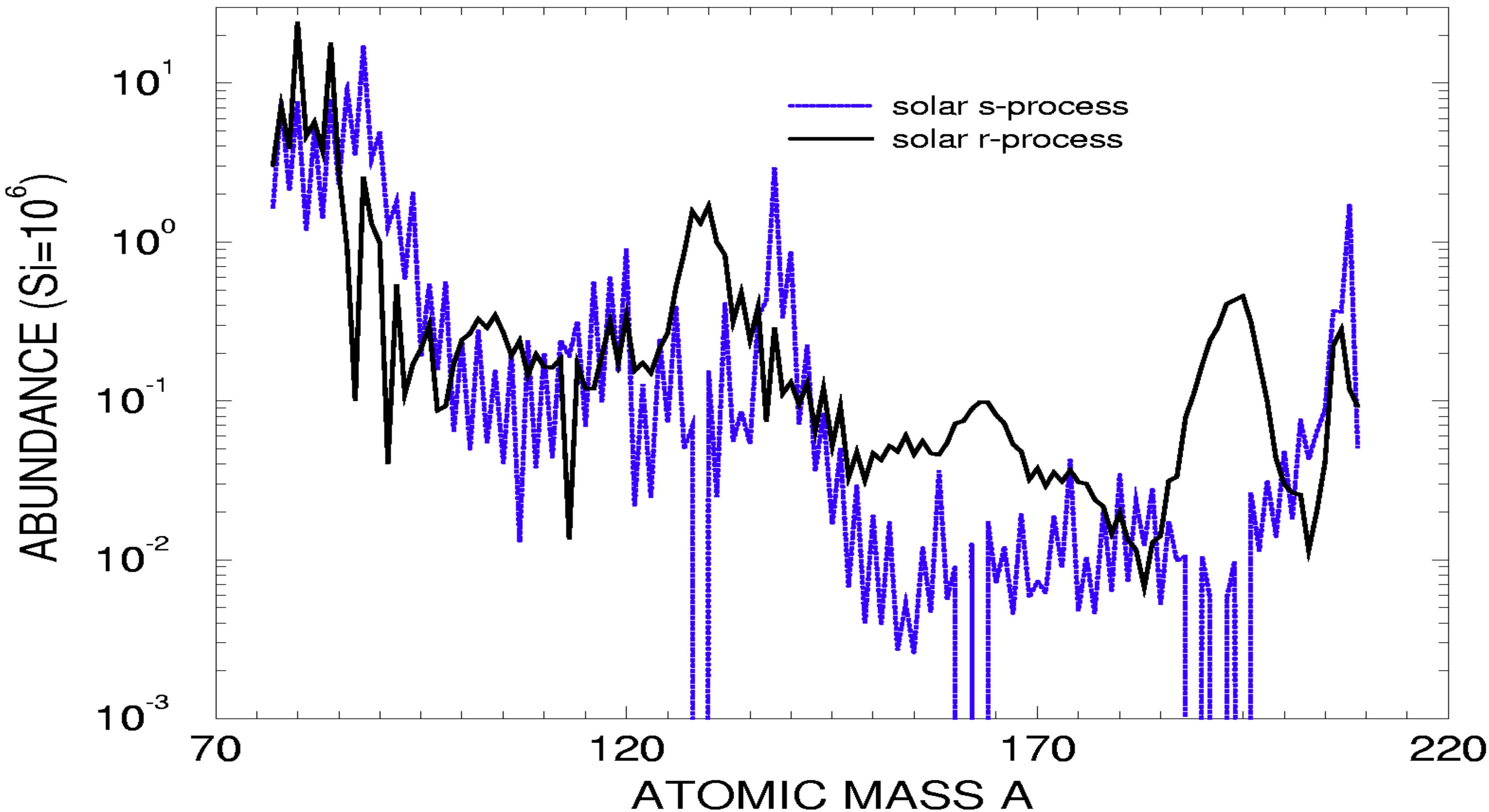
r-Process Nucleosynthesis:

nuclear input, required environment conditions, astrophysical sites, and its role in galactic evolution

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

“full” s- and r-composition



after “understanding” the solar s-process, subtraction of the s-abundances from the full abundance curve leads to the solar r-process abundances. How can we locate the correspondig reaction path in the nuclear chart?

Is this a unique process of a superposition from different production sites?

The classical r-process

How to predict abundance changes?

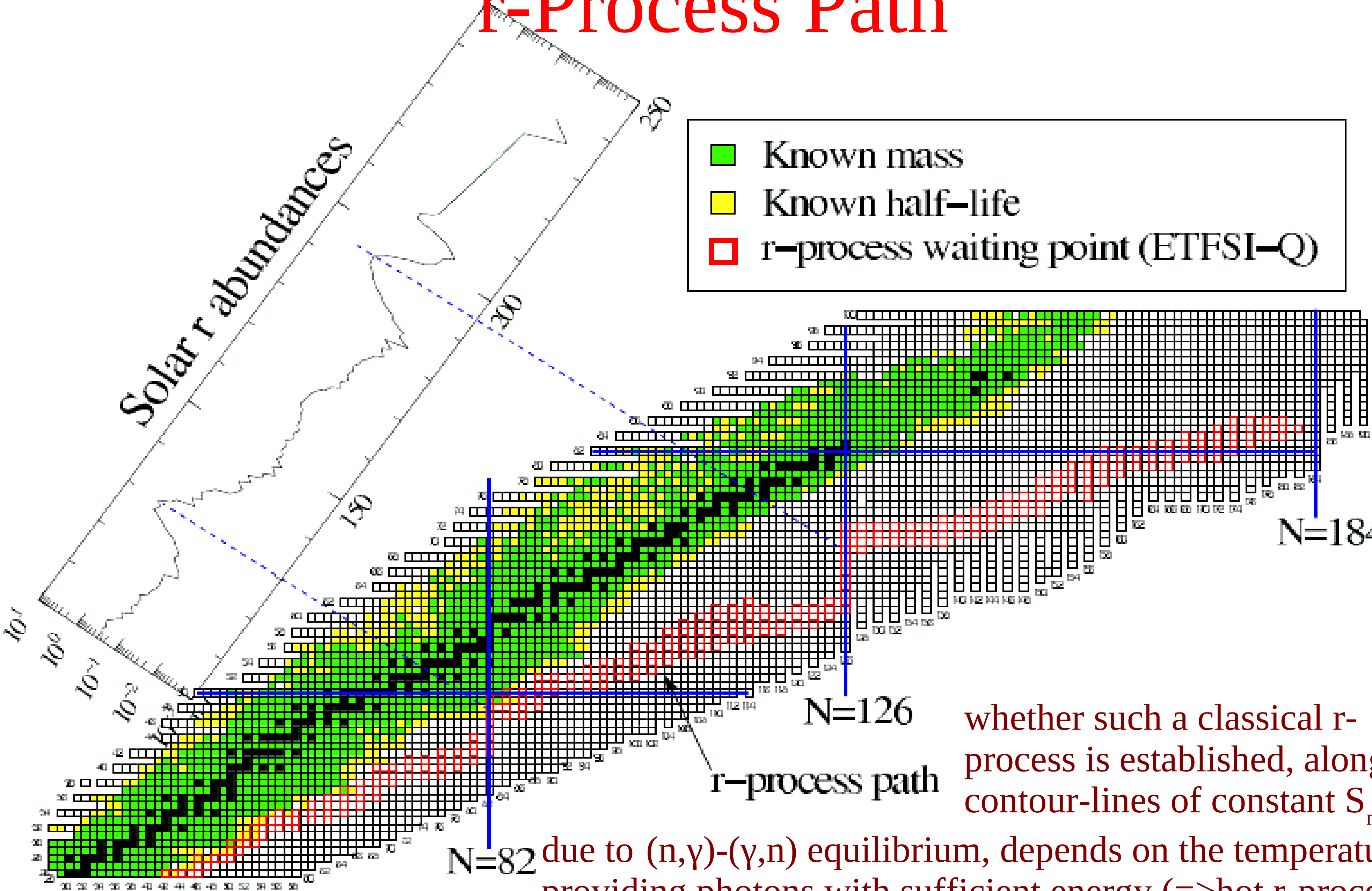
- $\dot{Y}(Z,A) = \sum \lambda_{Z',A'} Y_{Z',A'} + \sum \rho N_A < \sigma v >_{Z',A'} Y_{Z',A'} Y_n$
with $n_n = \rho N_A Y_n$
- $\dot{Y}(Z,A) \approx \lambda_\gamma(Z,A+1)Y(Z,A+1) - < \sigma v >_{Z,A} Y_{Z,A} n_n$ in case (n,γ), (γ,n) rates dominate
- $\dot{Y}(Z,A) = 0$ in chemical equilibrium,
$Y(Z,A+1)/Y(Z,A) = f(n_n, T, S_n)$ due to detailed balance relation between $\lambda_\gamma(Z,A+1)$ and $< \sigma v >_{Z,A}$
- abundance maxima for all Z's at same S_n
- $\dot{Y}(Z) = \lambda_\beta(Z-1)Y(Z-1) - \lambda_\beta(Z)Y(Z)$ for summed abundances in isotopic chain and averaged decay rates

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{< \sigma v >_{n,\gamma}(A)}{\lambda_{\gamma,n}(A+1)} n_n$$

$$\lambda_{\gamma,n}(A+1) = \frac{2G(Z,A)}{G(Z,A+1)} \left[\frac{A}{A+1}\right]^{3/2} \left[\frac{m_u kT}{2\pi\hbar^2}\right]^{3/2} \langle \sigma v \rangle_{n,\gamma}(A) \exp(-S_n(A+1)/kT)$$

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A}\right]^{3/2} \left[\frac{2\pi\hbar^2}{m_u kT}\right]^{3/2} \exp(S_n(A+1)/kT)$$

r-Process Path

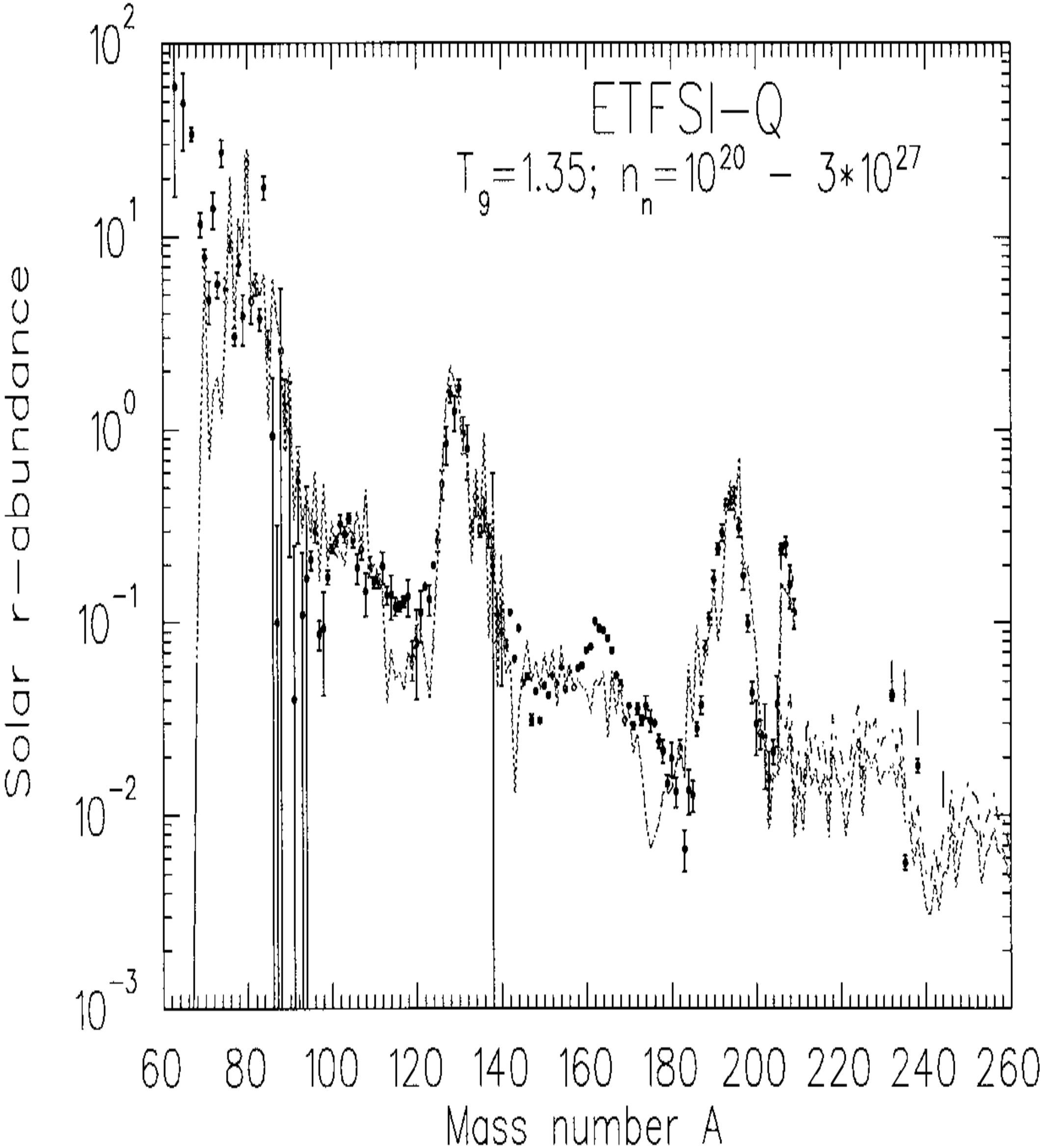


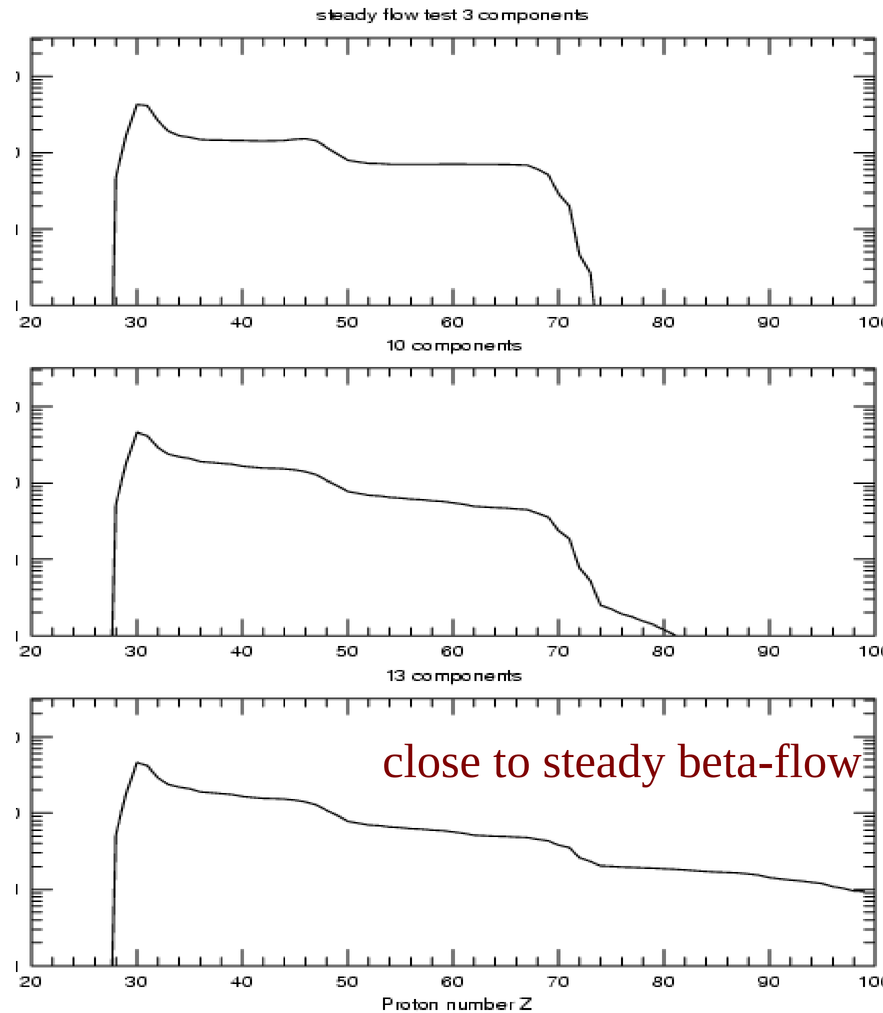
whether such a classical r-process is established, along contour-lines of constant S_{n}, due to (n,γ)-(γ,n) equilibrium, depends on the temperature, providing photons with sufficient energy (=>hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might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

G. Martinez-Pinedo

Multi-components and steady beta-flow?

Kratz, Bitouzet, Thielemann, Möller, Pfeiffer and permutations 1993-1999





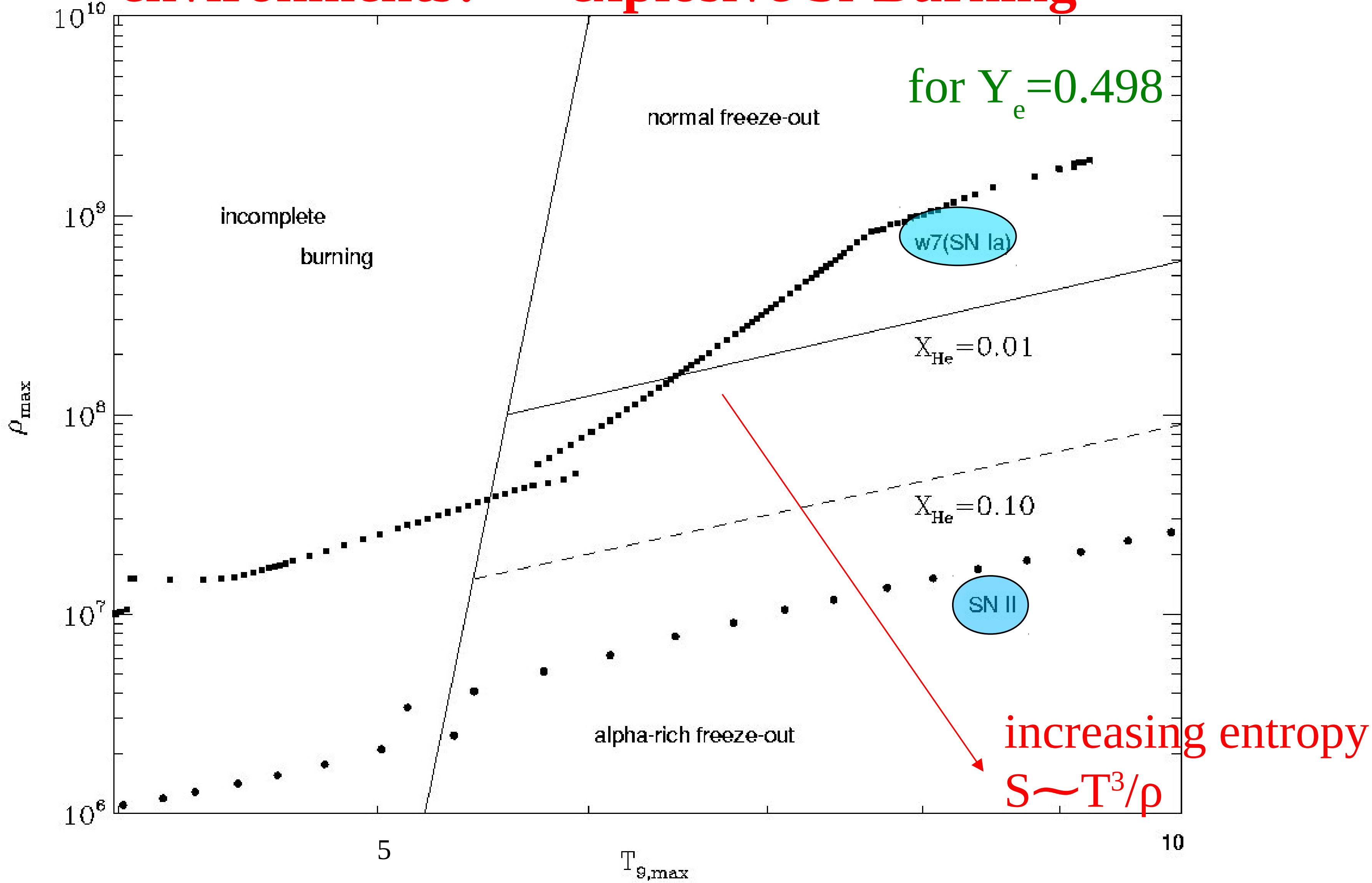
superposition with weights

$w(n_n)=8.36\ 10^{6} n_n^{-0.247}$ and $t(n_n)=6.97\ 10^{-2}\ n_n^{0.062}$s

for const n_n, durtation $t(n_n)$, subsequent decay

decay rate of complete Z-chain multiplied with total abundance of Z-chain close to constant in between magic numbers (where long half-lives are encountered).

