# How many processes contribute to the heavy element abundances in the Fe-group and beyond and what are/could be their astrophysical sites?

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

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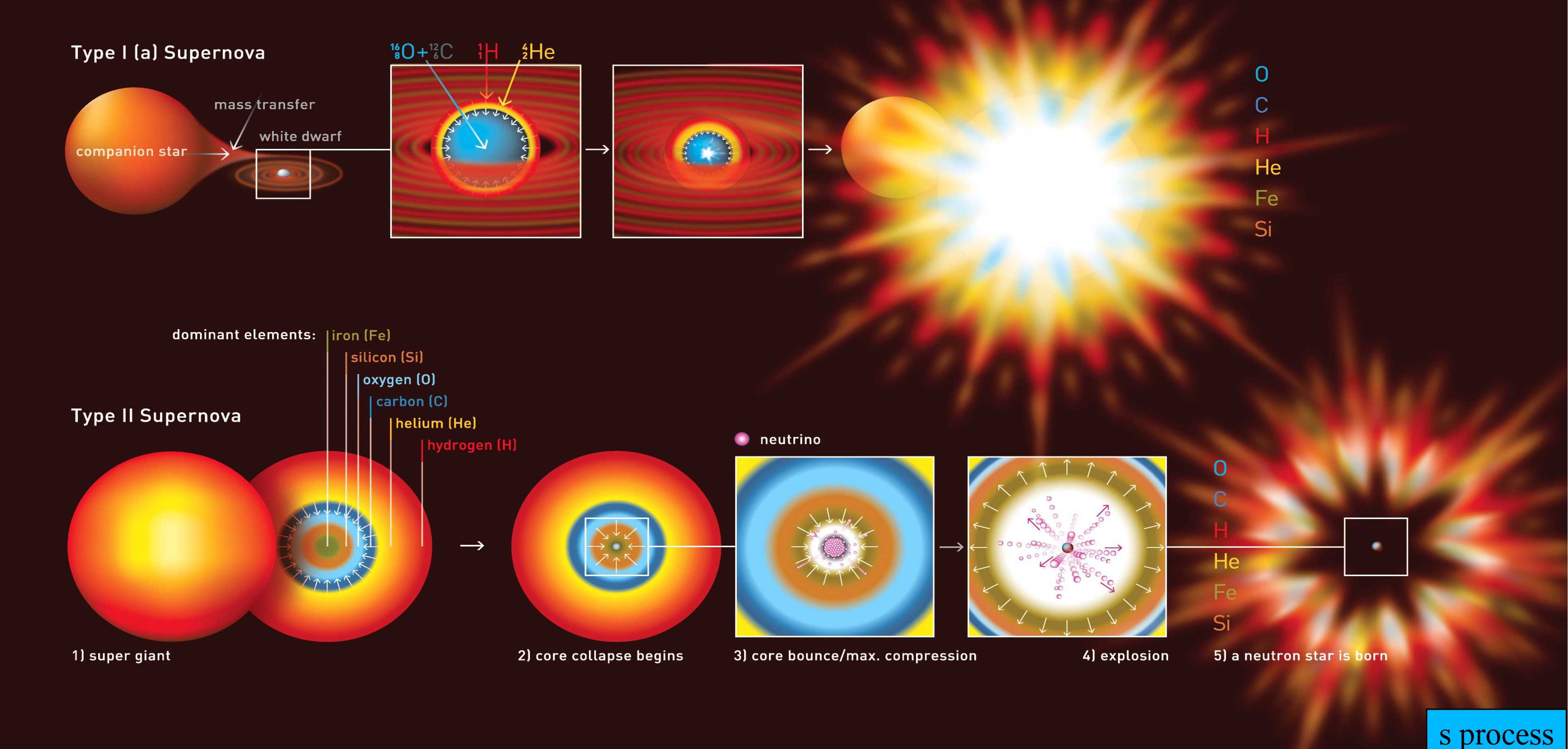
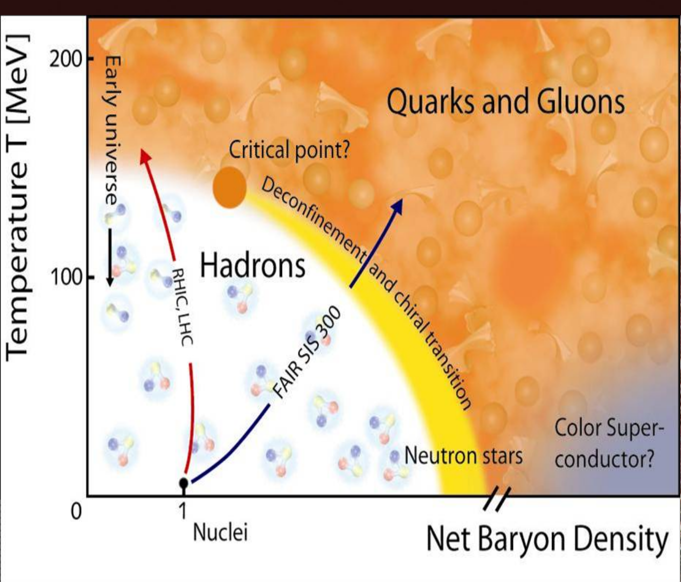
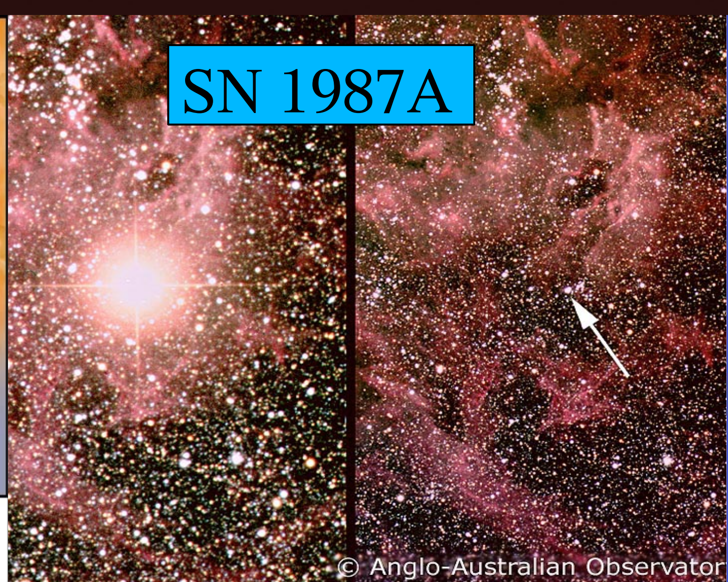
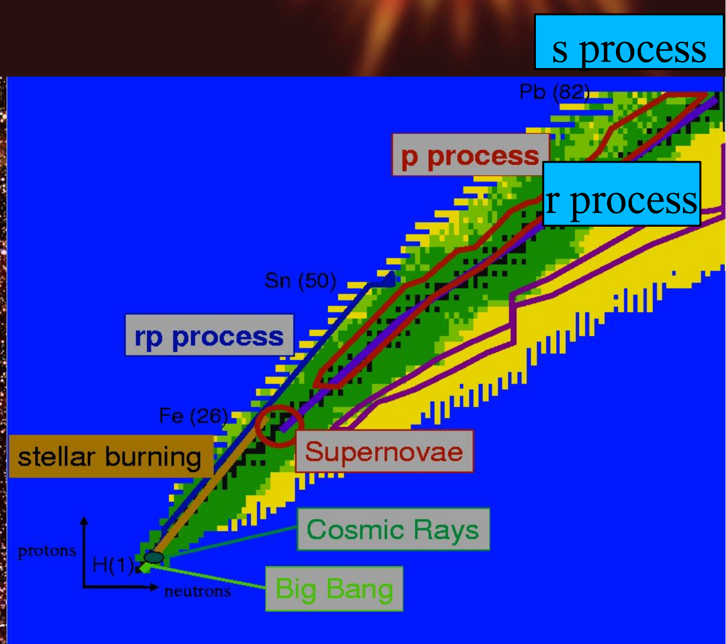
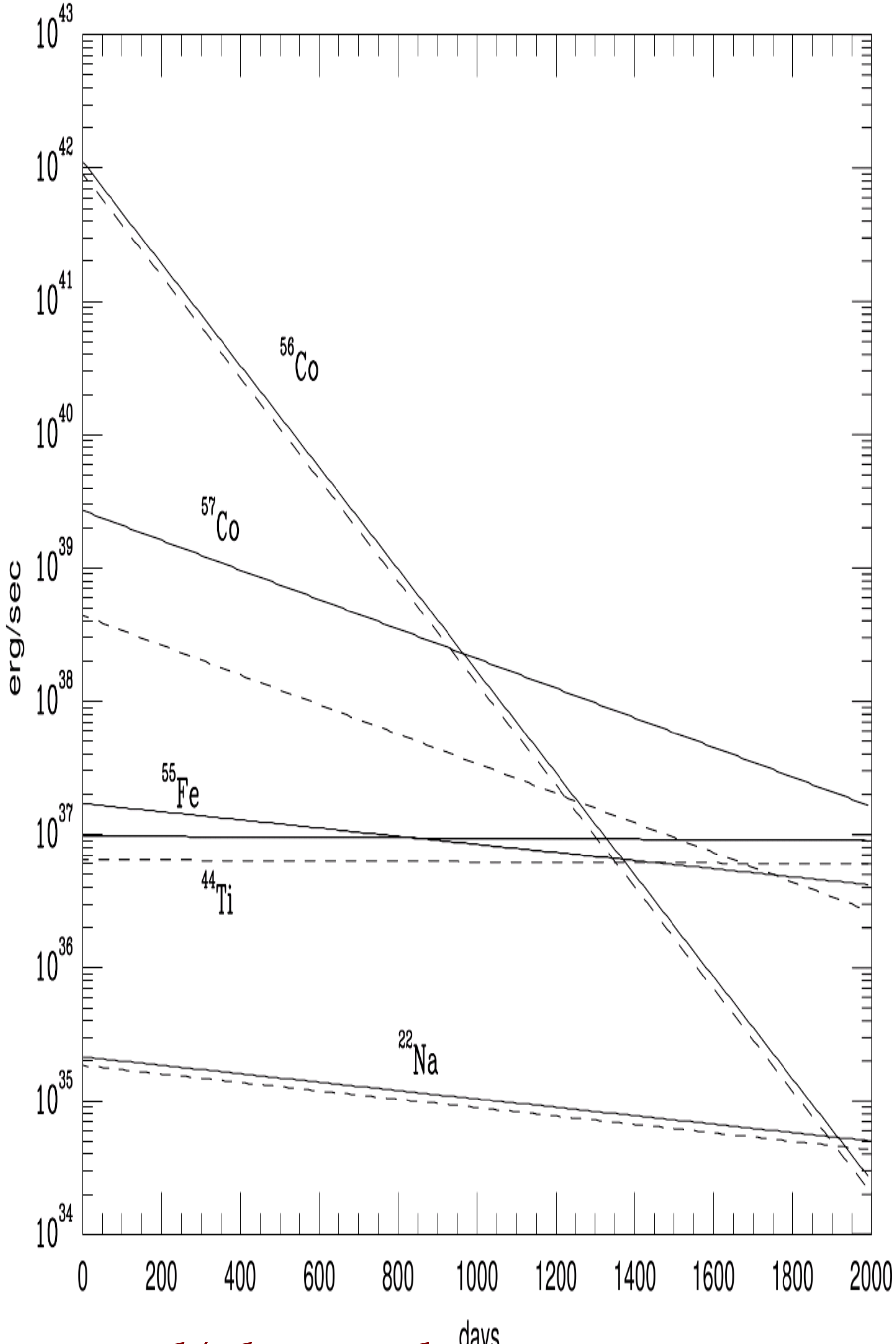

Type I (a) Supernova
$^{16}_{8}O + ^{12}_{6}C$
$^{1}_{1}H$
$^{4}_{2}He$
mass transfer
white dwarf
companion star
O
C
H
He
Fe
Si
dominant elements:
iron (Fe)
silicon (Si)
oxygen (O)
carbon (C)
helium (He)
hydrogen (H)
Type II Supernova
neutrino
O
C
H
He
Fe
Si
1) super giant
2) core collapse begins
3) core bounce/max. compression
4) explosion
5) a neutron star is born


Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-
conductor?
1
Nuclei
Net Baryon Density

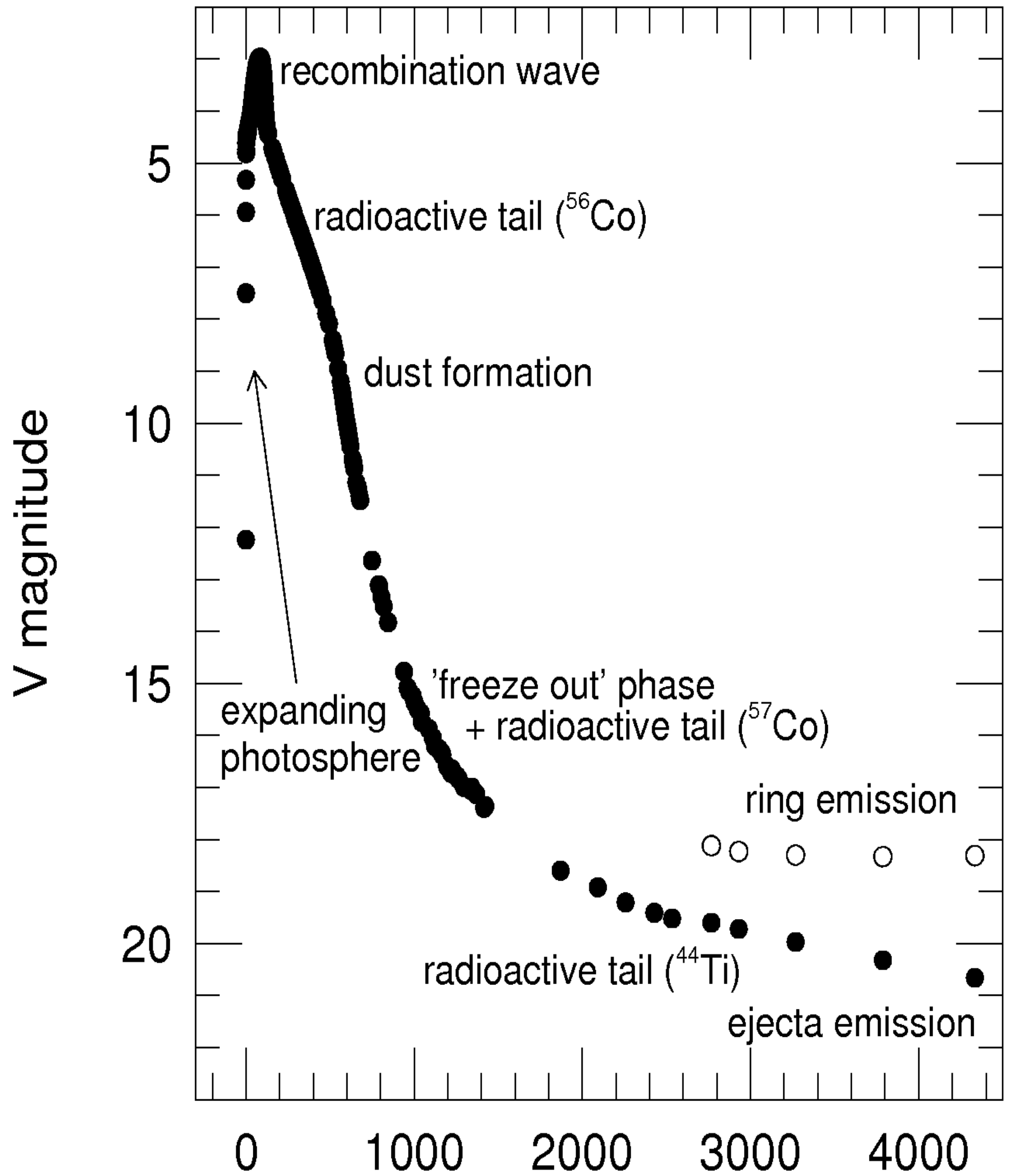

SN 1987A
© Anglo-Australian Observator


s process
Pb (82)
p process
r process
Sn (50)
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

