What is the Role of Fission in r-Process Environments: What is the site of the r-Process and its role in galactic evolution (supernovae vs. neutron star mergers)?

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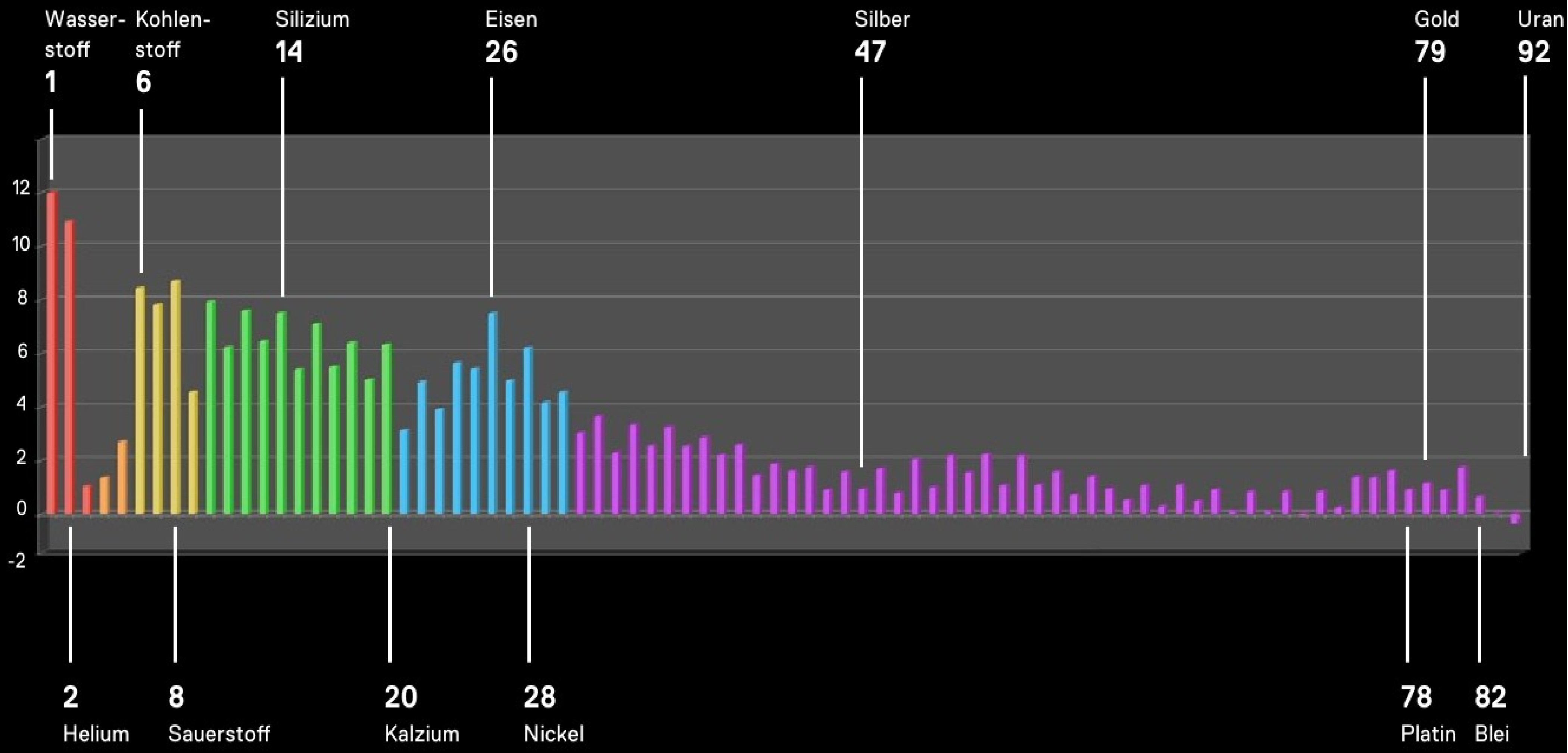
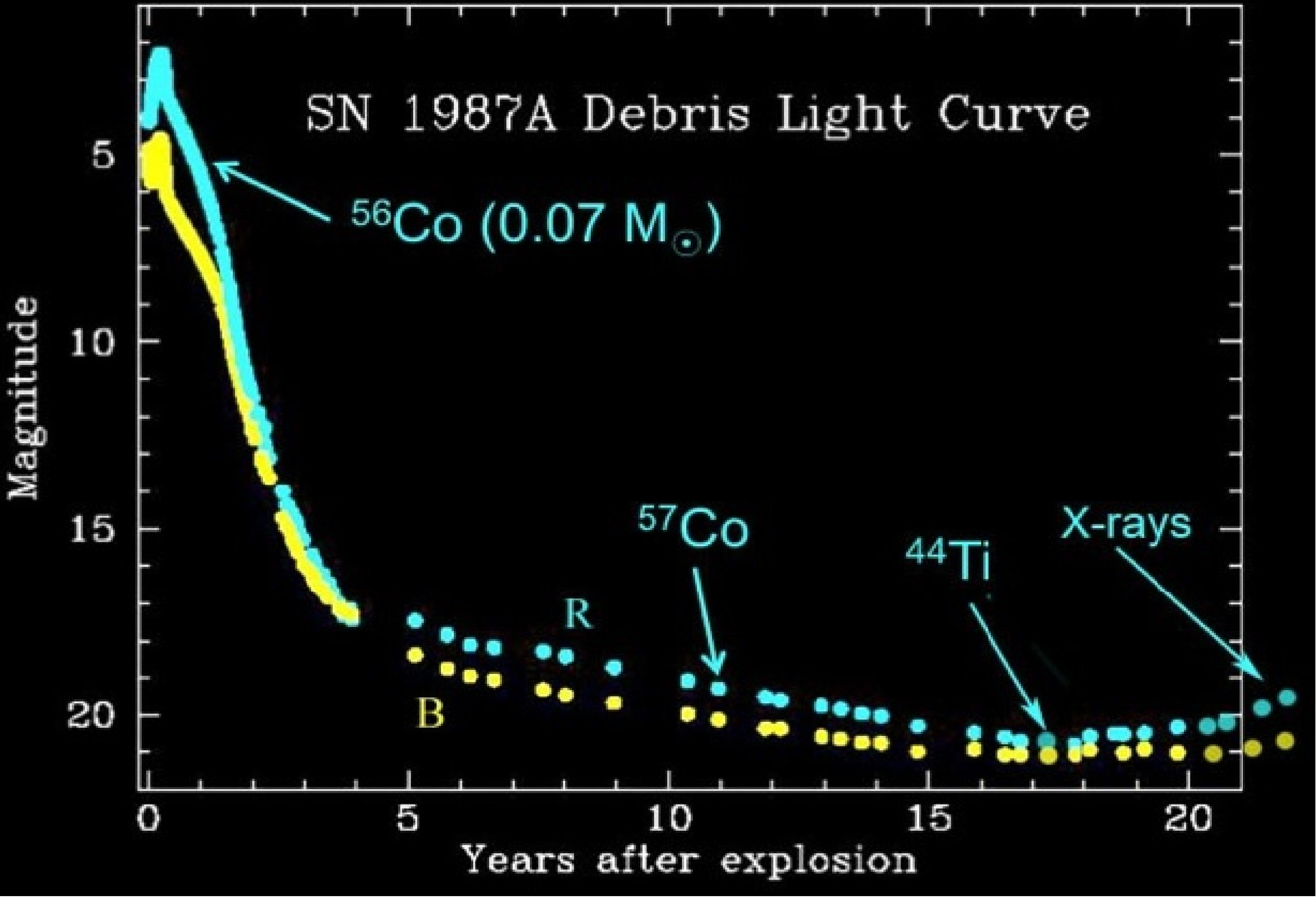
With the help of many collaborators!!

HÄUFIGKEITSVERTEILUNG IM SONNENSYSTEM

(AUS KOHLIGEN CHONDRITEN UND SOLAREN ABSORPTIONSSPEKTREN)



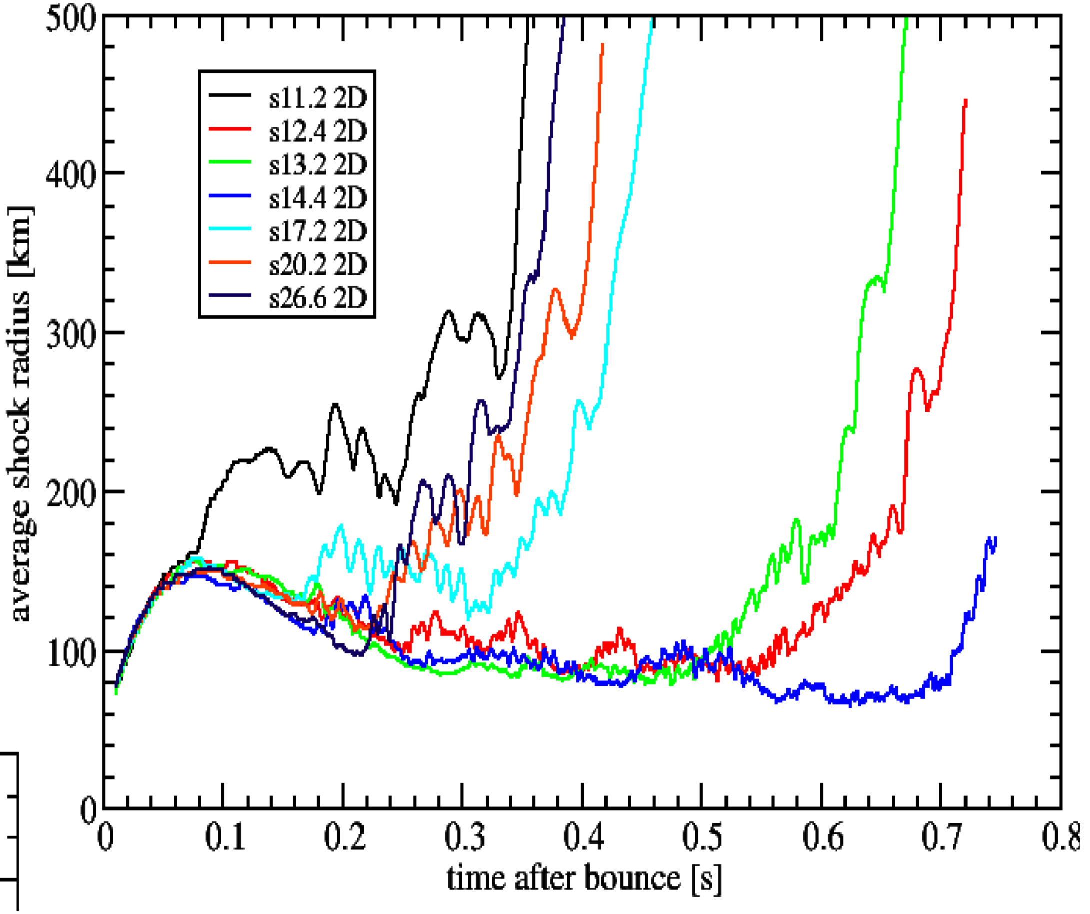
A unit on the y-axis corresponds to a factor of 10, i.e. hydrogen is about 10^{12} time more abundant than lead



Stolen from one of Dick McCray's talks

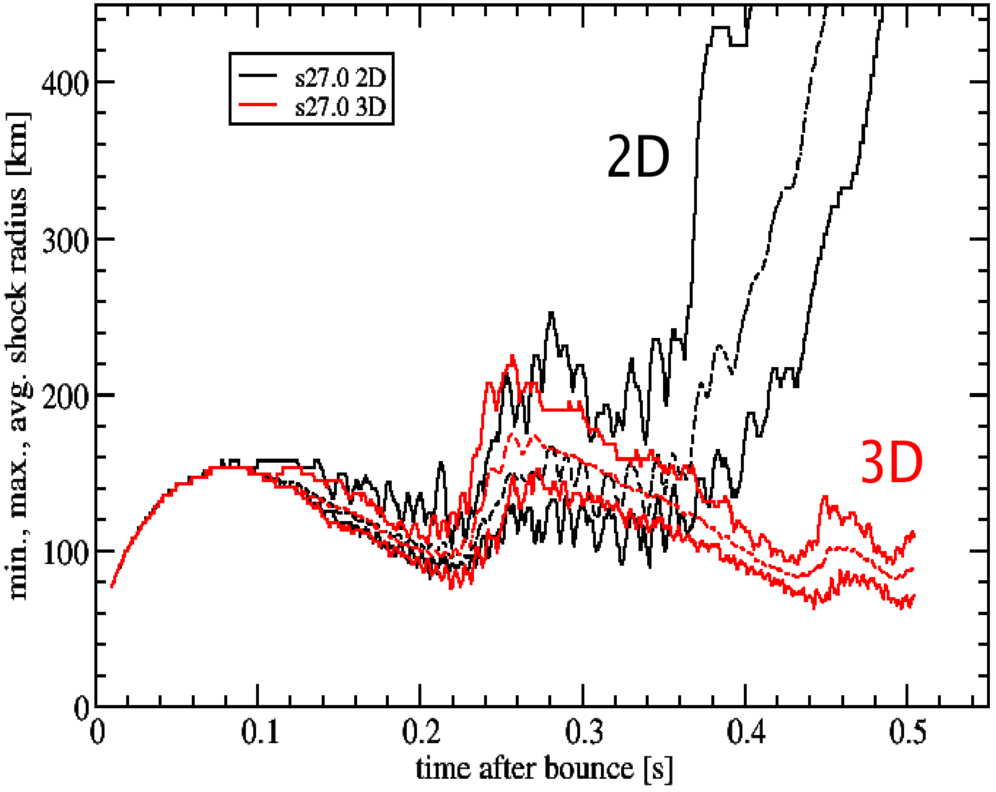
Growing set of 2D CCSN Explosions

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

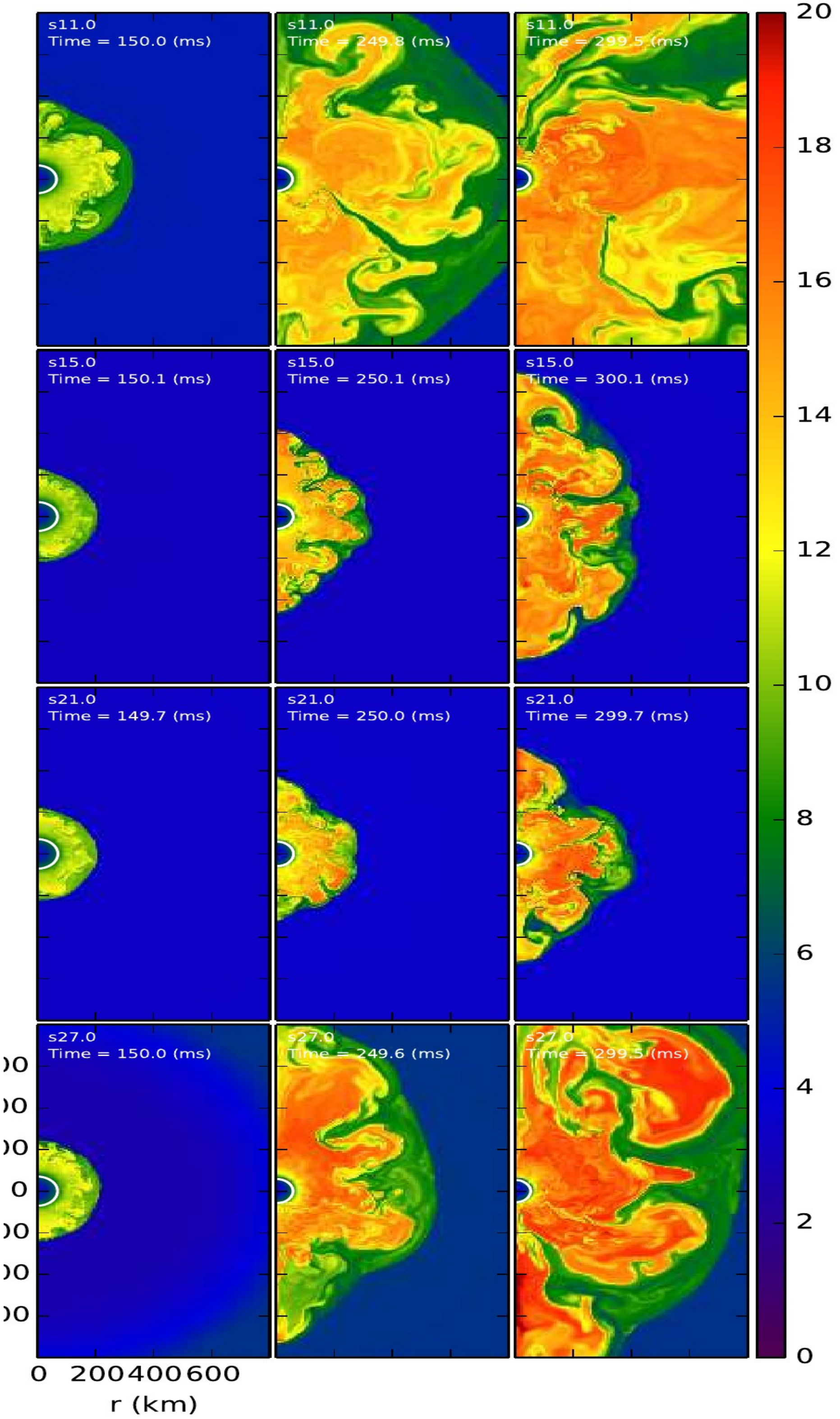


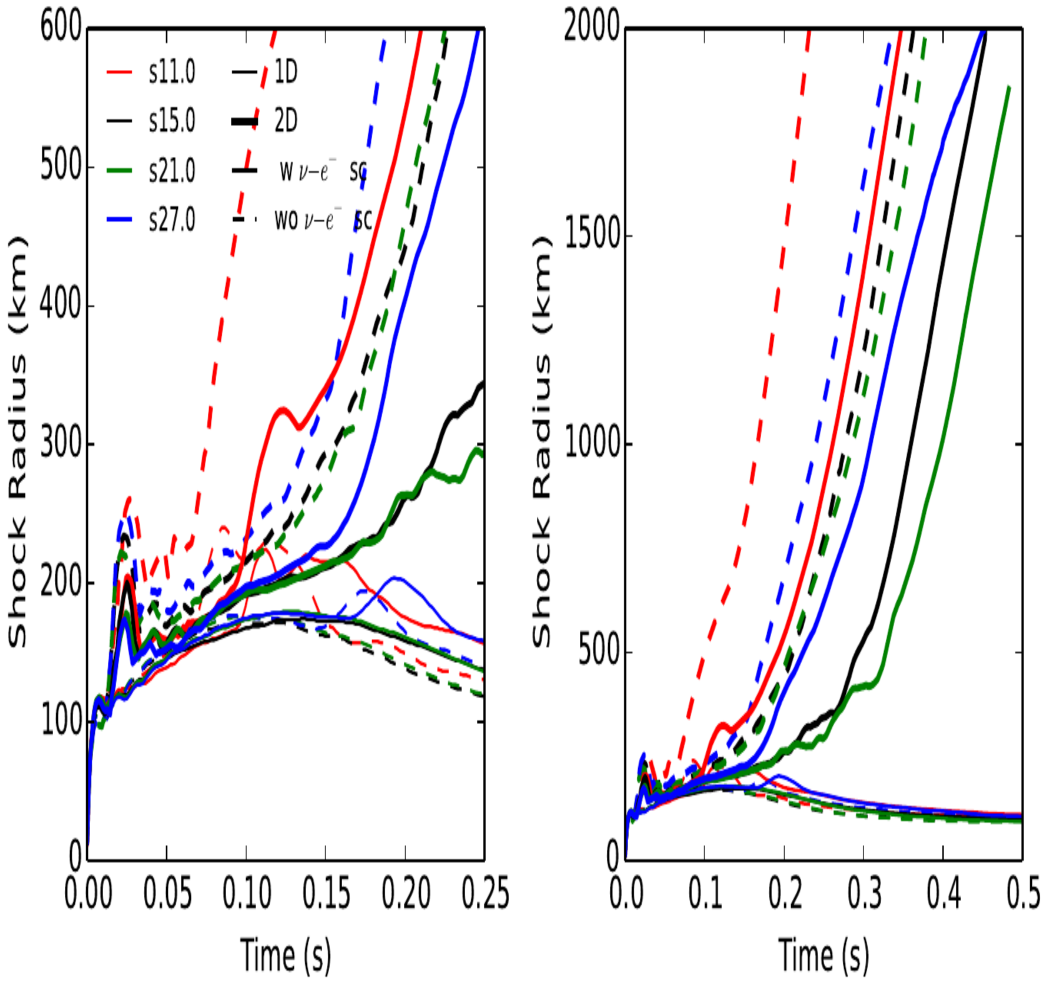
But 3D still somewhat open!

Positions of shock radii



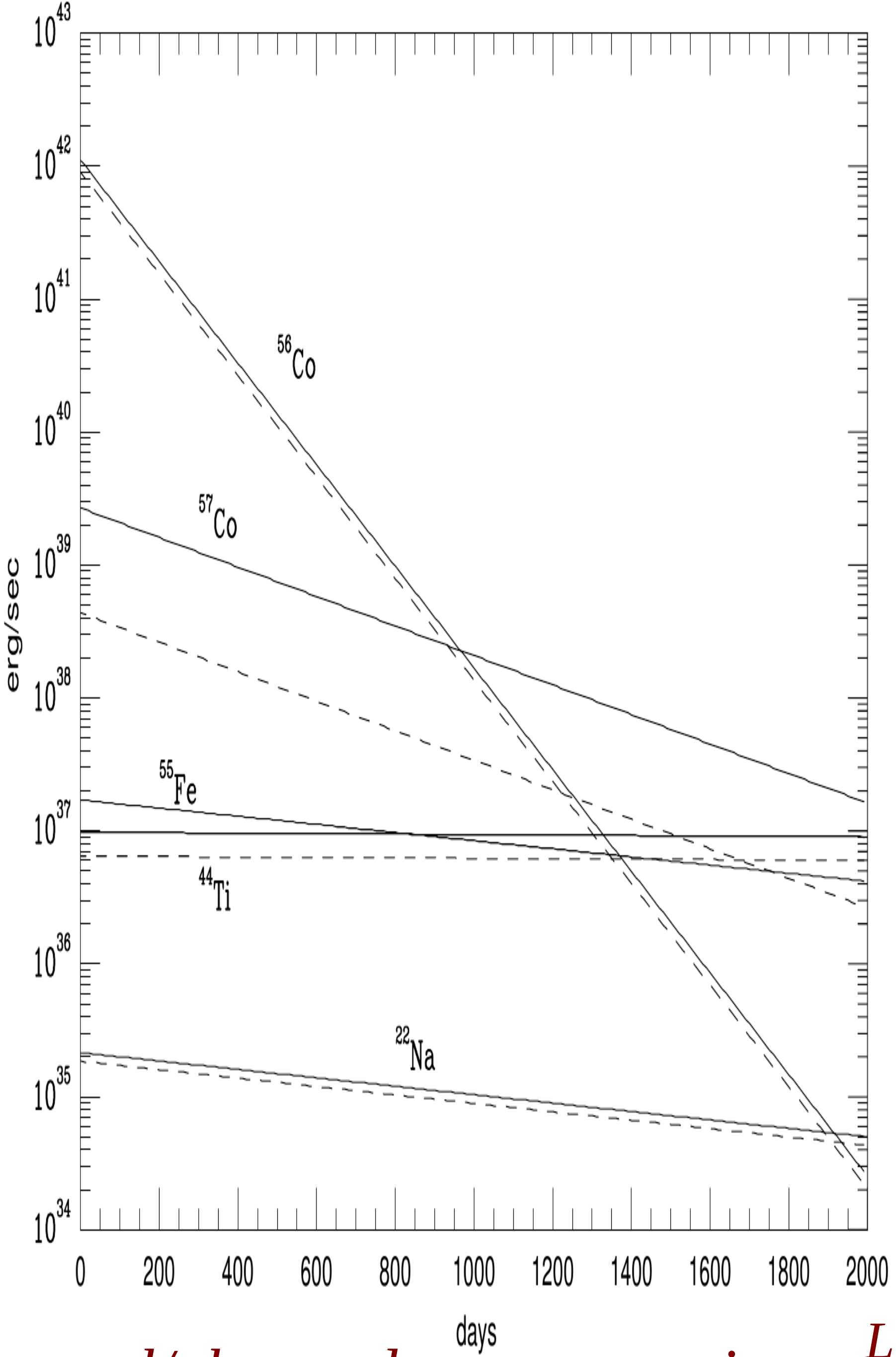
Recent Basel Efforts in 2D (Pan, Liebendörfer, Hempel, Thielemann 2015)

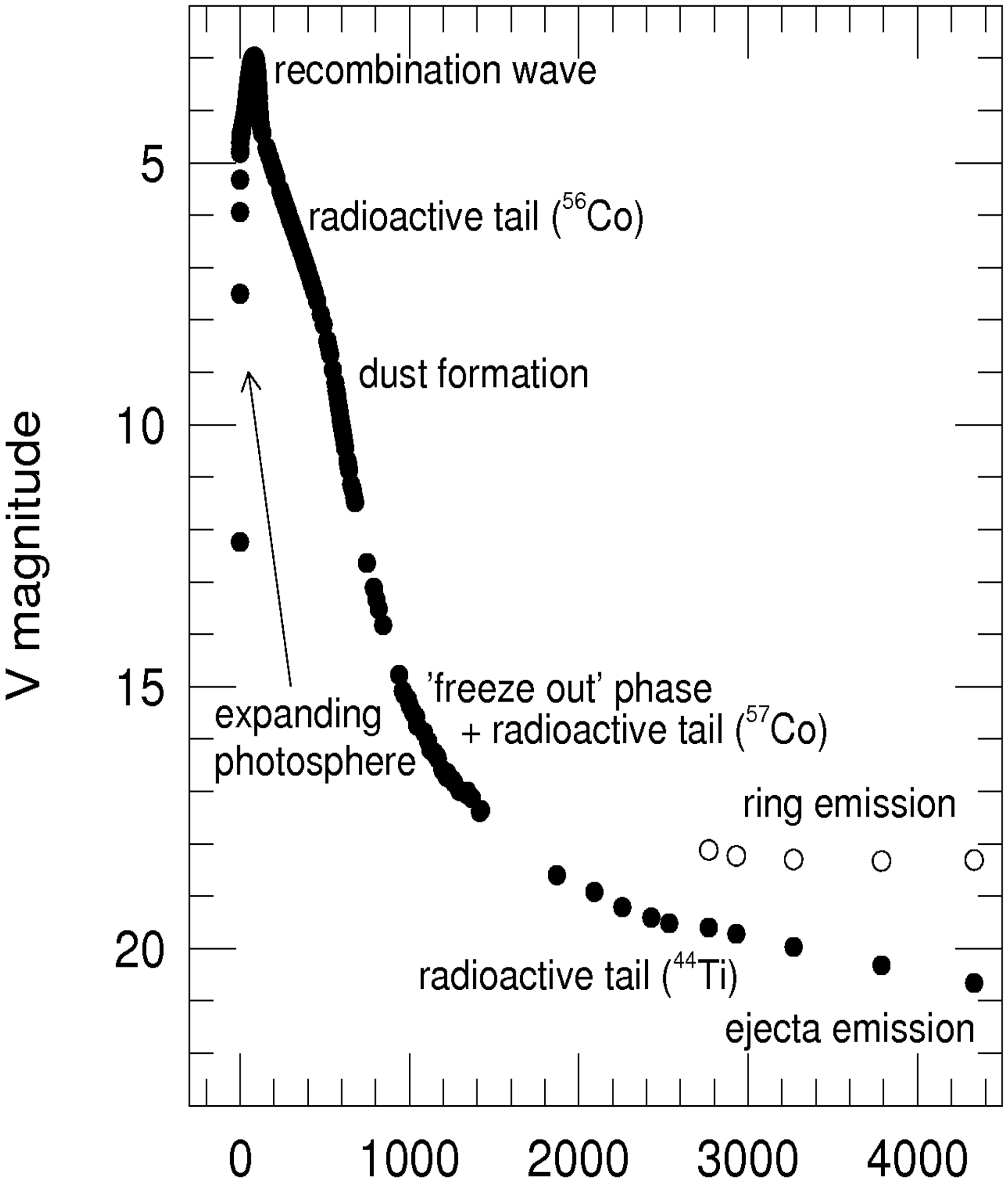




But there are still considerable uncertainties, also between different groups → nucleosynthesis predictions are still made in induced spherical explosion models

