Formation of the Heaviest Elements: Necessary Conditions, Astrophysical Sites, Nuclear Input

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

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The classical r-process

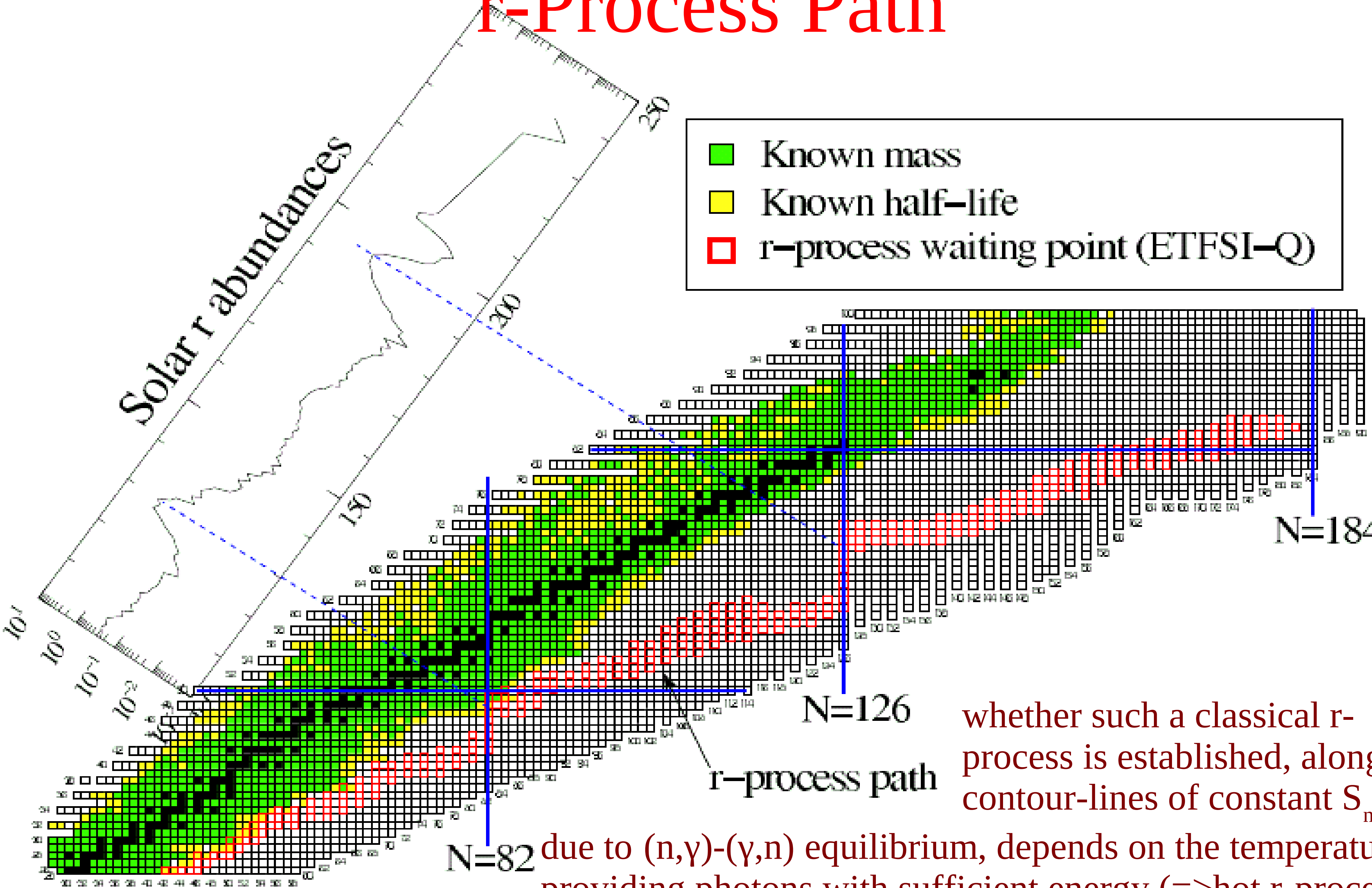
- Assume conditions where after a charged-particle freeze-out the heavy QSE-group splits into QSE-subgroups containing each one isotopic chain Z, and a high neutron density is left over
- In each of these QSE-subgroups (isotopic chains) a chemical equilibrium between neutron captures and photodisintegrations 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

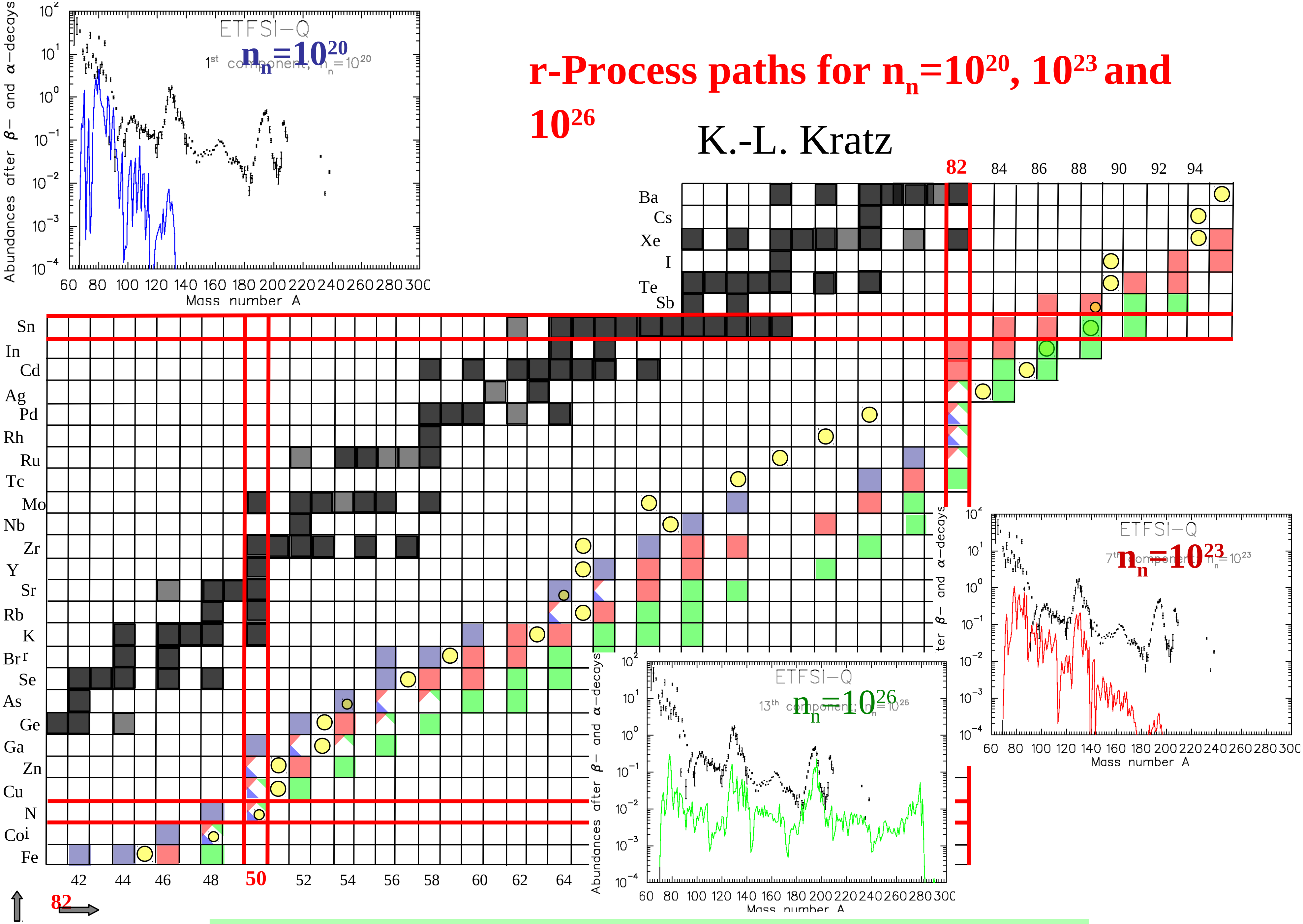


whether such a classical r-process is established, along contour-lines of constant S_{n}, due to (n,γ)-(γ,n) equilibrium, depends on the temperature, providing photons with sufficient energy (=>hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might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

G. Martinez-Pinedo

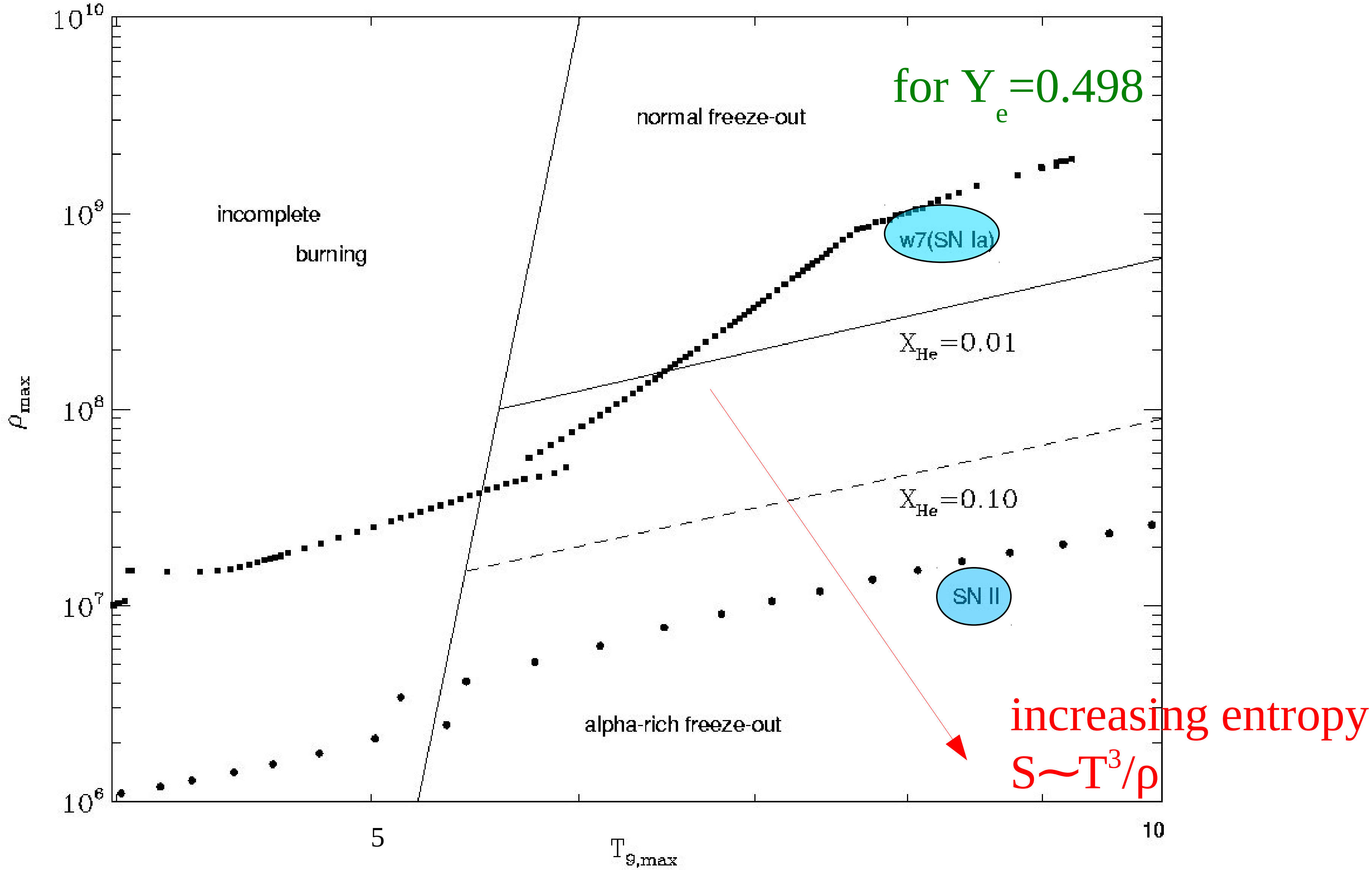
r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26}

K.-L. Kratz



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

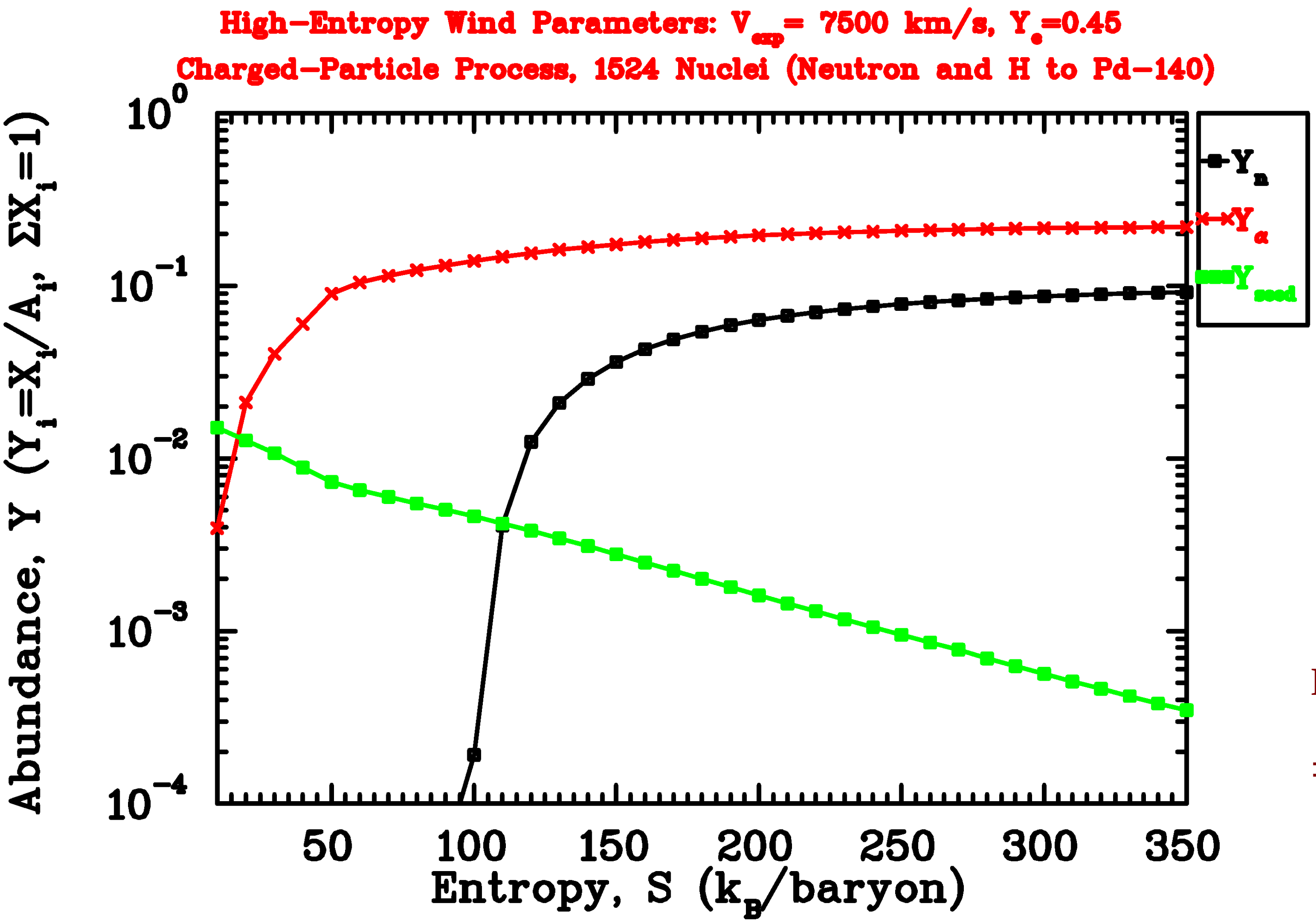
Explosive Si-Burning



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 ^{4}He 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)

