Understanding Massive Stars:

Evolution and Nuclear Burning Stages, Supernova Explosion Mechanism(s), Nucleosynthesis Ejecta, and their Impact on Chemical Evolution

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IPs and APs and *Interest Groups*

(in alphabetical order)

University of Basel

Clemson University, North Carolina

GSI/TU Darmstadt, GSI/U. Frankfurt, GSI/U. Giessen

ATOMKI Debrecen

TU Dresden/ FZ Rossendorf

MPIs Garching (MPE*)

MPI for Nuclear Physics Heidelberg

University of Keele

Kocaeli University

Excellence Cluster Munich/Garching (including TU, ESO)*

IAP Paris

IASF Rome

University of Stockholm*

Trieste Observatory

U of Vienna

***observations, covered in Roland's talk**

Nuclear Physics Input

Experiment:

• Fusion reactions for stellar evolution and s-process (Dresden: Bemmerer, Zuber; Debrecen: Fülöp, Gyürky; GSI/F: Heil, Reifarth.... *Dresden and Debrecen connection to **LUNA***)

• Explosive Burning, p-Process, r-process, properties far from stability (especially mass determinations and fission barriers) (Debrecen; GSI: Kelic; GSI/G: Dillmann; Kocaeli: Ozkan, Guray; TU Munich: Bishop; MPI Heidelberg: Blaum, Litvinov .. *Kocaeli connection to **JINA***) – also Wallner &Vockenhuber

Theory: ***(Masche and CoDustMas)***

• Prediction of reaction cross section and rates, optical potentials, level densities, giant resonances, fission properties (Basel: Rauscher, FKT; GSI/TUD: Martinez-Pinedo + group, connection to ***EXNUC** and **NAVI)***

• weak interactions (GSI: Martinez-Pinedo + group)

• nuclear EoS (GSI: Typel, Basel: Hempel, connecton to ESF network ***COMPSTAR***)

Stellar Evolution

Stellar Evolution Codes:

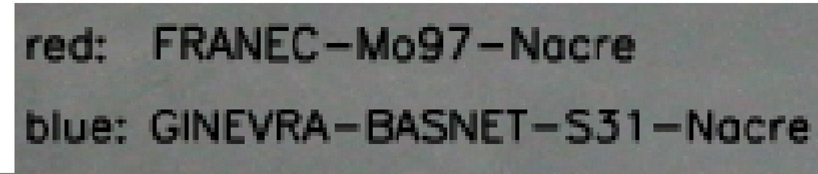
FRANEC (historically Frascati)
Rome: Chieffi, Limongi – through all phases of stellar evolution up to collapse

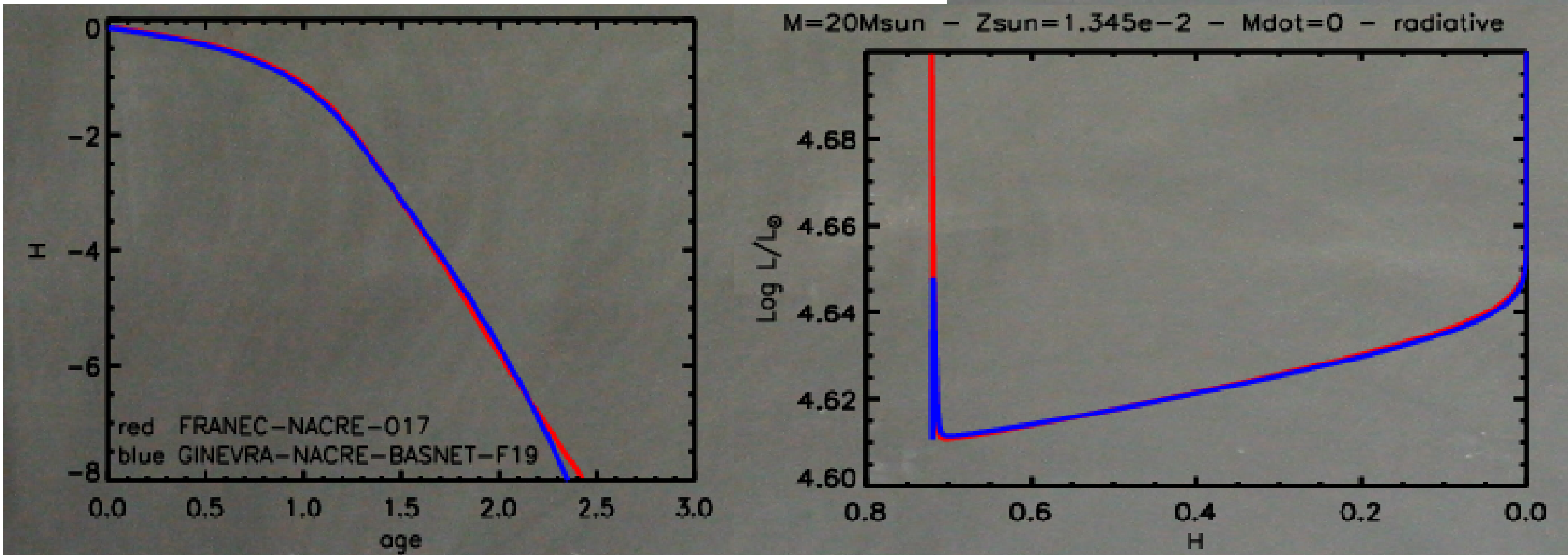
GENEVA Code
Keele: Hirschi – with connections to Geneva (Maeder, Meynet ..), Basel: Frischknecht - through all burning stages, with rotation

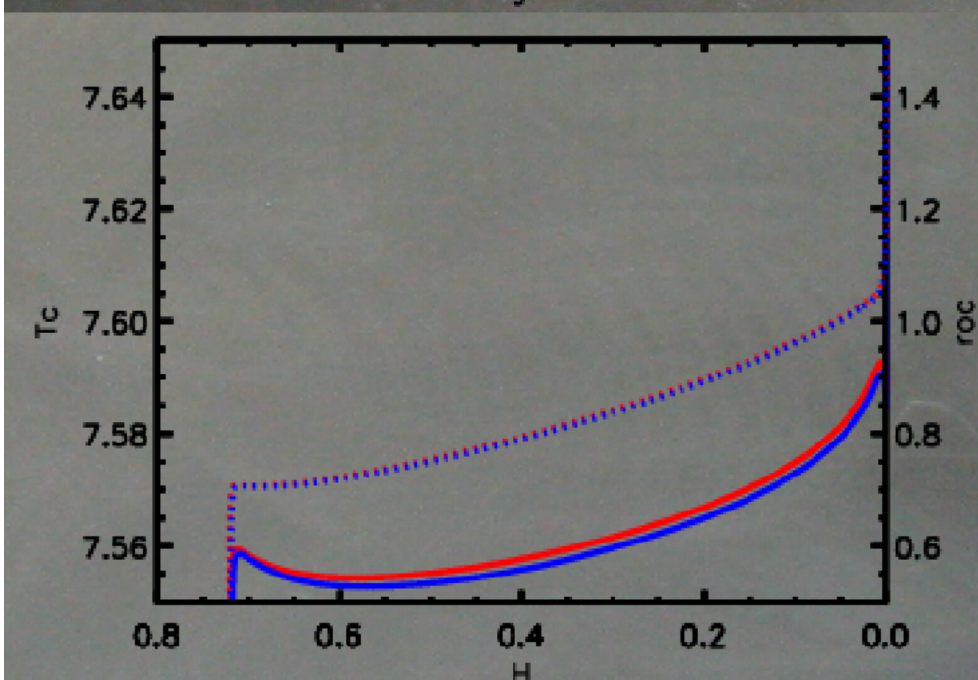
MESA Code
Basel: Pignatari; Battino - through all burning stages

*i**nfluence on final outcome via treatment of convective mixing and mass loss, stellar winds (connection to CoDustMas), rotation, metallicity, magnetic fields, reaction cross sections, e-capture in late burning stages***

Comparison FRANEC (Chieffi/Limongi) Geneva/Keele (Hirschi)



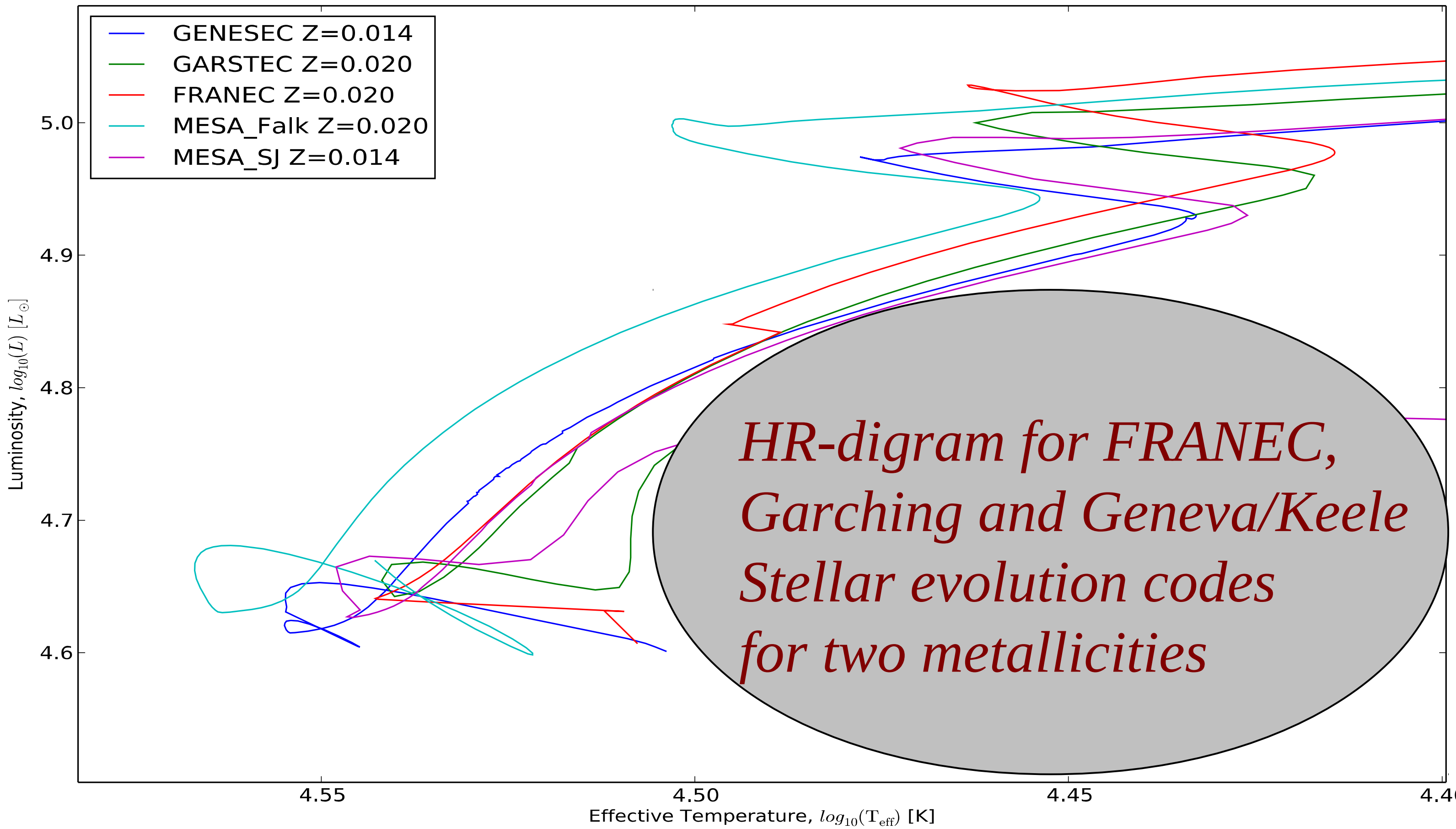




Goal: understand differences among different evolutionary codes. => found an excellent fit between the Geneva and the FRANEC code but only for the extremely simple case of radiative H burning (i.e. by dropping the mixing in the convective core)

But, full and detailed comparison too time consuming!

Main sequence H-burning phase for 20 Msol star



Less demanding task:
show, describe (instead of full understanding) the comparison among different codes and just try to discuss the probable reason of the differences. Keele is continuing this task for all late burning stages.

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
   - $^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $\quad$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   - $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C((\alpha,n)^{16}O)$

3. Carbon Burning — $T=(6\text{-}8)\times10^{8}$ K
   - $^{12}C(^{12}C,\alpha)^{20}Ne$ $\quad$ $^{23}Na(p,\alpha)^{20}Ne$
   - $^{12}C(^{12}C,p)^{23}Na$ $\quad$ $^{23}Na(p,\gamma)^{24}Mg$

4. Neon Burning — $T=(1.2\text{-}1.4)\times10^{9}$ K
   - $^{20}Ne(\gamma,\alpha)^{16}O$
   - $^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$ $\quad$ $30kT = 4MeV$

5. Oxygen Burning — $T=(1.5\text{-}2.2)\times10^{9}$ K
   - $^{16}O(^{16}O,\alpha)^{28}Si$ $\quad$ $^{31}P(p,\alpha)^{28}Si$
   - $......,p)^{31}P$ $\;$ $...,n)^{31}S(\beta^{+})^{31}P$ $\quad$ $^{31}P(p,\gamma)^{23}S$

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

   (all) photodisintegrations and capture reactions possible

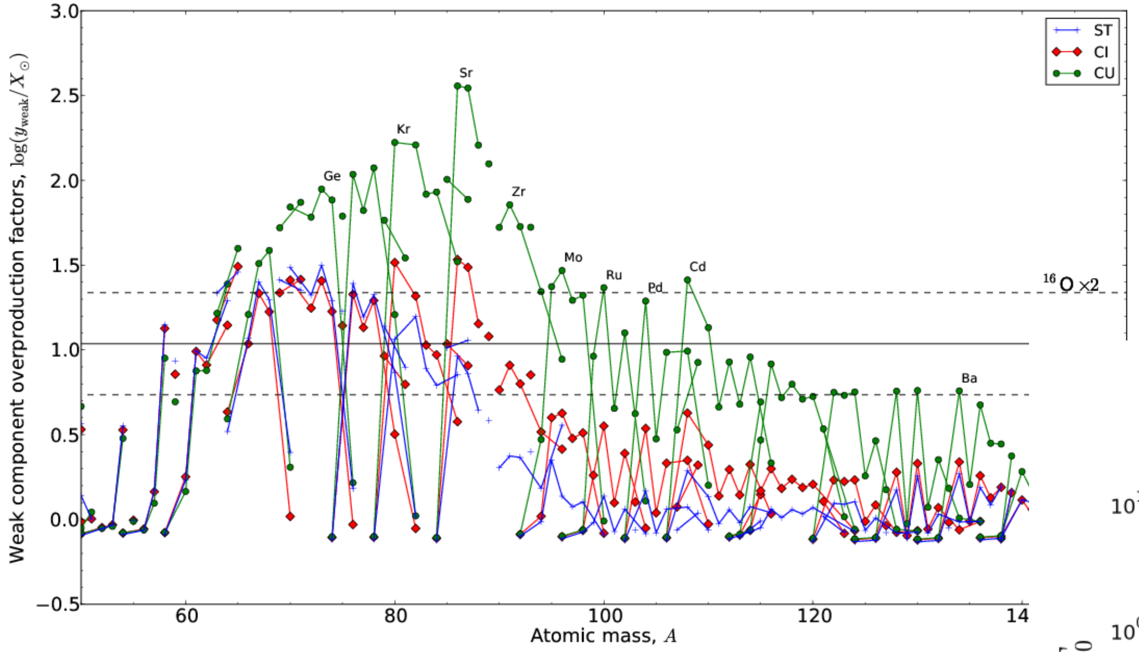
   ⇒ thermal (chemical) equilibrium

Ongoing measurements of key fusion reactions at low energies; neutron sources and sinks, and s-process n-capture cross sections (Dresden, Debrecen, GSI/Frankfurt)

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

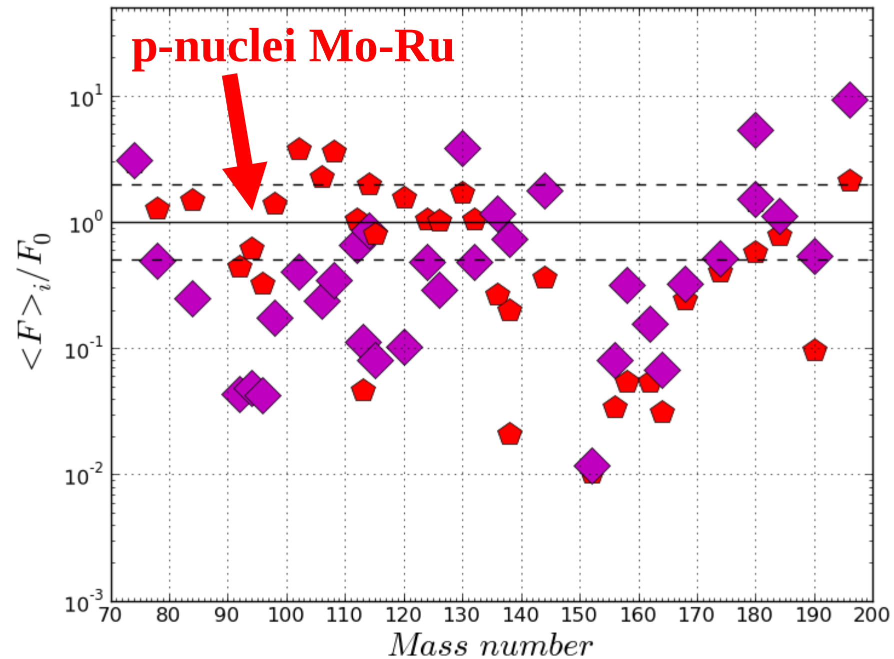
Constraining Nuclear Physics with stellar evolution: ^{12}C-^{12}C rate, 3α

- Full massive star models + post-processing using MPPNP (www.nugridstars.org)



Pignatari et al. 2013, ApJ
Impact study:
- C12+C12a,p,n channels
- s-process, p-process (including production of Mo92-94,Ru96-98)

Bennett et al. 2012, MNRAS
Impact study on different masses using different C12+C12 rates

