Nucleosynthesis of Massive Stars and Their Supernovae:

an attempt to put the finger on open questions....

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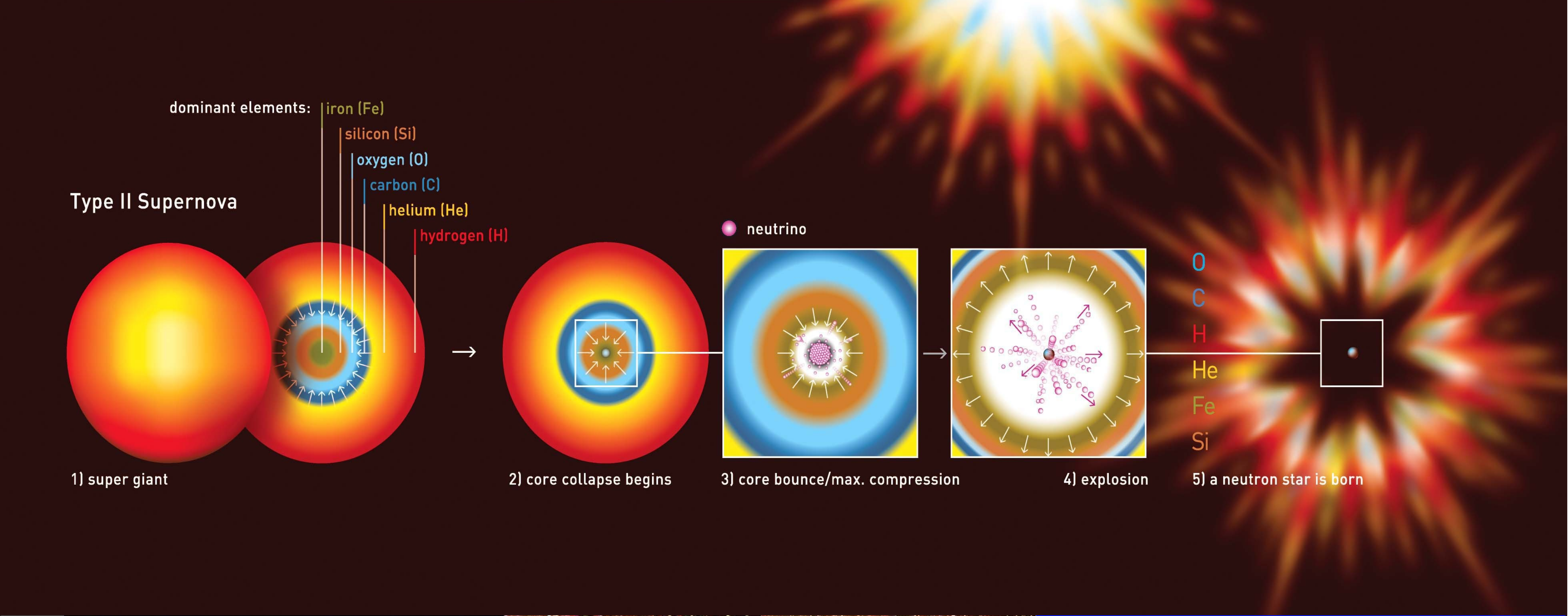

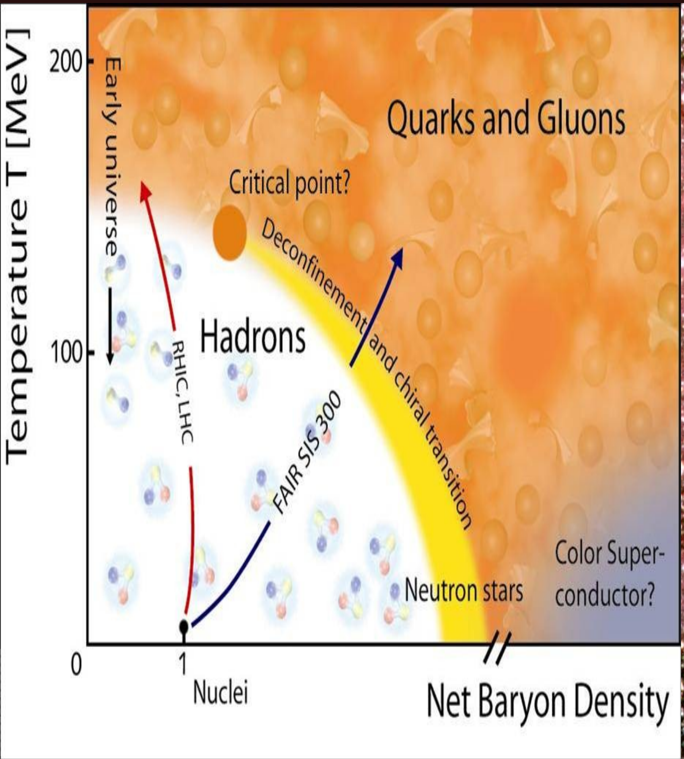

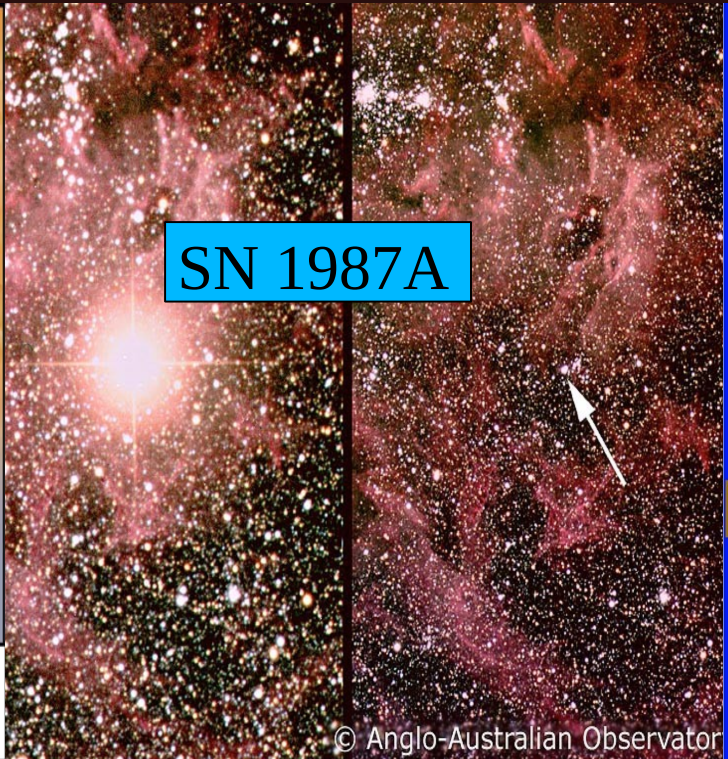

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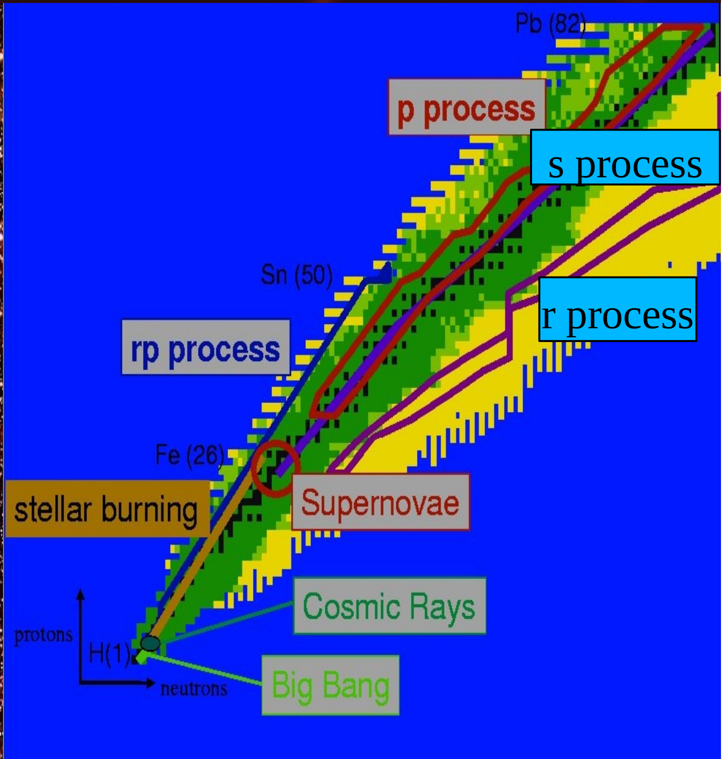
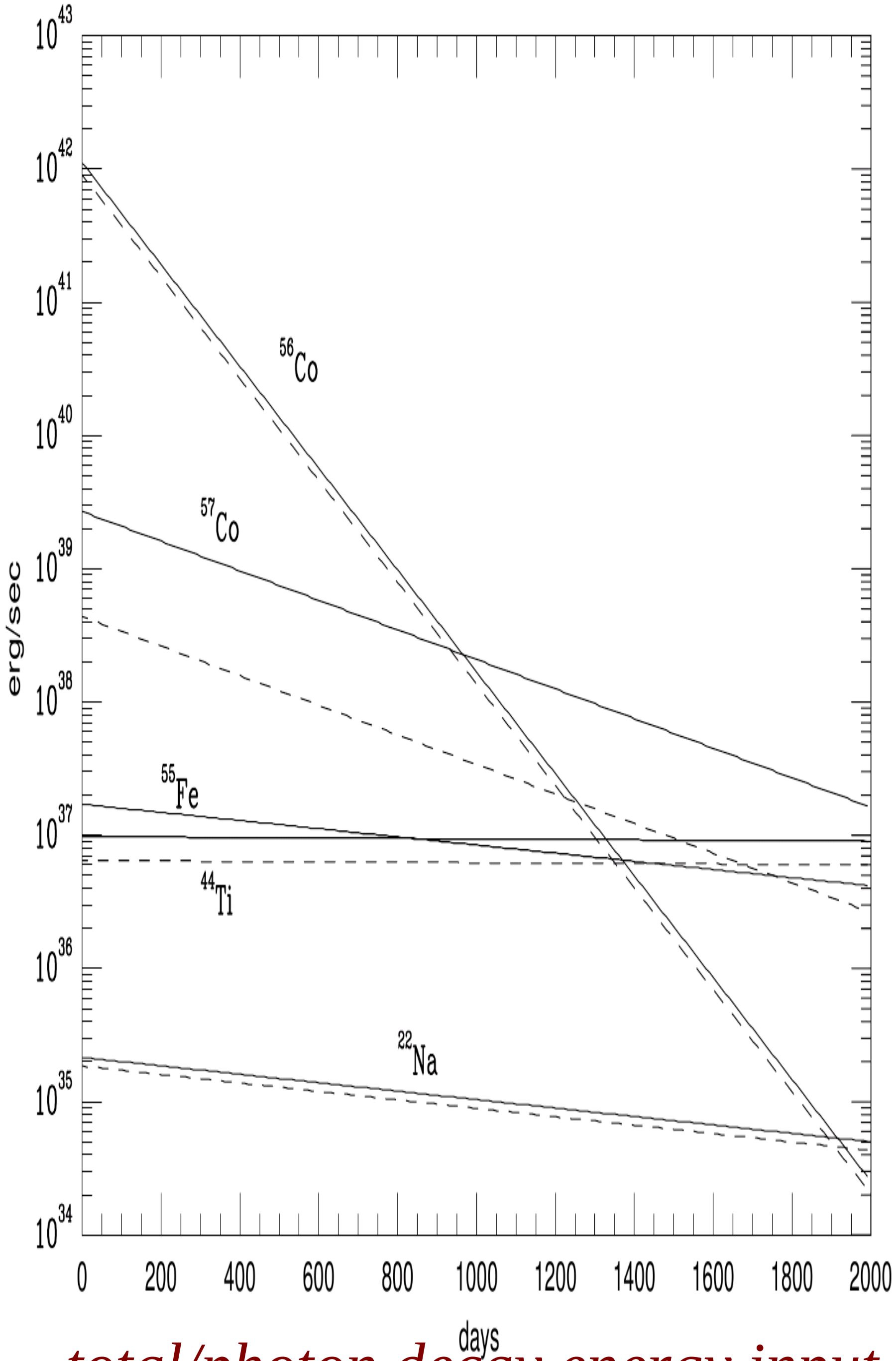
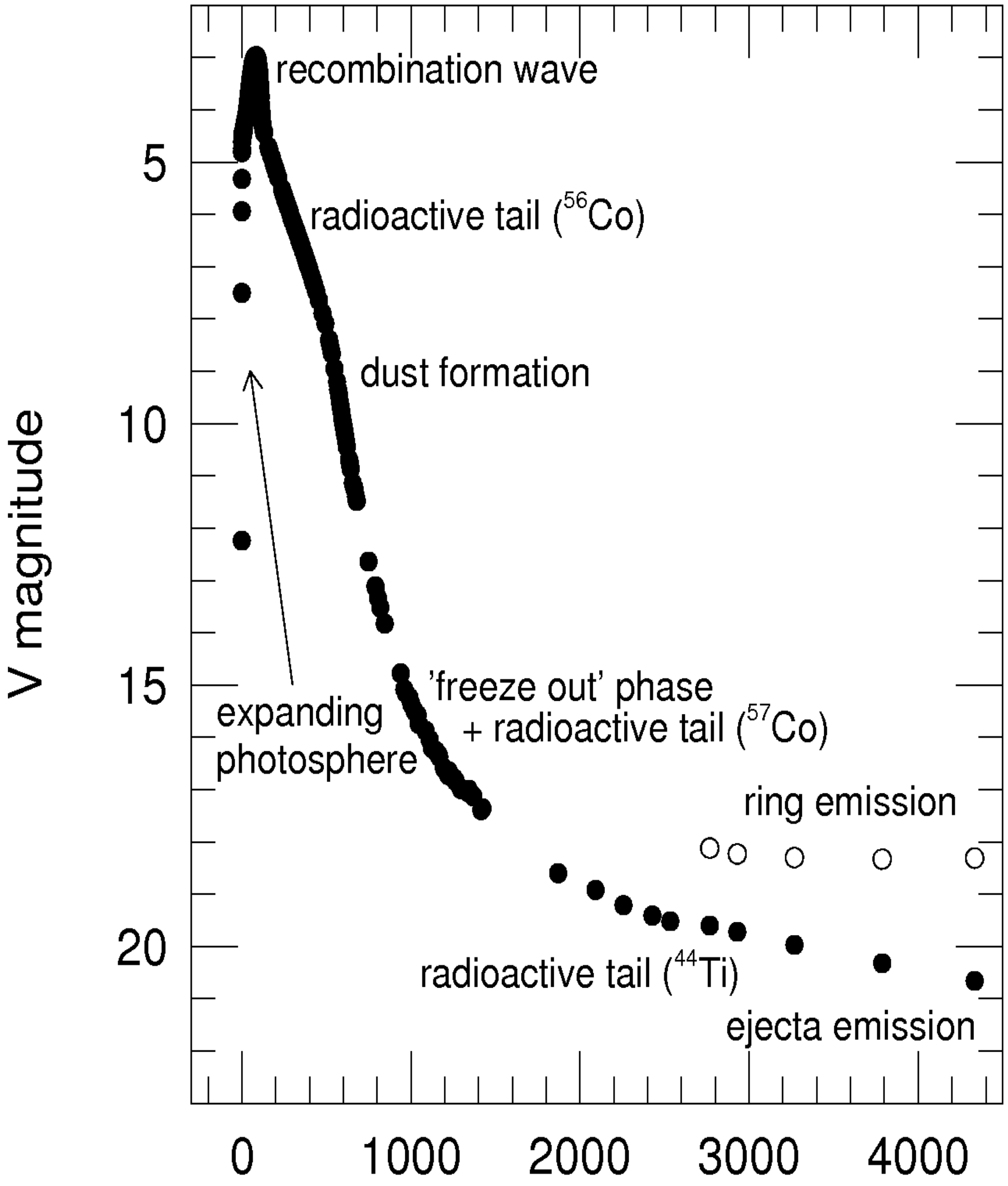


Radioactivity Diagnostics of SN1987A: ^{56}Ni/Co, ^{57}Ni/Co, ^{44}Ti

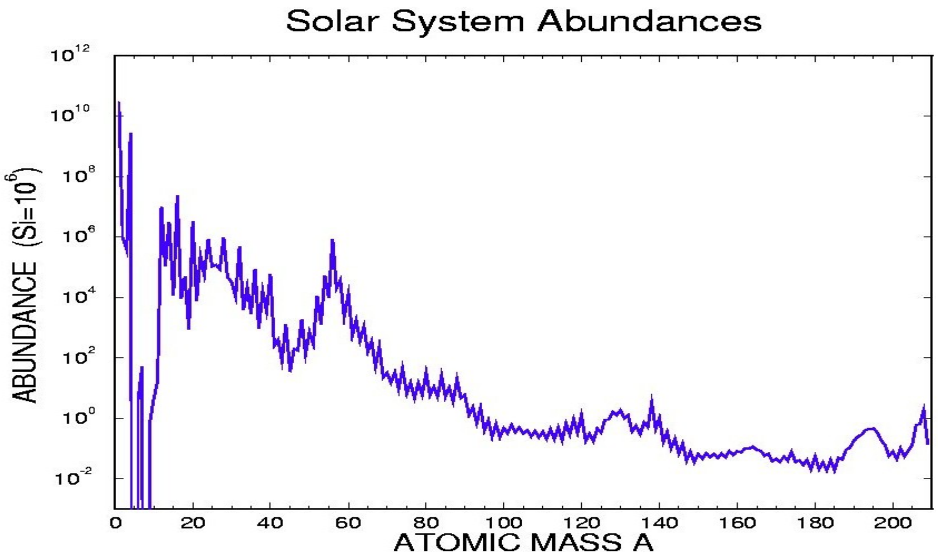


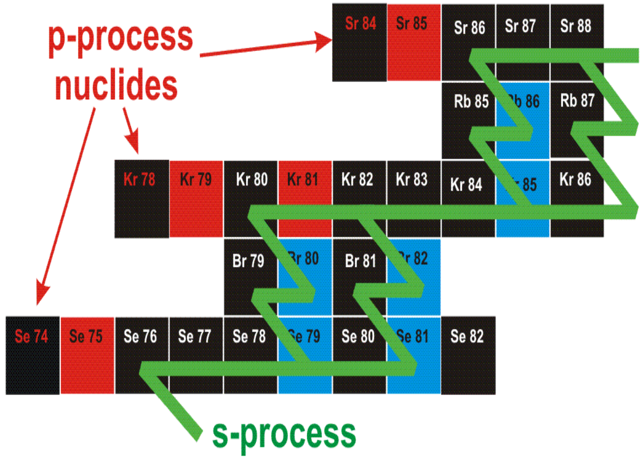
total/photon decay energy input



Leibundgut & Suntzeff 2003

Solar System Abundances and Decomposition of the heavy elements





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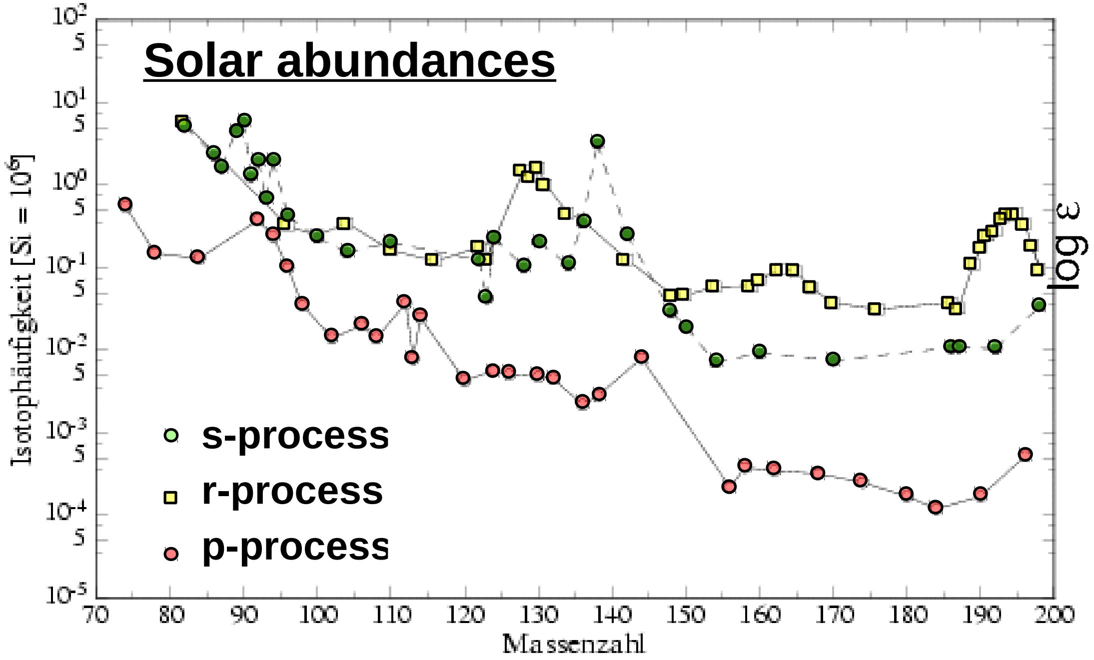
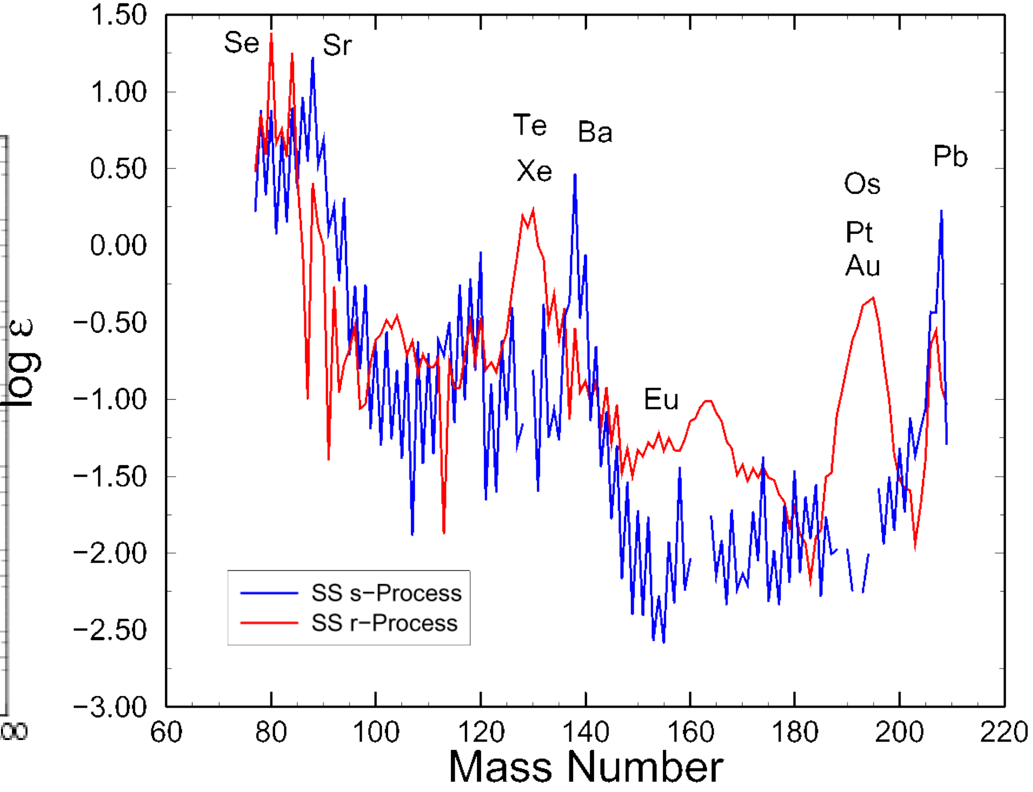




How do massive stars contribute to s-, r-, and p-process abundances?

