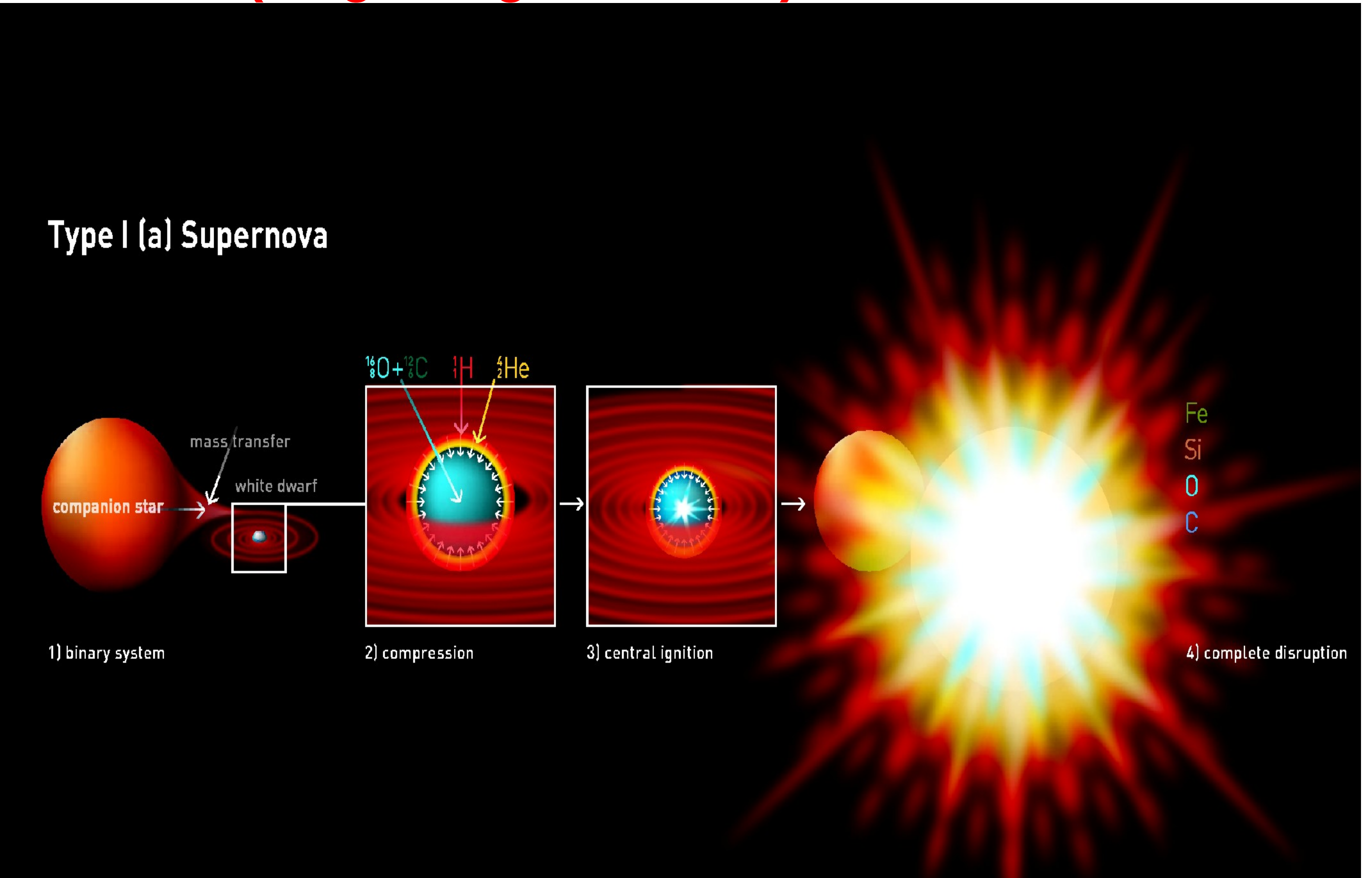
A few Thoughts on Supernovae, r-Process Sources, and Galactic Chemical Evolution

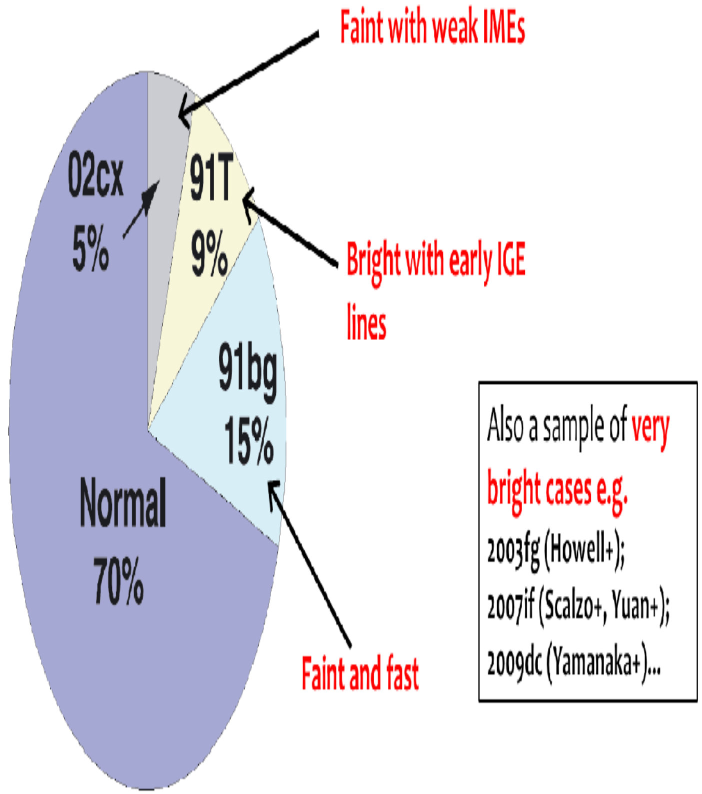
Friedrich-Karl Thielemann
Department of Physics
University of Basel
Switzerland

UNI BASEL

Branch-normal, Chandrasekhar mass models (single degenerates?)

We didn't talk (much) about Type Ia supernovae, their subclasses and possible understanding



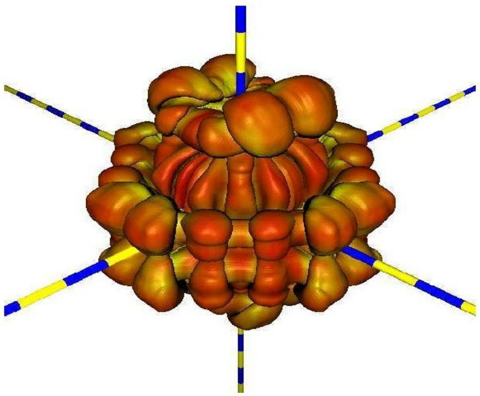


- binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)
- - white dwarfs (novae, type Ia supernovae = called single degenerate)

Li et al. (2011), Sim (2012)

Possible explanations: He-accretion caused (double) detonations (Bildsten ...), white dwarf mergers (Röpke …) & collisions (Rosswog, Pakmor, Raskin, Cabezon)

Present and future 3D models

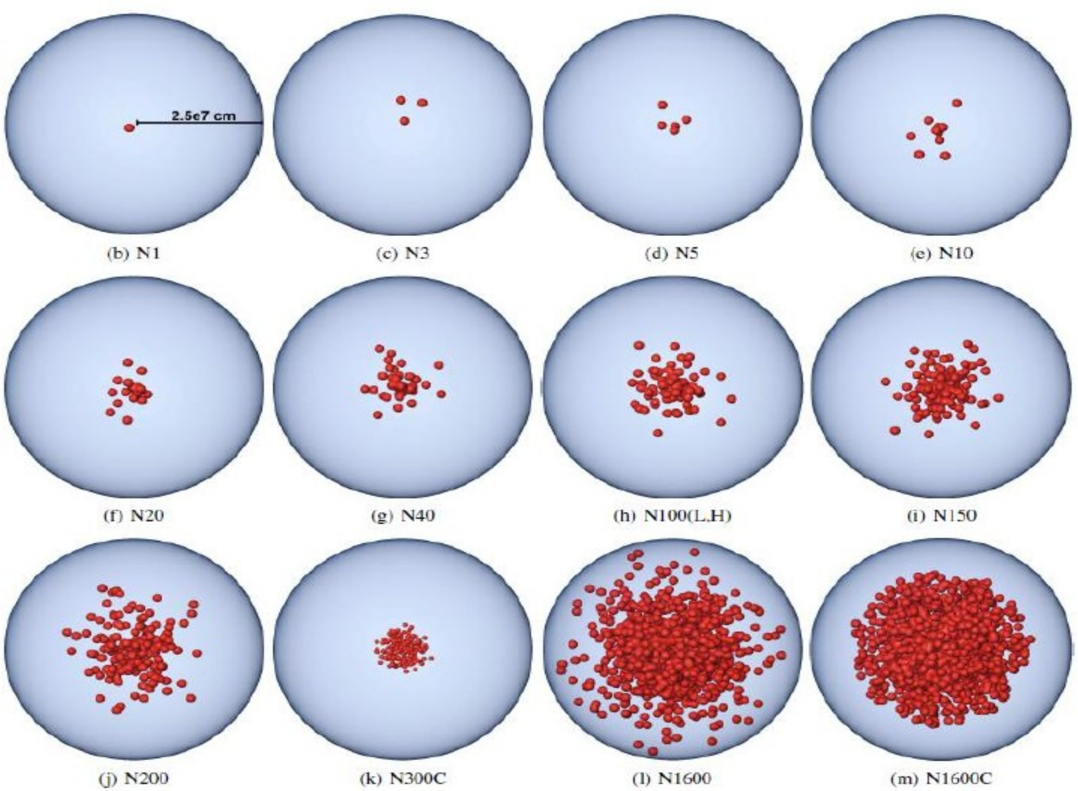


consistent treatment needed instead of parametrized spherical propagation, MPA Garching/Würzburg (Röpke et al.), U. Chicago/ SUNY Stony Brook (Calder et al.)

- distribution of ignition points uncertain (deflagration, centrally ignited delayed detonation, off-center delayed detonation)

- hydrodynamic instabilities determine propagation

- deflagration/detonation transition



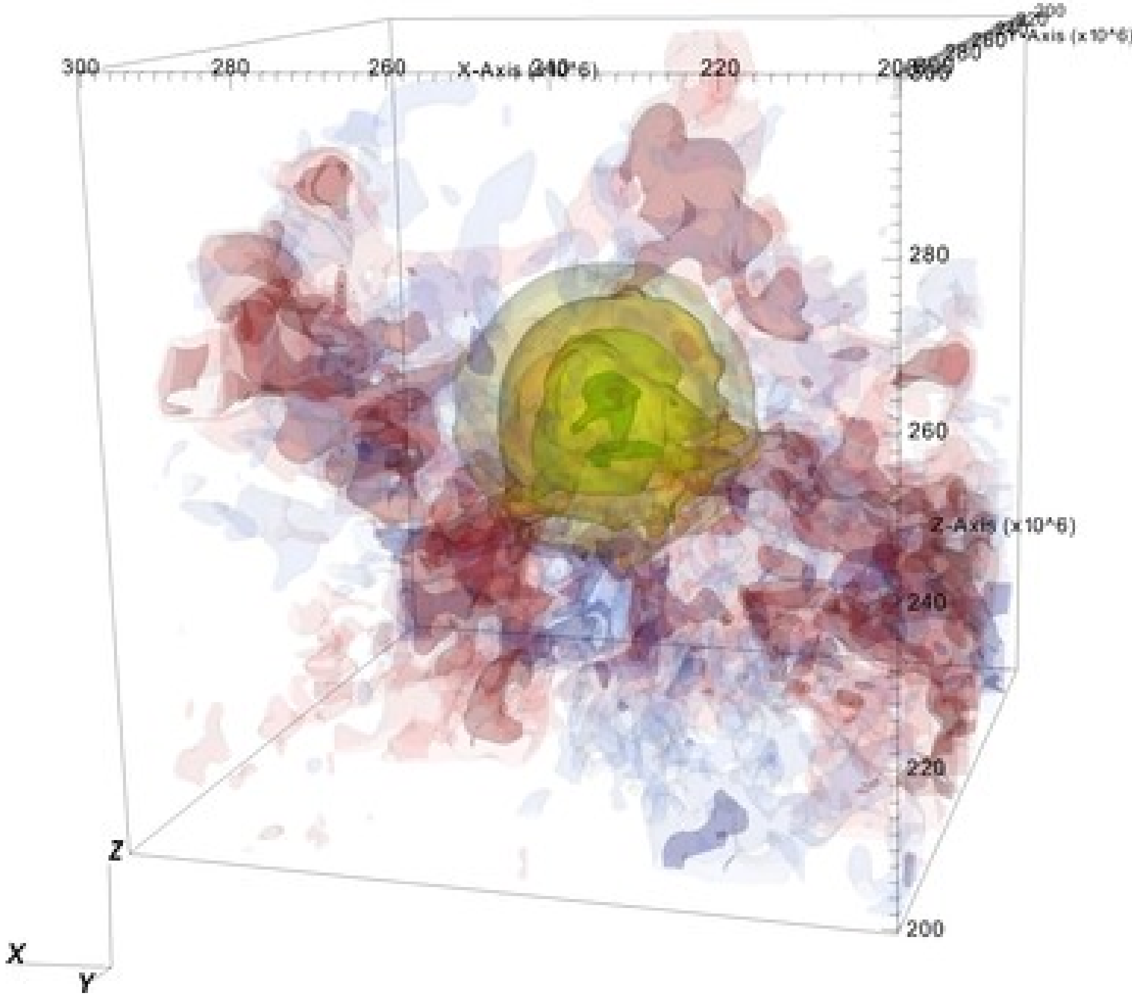
Changing **ignition geometry/number of sparks** provides handle to obtain different realizations of the DDT model