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

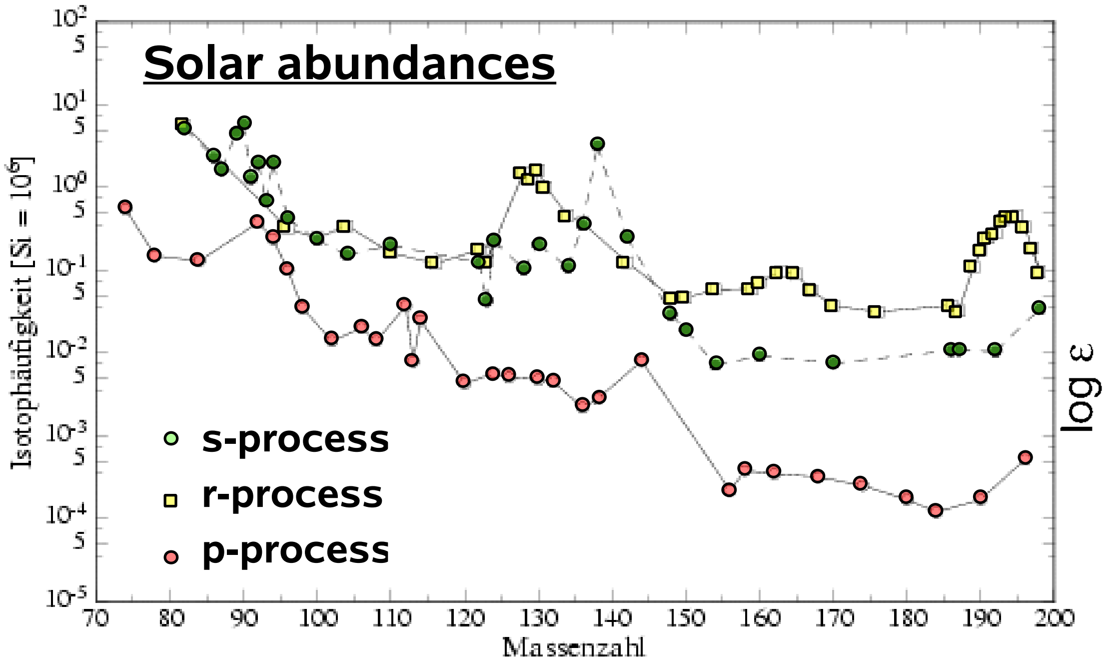


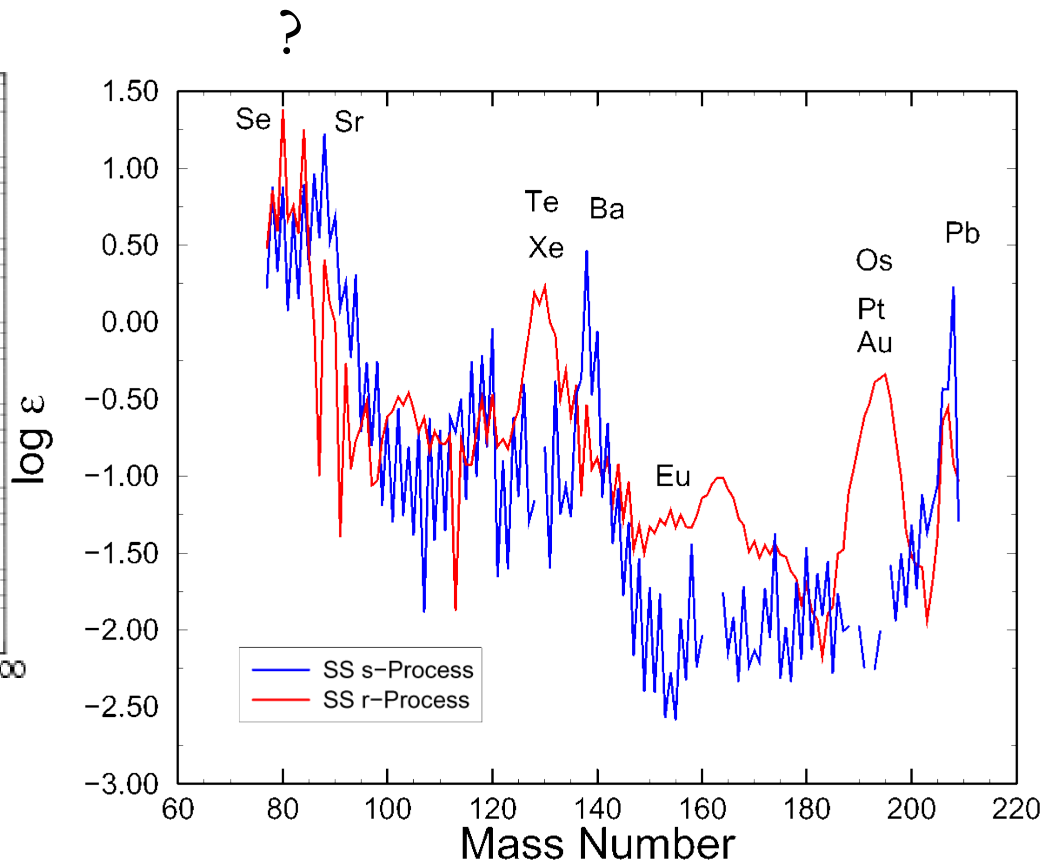

*total/photon decay energy input*



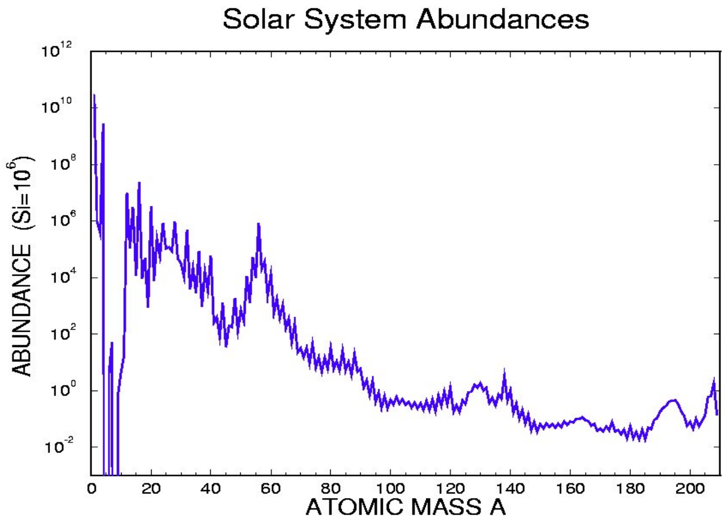

*Leibundgut & Suntzeff 2003*

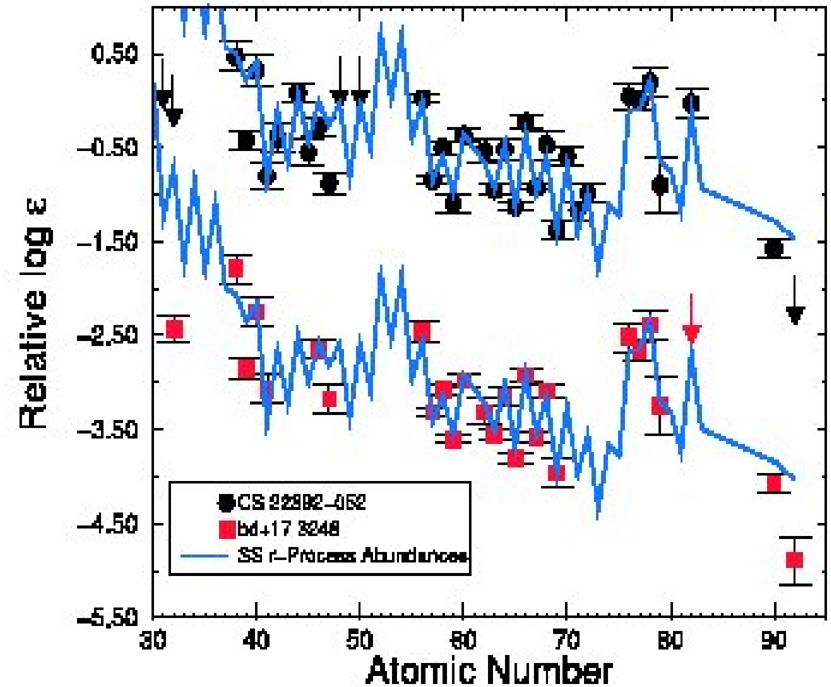
# Decomposition of the heavy elements



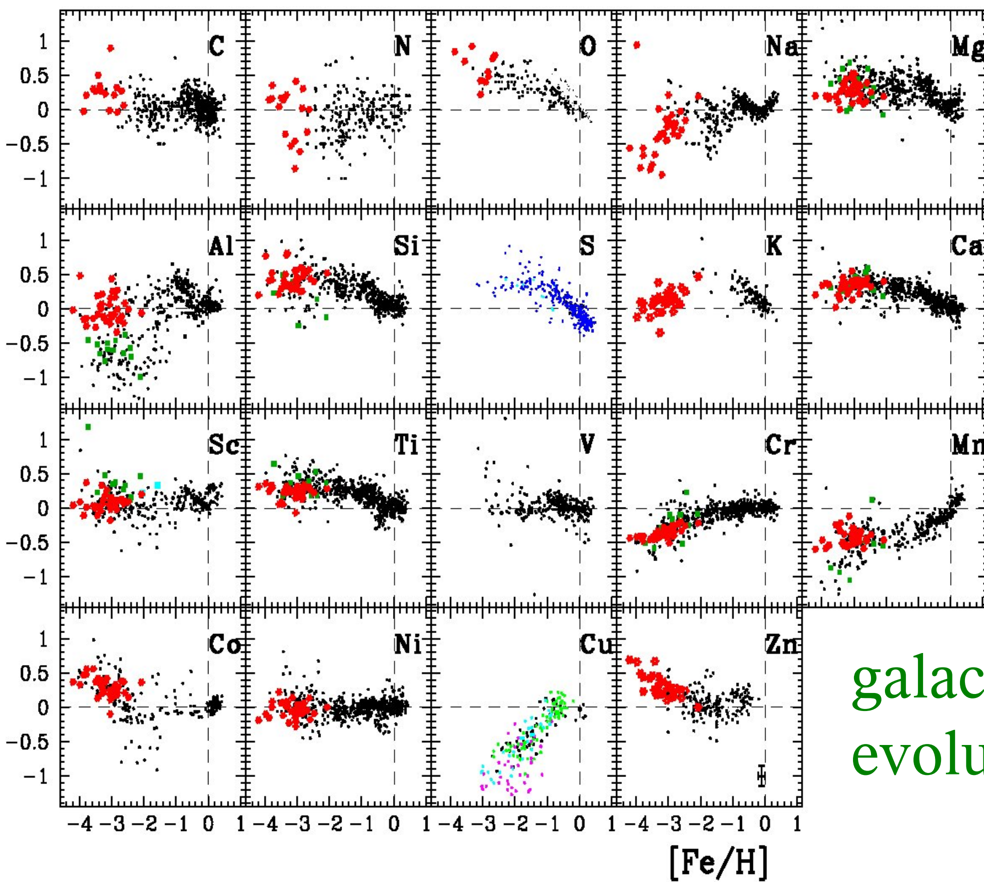

How do massive stars contribute to s-, r-, and p-process abundances?



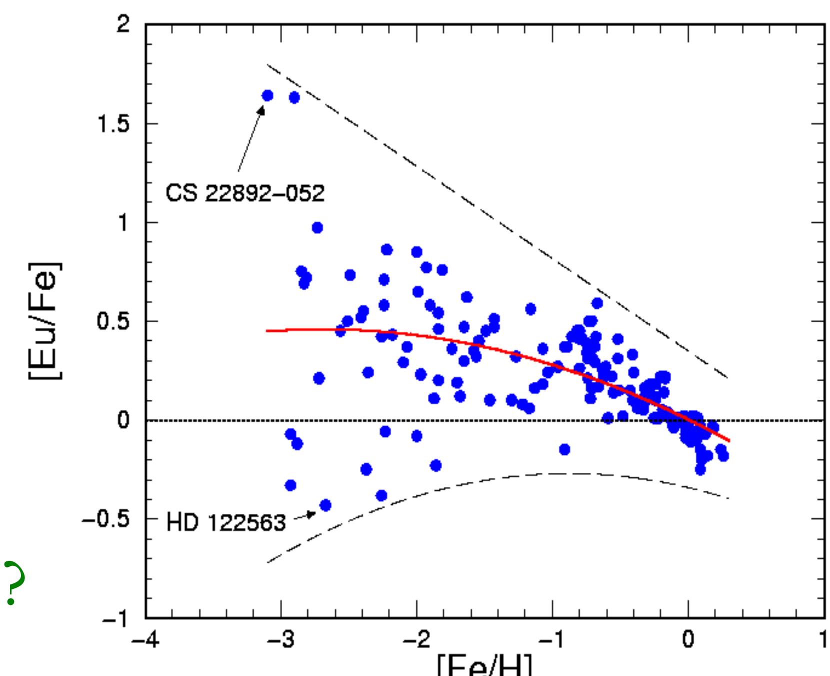




How do we understand: solar system abundances..

low metallicity stars ...



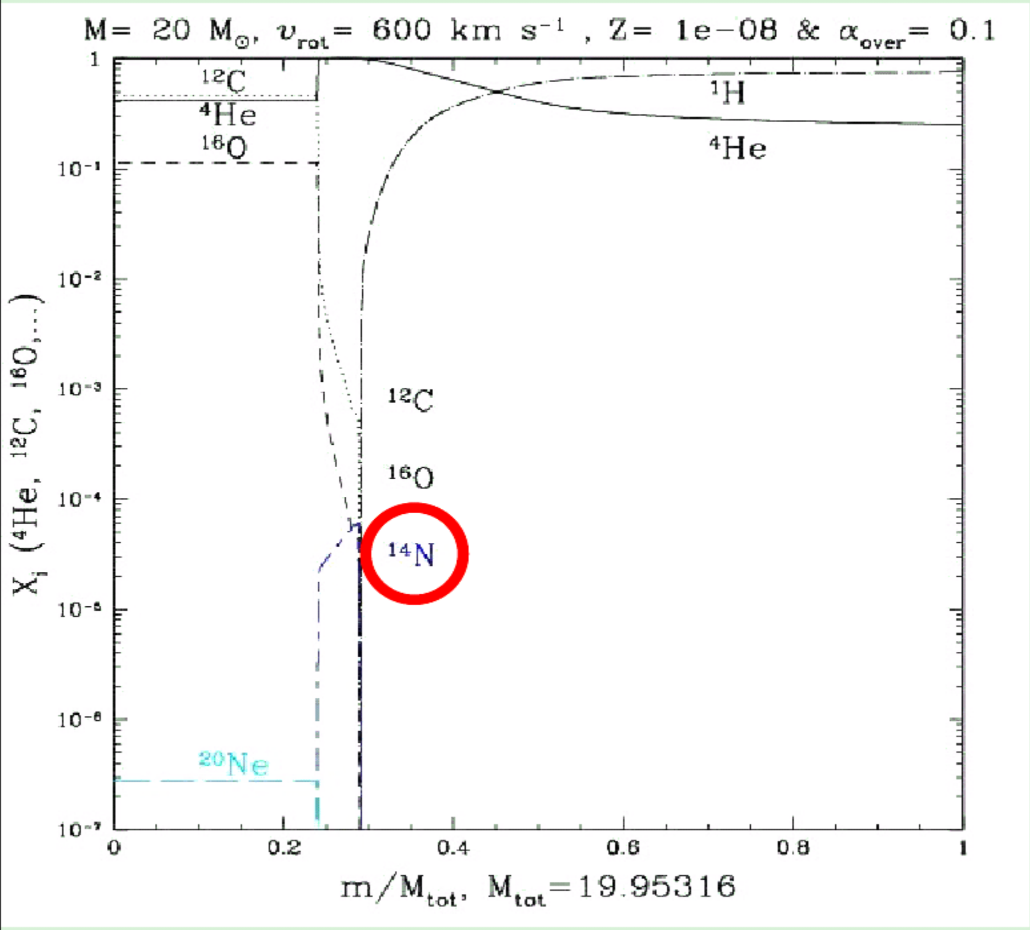

galactic evolution?

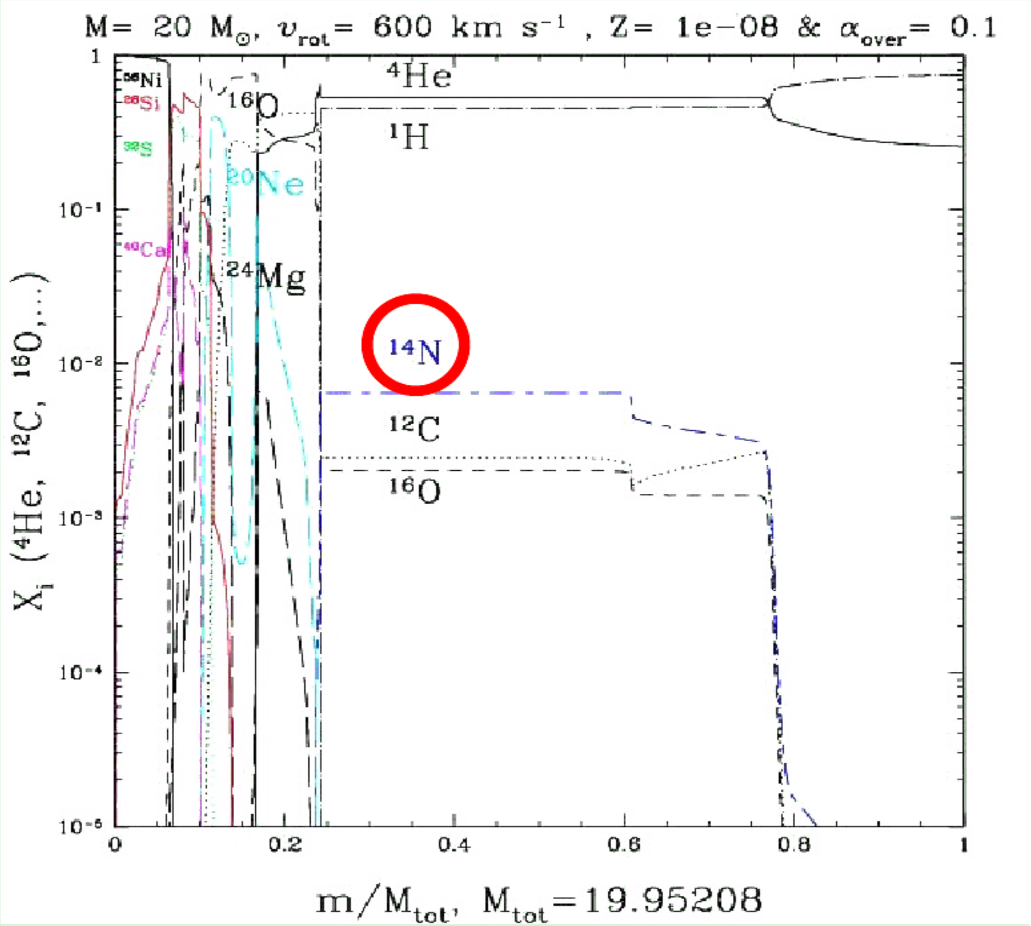


# Rotation induced mixing @ low Z

**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, $Z=10^{-5}$

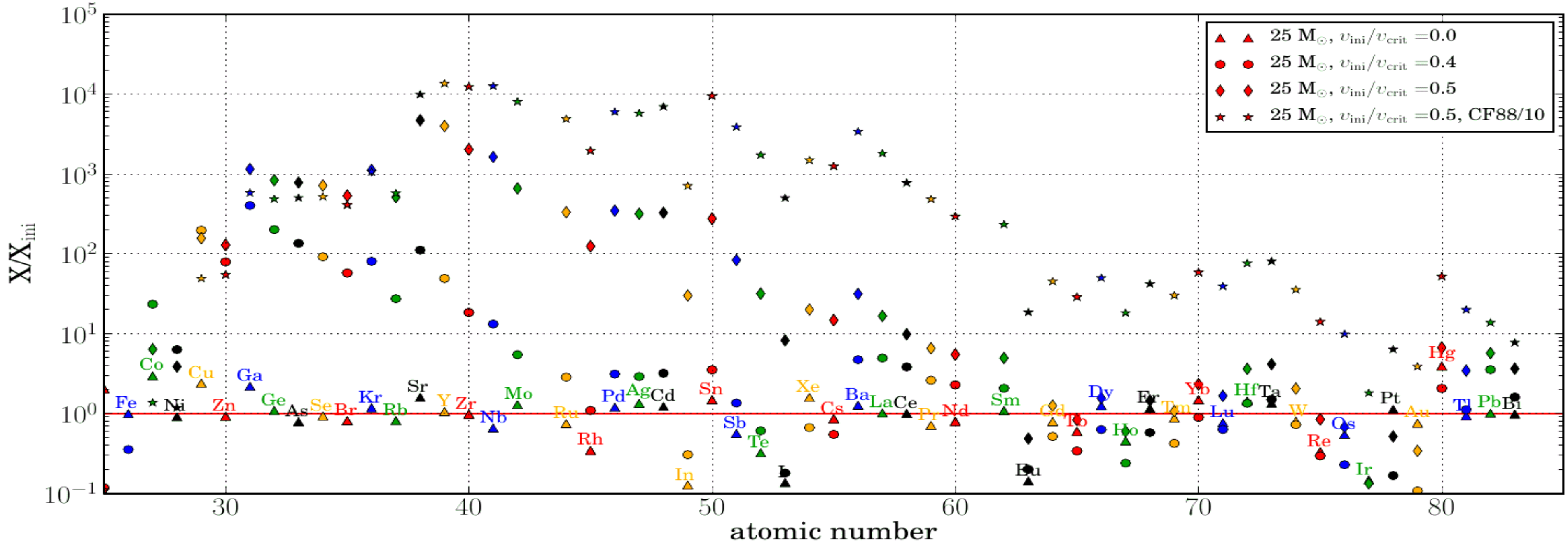



**Fig. 1.** Overproduction factors (abundances divided by their initial values) for the 25 M$_\odot$ models with $Z = 10^{-5}$ after the end of core He-burning. The model without rotation (triangles) does not produce s-process efficiently whereas the rotating models (filled circles, B1 and diamonds, 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 2011)

