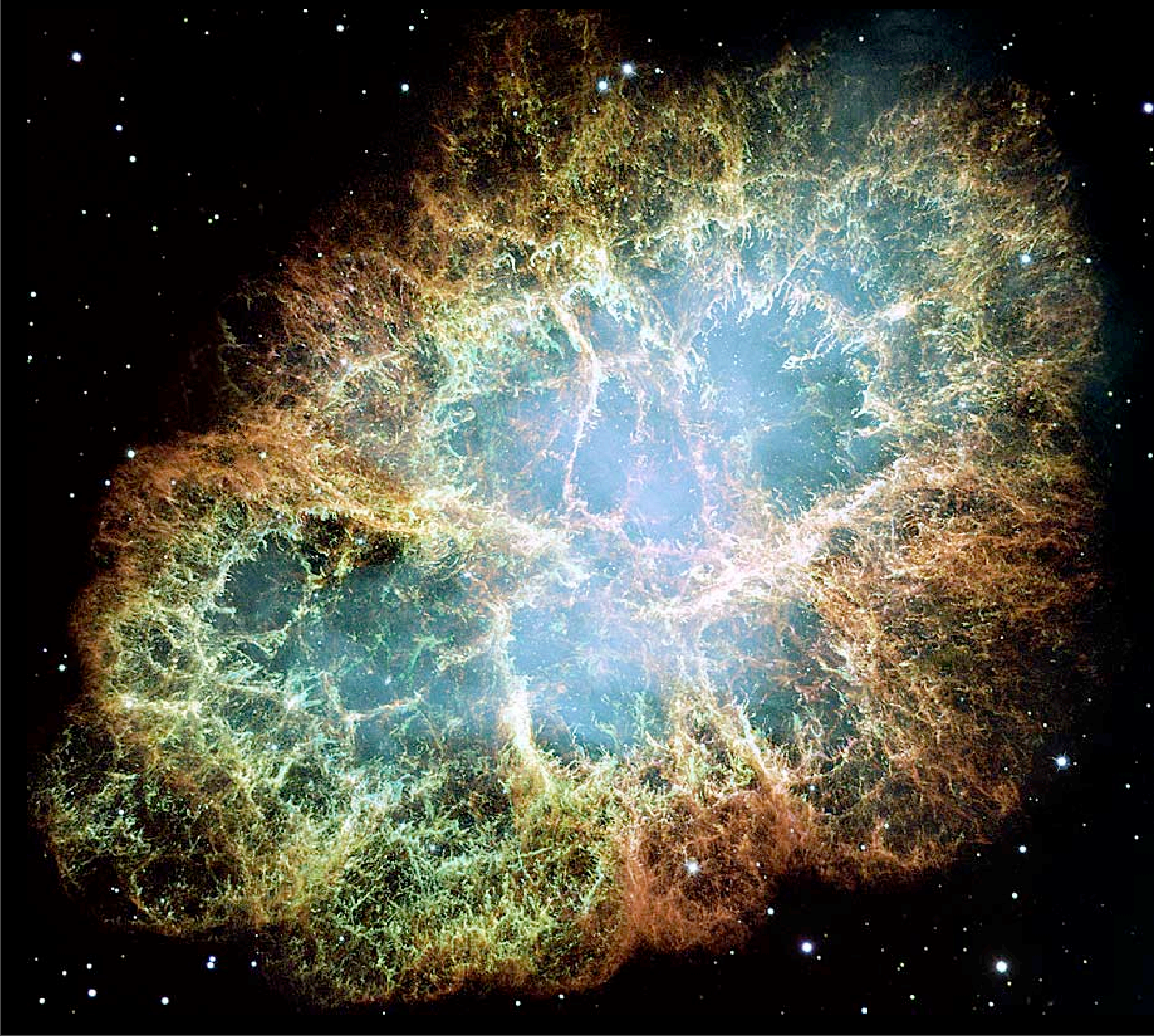
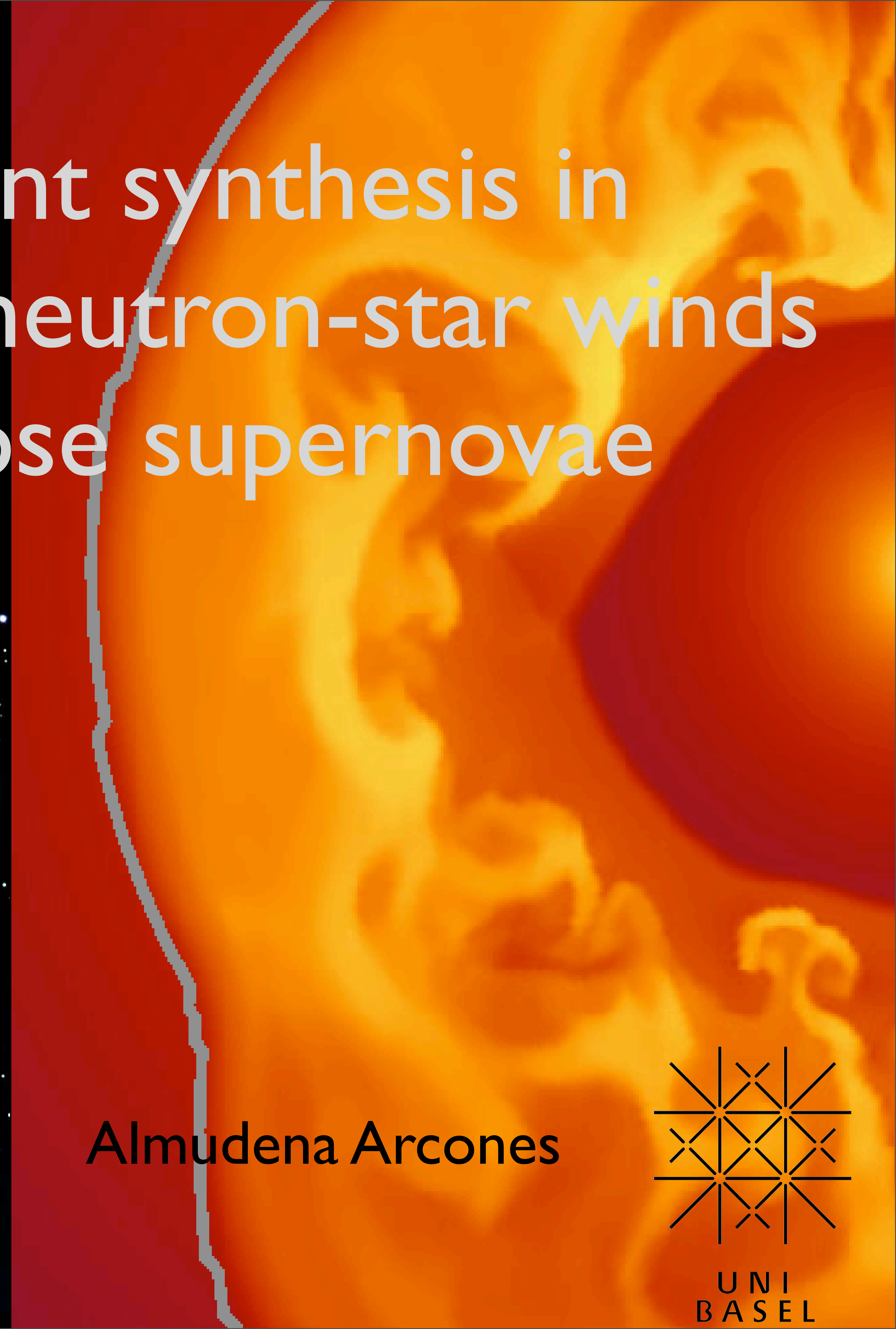
Heavy element synthesis in neutrino-driven neutron-star winds of core collapse supernovae





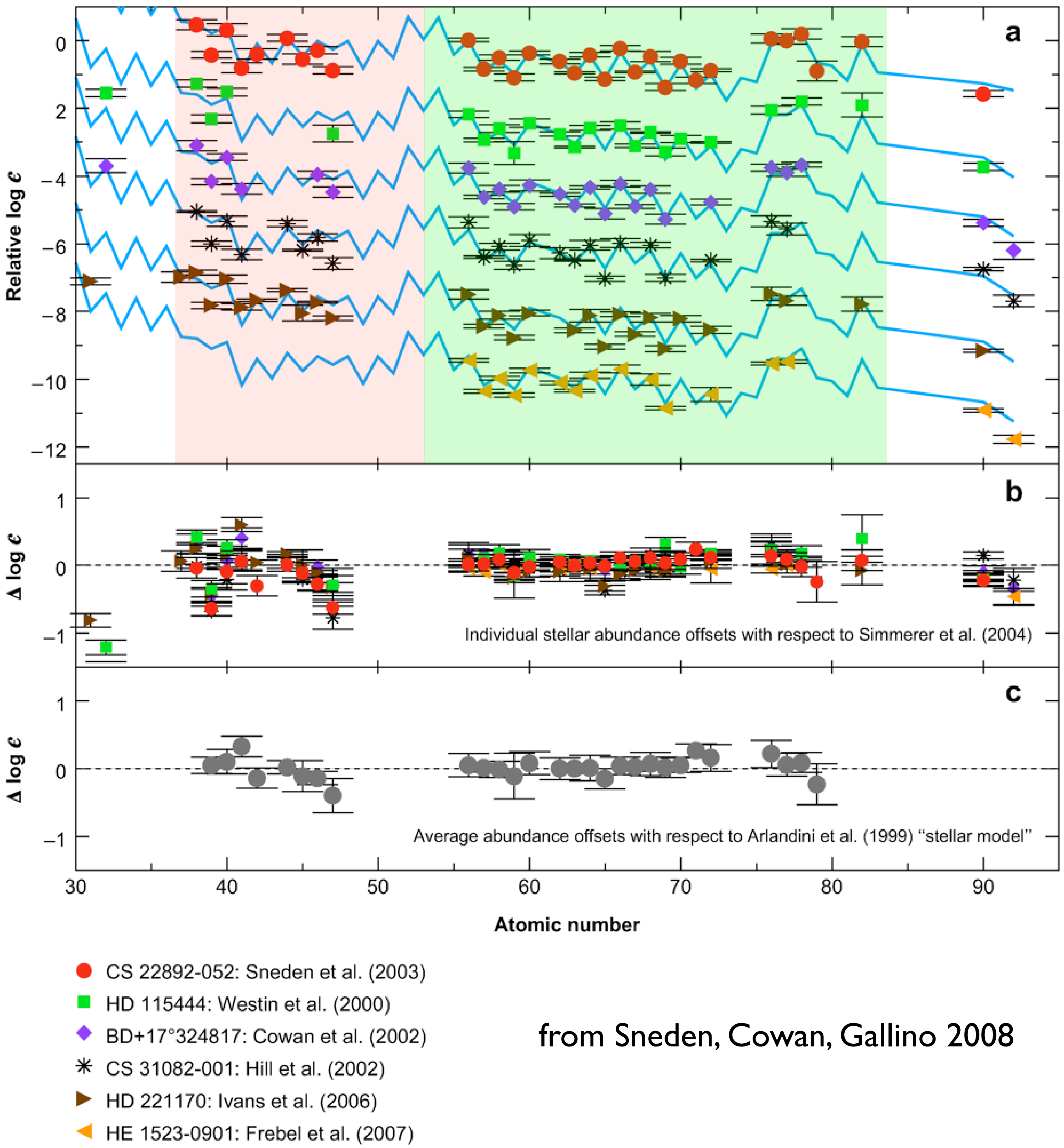
Almudena Arcones

UNI BASEL

Outline

- Introduction and motivation
  - observations
  - neutrino-driven winds
- Nucleosynthesis of the light component of heavy nuclei:
  - results from neutrino-driven wind simulations
  - impact of the electron fraction and uncertainties
- Key aspects for the r-process:
  - long-time dynamical evolution
  - nuclear physics input: nuclear masses
  - way back to stability: beta-delayed neutron emission vs. neutron capture
- Neutron-star mergers: r-process heating and light curve
- Conclusions

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)

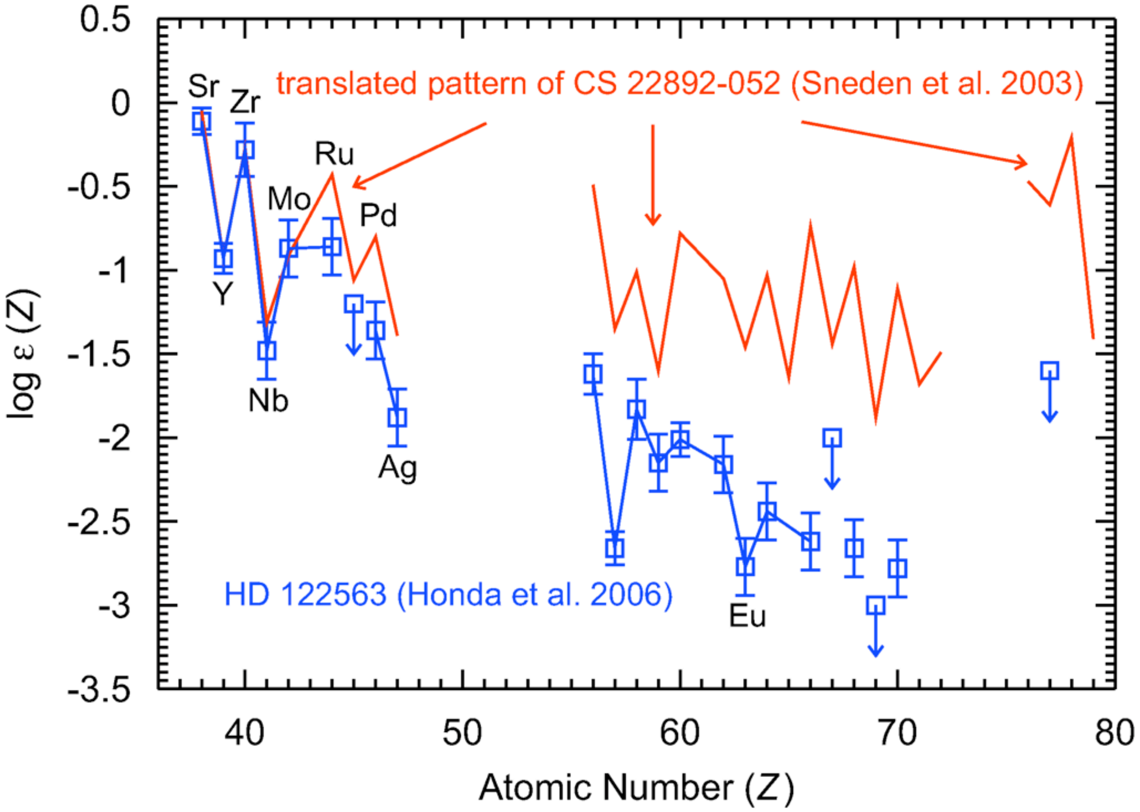
Only few nucleosynthesis events have contributed to the abundances present in old stars.

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.



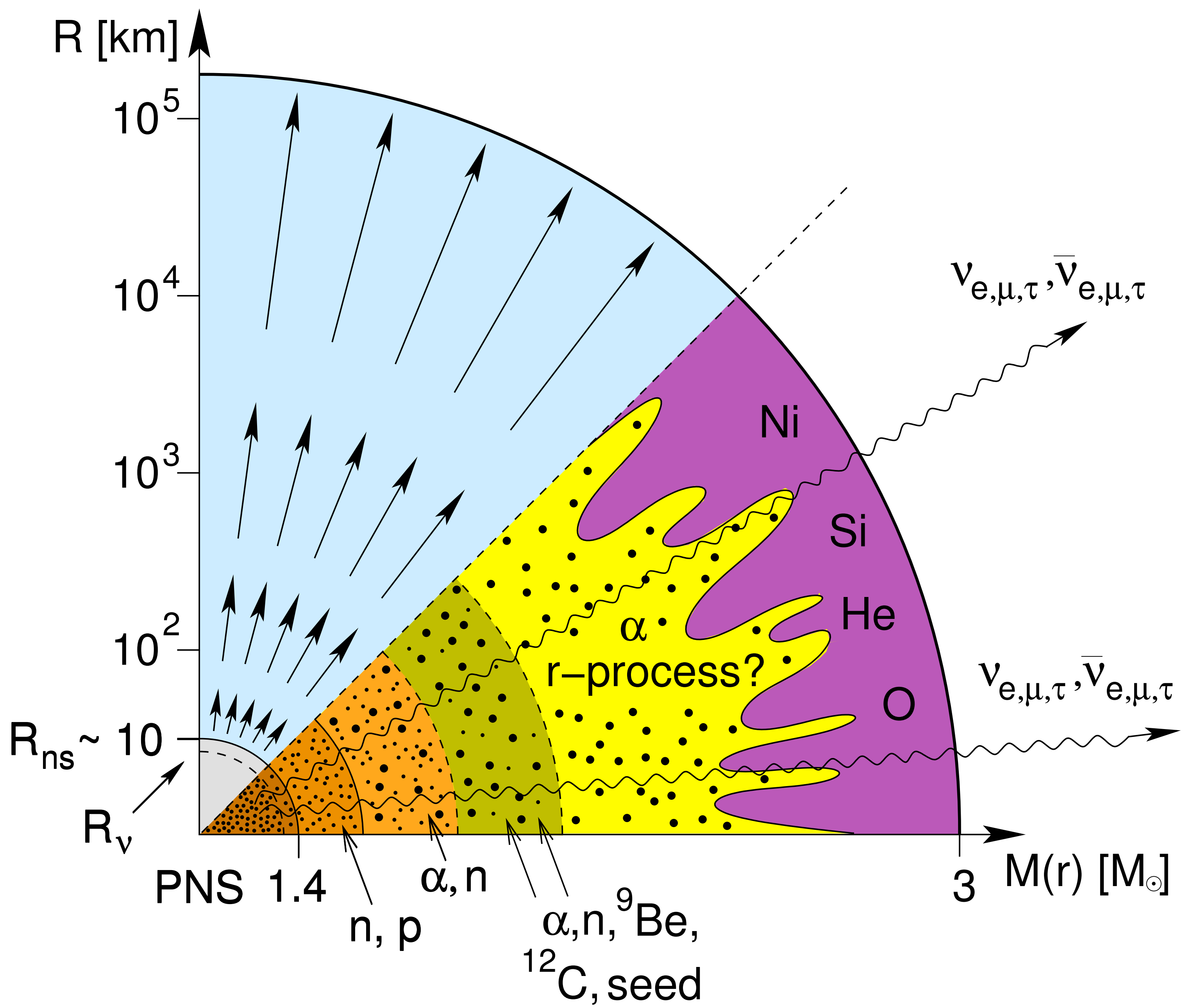
- In neutrino-driven winds when a neutron star forms, charged-particle reactions (CPR) produce nuclei with A~90-110 (Z<47).
- Observations of low-metallicity stars show that sites producing heavy r-nuclei do not produce Fe or any other elements between N and Ge. This suggest that heavy r-nuclei with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

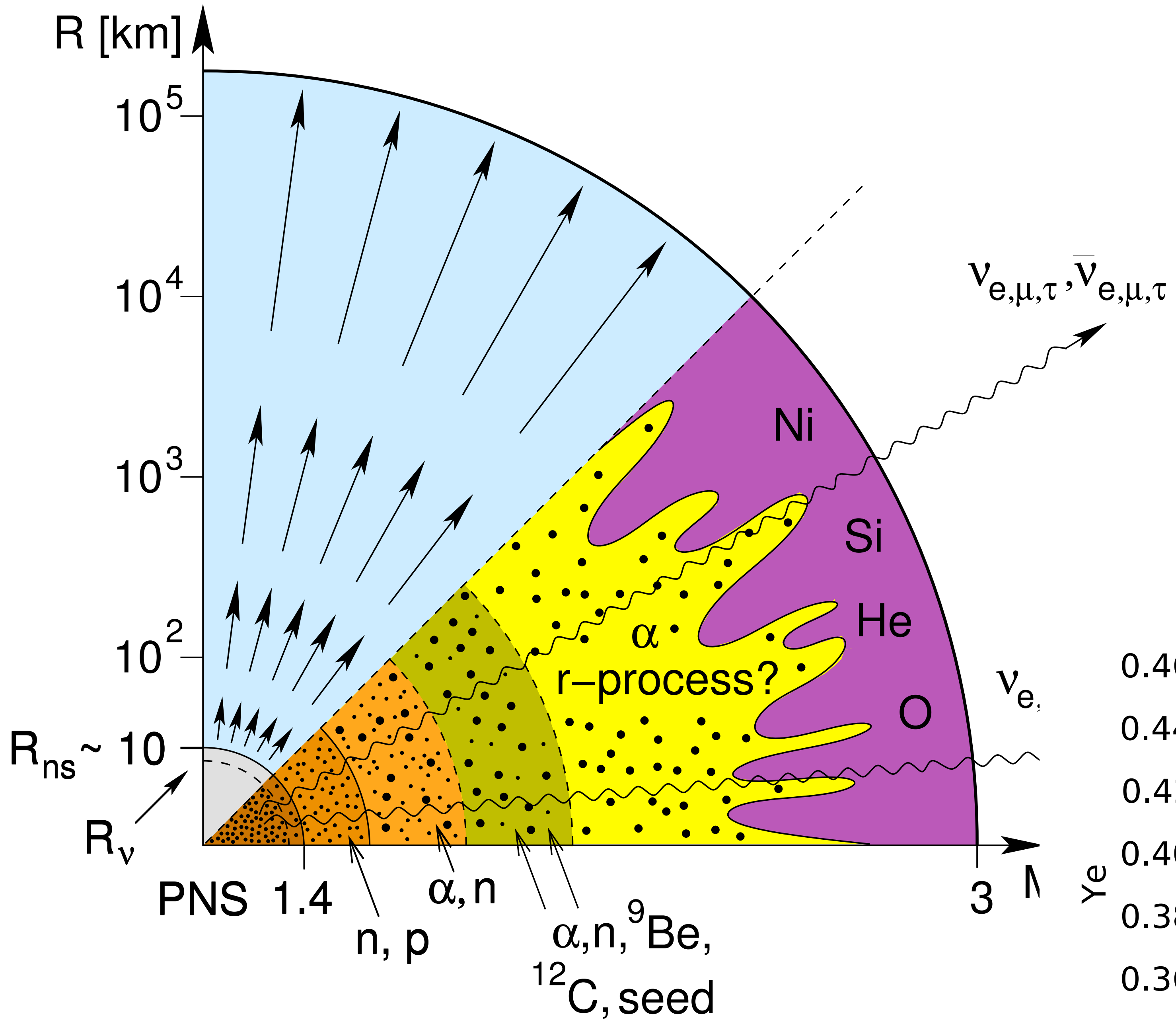
Neutrino-driven winds



Necessary conditions for the production of heavy elements (A>130) by the r-process (Y_n/Y_{seed} ↑):

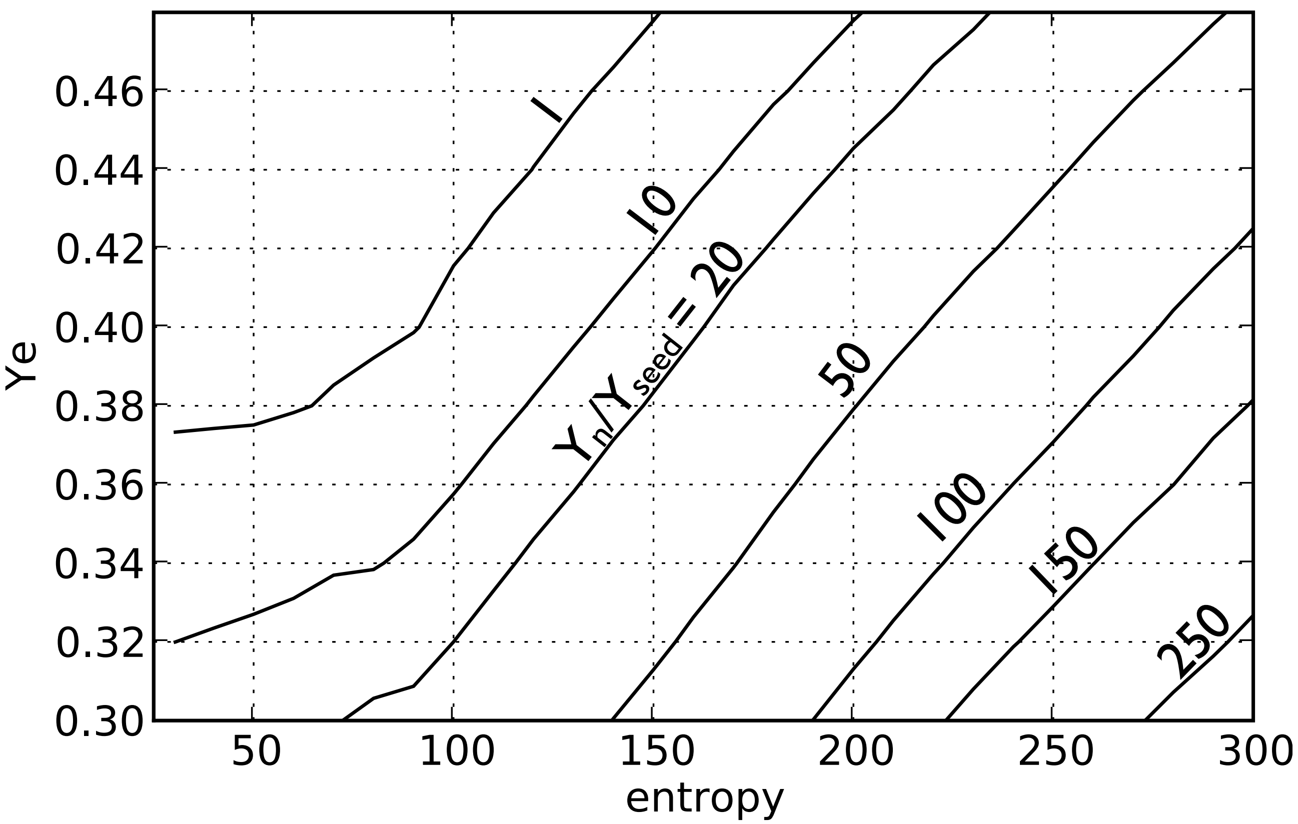
- fast expansion inhibits the alpha-process and thus the formation of seed nuclei
- $Y_e = n_p/(n_n+n_p) < 0.5$ (neutron rich)
- high entropy is equivalent to high photon-to-baryon ratio. Photons dissociate seed nuclei into nucleons.

