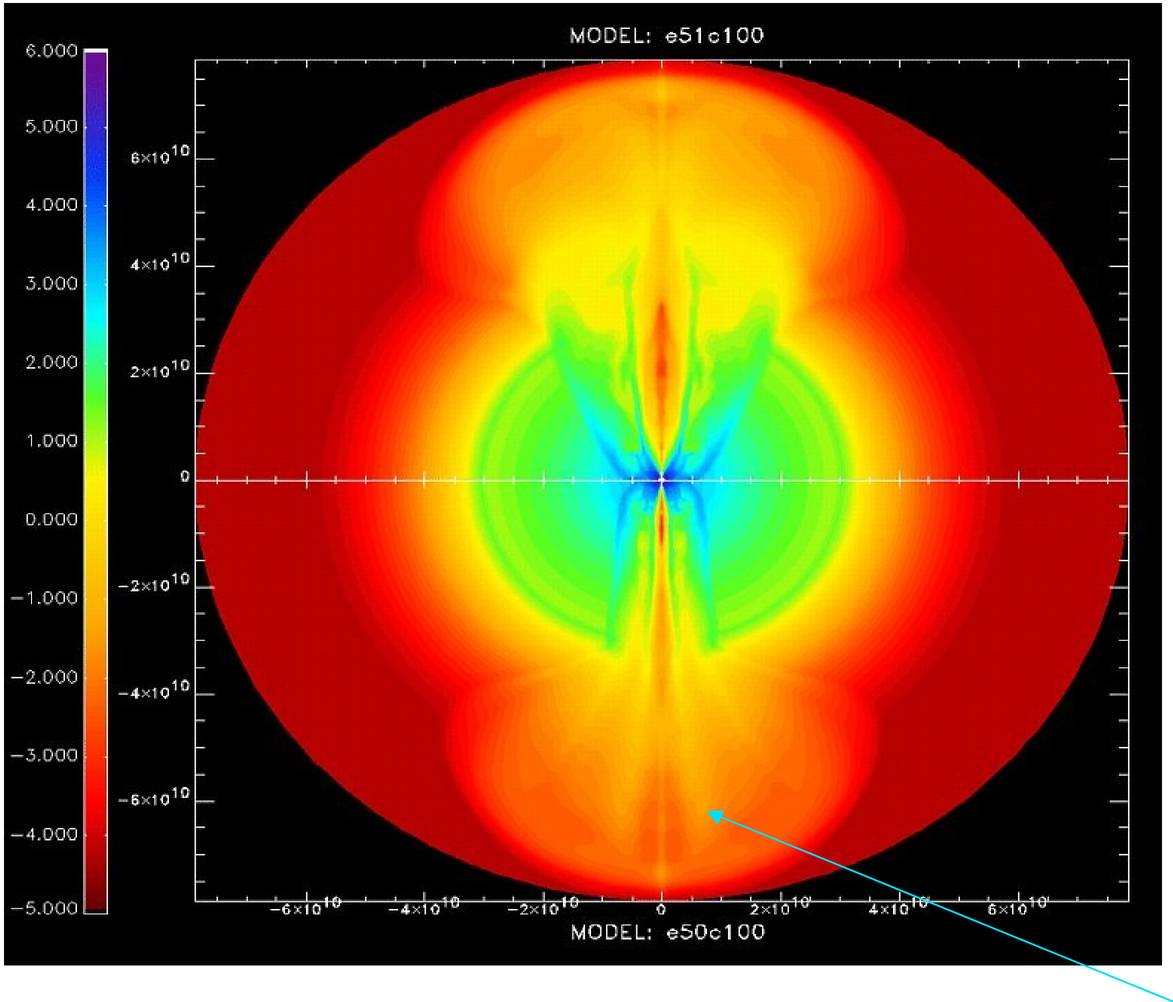
Quark-Hadron EoS Explosion (Nishimura, Fischer, Thielemann et al. 2012.), *ejection of initially neutronized matter, but only weak r-process*







How about Gamma-Ray Bursts and Black Holes?



- Higher mass end of core collapse events will lead to cores in excess of maximum neutron star mass, i.e. a **black hole** is formed
- Accretion of envelope onto the black hole (accretion disk) causes polar Jets, responsible for a GRB

or?

