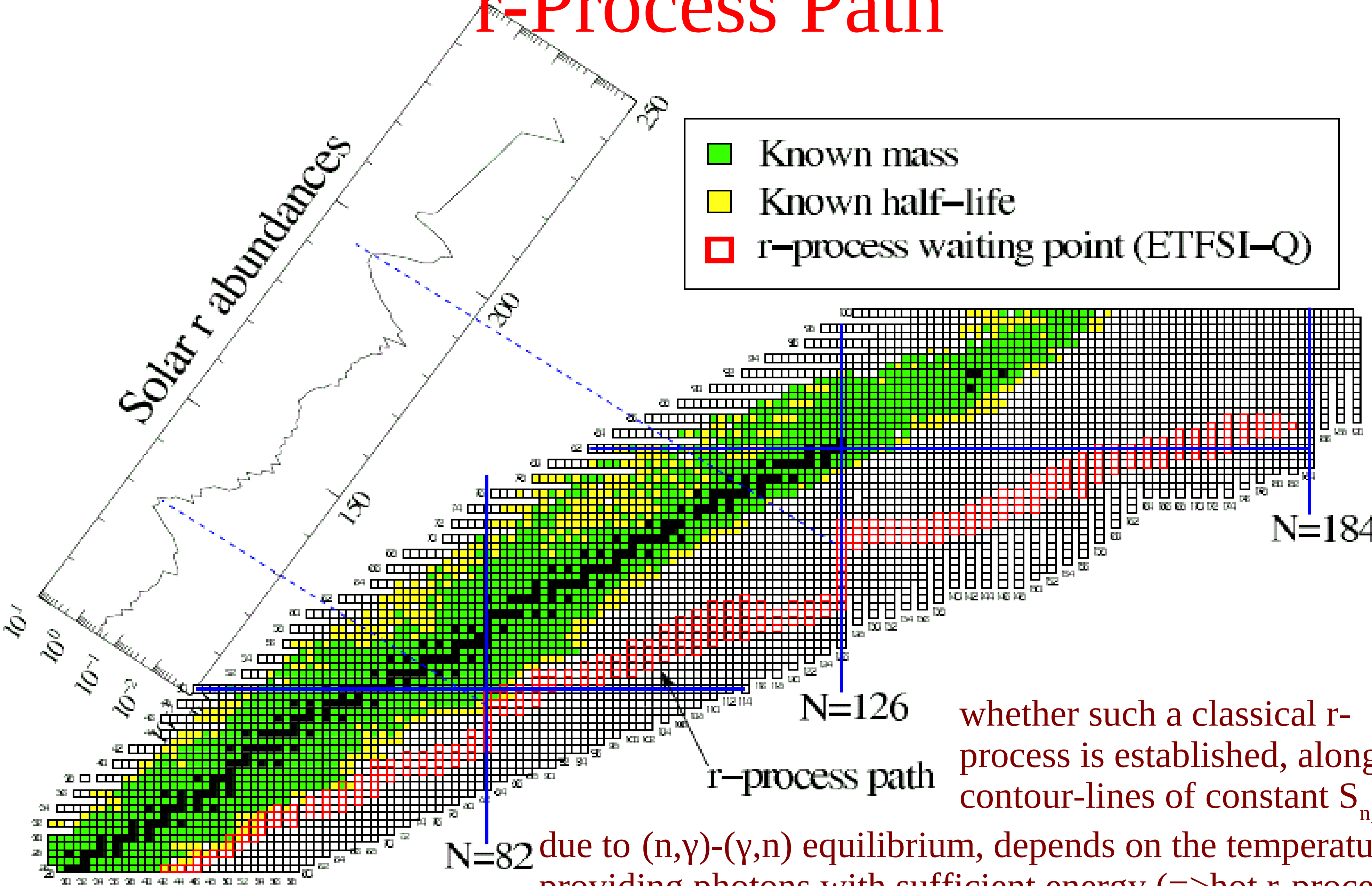
What are the sites responsible for producing the r-process abundance pattern(s)

Friedrich-K. Thielemann
Dept. of Physics
University of Basel

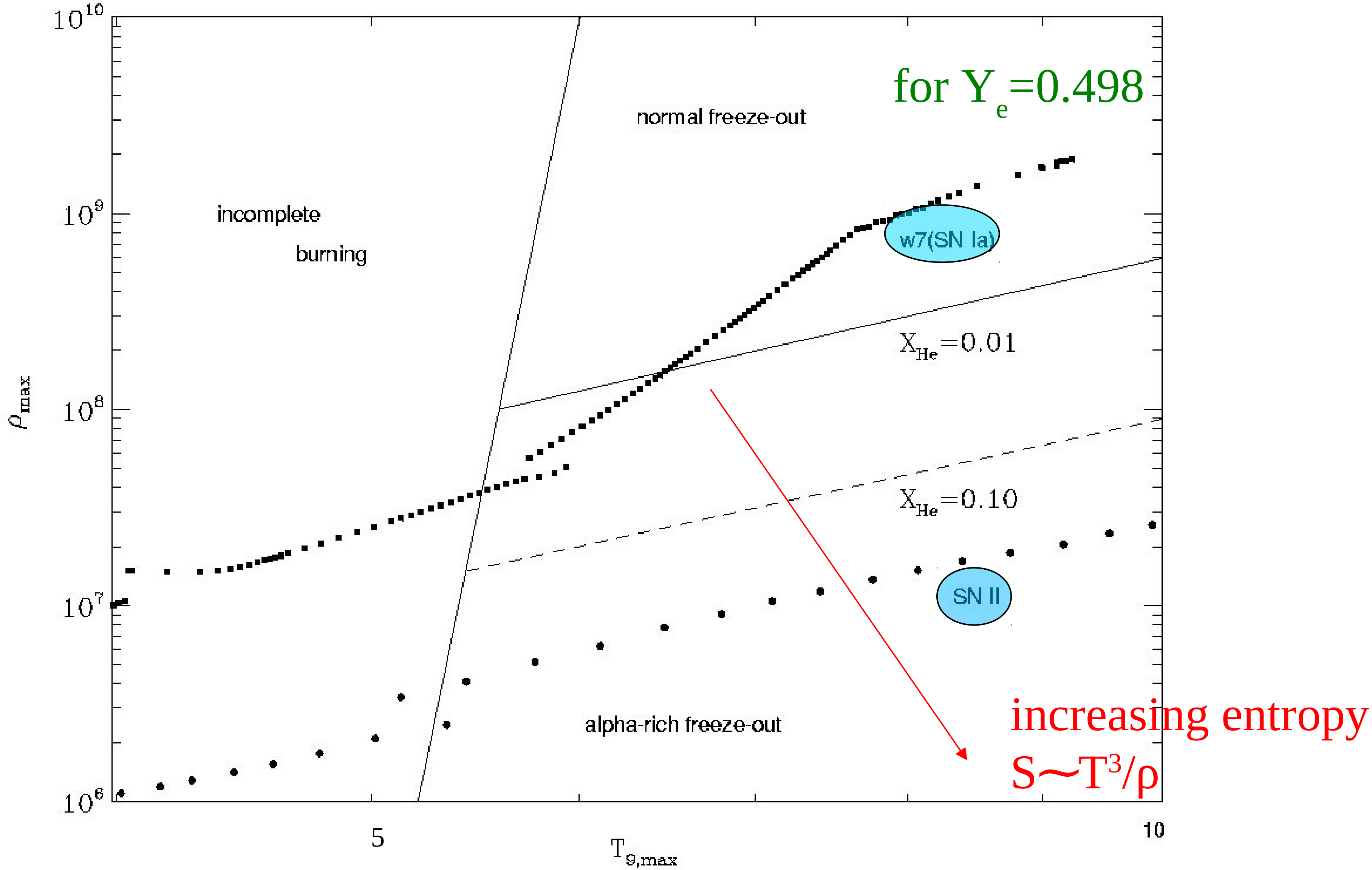
r-Process Path



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

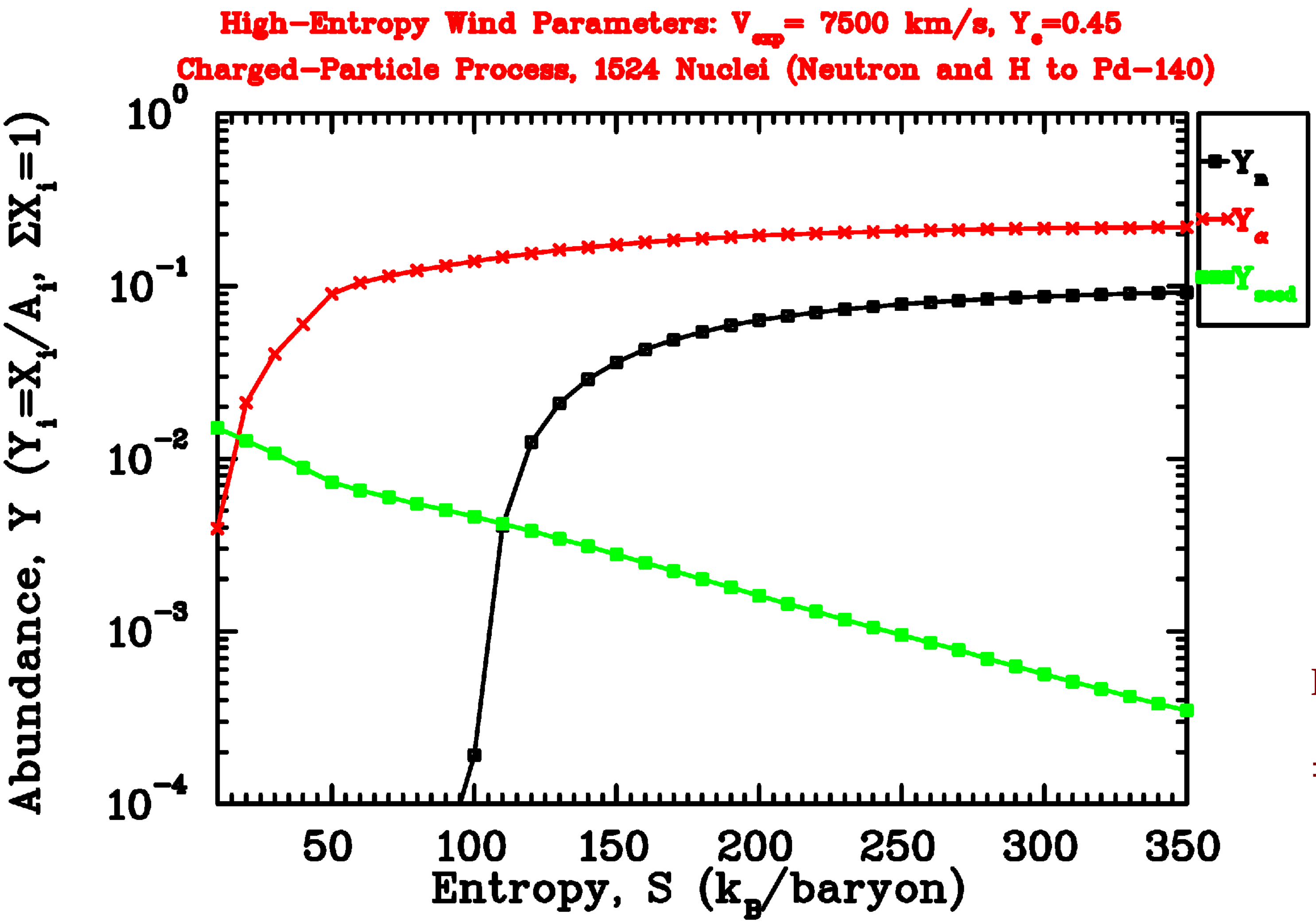
Explosive Si-Burning



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)