Neutrino-driven winds

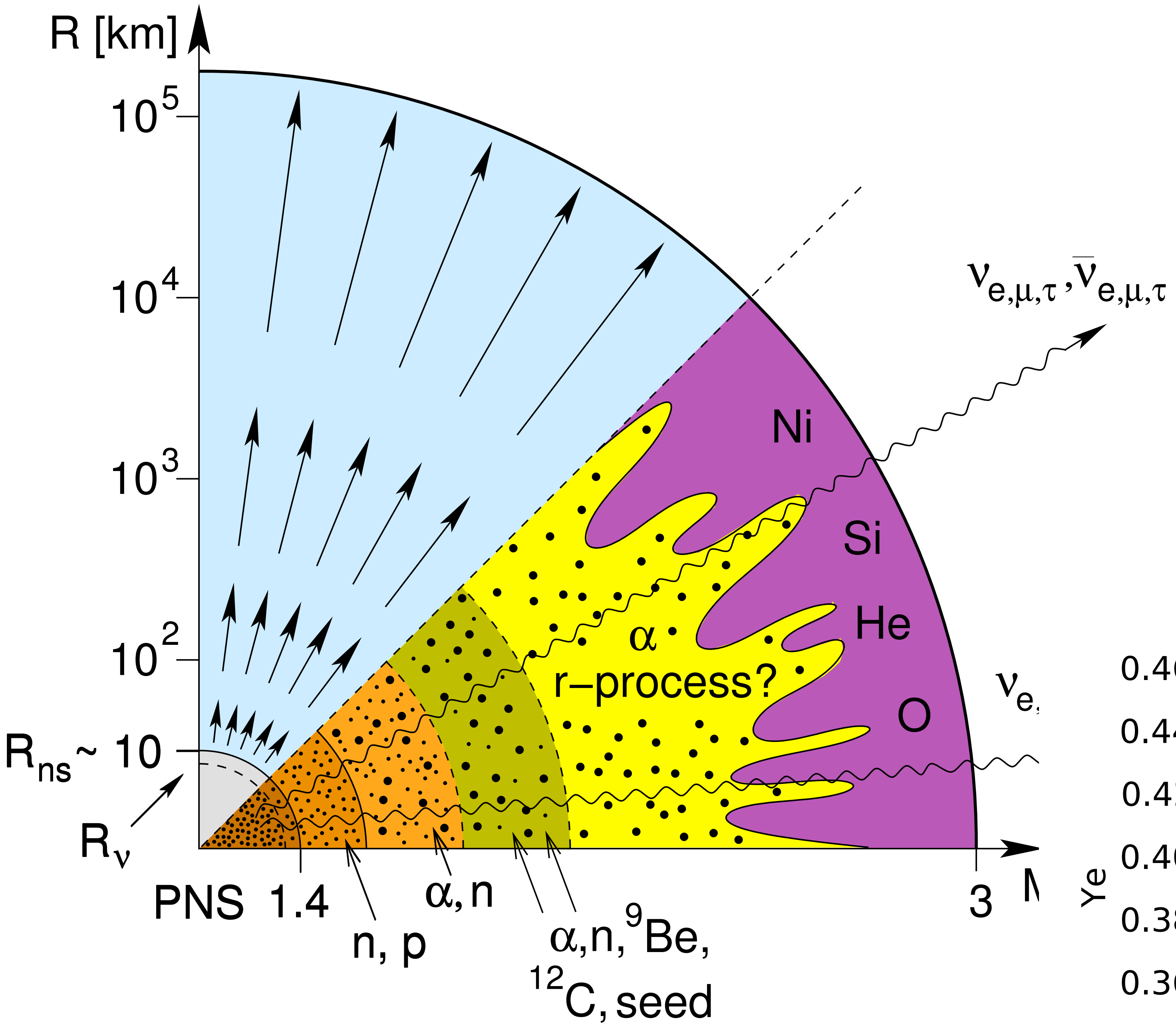


Necessary conditions for the production of heavy elements (A>130) by the r-process (Y_n/Y_{seed} ↑):

- fast expansion inhibits the alpha-process and thus the formation of seed nuclei
- $Y_e = n_p/(n_n+n_p) < 0.5$ (neutron rich)
- high entropy is equivalent to high

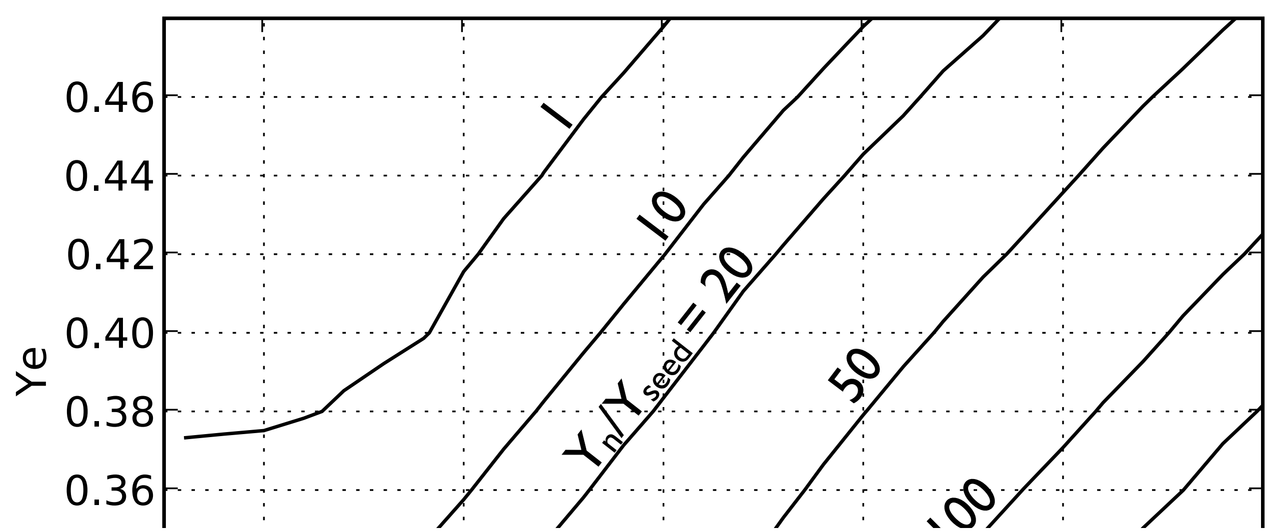


Neutrino-driven winds



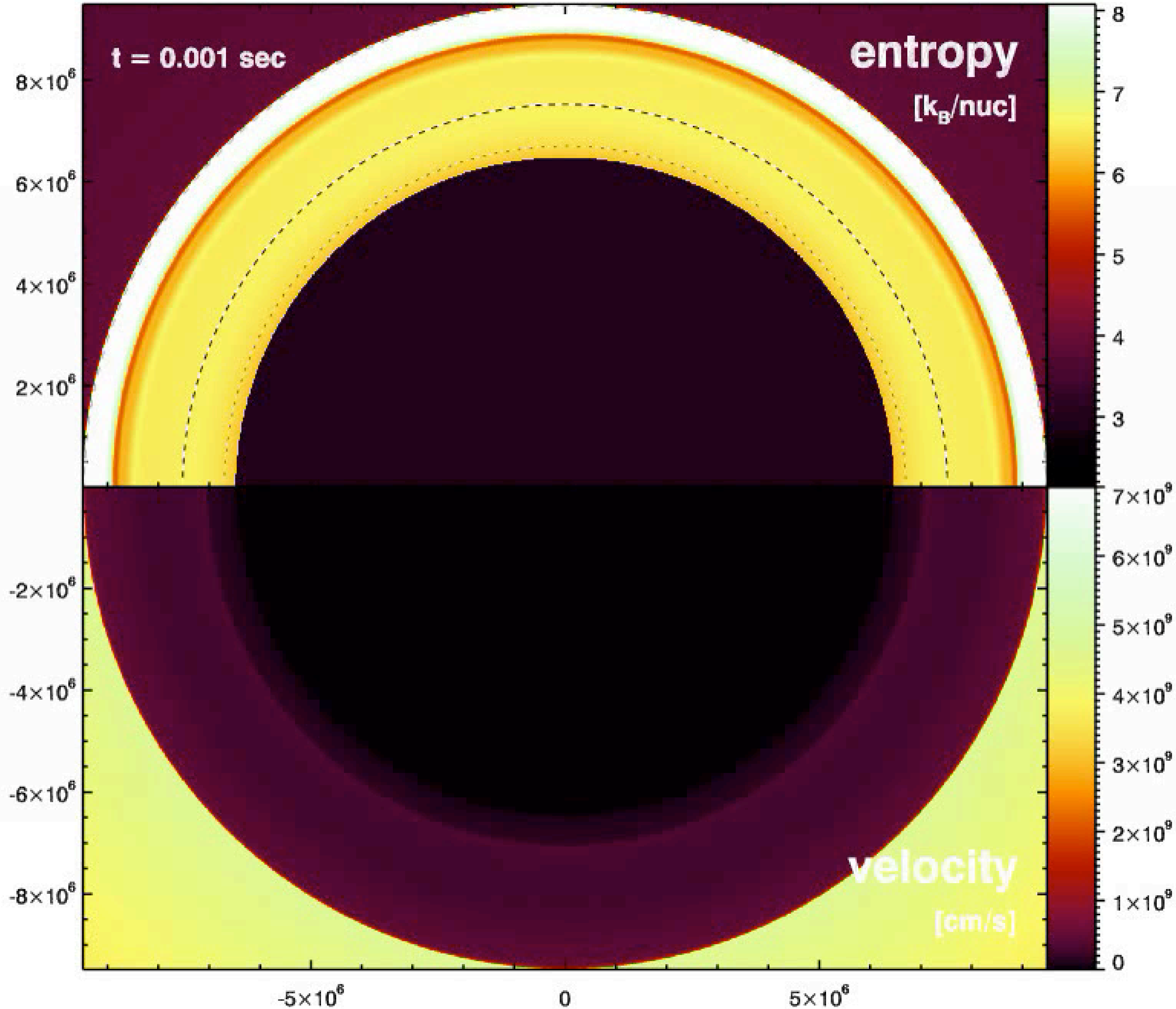
Necessary conditions for the production of heavy elements (A>130) by the r-process (Y_n/Y_{seed} ↑):

- fast expansion inhibits the alpha-process and thus the formation of seed nuclei
- $Y_e = n_p/(n_n+n_p) < 0.5$ (neutron rich)
- high entropy is equivalent to high



Are these conditions reached in state-of-the-art neutrino-driven wind simulations?
Do supernovae produce the heavy r-process nuclei?

Arcones & Janka (in prep.)



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 2000-2010)
- 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

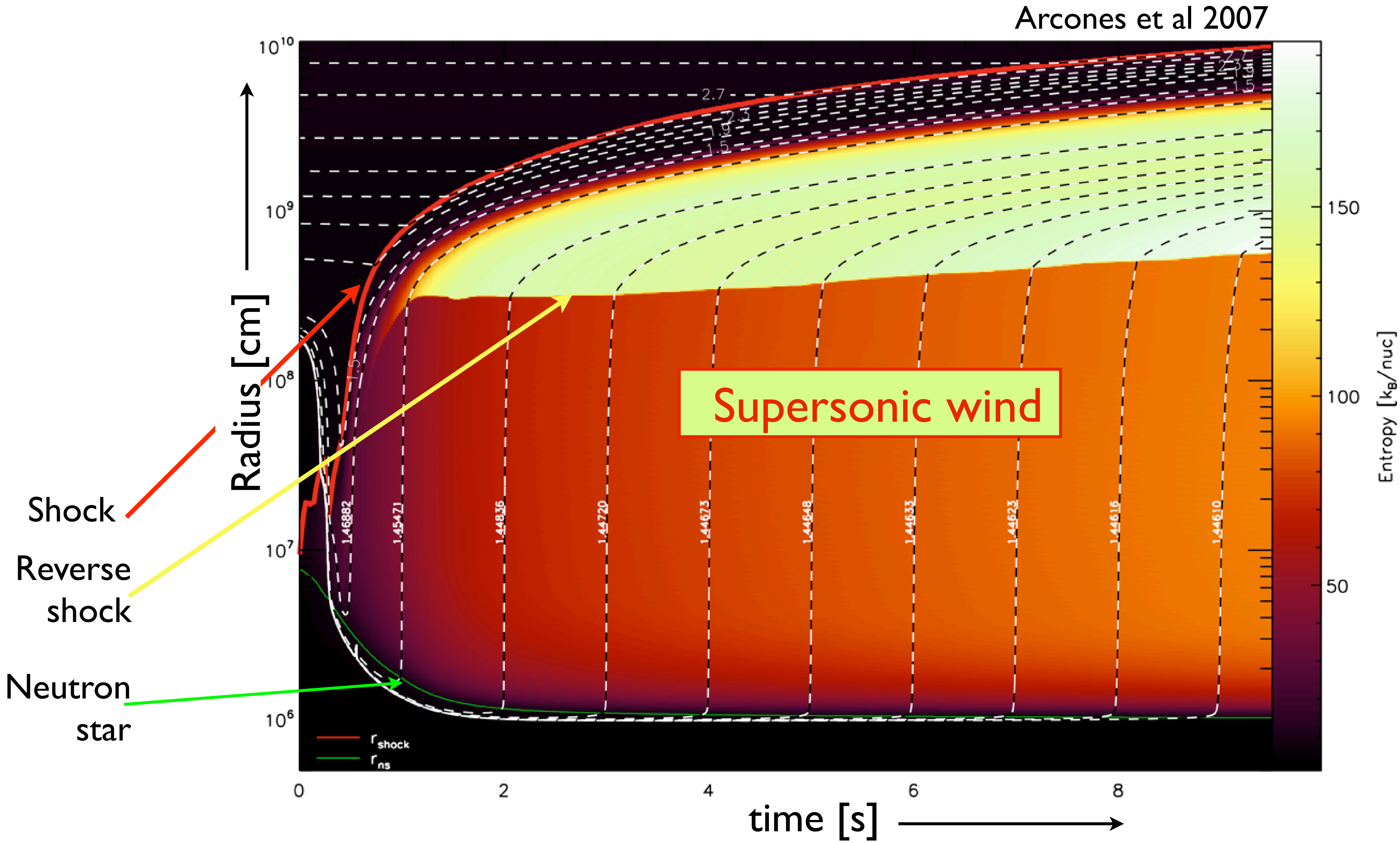
- Network input: trajectories (ρ,T) from hydrodynamical simulations + initial Y_e.
- Starting composition at 10GK is given by NSE.
- Before alpha-rich freeze out: extended nuclear reaction network including neutral and charged particle reactions from REACLIB (Fröhlich et al 2006), and weak-reaction rates (Fuller et al. 1999, Langanke&Martinez-Pinedo 2000).
- After alpha-rich freeze out: fully implicit r-process network including neutron capture (Rauscher & Thielemann 2000), photodissotiation, beta decay (Möller et al 2003, NuDat2), and fission (Panov et al 2009).

Neutrino-driven wind simulations

Our aim was not to prove that the explosion mechanism itself works (studied with Boltzmann neutrino transport simulations), but to follow the evolution of the outflow for several seconds: faster code necessary, less details required.

- Initial data provided by Boltzmann simulations (10ms after bounce).
- We replace the inner part of the neutron star ($\rho > 10^{13}$ g/cm^3) by an inner boundary to avoid strong time step limitations and to have a degree of freedom for systematic variations.
- We prescribe a shrinking inner boundary radius, which mimics the contraction of the neutron star.
- Neutrino luminosity is given by hand at the inner boundary. The values are chosen such that the explosion energy agrees with observations.
- We use a simplified neutrino transport which reproduces qualitatively the results of Boltzmann-transport simulations. However, quantities like the electron fraction should be taken with caution.
- Newtonian hydrodynamics plus general relativistic corrections for the gravitational potential yields results which are in good agreement with full relativistic steady-state calculations (Otsuki et al.2000, Thompson et al. 2001).

Neutrino-driven wind results



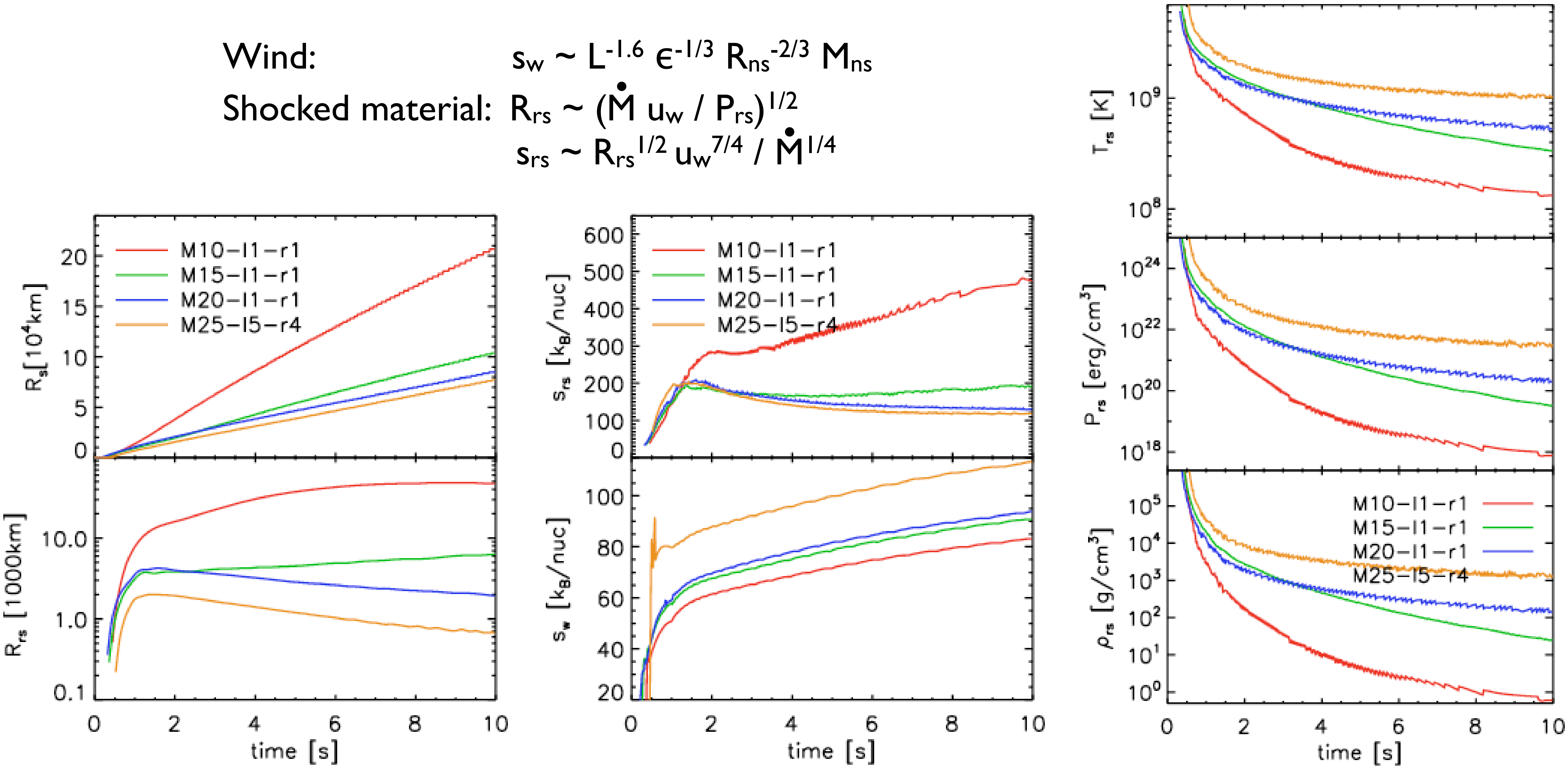
Neutrino-driven wind results: progenitor variation

- Massive progenitor → M_{ns}↑ → s_w↑
- Low mass progenitor → steep $\nabla\rho$ → R_s↑ → P_{rs}↓ → R_{rs}↑ → s_{rs}↑, T_{rs}↓

Wind: $s_w \sim L^{-1.6}\,\epsilon^{-1/3}\,R_{ns}^{-2/3}\,M_{ns}$

Shocked material: $R_{rs} \sim (\dot{M}\,u_w / P_{rs})^{1/2}$

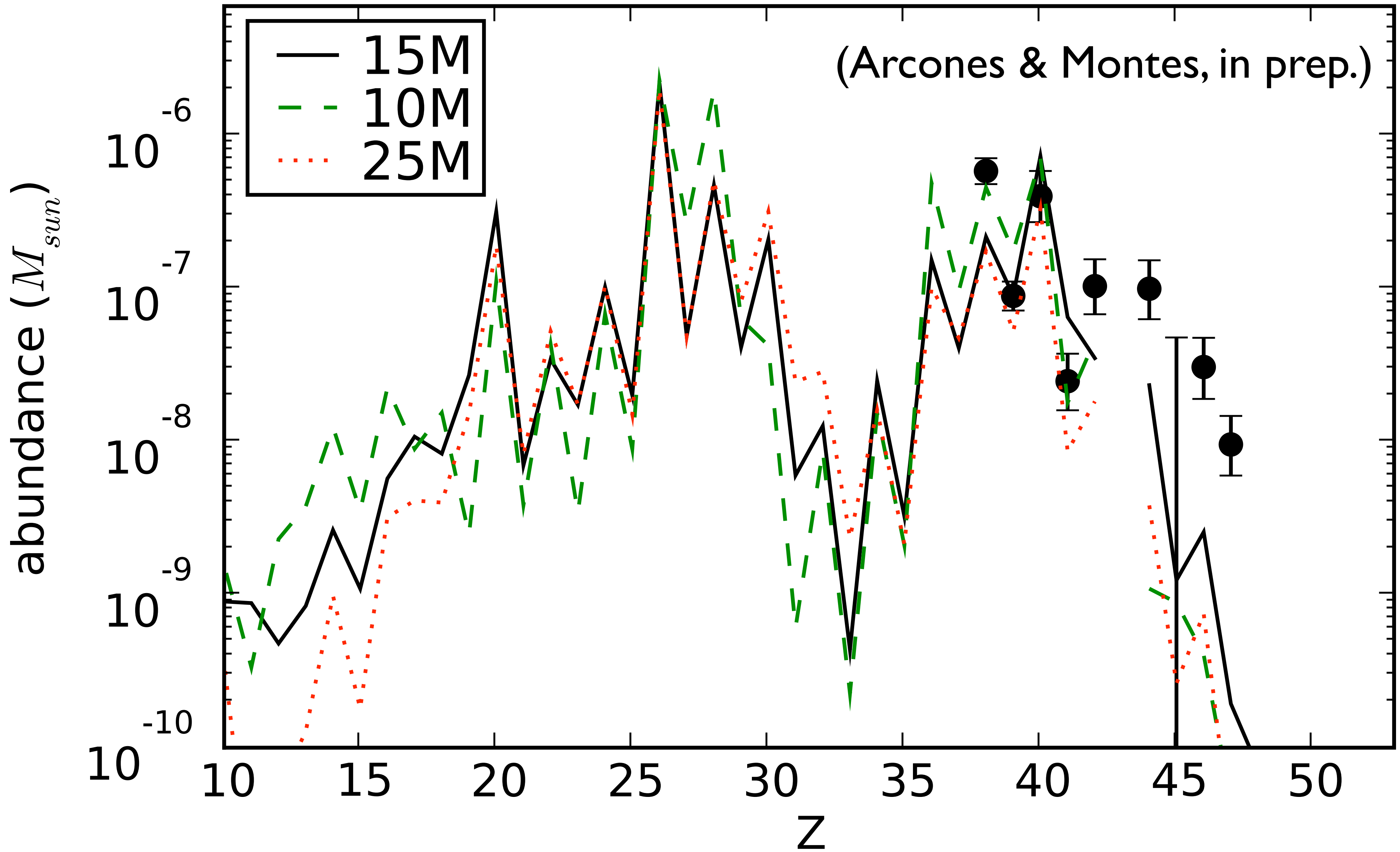
$s_{rs} \sim R_{rs}^{1/2}\,u_w^{7/4} / \dot{M}^{1/4}$



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.



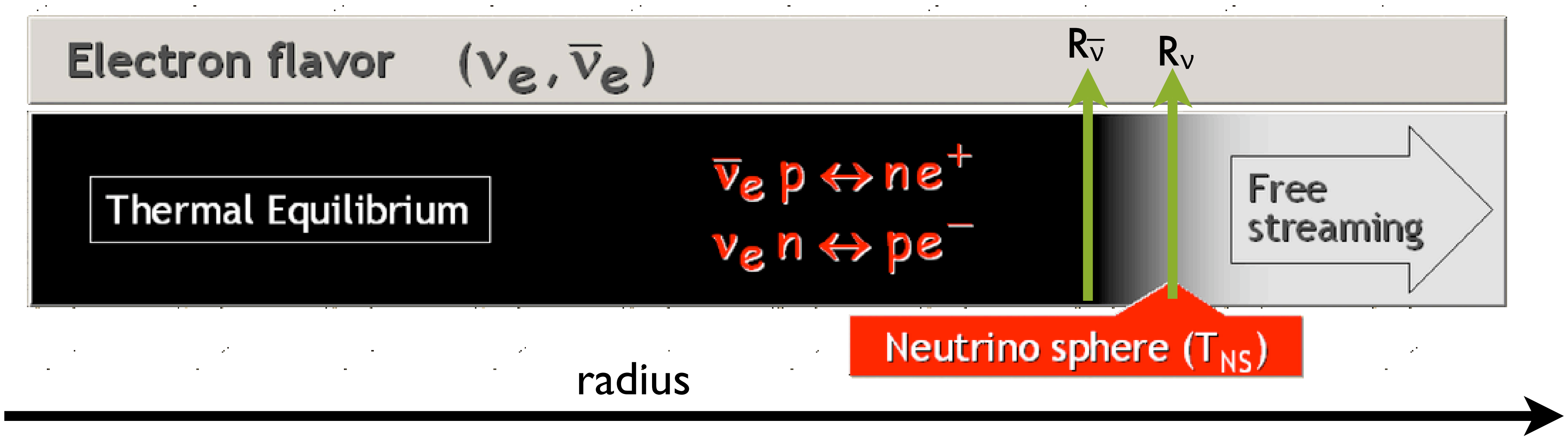
Electron fraction and uncertainties

Entropy and expansion timescale based on hydrodynamic evolution, 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

Light nuclei (A<4) are present in the outer layers of the proto-neutron star and are important for determine the position of the neutrinosphere (Arcones et al 2008).

Light nuclei: Equations of State

• 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).

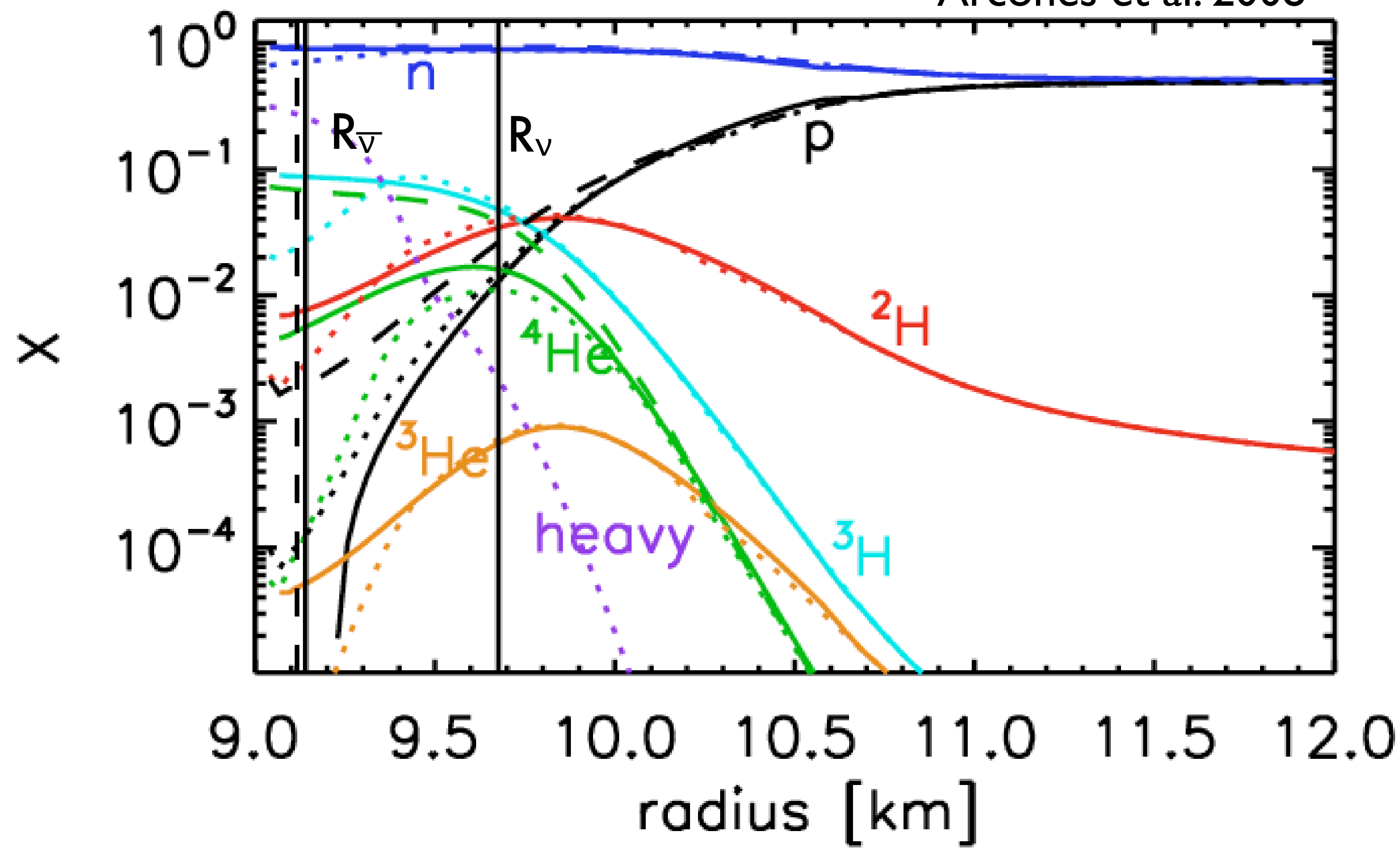
We have compared 3 EOS:

• 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: Equations of State

• The EO … cles, and a
representa … S based on
NSE). This

• Howeve … resent for
densities …

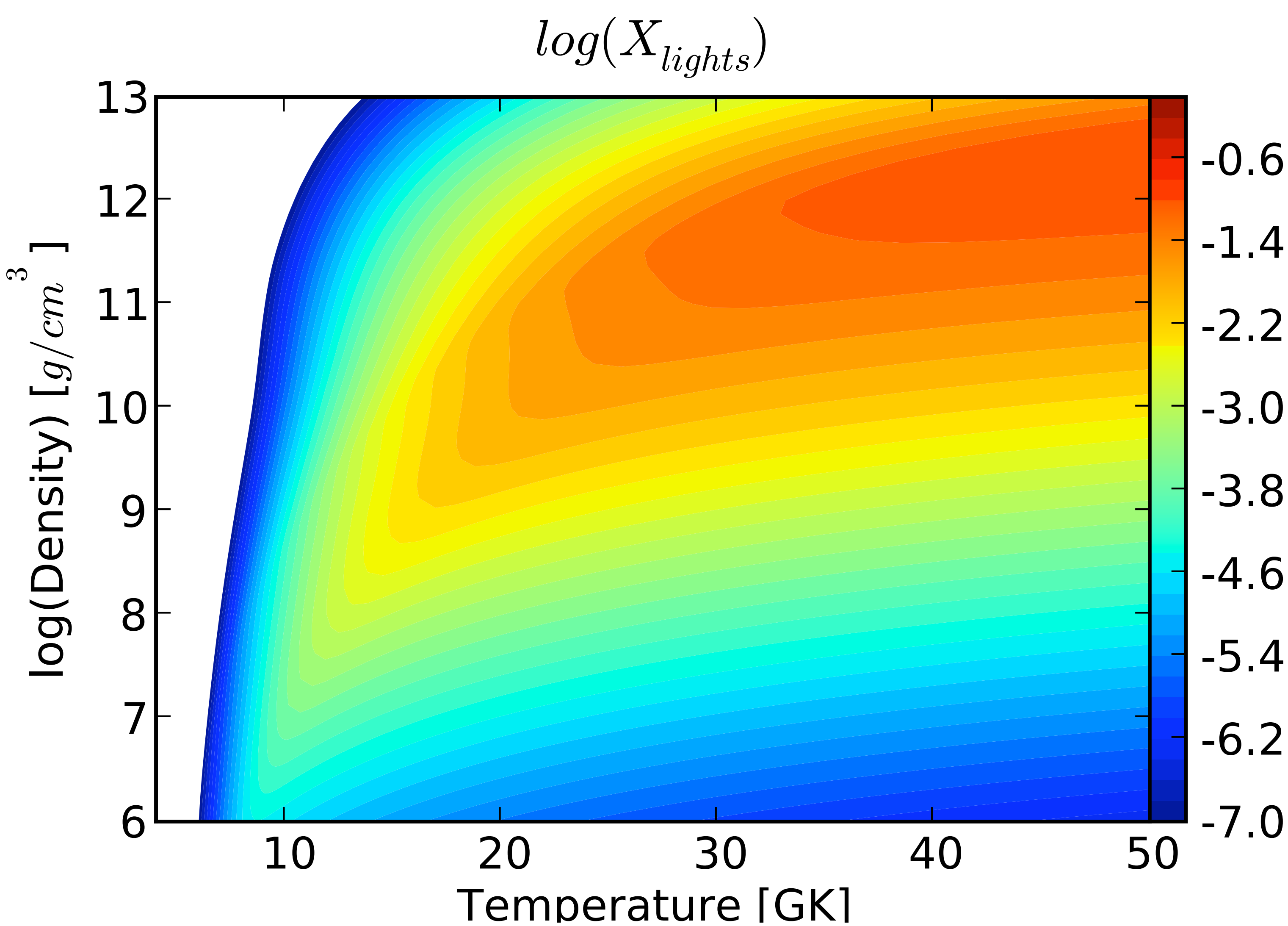
We have …

• non-inte…
(dashed li…

• Virial (H…
nuclei wit…
(solid line…

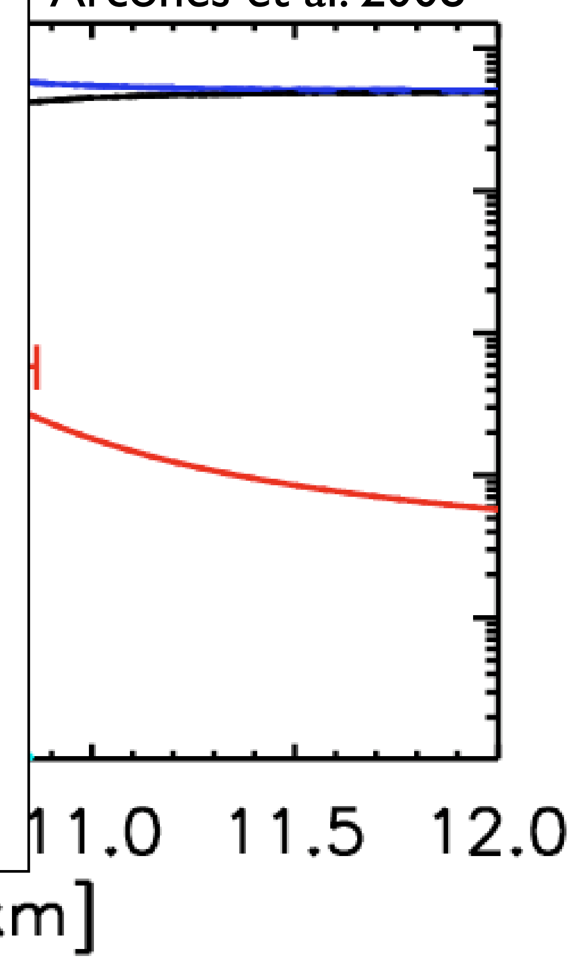
• NSE: sev…
(dotted li…

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



Arcones, Martinez-Pinedo, Roberts, Woosley 2010 (submitted A&A)

Arcones et al. 2008



Light nuclei: Equations of State

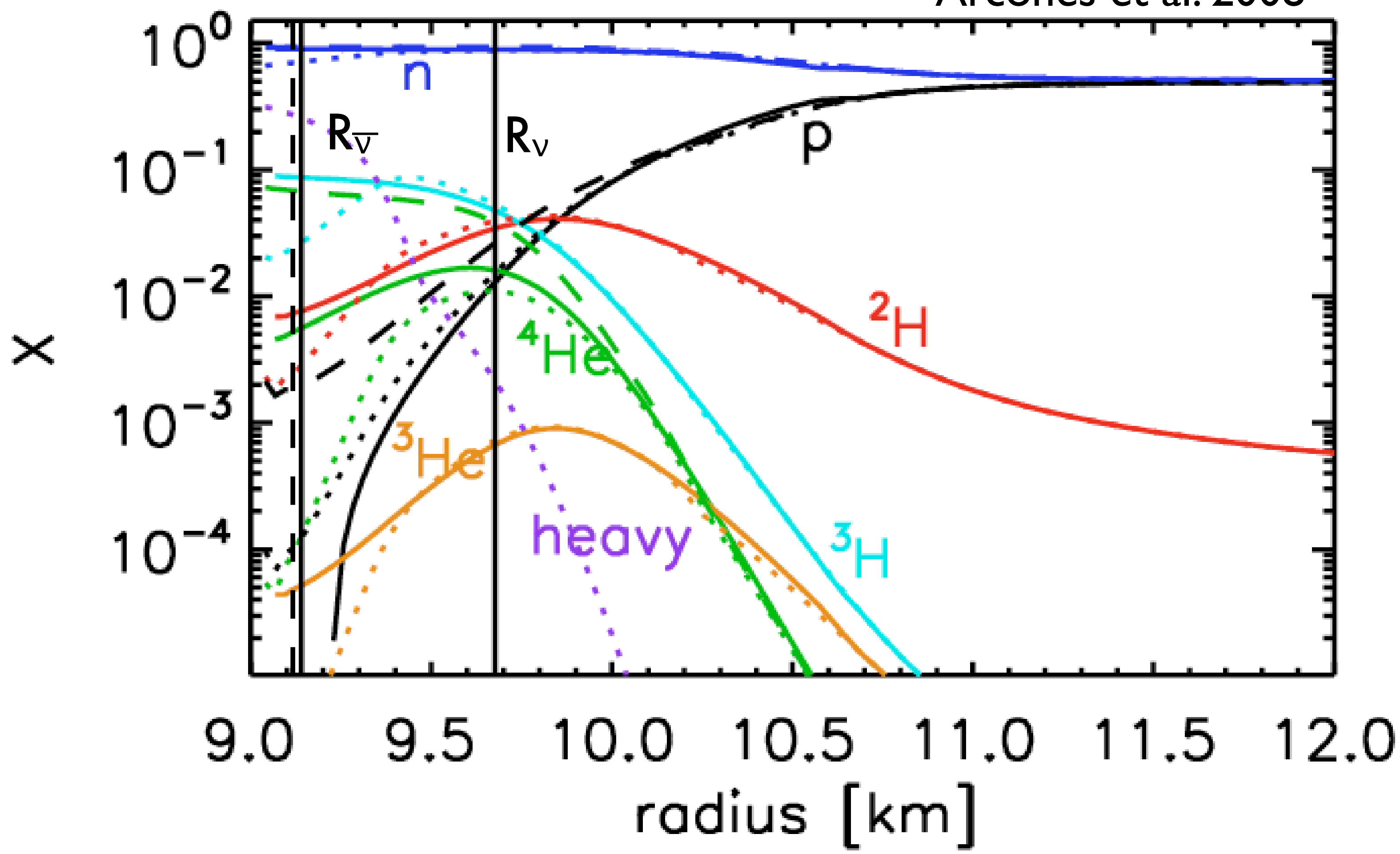
- The EOS used in supernova simulations include neutron, protons, alpha-particles, and a representative heavy nucleus (Lattimer & Swesty 1991, Shen et al. 1998, or EOS based on NSE). This is o.k. for low densities and high temperatures.

- 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).

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)

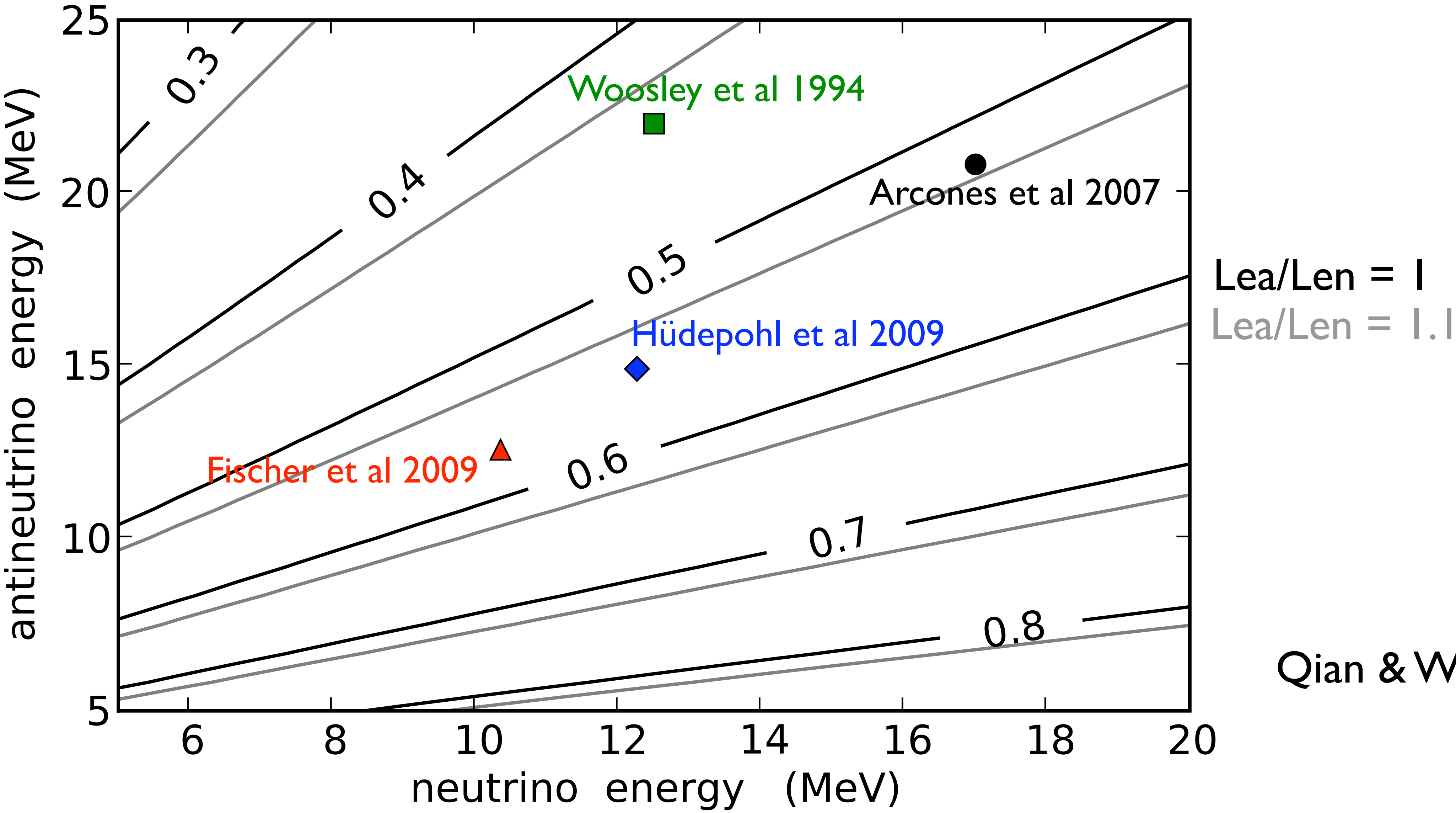
Arcones et al. 2008



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

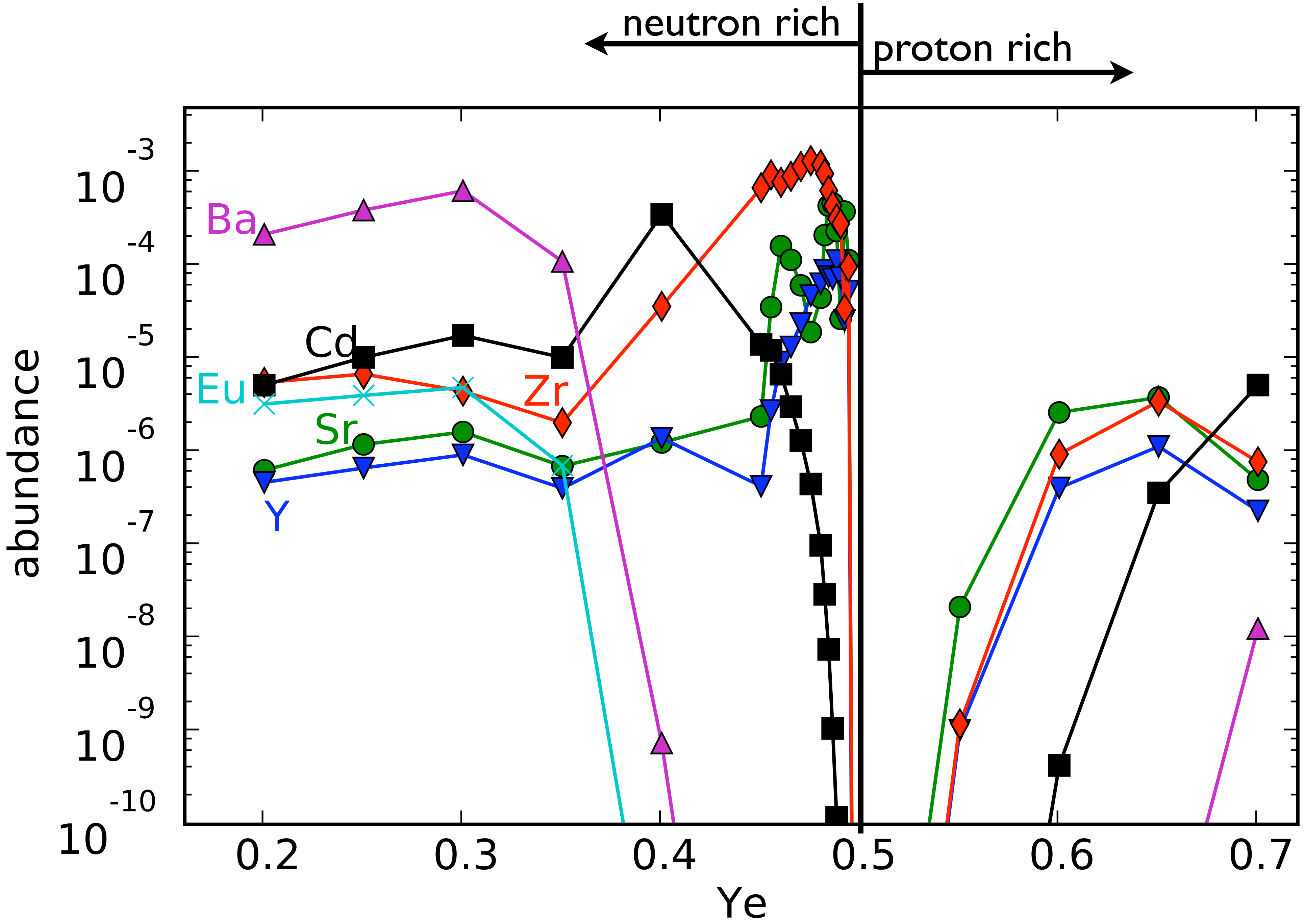


Qian & Woosley 1996

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

Nucleosynthesis and electron fraction

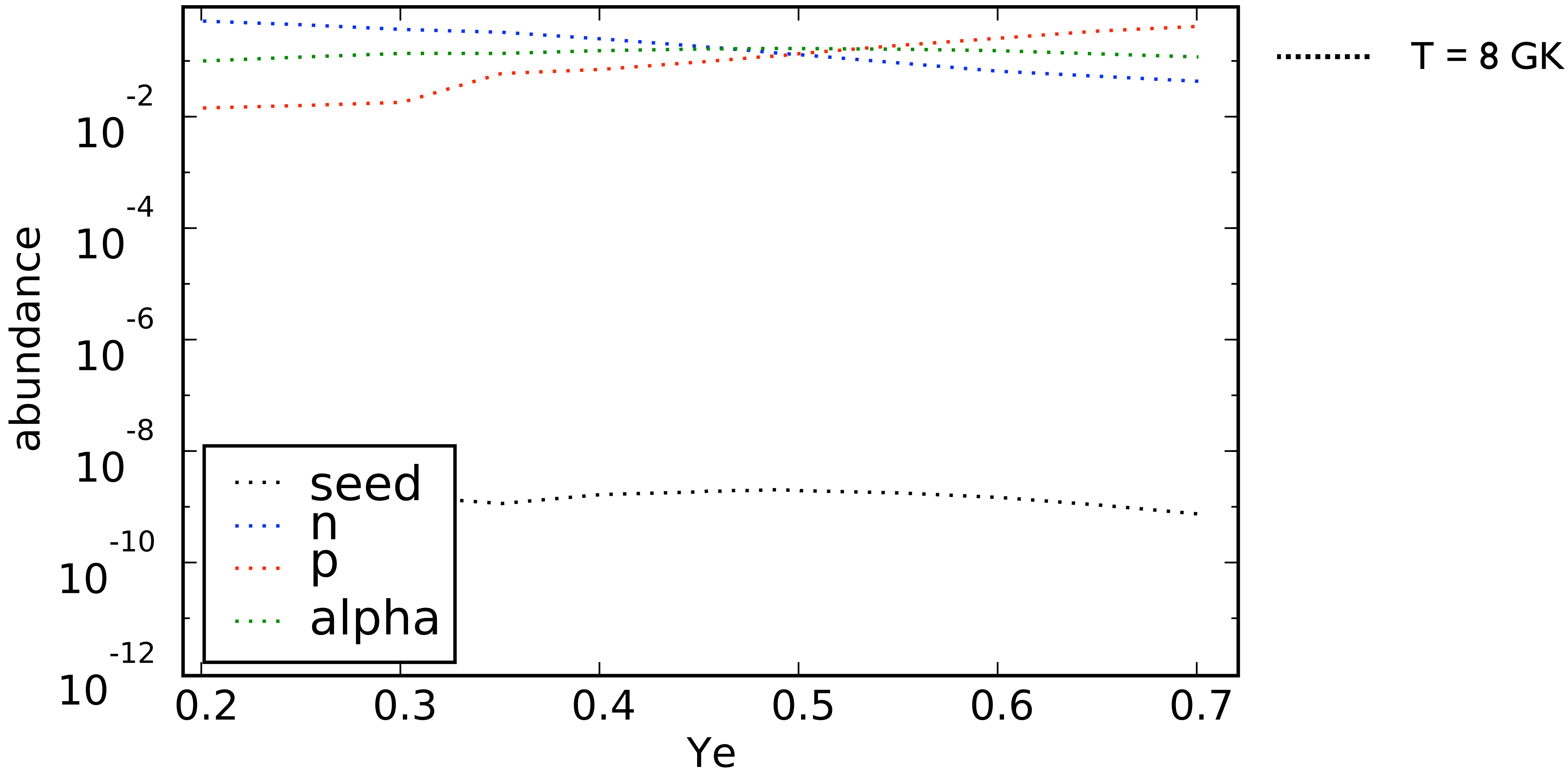
Study the impact of the electron fraction on the production of LEPP elements (Sr, Y, Zr)
(Arcones & Montes, in prep.)



LEPP elements in neutron- and proton-rich conditions

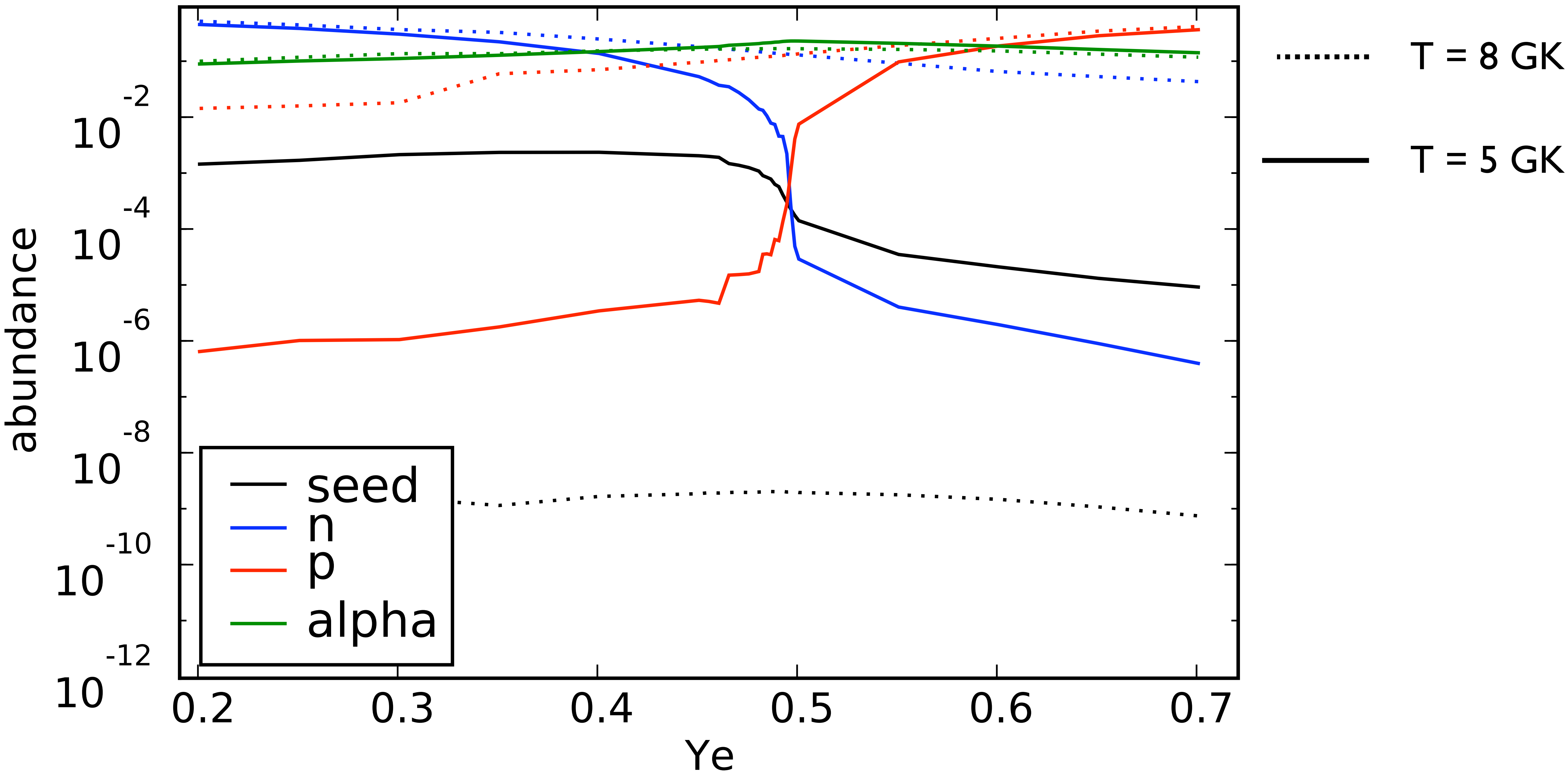
Nucleosynthesis and electron fraction

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.

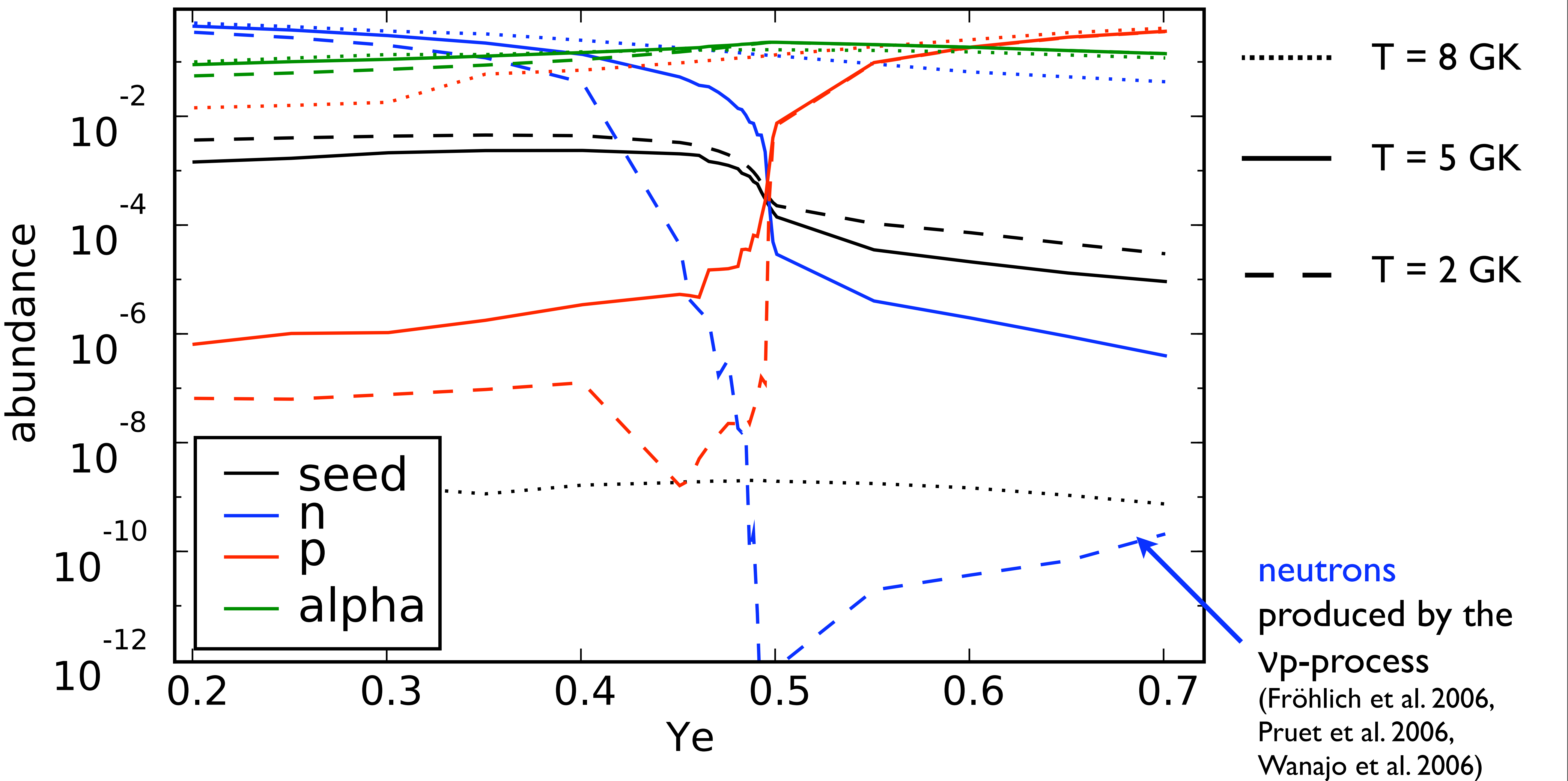


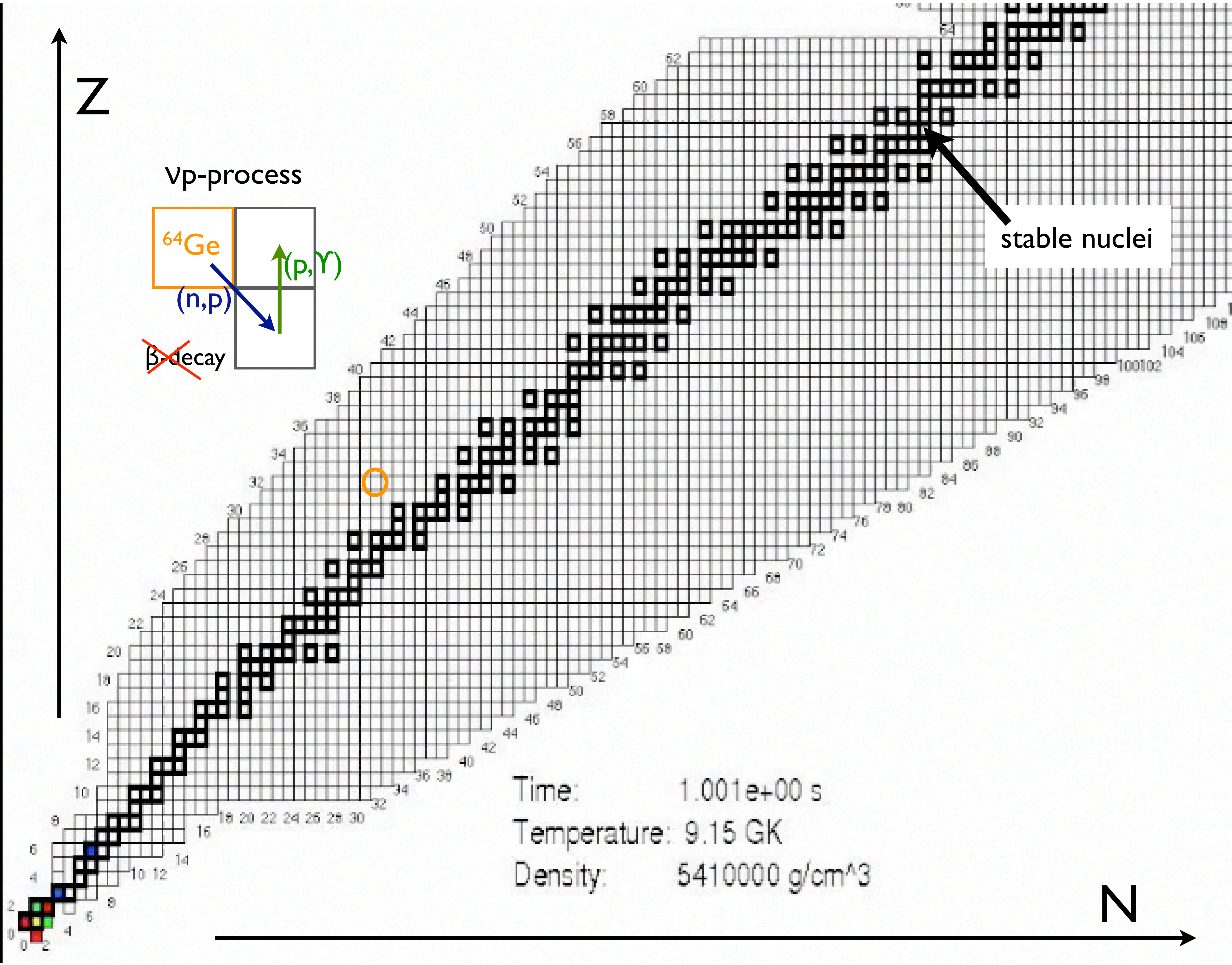
Nucleosynthesis and electron fraction

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

Alpha particles recombine forming seed nuclei.