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

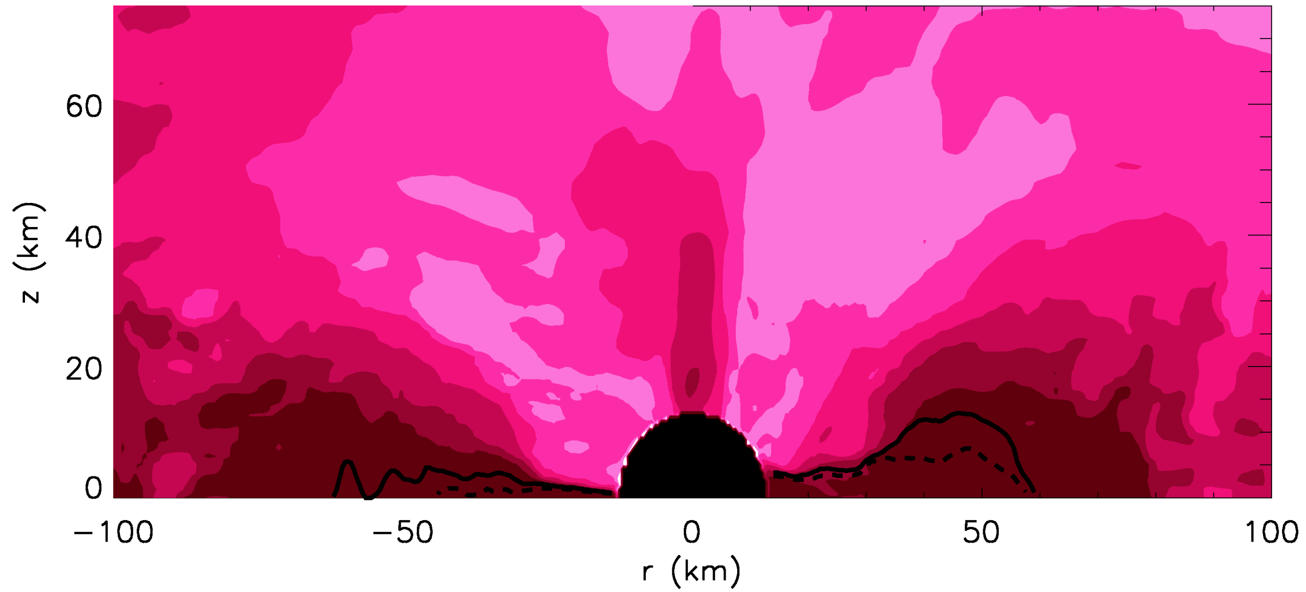


Fig. 2.— Shows density along a vertical slice of the disk. The shaded regions, from lightest to darkest, show densities of $10^{8.5}$, 10^{9}, $10^{9.5}$, 10^{10}, $10^{10.5}$, and 10^{11} g/cm^3. The solid line shows the electron neutrino surface while the dashed line shows the electron antineutrino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

r-process discussed for a variety of conditions, depends strongly on neutrino interaction with matter (McLaughlin and collaborators)