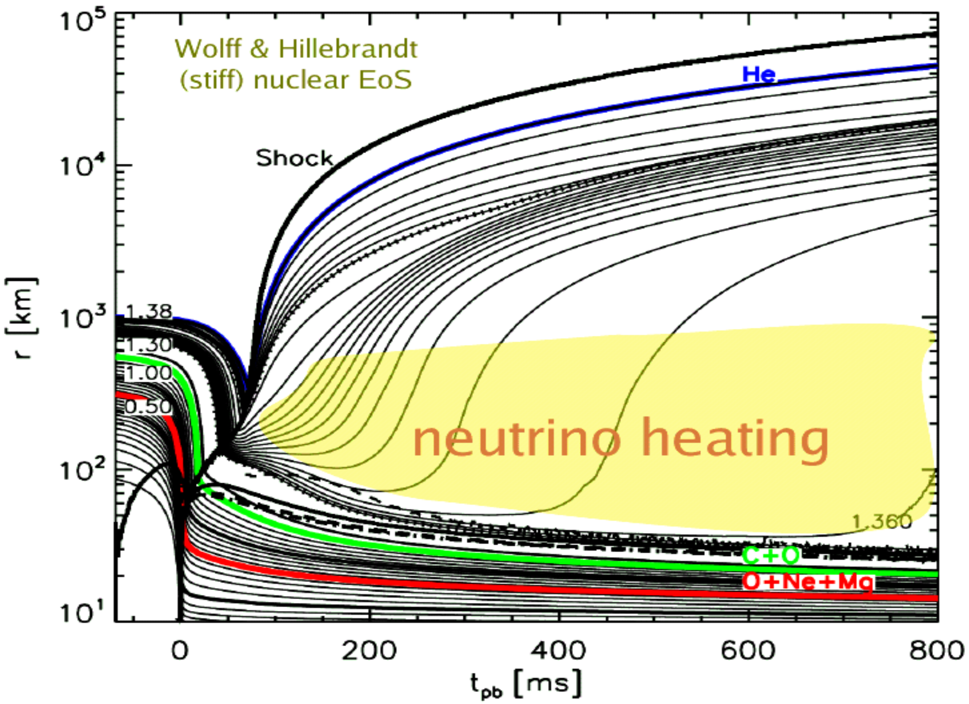
# Core Collapse Supernovae

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

# Supernovae in 1D

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

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

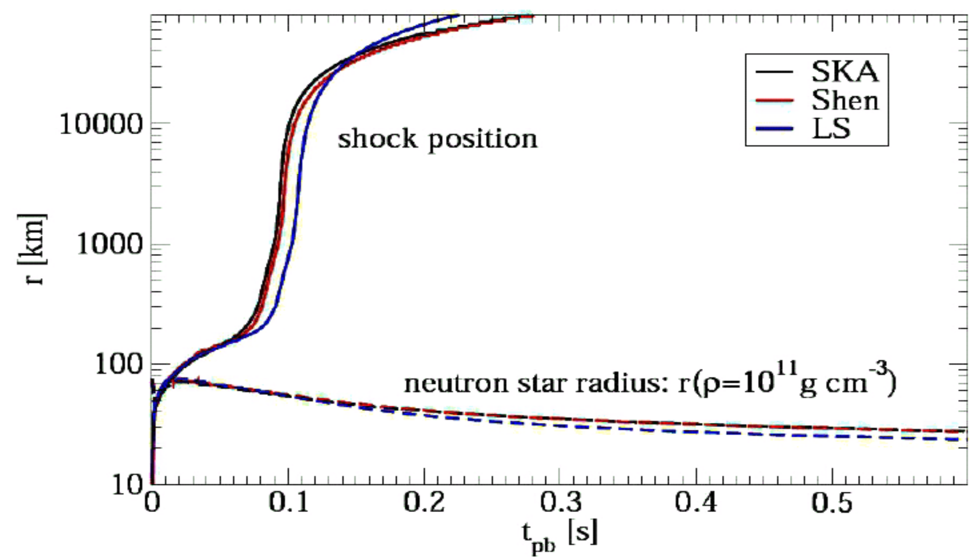



Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

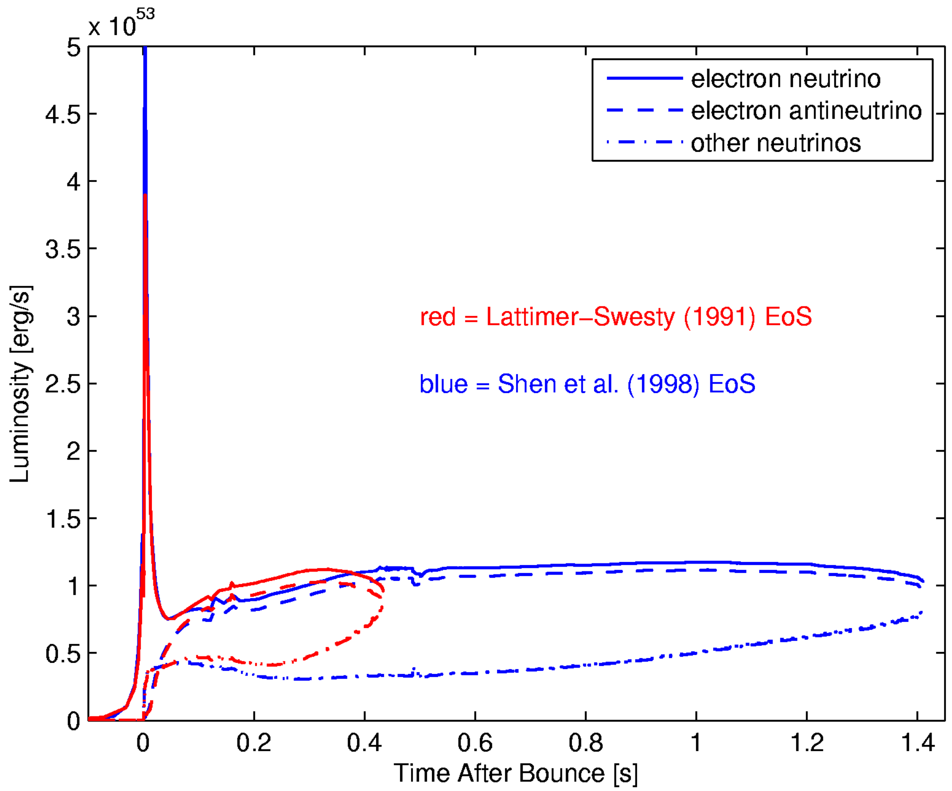
Fischer et al. 2010

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

- 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)



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

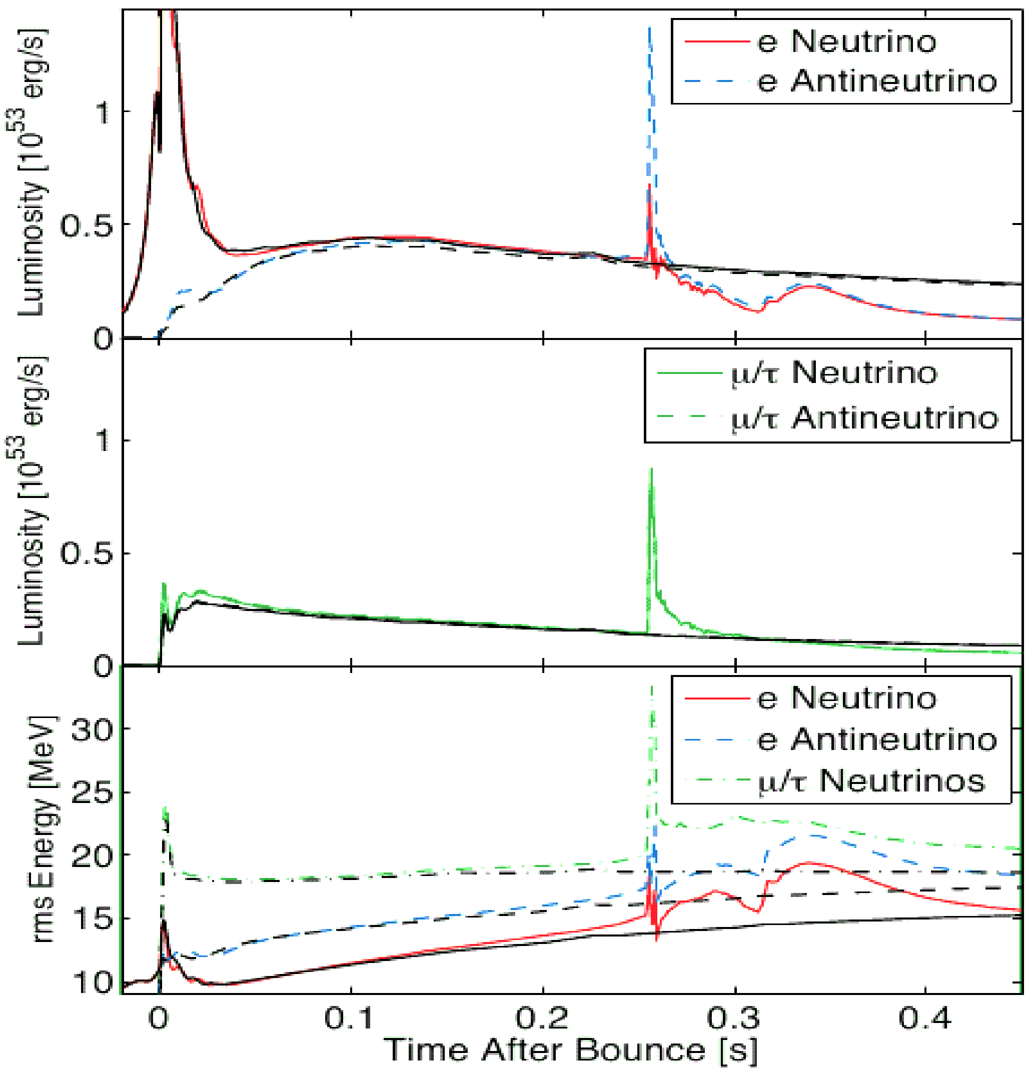



# Neutrino Emission

(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

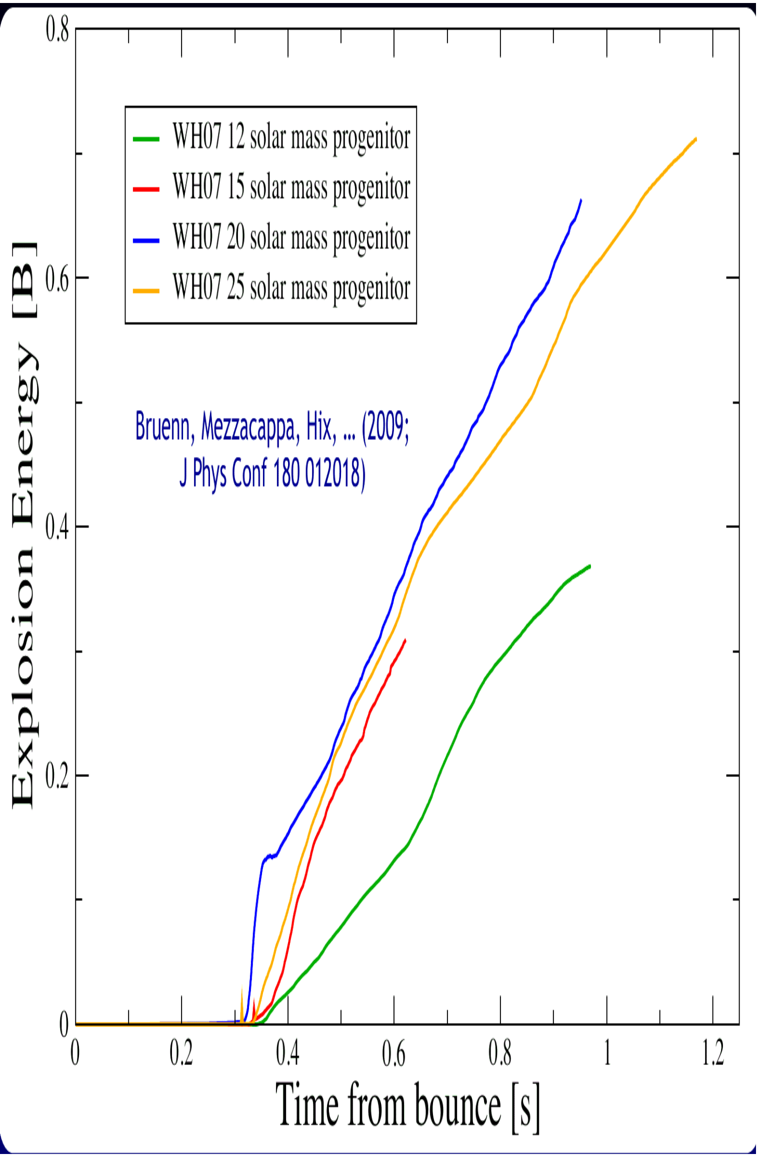
Fischer et al. (2009), effects purely due to nuclear equation of state

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



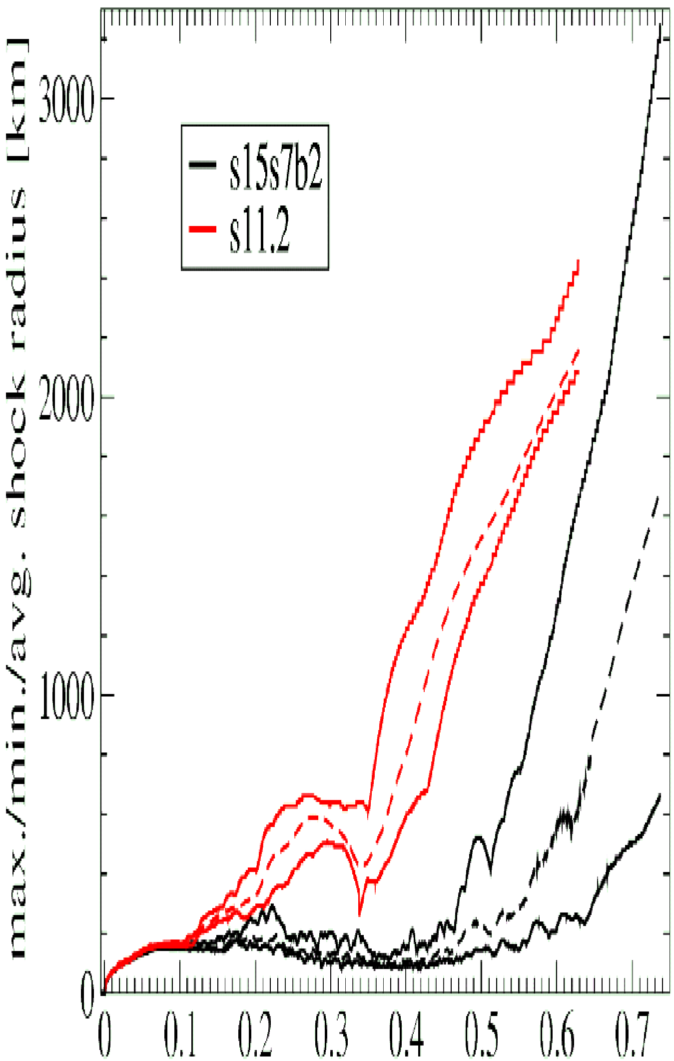

Shown is a simulation of a $10M_{sun}$ star containing ($B^{1/4} = 162$) quark matter compared to one with hadronic matter only (black lines)