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





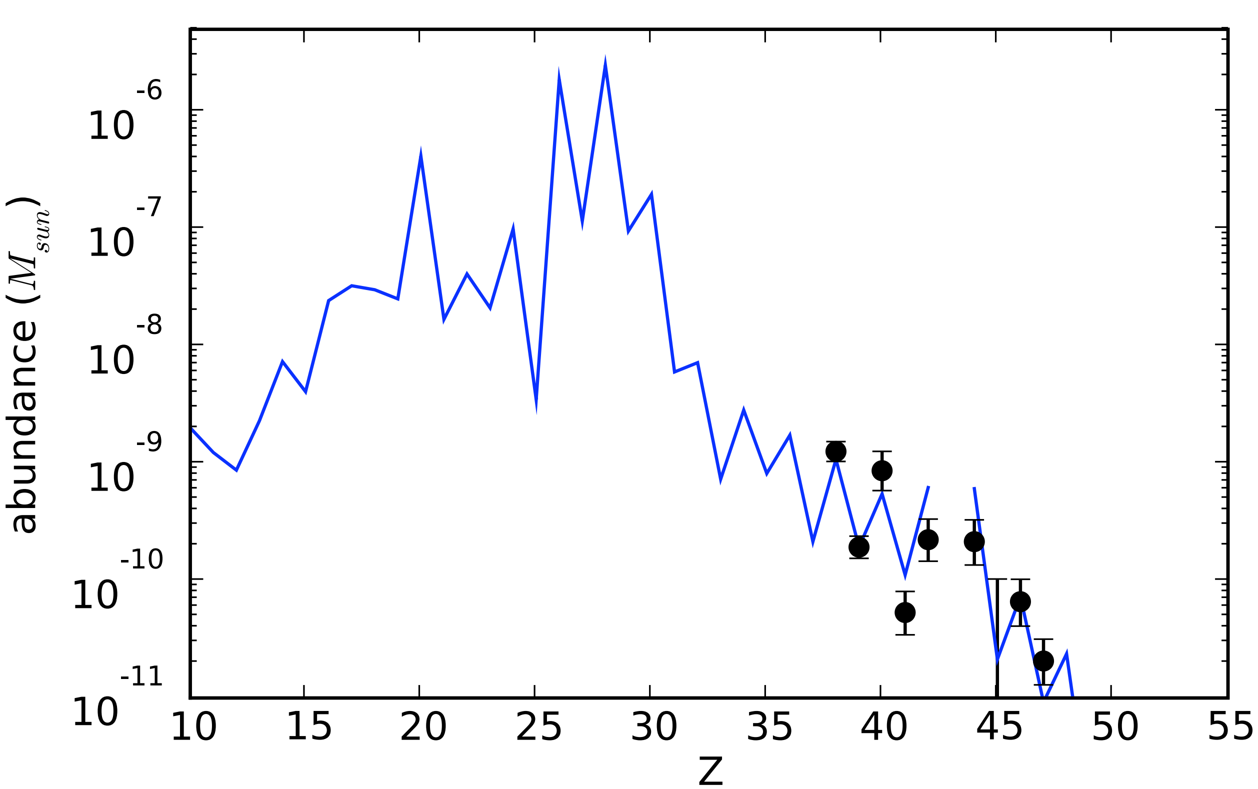
Z
νp-process
^{64}Ge
(p,γ)
(n,p)
~~β-~~decay
stable nuclei
Time: 1.001e+00 s
Temperature: 9.15 GK
Density: 5410000 g/cm^3
N

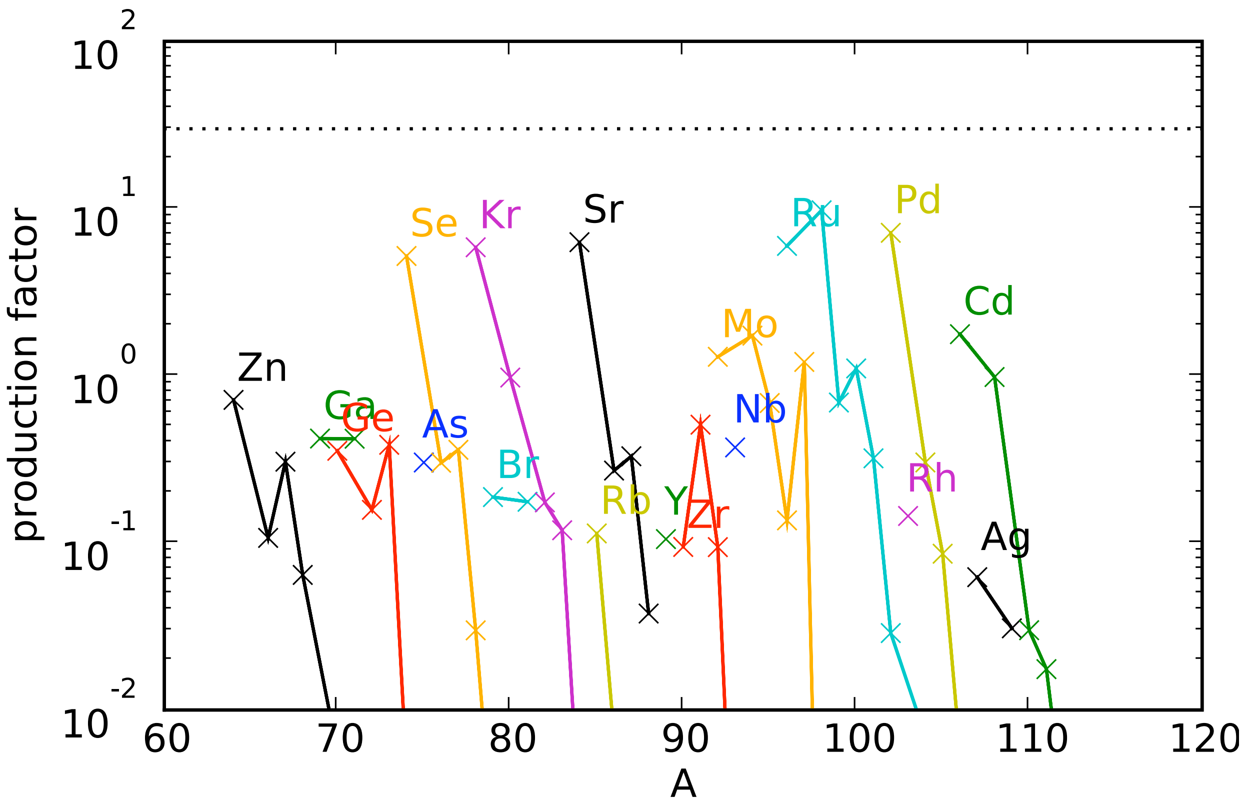
LEPP in proton-rich ejecta

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.





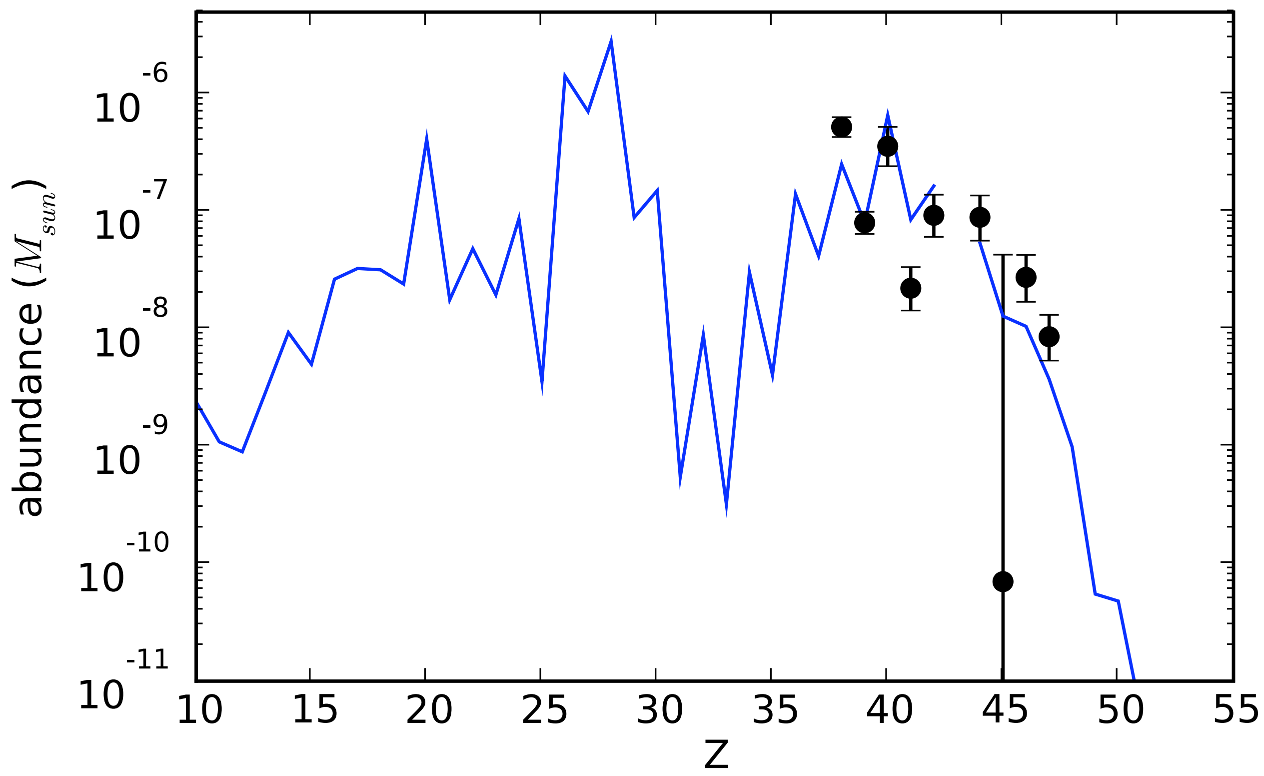
Problem: in the LEPP component of the solar system there are also neutron-rich nuclei.

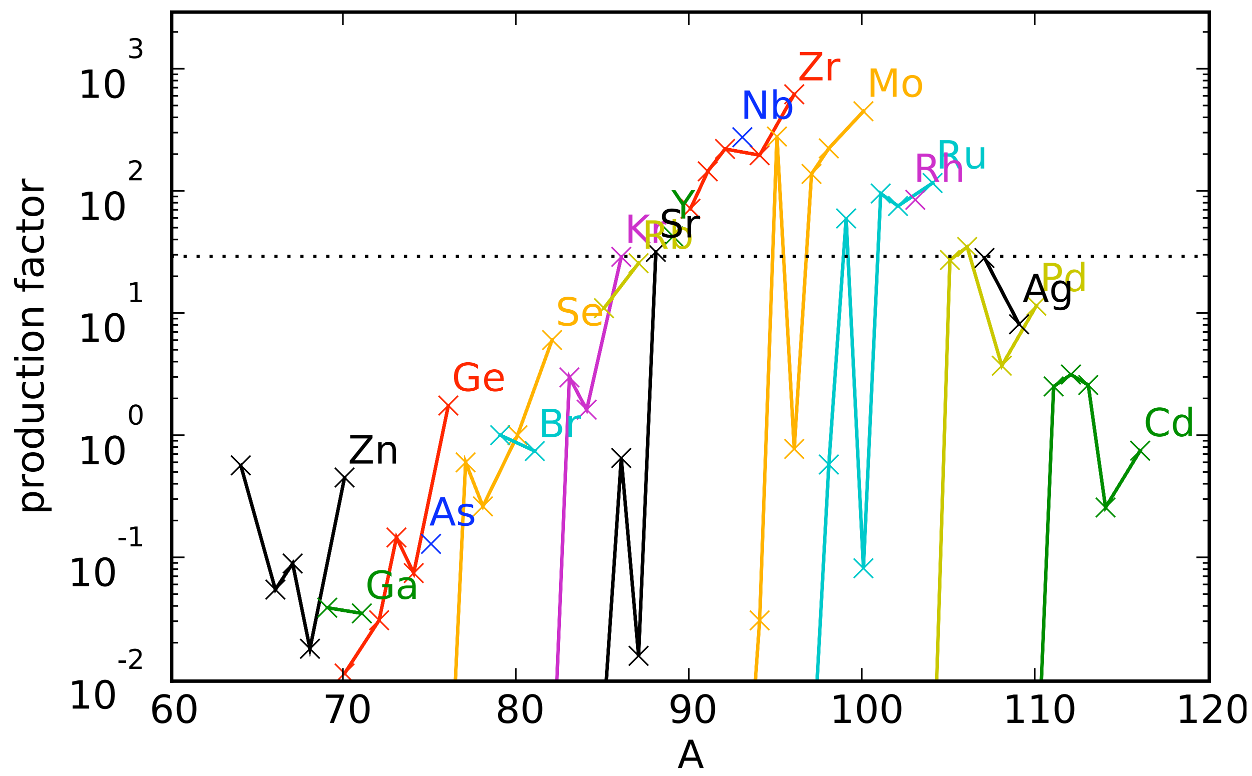
Isotopic abundances from UMP stars will give rise new insights.

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.

Conclusions (LEPP)

- First comparison of the LEPP pattern and nucleosynthesis calculations (Arcones&Montes, in prep.) based on hydrodynamical wind simulations (Arcones et al. 2007).

- 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 (Arcones et al. 2008).

- LEPP pattern is reproduced in neutron- and proton-rich ejecta.

and outlook

- Multi-dimensional simulations with detailed neutrino transport.

- Include light elements and corresponding neutrino reactions.

- Use abundances to constrain Y_e evolution.

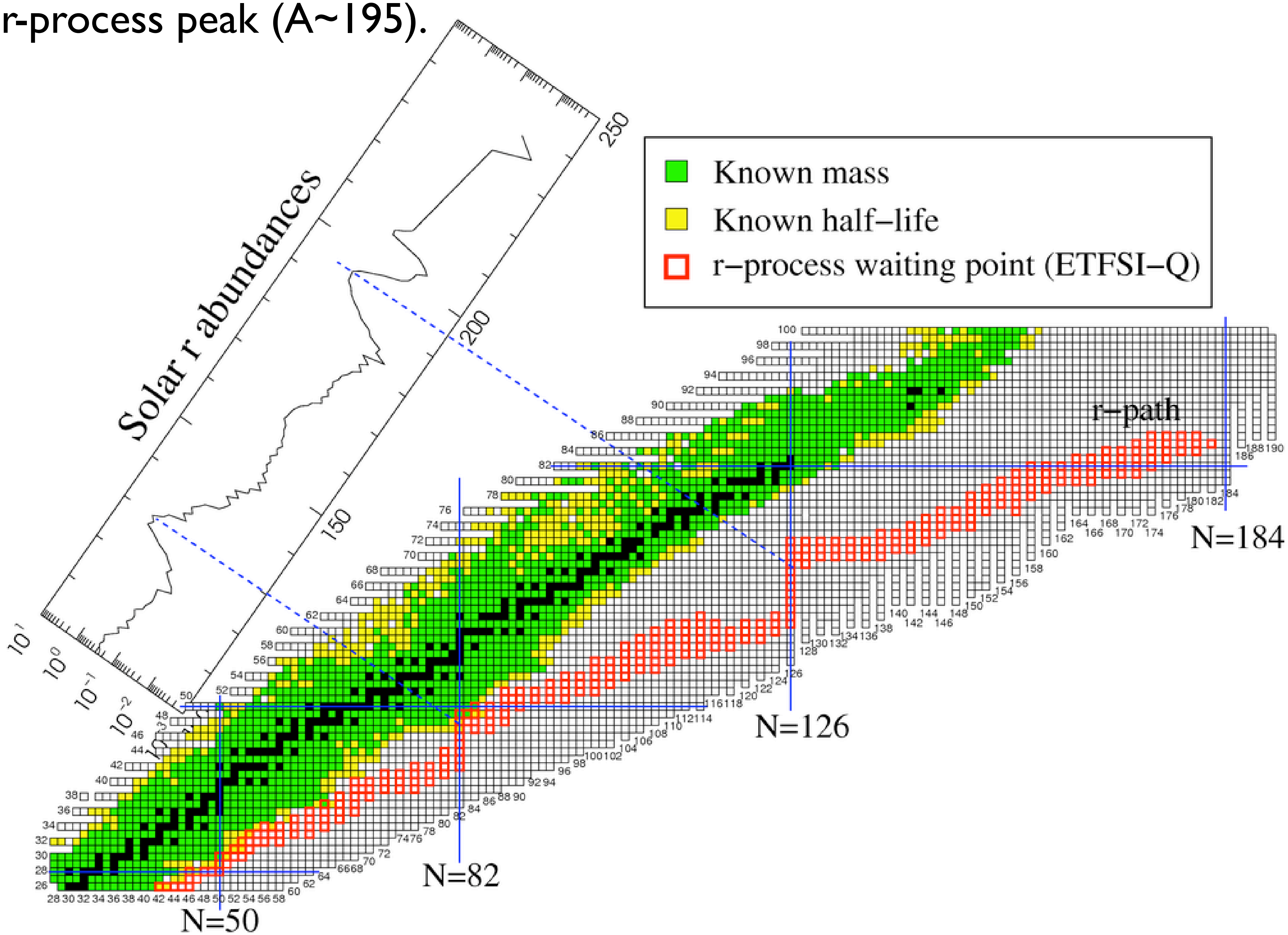
- Observations of isotopic abundances in old stars can discriminate.

r-process

Current supernova simulations produce too low neutron-to-seed ratio for the r-process.

But can be used as basis to study the impact of nuclear physics input.

We artificially increase the entropy to reach high enough neutron-to-seed ratio to form the third r-process peak (A~195).



r-process: long-time evolution and reverse shock

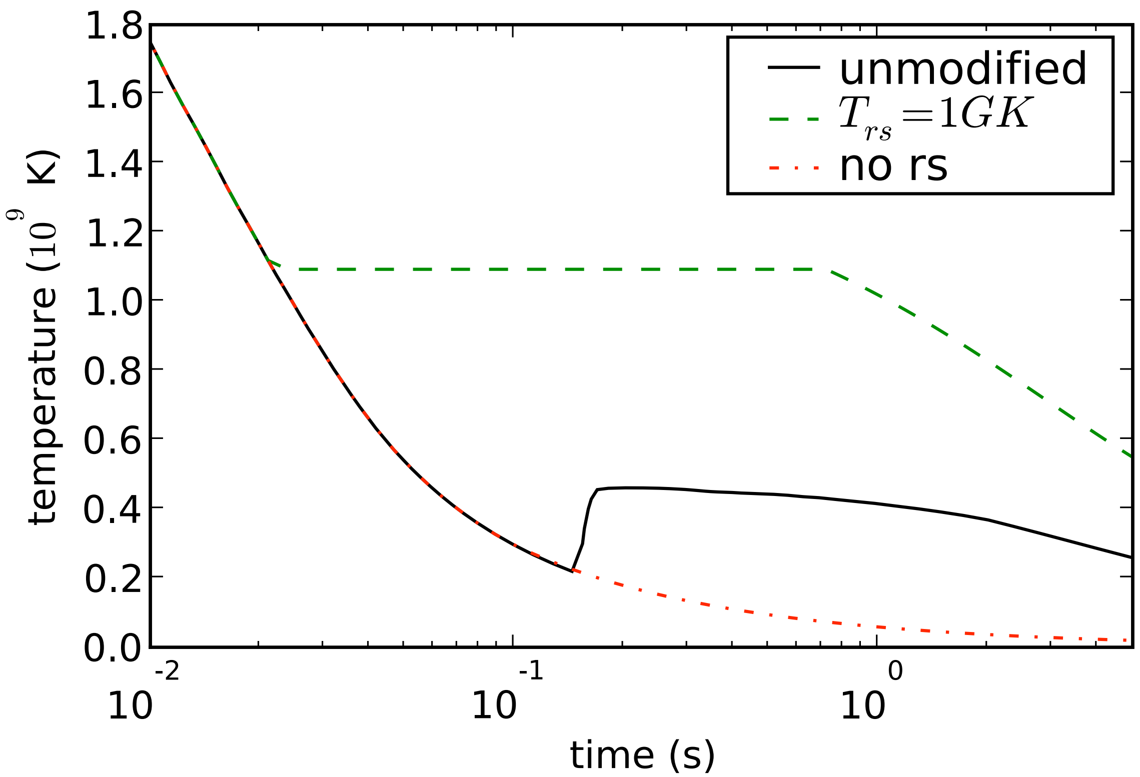
Evolution of T and ρ during the alpha-process determines the neutron-to-seed ratio and thus the possibility of forming heavy elements.

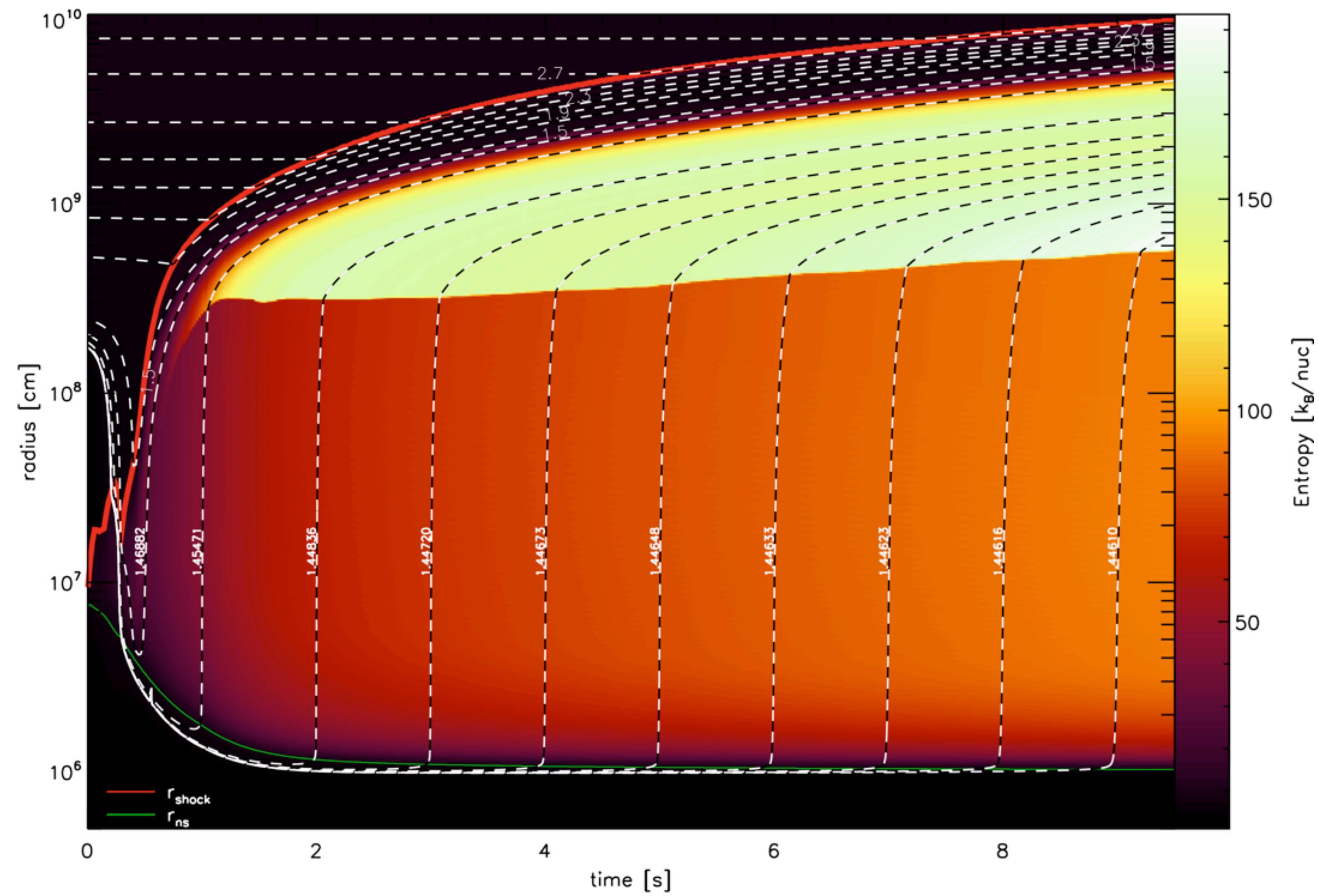
However, the dynamical evolution after the freeze-out of charged-particle reactions is also important for understanding the final abundances.

We use one trajectory from our hydrodynamical simulations with the entropy increased: “unmodified”.

Vary the long-time evolution (and later the nuclear mass model):

- reverse shock at 1GK
- no reverse shock





r-process: long-time evolution and reverse shock

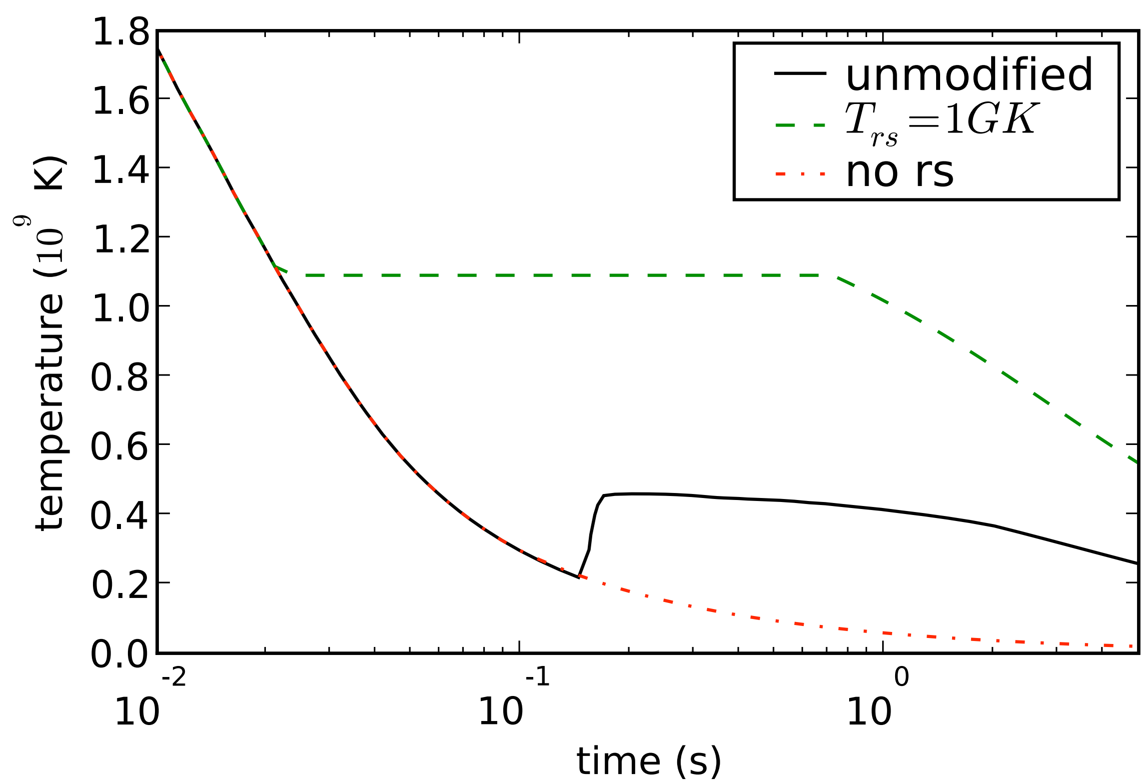
Evolution of T and ρ during the alpha-process determines the neutron-to-seed ratio and thus the possibility of forming heavy elements.

However, the dynamical evolution after the freeze-out of charged-particle reactions is also important for understanding the final abundances.