Radioactivity Diagnostics of SN1987A: ^{56}Ni/Co, ^{57}Ni/Co, ^{44}Ti

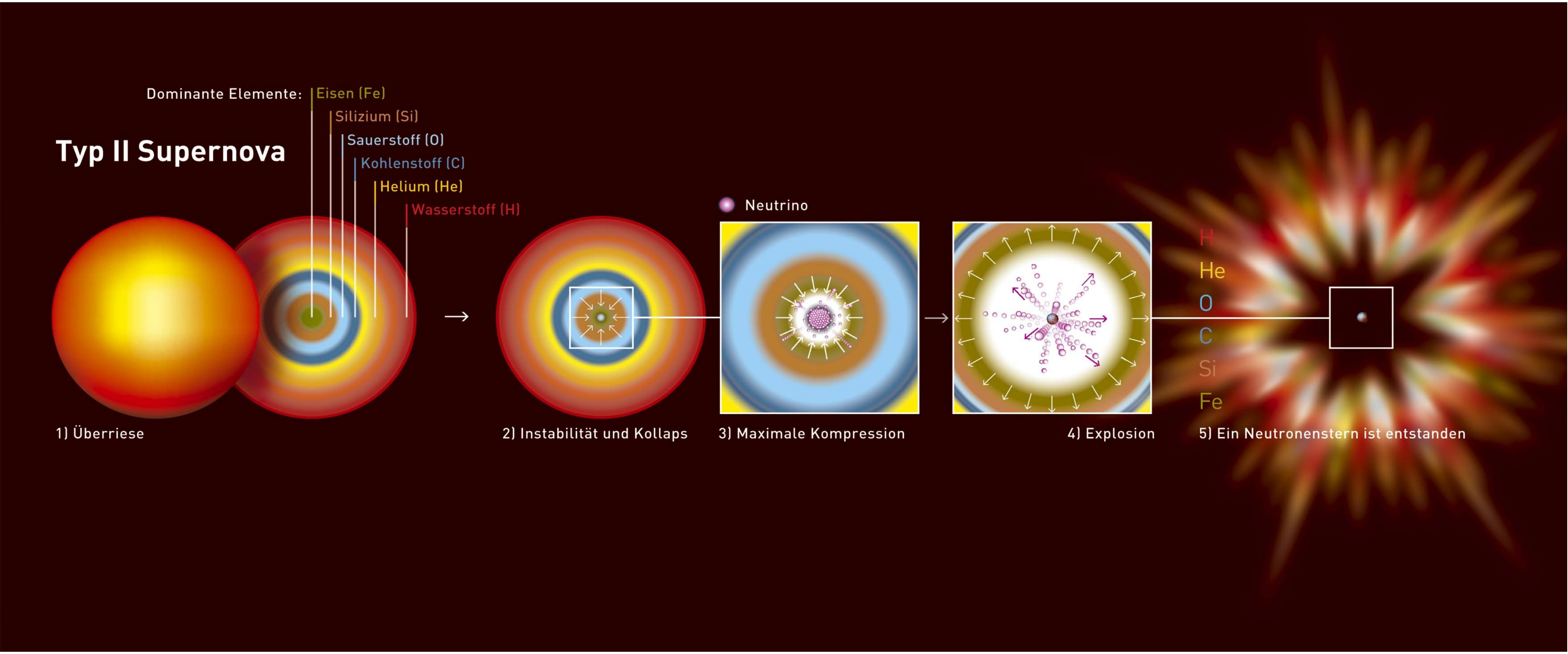




total/photon decay energy input from models (THN)

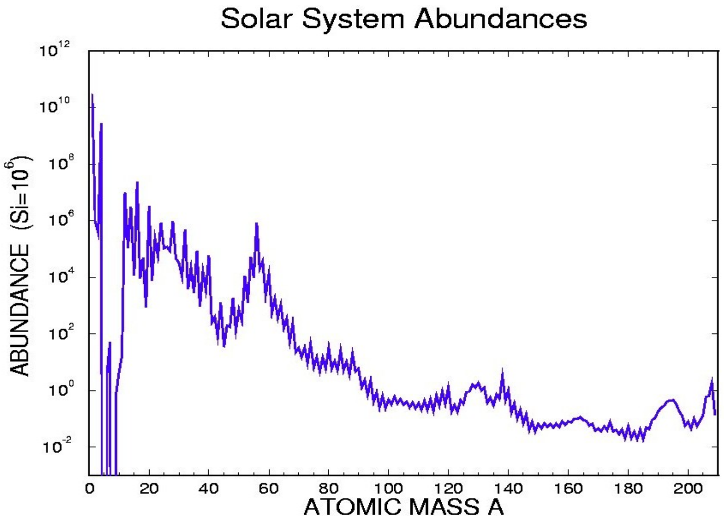
Leibundgut (ESO) & Suntzeff 2003, ***other determinations (e.g. ^{44}Ti undertaken by Fransson+ Stockholm)***

Core-Collaps-Supernovae and Neutron Stars as End Stages of massive Stars

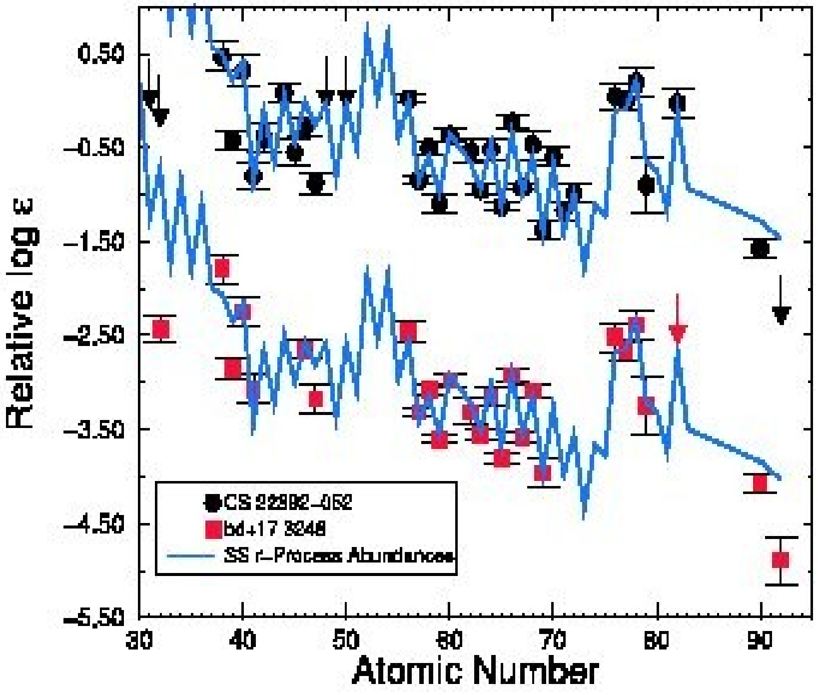


Main products: O, Ne, Mg, S, Ar, Ca, Ti and some Fe/Ni

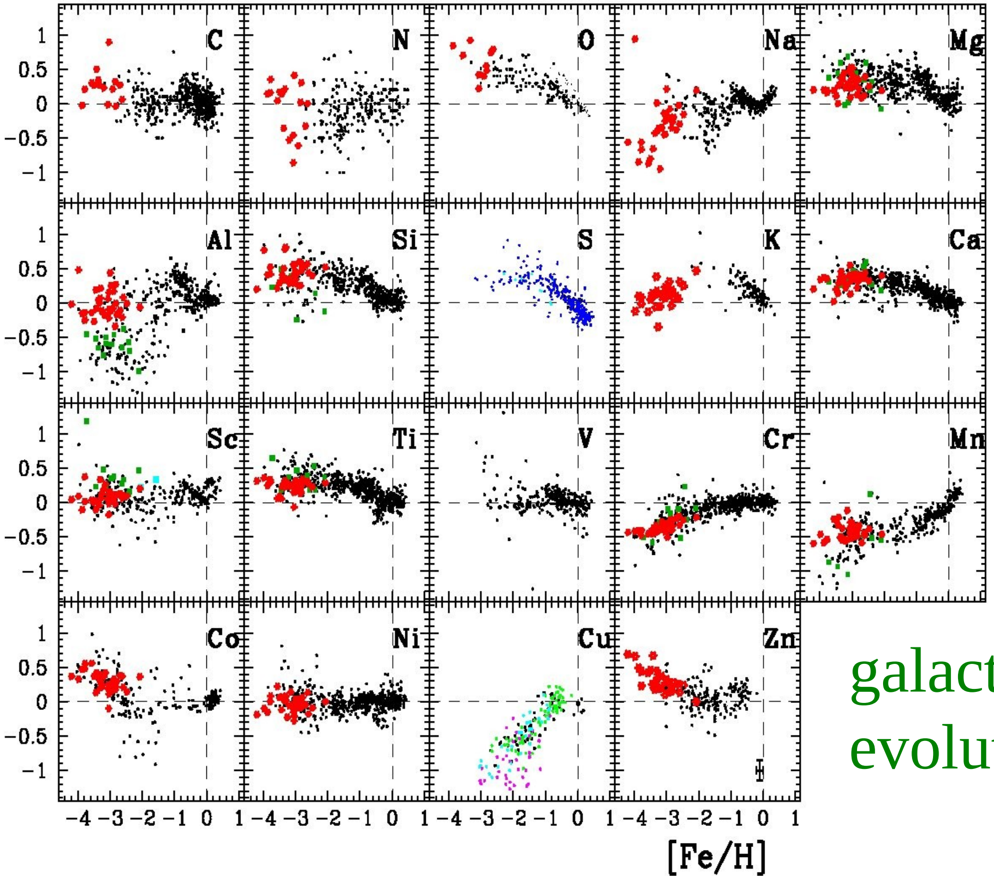
How about the r-process?????????



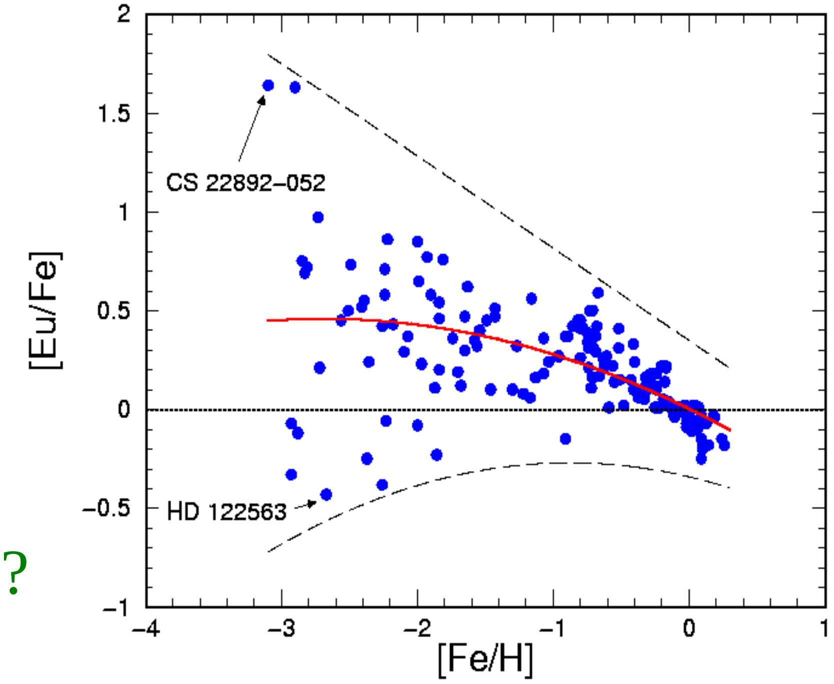
How do we understand: solar system abundances..



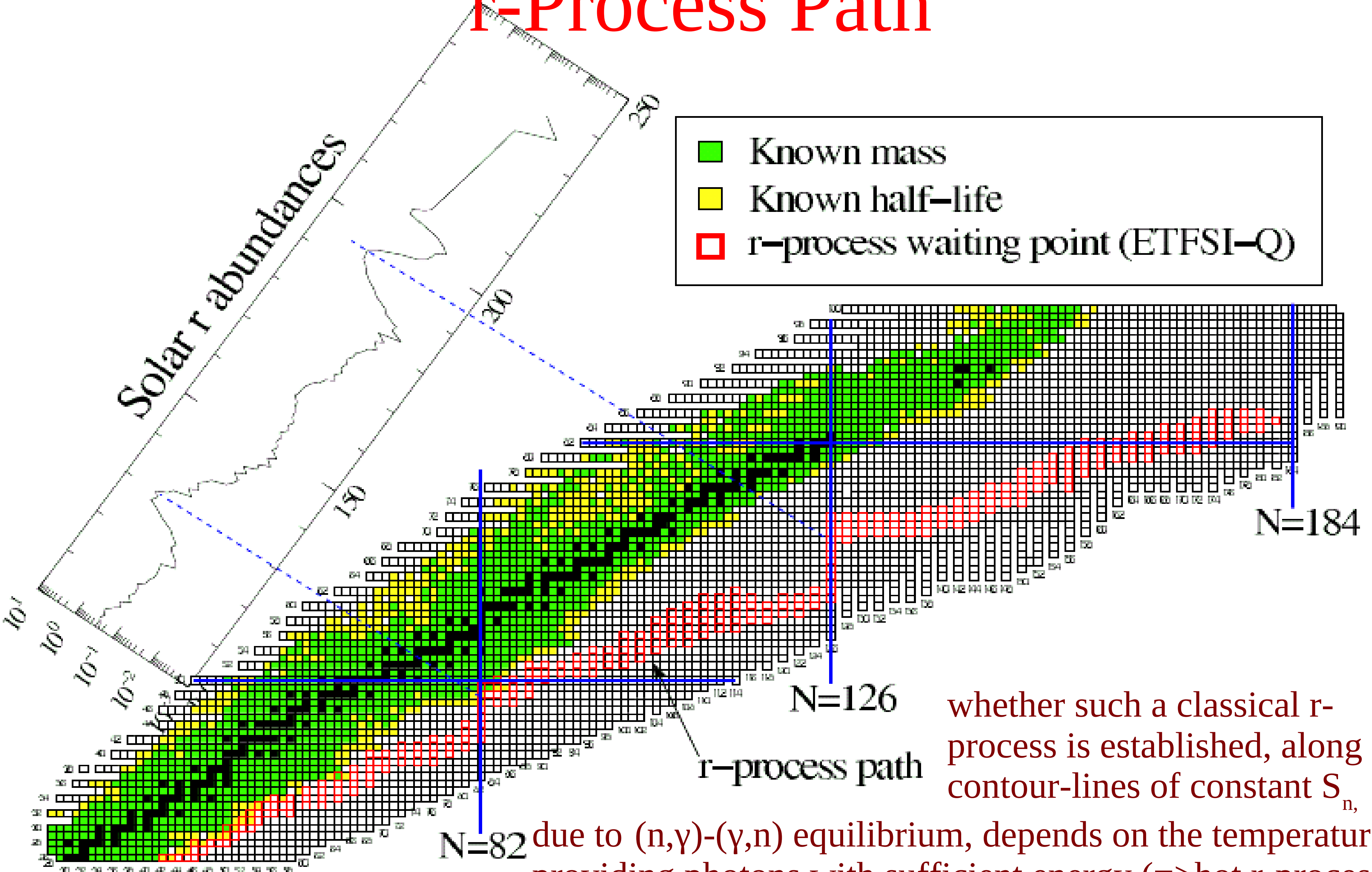
low metallicity stars ...



galactic evolution?



r-Process Path

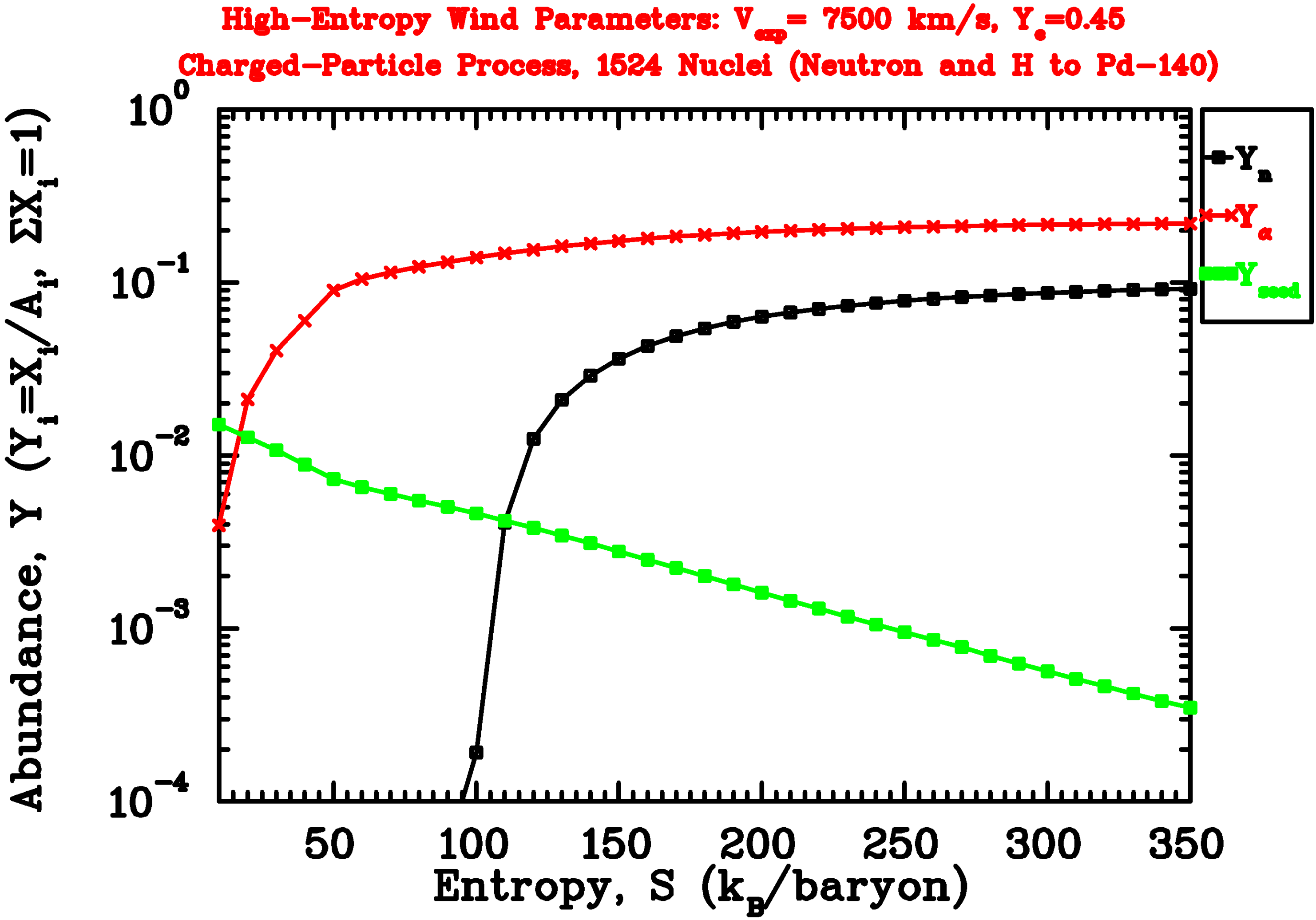


whether such a classical r-process is established, along contour-lines of constant $S_{n,}$ due to (n,γ)-(γ,n) equilibrium, depends on the temperature, providing photons with sufficient energy (=>hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might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

B. Pfeiffer

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

Farouqi et al. (2010)



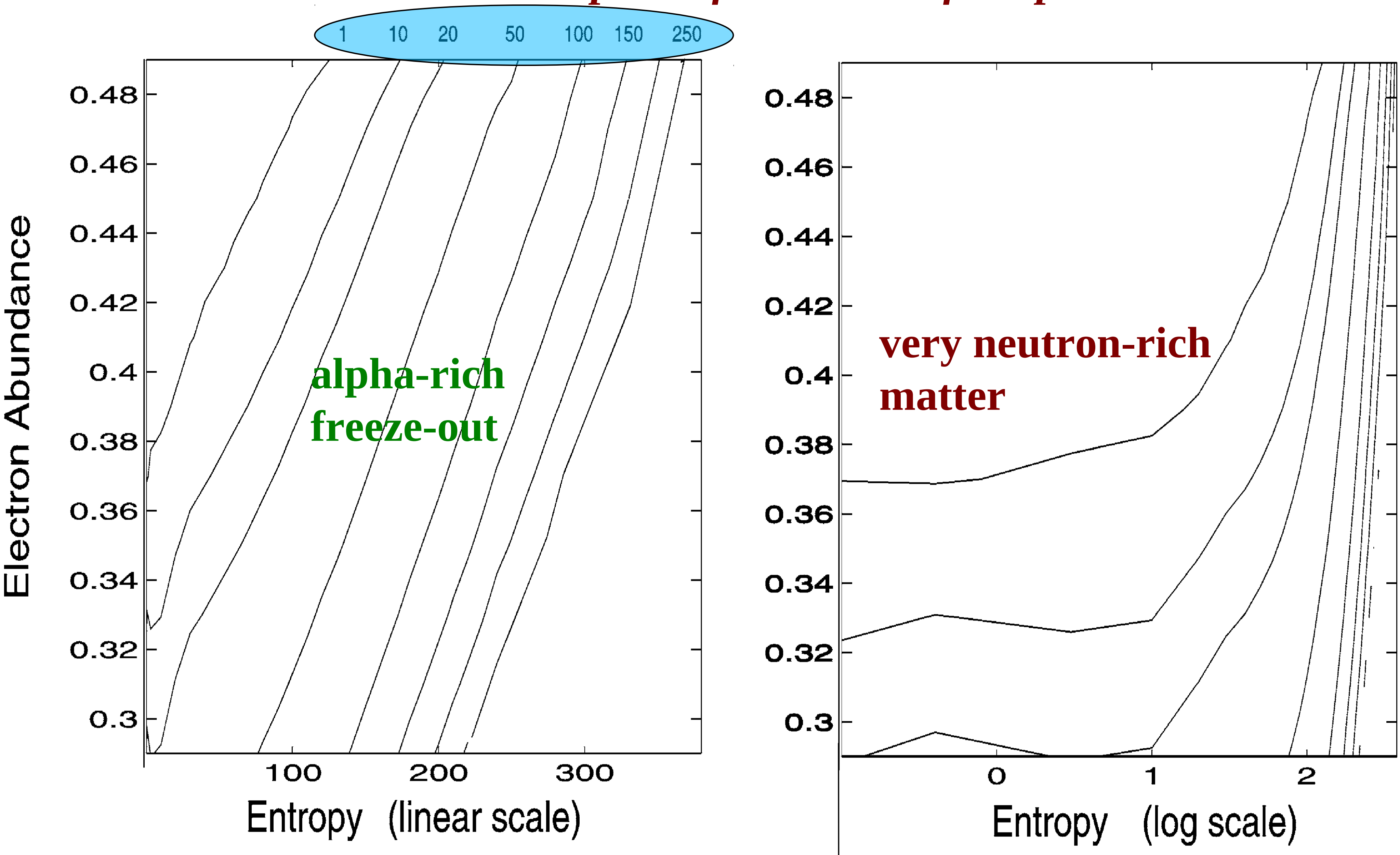
n/seed

$=Y_n/Y_{seed}$

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



alpha-rich freeze-out

very neutron-rich matter

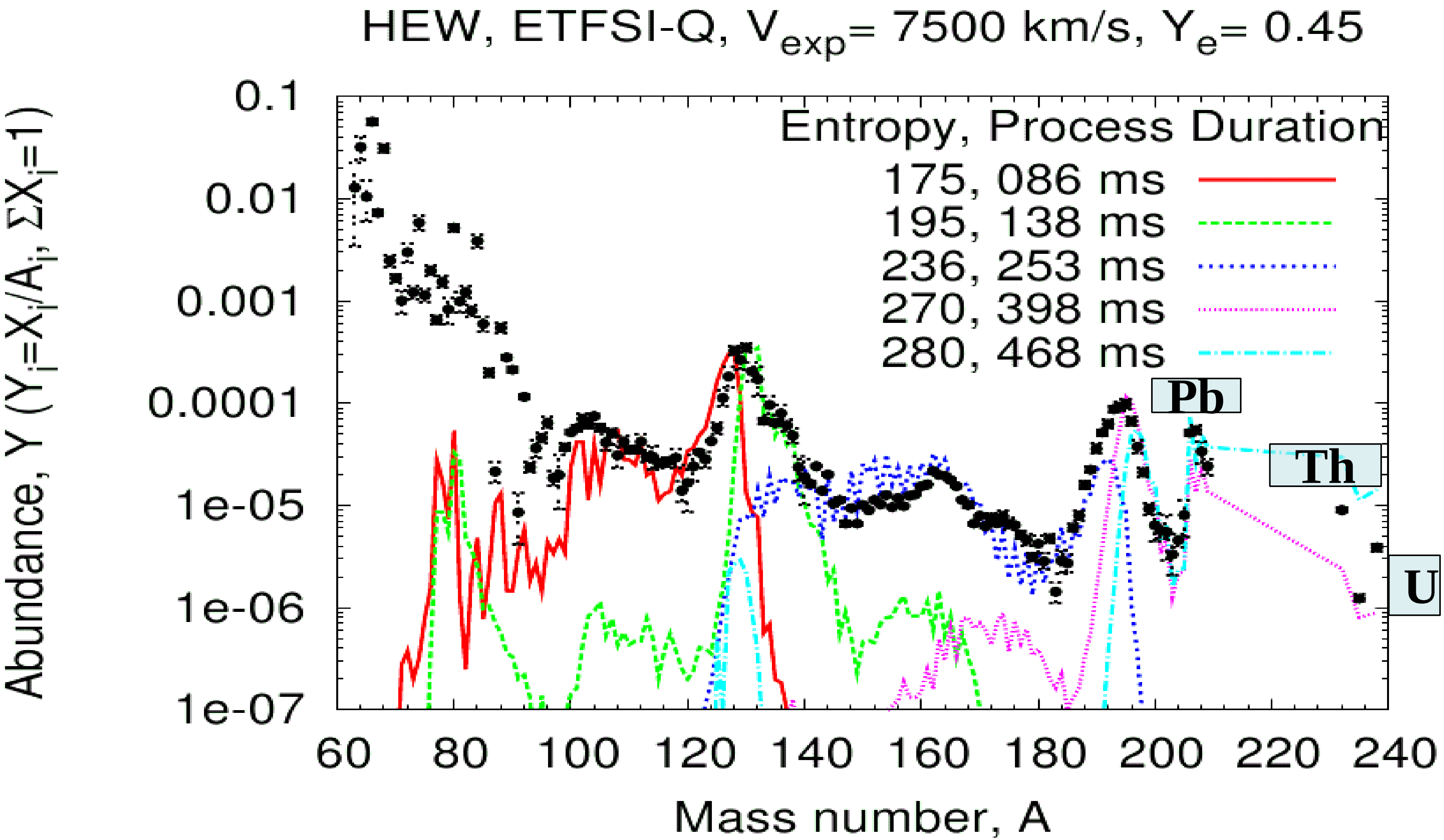
neutrino wind?

Freiburghaus et al. (1999)

Neutron star mergers and polar jets?