# 2D and 3D simulations



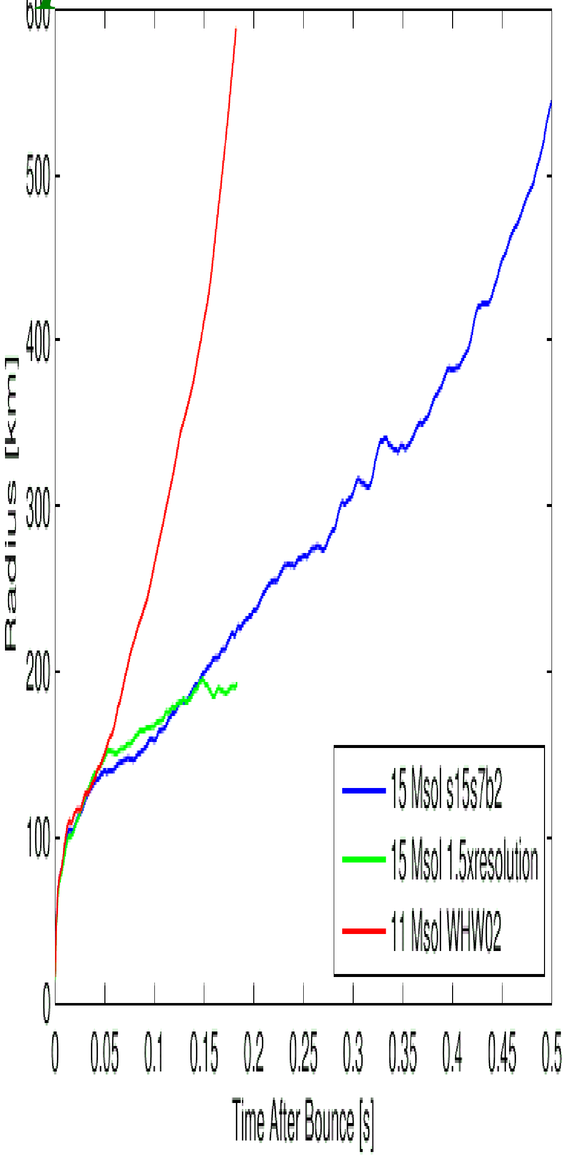

Oak Ridge

Shock radii




Garching

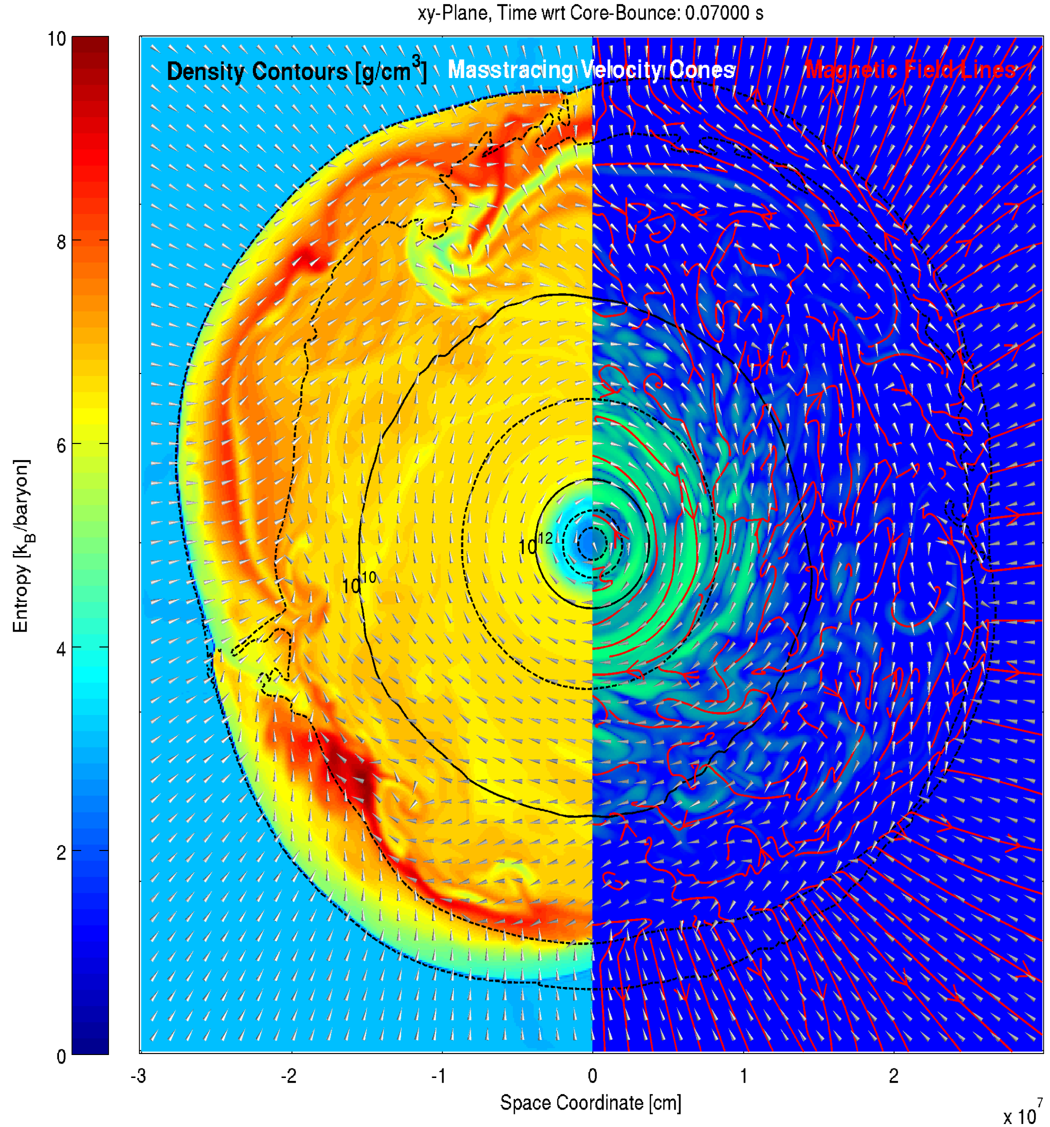
***can we be optimistic?***

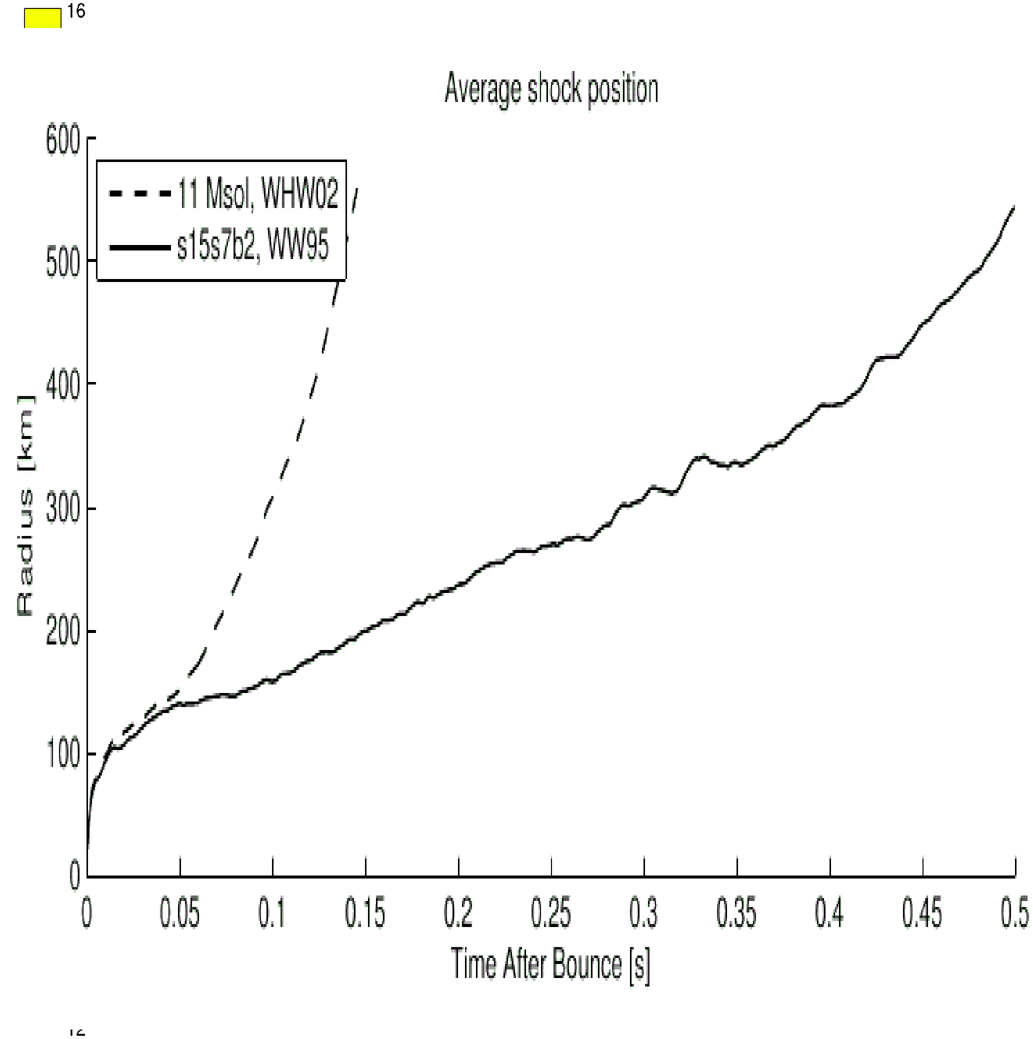



Basel

# Simulations in 3D

Liebendörfer et al.



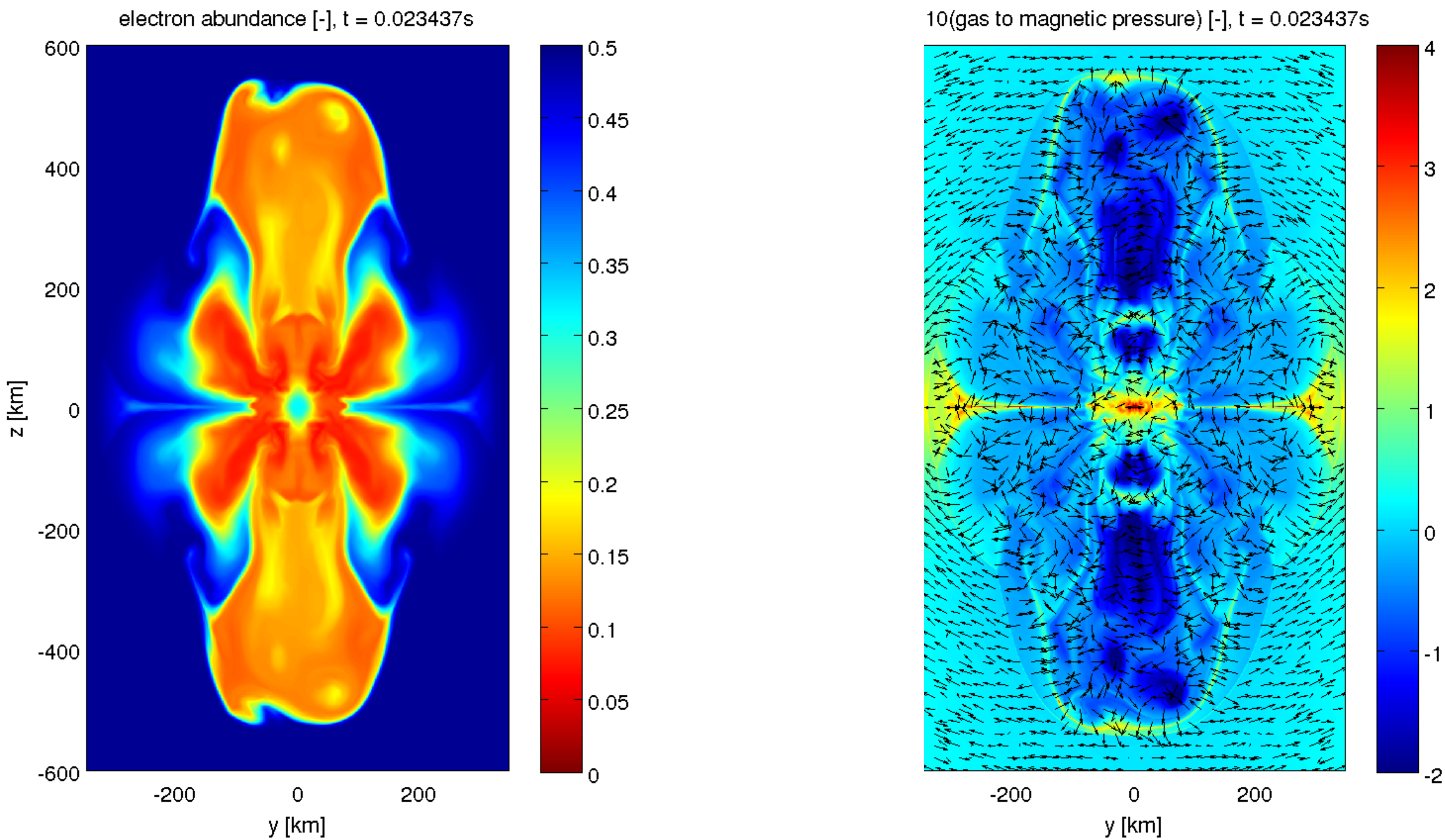




*Multi-D explosion calculations are optimistic!* *(but EoS dependence, $2M_{sol}$ neutron star)*

*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???*

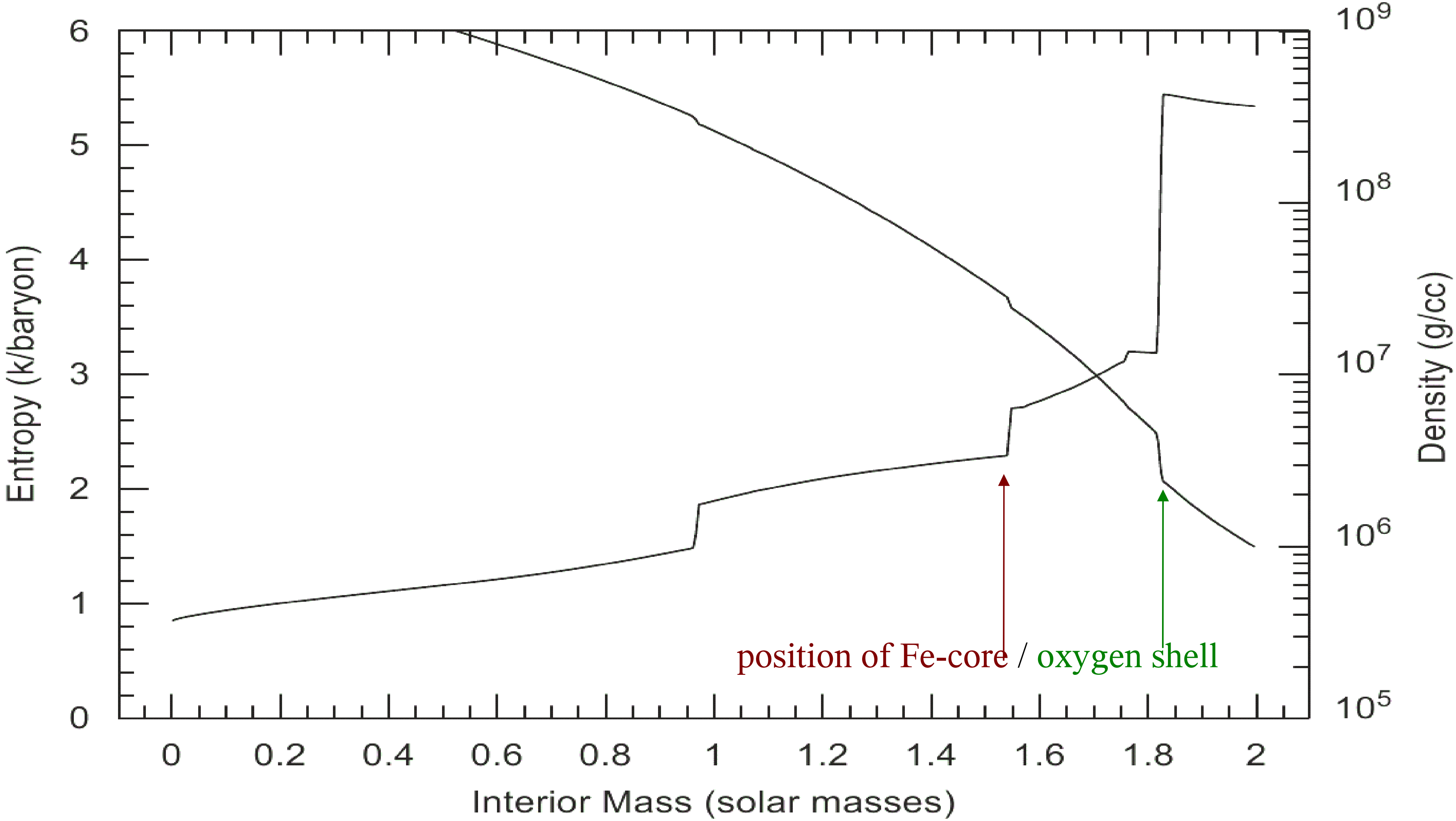
# 3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 $M_{sol}$ progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 $x10^{12}$ Gauss




*3D simulations by R. Käppeli, M. Liebendörfer et al. 2011 , preliminary results!*

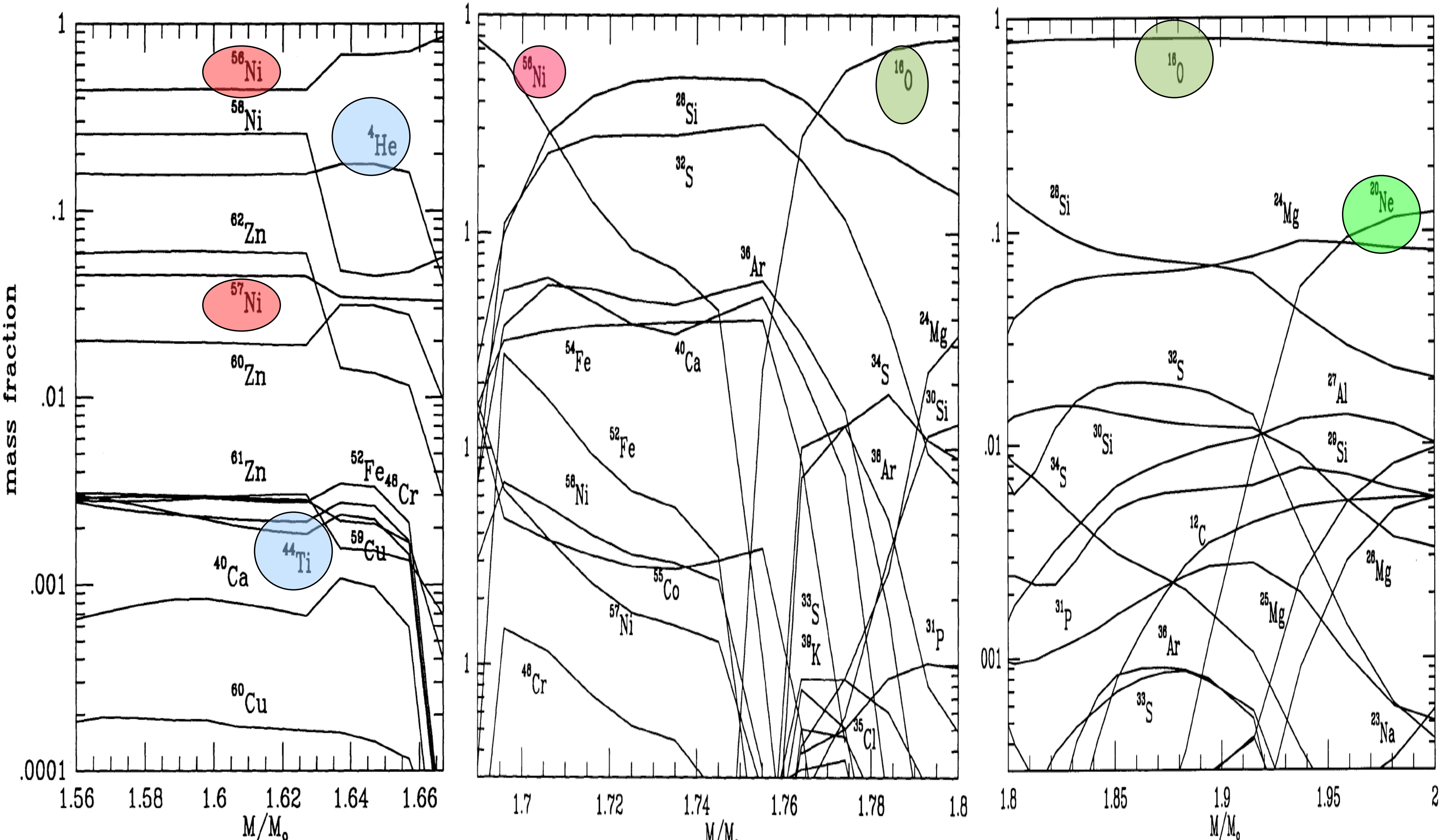
# How to invoke induced explosions for nucleosynthesis purposes?