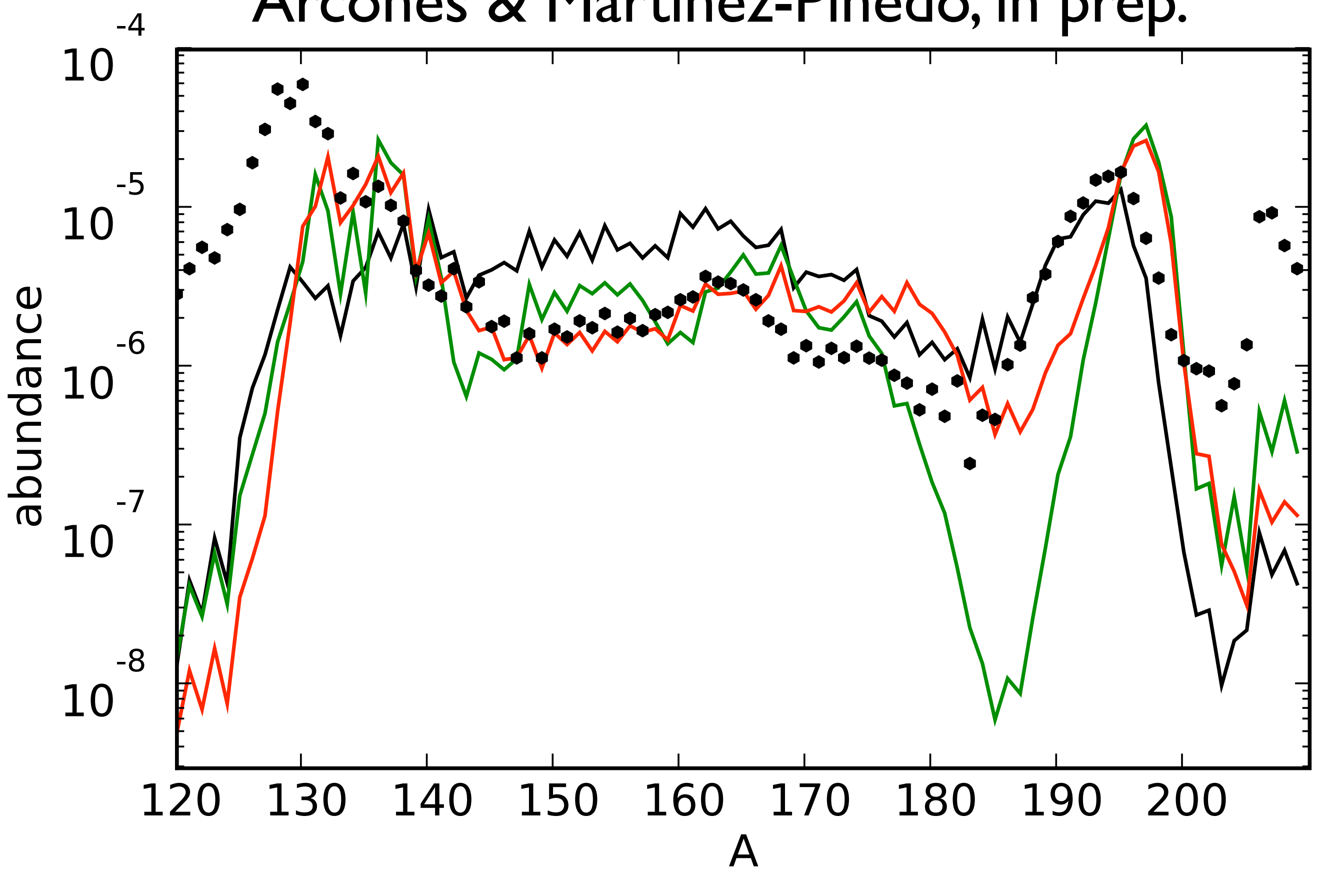
We use one trajectory from our hydrodynamical simulations with the entropy increased: "unmodified".

Vary the long-time evolution (and later the nuclear mass model):

- reverse shock at 1GK
- no reverse shock

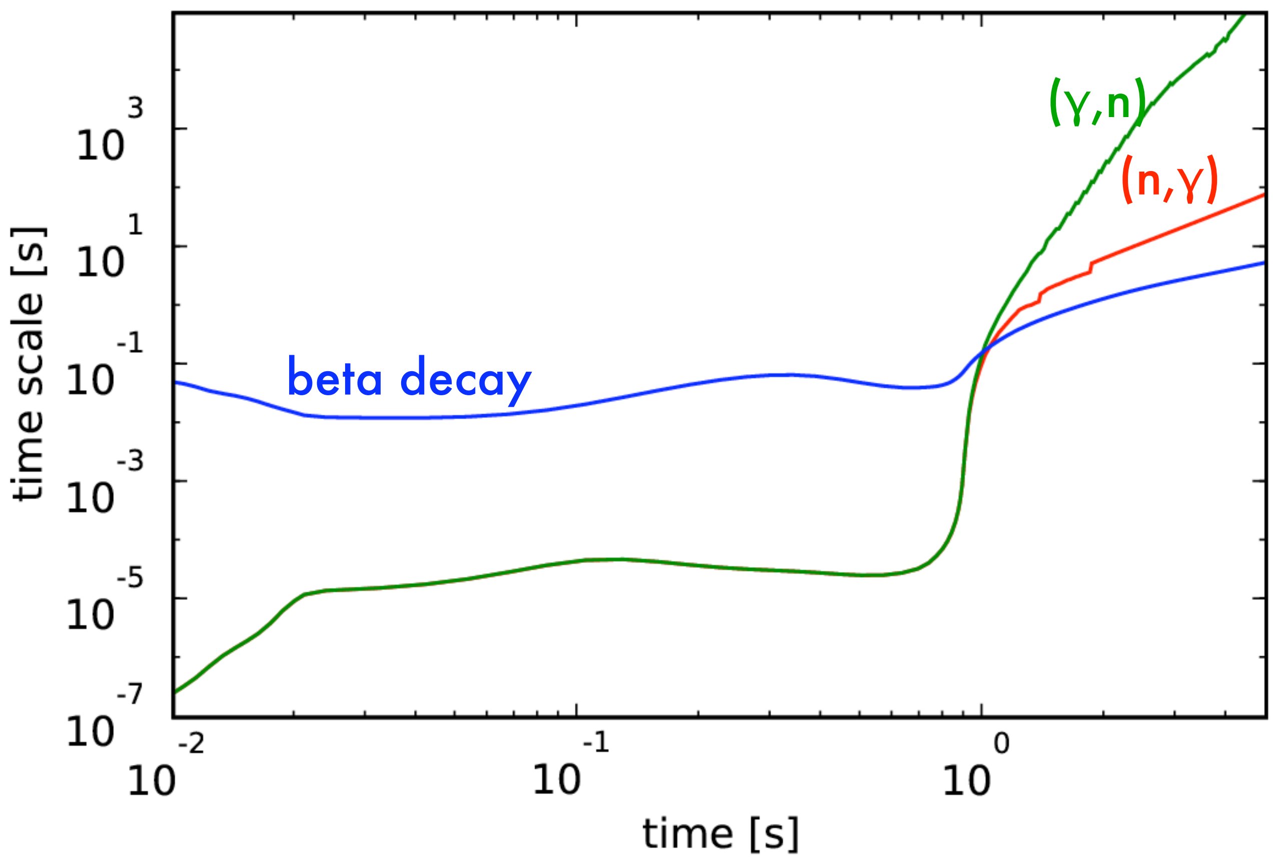


Arcones & Martinez-Pinedo, in prep.



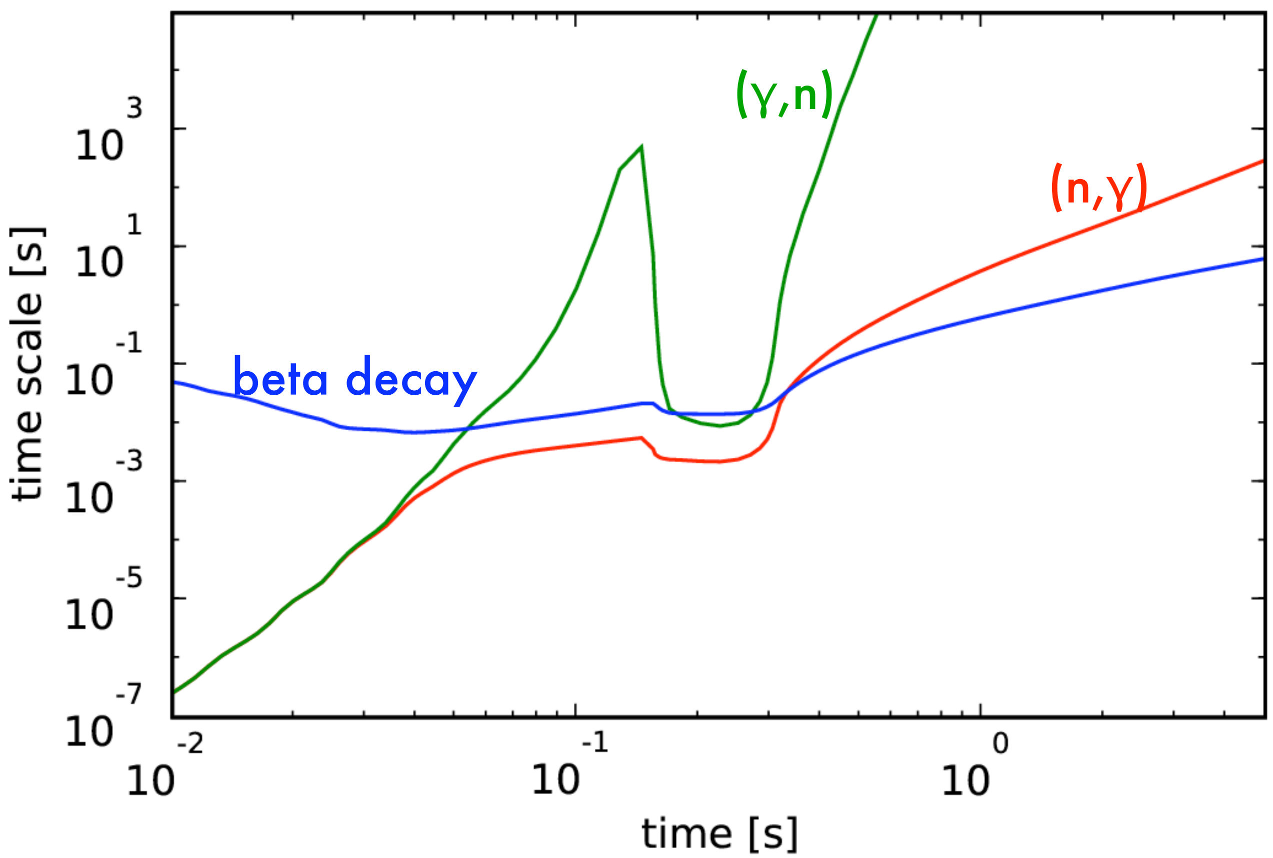
Long-time evolution: high vs. low temperature

High temperature



The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Kratz et al. 1993).

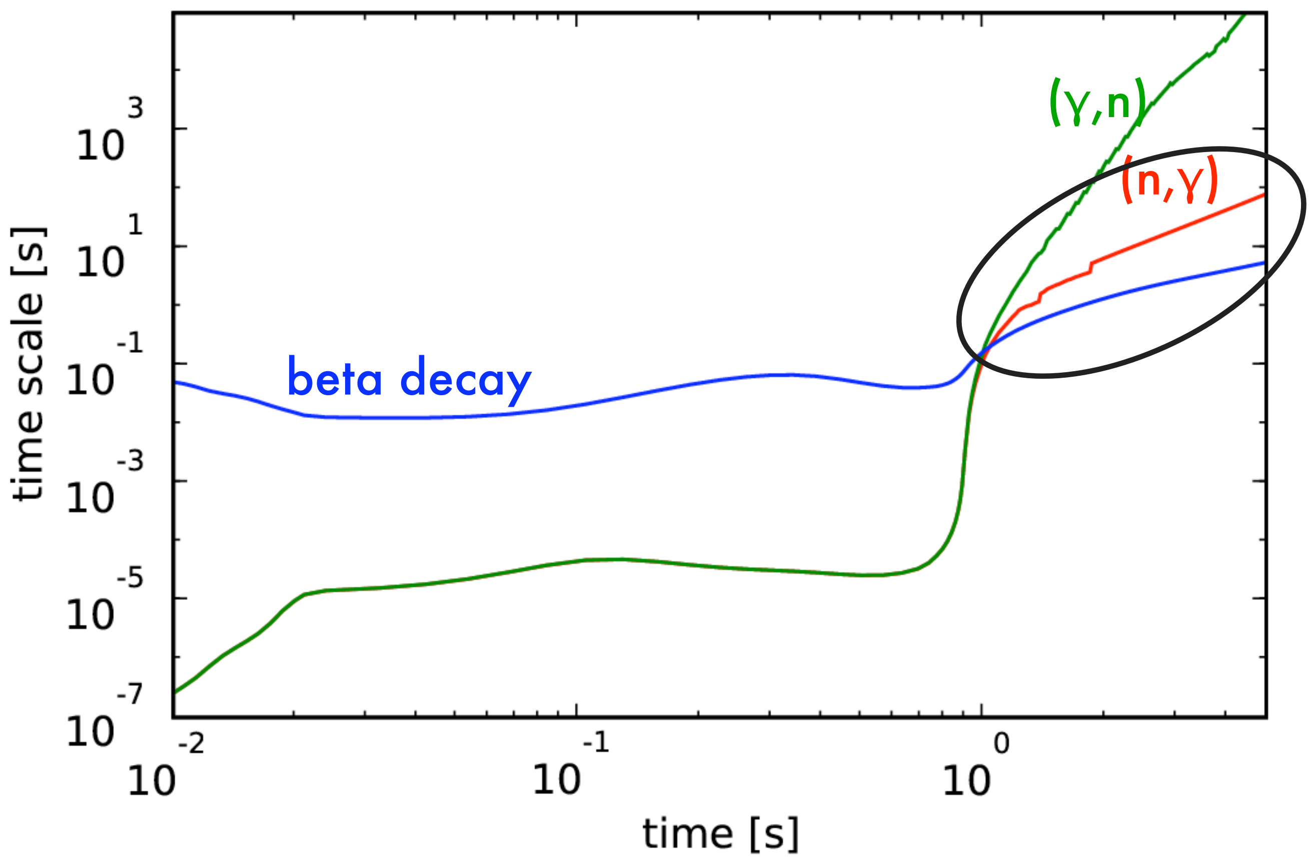
Low temperature



Competition between beta decay and neutron capture (Blake & Schramm 1976): cold r-process (Wanajo 2007)

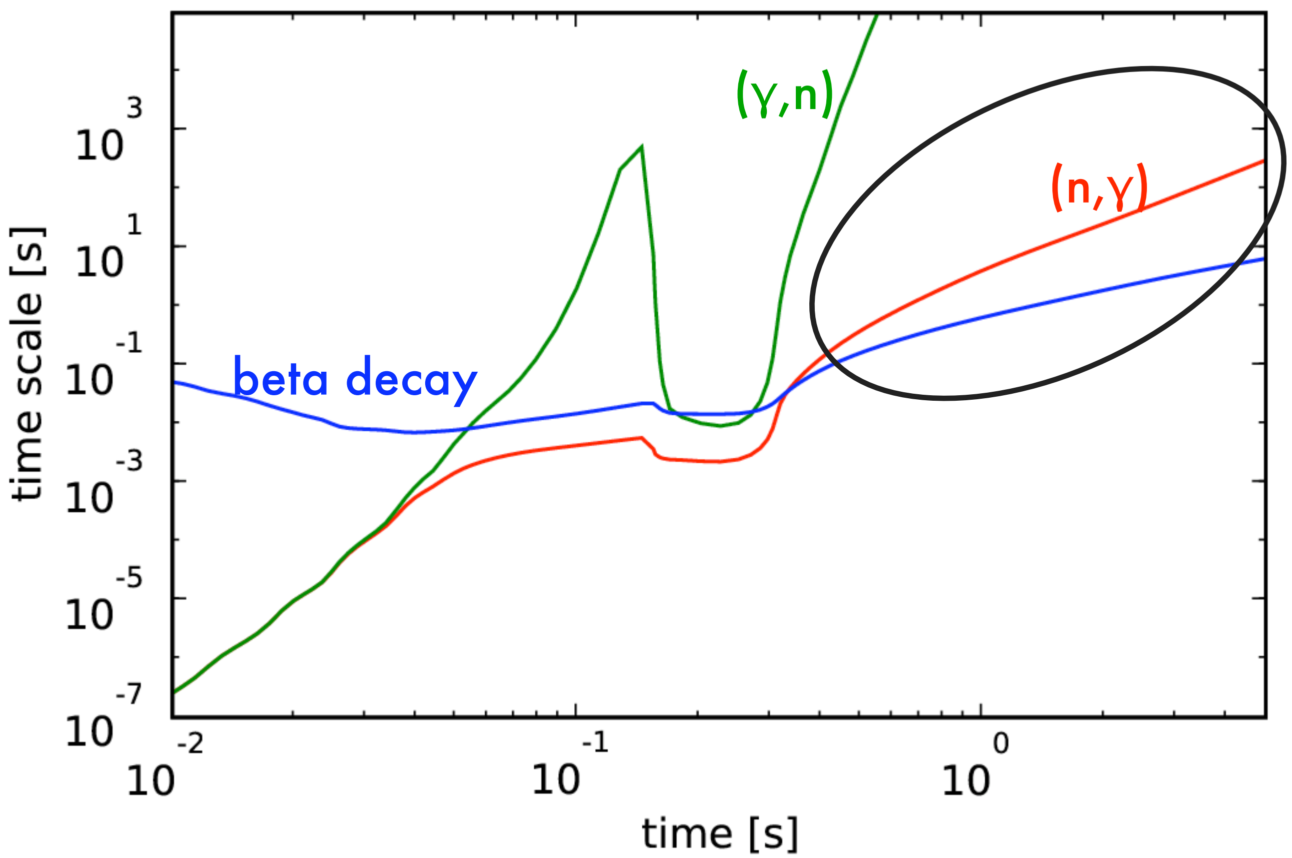
Long-time evolution: high vs. low temperature

High temperature



The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Kratz et al. 1993).

Low temperature



Competition between beta decay and neutron capture (Blake & Schramm 1976): cold r-process (Wanajo 2007)

Final abundances are strongly affected by neutron captures and beta decays that compete when matter moves back to stability.

Sensitivity to mass models

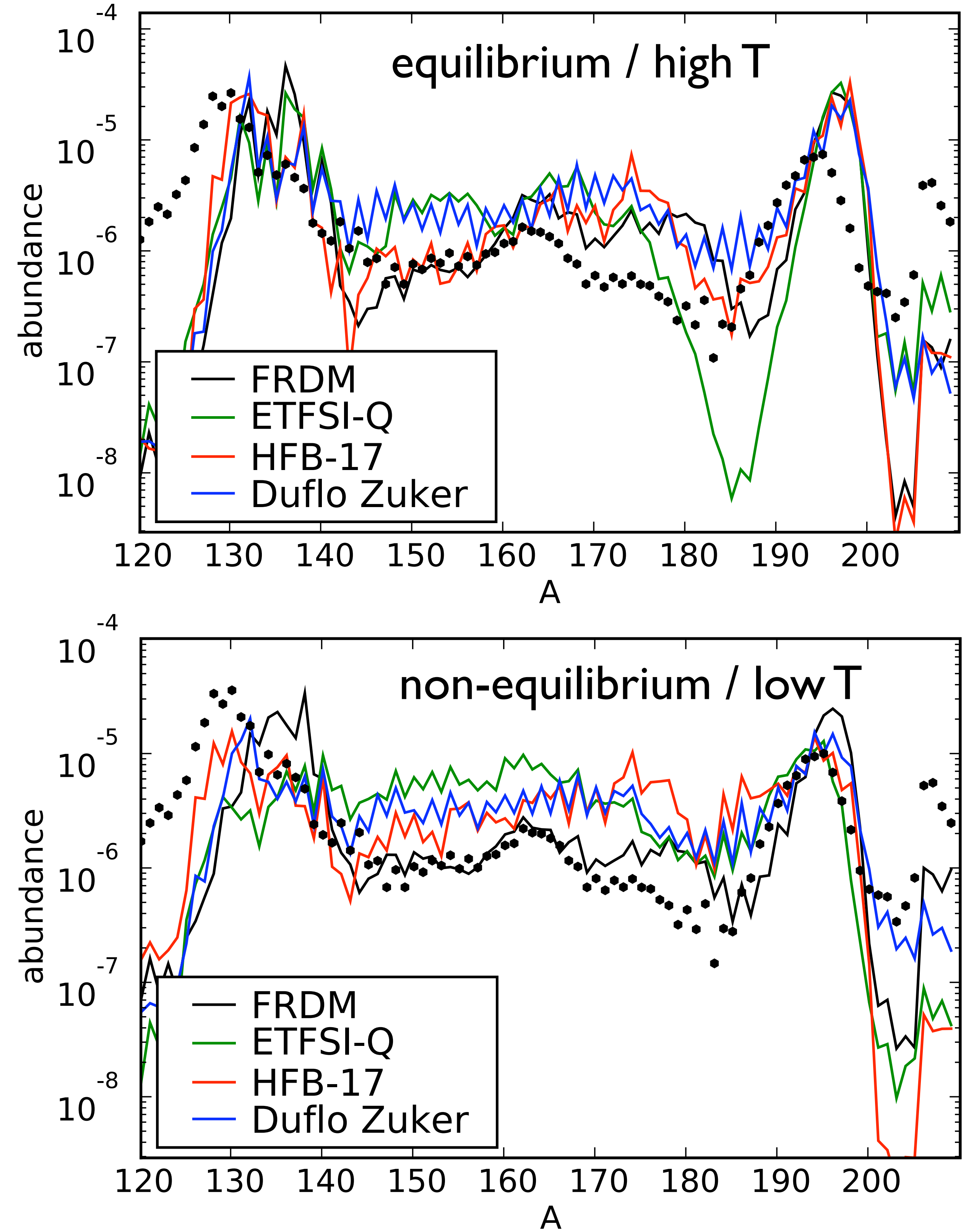
Compare four different mass models:

- FRDM (Möller et al. 1995)
- ETFSI-Q (Pearson et al. 1996)
- HFB-17 (Goriely et al. 2009)
- Duflo&Zuker mass formula

two cases: (n,γ)-(γ,n) equilibrium and non-equilibrium.

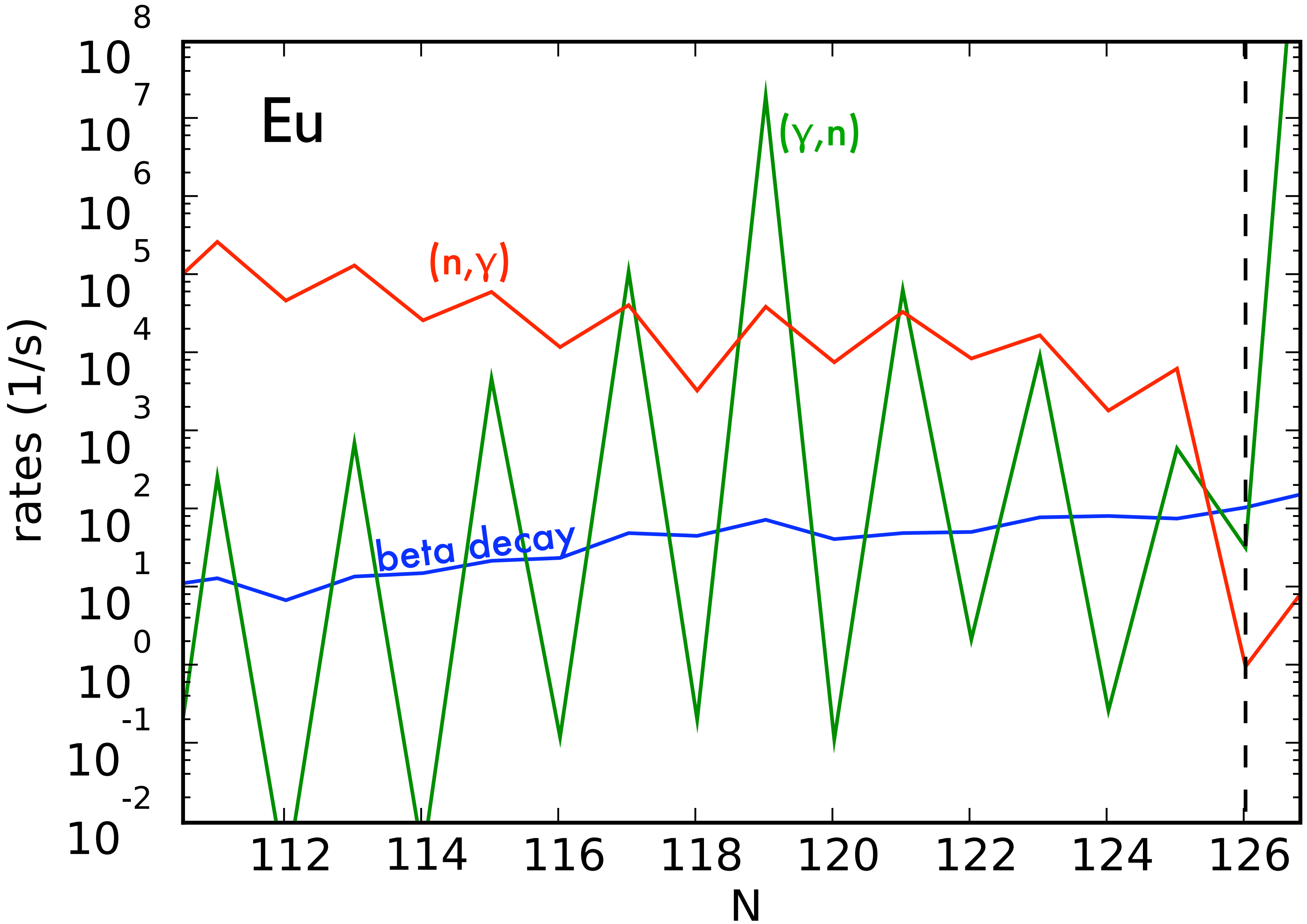
The nuclear physics input affects the final abundances differently depending on the long-time dynamical evolution.

Can we link the behavior of the neutron separation energy to the final abundances?



Arcones & Martinez-Pinedo (in prep.)

Neutron separation energy and rates



Neutron capture:

$\lambda_{(n,\gamma)} = N_n \langle \sigma v \rangle \propto S_n$

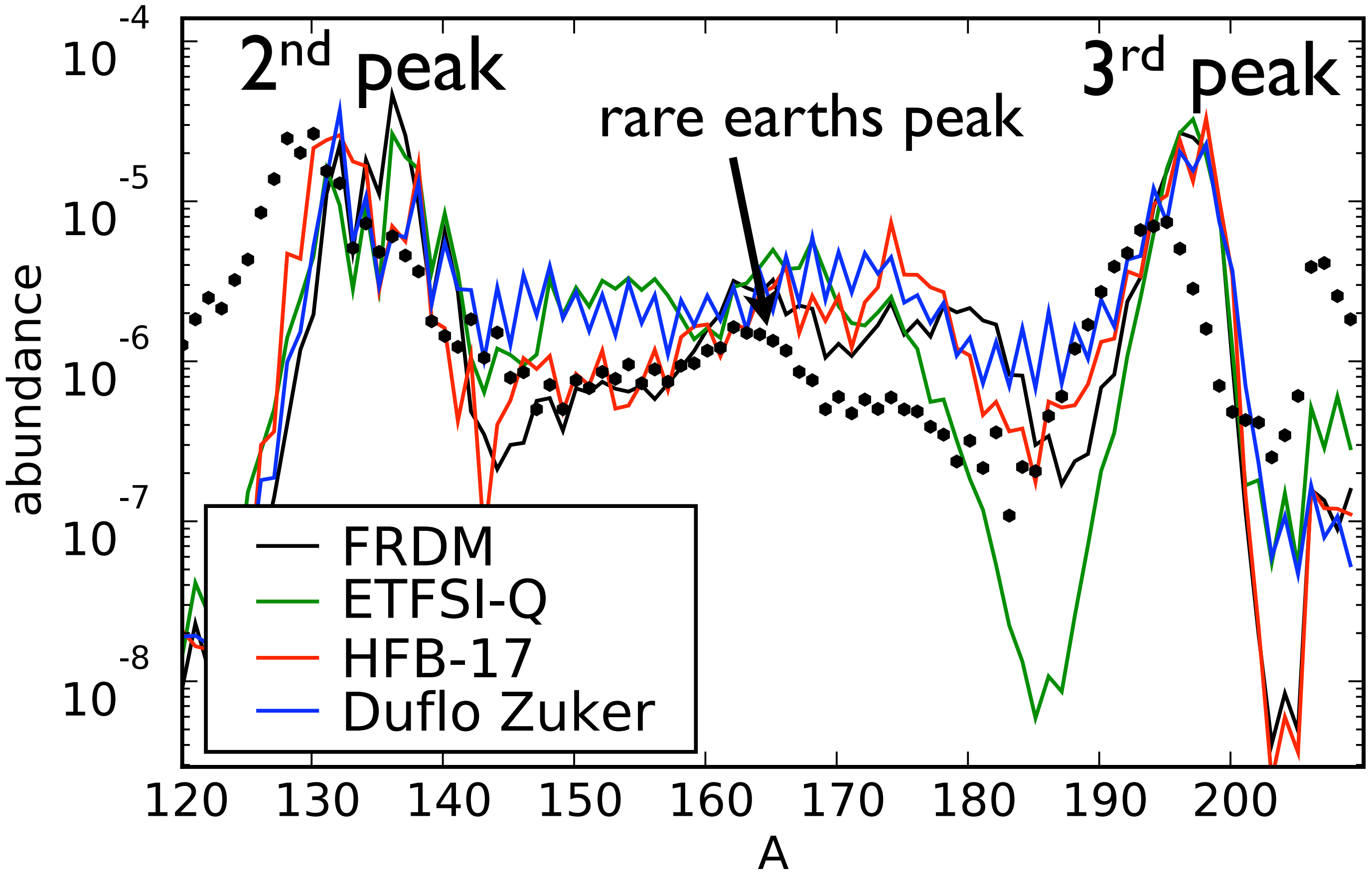
Photo-dissociation:

$\lambda_{(\gamma,n)} \propto \exp(-S_n/kT)$

S_n drops abruptly (magic number): neutron captures become smaller and photo-dissociation larger. Matter accumulates forming a **peak** in the abundance

Constant S_n: neutrons are captured inmediatly and a **hole** appears.