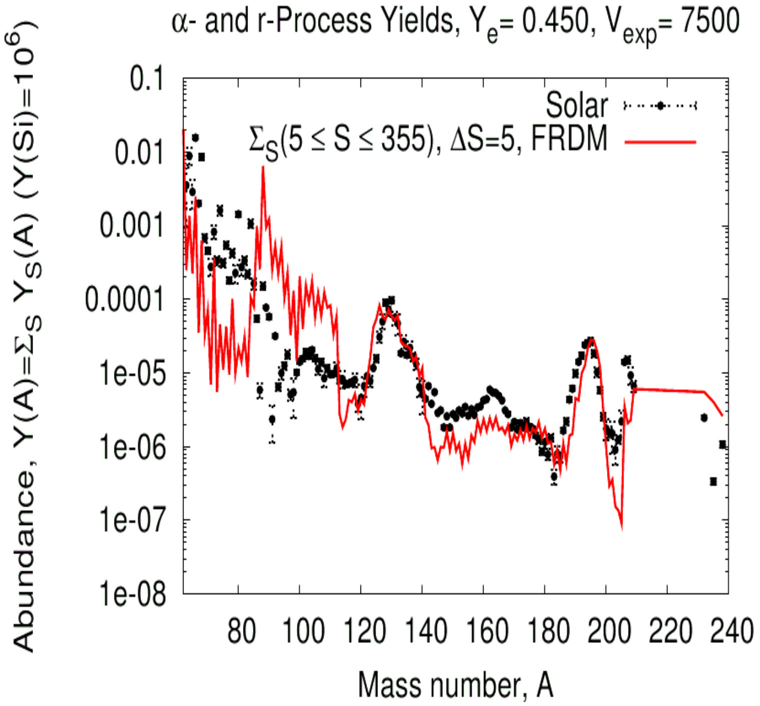
Individual Entropy Components

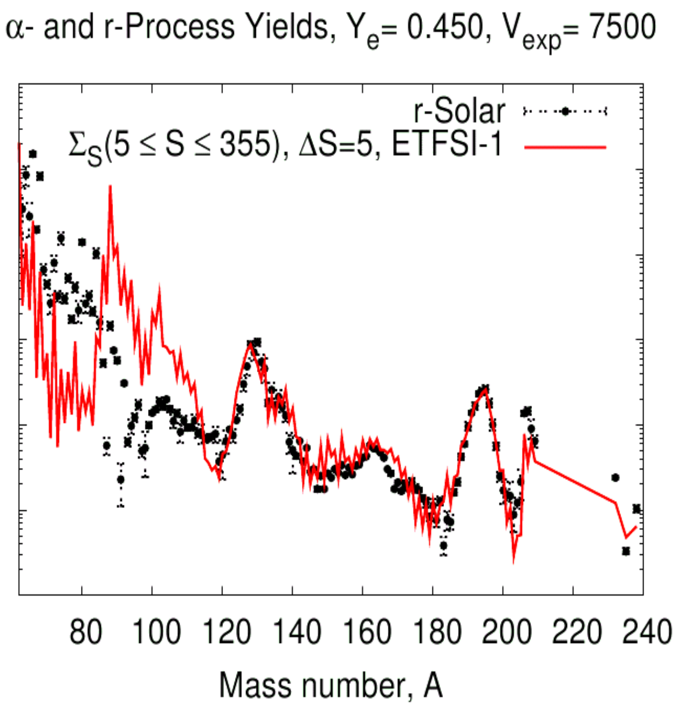
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in

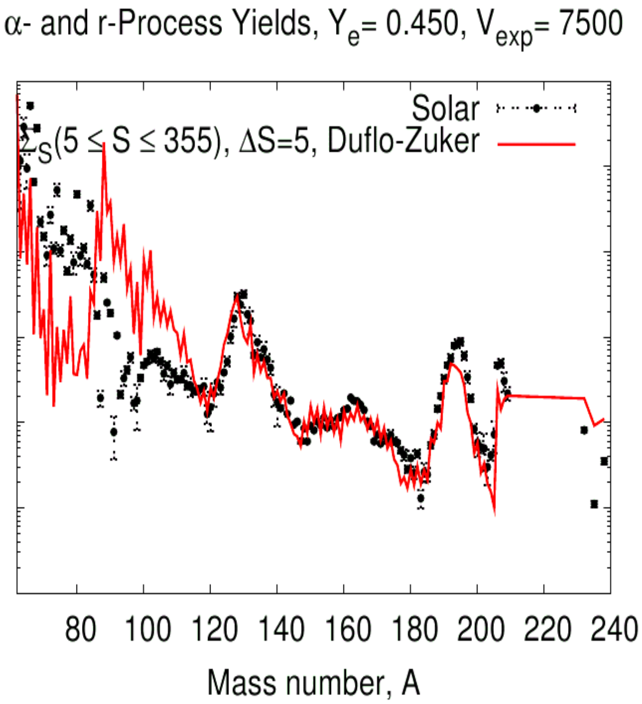


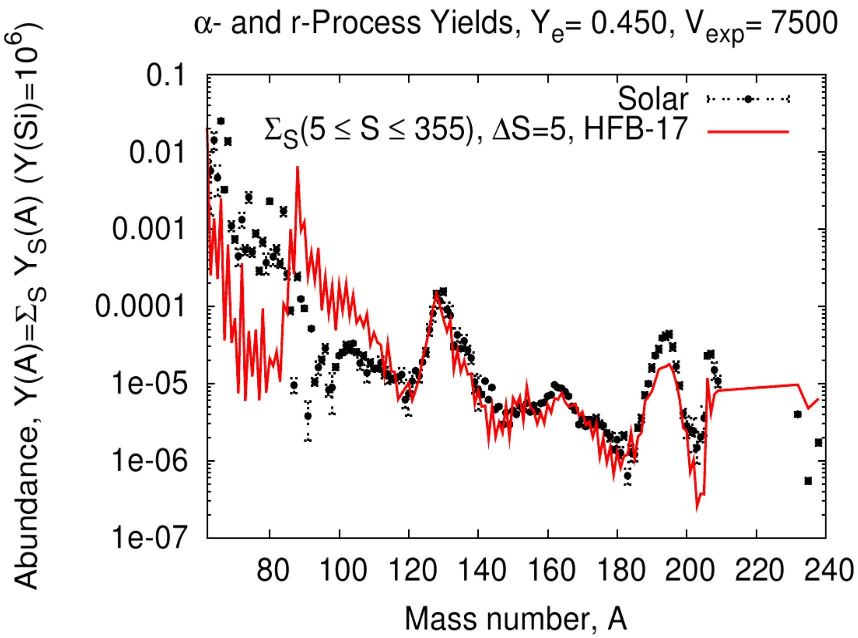
A parameter game: Assuming entropy S, initial Ye, and expansion velocity (related to an expansion time scale) of the hot matter

Superposition of entropies and test for different mass models





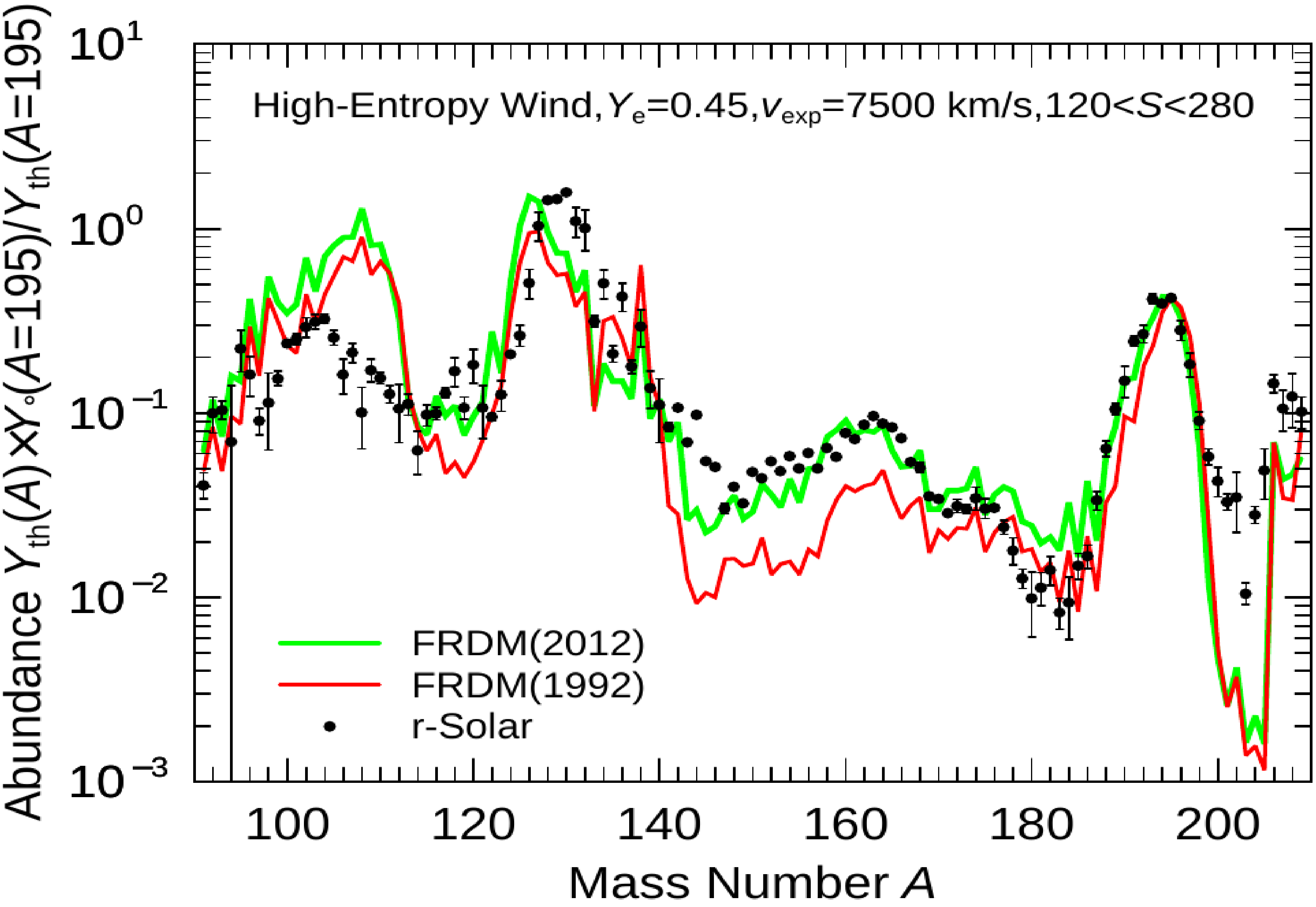




Farouqi et al. (2010)

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.

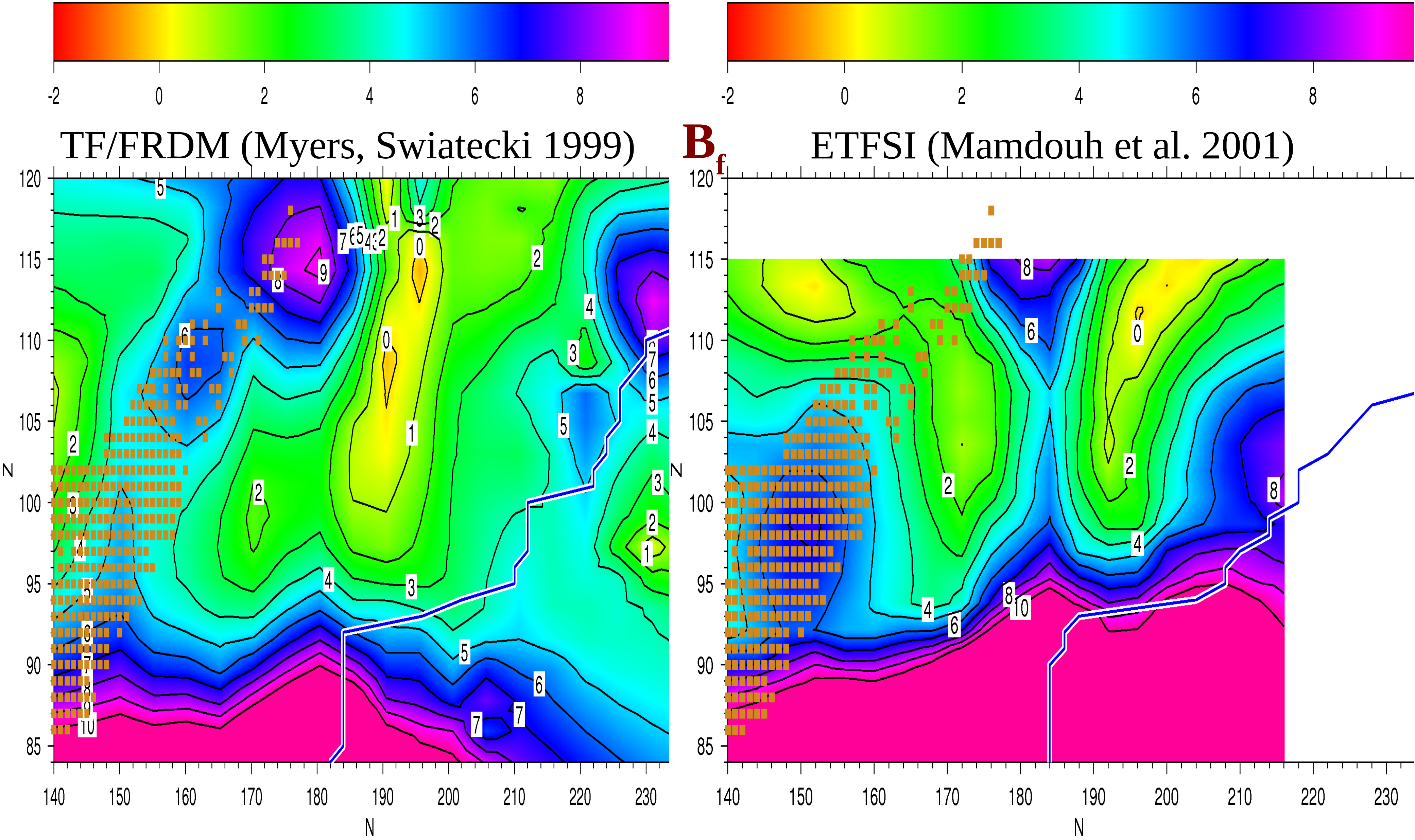


Kratz et al. (2014): Update from FRDM (1995) to FRDM (2012). Problem at A=138 is reduced and rare earths better filled up.

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)!!



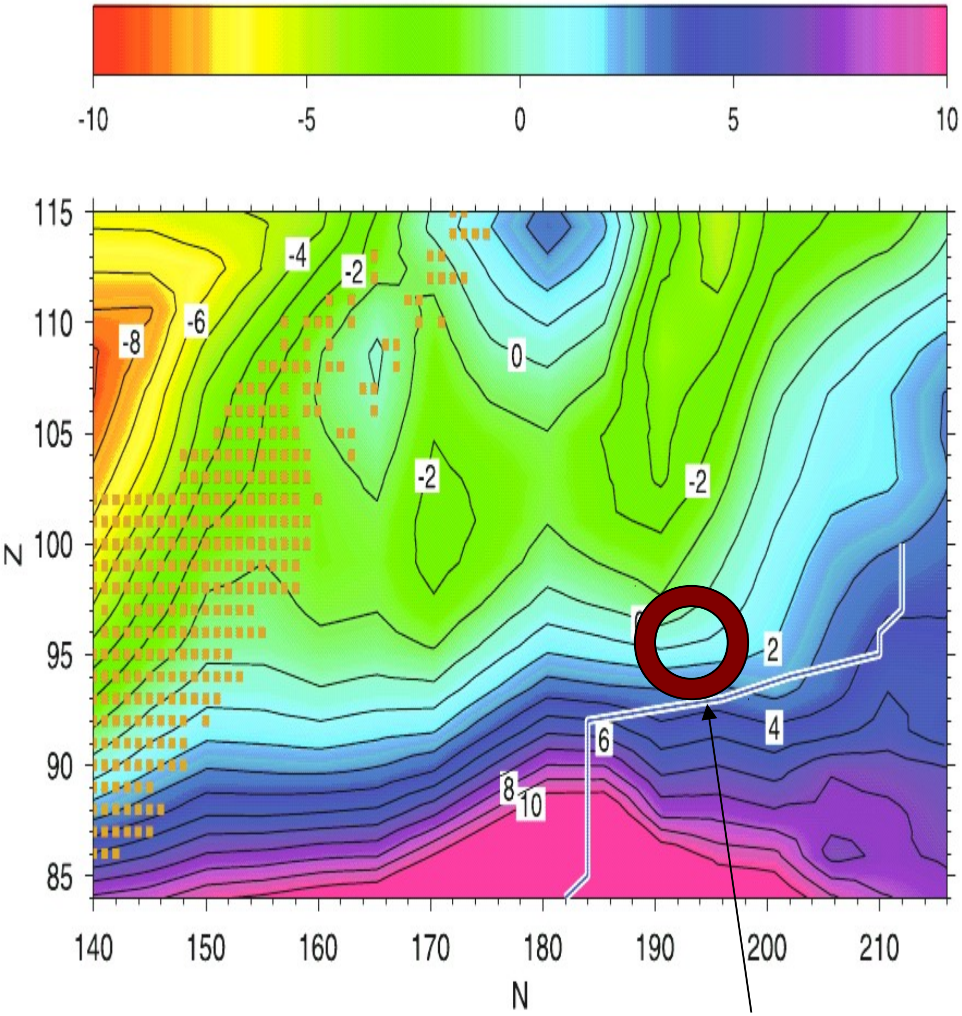
TF/FRDM (Myers, Swiatecki 1999)

B_f

ETFSI (Mamdouh et al. 2001)

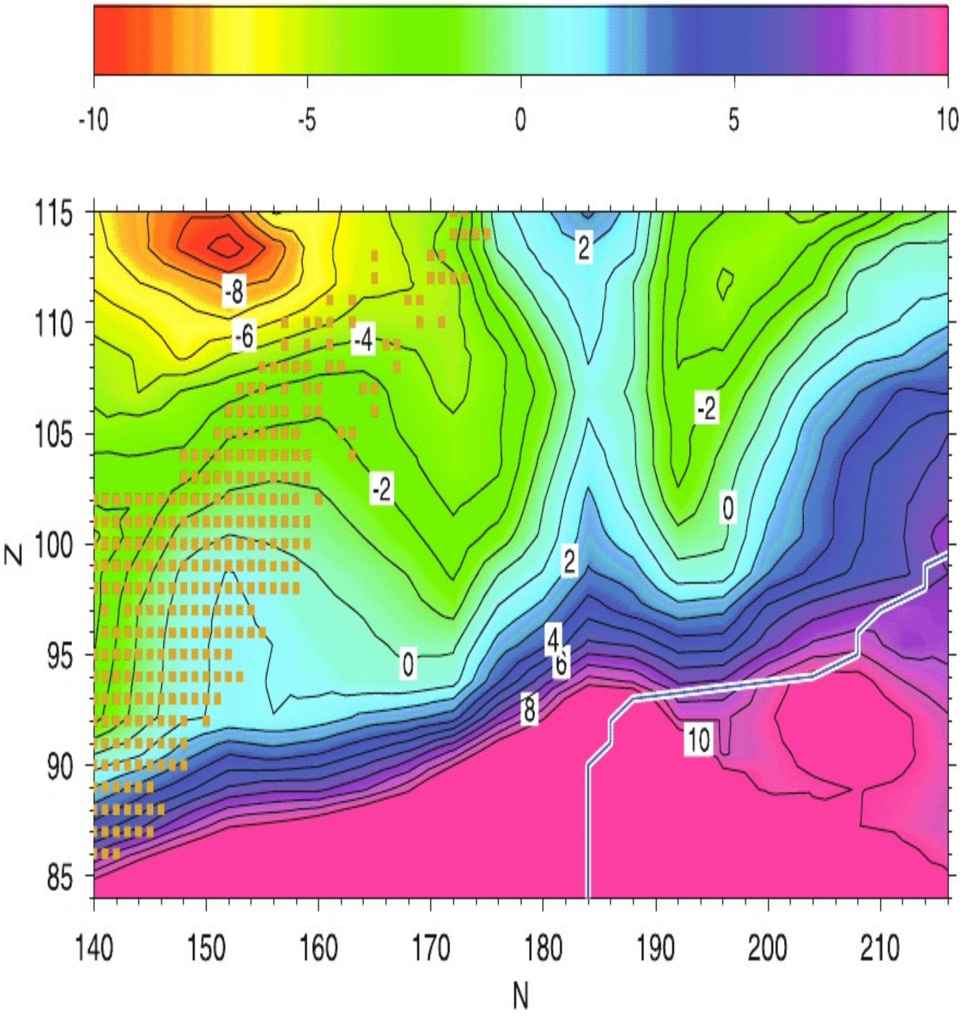
Fission Barriers (B_f-S_n) and the r-Process

(if negative => neutron-induced fission)



Myers & Swiatecki barriers (TF/FRDM)

narrow path without n-induced fission!

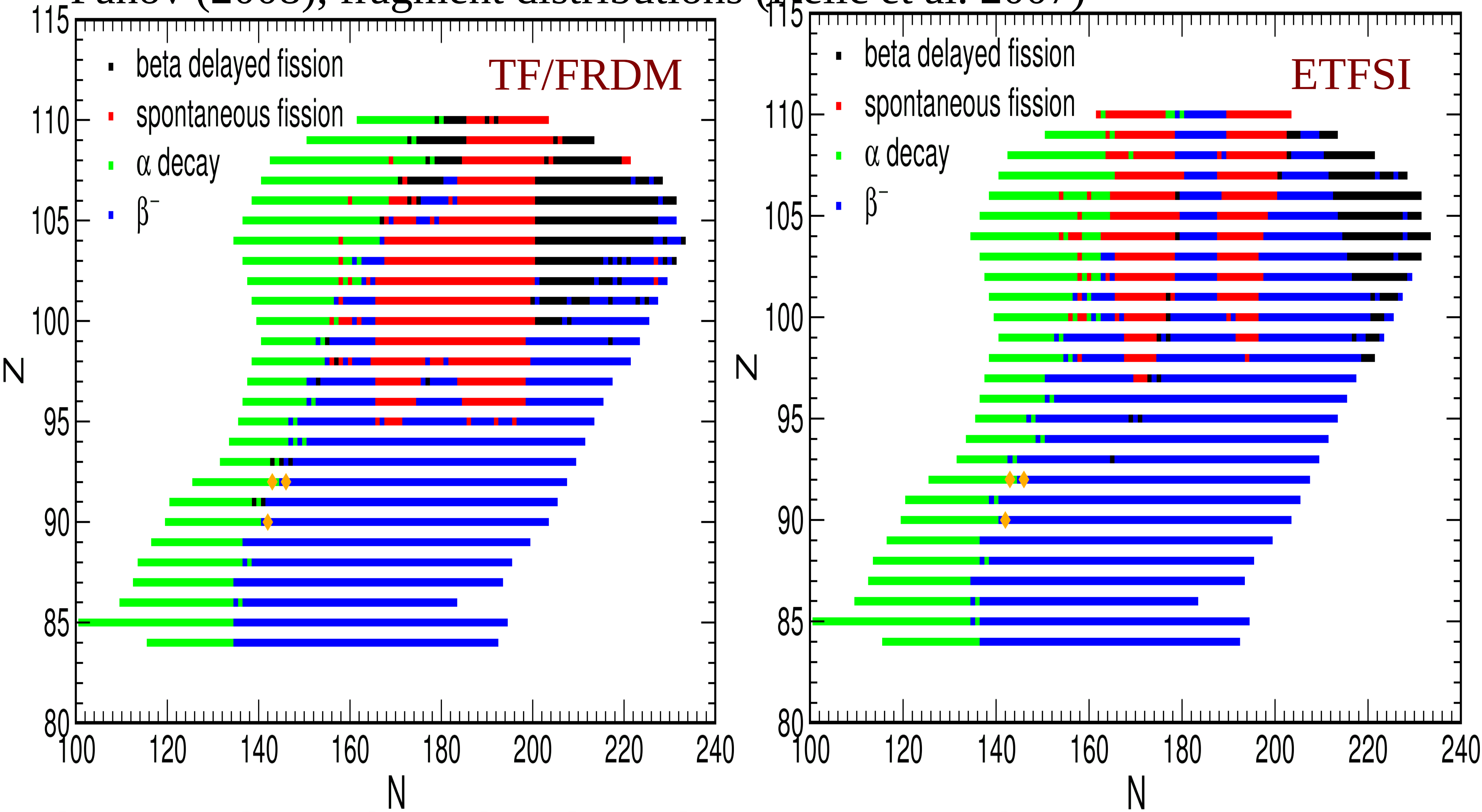


Mamdouh et al. barriers (ETFSI)

typically higher barriers

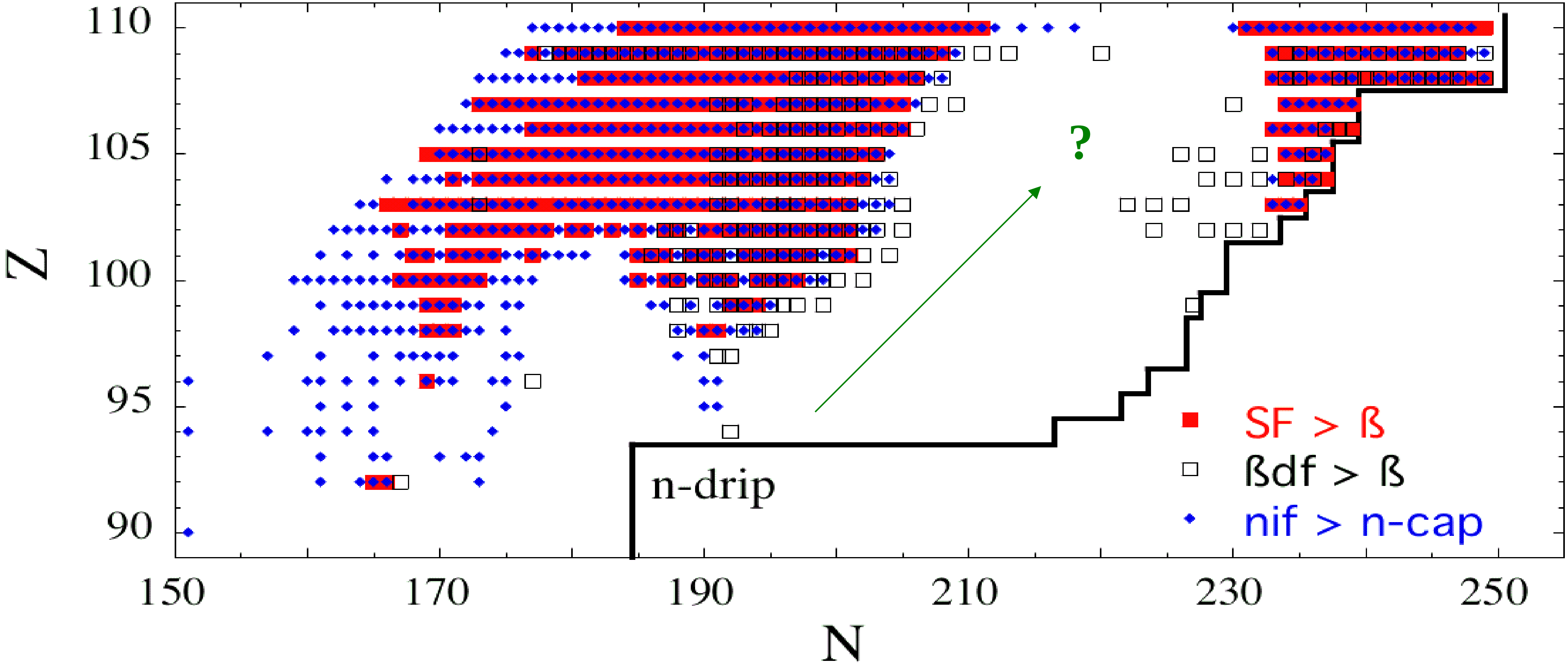
Inclusion of Decay Channels

Petermann et al (2012), Martinez-Pinedo et al. (2007), Panov et al. (2005), Panov (2008), fragment distributions (Kelic et al. 2007)



dominant decay channels indicated, important to utilize consistent sets (i.e. based on same mass model), spontaneous fission preliminary results ...

Goriely et al. (2015) HFB



a) double finger shape of sf exists down to Z (=102)

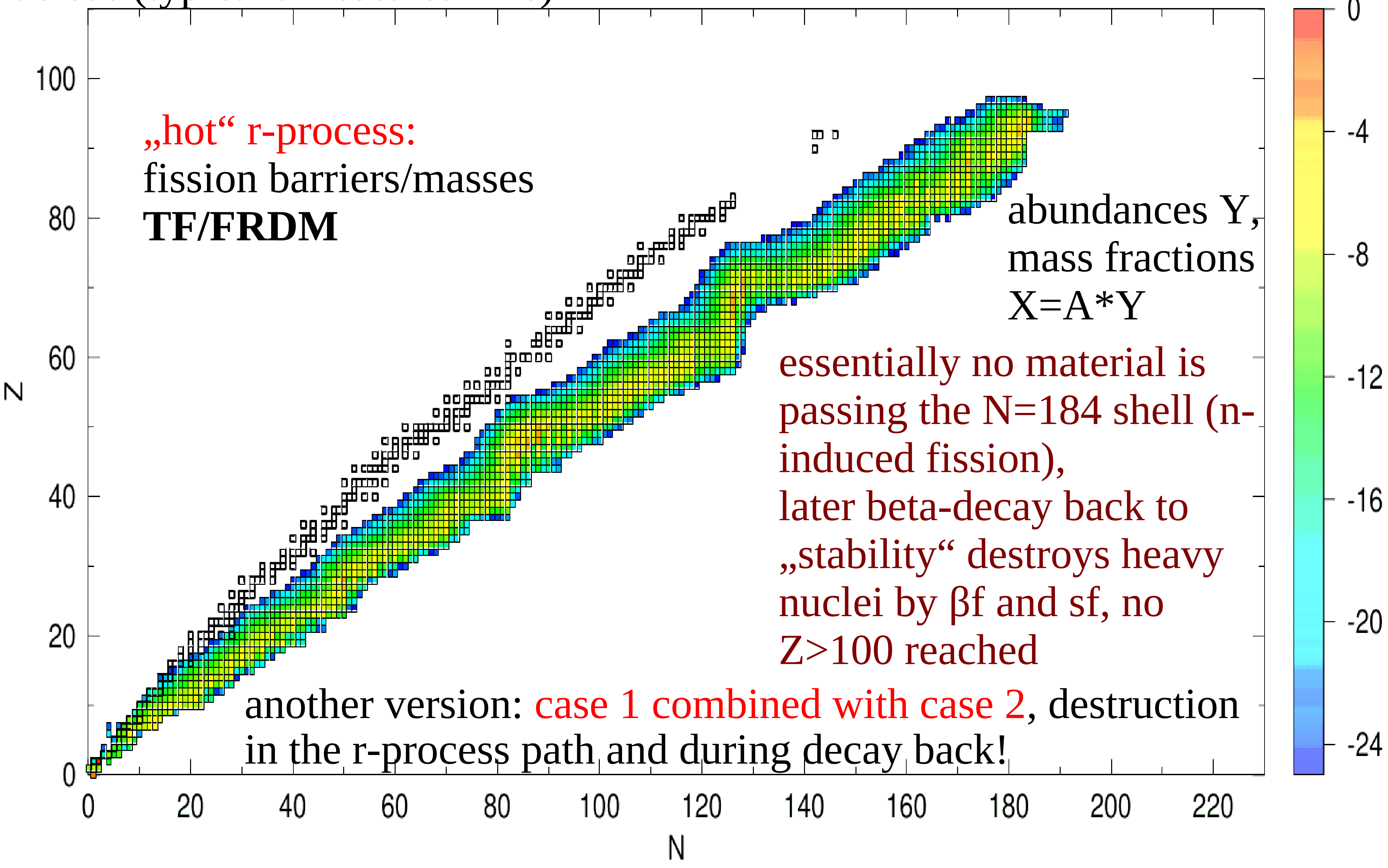
b) nf reaches close to the dripline at N=190

c) is there a chance to pass around the „fission island?“ to higher Z and reach stability? (**further investigations beyond Z=110!** (Erler, Reinhard et al. 2013 **no!**))

b*) all mass model/fission barrier combinations discussed here lead to (n,f) close to N=184 and thus to a fission fragment distribution including the A=130 r-process peak. If this is not the case (like for the KTUY mass model??), matter would proceed up to A>300 and fission fragments might largely miss A=130.