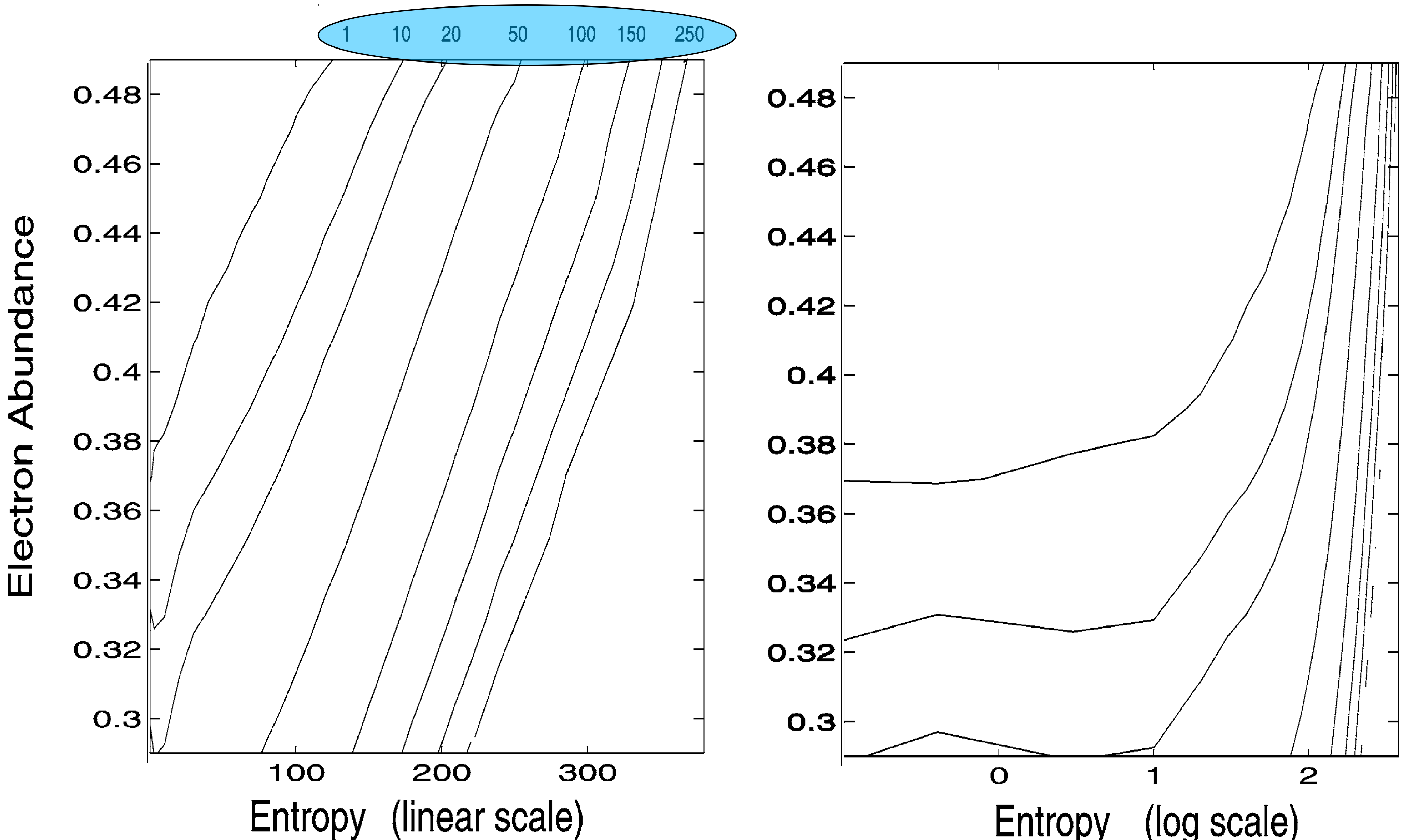


n/seed

$=Y_n/Y_{seed}$

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



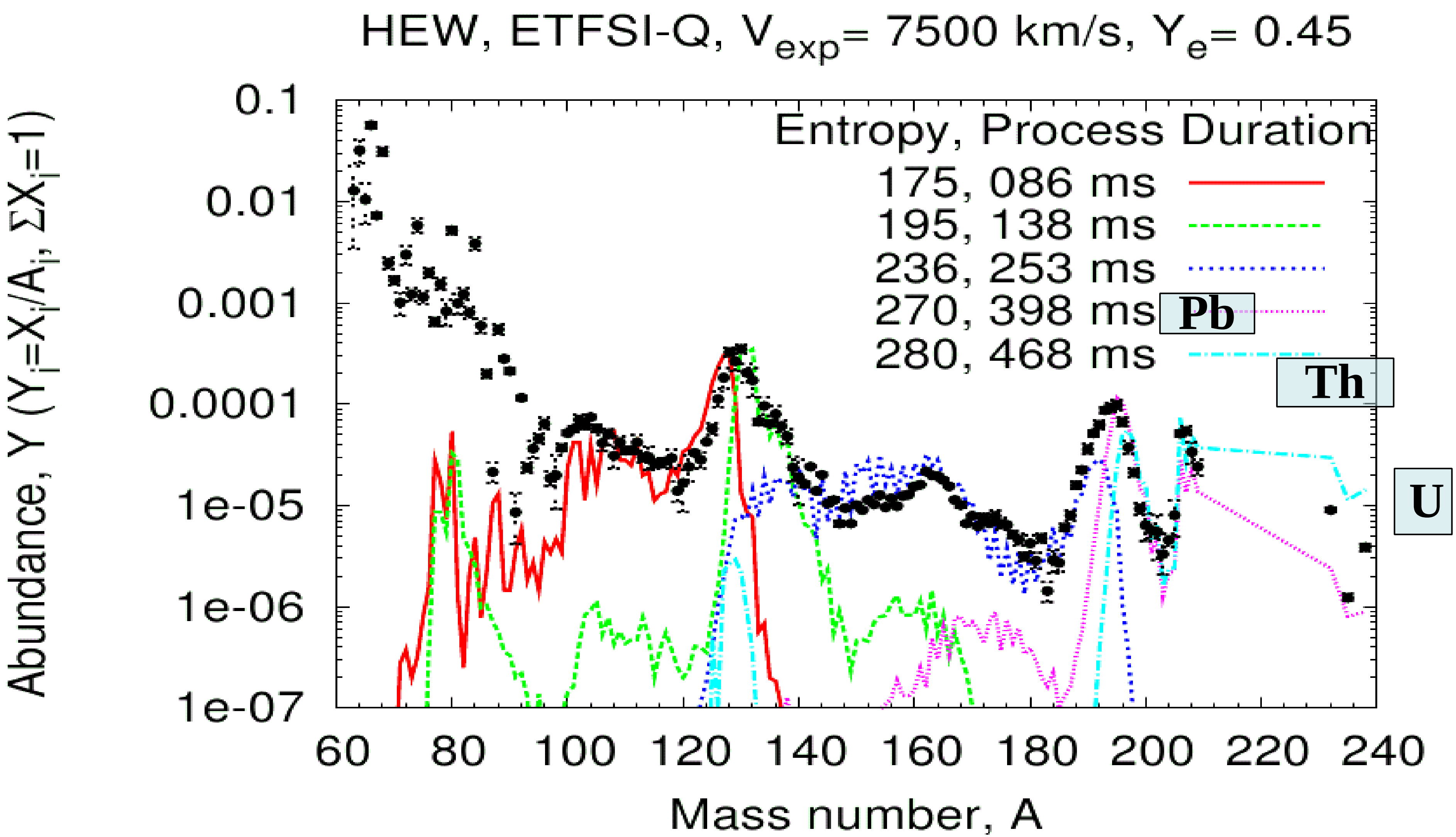
neutrino wind

Freiburghaus et al. (1999)

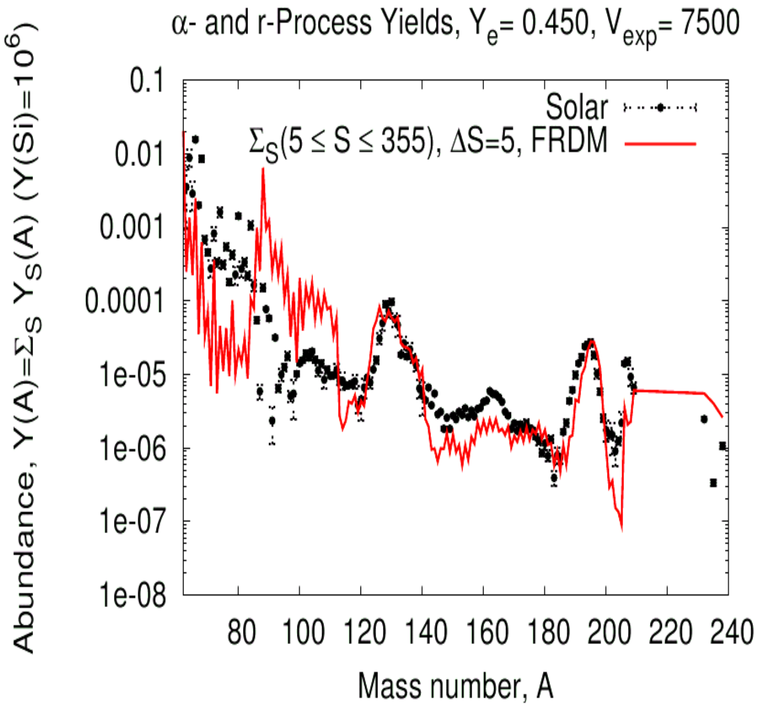
Neutron star mergers and polar jets

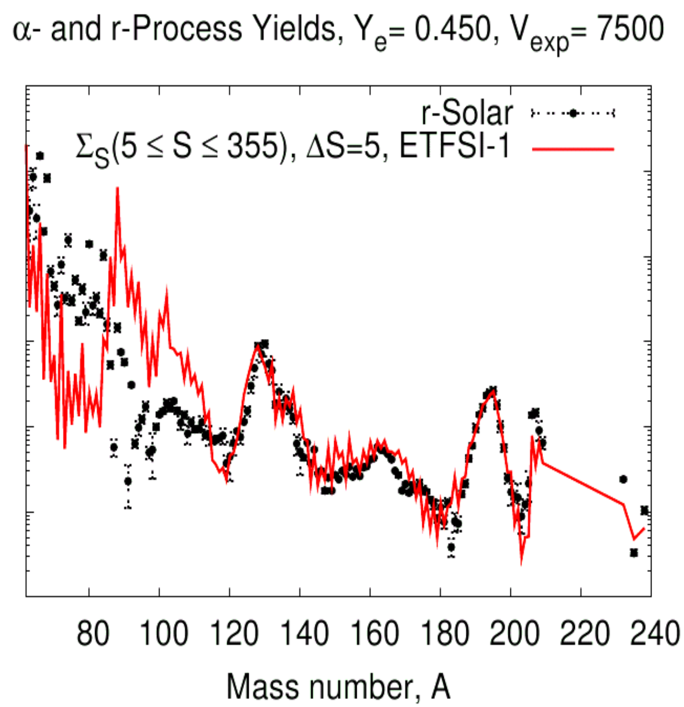
Individual Entropy Components in high entropy neutrino wind (hot r-process)

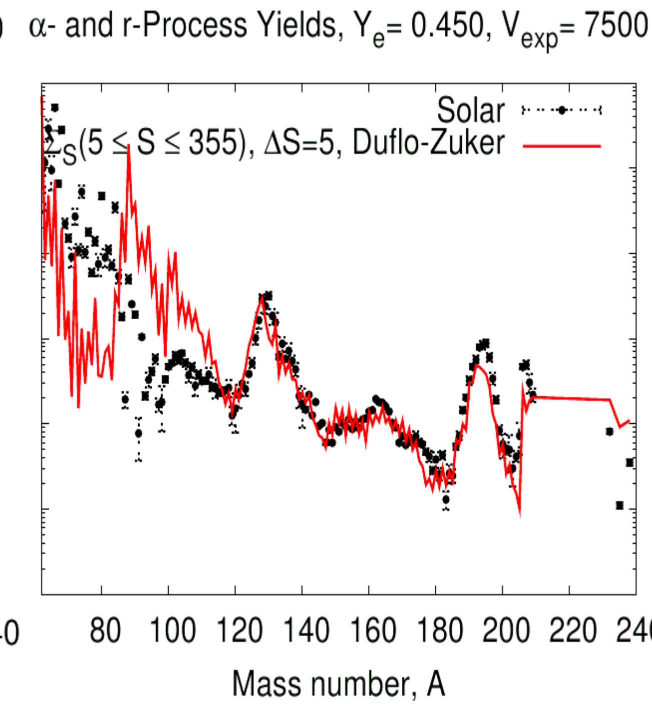
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in



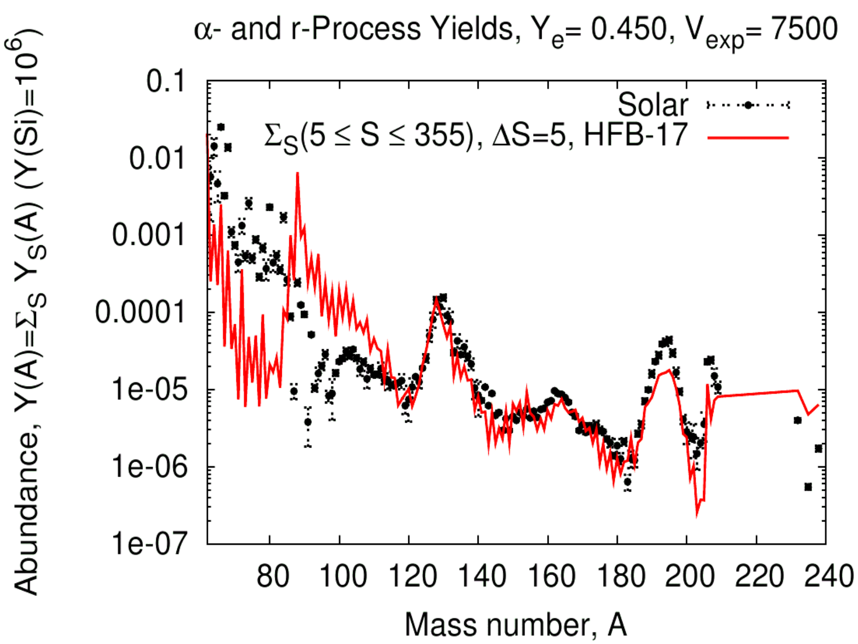
Superposition of entropies for different mass models







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.

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

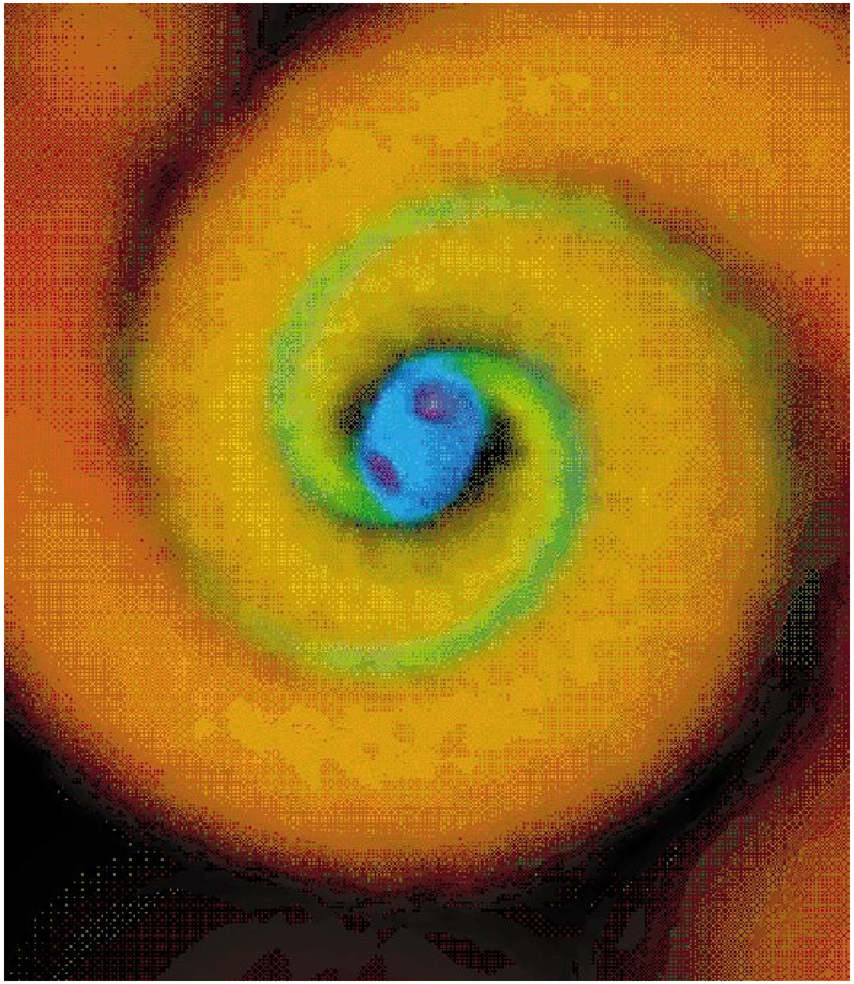
(many parameter studies: Meyer, Howard, Takahashi, Janka, Hoffman, Qian, Woosley, Freiburghaus, Thielemann, Mathews, Kajino, Wanajo, Otsuki, Terasawa, Mocelj, Farouqi, Kratz, Goriely, Martinez-Pinedo, Langanke, Arcones, Panov, Petermann ...)

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

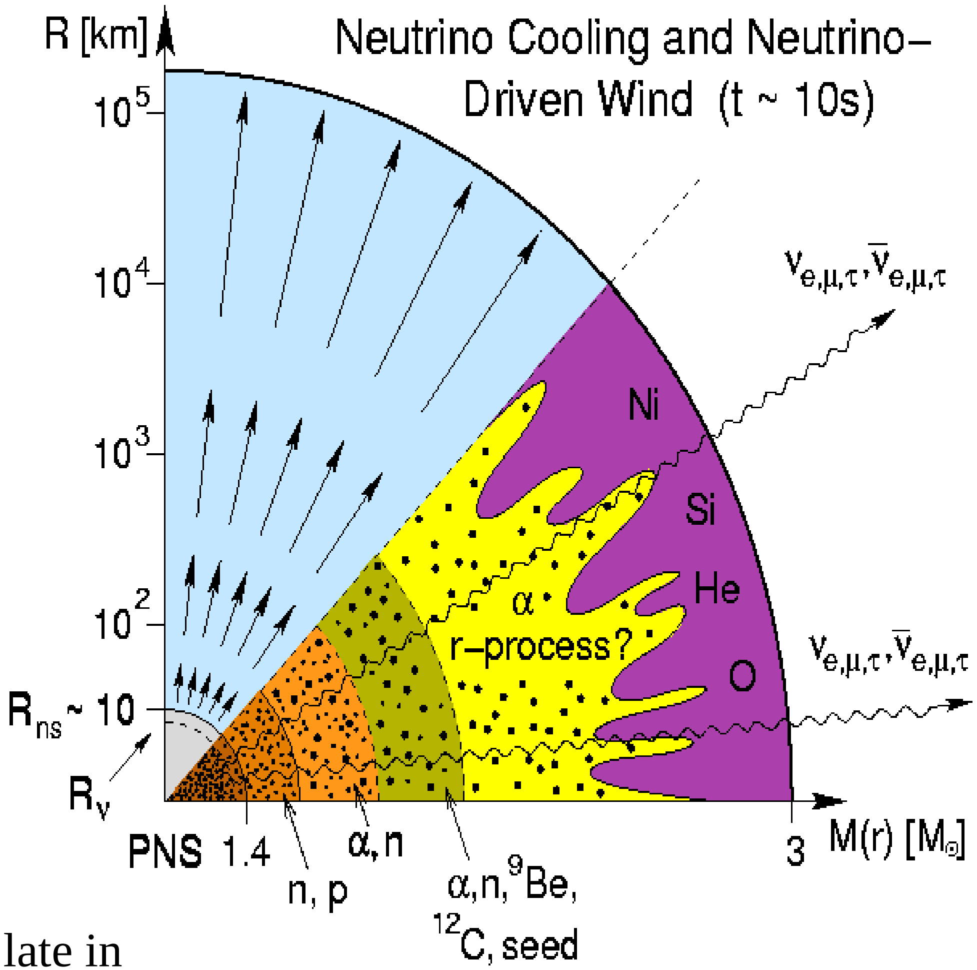
(Freiburghaus, Rosswog, Thielemann, Panov, Goriely, Janka, Martinez-Pinedo, Korobkin, Arcones, Winteler, Nishimura, Fujimoto)