Brief Summary of Burning Stages (Major Reactions)

1. Hydrogen Burning T = $(1\text{-}4)\times10^{7}$K

pp-cycles -> $^{1}H(p,e^{+}\nu)^{2}H$

CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$

2. Helium Burning T=$(1\text{-}2)\times10^{8}$K

$^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C((\alpha,n)^{16}O)$

3. Carbon Burning T=$(6\text{-}8)\times10^{8}$K

$^{12}C(^{12}C,\alpha)^{20}Ne$ $^{23}Na(p,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$ $^{23}Na(p,\gamma)^{24}Mg$

4. Neon Burning T=$(1.2\text{-}1.4)\times10^{9}$K

$^{20}Ne(\gamma,\alpha)^{16}O$

$^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$ 30kT = 4MeV

5. Oxygen Burning T=$(1.5\text{-}2.2)\times10^{9}$K

$^{16}O(^{16}O,\alpha)^{28}Si$ $^{31}P(p,\alpha)^{28}Si$

$\ldots\ldots,p)^{31}P$ $\ldots,n)^{31}S(\beta^{+})^{31}P$ $^{31}P(p,\gamma)^{23}S$

6. “Silicon” Burning T=$(3\text{-}4)\times10^{9}$K

(all) photodisintegrations and capture reactions possible

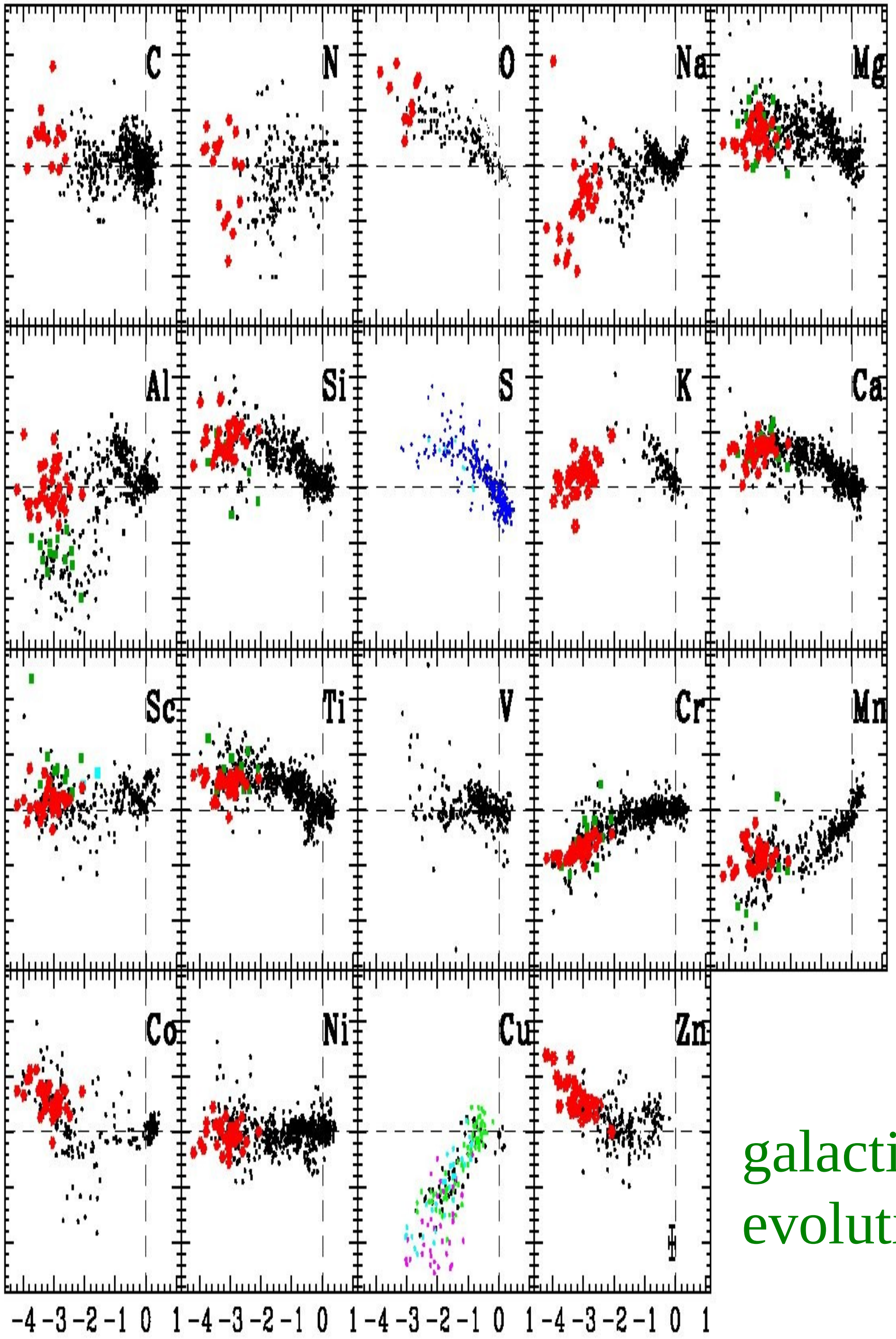
⇒ thermal (chemical) equilibrium

ongoing measurements of key fusion reactions at low energies

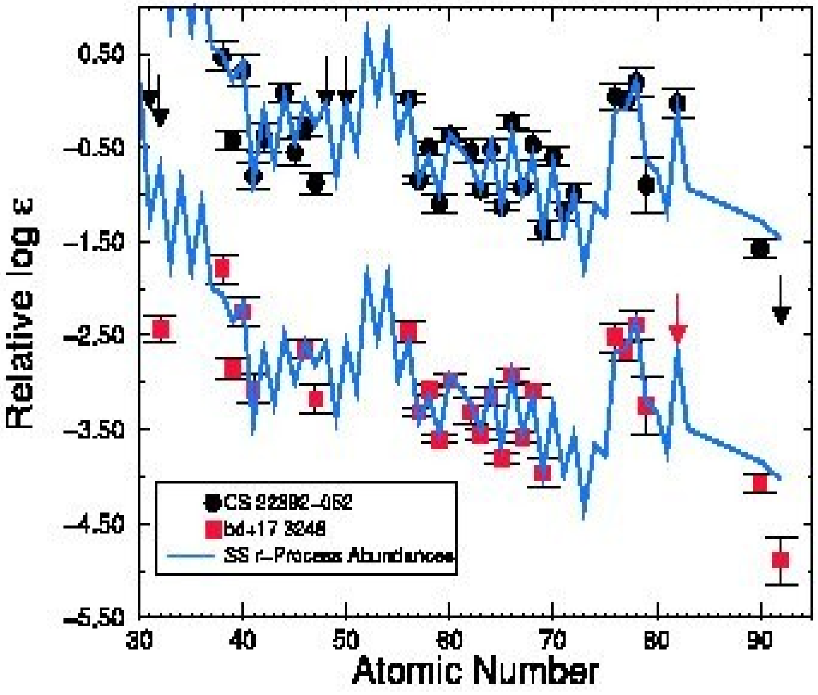
proton/nucleon Ratio Ye decreases with enrichment of metals!!

proton/nucleon Ratio Ye decreases with enrichment of metals!!

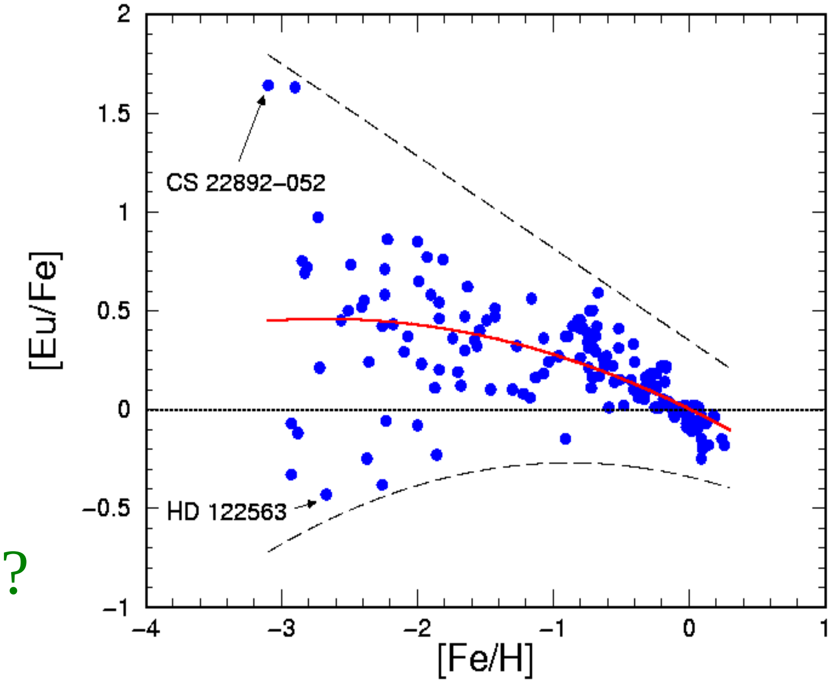
How do we understand:



galactic evolution?

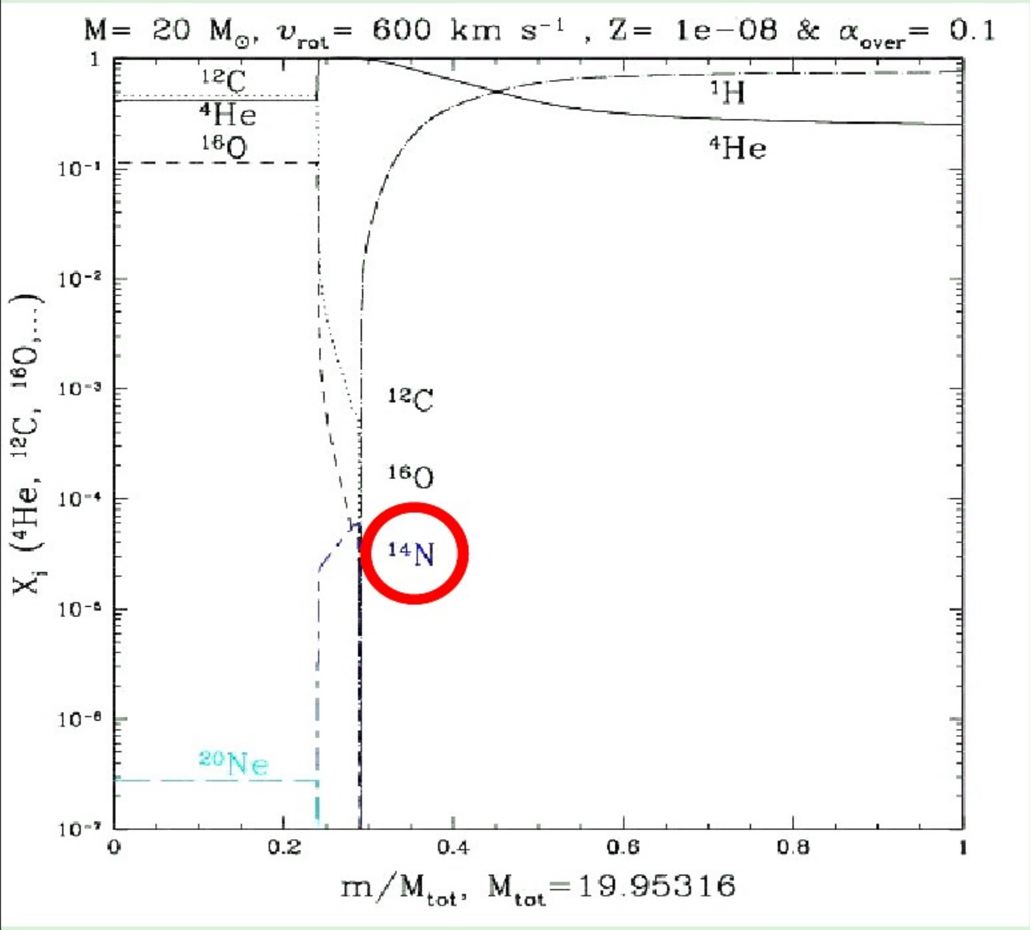


low metallicity stars ...

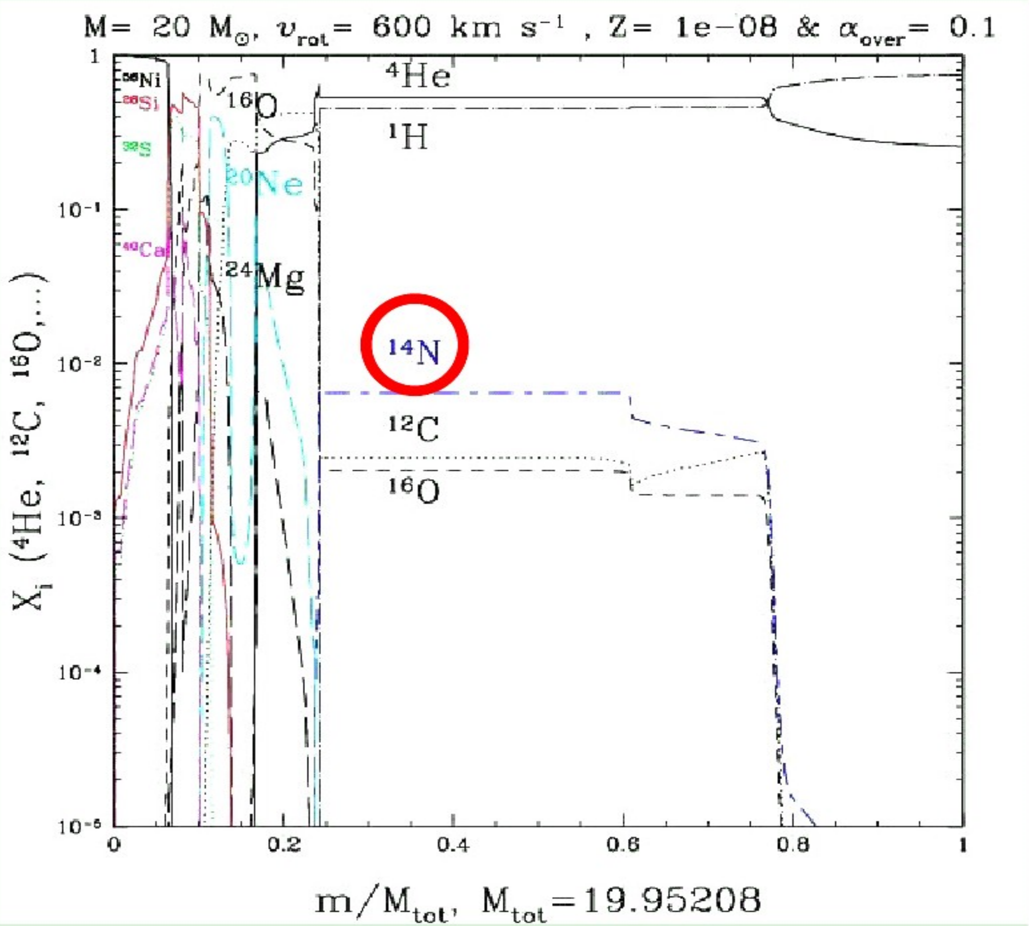


Rotation induced mixing @ low Z

Before H-shell boost



Pre-SN stage



rotation produces primary nitrogen and later ^{22}Ne => enhances mass loss and s-process source

s-Processing in rotating low-metallicity stars, $Z=10^{-5}$

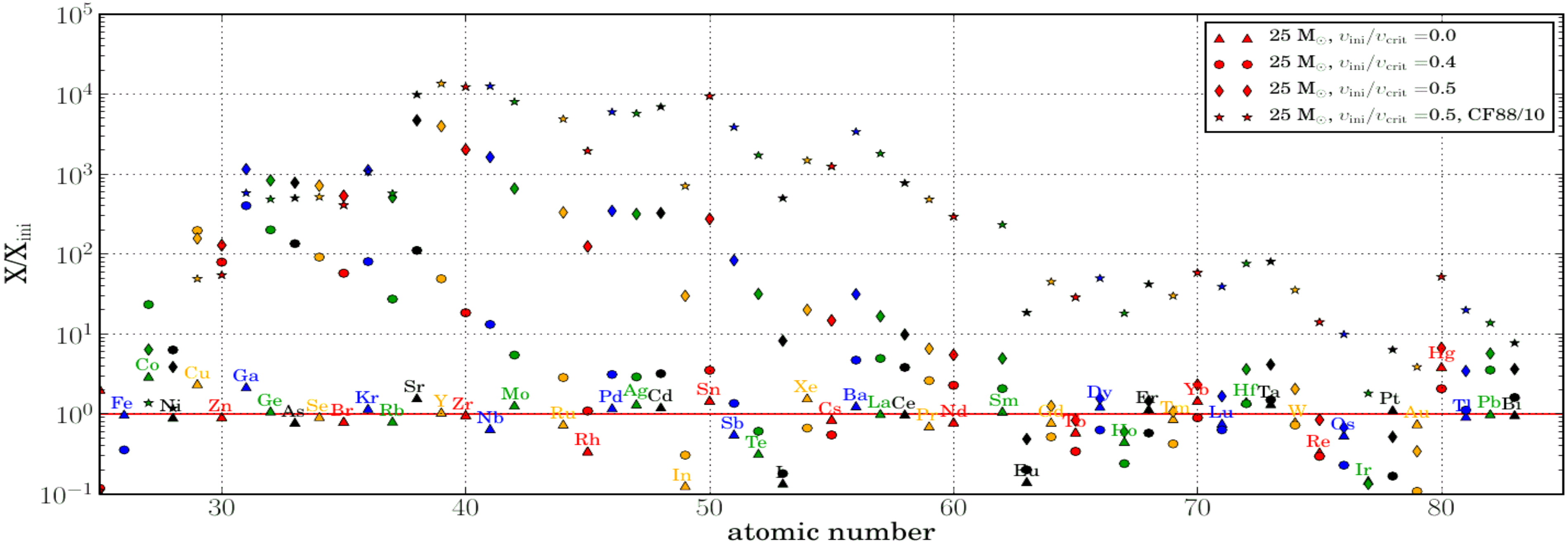


Fig. 1. Overproduction factors (abundances divided by their initial values) for the 25 M⊙ models with $Z = 10^{-5}$ after the end of core He-burning. The model without rotation (triangles) does not produce s-process efficiently whereas the rotating models (filled circles, B1 and diamonds, B3) produce significant quantities of s-process. The additional rotating models with reduced $^{17}O(\alpha, \gamma)$ rates (B4, CF88/10) highlights the uncertainty linked to the neutron poison ^{16}O.

Dependence on rotation and ^{16}O neutron poison via $^{16}O(n,\gamma)^{17}O(\alpha,\gamma)$ or $^{17}O(\alpha,n)$ (Frischknecht, Hirschi, Thielemann 2012)

Core Collapse Supernovae

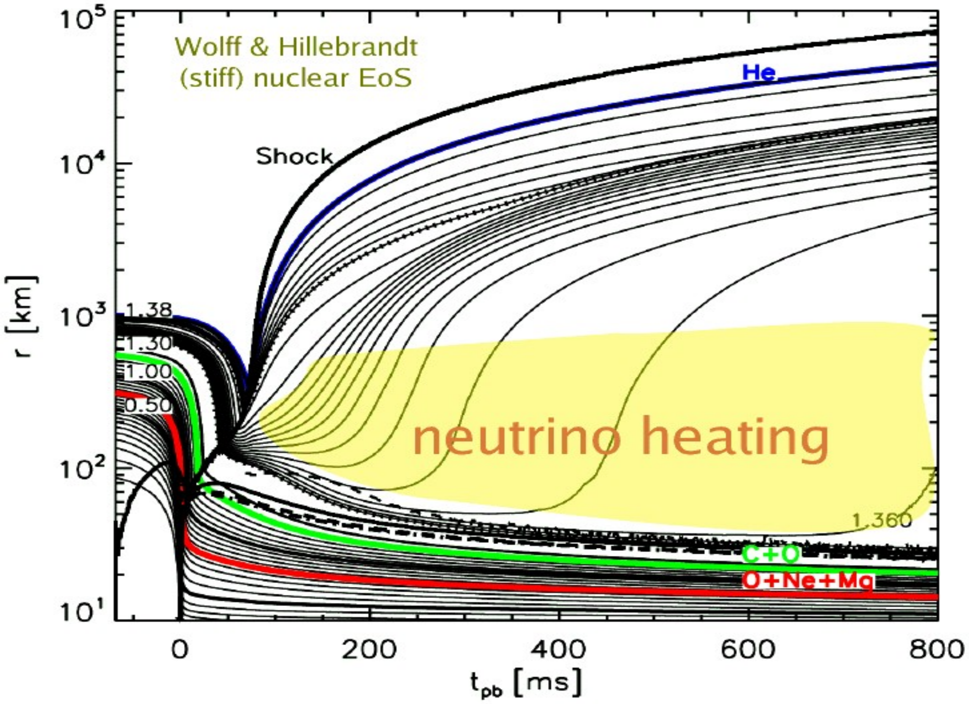
- (The Supernova Mechanism)
- The p-process
- The role of neutrinos (and the explosion mechanism) for the (early) innermost ejecta (the νp-process)
- The late neutrino wind and the r-process?
- Alternative scenarios

Supernovae in 1D

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

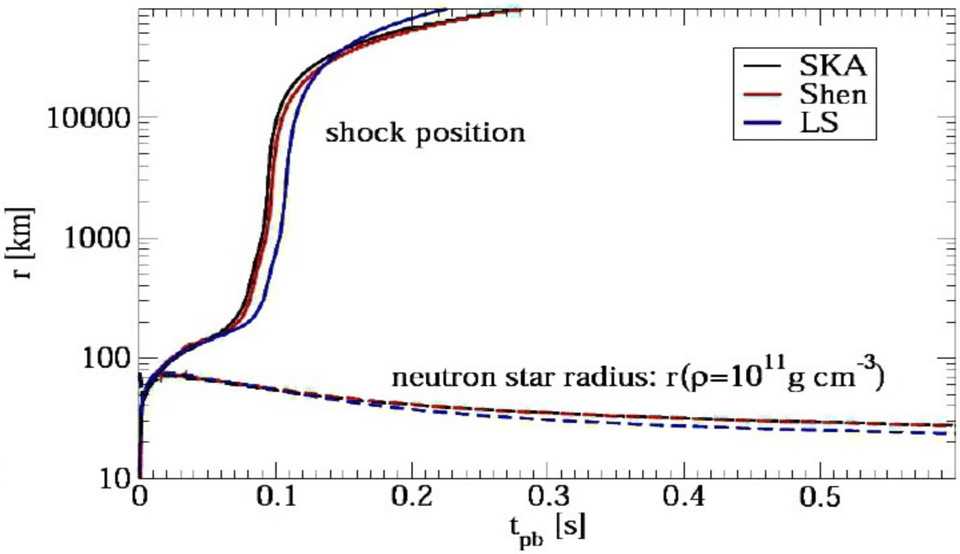
"Electron-capture supernovae"
or "ONeMg core supernovae"

- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



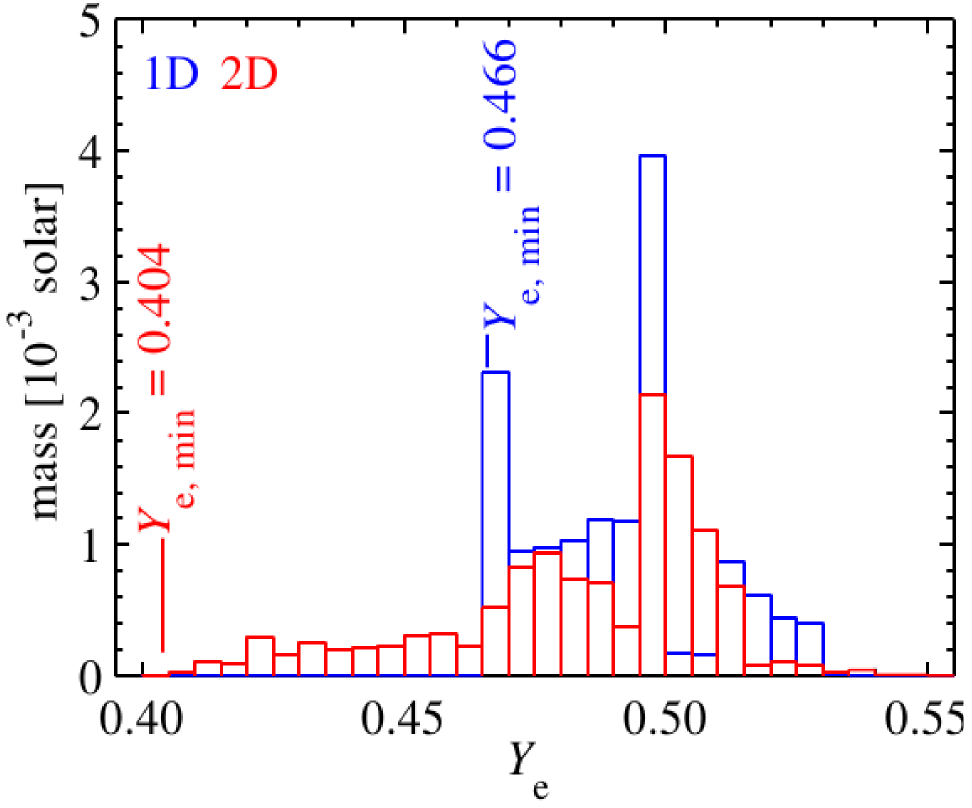
Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

