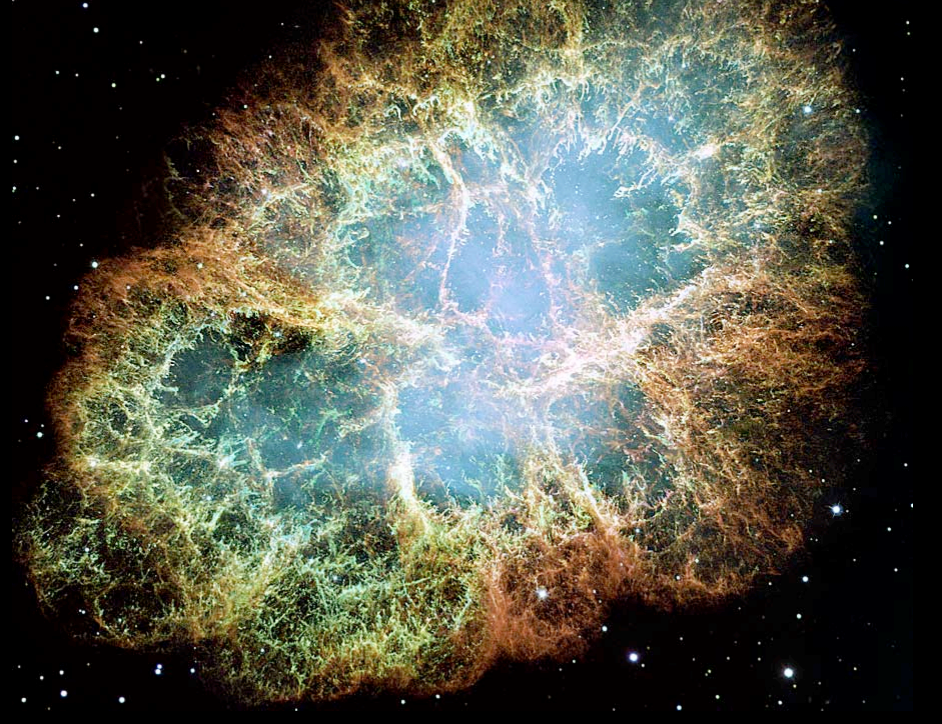
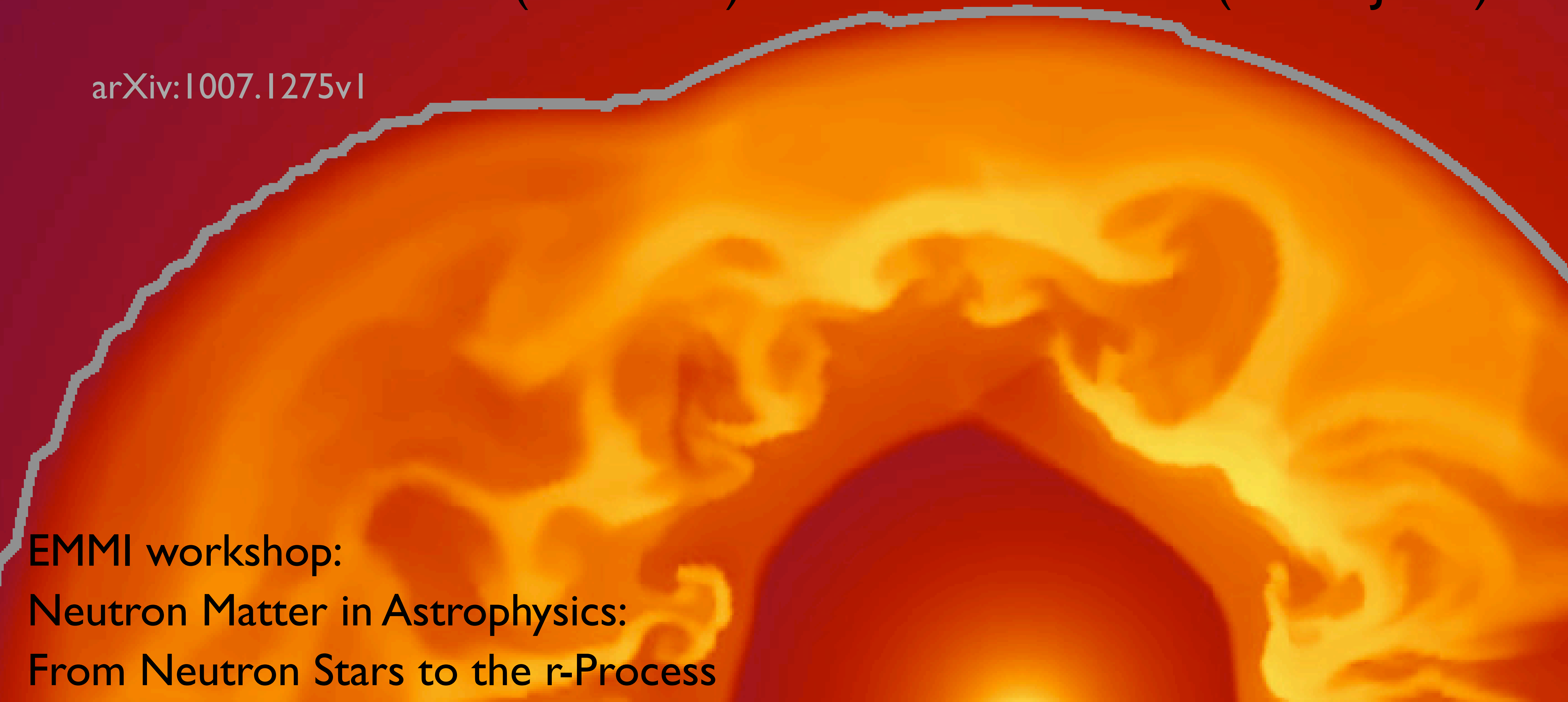
Origin of the LEPP nuclei in supernovae



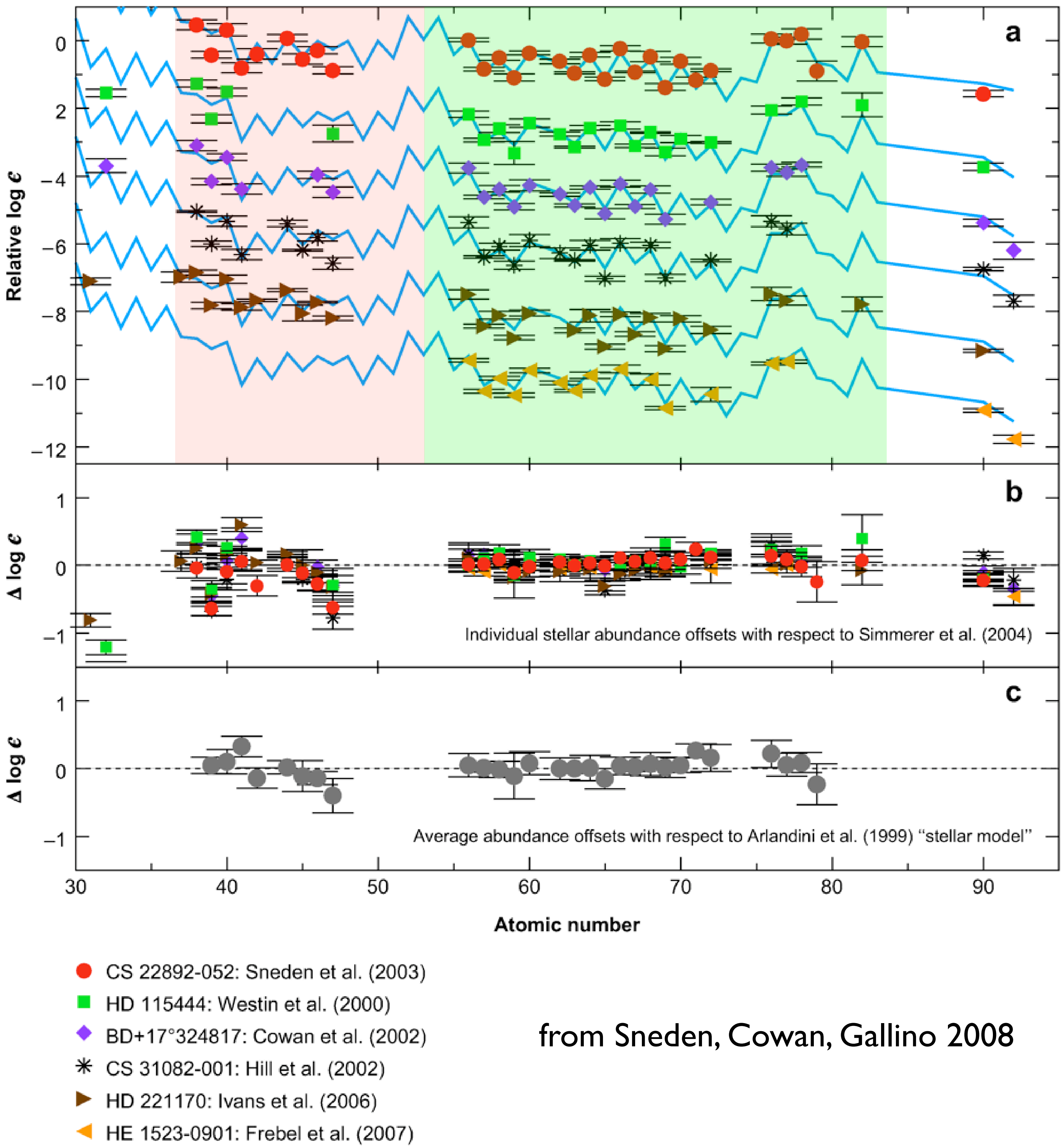
Almudena Arcones (Uni Basel) & Fernando Montes (NSCL/JINA)



arXiv:1007.1275v1

EMMI workshop:
Neutron Matter in Astrophysics:
From Neutron Stars to the r-Process

Observations



from Sneden, Cowan, Gallino 2008

Abundances of "r-process" elements: r-process-rich galactic halo (old) stars vs. Solar system abundances (r-process only)

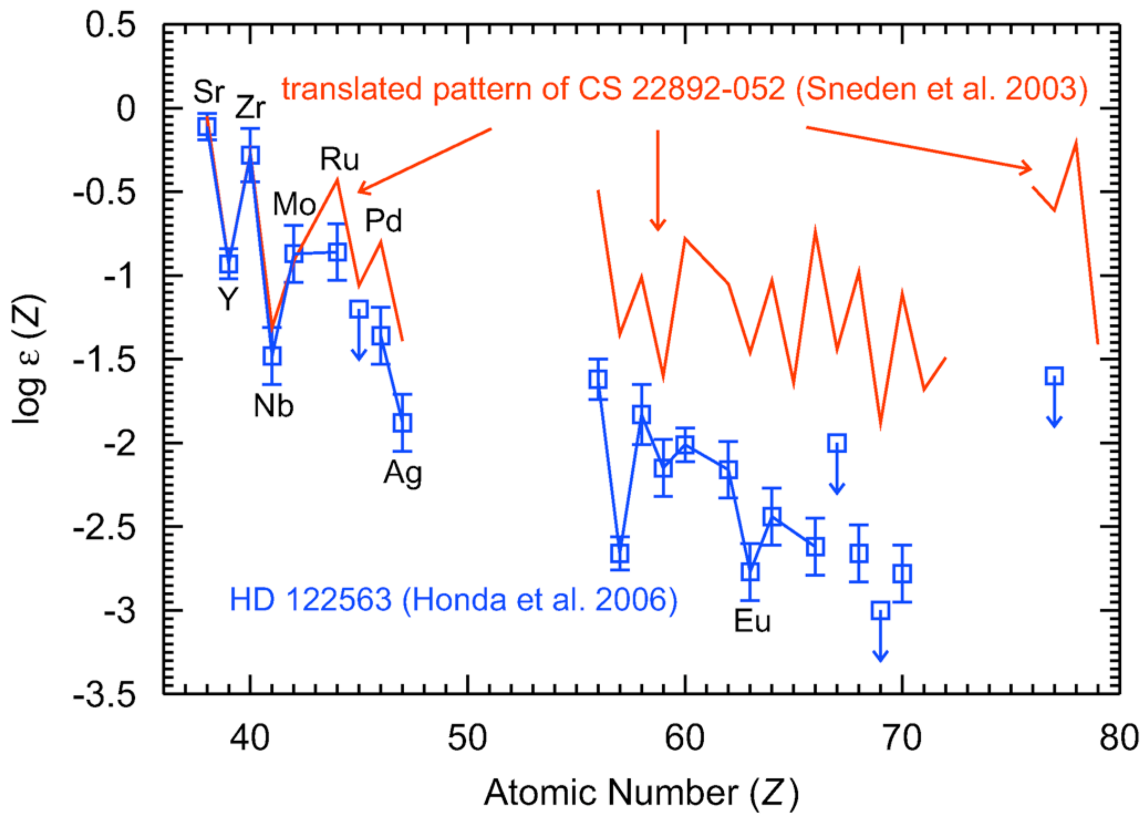
Only few nucleosynthesis events have contributed to the abundances present in old stars.

Robust r-process for 56<Z<83 but some scatter for Z<47

Suggestive of two components or sites: Qian & Wasserburg 2001..., Truran et al. 2002, Travaglio et al. 2004, Aoki et al. 2005, Otsuki et al. 2006.

Two components of heavy element nucleosynthesis

Qian & Wasserburg: developed a model based on stars with high and low enrichment of heavy r-nuclei.