Series of parametrized r-process calculations for a hot and a cold r-process:

starting with a n/seed ratio of 200, results shown when 1 neutron left per heavy nucleus (typical timescales 1-2s)

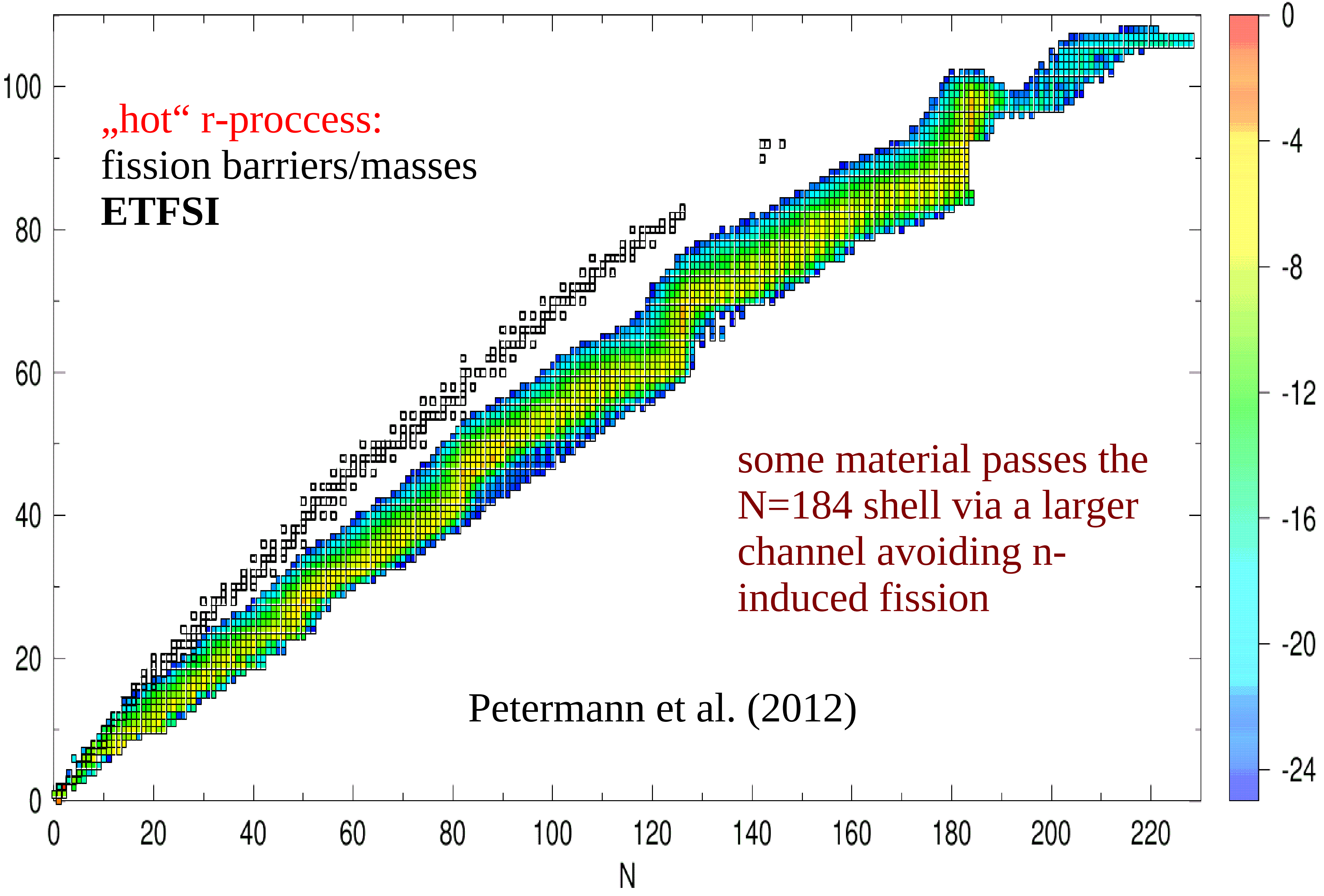


„hot“ r-process:
fission barriers/masses
TF/FRDM

abundances Y,
mass fractions
X=A*Y

essentially no material is passing the N=184 shell (n-induced fission), later beta-decay back to „stability“ destroys heavy nuclei by βf and sf, no Z>100 reached

another version: case 1 combined with case 2, destruction in the r-process path and during decay back!

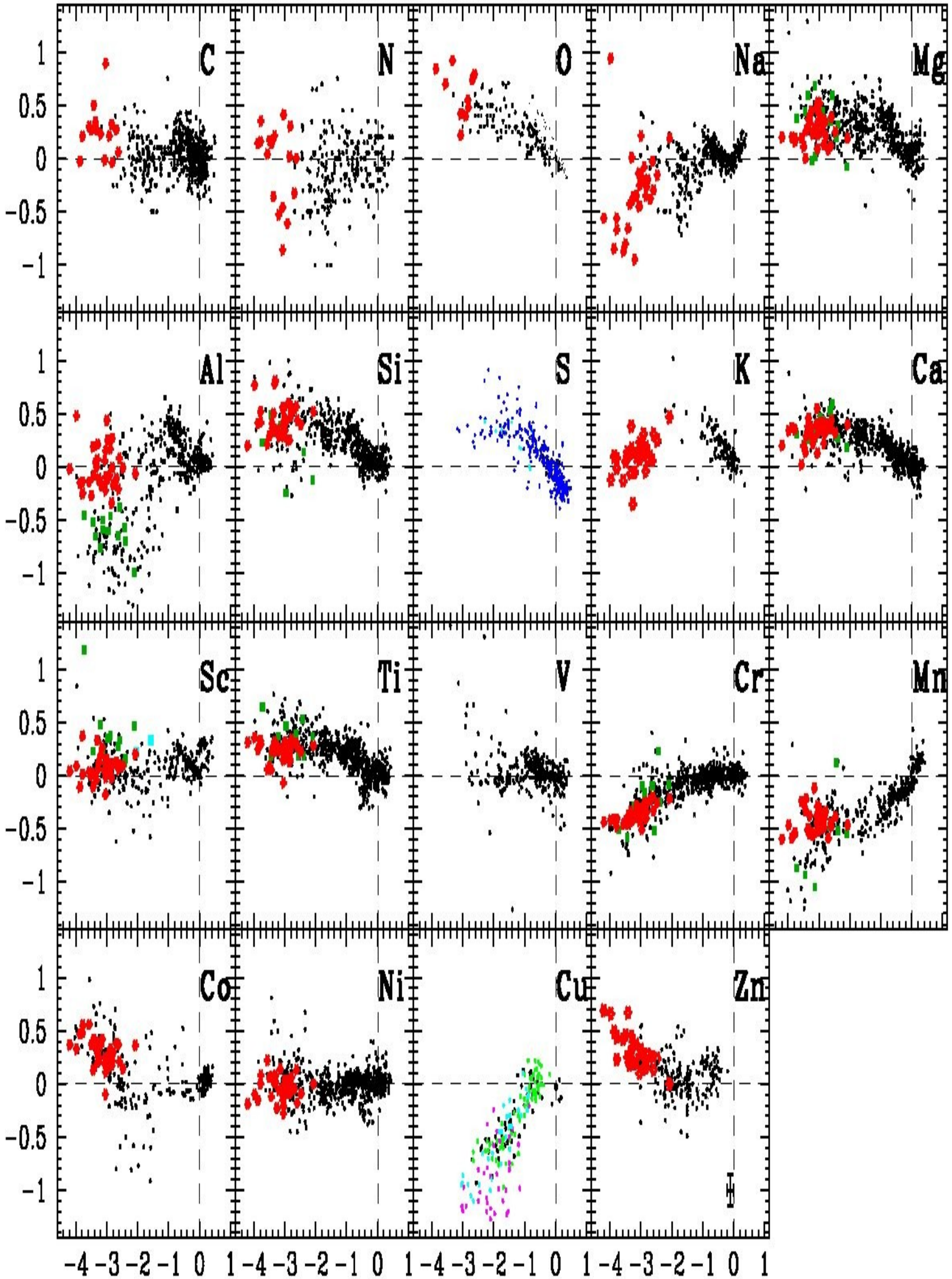


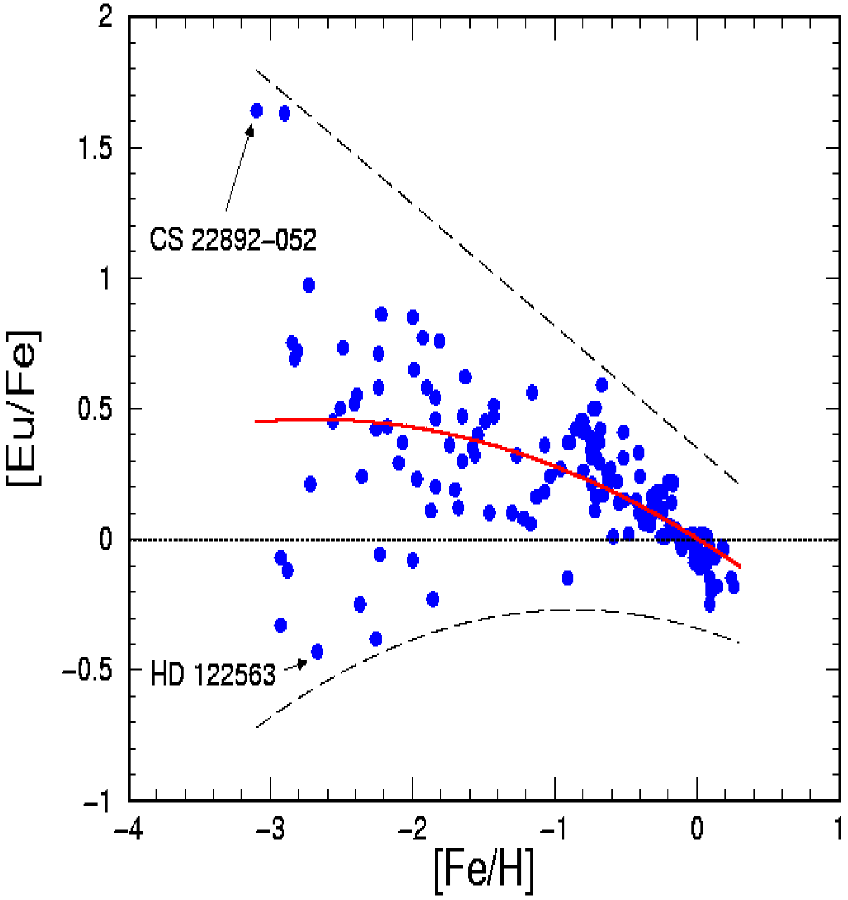
„hot“ r-proccess:
fission barriers/masses
ETFSI

some material passes the N=184 shell via a larger channel avoiding n-induced fission

Petermann et al. (2012)

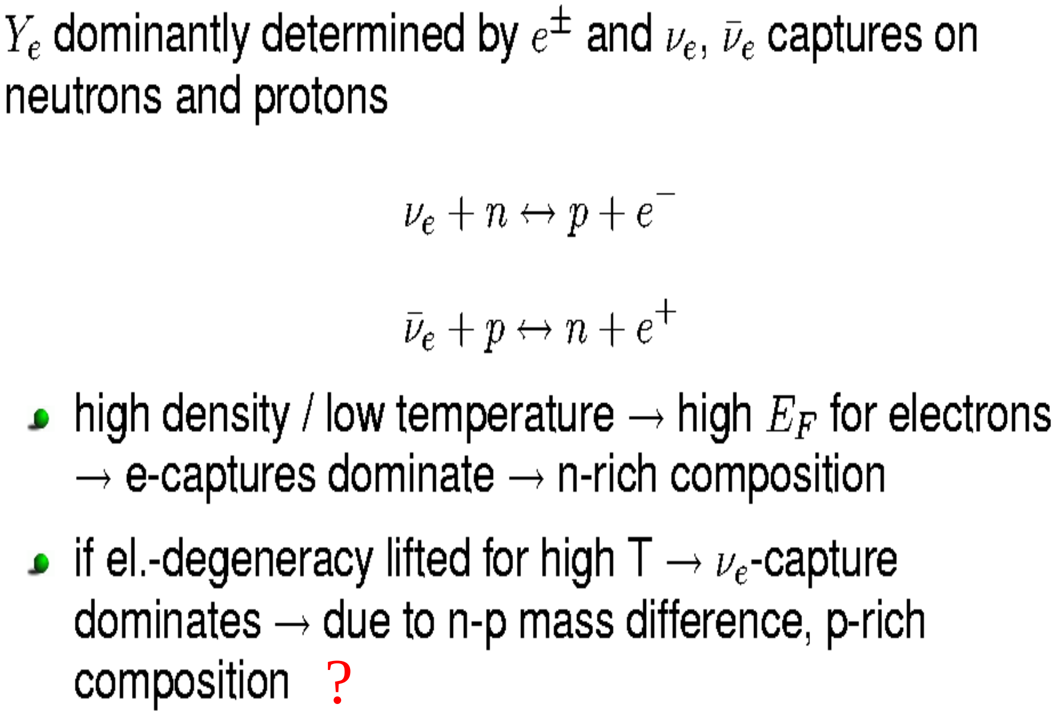
How do we understand: low metallicity stars ... galactic evolution?





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

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

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

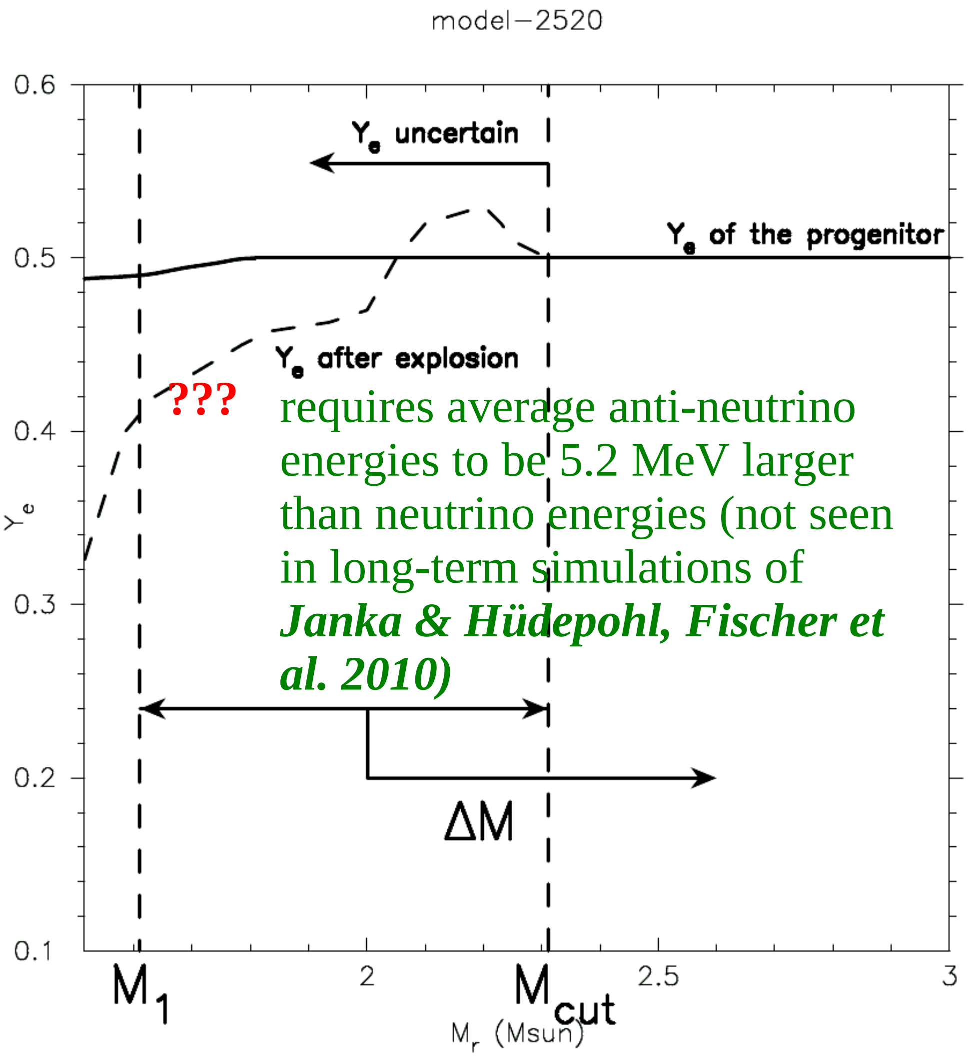
- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition ?

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, vp-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

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

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

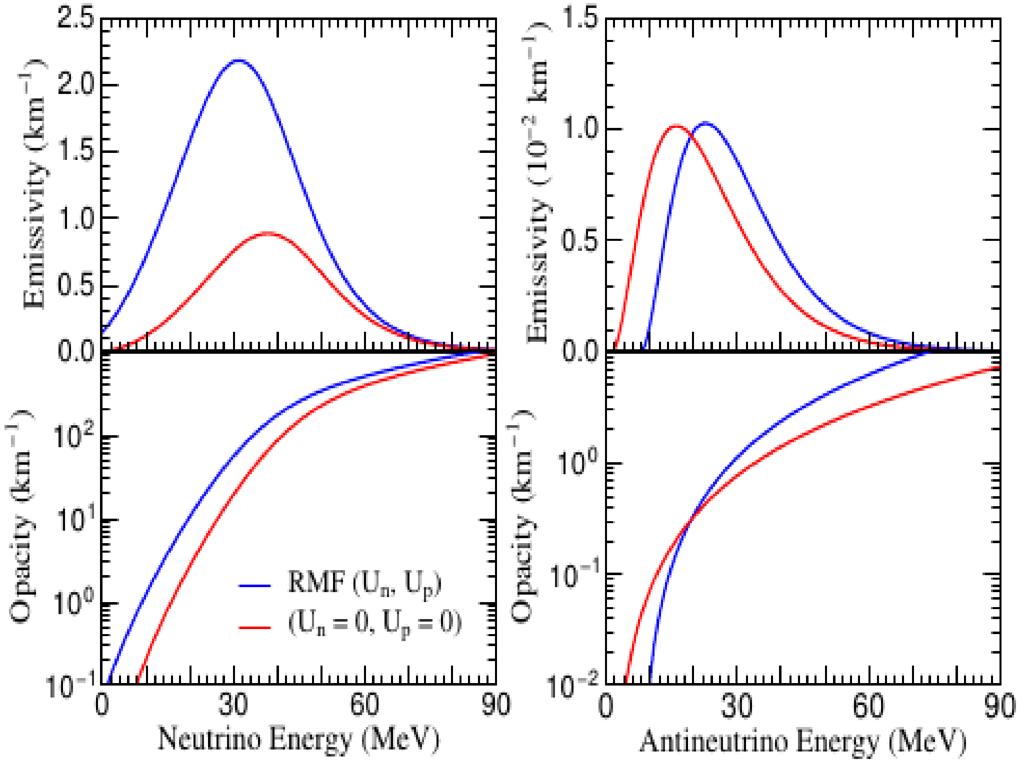


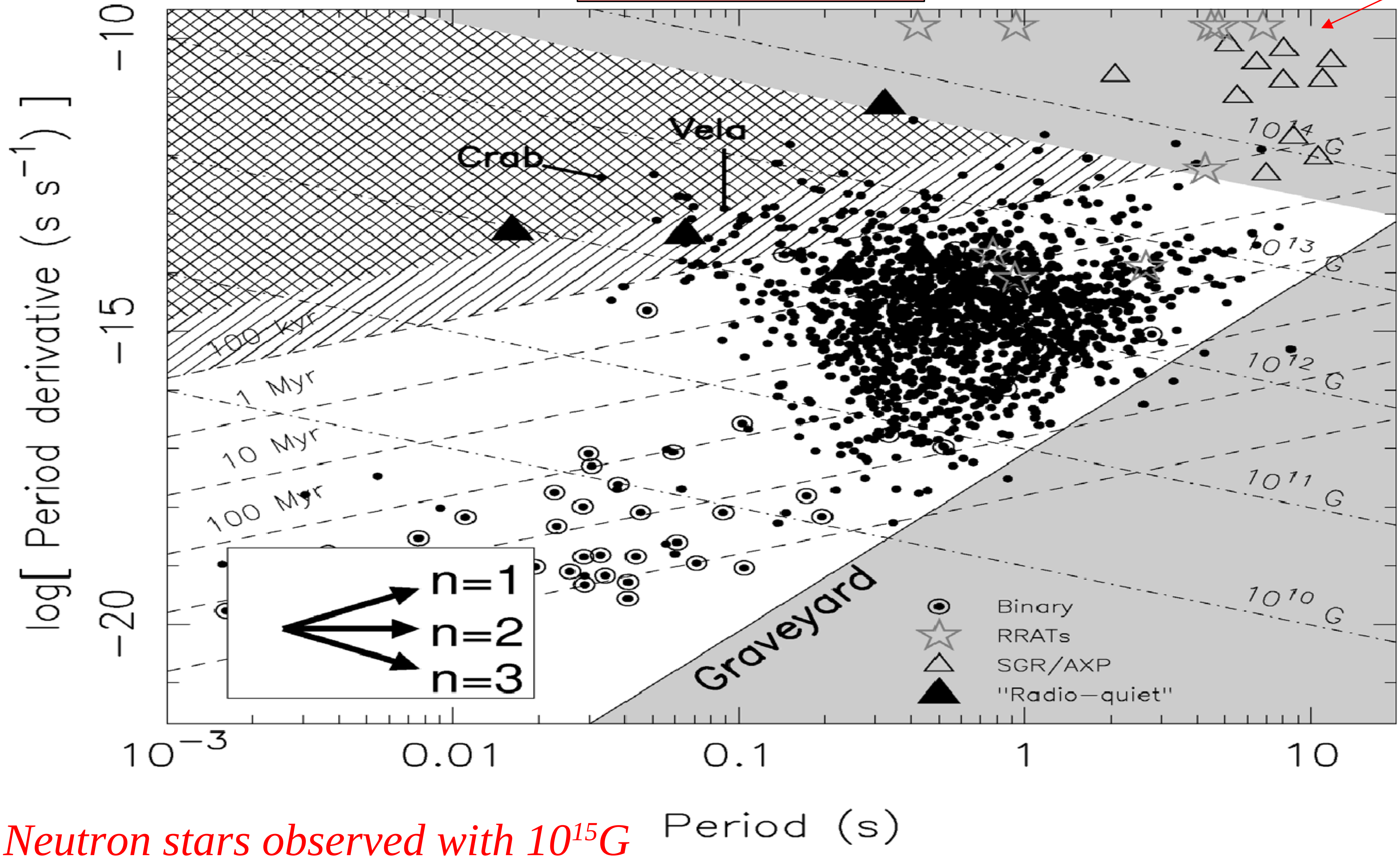
FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4! (further applications to supernova models result only 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, but no strong r-process in regular core-collapse supernovae!)

M. Kramer (2009)

Alternatives?



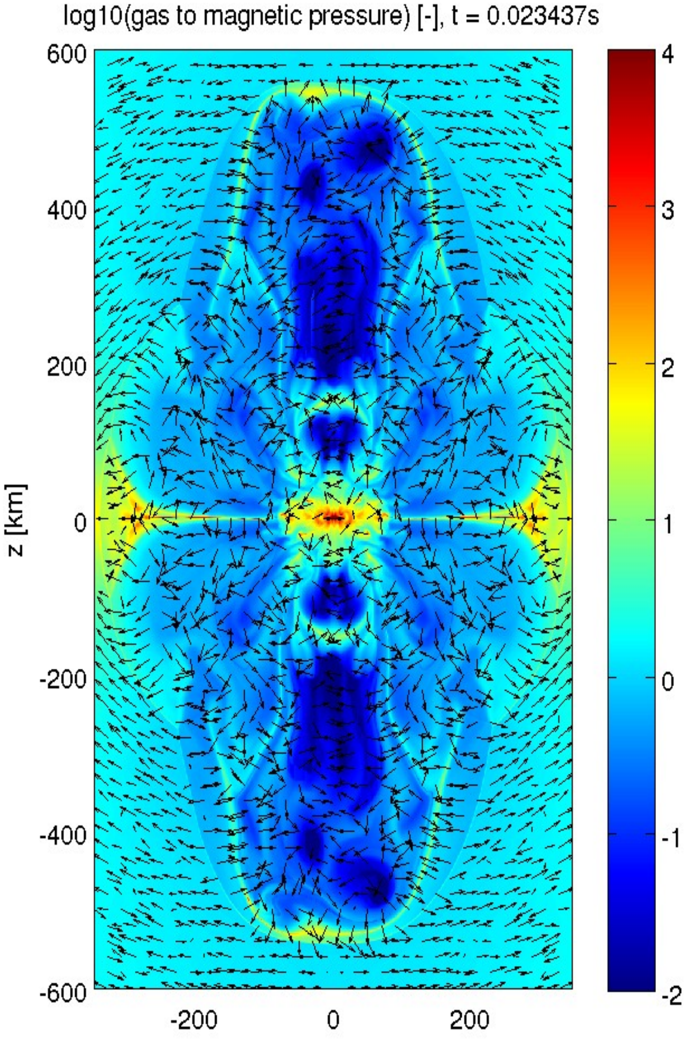
Neutron stars observed with 10^{15}G

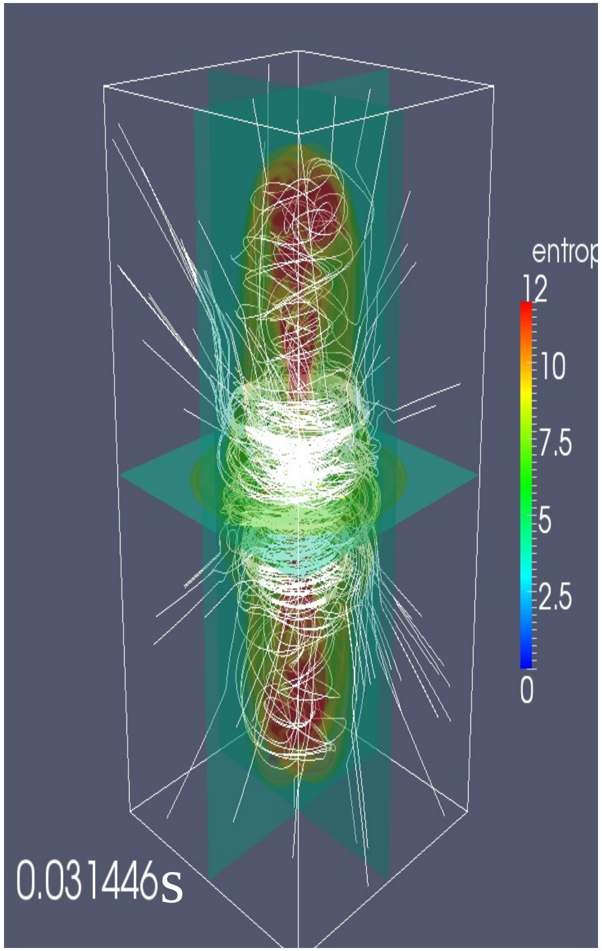
Figure 2. The P–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, 'radio-quiet' pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age τ_c and magnetic field B are also shown. The single hashed region shows 'Vela-like' 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.