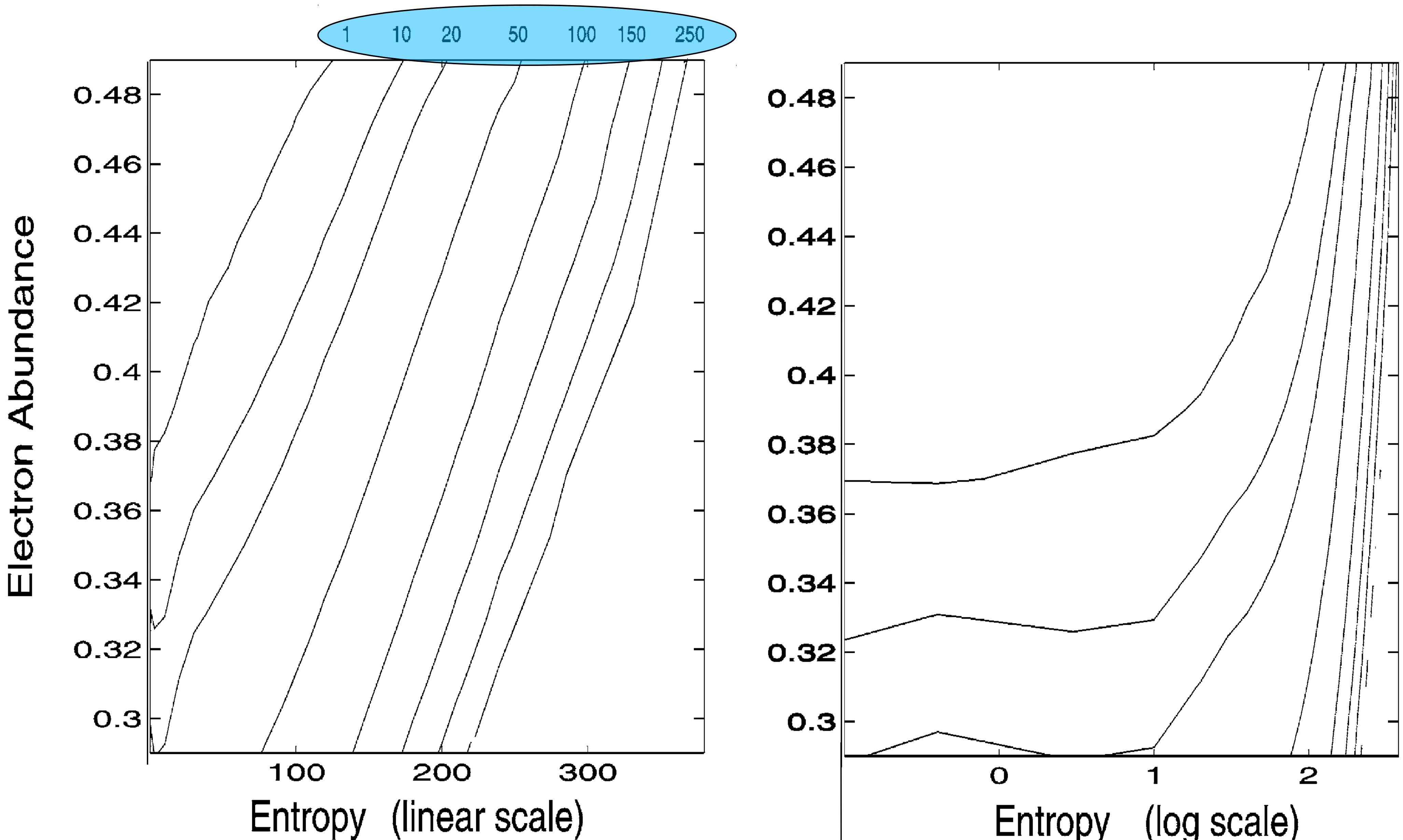


n/seed

$=Y_n/Y_{seed}$

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



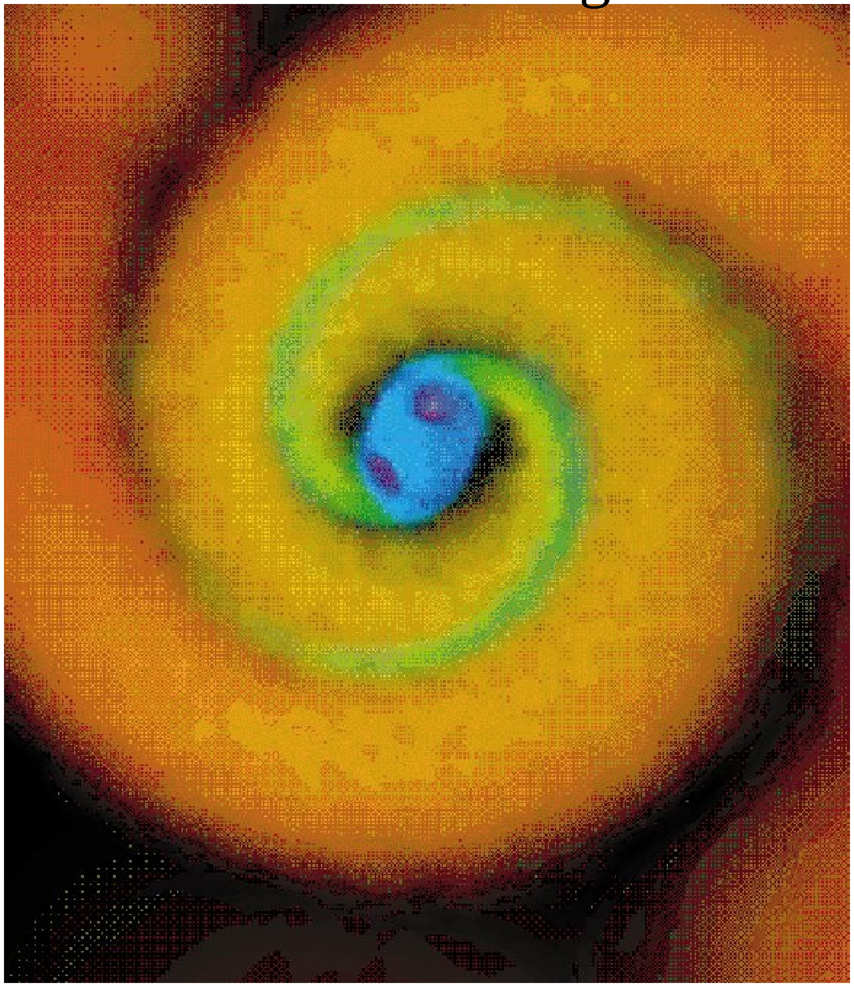
neutrino wind?

Freiburghaus et al. (1999)

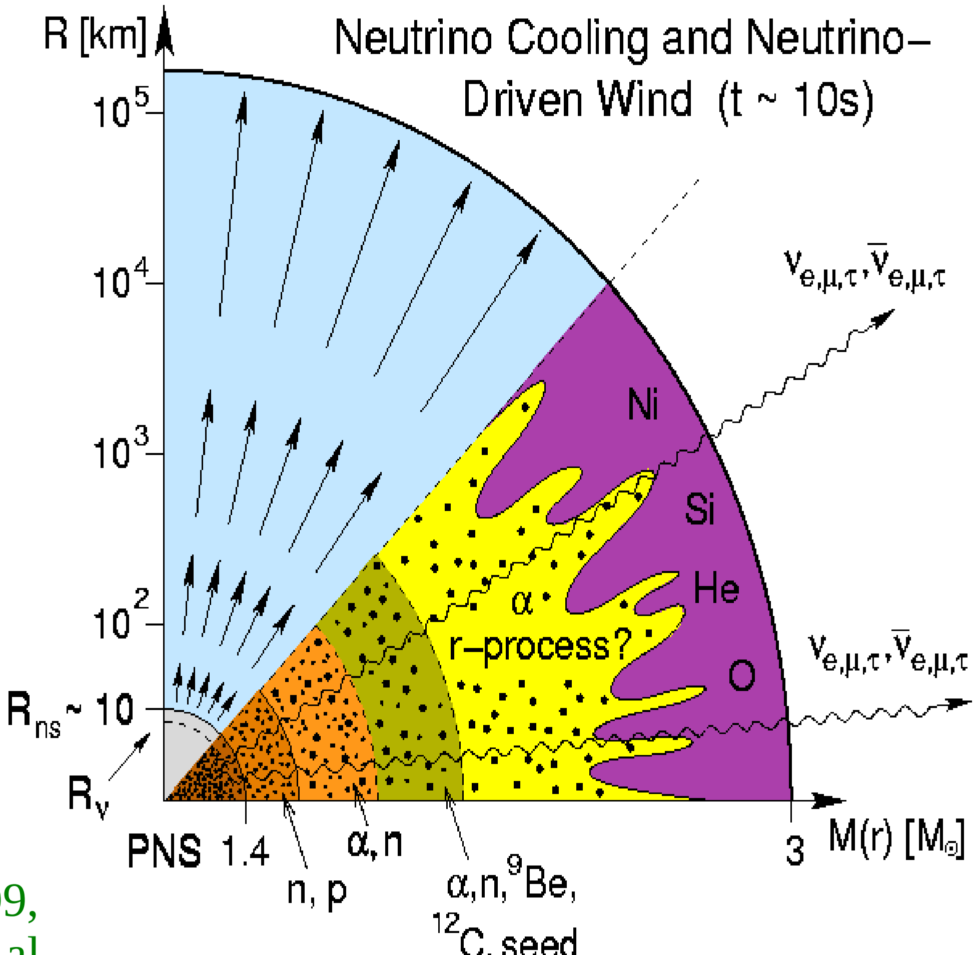
Neutron star mergers and polar jets?

What is the site of the r-process?

from S. Rosswog



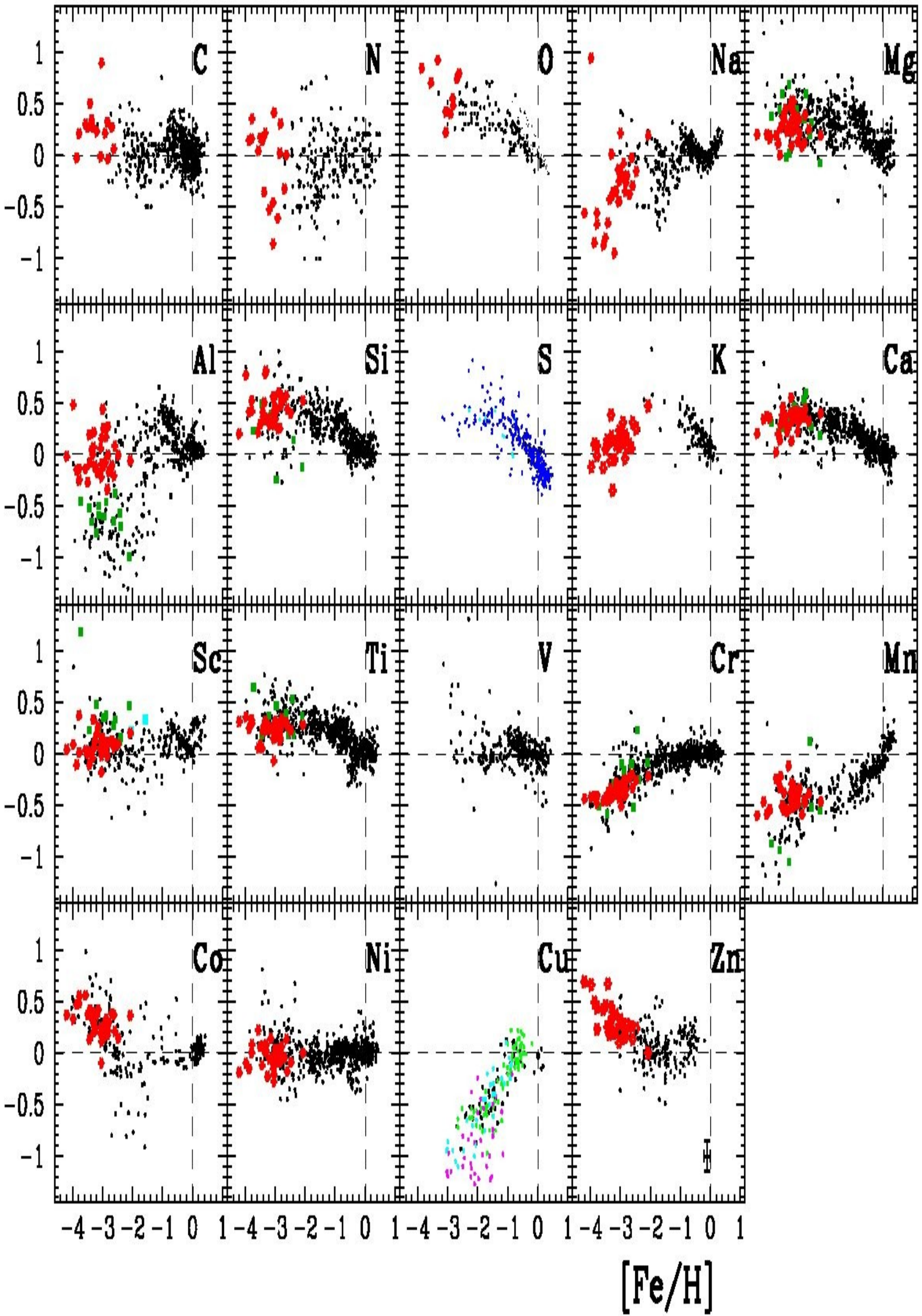
from H.-T. Janka

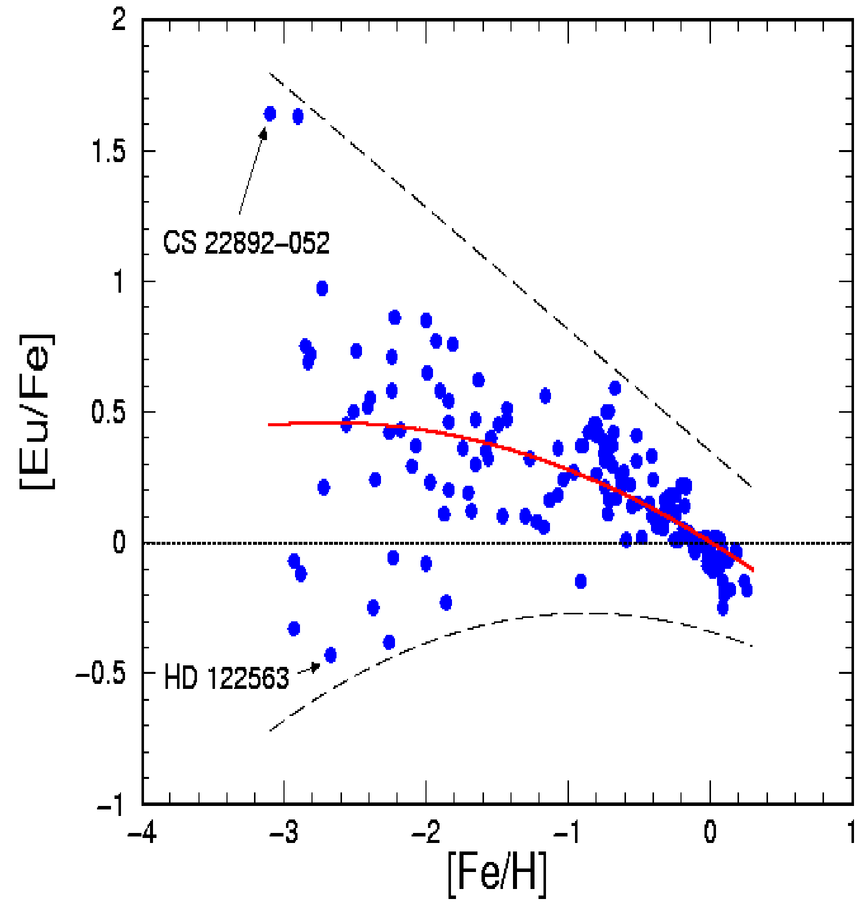


NS mergers, BH-NS mergers (Freiburghaus et al. 1999, Rosswog.., Panov et al., Bauswein et al., Korobkin et al. 2012.)
or alternatively polar jets from supernovae (Cameron 2003, Fujimoto et al. 2008, Winteler et al. 2012)

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

How do we understand: low metallicity stars ... galactic evolution?





Average r-process (Eu) behavior resembles CCSN contribution, but large scatter at low metallicities!!

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 (massive stars as well as neutron star mergers, neutrino properties) ***MacLaughlin, Surman, Wanajo, Janka, Ruffert***

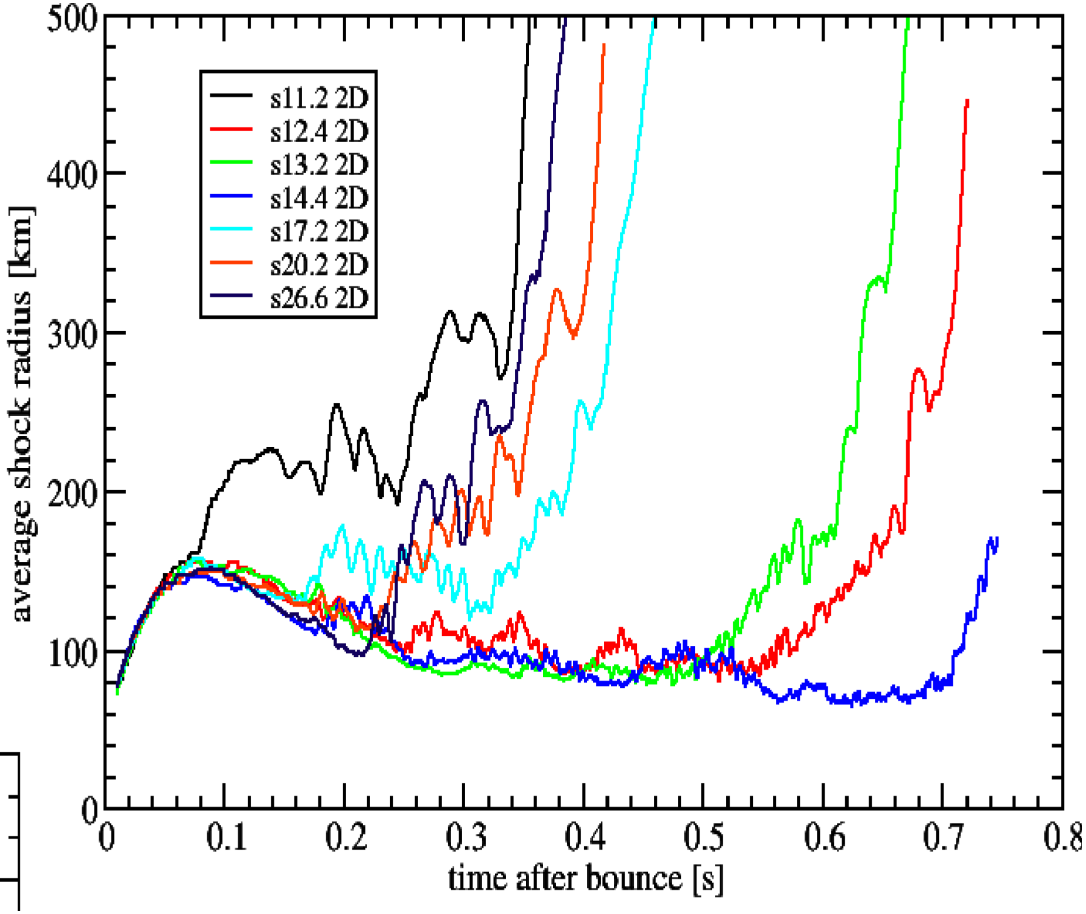
- Explosive He-burning in outer shells (???) ***Cameron, Cowan, Truran, Hillebrandt, FKT, Wheeler, Nadyozhin, Panov***

