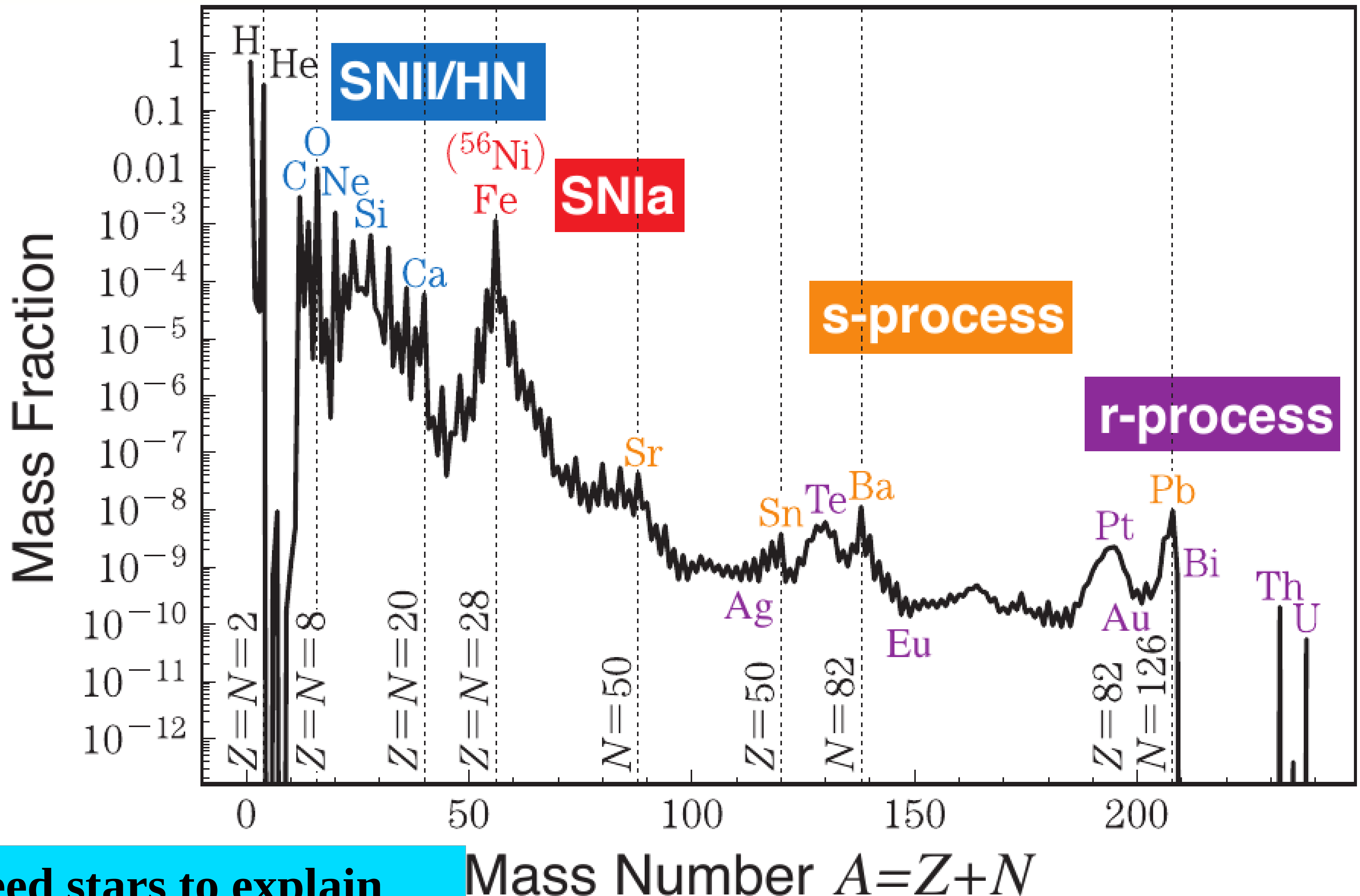
MAKING THE (HEAVIEST) ELEMENTS IN THE UNIVERSE: The r-Process in Supernovae and Neutron Star Mergers

(Astrophysical Sites, Nuclear Physics, Constraints from Galactic Evolution and Latest Radioactive Additions on Earth)

The Nuclear Astrophysics Group
Dept. of Physics
University of Basel

FNSNF UNI BASEL compstar erc European Research Council

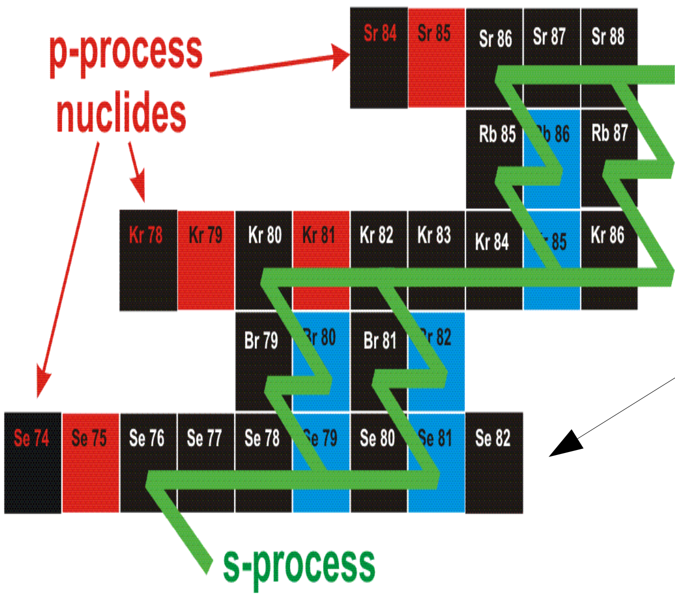
Big Bang Nucleosynthesis: 1H, 2H, 4He, 7Li



We need stars to explain the remaining elements, not made in the Big Bang!

from C. Kobayashi

s-, r-, and p-decomposition of heavy elements above Fe-group

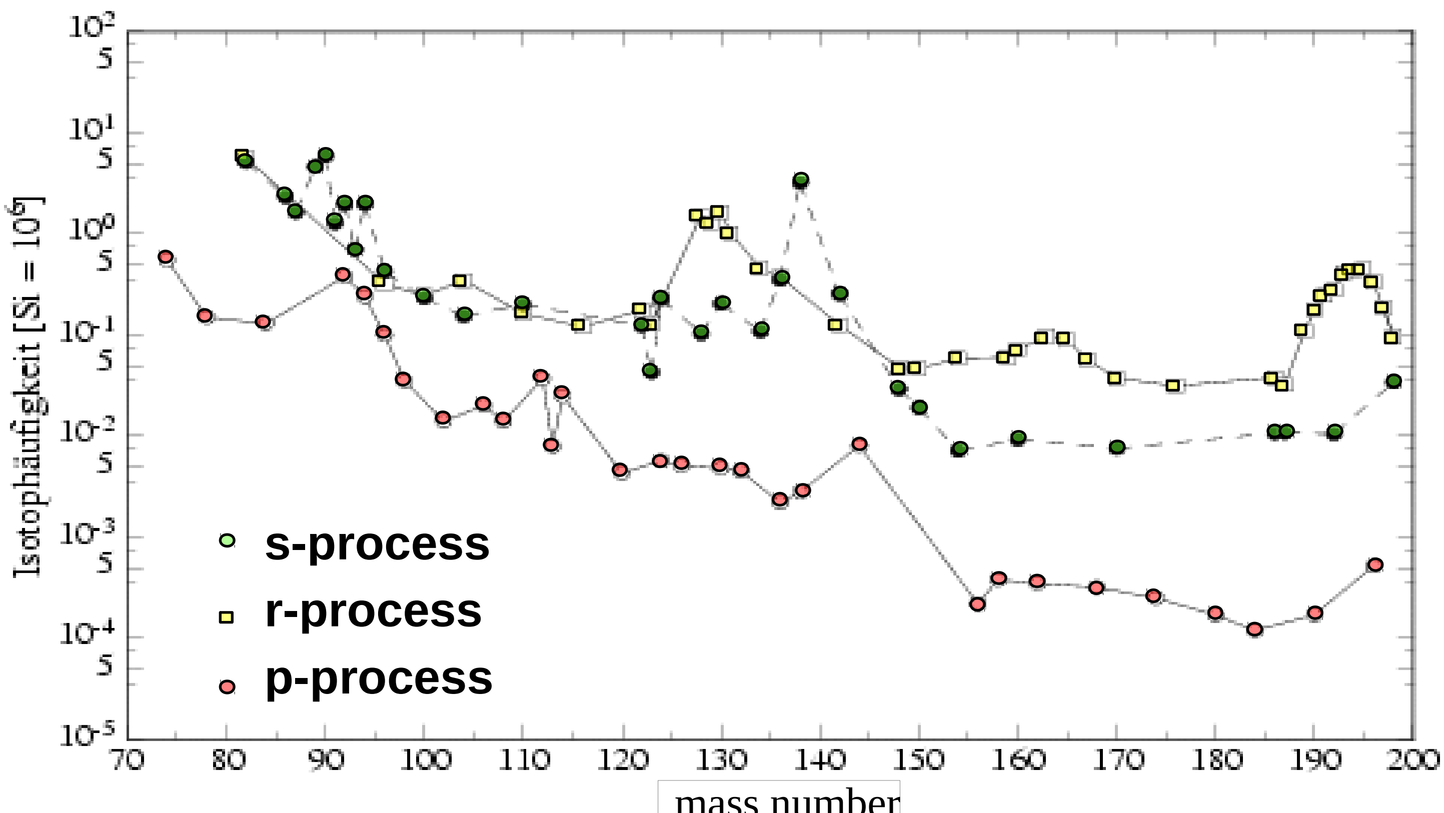


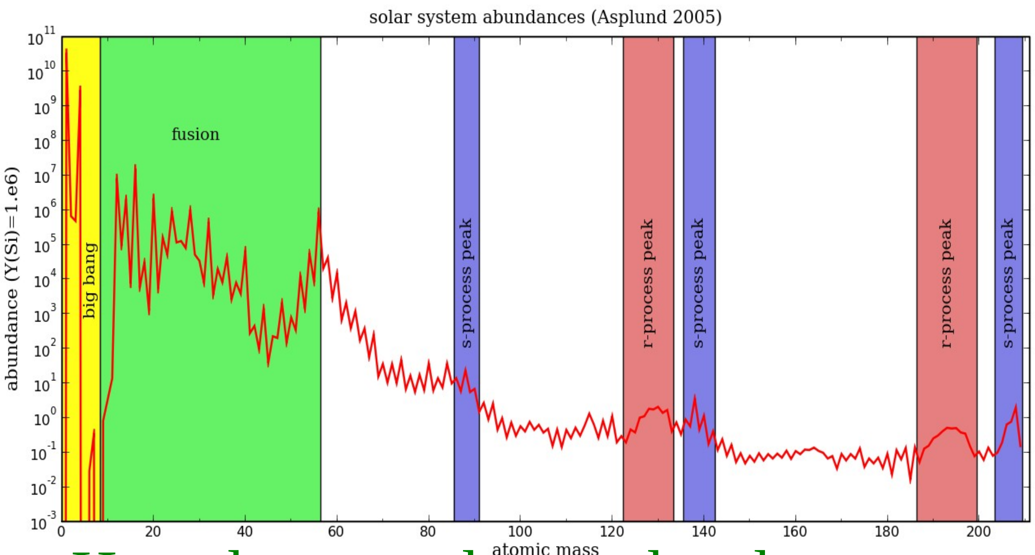
of pure s-, r-, or p-nuclei

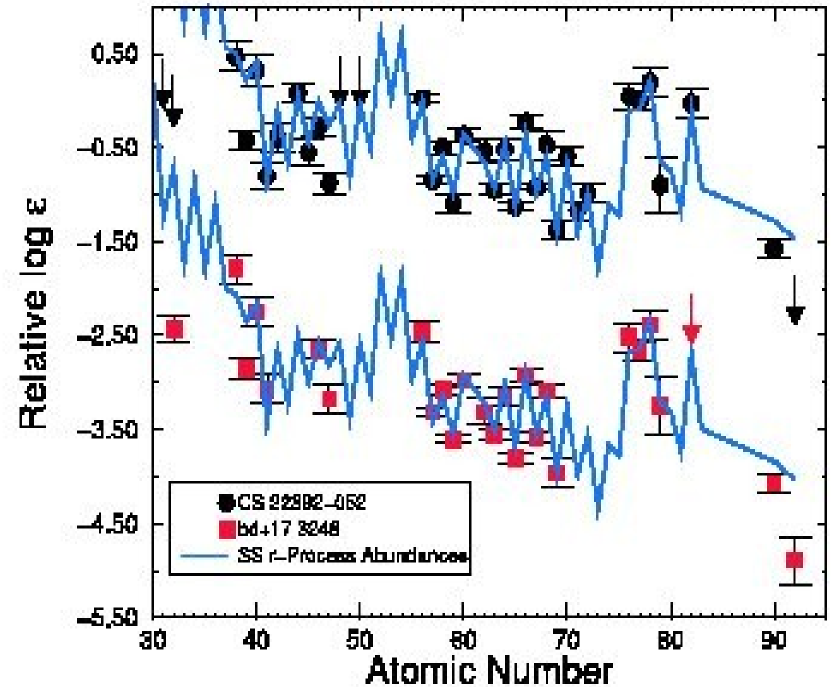
r-process

Solar abundances (Anders & Grevesse)

Abundance, normalized to Si = 10^6

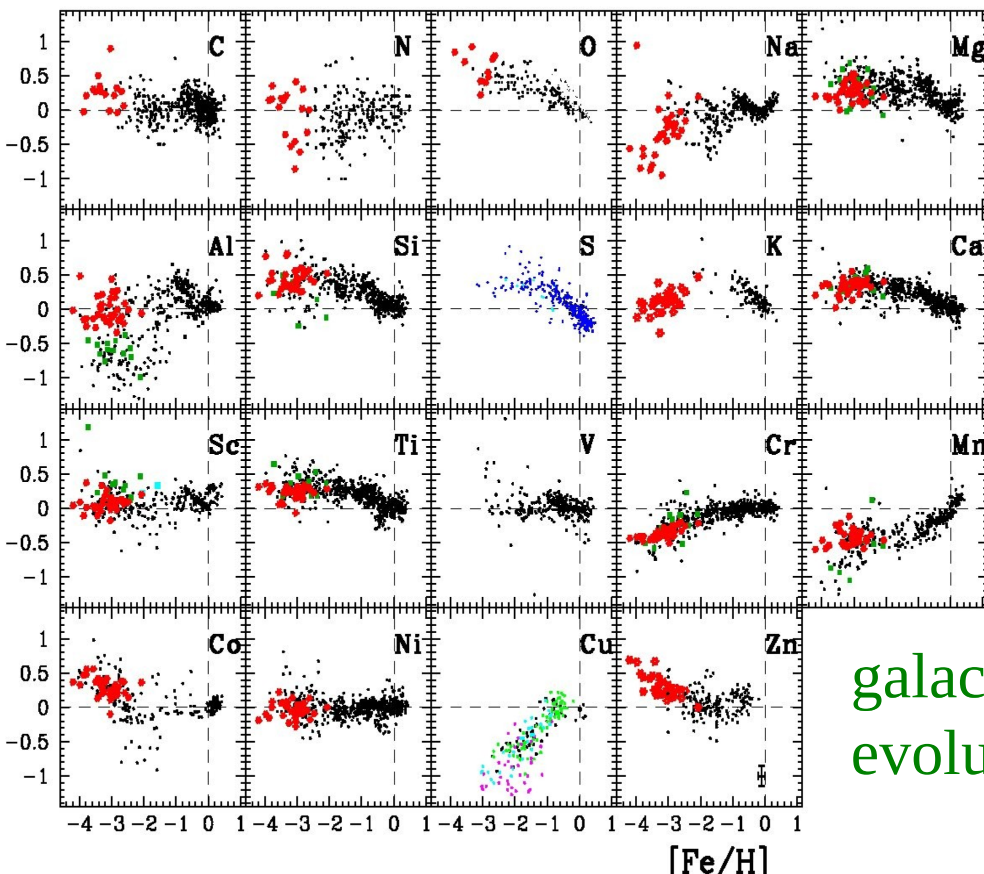




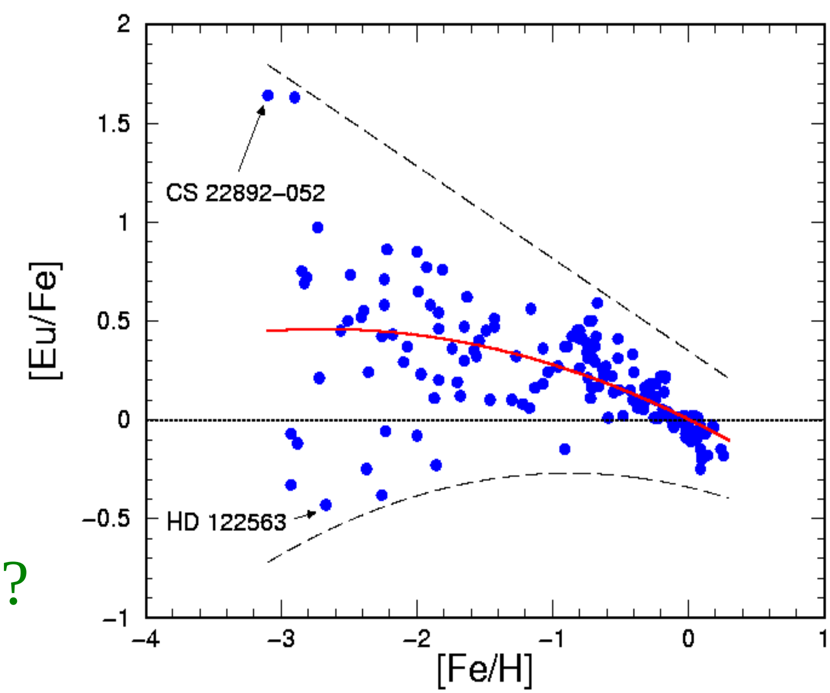


How do we understand: solar system abundances..

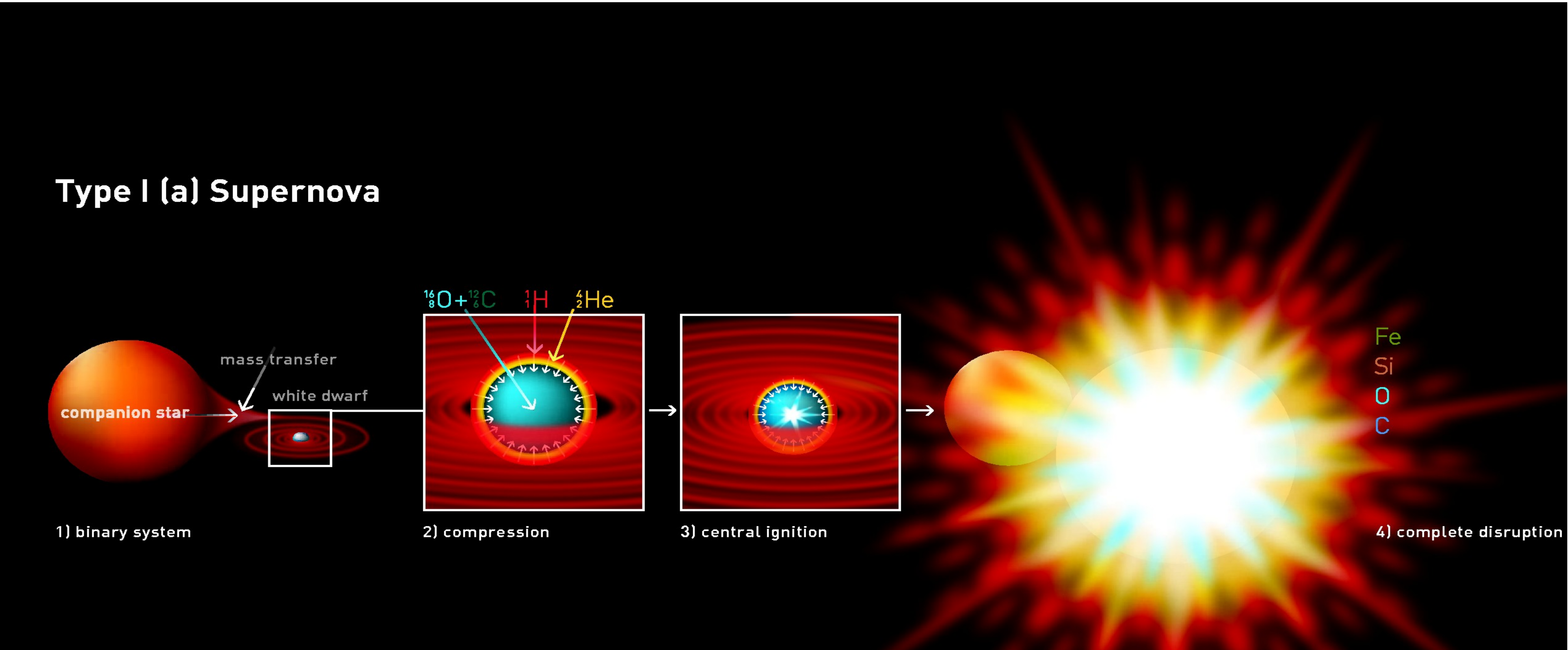
low metallicity stars ...



galactic evolution?