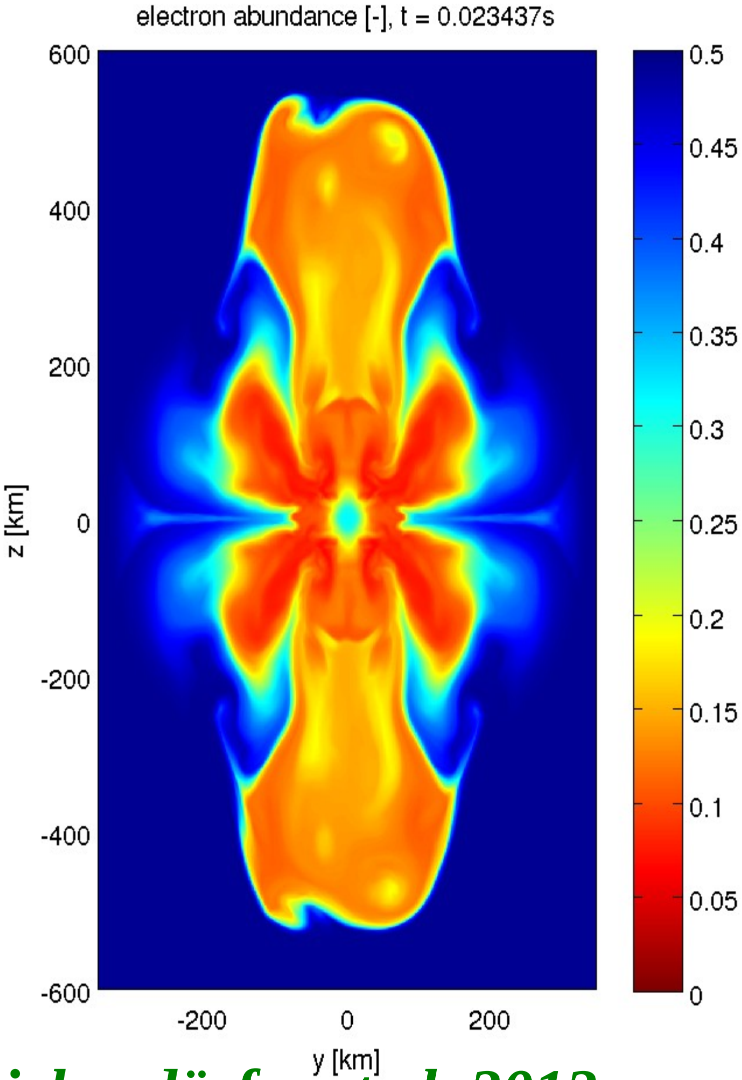
3D Collapse of Fast Rotator with Strong Magnetic Fields:

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





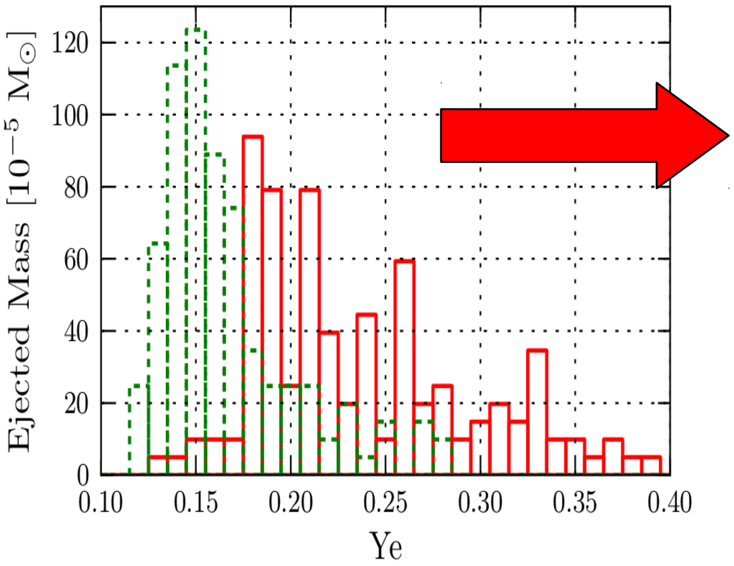


3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012

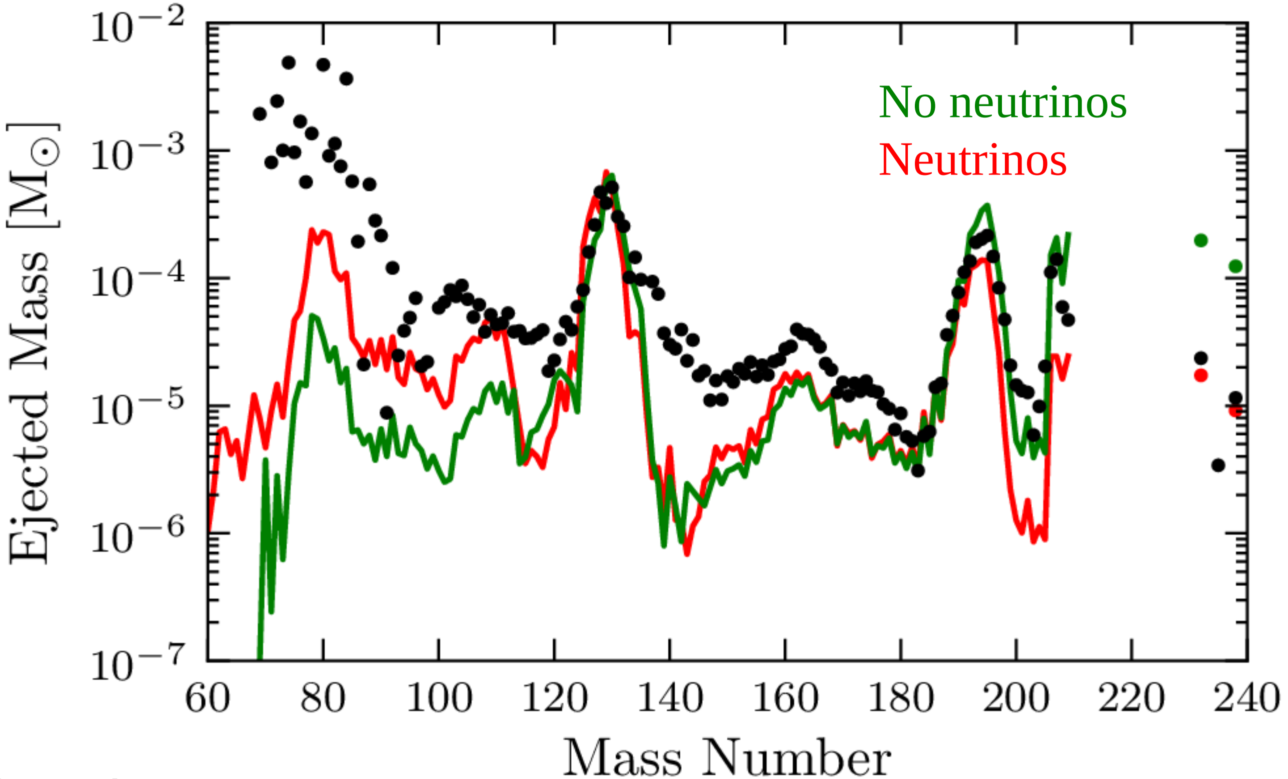
Eichler et al. 2013

Nucleosynthesis results

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



neutrino effect small opposite to neutrino wind with slow expansion velocities



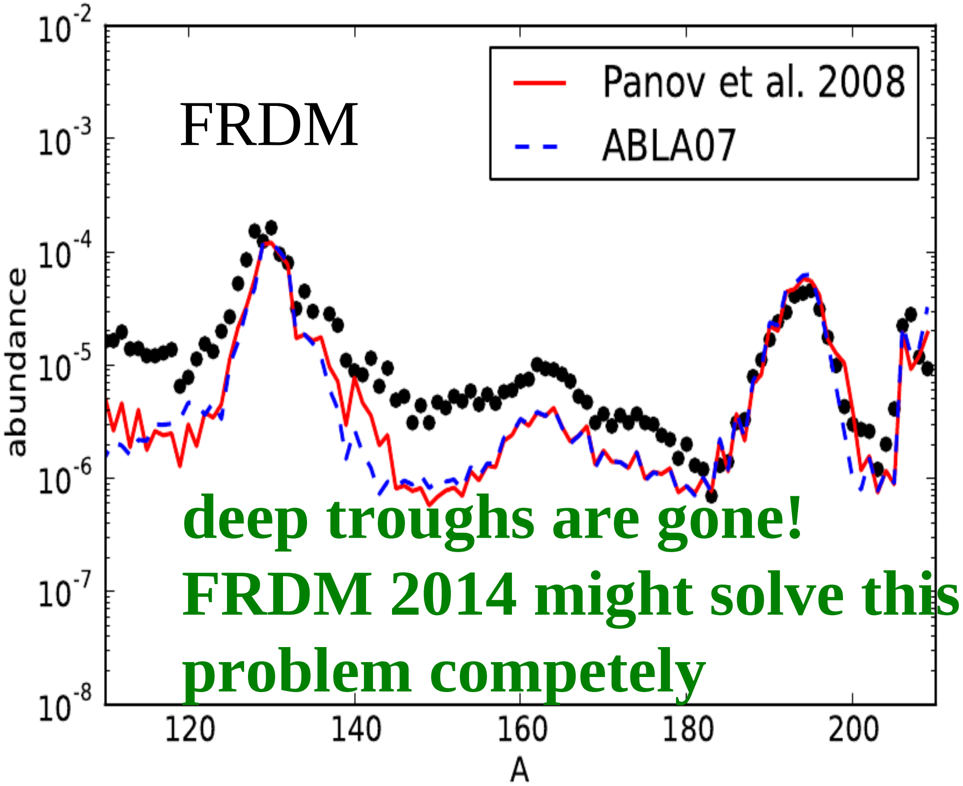
- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

similar to mergers!!!

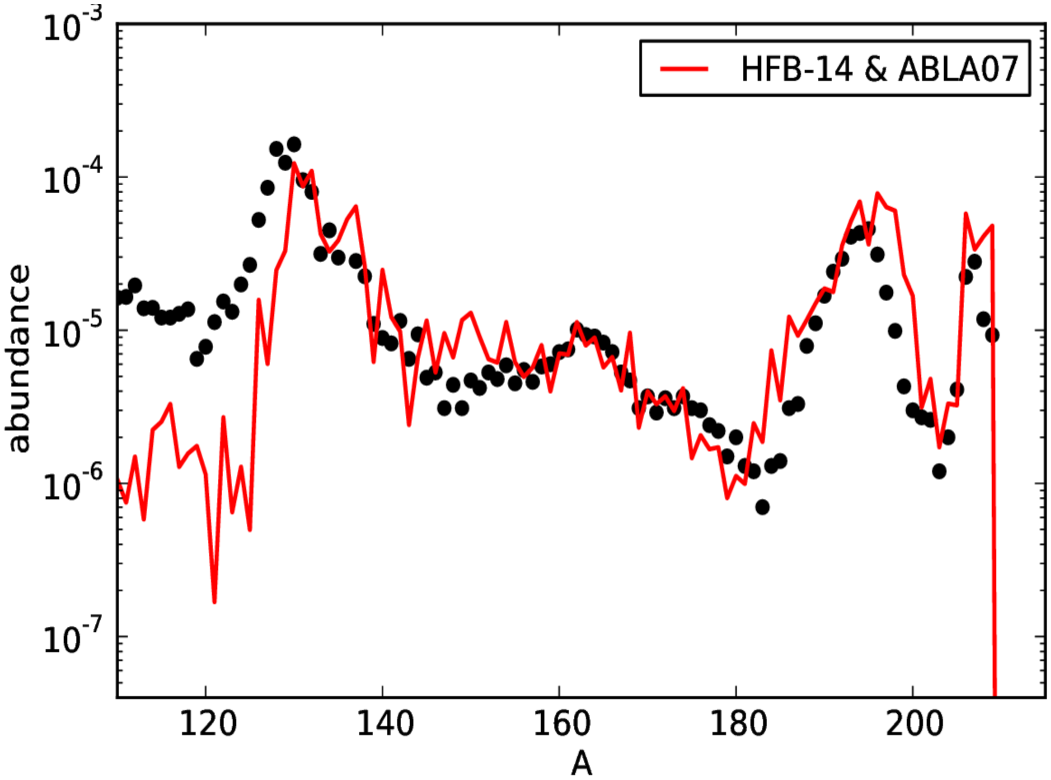
$$M_{\rm r,ej} \approx 6 \times 10^{-3}\ M_\odot$$

Effect of Mass Model and Fission Yield Distribution

(Eichler et al. 2014, 2015)



deep troughs are gone!
FRDM 2014 might solve this problem competely



In all fission-cycling environments HFB permits too much n-capture due to fission neutrons and shifts peaks, but effect generally not strong and overall good fit in such “weak“ fission-cycling environments!

Another 3D Study (Mösta et al. 2014)

25 M_{sol} progenitor (Heger+ 2000), magnetic field in z-direction of 10^{12} Gauss

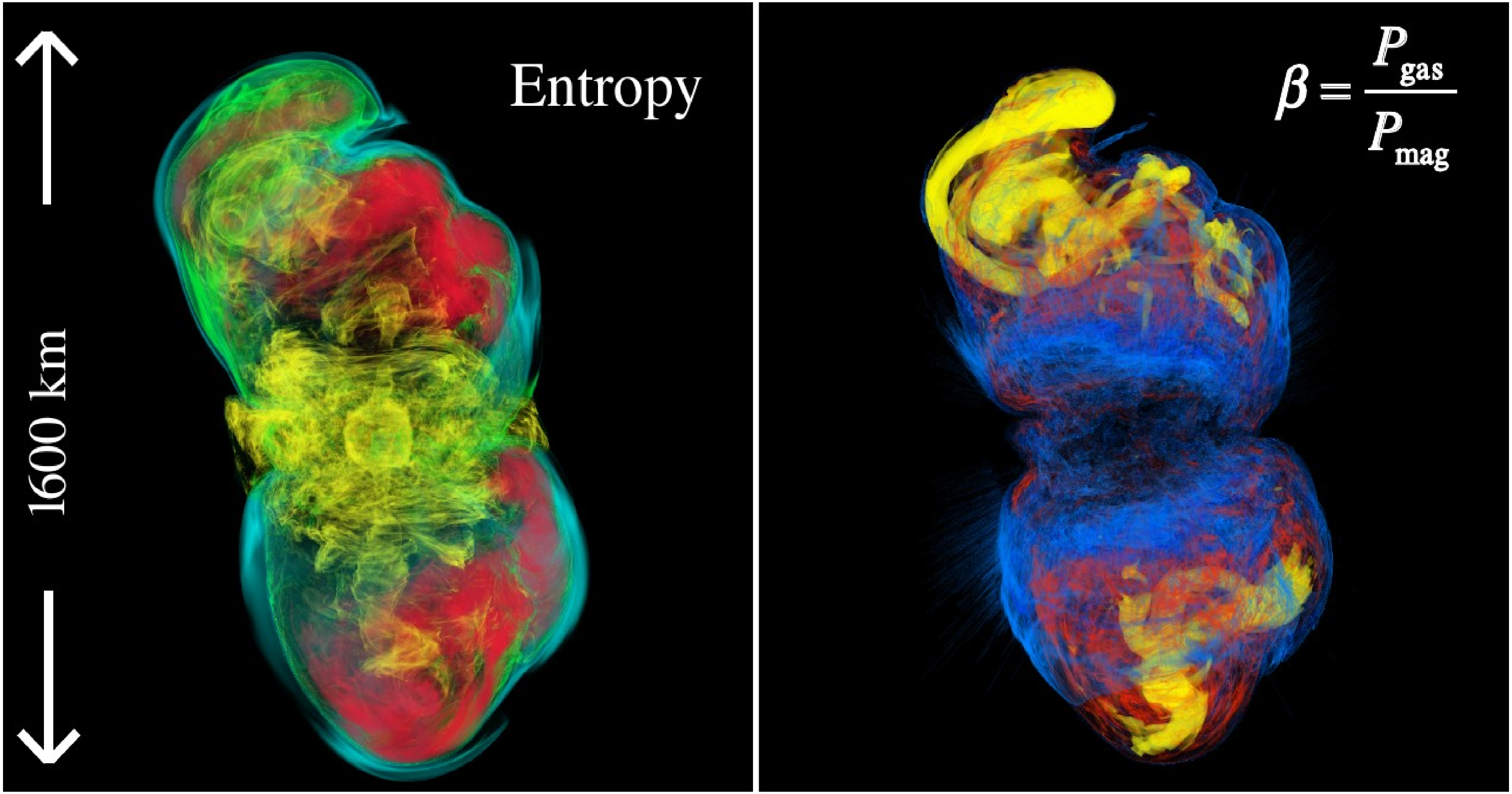
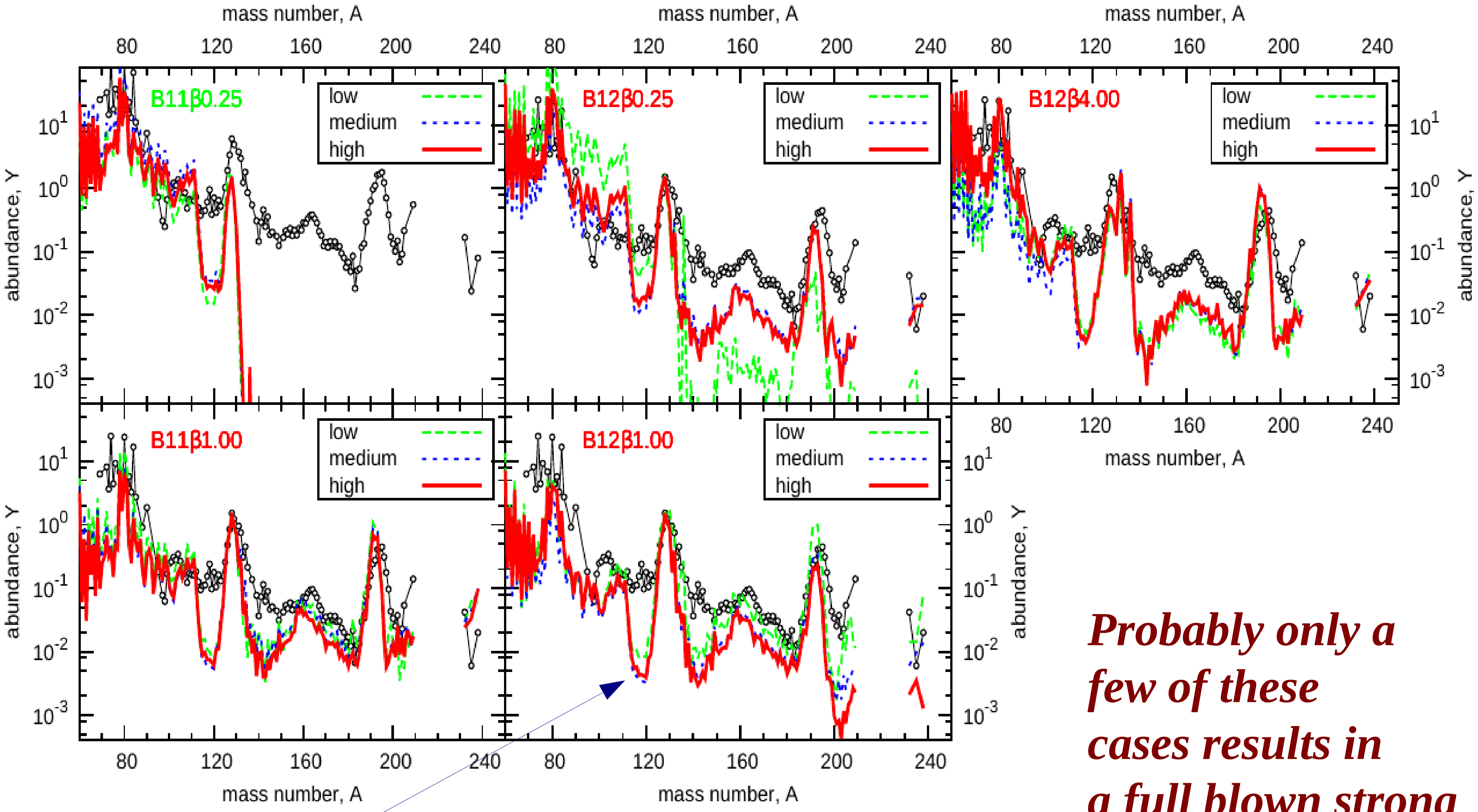


Figure 4. Volume renderings of entropy and β at $t - t_b = 161$ ms. The z-axis is the spin axis of the protoneutron star and we show 1600 km on a side. The colormap for entropy is chosen such that blue corresponds to $s = 3.7 k_b\,\text{baryon}^{-1}$, cyan to $s = 4.8 k_b\,\text{baryon}^{-1}$ indicating the shock surface, green to $s = 5.8 k_b\,\text{baryon}^{-1}$, yellow to $s = 7.4 k_b\,\text{baryon}^{-1}$, and red to higher entropy material at $s = 10 k_b\,\text{baryon}^{-1}$. For β we choose yellow to correspond to $\beta = 0.1$, red to $\beta = 0.6$, and blue to $\beta = 3.5$. Magnetically dominated material at $\beta < 1$ (yellow) is expelled from the protoneutron star and twisted in highly asymmetric tubes that drive the secular expansion of the polar lobes.

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



Probably only a few of these cases results in a full blown strong r-process

See discussion of fission fragment distributions and mass model

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!)*

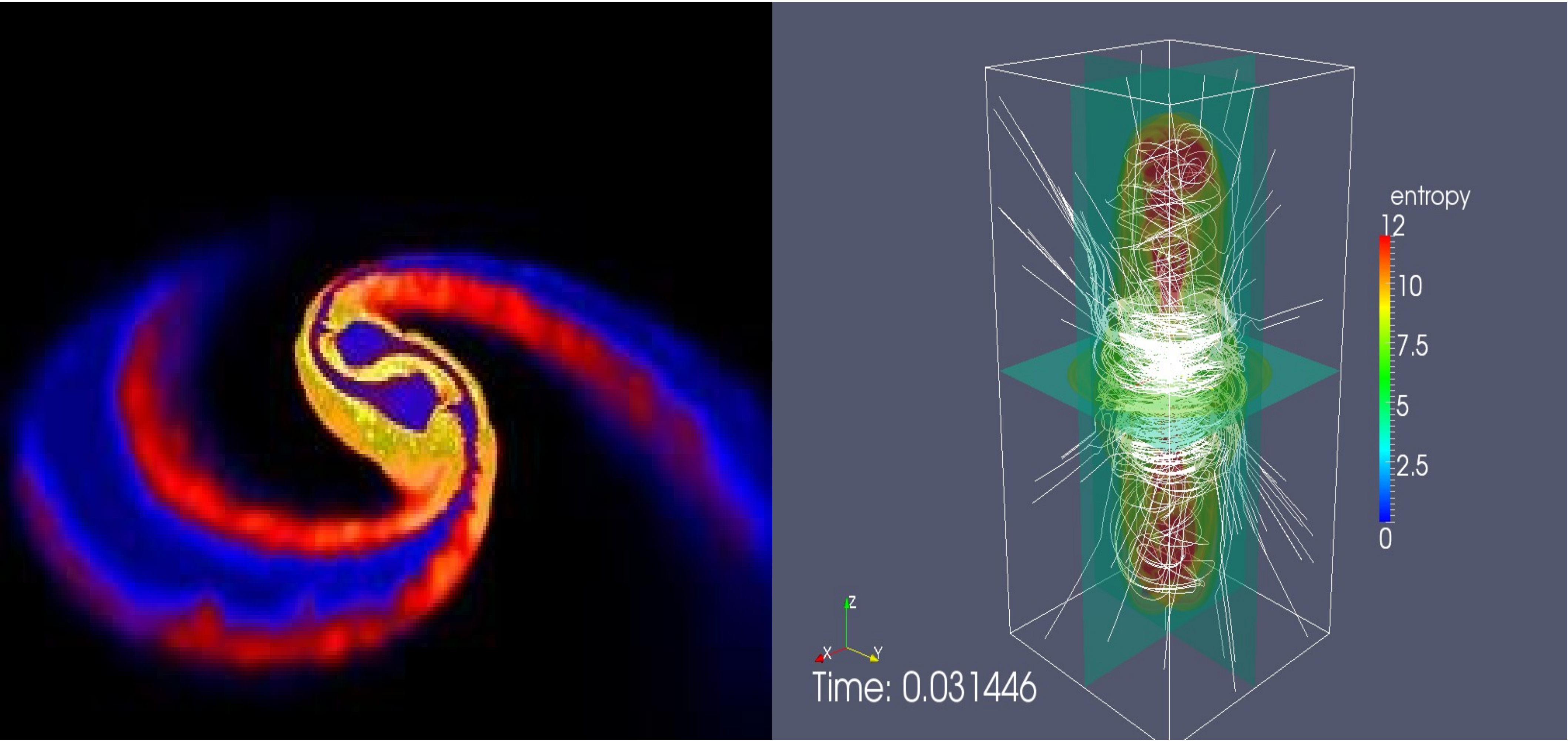
- **Neutron Star Mergers?** ***Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin, Wanajo, Just, Martin, Perego***
- **Black Hole Accretion Disks (massive stars as well as neutron star mergers, neutrino properties)** ***MacLaughlin, Surman, Wanajo,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

Which events contribute to the strong r-Process??

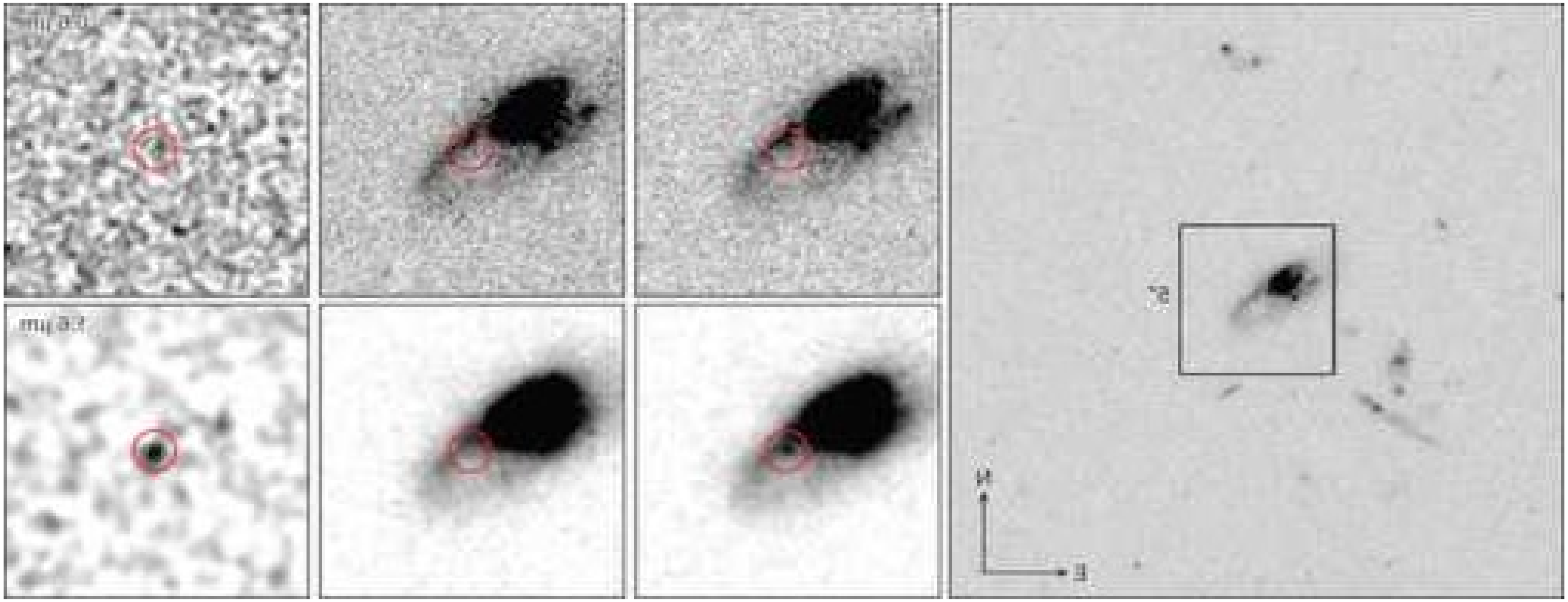


Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Neutron Star Mergers are observed

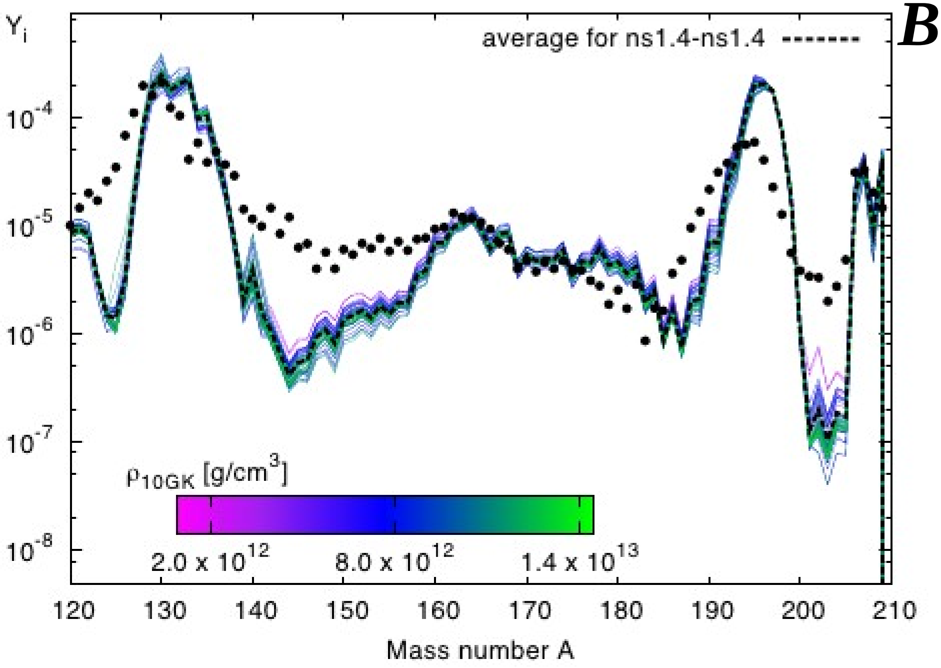
A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

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.***

Based on early ideas by Lattimer and Schramm, first detailed calculations by Freiburghaus et al. 1999, Fujimoto/Nishimura 2006-08,Panov et al. 2007, 2009, Bauswein et al. 2012, Goriely et al. 2012...