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

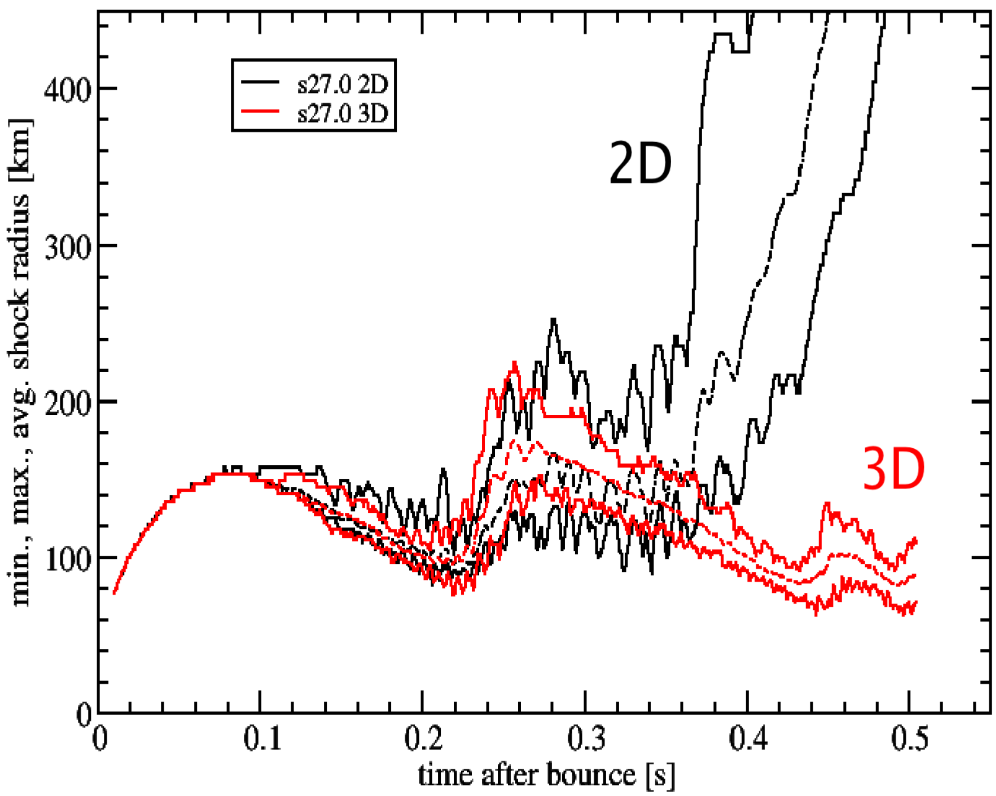
- **Polar Jets from Rotating Core Collapse?** ***Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura, Nishimura, Takiwaki, FKT, Winteler***

Growing set of 2D CCSN Explosions

(i.e., core collapse supernovae are finally also exploding in computations, here Hanke & Janka 2013 – MPA Garching)



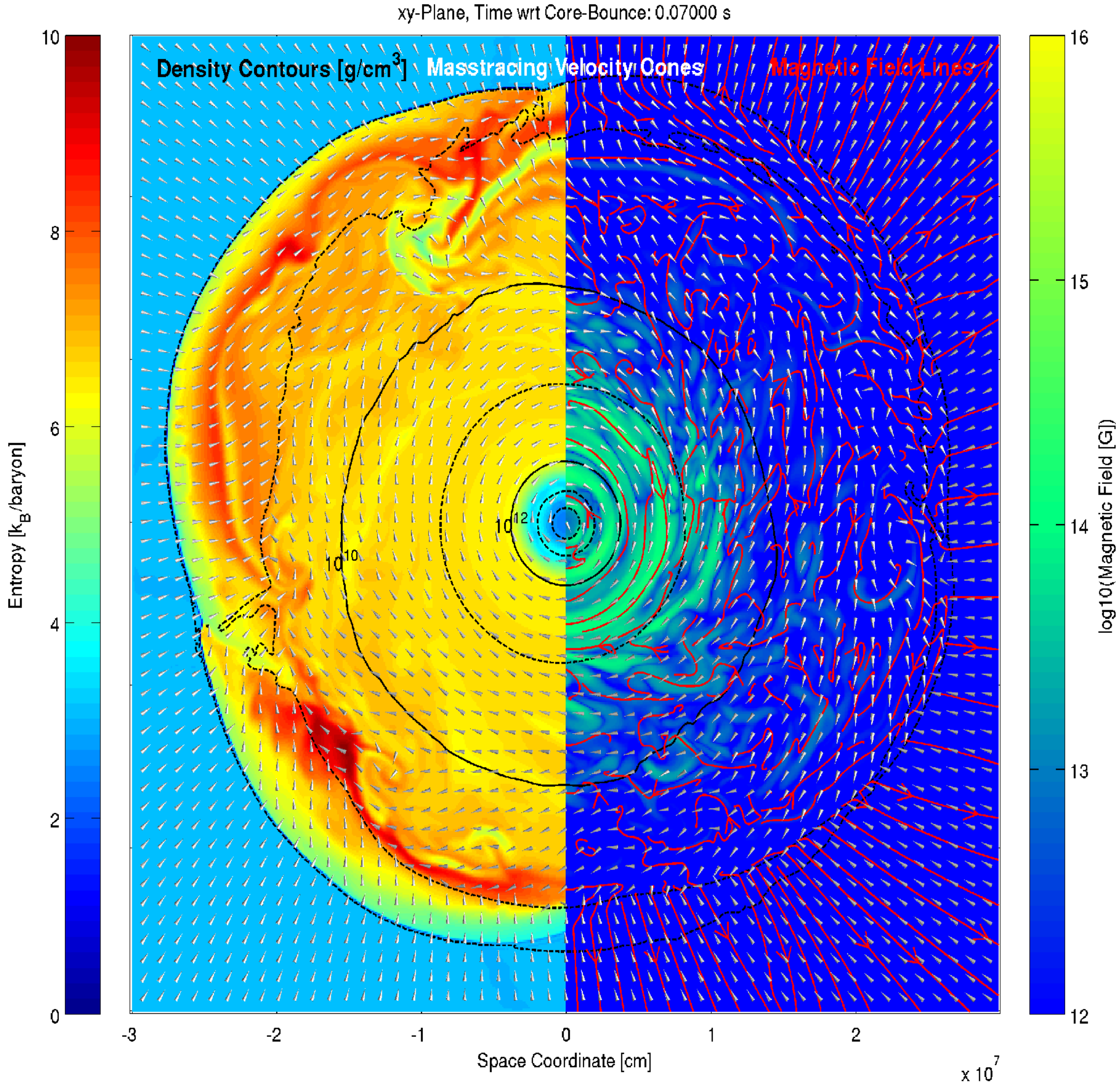
But 3D still somewhat open!

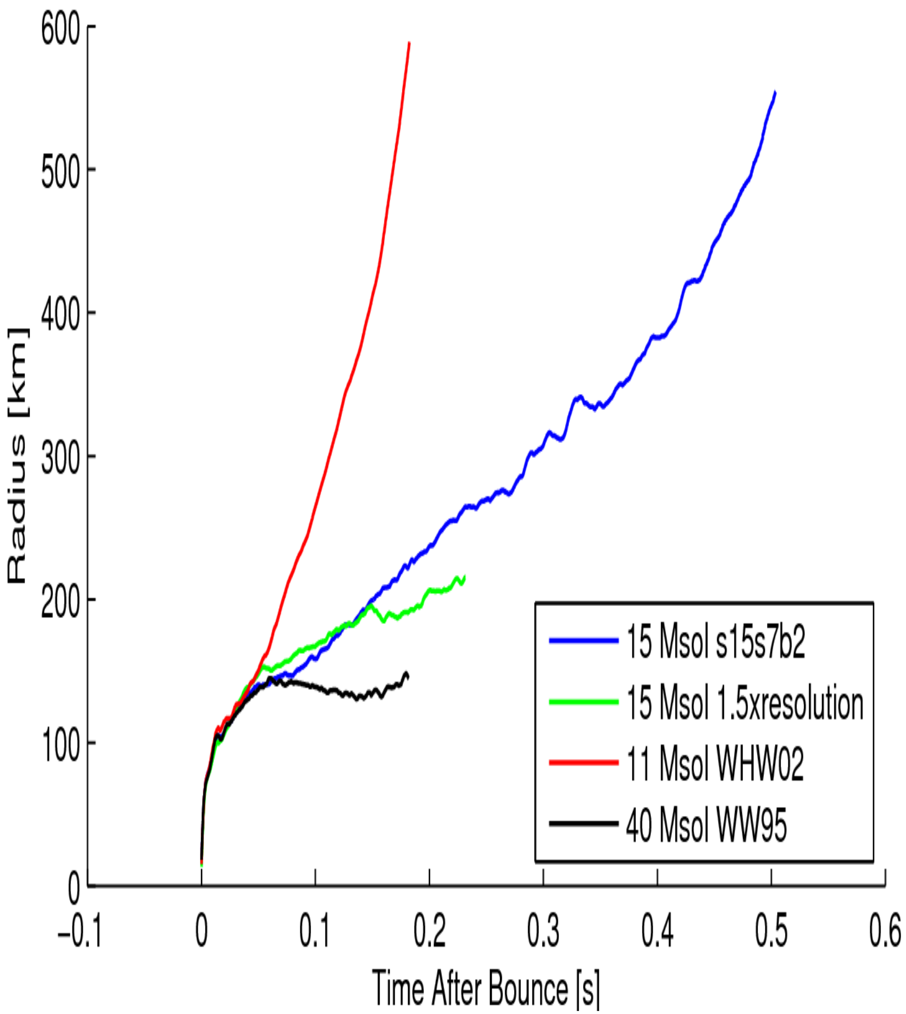


Positions of shock radii

Simulations in 3D

Liebendörfer et al. (Basel)





*Finally multi-D core collapse supernovae calculations lead to explosions! (see T. Janka, A. Mezzacappa, C. Ott, etc.; **here the Basel version**).*

There are two transitions: (i) 8-10M_{sol} progenitors even explode in spherical symmetry, (ii) from regular core collapse SNe with neutron star formation - to faint SNe with fall back and BH formation - BH formation and hypernovae???

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

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

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

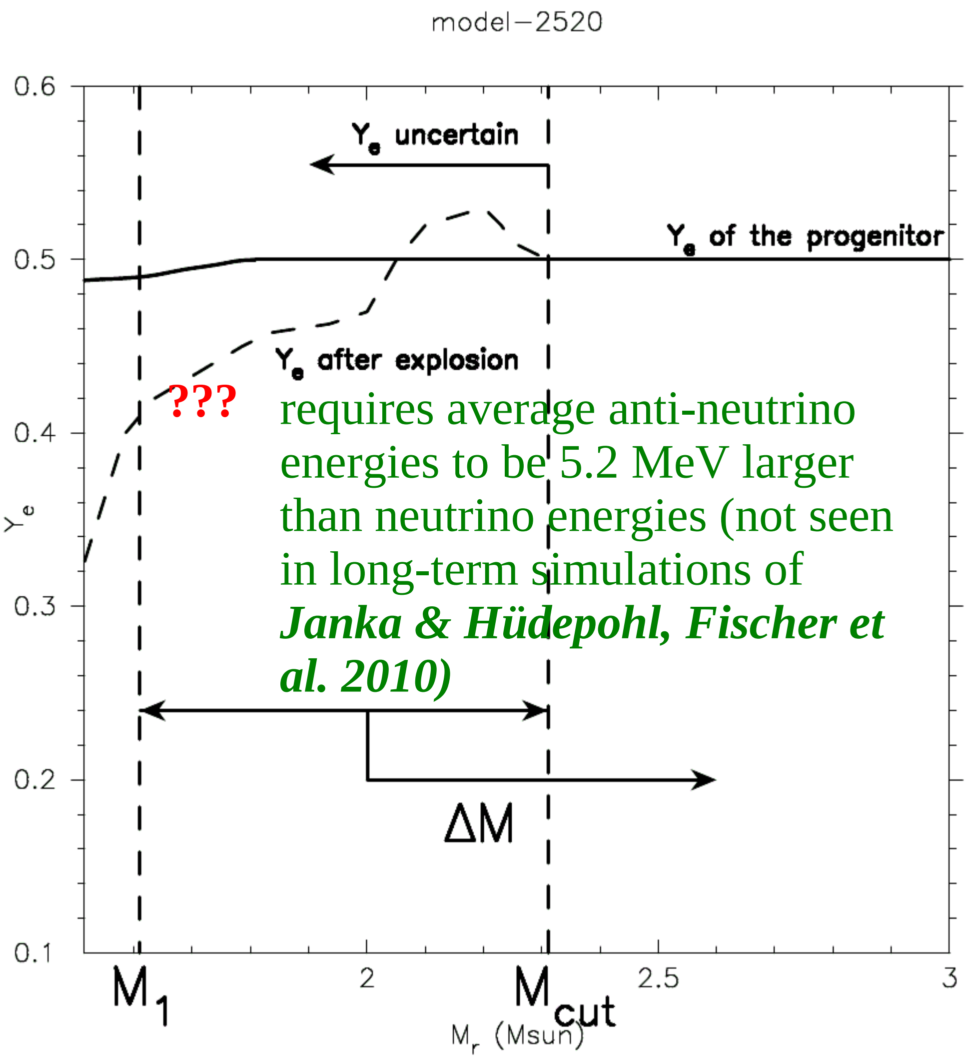
- high density / low temperature $\rightarrow$ high E_F for electrons $\rightarrow$ e-captures dominate $\rightarrow$ n-rich composition
- if el.-degeneracy lifted for high T $\rightarrow$ ν_e-capture dominates $\rightarrow$ due to n-p mass difference, p-rich composition ?

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

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)

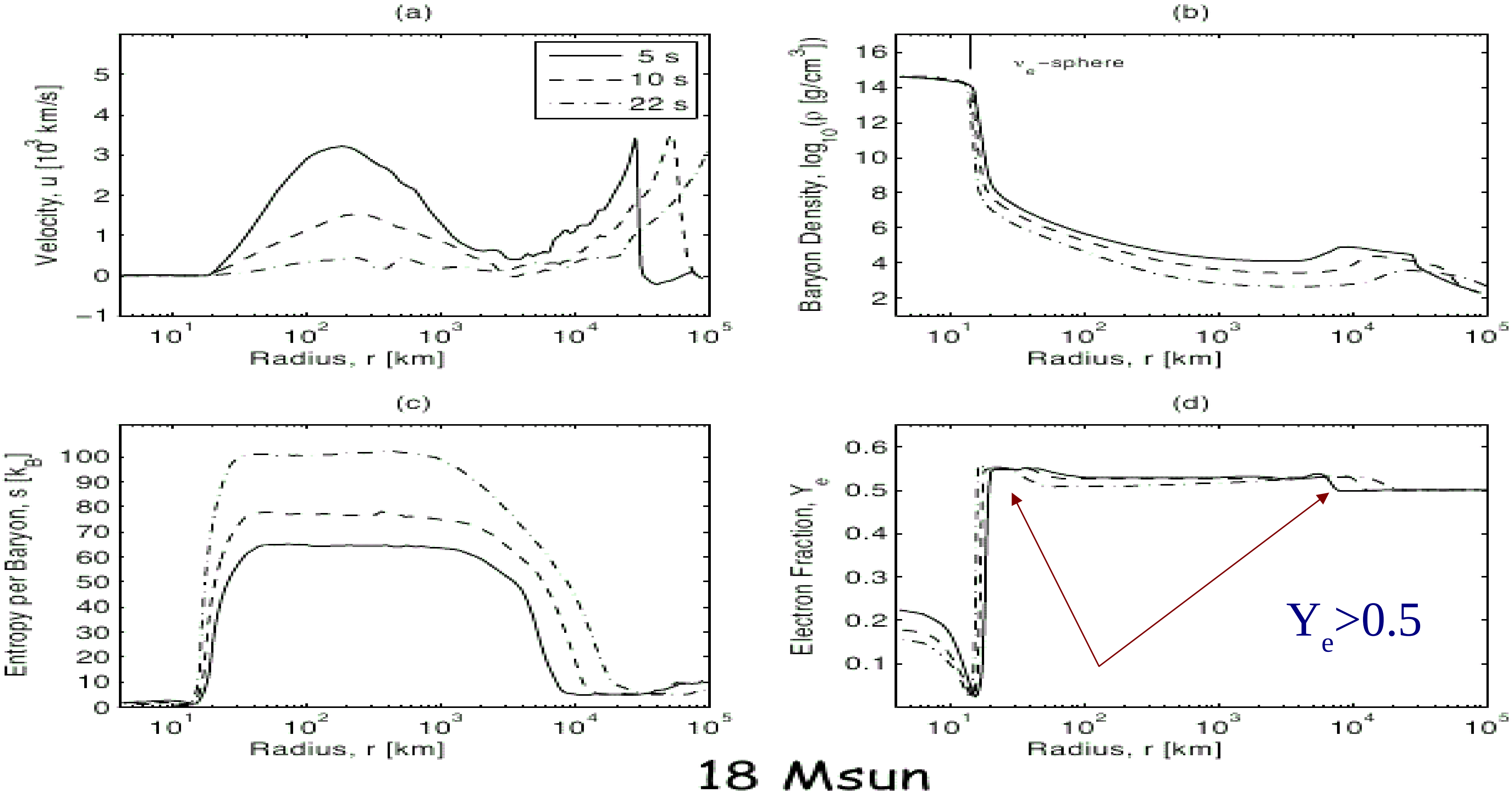
- *regular explosions with neutron star formation, neutrino exposure, νp-process.*
- *How to obtain moderately neutron-rich neutrino wind and weak r-process or more* **??** *(see e.g.* ***Arcones & Montes 2011****, Roberts et al. 2010,* ***Arcones & Thielemann 2013****)*
- *under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?*

Innermost ejecta as a function of initial radial mass and also time of ejection, innermost zones ejected latest in the wind!