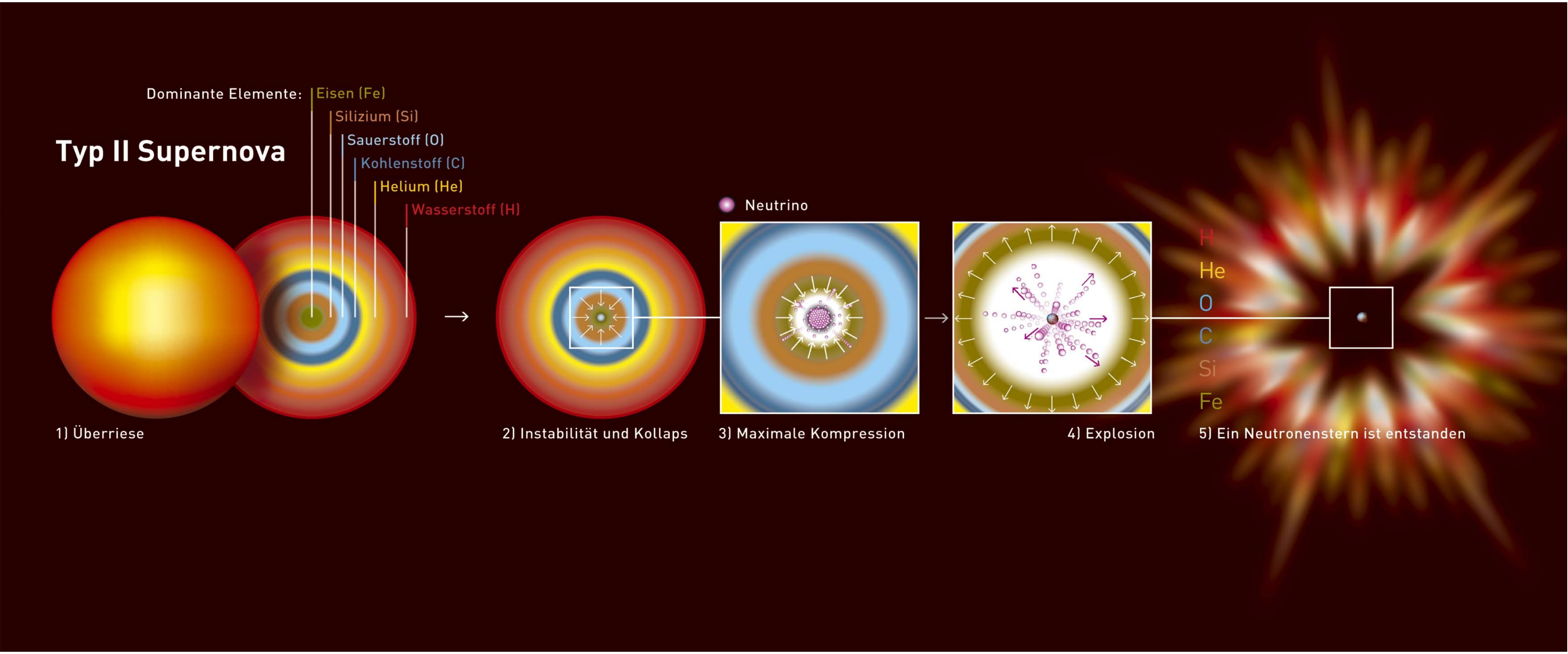
Explosions caused by accretion in binary stellar systems



binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

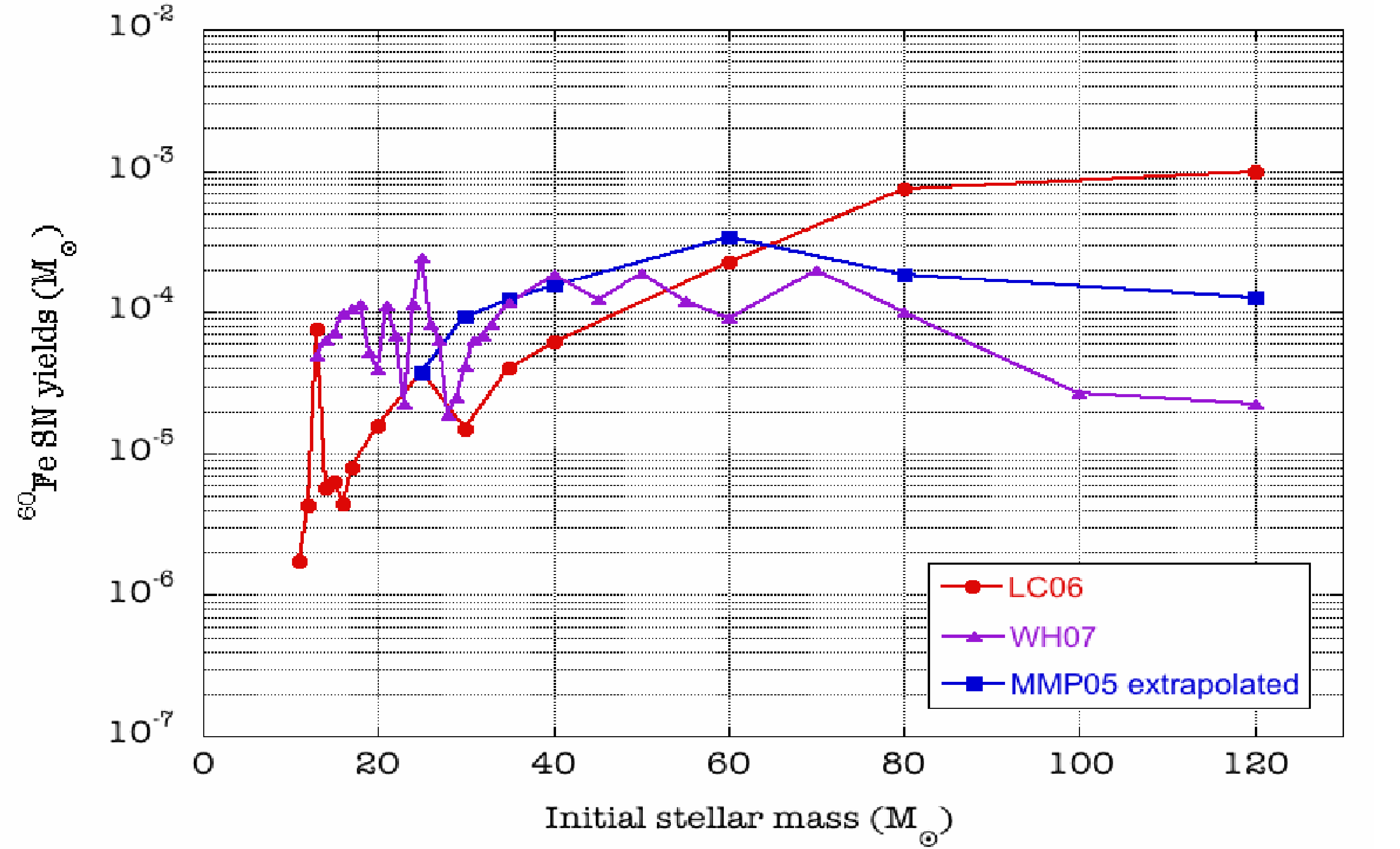
- white dwarfs (novae, **type Ia supernovae->main products Fe/Ni**)
- neutron stars (type I X-ray bursts, superbursts?)

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 heavier nuclei and the r-process?????



^{60}Fe (half-life 2.6 10^6 y) 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

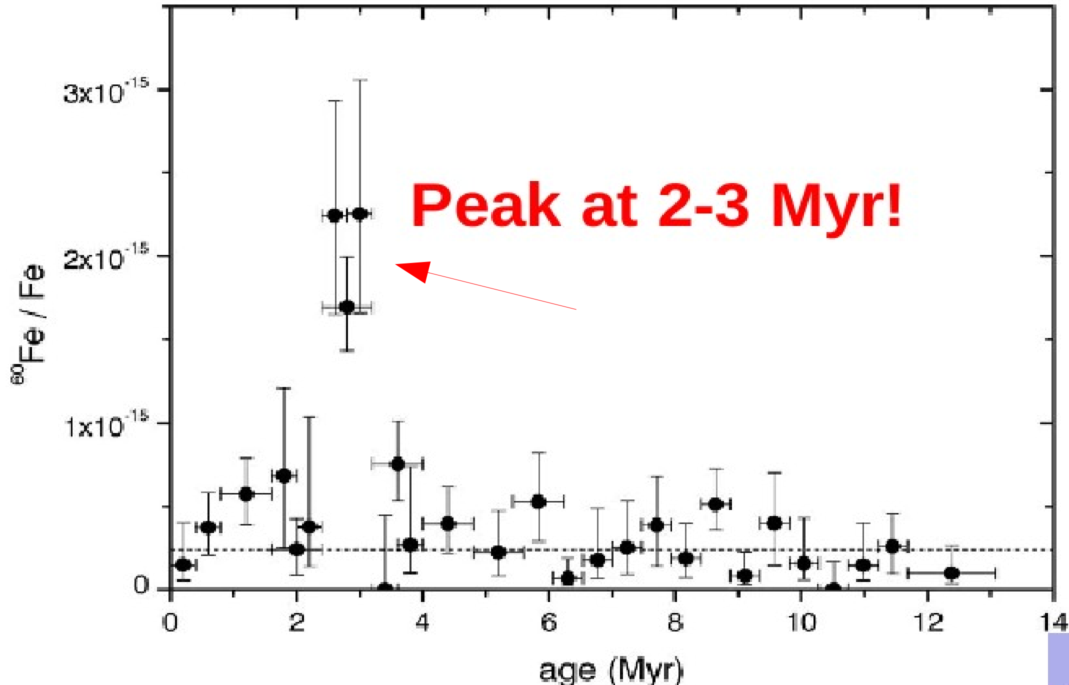
deep-sea mangenese crusts & sediments

oceanexplorer.noaa.gov

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

AMS at Munich

half-life of 2.6 My



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

background level

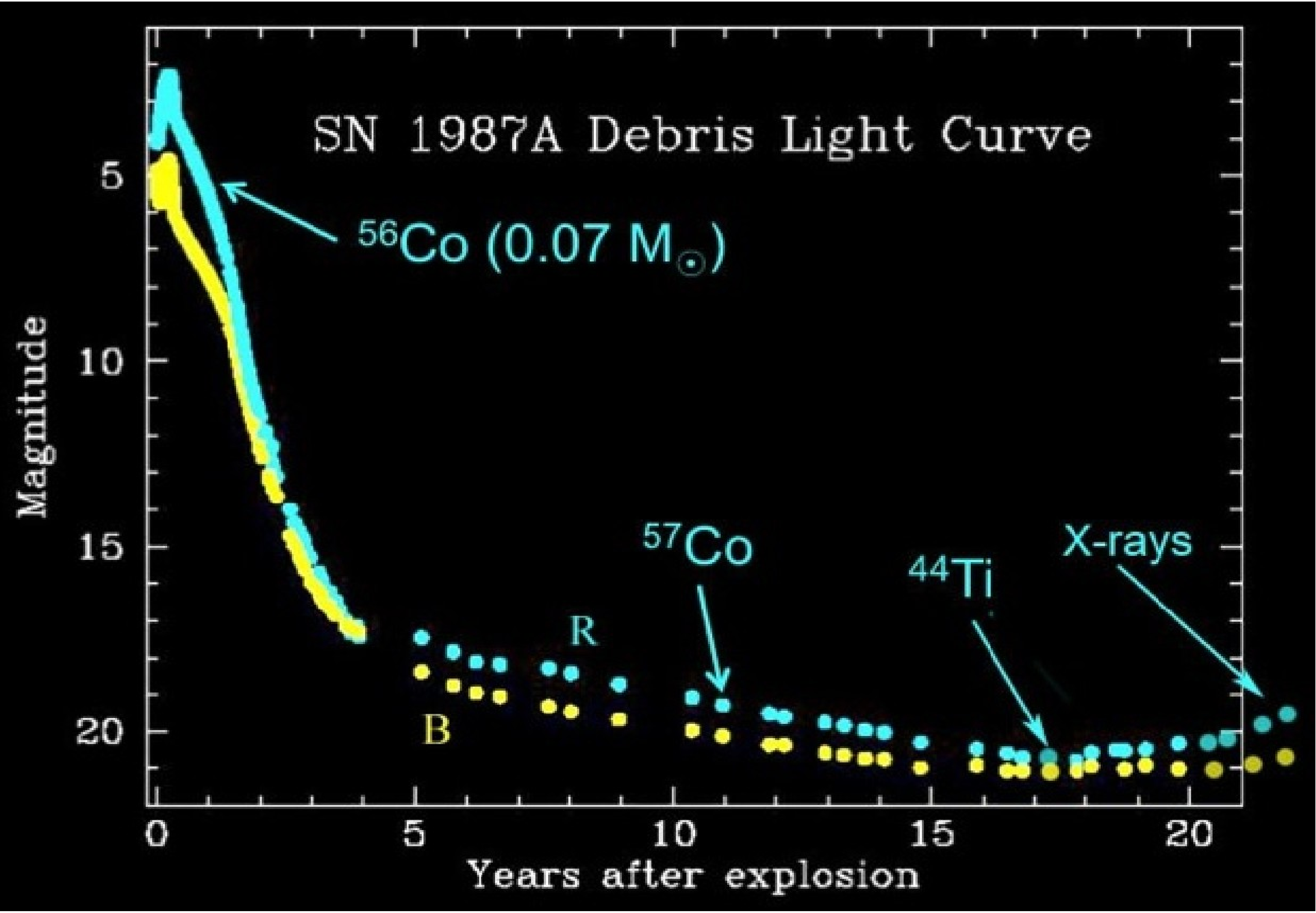
- ***the only lab yet !***

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

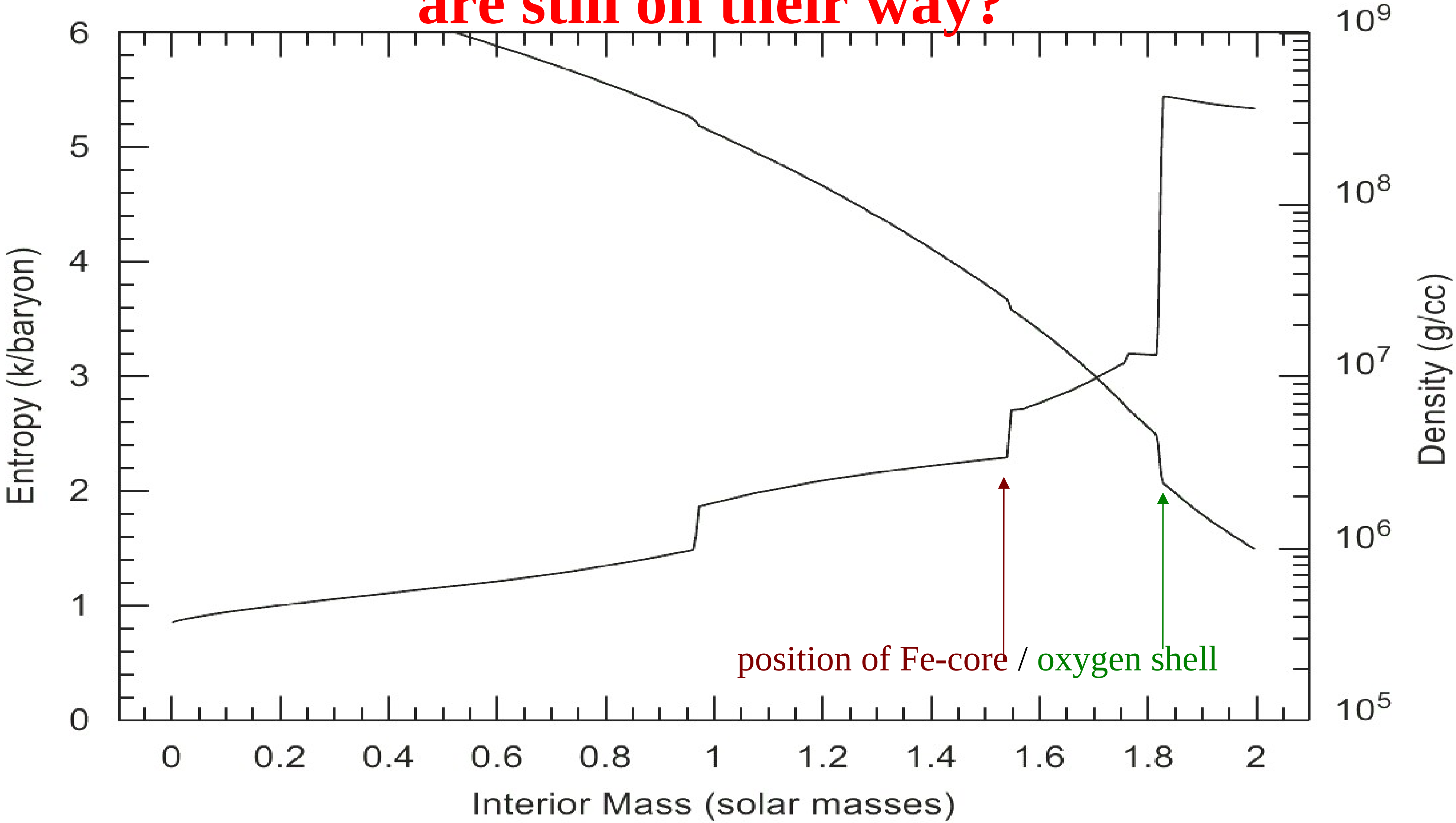
K. Knie,[1] G. Korschinek,[1,*] T. Faestermann,[1] E. A. Dorfi,[2] G. Rugel,[1,3] and A. Wallner[1,3]

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



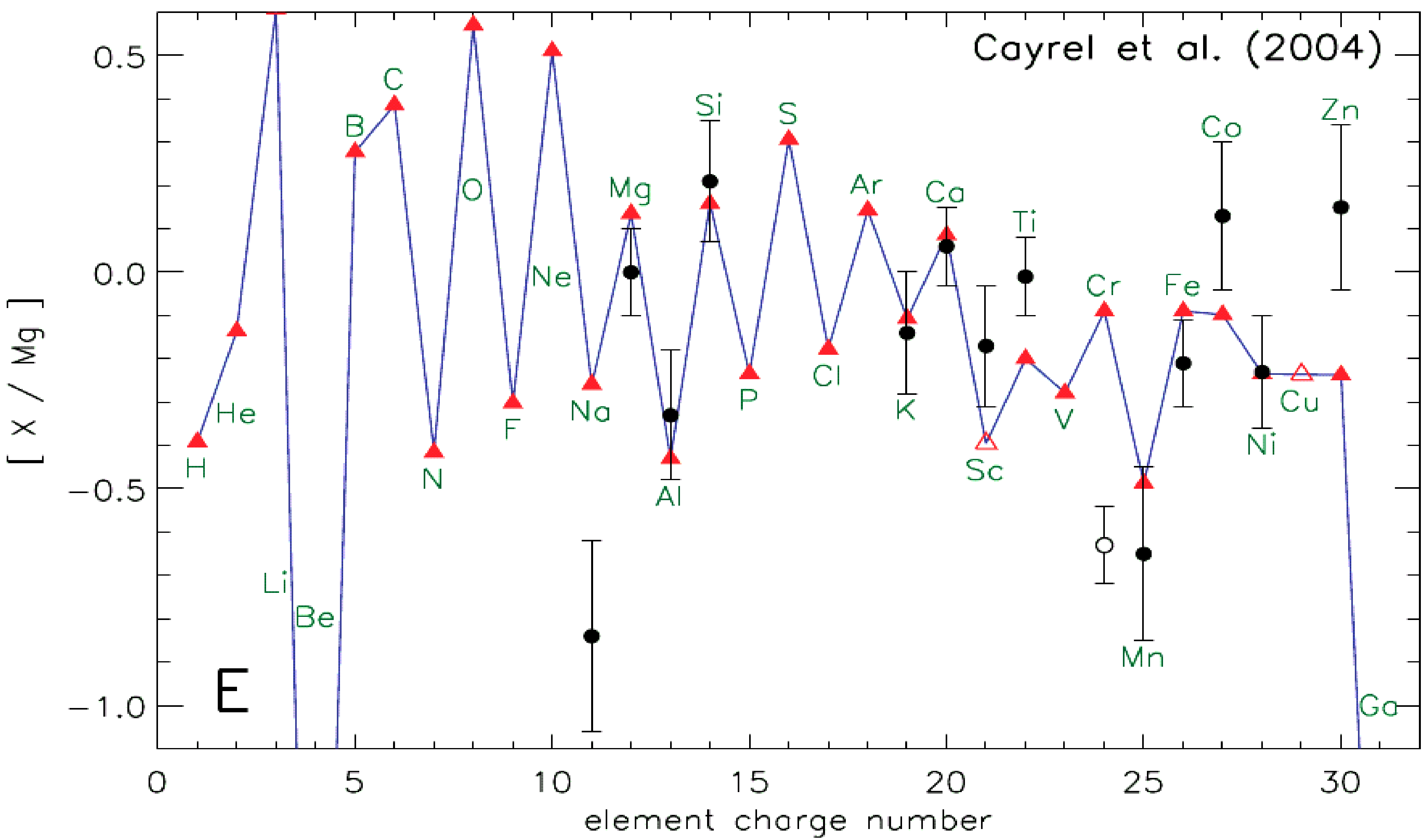
From R. McCray

How to invoke induced explosions for nucleosynthesis purposes if multi-D models are still on their way?



without a self-consistent mechanism nucleosynthesis can only be calculated with induced explosions. Woosley & Heger position a piston with 1.2B at $S=4k_B/b$, Nomoto/Umeda/Thielemann applied thermal bomb and integrate from outside until expected ^{56}Ni-yield.