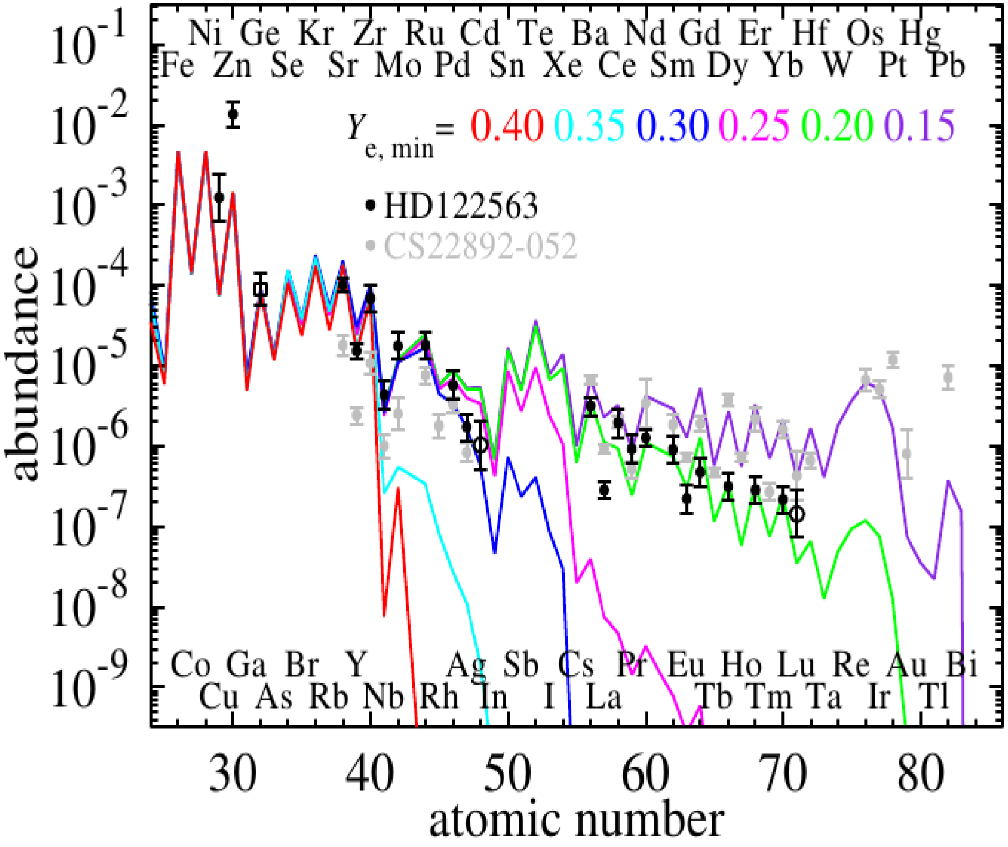
Fischer et al. 2010



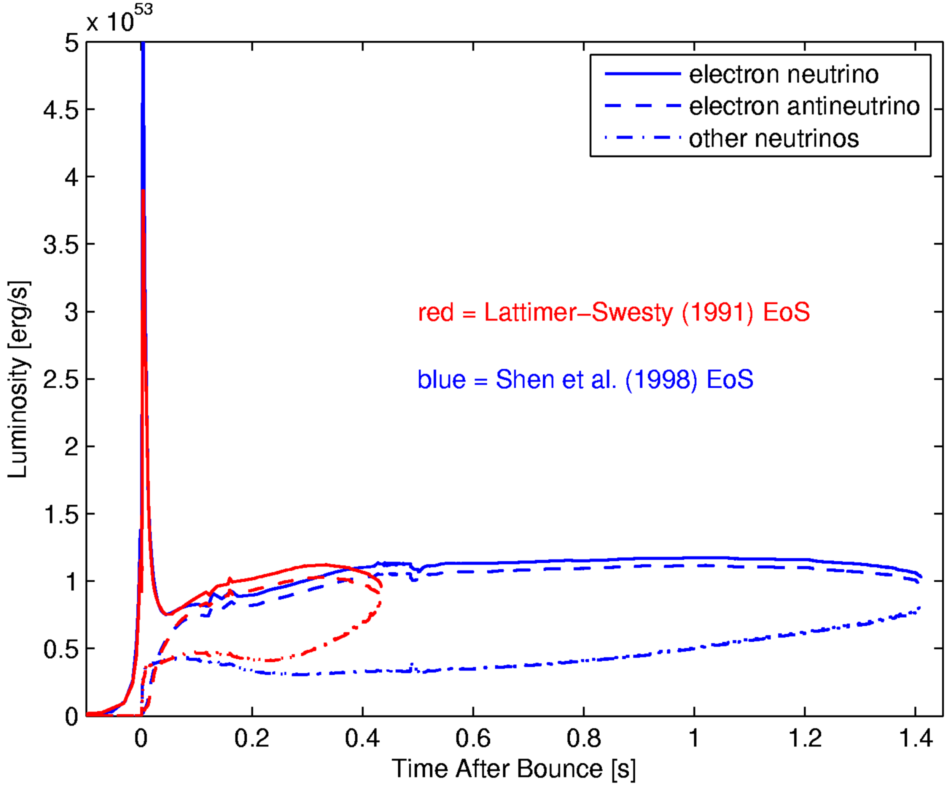
Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

Wanajo & Janka 2011, EC Supernovae in 1 and 2D





Black hole formation after 0.4 or 1.4s for 40M$_{sol}$ star??

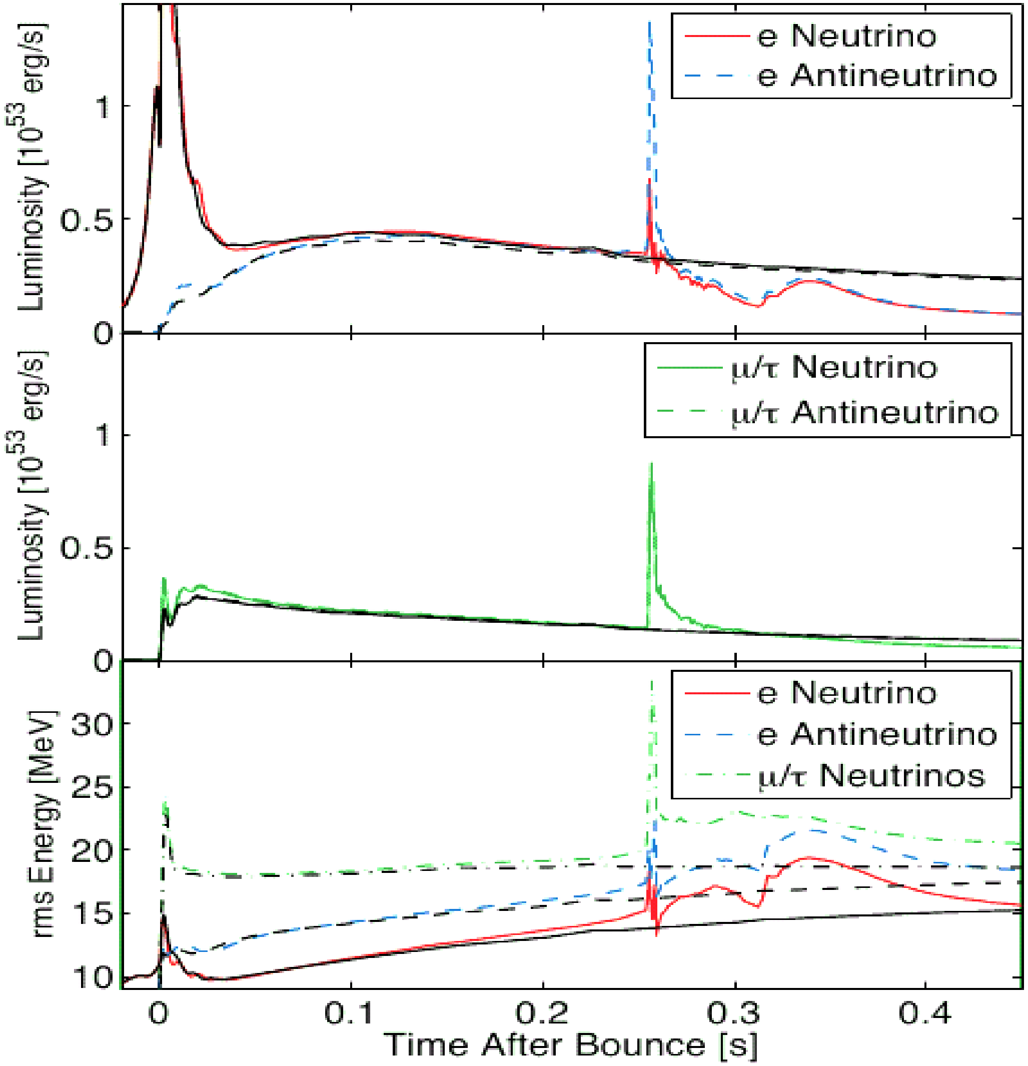


Neutrino Emission

(luminosity and mean energy)
for a variety of stellar progenitors
(13, 15, 20, 25, 30, 35, 40 M$_{sun}$)
by
Liebendörfer et al. (2004)
first peak in electron neutrinos due to electron captures on protons and nuclei when shock front reaches neutrino sphere

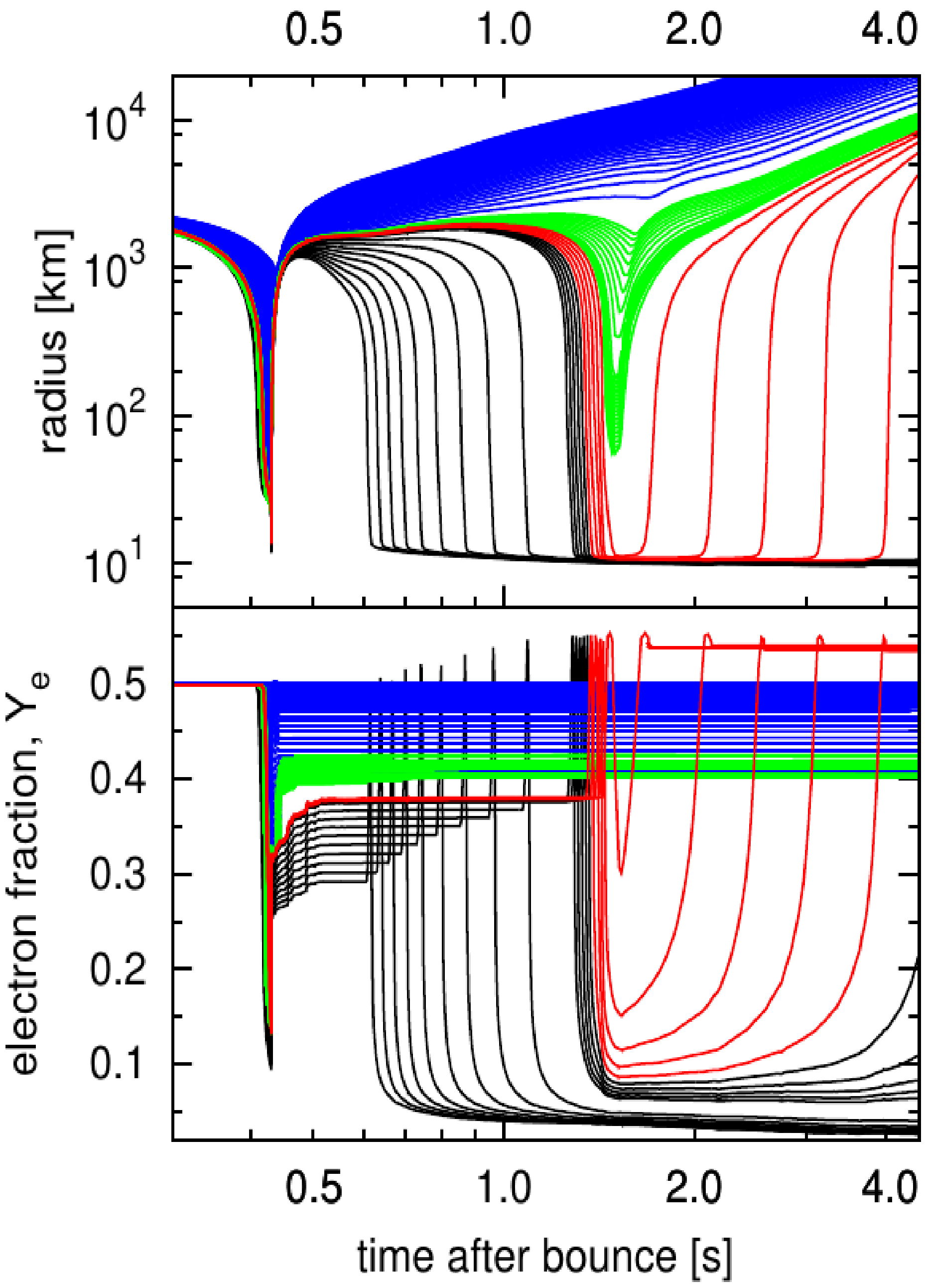
Fischer et al. (2009), effects purely due to nuclear equation of state

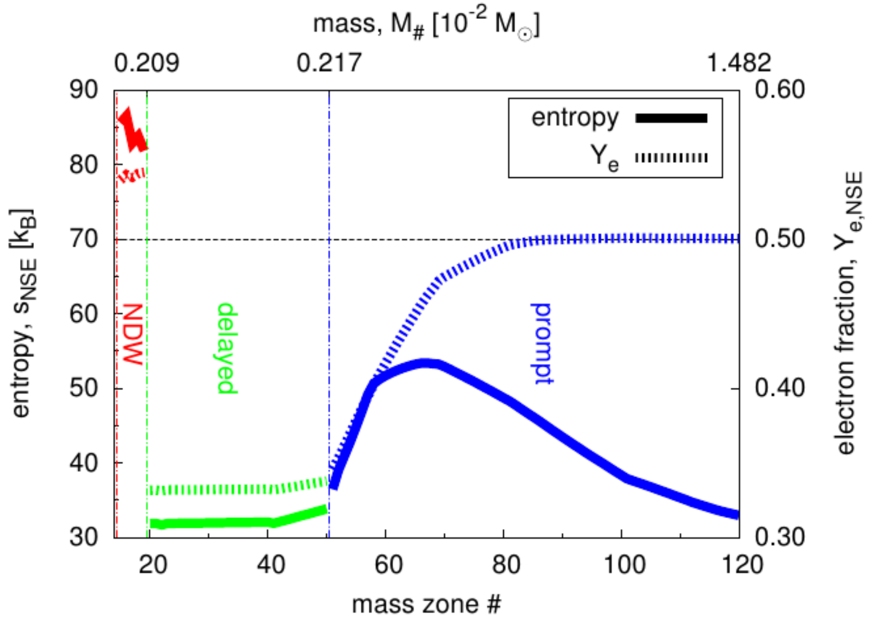
Core Collapse with EOS utilizing MIT Bag Model (Sagert et al. 2009, Fischer et al. 2011)

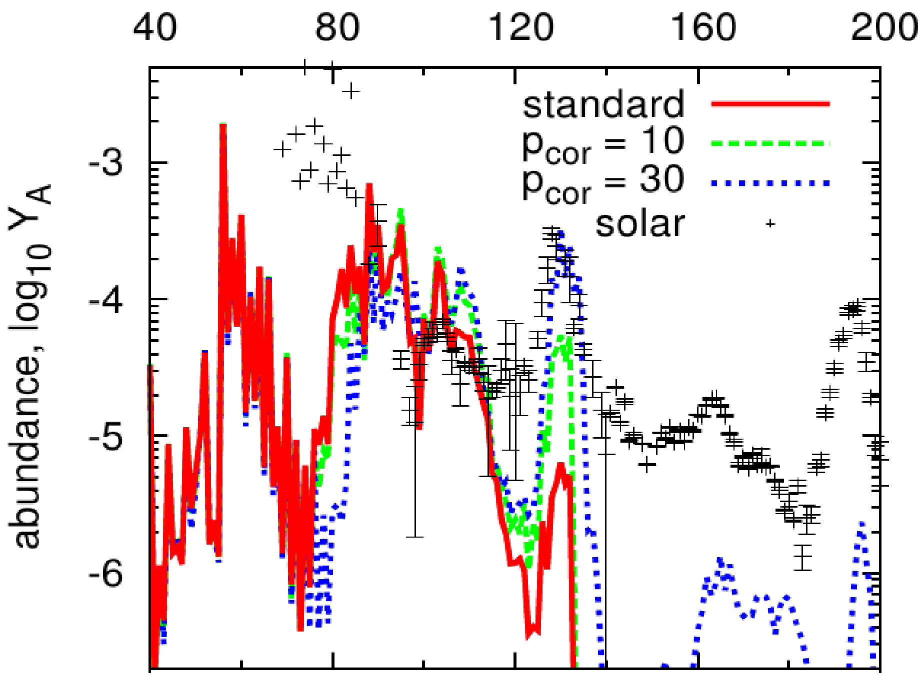


Shown is a simulation of a $10M_{sun}$ star containing ($B^{1/4}$ =162) quark matter compared to one with hadronic matter only (black lines)

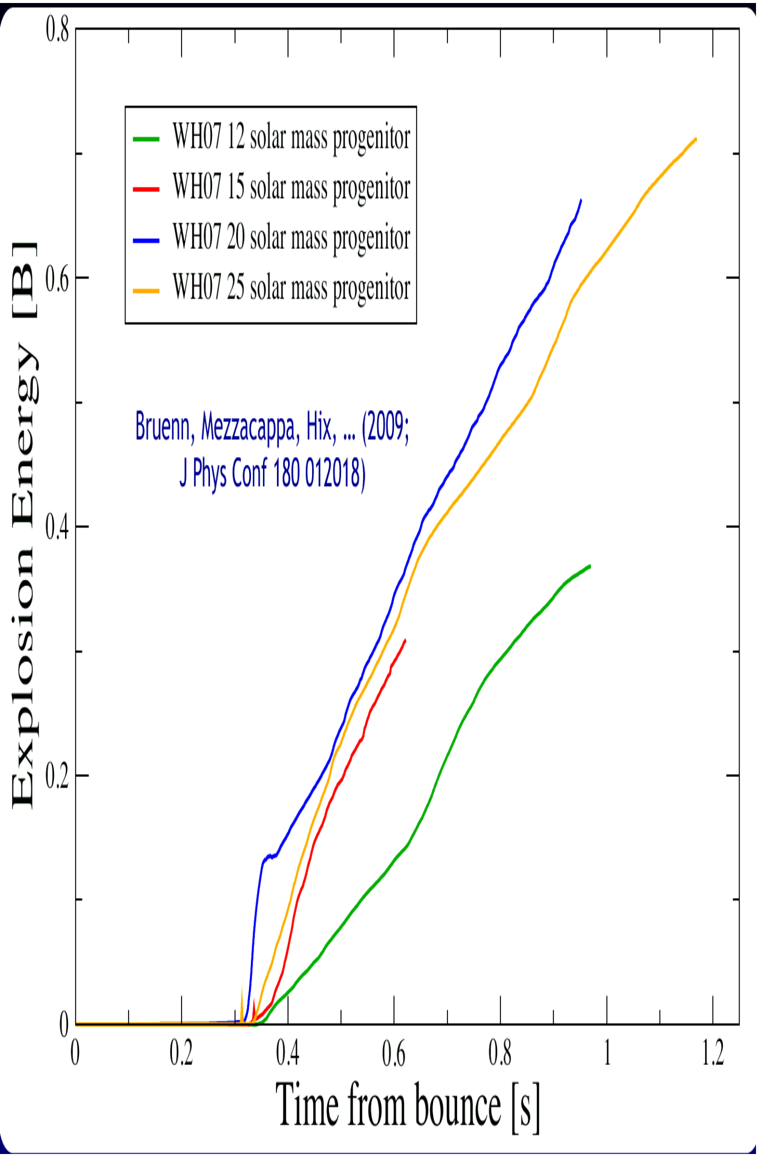
Quark-Hadron EoS Explosion (Nishimura, Fischer, Thielemann et al. 2012.), *ejection of initially neutronized matter, but only weak r-process*





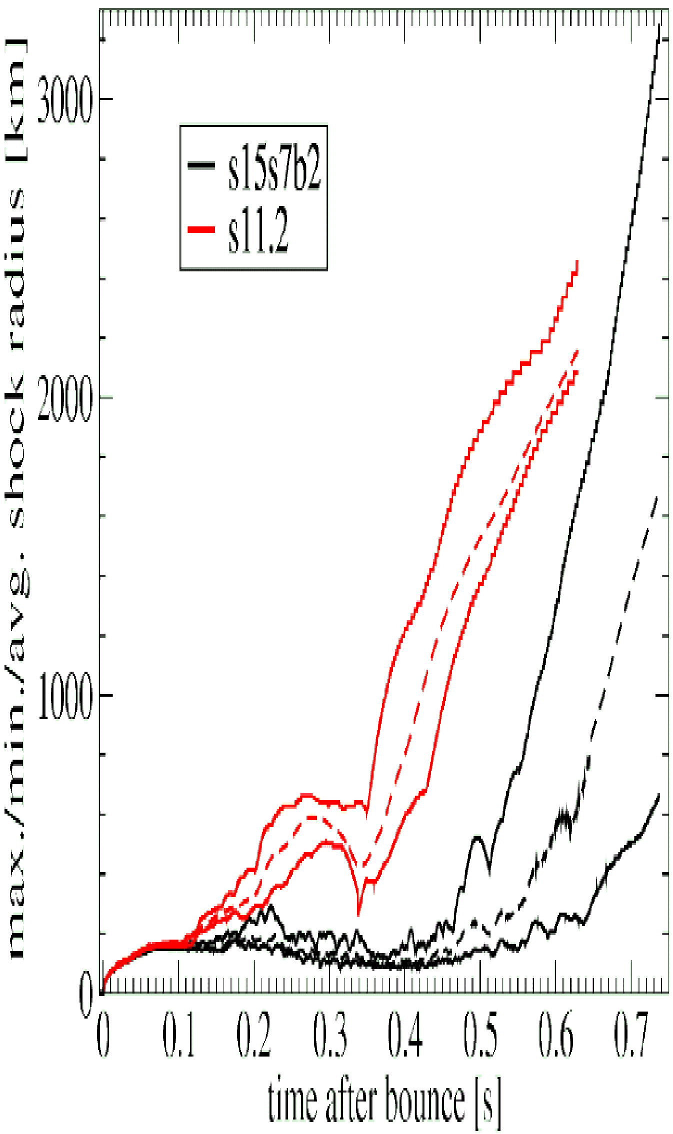


2D and 3D simulations



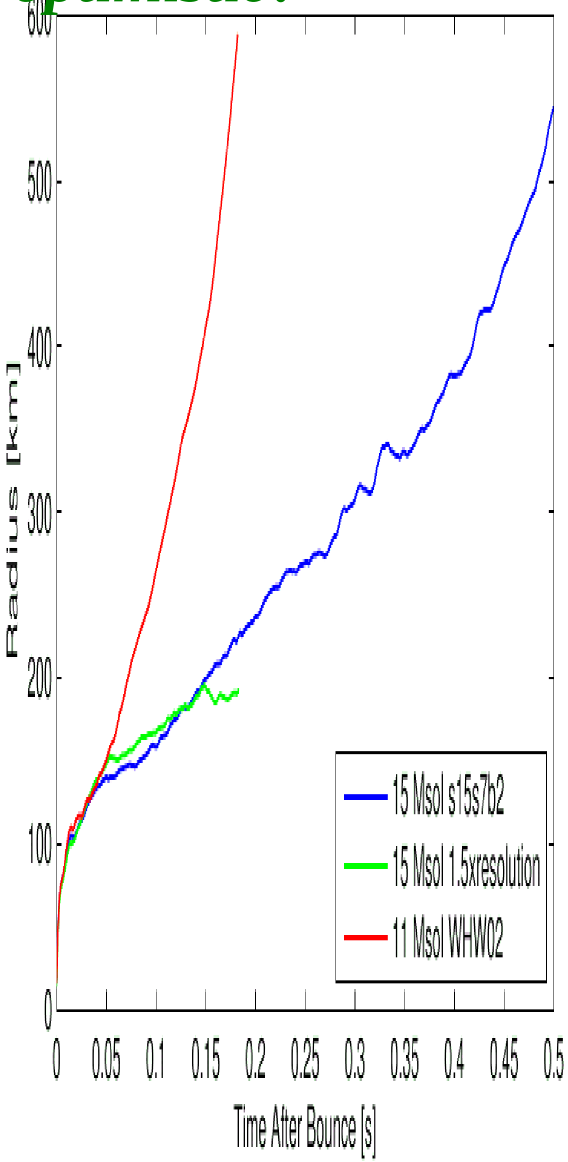
Oak Ridge

Shock radii



Garching

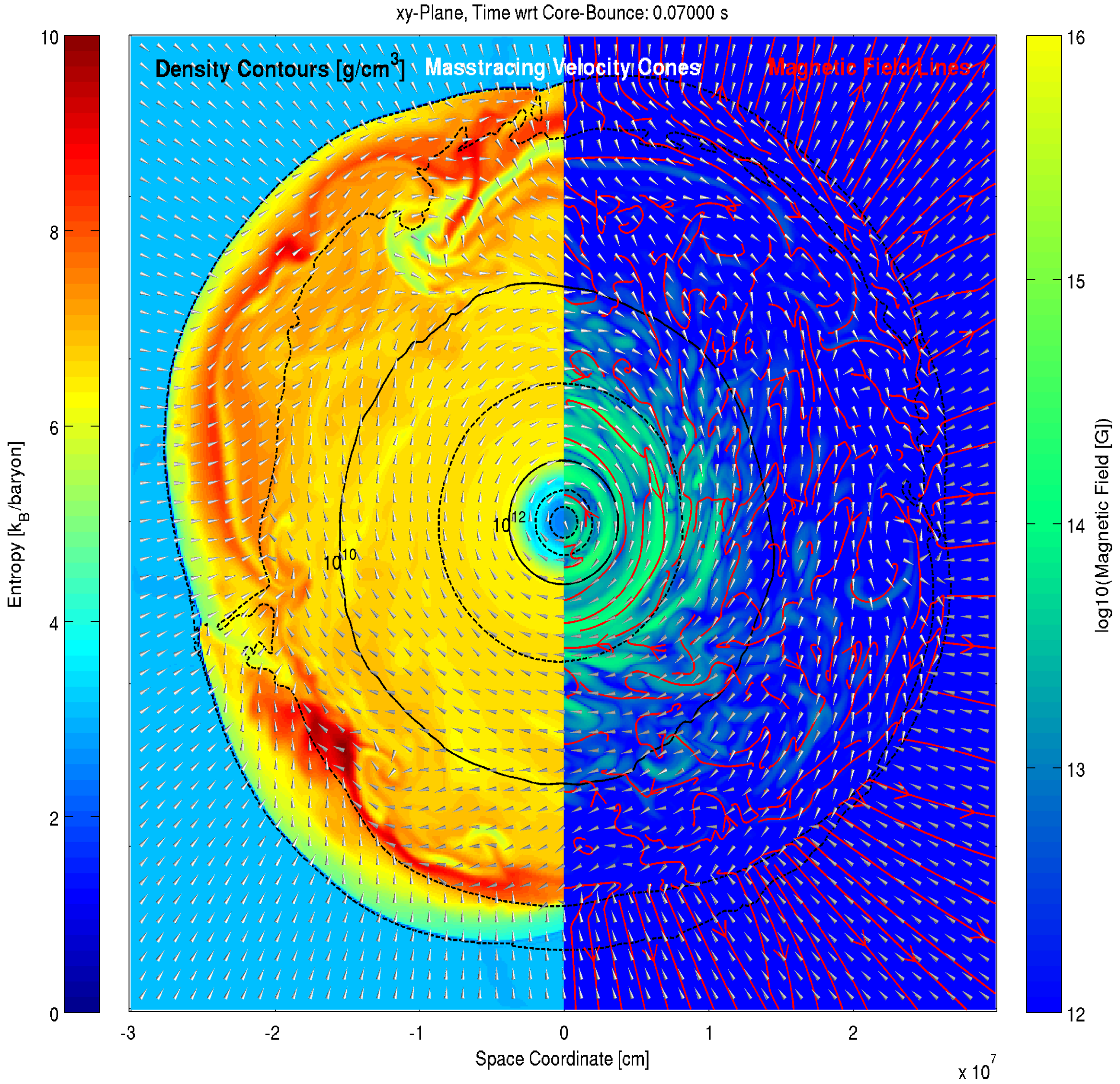
can we be optimistic?