*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.*

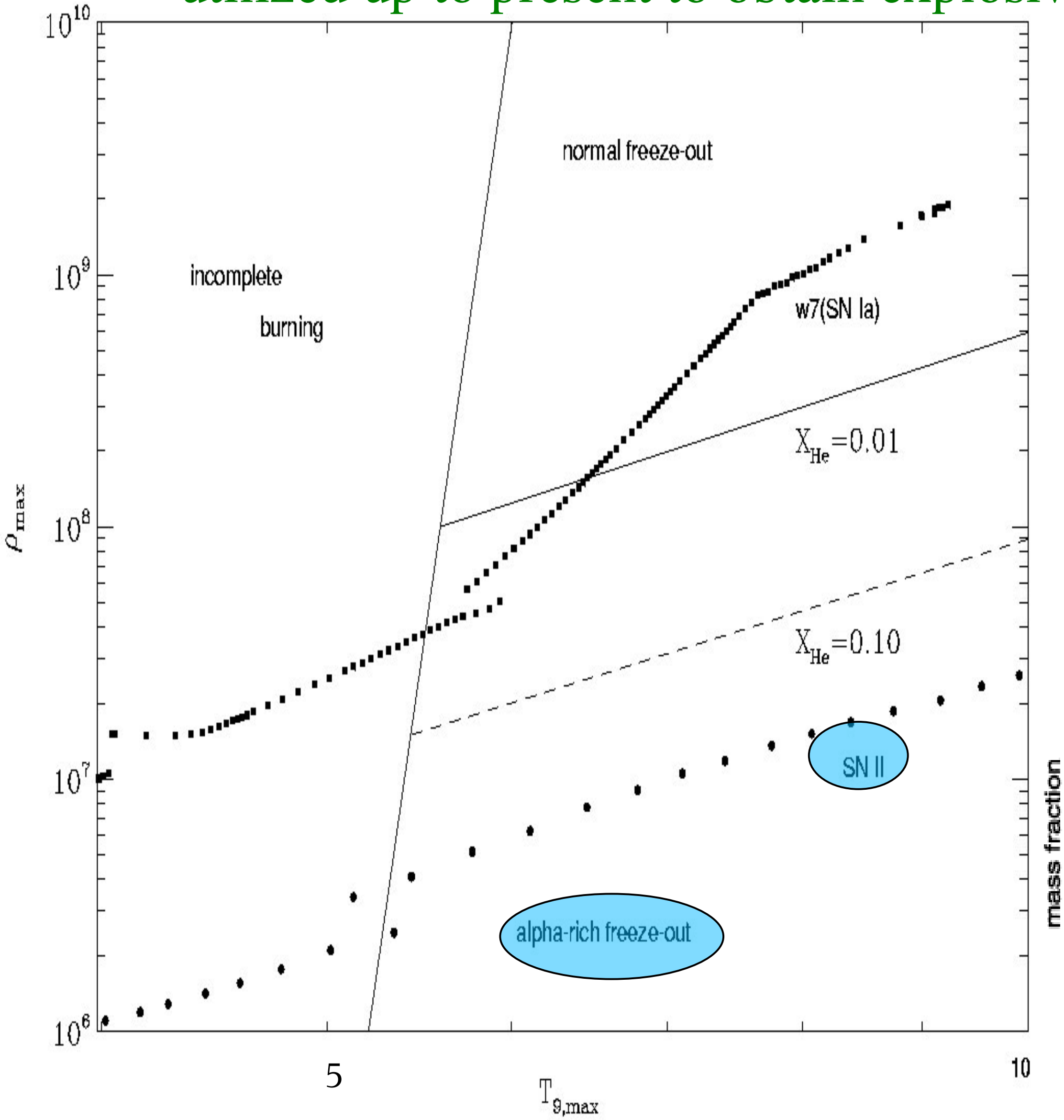
# (Radioactive) Products of Explosive Burning (20 $M_{sol}$)

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

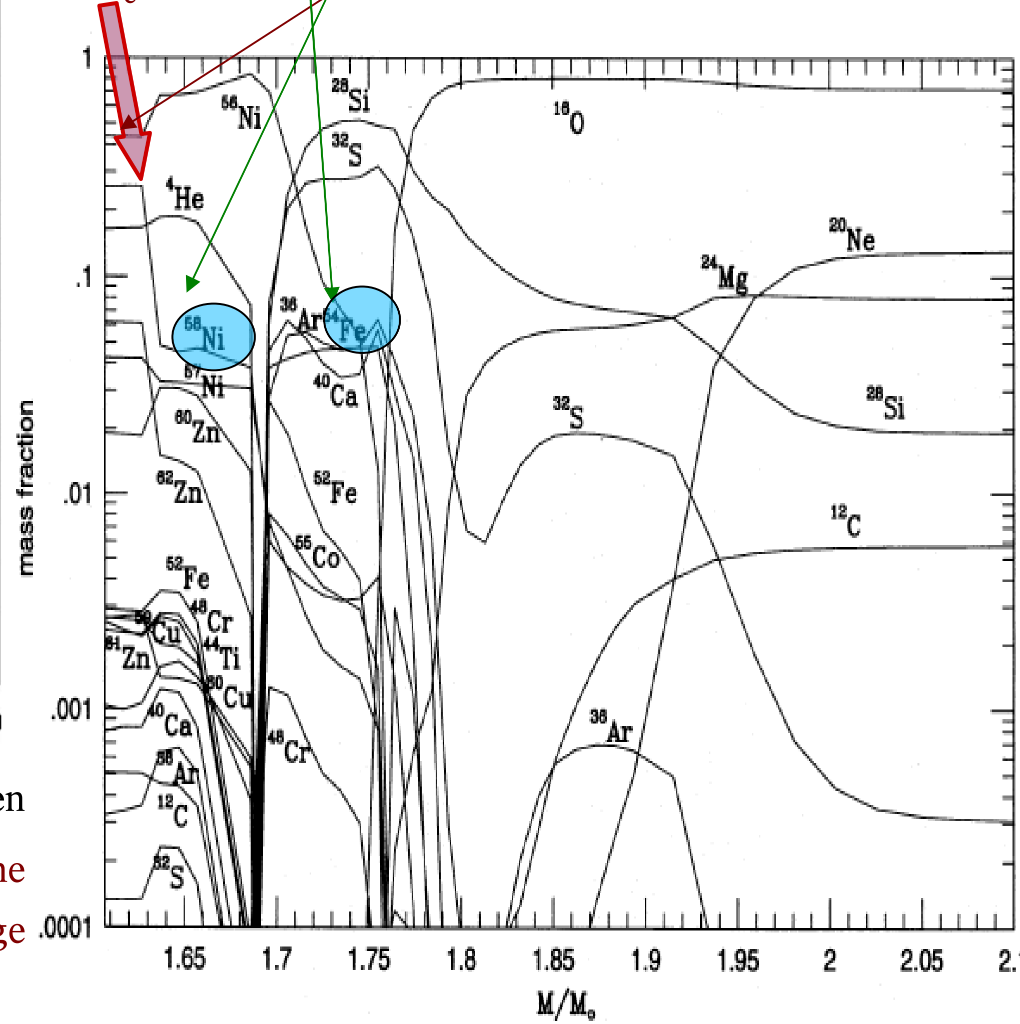



*explosive Si-burning (alpha-rich, incomplete), O-burning, Ne-burning*

# 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

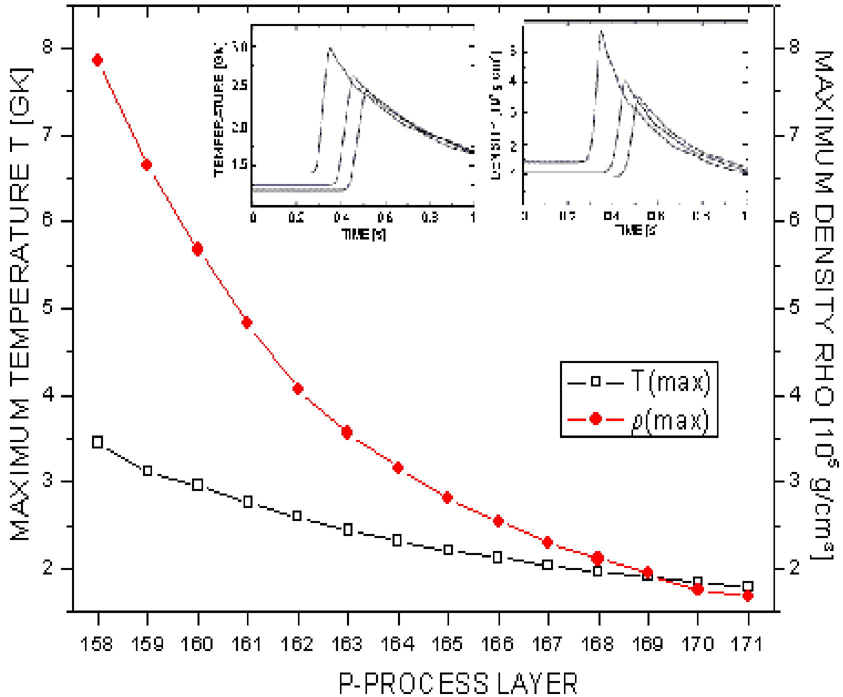


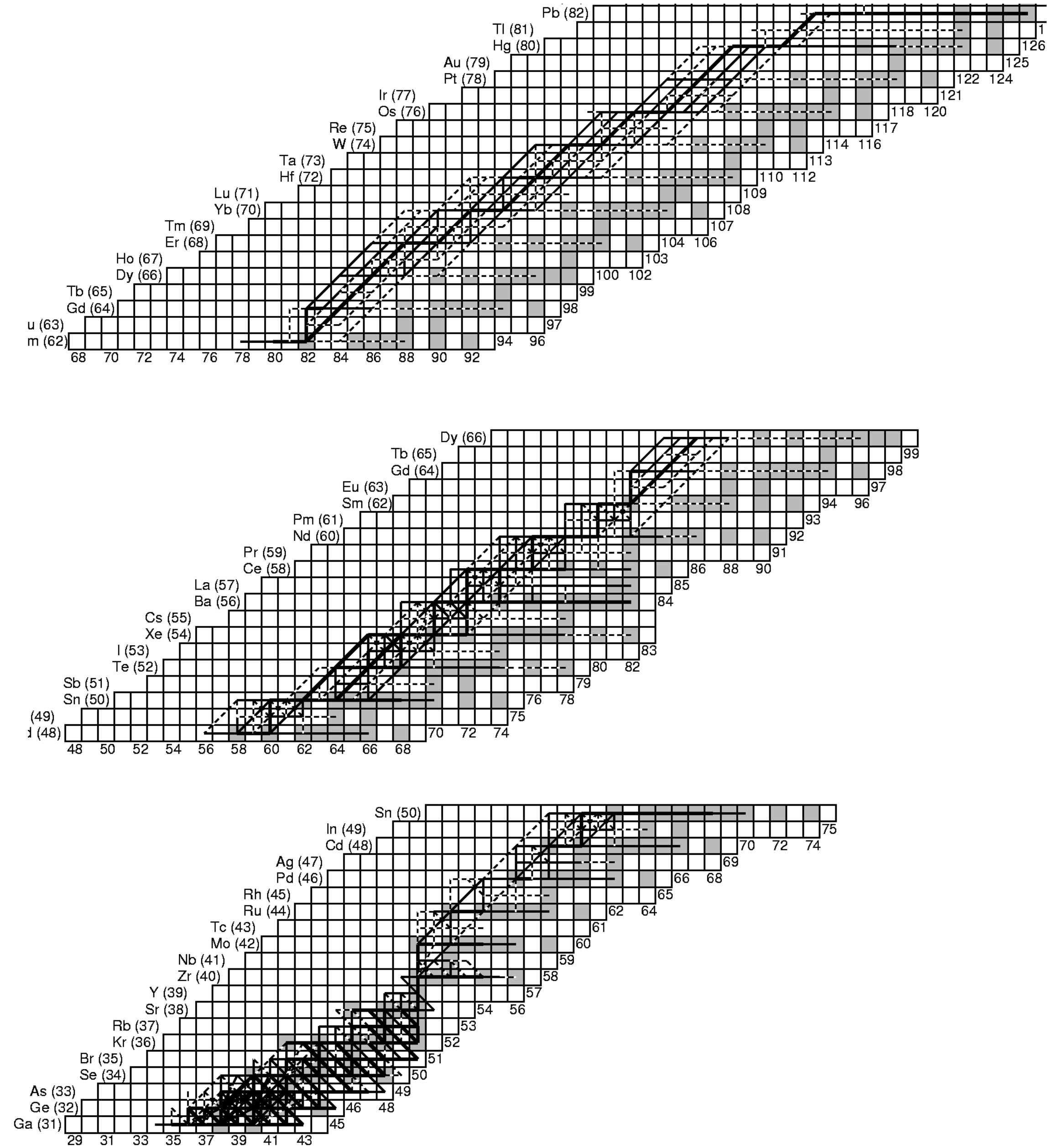

disconnected light element (n,p,He) and Si-Fe QSE-cluster, high alpha-abundance prefers alpha-rich nuclei ($^{58}$Ni over $^{54}$Fe), $Y_e$ determines dominant QSE-isotopes.




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!

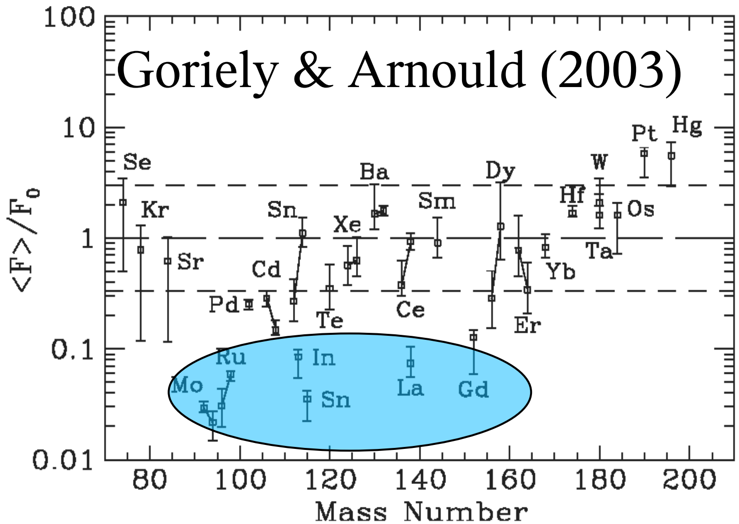
# p-process in explosive Ne/O-Burning zones

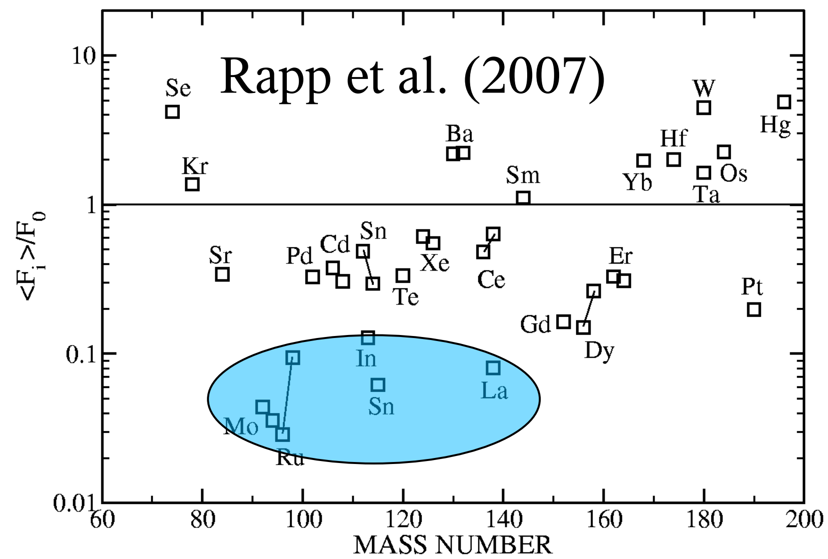


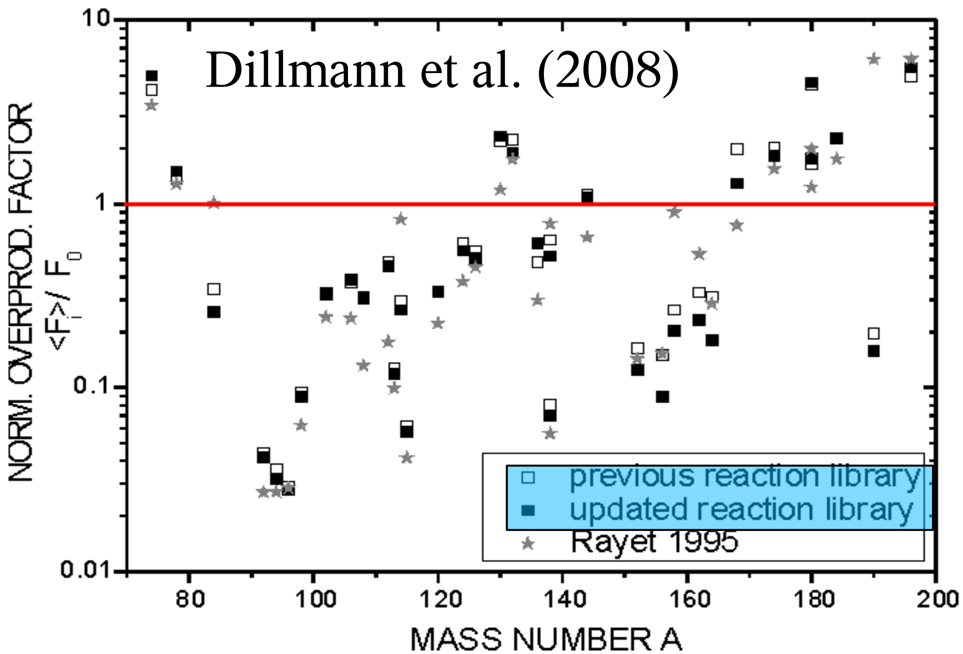



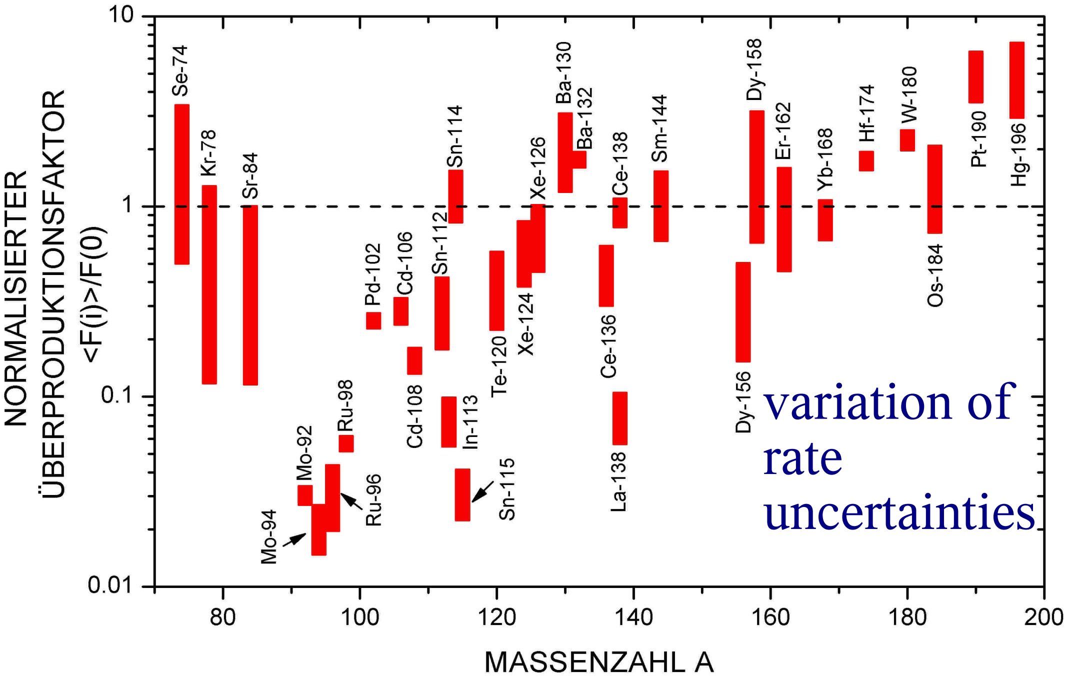
Rapp et al. (2007), following p-(gamma)-process calculations within the framework of Rayet et al. (1995) for a 25M$_{sol}$ star of Yoshida et al. (2002) to verify the impact of nuclear uncertainties.

