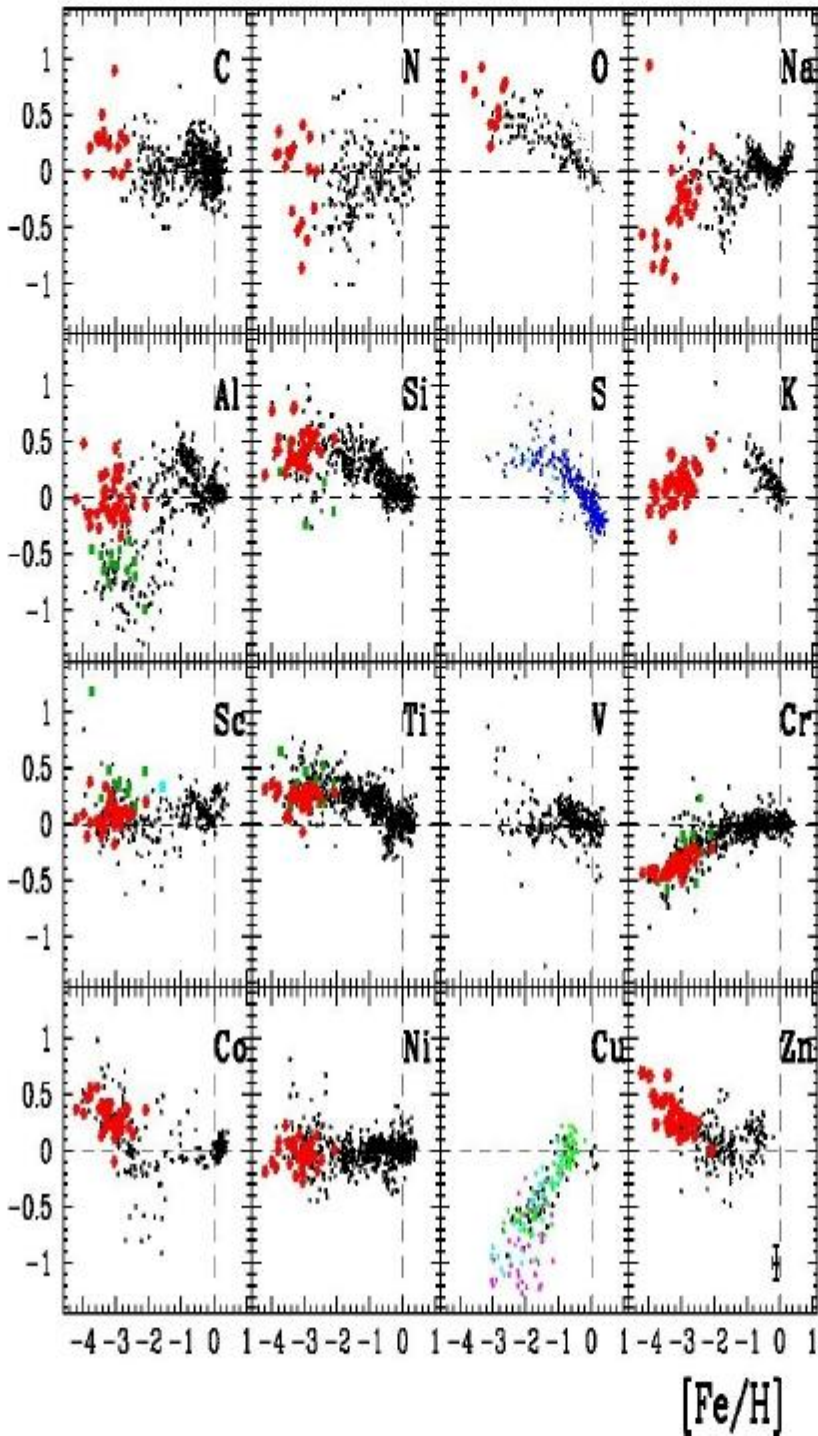
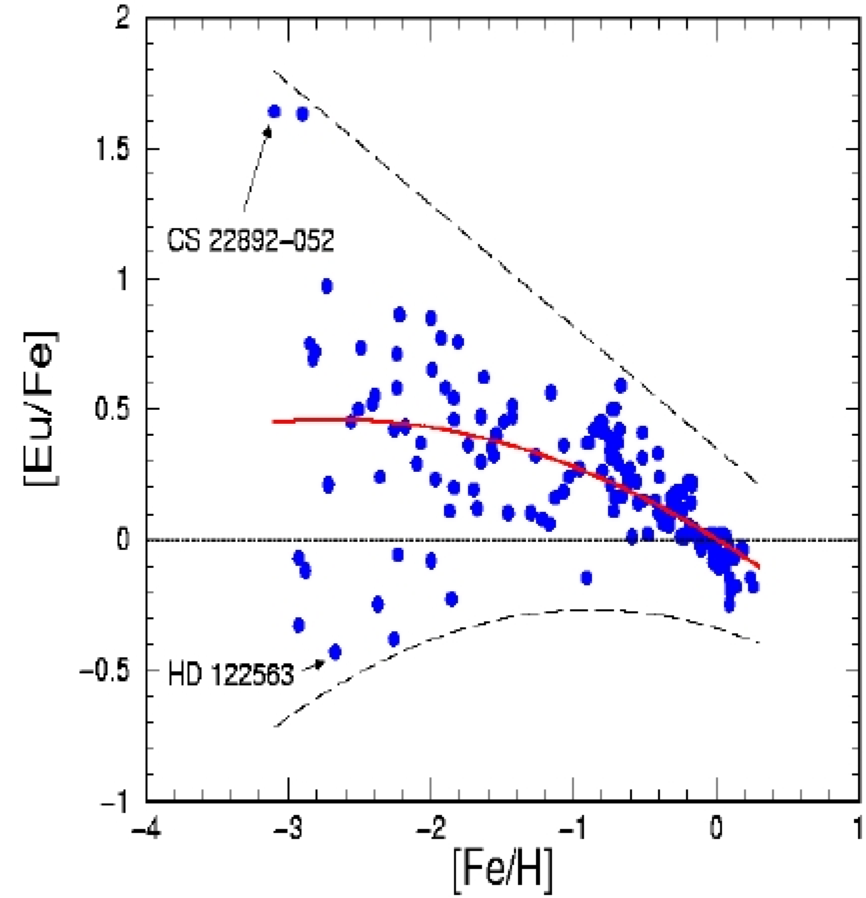
Nucleosynthesis in Compact Object Mergers and their Impact on Galactic Evolution

Friedrich-Karl Thielemann
Department of Physics
University of Basel
Switzerland

Cost Action
ChETEC

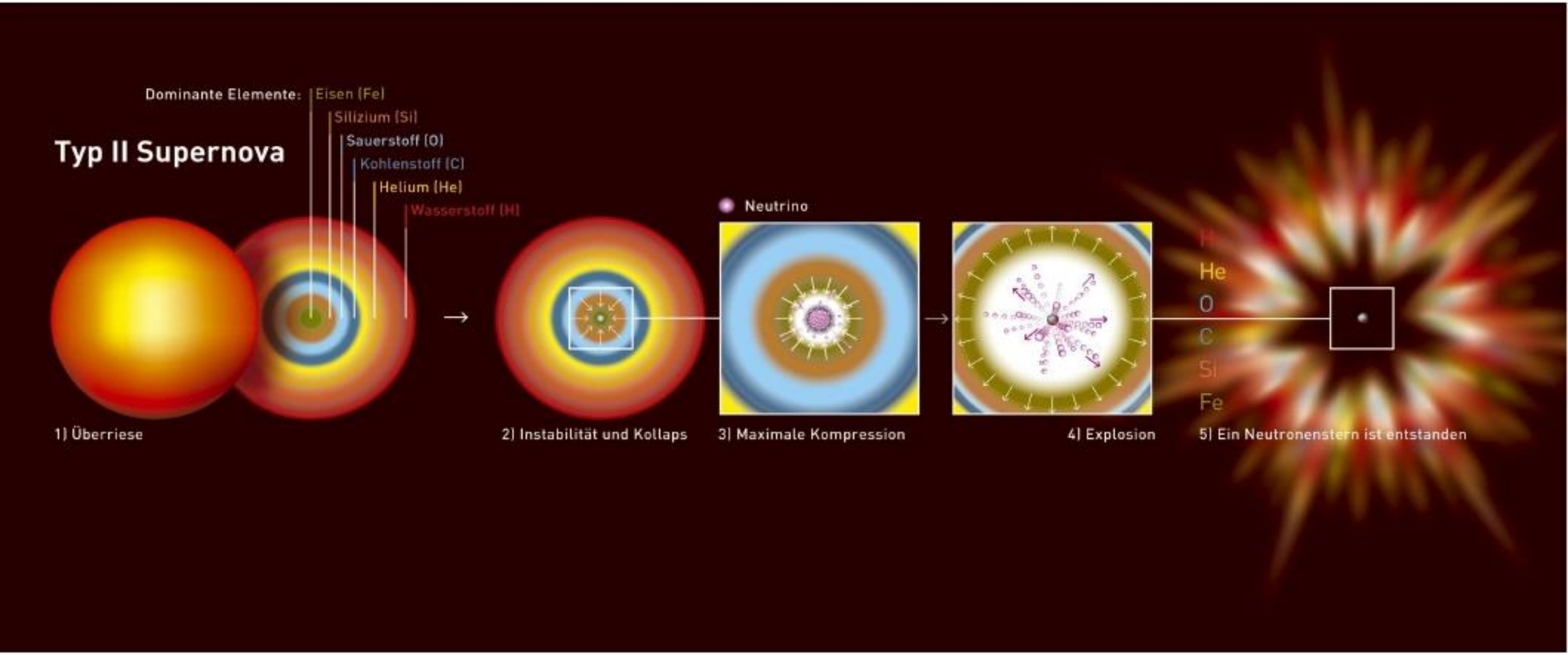
How do we understand: low metallicity stars ... galactic evolution?





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

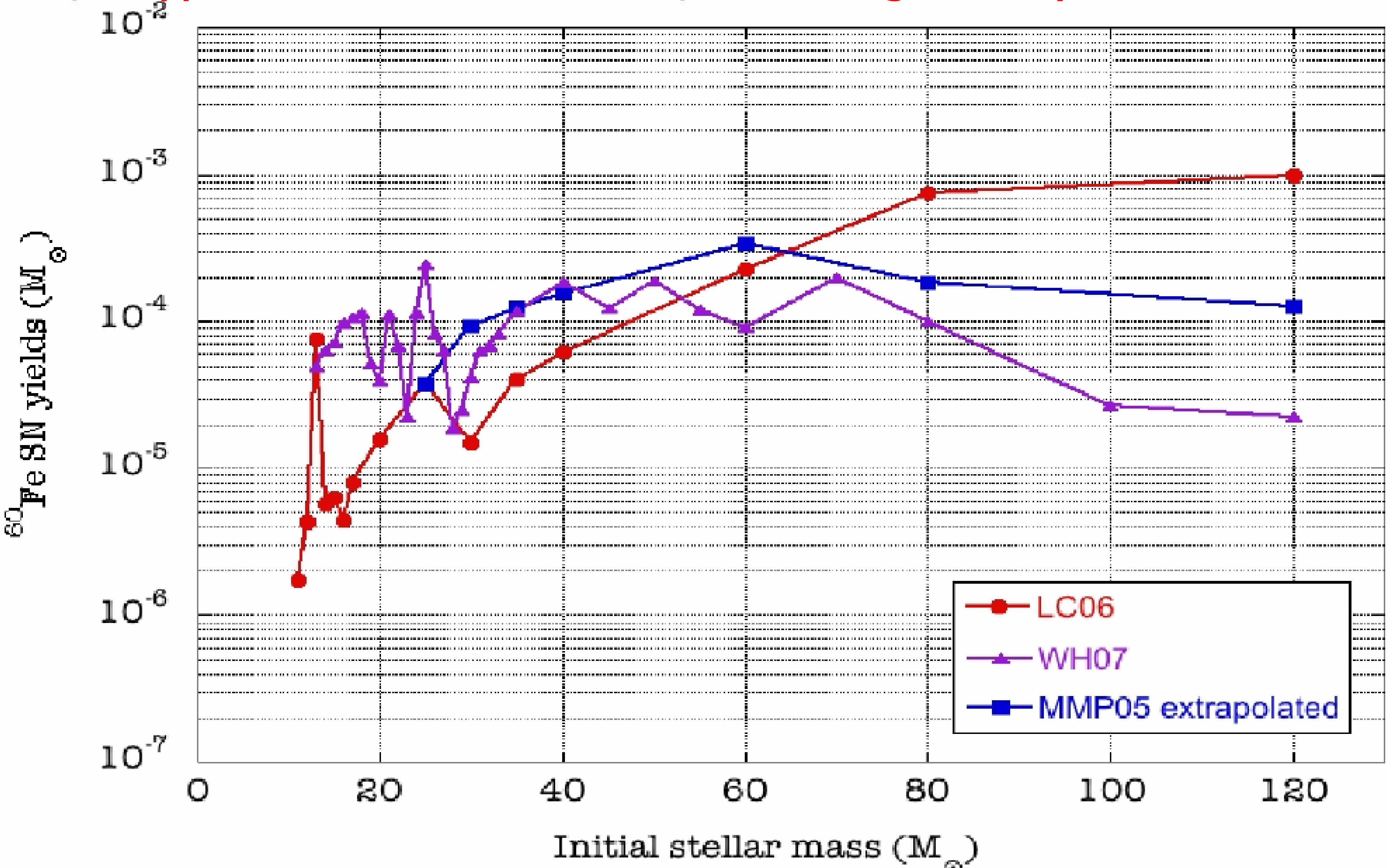
Core-Collaps-Supernovae and Neutron Stars as End Stages of Massive Stars



Main products: O, Ne, Mg, Si, S, Ar, Ca, Ti and some Fe/Ni: How about heavier nuclei (Zn .. Sr, Y, Zr)

and the r-process ?????

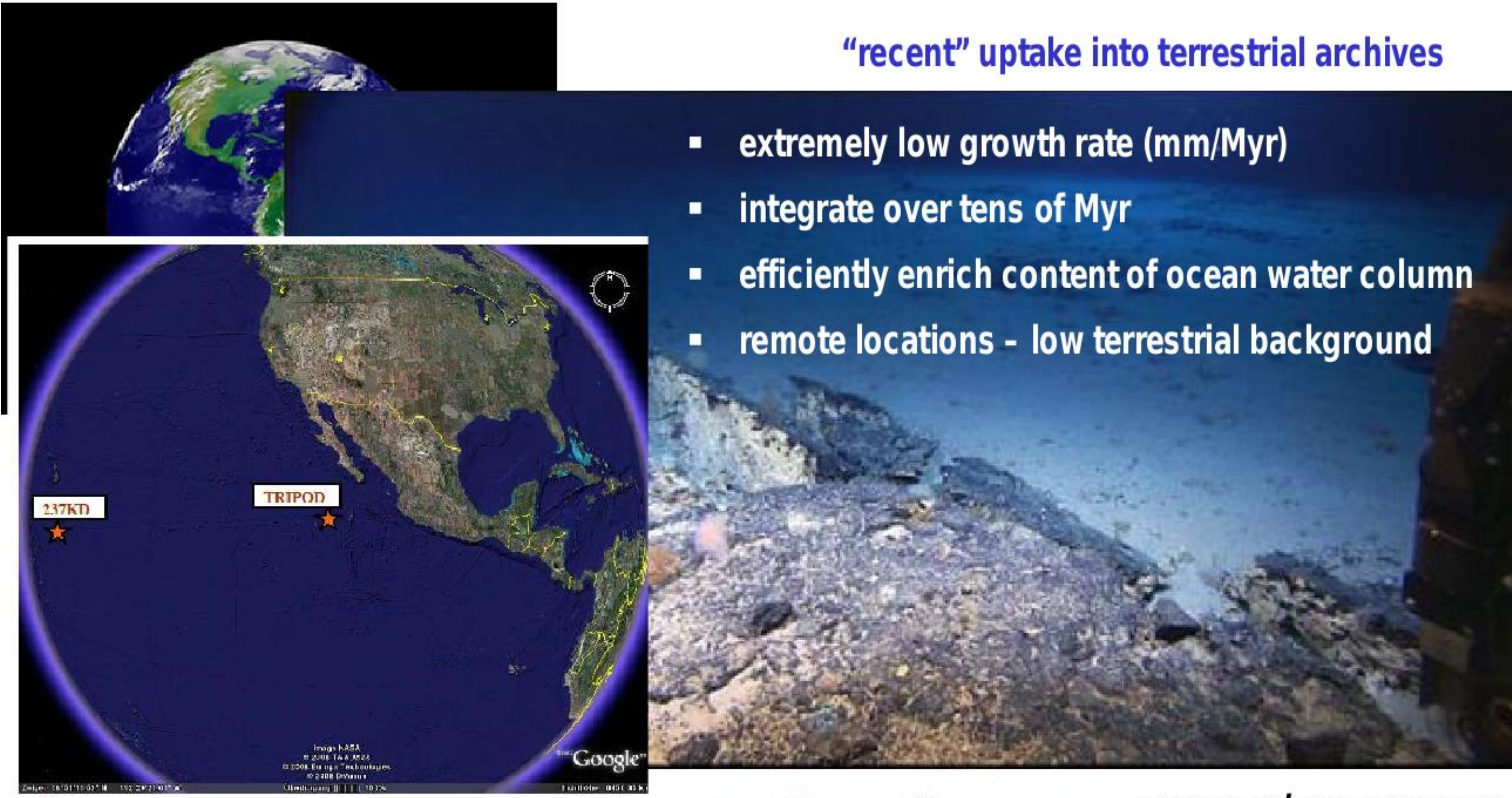
^{60}Fe, a byproduct of massive stars, stemming from hydrostatic burning



^{60}Fe (half-life 2.6 10^6y) yields from Limongi & Chieffi; Woosley & Heger; Maeder, Meynet & Palacios , produced in He-shell burning of massive stars in late phases after core C-burning and ejected afterwards in CCSNe

Extraterrestrial Radionuclides on Earth

"recent" uptake into terrestrial archives



- extremely low growth rate (mm/Myr)
- integrate over tens of Myr
- efficiently enrich content of ocean water column
- remote locations – low terrestrial background