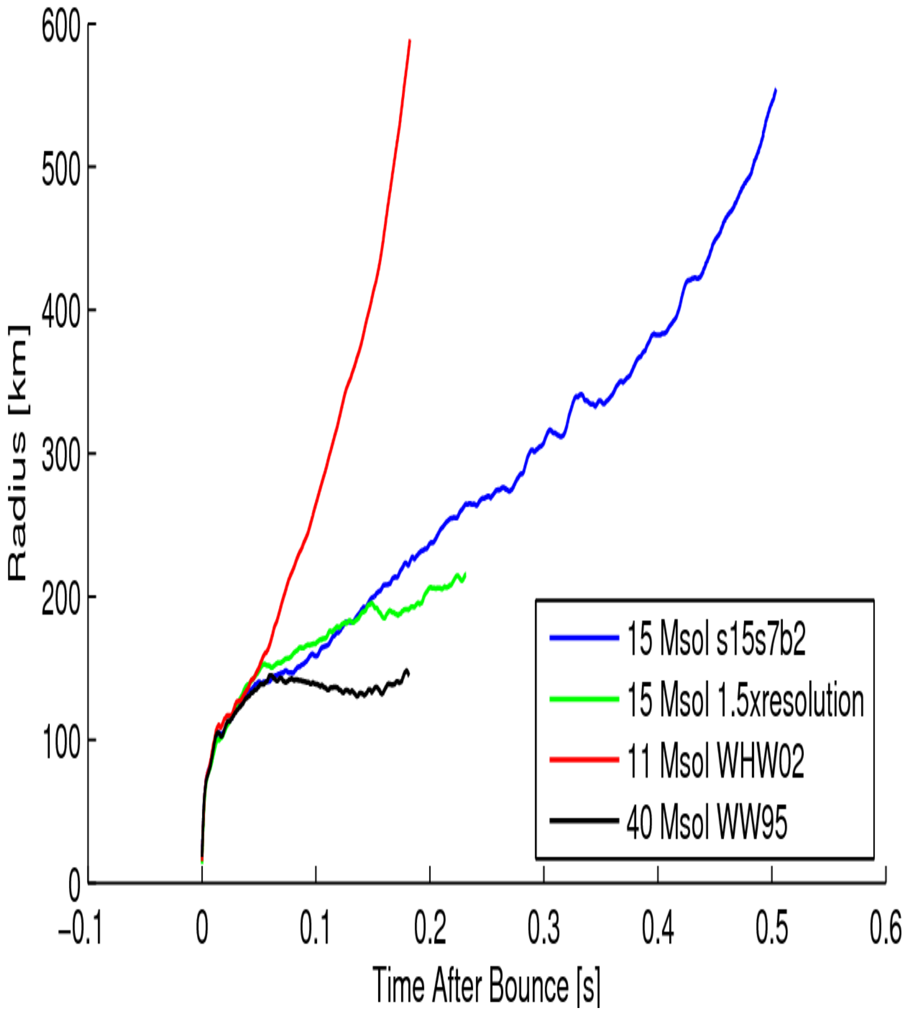


Basel

Simulations in 3D

Liebendörfer et al.





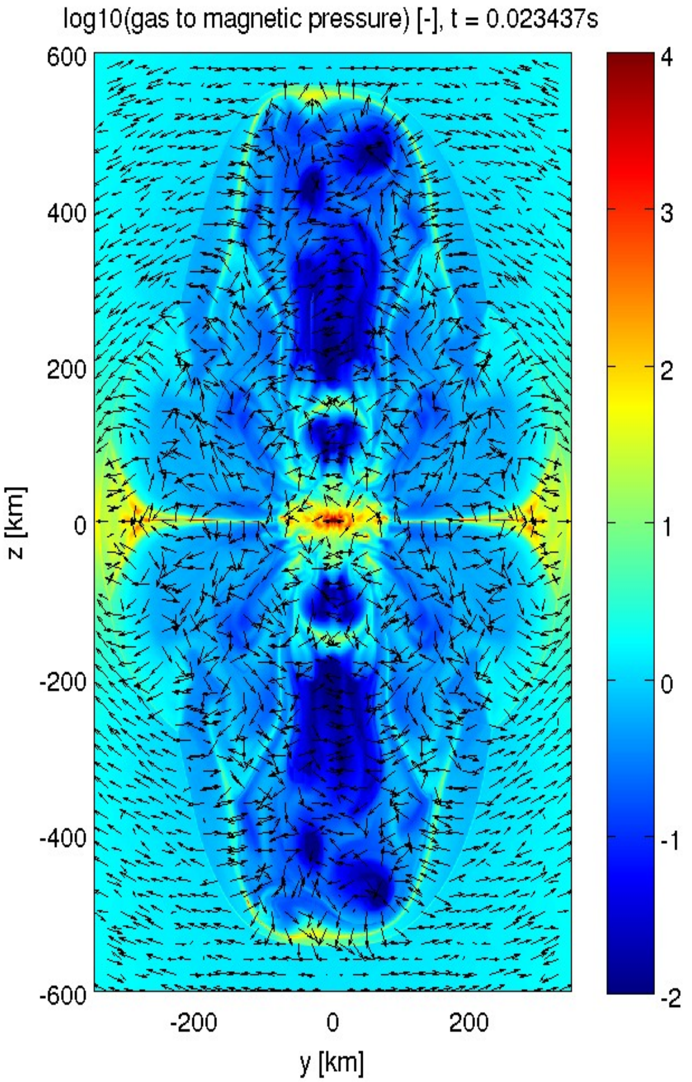
Multi-D explosion calculations are optimistic! (but EoS dependence, 2M$_{sol}$ neutron star)

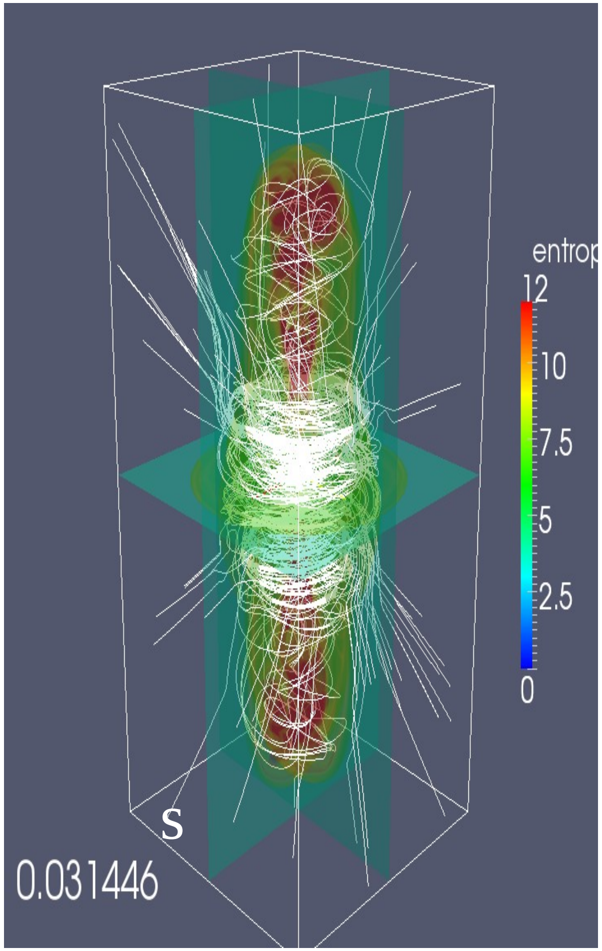
When do we understand transition from regular core collapse SNe with neutron star formation - to faint SNe with fall back and BH formation - BH formation and hypernovae???

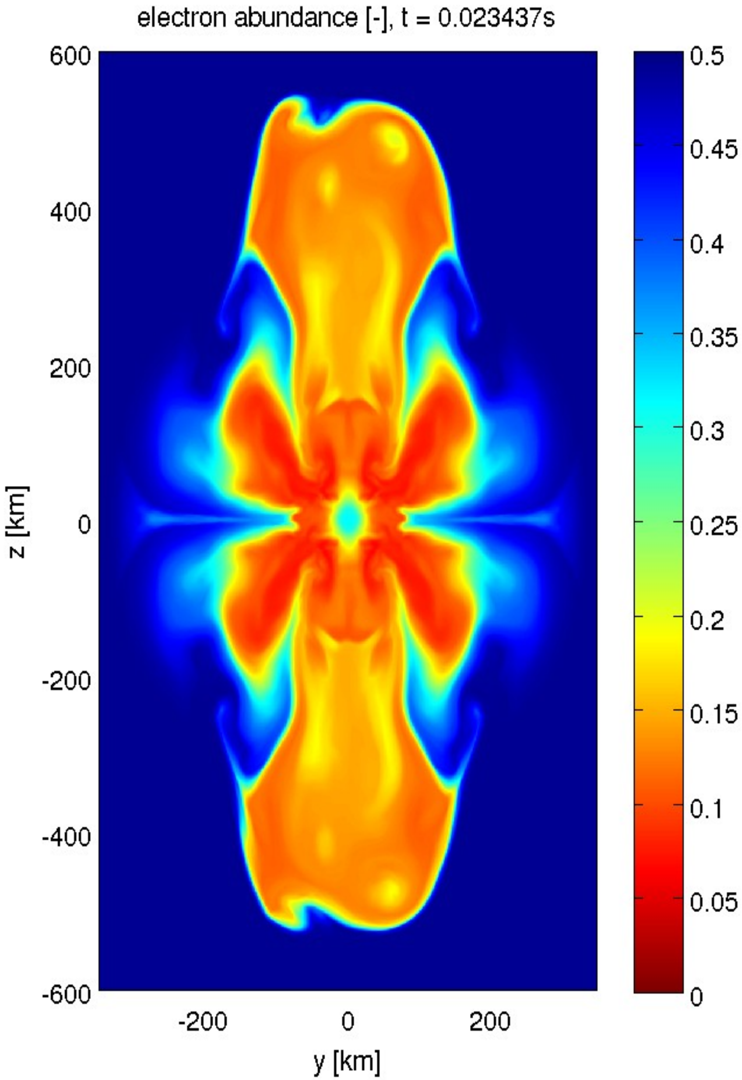
3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 $\times 10^{12}$ Gauss,

results in 10^{15} Gauss neutron star

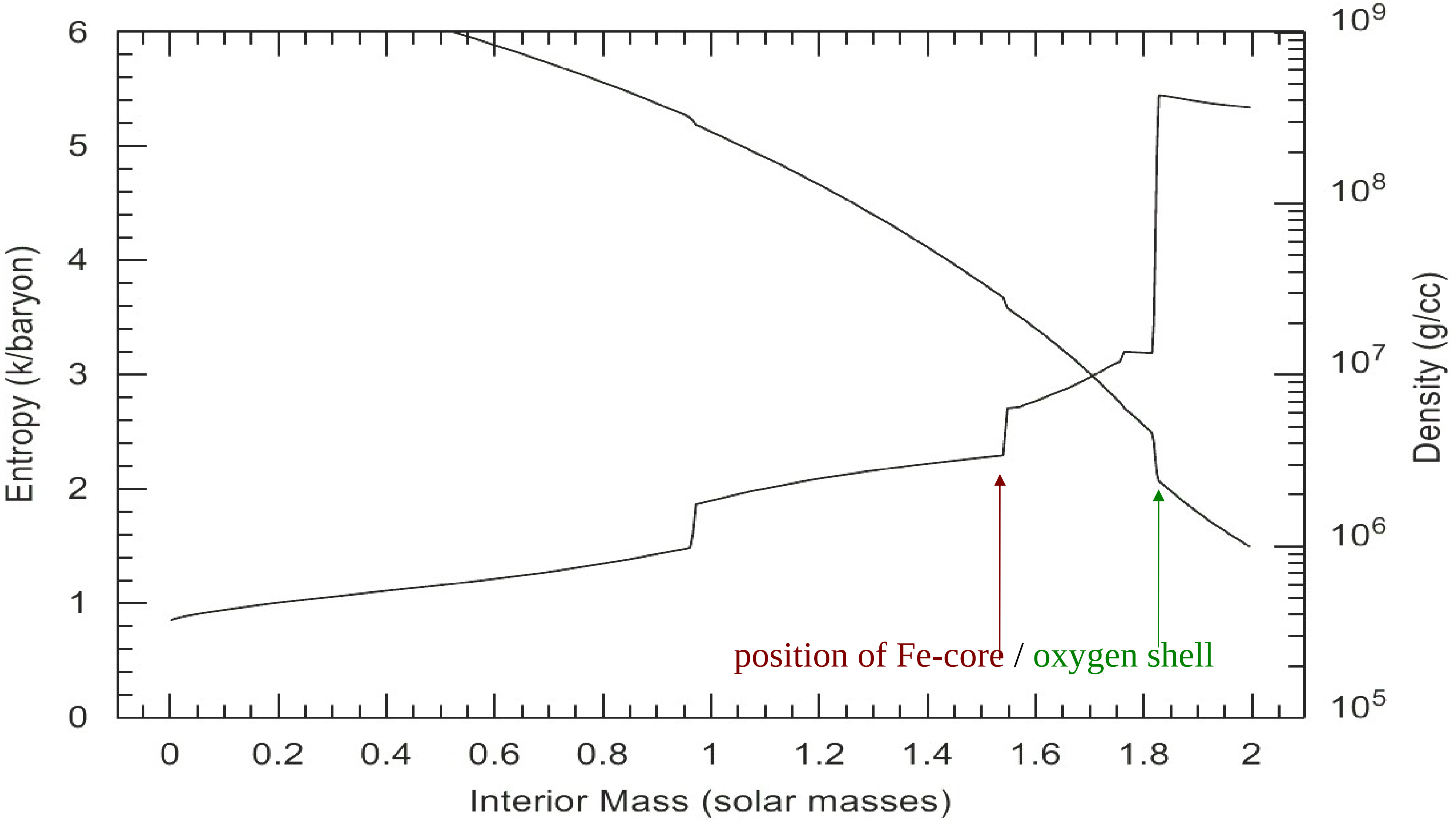






3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012

How to invoke induced explosions for nucleosynthesis purposes?

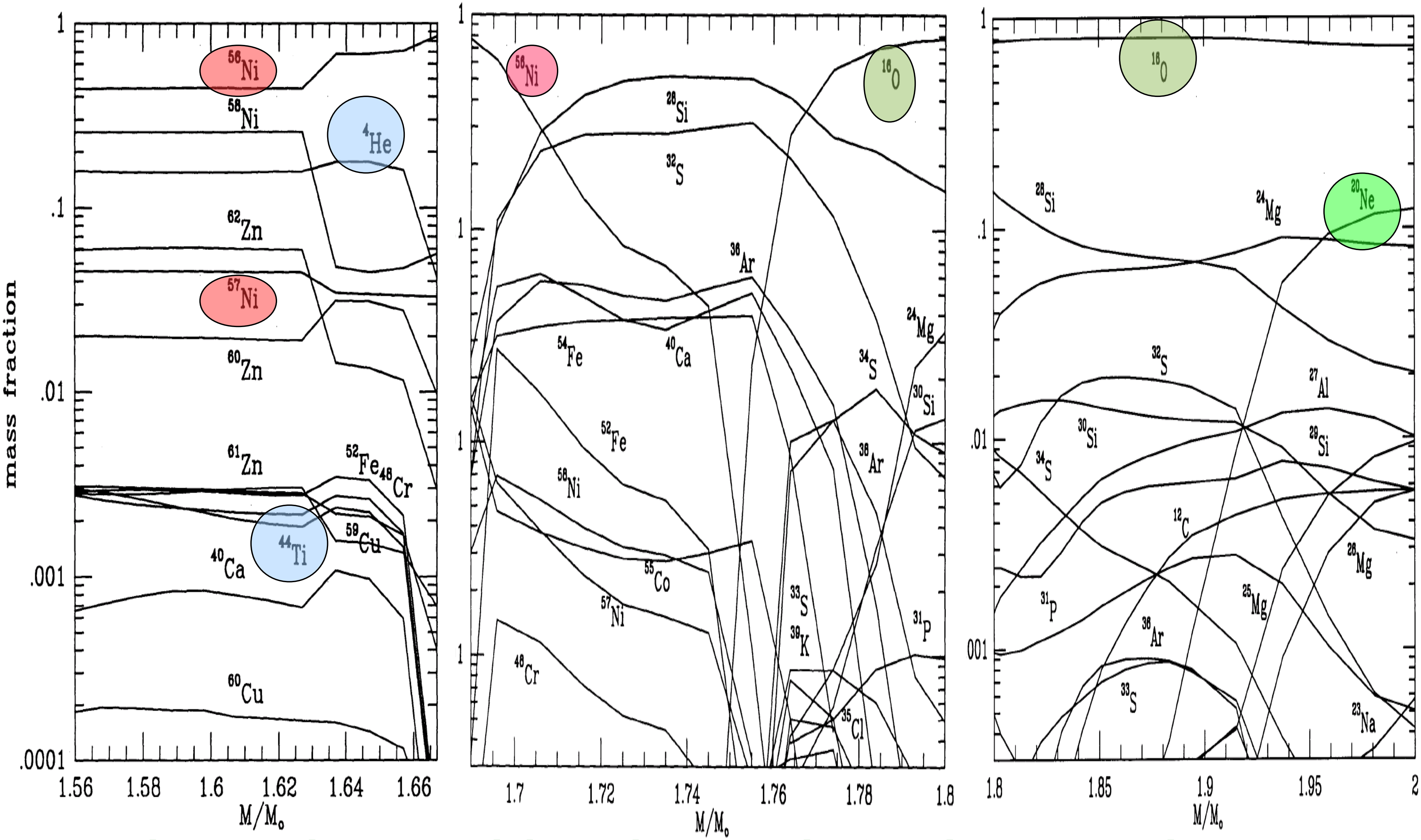


position of Fe-core / oxygen shell

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.

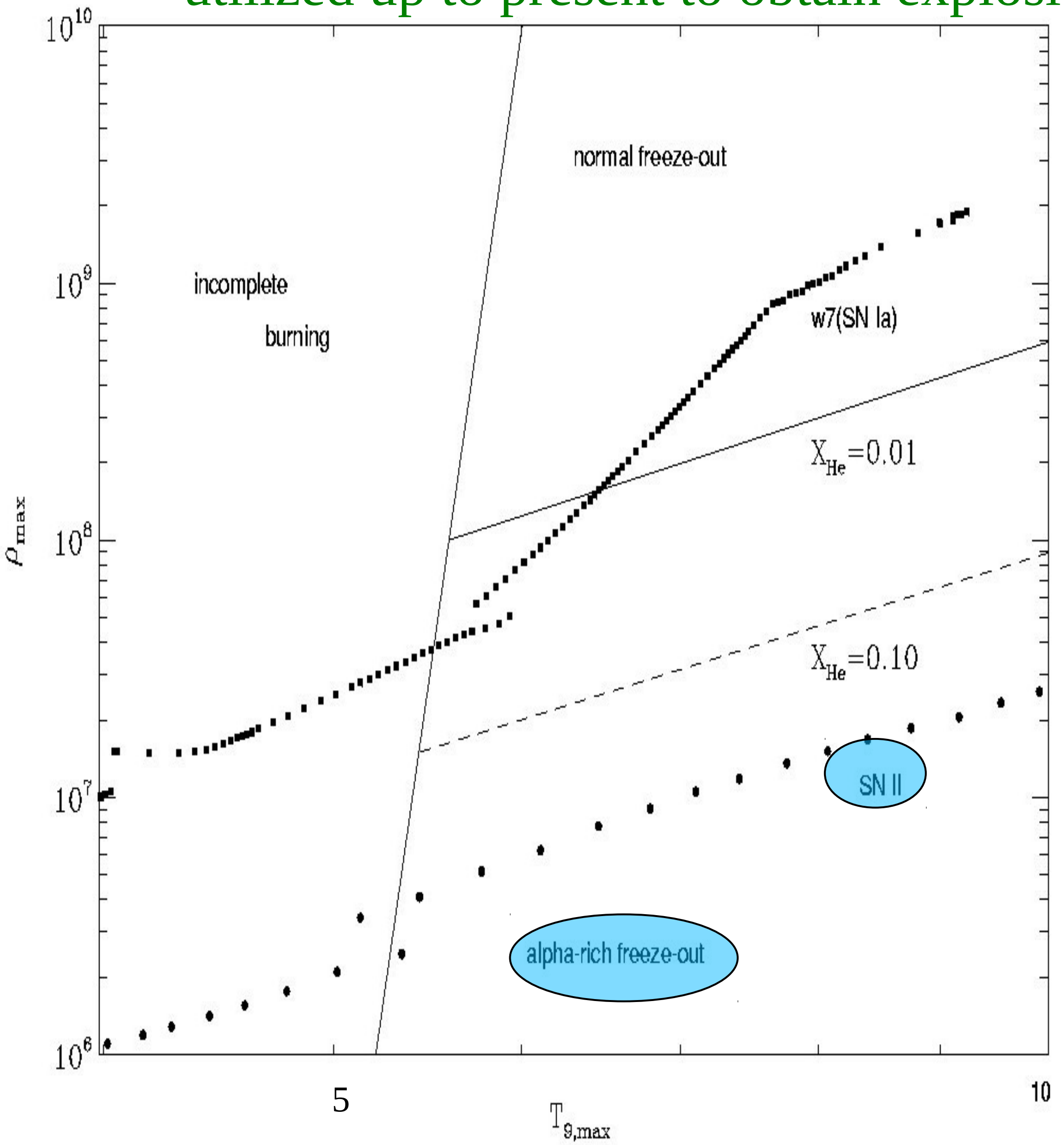
Products of explosive burning (20Msol star)