What is the site of the r-process?

from S. Rosswog



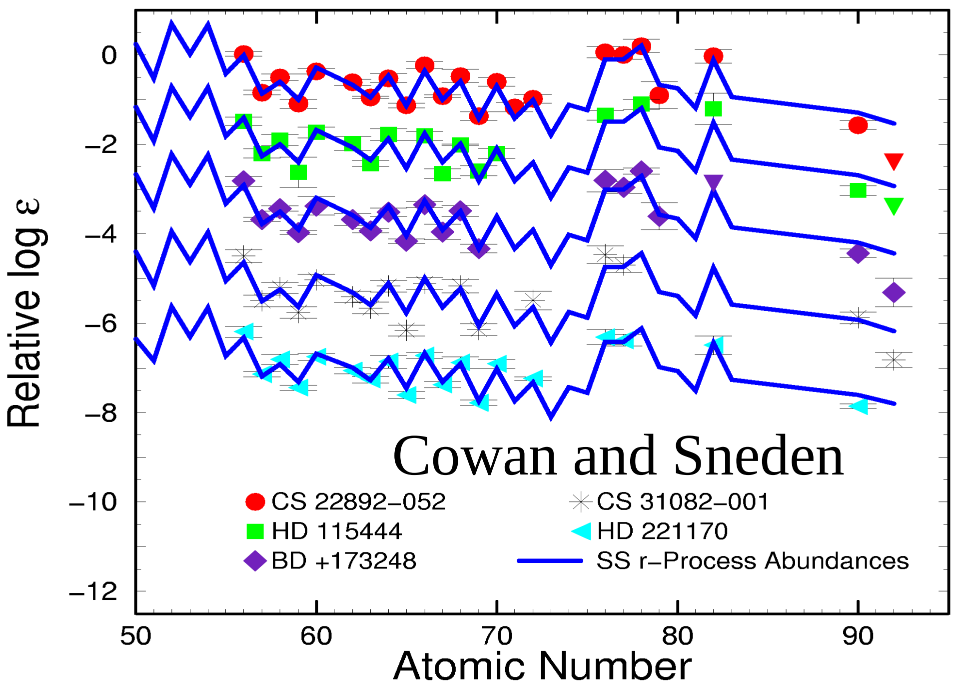
from H.-T. Janka



NS mergers, BH-NS mergers, problems: ejection too late in galactic evolution?
(or alternatively polar jets from supernovae, Cameron 2003, Fujimoto et al. 2008, Winteler et al. 2012)

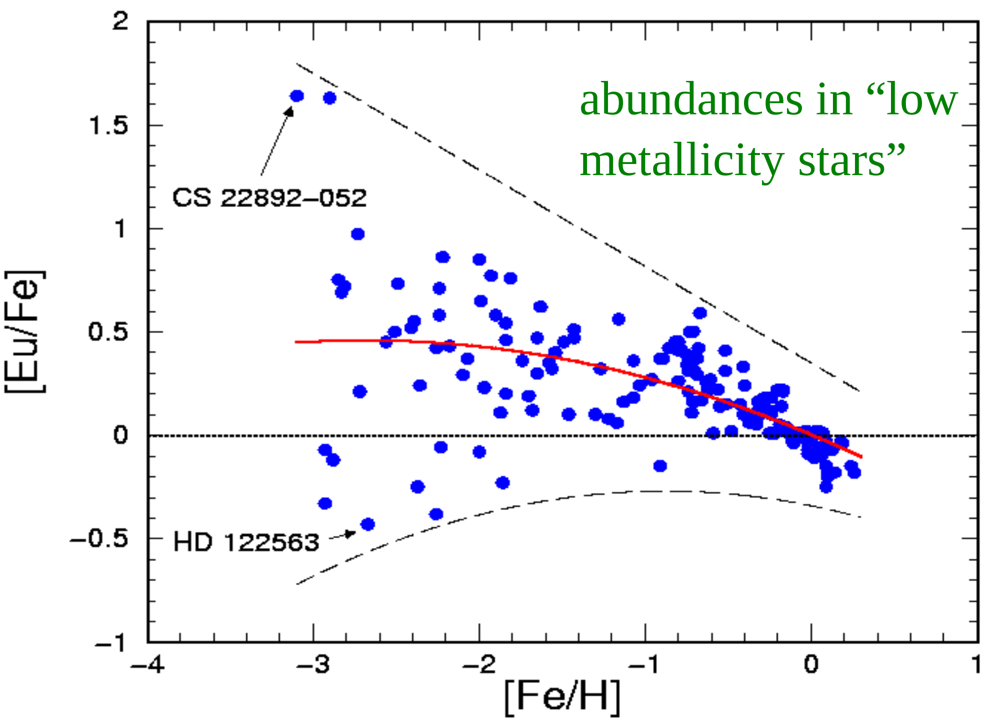
SN neutrino wind, problems: high enough entropies attained? Ye<0.5?
neutrino properties???

Observational Constraints on r-Process Sites

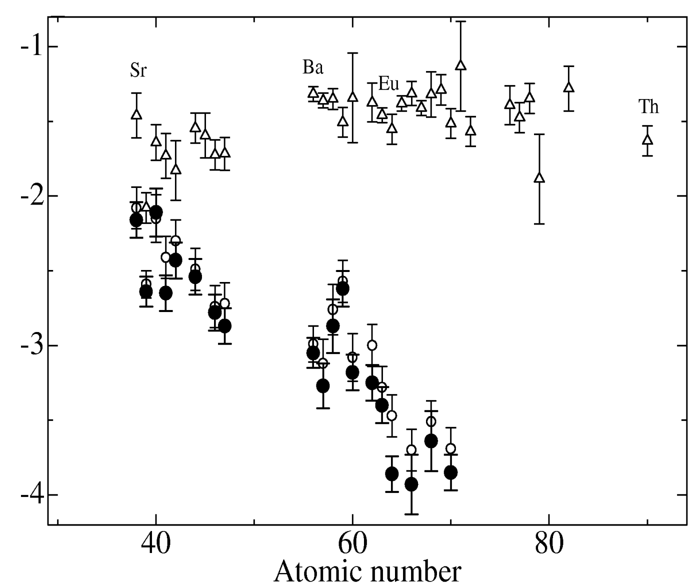


apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event which nevertheless consists of a superposition of ejected mass zones

"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)

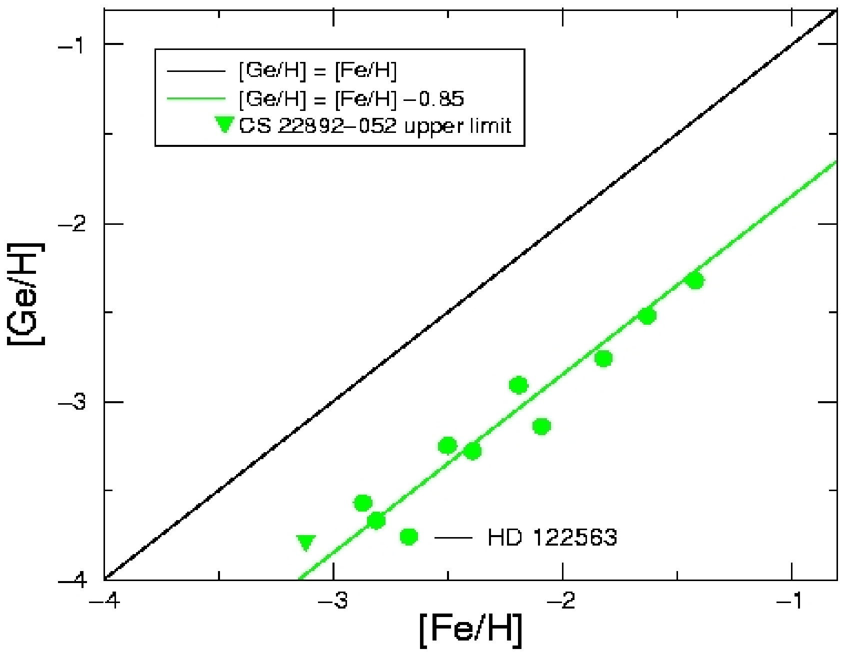


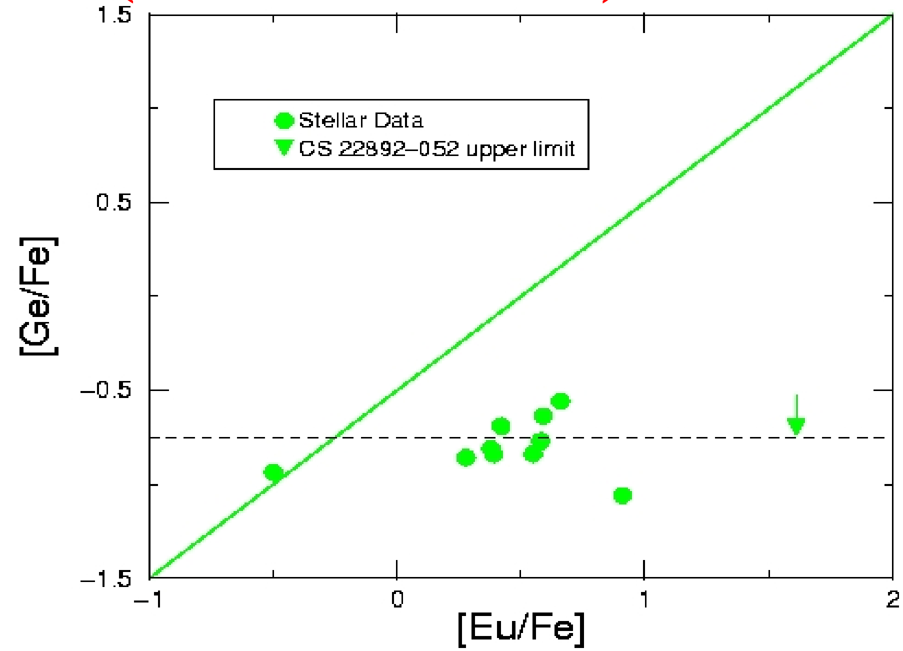
Observations of the weak r-process?

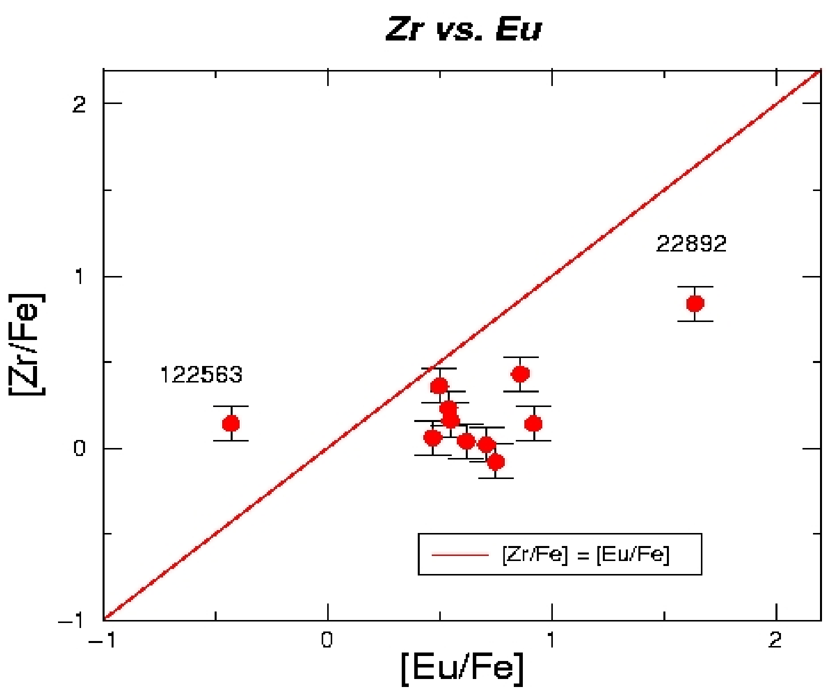


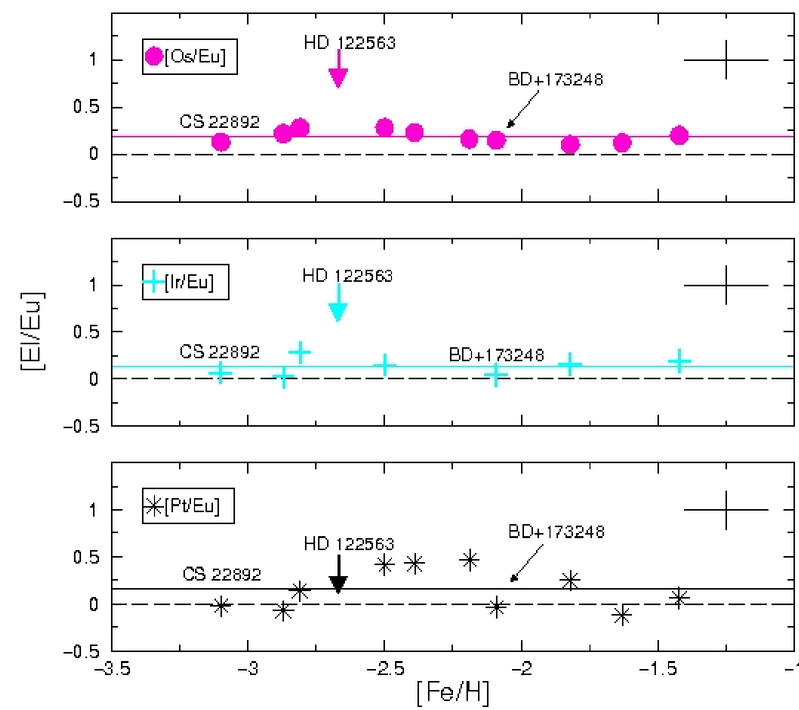
Honda et al. (2007)

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)



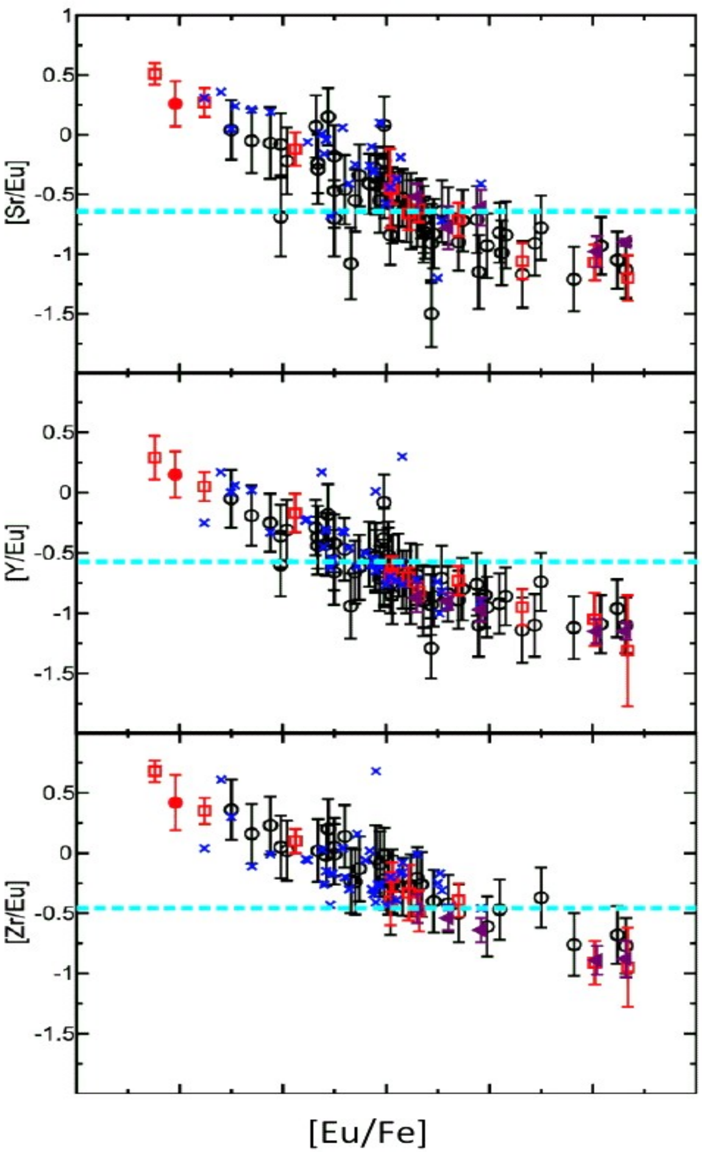


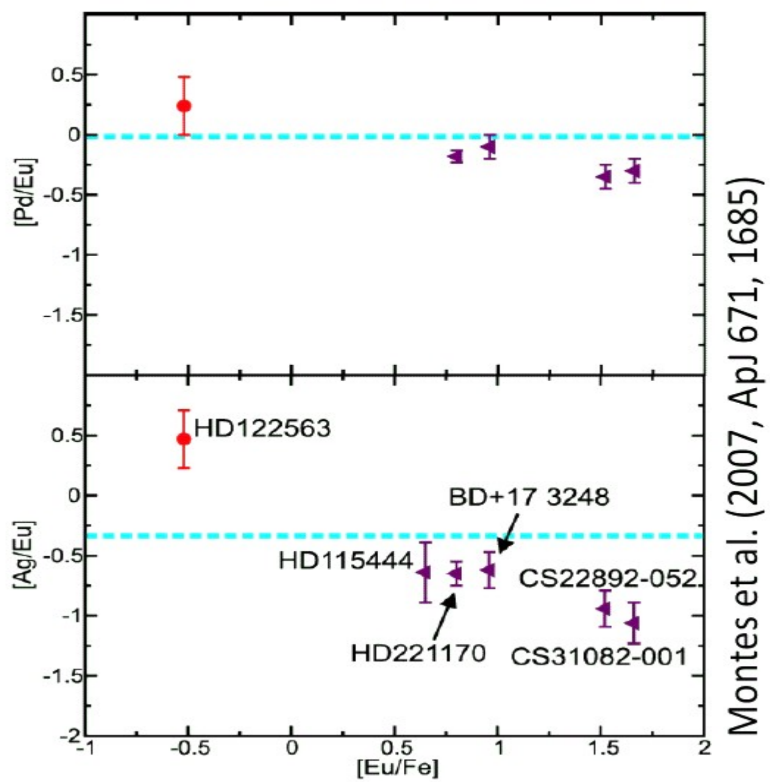




No Correlation between light and heavy „neutron capture“ elements (*N. Christlieb*)

Light neutron-capture elements





Conclusion: the light (38 ≤ Z ≤ 47) and heavy (Z > 47) neutron-capture elements were produced in two independent nucleosynthesis processes.