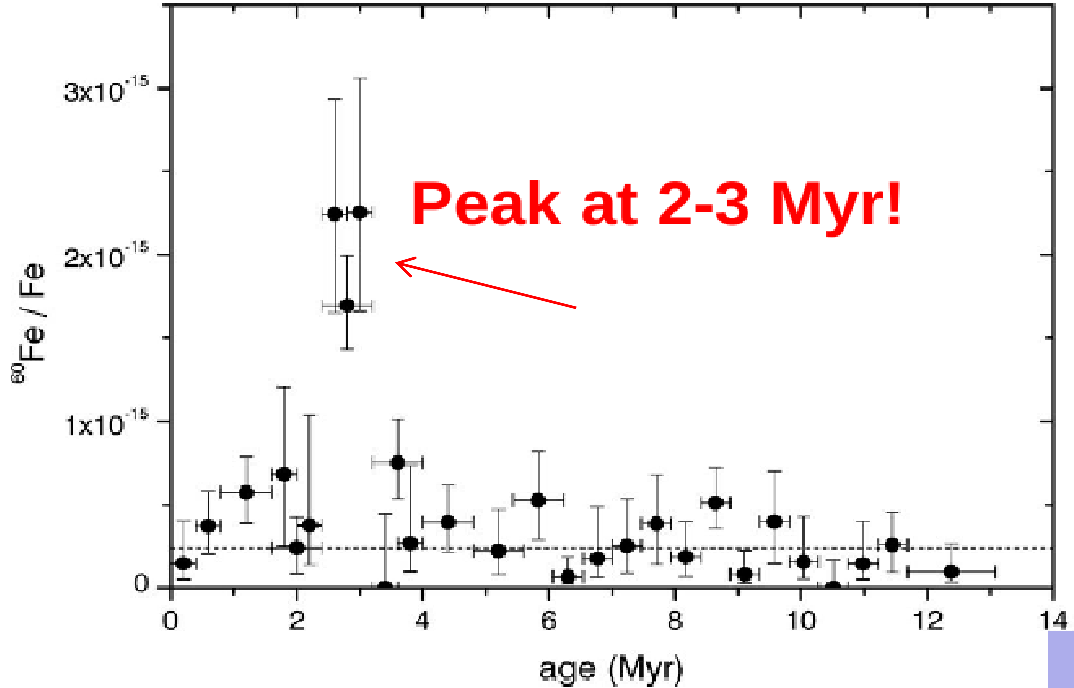
deep-sea mangenese crusts & sediments

oceanexplorer.noaa.gov

from A. Wallner

^{60}Fe-signal in a deep-sea crust

AMS at Munich



AMS measurement of ^{60}Fe content of crust at TU Munich

background level

- *the only lab yet !*

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

^{60}Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source

K. Knie,[1] G. Korschinek,[1,*] T. Faestermann,[1] E. A. Dorfi,[2] G. Rugel,[1,3] and A. Wallner[1,3]

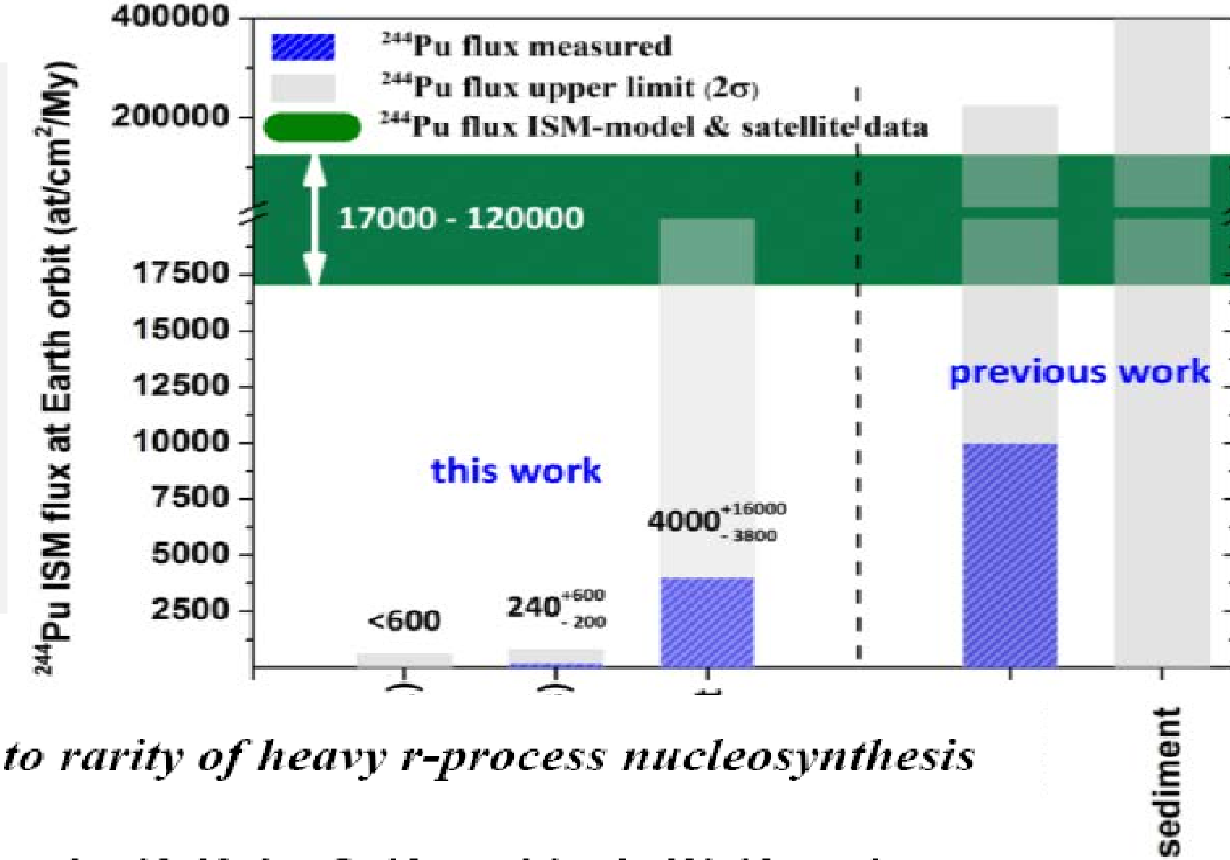
Witnessing the last CCSNe near the solar system, see also recent theses by J. Feige (Vienna) and P. Ludwig (Munich)

^{244}Pu, half-life 81 My
Status:

^{244}Pu in terrestrial crust:

- ***crust: dust collection over 25 Myr***
- ***^{244}Pu: time window - alive a few 100 Myr***
- ***neutron star mergers?***

100:1 estimated vs measured



New limit of ^{244}Pu on Earth points to rarity of heavy r-process nucleosynthesis

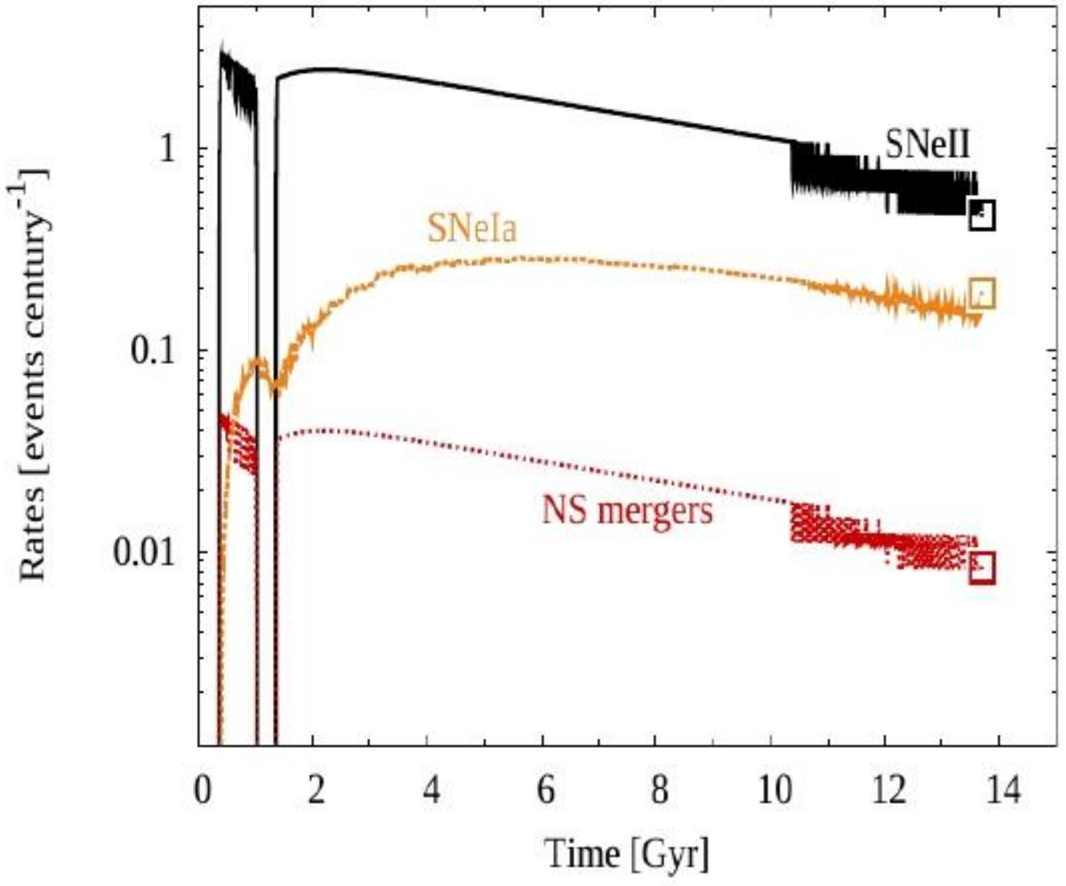
A. Wallner, T. Faestermann, C. Feldstein, K. Knie, G. Korschinek, W. Kutschera, A. Ofan, M. Paul, F. Quinto, G. Rugel & P. Steier 2015, Nature Communications

The continuous production of ^{244}Pu in regular CCSNe (10^{-4}-10^{-5} Msol each, in order to reproduce solar system abundances) would result in green band → no recent (regular) supernova contribution. Rare events with appropriatly enhanced ejecta could also explain solar abundances, but the last event occurred in a more distant past and Pu has decayed (see also. Hotokezaka)

SN II and Ia rates compared to NS merging rate
(from Matteucci 2014)

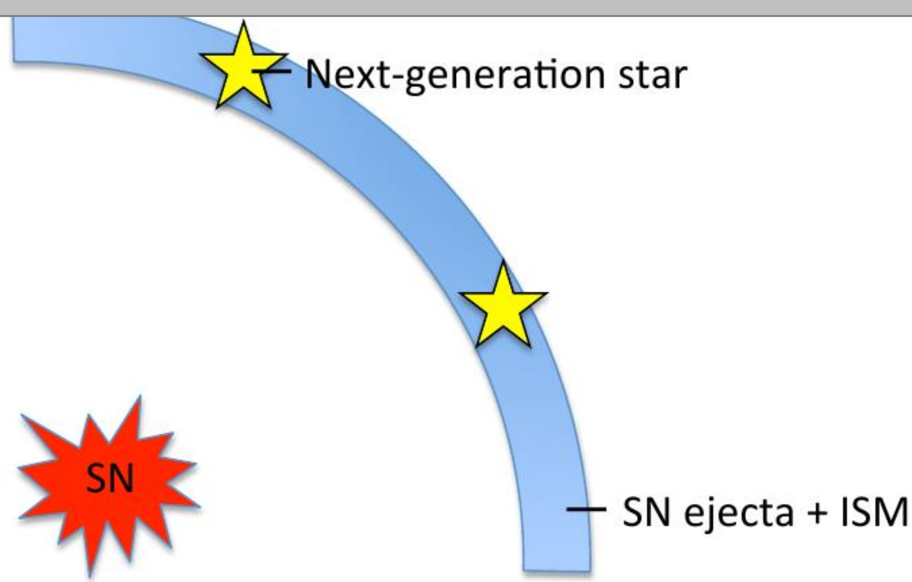
The rate of mergers is by a factor of about 100 smaller than CCSNe,
but they also produce more r-process by a factor of 100 than required if CCSNe would be the origin

-> this would be one option to explain such findings



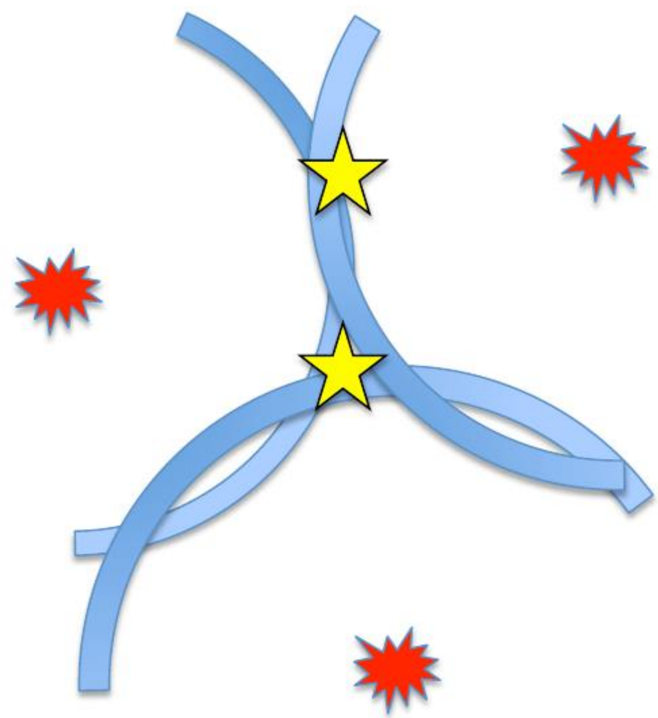
Stellar Abundances

Inhomogeneous „chemical evolution“ Models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 5 10^4 Msol. After many events an averaging of ejecta composition is attained (Argast et al. 2004)



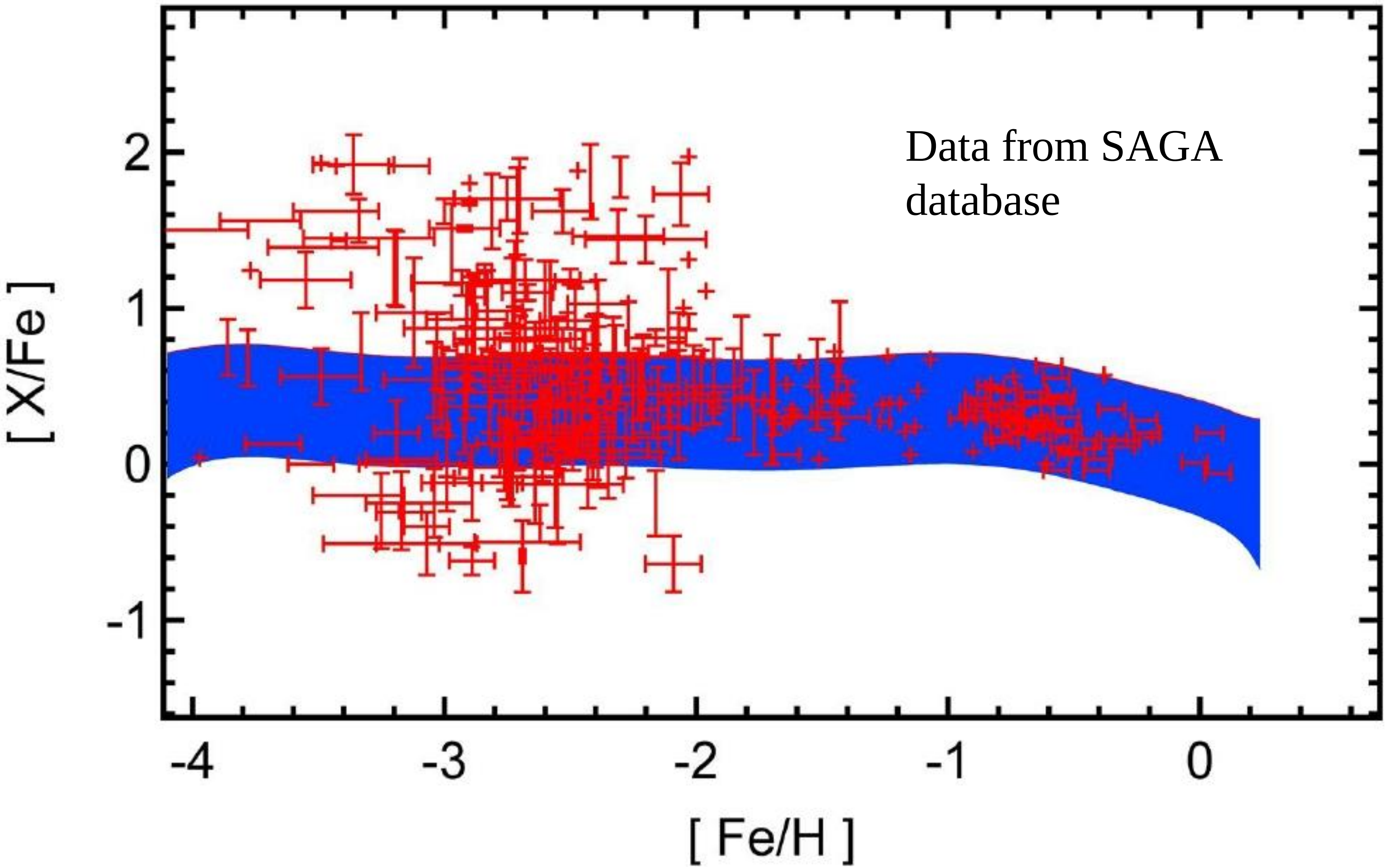
In the later phase

Contribution from multiple CCSNe
(unknown → average weighted by IMF)



Inhomogenous models undertaken by Van de Voort+ (2015), Shen+ (2015), Cescutti+ (2014), Wehmeyer+ (2015), Hirai+ (2016)

Rare events lead initially to large scatter before an average is attained!



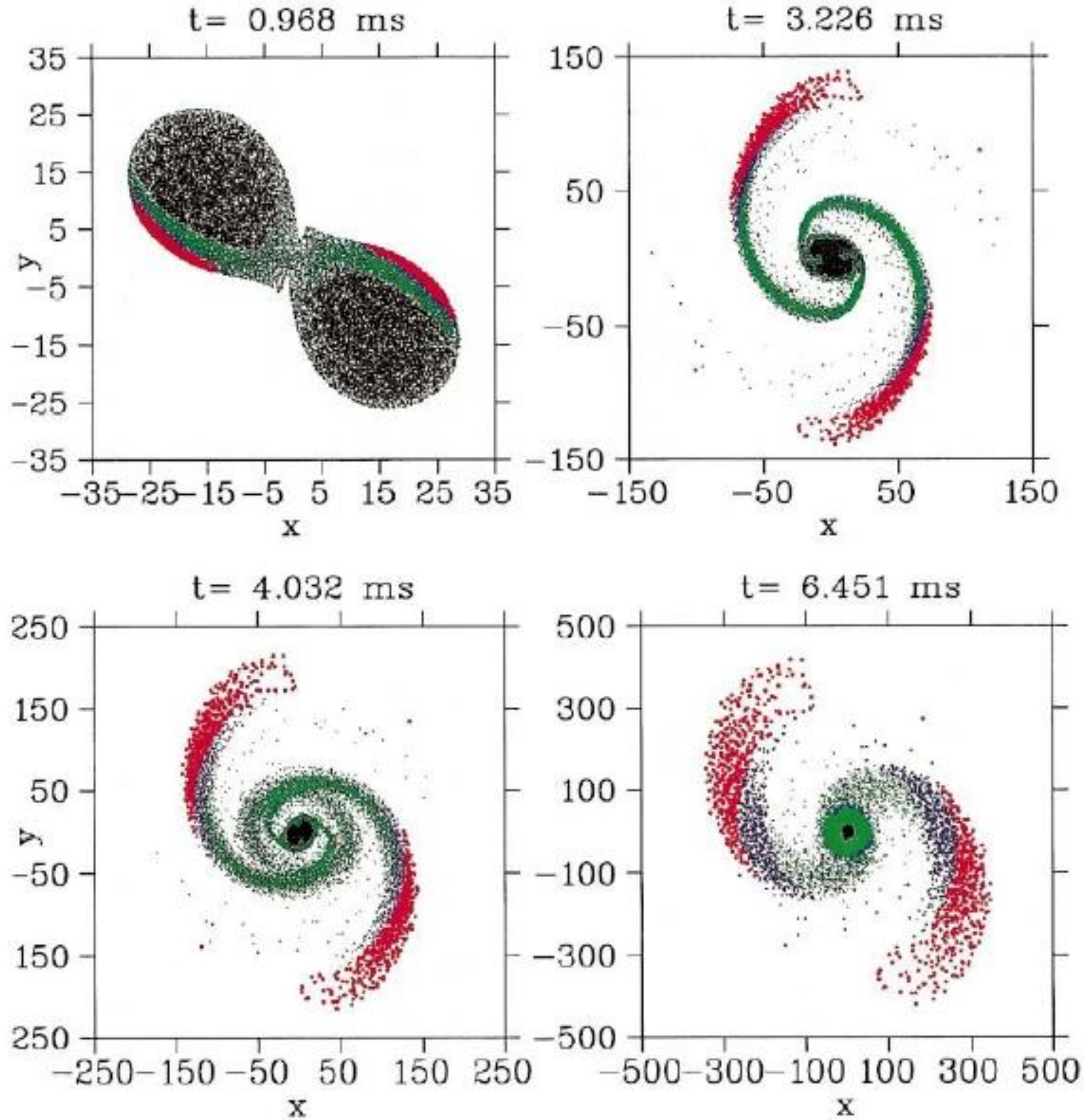
Blue band: Mg/Fe observations (95%), red crosses: individual Eu/Fe obs.