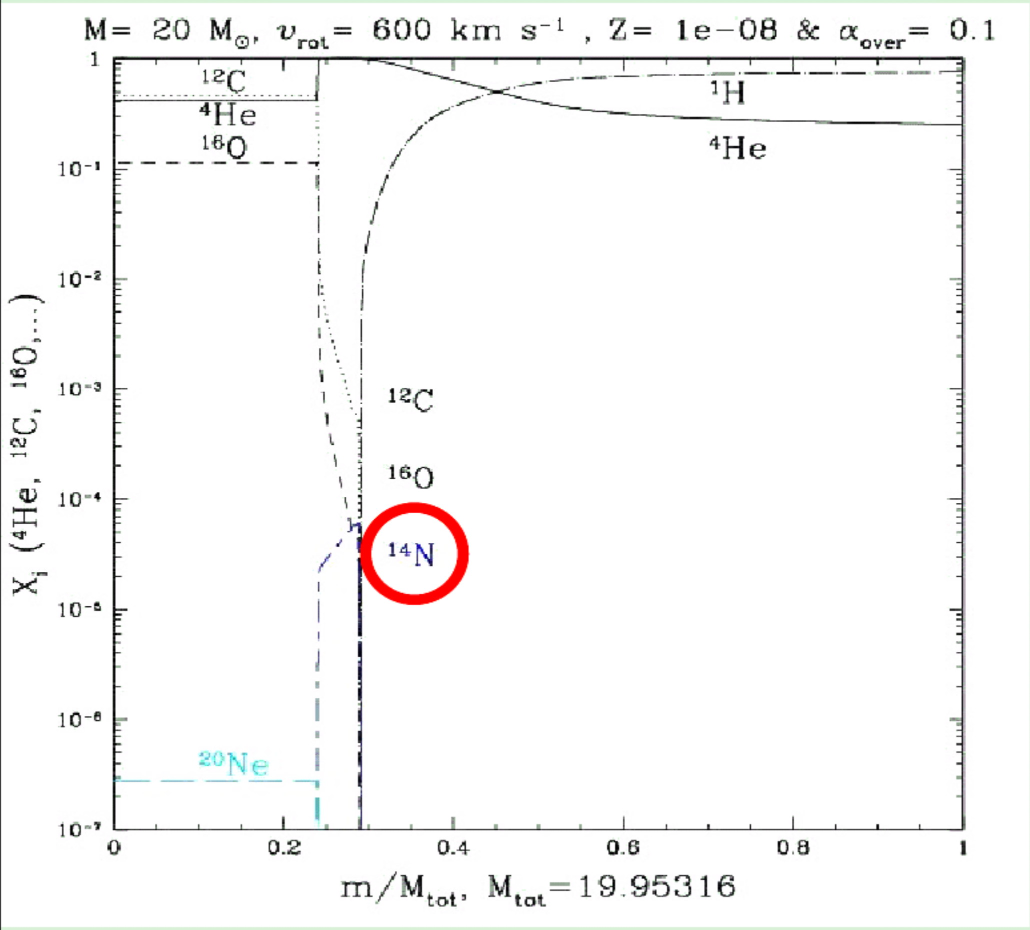


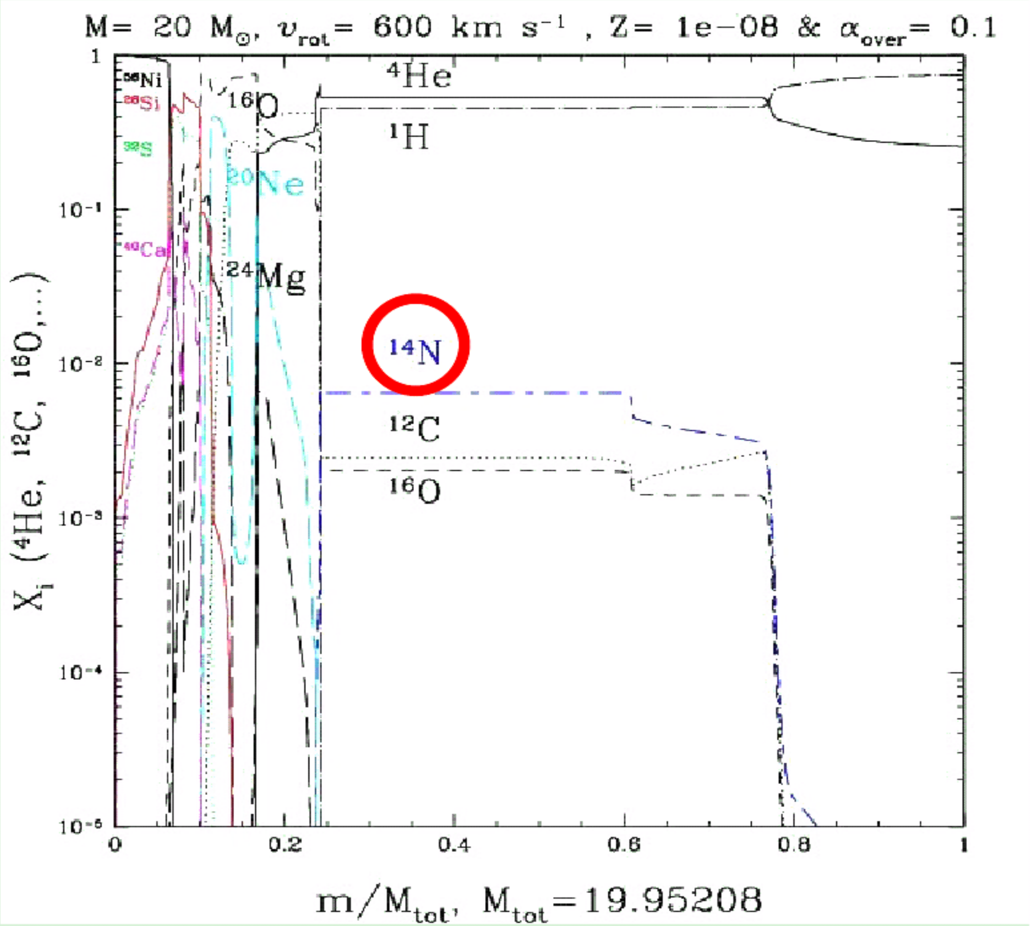
See Suda et al 2011 for a study constraining 3α reaction

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, $Z=10^{-5}$

Connection to chemical evolution, Chiappini et al. (2011) FirstStars

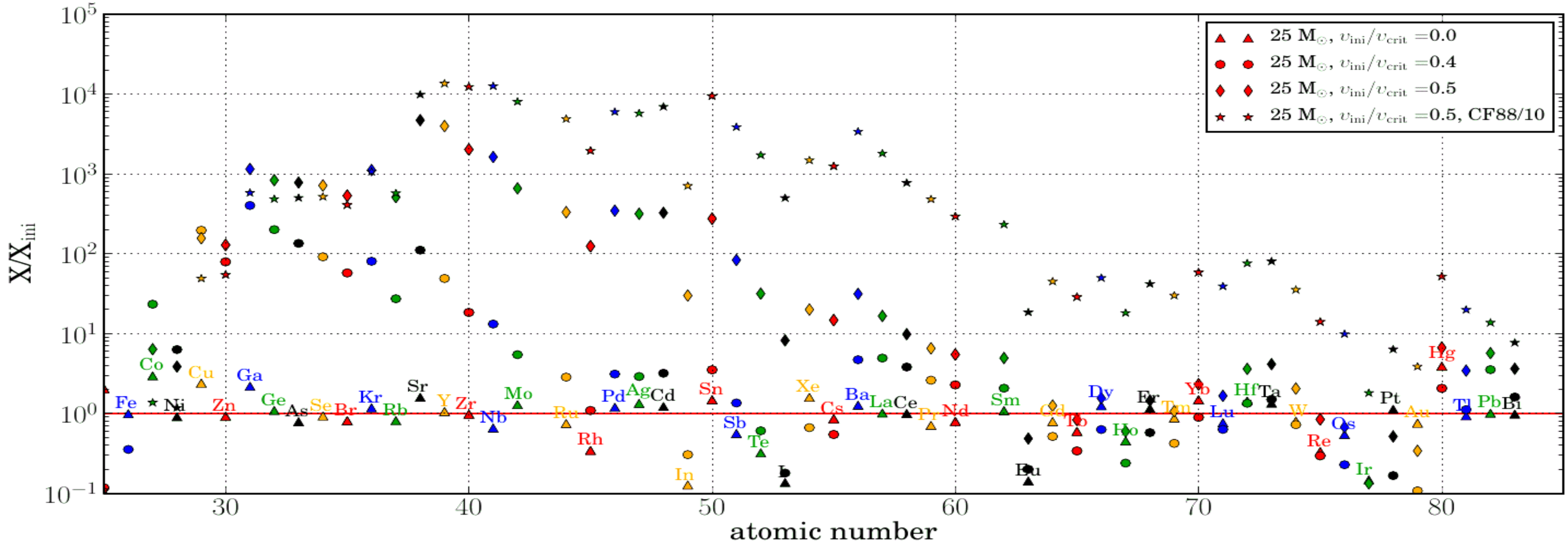


Fig. 1. Overproduction factors (abundances divided by their initial values) for the 25 $M_\odot$ models with $Z = 10^{-5}$ after the end of core He-burning. The model without rotation (triangles) does not produce s-process efficiently whereas the rotating models (filled circles, B1 and diamonds, B3) 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 2012)

still unclear, Görres (2012) vs. Fulton (2013))

Simulations of Core Collapse SNe

1-2-3D simulations with rotation and magnetic flields:

Liebendörfer et al (Basel) ,
Fischer (GSI/TUD)
Janka et al. (MPA Garching)

Nuclear Input:

GSI/TUD (weak interactions, Martinez-Pinedo;
EoS, Typel)
Basel EoS, Hempel + *COMPSTAR*)

Reaction rates and nucleosynthesis:

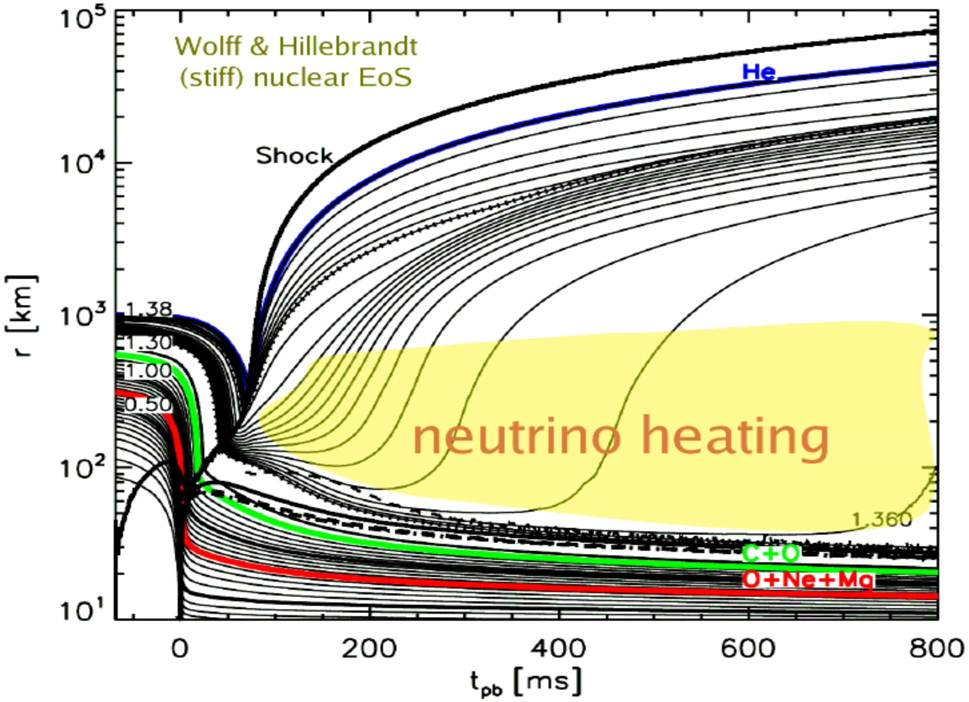
Basel (Rauscher, Pignatari, Thielemann),
GSI/TUD (Martinez-Pinedo et al., Arcones)

Questions: *What is the site of the r-process, p-process? How far reaches the νp-process? How much mass is ejected in radioactive elements?*

Supernovae in 1D

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

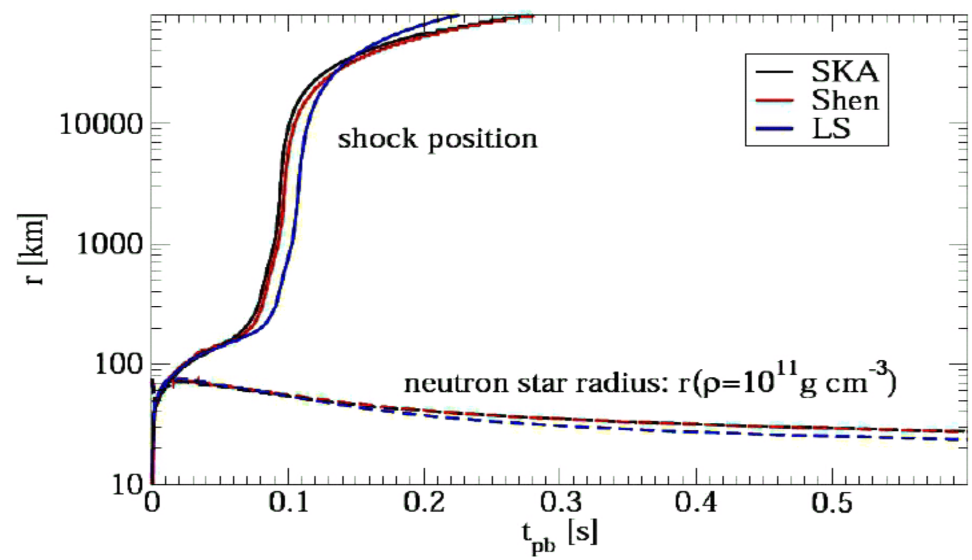
"Electron-capture supernovae"
or "ONeMg core supernovae"



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

- 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)

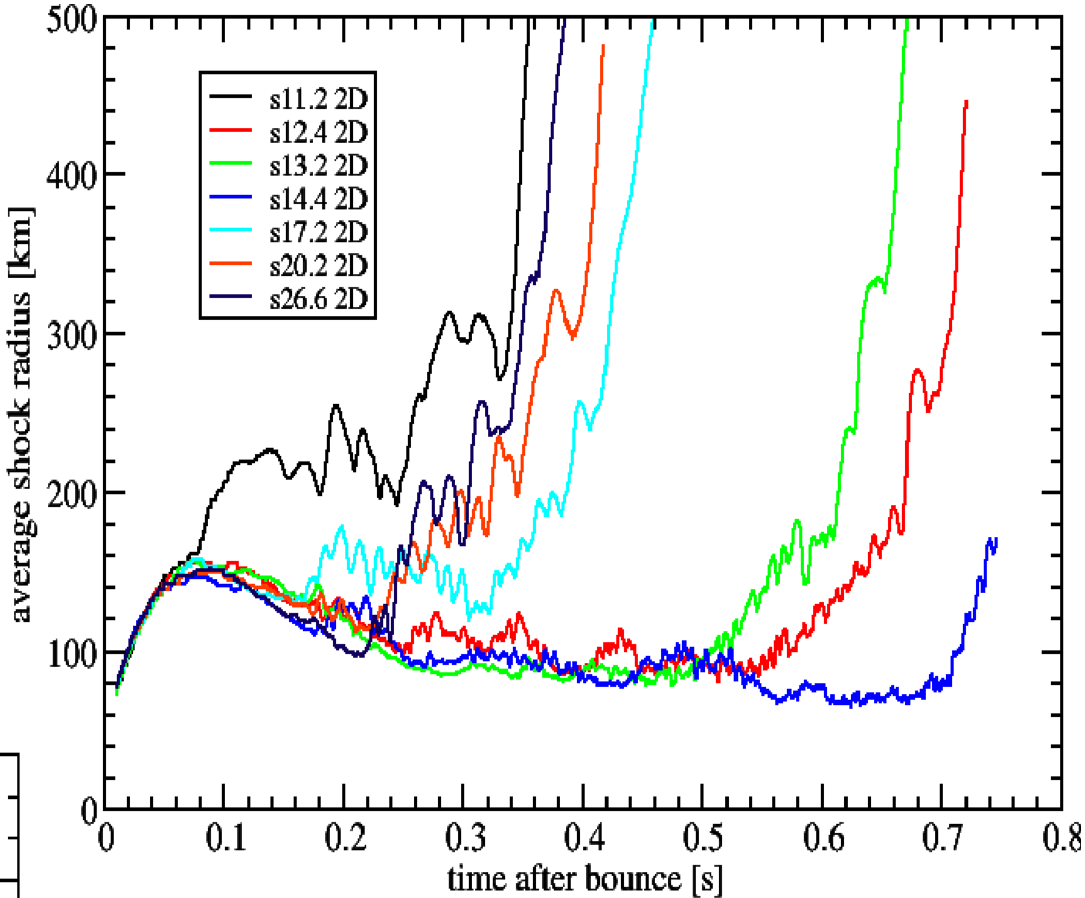
Fischer et al. 2010



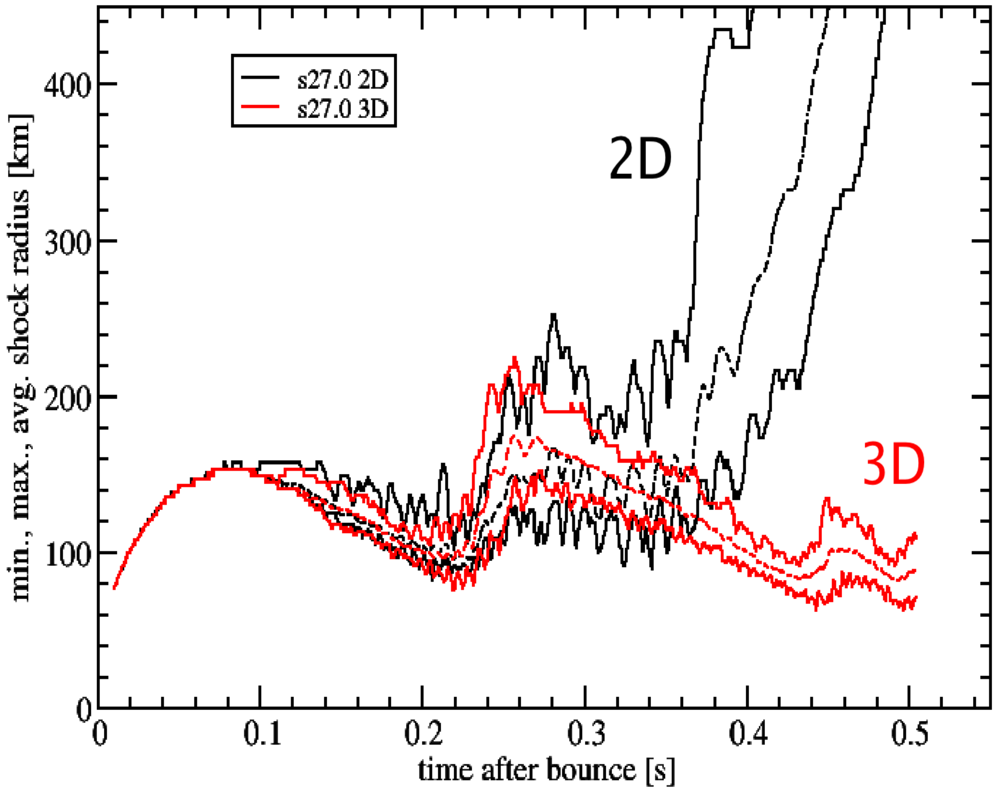
Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

Growing set of 2D CCSN Explosions

(here Hanke & Janka 2013 – MPA Garching)



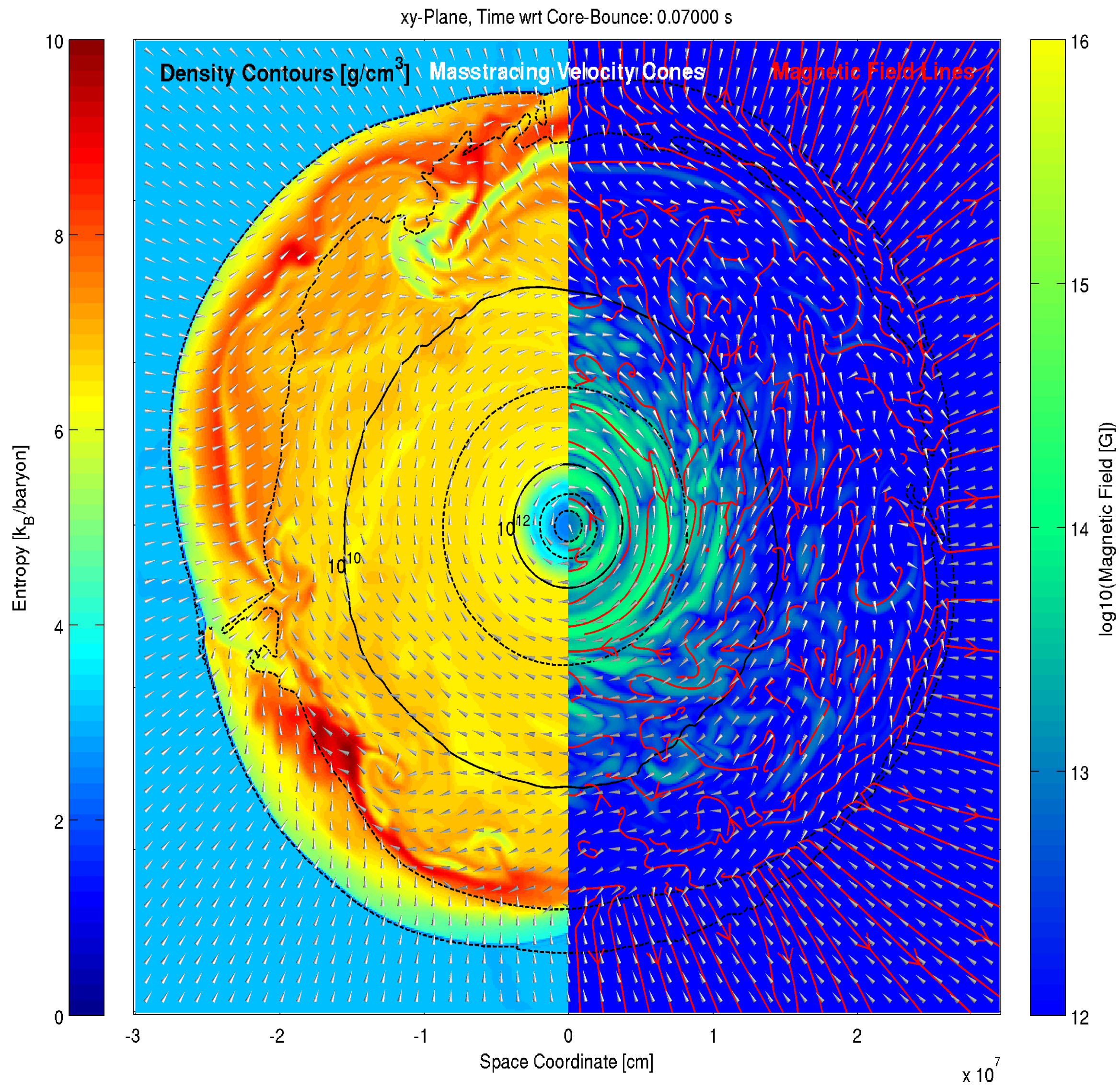
But 3D still somewhat open!