Pop III yields (Heger & Woosley 2010)
Evolution of metal-free stars



Cayrel et al. (2004). taken as representative sample for low metallicity stars (representing core-collapse supernova yields). E: **“Standard” IMF integration of yields from M = 10 − 100 $M_\odot$, explosion energy E = 1.2 B** (underproduction of Sc, Ti, Co and Zn).

Nucleosynthesis problems in "induced" piston or thermal bomb models

utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of 10^{51} erg

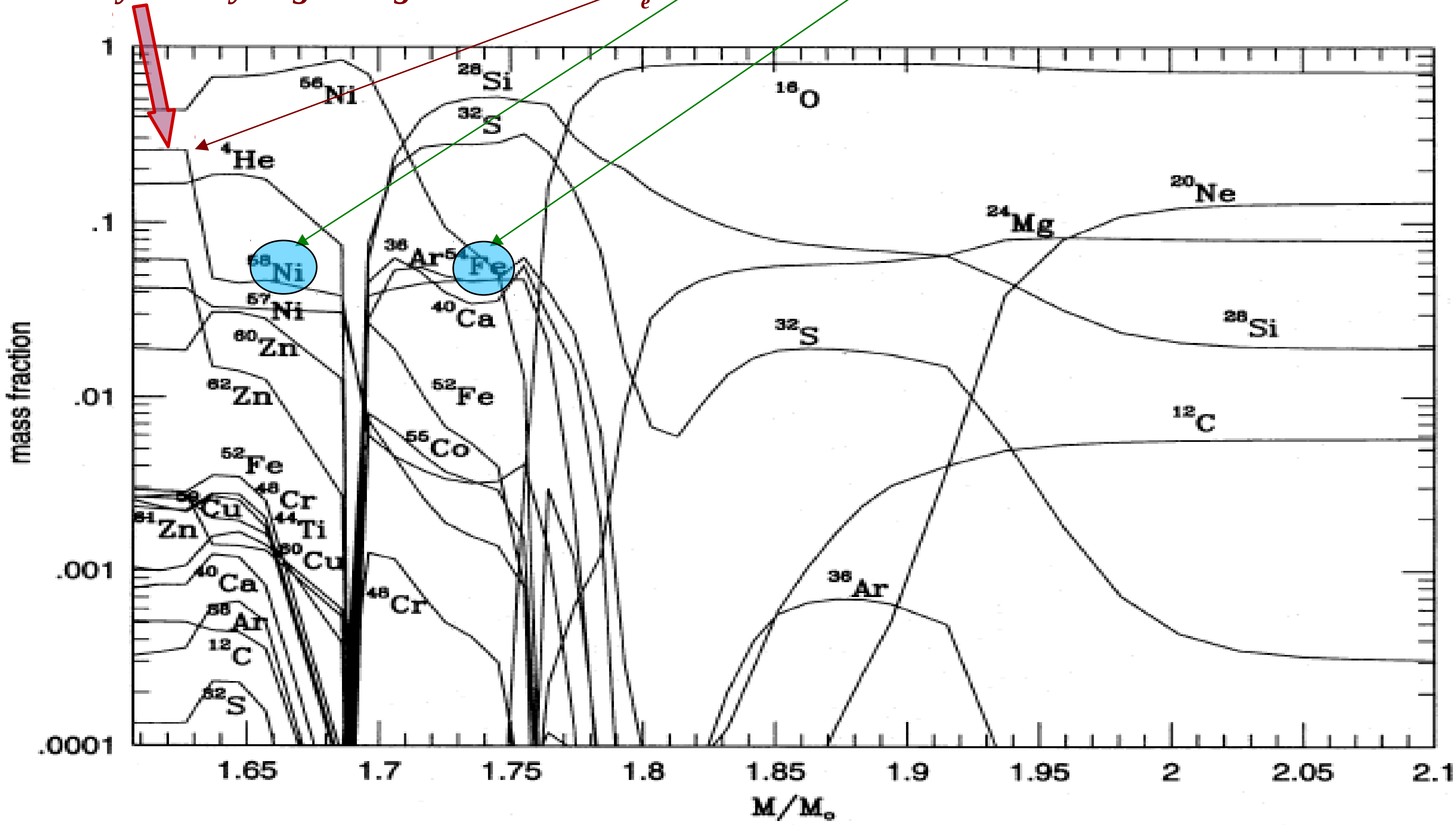
prior results made use of initial stellar structure (and Y_e!) when inducing artificial explosion. ***This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go much beyond Ni!***

- high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe), measures energy/ entropy of explosion
- Y_e determines Fe-group isotopes.

Two aspects:

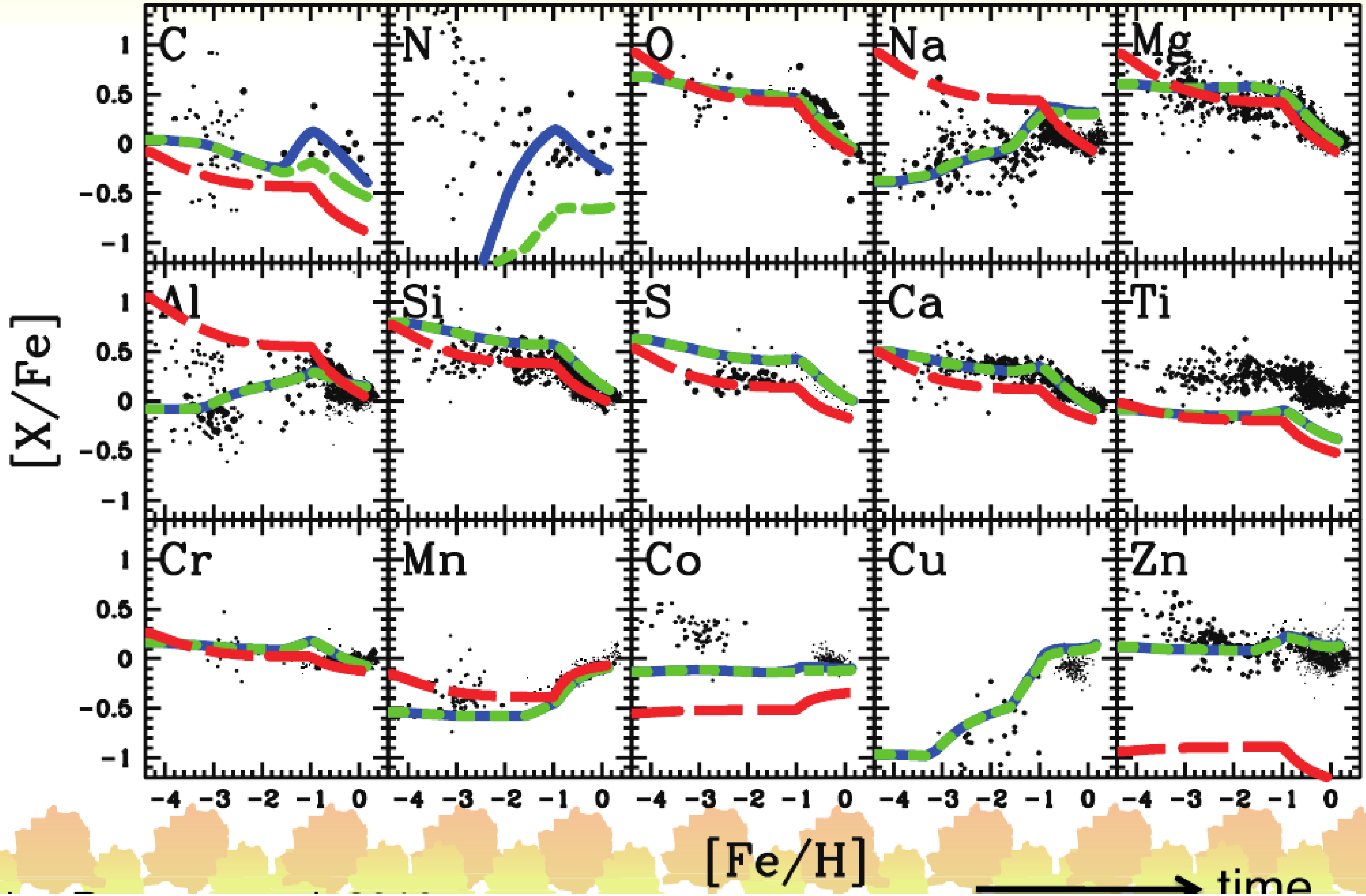
(i) even in spherical symmetry neglecting neutrinos -> Y_e

(ii) multi-D



[X/Fe]-[Fe/H] relations

SN+HN+AGB (CK, Karakas, Umeda 2011), SN+HN; old SN yields only



from C. Kobayashi 2015

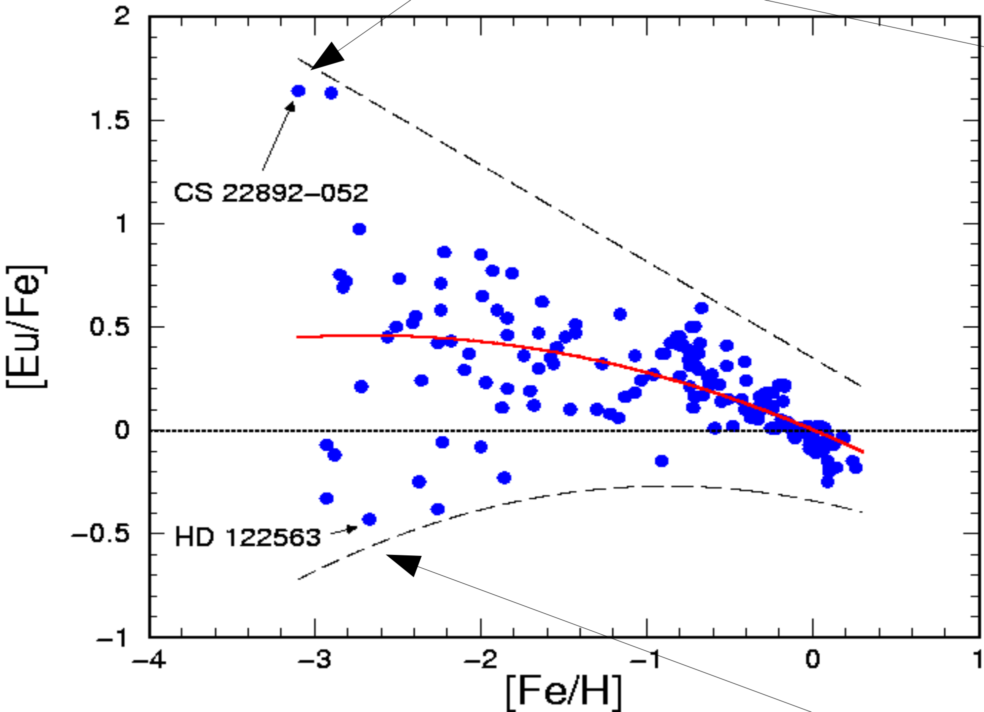
but where does the r-process take place??

Observational Constraints on r-Process Sites

abundances in “low metallicity stars”

Sneden-type stars, identical to solar r-process

N-star mergers, jets, black hole accreation disks?
But which of these for [Fe/H]<-3???



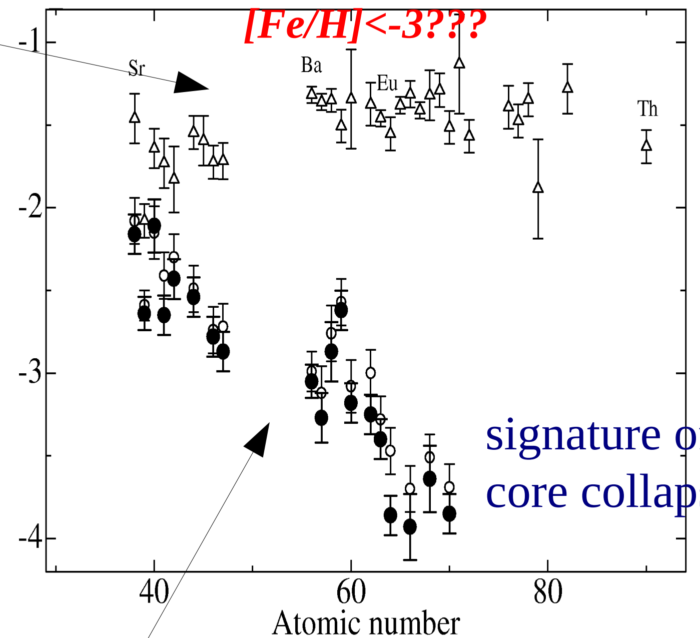


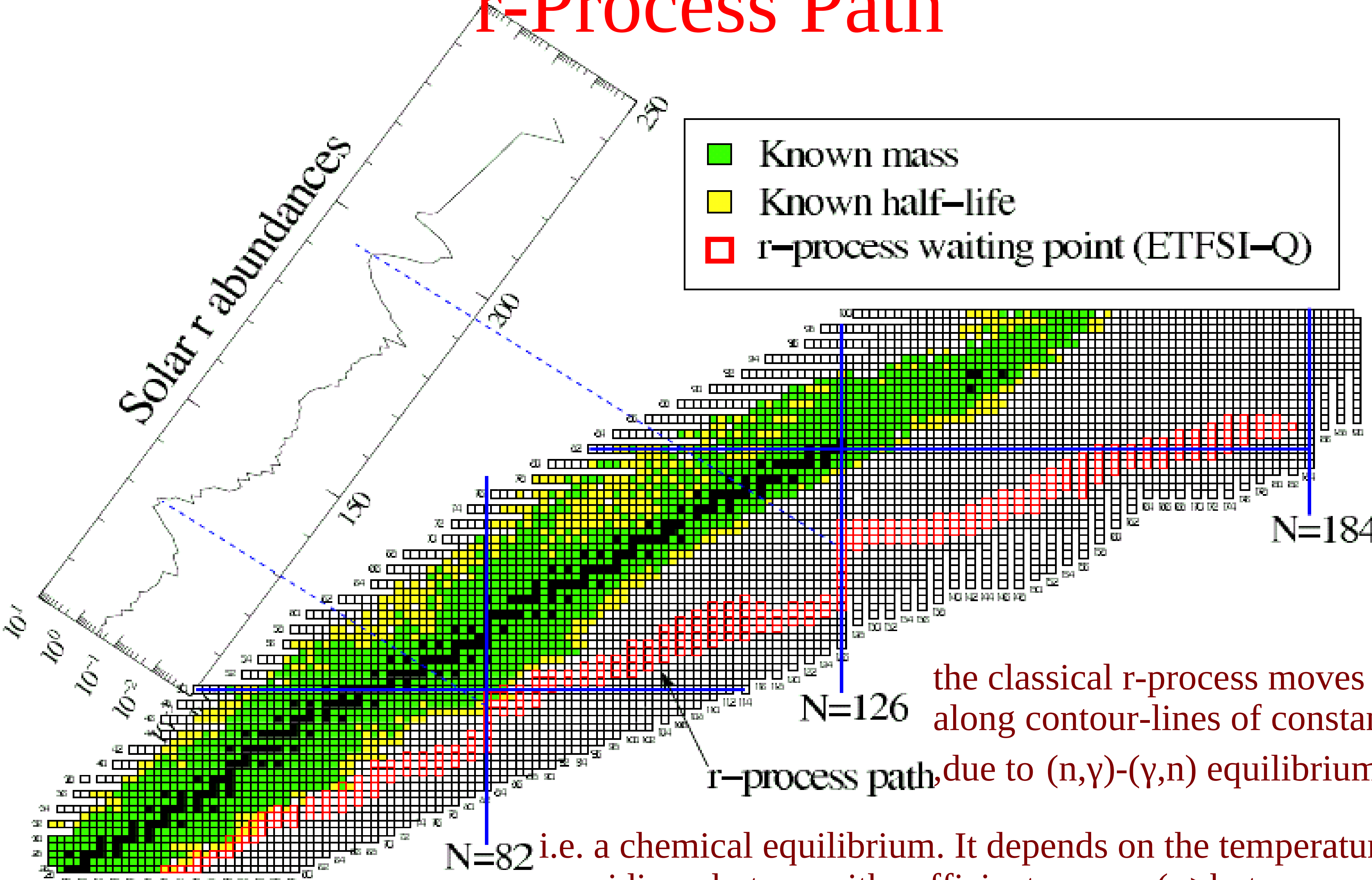
Fig. 5.— Logarithmic differences from the solar system r-process pattern ($\log\varepsilon_{\mathrm{object}} - \log\varepsilon_{\mathrm{solar-r}}$). The open triangles mean CS 22892-052, the open circles mean HD 122563, and the filled circles mean HD 88609.

signature of regular core collapse SNe?