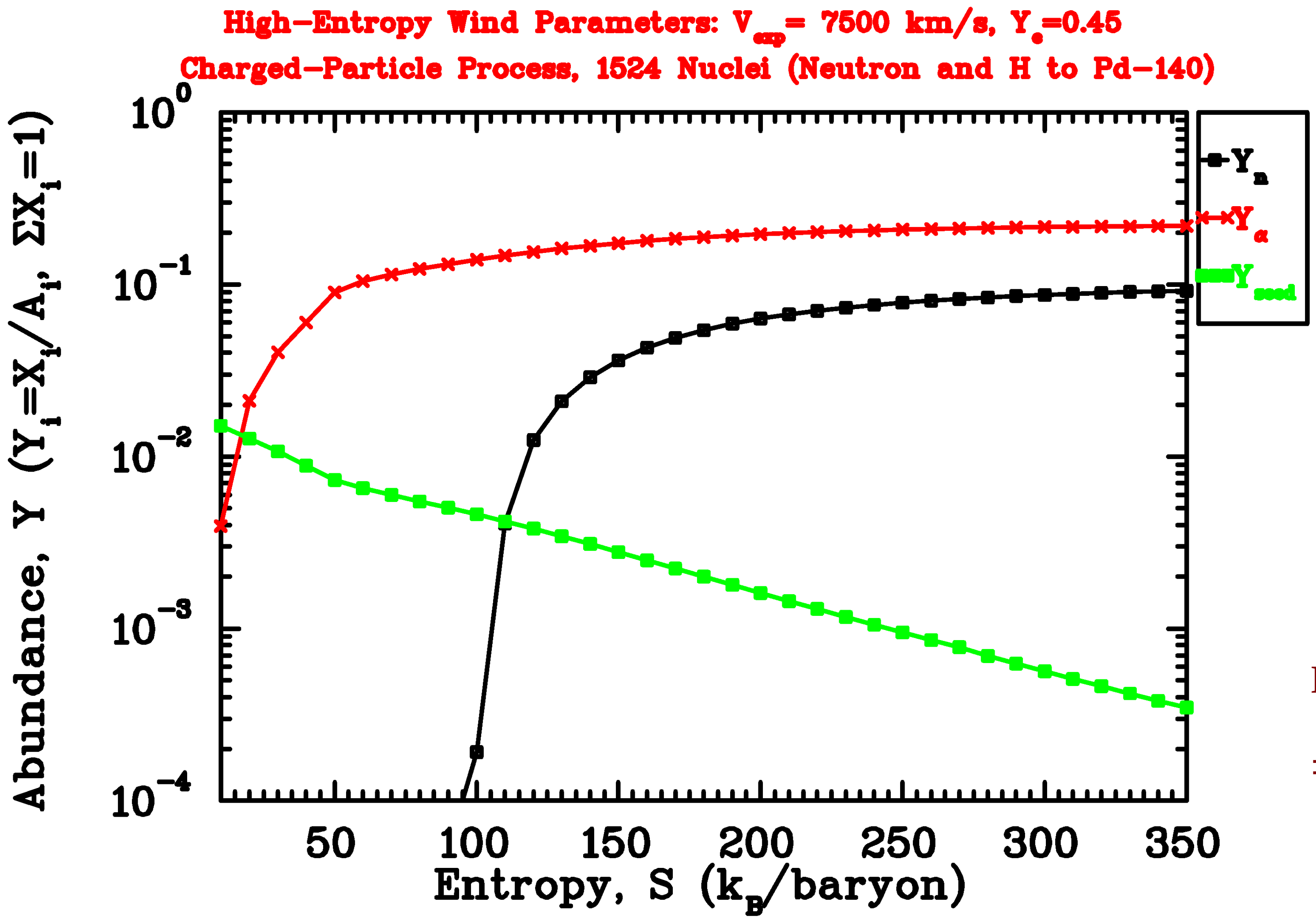
But how can one obtain such neutron densities in realistic environments? → explosive Si-Burning



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 ^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)



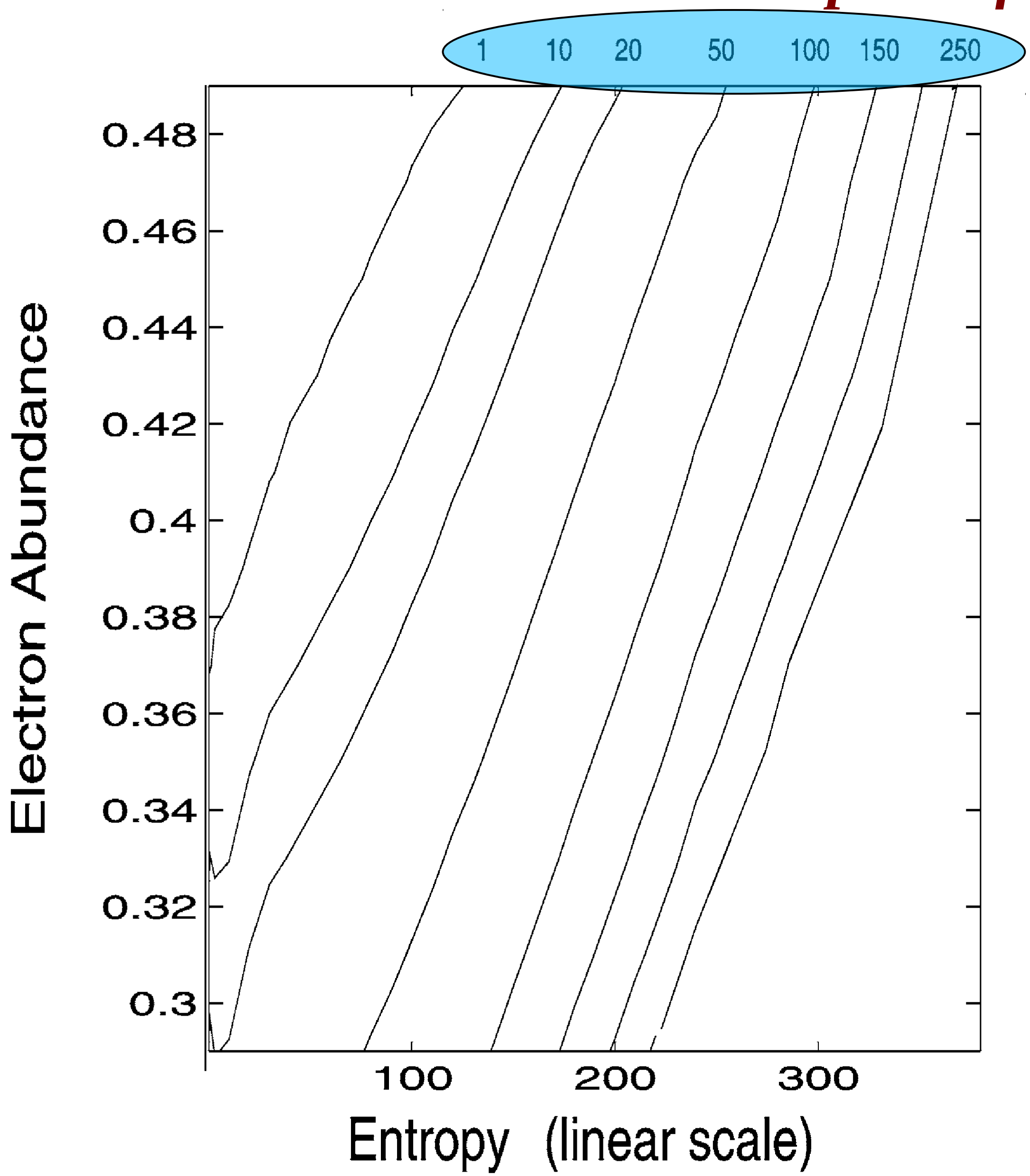
n/seed

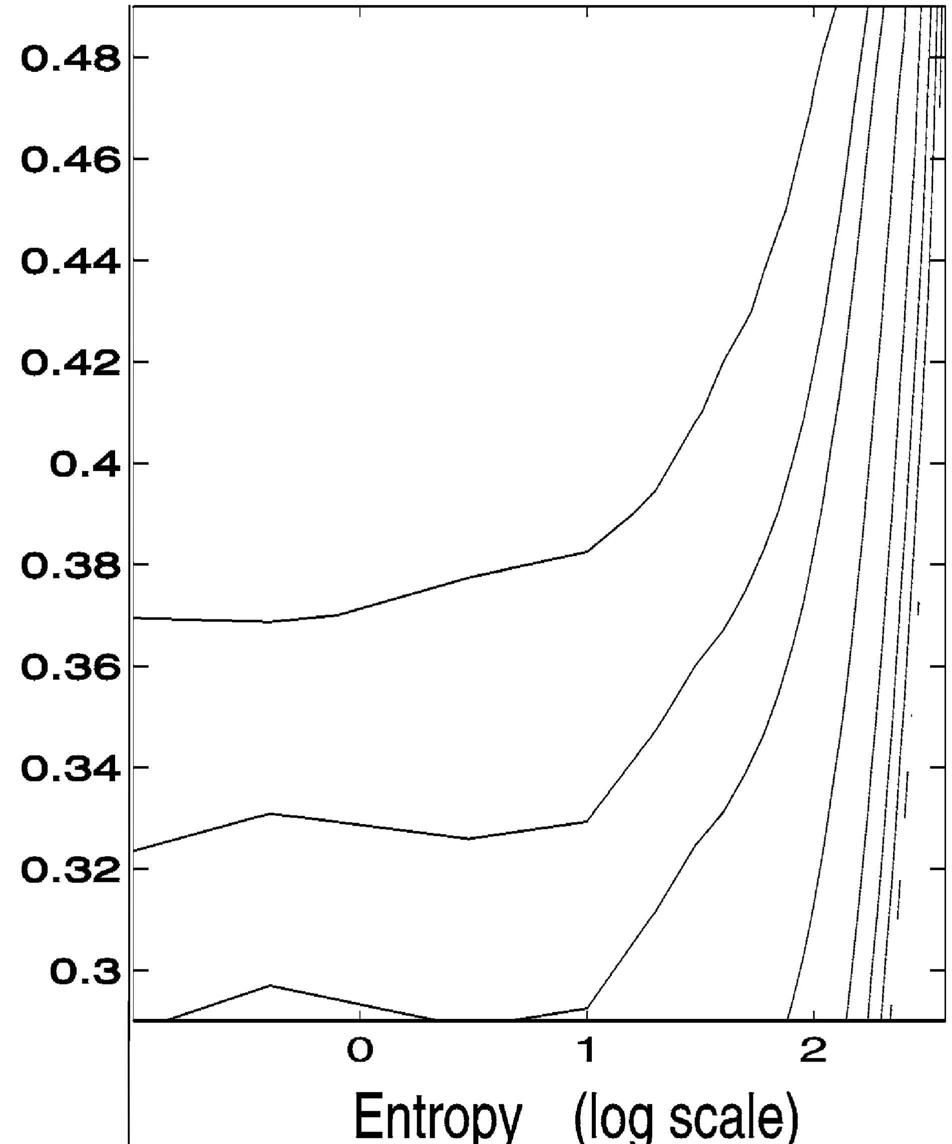
$=Y_n/Y_{seed}$

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

Two options for a successful r-process



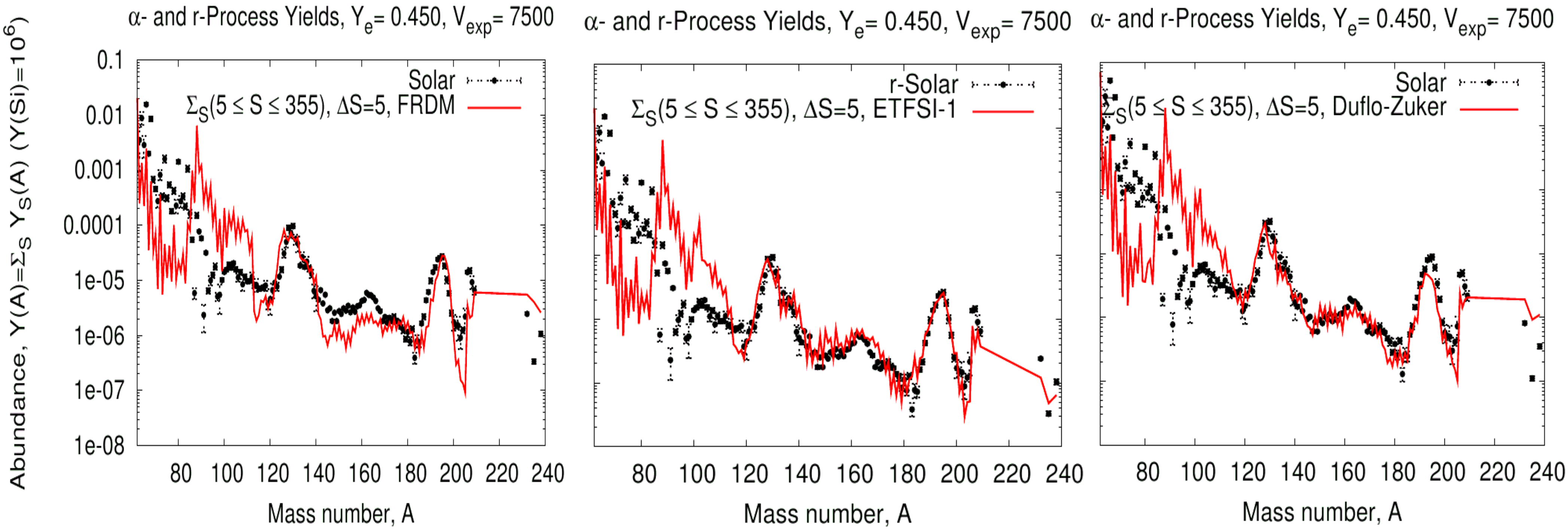


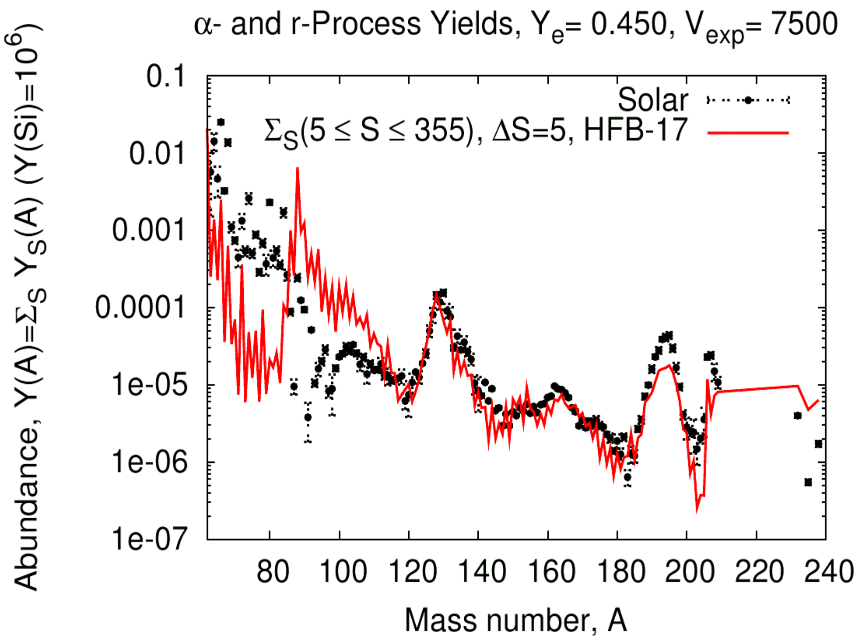
neutrino wind?

Freiburghaus et al. (1999)

Neutron star mergers and polar jets?

Superposition of entropies and test for different mass models

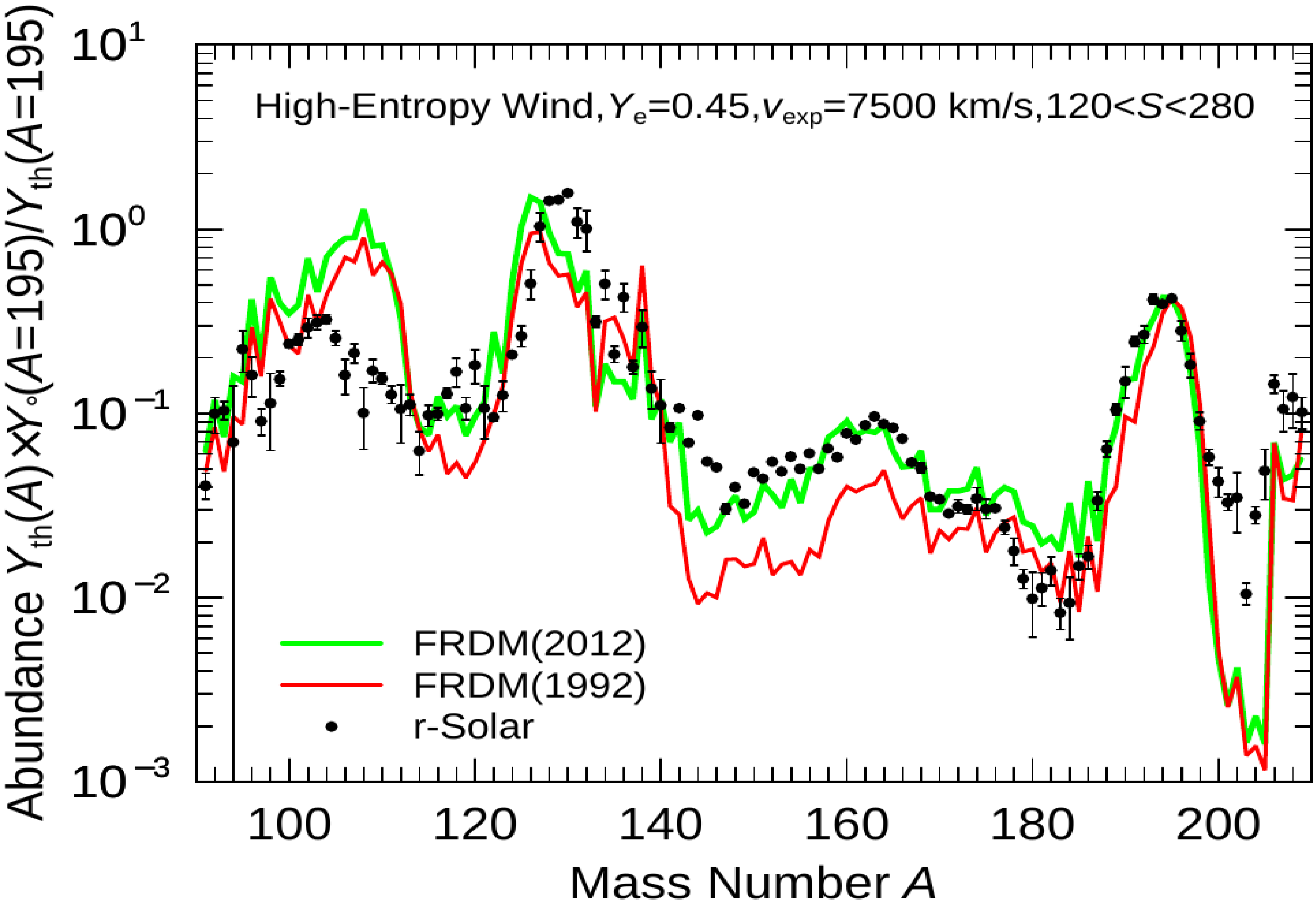




Farouqi et al. (2010)

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

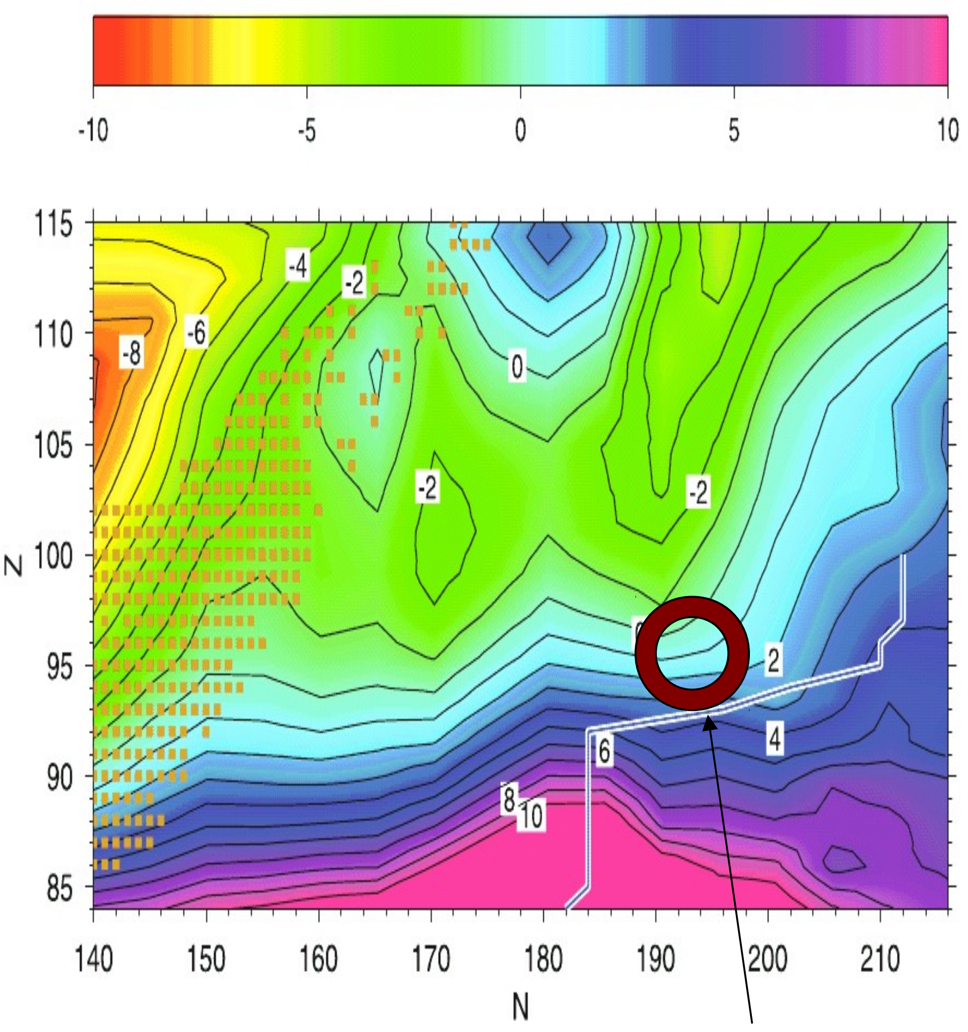
A superposition of expansion velocities might be needed as well, if running into preexpanded material, shocks etc. (Arcones et al. 2007, Panov & Janka 2009, Wanajo 2008). That relates also to the question whether we have a "hot" or "cold" r-process, if chemical equilibria are attained and how long they persist.