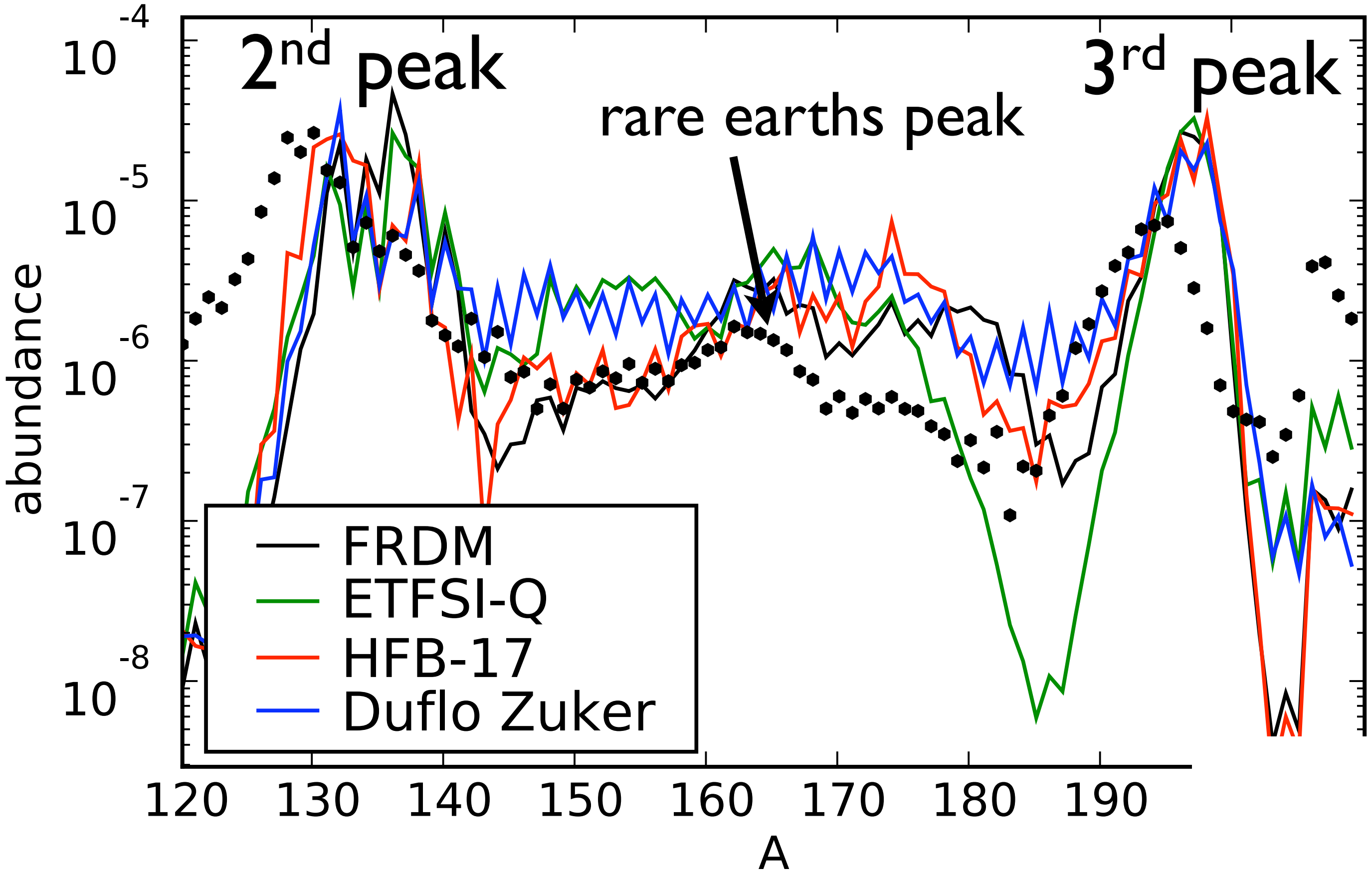
Peaks and holes



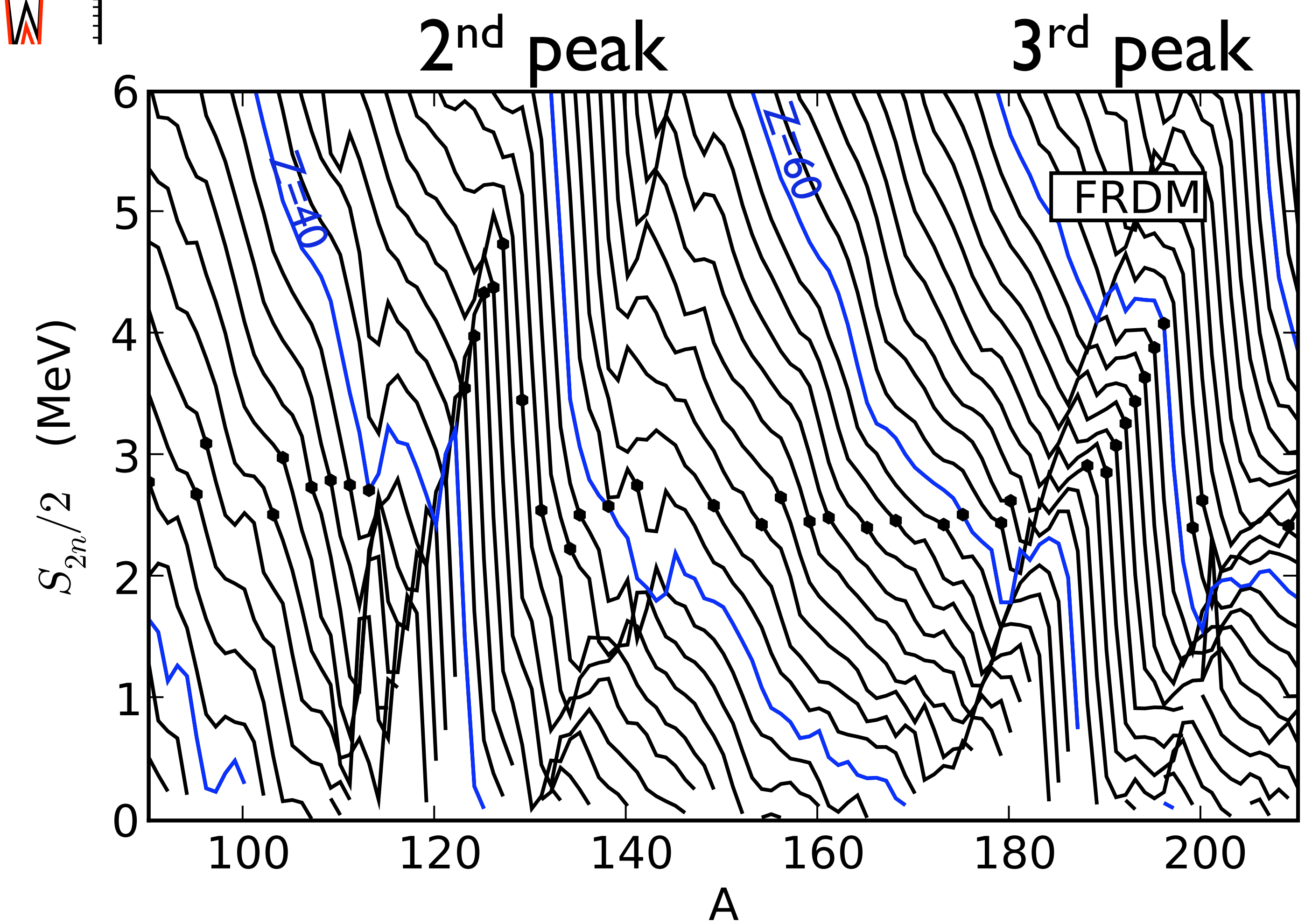
equilibrium / high T

Rare earth peak: Surman et al. 2008

Peaks and holes

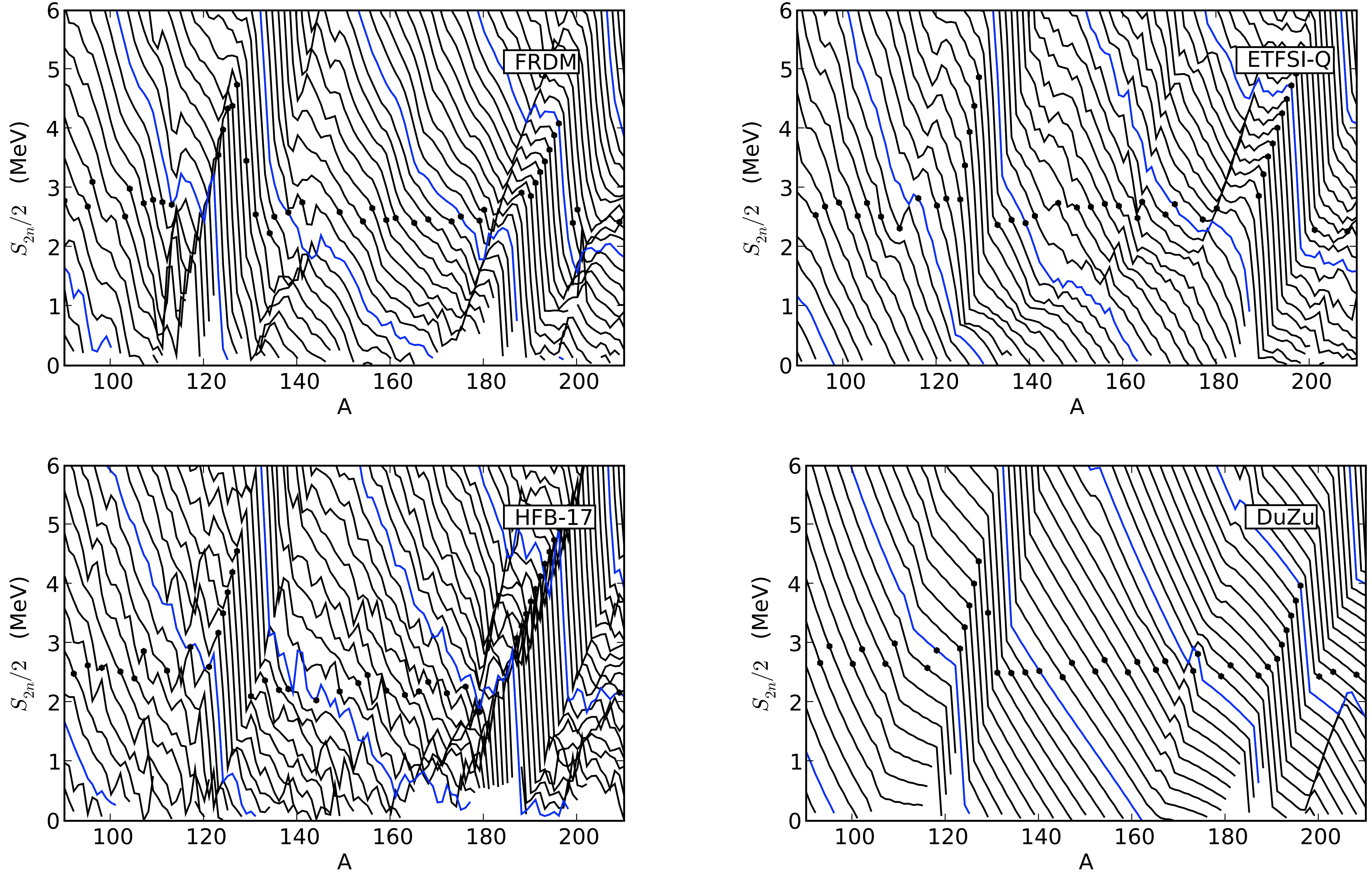


equilibrium / high T

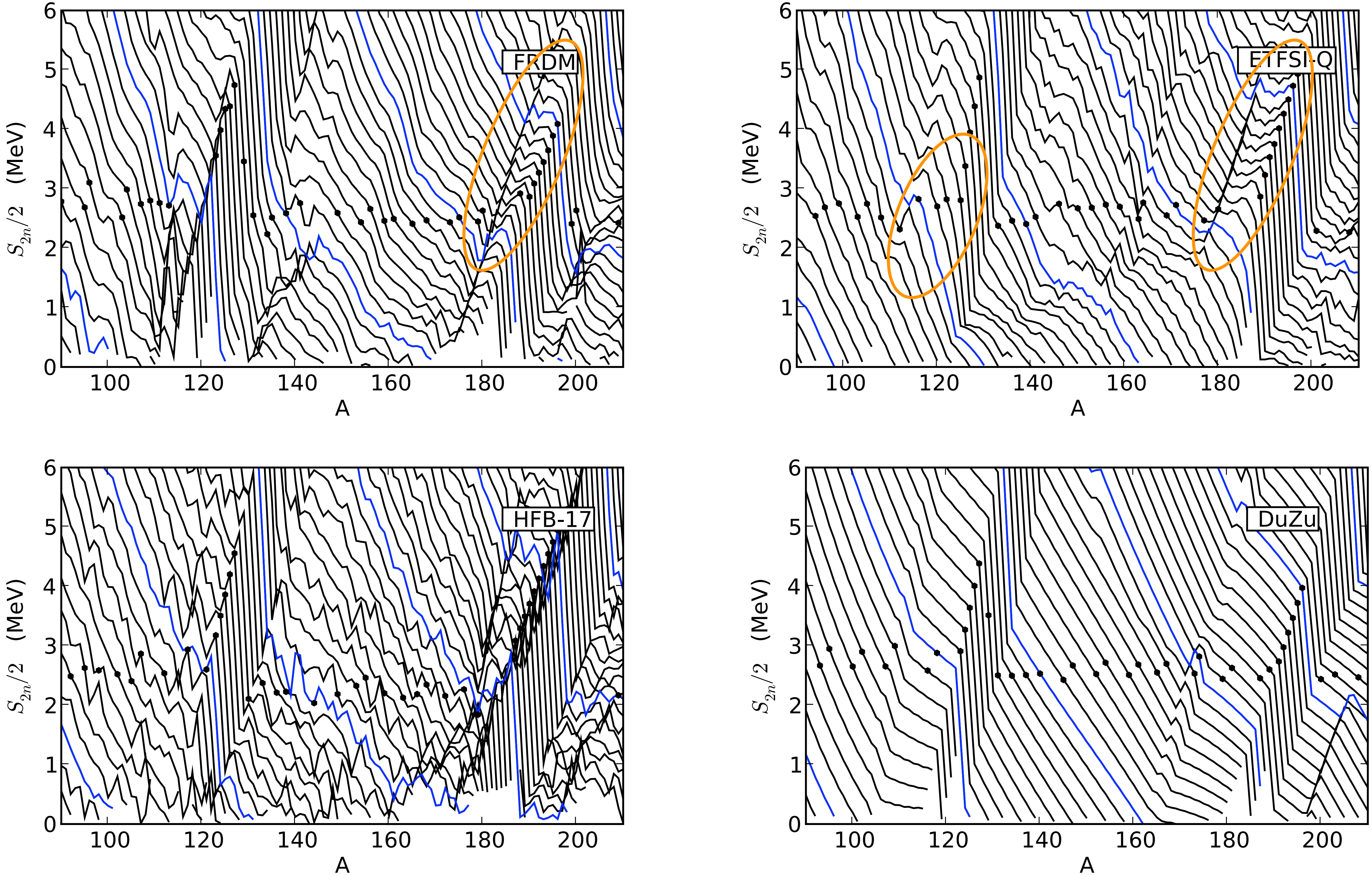


Rare earth peak: Surman et al. 2008

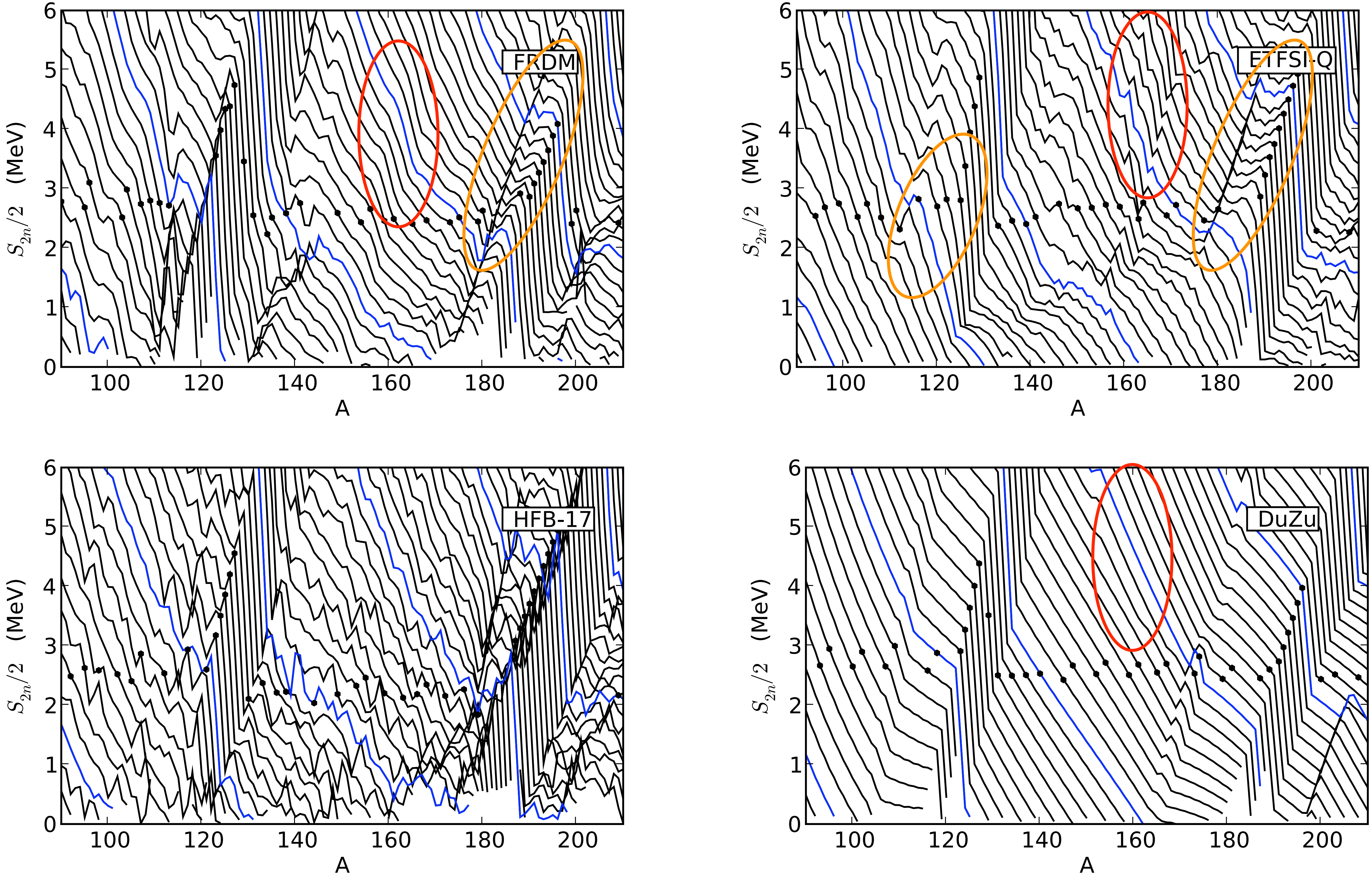
Aspects of different mass models



Aspects of different mass models



Aspects of different mass models

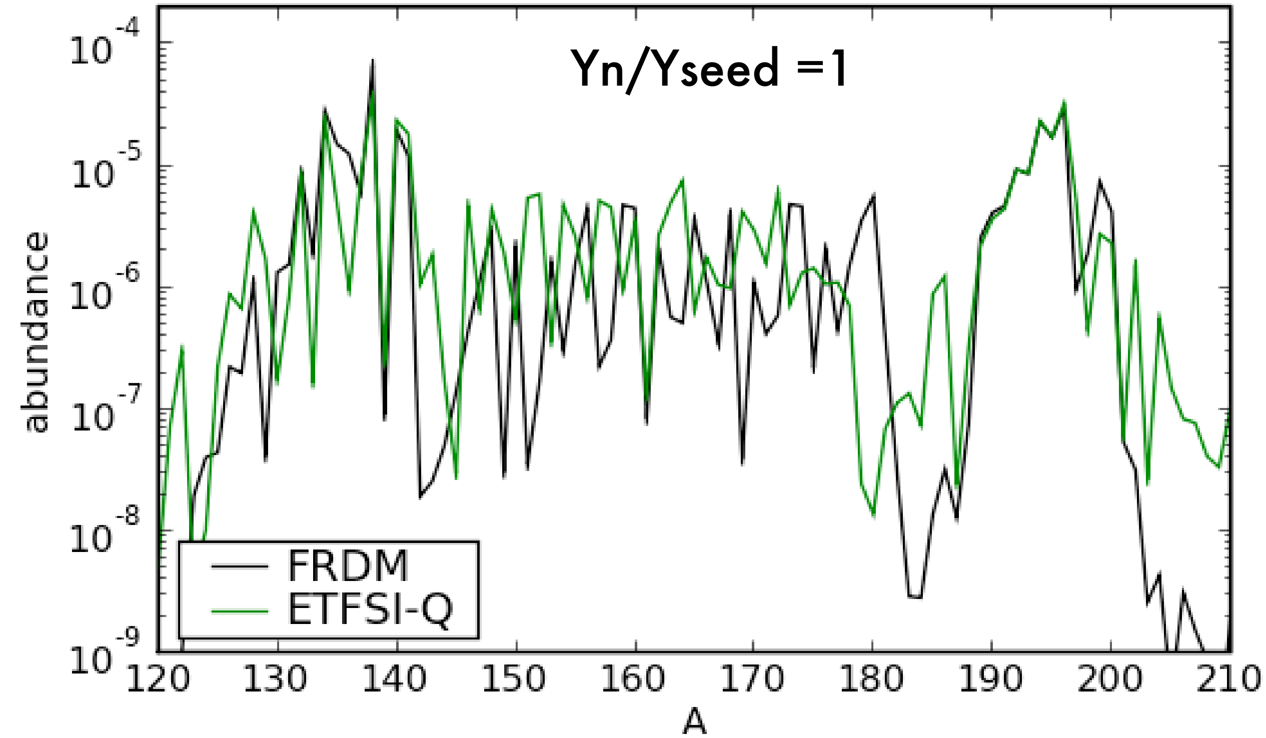


Way back to stability

High temperature evolution:

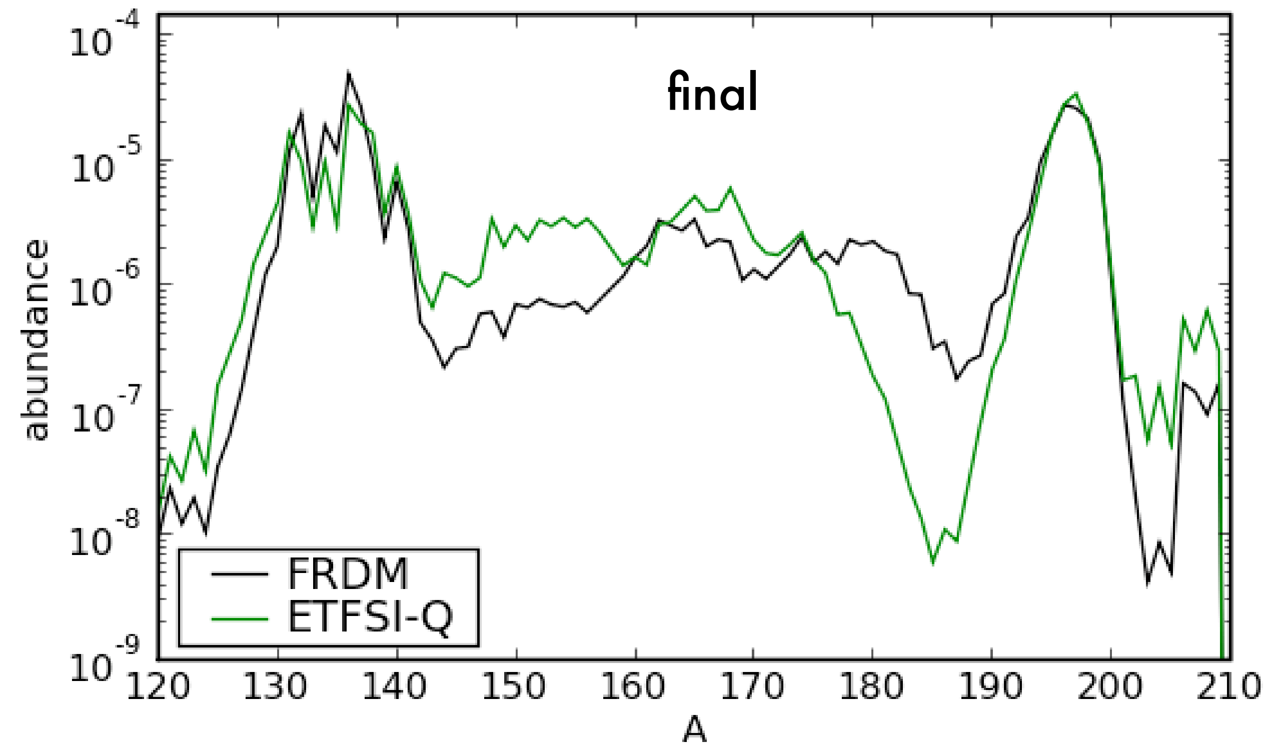
Abundances at freeze-out (Yn/Yseed=1) show odd-even effects following the behavior of the neutron separation energy.

While final abundances are smoother like solar abundances.



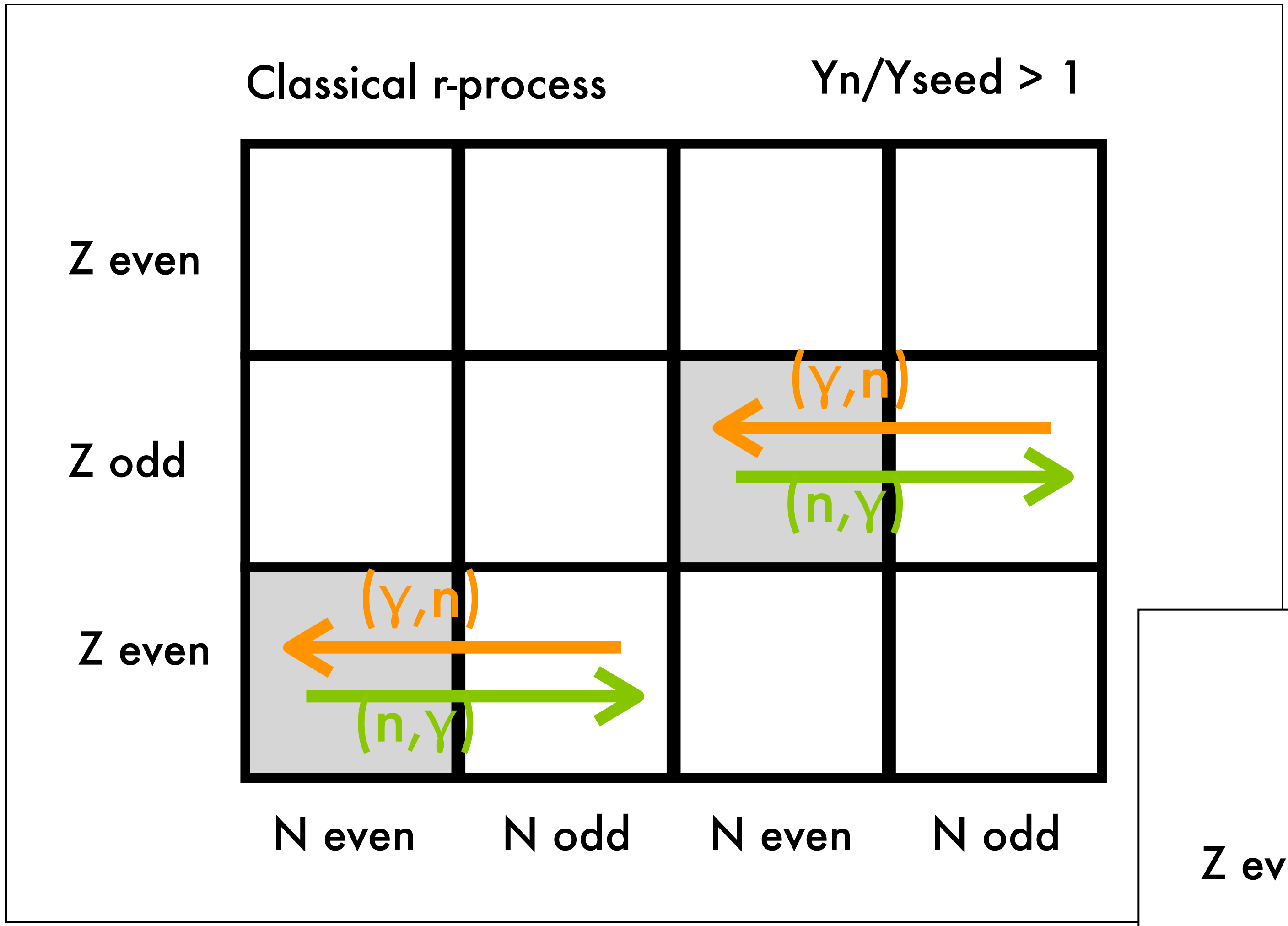
Why does the abundance pattern change?