Ye evolution with neutrinos

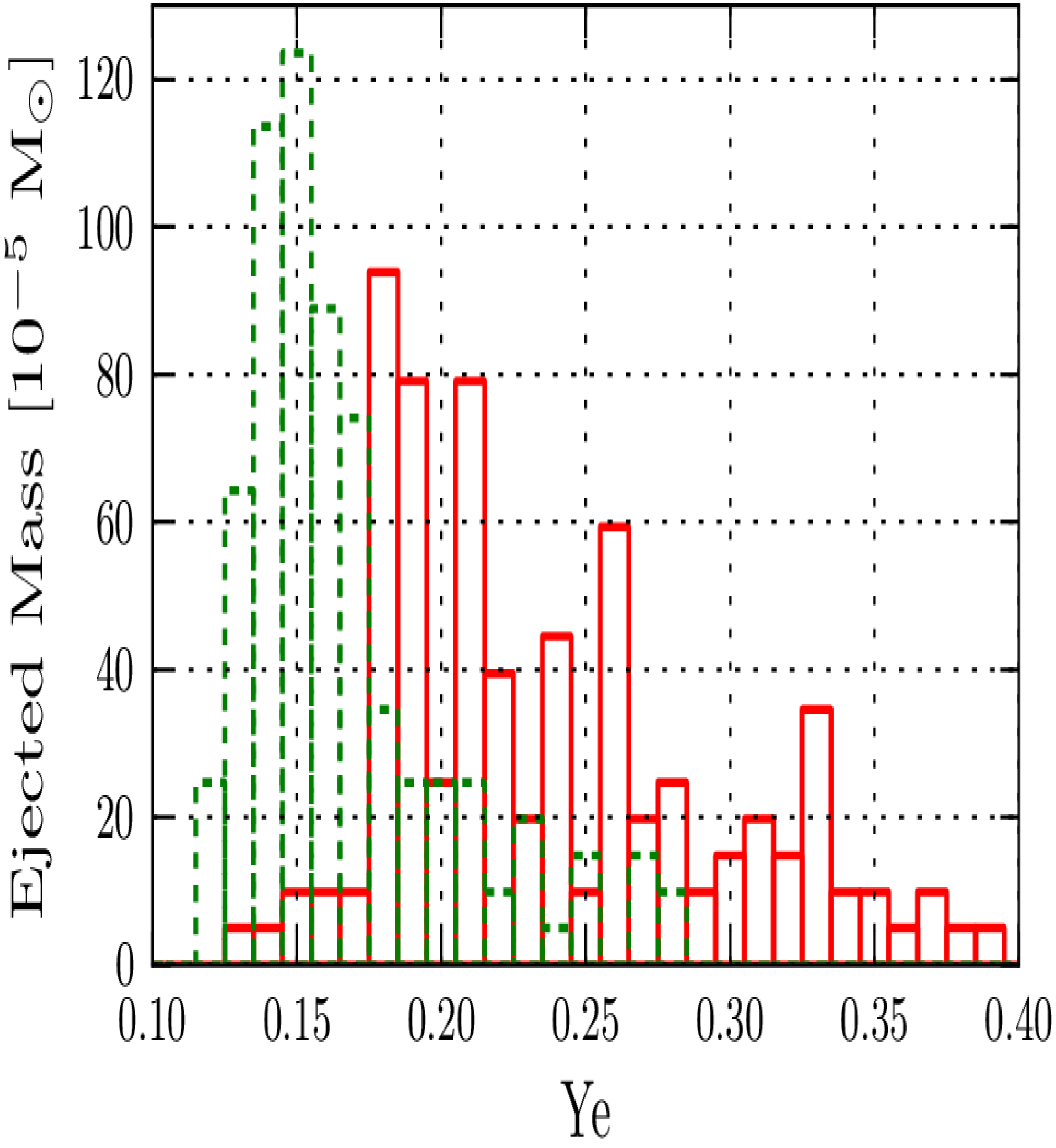
$$\bar{\nu}_e + p \rightarrow Y_e$$

$$\nu_e + n \rightarrow Y_e$$

As usual, due to fact that antineutrino energy not larger by 5.2MeV (4 times neutron-proton mass difference),