# Comparison with solar p-only nuclei



# Ideas for solutions

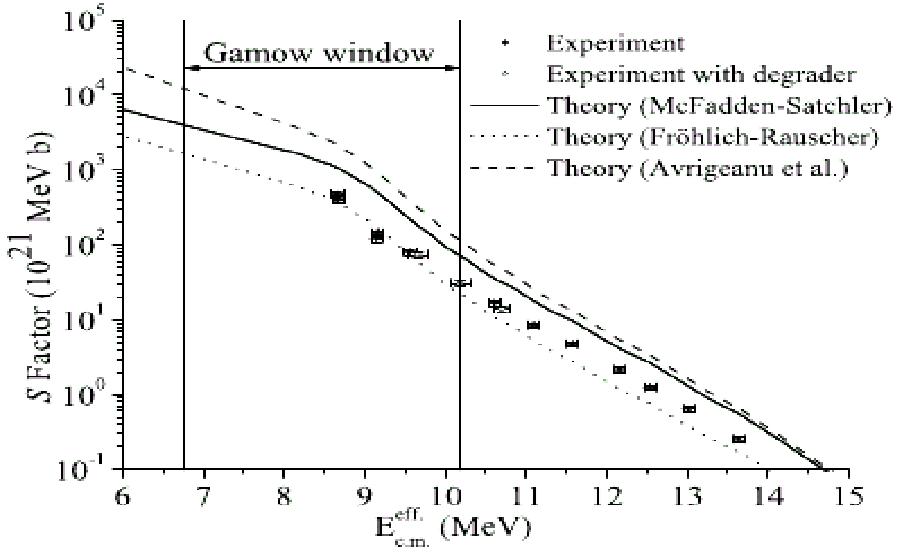



FIG. 3: Measured $S$ factors of $^{113}$In$(\alpha,\gamma)^{117}$Sb reaction compared to theory using the NON-SMOKER$^{\mathrm{WEB}}$ v5.4.2w code [30] with different $\alpha$+nucleus potentials: by McFadden and Satchler [34], Fröhlich [35, 36], and Avrigeanu et al. [37]. The astrophysically relevant energy range, Gamow window, at 3 GK as an example is also shown.

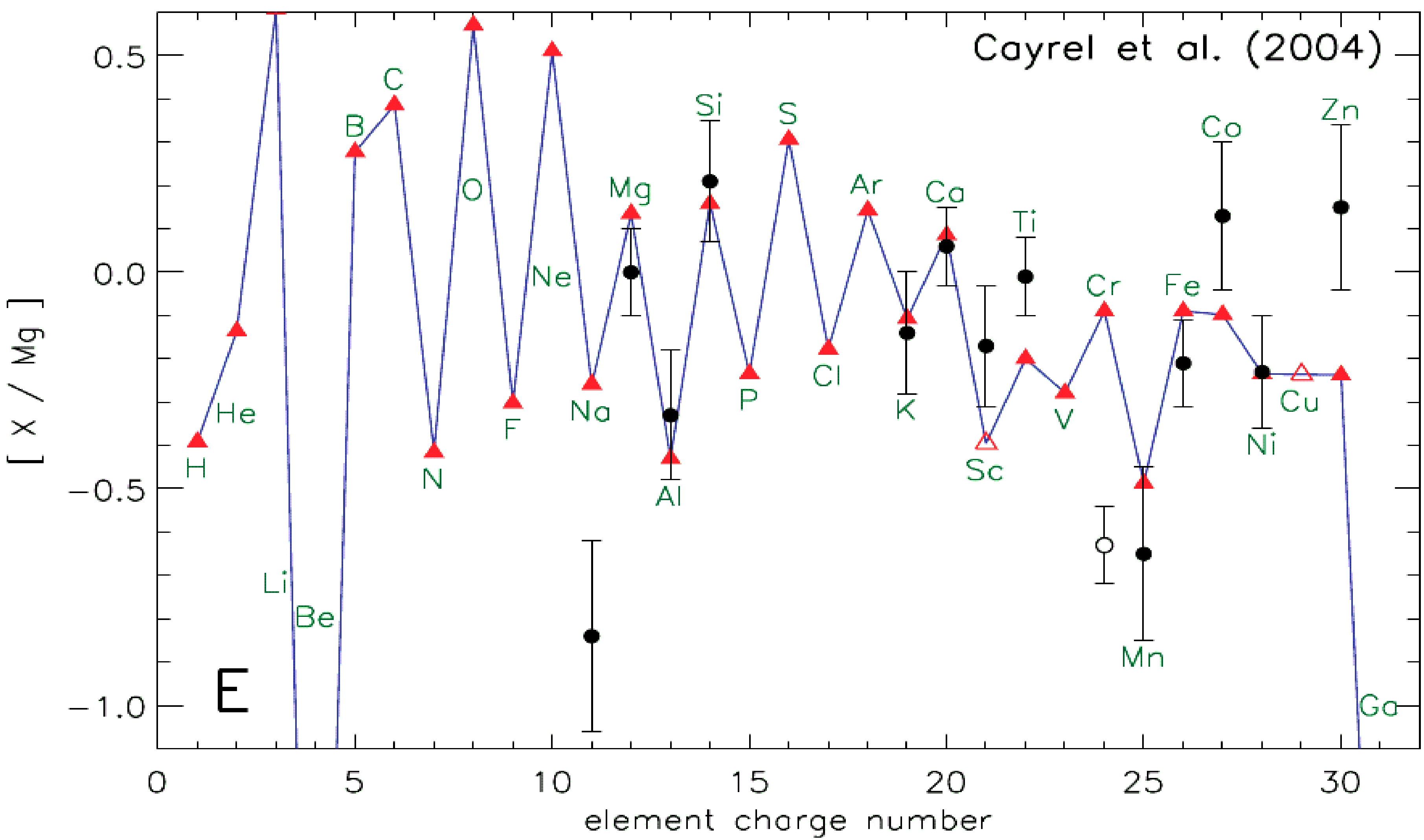
There have been many investigations in p-process related reactions (Gyürky, Hasper, Kiss, Yalcin, Mohr, Sonnabend, Dillmann, Rauscher..) which led to improved understanding of alpha and proton optical potentials, but the problem seems not to be solved by nuclear rate uncertainties. The major difficulty 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:

(a) analyze environments which start with a different seed composition being then exposed to the photon flux (e.g. 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) invent different environment with capture reactions for light p-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 $M = 10 - 100\ M_{\odot}$, 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)

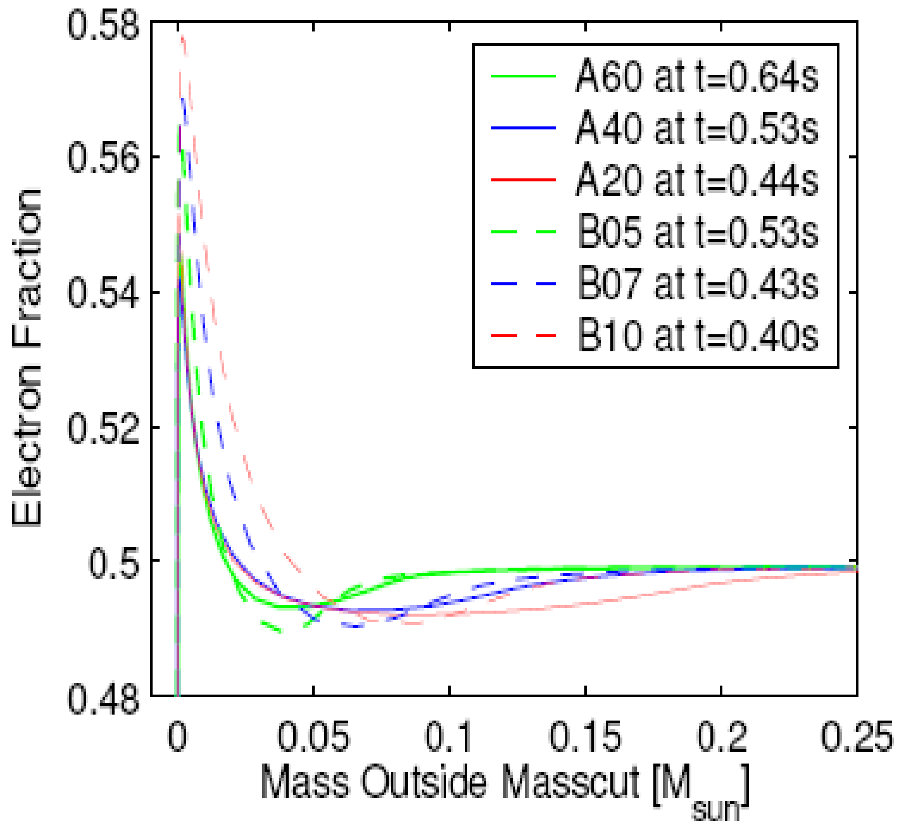
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

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

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

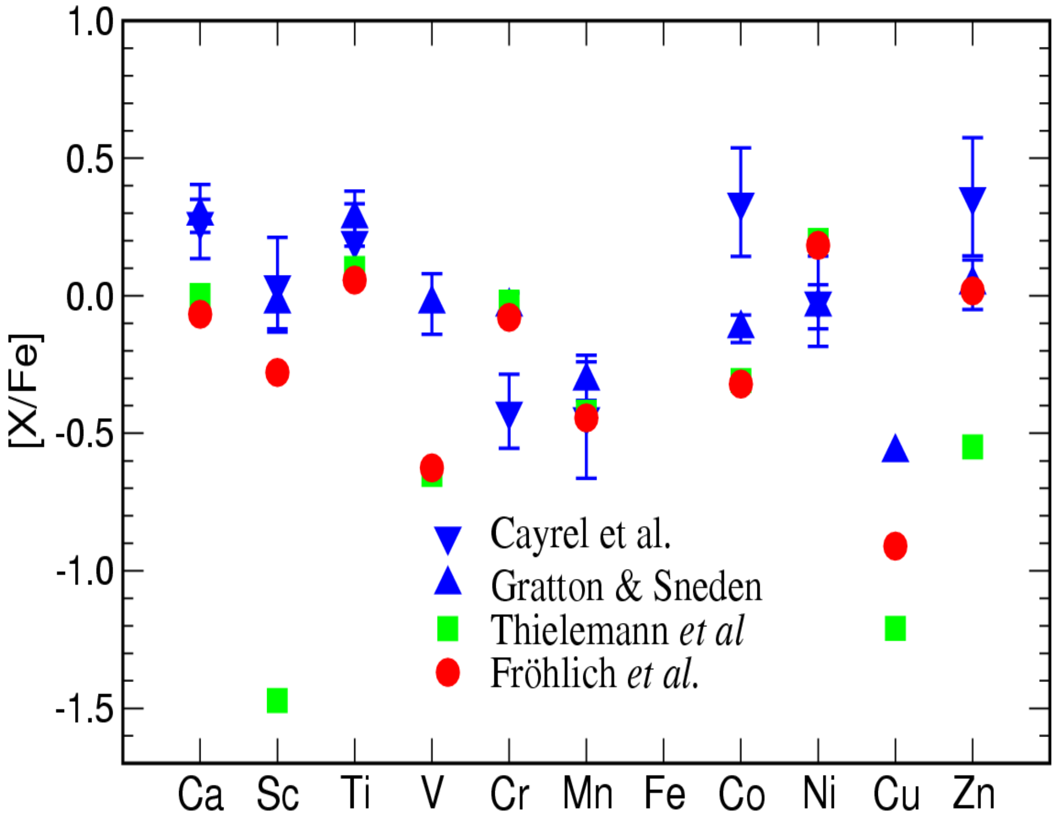
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- high density / low temperature $\rightarrow$ high $E_F$ for electrons $\rightarrow$ e-captures dominate $\rightarrow$ n-rich composition
- if el.-degeneracy lifted for high T $\rightarrow$ $\nu_e$-capture dominates $\rightarrow$ 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 $\rightarrow$ higher luminosity, dominate in neutrino wind $\rightarrow$ neutron-rich ejecta




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

# Improved Fe-group composition

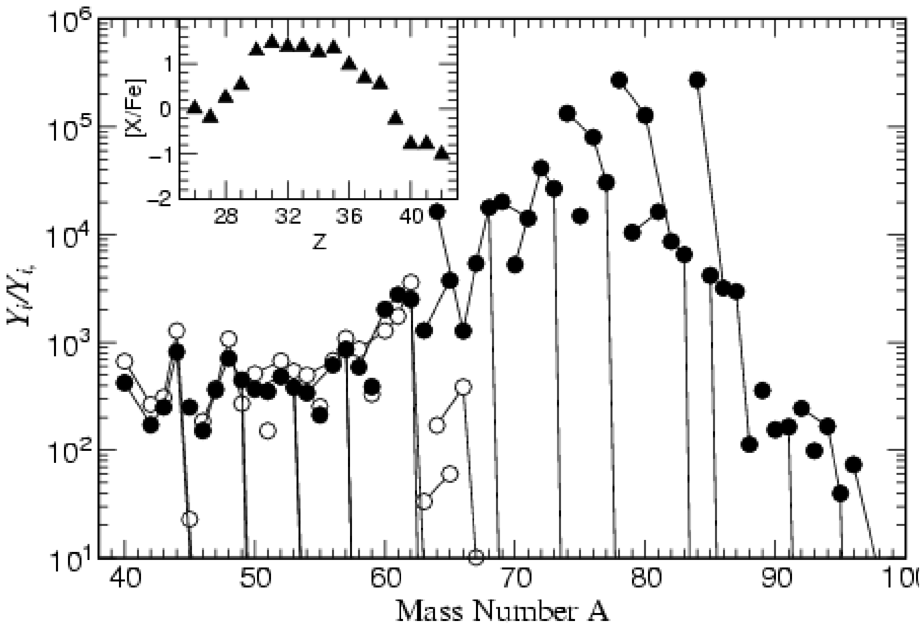


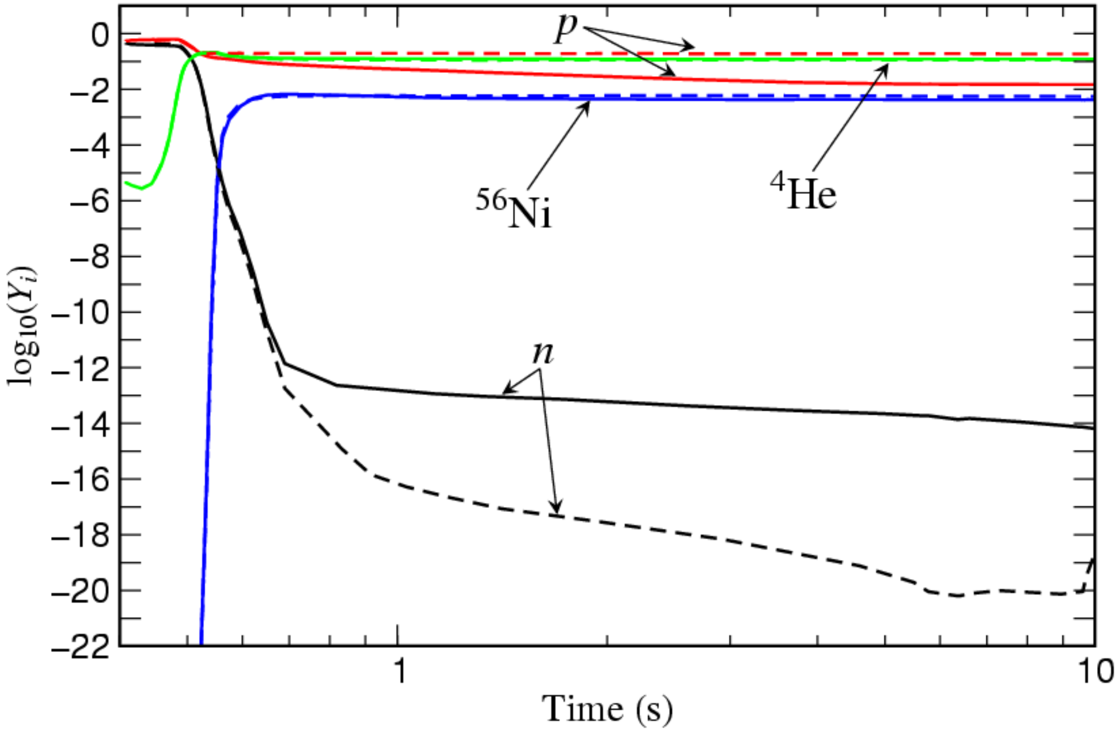

Models with $Y_e$>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at $^{64}$Ge, due to (low) densities and a long beta-decay half-life (decaying to $^{64}$Zn).
This effect improves the Fe-group composition in general (e.g. Sc) and 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???*

# $\nu p$–process

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

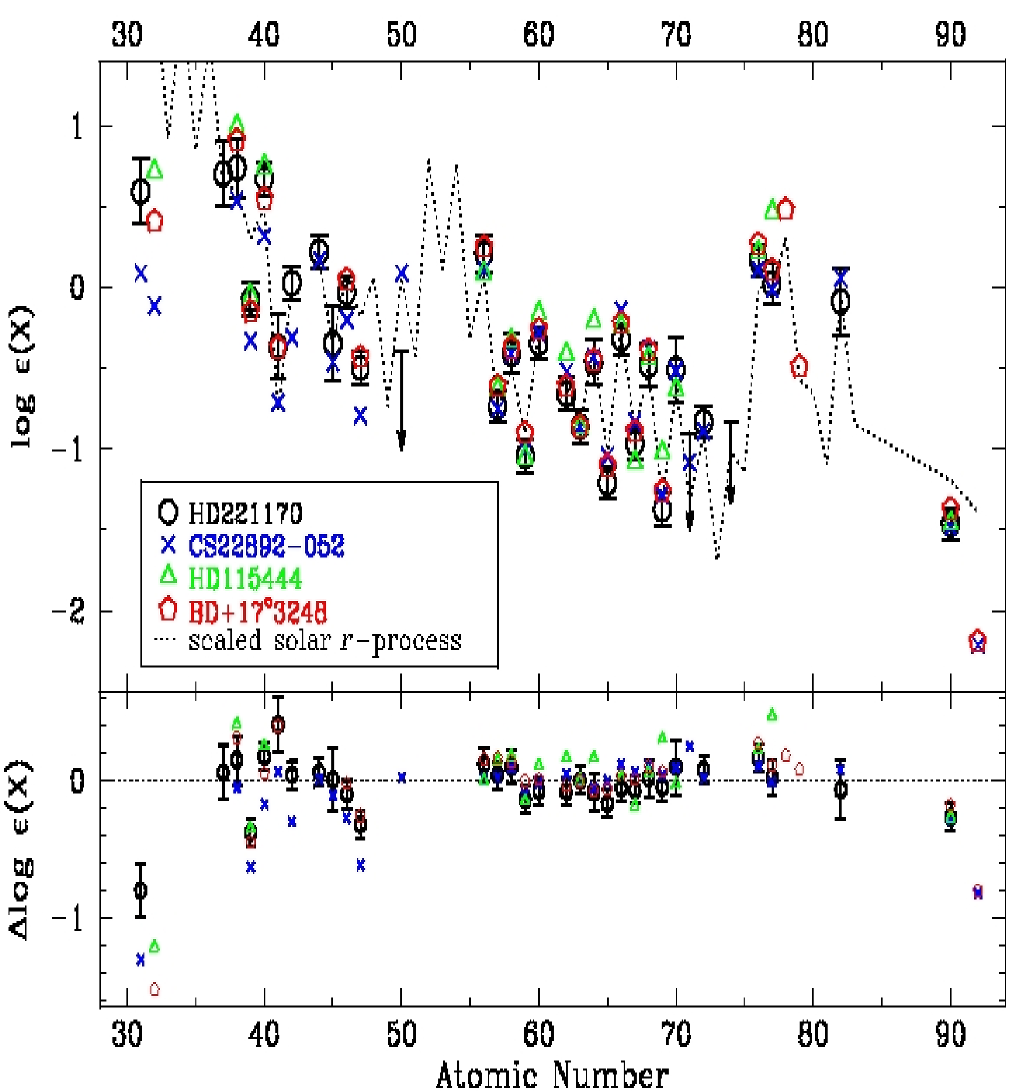



Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei) see also Pruet et al. (2006), Wanajo (2006).
Recent analysis by Wanajo, Janka, Kubono (2010) with variation of neutron star masses and reverse shock position

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.