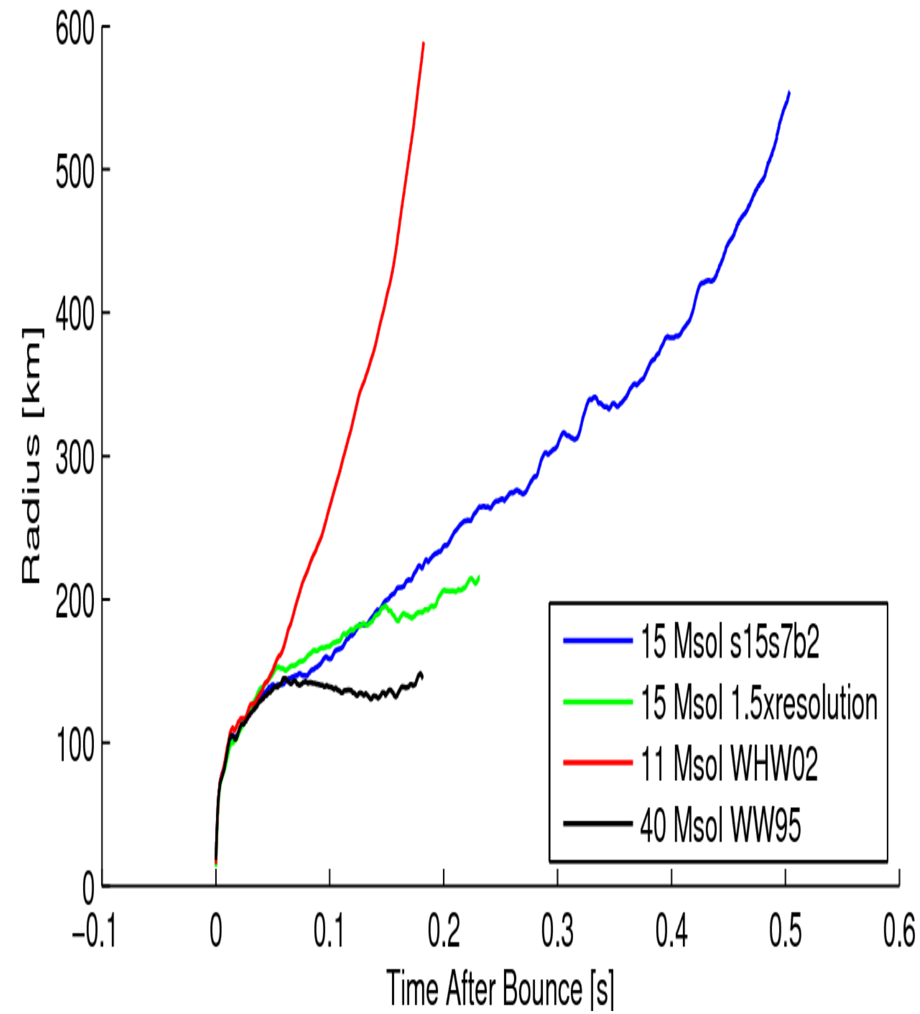


Positions of shock radii

Simulations in 3D

Liebendörfer et al. (Basel)





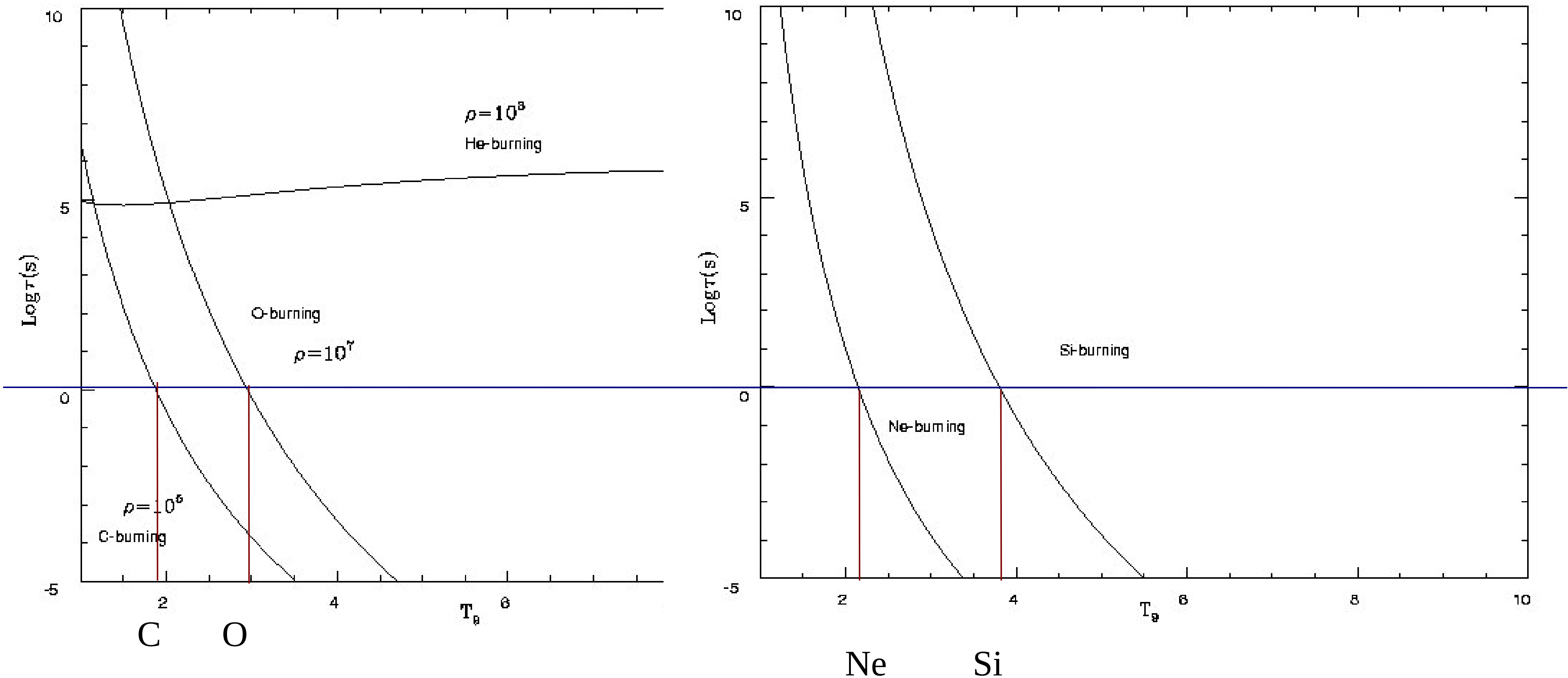
*Finally multi-D core collapse supernovae calculations lead to explosions! (see T. Janka, A. Mezzacappa, C. Ott, etc.; **here the Basel version**).*

There are two transitions: (i) 8-10M$_{sol}$ progenitors even explode in spherical symmetry, (ii) from regular core collapse SNe with neutron star formation - to faint SNe with fall back and BH formation - BH formation and hypernovae???

Core Collapse Supernovae

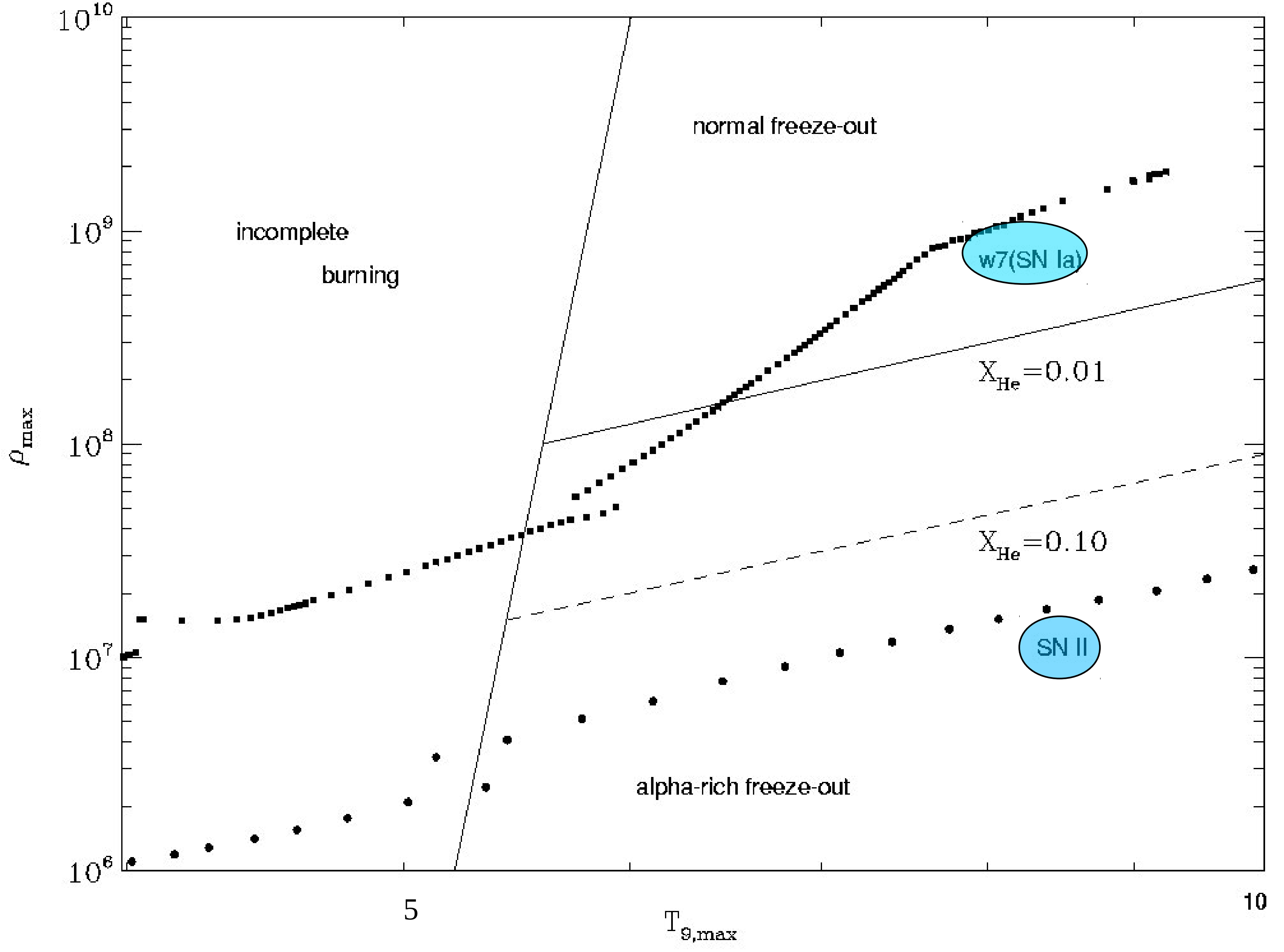
- Explosive nucleosynthesis from “induced“ explosion calculations
- The p-process
- The Supernova Mechanism and the innermost ejecta
- The role of neutrinos for the (early) innermost ejecta (the νp-process)
- The late neutrino wind
- Passing through the IMF

Explosive Burning



typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent

Explosive Si-Burning



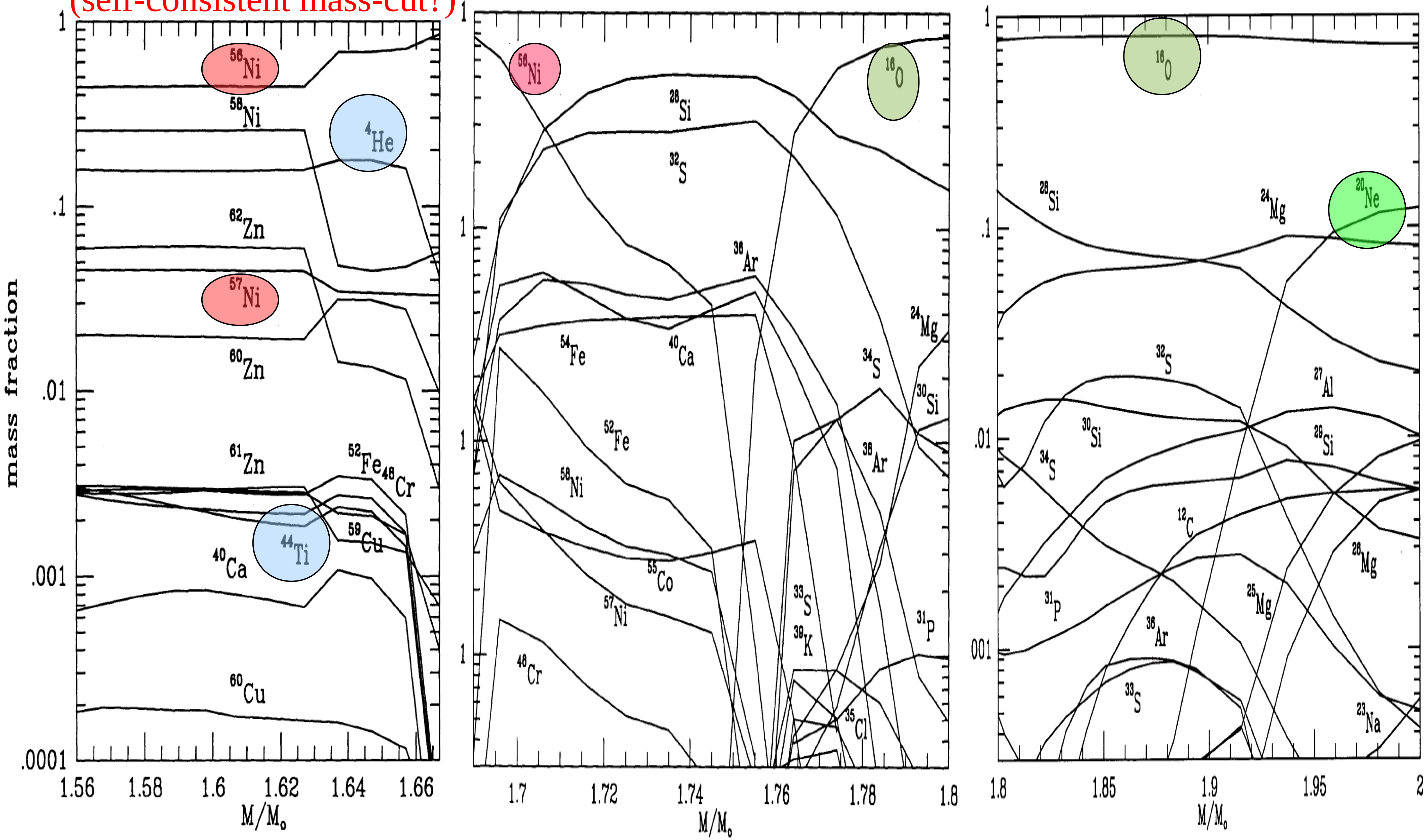
Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^{4}He to C and beyond freeze out earlier (alpha-rich freeze-out).

Products of explosive burning (20Msol star)

Results from "thermal bomb" energy deposition in progenitor model (Nomoto-style)

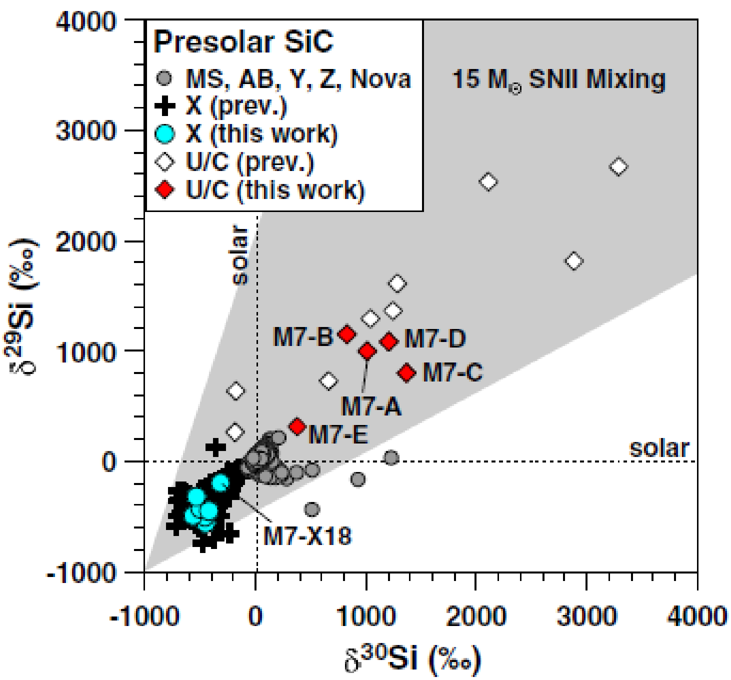
Fe-group composition depends on Y_e and entropy (alpha-rich freeze-out)

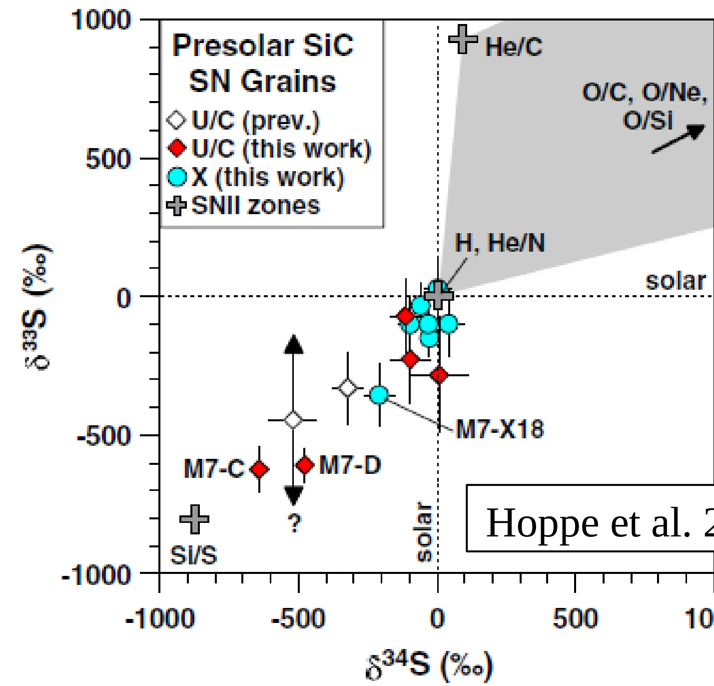
(self-consistent mass-cut?)



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

Constraining the ejecta from old CCSN explosions with the isotopic signature of presolar grains





Hoppe et al. 2012, ApJL

- Pignatari et al. 2013, ApJL:

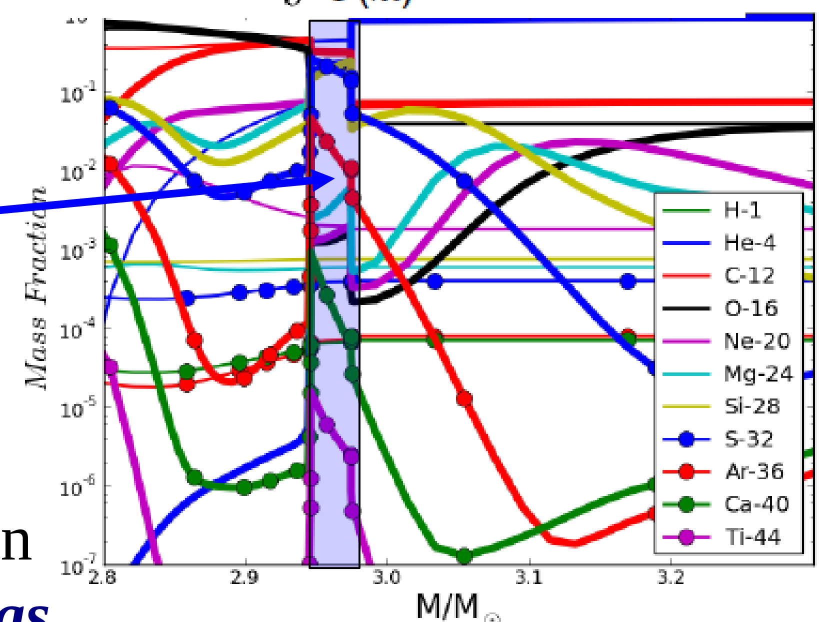
SiC-X and LD graphites as tracers of the high velocity of the CCSN shock, carrying the signature of the C-rich **C/Si zone**, at the bottom of the He/C zone.