This set gives about a factor of three variation in 56Ni mass (0.4 – 1.1 M_{sun})

Seitenzahl et al. 2013

Explicit hydro-codes cannot handle transition to thermonuclear runaway => assumed ignition conditions

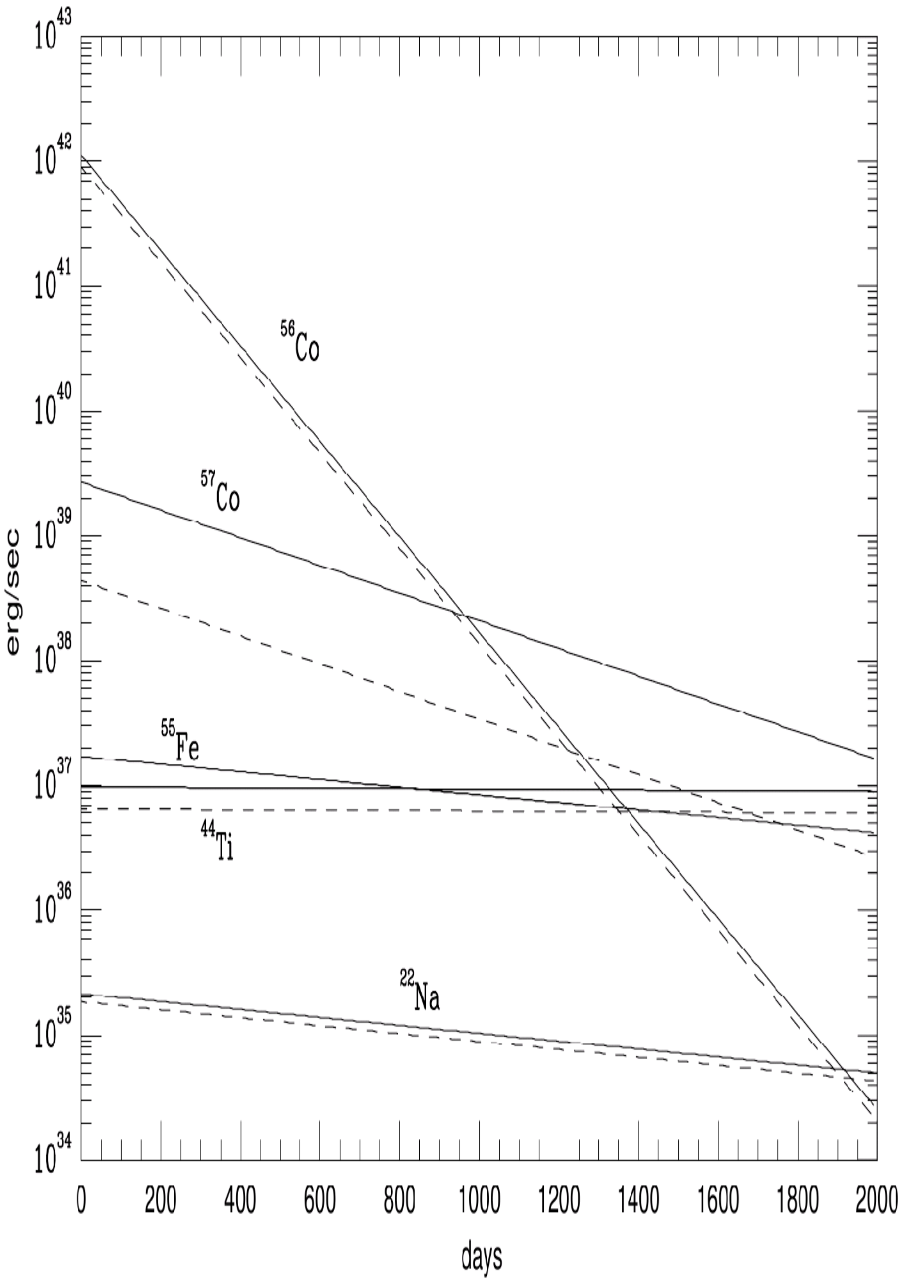
Attempts to overcome constraints of explicit 3D hydrocodes



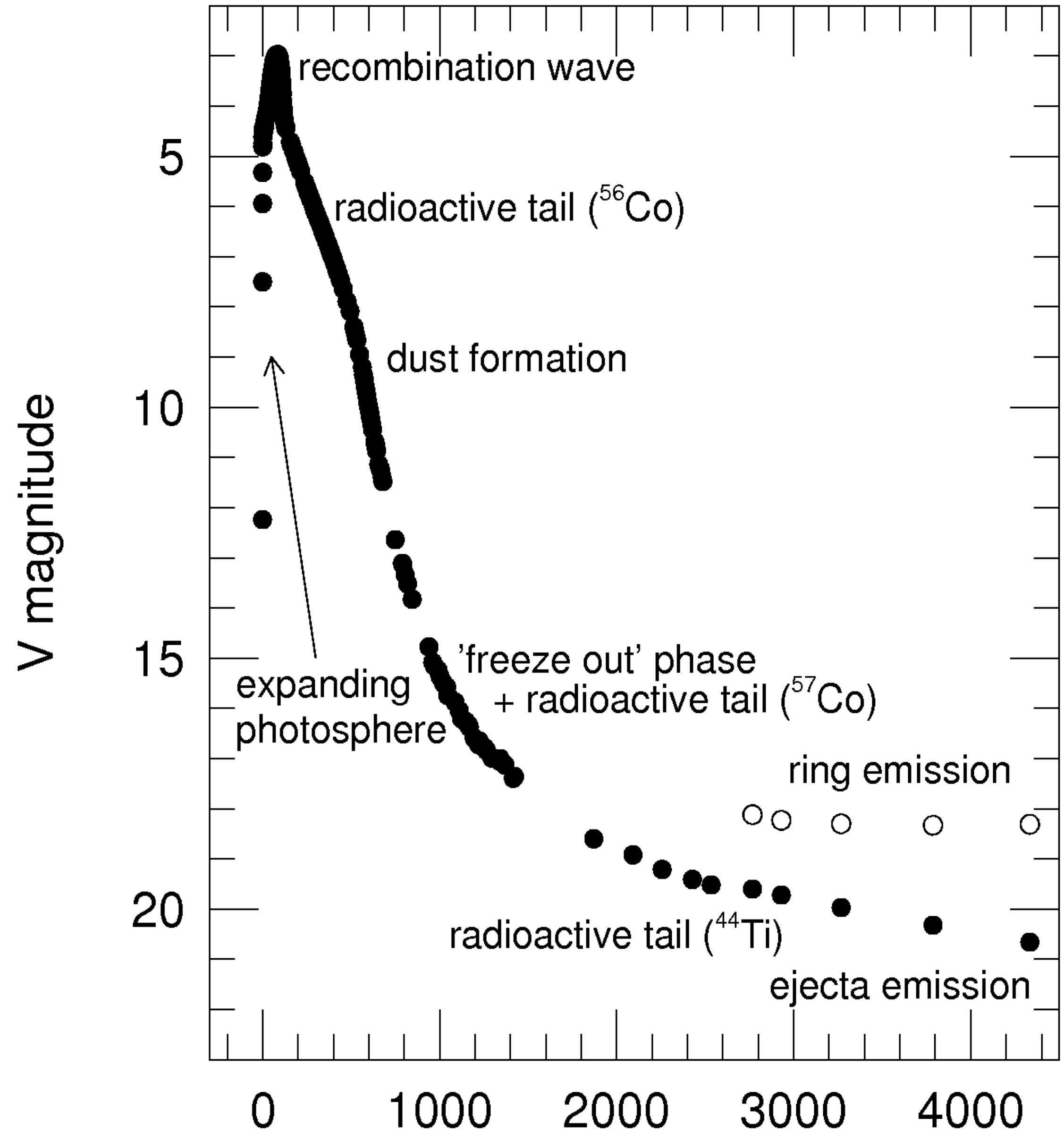
low Mach number hydrodynamics algorithms filter soundwaves from the system, allowing for the efficient simulation of long timescale processes (not constrained by Courant condition, permitting only timesteps of the sound crossing time between gridpoints). **Zingale (2013, Maestro code)**, Shown energy generation in convective region during simmering phase before SN Ia explosion. **Slightly off-center ignition likely in a single point!?**

Present situation: (a) the ignition in single-degenerate scenarios is not self-consistently solved yet, it could range from central deflagrations, turning into detonations, to off-center ignition and gravitationally confined detonations. (b) we do not yet understand the importance of other options (He-accretion, double-degenerate mergers, collisions ..) *but still use W7 (or updates) for chemical evolution studies!*

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

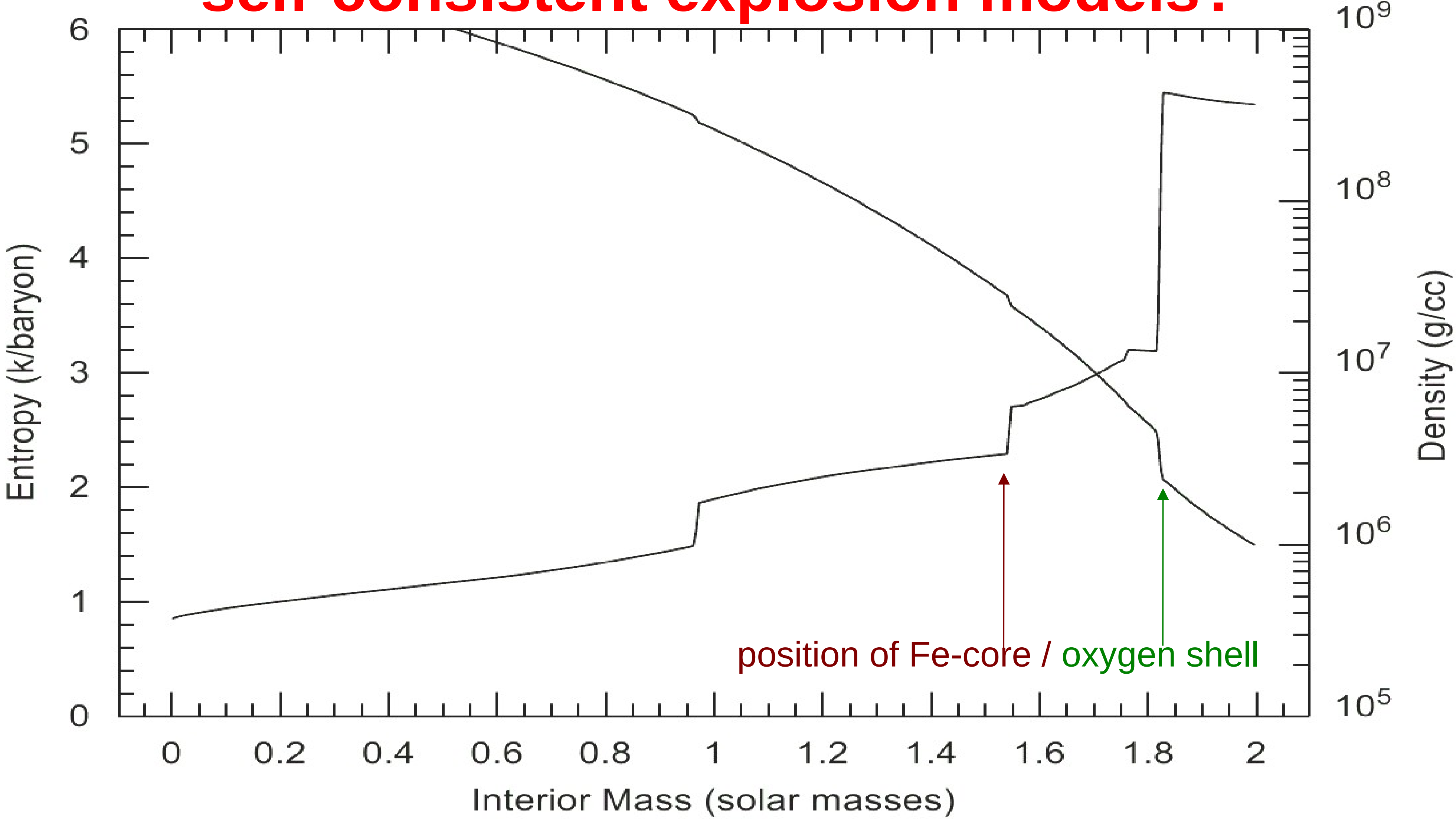


total/photon decay energy input from models



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

How to invoke induced explosions for nucleosynthesis purposes, if we do not yet have self-consistent explosion models?