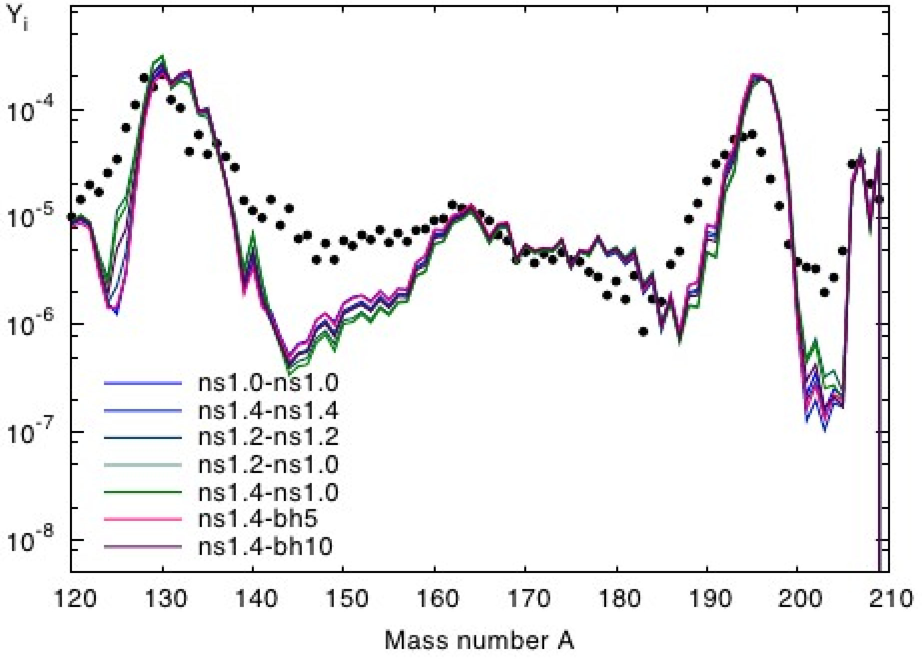
Neutron star merger updates (Korobkin et al. 2012)

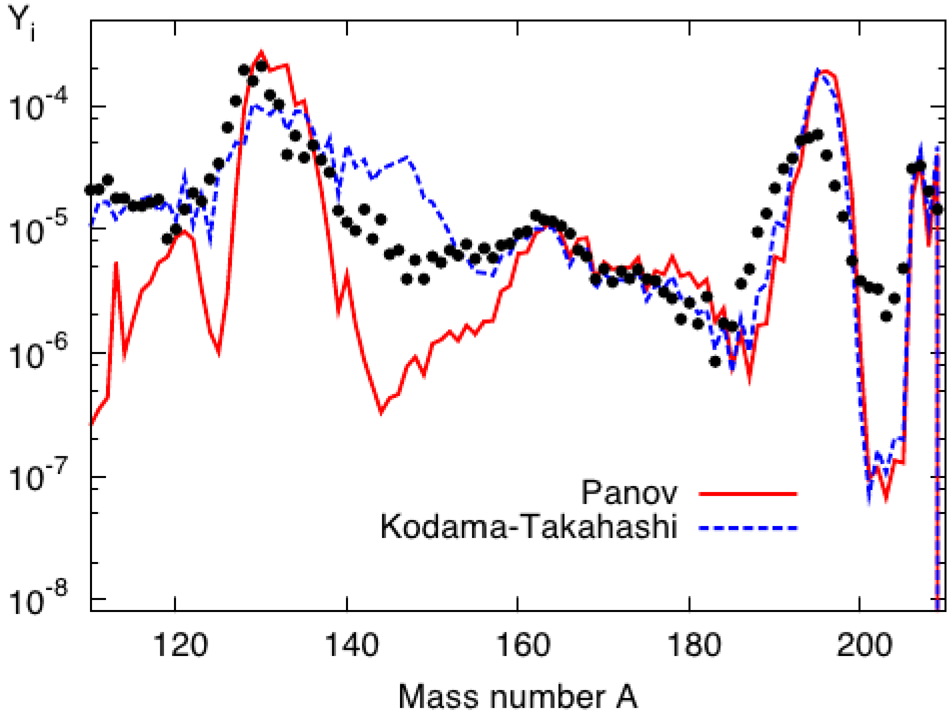
Variation in neutron star masses

fission yield prescription

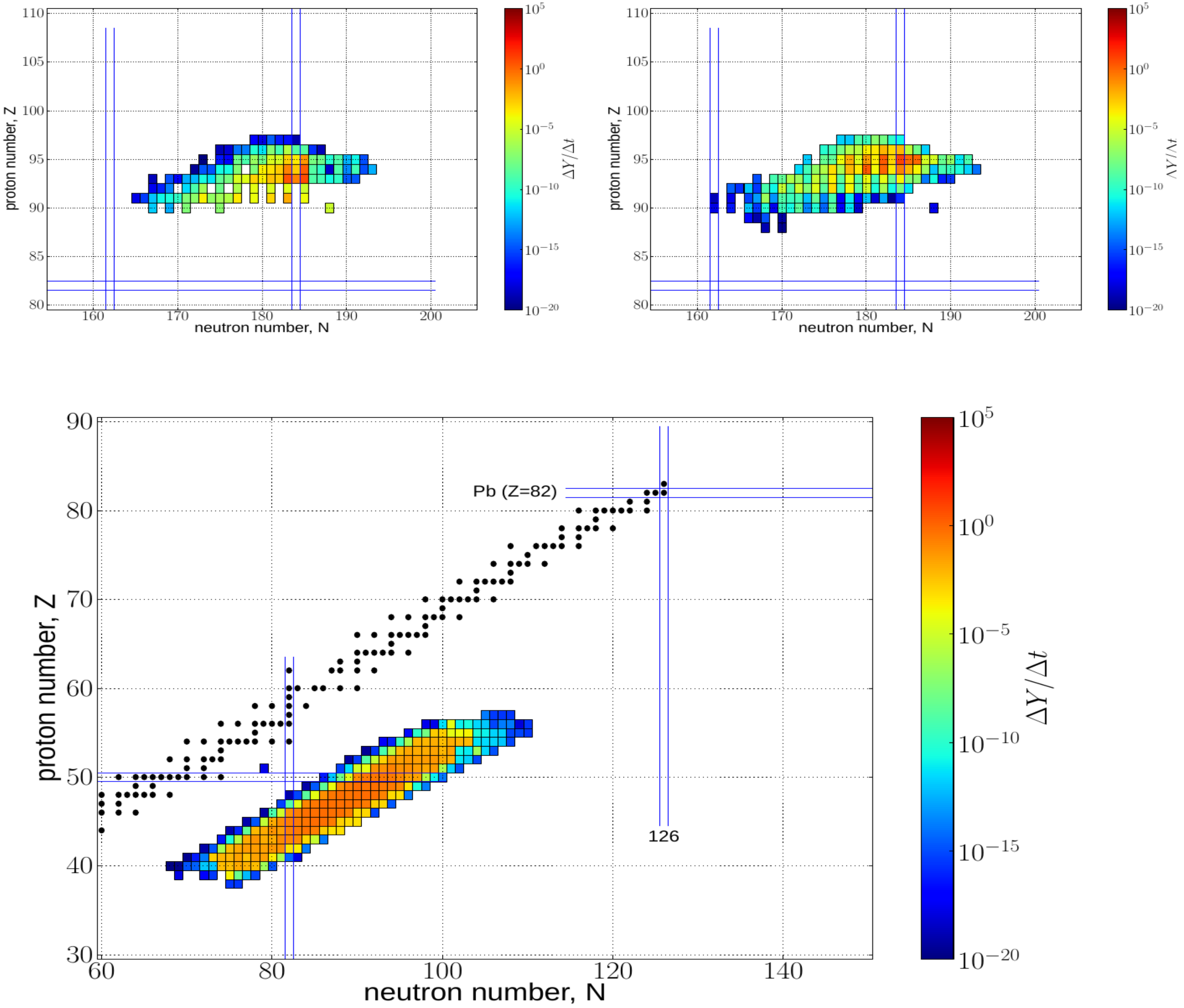
Fission yields affect abundances below A=165,

The third peak seems always shifted to heavier nuclei

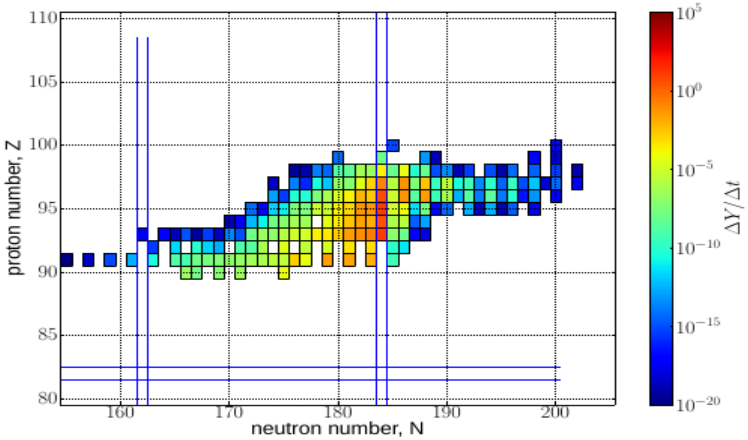




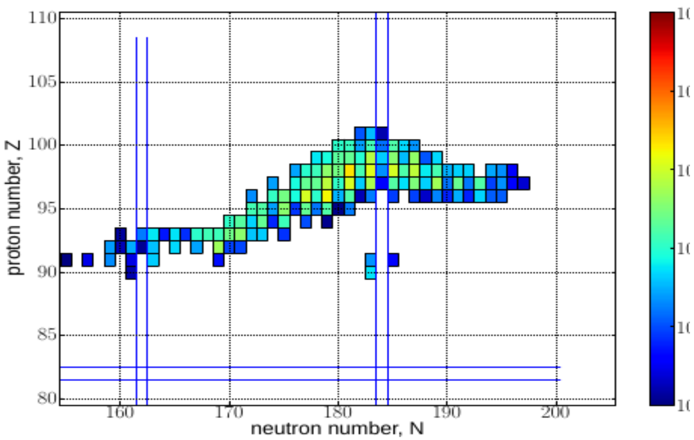
(n,f), (β,f) and fission yield distribution FRDM/TF (Eichler et al. 2014, 2015)



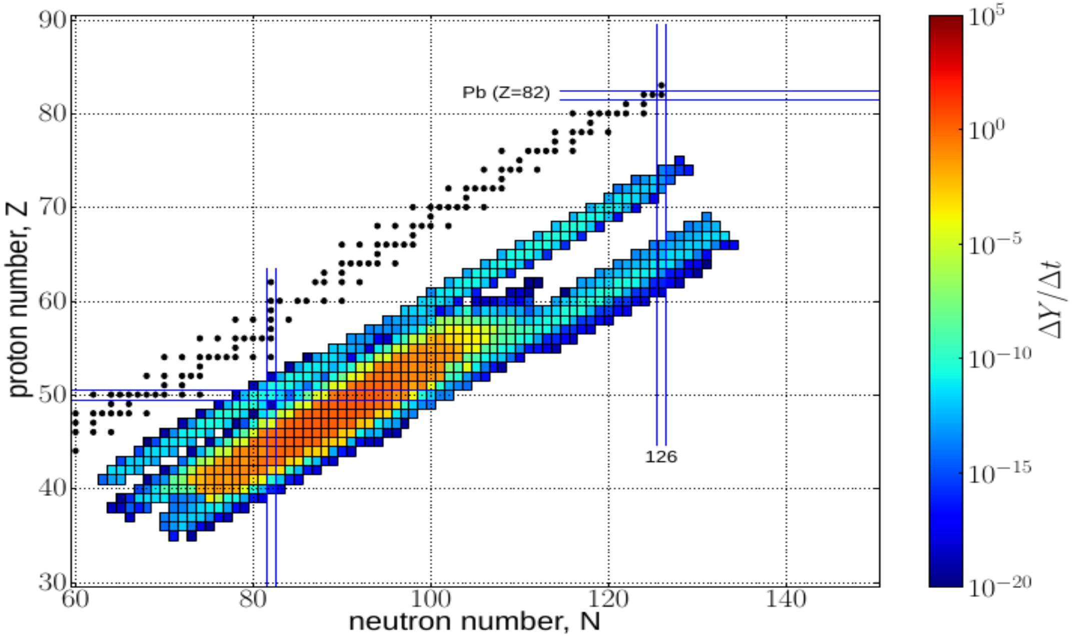
HFB and barriers from ETFSI



(a) β-delayed fission



(b) neutron-induced fission



(c) fission fragments

Petermann et al. (2012), hot and cold r-process with f-cycling

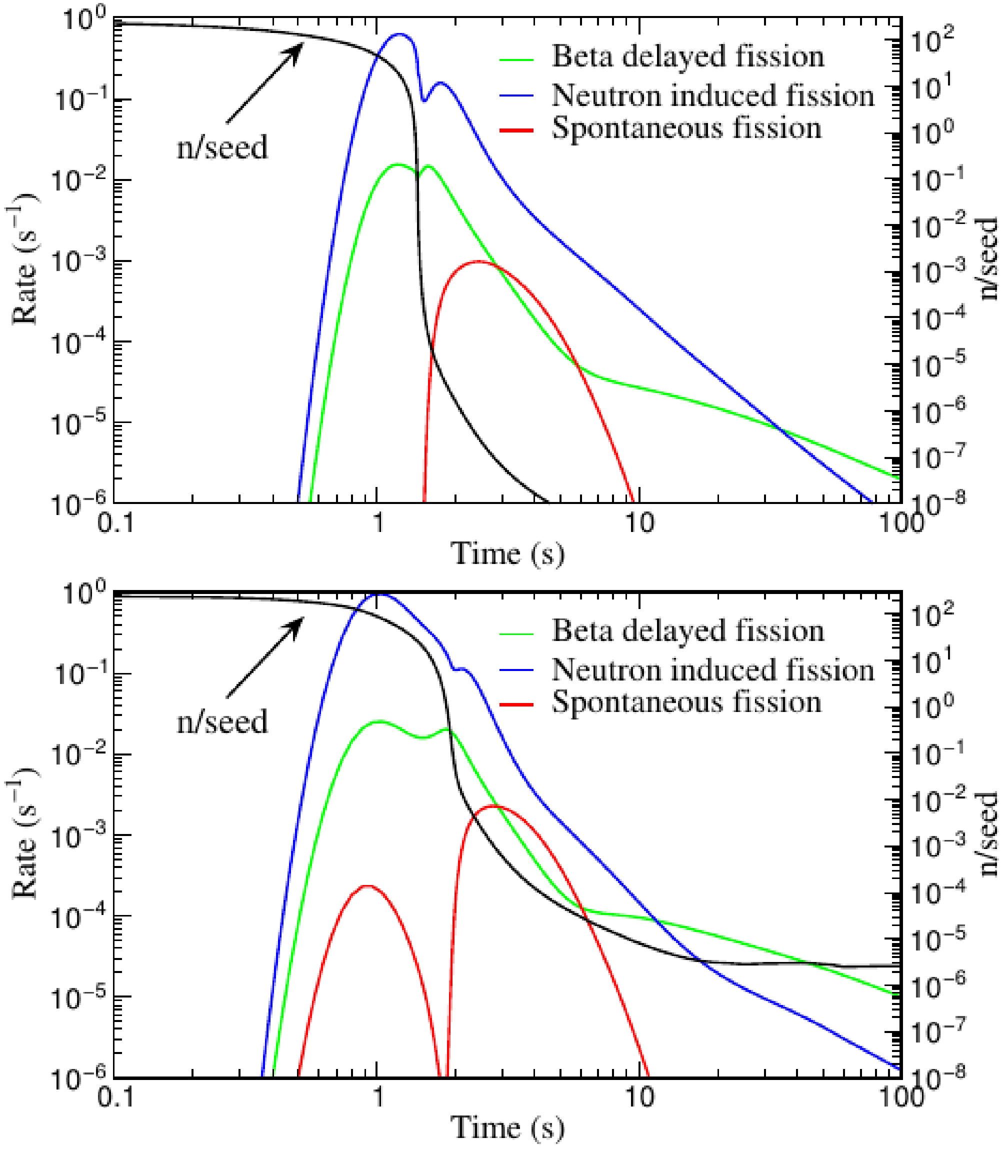


Fig. 9. The evolution of fission rates for the different channels shown for a hot (top) and cold (bottom) r-process with the fission barrier/mass model selection TF/FRDM.

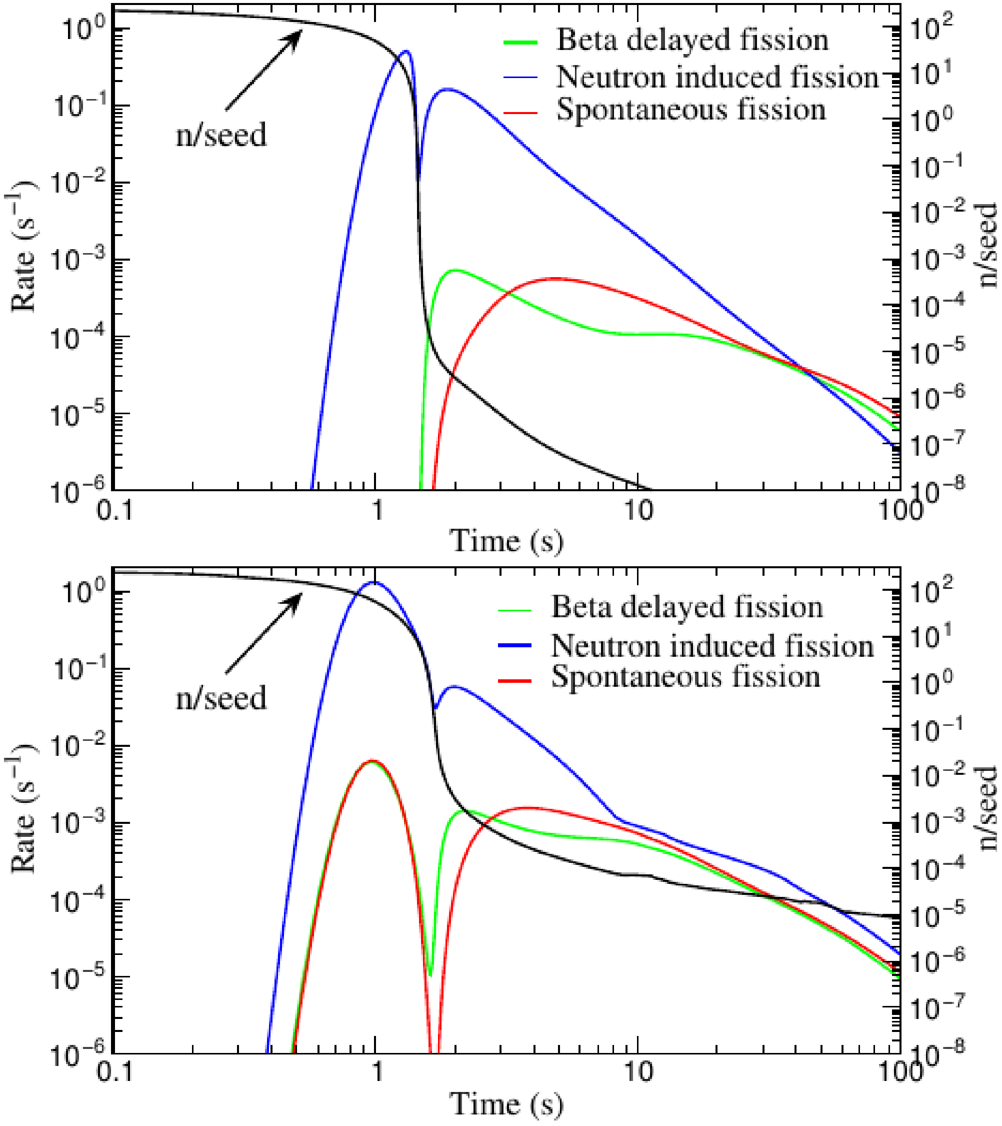
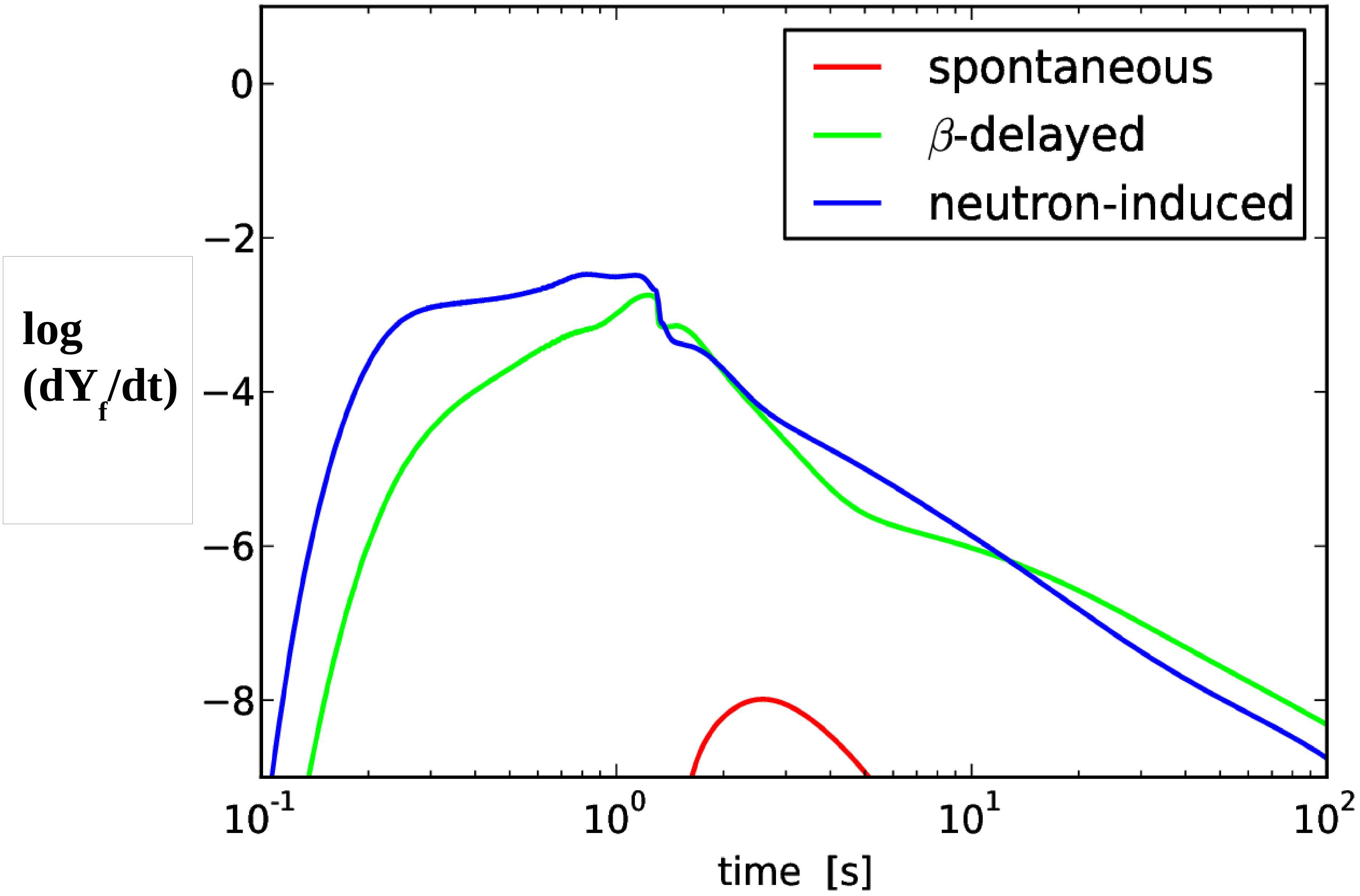


Fig. 10. Similar to Fig. 9, the evolution of fission rates for the different channels shown for a hot (top) and cold (bottom) r-process, but with the fission barrier/mass model selection ETFSI/ETFSI.

Importance of Fission Modes in Dynamic r-Process Ejecta
FRDM/ETFSI (Eichler et al. 2015)



(n,γ)-(γ,n) equilibrium is in place up to about 1s

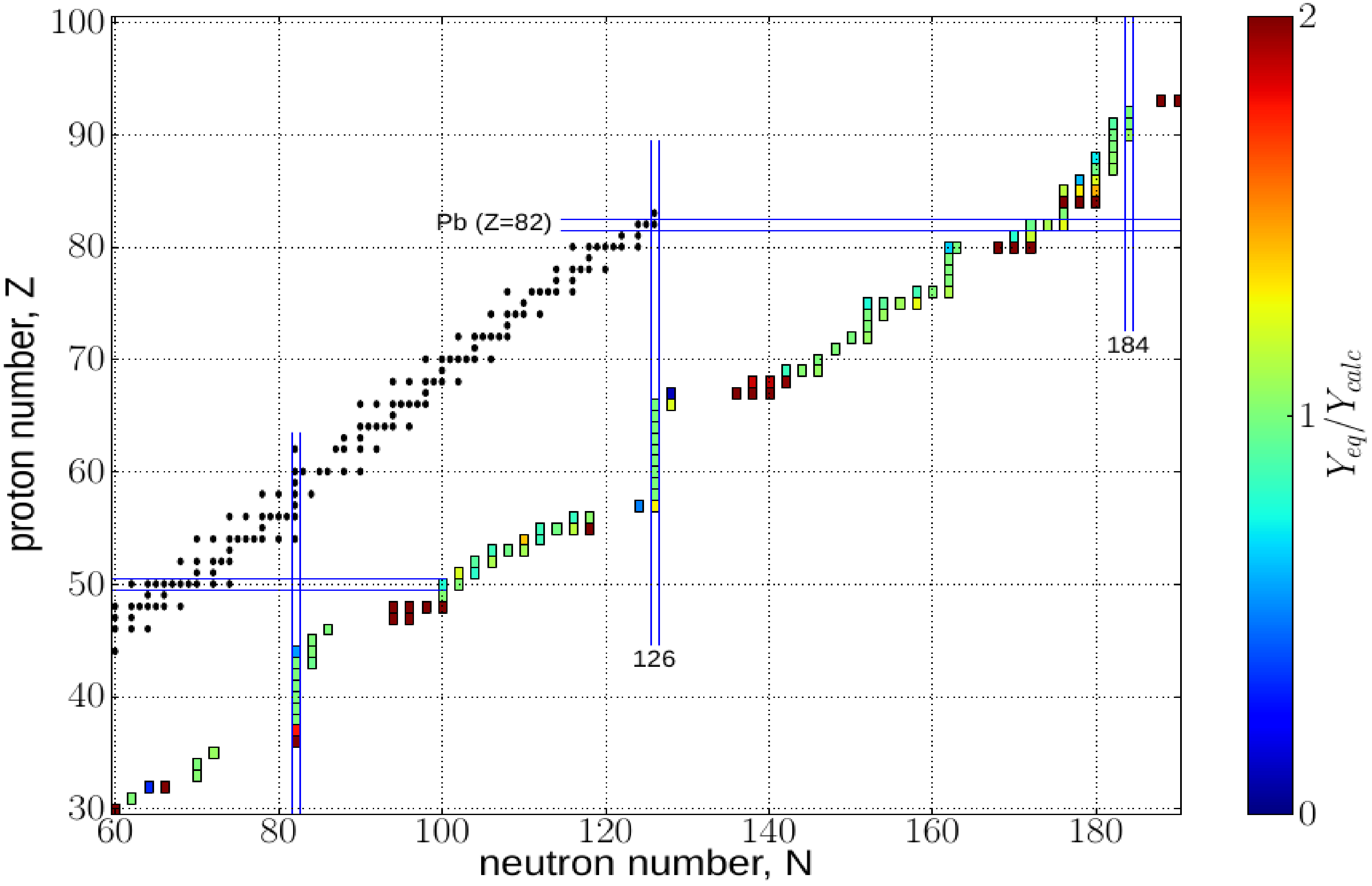
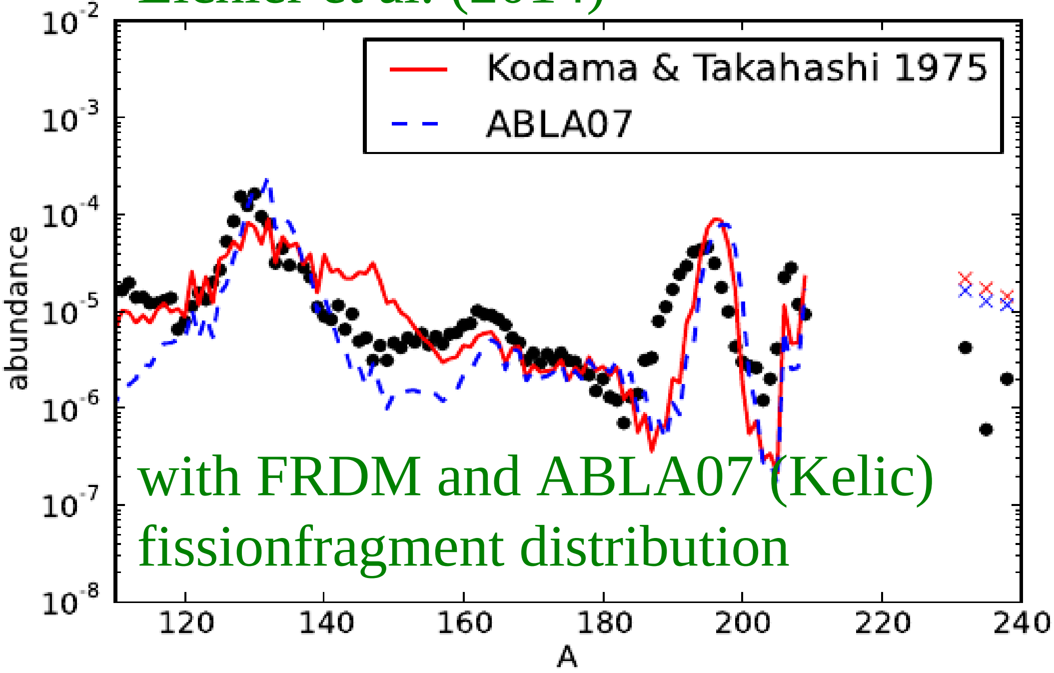
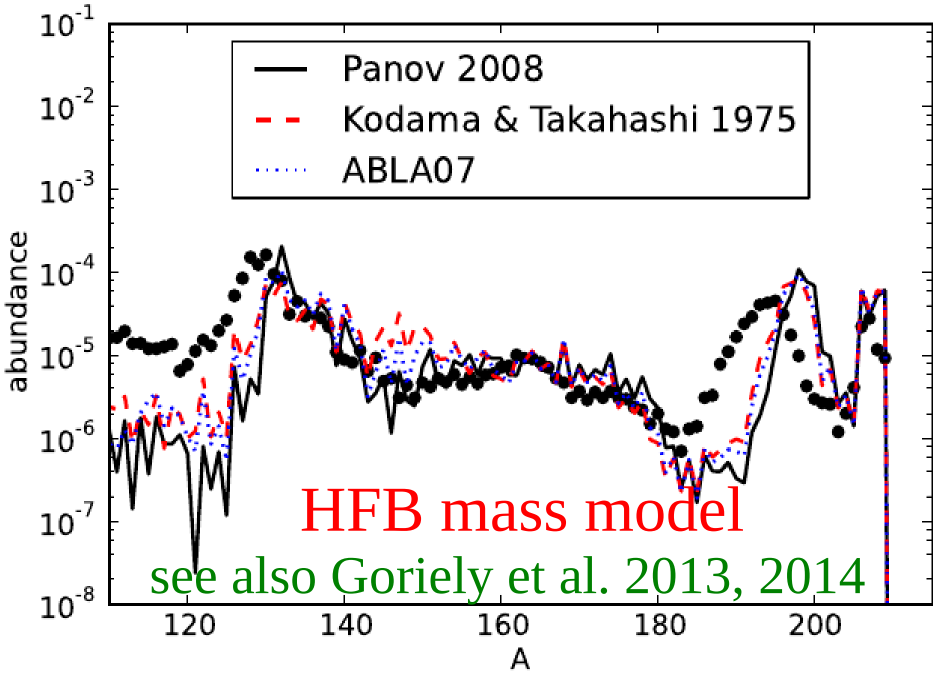


Fig. 7.—: Comparison of abundances from our calculations with (n,γ)-(γ,n) equilibrium abundances on the r-process path for the FRDM mass model. The colours show the factor Y_{eq}/Y_{calc}. Only the most abundant nuclei are shown for each isotopic chain. See text for details.