Honda-type stars, showing a weak r-process

Roederer and Cowan (2013)

r-Process Path

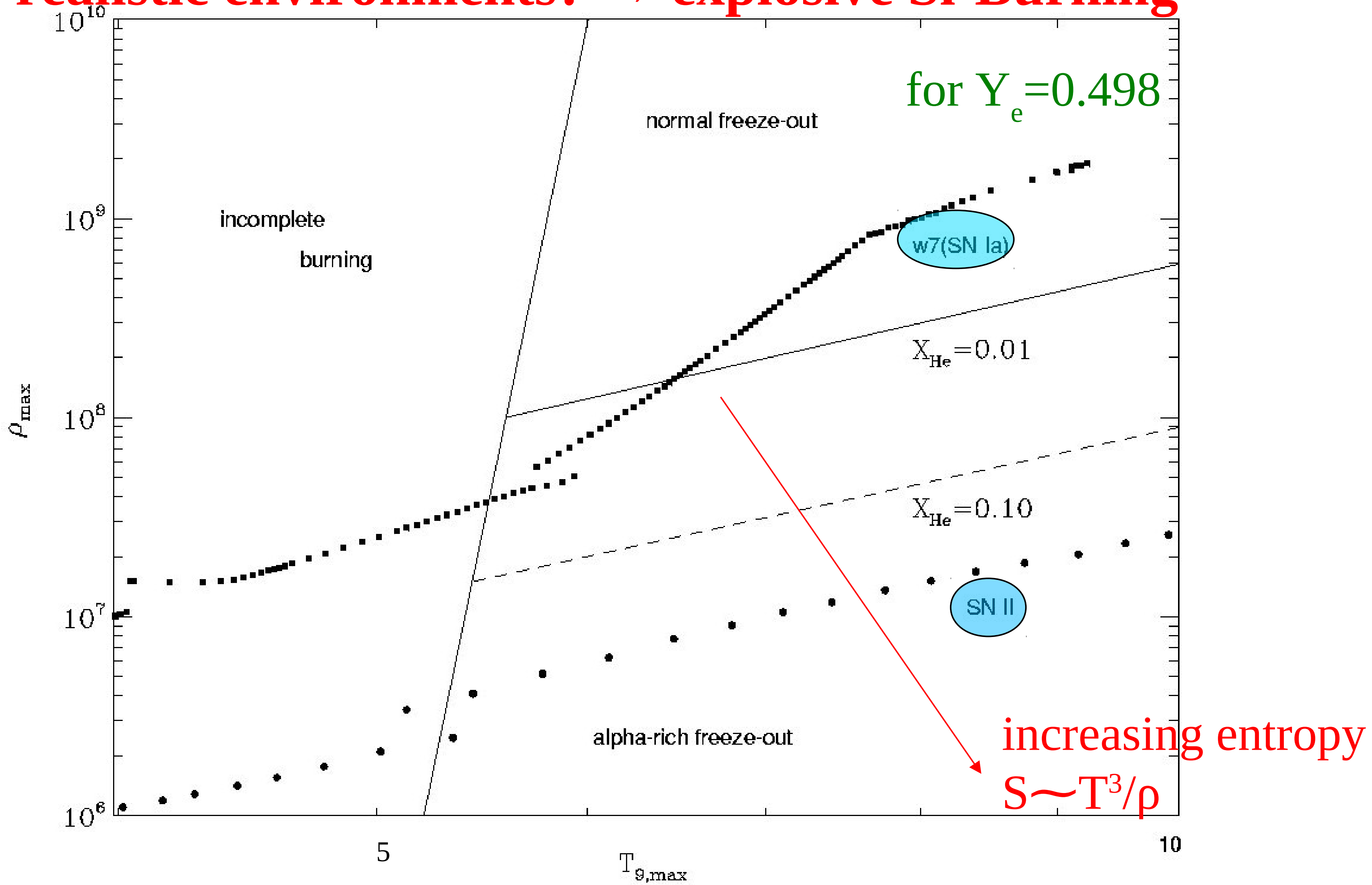


the classical r-process moves along contour-lines of constant S_n due to (n,γ)-(γ,n) equilibrium

i.e. a chemical equilibrium. It 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

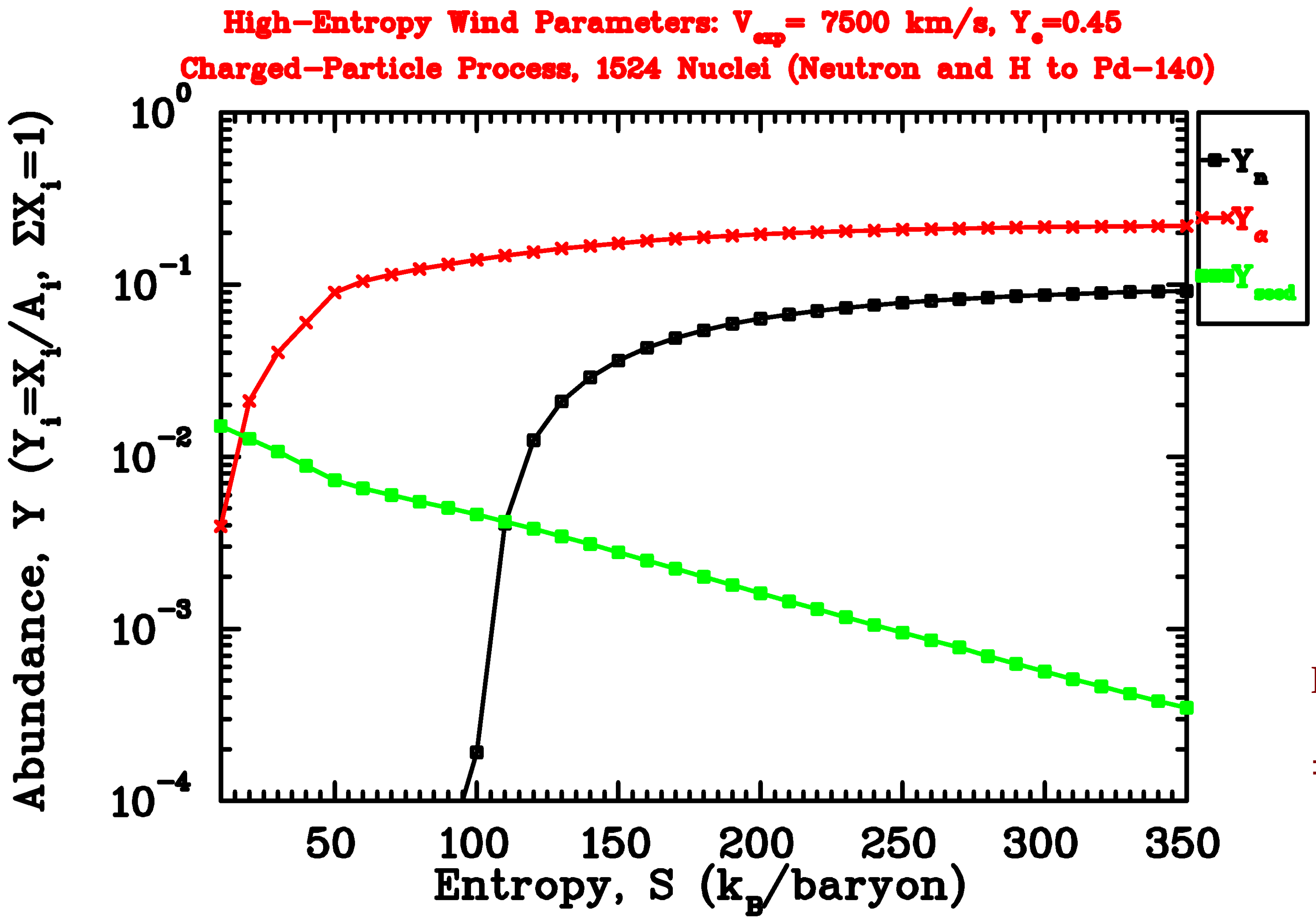
But how can one obtain the required neutron densities in realistic environments? → explosive Si-Burning



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 a function of entropy

Farouqi et al. (2010)



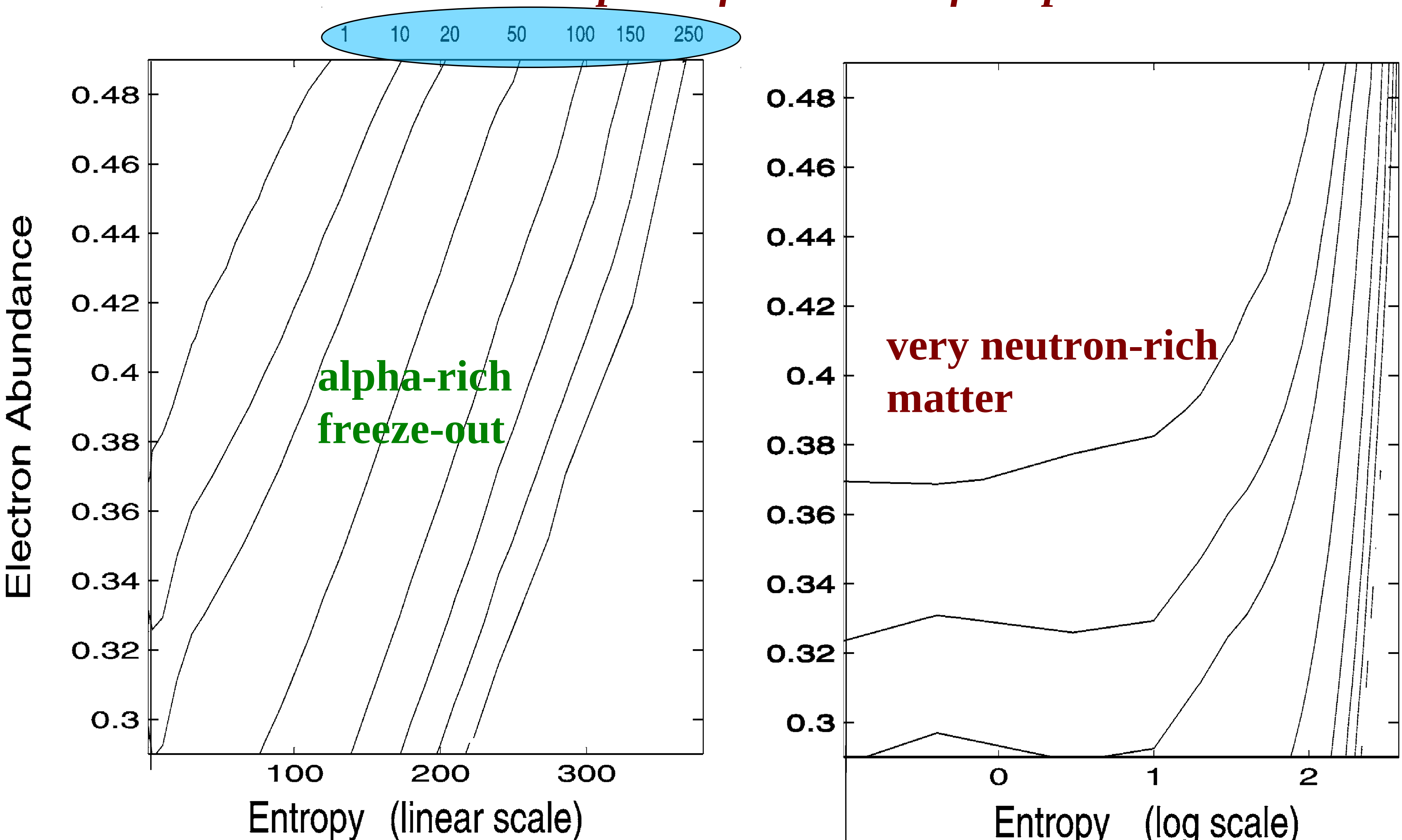
n/seed

$=Y_n/Y_{seed}$

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



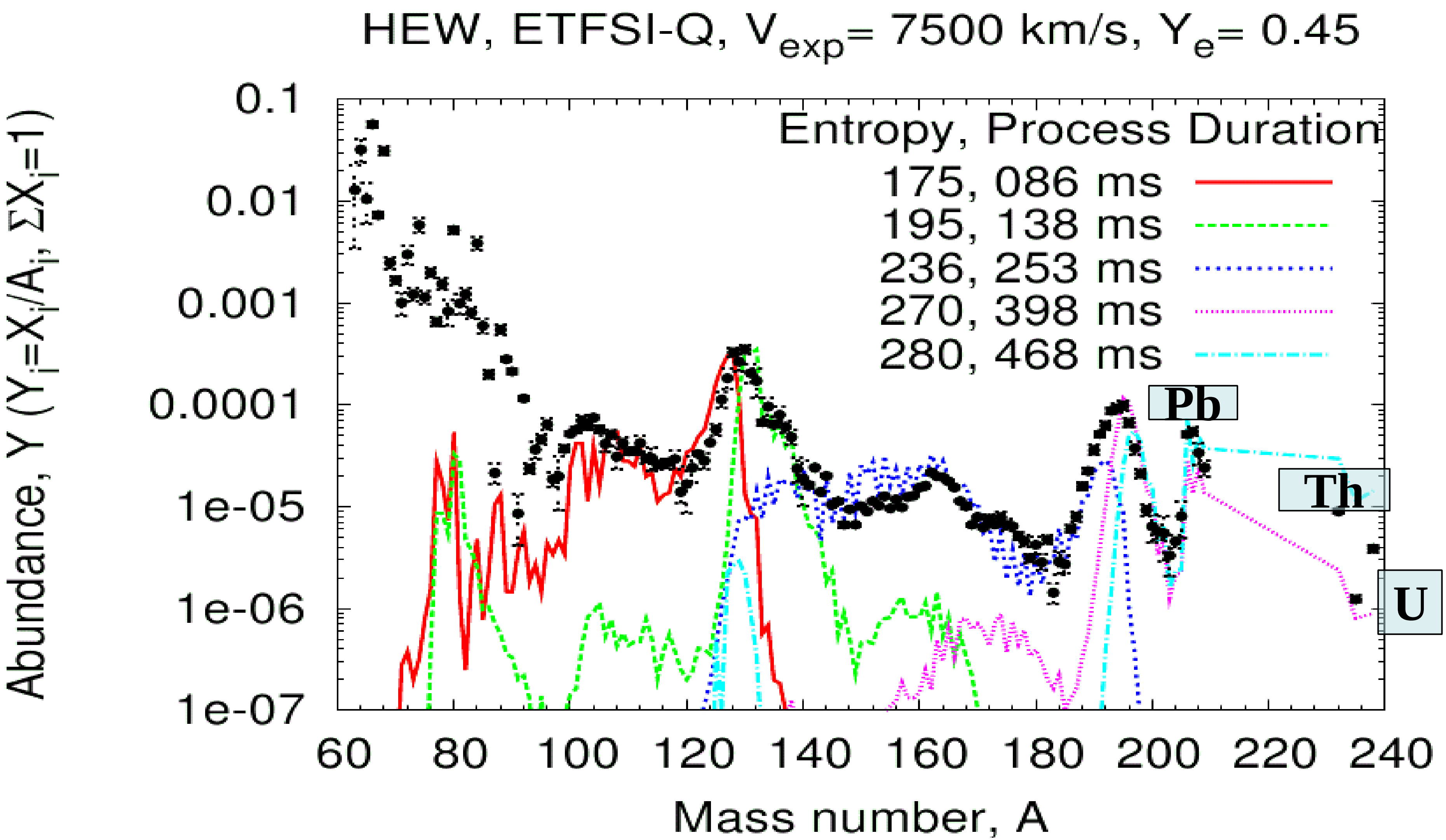
neutrino wind?

Freiburghaus et al. (1999)

Neutron star mergers and polar jets?

Individual Entropy Components

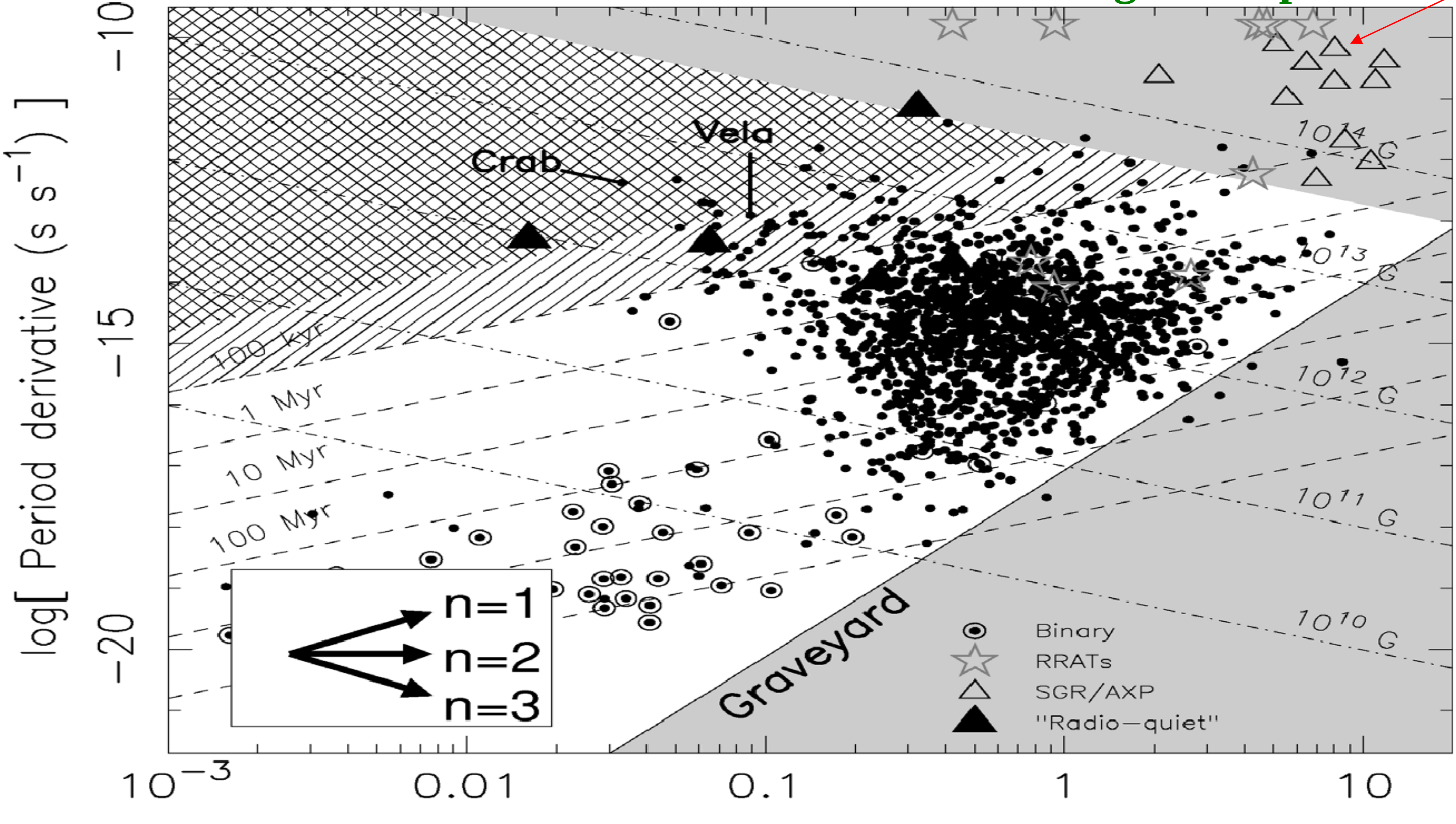
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in



A parameter game: Assuming entropy S, initial Ye, and expansion velocity (related to an expansion time scale) of the hot matter. With our present knowledge such Ye's and entropies cannot be attained in regular CCSNe!

M. Kramer (2009)

Resulting from special SNe?