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

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 Ye!) 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!

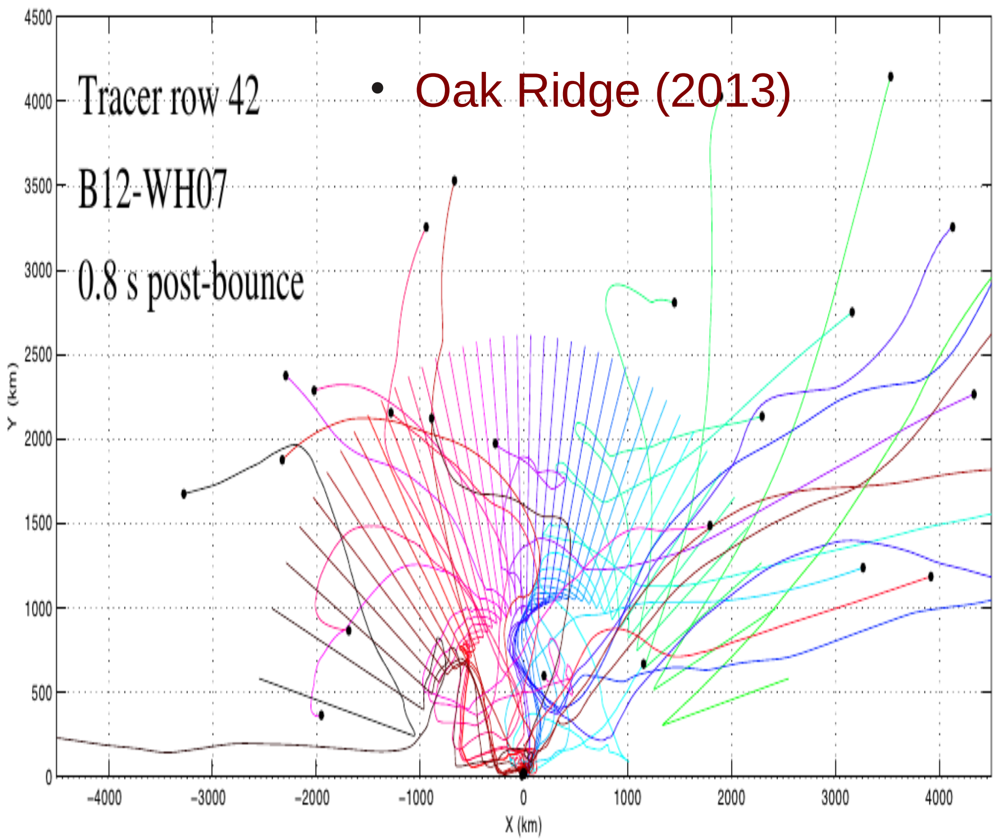
Two aspects:

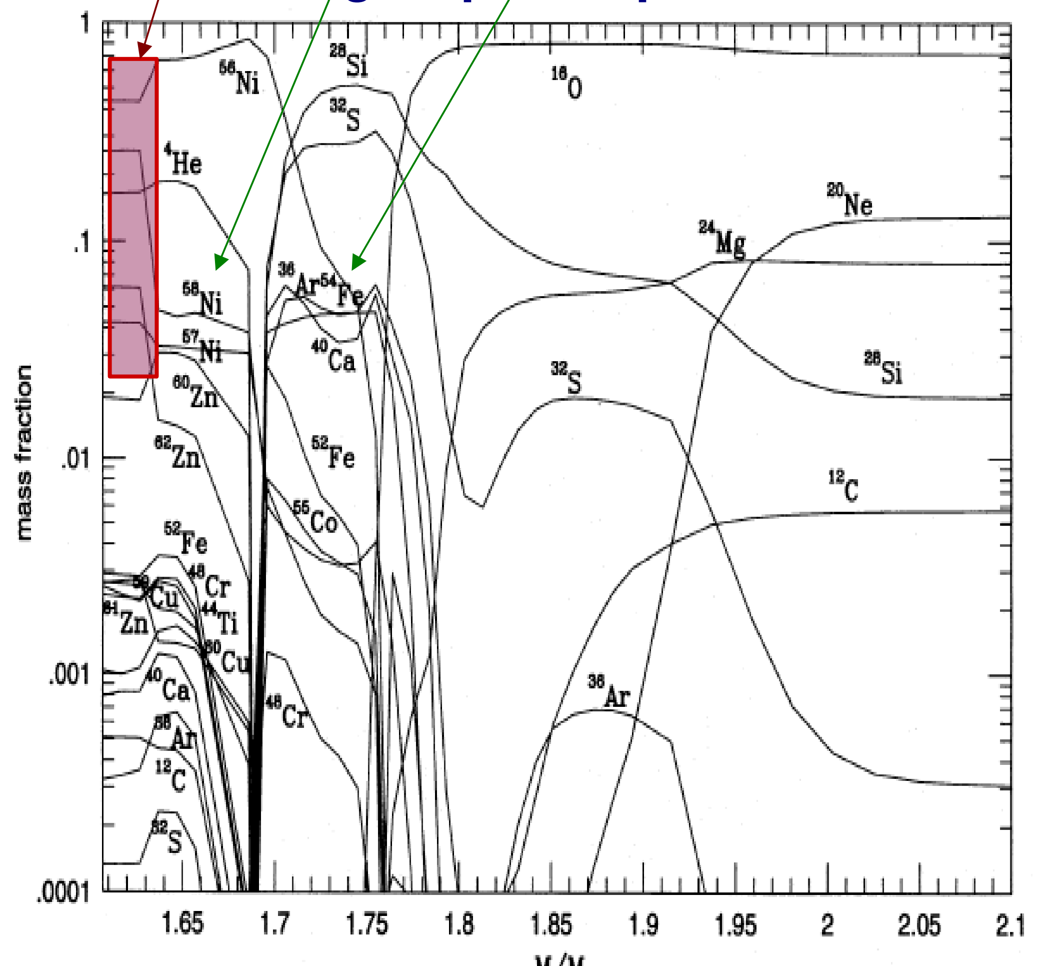
(i) even in spherical symmetry neglecting neutrinos -> Ye

(ii) multi-D

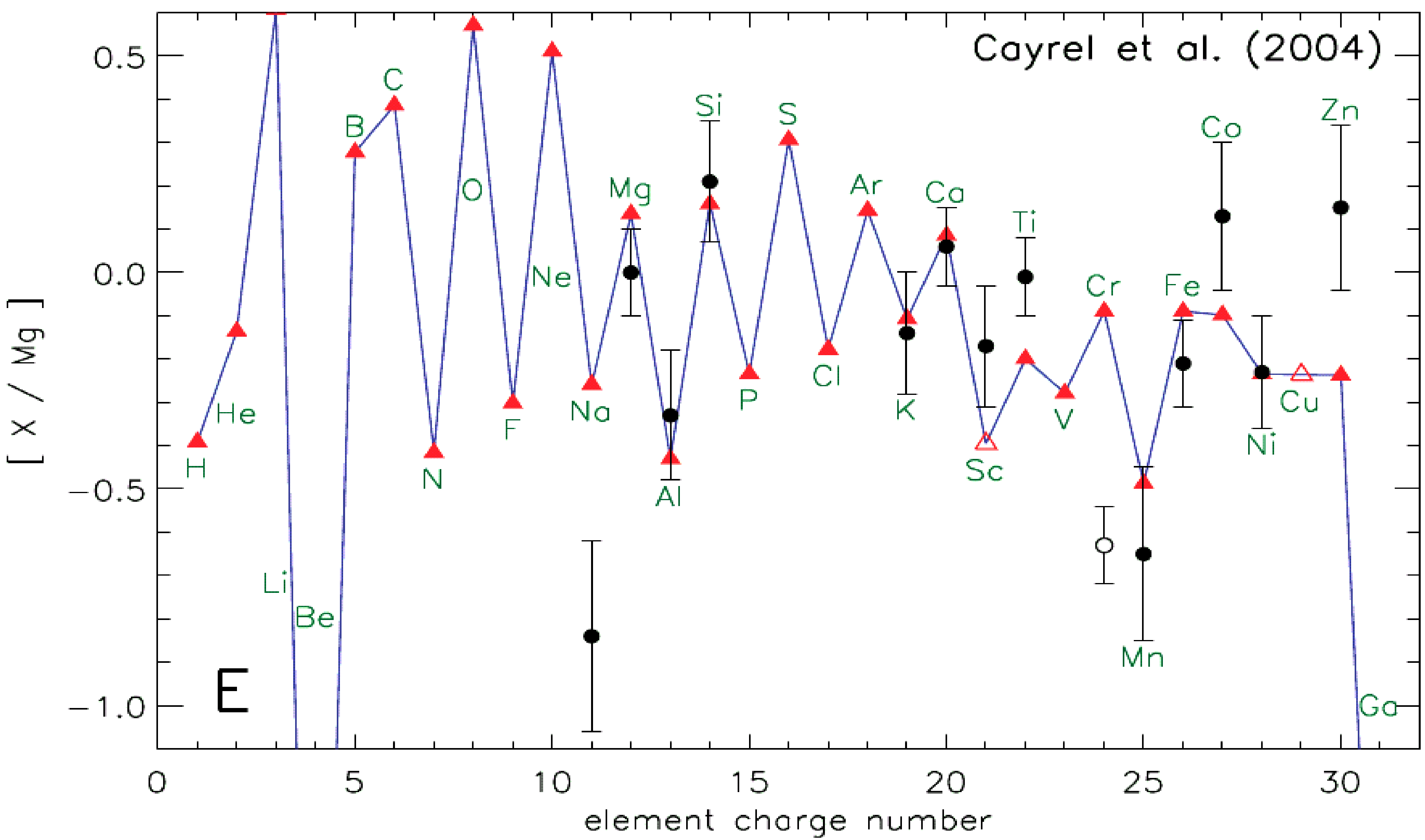
high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe),

Ye from progenitor models (not self-consistent explosions) determines Fe-group isotopes.





Pop III yields (Heger & Woosley 2009) Evolution of metal-free stars



Cayrel et al. (2004). taken as representative sample for low metallicity stars (representing type II supernova yields). E: “Standard” IMF integration of yields from M = 10 − 100 M⊙, explosion energy E = 1.2 B (with piston underproduction of Sc, Ti, Co and Zn).

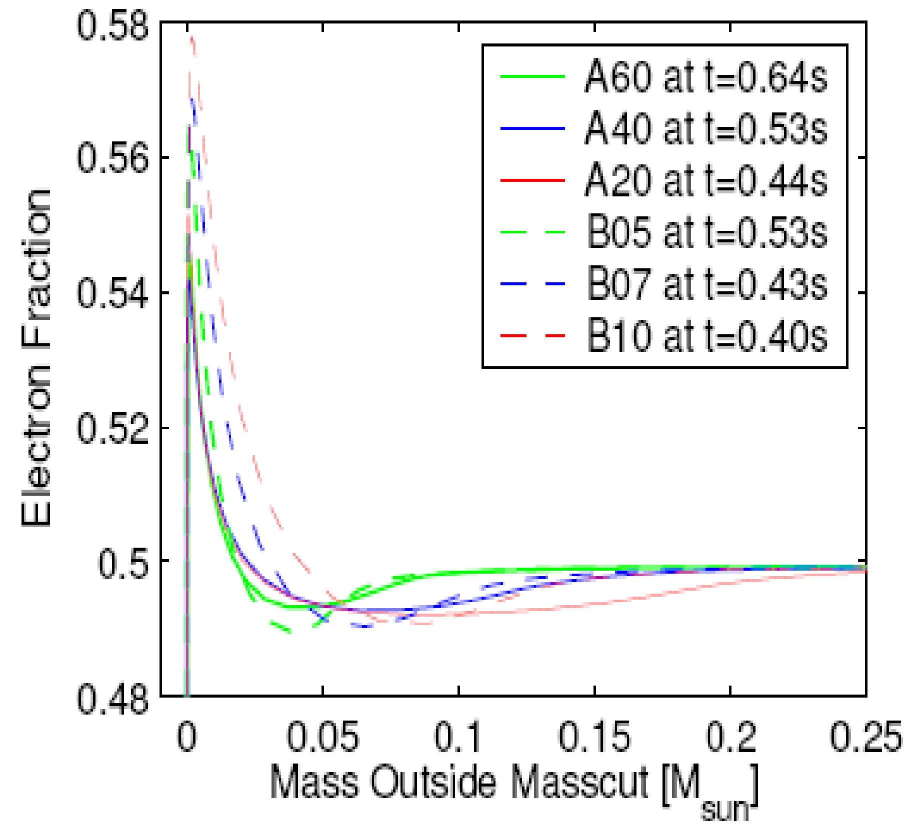
In exploding models matter in innermost ejected zones becomes proton-rich (Ye>0.5), *improves Sc, Ti, Cu, Zn!*

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
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity → higher luminosity, dominate in neutrino wind → neutron-rich ejecta ?