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?



Inclusion of medium Effects, potential U in dense medium

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

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

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

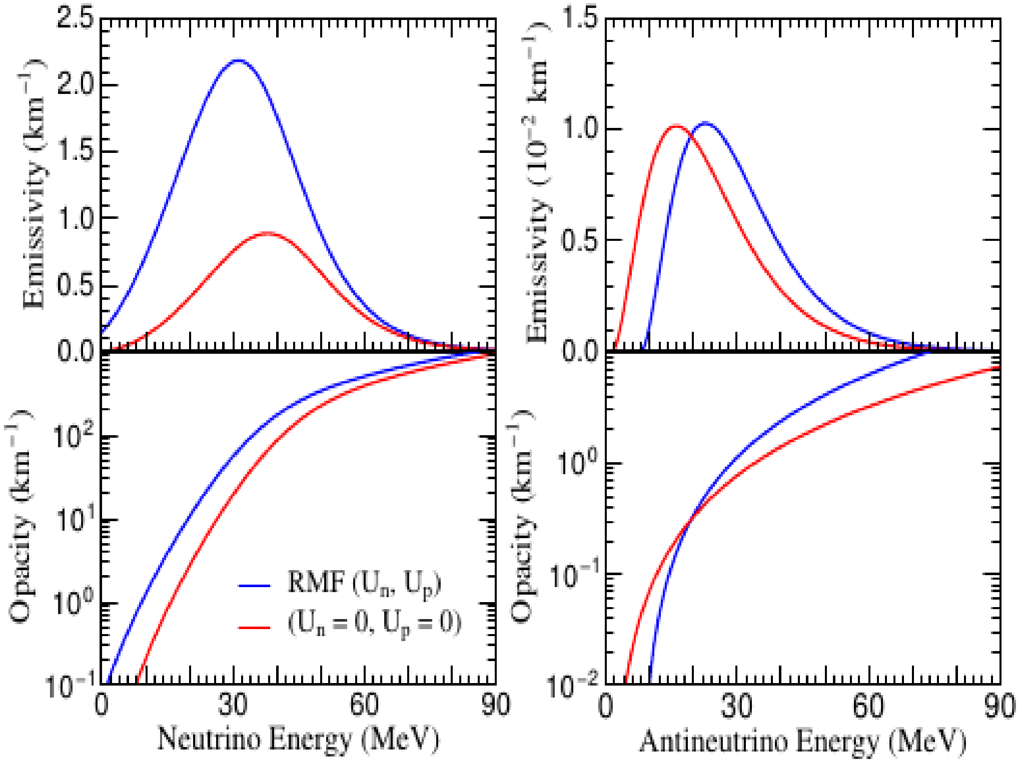


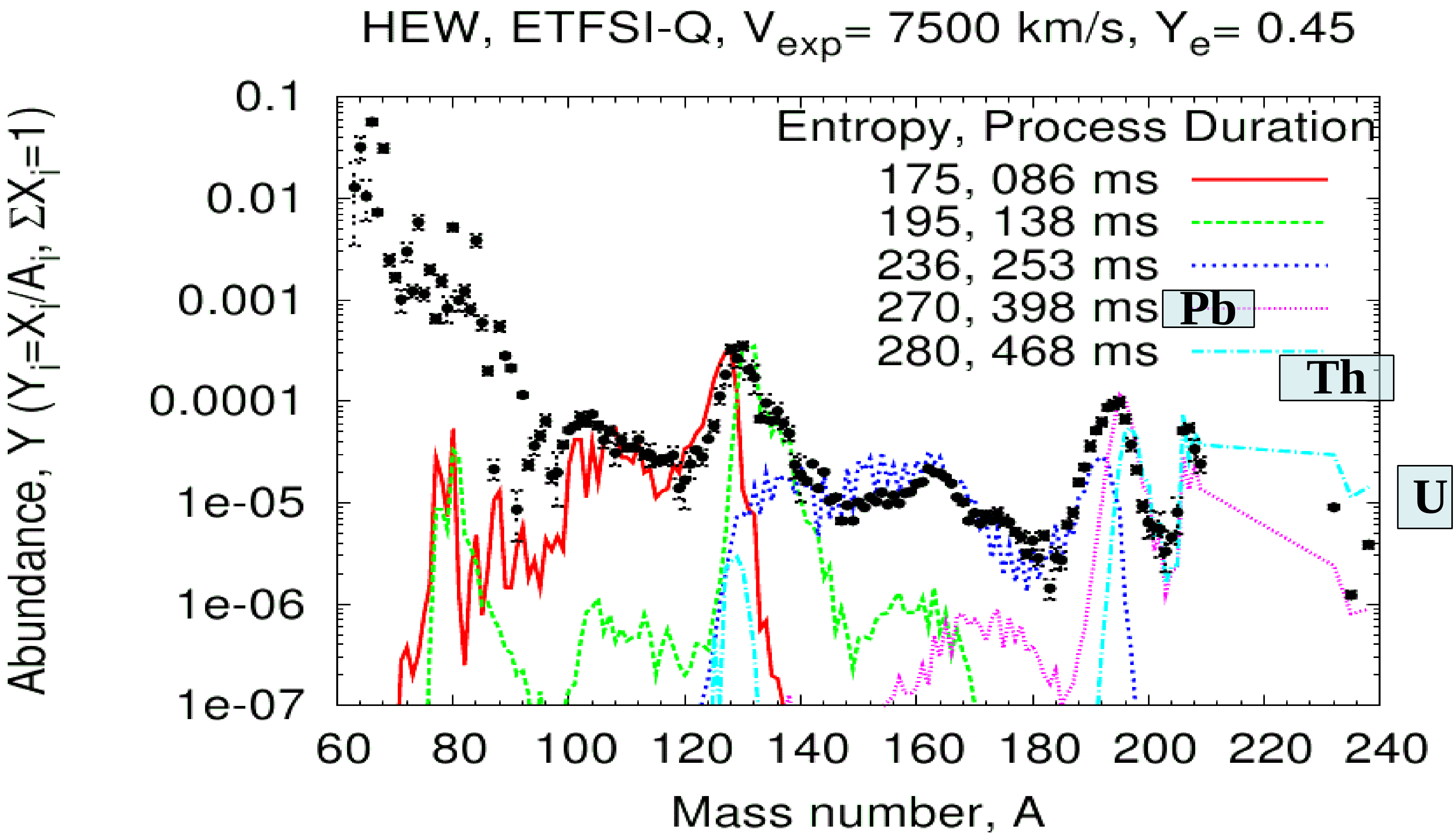
FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4!

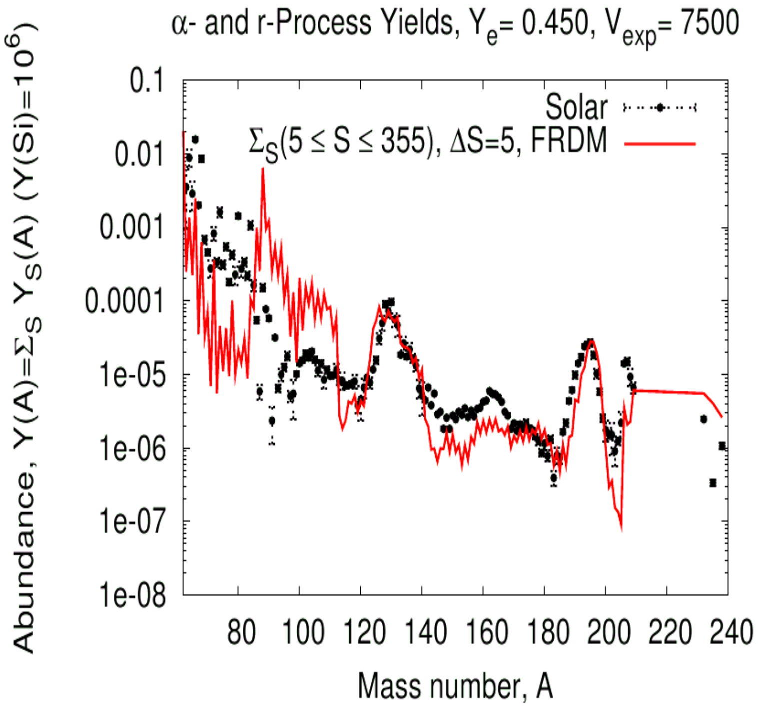
Individual components for high entropies, if such entropies are attained in SNe

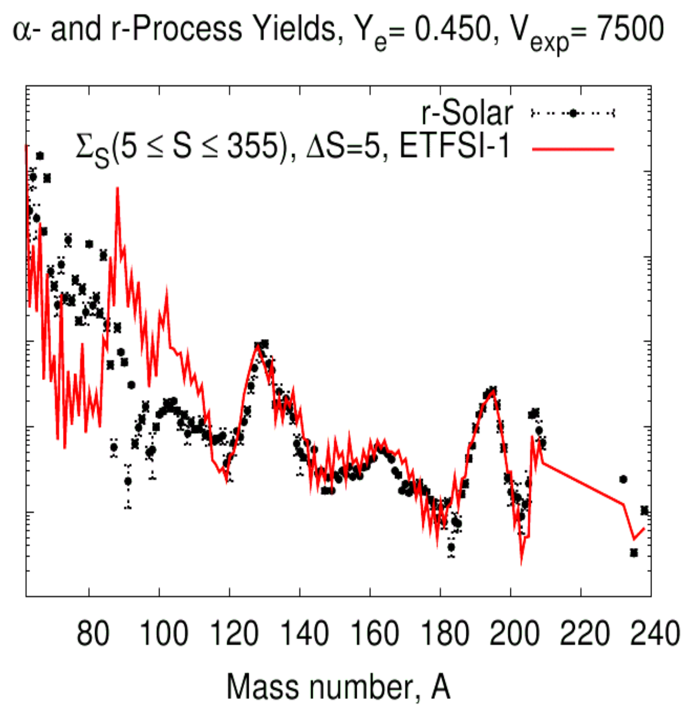
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in

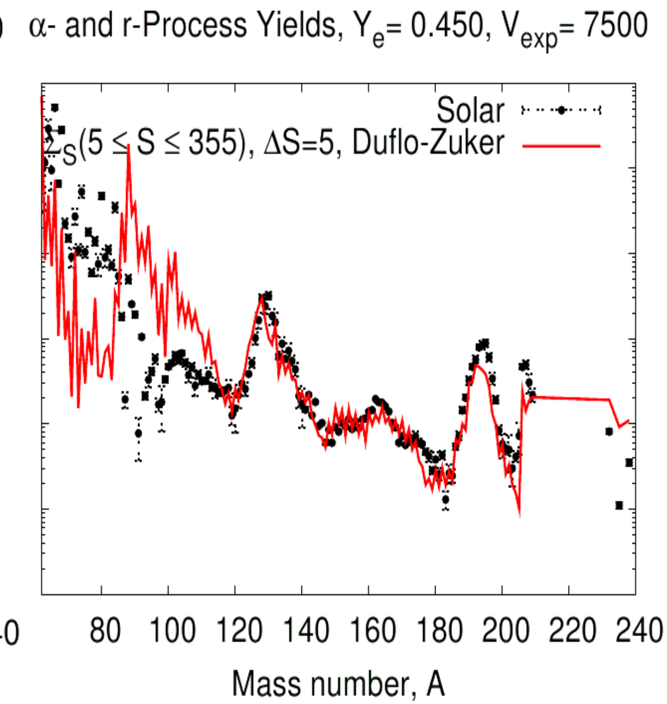
such high entropies are apparently not obtained in present models!!!