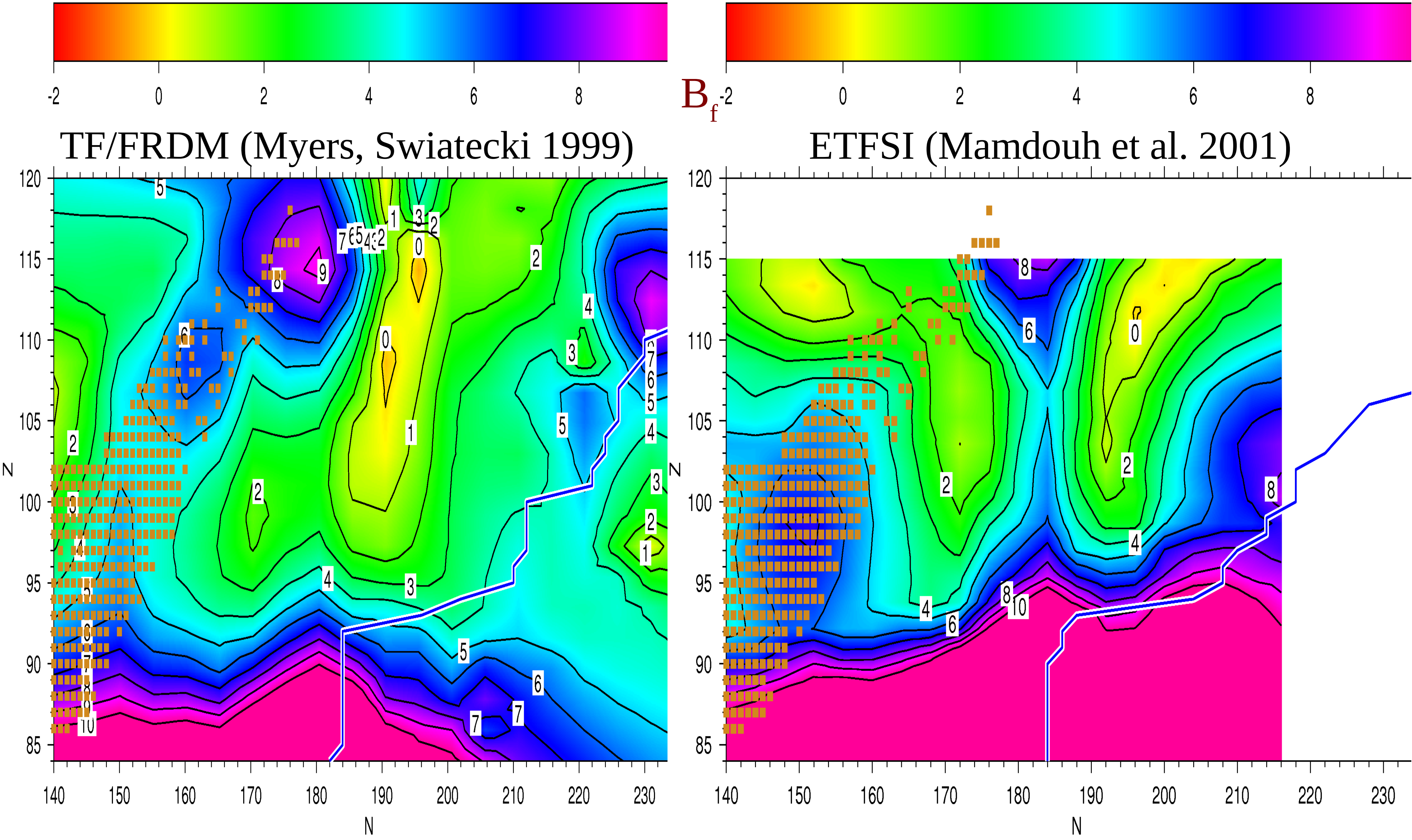
- Distribution shifted to the right
- Broadened towards higher values

Neutrino reaction wins and moves to more proton-rich conditions. But effect small due to fast expansion/ejection and 1/r^2 decline



A different question: How far does the r-process proceed? (suggested first by Schramm & Fowler 1971)