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, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin***

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

- **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 ν_e, $\bar{\nu}_e$ captures on neutrons and protons

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

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

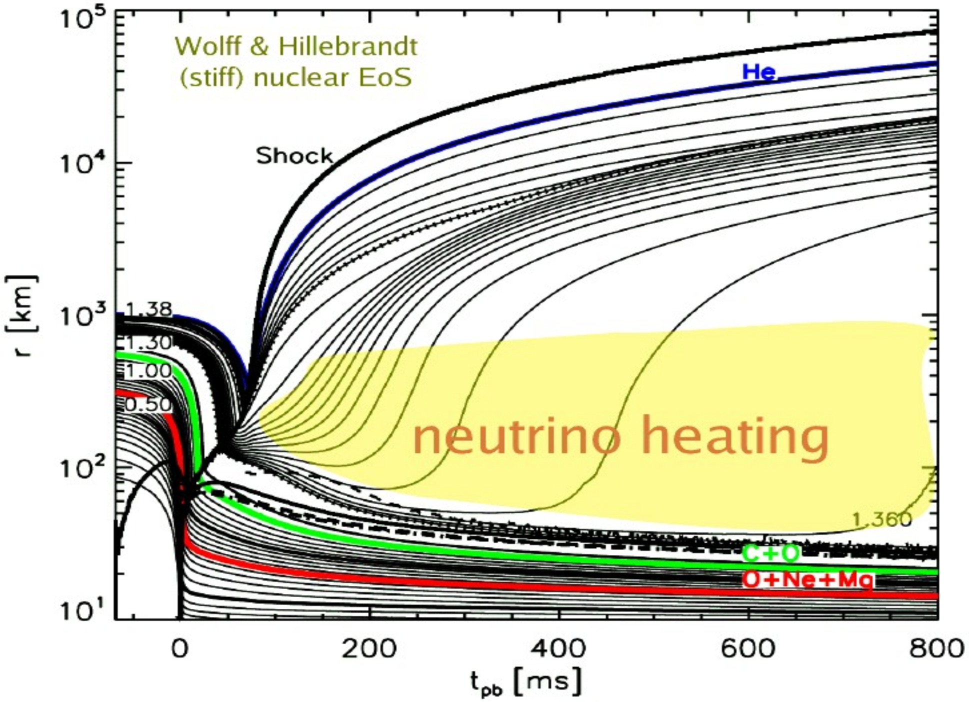
- high density / low temperature $\rightarrow$ high E_F for electrons $\rightarrow$ e-captures dominate $\rightarrow$ n-rich composition
- if el.-degeneracy lifted for high T $\rightarrow$ ν_e-capture dominates $\rightarrow$ due to n-p mass difference, p-rich composition
- in late phases when proto-neutron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

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 $E_{av,\bar{\nu}}-E_{av,\nu}>4(m_n-m_p)$ lead to $Y_e<0.5$!

Supernovae in 1D

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

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

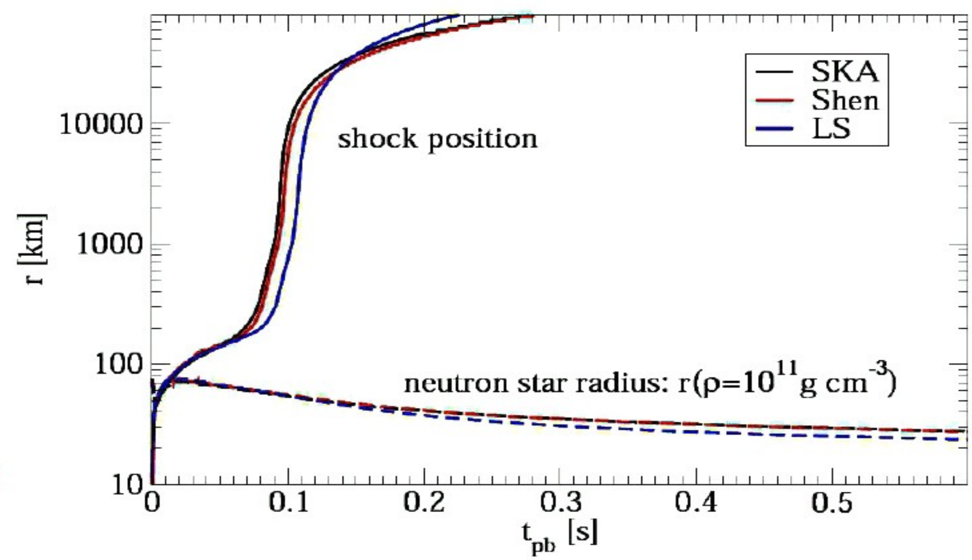


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

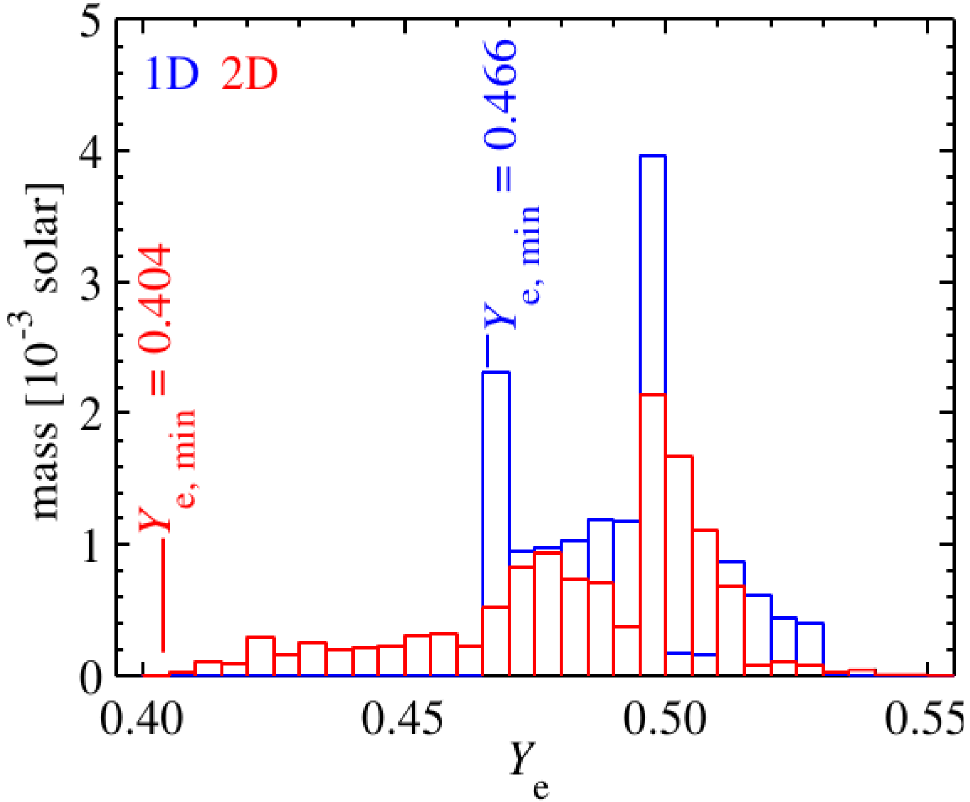
Fischer et al. 2010

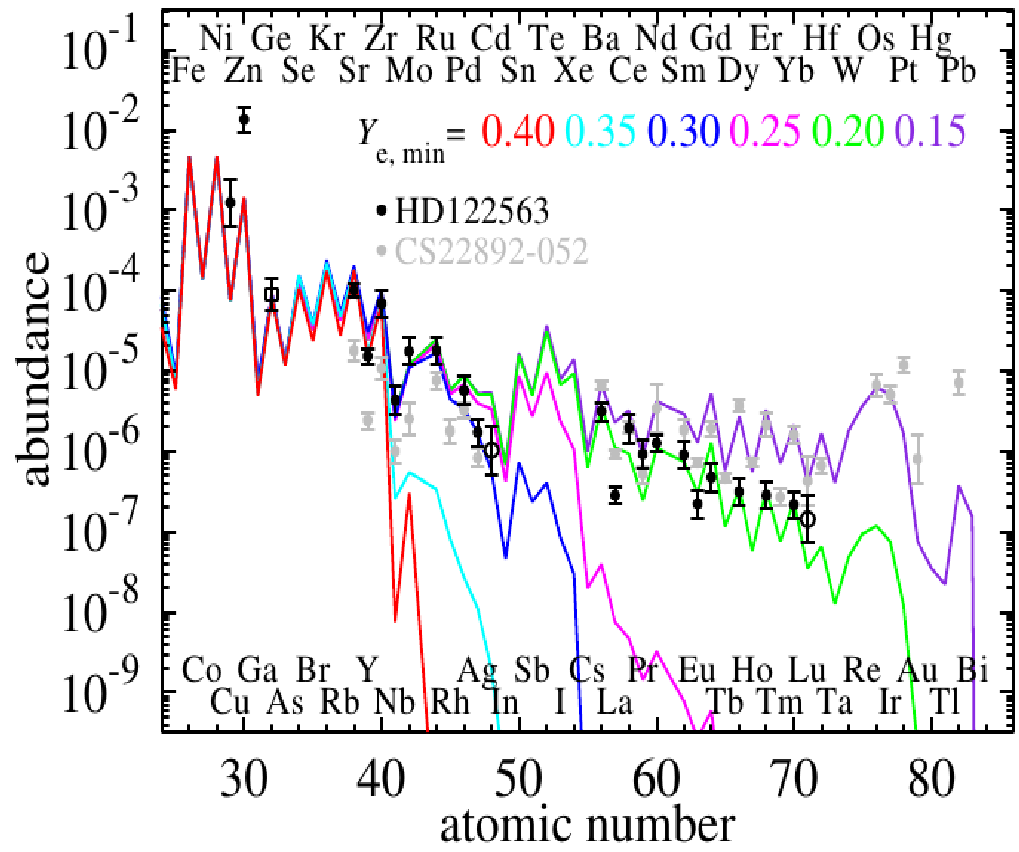
Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

- 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)

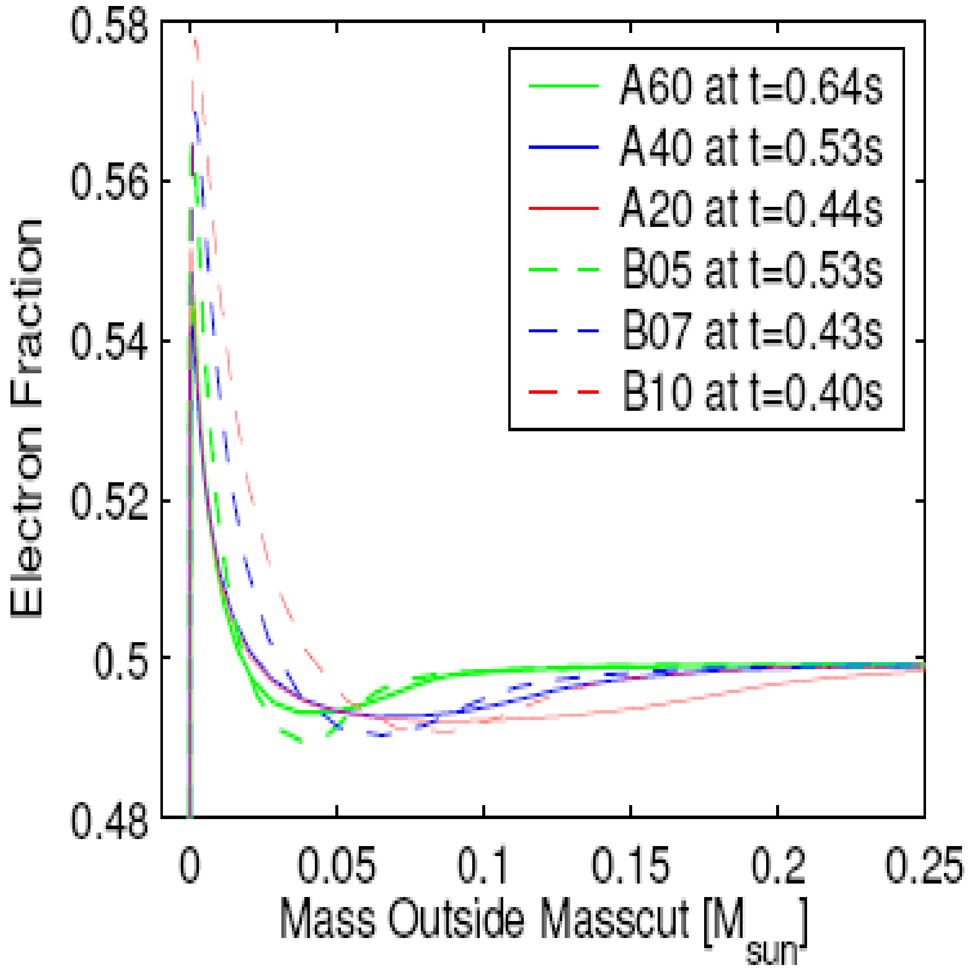


Wanajo & Janka 2011, EC Supernovae in 1 and 2D





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

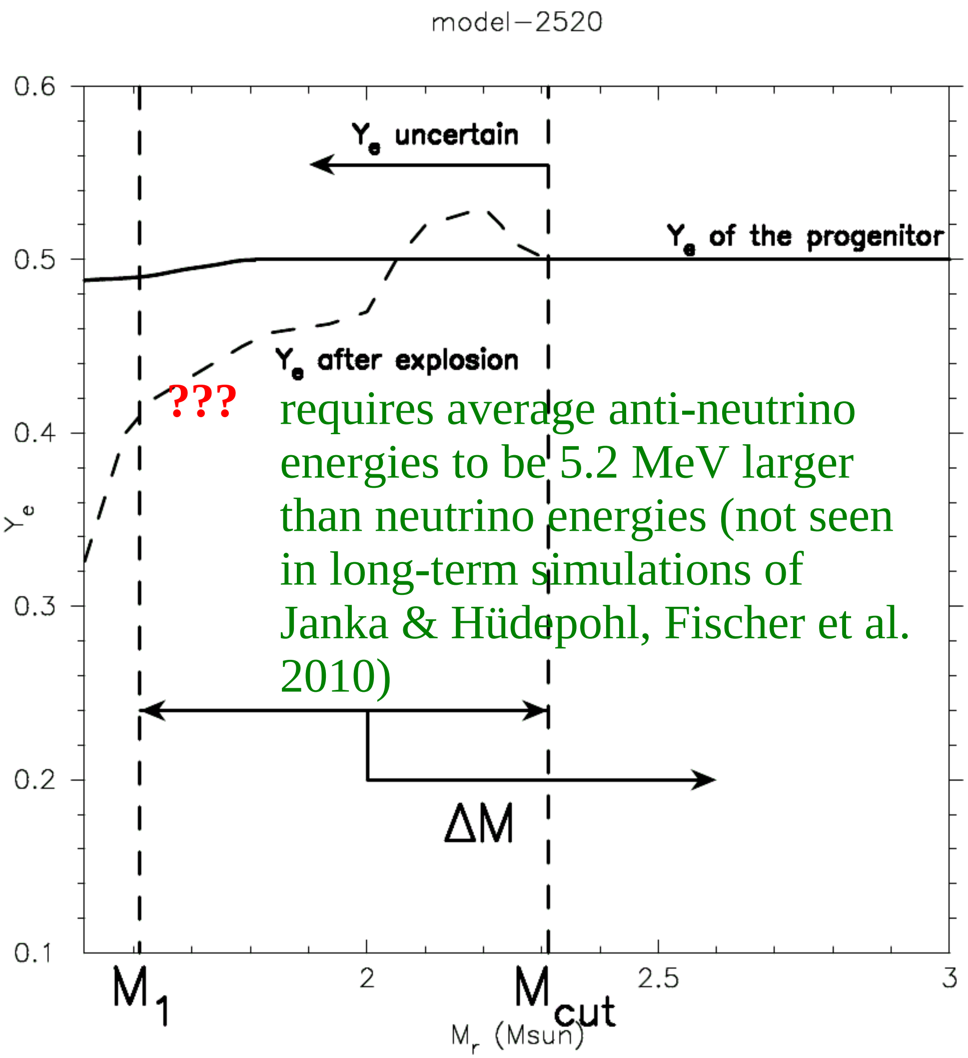


Liebendörfer et al. (2003),
Fröhlich et al. (2006a,b),
Pruet et al. (2005, 2006)
Wanajo (2007)

Discovery of the νp-process!