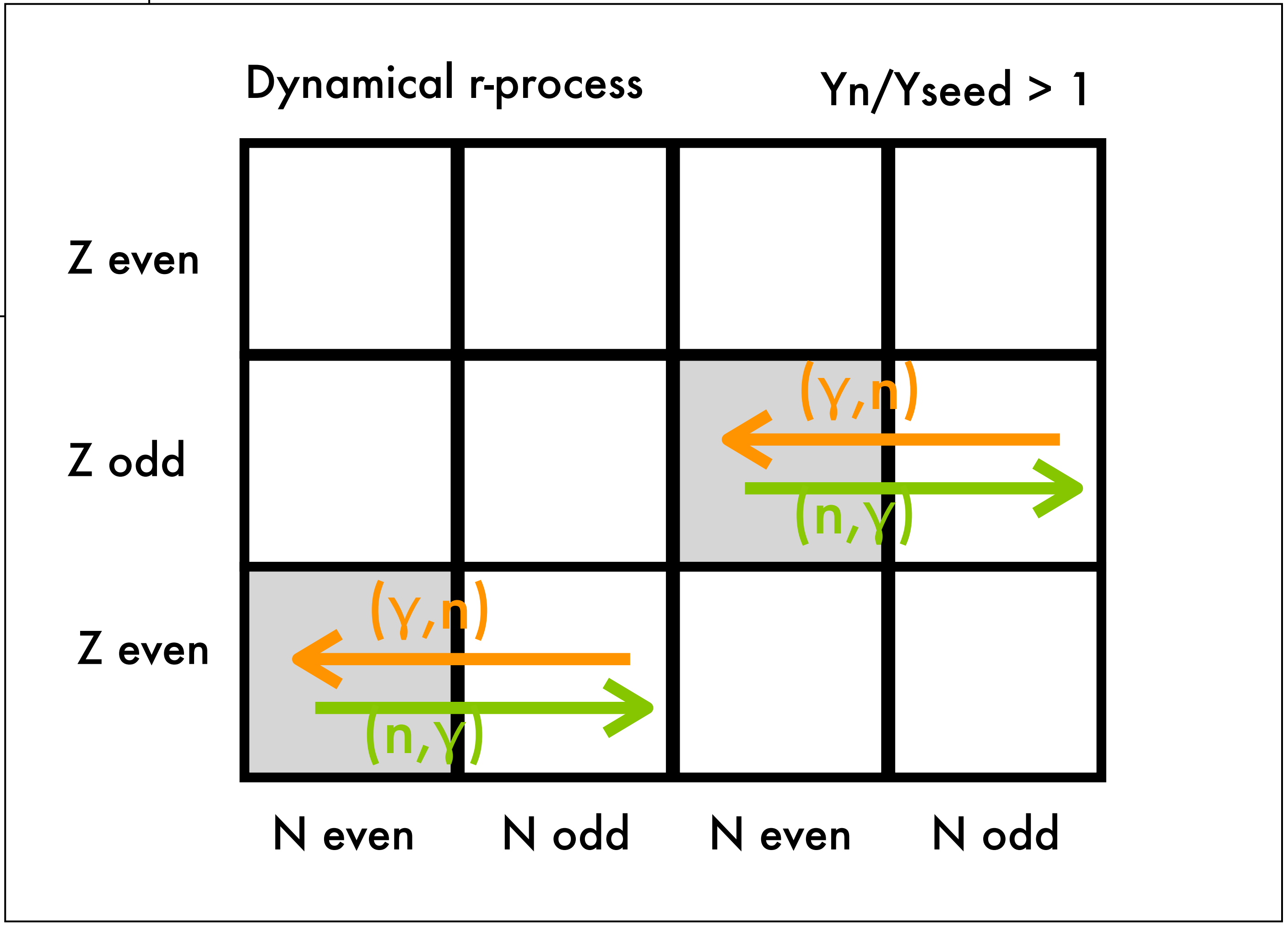
In the classical r-process (waiting point approximation) this is explained by beta delayed neutron emission (Kodama & Takahashi 1973, Kratz et al. 1993).



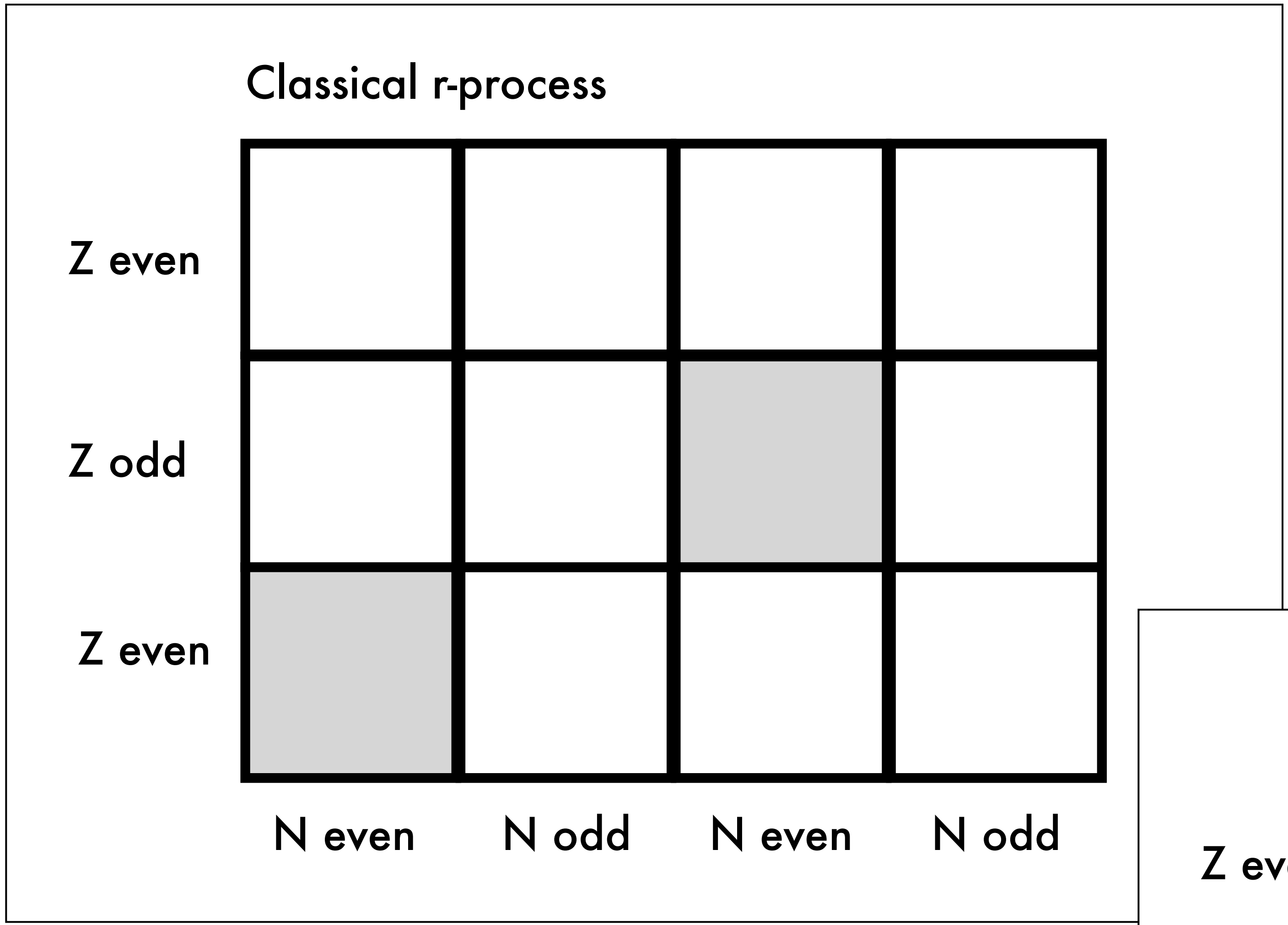
Dynamical r-process: neutron capture and beta-delayed neutron emission

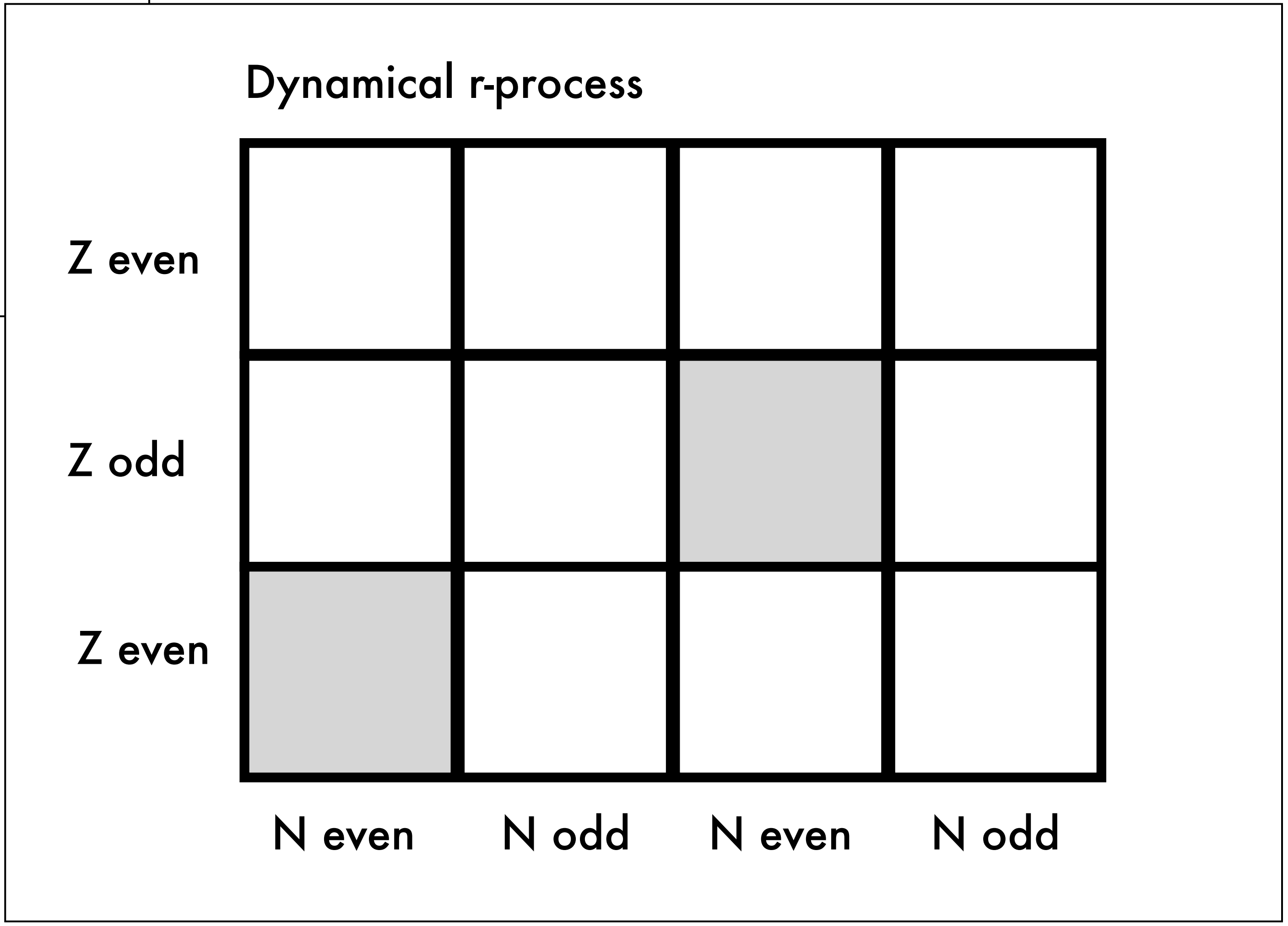
Classical vs. dynamical r-process



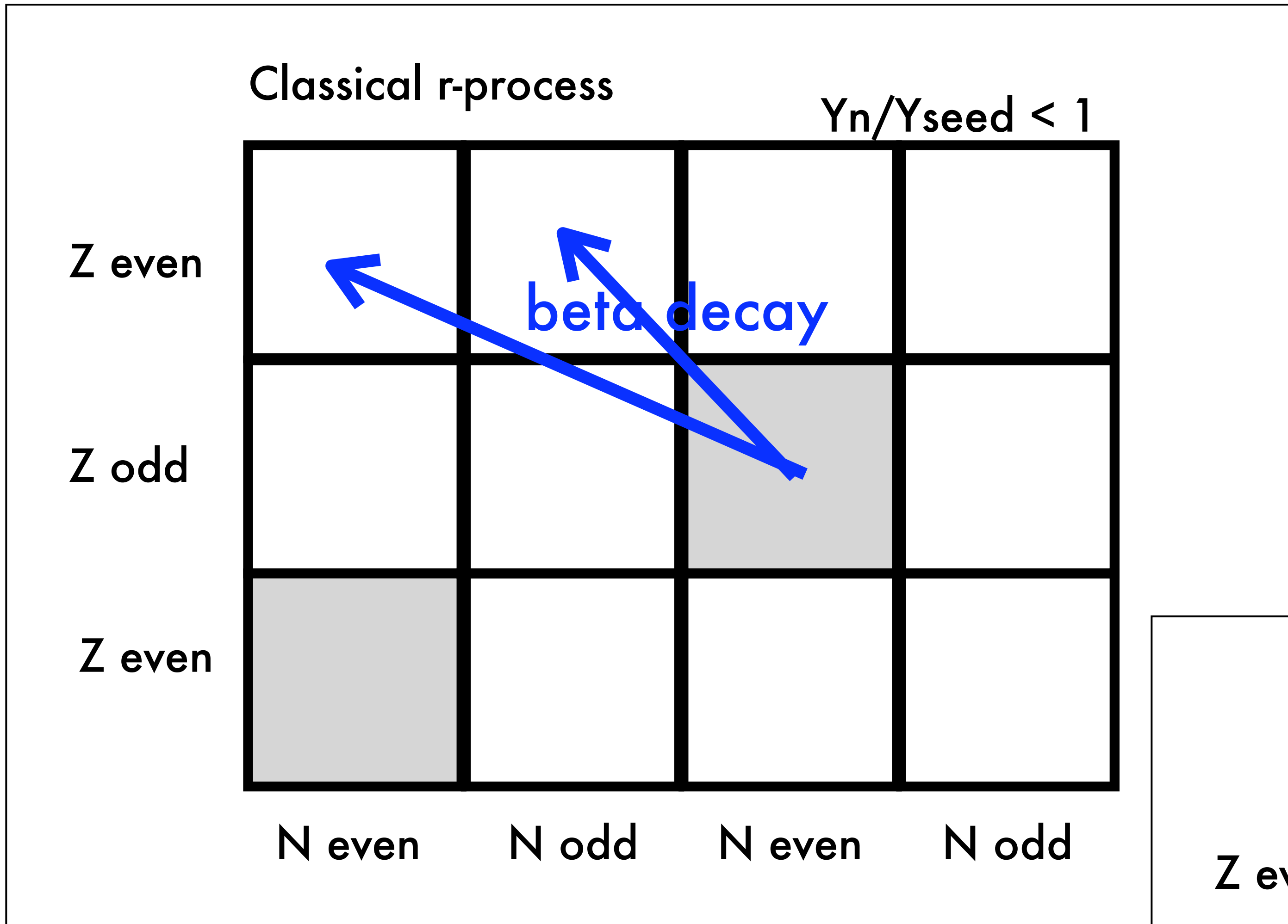


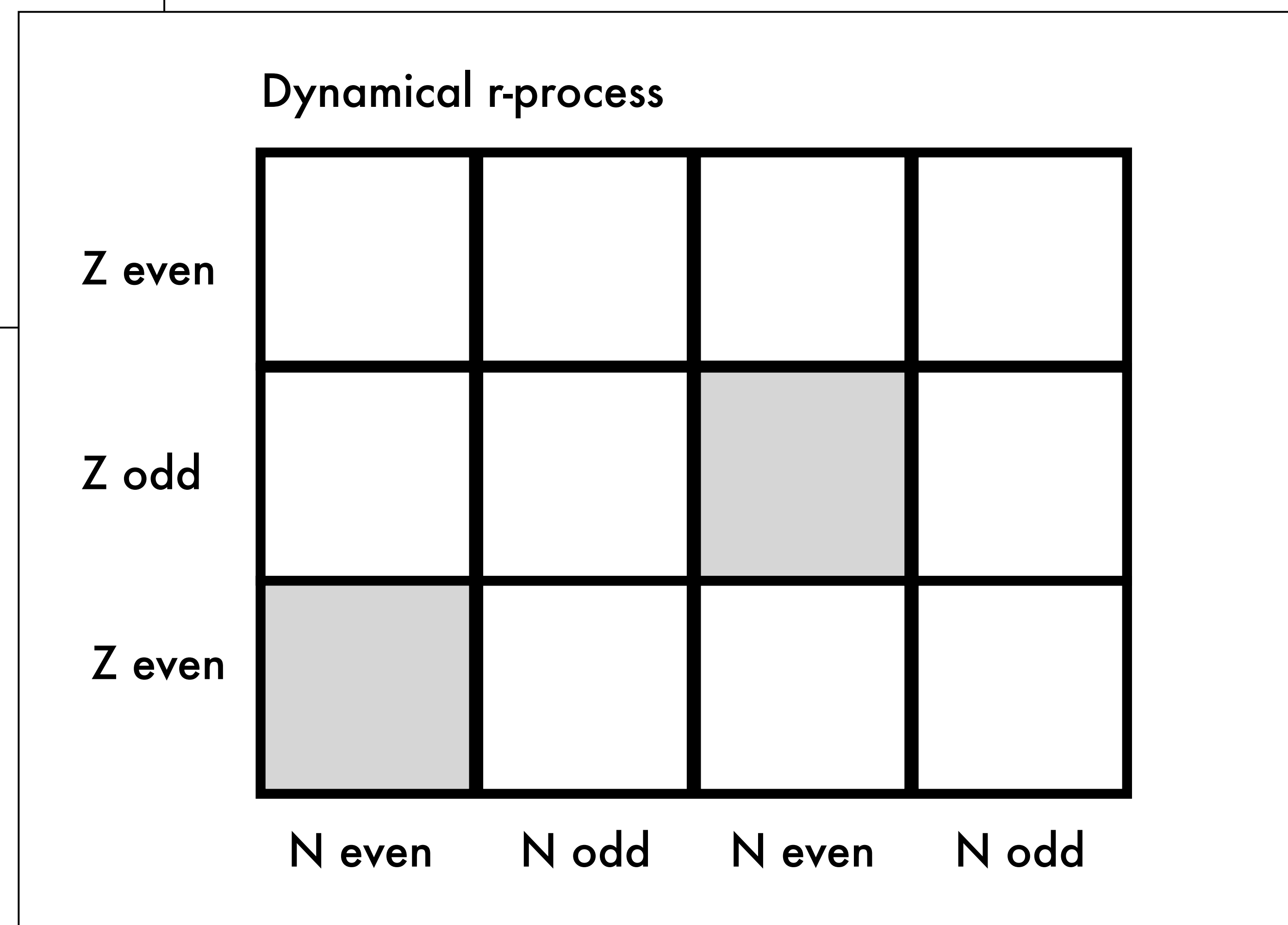
Classical vs. dynamical r-process



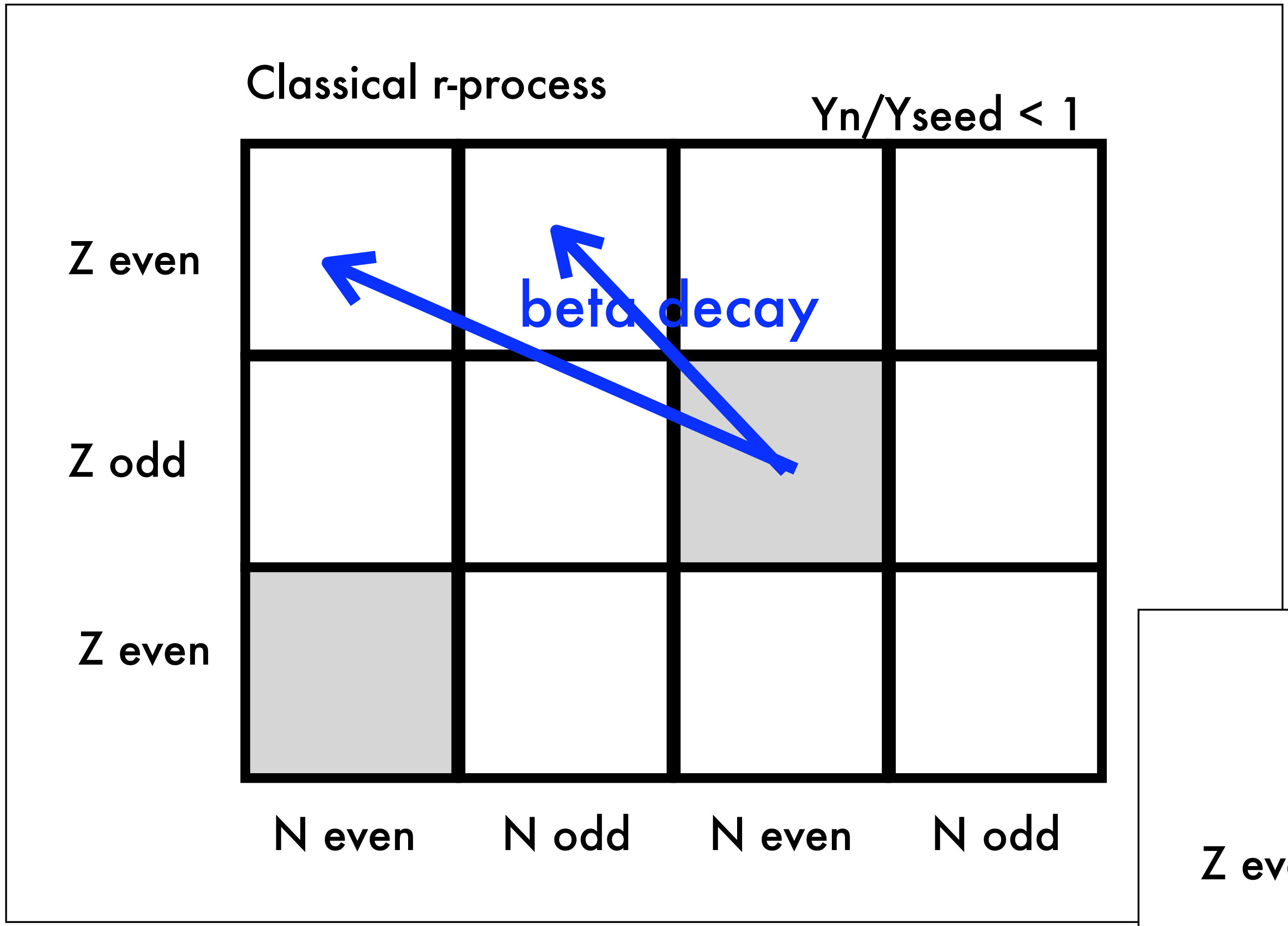


Classical vs. dynamical r-process

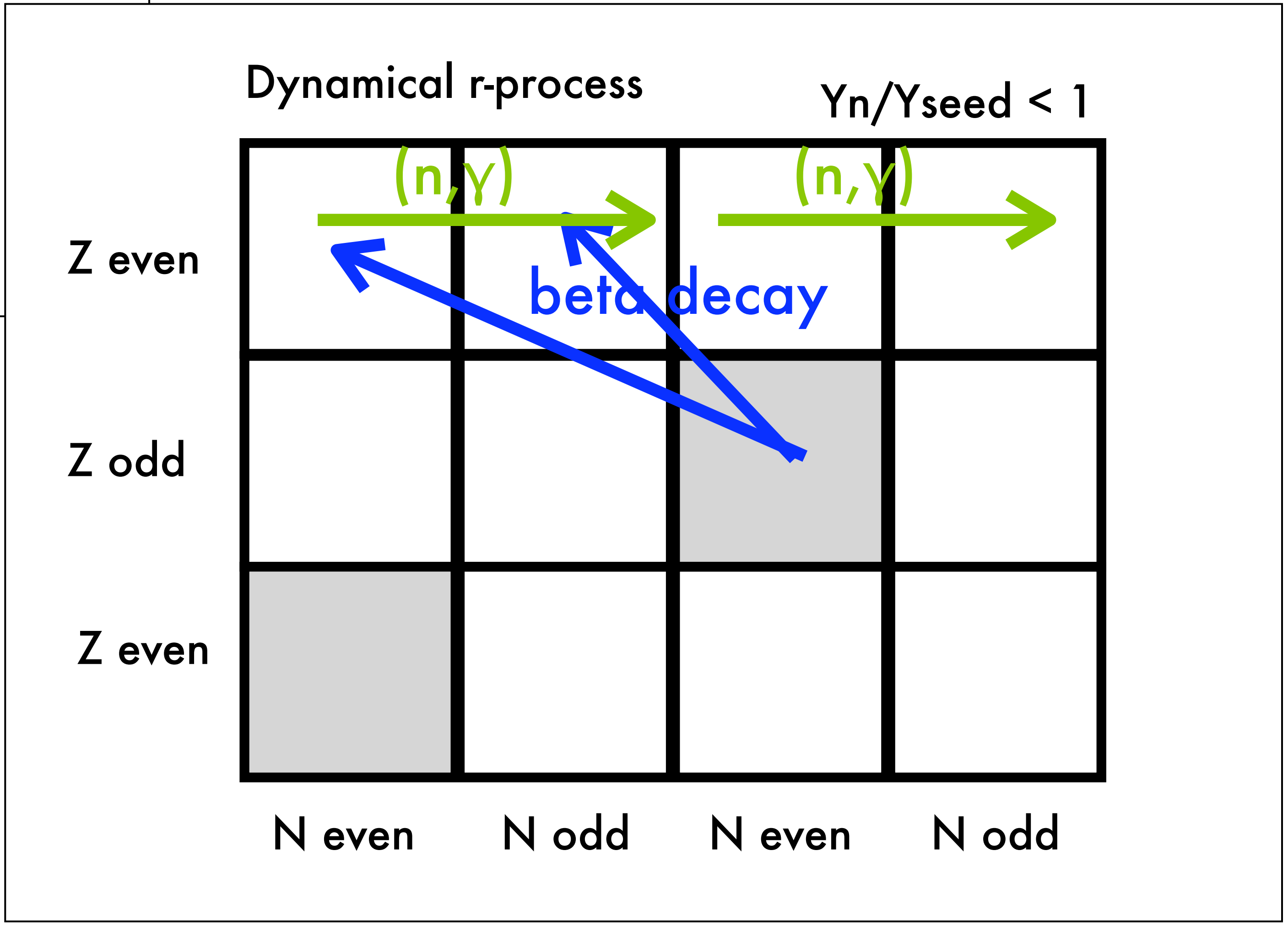




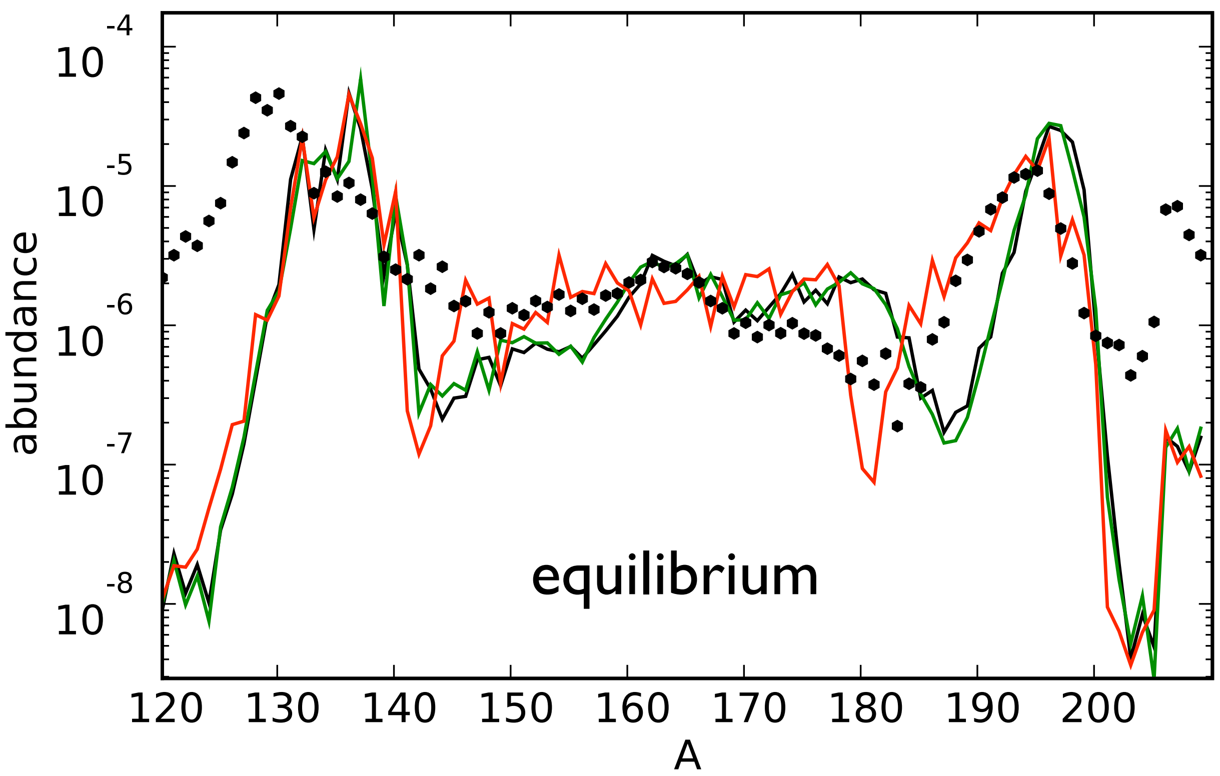
Classical vs. dynamical r-process



Neutron captures on the way back to stability determine final abundances!