A bit of (selected?) History

- Lattimer & Schramm (1974/76) suggested neutron star and neutron star – BH mergers as r-process sites
- Nucleosynthesis from the decompression of initially cold neutron star matter (Meyer & Schramm 1988, general decompression consideration)
- Nucleosynthesis, neutrino bursts & gamma-rays from coalescing neutron stars (Eichler, Livio, Piran, Schramm 1989, setting up the scheme)
- Merging neutron stars. 1. Initial results for coalescence of noncorotating systems (Davis, Benz, Piran, Thielemann 1994, estimate: obout $10^{-2} M_{\odot}$ of ejecta)
- Mass ejection in neutron star mergers (Rosswog, Liebendörfer, Thielemann, Davies, Benz, Piran 1999, 4×10^{-3} – 4×10^{-2} $M_{\odot}$ get unbound in realistic simulations)
- r-Process in Neutron Star Mergers (Freiburghaus, Rosswog, Thielemann 1999, **first detailed abundance distribution prediction**)

Early SPH simulations

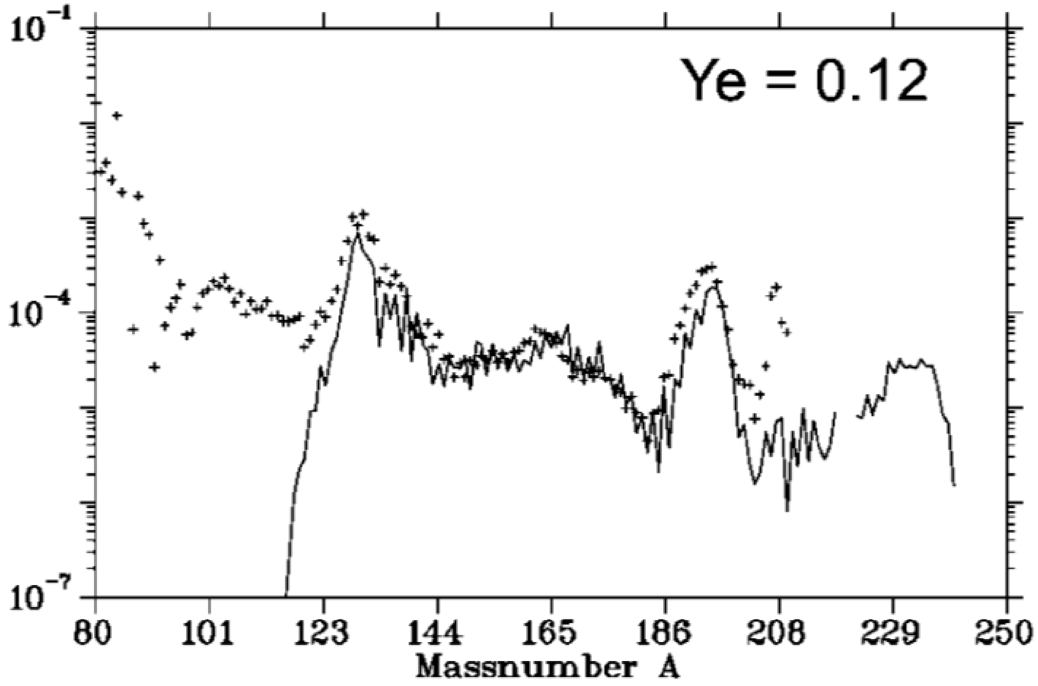
„Classical“ r -process site: NSM



Rosswog et al.
A&A 341 (1999)
499

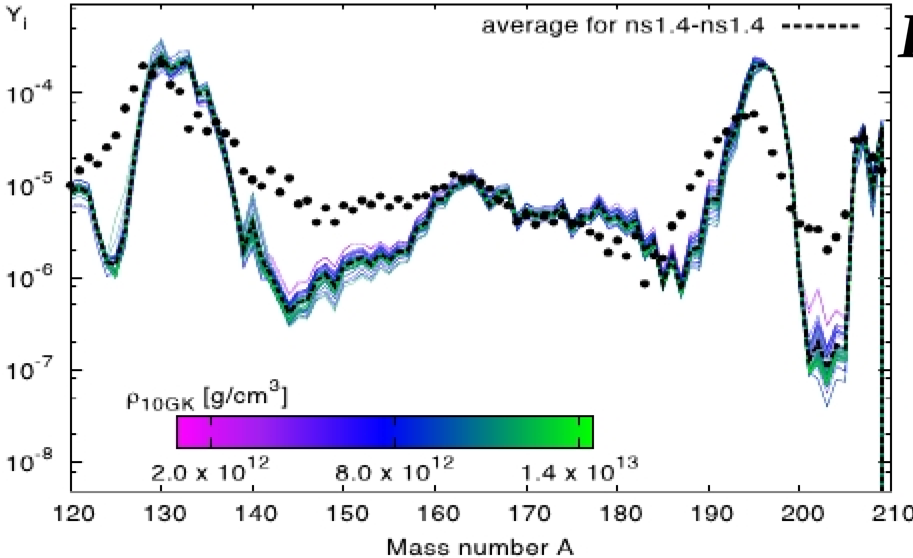
Newtonian SPH simulaton, FRDM mass model, assuming Ye of ejecta to be 0.12, simple fission description, symmetric fission for nuclei above A=250

Freiburghaus, Rosswog, Thielemann 1999



Since then many upgrades, including Panov, Rosswog, Korobkin .. with increasing resolution, improved SPH prescriptions permitting modeling of shocks, EoS, nuclear mass models, fission barriers….

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...

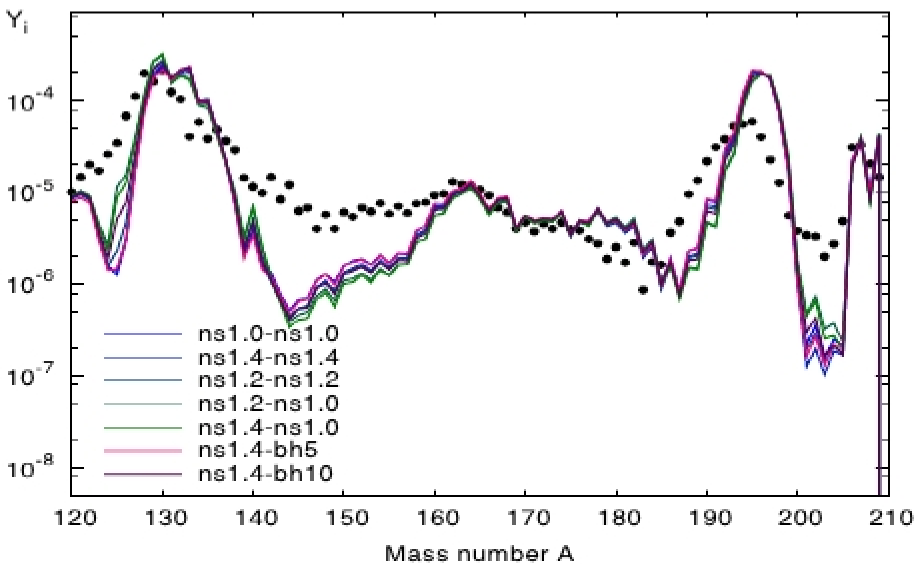


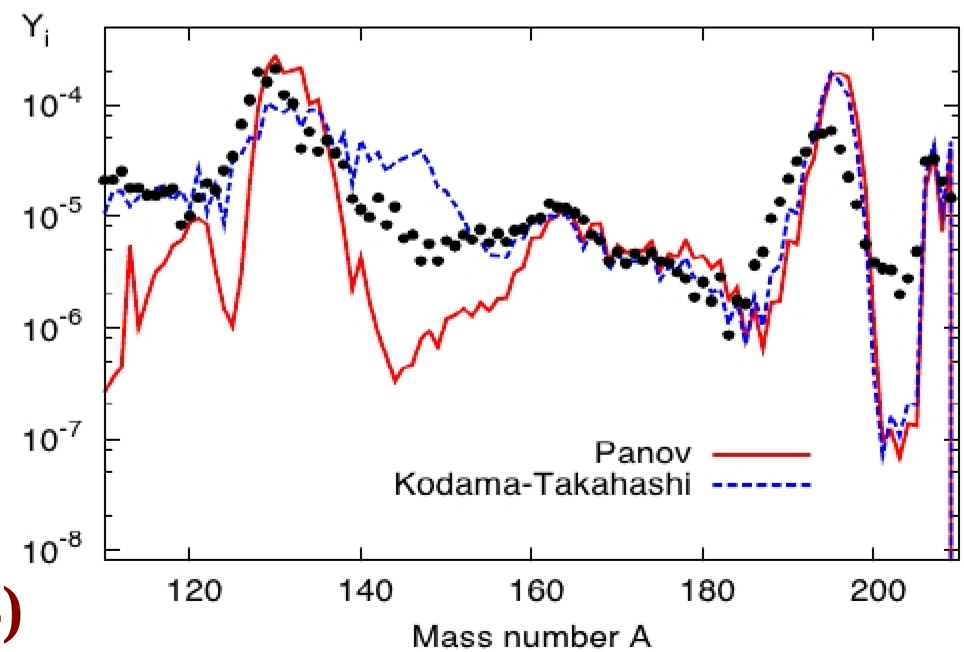
Neutron star merger updates of *dynamic ejecta* in non-relativistic calculations (Korobkin et al. 2012)

Variation in neutron star masses

fission yield prescription

Fission yields affect abundances below A=165, the third peak seems always shifted to heavier nuclei



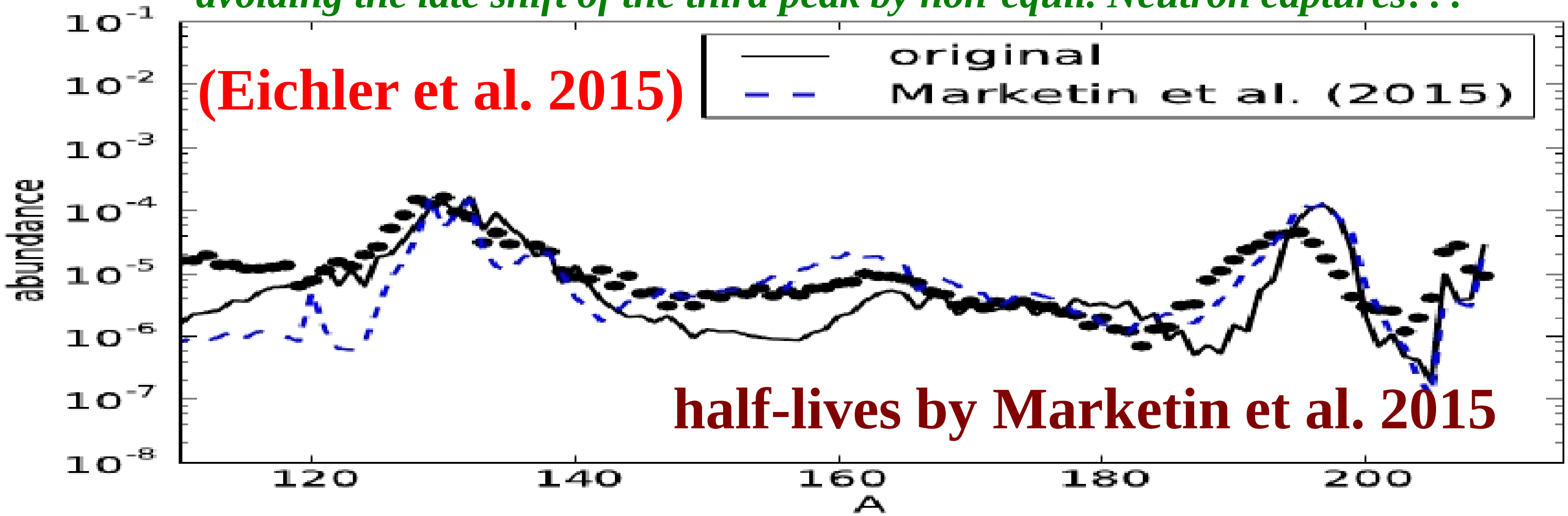


Ejected mass of the order 10^{-2} M$_{sol}$

conditions very neutron-rich (Ye=0.04)

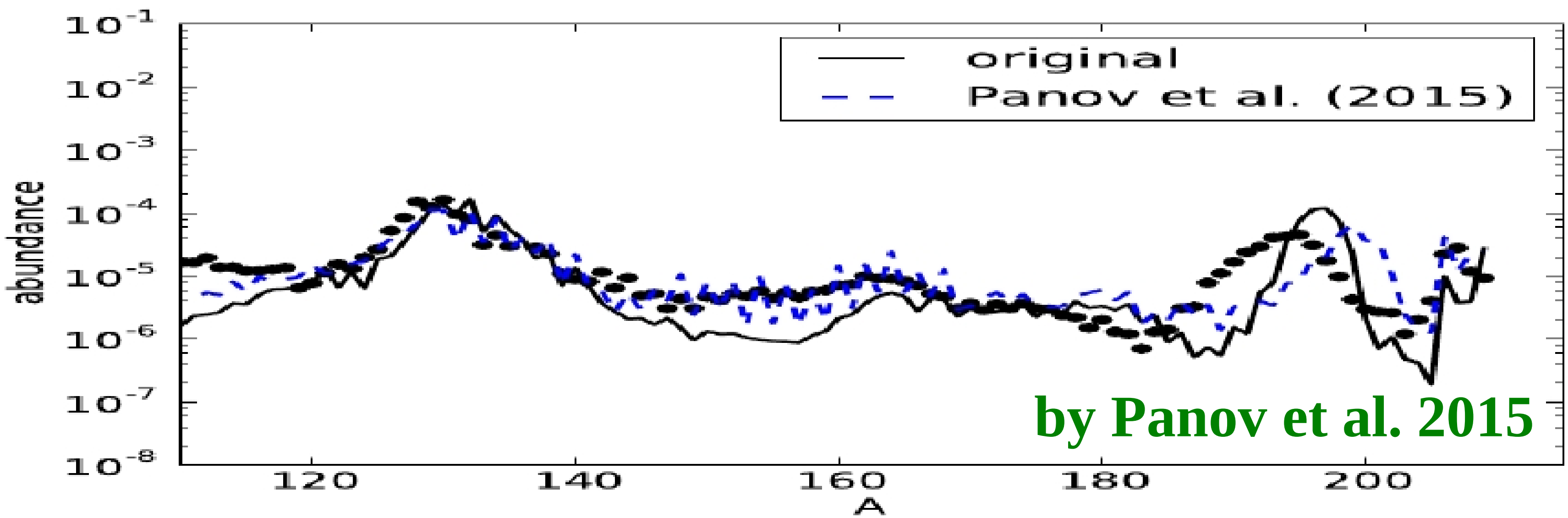
Exploring variations in beta-decay rates and fission fragment distributions

Shorter half-lives of heavies release neutrons (from fission/fragments) earlier ***(still in n,γ - γ,n equilibrium) , avoiding the late shift of the third peak by non-equil. Neutron captures???***



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

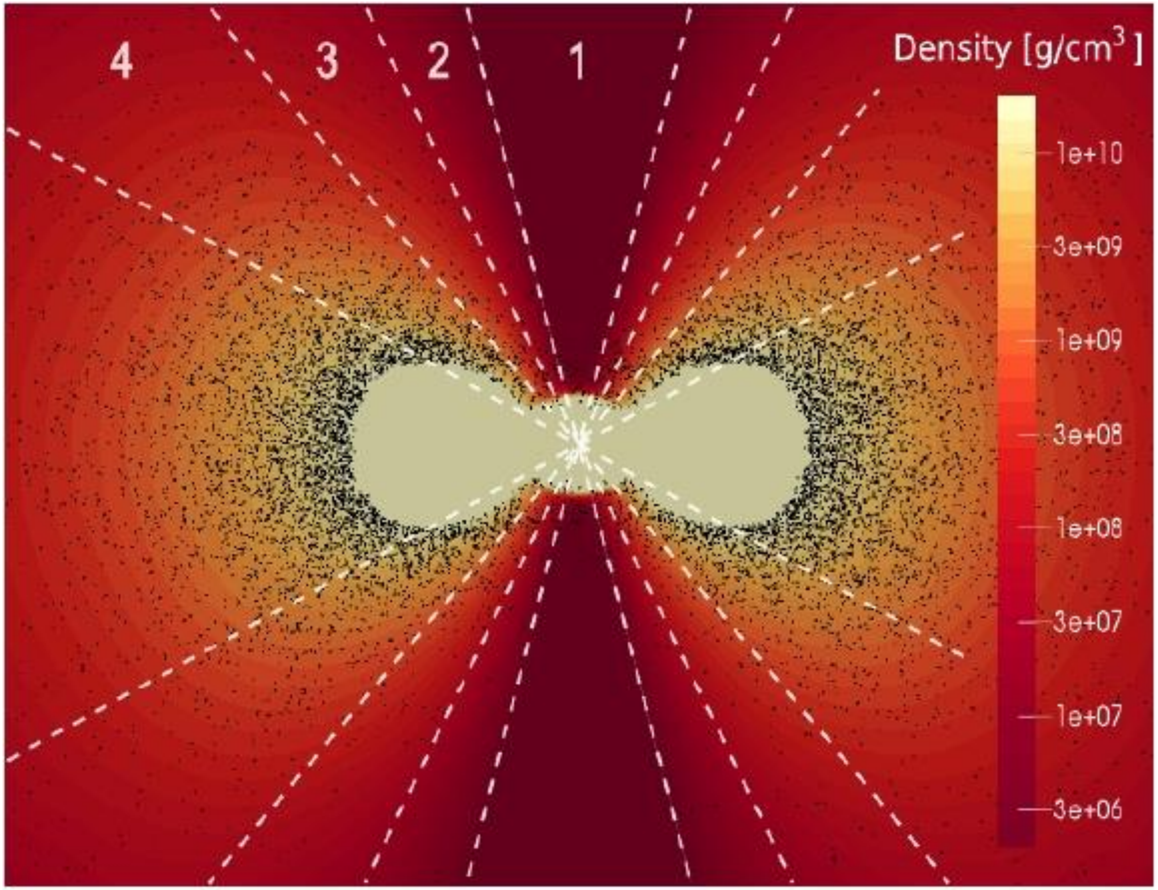
(a) FRDM, Marketin (2015)

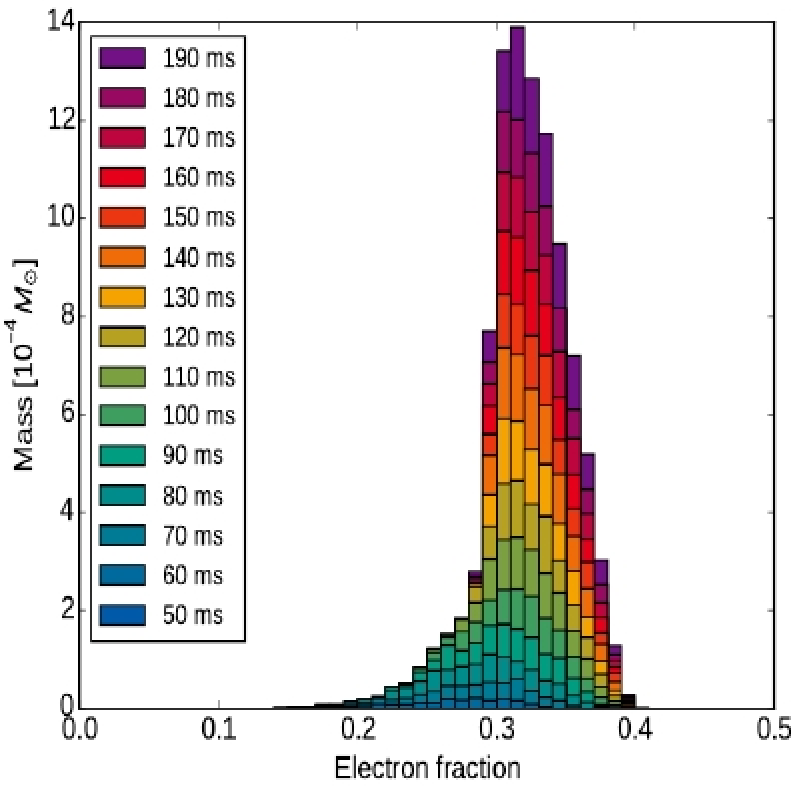


Longer half-lives give the opposite effect

(c) FRDM, Panov (2015)