Eichler et al. (2014)



with FRDM and ABLA07 (Kelic) fissionfragment distribution

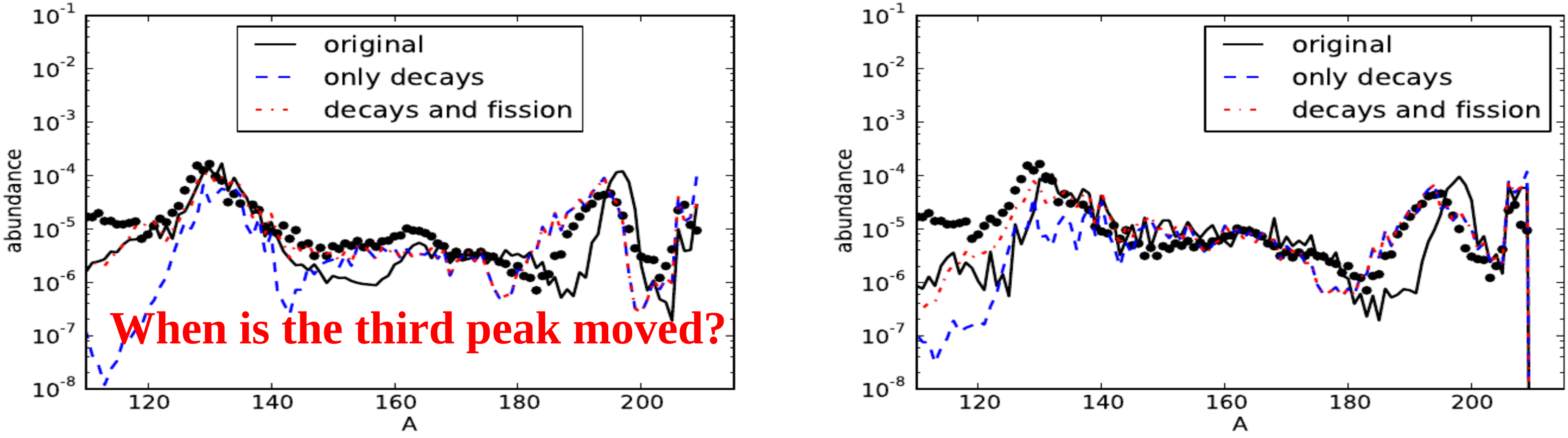


HFB mass model

see also Goriely et al. 2013, 2014

Variations in mass models and fission fragment distributions

Late time neutron captures, after freeze-out of (n,γ)-(γ,n) equilibrium, move 3rd peak to higher masses.



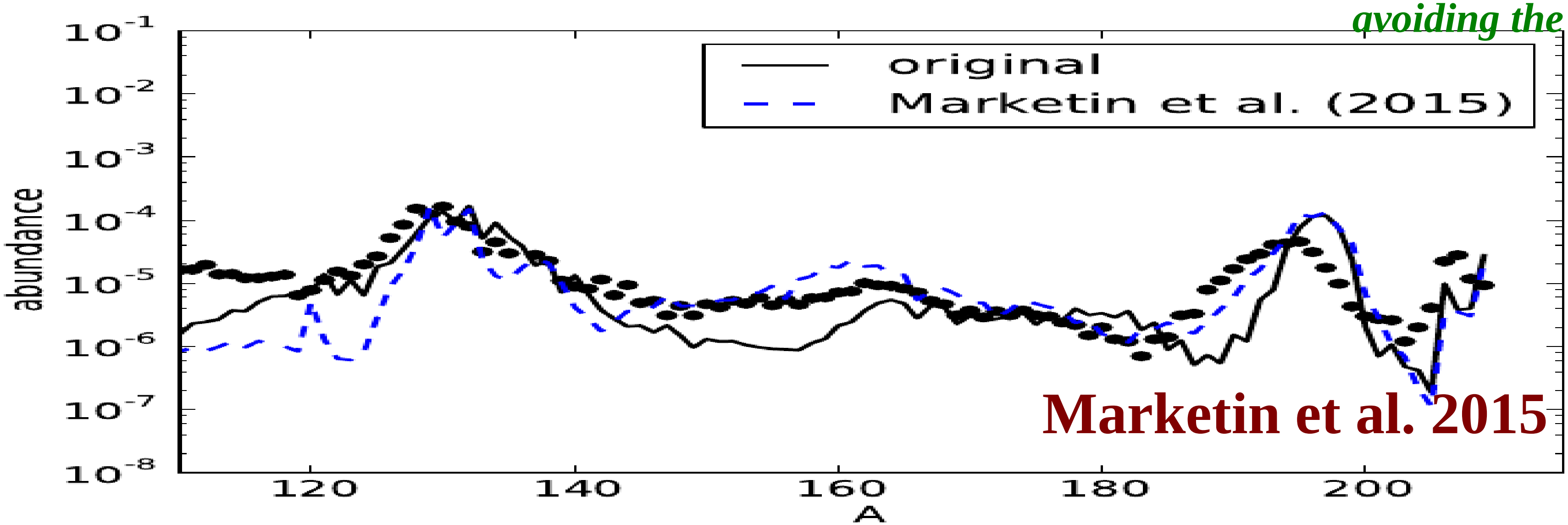
When is the third peak moved?

(a) FRDM

(b) HFB-14

Exploring variations in beta-decay rates

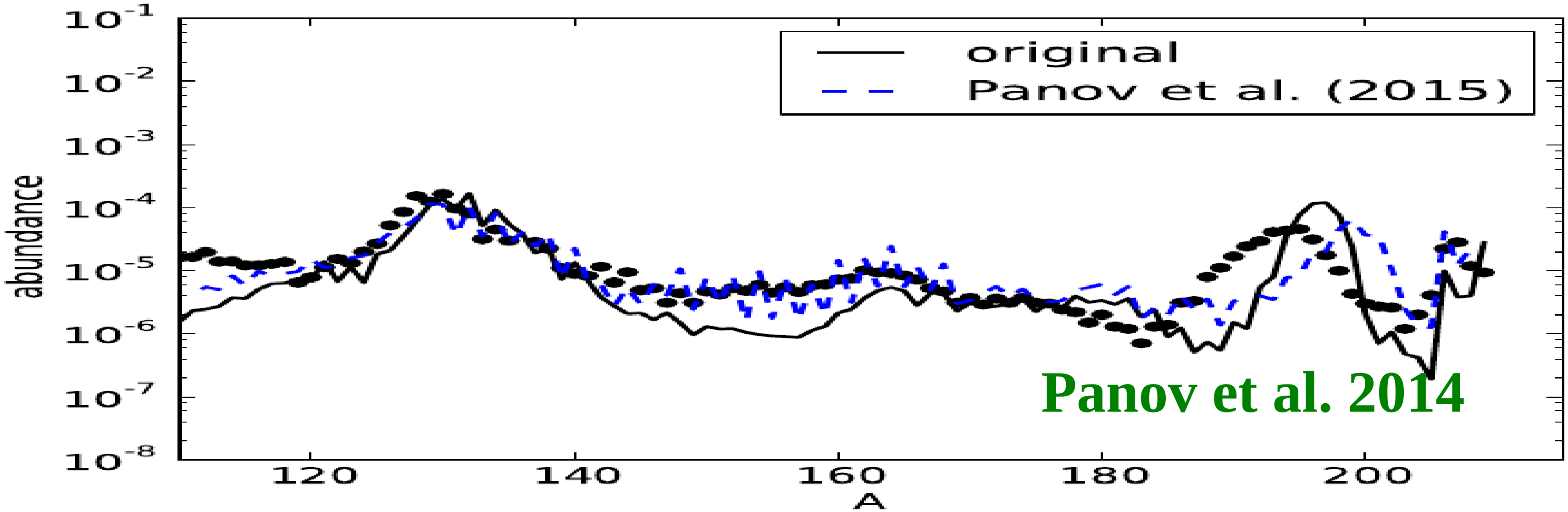
Shorter half-lives of heavies release neutrons (from fission/fragments) earlier ***(still in n,γ-γ,n equilibrium), avoiding the late shift???***



Marketin et al. 2015

Similar results seen in Caballero et al. (2014), due to DF3 half-lives (Borzov 2011)

(a) FRDM, Marketin (2015)

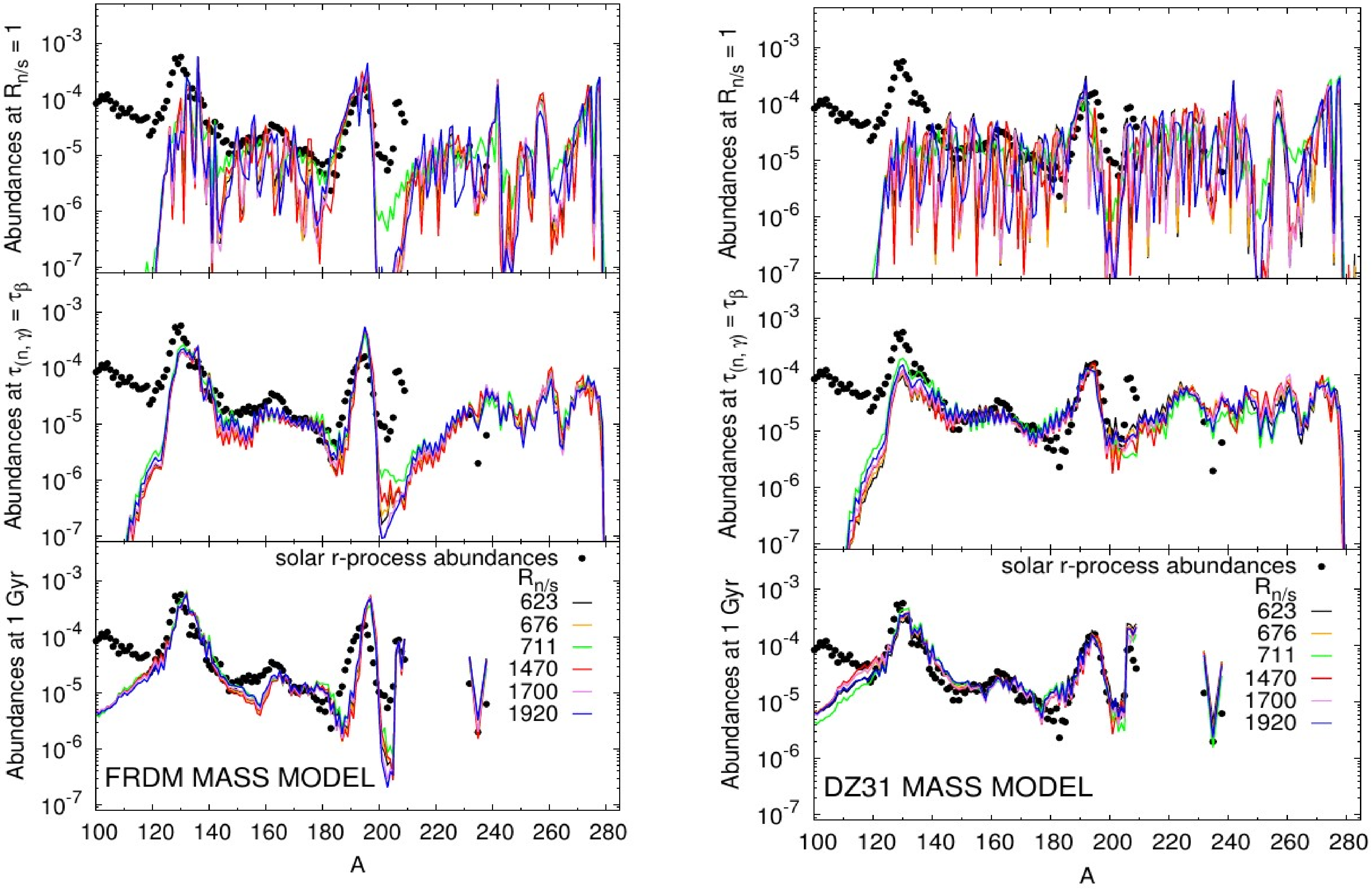


Panov et al. 2014

Longer half-lives give the opposite effect

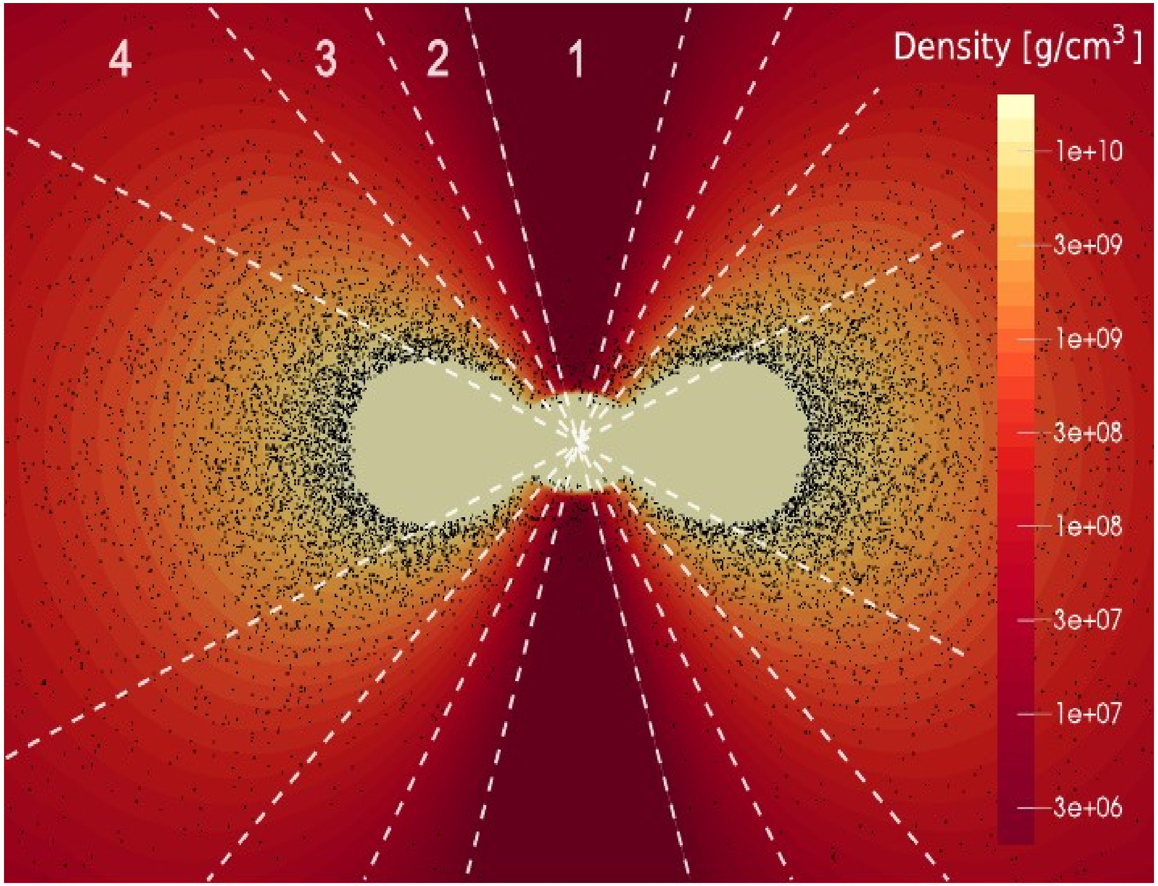
(c) FRDM, Panov (2015)

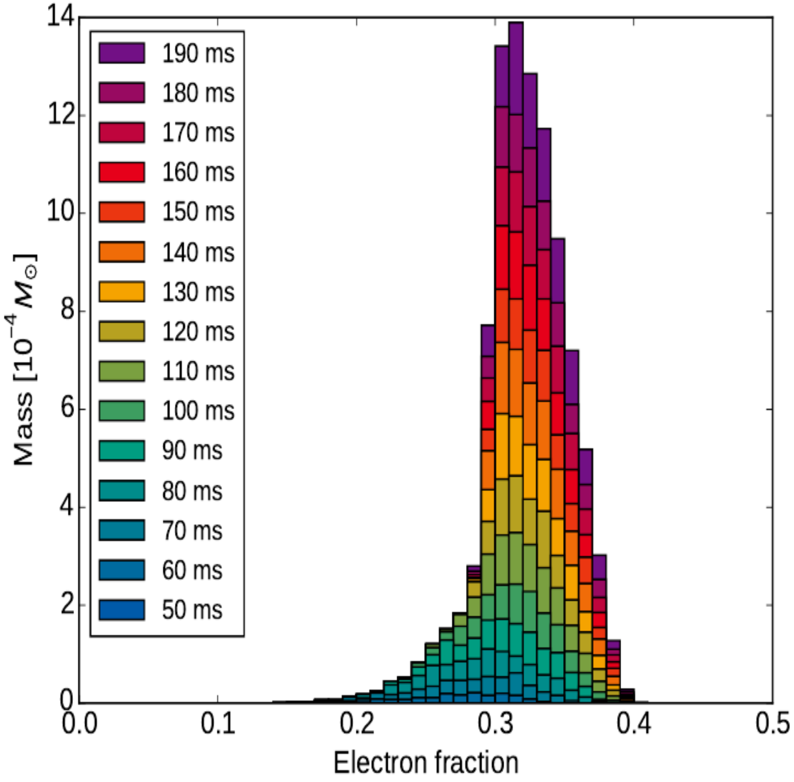
Mendoza-Temis et al. (2014)



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

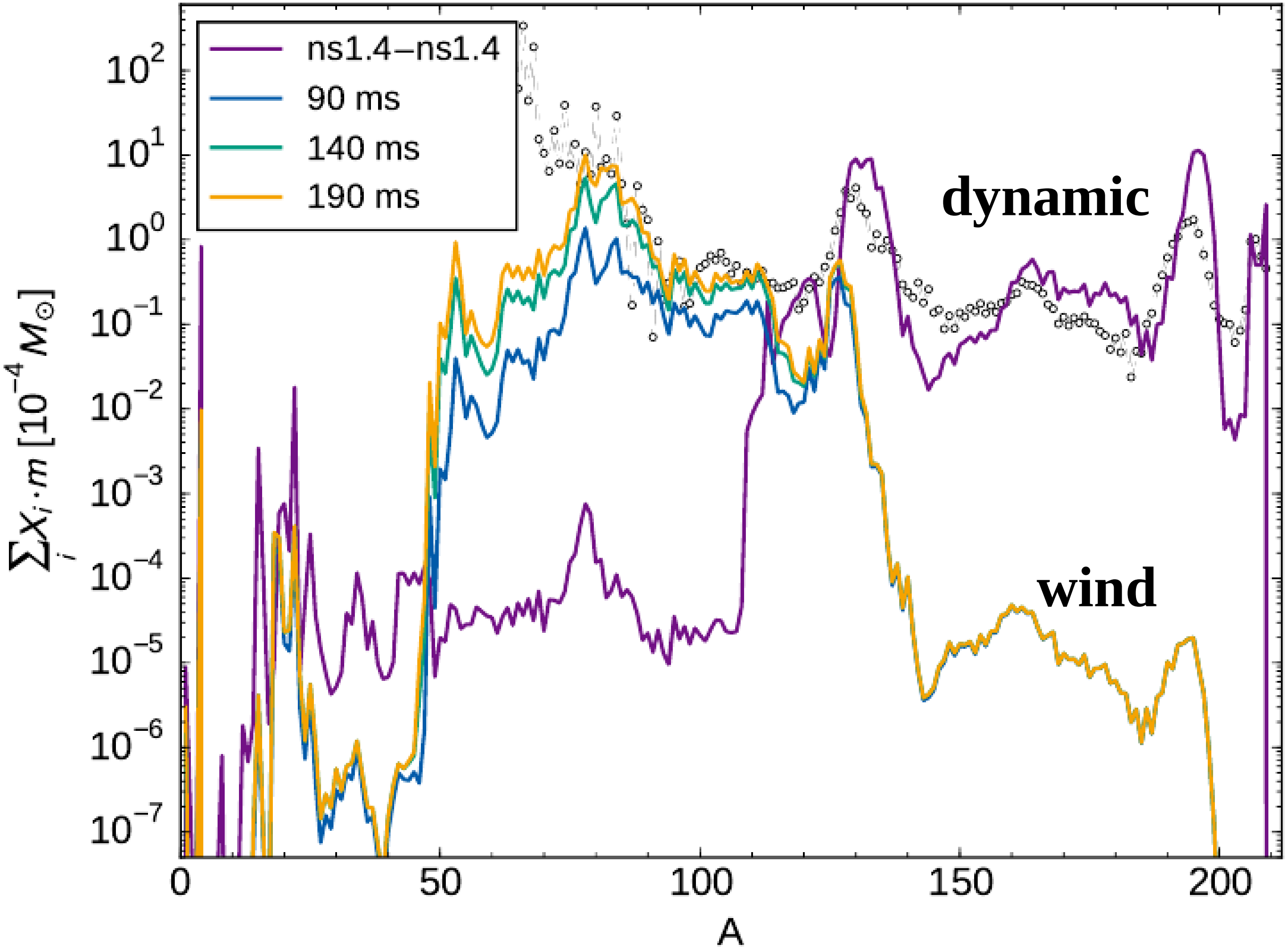
Dynamic Ejecta and Wind Contribution (Martin et al. 2015)





Ye in neutrino wind

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, Perego et al. 2014)



Martin et al. (2015) with neutrino wind contributions from matter in more polar directions (of course the problem with with the dynamical ejecta composition persists).

Martin et al. (2015) light curve predictions

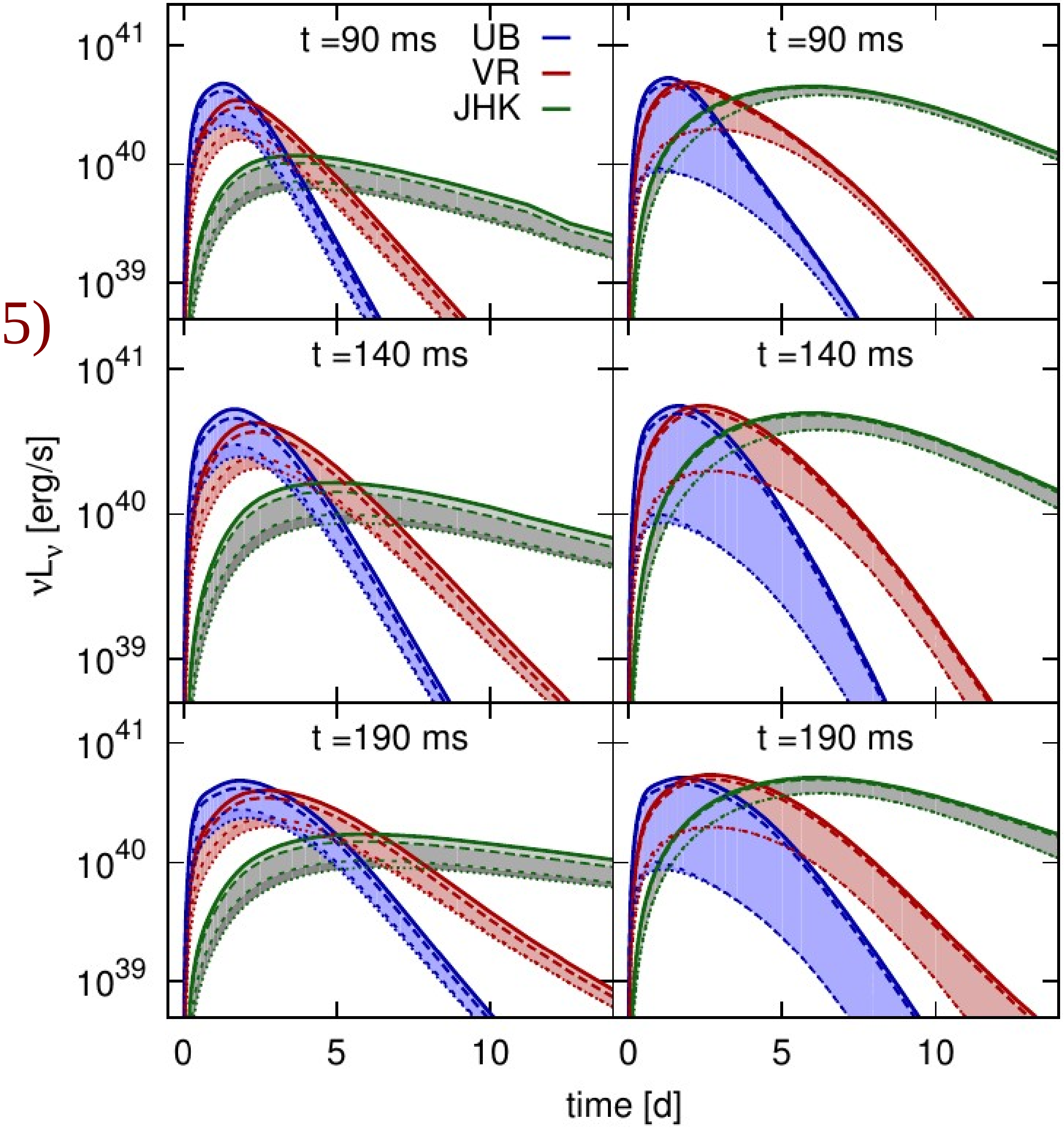
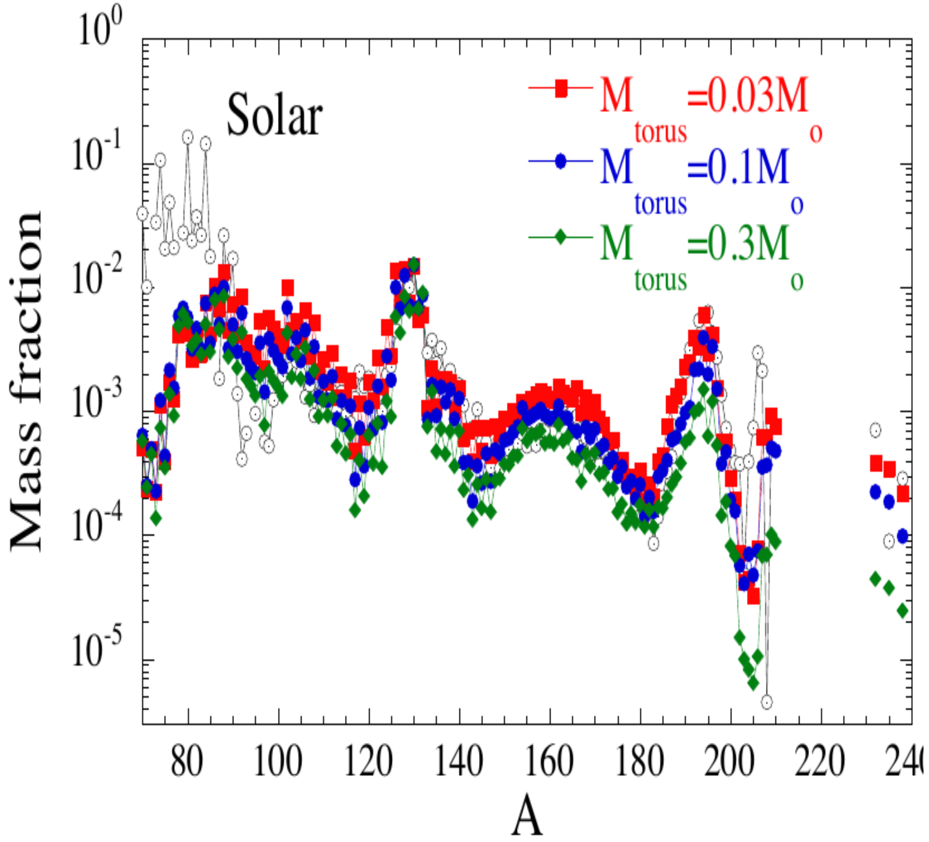
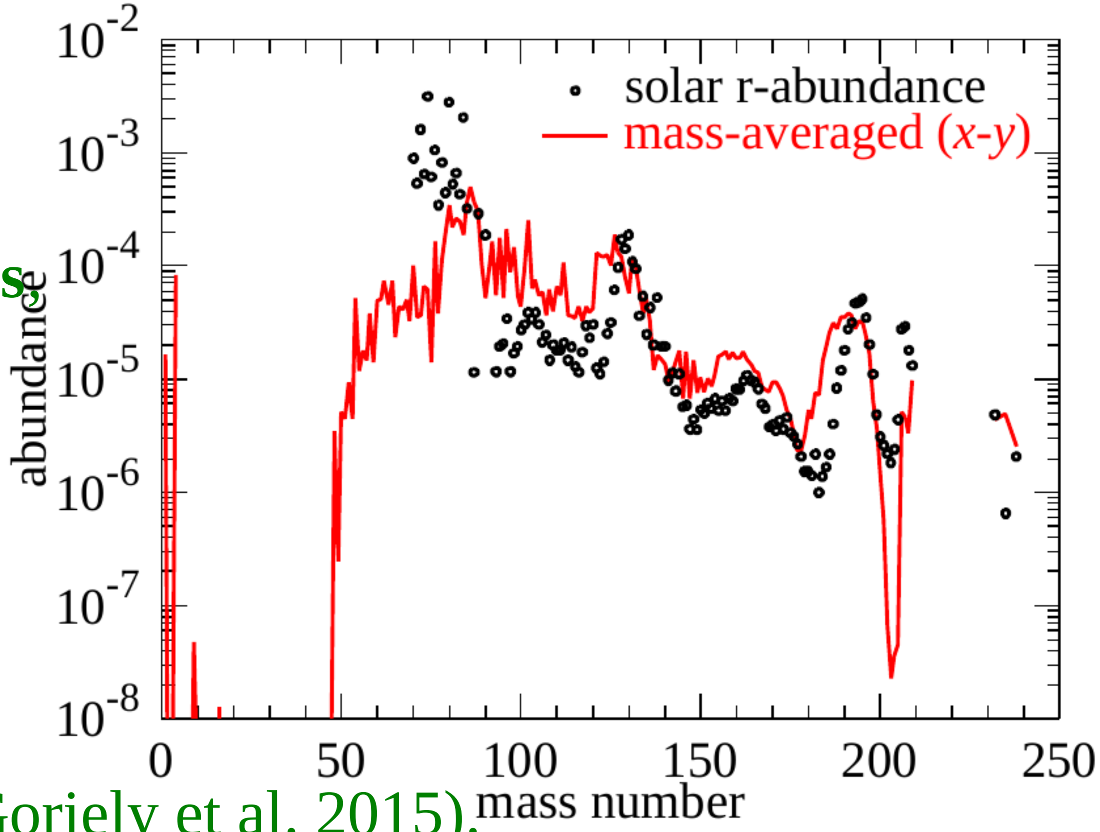


FIG. 18.— Broadband light curves of the wind outflow (left panel) and wind+dynamic ejecta (right panel), showing the combined blue (U+V bands), red (V+R) and infrared (J+H+K) contributions. The top, middle and bottom rows show the three cases of MNS collapse times: 90 ms, 140 ms and 190 ms, respectively. The range for each light curve spans possible inclination angles of the system axis with respect to the observer: 0° (solid) – view from the top, 30° (dashed), 60° (short dashes) and 90° (dotted) – view "edge-on".