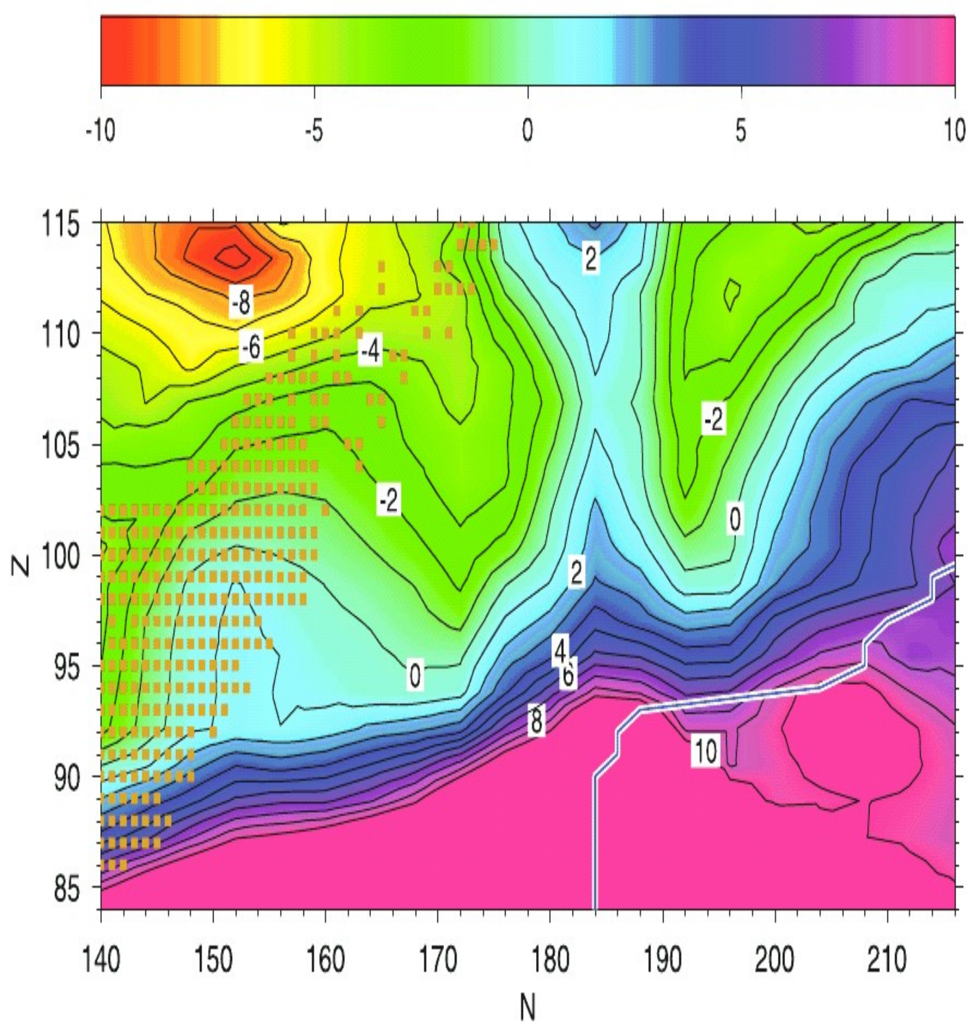


Kratz et al. (2014): Update from FRDM (1995) to FRDM (2012). Problem at A=138 is reduced and rare earth better filled up.

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

(if negative => neutron-induced fission)

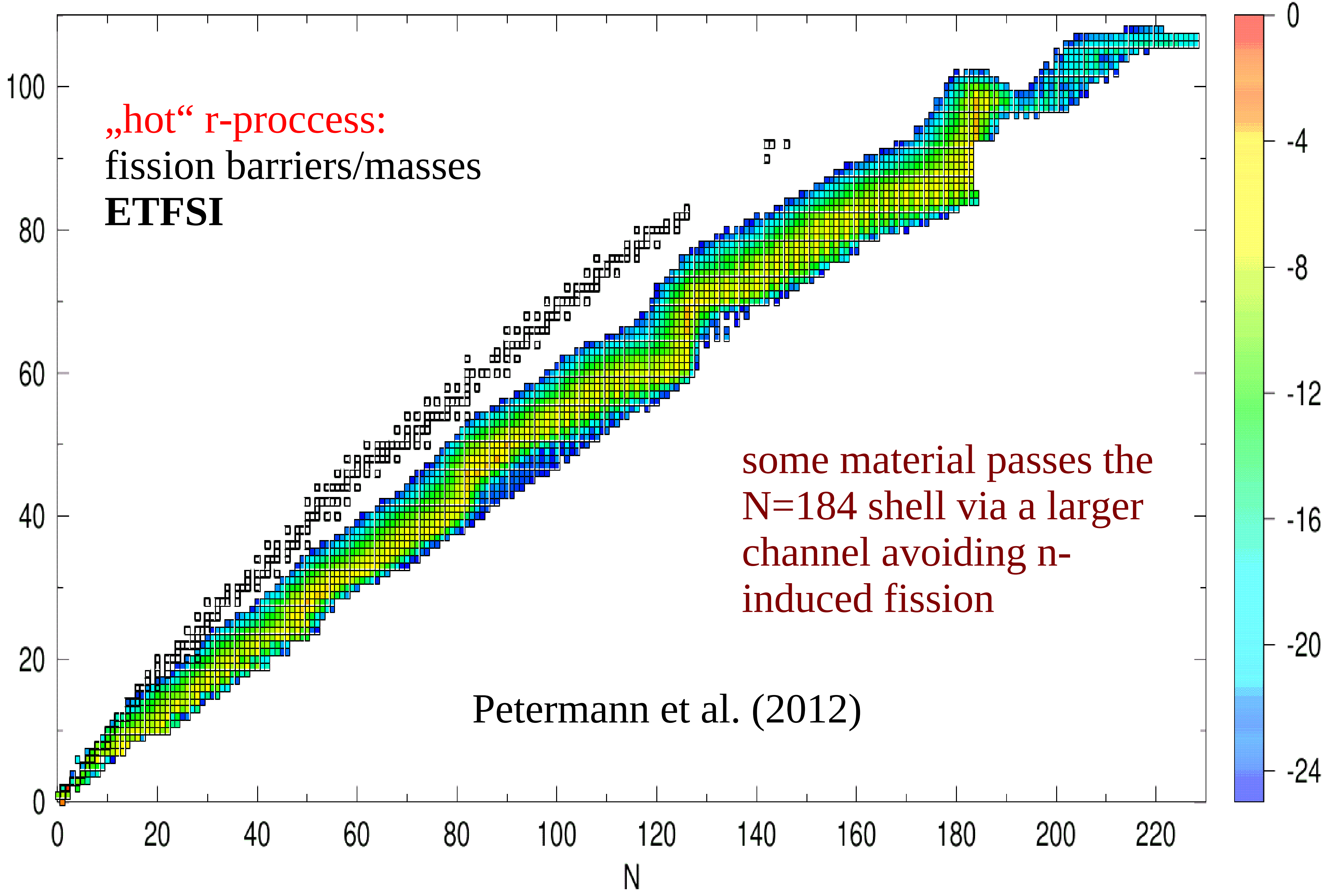




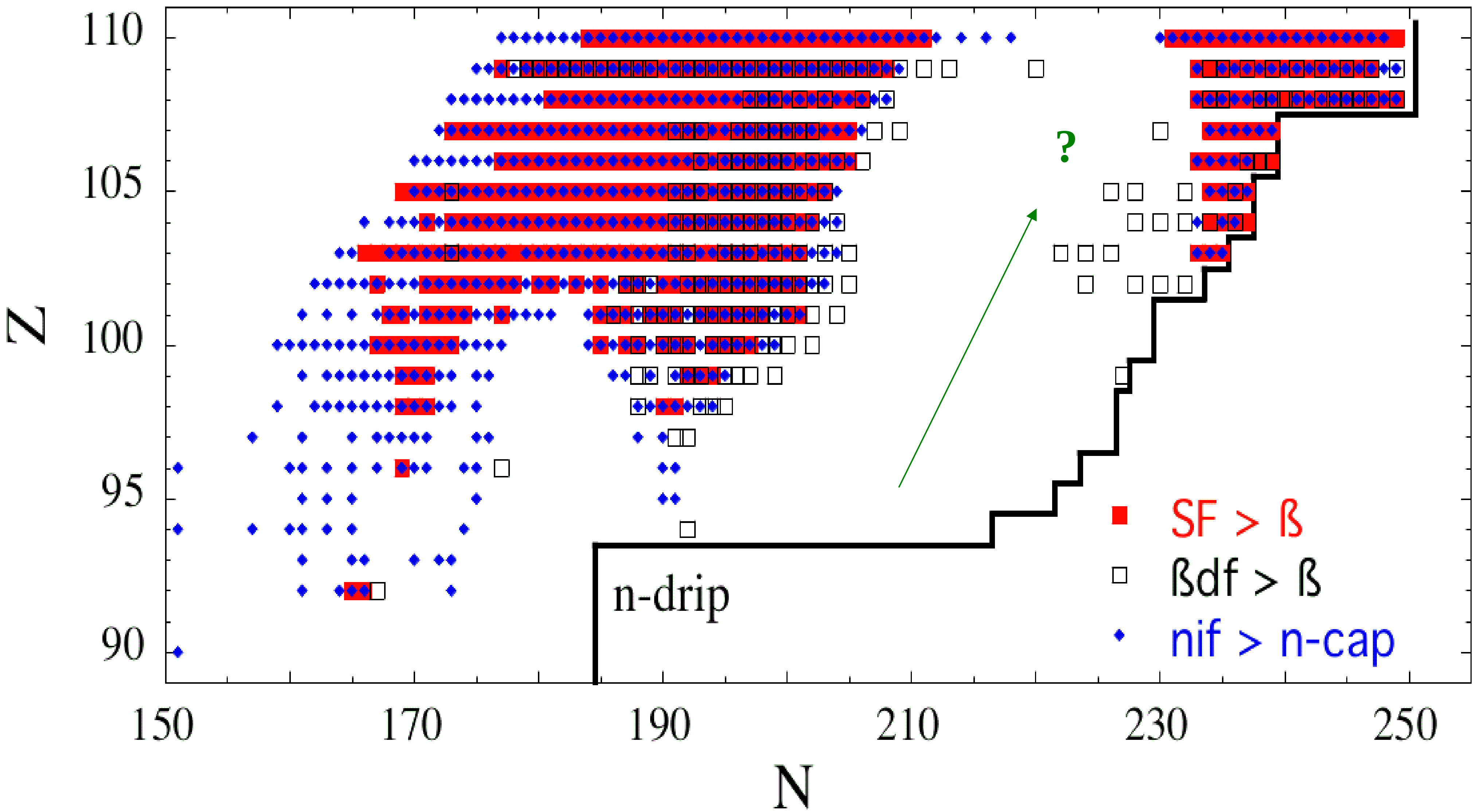
Myers & Swiatecki barriers (TF/FRDM)

narrow path without n-induced fission!

Mamdouh et al. barriers (ETFSI) typically higher barriers

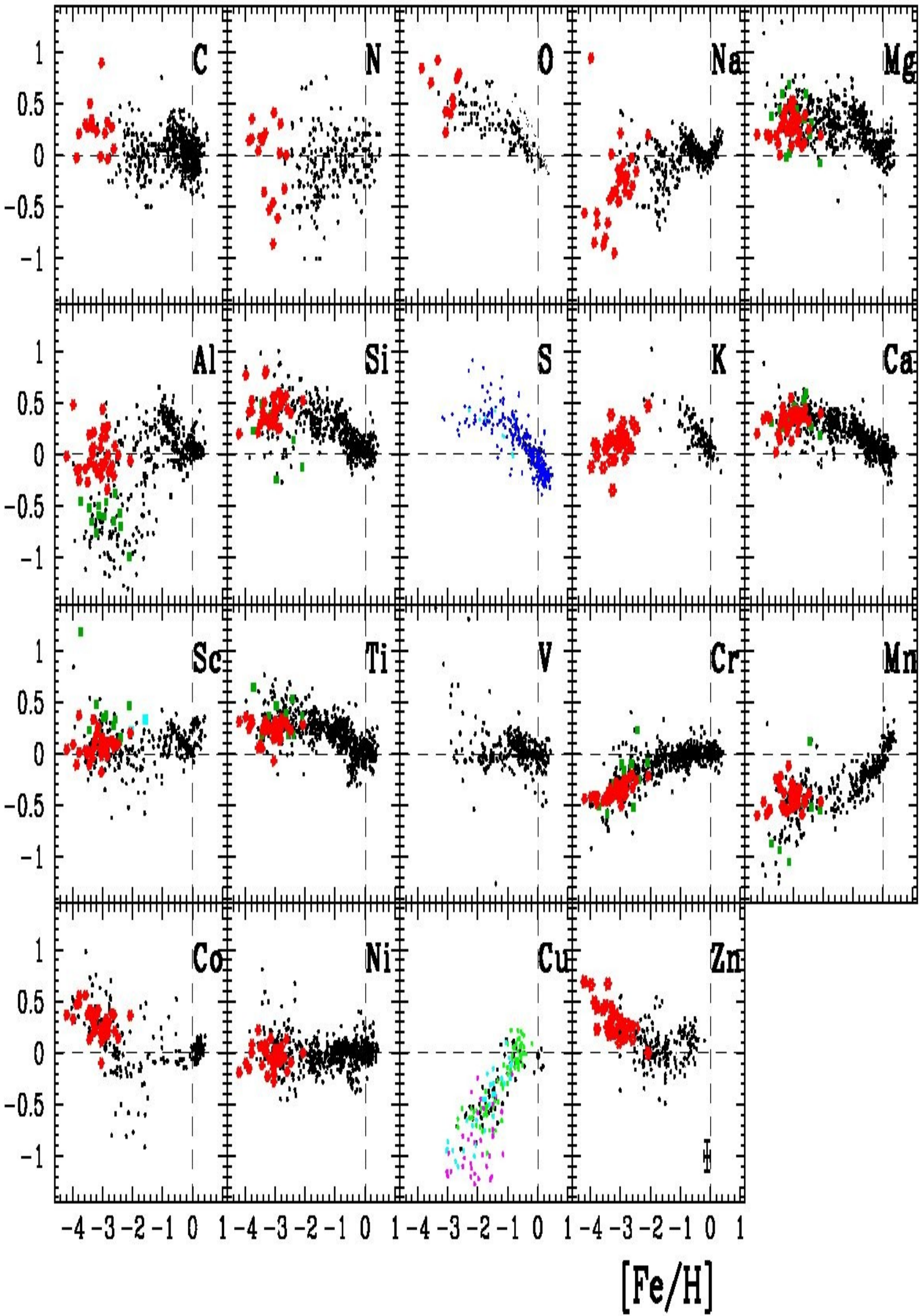

„hot“ r-proccess:
fission barriers/masses
ETFSI
some material passes the N=184 shell via a larger channel avoiding n-induced fission
Petermann et al. (2012)
N
0
20
40
60
80
100
120
140
160
180
200
220
0
20
40
60
80
100
0
-4
-8
-12
-16
-20
-24

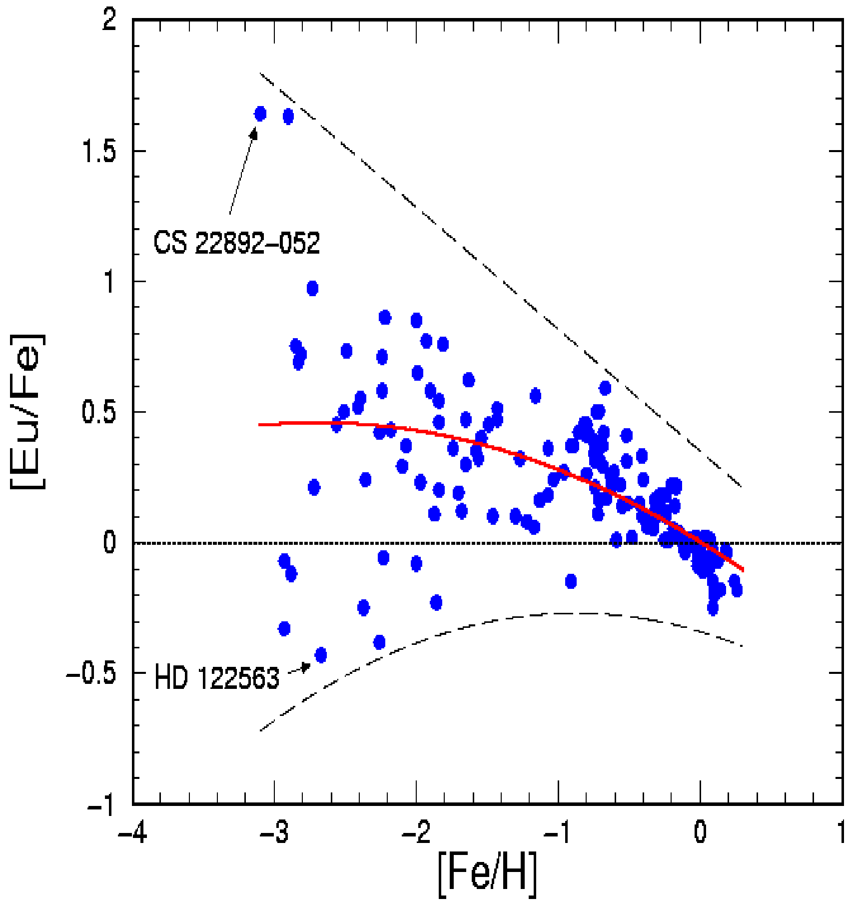
Goriely et al. (2013) HFB



a) double finger shape of sf exists, but moves to lower Z (=102)
b) nf reaches close to the dripline at N=190
c) is there a chance to pass around the „fission island?“ to higher Z and reach stability? **(case 3), further investigations beyond Z=110!** (Erler, Reinhard et al. 2013 **no!**)

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





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

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

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

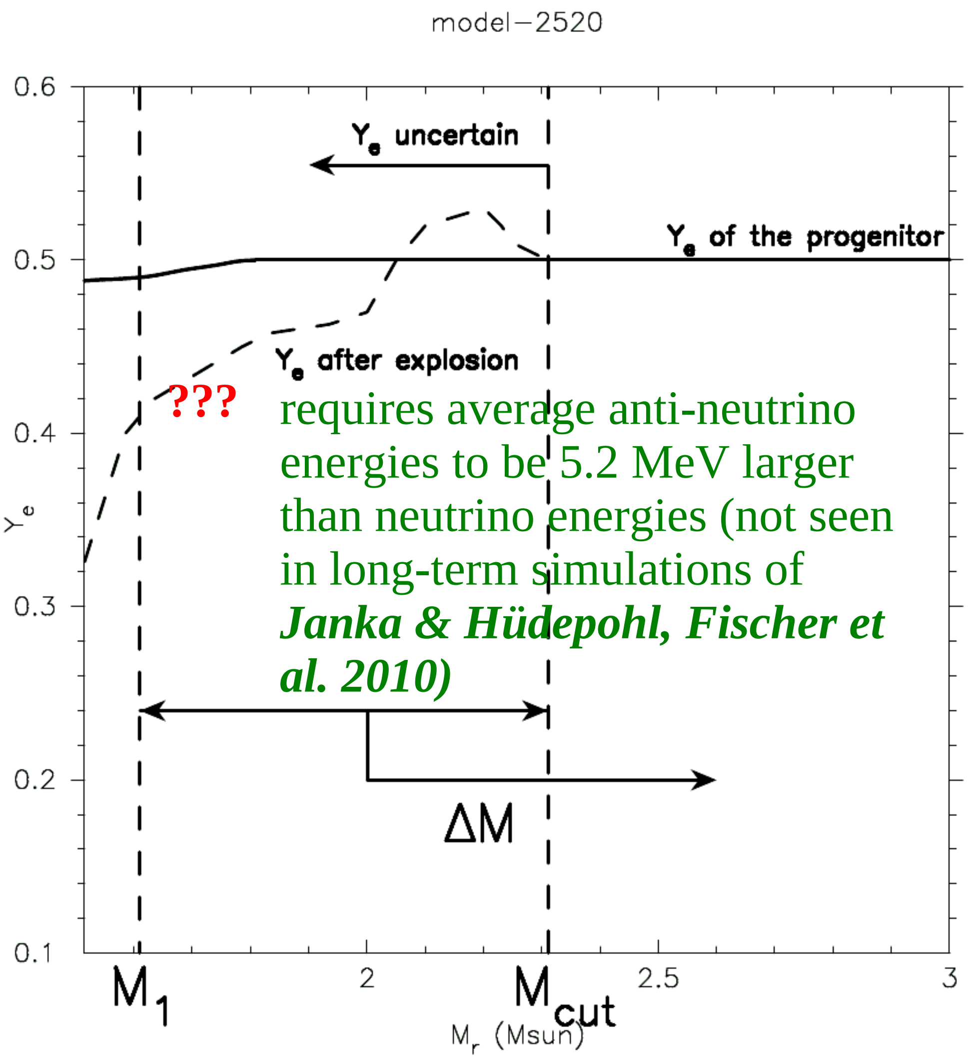
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- high density / low temperature → 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 $E_{av,\bar{\nu}}-E_{av,\nu}>4(m_n-m_p)$ 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
(status before including medium effects)



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!