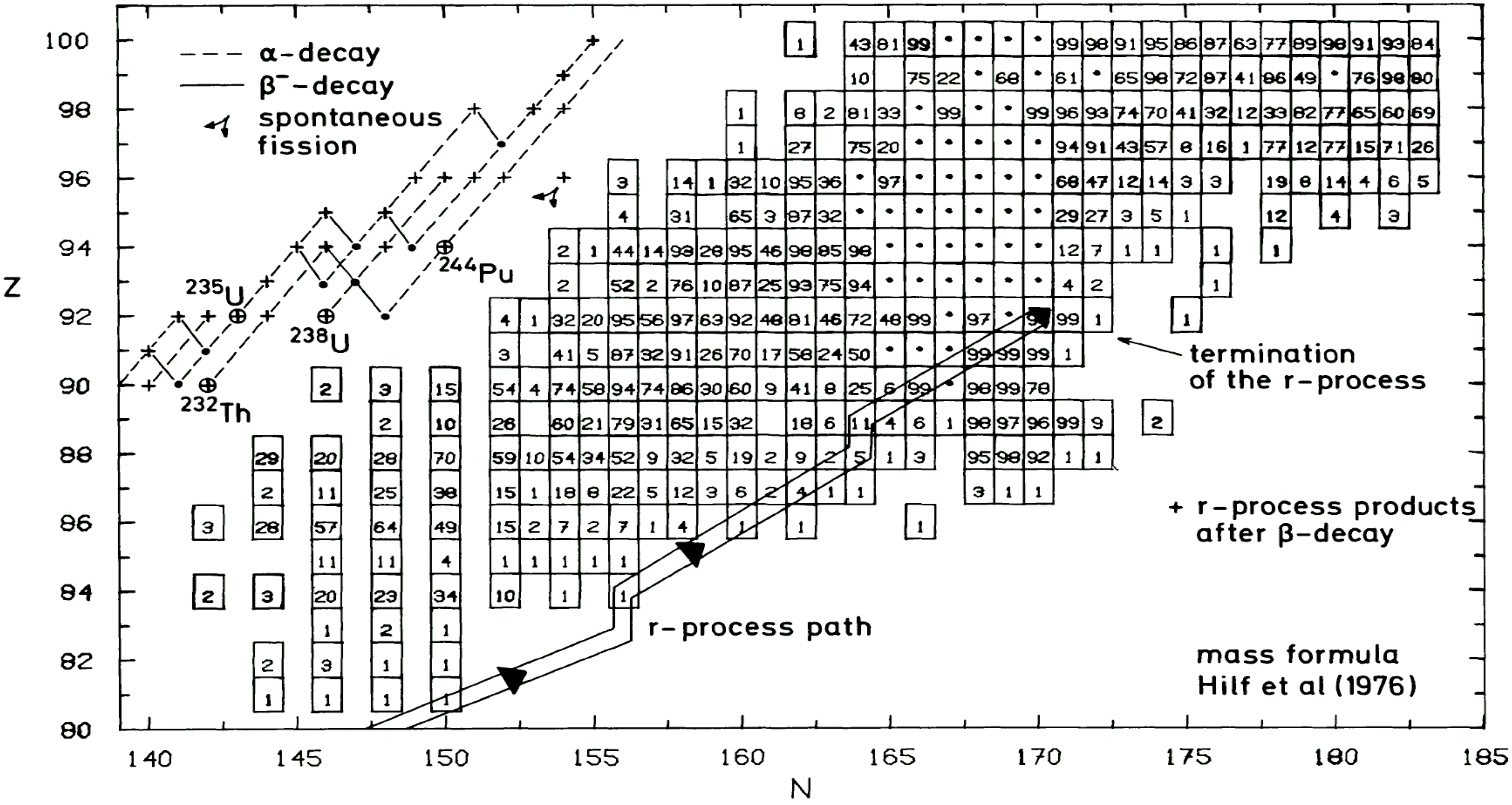
We need complete and accurate nuclear input (masses, fission barriers, reactions, decay channels)!!



TF/FRDM (Myers, Swiatecki 1999)

ETFSI (Mamdouh et al. 2001)

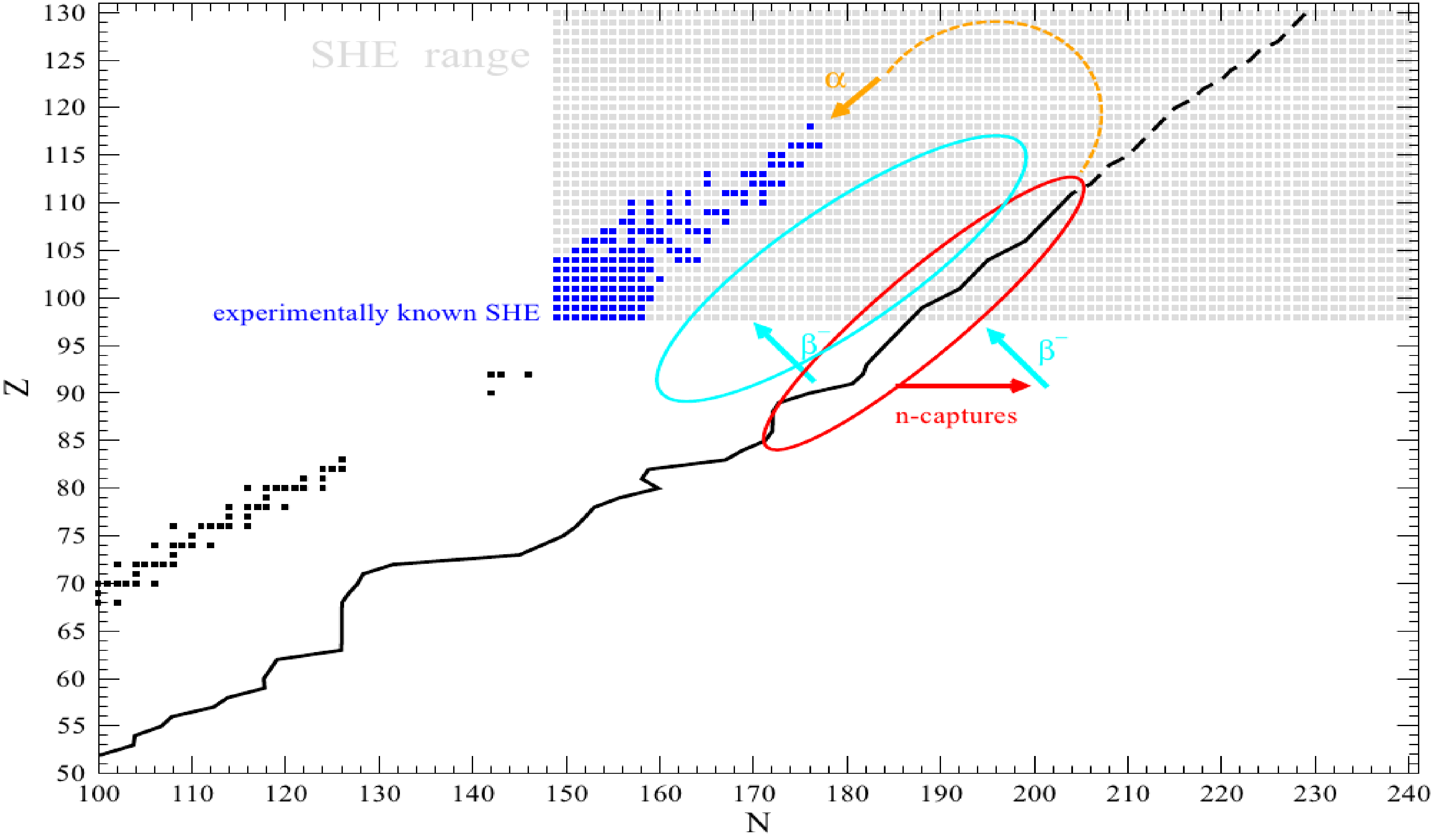
Some History: Thielemann, Metzinger, Klapdor (1983)