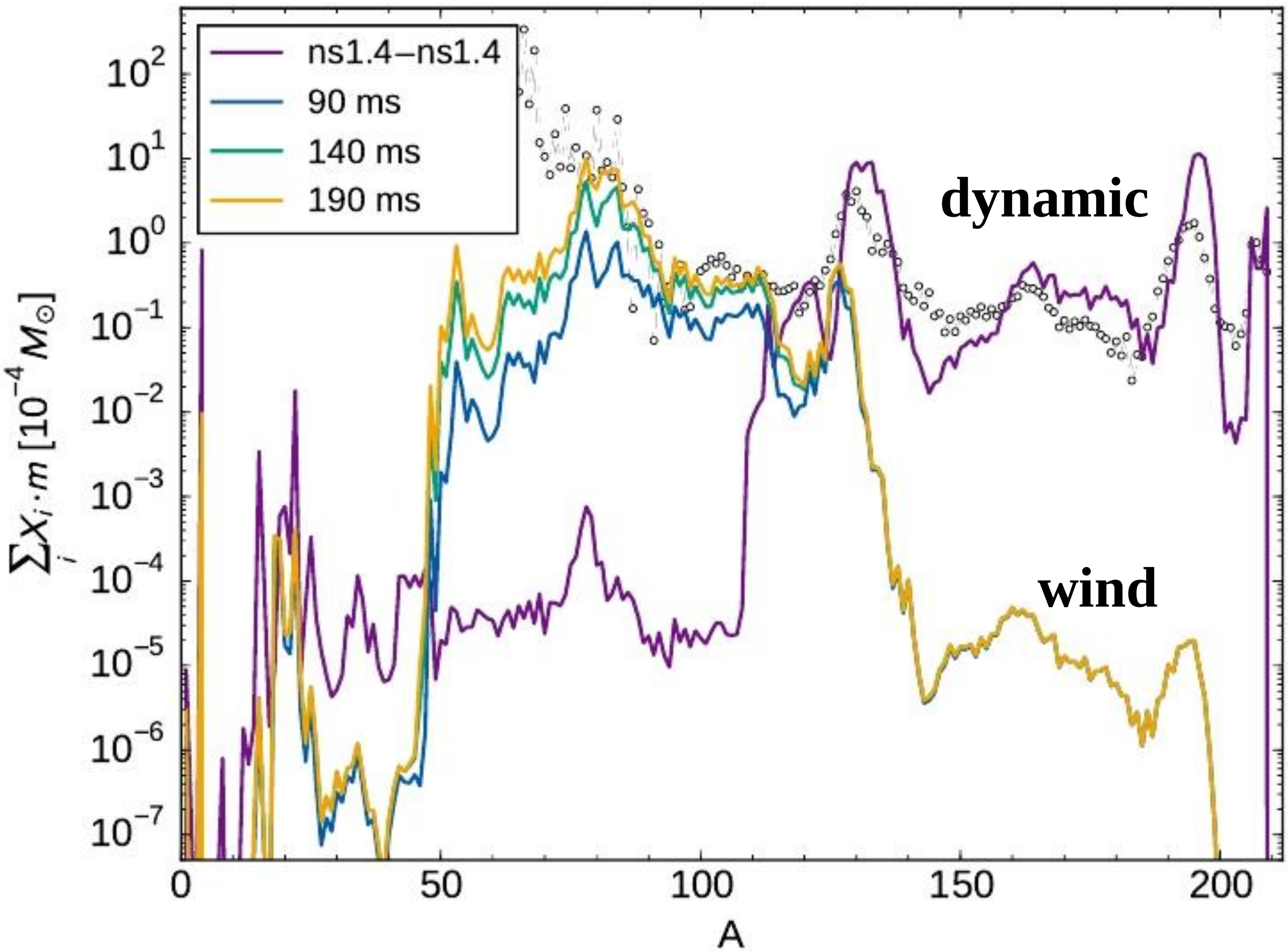
Dynamic Ejecta and Wind Contribution before BH formation (Martin et al. 2016)





Ye in neutrino wind

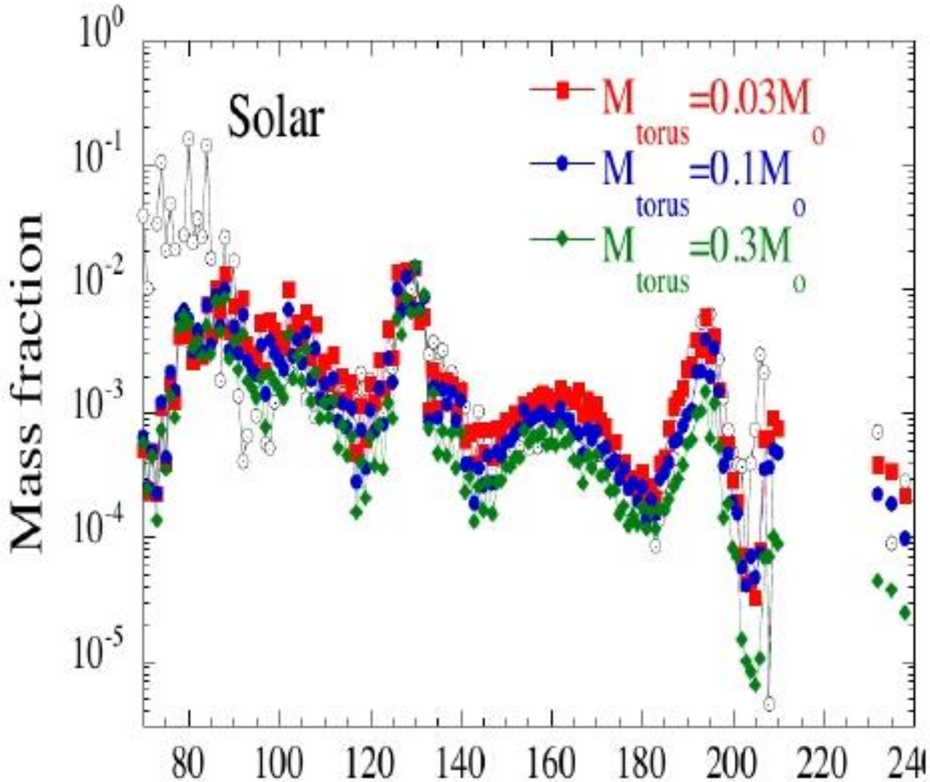
After ballistic/hydrodynamic ejection of matter, the hot, massive combined neutron star (before collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014)



Martin et al. (2016) with neutrino wind contributions from matter in polar directions (improvements for dynamical ejecta composition by Eichler et al. (2015)).

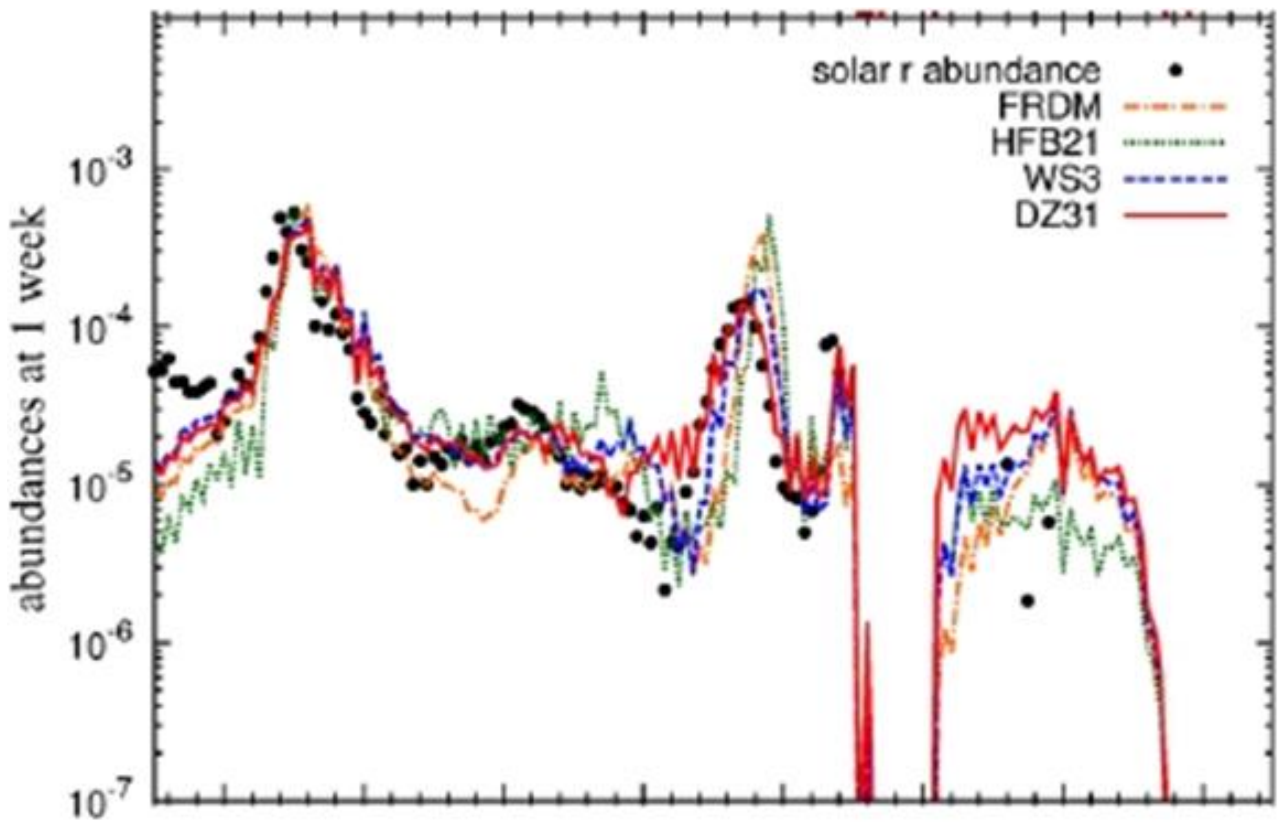
The Need to go beyond Newtonian Methods

- Conformally flat smoothed particle hydrodynamics application to neutron star mergers (Oechslin, Rosswog, Thielemann, 2002)
- The influence of quark matter at high densities on binary neutron star mergers (Poghosyan, Oechslin, Uryu, Thielemann, 2004)
- Evolving into the Garching conformal flat approach (Bauswein, Oechslin, Janka, Goriely, …



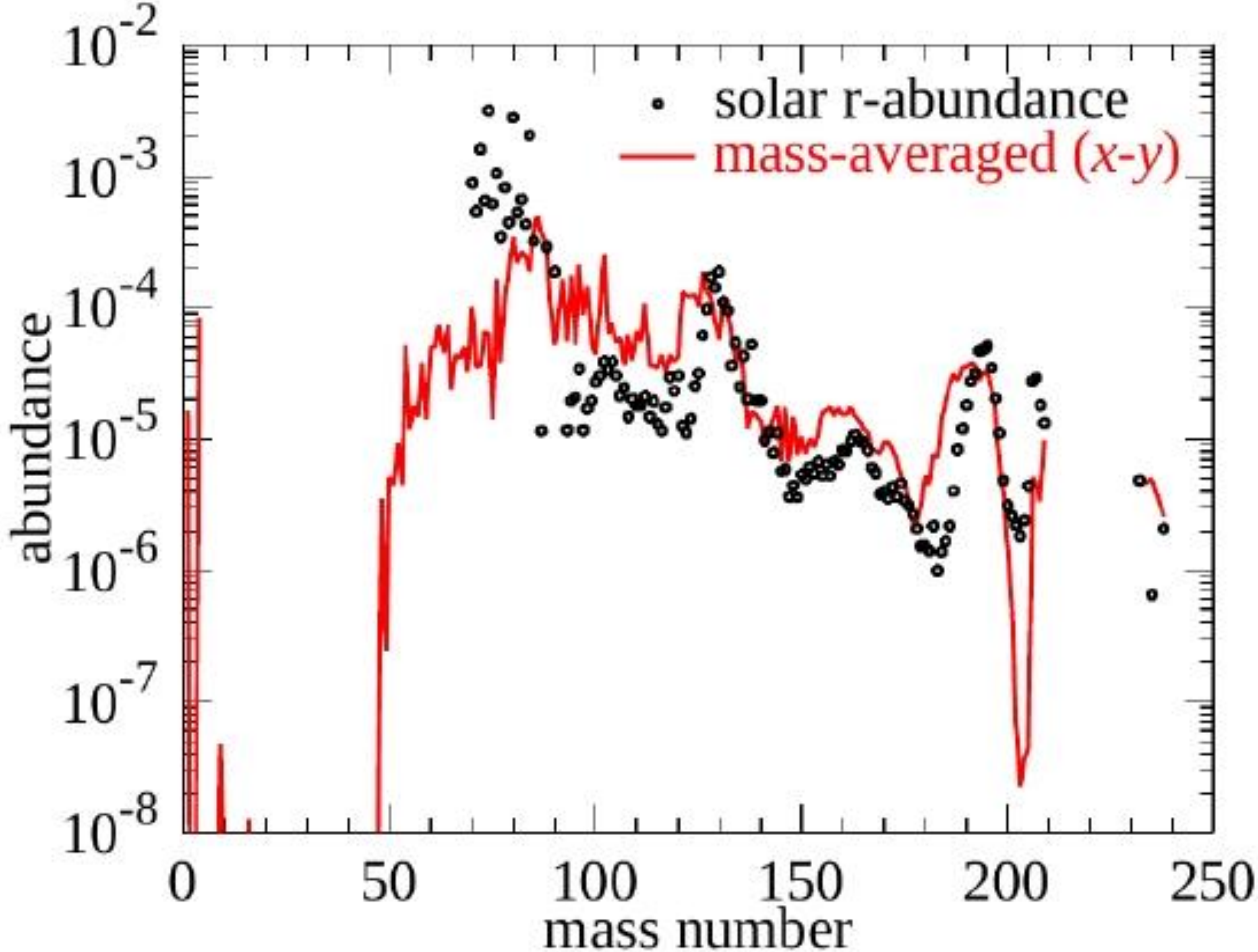
Full predictions with dynamic ejecta, viscous disk ejection, and late neutrino wind, **but neutron-less fission fragment distribution?** *(Just et al. 2015)* based on smooth particle hydrodynamics and conformal flat treatment of GR

Latest results within this approach (but only utilizing dynamic ejecta)

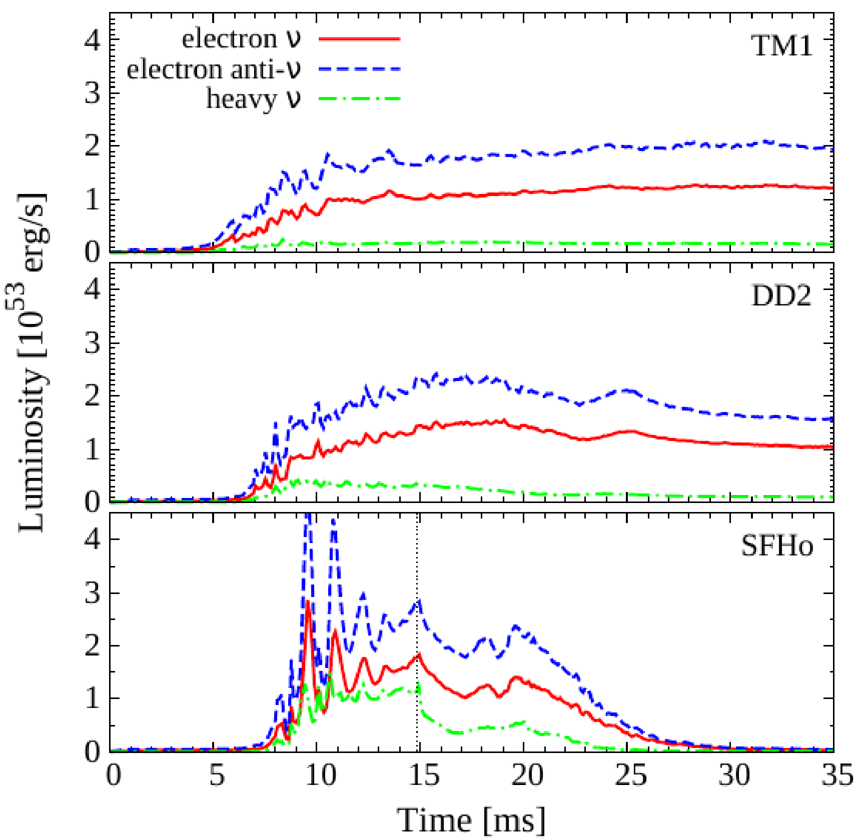


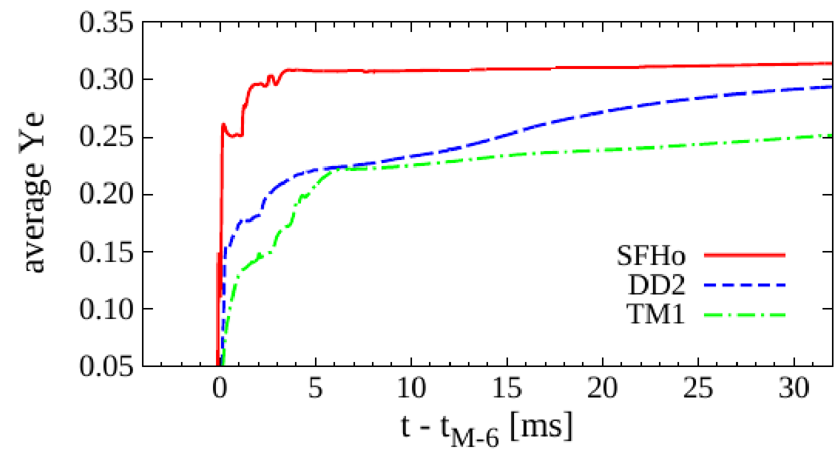
Variations based on different nuclear mass models.
Mendoza-Temis, Wu, Langanke, Martinez-Pinedo, Bauswein, Janka (2015)

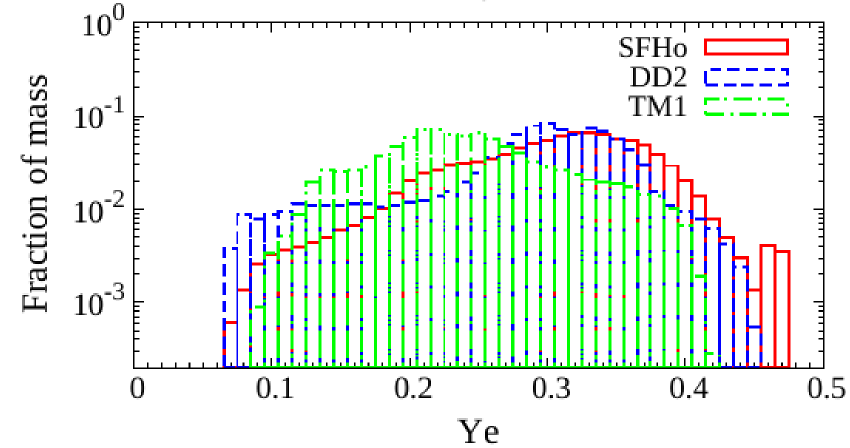
General relativistic calculations utilize grid methods, find hotter conditions, leading to e+e- pairs, which affect Ye and the position of the r-process peaks **(Wanajo et al. 2014)**



Sekiguchi et al. (2015), relativistic calculations lead to deeper grav. potentials, apparently also stronger shocks, both enhancing the temperature, higher neutrino luminosities, and e+e- pairs. All of this enhances Ye, permitting to have abundance distribution with A<130!.