Liebendörfer et al. (2003), Fröhlich et al. (2006a), Pruet et al. (2005)

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 Ye<0.5!

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***

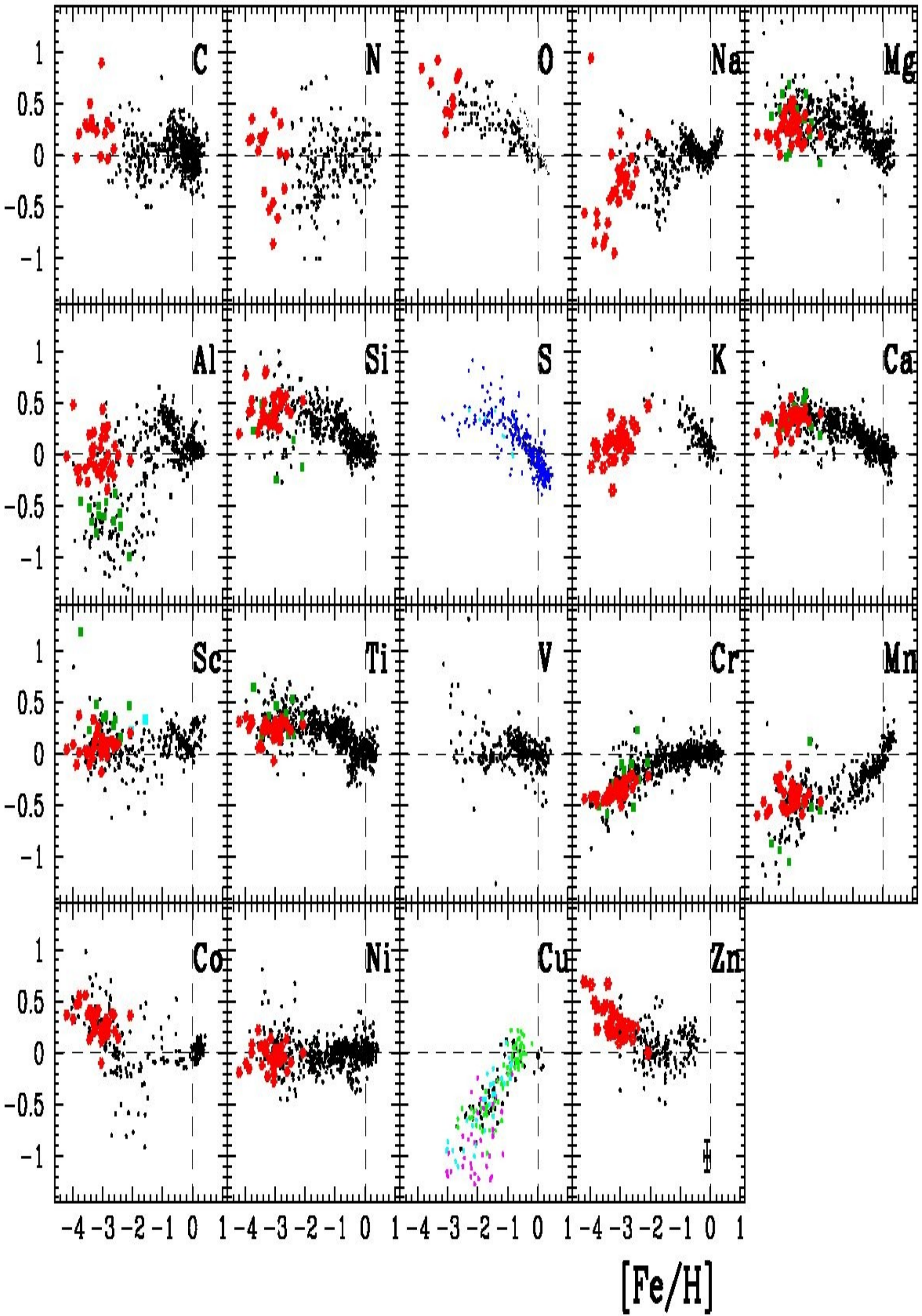
Black Hole Accretion Disks (massive stars as well as neutron star mergers, neutrino properties) ***MacLaughlin, Surman, Wanajo, Janka, Ruffert, Perego***

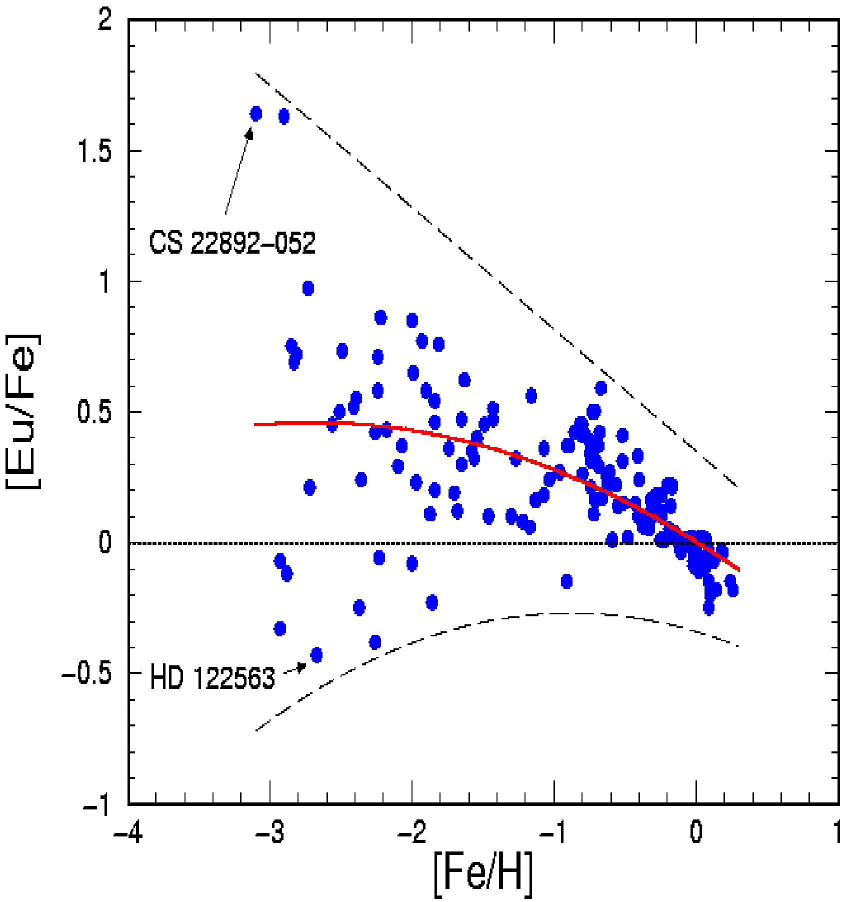
Explosive He-burning in outer shells (???) *Cameron, Cowan, Truran, Hillebrandt, FKT, Wheeler, Nadyozhin, Panov*

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***

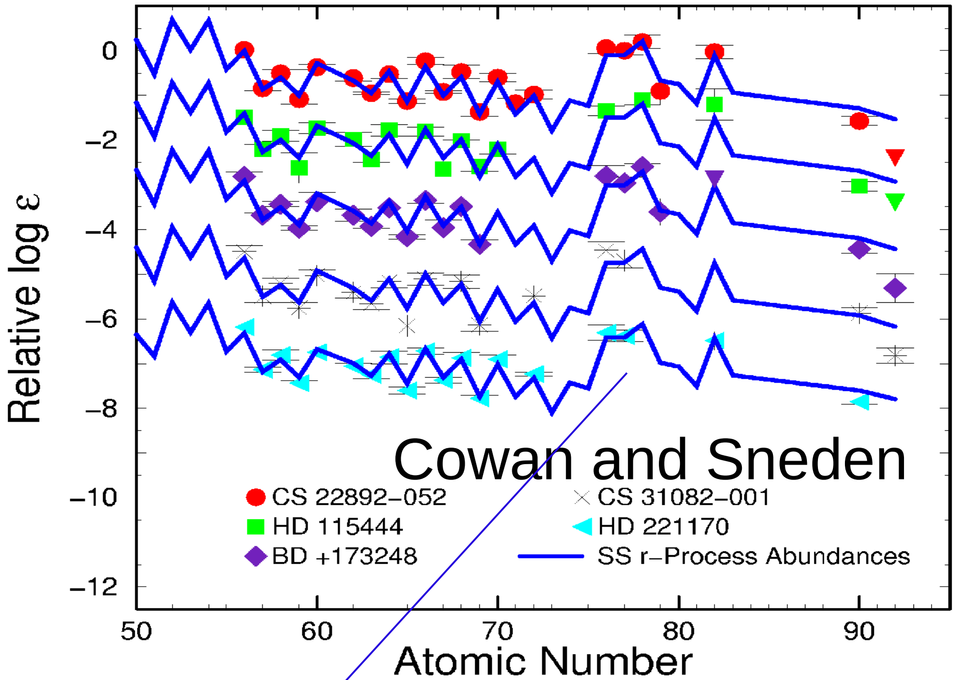
How do we understand: low metallicity stars ... galactic evolution?





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

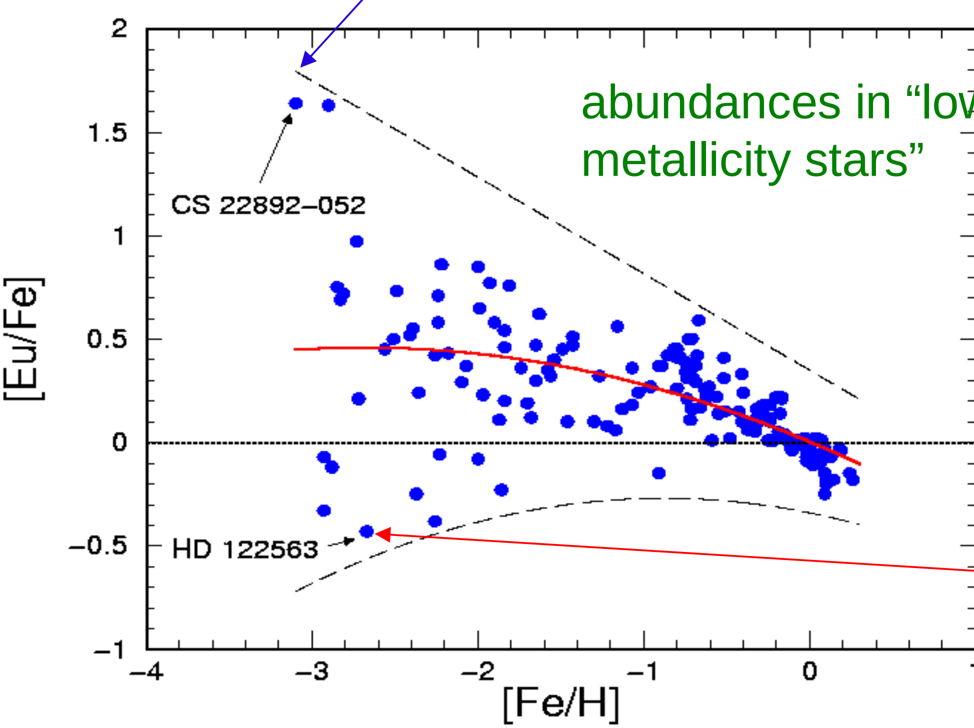
Observational Constraints on r-Process Sites



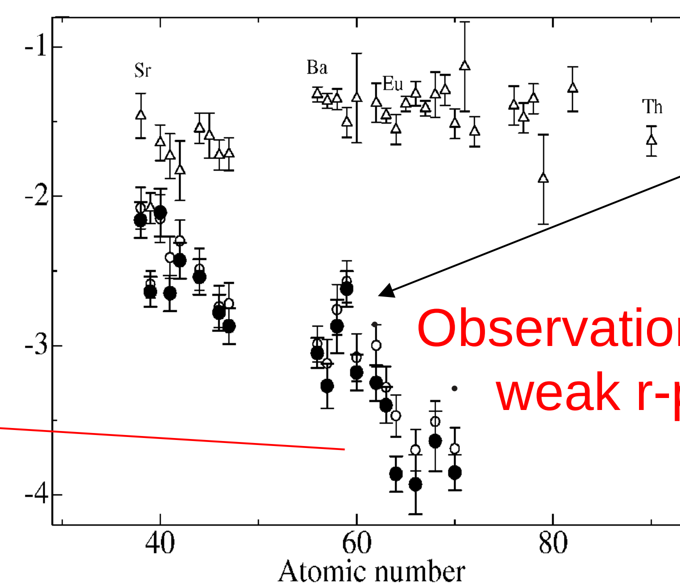
apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