- Pignatari et al. 2013, arXiv:

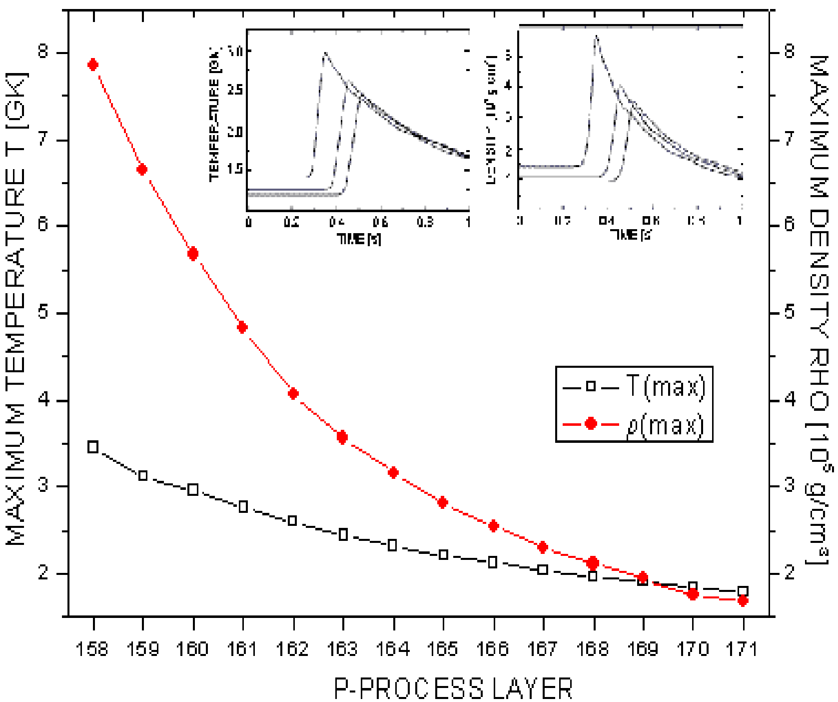
SiC-C grains, carrying the signature of the Neutron density in the explosive C-rich He-burning shell. **S32-rich grains from the decay of the radioactive Si32.**

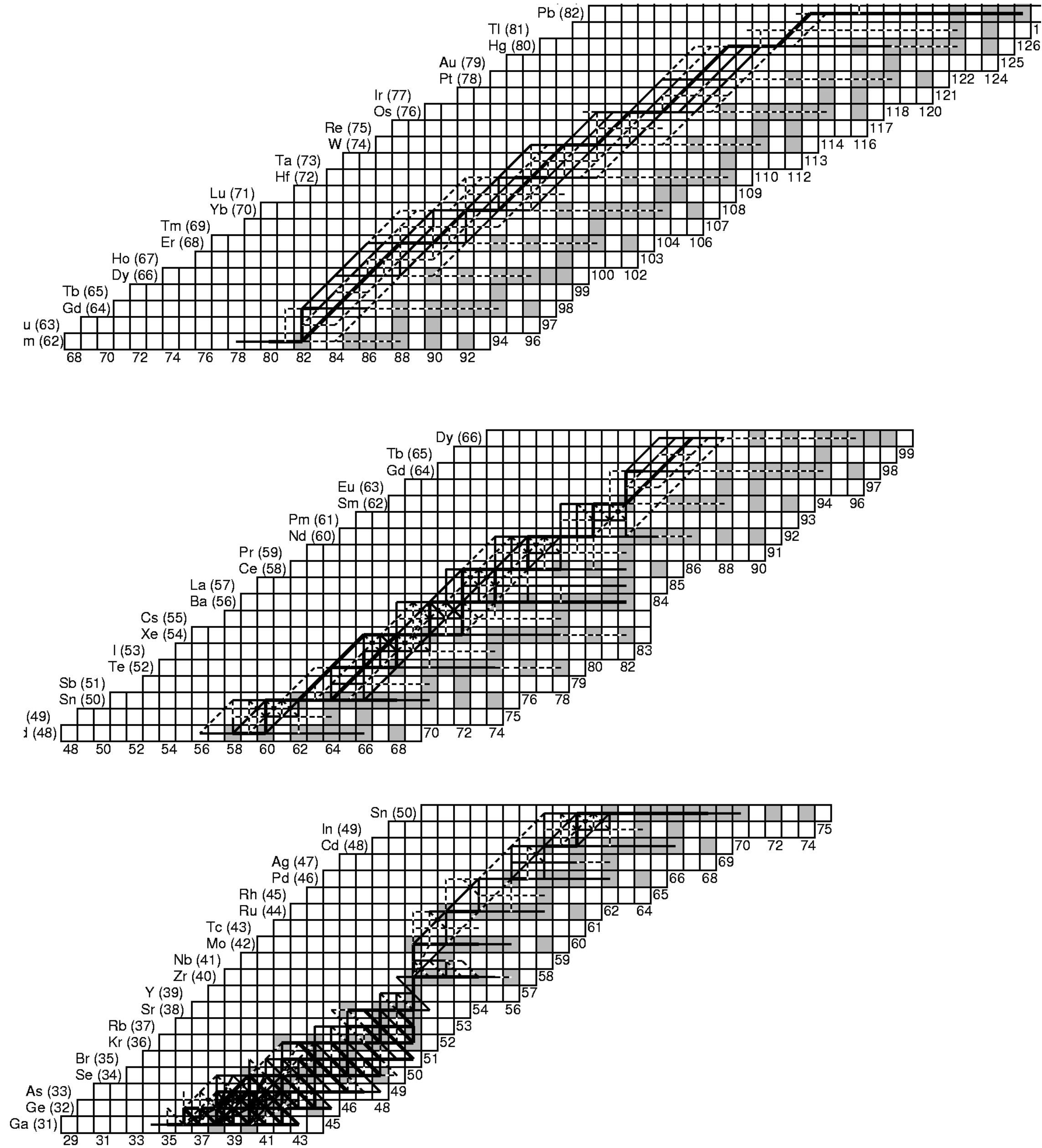
Connection

CoDustMas



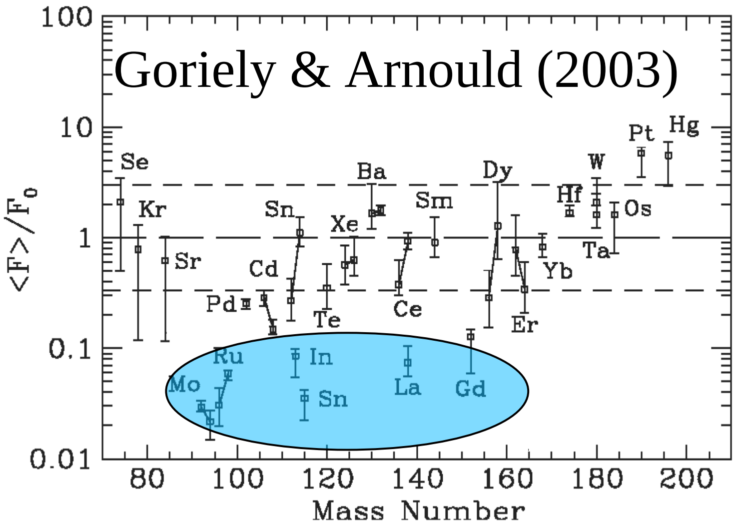
p-process in explosive Ne/O-Burning zones

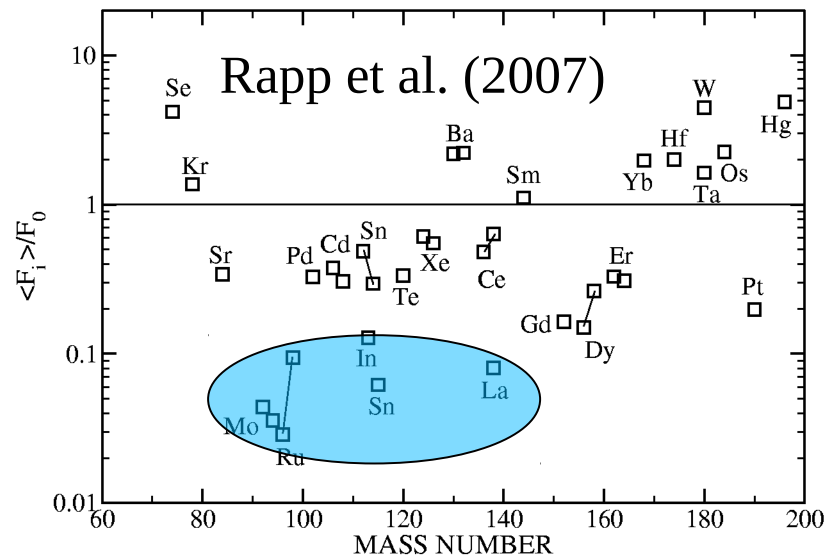


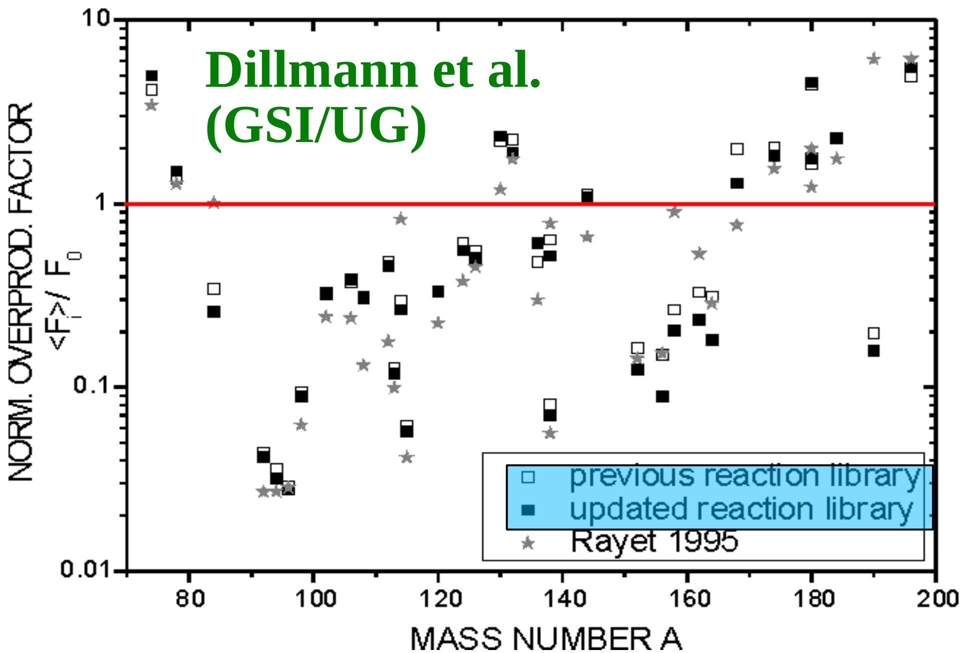


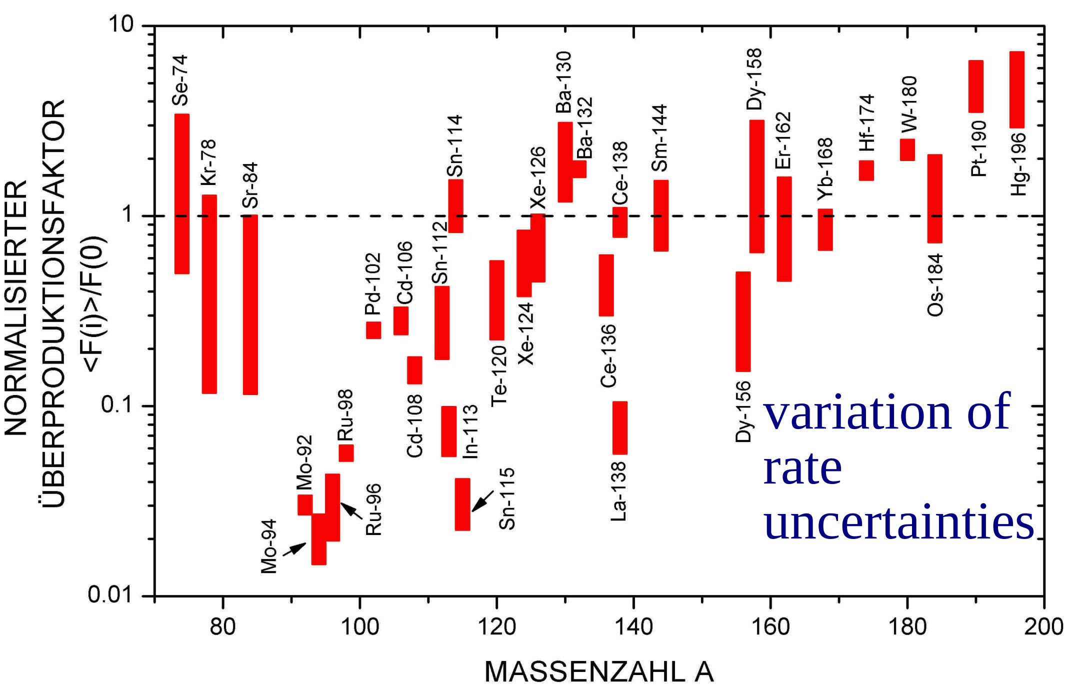
Rapp et al. (2007), following p-(gamma)-process calculations within the framework of Rayet et al. (1995) for a 25M_{sol} star of Yoshida et al. (2002) to verify the impact of nuclear uncertainties.

Comparison with solar p-only nuclei









Ideas for solutions

There have been many investigations in p-process related reactions (Gyürky, Fülöp, 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!
will be followed by Pignatari+Battino (Basel)
(b) change evolution of massive stars (e.g. $^{12}C+^{12}C$) which changes extent of s-processing before core collapse supernova explosion,
see previous slide Pignatari (Basel)
(c) invent different environment with capture reactions for light p-isotopes.
e.g. νp-process, ”weak r-process” (charged particle process)
(see below)

Despite the fact that these nuclear uncertainty tests and experiments **(Debrecen, Kocaeli, Dillmann-GSI/UG, Rauscher-Basel)** did not lead to a solution of the light p-nuclei problem, they were of immense importance for an improved understanding of charged-particle nuclear reactions with heavy nuclei!!!!!!!!!
and also led to.... **(Rauscher 2013)**

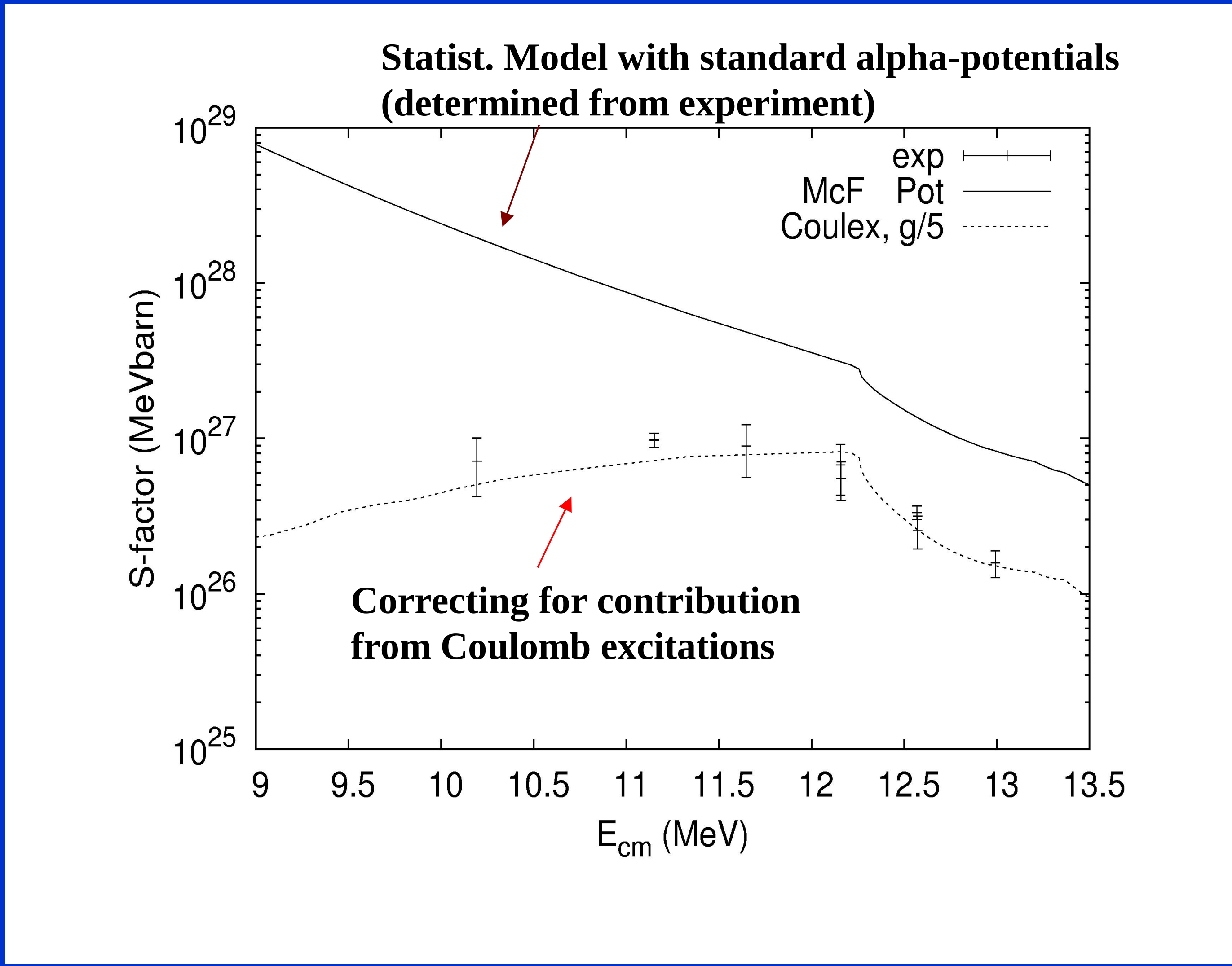
Resolving the long-standing mystery of alpha-potentials for heavy nuclei

Impact of low-energy Coulex on 144Sm(α,γ)

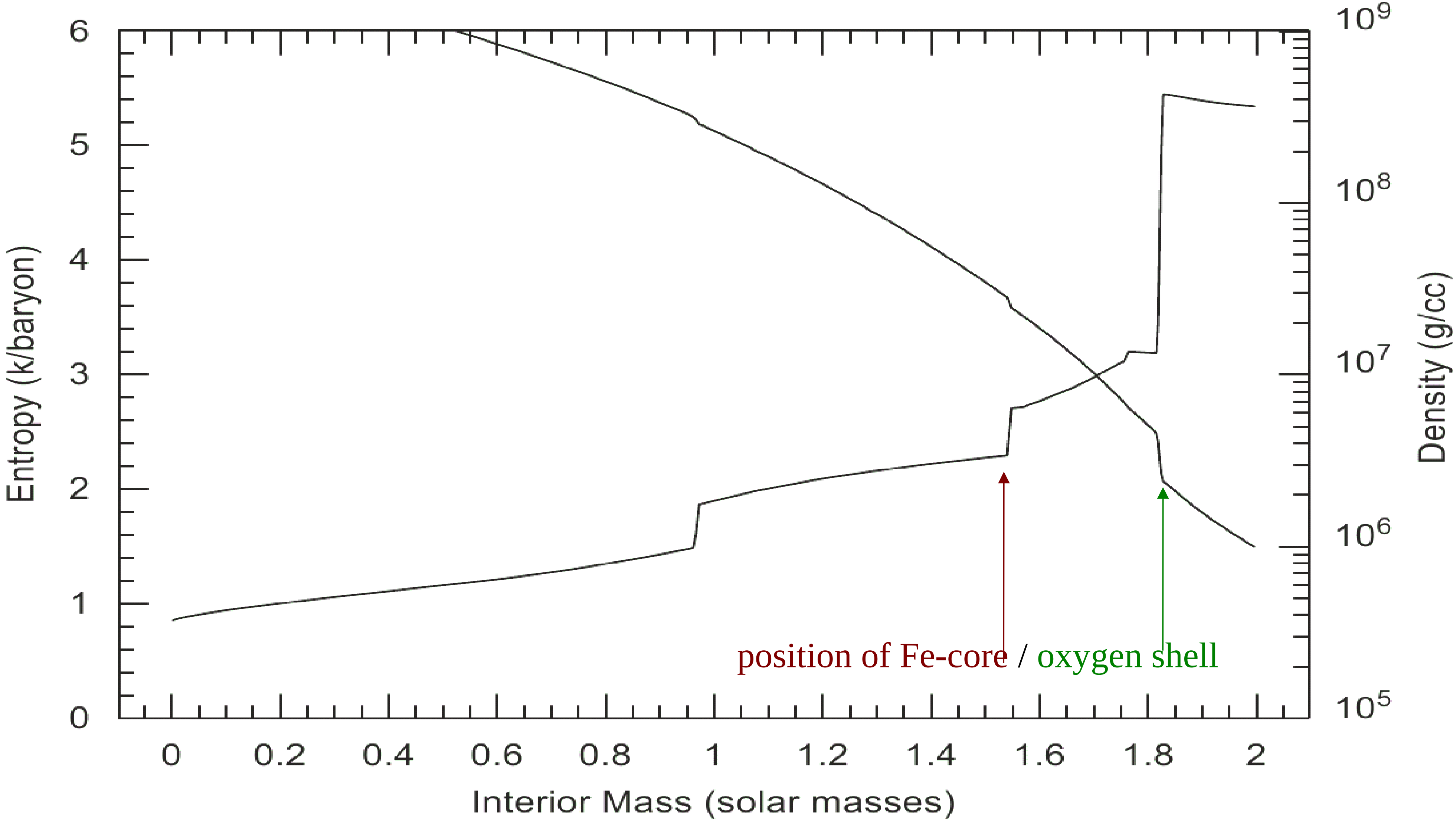
Utilizing standard alpha-potentials is ok!
If Coulomb excitations are included

- First 2+ at 1.66 MeV
- B(E2)=0.262

- Sensitivity check!
- Above 12 MeV:
  - γ-width
  - neutron width



How to invoke induced explosions for nucleosynthesis purposes?