Inclusion of medium Effects, potential U in dense medium
Martinez-Pinedo et al. 2012, Roberts et al., Roberts & Reddy 2012, changes neutrino and anti-neutrino energies

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

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

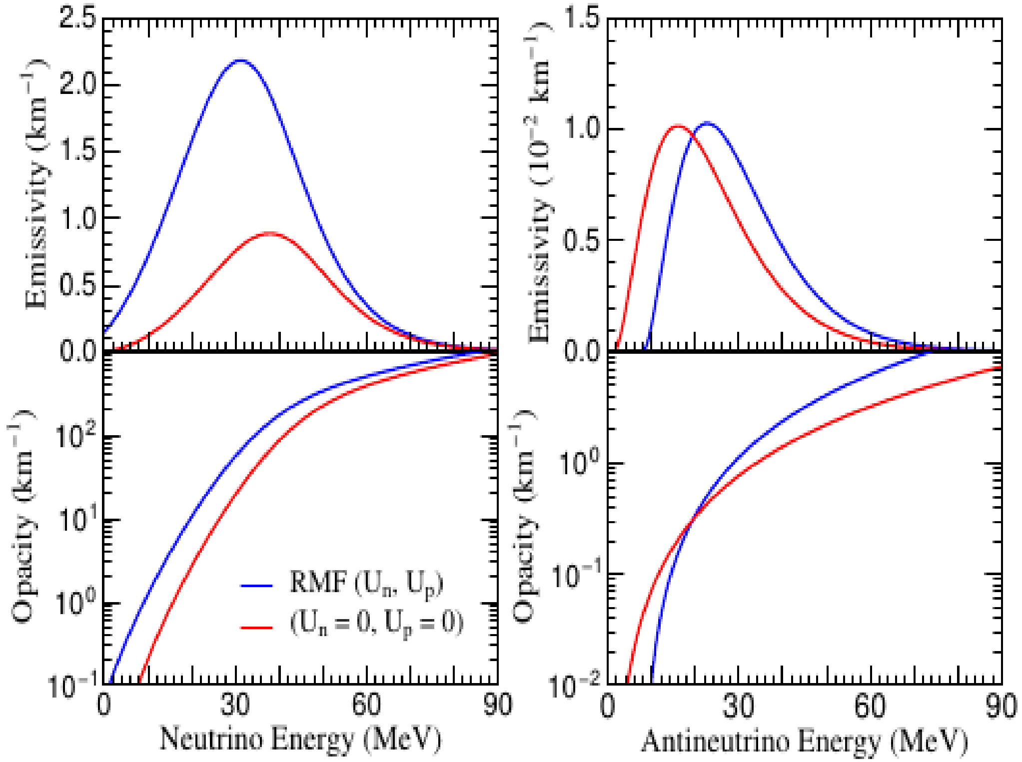


FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4! (further applications to supernova models result in weak r-process? (Lohs et al. 2014)

If including collective neutrinos oscillations, chance to also produce a weak component, but extending up to Eu? (Wu, Fischer, Huther, Martinez-Pinedo, Qian 2014)

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!)*

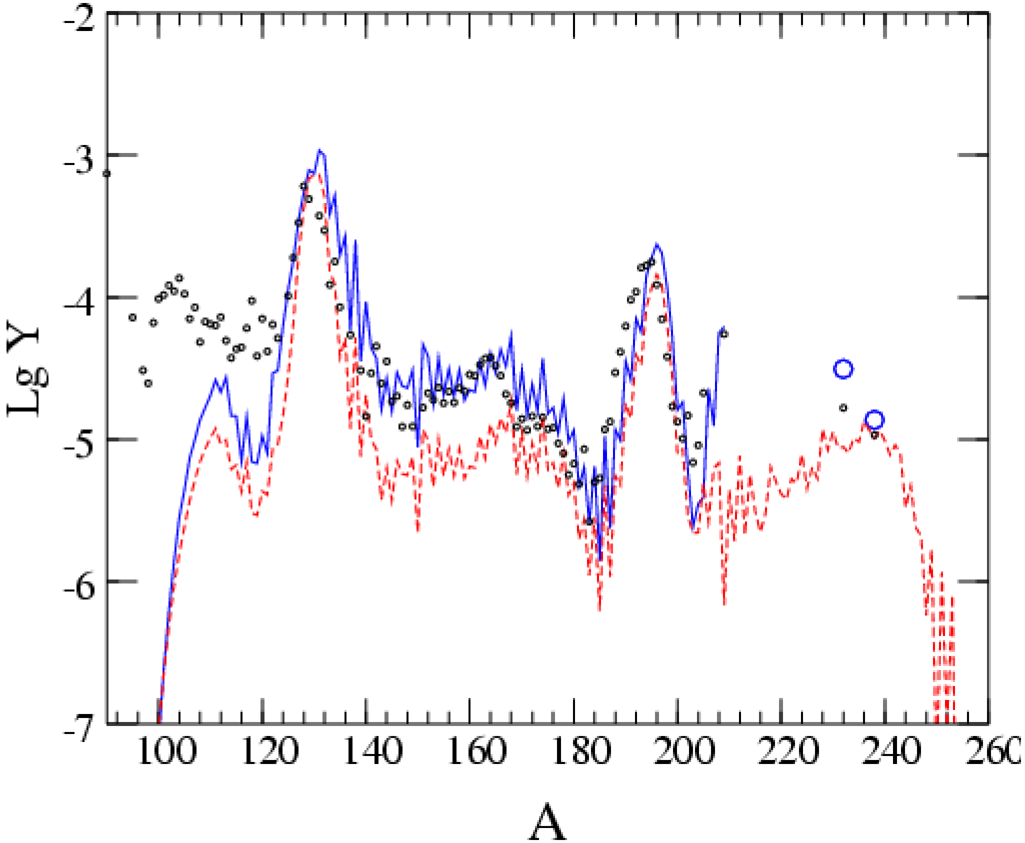
- **Neutron Star Mergers?** ***Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin, Wanajo, Just, Martin, Perego***
- **Black Hole Accretion Disks (massive stars as well as neutron star mergers, neutrino properties)** ***MacLaughlin, Surman, Wanajo, Janka, Ruffert, Perego***

- 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 ?)*

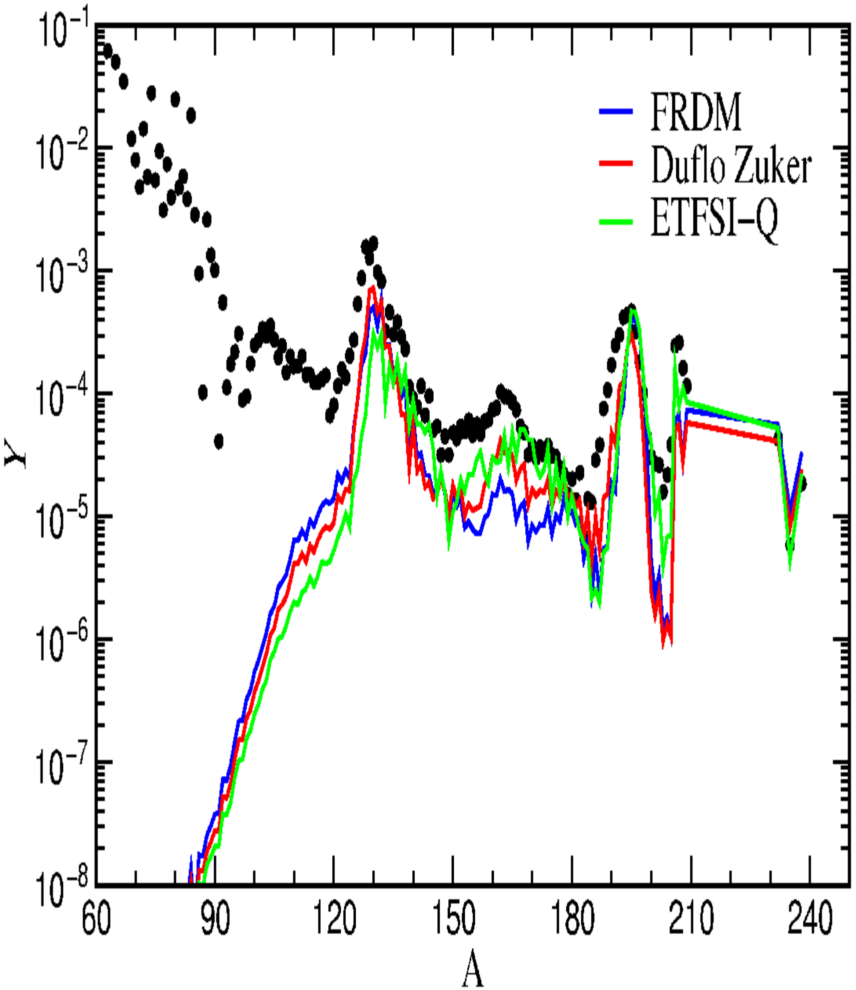
- **Polar Jets from Rotating Core Collapse?** ***Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura, Nishimura, Takiwaki, FKT, Winteler, Mösta, Ott***

Fission Cycling in Neutron Star Mergers

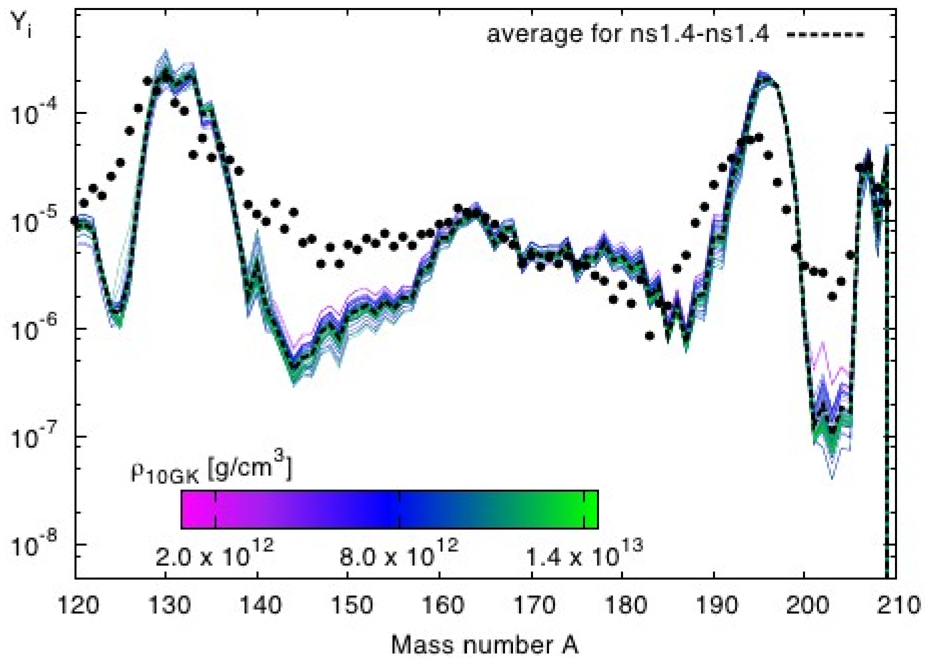


Panov, Korneev and Thielemann (2007, 2009) with parametrized fission yield contributions

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



Martinez-Pinedo et al. (2006)



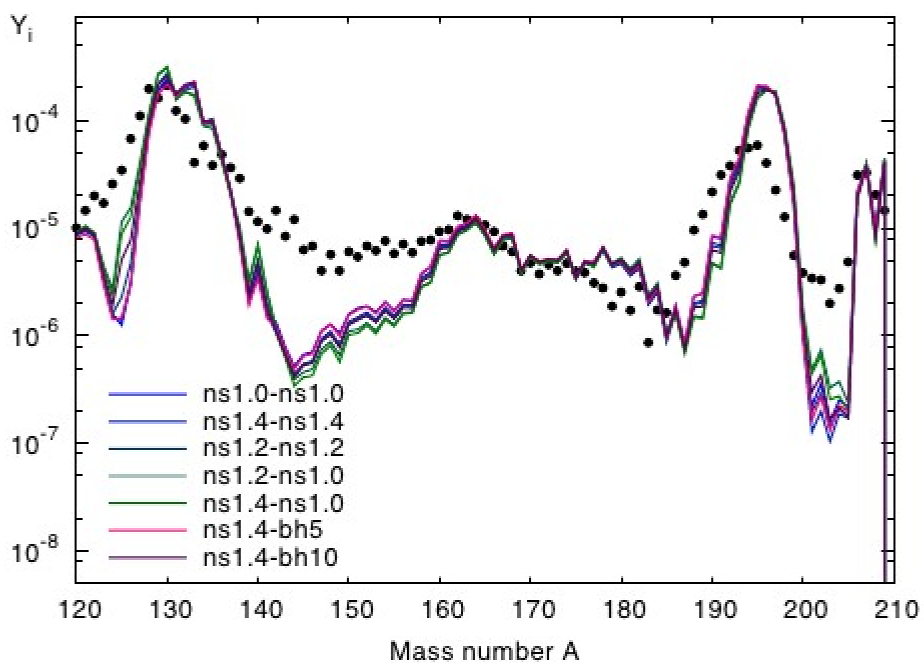
Neutron star merger updates (Korobkin et al. 2012)

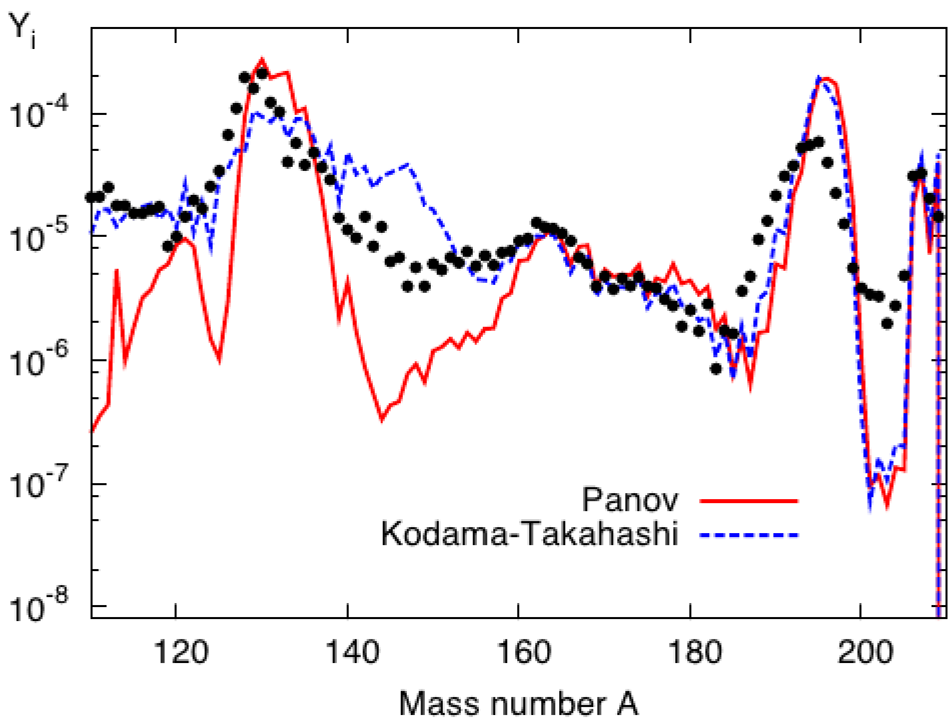
Variation in neutron star masses

fission yield prescription

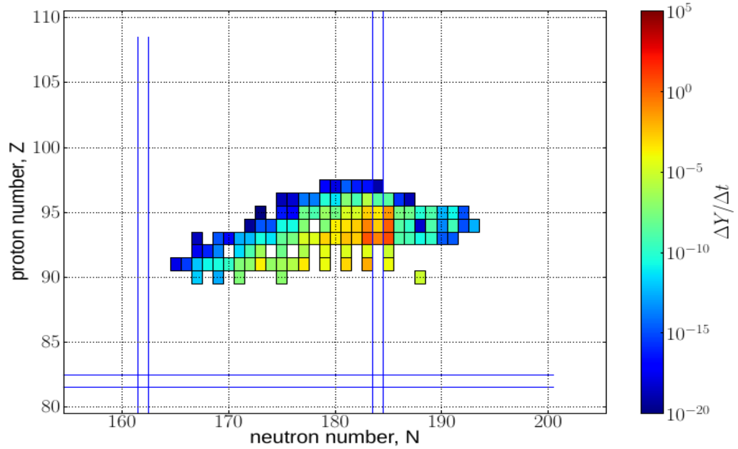
Fission yields affect abundances below A=165,

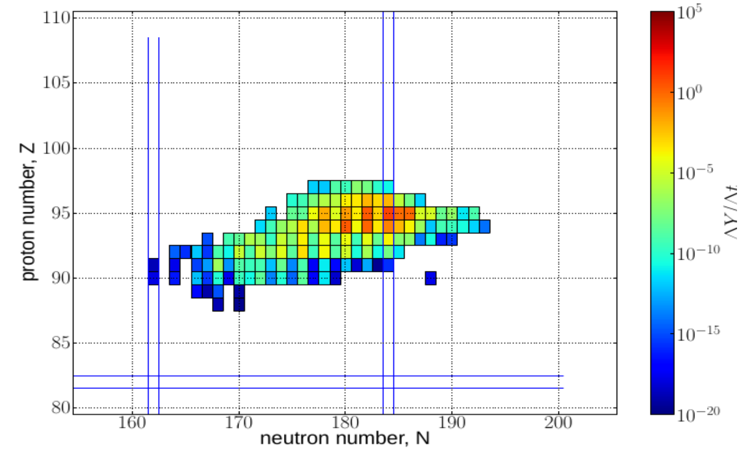
The third peak seems always shifted to heavier nuclei