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



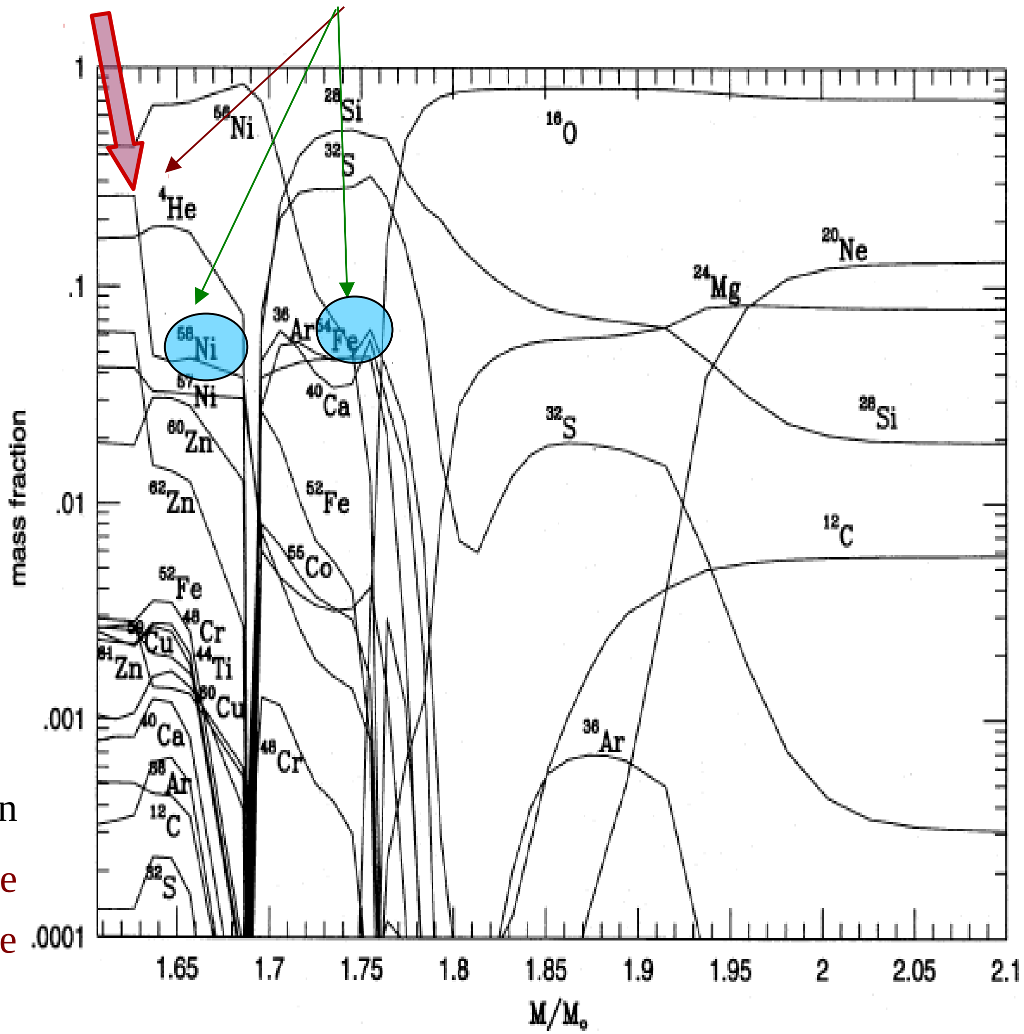
explosive Si-burning (alpha-rich, incomplete), O-burning, Ne-burning

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

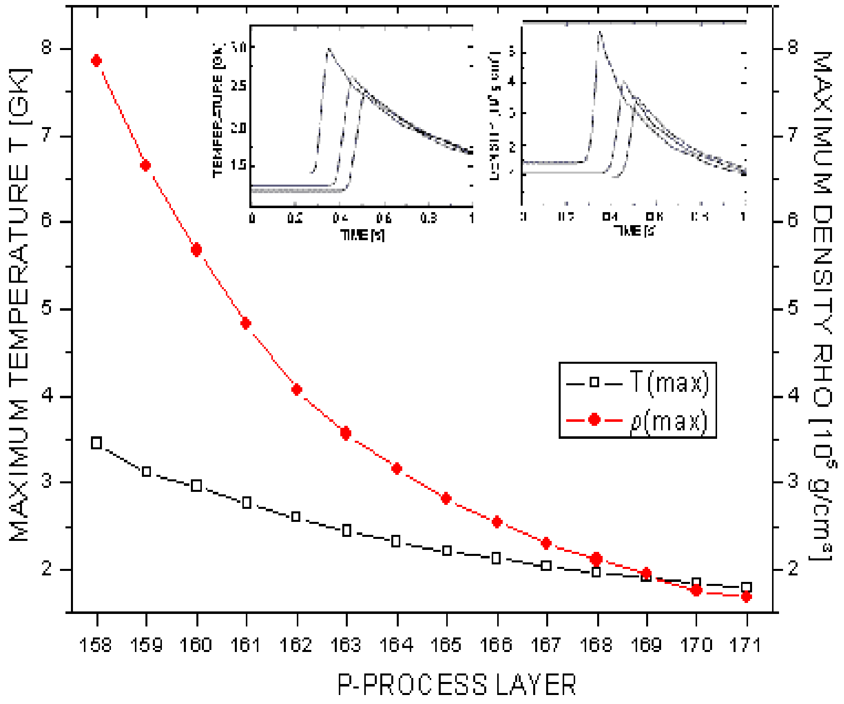


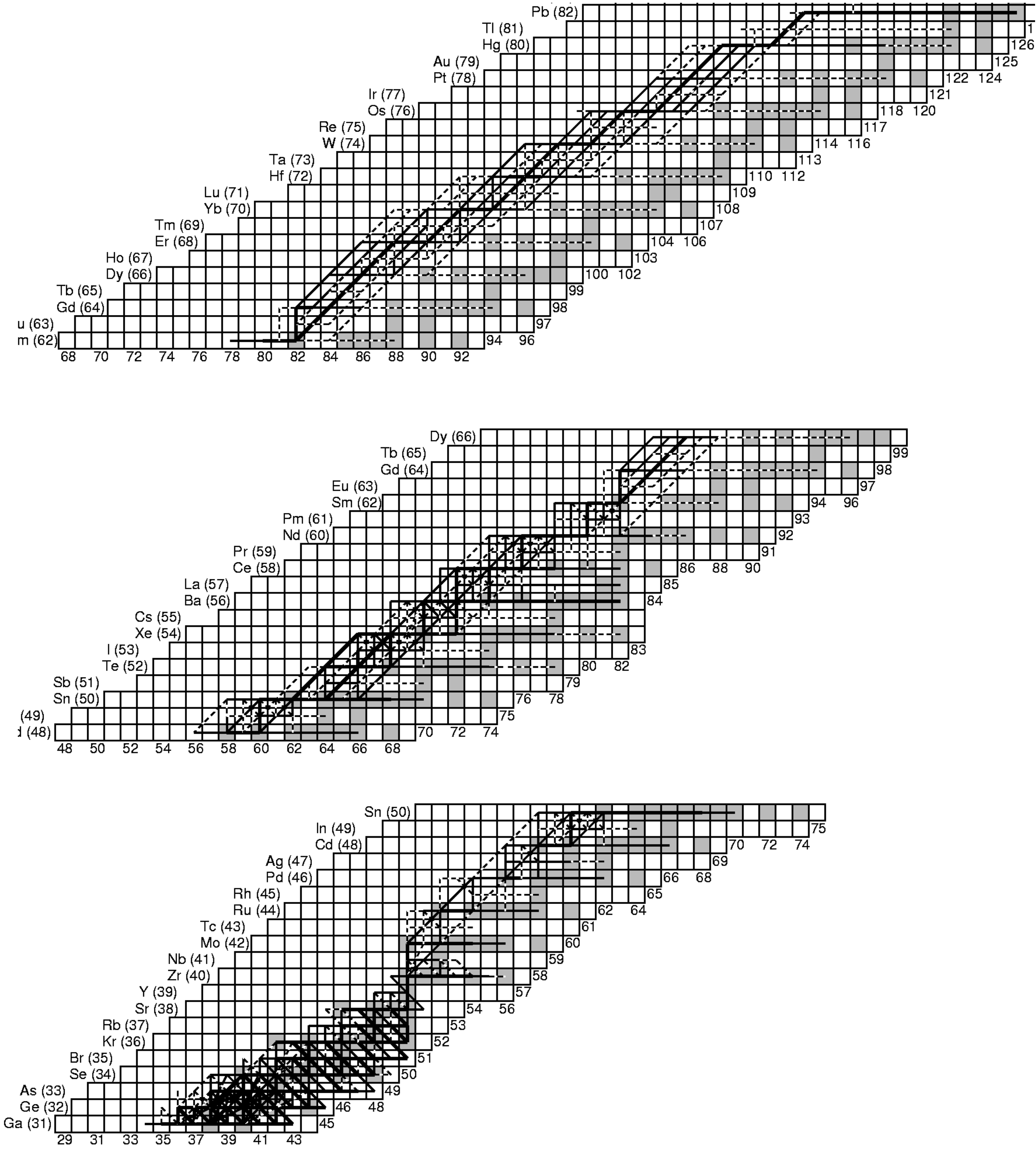
prior results made use of initial stellar structure (and Y_e!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go much beyond Ni!

disconnected light element (n,p,He) and Si-Fe QSE-cluster, high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe), Y_e determines dominant QSE-isotopes.



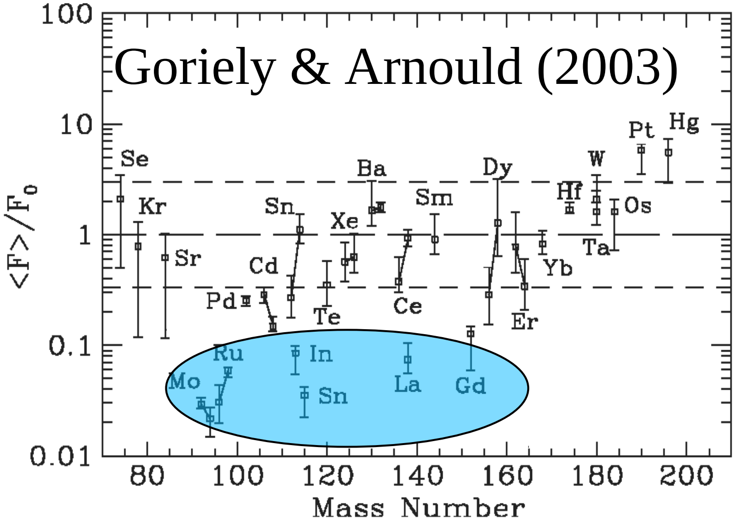
p-process in explosive Ne/O-Burning zones

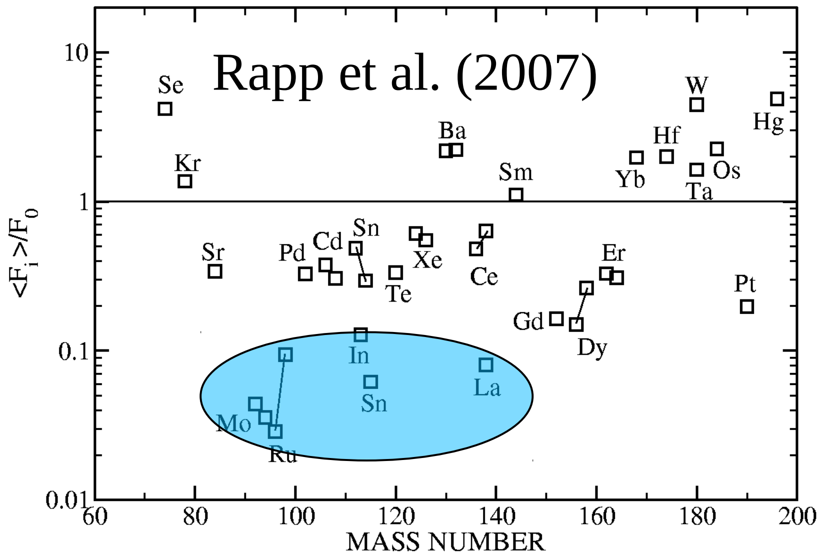


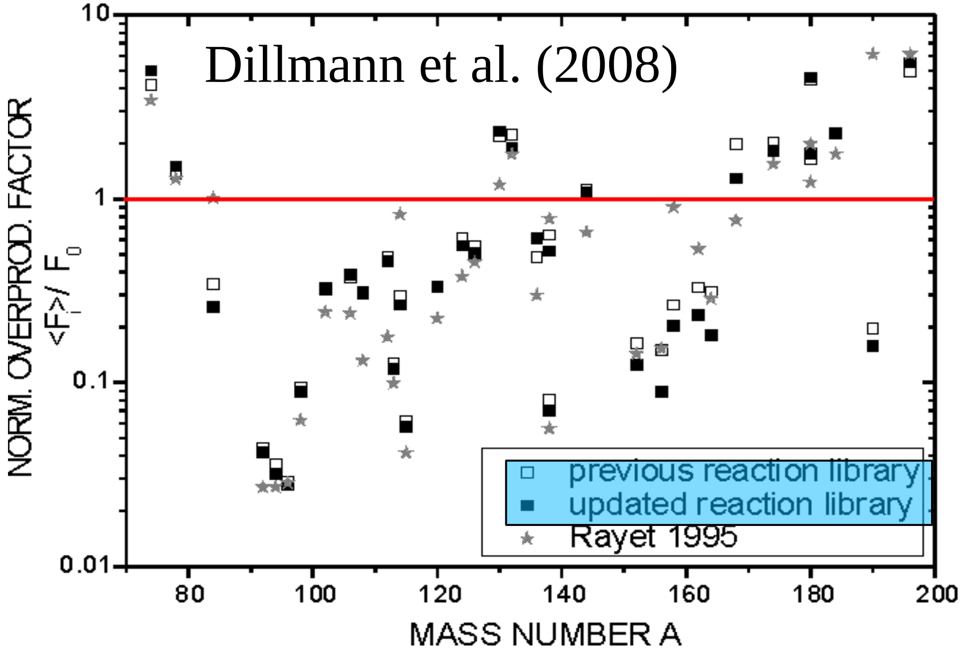


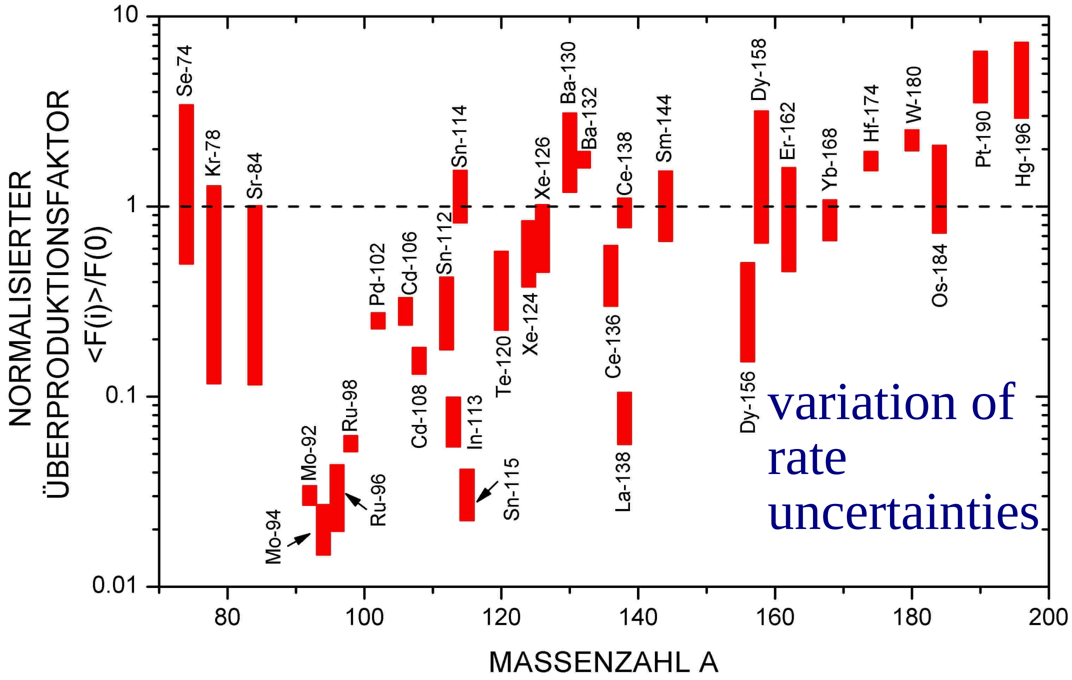
Rapp et al. (2007), following p-(gamma)-process calculations within the framework of Rayet et al. (1995) for a 25M$_{sol}$ star of Yoshida et al. (2002) to verify the impact of nuclear uncertainties.

Comparison with solar p-only nuclei


Goriely & Arnould (2003)


Rapp et al. (2007)


Dillmann et al. (2008)



variation of rate uncertainties

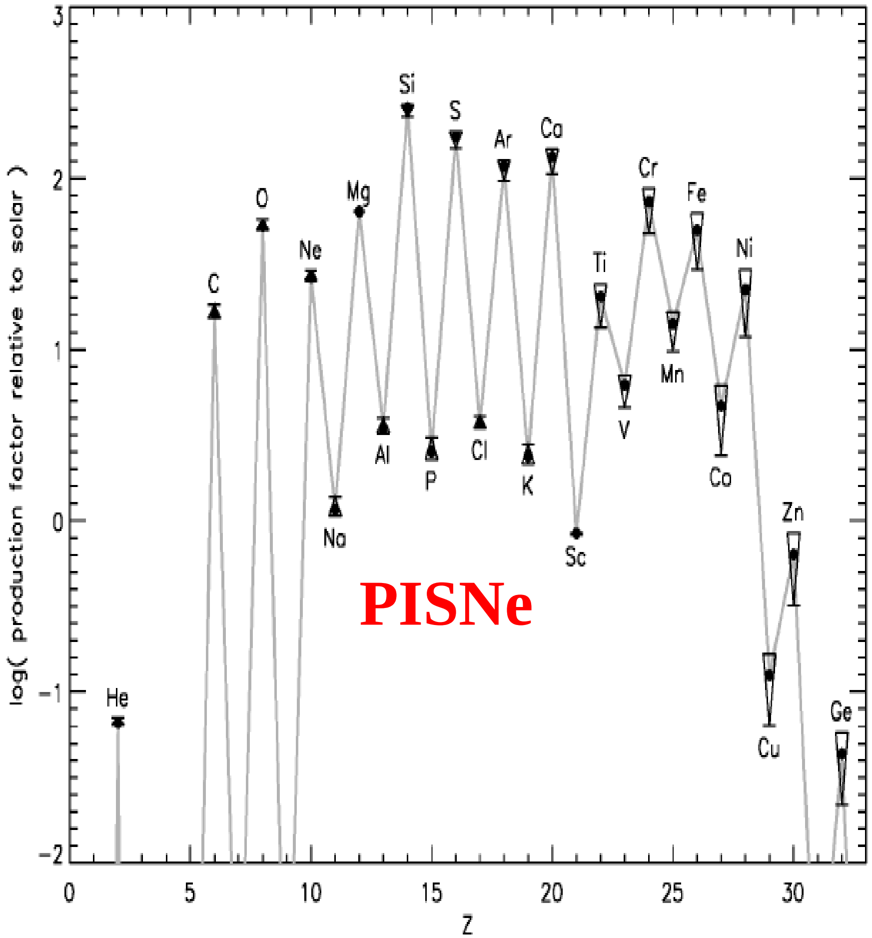
Ideas for solutions

There have been many investigations in p-process related reactions (Gyürky, Hasper, Kiss, Yalcin, Mohr, Sonnabend, Dillmann, Rauscher..) which led to improved understanding of alpha and proton optical potentials, but the problem seems not to be solved by nuclear rate uncertainties. The major difficulty is to produce the low-mass Mo and Ru isotopes, which also have a higher abundance than the typical 1% fraction of p-isotopes for heavier elements.

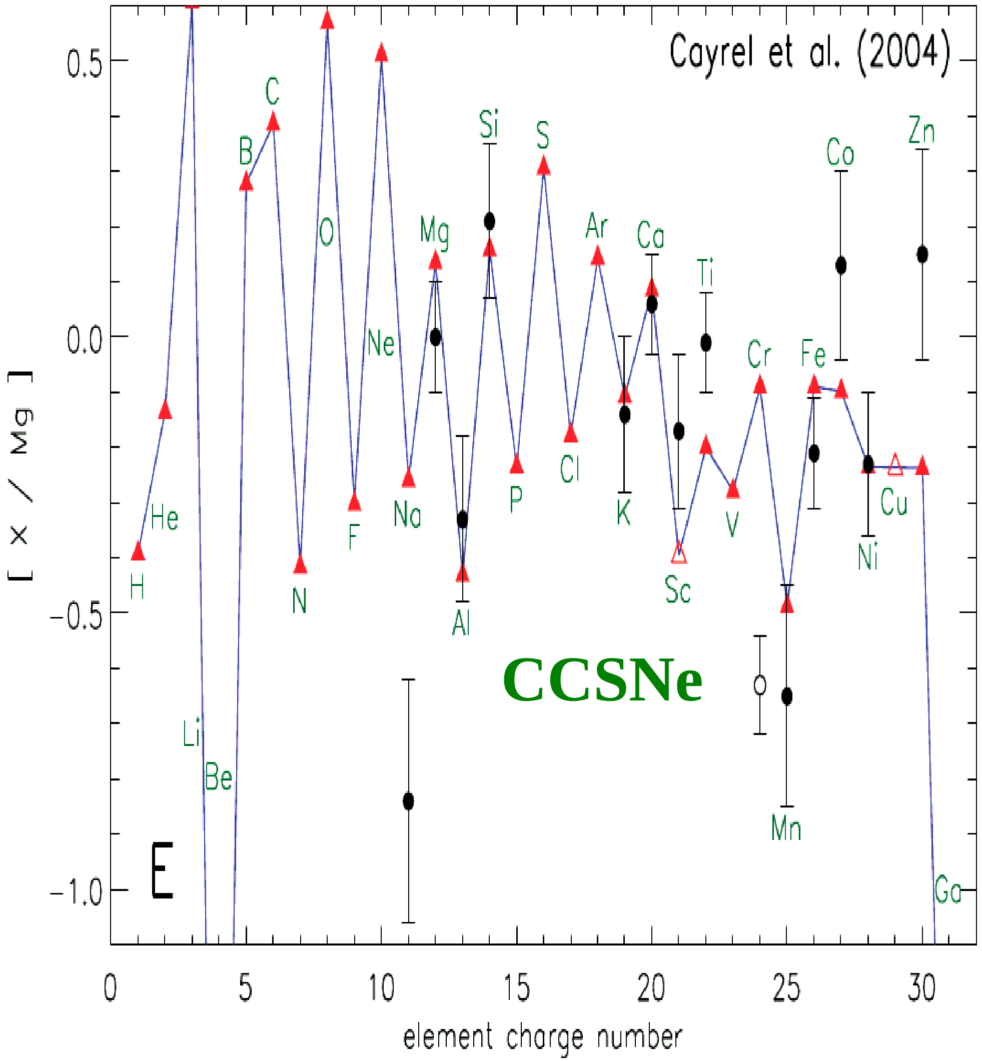
Possible solutions:
analyze environments which start with a different seed composition being then exposed to the photon flux
(a) extent of prior s-processing as possibly found in the accreted He-burning layers of SNe Ia, Howard et al. 1991, Kusakabe et al. 2009, Travaglio et al. 2010, but not a solution for LEPP elements at low metallicities!
(b) change evolution of massive stars (e.g. $^{12}C+^{12}C$) which changes extent of s-processing before core collapse supernova explosion.

(c) invent different environment with capture reactions for light p-isotopes.