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?



abundances in “low metallicity stars”

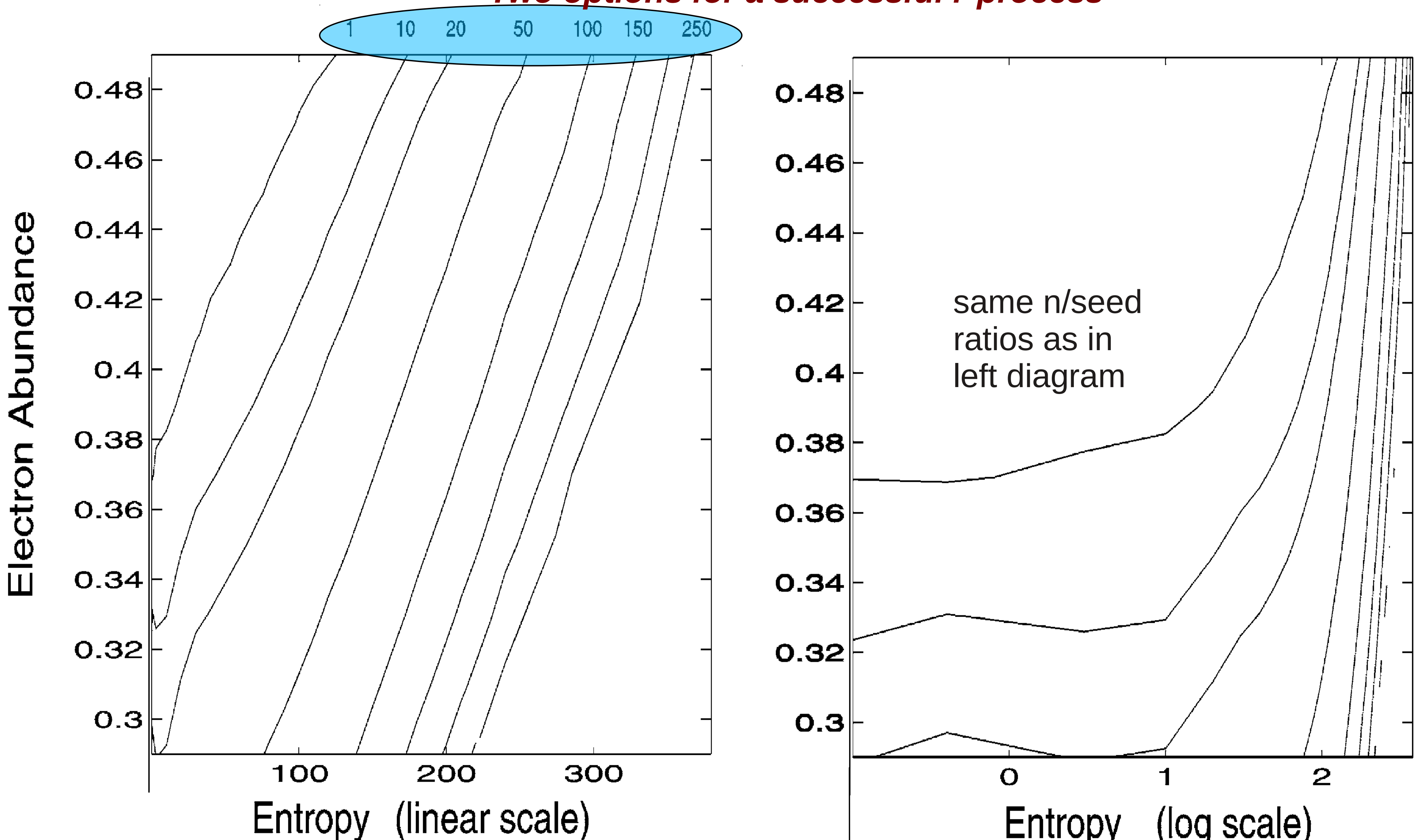


Honda et al. (2007)

Observations of a/the? weak r-process?

n/seed ratios as function of S and Y_e

Two options for a successful r-process



Freiburghaus et al. (1999)

neutrino wind?

Neutron star mergers / polar jets?

One more: 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 ?

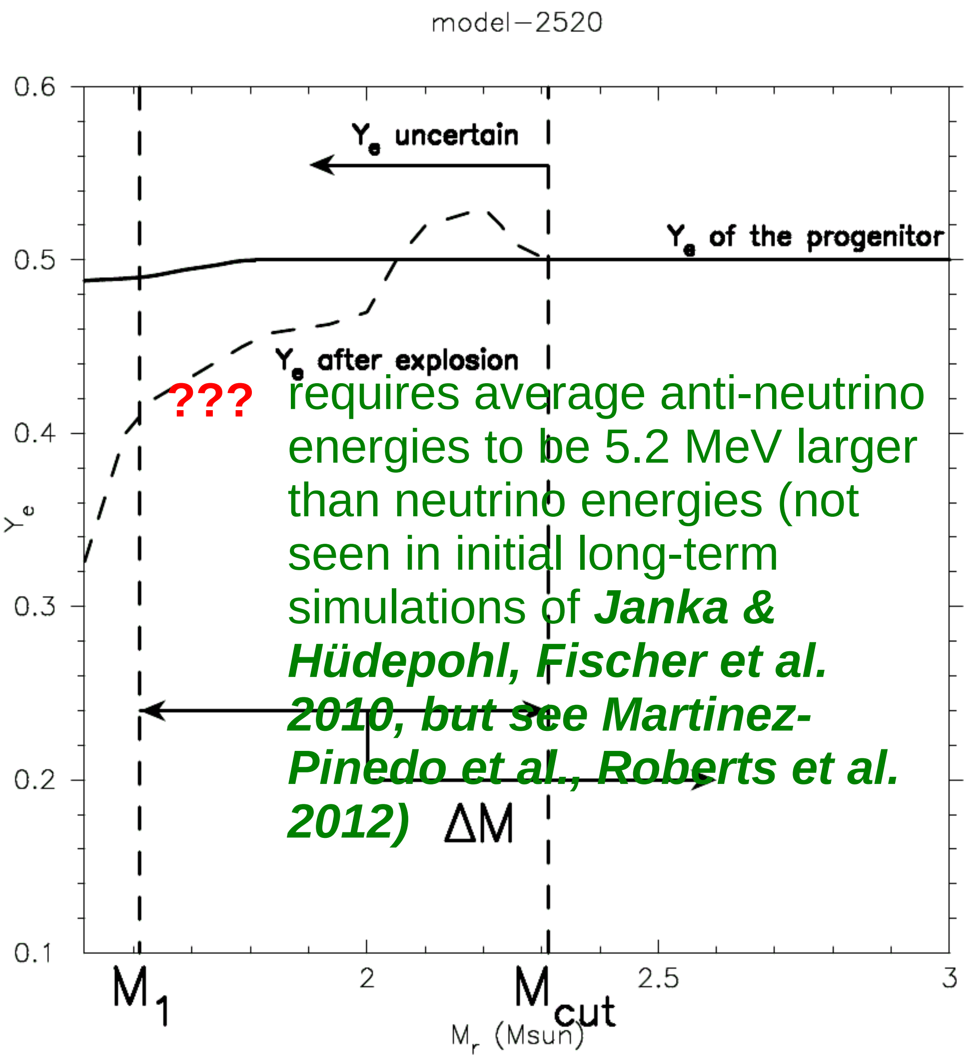
If neutrino flux sufficient to have an effect (scales with $1/r^2$), and total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with $E_{av,\bar{\nu}}-E_{av,\nu}>4(m_n-m_p)$ lead to $Y_e<0.5$!

General strategy for a successful r-process:

1. either highly neutron-rich initial conditions + fast expansion (avoiding neutrino interactions!)
2. have neutrino properties (or medium effects for neutrons and protons) to ensure (at least slightly) neutron-rich conditions (+ high entropies)
3. invoke (sterile?/collective) neutrino oscillations

Possible Variations in Explosions and Ejecta

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



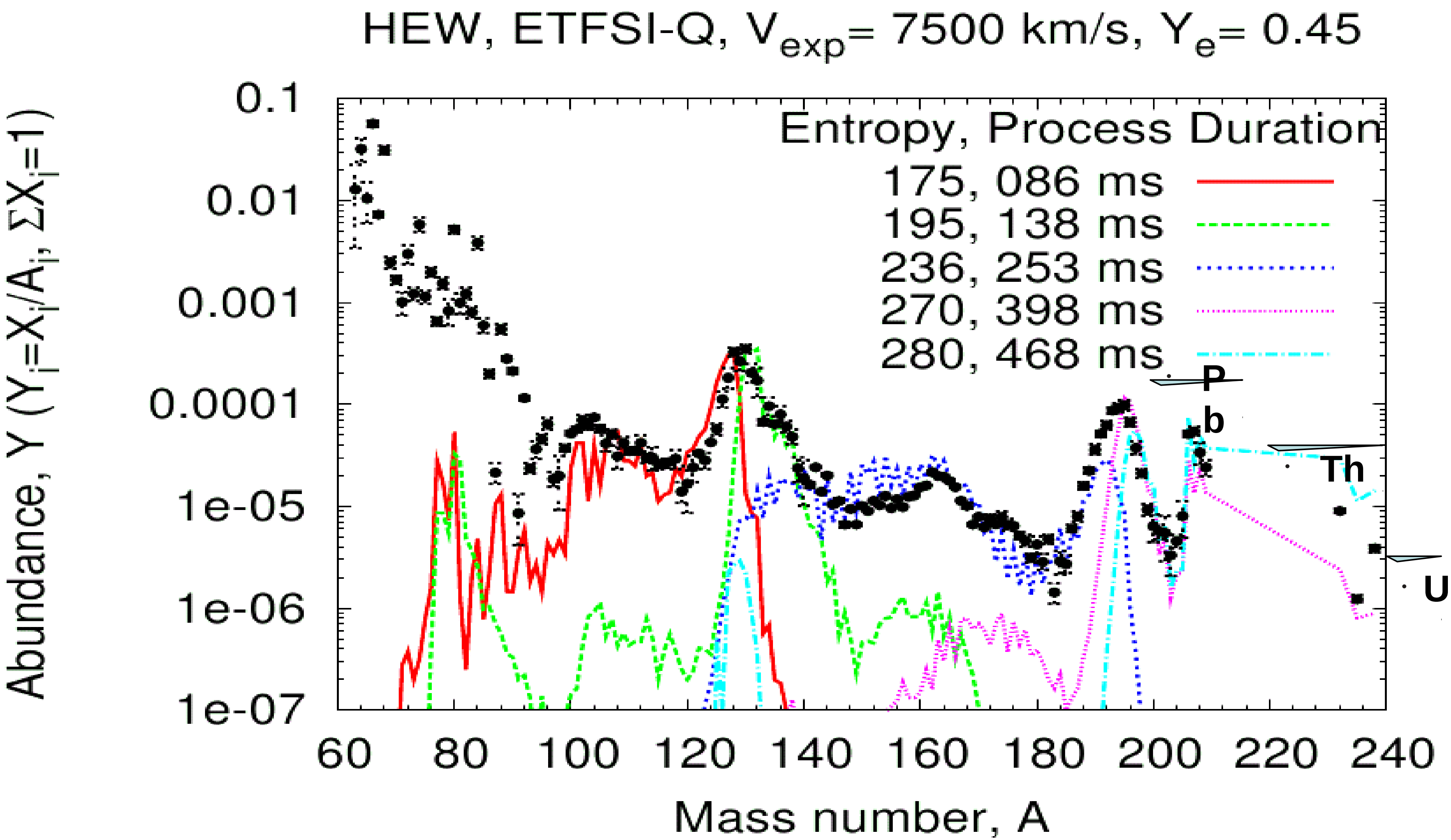
requires average anti-neutrino energies to be 5.2 MeV larger than neutrino energies (not seen in initial long-term simulations of ***Janka & Hüdepohl, Fischer et al. 2010, but see Martinez-Pinedo et al., Roberts et al. 2012)***

Izutani et al. (2009)

- *regular explosions with neutron star formation, neutrino exposure, vp-process (proton-rich!).*
- *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), the inclusion of medium effects for neutrons and protons can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4 (but propobly not sufficient entropies to cause strong r-process)!***
- *under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?*