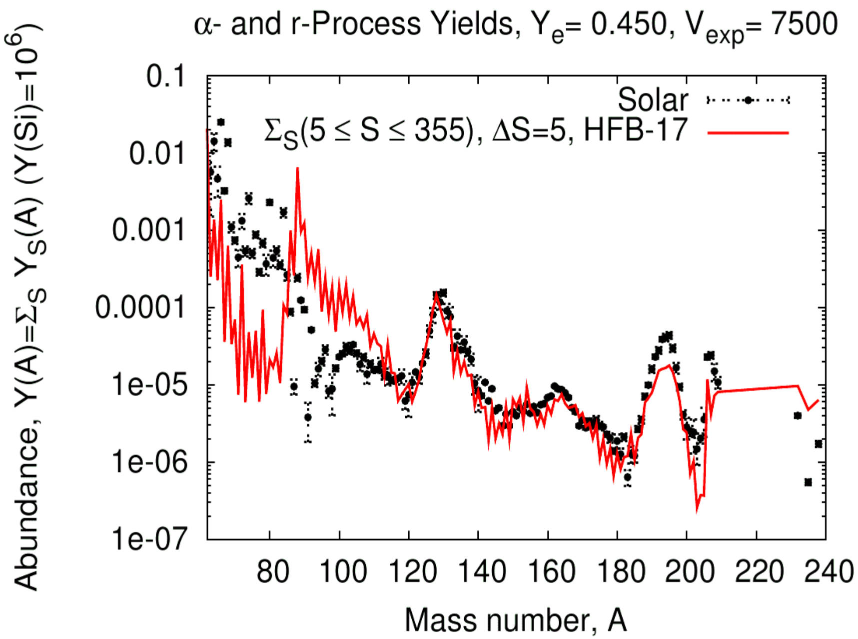


Superposition of entropies for different mass models









Farouqi et al. (2010)

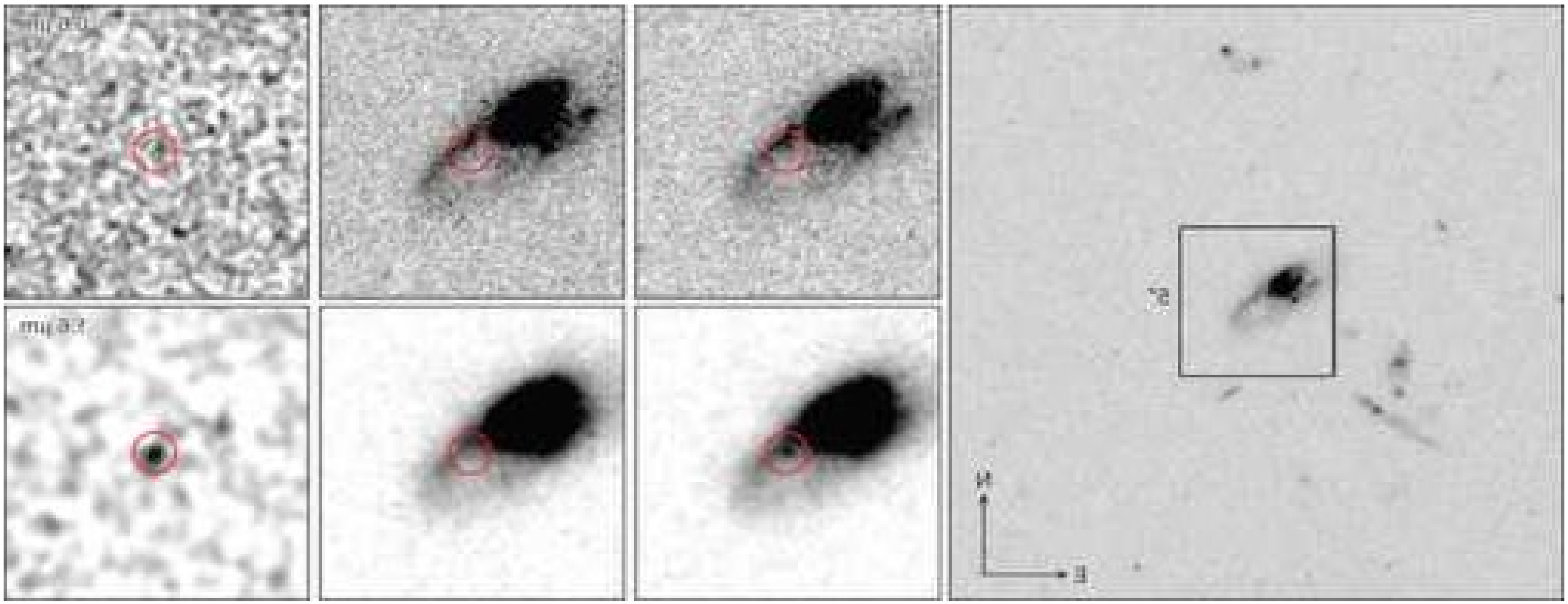
This is a set of superpositions of entropies with a given expansion speed (or timescale) and Y_e.

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.

Neutron Star Mergers are observed

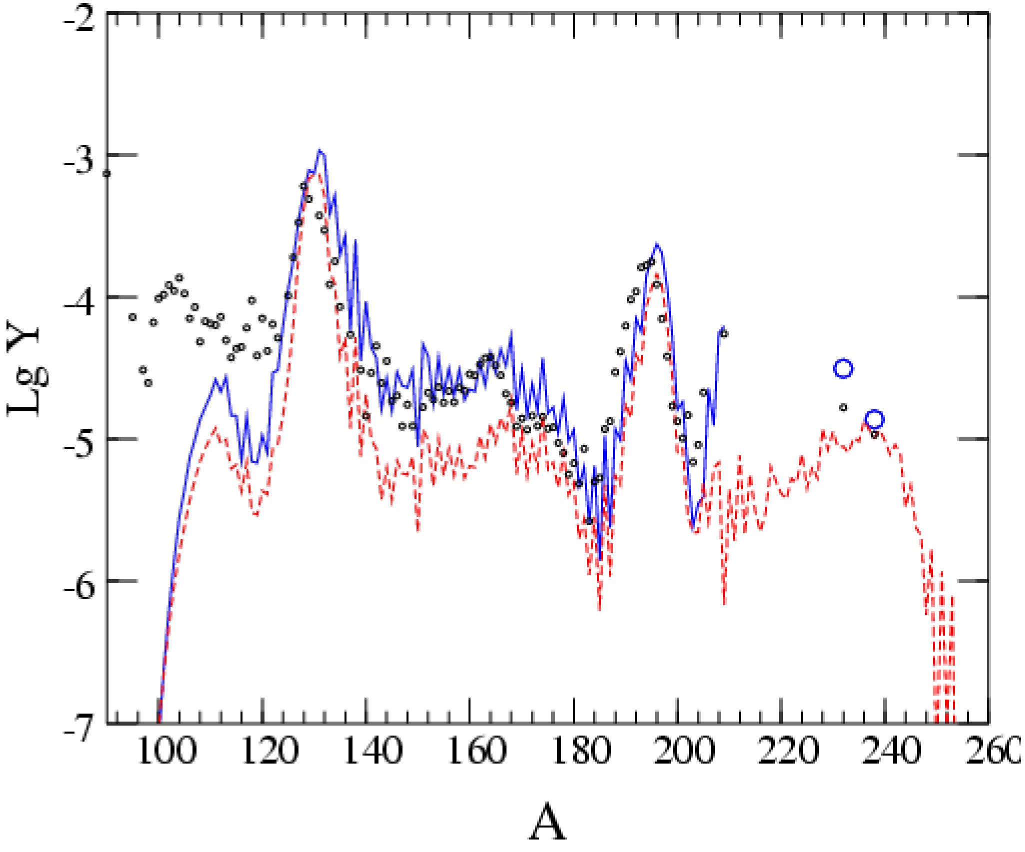
A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir, A. J. Levan, A. S. Fruchter, J. Hjorth, R. A. Hounsell, K. Wiersema, & R. L. Tunnicliffe (2013, Nature)



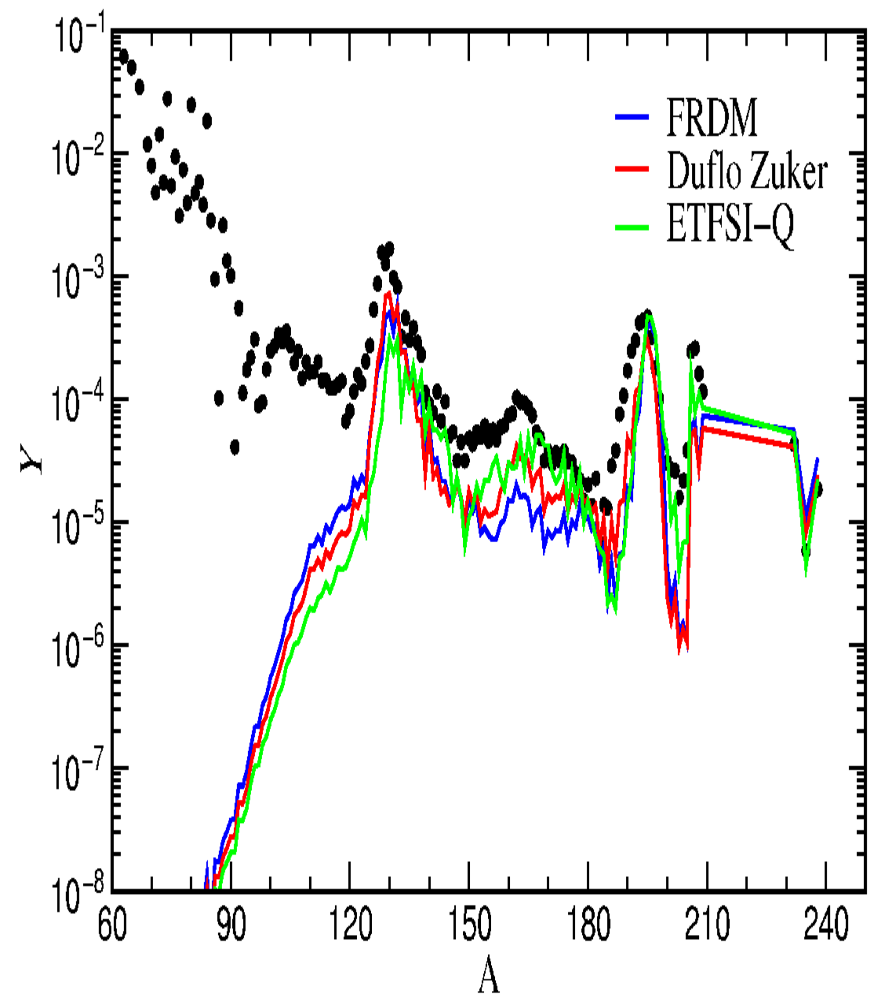
Short-duration γ-ray bursts (less than about two seconds) are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species, whose decay should result in a faint transient, known as a ‘kilonova’, in the days following the burst. Recent calculations suggest that much of the kilonova energy should appear in the near-infrared, because of the high optical opacity created by these heavy r-process elements. ***Here we report optical and near-infrared observations of such an event accompanying the short-duration γ-ray burst GRB 130603B.***

Fission Cycling in Neutron Star Mergers

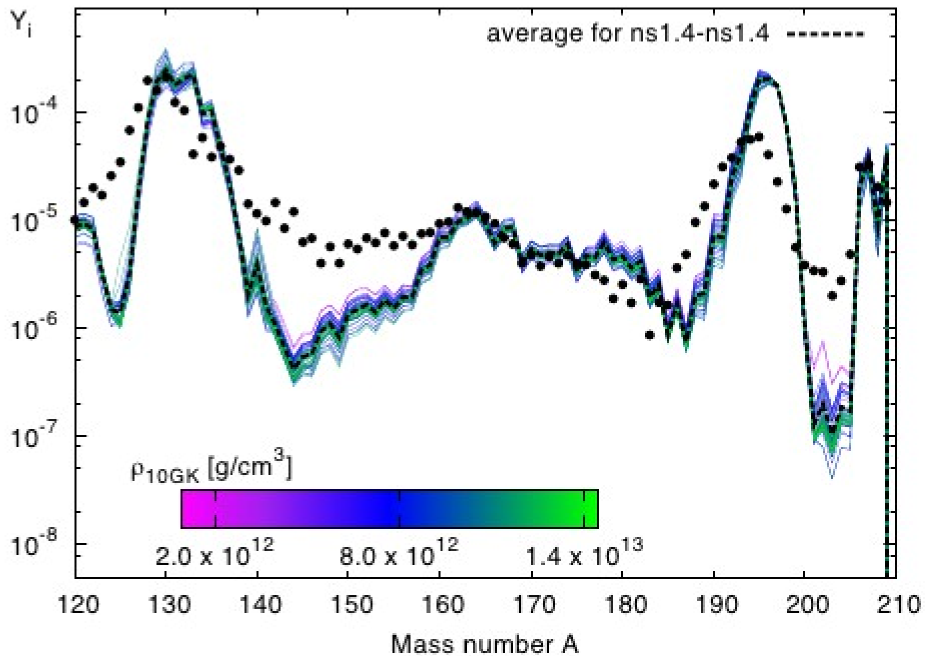


Panov, Korneev and Thielemann (2007, 2009)
with parametrized fission yield contribution
(see also Goriely, Bauswein, Janka 2011)

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

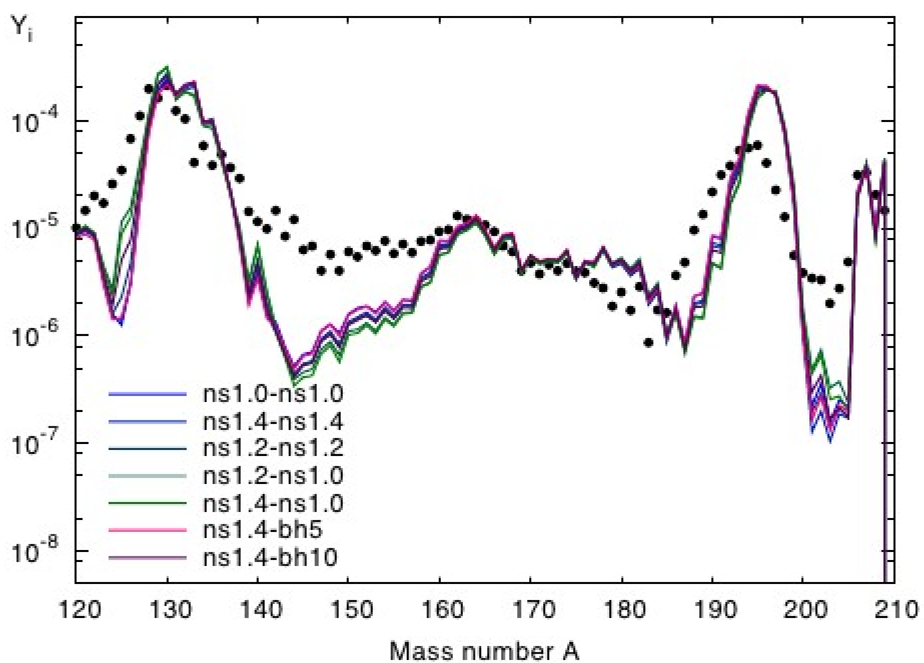


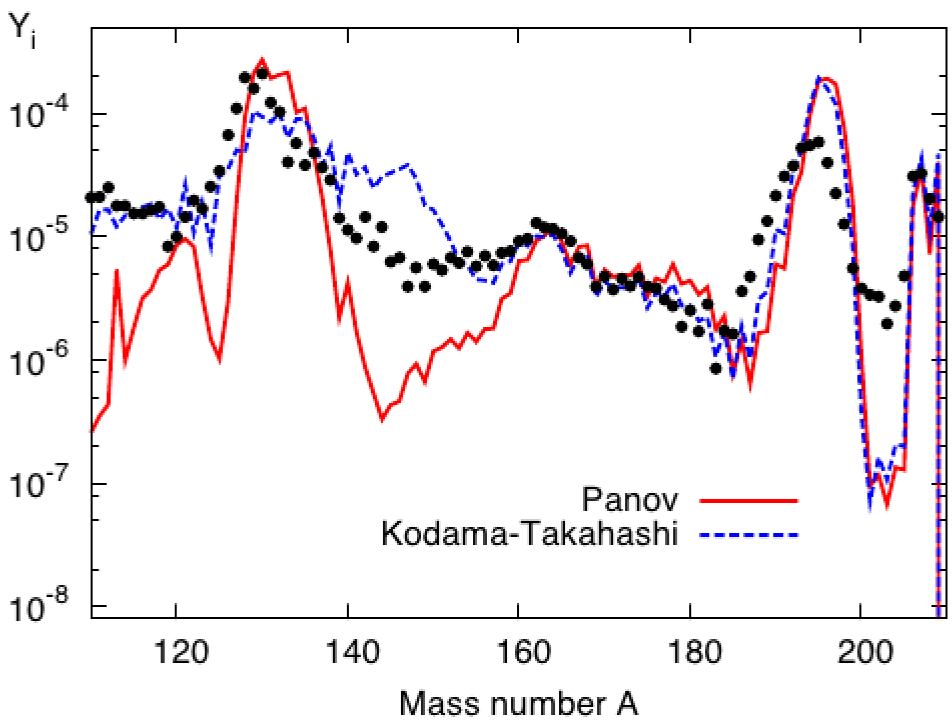
Martinez-Pinedo et al. (2006)