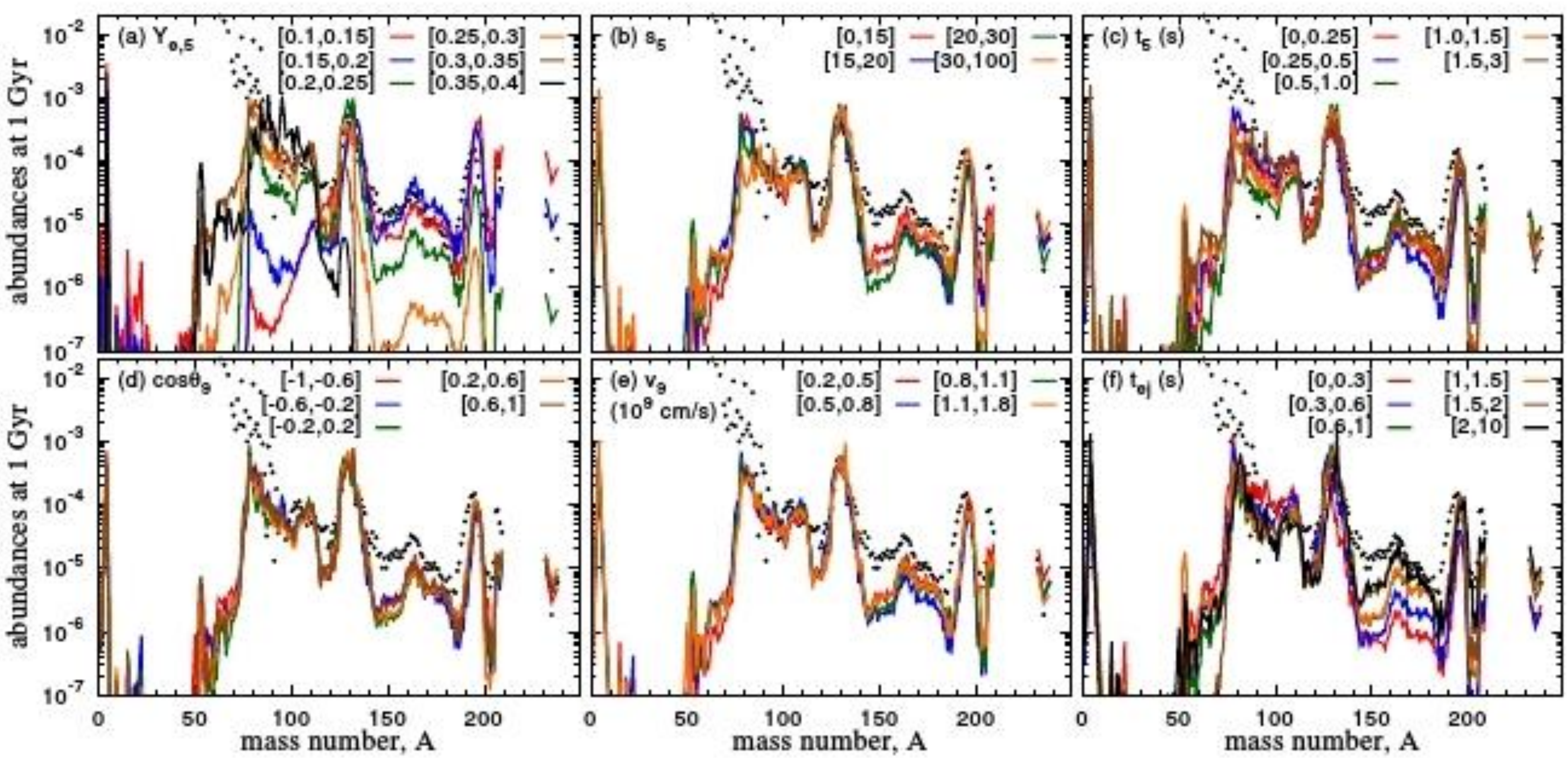




3 different EoS, TM1, DD2, and SFH

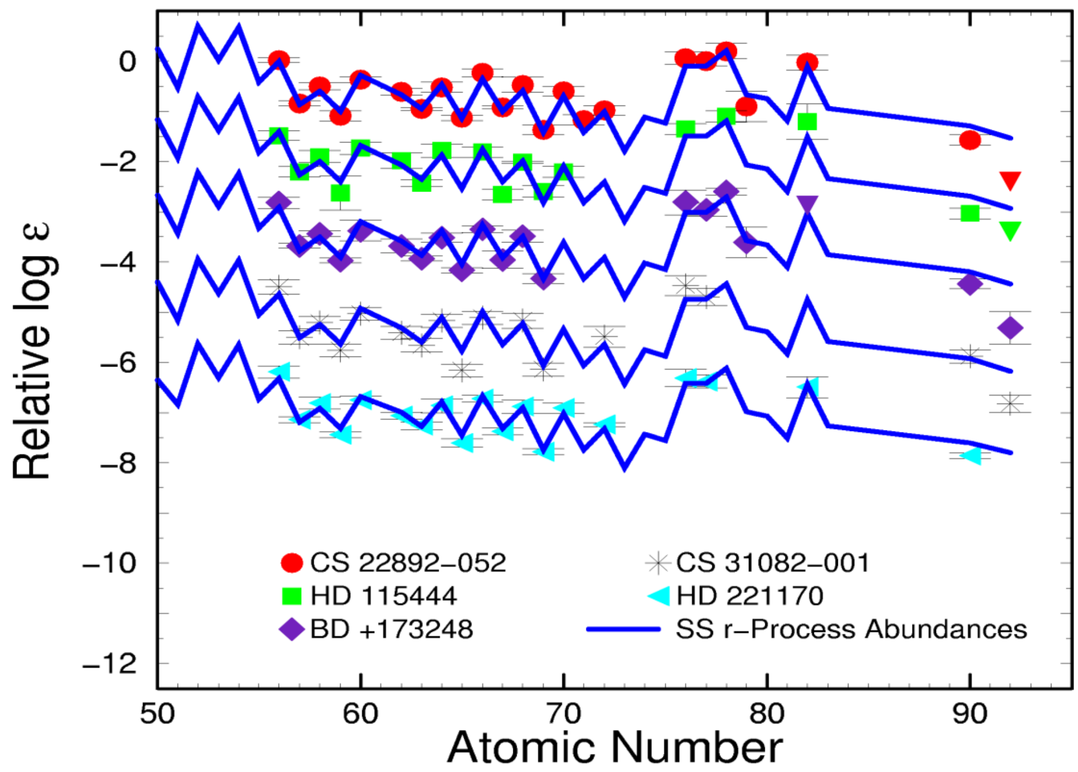
Nucleosynthesis from BH accretion disks (after merger and BH formation, but without dynamical ejecta)

Variations in BH mass, spin, disk mass, viscosity, entropy in alpha-disk models: r-process nuclides up to lantinides and actinides *can* be produced.



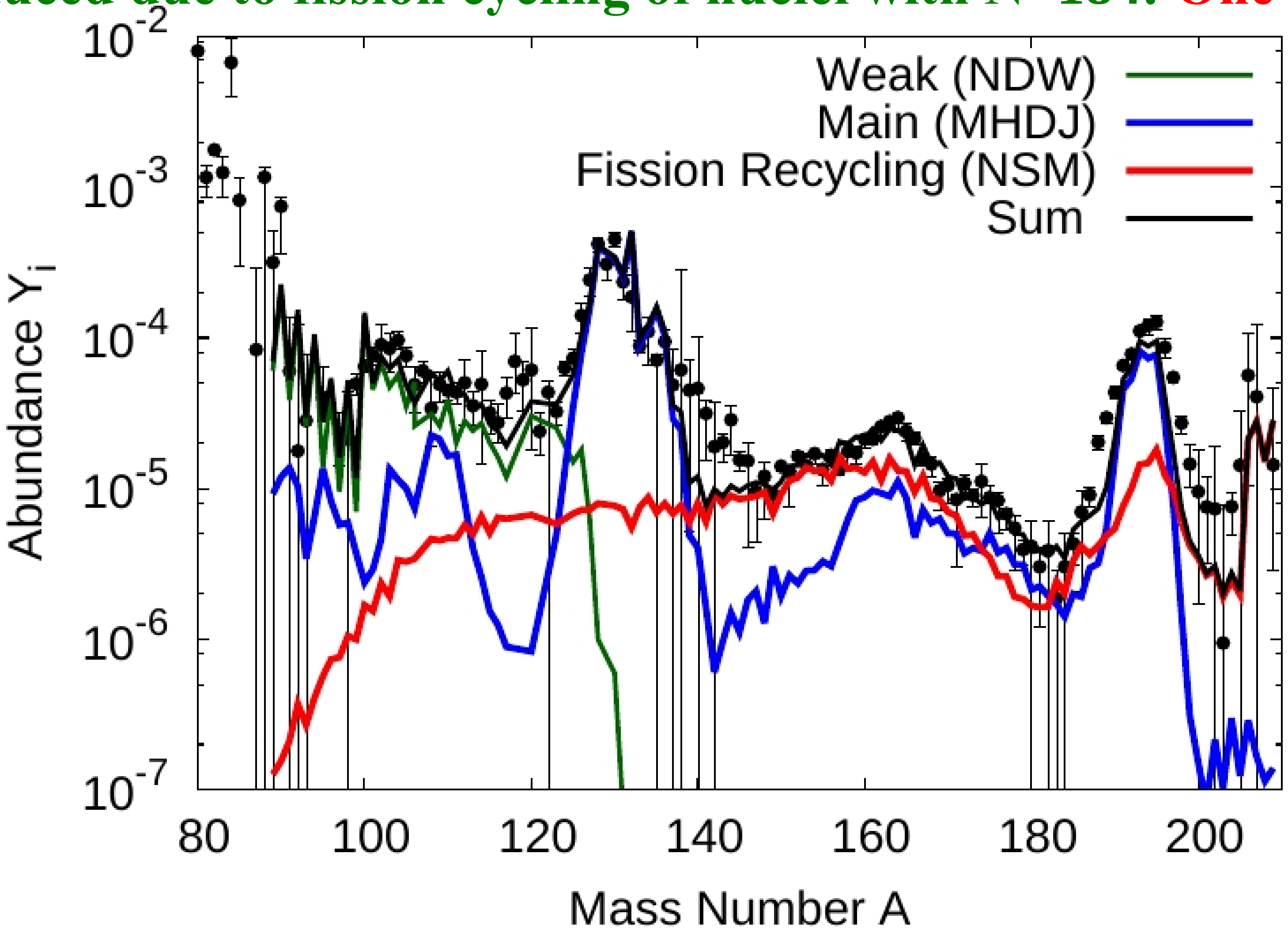
Wu, Fernandez, Martinez-Pinedo, Metzger (2016)

Thus, while there exist still uncertainties in modeling and nuclear input, it is probably a good assumption that neutron star mergers produce a robust abundance pattern resembling the solar r-process as seen in low metallicity stars, with possible variations for A<130, due to upper Ye-values reached in individual conditions.



Cowan & Sneden

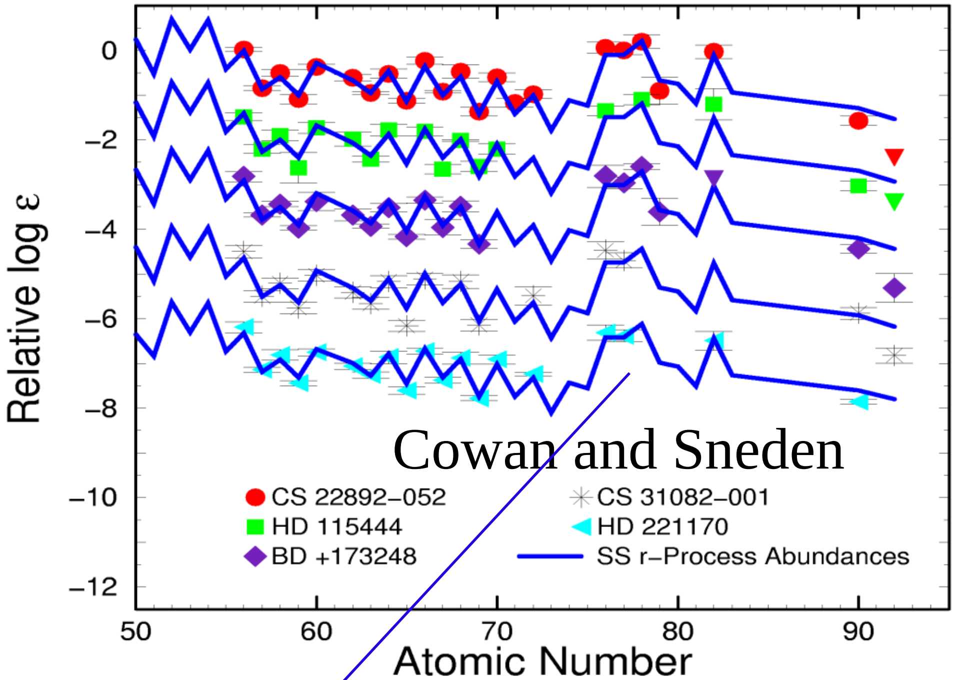
Essentially all presently utilized fission barrier predictions (ABLA,.. HFB ..) permit abundance distribution where the A=130 and 196 peak are reproduced due to fission cycling of nuclei with N≈184: One exception …



Shibagaki et al. 2015 with KTUY (2007) mass model and fission fragment distribution by Koura et al. (2005)

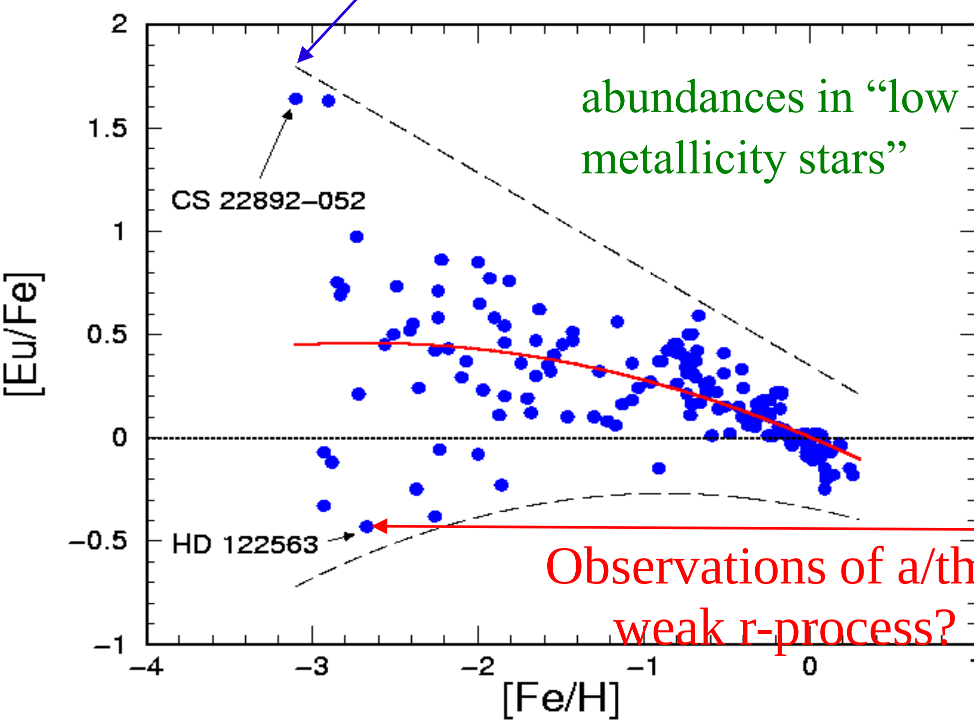
This specific choice of nuclear input permits fission only at A>300 and thus the fragments do not produce the second r-process peak

Can NSMs reproduce low-metallicity observations?



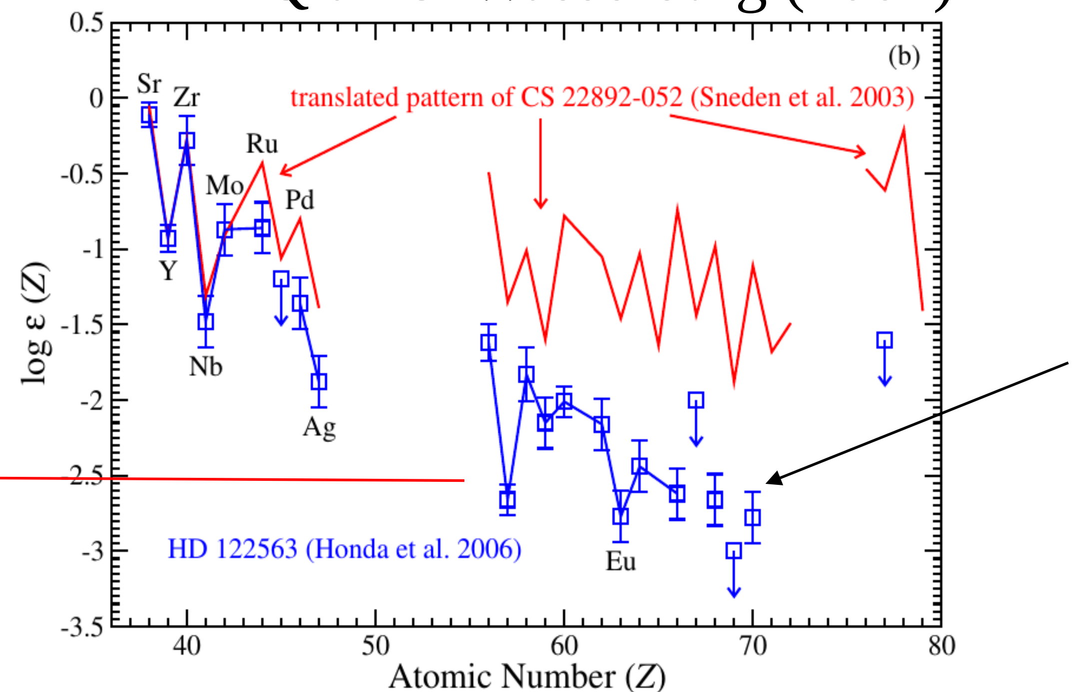
apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event for these "Sneden-type" stars

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



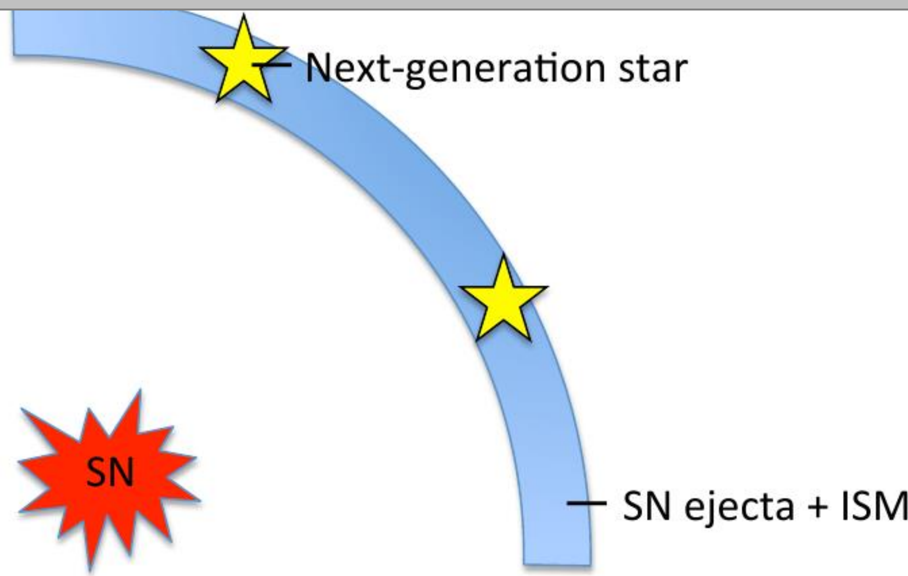
Observations of a/the? weak r-process?

Qian & Wasserburg (2007)



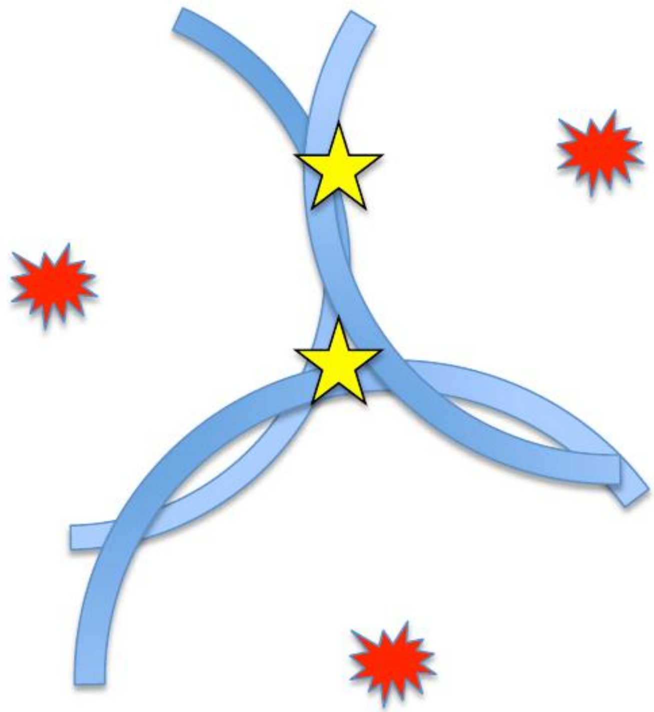
Stellar Abundances

Inhomogeneous „chemical evolution“ : Models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 5 10^4 Msol, according to Sedov-Taylor blast wave. After many events an averaging of ejecta composition is attained (Argast et al. 2004)