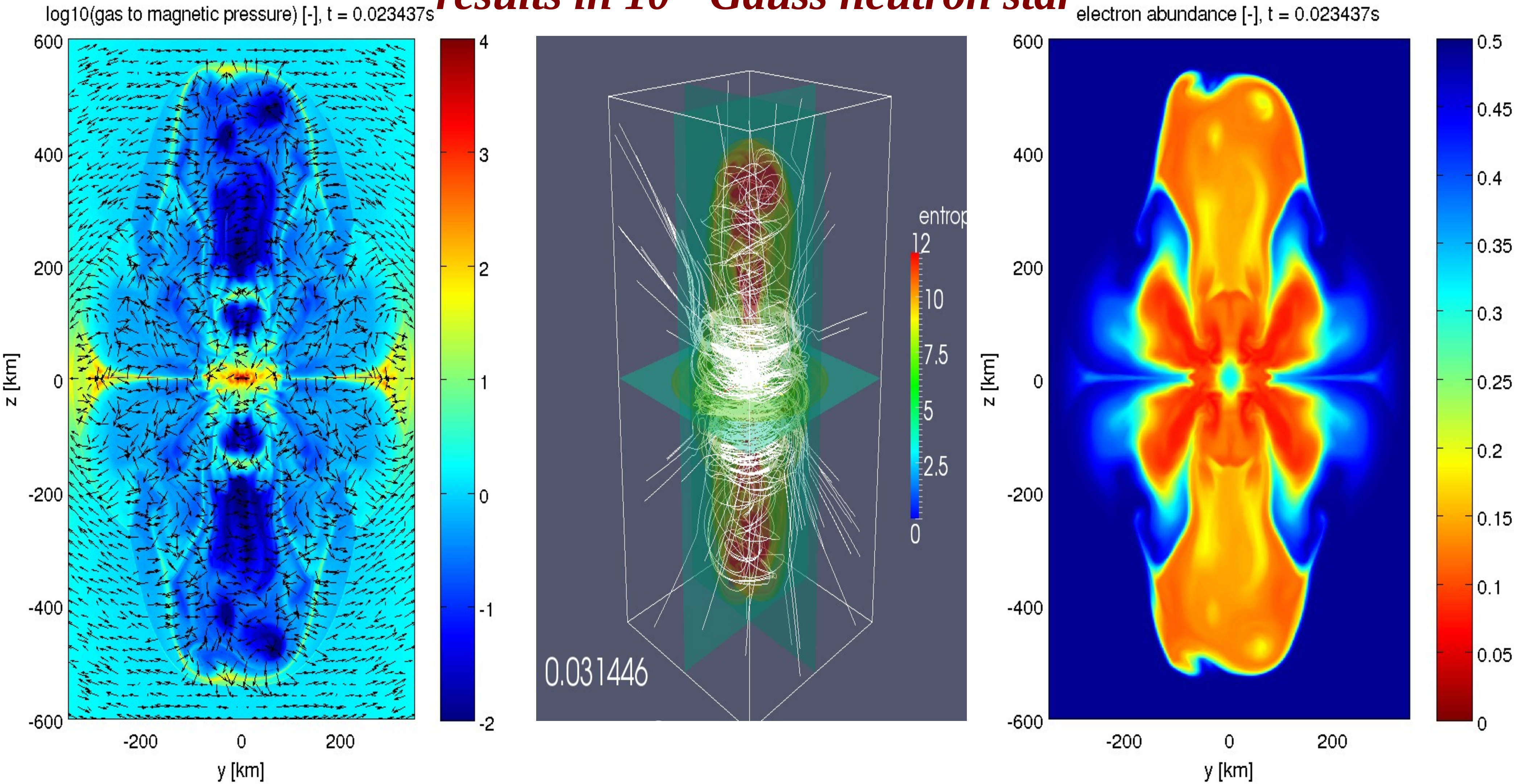
Neutron stars observed with 10^{15}G

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 Magn. 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,

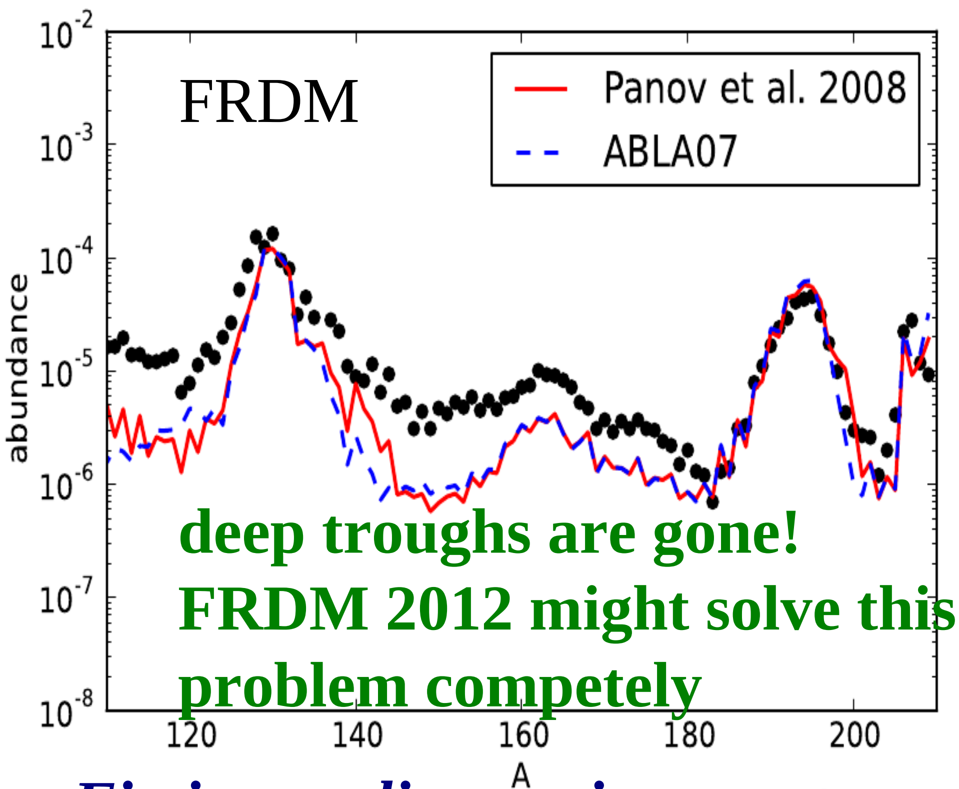
results in 10^{15} Gauss neutron star



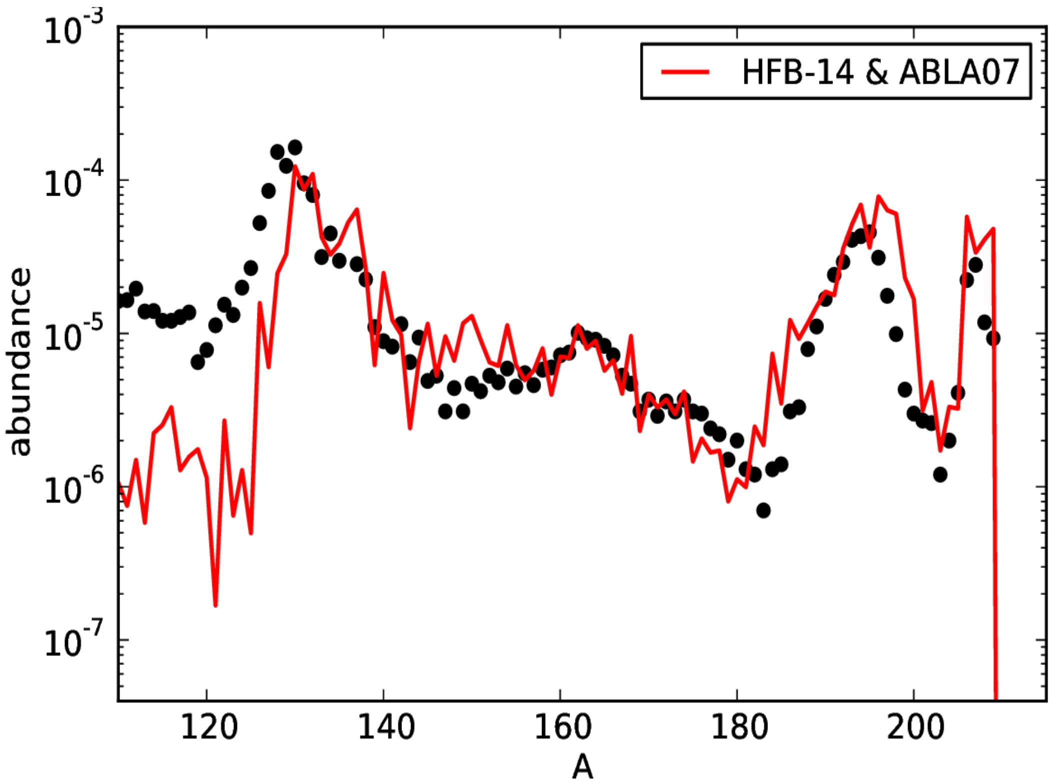
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2015 (resulting SN explosion with central magnetars are observed – Greiner et al. 2015, Nature)

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

(Eichler et al. 2015)



deep troughs are gone!
FRDM 2012 might solve this problem competely



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

What is the site of the r-process(es)? All options?

- **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!)***

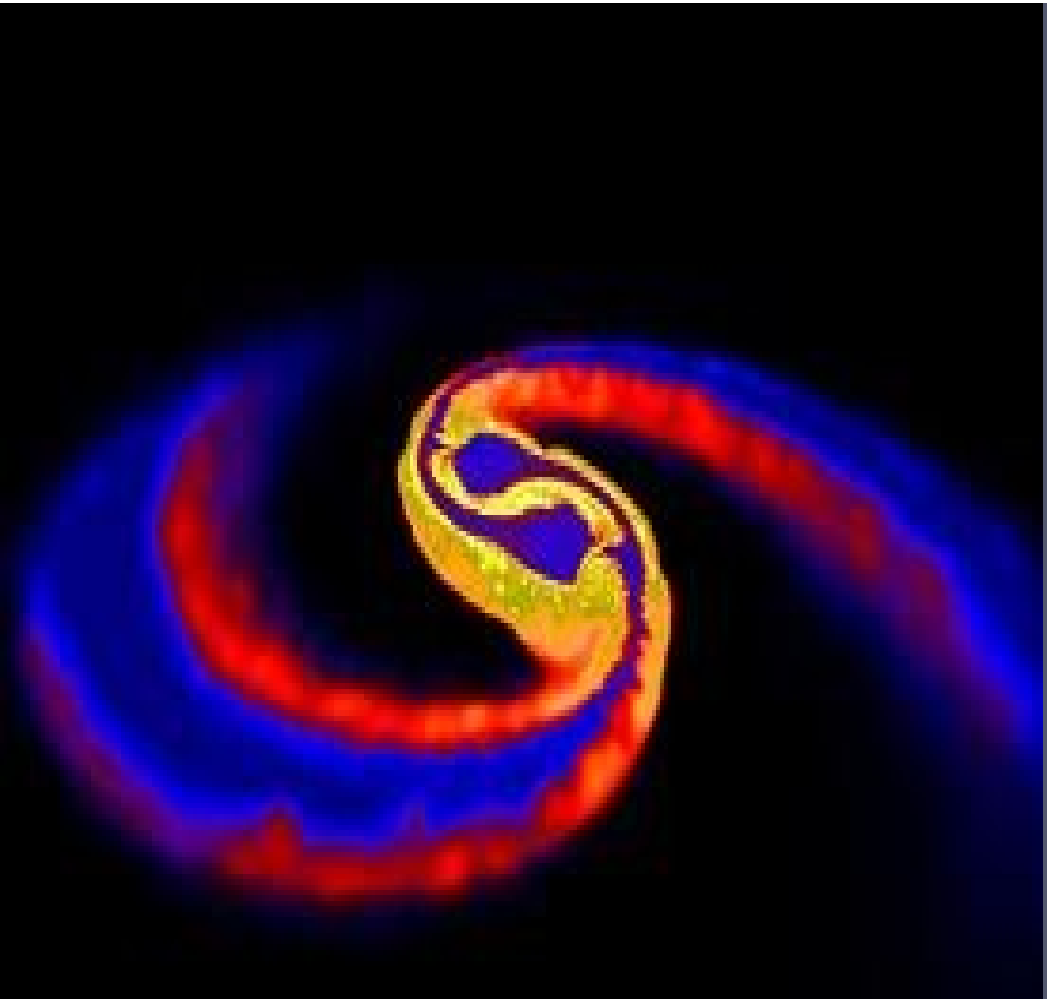
- SNe due to quark-hadron phase transition *Fischer, Nishimura, FKT (if? weak!)*

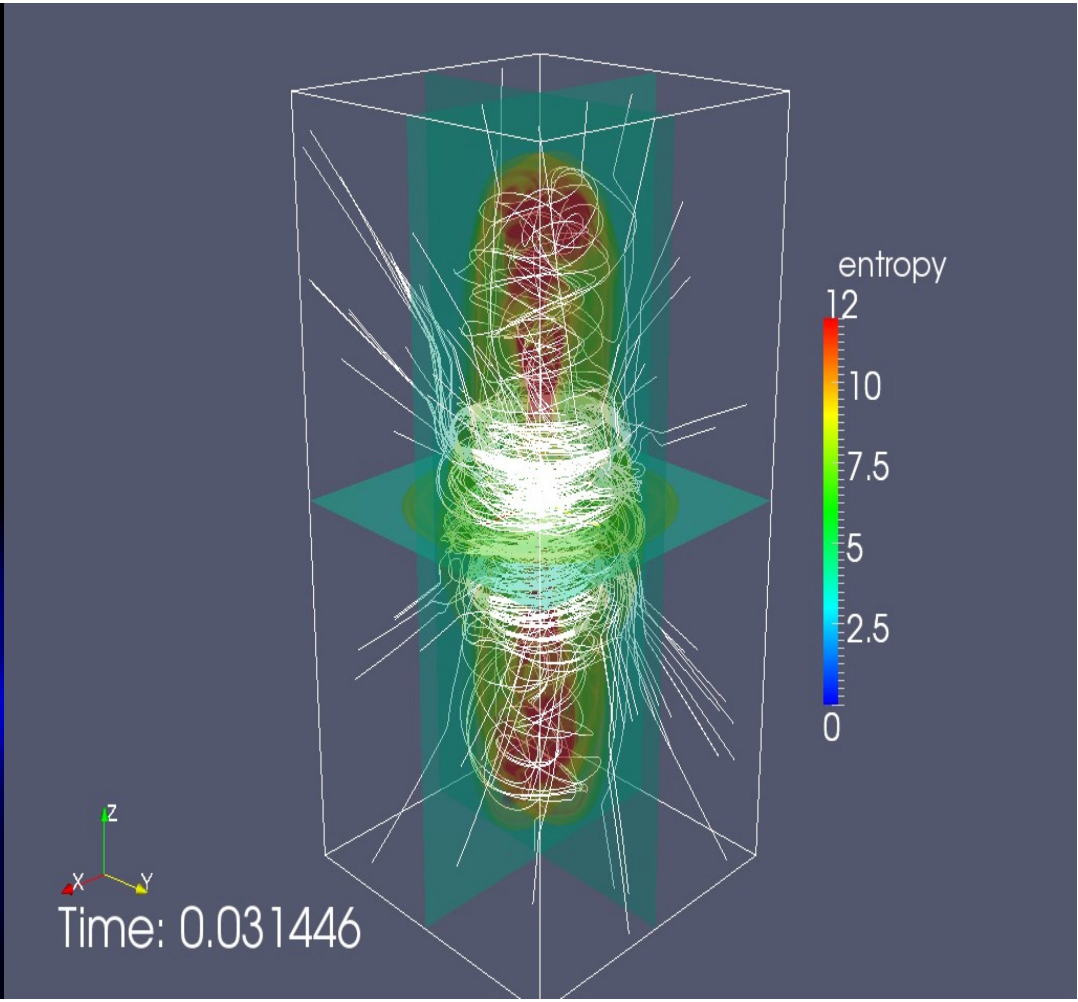
- **Neutron Star Mergers?** ***Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin, Wanajo, Just, Martin, Perego***
  Black Hole Accretion Disks (massive stars as well as neutron star and neutron star BH mergers, neutrino properties) ***MacLaughlin,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

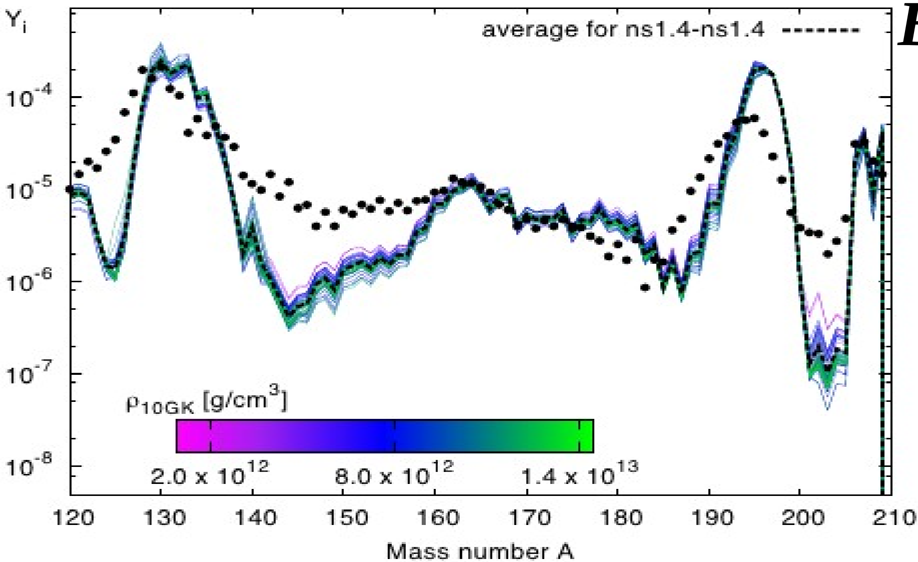
Which events contribute to the strong r-Process??





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

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...

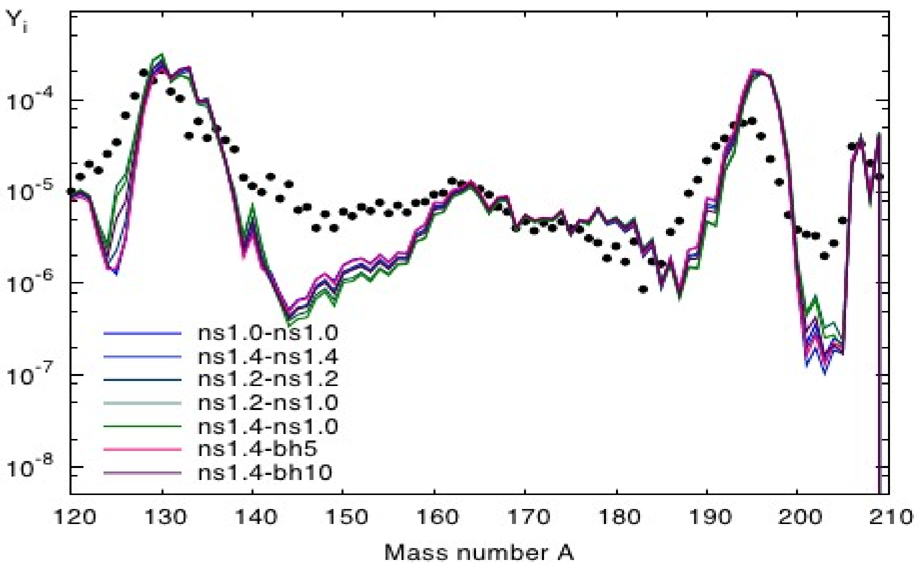


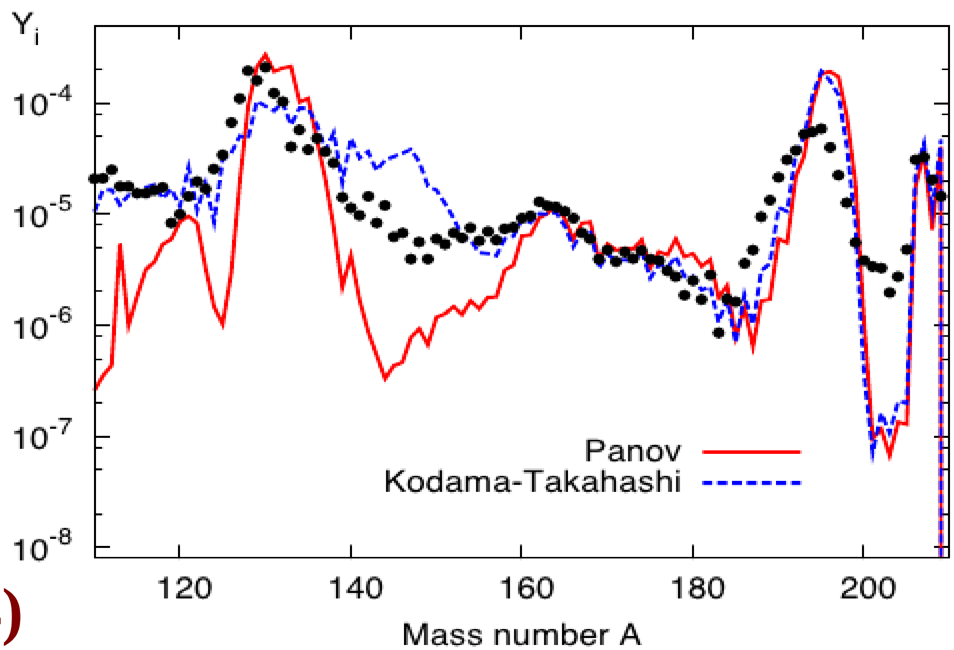
Neutron star merger updates of *dynamic ejecta* in non-relativistic calculations (Korobkin et al. 2012)