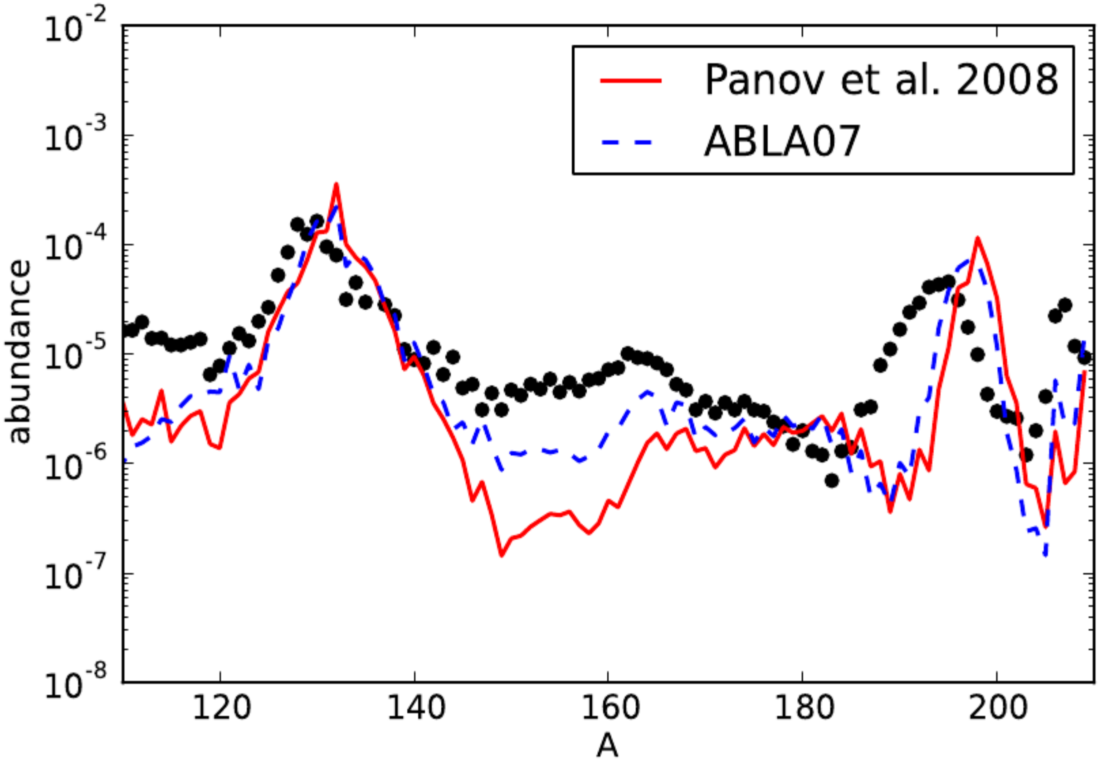


Recent neutron star merger updates (Korobkin et al. 2012)

Variation in neutron star masses fission yield prescription





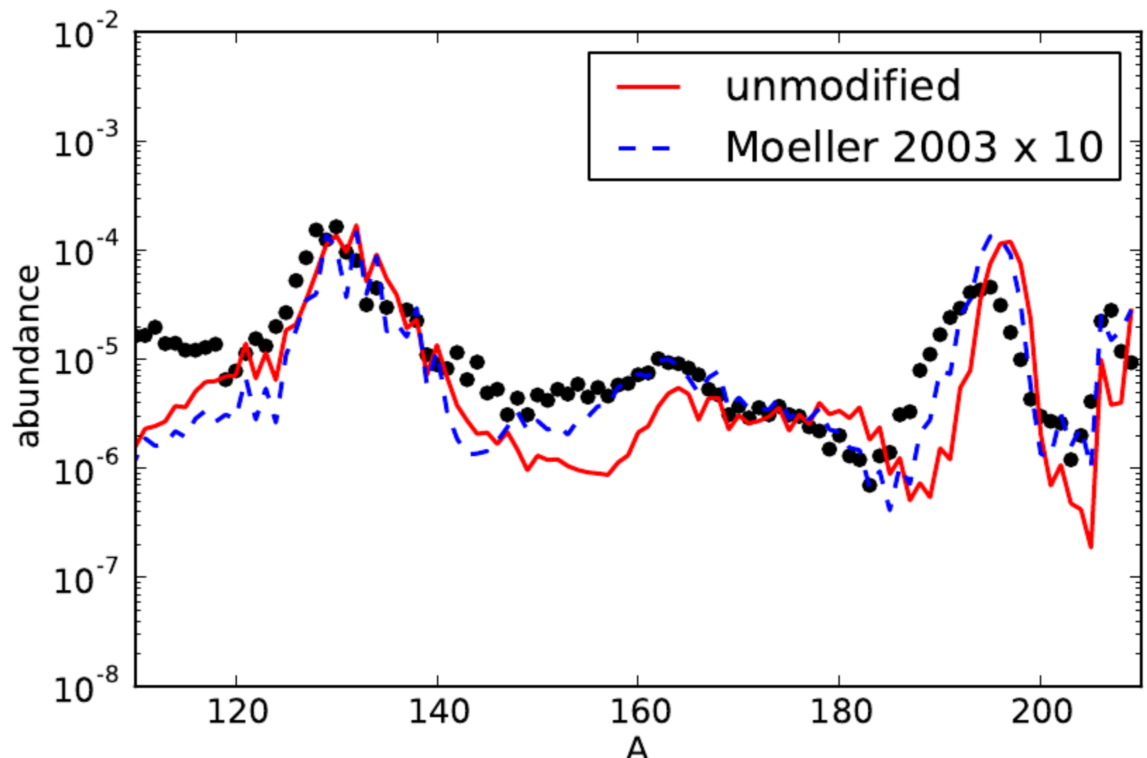


Eichler et al. (2013)

Variations in fission yield Distributions (ABLA from Kelic et al. GSI).

Fills somewhat A=140-160 gap and moves A=195 peak down slightly (related to fission yield distribution and corresponding neutron emission)

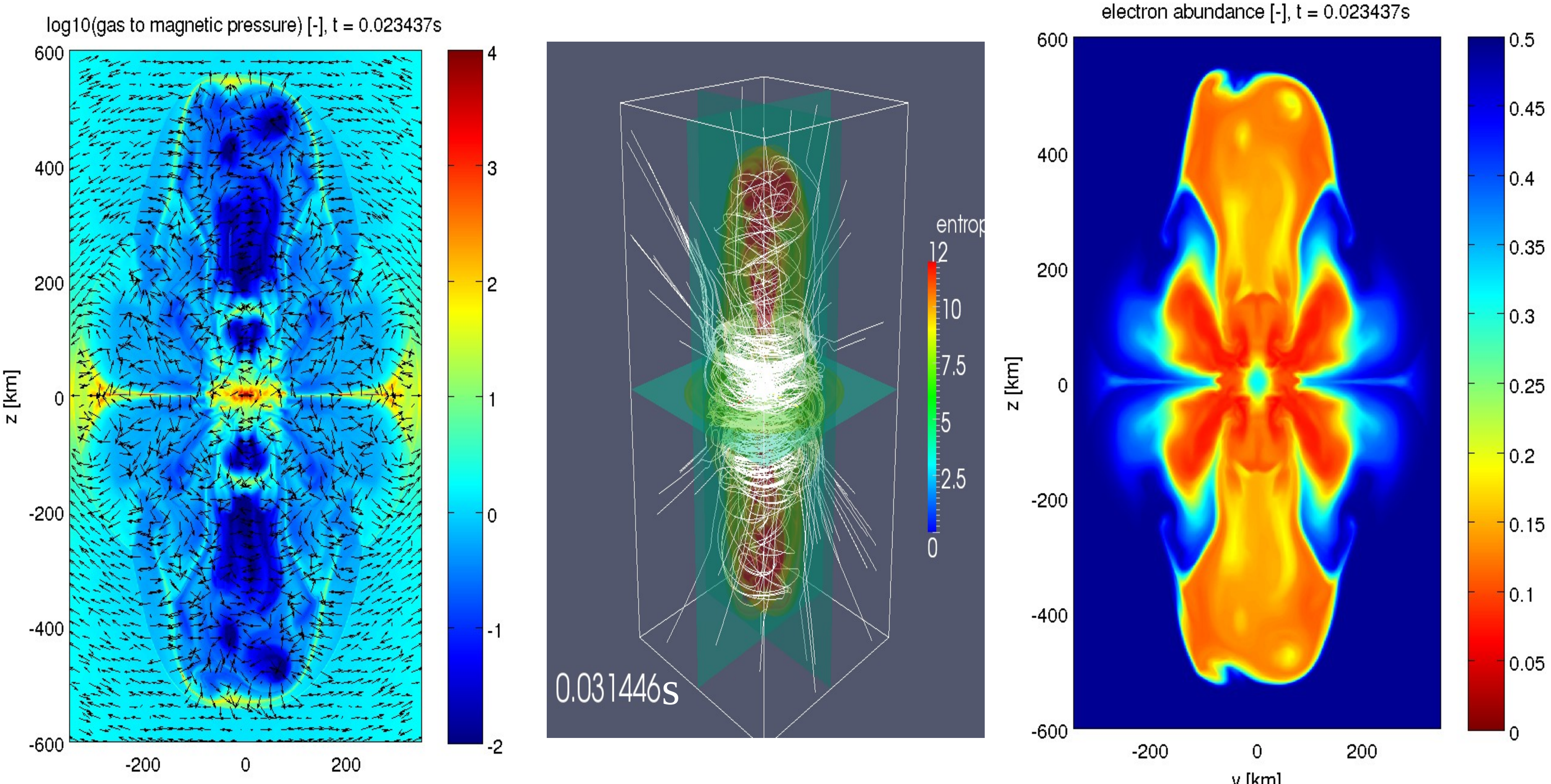
The final abundance pattern Also depends when the neutron capture from fission neutrons occurs. If still n,γ-γ,n equilibrium Persists, the fit is better than with late neutron capture in a type of n-process. The first is the case if beta-decay rates above Z=80 are faster (see Panov's talk).



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



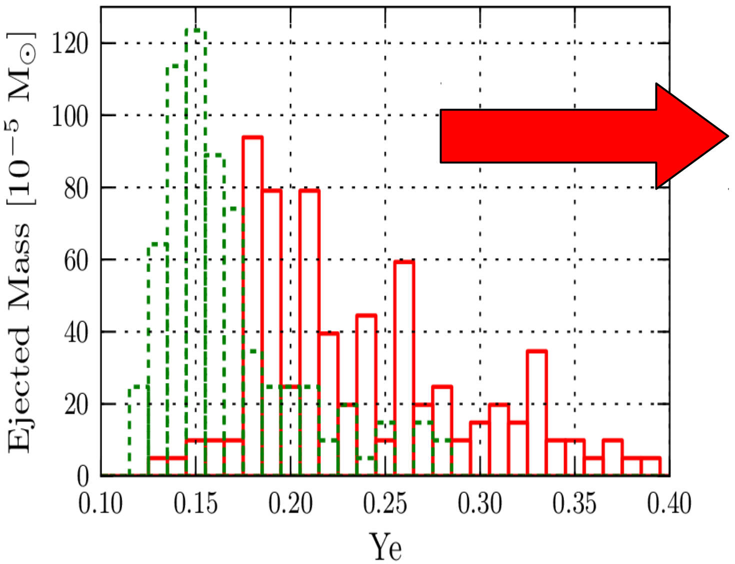
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012