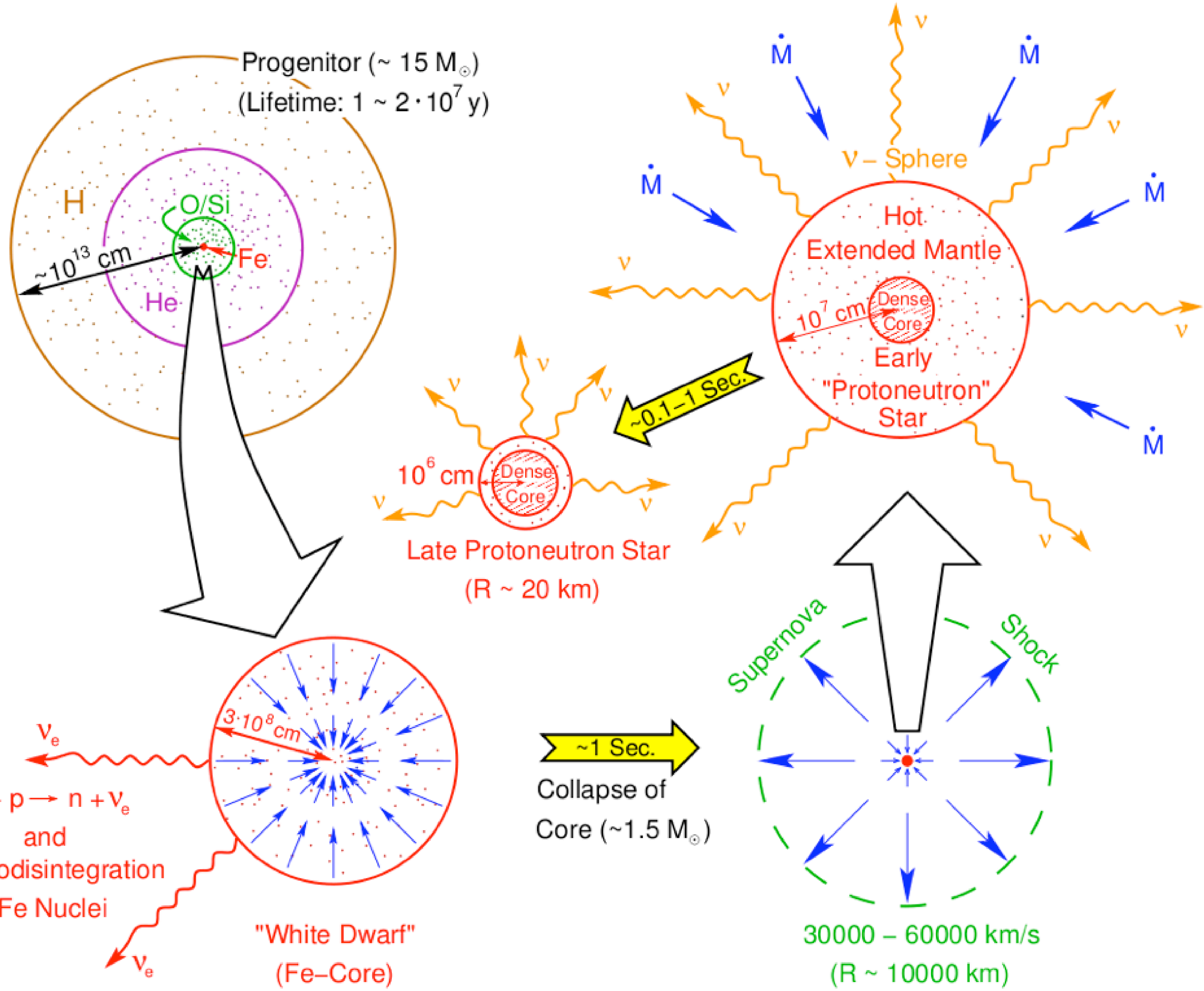
- In neutrino-driven winds when a neutron star forms, charged-particle reactions (CPR) produce nuclei with A~90-110 (Z<47).
- Observations of low-metallicity stars show that sites producing heavy r-nuclei do not produce Fe or any other elements between N and Ge. This suggest that heavy r-nuclei with A>130 (56<Z<83) cannot be produced in every neutrino-driven wind.

Travaglio et al 2004: Light Element Primary Process: LEPP = solar − r-process − s-process

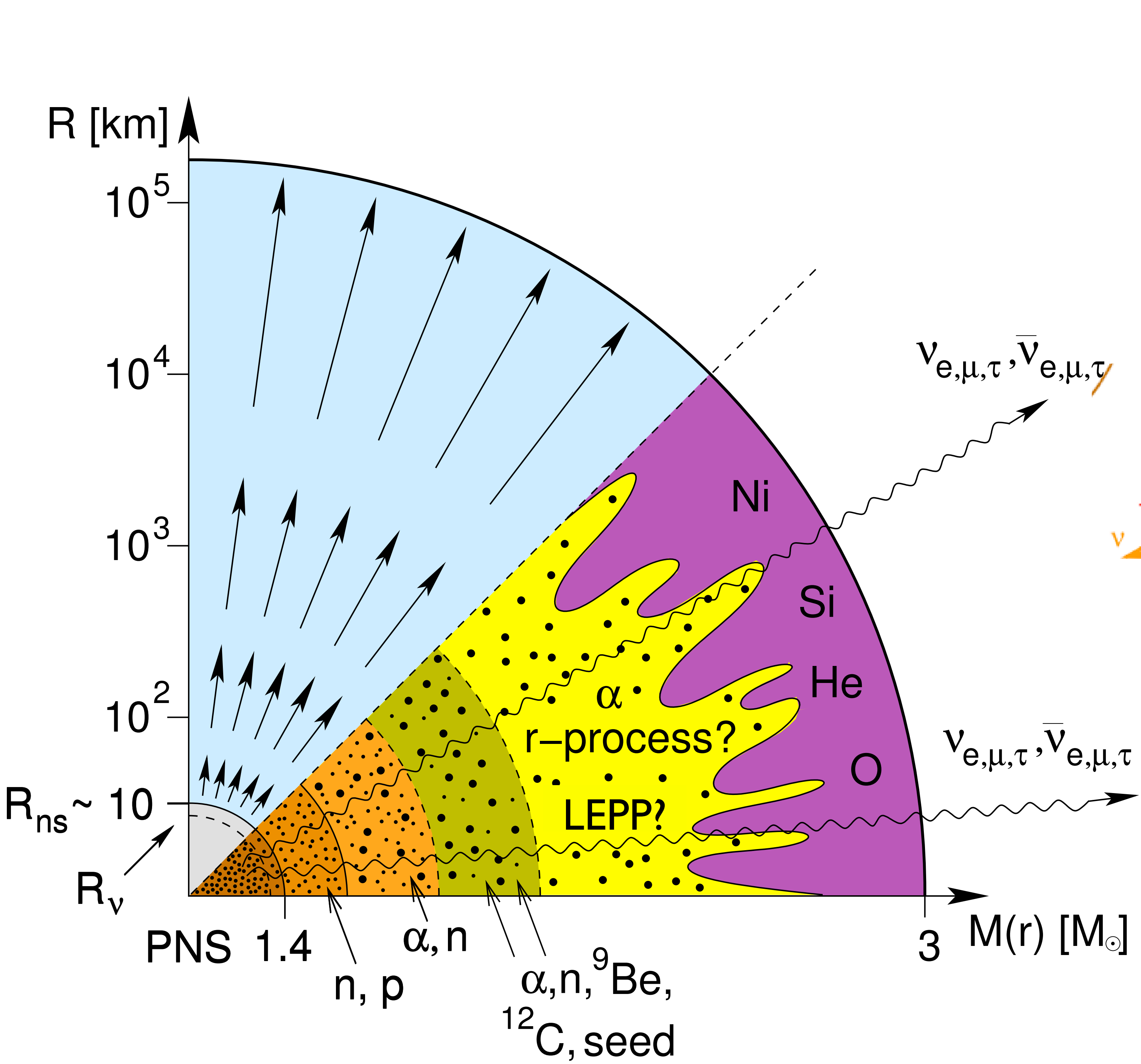
Montes et al. 2007: LEPP creates a uniform and unique pattern

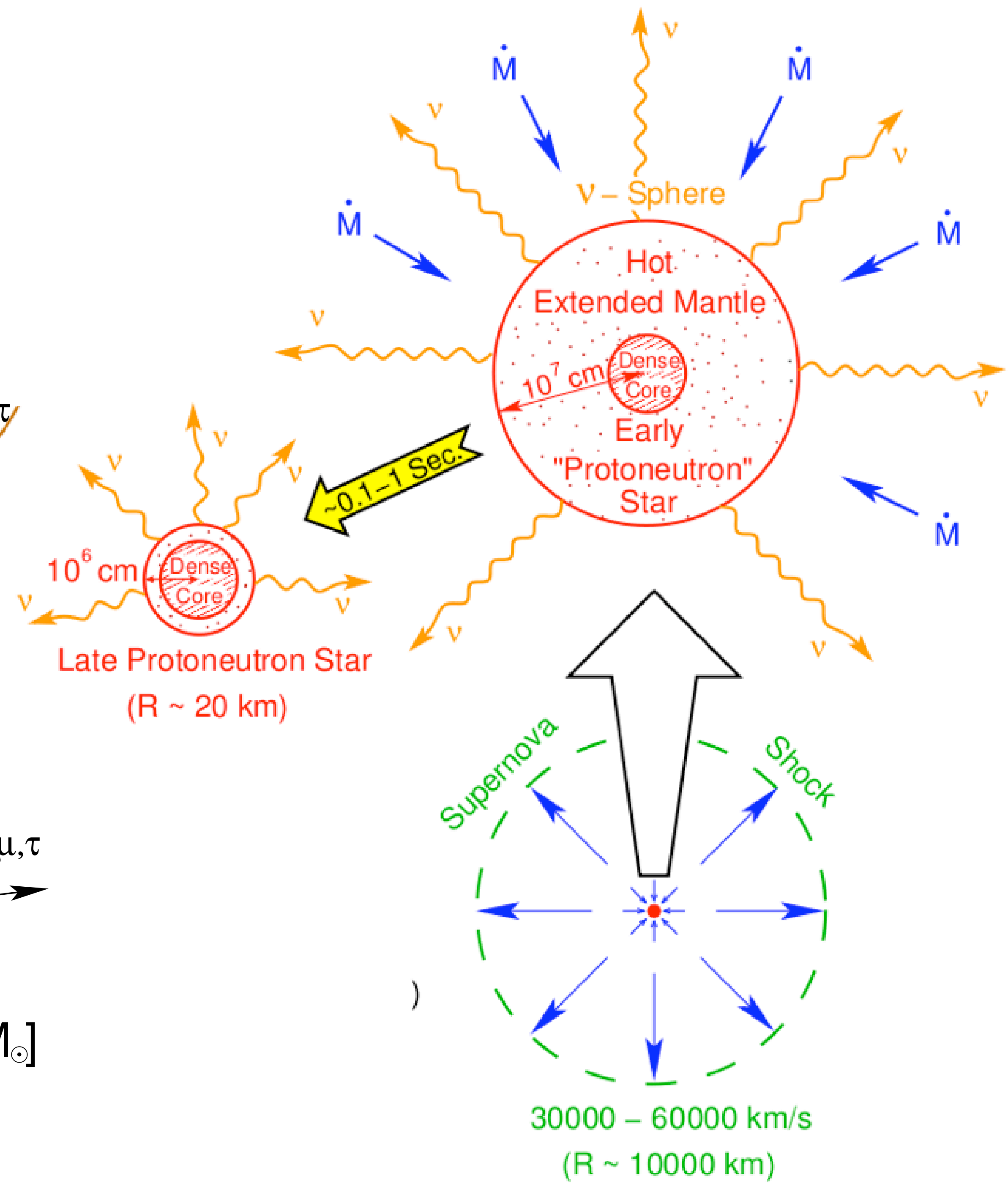
Can this be confirmed by state-of-the-art neutrino-driven wind simulations?
Do supernovae produce the LEPP pattern?