Pop III yields (Heger & Woosley 2003, 2010)
Evolution of metal-free stars



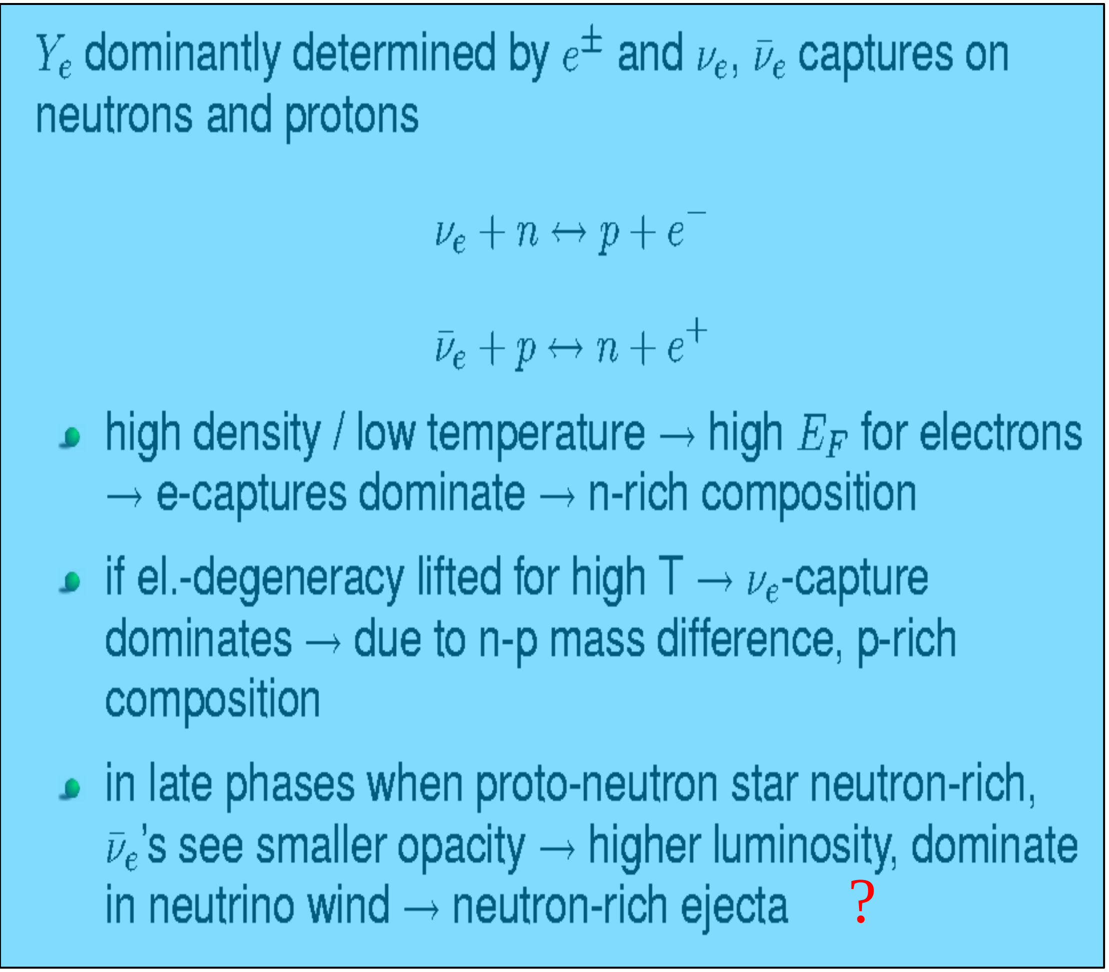
PISNe yields, too large odd-even Z scatter, not observed in low metallicity stars



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

In exploding models matter in innermost ejected zones becomes proton-rich ($Y_e>0.5$)

if the neutrino flux is sufficiant (scales with $1/r^2$)! :

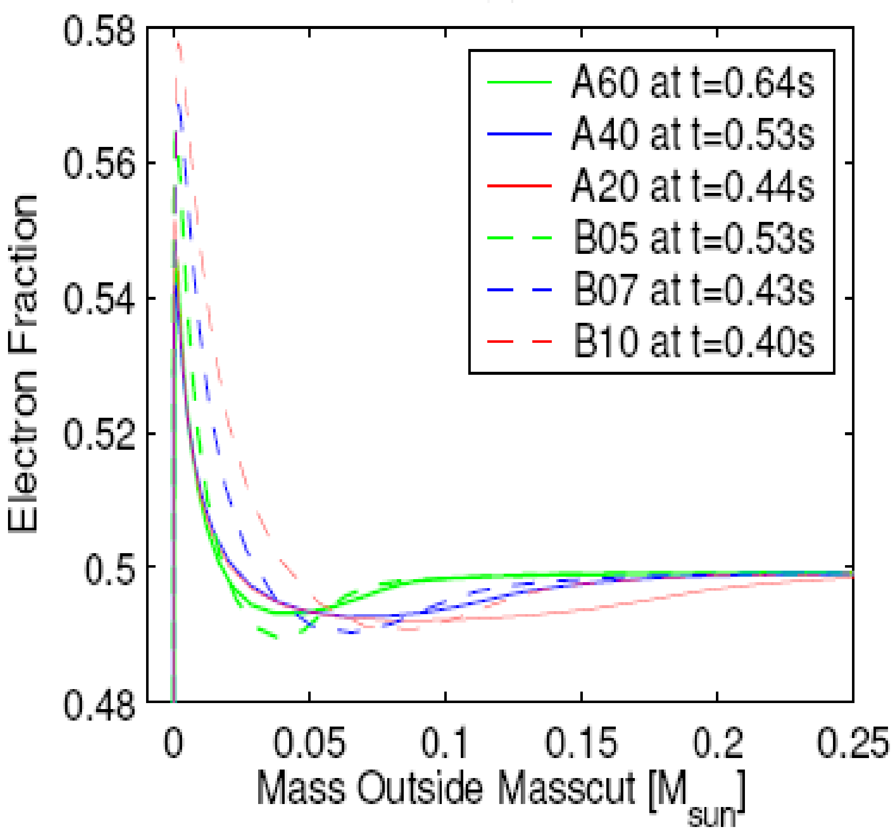


Y_e dominantly determined by $e^{\pm}$ and ν_e, $\bar{\nu}_e$ captures on neutrons and protons

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

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

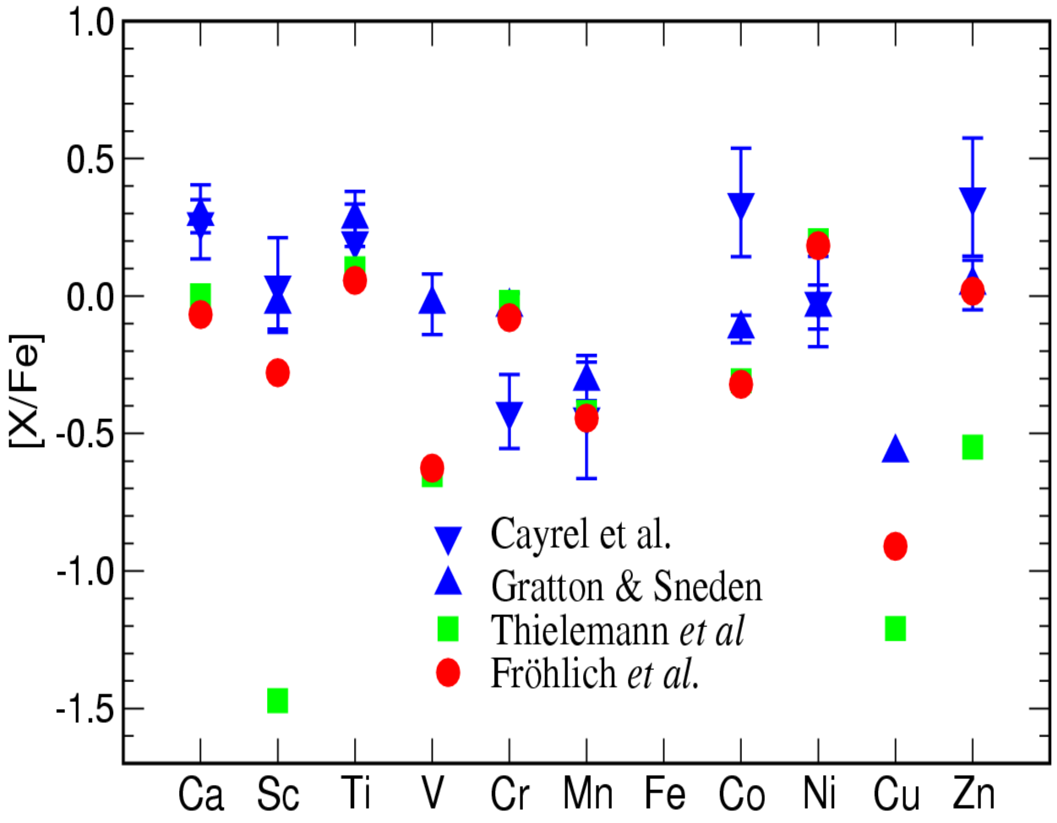
- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity → 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 $Y_e<0.5$!

Improved Fe-group composition



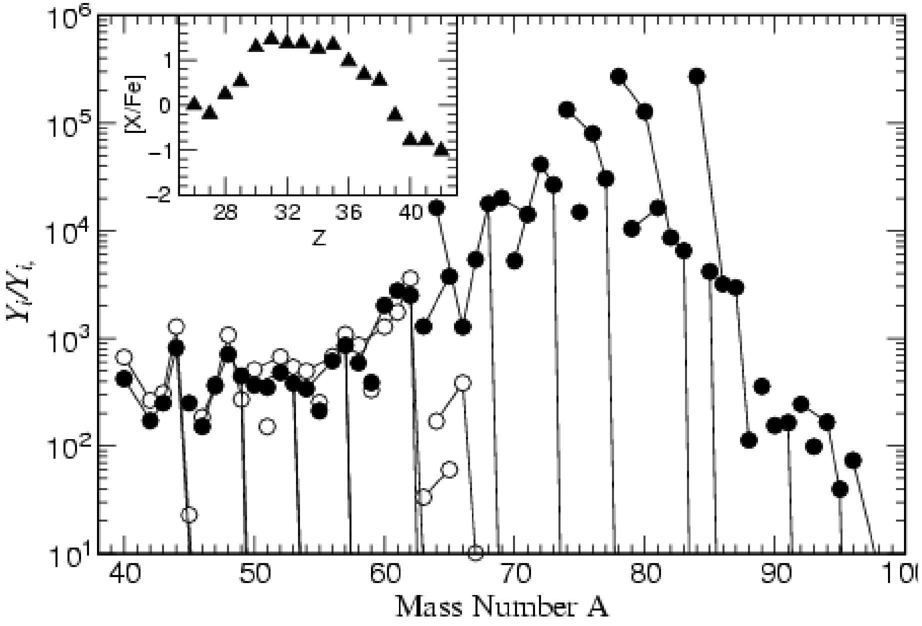
Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

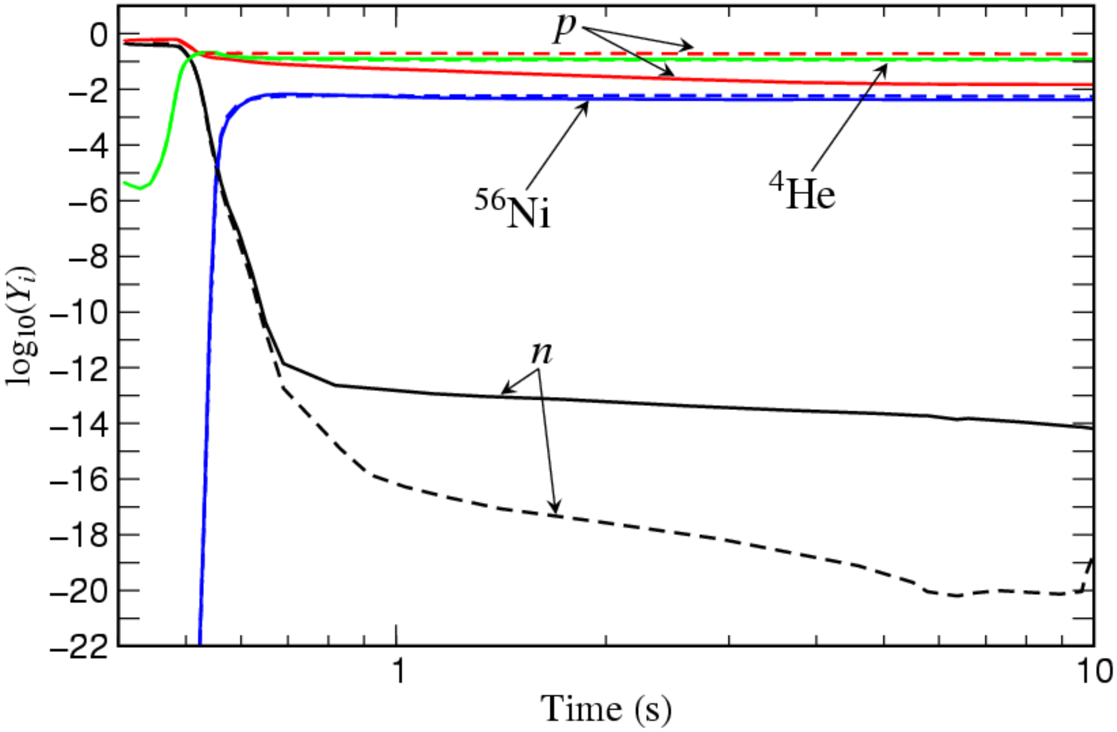
This effect improves the Fe-group composition in general (e.g. Sc) and extends it to Cu and Zn!

Fröhlich et al. (2004, 2006a), see also Pruet et al. (2005), *but see also Izutani & Umeda (2010) for hypernova conditions; main question: which fraction of massive stars have to become hypernovae in order to produce solar Zn???*

νp-process

$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$$

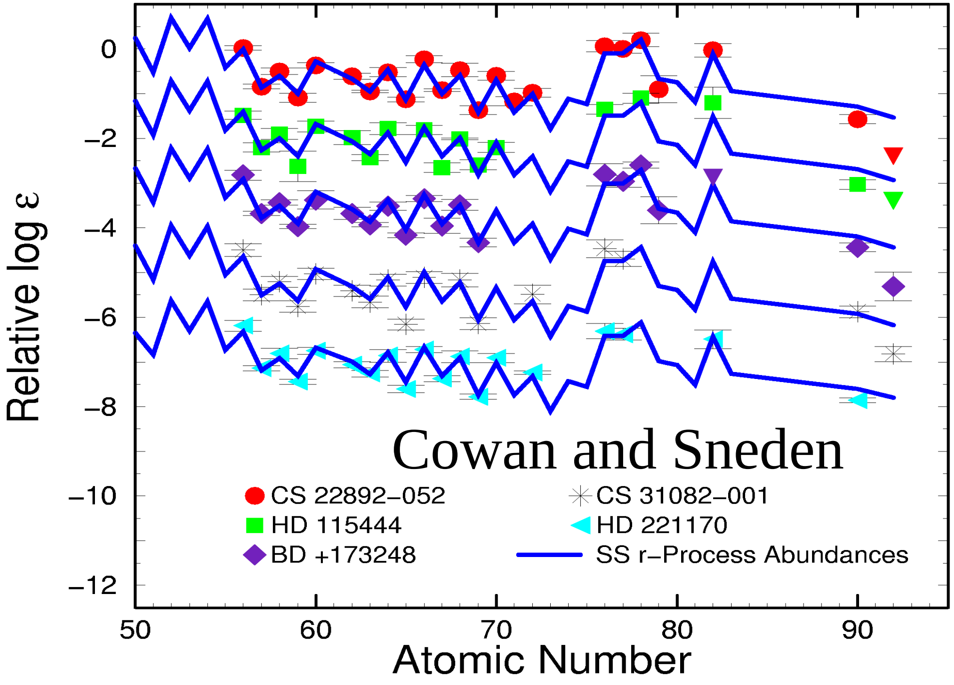




Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei) see also Pruet et al. (2006), Wanajo (2006).
Recent analysis by Wanajo, Janka, Kubono (2010) with variation of neutron star masses and reverse shock position

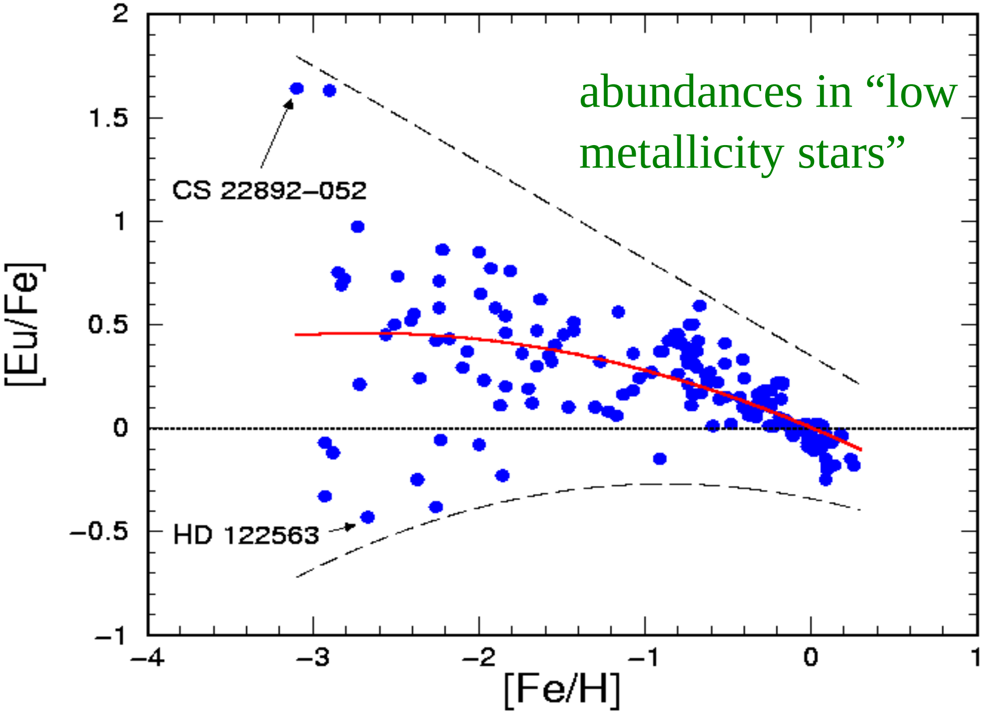
A new process, which could solve some observational problems of Sr, Y, Zr in early galactic evolution and the problem of light p-process nuclei.
Anti-neutrino capture on protons provides always a small background of neutrons which can mimic beta-decay via (n,p)-reactions.

Observational Constraints on r-Process Sites

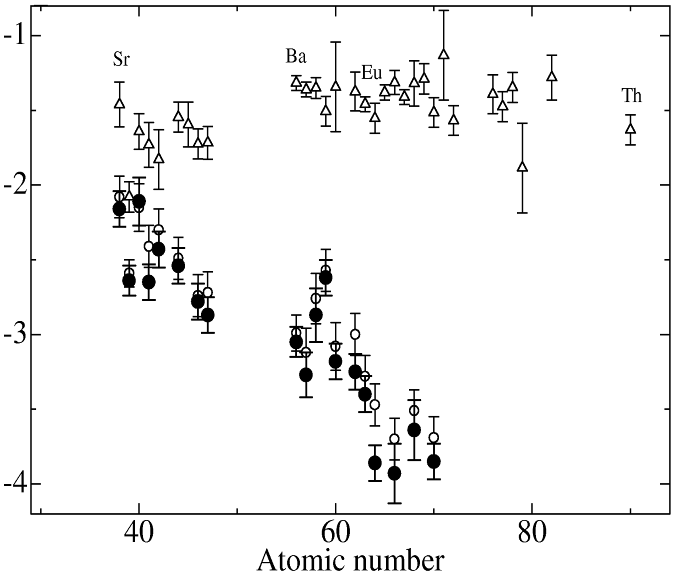

Cowan and Sneden

apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event which nevertheless consists of a superposition of ejected mass zones

"rare" event, which must be related to massive stars due to "early" appearance at low metallicities (behaves similar to SN II products like O, but with much larger scatter)


abundances in "low metallicity stars"

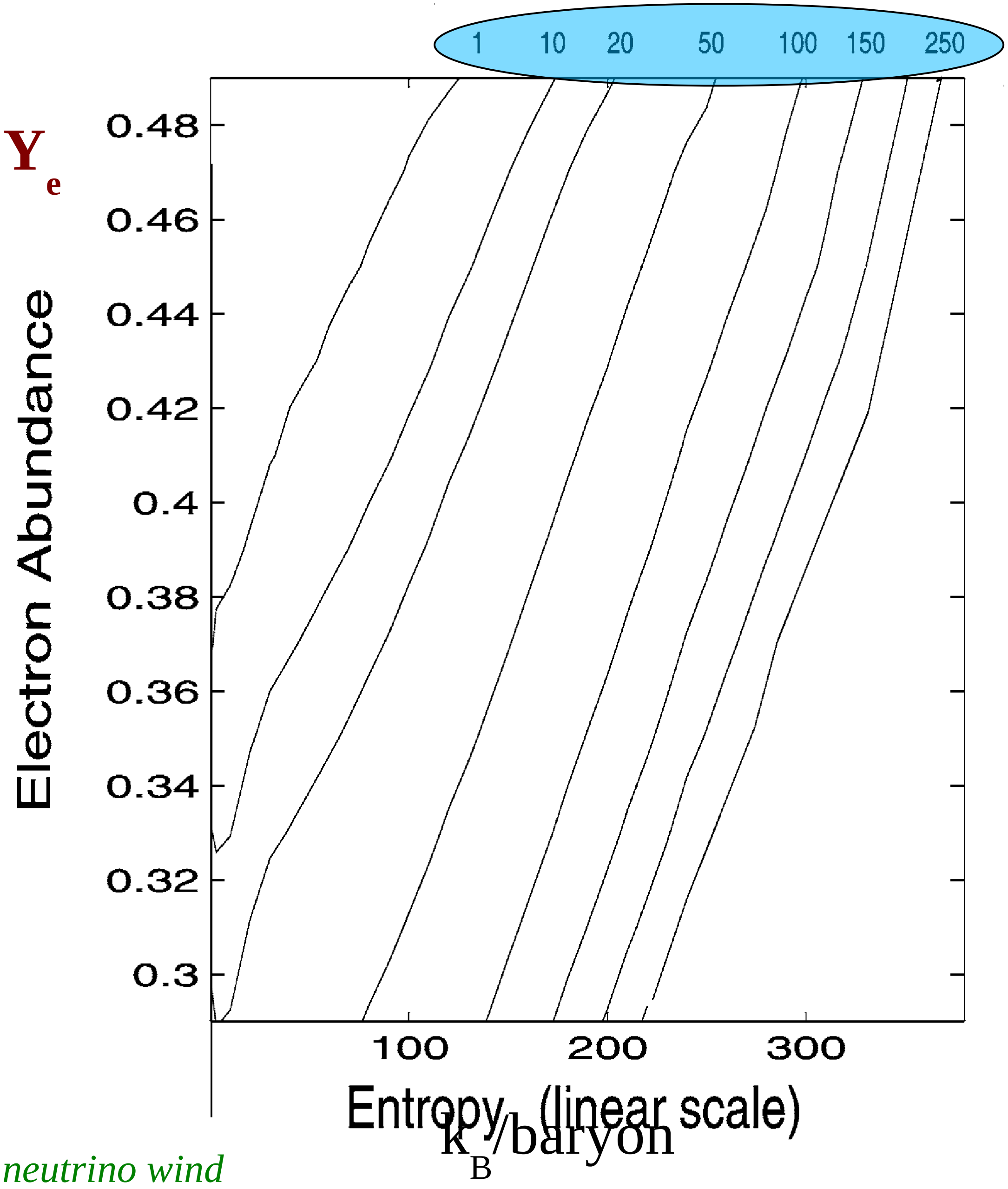
Observations of the weak r-process?



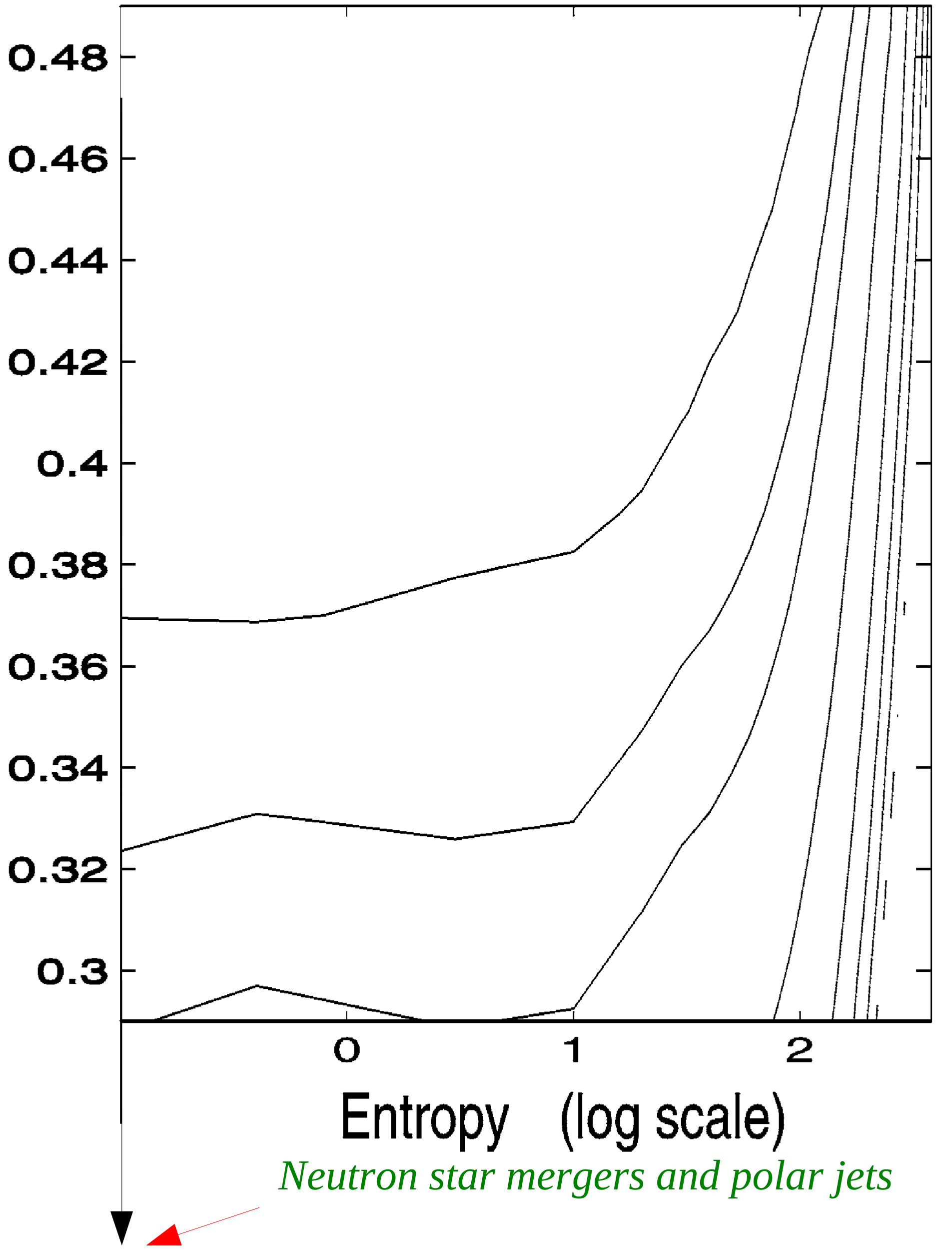
Honda et al. (2007)

n/seed ratios as function of S and Y_e

Freiburghaus et al. (1999)