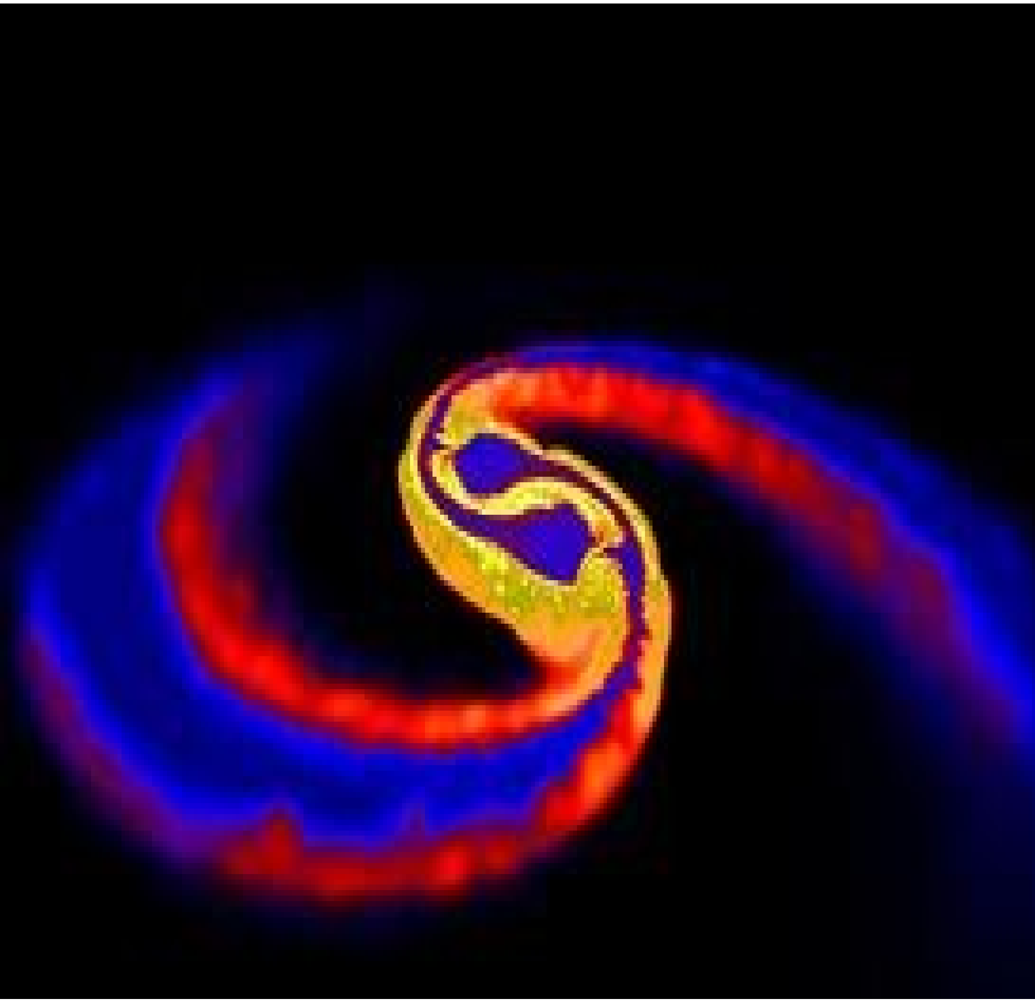
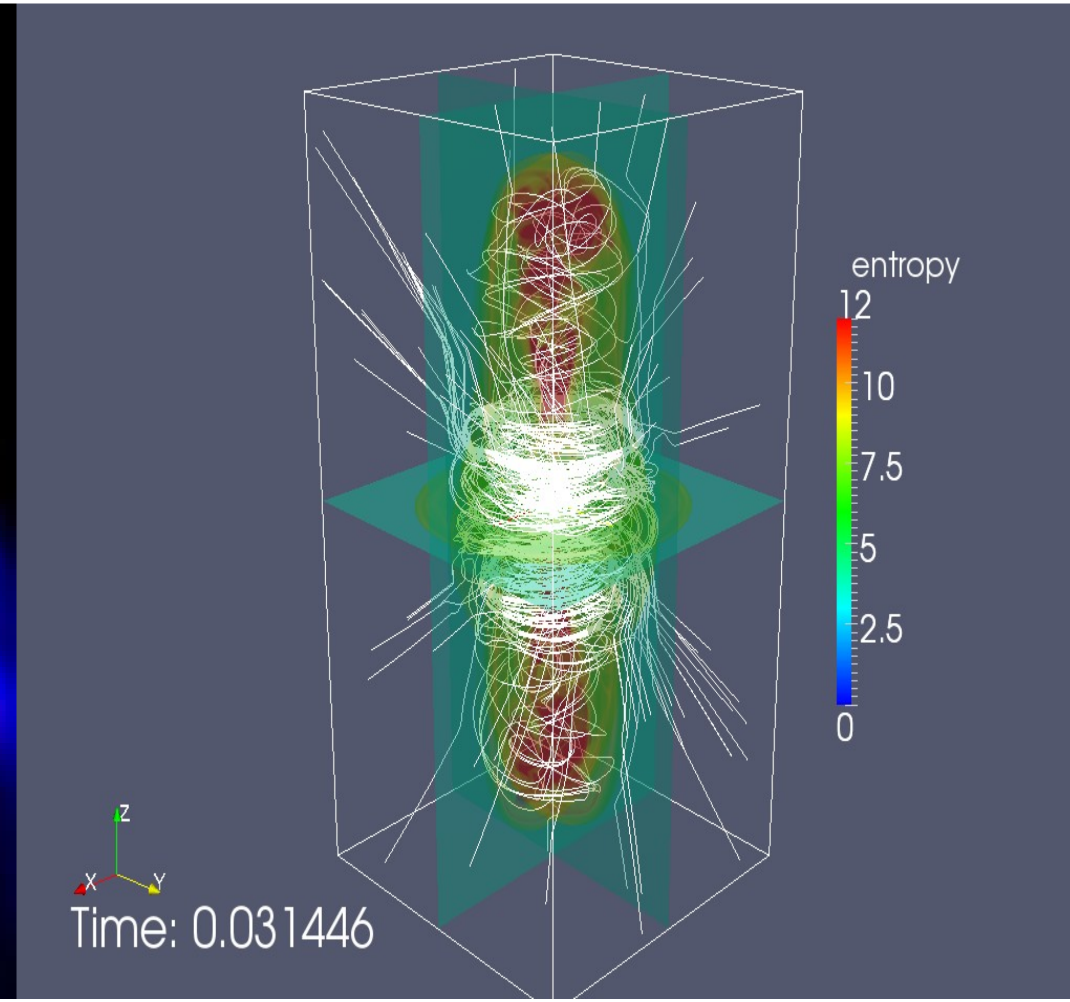
Individual Entropy Components

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



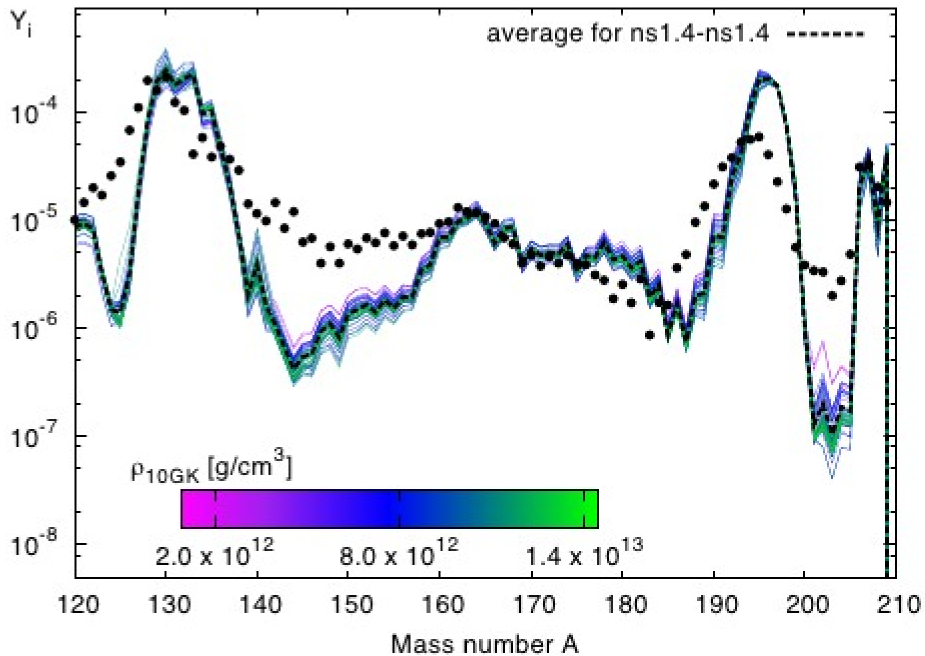
With present knowledge on entropies and Ye, CCSNe could only (if at all!) be the site of a weak r-process (up to Eu, but not up to actinides = Honda style)!

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**

Fission Cycling in Neutron Star Mergers

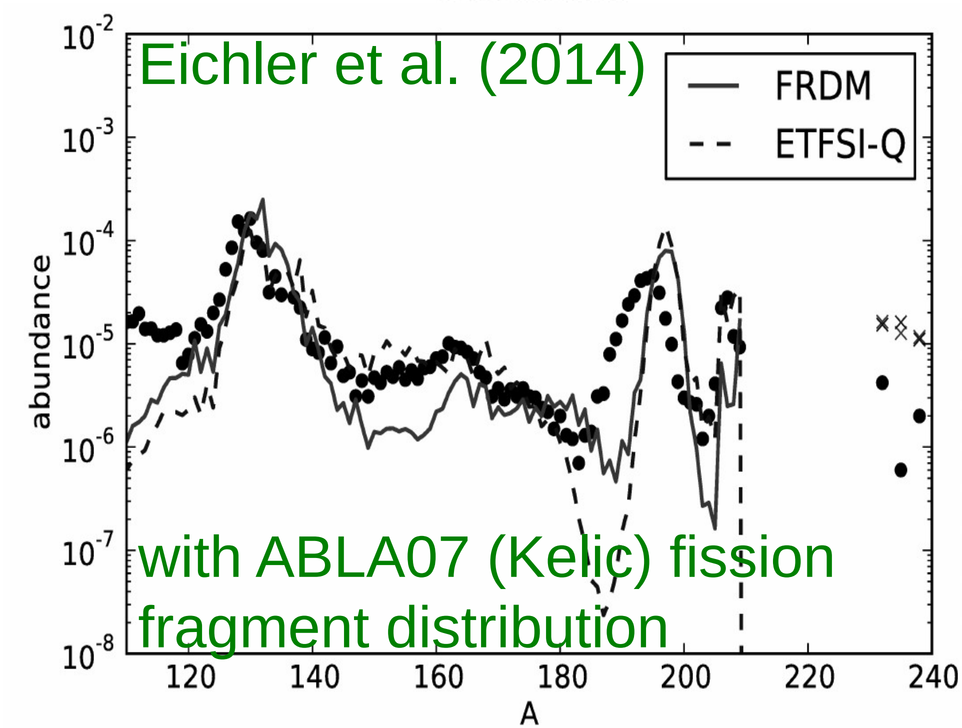


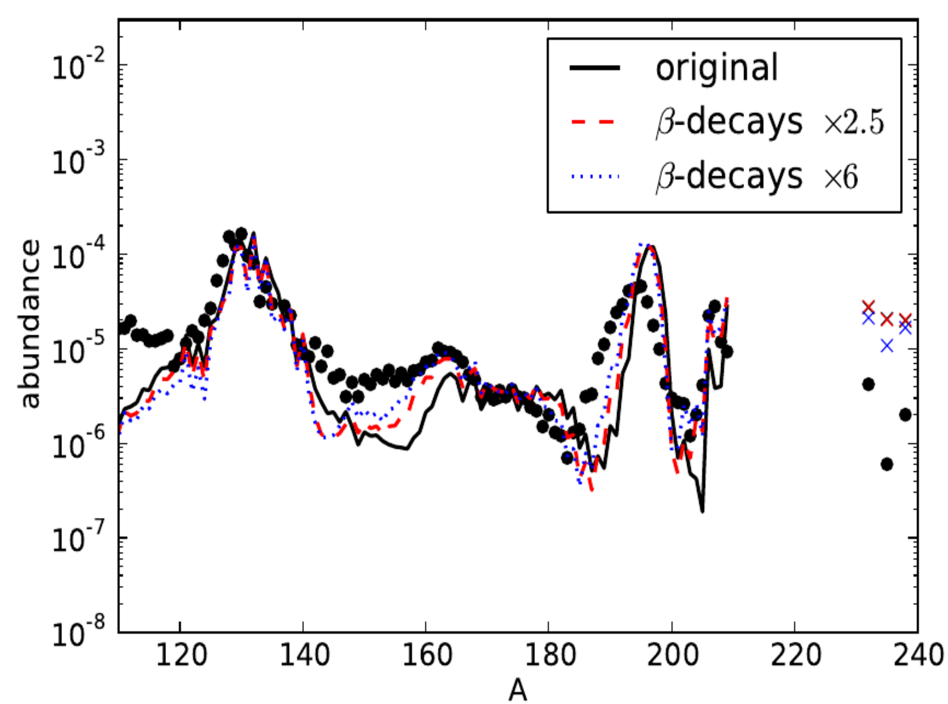
Recent neutron star merger updates (Korobkin et al. 2012)