Case 1: the r-process ends in a region of 100% beta-delayed fission, no chance to produce SHE! Background, inconsistent data sets (fission barriers from Howard & Möller 1980 – underestimation, mass formula too steep – overestimation of Q_β)

Three options:

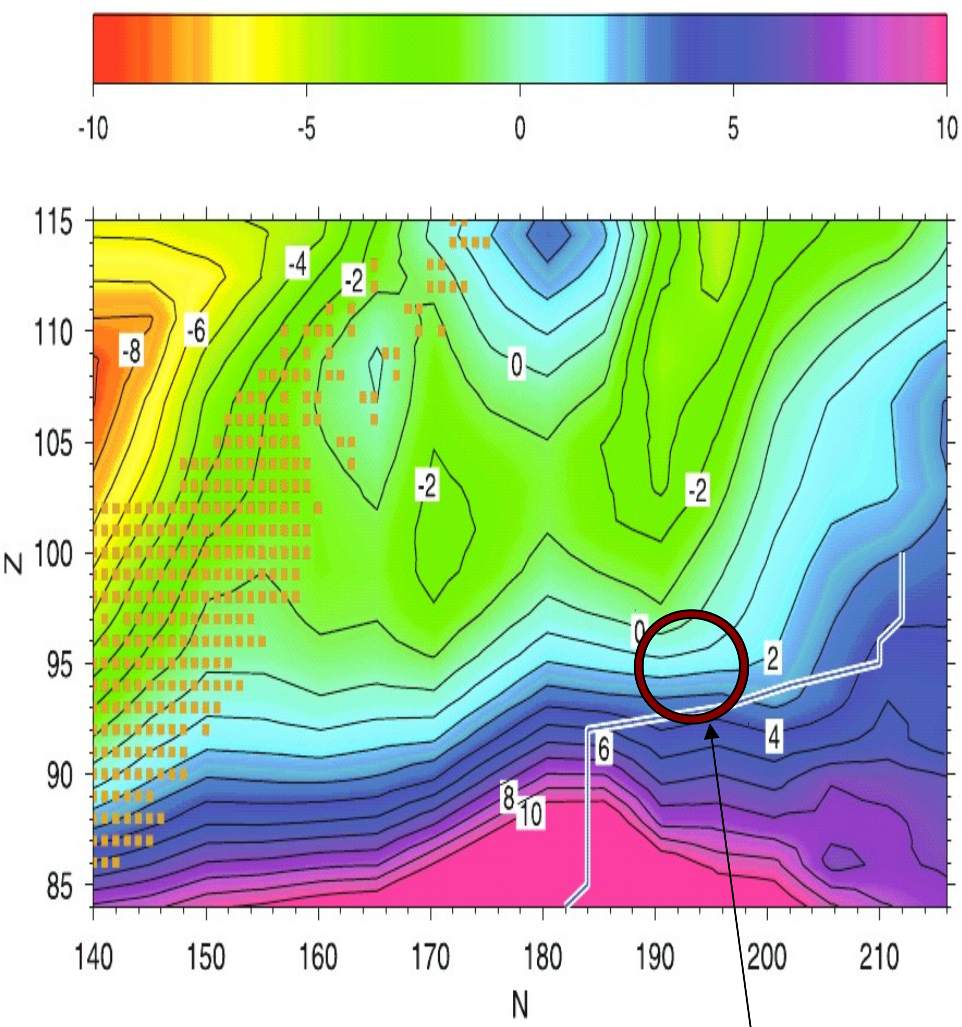
1. the r-process passes through fission-dominated regions and buildup stops
2. the r-process produces superheavies far from stability but fission is encounered during beta-decay back to stability
3. fission region(s) are circumvented and beta/alpha-decay leads to superheavy island