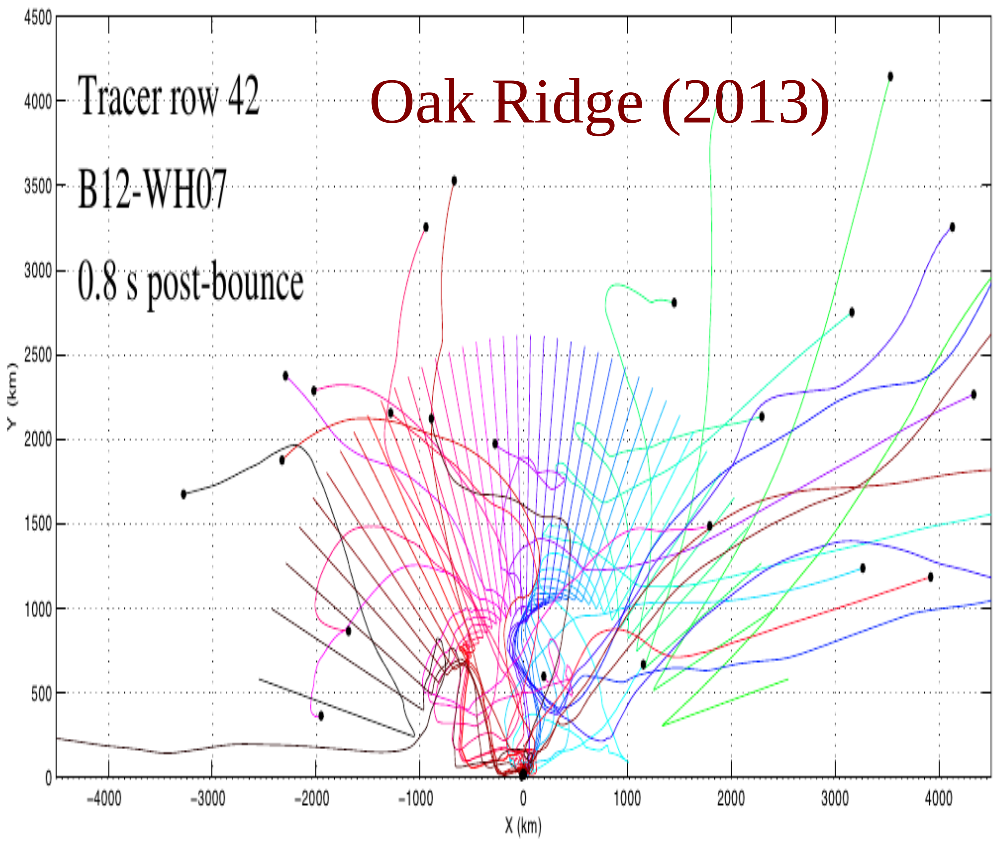


without a self-consistent mechanism nucleosynthesis can only be calculated with induced explosions. Woosley & Heger position a piston with 1.2B at $S=4k_B/b$, Nomoto/Umeda/Thielemann applied thermal bomb and integrate from outside until expected ^{56}Ni-yield.

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

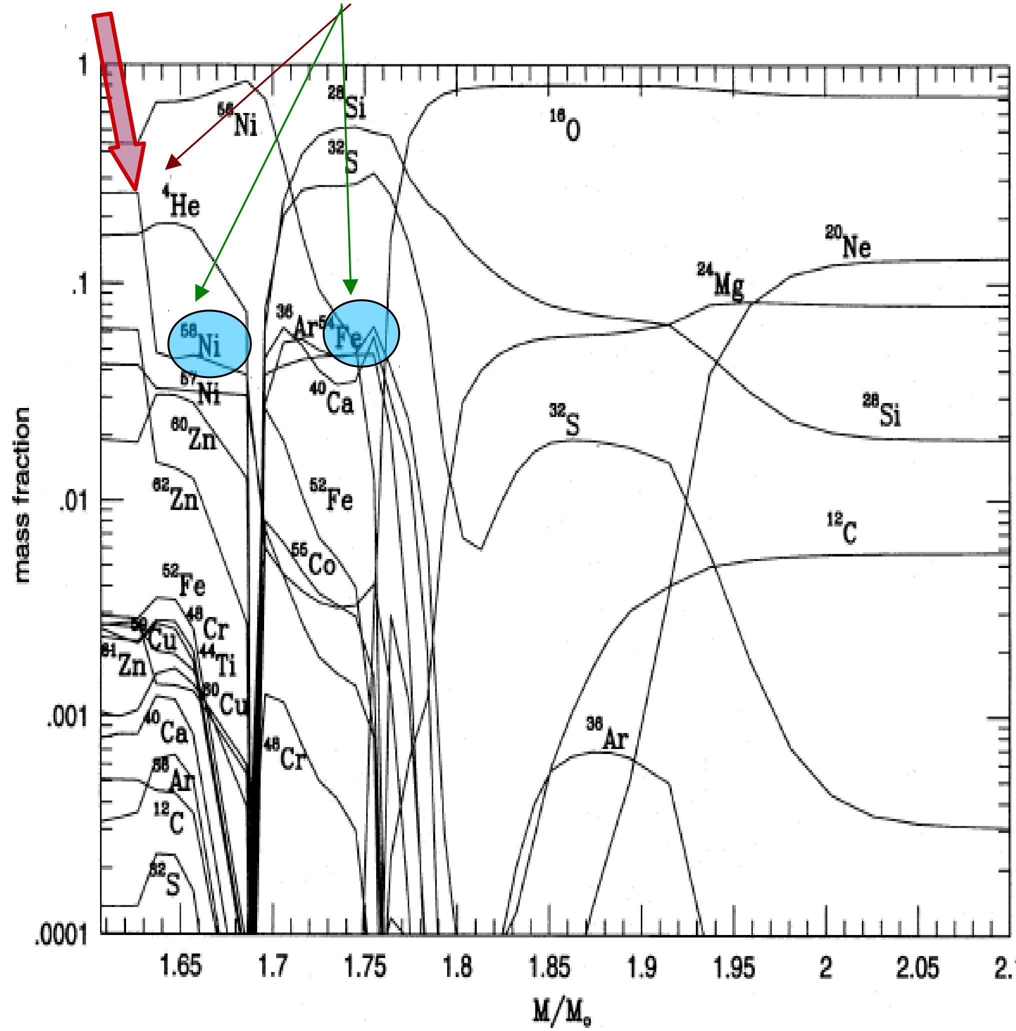
prior results made use of initial stellar structure (and Y_e!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go much beyond Ni!

Two aspects:
(i) even in spherical symmetry neglecting neutrinos -> Y_e
(ii) multi-D

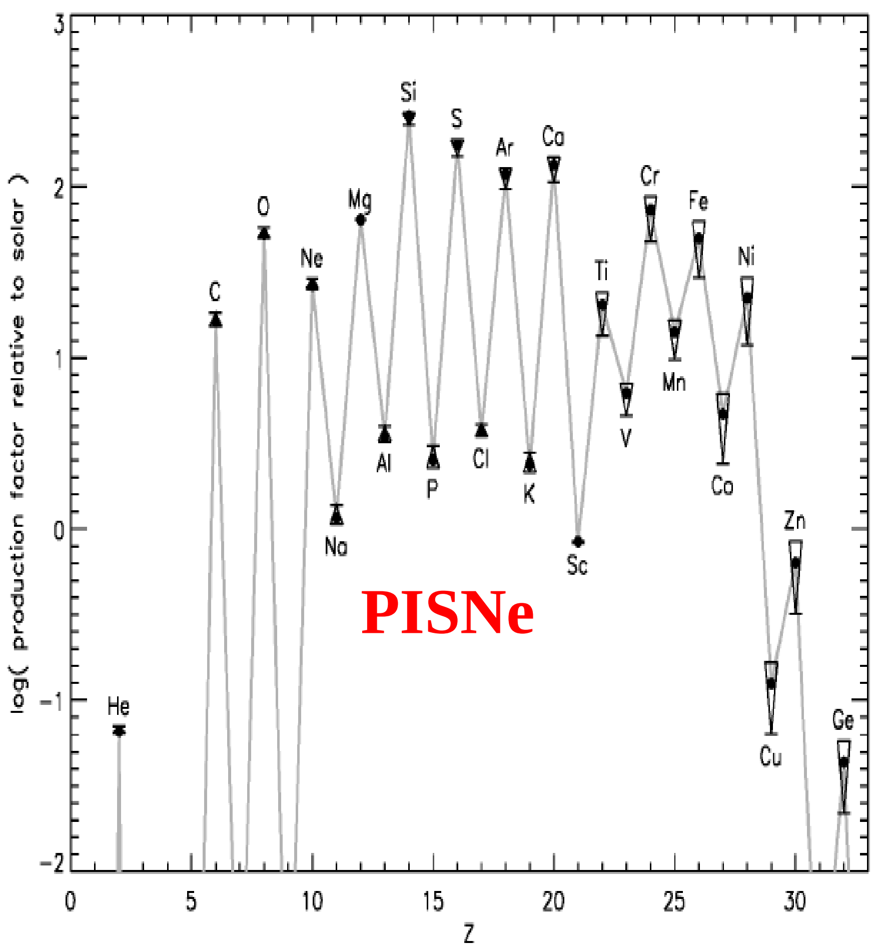


high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe),

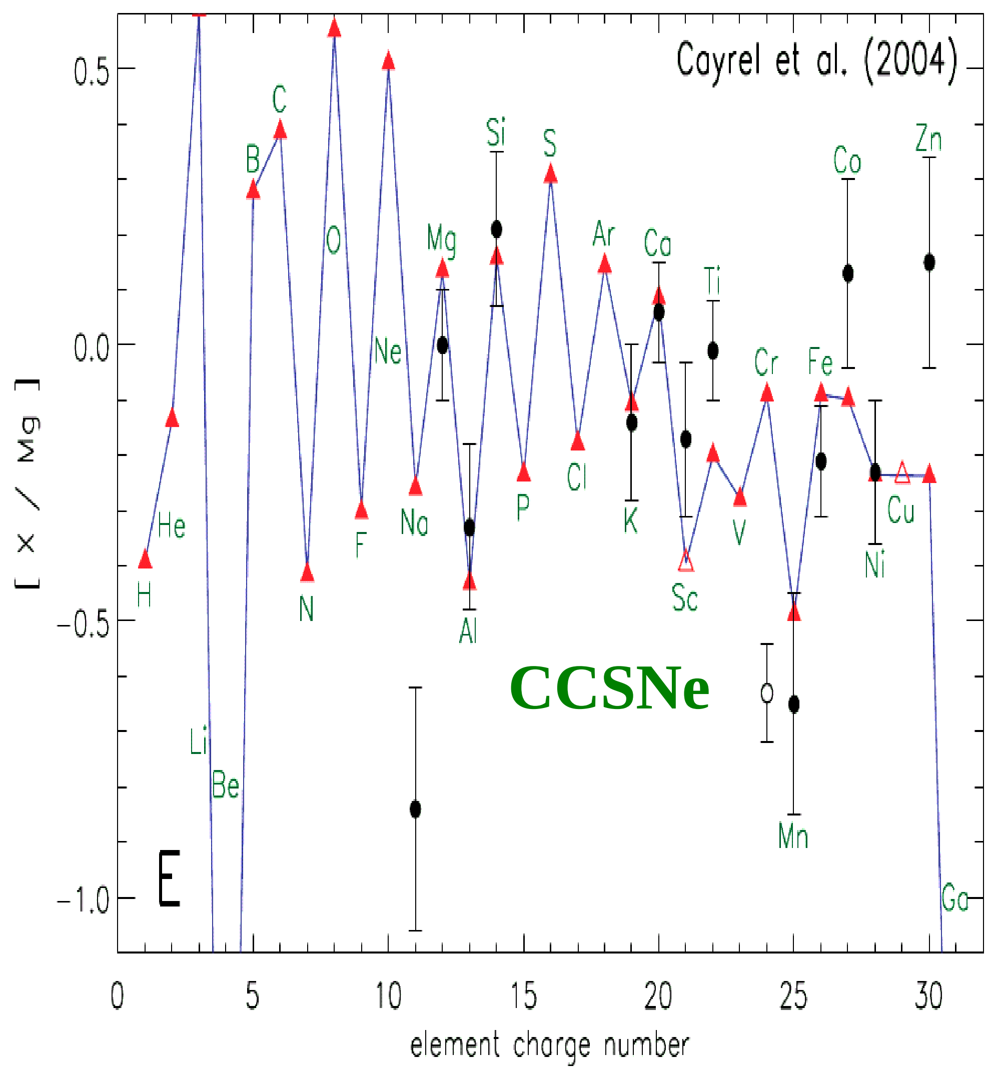
Y_e determines Fe-group isotopes.



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)

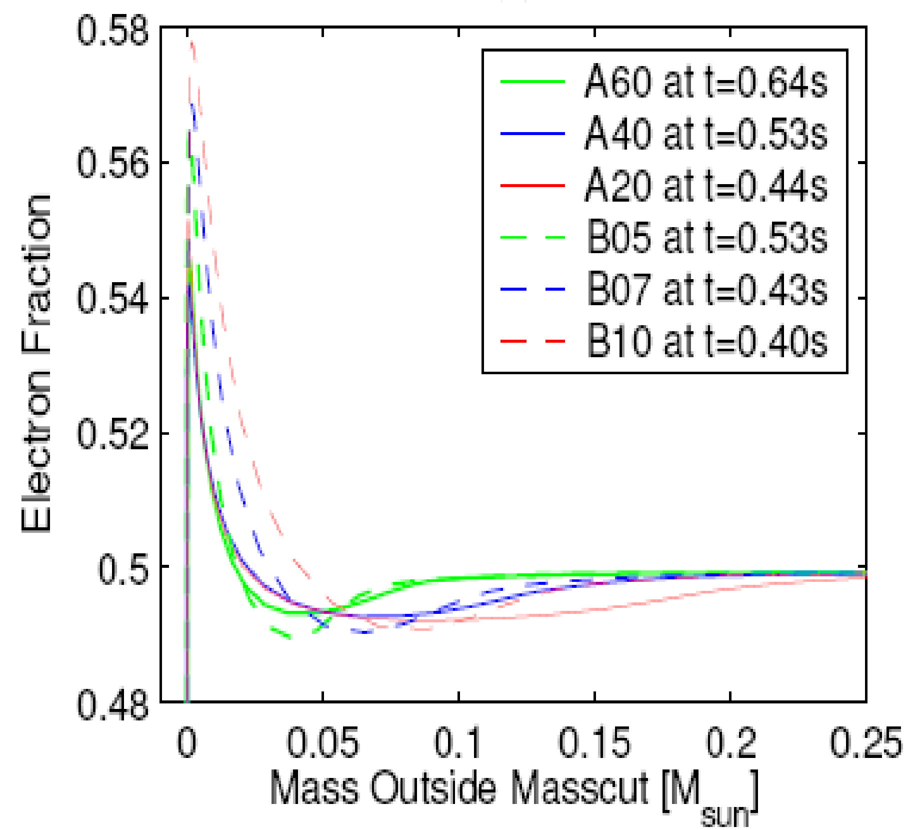
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

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

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

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

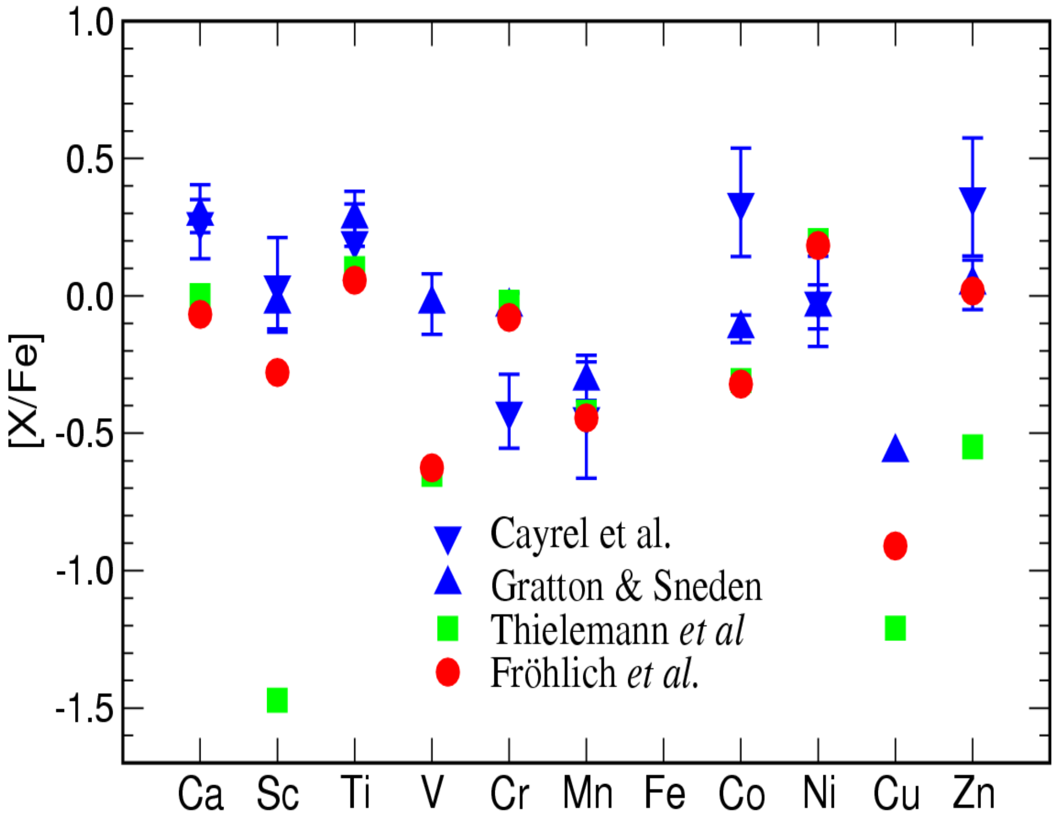
- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity → 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 $E_{av,\nu}$-$E_{av,\nu}$>4(m_n-m_p) lead to Y_e<0.5!