Variation in neutron star masses

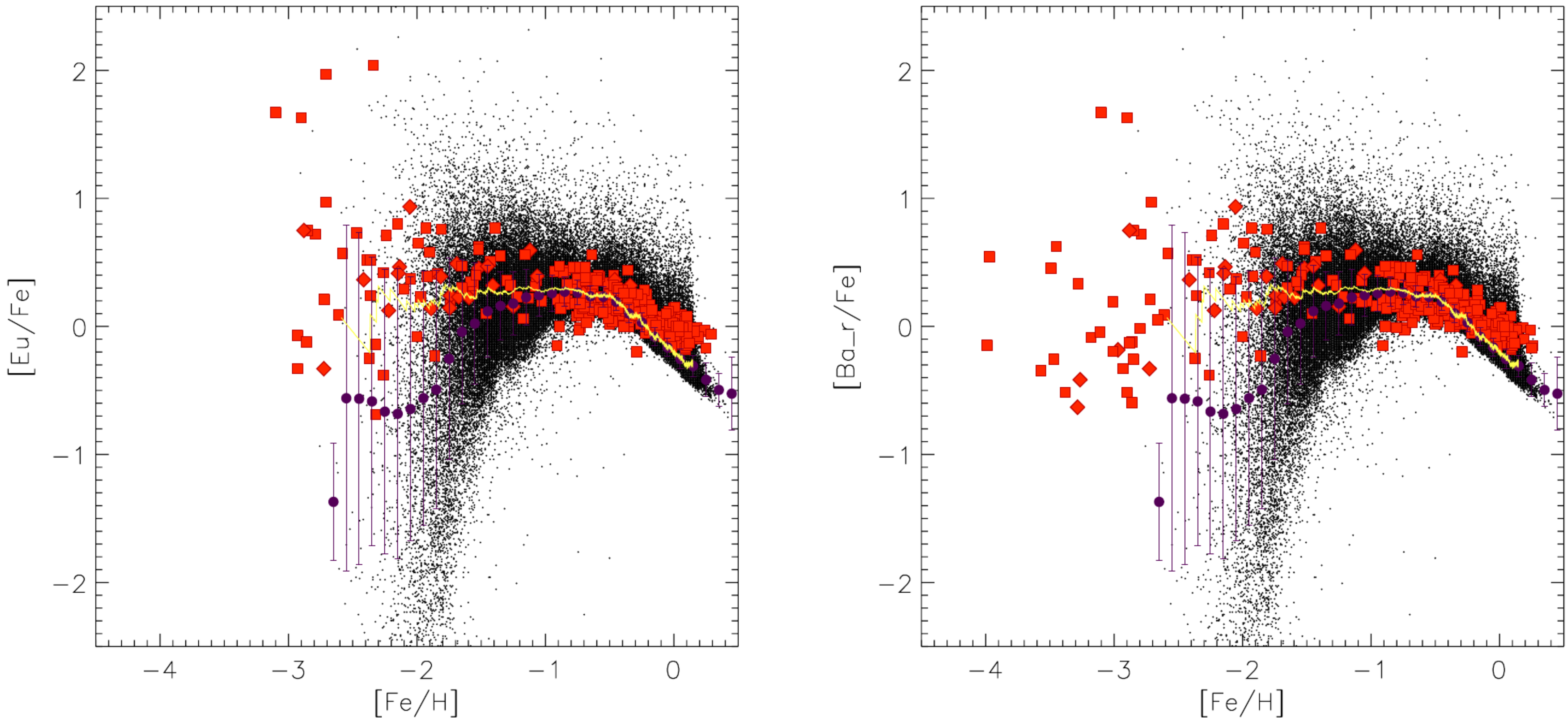
fission yield prescription

Fission yields affect abundances below A=165, the third peak seems always shifted to heavier nuclei (see also Bauswein+ 2012, Goriely+ 2013, Just+ 2014, Wanajo+ 2014, Rosswog+ 2014)



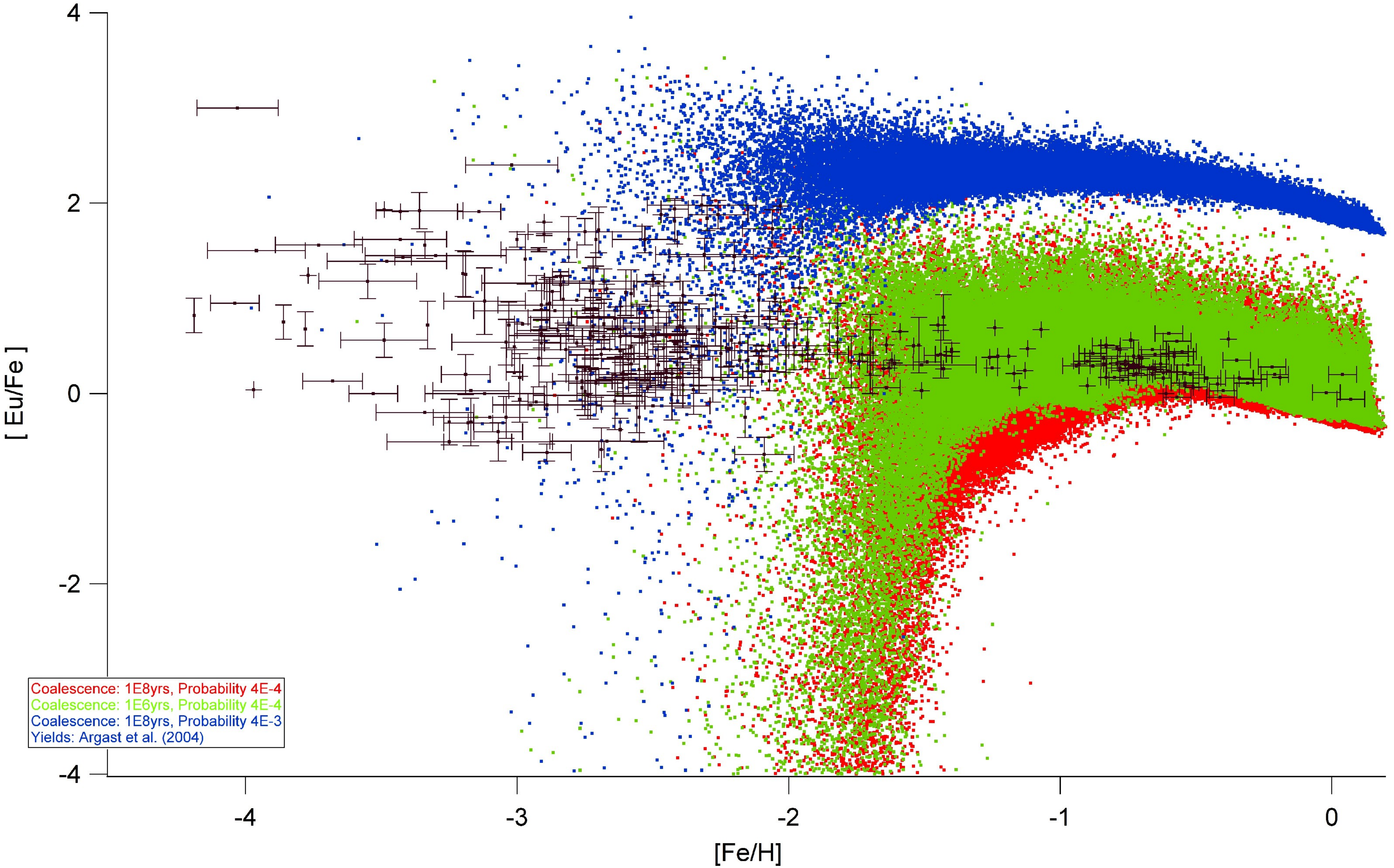


Argast, Samland, Thielemann, Qian (2004): Do neutron star mergers show up too late in galactic evolution, although they can be dominant contributors in late phases?



'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!!!

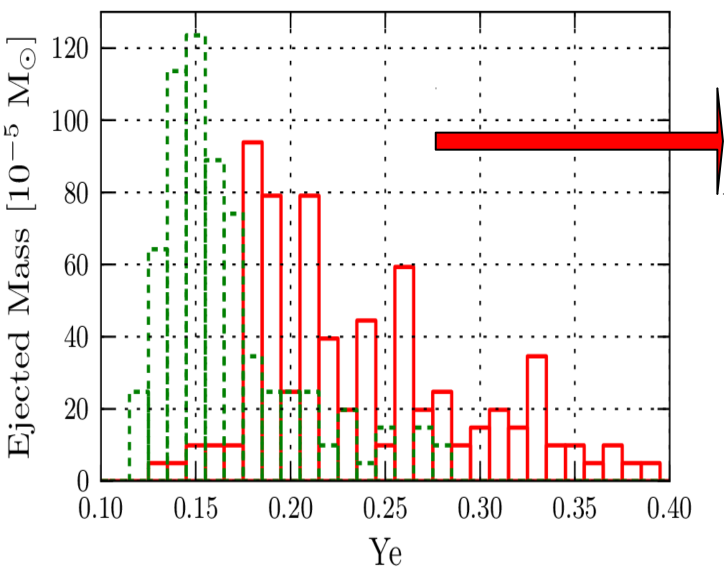


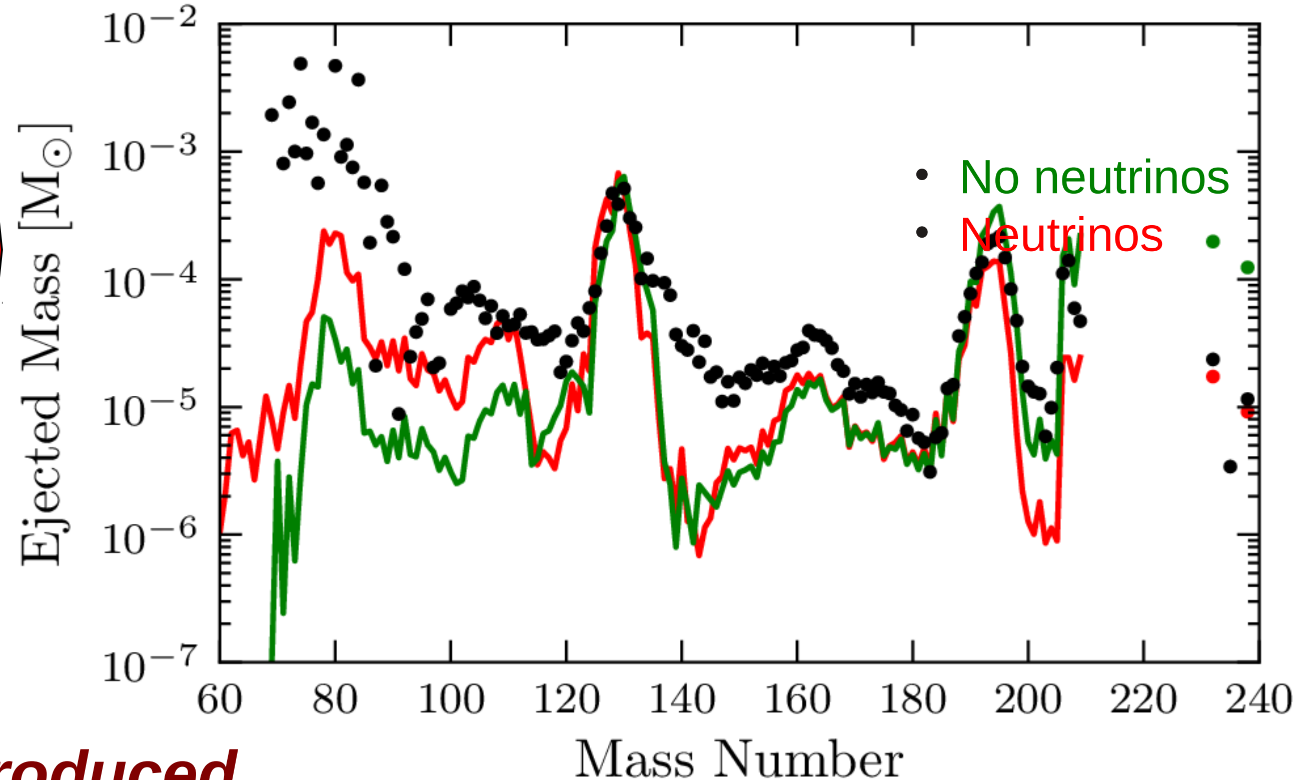
Update by Wehmeyer et al. (2014), green/red different merging time scales, blue higher merger rate (not a solution)