Variation in neutron star masses

fission yield prescription

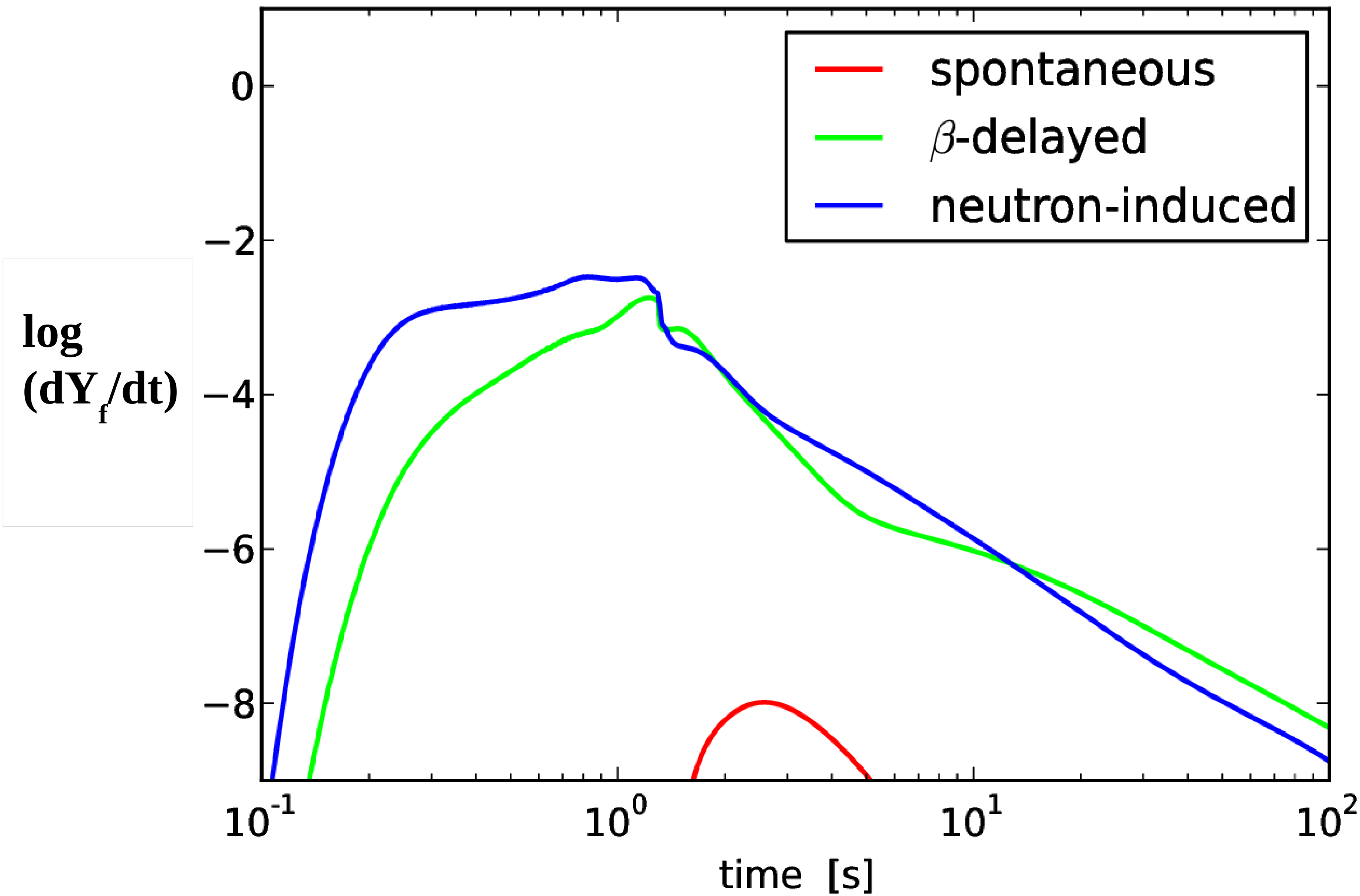
Fission yields affect abundances below A=165, the third peak seems always shifted to heavier nuclei

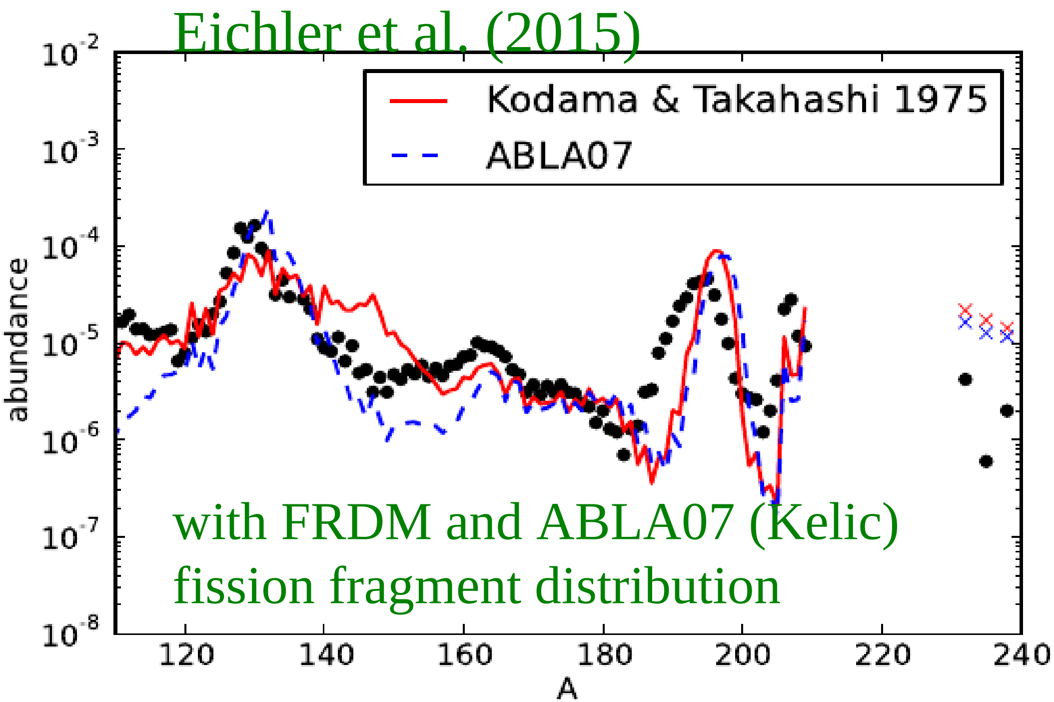


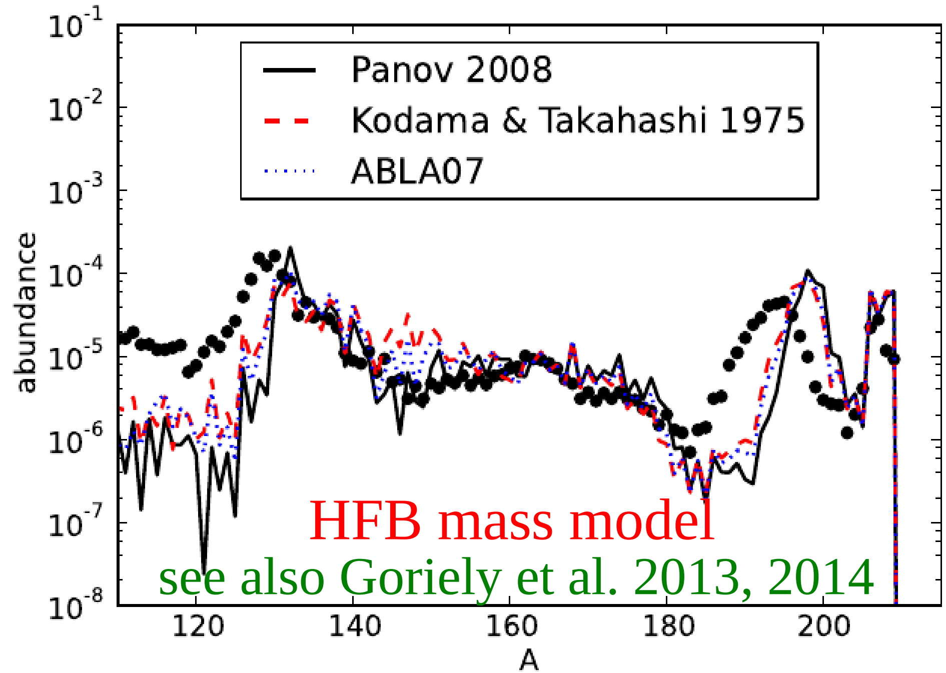


Ejected mass of the order 10^{-2} M_{sol}
conditions very neutron-rich (Ye=0.04)

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

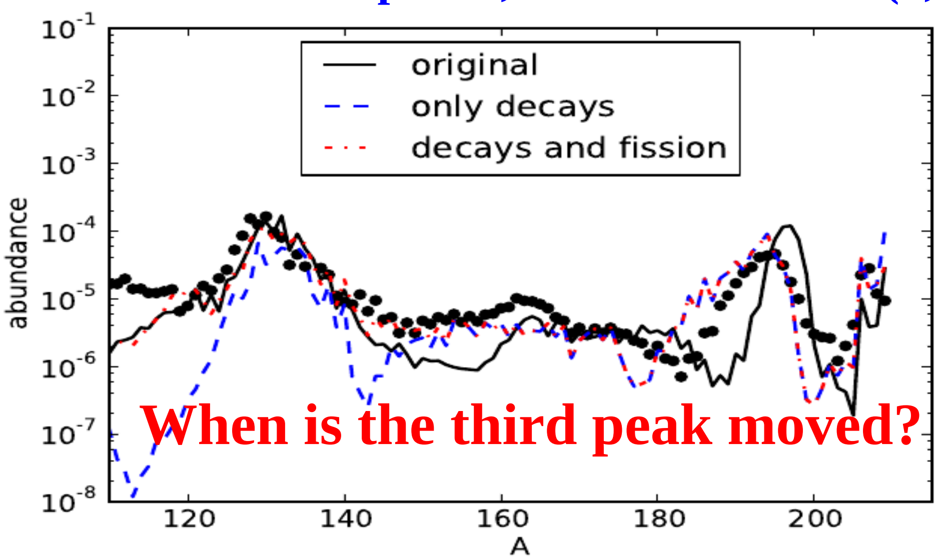




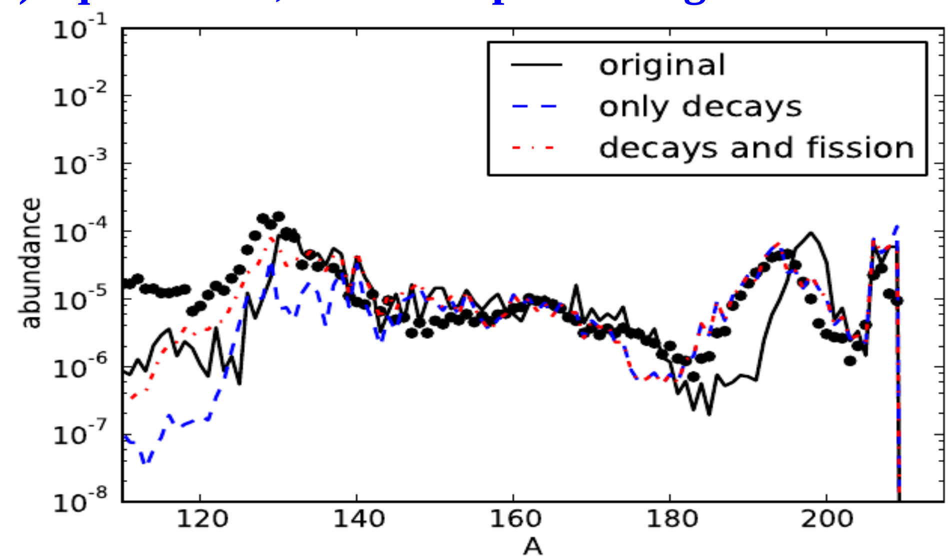


Variations in mass models and fission fragment distributions

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



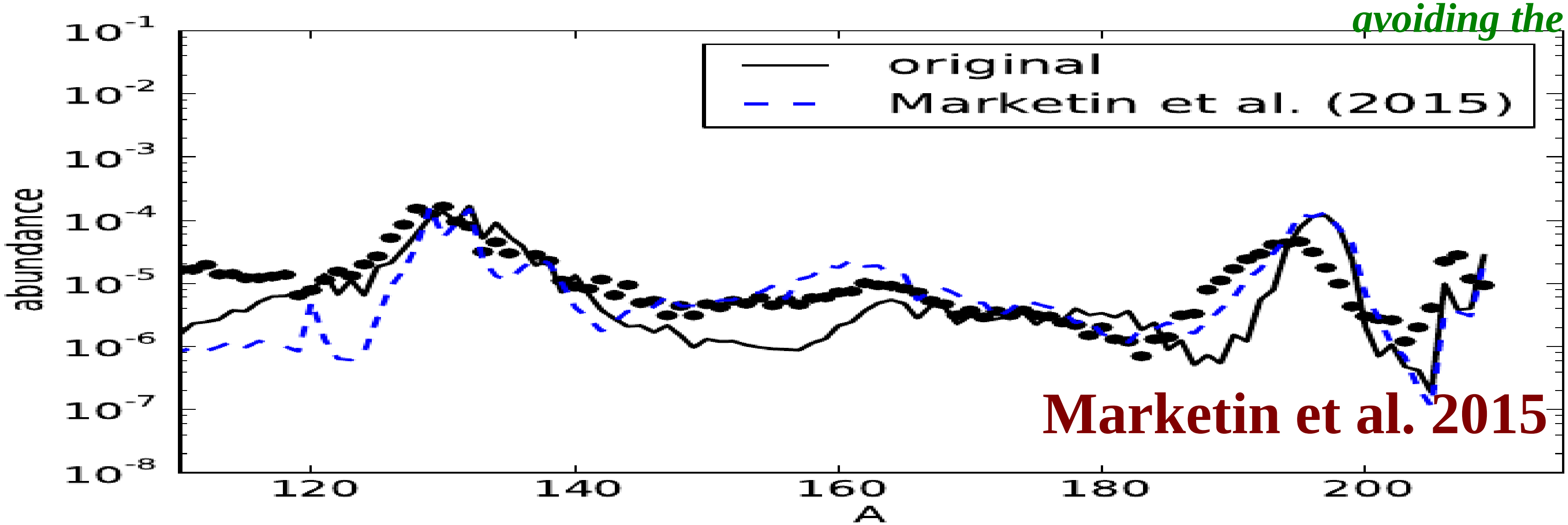
(a) FRDM



(b) HFB-14

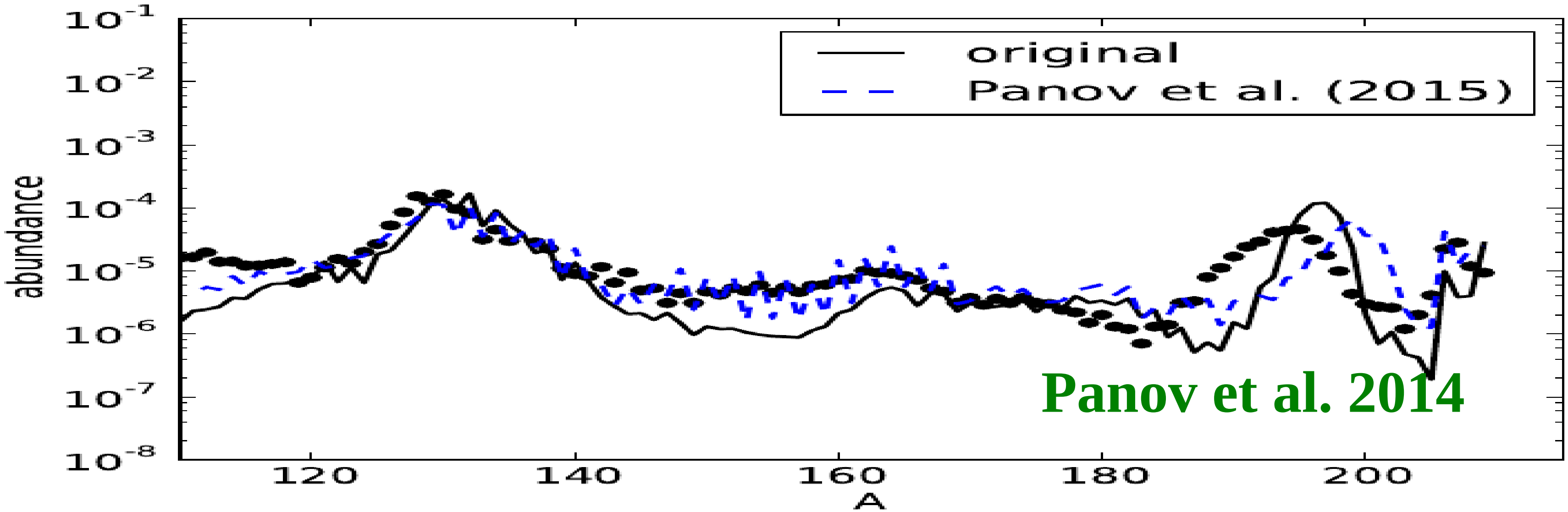
Exploring variations in beta-decay rates

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



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

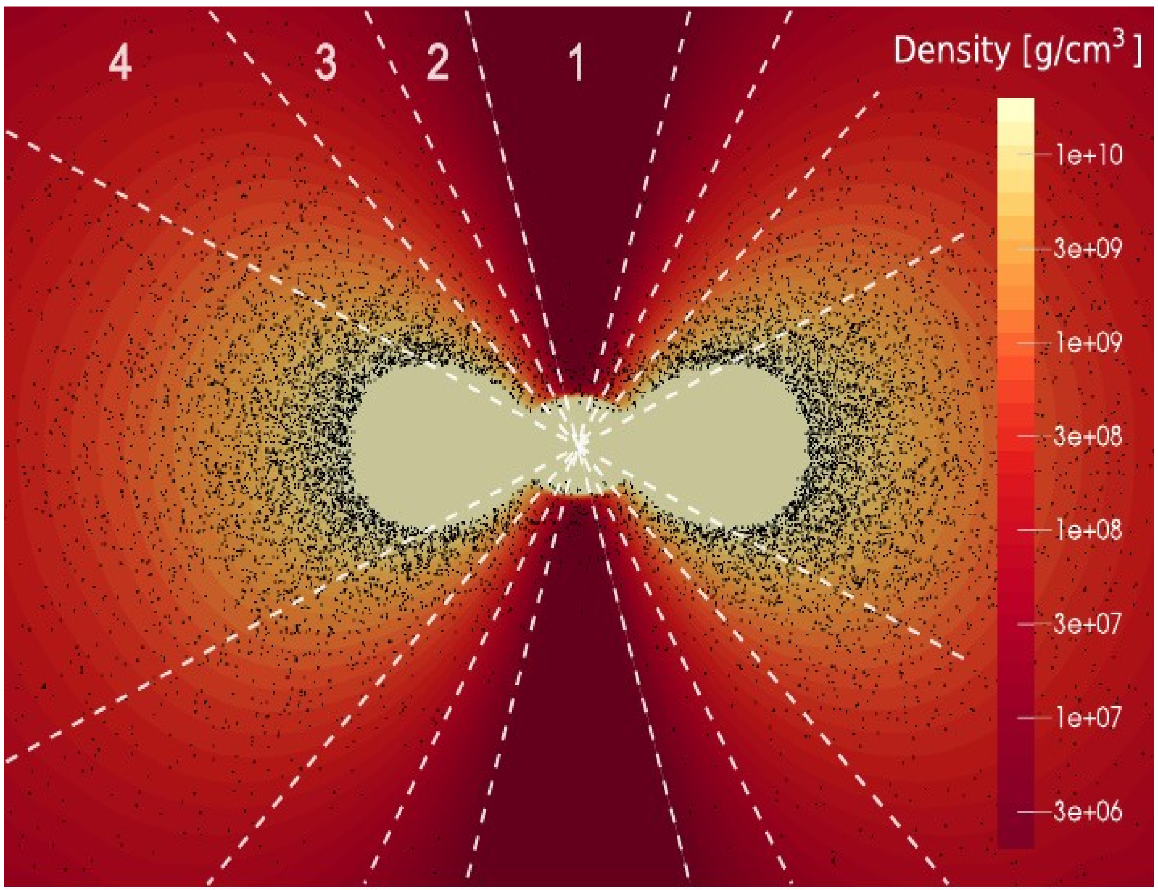
(a) FRDM, Marketin (2015)