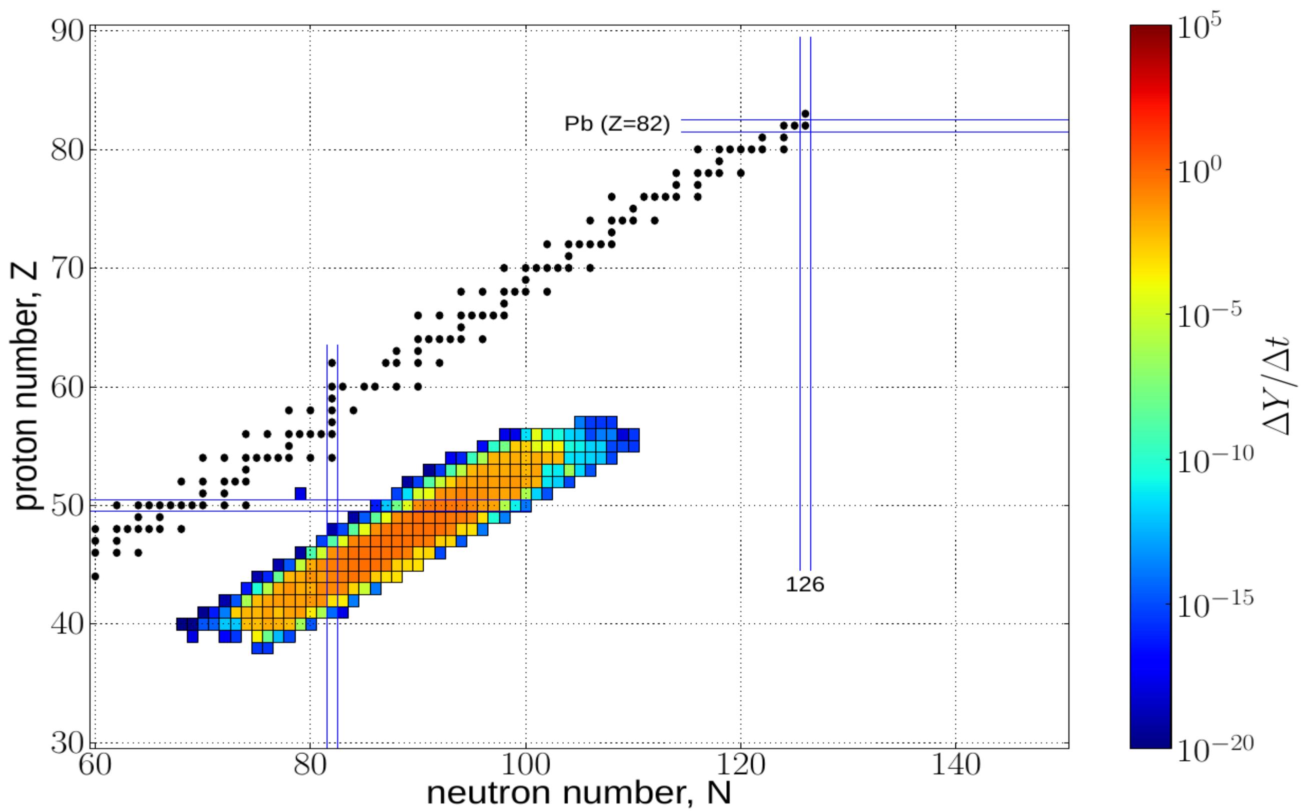




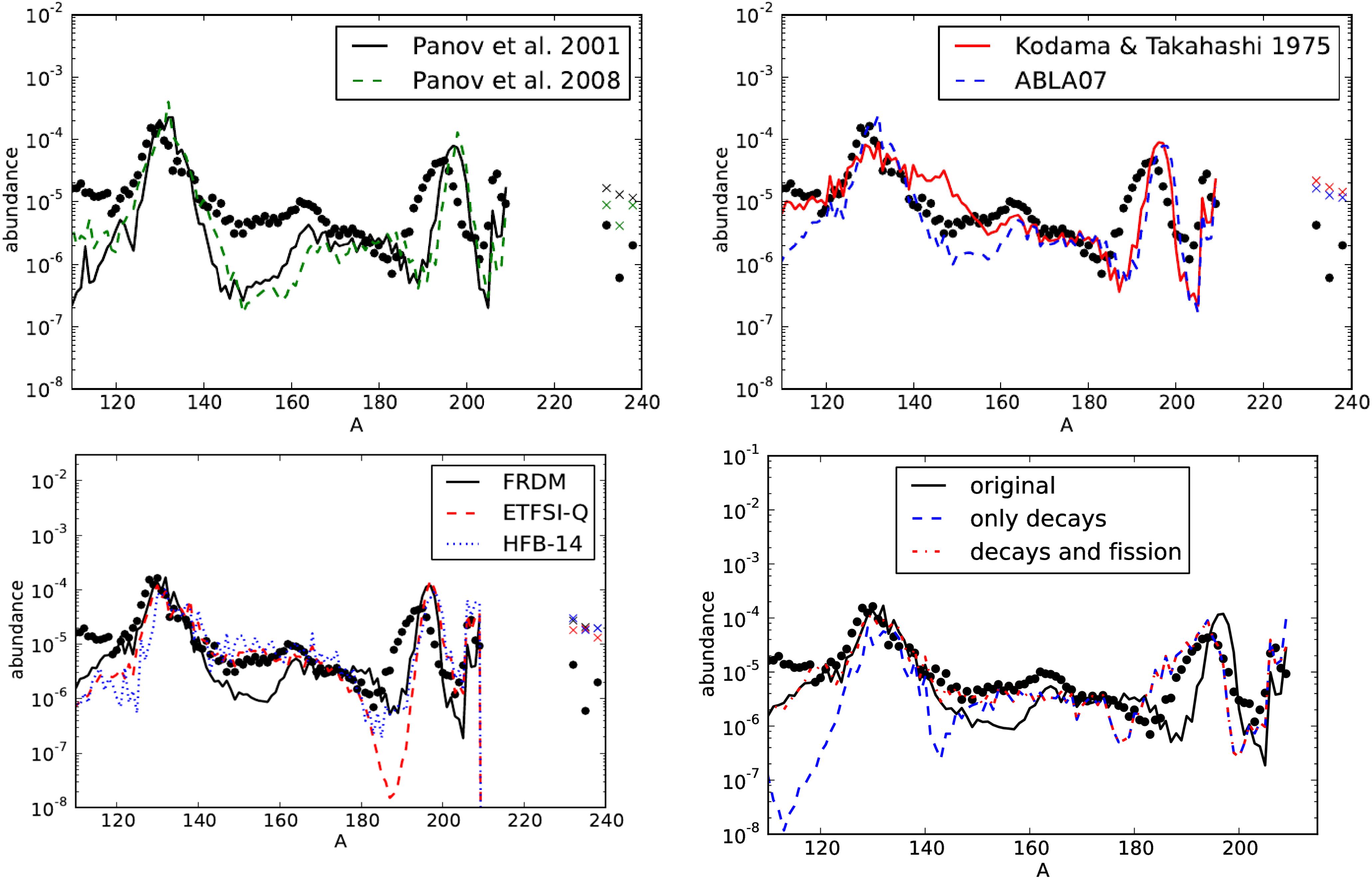
(n,f), (β,f) and fission yield distribution (Eichler et al. 2014, 2015)

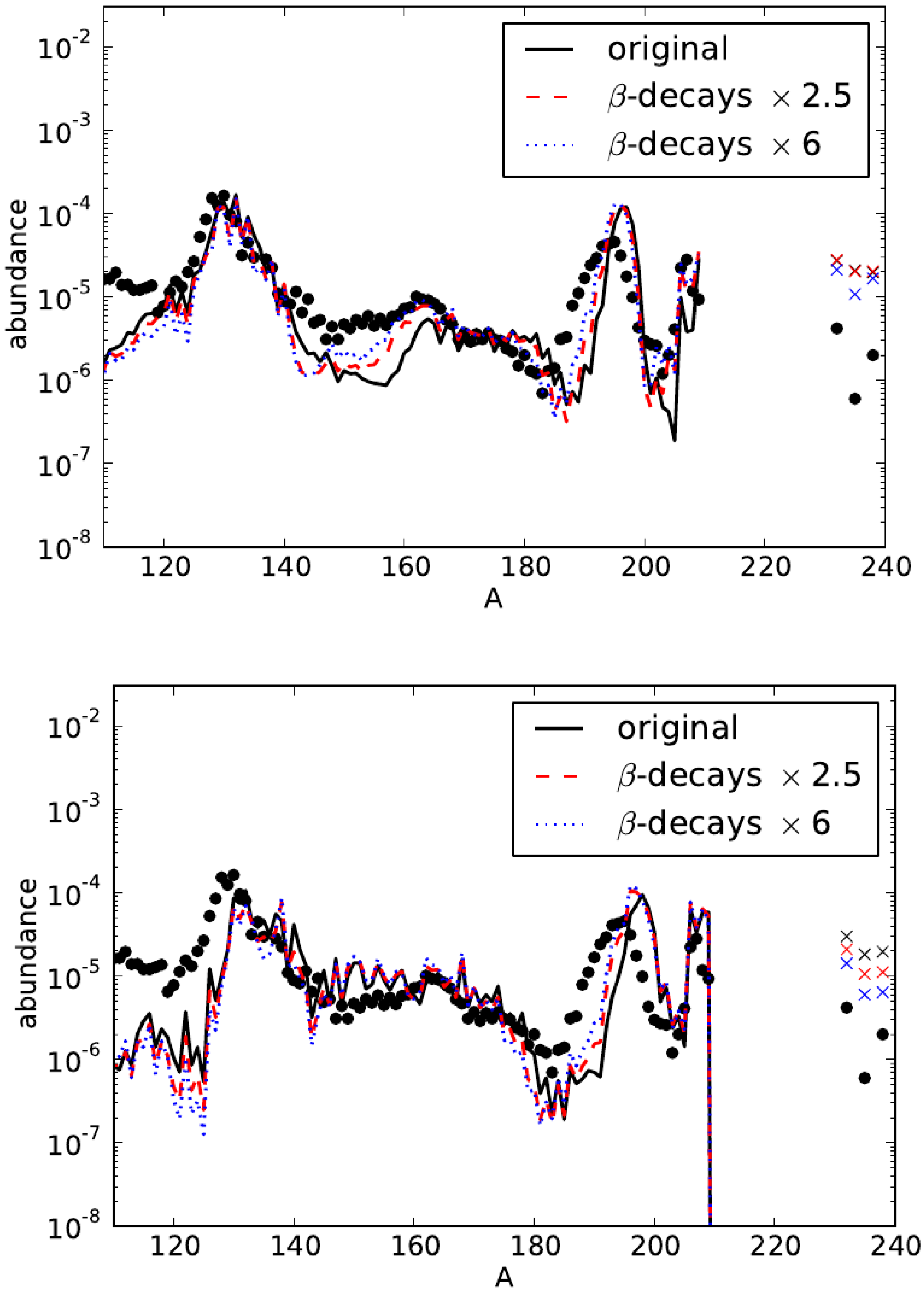






Further Tests: Eichler et al. (2014, 2015)





Varying beta-decay rates for Z>80

Leading to earlier fission of heaviest nuclei, earlier neutron release (before n,g-g,n freeze-out

Avoiding the shift of the third Peak to some extent

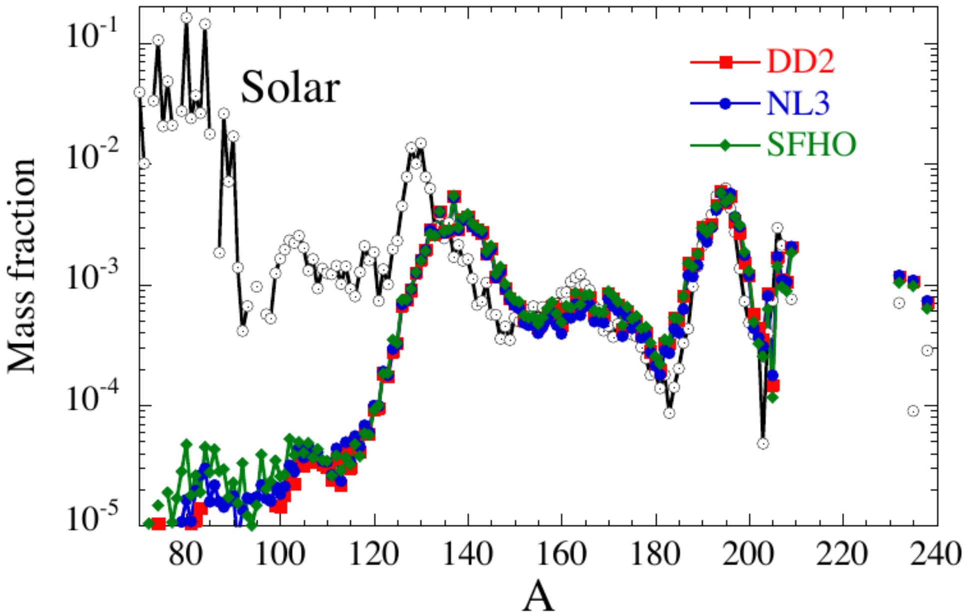
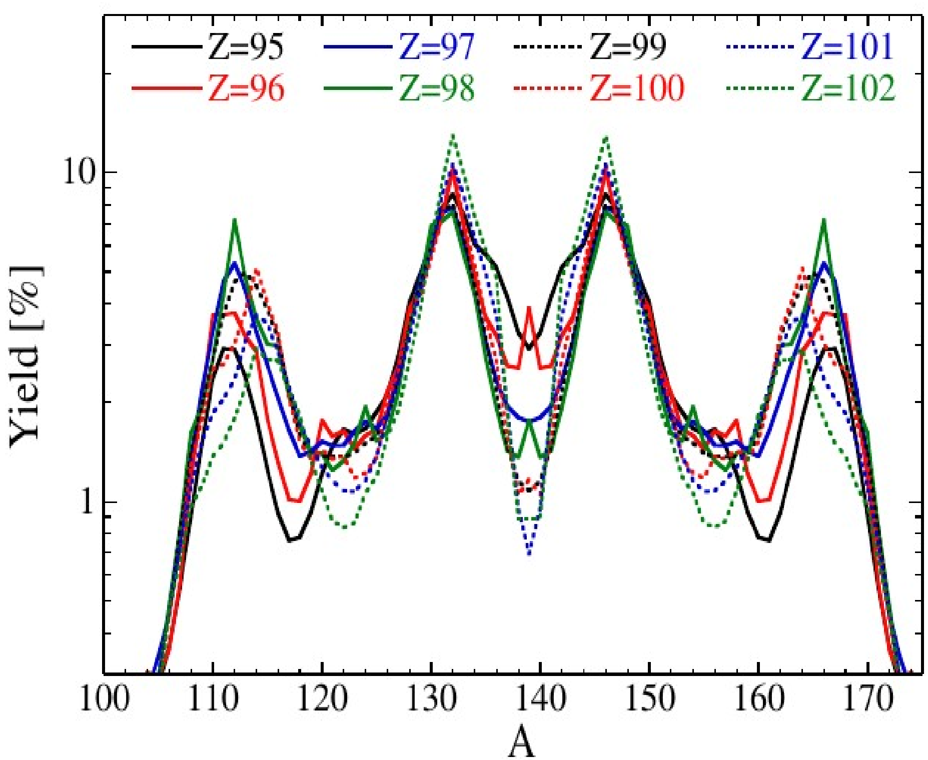
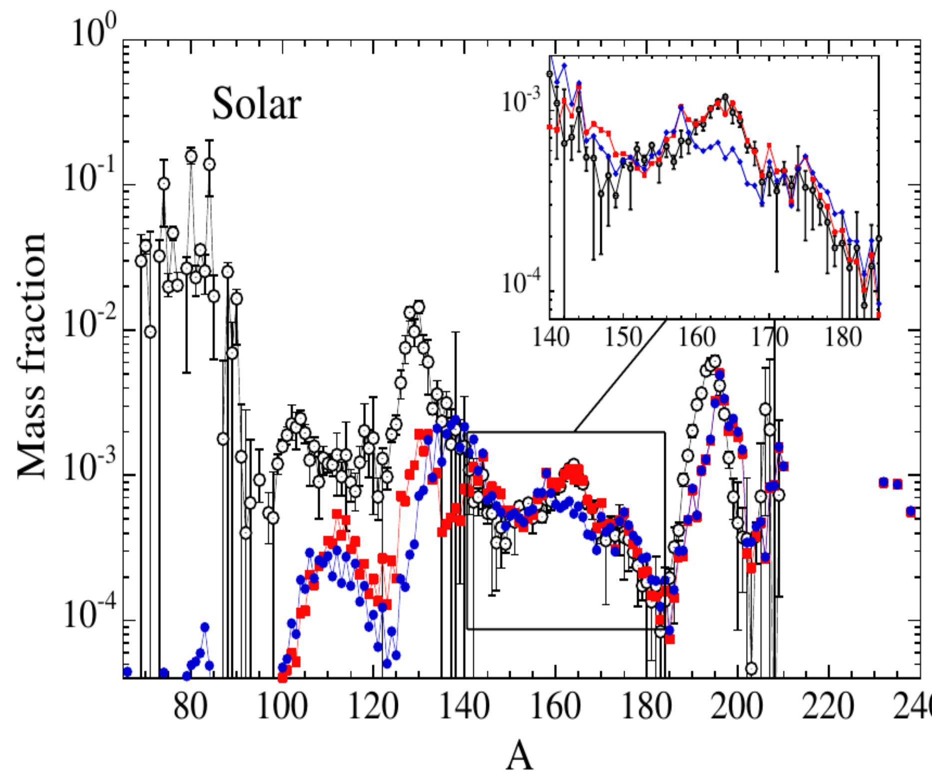


FIG. 9.— Nuclear abundance pattern for the 1.2-1.5 $M_\odot$ mergers with the NL3 (blue), DD2 (red) and SFHO (green) EoSs compared to the solar r-process abundance distribution (black).

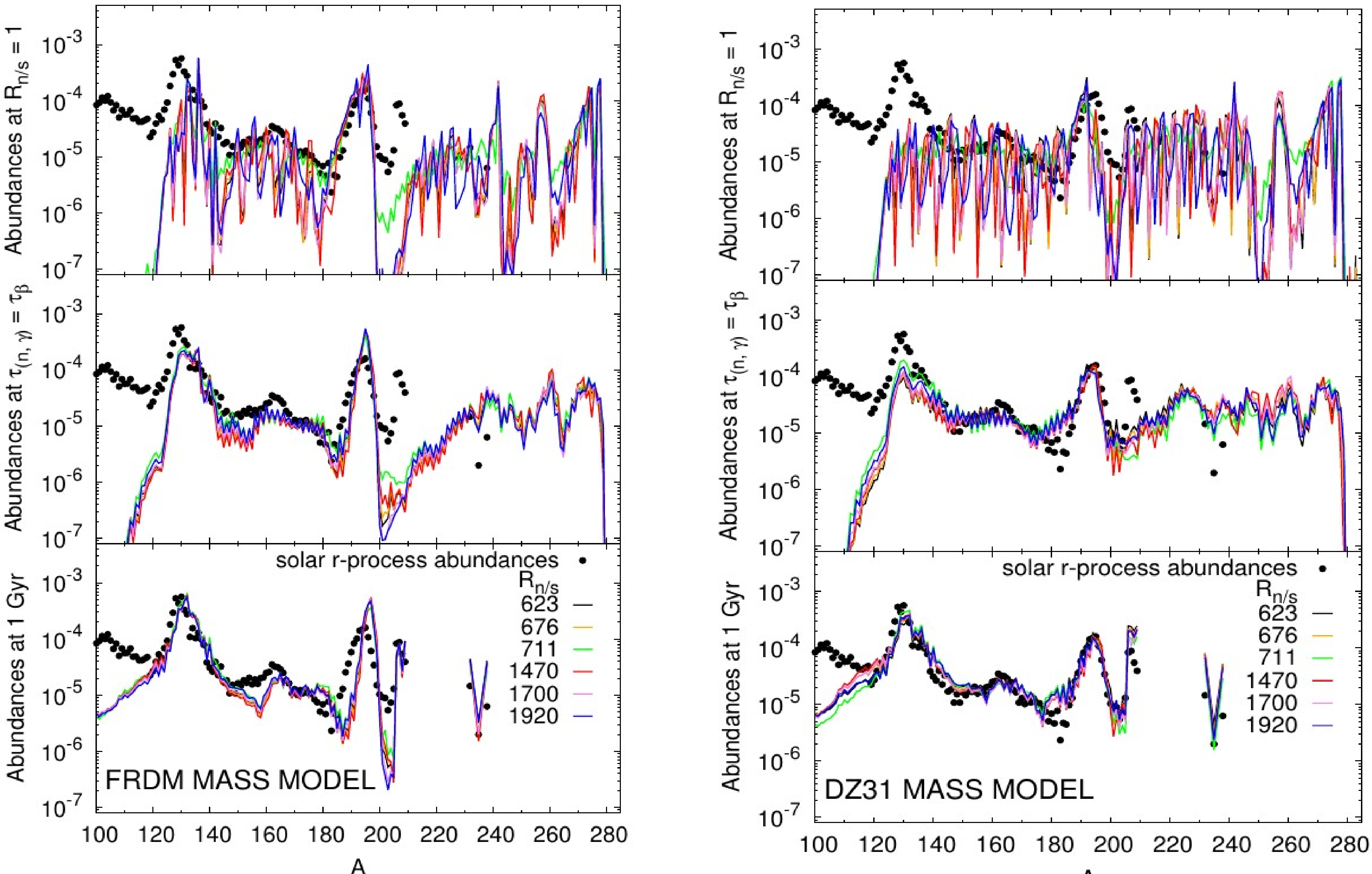
← Results by Bauswein et al. (2012), utilizing different neutron star equations of state (no neutrons included in fragment distribution)

fragment distribution from new scission-point model, including neutron release (SPY, Goriely et al. 2013), **improved rare-earth peak, but also now shift or 3rd peak!!**