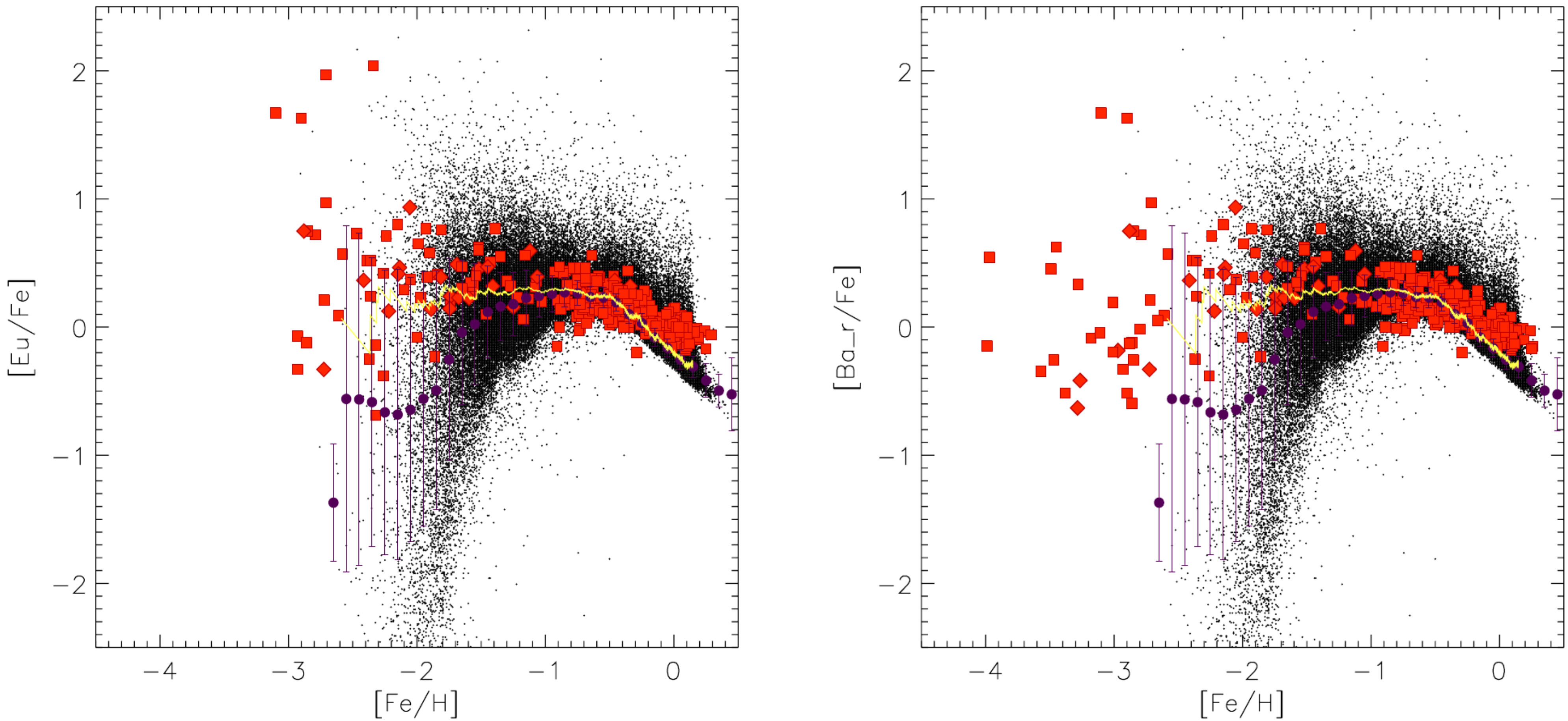
In the later phase

Contribution from multiple CCSNe
(unknown → average weighted by IMF)



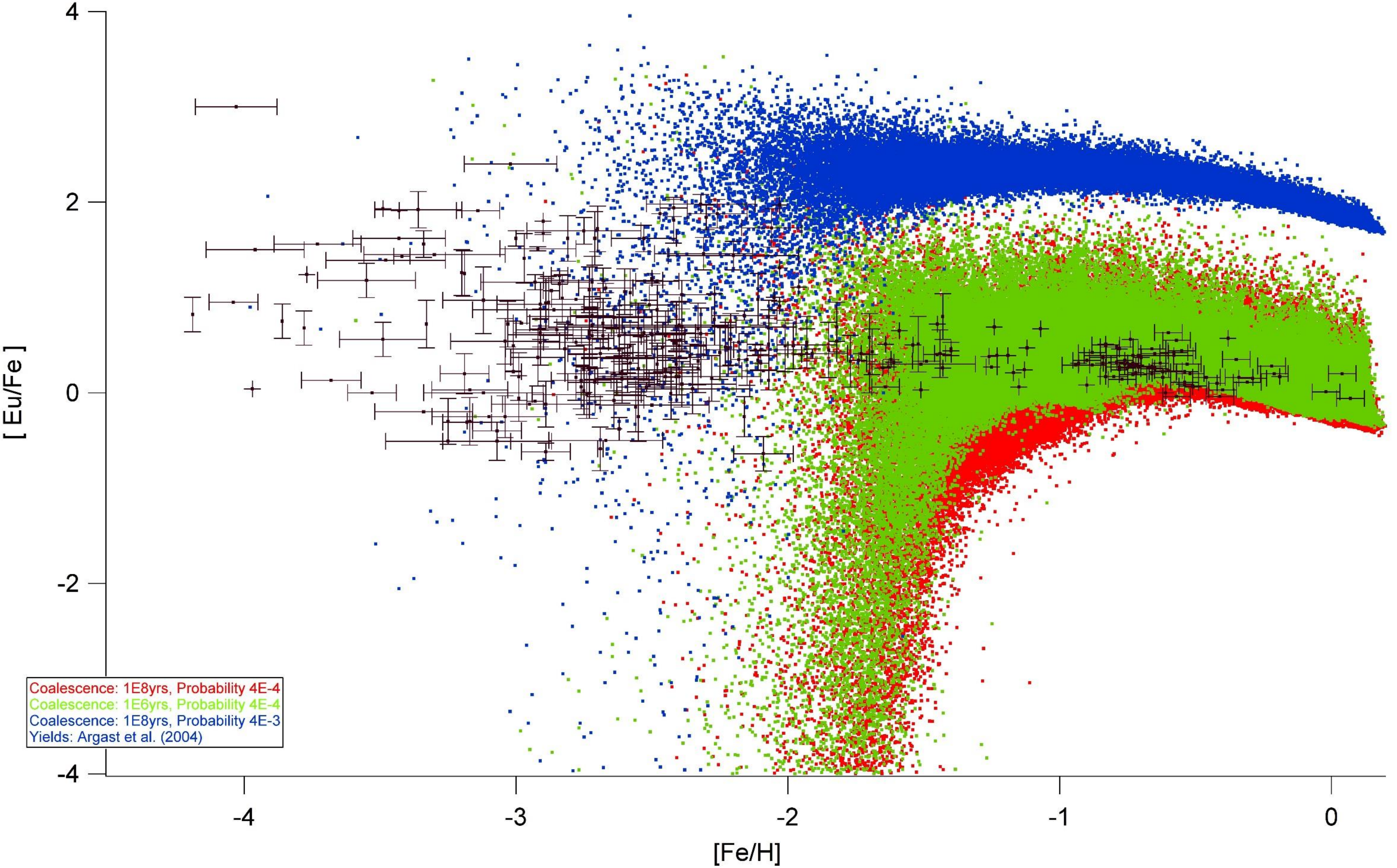
Inhomogenous models undertaken by Van de Voort+ (2015), Shen+ (2015), Cescutti+ (2014), Wehmeyer+ (2015), Hirai+ (2016)

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



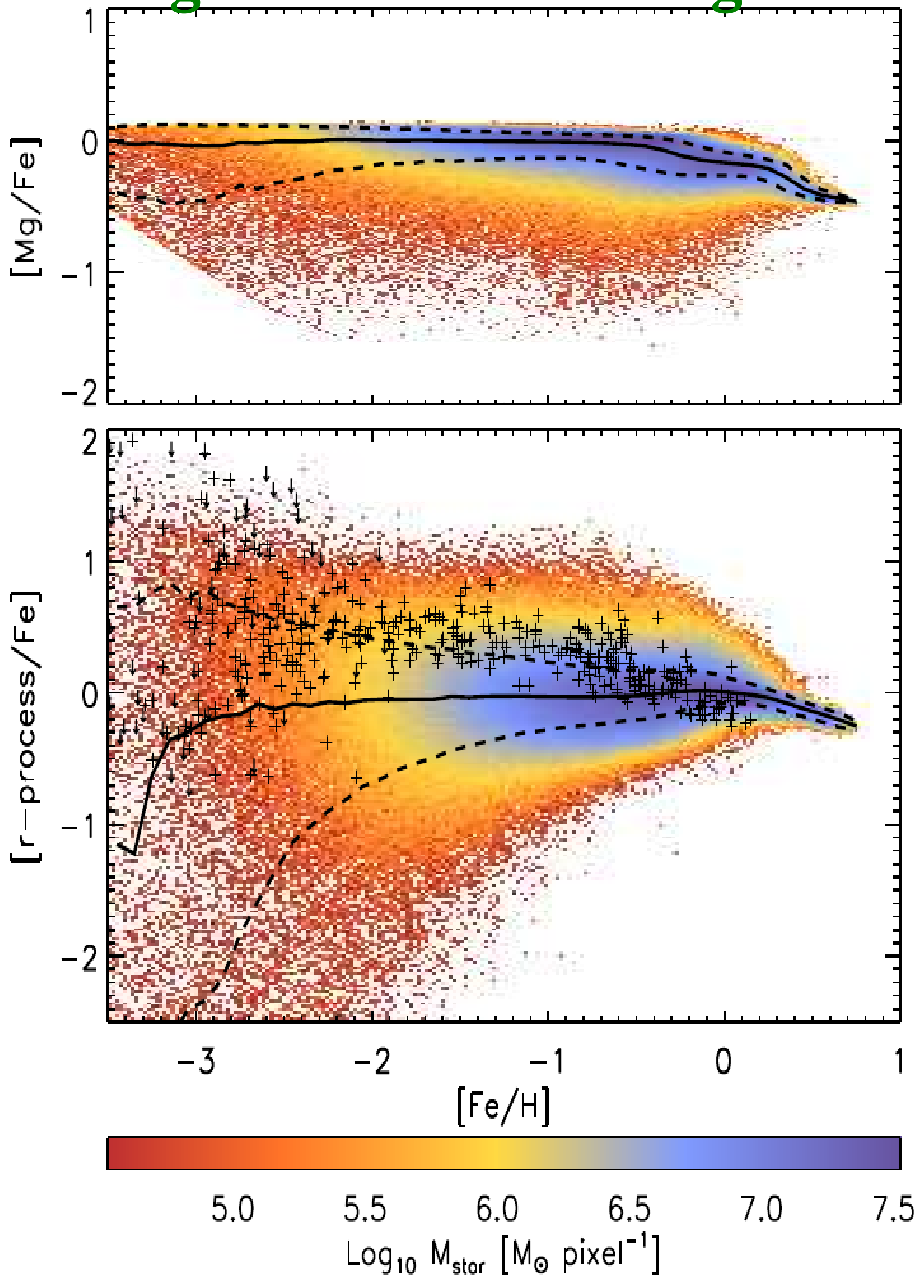
'ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

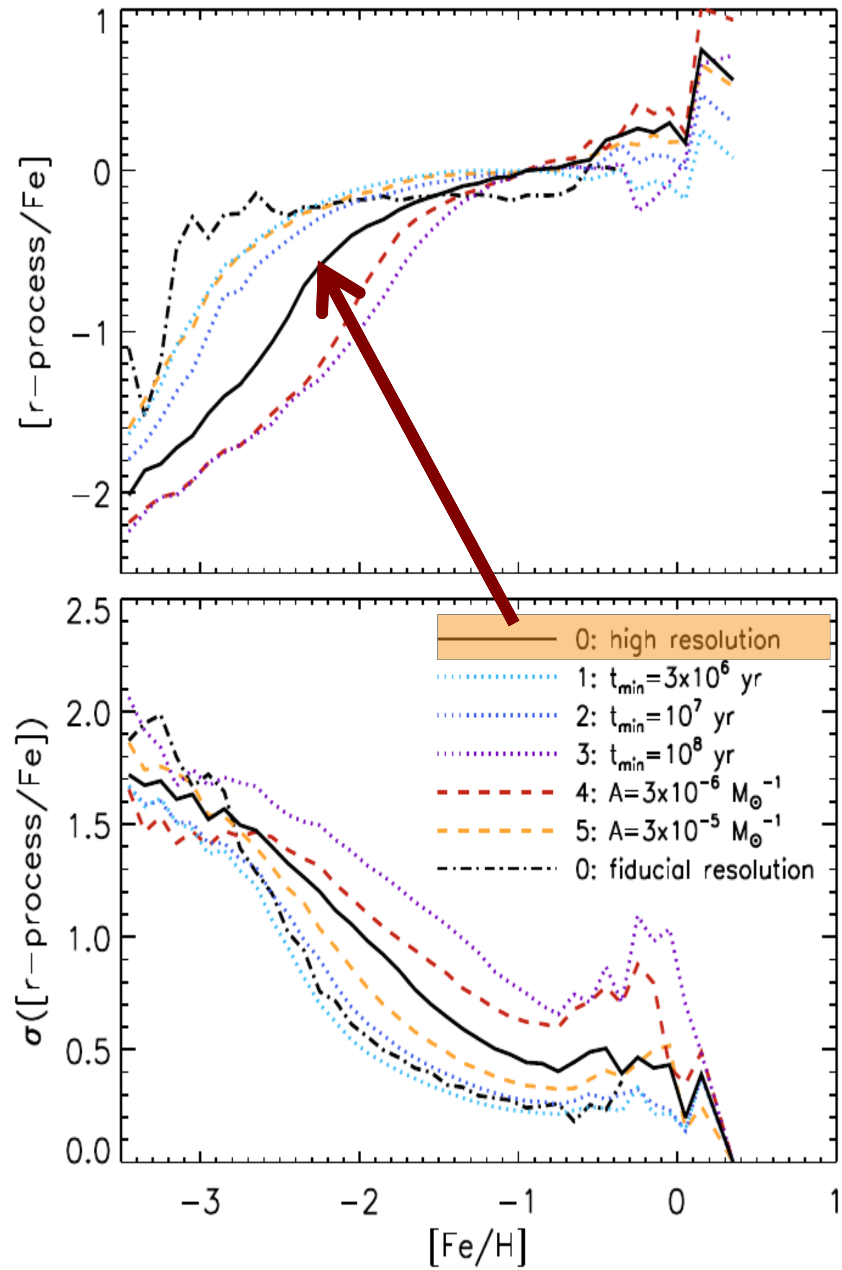
This is the main question related to mergers, ([Fe/H] can be shifted by different SFR in galactic subsystems), Is inhomogenous galactic evolution implemented correctly??
The problem is that the neutron star-producing SNe already produce Fe and shift to higher metallicities before the r-process is ejected!!!



Update by Wehmeyer et al. (2015), green/red different merging time scales, blue higher merger rate (not a solution, but (i) turbulent mixing would shift the onset to lower metallicities, (ii) different SFR in initial substructures can do so)

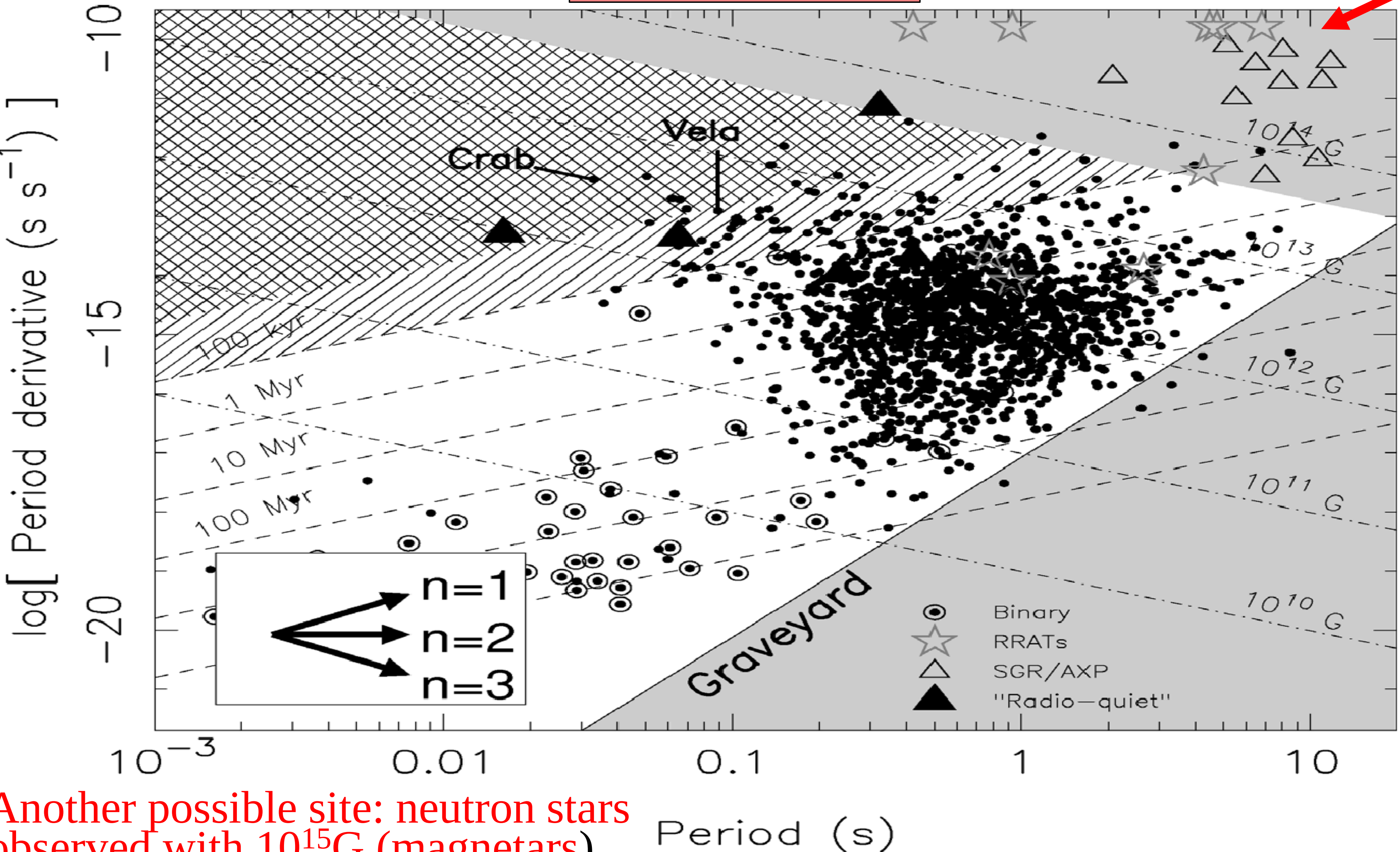
Inhomogeneous Chemical Evolution with SPH (van de Voort et al. 2015), Left ejecta mixed in $5x10^6$ Msol, right high resolution mixed in $5x10^4$ Msol, leading also to a late emergence of [Eu/Fe] (see also Shen et al. 2015)





If large-scale turbulent mixing would occur, this feature *could* be moved to lower metallicities!