Core-collapse supernovae



Neutrino-driven wind





Neutrino-driven wind simulations and nucleosynthesis networks

Simulations of core-collapse supernovae and the subsequent neutrino-driven winds

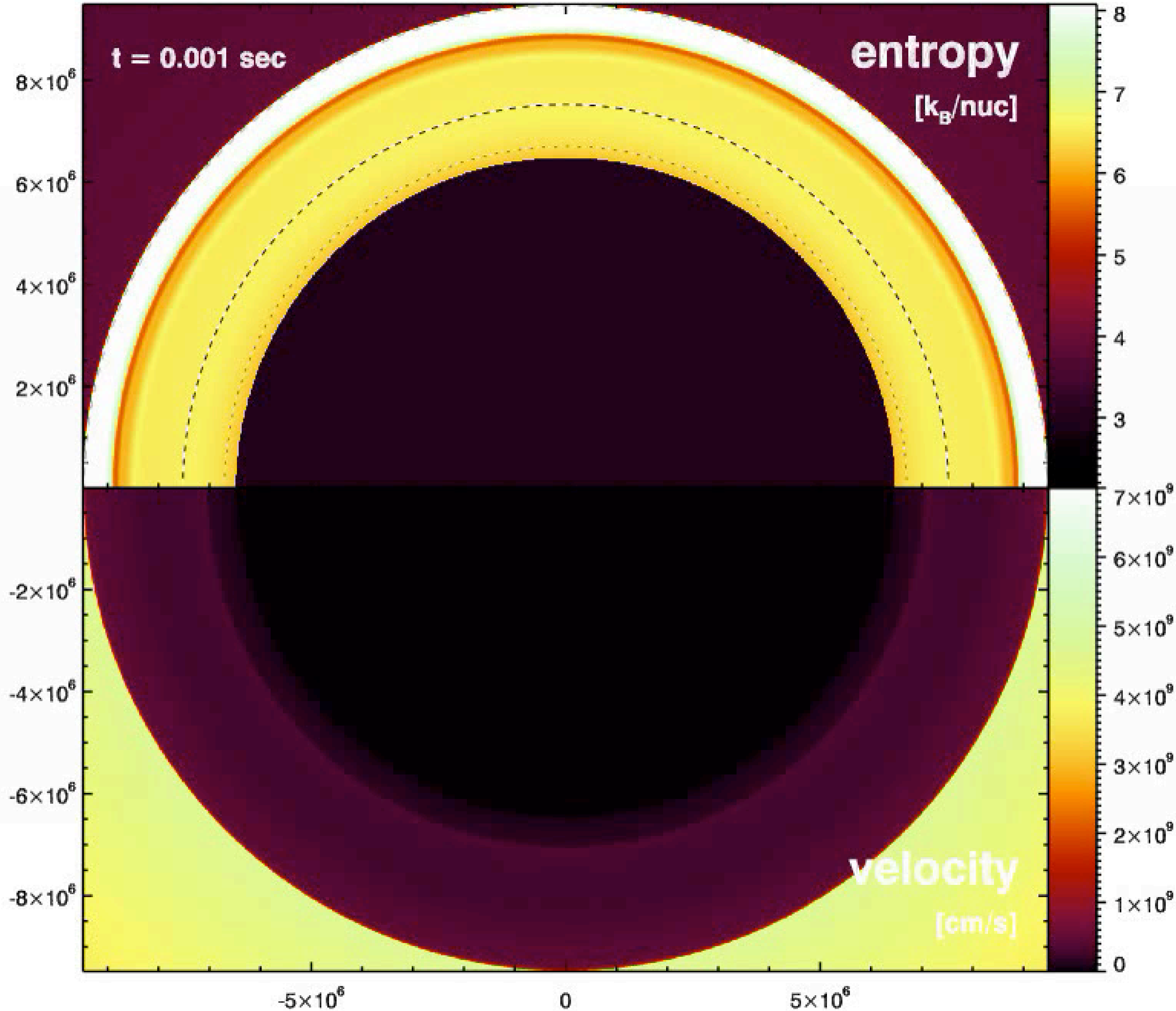
Problems: - explosion mechanism
- simulations are computationally very expensive to follow the wind phase

Solutions: - steady-state wind models (Otsuki et al. 2000, Thompson el al. 2001, Wanajo)
- one-dimensional simulations with an artificial explosion (Arcones et al. 2007 (also 2d), Fischer et al. 2009)

Nucleosynthesis network including over 5000 nuclei from stability to drip lines

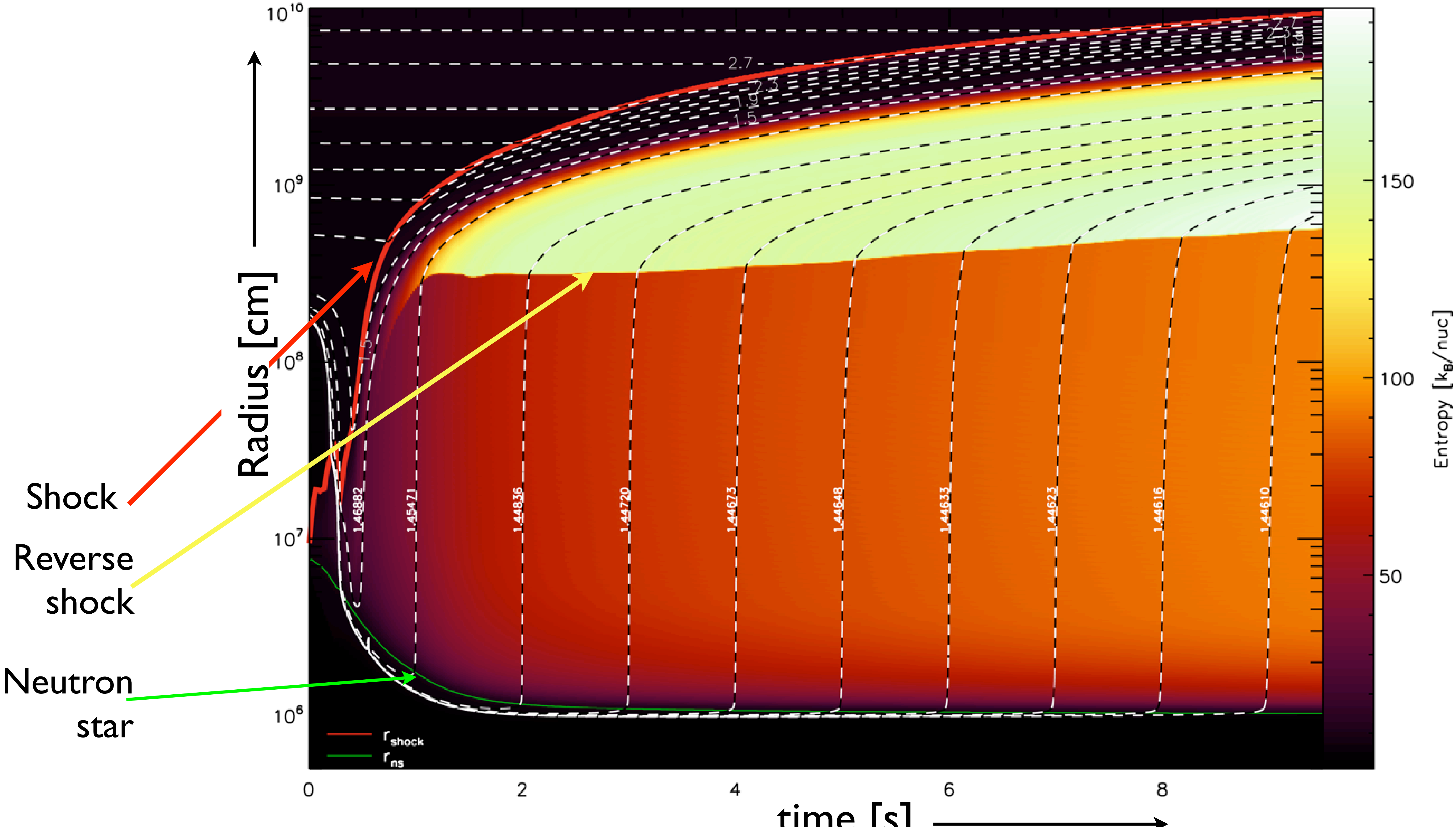
- Network input: trajectories (ρ,T) from hydrodynamical simulations + initial Y_e.
- Starting composition at 10GK is given by nuclear statistical equilibrium (NSE).
- Extended nuclear reaction network including neutral and charged particle reactions from REACLIB (Fröhlich et al. 2006), and weak-reaction rates (Fuller et al. 1999, Langanke & Martinez-Pinedo 2000).

Arcones & Janka (in prep.)



Neutrino-driven wind results

Arcones et al 2007



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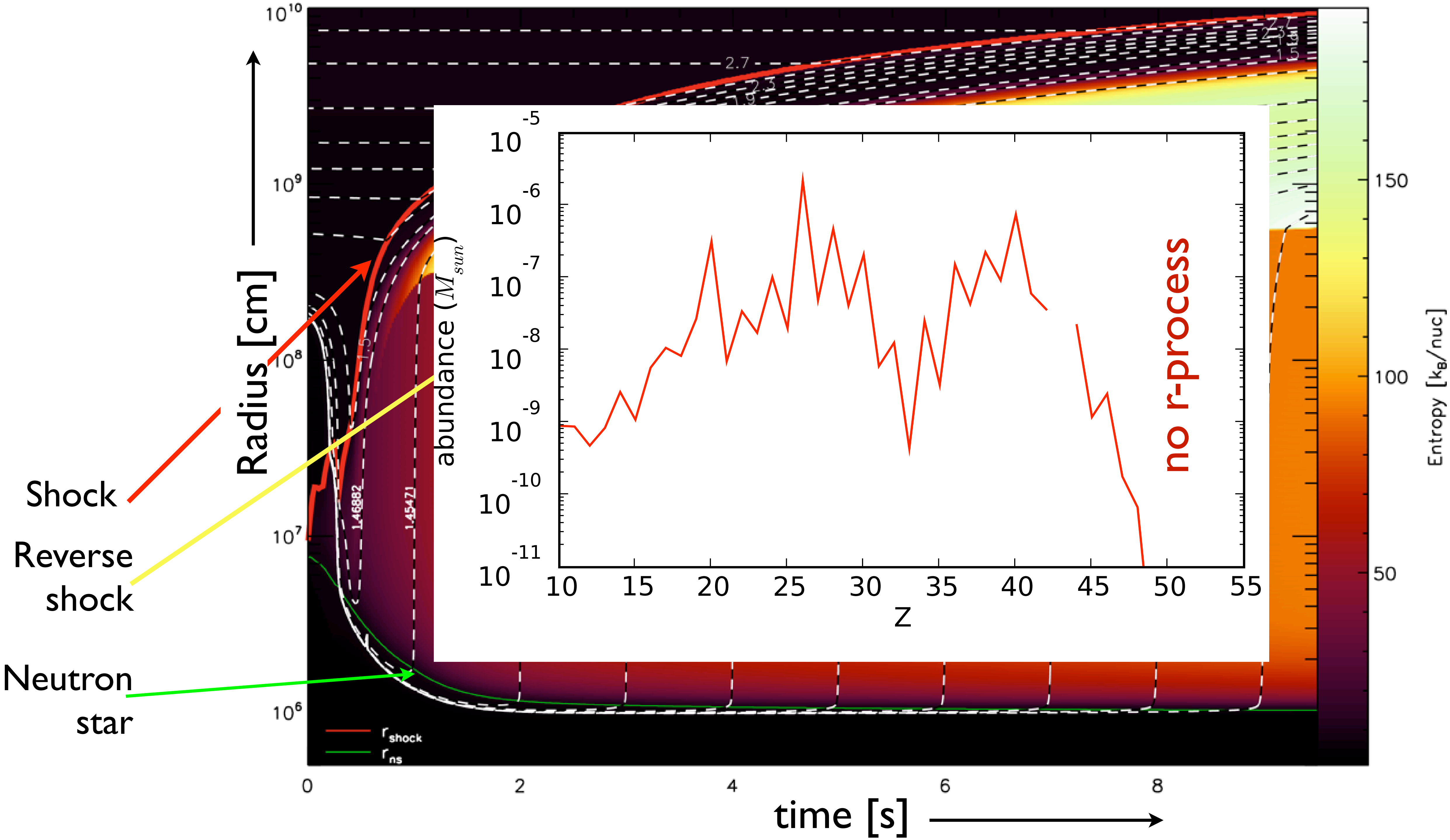
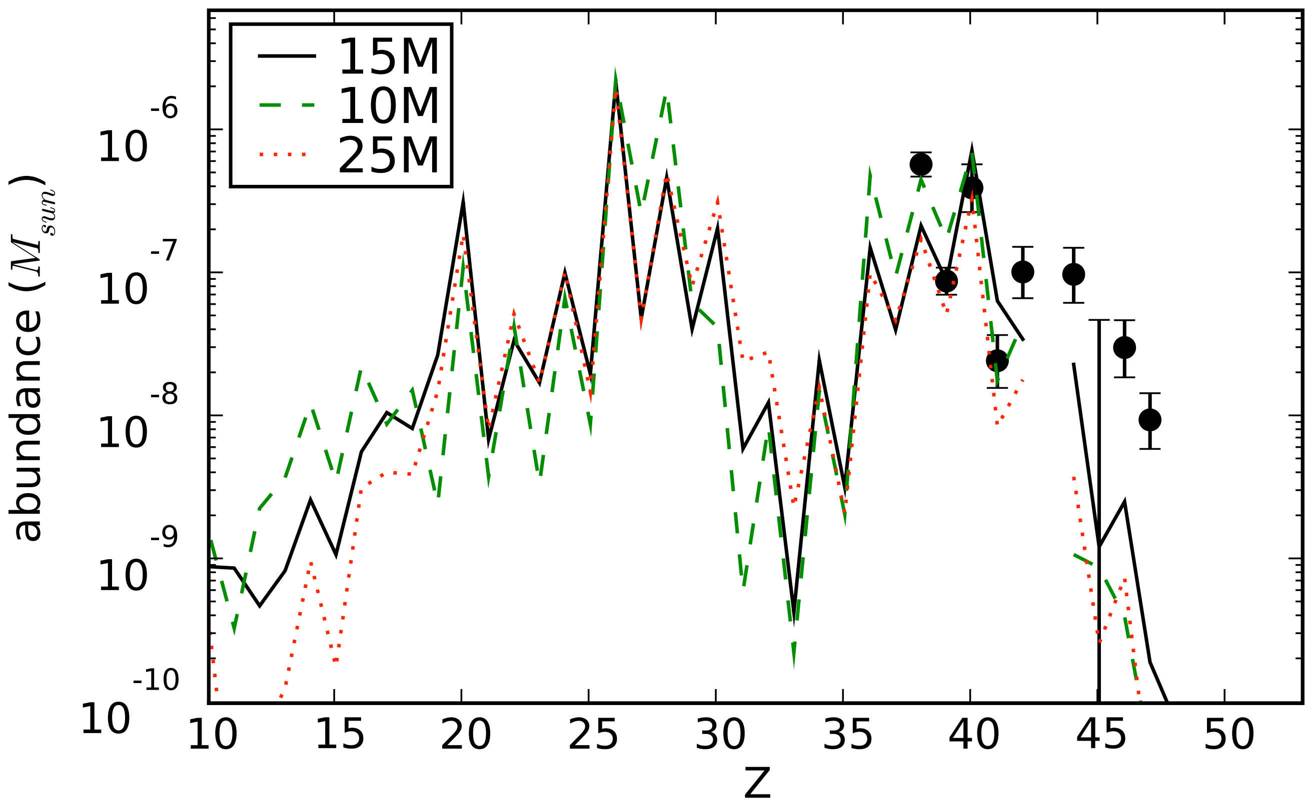
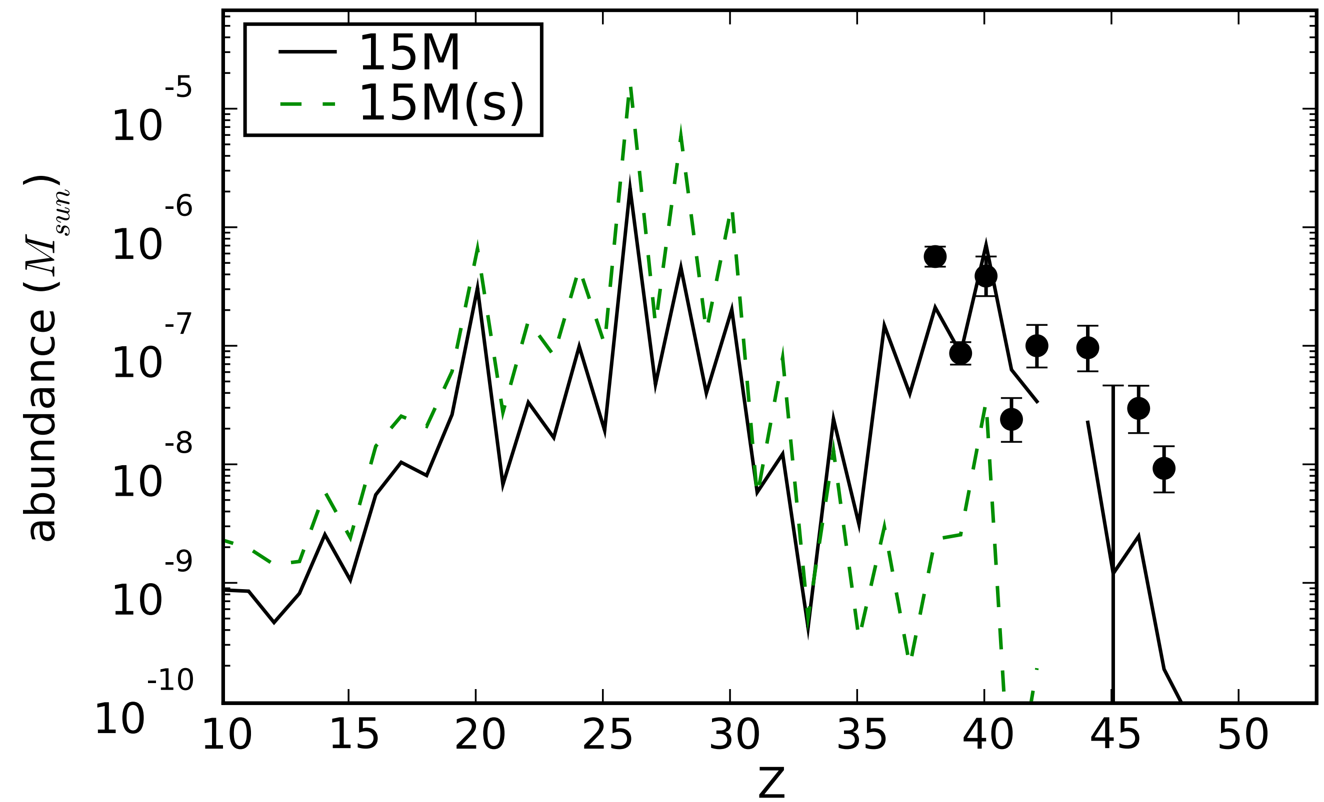