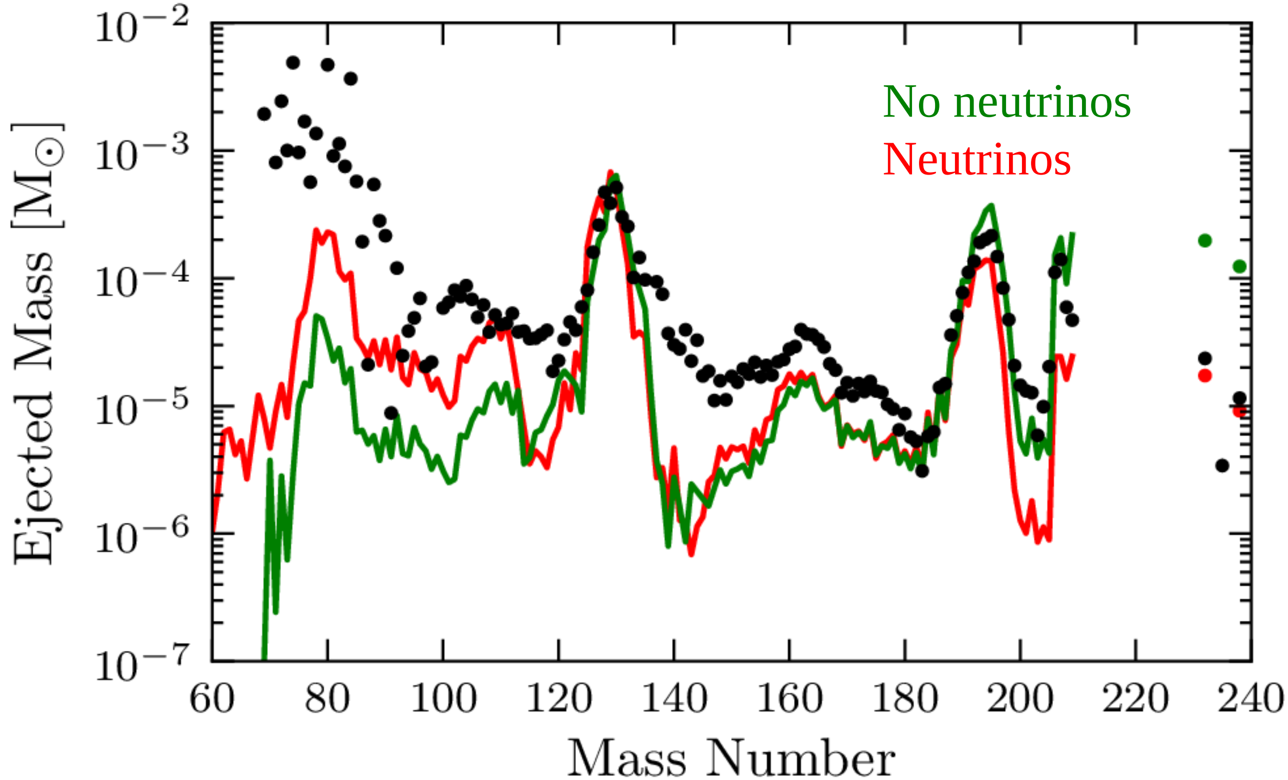
Eichler et al. 2013

Nucleosynthesis results

From fast rotators with strong magnetic fields, i.e polar jets

neutrino effect small opposite to neutrino wind with slow expansion velocities



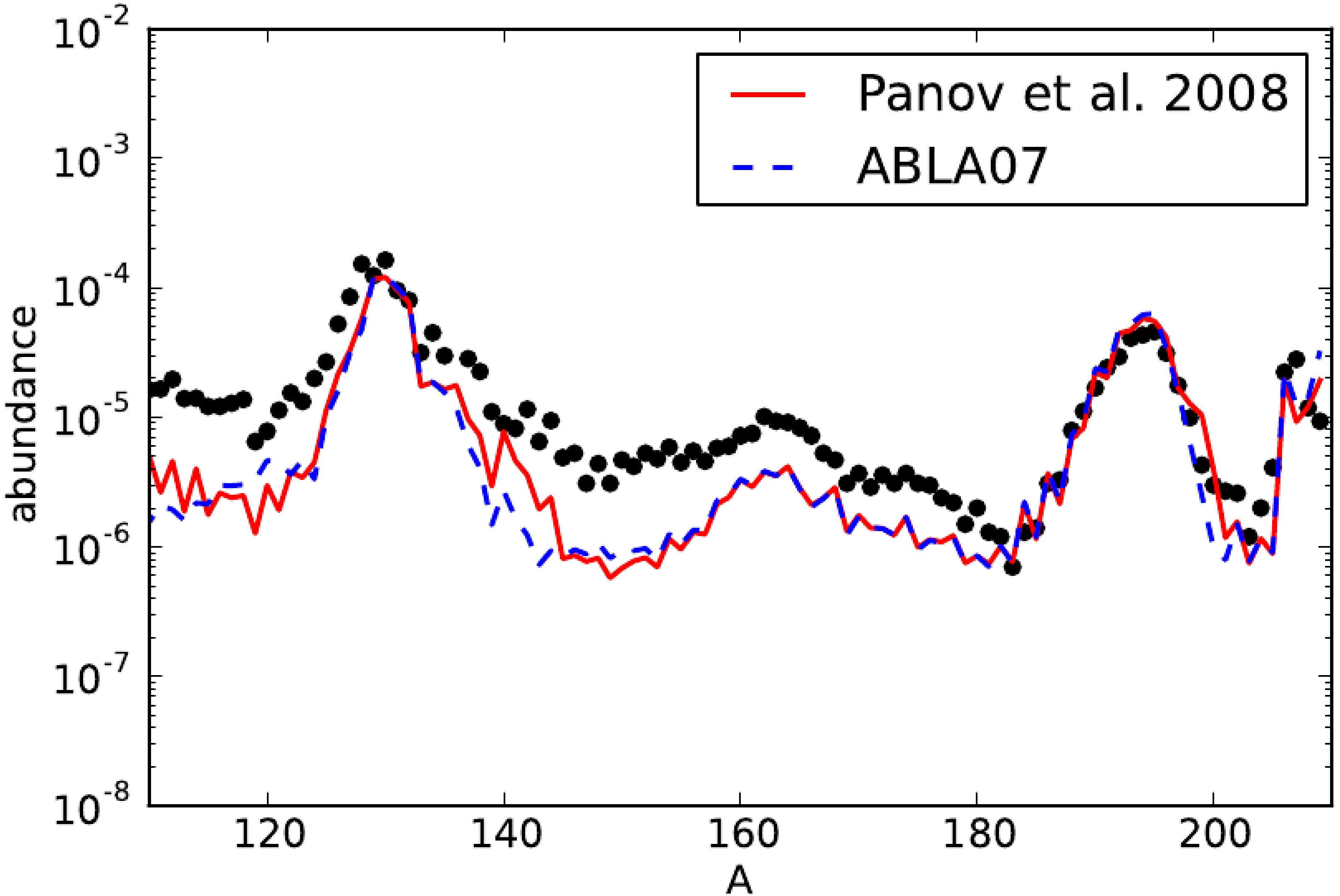


- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

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

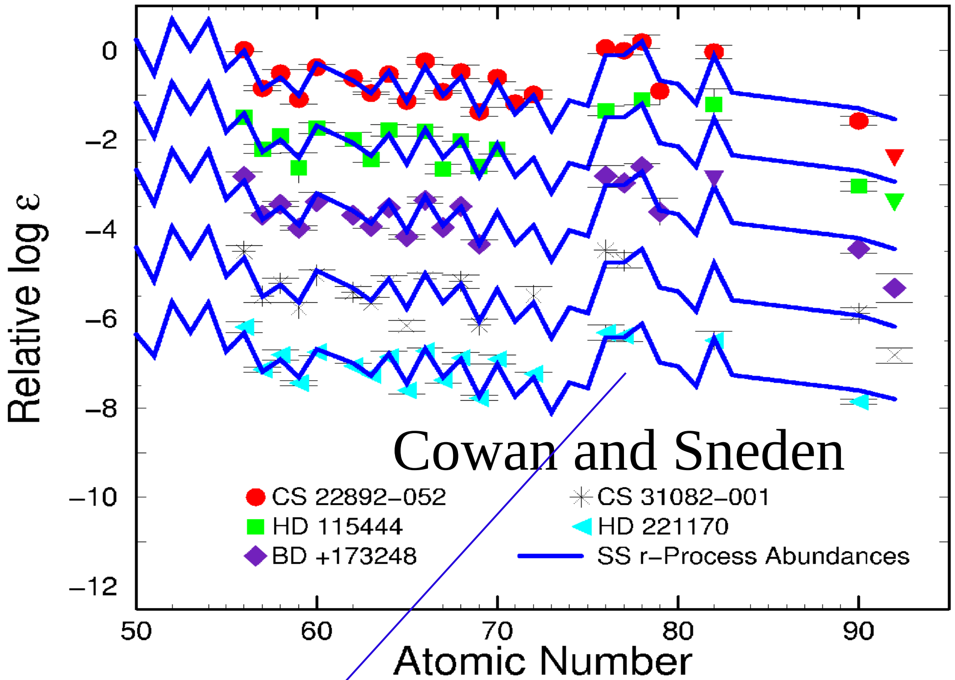
Effect of Fission Yield Distribution

(Eichler et al. 2013)



Effect not as strong as in neutron star merger case, as conditions slightly less neutron-rich and influence of fission less prominent.

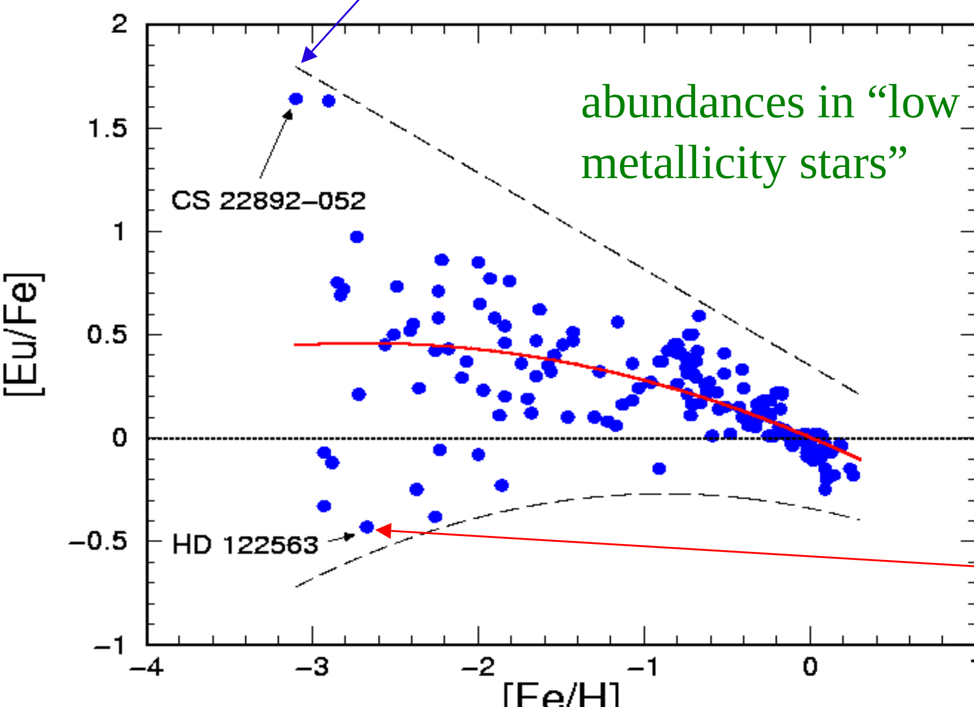
Observational Constraints on r-Process Sites

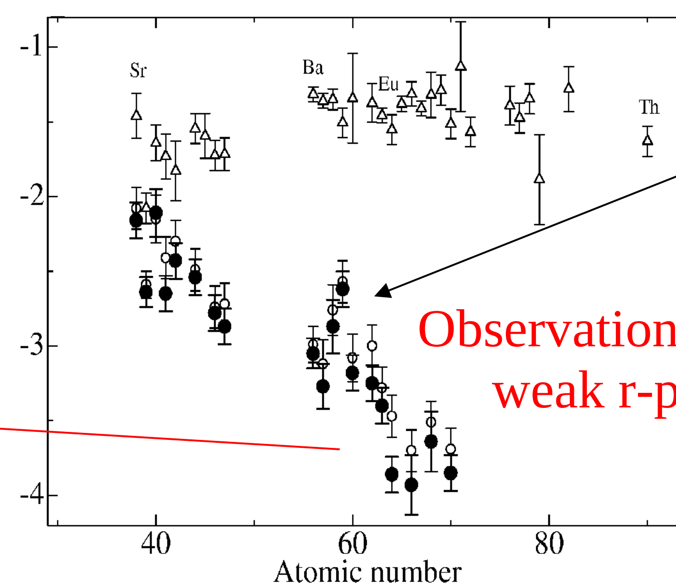


apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

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), why the large scatter?

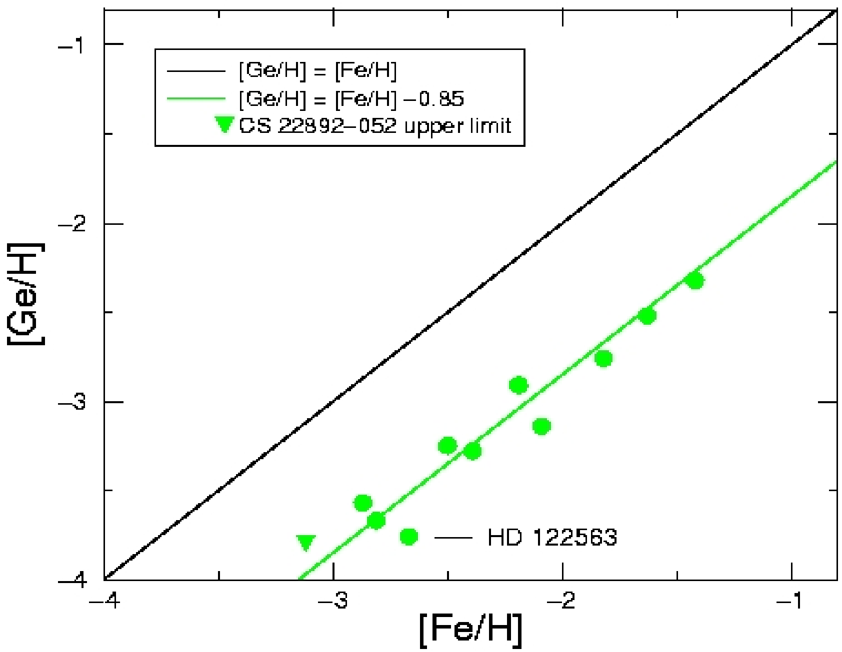


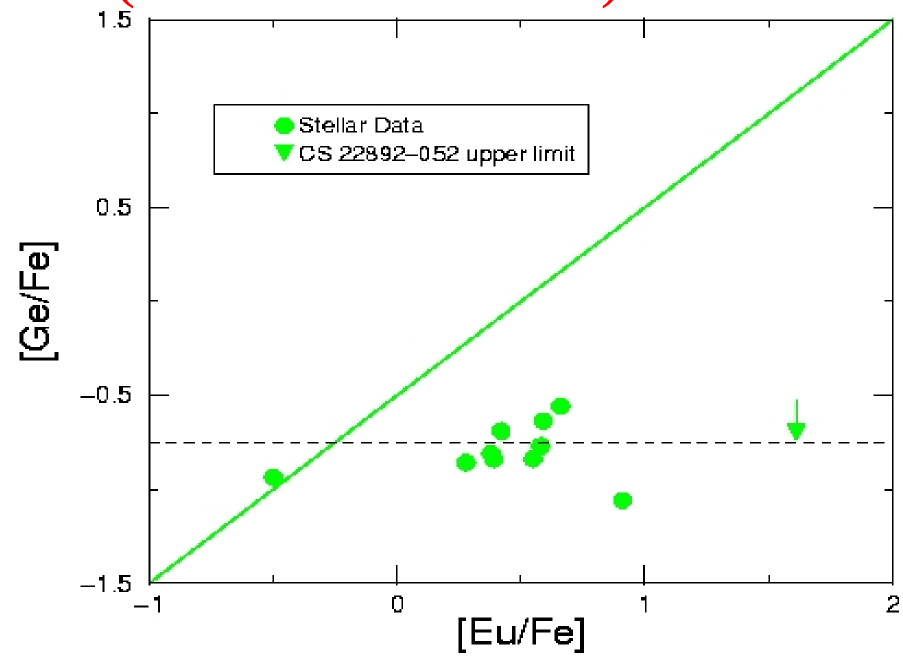


Honda et al. (2007)

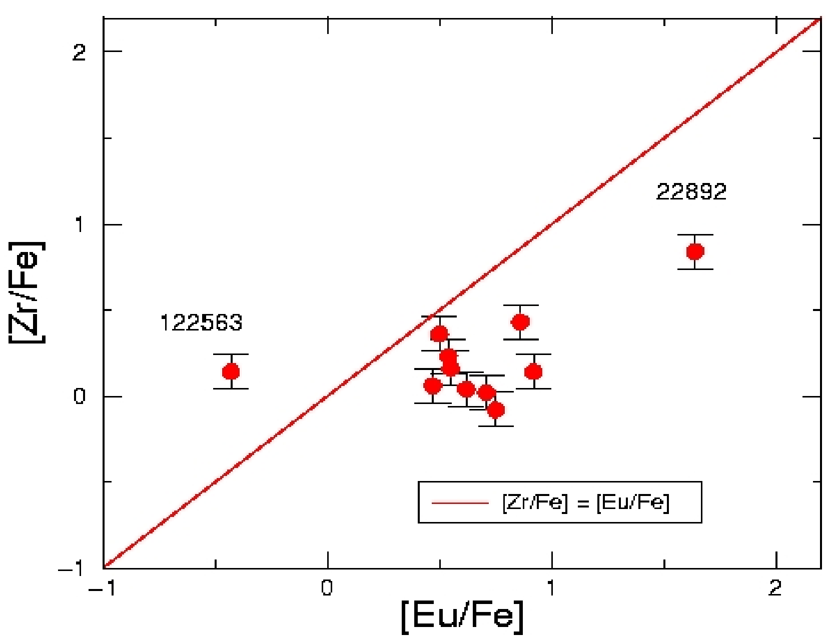
Observations of a/the? weak r-process?