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

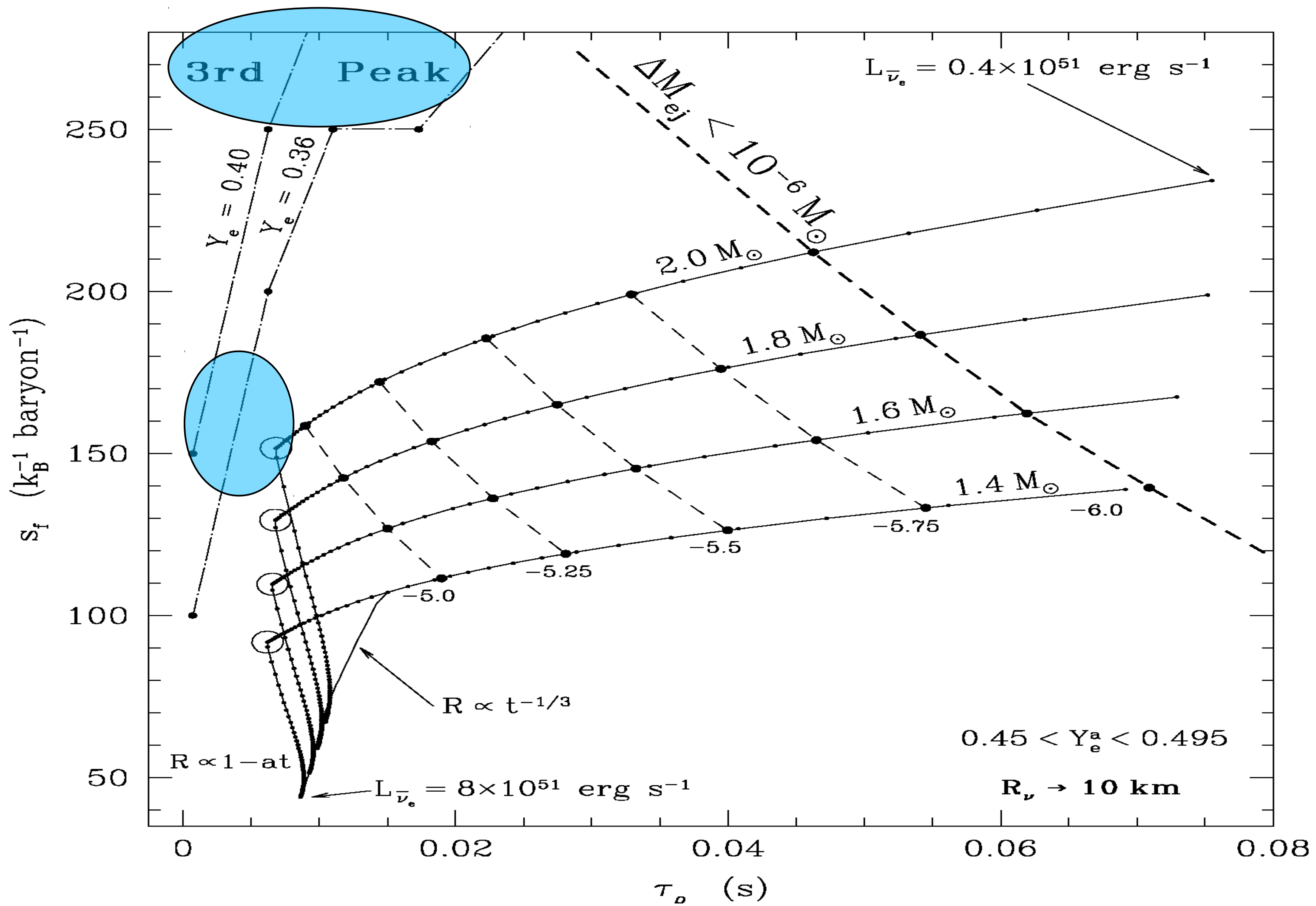
Possible Variations in Explosions and Ejecta



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? (Wanajo et al. 2010, neutron-rich lumps in EC-Supernovae?? jets: e.g. Cameron 2003, Fujimoto et al. 2008?; very high entropy and neutron-rich neutrino wind?)*

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

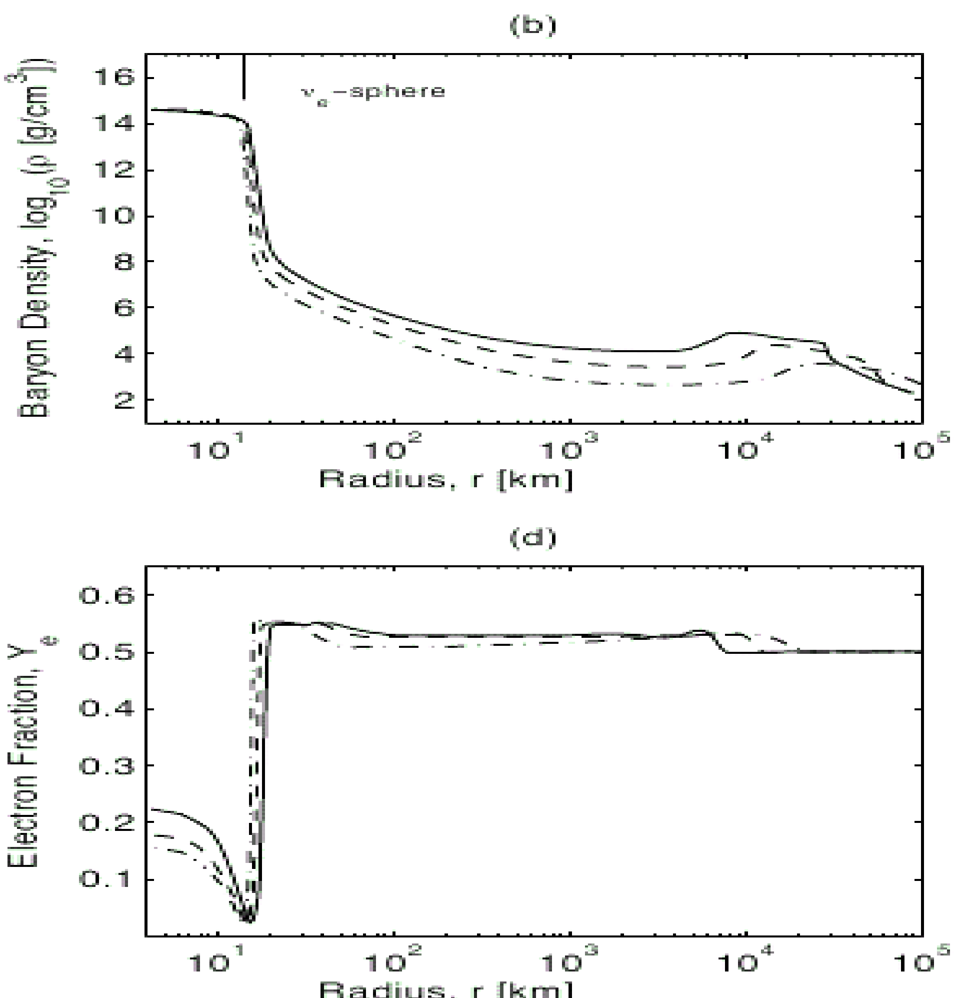


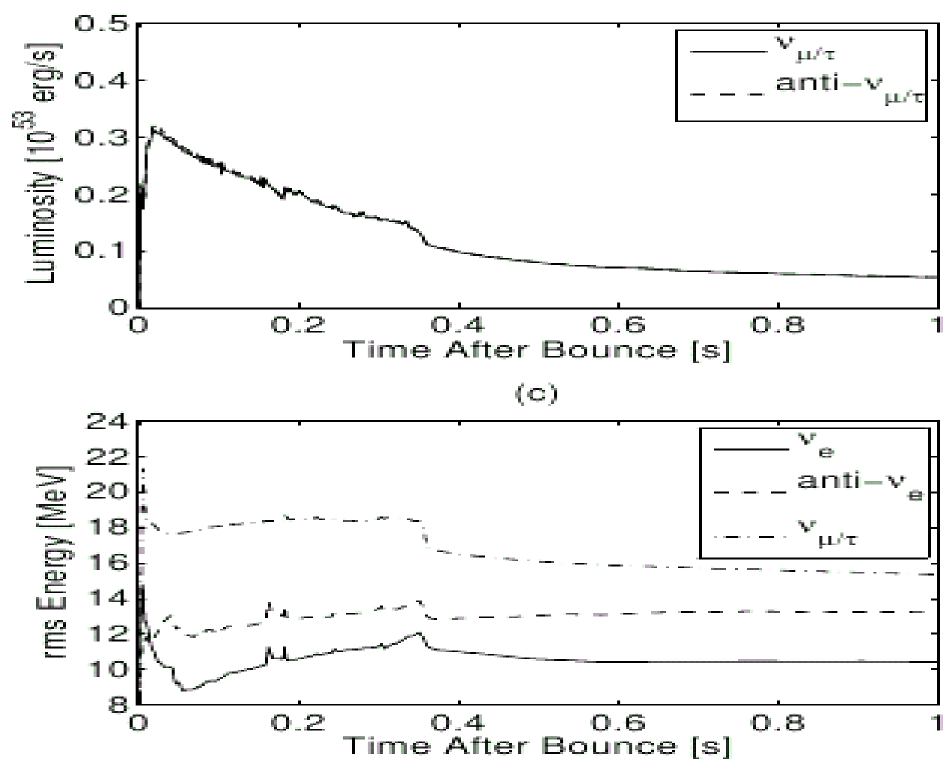
Only very massive neutron stars seemed to come close to conditions (entropies) which can produce the third peak!!!

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

Fischer et al. (2010)

these findings see 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

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

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

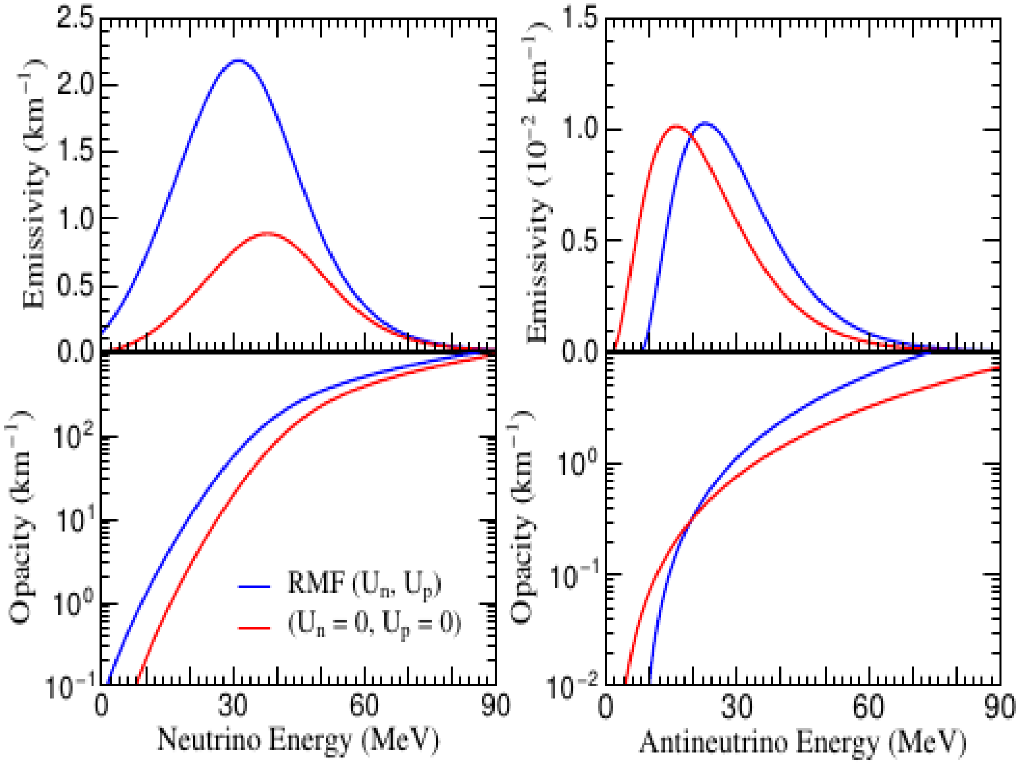
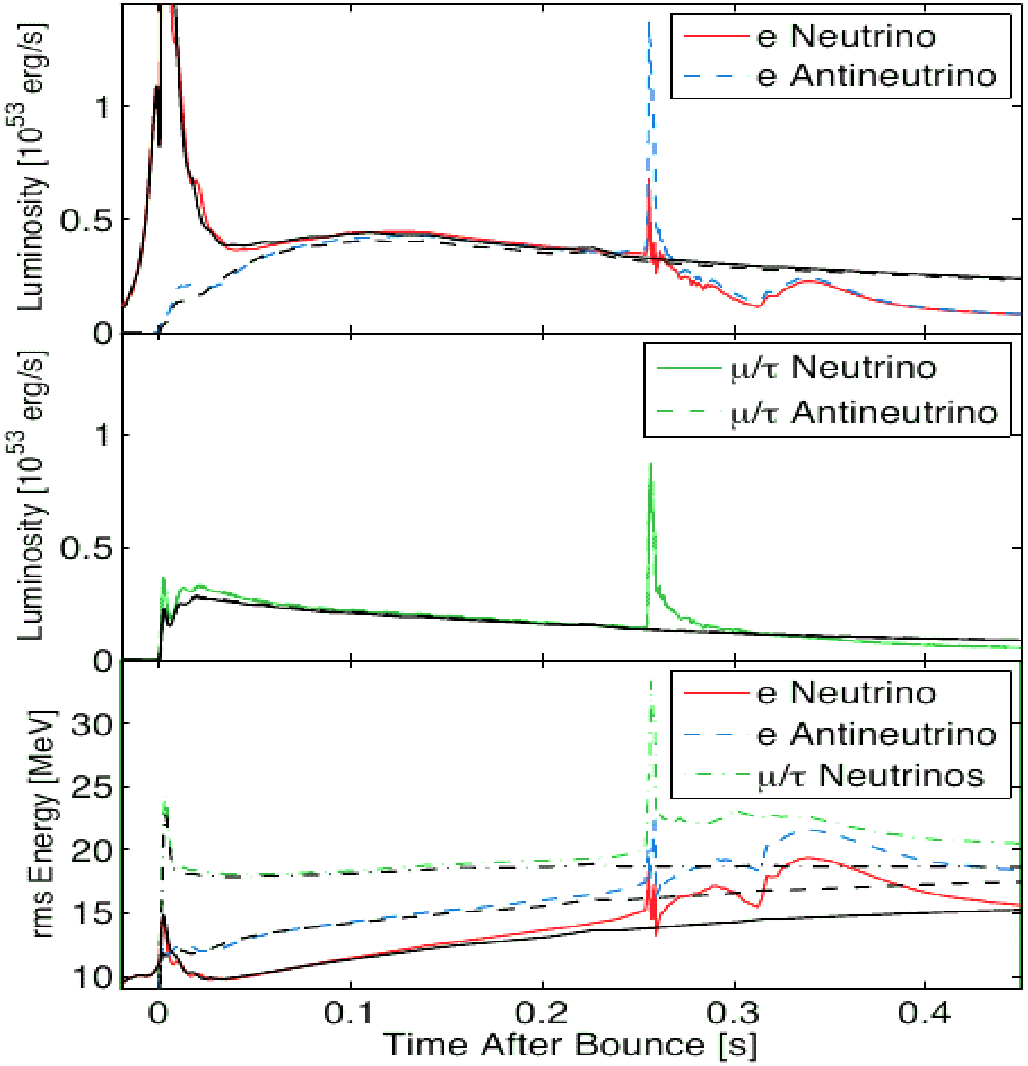


FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

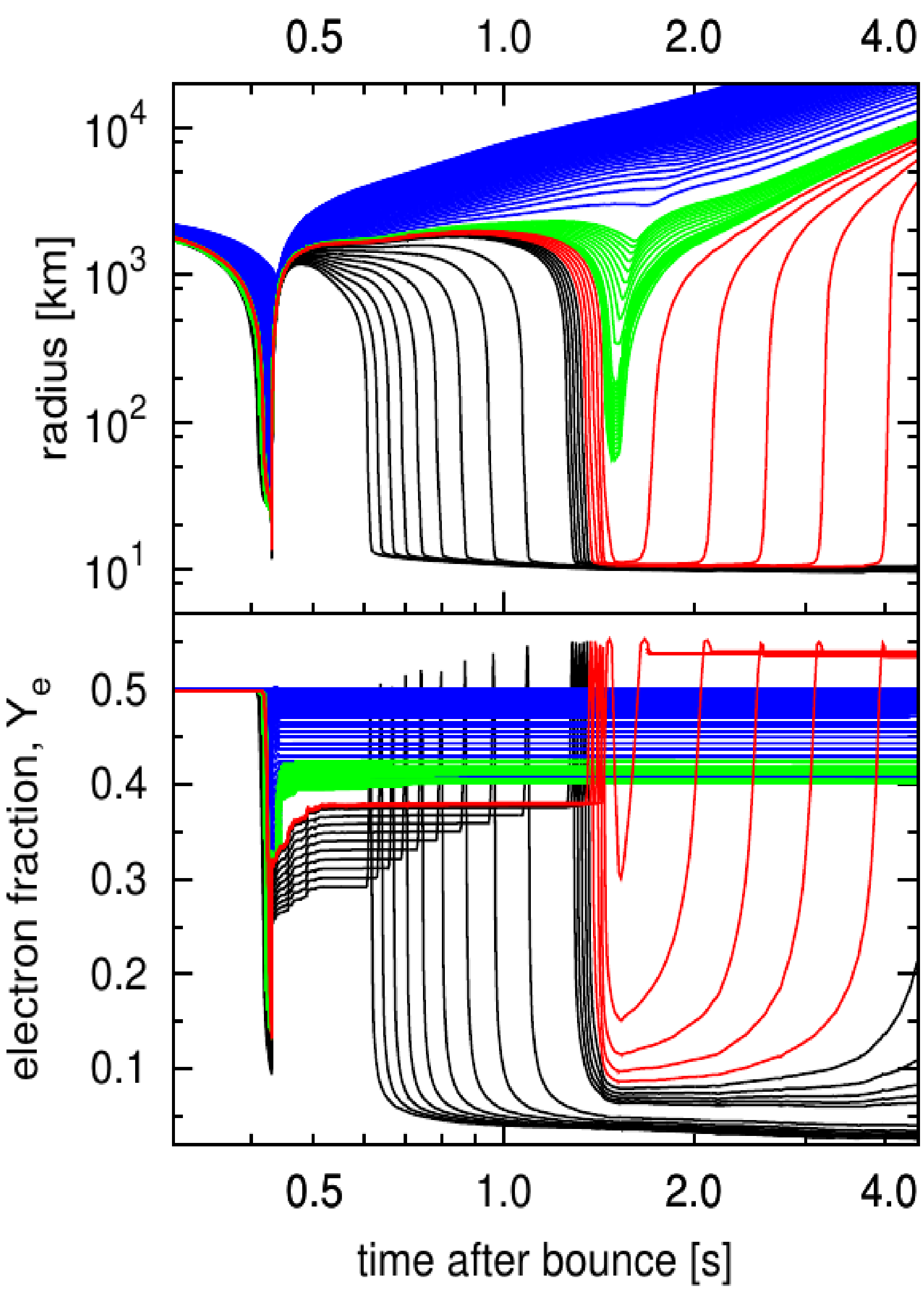
Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4! *Effect still not fully tested for hot neutrino wind?*