# Almost identical behavior of heavy r-element abundances, variations in light r-elements, often underabundances in comparison to solar r-abundances




Ivans et al. (2006)

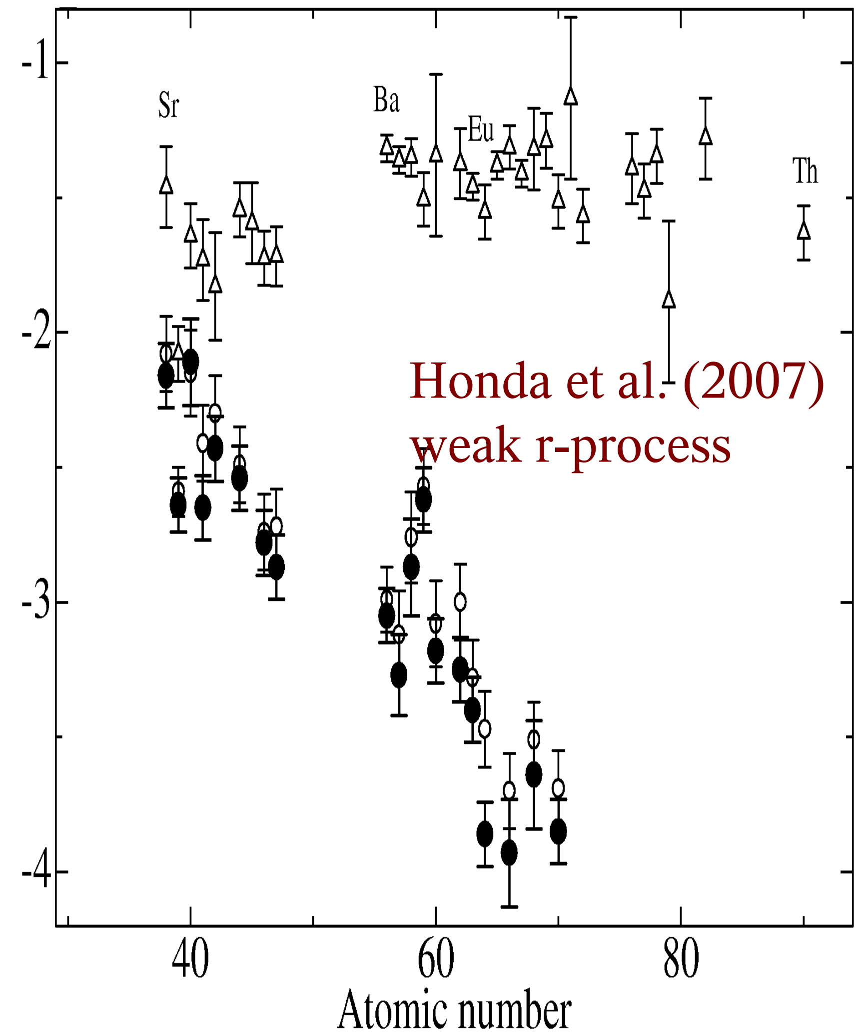
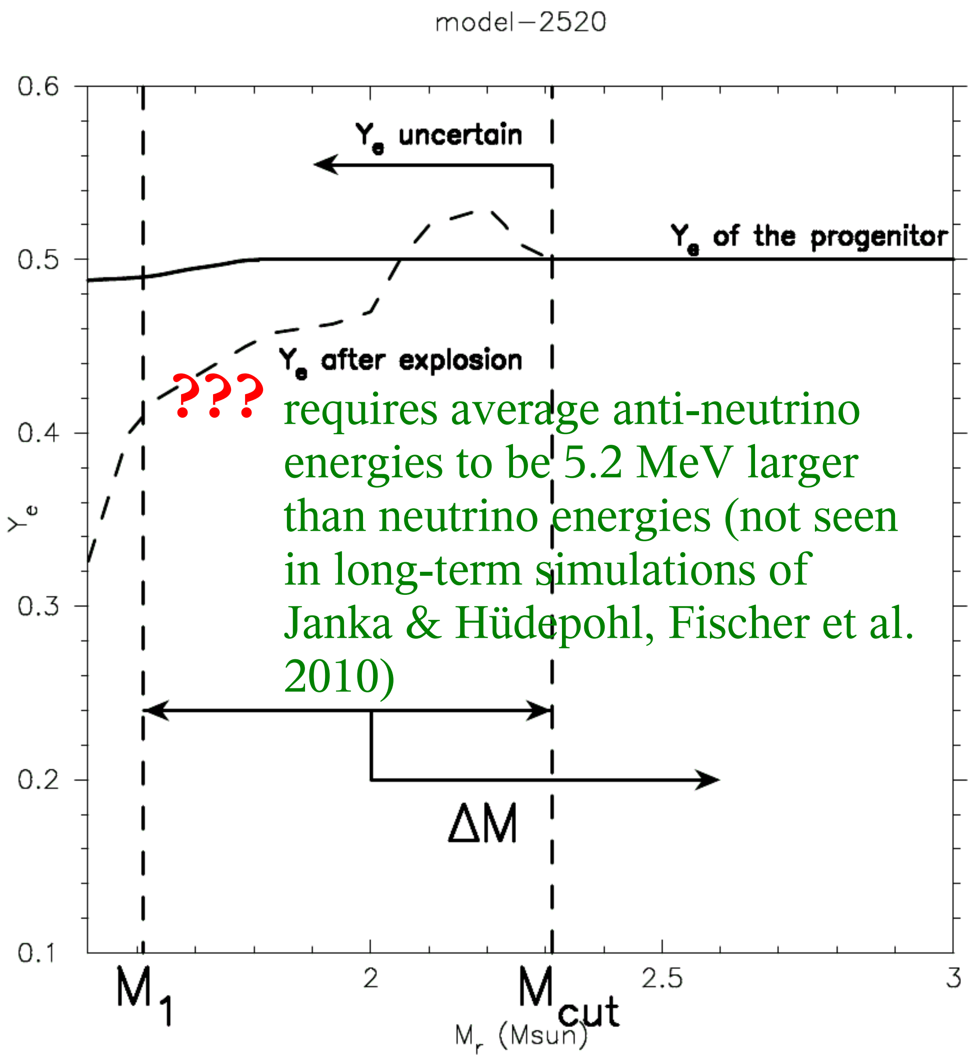



Fig. 5.— Logarithmic differences from the solar system r-process pattern ($\log\varepsilon_{object} - \log\varepsilon_{solar-r}$). The open triangles mean CS 22892-052, the open circles mean HD 122563, and the filled circles mean HD 88609.

Honda et al. (2007)
weak r-process

# Possible Variations in Explosions and Ejecta

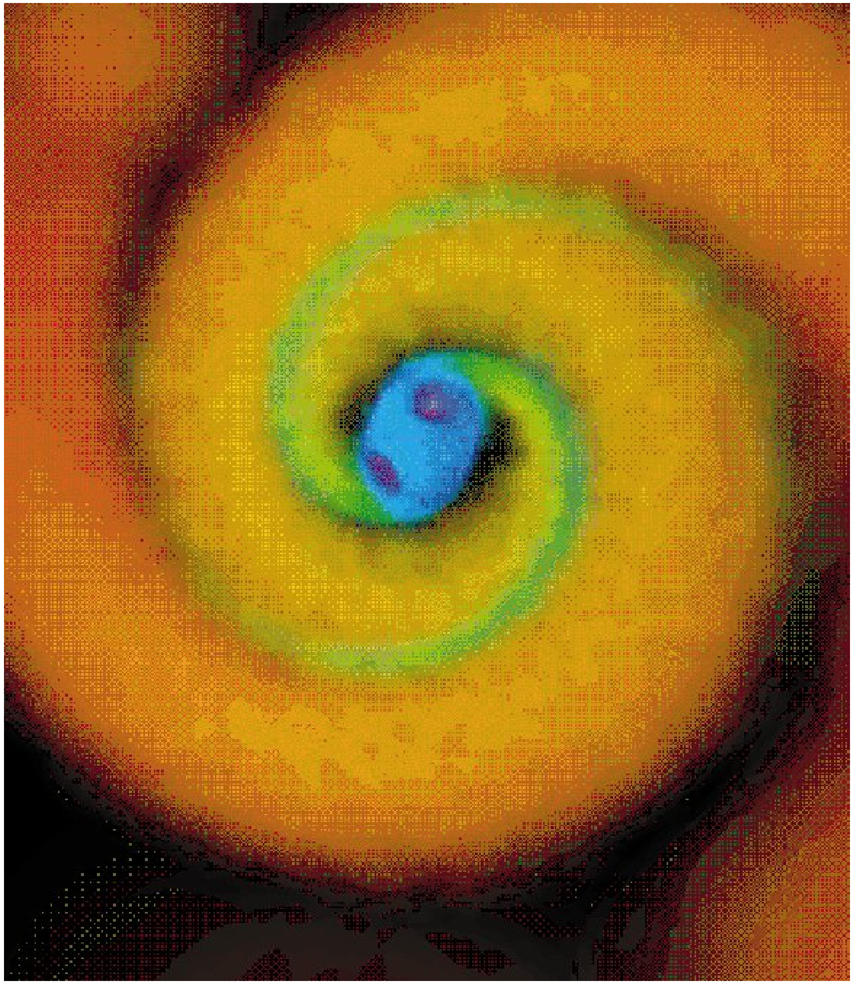



Izutani et al. (2009)

- *massive stars experience fallback and delayed black hole formation: small amount of Fe-group ejecta (e.g. Moriya et al. 2010, faint supernovae)?*
- *regular explosions with neutron star formation, neutrino exposure, νp-process, moderately neutron-rich neutrino wind and weak r-process?? (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?)*

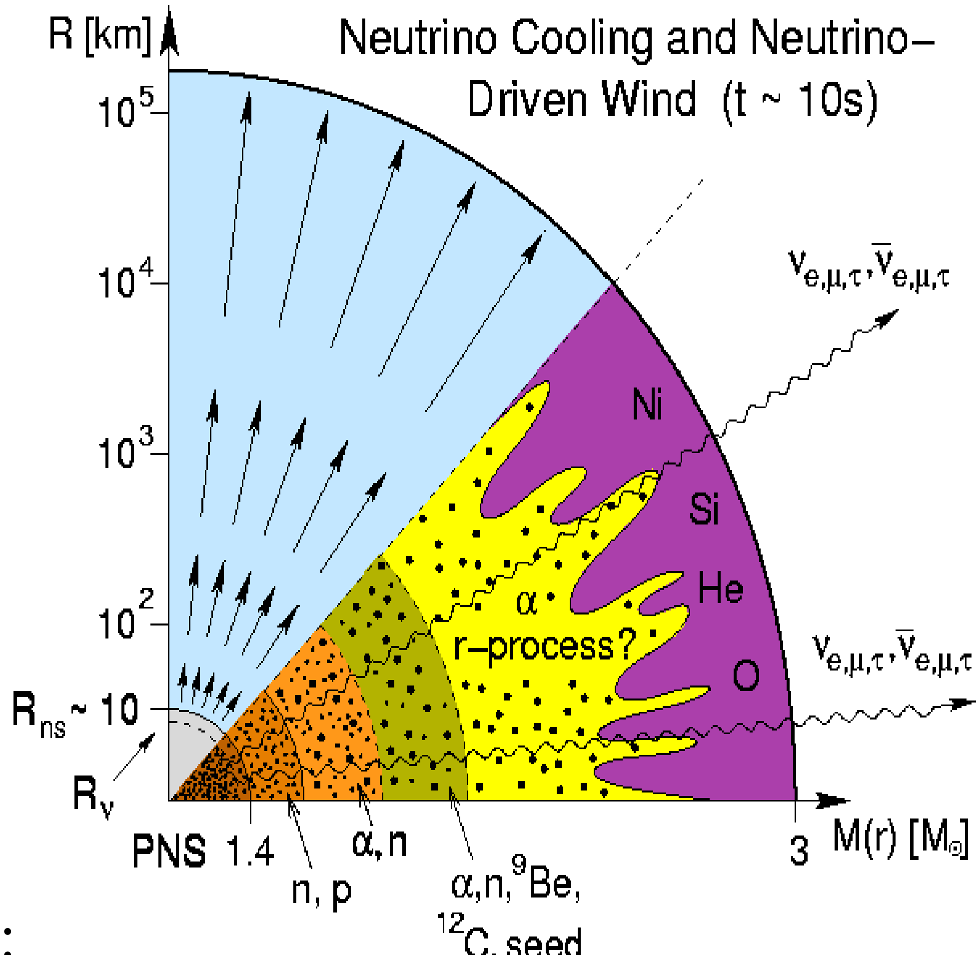
# What is the site of the r-process?