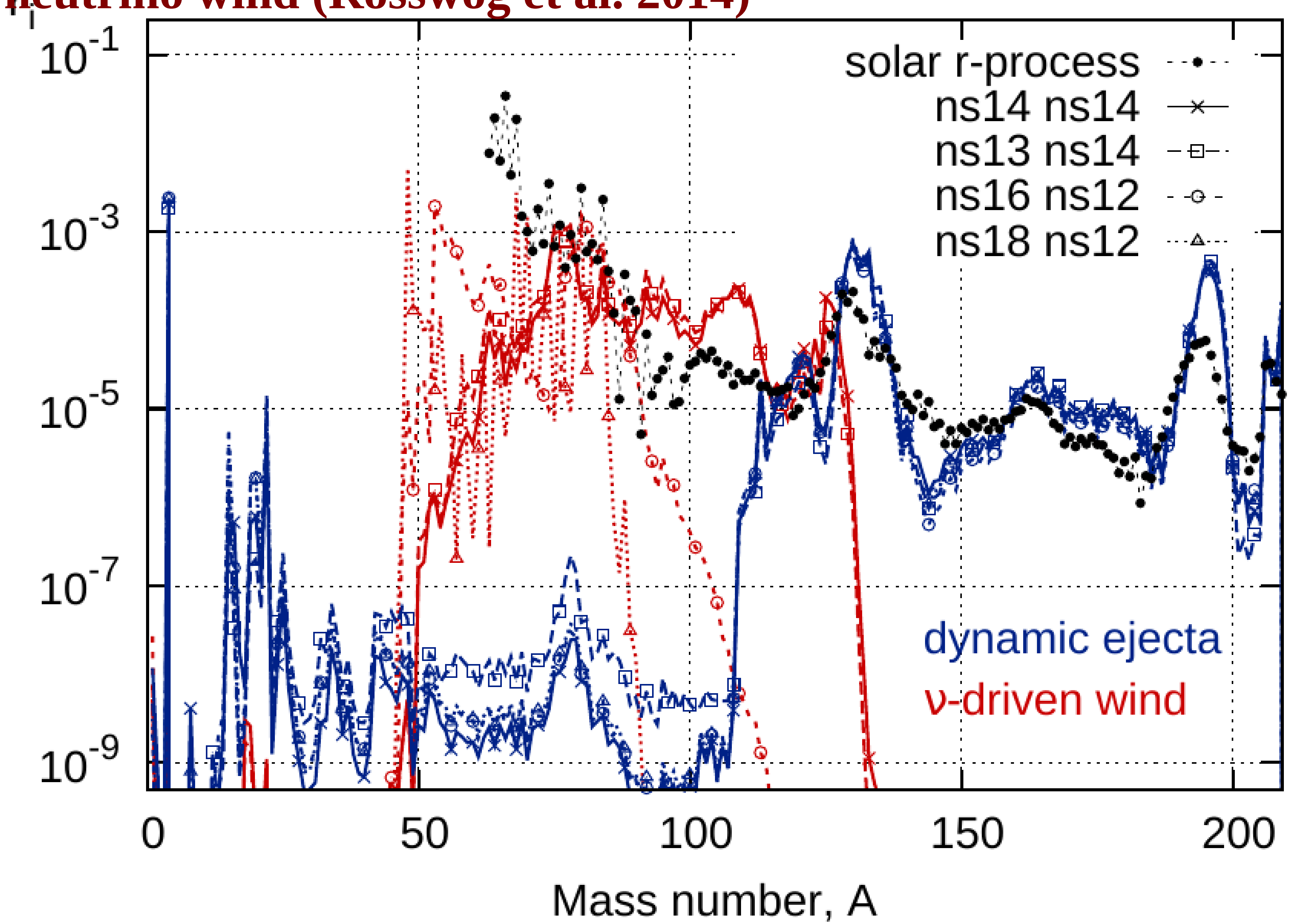


Mendoza-Tenis et al. (2014)

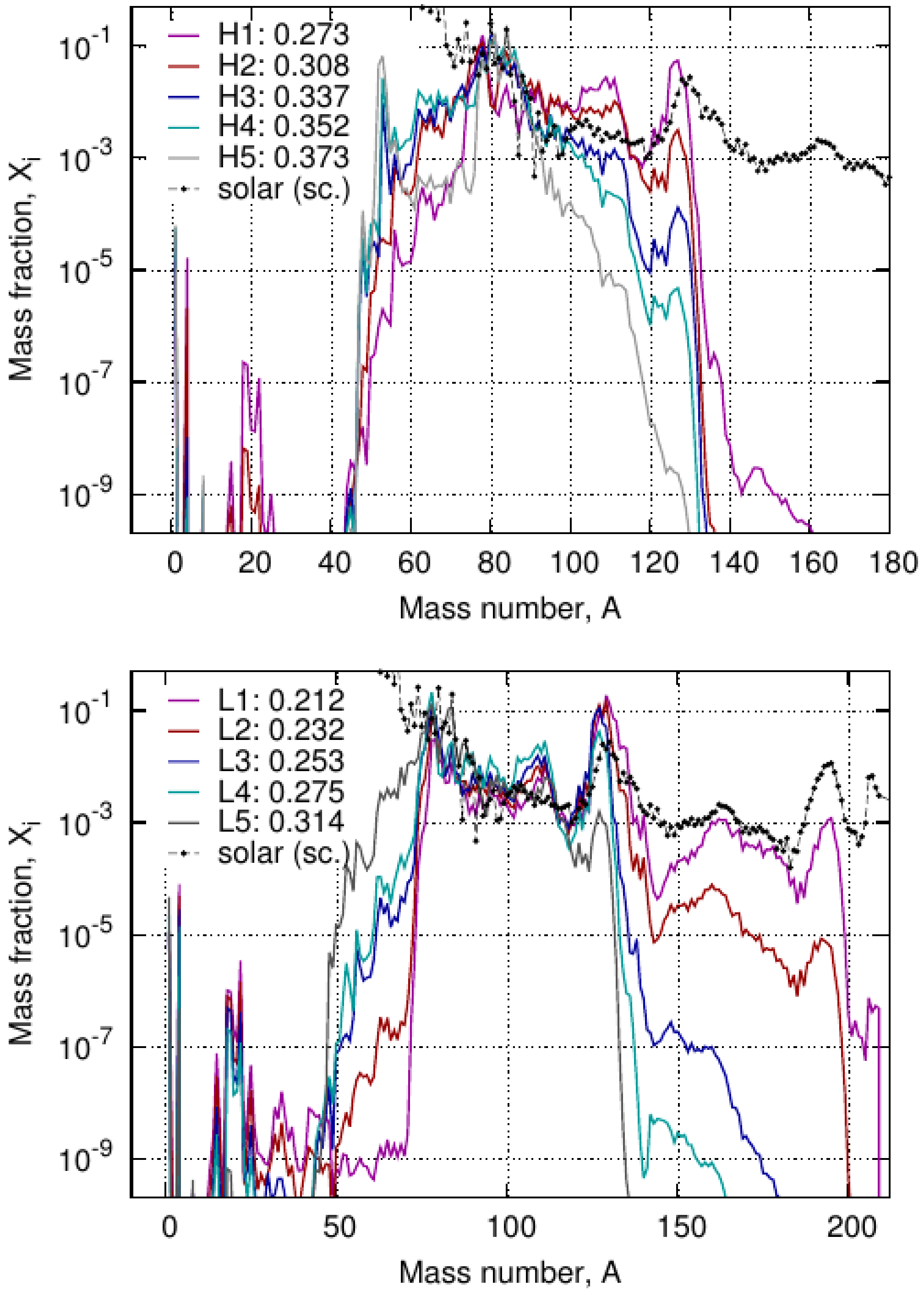


at n/seed=1, n-capture rates = beta rates, and final distribution after decay

After ballistic/hydrodynamic ejection of matter, the hot, massive combined neutron star (before collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014)

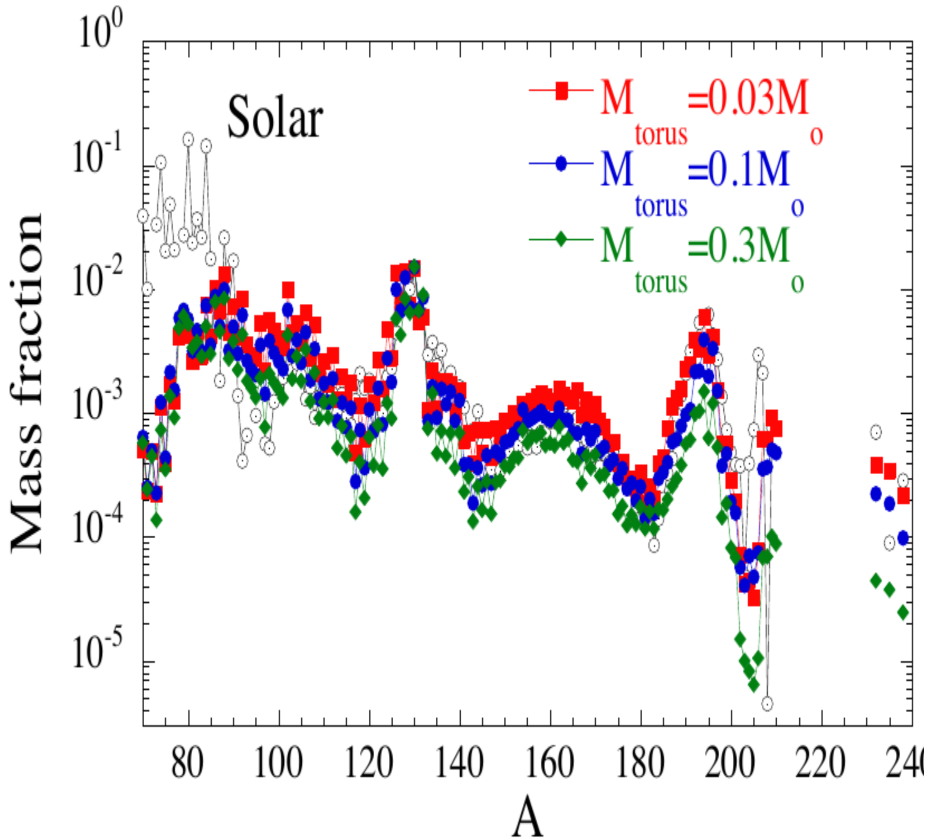


Further work on neutrino wind by A. Perego et al. (2014), A. Perego, D. Martin, A. Arcones, O. Korobkin et al.



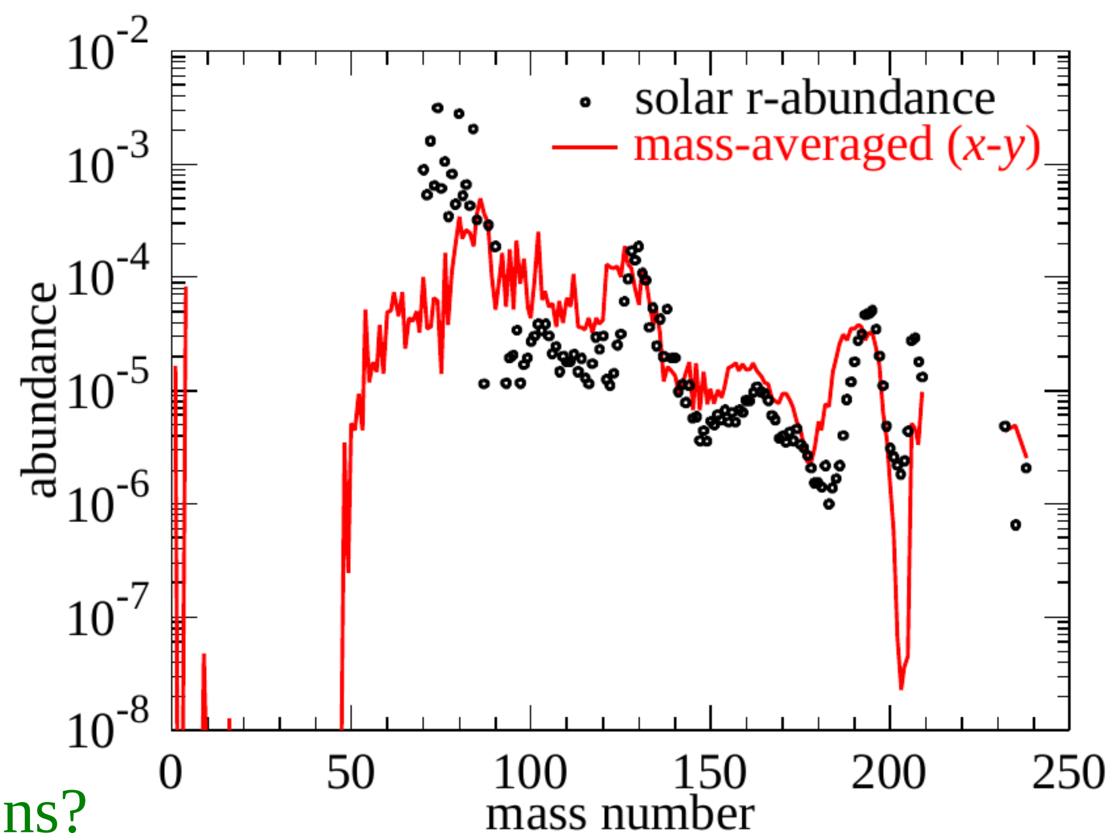
Perego, Martin, Arcones et al (2014):

Neutrino wind ejecta from neutron star mergers



Full predictions with dynamic ejecta, viscous disk ejection, and late neutrino wind, but old (neutron-less) fragment distribution *(Just et al. 2014)*, based on smooth particle hydrodynamics and conformal flat treatment of GR.

General relativistic grid calculations, possibly leading to hot shocks, and e+e- pairs, which affect Ye and the position of the r-process peaks **(Wanajo et al. 2014)** ? Higher Ye alone would shift peaks to the right (r-path closer to stability), high temperatures from heating as well. What is the reason for the peak positions?



SN rates and NS merging rate (from Matteucci 2013)

The SN II and Ia rates compared with the NS merger rate (100 yr^{-1})

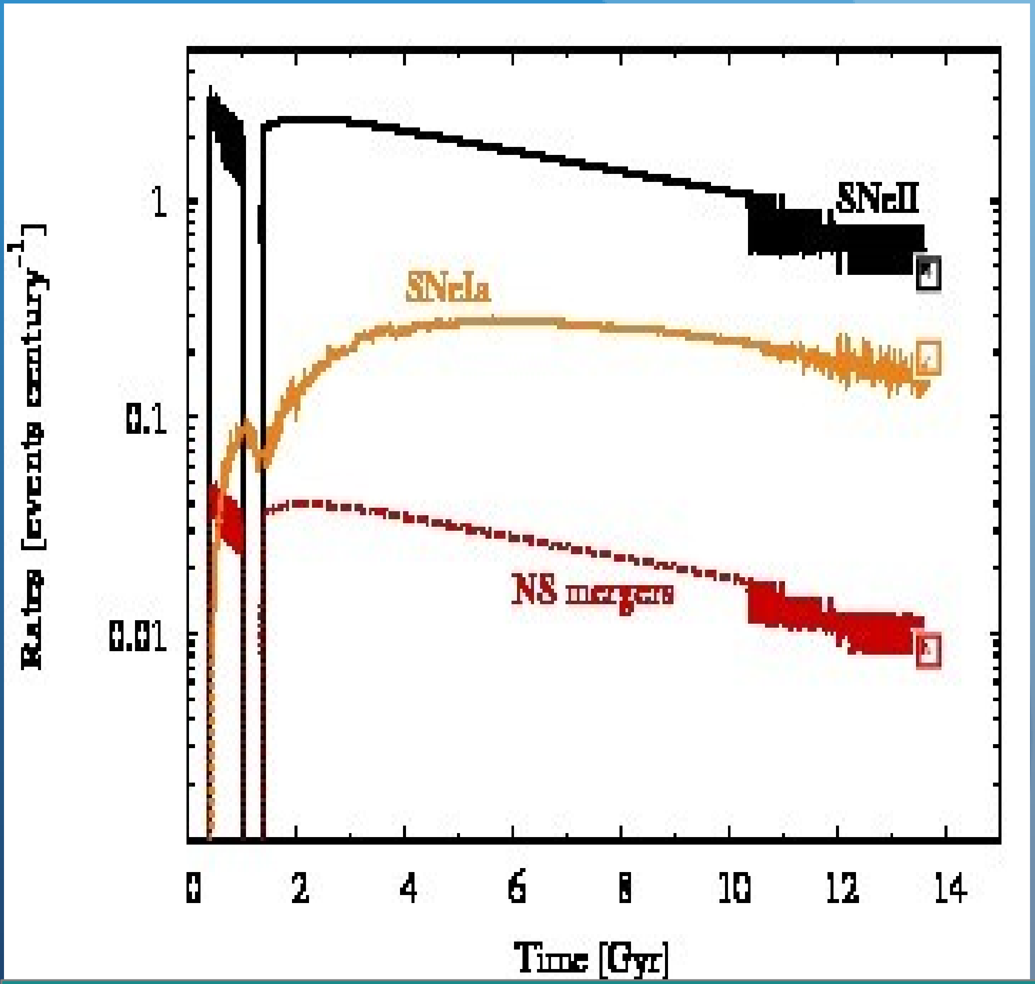
The present time NS merger rate reproduces the observed present time NS merger rate of 83/Myr (Kalogera et al. 2004)

This is obtained with alpha=0.018

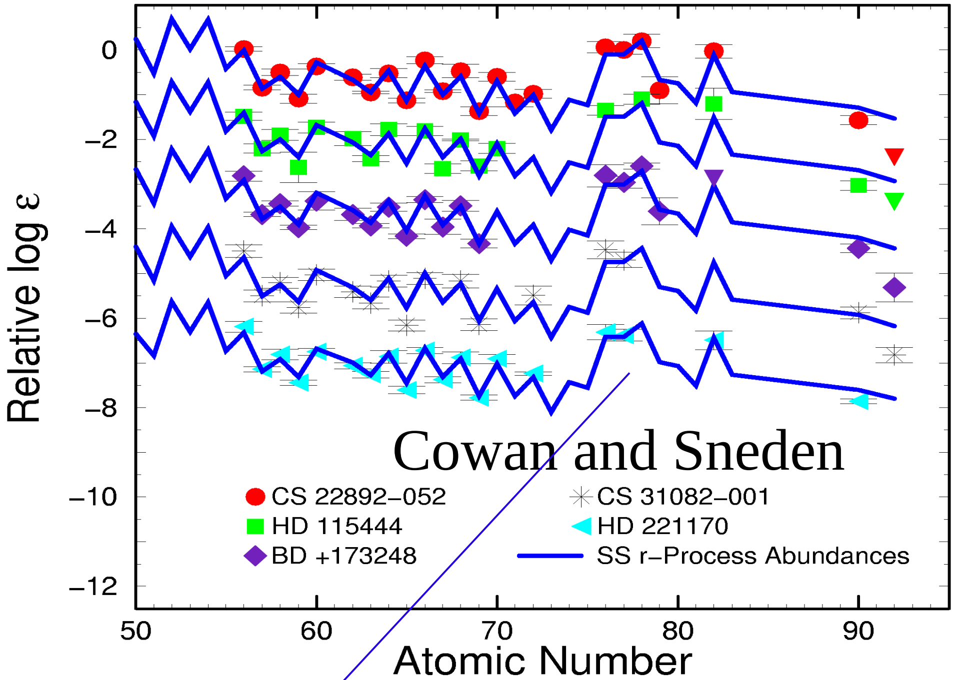
(fraction of NS mergers from total NS production rate).