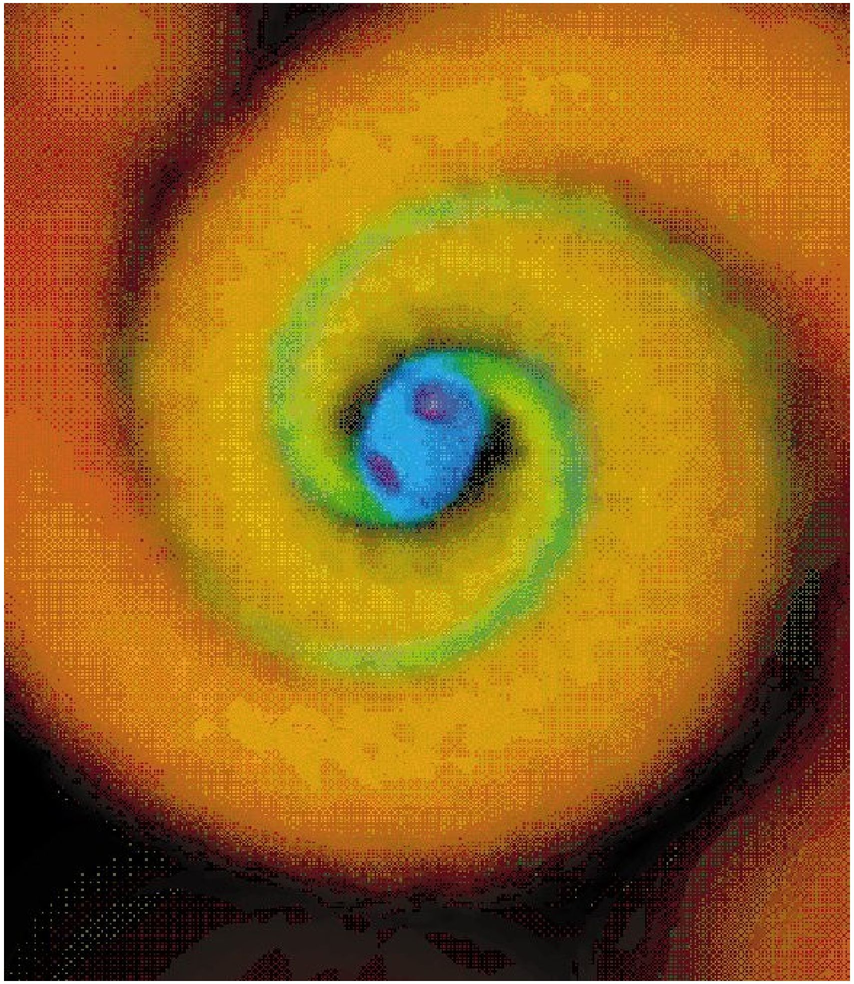
neutrino wind

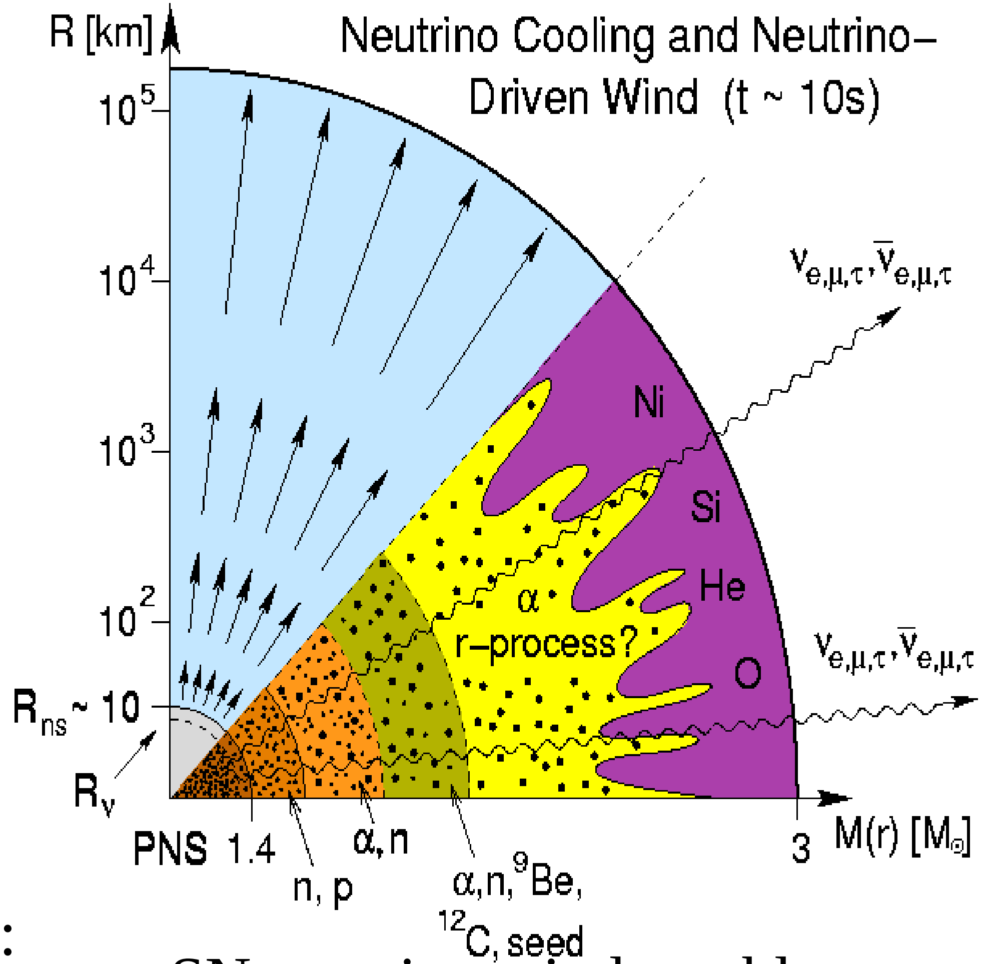


Neutron star mergers and polar jets

Requirement for actinide-producing r-process: A_{seed} + n/seed = $A_{actinide}$!

What is the site of the r-process?

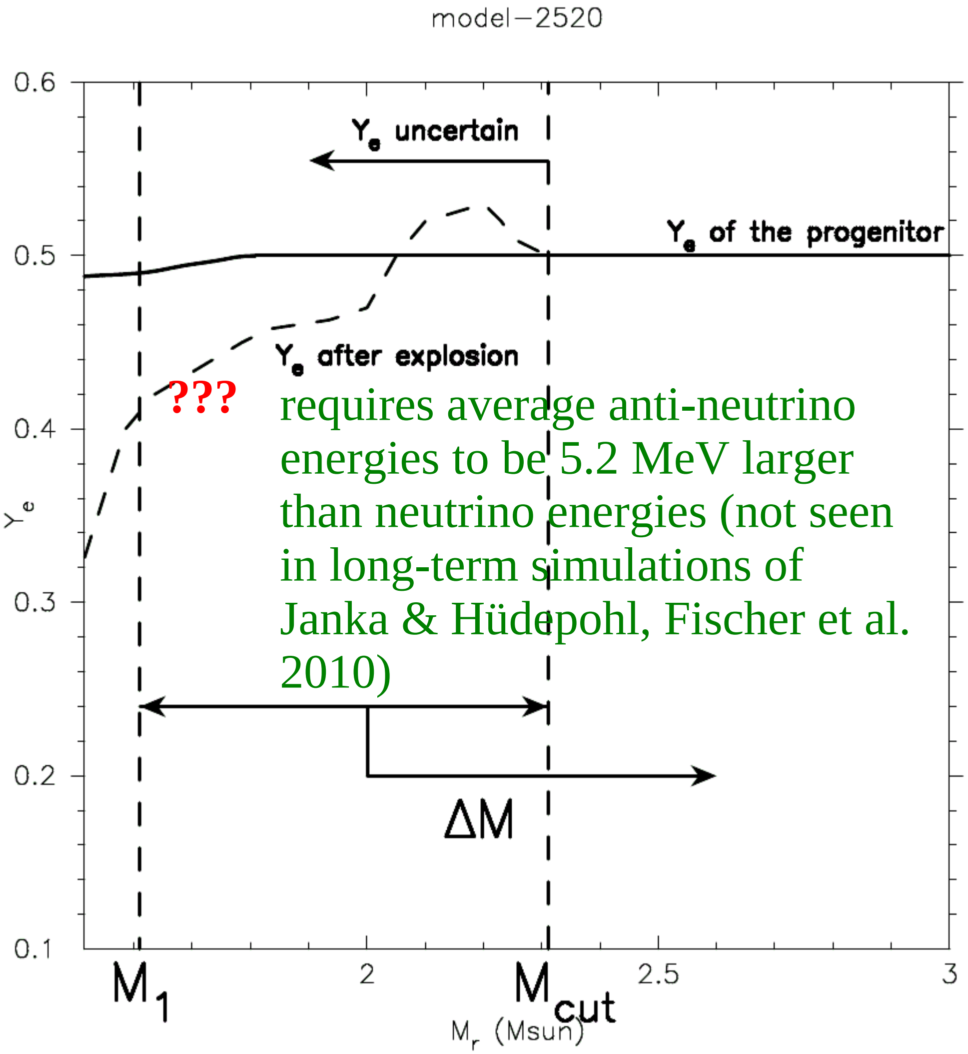

from S. Rosswog


from H.-T. Janka

NS mergers, BH-NS mergers, problems:
ejection too late in galactic evolution
(or alternatively polar jets from supernovae,
Cameron 2003, Fujimoto et al. 2008)

SN neutrino wind, problems:
high enough entropies attained?
neutrino properties???

Possible Variations in Explosions and Ejecta



???

requires average anti-neutrino energies to be 5.2 MeV larger than neutrino energies (not seen in long-term simulations of Janka & Hüdepohl, Fischer et al. 2010)

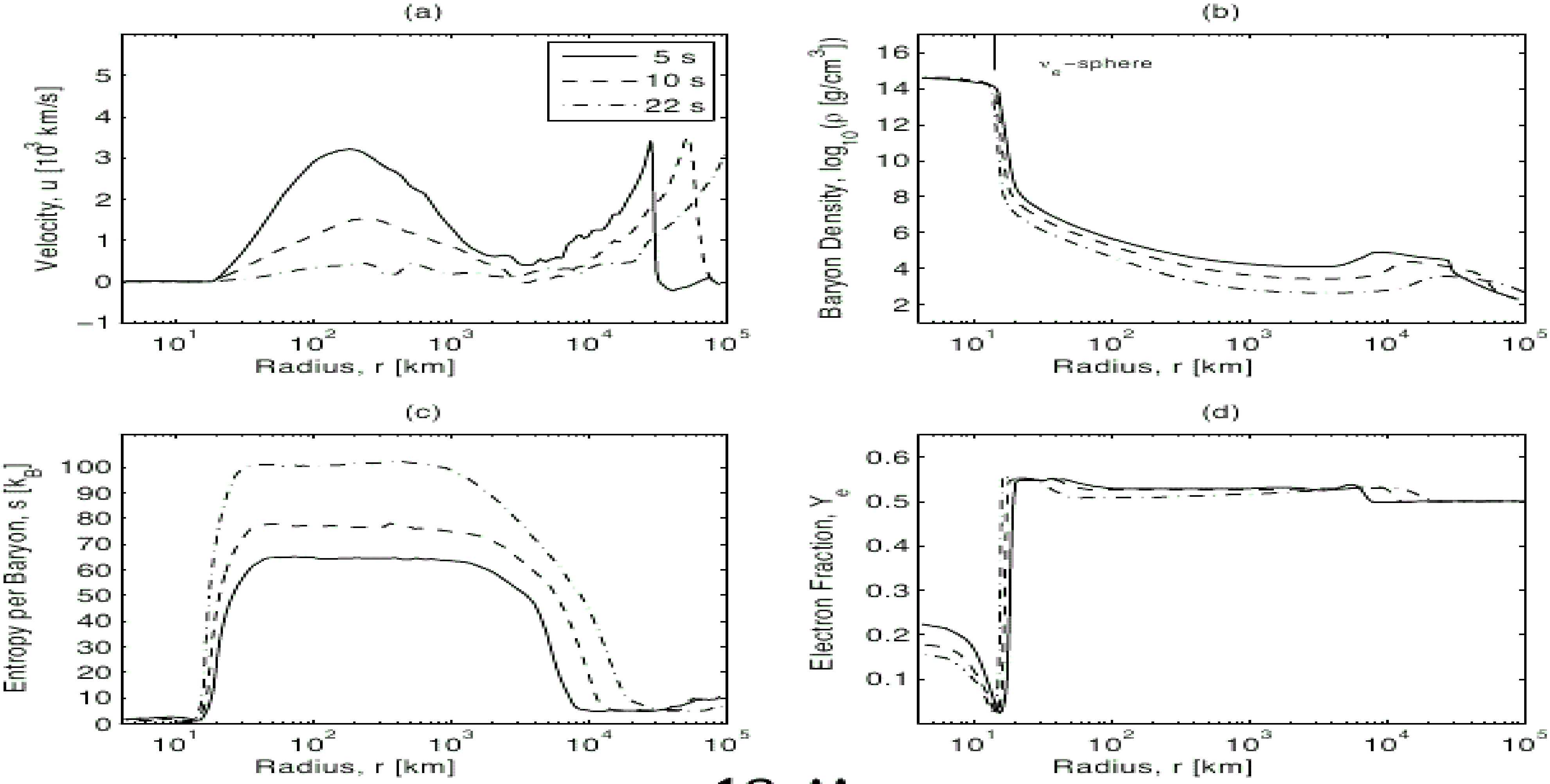
Izutani et al. (2009)

- *regular explosions with neutron star formation, neutrino exposure, νp-process, moderately neutron-rich neutrino wind and weak r-process or more* **??** *(see e.g. Arcones & Montes 2011, Roberts et al. 2010)*
- *under which (special?) conditions can very high entropies or very neutron-rich ejecta be obtained which produce the main r-process nuclei? (Wanajo et al. 2010, neutron-rich lumps in EC-Supernovae?? jets: e.g. Cameron 2003, Fujimoto et al. 2008?; very high entropy and neutron-rich neutrino wind?)*

Long-term evolution up to 20s, transition from explosion to neutrino wind phase

Fischer et al. (2010)

these findings see a longterm proton-rich composition, late(r) transition to neutron-rich ejecta possible?



18 Msun

Inclusion of medium Effects, potential U in dense medium

Martinez-Pinedo et al. 2012, see also Roberts et al., Roberts & Reddy 2012

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

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

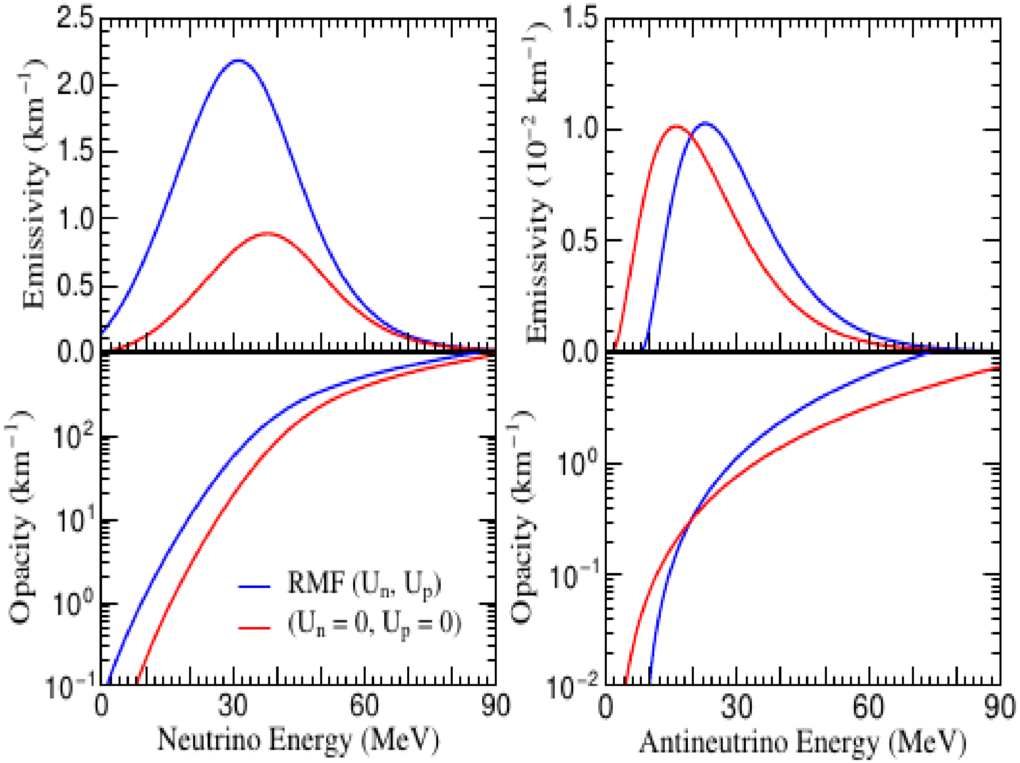
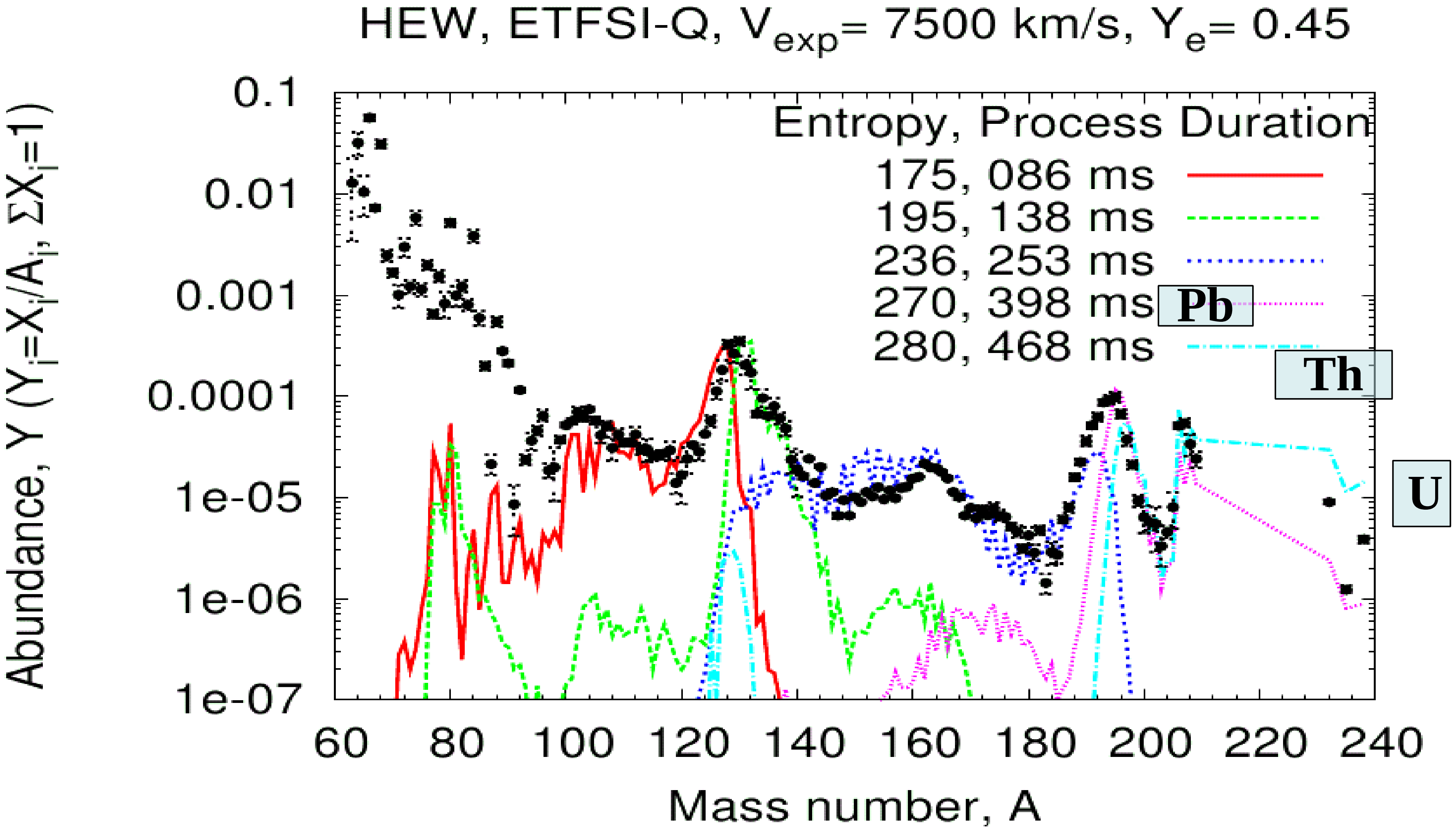


FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

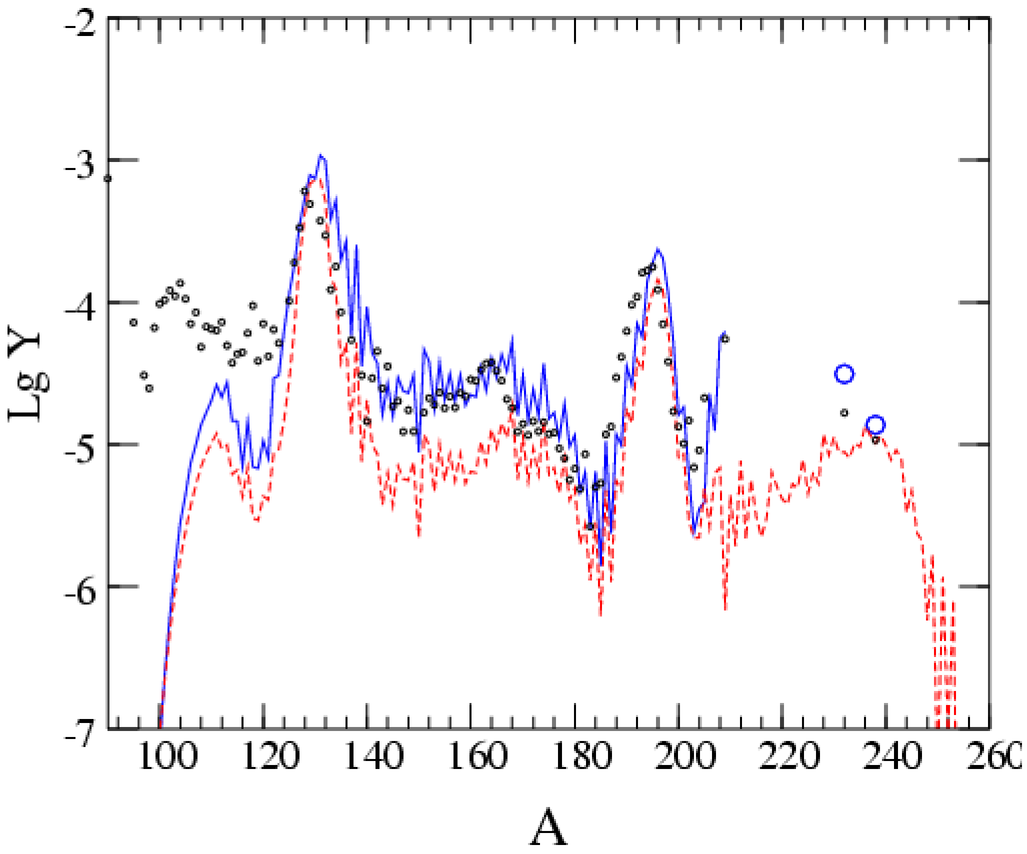
Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4!