Nucleosynthesis results

Integrated abundances based on the neutrino-driven wind trajectories compared to LEPP pattern (Montes et al. 2007)

LEPP elements are produced, but no heavy r-nuclei (Arcones & Montes, submitted).





Progenitor variation with same proto-neutron star evolution (cooling and contraction).

Variation of proto-neutron star evolution:
- 15M(s): slow contraction to 15km, S≈50k_B/nuc
- 15M: fast contraction to 11km, S≈80k_B/nuc

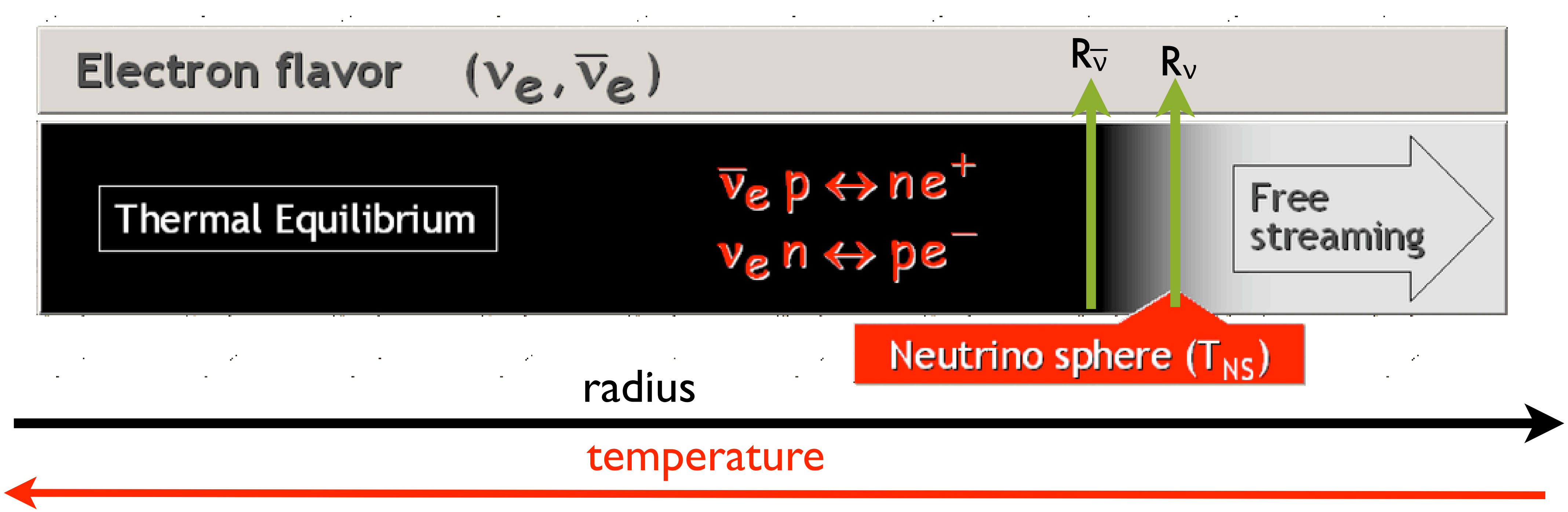
Electron fraction and uncertainties

Electron fraction depends on accuracy of the supernova neutrino transport and on details of neutrino interactions in the outer layers of the neutron star.

$$Y_e = \frac{\lambda_{\nu_e,n}}{\lambda_{\nu_e,n} + \lambda_{\bar{\nu}_e,p}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\varepsilon_{\nu_e}}\right]^{-1}$$

($\Delta = m_n - m_p$)

The neutrino energies are determined by the position (temperature) where neutrinos decouple from matter: neutrinosphere



Raffelt 2001, ApJ, 561,890

$\epsilon_{\bar{\nu}} > \epsilon_{\nu}$

Light nuclei

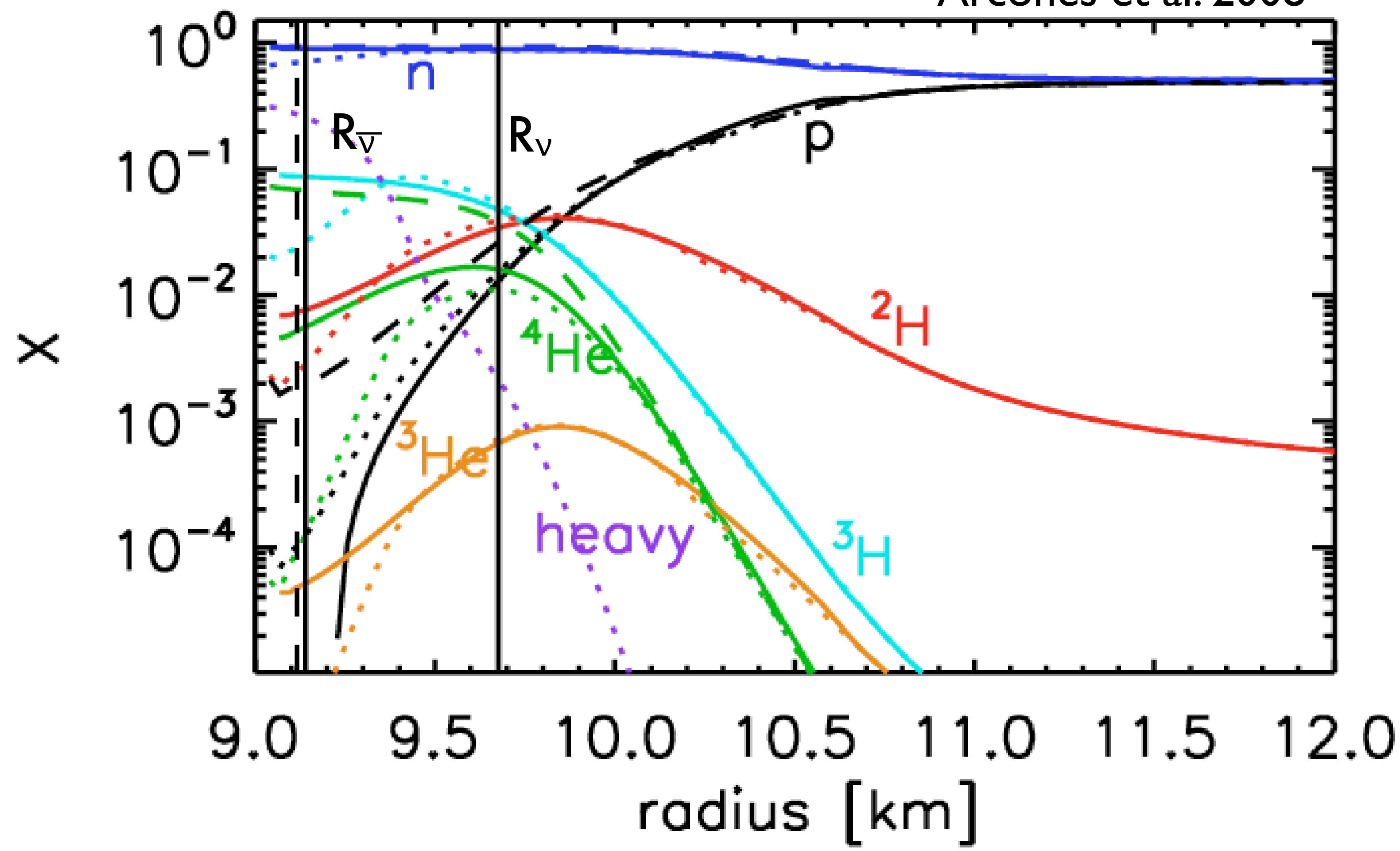
- The EOS used in supernova simulations include neutron, protons, alpha-particles, and a representative heavy nucleus (Lattimer & Swesty 1991, Shen et al. 1998, or EOS based on NSE). This is o.k. for low densities and high temperatures.

- However, they don't allow for the presence of light nuclei (A≤4) which are present for densities $\rho \approx 10^{12}$g/cm^3 (O'Connor et al. 2007, Sumiyoshi & Ropke 2008, Typel et al. 2009).

We have compared 3 EOS:

- non-interaction ideal gas of n,p,α (dashed lines)
- Virial (Horowitz & Schwenk 2006): nuclei with A≤4 and interactions (solid lines)
- NSE: several thousands nuclei (dotted lines)

Arcones et al. 2008



Light nuclei

• The EOS use … and a representative … sed on NSE). This is o…

• However, the … t for densities ρ≈10 … 2009).