Improved Fe-group composition



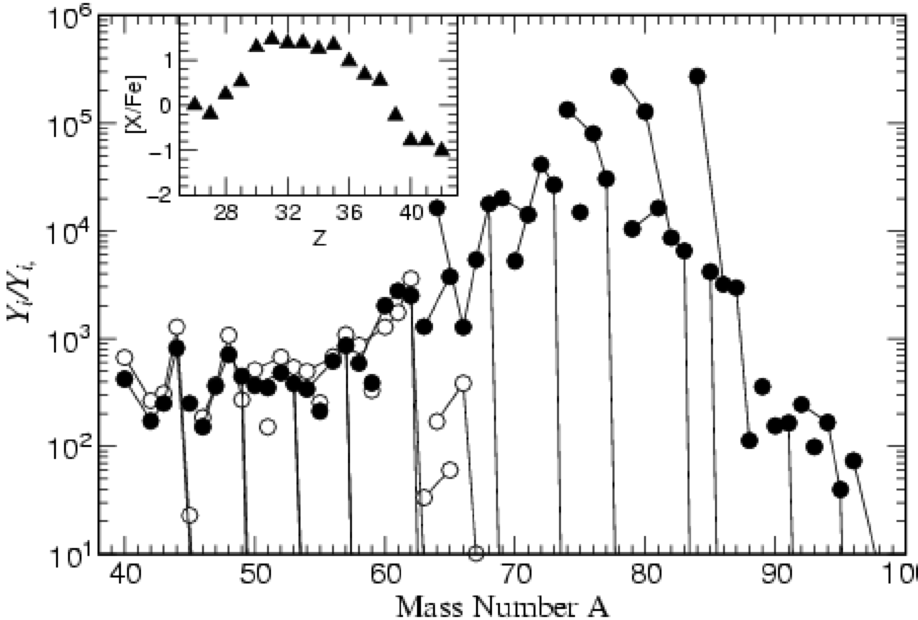
Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

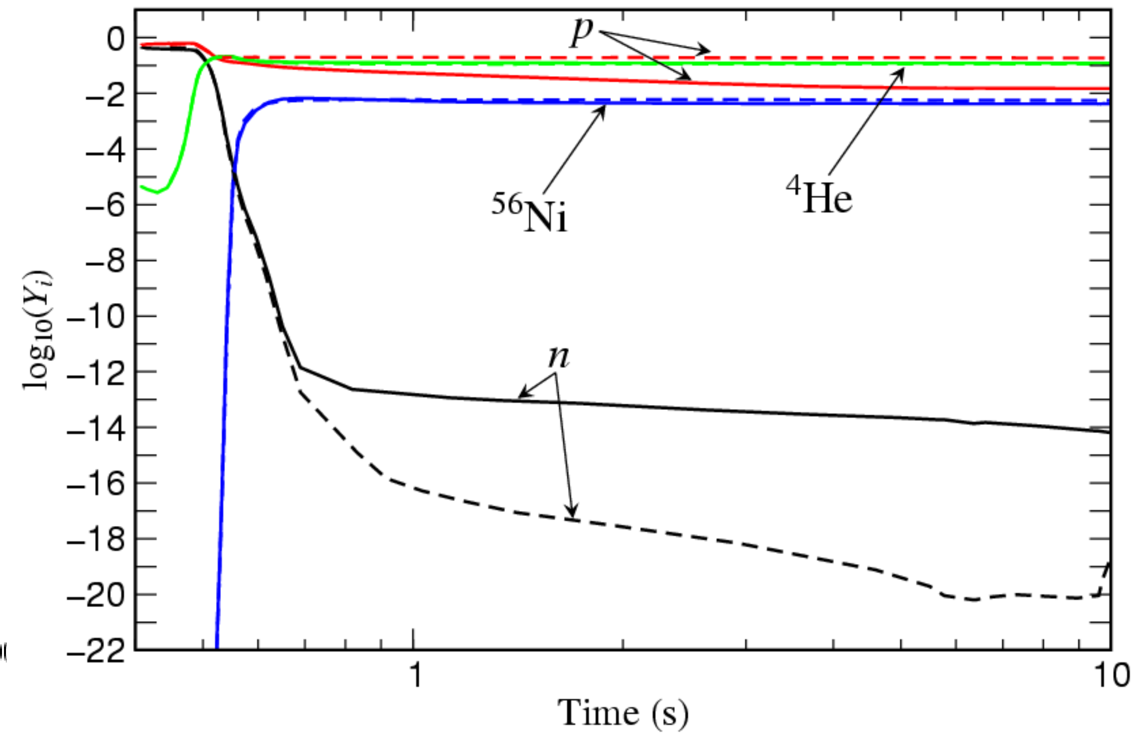
This effect improves the Fe-group composition in general (e.g. Sc) and extends it to Cu and Zn!

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

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





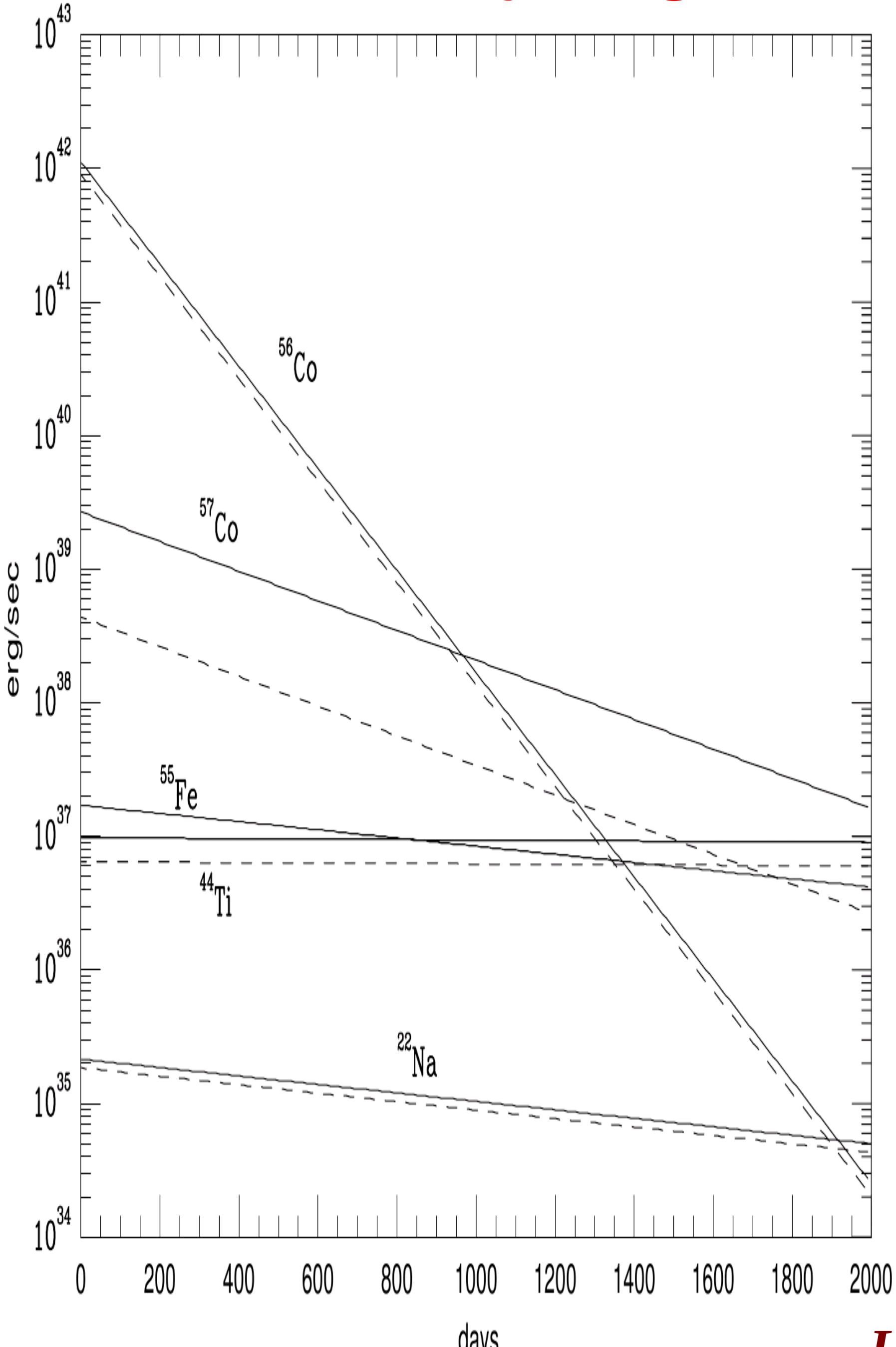
Fröhlich et al. (2006b);
also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei) see also Pruet et al. (2006), Wanajo (2006).

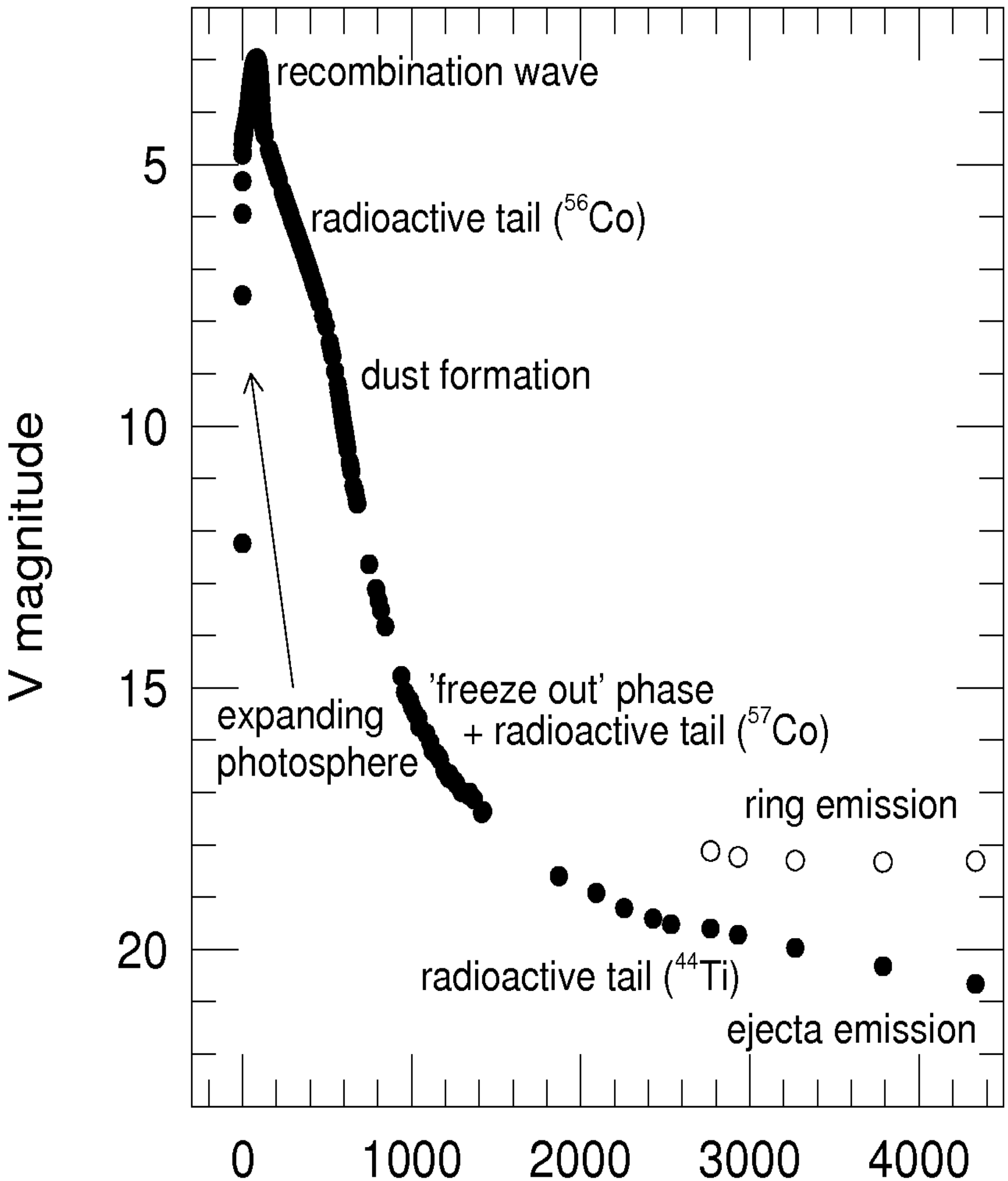
Recent analysis by Wanajo et al. (2010, MPA Garching), Arcones et al. (2011, Basel/GSI/TUD) with variation of neutron star masses and reverse shock position

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.

Radioactivity Diagnostics of 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)

Impact on Chemical Evolution of Galaxies

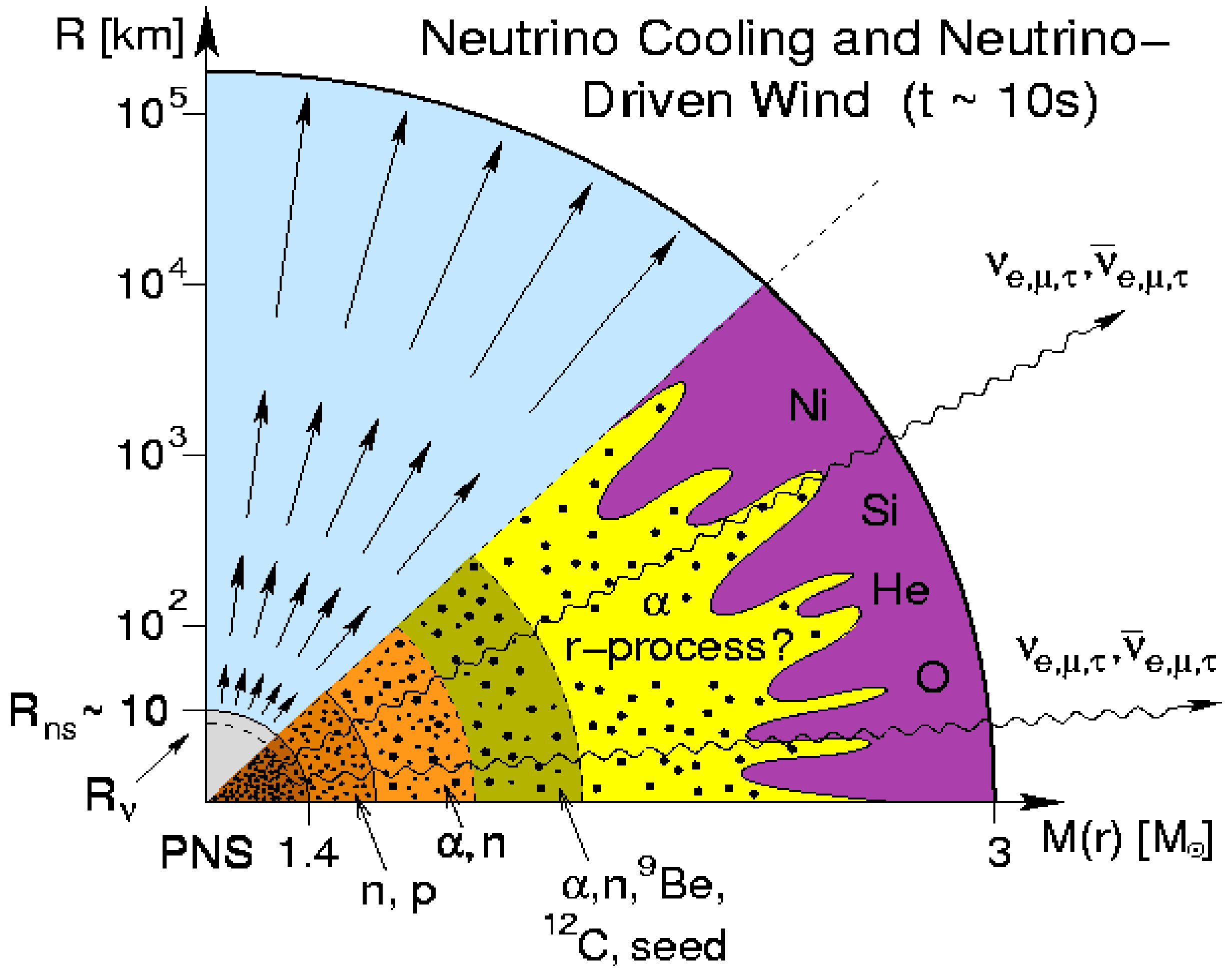
Present nucleosynthesis predictions (pistons or thermal bombs) cannot correctly describe the ejecta of the innermost zones which are affected by the explosion mechanism (e-captures and neutrino interactions $\rightarrow$ Ye).

Two (still spherically symmetric) approaches with full collapse calculations and approximations for neutrino heating (**PUSH – Basel-Darmstadt-Raleigh/NC, Liebendörfer, Perego, Ebinger, Hempel, Casanova, Fröhlich; Neutrino-Driven-Supernovae - Darmstadt, Garching, Ugliano, Arcones, Janka**) are on the way to improve that part and predict nucleosynthesis ejecta which include an improved treatment for the innermost ejected zones.

This will permit improved chemical evolution modeling!

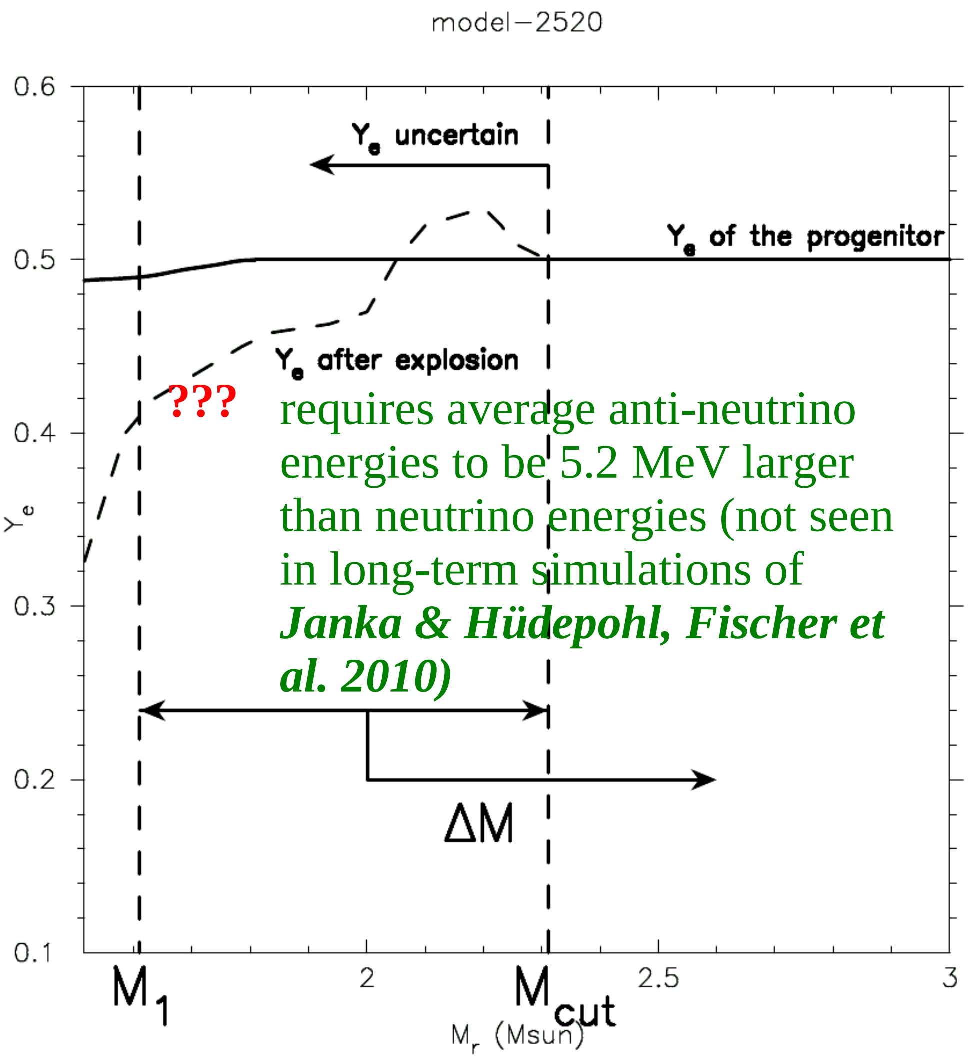
N. Prantzos, IAP
F. Matteucci, Trieste
F. Primas, ESO
F. Chiappini, Geneva/Potsdam → ***First Stars***

What is the site of the r-process?