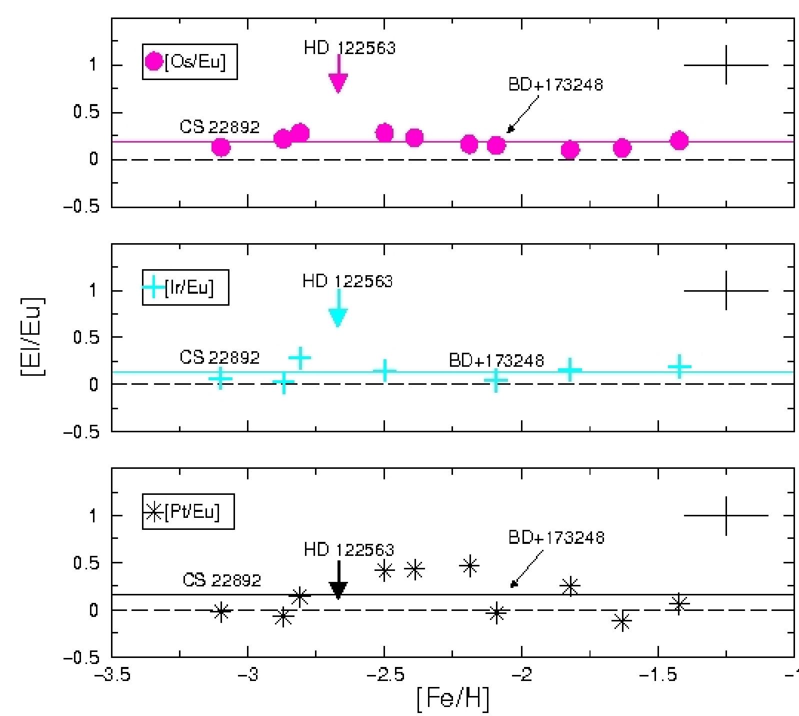
Observational indications: heavy r-process and Fe-group uncorrelated, Ge member of Fe group, Zr intermediate behavior, weak correlations with Fe-group as well the heavy r-elements (Cowan et al. 2005)



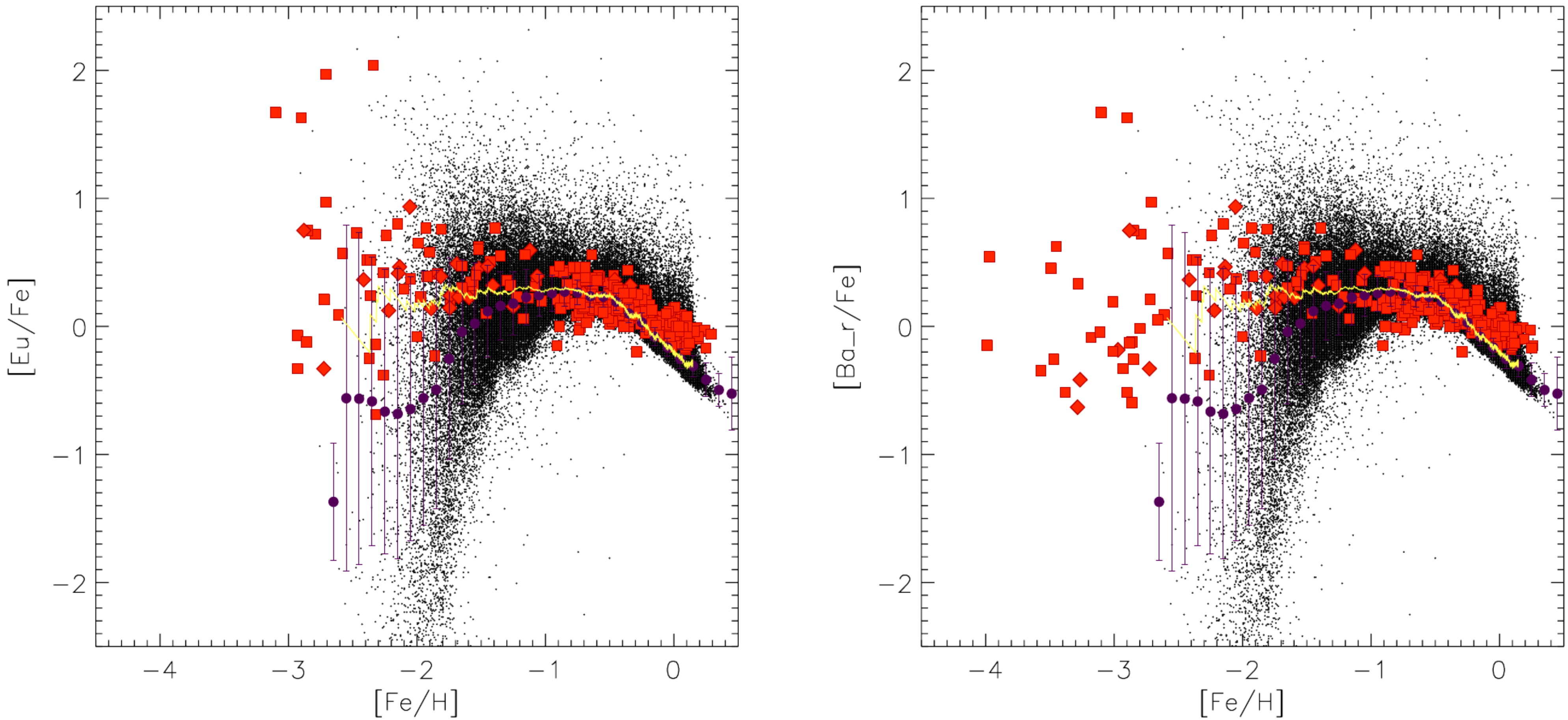


Zr vs. Eu





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

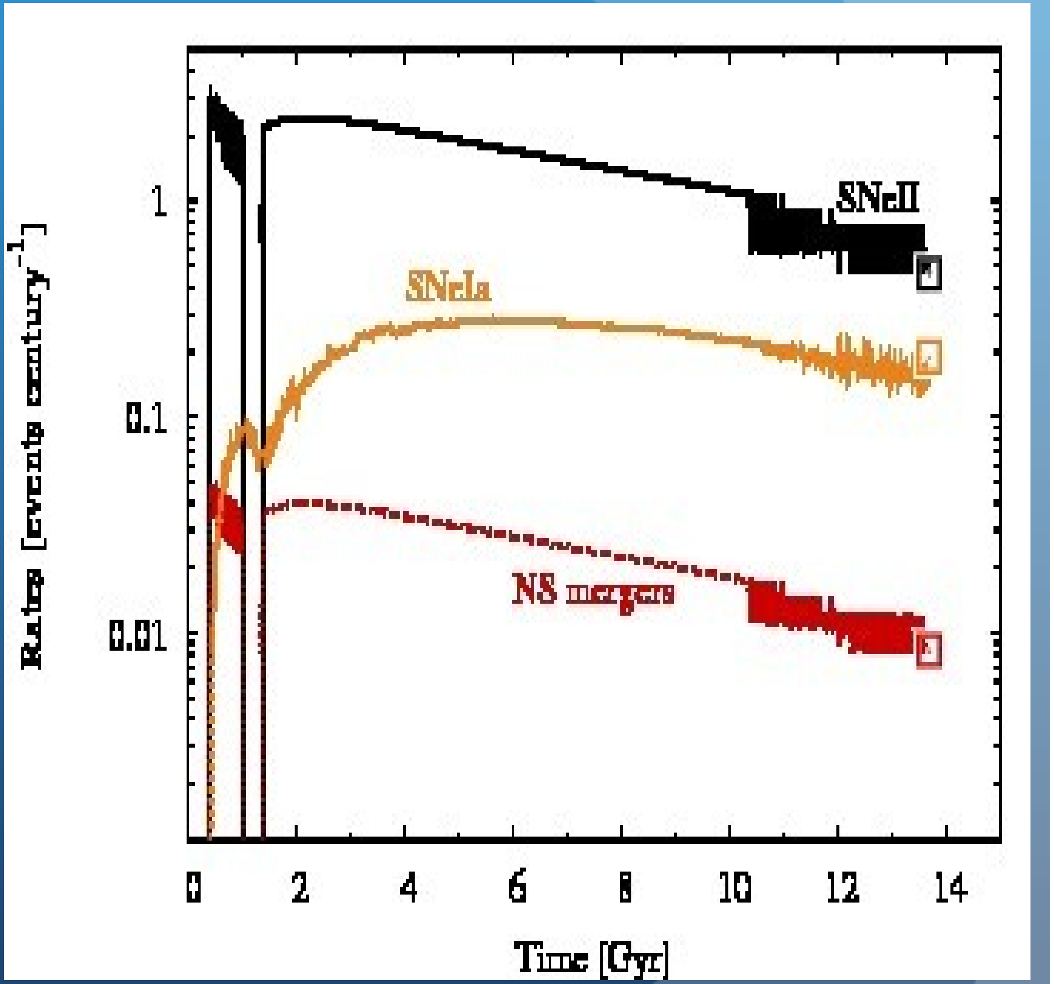


ig. 4. Evolution of [Eu/Fe] and [Ba^{r}/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^{6} yr and 10^{-3} $M_{\odot}$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

Although they can be the dominant contributors in late phases?

SN rates and NS merging rate (from Matteucci 2013)

The SN II and Ia rates compared with the NS merger rate (100 yr $^{-1}$)
The present time NS merger rate reproduces the observed present time NS merger rate of 83/Myr (Kalogera et al. 2004)
This is obtained with alpha=0.018 (fraction of NS mergers from total NS production rate).



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]

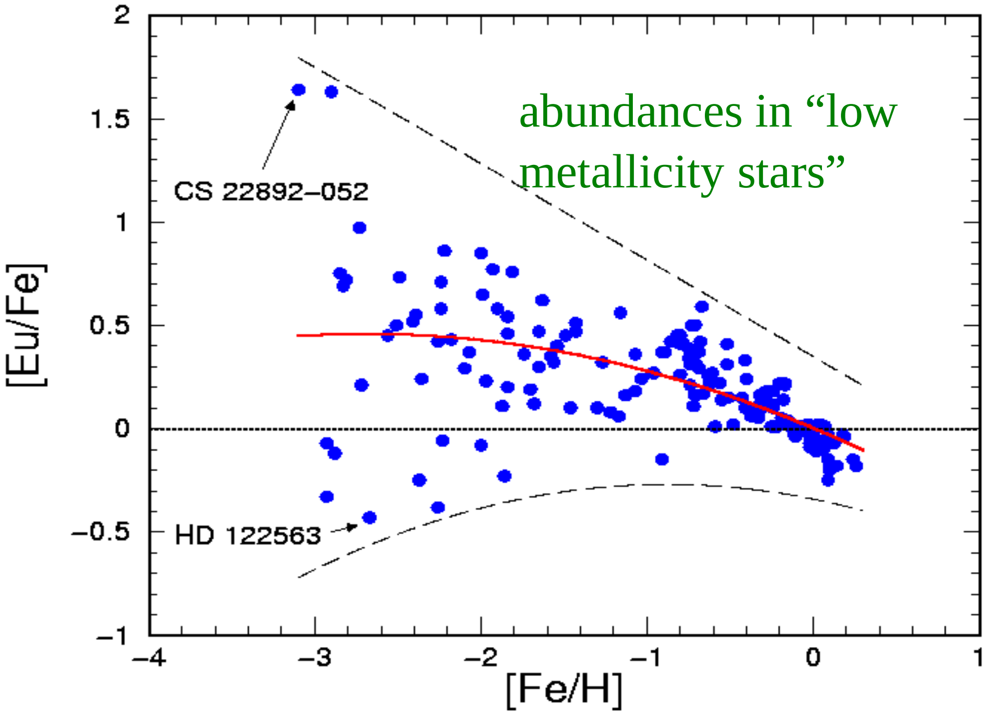
(neutron star mergers would have similar behavior in frequency and ejecta, only deficiency: occurrance too late???)

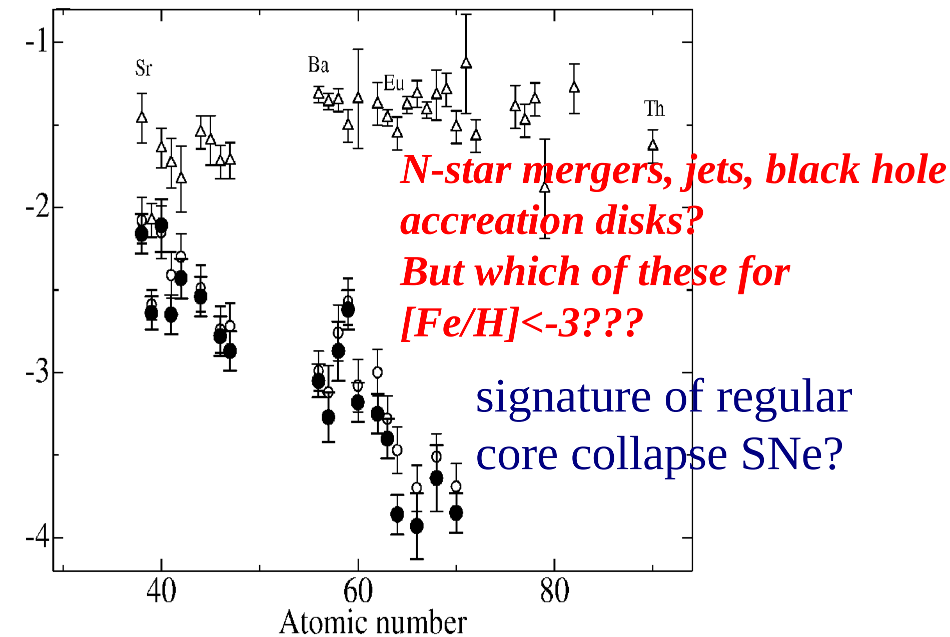
  - *only needed at low [Fe/H], later neutron star mergers could take over*

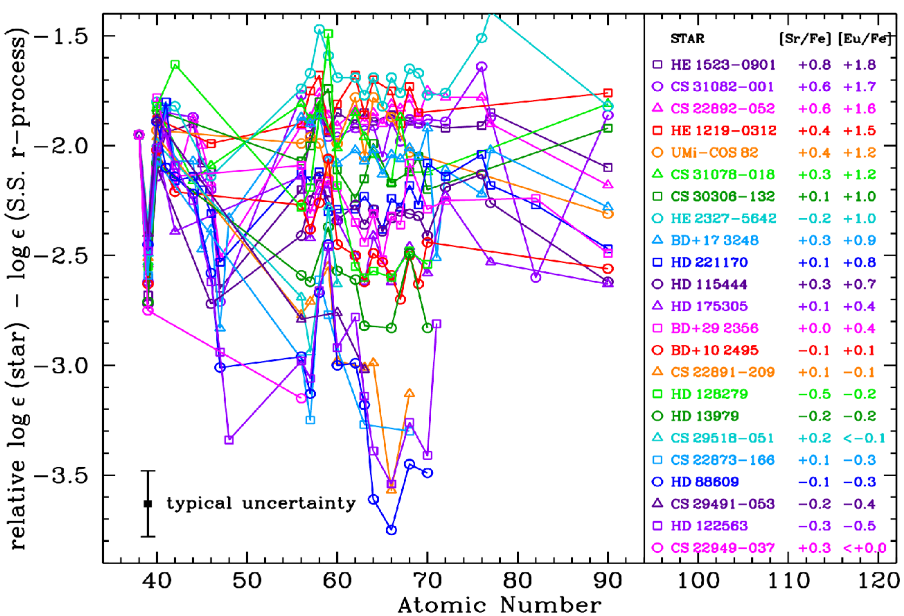
- progenitor configuration (B, Ω):
  - Not reached in common evolutionary paths (Heger 2005)
  - Possible for small fraction (~1%) of low metallicity models (Woosley&Heger 2006)

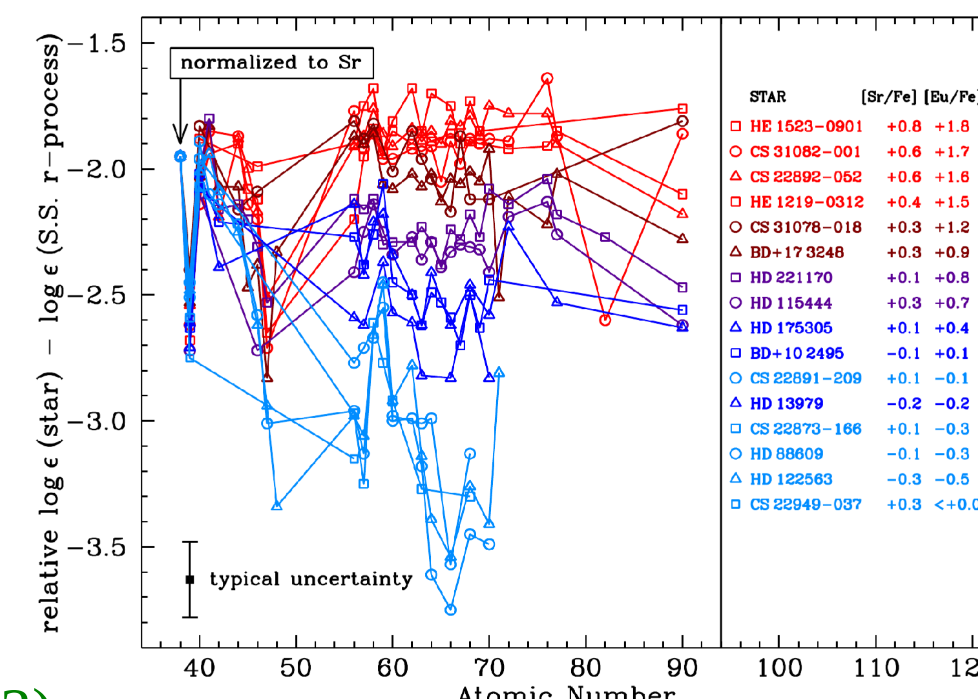
- *present magnetar knowledge permits ~1% of CCSNe resulting in magnetars (Kramer 2009, Koveliotou et al. 1998)*

Observational Constraints on r-Process Sites









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?