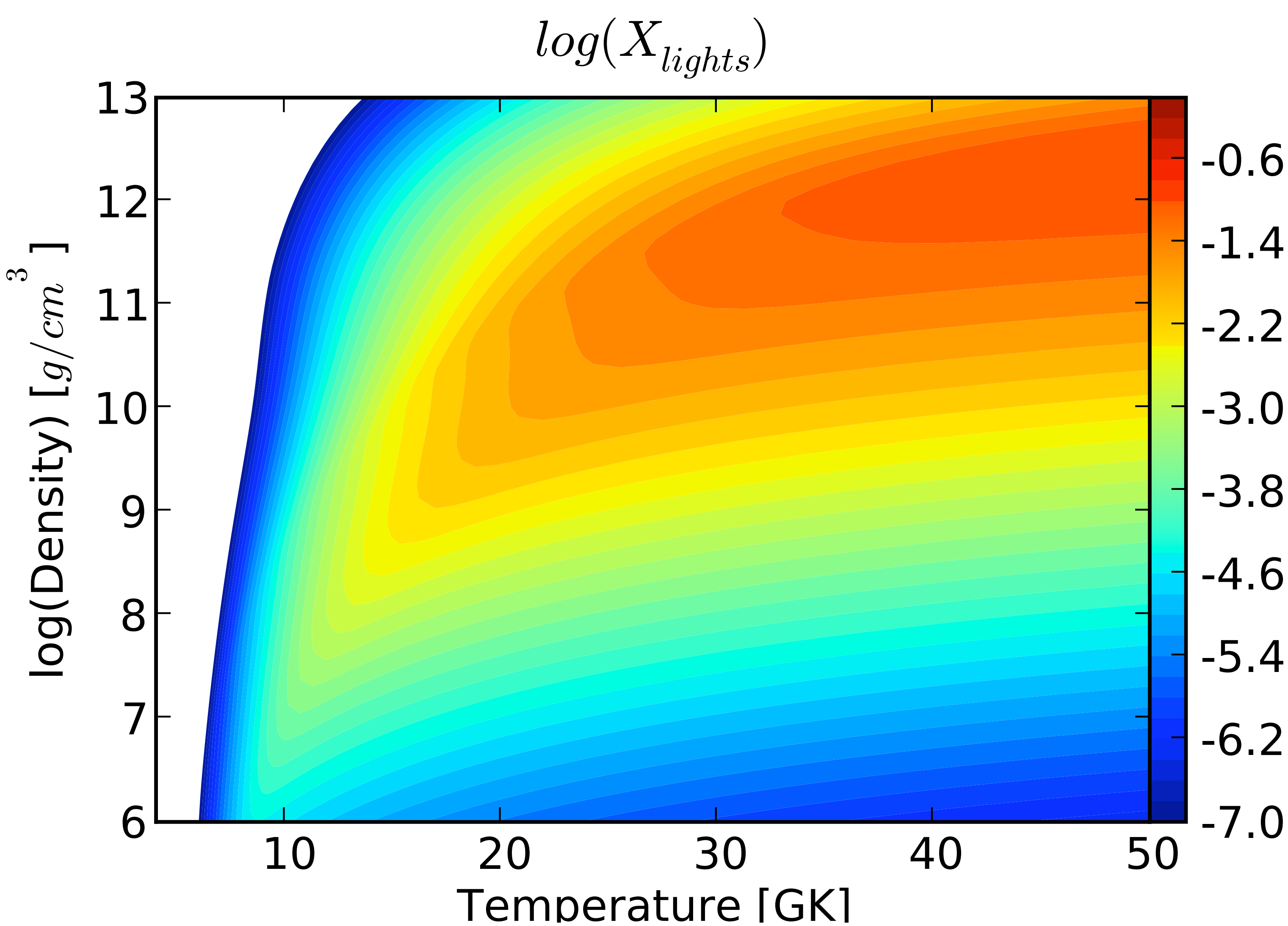
We have comp…

• non-interacti… (dashed lines)

• Virial (Horow… nuclei with A≤… (solid lines)

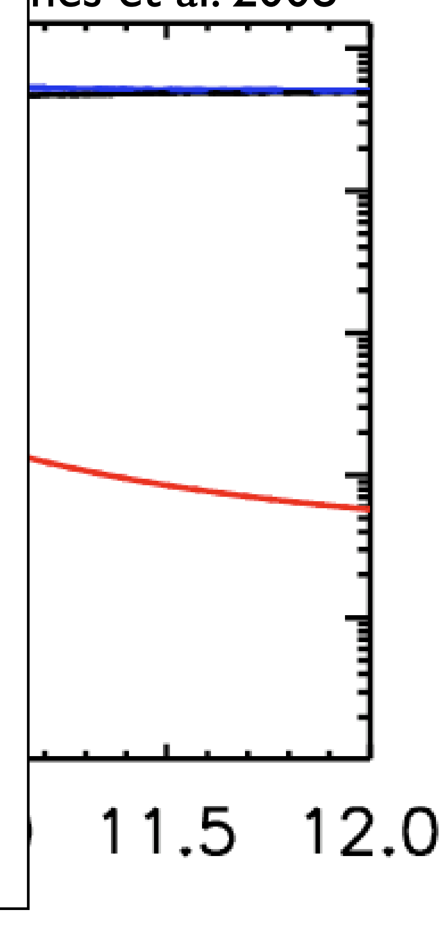
• NSE: several … (dotted lines)

Under general assumptions (NSE+beta equilibrium) 1<A<4



Arcones, Martinez-Pinedo, Roberts, Woosley 2010

…nes et al. 2008



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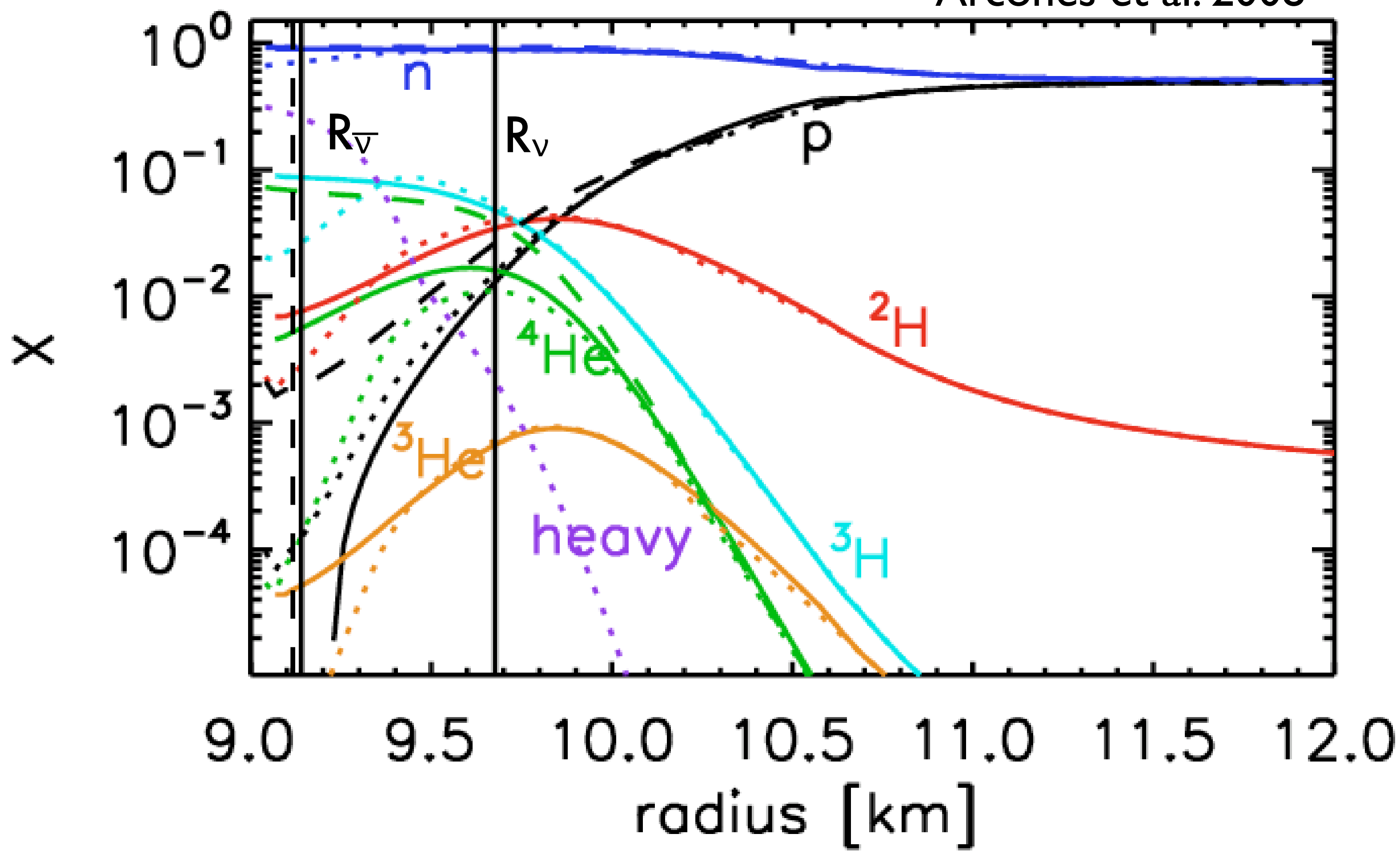
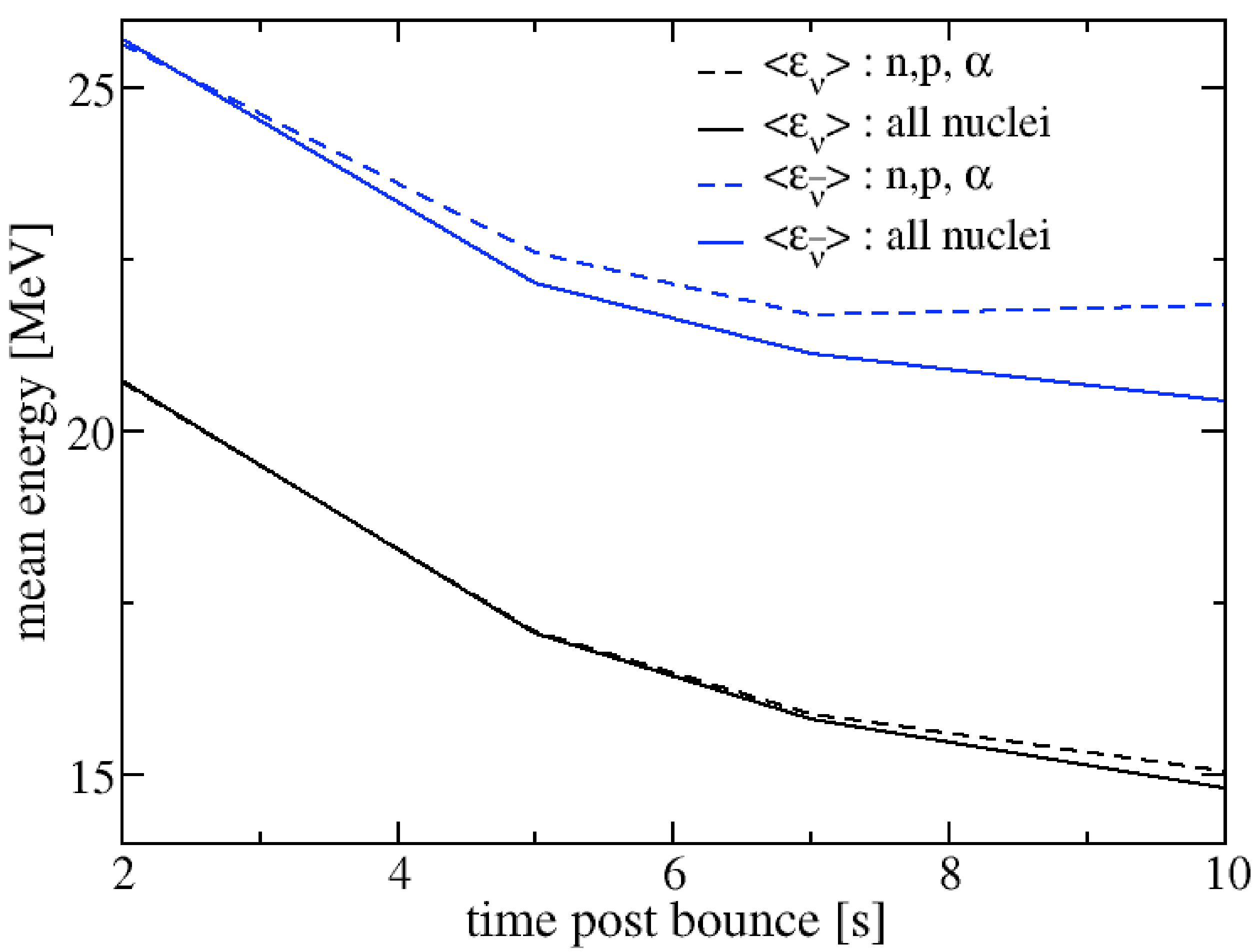
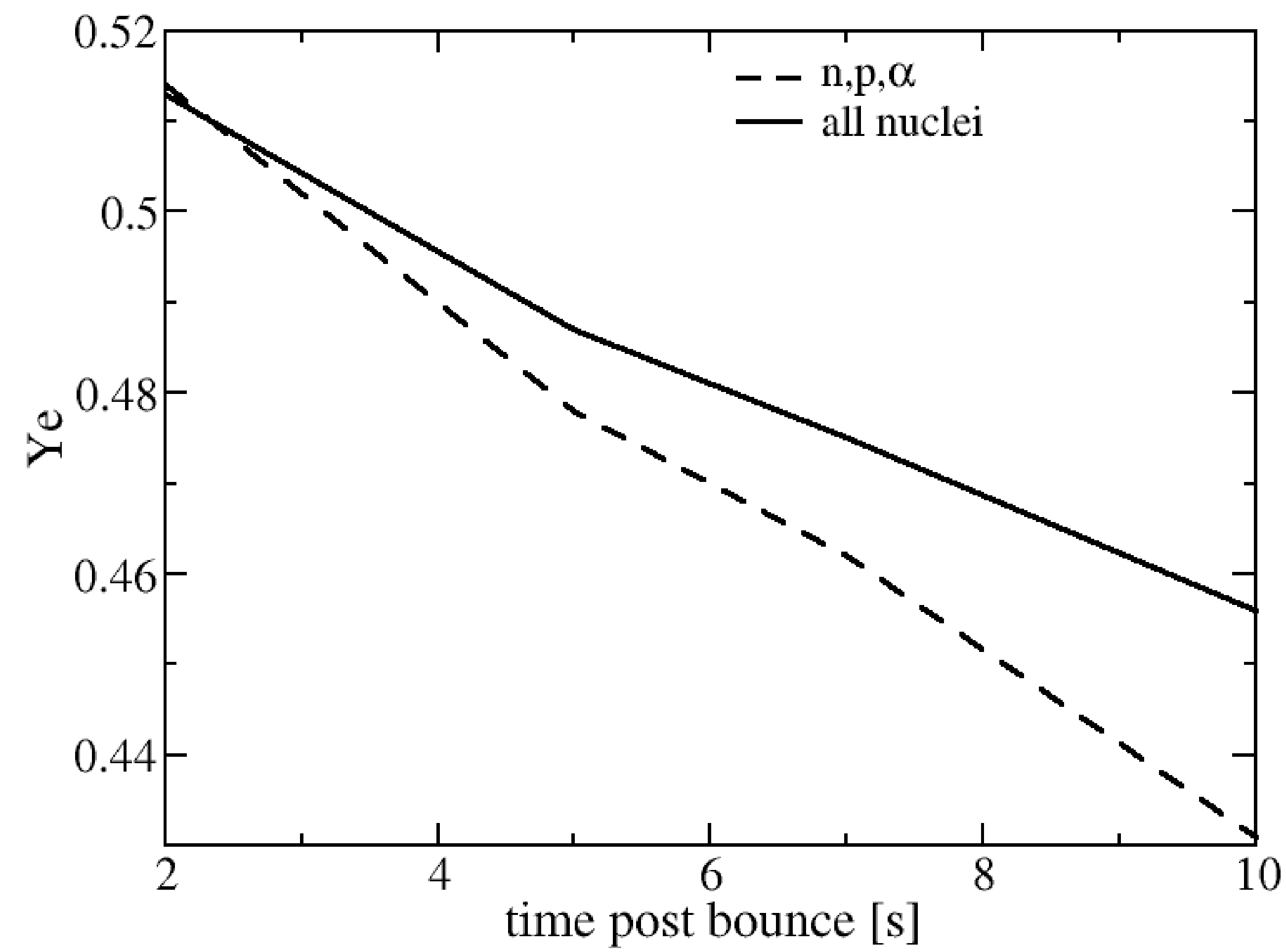