Individual Entropy Components

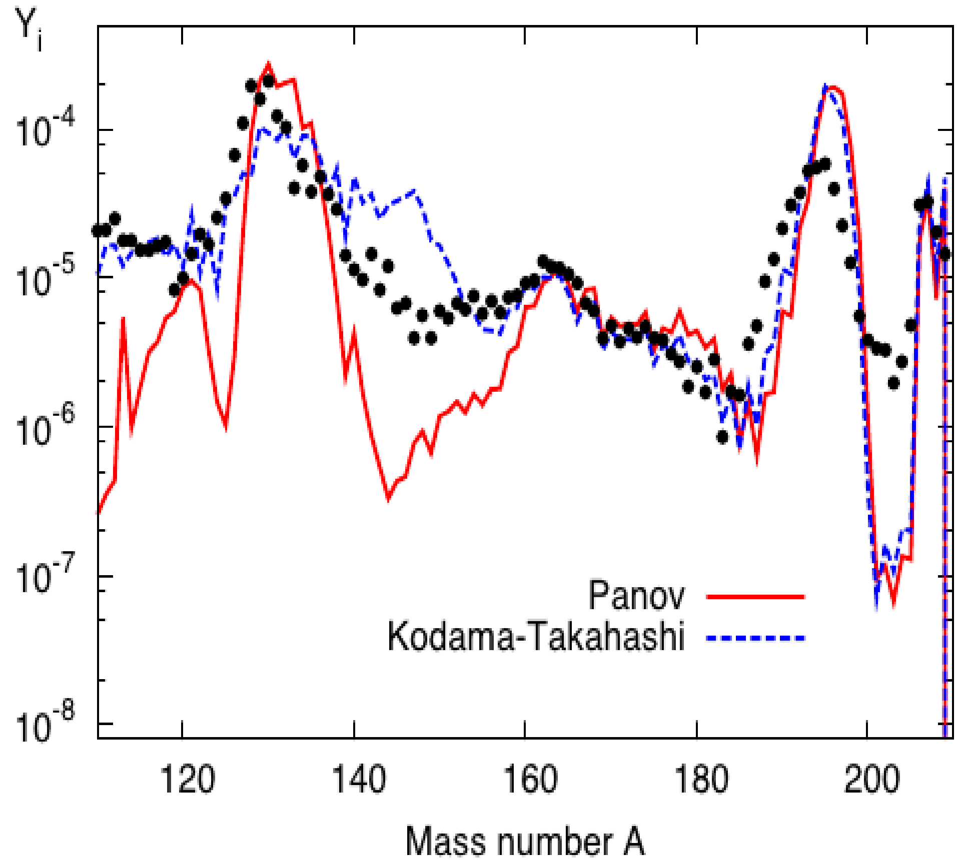
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in



Fission Cycling in Neutron Star Mergers



Panov, Korneev and Thielemann (2007, 2009) with parametrized fission yield contribution (see also Goriely, Bauswein, Janka 2011)

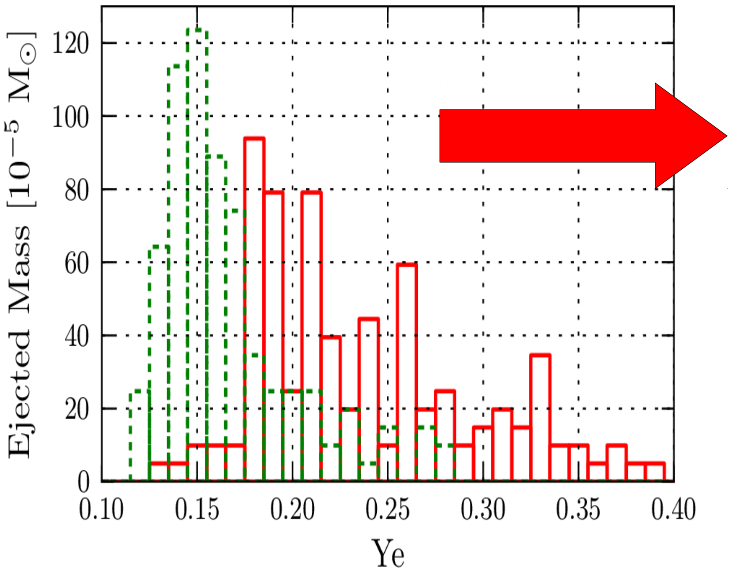


Recent neutron star merger update by Korobkin et al. (2012)

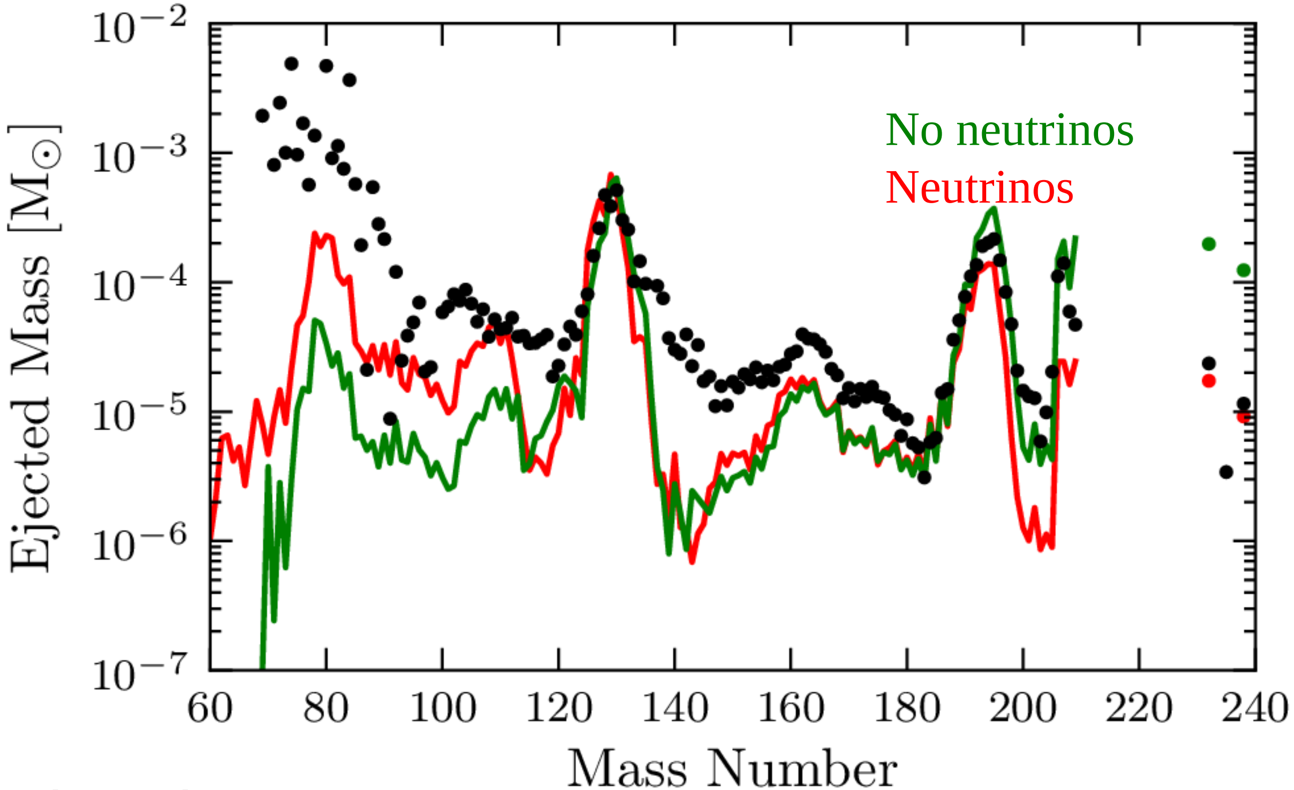
in principle contradicted from gal. evol. calc. (however, see Ishimura & Wanajo 2010), but similar conditions in SN polar jets? (Cameron 2003, Fujimoto 2008)

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):

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

Summary

The explanation of solar system abundances up to Fe reasonably well understood, if one knows SN explosion energies

Fe-group composition depends on Y_e dialed in the explosion

s-process is secondary, but are some features of rotation-enhanced ^{22}Ne visible?

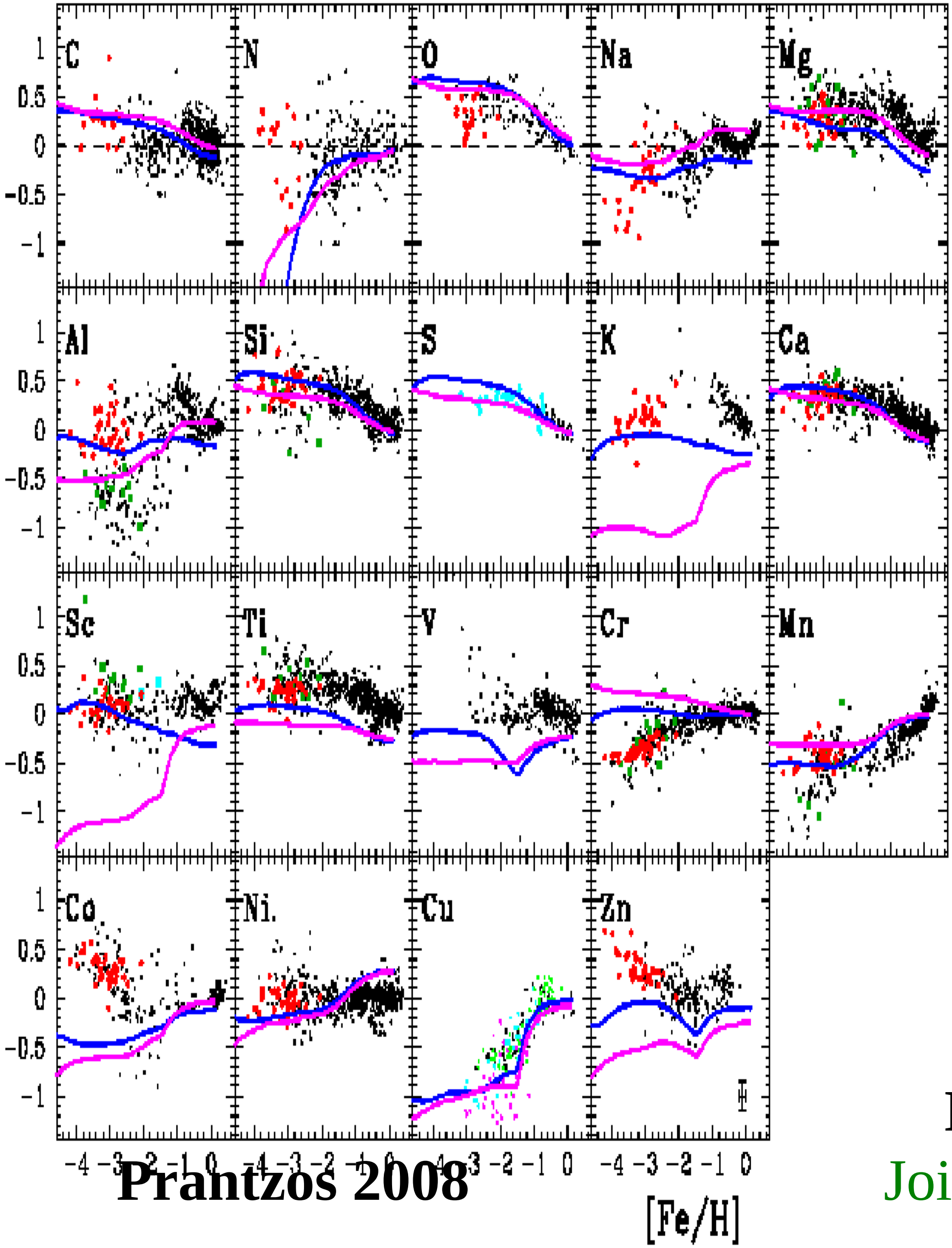
Does neutrino wind always lead to proton-rich conditions and νp-process, or also weak r-process?

Nucleosynthesis beyond Fe more complicated than originally envisioned (r- and p-process).

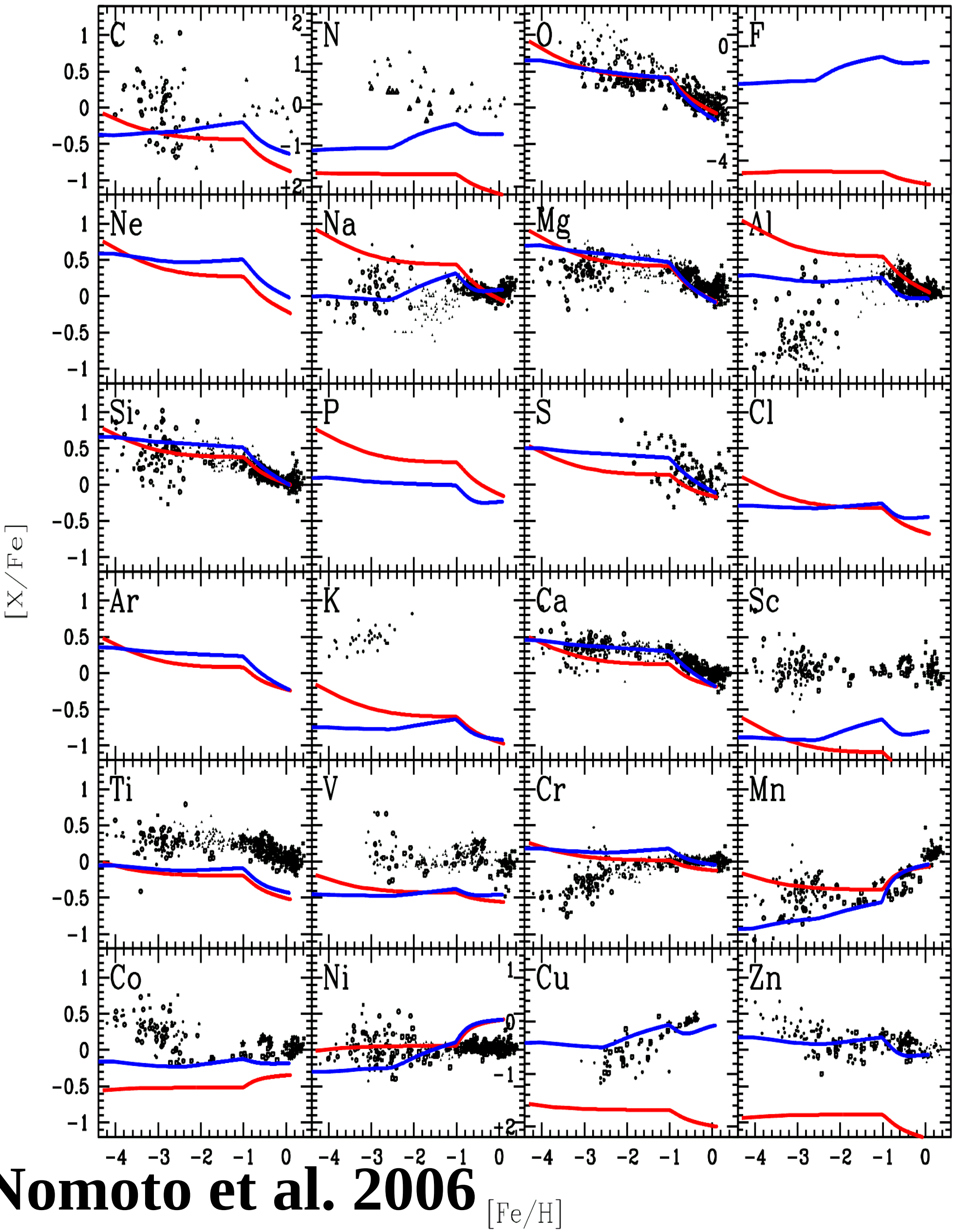
The classical p/γ-process cannot reproduce the light p-isotopes and another process has to contribute these nuclei (νp-process) and/or p/γ-process in different locations..

Also the r-process comes in at least two versions (weak-main/strong). Weak r-process possible in EC SNe and Quark-Hadron EoS SNe. Any chance to become neutron-rich in the late neutrino wind?

The main/strong r-process comes apparently in each event in solar proportions, but the events are rare. The site is not found, yet. Speculations include rotating core collapse events with jet ejection, neutron star mergers and accretion disks around black holes.



Prantzos 2008



Nomoto et al. 2006

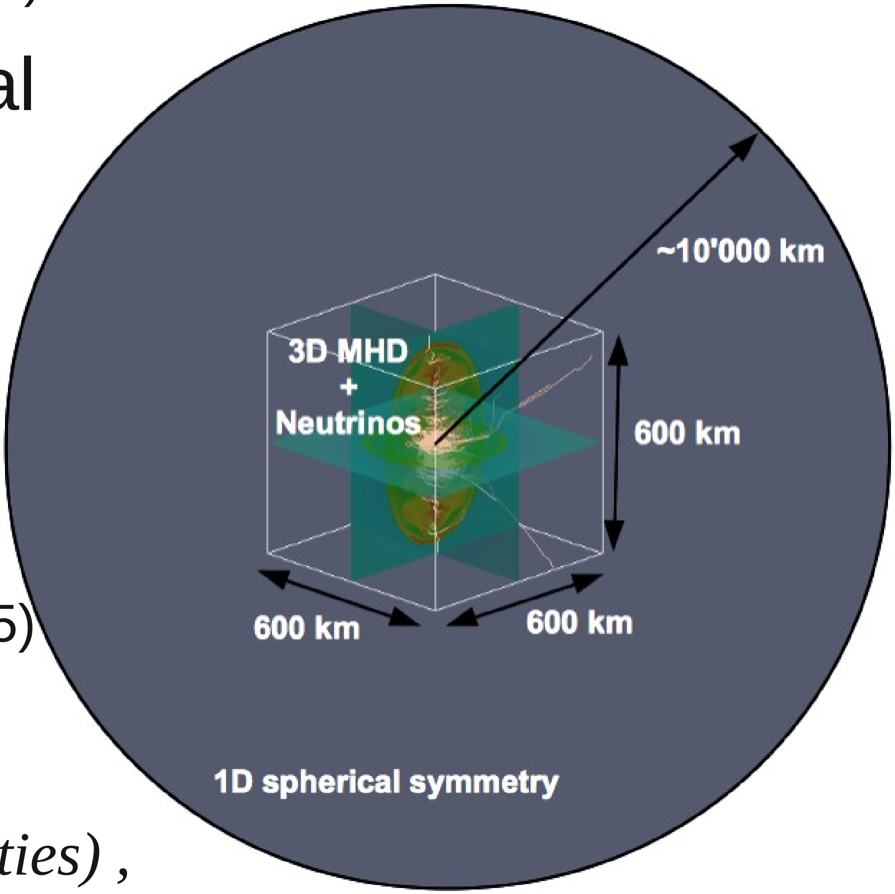
Joint problems for K, Sc, Ti, V, Cr, Co, Zn

Chemical evolution calculations Prantzos 2008 and Nomoto et al. 2006 with Weaver& Woosley, and Limongi&Chieffi yields vs. Nomoto et al. yields with and without hypernovae (50% of IMF)

r-process in MHD Jets from fast rotating models with high magnetic fields?

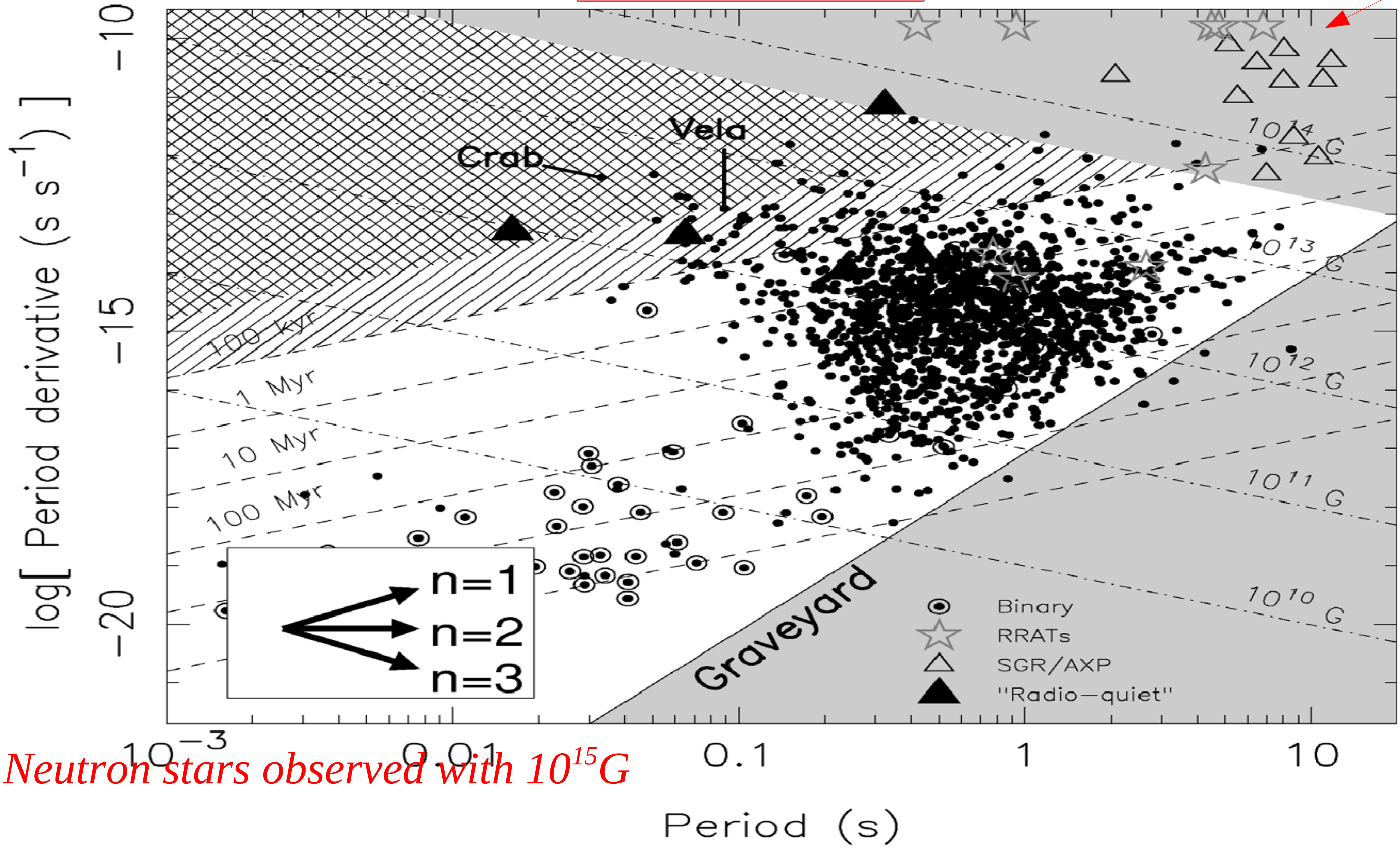
Details of 3D MHD CCSN Model

- 3D inner $(600\text{km})^3$ cube
  - MHD code FISH (Käppeli et al 2011)
  - Neutrino transport: 3D spectral leakage scheme (A.Perego)
- Outside followed by 1D spherically symmetric code AGILE (Liebendörfer et al. 2002)
- Progenitor: $15M_{sol}$ (Heger et al 2005)



Low entropy, low Ye (compression to high densities) ,

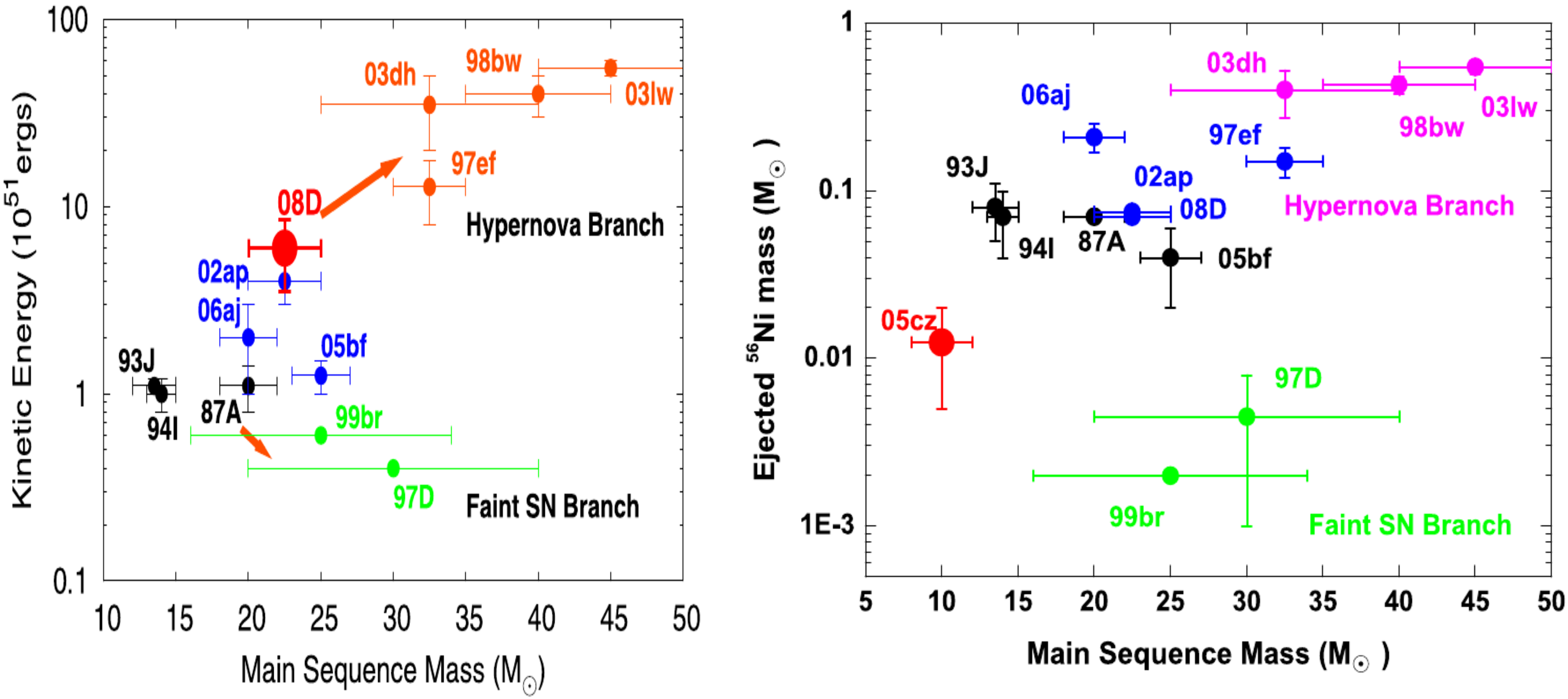
fast expansion; earlier promising r-process results in 2D (Nishimura et al 2006, 2008)



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.

Transition Supernovae to Faint Supernovae and Hypernovae



Nomoto et al. (2011)