Petermann, Langanke, Martinez-Pinedo, Reinhard, FKT (2012)

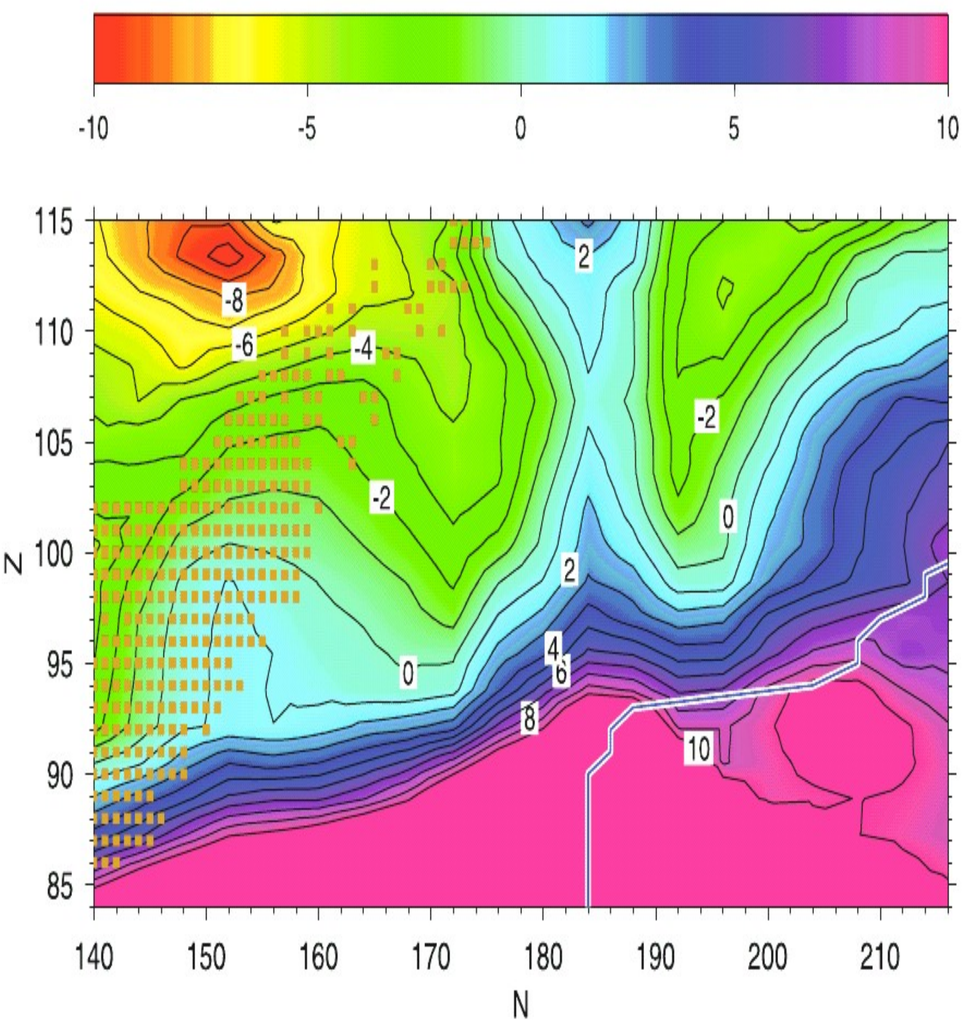
Fission Barriers (B_f-S_n) and the r-Process