M. Kramer (2009)



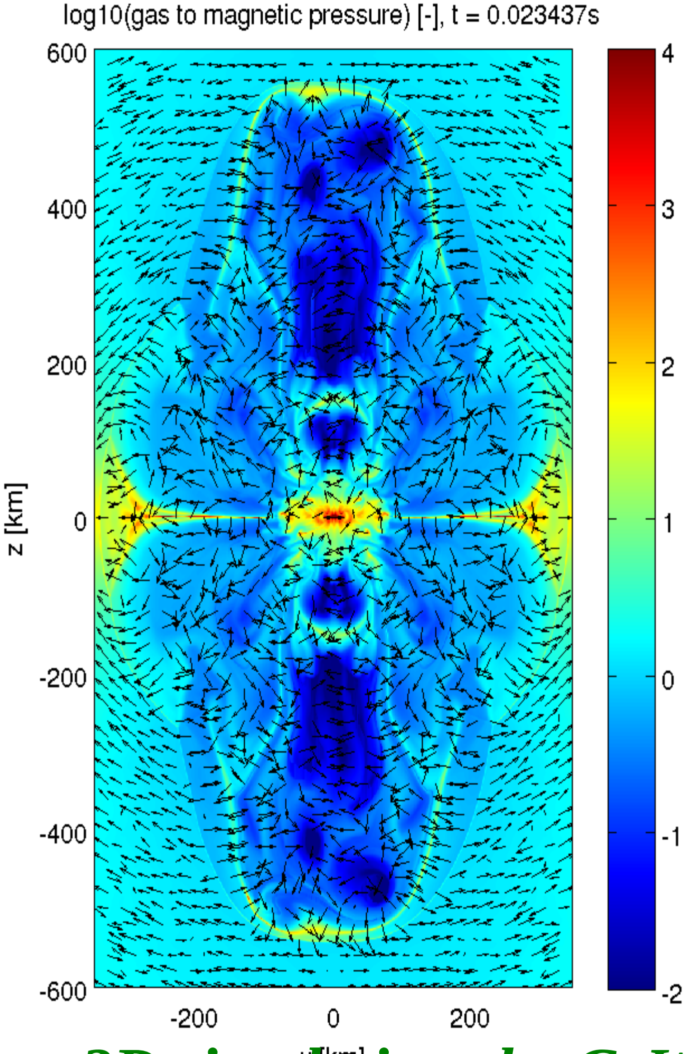
Another possible site: neutron stars observed with 10^{15}G (magnetars)

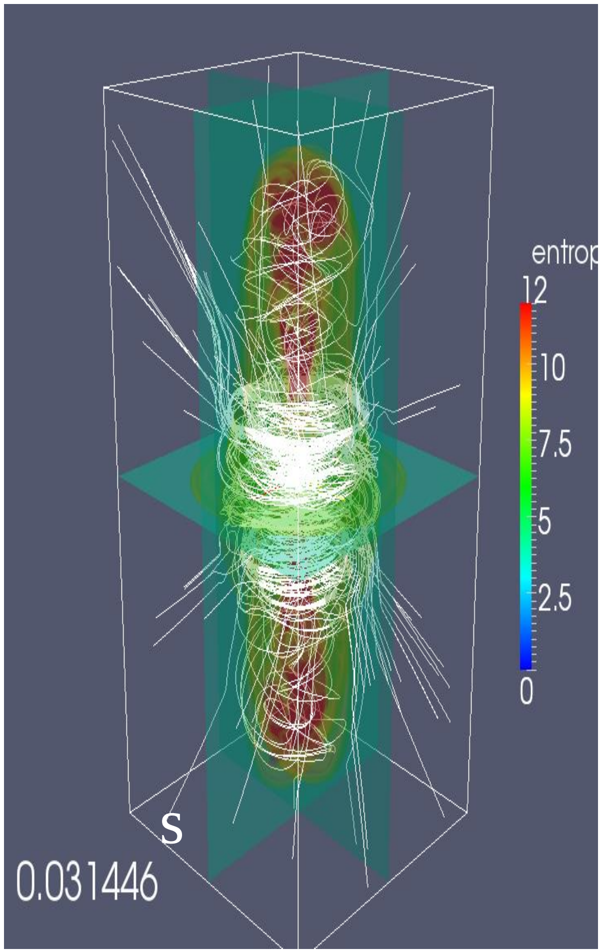
Figure 2. The P–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, 'radio-quiet' pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age τ_c and magnetic field B are also shown. The single hashed region shows 'Vela-like'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

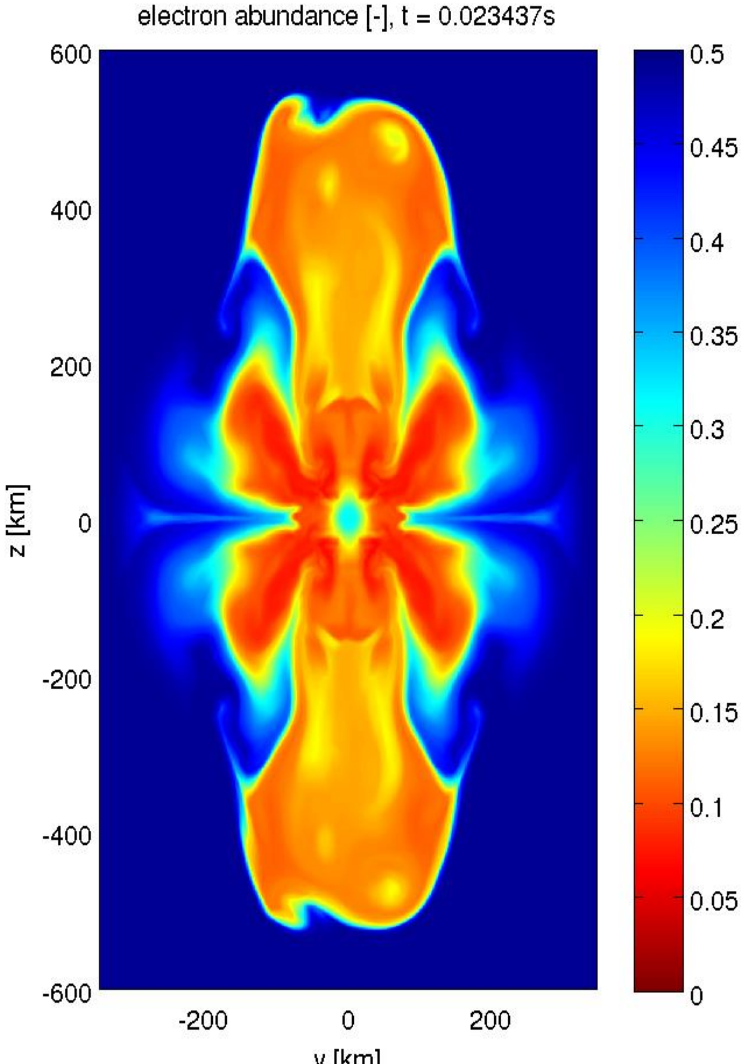
3D Collapse of Fast Rotator with Strong Magnetic Fields:

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





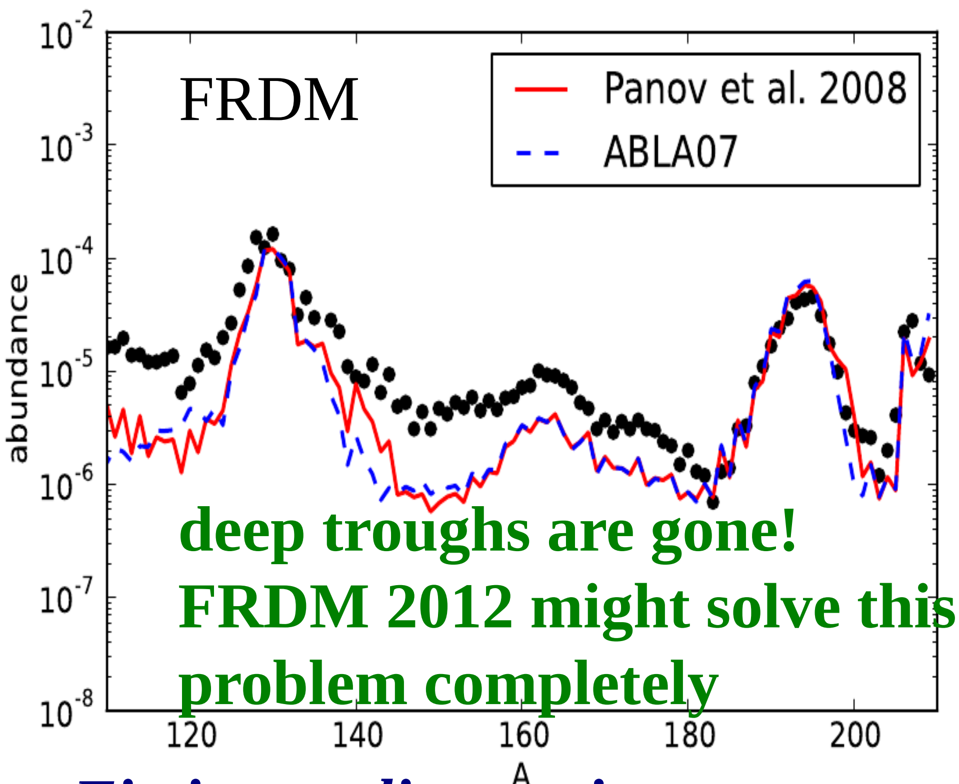


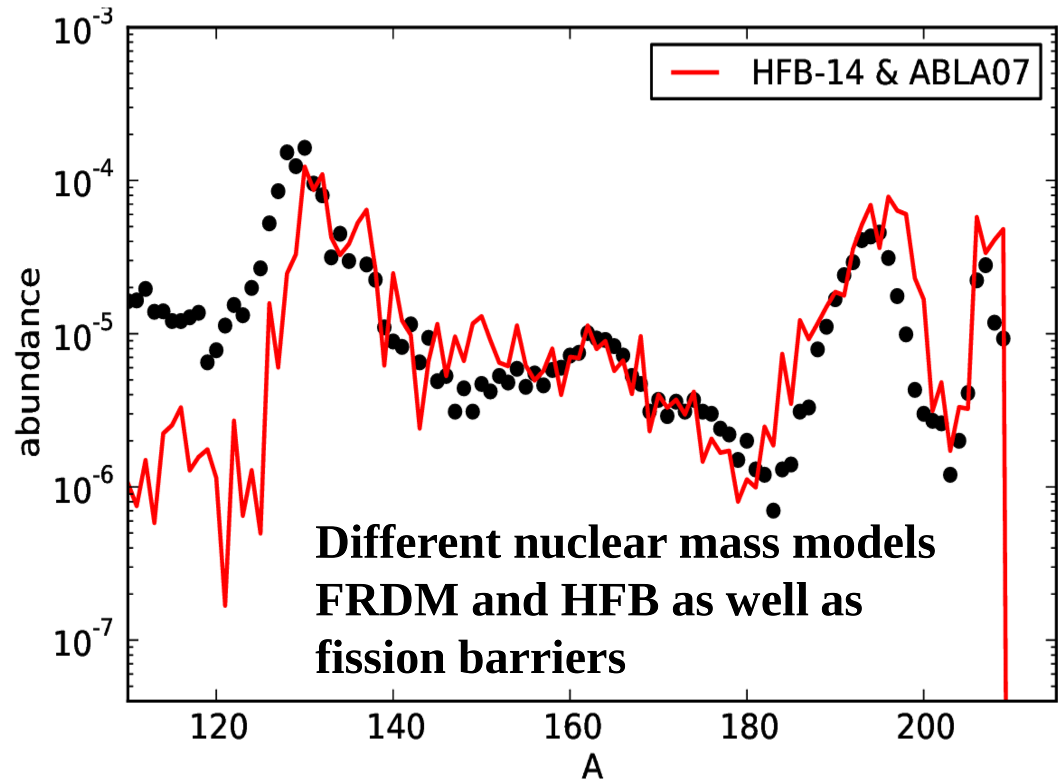
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012

Eichler et al. 2015

Nucleosynthesis results, utilizing Winteler et al. (2012) model with variations in nuclear Mass Model and Fission Yield Distribution

(Eichler et al. 2015)





Fission-cycling environments permit n-capture due to fission neutrons in the late freeze-out phase and shifts peaks, but effect generally not strong and overall good fit in such "weak" fission-cycling environments!

Ejected matter with A>62 $M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_{\odot}$

Another 3D Study (Mösta et al. 2014)

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

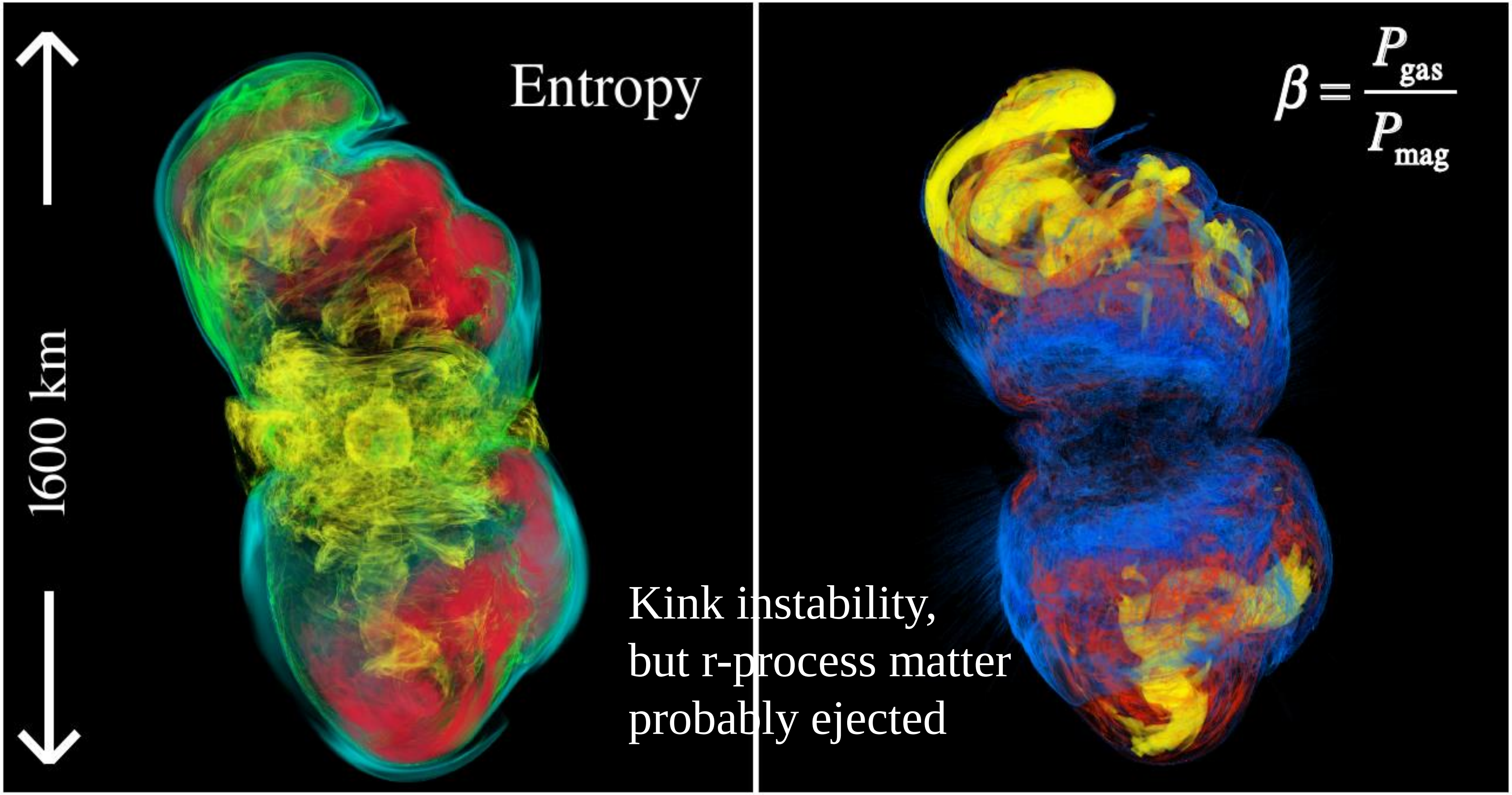
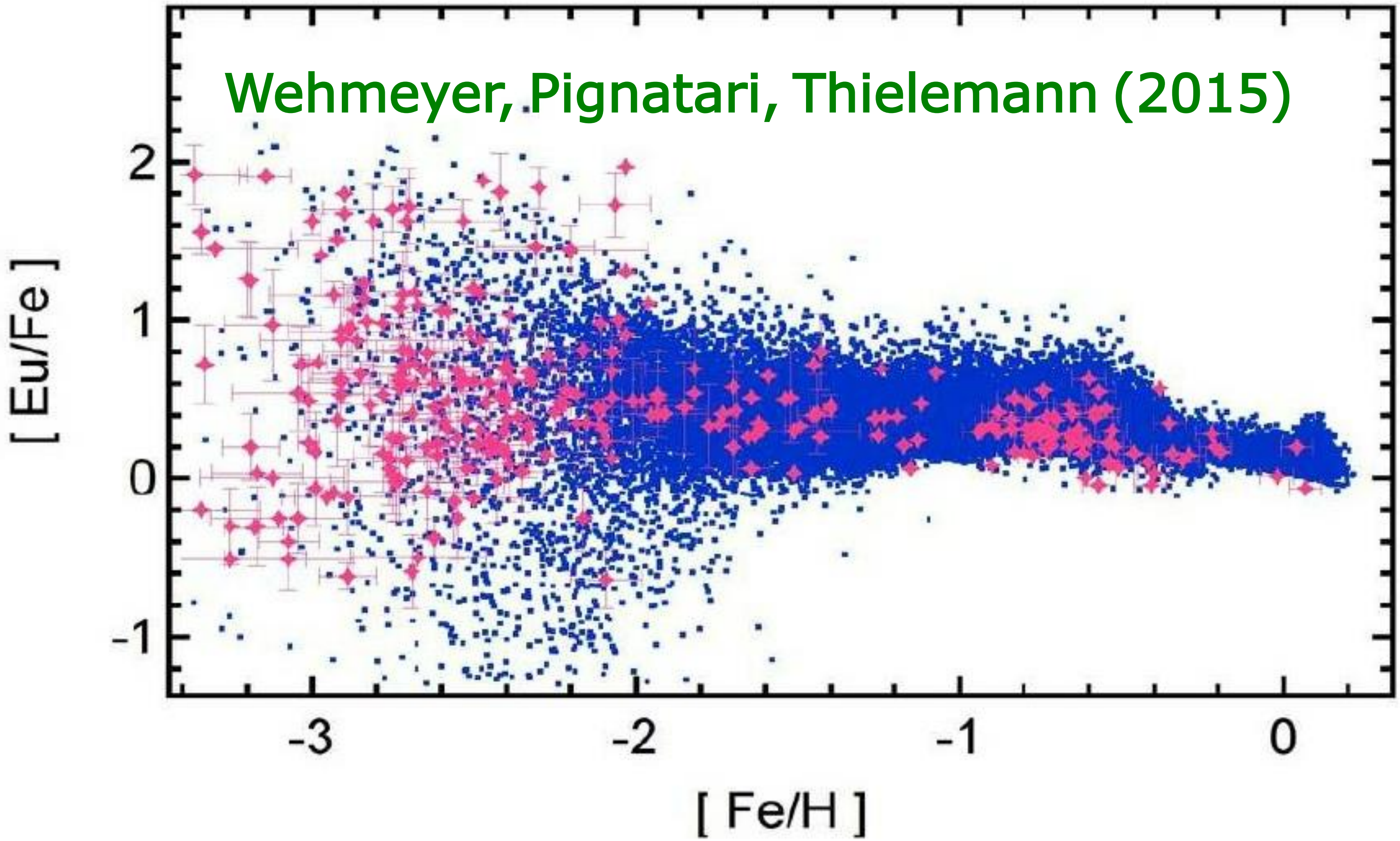


Figure 4. Volume renderings of entropy and β at $t - t_b = 161$ ms. The z-axis is the spin axis of the protoneutron star and we show 1600 km on a side. The colormap for entropy is chosen such that blue corresponds to $s = 3.7 k_b$ baryon^{-1}, cyan to $s = 4.8 k_b$ baryon^{-1} indicating the shock surface, green to $s = 5.8 k_b$ baryon^{-1}, yellow to $s = 7.4 k_b$ baryon^{-1}, and red to higher entropy material at $s = 10 k_b$ 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.

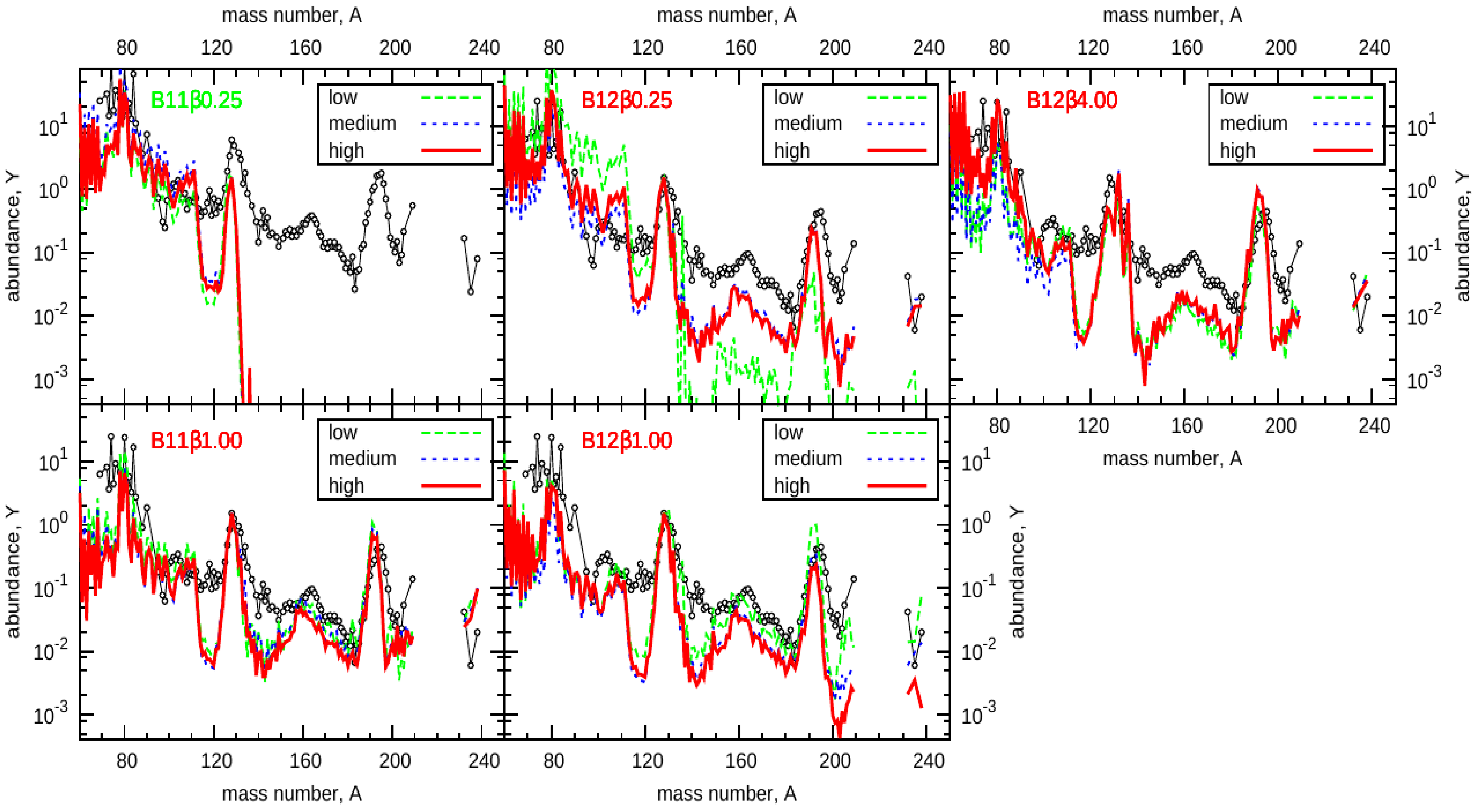
Combination of NS mergers and magneto-rotational jets in (stochastic) inhomogeneous GCE



=> in either case, the strong r-process which also produces the actinides is a rare event!!!!!!!!!!!!!