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)***

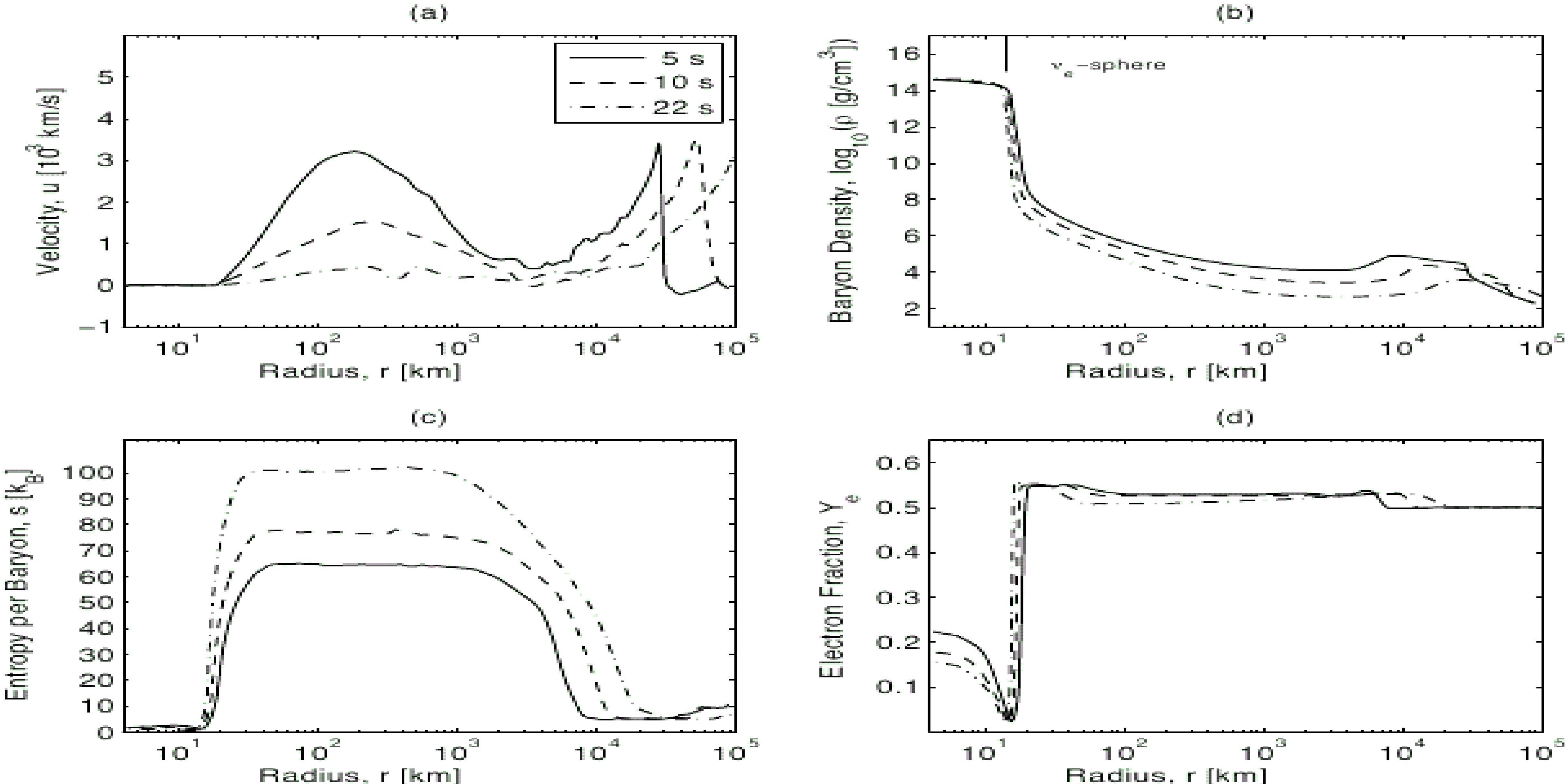
Izutani et al. (2009)

- *regular explosions with neutron star formation, neutrino exposure, νp-process.*
- *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****)*
- *under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?*

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

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

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

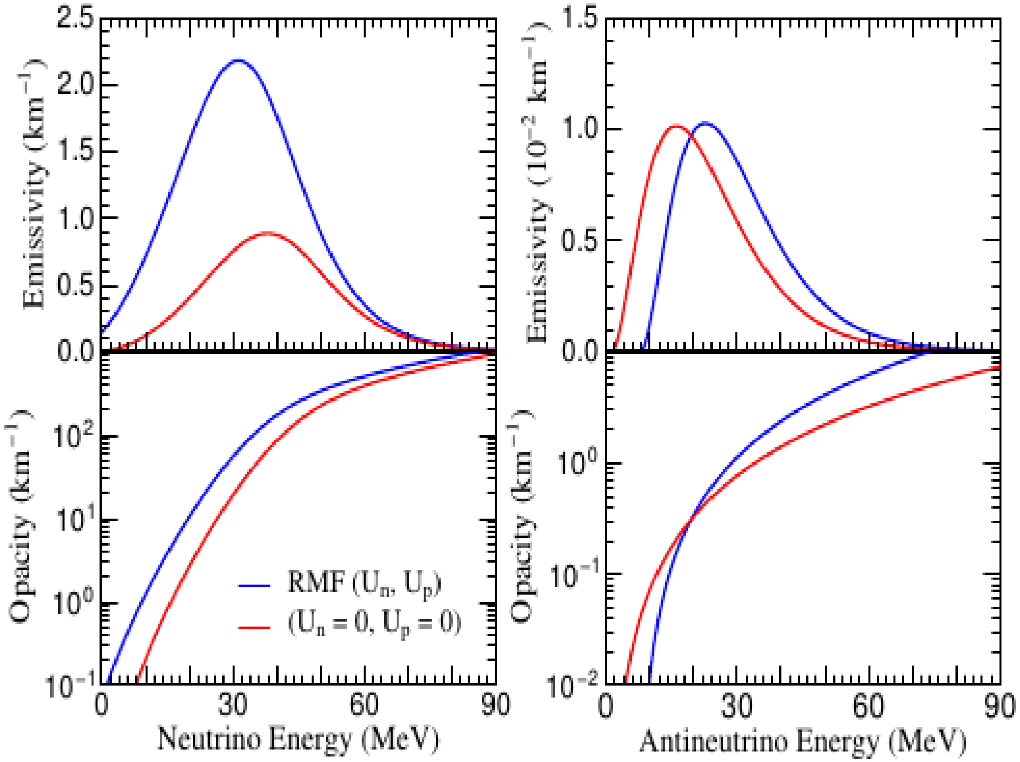


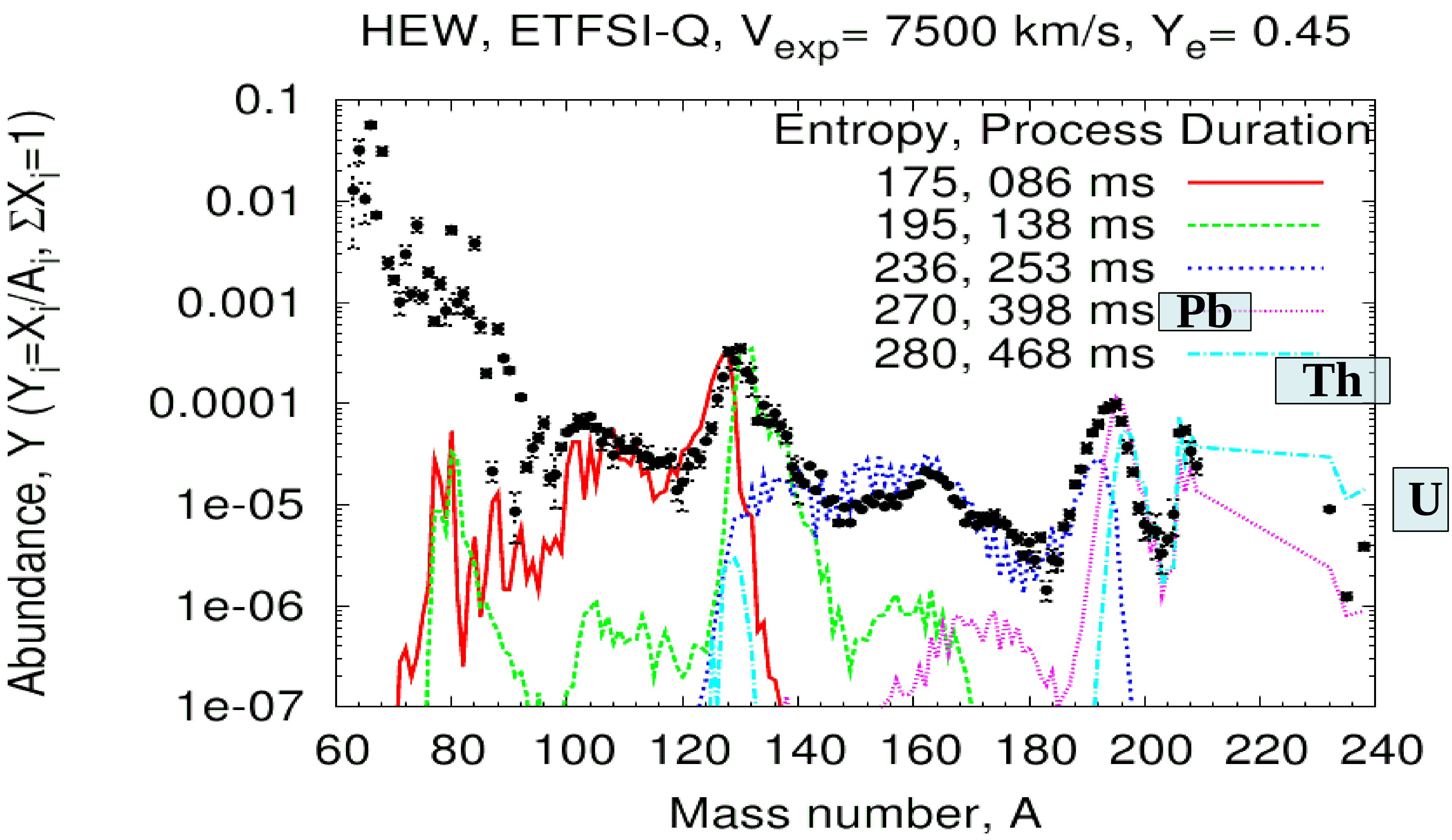
FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions $\rho = 2.1 \times 10^{13}$ g cm^{-3}, $T = 7.4$ MeV and $Y_e = 0.035$.

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

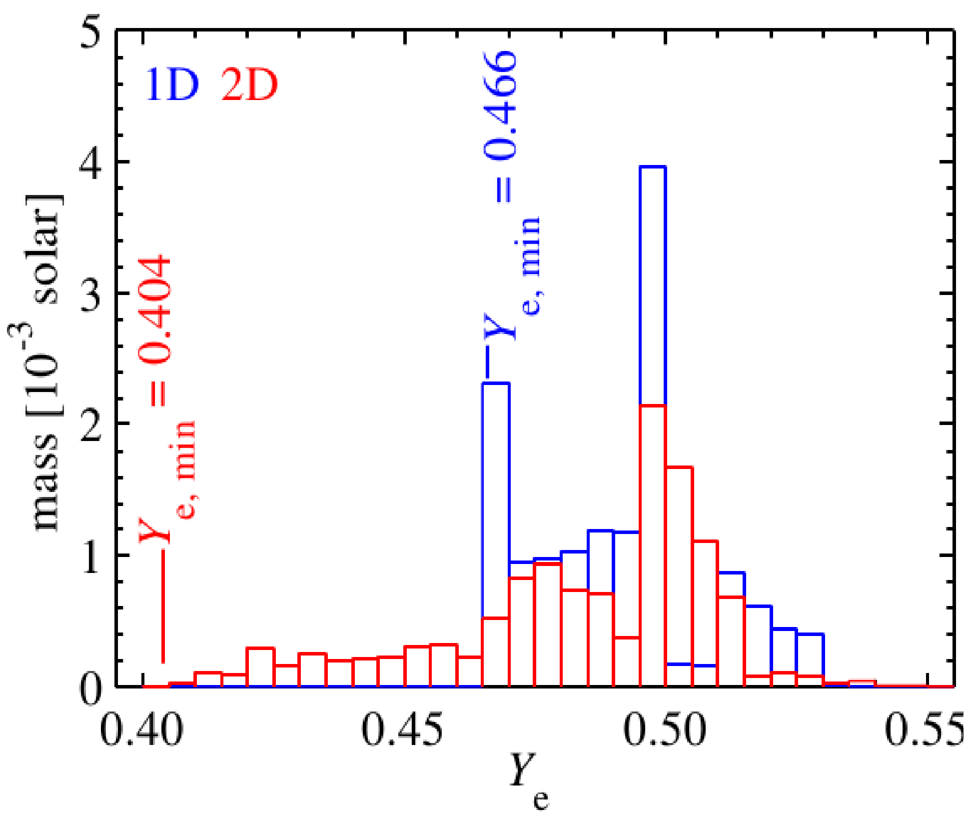
Individual Entropy Components

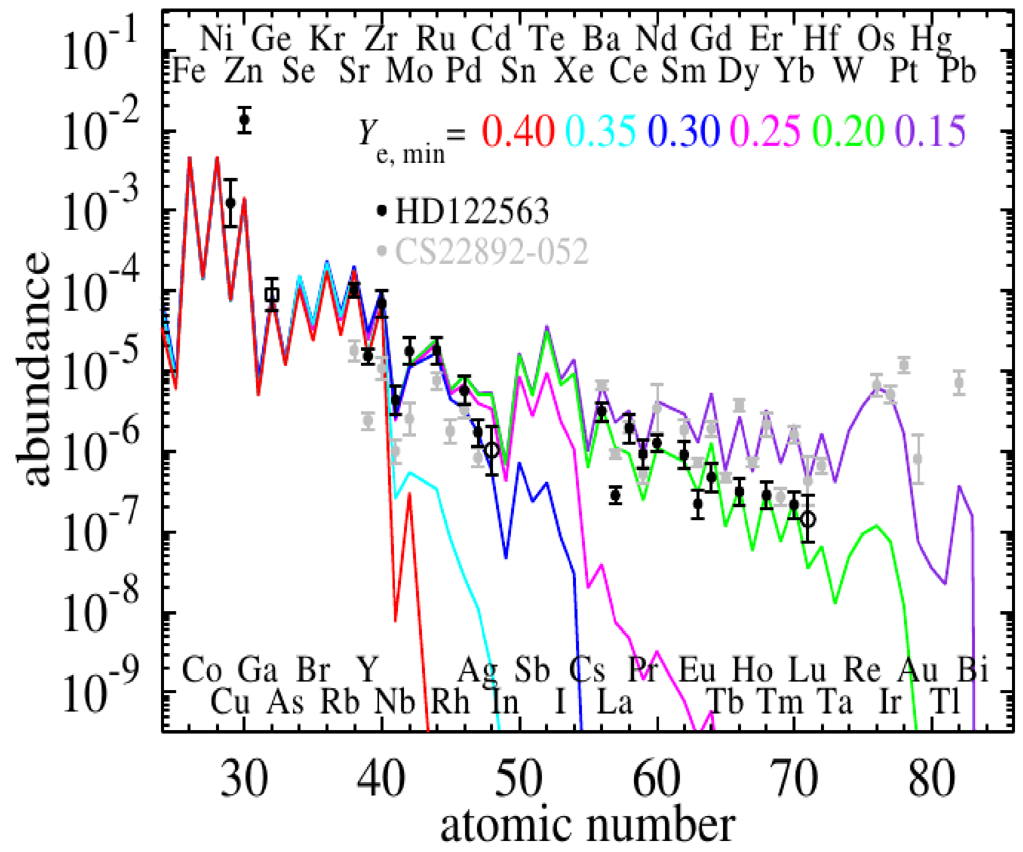
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in

such high entropies apparently not obtained!!!

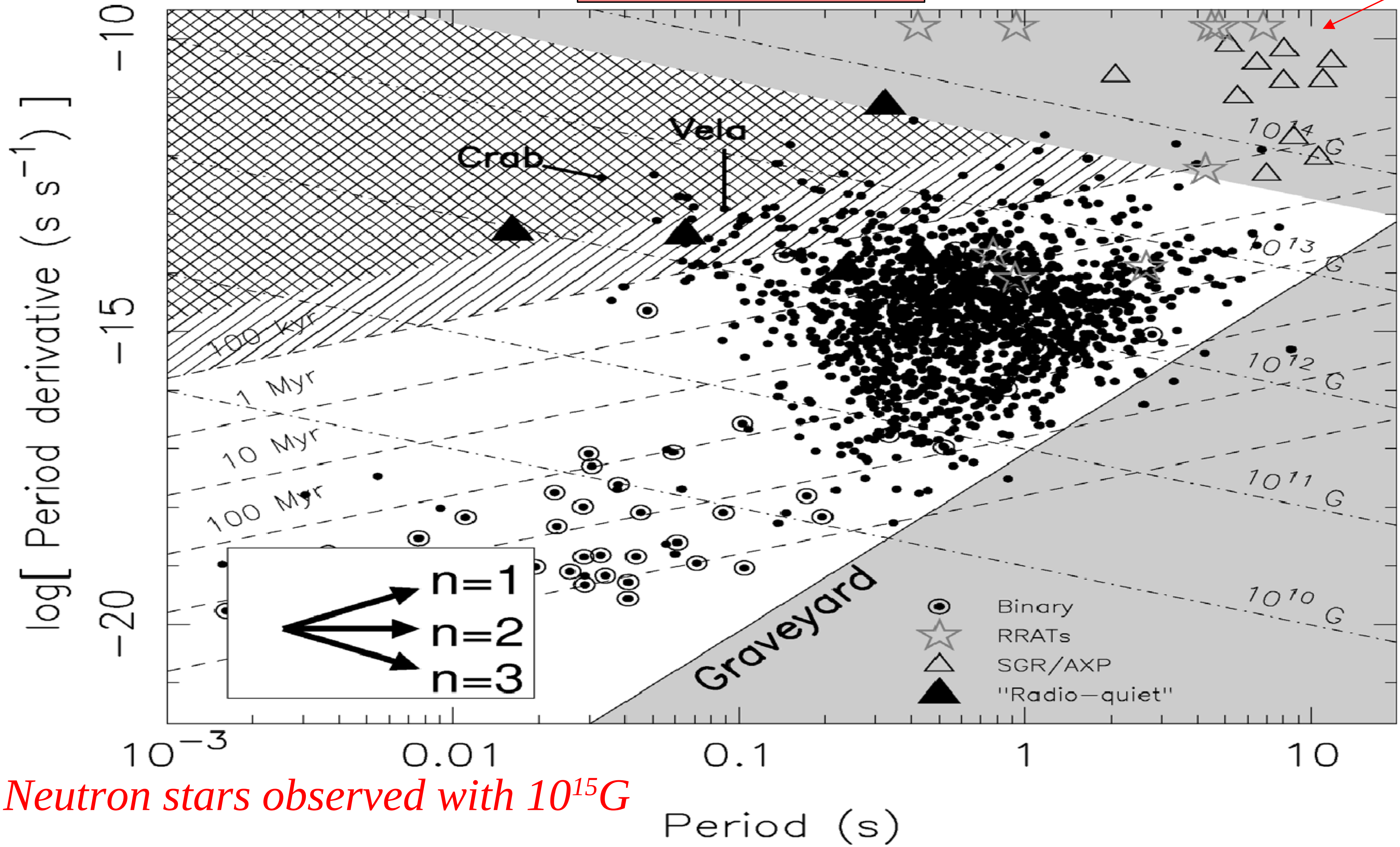


Wanajo & Janka 2011, EC Supernovae in 1 and 2D





M. Kramer (2009)



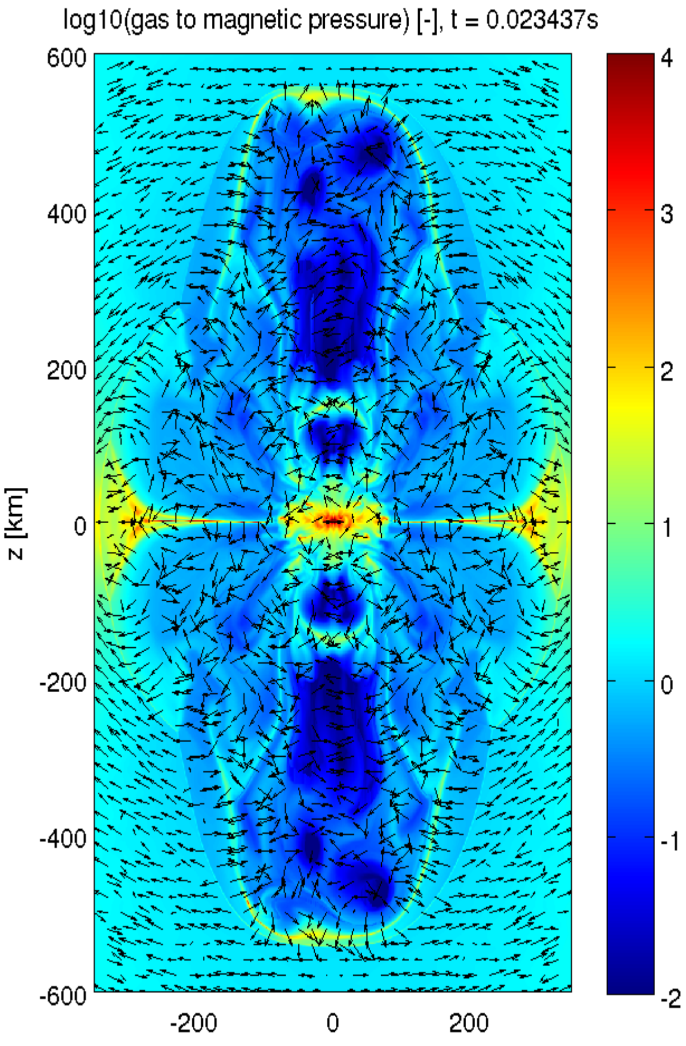
Neutron stars observed with 10^{15}G

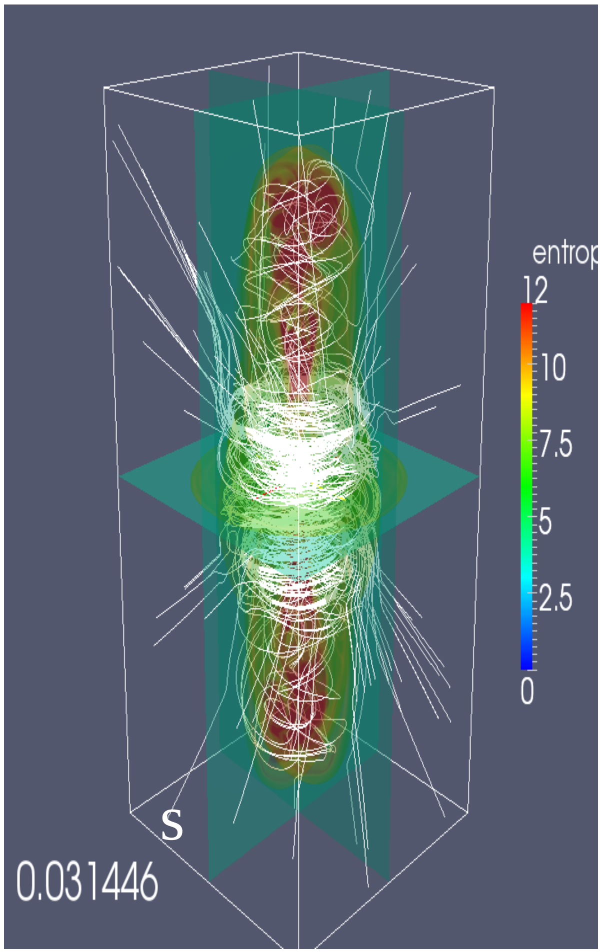
Figure 2. The P–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, 'radio-quiet' pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age τ_c and magnetic field B are also shown. The single hashed region shows 'Vela-like'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