(if negative => neutron-induced fission)



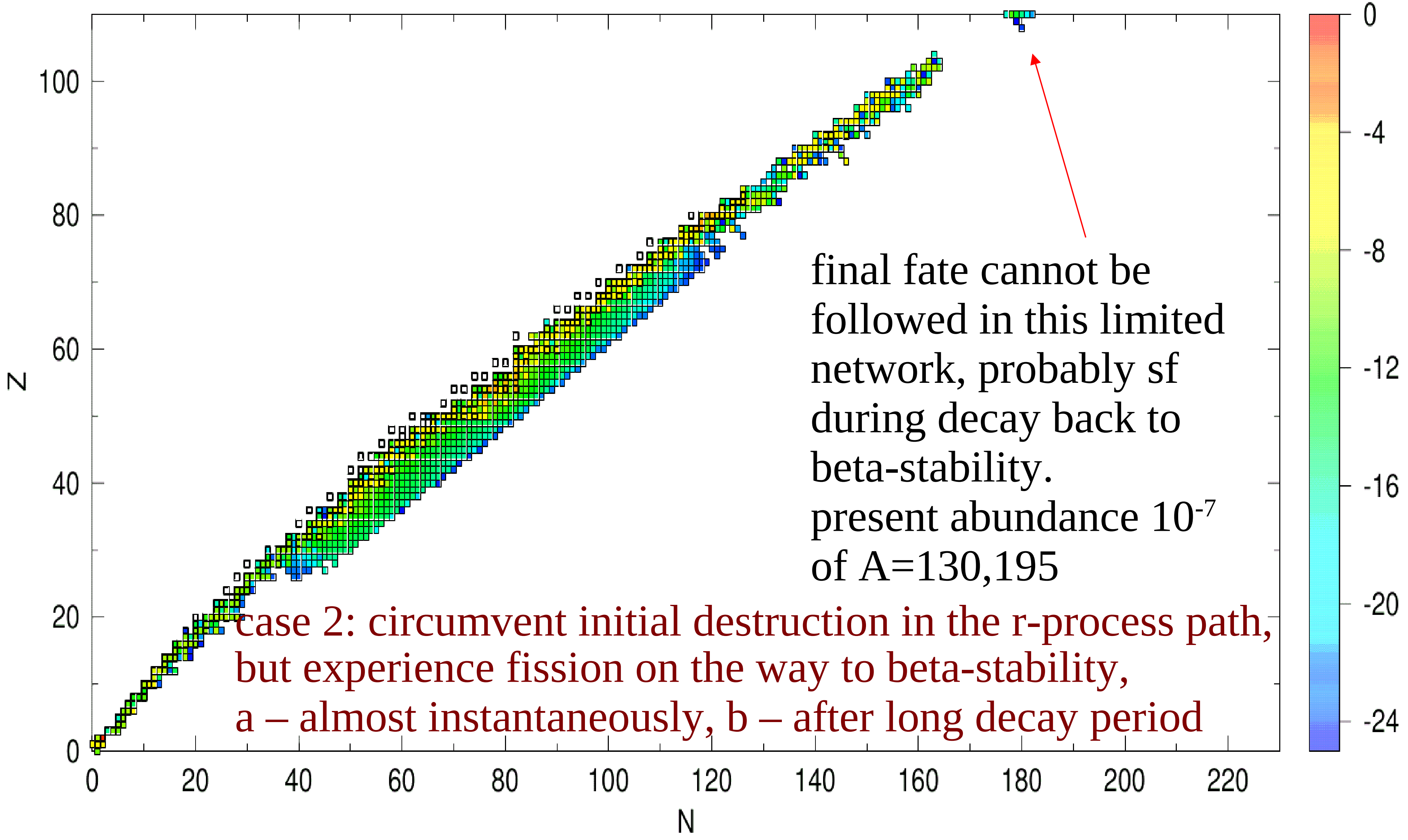
Myers & Swiatecki
barriers (TF/FRDM)

narrow path without
n-induced fission!



Mamdouh et al. barriers (ETFSI)

Products of cold r-process (ETFSI) after 1.3 10^6 s (15 days)



final fate cannot be followed in this limited network, probably sf during decay back to beta-stability.
present abundance 10^{-7} of A=130,195

case 2: circumvent initial destruction in the r-process path,
but experience fission on the way to beta-stability,
a – almost instantaneously, b – after long decay period