(see also Van de Voort+, Shen+, Hirai, Ishimaru+, Cescutti+)

Nishimura, Takiwaki, Thielemann (2015), varying rotation rates and magnetic fields in 2D study of MHD-SNe →
results varying from a weak up to a strong r-process!



Full MHD calculations resolving the magneto-rotational instability MRI (Nishimura, Sawai, Takiwaki, Yamada, Thielemann, 2016, submitted 7/11/16)

IN MAGNETOROTATIONAL CC-SNE 5

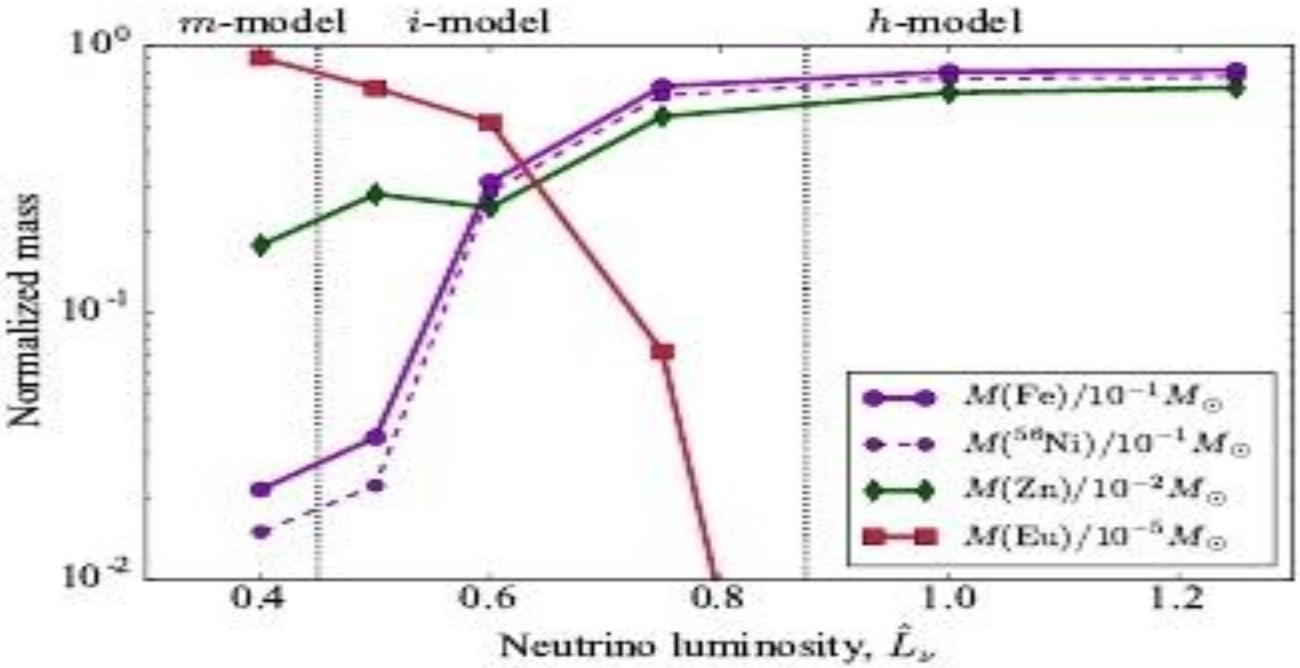
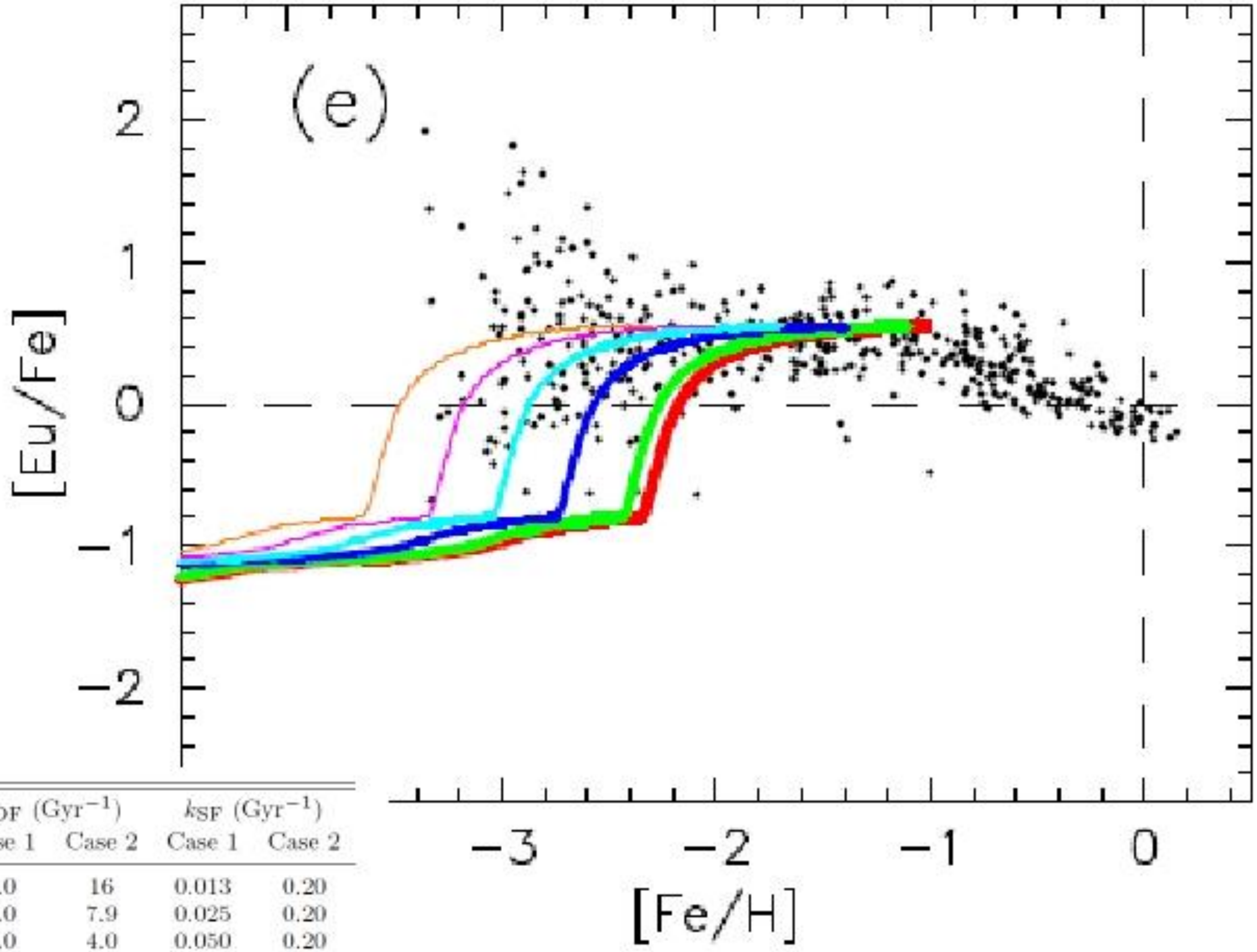


Figure 5. Ejected masses of Fe, ^{56}Ni (before decay), Zn and Eu as a function of $\hat{L}_\nu$. Each mass is normalized by a typical value, i.e. 10^{-1}, 10^{-1}, 10^{-2} and $10^{-5} M_\odot$, respectively.

Dependent on the ratio between neutrino luminosity and magnetic fields the nucleosynthesis behavior changes from regular CCSNe to neutron-rich jets with strong r-process. ***Could this be the explanation of the lowest-metallicity behavior???***

The role of sub-halos, i.e. substructures with different star formation rates (treated within the instantaneous mixing approximation IMA of ejected matter)

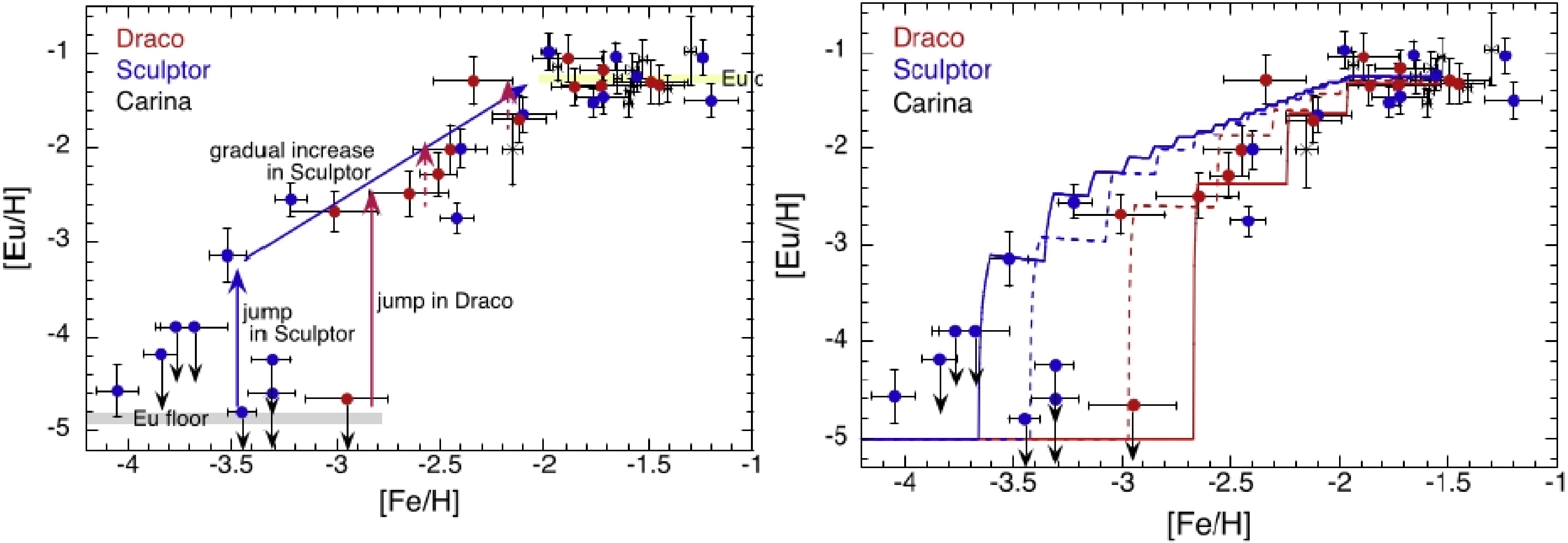


M_* ($M_\odot$)	η	k_{OF} (Gyr^{-1}) Case 1	k_{OF} (Gyr^{-1}) Case 2	k_{SF} (Gyr^{-1}) Case 1	k_{SF} (Gyr^{-1}) Case 2
10^4	79	1.0	16	0.013	0.20
10^5	40	1.0	7.9	0.025	0.20
10^6	20	1.0	4.0	0.050	0.20
10^7	10	1.0	2.0	0.10	0.20
10^8	5.0	1.0	1.0	0.20	0.20
2×10^8	4.1	1.0	0.81	0.25	0.20

The average over a finally merged galaxy could possibly explain observations?

Ishimaru, Wanajo, Prantzos (2015)

Thus, one should have a look at such substructures, i.e. dwarf galaxies



One realizes steps/jumps in [Eu/Fe] at low metallicities

Tsujimoto & Nishimura (2015)

Trying to fit Draco with NSMs alone, varying coalescence times (Wehmeyer et al. 2016)

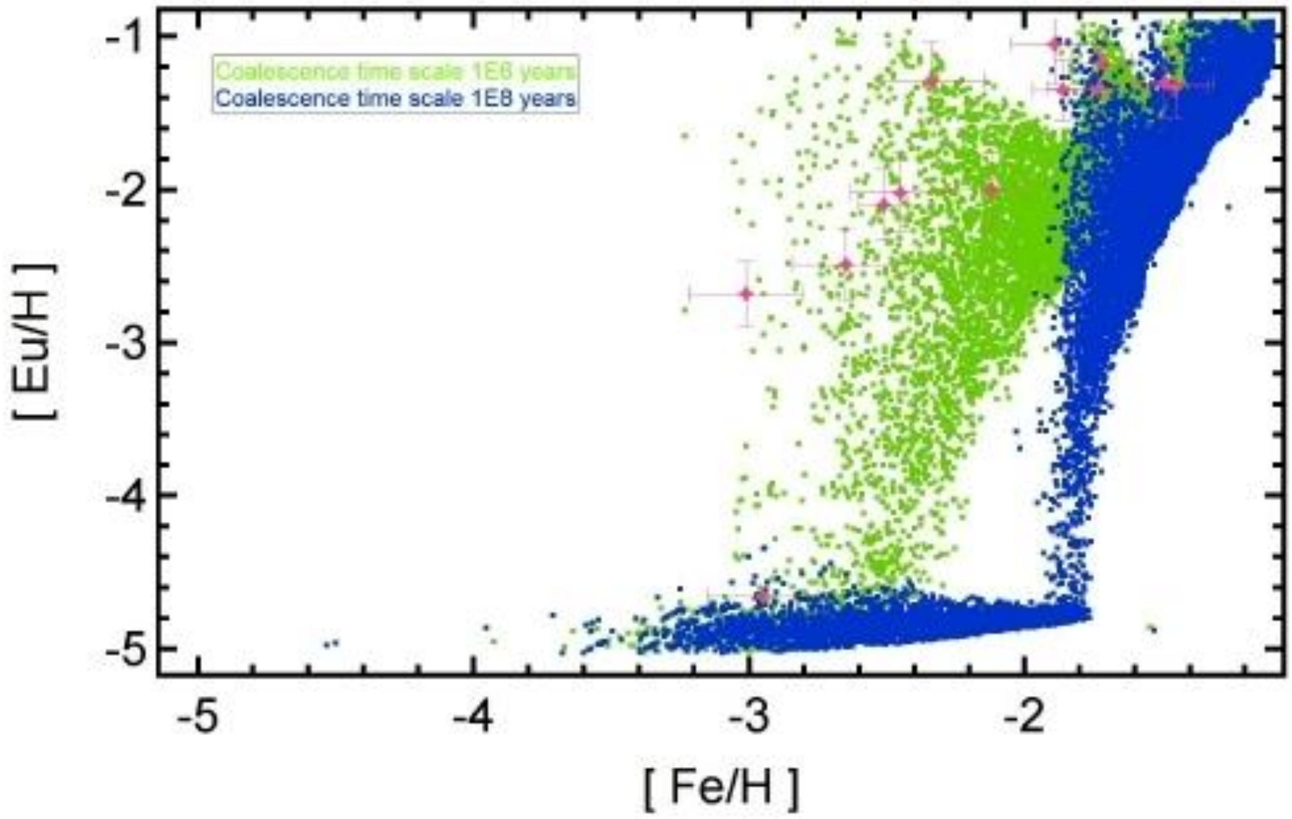


Fig. 3.7: Effect of different coalescence time scales on r-process enrichment when neutron star mergers act as exclusive r-process site. Pink stars represent observations. Green dots represent model stars with a when neutron stars mergers have a fixed coalescence time scale of the order of 10^6 years, blue dots represent model stars with a when neutron stars mergers have a fixed coalescence time scale of the order of 10^8.

Utilizing a combination of MHD-SNe and NSMs with varying probabilities, i.e. 0.005 = 0.5% of all CC-SNe, 0.007 = 0.7% of CC-SNe

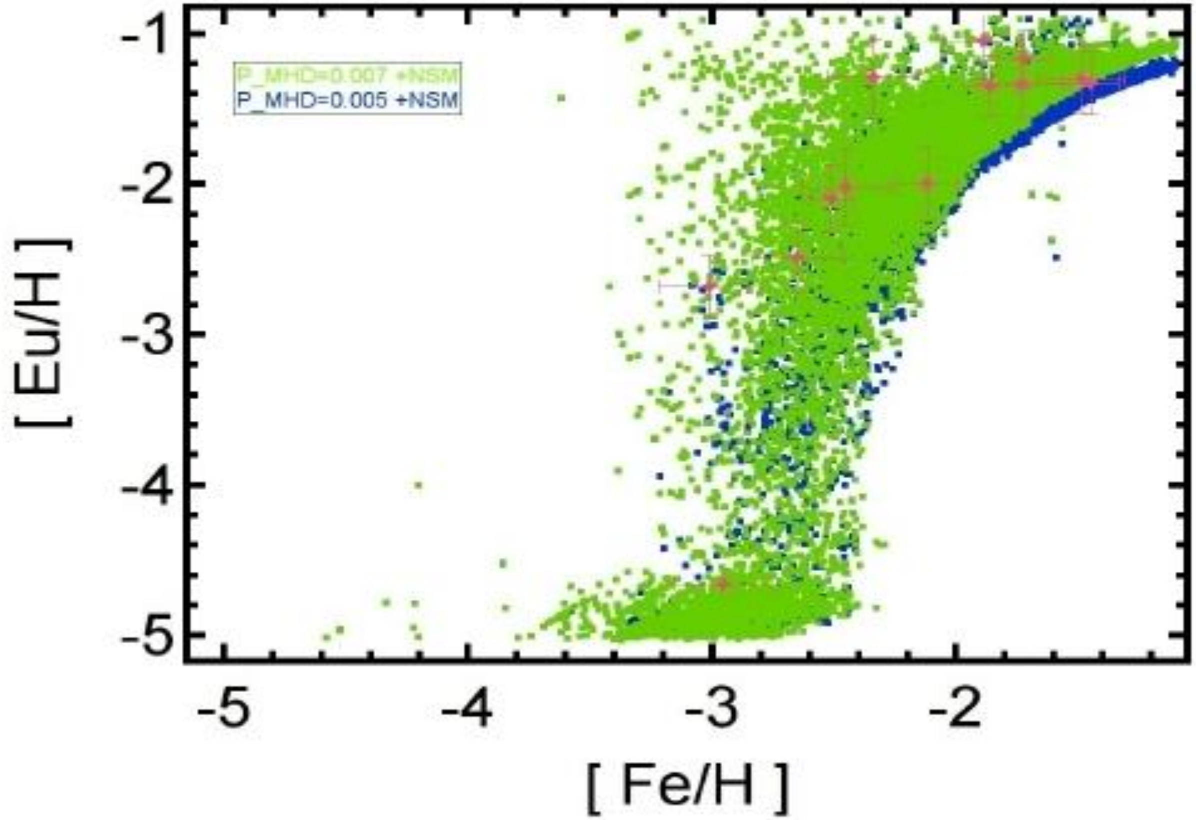


Fig. 3.12: Comaprison between high (0.007; model stars: green dots) and low (0.005; model stars: blue dots) probability of MHD-SNe when considering both MHD-SNe and NSMs (with long coalescence time scale of 10^8 years) as r-process production sites. While both models might explain the observations (pink stars) the lower MHD-SNe probability model (blue dots) explains observations better when assuming maximum observational errors, especially at higher metallicities.

Conclusions

- One can (very probably) reproduce solar system r-process abundances with NSM mergers, the abundances below A=130 might vary, due to individual Ye's obtained in NS winds or viscous disk ejecta
- MHD- (or MR magneto-rotational)-SNe can in the case of fast rotation and high magnetic fields also produce a strong r-process in polar jets; there are probably also intermediate cases leading to a weak r-process or no r-process, the latter essentially resembling regular CC-SNe
- Both types of events are rare processes with large ejection masses
- NSMs might have problems explaining the r-process history of low-metallicity stars with [Fe/H]<-2.5
- Possible solutions: large-scale turbulent mixing (to be explained and pushing results towards IMA) or different SFRs in early galactic substructures
- This can be tested in such substructures, i.e. dwarf galaxies
- In all cases (for dwarfs and the entire Galaxy) a better fit is obtained when also including MR-SNe, which might also explain the observed variation (spread) in [Eu/Fe] at lowest metallicites and also varying U/Th/Eu.