from S. Rosswog



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

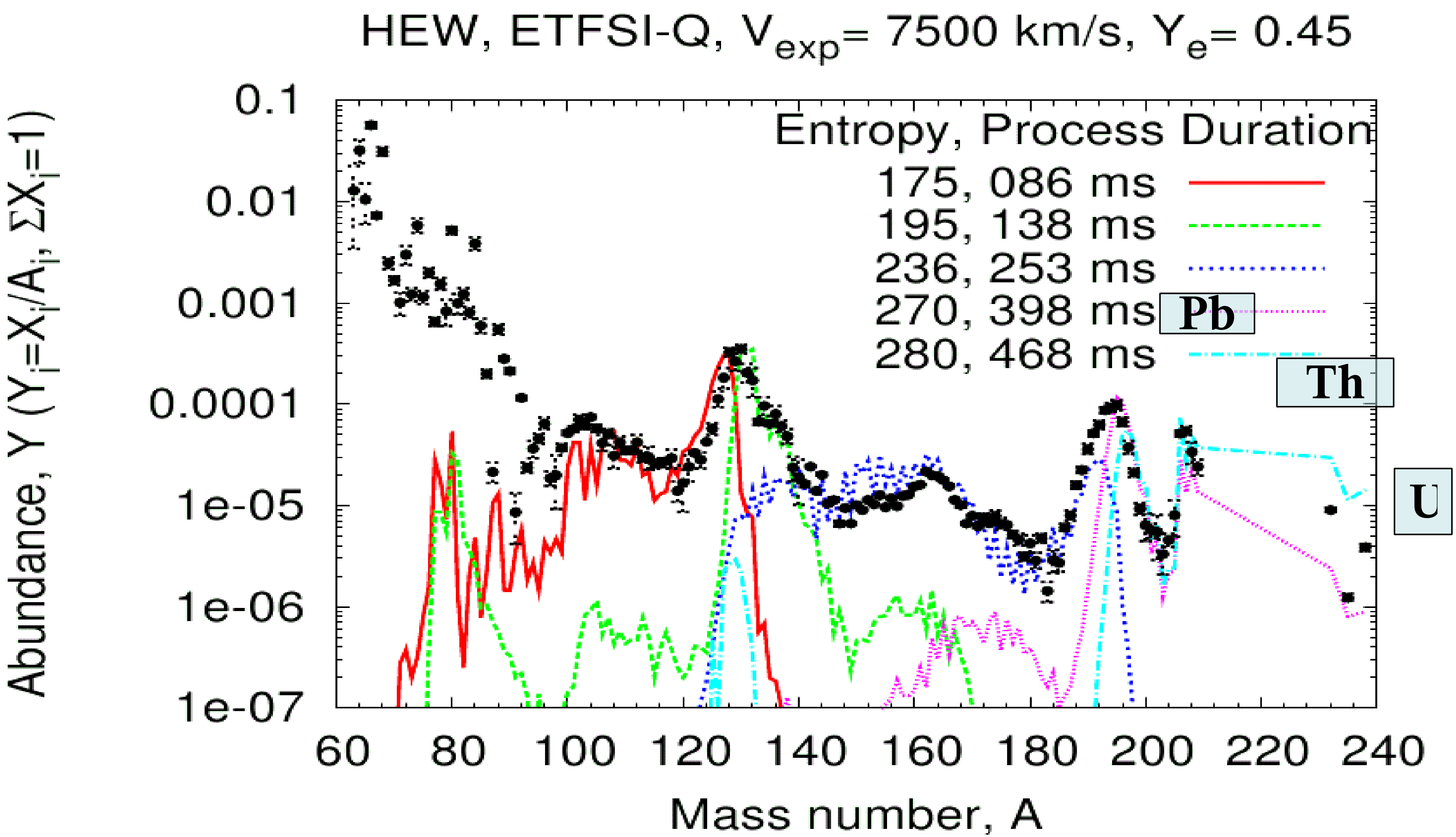
from H.-T. Janka




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

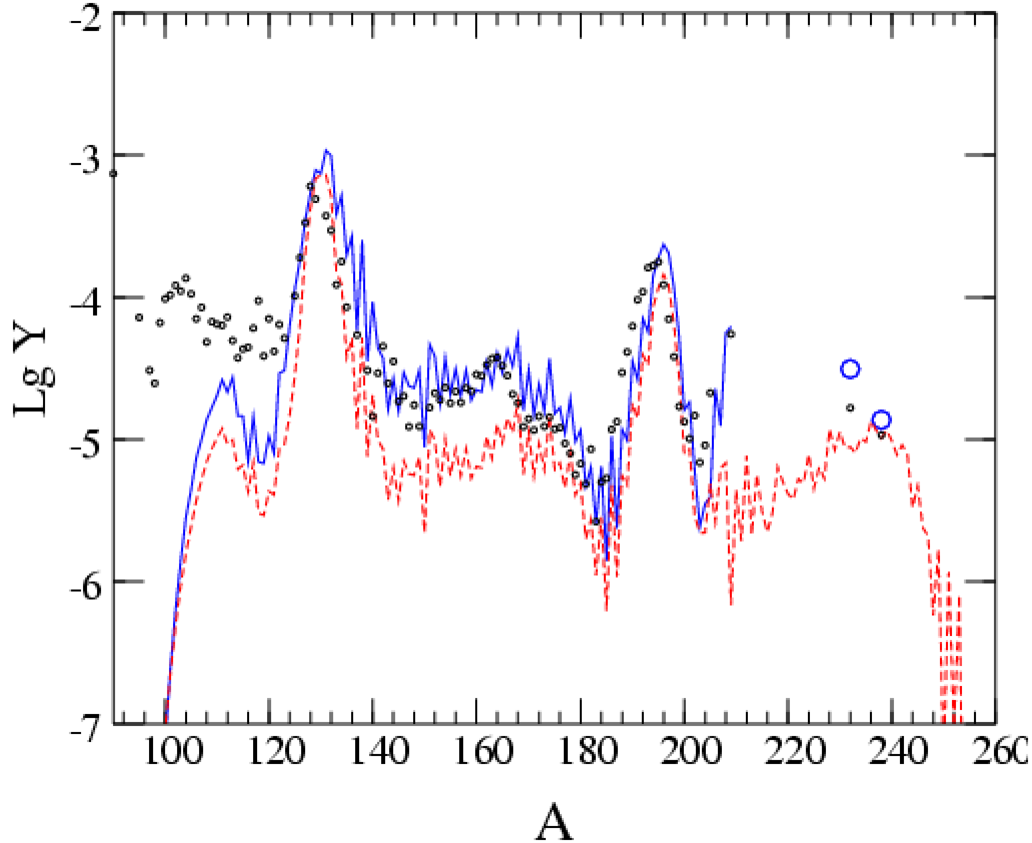
# Individual Entropy Components

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

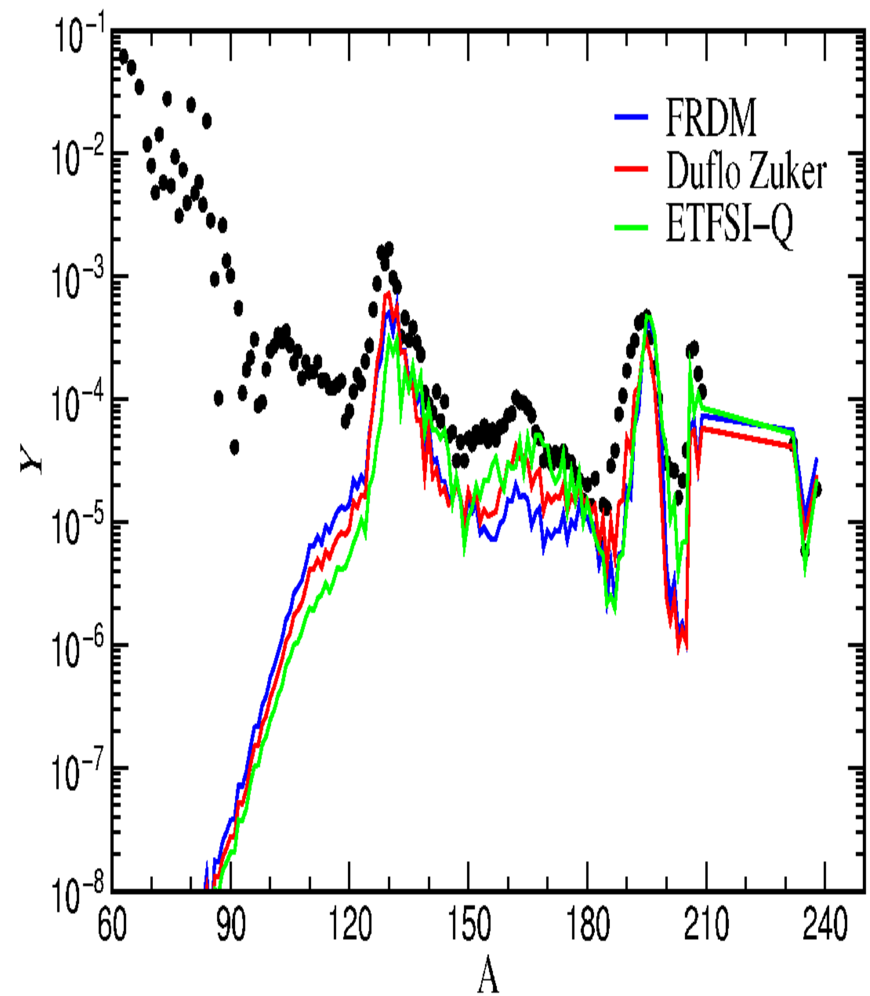


# Fission Cycling in Neutron Star Mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999
$(Y_e = 0.1, n/Seed = 238)$.



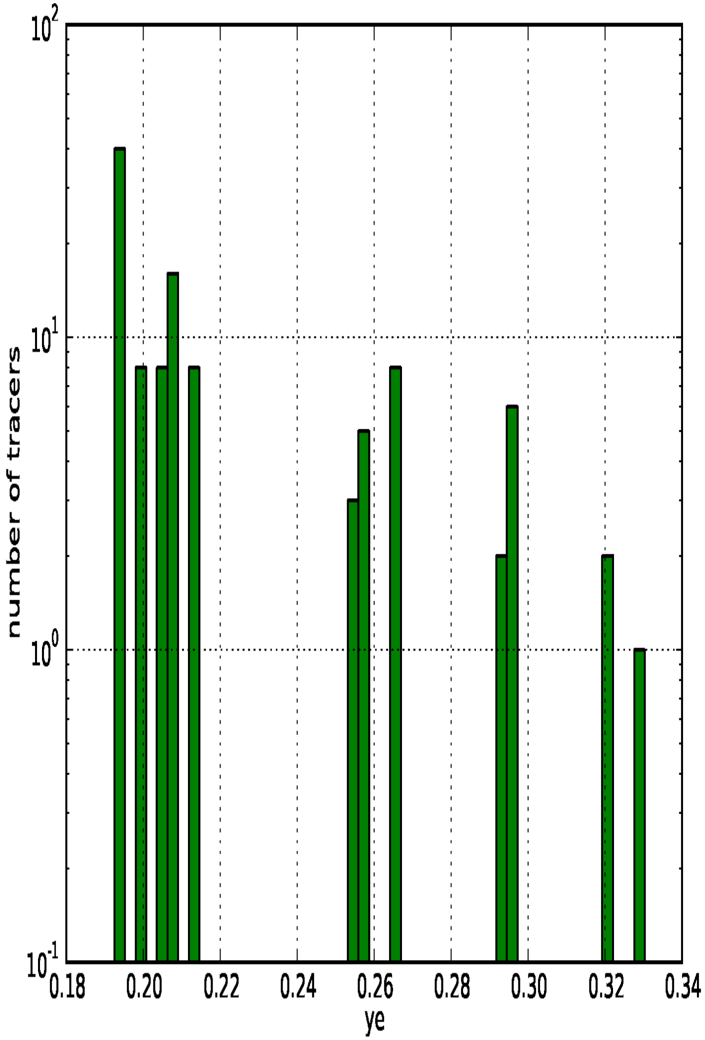

Panov, Korneev and Thielemann (2007, 2009)
with parametrized fission yield contribution
(see also Goriely, Bauswein, Janka 2011)

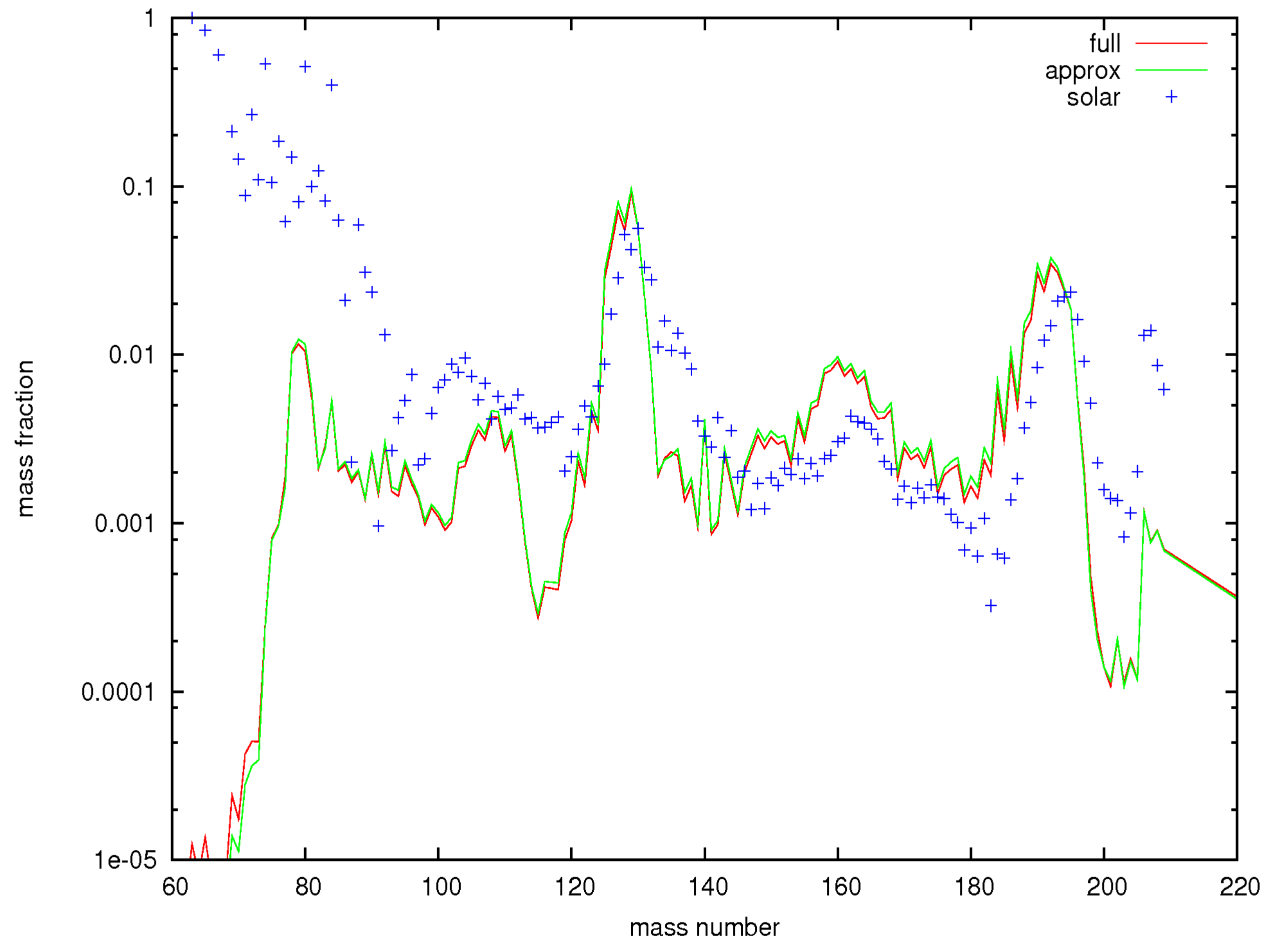



Martinez-Pinedo et al. (2006)

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

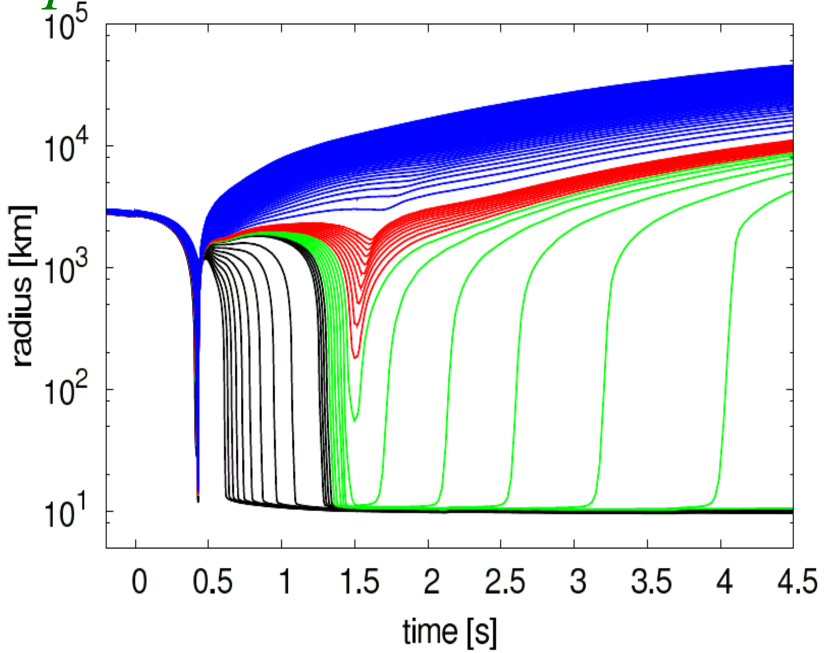
# Preliminary Results of Jet Ejection from fast rotating collapse with large magnetic fields

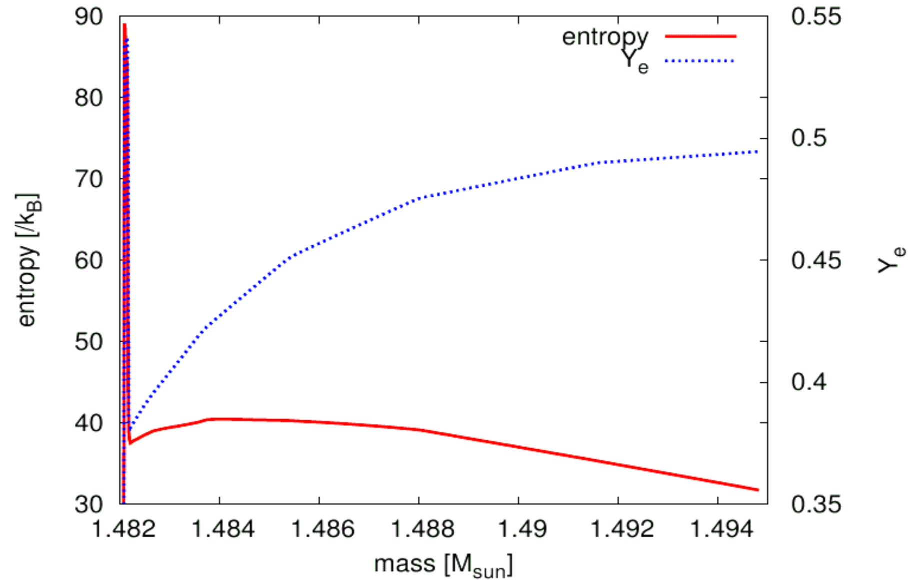


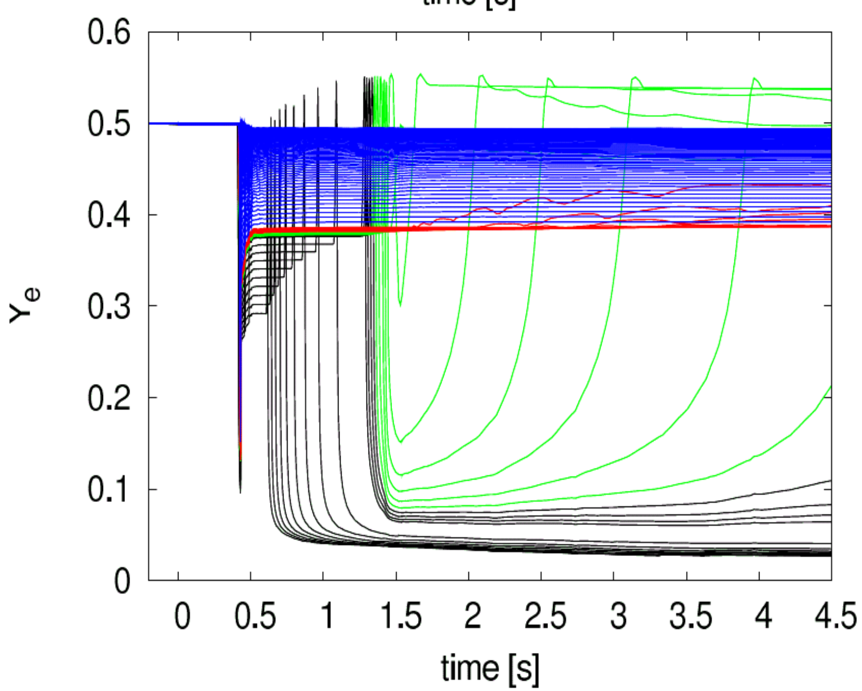



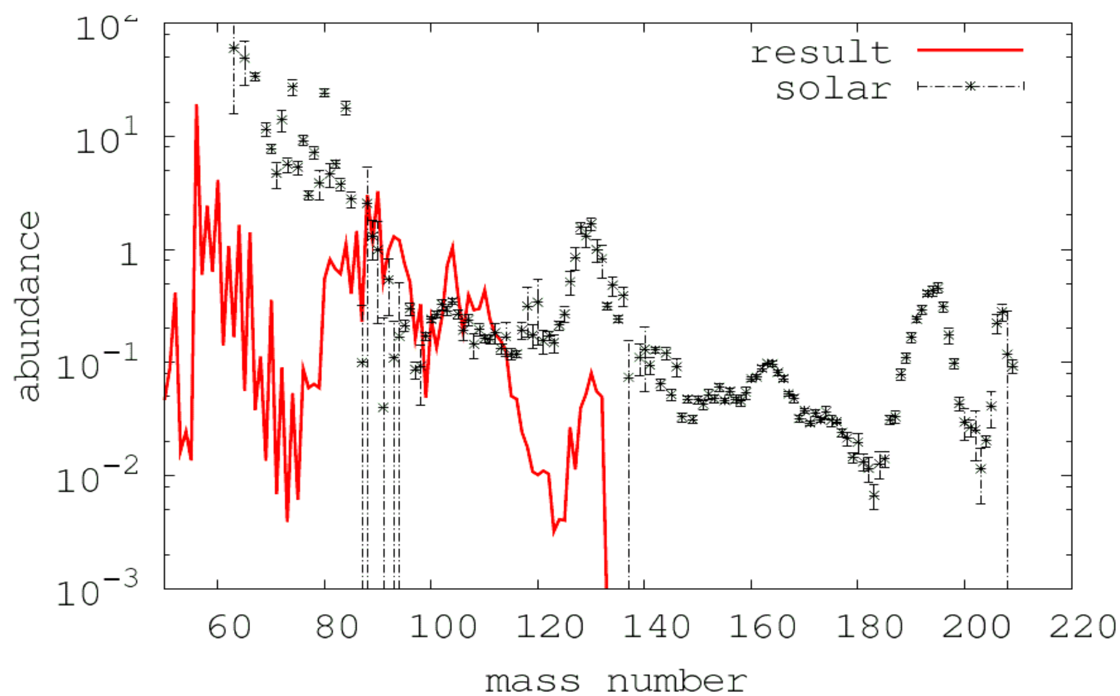

*total ejected mass: few times $10^{-3}$ Msol; C. Winteler, N. Nishimura, R. Käppeli et al. 2011, in prep., final abundances depend on extrapolated expansion after end of present hydro simulation.*

Preliminary Results: Quark-Hadron EoS Explosion (Nishimura, Fischer et al. 2011, in prep.), *ejection of initially neutronized matter, but only weak r-process*



# 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*

*Neutrino wind seems always to lead to proton-rich conditions and νp-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.*