Nucleosynthesis results of MHD jets

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

neutrino effect small opposite to neutrino wind with slow expansion velocities





r-process peaks well reproduced

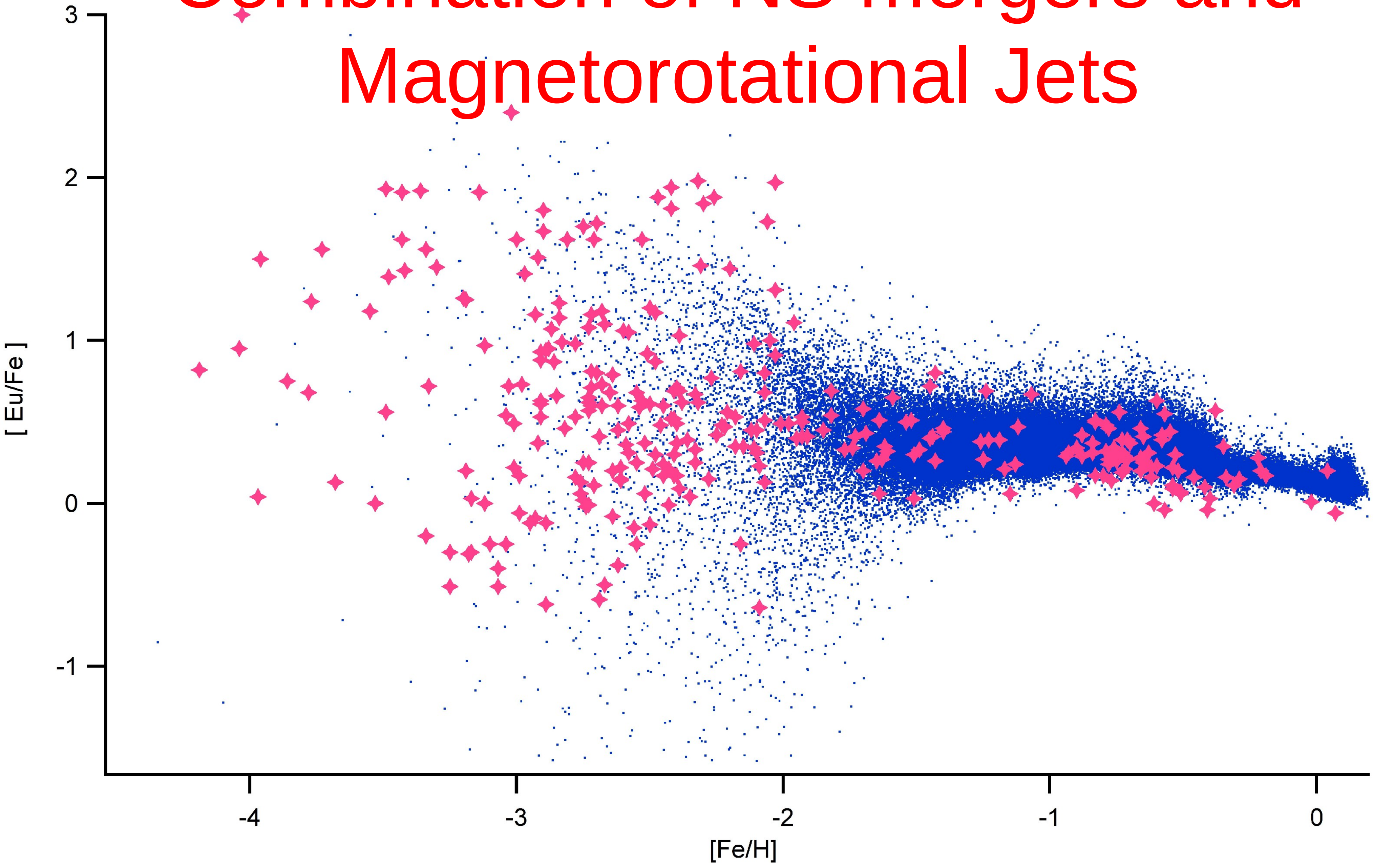
Trough at A=140-160 due to FRDM and fission yield distribution

A = 80-100 mainly from higher Ye

A > 190 mainly from low Ye

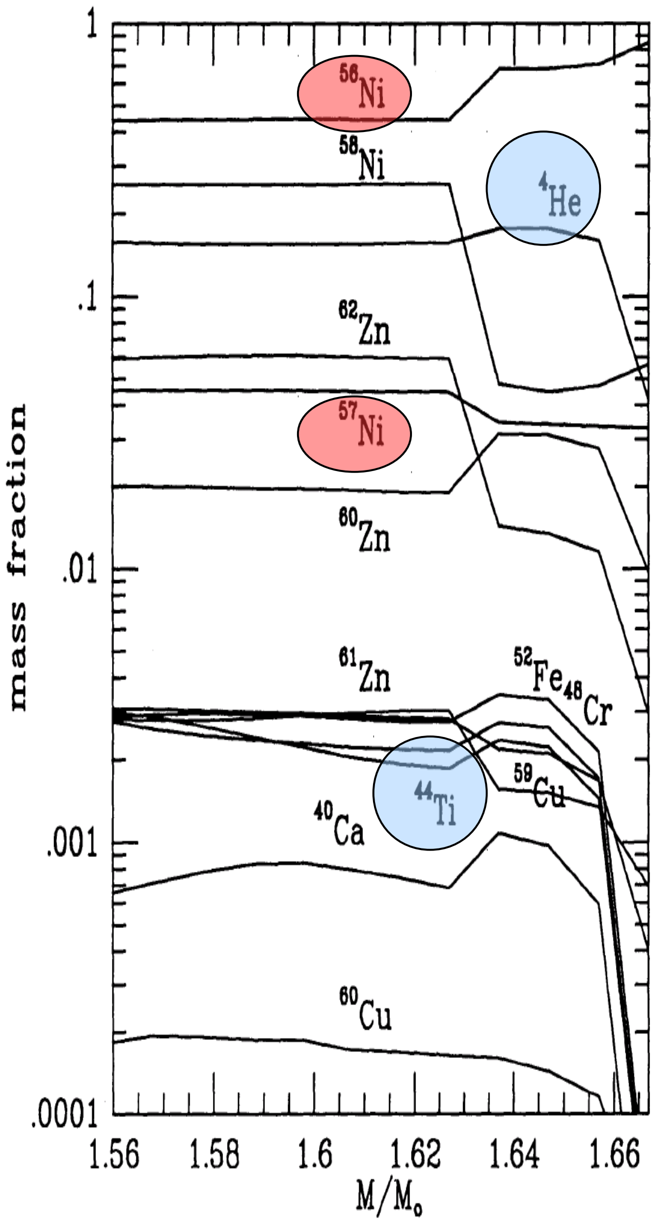
Ejected r-process material (A > 62): $M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_\odot$

Combination of NS mergers and Magnetorotational Jets



Wehmeyer et al. (2014)

Why should the alpha/Fe scatter be smaller for low metallicties than the Eu/Fe scatter?



explosive Si-burning (alpha-rich)

Products of explosive burning (20Msol star)

Fe-group composition depends on Y_e, explosion Energy, and entropy (alpha-rich freeze-out)

Is there a chance to provide a reliable data base from supernova observations for ^{56}Ni, ^{57}Ni and ^{44}Ti? This would provide an enormous help for understanding the (bulk) innermost ejecta and thus the explosion mechanism and conditions

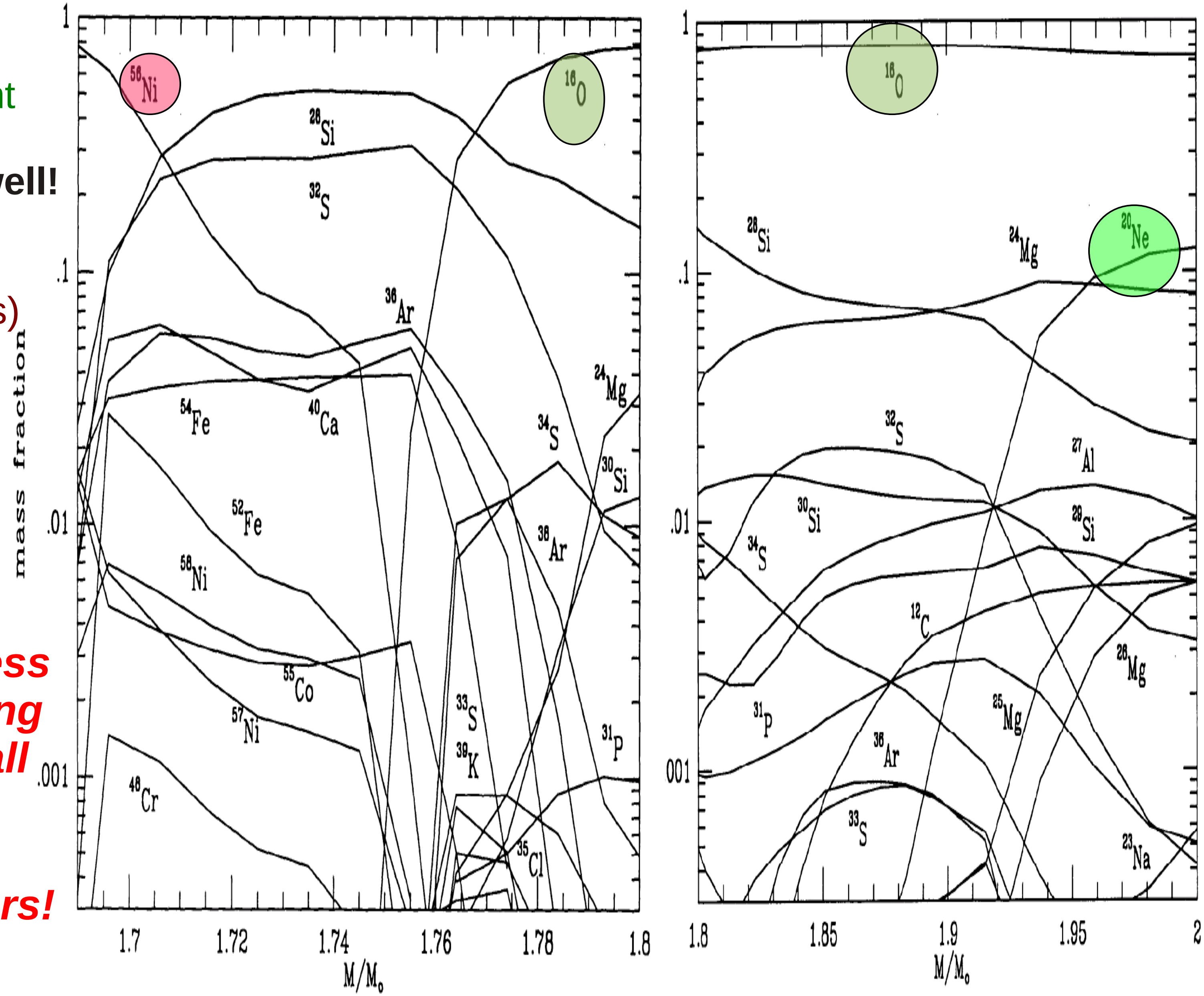
Larger explosion energies would/could produce higher Ni(Fe) masses!

Products of explosive burning (20Msol star)

The amount of Si, S, Ar, Ca is essentially only dependent on the explosion energy,
The amount of Ni(Fe) as well!

O, Ne, and Mg (ejected hydrostatic burning products) depend strongly on the progenitor mass!

If the explosion energy depends on compactness of stellar core, increasing with progenitor mass, all can go together and alpha/Fe is not varying strongly with progenitors!



Explosive Si-burning (incomplete), O- and Ne-burning

Two of maybe a number of major questions

While probably from [Fe/H]=-2.5 on, we might have a well mixed ISM (and an average of results from stars over the whole IMF), this should not be the case at smaller metallicities. Interpreting abundance trends there in terms of yields as a function of progenitor mass from homogeneous galactic evolution models is dangerous.
One should treat lower metallicities with inhomogeneous evolution models.

But, if we have nucleosynthesis variations among supernovae of different mass, we would expect then also a large scatter in these elements (e.g. alpha-elements) at low metallicities. Why do we not see that? Maybe our present nucleosynthesis yields of supernovae, all artificially induced with 1 or 1.2 Bethe, rather than varying with progenitor mass and compactness, are incorrect!

Possible explanation: We might actually see individual remnants, which have their [Fe/H] from a supernova with a specific explosion energy. If the family of CCSNe has a smooth behavior, i.e. more energetic explosions (varying with compactness and progenitor mass) give more Fe and also more (explosive as well as hydro-static) alpha-elements, their ratio still stays close to constant and exhibits the observed behavior!!

In addition: The explosion energy also determines the metallicity where these remnants would be seen in [Fe/H] (more energetic explosions mix with more ISM).

But why then a large scatter for other elements?

This smooth behavior e.g. with explosion energy (and [Fe/H]) would only be established, if it results from a smoothly varying family of sources, like CCSNe.

If two very different sources contribute, one of them possible without sizable Fe-production, a large scatter would show up. This is the case for the r-process!!!

Thus, a possible explanation of the r-process pattern could be obtained via a relatively continuous (Honda-type) production in CCSNe, which does not produce heaviest r-nuclei. In addition, rare but efficitent objects like neutron star mergers or core collapse jets (also with negligible Fe-production in comparison to Eu) contribute the full/heavy r-process in a rare fashion. The solar average is only established at about [Fe/H]=-2.5, when we have a well mixed ISM. It is important to find out, whether Honda-type events are pure events or already a mixture of two sources (see Arcones).

These individual contributions should also be analyzed for their specific features (e.g. Sr/Eu, Ba/Eu etc., see Mashonkina)