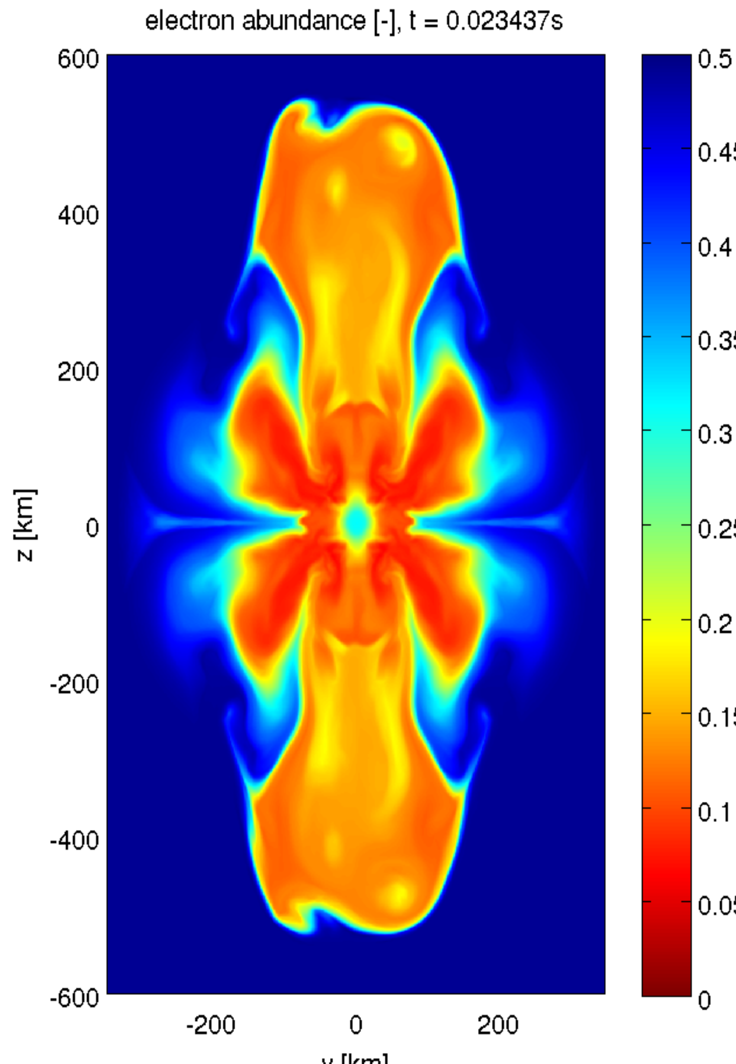
3D Collapse of Fast Rotator with Strong Magnetic Fields:

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

results in 10^{15} Gauss neutron star





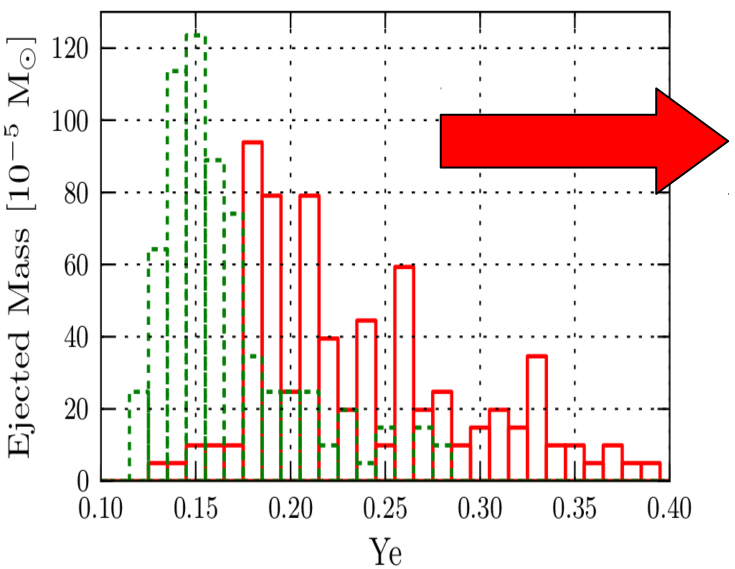


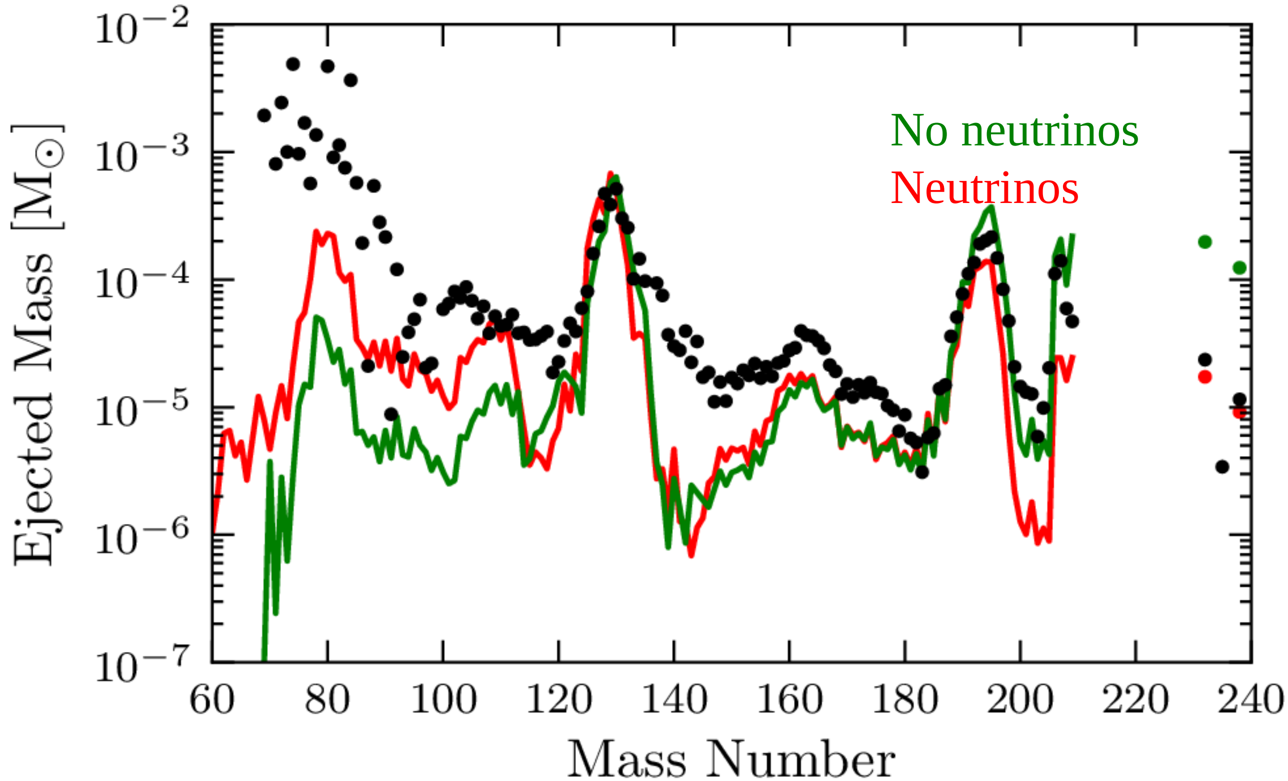
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012
Eichler et al. 2013

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?

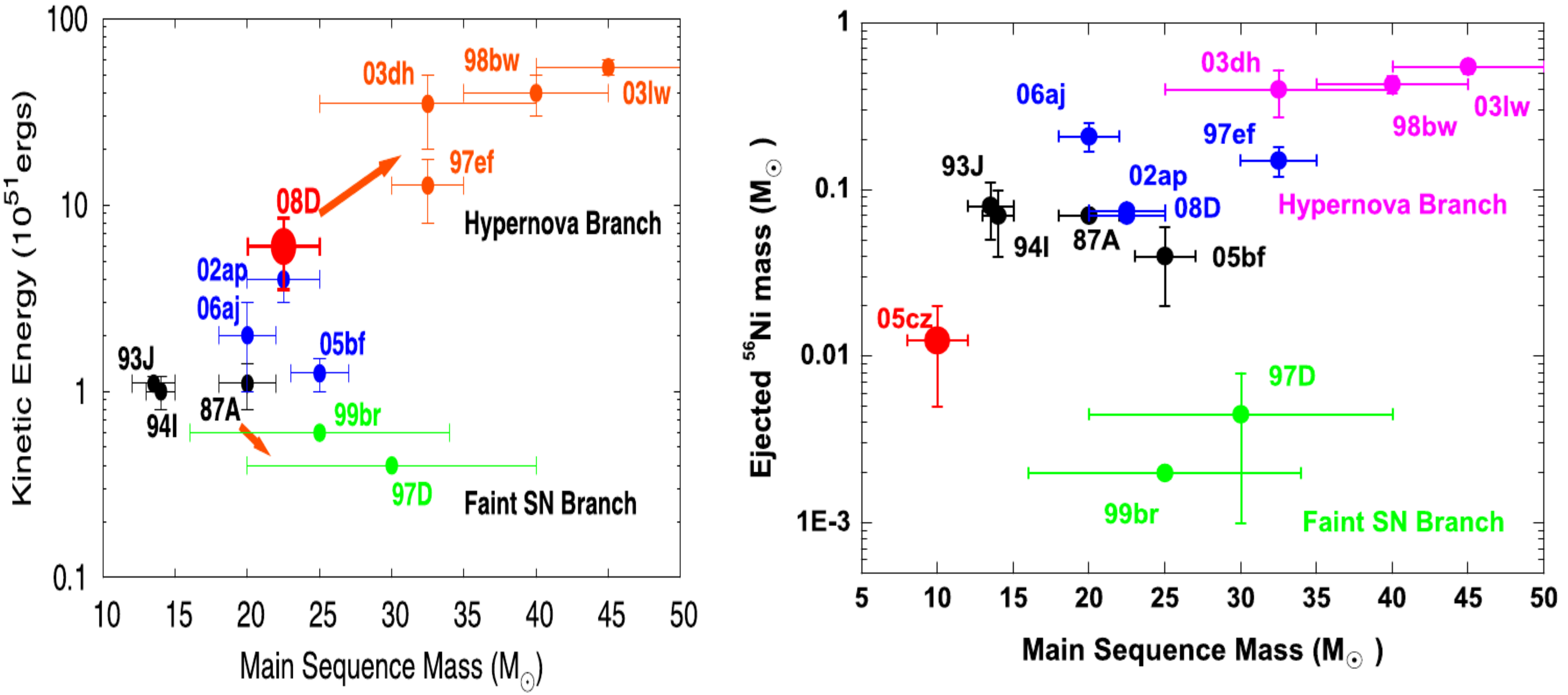
Nucleosynthesis beyond Fe more complicated than originally envisioned (r- and p-process).

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..

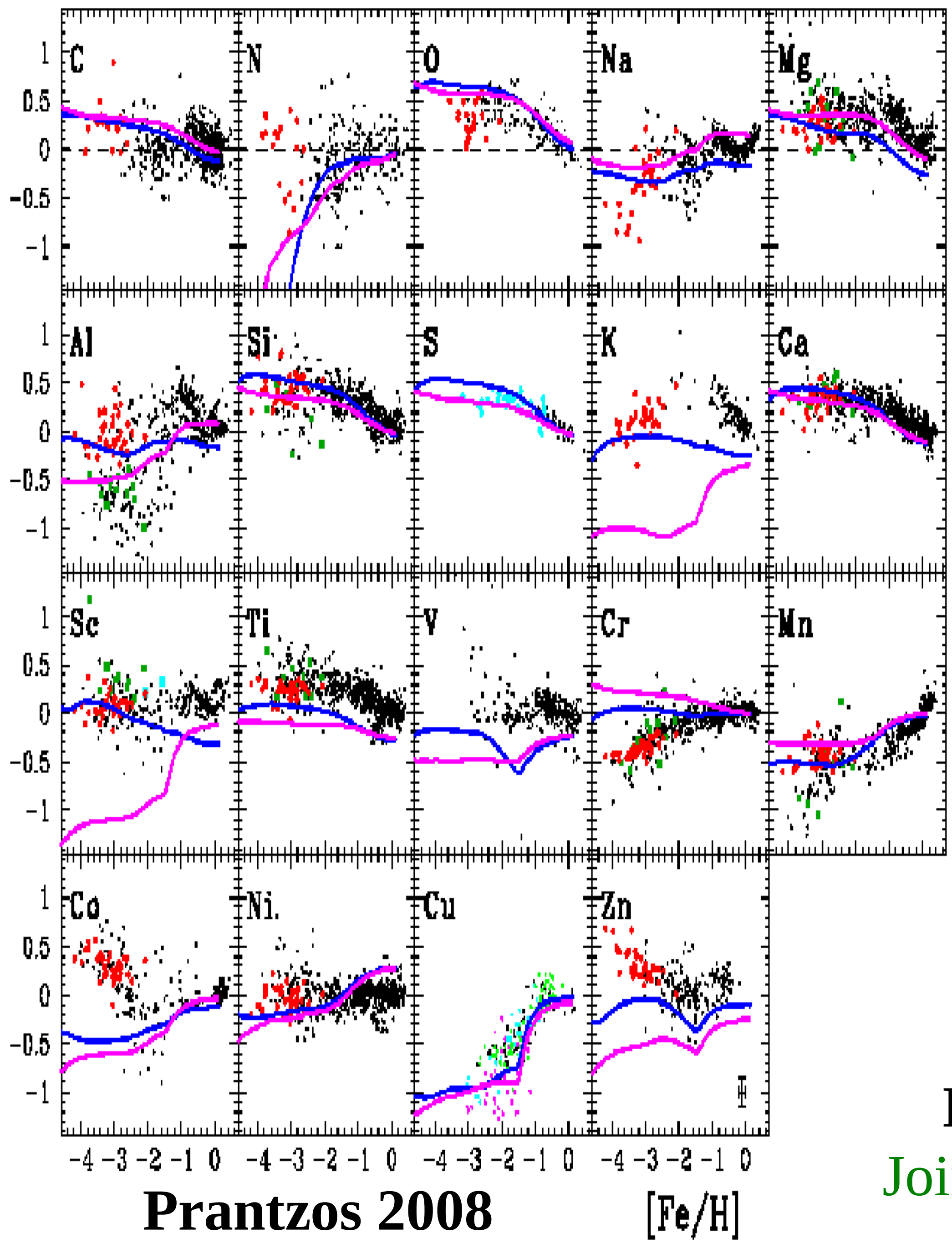
Also the r-process comes in at least two versions (weak-main/strong). Weak r-process possible in EC SNe (and Quark-Hadron EoS SNe). Any chance to become neutron-rich in the late neutrino wind?

The main/strong r-process site still open? Rotating core collapse events with jet ejection? Primary ^{22}Ne neutron source in rotating models with shear motion combined with supernova shock wave? Neutrino-induced effects in outer layers?

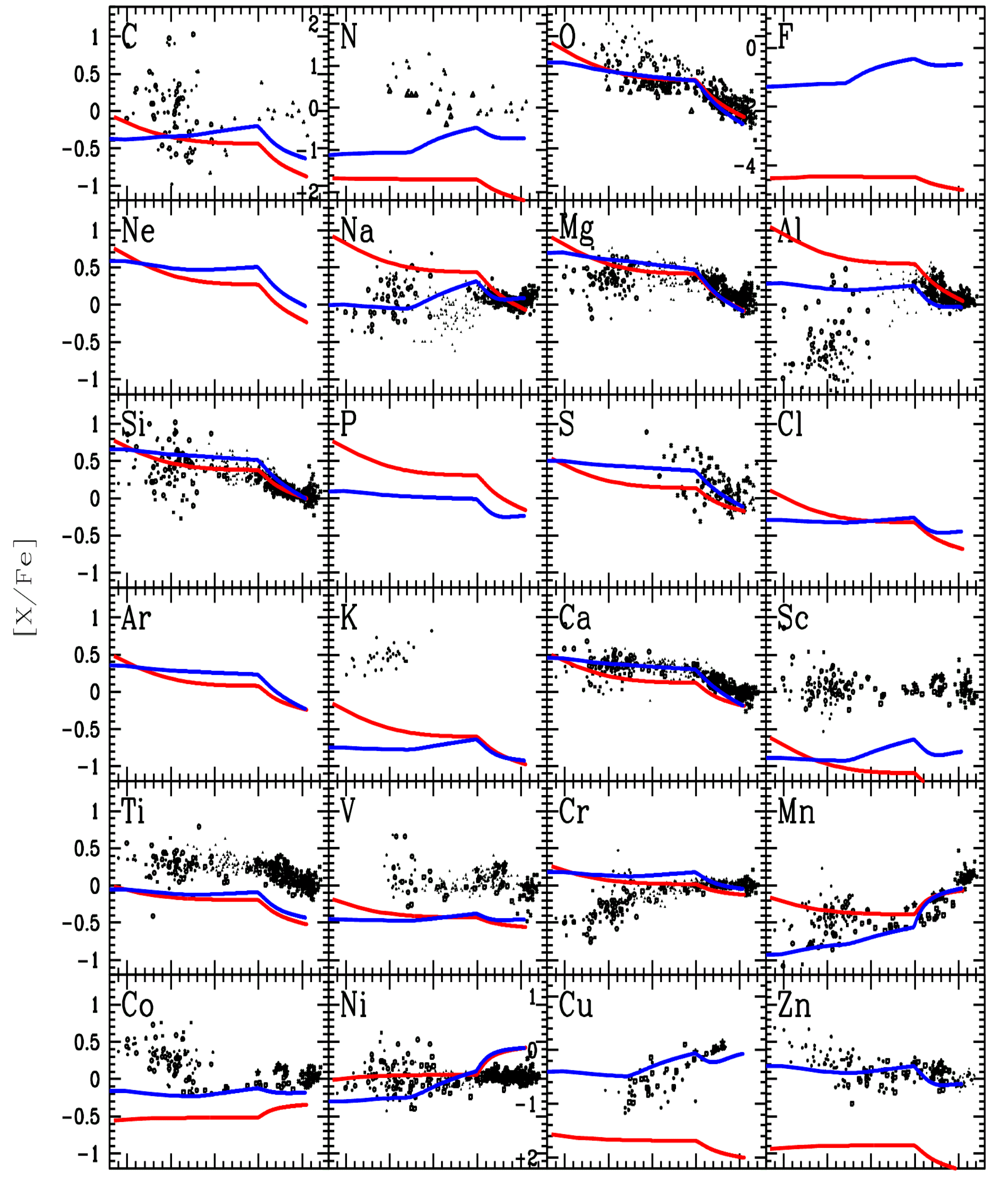
Transition Supernovae to Faint Supernovae and Hypernovae



Nomoto et al. (2011)



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)

Positive conspiracy among supernova yields which could lead to understanding small variations in alpha/Fe ratios in low metallicity stars (apparently originating from progenitors with different masses)?

- **O and Mg (from stellar evolution) increase with stellar mass**
- **Si, S, Ar, Ca, Ti (and also Ni/Fe) increase with supernova explosion energies**
- ***if explosion energies increase with progenitor mass (up to black hole formation transition), one would expect an overall increase of all alpha-elements with Fe/Ni and thus expect comparable alpha/Fe ratios for different progenitor masses.***