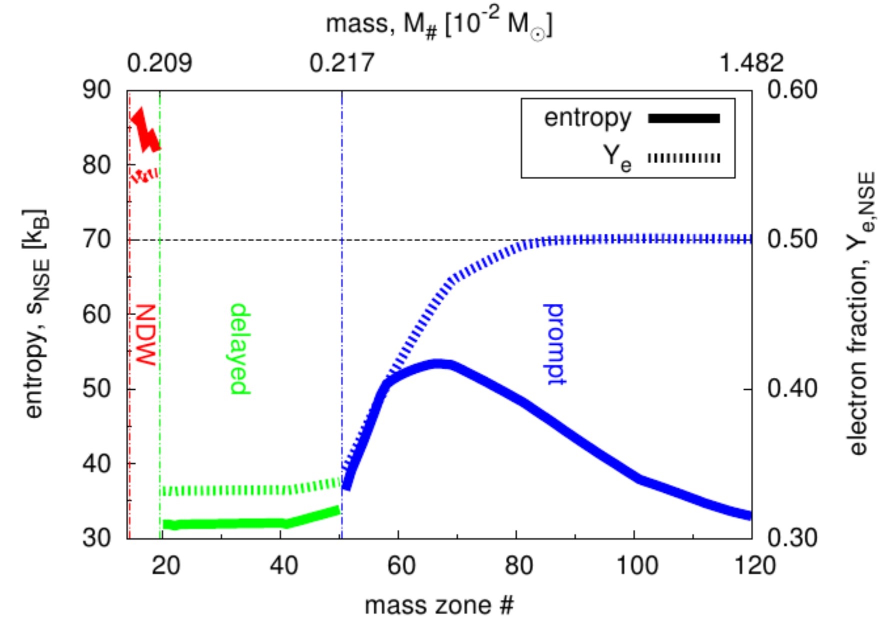
Core Collapse with EOS utilizing MIT Bag Model (Sagert et al. 2009, Fischer et al. 2011)

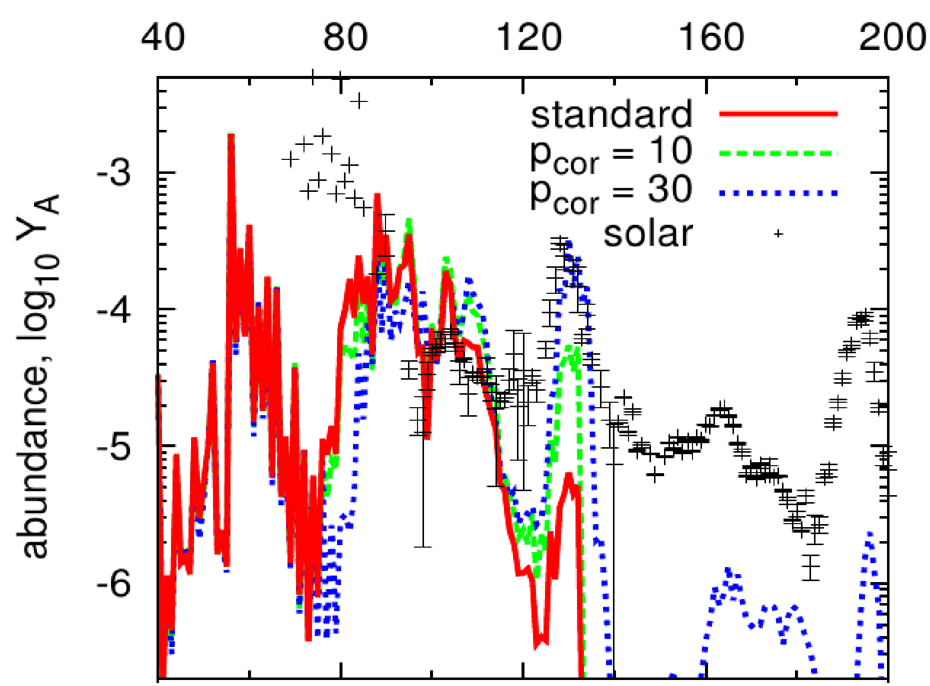


Shown is a simulation of a $10M_{sun}$ star containing ($B^{1/4}=162$) quark matter compared to one with hadronic matter only (black lines)

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

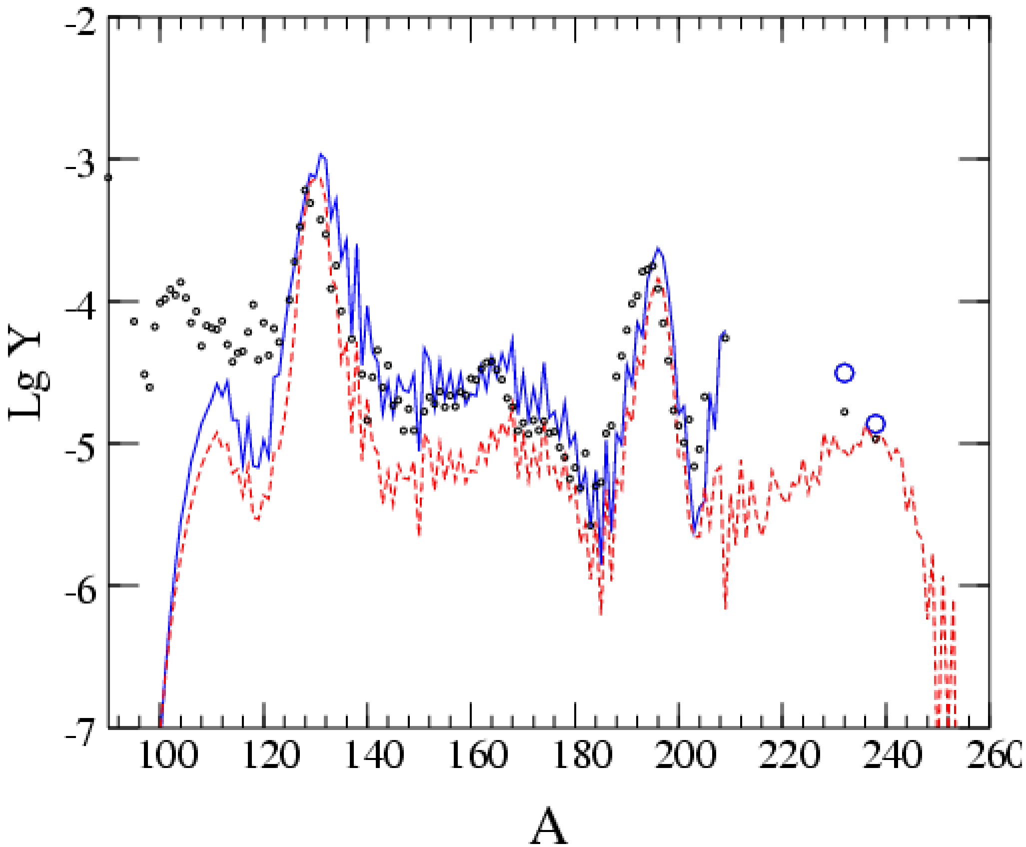




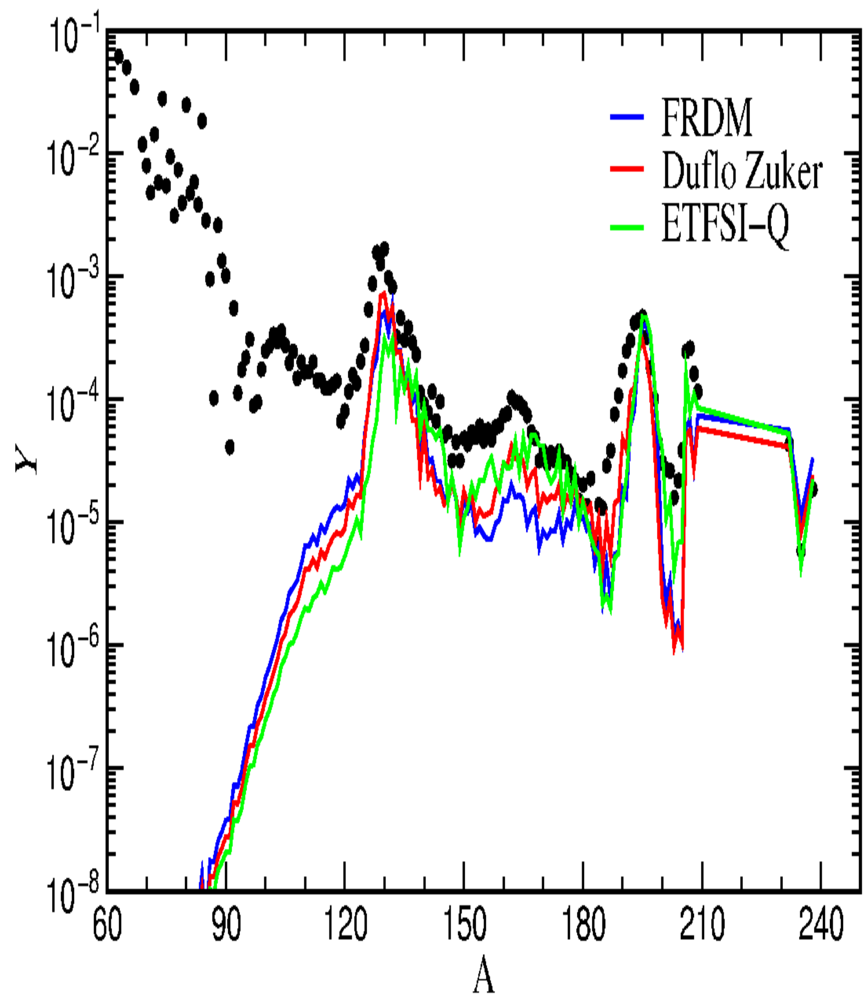


Fission Cycling in Neutron Star Mergers

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



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

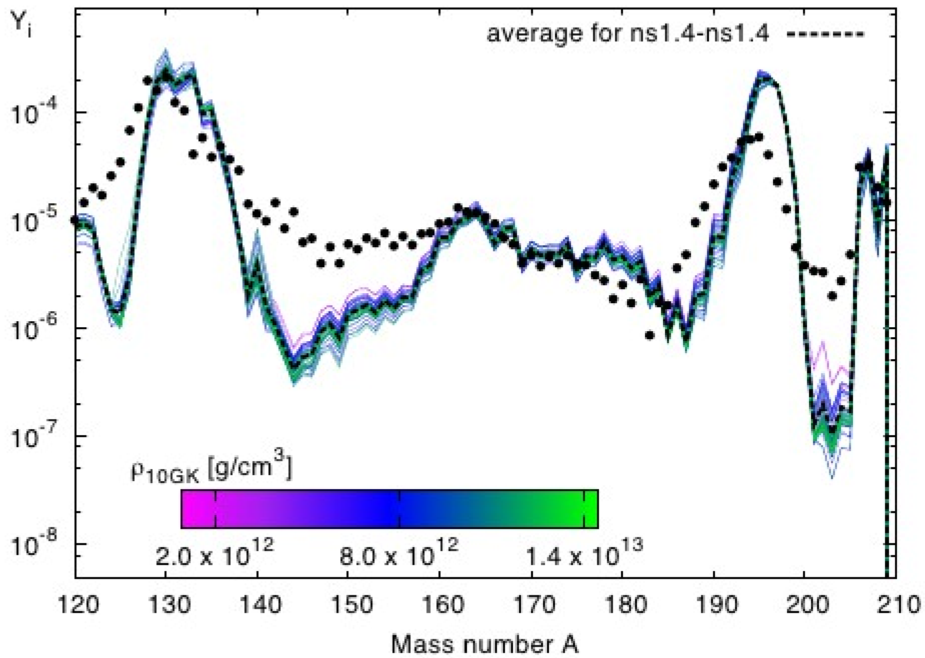


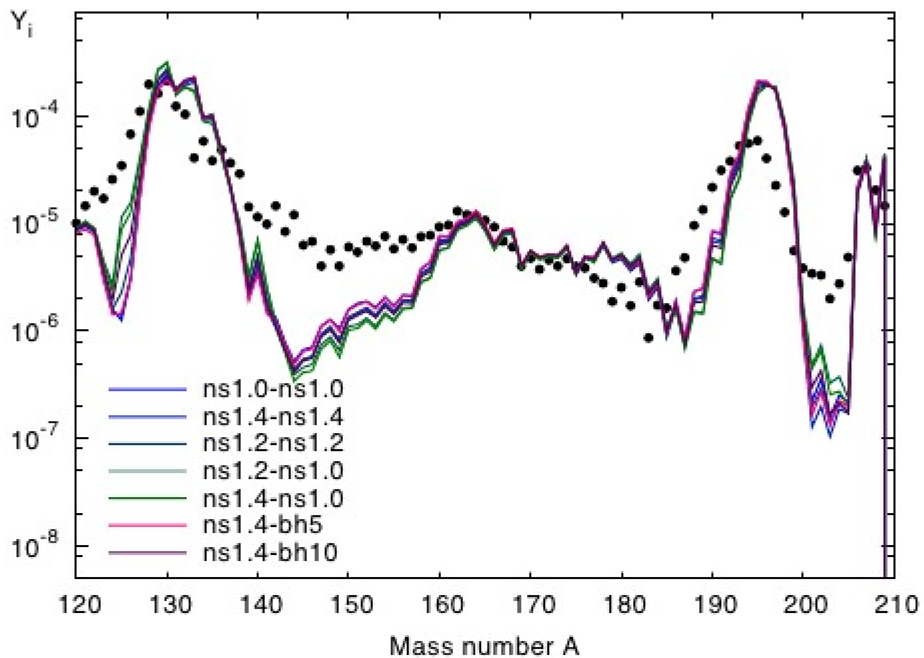
Martinez-Pinedo et al. (2006)

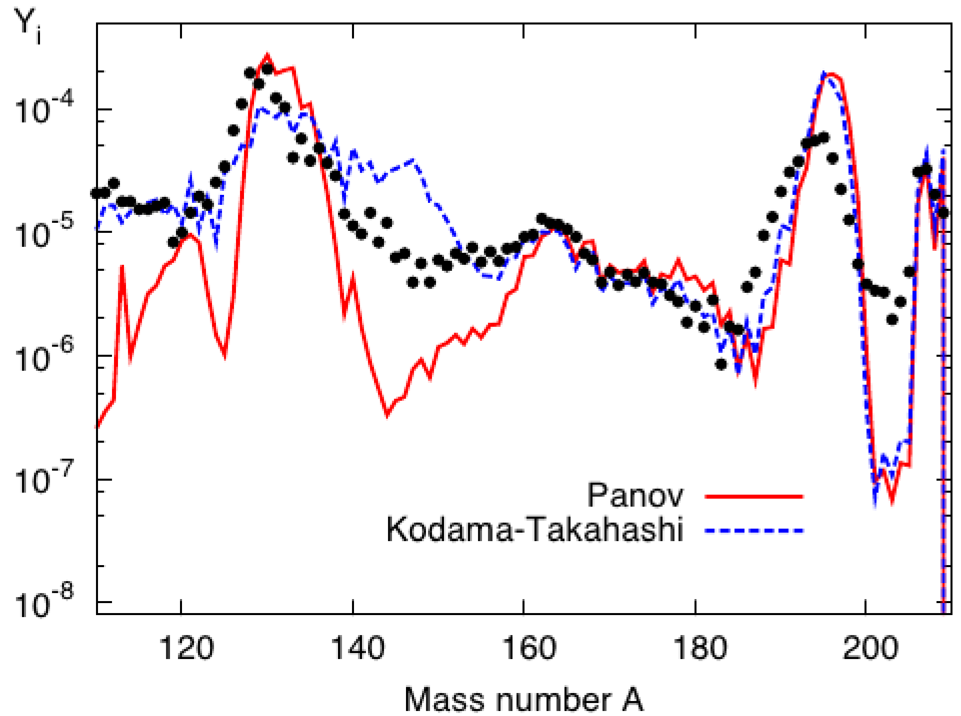
in principle contradicted from gal. evol. calc. (however, see Ishimura & Wanajo 2010), but similar conditions in SN polar jets? (Cameron 2003, Fujimoto 2008)

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

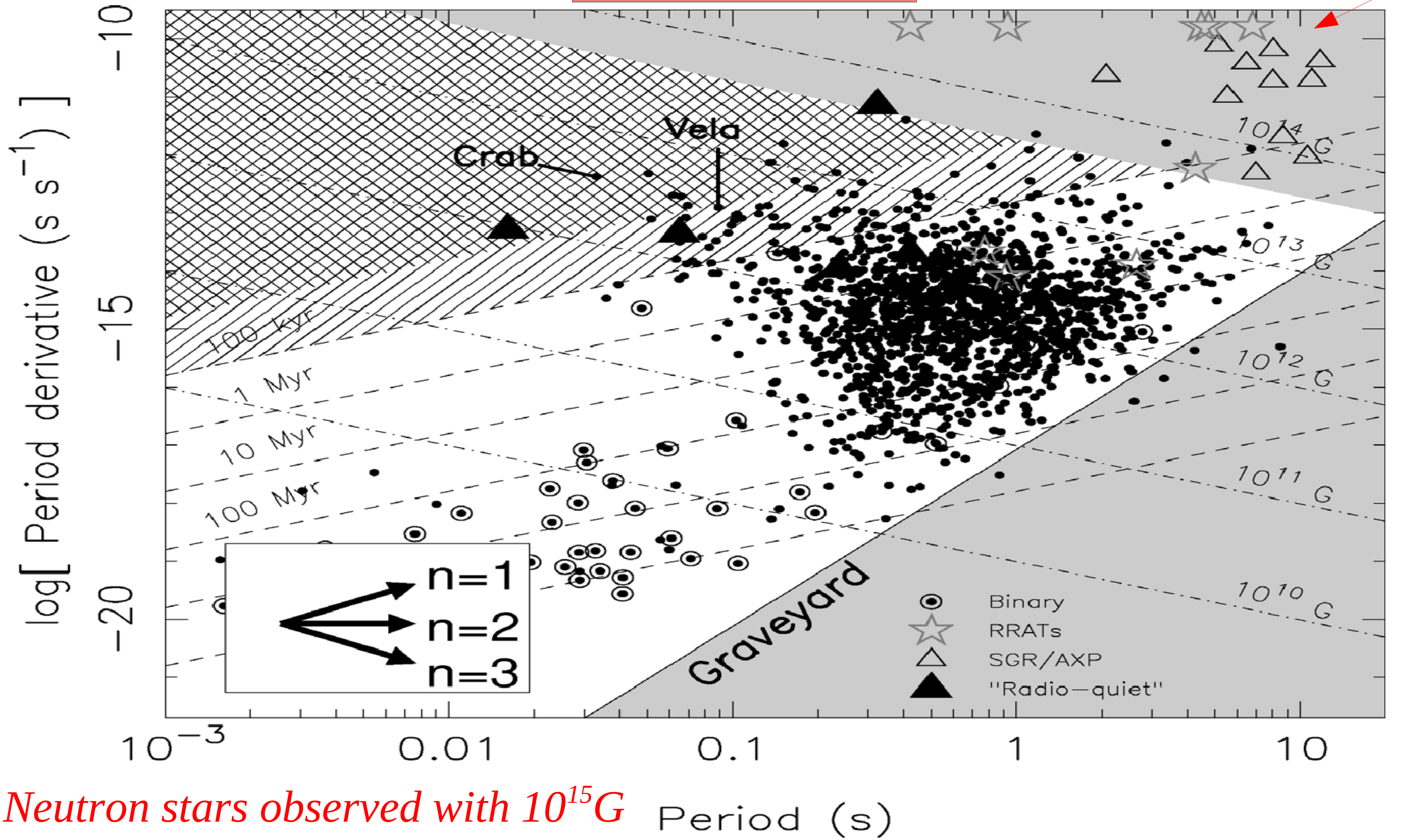
Variation in neutron star masses
fission yield prescription