The rate of mergers is by a factor of about 100 smaller than CCSNe,

but they also produce more by a factor of 100 than required if CCSNe would be the origin



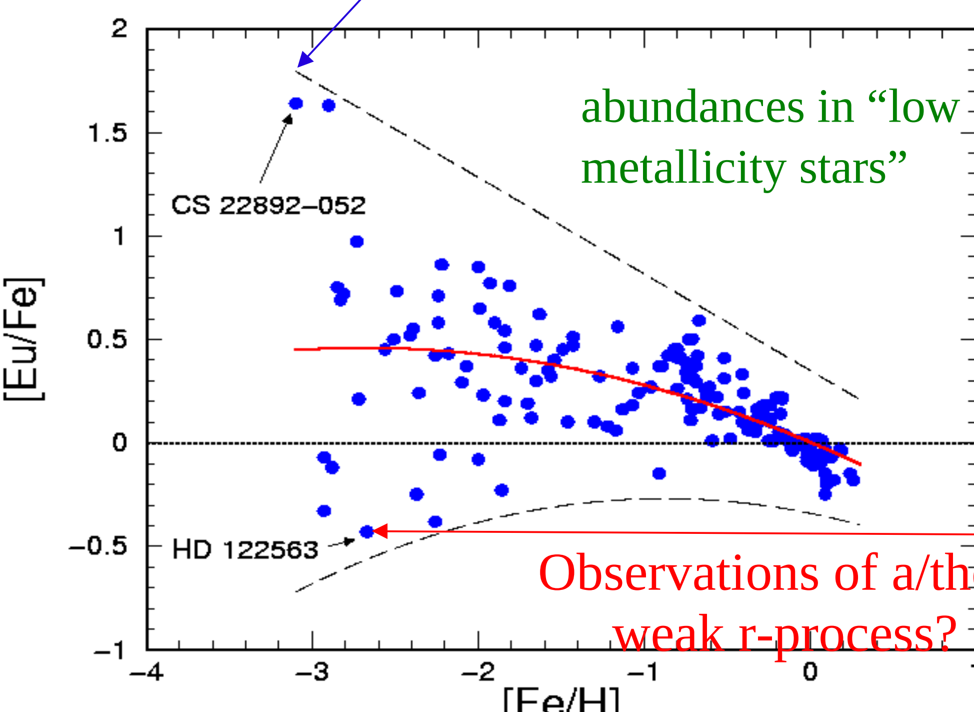
Observational Constraints on r-Process Sites



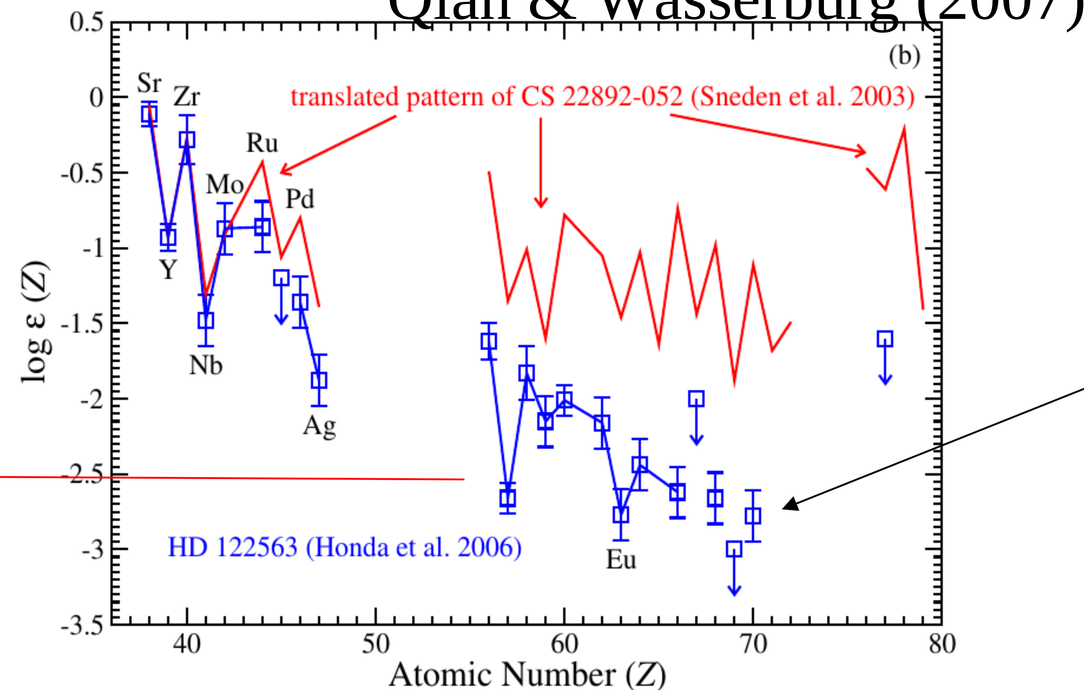
apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event for these "Sneden-type" stars

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

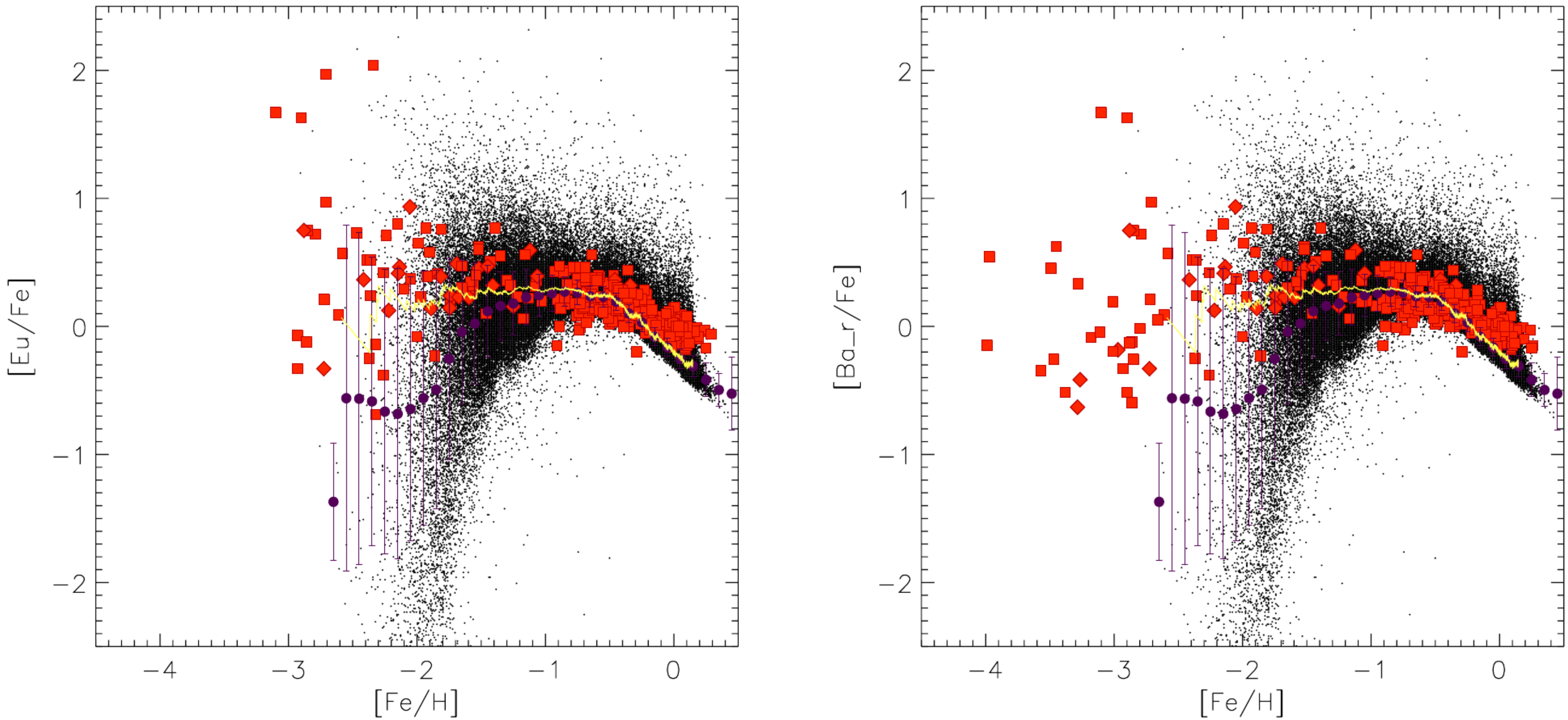
related to massive stars due to "early" appearance at low metallicities (behaves similar to SN II products like O, but with much larger scatter), why the large scatter?



Qian & Wasserburg (2007)



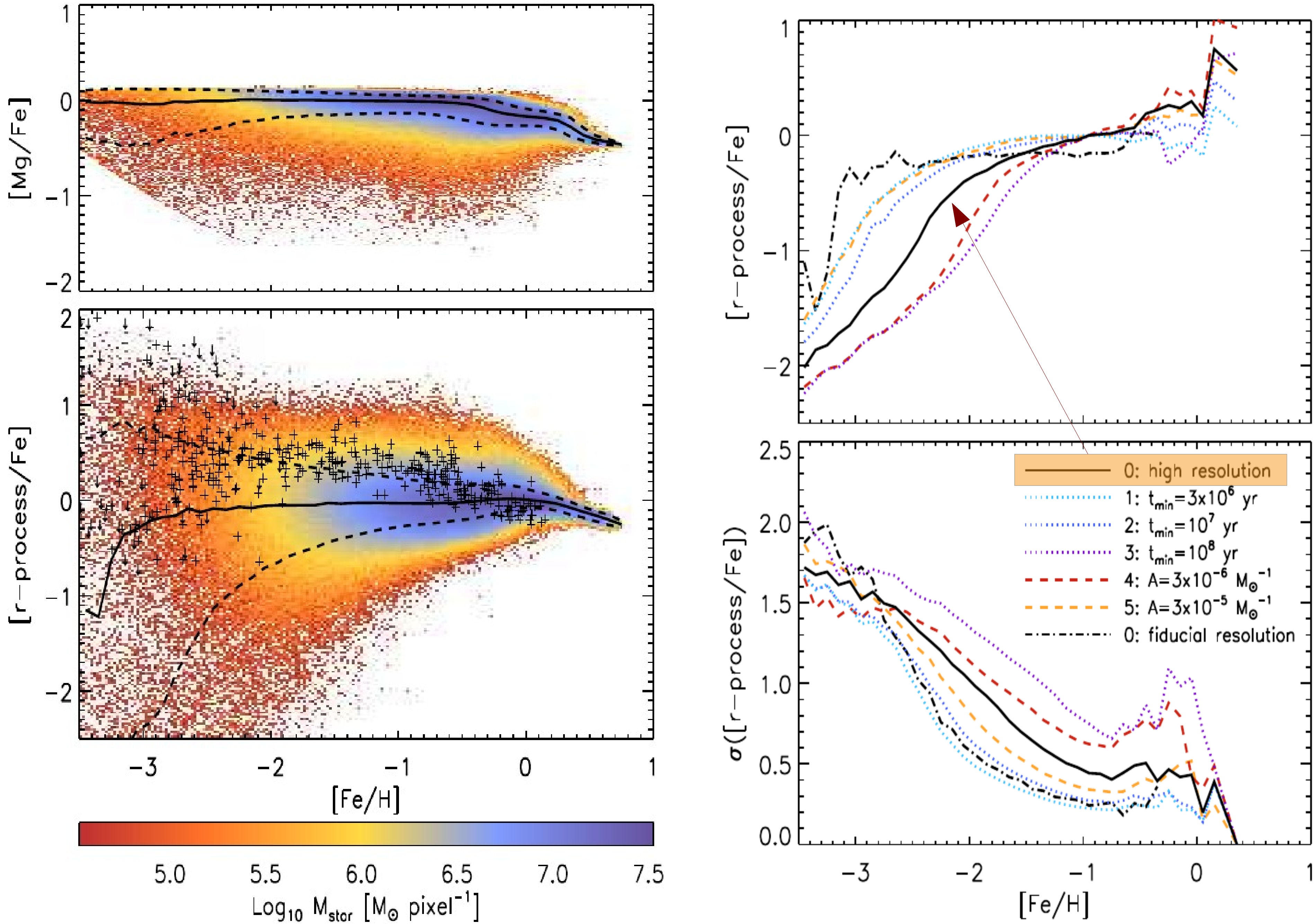
Argast, Samland, Thielemann, Qian (2004): Do neutron star mergers show up too late in galactic evolution, although they can be dominant contributors in late phases?

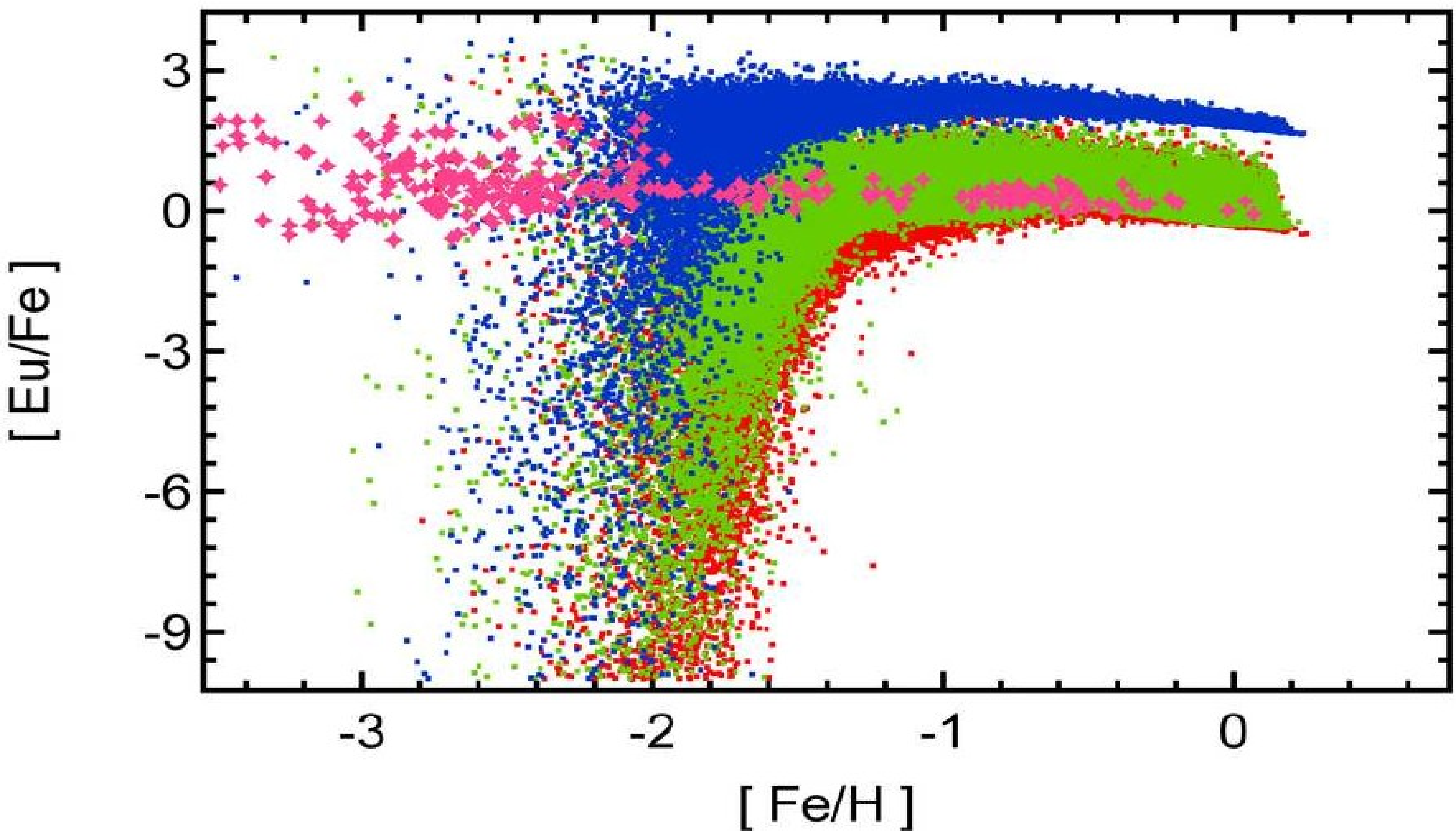


'ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

This is the main question related to mergers, ([Fe/H] can be shifted by different SFR in galactic subsystems), Is inhomogenous galactic evolution implemented correctly??
The problem is that the neutron star-producing SNe already produce Fe and shift to higher metallicities before the r-process is ejected!!!

Inhomogeneous Chemical Evolution with SPH (van de Voort et al. 2015), Left ejecta mixed in $5x10^6$ Msol, right high resolution mixed in $5x10^4$ Msol



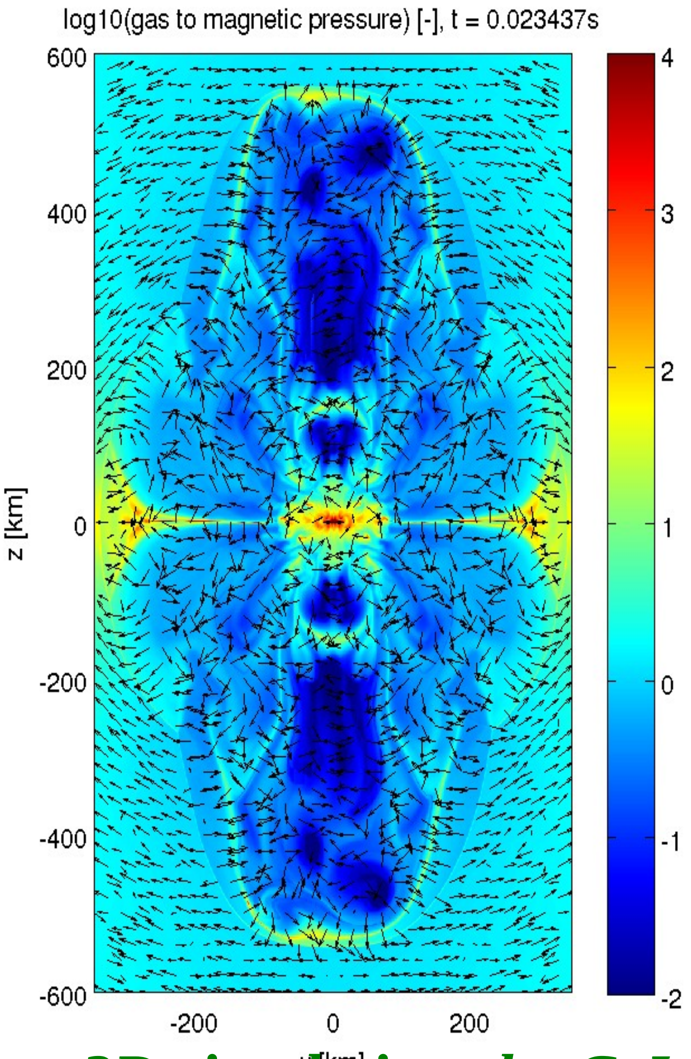


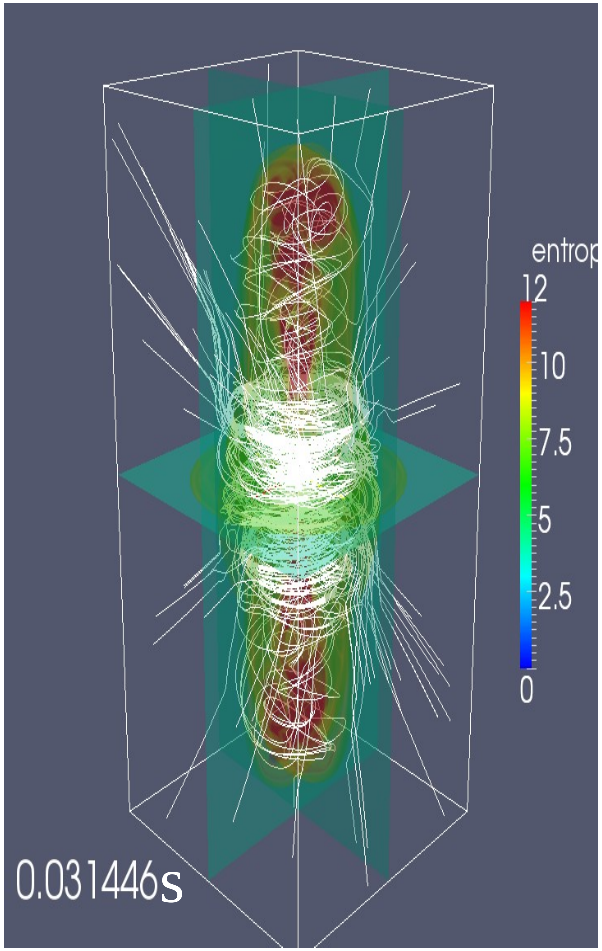
Update by Wehmeyer et al. (2015), green/red different merging time scales, blue higher merger rate (not a solution)

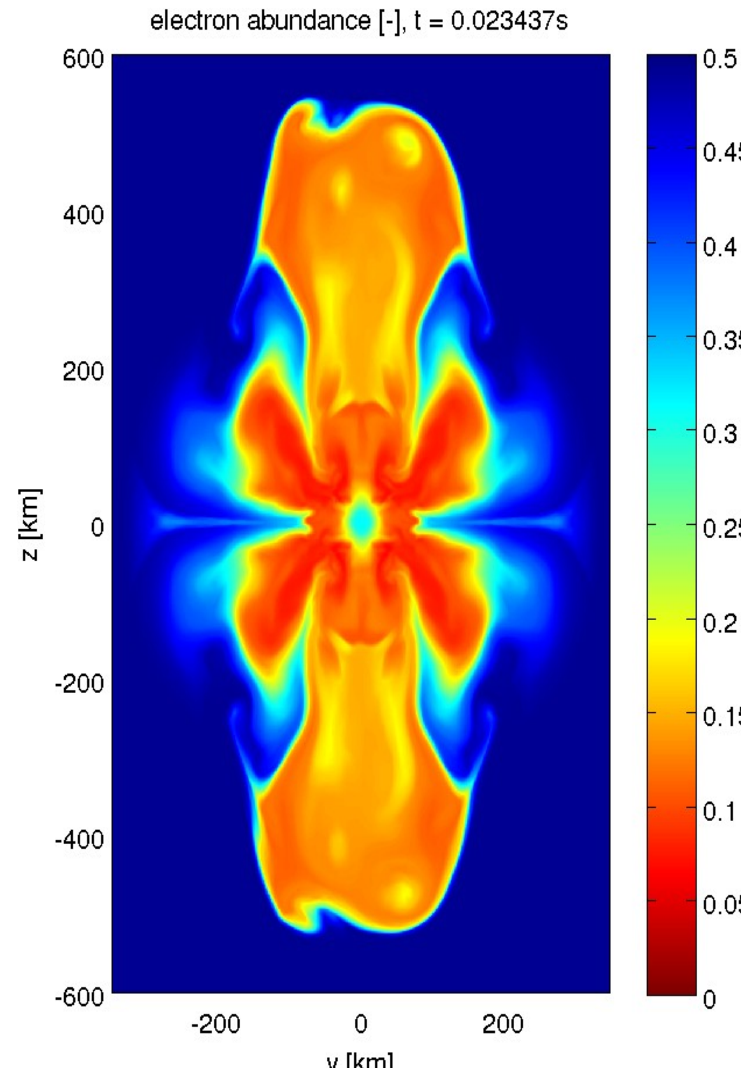
3D Collapse of Fast Rotator with Strong Magnetic Fields:

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





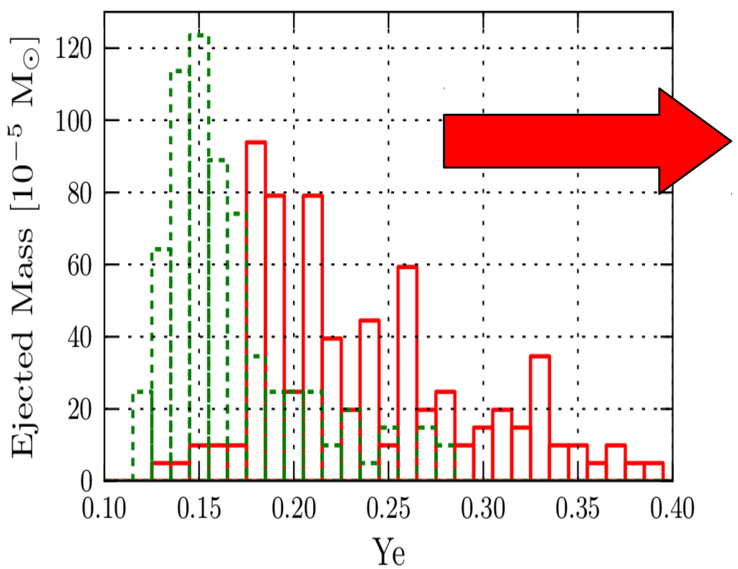


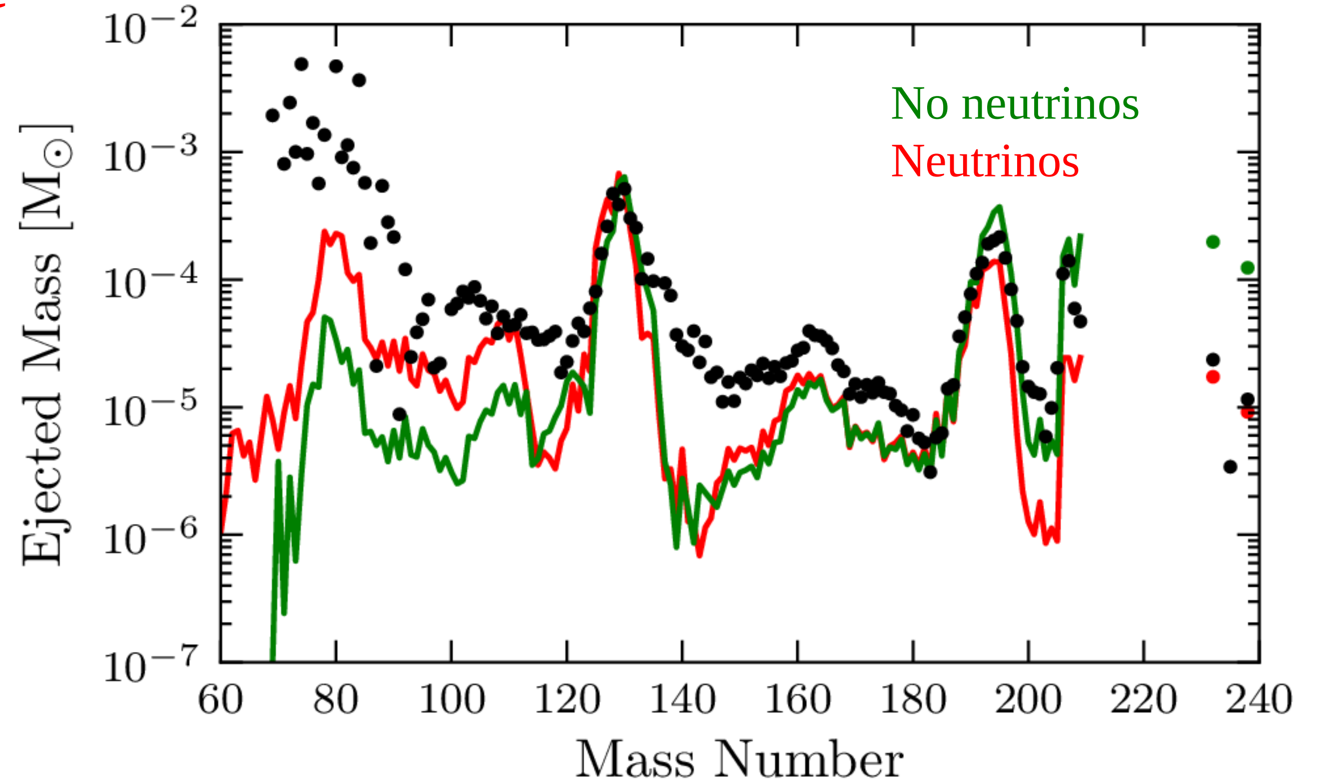
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012
Eichler et al. 2013

Nucleosynthesis results

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

neutrino effect small opposite to neutrino wind with slow expansion velocities



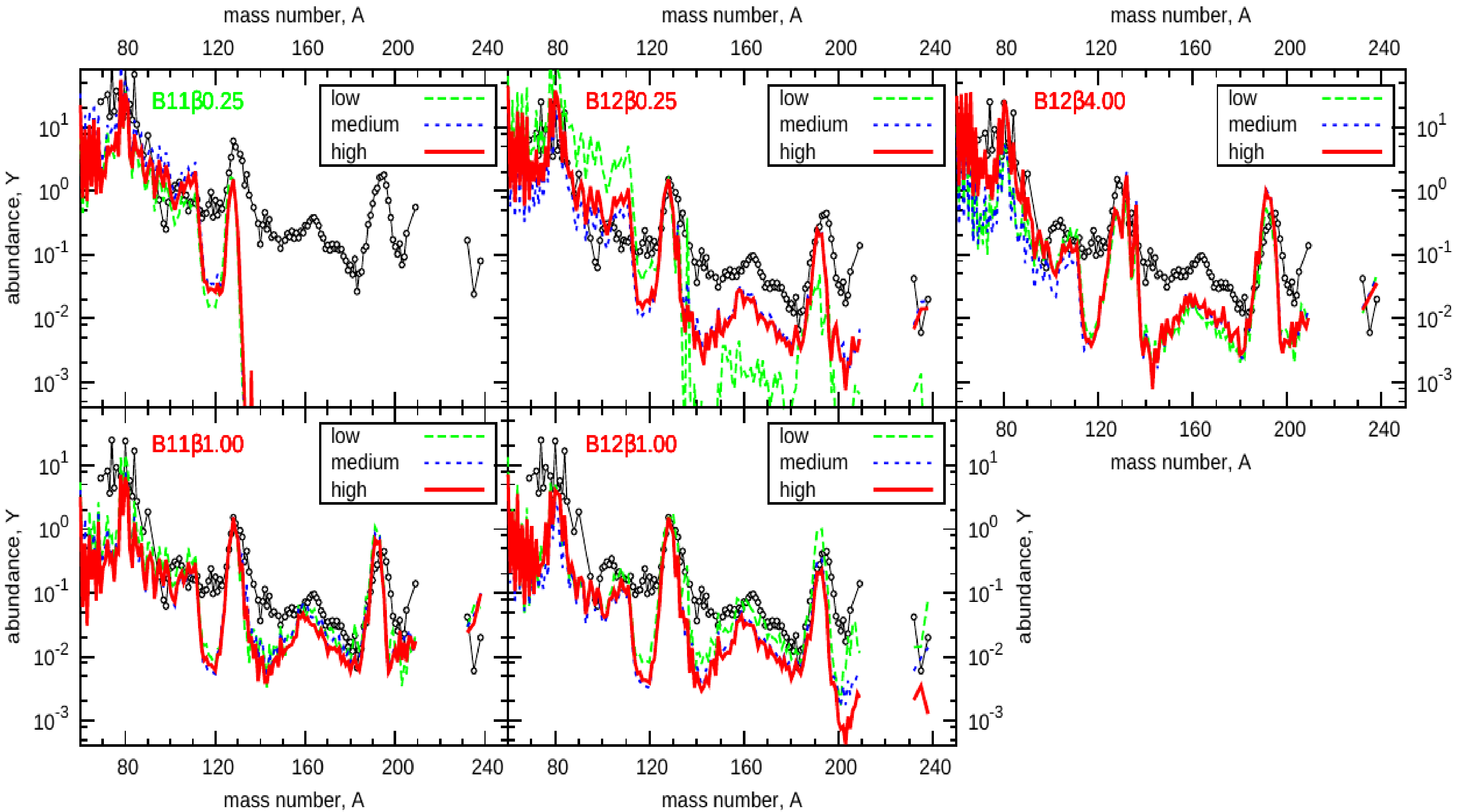


- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

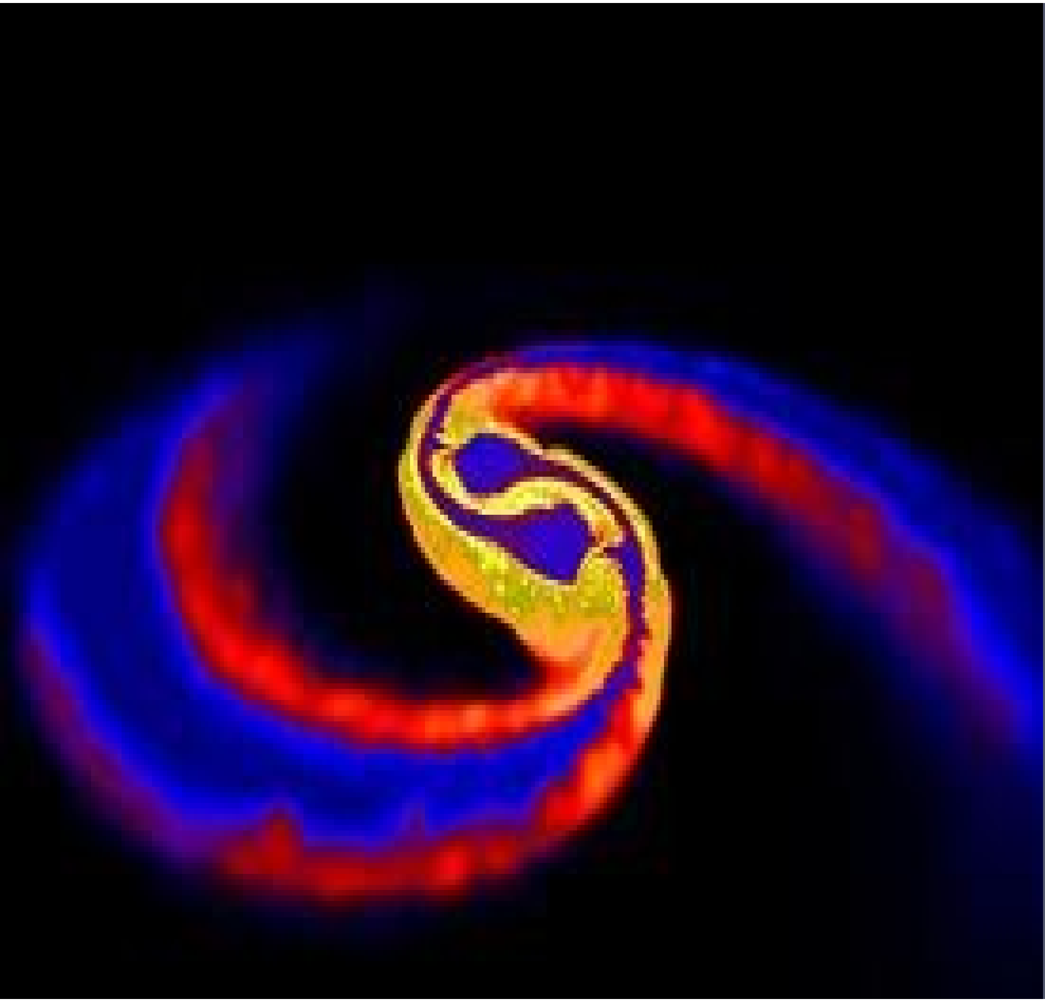
similar to mergers!!!

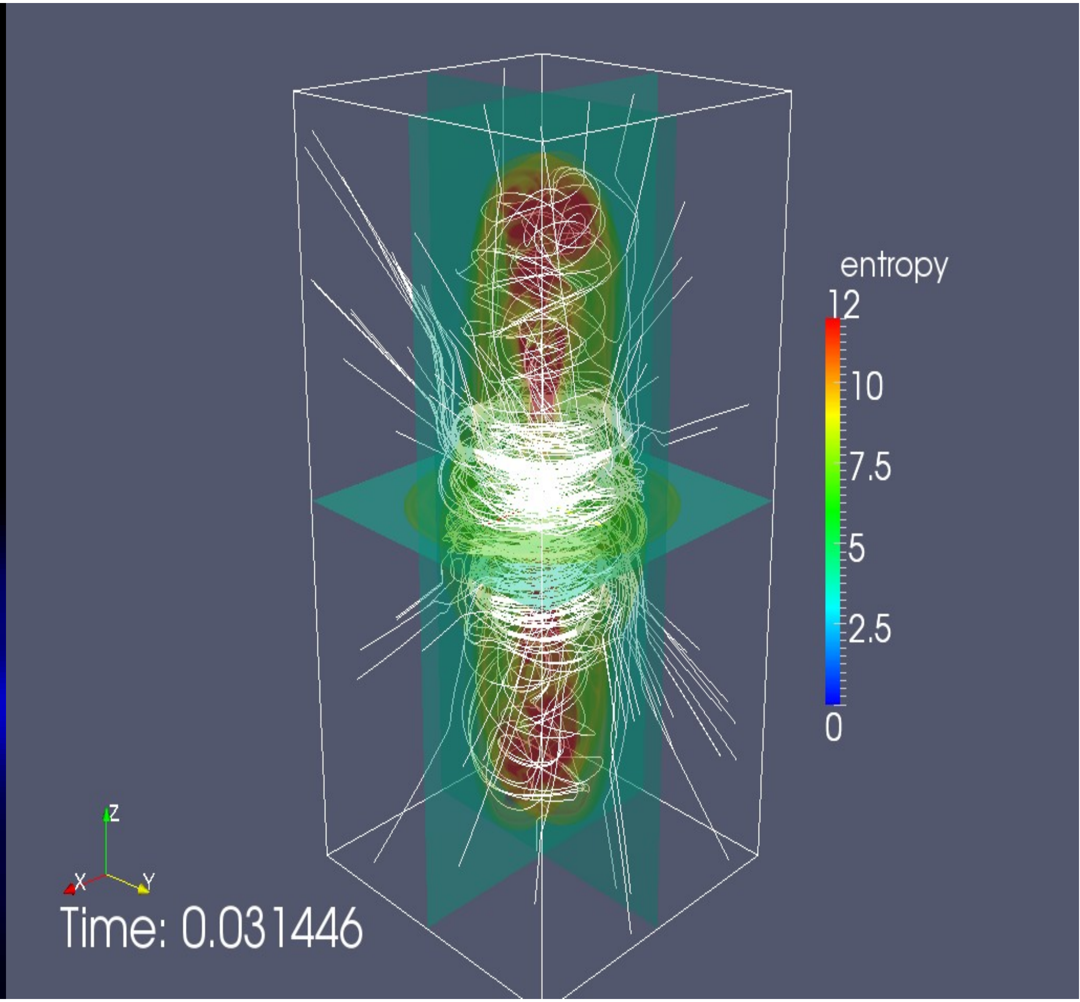
$$M_{\rm r,ej} \approx 6 \times 10^{-3}\ M_\odot$$

Nishimura, Takiwaki, Thielemann (2015), varying rotation rates and magnetic fields → from a weak to a strong r-process!



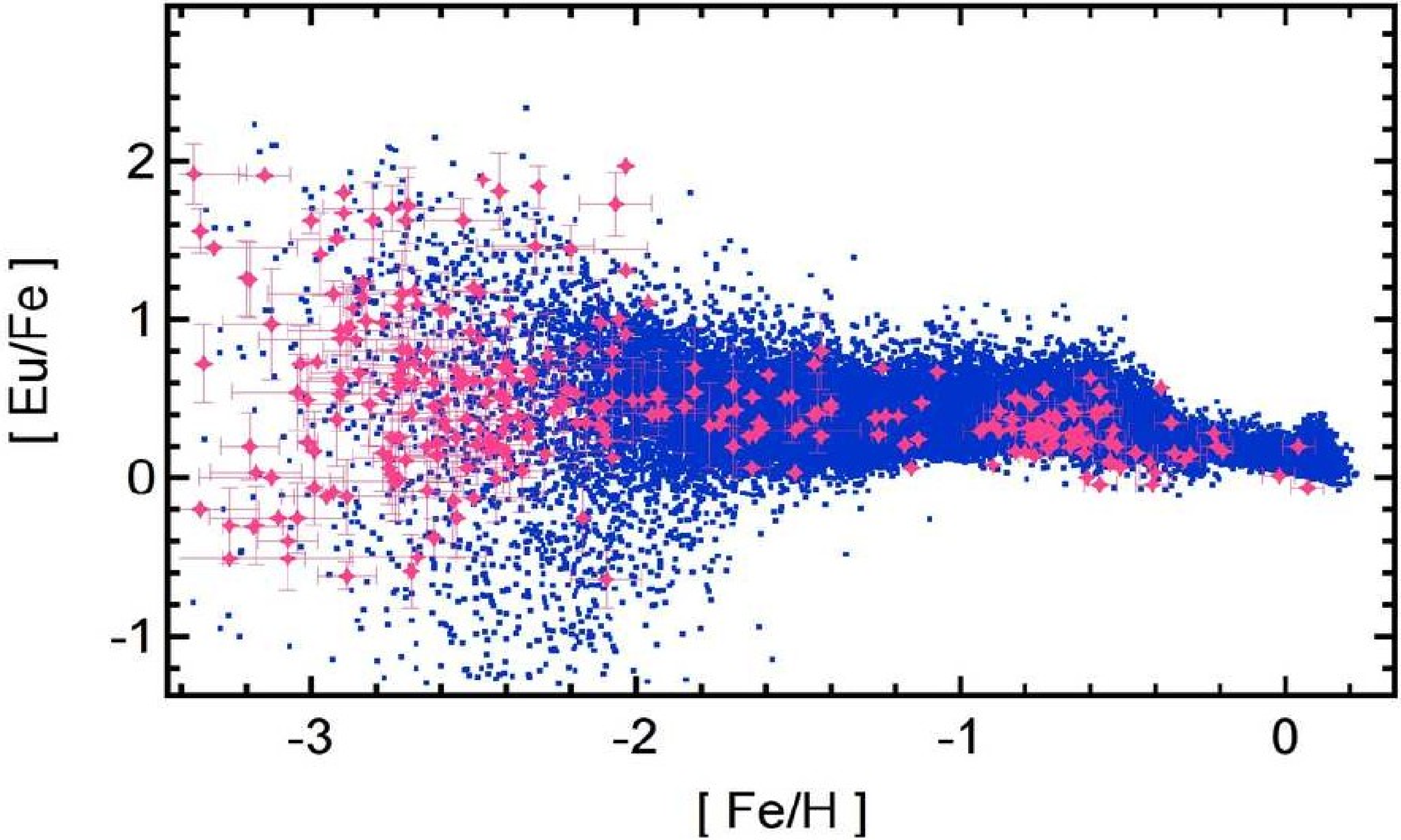
Which events contribute to the strong r-Process??





Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Combination of NS mergers and magnetorotational jets



Wehmeyer, Pignatari, Thielemann (2015)

Summary

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)?

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).
Findings by Wallner et al. (2014) with 60Fe detection from latest nearby supernova, but no Pu from r-process give an additional indication that heavy r-process is not coming from regular supernovae but only from rare events!

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