Light nuclei: antineutrino energy

We have followed the evolution of the neutrinosphere taking into account the presence of light clusters in the outer layers of the neutron star (Arcones et al. 2008) and the neutrino interction with them

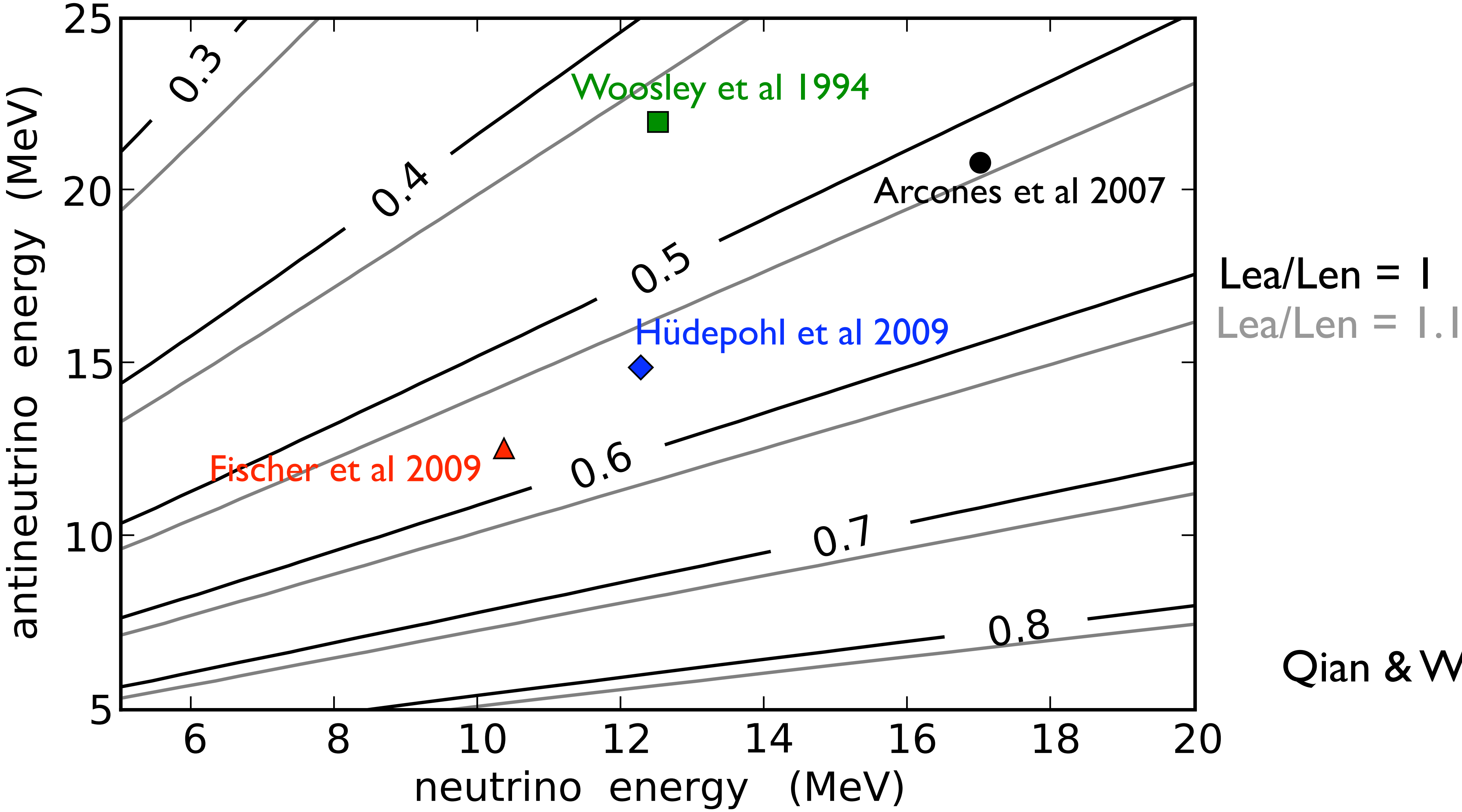




Wind models and electron fraction

Neutrino energies change with more realistic neutrino physics input

More recent simulations obtain lower antineutrino energies and therefore proton-rich conditions



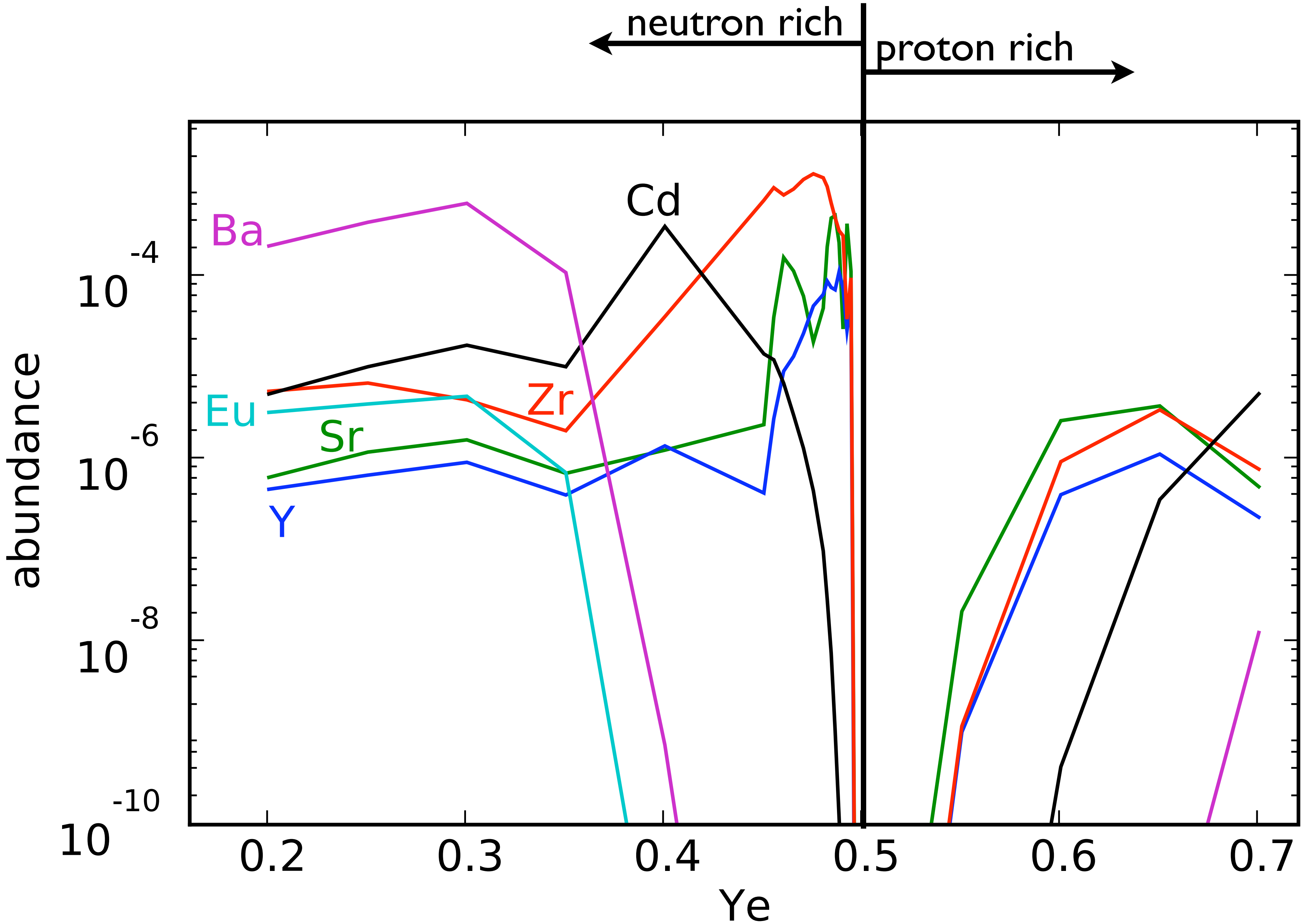
Qian & Woosley 1996

$$Y_e = \frac{\lambda_{\nu_e,n}}{\lambda_{\nu_e,n} + \lambda_{\bar{\nu}_e,p}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\varepsilon_{\nu_e}}\right]^{-1}$$

$Y_e > 0.5$: $\epsilon_{\bar{\nu}} - \epsilon_{\nu} < 4\Delta$

Nucleosynthesis and electron fraction

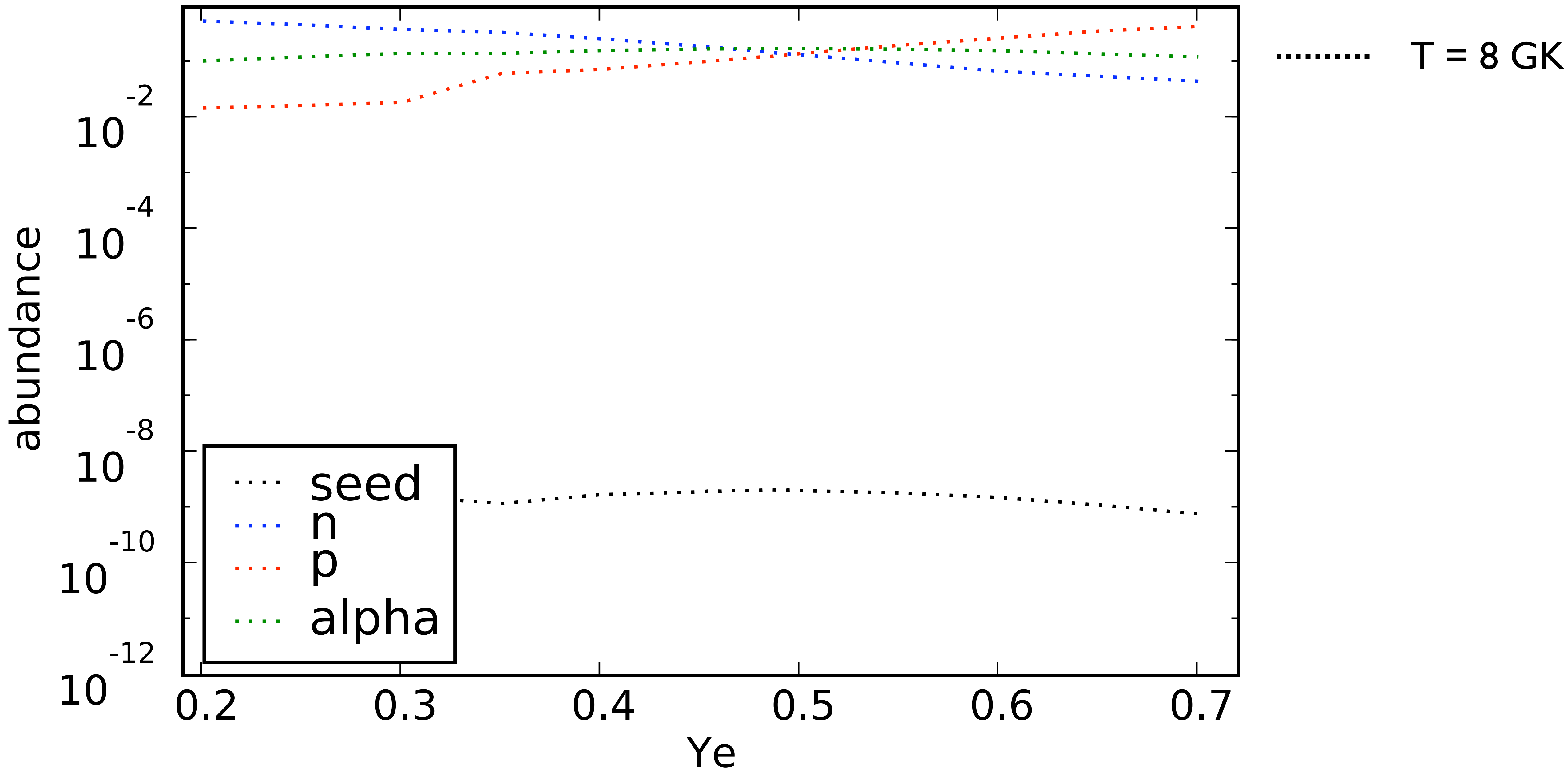
Study the impact of the electron fraction on the production of LEPP elements (Sr, Y, Zr) (Arcones & Montes)