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 leads to similar results as in jets. (see also recent calculations with parametrized neutrino properties by Goriely et al. 2015).



SN rates and NS merging rate (from Matteucci 2013)

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

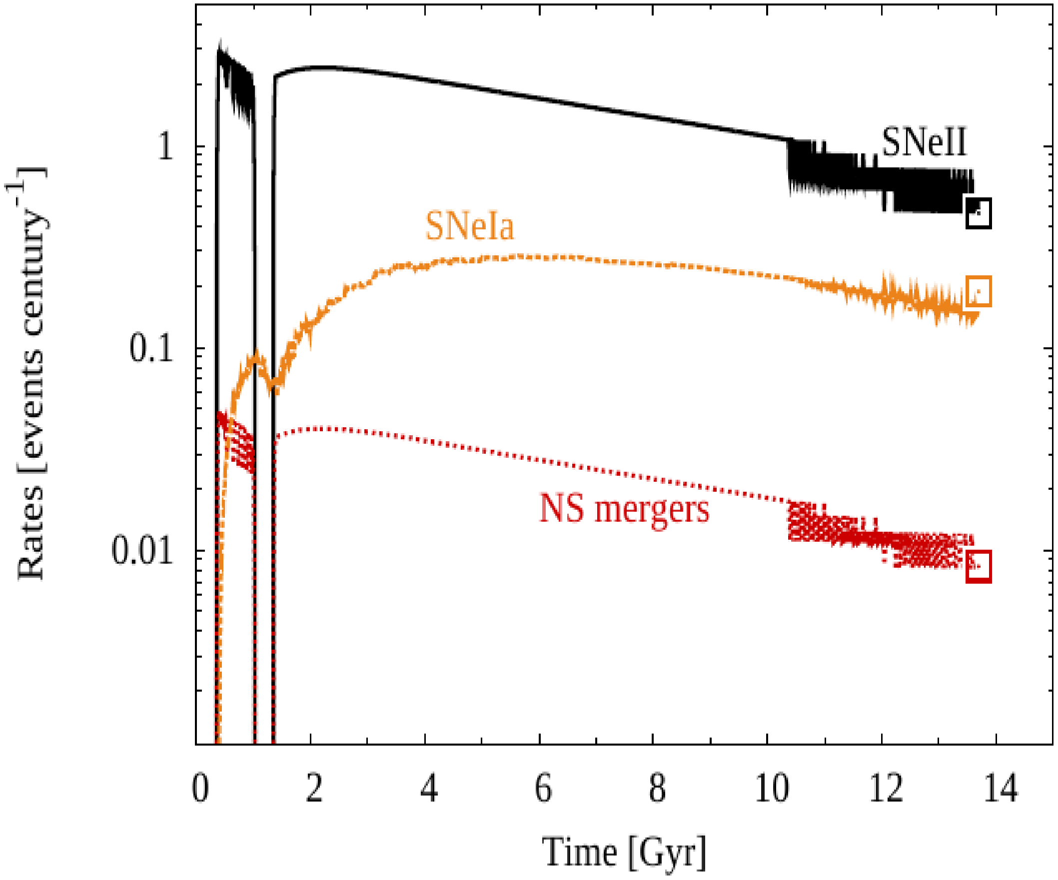
The present time NS merger rate reproduces the observed present time NS merger rate of 83/Myr (Kalogera et al. 2004)

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



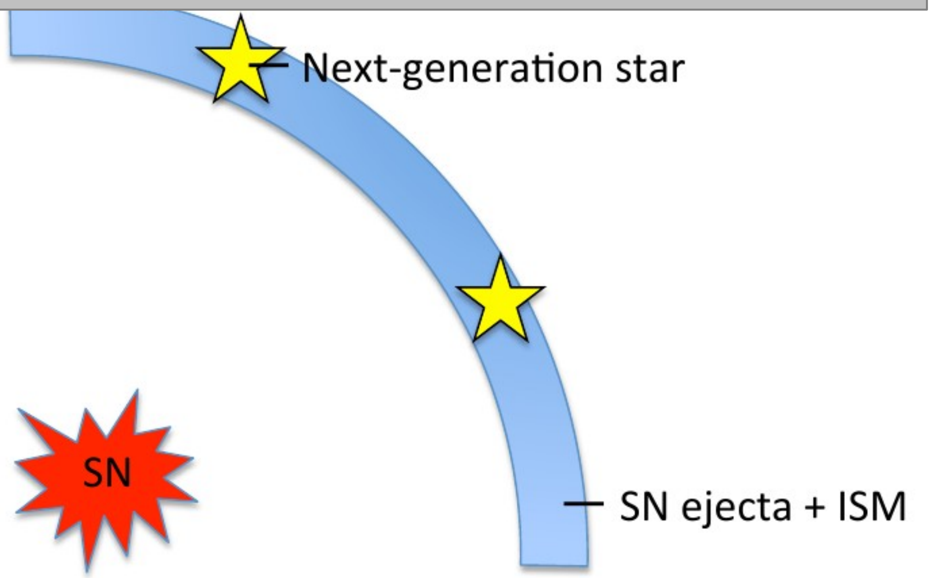
Stellar Abundances

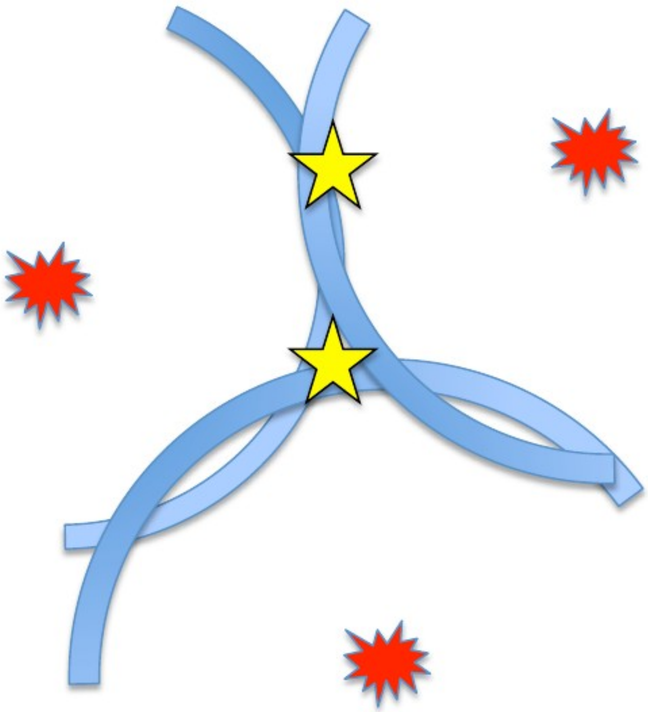
Inhomogeneous „chemical evolution“ Models due not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 10^5 Msol. After many events an averaging of ejecta composition is attained (Argast et al. 2004)

In the later phase

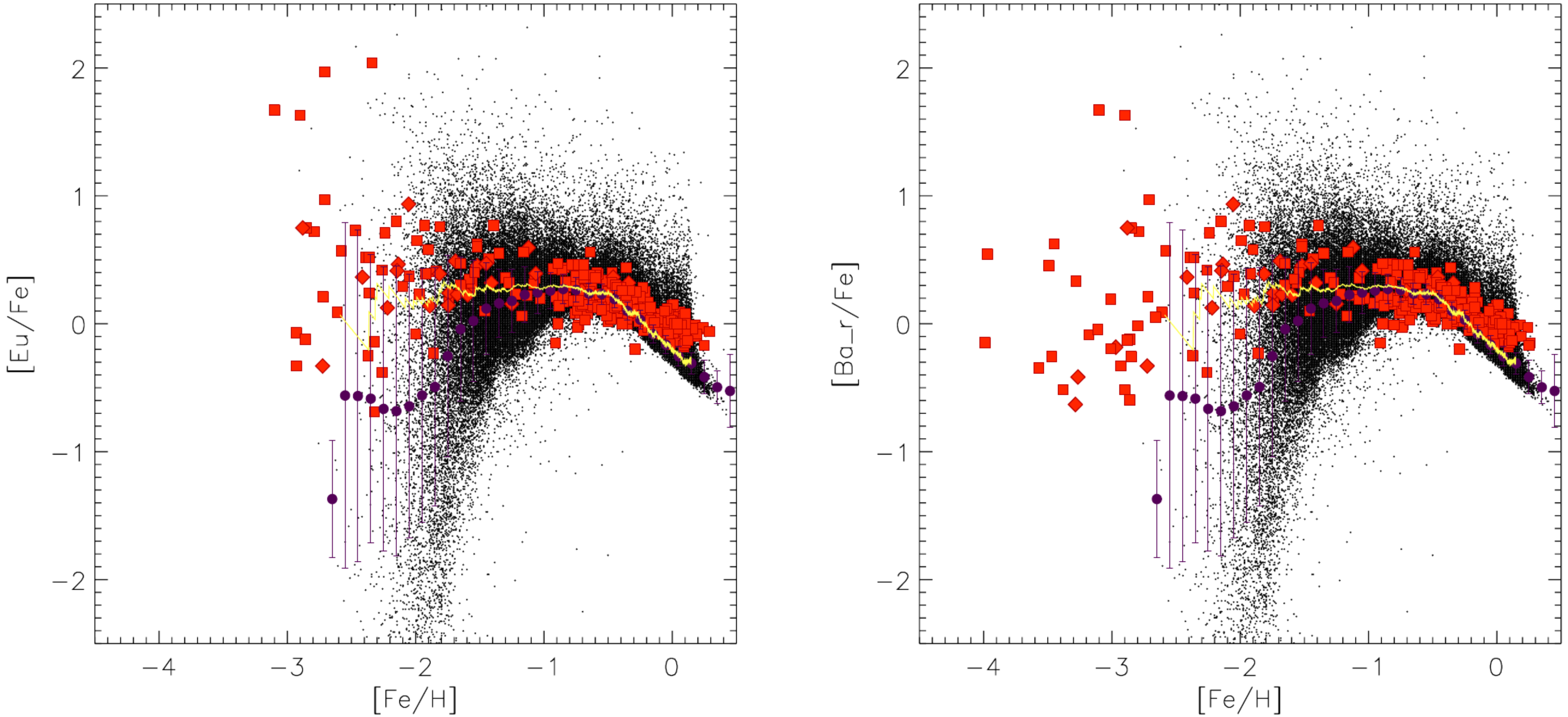
Contribution from multiple CCSNe

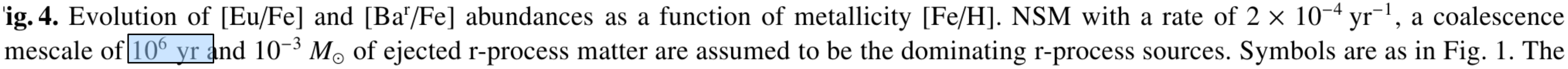
Plot “stolen“ from Ko Nakamura





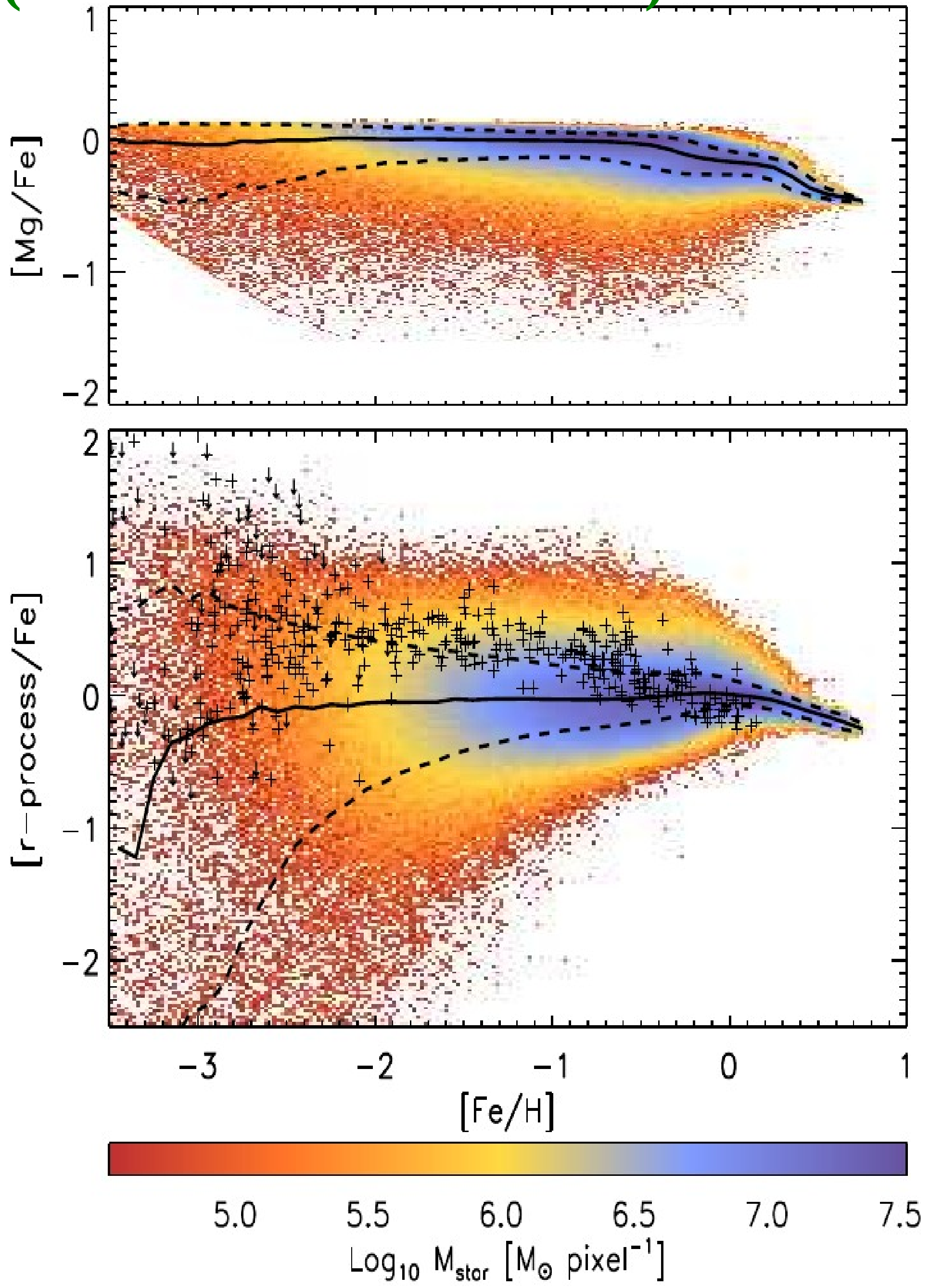
Argast, Samland, Thielemann, Qian (2004): Do neutron star mergers show up too late in galactic evolution, although they can be dominant contributors in late phases?

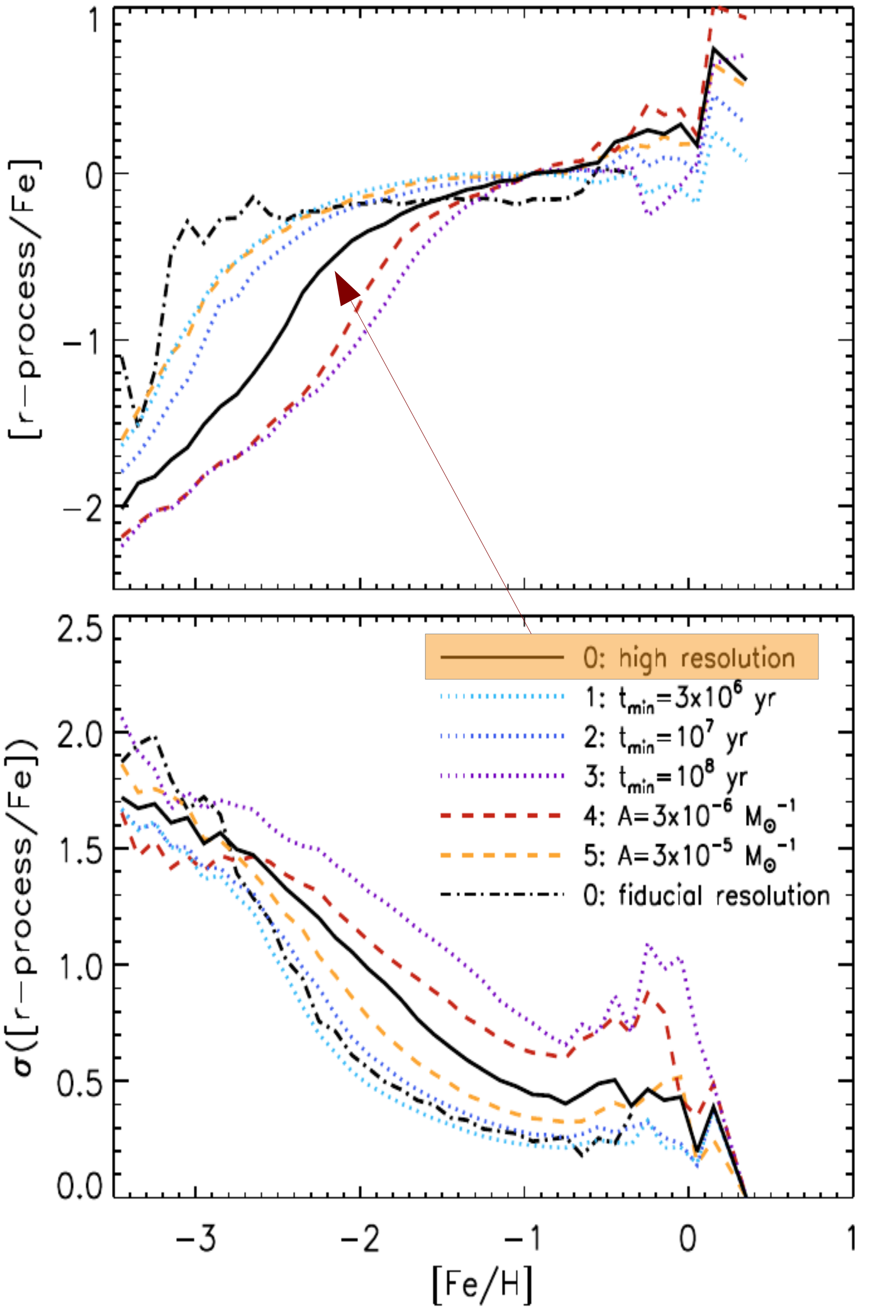


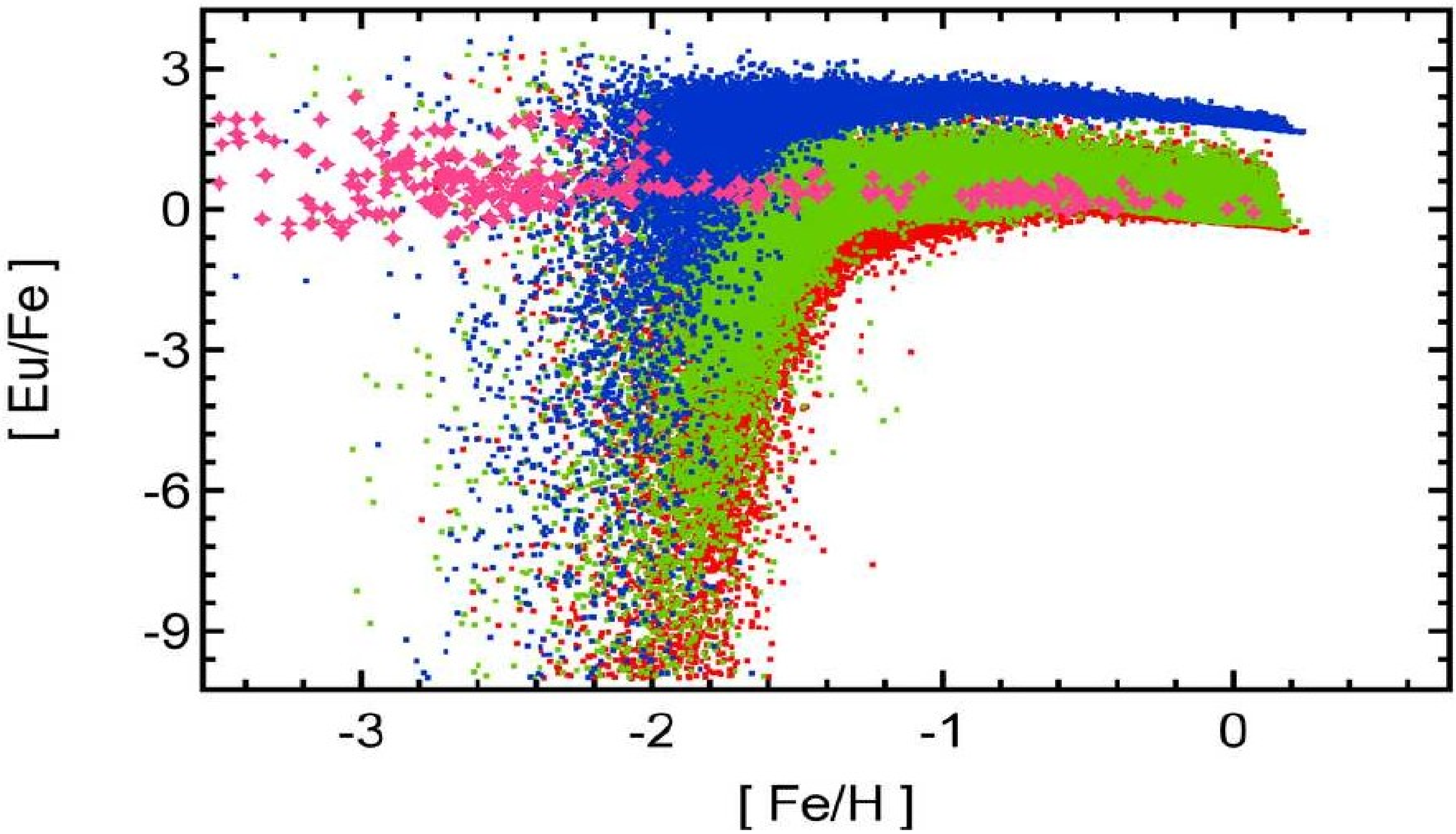

ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

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 (see also Shen et al. 2015)

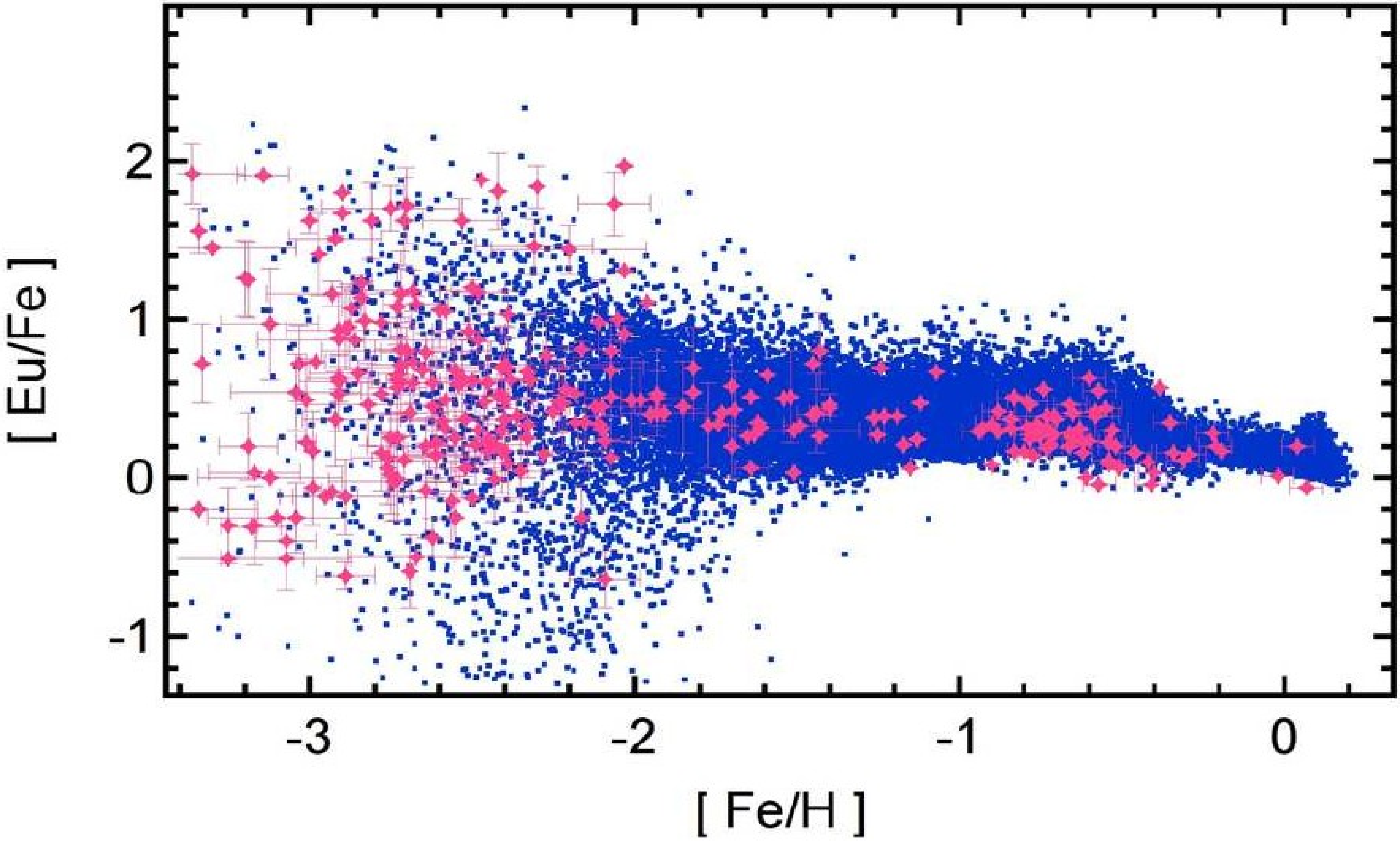






Update by Wehmeyer et al. (2015), green/red different merging time scales, blue higher merger rate (not a solution)

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 vp-process) 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!

Do all simulatutions with the best available microphysics and attempt to identify the signatures in chemical evolution for these different contributions!
(only low metallicity r-observations of U and Th seem to show variations in their contributions – sign of different r-process strength in MHD-jets, opposite to robust abundances in mergers?)