Neutron captures and beta-delayed neutron emission

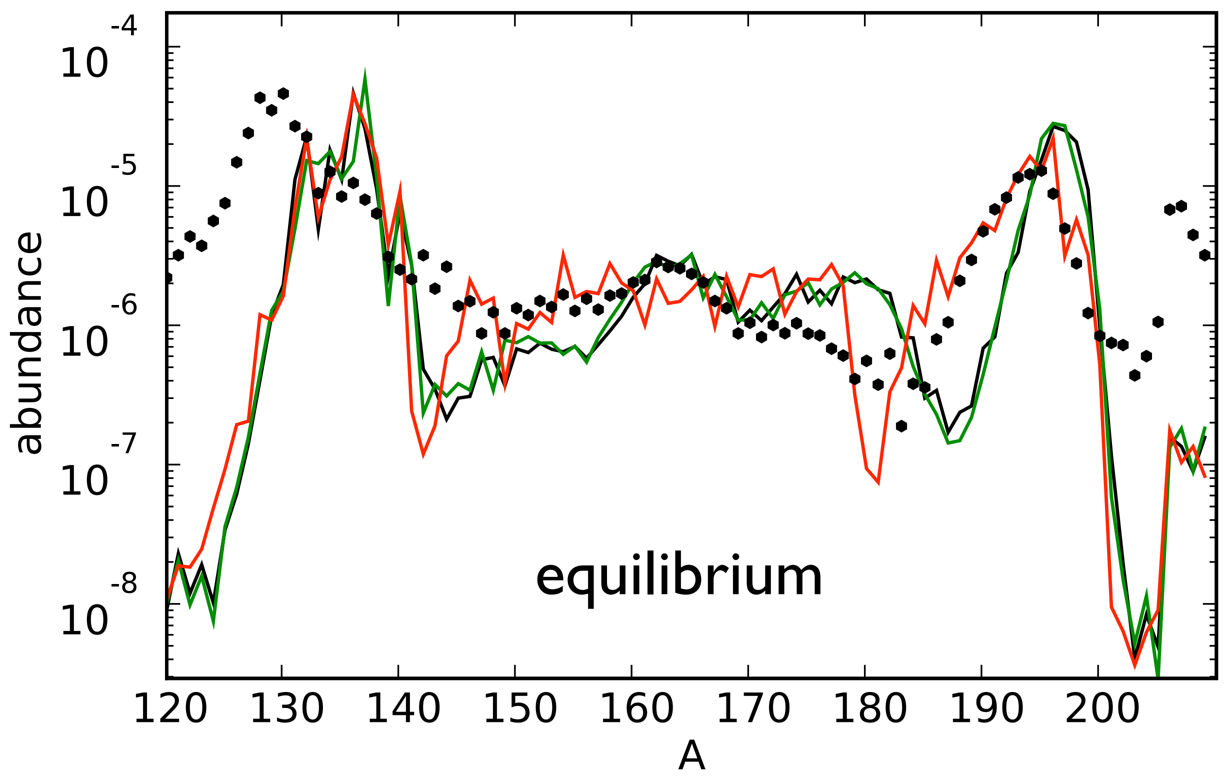


We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

Neutron captures important for the final abundances (for example A=180-190).

Arcones & Martinez-Pinedo, in prep.

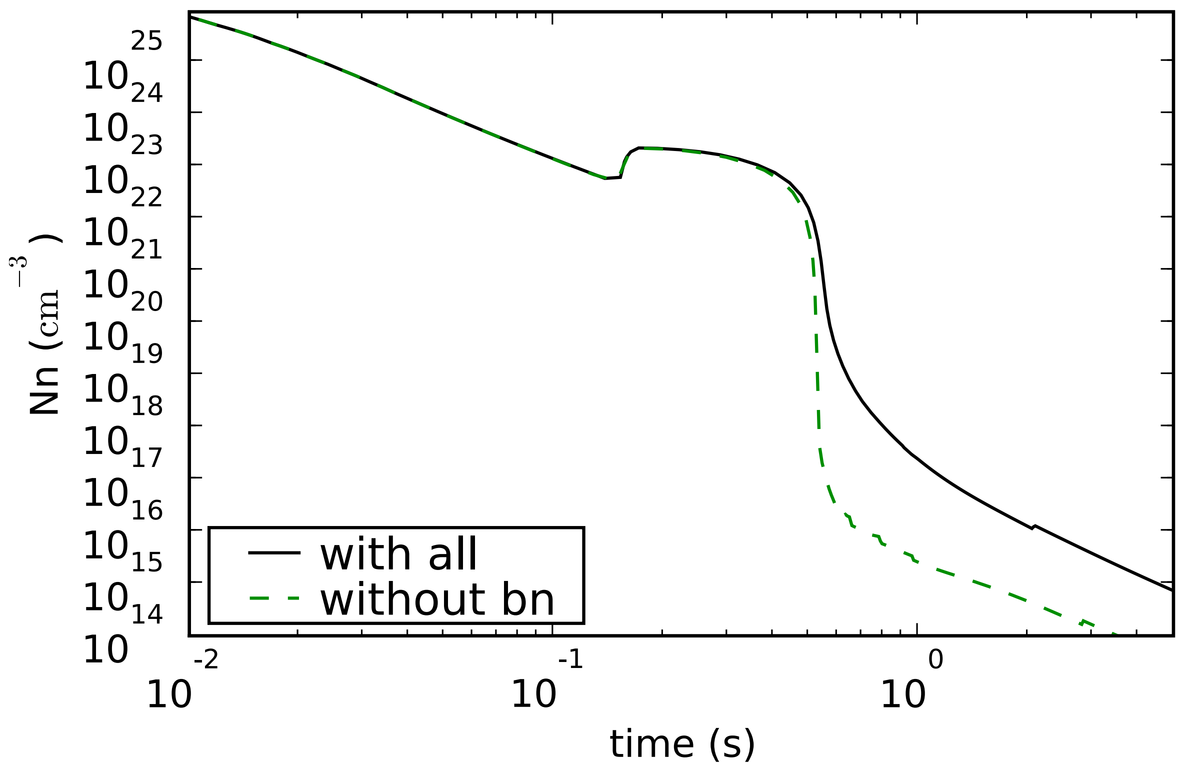
Neutron captures and beta-delayed neutron emission

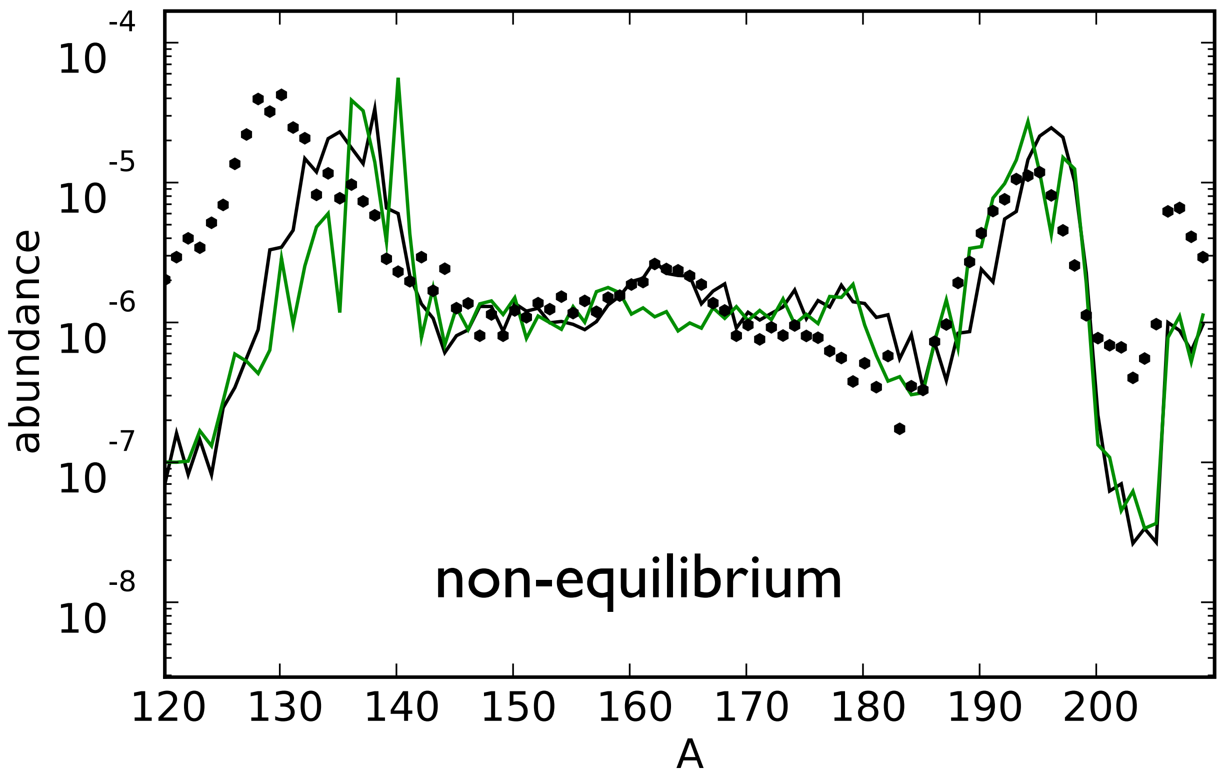


We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

Neutron captures important for the final abundances (for example A=180-190).

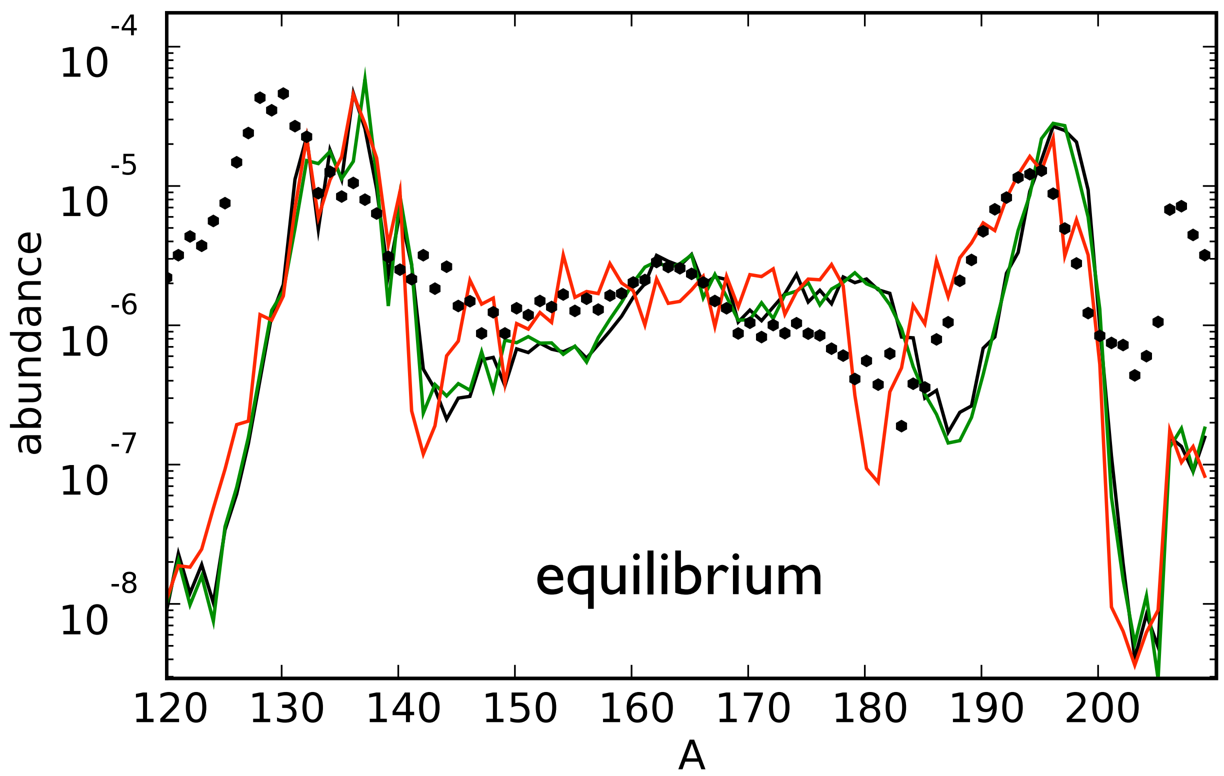
The main role of the beta-delayed neutron emission is to supply neutrons.





Arcones & Martinez-Pinedo, in prep.

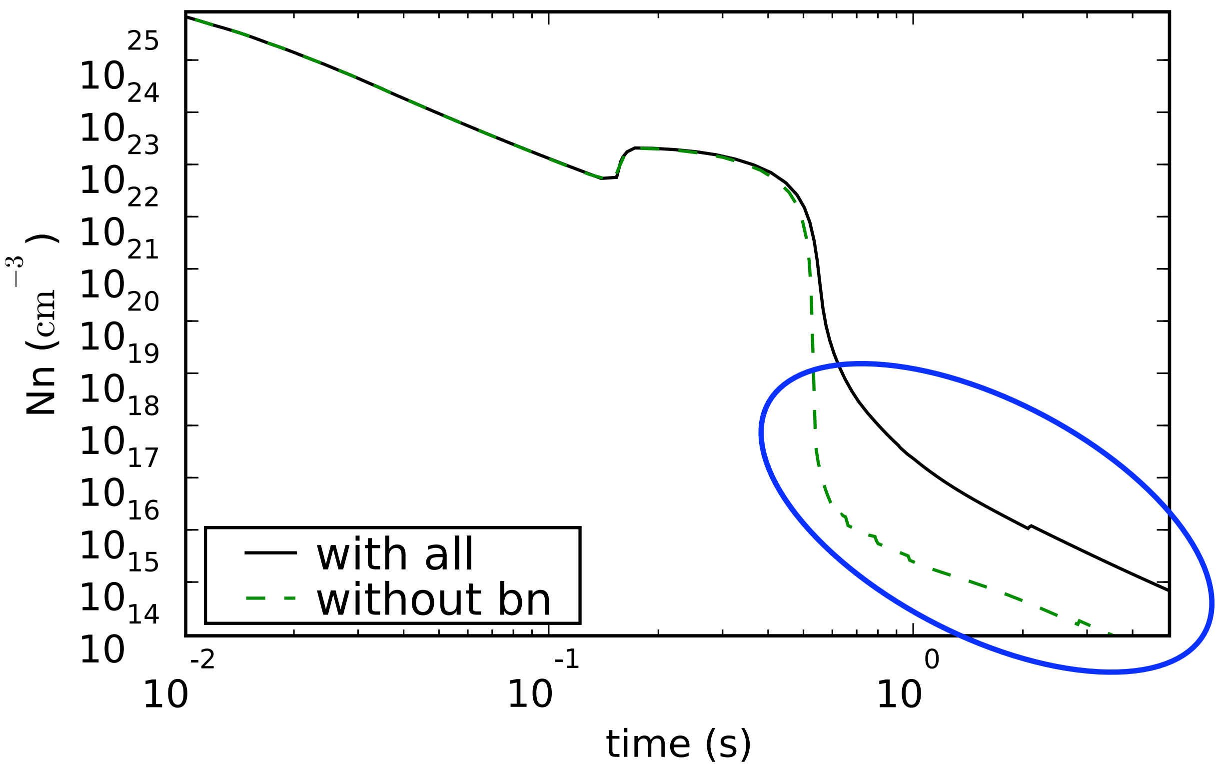
Neutron captures and beta-delayed neutron emission

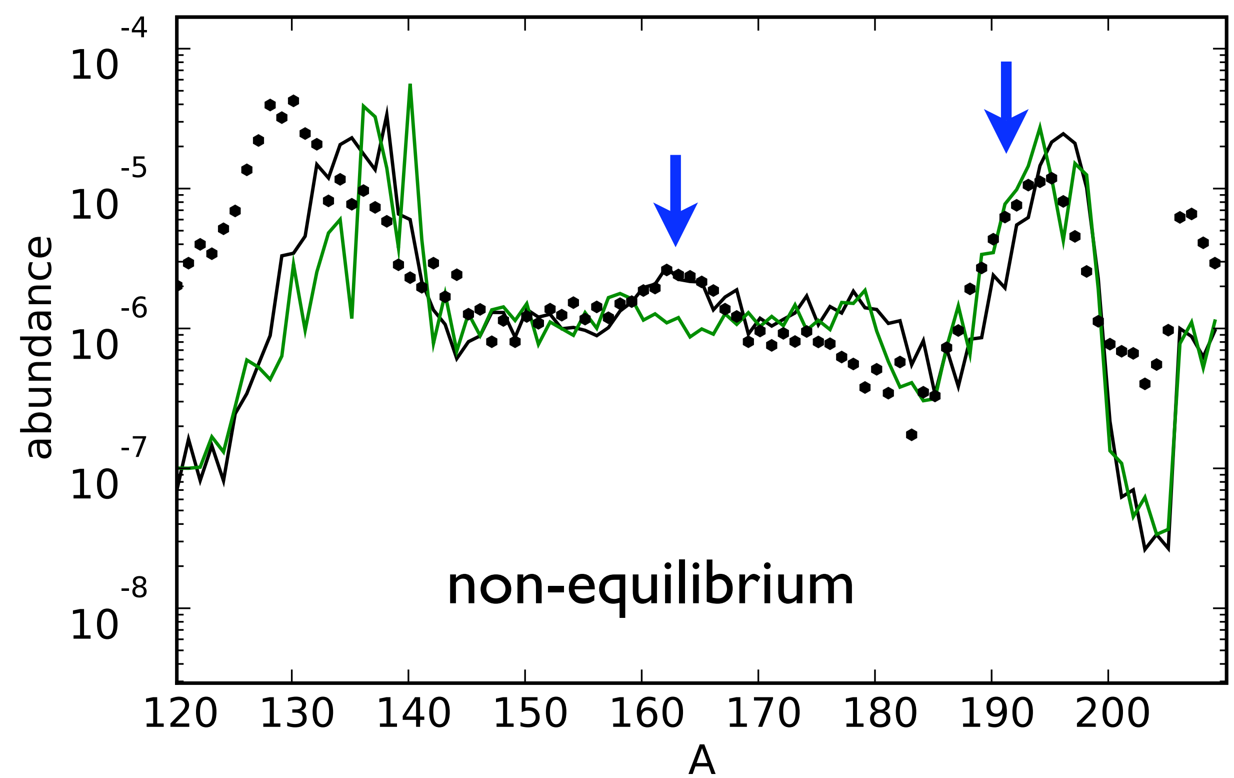


We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

Neutron captures important for the final abundances (for example A=180-190).

The main role of the beta-delayed neutron emission is to supply neutrons.

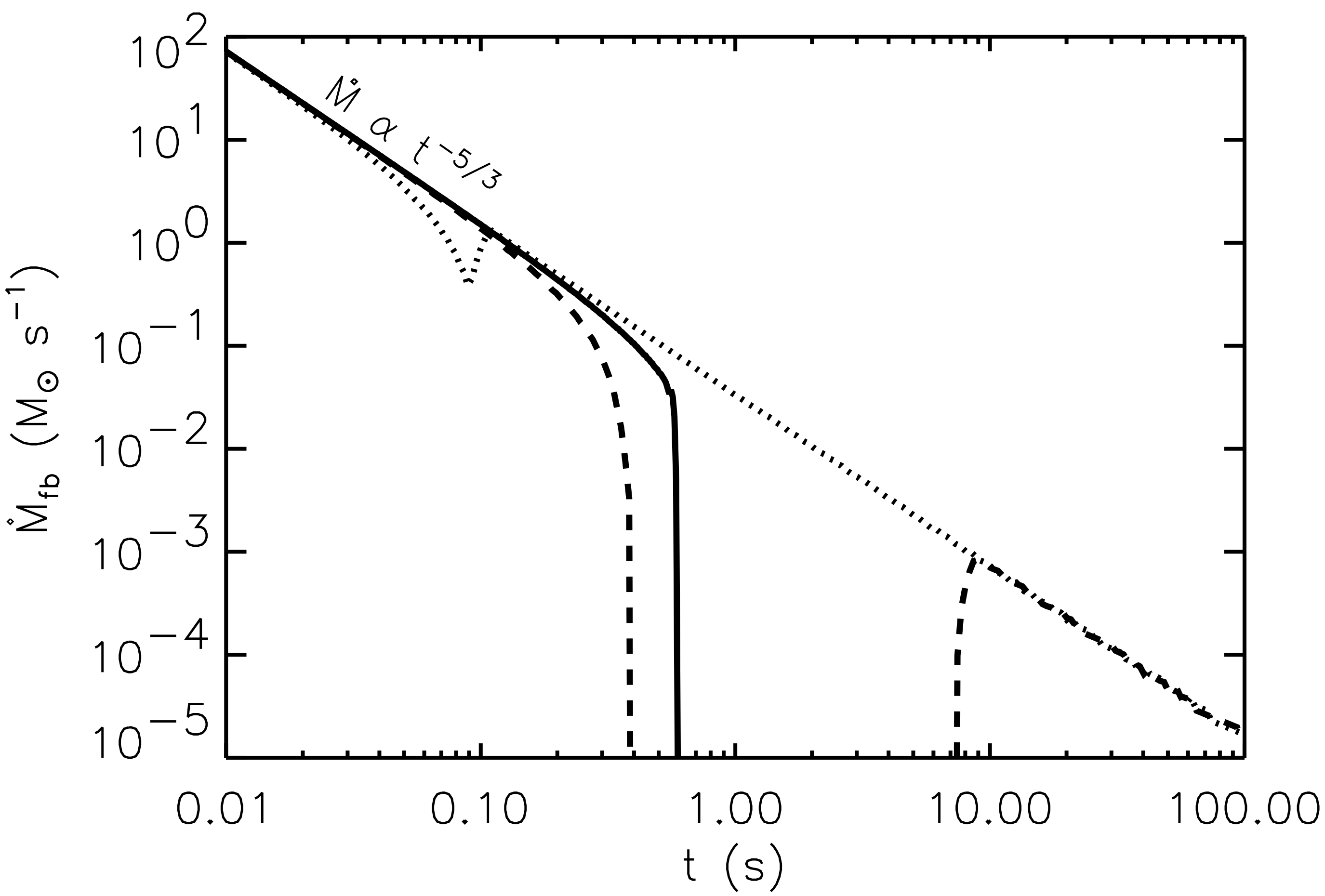


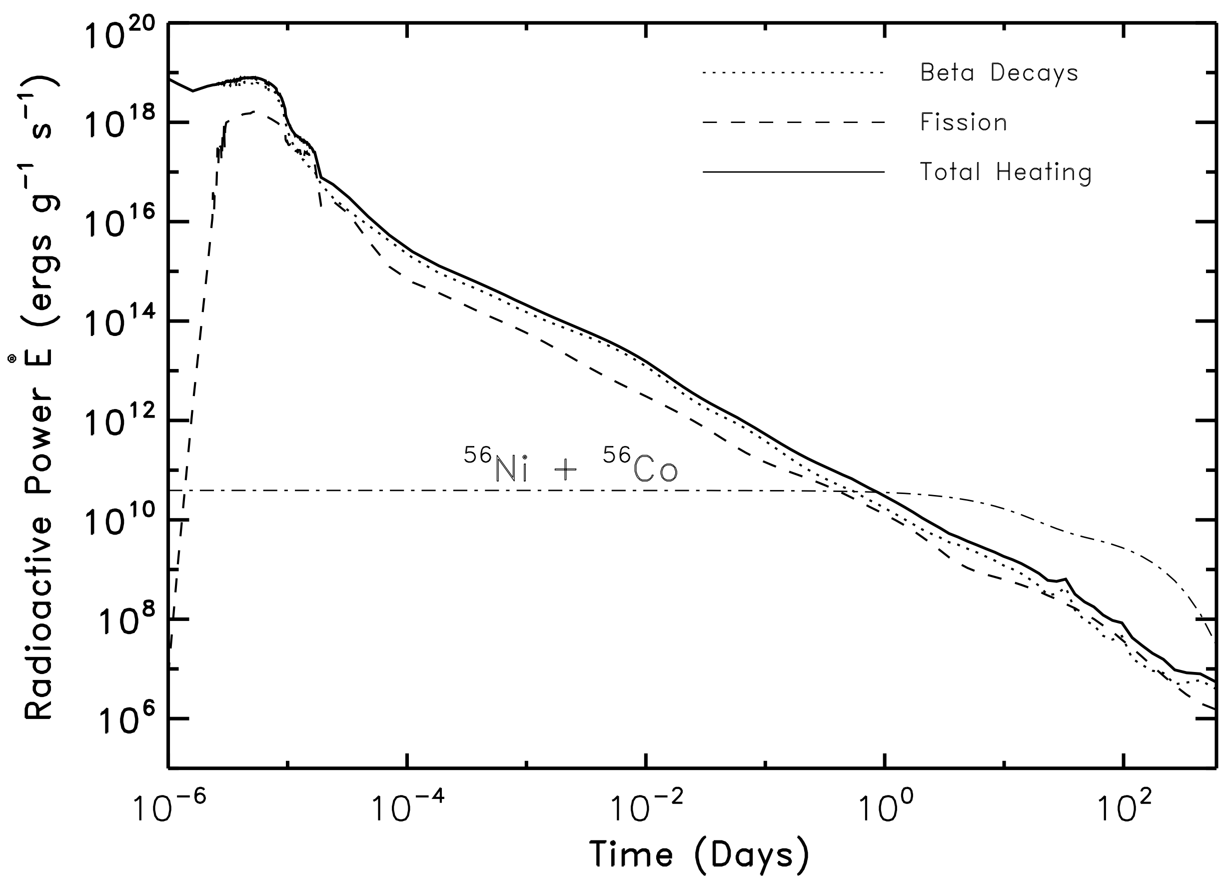


Arcones & Martinez-Pinedo, in prep.

Neutron star mergers

- The r-process takes place in neutron star mergers (Freiburghaus et al. 1999) but cannot explain the observations of halo stars (Qian 2000).
- Energy generated during the r-process affects the dynamics of the mergers and could explain late X-ray emission observed in short gamma-ray bursts (Metzger, Arcones et al.2010)
- EM emission from neutron star mergers powered by radioactive decay during the r-process. Metzger et al 2010: light curve of these "kilonova".





Conclusions

- First comparison of the LEPP pattern and nucleosynthesis calculations (Arcones&Montes, in prep.) based on hydrodynamical wind simulations (Arcones et al. 2007).
- 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 (Arcones et al. 2008).
- LEPP pattern is reproduced in neutron- and proton-rich ejecta.
- Our simulations provide a good basis to study and understand the main impact of the long-time dynamical evolution and of nuclear masses on the abundances (Arcones & Martinez-Pinedo, in prep.).
- As matter moves back to stability neutron captures are as important as beta-delayed neutron emission.
- In neutron star mergers the heating from the r-process affects the dynamics and observations (Metzger et al. 2010).

Conclusions and outlook

- First comparison of the LEPP pattern and nucleosynthesis calculations (Arcones&Montes, in prep.) based on hydrodynamical wind simulations (Arcones et al. 2007).
  → multi-dimensional simulations with detailed neutrino transport
- 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 (Arcones et al. 2008).
  → improve treatment of ν and composition. Use abundances to constrain Y_e evolution.
- LEPP pattern is reproduced in neutron- and proton-rich ejecta.
  → observations of isotopic abundances in old stars can discriminate
- Our simulations provide a good basis to study and understand the main impact of the long-time dynamical evolution and of nuclear masses on the abundances (Arcones & Martinez-Pinedo, in prep.). → experiments for masses, improve theoretical models
- As matter moves back to stability neutron captures are as important as beta-delayed neutron emission. → explore the impact of beta decays
- In neutron star mergers the heating from the r-process affects the dynamics and observations (Metzger et al. 2010). → simulations of neutron star merger including r-process heating

Conclusions and outlook

- First comparison of the LEPP pattern and nucleosynthesis calculations (Arcones&Montes, in prep.) based on hydrodynamical wind simulations (Arcones et al. 2007).
  → multi-dimensional simulations with detailed neutrino transport
- 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 (Arcones et al. 2008).
  → improve treatment of ν and composition. Use abundances to constrain Y_e evolution.
- LEPP pattern is reproduced in neutron- and proton-rich ejecta.
  → observations of isotopic abundances in old stars can discriminate
- Our simulations provide a good basis to study and understand the main impact of the long-time dynamical evolution and of nuclear masses on the abundances (Arcones & Martinez-Pinedo, in prep.). → experiments for masses, improve theoretical models
- As matter moves back to stability neutron captures are as important as beta-delayed neutron emission. → explore the impact of beta decays

- In neutron star mergers the heating from the r-process affects the dynamics and observations (Metzger et al. 2010). → simulations of neutron star merger including r-process heating

Thank you
I. Borzov, C. Frölich, H.-Th. Janka, K. Langanke, G. Martinez-Pinedo, B. Metzger,
F. Montes, E. Quataert, L.F. Roberts, K.-F. Thielemann, S. Woosley