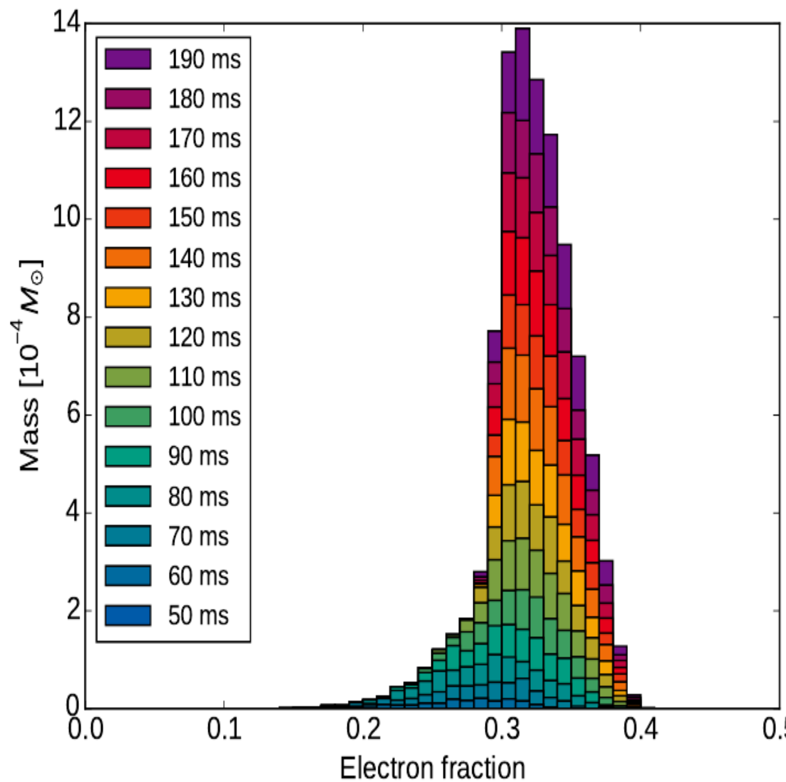


Longer half-lives give the opposite effect

(c) FRDM, Panov (2015)

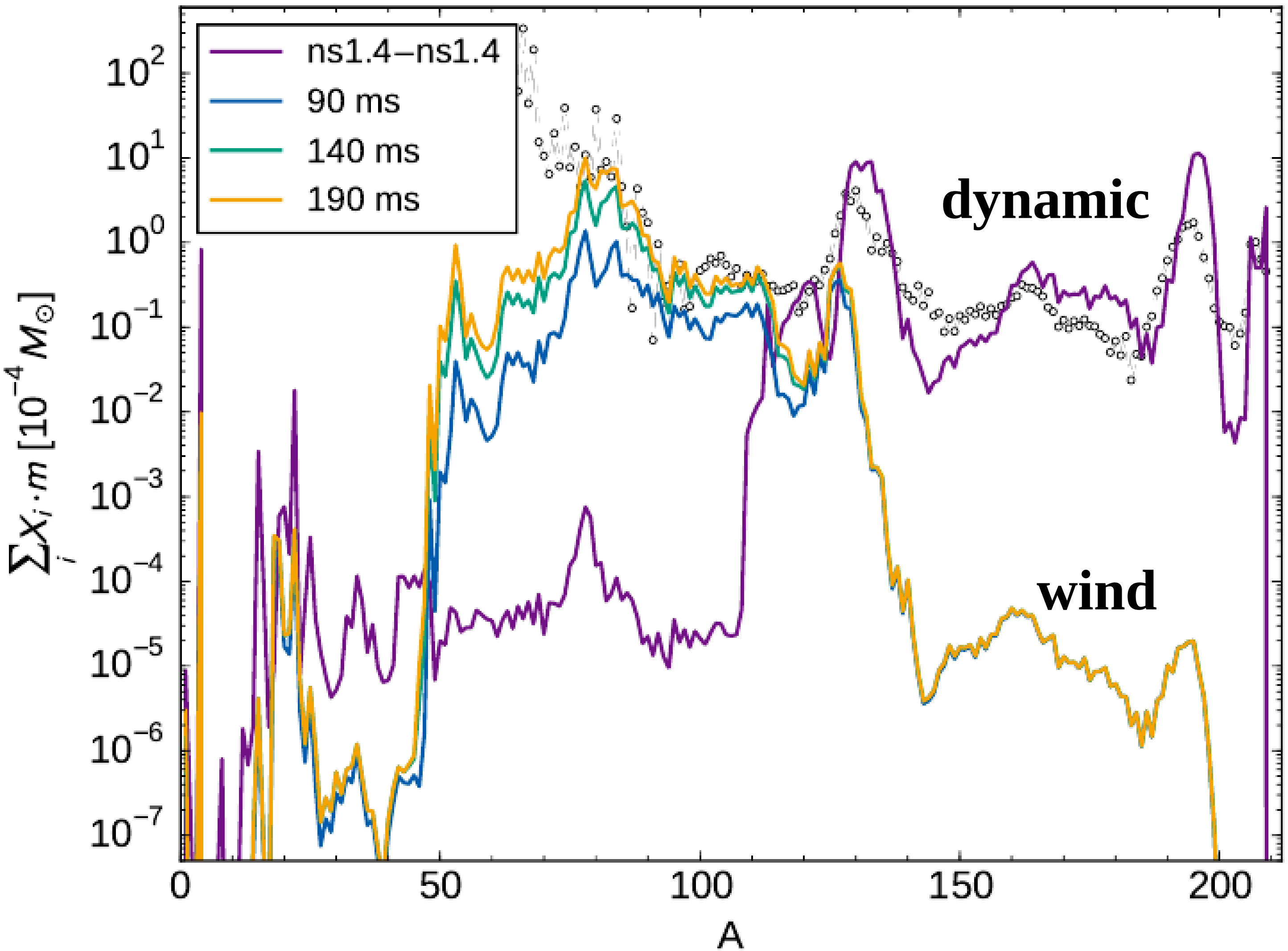
Dynamic Ejecta and Wind Contribution before Formation of Black Hole (Martin et al. 2015)





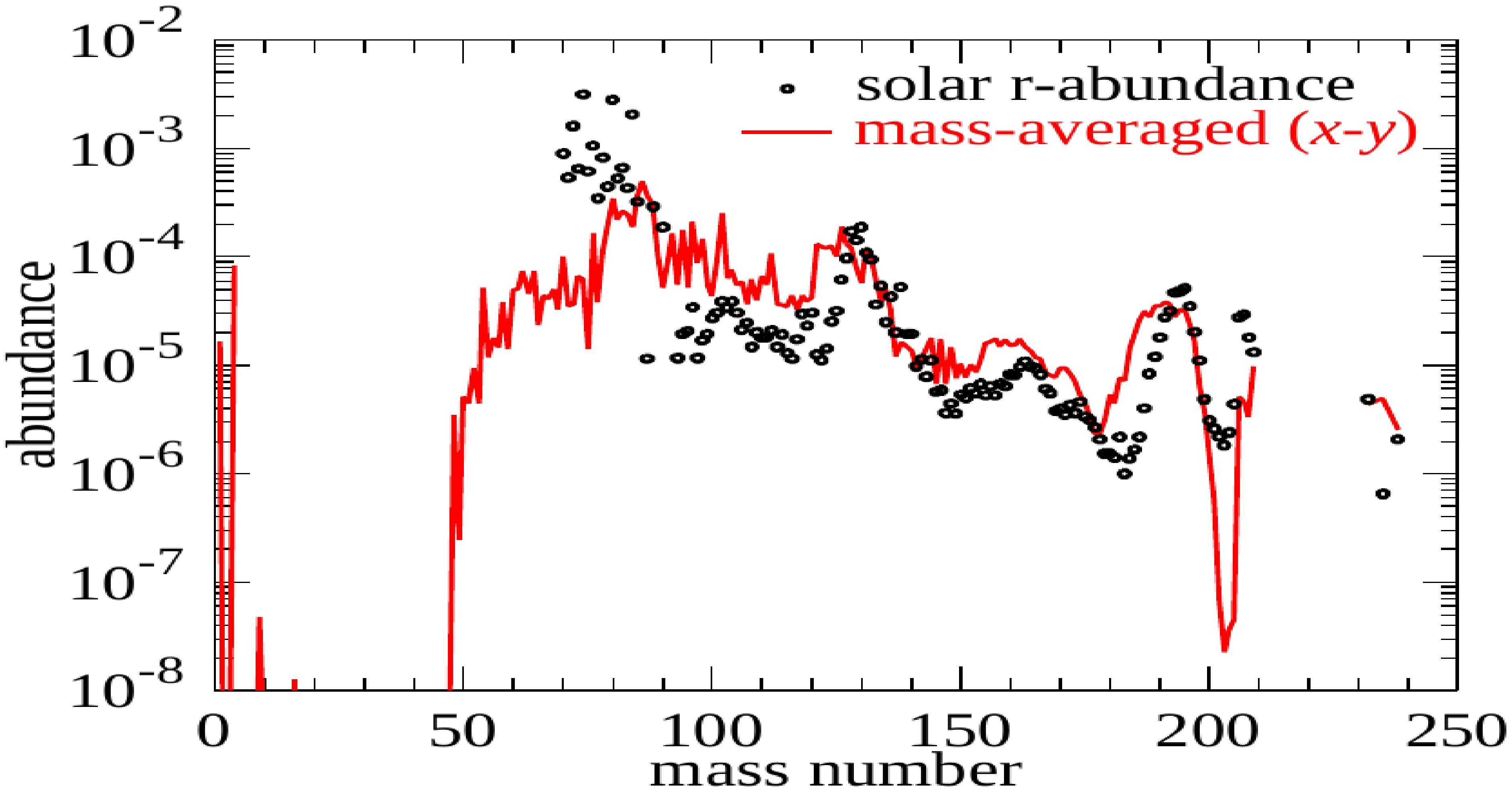
Ye in neutrino wind

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 the dynamical ejecta composition persists).

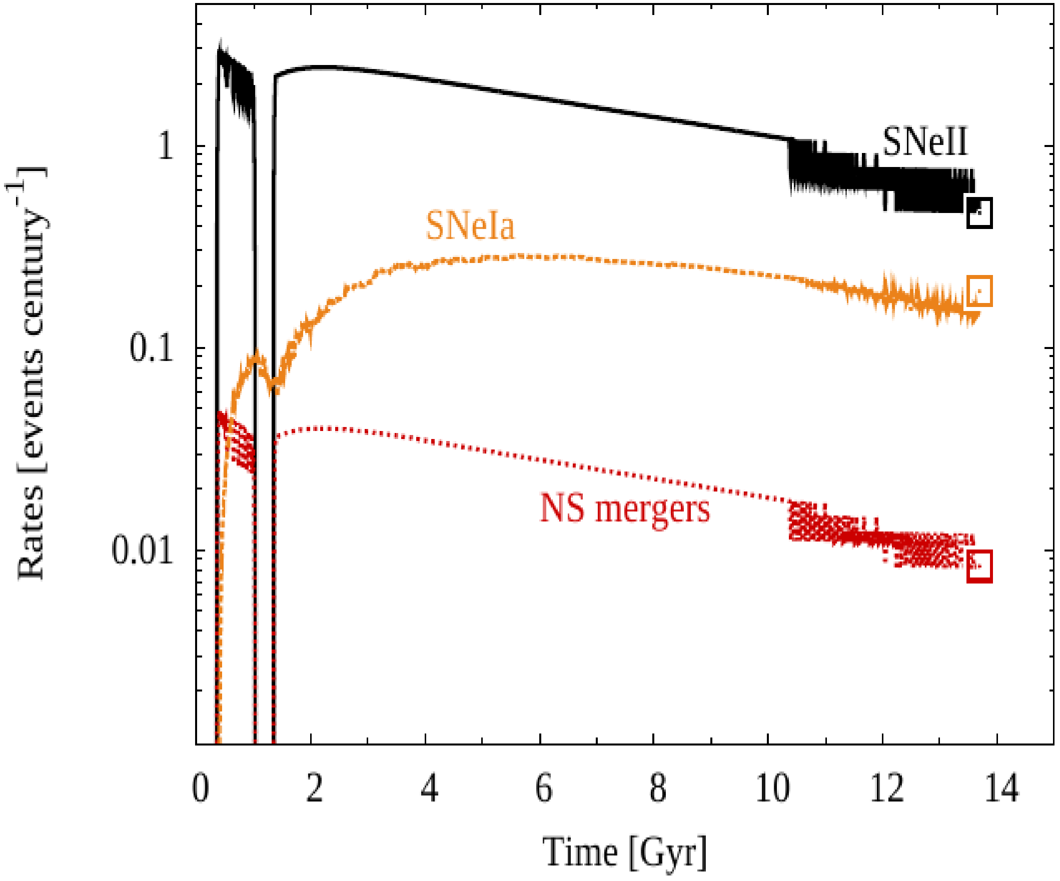
Full predictions with dynamic ejecta, viscous disk ejection, and late neutrino wind, but done in **General Relativistic grid calculations**, possibly leading to hot shocks, and e+e- pairs, which affect Ye and the position of the r-process peaks **(Wanajo et al. 2014).** Higher Ye leads to similar results as in jets.



see also Sekiguchi et al. 2015, Goriely et al. 2015

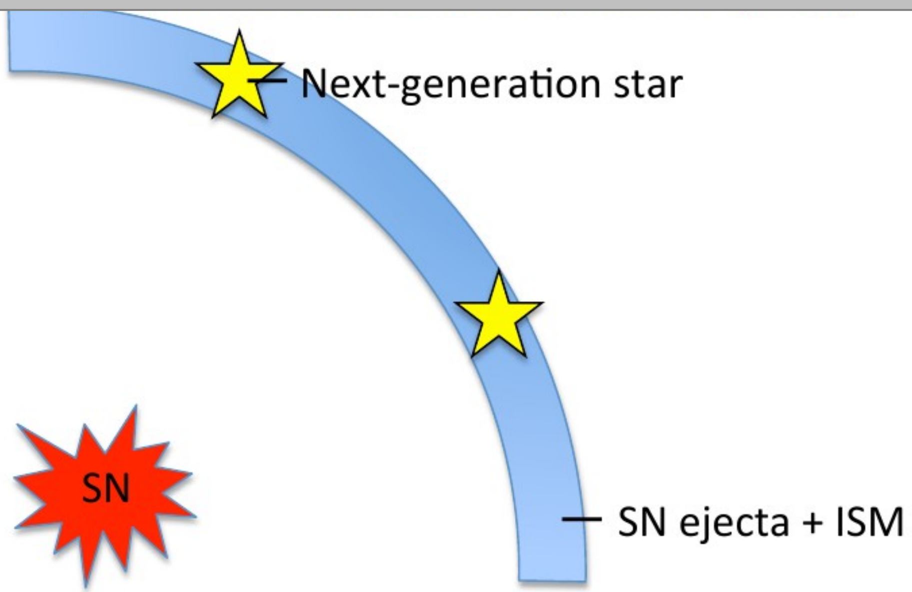
SN II and Ia rates compared to NS merging rate (from Matteucci 2014)

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



Stellar Abundances

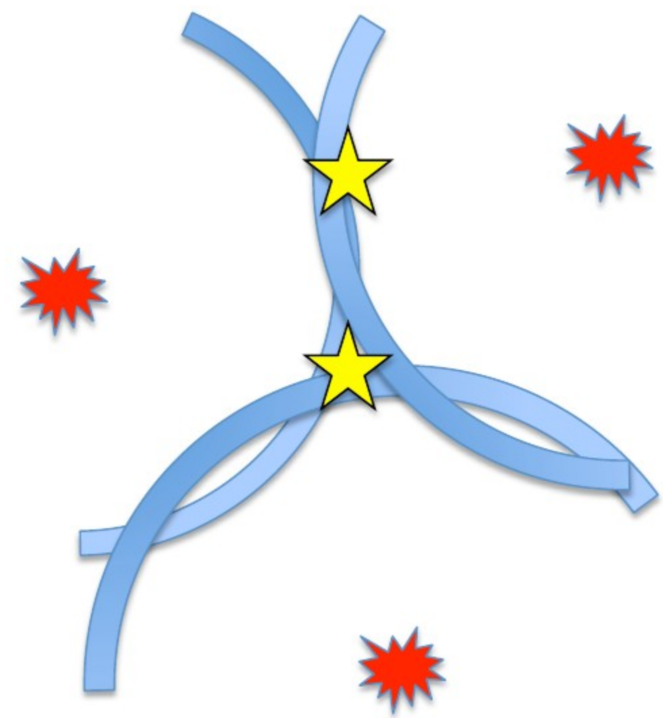
Inhomogeneous „chemical evolution“ models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about about $5x10^4$ Msol. After many events and averaging of ejecta composition is attained (Argast et al. 2004)