LEPP elements in neutron- and proton-rich conditions

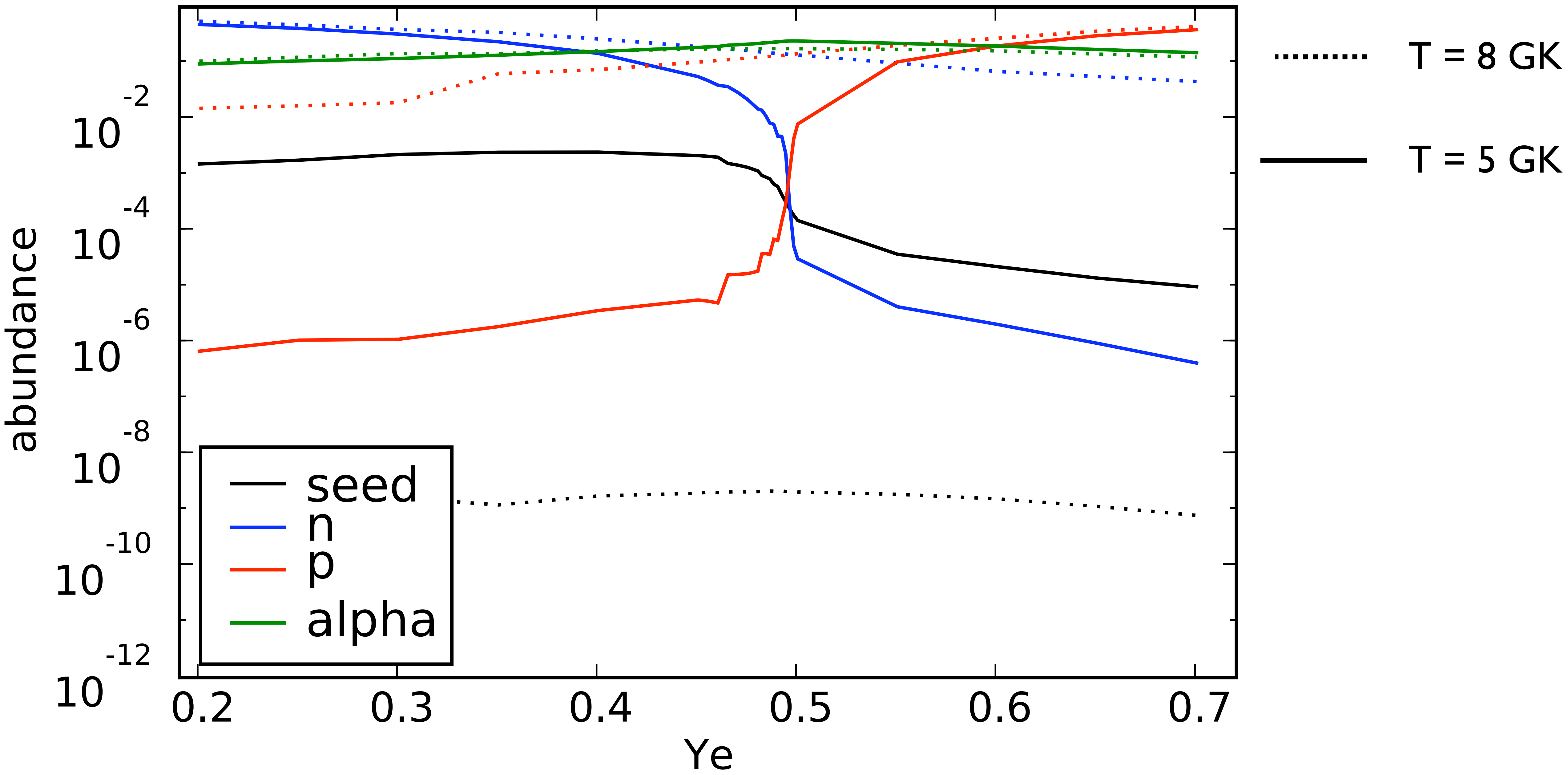
Nucleosynthesis and electron fraction

Initial composition is given by NSE, at high temperatures only n, p and alphas.



Nucleosynthesis and electron fraction

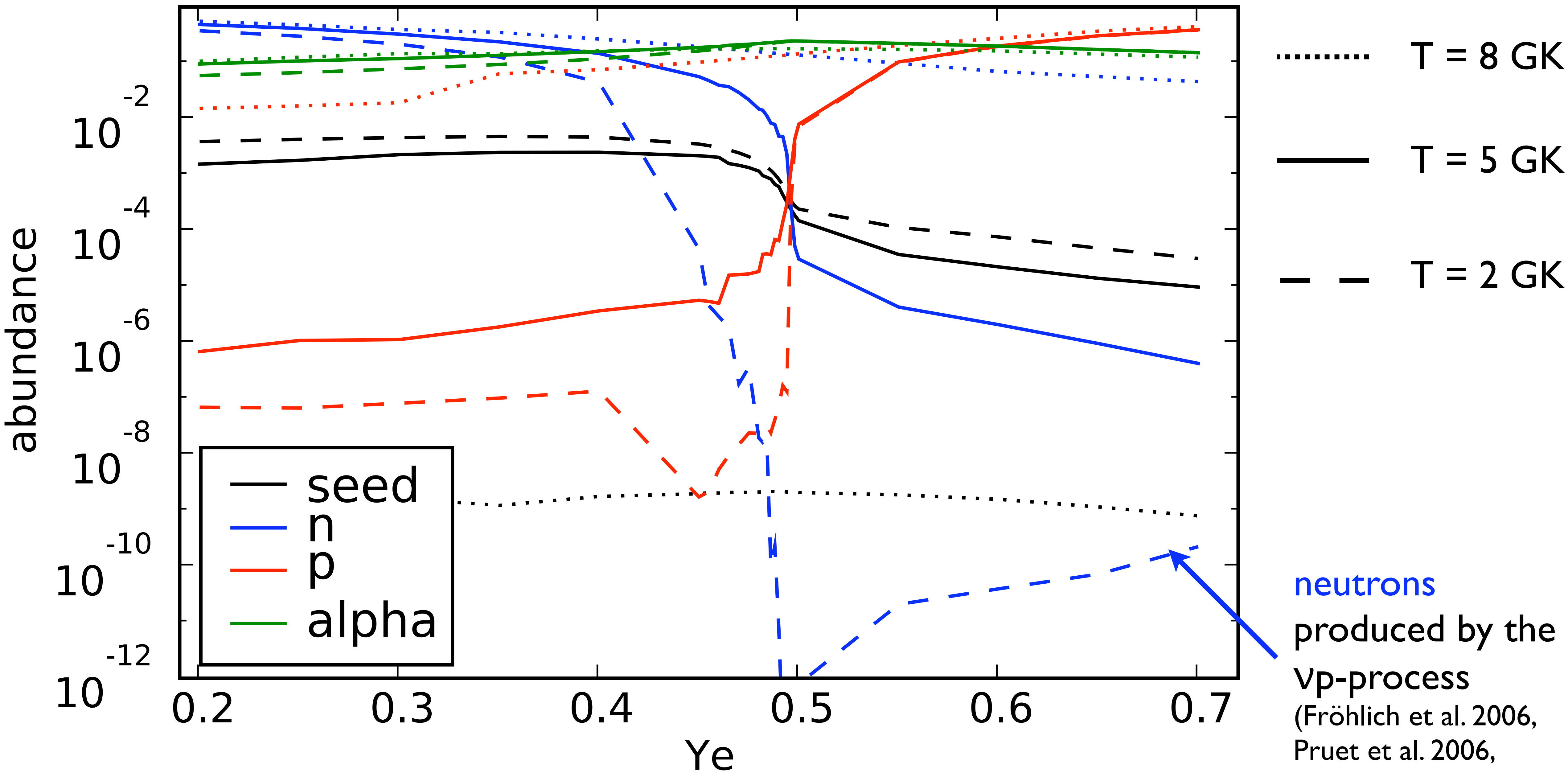
Initial composition is given by NSE, at high temperatures only n, p and alphas.
Alpha particles recombine forming seed nuclei.



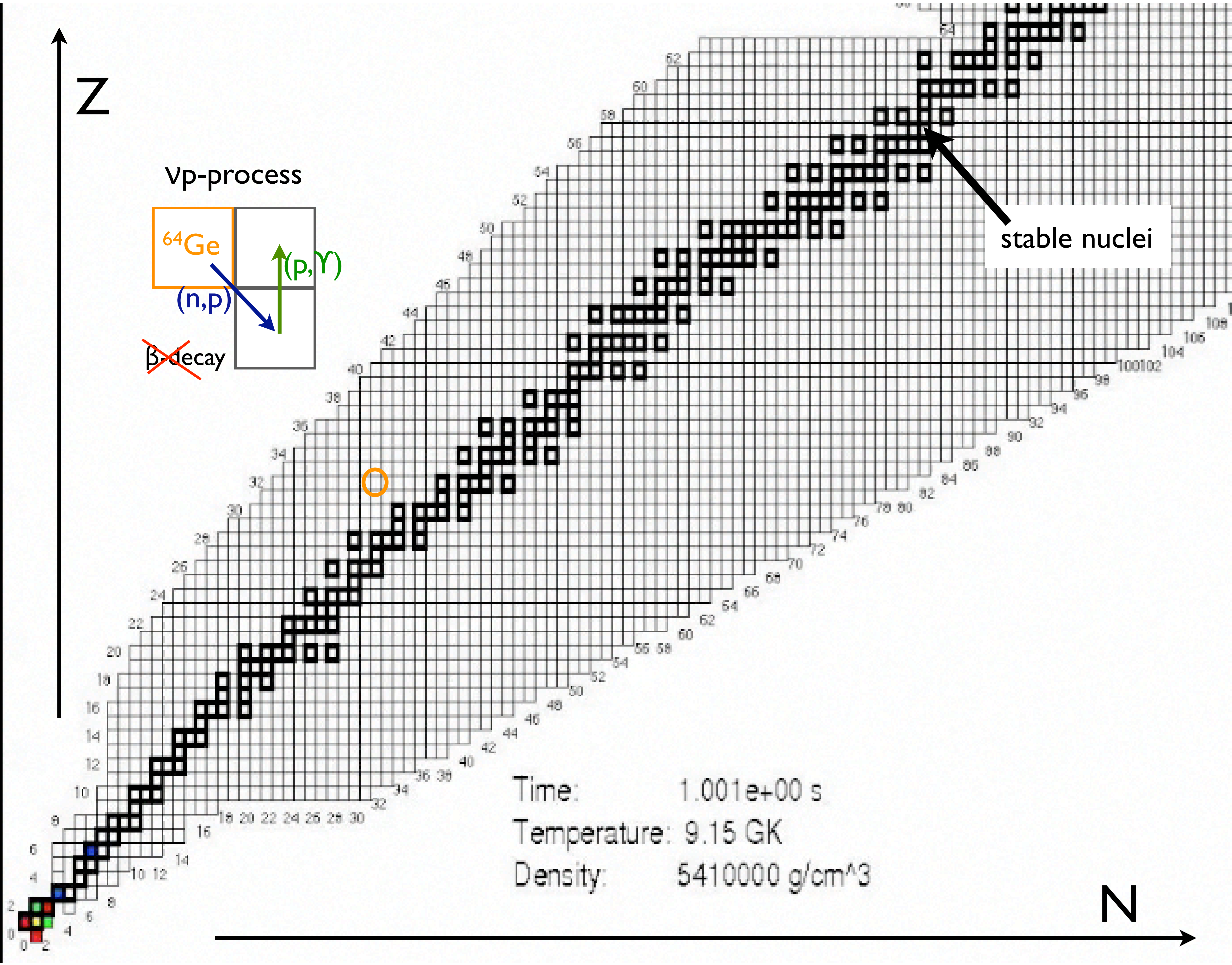
Nucleosynthesis and electron fraction

Initial composition is given by NSE, at high temperatures only n, p and alphas.
Alpha particles recombine forming seed nuclei.