M. Kramer (2009)



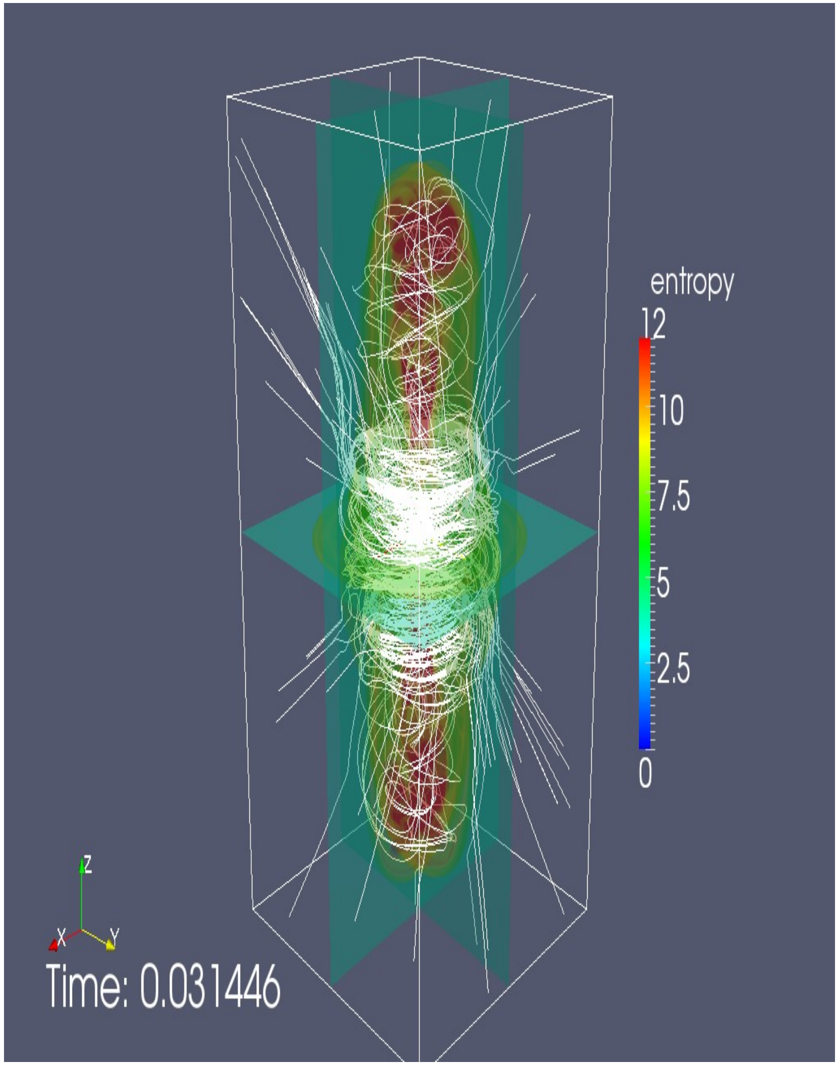
Neutron stars observed with 10^{15}G

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)



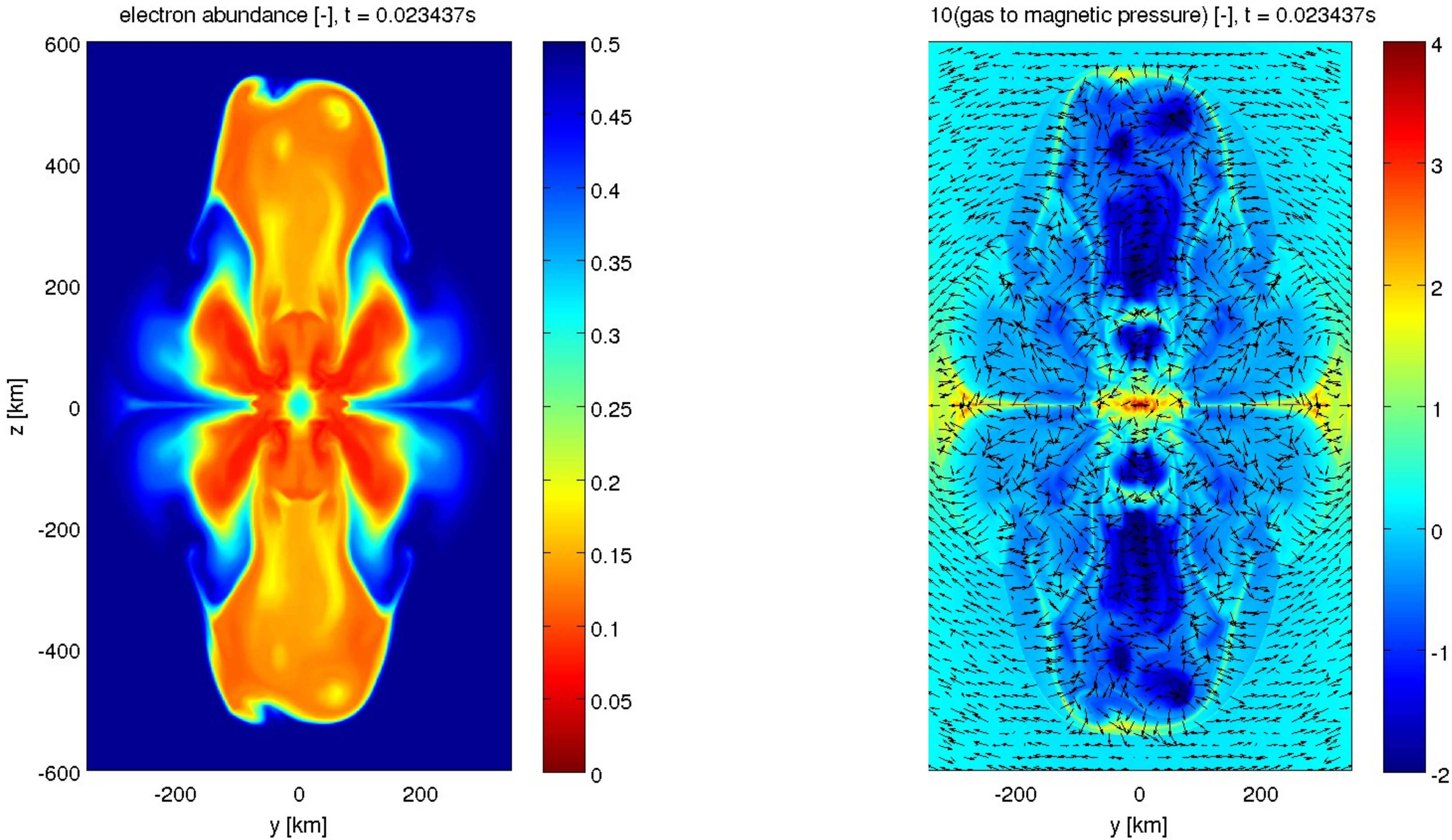
Low entropy, low Ye (compression to high densities) ,

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 $\times 10^{12}$ Gauss,

results in 10^{15} Gauss neutron star



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

Ye evolution with neutrinos

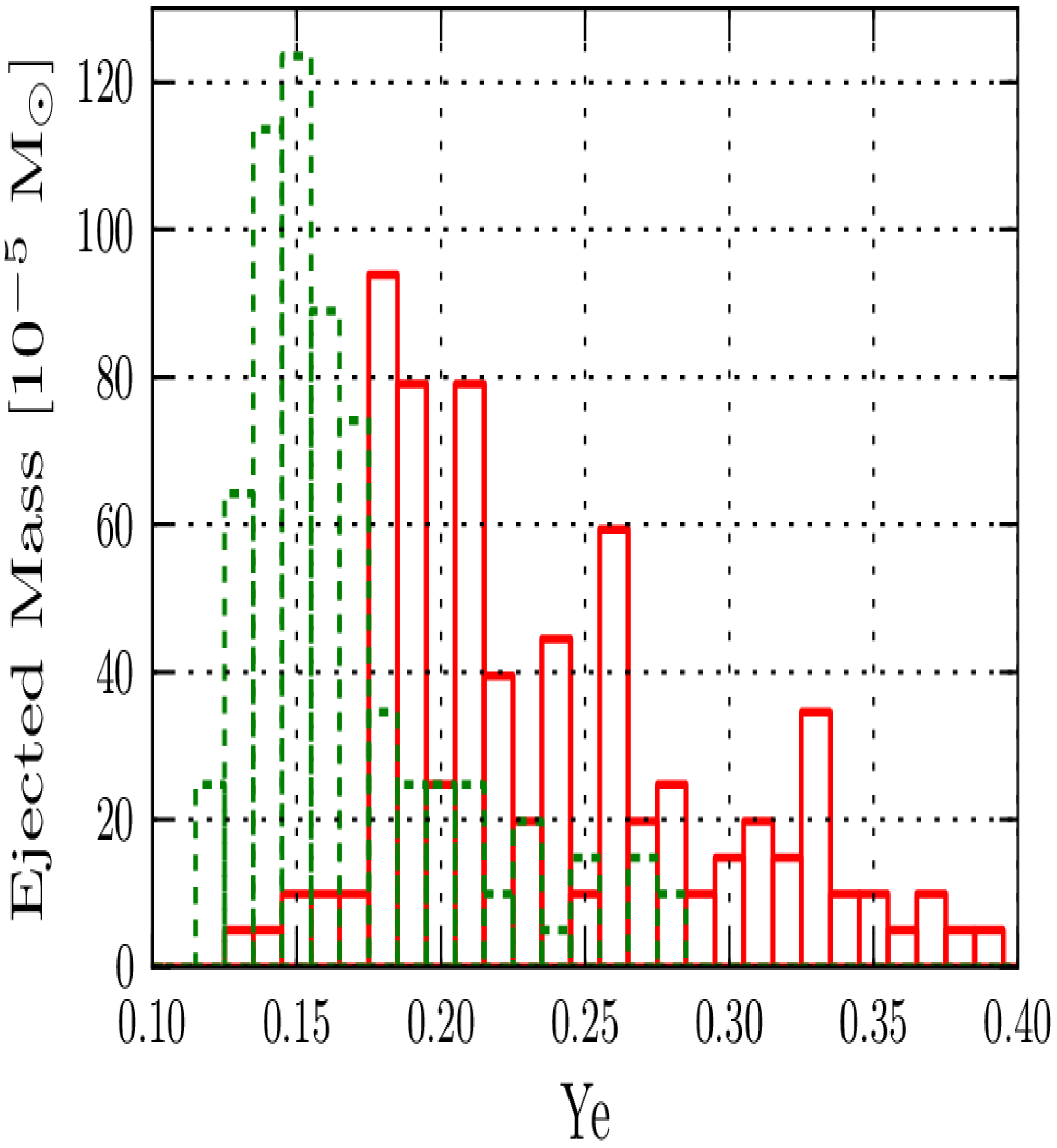
$$\bar{\nu}_e + p \rightarrow Y_e$$

$$\nu_e + n \rightarrow Y_e$$

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

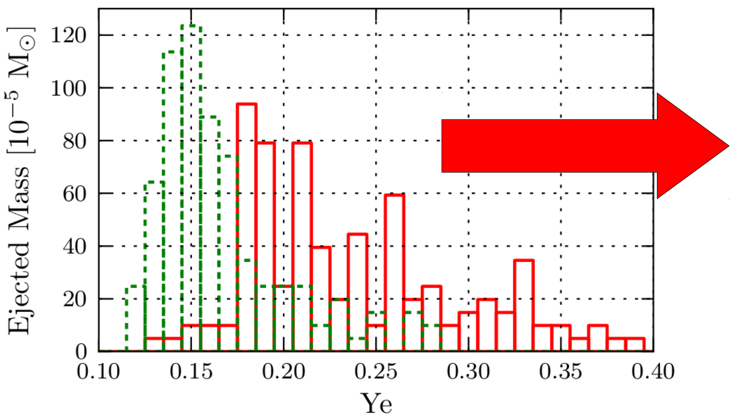
- Distribution shifted to the right
- Broadened towards higher values

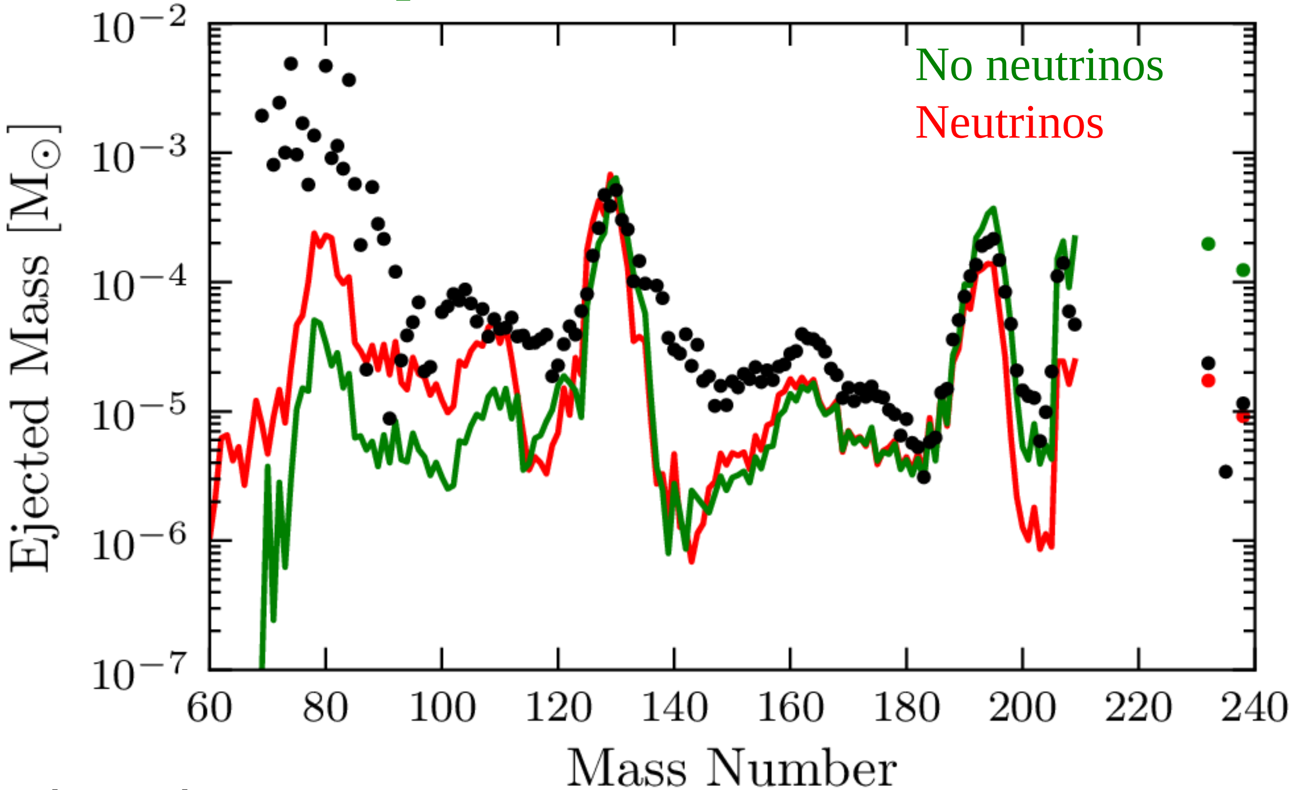
Neutrino reaction wins and moves to more proton-rich conditions. But effect small due to fast expansion/ejection and $1/r^2$ decline



Nucleosynthesis results

neutrino effect small opposite to neutrino wind with slow expansion velocities





- 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):

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

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]