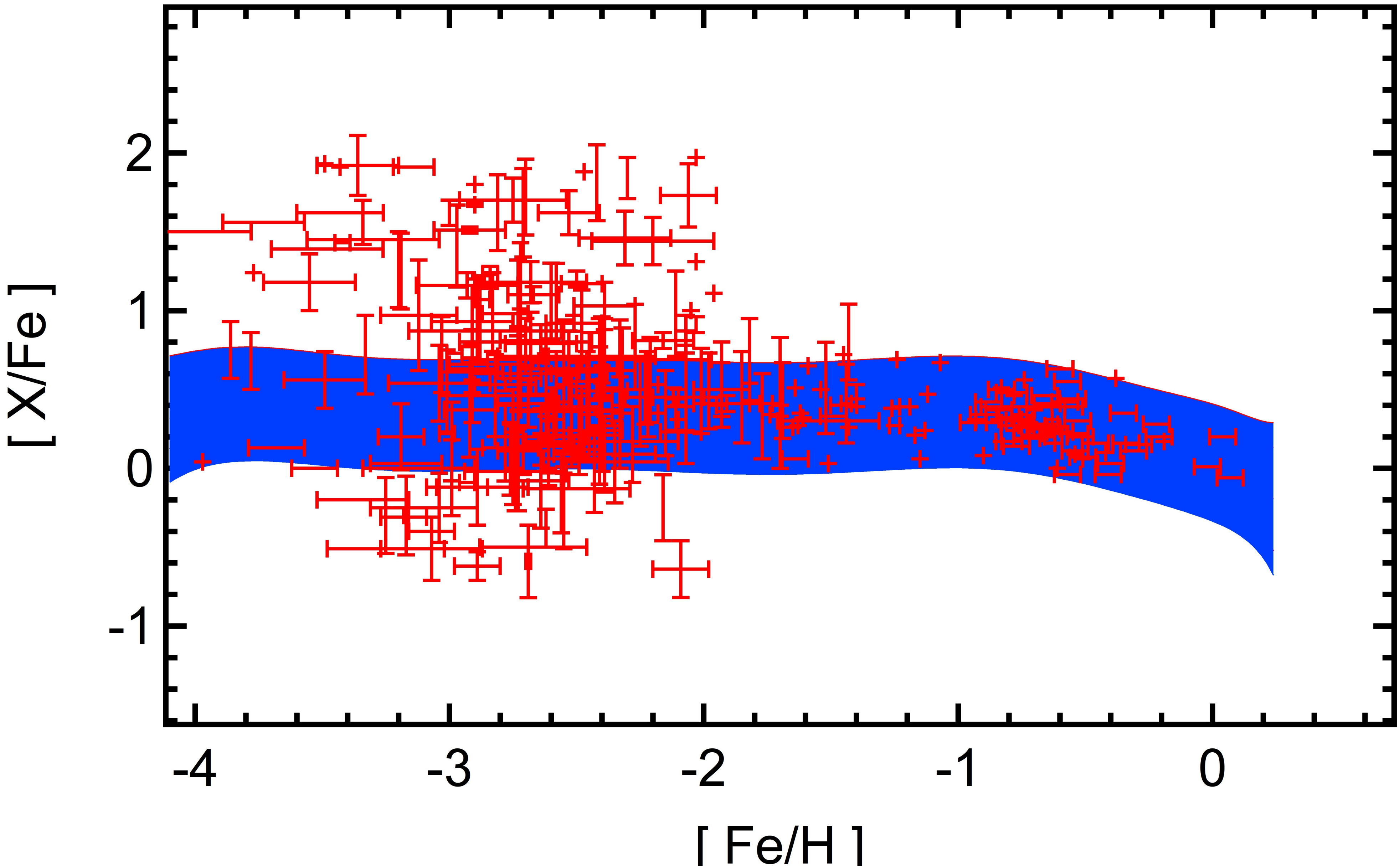
In the later phase

Contribution from multiple CCSNe

from Ko Nakamura

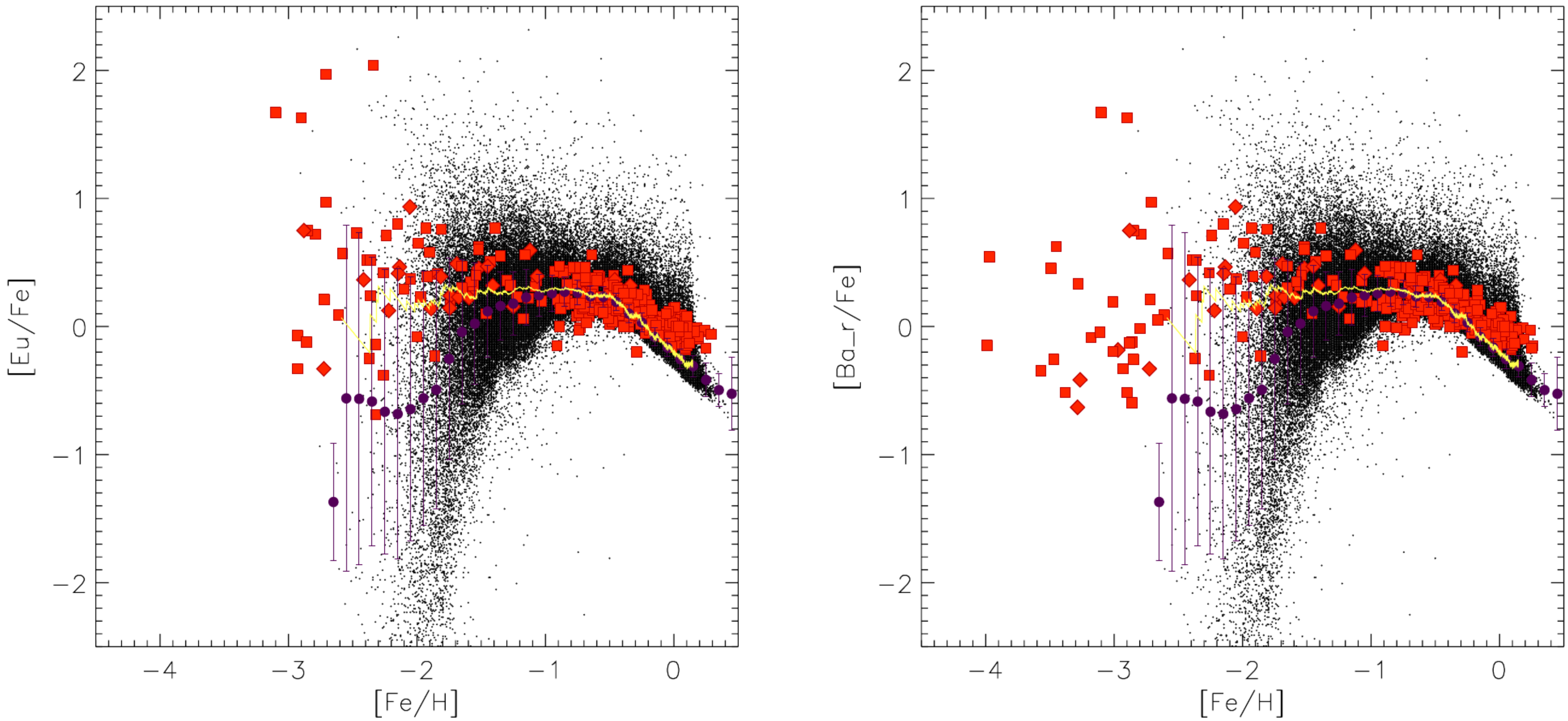


Rare events lead initially to large scatter before an average is attained!



Blue band: Mg/Fe observations (95%) from regular CCSNe with high occurrance rate, red crosses: individual Eu/Fe obs., indicating low occurrance and averaging is attained later in galactic evolution.

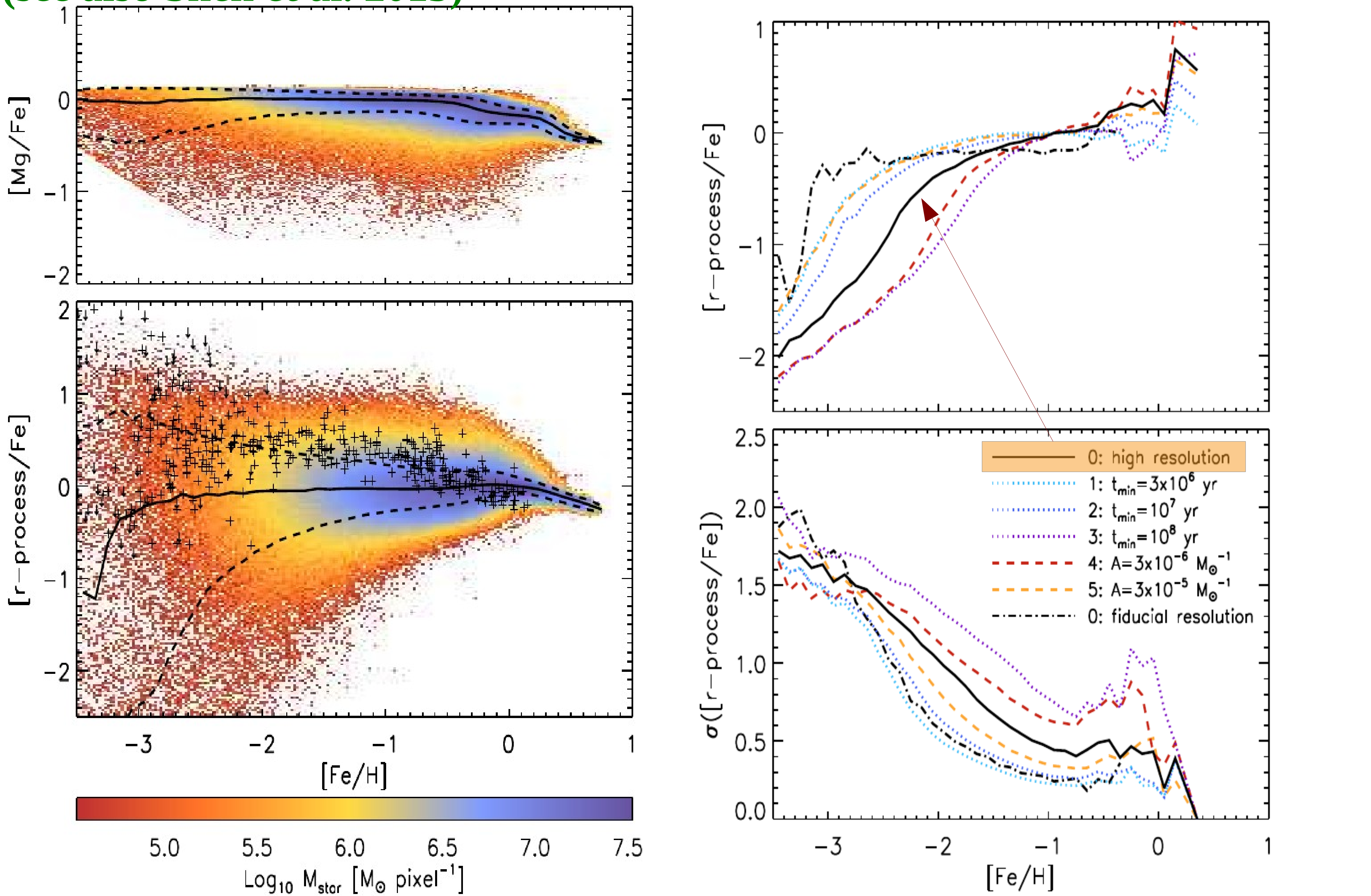
Argast, Samland, Thielemann, Qian (2004): But do neutron star mergers show up too late in galactic evolution, although they can be dominant contributors in late phases?

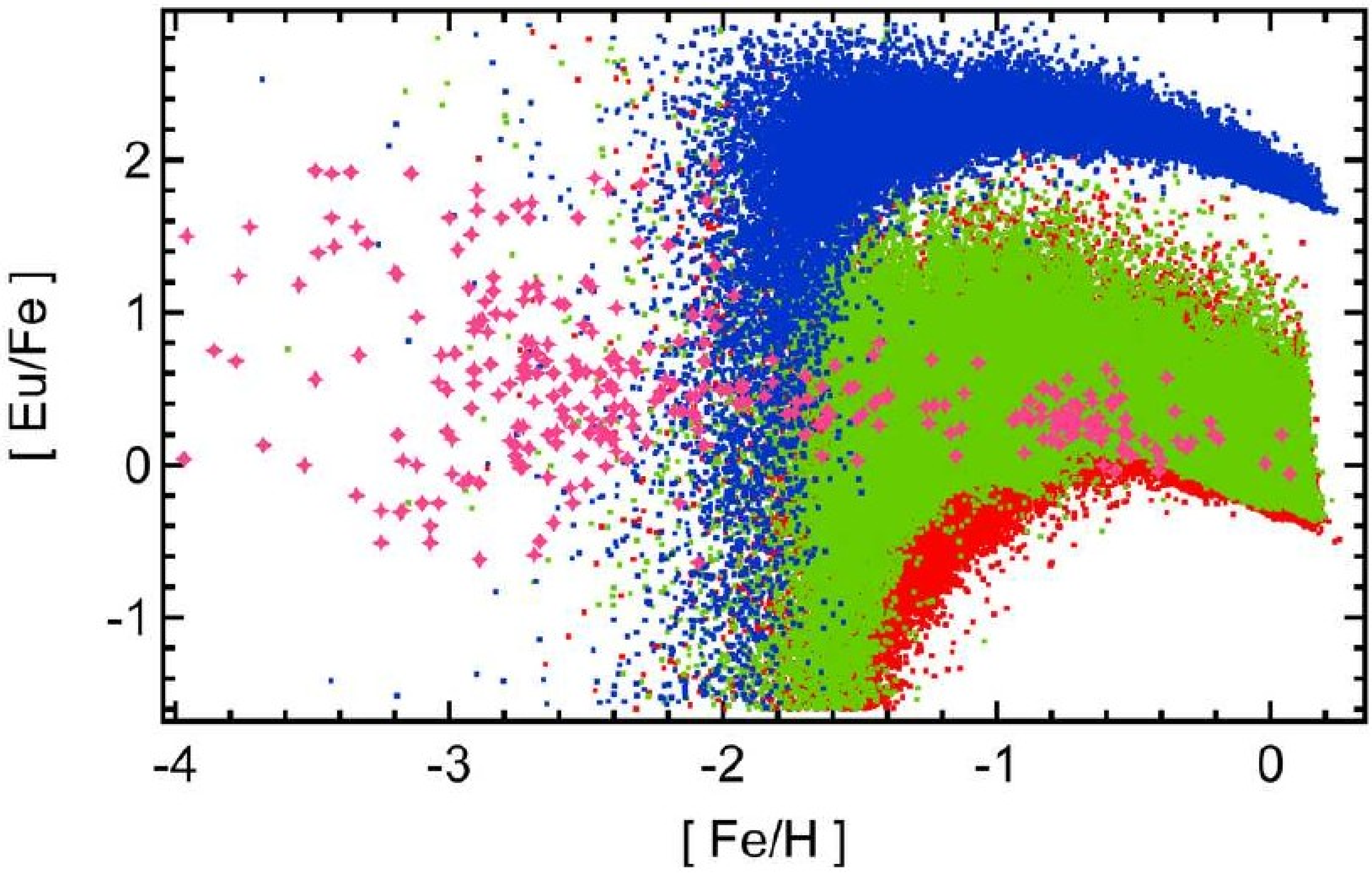


ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

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!!!

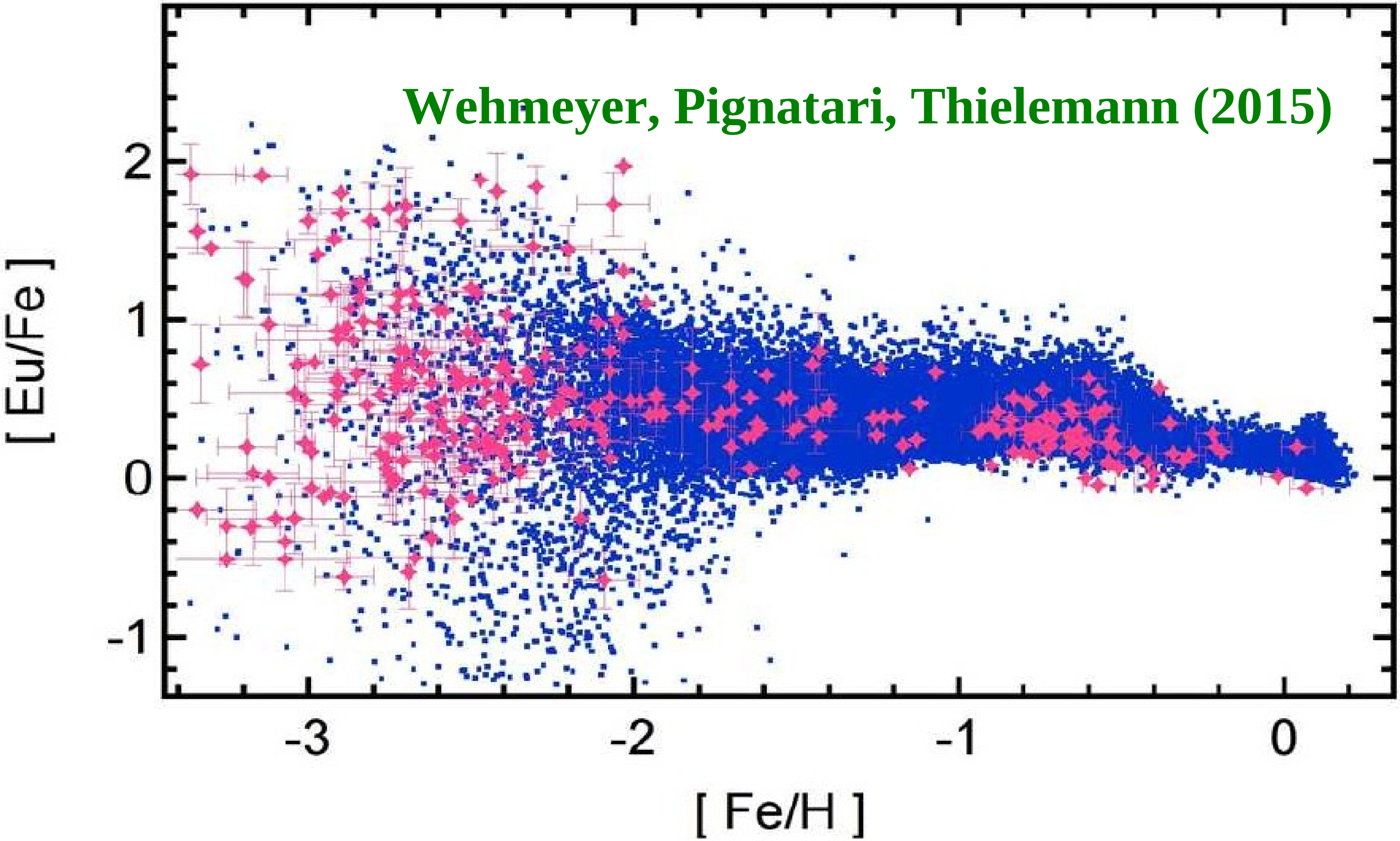
Inhomogeneous Chemical Evolution with SPH (van de Voort et al. 2015), Left ejecta mixed in $5x10^6$ Msol, right high resolution mixed in $5x10^4$ Msol (see also Shen et al. 2015)





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

Combination of NS mergers and magneto-rotational jets



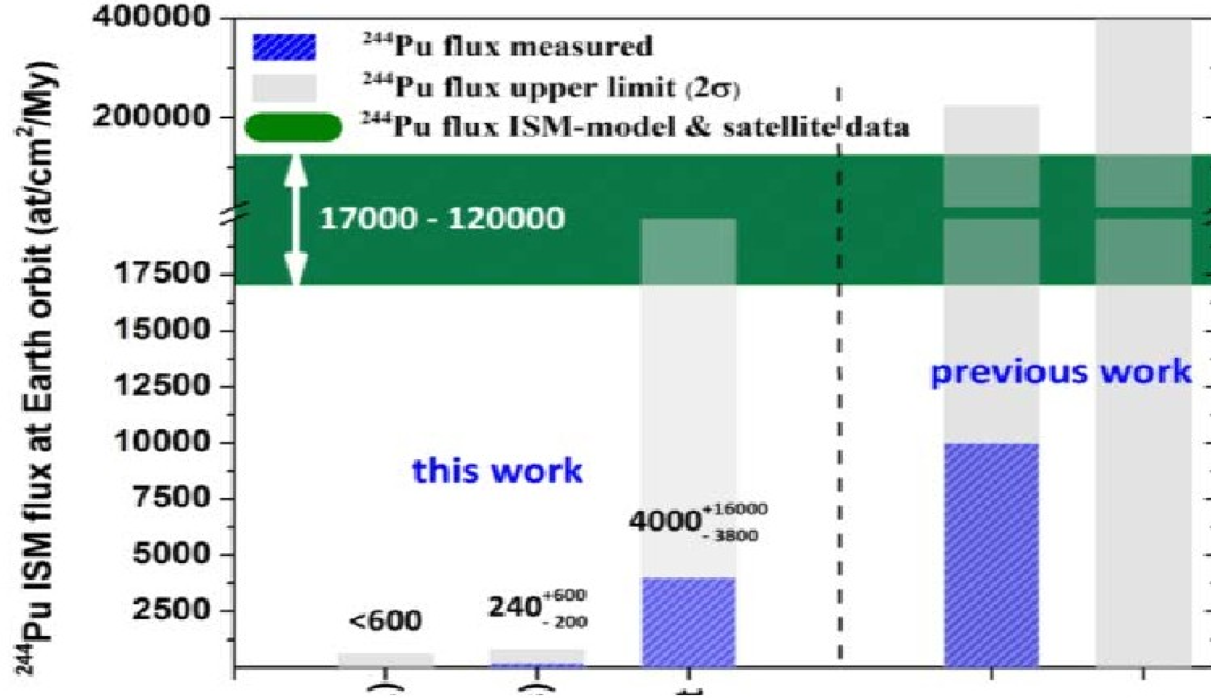
=> in either case, the strong r-process which also produces the actinides is a rare event!!!!!!!!!!!!!

^{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. Neutron star mergers cause large variations due to rarity of events, large amounts of ejecta, but due to last event in distant past, Pu has essentially decayed.