At freeze-out neutron- and proton-to-seed ratio determine production of heavy elements.



neutrons produced by the νp-process (Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)

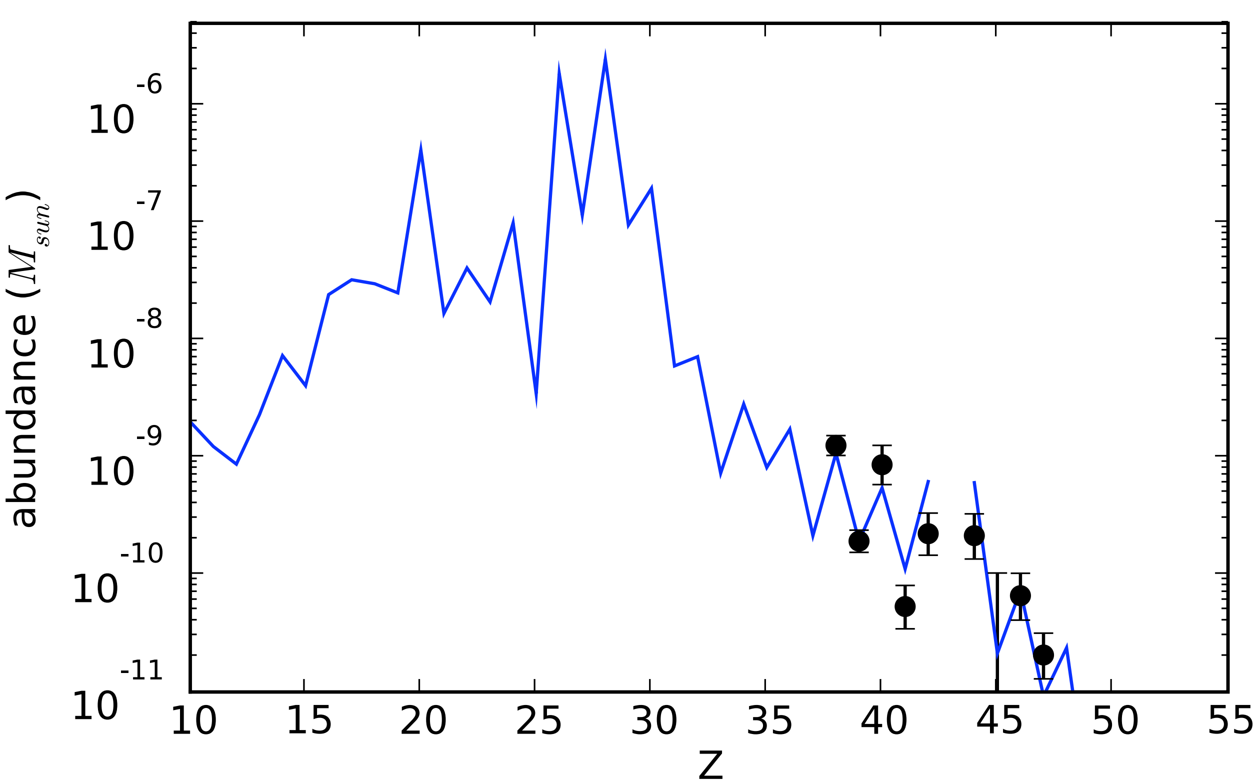

Z
N
νp-process
^{64}Ge
(n,p)
(p,γ)
β-decay
stable nuclei
Time: 1.001e+00 s
Temperature: 9.15 GK
Density: 5410000 g/cm^3

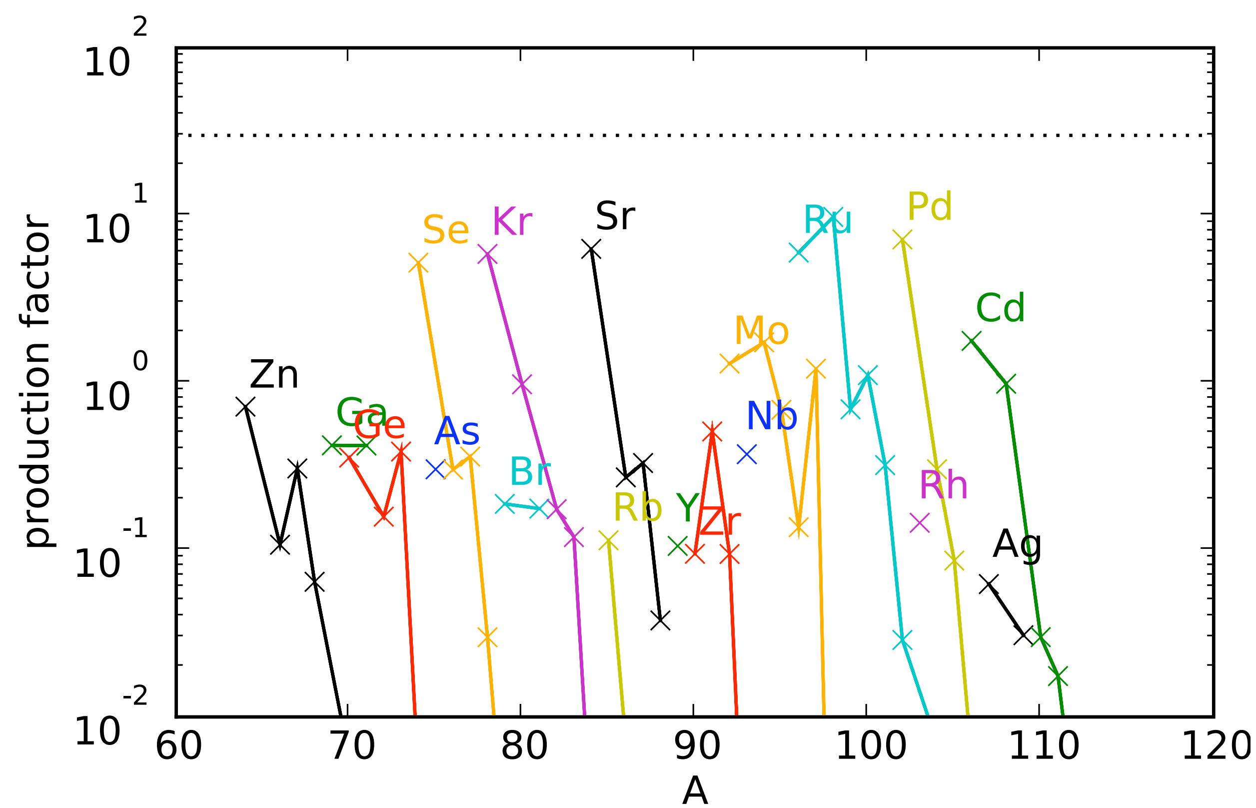
LEPP in proton-rich ejecta

Exploration of the time dependence of the electron fraction.

Superposition of trajectories with Ye > 0.5 following most recent simulations (Basel and Garching 2009). Compare to LEPP pattern (rescaled to Z=39).

Our results can explain the LEPP abundances in old halo stars and the origin of p-nuclei.





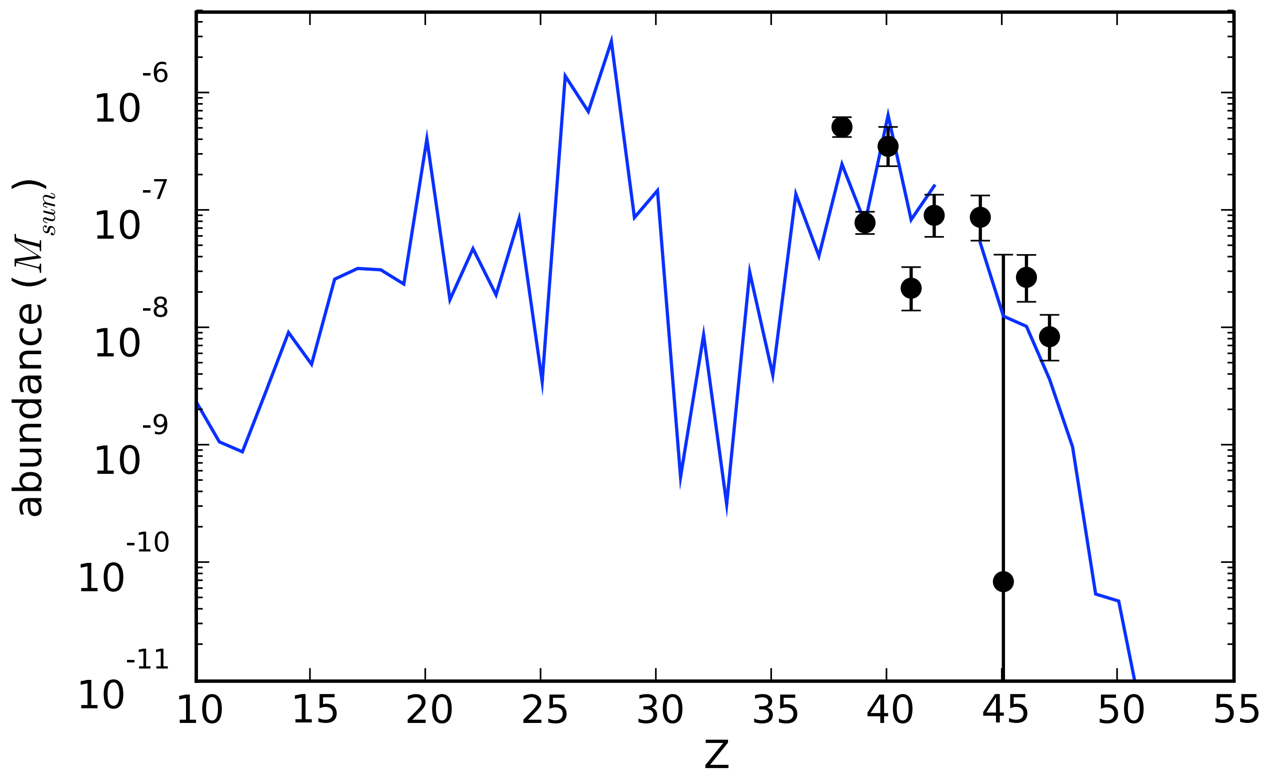
Problem: in the LEPP component of the solar system there are also neutron-rich nuclei.

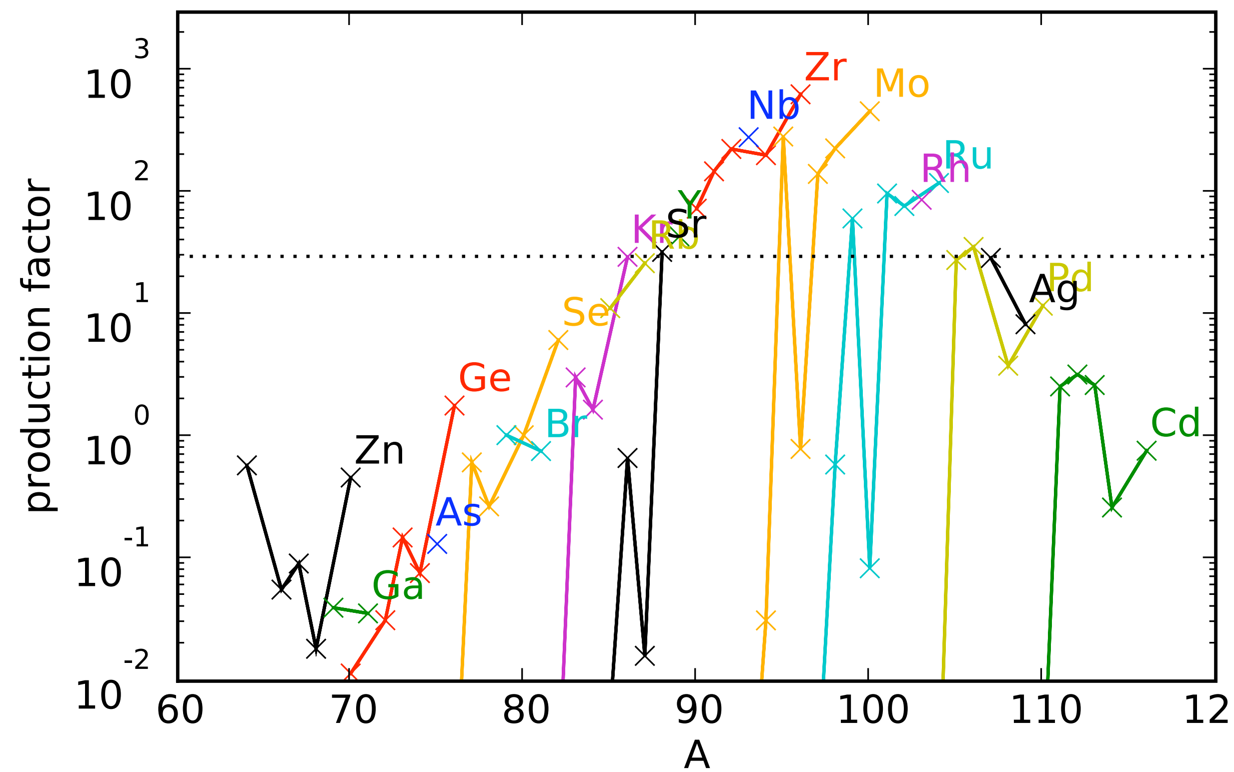
Isotopic abundances from UMP stars will give rise new insights.

LEPP in neutron-rich ejecta

Superposition of trajectories with neutron-rich conditions: 0.5 > Ye > 0.45.

LEPP elements are produced and also neutron-rich isotopes.





Problem: overproduction at A=90 for magic neutron number N=50 (Hoffman et al. 1996).

Suggest that if only a fraction of the supernovae eject neutron-rich material ⟶ can explain LEPP in the solar system.

LEPP: neutron vs. proton-rich winds

Proton-rich wind:

- reproduces LEPP pattern found in UMP stars
- robust under small variations of wind parameters
- no overproduction but mainly p-nuclei produced, no neutron-rich isotopes as in solar system
- results depend strongly on neutrino properties: νp-process

Neutron-rich wind:

- produces LEPP elements with neutron-rich isotopes, it could explain LEPP component in solar system
- no robustness under small variations of wind parameters
- overproduction at A~90, only subset of supernovae or small amount of their ejecta can be neutron rich

Conclusions

- First comparison of the LEPP pattern and nucleosynthesis calculations based on hydrodynamical wind simulations.
- Electron fraction is key for abundances and depends on details of the composition and neutrino interactions in the outer layers of the proto-neutron star.
- Light elements are present in the outer layer of the proto-neutron star.
- LEPP pattern is reproduced in neutron- and proton-rich ejecta.

and outlook

- Multi-dimensional simulations with detailed neutrino transport.
- Include light elements and their corresponding neutrino reactions.
- Observations of isotopic abundances in old stars can discriminate.
- Use abundances to constrain Y_e evolution.
- Galactic chemical evolution models.

Thank you!

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H. Schatz, F. K. Thielemann

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