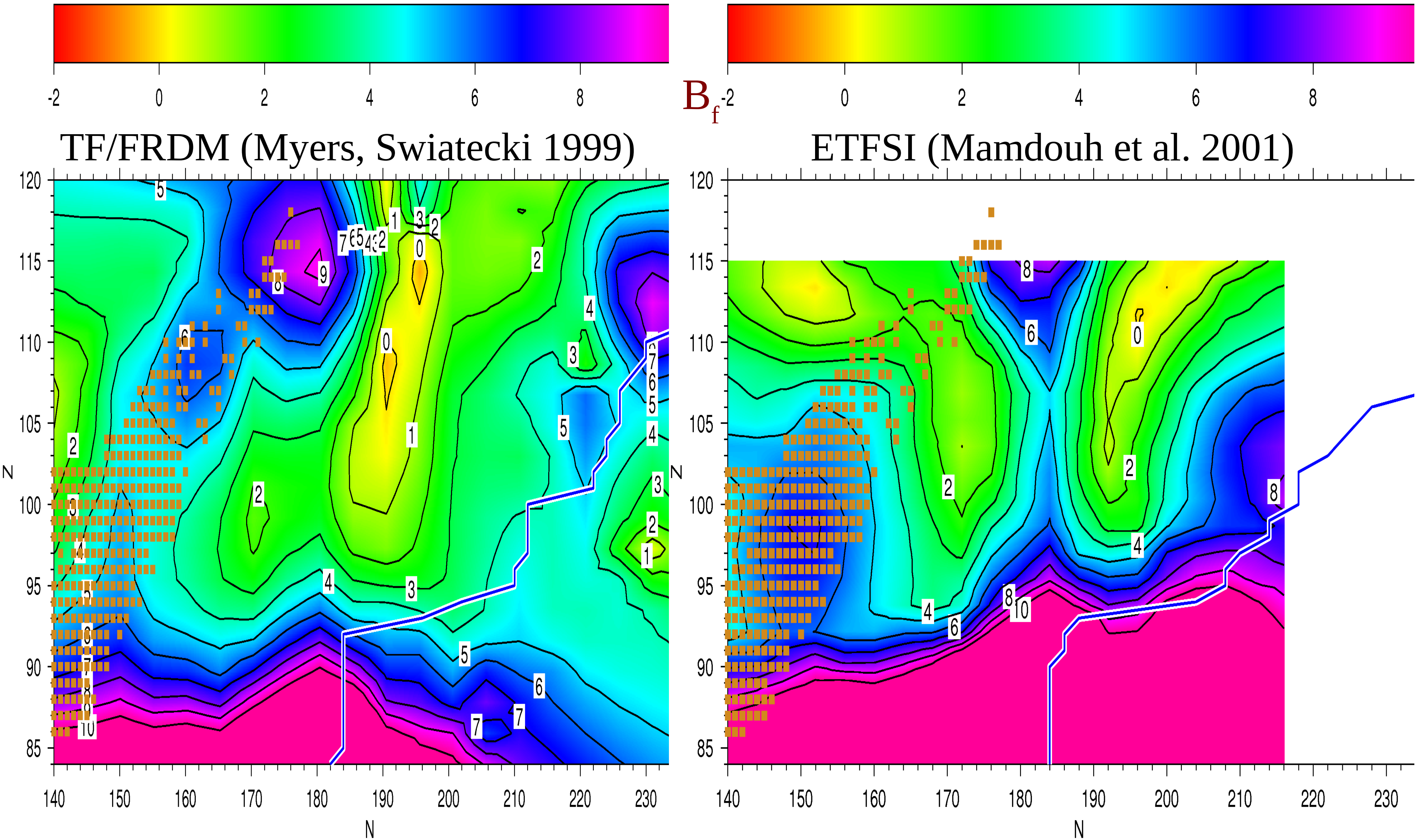
  - *only needed at low [Fe/H], later neutron star mergers could take over*

- progenitor configuration (B, Ω):
  - Not reached in common evolutionary paths (Heger 2005)
  - Possible for small fraction (~1%) of low metallicity models (Woosley&Heger 2006)

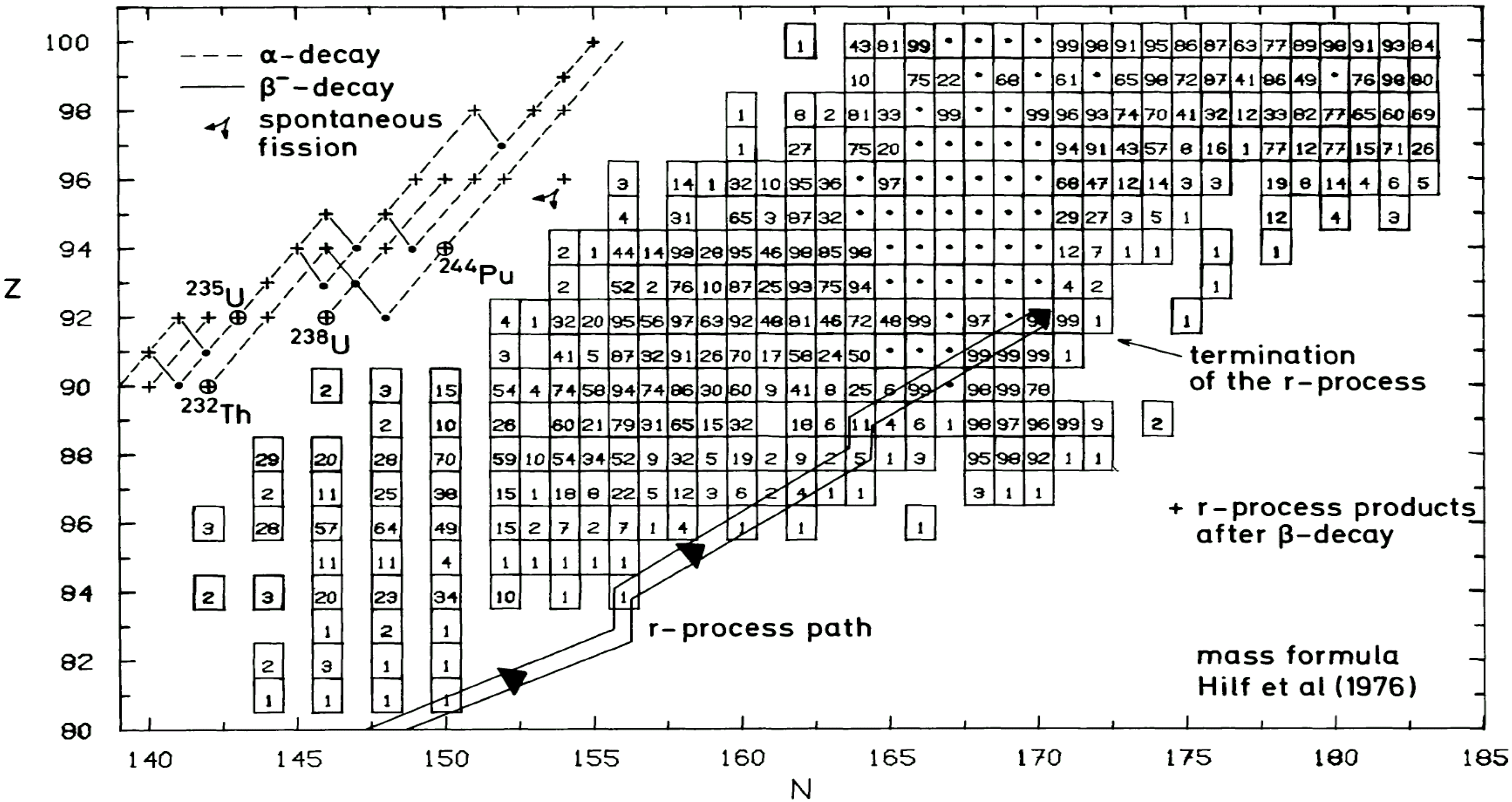
- *present magnetar knowledge permits ~1% of CCSNe resulting in magnetars (Kramer 2009, Koveliotou et al. 1998)*

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)!!



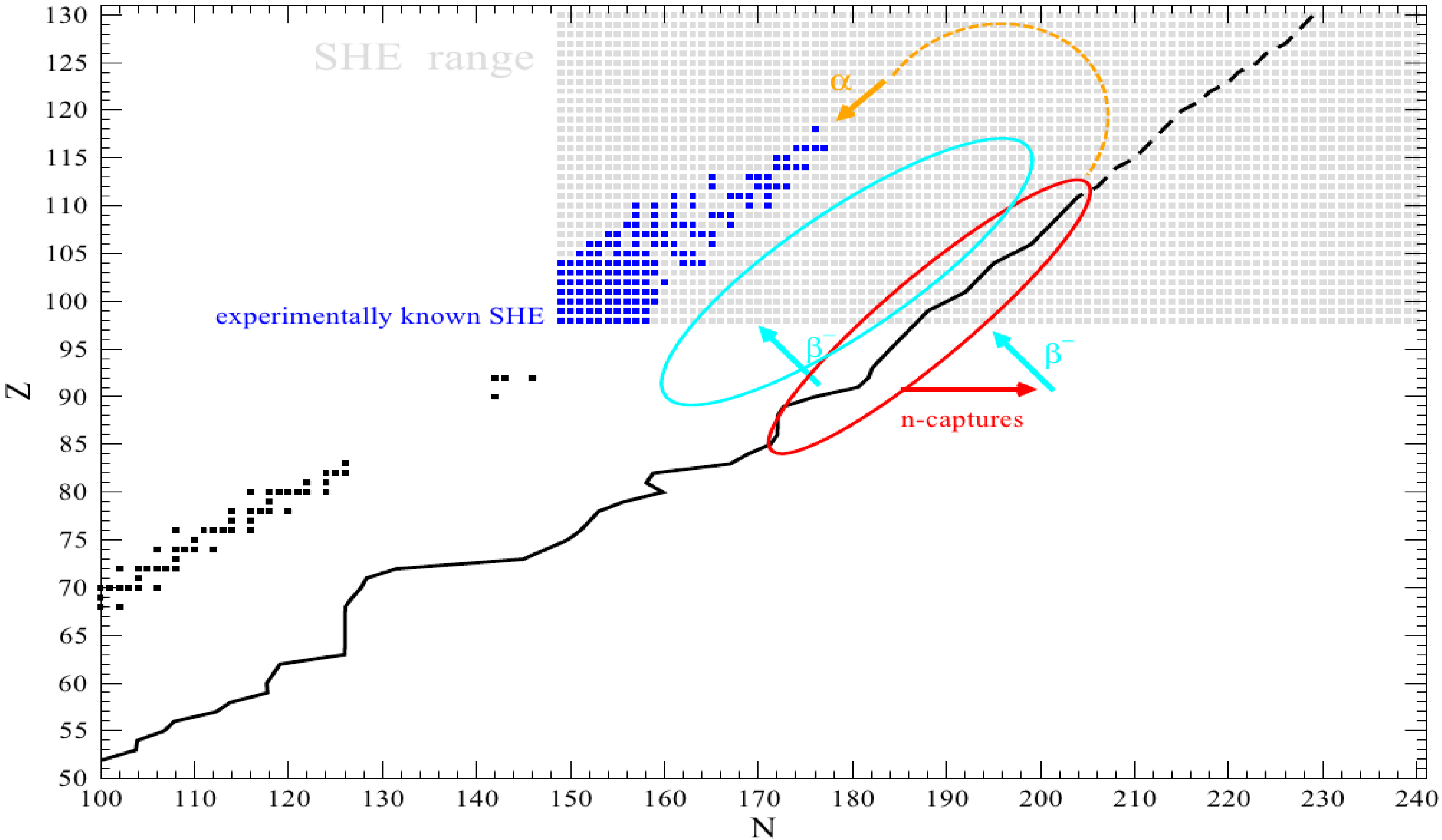
Some History: Thielemann, Metzinger, Klapdor (1983)



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:

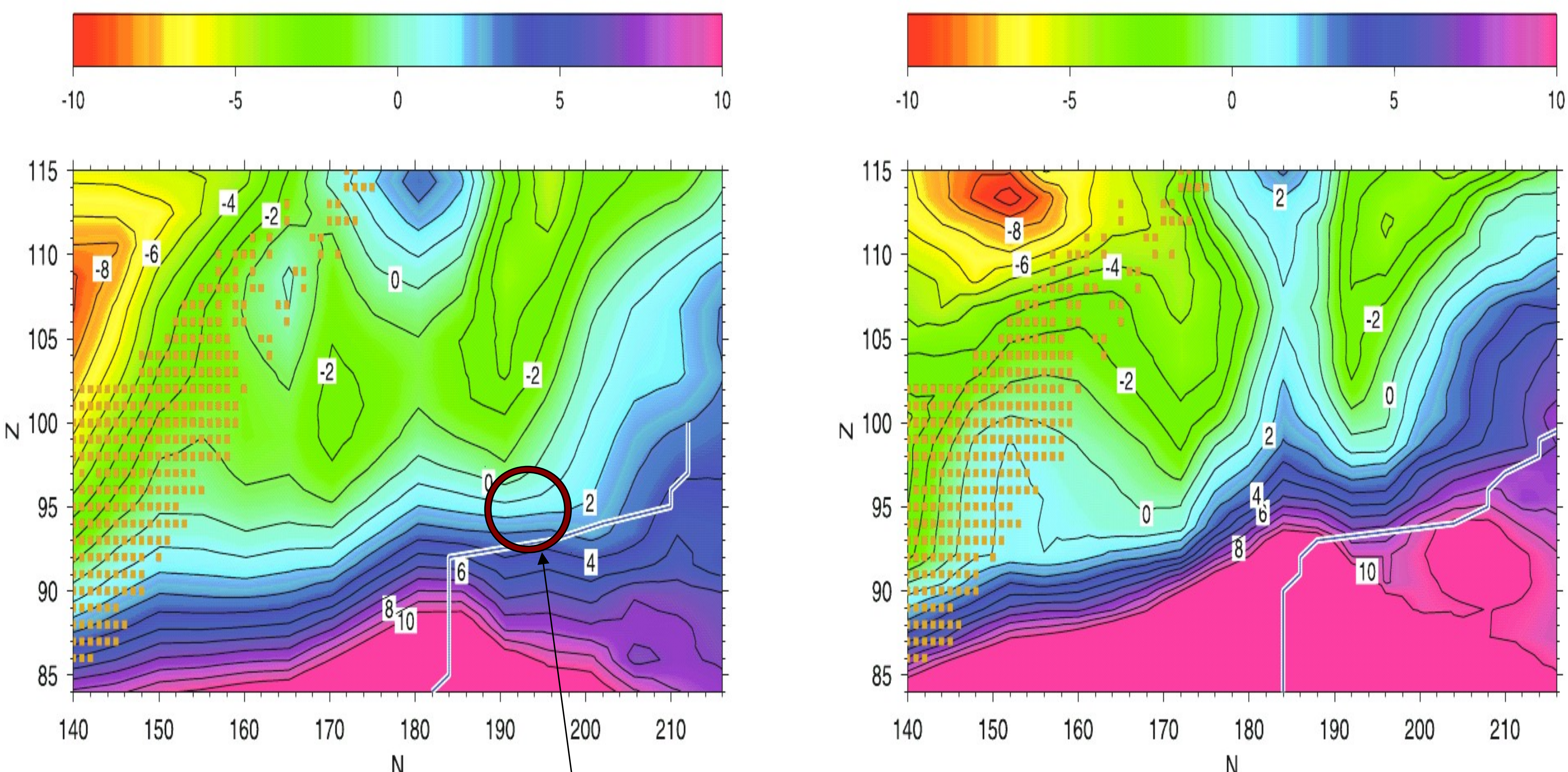
1. the r-process passes through fission-dominated regions and buildup stops
2. the r-process produces superheavies far from stability but fission is encounered during beta-decay back to stability
3. fission region(s) are circumvented and beta/alpha-decay leads to superheavy island



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

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

(if negative => neutron-induced fission)

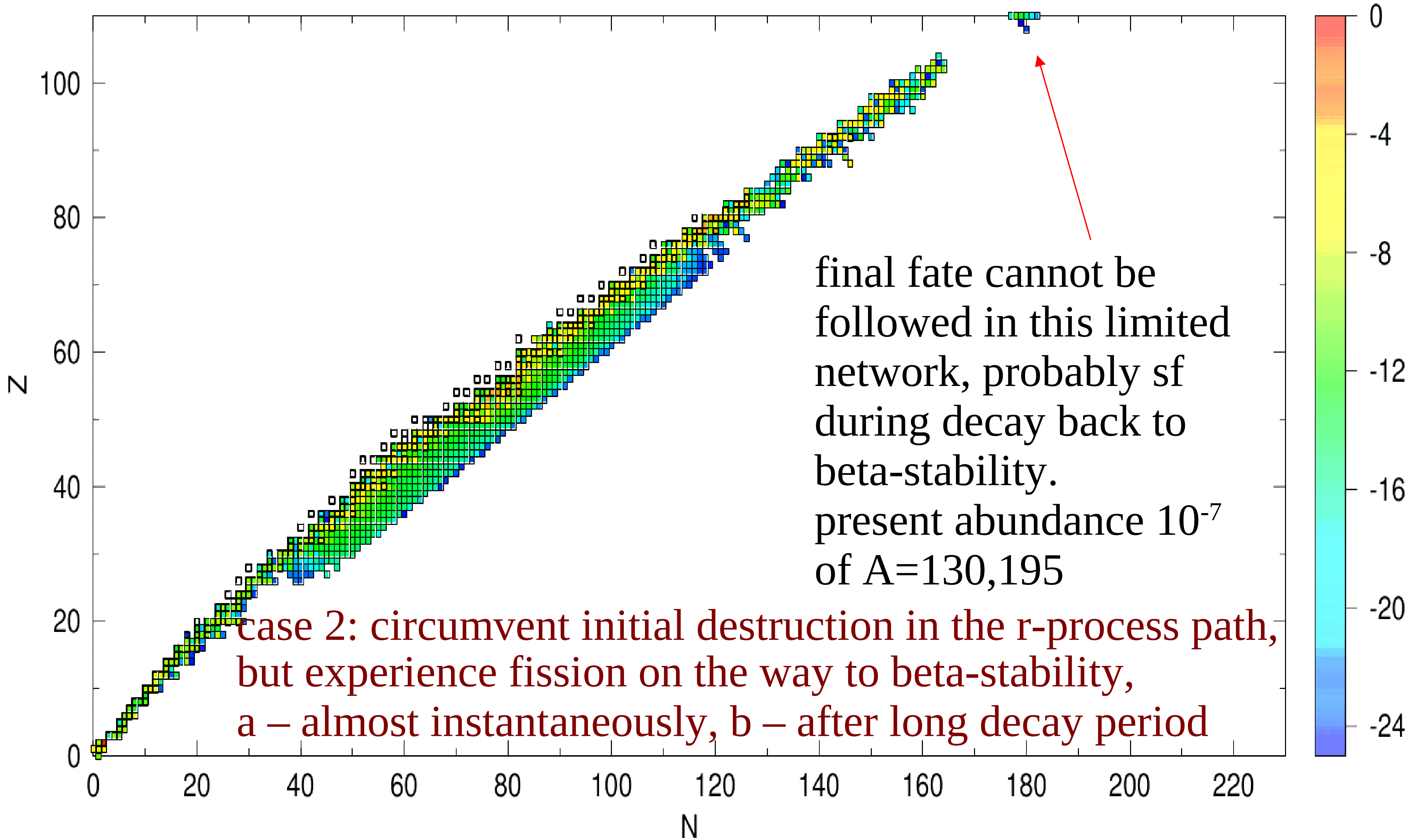


Myers & Swiatecki barriers (TF/FRDM)

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